

An artistic illustration of space exploration. In the foreground, a large, brown, hexagonal structure, resembling a space station or a large satellite component, is shown in a partially open or deployed state. It has a metallic, reflective surface. To its right, a smaller, more complex structure with solar panels is visible. The background is a vast, dark space filled with swirling nebulae, a bright orange sun with rays, a small blue planet, and a large, detailed spiral galaxy. The overall style is painterly and dramatic, with a focus on the textures of the celestial bodies and the metallic surfaces of the spacecraft.

HWO Japan Science Workshop 2

Proceedings

15-16 July 2026

ISAS/JAXA, Japan

HWO-J July 2026 Workshop Foreword

On July 15 and 16, 2026, more than 100 Japan-based scientists attended, either in person or online, a workshop held at ISAS/JAXA to explore Japanese participation in the Habitable Worlds Observatory (HWO). The workshop goals were:

1. Strengthen and connect the Japanese HWO science and instrumentation community
2. Explore Japanese science interests to guide Japan's instrument and science contributions to HWO
3. Foster collaboration across science, instrumentation, and ground- and space-based astronomy
4. Prepare the Japanese community for future international HWO collaborations

The breadth of interest was strong, but we have a lot of opportunities to explore how to expand this to a much greater community. A key conclusion was the need to maximize the potential for transformative exoplanet research while ensuring that the broader revolutionary astrophysics enabled by HWO is fully understood across the Japanese community. Noteworthy was the interest from both the Japanese-based solar-system and planetary-defense communities, with presentations on both areas at the meeting.

In attendance and serving on the panel discussion on the future coordination and plans of HWO-J were ISAS/JAXA Director General Fujimoto-san and NAOJ Director General Doi-san. The panel also included Ouchi-san, Seki-san, Ueno-san and Kusakabe-san, and was moderated by Packham-san. The workshop was opened by Sumi-san, who placed the meeting within the broader development context of HWO. This context was then presented in greater depth by the HWO Deputy Principal Architect, Dr. Sitarski. Numerous review talks and contributed presentations were delivered by participants, followed by lively questions and discussion. The science cases contained in the existing Science Case Definition Documents (SCDDs) were reviewed to give participants a comprehensive understanding of current HWO science plans, and the workshop sessions were structured around the themes represented in those documents. Finally, Subaru Telescope Director Miyazaki-san provided a summary of the workshop and brought the event to a close.

Japan's existing facilities—including the Subaru 8.2 m Telescope and its heritage of space-based observatories—together with its broad academic base, world-leading industries, and enthusiastic HWO-J community, were clearly demonstrated. We look forward to continued engagement and deeper connections with the HWO partnership as we explore the universe with the unprecedented capabilities afforded by HWO.

We thank ISAS/JAXA for hosting the meeting and NAOJ for providing travel support. The HWO engineering concept shown on the front cover is based on imagery provided by NASA's Goddard Space Flight Center.

HWO-J Workshop 2 SOC/LOC, August 2026

HWO-J Workshop 2 SOC/LOC Members

Takahiro Sumi (Osaka University, Chair)

Masahiro Ikoma (ABC, Co-chair)

Shohei Aoki (The University of Tokyo)

Keigo Enya (JAXA)

Yuichi Harigane (The University of Tokyo)

Yuichi Ito (ABC)

Shingo Kameda (Rikkyo University)

Satoshi Miyazaki (NAOJ)

Masami Ouchi (NAOJ / The Uni. of Tokyo)

Chris Packham (UT San Antonio)

Fuminori Tsuchiya (Tohoku University)

Toru Yamada (JAXA)

Atsushi Yamazaki (JAXA)

Go Murakami (JAXA)



Group photograph of in-person participants at ISAS/JAXA, 15 July 2026.

Workshop WWW site: <https://sites.google.com/view/hwo-j-sws2/>

HWO-J Workshop 2 Registered Participants

Akihiko Fukui	Arihiro Kamada	Breann Sitarski
Chris Packham	Go Murakami	Haruka Kusakabe
Hibiki Yama	Hideki Umehata	Hideo Sagawa
Hiroki Harakawa	Ichi Tanaka	Janice Lee
Jared Landry	John Christopher Coulter	John Schneider
Kanako Seki	Kazuki Daikuhara	Kazuo Yoshioka
Keigo Enya/塩谷圭吾	Kento Masuda	Kimihiko Nakajima
Kosuke Kushibiki	Kouchiro Nakanishi	Makoto Yoshikawa
Mamoru Doi 土居 守	Mariko Kubo	Masafusa Onoue
Masahiro Takada	Masami Ouchi	Masashi Omiya
Masayuki Kuzuhara (葛原昌幸)	Misato Fukagawa	Motohide Tamura
Olivier Guyon	Rieko Momose	Satoshi Miyazaki
Shin Watanabe	Shingo Kameda	Sho Sasaki
Shota Miyazaki	Soma Yoshikawa	Stevanus Kristianto Nugroho
Taiki Kawamuro	Takanori Kodama	Takashi Moriya
Takehiko Wada	Teruyuki Hirano	Toru Misawa
Vigneshwaran Krishnamurthy	YAMAZAKI Atsushi	Yao-Lun Yang
Yo Kawamura	Yoshiki Matsuoka	Yuichi Ito
Yuichiro Ueno	Yuki Hirao	中山陽史
亀谷和久	今井正亮	伊藤 哲司
伊藤孝士	住 貴宏	佐藤理究
前原 瑚菜	加藤龍雅	古賀亮一
吉川 一朗	吉田辰哉	土屋史紀
坂田遼弥	堺正太郎	多田将太郎
大符航未	宮原ひろ子	家正則
家田章正	小島礼己	小松勇
小野里宏樹	尾崎忍夫	尾崎和海
山本和弘	山田亨	川島 由依
成田憲保	播金優一	新井千紘
本田充彦	村上 尚史	東田拓斗
松尾太郎	桑原正輝	桑田敦基
森万由子	森下貴弘	榎木谷 海
樋口太郎	永井 誠	滝澤謙二
狩生宏喜	生田ちさと	生駒大洋
田中匠	田村隆幸	秋田谷 洋
米田 謙太	能勢千鶴	藤田麻誉
西岡 知輝	西川 淳	諸隈 佳菜
諸隈智貴	谷口啓悟	近藤依央菜
野津 翔太	野津湧太	鈴木悠太
青木翔平	鳥海 森	齋藤 正雄

Day 1 - Wednesday, 15 July 2026

Opening Session

Towards the Habitable Worlds Observatory

09:15-09:45 | Breann Sitarski (NASA HQ/GSFC, Remote)

Abstract and slides not available

HWO CSIT: Progress, Priorities, and Mission Context

09:45-10:10 | Chris Packham (UT San Antonio)

[Abstract p. 9](#) [Slides p. 10](#)

Overview of HWO Science and Case Development

10:10-10:35 | Janice Lee (STScI)

[Abstract p. 30](#) [Slides p. 31](#)

Session 1 - Japanese Instrumental Contributions to HWO

Report from the ISAS HWO Task Force: Japan's Potential Contribution to HWO and its Coronagraph

10:55-11:10 | Keigo Enya (JAXA/ISAS)

[Abstract p. 82](#) [Slides p. 83](#)

Current Status of UV Technology Development towards the Habitable Worlds Observatory

11:10-11:25 | Shingo Kameda (Rikkyo University)

[Abstract p. 104](#) [Slides p. 105](#)

Session 2 - Evolution of the Elements

Review on the Science Theme "Evolution of the Elements"

11:25-11:50 | Takashi Moriya (NAOJ)

[Abstract p. 122](#) [Slides p. 123](#)

Cosmology with HWO

11:50-12:15 | Masahiro Takada (Kavli IPMU)

[Abstract p. 147](#) [Slides p. 148](#)

Session 3 - Galaxy Growth (Part I)

Galaxy Observations Toward Future Studies with the Habitable Worlds Observatory

13:45-14:10 | Masami Ouchi (NAOJ / UTokyo)

[Abstract p. 170](#) [Slides p. 171](#)

Session 4 - Living Worlds (Part I)

Living Worlds Overview (Tentative)

14:10-14:35 | Kenji Takizawa (ABC)

[Abstract p. 207](#) [Slides p. 208](#)

How Planets Make Life?: Emergence and Evolution of Living Systems

14:35-15:10 | Yuichiro Ueno (Institute of Science Tokyo)

Abstract and slides not available

Day 1 - Wednesday, 15 July 2026

Session 5 - Solar Systems in Context (Part I)

Review of Exoplanet Characterisation in HWO SCDD

15:40-15:55 | Yuichi Ito (ABC/NAOJ)

[Abstract p. 229](#) [Slides p. 230](#)

Review of Solar System Science Cases in the HWO SCDD

15:55-16:10 | Shohei Aoki (UTokyo)

[Abstract p. 242](#) [Slides p. 243](#)

Atmospheric Evolution of Terrestrial Planets under Stellar Forcing: Solar System Lessons for HWO

16:10-16:35 | Kanako Seki (RCAST, UTokyo)

Abstract and slides not available

Day 2 - Thursday, 16 July 2026

Session 6 - Instrumentation for HWO

Efficient NIR Spectroscopy of Habitable Planets: Concept and Technology Validation Plan with Subaru Telescope

09:00-09:15 | Olivier Guyon (Subaru Telescope)

[Abstract p. 254](#) [Slides p. 255](#)

The Coronagraph Instrument for the Nancy Grace Roman Space Telescope

09:15-09:30 | Naoshi Murakami (ABC)

[Abstract p. 273](#) [Slides p. 274](#)

Key Technology Developments on UV Instrumentation for LAPYUTA and HWO

09:30-09:45 | Go Murakami (JAXA)

Abstract and slides not available

Development of Astro-Photonic Integrated Circuits for Direct Imaging of Exoplanets

09:45-10:00 | Reiki Kojima (Nagoya University)

[Abstract p. 286](#) [Slides p. 287](#)

A Bar-coronagraph with a Small Inner Working Angle: The One-dimensional Diffraction-limit Coronagraph (1DDL)

10:00-10:15 | Satoshi Ito (U of Osaka)

[Abstract p. 294](#) [Slides p. 295](#)

Session 7 - Galaxy Growth (Part II)

Galaxy Evolution with HWO: Exploring the First Enriched Worlds

10:45-11:10 | Takahiro Morishita (Tohoku University)

[Abstract p. 308](#) [Slides p. 309](#)

UV-to-NIR Spectroscopy with HWO: Connecting High-Redshift and Local Galaxy Evolution

11:10-11:25 | Kimihiko Nakajima (Kanazawa University)

[Abstract p. 327](#) [Slides p. 328](#)

Day 2 - Thursday, 16 July 2026

Session 7 - Galaxy Growth (Part II)

Fossil Records of Massive Black Hole Seeds Probed by HWO

11:25-11:40 | Masafusa Onoue (Waseda University)

[Abstract p. 345](#) [Slides p. 346](#)

Session 8 - Living Worlds (Part II)

Importance of the 1.6 μm CO Absorption Feature for Future Direct Imaging of Earth-like Planets

11:40-11:55 | Yui Kawashima (Kyoto University)

[Abstract p. 364](#) [Slides p. 365](#)

Ocean Color as an Observational Indicator of Surface Oceans on Exoplanets

11:55-12:10 | Chihiro Arai (U of Osaka)

[Abstract p. 371](#) [Slides p. 373](#)

Session 9 - Planetary Defense

Planetary Defense and Space Telescopes

13:25-13:50 | Makoto Yoshikawa (JAXA)

[Abstract p. 393](#) [Slides p. 394](#)

Session 10 - Living Worlds (Part II continued)

Ultra-Doppler: How to Detect the Nearby Earth-twins for HWO?

13:50-14:05 | Motohide Tamura (ABC/UTokyo)

Abstract and slides not available

Next-Generation Climate Modeling for Habitable Worlds

14:05-14:20 | Takanori Kodama (Institute of Science Tokyo)

[Abstract p. 426](#) [Slides p. 427](#)

Strong Control of Ice Cover on Exo-terrestrial Planets by Continentally Constrained Ocean Circulation

14:20-14:35 | Taro Higuchi (Institute of Science Tokyo)

[Abstract p. 449](#) [Slides p. 451](#)

Long-Term Water Redistribution and Observable Habitability on a Tidally Locked Terrestrial Planet

14:35-14:50 | Arihiro Kamada (Institute of Science Tokyo)

[Abstract p. 466](#) [Slides p. 467](#)

The Detectability of Escaping Atmosphere from Terrestrial Exoplanets in Runaway Greenhouse State by Ultraviolet Transit Spectroscopy

14:50-15:05 | Ryuga Kato (Rikkyo University)

[Abstract p. 480](#) [Slides p. 481](#)

Exoplanet atmospheres and escape in the HWO era: What JWST is teaching us

15:05-15:20 | Vigneshwaran Krishnamurthy (Tohoku University)

[Abstract p. 499](#) [Slides p. 500](#)

Day 2 - Thursday, 16 July 2026

Session 11 - Solar Systems in Context (Part II)

Overview of the UV Space Telescope Mission LAPYUTA

15:40-15:55 | Fuminori Tsuchiya (Tohoku University)

[Abstract p. 521](#) [Slides p. 522](#)

Electron-impact C I 156.1 nm Emission as a Probe of Martian Ionospheric Variability

15:55-16:10 | Shotaro Sakai (Keio University)

[Abstract p. 533](#) [Slides p. 536](#)

From Roman to Habitable Worlds: Science Planning for the Future of Exoplanet and Disk Imaging

16:10-16:25 | Masayuki Kuzuhara (ABC)

[Abstract p. 543](#) [Slides p. 544](#)

Closing Session

Final Discussion Summary

Attendees

[Slides p. 569](#)

HWO CSIT: Progress, Priorities, and Mission Context

Chris Packham

Lead author: Chris Packham

Abstract: I present the status and activity of the HWO Community Science and Instrumentation Team. The purpose of the team is to work closely with the HWO Technology Maturation Project Office (TMPO) to help mature HWO technologies and mission concept, in preparation for the Mission Concept Review (MCR). I discuss how CSIT members execute scientific studies to support the definition of a baseline mission concept, analyze potential science instruments, and provide input to HTMPO. Finally I stress how CSIT members serve as ambassadors to the broader science and technology communities.



National Aeronautics and
Space Administration

Habitable Worlds Observatory's Community Science & Instrument Team

Chris Packham

UT at San Antonio & NAOJ Visiting Professor
CSIT Member, Gemini Board Chair

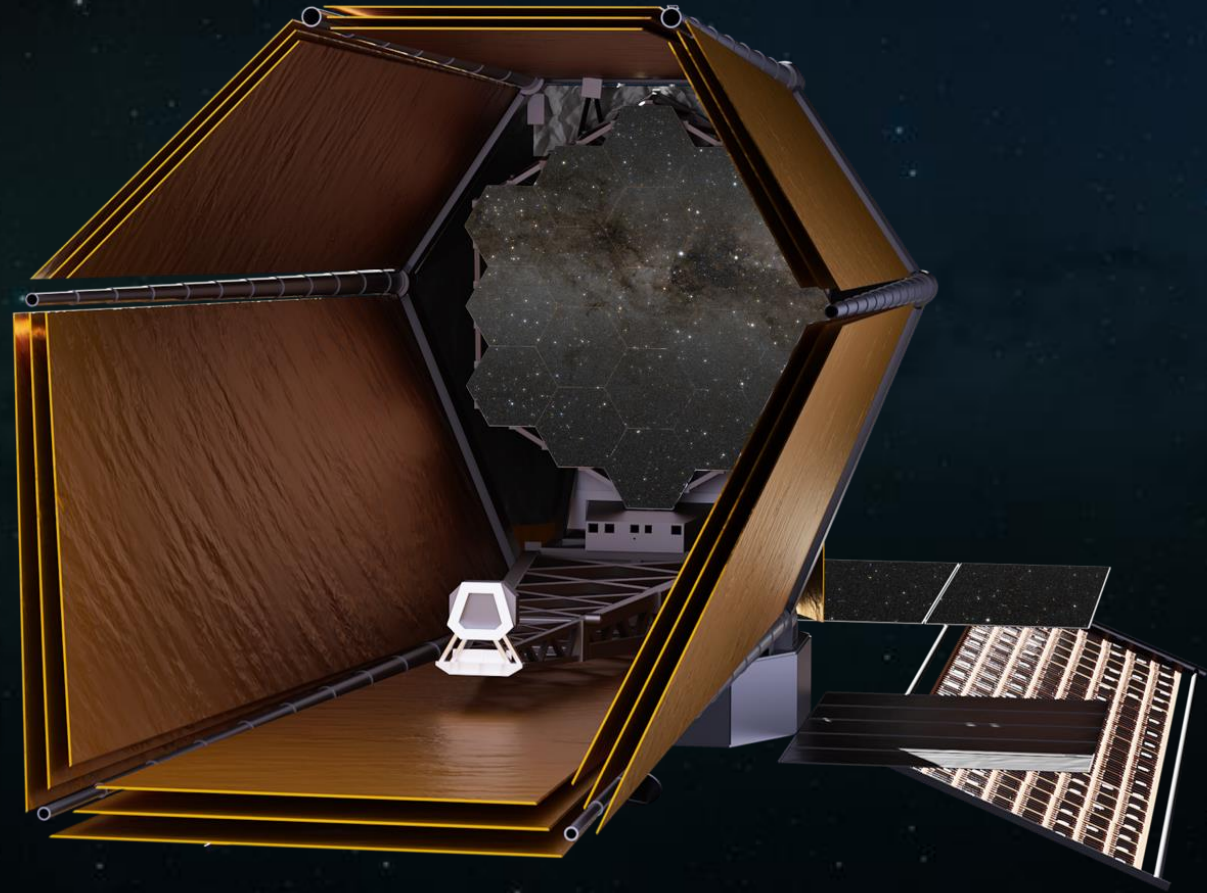
Slides kindly provided by CSIT Chairs Shkolnik & Charbonneau

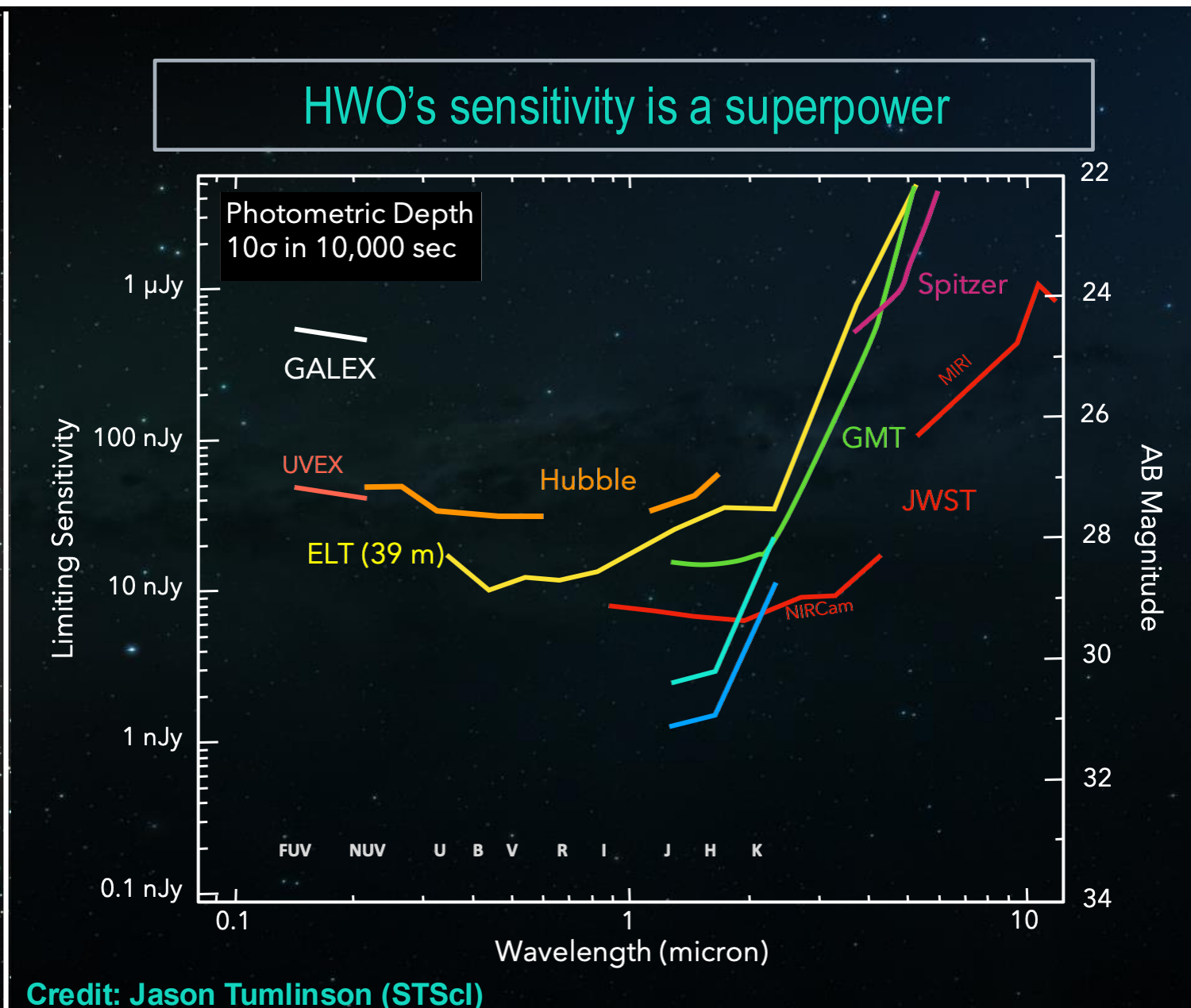


National Aeronautics and
Space Administration

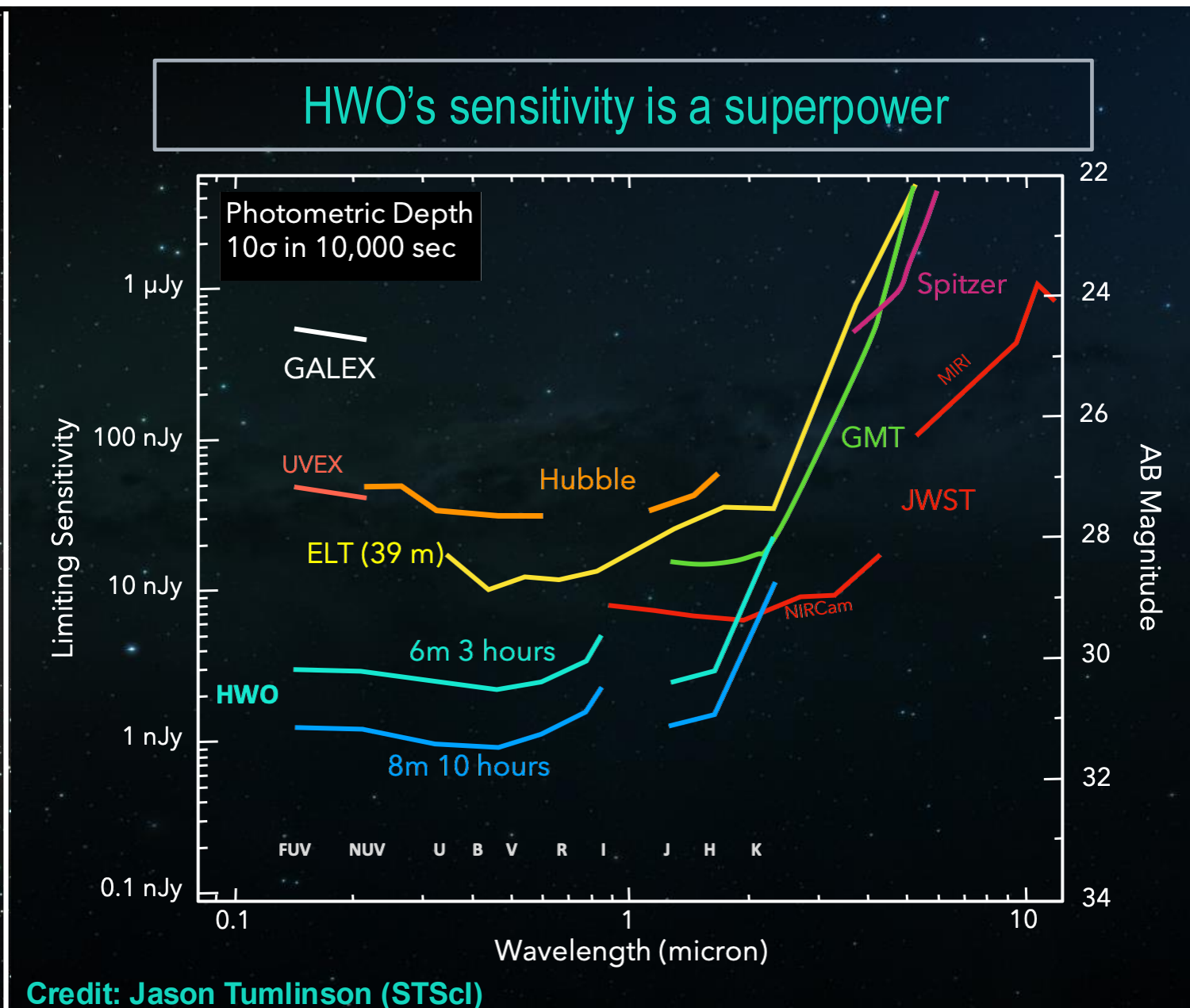
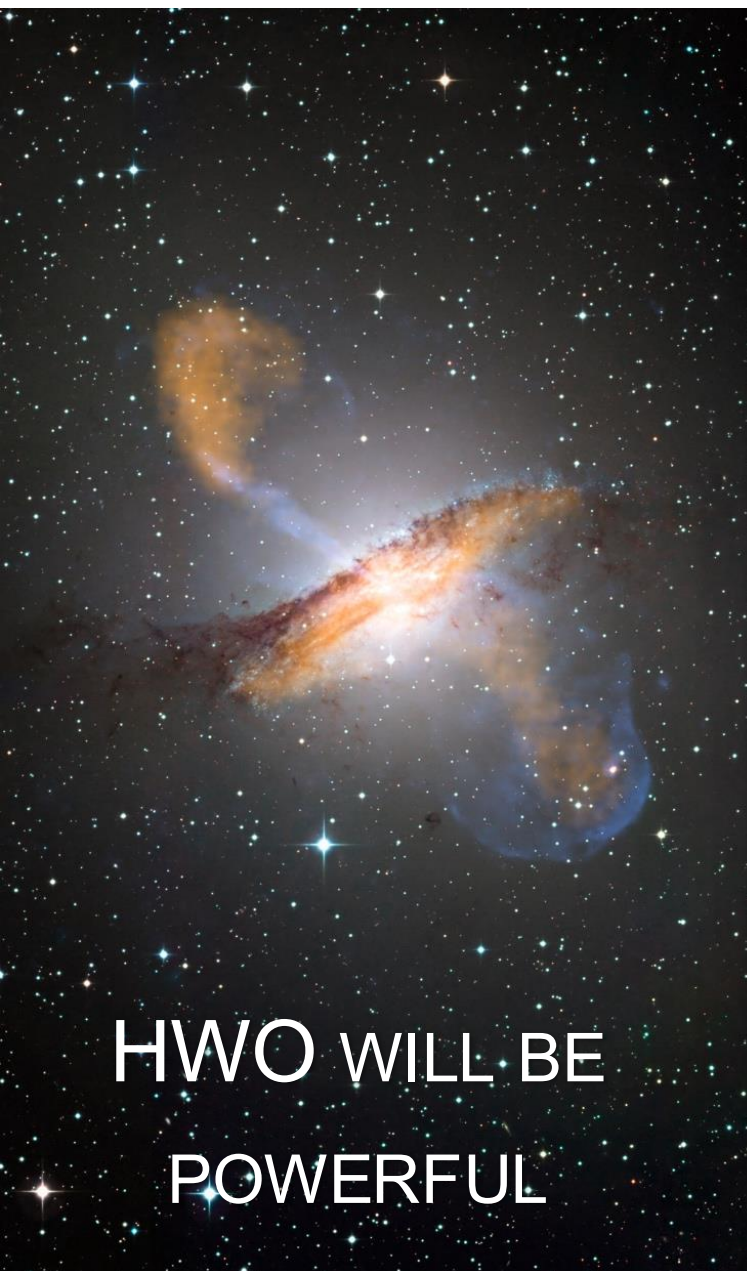
HWO is NASA's next flagship
mission concept
recommended by Astro2020
Decadal Survey

Large-aperture
UV / Optical / NIR space telescope
for transformative astrophysics and
the first designed to search for
signs of life on exoplanets





Credit: Jason Tumlinson (STScI)



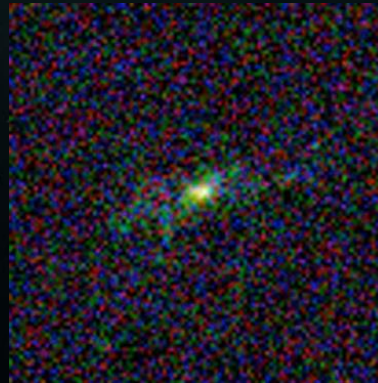


HWO's resolution is a superpower

Hubble /
Roman PSF

HWO
PSF

HWO will have ~3x better
resolution than
Hubble/Roman at similar
wavelengths



Low-mass (10^9 solar-masses) galaxy at $z=2$
140 hour simulated exposure (typical of deep field campaign)

From Recommendation to Reality

Decadal → GOMAP → CSIT → Mission Architecture

Science and technology co-evolved

designs are iterated over time

and decisions are informed by tech maturity

From Recommendation to Reality

Decadal → GOMAP → CSIT → Mission Architecture

Community Science and Instrument Team

WHAT THE CSIT DOES



Translate science → requirements

Translate community science priorities into Driving Science Cases that inform HWO mission-level requirements.



Coordinate community → design

Coordinate across PAGs, SIGs, and partners to ensure continued broad community participation and that science priorities are reflected in HWO design.



Evaluate trades → instruments

Help evaluate instrument concepts and technology maturity to define a scientifically optimized core instrument suite for the Mission Concept Review.



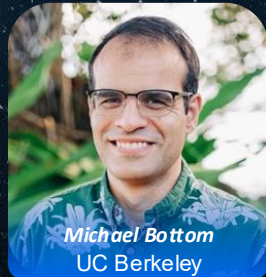
Advocate science → stakeholders

Serve as ambassadors for the community, articulating the scientific value of HWO across stakeholder groups.

habitableworldsobservatory.org

HWO's Community Science & Instrument Team (CSIT)

National Aeronautics and
Space Administration

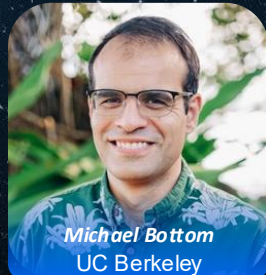


International ex-officio

Exoplanets & Habitability • Solar System • Stars & Stellar Environments • Galaxies & Cosmic Ecosystems • Extreme Astrophysics & Transients • Instrumentation & Analysis

HWO's Community Science & Instrument Team (CSIT)

National Aeronautics and
Space Administration

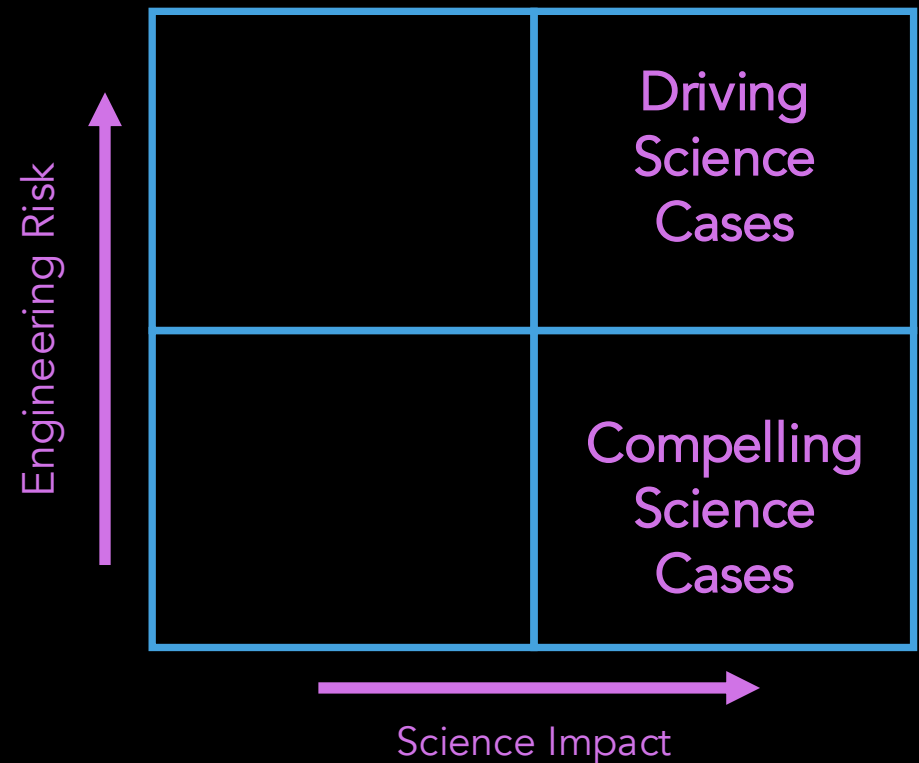


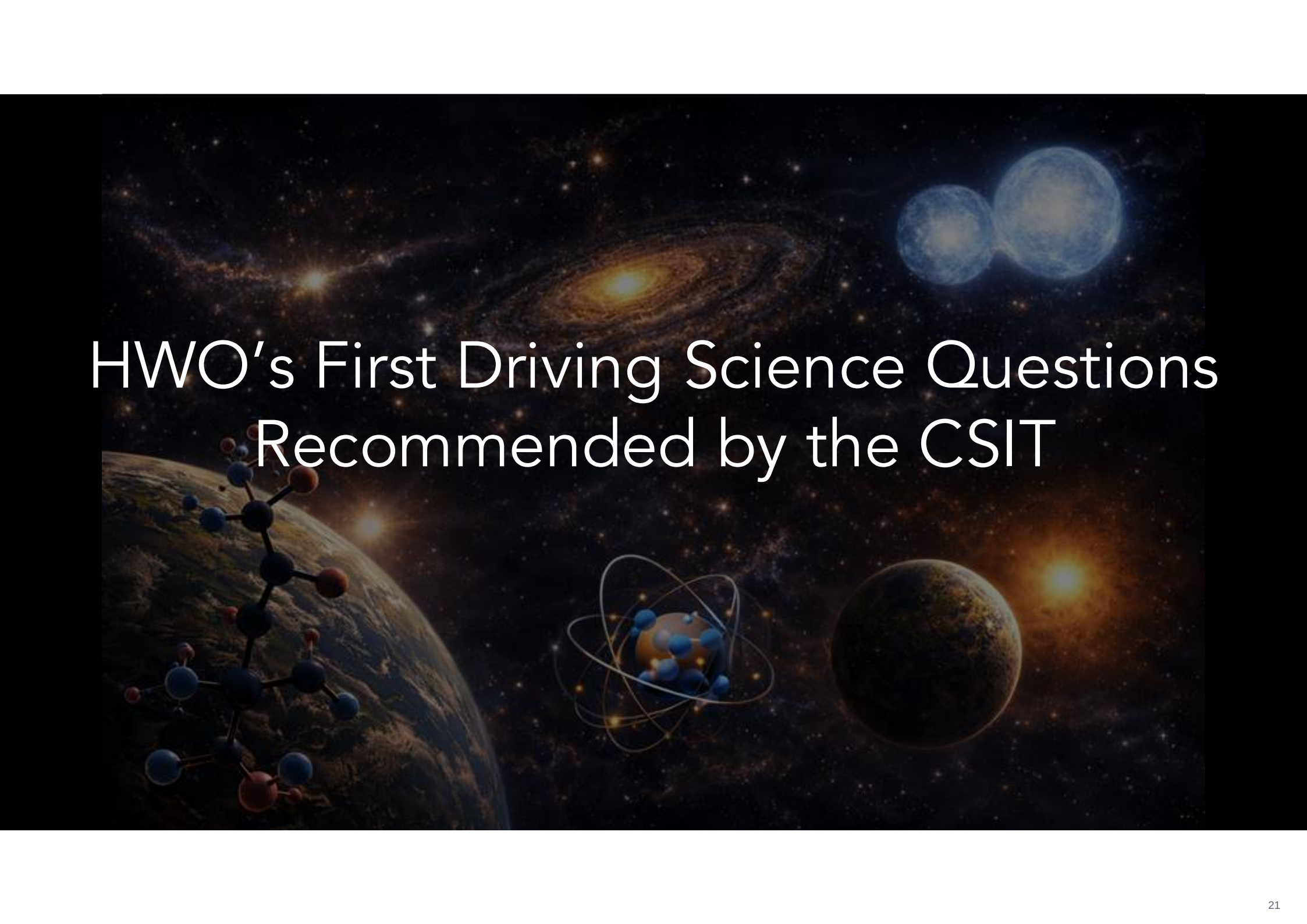
Exoplanets & Habitability • Solar System • Stars & Stellar Environments • Galaxies & Cosmic Ecosystems • Extreme Astrophysics & Transients • Instrumentation & Analysis

SCIENCE DRIVES MISSION DESIGN

The CSIT reviewed all community Science Case Development Documents (SCDD) to identify potential:

- 1) **Driving Science Cases (DSC)** that inform draft Level 1 science requirements (baseline and threshold) by mapping science objectives to capabilities.
- 1) **Compelling Science Cases (CSC)** needed for explorations of trade space and Design Reference Missions (DRMs)



The background is a dark, star-filled space. In the upper left, a spiral galaxy is visible. In the upper right, two blue, gaseous celestial bodies are shown. In the lower left, a molecular structure with blue and red spheres is depicted. In the lower center, an atom with a blue nucleus and orbiting electrons is shown. In the lower right, a planet resembling Earth is visible next to a bright, glowing star.

HWO's First Driving Science Questions Recommended by the CSIT



HOW DO IONIZING
PHOTONS DRIVE THE
EVOLUTION OF COSMIC
STRUCTURE?

HOW DO MASS AND ENERGY
FLOW IN AND OUT OF
GALAXIES?

WHAT ARE THE MOST
EXTREME STARS AND
STELLAR POPULATIONS?

ARE WE ALONE?

WHAT ARE THE ORIGINS OF
THE HEAVY ELEMENTS?

THE DISTANCE LADDER
REVISITED

HOW DO IONIZING
PHOTONS DRIVE THE
EVOLUTION OF COSMIC
STRUCTURE?

WHAT ARE THE MOST
EXTREME STARS AND
STELLAR POPULATIONS?

More details from Janice to follow

HOW DO MASS AND ENERGY
FLOW IN AND OUT OF
GALAXIES?

ARE WE ALONE?

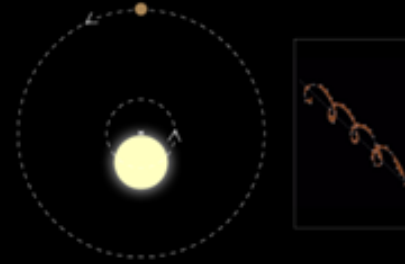
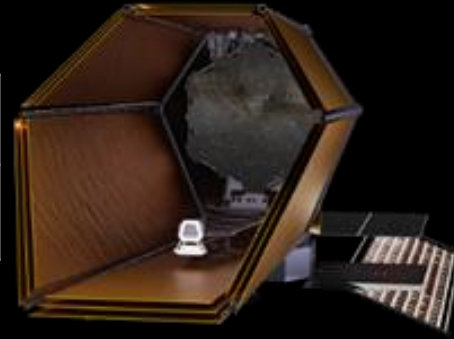
THE DISTANCE LADDER
REVISITED

WHAT ARE THE ORIGINS OF
THE HEAVY ELEMENTS?

PRELIMINARY OBSERVATORY GOALS FLOWING FROM THE FIRST DRIVING SCIENCE CASES

Telescope

Diameter	~8 m
Bandpass	~97 to ~1700 nm



High-Resolution Imager

Vis and NIR imaging & High-precision astrometry

Bandpass	~400–2500 nm (TBC)
Field-of-View	~3' x 2'
Astrometry Precision	~0.3 μ as per epoch

Coronagraph(s)

High-contrast imaging and imaging spectroscopy

Bandpass	~450-1700 nm
Final Planet-Star Flux Ratio	~10 ⁻¹⁰
IWA	~50 mas
R ($\Delta\lambda$)	NUV: ~7 ; Vis: ~140 ; NIR: ~70

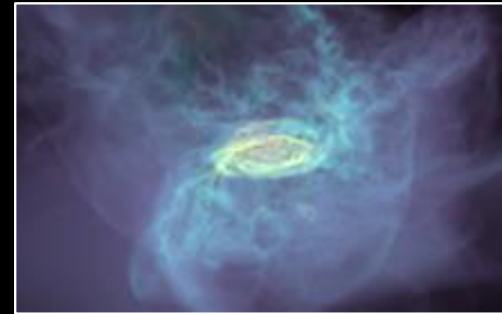


PRELIMINARY OBSERVATORY GOALS FLOWING FROM THE FIRST DRIVING SCIENCE CASES

Multi-Object Spectrograph (MOS)

FUV and NUV spectroscopy and FUV imaging

Bandpass	$\sim 100 - 1000 \text{ nm}$
Field-of-View	$\sim 3' \times 3'$
Angular Res.	$\sim 0.05''$
R ($\lambda/\Delta\lambda$)	~ 500 $\sim 40,000$ $\sim 100,000$ (point-source)



Integral Field Unit (IFU)

FUV and NUV spectroscopy and imaging

Bandpass	$\sim 100 - 400 \text{ nm}$
Field-of-View	$\sim 3'' \times 1.5-3''$
Angular Res.	$\sim 0.02''$
R ($\lambda/\Delta\lambda$)	$\sim 4,000$



Other candidate
instruments will
also be
considered

Slide Taken From Pre-Proposal Workshop (May 2026)



Instrument Capabilities

The candidate instrument capabilities within scope of this study are listed below. Other instrument capabilities not listed here may be within the scope, if the study convincingly demonstrates sufficient traceability to HWO science goals.

- **Coronagraphy (*see note below):**
 - Near-IR coronagraphic imaging and spectroscopy
 - Near-UV coronagraphic imaging
- **Spectroscopy:**
 - UV / visible integral field spectroscopy
 - UV / visible multi-object spectroscopy
- **Imaging:**
 - High-resolution near-UV / visible / near-IR imaging
 - Visible wavelength high-precision astrometry
 - Observatory guiding and wavefront sensing

Note that visible coronagraphic imaging and spectroscopy are excluded from this study, as the visible coronagraph is being designed as directed work within HTMPO.

WORKSHOP GOALS

Strengthen and
connect the
Japanese HWO
science and
instrumentation
community

Explore Japanese
science interests
to guide Japan's
instrument &
science
contributions to
HWO

Foster
collaboration
across science,
instrumentation,
and ground- and
space-based
astronomy

Prepare the
Japanese
community for
future international
HWO
collaborations

H A B I T A B L E
W R L D S
O B S E R V A T O R Y

6 PANEL QUESTIONS

1

- What HWO science is most compelling to the Japanese community, and where could Japan provide distinctive scientific leadership?

2

- Based on Japan's existing strengths, what possible scientific, technical, or instrumentation contributions should be explored?

3

- How should Japanese science priorities guide the evaluation of possible contributions, including—but not limited to—NIR coronagraphy & UV spectroscopy?

4

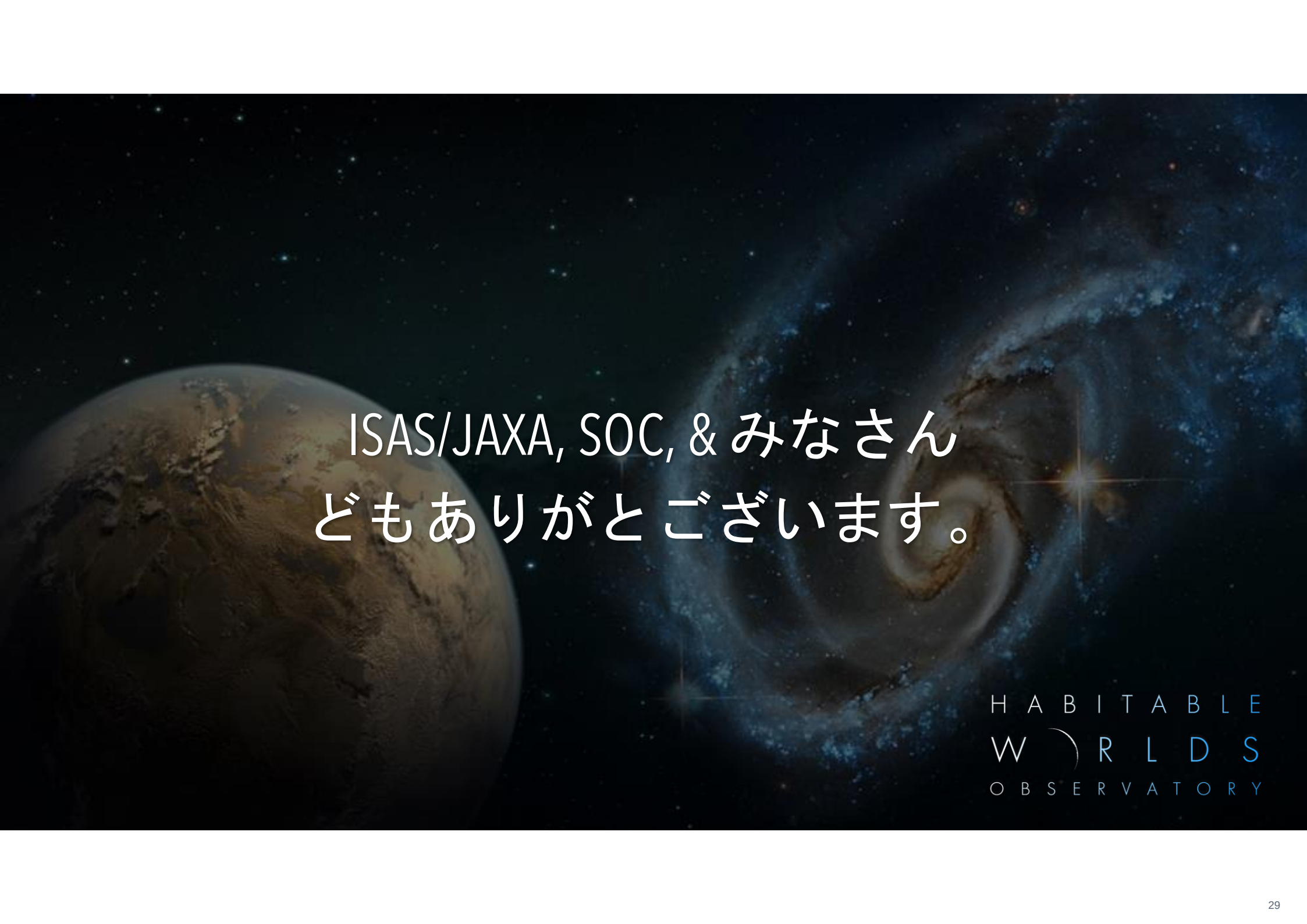
- What organizational framework is needed to connect Japan's science, instrumentation, ground-based, and space-based communities?

5

- What specific actions should the Japanese community complete during the next 12 months to prepare for future international HWO collaboration?

6

- When we meet again at the next HWO-J workshop, what concrete evidence would convince you that the Japanese HWO community has made significant progress?

The background of the slide is a composite image. On the left, a portion of the Earth is visible, showing brown and tan landmasses and blue oceans. On the right, a large, detailed spiral galaxy is shown, with a bright central core and glowing blue and white spiral arms. The entire scene is set against a dark, star-filled space background.

ISAS/JAXA, SOC, & みなさん
どもありがとうございます。

H A B I T A B L E
W R L D S
O B S E R V A T O R Y

Janice C. Lee

Title: HWO and the Scientific Frontier: Current Science Cases & Development Process

Lead author: Janice Lee

Abstract:

How were ~70 HWO science cases, spanning a broad range of frontier astrophysics and planetary science, developed and published during 2024–25? In this talk, I describe the coordinated effort to engage the scientific community in HWO mission development. The process began with the organization of four HWO Science Working Groups (Evolution of the Elements, Galaxy Growth, Solar Systems in Context, and Living Worlds) and fourteen sub-working groups. It then proceeded by establishing a structured timeline for the release of science cases for community review, signatories, and publication. These activities culminated in the presentation of the science cases at the HWO25 conference in Washington, DC, which brought together science, engineering, and policy communities to discuss mission priorities and development needs. I conclude with an overview of the current “driving” science cases subsequently identified by the NASA HWO Community Science and Instrument Team.

Science Case Summary

As a prelude to the more detailed presentations at this workshop, I provide brief overviews of the current HWO “driving” science cases:

- How is matter recycled by galaxies: how do metals, gas, and dust flow into and out of galaxies?
- How do hydrogen-ionizing photons drive the evolution of cosmic structure?
- How did the universe’s earliest stars form and evolve, as revealed by extremely primitive stars in the local universe?
- How are the heavy elements forged in neutron star mergers? What is the expansion rate of the Universe?
- What are the characteristics of near-Earth objects (asteroids, comets, and interstellar objects), and what risks do they pose to humans on Earth, the Moon, and Mars?

These science cases complement the flagship Habitable Worlds science case -- identifying biosignatures on an Earth-like planet -- which was presented in the opening talk by Breann Sitarski.



HWO and the Scientific Frontier: Current Science Cases & Development Process

Janice C. Lee
Space Telescope Science Institute
Laboratoire Lagrange, Université Côte d'Azur
15 July 2026 @ JAXA HWO Workshop

HWO and the Scientific Frontier:

Current Science Cases & Development Process



*Janice C. Lee
Space Telescope Science Institute
Initiative of Excellence Sabbatical Research Chair
Laboratoire Lagrange, Université Côte d'Azur*

"If planets like Earth are rare, our own world becomes even more precious.

If we do discover the signature of life in another planetary system, it will

US National Academies of Sciences, Engineering, and Medicine Astro2020 Decadal Survey Report (Nov 2021)
change our place in the universe in a way not seen since the days of Copernicus."



more precious.

change our place in survey report (nov 2021) "the earth since the
days of Copernicus."



more precious.

If **we** do discover the signature of life in another planetary system..., it will

Who is **we**?



HWO25 | JULY 28 – 31, 2025

Towards the

HABITABLE WORLDS OBSERVATORY

VISIONARY SCIENCE AND TRANSFORMATIONAL TECHNOLOGY



HWO25 | JULY 28 – 31, 2025

Towards the

H A B I T A B L E W  R L D S
O B S E R V A T O R Y

SPBARSETR



HWO25 | JULY 28 – 31, 2025

Towards the

H A B I T A B L E W O R L D S O B S E R V A T O R Y

VISIONARY SCIENCE AND TRANSFORMATIONAL TECHNOLOGY

HWO25 International Partnerships Panel

NASA

USA



**Shawn
Domagal-Goldman**
*Astrophysics Division
Director (Acting)*

UKSA

United Kingdom



**Caroline
Harper**
*Head of
Space Science*

JAXA

Japan



**Keigo
Enya**
*HWO Study
Task Force Lead*

ESA

Europe



**Paul
McNamara**
*Astronomy & Astrophysics
Coordinator*

CSA

Canada



**Jean
Dupuis**
*Space Astronomy
Senior Mission Scientist*



HWO25 | JULY 28 – 31, 2025

“What we’ve learned from 50 years of space is that when we collaborate, the harder becomes much easier.”

P. McNamara (ESA)

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Towards the

H A B I T A B L E W R L D S O B S E R V A T O R Y



ENYA Keigo (JAXA/ISAS HWO Task Force Lead)
“Japan's possible contribution to the HWO coronagraph”



KAMEDA Shingo (Rikkyo & JAXA/ISAS HWO Task Force sub-lead)
“Far UV Integral Field Spectrograph & High Resolution Spectrograph”



HARIKANE Yuichi (Asst Professor, U Tokyo)
Invited talk: “Galaxy Formation with HWO”

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Towards the

H A B I T A B L E W O R L D S O B S E R V A T O R Y

VISIONARY SCIENCE AND TRANSFORMATIONAL TECHNOLOGY

>100 talks (~50 plenary, ~70 parallel)

>150 posters

> 400 in person; ~500 with remote

>500 person reception industry-sponsored

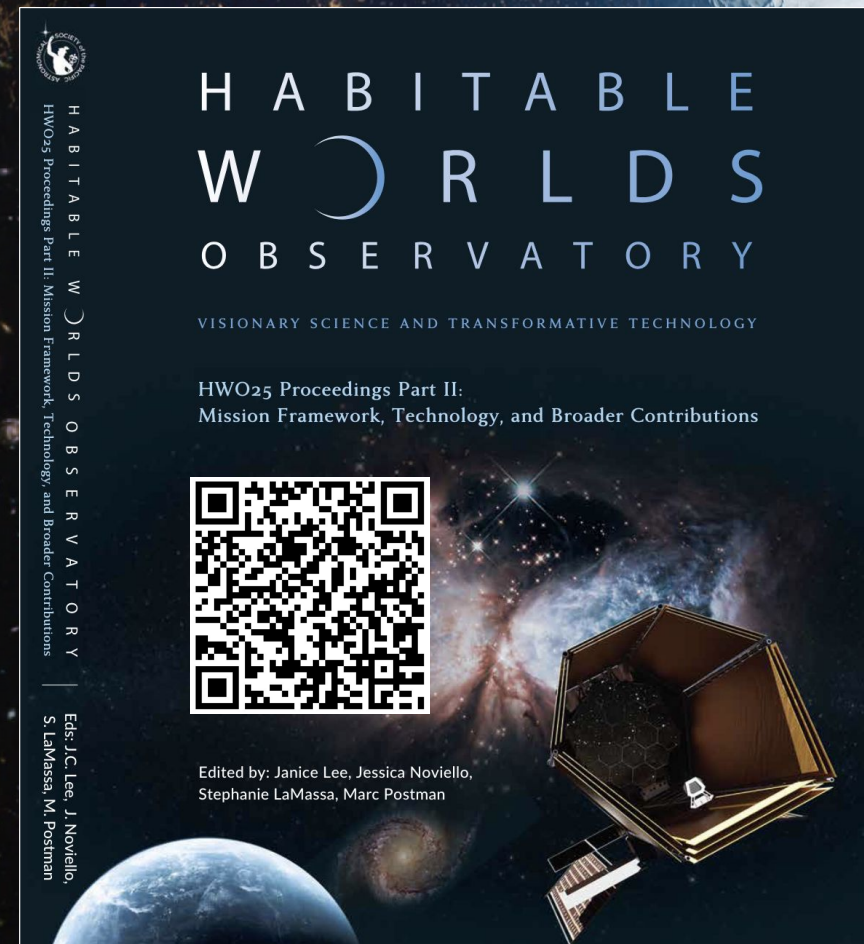
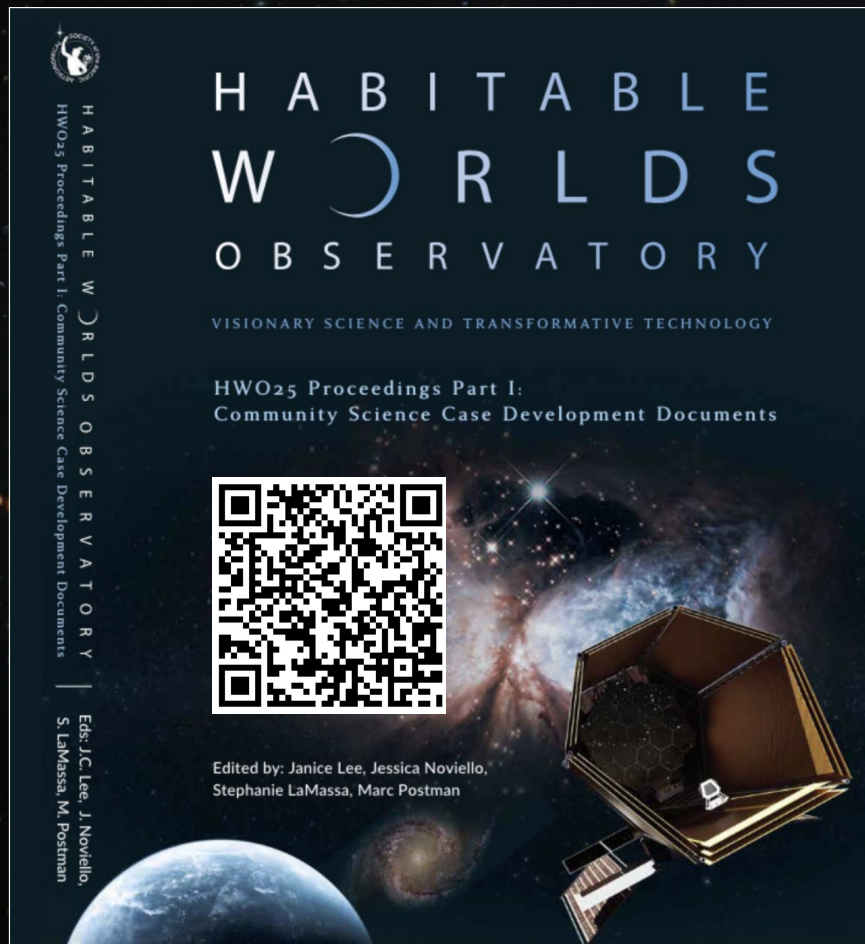
Reps from 7 potential partner countries

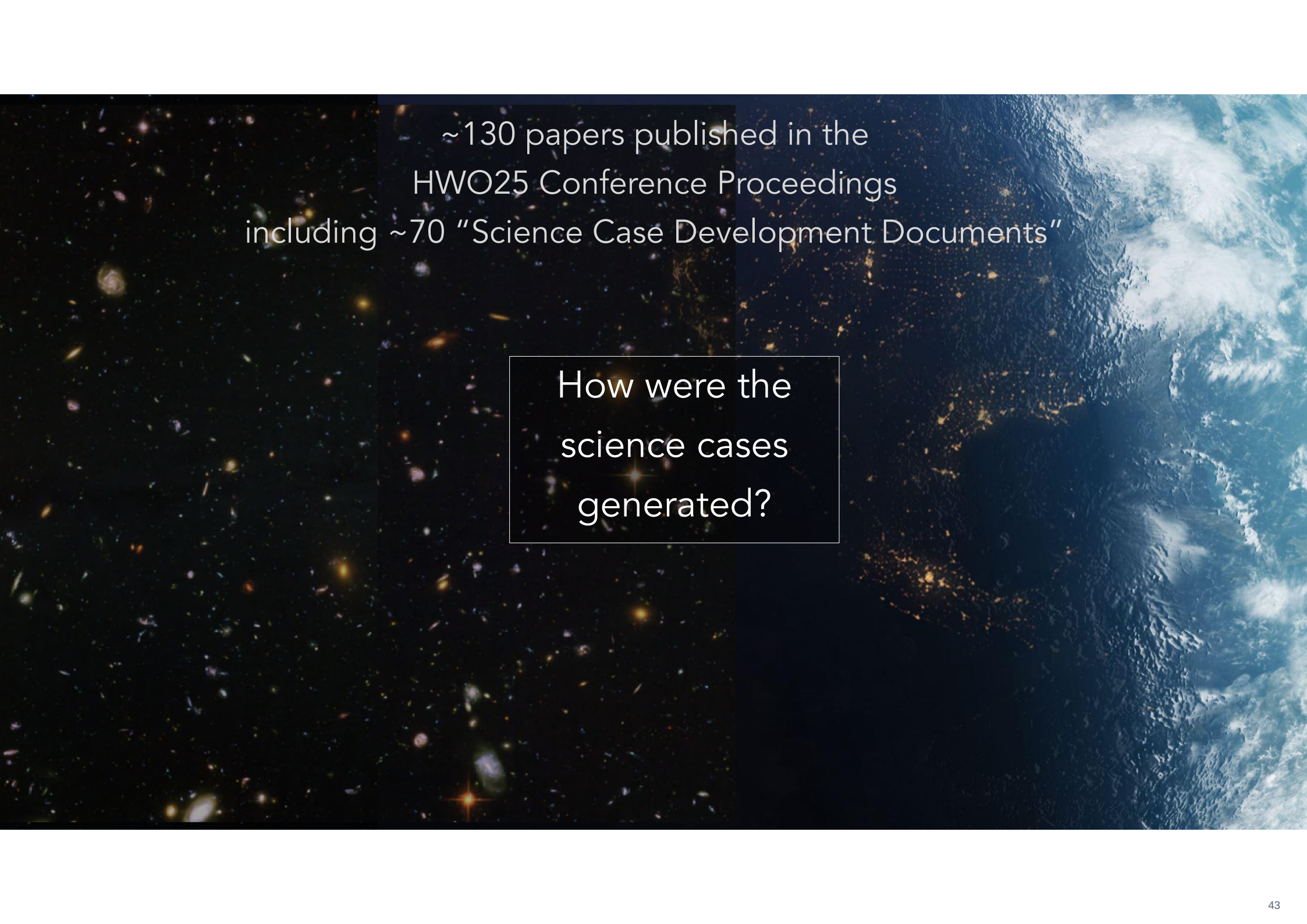
10 Discussion Panels

- Solar System & Planetary Protection
- Space Observatory Servicing
- Target Stars & Eta-Earth
- Cross Observatory Synergies
- Roman as a Pathfinder
- Biosignatures
- Cosmic Origins
- Emerging Tech
- Industry Partnerships
- International Partnerships

Video  ings

~130 papers published in the
HWO25 Conference Proceedings
including ~70 "Science Case Development Documents"





~130 papers published in the
HWO25 Conference Proceedings
including ~70 "Science Case Development Documents"

How were the
science cases
generated?

HWO Science Case Development Process

January 2024 - July 2025

SCIENCE WORKING GROUPS

Galaxy Growth
Ravindranath & Postman

Solar Systems in Context
Robinson & Shkolnik

Living Worlds
Arney & Parenteau

Evolution of the Elements
Lee & Scowen

Four science working groups
delivered ~70 science cases

HWO Science Case Development Process

14 science sub-working groups

Swara Ravindranath (COR; GSFC) & Marc Postman (STScI)

IGM & CGM	Sanchayeeta Borthakur (Arizona State University) & Joe Burchett (New Mexico State University)
AGN	Chris Packham (University of Texas San Antonio) & Vivian U (University of California, Irvine)
Ionizing Photons	Stephen McCandliss (Johns Hopkins University) & Allison Strom (Northwestern University)
Dark Sector	Richard Massey (Durham University) & Jason Rhodes (JPL)

Janice Lee (STScI) & Paul Scowen (GSFC)

Stars & Stellar Populations	Martin Barstow (University of Leicester) & Peter Senchyna (Carnegie Observatories)
Star Formation	Roberta Paladini (IPAC-Caltech) & Samir Salim (Indiana University)
Cosmic Explosions	Eric Burns (Louisiana State University) & Jennifer Andrews (Gemini-North/NOIRLab)

Tyler Robinson (University of Arizona) & Evgenya Shkolnik (Arizona State University)

Characterizing Exoplanets	Reny Hu (JPL) & Michiel Min (ESA)
Solar System Observations	Richard Cartwright (JHU Applied Physics Laboratory) & Lynnae Quick (GSFC)
Demographics & Architectures	Jessie Christiansen (Caltech/IPAC-NExScI) & Malena Rice (Yale University)
Birth & Evolution	Yasuhiro Hasegawa (JPL) & Meredith MacGregor (Johns Hopkins University)

Giada Arney (GSFC) & Niki Parenteau (ARC)

Biosignature Possibilities	Eddie Schwieterman (University of California, Riverside) & Sara Walker (Arizona State University)
Biosignature Interpretation	Josh Krissansen-Totton (University of Washington) & Stephanie Olson (Purdue University)
Target Stars & Systems	Natalie Hinkel (Louisiana State University) & Eric Mamajek (ExEP/JPL)

SUPPORT CASE DEVELOPMENT WITH EXPLORATORY EXPOSURE TIME CALCULATORS (ETCs)

Habitable Worlds
OBSERVATORY

Science Planning

Find tools to help you plan simulated observations with the Habitable Worlds Observatory.

Exploratory Exposure Time Calculators (ETCs)

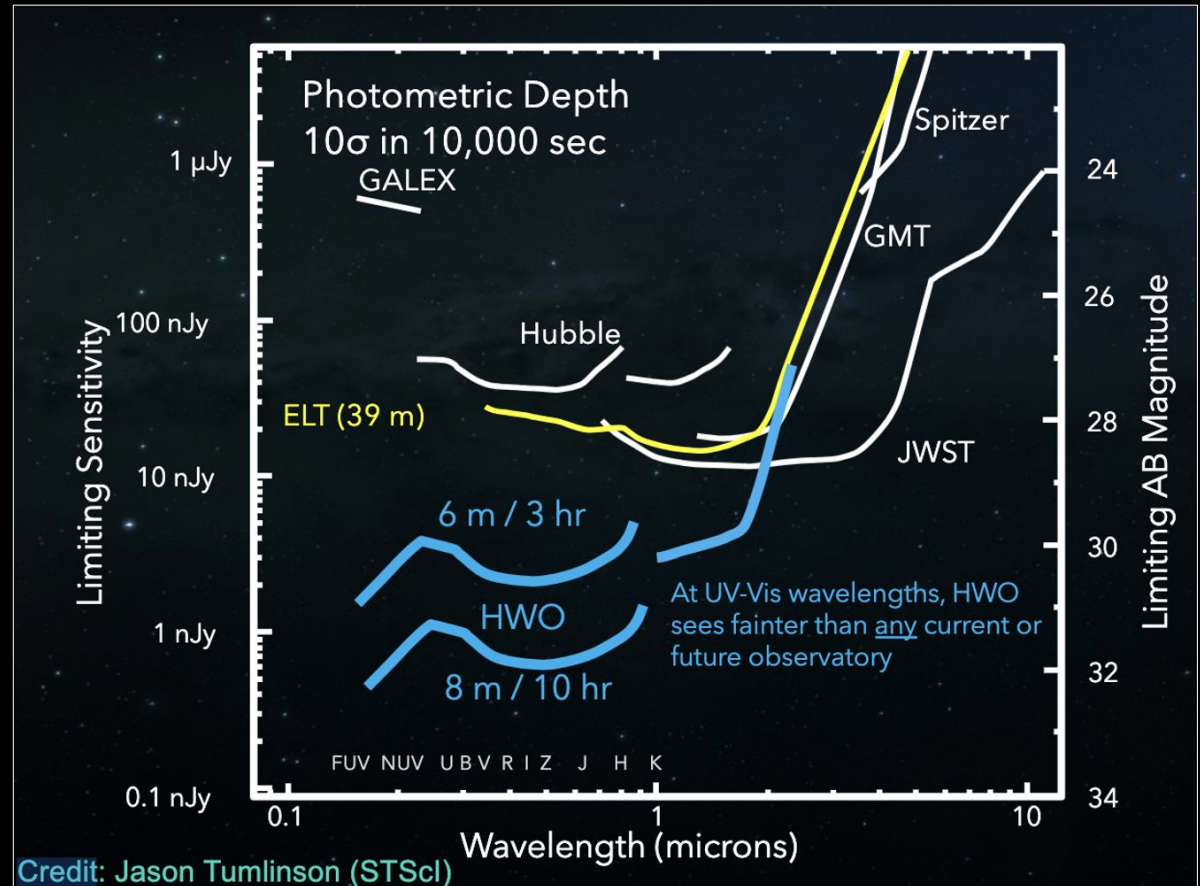
Find downloadable code and instructions to run these tools locally on [GitHub](#), and provide feedback and ask questions on the #jwg_sei channel on the [HWO Slack community](#).

Imaging Camera

Coronagraph Spectrum Simulator

UV Spectrograph





<https://habitableworldsobservatory.org/science/science-planning>

HWO Science Case Development Process

January 2024 - July 2025

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delivered ~70 science cases

*Drafts publicly released, and
opened for comments and
endorsement by science community
from May-August 2025*

Proposed HWO Science Cases

Habitable Worlds Observatory Science Case Portal

The [Habitable Worlds Observatory](#) (HWO) Science Case Development Documents (SCDDs) are central to building a transformative mission that addresses the priorities of the scientific community and the Astro2020 US Decadal Survey. Science cases sourced from the research community will shape top-level science objectives, instrument needs, and overall mission architecture for HWO.

The portal hosts all 60 current SCDDs, with documents being added through May 30. A subset of the authors are inviting feedback, while all welcome endorsement from members of the broader community. This open, transparent process ensures shared ownership of HWO's scientific direction and supports future planning by the HWO Technology Maturation Project Office and the forthcoming Community Science and Instrument Team (CSIT).

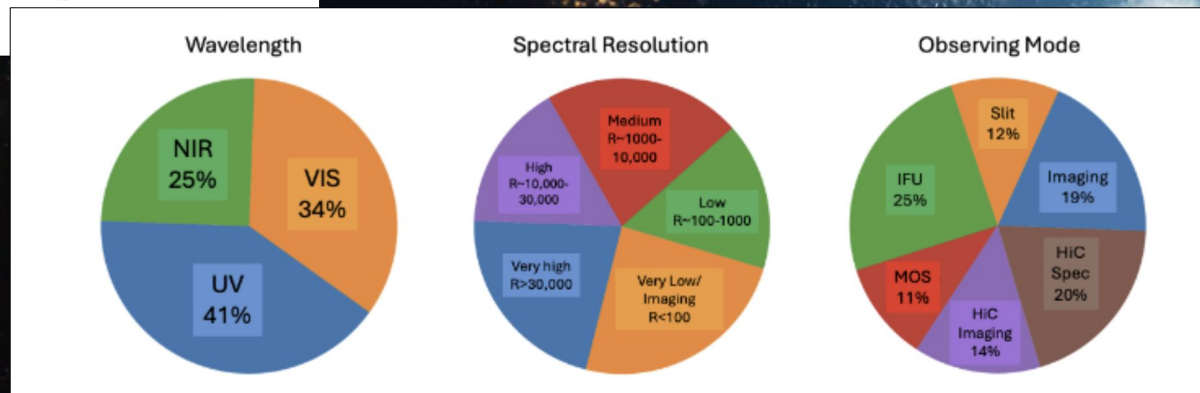
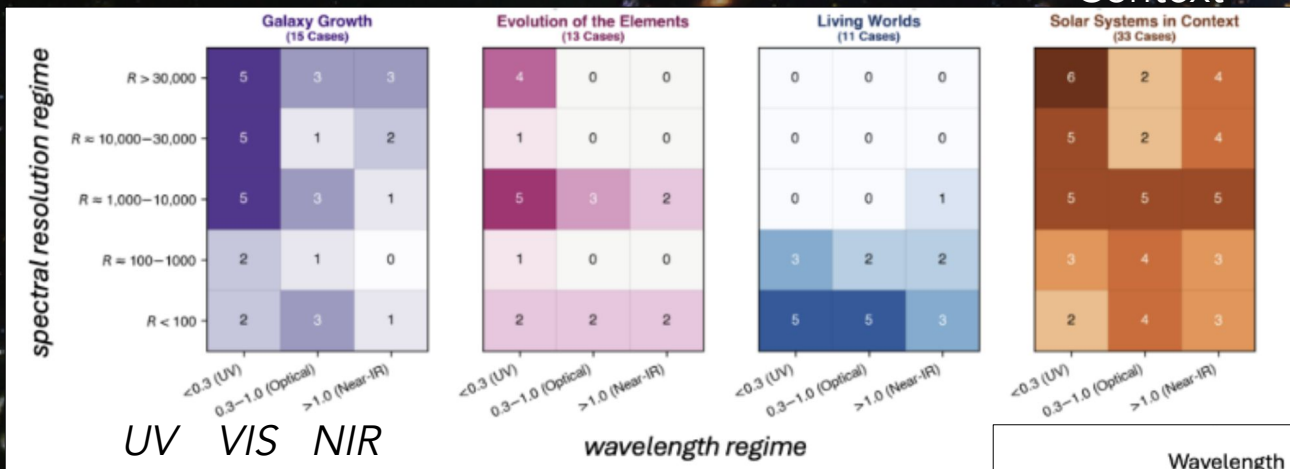
HWO Science Cases: Current Distribution

Galaxy
Growth

Evolution of the
Elements

Living
Worlds

Solar
Systems in
Context



JCL+26 (charts prepared by M. Sosey, STScI)

January 2024 - July 2025

SCIENCE WORKING GROUPS

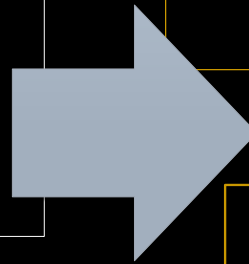
Galaxy Growth
Ravindranath & Postman

Solar Systems in Context
Robinson & Shkolnik

Living Worlds
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Four science working groups
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Summer 2025 - MCR

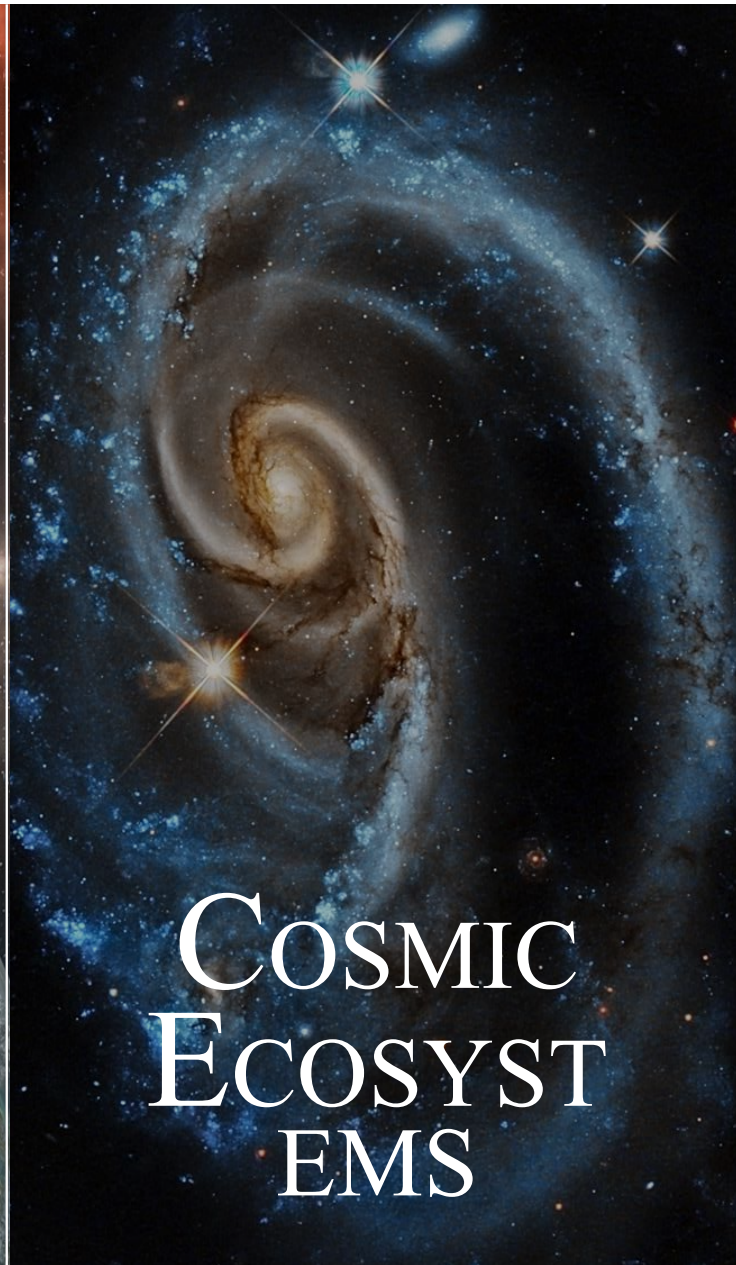
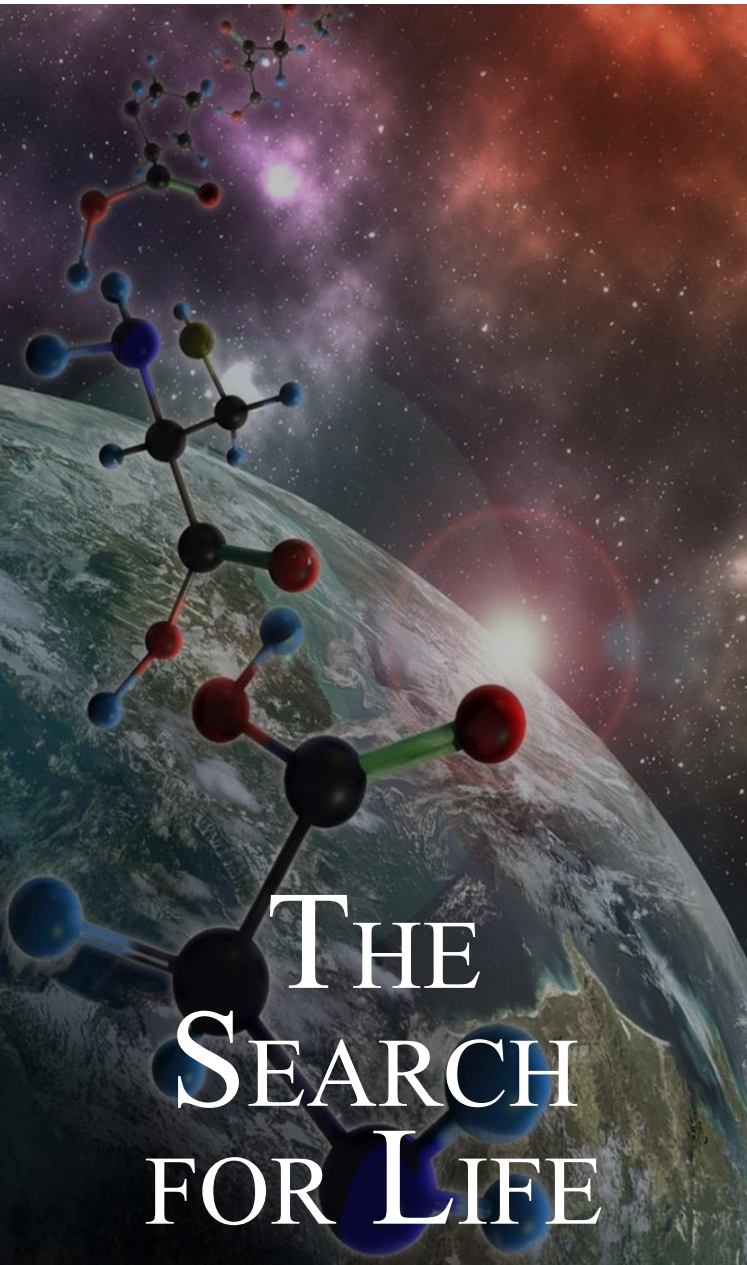
COMMUNITY SCIENCE & INSTRUMENT TEAM

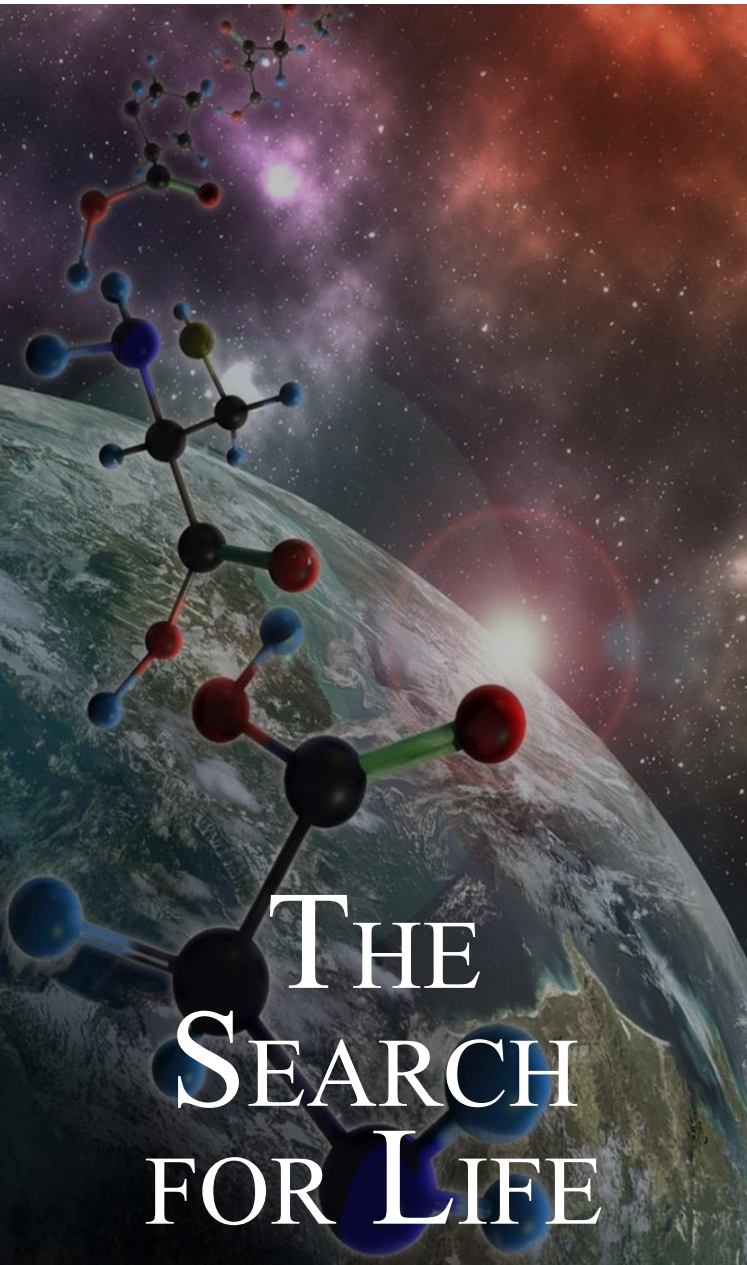
13 US Members
4 International Reps

2 co-chairs

CSIT will help project explore scientific &
instrumental trade space, develop draft science
requirements, serve as community ambassadors

Driving Science Cases





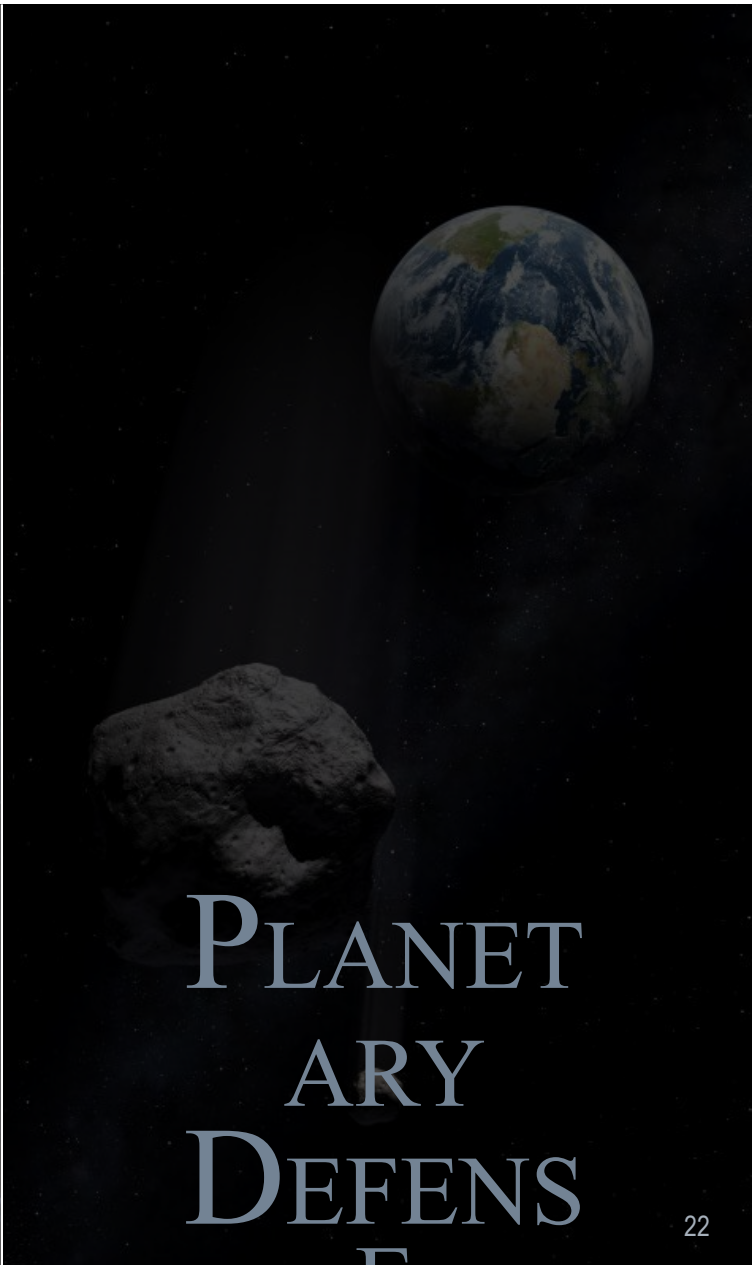
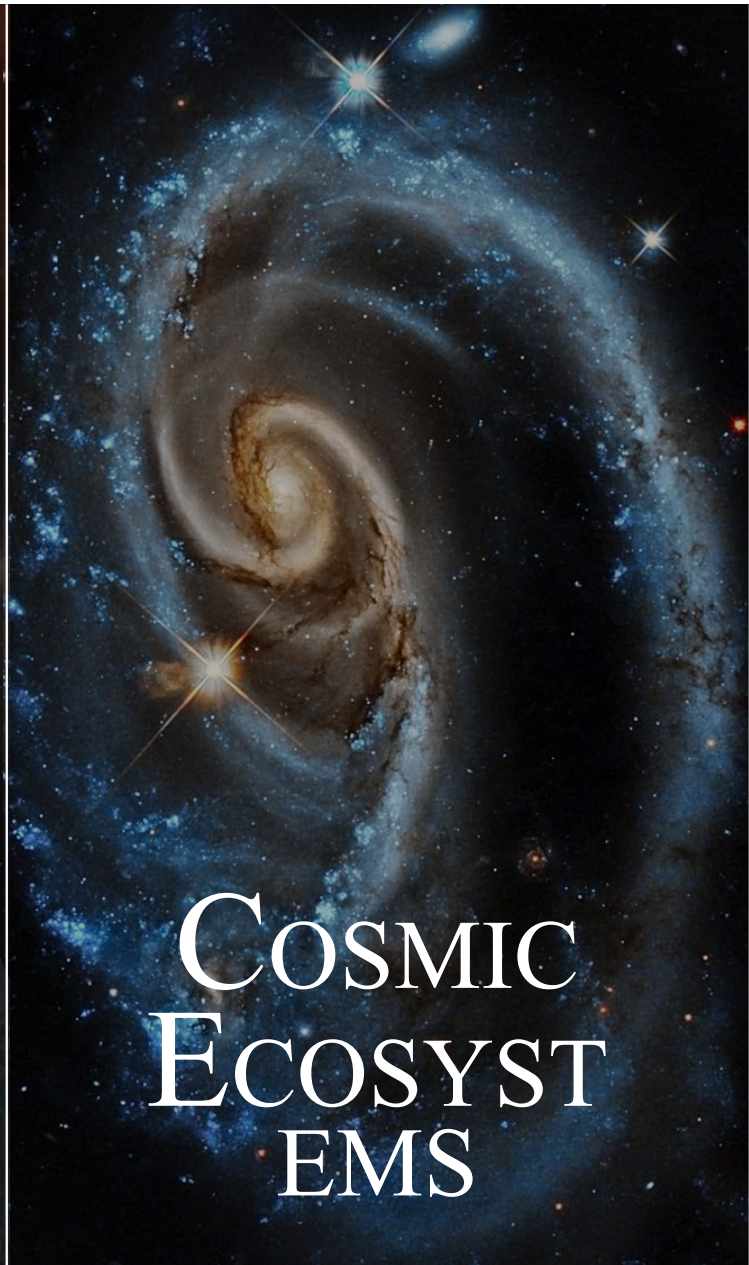
THE SEARCH FOR LIFE

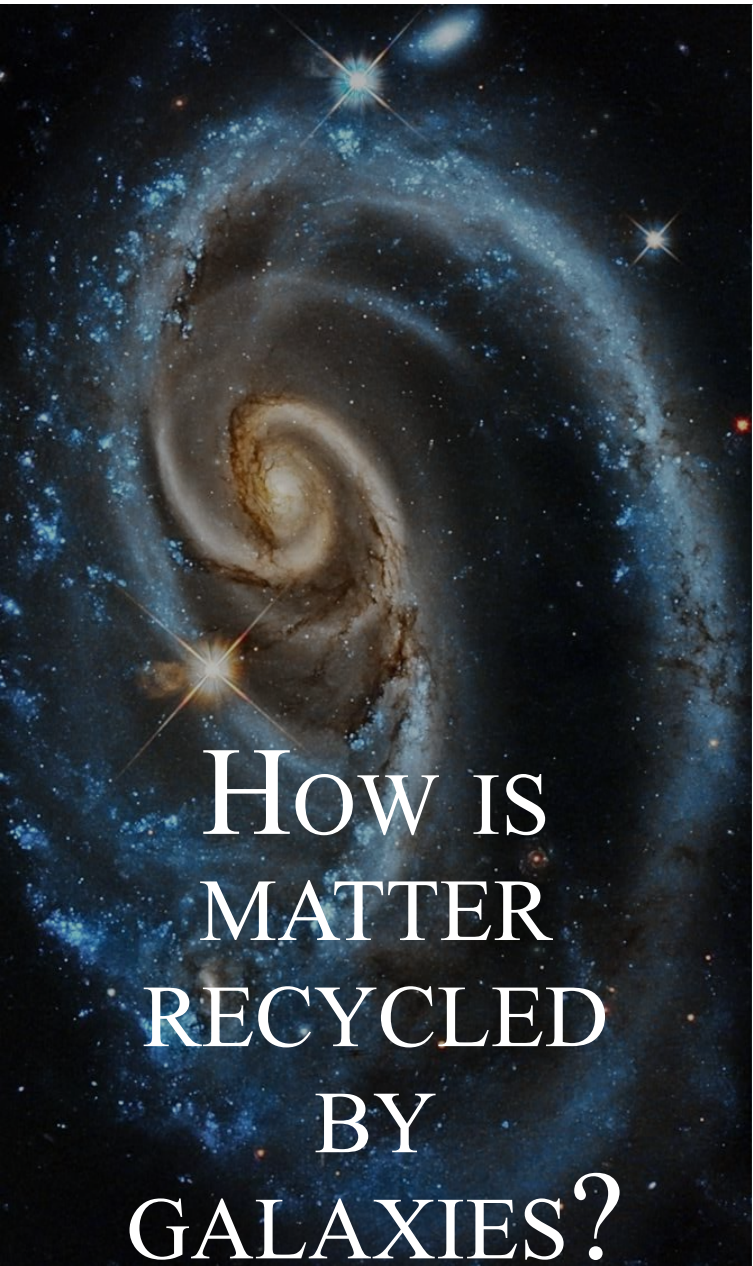


COSMIC ECOSYSTEMS

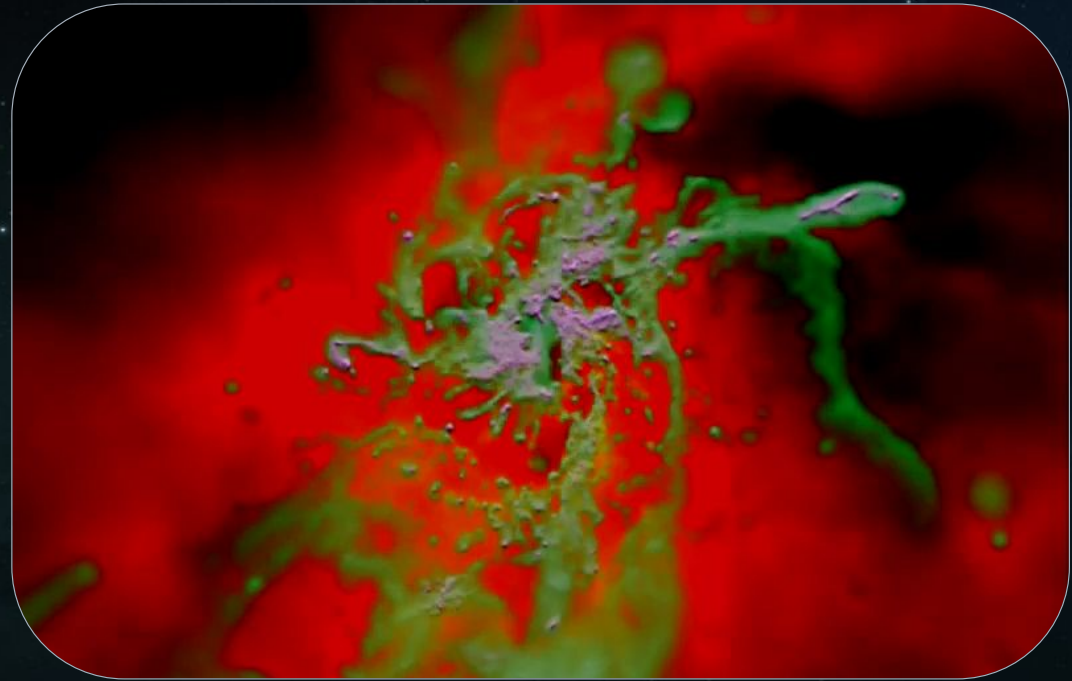


PLANETARY DEFENSE



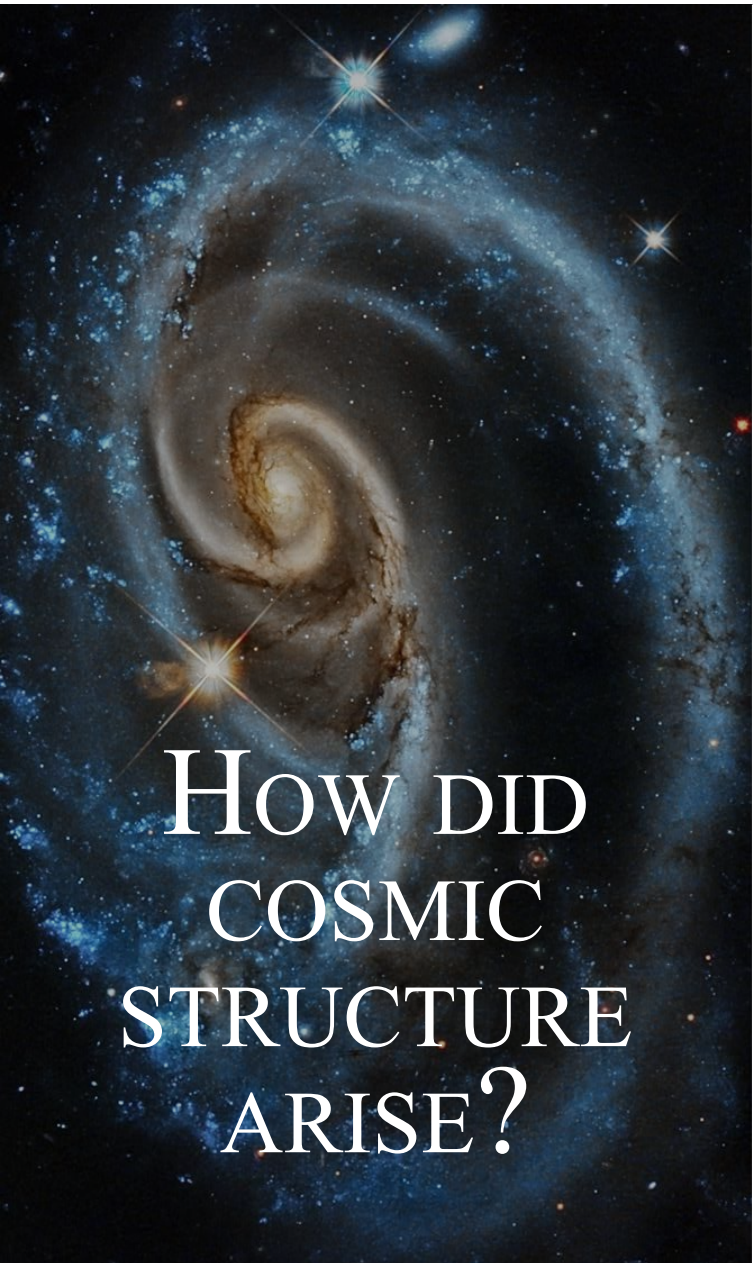


HOW IS MATTER RECYCLED BY GALAXIES?



Illuminate the flows of gas, metals, and dust
into and out of galaxies

Requires sensitive, high-resolution far-UV spectroscopy

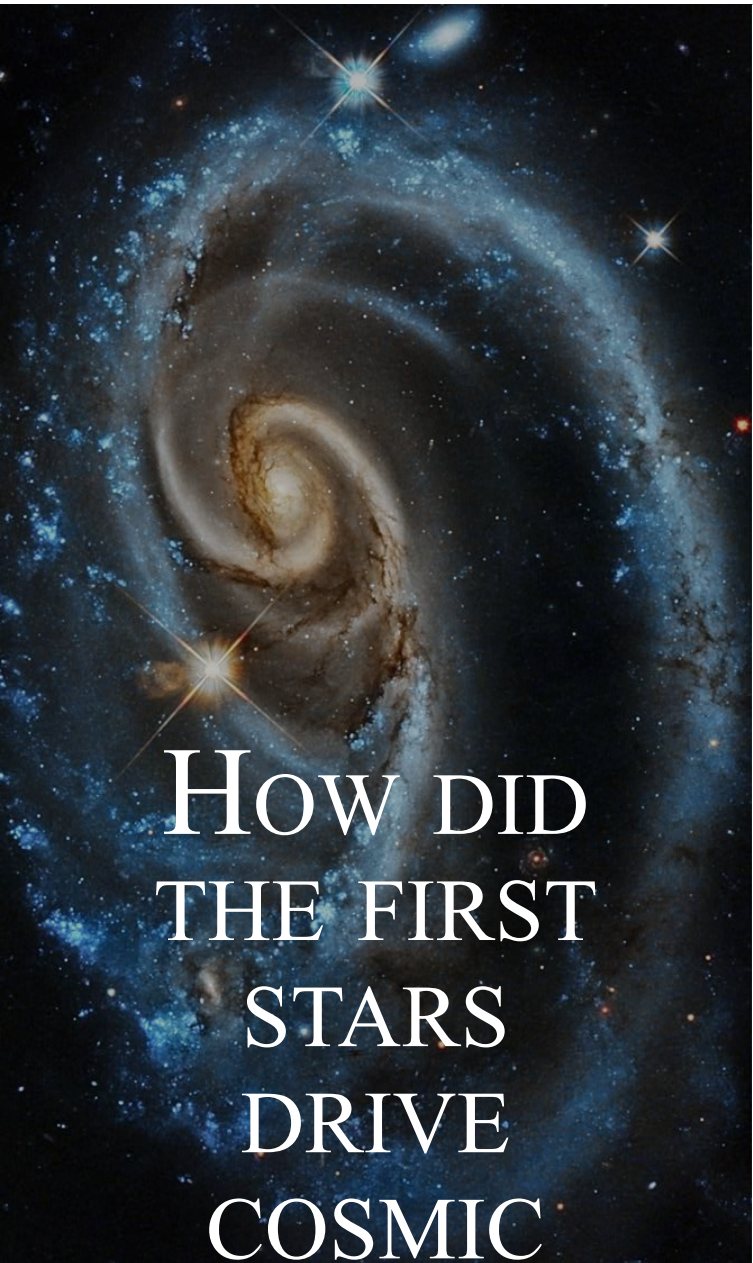


HOW DID COSMIC STRUCTURE ARISE?



Reveal how ionizing photons drove the evolution of
cosmic structure

Requires highly sensitive multi-object
far-UV ($\gtrsim 100$ nm) spectroscopy

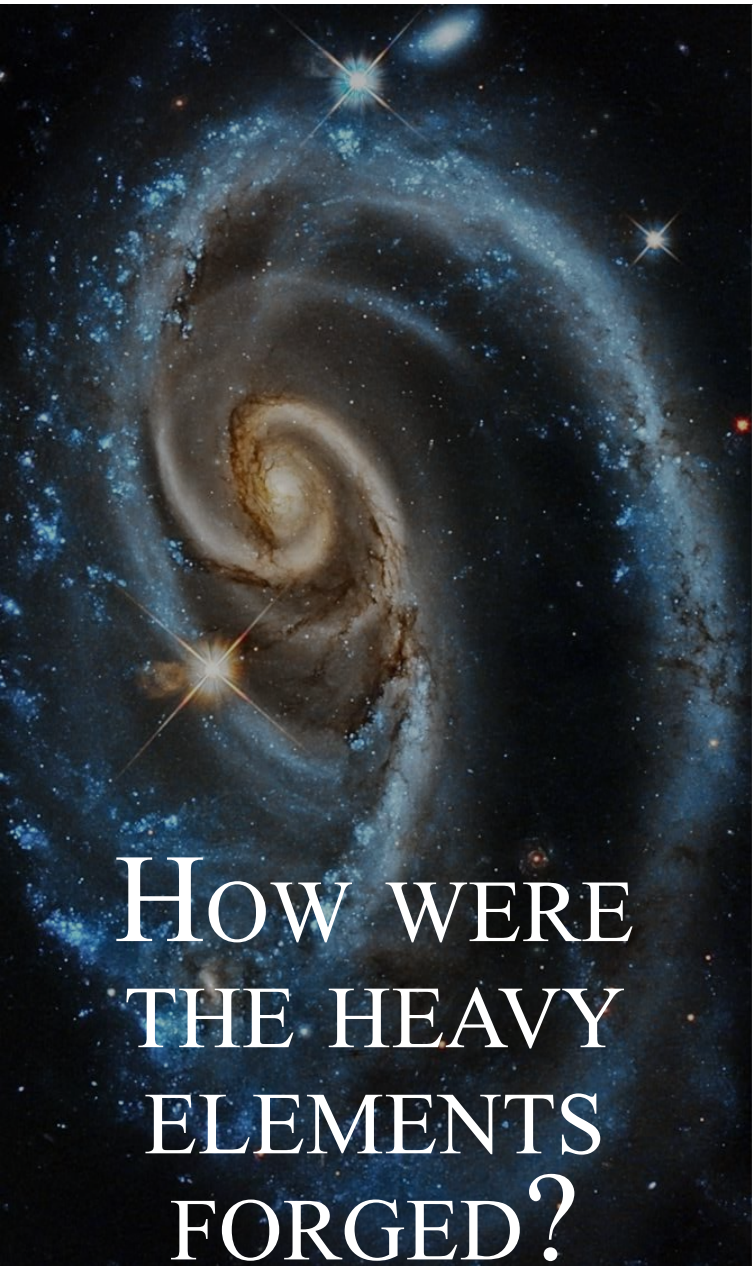


HOW DID THE FIRST STARS DRIVE COSMIC



Study the universe's earliest stars by characterizing extremely primitive stars in the local universe

Requires far-UV integral field spectroscopy & high angular resolution



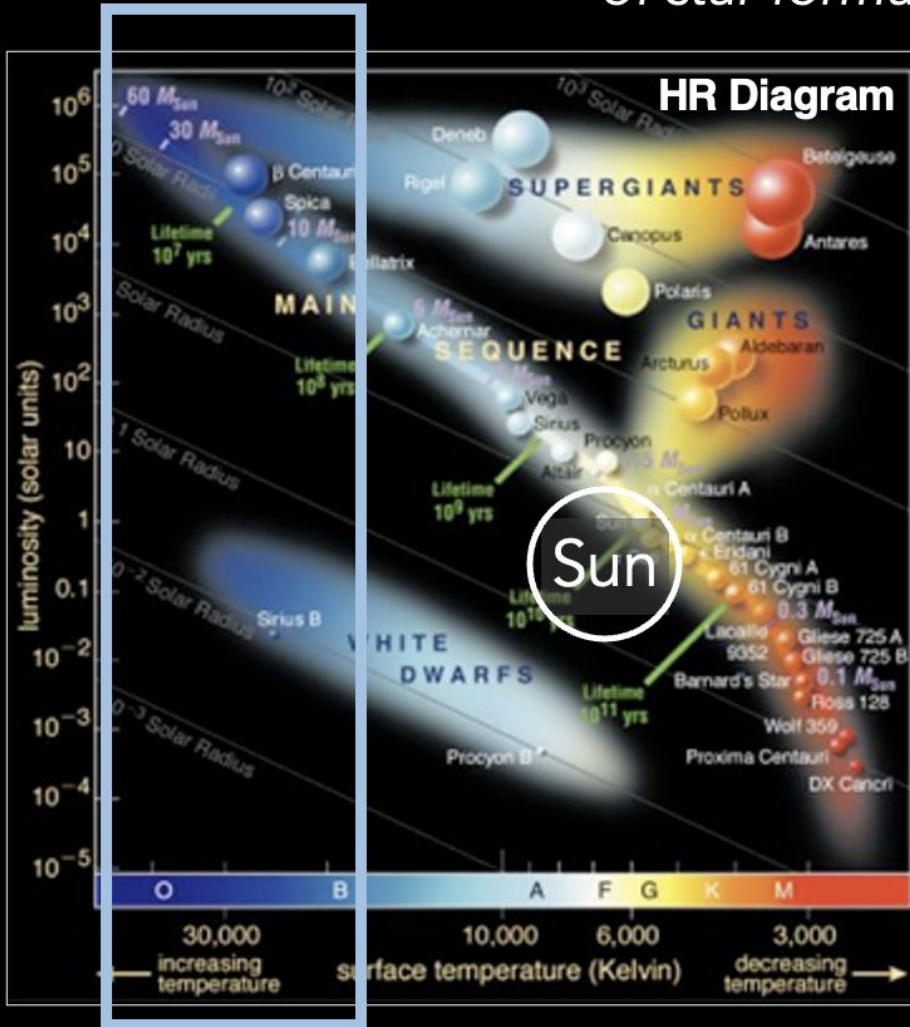
HOW WERE
THE HEAVY
ELEMENTS
FORGED?



Understand the formation of heavy elements in
neutron star mergers

Requires fast response time for transient events

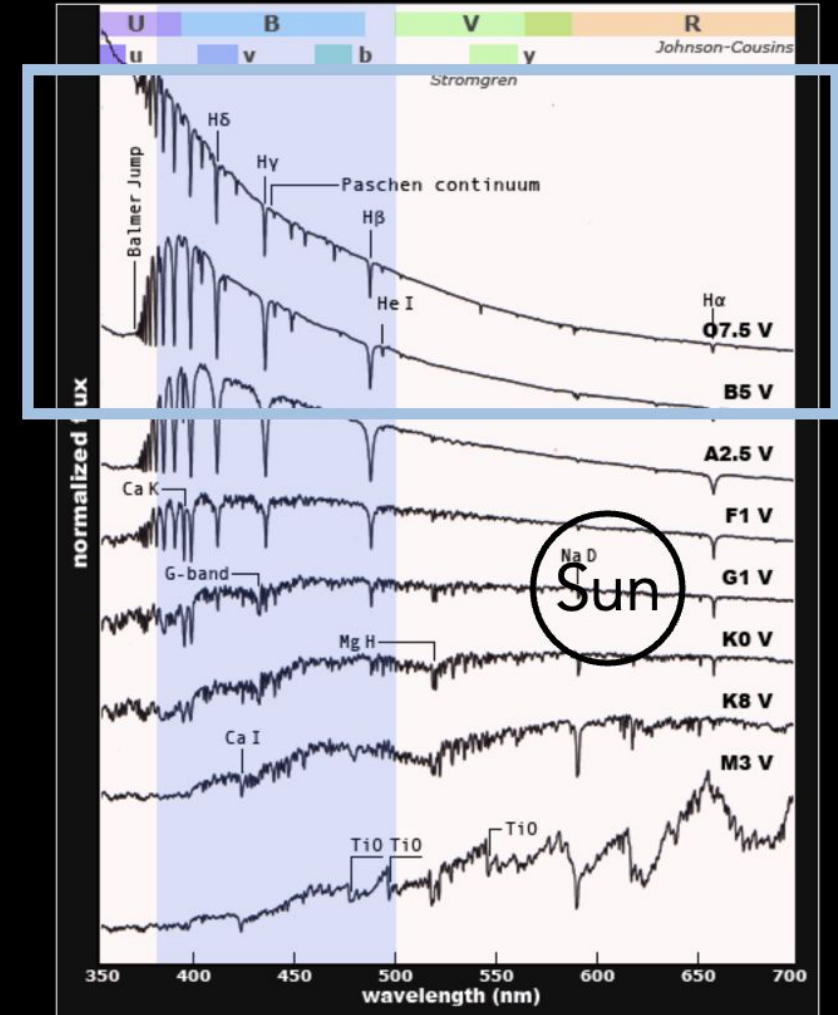
Blue/UV observations are critical for the study
of star formation & massive (HOT) stars

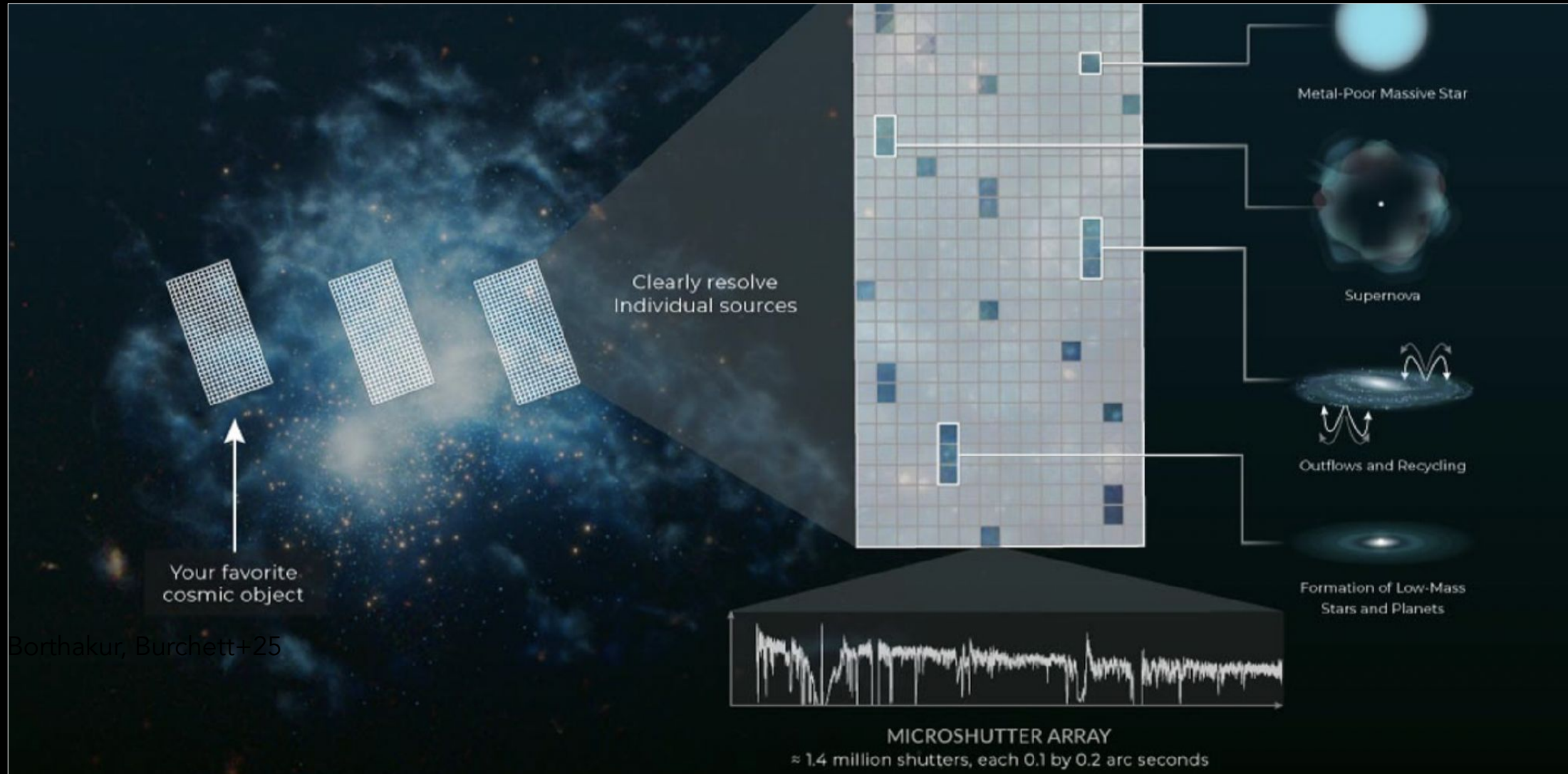


O & B stars
photospheric
emission
peaks in UV

UV flux is a
principle
SFR tracer

*esp for low
metallicity
dwarf galaxies
(Lee+09ab)





Borthakur, Burchett+25

Tracers

A wide array of lines is available to probe the multi-phase nature of the flows.

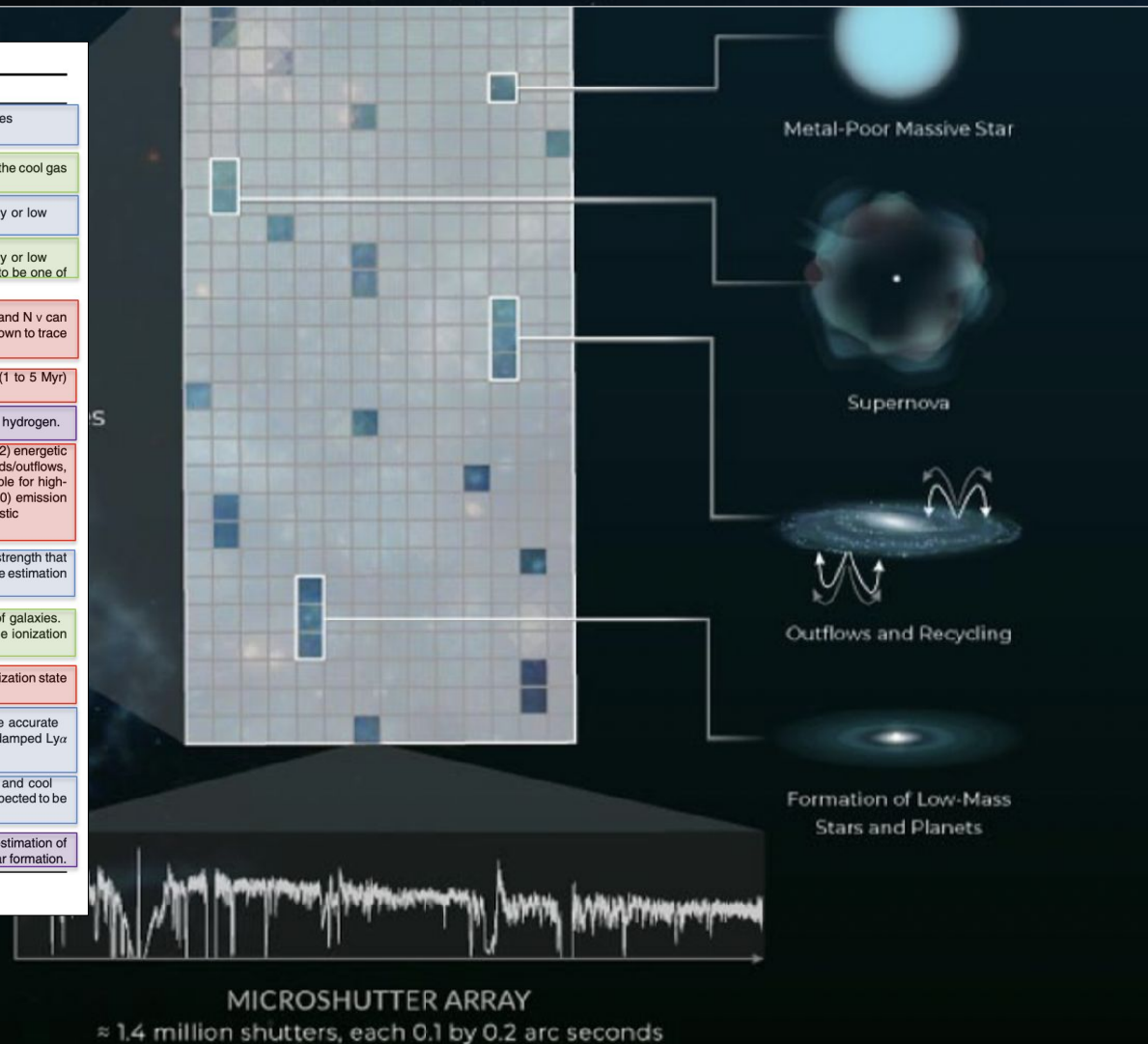
Cold/neutral molecular
Cool/low ion
Warm/medium ion
Hot/high ions

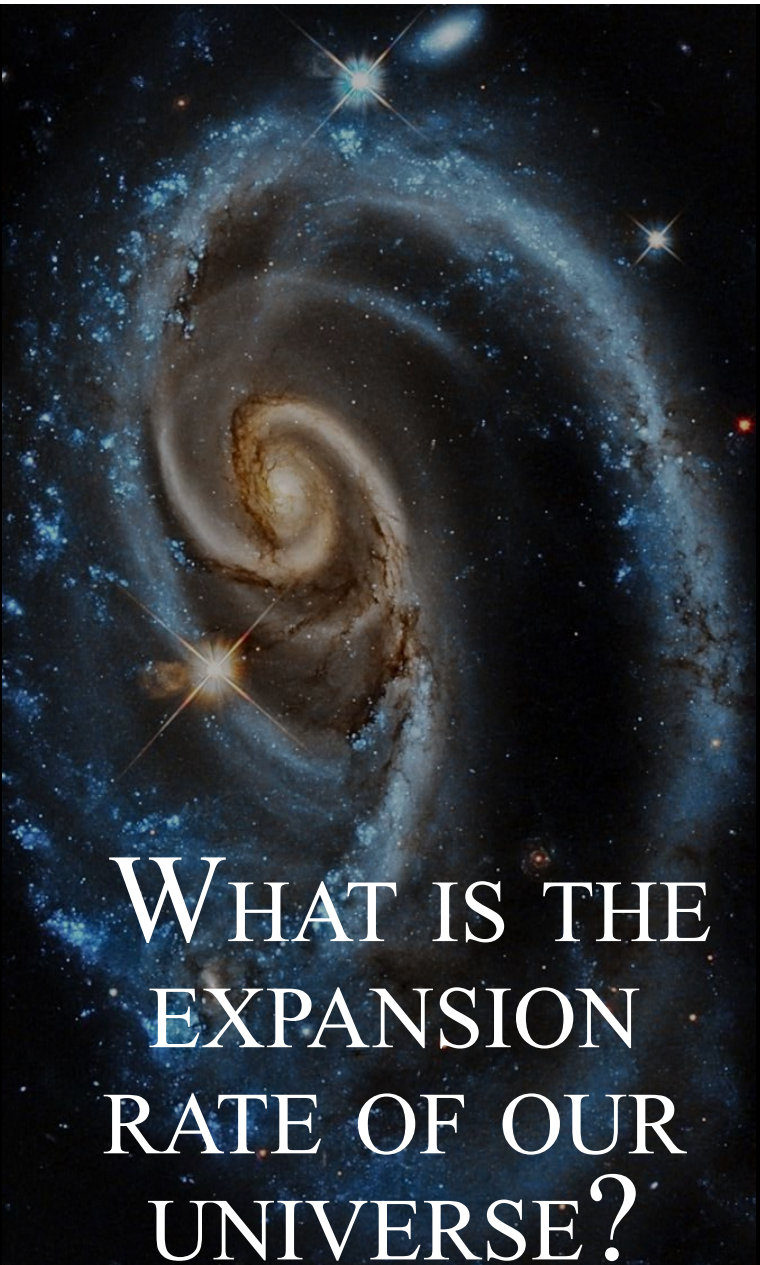
Borthakur, Burchett+25

Table 1 Lines of interest and their associated phenomenon.

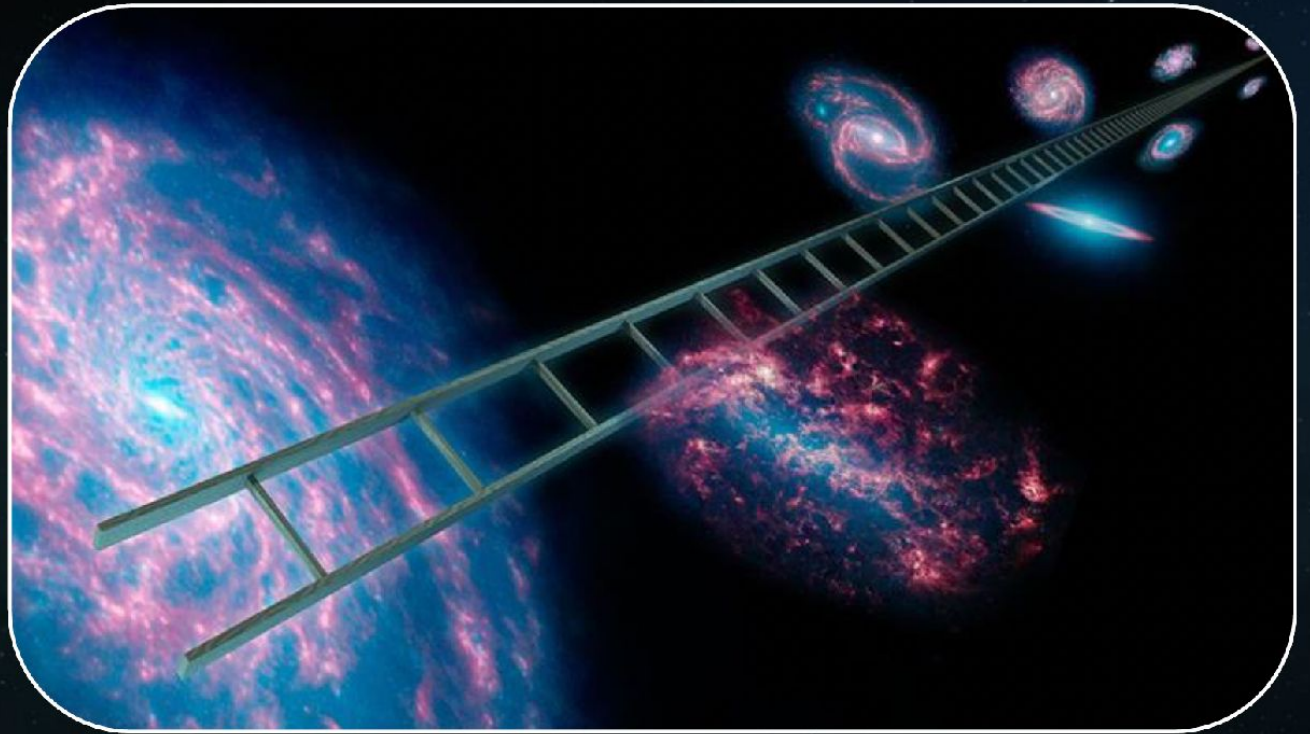
Transitions	Wavelength (Å)	Importance
H I ^a	Lyman series (1215 to 920)	Traces neutral gas content at low and intermediate temperatures ($T = 10^{1-5}$ K). The most common set of absorption lines.
Lyman $\alpha^{a,e}$	1215	Strongest emission line tracing neutral hydrogen and the bulk of the cool gas mass in the CGM.
C II ^a	1036, 1334	One of the strong metal lines suitable for probing low metallicity or low column density gas at low-ionization states.
C III ^{a,e}	977	One of the strong metal lines suitable for probing low metallicity or low column density gas at intermediate ionization states. Expected to be one of the strongest metal emission lines.
C IV ^a	1548, 1550	Strong lines tracing higher ionization states. Together with O VI and N V can be a powerful tool to identify non-equilibrium processes. Also, known to trace interactions of galactic winds and the CGM.
N V ^a	1238, 1242	Coronal lines with powerful diagnostic power to identify young (1 to 5 Myr) stellar population and non-equilibrium processes.
O I ^a	1025, 1039, 1302	Strong tracer of primarily neutral gas and is coupled to neutral hydrogen.
O VI ^{a,e}	1031, 1038	Tracer of (1) gas at the virial temperature of 0.1 to 1 L_* galaxies, (2) energetic interactions expected between the cool CGM clouds and hot winds/outflows, (3) photoionized gas; and (4) non-equilibrium processes. Suitable for high-resolution ($R > 50,000$) absorption and low-resolution ($R \approx 5000$) emission spectroscopy. One of the most powerful high-ionization diagnostic transitions.
Si II ^a	1190, 1193, 1260, 1304, 1526	Commonly observed species with five lines of different intrinsic strength that enable characterization of the saturation level and hence accurate estimation of column densities.
Si III ^a	1206	The most common metal line seen in absorption in the halos of galaxies. Together with Si II and Si IV allows for accurate measuring of the ionization state of the gas.
Si IV ^a	1393, 1402	Together with Si II and Si III enables accurately measuring the ionization state of the gas.
S II ^a	1250, 1253, 1259	Weak lines associated with a low-depletion species that enable accurate metal measurement for high column density systems such as damped Ly α systems.
Mg II ^{a,e}	2796, 2803	Commonly traced species associated with extended gas disks and cool outflowing material. Extensive literature on this line at $z > 0.5$. Expected to be detectable in emission.
H ₂ ^a	Bands from 1150 to 912	Traces the bulk of the cold molecular gas. Critical for accurate estimation of the baryon budget and gas flows that may support short-term star formation.

^a lines suitable for absorption-line spectroscopy.
^e lines suitable for emission-line spectroscopy.



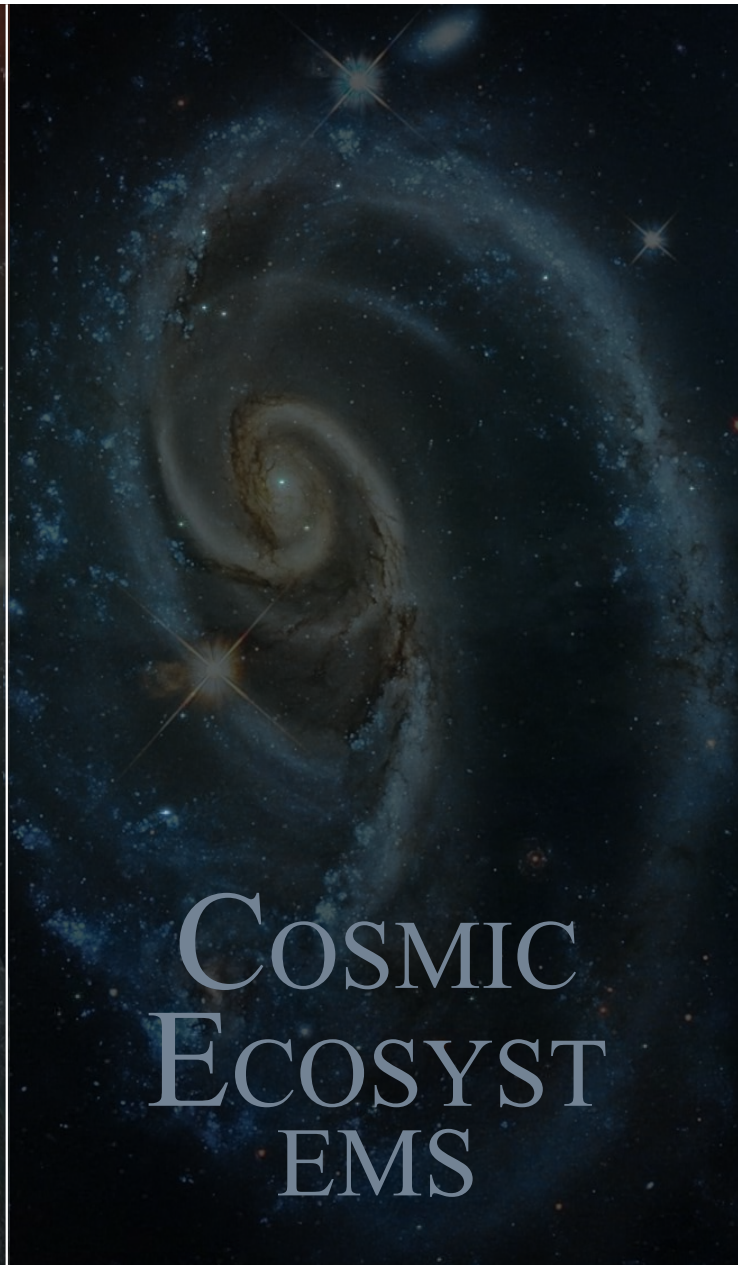


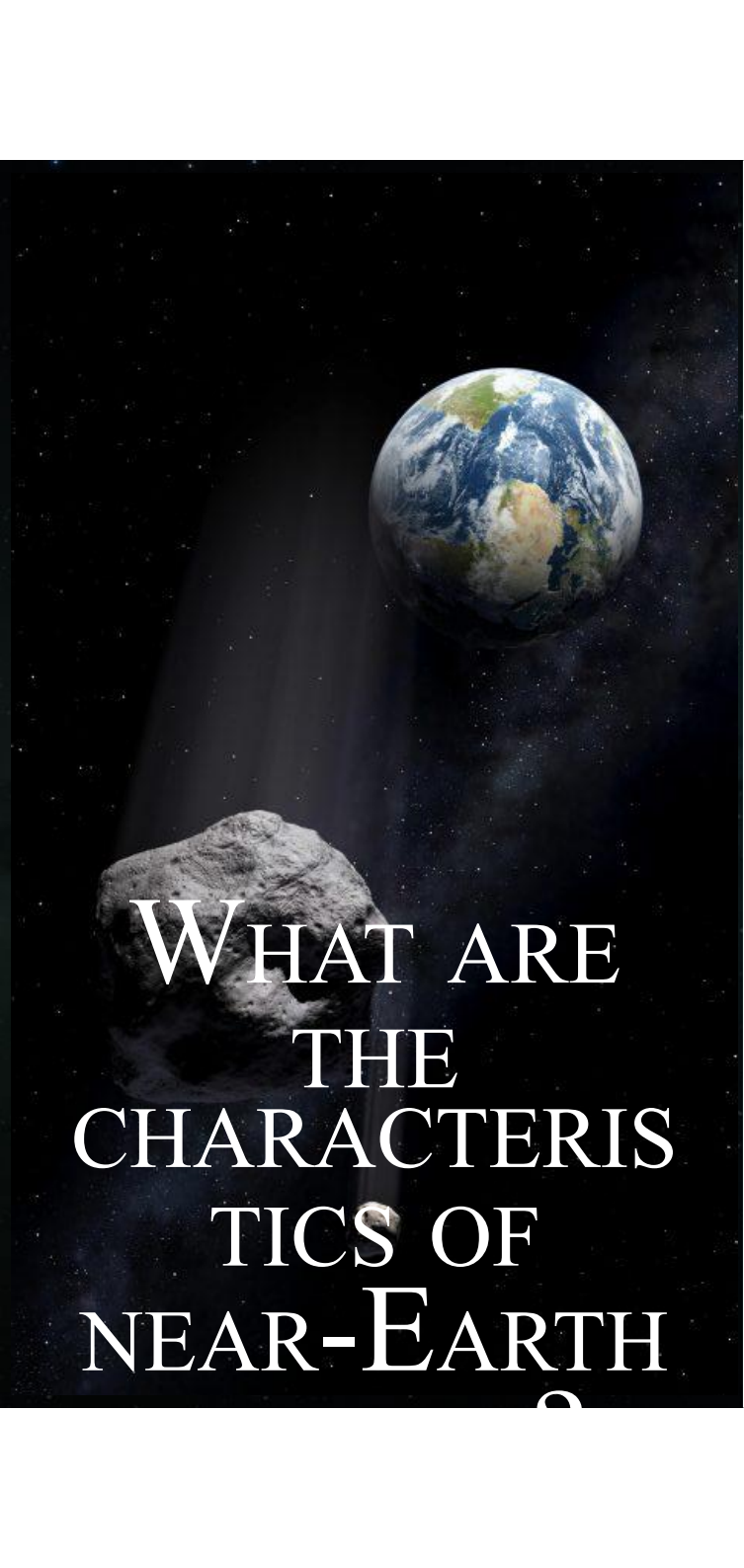
WHAT IS THE EXPANSION RATE OF OUR UNIVERSE?



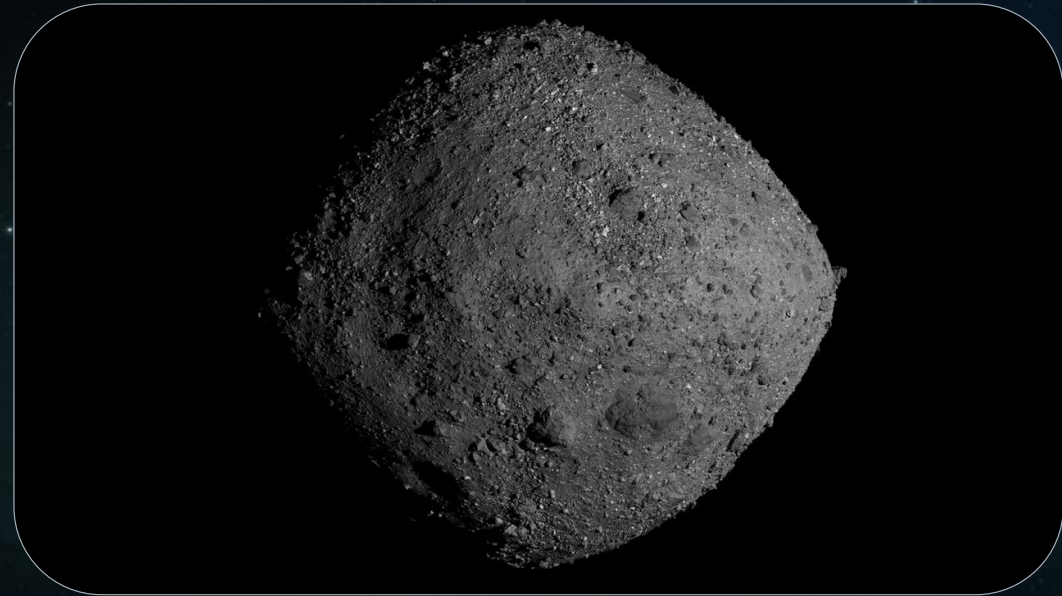
Measure fundamental distance parameters to probe the expansion of our universe and anchor studies of dark energy

Requires precise photometric accuracy in the visible and NIR, a large imaging field-of-view, and precision astrometry





WHAT ARE THE CHARACTERIS TICS OF NEAR-EARTH



Assess risks for humans on the Earth, Moon, and Mars from potentially hazardous asteroids, comets, & interstellar objects

Requires fast moving target tracking, large field-of-regard, and rapid response time



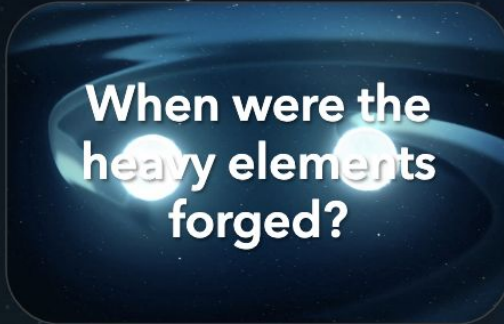
How is matter recycled by galaxies?



How does our solar system fit among other planetary systems?



How do stars and planets form?

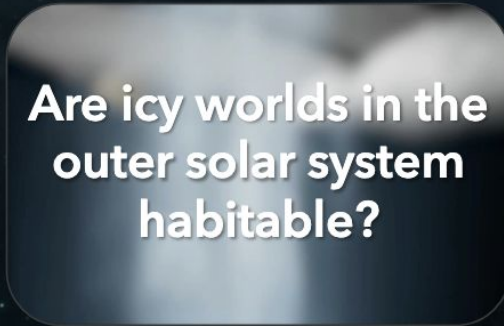


When were the heavy elements forged?



How many black holes are in the Milky Way?

H A B I T A B L E
W O R L D S
O B S E R V A T O R Y



Are icy worlds in the outer solar system habitable?



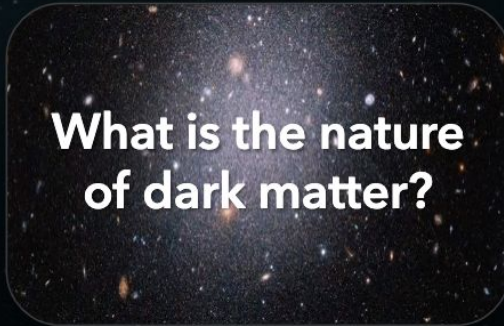
What are the characteristics of near-Earth asteroids?



How do the most massive stars live and die?



Is there life on exoplanets?



What is the nature of dark matter?

Your idea here

Your idea here

Your idea here

Your idea here

Your idea here

H A B I T A B L E
W R L D S
O B S E R V A T O R Y

Your idea here

Your idea here

Your idea here

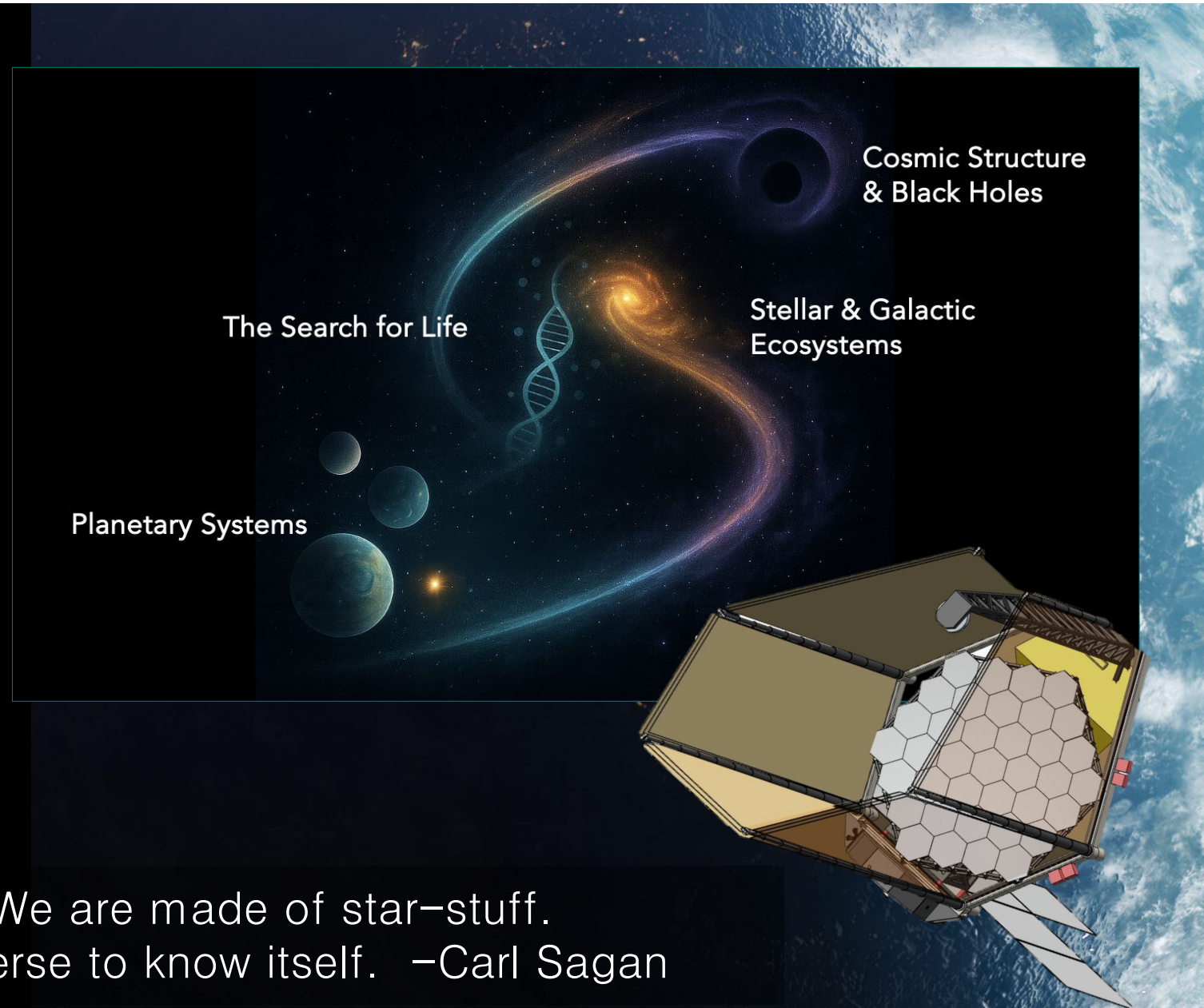
Your idea here

Your idea here

What is HWO?

A Super Hubble!

the next inevitable step
in Search of Earth 2.0
&
Our Cosmic Origins



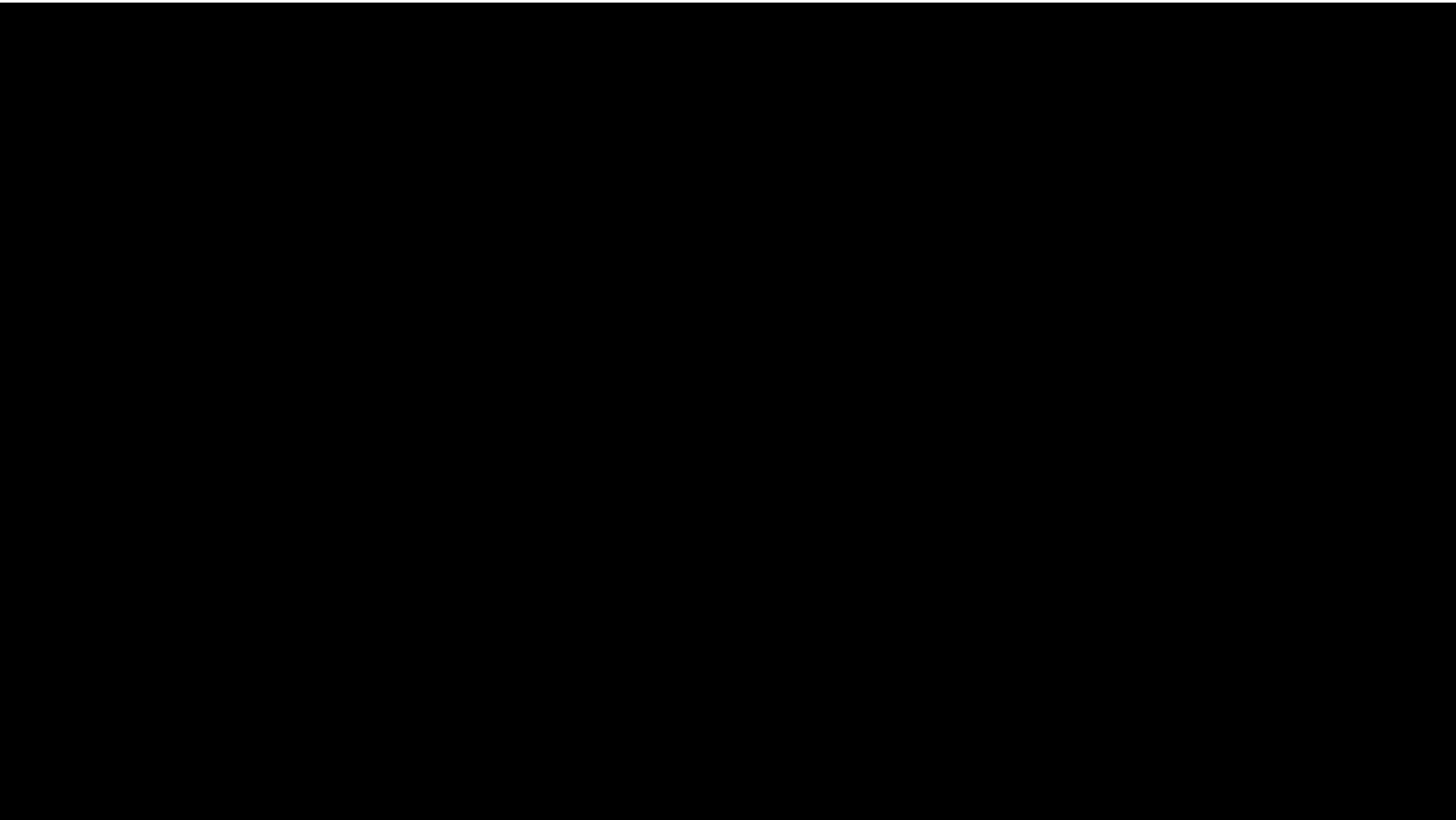
The cosmos is within us. We are made of star-stuff.
We are a way for the universe to know itself. –Carl Sagan

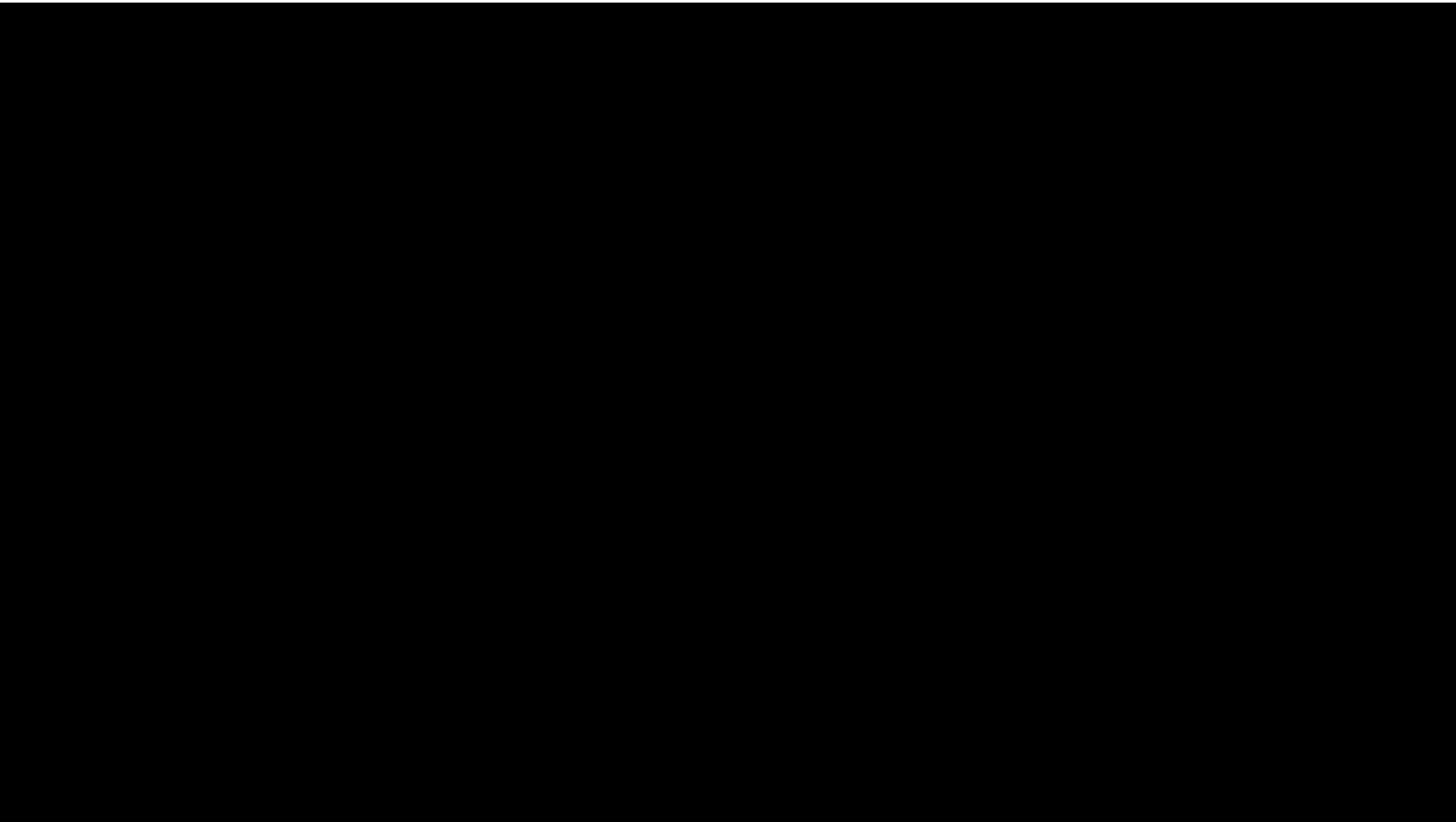
"If planets like Earth are rare, our own world becomes even more precious.

If **we** do discover the signature of life in another planetary system..."

ご清聴 ありがとうございます
~it will be by working together~







Organization of the HWO Science Community

January 2024 - July 2025

SCIENCE WORKING GROUPS

Galaxy Growth
Ravindranath & Postman

Solar Systems in Context
Robinson & Shkolnik

Living Worlds
Arney & Parenteau

Evolution of the Elements
Lee & Scowen

Four science working groups
delivered ~70 science cases

Summer 2025 - MCR

COMMUNITY SCIENCE & INSTRUMENT TEAM

13 US Members
4 International Reps

2 co-chairs

CSIT will help project explore scientific & instrumental trade space, develop draft science requirements, serve as community ambassadors

HWO SCIENCE INTEREST GROUP

Joint between ExoPAG,
PhysPAG, COPAG

Managed by community

Open membership

Habitable Worlds Observatory Evolution of the Elements Working Group



Janice Lee, STScI
Paul Scowen, NASA-GSFC

Which decadal science questions can
HWO help address?

What observations do we need to
answer those questions?

What capabilities will deliver those
observations?

Star Formation

Roberta Paladini, IPAC/Caltech
Samir Salim, Indiana U



Cosmic Explosions

Eric Burns, Louisiana State
Jennifer Andrews, Gemini/NOIRLab



Stellar Populations & Evolution

Peter Senchyna, Carnegie
Martin Barstow, U Leicester



Habitable Worlds Observatory Galaxy Growth Working Group



Swara Ravindranath, NASA-GSFC
Marc Postman, STScI

Which decadal science questions can
HWO help address?

What observations do we need to
answer those questions?

What capabilities will deliver those
observations?

AGN over Cosmic Time

Vivian U, UC Irvine
Chris Packham, UT San Antonio



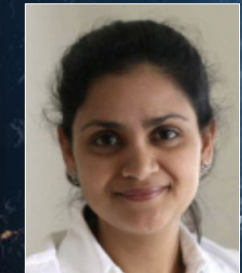
Ionizing Photons & their History

Stephan McCandliss, JHU
Allison Strom, Northwestern



IGM & CGM

Sanchayeeta Borthakur, ASU
Joe Burchett, New Mexico State



The Dark Sector

Jason Rhodes, JPL
Richard Massey, Durham U



HWO25 | JULY 28 – 31, 2025

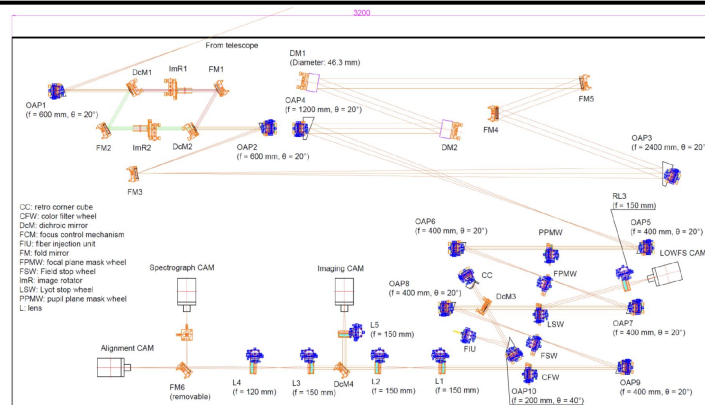
Towards the

HABITABLE WORLDS OBSERVATORY



ENYA Keigo (JAXA/ISAS HWO Task Force Lead)
“Japan's possible contribution to the HWO coronagraph”

A Voluntary study for entire IR coronagraph design



Drawing: by Kenta Yoneta

An example

Broadband coronagraphic masks

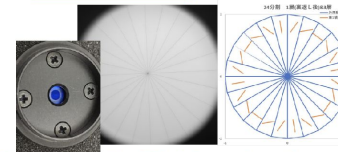
• Photonic-crystal coronagraphic masks

- **Multi-layer** phase masks → broadband stellar suppression
- **4th- and 6th-order** phase masks → robust against telescope pointing jitters

Nishikawa(NAOJ).
Murakami(et al.

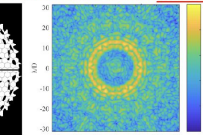
フォトニック結晶24分割位相マスク

Photonic-crystal phase mask (three-layer,
IWA~ 2λ/D 4-sector vortex)
IWA~ 3λ/D for 4th-order
IWA=3λ/D for 6th-order

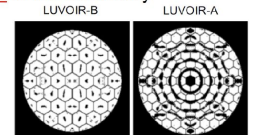


• Shaped pupils (SPs) for enhancing coronagraphic performance (LUVOIR, TMT, Subaru)

- TMT- and Subaru-optimized SPs have been **fabricated and tested** in the laboratory



Fabricated TMT (segmented mirror)-
optimized SP for the 24-sector vortex



SPs optimized for LUVOIR-A and -B with
8-octant phase mask. (Nishikawa et al.
(2020), Proc. SPIE, 11447, 114474T)

Leveraging synergies with NAOJ
Subaru Telescope in Hawaii for
technology development

HWO25 | JULY 28 – 31, 2025

Towards the

H A B I T A B L E W O R L D S O B S E R V A T O R Y



KAMEDA Shingo (Rikkyo & JAXA/ISAS
HWO Task Force sub-lead)
*“Far UV Integral Field Spectrograph &
High Resolution Spectrograph”*



JAXA UV Technology
Development Program
June 2025-

Collaboration with
Japanese Industry



I knew this at the meeting on 80
gratings with Shimadzu

It was written in their catalog
in 1882.

“We will manufacture
anything according to your
preferences.”

(if possible)

HWO25 Proceedings Editors

Postman, Lee, La Massa, Noviello



HST New and Important Features

Search HST Science Policy



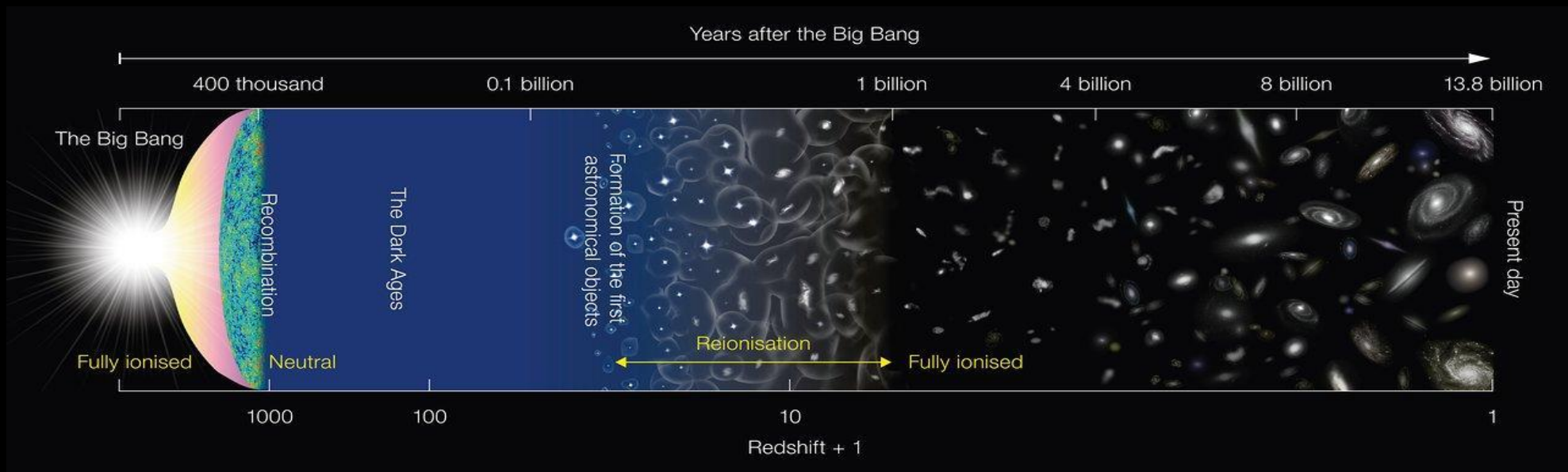
What's New for Cycle 34

The following are new policies, opportunities and features for proposers to consider this Cycle:

- **New Habitable Worlds Observatory (HWO) Precursor Science Initiative:**
 - STScI is introducing a new Habitable Worlds Observatory Precursor Science (HPS) initiative, aimed at encouraging observations with HST that will help guide HWO's science cases and early development. For more information, see [HST Special Initiatives](#).

HOW DO IONIZING PHOTONS DRIVE THE EVOLUTION OF COSMIC STRUCTURE?

Measure ionizing UV photon production and escape at low redshift ($z < 1.2$) to trace cosmic ionization, which sets how baryons cool, collapse, and form galaxies.



→ Multi-object spectroscopy at FUV wavelengths at low spectral resolving power ($R < 1000$) over several square arcmin

Credit: NAOJ

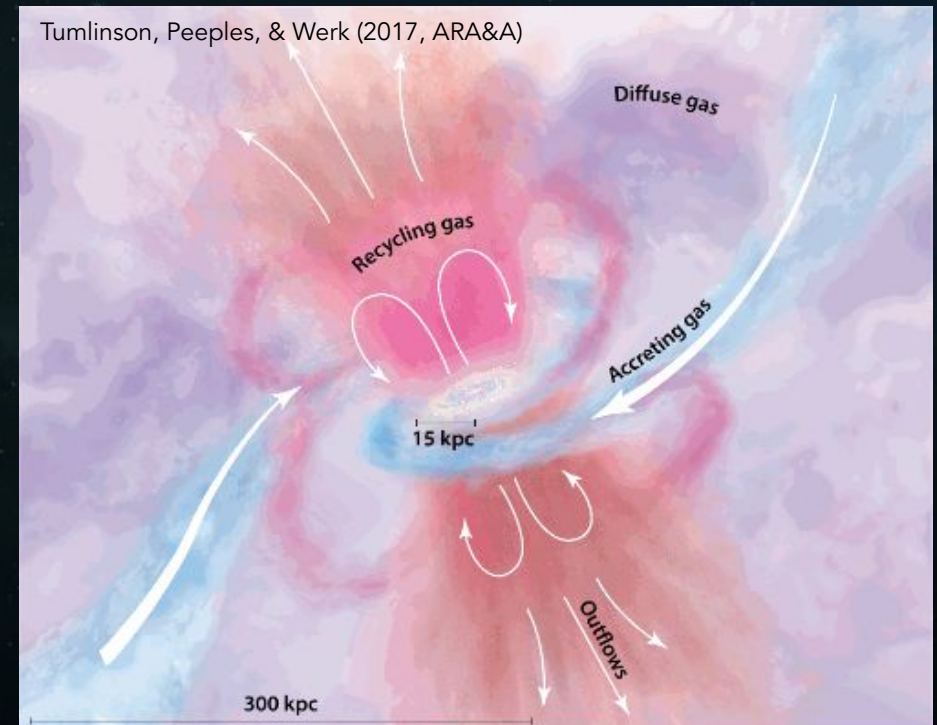
HOW DO MASS AND ENERGY FLOW IN AND OUT OF GALAXIES?

Measure how matter and energy flow into and out of galaxies.

This circulation of gas and energy through the circumgalactic medium (CGM) regulates star formation, feedback, and galaxy growth.

The gas and energy come from stellar winds, supernovae, and AGN.

→ UV absorption and emission spectroscopy from medium to high resolution over wide fields

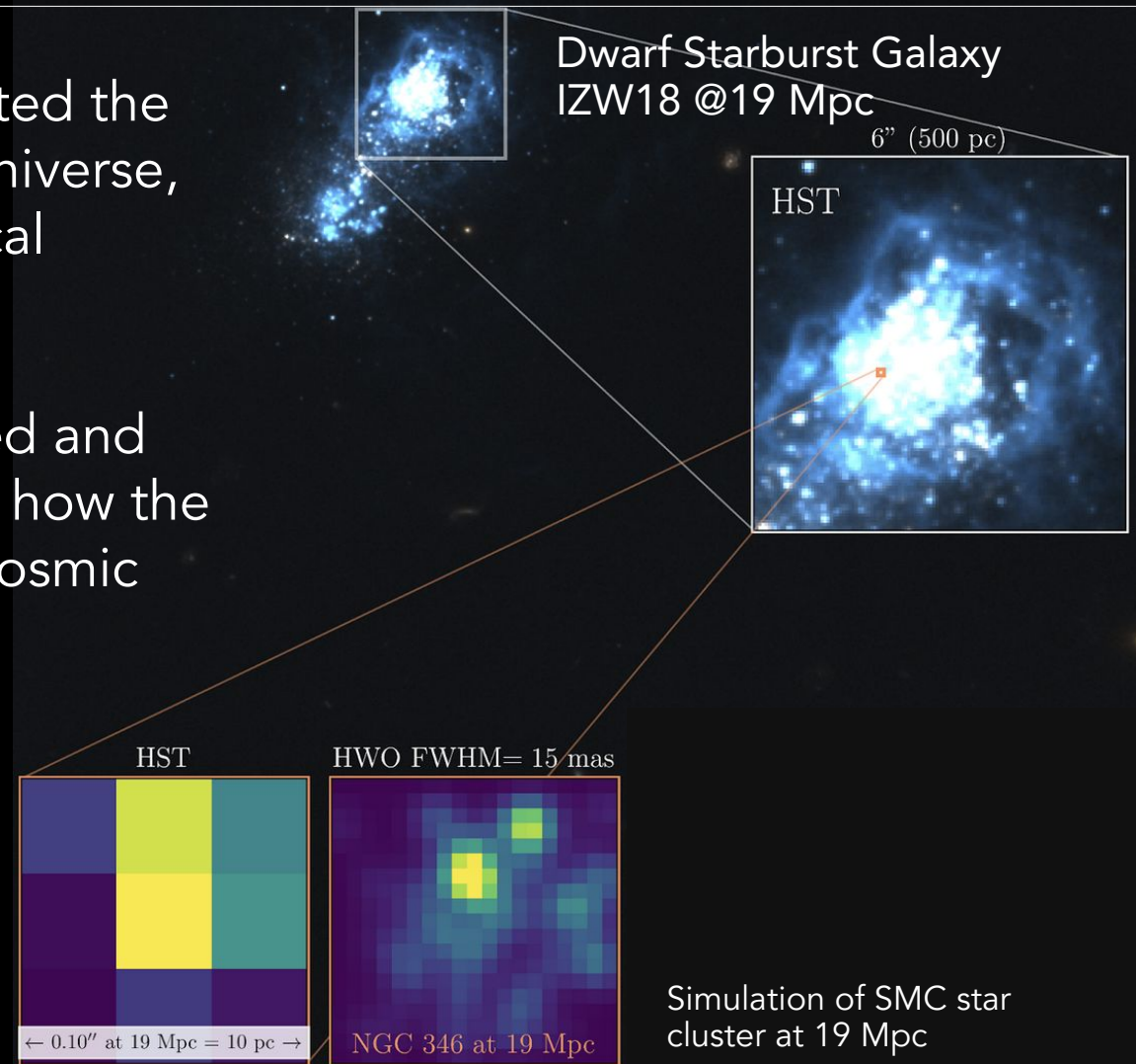


WHAT ARE THE MOST EXTREME STARS AND STELLAR POPULATIONS?

Massive, low-metallicity stars dominated the radiation and feedback of the early universe, shaping galaxy formation and chemical enrichment.

Understanding how these stars formed and evolved is essential to understanding how the first galaxies, and ultimately today's cosmic structure, came to be.

□ UV integral-field spectroscopy ($R \sim 5000$) to resolve clusters of massive stars in I Zwicky 18, the nearest chemically primitive ($\sim 1/50 Z_{\text{sun}}$) galaxy.

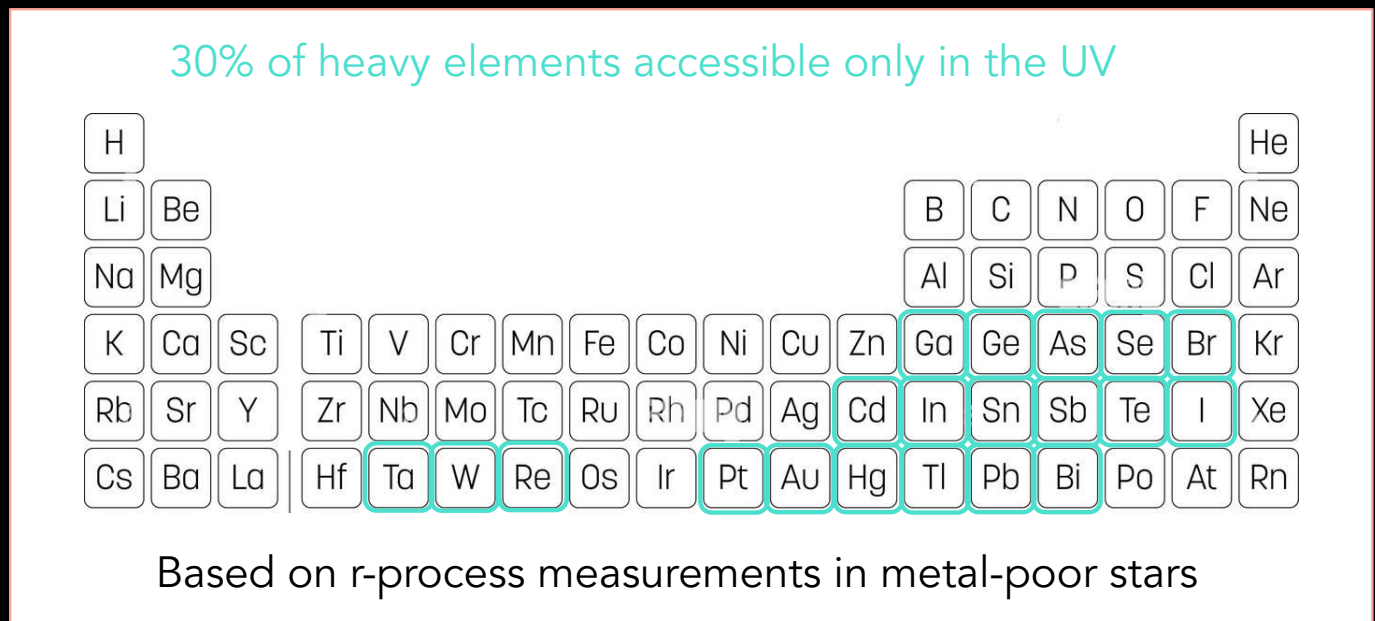


Senchyna & Hawcroft+25

WHAT ARE THE ORIGINS OF THE HEAVY (R-PROCESS) ELEMENTS ?

Chemical inventory of rapid neutron-capture process (r-process) elements and abundance patterns in cool (FGK) stars

Mapping the heavy element enrichment history of the Milky Way, to compare with rapid observations of neutron star mergers, and other possible sources of r-process nucleosynthesis

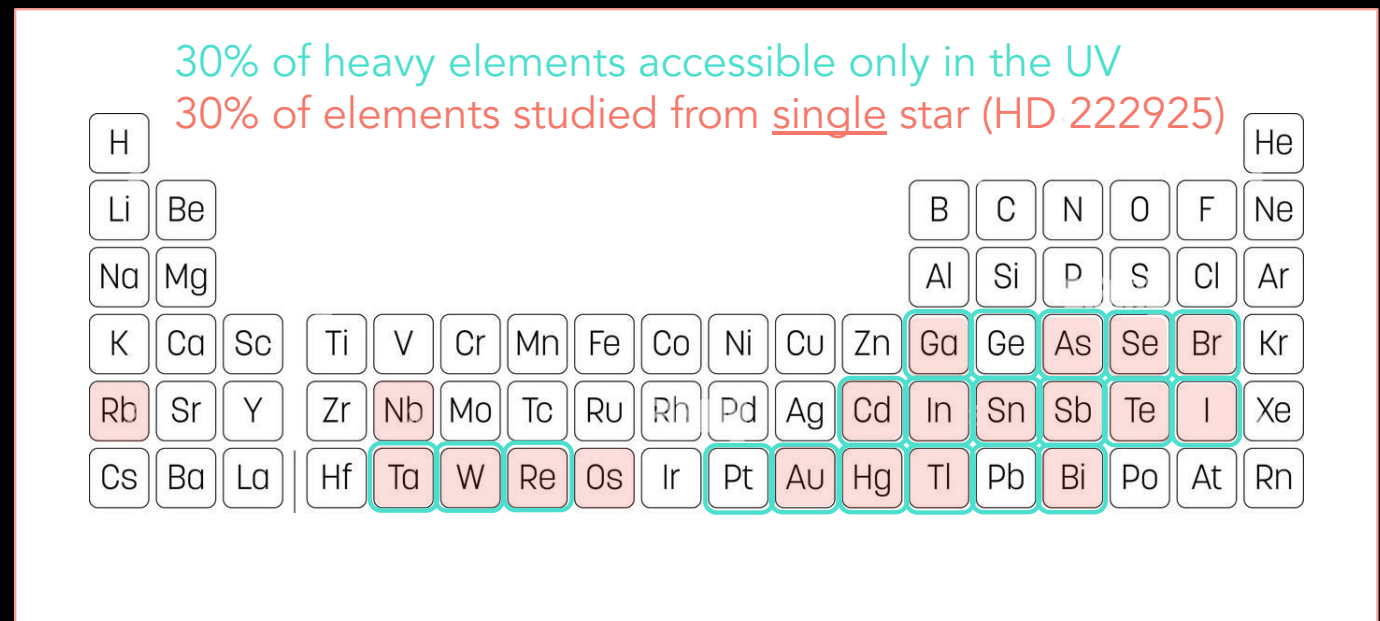


→ High-resolution UV spectroscopy ($R \sim 100,000$) of large stellar samples

See Roederer & Ezzeddine+25

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→ High-resolution UV spectroscopy ($R \sim 100,000$) of large stellar samples

See Roederer & Ezzeddine+25

ARE WE ALONE?

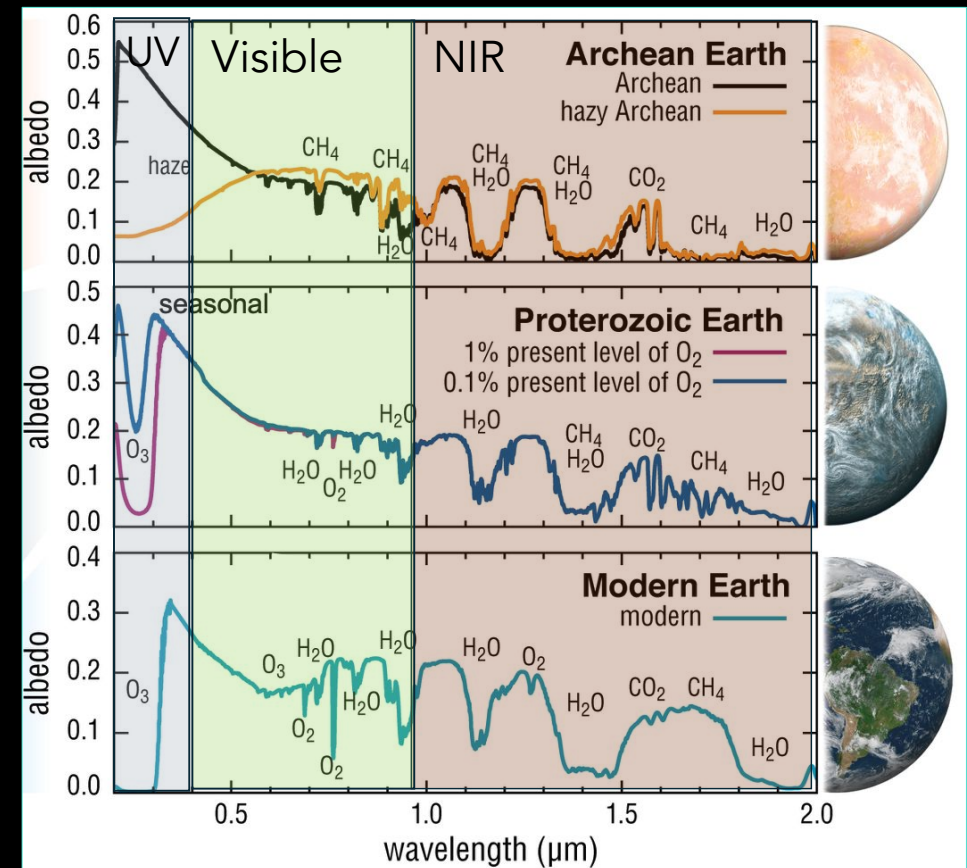
Detect and interpret biosignatures on Earth-like planets by measuring their atmospheres and surfaces in context.

And reveal surfaces and oceans via phase-dependent photometry

→ Need post-processed starlight suppression for planet-to-star flux ratios $\sim 10^{-10}$ and inner working angle of ~ 50 mas.

→ Need coronagraphic wavelength reaching into the NUV and NIR

→ Planetary masses via astrometry (or RVs)



Title: Report from the ISAS HWO Task Force: Japan's Potential Contribution to HWO and its Coronagraph

Lead author: Keigo Enya

Abstract: We present a report from the ISAS HWO Task Force (TF), which represents Japanese participation in the Habitable Worlds Observatory (HWO). First, we briefly outline the scientific interests and the research communities in Japan that form the background of our participation in HWO. Next, we report on the role of the TF and its activities so far. Currently, regarding Japanese hardware contributions to HWO, participation in both the coronagraph and the UV instruments is considered. Various scales of contribution are under consideration for each instrument, ranging from system level to component level. Finally, we highlight Japan's technological heritage relevant to these instruments. We also provide a brief overview of the current status of our studies regarding the coronagraph.

Report from the ISAS HWO Task Force: Japan's Potential Contribution to HWO and its Coronagraph



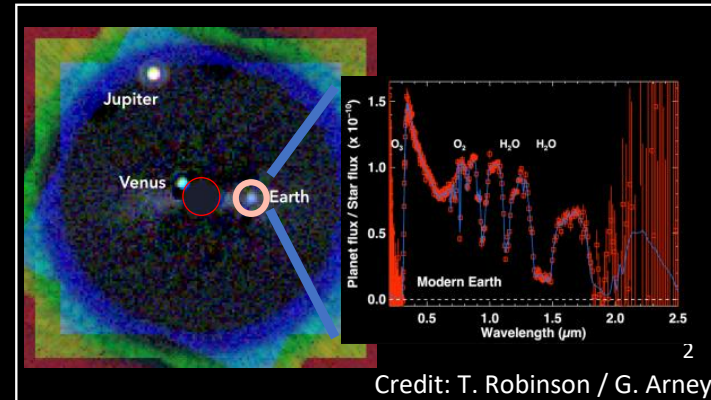
2026-07-15

Keigo Enya (JAXA/ISAS)

Key questions and motivation for Japan's participation in HWO

- *How do habitable worlds form?*
- *How common/rare is Earth?*
 - Search for Habitable Worlds
 - Atmospheric Evolution of Terrestrial Planets
 - Galaxy Formation. Elemental Distribution

Extra-solar system



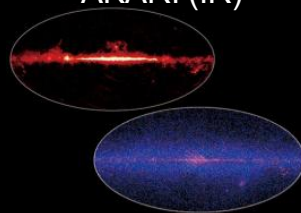
In the solar system



- The HWO's scientific objectives, for *exoplanet*, *solar system planet*, and *advanced astrophysics*, are truly important, and Japan is highly motivated to participate in HWO.

Number of members of the academic society

- Japan Geoscience Union (JpGU): ~10,000
- Astronomical Society of Japan (ASJ): 3,300
- Society of Geomagnetism and Earth, Planetary and Space Sciences (SGEPS): ~700
- The Japanese Society for Planetary Sciences (JSPS): ~600
- NASA/Roman Coronagraph Community Participation Program (CPP): ~20



ISAS/JAXA HWO study task force

Representative of JP HWO participation

- It should be noted that two ISAS/JAXA representatives, [Takahiro Sumi \(Osaka Univ.\)](#) and [Satoshi Miyazaki \(NAOJ\)](#), participated in HWO/START activities previously.
- **ISAS/JAXA created the “ISAS HWO study task force (TF)” team in Dec. 2024** ([Keigo Enya\(lead\)](#) + 7 persons).
- Main role of the TF
 - Representative of effort of Japan HWO participation Works in ISAS/JAXA toward participation in HWO
 - Information hub among Japanese communities (NAOJ, institutes, universities) that participate in the HWO (contributions by hardware and/or science)
 - International coordination with NASA’s HWO project office and other institutes as the PoC of Japan for HWO.

ISAS/JAXA HWO study task force

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These movements are evidence toward participating to HWO by ISAS/JAXA together with Japanese community, not only interest by individual scientists

- Receiving a request from NASA, CSIT ex. officio of Japan and Hardware POC has been determined as below.
 - CSIT ex. officio of Japan
 - Takahiro Sumi (Univ. of Osaka)
 - Hardware POC
 - For coronagraph: Keigo Enya (ISAS/JAXA)
 - For UV hardware: Shingo Kameda (Rikkyo Univ., ISAS/JAXA), (cc Keigo Enya)



ISAS/JAXA HWO TF's first visit to GSFC HTMPO (2025 Feb. 25)

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The TF is preparing to upgrade itself to the ISAS HWO Study Team.

ISAS/JAXA HWO TF's first visit to GSFC HTMPO (2025 Feb. 25)

Considered contributions from Japan to HWO

Coronagraph hardware

- The TF and colleagues in NAOJ and Japanese community (TF+) are considering the possibility of hardware contributions of any scale.
- (1) The first preference in coronagraph at this time is the **Japanese-led Near Infrared (NIR) coronagraph arm**.
- (2) The second preference is **to contribute to coronagraph of any wavelength range by providing medium or small-scale component**.

** Even if (1) is realized, possibility of (2) is not excluded automatically (e.g., (1) + a very small mask for visible (VIS) coronagraph is potentially possible).*

UV(+VIS) hardware

- The TF+ are considering hardware contribution by **Japanese-led Integral Field Spectrometer (IFS) for UV (covering part of VIS) and UV High Resolution Spectrometer (HRS)**
- The TF+ are developing High-QE Large-Format FUV detector for **IFS**, **HRS**, and also for **MOS**.
- The TF+ are willing to consider/discuss any international collaboration to prepare the best instruments.

** For more detail, see S. Kameda's presentation*

Others

- Possibility of other contributions are also not ruled out. For example, contribution for servicing mission.
- Participation in the activity not only on hardware development but observation planning., etc.
- Scientist exchange program (particularly for young researchers).

Providing one big picture of comprehensive contribution to exoplanet and other science, composed of multi-wavelength hardware, science, and human resources.

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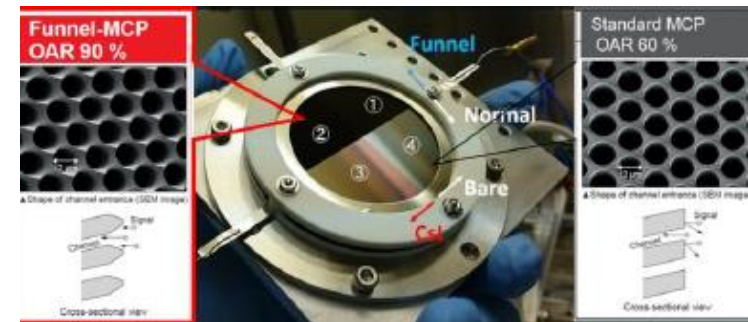
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Ongoing development using ISAS/JAXA technology Front Loading (FL) program

- FL is an ISAS/JAXA internal program to develop key technologies ahead of missions to make TRL=3 to TRL=5.
- The following two HWO-related themes have been selected and are currently under development toward the HWO MCR. These were started in 2025 and will end 2029 (TBC). Schedule of work is flexible.
- **Coronagraph technology** (~2M USD in these four years):
 - Segmented phase masks (coronagraph mask) and experiment system for it.
- **UV instrument technology** (~2 M USD in these four years):
 - Microchannel Plate (MCP) detector, Integral Field Unit (IFU), Holographic Blazed grating, Echelle grating, FUV coating, and FUV Large Format Detector.



Example of phase masks for coronagraph (Photo. of previous version) and a vacuum testbed under development (Nishikawa+).



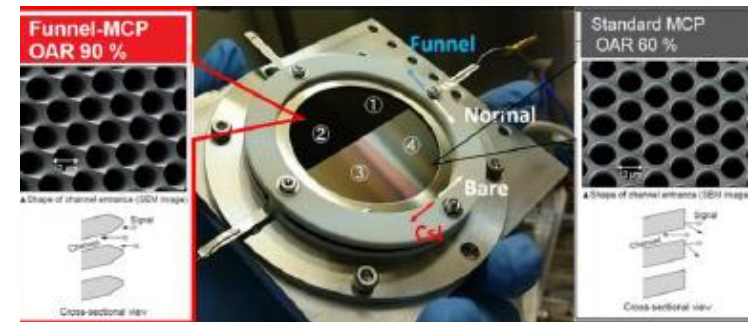
FUV large format detector (Photo. of previous version) ([Matoba et al 2011 Jpn. J. Appl. Phys]).

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FUV large format detector (Photo. of previous version) ([Matoba et al 2011 Jpn. J. Appl. Phys])

TF is currently preparing to expand the membership of FL.

Heritage of Space-based UV instrumentation in Japan

More details are
in presentation
of S. Kameda

LAPYUTA (2032?-)

Hisaki/EXCEED
(2013-2023)

Space
telescope

UV observation is one of
key technologies in Japan

Solar System
explorations

Kaguya/UPI-TEX (2007-2009)

Nozomi/UVS (1998-2003)

PROCYON/LAICA (2014-2015)

ISS-JEM/IMAP-EUVI (2012-2015)

Earth's upper
atmosphere

EQUULEUS/PHOENIX (2021-2024)

Comet Interceptor/Hi (2029-)

Nozomi

Kaguya

ISS/IMA

Hisaki

BepiColombo

Comet

Interceptor

LAPYUTA

EQUULEUS

2000

2005

2010

2015

2020

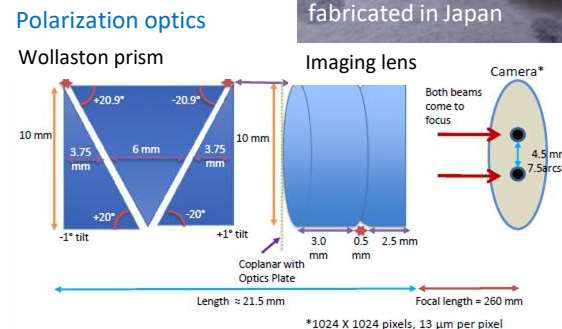
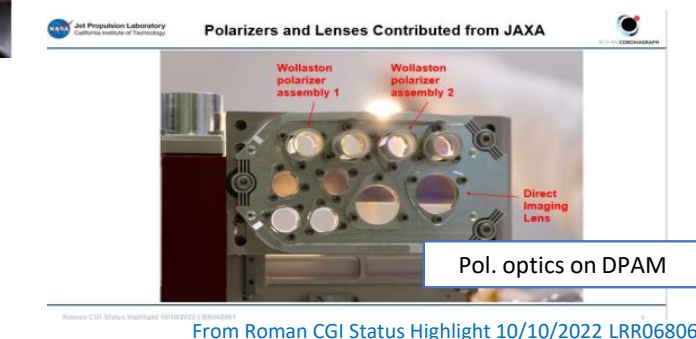
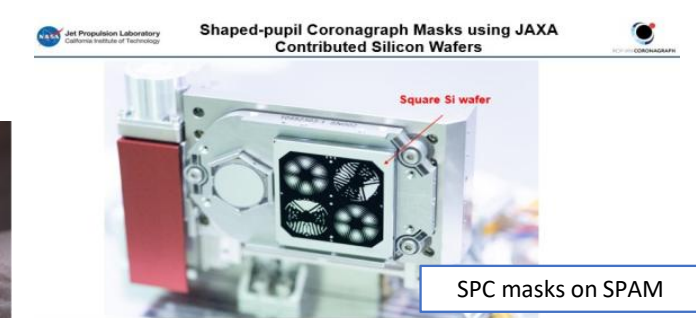
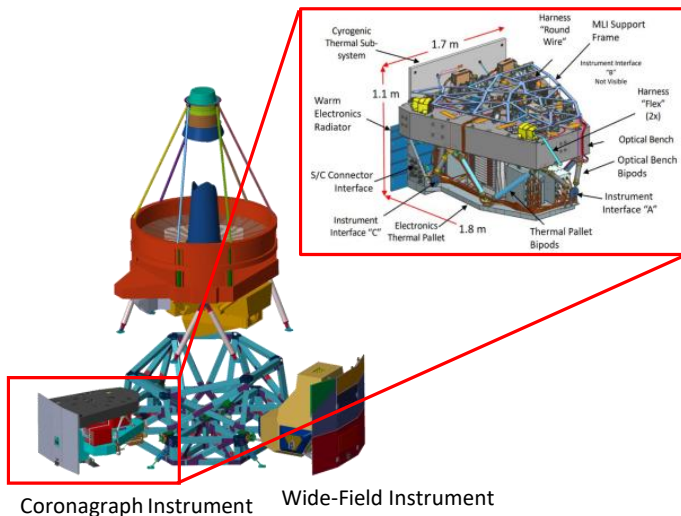
2025

2030

Project level background of Japan for HWO coronagraph: (1/3) ISAS/JAXA Contribution for Roman Coronagraph Instrument

- Substrates for coronagraphic masks
- Wollaston prisms and imaging lenses for polarimetric mode
- Currently, about 20 researchers join the Coronagraph Community Participation Program (CPP) through ISAS/JAXA.

**Subaru with 100 nights observation and Ka band communication and PRIME telescope with ISAS/JAXA also contribute to RST.*

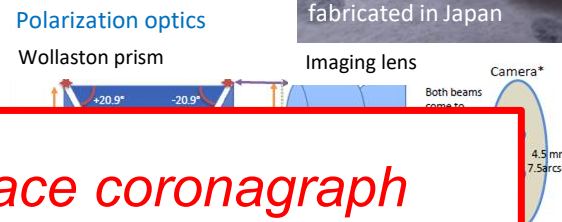
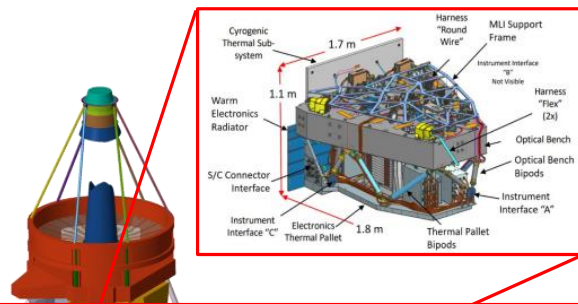
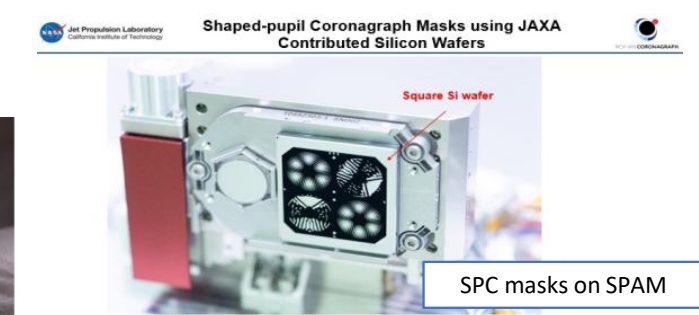


From Roman CGI Status Highlight 10/10/2022 LRR068061

Project level background of Japan for HWO coronagraph: (1/3) ISAS/JAXA Contribution for Roman Coronagraph Instrument

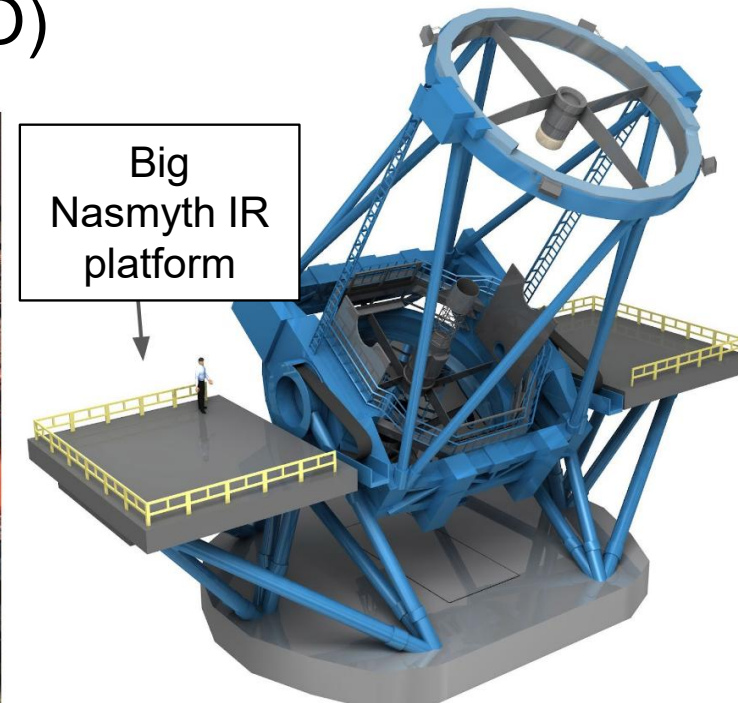
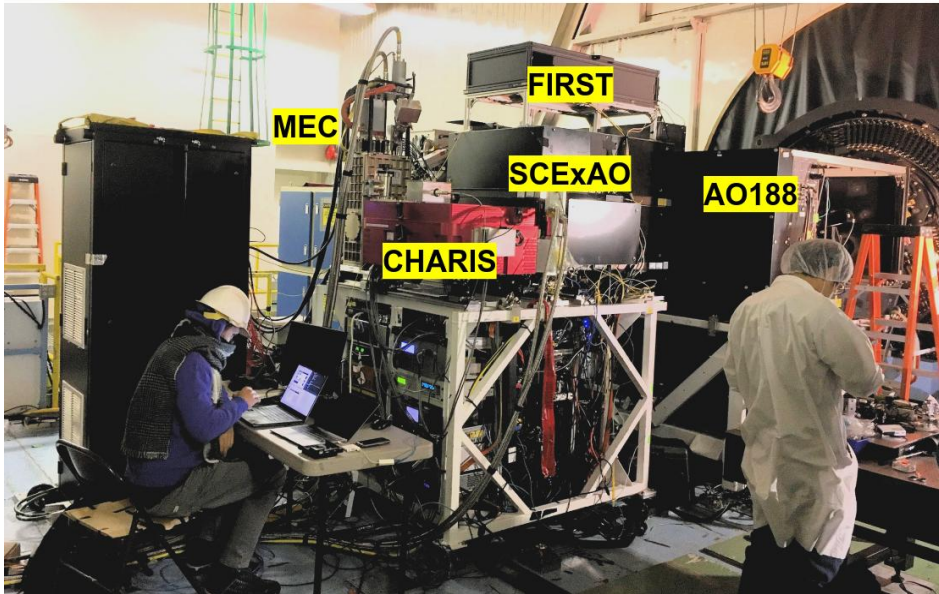
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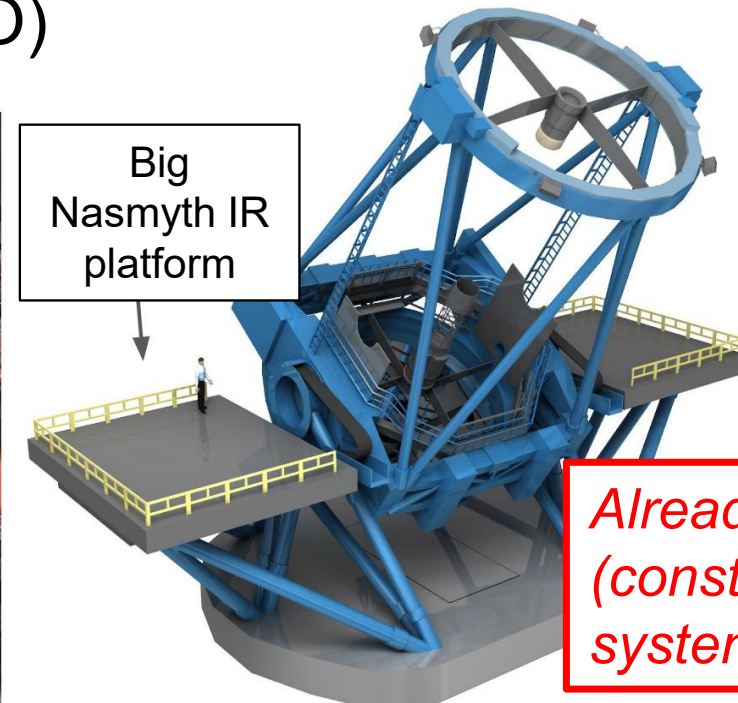
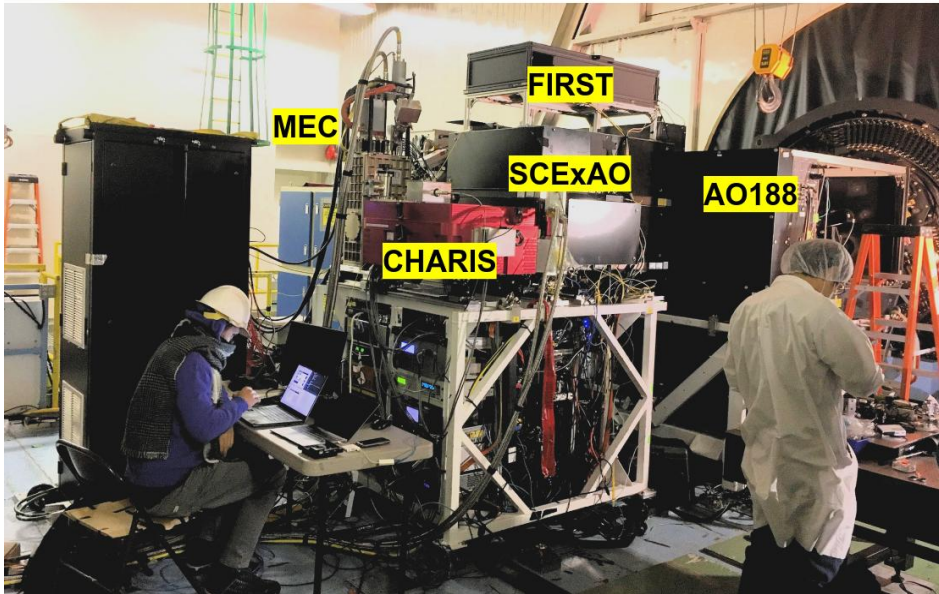
H/W contribution to a real space coronagraph project, experience of international collaboration

(2/3) Subaru Coronagraphic Extreme Adaptive Optics (SCExAO)



- SCExAO to be used for
 - System-level technology validation of the HWO-J coronagraph at intermediate ($\sim 10^{-8}$) contrast
 - Scientific observations
 - Workforce development
 - Development of the NIR photonic (fiber-based) spectrograph concept
- More details are in presentation of Guyon*

(2/3) Subaru Coronagraphic Extreme Adaptive Optics (SCExAO)



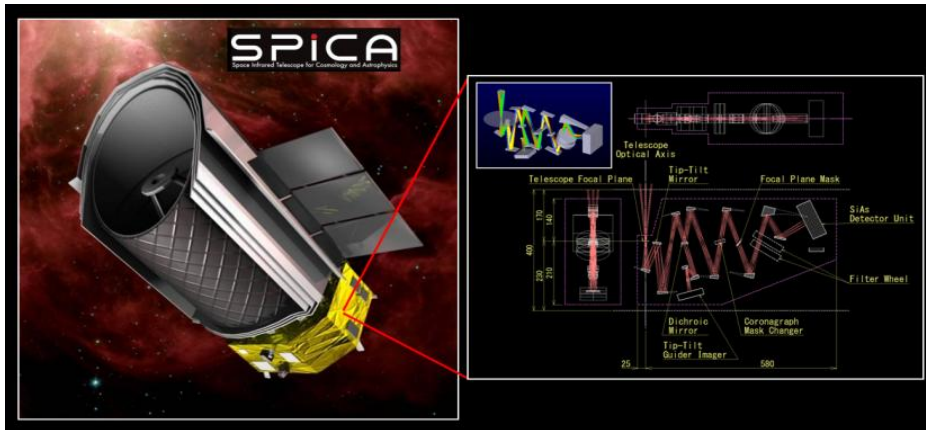
Already working system (constantly evolving system). This is unique!

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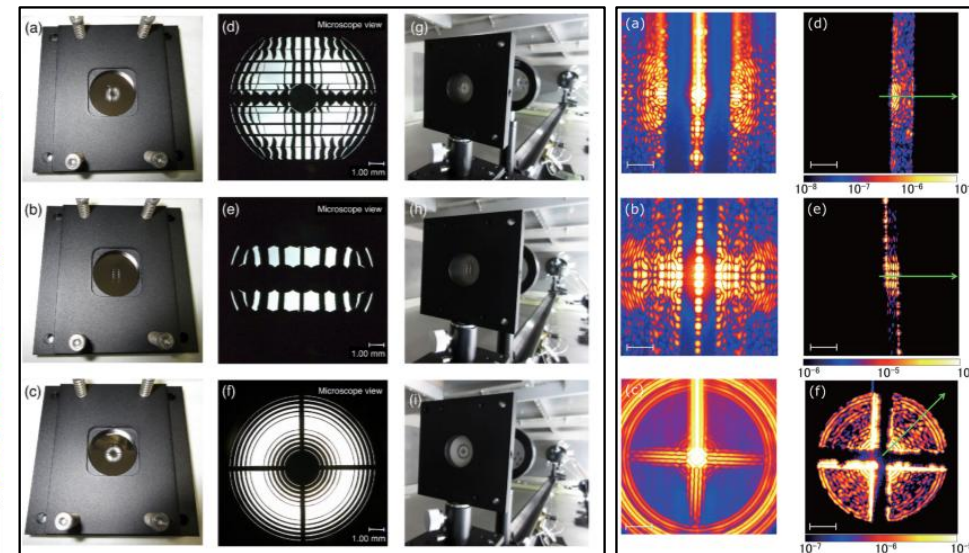
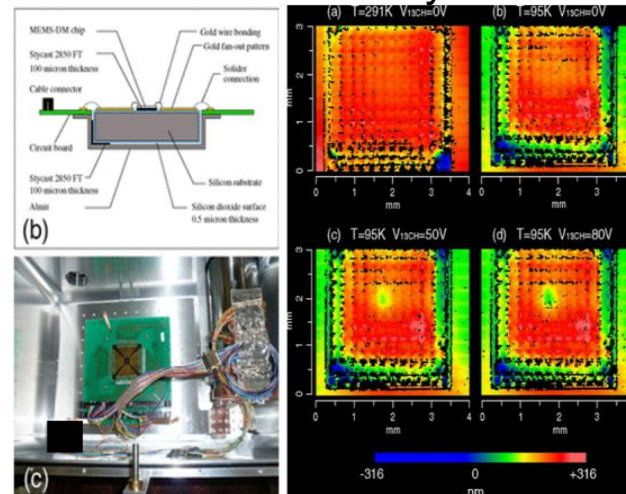
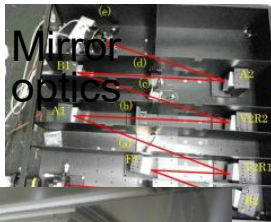
(3/3) SPICA Coronagraph Instrument (SCI)

Reference list is in Appendix



Main science objective	direct imaging of exoplanet & spectroscopy for exoplanet atmosphere
Main target	Jovian exoplanet
Core wavelength	3.5–28 μm
Contrast	10^{-7}
Coronagraph type	Shaped pupil mask (Transmissive)
Instrument environment temp.	$\sim 5\text{ K}$

- For SPICA, previously we were developing a coronagraph instrument and high contrast technology for it.
- Finally, both the SPICA and SCI projects were canceled.



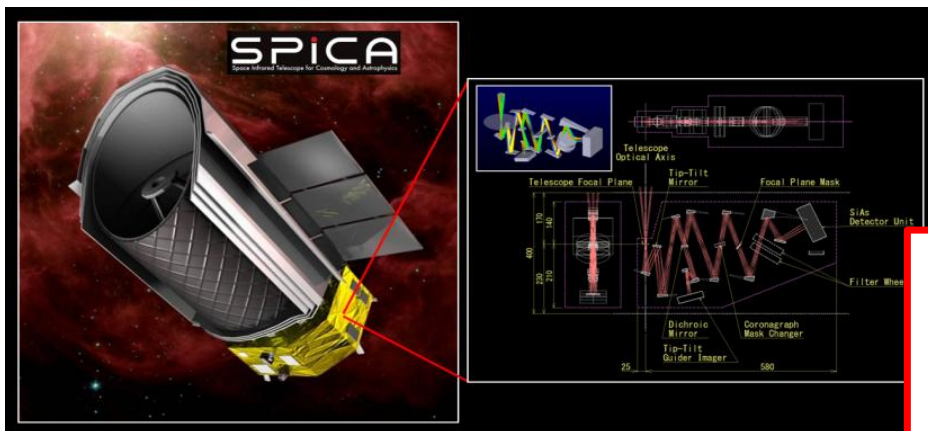
Coronagraph masks



Vacuum chamber

(3/3) SPICA Coronagraph Instrument (SCI)

Reference list is in Appendix

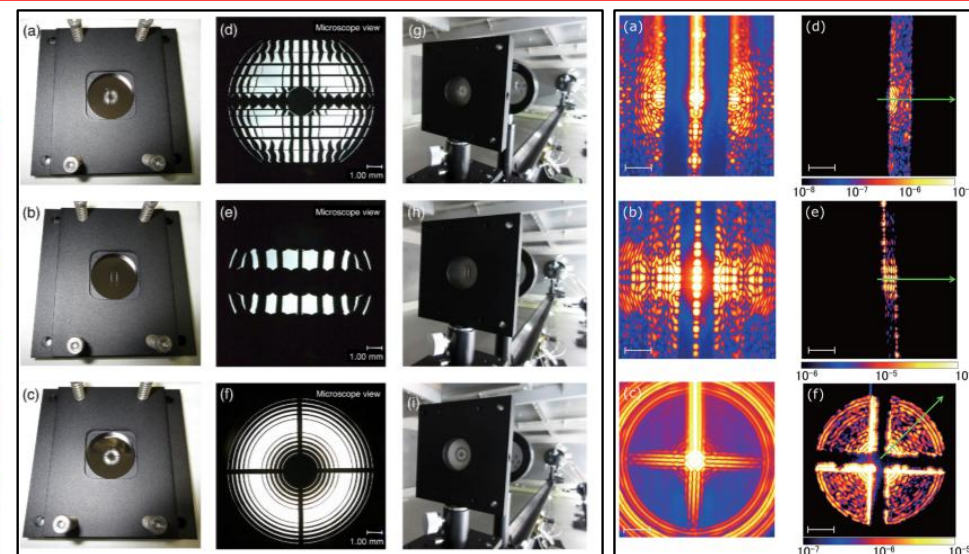
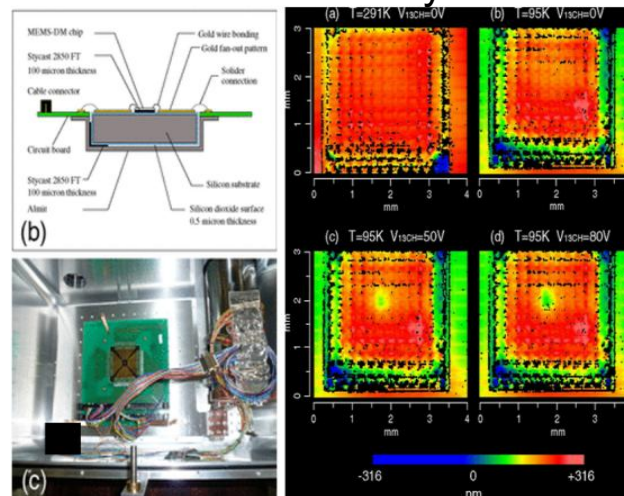
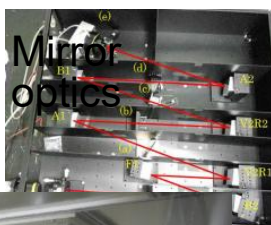


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Canceled, but we obtained various experiences in designing an entire space-borne coronagraph instrument and developing technologies such as the coronagraph masks (10^{-7} contrast w/o DM).

- For SPICA, previously we were developing it.
- Finally, both the SPICA and SCI projects were canceled.

Cryo. DM



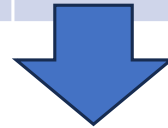
Coronagraph masks



Vacuum chamber

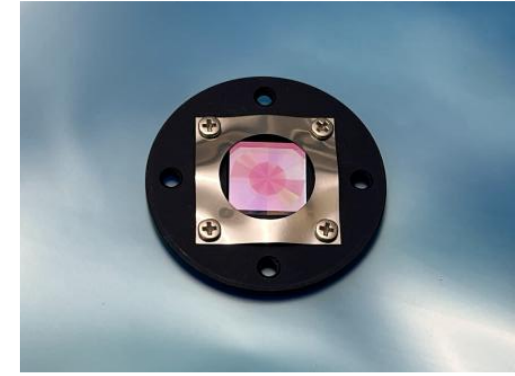
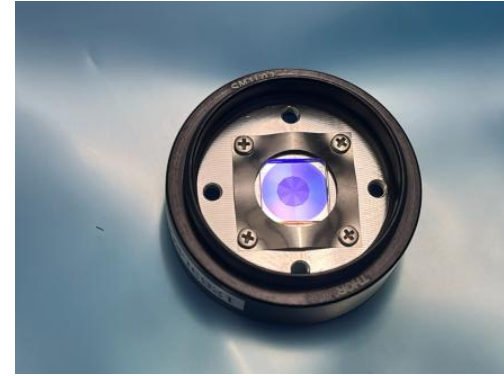
The three backgrounds are complementary

	High contrast technology	Instrument/ System level scale?	Space mission?	Finally realized?
(1) Participation to NASA/Roman	~Yes	No	Yes	Yes
(2) SCExAO (SUBARU)	Yes	Yes	No	Yes
(3) SPICA coronagraph instrument	Yes	Yes	Yes	No



Toward Japan's H/W contribution to the HWO coronagraph!

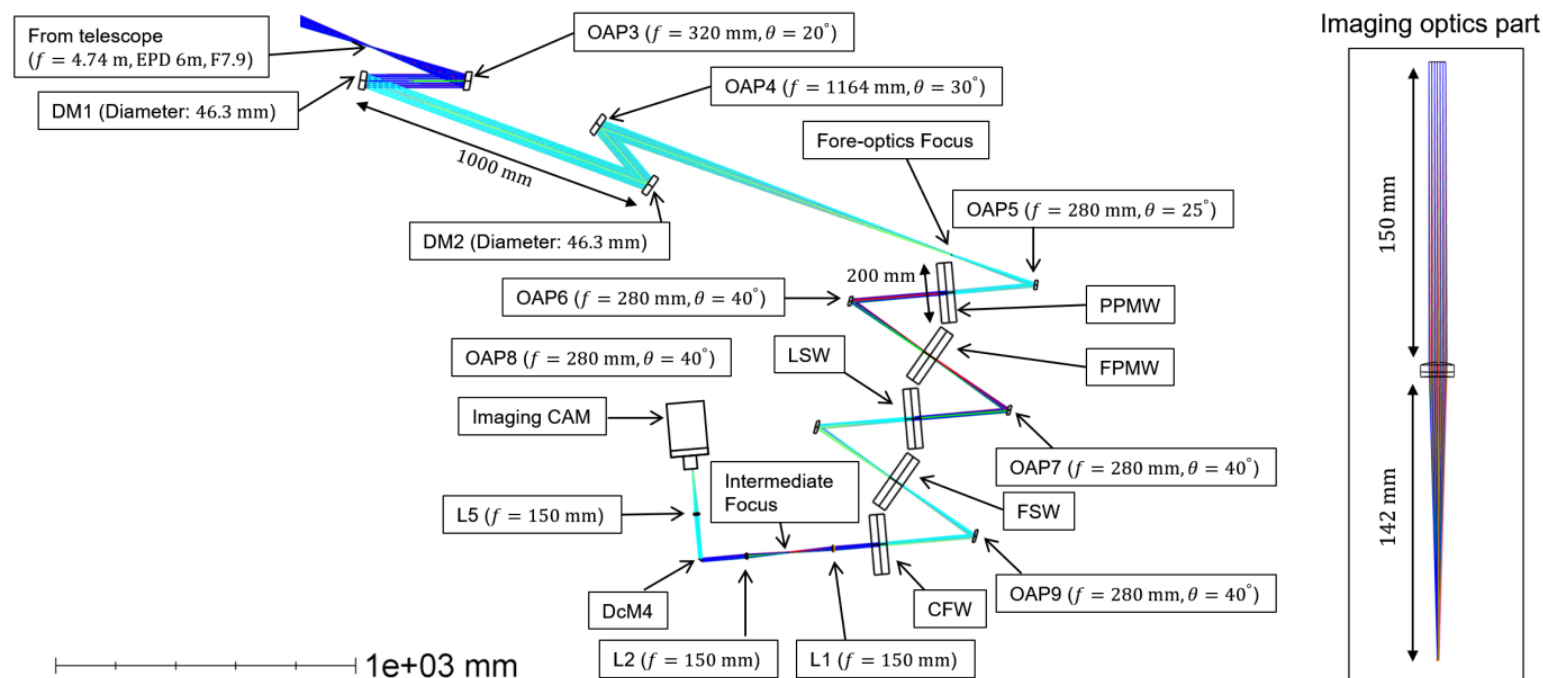
Coronagraph technology currently under development by HWO-J



Manufactured segmented photonic-crystal phase mask for VIS (left) and for NIR (right).

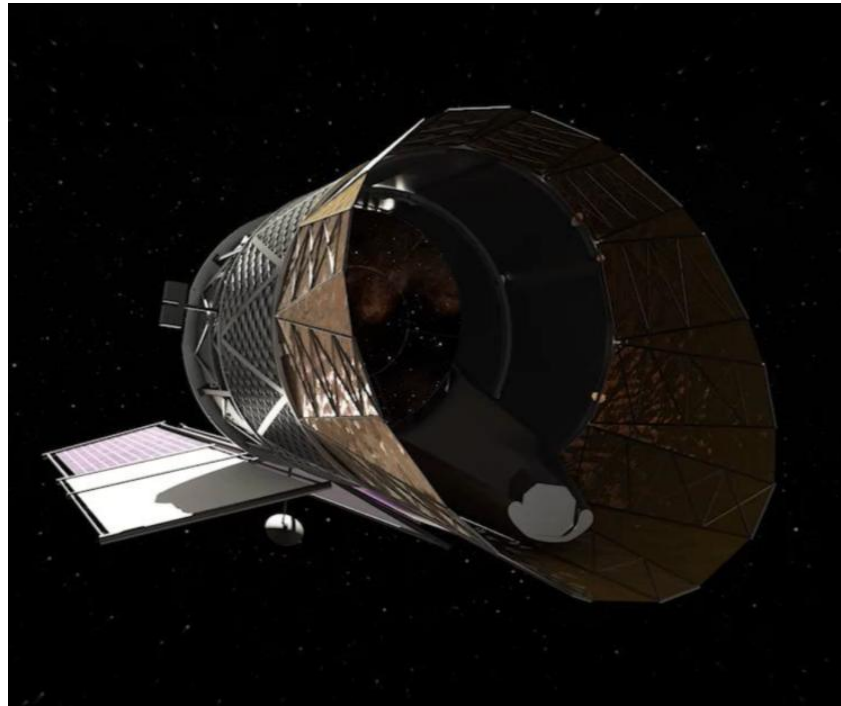
- Segmented photonic-crystal phase mask for coronagraph (ISAS Tec. FL program) (*e.g., Mukarami, Nishikawa, et al. Proc. SPIE, in press*)
- Efficient NIR Spectroscopy of Habitable Planets: Concept and Technology Validation Plan with Subaru Telescope → *O. Guyon, Day-2 09:00-*
- Development of Astro-Photonic Integrated Circuits for Direct Imaging of Exoplanets → *R. Kojima, Day-2 09:30-*
- A Bar-coronagraph with a Small Inner Working Angle: The One-dimensional Diffraction-limit Coronagraph (1DDL) → *S. Itoh, Day-2 10:00-*

Optical design for the NIR Coronagraph channel



- Example of the optical design for the NIR coronagraph
- The purpose of this design is our own study and understanding of the size.
- Our own sensitivity calculation is ongoing.
- We are planning comparative study of optical designs incorporating individual coronagraph technology.

Thank you for your listening!



Title: Status of UV Technology Development (Instrument Study) towards the Habitable Worlds Observatory

Lead author: Shingo Kameda

Abstract:

We performed a conceptual design study on a high-resolution spectrograph (HRS) and an integral field spectrograph (IFS) for far UV (FUV) as potential contribution to HWO by JAXA. We are developing a large-format high-efficiency funnel microchannel plate (MCP) for photon counting and high-reflectivity coating. In design, the spectral resolution of HRS is $> 120,000$ with the spectral range of 100-180 nm, which covers H, C, N, and O atomic emission lines and C and N ionic emission lines. The IFS is composed of an image slicer, 80 gratings and 4 MCP detectors, which a wide FoV mode (FoV $> 5'' \times 5''$, slit width of $\sim 0.03''$, R ~ 5000) and a narrow FoV mode (FoV $> \sim 2'' \times 5''$, slit width of $\sim 0.07''$, R ~ 2000) with the spectral range of 94-174 nm.

Science Case Summary

Earth-like planets have been detected in the habitable zone of low-mass stars. However, transit spectroscopy requires extremely high precision to observe the thin layer of lower atmosphere of a small terrestrial planet, and at present no atmospheres of terrestrial exoplanets have been detected. On the other hand, strong XUV radiation of low-mass stars may cause the far-extended upper atmospheres. We investigate the possibility of detecting the upper atmospheres of terrestrial exoplanets by transit spectroscopy with future ultraviolet space telescopes, LAPYUTA and Habitable Worlds Observatory (HWO). There are several atomic and ionic emission lines (H, C, N, and O) in the far UV spectral range which will be helpful for understanding the surface environment of the exoplanet especially in case the lower atmosphere cannot be detected. In addition, icy moons in the solar system have water plumes. H and O atoms are generated by dissociation and could be detected by far UV imaging spectroscopy.

STATUS OF UV TECHNOLOGY DEVELOPMENT (INSTRUMENT STUDY) TOWARDS THE HABITABLE WORLDS OBSERVATORY

Shingo Kameda
Rikkyo University

JAXA/ISAS HWO Task Force
HWO-J-UV team

KEY QUESTIONS/SCIENCE DRIVERS FOR HWO

How do habitable worlds form?

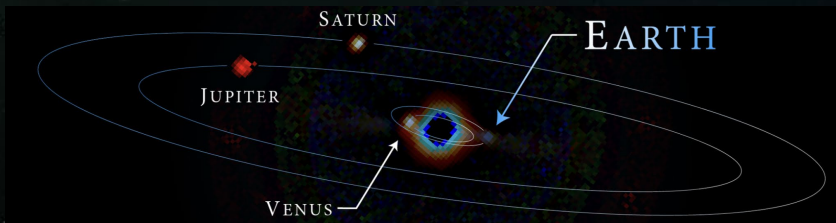
How common/rare is Earth?

Search for
Habitable Worlds
in Solar System

Atmospheric
Evolution of
Terrestrial Planets

Galaxy Formation
Elemental Distribution

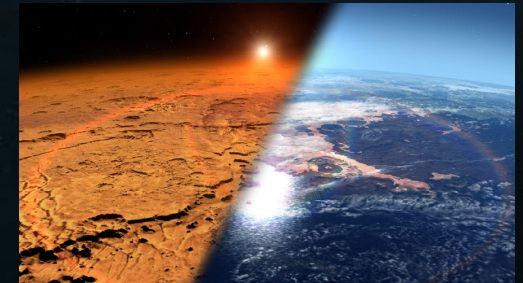
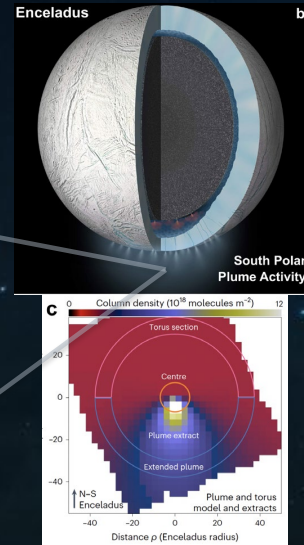
→UV observation



In addition to Direct Imaging of Exo-Earth,



Cartwright+2026



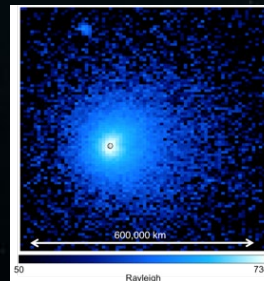
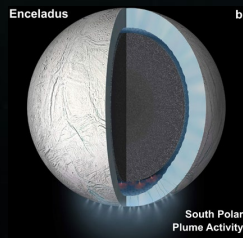
REQUEST FOR UV OBSERVATION

Please see
Kato+ presentation
in session 10

Summary of the requests from Planetary Scientists and Astronomers in Japan, and CSIT

	Icy Moons	Martian Atmosphere	Escaping Atmosphere of Earth-sized Exoplanet	Galaxy	CSIT Recommendation for IFS (Feb. 11)
Angular Resolution	0.03"	0.06" (0.1" for D/H)	(Point Source)	<0.05"	~0.02"
Field-of-View	3" x 3"	3"x3" (<0.1"x>8" for D/H)	(Point Source)	3" x 3" (+10" x 10")	~3" x 3"
R ($\lambda/\Delta\lambda$)	5000 (>3000)	3000 (40000 for D/H)	~120,000	5000	~4000
Spectral Range	~100 nm -	~100 nm -	~100 nm -	~100 - 300 nm	~100 – 400 nm
	H, C, N, O	H ₂ , H(D), C, N, O	H, C, N, O, Temperature	O IV ,,,,,, MgII	

Avoiding oxygen geocorona is essential (especially for Planetary Science)



Emission in Far UV
H I: 121.6 nm, 102.6 nm
O I: 130.5 nm
N I: 113.4 nm, (120.0 nm)
C I: 156 nm, 165.7 nm (, ~110nm)

N II: 108.4 nm
C II: 133.5 nm, 103.6 nm

TMPO STUDIED INSTRUMENTS FOR EAC 5

Telescope

Diameter	≥ 6.0 m
Bandpass	~100–2500 nm
Diff. Limit @	~500 nm



UV Integral Field Spectrometer (IFS/IFU)

UV integral field spectroscopy

Bandpass	~100–400 nm
Field-of-View	~3" x (1.5–3)"
Angular res.	~20 mas
R ($\lambda/\Delta\lambda$)	~4000

UV Multi-Object Spectrograph

UV / Vis multi-object spectroscopy and FUV imaging

Bandpass	~100–1000 nm
Field-of-View	~3' x 3'
Apertures	~840 x 420
R ($\lambda/\Delta\lambda$)	~500 & 50,000

High-Resolution Imager

UV / Vis and NIR imaging

Bandpass	~200–2500 nm
Science FoV	~3' x 2'
Astrometry FoV	~12 sq. arcmin
~40 science filters & grism	

VIS / NIR Coronagraph

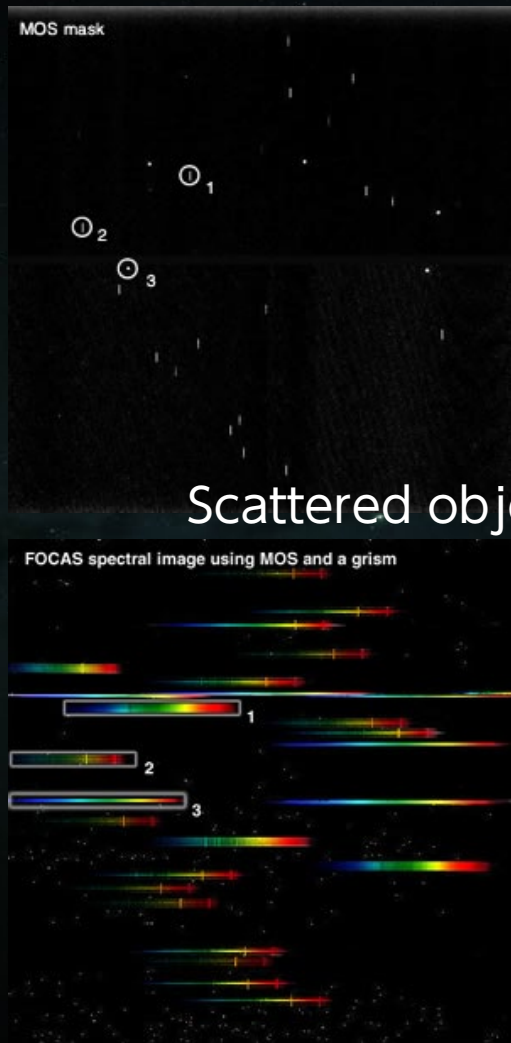
High-contrast imaging and imaging spectroscopy

Bandpass	~450–1700 nm
Contrast	$\lesssim 1 \times 10^{-10}$
R ($\lambda/\Delta\lambda$)	Vis: ~140 NIR: ~70

Possible open bay

International contributions
will be considered

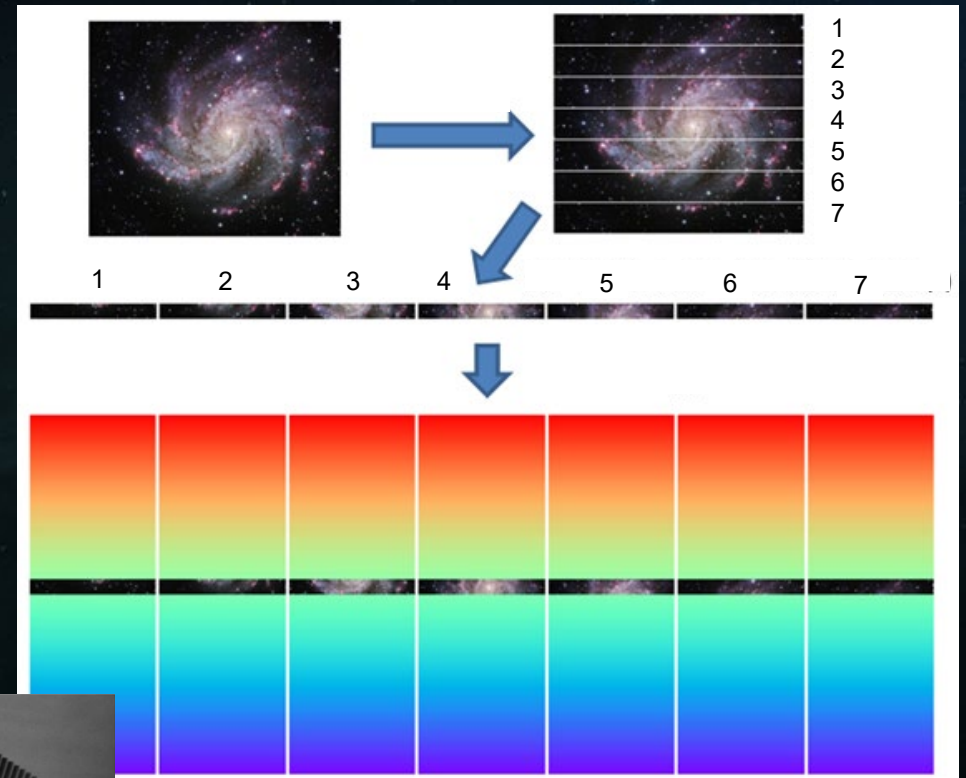
MULTI OBJECT SPECTROGRAPH (MOS)



Scattered objects

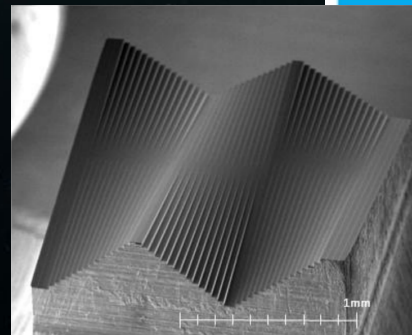
NAOJ

INTEGRAL FIELD SPECTROGRAPH (IFS)



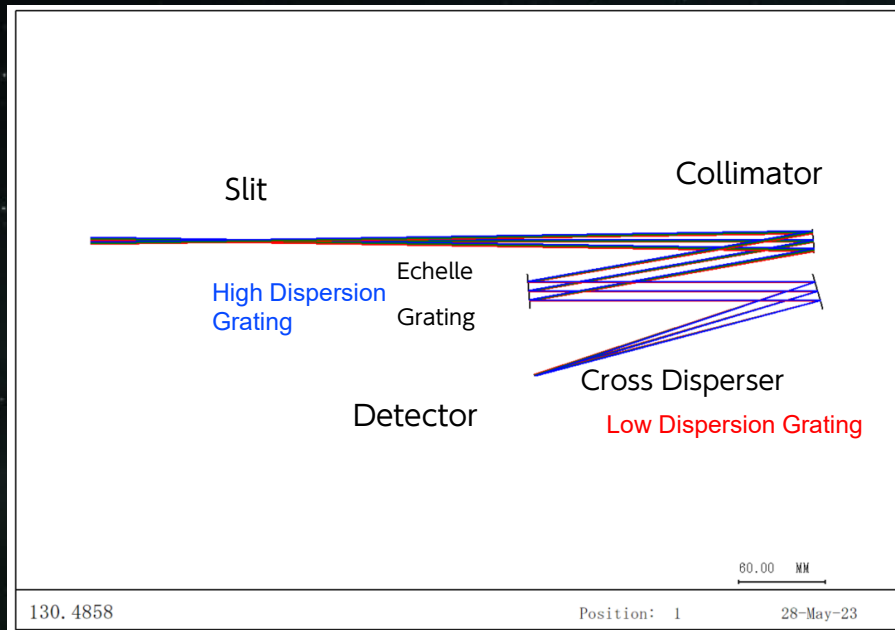
NAOJ (modified)

expanded object
Galaxy
Icy moons, Titan
Mars, Venus, Comets

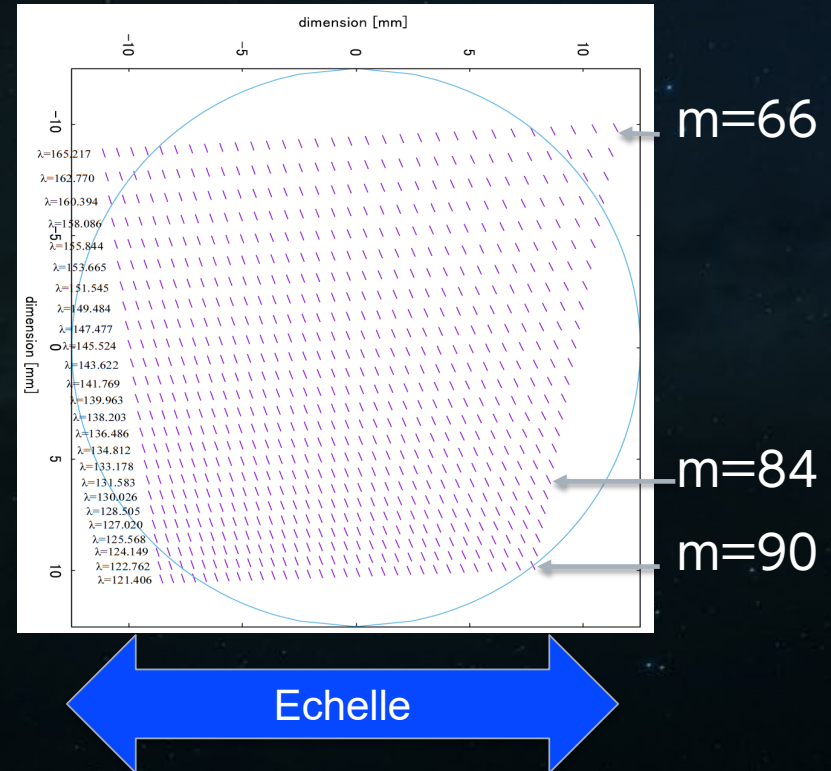


[Suematsu+2016]

FUV HIGH RESOLUTION SPECTROGRAPH (HRS) WITH ECHELLE GRATING

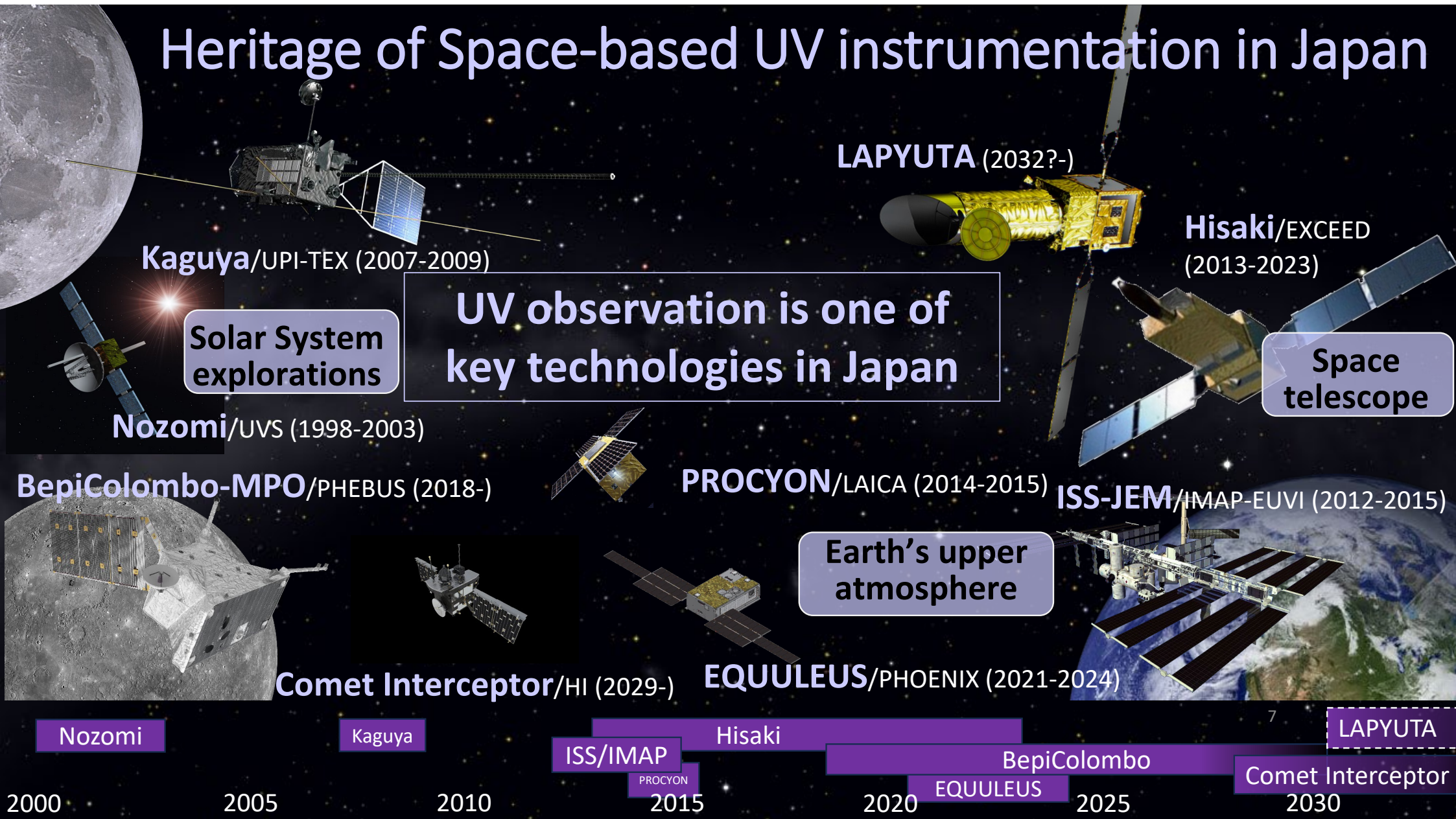


Optical Design of LAPYUTA/HRS



Wide spectral range (100-190 nm) with
High spectral resolution ($R \sim 120,000$) (and a narrow FoV)

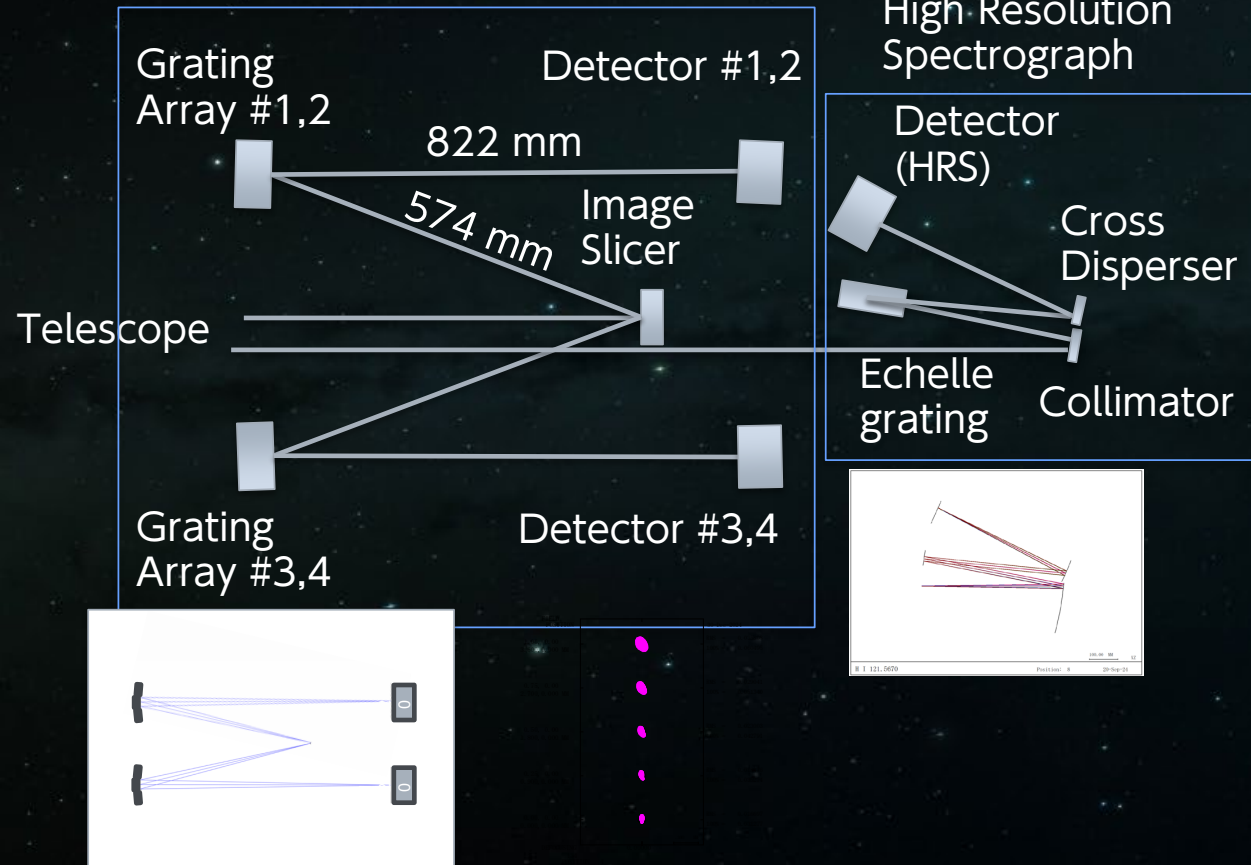
Heritage of Space-based UV instrumentation in Japan



DESIGN STUDY OF FAR UV IFS + HRS

Integral Field Spectrograph

High Resolution Spectrograph

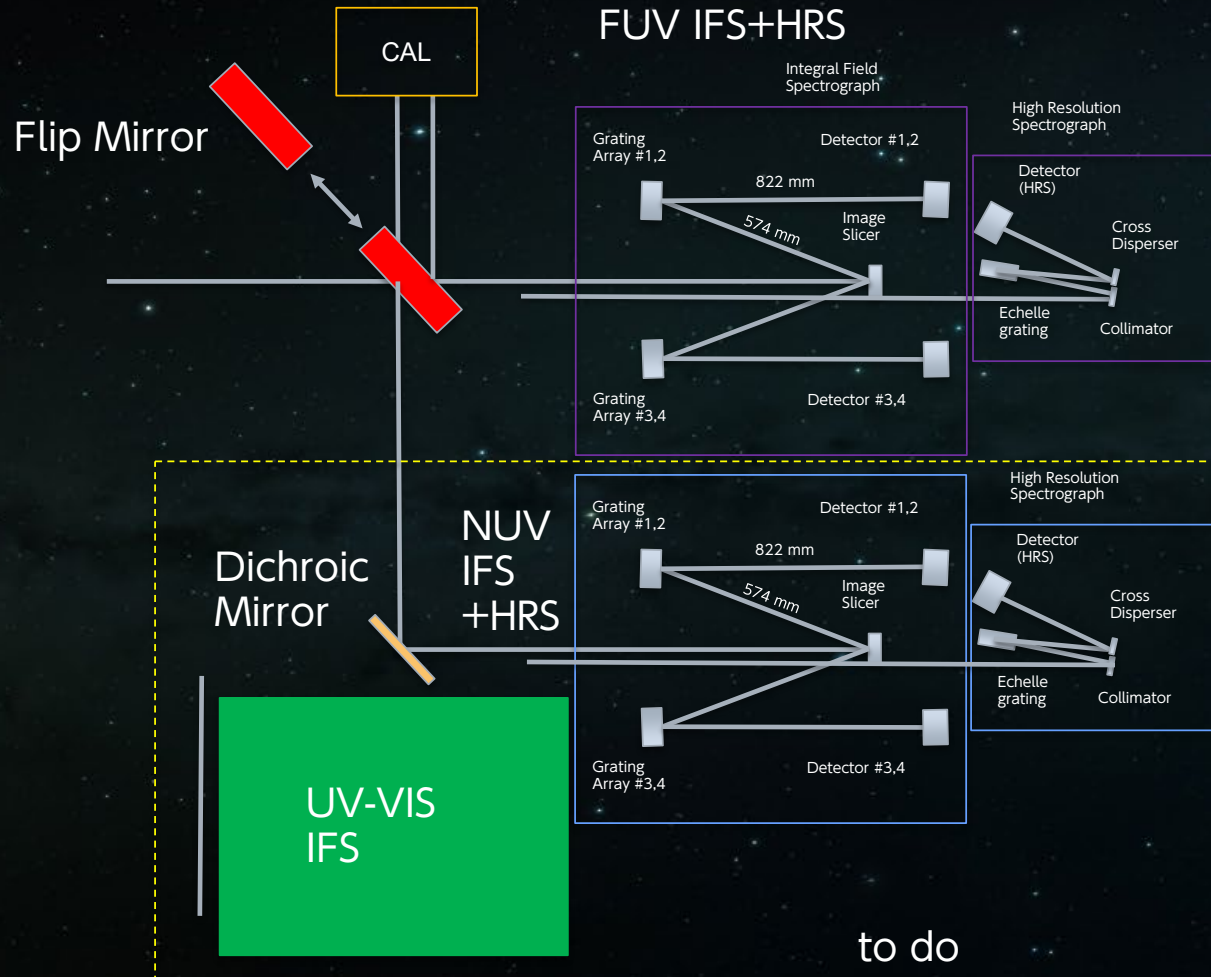


	Request For IFS	Request For HRS	CSIT Recommendation for IFS
Angular Resolution	0.03"	0.06"	~0.02"
Field-of-View	3" x 3" (10"x10")	<0.1"x>8"	~3" x 3"
R ($\lambda/\Delta\lambda$)	3000-5000	120,000	~4000
Spectral Range	~100 -300 nm -	~100 nm -	~100 – 400 nm



	FUV-IFS	FUV-HRS
Angular Resolution	0.03" (0.015"/px)	0.05" (0.025"/px)
Field-of-View	5.4" x 2.4" +Wide FoV mode 5.4" x 5.4"	Point source (< 4")
R ($\lambda/\Delta\lambda$)	5000@100nm ($\Delta\lambda=0.02$ nm) 0.015 nm/pix	~120,000
Spectral Range	(94)100-174 nm	(94)100-190 nm

UV-IFS+HRS INSTRUMENT SUITE CONCEPT



In addition to FUV,
NUV/VIS coverage is requested.

MCP for FUV, CMOS for NUV/VIS

No (good) Dichroic mirror for FUV/NUV
→ Flip Mirror
+Calibration light source

FUV (MCP)

Spectral range: (94)100-174 nm

NUV (CMOS)

Spectral range: 170-340 nm

(Optical design for NUV can be similar to that for FUV)

(UV-)VIS (CMOS)

Spectral range: 330-600 nm

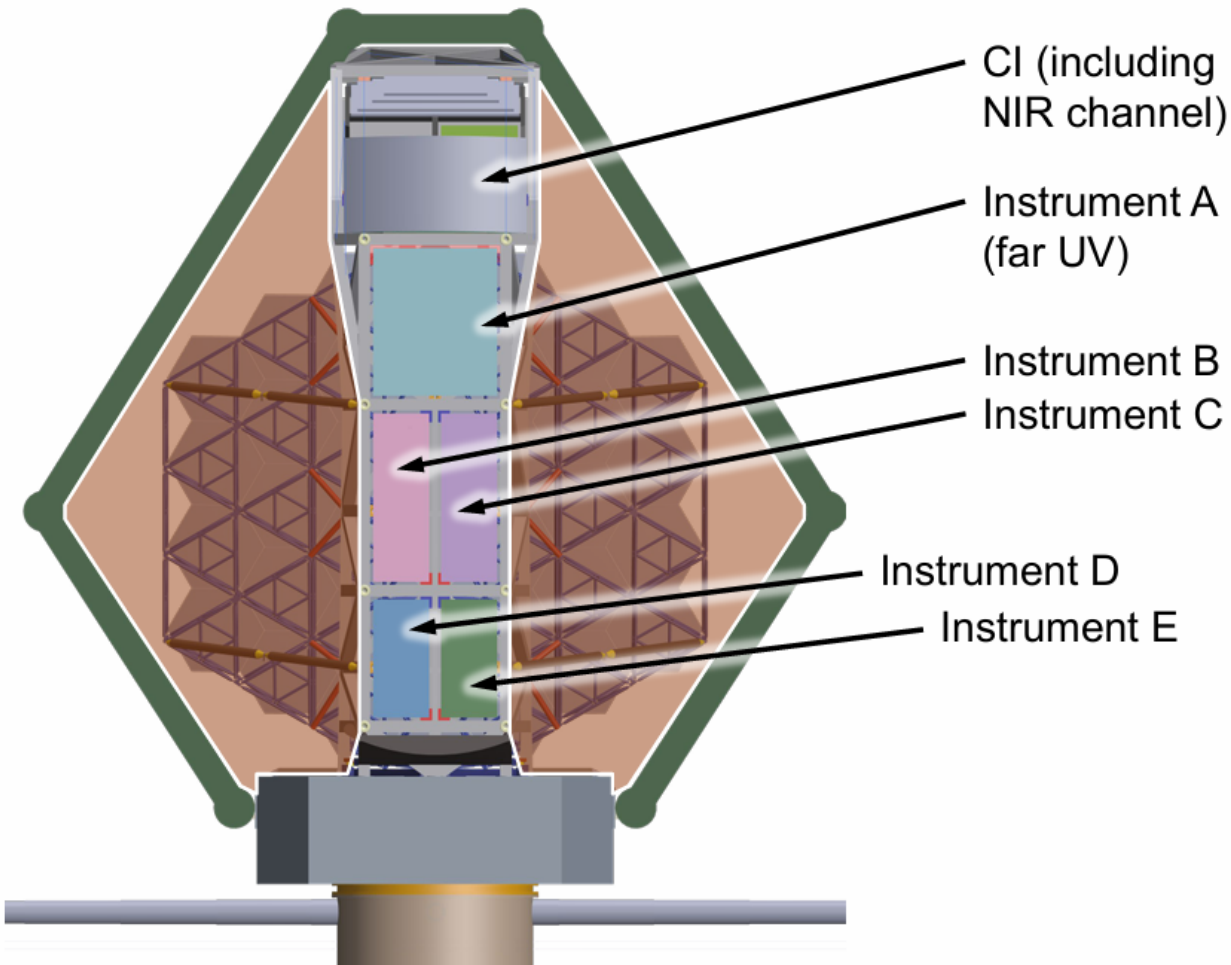
FUV

NUV

UV/VIS



Instrument & Guider Assembly for Instrument Studies

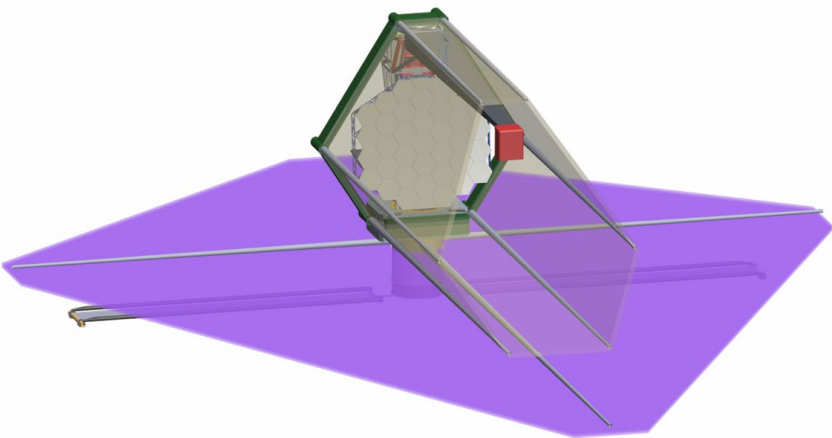


- The observatory accommodates a total of six instrument bays for science instruments and guiders.
- **Instrument Location Guidelines**
 - **CI NIR Channel:** Positioned on the cold side of the observatory to enable passive cooling of detectors
 - **Instrument A (w/ far UV):** Located under CI bay to minimize number of reflections
 - **All Other Instruments and Guiders:** May be located in any of the remaining instrument bays (B–E) or across multiple bays

From Instrument Study PreProposal WS



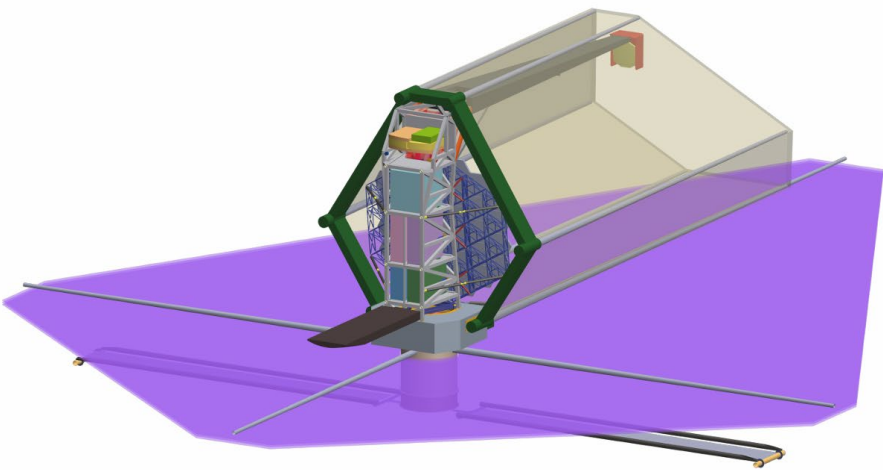
EAC5 Observatory Overview: Front View



05/04/2026



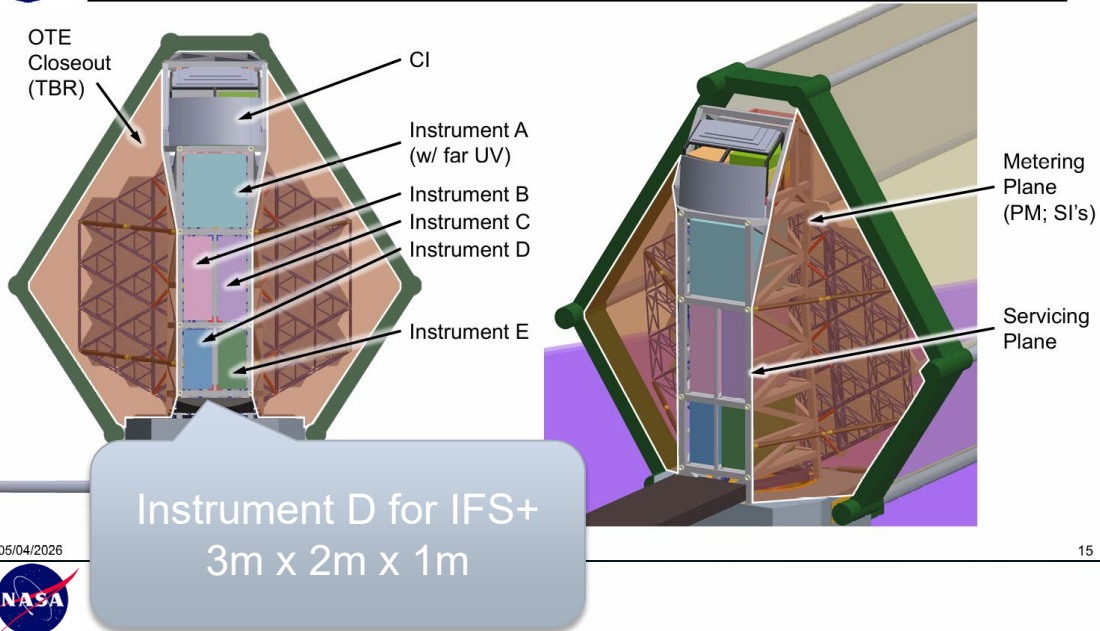
EAC5 Overview: Rear View (radiators, OTE closeout not shown)



05/04/2026



EAC5 Instrument & Guider Assembly Overview (radiators not shown)

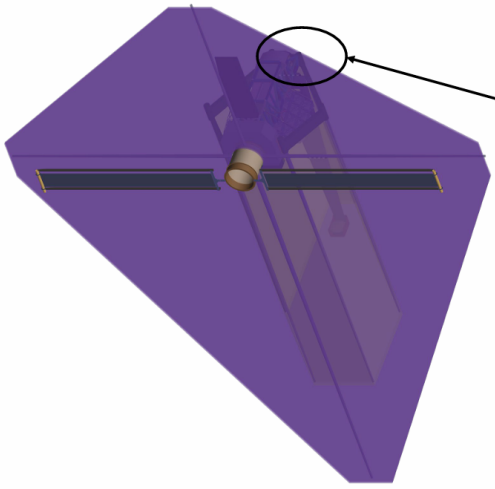


12

05/04/2026



15



Large flat sunshade precludes solar impingement on SI radiators over FOR ($\pm 45^\circ$ pitch, $\pm 22.5^\circ$ roll)

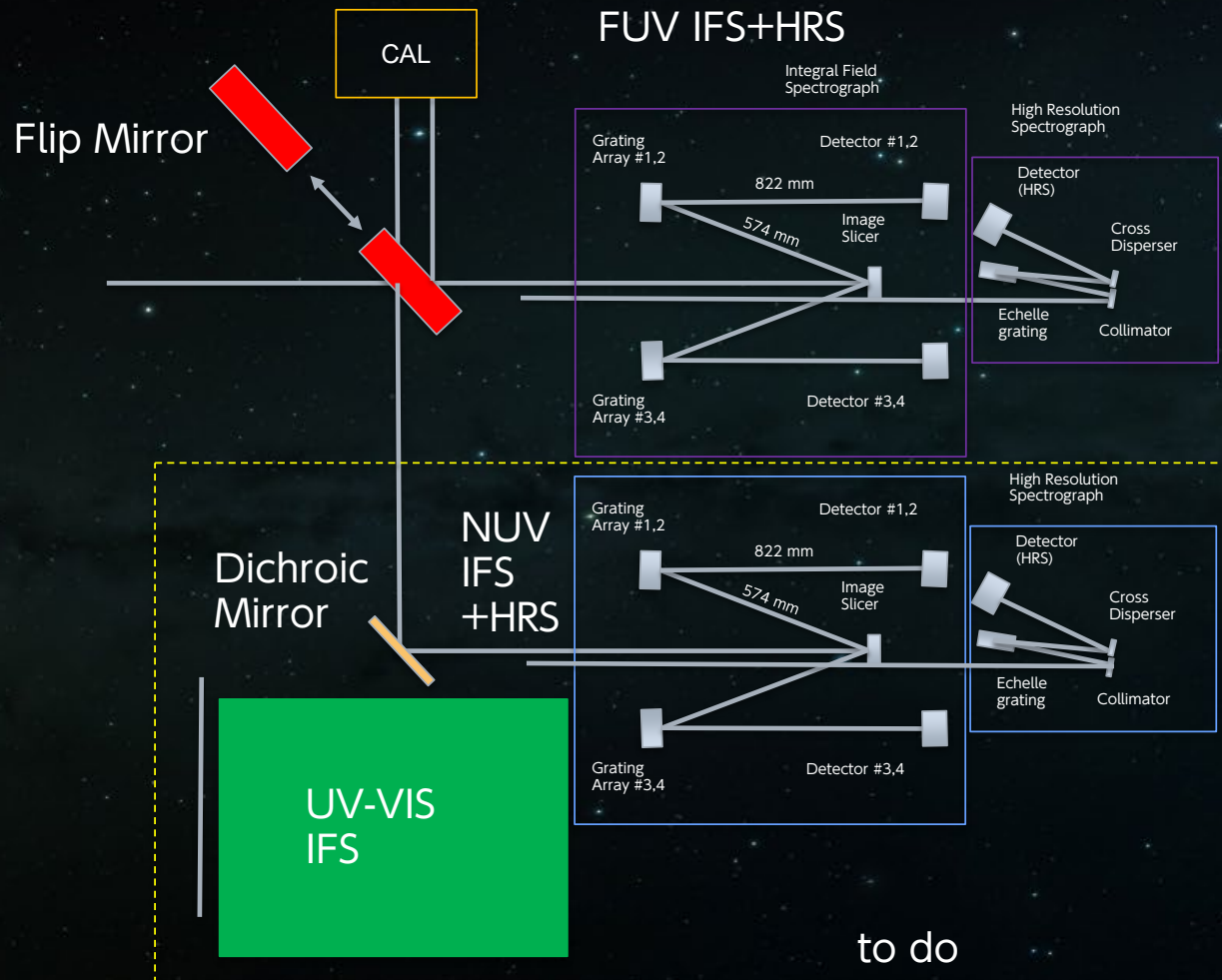
From Instrument Study PreProposal WS

13

05/04/2026

16

UV-IFS+HRS INSTRUMENT SUITE CONCEPT



In addition to FUV,
NUV/VIS coverage is requested.

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→ Flip Mirror
+Calibration light source

FUV (MCP)

Spectral range: (94)100-174 nm

NUV (CMOS)

Spectral range: 170-340 nm

(Optical design for NUV can be similar to that for FUV)

(UV-)VIS (CMOS)

Spectral range: 330-600 nm

FUV

NUV

UV/VIS

Options of JAXA's contribution to UVI

Option 1: Instrument System/Package Level

1-a: IFS+HRS (+Serviceable(removable) design)

1-b: IFS

Instrument D

Option 2: Instrument/Subsystem level

(in US-led UV package e.g. LASP)

2-a: IFS+HRS (with FUV and/or NUV mode)

2-b: IFS

2-c: HRS

Instrument A

Option 3: Component level

(Major) FUV Detector, IFS optics

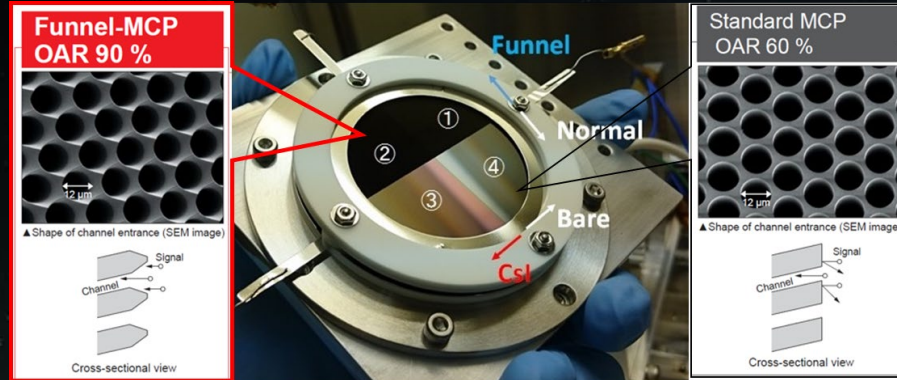
(Minor) Image Slicer, Echelle Grating, Holographic Grating

KEY TECHNOLOGY: FUV DETECTOR SYSTEM (TAPERED MCP)

Please see
Go Murakami+
presentation
in session 6

Tapered MCP

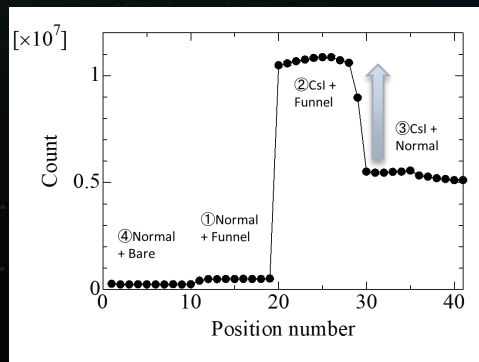
OAR=Open Area Ratio



HAMAMATSU
PHOTON IS OUR BUSINESS

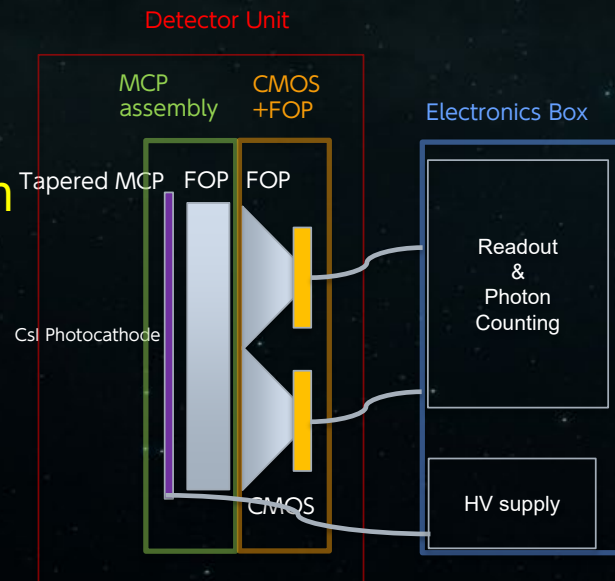
Tapered MCP was developed for ion detection [Matoba et al 2011 Jpn. J. Appl. Phys]

+CsI Photocathode → **QE 37%@121.6nm**

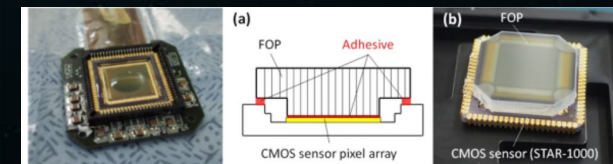


For Spectral width of 80 nm and spectral resolution of 0.02 nm, **120-mm MCP** is necessary. (80 nm is the limit of current facility) → New facility under study (Tech. FL)

Hamamatsu



Multiplied electrons are converted to visible photons at the phosphor on fiber optic plate (FOP) → detected by CMOS image sensor. Using tapered FOPs, multiple image sensors work for this.



[Murakami+2016SPIE]

→Vib. and Temp. Test passed

KEY TECHNOLOGY: GRATING AND SLICER WITH NEW COATING

Please see
Go Murakami+
presentation
in session 6

Grating:

Toroidal holographic blazed gratings for Hisaki, etc.

[Yoshioka+2013PSS, Kameda+2020SPIE]

High diffraction efficiency: ~60% (2400gr/mm) -70%(1200gr/mm).

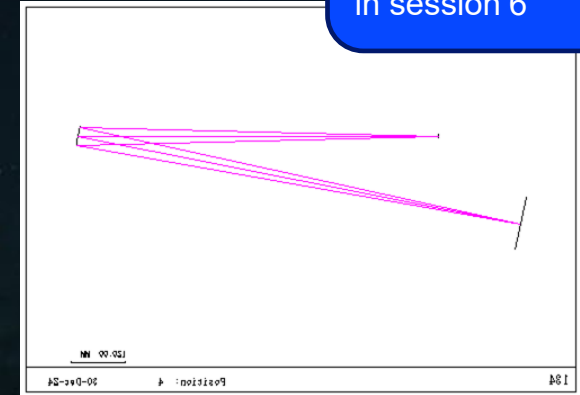
The potential issue is the manufacturing time for 80 gratings.

→Sinusoidal grating, ~30-50% lower efficiency but with less stray light, with shorter lead time. (80 gratings ~ 1 year by Shimadzu)

→We received a new sinusoidal grating this month for stray light eval. for trade-off study.



Concave
Grating
By Shimadzu



Top view (for 1 grating)

Image slicer and Echelle Grating:

Canon has experiences on image slicer and Echelle grating

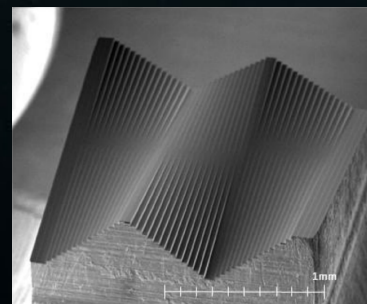
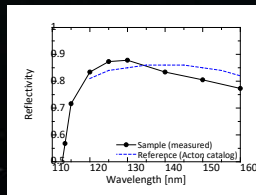
(e.g. FUV-IFU in INFUSE [Alex Haughton+2024SPIE])

Element width of 20 um for Image Slicer

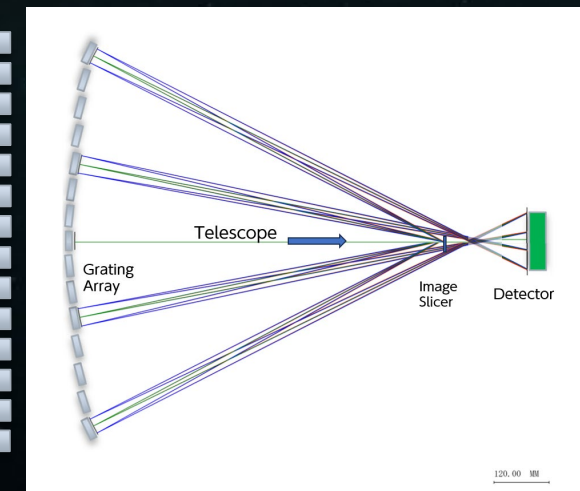


FUV coating:

Al+MgF₂ (~90%@130nm) → XeLiF for 100 nm for gratings and slicer (2027-)



[Suematsu+2016]



Side view

TECHNOLOGY DEVELOPMENT PLAN

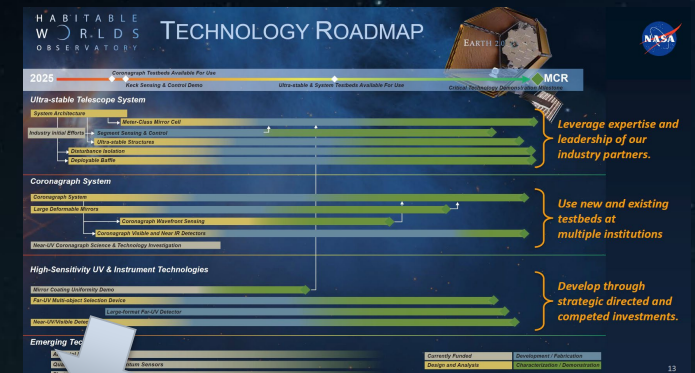
2026-2029 Technology Front-Loading Program in JAXA toward HWO MCR

- (1) Large Format MCP (**120 mm x 120 mm**)
with Large Format CMOS image sensor
- (2) Readout electronics and logic
- (3) Gratings (IFS, echelle) and Image Slicer
with new coating (XeLiF)
- (4) Grating trade off study: Efficiency,
Stray Light, Lead time, etc.

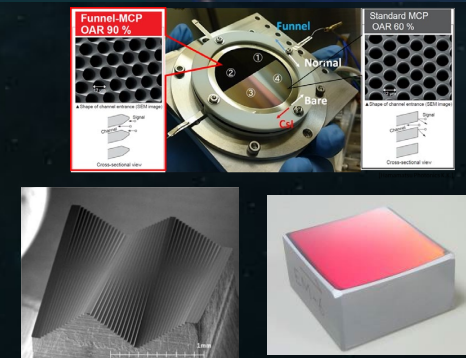
~2030- Pathfinders for HWO

LAPYUTA (60cm UV space telescope) (down selection in 2026(?))
Target Launch: 2032 → (1-3) will be used/demonstrated (TRL8-9)

MAGPIE (UV space telescope with **IFS**) (in prep., led by CU/LASP)
Optics (~10 gratings and image slicer) will be demonstrated.



Large-format Far-UV Detector



SUMMARY

- UV observation is essential for HWO science:
Icy moons, planetary escaping atmospheres, and galaxy evolution
→ How do habitable worlds form?/How common/rare is Earth?
- Strong community-driven demand in Japan for UV-IFS + HRS
→ Requirements are ~satisfied in the conceptual design study
- Heritage of Japanese UV space instrumentation
- Key technologies are mature and advancing:
FUV detectors (tapered MCP), high-efficiency gratings and Coating
- Development path:
2025–2029 Front-Loading → 2030- pathfinders (e.g. LAPYUTA, MAGPIE) → **HWO**
- Various options/possibilities of collaboration

Title: Evolution of the Elements

Lead author: Takashi Moriya

Abstract: The science cases to investigate the evolution of the elements are reviewed, with special focuses on primordial massive star evolution, nucleosynthesis, and explosive transient phenomena. They are tightly related to “Cosmic Ecosystem” and “New Messengers and New Physics” highlighted in the Decadal Survey 2020.

Science Case Summary

Understanding massive stars in low metallicities are essential to interpret observations of high-redshift galaxies. By resolving nearby low-metallicity massive stars and obtaining their individual spectra in UV, we can constrain massive star evolution in low metallicities. High-resolution UV spectroscopy of metal-poor stars can constrain the nucleosynthesis in the first-generation supernovae. Follow-up observations of explosive transients like kilonovae and supernovae can constrain their nucleosynthesis and progenitor properties. Such follow-up observations require rapid telescope response within a couple of days.

Evolution of the Elements

Takashi Moriya
National Astronomical Observatory of Japan



Evolution of the Elements

Massive star evolution at low metallicities

Probing massive star physics to understand primordial elemental abundances

Metal-poor star observations

Investigating the nucleosynthesis of the first supernovae

Explosive transient phenomena

Catching ongoing nucleosynthesis and late-stage stellar evolution

Massive stars are a key to understand the cosmic history

Massive stars are origins of the elements

Nucleosynthesis mainly occurs during their evolution and supernovae.
They leave behind neutron stars and black holes.

Massive stars dominate the light we observe, especially in UV

A $1 M_{\odot}$ star emits $1 L_{\odot}$. A $100 M_{\odot}$ star emits $10^6 L_{\odot}$.

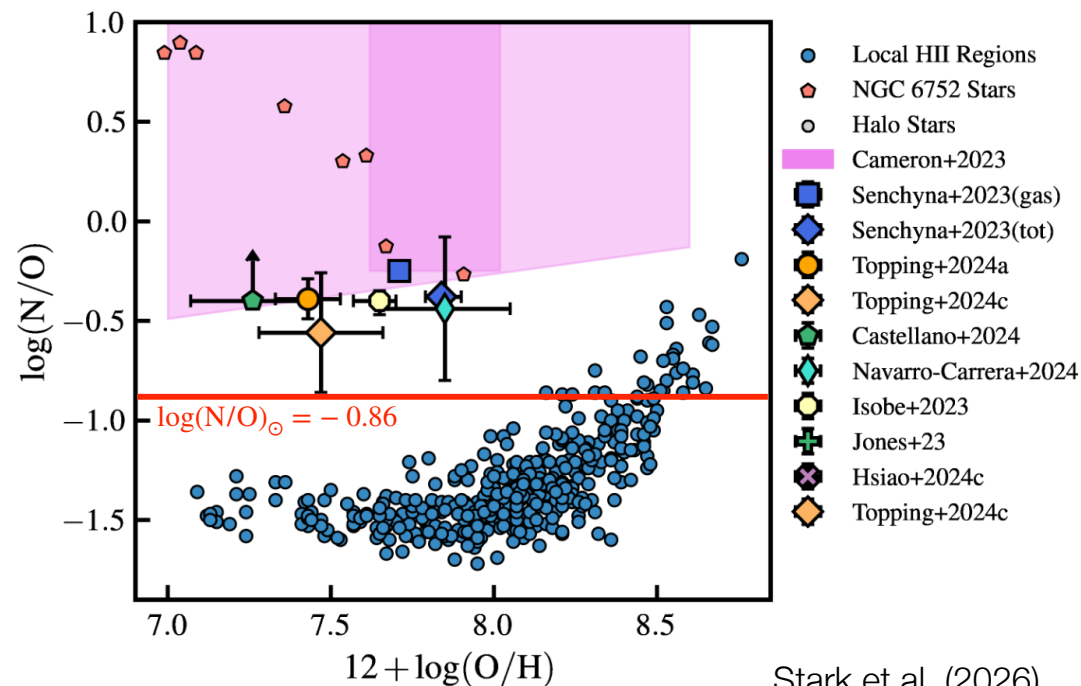
Primordial galaxies are observed in the rest-frame UV.

Massive stars drive the evolution of the Universe

Huge radiation energy & mechanical energy are released by massive stars.

Primordial massive star evolution

Chemical peculiarities observed in the first-generation galaxies from JWST



Observed in young environments: **Only massive stars can contribute.**

SN explosions make $\log(N/O) \simeq -1$: No SN contaminations allowed!

N enhancement in massive stars

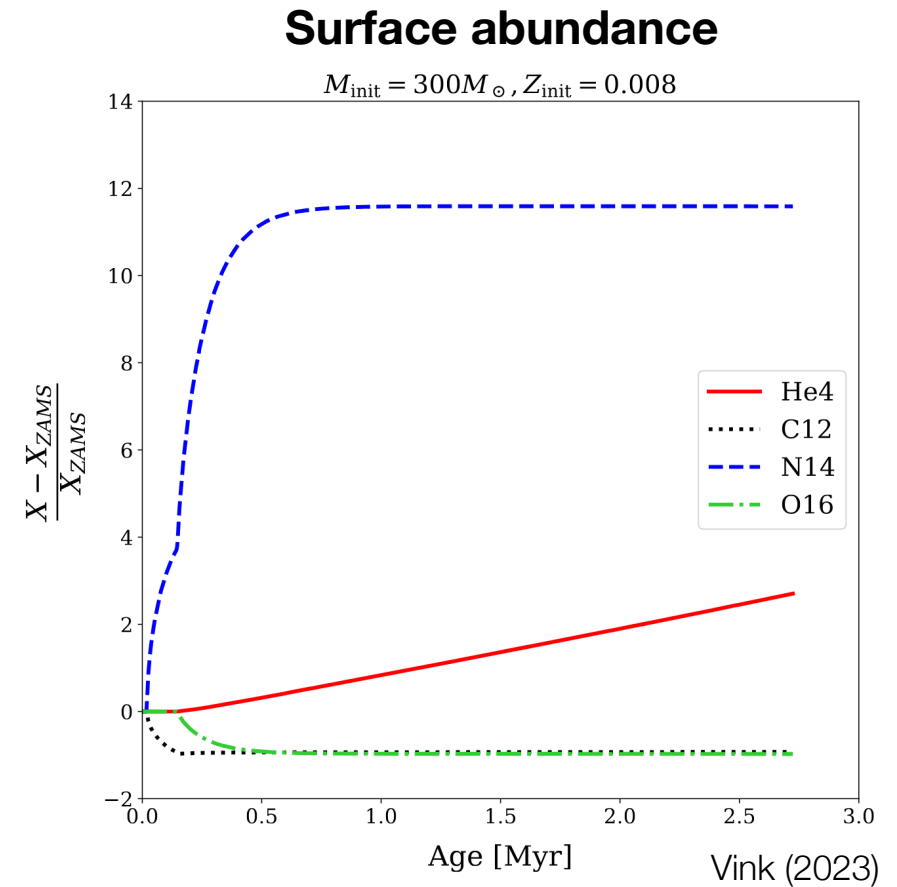
N synthesized by the CNO cycle.



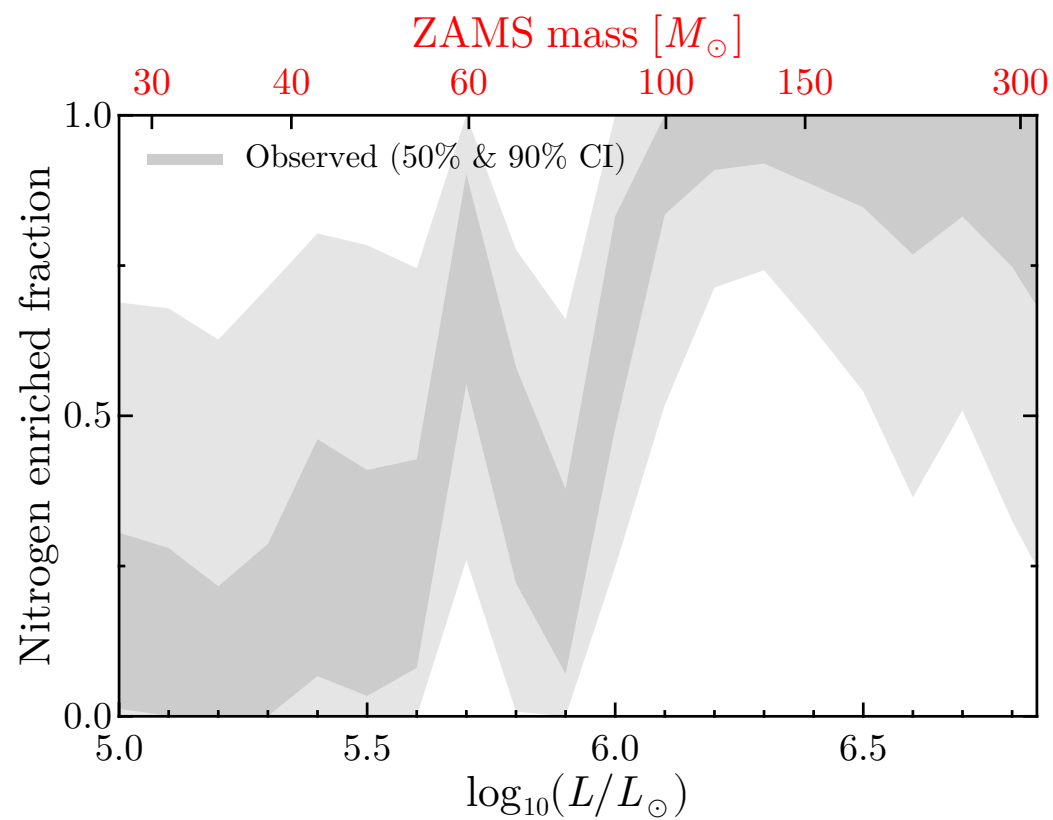
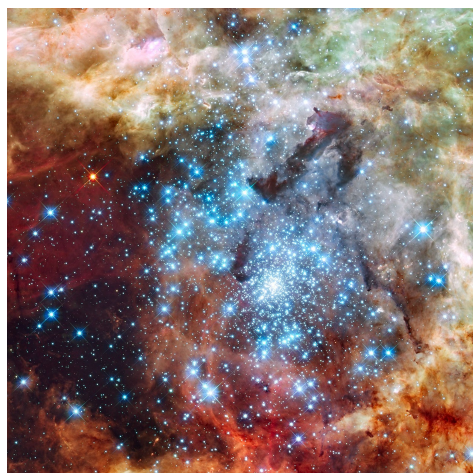
If mixing of the stellar interior is efficient,
the synthesized N reaches the surface.



N can be released into ISM
through stellar mass loss.

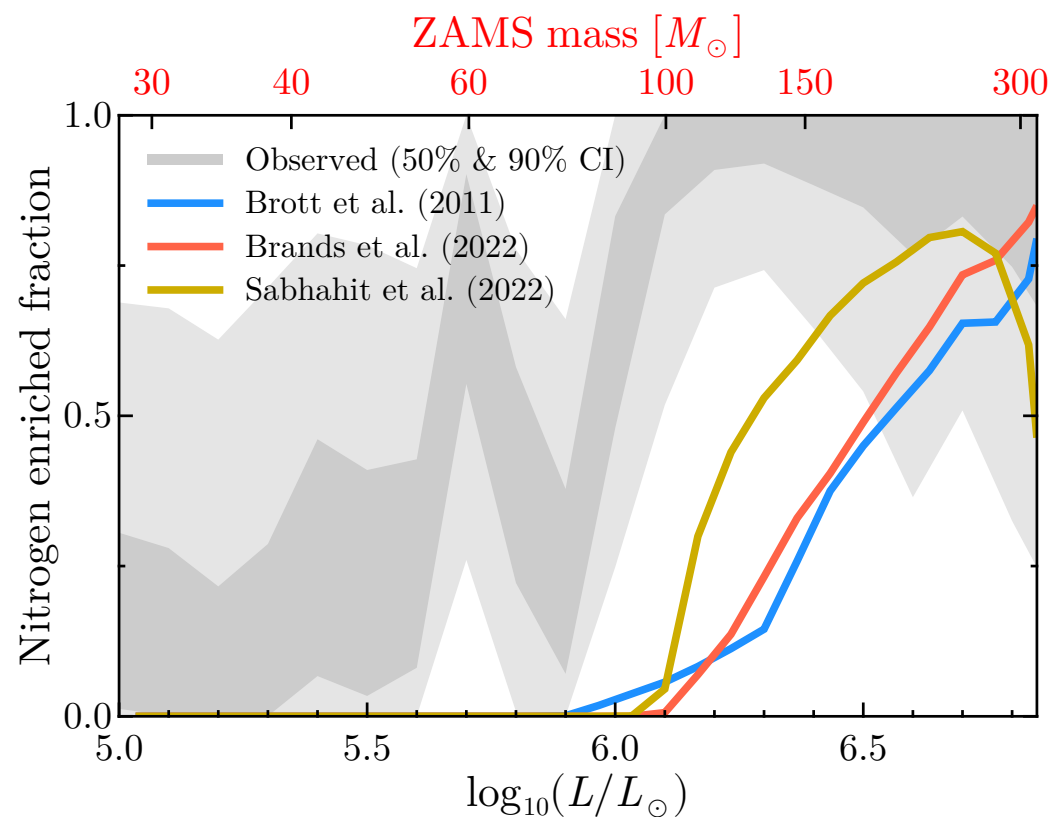
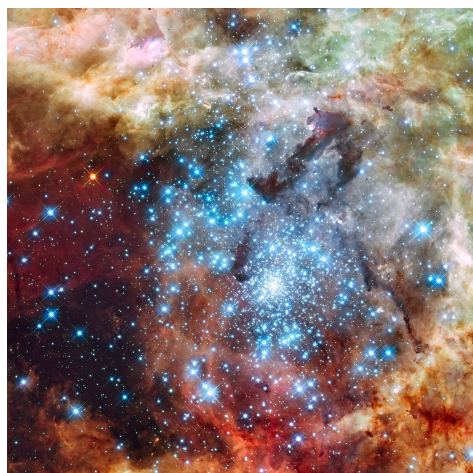


N enhancement observed in 30 Dor in LMC ($0.5 Z_{\odot}$)



Marchant & Shenar (2026)

N enhancement observed in 30 Dor in LMC ($0.5 Z_{\odot}$)

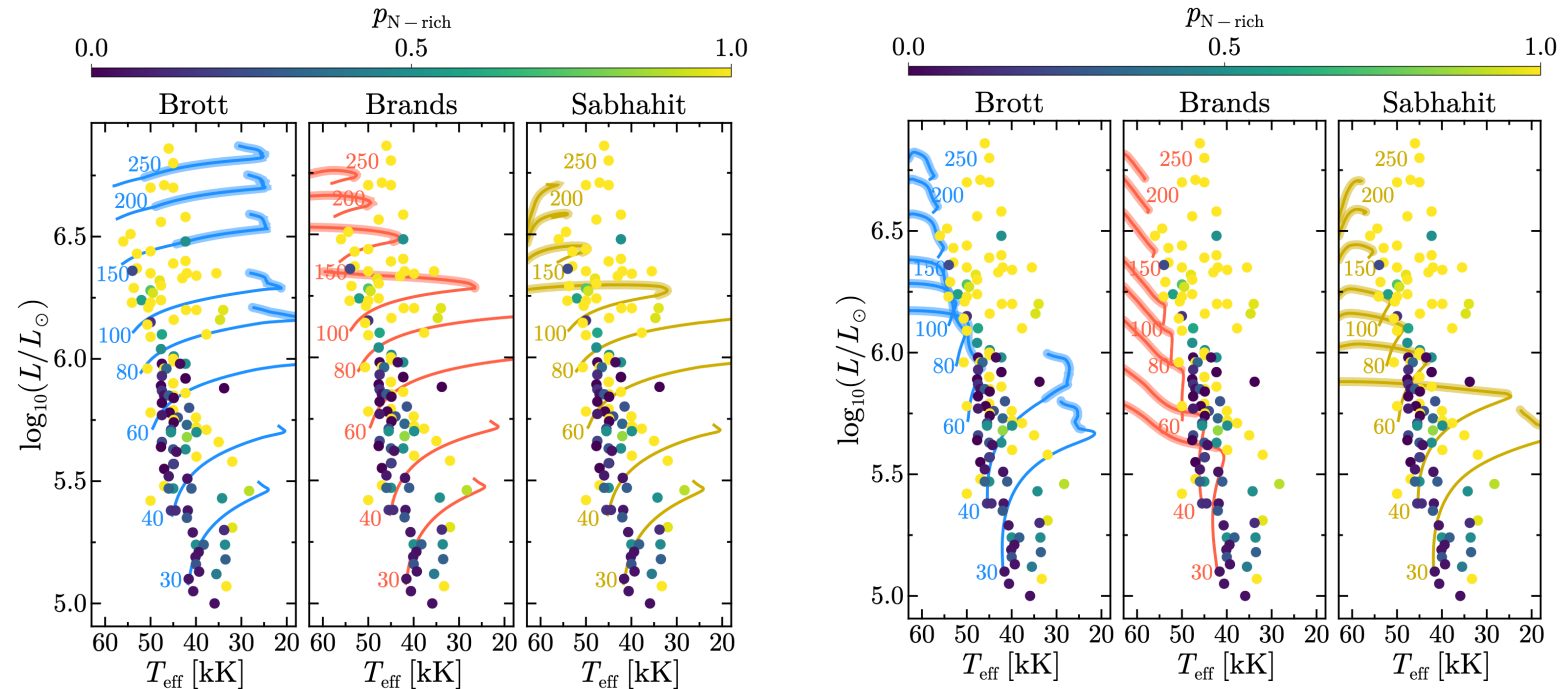


Stellar evolution theory fails to explain N enrichment even at the LMC metallicity.

Marchant & Shenar (2026)

N enhancement observed in 30 Dor in LMC ($0.5 Z_{\odot}$)

Mixing enhancement by, e.g., overshooting or rotation?



Enhanced mixing makes the HR diagram inconsistent.

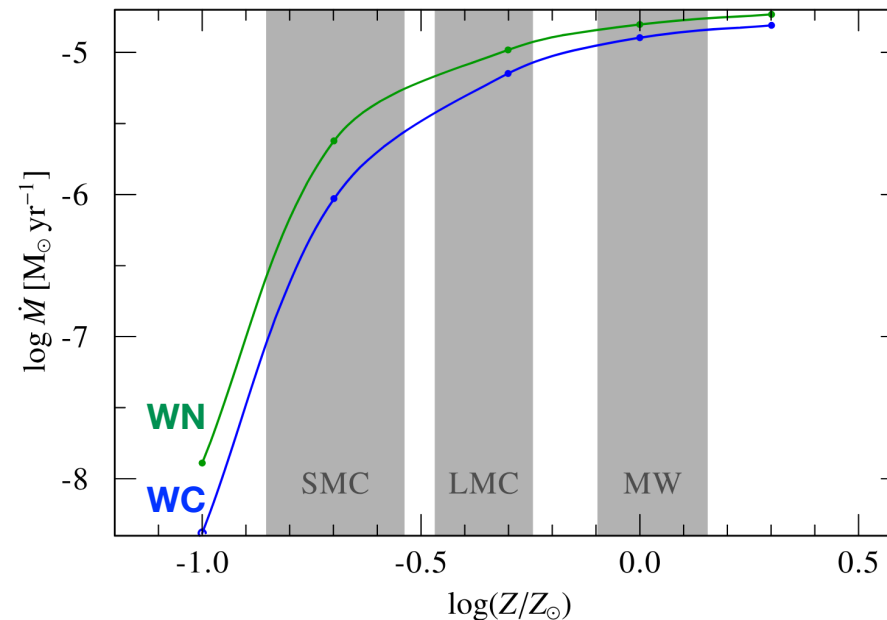
Marchant & Shenar (2026)

Another big issue: Stellar mass loss

N-enhanced materials need to be released from massive stars

Mass loss from massive stars is line-driven

→ *Mass-loss rates are significantly reduced at low metallicities*

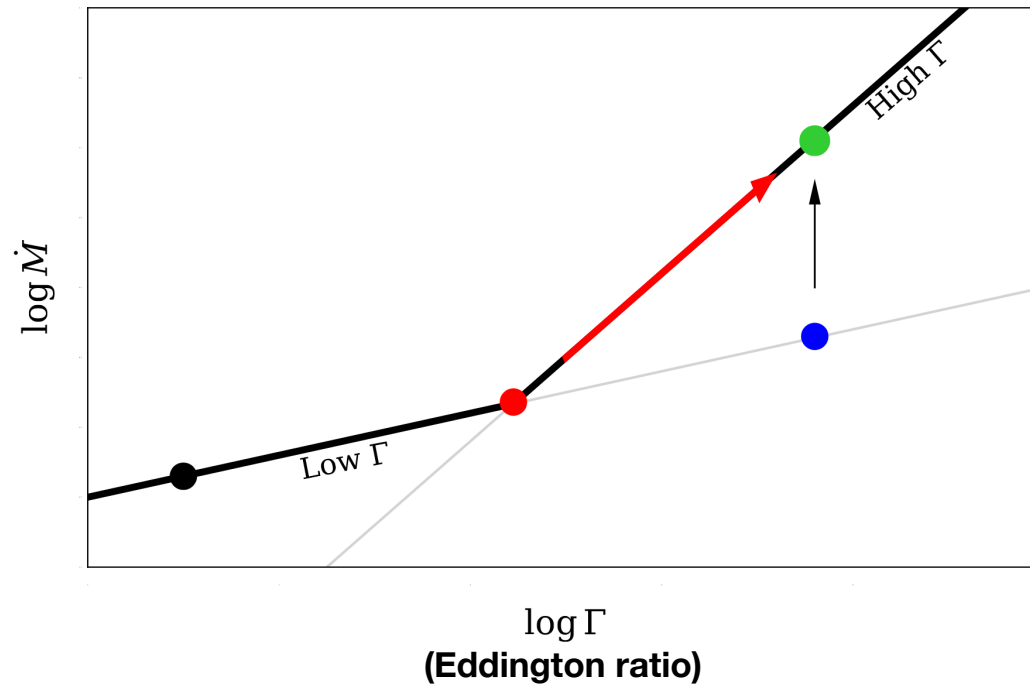


How do we release N from the stellar surface?

Sander et al. (2020)

Another big issue: Stellar mass loss

Massive stars are near the Eddington luminosity.



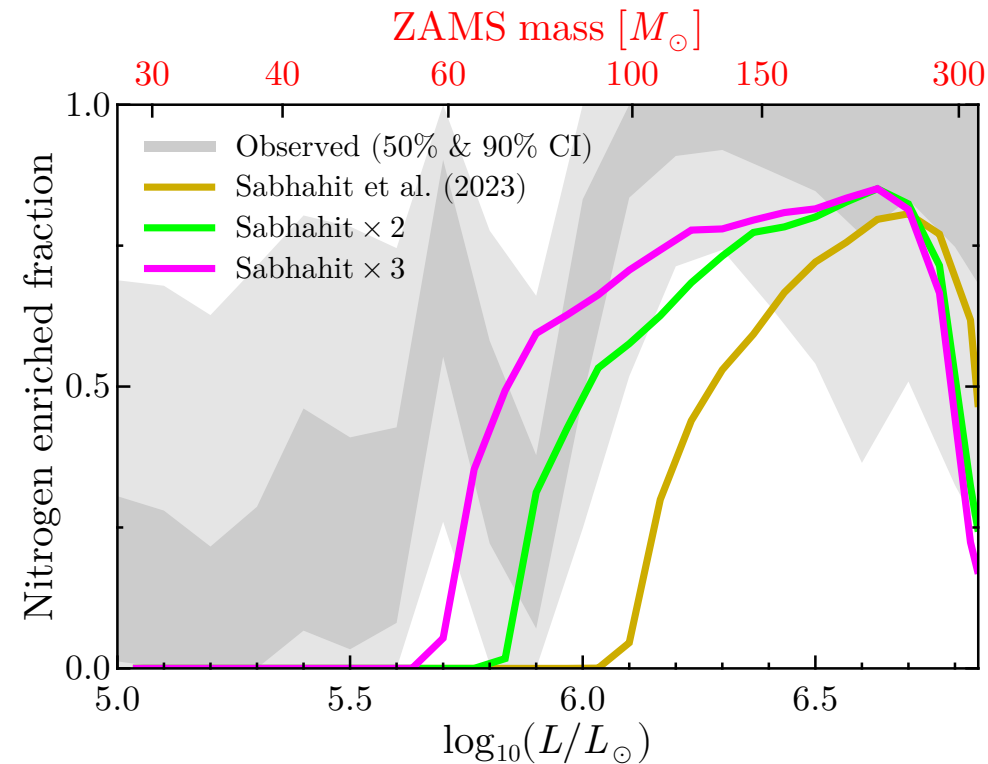
Mass loss near the Eddington luminosity is likely *continuum driven*.

→ **less affected by metallicities?**

Vink (2026)

Another big issue: Stellar mass loss

Models with artificial mass-loss enhancement



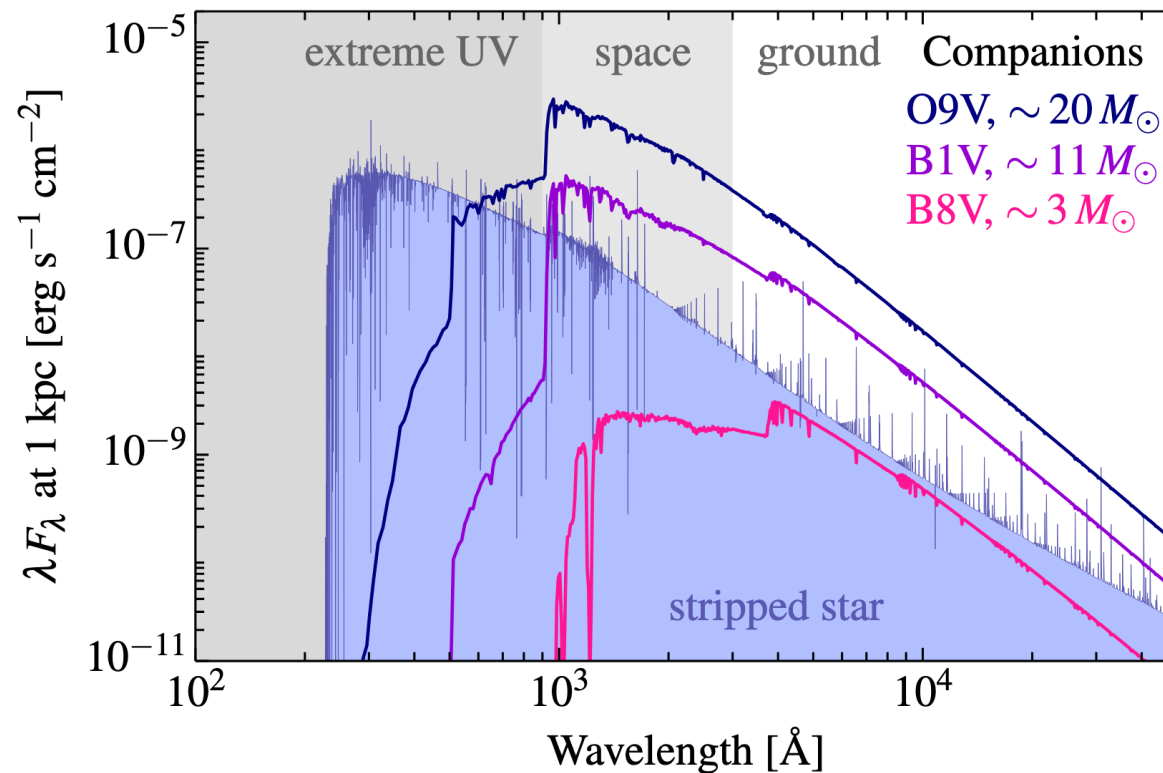
Better understanding of mass loss at low metallicities is crucial!

Marchant & Shenar (2026)

How do we estimate stellar properties such as mass loss?

Massive stars are bright in UV

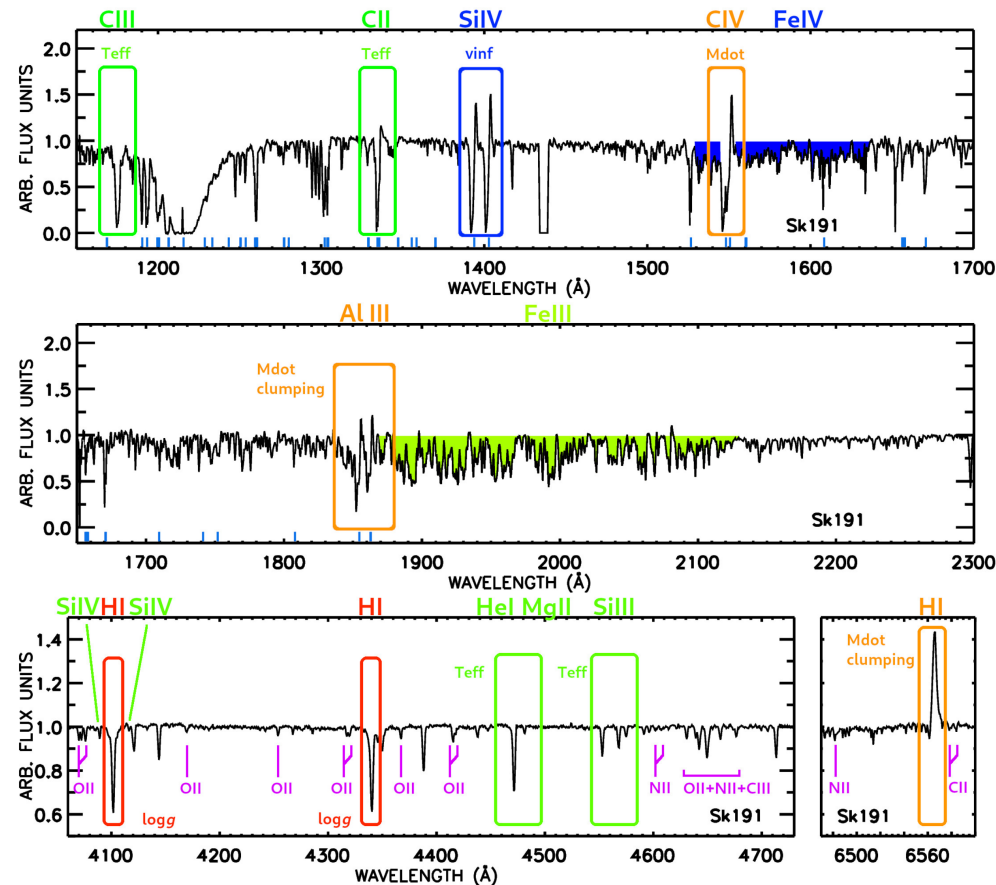
providing a significant fraction of ionizing photons



Götberg et al. (2017)

UV spectroscopy is essential in estimating stellar properties

An example of the UV (and optical) spectrum of a massive star in SMC from HST



Vink et al. (2023)

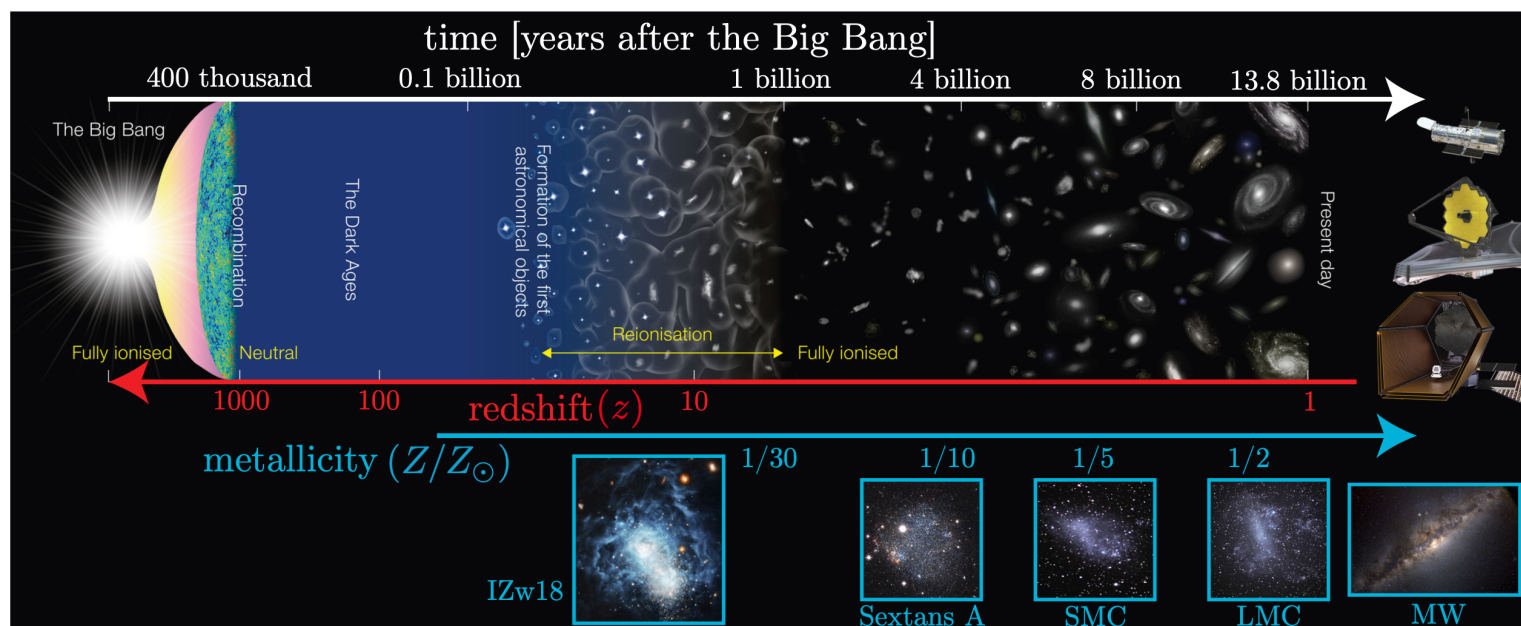
Massive star properties at low metallicities

Spectroscopic observations of individual stars at low metallicities are required.

Spacial resolution + UV spectroscopic capabilities are the keys.

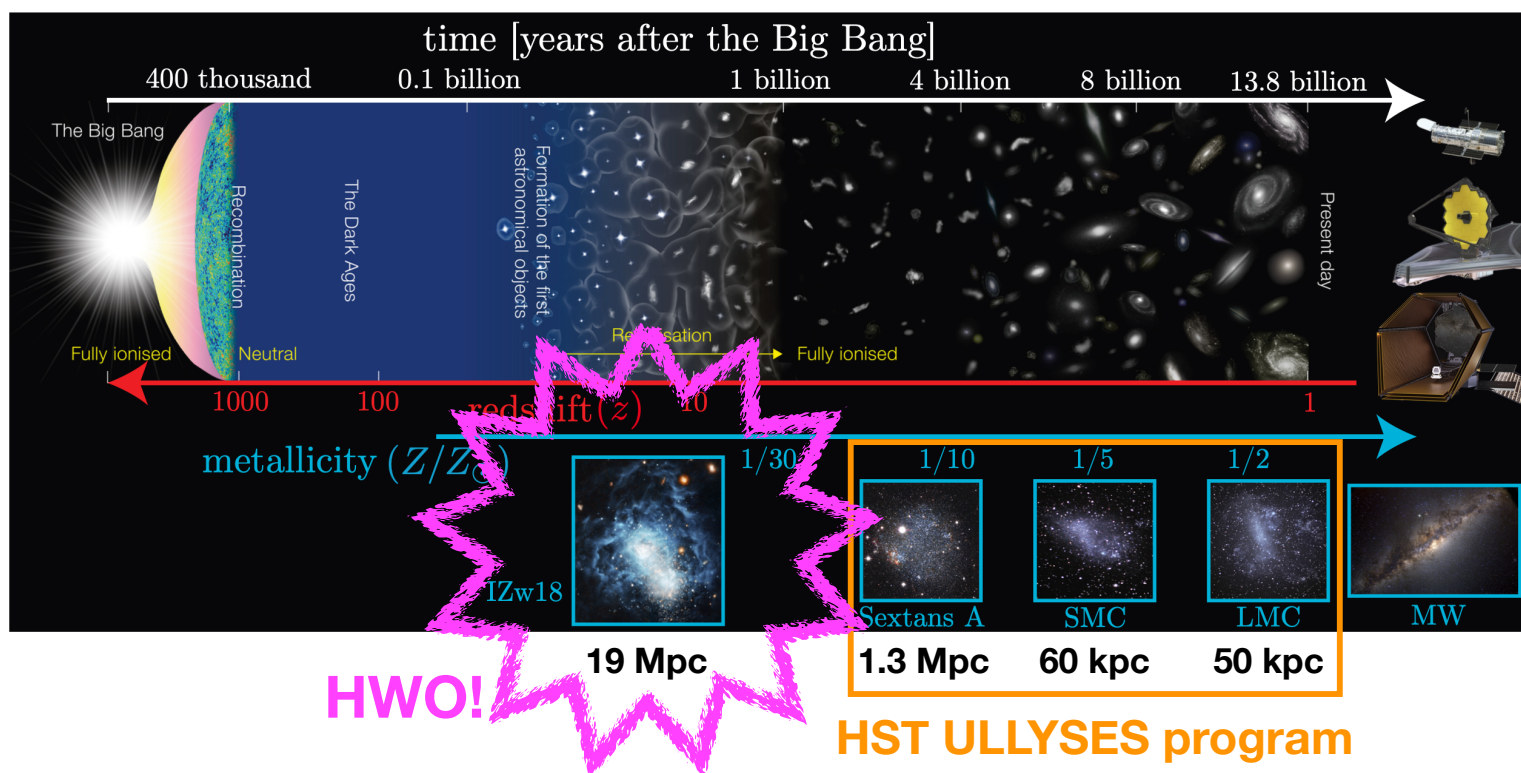
It's difficult to observe individual massive stars at high redshifts.

We can observe nearby metal-poor massive stars.



Senchyna et al. (2025)

Massive star properties at low metallicities

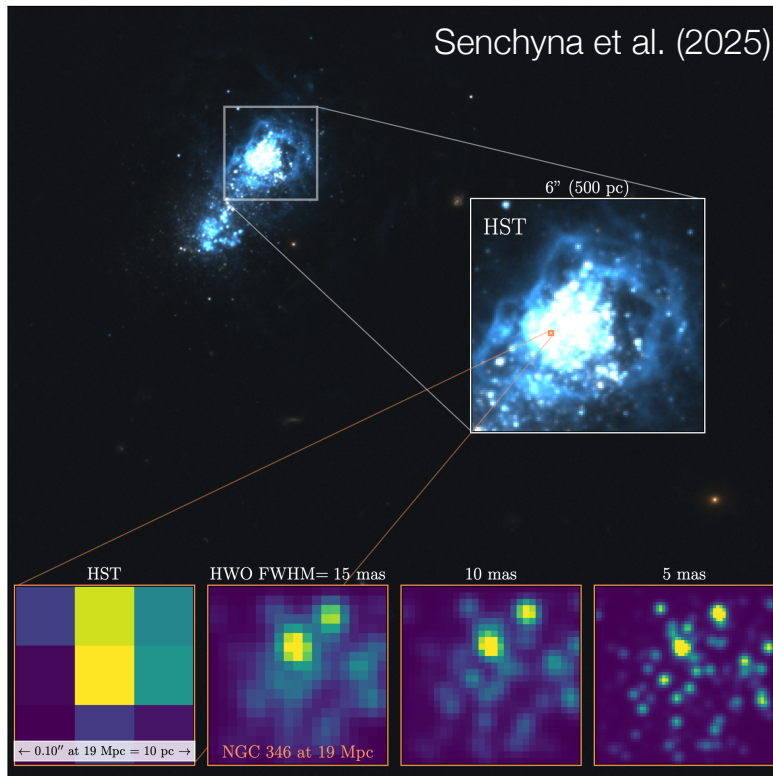


Magnetic field information can be accessible through HWO (David-Uraz et al. 2025).
Individual faint low-mass stars can be resolved by HWO (Smercina & Fetherolf 2025).

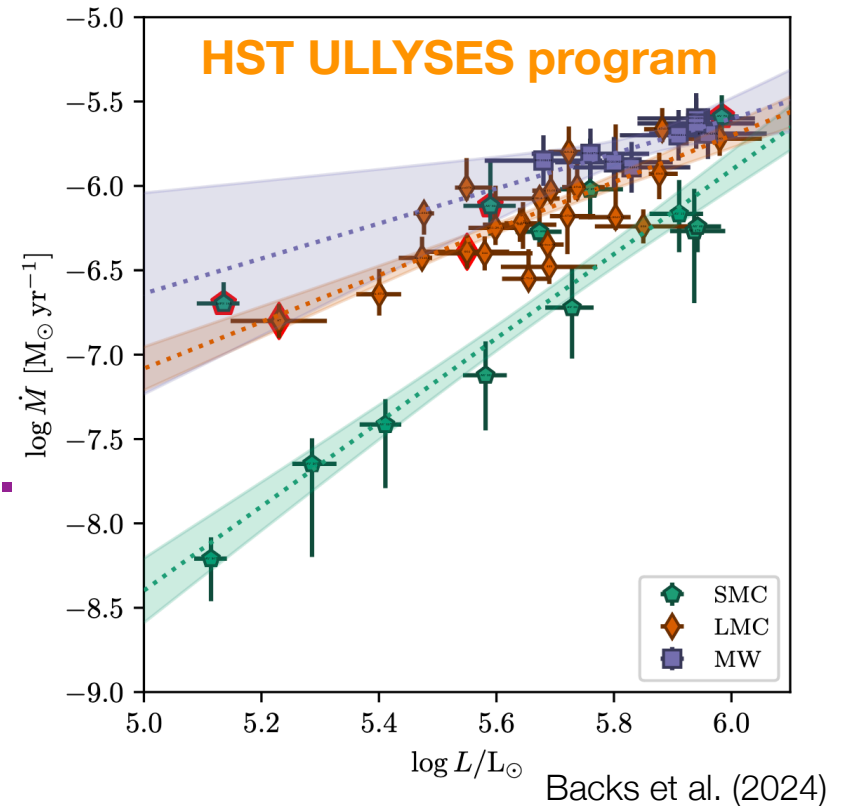
Senchyna et al. (2025)

I Zw 18

One of the nearest low-metallicity star-forming galaxies containing massive stars (Martins et al. 2025)



UV spec.



Requirements

Table 3: Constraints on Metal-Poor Massive Star Physics as a Function of Science Return

	Current State of the Art	Incremental Progress	Substantial Progress	Major Progress / <i>The Dream</i>
Type of analysis	Comparison of integrated stellar+nebular galaxy light to population synthesis models	Comparison of integrated clusters+nebular emission to population synthesis models	Semi-resolved clusters: some resolved stars/clumps, spatially-resolved high-ionization nebular structure	Resolved stars and compact associations within clusters; <i>The Dream: majority of O-stars resolved at 19 Mpc</i>
Degeneracies	star formation histories, IMF, unresolved gas physics	cluster ages, IMF	contents of blended clumps and clusters	contents of the most crowded cluster regions

Table 4: Capabilities Needed to Enable Different Levels of Scientific Return

	Current State of the Art	Incremental Progress	Substantial Progress	Major Progress	<i>The Dream</i>
Observation type for extremely low- Z massive stars	Imaging, slit/fiber spectroscopy	UV MOS	UV IFU [fallback: MOS]	UV-optical IFU [fallback: MOS]	UV-optical IFU
Wavelength range	panchromatic	900–2000 Å	900–2000 Å	900–2000, 3000–5000 Å	900–5000 Å
Spectral resolution	$R \sim 16000$ (highest achieved in UV with HST/COS)	$\mathcal{R} = 3000$	$\mathcal{R} = 3000$	$\mathcal{R} \gtrsim 5000$	$\mathcal{R} \gtrsim 5000$
Angular resolution/spaxel size for spectroscopy	$\gtrsim 0.1''$ (smallest effective spaxel size achievable in the UV with HST/STIS)	$0.05''$	$0.03''$	$\lesssim 0.02''$	$\sim 0.005''$ (8-m diffraction-limit at 1500 Å)
Spatial resolution for massive stars at 19 Mpc (1 Zw 18)	$\gtrsim 10$ pc	5 pc	3 pc	$\lesssim 2$ pc	0.5 pc
Fraction of NGC 346 O-stars resolved at 19 Mpc	$\sim 0\%$	$\sim 0\%$	5%	$\gtrsim 10\%$	60%

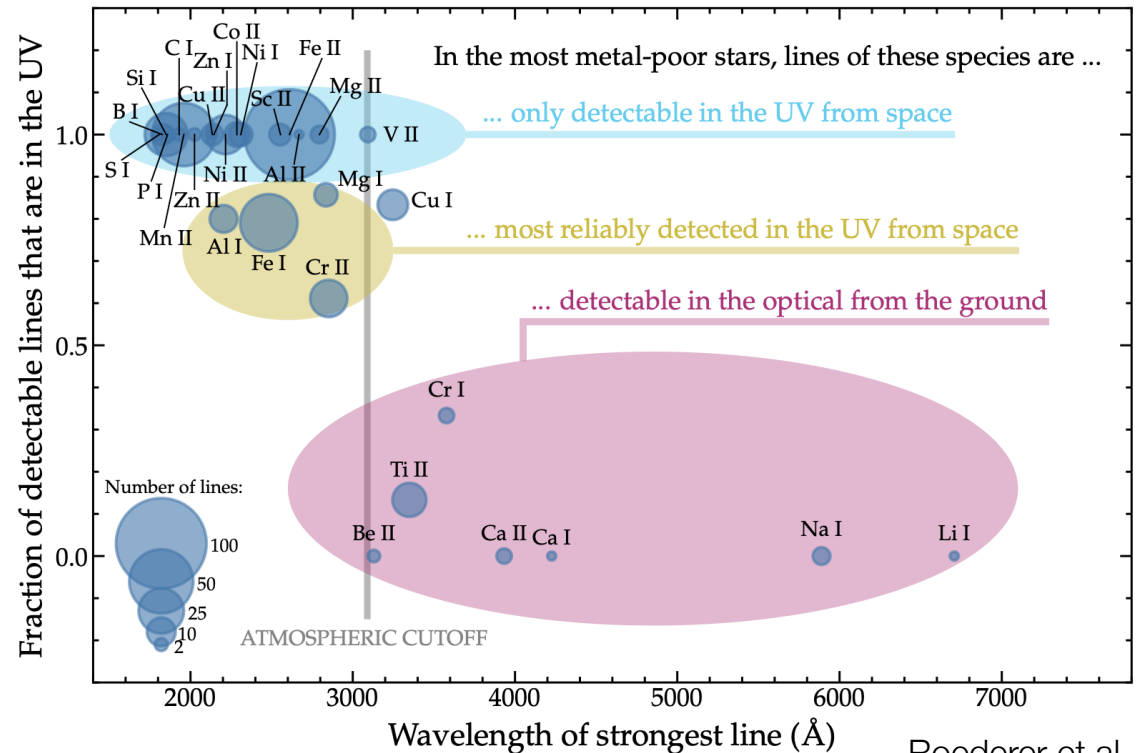
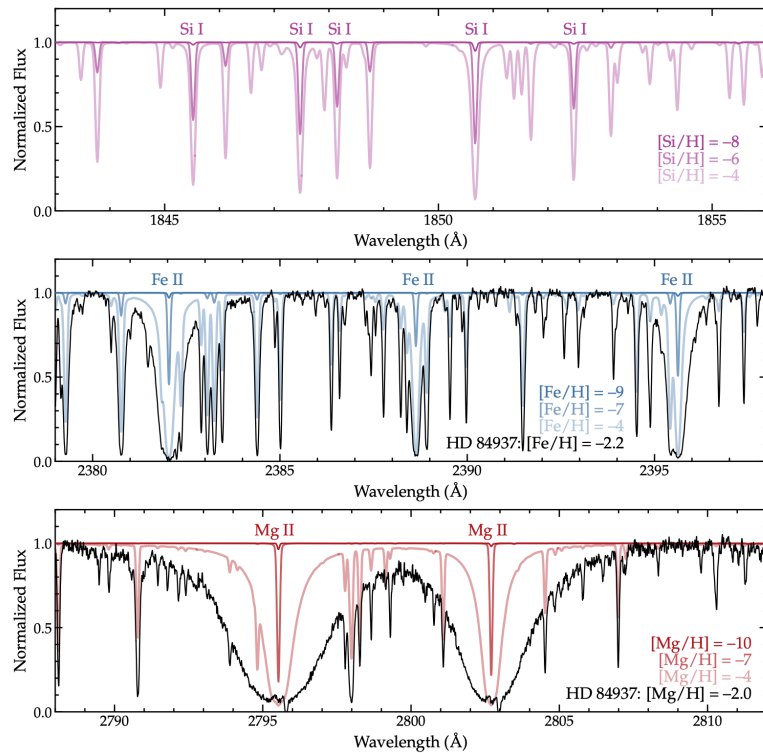
UV IFU!

Senchyna et al. (2025)

Investigating early chemical evolution through metal-poor stars

Metal-poor stars contains primordial chemical information.

e.g., nucleosynthesis of the first supernovae



Roederer et al. (2025)

Investigating early chemical evolution through metal-poor stars

Metal-poor stars contains primordial chemical information.
e.g., nucleosynthesis of the first supernovae

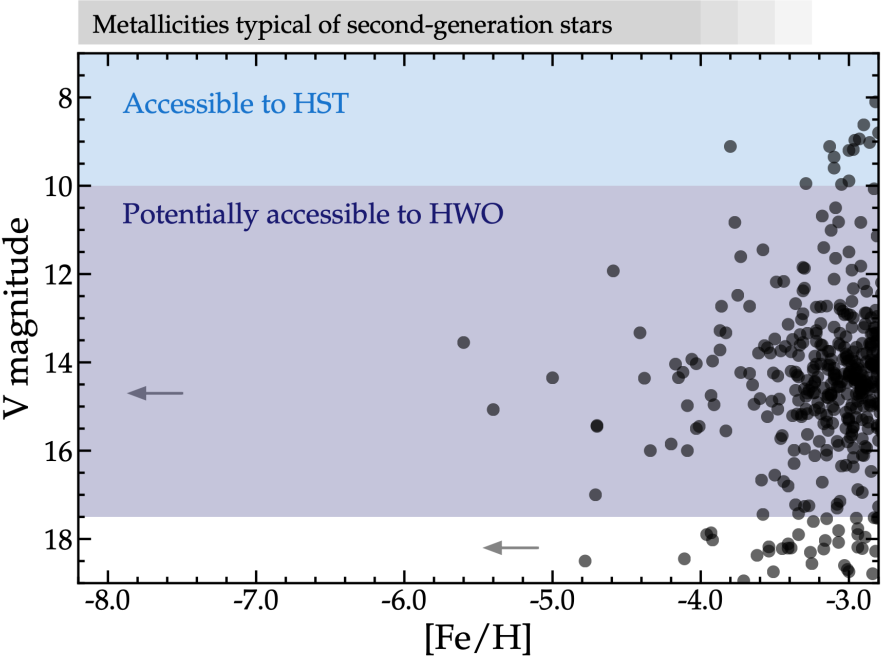


Table 1: Physical Parameters

Physical Parameter	State of the Art	Incremental Progress (Enhancing)	Substantial Progress (Enabling)	Major Progress (Breakthrough)
Number of stars with $[Fe/H] < -4$	1 observed in the UV	3	10	50
Number of elements per star	5–10, including optical detections	10	15	20

Table 2: Observational Requirements

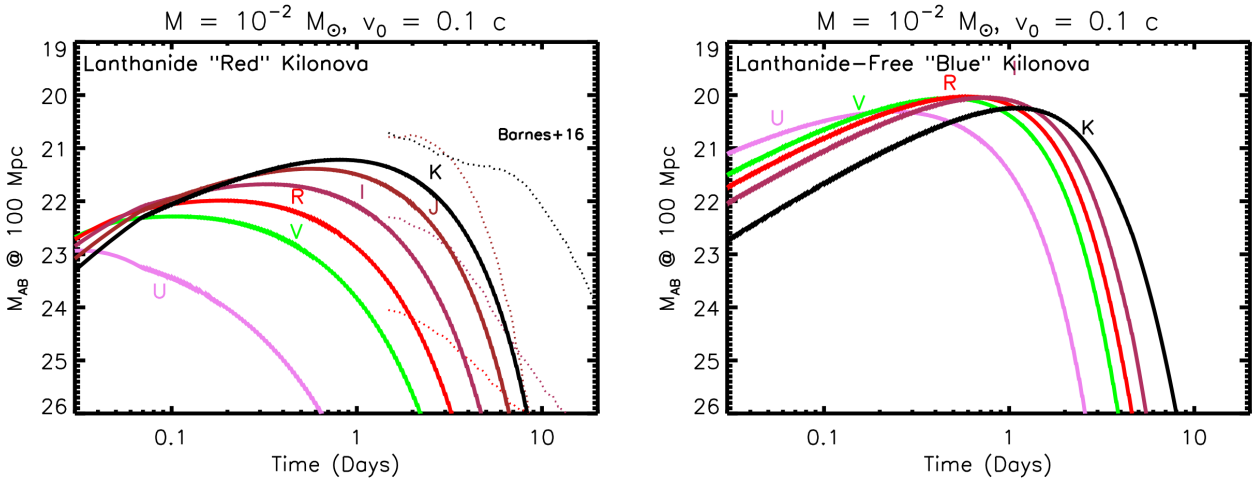
Observational Requirement	State of the Art	Incremental Progress (Enhancing)	Substantial Progress (Enabling)	Major Progress (Breakthrough)
V magnitude of star with $[Fe/H] < -4$	10	12	14	18
Spectroscopic resolving power	30,000	60,000	100,000	100,000
Wavelength range (Å)	1800–3100	1800–3100	1800–3100	1400–3100
S/N after co-adds	20	50	100	100
FOV	(one point source)	(one point source)	(one point source)	(one point source)
Angular resolution at 2000 Å	$< 0''.1$	$< 0''.1$	$< 0''.1$	$< 0''.1$
Number of fields	1	3	10	50

Roederer et al. (2025)

Explosive transient phenomena

Nucleosynthesis in neutron-star mergers is still an unresolved issue.

UV flux from kilonovae contains nucleosynthesis information.



Metzger et al. (2025)

Table 2: Summary of the needed observations, current state of the art, and what is required for various levels of progress. Note that Swift UVOT enables on-target time on the order of minutes, but it is not sensitive enough for the science case described here.

Observation	State of the Art	Incremental Progress	Substantial Progress	Major Progress
Imaging <2 days	Imaging 2–4 days	< 26 th mag in UV	Limiting < 28 th mag in UV	< 30 th mag in UV
	Limiting mag ~22	10 objects per epoch	10 objects per epoch	10 objects per epoch
Spectroscopy <2 days	2–4 days	1 detection	5 detections	10 detections
Rapid response	2–4 days for HST			

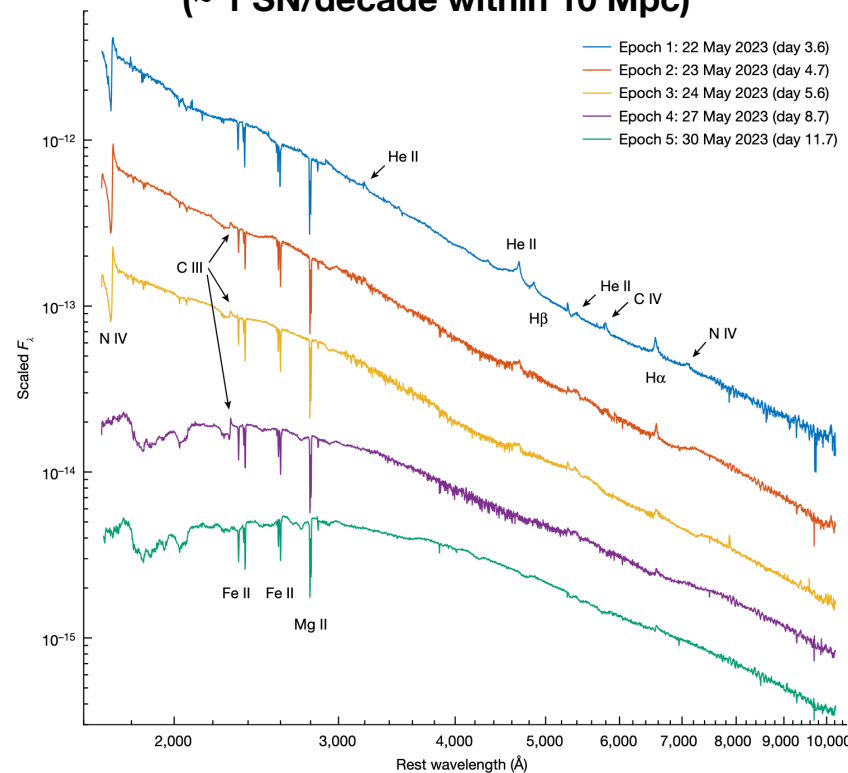
Rapid response!
< 3 days

Explosive transient phenomena

Supernova UV spectra contain their progenitor evolution and nucleosynthesis.

HST spectra of core-collapse SN 2023ixf at 7 Mpc

(~ 1 SN/decade within 10 Mpc)



Rapid response!
< 3 days

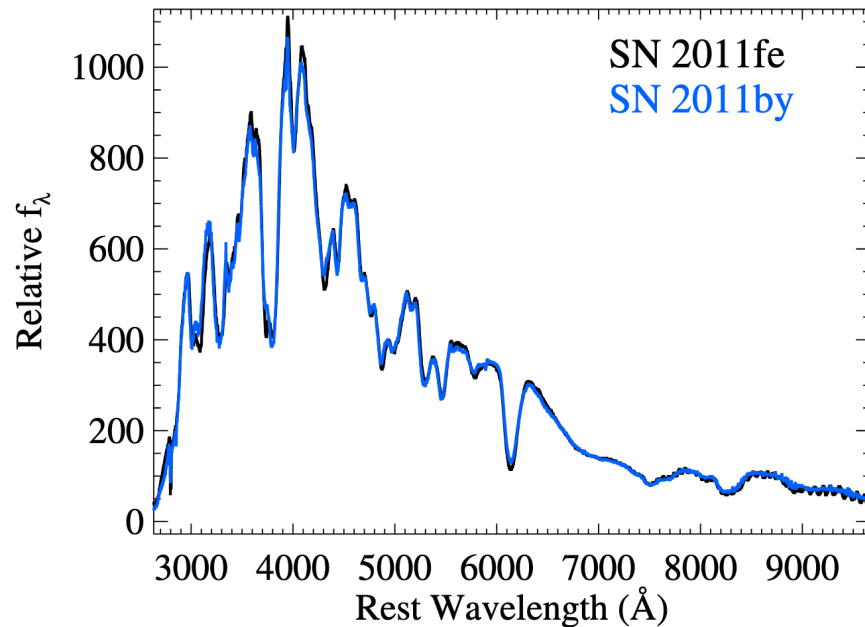
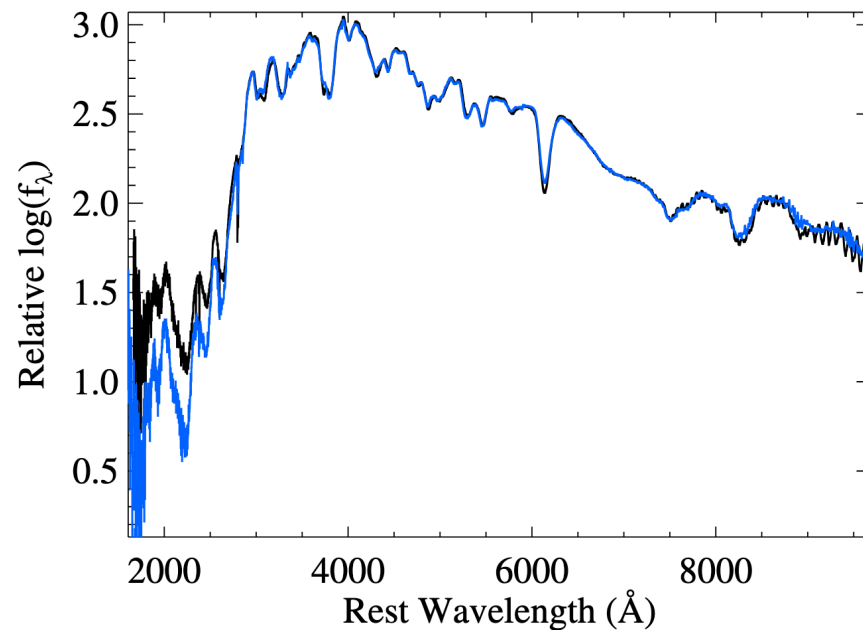
Zimmerman et al. (2024)

Explosive transient phenomena

Supernova UV spectra contain their progenitor evolution and nucleosynthesis.

Type Ia supernovae show diversities in UV.

Progenitor metallicities? *Essential for their cosmological applications.*



Rapid response! (< 1 week)

Foley et al. (2013)

What can Japan contribute?

- Japan has a strong theoretical background for massive star research.
 - Especially at low metallicities
 - Japan can contribute to the development of theoretical ideas to consolidate observational programs.
- Metal-poor star observations are active in Japan
 - Subaru, etc.
 - Japan can contribute to provide metal-poor star candidates to observe.
- Transient science is also active in Japan, both theoretically and observationally.
 - Japan can theoretical models to interpret the observations, for example.

Summary

- Massive star evolution at low metallicities is essential to understand peculiar abundance profiles observed in the primordial galaxies.
 - HWO can obtain UV spectra of massive stars with very low metallicities by resolving them.
- UV spectroscopy of faint metal-poor stars by HWO can reveal the diverse nucleosynthesis of the first supernovae.
- Rapid UV follow-up observations of explosive transients can uncover nucleosynthesis in play.
- Japan can contribute to the HWO studies of Origins of the Elements in various ways.

Title: Probing invisible gravitational sources with unprecedented high-precision astrometry

Lead author: Masahiro Takada

Abstract:

The unprecedented astrometric precision of approximately 1–10 microarcseconds envisioned for HWO will enable us to probe gravitational sources that cannot be detected directly through electromagnetic radiation by measuring stellar motions with exquisite precision. For example, by precisely measuring the proper motions of member stars in globular clusters and dwarf galaxies in the Milky Way (MW), and by identifying stars moving faster than the escape velocities of those systems, HWO may enable searches for intermediate-mass black holes. Likewise, by measuring not only the proper motions but also the proper “accelerations” of stars in the MW halo, HWO could probe isolated black holes and CDM subhalos. Furthermore, just as HST has measured the proper motions of the Magellanic Clouds, HWO may be able to measure the systemic proper motion of the Andromeda Galaxy and thereby clarify when and how M31 will eventually collide with the MW. These are examples of science cases that will either become possible for the first time with HWO or be advanced dramatically by it, and the range of potential applications is extremely broad. In addition, such high-precision astrometric measurements will be highly complementary to line-of-sight velocity measurements obtained from spectroscopic observations with the Subaru Telescope. Combining the two will therefore offer substantial scientific synergy.

Science Case Summary:

- Search for central black holes (BHs), including intermediate-mass BHs – the missing link between stellar-mass and supermassive BHs – through unprecedentedly precise measurements of the proper motions of member stars in globular clusters and dwarf galaxies
- Search for isolated BHs and CDM subhalos in the Milky Way halo region through precise measurements of stellar proper accelerations – that is, curvature in their trajectories across the sky – to probe the nature of dark matter and perform stringent tests of CDM structure formation on small scales
- Measure the systemic (bulk) proper motion of the Andromeda Galaxy (M31) through precise statistical measurements of the proper motions of individual stars in M31 as a test of CDM structure formation on megaparsec scales

Cosmology with HWO

Masahiro Takada

(Kavli Institute for the Physics and Mathematics of the Universe)

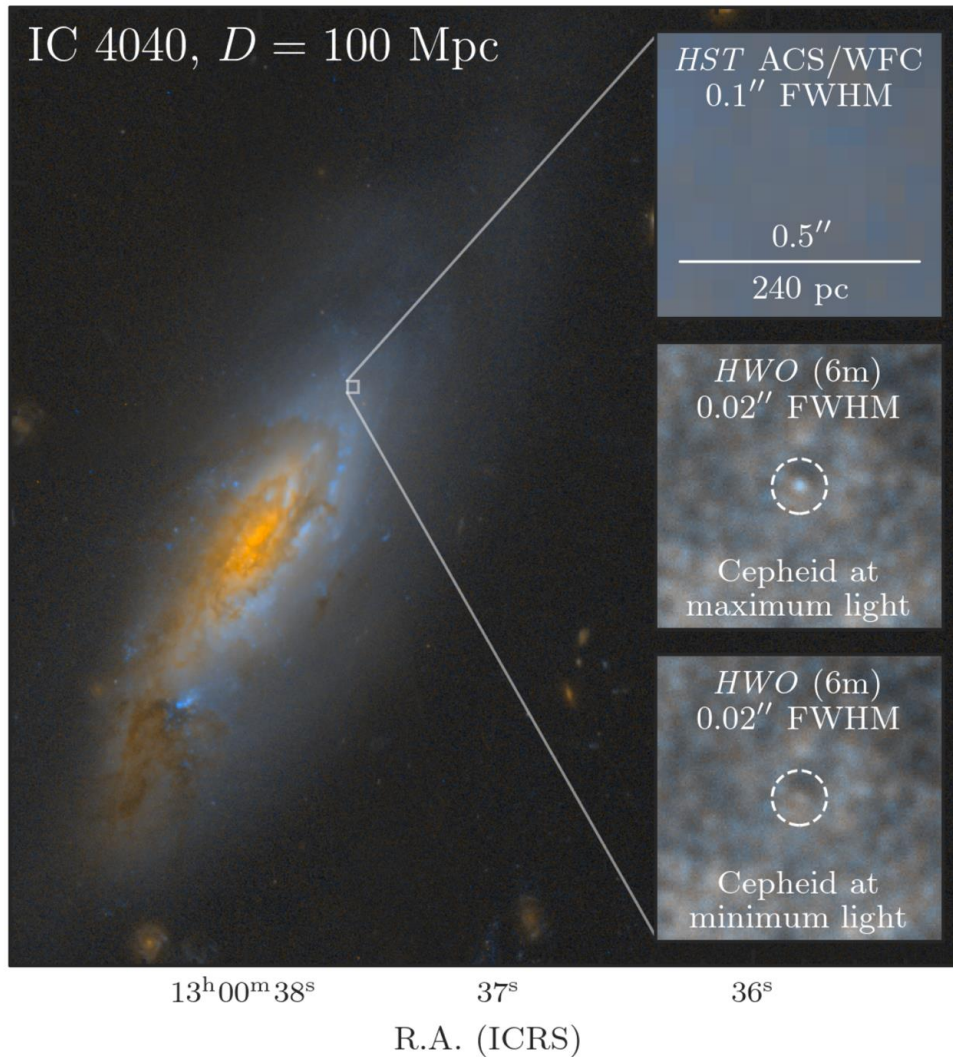
Cosmology in the HWO (2040's) era?

- The nature of dark energy $\triangle$ (H0 tension)
- Physics of inflation $\times$
- The nature of dark matter (including structure formation) $\checkmark$
- Neutrino mass $\times$
-

Note: here I include **black holes (BHs)** as a part of dark matter because they are invisible (and particularly interesting)

HWO – a dream telescope/observatory!

HWO White Paper by Anand, Durbin & Beaton



Thanks to its exquisite spatial resolution and sensitivity, HWO will be able to detect **individual stars** (a Cepheid in this simulation) out to a **distance of 100 Mpc** (the limiting magnitude is ~ 30 mag)

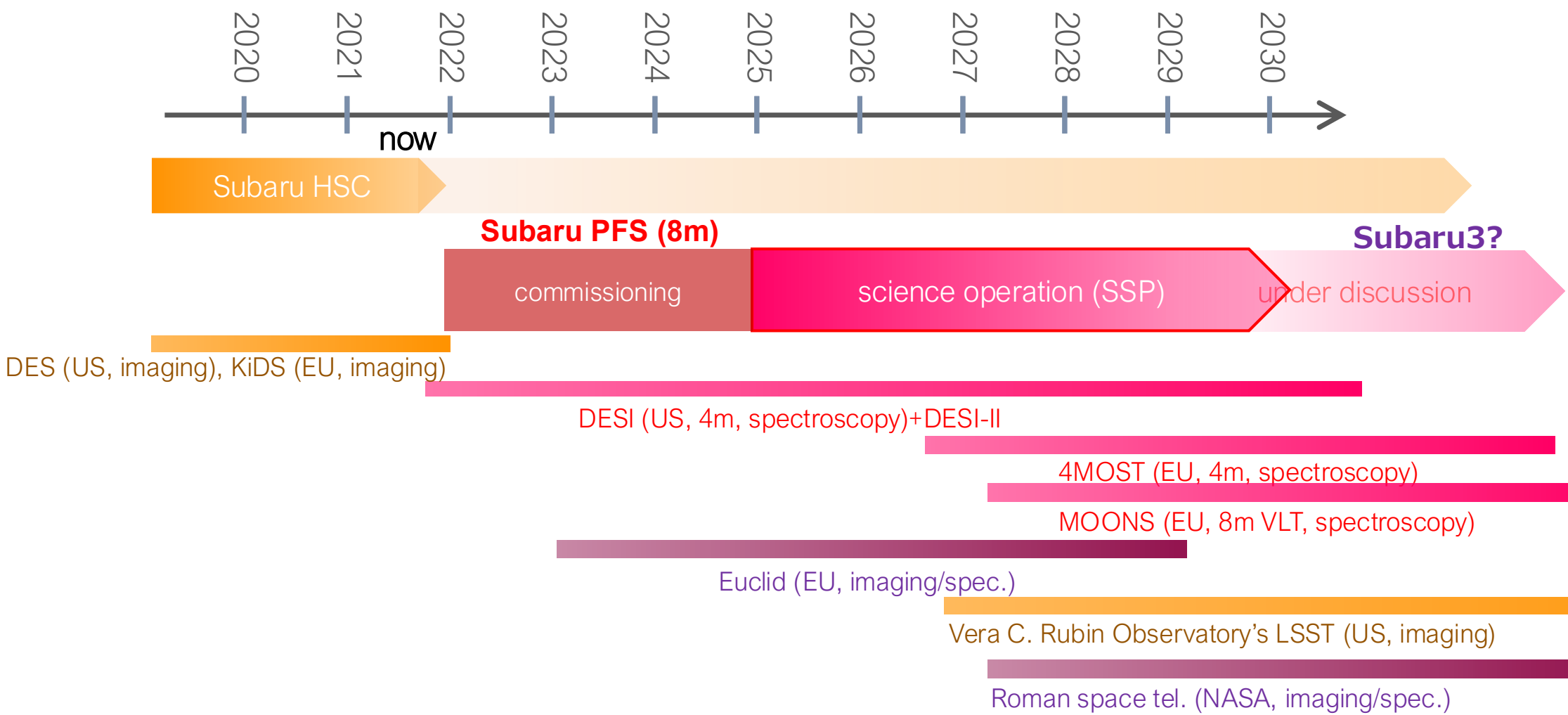
HWO instrument specification

from HWO white paper (or Science Development Documents)

Telescope	
Diameter	~6 - 8 m (inner)
Bandpass	~100 - 2500 nm
High-Resolution Imager	
Bandpass	~200 - 2200 (TBD) nm
Field of view	~3' × 2'
60+ science filters and grisms	
High-precision astrometry	
UV Multi-Object Spectrograph	
Bandpass	~90 - 700 nm
Field of view	~ 2' × 2'
Apertures	~ 840 × 420
R ($\lambda/\Delta\lambda$)	~500 - 60000

Assume ~0.01" pixel scale
Astrometry precision: ~10 μ as ?

Landscapes in 2020s cosmology



LETTER

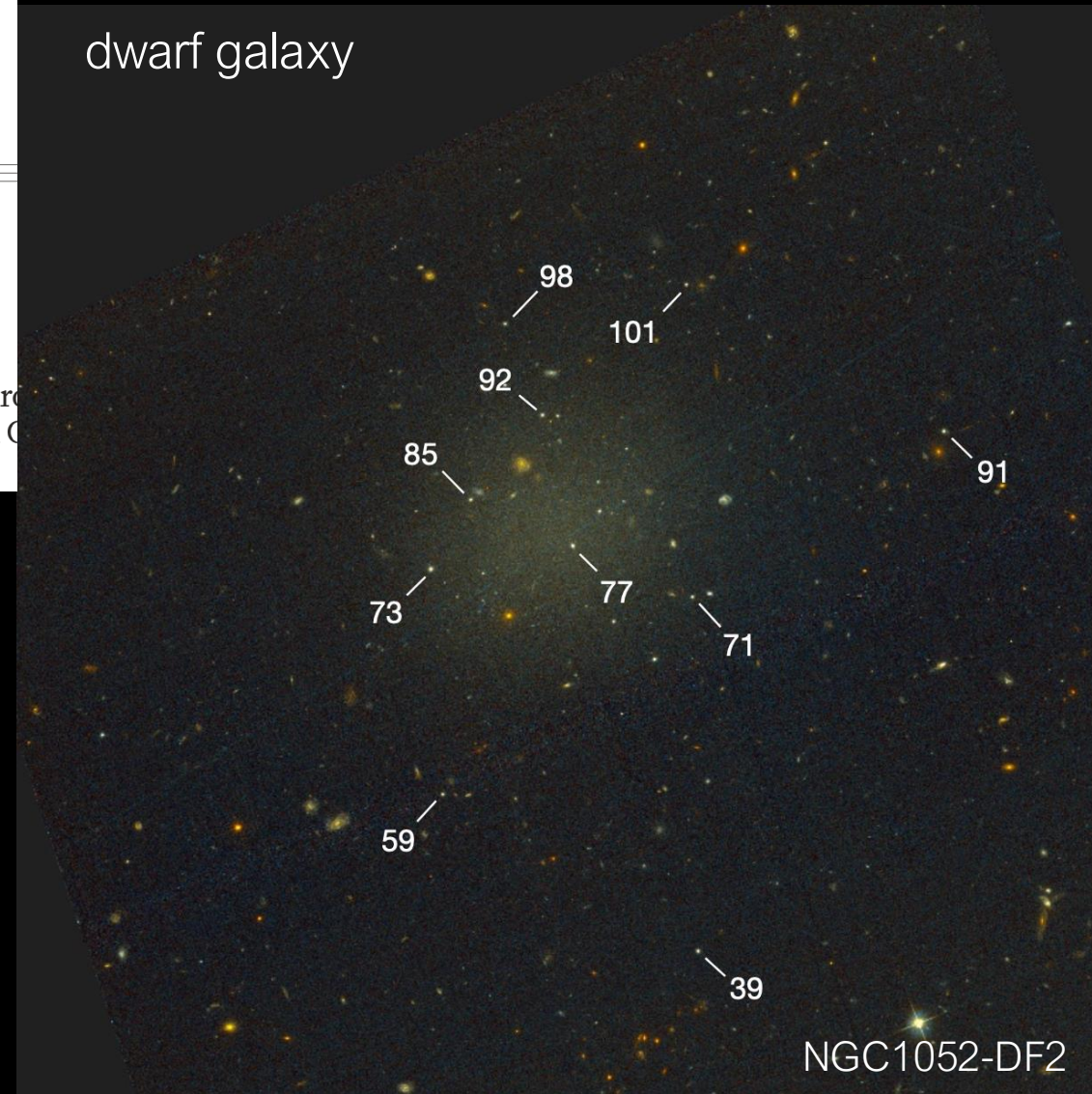
A galaxy lacking dark matter

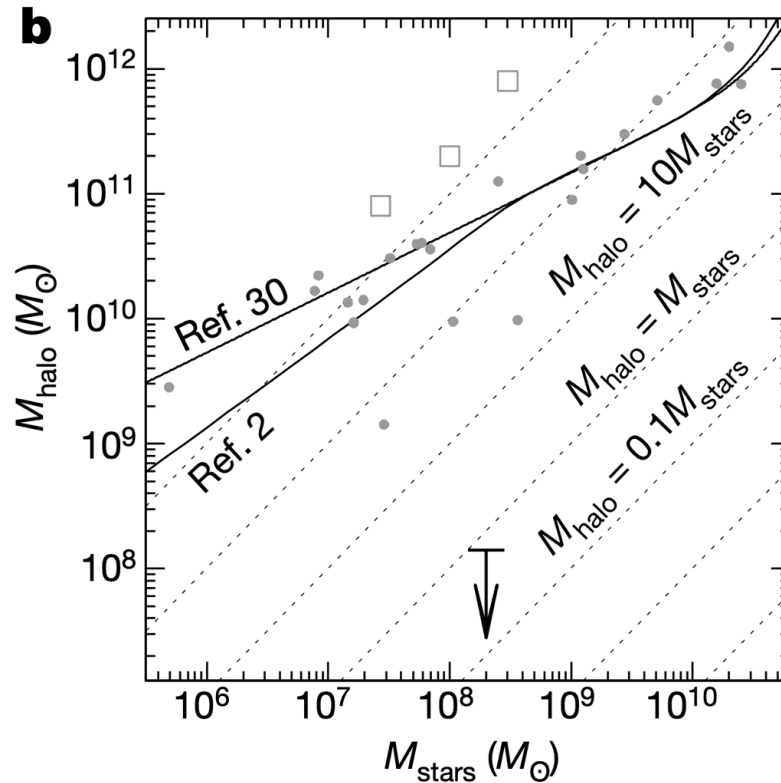
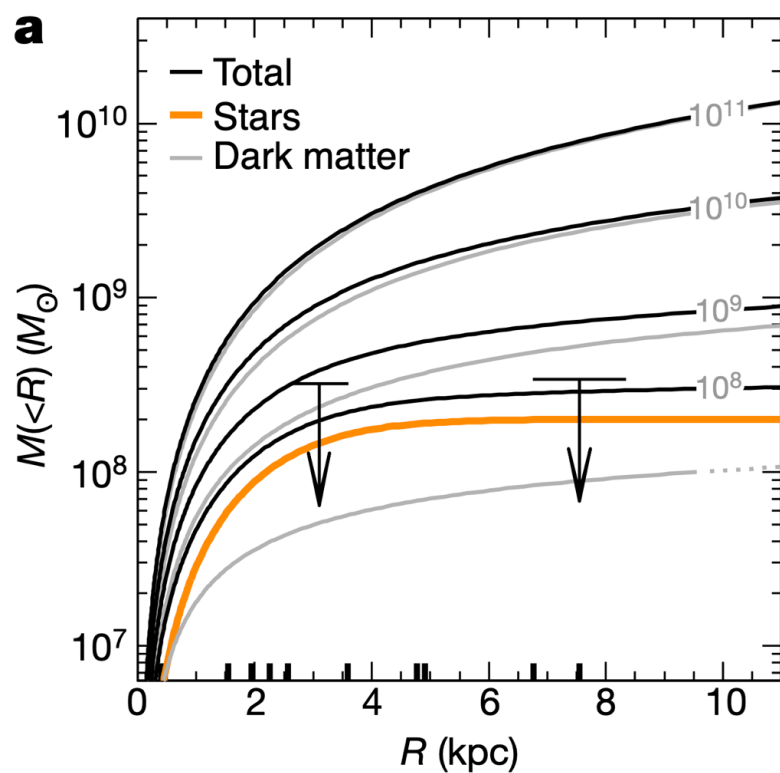
Pieter van Dokkum¹, Shany Danieli¹, Yotam Cohen¹, Allison Merritt^{1,2}, Aaron
Jean Brodie⁴, Charlie Conroy⁶, Deborah Lokhorst⁵, Lamiya Mowla¹, Ewan O

van Dokkum+ Nature 2018

- How can galaxies be formed without dark matter?
- Due to non-WIMP dark matter?
- Rubin Observatory LSST will find “many” similar galaxies

dwarf galaxy





- stellar mass

$$M_* \propto (\pi R_{\text{hl}}^2) L \propto D^2$$

- dynamical mass

$$M_{\text{dyn}} \sim \frac{\sigma_v^2 R}{G} \propto D$$

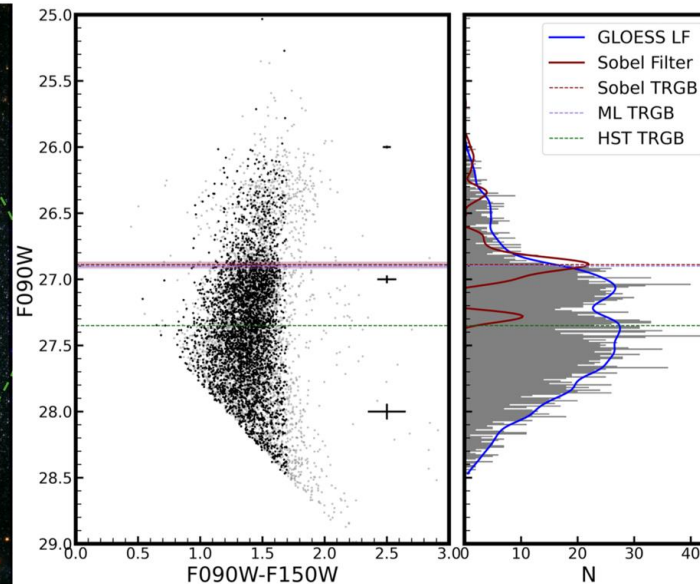
- Different dependences on the distance to DF2
- van Dokkum+ assumed $D \sim 20 \text{ Mpc}$
- Trujillo+(2018) argued that $D \sim 13 \text{ Mpc}$ can resolve the DM anomaly

New Measurements of Distances to Galaxies in the NGC 1052 Field with the Hubble and James Webb Space Telescopes: Testing the Bullet-Dwarf Origin of the Trail

YIMENG TANG ¹ GAGANDEEP S. ANAND ² AARON J. ROMANOWSKY ^{1,3} PIETER G. VAN DOKKUM ⁴ AND
KEVIN A. BUNDY ¹

Table 1. Properties of NGC 1052, NGC 1035, and eight dwarf galaxies on the trail studied in the work.

Galaxy	RA	Dec	Radial Velocity	$g - i$	$\bar{m}_{F814W}$	$D_{\text{SBF,HST}}$	$D_{\text{TRGB,HST}}$	$D_{\text{TRGB,JWST}}$
	[deg]	[deg]	[km s ⁻¹]	[mag]	[mag]	[Mpc]	[Mpc]	[Mpc]
NGC 1052	40.26999	-8.25576	1488 ⁺⁵ ₋₅	1.07 ± 0.01	30.23 ± 0.03	21.3 ± 1.7	—	—
NGC 1035	39.87145	-8.13328	1288 ⁺⁴ ₋₄	0.85 ± 0.01	29.04 ± 0.03	13.8 ± 1.1	—	—
DF2 (RCP 29)	40.44531	-8.40297	1805 ⁺¹ ₋₁	0.86 ± 0.01	29.65 ± 0.03	17.7 ± 1.4	21.7 ± 1.2	17.6 ± 0.6



HST 66hrs

HWO will provide a definite answer

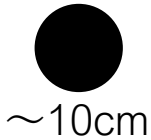
arXiv:2606.05144

Searching for black holes

- **BHs** are among the most fascinating objects in astronomy, both scientifically and for the public
- There is still no clear evidence for Intermediate massive BHs (**IMBHs**), the missing link between stellar BHs (up to $\sim 100 M_{\text{sun}}$) and supermassive BHs ($> 10^6 M_{\text{sun}}$)
- BHs with **$< 1-2 M_{\text{sun}}$** should be “primordial” (**PBHs**), having formed in the early universe after inflation (Hawking 1971)
- BH can be searched for using gravitational waves, **gravitational microlensing** (ask Sumi-san), **kinematic methods**, ...

Searching for a Black Hole in the Outer Solar System

10M_Earth BH



Edward Witten

*Institute for Advanced Study
Einstein Drive, Princeton, NJ 08540 USA*

If we discover a BH in the vicinity of the Solar System, we may be able to investigate its properties in detail

Abstract

There are hints of a novel object (“Planet 9”) with a mass $5 - 10 M_{\oplus}$ in the outer Solar System, at a distance of order 500 AU. If it is a relatively conventional planet, it can be found in telescopic searches. Alternatively, it has been suggested that this body might be a primordial black hole (PBH). In that case, conventional searches will fail. A possible alternative is to probe the gravitational field of this object using small, laser-launched spacecraft, like the ones envisioned in the Breakthrough Starshot project. With a velocity of order $.001 c$, such spacecraft can reach Planet 9 roughly a decade after launch and can discover it if they can report timing measurements accurate to 10^{-5} seconds back to Earth.

astrometry and proper motion

- proper motion

$$\mu = \frac{\theta(t_2) - \theta(t_1)}{t_2 - t_1}$$

← astrometry of individual stars at each epoch

← time baseline

HWO

$$\sigma(|\theta|) \sim O(\mu\text{as})$$

$$t_2 \gtrsim 2040'\text{s}$$

current data (HST, Gaia, JWST, etc.)

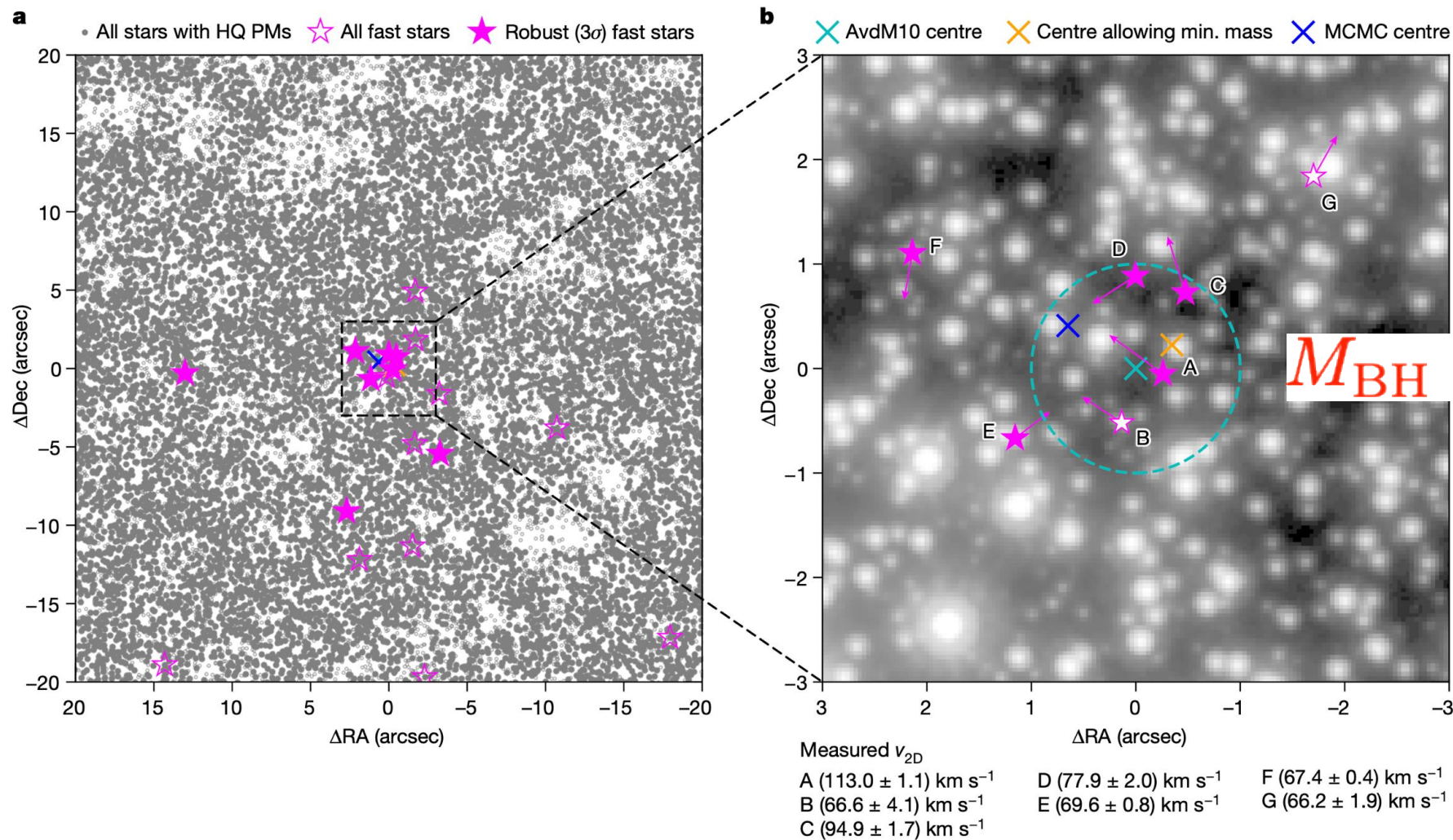
$$\sigma(|\theta|) \sim O(0.1 - 1\text{mas})$$

$$t_1 \sim 2000 - 2020'\text{s}$$

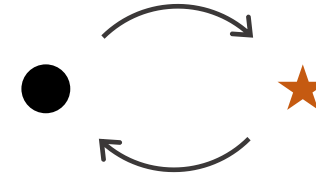
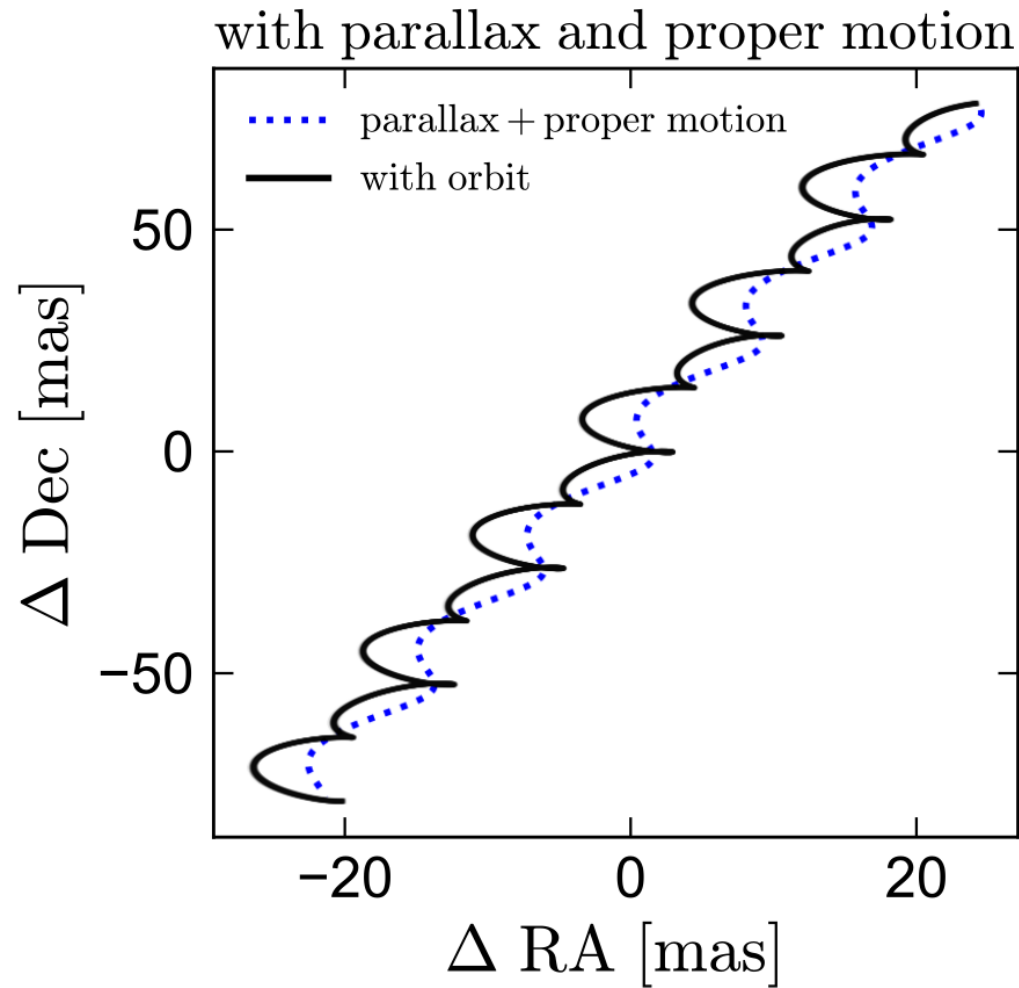
note: a longer time baseline enables more precise proper-motion measurements

fast-moving stars around IMBH in ω Centauri (Haberle+2024, Nature)

$D = 5.43\text{kpc}$ HST obs at 286 epochs over 20.6-year baseline $O(0.1 \text{ mas yr}^{-1})$ ($\approx O(1 \text{ km s}^{-1})$)



Hunting BHs with “wandering” stars



- star-BH binary (even triplet)
- A visible star exhibits a wandering motion on the sky
- GAIA DR4 (scheduled on Dec 2, 2026) will reveal many BH (and NS) candidates
- Follow-up observations needed; astrometric and proper motion measurements are needed over a longer time baseline

Gaia BH1 (El-Badry+2022)

$$d \simeq 480 \text{ pc}$$

$$M_* = 0.93 \pm 0.05 M_{\odot}$$

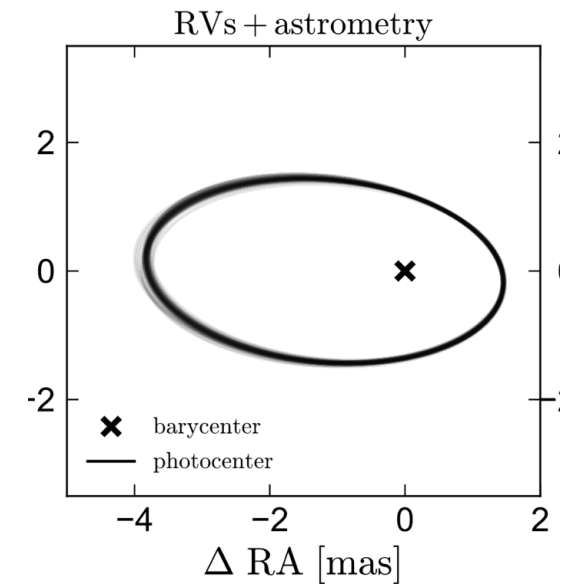
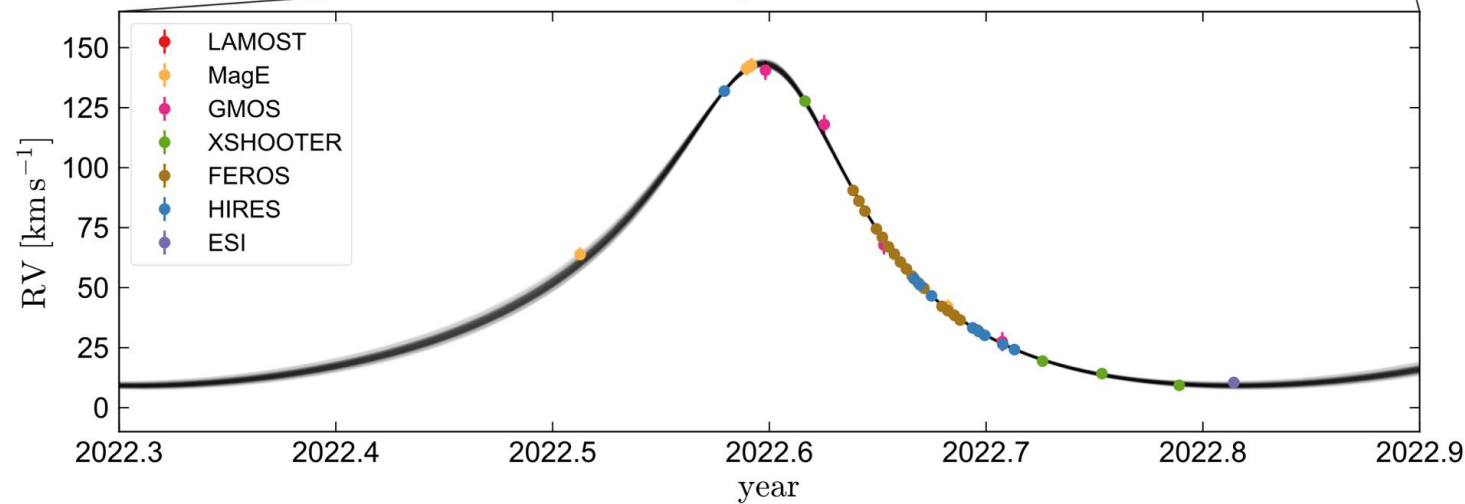
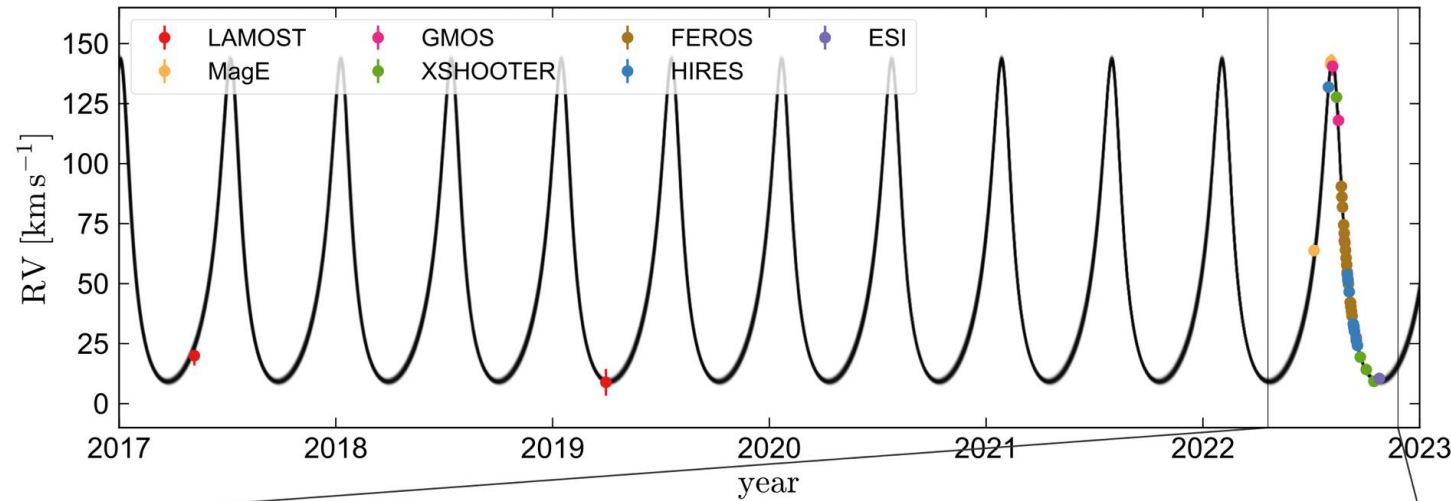
$$M_{\text{BH}} = 9.62 \pm 0.18 M_{\odot}$$

$$P_{\text{orb}} = 185.59 \pm 0.05 \text{ days}$$

$$a = 1.40 \pm 0.01 \text{ AU}$$

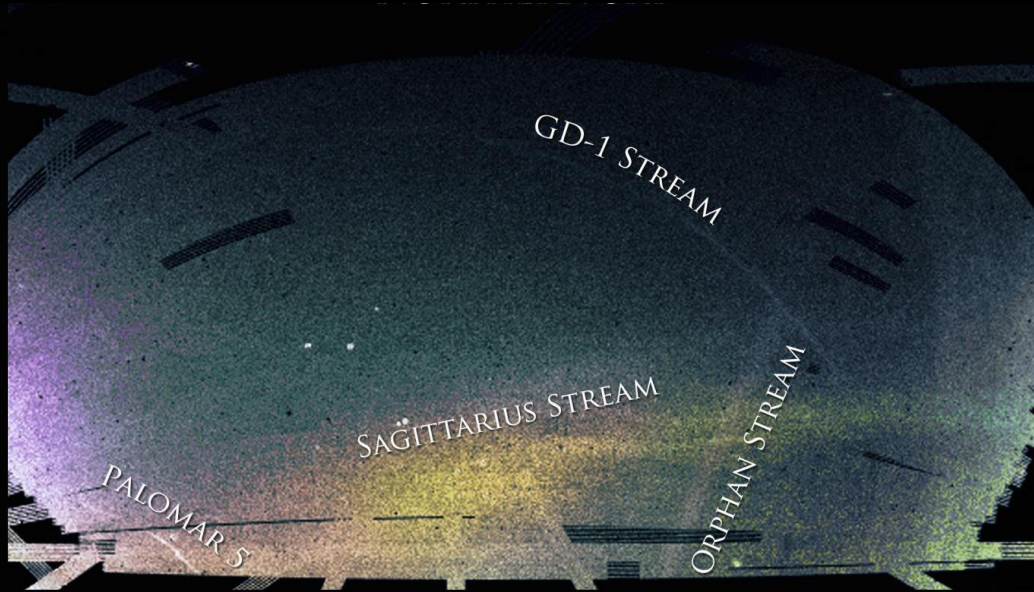
$$e = 0.451 \pm 0.005$$

$$i = 126.6 \pm 0.4 \text{ deg.}$$

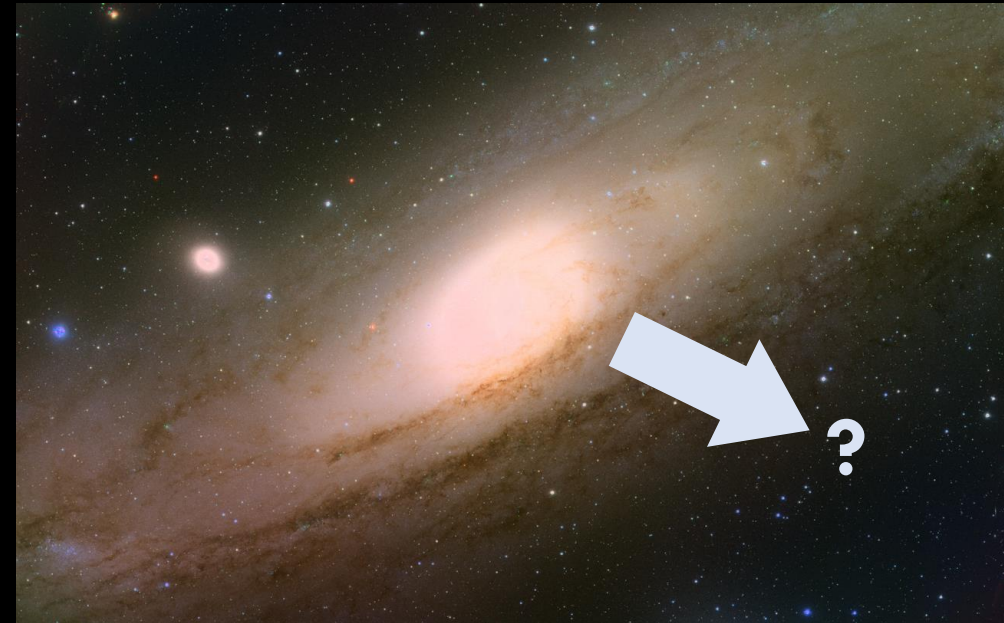


many other exciting science opportunities with precise astrometry

stellar stream, dwarf galaxies...



- Measure not only the proper motion, but also its time variation, i.e., **acceleration (gravity)**
- The Milky Way potential
- dark matter substructures
- black hole
- ...



- Measure the **bulk motion of Andromeda Galaxy** (800kpc) over a baseline of a few decades (towards the MW?)
- for an individual star in Andromeda (stars are resolved, and their astrometries can be measured)

$$\Delta\theta \sim 1 \text{ mas} \times \left(\frac{v_{\text{bulk}}}{200 \text{ km s}^{-1}} \right) \left(\frac{t_{\text{baseline}}}{30 \text{ yrs}} \right)$$

Microlensing lensing – very powerful means of finding “invisibles”

- Einstein radius $R_E = \sqrt{\frac{4\pi G M_{\text{lens}} d(1 - d/d_s)}{c^2}}$

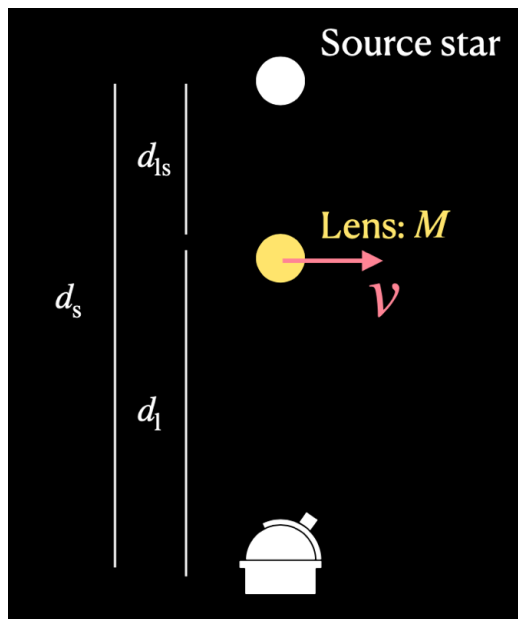
Subaru-HBO for the northern hemisphere

Rubin-HBO for the south

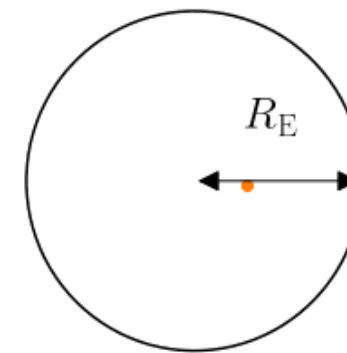
- Light curve timescale (=time duration with $A > A(R_E) = 1.34$)

$$t_E \sim \frac{2R_E}{v_{\text{rel}}} \quad t_E \sim \text{a few hours for a Earth-mass lens}$$

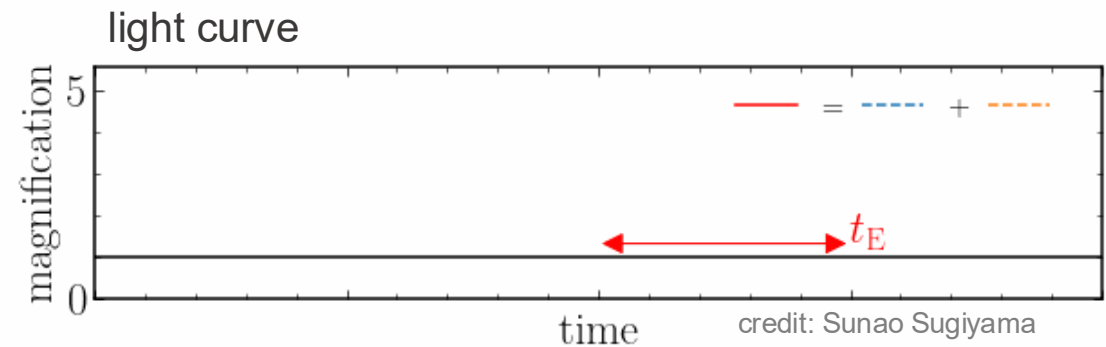
$$t_E \sim \text{a month timescale for a } M_{\odot} \text{ lens}$$



on the sky

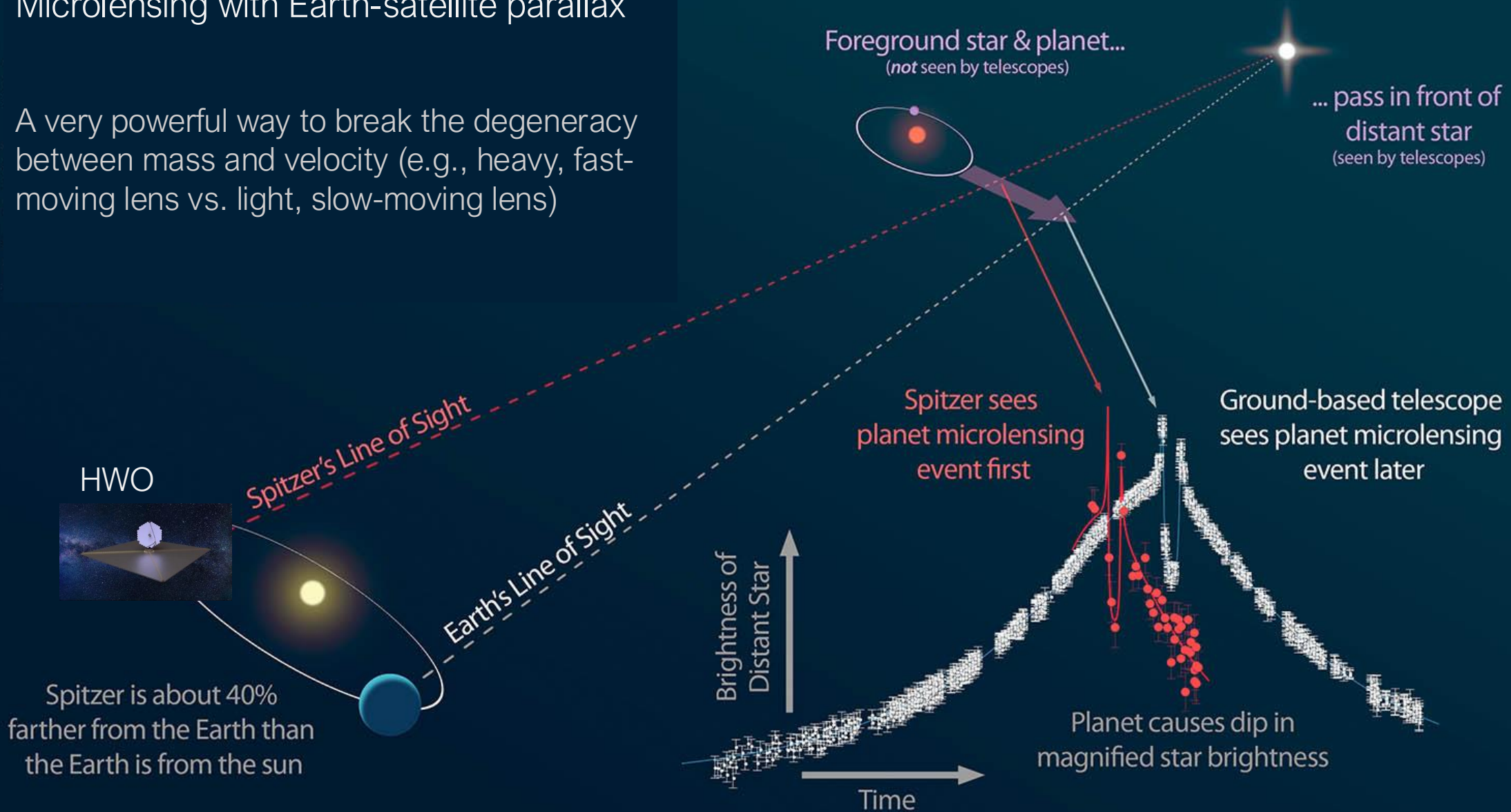


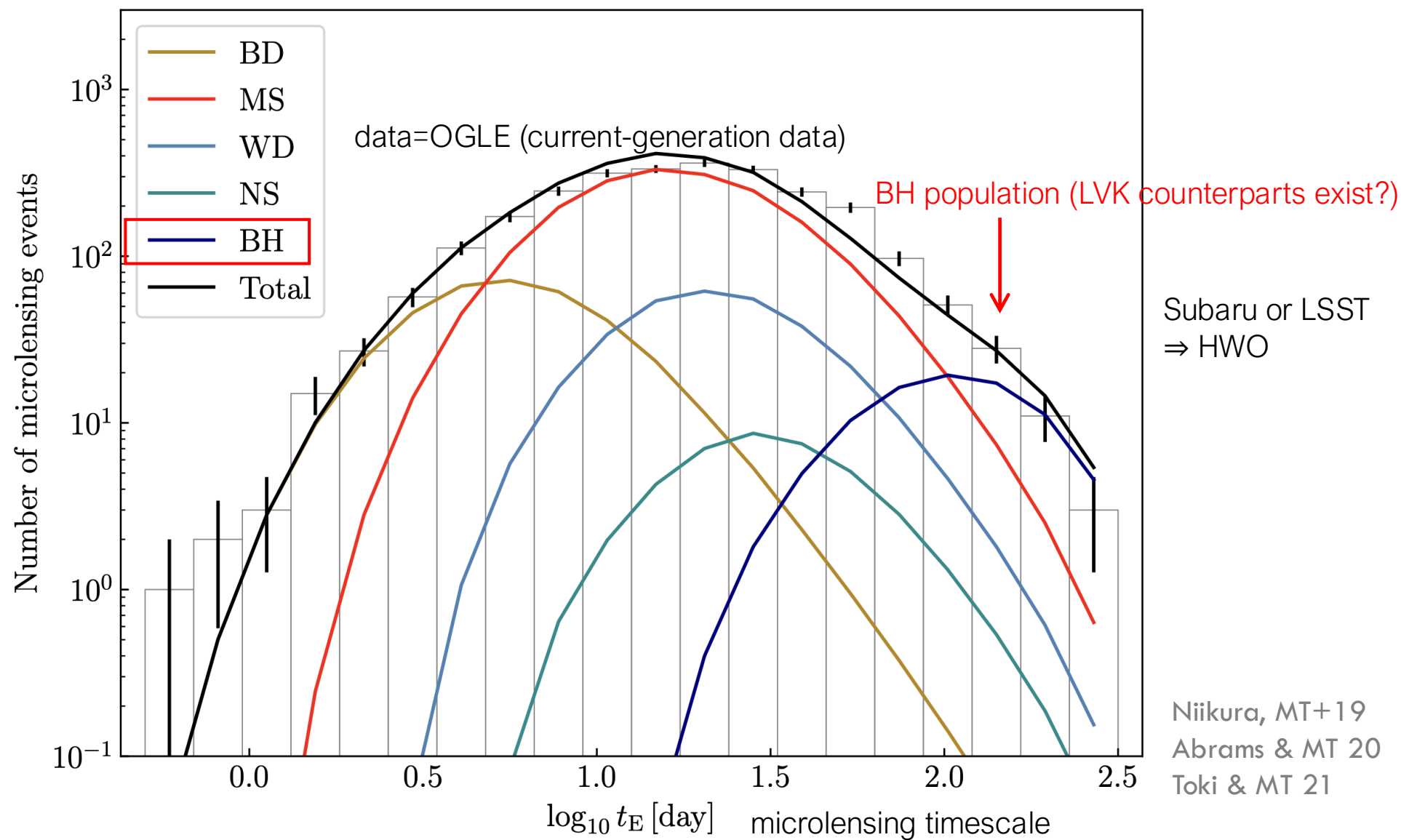
- source
- image 1
- image 2



Microlensing with Earth-satellite parallax

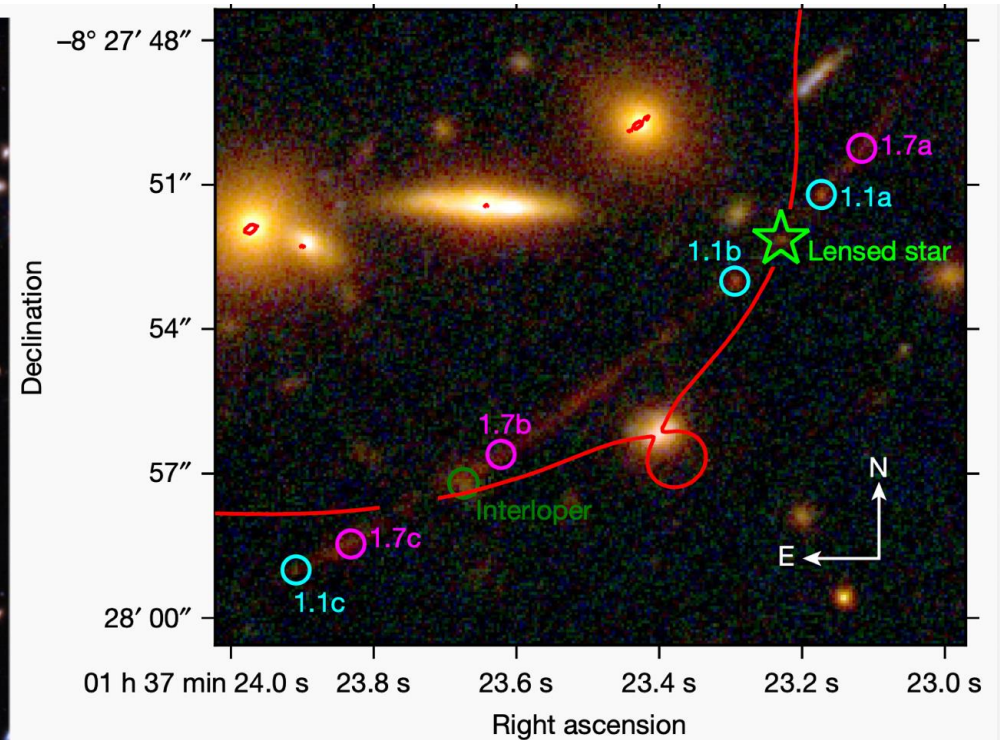
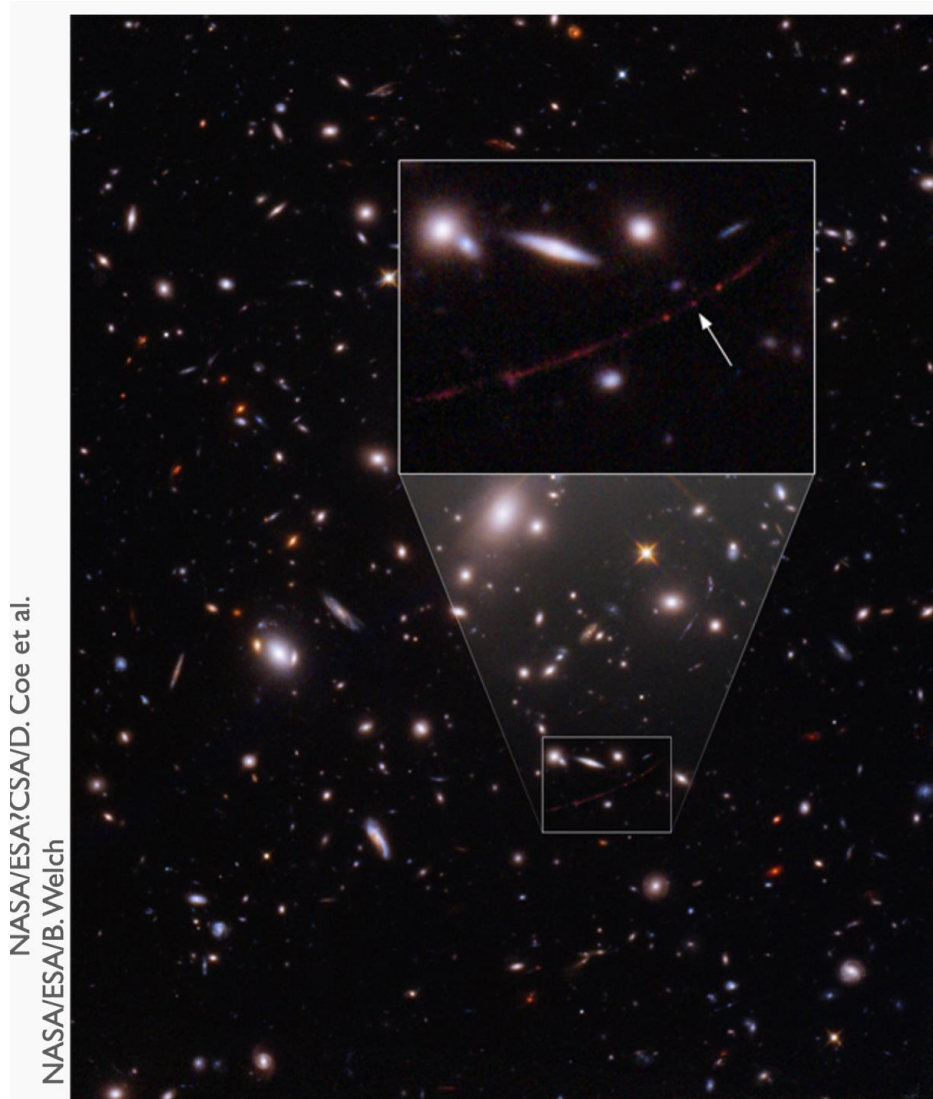
A very powerful way to break the degeneracy between mass and velocity (e.g., heavy, fast-moving lens vs. light, slow-moving lens)





cluster lensing – lensing of a single star

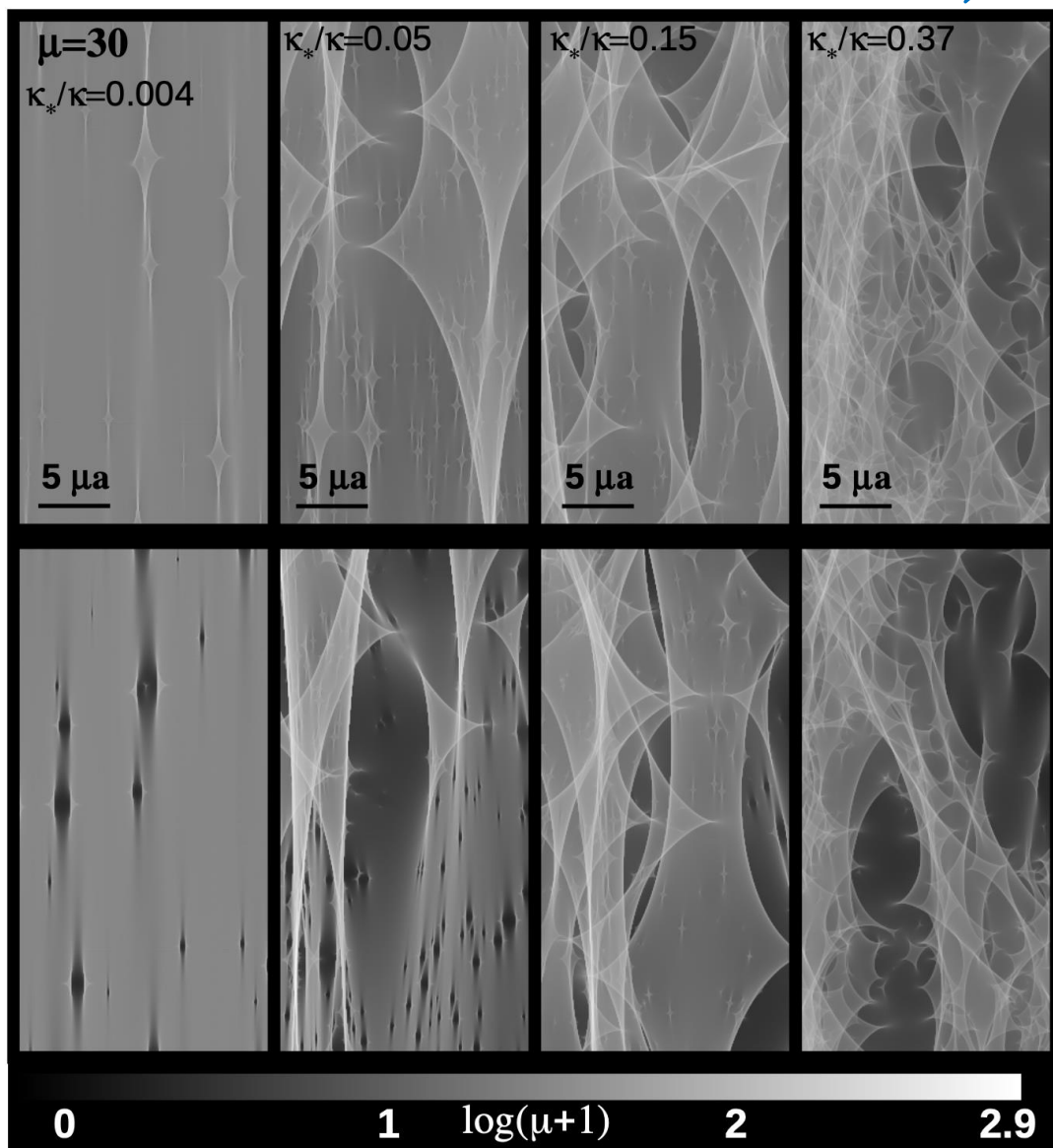
Welch+(including Oguri) Nature (2022)



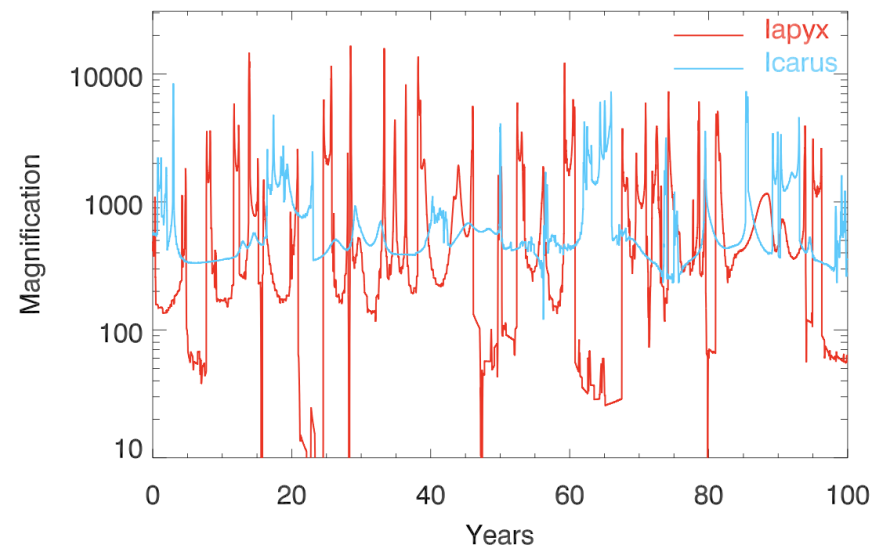
- “Earendel”: lensing of a single star at $z=6.2$.
 $T \sim 13000\text{--}16000\text{K}$ from the SED fitting
- magnification $\sim 10000(?)$

only CDM

CDM + compact objects (stars, BHs, ...)



Caustic network

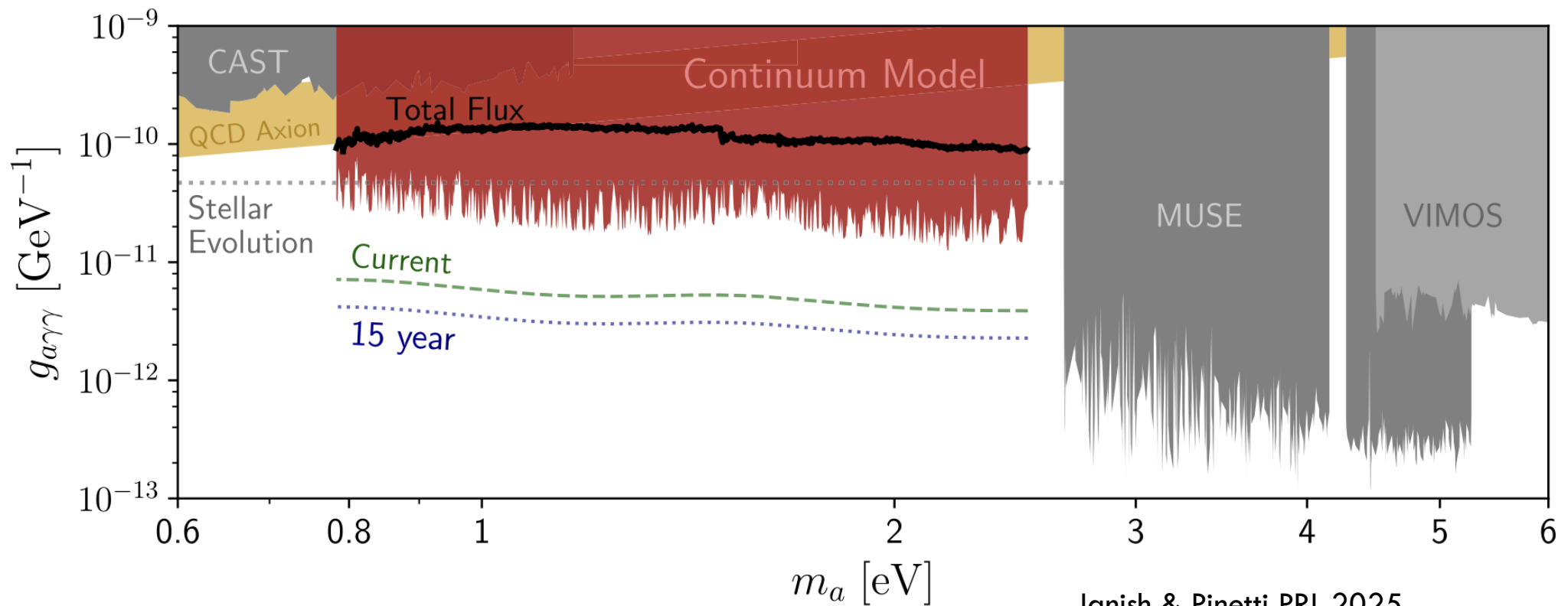


- The time variability of a highly magnified star can be monitored over a human lifetime
- Simulated caustic network in the source plane, produced by smooth CDM and compact objects
- Lighter-colored regions have higher magnification
- Compact objects include (intra-cluster-light) stars, PBHs, clumps due to wave-like dark matter, ...

Diego+ (including Oguri) 2018

O(eV) dark matter

- Search for “unknown” emission line in the deepest (optical and IR) spectra
- The emission line is produced by the decay of O(eV) dark matter
- The following work used the JWST spectra to search for unknown lines



Janish & Pinetti PRL 2025

My answer to the homework (cosmology with HWO)

- HWO is **a dream observatory**, with exquisite spatial resolution and sensitivity
- High-precision measurements of **individual stars out to $\sim 100\text{Mpc}$** (photometry, astrometry, proper motion, ...); **Subaru (CMOS?) -HWO microlensing survey**
- Strongly lensed high-redshift stars behind galaxy clusters (substructures, compact objects, ...)
- Scientific objects
 - The nature of dark matter – PBHs, substructures, ... via HWO observations of wandering stars, time-variability of proper motions, strong lensing, ...
 - Tests of small-scale structure formation – dark matter deficit galaxies (dwarf galaxies), the bulk motion of Andromeda Galaxy (when it will collide with the Milky Way?)
 - HWO white papers: distant ladder (H_0 tension), small-scale structures, dark matter, IMBH, ...
 - ...

Galaxy Observations Toward Future Studies with the Habitable Worlds Observatory

Lead author: Masami Ouchi

Abstract:

This talk reviews recent progress in galaxy observations with space telescopes, particularly JWST, and discusses how these results motivate and inform galaxy science cases currently being developed within the Habitable Worlds Observatory (HWO) community. The talk highlights key open questions in galaxy formation and evolution and discusses how HWO could help address them in the 2040s.

Science Case Summary

The Habitable Worlds Observatory (HWO) is a next-generation, large-aperture space telescope designed to observe optical and near-infrared light, with a primary focus on ultraviolet (UV) wavelengths. Leveraging the unprecedented sensitivity and spatial resolution of HWO's large-aperture UV capabilities, observational proposals targeting stars and galaxies in the local Universe are currently being discussed within the US HWO community. On the other hand, observations of stars and galaxies in the early (high redshift) Universe utilizing its high optical and near-infrared sensitivity have not yet been investigated, making it an urgent priority to proceed with such studies.

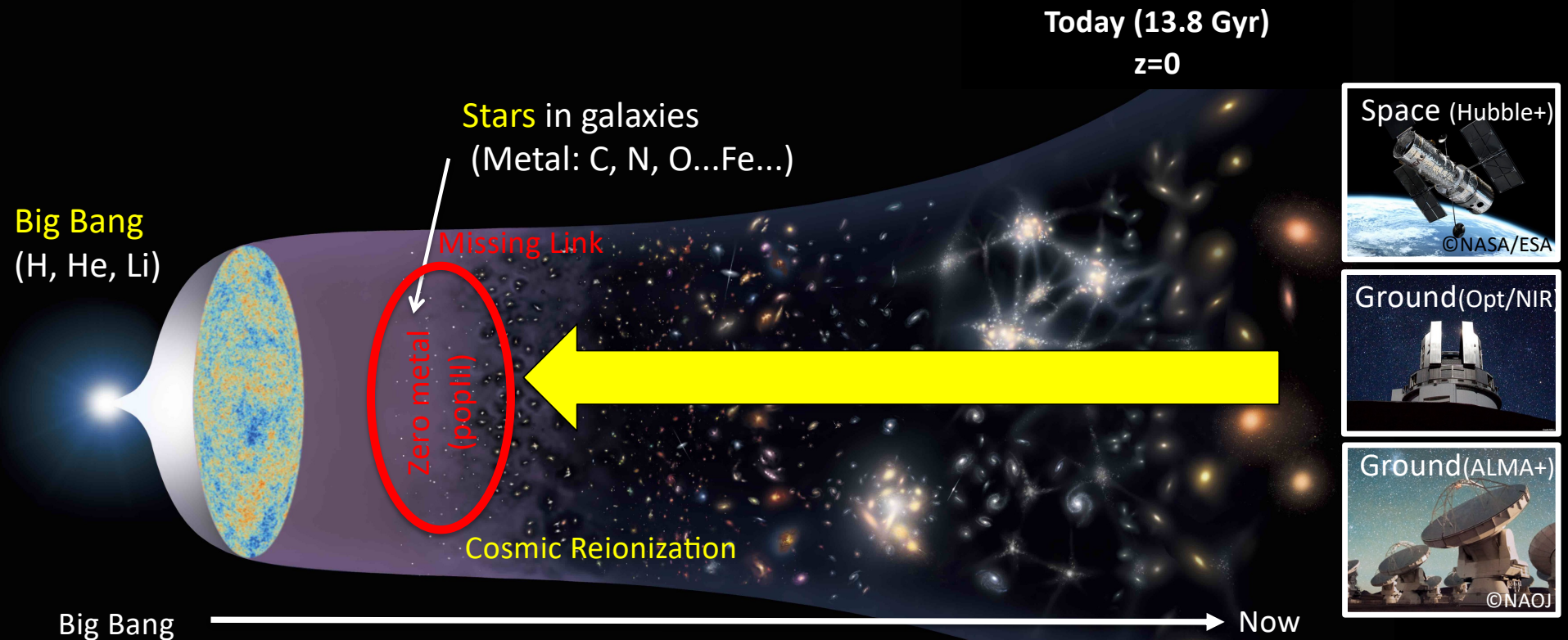
Galaxy Observations Toward Future Studies with the Habitable Worlds Observatory



Masami Ouchi
NAOJ / U.Tokyo

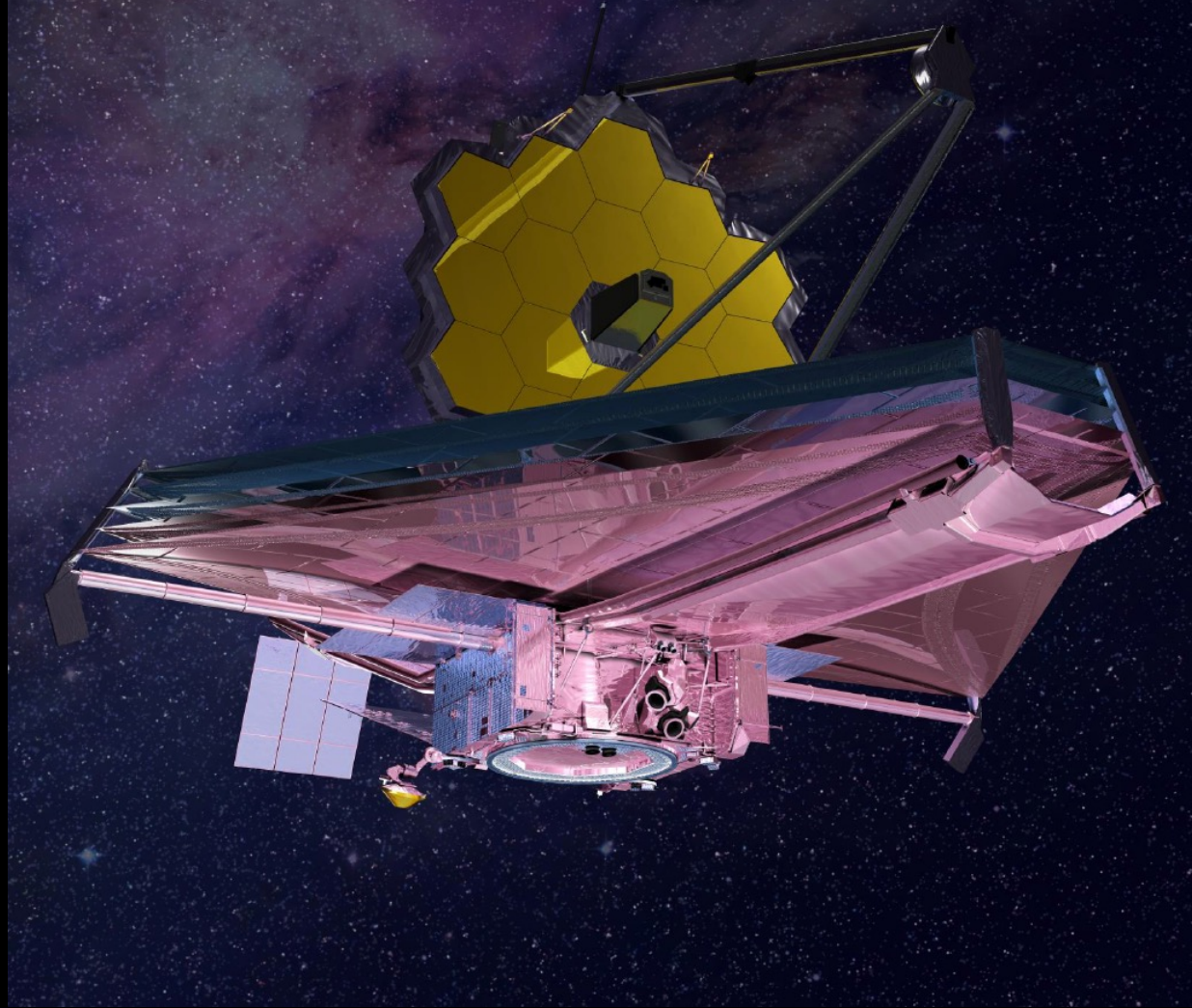
<https://science.nasa.gov/astrophysics/programs/habitable-worlds-observatory/>

Galaxy Formation



- Big Bang nucleosynthesis (H, He, Li)
- Structure formation for dark matter halos
- Star-formation in dark matter halos $\rightarrow$ Chemical enrichment (C, N, O,...Fe...) and dust
 - In galaxy growing, exchanging matter and energy via matter inflow/outflow and radiation

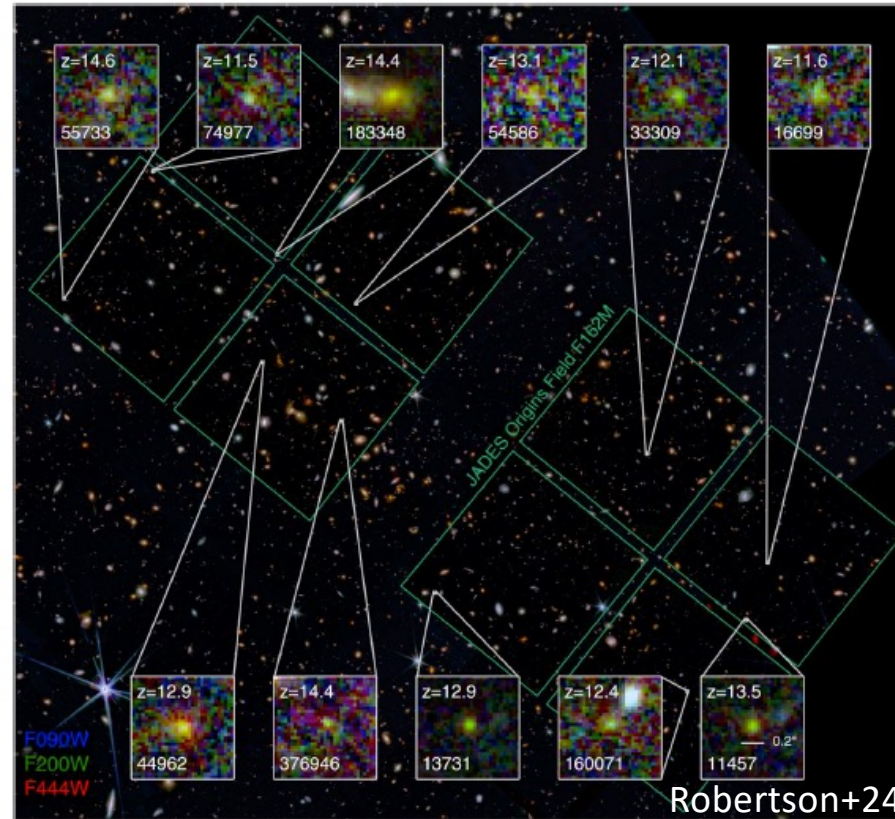
James Webb Space Telescope



c) Space Telescope Science Institute (STScI)

Early Galaxy Observations (rest-frame UV)

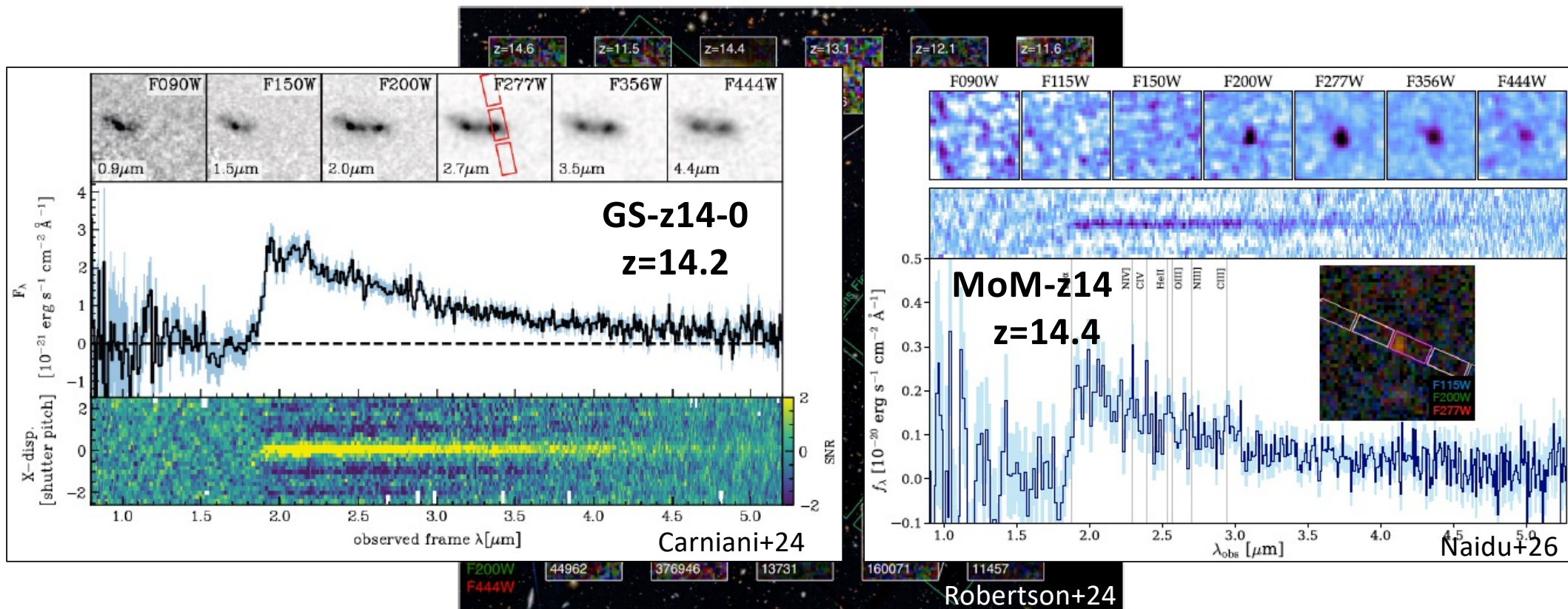
Reaching the Epoch $\sim 200\text{-}300$ Myr after BB



- Galaxy candidates up to $z(\text{phot}) \sim 15\text{-}30$
 - Confirmed at $z(\text{spec})=14.2$ (Carniani+24/+25, Schouws+24) & up to $z(\text{spec})=14.4$ (Naidu+26) with the **rest-frame UV (+optical) spectra** (HWO will conduct similar observations, but for local galaxy w the **UV+opt** capability)
- See also Naidu+22, Castellano+22/+23/+25, Finkelstein+22, Bouwens+23a,b, Donnan+23,24, Finkelstein+22,23a,b, Harikane+23/+24/+25, Arrabal Haro+23a,b, McLeod+24/+26, Robertson+24/+25; Perez-Gonzalez+23; Willott+23, Kokorev+25, and more

Early Galaxy Observations (rest-frame UV)

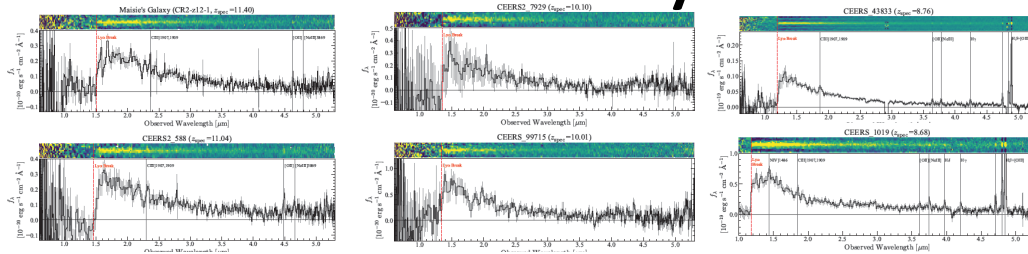
Reaching the Epoch $\sim 200\text{-}300$ Myr after BB



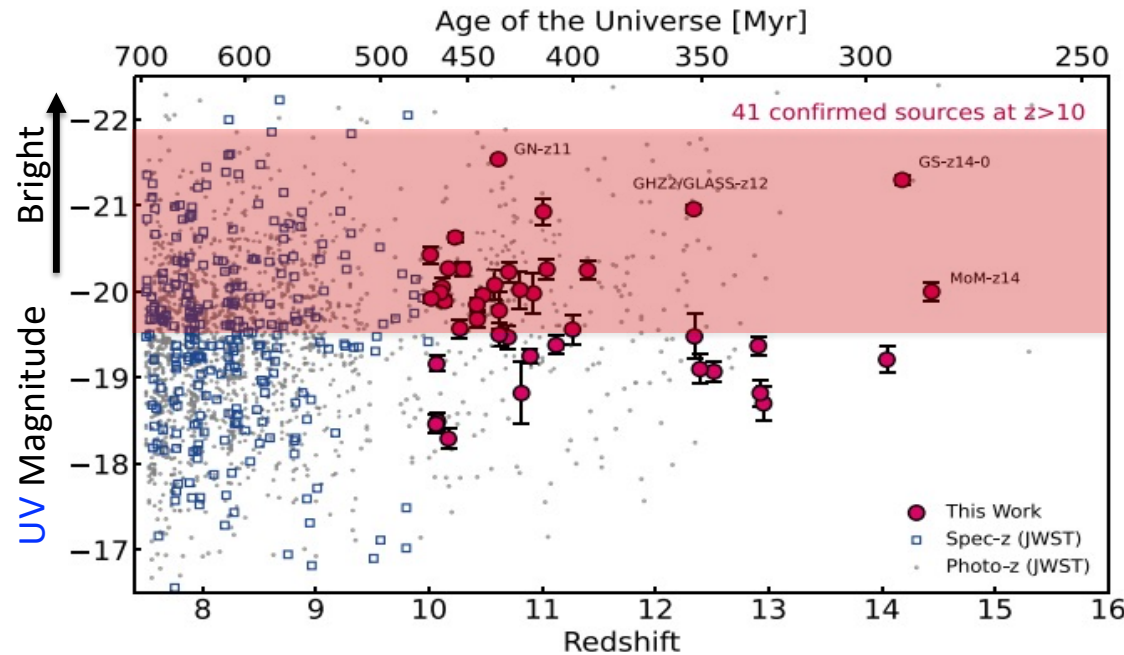
- Galaxy candidates up to $z(\text{phot}) \sim 15\text{-}30$
- Confirmed at $z(\text{spec}) = 14.2$ (Carniani+24/+25, Schouws+24) & up to $z(\text{spec}) = 14.4$ (Naidu+26) with the **rest-frame UV (+optical) spectra** (HWO will conduct similar observations, but for local galaxy w the **UV+opt** capability)

See also Naidu+22, Castellano+22/+23/+25, Finkelstein+22, Bouwens+23a,b, Donnan+23,24, Finkelstein+22,23a,b, Harikane+23/+24/+25, Arrabal Haro+23a,b, McLeod+24/+26, Robertson+24/+25; Perez-Gonzalez+23; Willott+23, Kokorev+25, and more

Many Overluminous Galaxies



Harikane+24,+25

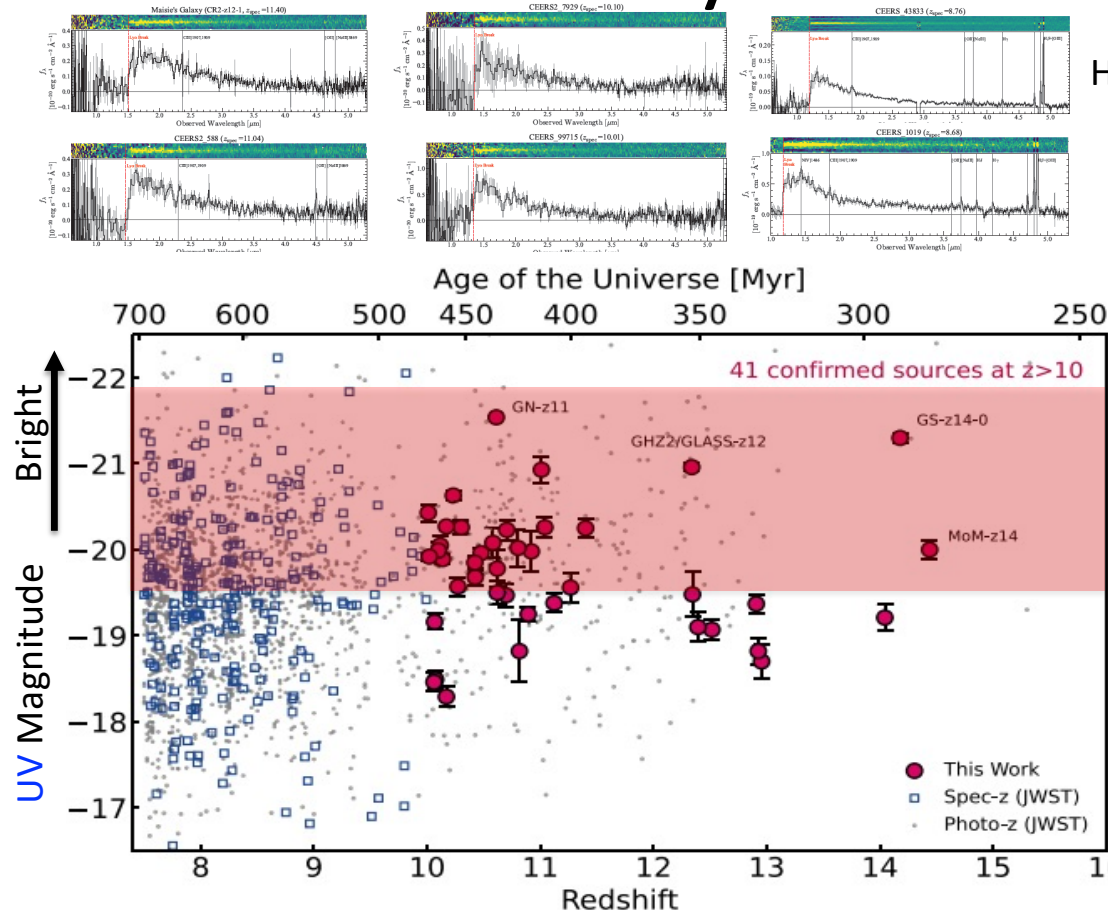


Roberts-Borsani+26

- >40 galaxies at $z(\text{spec}) > 10$ (JADES and various GO, ERS, DDT programs)
- Secure lower limits of **UV luminosity func.** by spec. → Abundant overluminous galaxies
 - 1) Efficient SF at $z > 10$? 2) Top-heavy IMF(+Pop-III) 3) Bursty SF 4) Attenuation free 5) cosm. flaw, 6) AGN

See+ Curtis-Lake+23, Arrabal-Haro+23a,b, Bunker+23, Roberts-Borsani+23, Boyett+23, Cameron+23, Hsiao+23, Fujimoto+23, Castellano+23, D'Eugenio+24, Carniani+24 and more...

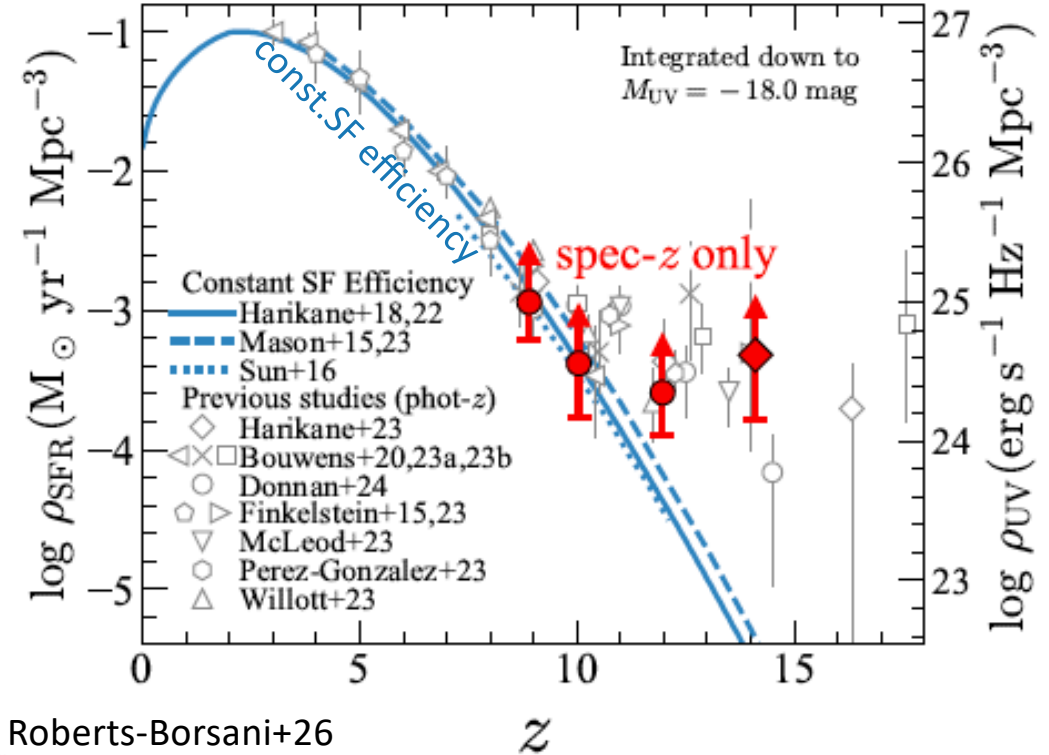
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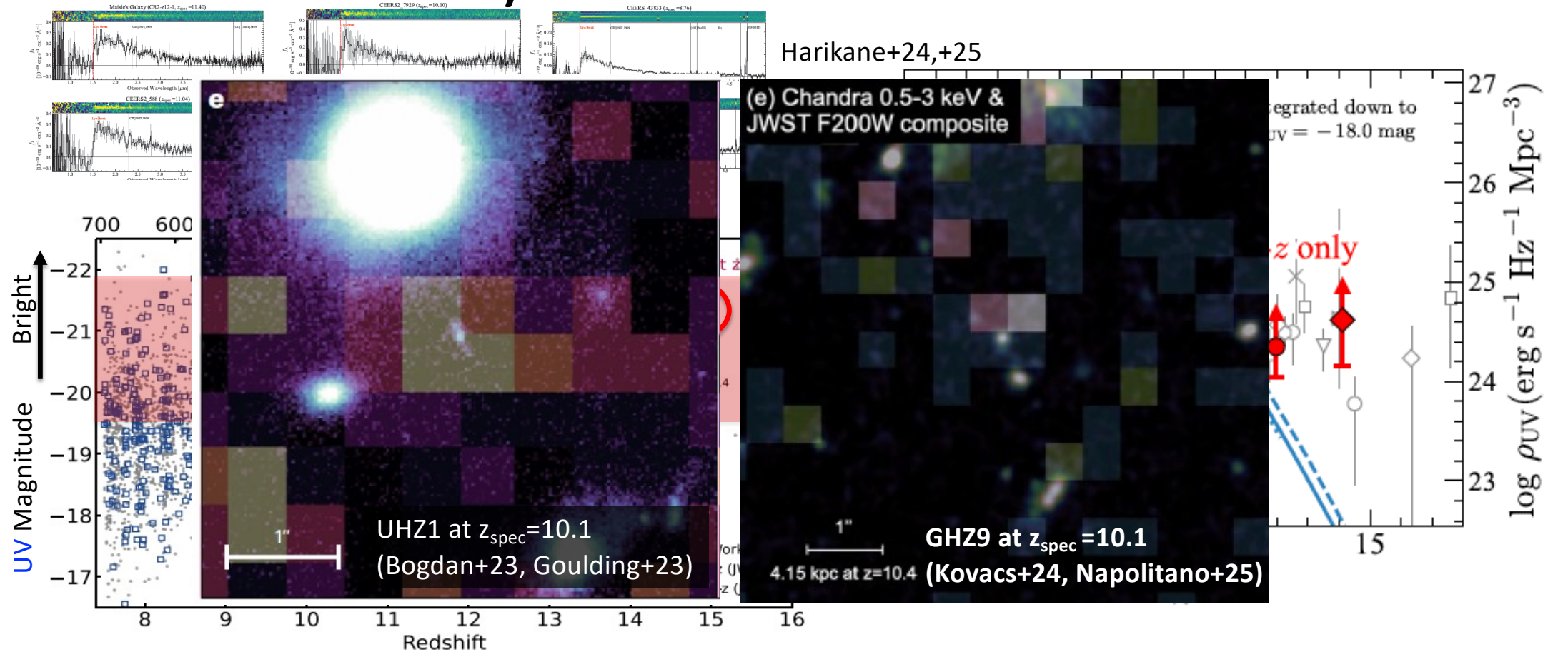
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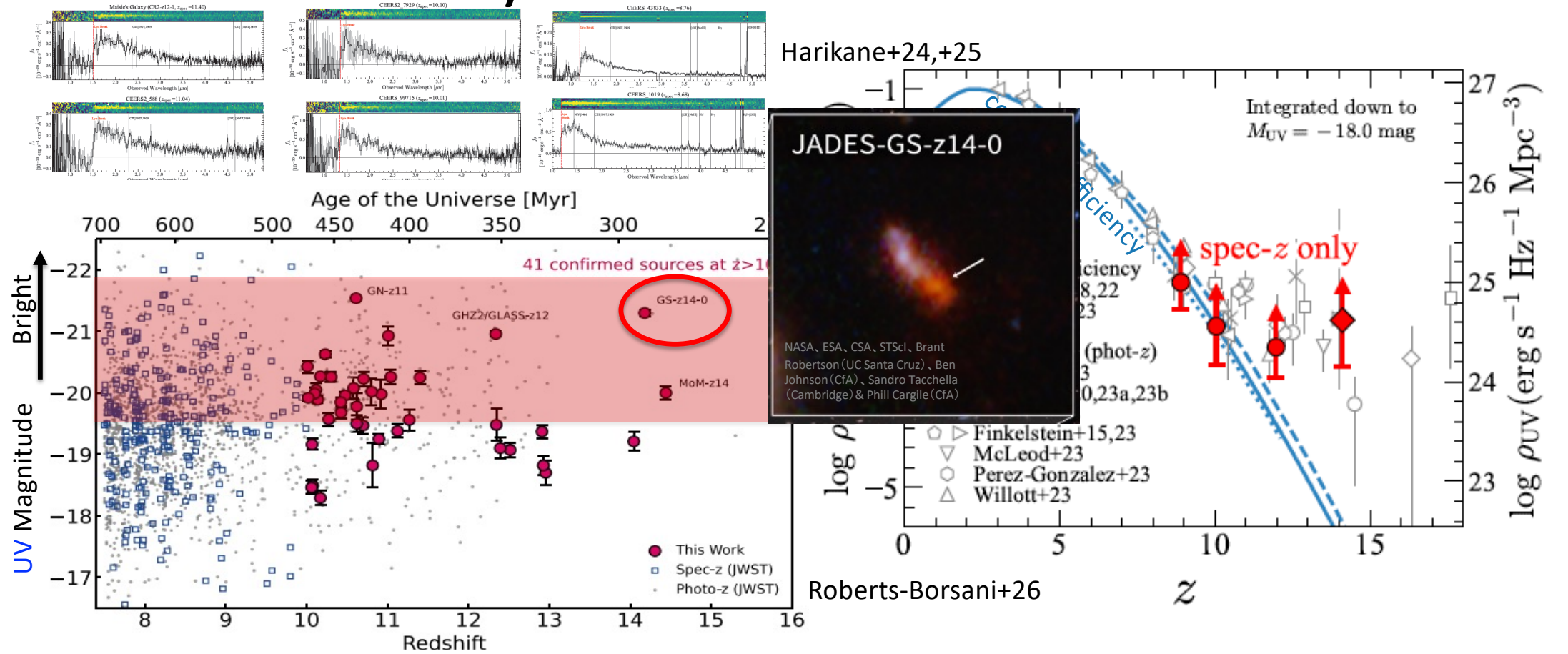
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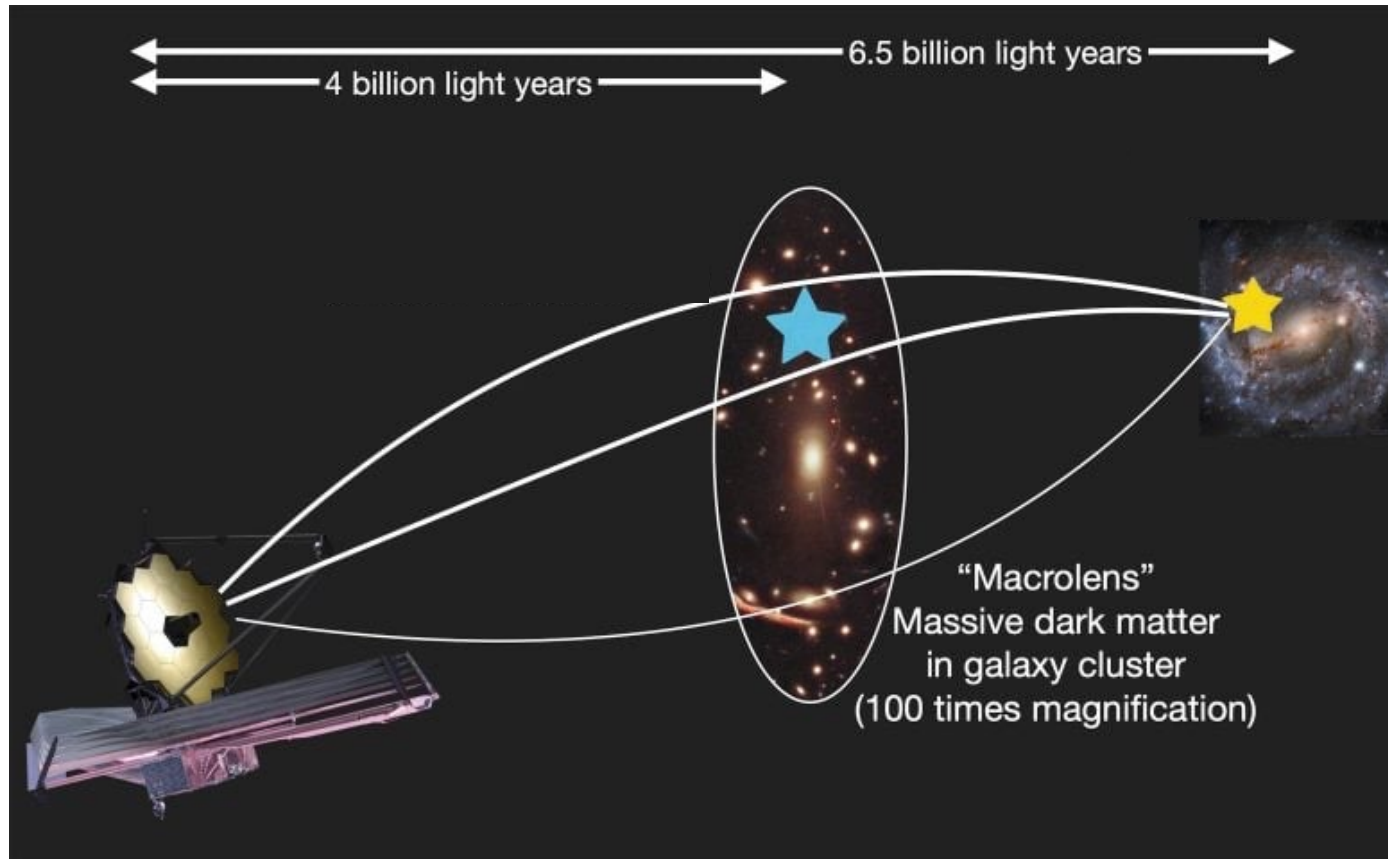
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Exploiting Gravitational Lensing Effects

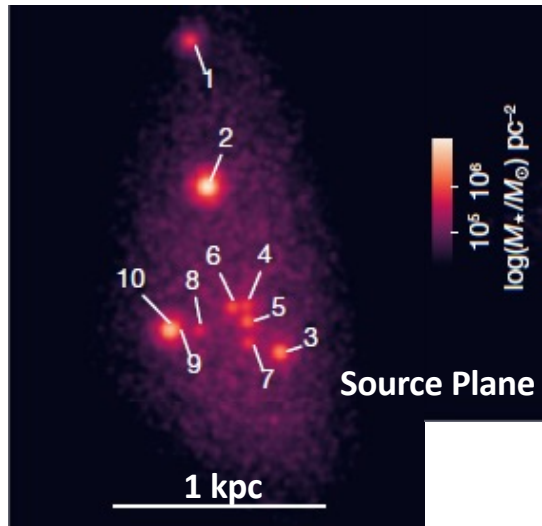


c) SciTechDaily
<https://scitechdaily.com/44-hidden-stars-revealed-gravitational-lensing-unlocks-the-secrets-of-the-dragon-arc/>

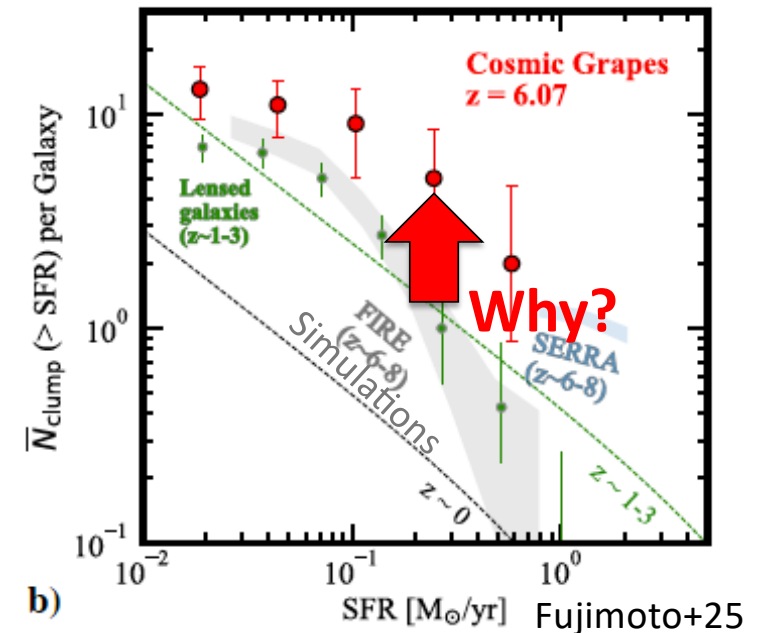
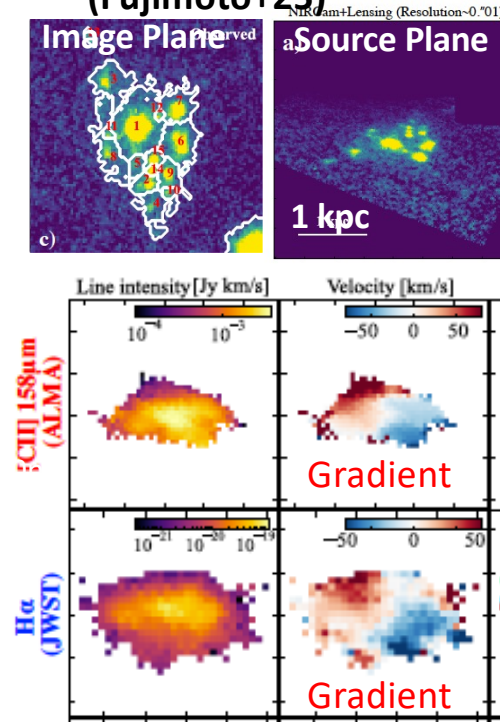
- Magnifying the structures at high redshift

High-z Galaxies are Clumpy

Firefly Sparkle at $z=8.3$
(Mowla+24)

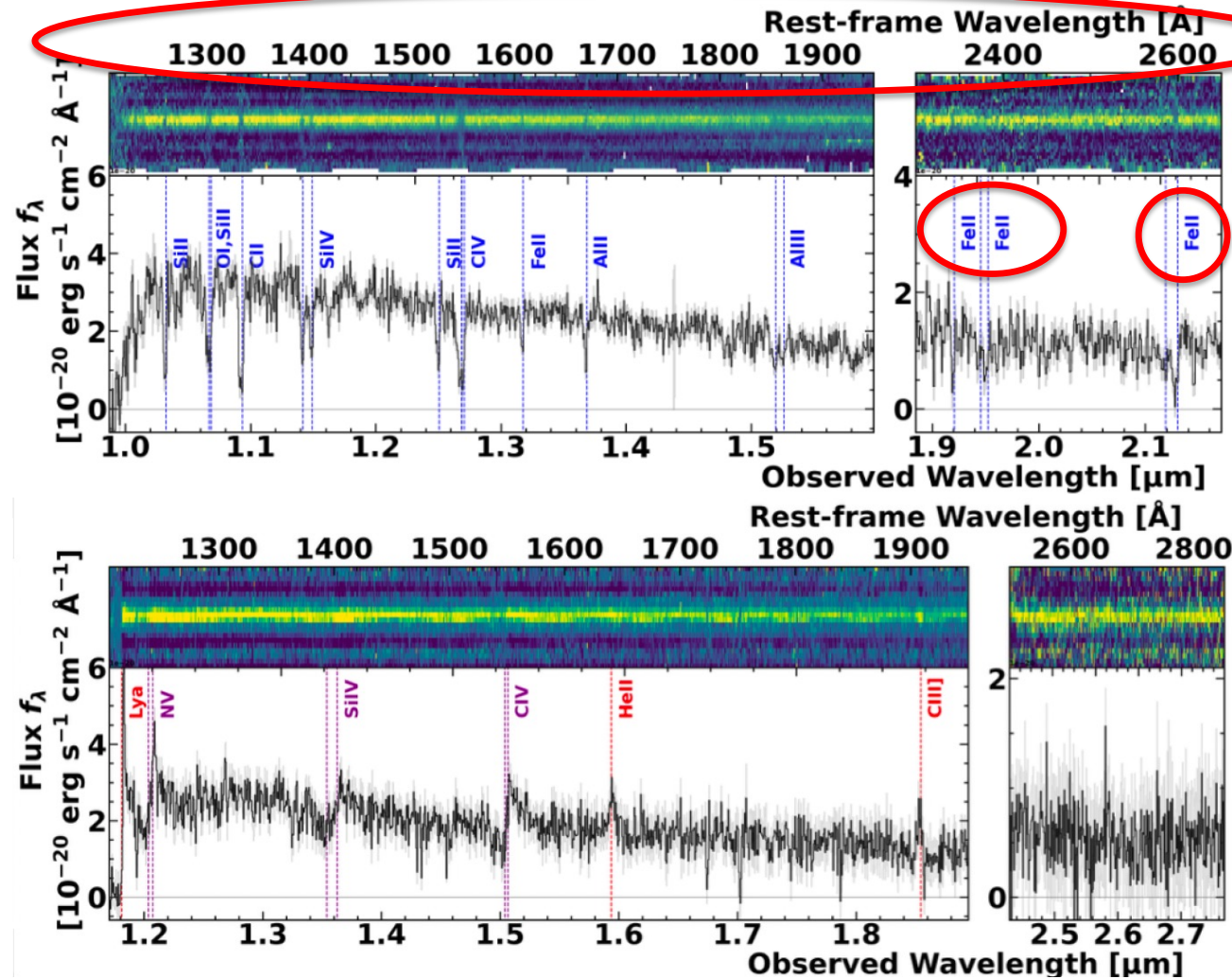


Cosmic Grapes at $z=6.1$
(Fujimoto+25)



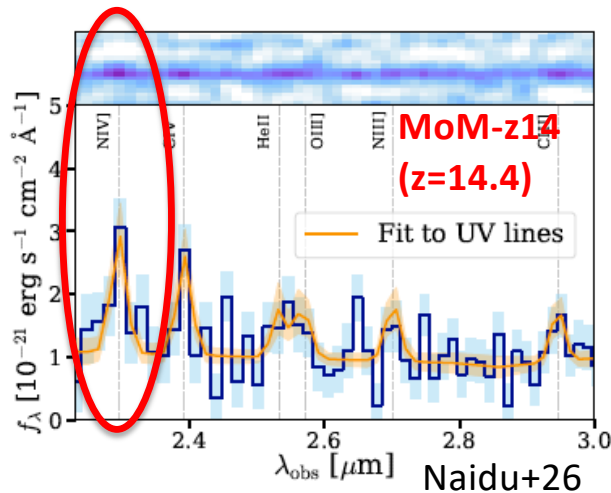
- Star-forming clumps over a galaxy
 - Clumps w $M^* \sim 10^6 M_\odot$ and $R_e \sim 1 \text{ pc}$ ($\mu \sim 100$) $\rightarrow$ Proto globular clusters? (Adamo+24, Messa+26)
 - Clumps w $M^* \sim 10^7 M_\odot$ and $R_e \sim 10\text{-}100 \text{ pc}$ ($\mu \sim 10\text{-}30$; Mowla+24, Fujimoto+25, Bradac+25, Nakane+26)
 - Stellar masses of $\sim 30\text{-}70\%$ (or more) in the clumps
 - On a rotating disk ($\sim 70 \text{ km/s}$)? Cold [CII]158um (ALMA) & warm H α gas (JWST) (Fujimoto+25)
 - Numerical simulations do not reproduce clumpy structures? Why?

Chemical Enrichment: Nitrogen Enhanced Galaxies



Nakane+26 (See +Chen+26, Zhu+26, Marques-Chaves+26, Keerthi+26; data from SPURS team)

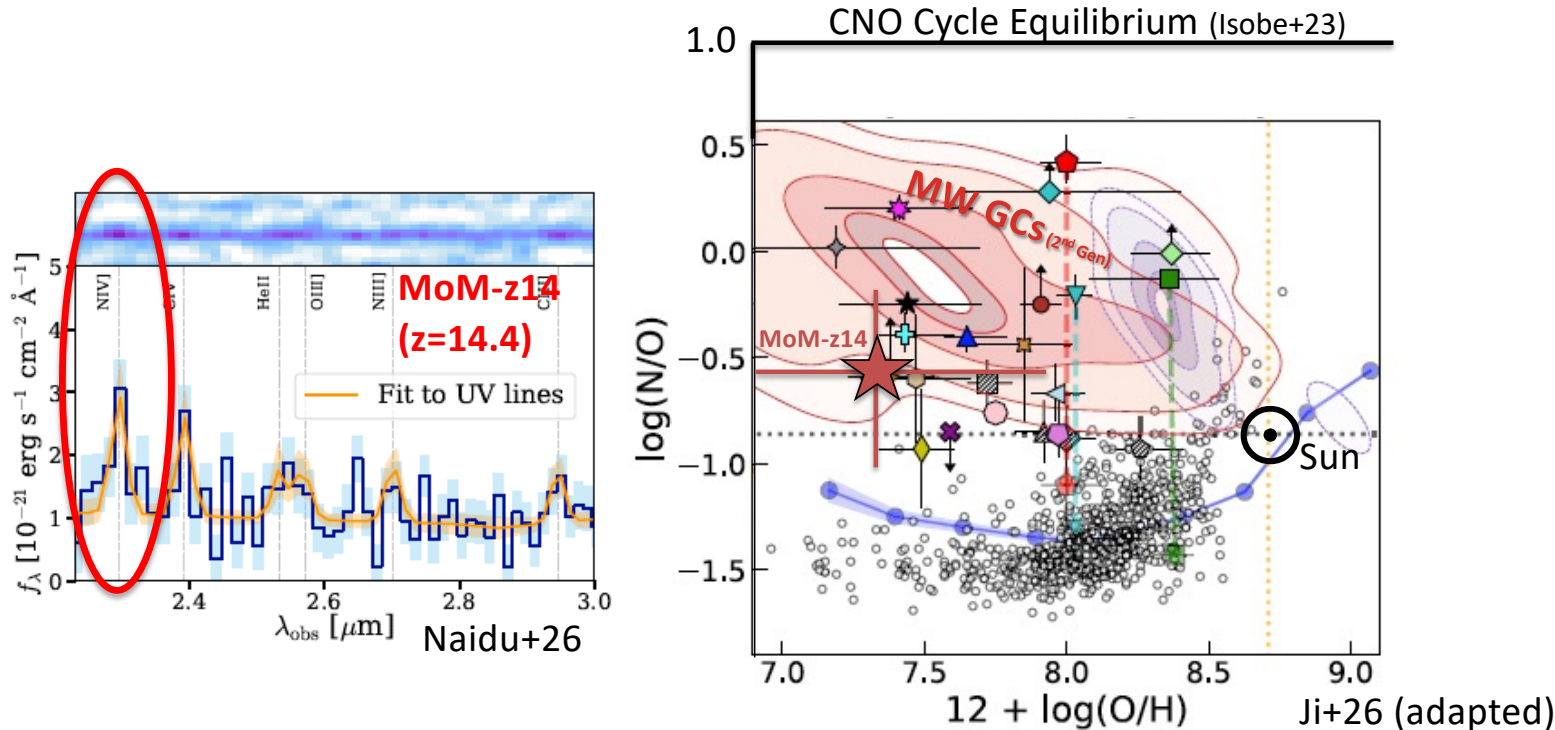
Chemical Enrichment: Nitrogen Enhanced Galaxies



- UV metal lines by JWST for galaxies up to $z \sim 14$ (+ALMA FIR). Suggesting Chemically matured ($Z \gtrsim 0.1 Z_{\odot}$; Schouws+24, Carniani+2
- **Abundance patterns** → Nitrogen rich galaxies at $z \sim 10$. $\gtrsim 20$ galaxies including GN-z11, GHZ2, and MoM-z14
 - Similar to globular cluster stars (+WR galaxy). Forming **globular clusters (GCs)**?
 - Characteristic abundance ratios → Something special in **early star formation/chemical enrichment**?
- CNO ratios: Abundance ratios skewed toward the CNO-cycle equilibrium
- Physical origins: 1) AGB stars, 2) Wolf-Rayet stars, 3) super massive stars (SMS), 4) tidal disrupt. event (TDE)?? → Open question

Cameron+23, Isobe+23, Nagele&Umeda+23, Charbonnel+23, Senchyna+24, Schaerer+24, Topping+24, Watanabe+24/+26, Kobayashi&Ferrara+24, Nandal+25, Ebihara+26, Naidu+26, Roberts-Borsani+26, and more

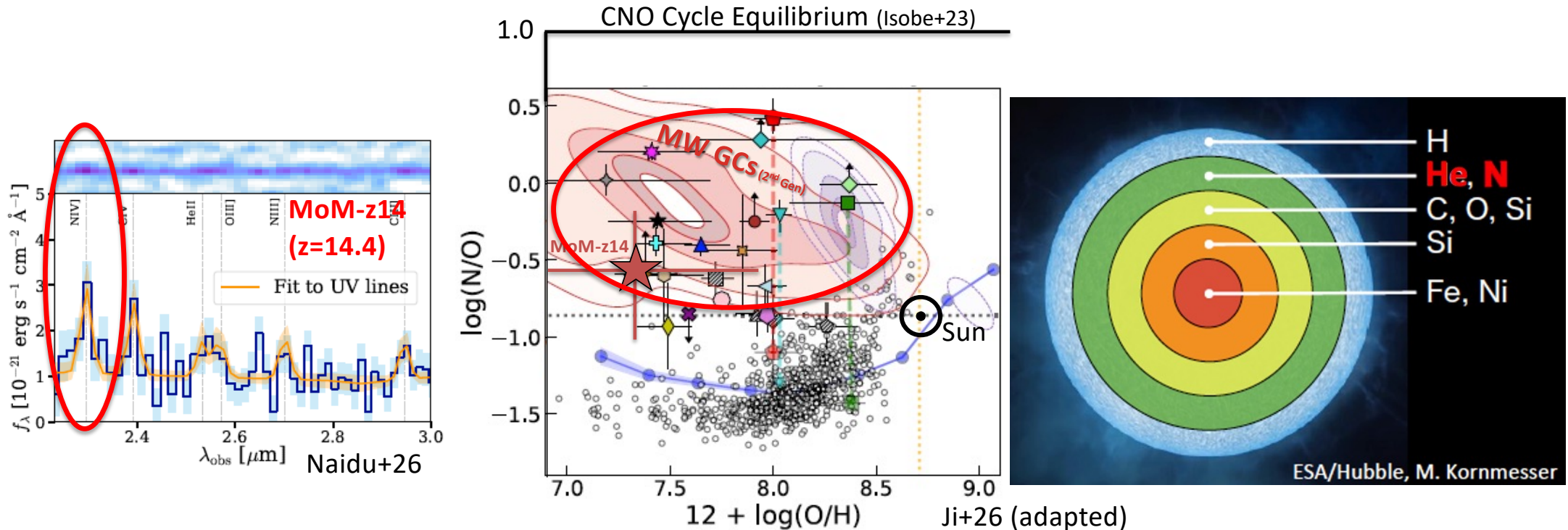
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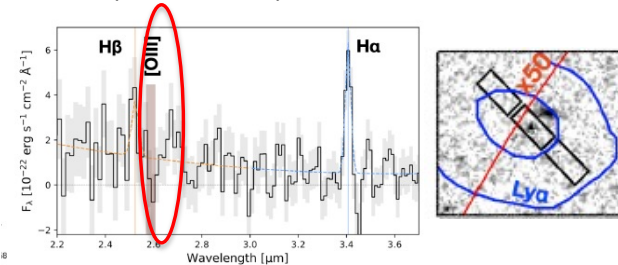


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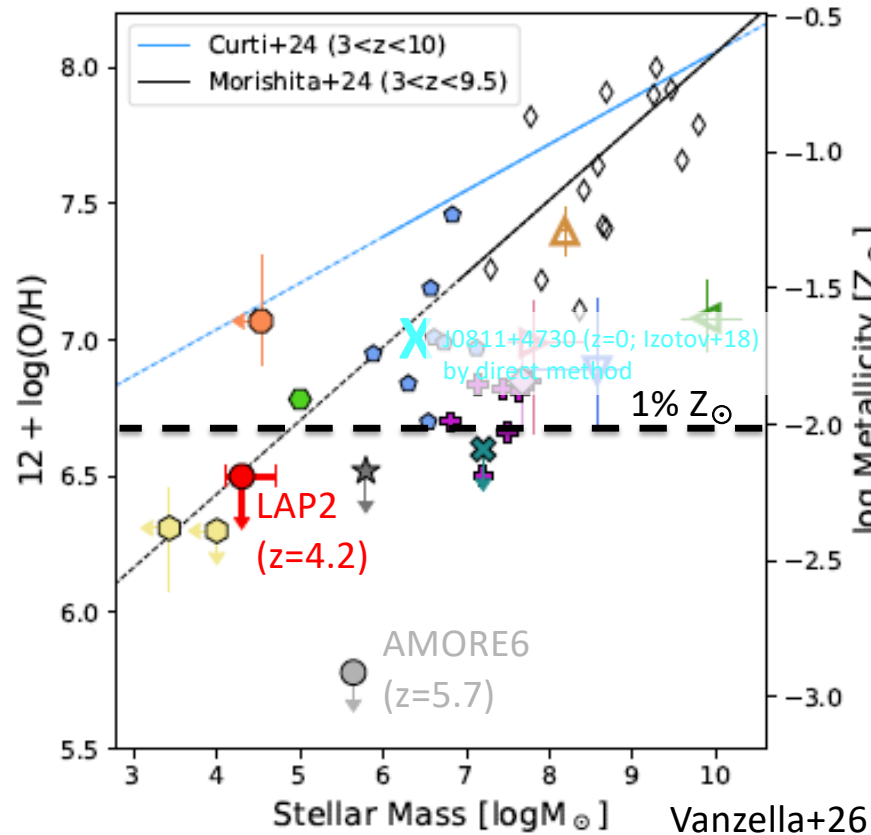
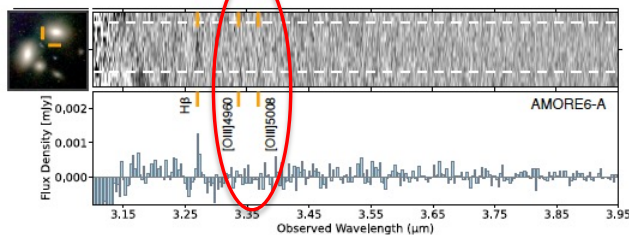
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Where are Zero Metal Objects (Pop III)?

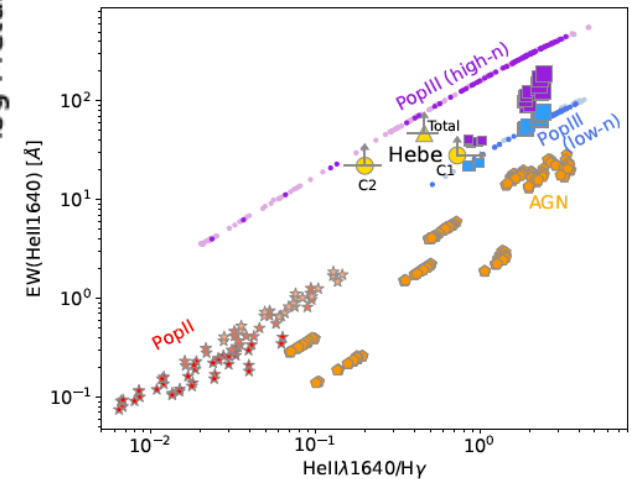
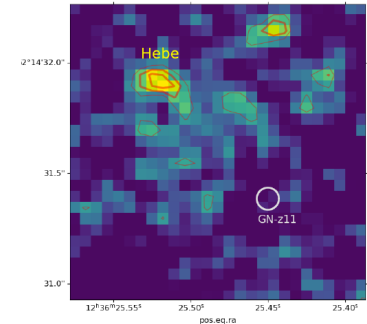
LAP2 ($<0.6\%Z_{\odot}$) at $z=4.2$
(Vanzella+26)



AMORE 6 ($<0.1\%Z_{\odot}$) at $z=5.7$
(Morishita+25)



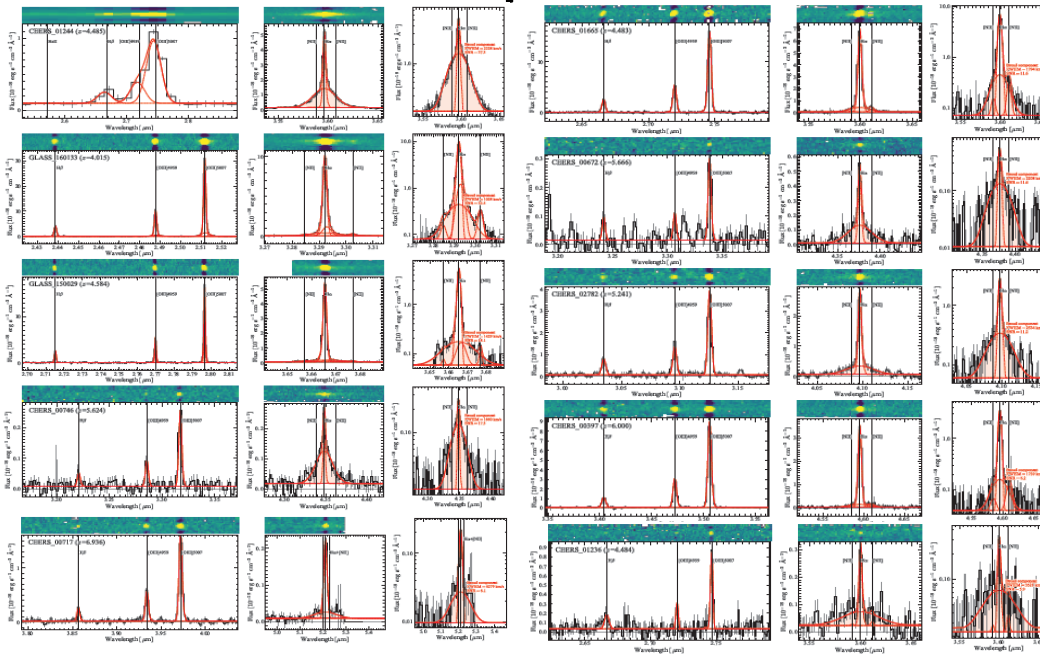
Hebe (popIII??) (Maiolino+26)



- Galaxies w $Z < 1\% Z_{\odot}$ reported at $z=3-7$ [via $R3 (= [\text{OIII}]/\text{H}\beta)$ index]
 - cf. reported local most metal poor gal $Z = 2\% Z_{\odot}$ (J0811+4730; Izotov+17)
- Hebe: UV HeII1640 emitter nearby GN-z11 at $z=10.6$ (Maiolino+24/+26)
 - Strong HeII emission (hard ionizing photons) $\rightarrow$ Consistent w popIII (zero metal) stars?
- Identifications of popIII galaxies are under debate

Many Broad Line Objects

Hints for Super Massive Black Hole (SMBH) Formation?



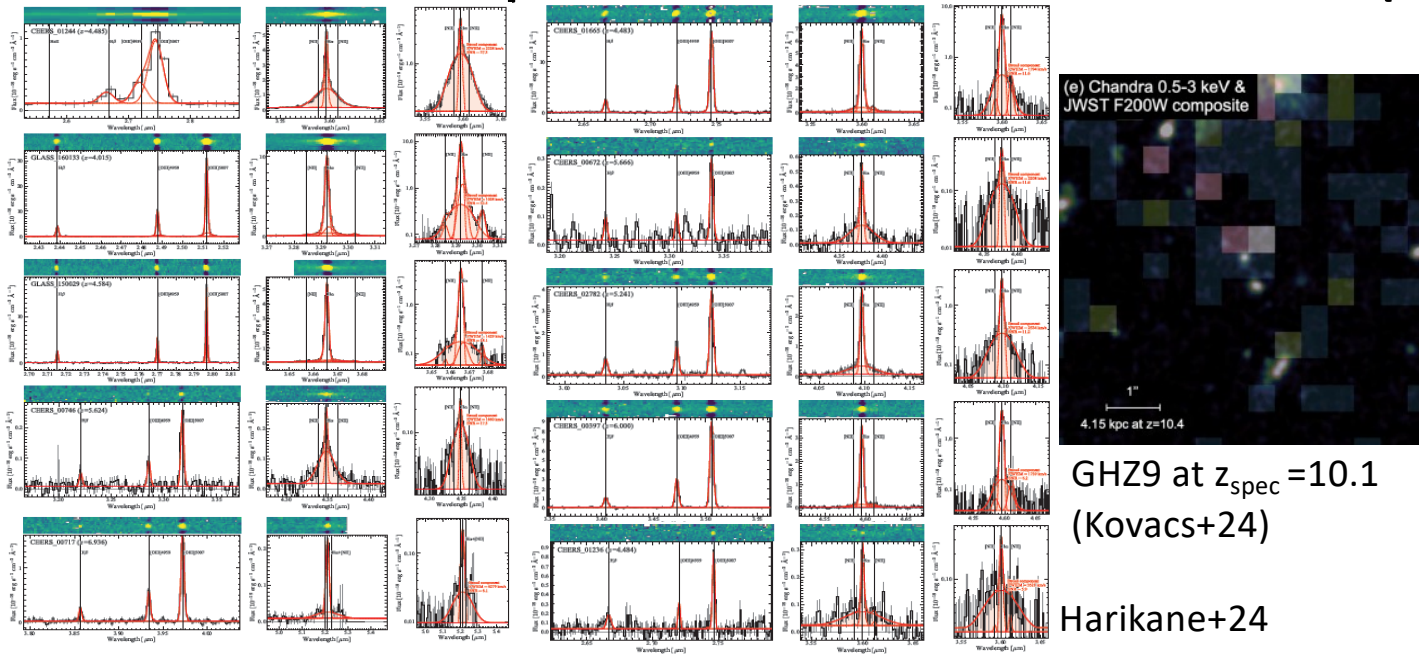
Harikane+24

- 10-30% of high-z galaxies at $z \sim 4-7$: Broad lines in H α /H β with $>1000 \text{ km s}^{-1}$
 - No broad lines in forbidden line of [OIII] (low critical density) $\rightarrow$ indicative of emission from BLRs of AGN?
- GHZ9 and UHZ-1 at $z_{\text{spec}}=10$: $4-5\sigma$ X-ray, $L_x \sim > 10^{44} \text{ erg s}^{-1}$ (Bogdan+23, Goulding+23; Kovacs+24, Naplitano+25)
- GN-z11 at $z_{\text{spec}}=11$: [NeIV]2423+CII*1335 & high density ($>10^9 \text{ cm}^{-3}$) (Maiolino+24)
 - $\rightarrow$ AGN? If these AGN candidates are real, formation scenario? Stellar remnant, cluster, direct collapse BHs, can explain by accretion. What are the **seed black holes**? $\rightarrow$ Intermediate mass black hole (IMBH)

See also, Ubler+23, Kocevski+23, Harikane+23, Matthee+23, Larson+23, Greene+23, Bogdan+23, Goulding+23, Naplitano+25 and more

Many Broad Line Objects

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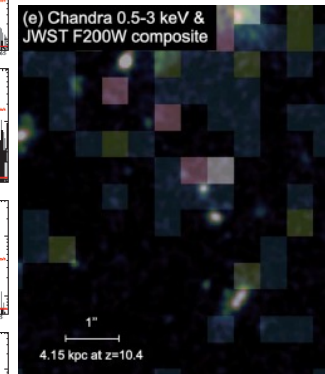
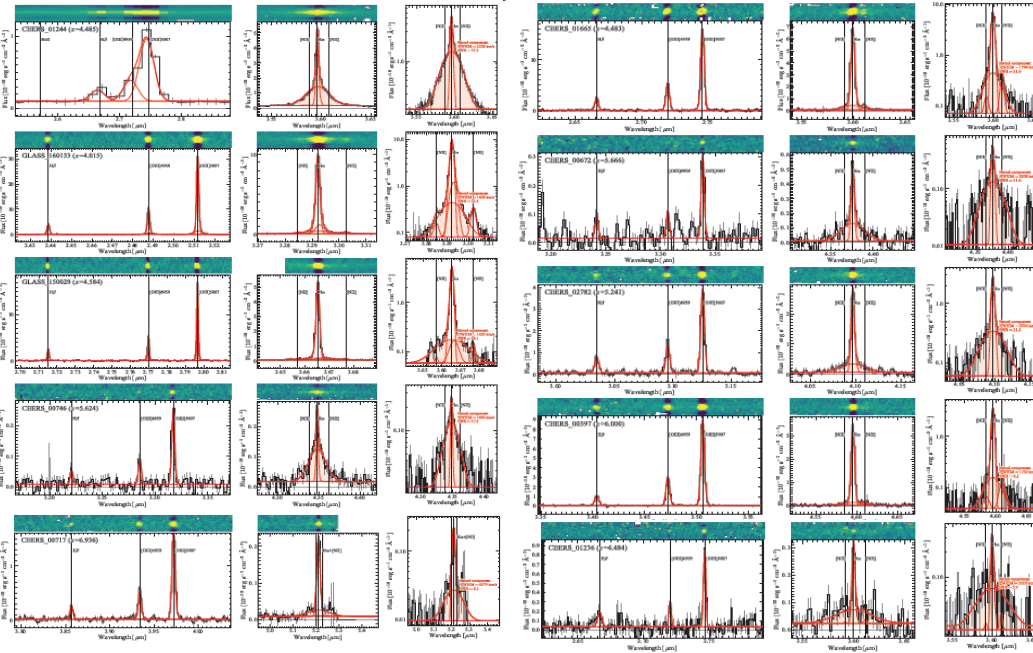


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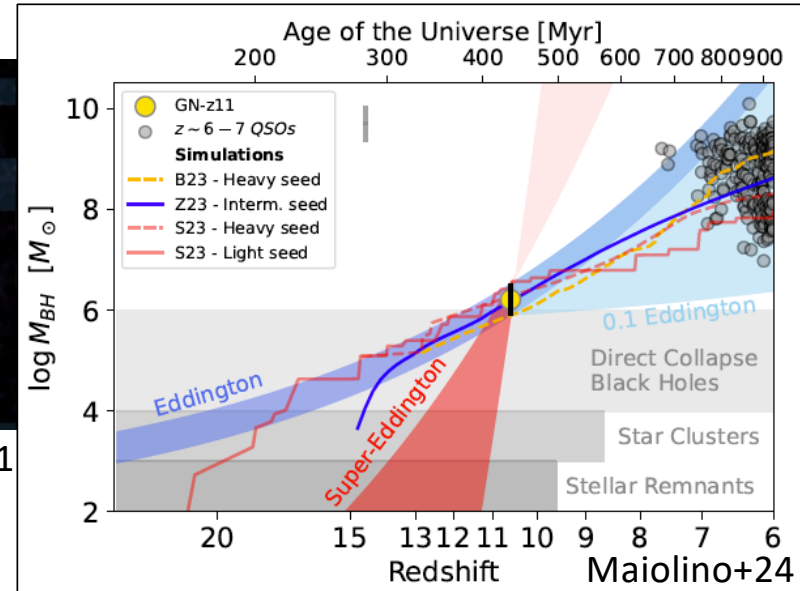
Many Broad Line Objects

Hints for Super Massive Black Hole (SMBH) Formation?



GHZ9 at $z_{\text{spec}}=10.1$
(Kovacs+24)

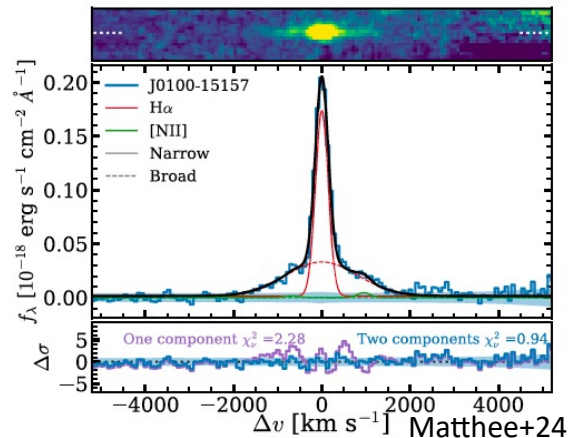
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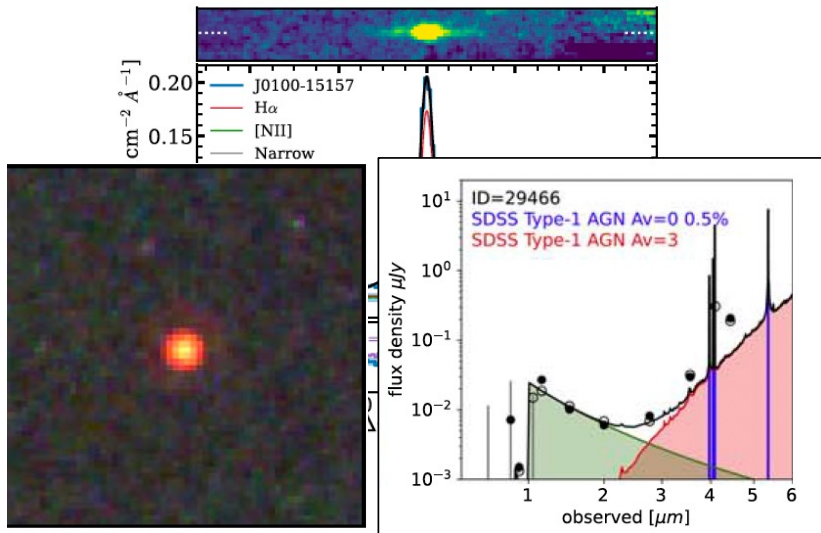
Little Red Dots (LRDs)



- Many of broad Balmer line objects $\rightarrow$ Red at rest $>0.4\mu\text{m}$ & Blue at rest UV. (+compact at $>0.4\mu\text{m}$)
 $\rightarrow$ Little red dots (LRDs)
 - Early studies: Dust reddened AGN in a blue galaxy??
 - Cont.: Strong $4000\text{\AA}$ break ($\sim$ modified black body) $\rightarrow$ Thermalized like a stellar photosphere or Strong nebular cont. $\rightarrow$ Very dense $n_{\text{H}} \gtrsim 10^{25-26}/\text{cm}^3$
 - Absorption line: Balmer line (H α , H β) $\rightarrow$ a lot of electrons at $n=2$ (Balmer series) $\rightarrow$ Very dense $n_{\text{H}} \sim 10^{25-26}/\text{cm}^3$
- Black hole ($\sim$ IMBH?) with thick gas envelope, Black hole star?? (Naidu+25 etc) or thick gas clumps? (e.g. Maiolino+25, Ji+26, Ma+26)
- What are LRDs? $\rightarrow$ Unknown. Their origins are very very actively discussed.

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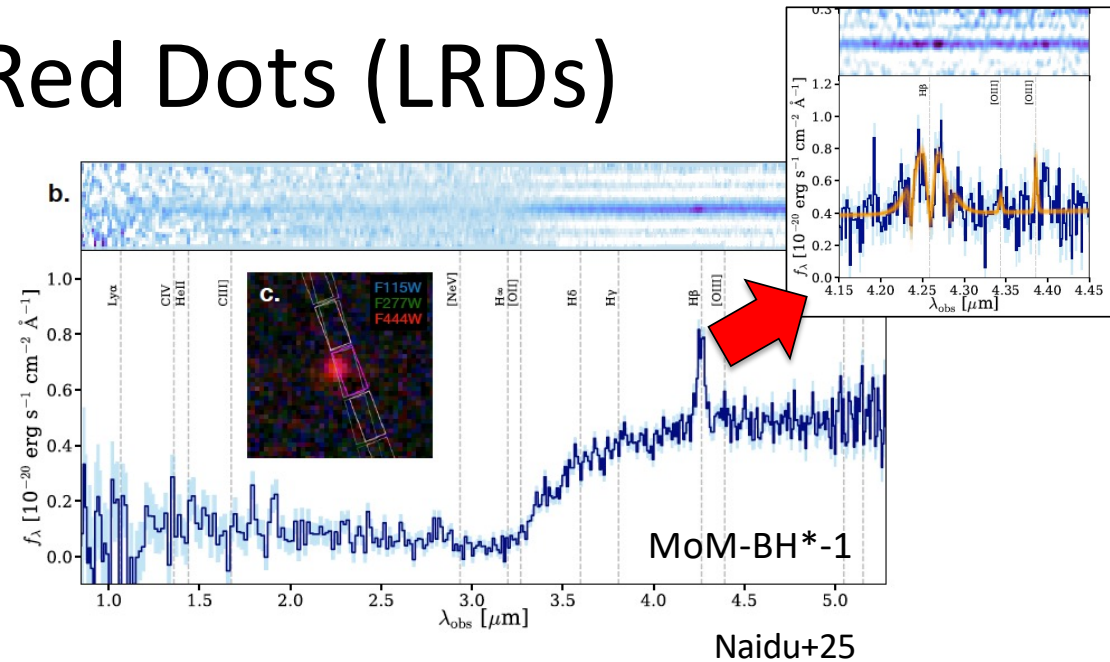
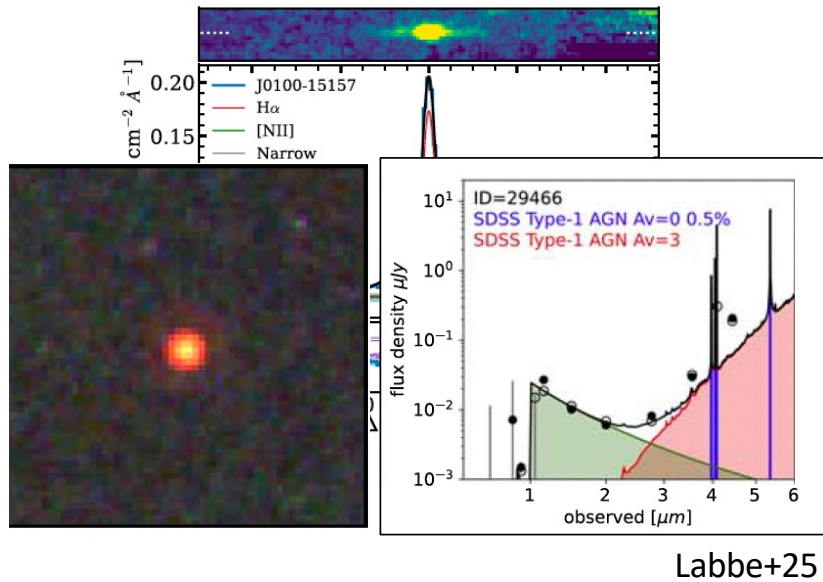


Labbe+25

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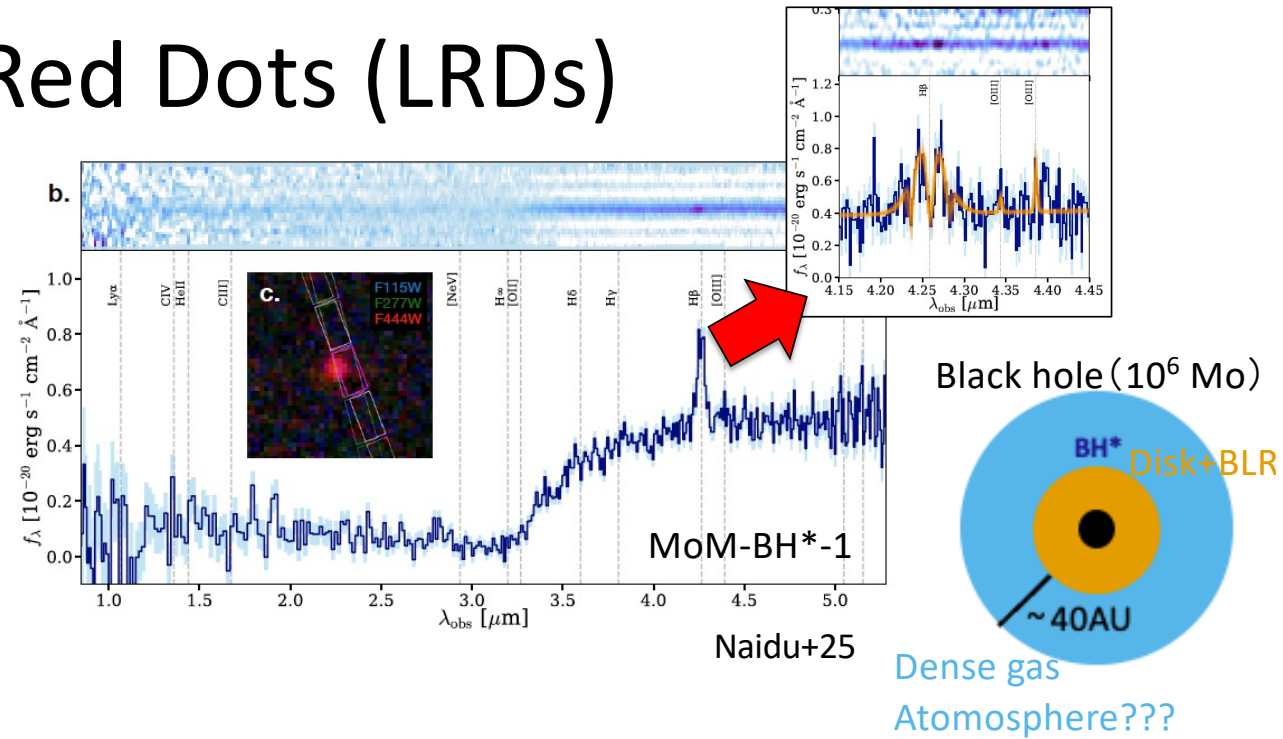
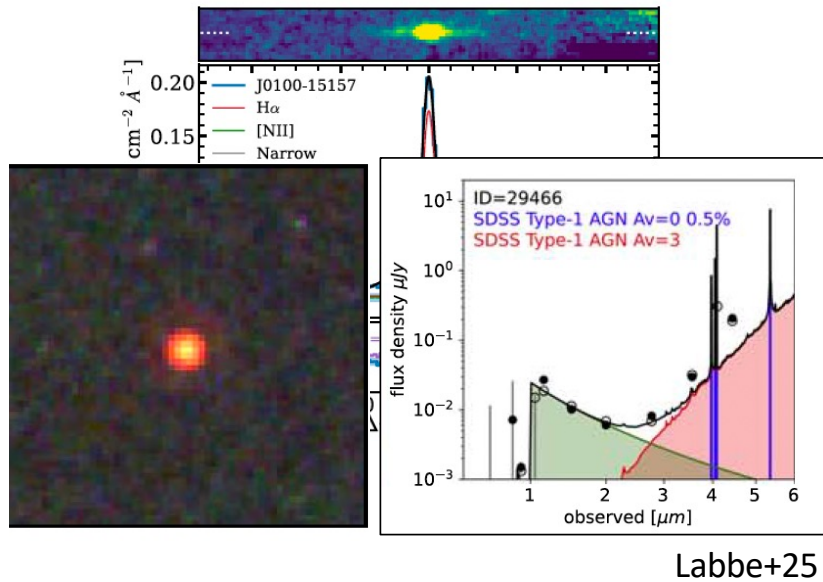
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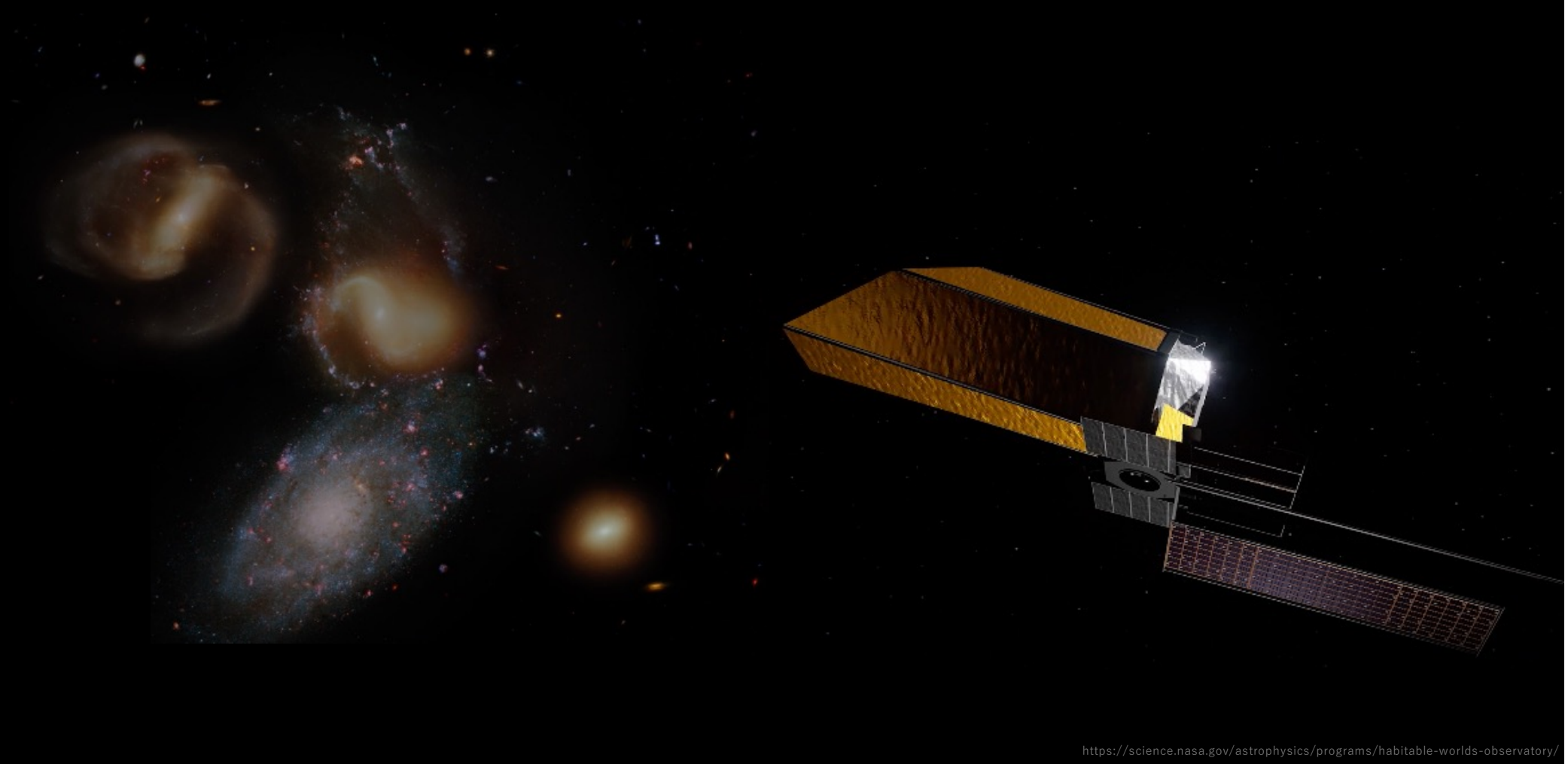
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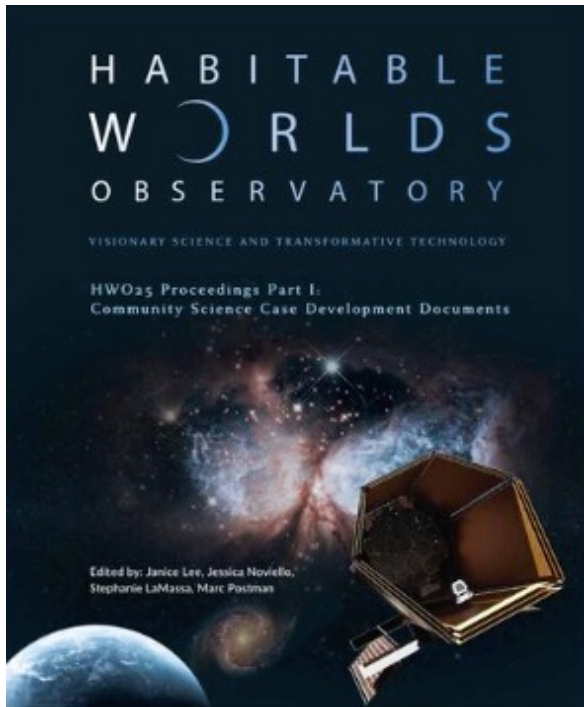
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Habitable Worlds Observatory



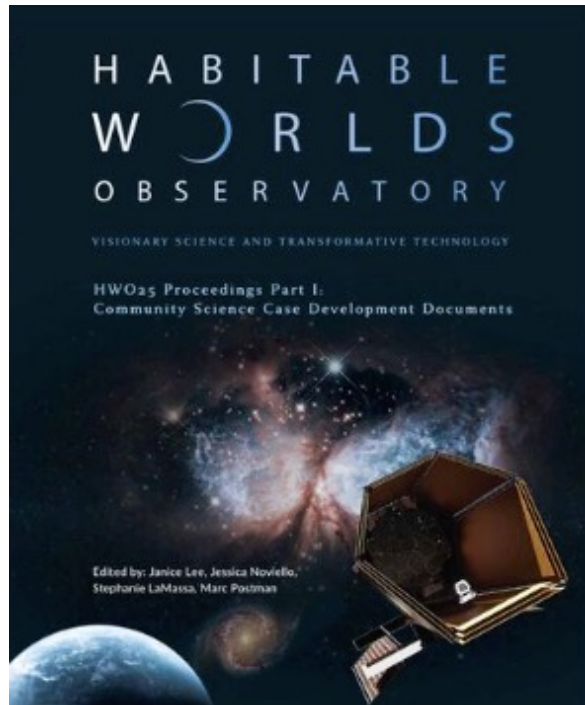
<https://science.nasa.gov/astrophysics/programs/habitable-worlds-observatory/>

HWO25 Proceedings for Community Science Case



- Galaxy studies (21 proceedings) distribute both in
 - Evolution of the Elements
 - Galaxy Growth

HWO25 Proceedings for Community Science Case

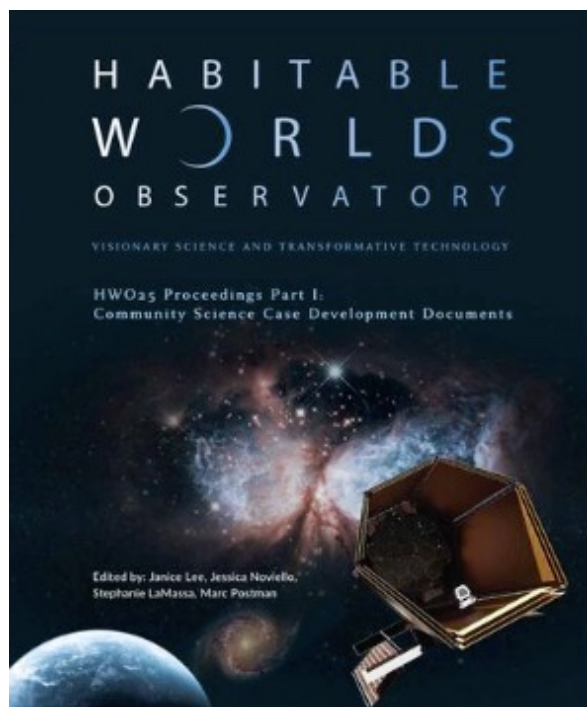


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- Galaxy studies (21 proceedings) distribute both in
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HWO25 Proceedings for Community Science Case

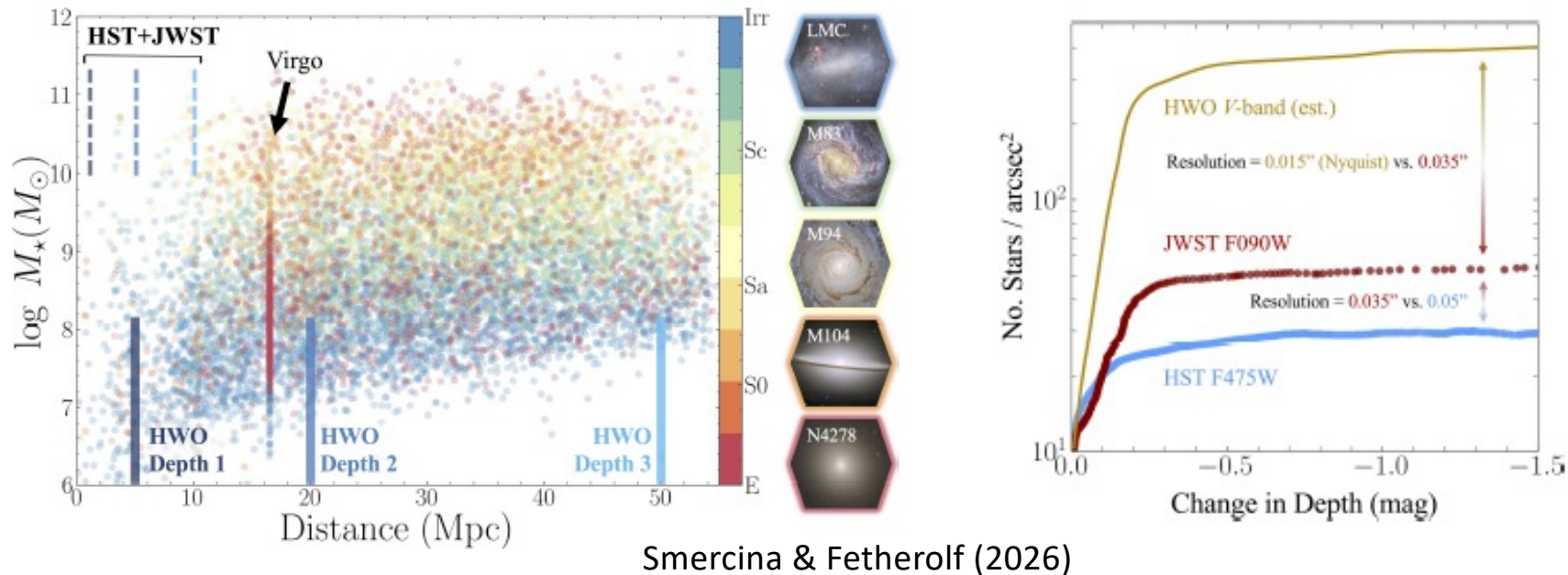


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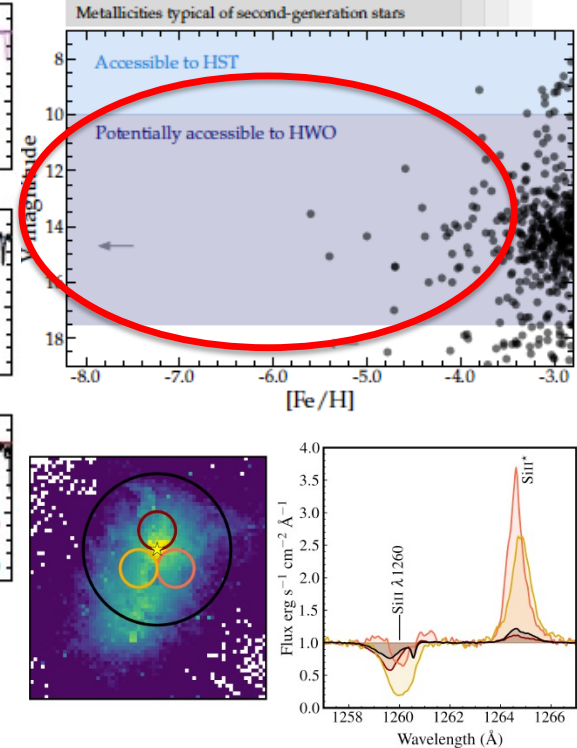
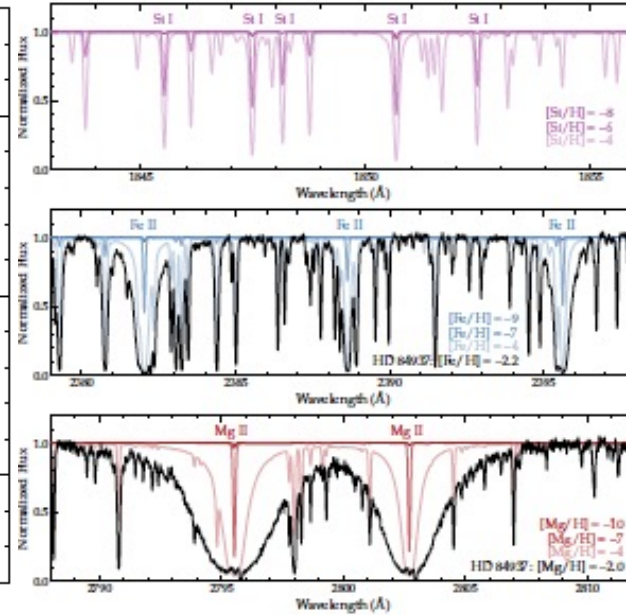
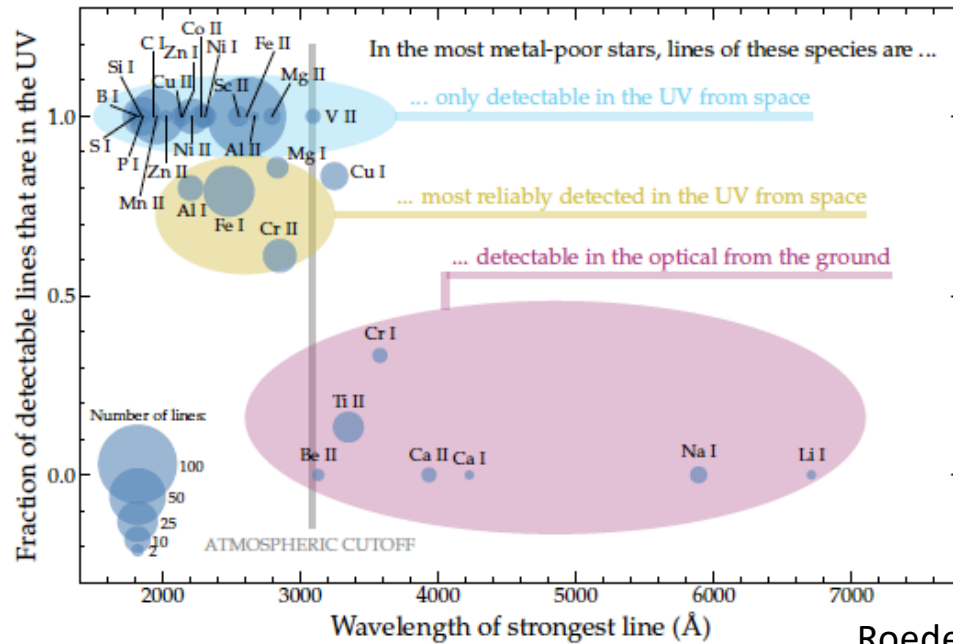
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Spatially Resolving Nearby Galaxies



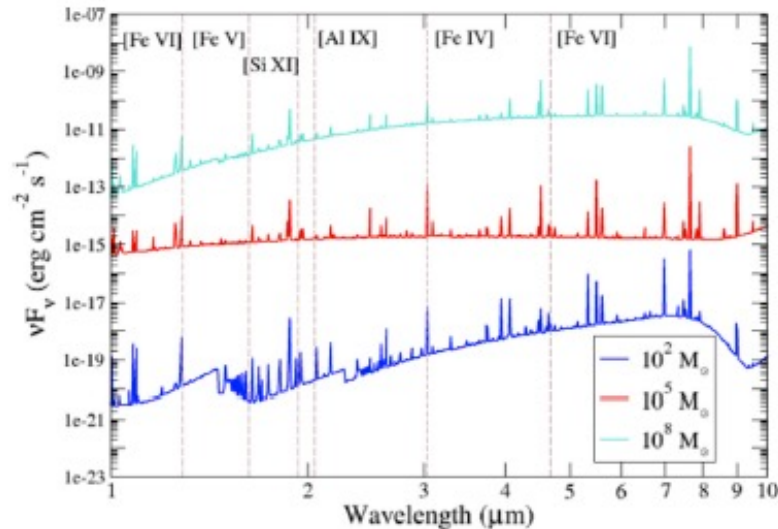
- Resolving galaxies beyond the local group (>1 Mpc) that cannot be accomplished in optical obs with ELTs
 - Nearest galaxies (at ~5 Mpc) : Resolving **oldest main sequence turnoff** -> Up to earliest star formation
 - Nearby galaxies (at ~20 Mpc) : Resolving **stars below the red clump**. Statistics of ~100s of galaxies covering the entire Hubble sequence (including metal poor/young galaxy, [I Zw 18](#); Senchyna et al. 2026)
 - galaxies out to ~50 Mpc : **Morphology (clumpy SF regions), stellar abundances, and dust content** for ~1000s of galaxies
- Characterising **star-formation histories** of various galaxies (beyond MW, LMC, and SMC)

Metal Lines by Deep UV Spectroscopy

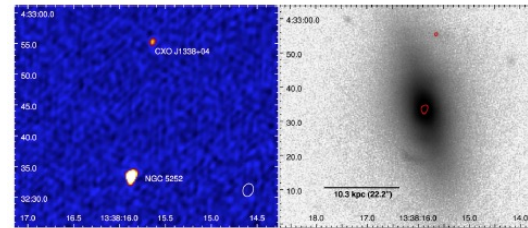
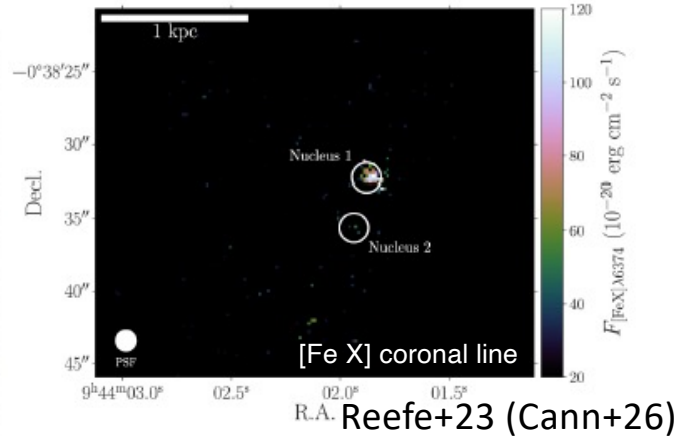


- Numerous strong absorption lines in the UV (for MW and nearby galaxies)
- Si, Fe, and Mg are detectable down to very metal poor regime, $[X/H] \sim -10$
- Such metal poor stars down to faint magnitude ($V \sim 18$) can be probed
 - Opening the new studies of second generation stars
 - Understanding early star-formation complementary to the JWST studies
 - Fe-enhanced (low Mg/Fe) stars with very low Fe/H such **abundance pattern found in JWST** (Nakane+24/26, Ji+24/25, Isobe+26)? Physical origin??
- Spatially resolved spectroscopy in galaxies for the ISM → Feedback, star-ISM connection, multi-phase element/mixing (James+2)

Intermediate Mass Black Hole (IMBH)



Cann+18 (Cann+26)

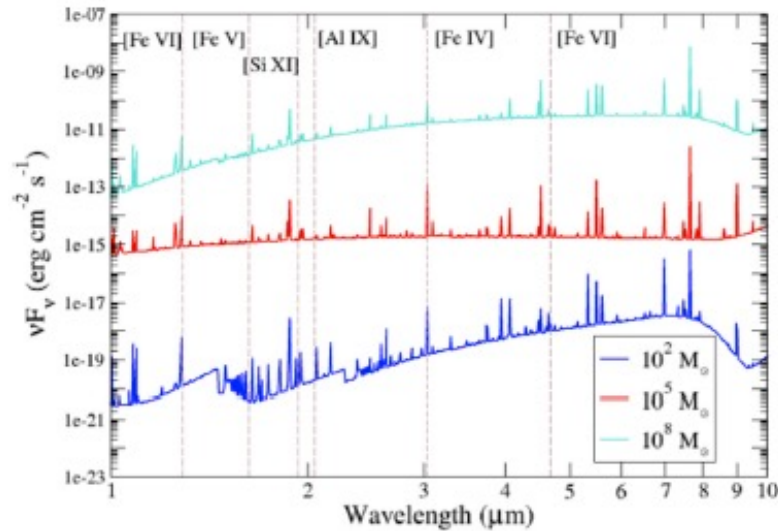


Smith+23 (Cann+26)

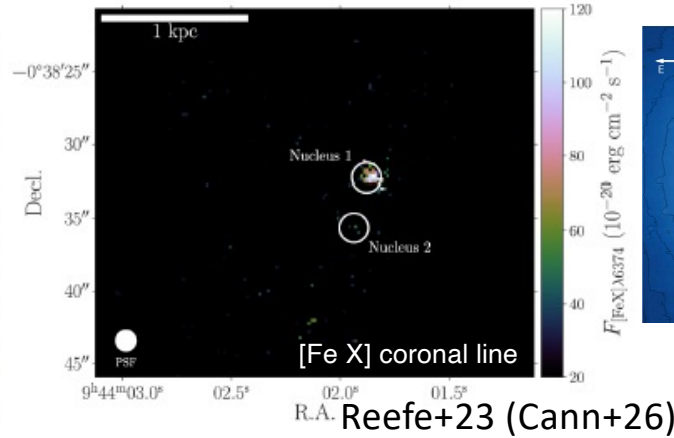
- Black holes w mass of $<10^6 M_{\odot}$ (IMBHs). Tightly related to the question from JWST studies: [Seeds of SMBHs?](#)
- Using coronal lines: e.g. [Ne V] λ 3345, 3425A(97eV), [Fe VII] (99eV) lines ($\sim 5000\text{--}6000\text{\AA}$), and [Fe X] λ 6374A (234 eV)
- Identifying a statistical number of IMBHs (from ~ 20 to >200 or more) in low mass (from $M_{\text{BH}} \sim 10^{4.5} M_{\odot}$ to $\sim 10^3 M_{\odot}$)
 - Characterising the IMBHs: Statistics of accretion rates and spins
- Dynamical properties at the centers of dwarf galaxies $\rightarrow$ Determining mass of massive BHs
 - Dynamics measured by Ca II (Mg b) triplet absorption (e.g. Waters+24)
 - Massive BHs down to $\sim 10^{4.5} M_{\odot}$ (cf. $>10^6 M_{\odot}$ w HST and 8m-class telescopes)

Issues: How are the IMBHs related to the seed BHs in the early universe.

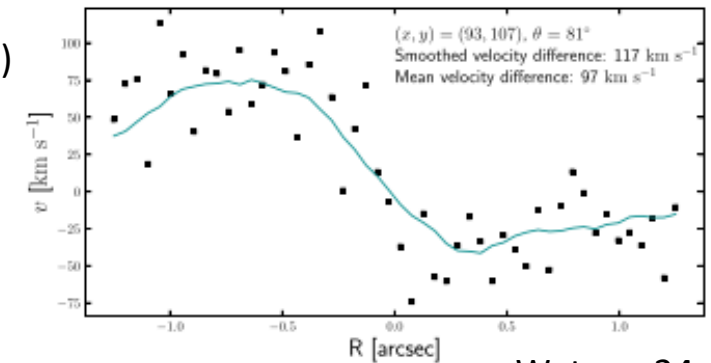
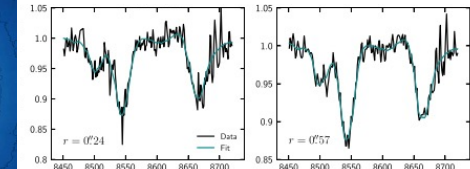
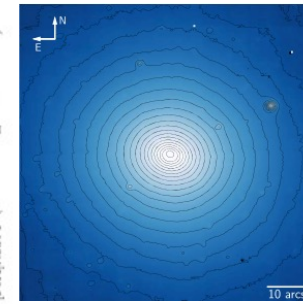
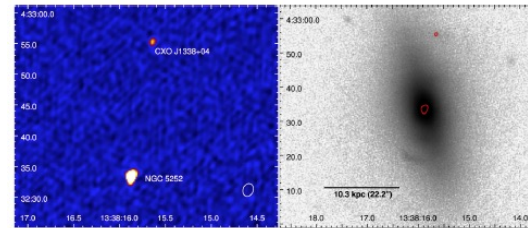
Intermediate Mass Black Hole (IMBH)



Cann+18 (Cann+26)



Smith+23 (Cann+26)

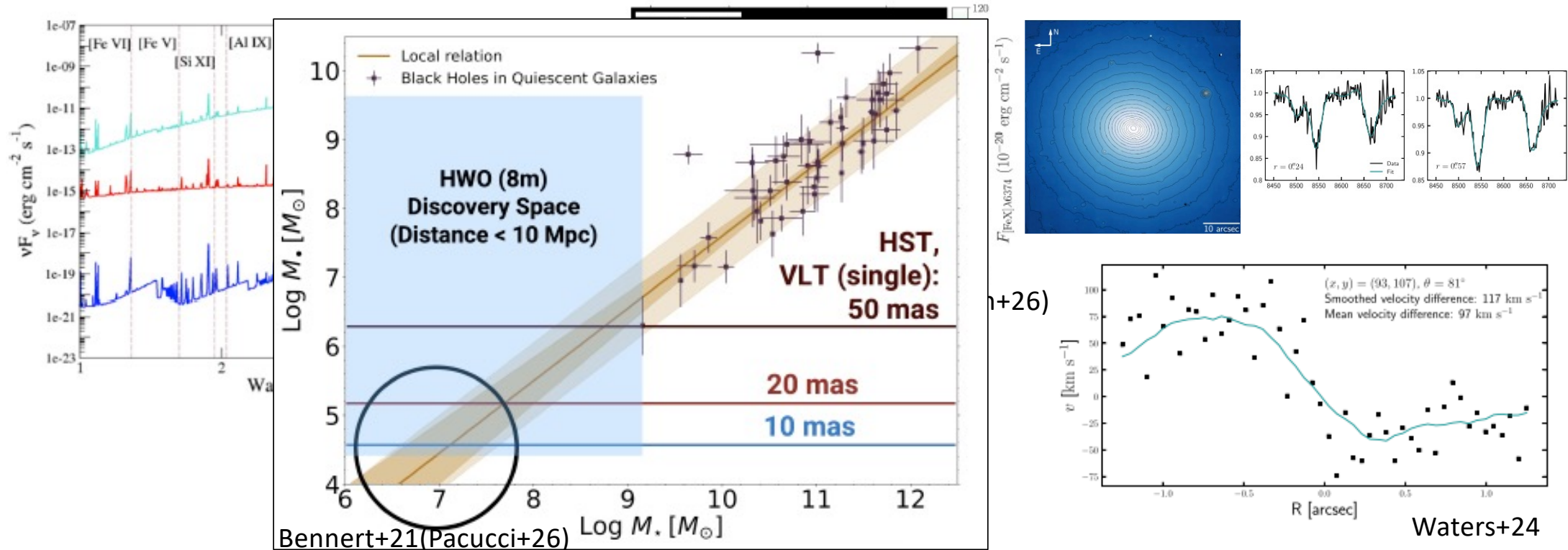


Waters+24

- Black holes w mass of $<10^6 M_\odot$ (IMBHs). Tightly related to the question from JWST studies: [Seeds of SMBHs?](#)
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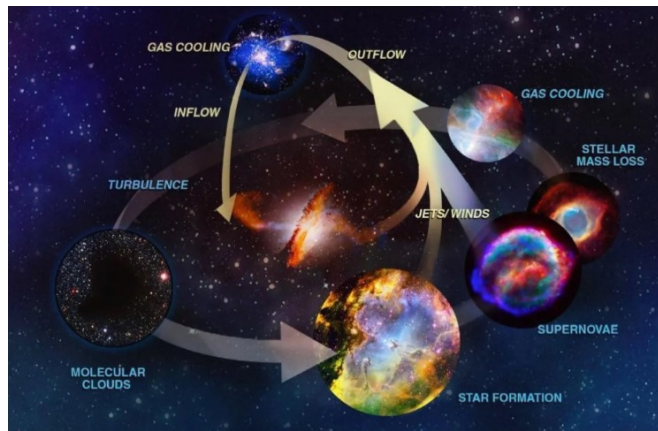
Intermediate Mass Black Hole (IMBH)



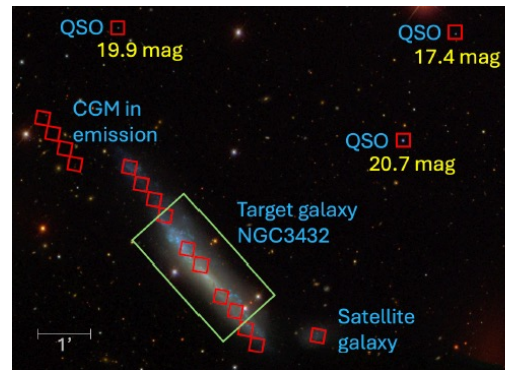
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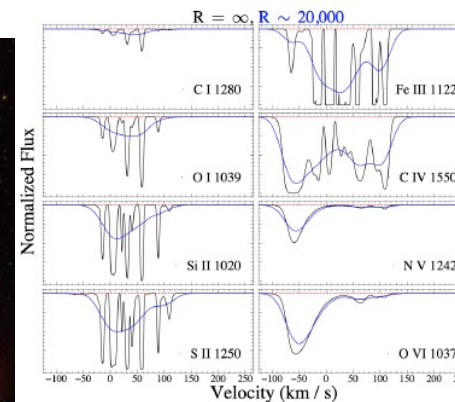
Cosmic Ecosystem (incl. Reionization)



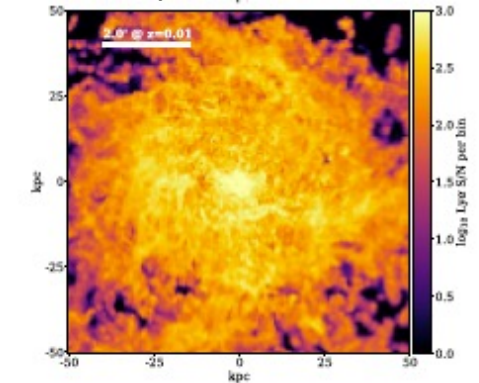
National Academies / Astro2020 decadal survey



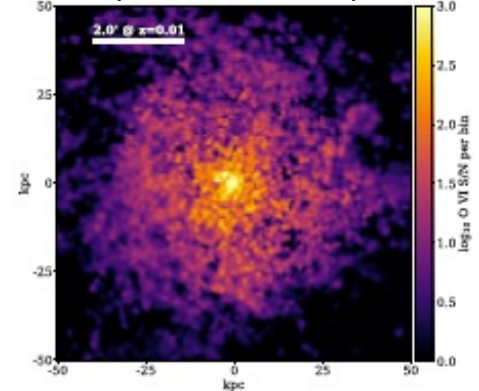
Borthakur et al. (2026)



Simulation for HWO obs
(Ly α emission)



(O VI emission)

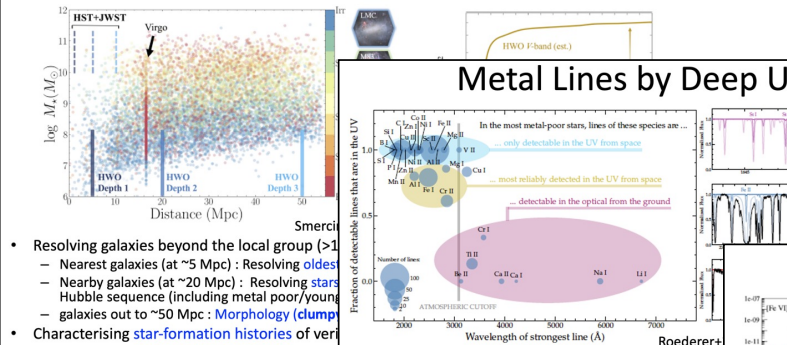


Burchett et al. (2026)

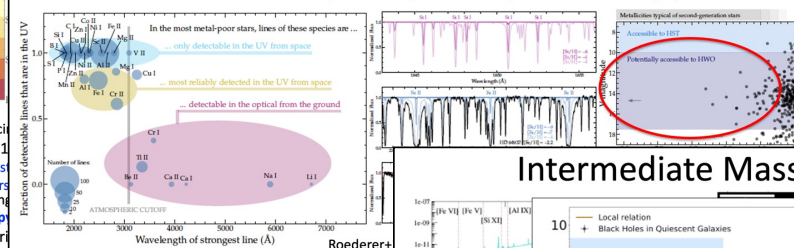
- Galaxy-CGM/IGM connection (Astro2020)
 - Gas inflows probed by QSO UV absorption lines (Borthakur+26)
 - Gas outflows/CGM probed by UV emission lines (Burchett+26)
 - Feedback strengths constrained by statistics of Ly α forest doppler broadening param. b (sensitive to temperature; Tillman+26)
- Reionization (Sources of reionization)
 - Spatially resolved LyC detections $\rightarrow$ Ionizing photon (LyC) escape mechanisms in low- z ($\sim$ local) galaxies (Carr+26)
 - Statistical studies $\rightarrow$ Calibrating f_{esc} against indirect indicators (galaxy line ratios, profiles etc; Citro and Scarlata 26, McCandliss+26)
- Issues: Is f_{esc} no evolution from local/low- z to the epoch of reionization ($z>5$)?

HWO25 Science Cases

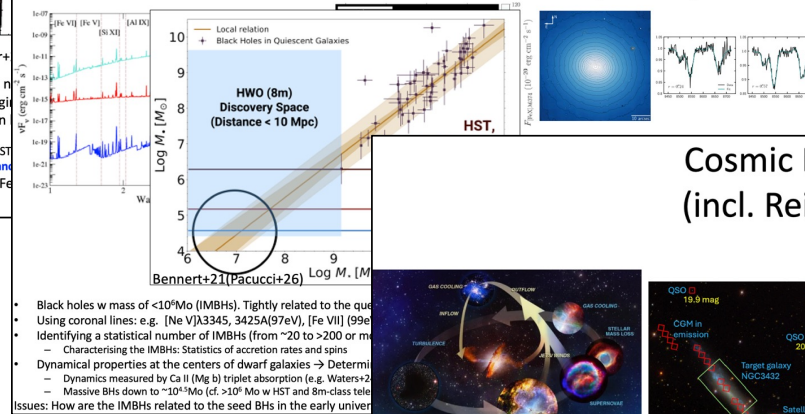
Spatially Resolving Nearby Galaxies



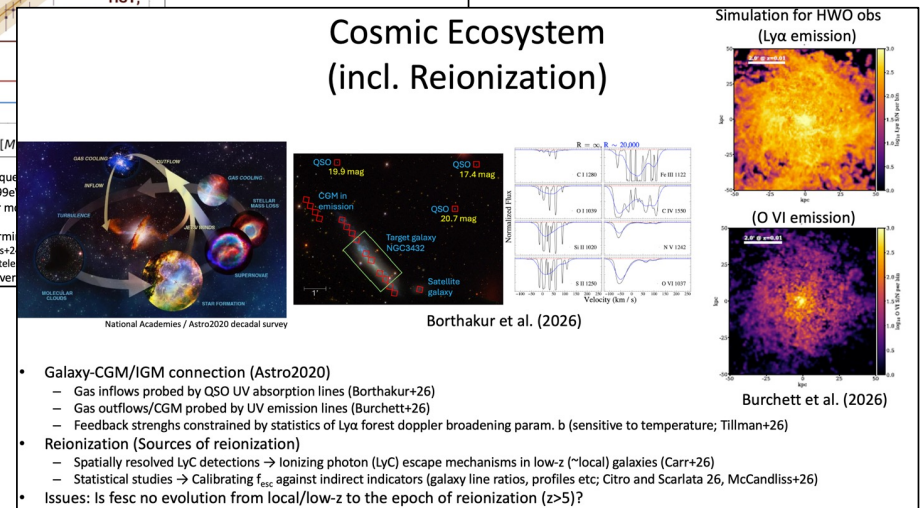
Metal Lines by Deep UV Spectroscopy



Intermediate Mass Black Hole (IMBH)



Cosmic Ecosystem (incl. Reionization)



HWO25 Science Cases

Spatially Resolving Nearby Galaxies

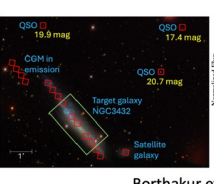
These science cases are **limited to local/low-z objects...**

Shall we make more science cases?

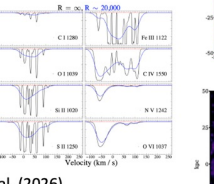
- HWO rest-frame UV obs for **high-z galaxies/AGNs/LRDs** in opt-NIR, complementing the coming ELTxAO observations



National Academies / Astro2020 decadal survey



Borthakur et al. (2026)



Burchett et al. (2026)

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Issues: How are the IMBHs related to the seed BHs in the early univ...

Summary

- Reviewing **galaxy observations** and **open questions** (esp. studies w JWST driving this field)
 - **UV overluminous galaxies** (up to $z_{\text{spec}}=14.4$) : Physical origin?
 - **Nitrogen enhanced galaxies**: What are the sources of abundant nitrogen (CNO-cycled gas)?
 - **PopIII search**: Where are zero-metal galaxies?
 - **Clumpy high-z galaxies**: What produces the abundant stellar clumps?
 - **Numerous broad-line objects**: Seed black holes for SMBH / Physical origins of LRDs?
- Reviewing the **HWO25 science cases** and **JWST connections**: Evolution of the Elements & Galaxy Growth
 - **Spatially resolving nearby galaxies** : **Clumpy galaxies**?
 - **Metal lines by deep UV spectroscopy** : **N or Fe enhancements**?
 - **Intermediate mass black holes** : **Seed black holes**?
 - **Cosmic ecosystem (incl. reionization)** : **Sources of reionization**?

Limited to local/low-z objects. Making science cases for **HWO high-z galaxy/AGN/LRD obs** in opt-NIR bands?

Living Worlds Overview

Lead author: Kenji Takizawa

Abstract:

The Living Worlds Science Working Group plays a crucial role in shaping the Habitable Worlds Observatory (HWO) mission by translating biological principles into foundational instrument requirements and observational strategies needed to evaluate planetary habitability and search for life. From the insights presented by this group, which were compiled in HWO25 Proceedings Part 1, I summarized those with a particularly strong biological focus. HWO mission success relies on adopting an “Earth through time” framework using broad multi-wavelength spectroscopy (0.25-1.7 μm) to detect key atmospheric gases across different evolutionary stages while ruling out false positives. Seasonal oscillations in biosignature gases dramatically increase confidence in life detection. Surface biosignatures, such as the Vegetation Red Edge, provide direct, physical evidence of surface life.

Science Case Summary

The efforts of the Living Worlds Science Working Group are essential because they translate biological realities into the fundamental engineering and operational requirements necessary for HWO to detect life on exoplanets. Specifically, their work ensures mission success through three main contributions: maximizing observation efficiency, preventing false negatives, and preventing false positives.

Living World Overview

2026/07/15

Astrobiology Center

Kenji Takizawa



Title: ***HWO25 Proceedings Part I: Community Science Case Development Documents***

Monograph: 10

Year: 2026

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305- Testing Origin-of-Life Theories with the Habitable Worlds Observatory

309- Prebiosignatures with the Habitable Worlds Observatory

317- Technosignatures

325- Searching for Life as We Don't Know It

331- Detecting Alien Living Worlds and Photosynthetic Life using Imaging Polarimetry with the HWO Coronagraph

353- Geochemical Habitability

357- [Testing False Positive Biosignature Scenarios with the Habitable Worlds Observatory](#)

365- Masses of Potentially Habitable Planets Characterized by the Habitable Worlds Observatory

377- [Breathing Worlds: Leveraging Seasonality for Exo-Earth Biosphere Characterization with HWO](#)

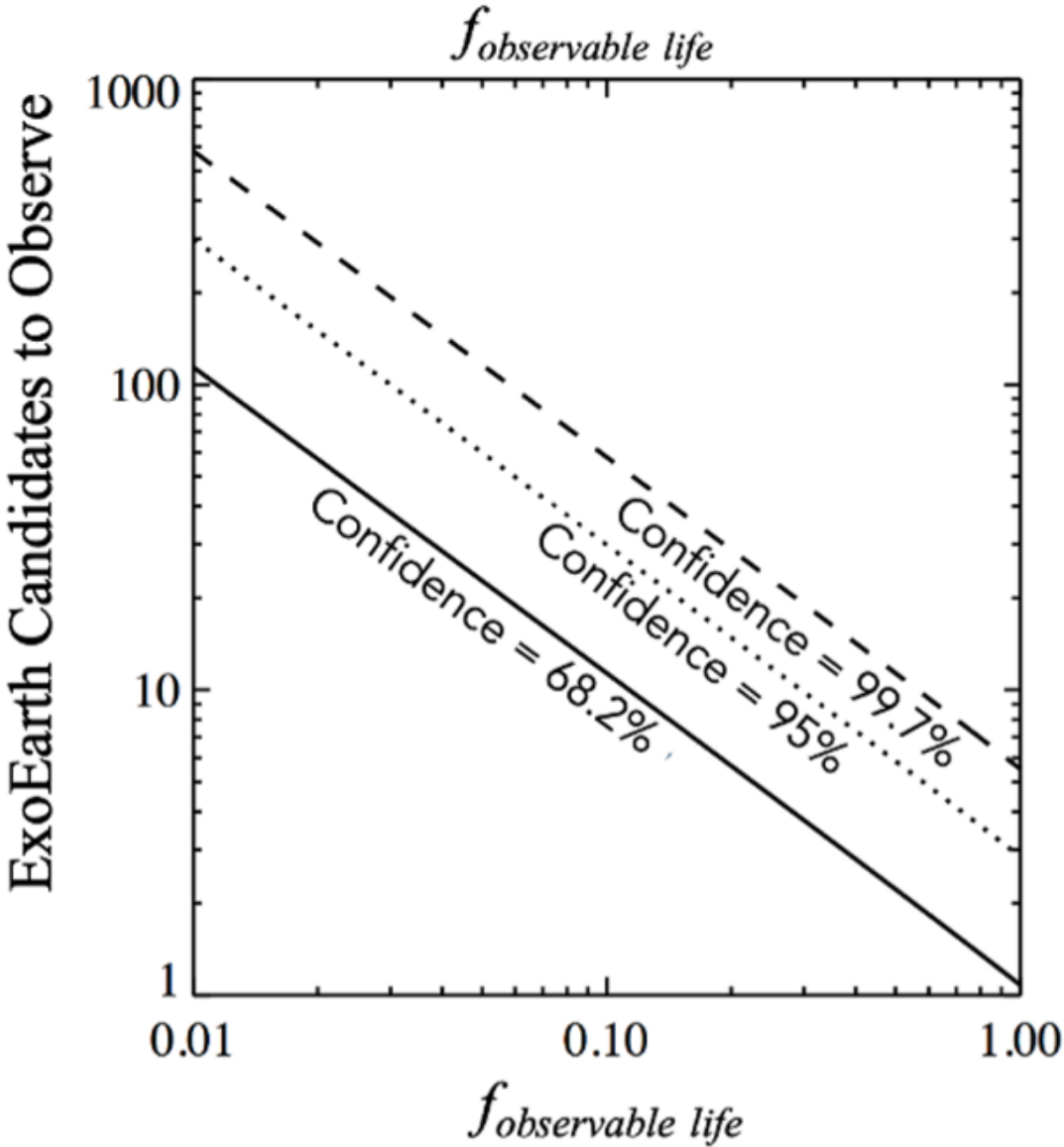
393- [Living Worlds Working Group: Surface Biosignatures on Potentially Habitable Exoplanets](#)

https://www.aspbbooks.org/a/volumes/table_of_contents/542

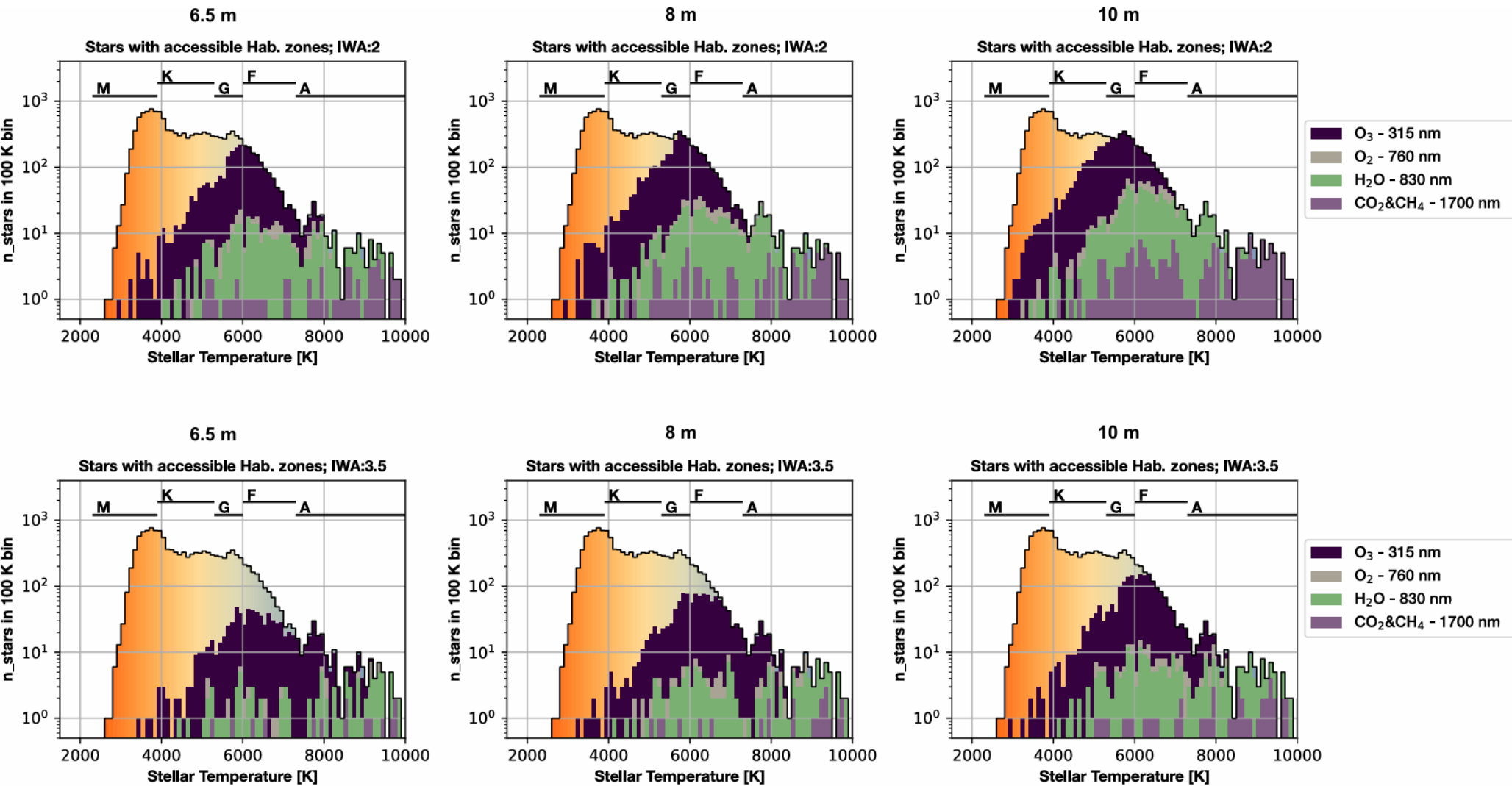
Detecting one planet with biosignatures by HWO

Astro2020 suggests that HWO examine ~25 terrestrial planets in their stars' habitable zones for signs of habitability and life. This sample size would guarantee seeing at least one planet with biosignatures at 95% confidence, if the frequency of inhabited planets with observable global biospheres is 10% of all candidates.

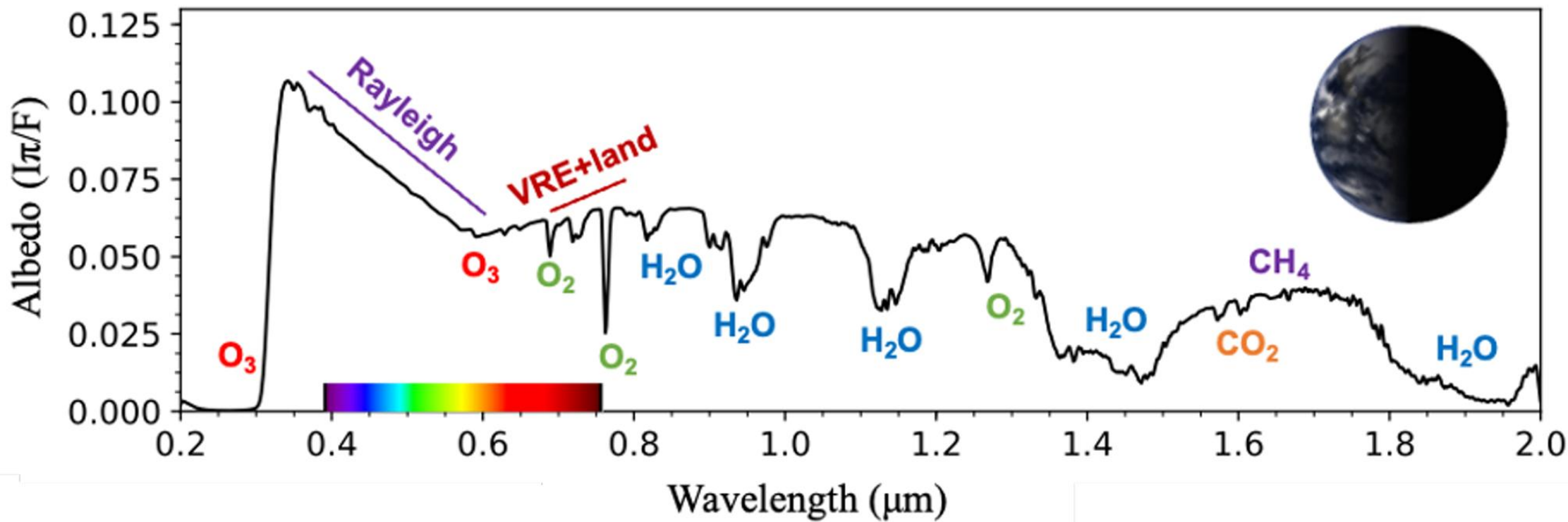
ExoEarth candidate yield required to constrain



The distribution of potential target stars from the HWO Preliminary Input Catalog

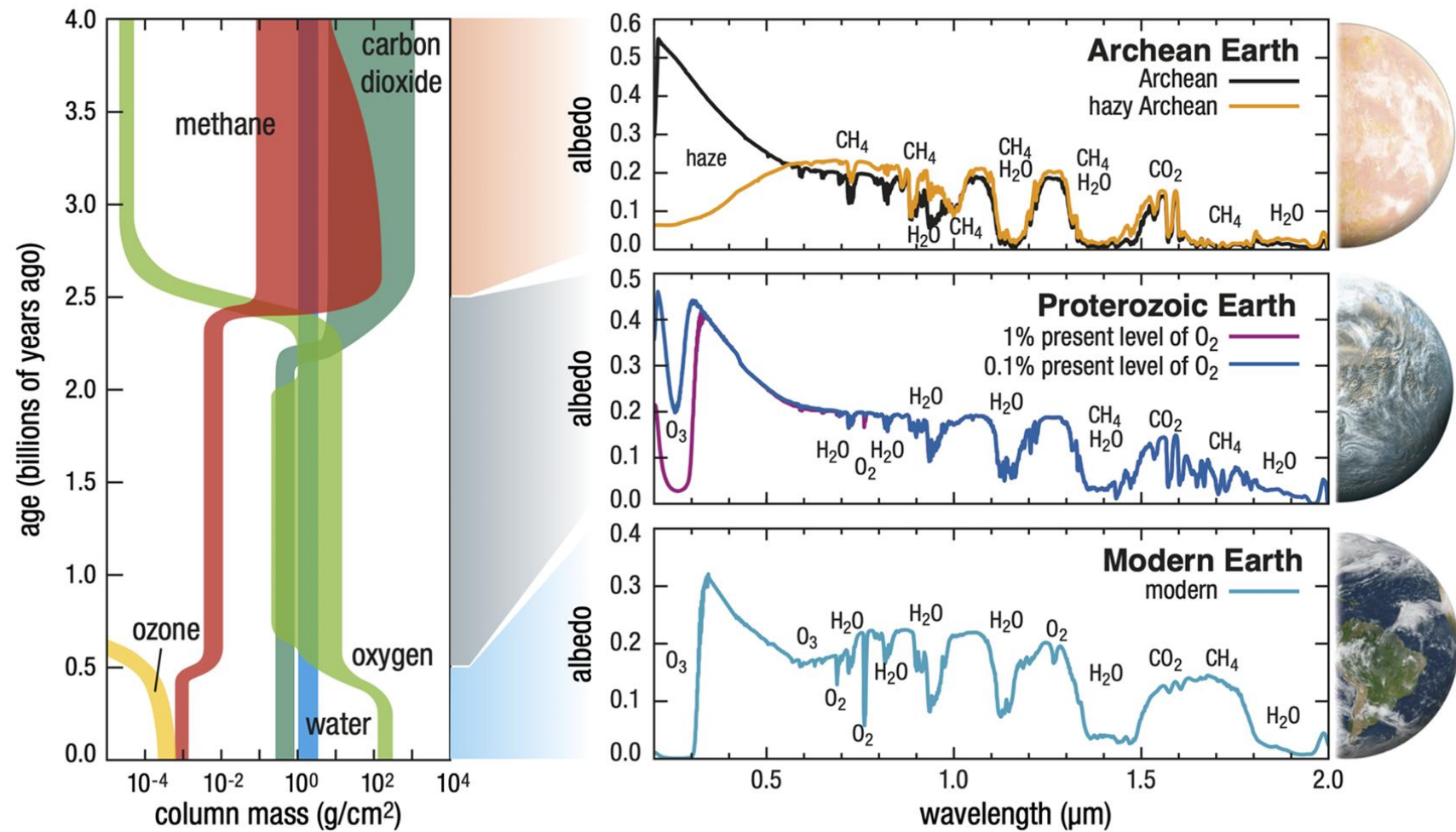


Spectral features of Modern Earth at quadrature phase



The biosignatures of Earth are useful spectral features to seek on exoplanets with HWO.

Biosignatures and habitability indicators of Earth through time

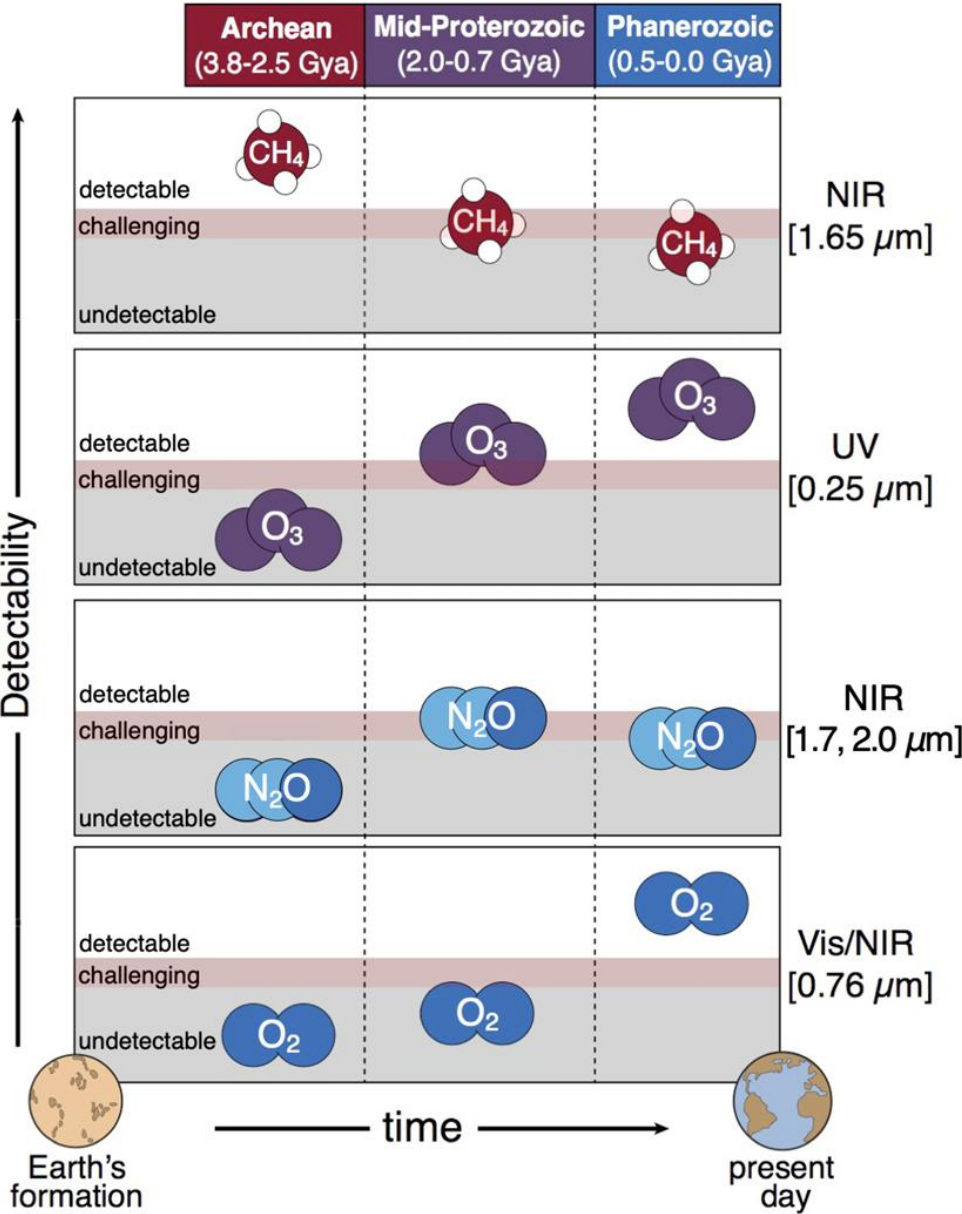


The biosignatures of Earth through time are a useful minimum set of spectral features to seek on exoplanets with HWO.

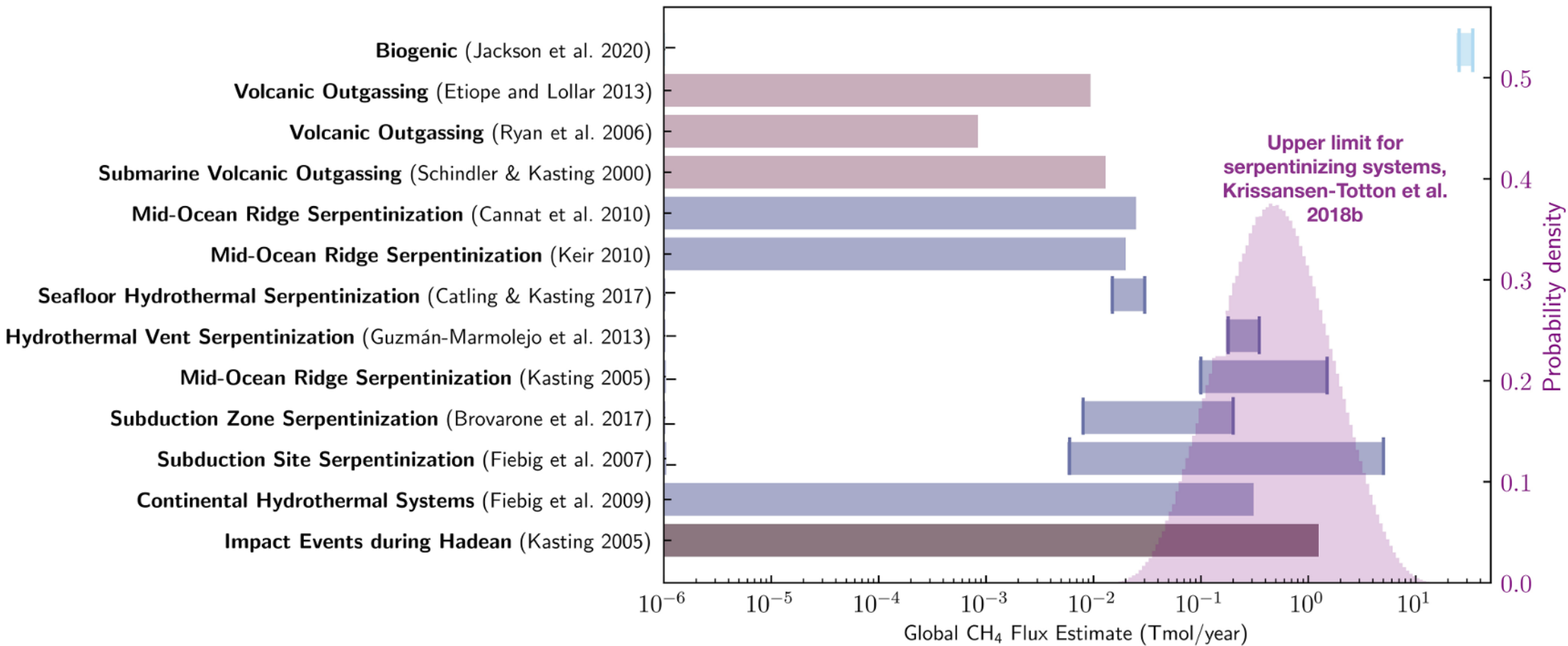
The dominant biosignatures of Earth, and their detectability

Different photochemistries around different stars can also alter the relative detectability of biosignatures.

A wavelength range from the NUV to the NIR ensures that the dominant biosignatures over Earth history can be detected on exoplanets.

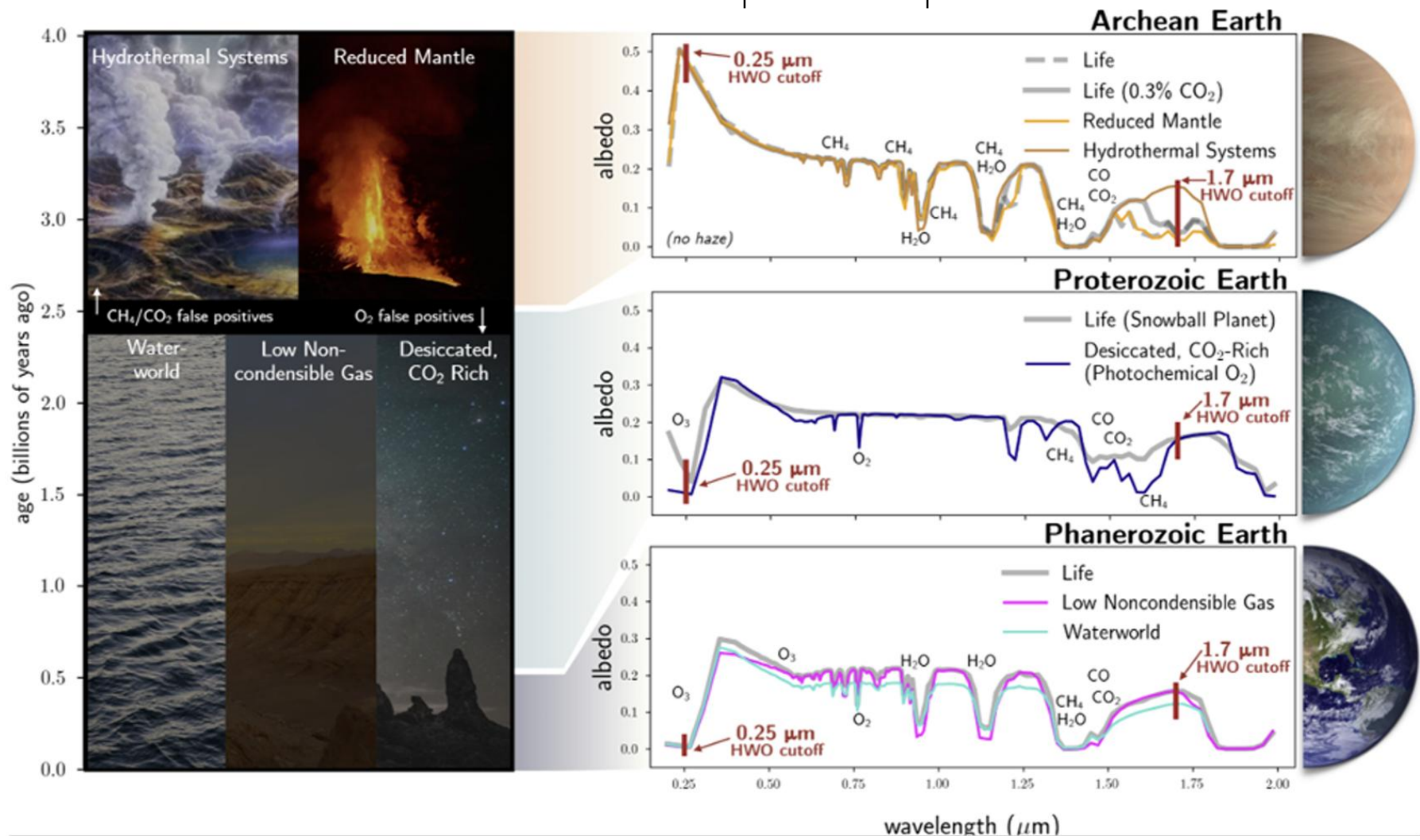


Abiotic sources of methane compared to Earth's modern biogenic flux



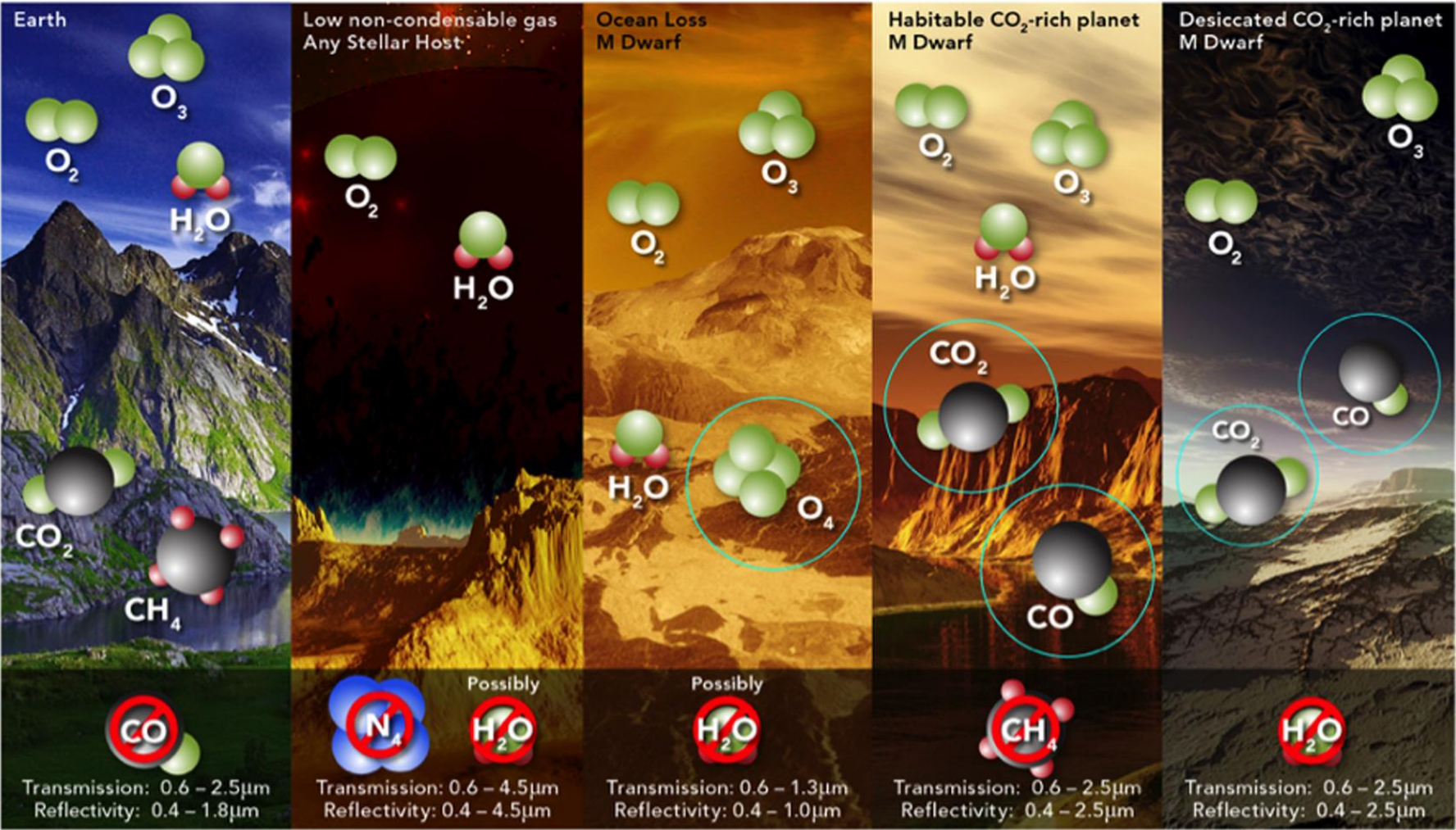
Biogenic CH₄ flux is more rapid than all abiotic sources.

Possible false positive planets



Biosignatures must be considered in the context of their environments to rule out false positives.

Planetary processes that could lead to detectable abiotic O₂ and/or O₃



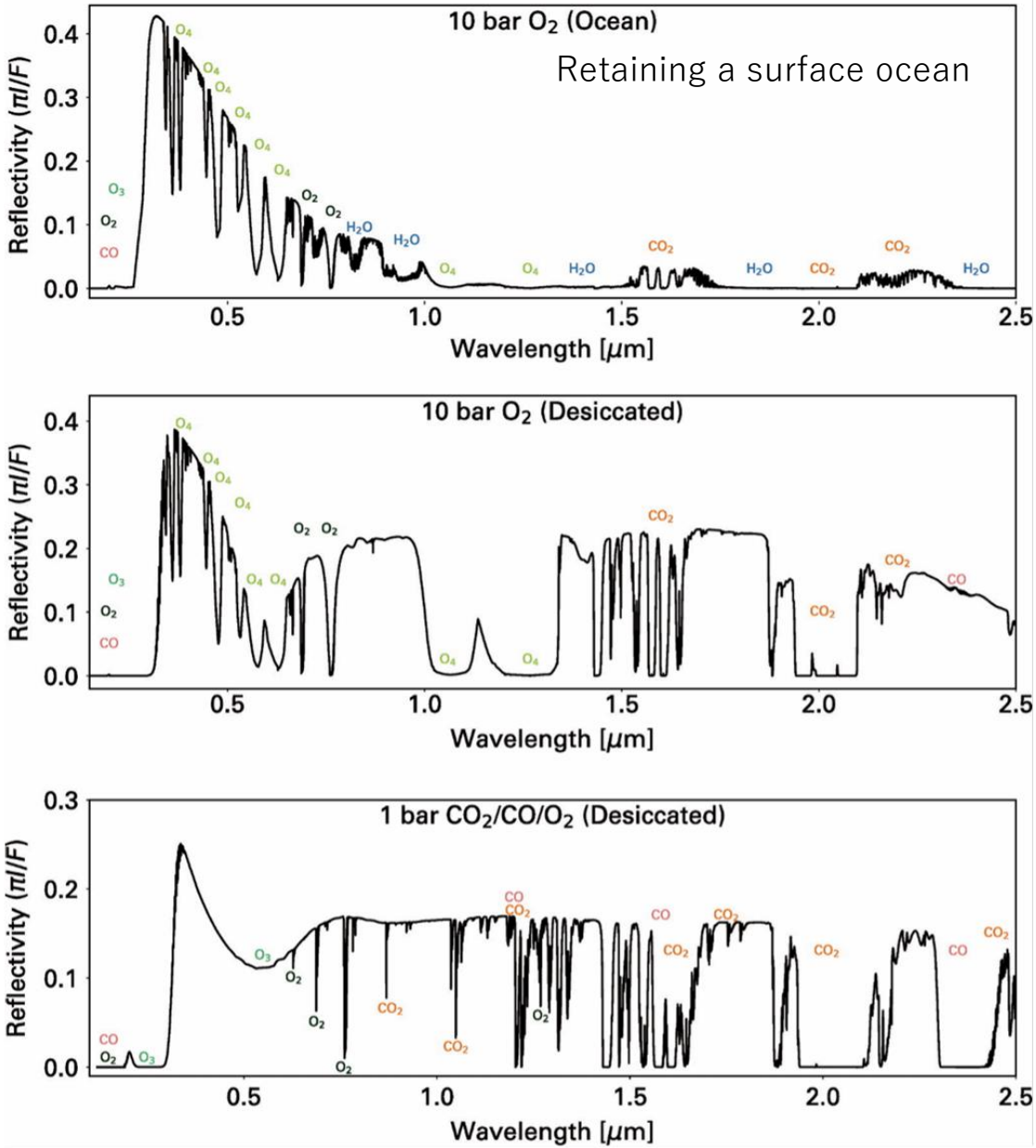
Multiple scenarios for abiotic O₂ buildup have been proposed that could operate in the HZ, including H loss from runaway greenhouses and photochemical decomposition of CO₂ atmospheres.

Simulated spectra of planets with abiotic O₂

First panel: 10-bar, abiotic, O₂-rich atmosphere retaining a surface ocean.

Second panel: 10-bar, abiotic, O₂-rich atmosphere following complete desiccation and loss of the ocean.

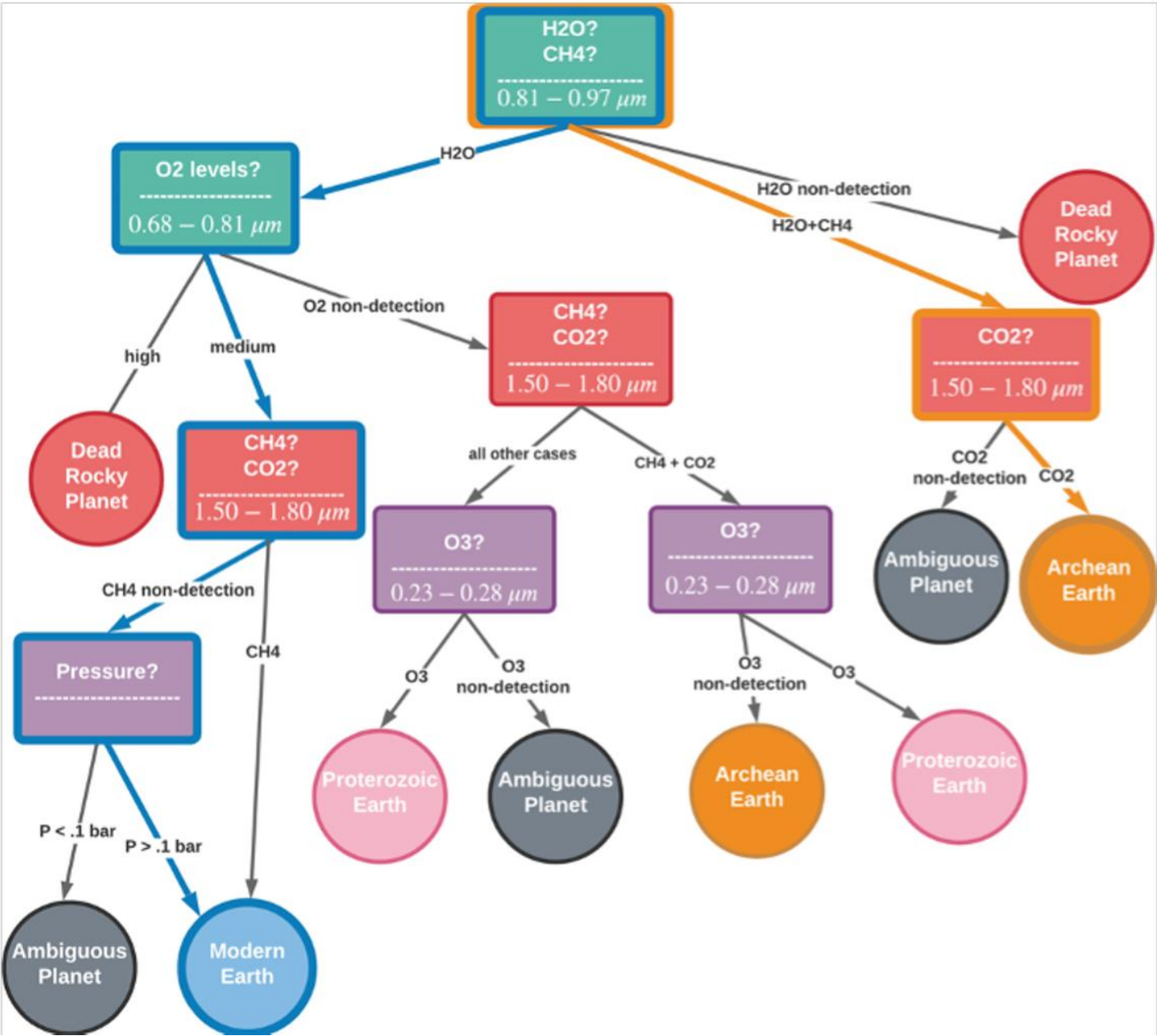
Bottom panel: desiccated, CO₂-rich atmosphere photochemically altered to CO₂/CO/O₂ due to the absence of hydrogen-dependent catalysts.



A decision tree strategy for characterizing Earth-like exoplanets

This tree indicates which gasses to observe, and in which order, to detect the biosignatures of Earth through time and rule out relevant false positives.

The blue path:
Spectral retrievals to categorize modern Earth

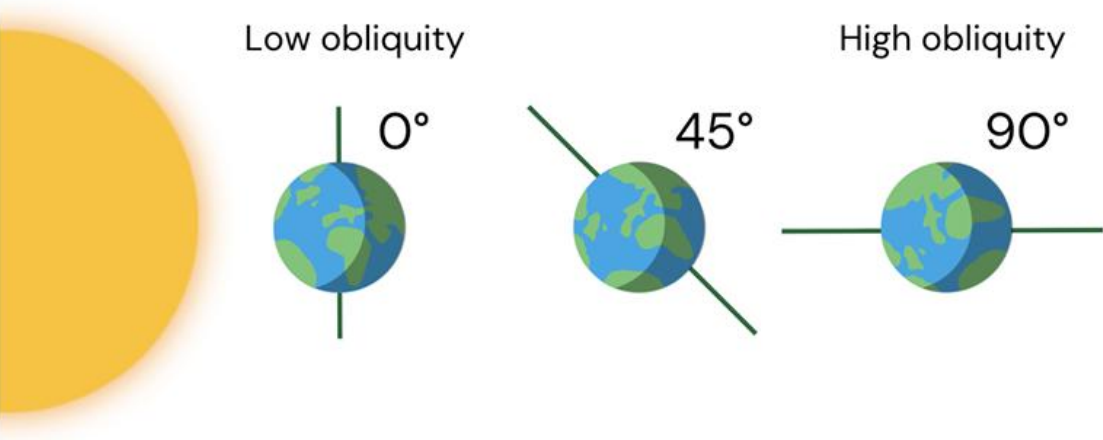


How prevalent are abiotic planetary processes that produce O₂ and/or O₃?

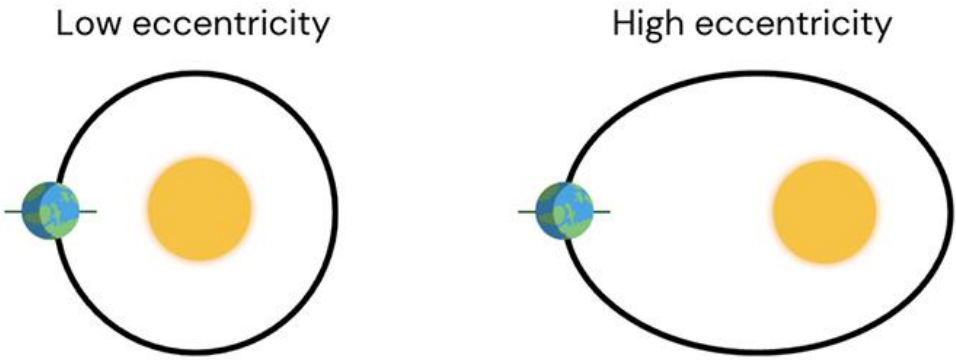
"False Positive" Biosignatures	common	Prediction: O₂/O₃ detected preferentially in Venus zone (due to H escape) or other contexts incompatible with habitability. False positive indicators (e.g., O₄) detected. Interpretation: Detectable global biospheres are rare in the solar neighborhood. Abiotic processes mimicking some biosignatures are common. Confidence: Medium.	Prediction: O₂, O₃, and CH₄ detection in contexts consistent with varied origins (e.g., inside and outside HZ). False positive indicators present in some targets. Interpretation: Abiotic processes mimicking some biosignatures are common. More detailed spectral analysis is required for compelling targets. Confidence: Low to Medium.
	rare	Prediction: No detection of O₂, O₃, or levels of CH₄ on a temperate planet indicative of biological activity. No detection of alternative biosignatures. Interpretation: Detectable global biospheres are rare in the solar neighborhood. Confidence: High.	Prediction: Detection of O₂, O₃, CH₄, and/or alternative biosignatures on multiple HZ planets. No detection of abiotic O₂/O₃ in the Venus zone or other contexts. No false positive indicators. Interpretation: Detectable global biospheres are common in the solar neighborhood. Confidence: Medium to High.
		rare	common
"True Positive" Biosignatures			

Simple logic matrix describing testable hypotheses and resulting interpretations of "True Positive" and "False Positive" biosignatures depending on how intrinsically rare or common they are.

Exo-Earths observed with the HWO likely experience seasons as Earth

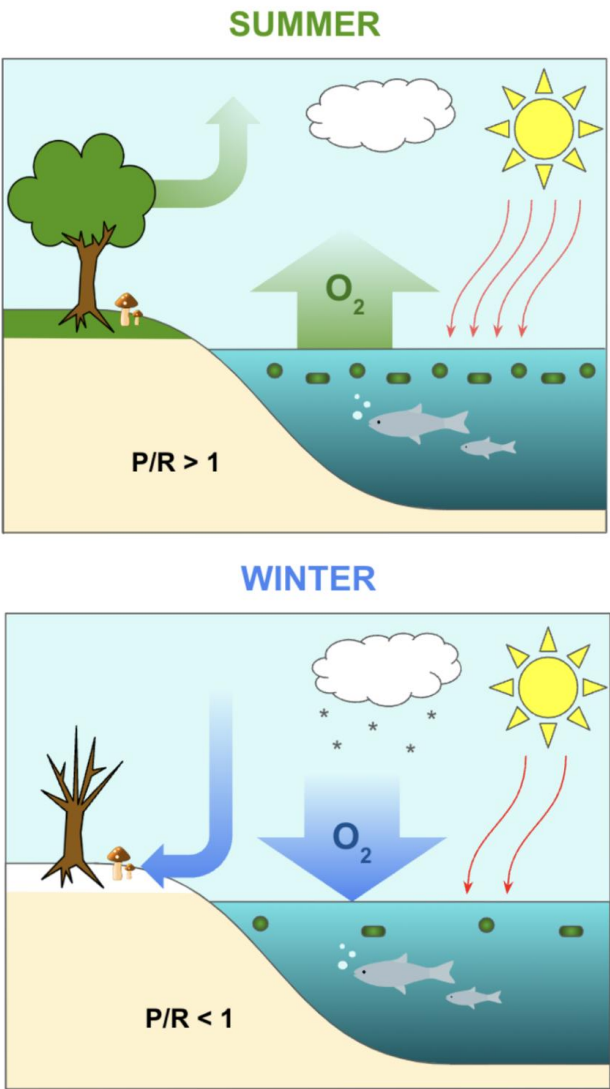
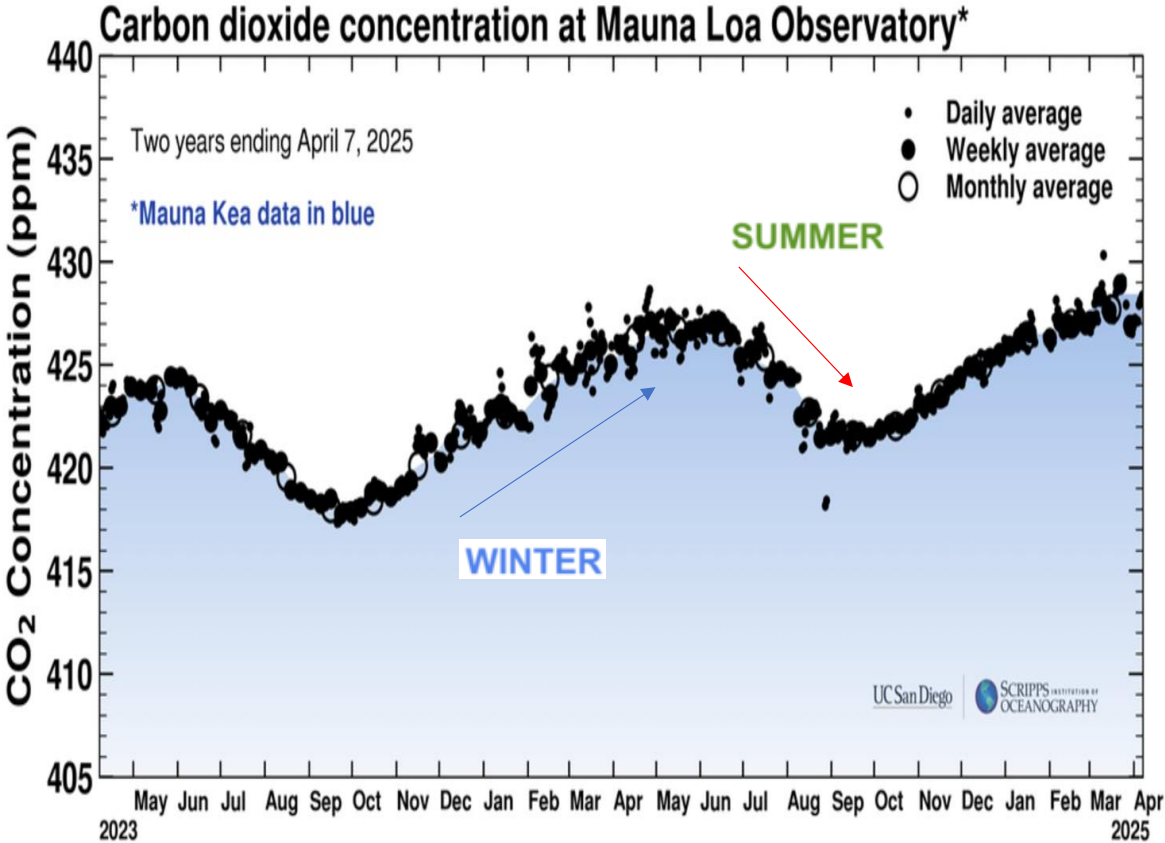


Orbital configurations of an exo-Earth with obliquity, resulting in hemispherically opposing seasons.

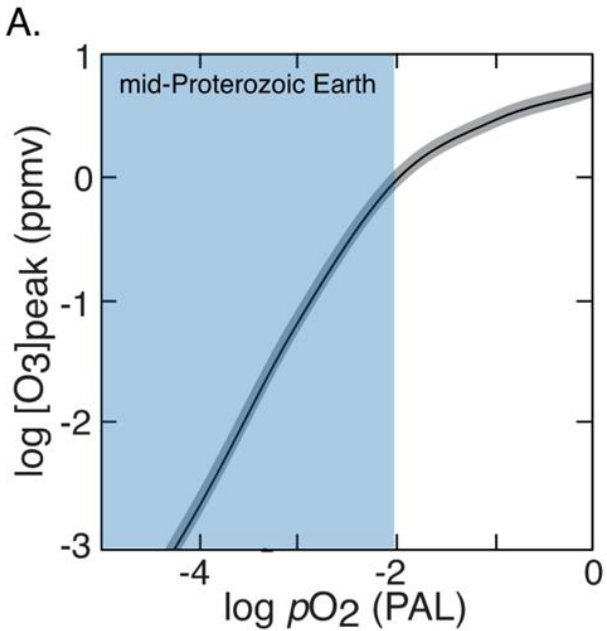


Orbital eccentricity induces global seasons.

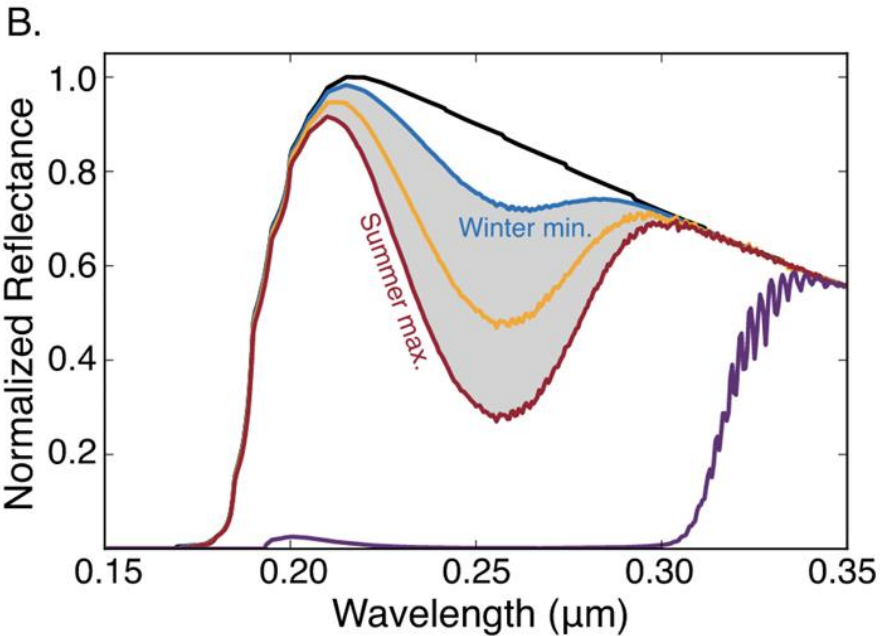
Atmospheric CO₂ levels on modern Earth vary seasonally



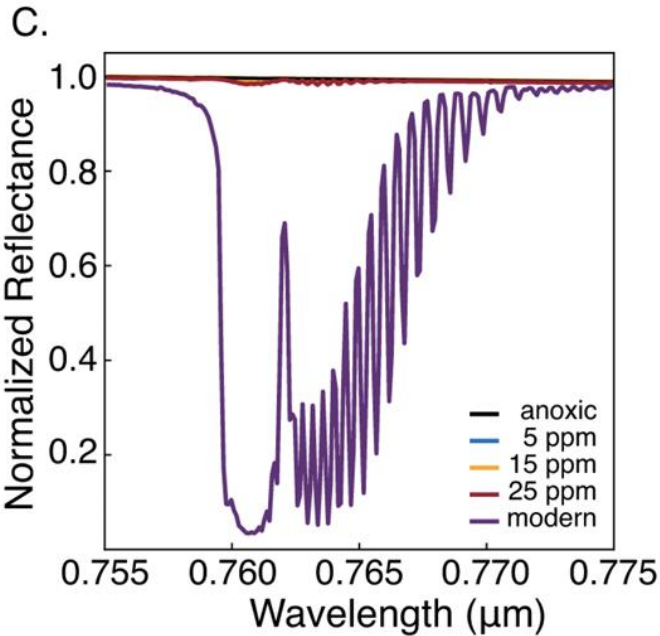
Seasonal O₂ oscillation potentially observable O₃ seasonality



O₃ sensitivity to pO₂



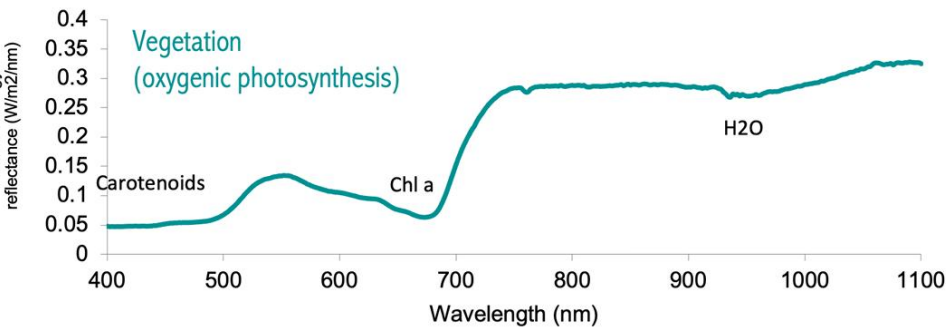
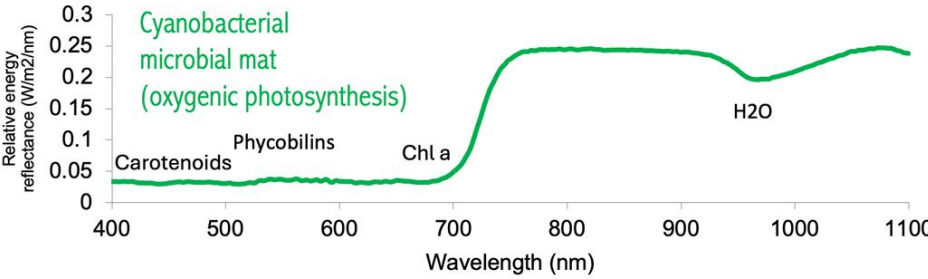
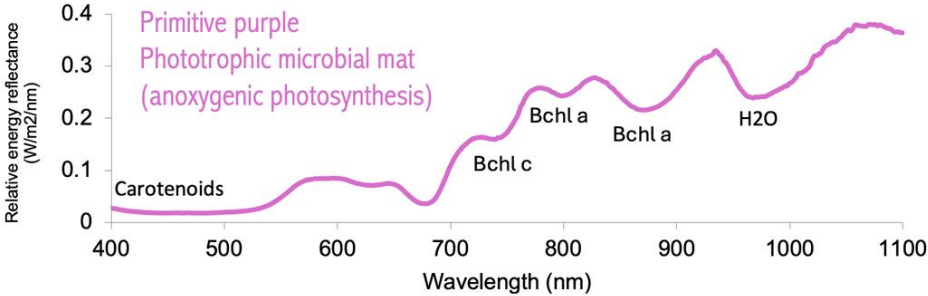
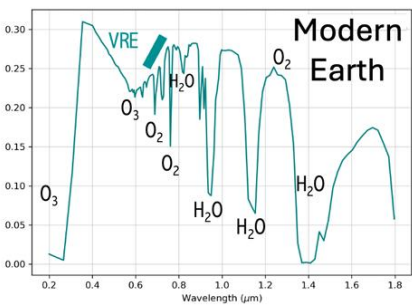
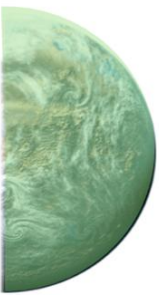
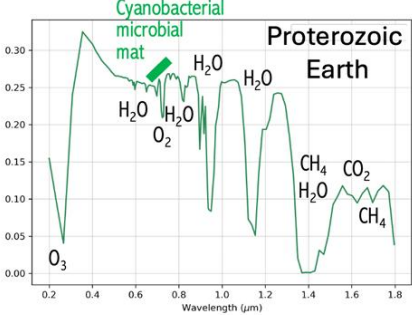
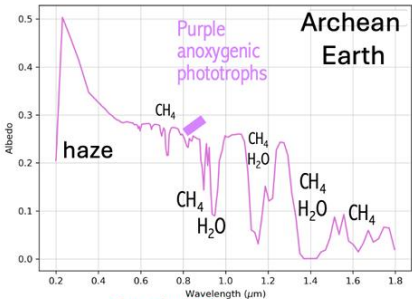
Seasonal oscillation in synthetic spectra centered on the O₃ band



Seasonal oscillations would be unobservable in the O₂-A band

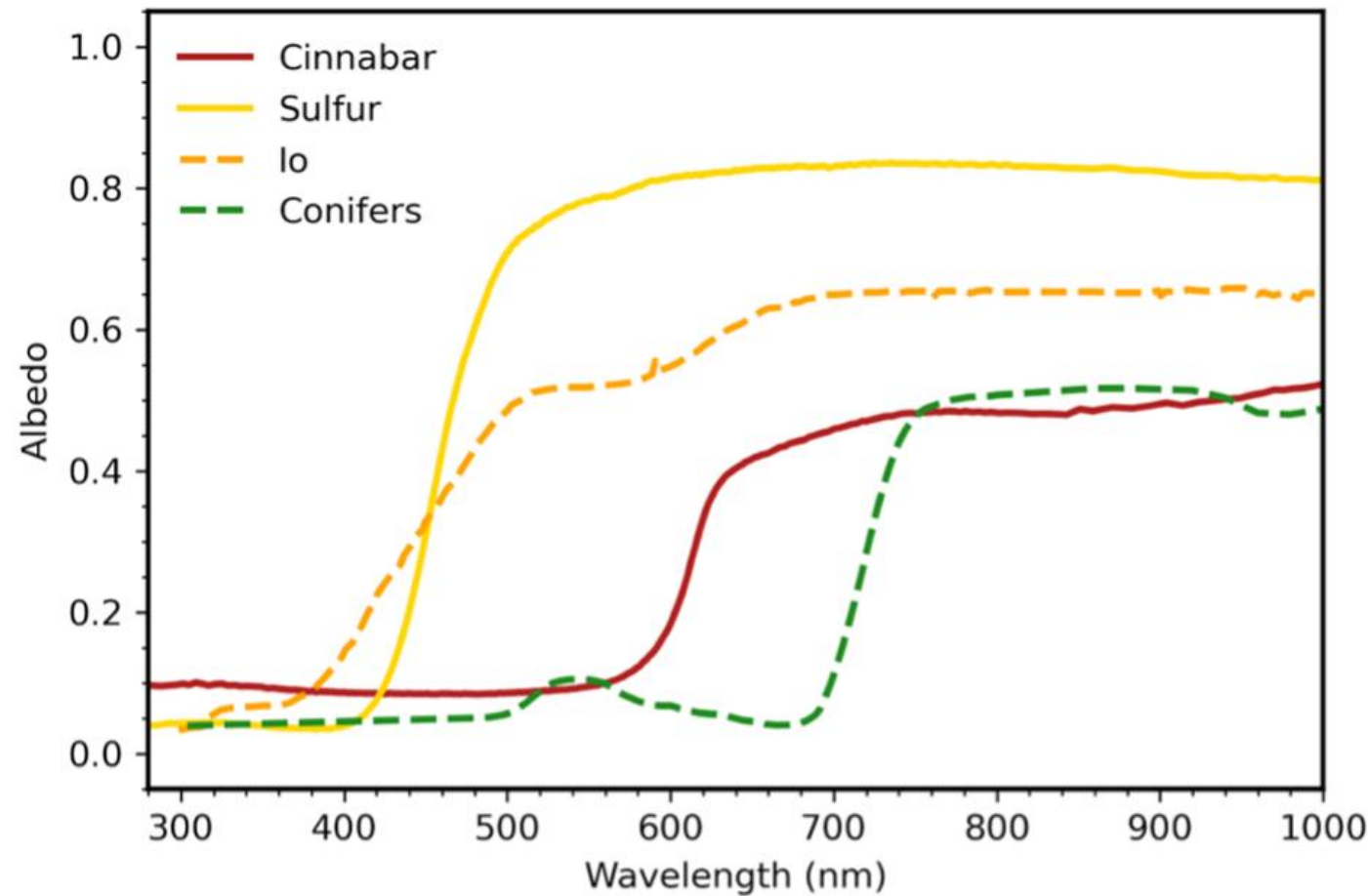
Surface Biosignatures on Potentially Habitable Exoplanets

Reflectance spectra of planets



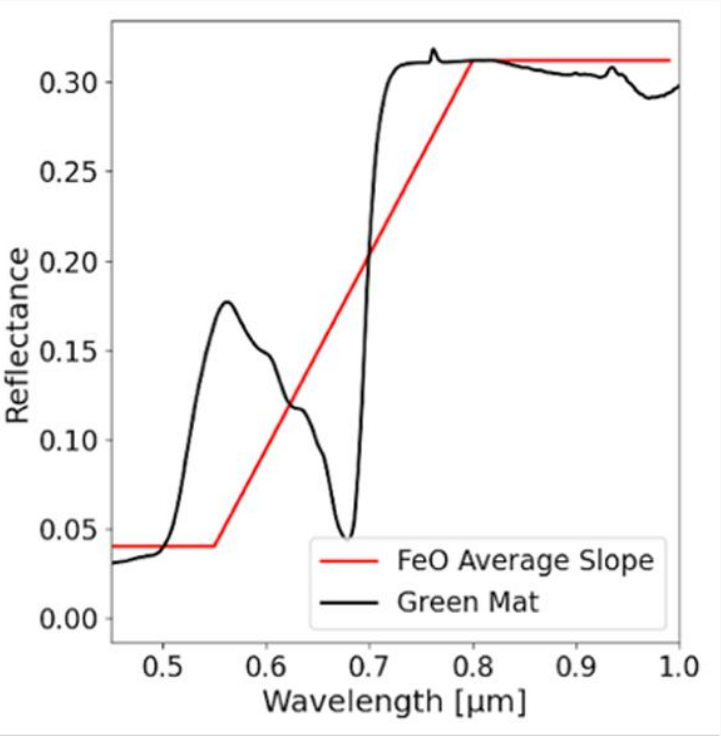
Reflectance spectra of photosynthetic organisms

Comparison of VRE and false positive mineral “edge” features

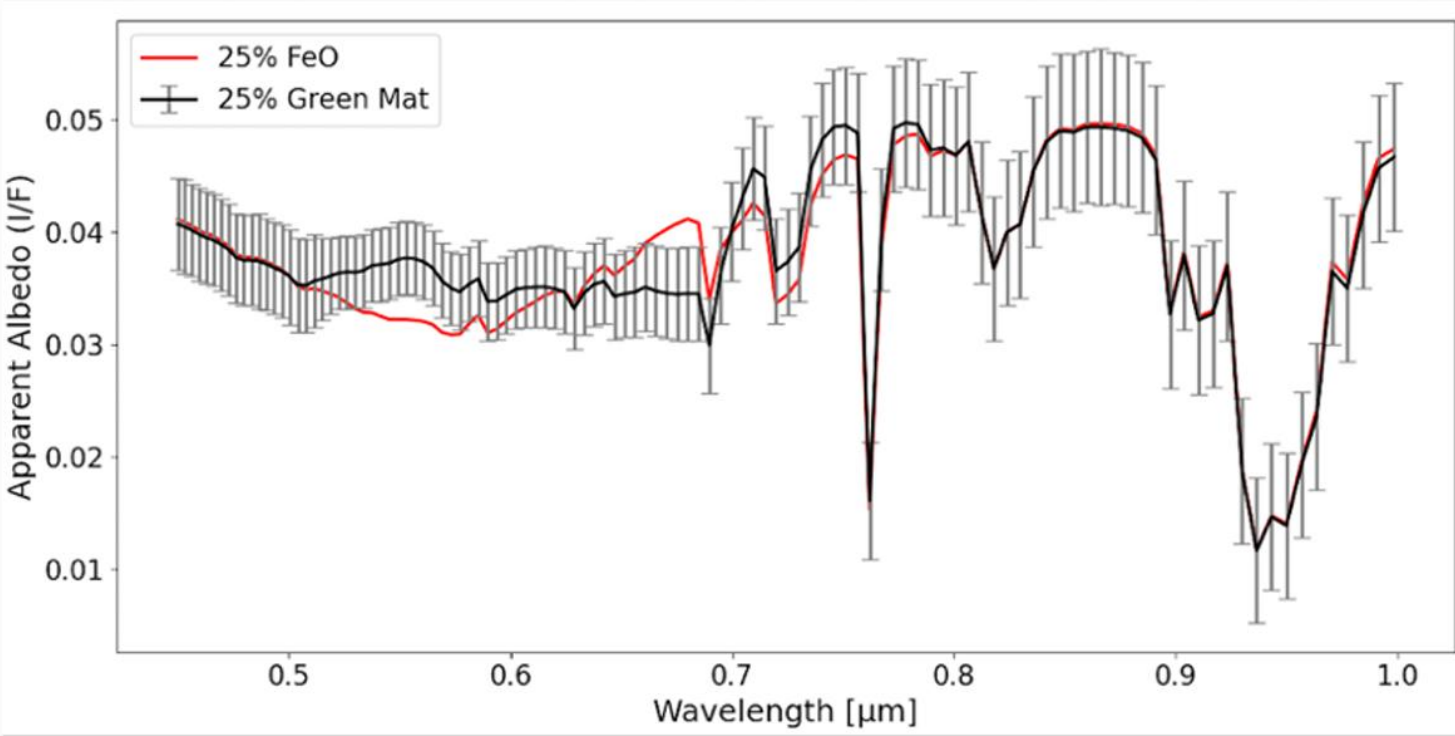


Shown are the reflectance spectra of elemental sulfur, cinnabar (HgS), the jovian moon Io, and a conifer forest.

Comparison of VRE and false positive mineral “edge” features



Reflectance spectrum of a microbial mat composed of cyanobacteria and an iron oxide.



Two synthetic reflectance spectra of exoEarths at 10 pc, one inhabited and one uninhabited, observed with an HWO-like telescope. The surface is composed of 25% green mat or iron oxide.

The red edge feature could be potentially differentiated from the gentler upslope of FeO.

Biosignature and Habitability Search with HWO

1. Biosignature Exploration Framework by HWO:

The HWO is designed to place the first statistical constraints on the frequency of inhabited worlds by searching for global, planet-wide biosignatures while rigorously evaluating potential abiotic false positives.

2. The "Earth through Time" Multi-Wavelength Strategy:

Because Earth's atmosphere and biosignatures have evolved drastically across its 4-billion-year history, broad spectral coverage spanning from the NUV to the NIR is required to detect life at various evolutionary stages.

3. Contextualizing CH₄ in Anoxic Atmospheres:

Methane is the most promising biosignature for anoxic planets like Archean Earth; however, to rule out abiotic geological or photochemical false positives, astronomers must simultaneously constrain the abundances of CO₂ and CO.

4. O₃ as a Crucial Biosignature for Weakly Oxygenated Worlds:

For planets with low atmospheric O₂ levels, the NUV ozone absorption band is highly sensitive and detectable even when O₂ itself is invisible.

5. Leveraging Seasonality as a Temporal Biosignature:

Seasonal oscillations in biosignature gases reflect active interactions between a biosphere and its environment, serving as an orthogonal line of evidence that dramatically increases confidence in life detection.

6. Surface Biosignatures to Corroborate Life:

Surface biosignatures, such as the Vegetation Red Edge provide direct, physical evidence of surface life for biogenic O₂ production.

7. Instrumentation and Observation Requirements:

To successfully characterize habitable worlds and exclude false positives, HWO requires a continuous spectral range of at least 0.25 to 1.7 μm .



Title: ***HWO25 Proceedings Part I: Community Science Case Development Documents***

Monograph: 10

Year: 2026

[View this Volume on ADS](#)

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Part III: HWO Science Development Papers from the Living Worlds Science Working Group

Page- Paper Title

279- [The Search for Life on Potentially Habitable Exoplanets](#)

305- Testing Origin-of-Life Theories with the Habitable Worlds Observatory

309- Prebiosignatures with the Habitable Worlds Observatory

317- Technosignatures

325- Searching for Life as We Don't Know It

331- Detecting Alien Living Worlds and Photosynthetic Life using Imaging Polarimetry with the HWO Coronagraph

353- Geochemical Habitability

357- [Testing False Positive Biosignature Scenarios with the Habitable Worlds Observatory](#)

365- Masses of Potentially Habitable Planets Characterized by the Habitable Worlds Observatory

377- [Breathing Worlds: Leveraging Seasonality for Exo-Earth Biosphere Characterization with HWO](#)

393- [Living Worlds Working Group: Surface Biosignatures on Potentially Habitable Exoplanets](#)

https://www.aspbooks.org/a/volumes/table_of_contents/542

Title: Review of Exoplanet Characterisation in HWO SCDD for Solar Systems in Context

Yuichi Ito(ABC/NAOJ)

Lead author: Yuichi Ito

Abstract: HWO will observe numerous planetary systems, placing Solar Systems in a broader context. In this talk, I reviewed Solar Systems in Context SCDD of HWO25 Proceedings focusing on exoplanet and star observations.

Review of Exoplanet Characterisation in HWO SCDD for Solar Systems in Context



Image credit : NASA's Goddard Space Flight Center Conceptual Image Lab

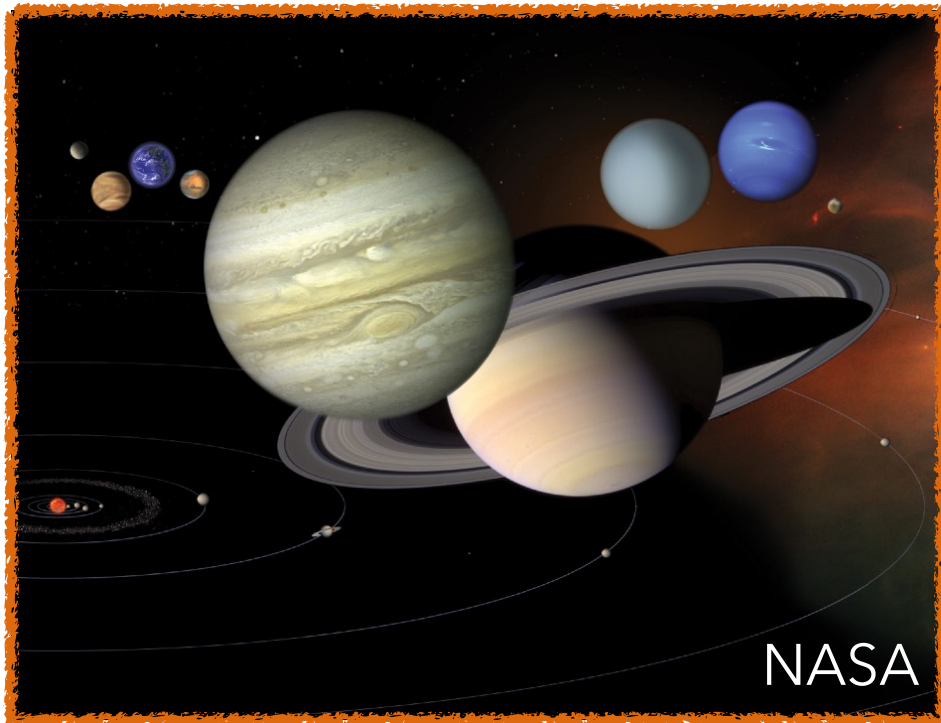
Yuichi Ito
(ABC/NAOJ)

HWO Japan Science WS 2, JAXA, 15/7/2026

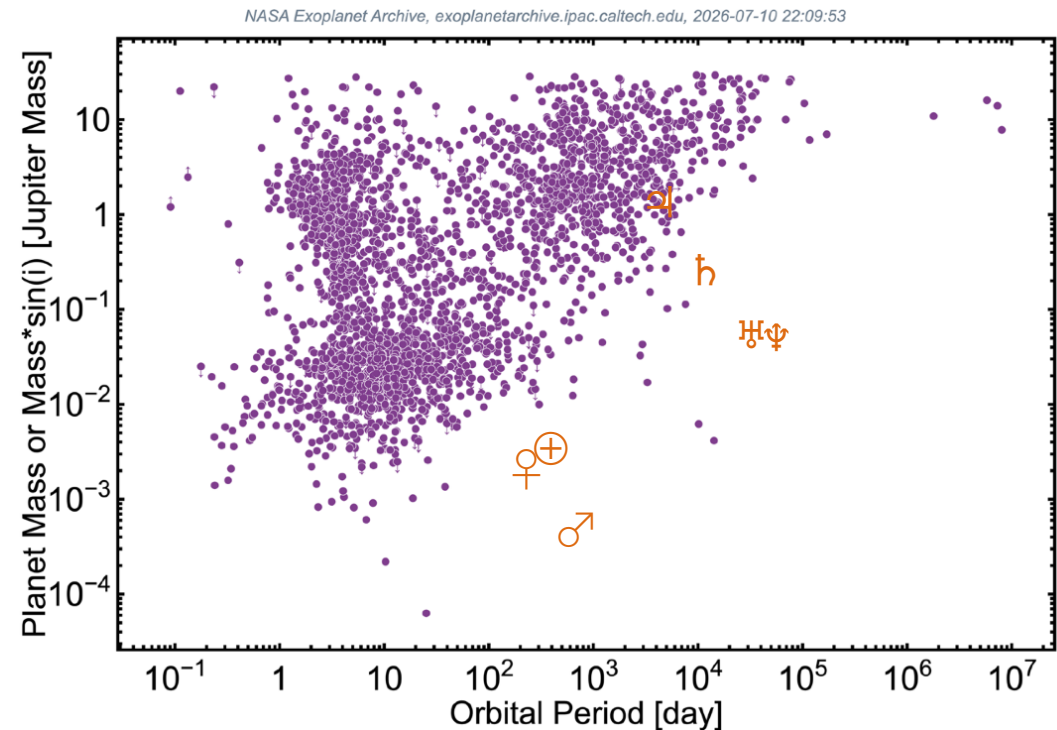
SSiC: Solar Systems in Context

Our Solar System hosts a remarkable diversity of planets, moons, and small bodies.

Exoplanetary systems reveal an even greater diversity.



Orbit and Mass of exoplanets

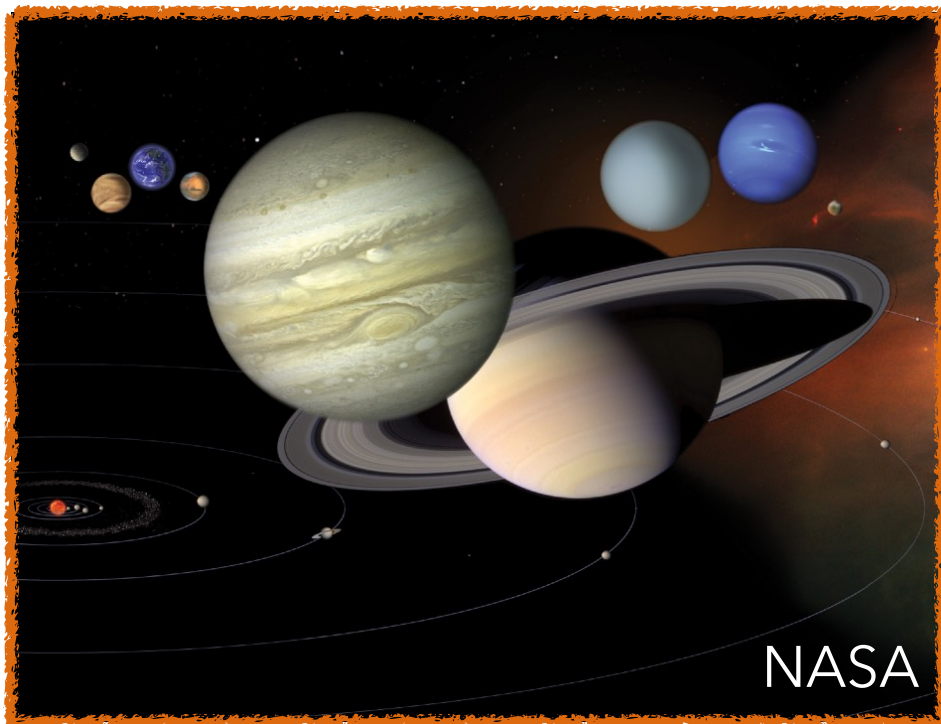


SSiC: Solar Systems in Context

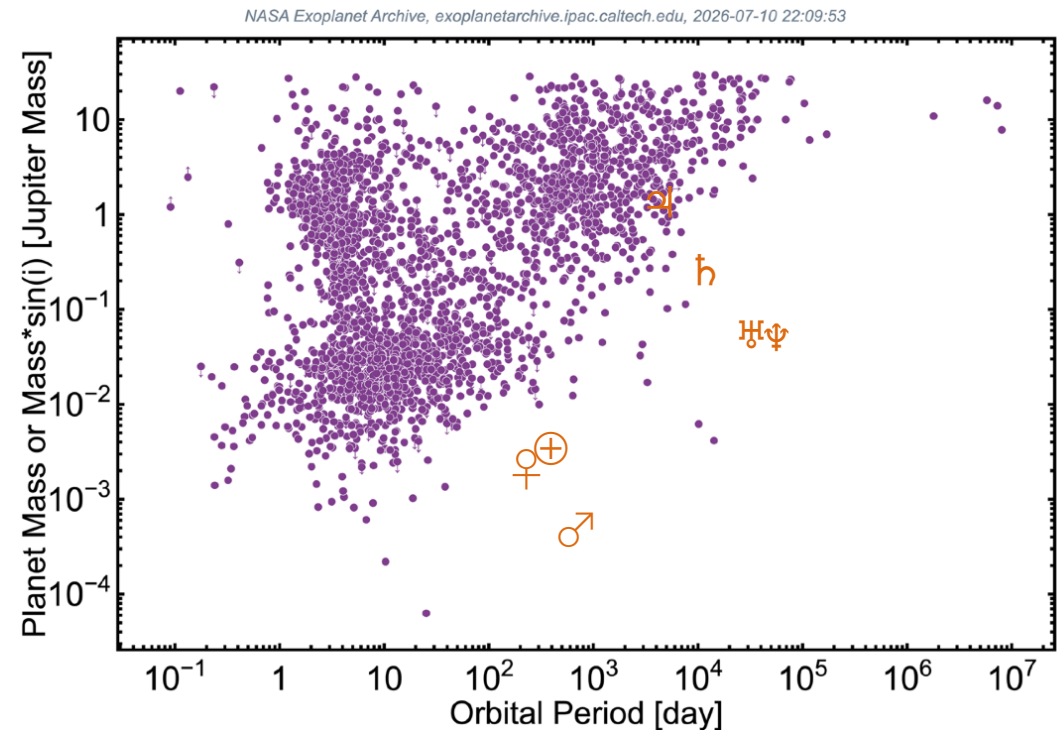
How do planetary systems **form** and **evolve**?

How **diverse** are composition/systems & **water-environment**?

HWO will observe numerous planetary systems, placing
Solar Systems in the broader context



Orbit and Mass of exoplanets



Exoplanet observation in HWO25 SSiC SCDD

In Solar Systems in Context (SSiC) SCDD of HWO25 Proceedings, there are 13 Science cases for Exoplanet & Star observations

How do planetary systems **form**?

SSiC-6, 34

How do planetary systems **evolve**?

SSiC-14, 24, 26

How **diverse** are planetary systems?

SSiC-3, 15, 16, 19

How **diverse** are **water-environment**?

SSiC-2, 4, 17, 18

*The number comes from PDF file name (SCDD-SSiC-"XX".pdf)
at the link of HWO25 Proceedings

***HWO solar system & disk observations will be reviewed by Aoki-san's talk**

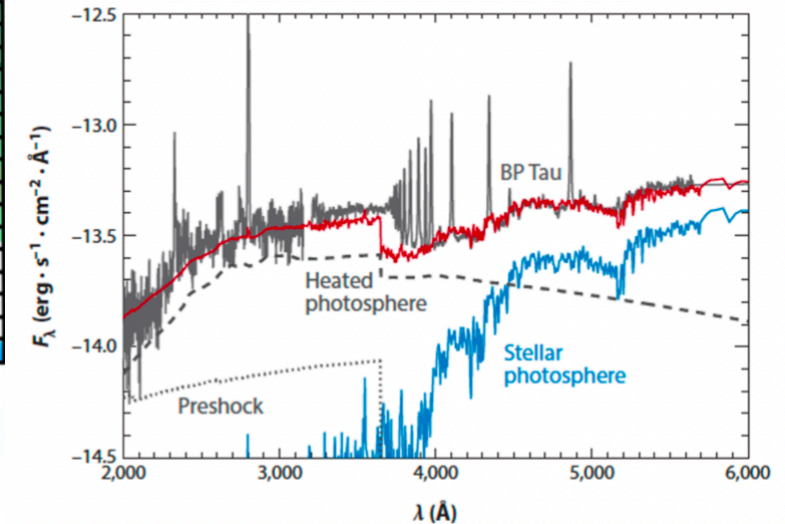
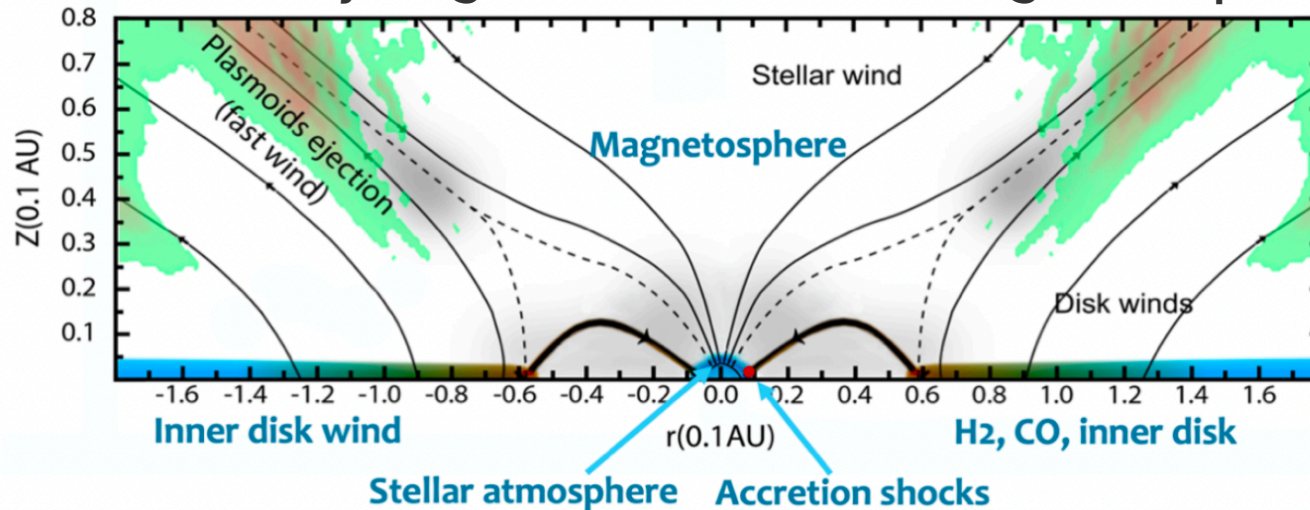
How do planetary systems **form**?

Investigating the Role of Magnetic Fields in shaping young planet systems

UV to NIR spectro-polarimetry monitoring of young stars and accreted flow

(A. I. Gómez de Castro, E. Alecian, et al., SSiC-34)

Illustration of young star, disk and basic magnetic topology Spectra of T Tauri star, BP Tau



Investigating the Role of Stellar Multiplicity in small cool planet formations

Searching small, cool planets in close-in ($<100 \text{ AU}$) stellar companion-systems

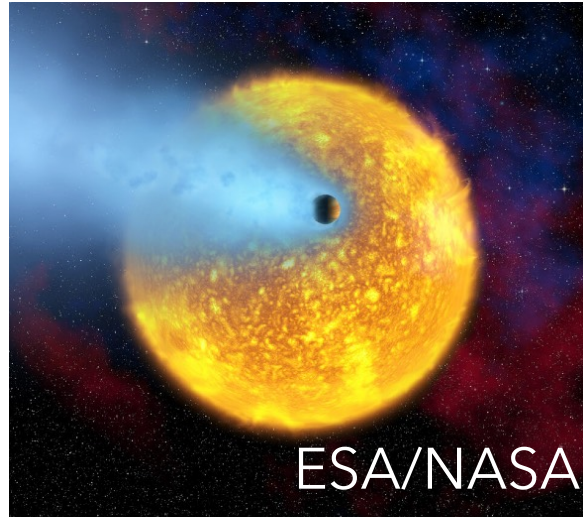
(E. Newton et al., SSiC-6)

Studies on Protoplanetary and Debris disk

(SSiC-8, 9, reviewed by Aoki-san's talk)

How do planetary systems **evolve**?

Atmospheric escape is a key process shaping planet demographics

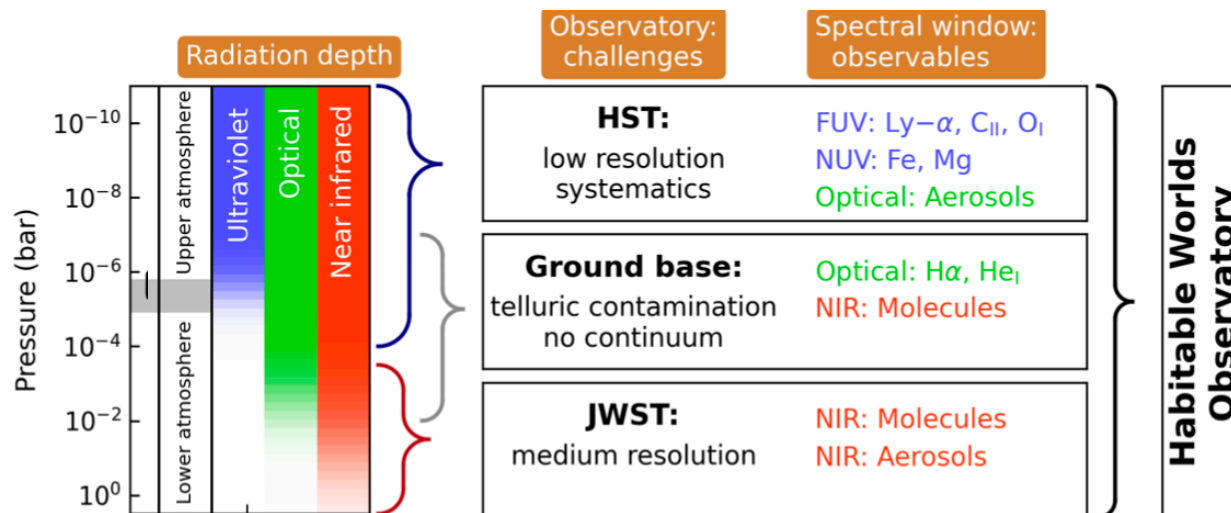


Then, how do planets retain their atmospheres and remain habitable?

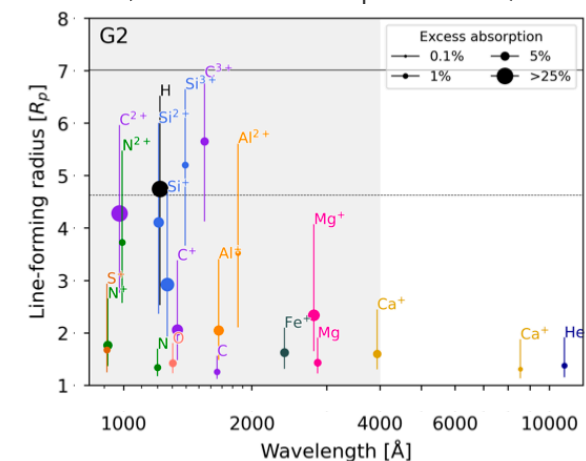
Needs to understand the role of atmospheric composition, planetary properties, and magnetic fields in mass-loss rates

Investigating the Role of Atmospheric Composition in atmospheric escape

UV-NIR high-resolution ($R > 60000$) transit spectroscopy (P E. Cubillos et al., SSiC-24)



Tracers of an upper atmosphere (Linssen & Oklopčic 2023)



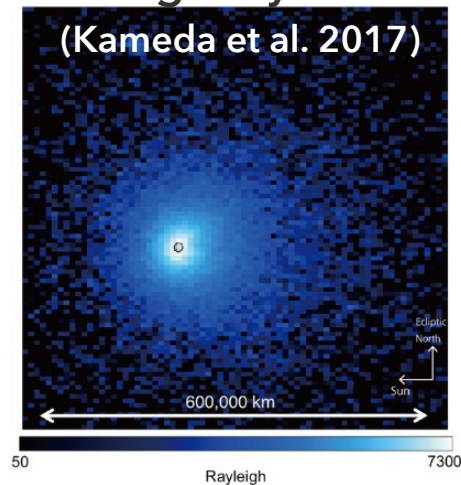
How do planetary systems **evolve**?

Investigating the Role of Planet Properties and Magnetic Field in escape

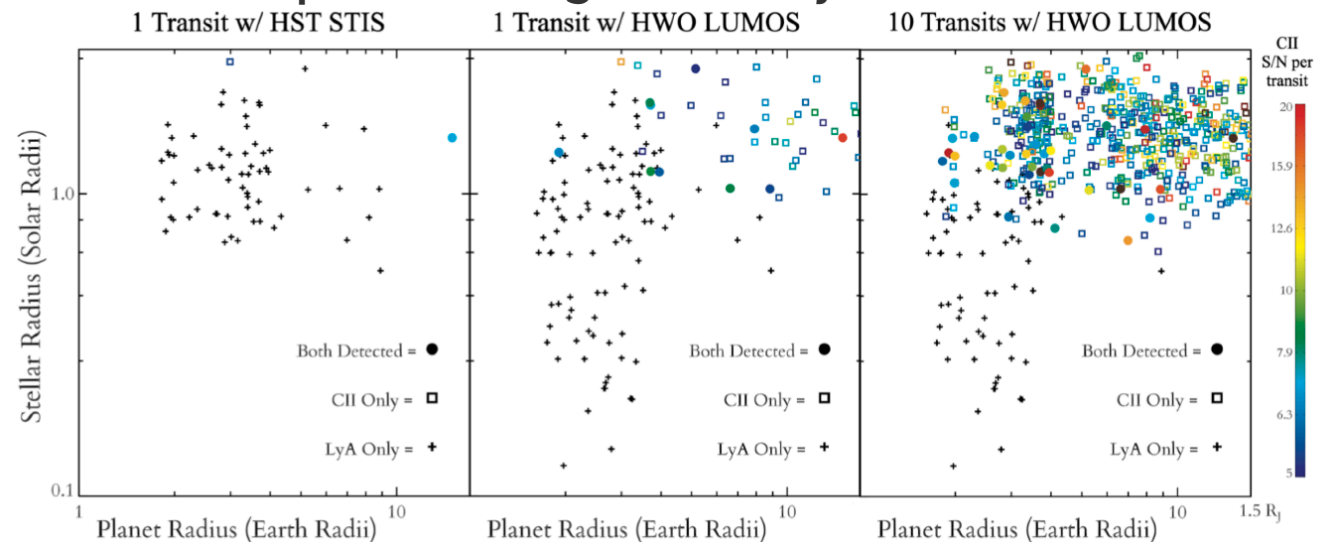
UV-NIR high-resolution transit spectroscopy (L. A. Dos Santos et al., SSiC-14)

UV-NIR high-resolution transit spectro-polarimetry (A. Strugarek et al., SSiC-26)

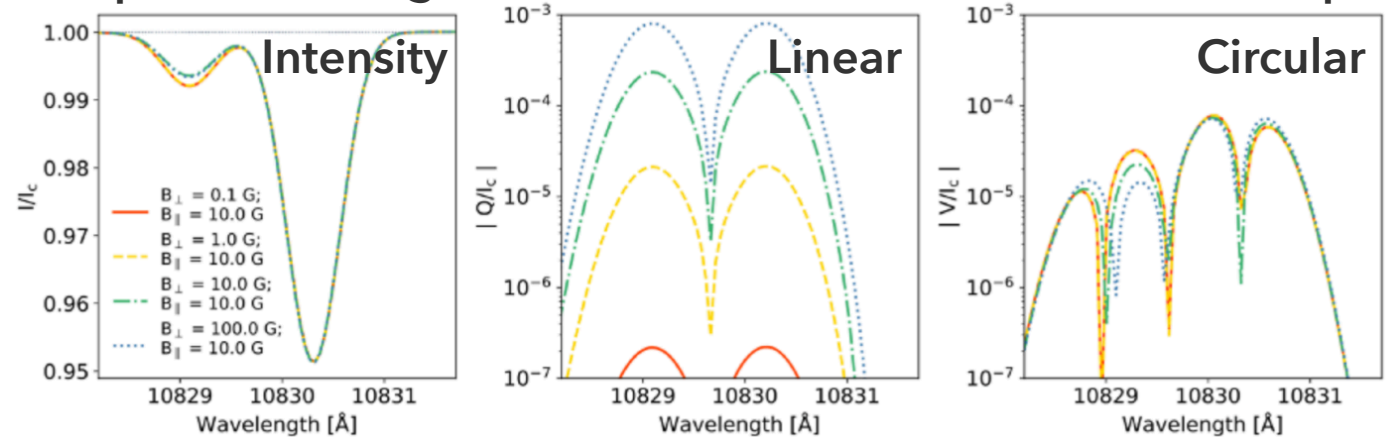
Scattering H Ly α of Earth



HWO potential targets for H Ly α & C II detections

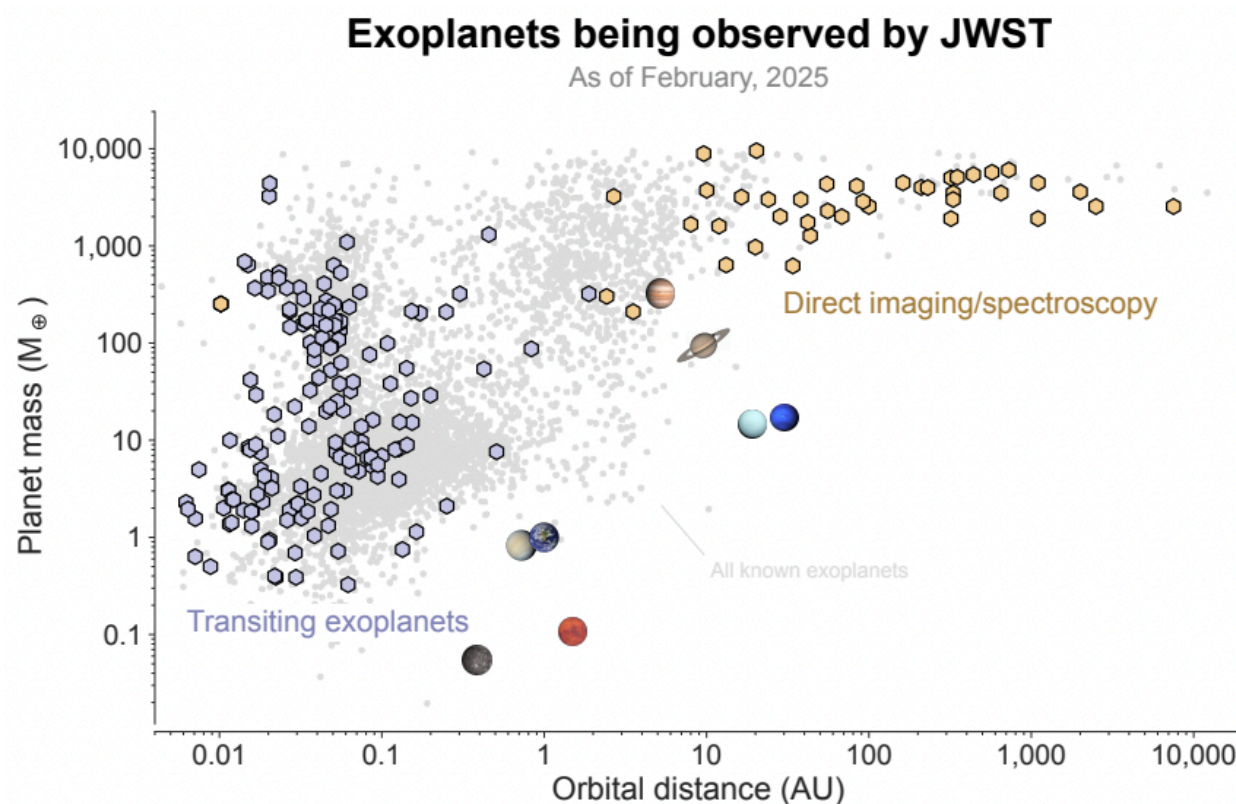


Dependence of polarization profile on magnetic field at the He I 1083 nm for hot Jupiters

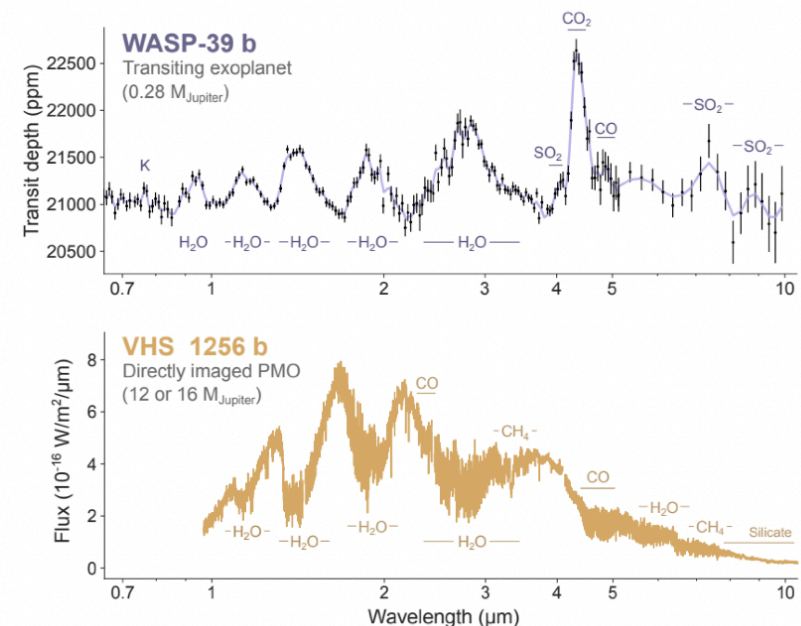


How **diverse** are planetary systems?

JWST has revealed chemical & system nature of many exoplanets



Observed spectra with JWST
(N. Espinoza & M. Perrin 2025)



but our view remains incomplete for comparative planetology

e.g., cool (0.2-10AU) gas giants, sub-Neptunes, rocky planets

SSiC-15,16

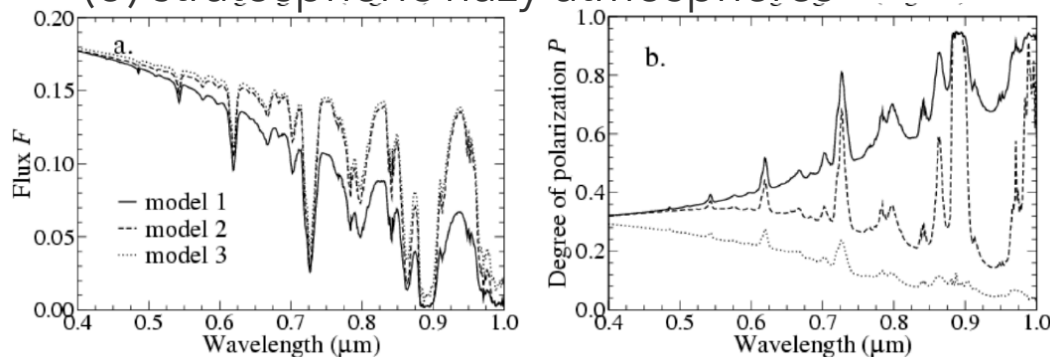
SSiC-3

SSiC-2,4,17,18

How **diverse** are planetary systems?

Reflected stellar-light flux and polarisation from Jupiter-like planets (Stam et al. 2003)

with (1) clear, (2) tropospheric cloudy, (3) stratospheric hazy atmospheres



For cool gas giants

Identifying atmospheric dynamics/chemistry, clouds & hazes properties

Vis-NIR phase-curve spectro-polarimetry of transiting planets (H. R. Wakeford et al., SSiC-16)/Vis-NIR imaging spectro-polarimetry (M. Min et al., SSiC-15)

For cool sub-Neptunes/super-Earths

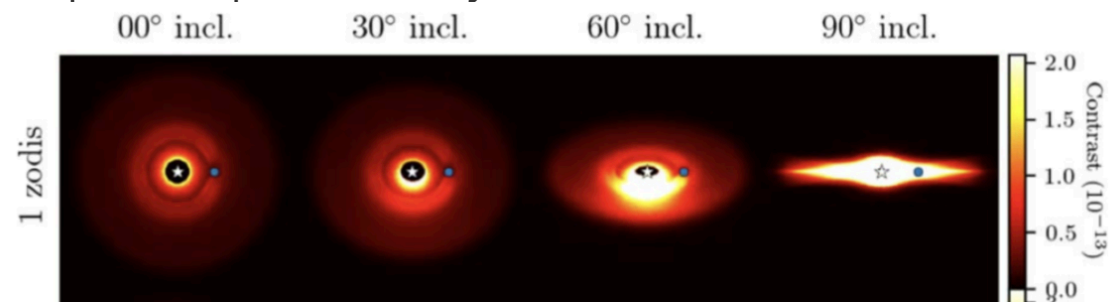
Identifying rocky or water interior by observing volcanic & soluble gases

Vis-NIR imaging spectro-polarimetry (R. Hu et al., SSiC-3)

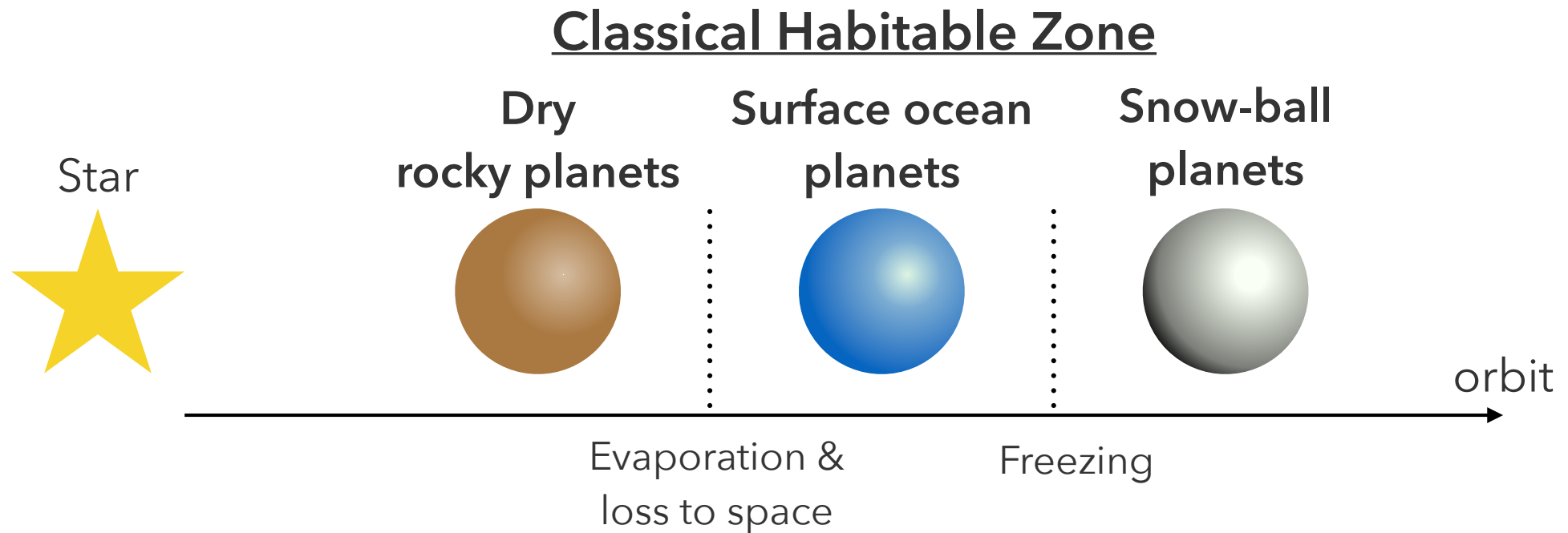
Searching and Characterisation of exozodi

Vis-NIR reflected light spectro-polarimetry (J. H. Dedes et al., SSiC-19)

Identifying
frequency, (sub)structure,
mass, composition
& whether they hide planets



How diverse are **water-environment**?



(It is primarily **defined by stellar irradiation** with 1D Sim., Kasting et al. 1993, Kopparapu et al. 2013)

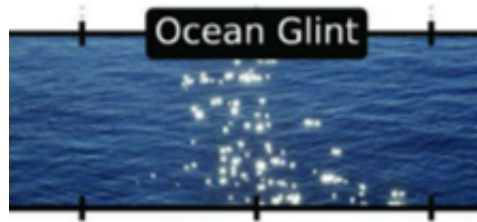
Recent climate models have shown that **the habitable zone also depends on planetary properties, such as atmospheric composition, clouds, rotation, land fraction and water amount** (e.g., Abe et al. 2011; Pierrehumbert & Gaidos 2011; Leconte et al. 2013; Yang et al. 2013; Kodama et al. 2018)

Planets may have sub-surface ocean environments like Europa/Enceladus

How diverse are **water-environment**?

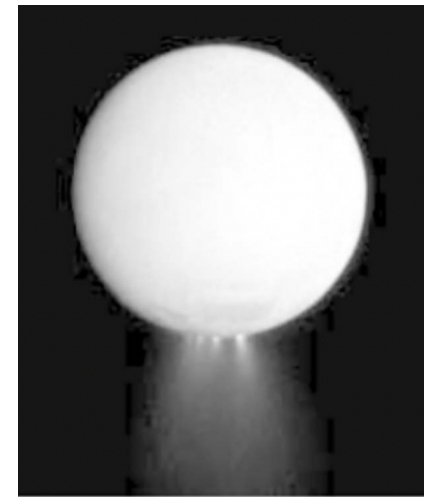
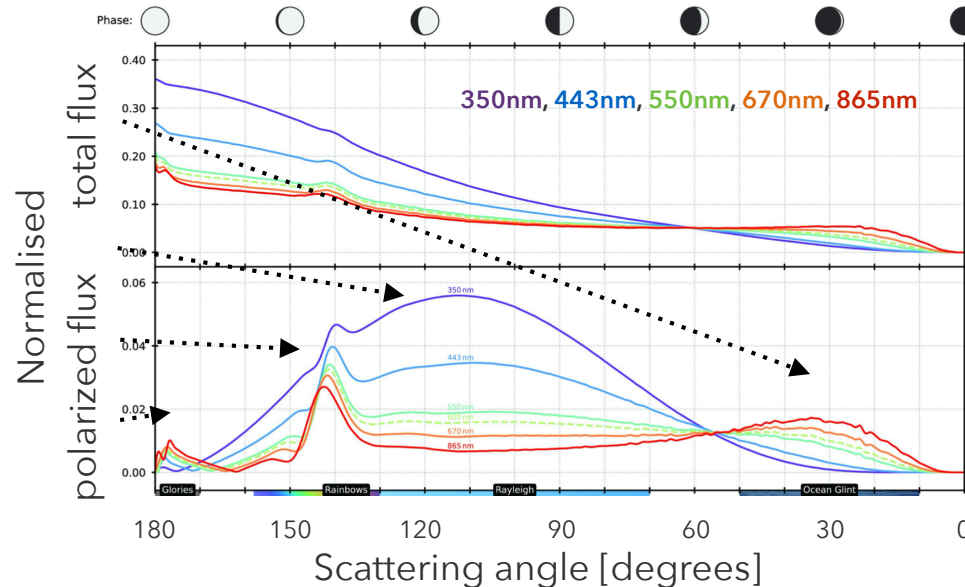
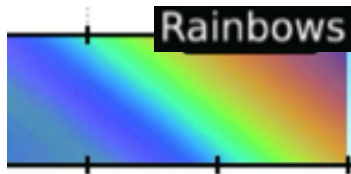
Detecting surface ocean

Vis imaging spectro-polarimetry (J. Lustig-Yaeger et al., SSiC-4)



Scattered light from partially cloudy & ocean planets

Rayleigh scattering



Plume of Enceladus
(NASA/JPL-Caltech/SSI)

Detecting Geyser-like Plume from ice-covered sub-surface ocean

Vis-NIR imaging spectroscopy (L. Quick et al., SSiC-17)

Detecting and Characterizing Venus Analogs (focusing on Sulfur-haze)

UV-NIR transit & imaging spectro-polarimetry (S. R. Kane et al., SSiC-18)

Identifying water abundance correlation with the presence of outer Giants

Vis-NIR imaging spectroscopy (Y. Hasegawa et al., SSiC-2)

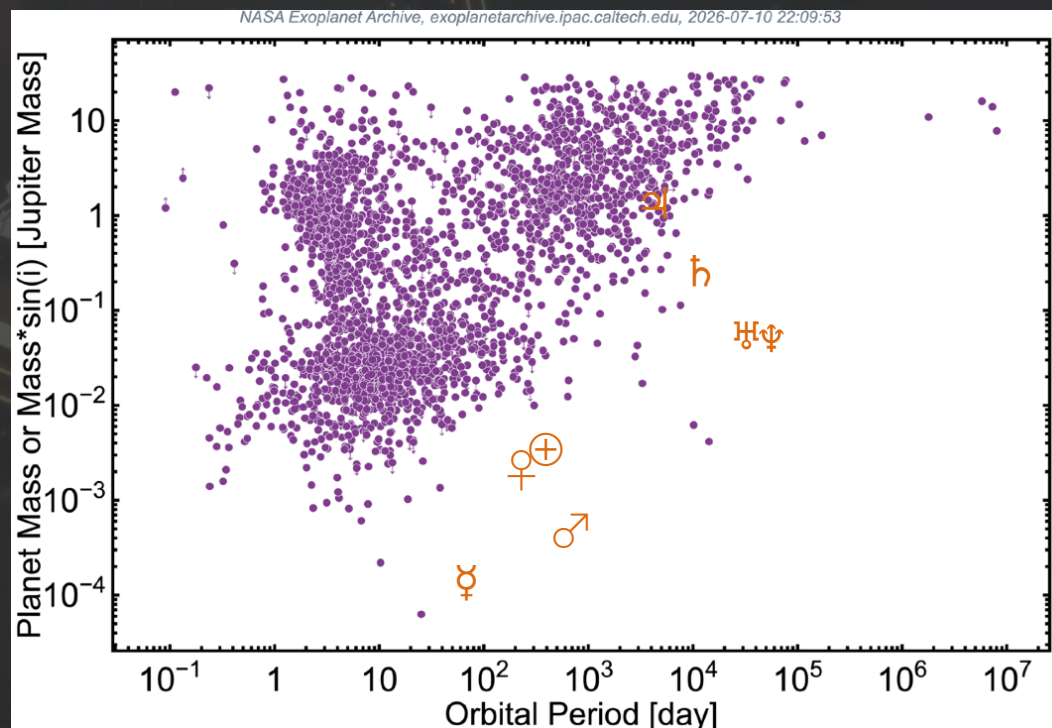
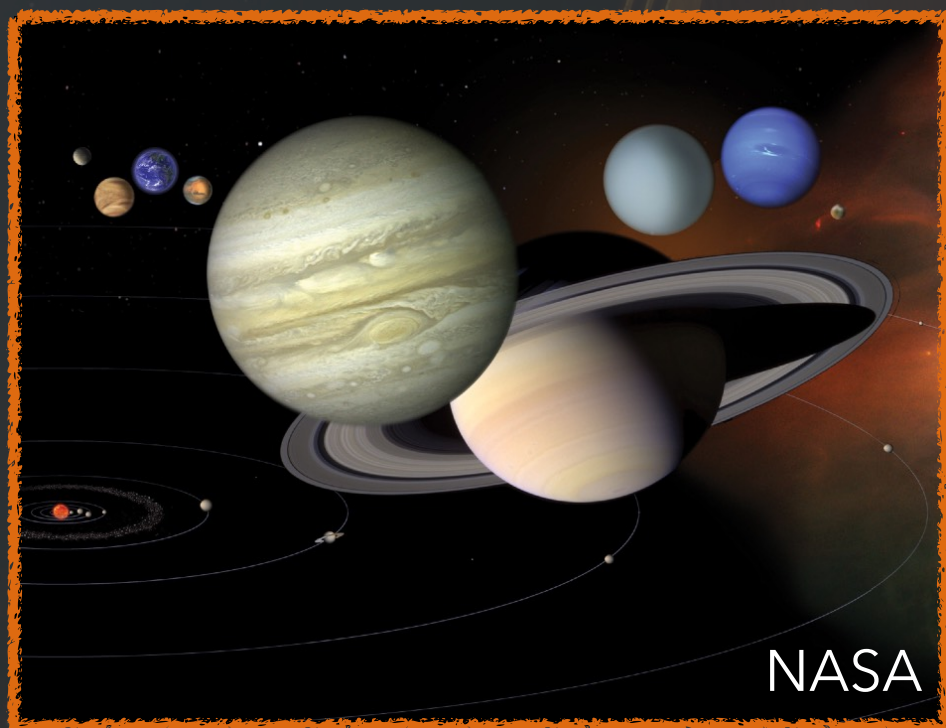
Summary

HWO will observe numerous planetary systems, placing
Solar Systems in the broader context

How do planetary systems **form** and **evolve**?

How **diverse** are composition/systems & **water-environment**?

See SSiC-6, 34, 14, 24, 26, 3, 15, 16, 19, 2, 4, 17, 18 for the detail
at HWO25 Proceedings Part I: Community SCDD



Review of Solar System Science Cases in the HWO SCDD

Lead author: Shohei Aoki

Abstract: This presentation reviews the Solar System science cases presented in the Habitable Worlds Observatory Science Case Development Documents, focusing on the “Solar System in Context” theme. The topics include Venus, ocean worlds, giant planets, comets, Solar System origins, debris disks, protoplanets and protoplanetary disks, and planetary defense. The main science goals and observational requirements are summarized to support the development of future HWO science cases by the Japanese community.

HWO Solar System Science Review

Review of 9 Solar system papers from “Solar Systems in Context” at Science Case Development Documents

1. Venus Direct Observation

Izenberg et al. | Venus

Resolved Venus as a nearby analog for hot terrestrial exoplanets and runaway greenhouse states.

2. Ocean World Habitability

Cartwright et al. | Ceres, Europa, Enceladus, Ariel, Triton

UV/VIS IFS to detect geysers and surface-interior exchange relevant to habitability.

3. Particle Precipitation

Chaufray et al. | Giant-planet aurorae: Jupiter, Saturn, Uranus, Neptune

UV aurorae reveal precipitation, heating, chemistry, and dynamics in giant-planet atmospheres.

4. Giant Planets

Fletcher et al. | Jupiter, Saturn, Uranus, Neptune

UV-visible observations of atmospheres, aerosols, airglow, and aurorae as exoplanet analogs.

5. Amino Acids in Comets

Gomez de Castro & de Isidro-Gomez | Comets within ~1 AU of Earth

UV spectropolarimetry could remotely detect alanine and prebiotic chirality in comets.

6. Solar System Origins

Mandt et al. | Comets, asteroids, TNOs, centaurs, interstellar objects

Small-body composition and isotopes to reconstruct volatile delivery and giant-planet migration.

7. Debris Disks

Rebollido et al. | Debris disks

Resolve inner debris disks to infer dust properties, architecture, and hidden rocky planets.

8. Protoplanets and Disks

Ren | Protoplanets and protoplanetary disks

High-contrast imaging/spectroscopy to expand the sample of directly detected forming planets.

9. Planetary Defense

Dotson et al. | Potentially hazardous asteroids and comets

Extend astrometric arcs and constrain composition when objects become faint or enter daytime sky.

Venus Direct Observation with the Habitable World Observatory

Noam R. Izenberg, Tyler Robinson, Courtney Dressing, et al.

Science goal

Use Venus as a **directly resolvable analog of hot rocky exoplanets and post-runaway greenhouse worlds**

Science objectives

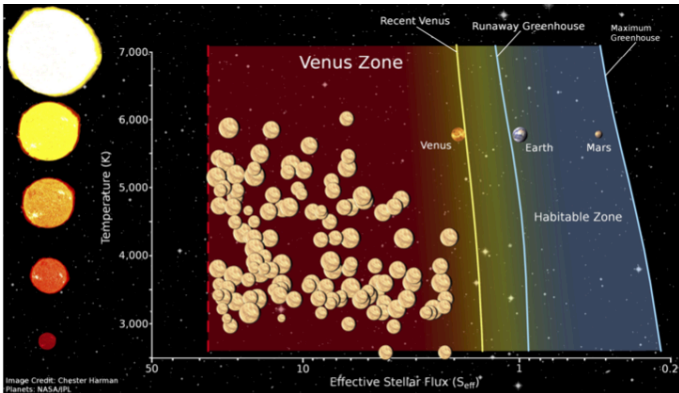
- Constrain **surface composition** through nightside emission in near-IR atmospheric windows.
- Constrain **atmospheric escape** through exospheric UV emissions.
- Characterize **clouds, hazes, aerosols, unknown UV absorber**, and **radiative balance**.
- Search for time-variable atmospheric signatures of **volcanic outgassing**.

Measurement objectives / instrument

Spatially resolved **UV-VIS-NIR imaging** and **spectroscopy** of the Venus dayside and nightside, repeated over hours to days.

Requires **bright-target handling** and **access to small solar elongations**.

Target: Venus



As of March 2024, there are over 330 potential Venus-like worlds

Table 2: Capabilities and requirements for direct observation of Venus.

Capability or Requirement	Necessary	Justification	Comments
UV observations (0.2–0.4 μm)	Yes	Cloud Variation, UV absorber.	0.22–0.32 μm (S Gases) 0.3–0.4 μm (UV Absorber) 0.1–0.2 μm (Lyman alpha)
Long wavelength observations ($> 1.5 \mu\text{m}$)	No	Near IR is most useful. Longer IR has cloud mapping/tracking utility.	Thermal challenges are great enough without going far into the IR.
Timing of observations in different bands	Yes	Cloud variation over time is important.	Hours-to-days observation periods, or return observations over a 4-day period for superrotation.
High spatial resolution	Yes	Resolving Venus cloud patterns and changes from Earth L2.	1000+ pixels across the planet minimum.
High spectral resolution	No R = 100–200 is sufficient	Creating Venus analogs for exoVenus spectra.	Comparable to exoplanet observations.
Large field of view	Moderate	Venus is 10–66'' seen from Earth.	Want to capture full disk around quadrature $\sim 30\text{--}40''$.
Large field of regard	Yes	FoR must be large enough to include Venus around quadrature.	FoR defined by Sun's exclusion zone.
Rapid response	No	Venus observations should be planned.	Rapid response in this case means being able to track Venus's motion across the sky. Venus will likely be among the fastest targets for HWO.

Assessing Ocean World Habitability with HWO

R. J. Cartwright, L. C. Quick, M. Neveu, et al.

Science goal

Determine whether large icy bodies and moons harbor **habitable interior environments**.

Science objectives

- Detect/monitor **geysers** and **transient exospheres** by measuring emission lines of H, C, O, Na, Mg, S, Cl, K, and Ca.
- Determine **surface composition** by mapping H₂O ice, trapped volatiles and ices (such as H₂O₂, O₂, and O₃) and irradiated organic/ carbonaceous residues.

Measurement objectives / instrument

UV/VIS IFS (+VNIR) : 90-800 nm; R~3,000-5,000; <=0.03 arcsec with 3"x3" FOV. Needs long-term monitoring (complementary with missions such as Europa-clipper/Juice).

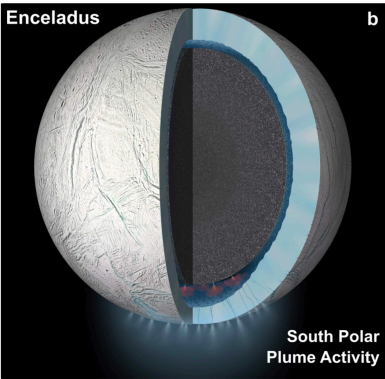


Table 1: Physical parameters of ocean worlds required to address the scientific objectives.

Observation Requirement	State of the Art from Existing Data	Incremental Progress (Enhancing)	Substantial Progress (Enabling)	Major Progress (Breakthrough)
Geysers activity and composition: Searches, measurements, and monitoring	JWST and Cassini measured H ₂ O vapor at Enceladus; HST detected O emission at Europa; Voyager 2 imaged geysers at Triton	Determine if Enceladus geysers change over time; confirm Europa geysers; measure the composition of Triton's geysers	Measure non-H ₂ O gases in Enceladus geysers (CO ₂ , NH ₃ , H ₂ , etc); Determine Europa's geysers composition and eruption cadence; detect geysers elsewhere	Define the spectrum and sources of geysers activity across the Solar System (spatial distribution, temporal variation, composition)
Surface composition: Identify and measure ocean-derived components	Distribution of NaCl and association with young geologic terrains on Europa; detection of NH ₄ and carbonates on Ceres	Detection and measurement of salts and other ocean-derived products on other icy bodies	Determine which specific salts (carbonates, sulfates, chlorides, etc.) are present; infer ocean conditions and geochemistry (pH, etc.)	Confirm linkage between astrobiologically-relevant components (organics, phosphates, etc) and geologic conduits to subsurface oceans
Exosphere composition: Identify, measure ocean-derived components	Detection of Na and K in Europa's exosphere, H ₂ O vapor at Enceladus; CO ₂ gas at Ganymede and Callisto; N ₂ at Triton	Detection of ions, and molecular gases at the Uranian moons and other icy bodies	Long-term monitoring of exospheres and mapping of gas distributions to investigate volatile cycling	Ascertain composition, sources, and sinks of exospheric species at ocean worlds across the Solar System

Target: Ceres, Europa, Enceladus, Ariel, Triton

Atmospheric Effects of Energetic Particle Precipitations on Giant Planets with HWO

J-Y. Chaufray, W. Dunn, L. N. Fletcher, et al.

Science goal

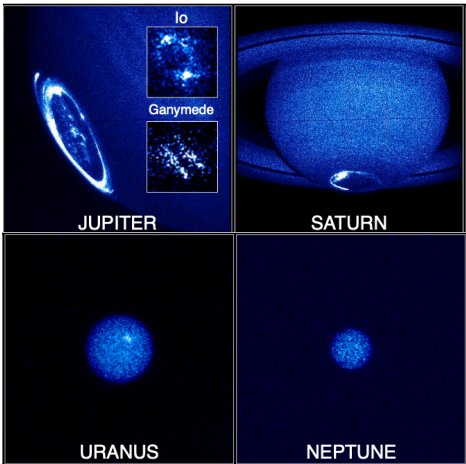
Understand **how energetic particle precipitation modifies giant-planet atmospheres**, particularly at **Uranus** and **Neptune**.

Science objectives

- Determine **precipitating particle energy and flux**.
- Determine **impacts on atmospheric composition, heating, dynamics**.

Measurement objectives / instrument

UV imaging/spectroscopy of H and H₂ auroral emissions
Propose **high spectral resolution** (<20 mÅ) at 110-200 nm for resolving different H₂ emission bands and their line shapes to investigate temperature and wind (+ broader UV-visible coverage for hydrocarbons)



UV auroral emissions from giant planets are produced by extra-atmospheric energetic particles interacting with an atmosphere

Table 1: Performance Goals				
Physical Parameter	State of the Art	Incremental Progress	Substantial Progress	Major Progress
Electron energy	Juno, Cassini, HST, ...	Color ratio	Observations of numerous individual H ₂ rotational lines	Measurements of the spectral linewidth of the H ₂ rotational lines
Atmospheric Composition	Juno, Cassini, HST, JWST, ...	Reflectance between 160–500 nm with a spectral resolution of 0.2 nm	Observations of the individual absorption lines of hydrocarbon species	Observations of both brightness and polarization at spectral resolution of ~0.002 nm
Temperature (~10 ⁻⁵ to 10 ⁻⁸ bar)	Juno, Cassini, JWST, ESO-VLT, ...	Reflectance between 160–500 nm with a spectral resolution of 0.2 nm	Observations of numerous individual H ₂ rotational lines	Measurements of the spectral linewidth of the H ₂ rotational lines

Target: Giant-planet aurorae: Jupiter, Saturn, Uranus, Neptune

Exploring **Solar System Giant Planets** with the Habitable Worlds Observatory

Leigh N. Fletcher, Amy Simon, Michael H. Wong, et al.

Science goal

Use the four Solar System giant planets as laboratories to understand **atmospheric dynamics, chemistry, cloud formation, energy transport, and coupling to magnetospheric and solar-wind plasmas**, providing ground truth for giant exoplanets and brown dwarfs.

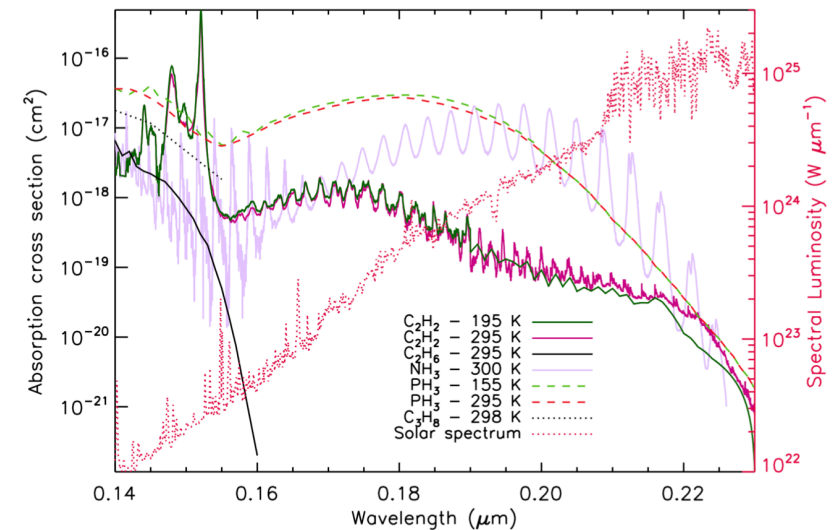
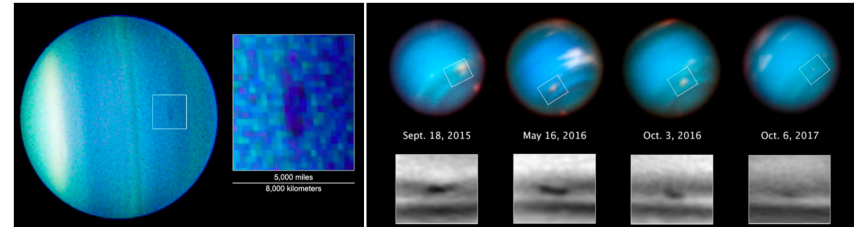
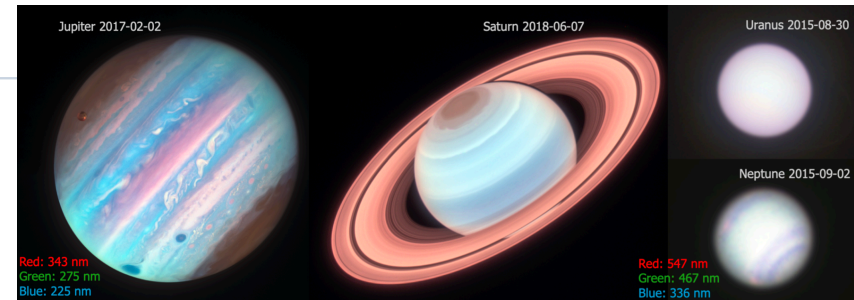
Science objectives

- Track **atmospheric dynamics** and **variability**, including winds, storms, vortices, waves, impacts, and aurorae, through time-resolved narrow-band imaging.
- Characterize **clouds** and **aerosols**, and map **tropospheric and stratospheric composition** (NH_3 , PH_3 , CH_4 , C_2H_6 , C_2H_2 , C_3H_8 , etc) with spatially resolved spectroscopy.

Measurement objectives / instrument

Time-resolved narrow-band imaging and spatially resolved UV-visible mapping spectroscopy from 80 to 900 nm.

Target: Jupiter, Saturn, Uranus, Neptune



Detection of Amino Acids in Comets

Ana I. Gomez de Castro and Ana I. de Isidro-Gomez

Science goal

Test whether **amino acids** and their **left-right molecular asymmetry** can be detected remotely in cometary material.

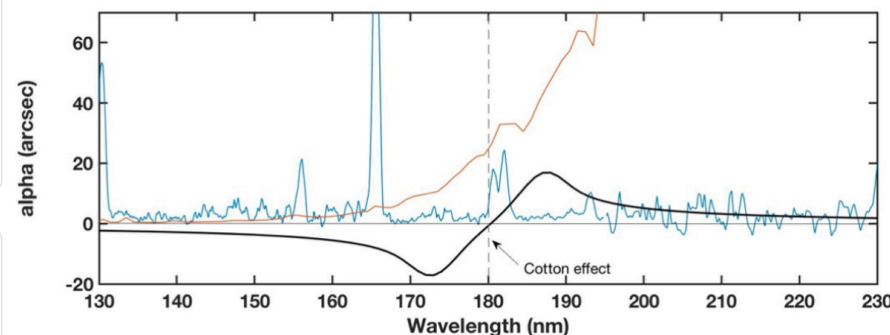
Science objectives

Detect **alanine**, the second most abundant amino acid, through the wavelength-dependent rotation of linear **UV polarization** produced by an imbalance between its left and right handed forms.

Measurement objectives / instrument

Low-dispersion **UV spectropolarimetry** over 140-220 nm.

Target: Comets within ~1 AU of Earth



Predicted wavelength-dependent rotation of the linear-polarization position angle caused by alanine in comet 67P, assuming 68 ppb alanine and a 10% enantiomeric excess (Black)

The direction of polarization rotation indicates whether the left-handed or right-handed form of alanine is more abundant.

Solar System Origins

Kathy E. Mandt, John Noonan, Darryl Seligman, et al.

Science goal

Constrain the **formation timing, locations, and migration of the giant planets**, and quantify **their effects on Solar System architecture** and volatile delivery to the inner Solar System.

Science objectives

- Measure and compare the compositions of **comets, asteroids, Centaurs, TNOs, interstellar objects, and giant-planet satellites**.
- Connect present-day small-body populations to their formation reservoirs.
- Test models of giant-planet migration and volatile delivery.

Measurement objectives / instrument

- Measure atomic and molecular emissions in active comae: H, C, O, S, CS, C₂, OH, S₂, constraining H₂O, CO, CO₂, and CS/CS₂.
- Characterize surface colors, ices, volatiles, and tenuous atmospheres of asteroids, Centaurs, TNOs, interstellar objects, and giant-planet satellites.
- **Requires high-sensitivity UV spectroscopy at 120-330 nm and vis imaging.**

Target: Comets, asteroids, TNOs, centaurs, interstellar objects

Table 1: Observational requirements for investigating Solar System Origins

Capability or Requirement	Necessary	Desired	Justification	Comments
UV observations	1200–2100 Å, 2500–3300 Å	1200–3300 Å	Atomic and molecular emissions of common cometary and atmospheric molecules from fluorescence, prompt emission, and dissociative electron impact	This bandpass allows characterization of column densities of H, C, O, S, CS, C ₂ , OH, and S ₂ as well as their typical parents H ₂ O, CO, CO ₂ , CS/CS ₂
Long wavelength observations (>1.5 microns)	2.5–4.8 μm	1.5–4.8 μm	H ₂ O emissions at 2.7 μm, CO ₂ and CO lines in the 4.2–4.8 μm range	H ₂ O emission and absorption bands present between 1.5 and 3.3 μm, 3 μm absorption feature for small bodies, CO ₂ and CO emissions between 4.2 and 4.8 μm JWST-comparable (legacy instrumentation)
High spatial resolution	0.1''/pix in VIS-IR ~1''×1'' aperture in UV (depends on spectrometer style)	The same	Nucleus resolution, fragment/moon/ring searches	JWST-comparable (legacy instrumentation)
High spectral resolution	UV: <3 Å FWHM at 1300–1900 Å (resolution of atomic transitions)	UV: <1 Å FWHM	UV: Ratio of atomic line transitions offer insight into characteristic temperatures of product species, help characterize interplay between incident radiation/energetic particles and neutrals.	Resolution of atomic and molecular transitions that are currently only available from lab data (and thus biased towards “non-lethal” chemicals)
Rapid response	Yes	Yes	Interstellar objects (ISO) detected by LSST will have observable apparitions typically < 3 months. A subset of LSST detected long period comets would require rapid response to fully characterize the pre- and post- perihelia behavior.	The majority of the observations discussed will not require rapid response, but newly discovered comets and interstellar objects (ISOs) will be very time sensitive and require rapid response.
Object tracking for solar system objects	150 mas/s (twice JWST capabilities)	500 mas/s (capable of tracking ‘Oumuamua-like interstellar object (ISO) at 0.16 AU close approach)	‘Oumuamua-like: 1800 arcsec/hr at closest approach (Δ=0.16 AU), Borisov-like: 120 arcsecond/hr at closest approach (Δ=2 AU)	ISOs will provide the most extreme use cases, but also highly compelling, for HWO

Debris Disks and their Properties with the Habitable Worlds Observatory

Isabel Rebollido, Yasuhiro Hasegawa, Meredith MacGregor, et al.

Science goal

Characterize the **structure** and **dust properties** of **debris disks**, especially in their **inner terrestrial-planet regions**, to trace planet formation and search for forming rocky planets using HWO's **improved spatial resolution**, and **inner working angle**.

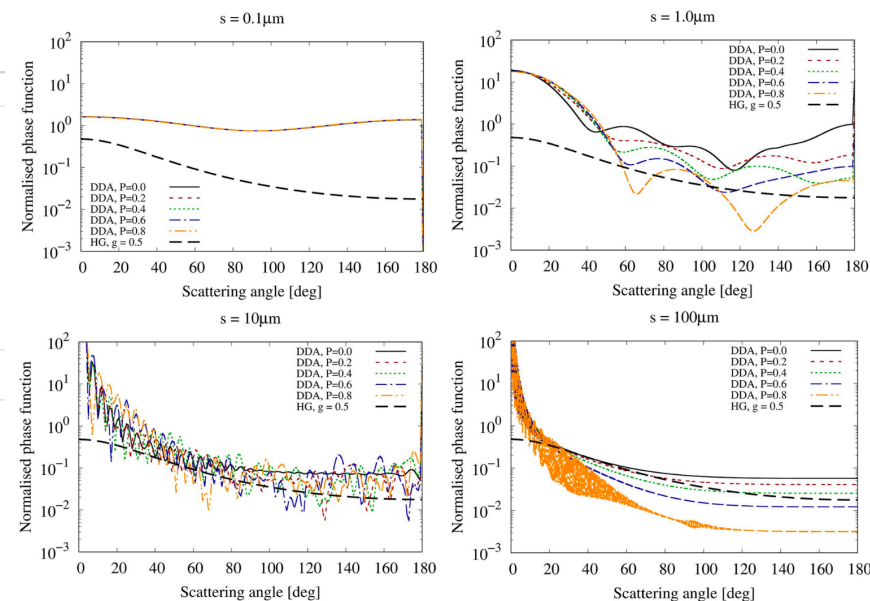
Science objectives

- Constrain **dust size distributions** and **composition** in fainter debris disks using scattering phase functions.
- Reveal fine **disk structures** with improved coronagraphy to understand the dynamics of planetary systems.
- Characterize recently discovered debris-disk **gas** and exocometary volatile delivery through high-resolution UV spectroscopy of CO, C I etc

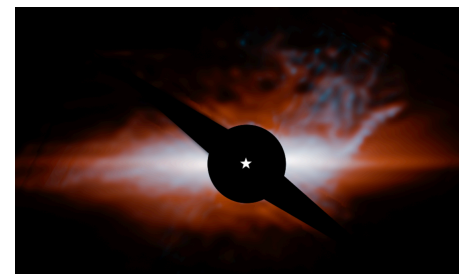
Measurement objectives / instrument

Multiwavelength coronagraphic imaging (and polarimetry) to measure dust scattering properties with $\sim 0.03''$ and a small IWA to resolve inner-disk structures; and high-resolution UV IFS ($R > 80,000$, $1400\text{--}1600\text{ \AA}$) to measure CO, C I, and other gas species.

Target: Debris disks



Phase function can distinguish size and property. HWO's higher sensitivity and spatial resolution will allow scattering phase functions to be measured for fainter and more compact disks, over a wider range of disk locations and scattering angles.



The debris disks around Beta Pictoris seen with JWST/MIRI. HWO aims for $\sim 0.03''$ spatial resolution, together with a smaller IWA and higher contrast than current facilities, enabling access to sub-au scales and terrestrial-planet regions in nearby debris disks.

Studying **Protoplanets** and Protoplanetary Disks with HWO

Bin B. Ren

Science goal

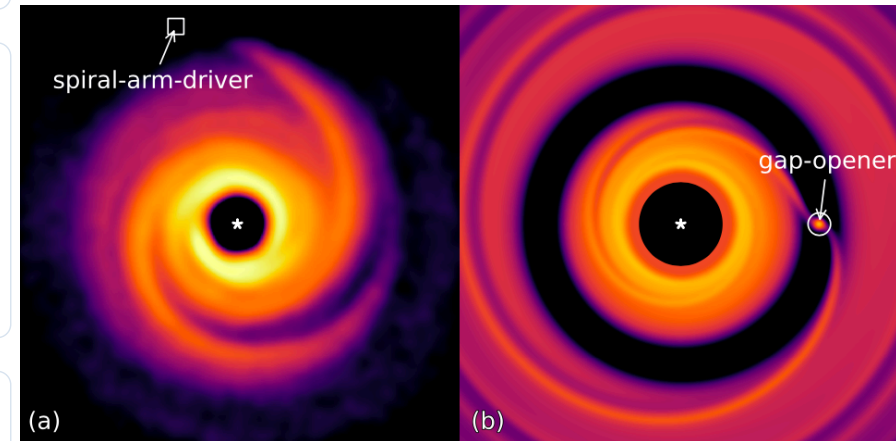
Directly detect and **characterize protoplanets** to understand how planetary systems form and evolve. HWO's **high-contrast coronagraphy** and **high spatial resolution** could expand the confirmed sample from **only three protoplanets** to **potentially ~200**.

Science objectives

- Characterize **protoplanet accretion** signatures and variability from NUV to NIR.
- Trace **young planets within disks** and **planet-disk interactions** using **polarized light imaging**, which helps separate planet light from polarized disk-scattered light.
- Determine the **mineral composition of dust** in protoplanetary disks and around **individual protoplanets** through spectroscopy and spectropolarimetry.

Measurement objectives / instrument

- High-contrast coronagraphic imaging with small IWA and ~ 0.1 -au spatial resolution.
- Polarimetry and spectropolarimetry to separate planet light from disk-scattered light and characterize dust properties.
- NUV-NIR spectroscopy, reaching $R \sim 10,000$, to resolve the shapes of emission lines produced by accretion.



Target: Protoplanets and protoplanetary disks

Utilizing Habitable Worlds Observatory for Planetary Defense

Jessie Dotson, Andrew S. Rivkin, Cristina Thomas, et al.

Science goal

Provide **timely, high-significance follow-up information** on the orbits and compositions of **potentially Earth-impacting objects** that are **too faint** or lie in the **daytime sky** for other facilities.

Science objectives

Extend **observational arcs** to **refine impact probabilities earlier**.
Use multiband photometry and lightcurves to constrain composition, density/mass, rotation, and shape.

Measurement objectives / instrument

High-sensitivity astrometry and broadband photometry from L2.
Needs target-of-opportunity response.

Target: Potentially hazardous asteroids and comets

*Evolution probability of 2024 YR4 as simulated on Feb. 5 2025.
Too faint for ground-based facilities after April 2025*

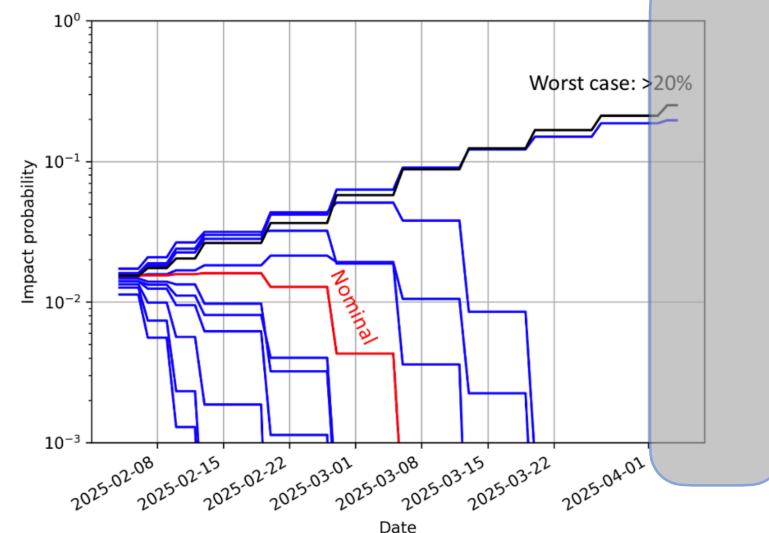


Fig. 1.— Evolution of the impact probability of 2024 YR4 as simulated on February 5, 2025. At that time 2024 YR4 had a 1% chance of impacting Earth in 2032. The lines represent a selection of the Monte Carlo orbital parameters consistent with the state of knowledge on February 5, 2025. Their evolution over time assumes that state of the art (~ 50 mas) ground based astrometry would continue as long as 2024 YR4 was observable with ground telescopes. After April 2025, 2024 YR4 was too faint for ground facilities. An impact of 2024 YR4 was ruled out prior to April 2025 - but it was possible that the impact probability at the end of the apparition would have been 20%. The observable arc of motion was too short to have identified a higher probability of impact. No ground based facilities would have been capable of providing the data required to refine that estimate until 2028. HWO will have the sensitivity to extend the observation period of an object like 2024 YR4 well beyond what is capable from the ground.

Impression from the Review

- Many objects are overlapped with the targets of LAPYUTA UV telescope
→ Needs to make a **strategic plan from LAPYUTA to HWO** for UV solar system observations.
- High-resolution UV spectroscopy for Venus/Mars (for D/H, H₂) and science cases for Mars/Titan/Io are missing in the SCDD.

Efficient NIR Spectroscopy of Habitable Planets: Concept and Technology Validation Plan with Subaru Telescope

Lead author: Olivier Guyon

Abstract:

Direct spectroscopy of habitable exoplanets must overcome low source flux and comparatively higher background, requiring exposure times of weeks for the HWO mission. Spectroscopy in the information-rich NIR regime is particularly challenging, as poorer angular resolution exacerbates background mixing, especially near the coronagraph inner working angle (IWA).

We propose to match the post-coronagraph exoplanet electric field to the input of a single-mode spectrograph using a photonic lantern (PL) positioned on the planet location, and feeding a photonic integrated circuit (PIC). We show that the approach offers an order of magnitude gain in exposure time, and extends exoplanet spectroscopy to the NIR regime by enabling a smaller IWA.

We discuss this approach as a NIR spectroscopy instrument for the HWO mission, and provide an overview of ongoing technology validation activities, including on-sky demonstration of its key elements at the Subaru Telescope.

Science Case Summary:

Extending exoplanet spectroscopy to NIR is critical to characterization of exoplanet atmospheres, including the search for biomarkers on habitable planets. We propose for HWO a NIR spectrograph instrument architecture combining coronagraphy and photonics (single mode fibers) to boost the NIR spectroscopy sensitivity. This solution can enable NIR spectroscopy of habitable exoplanets.

Efficient NIR Spectroscopy of Habitable Planets: Concept & Technology Dev. Plan

Olivier Guyon guyon@naoj.org

Ruslan Belikov, Mike Bottom, Mona ElMorsy, Keigo Enya, Michael Fitzgerald, Simon Gross, Chris Hamner, Elsa Huby, Satoshi Itoh, Nemanja Jovanovic, Sandrine Juillard, Hajime Kawahara, Yoo Jung Kim, Takayuki Kotani, Masayuki Kuzuhara, Sylvestre Lacour, Manon Lallement, Sergio Leon-Saval, Julien Lozi, Jared Males, Guillermo Martin, Taro Matsuo, Naoshi Murakami, Taro Matsuo, Jun Nishikawa, Barnaby Norris, Anusha Pai Asnodkar, Garima Singh, Nour Skaf, Peter Tuthill, Sebastien Vievard

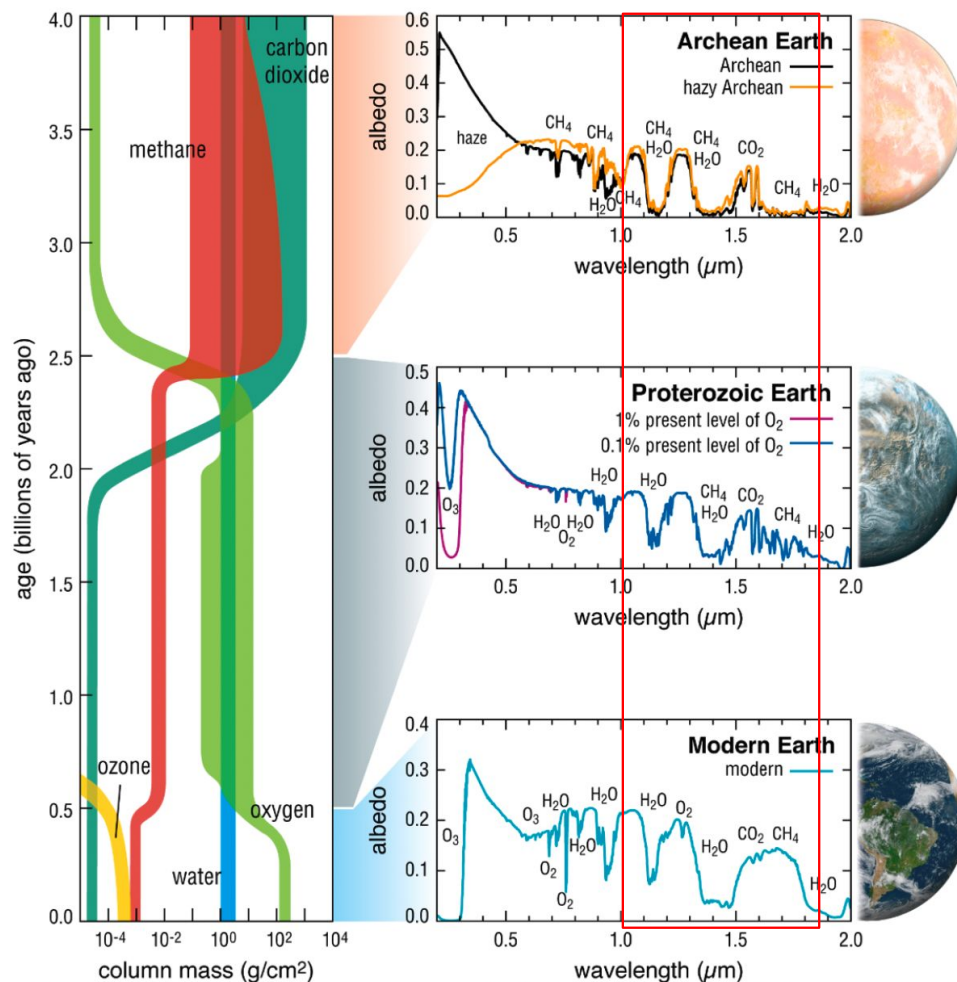


Figure 3.1-6. O₂, O₃, H₂O, CH₄ and CO₂ concentrations over Earth's history, during Archean, Proterozoic, and modern Earth eras. HabEx is required to be able to detect the gaseous byproducts from oxygen-producing synthesizers (all EECs) or methane-producing synthesizers (some EECs), if present at concentration levels similar to Earth over the last 3.5 Gy of its history. This covers part of the Archean Era as well as the full Proterozoic and Modern Eras during which life has been present on Earth. Credit: Britt Griswold, Giada Arney, and Shawn Domagal-Goldman.

Proposed instrument contribution: NIR Coronagraph Optimized for Exo-Earth Spectroscopy

Planet discovered by visible
coronagraph
How to acquire a NIR spectra?

We propose a hybrid coronagraph
+ photonics solution called MEFS
(Matched Electric Field
Spectrograph)

Integrates Japanese expertise in
coronagraph masks (small IWA),
fiber/photonics, NIR spectroscopy

HOW NIR spectroscopy of Hab planets

Challenges

- **Long exposure times** due to faint source and strong background
- **Detector noise** limits achievable spectral resolution
- Working at close IWA ($\sim 2 \lambda/D$) is essential at NIR, but leads to:
 - **distorted PSF**
 - **strong exozodi, stellar leak**
 - need to **track and control wavefront errors**

⚠ **Note:** NIR observations of hab planets will be background-limited due to (exo)zodi, stellar angular size leaks, and residual speckles.

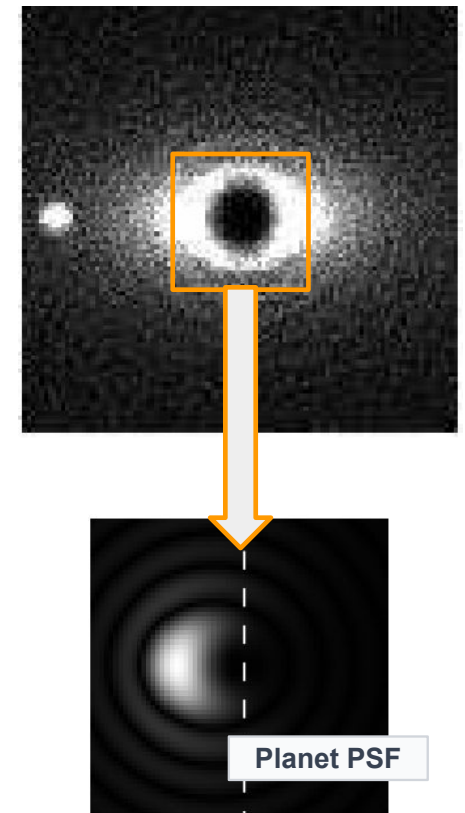
MEFS Solution

How MEFS addresses these challenges:

- **Concentrates** planet light in a single-mode fiber with minimal background and starlight
- Uses **one detector pixel per spectral bin** thanks to single mode fiber spectrograph
- **Tracks and corrects** residual WF errors during long spectroscopy exposure

📍 **Key Assumption:** Planet position must be known in advance.

Inner (habitable) planet is within incoherent light halo

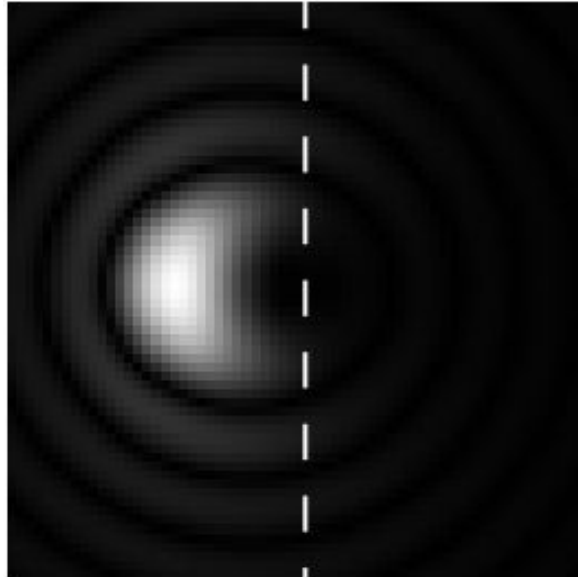


Incoherent (classical) Spectroscopy

“Classical” Incoherent spectroscopy

Sum (in intensity) light over an aperture, then disperse it

Examples: IFS, slit spectrographs, MMF spectrograph



Post-coronagraph PSF at small IWA is distorted

Choosing aperture size (area to integrate) is unhappy tradeoff between planet throughput and background contamination

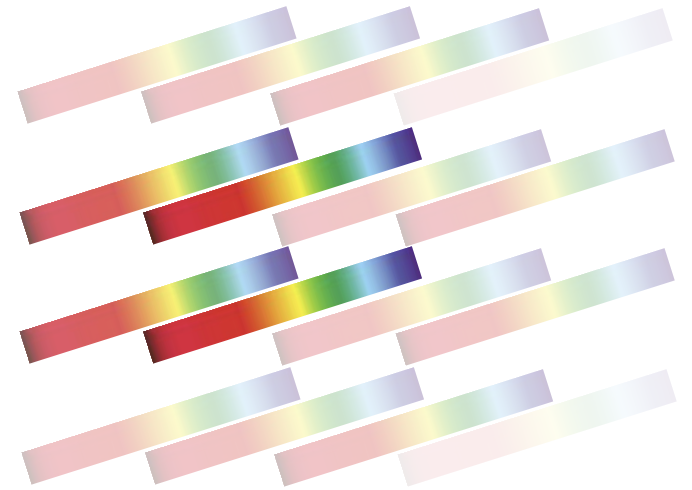
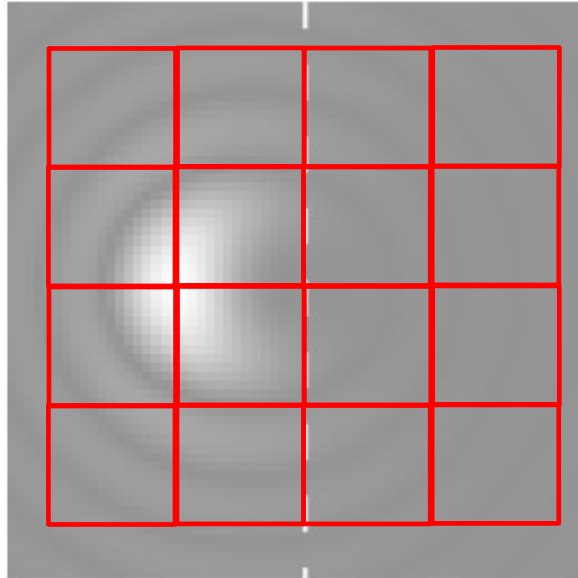


Incoherent (classical) Spectroscopy: IFS

“Classical” Incoherent spectroscopy

Sum (in intensity) light over an aperture, then disperse it

Examples: IFS, slit spectrographs, MMF spectrograph

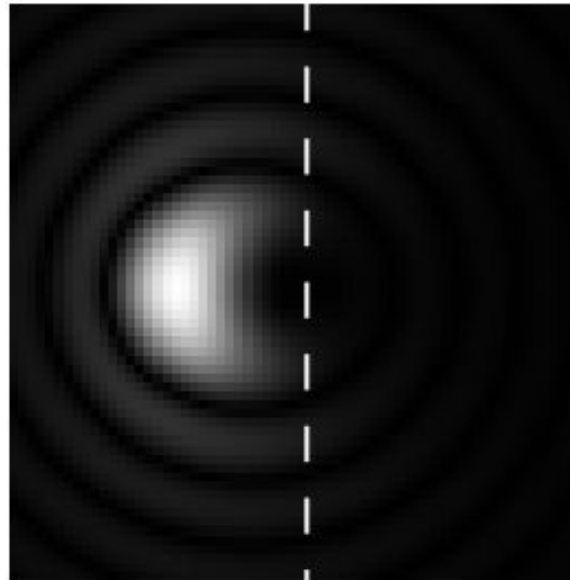
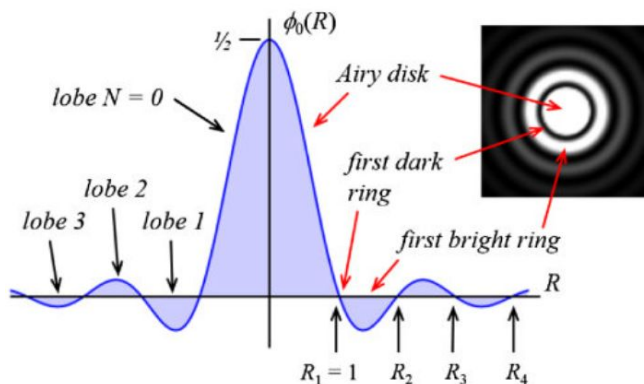


In this example, **most of the planet light is spread over 4x lenslets**. The corresponding spectra (right) will have **significant background light contamination**, and $>\sim 10$ pixels need to be read per spectral bin.

Coherent Spectroscopy (MEFS)

Coherent spectroscopy

Sum in electric field into a SMF, then disperse.



Use **interferometry** to match the complex-valued PSF electric field to the spectrograph mode (SMF).

Coupling is given by **overlap integral between the PSF and MEFS science mode complex amplitudes**

If they match:

- 100% planet throughput
- Minimum theoretical background contribution, equivalent to a $(4/\pi)(\lambda/D)^2$ sky area



Matching the PSF and MEFS science mode requires an actively control photonic device, to be configured for the PSF location and shape.

For an Airy disk, the modal function changes amplitude and sign according to the real-valued Airy function

MEFS offers ~3x~10x gain in exposure time

Exoplanet spectroscopy is in the **background-limited regime** -> we must maximize exoplanet flux ***F_p*** while minimizing background flux ***F_b***: $SNR \sim \sqrt{T} F_p / \sqrt{F_b}$

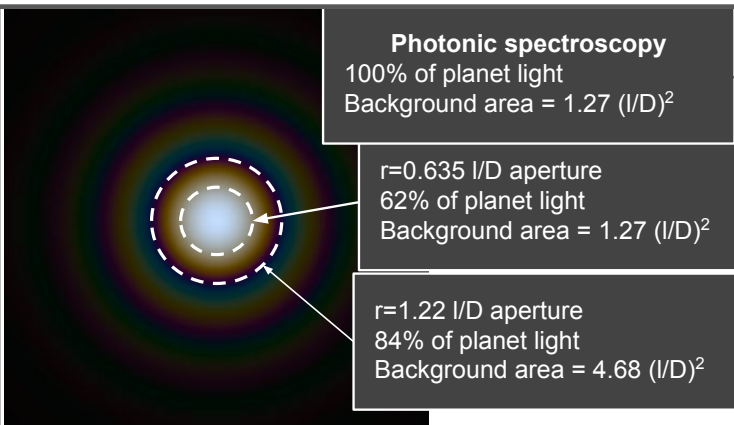
-> exposure time ***T*** required scales as ***F_b/F_p²***

Conventional spectrograph is defined by an aperture radius, within which planet light is collected according to encircled energy and background light is collected according to aperture area.

Photonic Spectrograph couples all planet light into a fiber while collecting the minimum background contribution from $(4/\pi) (\lambda/D)^2$ sky area.

Guyon, O. et al. "Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs" *ApJS* 167 81 (2006)

Martinod, MA., Norris, B., Tuthill, P. et al. "Scalable photonic-based nulling interferometry with the dispersed multi-baseline GLINT instrument" *Nat Commun* 12, 2465 (2021)

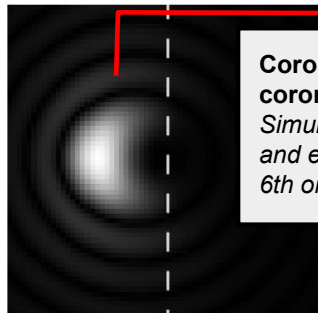


In the most favorable case for classical spectrograph (Airy), MEFS already gives **2.5x gain in etime**

	Fb area [(I/D) ²]	F _p	Relative efficiency F _p ² /F _b
Photonic spectrograph	4/π=1.27	1.0	1.0
Aperture r=0.5 I/D	0.79	0.47	0.36
Aperture r=0.635 I/D	1.27	0.625	0.39
Aperture r=1.22 I/D	4.68	0.84	0.19

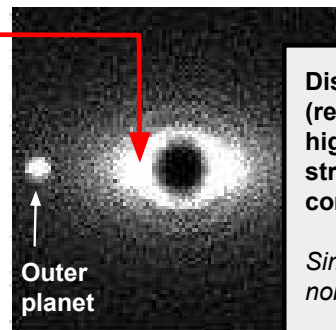
Photonic spectrograph is 2.5x more efficient that an optimally sized aperture feeding a non-photonic spectrograph.

Inner planet



Coronagraphic PSF is distorted by coronagraph near its inner working angle
Simulated planet PSF (noiseless, starlight and exozodi removed) for 2 I/D separation, 6th order optical vortex coronagraph

Aperture required to gather most planet light ~ 5 (I/D)²



Distorted PSF of inner planet (red arrow) is located in high-background area with strong exozodi and starlight components

Simulated exposure with photon noise

Coronagraph case: ~3-10x gain

Strongest gain when planet image distorted

MEFS system approach:

Shifting to a planet-centered Perspective

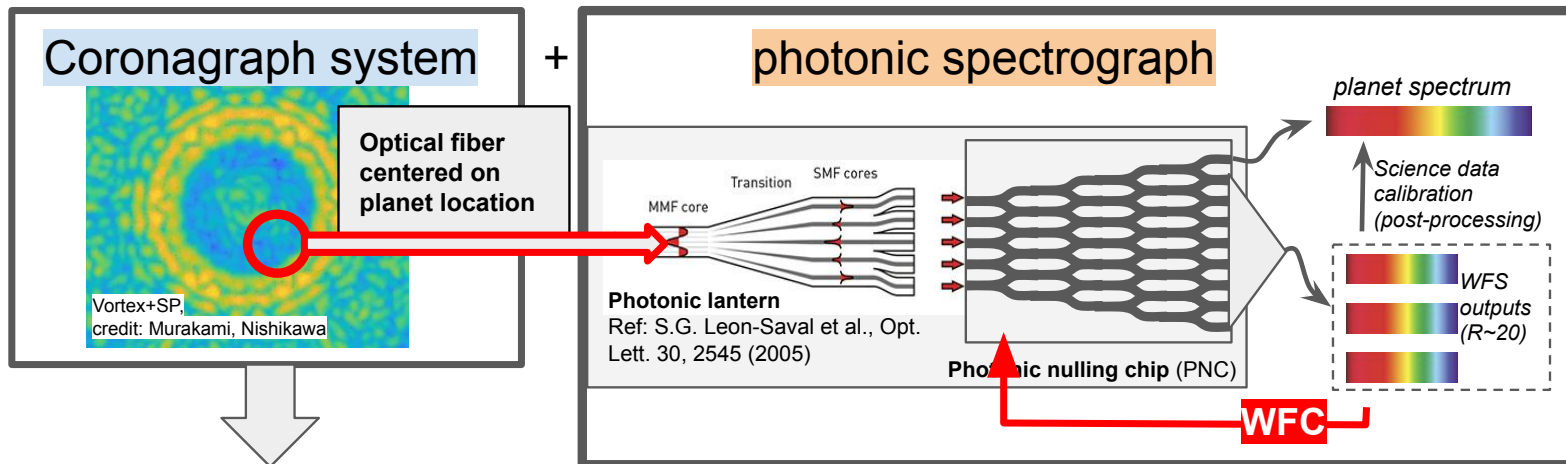
1. First, **remove most of the starlight** to make our job easier, using an **efficient small-IWA** coronagraph that preserves the planet light
2. Next, design an optical system that **concentrates all of the planet light in a single coherent waveguide**. This will have minimum background coupling.
3. Last, tweak the system to induce **destructive interference of residual starlight** within the planet waveguide. This tweak should induce minimum loss in efficiency

← **Realized with photonics**

Main differences with conventional HCI + IES:

- Higher efficiency, smaller IWA coronagraph, thanks to 2nd stage nulling
- No dark hole (very costly as many modes need to be controlled). Instead, control **only** the planet mode.
- Low background mixing, one pixel per spectral bin

MEFS system architecture



Creates a **high-contrast image** where most of the starlight is removed.

Optimized to preserve planet light:
small IWA and broadband performance
Does not need to achieve very deep contrast (~1e-7 OK)

Four fundamental advantages :

1. **Efficiency** gain: optimal separation of exoplanet light from background
2. **Optimal pixel use**: 1 pix per spectral element
3. **Starlight suppression** (2nd stage) with photonic nulling chip
4. **Self-calibrating** thanks to pure modal decomposition (can separate WF error from true signal)

Optimized for high-contrast **spectroscopy of planets with known position**; not optimal for search of new planets.

Uses 2nd stage (after coronagraph) optical fiber and photonic technologies to optimize sensitivity.

Key challenges: Throughput, Chromaticity

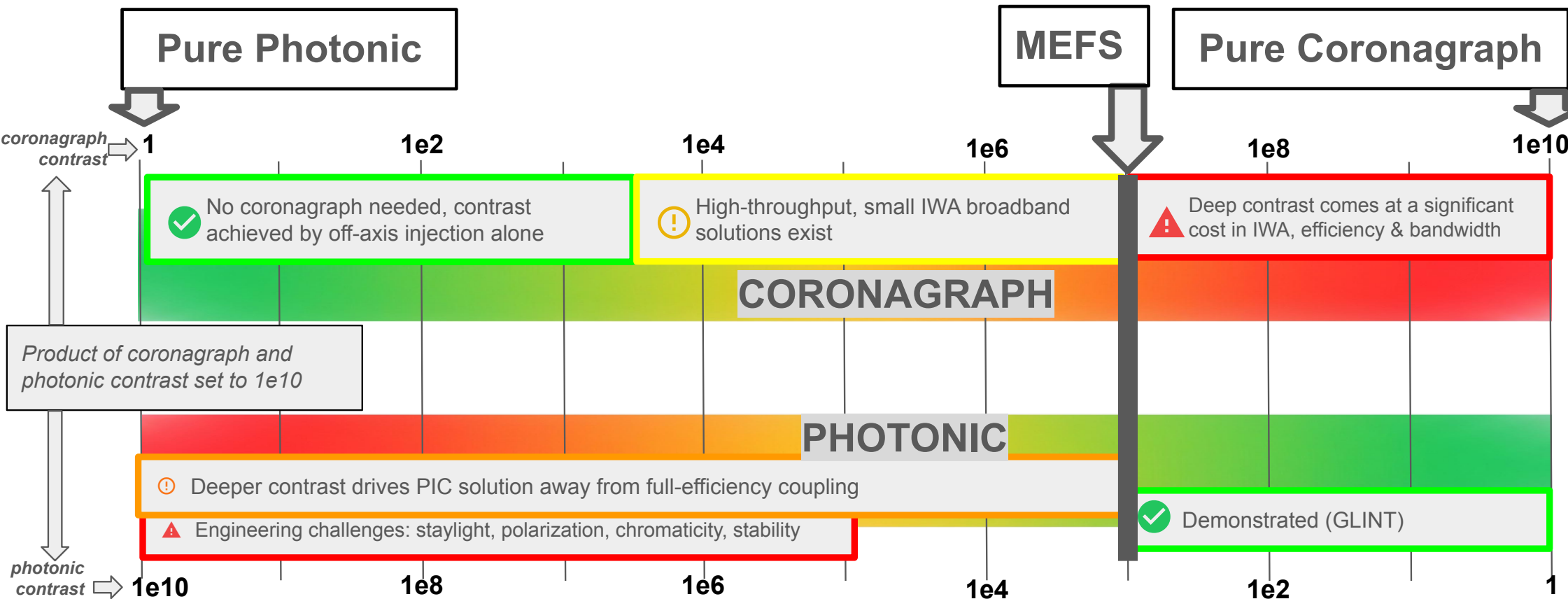
Starlight Suppression is shared between coronagraph & photonic

HWO goal contrast ($\sim 1e10$) to be achieved by coronagraph $\sim 1e7$ and photonic nulling $\sim 1e3$

This tradeoff is driven by **engineering challenges and technology maturity**

CORONAGRAPH: $1e7$ contrast allows for small-IWA, high throughput broadband

PHOTONIC: $1e3$ null accessible in broadband ($\sim 10\%$) light



Co-optimizing Coronagraph & Photonics

Coronagraph must deliver $\sim 1e7$ contrast in a small region around the known planet location

- > Can be optimized for small IWA and high throughput
- > Can operate in broadband light

As separate components, the coronagraph and PNC are within current engineering capabilities

Photonic nulling chip (PNC) must deliver $\sim 1e3$ null

- Small (~ 10) number of channels thanks to small entrance FOV (~ 2 I/D diameter)
- Total amount of starlight in the chip is small, so straylight can be managed.
- PNC is compact, so wavelength multiplexing possible (for example, one PNC per $\sim 5\%$ spectral band x12 for 60% band).

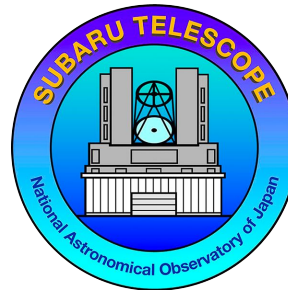
Coronagraph and PNC should be co-optimized as a system.

Future development for the concept will focus on system-level aspects, including:

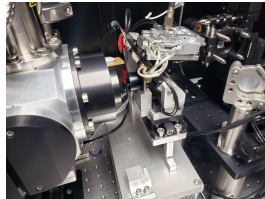
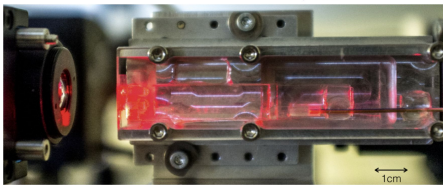
- **WFS/C using bright PNC outputs**
- **Self-calibration of residual starlight in null output**
- **Starlight suppression optimization between coronagraph and PNC**
- **Broadband operation (single broadband coronagraph feeding subbands PNCs)**

MEFS integration @ Subaru / SCExAO for HWO tech development

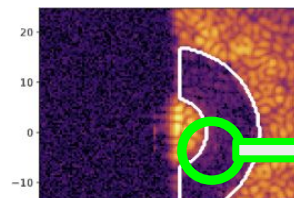
Key institutions leading system-level implementation at Subaru:



Implementation on Subaru/SCEXAO instrument



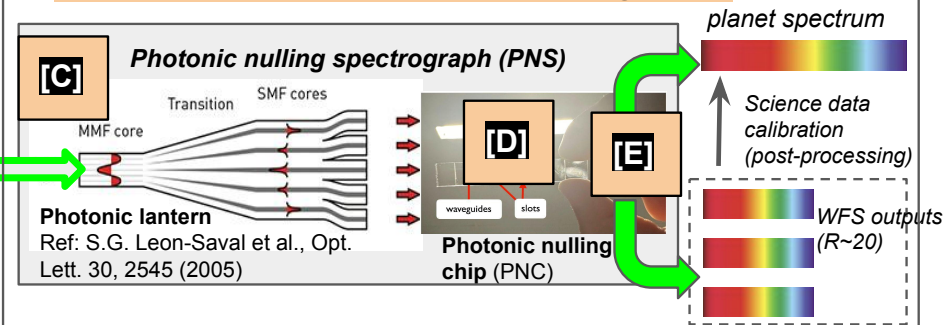
Coronagraph system



Optical fiber
centered on
planet location

“Conventional” high contrast
imaging system: [A] wavefront
control and coronagraph + [B]
imaging/IFS science detector

exoplanet photonic spectrograph



highly-efficient photonic spectrograph ([C], [D], [E]).

5 KEY STEPS TO EXOPLANET SPECTROSCOPY

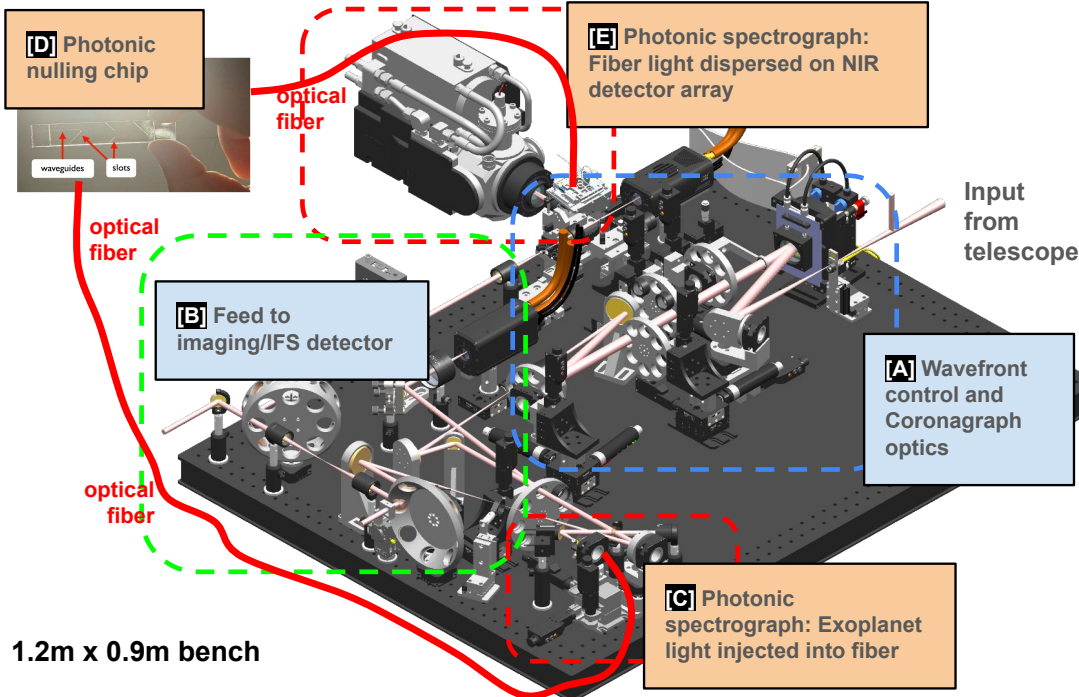
[A] Coronagraph system removes most of the starlight from the image

[B] Camera or Integral Field Spectrograph for (spectro-) imaging of planetary system

[C] A small field, centered on the exoplanet, is injected in a photonic lantern

[D] The output modes are processed by a photonic nulling chip that separates planet light from residual starlight

[E] Planet light is sent to a science spectrograph. Starlight used for tracking and controlling the residual starlight

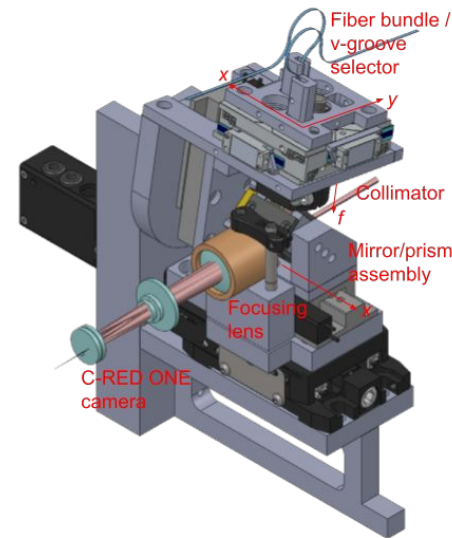
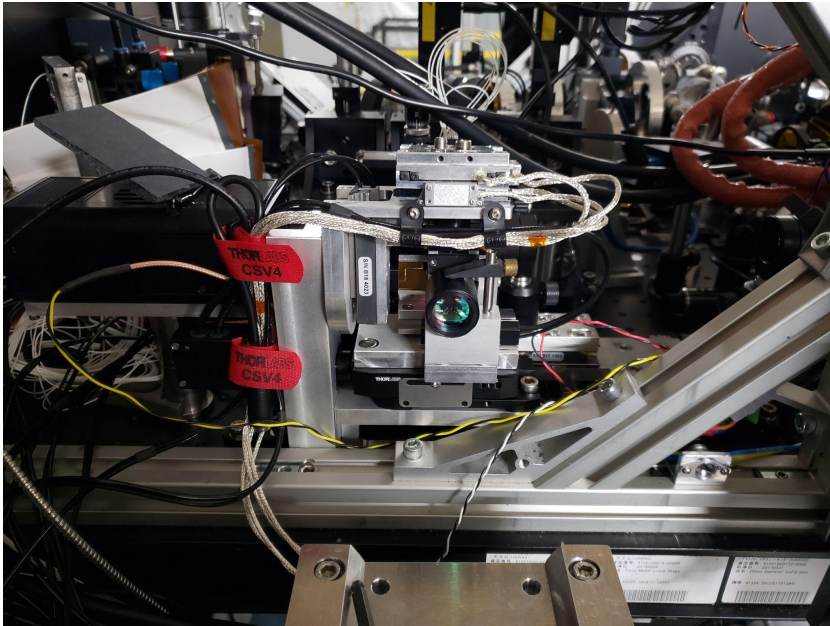


Ahn, K., Guyon, O., Lozi, J. et al. “SCEXAO: a testbed for developing high-contrast imaging technologies for ELTs” SPIE vol 11823 (2021)

NIR Photonic Spectrograph

Funding by NAOJ/TMT dev. fund, JSPS/GLINT
Design+realization: J. Lozi

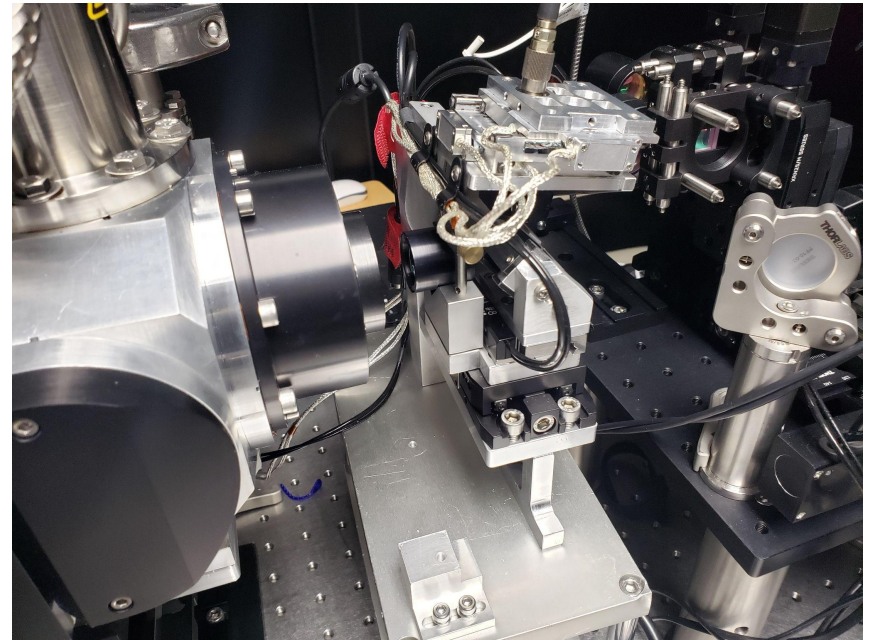
Looking into spectrograph optics from
the camera location (camera removed)



Fiber input to the spectrograph
at the top of the unit. Multiple
inputs selectable thanks to x/y
translation platform

Mirror/prism to select between
imaging (no dispersion) and
spectroscopy

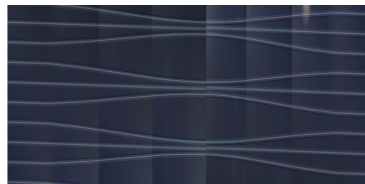
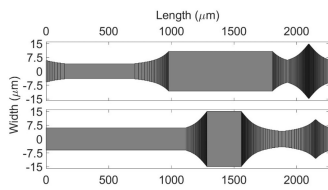
Side view, Camera on the left



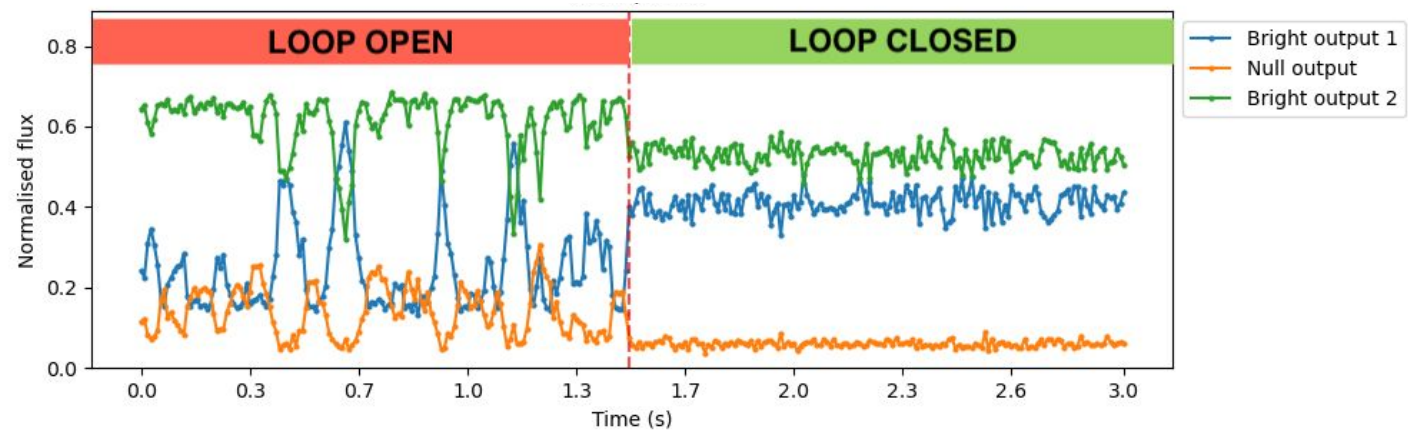
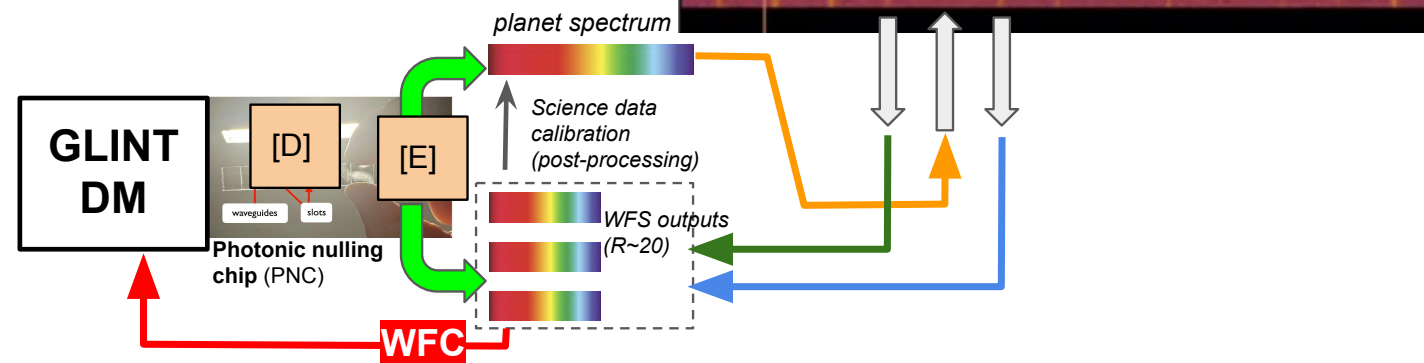
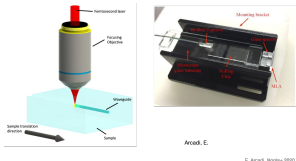
On-sky photonic nulling & closed loop WFS/C demo [may 2025, GLINT]

GLINT is a Japan/Australia collaboration
Japan contribution funded by JSPS (Kiban-S, Guyon)

High throughput (80% through chip)
Broadband null thanks to triclouplers + phase shifters

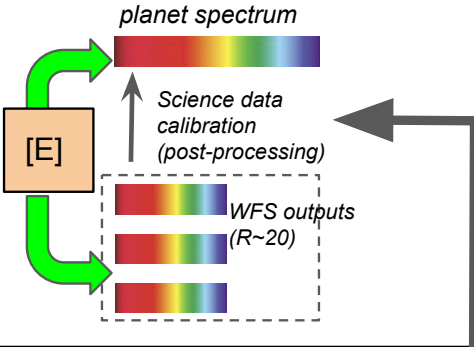


Manufactured @ Univ. Macquarie, Australia



GLINT team (Rossini-Bryson et al. 2025), in prep

Self-Calibration

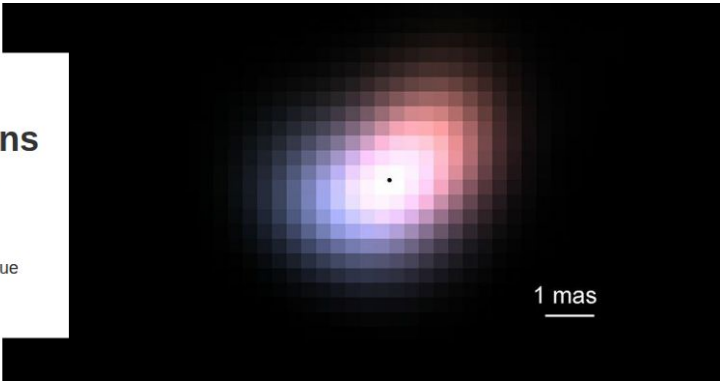


Thanks to the **modal decomposition**, the photonic spectrograph should **disambiguate true signal (exoplanet) from WF errors** (starlight leaking into science fiber)

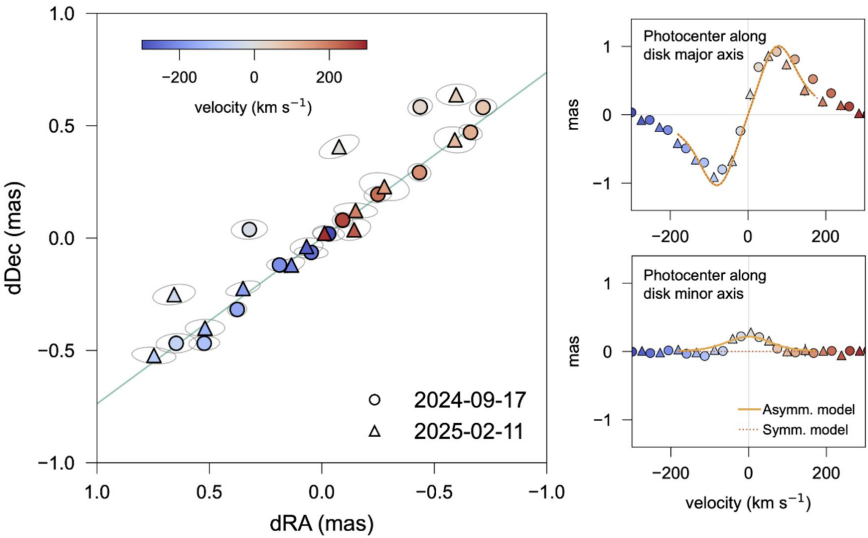
SCIENCE + TECHNOLOGY

Telescope hack opens a sharper view into the universe

It is the first time the novel imaging technique has been used on telescopes



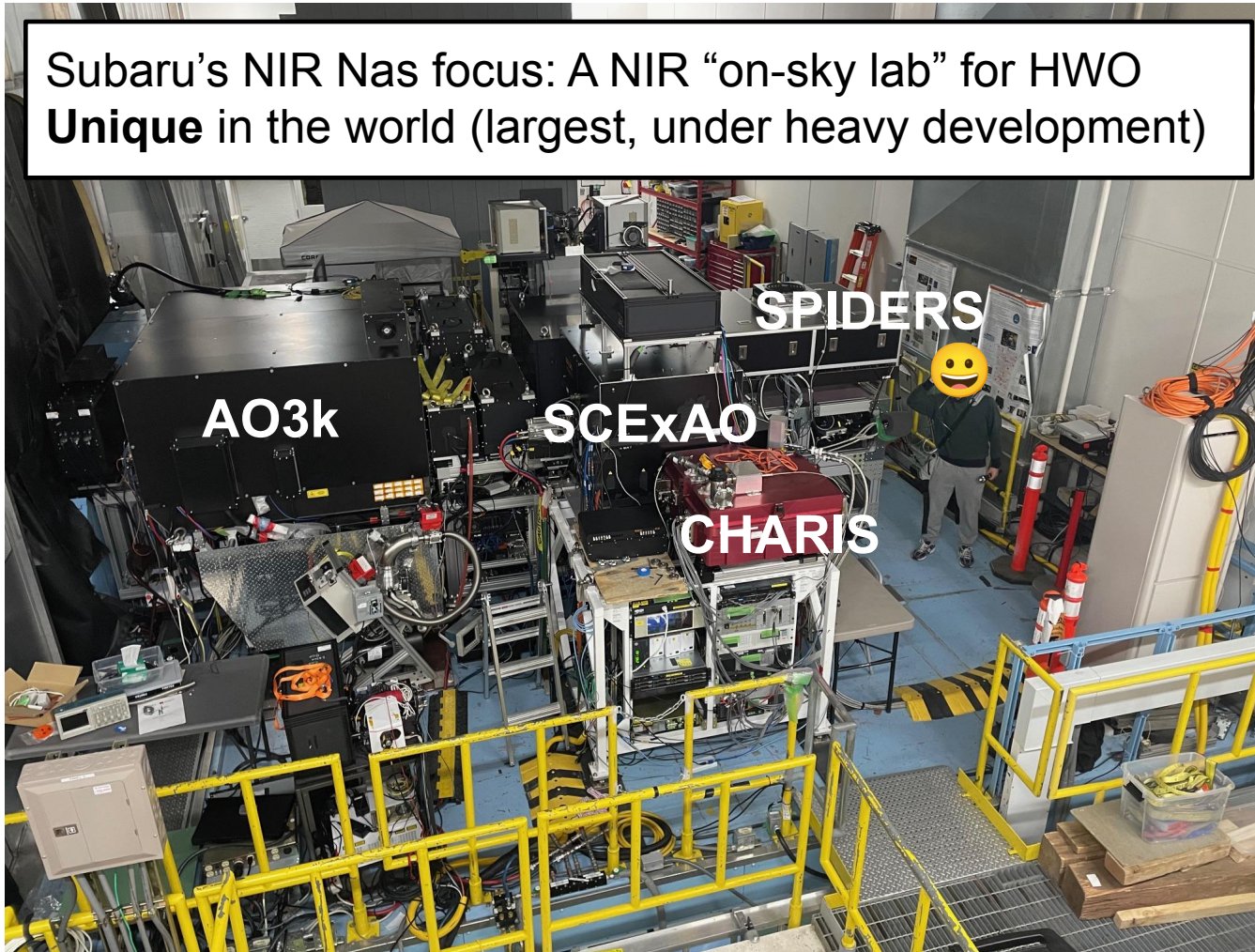
“On-sky Demonstration of Subdiffraction-limited Astronomical Measurement Using a Photonic Lantern” Yoo Jung Kim *et al* 2025 *ApJL* 993 L3



50 uas
precision per
spectral bin

System Integration & Validation @ Subaru for TRL5 in 2029

Subaru's NIR Nas focus: A NIR "on-sky lab" for HWO
Unique in the world (largest, under heavy development)



Small IWA masks designed & tested as components

Photonic circuits (NTT, ABC/NAOJ)

Subaru Testbed upgrades for stability and $1e-8$ broadband contrast

-> Integration on SCEXAO for system-level testing (WFC + Coronagraph + Photonics + Spectrograph)

Conclusions

MEFS is an architecture **optimized for efficiency spectroscopy of habitable exoplanets** with HWO, and can also be applied to ground-based ExAO systems.

MEFS **leverages the known planet position**: it is optically optimized to concentrate planet light and separate it from unwanted background light. Photonic technologies are essential to realize it.

Significant performance gains: reduced exposure time, access to smaller IWA.

We are demonstrating MEFS components and system in lab and on-sky.

Introduction to the Roman Coronagraph Instrument and Our Activities Toward HWO

Lead author: Naoshi Murakami

Abstract:

The Coronagraph Instrument aboard the Nancy Grace Roman Space Telescope is a technology demonstrator and an important stepping stone toward HWO. The Roman Coronagraph Instrument will perform on-orbit demonstrations of a variety of cutting-edge technologies for high-contrast imaging. In the first part of the presentation, I provide an overview of the Roman Coronagraph Instrument and the Community Participation Program (CPP), an international collaborative effort to prepare for upcoming observations. In the second part, I briefly report on our group's activities toward HWO, focusing on segmented vector vortex coronagraphs based on photonic-crystal technology.

Science Case Summary:

As we consider contributions to HWO, it is important to deepen our understanding of the Coronagraph Instrument aboard the upcoming Roman mission. As a potential technology for HWO, we are developing segmented vector vortex coronagraphs that may enable efficient detection of exoplanets very close to their host stars. This advantage is expected to be useful for the spectroscopic characterization of exo-Earths, particularly in the near-infrared wavelength regime.

16 July 2026 @ JAXA ISAS

Habitable Worlds Observatory Japan Science Workshop 2

Introduction to the Roman Coronagraph Instrument and Our Activities Toward HWO

Naoshi Murakami (Astrobiology Center, NINS)

Contents

1. Roman Coronagraph Instrument and Community Participation Program (CPP)

Naoshi Murakami, Masayuki Kuzuhara, Toshiyuki Mizuki (ABC), Shota Miyazaki, Kazuki Daikuhara, Toru Yamada (ISAS/JAXA), Takahiro Sumi (Osaka Univ.), Community Participation Program (CPP) Team

2. Coronagraph Technologies towards HWO

Naoshi Murakami, Jun Nishikawa (ABC), Kenta Yoneta, Natsuki Kawauchi, Miho Nagaki, Yuki Hatakeyama, Yosuke Tanaka (TUAT), Keigo Enya (ISAS/JAXA)

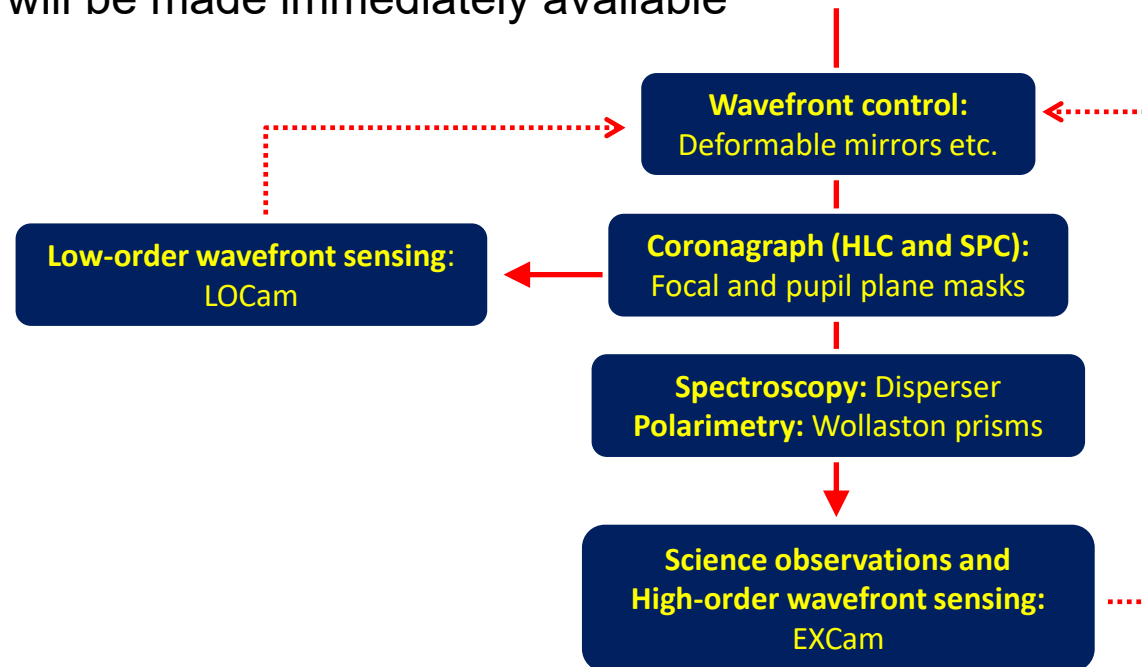
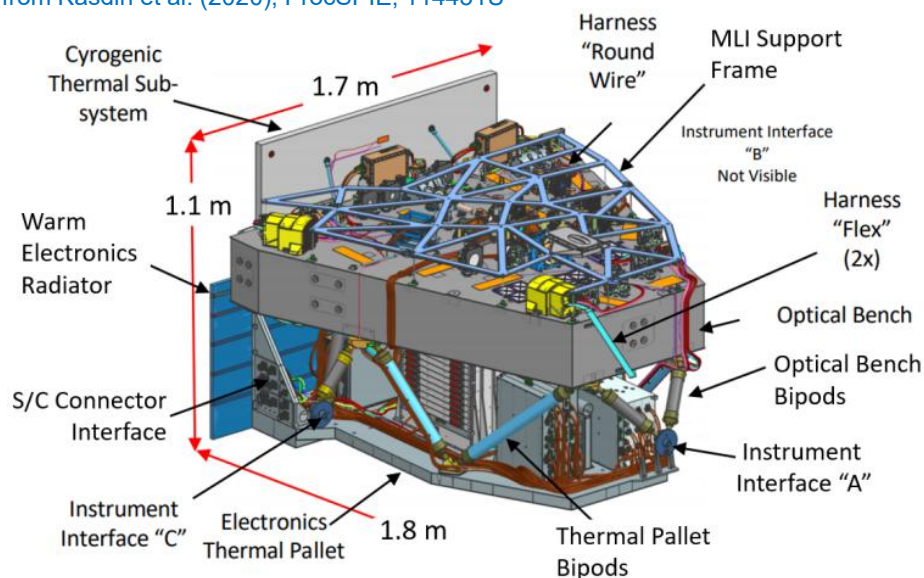
Roman Coronagraph Instrument

- **Nancy Grace Roman Space Telescope**

From Roman Coronagraph Primer
White Paper Town Hall Slides

- **Launch *readiness* date:** 30 August 2026
- **Coronagraph Instrument** as a technology demonstrator towards HWO
 - The first space-based coronagraph with active wavefront control
 - **Baseline:** 90 days (2,200 hours) during the first 18 months of the mission
 - **No proprietary period:** Roman data will be made immediately available

Figure from Kasdin et al. (2020), ProcSPIE, 114431U

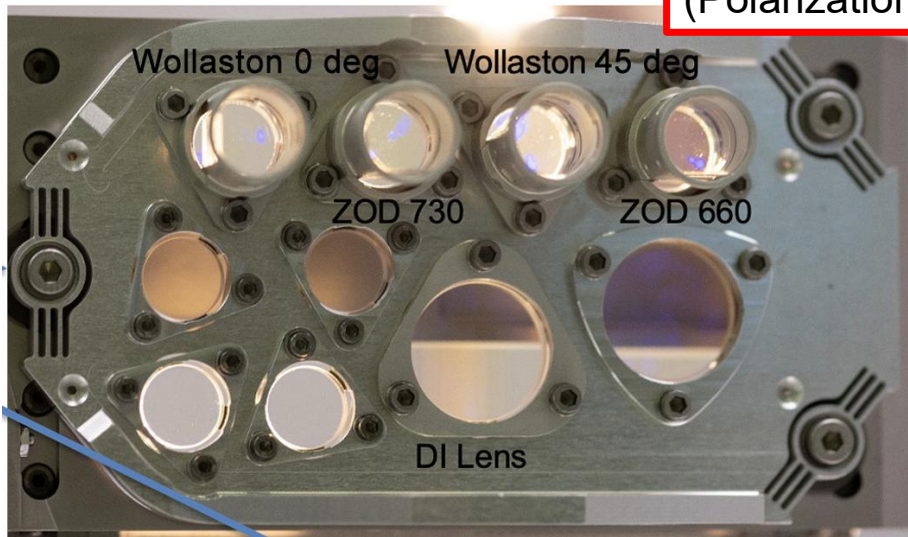


Contributions from JAXA

JAXA contributions

July 2020: Mask substrates delivered to NASA
Oct. 2021: Polarization optics delivered to NASA

Figure from Groff et al. (2025), JATIS, 11, 031510



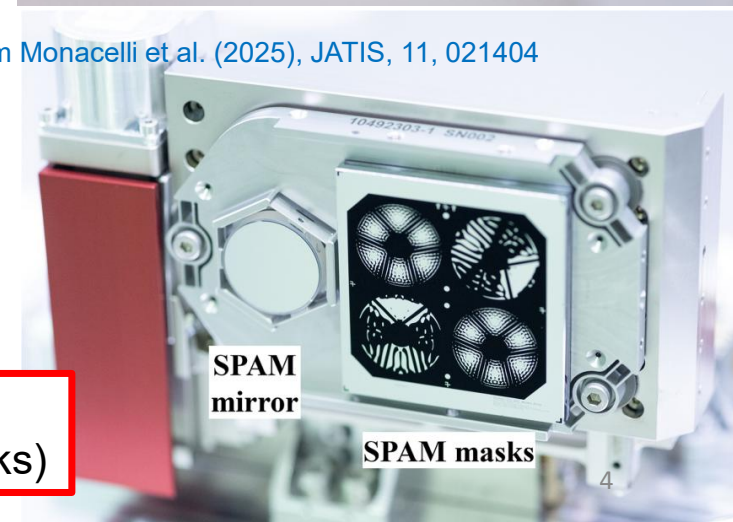
"DPAM" Unit
(Polarization optics)

"FPAM" Unit
(Focal-plane masks)



Credit: NASA/JPL-Caltech

Figure from Monacelli et al. (2025), JATIS, 11, 021404



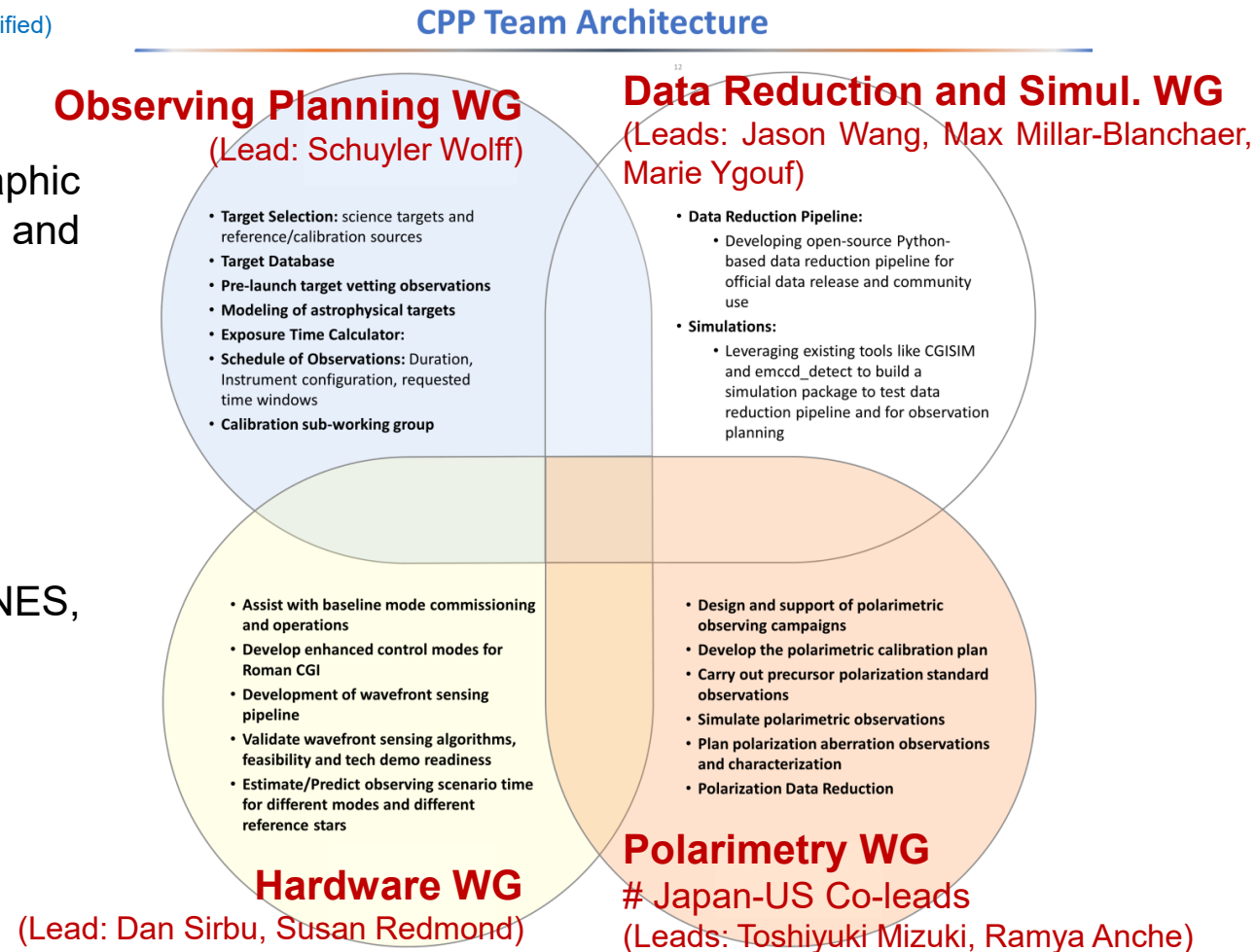
"SPAM" Unit
(Pupil-plane masks)

Coronagraph CPP (Community Participation Program)

Figure from Poster by Max Millar-Blanchaer et al., Spirit of Lyot 6 (Feb. 2026) (modified)

Roman Coronagraph CPP (since 2023)

- Prepare for the execution of the coronagraphic observations to maximize long-term science and technical value
- Organization (~150 members)
 - Chair: Vanessa Bailey (JPL)
 - Co-Chair: Schuyler Wolff (Arizona U.)
 - 11 US-based Teams
 - Members of the Roman Project Team
 - International Partner Teams from CNES, ESA, MPIA, and [JAXA](#)
 - WGs (right) and sub-WGs (below)
 - Reference star (Lead: Justin Hom)
 - Calibration (Lead: Bijan Nemati)
- Science planning: [Kuzuhara-san's talk](#)



(Data: <https://github.com/nasavbailey/DI-flux-ratio-plot/>)



- 10^{-7} : Roman's Level 1 requirement

- Few 10^{-9} : Roman's ambitious goal

10⁻¹⁰: HWO's goal

Higher contrast with smaller inner working angle (IWA) required

Contents

1. Roman Coronagraph Instrument and Community Participation Program (CPP)

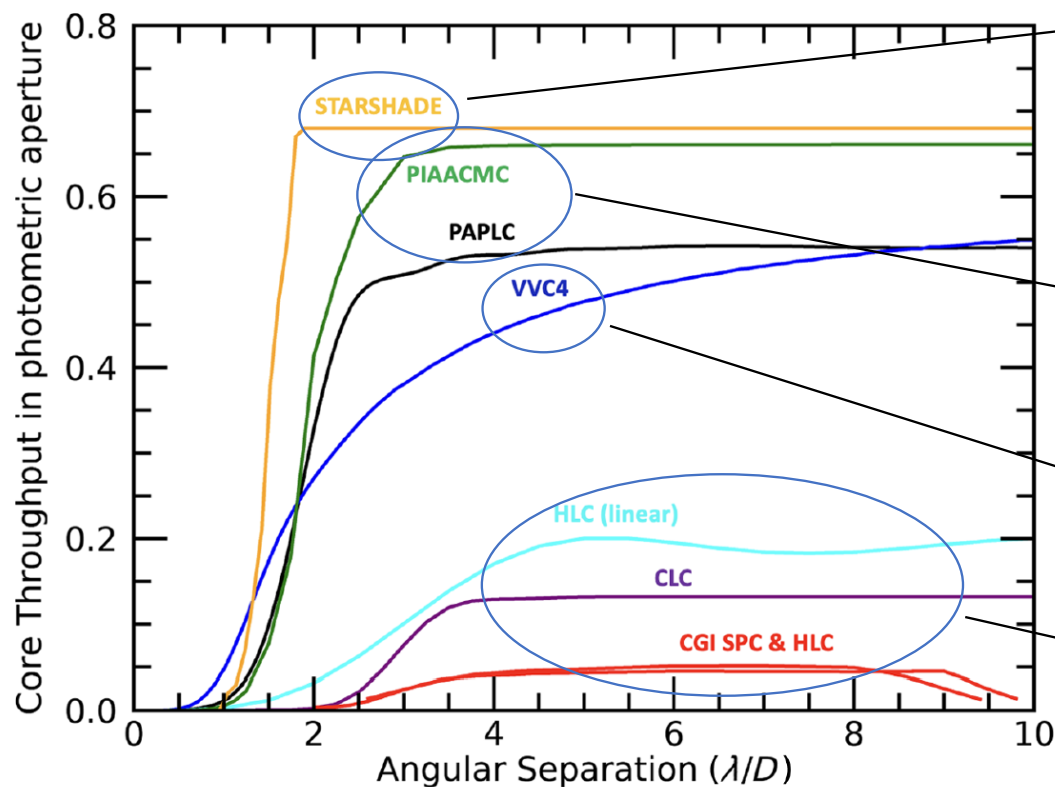
Naoshi Murakami, Masayuki Kuzuhara, Toshiyuki Mizuki (ABC), Shota Miyazaki, Kazuki Daikuhara, Toru Yamada (ISAS/JAXA), Takahiro Sumi (Osaka Univ.), Community Participation Program (CPP) Team

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Coronagraph towards HWO – Throughput is important

Core Throughput of Various Lab. Starlight-Suppression Setups



Starshade case:

- Theoretical core throughput is the highest
- No starshade has ever flown, and the technical maturity of a large space-based starshade can be considered low

Type 3:

- High possible core throughput
- Relatively low technical maturity

Type 2:

- Medium core throughput and technical maturity

Type 1 (including Roman Coronagraph):

- Low core throughput
- High technical maturity

Coronagraph towards HWO – Segmented vortex masks

Core Throughput of Various Lab. Starlight-Suppression Setups

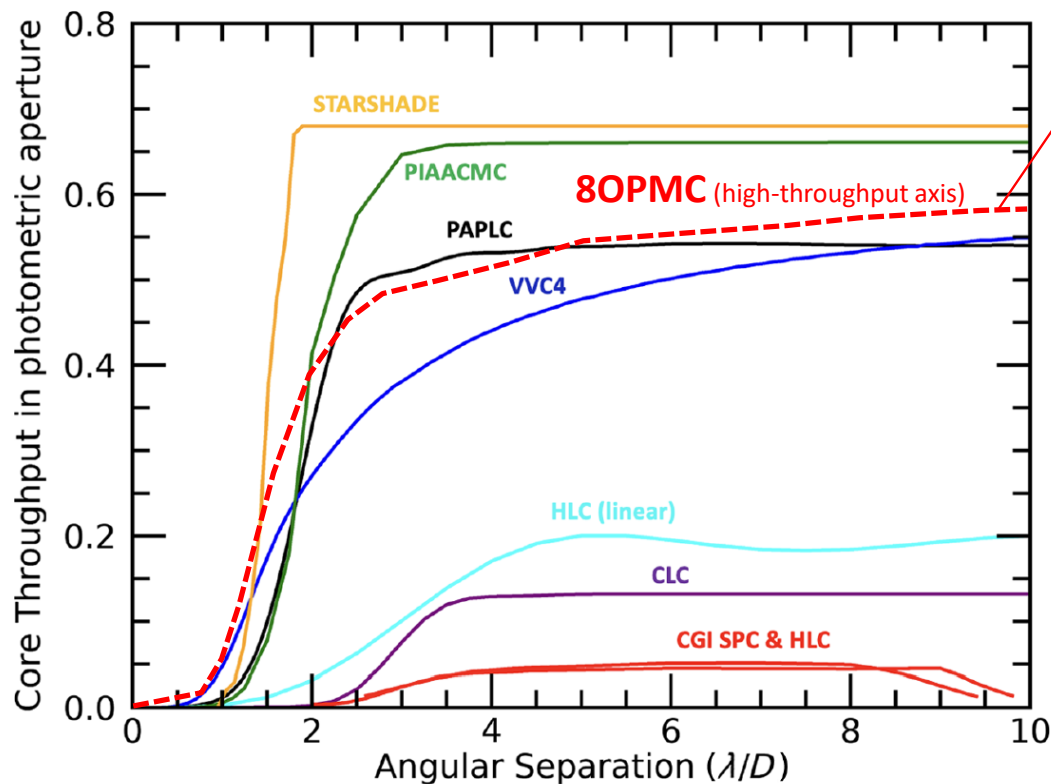
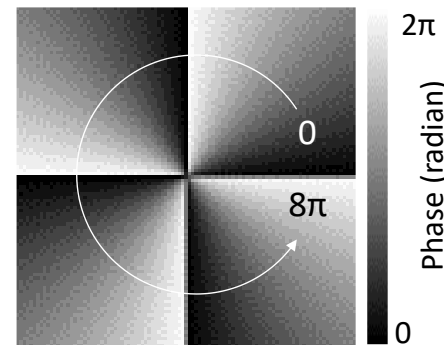


Figure from Mennesson et al. (2024), JATIS, 9, 035004-1

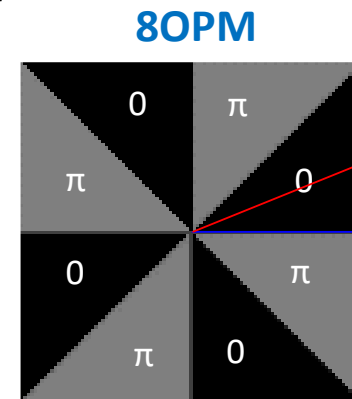
8OPMC (8-octant phase mask coronagraph):

- Family of Vector Vortex Coronagraph (VVC, Type 2)
- High core throughput with small IWA comparable to Type 3 coronagraphs
- Suited for spectral characterization



Charge-4 Vortex (VVC4)

Segmentation

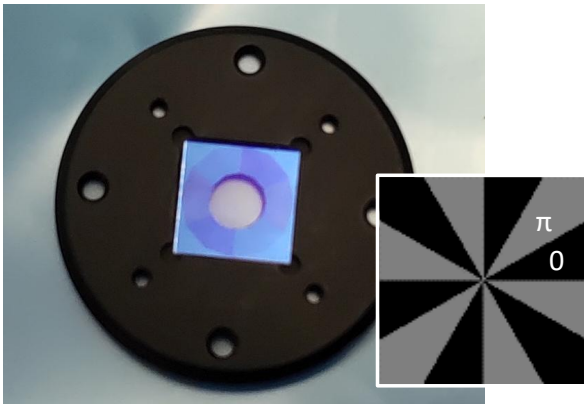


Murakami et al. (2008), PASP, 120, 1112.

Our Activities Towards HWO

Segmented vector vortex based on **photonic-crystal technology** towards **broadband** coronagraphy

Recent prototype mask
(12-segmented charge-6 vortex)



Ref: Murakami et al. (2026), *Proc. SPIE*, submitted

Coronagraph testbed (NAOJ/ATC)



Ref: Murakami et al. (2026), *Proc. SPIE*, submitted

Dark hole testbed (NAOJ/ATC)

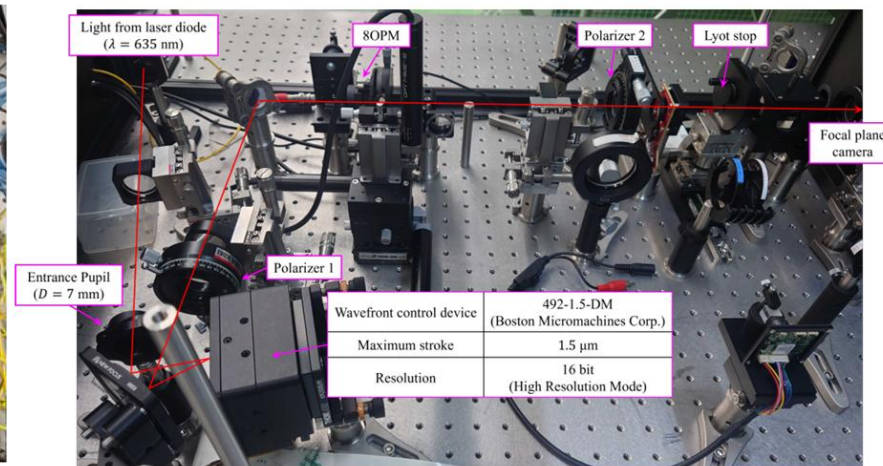


Figure from Yoneta et al. (2026), *HWO Proceedings Part II*, 209

- **Other on-going activities**

- Novel optical module “Planet Color Module (PCM)” for multi-band wavefront control
- Post process technique “Coherent Differential Imaging – Speckle Area Nulling (CDI-SAN)”
- Multi-star coronagraph and wavefront control techniques
- Two-stage coronagraph configuration
- ... etc.

Technology Development Plan (Coronagraph Masks, tentative)

- **FY2026**

- Fabrication of prototype mask and pol. optics, and lab. evaluation (VIS and NIR)
- NIR extension of the coronagraph testbed

- **FY2027**

- Fabrication of prototype mask and pol. optics, and lab. evaluation (VIS and NIR)
- NIR extension, broadband operation, and improved stability of the dark hole testbed

- **FY2028**

- Fabrication of prototype mask and pol. optics, and lab. evaluation (VIS and NIR)
- Design of NIR coronagraph configuration

- **FY2029**

- Design of NIR coronagraph configuration

Future possibilities, when/if opportunities arise (to be discussed)

- Integration testing with the NIR photonic spectrograph at Subaru/SCEExAO
- Vacuum testing toward 10^{-10} contrast demonstration

Summary

- **Roman Coronagraph Instrument**

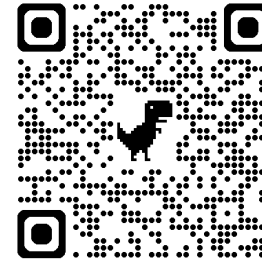
- **Launch *readiness* date:** 30 August 2026
- **Technology demonstration towards HWO**
 - The first space-based coronagraph with active wavefront control
- **L1 Requirement:** $<10^{-7}$ contrast
- **Ambitious Goal:** a few 10^{-9} contrast
- **Community Participation Program (CPP) is on-going**
 - CPP website: <https://sites.google.com/view/roman-cpp/home>
 - White Papers solicited by CPP: <https://zenodo.org/records/21203363>
 - Observation planning: Kuauhara-san's talk

- **Coronagraph Technologies Towards HWO**

- **Goal:** 10^{-10} contrast over broad wavelength range
- **Requirements:** higher throughput with smaller IWA
- **(One of) our activities**
 - Photonic-crystal segmented vortex masks etc.
 - Development on-going at ABC and NAOJ/ATC

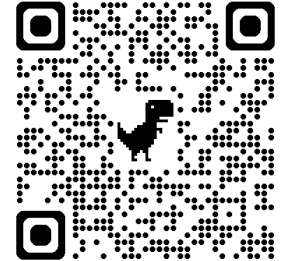
CPP Website

Information, documents, resources etc. available



White Papers (WPs)

CPP solicited WPs from the worldwide community



Title:

Development of Photonic Integrated Circuits (PICs) for direct imaging of exoplanets

Lead author: Reiki Kojima

Abstract:

Photonic integrated circuit (PIC), which integrate multiple optical components onto a single chip, offer a promising alternative to conventional bulk optical systems for astronomical instrumentation. While traditional spaceborne instruments are constrained by size, weight, and mechanical stability, PIC enable ultra-compact, highly stable, and reproducible optical systems, with the added benefit of cost reduction through mass production. In collaboration with Nagoya University, Osaka University, and NTT Device Technology Laboratories, we have designed and evaluated a PIC optimized for nulling interferometry. We report the results of the demonstration experiments and discuss the potential applications of this technology to future space missions.

Science Case Summary

Developing high-contrast imaging technologies is a key step for a direct detection and characterization of Earth-like exoplanets. Astro2020 Decadal Survey identifies the development and maturation of next-generation coronagraph technologies as necessary for future space mission. Our work contributes to these technology development efforts.

Development of Photonic Integrated Circuits (PICs) for direct imaging of exoplanets

Reiki Kojima (Nagoya University), Satoshi Itoh (University of Osaka),
Saki Nohara, Satomi Katayose, Toshikazu Hashimoto (Device Technology Labs., NTT, Inc),
Taro Matsuo (University of Osaka)

Photonic Integrated Circuits (PICs)

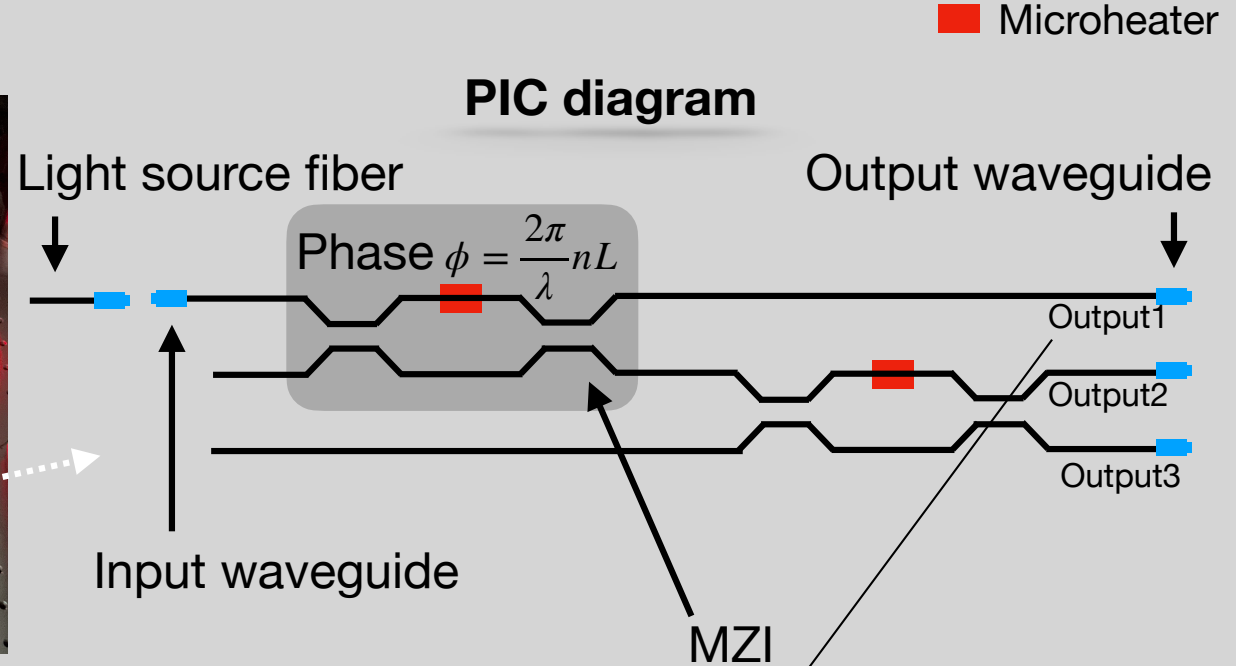
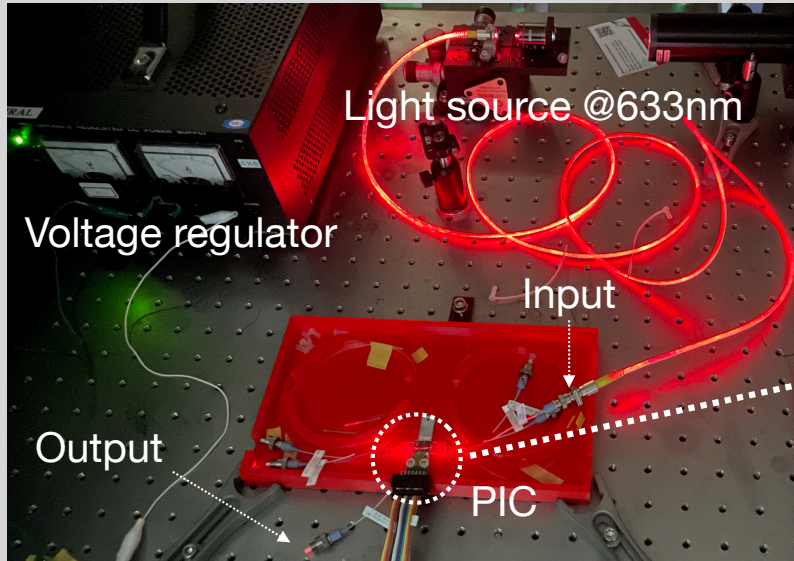
What is PICs?

- A PIC integrates optical components (e.g., splitters, filters) built from waveguides - micron-scale channels that guide light - onto a single chip, enabling optical signal processing.
- A PIC provides a **compact** and **stable** alternative to conventional bulk optical systems for astronomical instrumentation.

Device Technology Labs., NTT, Inc

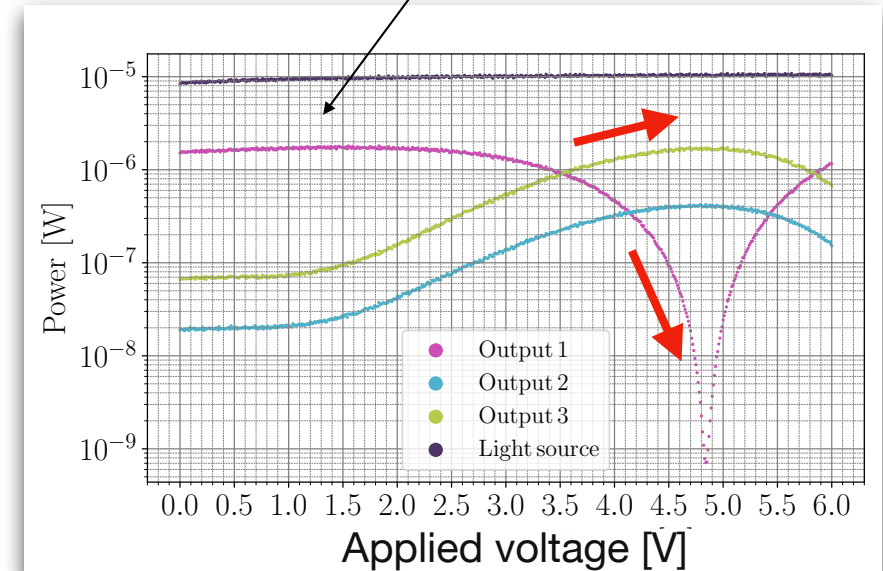
- NTT Device Technology Labs. has developed an ultra-low-loss silica-based PIC that integrates a wide range of optical functions onto a single chip.
- These functions include interferometry via Mach-Zehnder Interferometers (MZIs) and spectroscopy via Arrayed Waveguide Gratings (AWGs).
- Its mechanical and optical stability makes it a promising technology for next-generation space observation missions.

Photonic Integrated Circuits (PICs)



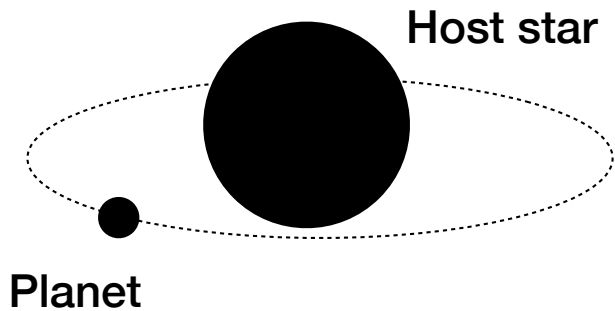
- A microheater changes the refractive index n through the thermo-optic effect.
- By controlling the applied voltage V , the microheater temperature ΔT is adjusted, changing the refractive index n in one arm of the MZI:

$$n = \frac{\partial n}{\partial T} \Delta T \propto \frac{\partial n}{\partial T} V^2$$

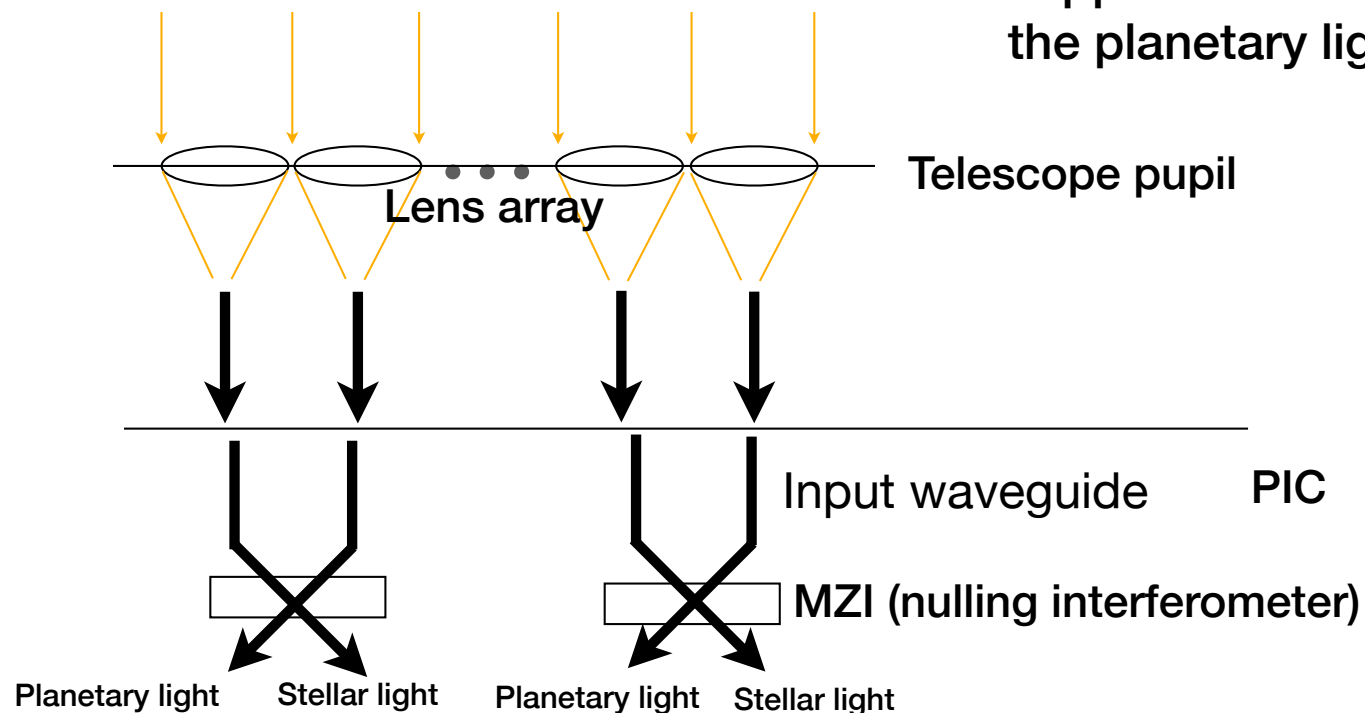


Photonic Integrated Circuits (PICs)

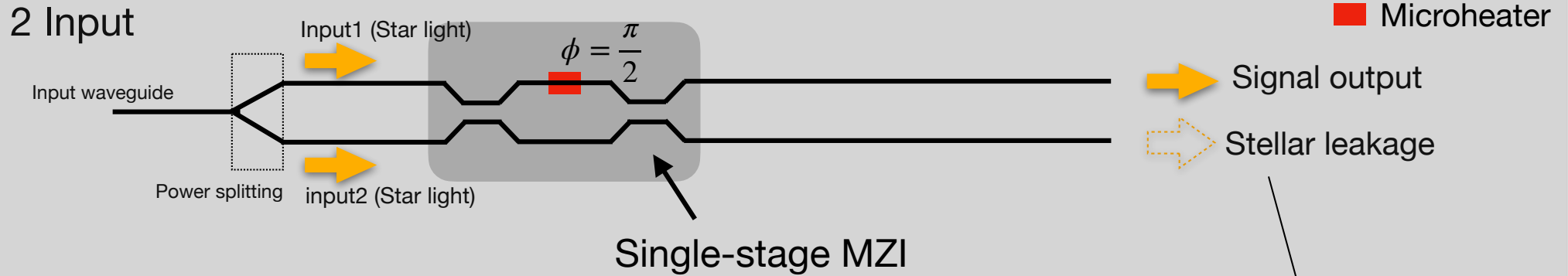
Concept of a **PIC-based nulling interferometer** for direct imaging of exoplanets



- Divide the telescope pupil into multiple wavefronts using a lens array.
- Inject the wavefronts into a PIC with only 5% optical loss.
- On a chip, a PIC combines the wavefronts to suppress the stellar light while transmitting the planetary light (nulling interferometry).



Preliminary Experiment (Single-stage MZI on a PIC)



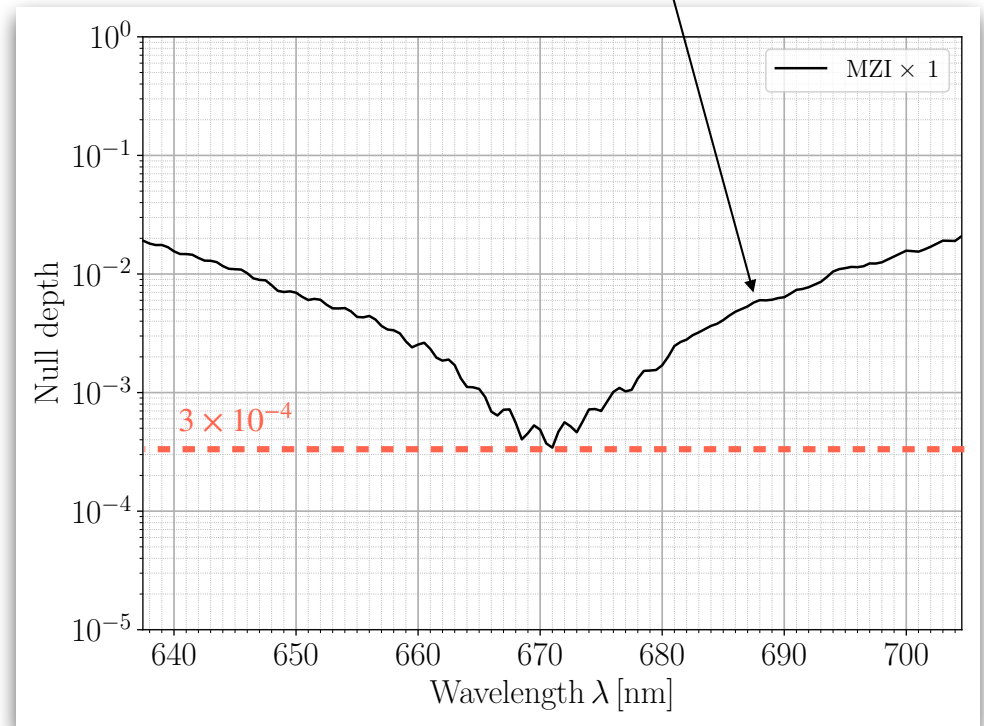
Experimental Results

- Achieve a contrast of 3×10^{-4} at a center wavelength of 670 nm.
- Achieve a contrast of 2×10^{-2} over a bandwidth of $\pm 5\%$.

Possible limiting factors for achieving the target contrast of 10^{-10}

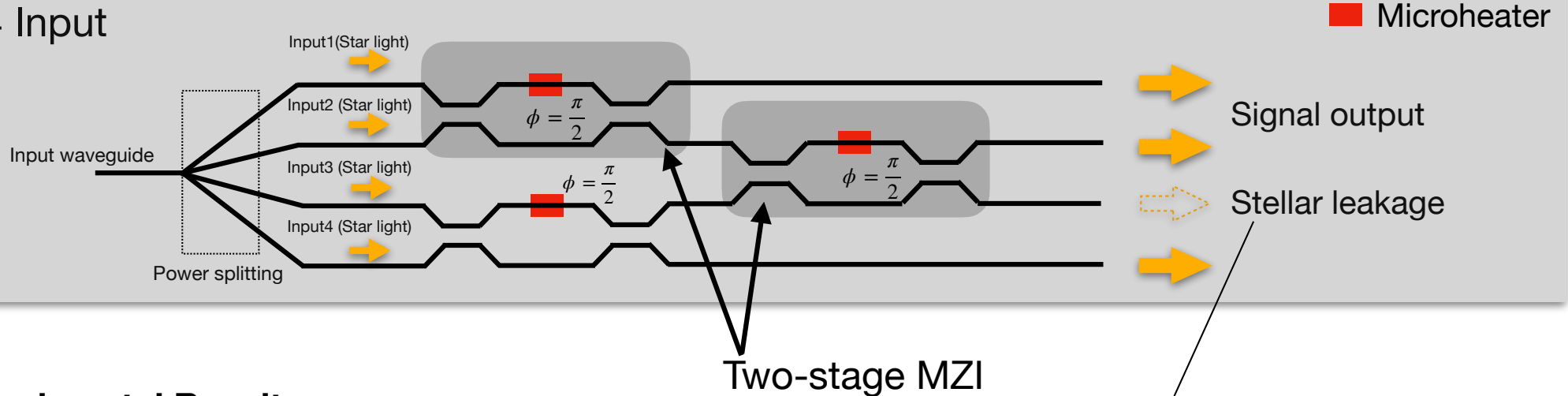
- Limited relative amplitude and phase control accuracy between the two beams.
- The input polarization was not perfectly TE, resulting in a measured TE:TM ratio of approximately 100:1.

Experimental Results of the Single-stage MZI



Preliminary Experiment (Two-stage MZI on a PIC)

4 Input

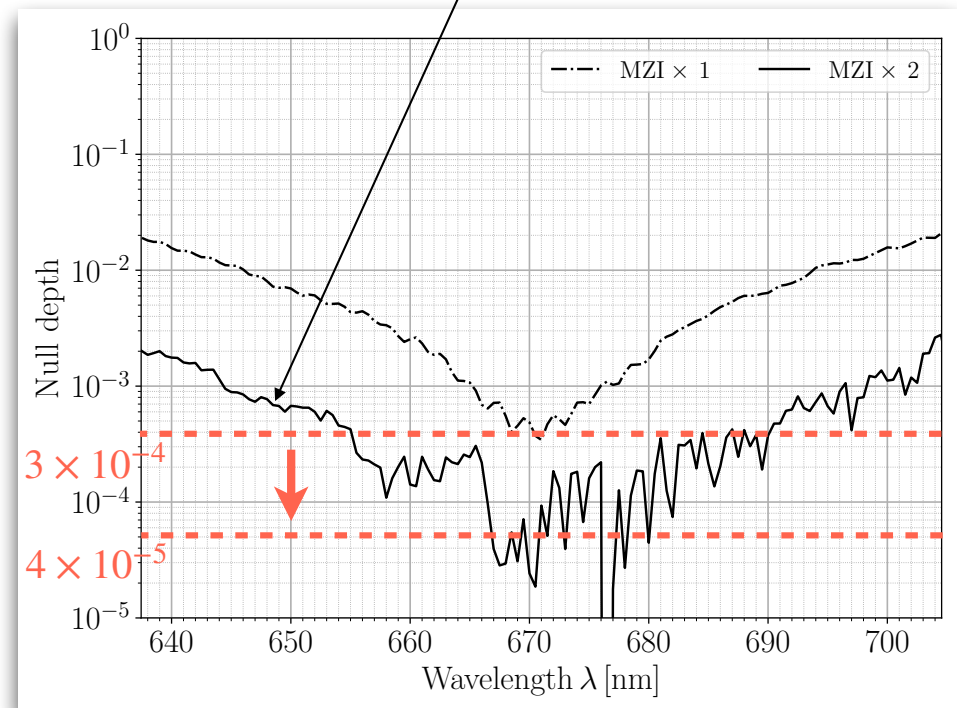


Experimental Results

- Achieve a contrast of 4×10^{-5} at a center wavelength of 670 nm.
- Achieve a contrast of 2×10^{-3} over a bandwidth of $\pm 5\%$.

Although the current performance of the single-stage MZI is limited by the relative amplitude and phase accuracy, as well as polarization, deeper nulling can be achieved by cascading multiple MZI stages.

Experimental Results of the Two-stage MZI



Summary and Future Work

- Photonic integrated circuits (PICs), which integrate multiple optical functions onto a single chip, offer a promising alternative to conventional bulk optical systems.
- We developed and demonstrated a PIC-based nulling interferometer in collaboration with Device Technology Labs., NTT, Inc.
- We achieved a laboratory contrast of 3×10^{-4} at a center wavelength using a single-stage MZI architecture.
- The two-stage MZI architecture has demonstrated improved null depth of 4×10^{-5} at a center wavelength, indicating that cascading additional MZI-stages provides a clear path toward deeper nulling.
- Future work includes developing an advanced system that combines nulling interferometry with spectroscopy using an arrayed waveguide grating (AWG).

A Bar-coronagraph with a Small Inner Working Angle: The One-dimensional Diffraction-limit Coronagraph (1DDLc)

Lead author: Satoshi Ito

Abstract:

The star-light suppression instrument---stellar coronagraph--- is a key to the HWO's primary science driver: habitable-world observation. We are developing a type of coronagraph that serves as a bar-coronagraph with a small inner working angle: the one-dimensional diffraction-limit coronagraph (1DDLc). Although the 1DDLc is not particularly popular now, it has massive potential as an additional option in the current HWO instrumentation lineup. This is mainly because it can achieve double-star suppression while transmitting light from the planet at the diffraction-limited (theoretical) separation angle. Our numerical simulation, which assumes the HWO-type segmented pupil geometry, showed that a type of 1DDLc can achieve about 10^{-8} times star-light suppression at $1\lambda/D$ (10% of the spectral bandwidth) when supported by two deformable mirrors with a sufficient number of actuators. In addition, when the 1DDLc is used as a fore-stage optics before a star-light suppression optics, such as a photonic integrated circuit (PIC) or fiber-nulling, it can achieve 10^{-10} times star-light suppression under the same conditions.

Science Case Summary

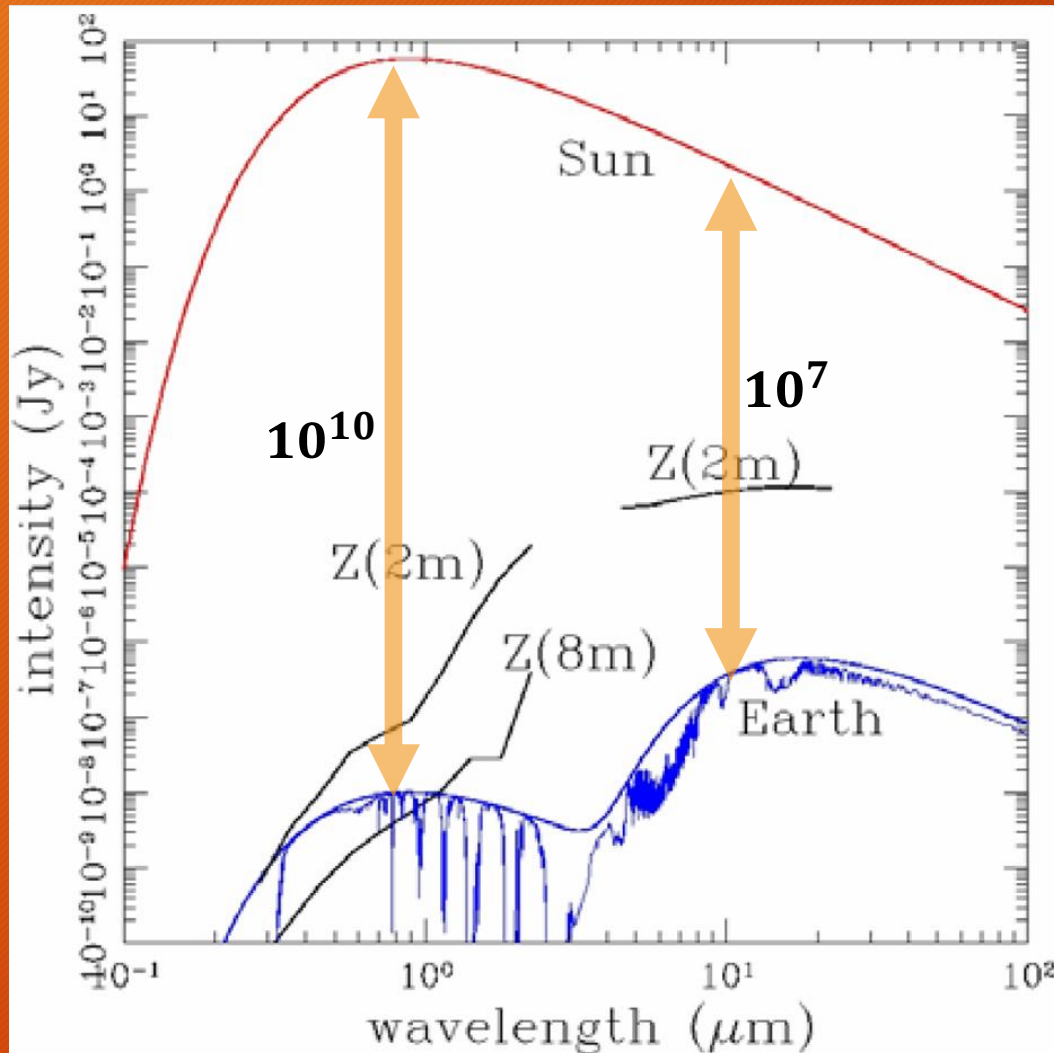
The two of the merits of 1DDLc can increase the HWO targets for the living-world observation with adding the capability to observe the planets around double-stars and planets with separation angles of near the diffraction-limit angle. NASA ExEP Mission star list currently excludes planets around double-stars and planets with separation angles near the diffraction-limit angle.

A bar-coronagraph
with a small inner working angle:
one-dimensional
diffraction-limit coronagraph (1DDL)

Talk: Satoshi Itoh
(U. Of Osaka)

Background: the comparison of the radiation flux of the Earth and Sun.

Sun/Earth contrast is about 10^{10} (in VIS)



We need to selectively suppress the stellar light (noise source) while transmitting the planetary light (signal).

Kasting et al. 2009

Background: explanation of how Lyot coronagraphs work.

Some stellar coronagraphs can do it. (in principle)

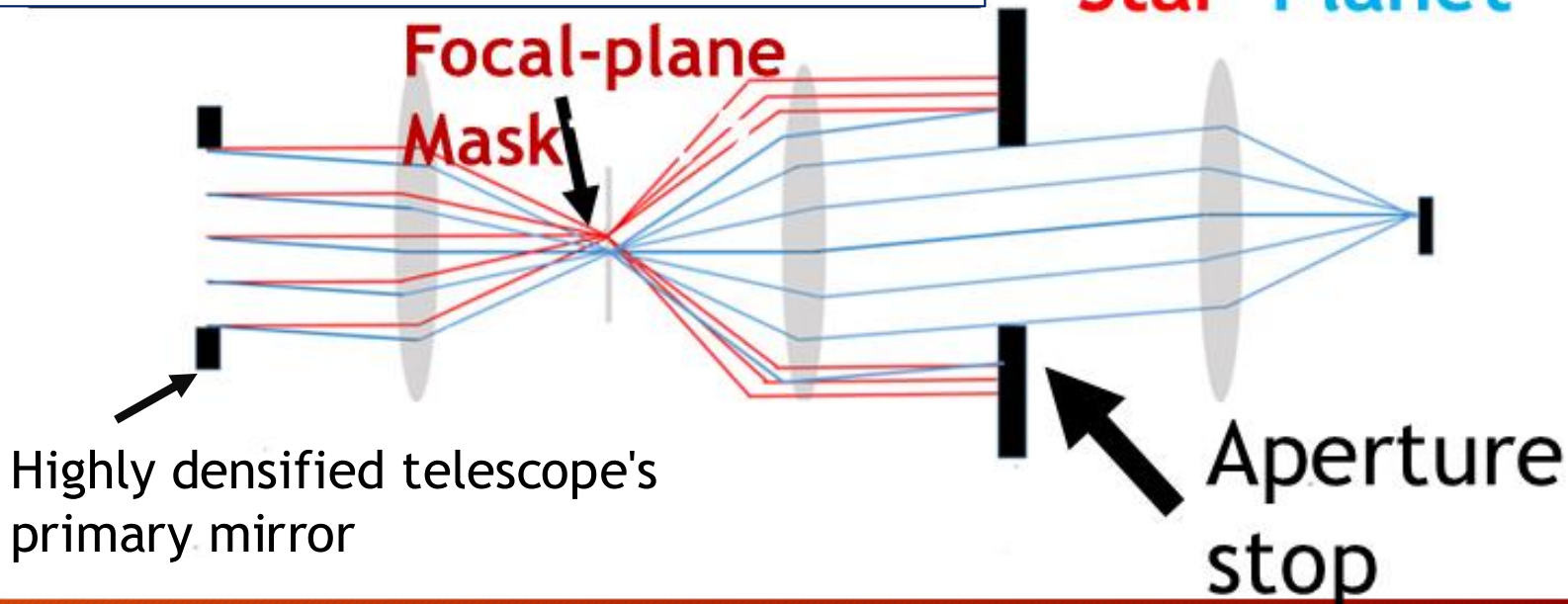


Bernard Lyot (1897-1952) invented the coronagraph to make an artificial total eclipse of the Sun.



Solar corona

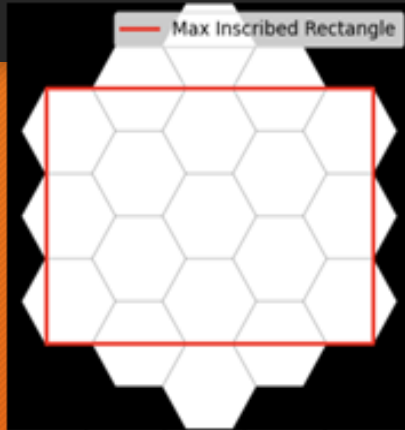
Lyot Coronagraph



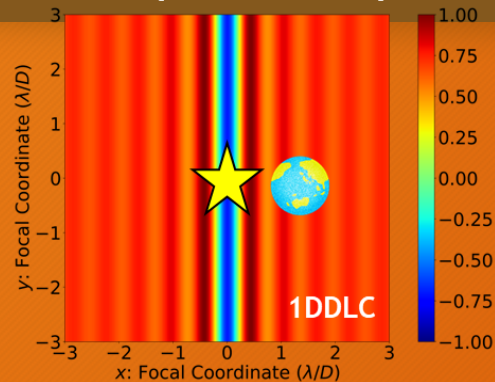
Topic of this talk.

One-Dimensional Diffraction-Limit Coronagraph (1DDLC)

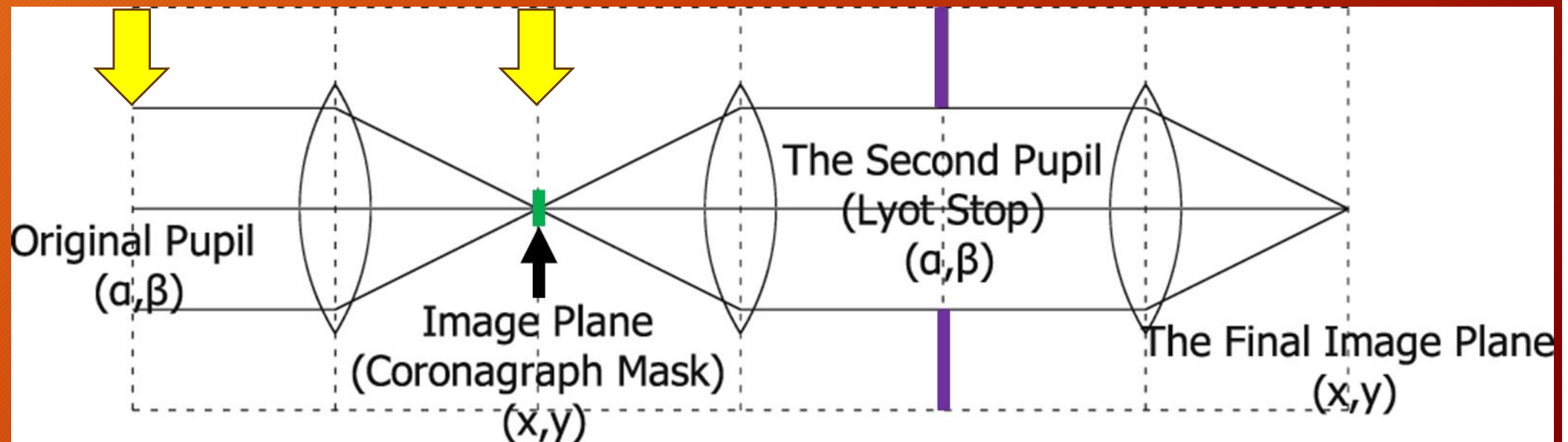
is a type of the Lyot coronagraph.



Bar-like
Focal-plane mask pattern

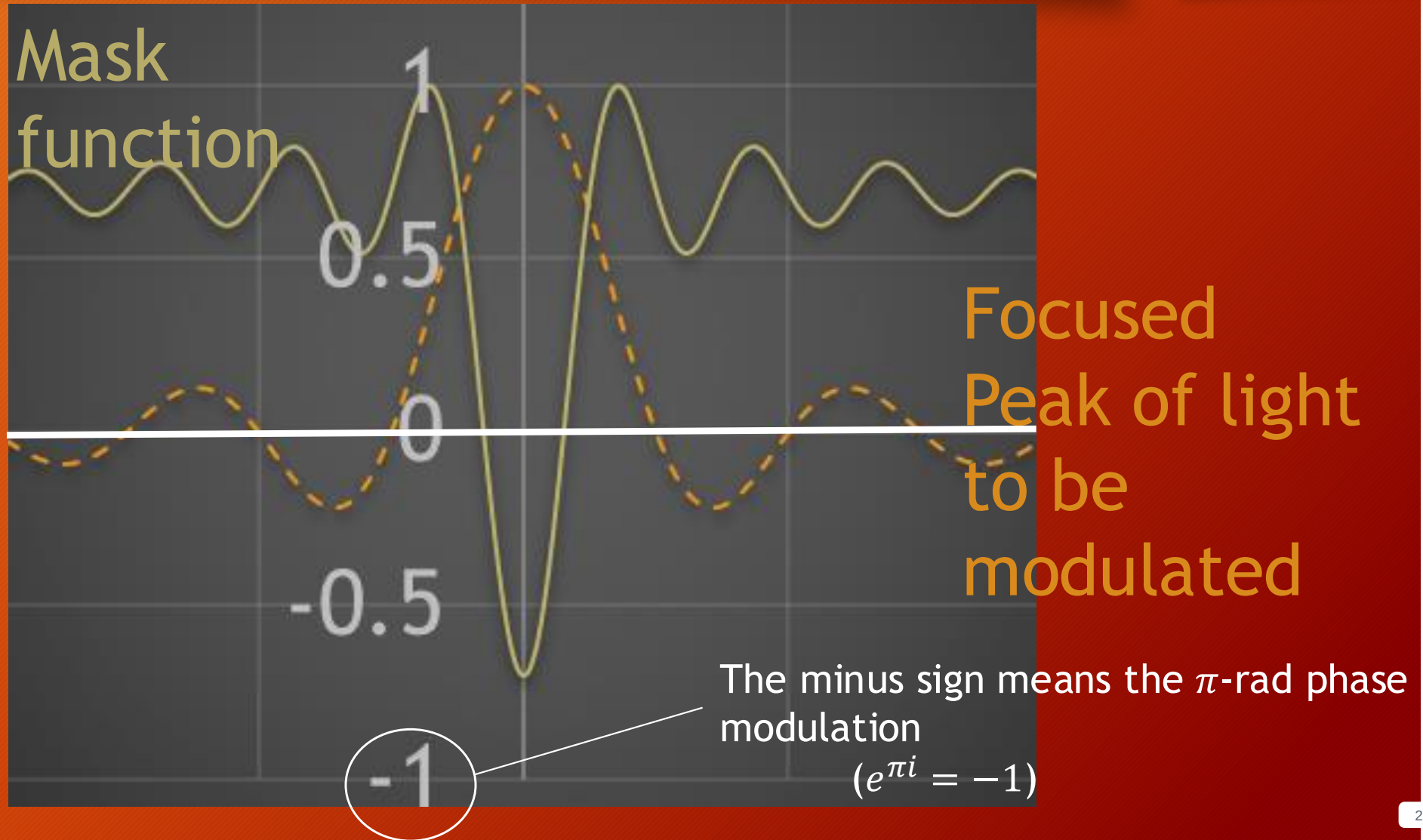


The 1DDLC uses a characteristic focal plane mask (FPM) and two rectangular pupil aperture before and after the FPM.



The 1-D cross section of the focal-plane mask function.

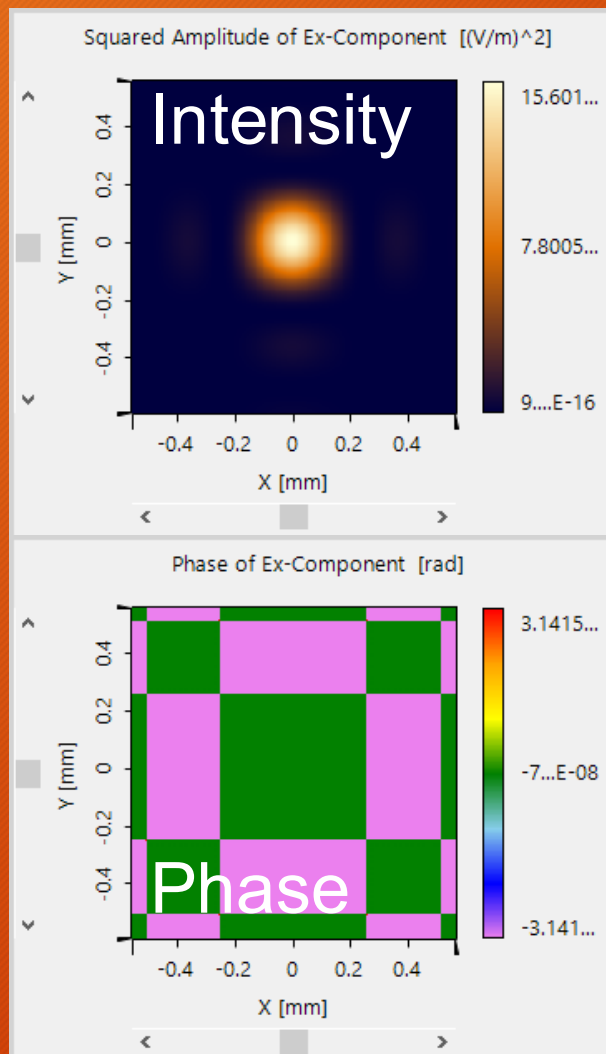
The FPM multiplies the focused electric field by real values (from -1 to 1).



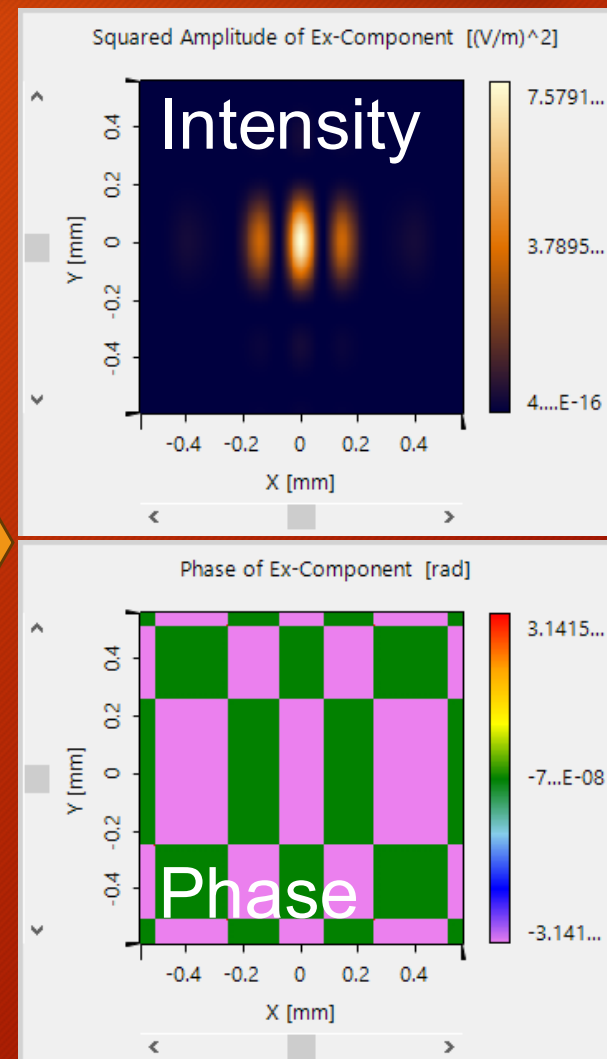
How the focal-plane mask modulates the stellar point spread function.

The FPM modulates the PSF into a Finer Wavelet.

Before



After



Focal
Plane
Mask

How to manufacture the 1DDLC's focal-plane mask.

FPM implementation method uses polarization of light.

Implementation
like the vector vortex mask.

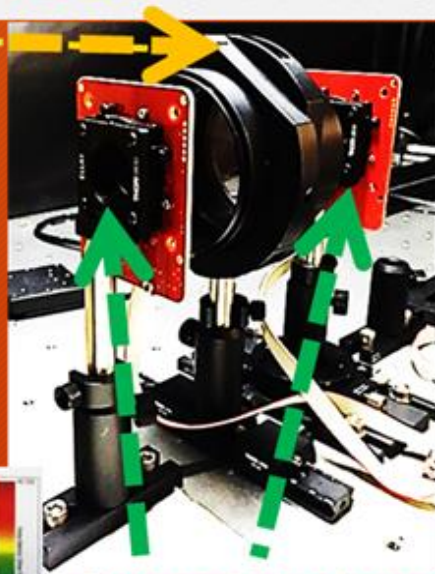
Custom-patterned
half-wave plate



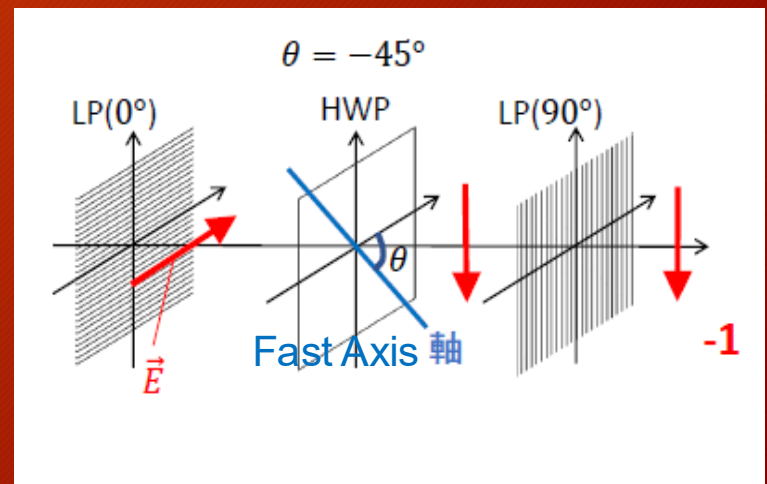
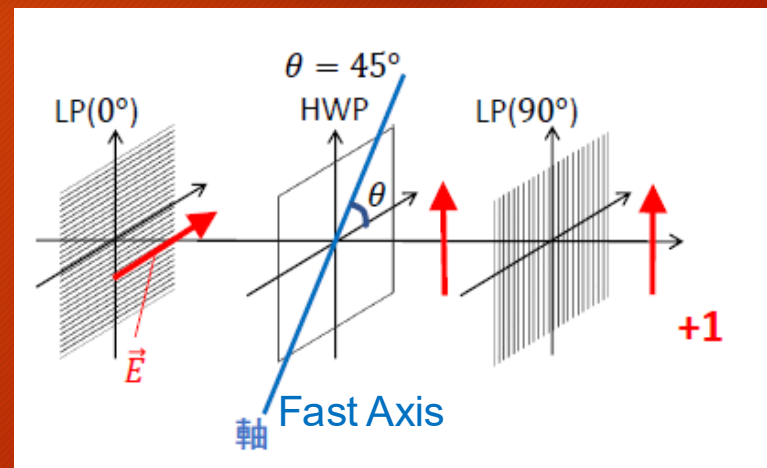
Measured fast-axis
orientation



1DDLC FPM unit



Linear Polarizers
 $\phi 25.4\text{mm}$

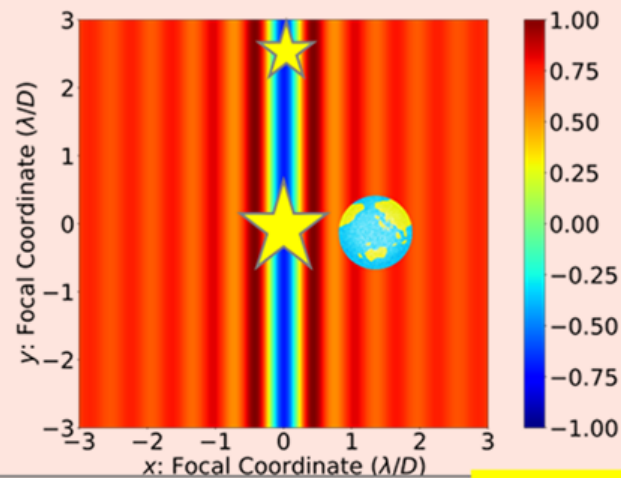


Different orientations of the fast axes lead to the different modulations.

Why we have to stick to the 1DDL.

There are two promising points.

(1) Double star nuller

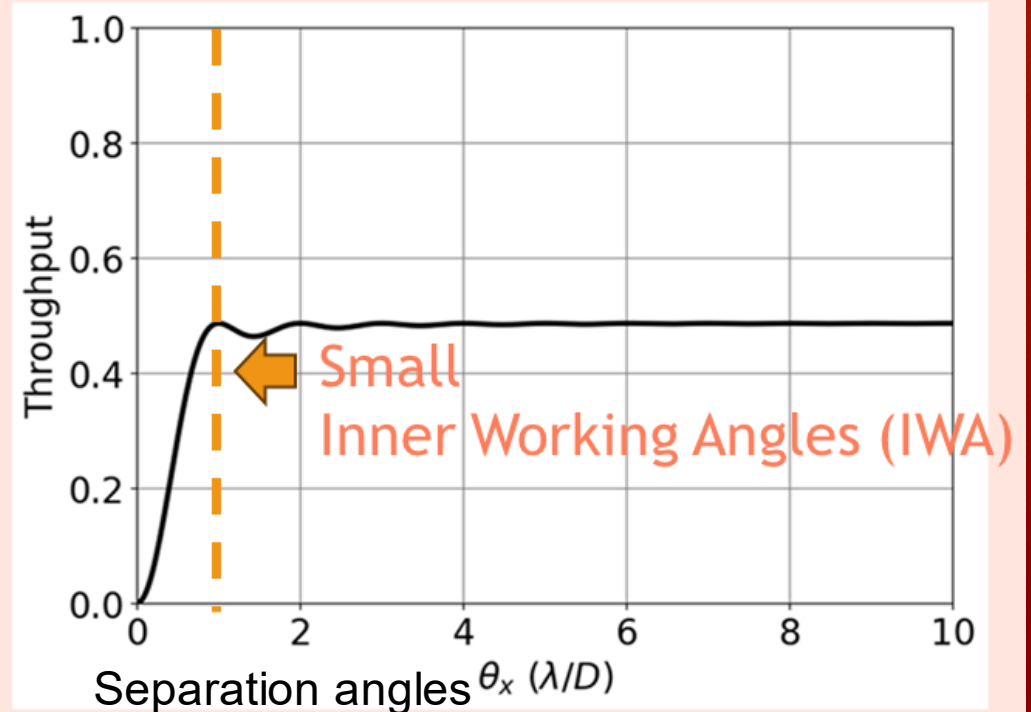


Theoretically perfect null for monochromatic **line** source.

The minus signs mean $e^{\pi i} (= -1)$.

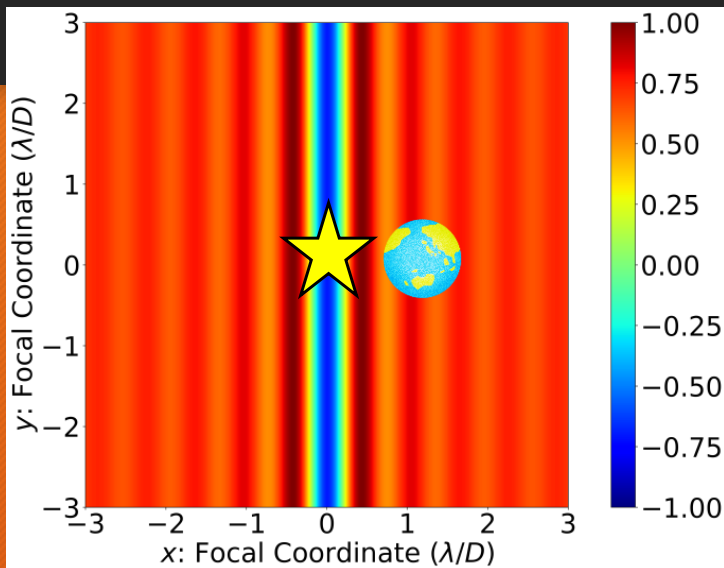
Double star nuller

(2) Small IWA



Another design option is more robust for spectral bandwidth/ stellar diameter.

Before robustification

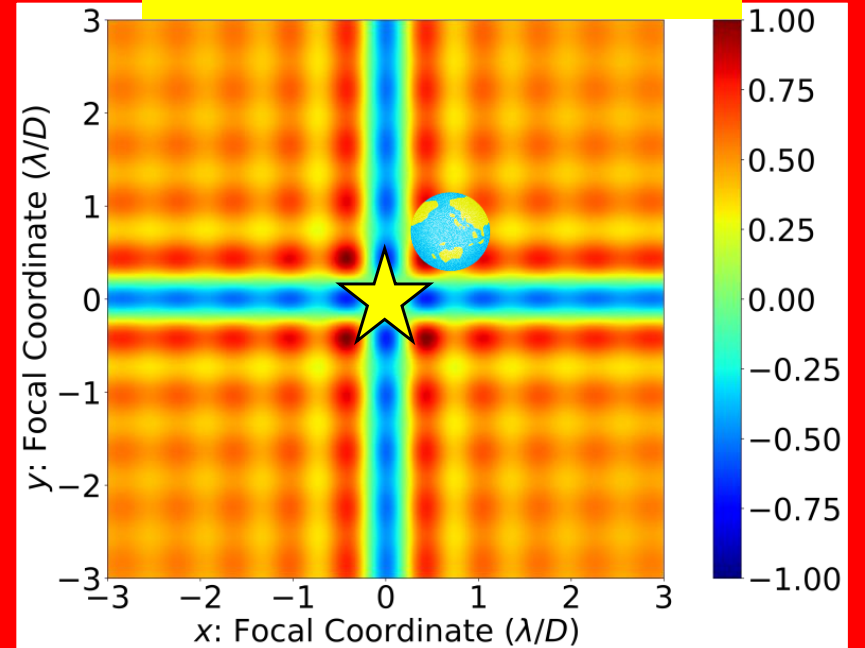


**Crossed
doubled
version**

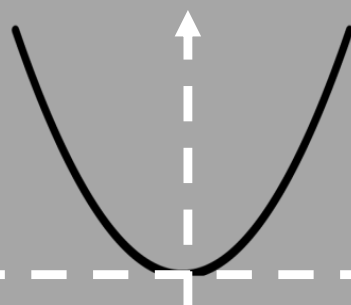


($\times 0.5$
In throughput)

After robustification



Stellar Leak intensity

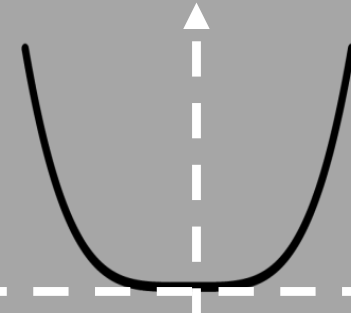


2nd-order

Spectral Bandwidth
(and Stellar diameter)



Stellar Leak intensity



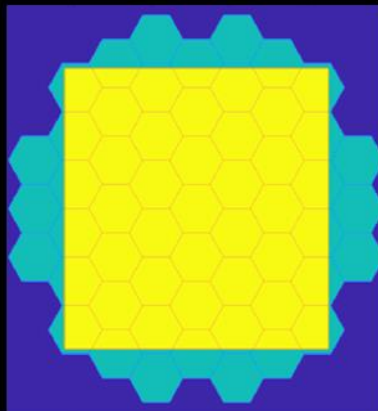
4th-order

Spectral Bandwidth
(and Stellar diameter)

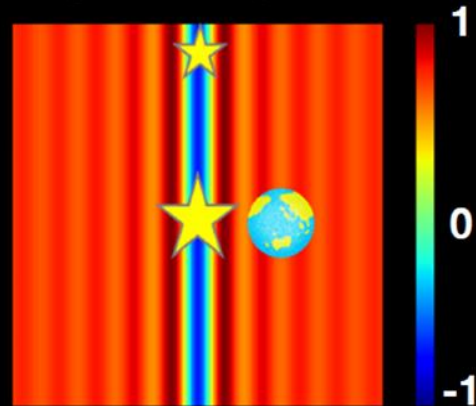
A simulation result assuming two DMs.

When with two deformable mirrors, 10^{-8} times star-light suppression at $1\lambda/D$ is achievable.

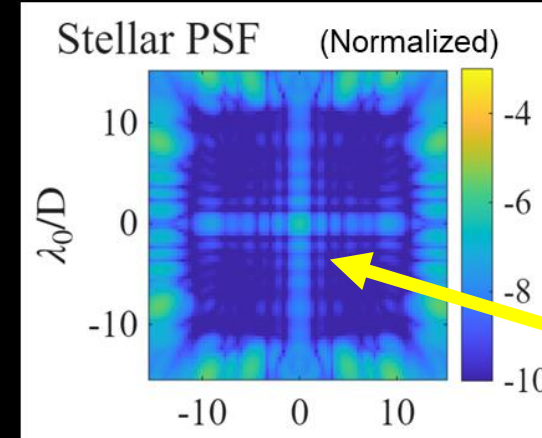
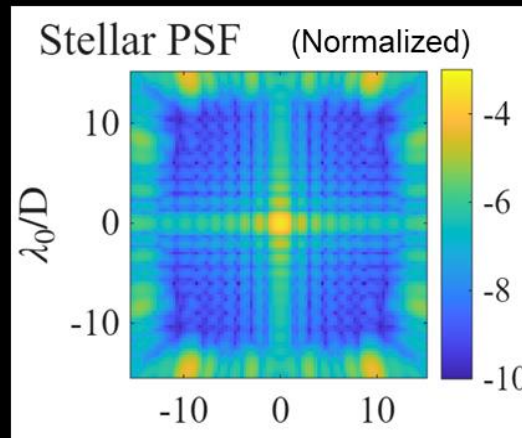
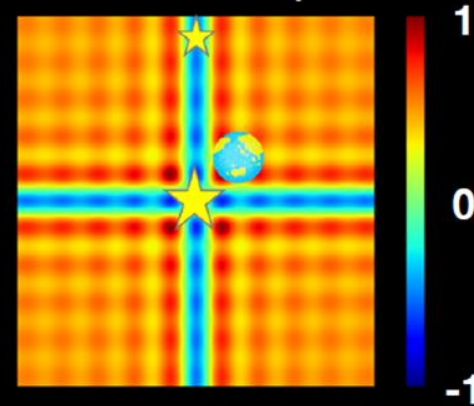
Dark hole
simulation
assuming
1) a segmented
pupil geometry
2) 10-%
spectral
bandwidth



Single focal plane mask



Crossed focal plane mask



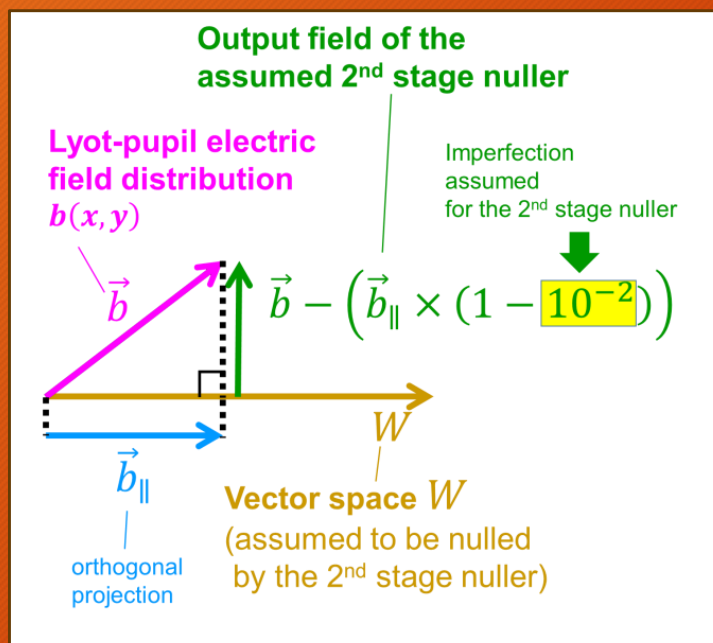
about 10^{-8}
star-light
suppression
at $1\lambda/D$

A simulation result assuming connection with another nuller.

When connected with another nuller,

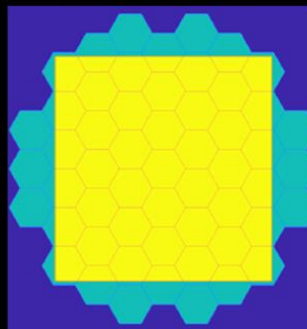
10^{-10} times star-light suppression at $1\lambda/D$ is achievable.

We can use the 1DDL as a **fore-stage optics** before a photonic integrated circuit (PIC) or fiber-nulling

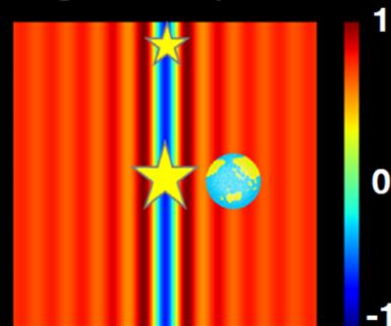


Dark hole simulation assuming

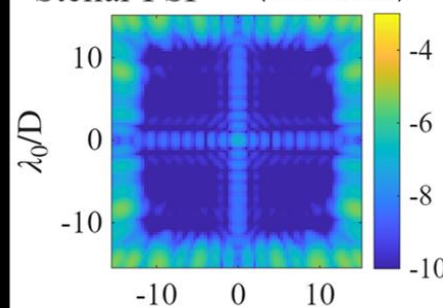
- 1) a segmented pupil geometry
- 2) 10-% spectral bandwidth



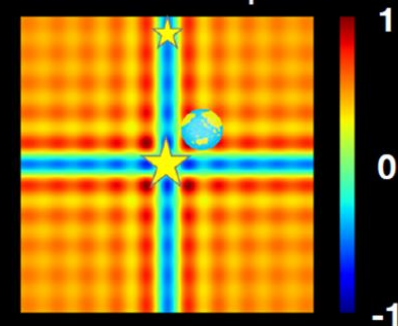
Single focal plane mask



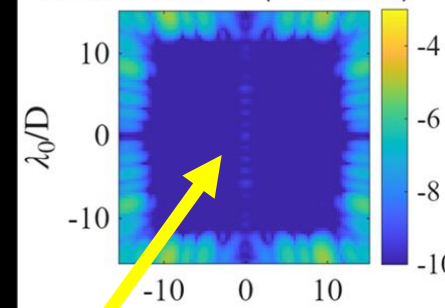
Stellar PSF (Normalized)



Crossed focal plane mask



Stellar PSF (Normalized)



10^{-10} star-light suppression at $1\lambda/D$

Toward 2029:

- 1) Testbed demonstration with two DMs (with 12×12 actuator) in VIS optics (if possible, NIR).
- 2) Detailed numerical simulation.

Summary

The 1DDLC is
a bar-coronagraph with a small inner working angle.

We can use the 1DDLC as
a fore-stage optics before an additional star-light
suppression instrument.

1DDLC:one-dimensional diffraction-limit coronagraph

Galaxy Evolution with HWO: Exploring the First Enriched Worlds

Lead author: Takahiro Morishita

Abstract: The James Webb Space Telescope (JWST) has transformed our understanding of galaxy formation in the first billion years of cosmic history. Observations have revealed surprisingly luminous galaxies at extreme redshifts, evidence for rapid chemical enrichment, candidate pristine galaxies, and unexpectedly diverse stellar populations, shifting the frontier from discovering the first galaxies to understanding the origin of heavy elements and the first generations of stars. Yet many of the key diagnostics of massive stars, stellar feedback, and chemical enrichment reside in the rest-frame ultraviolet, a wavelength regime that will become largely inaccessible in the coming era of Extremely Large Telescopes.

In this talk, I will discuss how the Habitable Worlds Observatory (HWO) can uniquely address these outstanding questions by providing deep ultraviolet spectroscopy, diffraction-limited UV imaging, and efficient slitless spectroscopic surveys. I will highlight recent JWST discoveries of extremely metal-poor and candidate pristine galaxies, and discuss how HWO can extend these studies to lower-mass systems and lower redshifts, where detailed investigations of the transition from pristine gas to chemically enriched galaxies become possible. I will also discuss the complementary roles of HWO, Roman, and ground-based ELTs in establishing a complete observational framework for galaxy evolution.

By tracing the emergence of the first enriched galaxies and the buildup of chemical complexity, HWO will connect the birth of the first stars to the physical conditions that ultimately enabled the formation of habitable worlds.

Science Case Summary

Galaxies transformed the early Universe by producing the first heavy elements needed for planets and life. HWO will uniquely observe the ultraviolet light from these young galaxies, allowing us to reveal how the first generations of stars enriched the Universe and paved the way for habitable worlds.



Galaxy Evolution with HWO

Exploring the First Enriched Worlds
in the Eras of JWST and ELTs

Takahiro Morishita
Tohoku University

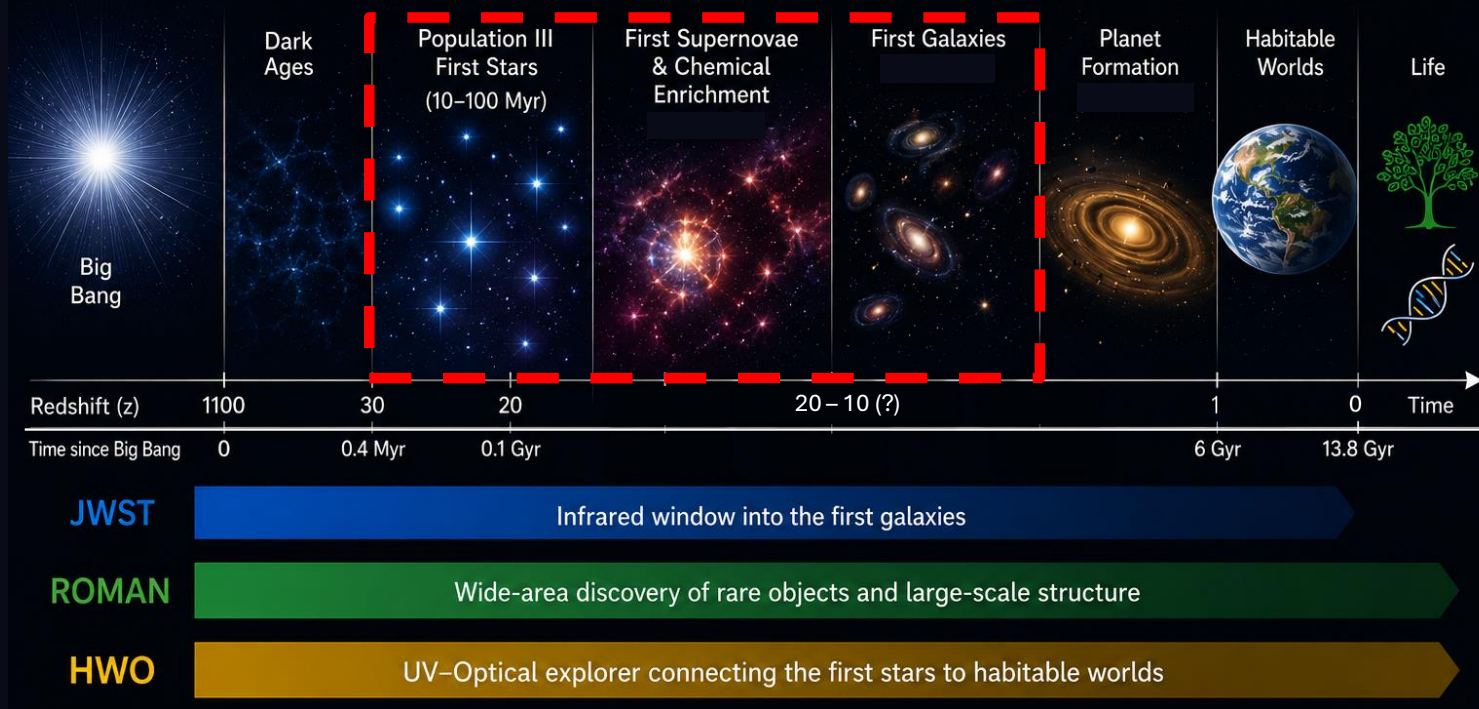
Habitable Worlds Observatory Japan Science Workshop 2
July 15-16, 2026 / JAXA ISAS Sagami-hara campus



ESA/Webb, NASA, CSA, A. Hirschauer, M. Meixner et al.

LIFE BEGINS LONG BEFORE PLANETS

*HWO will reveal the origin of chemical complexity
from the first stars to habitable worlds*

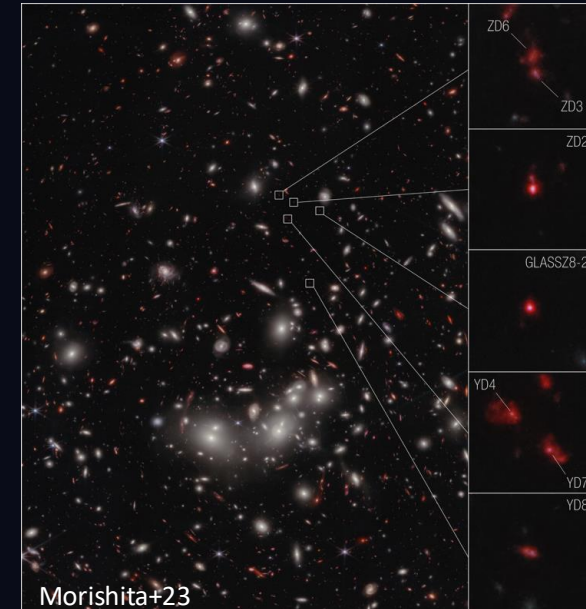
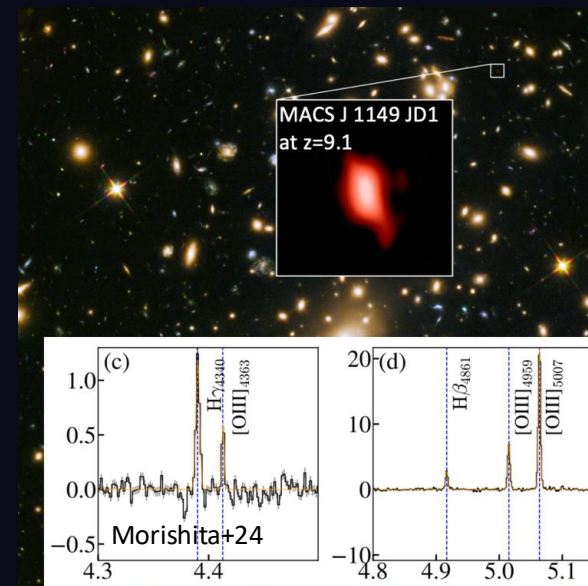
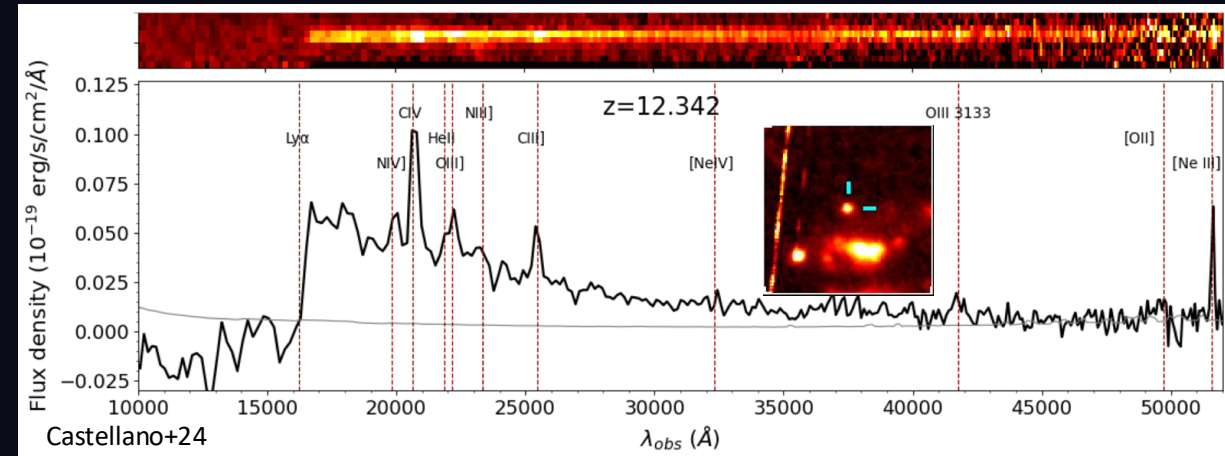
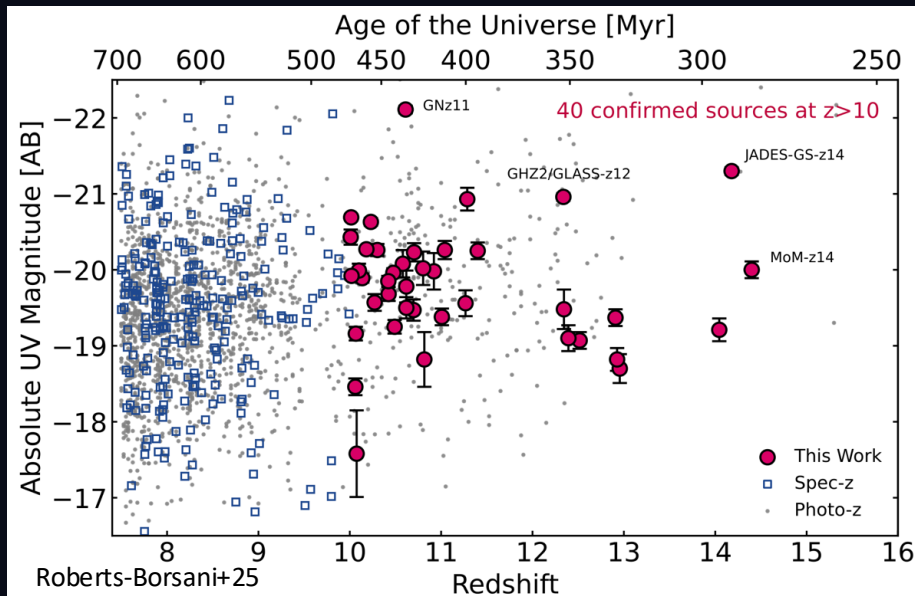


HWO is not only an exoplanet mission
It is the definitive observatory for the origin of
chemical complexity

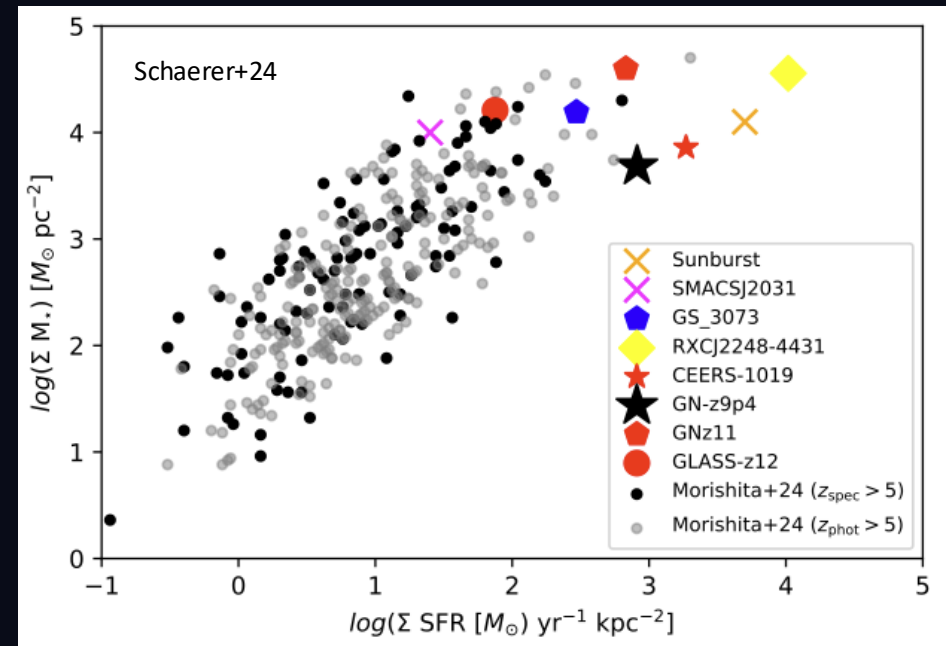
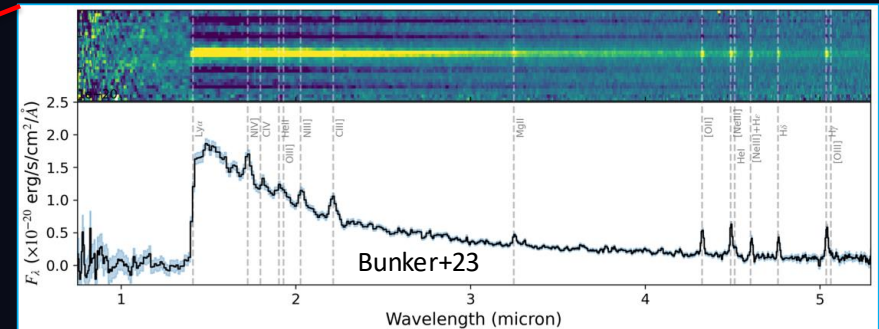
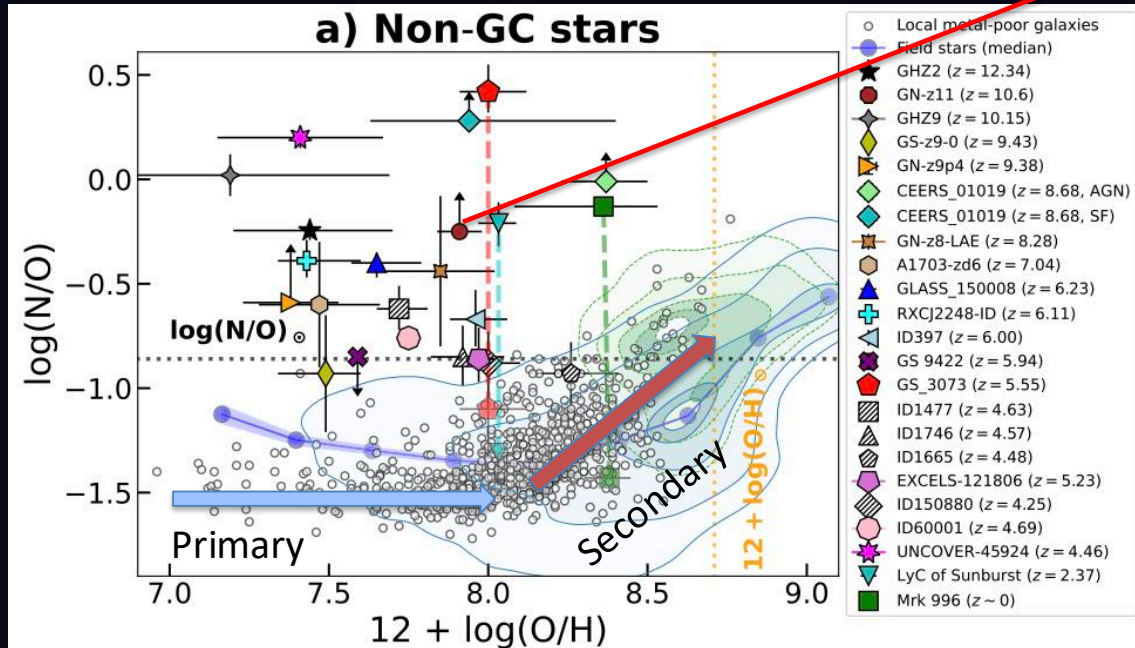
JWST Changed the Galaxy Evolution Landscape

JWST revealed...

- ✓ Many luminous galaxies at $z > 10$
- ✓ Heavy elements at $z > 10$
- ✓ Growth of large-scale structures
- ✓ Candidate pristine galaxies
- ✓ Extreme stellar populations



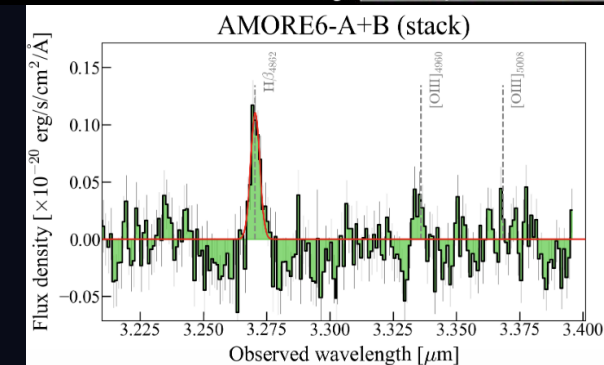
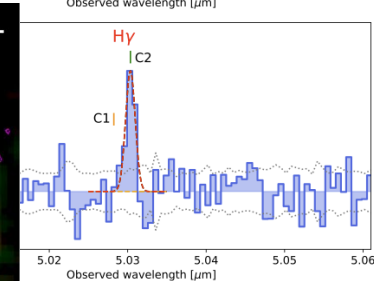
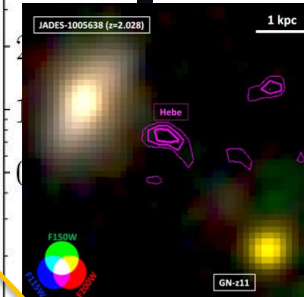
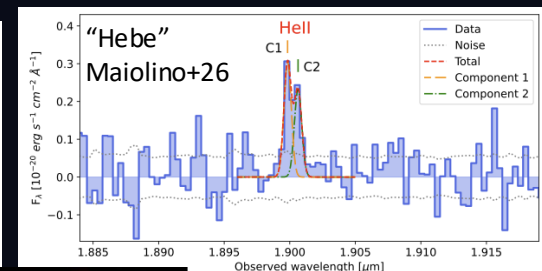
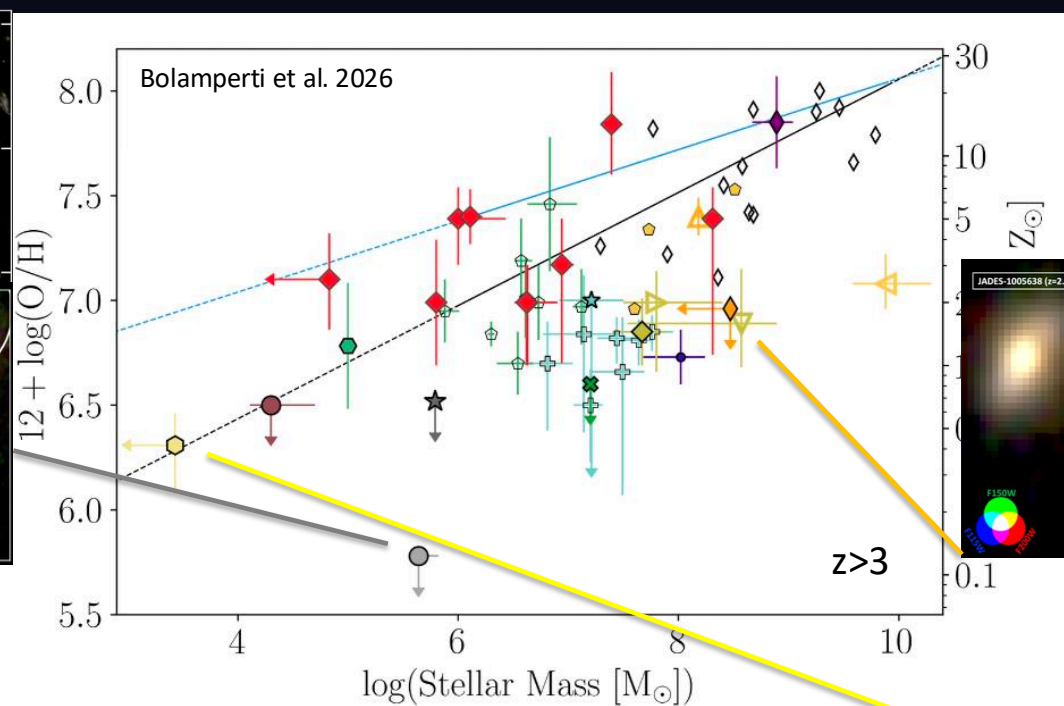
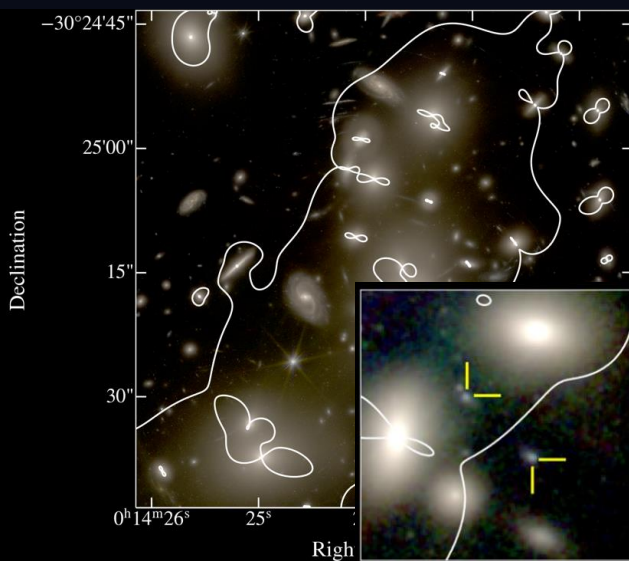
Discovery of Nitrogen-loud galaxies – Evidence of massive star formation?



- (1) Dilution by pristine gas?
- (2) Pollution by something exotic?
 - (1) Many Wolf-Rayet stars?
 - (2) Very massive stars?
 - (3) Tidal disruption event?

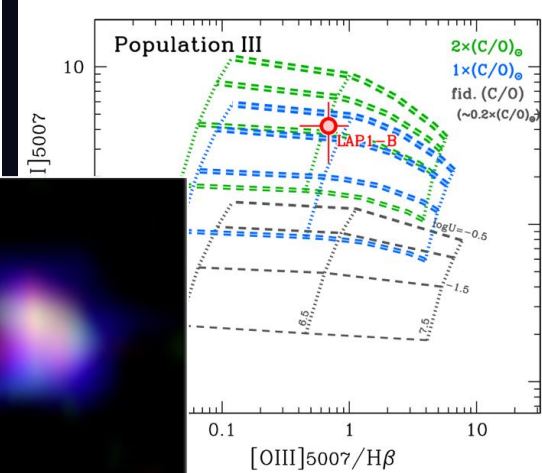
Is N-enrichment related to the bursty nature of high-z SFGs?

The Holy Grail in Galaxy Evolution – Pop-III galaxies: the key is UV diagnosis



- Curti+24, $z = 3.0 - 10$
- Morishita+24, $z = 3.0 - 9.5$
- ◇ Morishita+24, $z = 3.0 - 9.5$
- Cosmic Archipelago, $z \sim 6.14$, this work
- ◇ LAP1, $z = 6.6$, Vanzella+23, Nakajima+25
- LAP2-b, $z = 4.2$, Vanzella+25
- AMORE6 A+B, $z = 5.7$, Morishita+25
- ★ CR3, $z = 3.2$, Cai+25
- GNHeII J1236, $z = 2.98$, Mondal+25
- CAPERS-39810, $z = 3.65$, Cai&Yu26
- ★ Pseudo-LRD-NOM, $z = 5.96$, Caputi+25

- SAPPHIRES, $z = 5.7 - 6.8$, Hsiao+25
- GLIMPSE-16043, $z = 6.5$, Fujimoto+
- UNCOVER, $z = 6.0 - 7.7$, Chemerynsk
- Abell2744-QSO1, $z = 7.0$, Maiolino+2
- DREAMS.II, $z \sim 7$, Moka+25
- CANUCS-A370-z8-LAE, $z = 8.2$, W
- Firefly Sparkle, $z = 8.3$, Mowla+24
- EXCELS-63107, $z = 8.3$, Cullen+25
- CANUCS-LRD-z8.6, $z = 8.6$, Tripod
- JADES-GS-z9-0, $z = 9.4$, Curti+25
- Hebe, $z = 10.6$, Maiolino+26, Übler+26

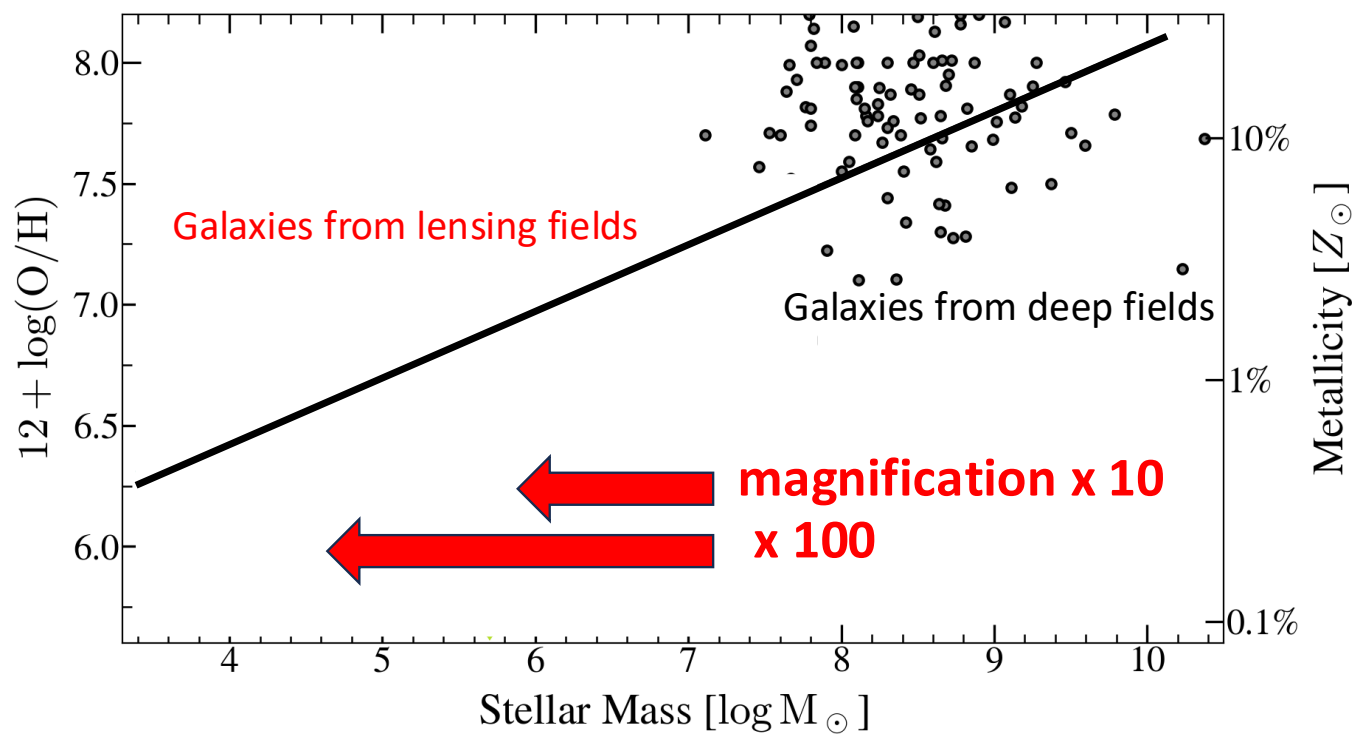


Detection of strong CIV in LAP1-B
(Nakajima et al. 2026)

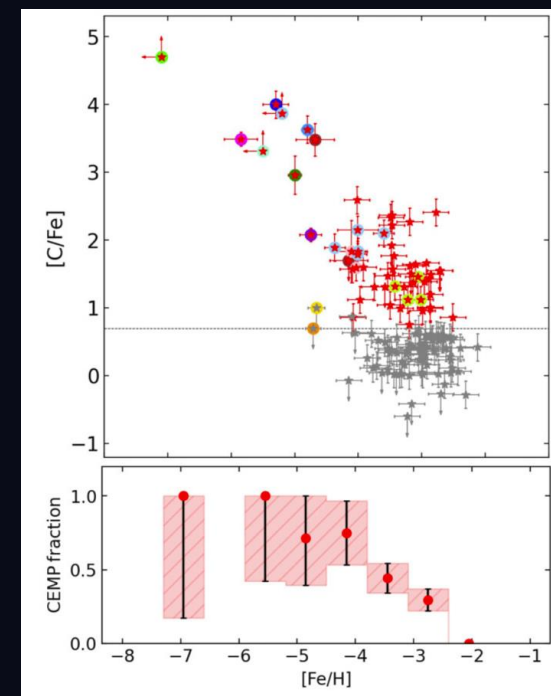
Extremely low O3/H β ratio seen with WFSS
(Morishita+25)

Takahiro Morishita @ HWO Japan Workshop 2026

JWST is not enough. Metallicity floor yet to break



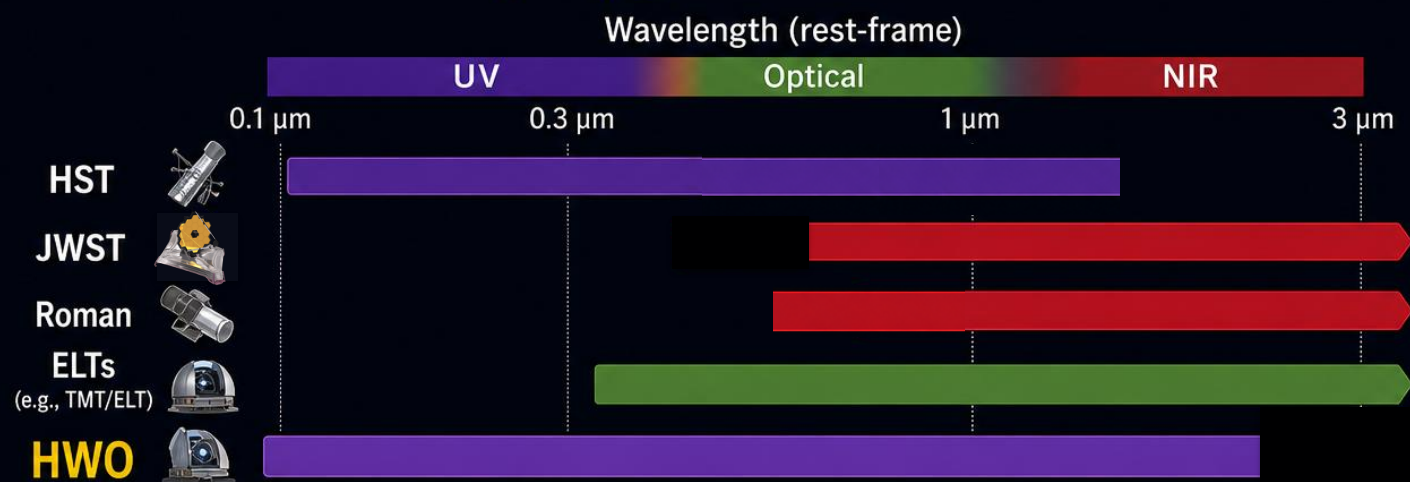
What theory defines Pop.III
($<10^{-4} - 10^{-5} Z_{\text{sun}}$)



MW metal-poor stars $[M/H] \sim -5$
(Vanni et al. 2023)

What does HWO mean to Galaxy Evolution, in the Eras of JWST&ELTs?

No facility provides deep UV spectroscopy of young galaxies at $2 < z < 6$.



Facility	Limitation
JWST	Cannot observe rest-UV at $z < 6$
ELTs	Atmosphere and bright sky background
Roman	Survey only, low spectral resolution
HST	Too small and retiring

The rest-frame UV—the direct probe of massive stars, metal enrichment, and feedback—will become inaccessible.
HWO fills this gap.

What does HWO mean to Galaxy Evolution, in the Eras of JWST&ELTs?

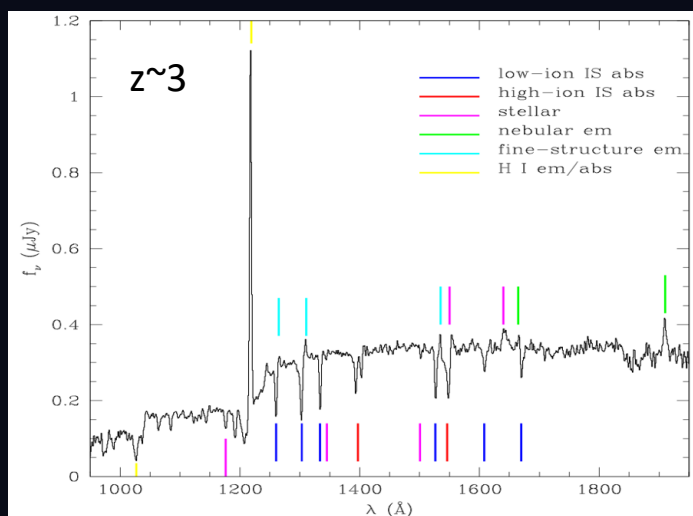
Scientific questions that can be addressed:

- Do extremely low-mass galaxies at $z < 6$ host pristine stars?
- Do they have the characteristic features that we are seeing in JWST galaxies? (Ouchi-san, Nakajima-san's talk)
- Do they allow us to study massive SF in further detail?
- Interplay between cold/warm gas and star formation & AGN? AGN and host galaxy co-evolution (Onoue-san's talk)

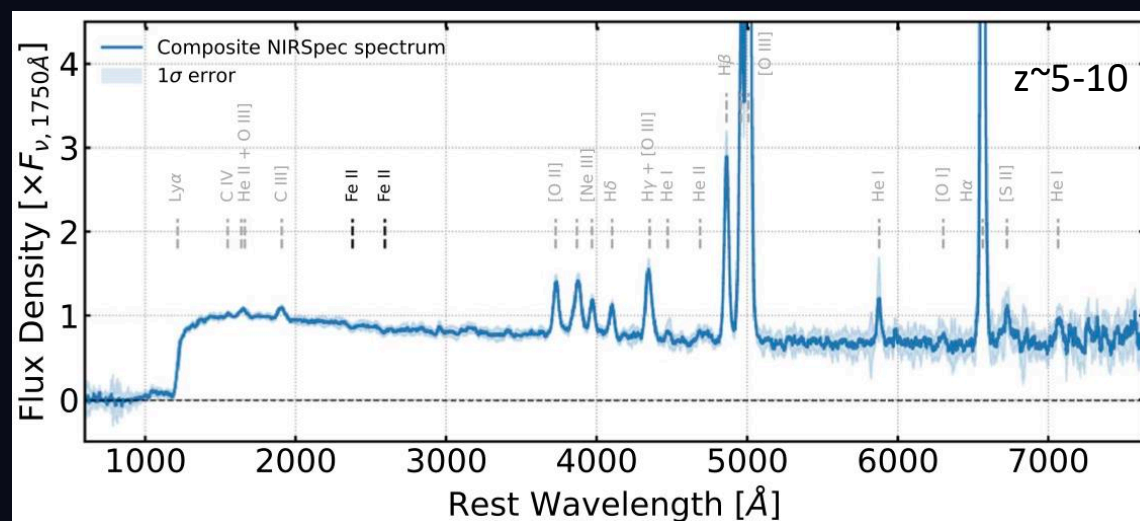
What does HWO mean to Galaxy Evolution, in the Eras of JWST&ELTs?

List of previous rest-UV galaxy surveys

Facility	Survey	Technique	Redshift
GALEX	AIS/MIS/DIS	UV imaging	0–1
HST	UVUDF, HDUV, UVCANDELS	UV imaging	1–3
VLT	VANDELS	MOS	2.5–5.5
VLT	VUDS	MOS	2–6
VLT	MUSE Deep/UDF	IFU	2.8–6.7
Keck	KBSS, MOSDEF (rest optical)	MOS	2–3
Subaru	PFS	MOS	3–7
JWST	NIRCam WFSS	slitless	4–15

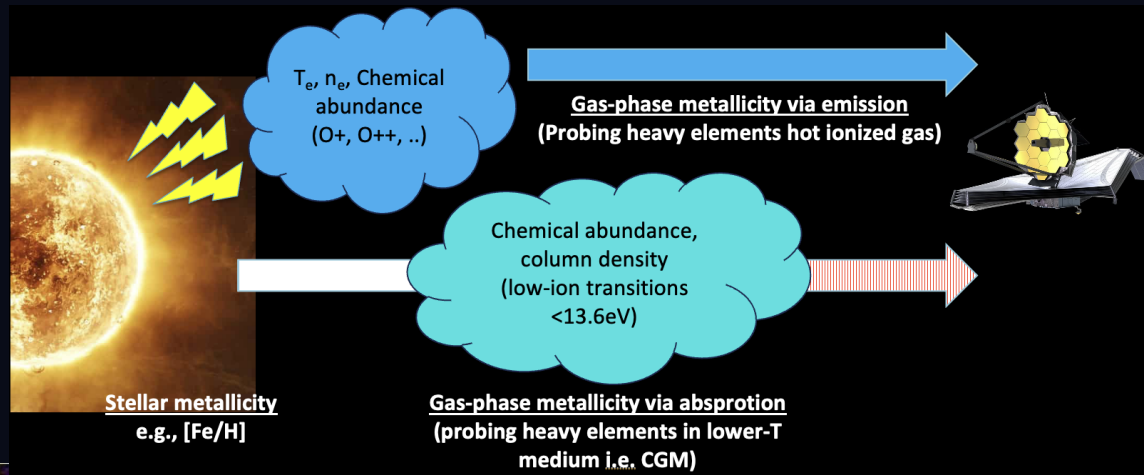


Composite spectrum of typical $z \sim 3$ LBGs (Shapley+03)

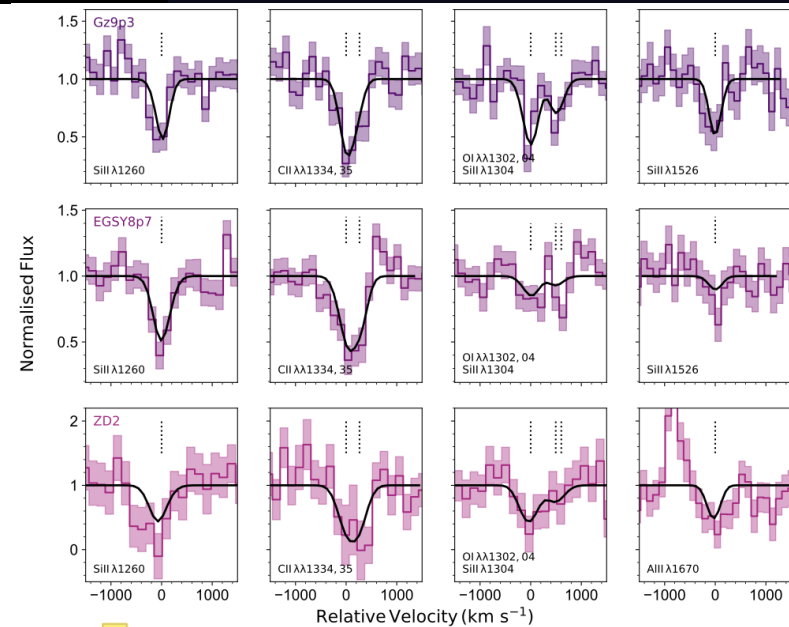
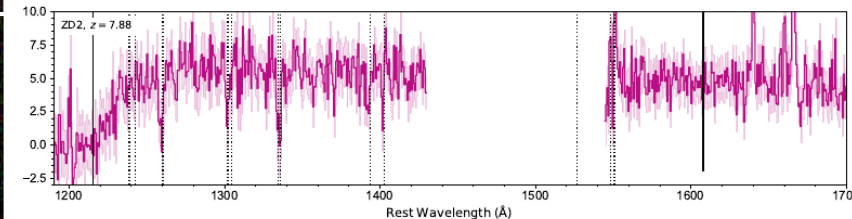
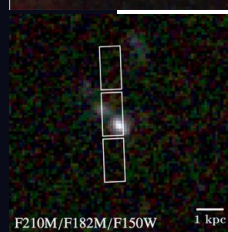
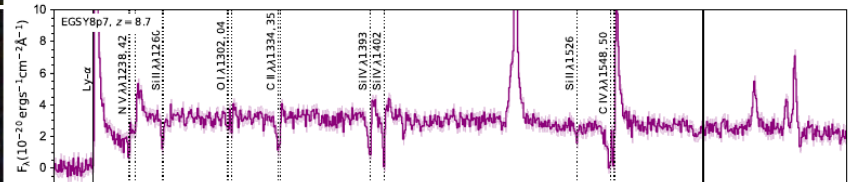
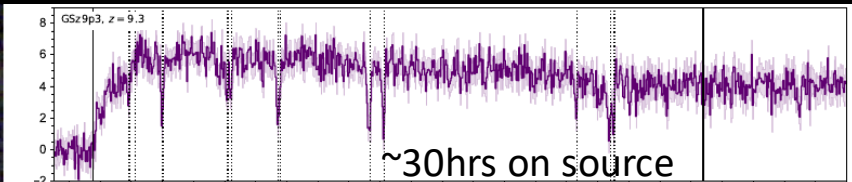


Composite spectrum of $z \sim 5-10$ JWST galaxies (Roberts-Borsani+24)

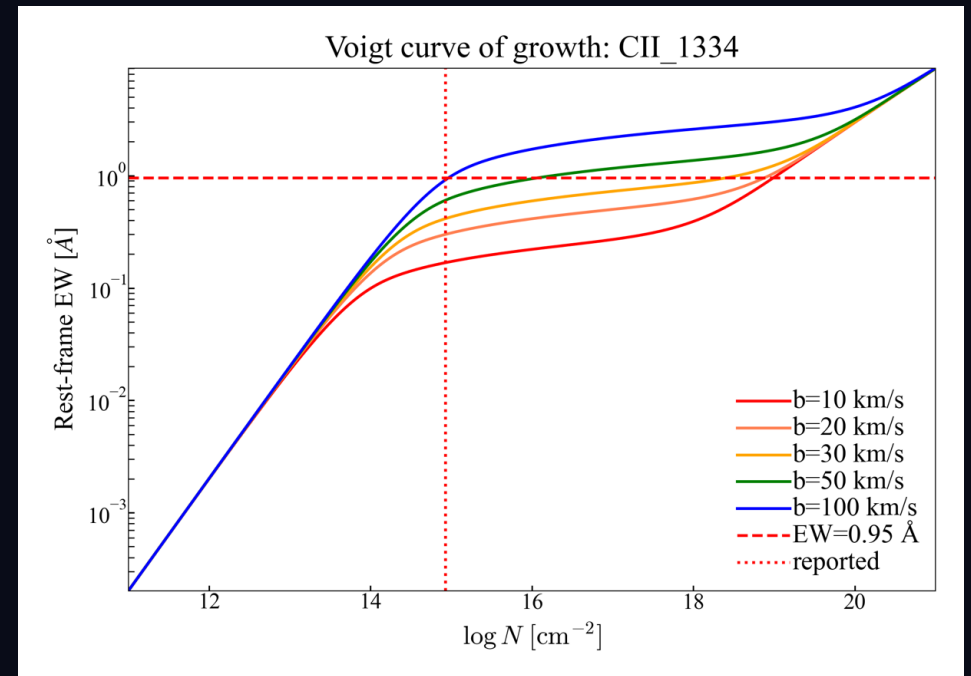
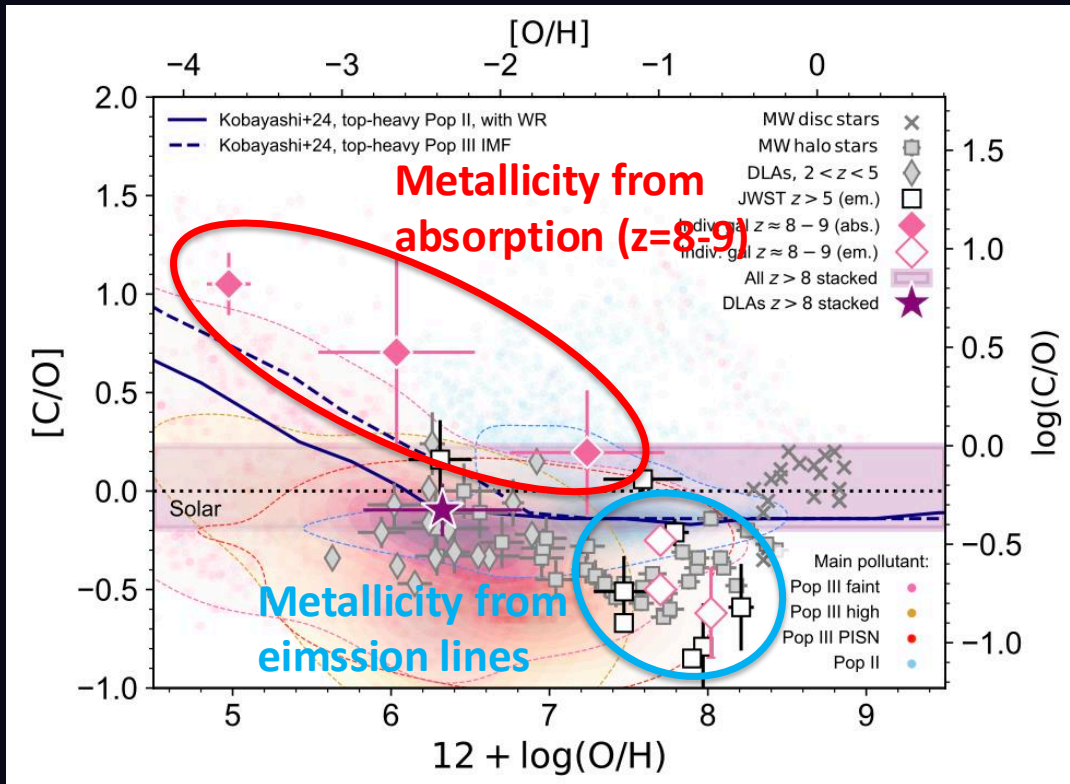
Break the metallicity floor with sensitive absorption spectroscopy



Pollock+26; also Chen+25,
Nakane&Ouchi26



Break the metallicity floor with sensitive absorption spectroscopy



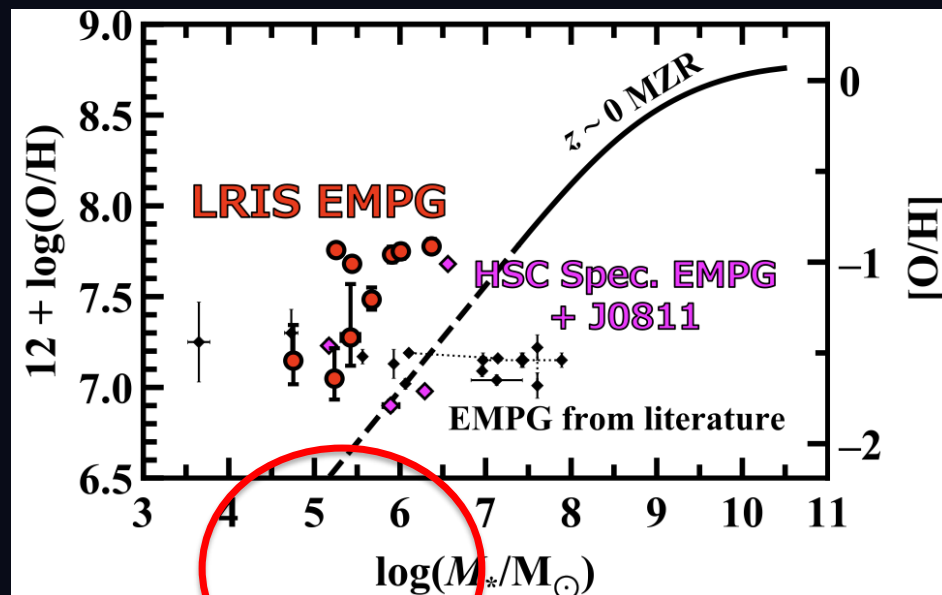
Note that these are at an assumed width, b .
 $R=1000$ spectrum may not be sufficient. +instrumental effect
 EW-Column density relation holds at optically thin

**Requires good UV sensitivity
 & high spectral resolution**

Cf. Nakane & Ouchi 26 for a more comprehensive analysis

Study of extremely low-mass galaxies at $2 < z < 6$

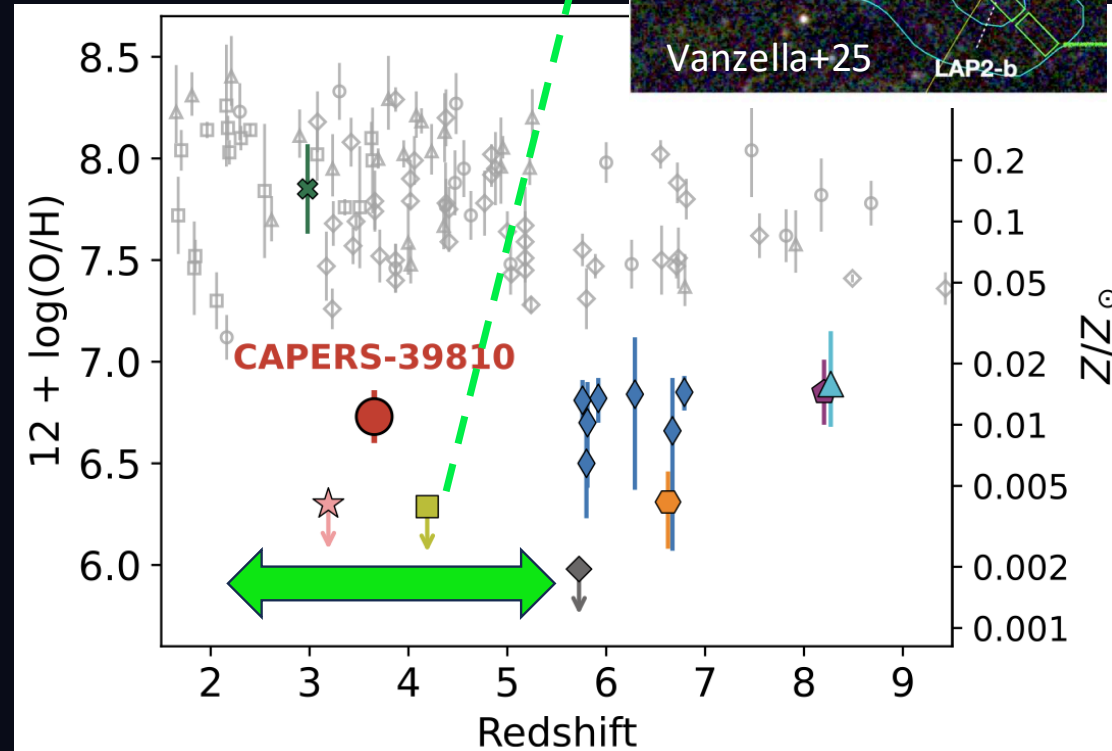
Isobe+22



**Target galaxies at $z \sim 2$ -
for HWO**

EMPGs, with $\sim 10^4$ - $10^6 M_\odot$:
Previously, only accessible at $z \sim 0$
Already enriched to $\gg 1\%$ Solar

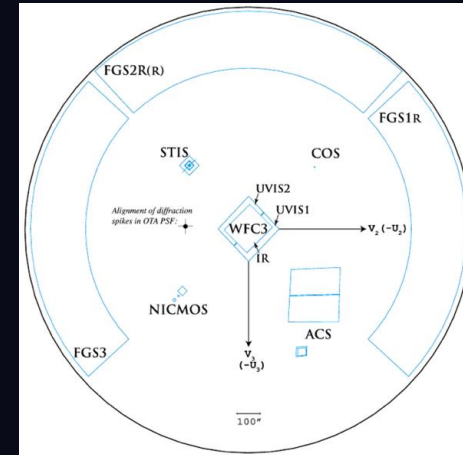
Yu&Cai26



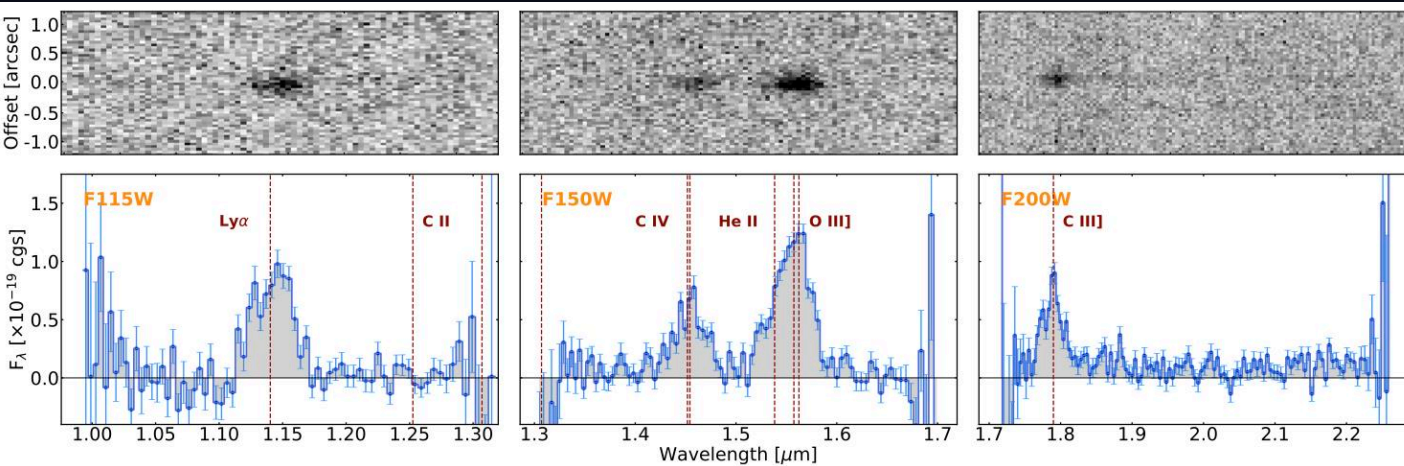
**Recent JWST surveys started seeing
pristine galaxy candidates at lower z s**

UV surveys with low-res slitless spectroscopy

- Slitless spectroscopy requires low BKG, unique in space
- 2x3 arcmin FoV (similar to HST)
- Survey in parallel mode too?
- ** AMORE6 was discovered in NIRCam WFSS serendipitously

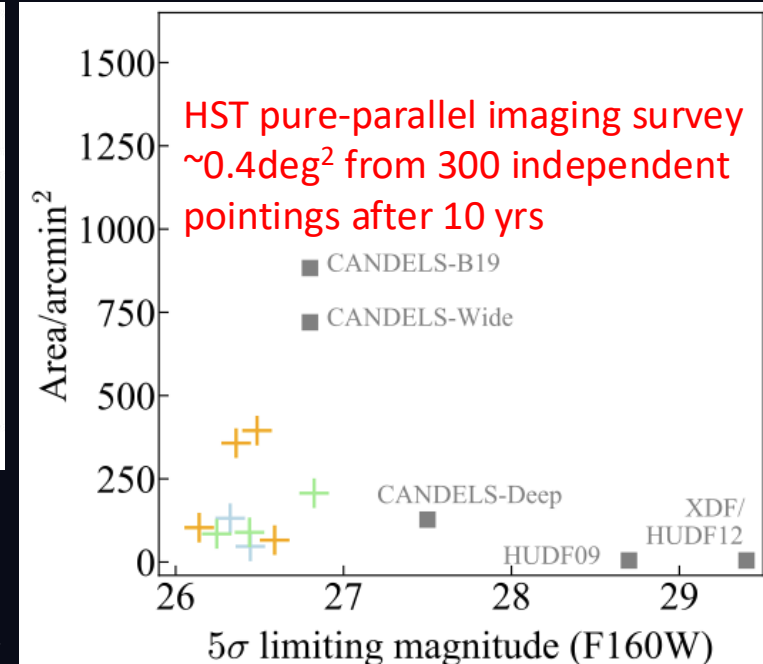


Focal plane of HST instruments



Slitless $R \sim 150$ spectroscopy simulation for JWST NIRISS (Treu+23)

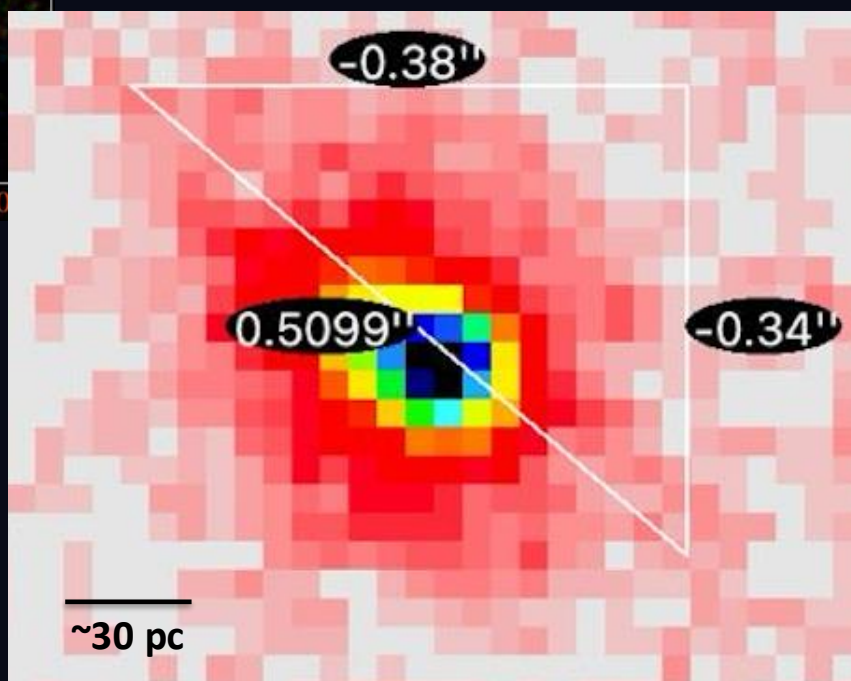
Morishita 2021



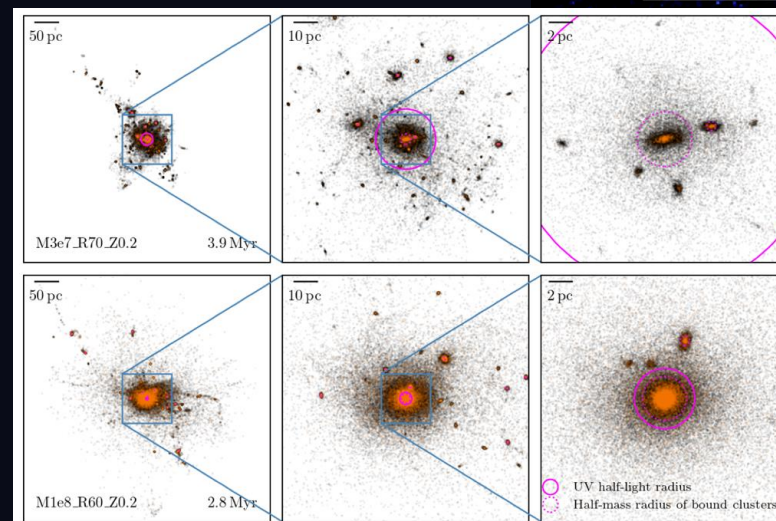
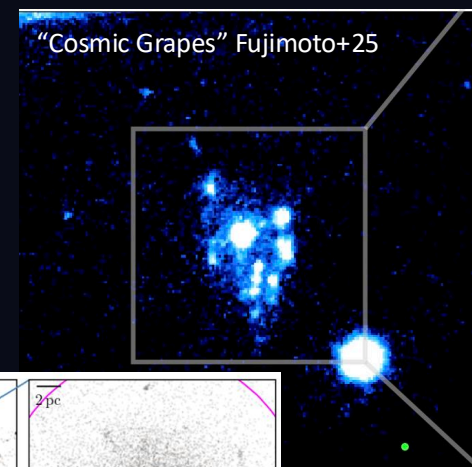
High-resolution UV imaging/IFU to spot the massive star forming region



A factor x80 magnification + JWST is not enough to resolve massive SF



AMORE6-B in JWST stack (courtesy: E. Vanzella)

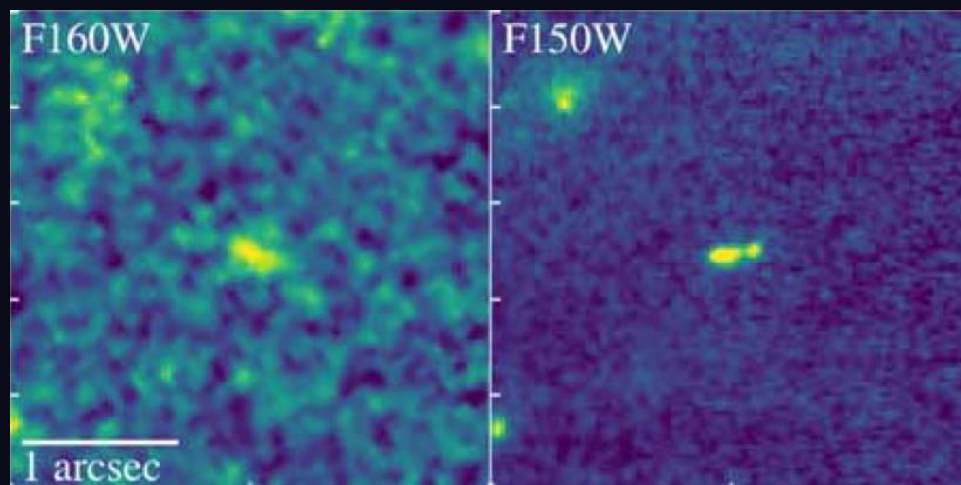


ELTs will better resolve but only at $>0.7\mu\text{m}$, leaving the distribution of massive stars (UV-bright) unconstrained

High-resolution UV imaging/IFU to spot the massive star forming region

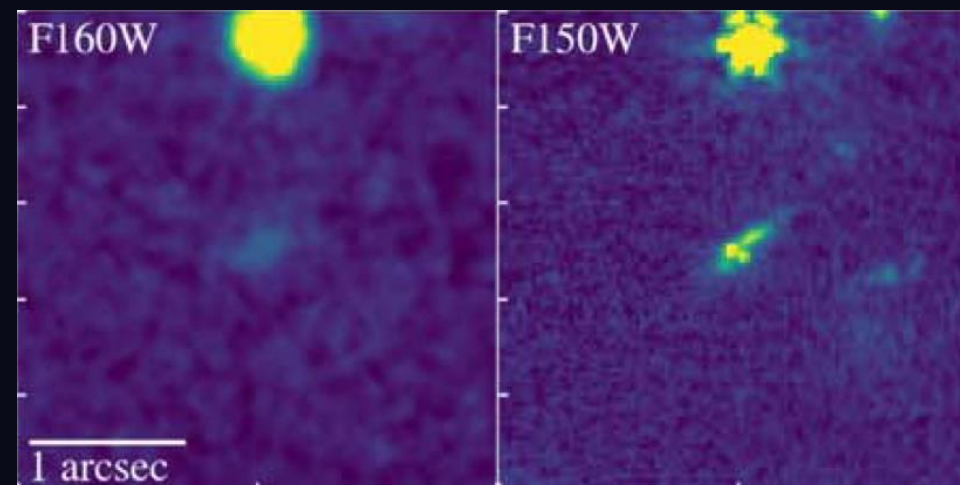
Hubble

JWST



Hubble

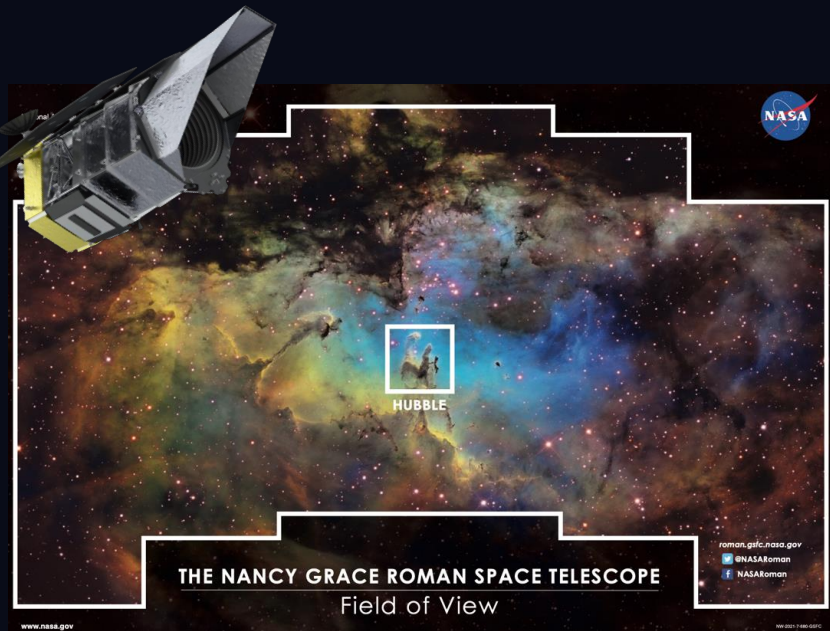
JWST



Morishita & Stiavelli 23

ELTs will better resolve but only at $>0.7\mu\text{m}$, leaving the distribution of massive stars (UV-bright) unconstrained

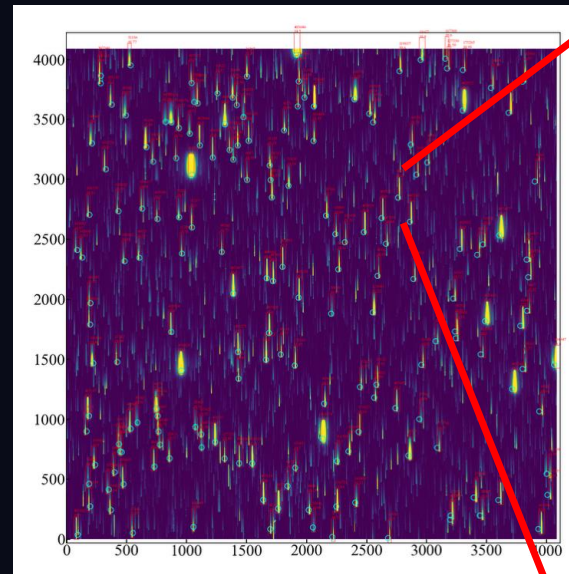
Roman to play important roles by finding high EW emitters



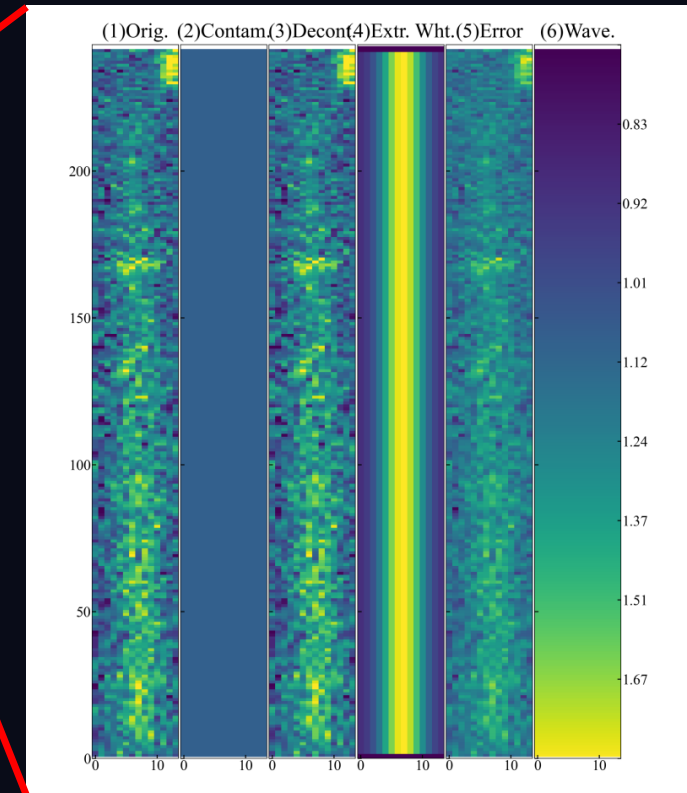
To be launched in Aug 2026

From HLWAS,

- ~10 million H α emitters at $z=1-2$
- ~2 million [OIII] emitters at $z=2-3$
- 500,000 LAE/LBGs at $z>5.5$ ($m<28$)
- 33,000 $>10^{11}M_{\text{sun}}$ galaxies at $1.5<z<3.7$



Roman slitless spectroscopy simulation



Processed 2D spectrum by G2DP

Exploring the First Enriched Worlds with HWO

Science & Requirement

Science Observable Requirement

Metallicity UV emi.&abs. lines High throughput, $R > 3000$

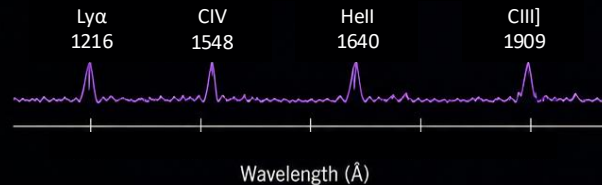
Massive star formation UV imaging/IFU Diffraction limit ($\sim 0.02''$ @ $0.5\mu\text{m}$?) Stable PSF

Spectroscopic survey RF UV lines $R \sim 100$, slitless (i.e. low-background preferred)
Slitless spectroscopy in parallel

1 Deep UV Spectroscopy

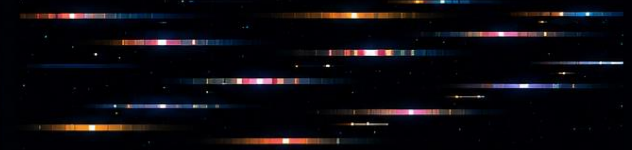
Measure the fingerprints of the first stars and their environments.

$\text{Ly}\alpha$, C IV, He II, O III], C IV emissions and LIS absorptions at $2 < z < 6$.



2 Parallel Slitless Surveys

Discover thousands of young, metal-poor galaxies efficiently without preselection.

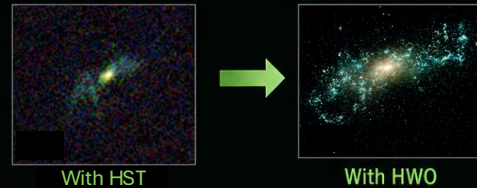


Simultaneous low- R spectroscopy ($R \sim 100$) over a wide field

3 Diffraction-limited UV Imaging/IFU

Resolve massive star-forming regions down to $\sim 0.02''$

(physical scales of a few pc at high- z).



4 Synergy Across the Next Generation

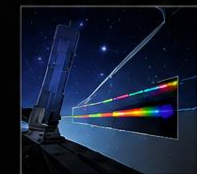
Roman

discovers 10^6 galaxies



HWO

characterizes metal-poor systems



JWST/ELTs

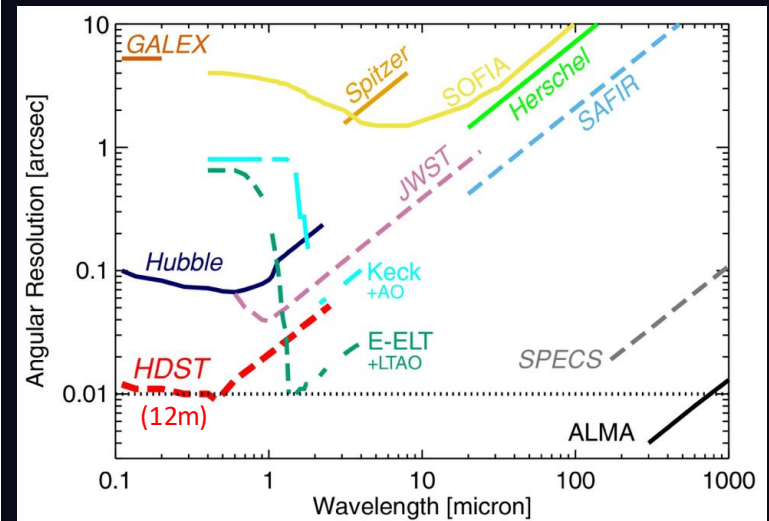
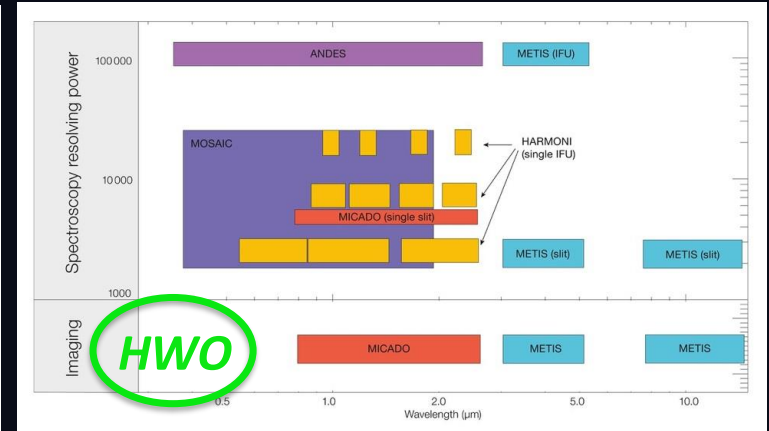
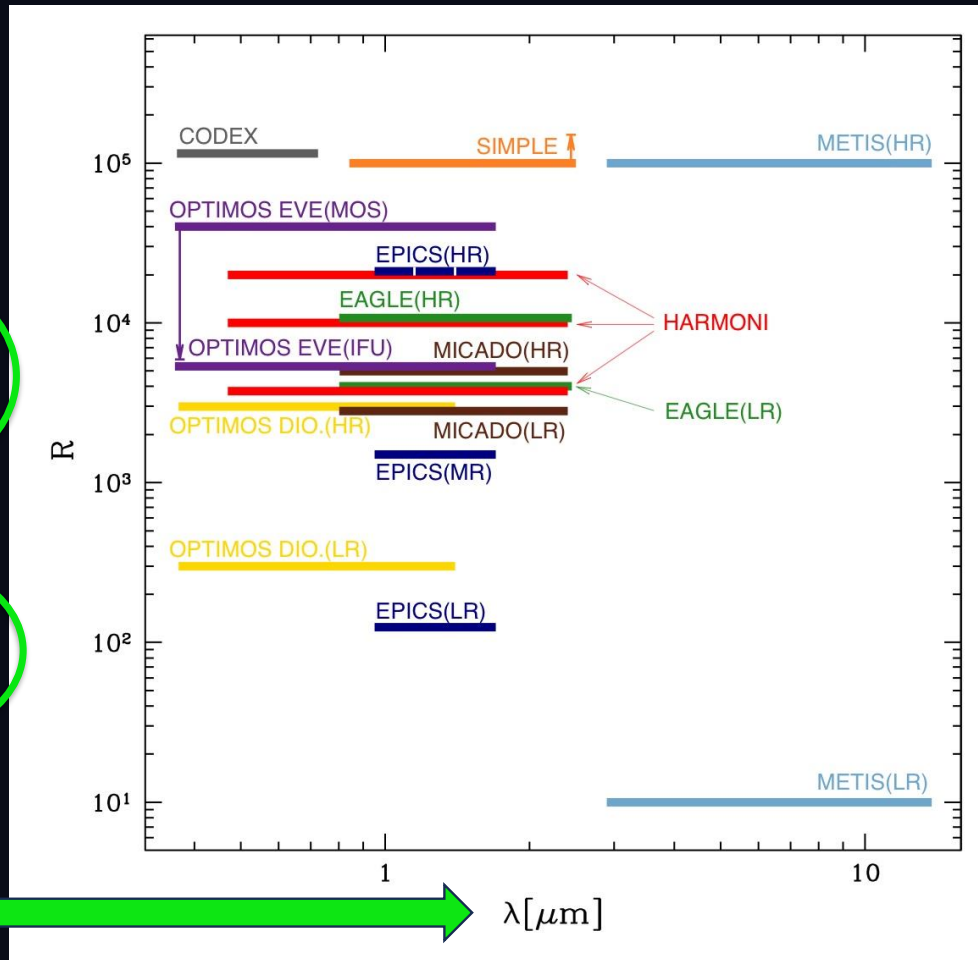
resolves star-forming regions



HWO is the bridge connecting the first stars to habitable worlds.

From the birth of chemical complexity to the origins of life.

Exploring the First Enriched Worlds with HWO



From <http://www.hdstvision.org/gallery-index>

Title:

UV-to-NIR Spectroscopy with HWO: Connecting High-Redshift and Local Galaxy Evolution

Lead author: Kimihiko Nakajima

Abstract:

The HWO will provide unprecedented sensitivity for the study of galaxy formation and evolution. From the perspective of high-redshift spectroscopy, this talk will explore the anticipated impact of HWO's UV-to-NIR capabilities. Specifically, I will highlight the scientific potential of the Imager's grism mode and discuss the importance of the inclusion of a NIR channel in the MOS/IFU. A dedicated NIR mode is essential for advancing our understanding of cosmic reionization and chemical evolution in the early universe. By linking these distant observations with local UV spectroscopic studies of Lyman continuum leakage and rest-frame UV diagnostics, HWO will provide a unified framework for tracing galaxy evolution across cosmic time.

Science Case Summary

We will trace the origins of the first heavy elements to understand how early stars chemically enriched primitive galaxies, while also determining how intense radiation from these sources escaped to clear the dense hydrogen fog of the early universe. Because these ancient light signatures are stretched into the near-infrared as they travel to us, while their local galaxy counterparts are visible in the ultraviolet, we absolutely need both capabilities. By combining ultraviolet and near-infrared spectroscopy, we can seamlessly connect these earliest cosmic milestones to the mature galaxies we see around us today.

HWO Japan Science Workshop 2
@ JAXA on July 16, 2026

UV-to-NIR Spectroscopy with HWO: Connecting High-Redshift and Local Galaxy Evolution

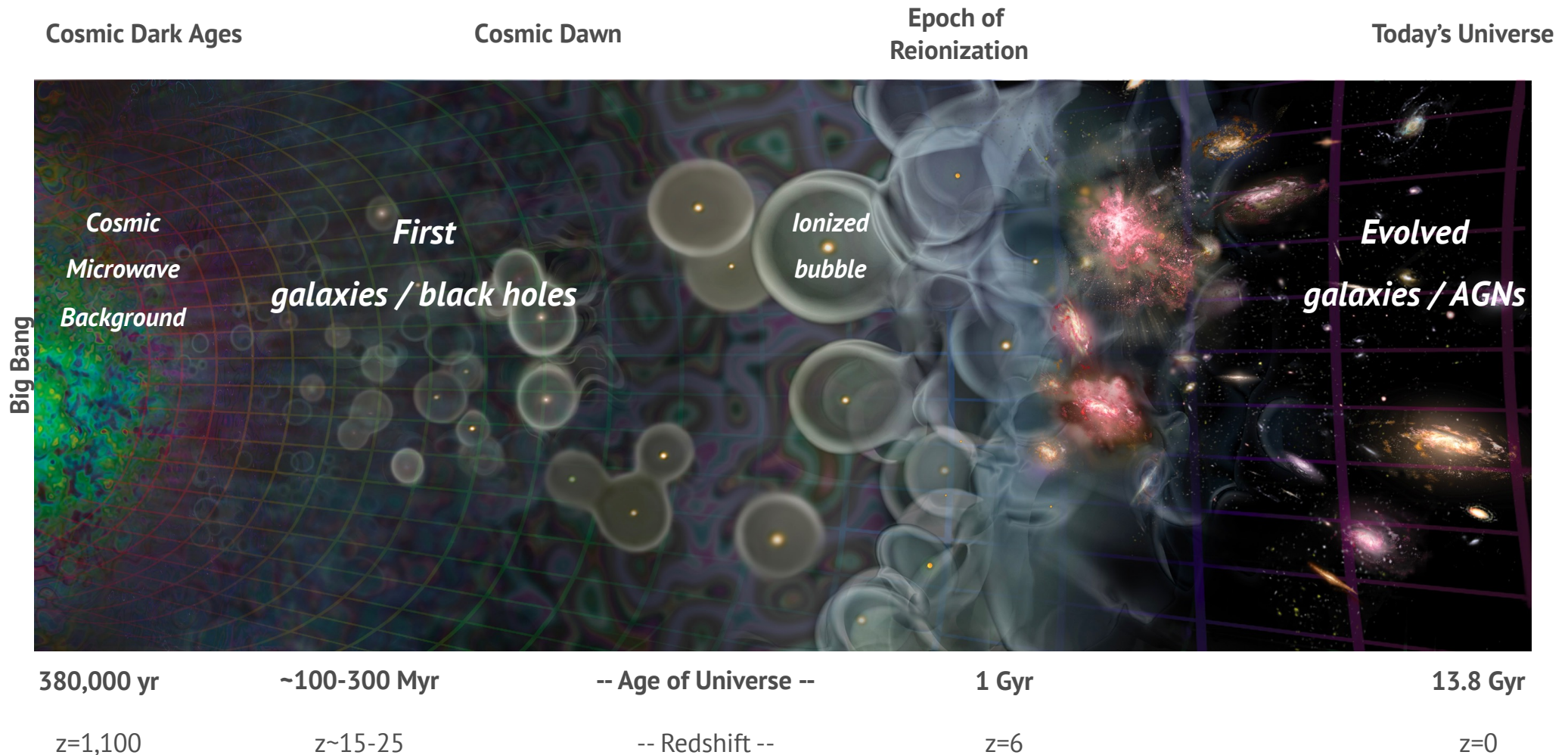
© Loeb 2006



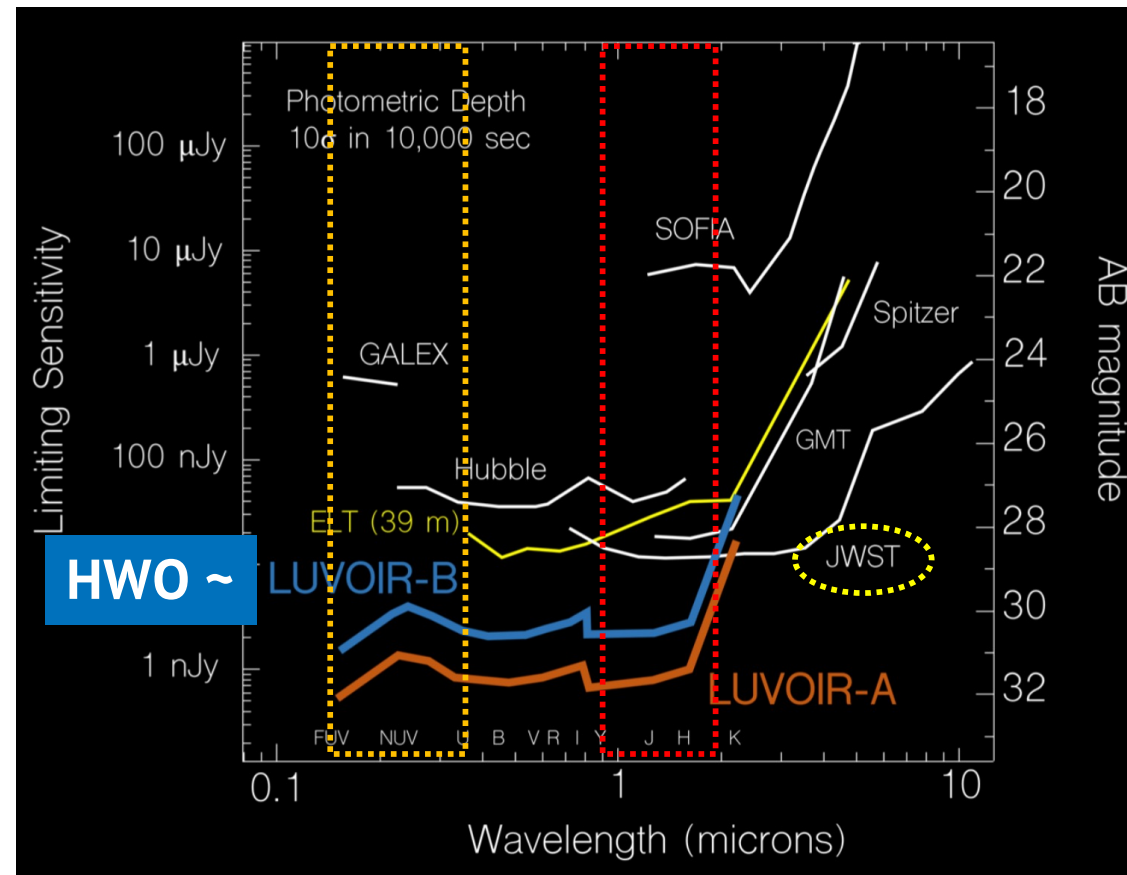
Kimihiko NAKAJIMA

Kanazawa Univ.

Key science of HWO: Evolution of Cosmic Structures, incl. How Galaxies Form and Develop Over Cosmic Time



UV-to-NIR Spec. capability will offer crucial final push for studies of galaxy formation and evolution in 2040+



LUVIR Final Report

Far UV (ideally, spatially resolved)

→ UV spec. properties in **local** galaxies

Nature of ionizing spectrum (Stars vs. Blackholes)

Origins of elements

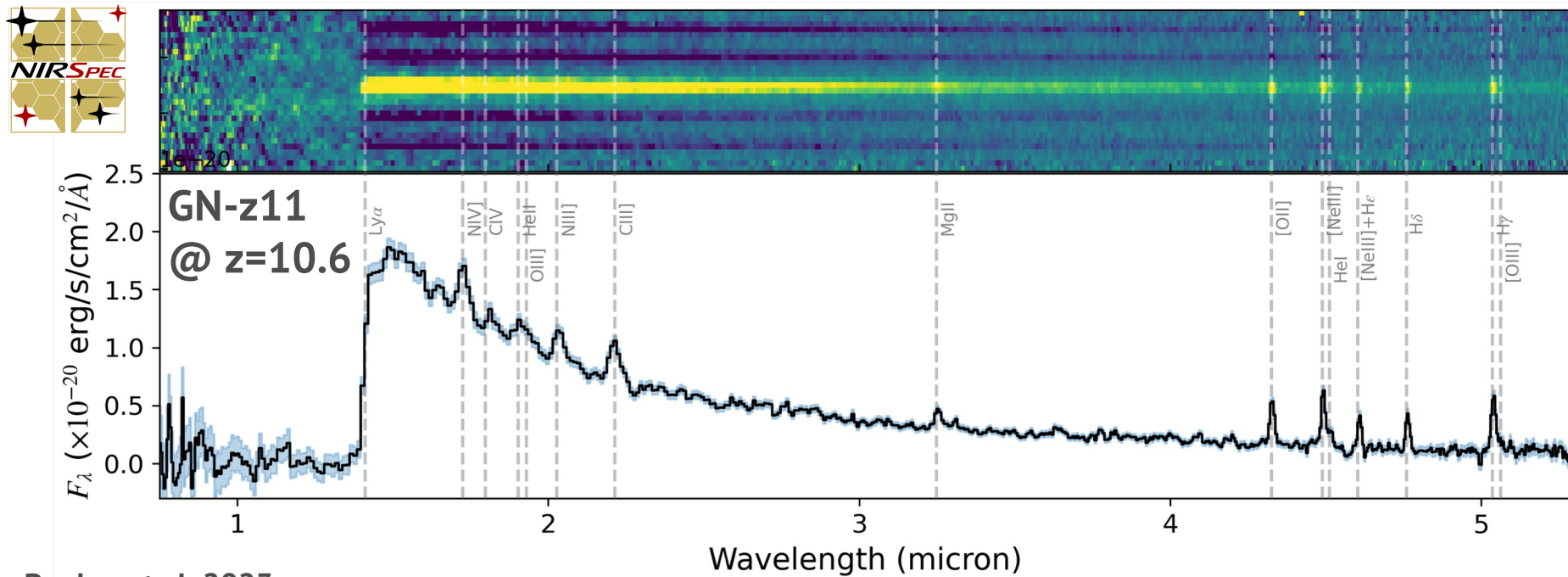
Ionizing photon escape (Cosmic Reionization)

Near IR

→ UV spec. properties in **high-redshift** galaxies

Nature of Ionizing Spectrum: Stars vs. Blackholes

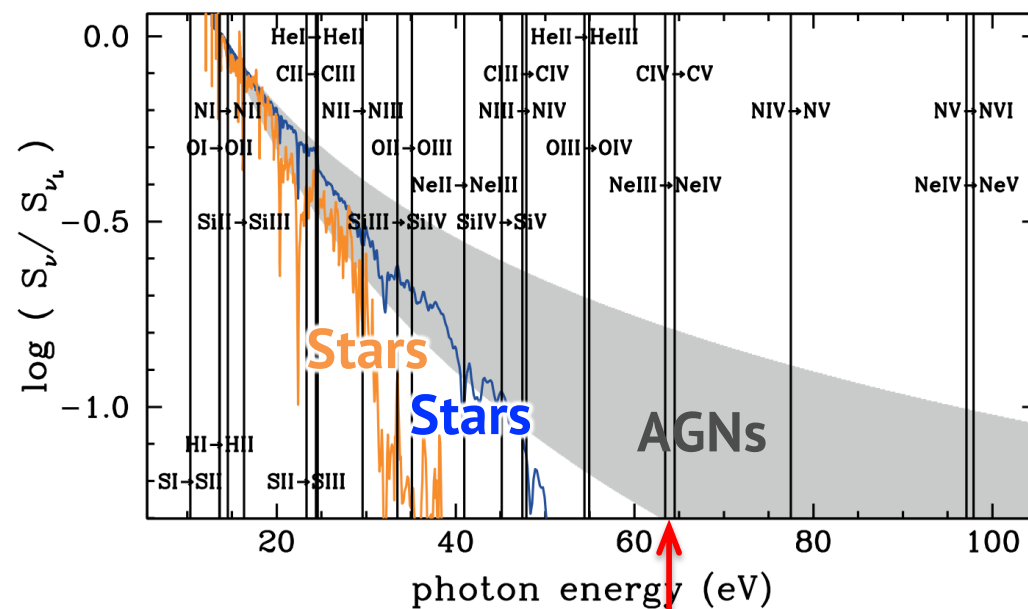
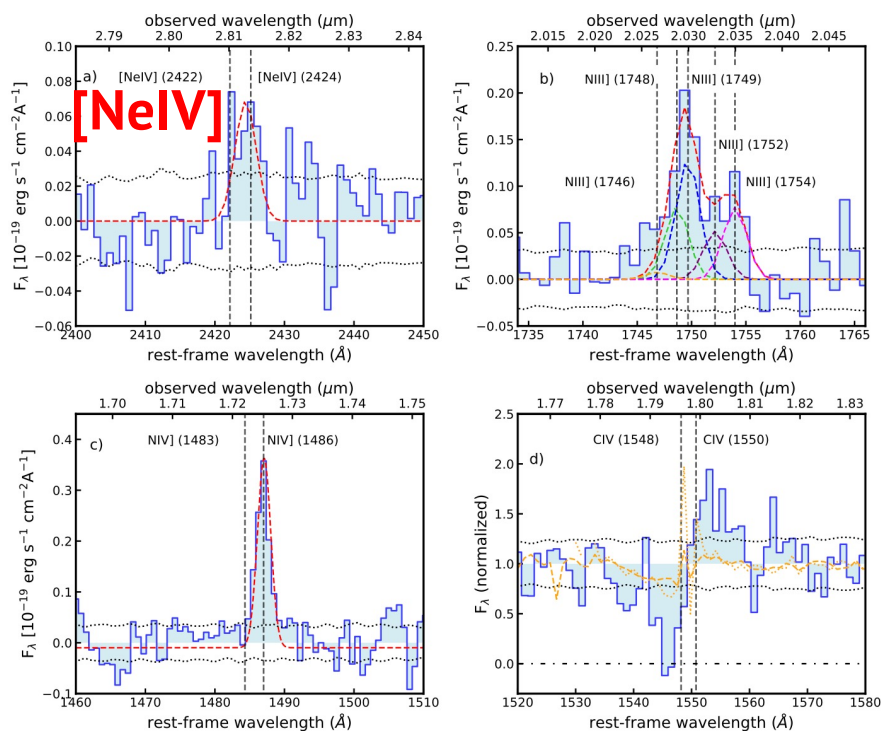
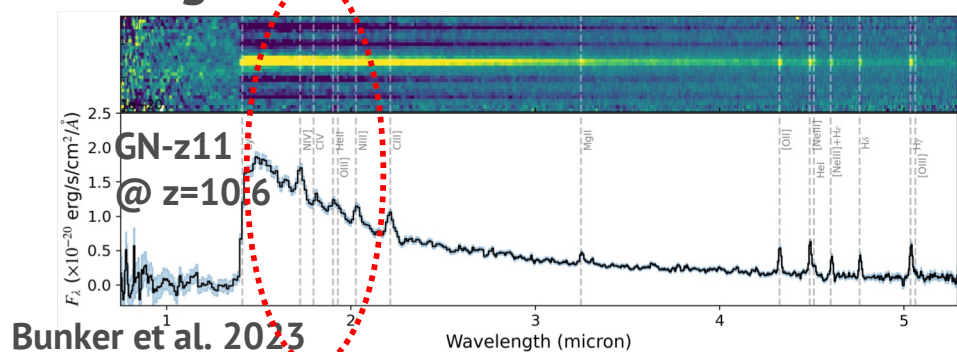
High ionization emission lines in rest-UV as probes of AGN



Bunker et al. 2023

Nature of Ionizing Spectrum: Stars vs. Blackholes

High ionization emission lines in rest-UV as probes of AGN



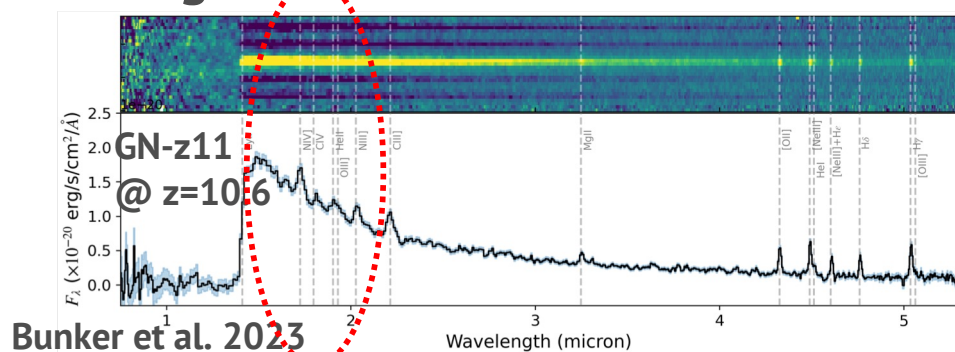
Feltre et al. 2016

High energy photons that cannot be produced by stars

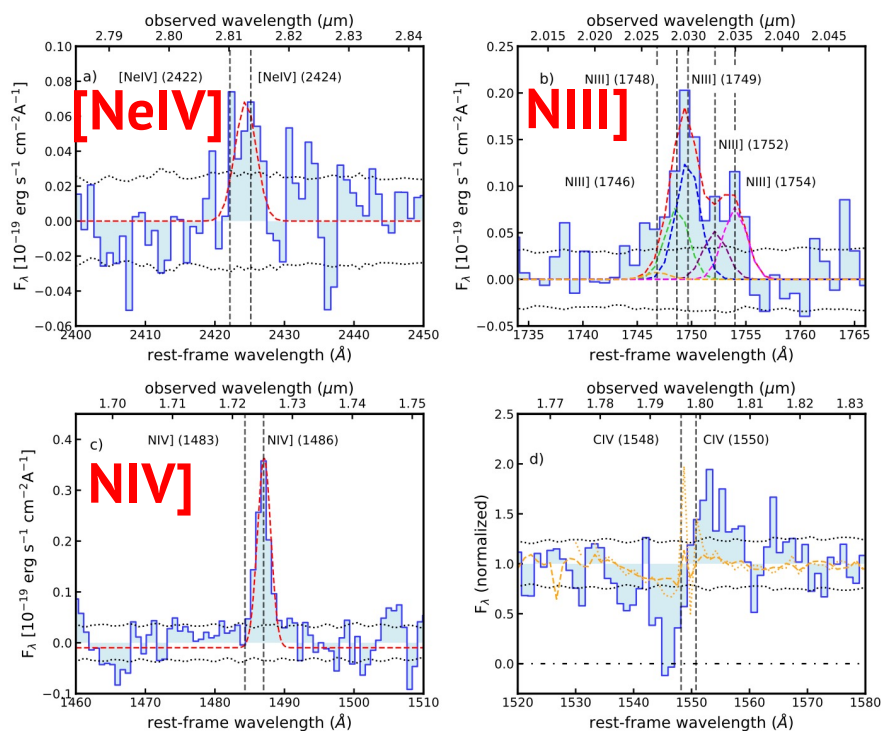
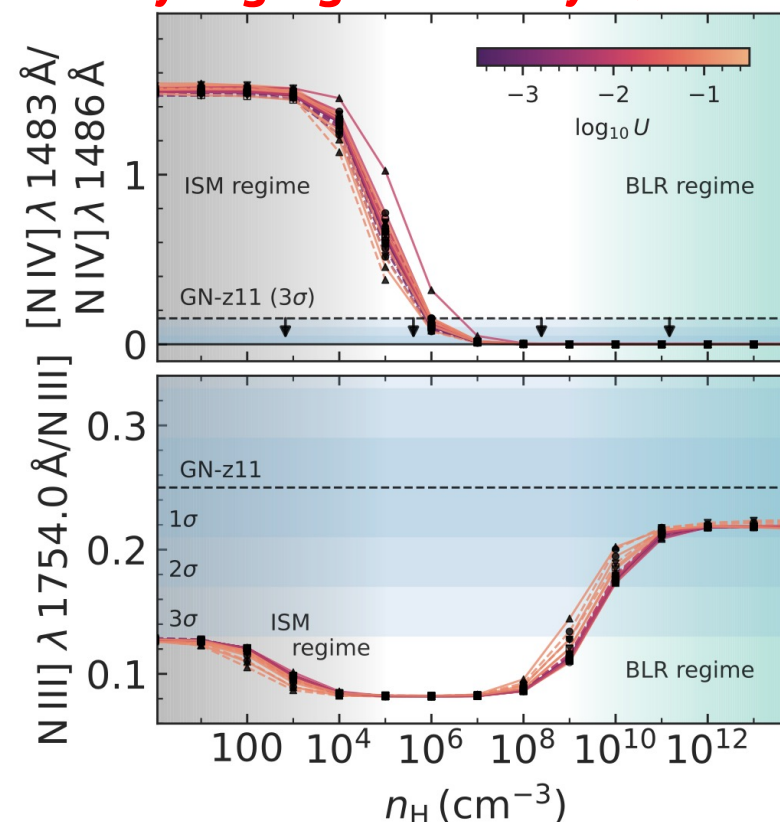
※ [NeV]3426 & NV1240 also useful
In addition to [NeIV]

Nature of Ionizing Spectrum: Stars vs. Blackholes

High ionization emission lines in rest-UV as probes of AGN



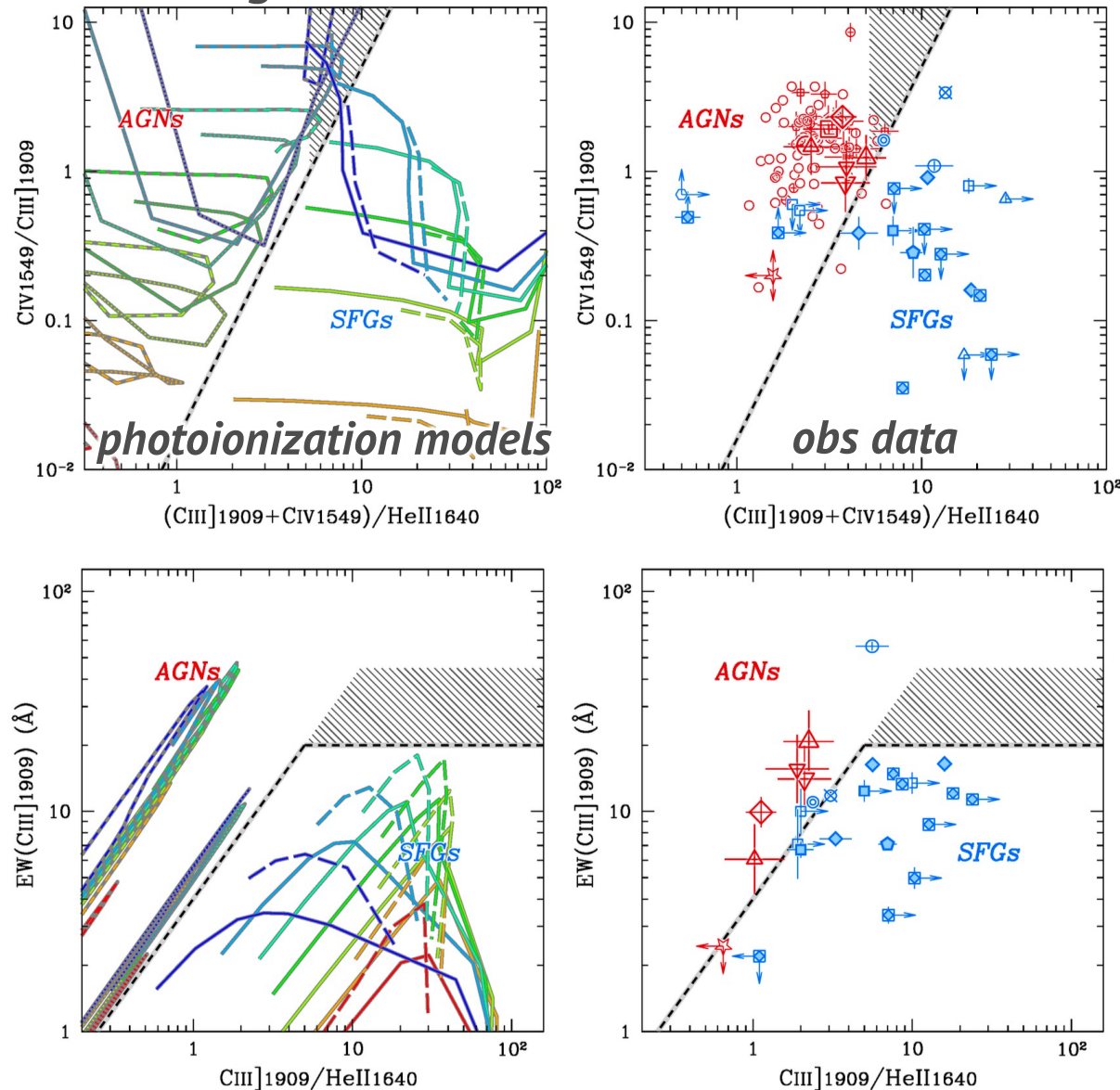
Very high gas density ($>\sim 10^{10}/\text{cc}$)



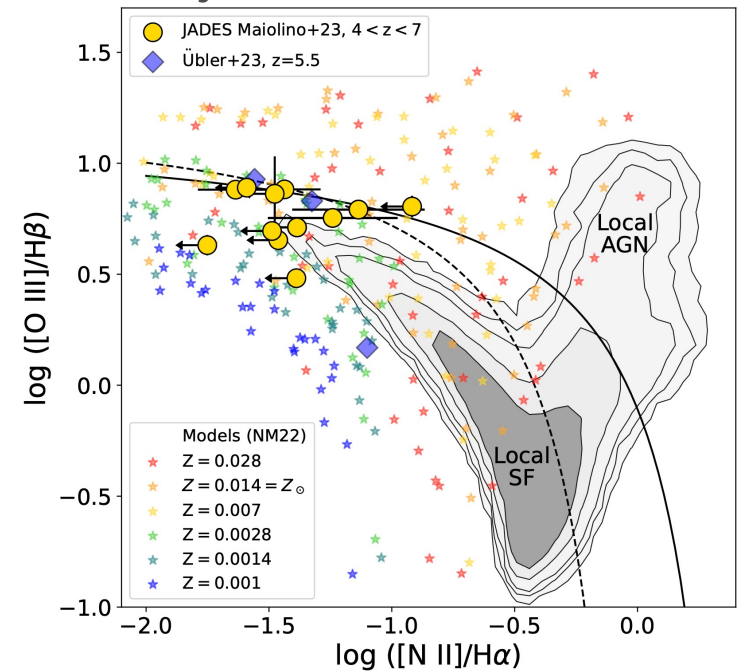
Rest-UV spectrum offering Key diagnostics of AGNs

Nature of Ionizing Spectrum: Stars vs. Blackholes

UV diagnostics of Stars vs. BHs



cf. conventional
optical diagnostics
may not work..

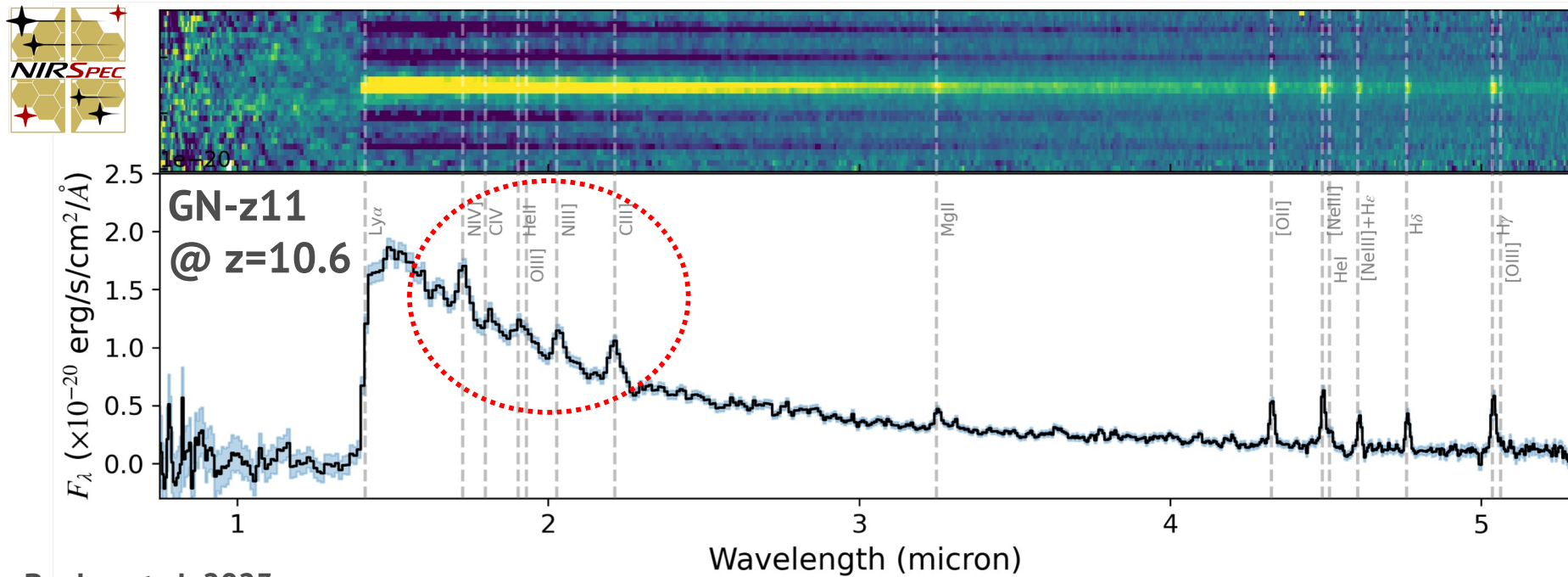


Harikane et al 2023b, Maiolino et al. 2023b

See also: Nakajima & Maiolino 2022
for theoretical predictions

Origins of Elements

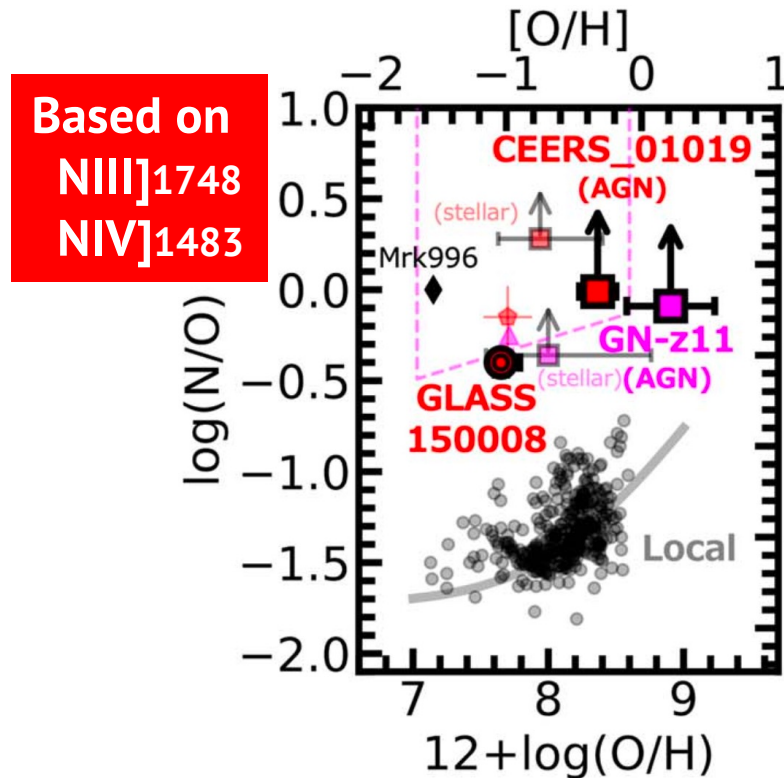
Metal lines in rest-UV as probes of chemical enrichment



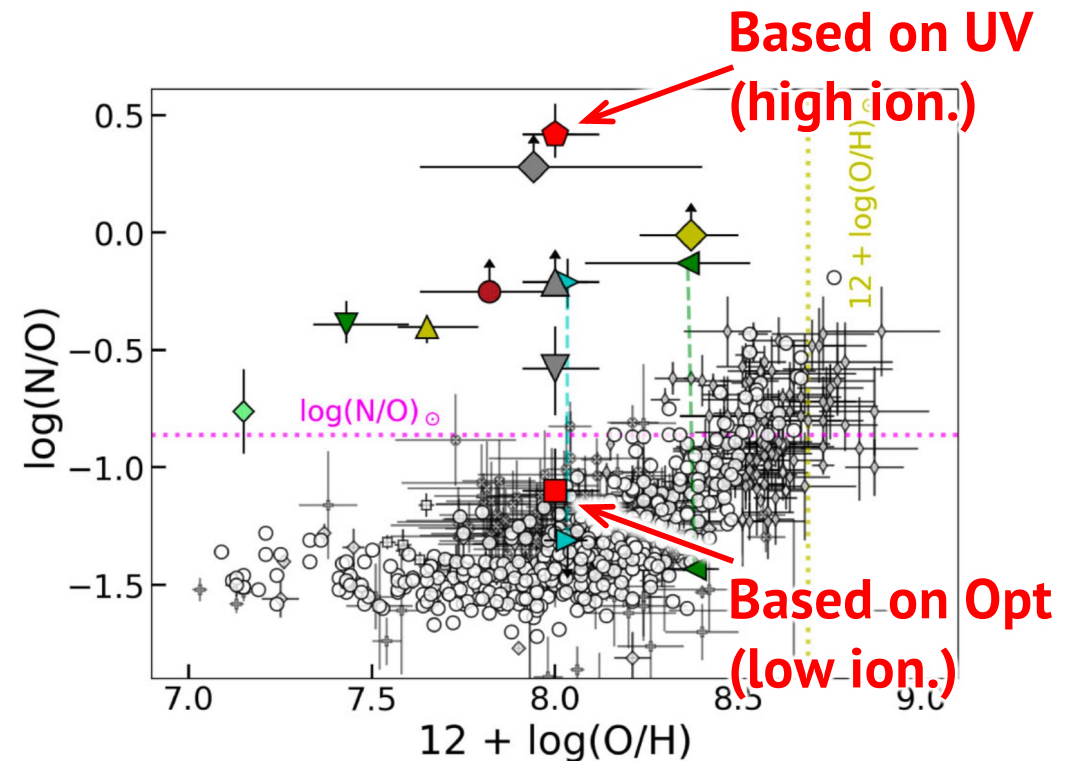
Bunker et al. 2023

Origins of Elements

Chemical element patterns being examined at high-redshift



Isobe, ..., Nakajima et al. 2023



Ji et al. 2024

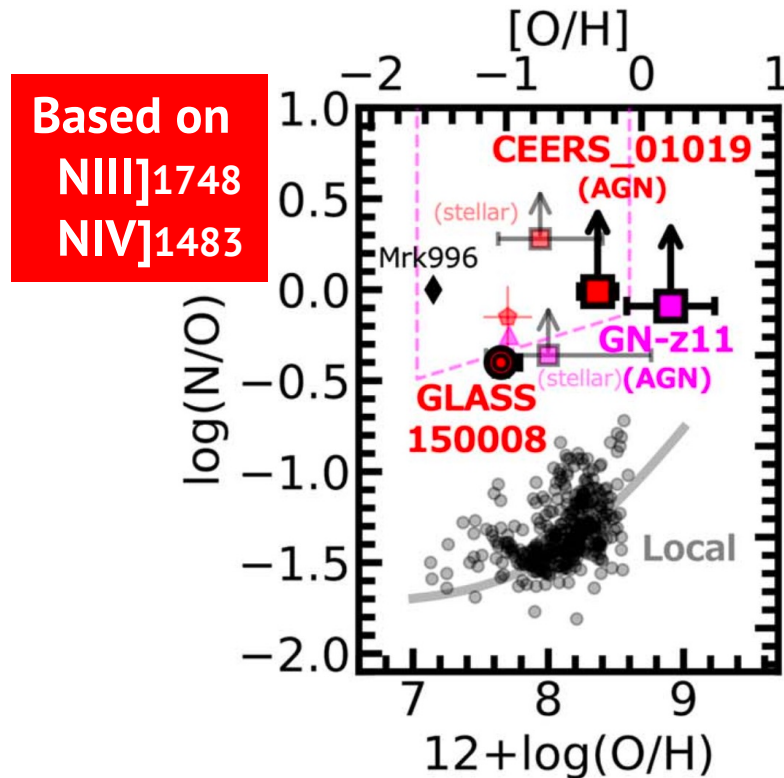
Multiple elements w/ diff. ionization/excitation states
analyzed using chemical evolution models

Their spatial variations (w/ IFU)

→ Chemical enrichment mechanism(s)

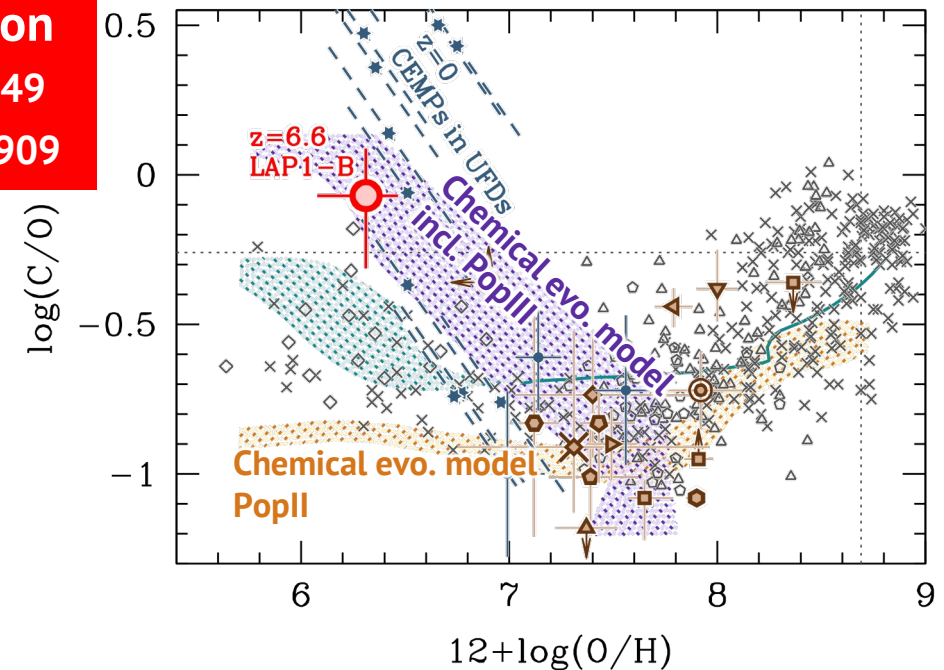
Origins of Elements

Chemical element patterns being examined at high-redshift



Isobe, ..., Nakajima et al. 2023

Based on
CIV]1549
CIII]1909



Nakajima et al. 2026

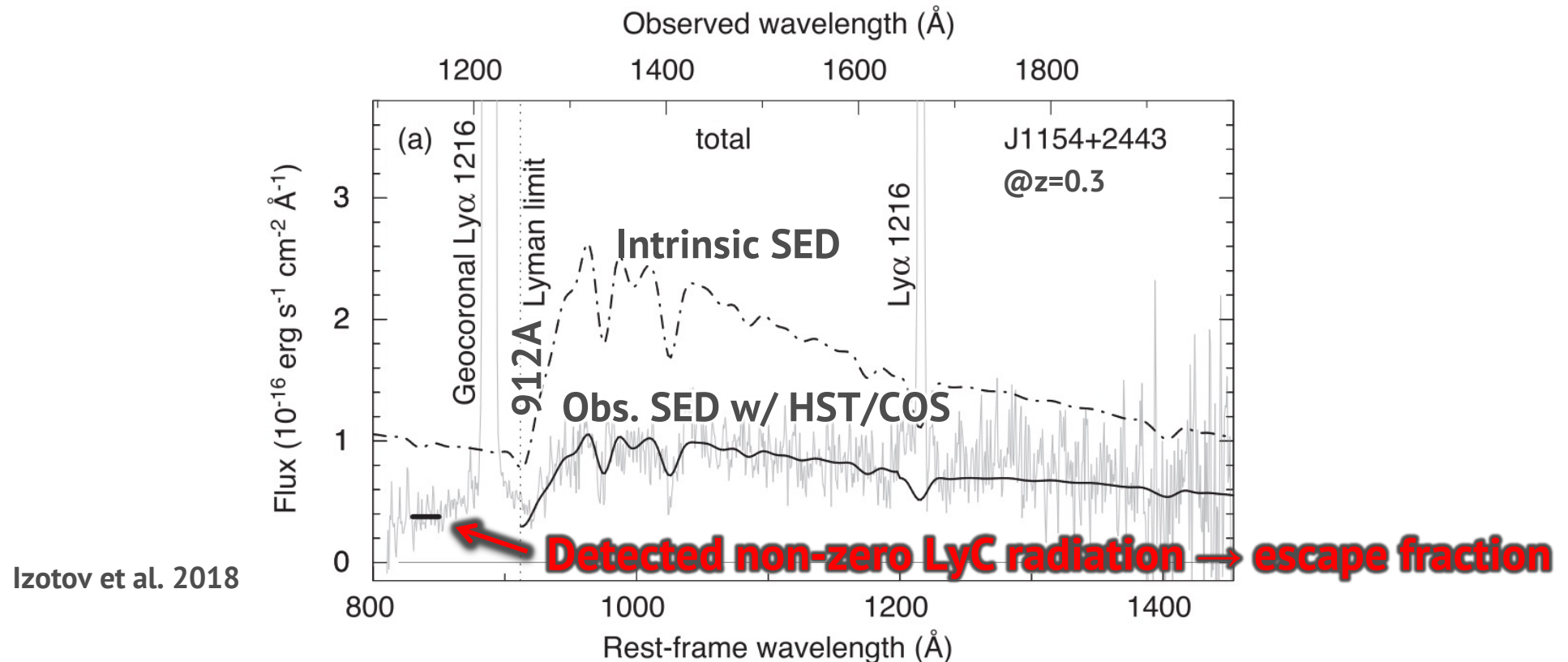
Multiple elements w/ diff. ionization/excitation states
analyzed using chemical evolution models

Their spatial variations (w/ IFU)

→ Chemical enrichment mechanism(s)

Cosmic Reionization

Direct investigation of escaping LyC radiation from sources at $z \sim 0.1$ (~ 1)



Highest spec. sensitivity in FUV will allow us to examine..

Escape fraction of ionizing photons (Sample provided by Roman, PFS,..)

Shape of ionizing spectrum

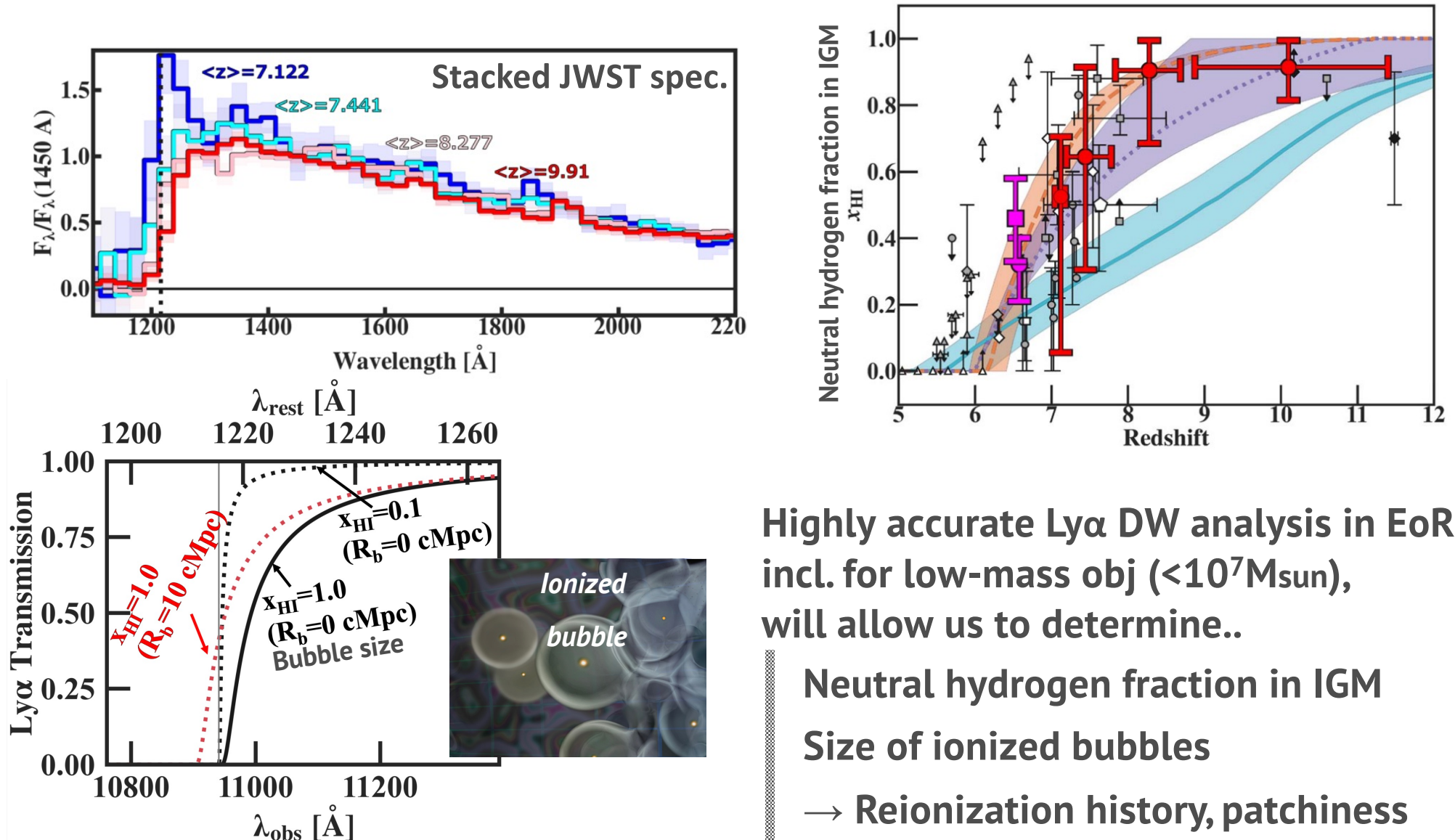
Their spatial variations (w/ IFU-UV)

→ Sources of Reionization

High spectral resolution
is not needed..

Cosmic Reionization

Ly α Damping Wing analysis through rest-UV continuum



Highly accurate Ly α DW analysis in EoR, incl. for low-mass obj ($<10^7 M_{\text{sun}}$), will allow us to determine..

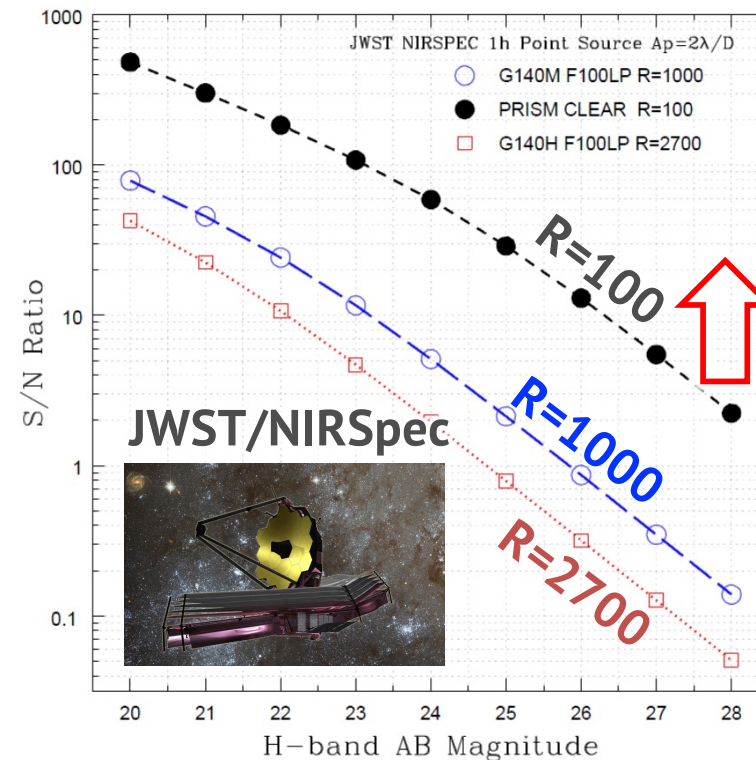
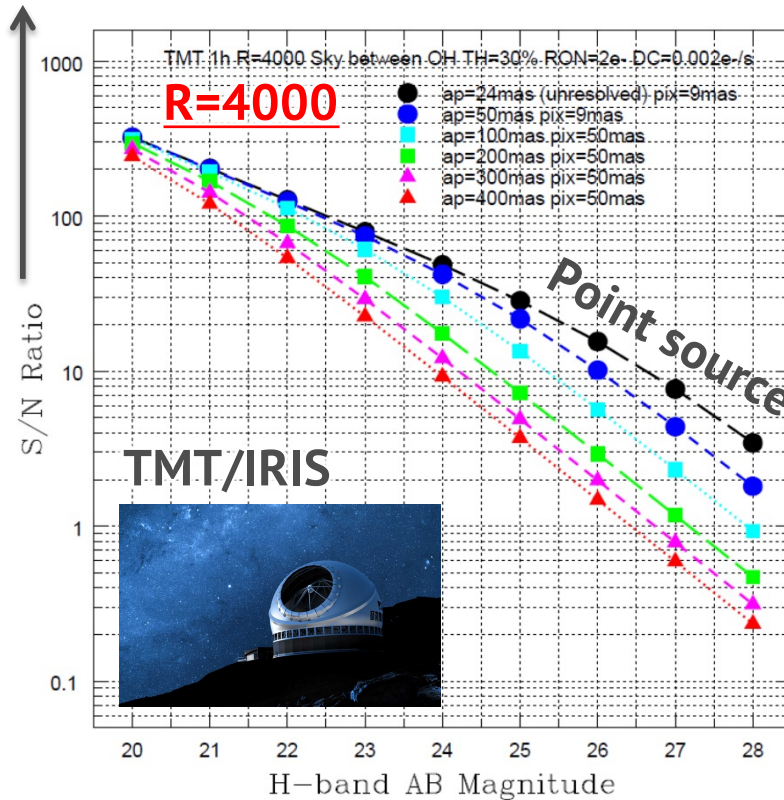
Neutral hydrogen fraction in IGM

Size of ionized bubbles

→ Reionization history, patchiness

HWO can provide deepest spec. sensitivity in NIR

Better Sensitivity



HWO:
~x10 better
sensitivity
in NIR

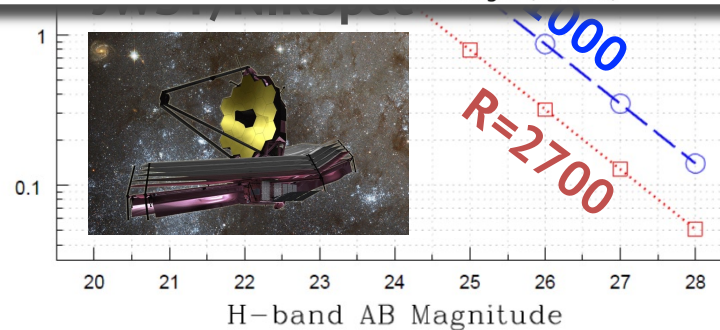
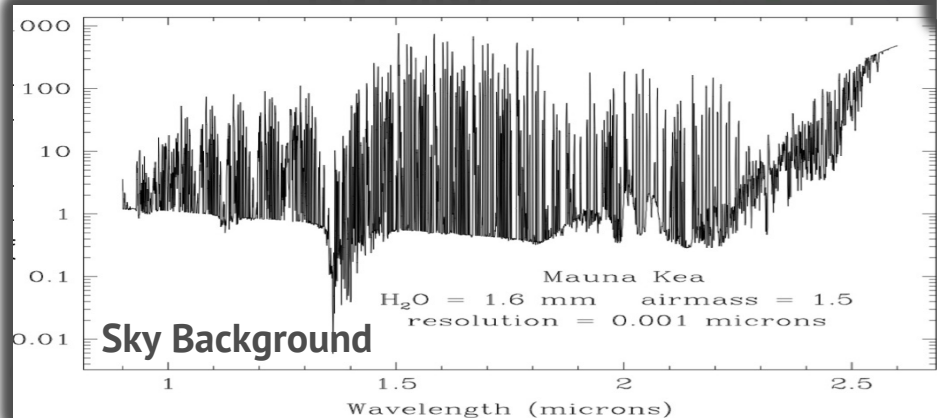
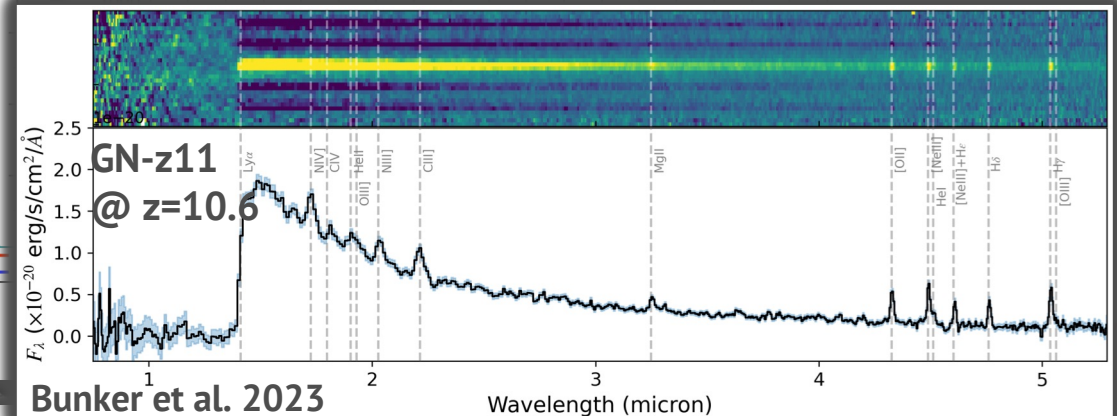
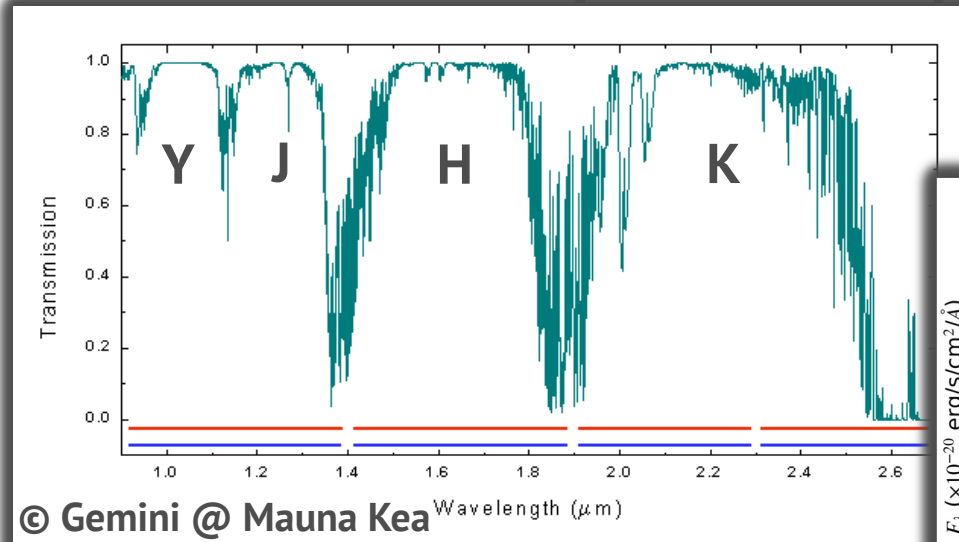
© TMT Detailed Science Case 2015

ELTs and HWO are complementary in NIR spec.

ELTs' high spec. resolution for reliable/careful emission line diagnostics

HWO's low spec. resolution, **w/ deep & seamless coverage**, for e.g. continuum studies

HWO can provide deepest spec. sensitivity in NIR



ELTs and HWO are complementary in NIR spec.

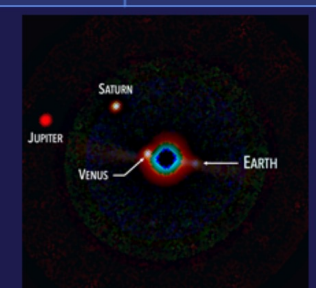
ELTs' high spec. resolution for reliable/careful emission line diagnostics

HWO's low spec. resolution, **w/ deep & seamless coverage**, for e.g. continuum studies

HWO can provide deepest spec. sensitivity in NIR

Better Sensitivity

HWO preliminary specs & candidate instruments

Telescope		Coronagraph*		High-Resolution Imager		UV Multi-Object Spectrograph	
Diameter	6+ meters	High-contrast imaging and imaging spectroscopy		UV/Vis and NIR imaging		UV/Vis multi-object spectroscopy and FUV imaging	
Bandpass	100 nm (TBR)-2500nm	Bandpass	.35um-1.7um	Bandpass	~200–2500 nm	Bandpass	~100–1000 nm
Diff. Lim. Wavelength, Line of Sight	.5um, .4mas LOS	Contrast	$\lesssim 1 \times 10^{-10}$	Field-of-View	~3' × 2'	Field-of-View	~2' × 2'
		R ($\lambda/\Delta\lambda$)	Vis: ~140 NIR: ~70, 200	~67 science filters + grism		Apertures	~840 × 420
				High-precision astrometry?		R ($\lambda/\Delta\lambda$)	500–50,000
Other Candidates: IFUs (UV+Optical/NIR) NUV High Contrast UV Spectropolarimeter							
		4 th Instrument Slot is Currently Empty					

D:
0 better
sensitivity

© TMT

© T. Greene, HWO

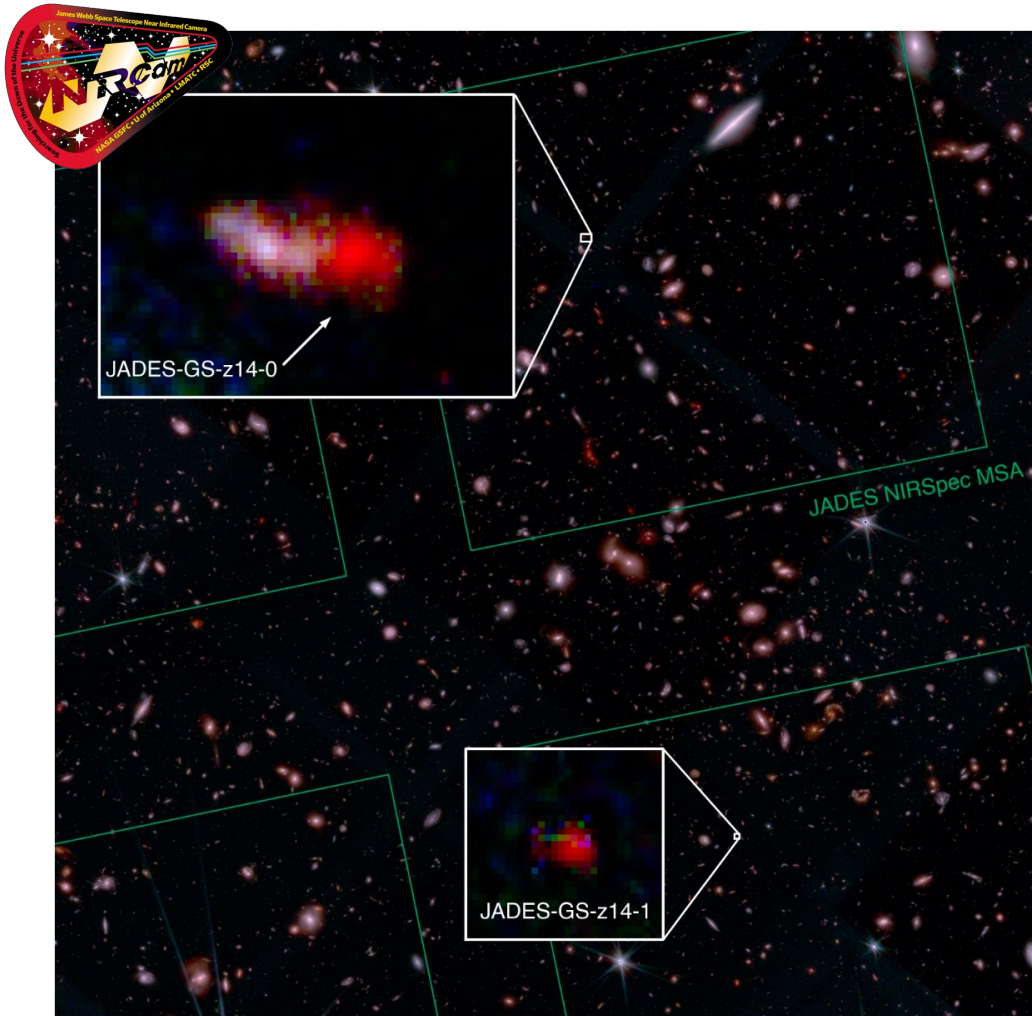
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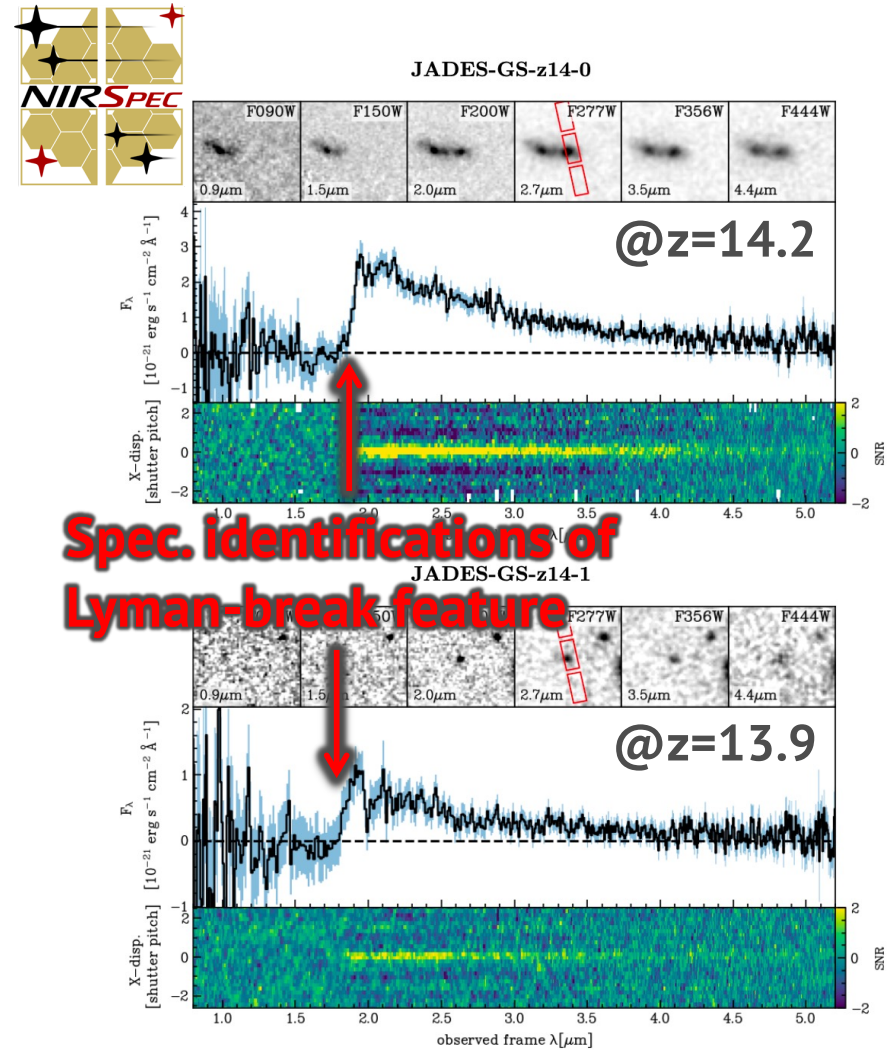
Very high-redshift universe

Photometry for candidate selection



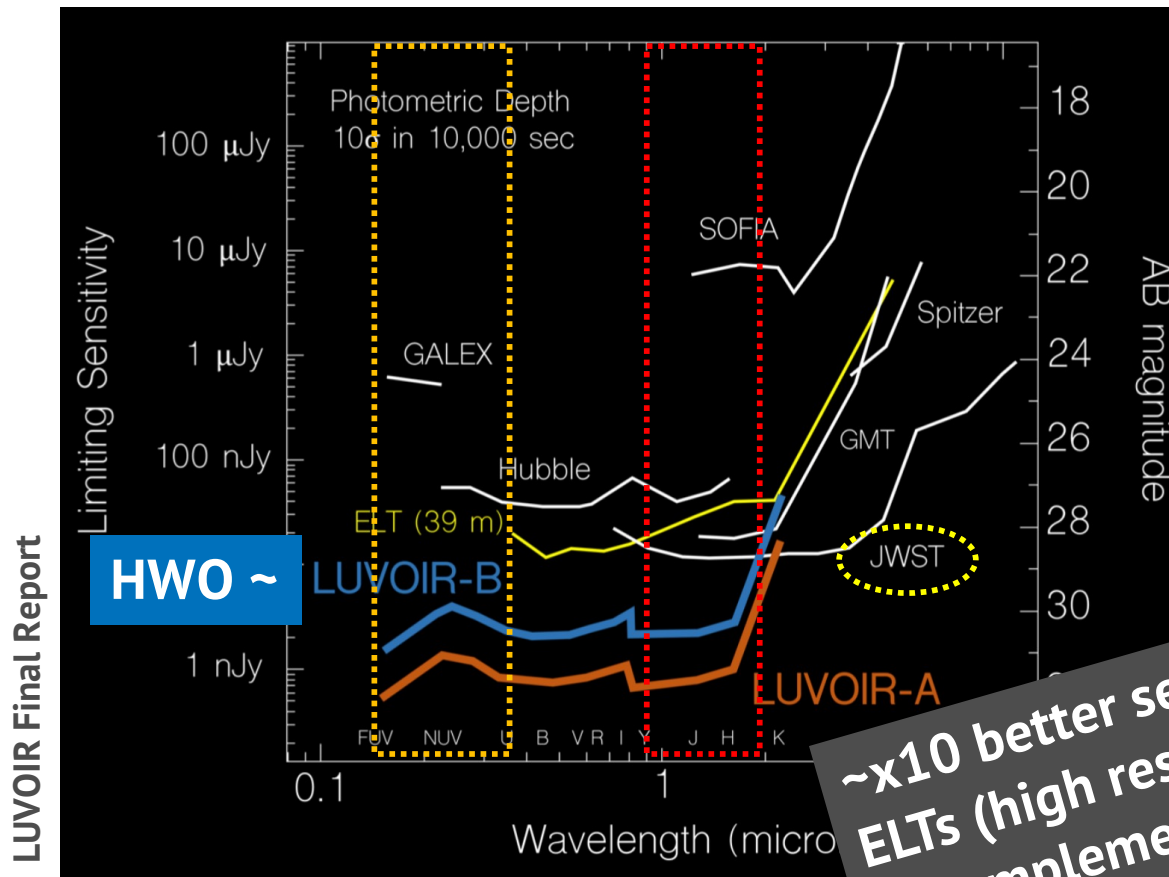
Carniani et al. 2024, Nature

Spectroscopy for characterizations



Highest spec. sensitivity in NIR is crucial..
cf. NIRSpec 20hr, $10^8 M_{\text{sun}}$

Summary: UV-to-NIR Spec. capability will offer crucial final push for studies of galaxy formation and evolution in 2040+



Unique

Far UV

→ UV spec. properties in **local** galaxies

Nature of ionizing spectrum (Stars vs. Blackholes)

Origins of elements

Ionizing photon escape (Cosmic Reionization)

~x10 better sensitivity than JWST
ELTs (high res.) & HWO (low res.)
complementary

Near IR

→ UV spec. properties in
high-redshift galaxies

Fossil Records of Massive Black Hole Seeds Probed by HWO

Lead author: Masafusa Onoue

Abstract: Wide-field surveys have revealed mature supermassive black holes (SMBHs) down to $z \sim 8$, while JWST is uncovering lower-mass AGN down to $z \sim 10$, including the Little Red Dots (LRDs) population. HWO will complement these high-redshift studies by providing sensitive UV spectroscopy and sharp, stable imaging of nearby galaxies. I discuss HWO will explore intermediate mass black holes (IMBHs) through stellar dynamics and UV radiation environments of nearby metal-poor dwarf galaxies.

Science Case Summary

IMBHs are the missing link between stellar-mass black holes and SMBHs, and provide a critical test of SMBH seed formation (Decadal survey B-Q4, D-Q3). With sharp space-based imaging and UV spectroscopy, HWO can search for IMBHs and probe the hard radiation fields required for heavy-seed formation in nearby metal-poor galaxies. The HWO's unique capability will also enable broader AGN studies, including He II reionization and resolved observations of nearby analogs of LRDs.

Fossil Records of Massive Black Hole Seeds Probed by HWO

Masafusa ONOUE

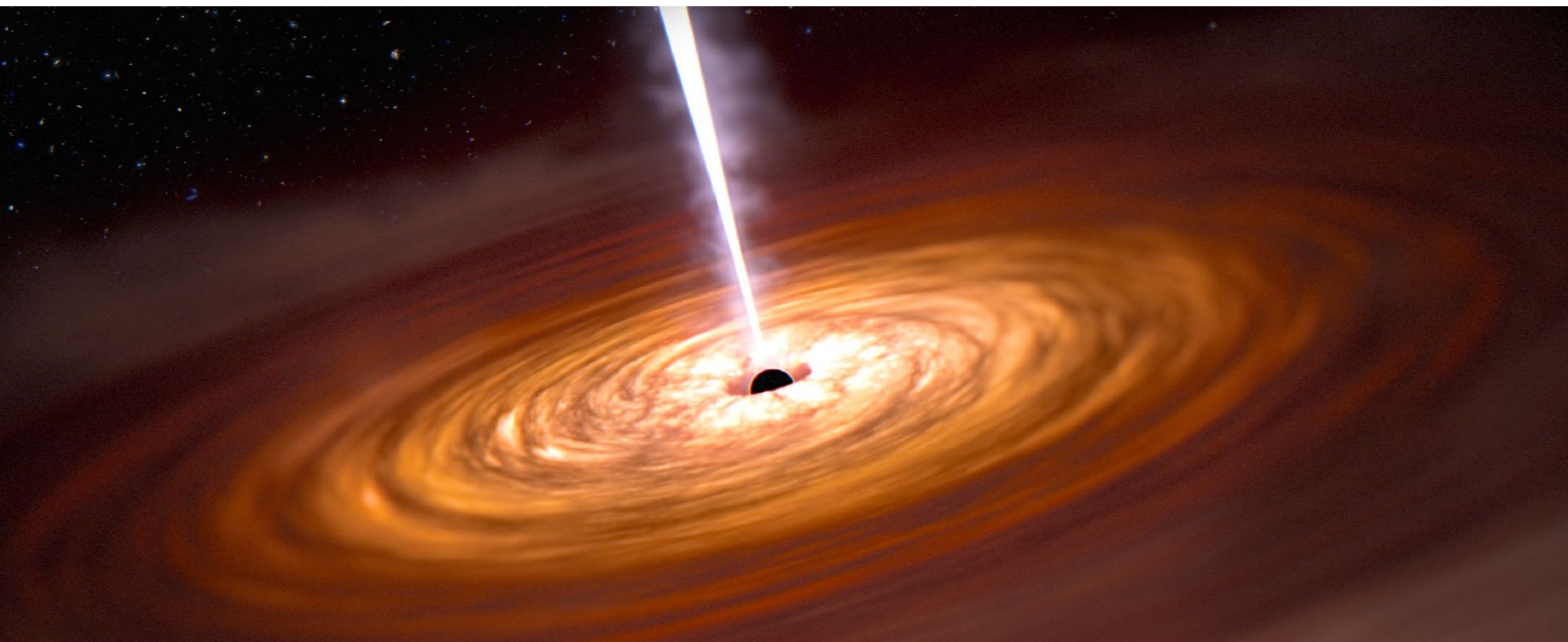
(Waseda University / Kavli IPMU)



WASEDA University

WIAS

IPMU INSTITUTE FOR THE PHYSICS AND
MATHEMATICS OF THE UNIVERSE

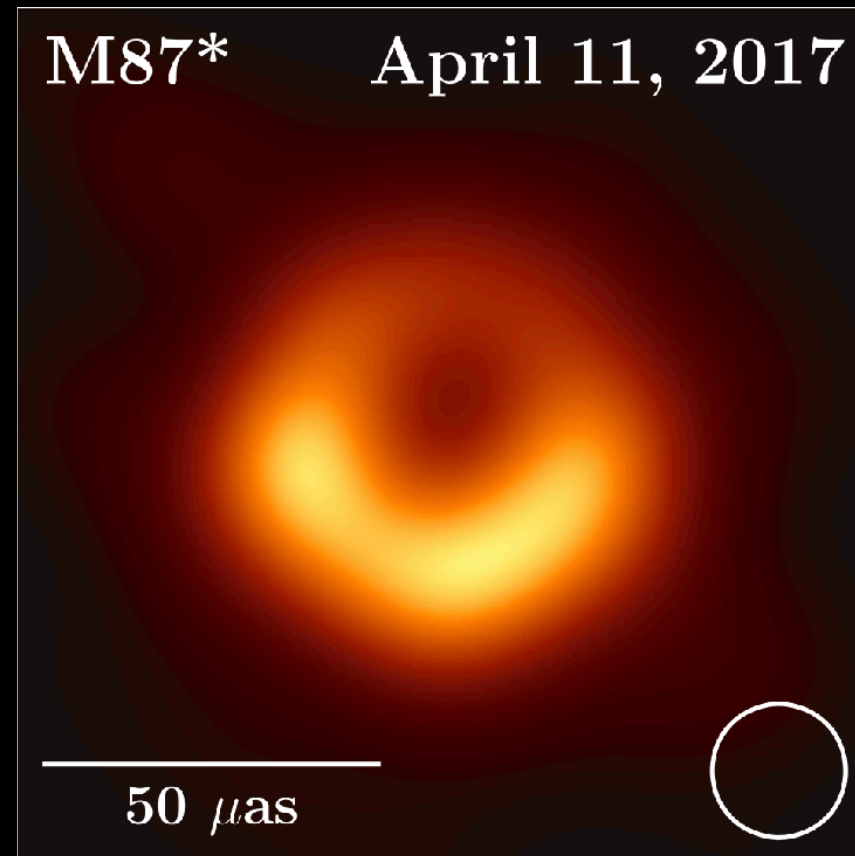
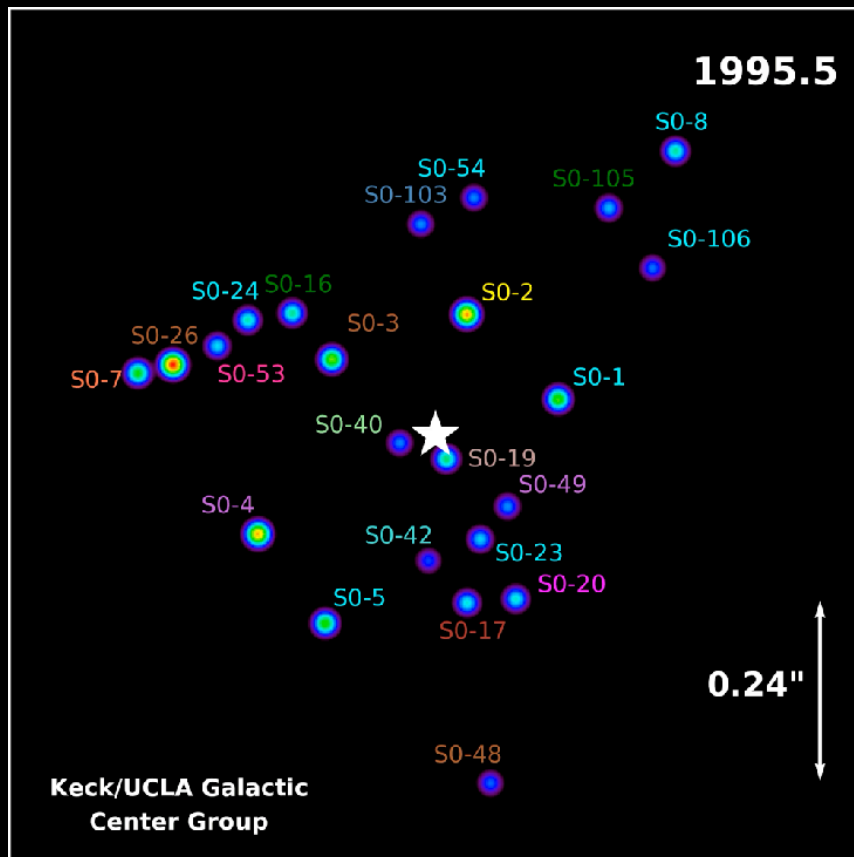


Super Massive Black Hole (SMBH)

- reside at galaxy centers
- $M_{\text{BH}} = 10^5\text{-}10^9 M_{\text{sun}}$
- can outshine host galaxies when active (=quasar/AGN)

Credit: NASA, ESA, CSA, Joseph Olmsted (STScI)

SUPERMASSIVE BLACK HOLES



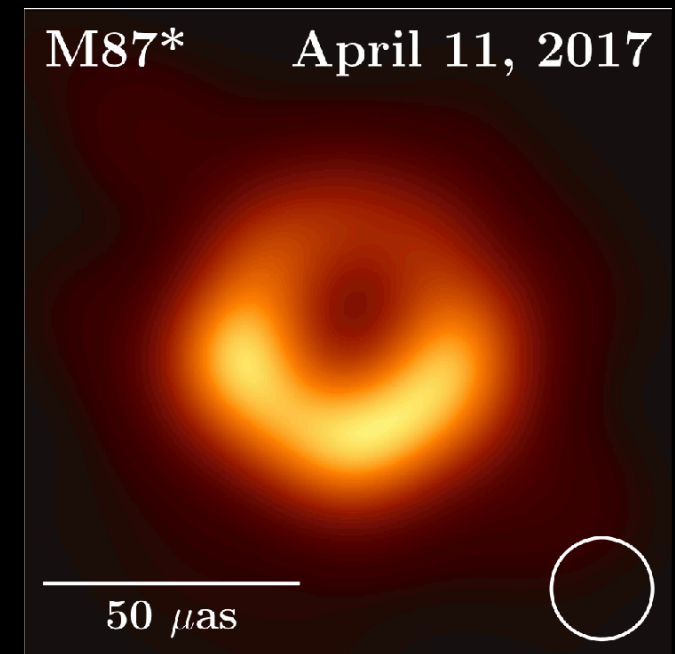
$4 \times 10^6 M_{\text{sun}}$ BH in Sgr A*

ULTIMATE GOALS FOR SMBH STUDIES

BH "seeds" at $z > 20$



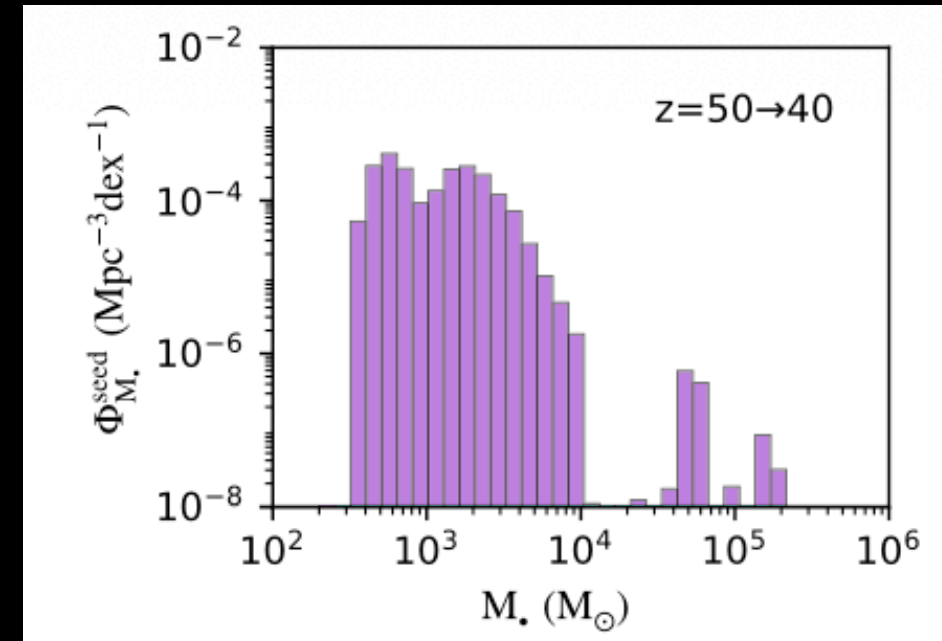
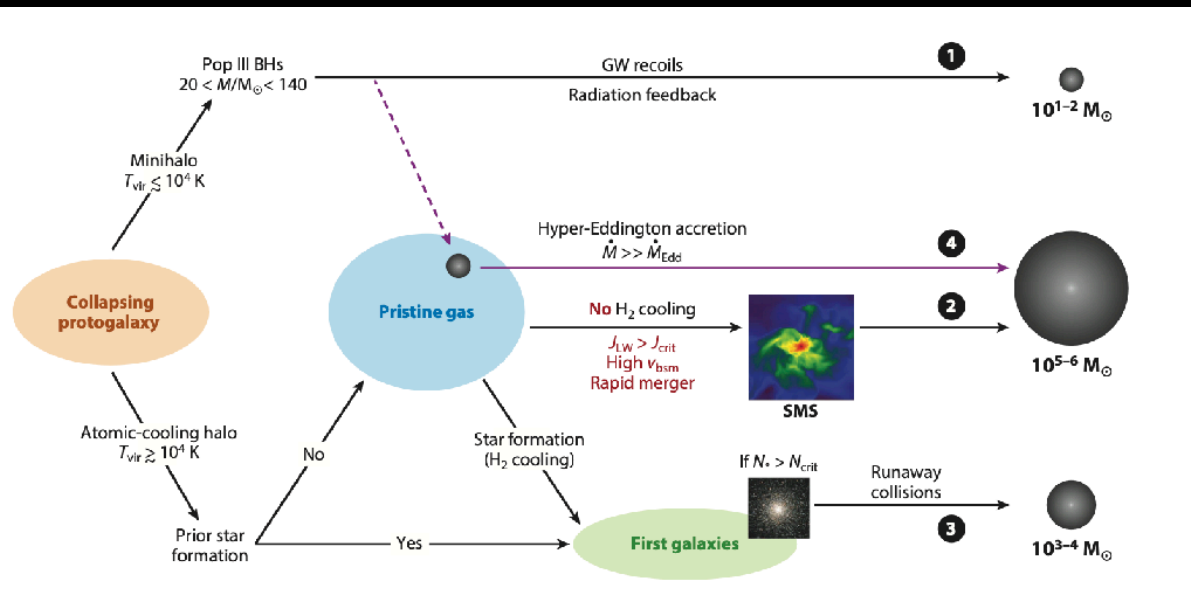
SMBH now



What is the origin of SMBHs?

(Pop-III remnants, direct collapse of $\sim 10^5 M_{\text{sun}}$ gas cloud, runaway collision of star clusters)

HOW DO WE APPROACH SMBH ORIGIN?

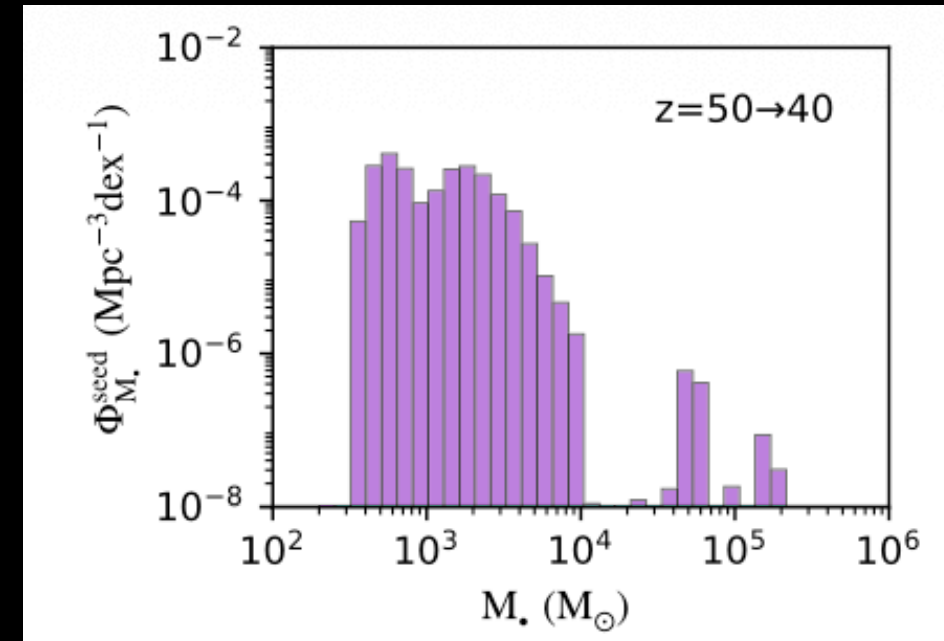
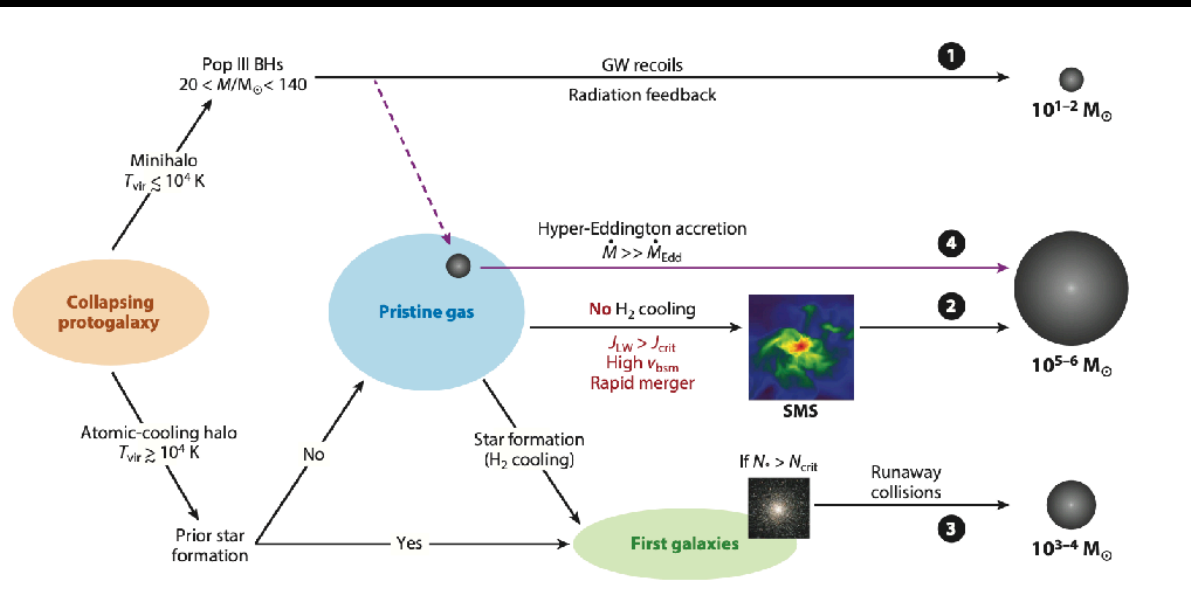


Probing the initial BH mass distribution

(Pop-III remnants, direct collapse of metal-poor gas cloud, runaway collision of star clusters)

Inayoshi+20; Li+23

HOW DO WE APPROACH SMBH ORIGIN?

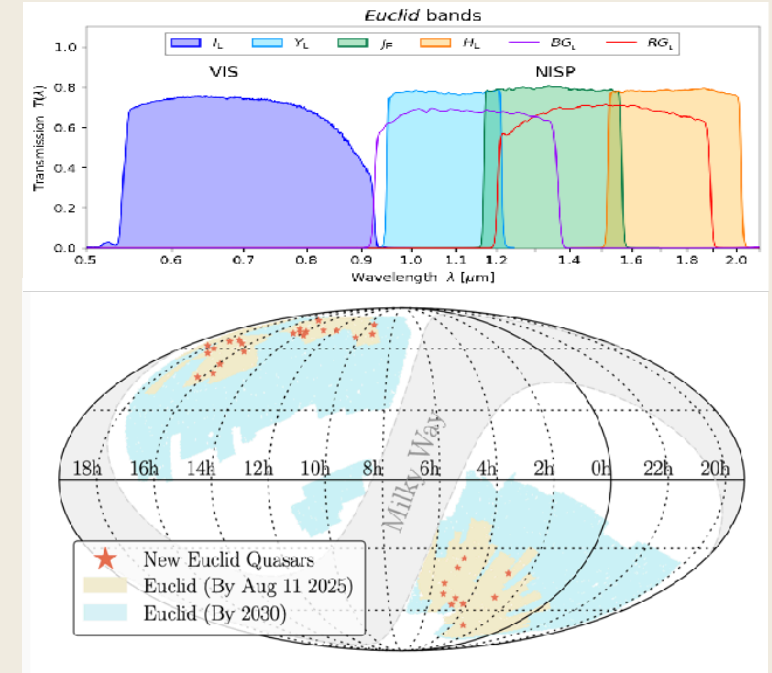
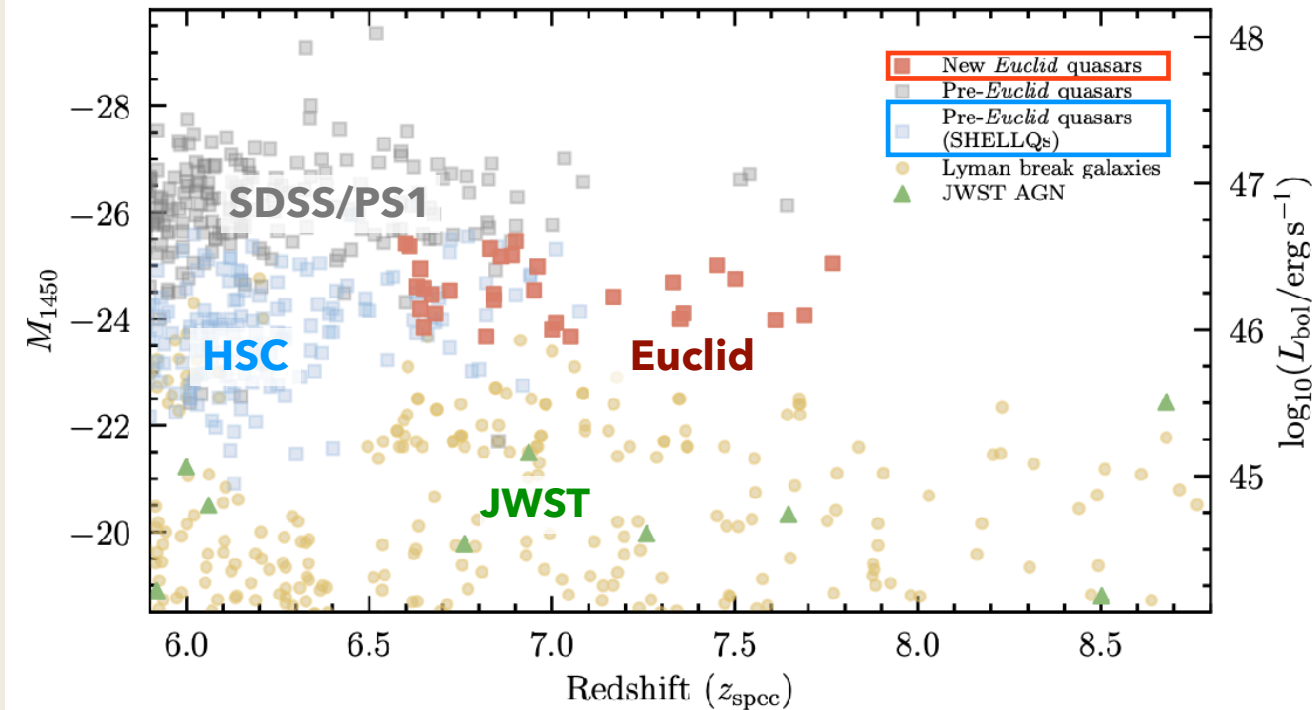


Current approach: matured BHs in high- z ($z > 6$, $t_{\text{Univ}} < 1 \text{ Gyr}$)



Euclid: Discovery of 31 new quasars at $6.6 < z < 7.8$ *

D. Yang^{★1}, J. F. Hennawi^{1,2}, F. Guarneri^{3,4}, J. Wolf⁵, S. Belladitta^{5,6}, J.-T. Schindler³, A. C. N. Hughes⁷, E. Bañados⁵, D. J. Mortlock^{7,8}, J. Yang⁹, F. Wang⁹, X. Fan¹⁰, K. Jahnke⁵, D. Stern¹¹, C. J. Willott¹², A. J. Barth¹³, H. J. A. Rottgering¹, R. G. Varadaraj¹⁴, R. Decarli⁶, A.-C. Eilers^{15,16}, [tbc]Meriam Ezziati¹⁷, Y. Fu^{1,18}, J. Huang², X. Jin^{9,19}, Y. Kang², L. N. Martinez-Ramirez^{5,20,21}, Y. Matsuoka²², M. Onoue^{23,24}, R. Pello²⁵, R. P. Remigio¹³,

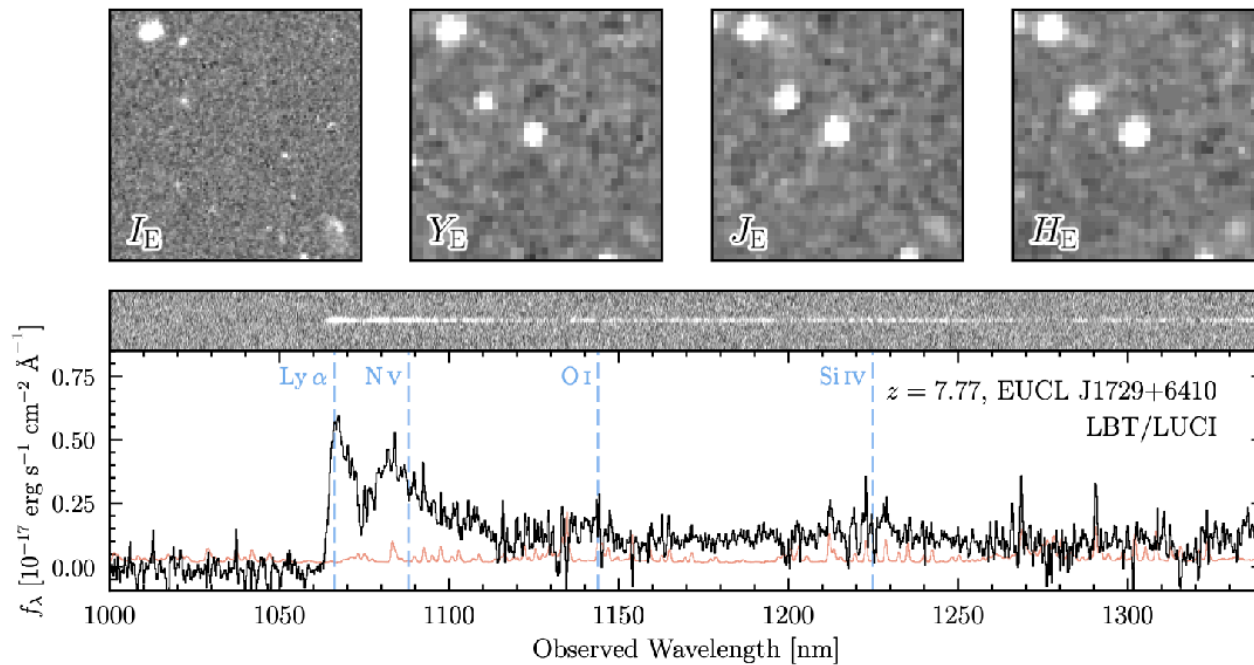


HSC-z available in the north (WISHES, PIs: Oguri, Osato)

Euclid × Subaru has found 31 $z \sim 7$ quasars from first 3,000 deg² ($Y_E/J_E/H_E = 24.5$ mag)



New Redshift Record: $z = 7.77$ ($t_U = 662$ Myr)

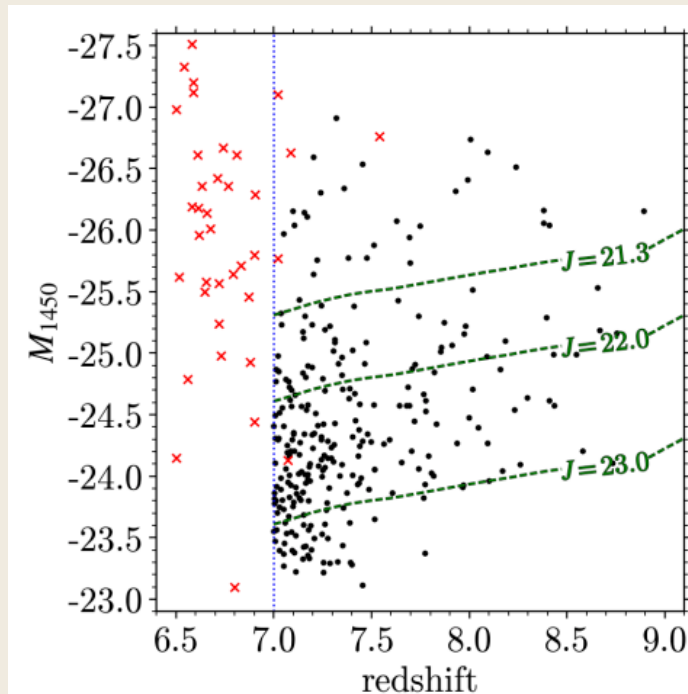


$$J_E = 22.6, M_{1450} = -25.1 \text{ mag}, M_{BH} > 10^8 M_{\text{sun}} (\lambda_{\text{Edd}} = 1)$$

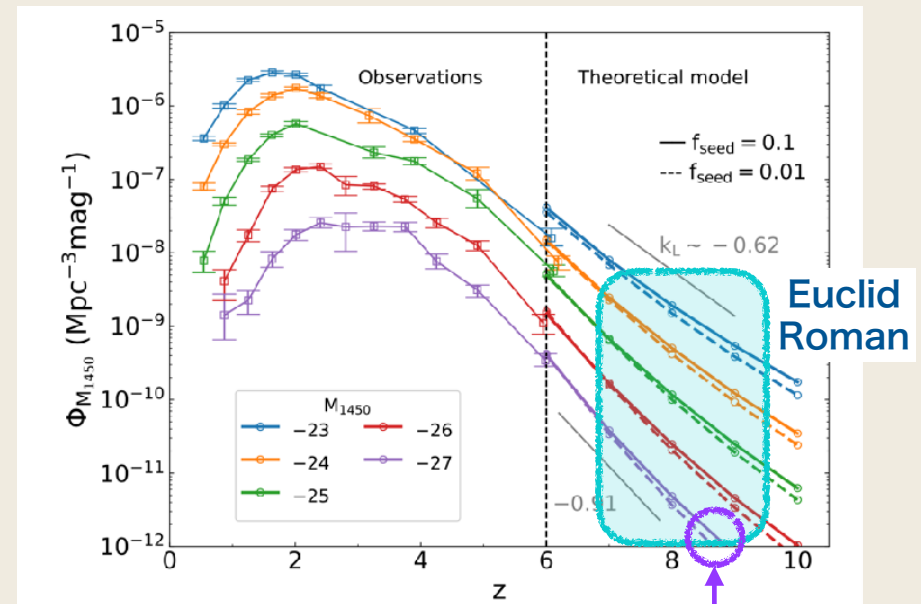


Golden Era of Highest- z Quasar Search

- Expected yield of Euclid (Bernett+19)



- Expected quasar number density at $z > 6$ (Li+23)

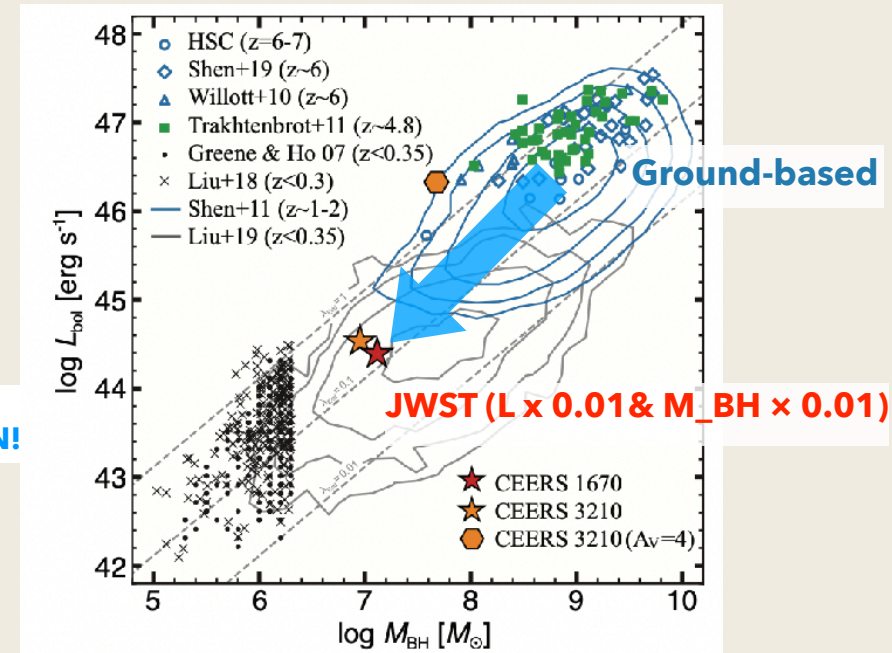
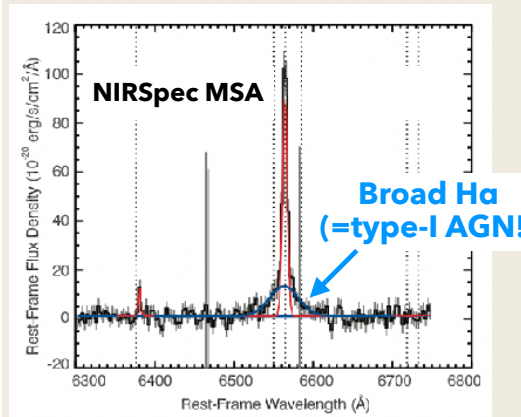
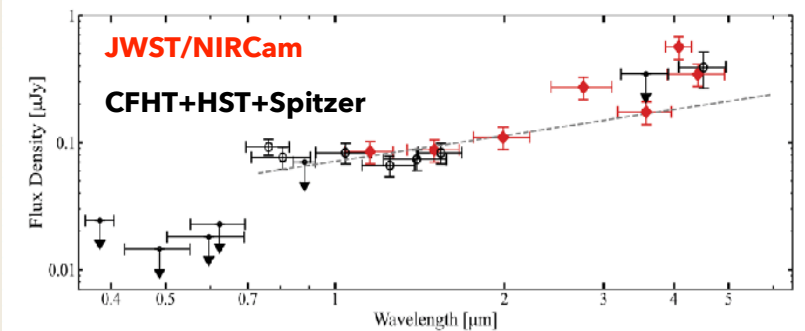
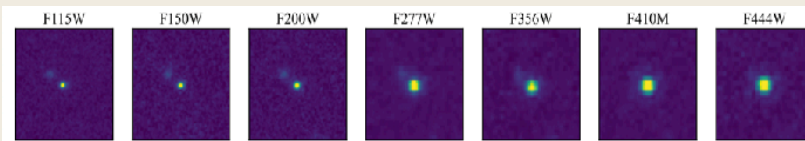


$N \sim 1$ in the entire sky!

**Euclid (15,000 deg², $J_{5\sigma} \sim 24.5$) and Roman (2,000 deg², $J_{5\sigma} \sim 26.4$)
will find a few hundreds of $7 < z < 9$ quasars**

Low-Luminosity AGN Discovery with JWST

CEERS 2782 ($z=5.2$, $F_{150W}=26.5$ mag, $L_{5100} = 4.5 \times 10^{43}$ erg/s, $M_{BH, H\alpha} = 1.3 \times 10^7 M_{\text{sun}}$)

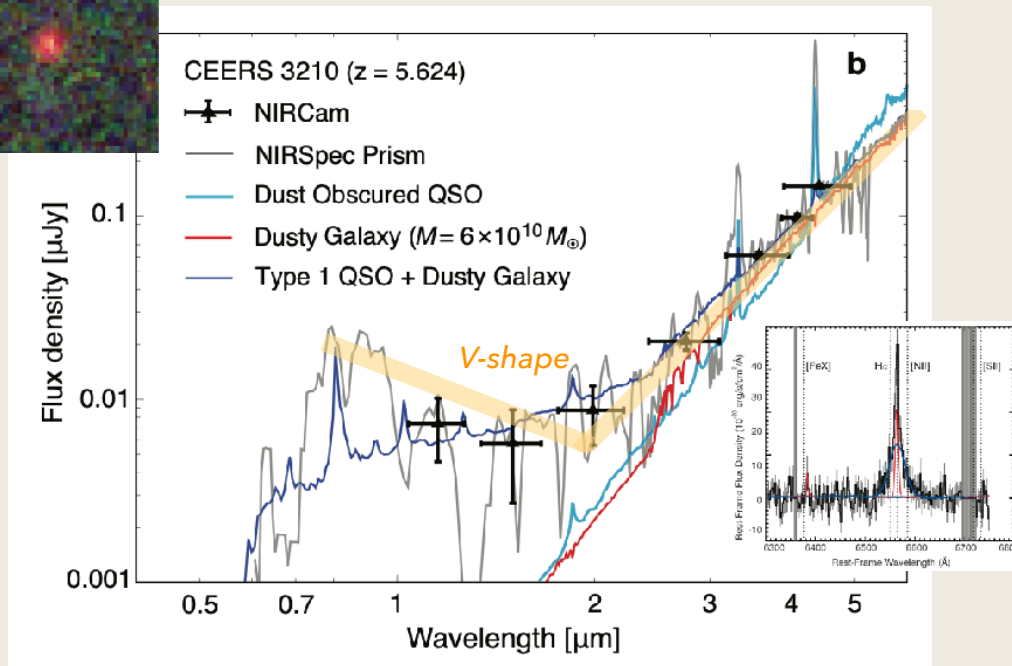
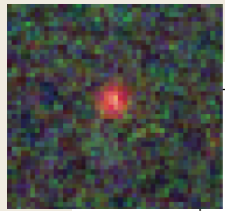


Lower-mass BHs being unveiled by JWST ($M_{BH} > 10^6 M_{\text{sun}}$)

(e.g., MO+23; Kocevski, MO+23; Harikane+23; Maiolino+23; Matthee+23; Taylor+25)

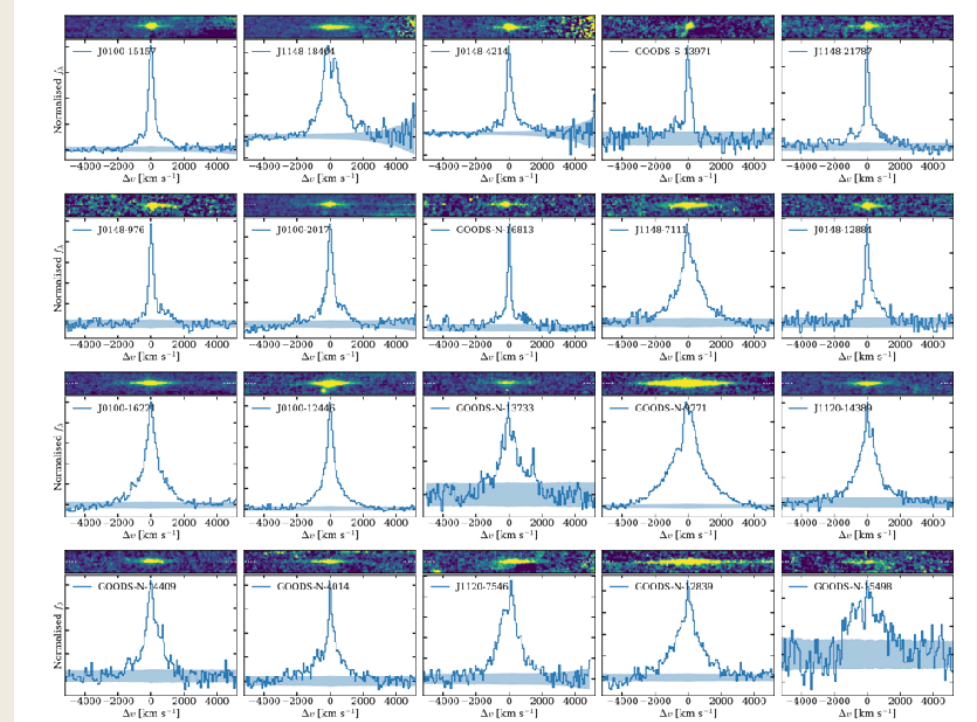
Many faint AGN / LRDs

► CEERS



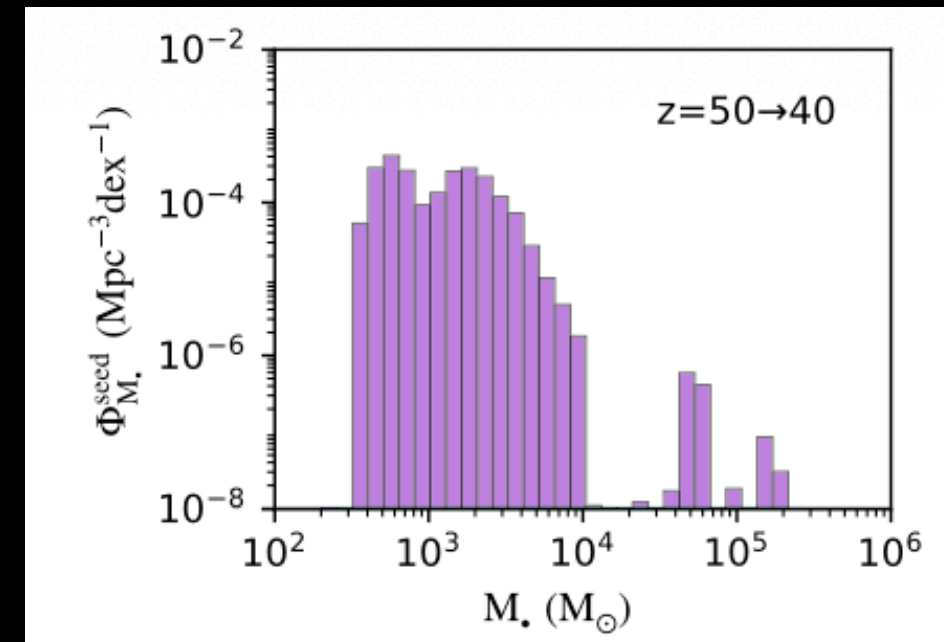
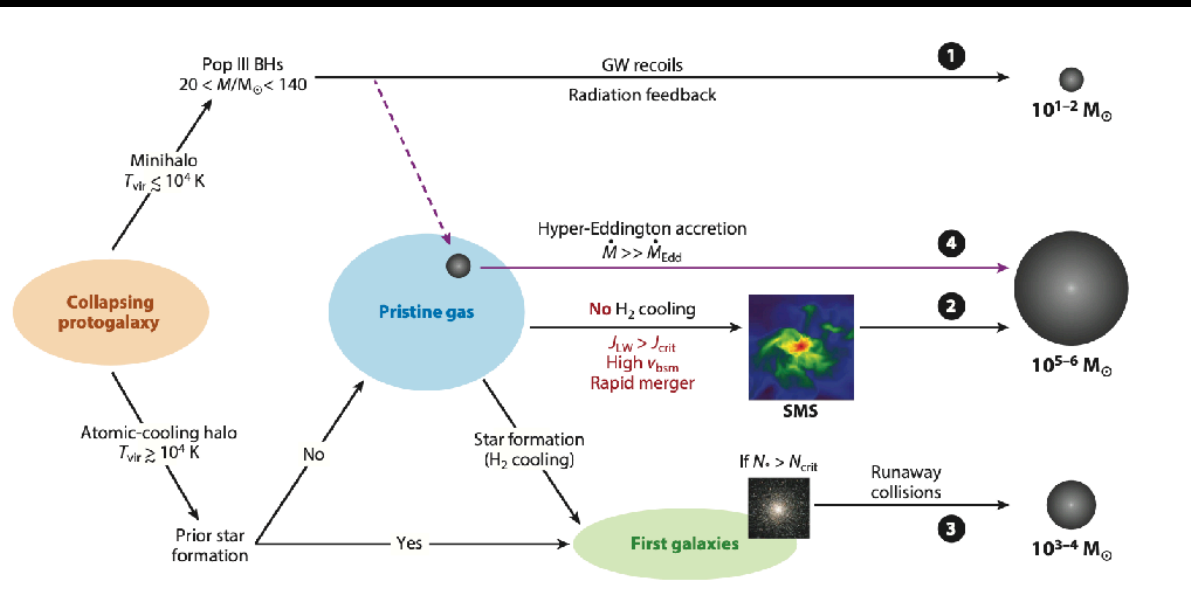
Kocevski, MO, Inayoshi+23

► EIGER + FRESCO



Matthee+24

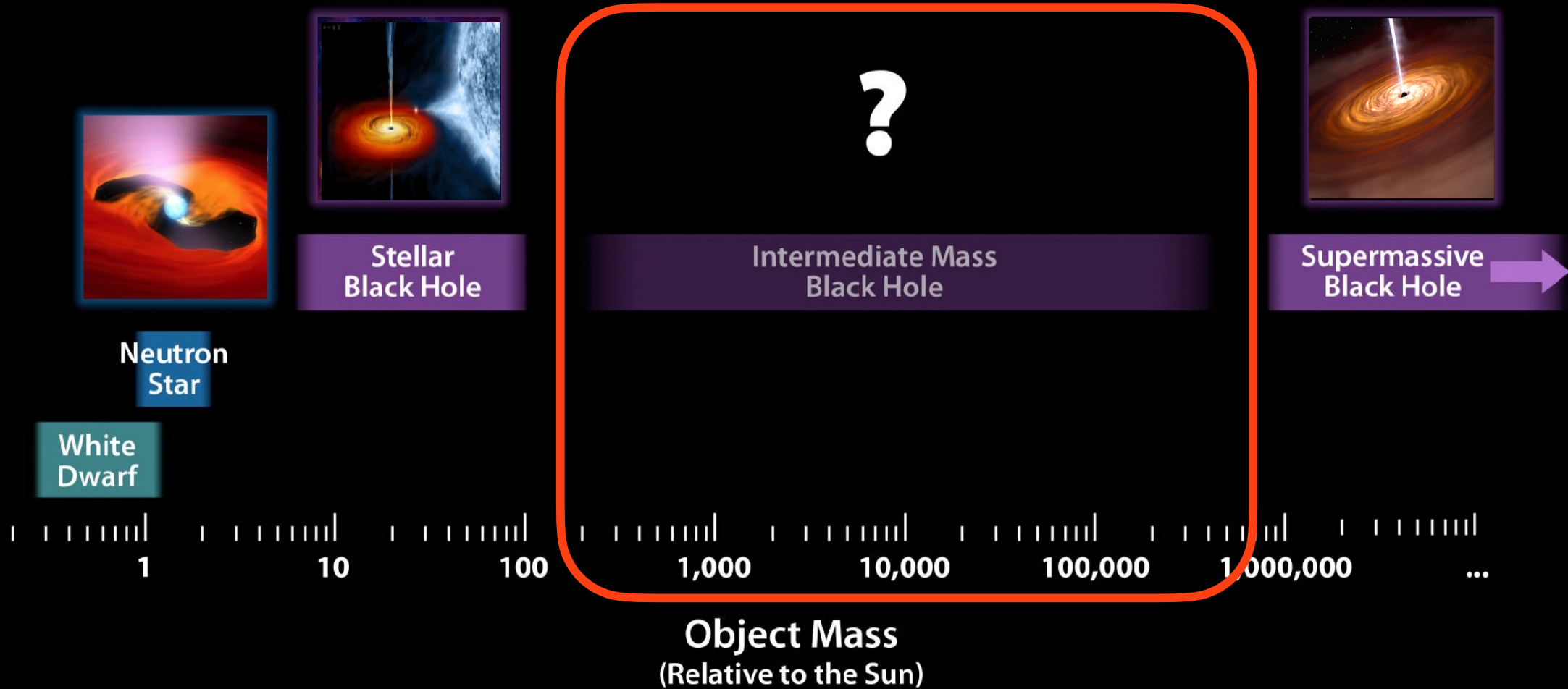
HOW DO WE APPROACH SMBH ORIGIN?



Current approach: matured BHs in high- z ($z > 6$, $t_{\text{Univ}} < 1 \text{ Gyr}$)

HWO: Intermediate mass BHs (IMBHs) in nearby universe (complementary to JWST)

Observed Mass Ranges of Compact Objects



Credit: NASA/JPL-Caltech

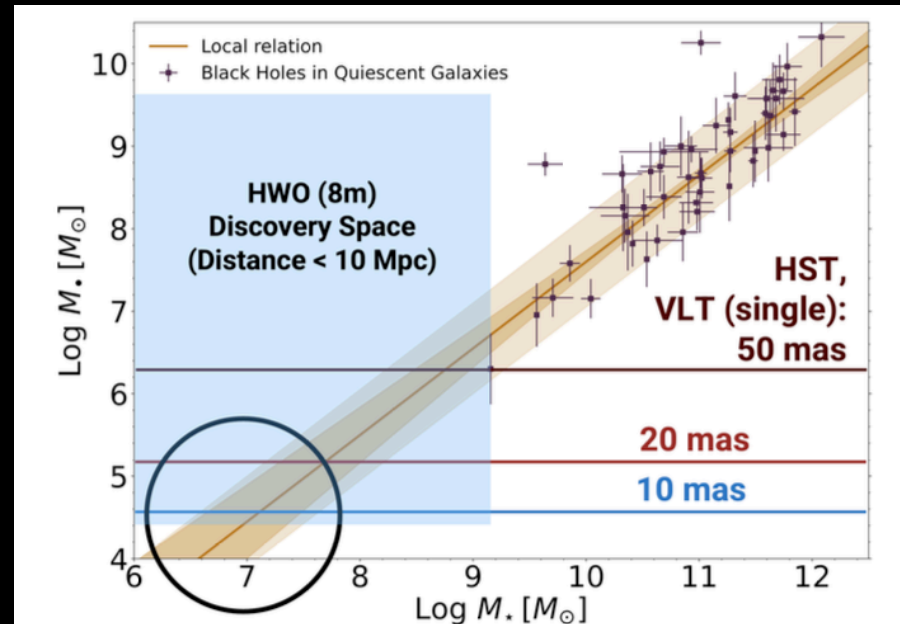
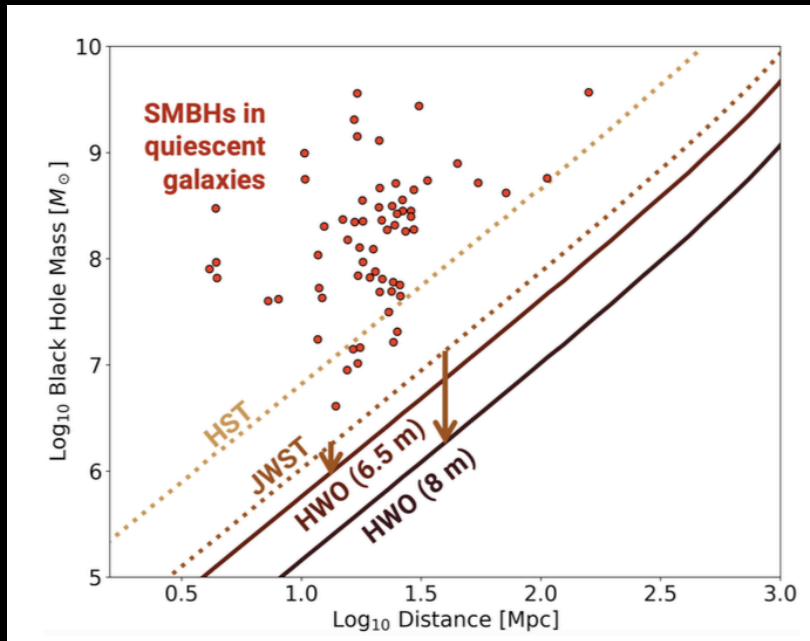
IMBH IN GLOBULAR CLUSTER



**HST time-lapse analysis of stellar proper motions suggests a candidate of
>8200 M_{sun} BH in Omega Centauri (d=5.45 kpc)**

Häberle+25

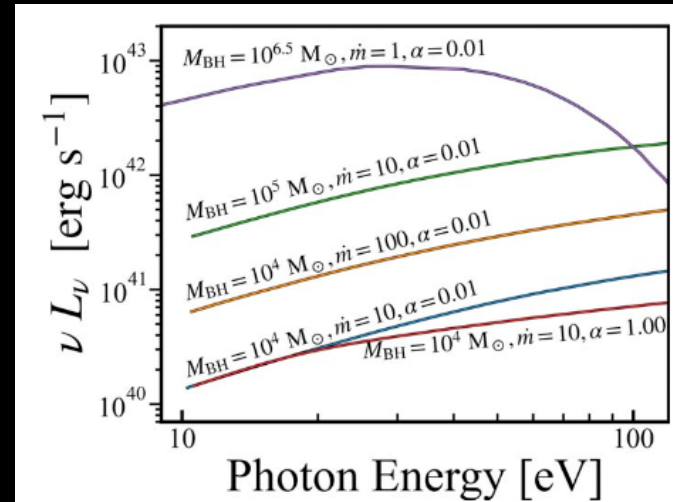
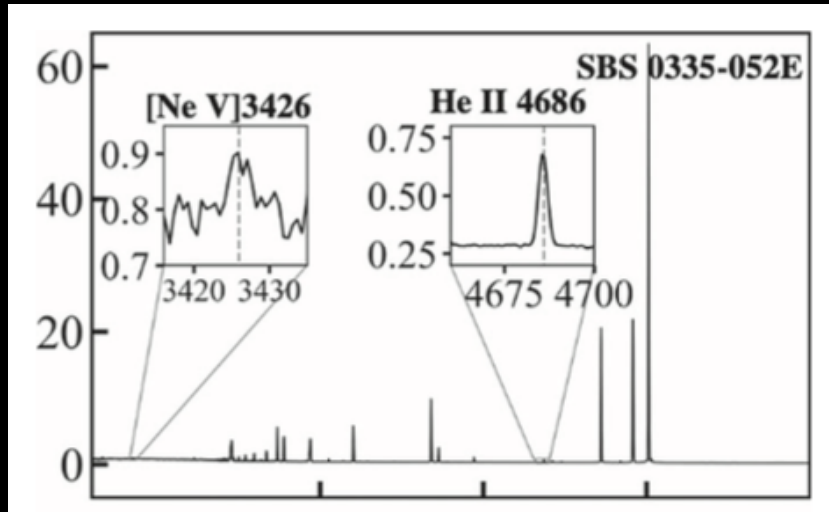
IMBH SEARCH IN DWARF GALAXIES



HWO's UV/optical MOS capability enables systematic IMBH searches in nearby dwarf galaxies via stellar kinematics (down to $M_{\text{BH}} = 10^{4.5} M_{\text{sun}}$)

HWO community science case: F. Paccuti

BH SIGNATURES IN UV/OPTICAL SPECTRA



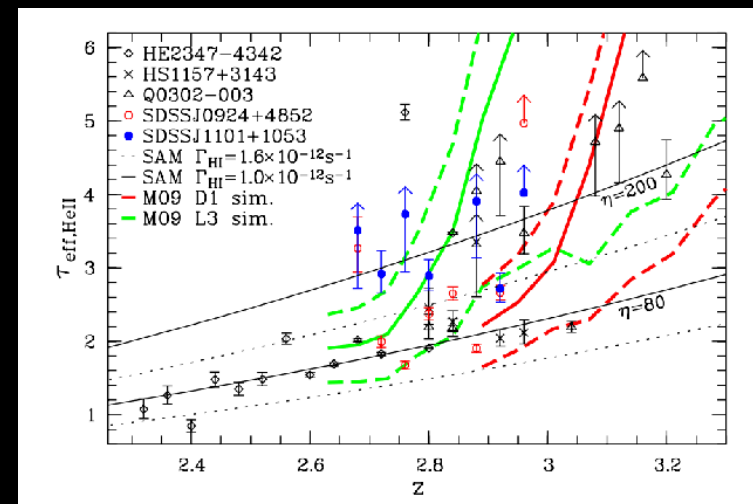
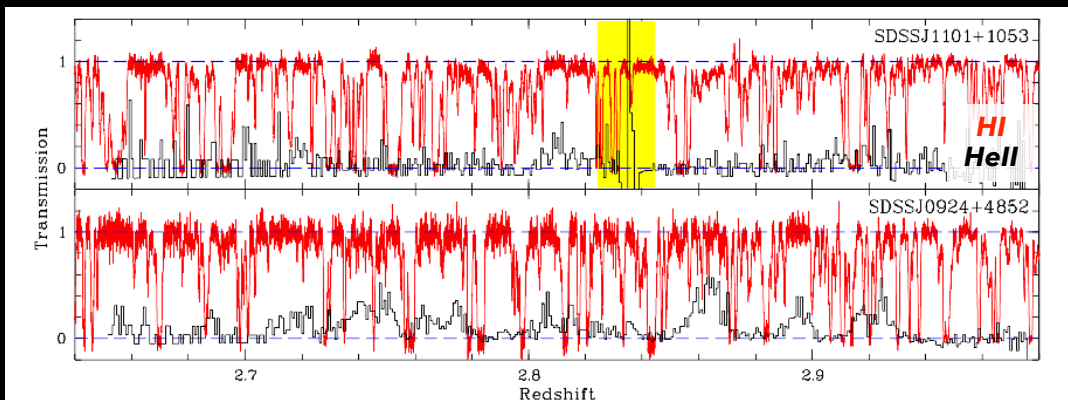
- Targets: Subaru's Extremely Metal-Poor Galaxy sample? ($Z < 0.1 Z_{\text{sun}}$; Kojima+19)
 - High ionization UV/Opt lines : NV $\lambda 1240$, CIV $\lambda 1549$, HeII 1640, [Ne IV] 2424, [Ne V] 3426 (ref. Ouchi-san's talk)
- UV coverage of HWO will probe Lyman Werner radiation (912-1108 Å), which prevents H_2 formation in metal-poor galaxies (formation channel for heavy BH seeds; Omukai01)

Kojima+19; Nishigaki+23; Hatano+23; Watanabe+24

OTHER POSSIBLE SCIENCE CASES

- **Resolved studies of Little Red Dots (origin of UV light: host SF or AGN?)**
 - UV IFU of local LRDs (e.g., Lin+25)
- **HeII reionization history at $z \sim 3$ (HeII Ly α : 303.8 Å)**
 - UV spectroscopy of $z > 3$ quasars ($\tau_{\text{HeII}}(z)$, patchiness, IGM tomography)

HST/COS spectra of $z \sim 3$ quasars



Worseck+11

SUMMARY

- ✦ **JWST and optical/IR wide-field surveys have identified matured SMBHs at $z > 6$**
- ✦ **HWO will provide complementary opportunities to probe SMBH formation in the nearby universe**
- ✦ **Resolved UV-to-IR observations of nearby dwarf galaxies will enable IMBH searches and characterize the hard UV radiation fields necessary for massive BH formation**

Importance of the 1.6 μm CO absorption feature for future direct imaging of Earth-like planets

Lead author: Yui Kawashima

Abstract:

The Habitable Worlds Observatory (HWO) aims to directly image Earth-like planets. Unlike the relatively hot, gaseous planets that currently dominate targets for exoplanet atmospheric characterization, the atmospheric compositions of Earth-like planets in habitable zones are expected to be shaped by a variety of factors that are difficult to predict a priori, including volcanic activity, plate tectonics, the presence of oceans, and potentially biological processes. Therefore, to characterize the surface environments of observed planets as comprehensively as possible, it is essential to constrain the abundances of key molecular species.

A previous study demonstrated that the abundances of water vapor, methane, and carbon dioxide in Archean- and Proterozoic-like planets can be retrieved with high precision, whereas constraining the abundance of carbon monoxide remains challenging. This difficulty arises because the CO absorption feature at 1.6 μm overlaps with CO₂ absorption lines. However, improved constraints on the CO abundance would substantially enhance our ability to infer the atmospheric and surface environments of Earth-like planets. This is because reliable assessments of deviations from thermochemical equilibrium and estimates of the total atmospheric carbon budget require simultaneous constraints on the abundances of all three major carbon-bearing species (CH₄, CO₂, and CO). These diagnostics are essential for indirectly inferring planetary interior and surface conditions, including volcanic activity, plate tectonics, the presence of oceans, and potentially biological activity. We present an investigation of the observational requirements for constraining the CO abundance through its 1.6 μm absorption feature.

Science Case Summary

Previous studies have shown that the provisional instrument specifications of the Habitable Worlds Observatory may make it difficult to constrain the abundance of carbon monoxide because of spectral overlap with other molecules. However, constraining the abundance of carbon monoxide, the only one of the three dominant carbon-bearing species that remains unconstrained, would significantly improve our ability to characterize the atmospheric and surface environments of Earth-like planets. We therefore investigated the instrumental requirements necessary to constrain its abundance.

Importance of the 1.6 μm CO absorption feature for future direct imaging of Earth-like planets

Yui Kawashima (Kyoto University)

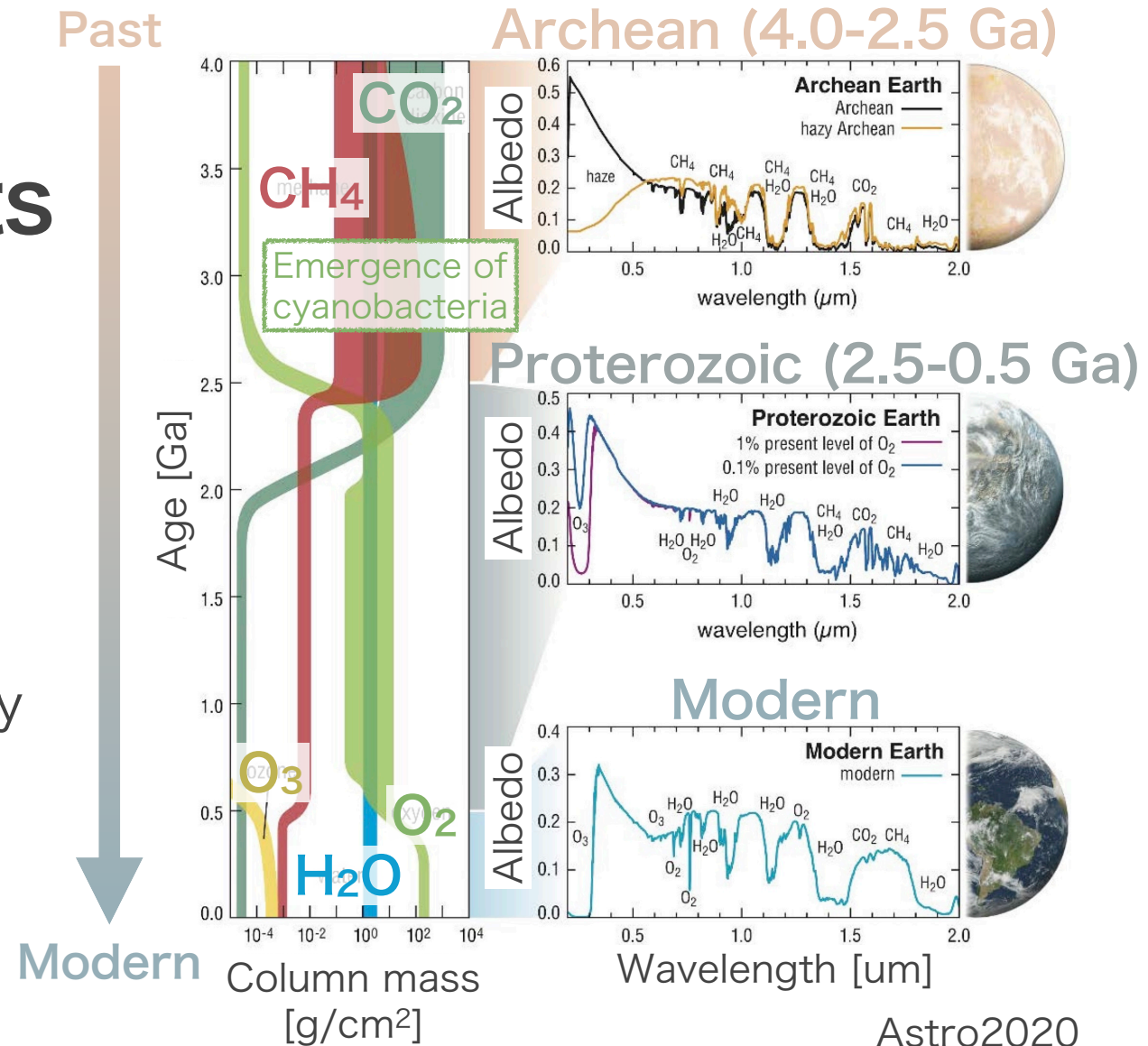
Yasuto Watanabe (NIES), Kazumi Ozaki, Yoshiaki Endo (Science Tokyo),
Hajime Kawahara, and Keigo Enya (JAXA/ISAS)

2026.7.15-16 Habitable Worlds Observatory (HWO) Japan Science Workshop 2

Spectra of Earth-like planets

- Dominated by H_2O , CH_4 , O_2 , and O_3
- However, extraterrestrial planets do not necessarily follow the same evolutionary path

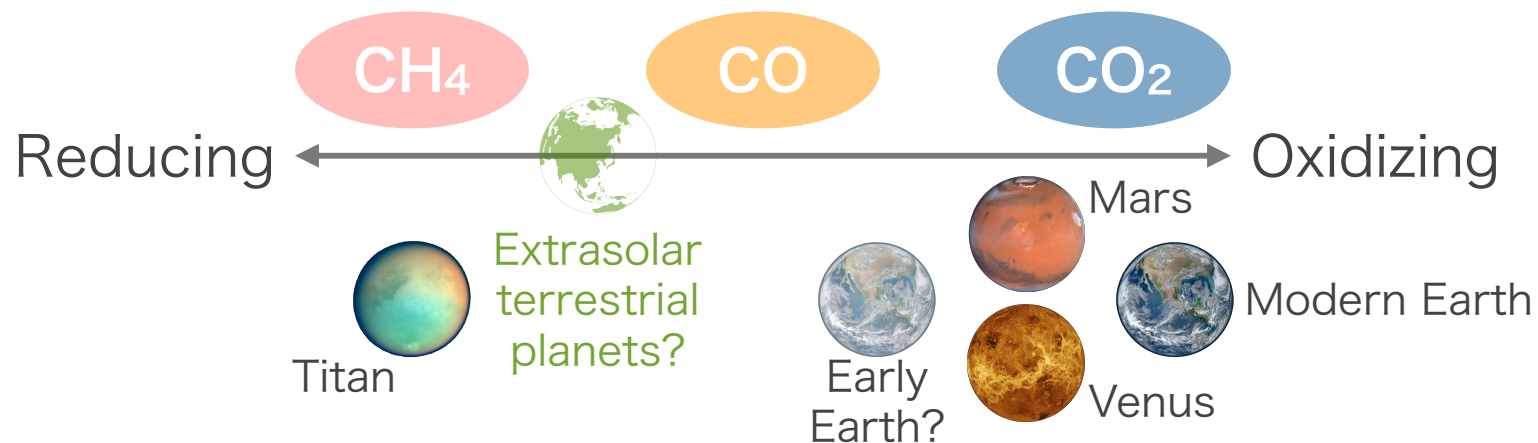
Important to be capable of characterizing a wide range of atmospheric scenarios



Why CO?

Given the large uncertainties in the parameters of **extrasolar terrestrial planets**, **simultaneously constraining all three dominant carbon-bearing species ($\text{CH}_4/\text{CO}/\text{CO}_2$)** is essential for drawing robust conclusions about:

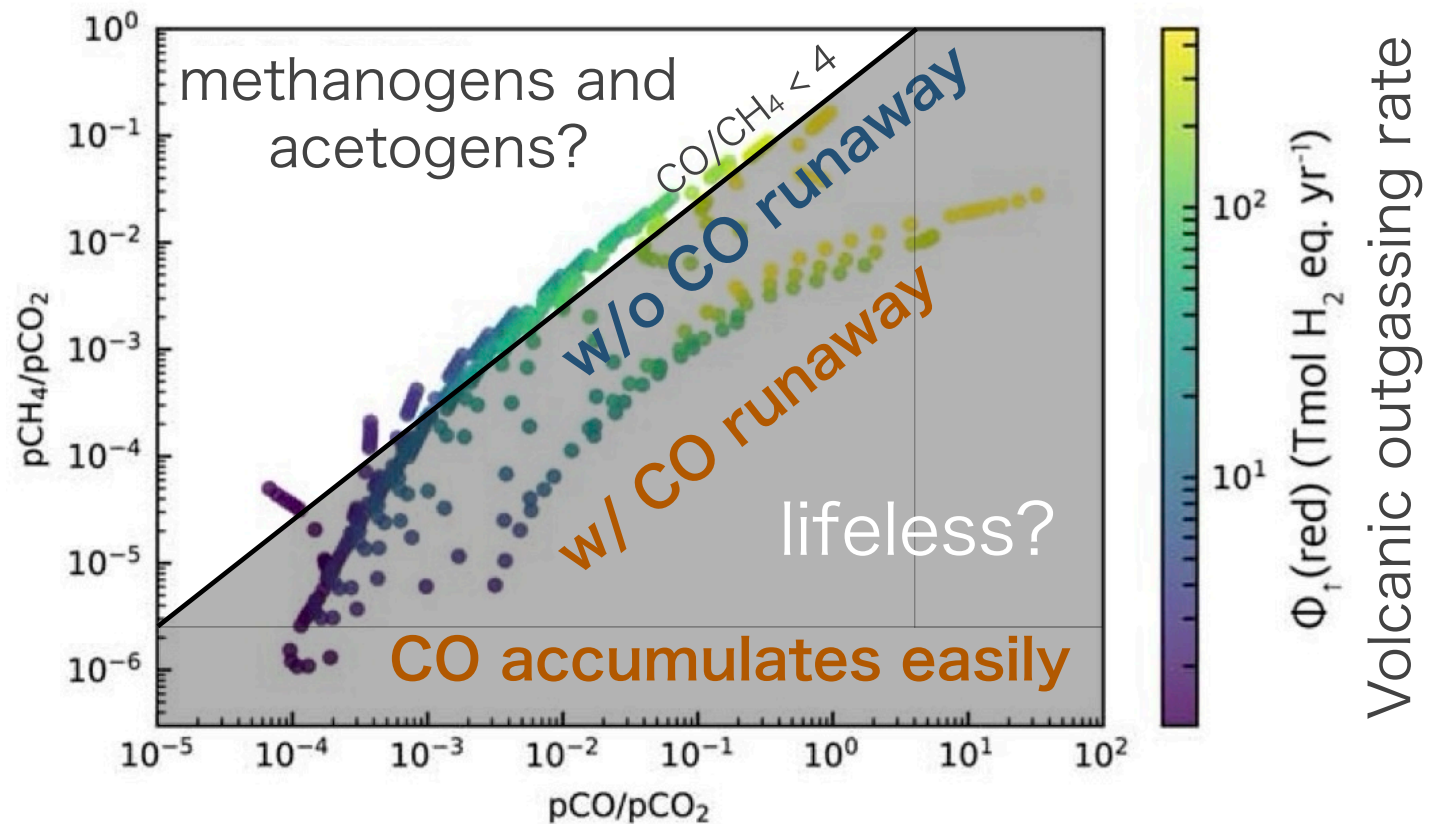
Atmospheric redox state, Thermochemical disequilibrium,
Total atmospheric carbon budget



Why CO?

$\text{CO}/\text{CH}_4 < 4$ is proposed as a possible biosignature because methanogenic and acetogenic metabolisms are thought to be among the easiest to evolve

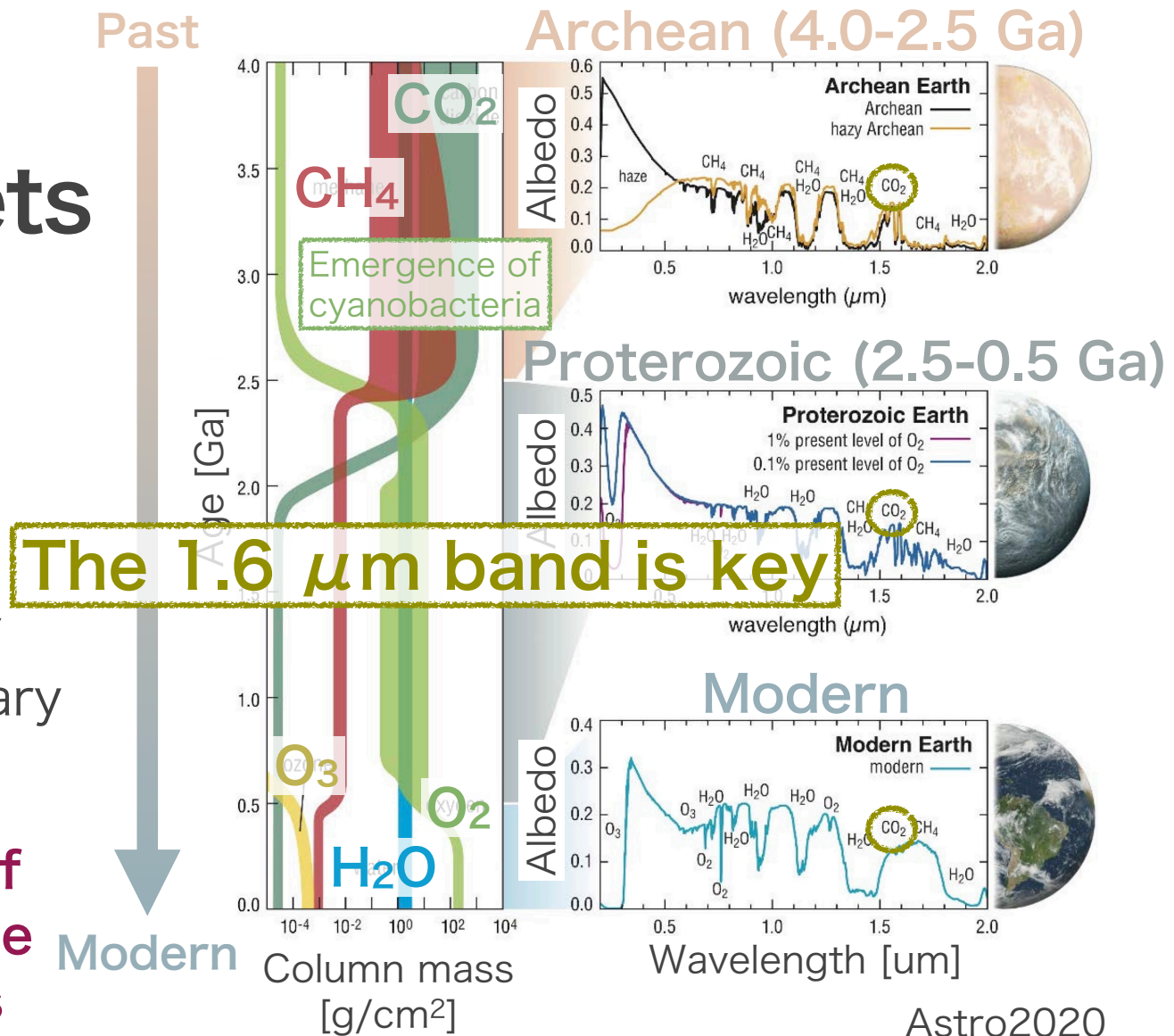
Watanabe & Ozaki (2024)



Spectra of Earth-like planets

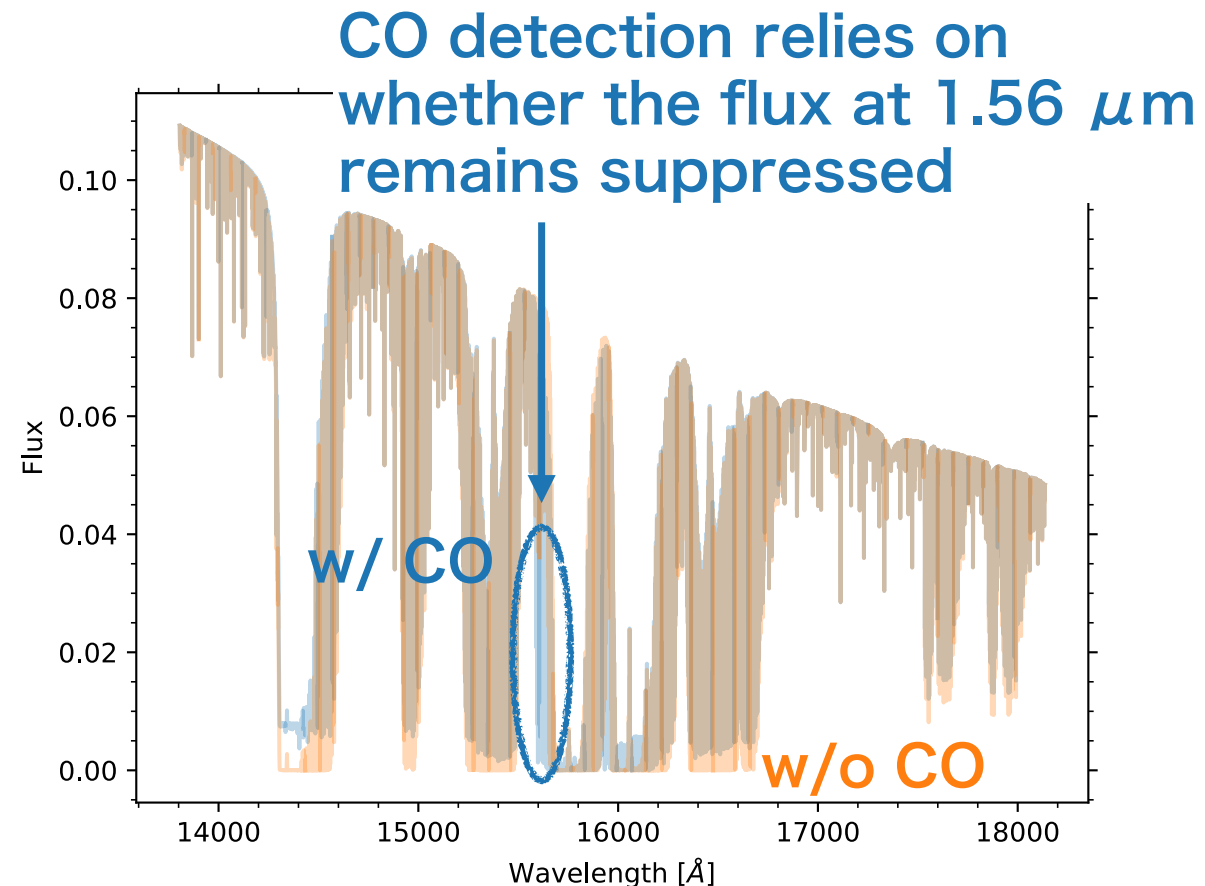
- Dominated by H_2O , CH_4 , O_2 , O_3 , and CO_2
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Important to be capable of characterizing a wide range of atmospheric scenarios



Spectral overlap between CO and CO₂

- The HWO-accessible 1.6 μm CO feature is embedded within numerous CO₂ absorption features
- Previous studies (e.g., Tokadjian et al. 2024) have suggested that constraining the CO abundance is challenging



What instrumental parameters are needed to overcome this problem?

Ocean Color as an Observational Indicator of Surface Oceans on Exoplanets

Lead author: Chihiro Arai

Abstract:

The Habitable Worlds Observatory (HWO) is expected to greatly advance the characterization of potentially habitable planets and the search for biosignatures by obtaining their reflected-light spectra. Identifying surface oceans is a key step toward assessing planetary habitability and is one of the primary science cases for HWO (Cowan et al. 2025).

Ocean reflectance spectra have typically been modeled based on the properties of modern Earth's oceans, often focusing on slightly blue but otherwise flat low reflectance and the strong anisotropy due to Fresnel reflection (ocean glint). Over Earth's history, however, the ocean's chemical environment evolved through gradual oxidation and biological activity. In particular, Archean oceans were likely enriched in dissolved silica and Fe(II) . Such conditions may have favored the presence of suspended silica and iron hydroxide particles, potentially producing reflectance spectra that differed substantially from today's.

In this work, we perform radiative-transfer simulations to evaluate how these suspended mineral particles modify ocean color and how these changes affect disk-integrated planetary reflectance spectra. Our results show that ocean reflectance spectra can be markedly modified by the combined effects of particle optical properties, and water absorption. Particle scattering increases visible reflectance, while water absorption suppresses red reflectance; iron hydroxide absorption further suppresses blue reflectance, making the ocean appear greener, whereas blue reflectance remains enhanced in the non-absorbing silica cases. The resulting characteristics also appear in disk-integrated planetary apparent albedo spectra. We further show that, in a color-color diagram chosen to capture these spectral features, particle-rich ocean scenarios can be distinguished from non-ocean surface environments even under partial cloud cover and with photometric uncertainties expected for HWO.

These findings suggest that particle-induced ocean-color signatures may open a new observational pathway for identifying surface oceans from observations at a single orbital phase, without requiring stringent phase constraints. This pathway complements glint-based ocean detection that requires observations over multiple orbital phases and can be limited by inner working angle constraints near crescent phases. Beyond identifying surface oceans, these signatures may also serve as a probe of the ocean environments that allow suspended particles to form and persist.

Science Case Summary

Detecting surface oceans on exoplanets is a key science case for the Habitable Worlds Observatory (Cowan et al. 2025). We propose a new approach to identifying surface oceans based on the ocean color induced by suspended particles. This approach may expand the observational opportunities for ocean detection and, beyond detection alone, offer a new means of characterizing ocean environments.

2026/07/16

Habitable Worlds Observatory Japan Science Workshop 2

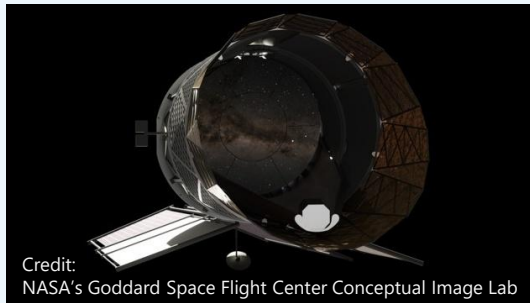
Ocean Color as an Observational Indicator of Surface Oceans on Exoplanets

Chihiro Arai ¹, Yuka Fujii ², Taro Matsuo ¹

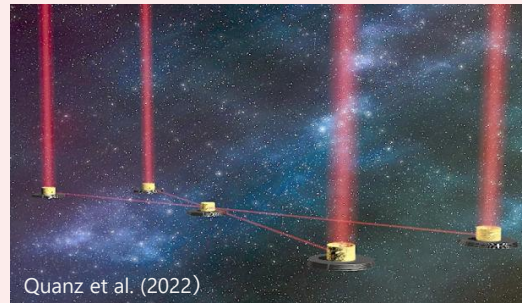
¹ The University of Osaka, ² National Astronomical Observatory of Japan

Searching for habitable worlds

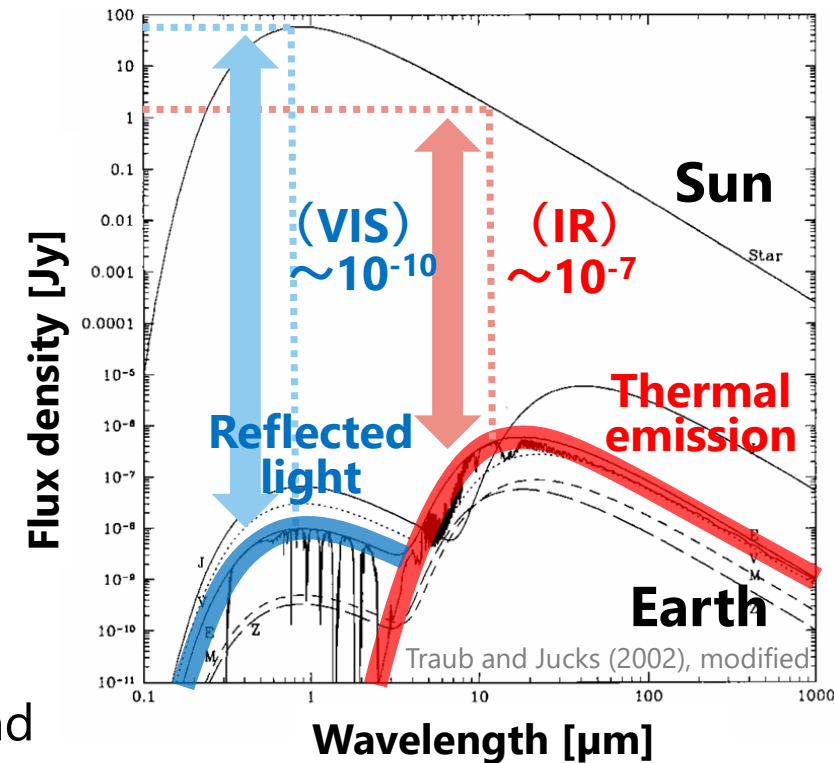
- ◆ **Direct Imaging of Earth-like planets in the 2040s will open a new window for habitable worlds.**



Habitable Worlds Observatory (HWO)
(UV-Visible-Near infrared)
Reflected light



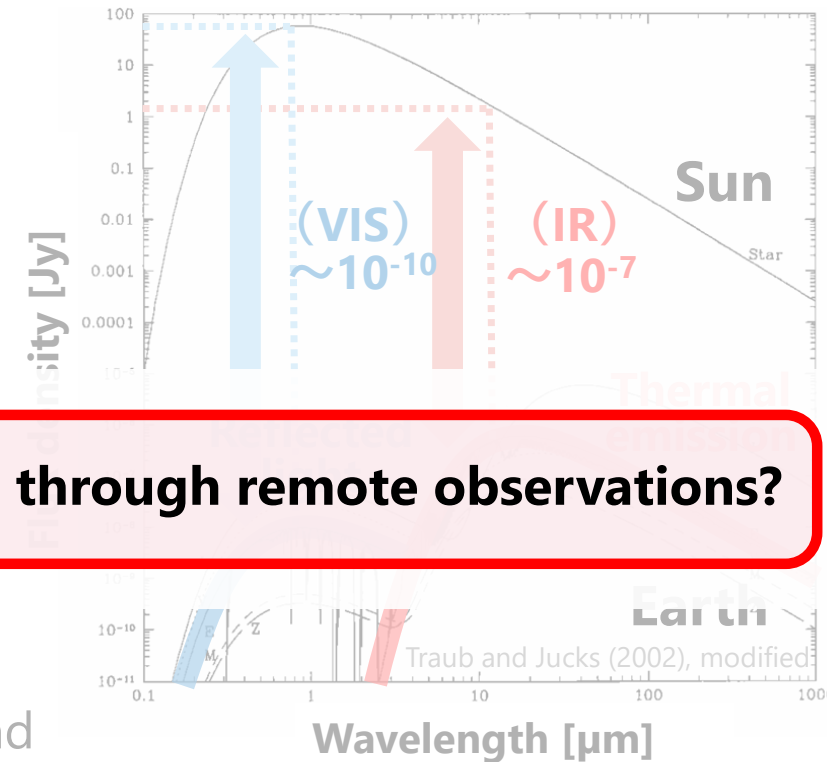
Large Interferometer For Exoplanets (LIFE)
(Mid infrared)
Thermal emission



- ◆ **HWO will characterize potentially habitable planets and search for biosignatures** thorough reflected-light spectroscopy.
- ◆ **Surface liquid water is a key indicator of habitability.**
 - ➔ **Detecting oceans is an important science goal for HWO.** (e.g., Cowan et al. 2025)

Searching for habitable worlds

- ◆ Direct Imaging of Earth-like planets in the 2040s will open a new window for habitable worlds.



- ◆ How can we identify surface oceans on exoplanets through remote observations?

(UV/Visible/Near-infrared)
Reflected light

(Mid-infrared)
Thermal emission

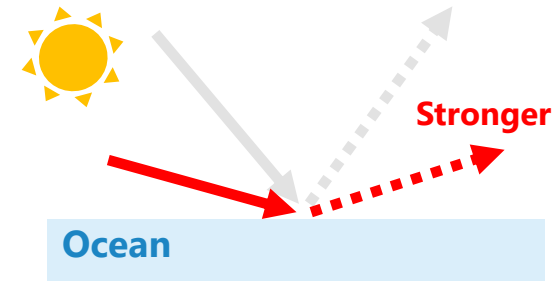
- ◆ HWO will characterize potentially habitable planets and search for biosignatures thorough reflected-light spectroscopy.
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Ocean glint: the conventional approach to surface-ocean detection

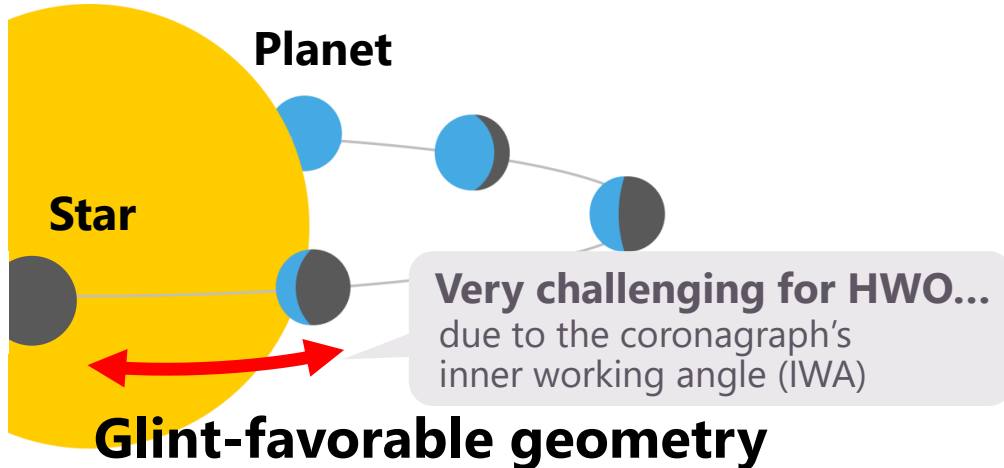
Previous main approaches

“Ocean glint”

: Specular reflection from the ocean surface



Phase changes in an edge-on orbit

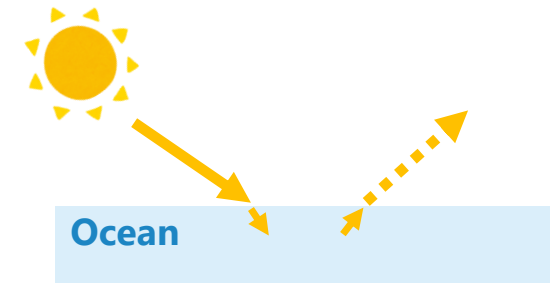


- ❑ Specular reflection becomes stronger at glancing illumination angle.
- ➔ Requires observations at near crescent phases, but **small planet-star separation limits accessibility** (Vaughan et al. 2023).
- ❑ Confirming **glint requires observations at multiple orbital phases**
- ➔ This **demands stable instrument performance** over months-long timescales (Cowan et al. 2025).

Ocean color of the modern Earth's oceans

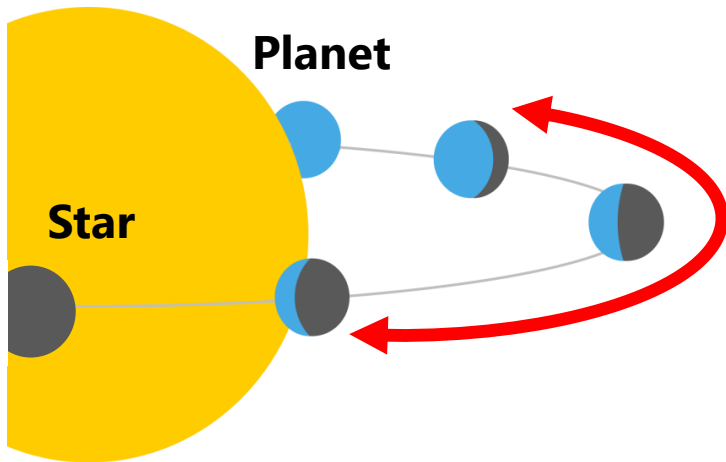
Another approach

"Ocean color" : Reflectance shaped by absorption and scattering within the ocean



Modern ocean

- ◆ **Low reflectance, slightly bluish**
(Modeled in previous studies)



◆ Advantage

Observable at broad orbital phases, avoiding strict inner working angle constraints

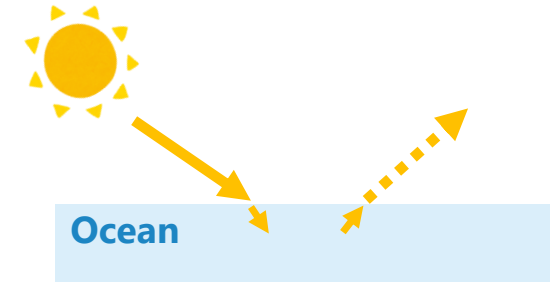
◆ Disadvantages

Lacking distinct spectral signatures, ocean color can be degenerate with other dark surface types (ex. dark rocks covered by a Rayleigh-scattering atmosphere)

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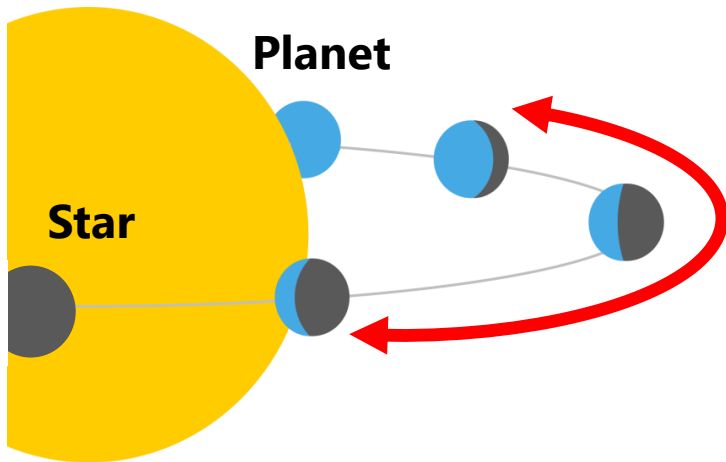
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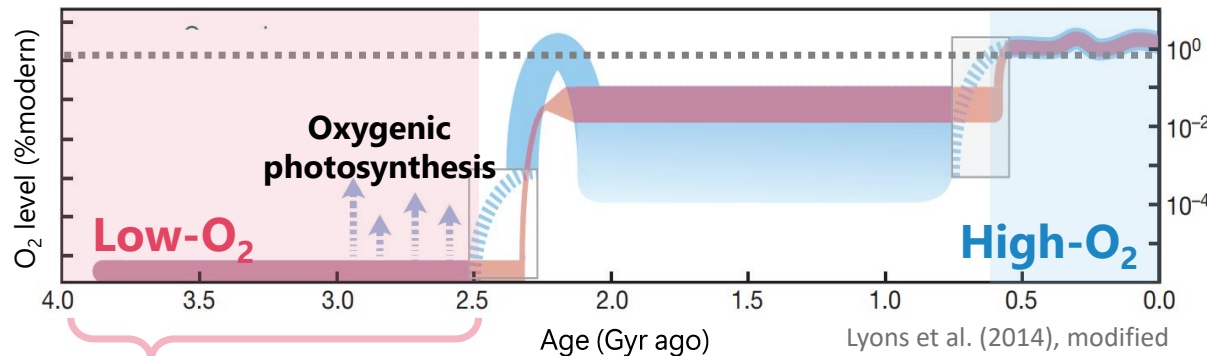
Lacking distinct spectral signatures, ocean color can be degenerate with other dark surface types (ex. dark rocks covered by a Rayleigh-scattering atmosphere)



However,
is the modern ocean representative of exoplanet oceans?

Particle-induced ocean color motivated by early Earth

With progressive oxidation and biological activity,
the ocean gradually evolved toward its modern state.



Archean (4.0-2.5 Gyr ago)

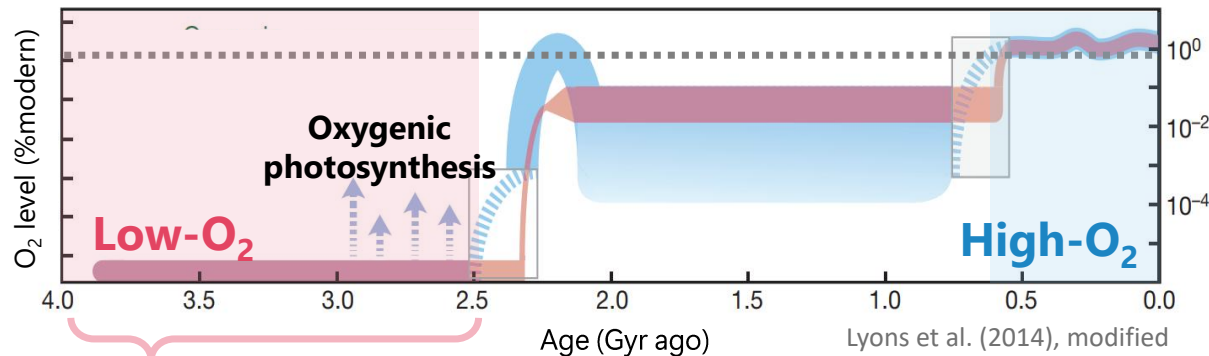
The emergence of oxygen-producing life (~3.0 Gyr ago)

➡ From a **low-oxygen environment** to an **oxygen-rich environment**

- ◆ **Fe²⁺ and Silica-rich oceans derived from hydrothermal sources (10³-10⁴×modern levels)**
 - ▶ **Iron hydroxide particles precipitated** due to the oxidation of dissolved Fe²⁺.
 - ▶ Dissolved **silica concentrations may have approached saturation**, allowing silica particles to form.

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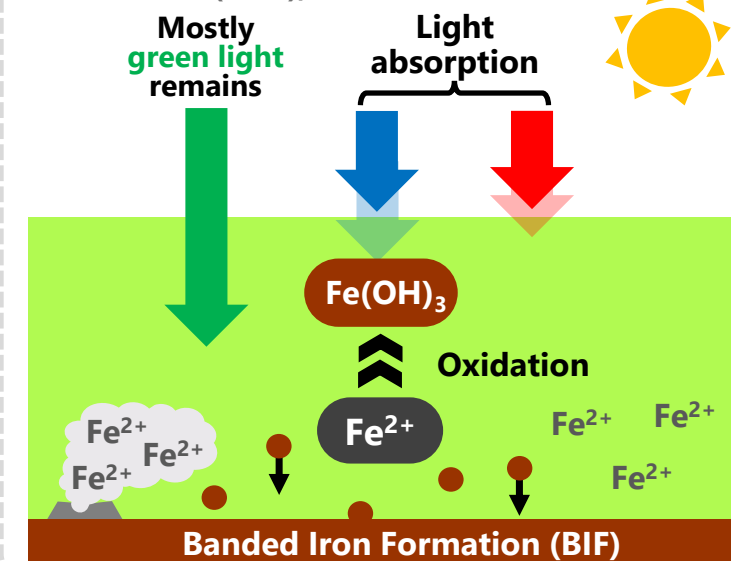
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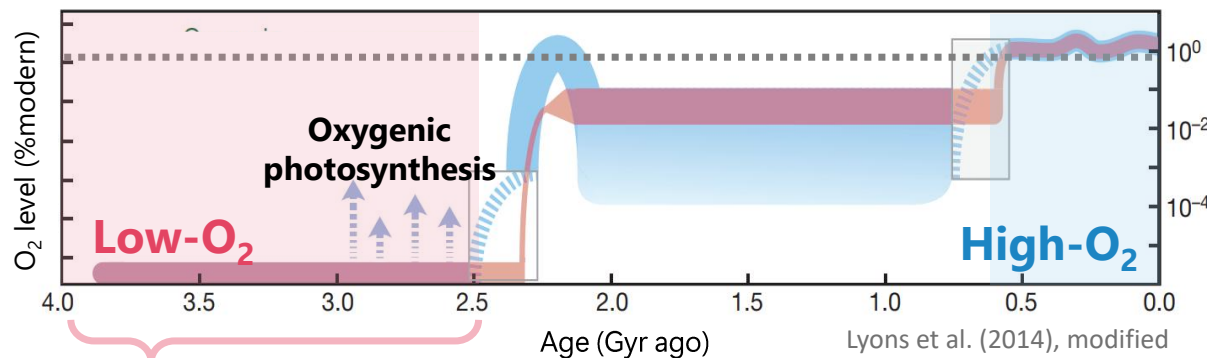
Green Ocean Hypothesis

Matsuo et al. (2025), *Nat Ecol Evol*



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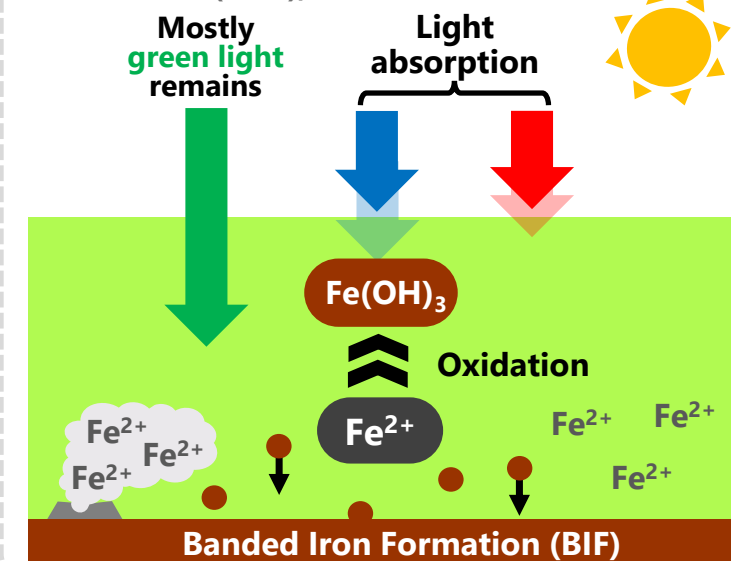
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Green Ocean Hypothesis

Matsuo et al. (2025), *Nat Ecol Evol*



► **Changes in ocean reflectance** driven by absorption and scattering by ocean constituents may provide clues to **the presence of oceans.**

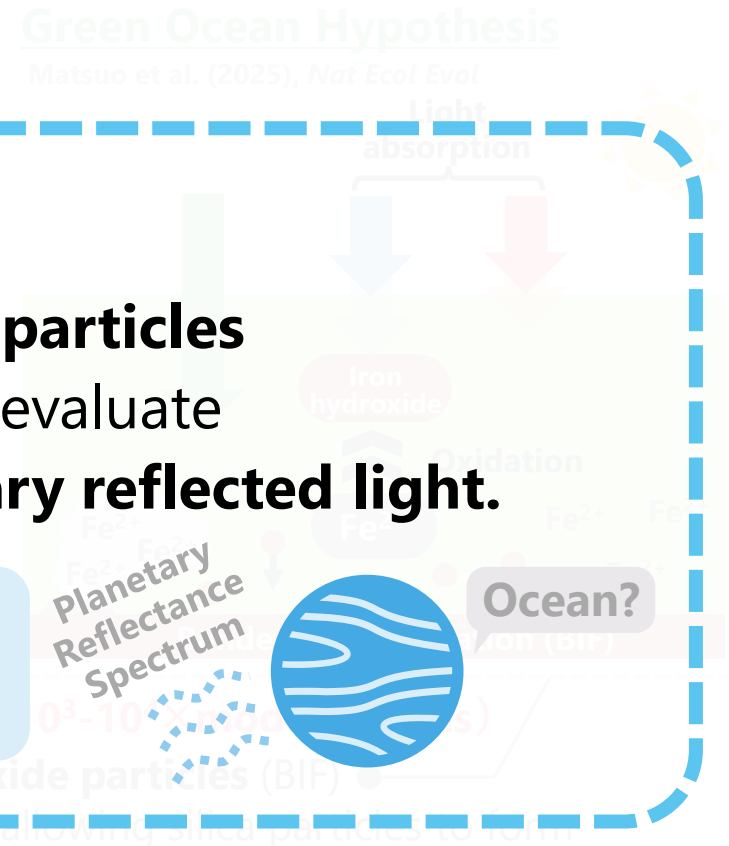
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the ocean gradually evolved toward its modern state.

Objective

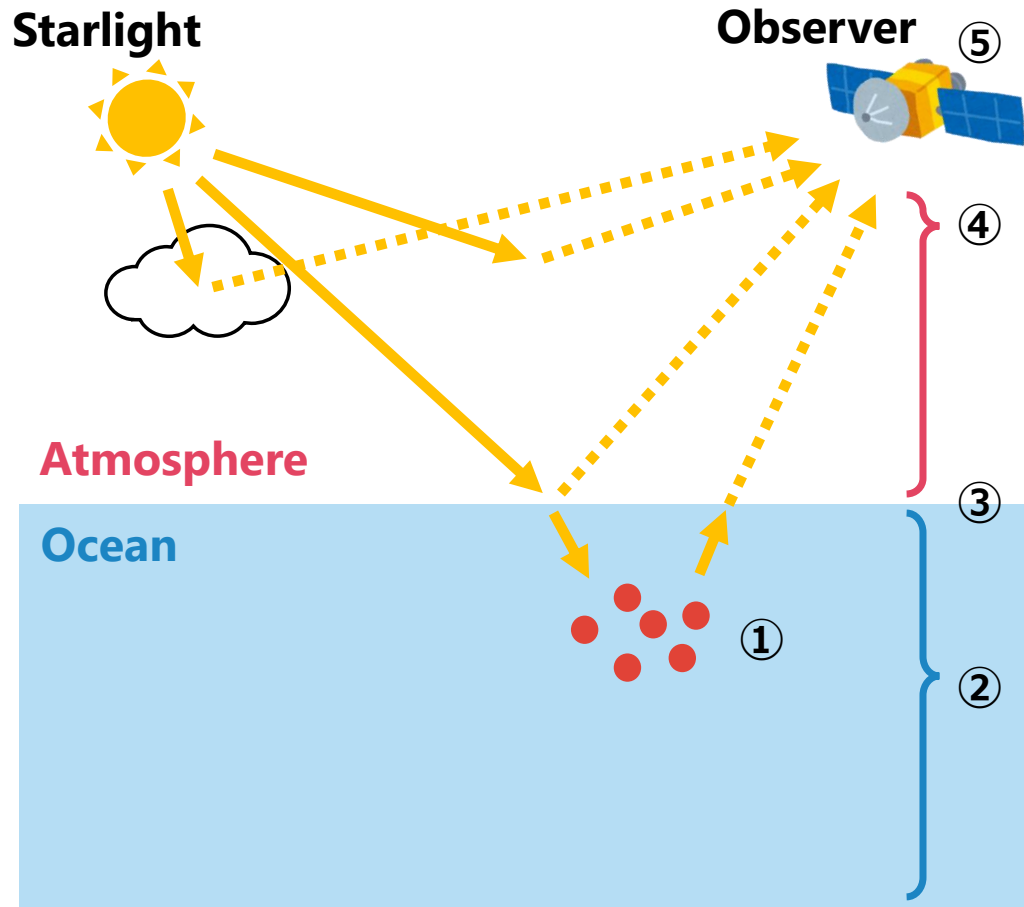
We examine **silica particles** and **iron hydroxide particles** as examples relevant to Archean-like oceans and evaluate **how they affect ocean reflectance and planetary reflected light**.

Ocean color potentially offers a new approach to detecting signs of surface ocean on exoplanets ?



Changes in ocean reflectance driven by absorption and scattering by ocean constituents may provide clues to the presence of oceans.

Calculation overview



⑤ Planetary reflectance spectrum

PICASO (Batalha et al. 2019)

④ Atmosphere-surface radiative transfer and disk integration

③ Ocean reflectance spectrum

Pythonic DISORT (Ho, 2024)

② Underwater radiative transfer

Measured values or Mie theory
(Matsuo et al. 2025)

① Ocean optical properties (water+particles)

Main model assumptions

Ocean

- ✓ Flat sea surface (no waves)
- ✓ Vertically uniform particle concentration
- ✓ Semi-infinite ocean
- ✓ No internal light sources or inelastic processes

We adopted **plausible particle concentrations based on previous studies of Archean oceans**:
("Si" and "Fe" denote the **concentrations of silica particles** and **iron hydroxide particles**, respectively.)

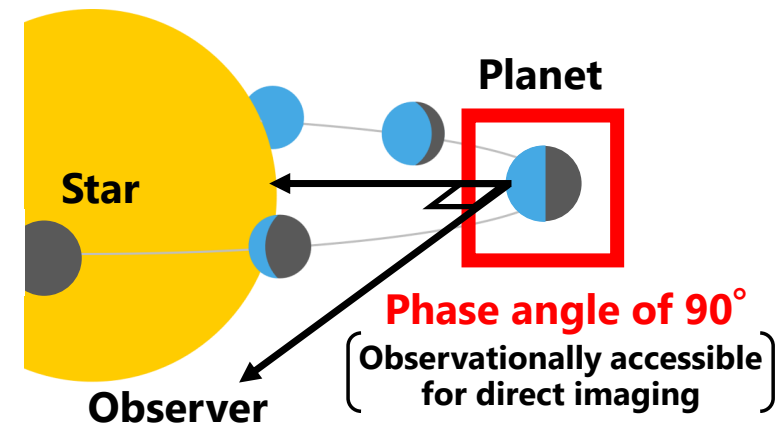
Three ocean scenarios

- ◆ **Clear ocean (no suspended particle)**
- ◆ **Silica-rich ocean**: $\text{Si} = 10, 30, 100, 300 \text{ } \mu\text{M}$ (※ $\text{M} = \text{mol L}^{-1}$: Molar concentration)
- ◆ **Iron hydroxide-rich ocean**: $\text{Fe} = 1, 3, 10, 30 \text{ } \mu\text{M}$

Planet

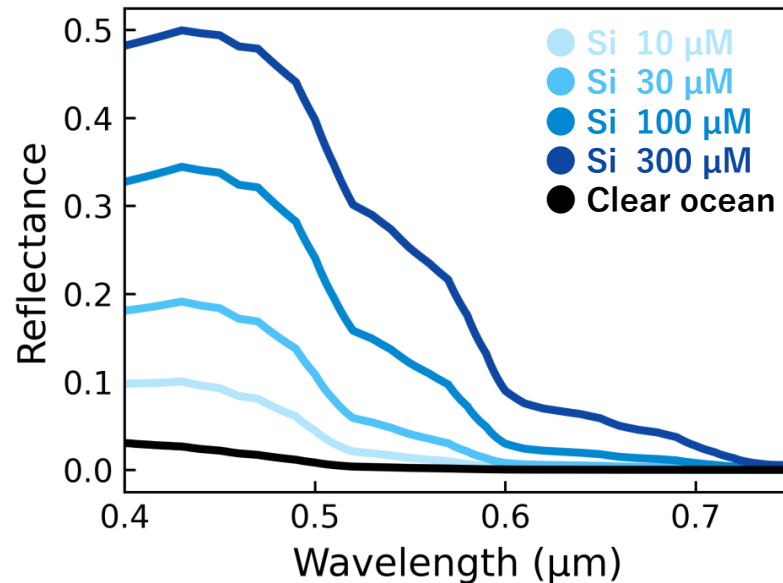
Ocean-covered terrestrial planet orbiting a Sun-like star

- ◆ **Atmosphere**: Archean-like reducing atmosphere
 - ▶ High methane (no haze), low oxygen
- ◆ **Cloud**: Gray water cloud with $\tau = 10$
- ◆ **Spectral resolution**: $R = 140$ (HWO-like condition)

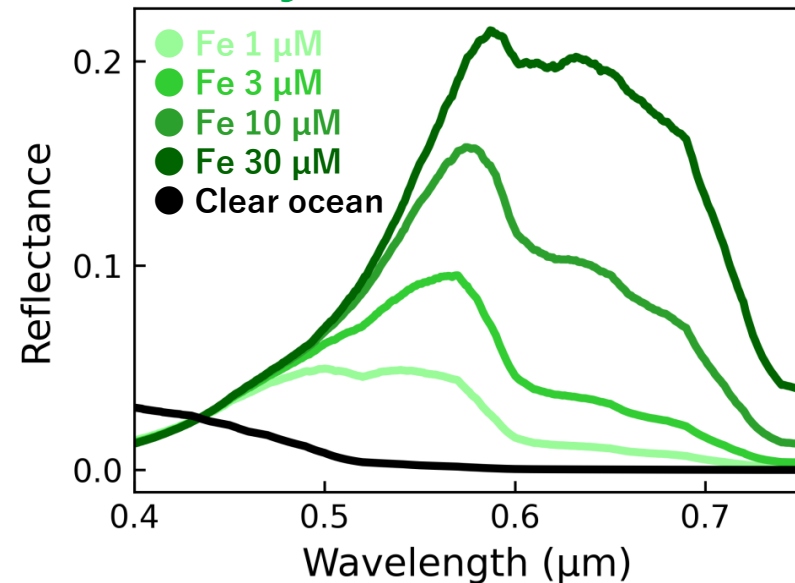


Ocean reflectance spectra (concentration-dependent)

Silica-rich ocean

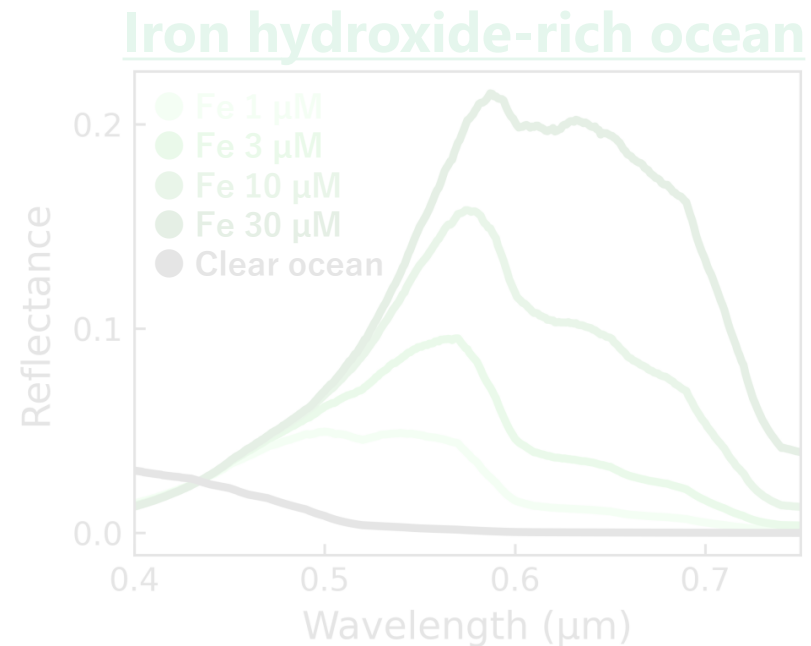
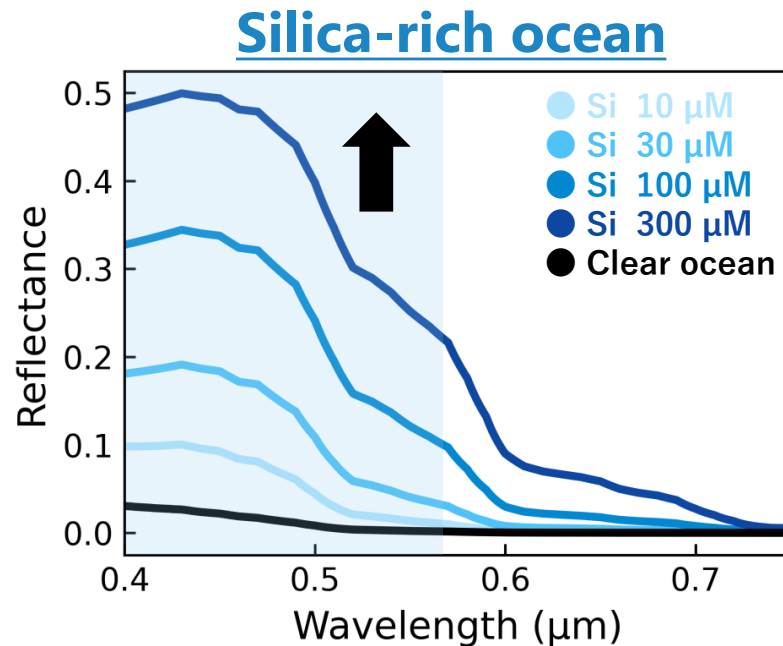


Iron hydroxide-rich ocean



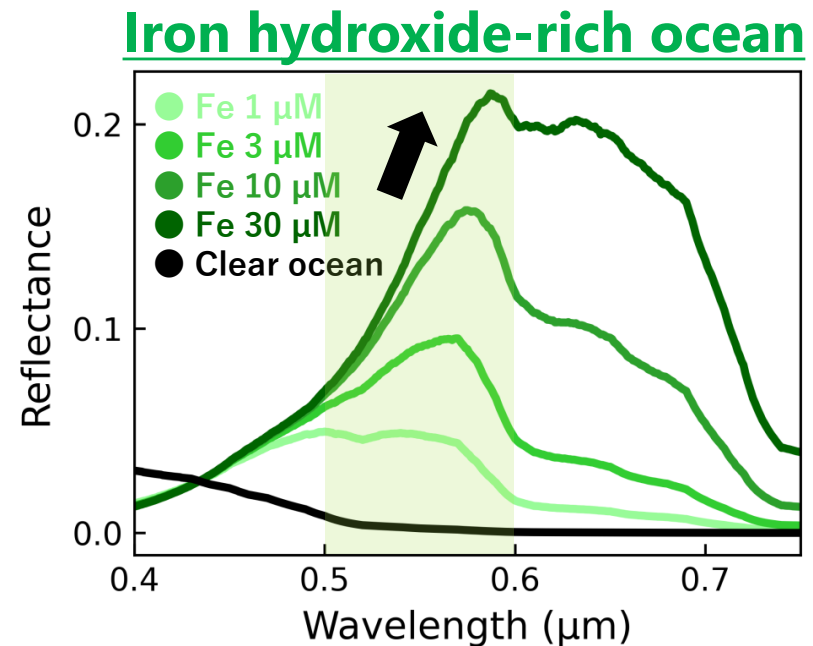
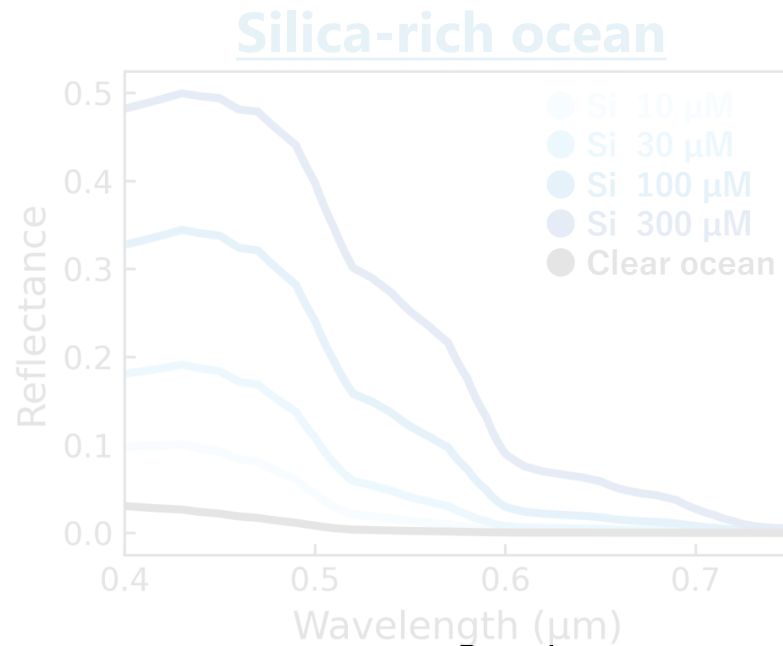
- The clear ocean shows very low reflectance due to weak scattering.
- Ocean reflectance spectra can be strongly modified by the combined effects of particle absorption and scattering, and water absorption at red wavelengths:

Ocean reflectance spectra (concentration-dependent)



- ❑ The clear ocean shows very low reflectance due to weak scattering.
- ❑ Ocean reflectance spectra can be strongly modified by the combined effects of particle absorption and scattering, and water absorption at red wavelengths:
 - ▶ Silica is non-absorbing, so particle scattering enhances reflectance at blue-green wavelengths.
 - ▶ Iron hydroxide produces an edge-like feature around 0.5-0.6 μm due to strong absorption at blue wavelength, in addition to scattering.

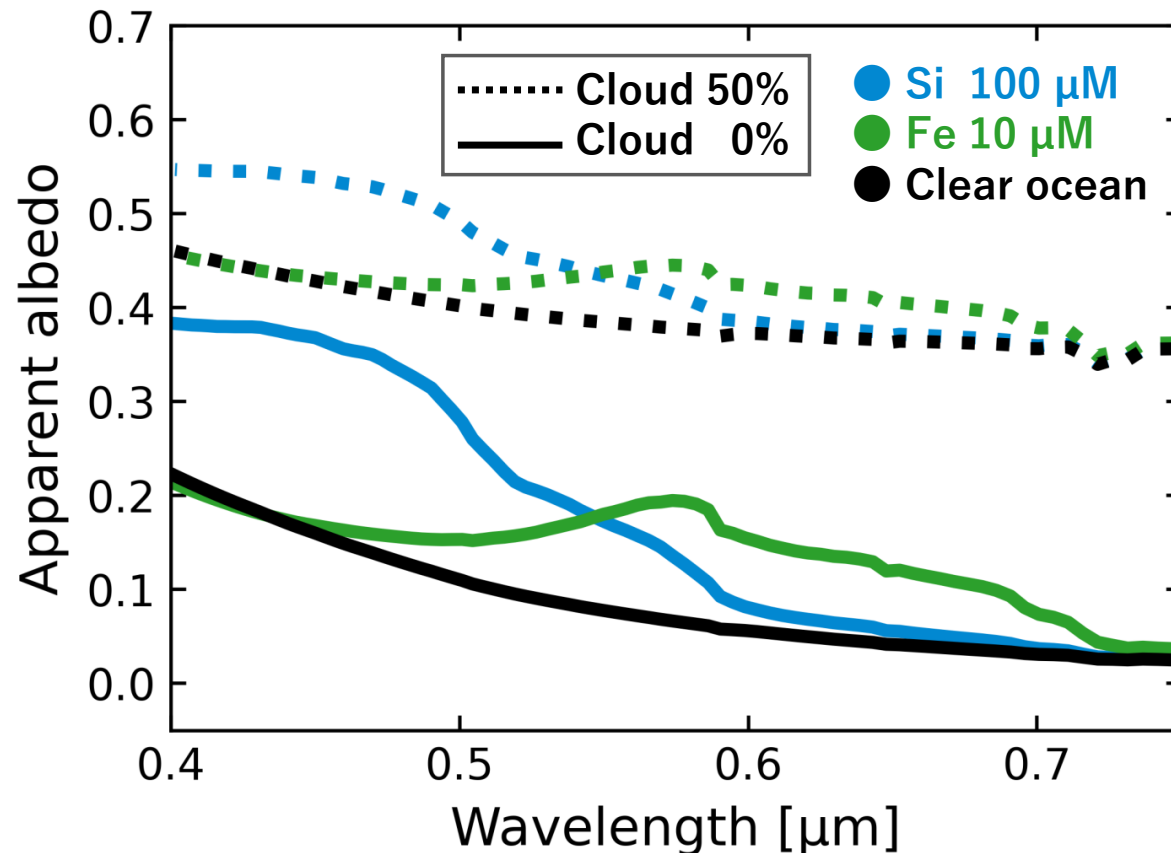
Ocean reflectance spectra (concentration-dependent)



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Apparent albedo spectra of ocean-covered planets

※ Surface specular reflection was neglected because its contribution is expected to be small at a phase angle of 90° .

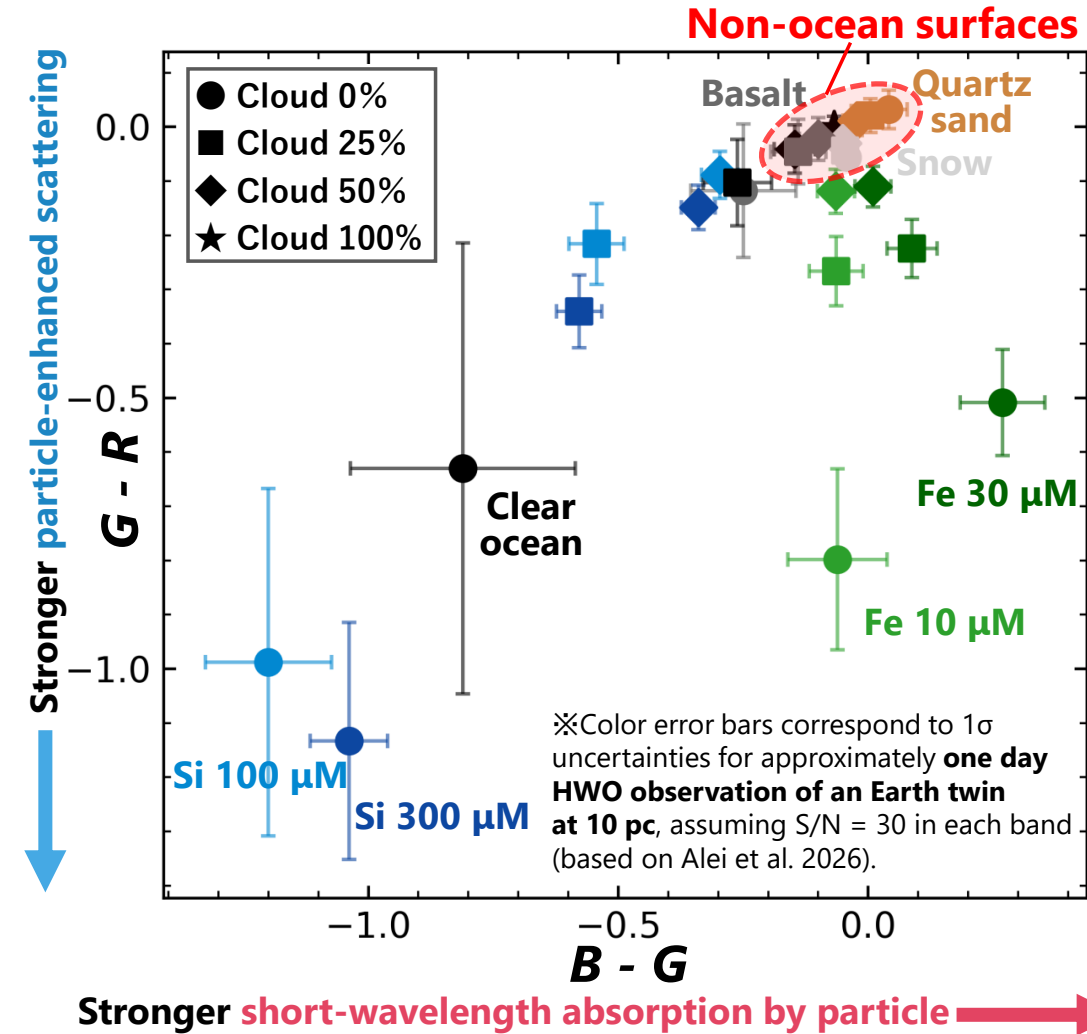


□ Ocean optical differences alter **both the brightness and spectral shape** of the apparent albedo spectra.

□ Clouds increase the overall reflectance but reduce these differences.

➡ However, **characteristic ocean-reflectance features can remain visible** even in cloudy cases.

Color-color diagram (comparison with non-ocean surfaces)



We use a **color-color diagram** to compare spectral shapes and assess observational distinguishability.

Color definition

$$A - B = -2.5 \log_{10} \left(\frac{\langle r_A \rangle}{\langle r_B \rangle} \right) \quad (\langle r_X \rangle: \text{Band-averaged apparent albedo})$$

Three bands selected to capture ocean-color features:

B (0.45-0.55 μm) / **G** (0.55-0.65 μm) / **R** (0.65-0.75 μm)

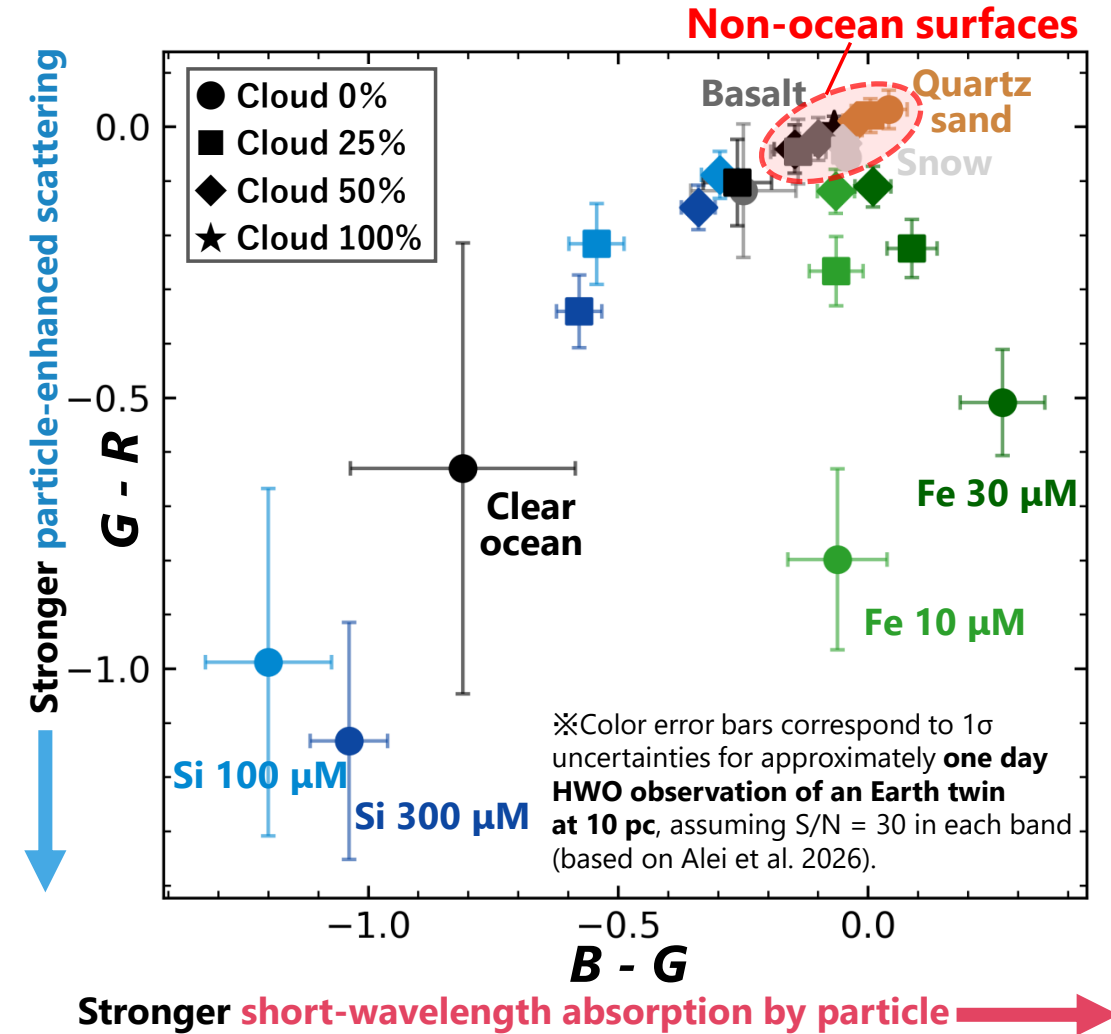
Iron hydroxide absorption

Particle scattering

Water absorption

- Without clouds (●), ocean-covered planets are clearly separated from non-ocean surfaces such as quartz sand, basalt, and snow.
- With clouds (■, ◆), the ocean cases move closer to non-ocean surfaces, but **particle-containing oceans generally remain more distinguishable**.

Color-color diagram (comparison with non-ocean surfaces)



We use a **color-color diagram** to compare spectral shapes and assess observational distinguishability.

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Iron hydroxide absorption

Particle scattering

Water absorption

Color-color diagrams provide a useful framework for identifying and classifying bright oceans containing particles.

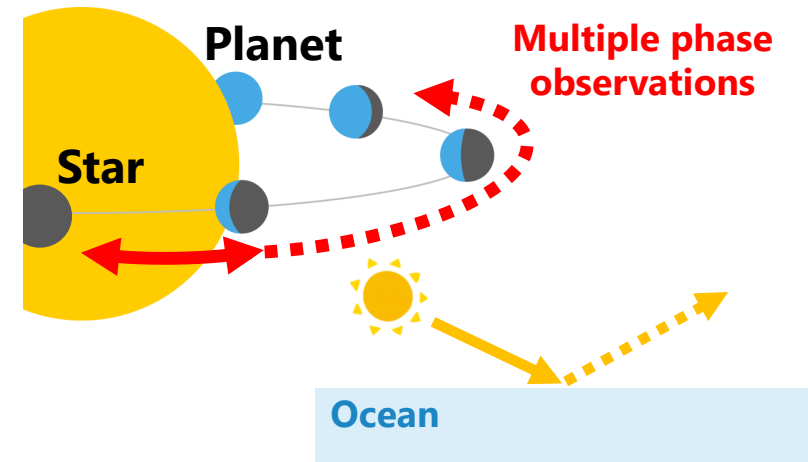
Comparison with glint-based ocean detection

“Ocean glint”

- ◆ Requires observations at multiple orbital phases, including the near crescent phases

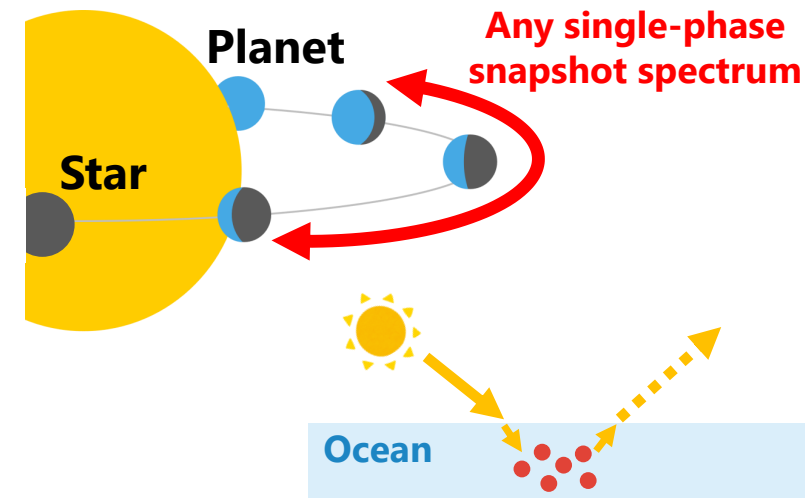
Key constraints for glint detectability:

- ▶ Coronagraph’s inner working angle
- ▶ Long-term instrumental stability



“Ocean color (driven by particles)”

- ◆ Potentially detectable from observations **at a single orbital phase without stringent phase-angle constraints**
- ◆ Ocean-color signatures may also **provide information about the ocean conditions that allow suspended particles to form and persist.**



Summary

- ◆ **Suspended mineral particles can produce distinct ocean-color signatures** through scattering and absorption within the ocean.
- ◆ **These signatures can remain visible in disk-integrated reflected-light spectra** and may be **distinguishable from other non-ocean surfaces**.
- ◆ **Particle-induced ocean color may provide a new pathway for identifying surface oceans and characterizing ocean environments.**

Planetary Defense and Space Telescopes

Makoto Yoshikawa (JAXA)

Lead author: Makoto Yoshikawa

Abstract:

Planetary defense is the effort to prevent natural disasters caused by celestial bodies colliding with Earth, and recently, that effort has become very active. The number of discovered asteroids has exceeded 1.55 million, and about 42,000 of them have been identified as near-Earth objects (NEOs) that approach Earth. This number is increasing rapidly. Exploration of NEOs is also being carried out, and so far probes have been sent to about 10 NEOs. The asteroids Itokawa and Ryugu explored by Japan's Hayabusa and Hayabusa2 are also NEOs. Furthermore, experiments to alter the orbit of an asteroid, such as the one conducted by the United States with the DART probe, are also being carried out. As planetary defense activities have progressed in this way, celestial bodies that could actually collide with the Earth are sometimes discovered. One of them is the asteroid 2024 YR4, which was discovered at the end of 2024. It was found in January 2024 that this asteroid could potentially collide with the Earth in 2032. Observations were urgently made by many telescopes, but with ground-based telescope observations, it became impossible to continue observing this asteroid before it was determined whether it would collide with the Earth or the Moon. However, observations made by the JWST made it clear that it would not collide with the Earth or the Moon. In this way, when observations from the ground become difficult, having a space telescope will make a major contribution to planetary defense. We anticipate that the HWO will also play a significant role in the observation of small solar system bodies located in very close proximity.

Science Case Summary

Planetary defense, which examines the issue of celestial bodies colliding with Earth, has become more active in recent years. As a result, celestial bodies such as asteroid 2024 YR4 that could collide with Earth have begun to be discovered. In particular, observations of this asteroid were carried out by JWST when observations with ground-based telescopes were not possible, and they provided important observational data for determining whether this asteroid would collide with the Earth or the Moon. Space telescopes are also important for planetary defense.

Planetary Defense and Space Telescope

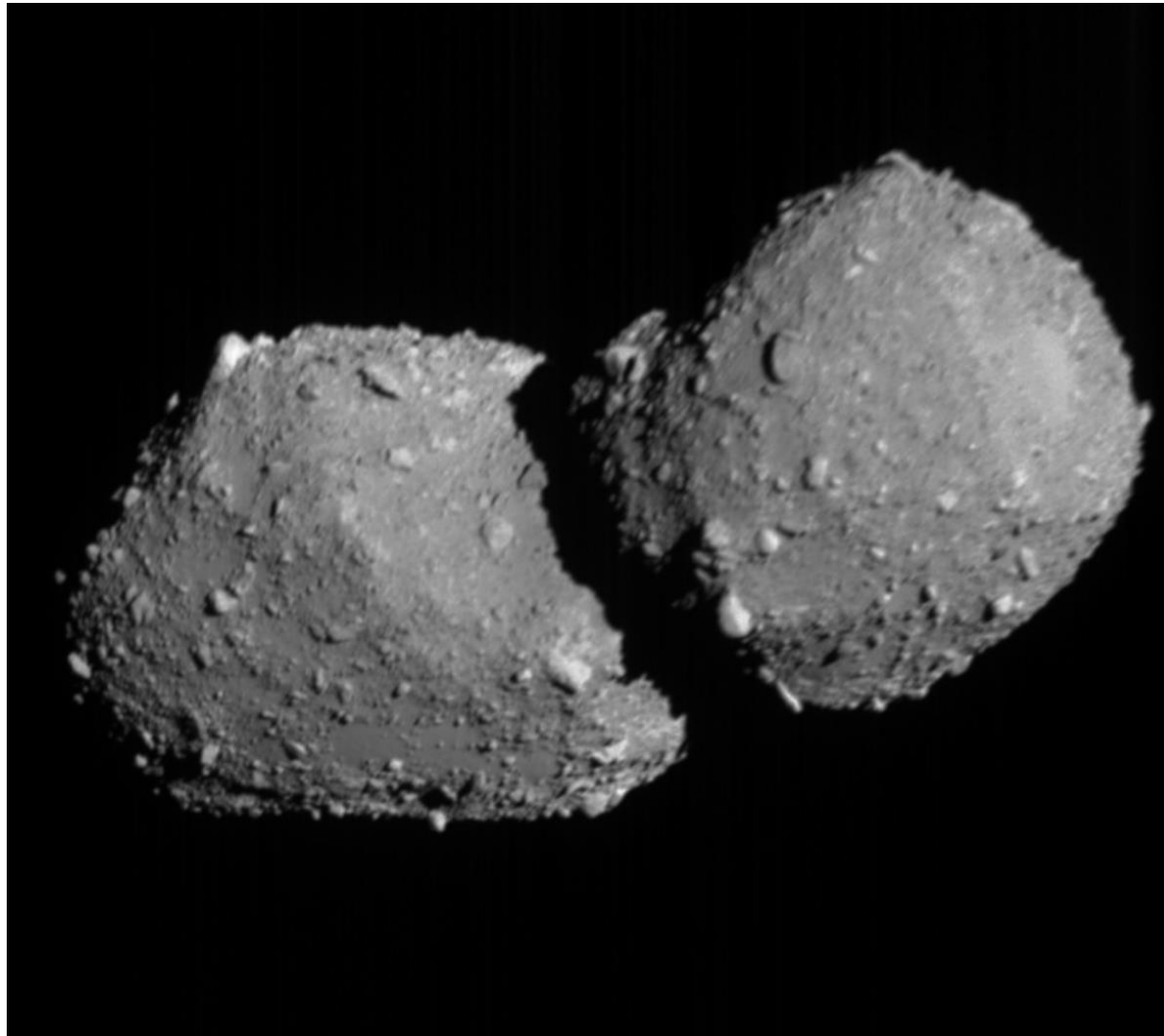
*Habitable Worlds Observatory
Japan Science Workshop 2*

July 16, 2026@ISAS/JAXA

Makoto Yoshikawa
(JAXA Planetary Defense Team)



This is Asteroid (98943) Torifune !



This image was taken at
5 July 2026, 09:29:59 UT.

The time in this presentation is preliminary.

**The flyby of Hayabusa2
was successful!**

Image credit: JAXA, The University of
Tokyo, Chiba Institute of Technology,
Institute of Science Tokyo, AIST, Paris
Observatory, IAC

Impacts of celestial bodies to the Earth

If a celestial body such as an asteroid or a comet collides with the Earth, a large natural disaster will occur.

■ 15 Feb. 2013 : Cheryabinsk meteorite in Russia



■ 30 June 1908 : Tsunguska event in Russia



■ about 66 million years ago : Mass extinction



We want to prevent such disasters in advance.
⇒ Planetary defense (Spaceguard)

What we should do for planetary defense

Step 1

Discover NEOs



**Follow-up observations for
precise orbit determination**



**Check of Earth collision by
orbit calculations**

**Investigate the physical
characteristics of NEOs**

Step 2

**Avoid collision
or
Minimize damage**

- **Change the orbit of near-Earth objects**
- **Protect the collision point**
- **Evacuate people**

Make international law

**Coordinate international
collaboration**

NEO : Near Earth Object

Asteroids and comets discovered up to now

NEO
Asteroid : 1,552,879 → **42,009**
Comet : 4,643 → **208**

Data as of 15 July 2026

MPC (Minor Planet Center), JPL Horizons

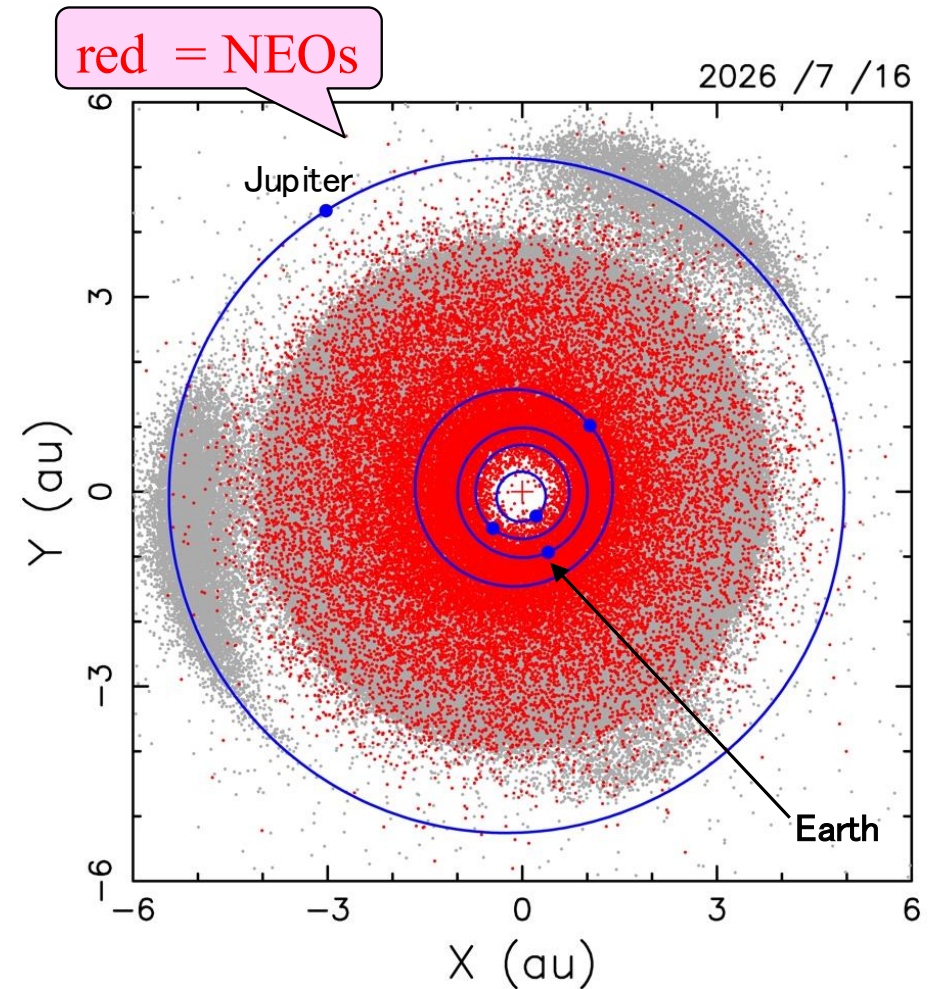
NEO = Near Earth Object

Definition :

Asteroids and comets whose
perihelion distance is less than 1.3 au

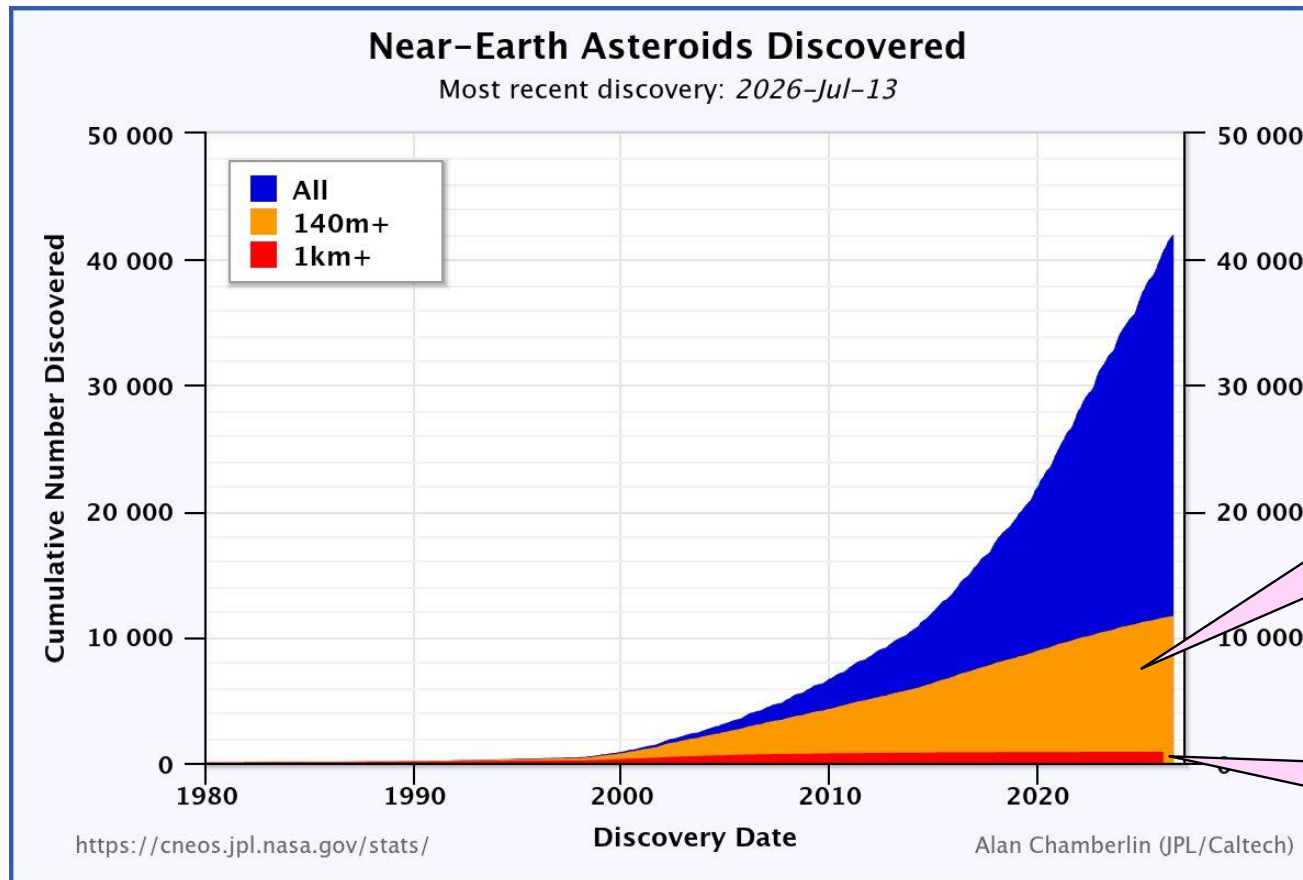
||

**Such objects have the probability to collide
with the Earth**



Distribution of asteroids

Current status of near-Earth asteroid discovery



NEO larger than 140 m :
About 40% were discovered.

NEO larger than 1 km :
About 95% were discovered.

JPL : The Center for Near-Earth Object Studies (CNEOS)
<https://cneos.jpl.nasa.gov/stats/totals.html>

Asteroids discovered before colliding with the Earth

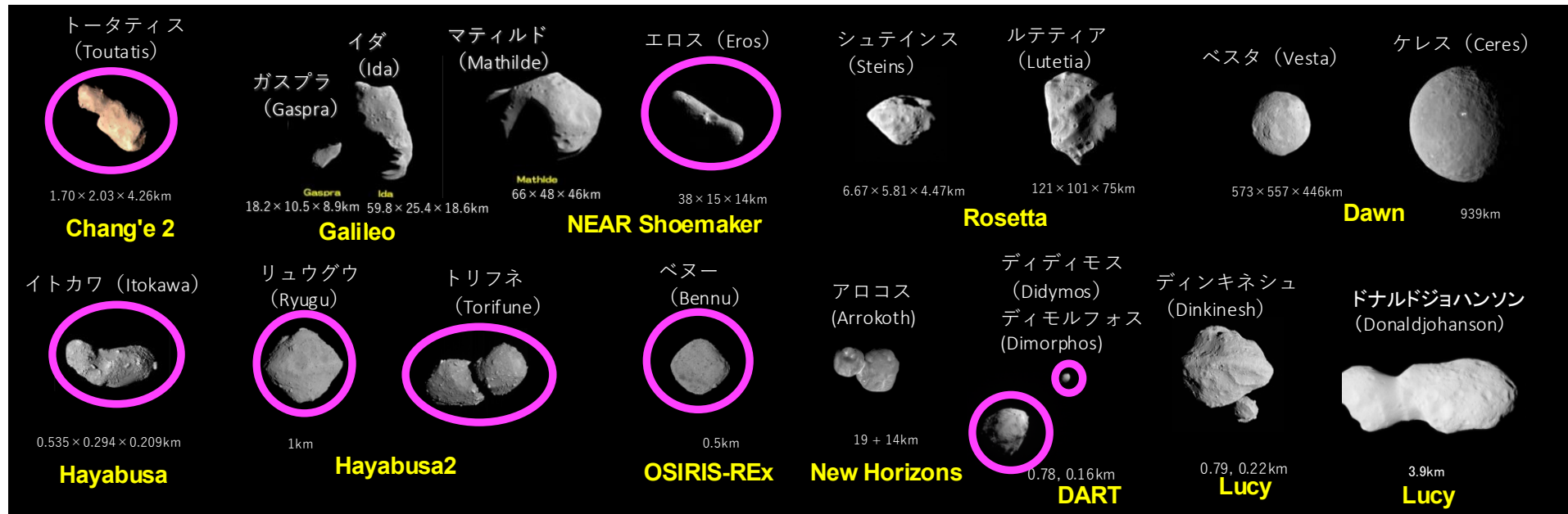
	Object	Size (m)	entry speed (km/s)	Discovery time Collision time	time from discovery to collision (h)	Impact place	discoverer
1	2008 TC3	~4	12.8	6 Oct. 2008, 06:39 UTC 7 Oct. 2008, 02:46 UTC	~20	northern Sudan	Catalina Sky Survey
2	2014 AA	2~4	11.7	1 Jan. 2014, 06:18 UTC 2 Jan. 2014, 01~04?	~21?	Atlantic Ocean	Catalina Sky Survey
3	2018 LA	2~4	17	2 June 2018, 08:22 UTC 2 June 2018, 16:44 UTC	~8	the border of Botswana and South Africa	Catalina Sky Survey
4	2019 MO	~3	16.1	22 June 2019 22 June 2019, 21:25 UTC	~12	the south coast of Puerto Rico	ATLAS
5	2022 EB5	~2	18	11 Mar. 2022 11 Mar. 2022, 21:22 UTC	~2	the Arctic Ocean southwest of the Norwegian island Jan Mayen	Konkoly Observatory's Piskéstető Station
6	2022 WJ1	~1		19 Nov. 2022, 04:53 UTC 19 Nov. 2022, 08:27 UTC	~3.5	Brantford, Ontario, Canada	Catalina Sky Survey
7	2023 CX1	~1	14.5	12 Feb. 2023, 20:18 UTC 13 Feb. 2023, 02:59 UTC	~7	the coast of Normandy, France along the English Channel	Konkoly Observatory's Piskéstető Station
8	2024 BX1	~1		20 Jan. 2024, 21:48 UTC 21 Jan. 2024, 00:33 UTC	~3	Berlin	Konkoly Observatory's Piskéstető Station

Asteroids and Comets observed by spacecraft

Asteroids



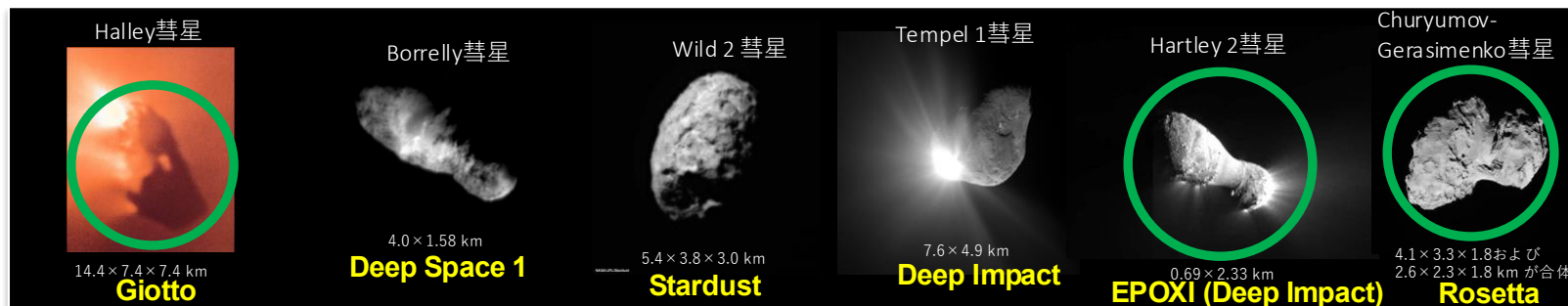
Near Earth Asteroids



Comets



Near Earth Comets



(黄色は探査した探査機名。画像は各ミッションより)

How to avoid asteroids collisions with the Earth

Destroying asteroids is not a good idea.

When an asteroid that will collide with the Earth is discovered, it is better to deflect the orbit.

How to deflect the orbit?

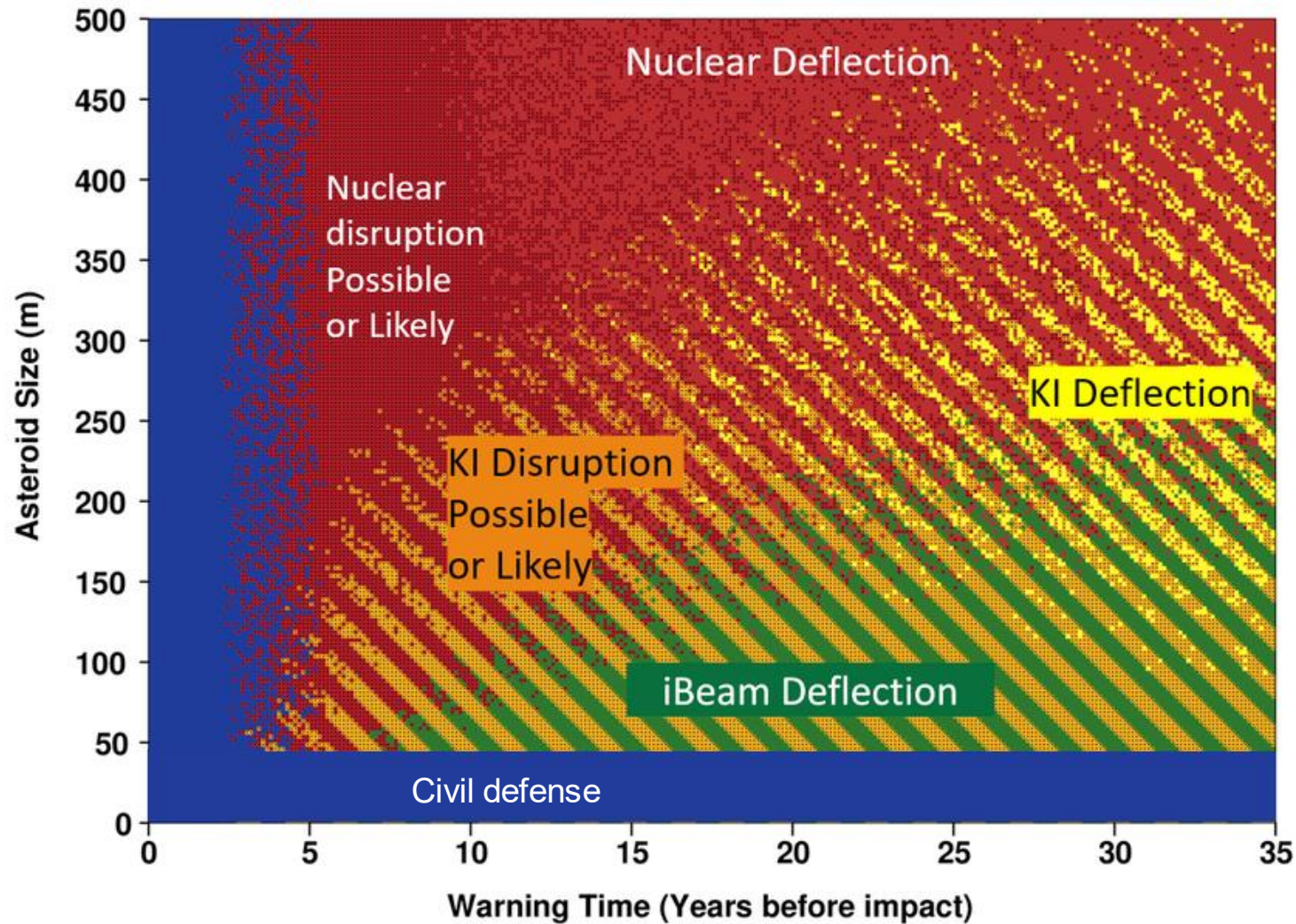
- Kinetic impactor (spacecraft impact)
- Gravity tractor
- Blast deflection (nuclear energy)
- Ion beam

DART & Hera

} possible?

- Laser beam, Sun light
- Solar radiation pressure, thermal effect
- Mass driver, Rocket propulsion
- Asteroid capture, Asteroid eaters?
-

How to avoid asteroids collisions with the Earth



Minduli C. Wijayatunga et al, 2024

AIDA : DART+ Hera

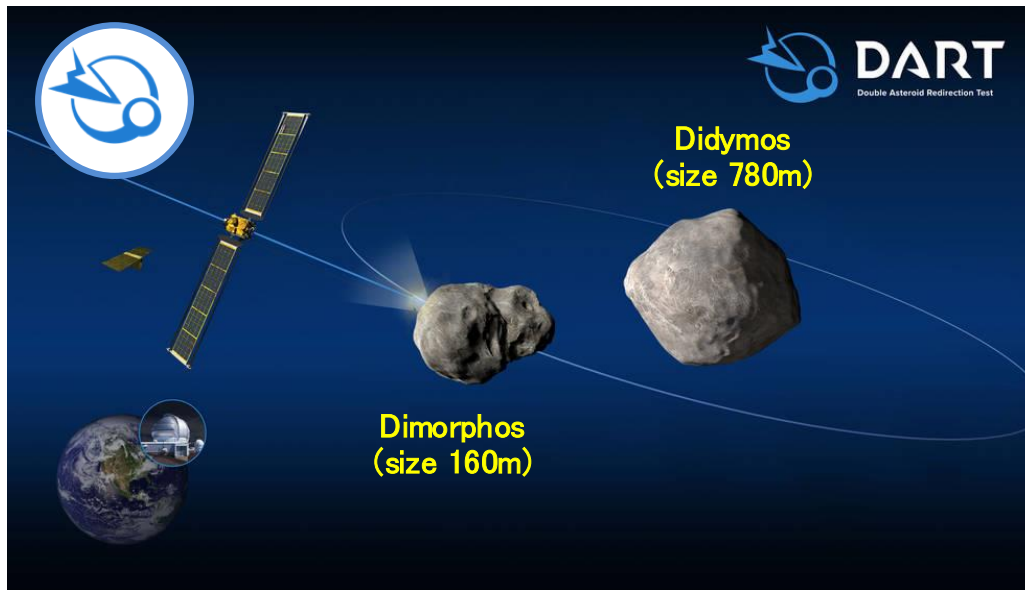
AIDA (Asteroid Impact & Deflection Assessment)

DART: An experiment to change the orbit of an asteroid by colliding spacecraft to the asteroid

Hera : Investigate the result of the impact by DART

★ **DART** (Double-Asteroid Redirection Test) by NASA

- Lunch : 24 Nov. 2021
- Impact : 26 Sept. 2022
- A DART spacecraft (about 600 kg) collided with Dimorphos at a speed of about 6 km/s to investigate orbital changes.

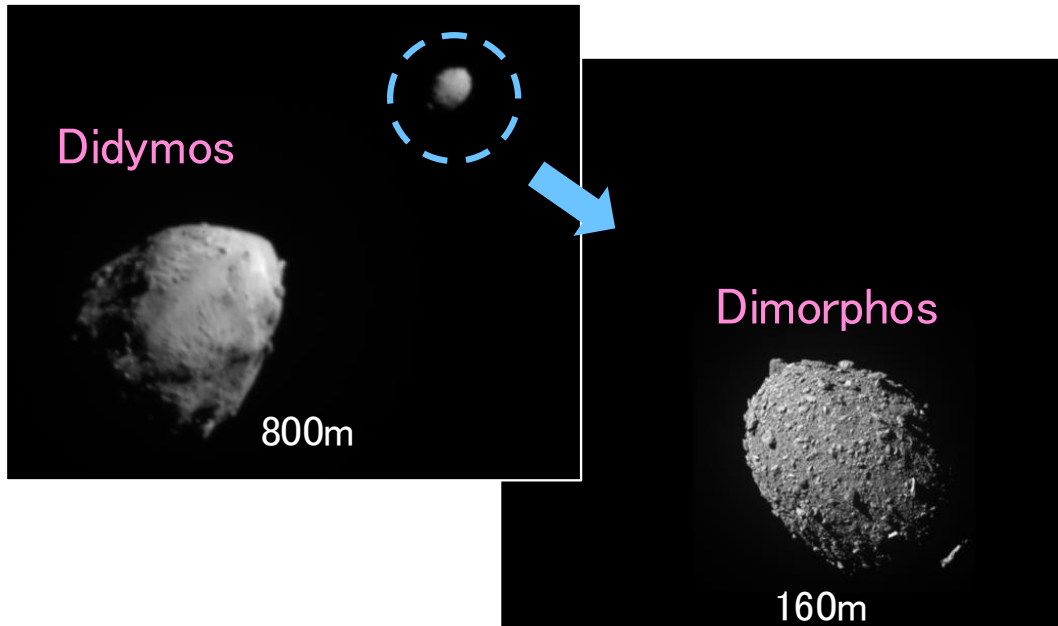


★ **Hera** by ESA

- Lunch : Oct. 2024
- Arrival : Nov. 2026
- A detailed exploration will be done for Didymos and Dimorphos.
- JAXA provided an infrared thermal imager.



The Results of DART



The orbital period of Dimorphos around Didymos was changed by the impact of the spacecraft.

Before : 11 hours 55 min

After : 11 hours 22 min → 33min shorter

Velocity change : 2.7mm/s

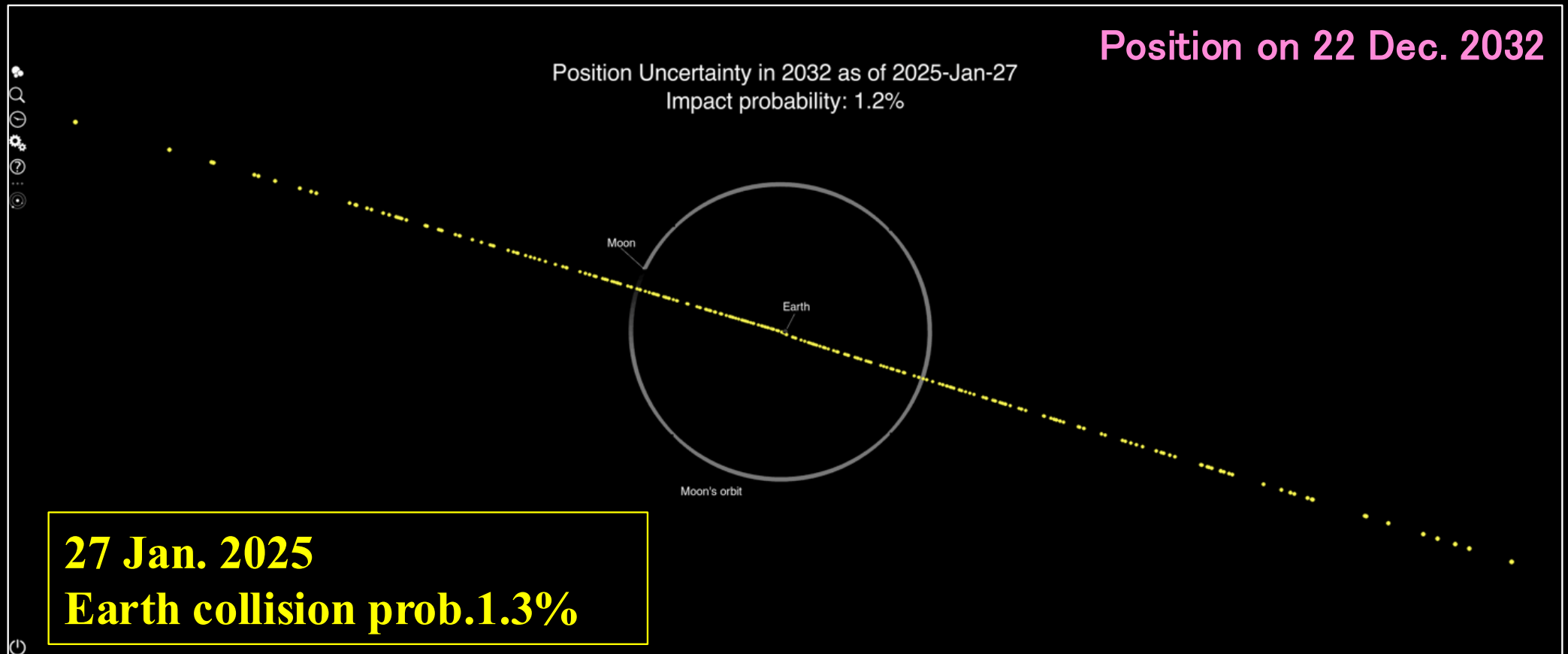
<https://dart.jhuapl.edu/Gallery/>

Asteroid 2024 YR4

Discovered at the end of 2024, it was identified as having a possibility of colliding with Earth on December 22, 2032.

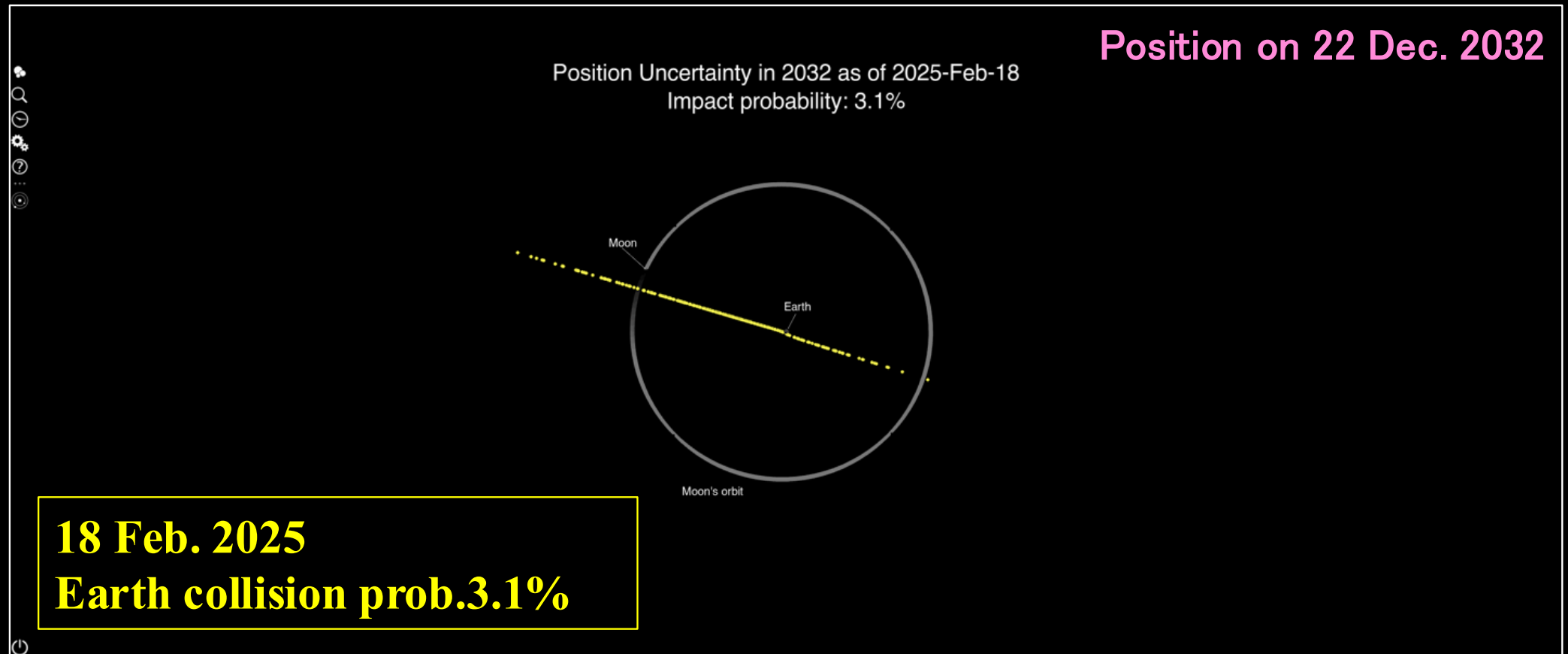
- 27 Dec. 2024 : Discovered by ATLAS. Size ~ 40-90 m
- 29 Jan. 2025 : The probability of collision with the Earth is 1.3% (announced by IAWN)
- 18 Feb. 2025 : Collision probability 3.1%
- 24 Feb. 2025 : Collision probability 0.004%
- 8 Mar. 2025 : First observation by **JWST** (24.3 mag)
- 26 Mar. 2025 : **JWST** observations estimate the diameter to be 60 ± 7 m.
- 2 Apr. 2025 : The collision probability with the moon is 3.8%
- 11 May 2025 : Last observation by **JWST** in 2025
- 3 June 2025 : The collision probability with the moon is 4.3%
- 18-26 Feb. 2026 : Observation by **JWST** in 2026 (~30 mag)
- 4 Mar. 2026 : The collision probability with the moon is 0%

Asteroid 2024 YR4 to Collide with Earth!?



(図はJPLより)

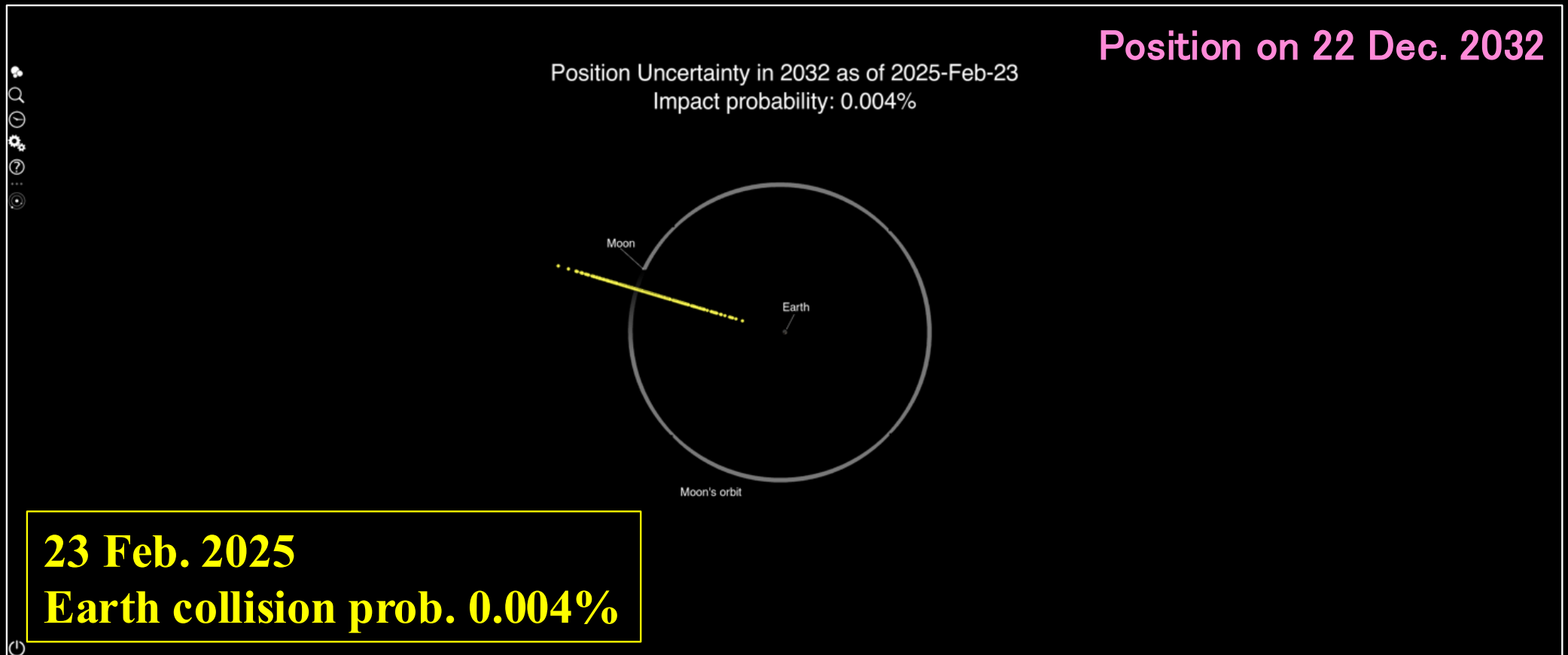
Asteroid 2024 YR4 to Collide with Earth!?



(図はJPLより)

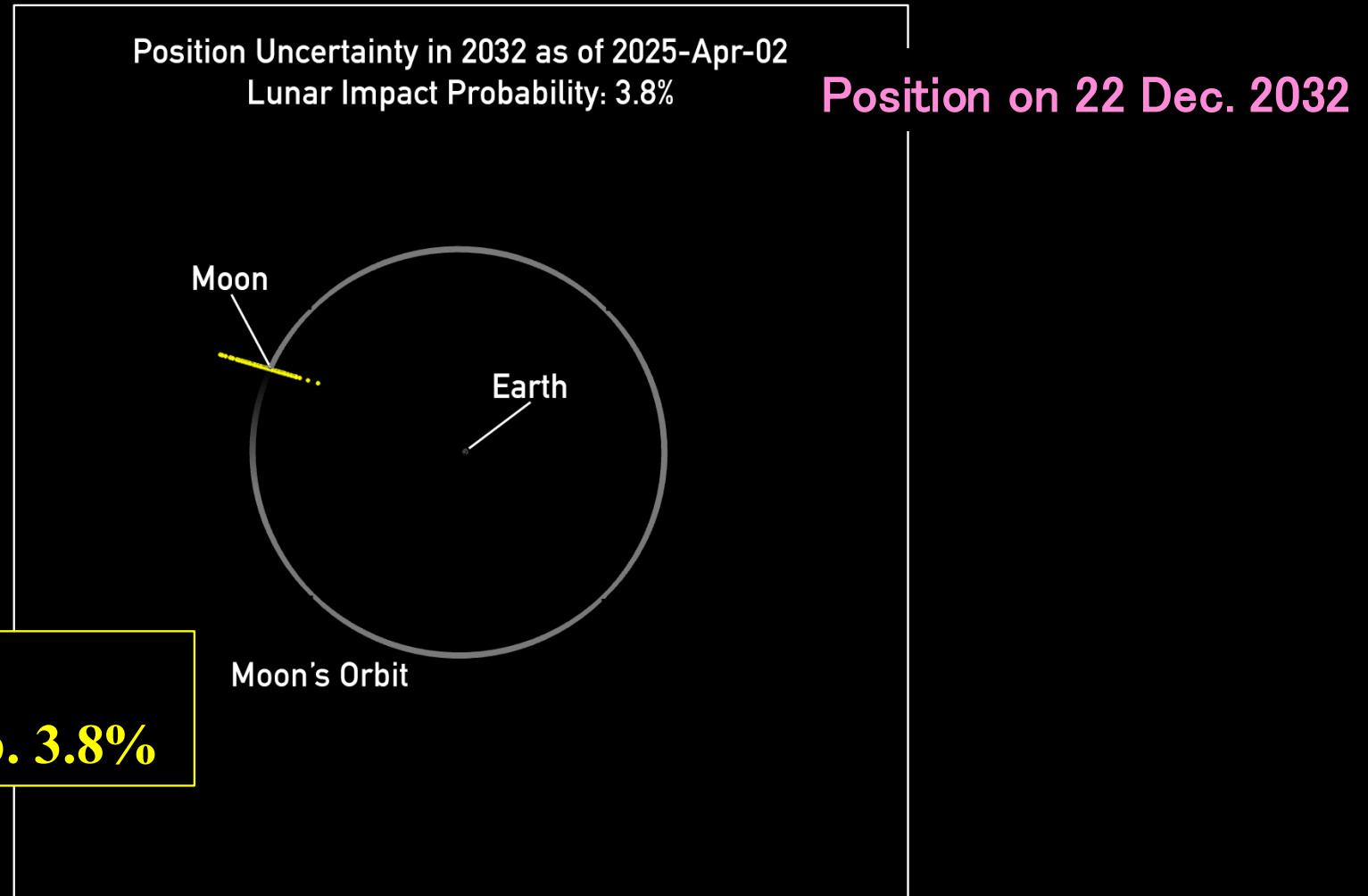
Asteroid 2024 YR4 to Collide with Earth!?

→ Does not collide



(図はJPLより)

Asteroid 2024 YR4 Colliding with the Moon!?



(図はJPLより)

Asteroid 2024 YR4 Colliding with the Moon!?

Position Uncertainty in 2032 as of 2025-Jun-03
Impact probability: 4.3%

Position on 22 Dec. 2032

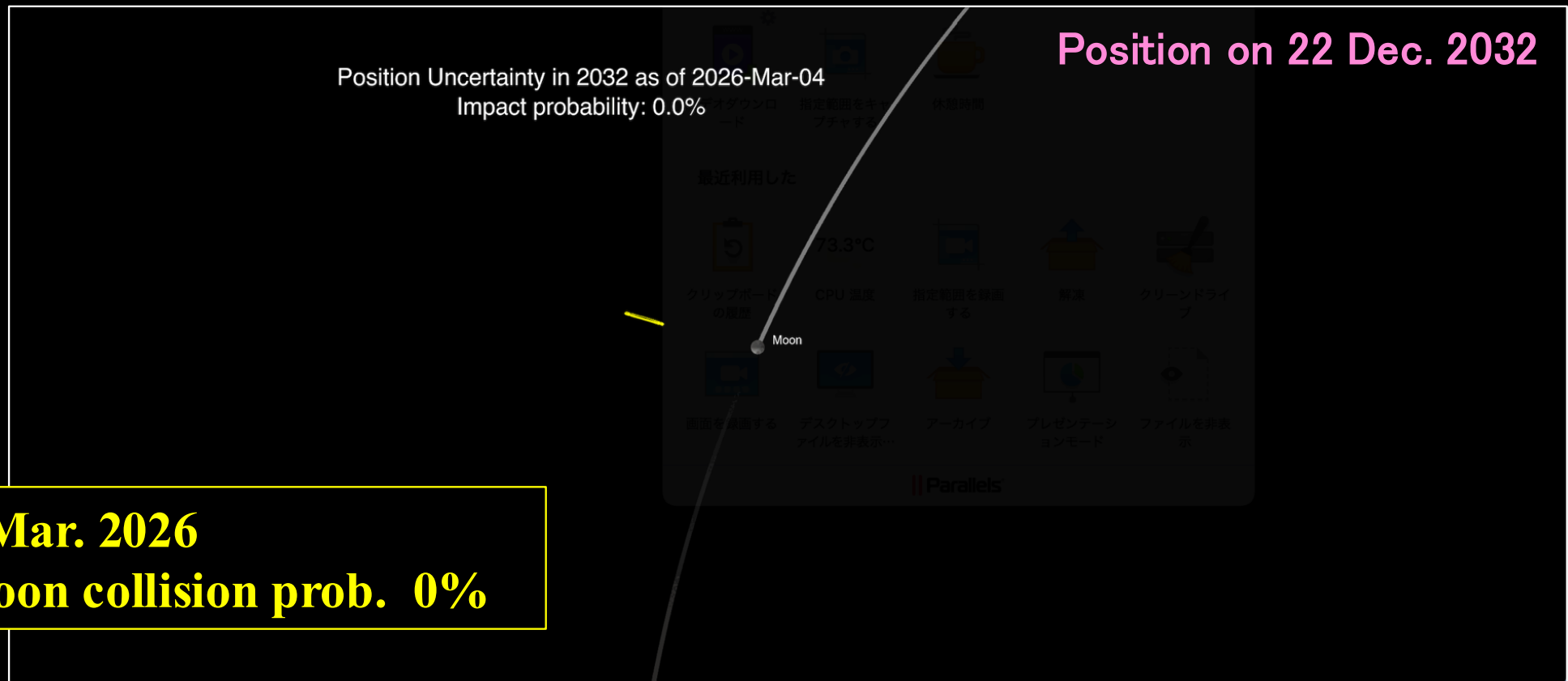


3 June 2025
Moon collision prob. 4.3%

(図はJPLより)

Asteroid 2024 YR4 Colliding with the Moon!?

→ Does not collide



(図はJPLより)

Observation data of 2024 YR4

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The International Astronomical Union

Minor Planet Center

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OBSERVERSDATANEWSTATUSDOCUMENTATION

EXTERNAL

2024 YR4

Initial reported observation by ATLAS Chile, Rio Hurtado on 2024-12-27.
(Discoverer will be defined when the object is numbered. See [this note](#) on how discoverers are determined.)

Orbit

Orbit type: Apollo
Near-Earth Object

Interactive Orbit Sketch

Note: WebGL enabled browser required.

epoch	2025-11-21.0	semimajor axis (AU)	2.5158349	uncertainty	1
epoch JD	2461000.5	mean anomaly (°)	89.80759	reference	MPO 988022
perihelion date	2024-11-22.99288	mean daily motion (°/day)	0.24699070	observations used	509
perihelion JD	2460536.89288	aphelion distance (AU)	4.180	oppositions	2
argument of perihelion (°)	134.36602	period (years)	3.99	arc length (days)	429
ascending node (°)	271.36386	P-vector [x]	0.69677799	first opposition used	2024
inclination (°)	3.40816	P-vector [y]	0.64003655	last opposition used	2026
eccentricity	0.6614720	P-vector [z]	0.32381114	residual rms (arc-secs)	0.46
perihelion distance (AU)	0.8516806	Q-vector [x]	-0.71482047	perturbbers coarse indicator	M-v
Tisserand w.r.t. Jupiter	3.1	Q-vector [y]	0.65700312	perturbbers precise indicator	0036k
ΔV w.r.t. Earth (km/sec)	7.0	Q-vector [z]	0.23953830	first observation date used	2024-12-25.0
		absolute magnitude	23.93	last observation date used	2026-02-26.0
		phase slope	0.15	computer name	Spoto

Minimum Orbit Intersection Distances (in AU)
for orbit epoch: 2461000.5, reference: E2026-E32

Mercury	0.53469
Venus	0.13992
Earth	0.0028
Mars	0.10408
Jupiter	1.26301
Saturn	5.72248
Uranus	14.5647
Neptune	26.2964

https://minorplanetcenter.net/db_search/show_object?utf8=v&object_id=2024+YR4

1 / 14

IAU Minor Planet Center

2026/06/30 7:38

Observations

512 total observations over interval: 2024 12 25.304941 – 2026 02 26.883517
These data are available for [download](#) ([format description](#)).

Date (UT)	J2000 RA	J2000 Dec	Magn	Location	Ref
2024 12 25.304941	12 43 47.961	-33 57 29.55	17.3 G	W68 – ATLAS Chile, Rio Hurtado	MPG 2322881
2024 12 26.422318	09 30 31.271	-07 15 21.76	16.0 G	703 – University of Arizona Catalina Sky Survey	MPG 2322881
2024 12 26.424567	09 30 21.995	-07 13 39.67	15.8 G	703 – University of Arizona Catalina Sky Survey	MPG 2322881
2024 12 26.426810	09 30 12.790	-07 11 58.22	16.3 G	703 – University of Arizona Catalina Sky Survey	MPG 2322881
2024 12 26.429060	09 30 03.567	-07 10 16.43	15.8 G	703 – University of Arizona Catalina Sky Survey	MPG 2322881
2024 12 26.762010	09 12 57.83	-03 40 43.7	16.2 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762071	09 12 57.66	-03 40 41.5	16.0 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762131	09 12 57.50	-03 40 39.7	16.1 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762192	09 12 57.32	-03 40 37.9	16.1 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762253	09 12 57.15	-03 40 36.1	16.0 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762313	09 12 56.97	-03 40 34.0	16.0 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762374	09 12 56.81	-03 40 32.5	16.1 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762434	09 12 56.65	-03 40 30.8	16.2 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762495	09 12 56.46	-03 40 28.6	16.1 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762555	09 12 56.29	-03 40 27.0	16.1 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762616	09 12 56.13	-03 40 25.1	16.2 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 26.762676	09 12 55.96	-03 40 23.3	16.1 W	O38 – Purple Mountain Observatory, Dayao	MPG 2338889
2024 12 27.238073	08 56 40.968	-00 16 11.93	16.54 O	W68 – ATLAS Chile, Rio Hurtado	MPG 2304664
2024 12 27.240334	08 56 36.905	-00 15 27.90	15.80 O	W68 – ATLAS Chile, Rio Hurtado	MPG 2304664
2024 12 27.267322	08 55 48.917	-00 06 50.04	16.28 O	W68 – ATLAS Chile, Rio Hurtado	MPG 2304664
2024 12 27.274648	08 55 36.048	-00 04 31.62	16.12 O	W68 – ATLAS Chile, Rio Hurtado	MPG 2304664
2024 12 27.389707	08 52 43.076	+00 21 33.25	16.6 G	I52 – Steward Observatory, Mt. Lemmon Station	MPG 2322881
2024 12 27.389877	08 52 42.810	+00 21 36.27	16.5 G	I52 – Steward Observatory, Mt. Lemmon Station	MPG 2322881
2024 12 27.390047	08 52 42.534	+00 21 39.23	16.4 G	I52 – Steward Observatory, Mt. Lemmon Station	MPG 2322881
2024 12 27.390228	08 52 42.249	+00 21 42.36	16.5 G	I52 – Steward Observatory, Mt. Lemmon Station	MPG 2322881
2024 12 27.421285	08 51 56.176	+00 30 28.30	16.87 I	I41 – Palomar Mountain–ZTF	MPG 2322881
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2024 12 27.703007	08 46 02.00	+01 49 02.9	17.1 V	Q62 – iTelescope Observatory, Siding Spring	MPG 2304664
2024 12 27.705000	08 45 59.51	+01 49 28.0	17.4 V	Q62 – iTelescope Observatory, Siding Spring	MPG 2304664
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2024 12 27.727432	08 45 31.397	+01 54 25.50	17.31 G	E55 – COTO South	MPG 2356281
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2024 12 27.868894	08 43 26.00	+02 15 19.7	16.2 R	MS2 – Sunny Transcarpathian, Mukachevo	MPG 2304664

https://minorplanetcenter.net/db_search/show_object?utf8=v&object_id=2024+YR4

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https://minorplanetcenter.net/db_search/show_object?utf8=v&object_id=2024+YR4

Observation data of 2024 YR4

[illegible][illegible][illegible][illegible][illegible][illegible][illegible][illegible][illegible][illegible]

Observation data of 2024 YR4

IAU Minor Planet Center										2024 YR4
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2025 02 21.409541	08 03 08.416	+13 29 59.24	25.1	G	F65 - Haleakala-Faulkes Telescope North	MPG	2338889			
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JWST

IAU Minor Planet Center										2024 YR4
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The Minor Planet Center is funded by NASA.

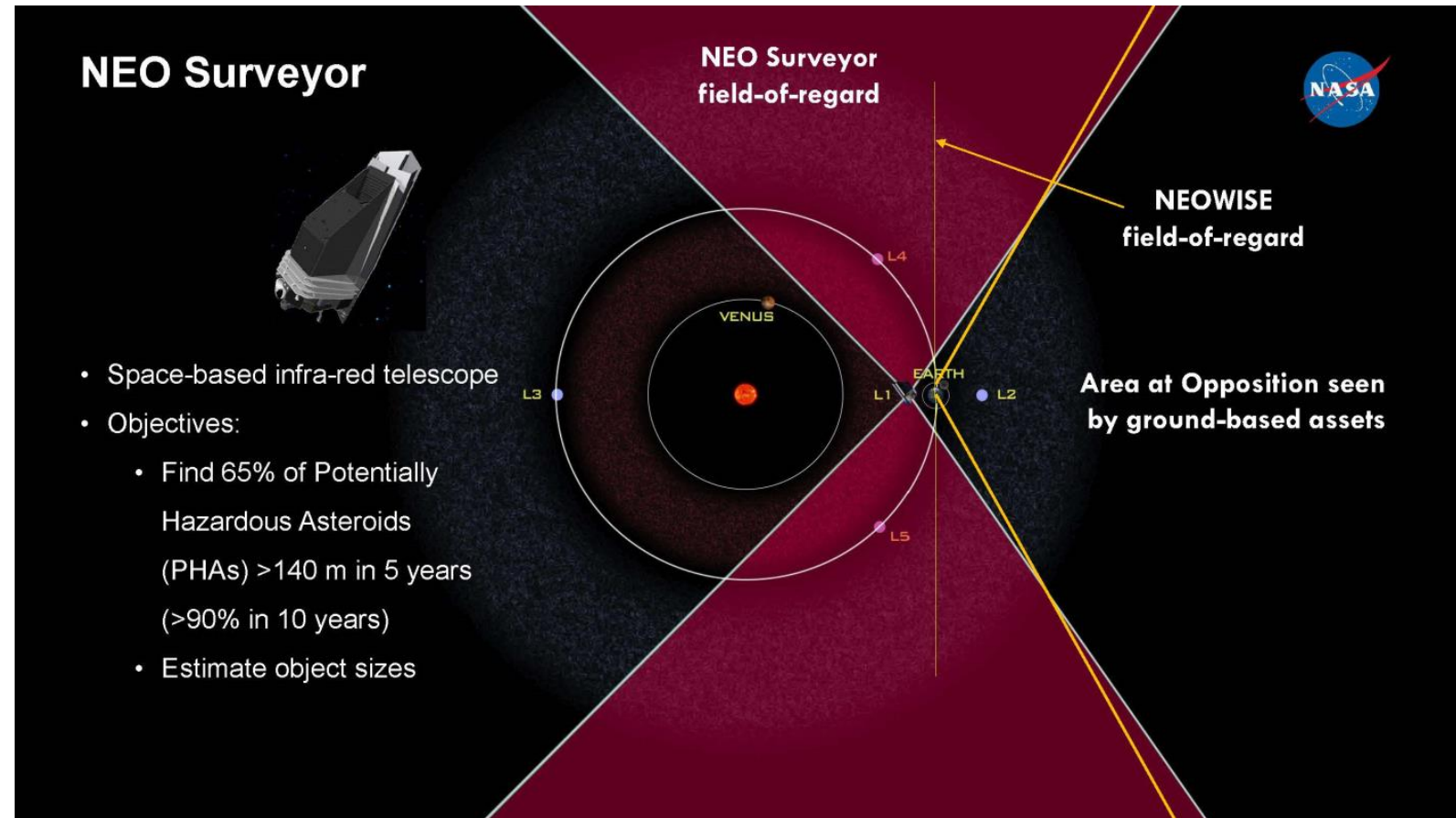
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https://minorplanetcenter.net/db_search/show_object?utf8=v&object_id=2024 YR4

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NASA: NEO Surveyor

- Observe NEOs from space
- 50cm infrared telescope
- Discover 2/3 NEOs larger than 140m in 5 years
- Discover 90% NEOs in 10-12 years



by Lindley Johnson (NASA)

JAXA's activities for planetary defense

※ Planetary defense team has been established in April 2024.

Observations

- Bisei Spaceguard Center
- Small telescopes for research
- Asteroid radar observation

Space Missions

- Hayabusa, Hayabusa2 (2#)
- DESTINY+, NGSR
- Hera (ESA), RAMSES (ESA/JAXA)

Orbit analysis

- Orbit propagation
- Orbit estimation
- Collision analysis

International activities

- SMPAG
- IAWN
- PDC
- IYAPD

Domestic activities

- Symposiums/meetings
- Academic activities

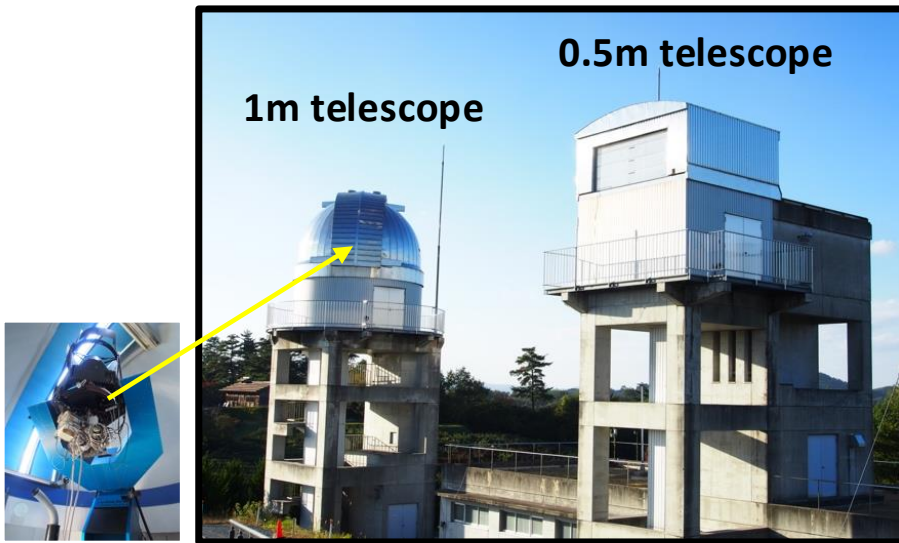
Outreach

- Asteroid Day
- APAON
- Public events

SMPAG : Space Mission Planning Advisory Group
IAWN : International Asteroid Warning Network
PDC : Planetary Defense Conference
IYAPD : International Year of Asteroid Awareness and Planetary Defence
APAON : Asia-Pacific Asteroid Observation Network

Asteroid observations in JAXA

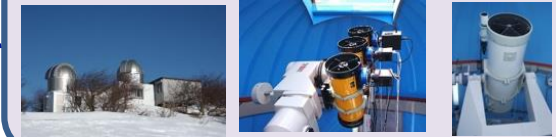
Bisei Spaceguard Center (BSGC) (Space Tracking and Communications Center)



- Built in 2000 and owned by the Japan Space Forum, it was transferred to JAXA in April 2017.
- The observation work is carried out by the Japan Spaceguard Association (NPO).
- Observation targets: Space debris, NEO (asteroids)

Observation facility of Research and Development Directorate

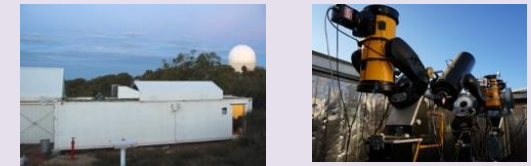
Mt. Nyukasa Observational facility



Chofu LEO Observational facility



Remote observation site at Siding Spring Observatory



Remote observation site at Zadko Observatory



NEO missions of JAXA

Hayabusa

(2003-2010)



Rendezvous in 2005



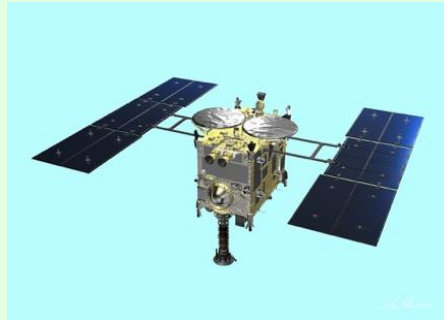
Release 051101-1 ISAS/JAXA

Itokawa

S-type, 530m

Hayabusa2

(2014-2020)



Rendezvous in 2018



UTC 2018-08-30 14:13

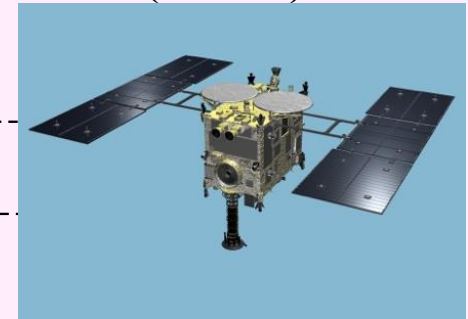
(c) JAXA, U. of Tokyo, Kochi U., Wako U., Nagoya U., ChibaTech, Meiji U., U. of Aizu, AIST

Ryugu

C-type, 1000m

Hayabusa2#

(2020 ~)



Flyby in 2026



Torifune

S-type, 450m ?

Rendezvous in 2031



1998 KY26

30m ? 11m?

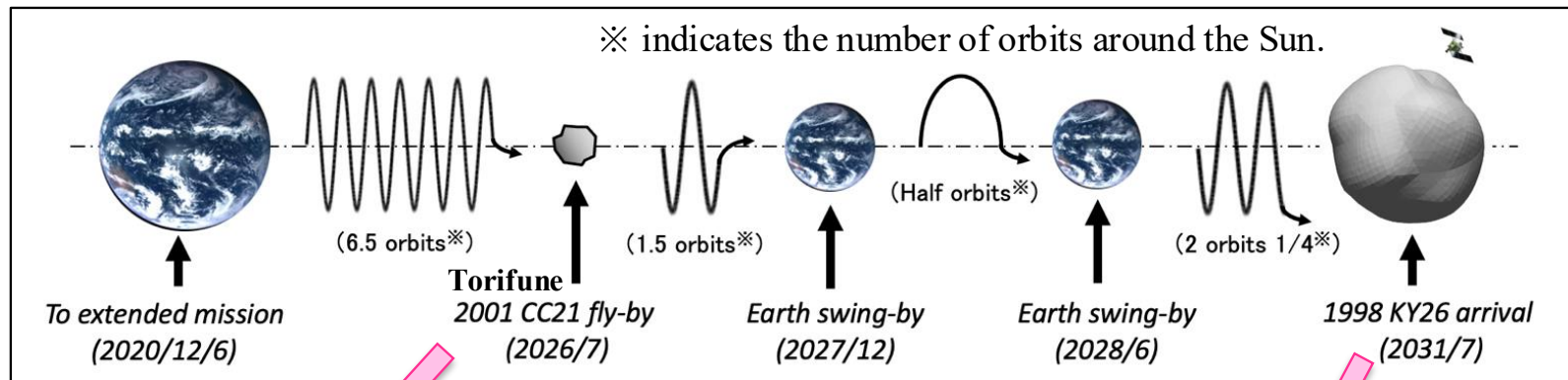
(Image credit: JAXA / A. Ikeshita)

Hayabusa2 Extended mission : Hayabusa2#

(SHARP) : Small Hazardous Asteroid Reconnaissance Probe

After Hayabusa2 returned the sample of Ryugu in Dec. 2020, we extended the mission for two more targets, (98943) Torifune (2001 CC21) and 1998 KY26.

The spacecraft is operated without major issues.



July 5, 2026

Relative velocity : 5.3km/s
Distance: ~800m
High accuracy navigation
is necessary.

Artist's illustration (by A. Ikeshita)



Asteroid size : ~30m or 11m?
(spin period : ~11 or 5min?)

The collision probability of
such asteroids with the Earth
is once in 100~200 years.

DESTINY⁺ and RAMSES

DESTINY⁺ (JAXA)



Dual launch
by H3 rocket
in early 2028

Apophis flyby in Feb. 2028



:



Phaethon flyby
in Nov. 2030

... additional
NEO flybys

RAMSES (ESA/JAXA)



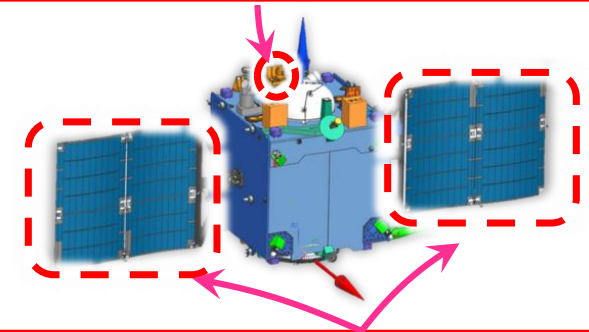
Apophis Rendezvous in Feb. 2028



Apophis
Sq-type, 340m

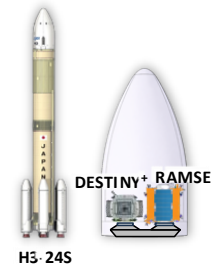
JAXA's contributions to RAMSES

★ Thermal InfraRed Imager (TIRI)



★ Lightweight Solar Array Wings
(SAWs)

★ H3 rocket



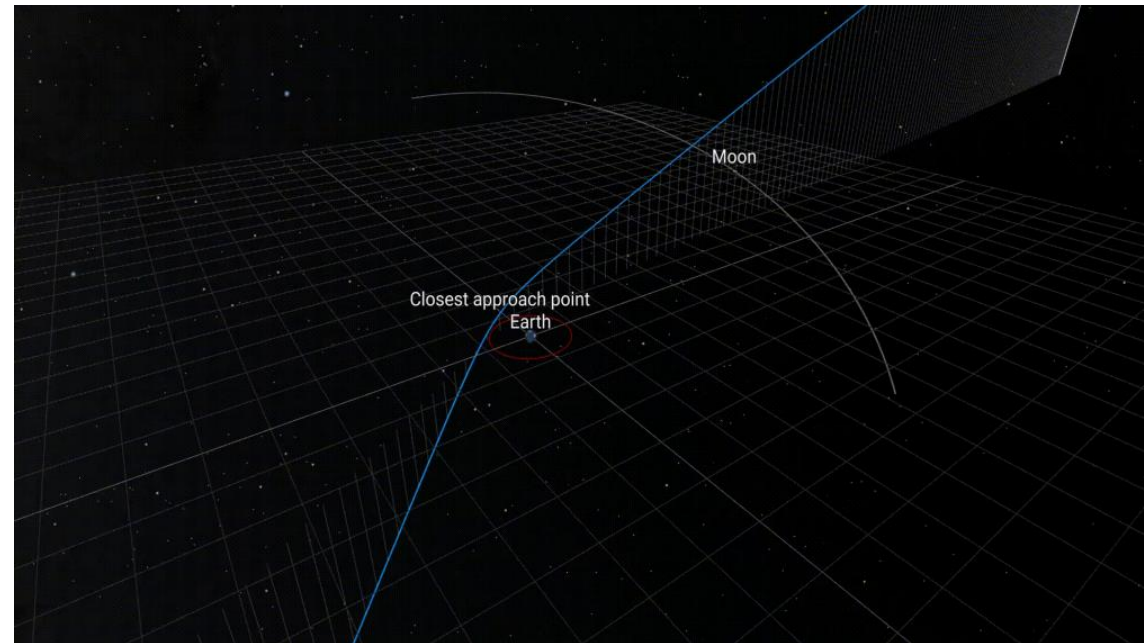
Why Apophis?

Friday, April 13, 2029

- *~32,000 km above Earth's surface, lower than the geostationary orbit altitude*
- *~340m-class near-Earth asteroid*
- Impact possibility has been ruled out but an extremely rare event for this size and distance
- Direct observation of tidal effects by Earth

The key point is not impact risk, but observational opportunity.

Apophis orbit diverted by Earth's gravity



CREDIT ESA

https://www.esa.int/Space_Safety/Planetary_Defence/Apophis

Key questions for Apophis explorations

How does an asteroid respond to an external force, Earth's tidal field?

Rotation: Will the **spin state** change?

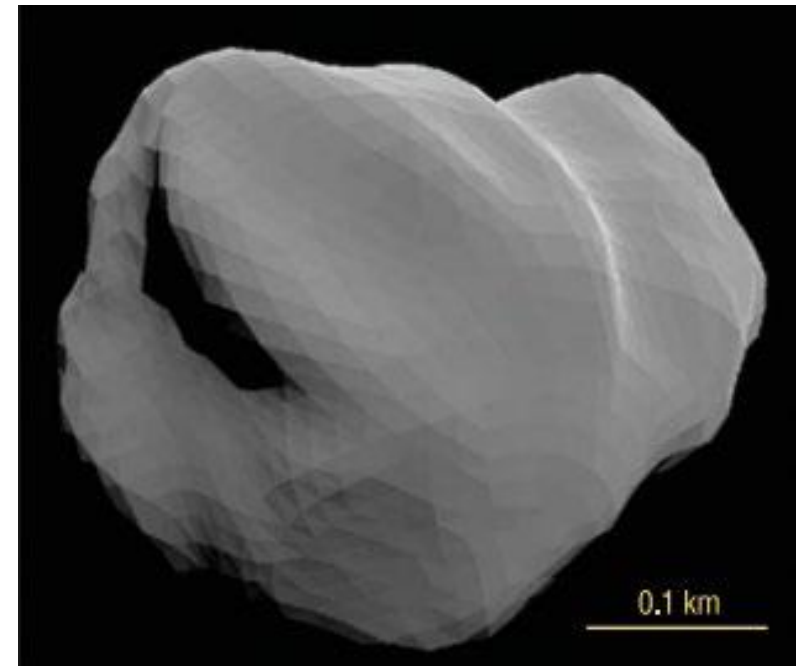
Surface: Will **landslides** or **regolith motion** occur?

Shape: Can **local deformation** or **resurfacing** be detected?

Interior: Can **density, porosity, and heterogeneity** be estimated?

Orbit: Can the **post-encounter orbit** be refined?

Apophis shape model



Da.N.DellaGiustina et al. (2023)

Interesting points in the near future

- **Asteroid 2024 YR4** → no collision (with Earth and Moon)
- **Hayabusa2 extended mission** : Asteroid Torifune flyby in July 2026
→ Successful
- **ESA's Hera** : Arrival at Didymos+Dimorphos in November 2026
- **NASA's NEO Surveyor** : Launch in 2027
- **DEDSTINY+, RAMSES** : Launch in 2028 → Apophis (2029)
- **Asteroid Apophis** : Earth approach on Friday, April 13, 2029

Year of 2029

= International Year of Asteroid Awareness and Planetary Defense

Summary

- 1. Planetary defense activities are becoming increasingly active worldwide.*
- 2. There is a high probability that celestial bodies capable of colliding with Earth will be discovered in the future.*
- 3. Observations using space telescopes particularly powerful—as in the case of 2024 YR4—when the celestial object is faint.*



Next Generation Climate Modeling for Habitable Worlds

Lead author: Takanori Kodama

Abstract:

The characterization of exoplanet atmospheres has rapidly advanced over the past decade, driven by both current and upcoming observational facilities. In particular, terrestrial planets located within the habitable zones of their host stars are becoming key targets in the search for life beyond the Solar System. To date, atmospheric general circulation models (AGCMs) have played a central role in investigating the climates of these planets, providing insights into atmospheric circulation, spatially heterogeneous distributions of water vapor and clouds, and the efficiency of day–night energy transport under diverse planetary conditions.

As the field enters an era of increasingly detailed observations, the next generation of exoplanet climate research requires more comprehensive modeling frameworks. The development of atmosphere–ocean coupled general circulation models (AOGCMs) and global cloud-resolving models (GCRMs) offers new opportunities to investigate climate processes that cannot be adequately represented by conventional AGCMs. These models enable the explicit treatment of ocean circulation, cloud organization, convection, and climate variability, which are expected to play critical roles in determining planetary habitability and observational signatures.

In this presentation, I review the current status of exoplanet climate studies, summarize recent progress in advanced climate modeling, and discuss future directions for the field. I will highlight key scientific questions that should guide the next phase of habitable world research and propose a roadmap toward a predictive understanding of planetary climates.

Science Case Summary

Detecting biosignatures will be a central goal during the HWO era, but a large gap remains between the traditional concept of planetary habitability and the interpretation of future observations. Bridging this gap requires habitable climate modeling, which aims to understand the climate systems inherent to terrestrial planets. Next generation models, particularly coupled atmosphere-ocean GCMs (AOGCMs) and global cloud-resolving models (GCRMs), will build the foundation for interpreting biosignatures and establishing a deeper physical understanding of habitable planets.

Next Generation ***Climate Modeling*** ***for Habitable Worlds***



Takanori Kodama (ELSI)

Collaborator: T. Higuchi, A. Kamada,

D. Takasuka(Tohoku), T. Obase(JAMSTEC),

T. Kawasaki(JAMSTEC), S. Sherriff(Ryukyu)



EARTH - LIFE SCIENCE INSTITUTE

HWO-J-SciWS@JAXA, 07/15/2026

Concept of Habitable Zone

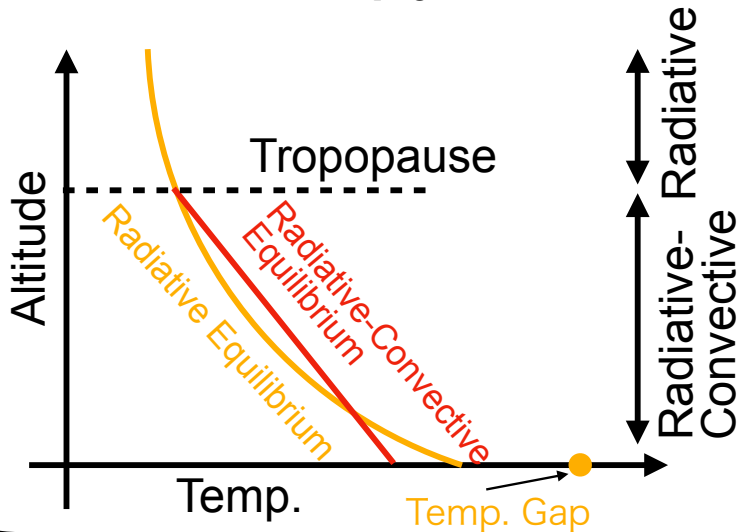
Estimation of the classical Habitable Zone with 1D Radiative-Convective Equilibrium Model

[e.g., Kasting+1993; Kopparapu+2013]



1D Radiative-Convective Equilibrium Model

[e.g., Manabe & Wetherald, 1967; Nakajima+1992]



Process of estimation

Initial condition

↓
Radiative Heating

↓
Convective adjustment
(Water vapor)

↓
Equilibrium state

Inner Edge of the Habitable Zone

Threshold of the Runaway Greenhouse state
Instantaneous limits caused by
imbalances in the radiative energy budget

Outer Edge of the Habitable Zone

Threshold of the complete freezing
Limit determined by the maximum
greenhouse effect of CO₂.

Habitable planets

Exploring the conditions for Earth(-like) planets

To understand the conditions and characteristics of surface environment based on Earth's climate

Coupled Atmosphere - Ocean GCM (AOGCM)

Discussing atmosphere-ocean interactions; captures the climate system

[e.g., Del Genio+2017; Way+2018; Kilic+2018; Yang+2019]

(Meridional 1-D) Energy Balanced Model

Surface environment considering spatial distribution

[e.g., Budyko1969; Williams&Kasting1997; Kadoya&Tajika2015; Haqq-Misra+2016 + many papers]

(High-resolution) Convection resolved / Cloud resolved Model (GCRM)

Resolves convection and cloud formation, and their impacts on the global climate

[e.g., Lafevre+2021; Kodama+2022; Yang+2023; Sergeev+2024, 2025; Gu+2024]

3-D General Circulation Model (AGCM)

Climate investigation that captures atmospheric circulation and allows discussion of spatial non-uniformity

[e.g. Manabe&Wetherald, 1975; Leconte+2013; Yang+2013; Way+2016; Turbet+2016, 2018; Wolf & Toon+2017, + many papers]

Vertically 1-D Radiative-Convective Equilibrium Model

Examination of the globally averaged environment

[e.g., Manabe&Stricker, 1964; Abe&Matsui, 1988; Kasting+1993; Kopparapu+2013 ; + many papers]

From Sun-like star(s) to M dwarfs

The TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI)



THAI protocol

- Stellar spectrum
2600 K BT-Settl with Fe/H = 0
- Period 6.1 days
- Irradiation 900 W / m²
- Radius 5804 km
- Gravity 9.12 m / s²

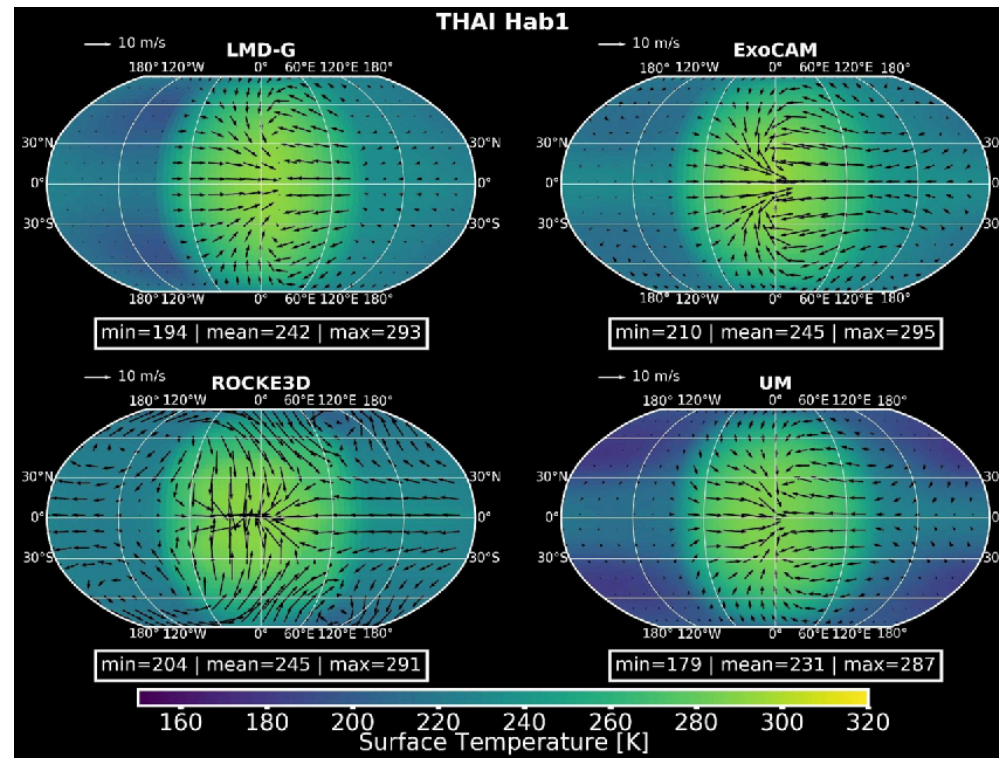
Atmosphere

- Comp. 1bar N₂ + 400ppm CO₂
or 1bar CO₂

Surface

- Comp. Land only
or Ocean planet

THAI Hab1 : Moist case with 1bar N₂ + 400 ppm CO₂



[Fauchez+2020; Turbet+2021; Sergeev+2021; Fauchez+2021]

From Sun-like star(s) to M dwarfs

The TRAPPIST-1 Habitable Atmosphere Intercomparison (THAI)



THAI protocol

- Stellar spectrum
2600 K BT-Settl with Fe/H = 0
- Period 6.1 days
- Irradiation 900 W / m²
- Radius 5804 km
- Gravity 9.12 m / s²

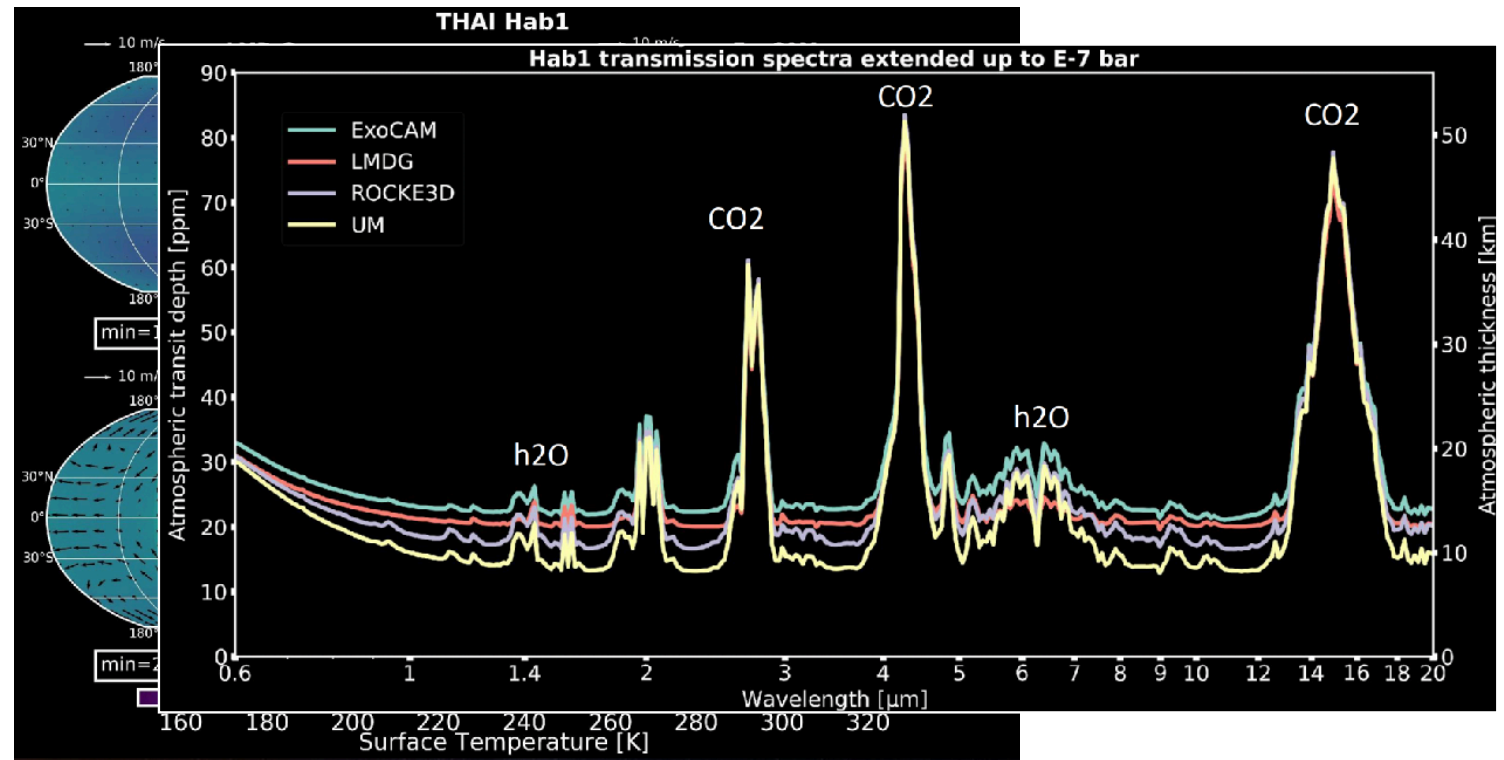
Atmosphere

- Comp. 1bar N₂ + 400ppm CO₂
or 1bar CO₂

Surface

- Comp. Land only
or Ocean planet

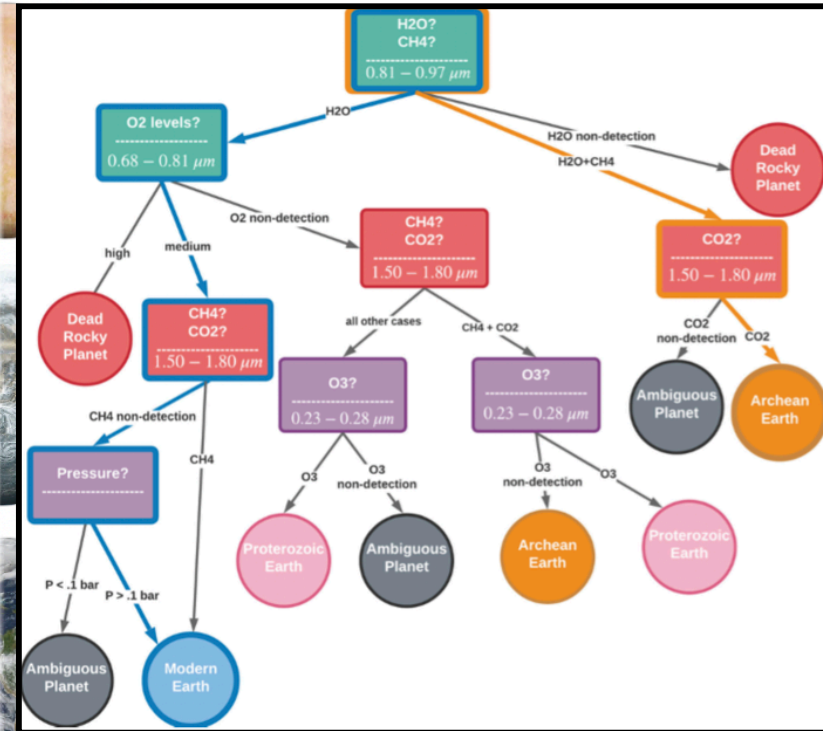
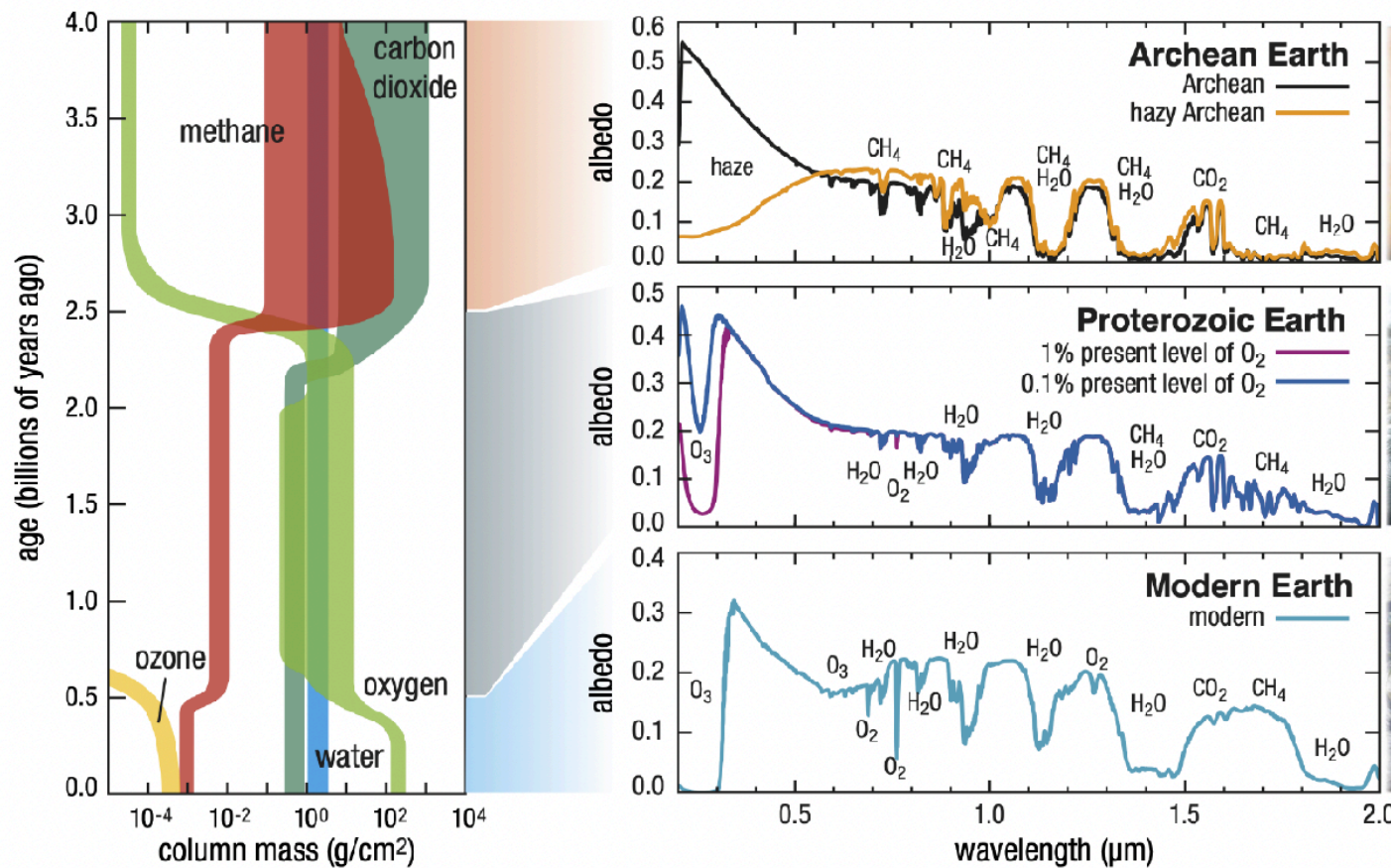
THAI Hab1 : Moist case with 1bar N₂ + 400 ppm CO₂



[Fauchez+2020; Turbet+2021; Sergeev+2021; Fauchez+2021]

What should we understand about *Habitable Worlds*?

The Habitable Worlds Paradigm shift: From Detection to Understanding *Observation → Biosignature*



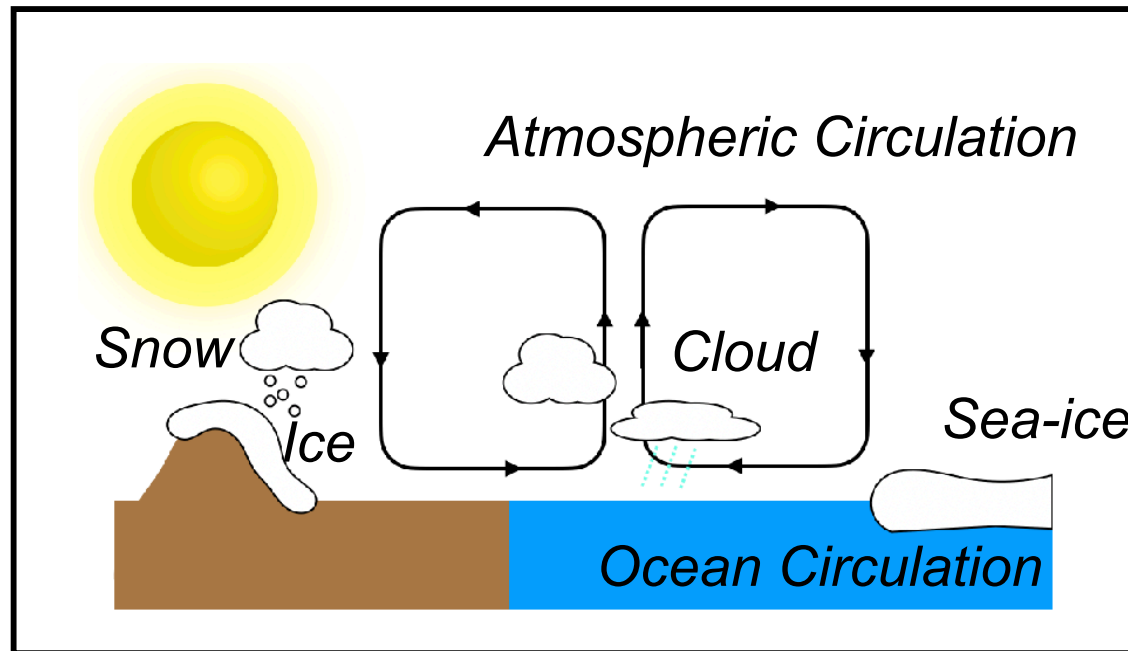
[Arney+2025/ Living Worlds Science WG]

What should we understand about *Habitable Worlds*?

The Habitable Worlds Paradigm shift: From Detection to Understanding
Observation → *Climate System* → *Surface Environment* → *Biosignature*

Conditions of a Habitable Surface Environment (Climate System)

$$X(\text{Surface environment}) = f(M_p, r_p, P_{\text{atm}}, \text{Gas}, P_{\text{rot}}, \dots)$$



Habitable planets

Exploring the conditions for Earth(-like) planets

Surface Environment - Climate System

Atmosphere

- Circulation
- Water vapor
- Clouds
- Precipitation
(Rain / Snow)

Continents

- Topography
- Erosion
- Weathering



Ice sheet

- Albedo
- Water transport
- Storage

Ocean

- Circulation
- Evaporation

To understand and constrain the conditions of the Earth from various interrelated sub-systems.

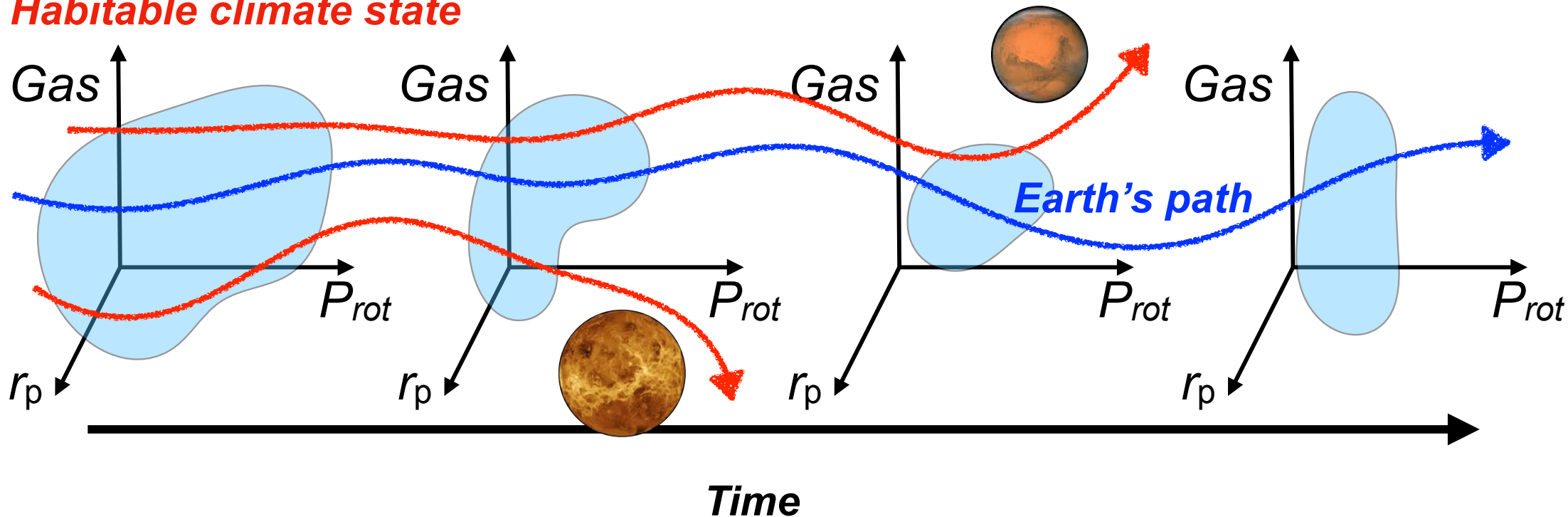
What should we understand about *Habitable Worlds*?

*The Habitable Worlds Paradigm shift: From Detection to Understanding Conditions of a **Habitable Environment** (Climate System)*

*Observation → **Climate System** → **Surface Environment** → Biosignature*

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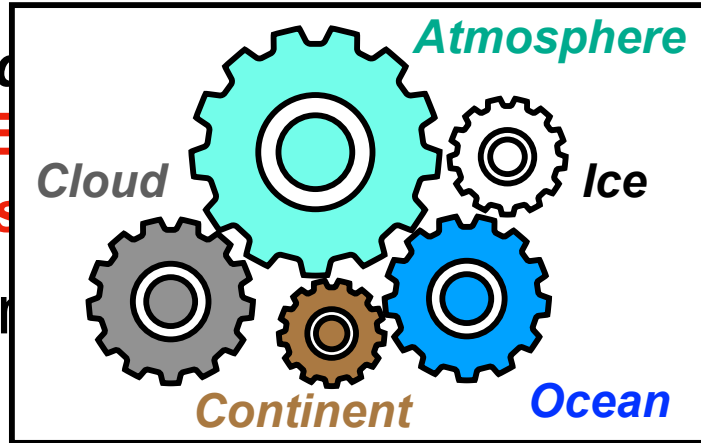
Habitable climate state



What should we understand about *Habitable Worlds*?

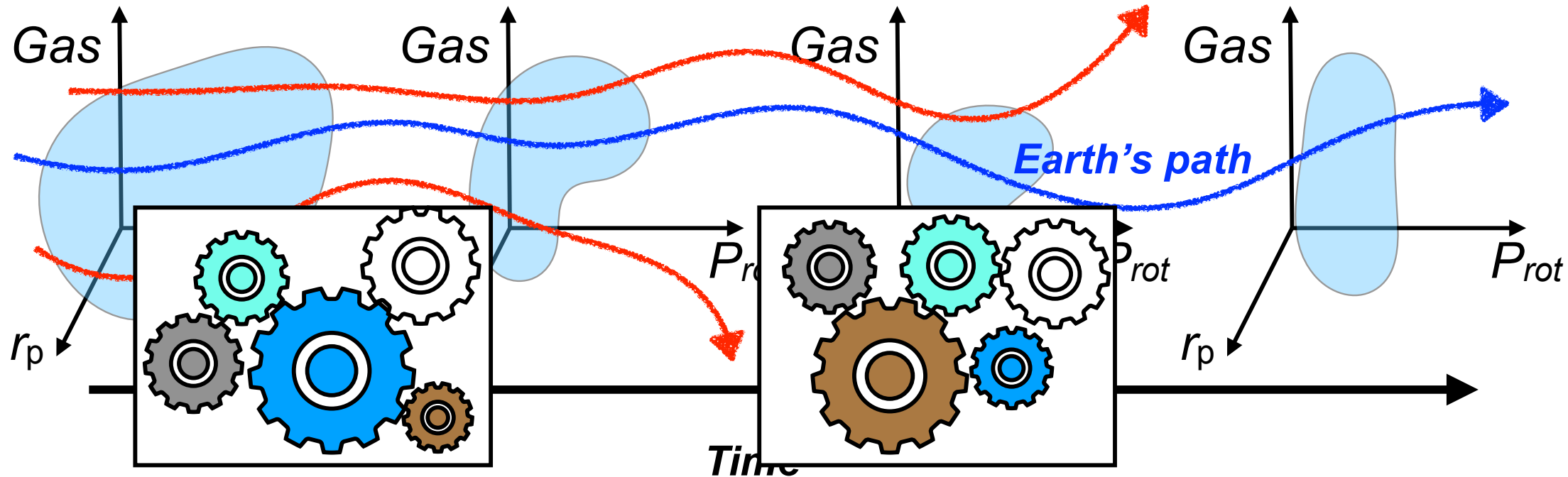
The Habitable Worlds Paradigm
 Conditions of a *Habitable Earth*
 Observation → *Climate System*

X (Surface environment)



to Understanding
 (tem)
 ent → *Biosignature*
 Gas, P_{rot} , ...)

Habitable climate state



Habitable planets

Exploring the conditions for Earth(-like) planets

To understand the conditions and characteristics of surface environment based on Earth's climate

Coupled Atmosphere - Ocean GCM (AOGCM)

Discussing atmosphere-ocean interactions; captures the climate system

[e.g., Del Genio+2017; Way+2018; Yang+2019]

(Meridional 1-D) Energy Balanced Model

Surface environment considering spatial distribution

[e.g., Budyko1969; Williams&Kasting1997; Kadoya&Tajika2015; Haqq-Misra+2016 + many papers]

(High-resolution) Convection resolved / Cloud resolved Model (GCRM)

Resolves convection and cloud formation, and their impacts on the global climate

[e.g., Lafevre+2021; Kodama+2022; Yang+2023; Sergeev+2024, 2025; Gu+2024]

3-D General Circulation Model (AGCM)

Climate investigation that captures atmospheric circulation and allows discussion of spatial non-uniformity

[e.g. Manabe&Wetherald, 1975; Leconte+2013; Yang+2013; Way+2016; Turbet+2016, 2018; Wolf & Toon+2017, + many papers]

Vertically 1-D Radiative-Convective Equilibrium Model

Examination of the globally averaged environment

[e.g., Manabe&Stricker, 1964; Abe&Matsui, 1988; Kasting+1993; Kopparapu+2013 ; + many papers]

Habitable planets

Exploring the conditions for Earth(-like) planets

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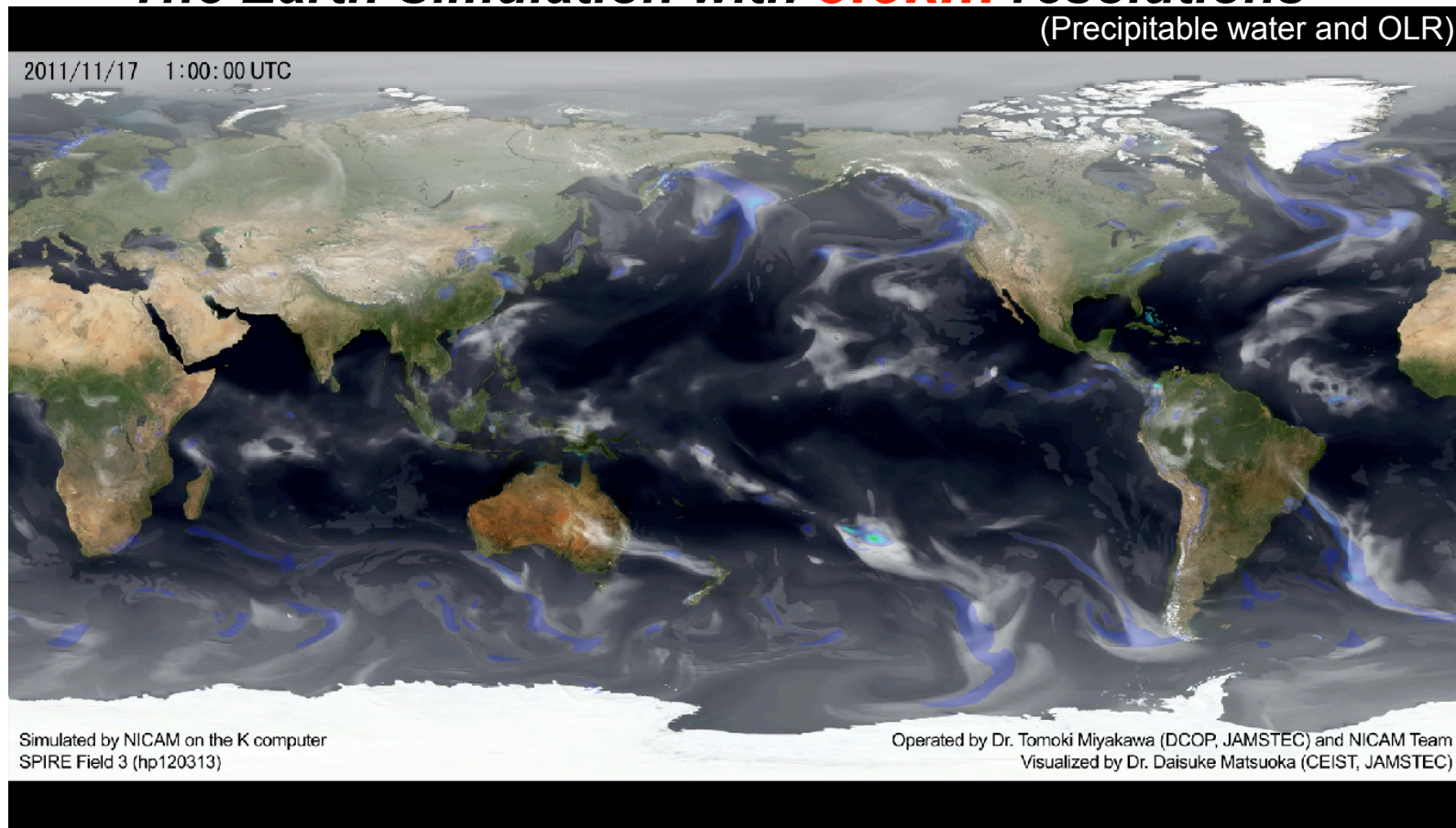
[e.g., Manabe&Stricker, 1964; Abe&Matsui, 1988; Kasting+1993; Kopparapu+2013 ; + many papers]

Next Generation Habitable Climate Modeling

Habitable Climate with **Global Cloud Resolving Model**

We can access super-computer and run a simulation using 3D cloud resolving climate model with high resolution.

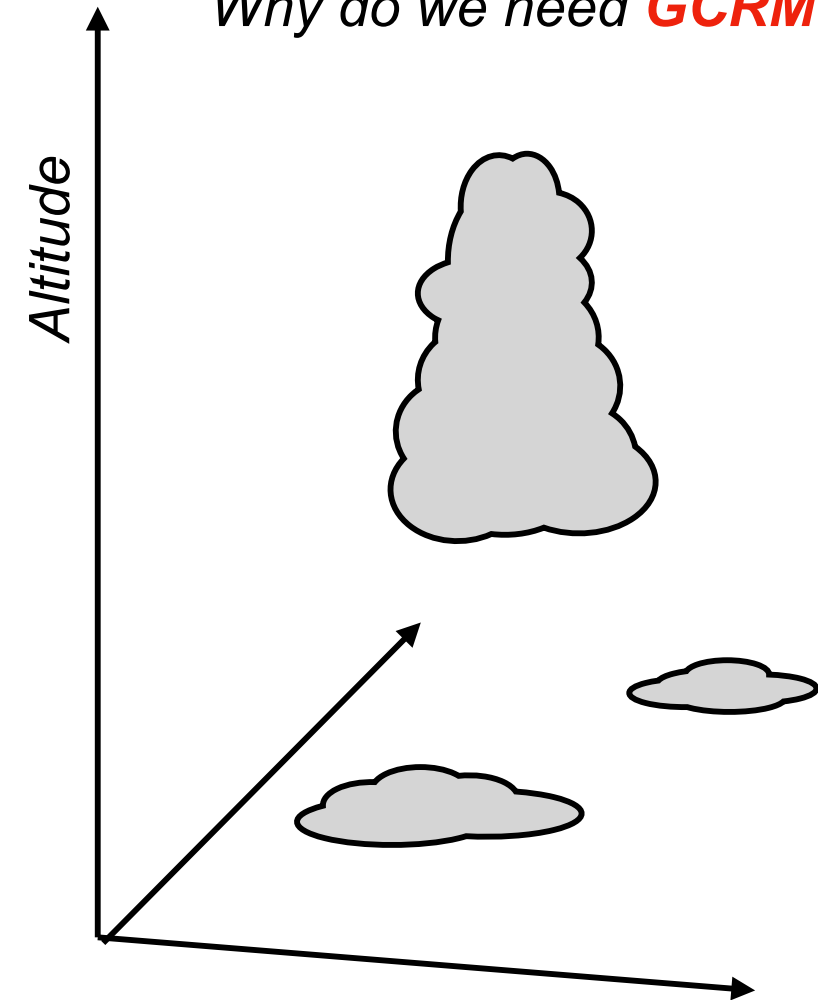
The Earth Simulation with **3.5km** resolutions



Next Generation Habitable Climate Modeling

*Habitable Climate with **Global Cloud Resolving Model***

Why do we need **GCRM**?



Next Generation Habitable Climate Modeling

Habitable Climate with **Global Cloud Resolving Model**

Why do we need **GCRM**?

Traditional GCM

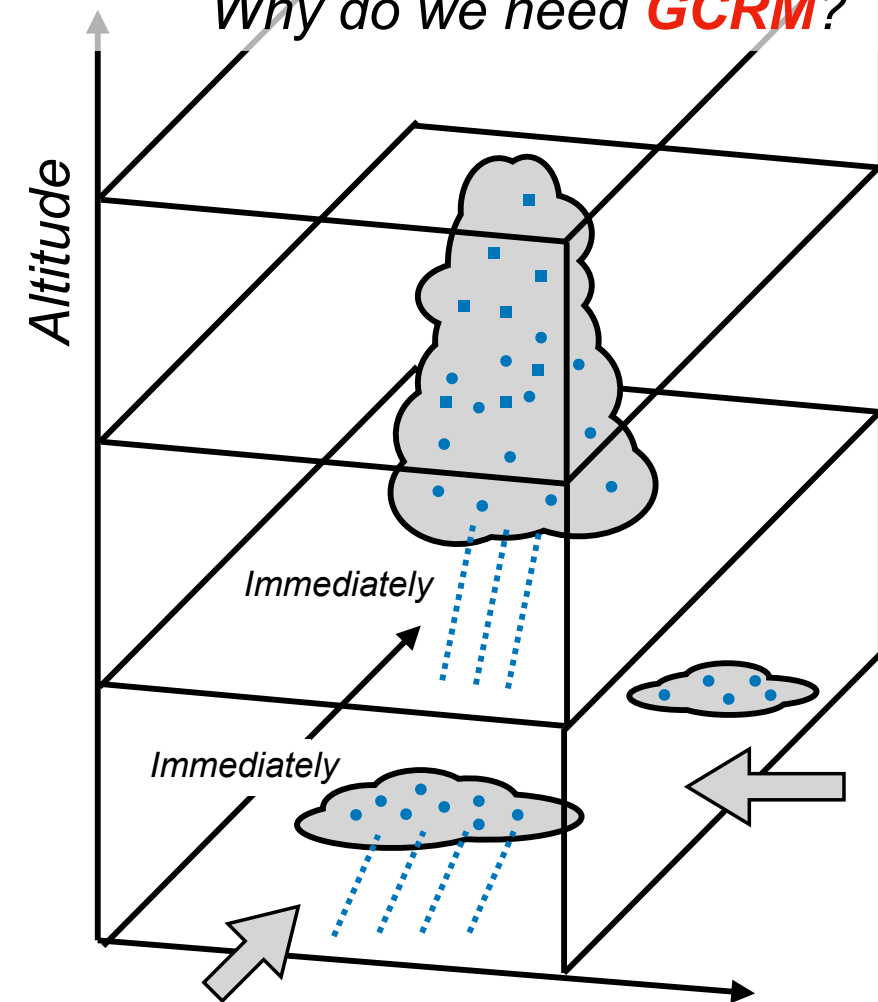
Large scale condensation

Precipitation in GCM grid scale / Precipitation following saturation conditions

Cumulus convection parameterization

Sub-grid scale precipitation / Precipitation associated with cumulus convection (statistical and empirical)

> *Cloud fraction and coverage within a grid cell*



Next Generation Habitable Climate Modeling

Habitable Climate with **Global Cloud Resolving Model**

Why do we need **GCRM**?

Traditional GCM

Large scale condensation

Precipitation in GCM grid scale / Precipitation following saturation conditions

Cumulus convection parameterization

Sub-grid scale precipitation / Precipitation associated with cumulus convection (statistical and empirical)

> Cloud fraction and coverage within a grid cell

Global Cloud Resolving Model

Non-hydrostatic equs. (no hydrostatic assumption):
explicit updrafts; resolved cumulus convection

← High-resolution sim.

Directly simulating cumulus convection and turbulent-scale motions.
(without parameterizations)

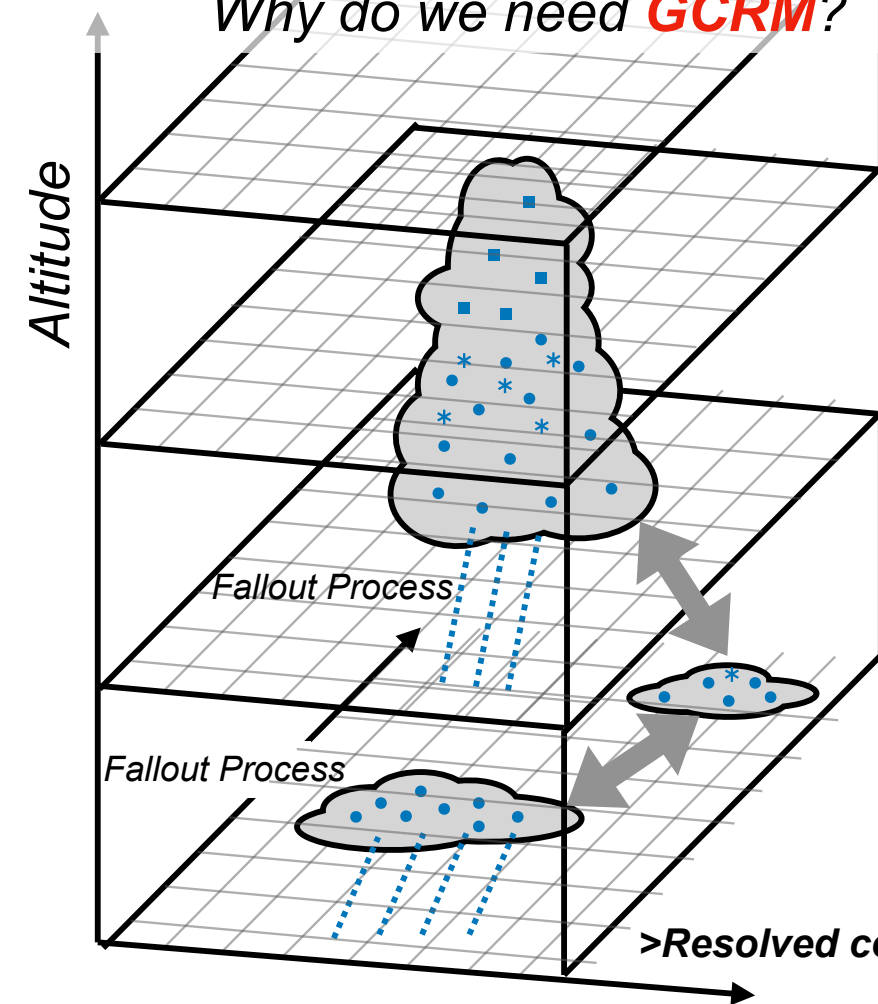
Cloud microphysics

Physics : Condensation • Evaporation / Freezing • Melting • Sublimation /
Self-aggregation & Fall-out / Onset and maintenance of free convection

Bulk scheme :

Single moment (mass mixing ratio) / Double moment (mass mixing ratio &
number density) (or Bin scheme: explicit tracking of the size spectrum)

> Resolved convection and clouds; **dynamics-cloud** and **radiation-cloud interactions**

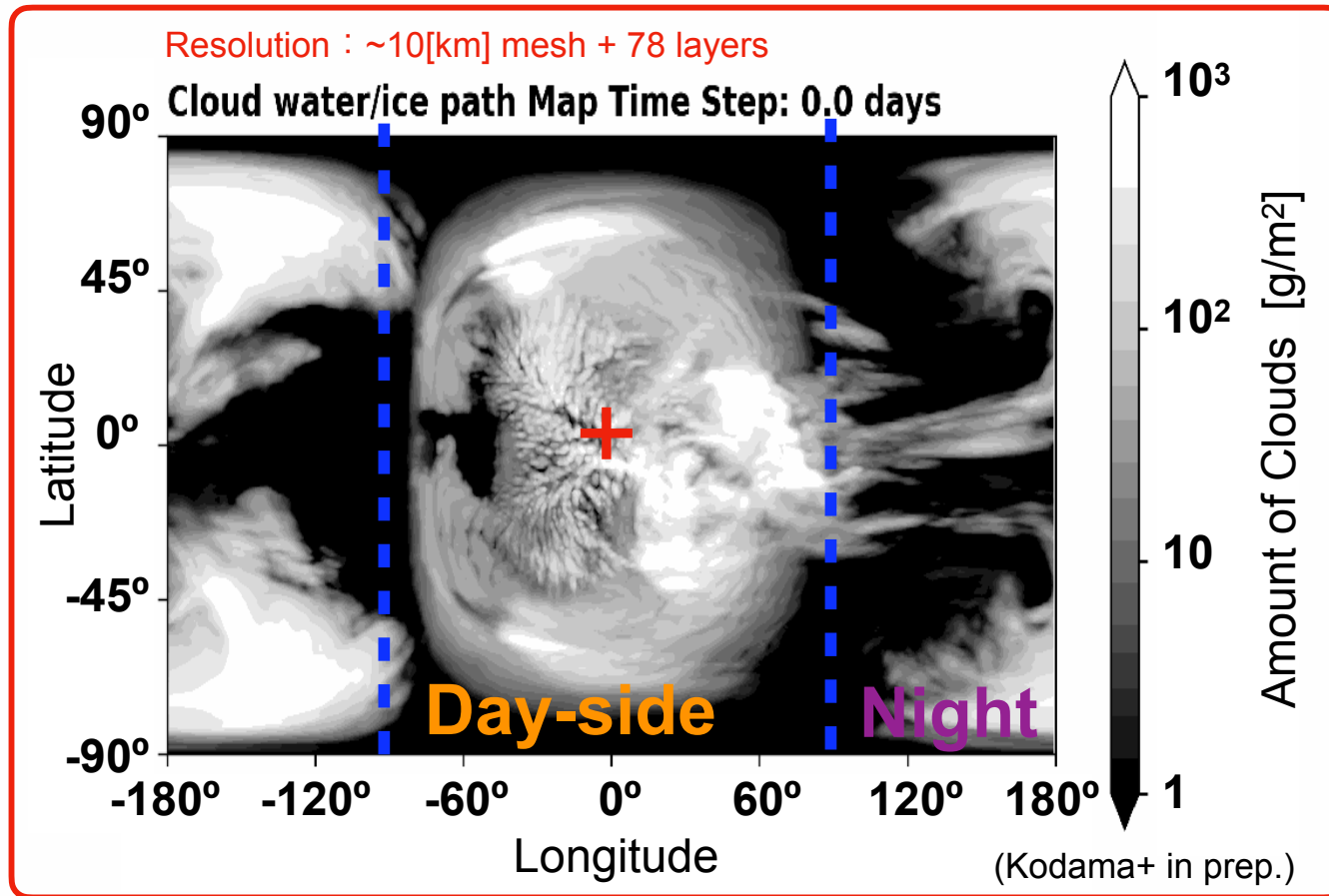
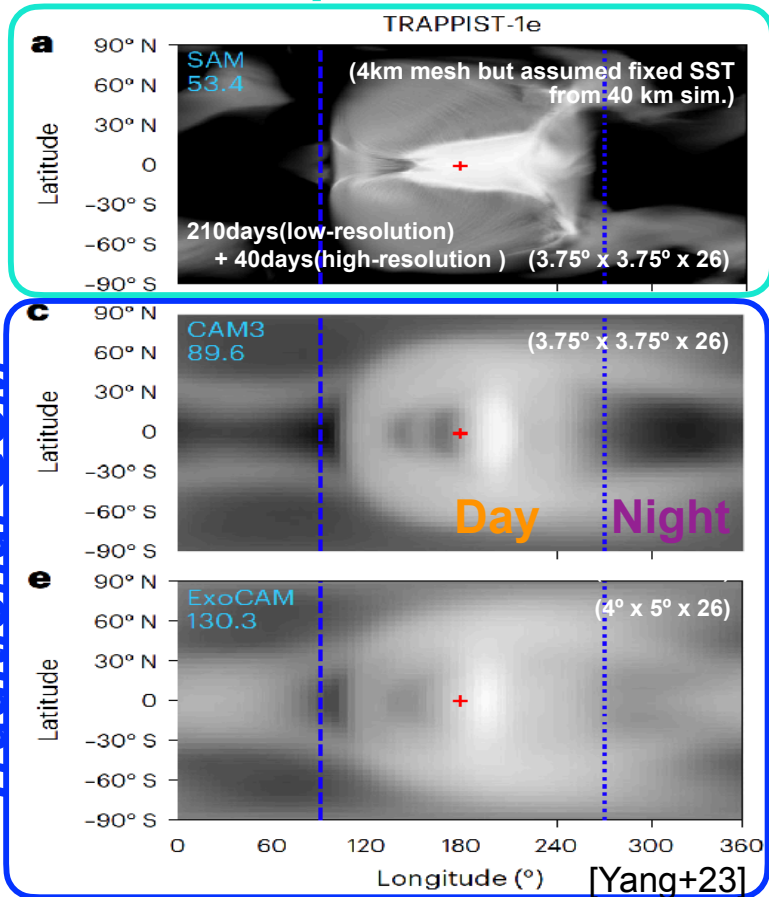


3D GCM vs 3D GCRM (Global Cloud Resolving Model)

Planet: TRAPPIST-1e with 6.1 days orbit

GCM with Super-Parameterization Global Cloud-Resolving Model (NICAM)

Traditional GCM

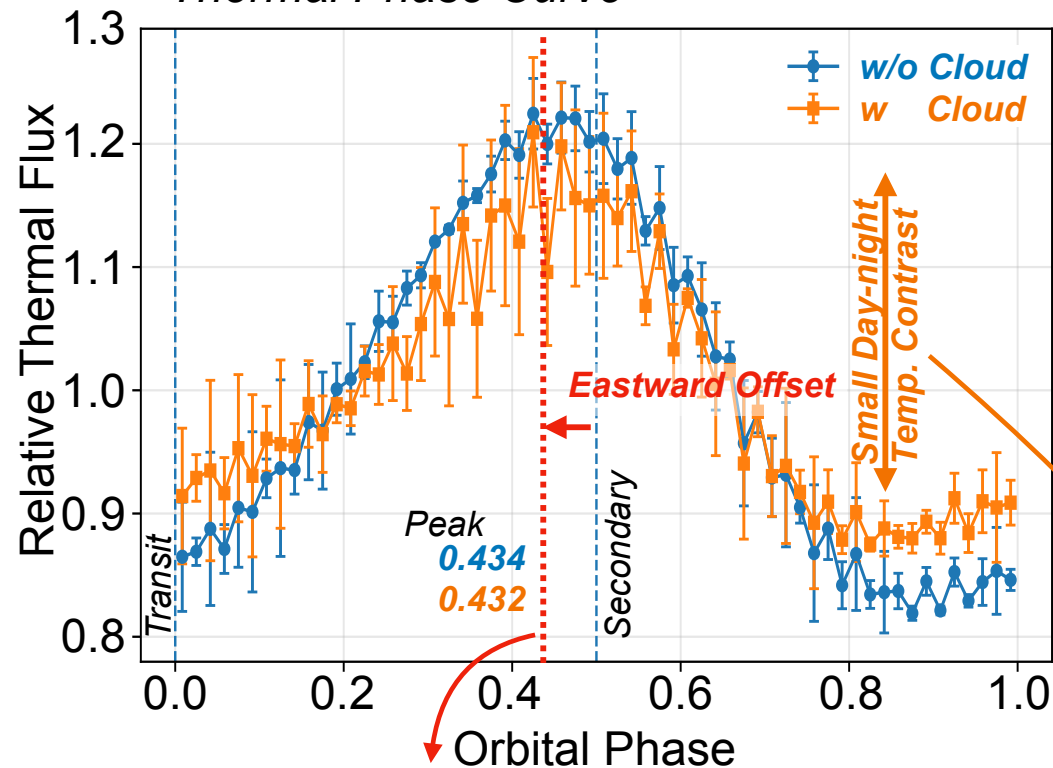


Role of Clouds in Observation

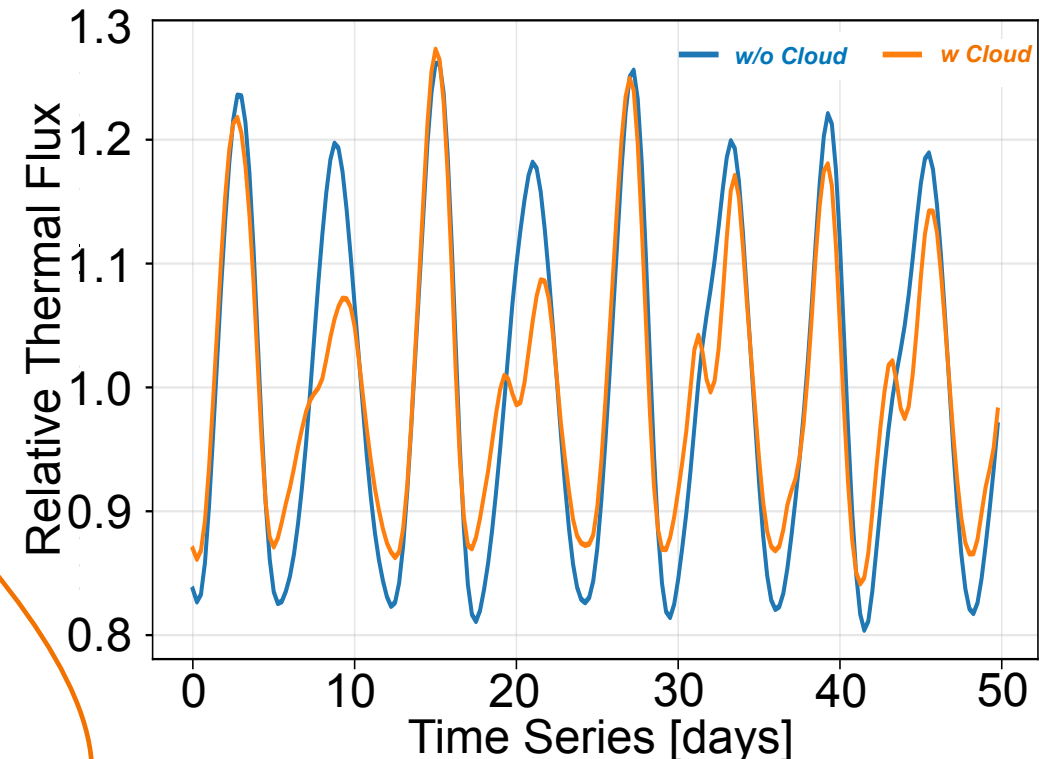
What Can We Learn from Observations?

A new observational signature: **dynamically variable habitable climates**

Thermal Phase Curve



Time Series of Relative Thermal Flux



The relative thermal flux fluctuates.

-> **Cloud structure & Circulation**

Weather-scale variability

The offset of the hottest point is the same.

Clouds have only **a minor impact** on the **atmospheric circulation**.

(The atmospheric circulation is primarily controlled by **planetary rotation**.)

Clouds reduce the **day-night temperature contrast**.

Role of Clouds in Observation: Future

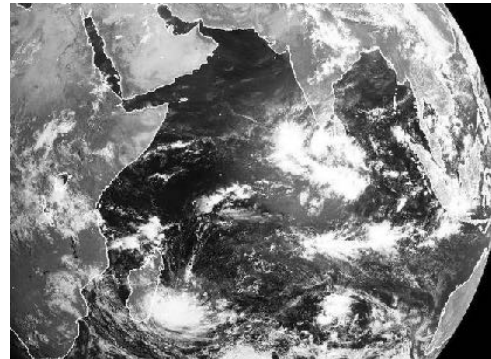
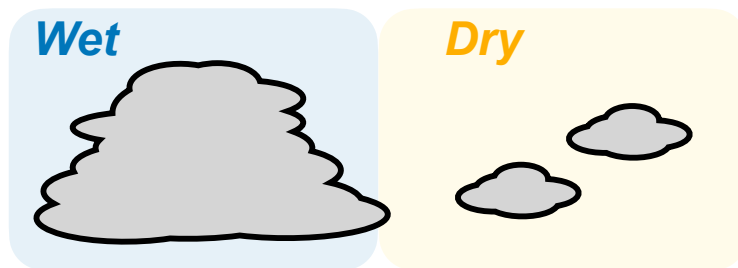
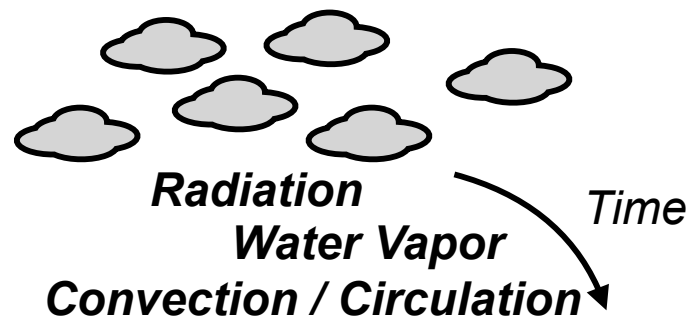
From Habitable Climates to the Earth

Exoplanet research can serve as a testbed for **the fundamental physics of Earth's meteorology**.

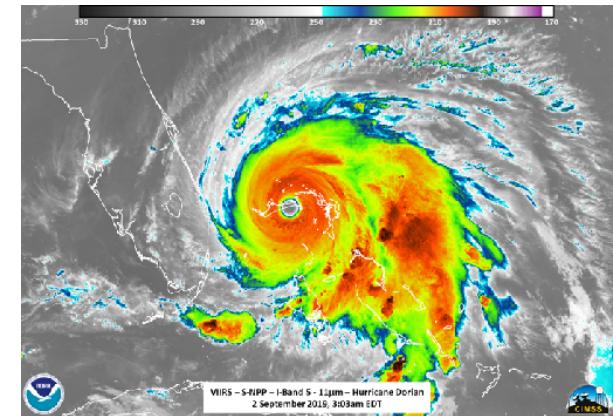
Temporal variability of phase curves × **cloud self-organization**

Cloud Self-Organization

Convective Cloud Formation



Madden–Julian Oscillation (MJO) event on 8 April 2009.
(Holloway+2017)



5 - 11um
Hurricane Dorian
2 September 2019, 3:03am EDT

Tidally locked planets are essentially like **a planet-scale tropics**.

Understanding **habitable planetary environments** deepens understanding of **the Earth's Climate**.

The Role of Japanese Climate Modeling in the HWO Era

Exo-Habitable Climate Modelings in the World



Met Office UM
(HadCM)

LFRic-A (GungHo)

Sergee+2020, 2023
etc.



MPI-gcm
(ECHAM)

ICON?

Paradise+2021
etc.



Yang+2023
Gu+2024
etc.



DCPAM
MIROC
NICAM



NCAR CAM3/4/5
exo-CAM / SP-CAM / Chem-CAM

MIT-gcm

ROCKR-3D
ExoPlaSim

SAM

MPAS-A

Kopparapu+2016, 2017
Haqq-Misra+2018
Wolf+2022
Salazar+2020
etc.



PCM (LMD-G)
DYNAMICO?

Turbet+2018, 2024
etc.

AGCM: Atmospheric GCM

AOGCM: Coupled Atmosphere Ocean GCM

GCRM: Global Cloud / Convective Resolved Model

The Role of Japanese Climate Modeling in the HWO Era



Habitable Climates

The field has transitioned from 1D estimates of habitability with HZ to **3D understanding of planetary climate** and **surface environment**.

From Detection to Understanding

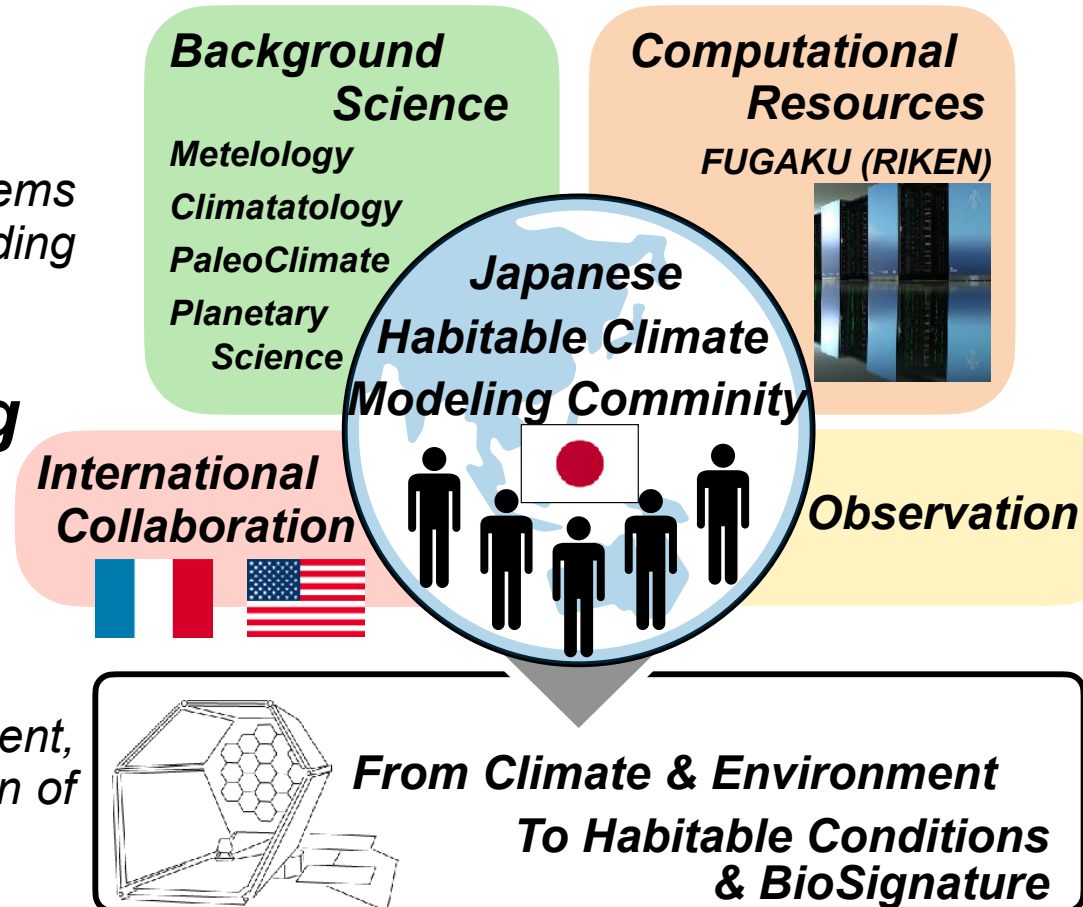
We must understand how planetary climate systems determine **habitable surface environments**, leading to robust **biosignature** interpretation.

Next Generation Climate Modeling

- **Coupled Atmosphere and Ocean Climate Model**
- **Global Cloud-Resolving Model**

From Exoplanets to the Earth

Finding a habitable world is a remarkable achievement, but we need to start to discuss beyond the detection of biosignatures.



Strong control of ice cover on exo-terrestrial planets

by continentally constrained ocean circulation

Taro Higuchi and Takanori Kodama

Earth-Life Science Institute, Institute of Science Tokyo

Lead author: Taro Higuchi

Abstract:

Future exoplanet observations are expected to directly image exo-terrestrial exoplanets, potentially providing broad constraints on continental distributions. Therefore, it is necessary to theoretically assess how continental variability influences the climate systems of exo-terrestrial planets. In the case of the Earth, the continental crust has formed, grown, and evolved through repeated cycles of assembly and dispersal driven by plate tectonics. Recent numerical studies using coupled atmosphere–ocean models have indicated that past continental changes significantly impacted Earth’s surface environment. Furthermore, some studies have indicated that continental distribution determines the pattern and strength of ocean circulation, thereby influencing planetary heat transport. However, it remains unclear how variation in continental distributions influence surface environments through ocean circulation. Also, many studies of habitable exoplanets using atmosphere–ocean coupled models assume aquaplanet conditions. Therefore, to investigate the influence of continental variations—including formation, growth, and migration—on the surface environments of exo-terrestrial planets, this study conducts climate simulations with an atmosphere–ocean model coupled, MIROC4m, using idealized and realistic continental conditions. In particular, we examine how ocean circulation responds to continental changes and the subsequent impacts on surface ice conditions, which could potentially be constrained by future exoplanet observations. Our simulations demonstrated that in scenarios with limited low-latitude land, changes in ocean circulation and heat transport determine the meridional temperature gradient and sea ice stability. Moreover, changes in continental configuration can impact sea ice stability as much as, or more than, a fourfold increase in CO₂. On the other hand, in the large continental cases, the increase in the planetary albedo induces extensive sea ice, regardless of the strength of ocean circulation. In addition, the expansion of sea ice suppresses deep ocean circulation by inhibiting heat exchange between the atmosphere and the ocean. These results suggest that future exoplanet observations might allow us to infer information about unobservable ocean circulation in exo-terrestrial planets from broad constraints on continental size and the distribution of sea ice, in addition to atmospheric composition and planetary parameters.

Science Case Summary

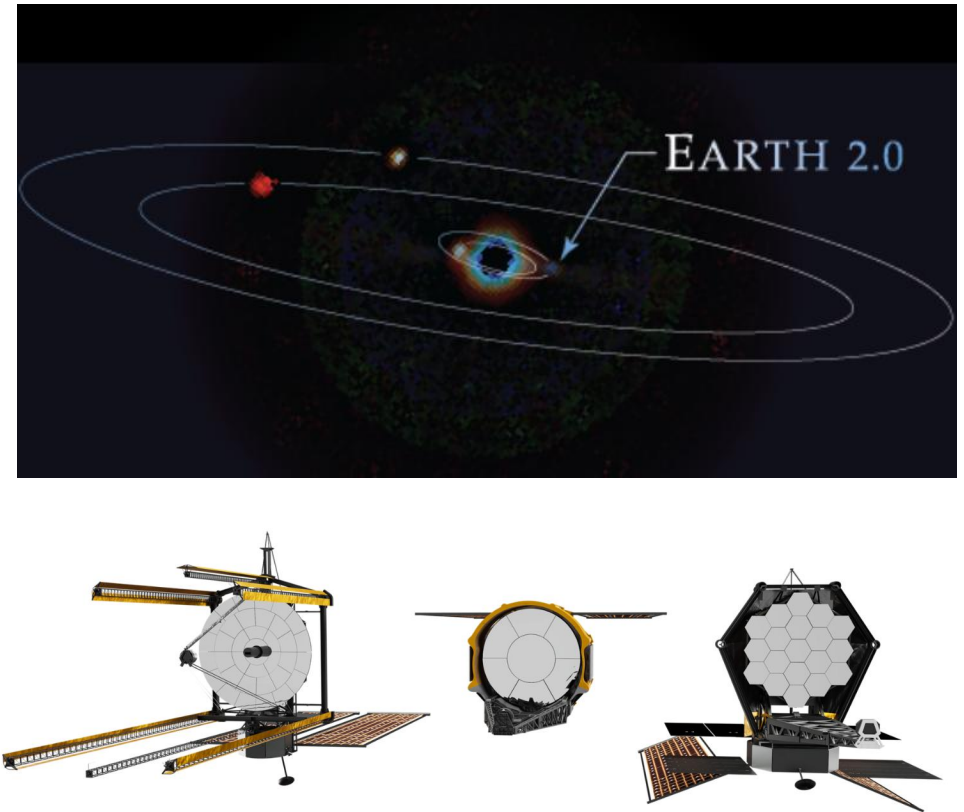
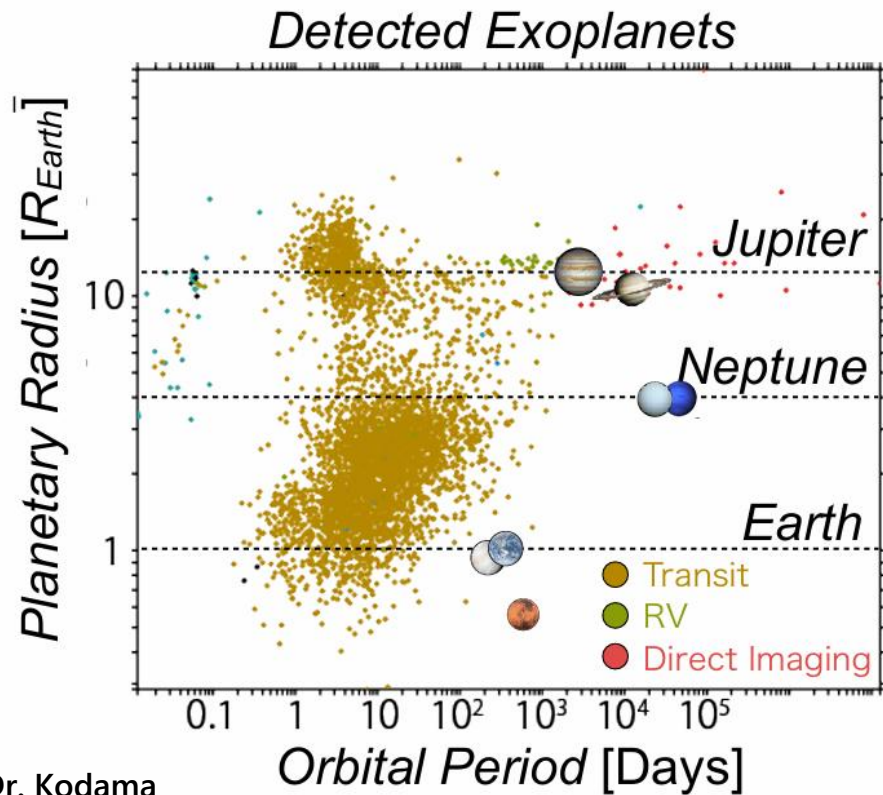
We found that the distribution of continents can determine the ice conditions on exo-terrestrial planets like the Earth, through controlling the ocean circulation and meridional ocean heat transport. Our results might imply that future direct observations of Earth-like exoplanets could be used to infer otherwise unobservable ocean circulation from the observed distribution of continents and sea ice. This work provides a theoretical framework for interpreting future observations of potentially habitable worlds.



Strong control of ice cover on exo-terrestrial planets by continentally constrained ocean circulation

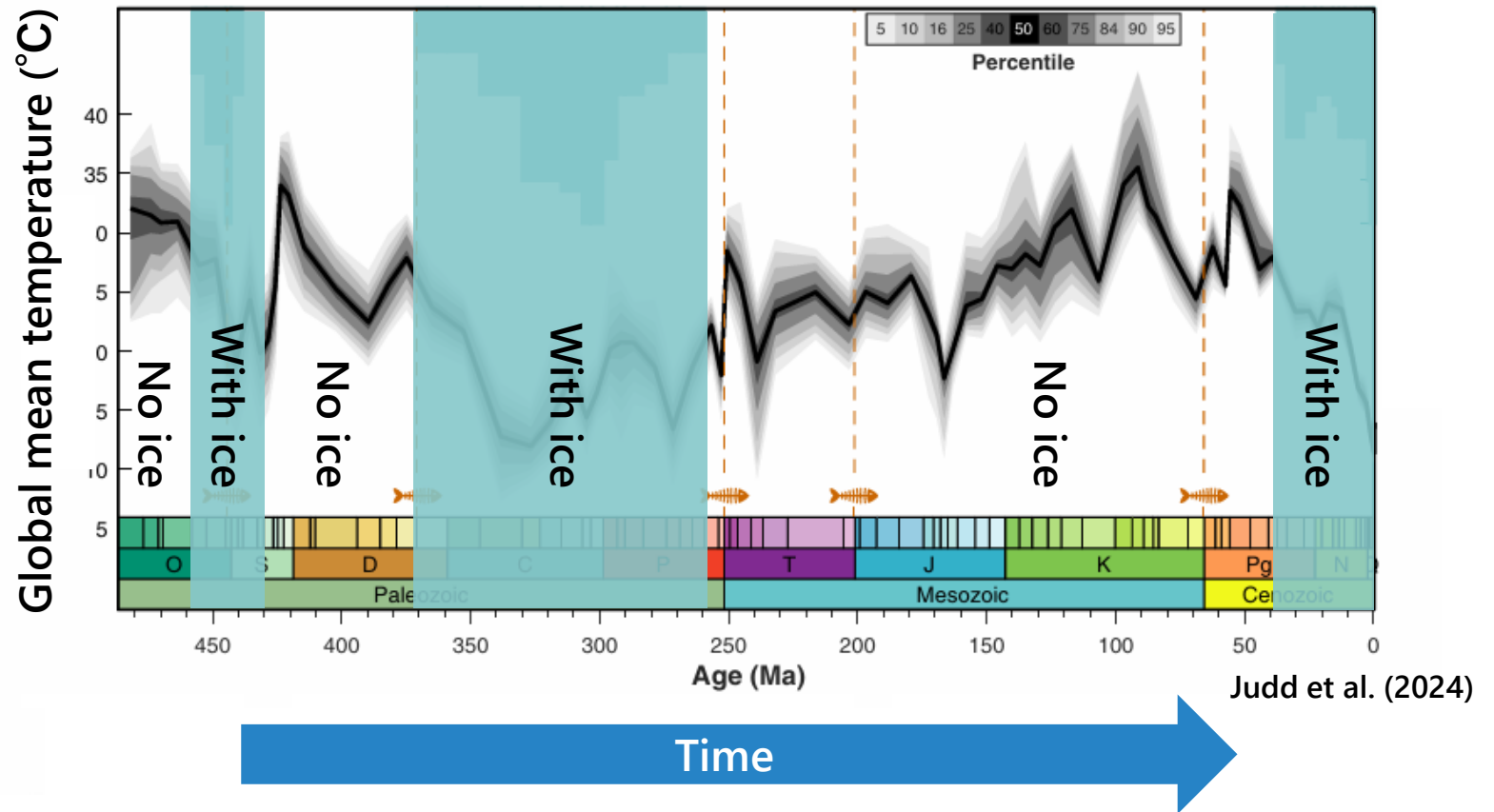
Taro Higuchi, Takanori Kodama
Earth-Life Science Institute (ELSI), Institute of Science Tokyo

Future Observation in Earth-like Terrestrial Exoplanets



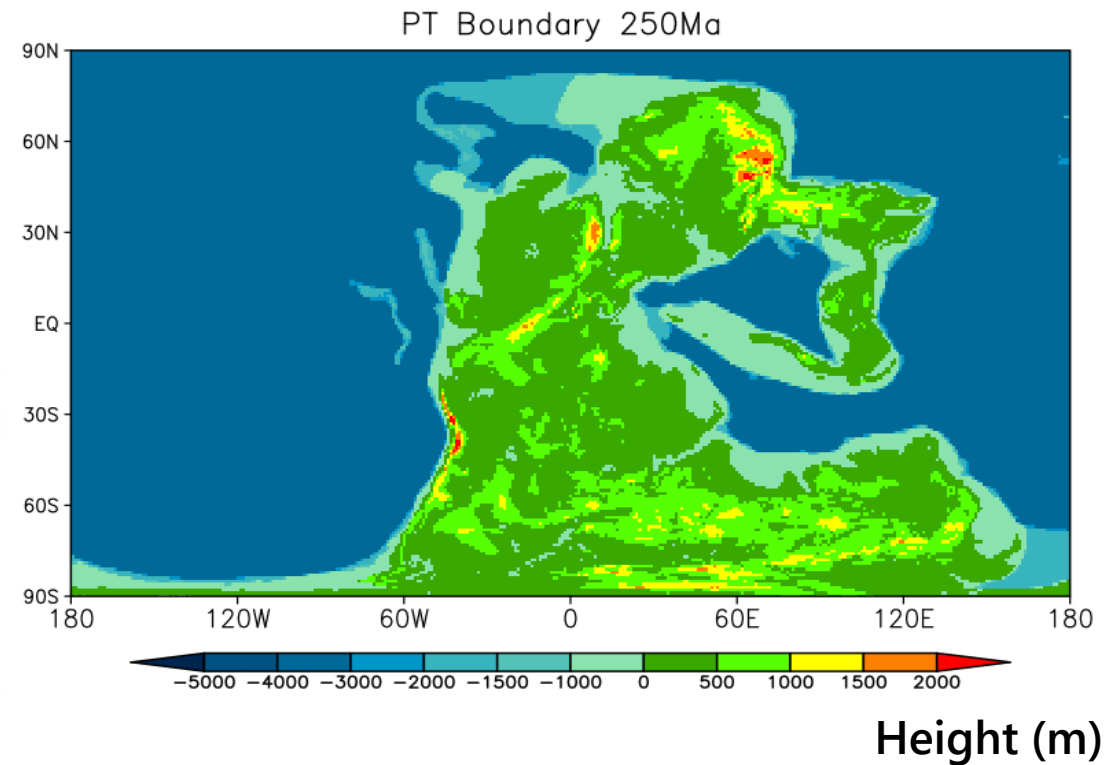
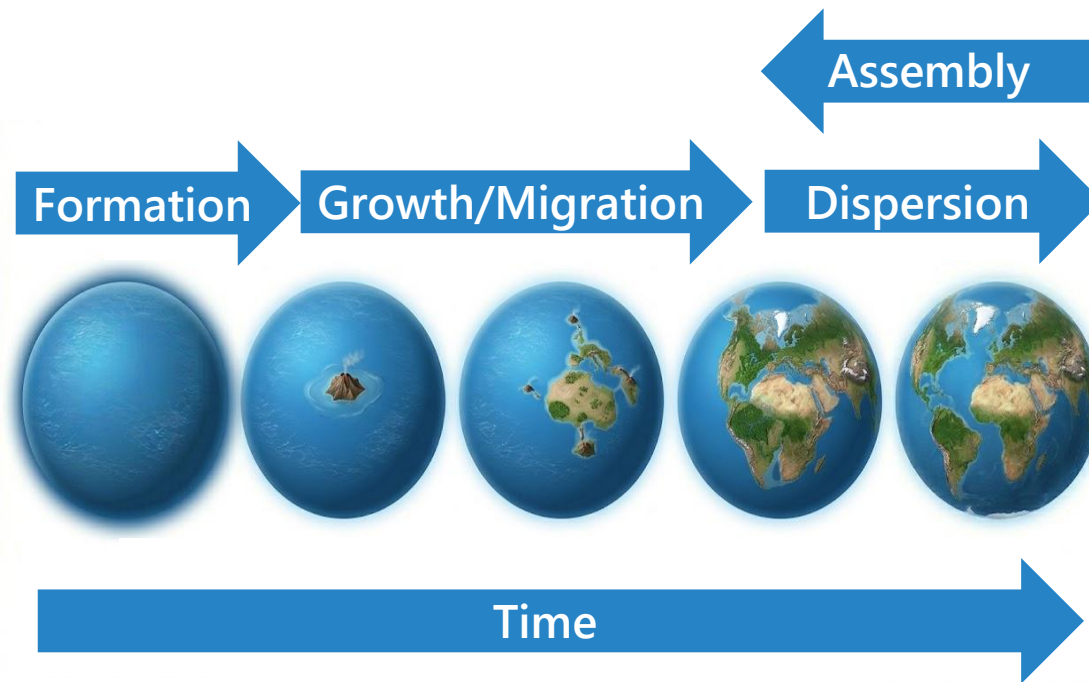
Future observations are expected to directly image Earth-like exoplanets

Diversity of Planetary Ice Conditions



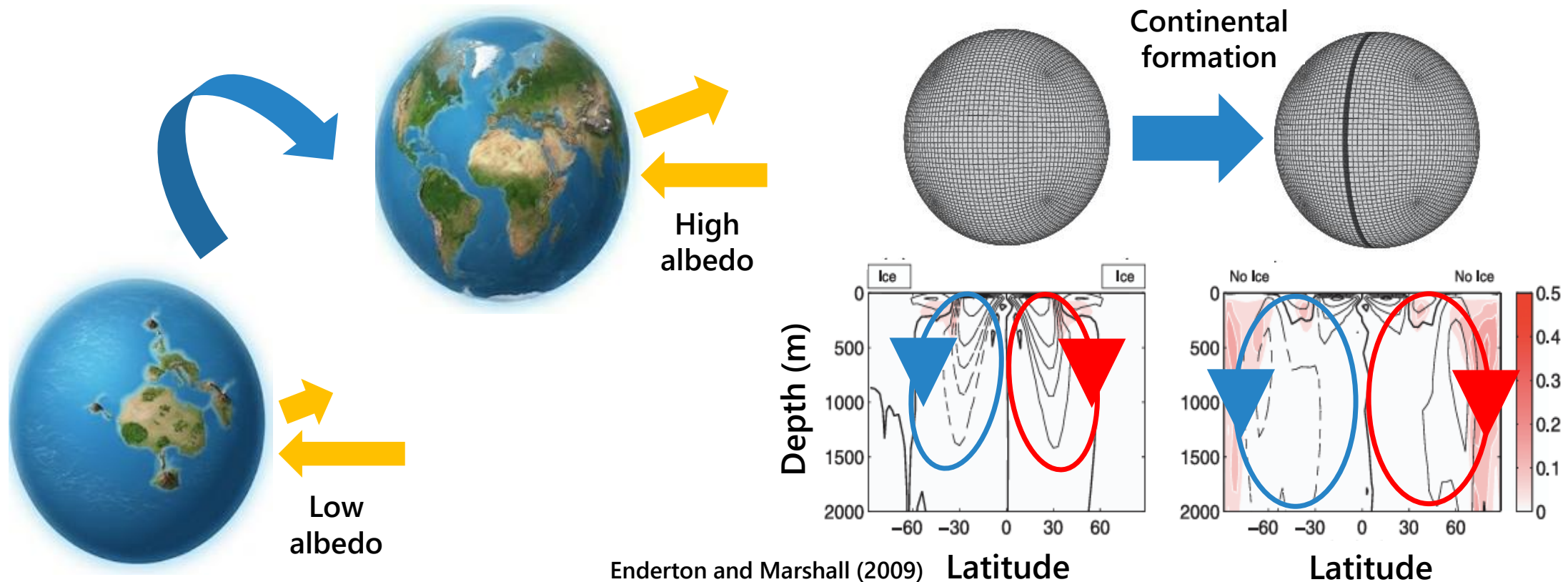
Earth-like planets can exhibit climate states with or without ice

Continental Evolution in the Earth's History



The size and distribution of continents on the Earth have changed

Impact of Continental Configuration Change on Climate



Continental area controls surface albedo; continental layout controls ocean circulation > Determine planetary surface thermal conditions

Question in This Study

- 1: To what extent do changes in continental configuration affect ice conditions on exo-terrestrial planets?
- 2: What are the dominant processes through which changes in continental configuration influence ice conditions on exo-terrestrial planets?

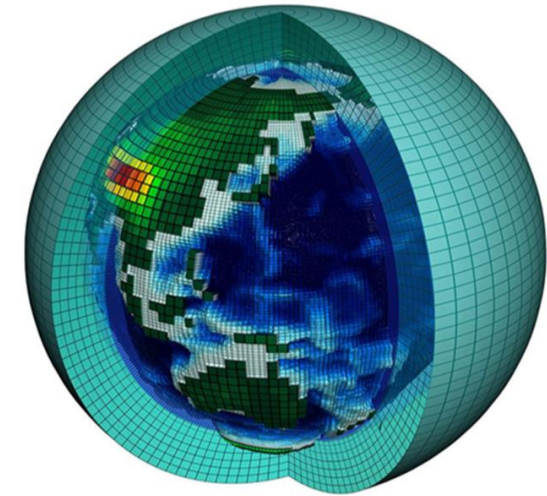
Model and Experimental Design

Model: Atmosphere-ocean coupled global climate model

MIROC4m (Hasumi and Emori 2004)

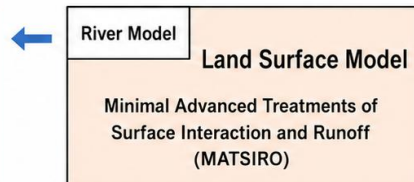
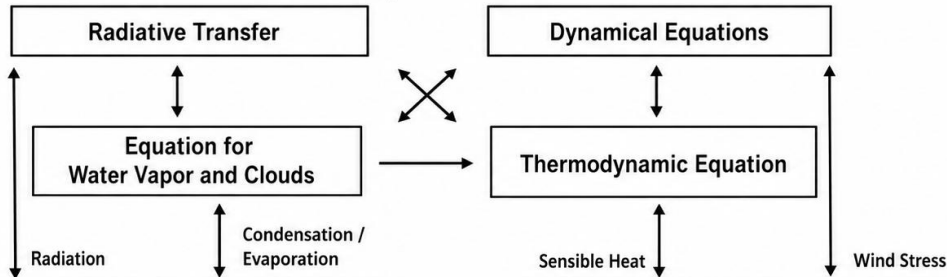
Atmospheric model: Horizontal ~300 km, Vertical 20 levels

Ocean model: Horizontal ~100 km, Vertical 43 levels



Climate Model MIROC4m
Model for Interdisciplinary Research on Climate

Atmospheric Model



Common experimental settings

- Land surfaces = Bare soil
- Atmospheric composition and orbital parameters = Modern
- No continental ice sheets
- Host star = Sun

Continental Distribution Settings

1:Idealized

(Ocean=5000m, Land=0m)

1-1: Aquaplanet

1-2: Continental growth

1-3: Gateway formation

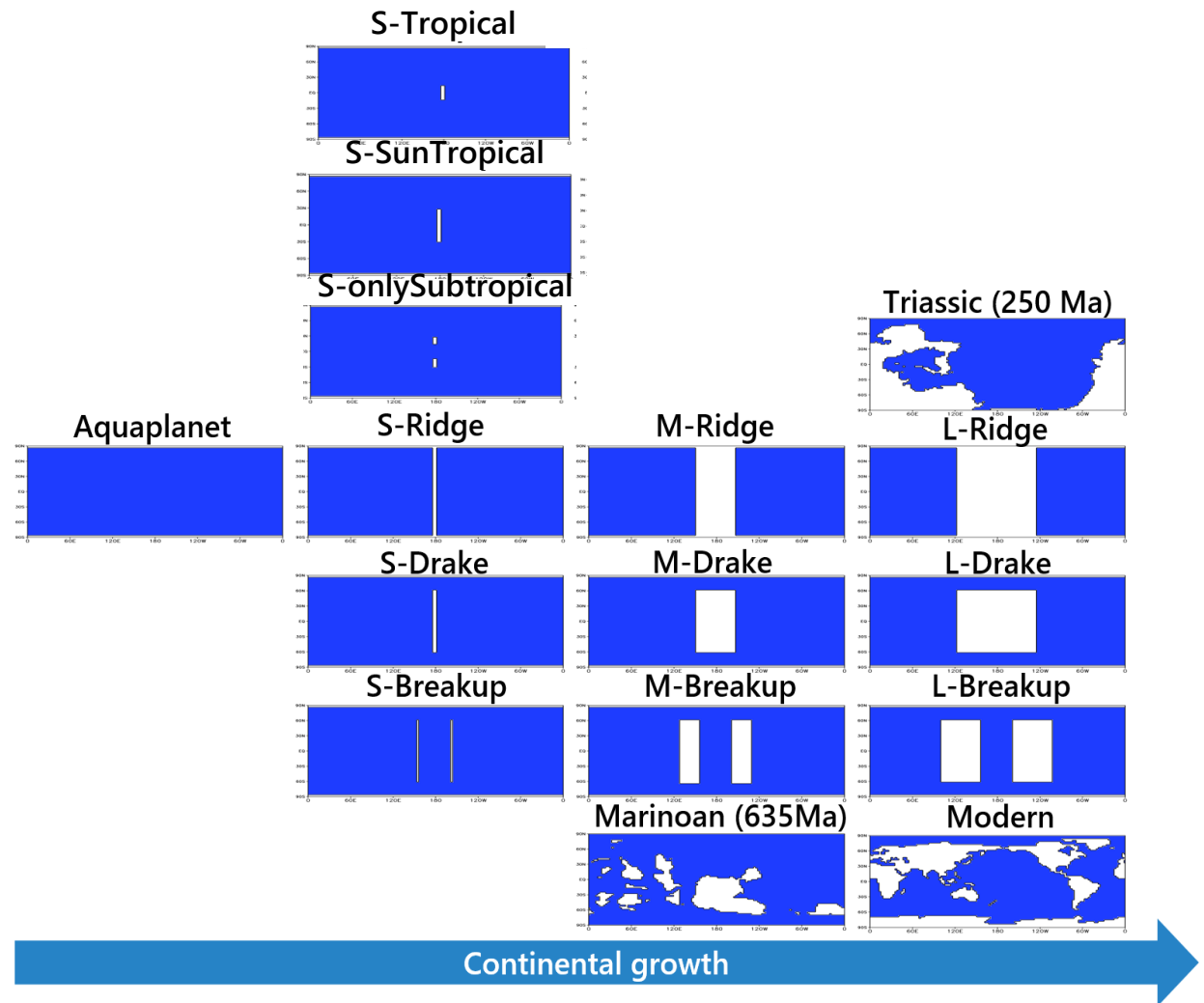
1-4: Continental breakup

2:Realistic

>Modern (0Ma)

>Triassic (250Ma)

>Marinoan (635Ma)

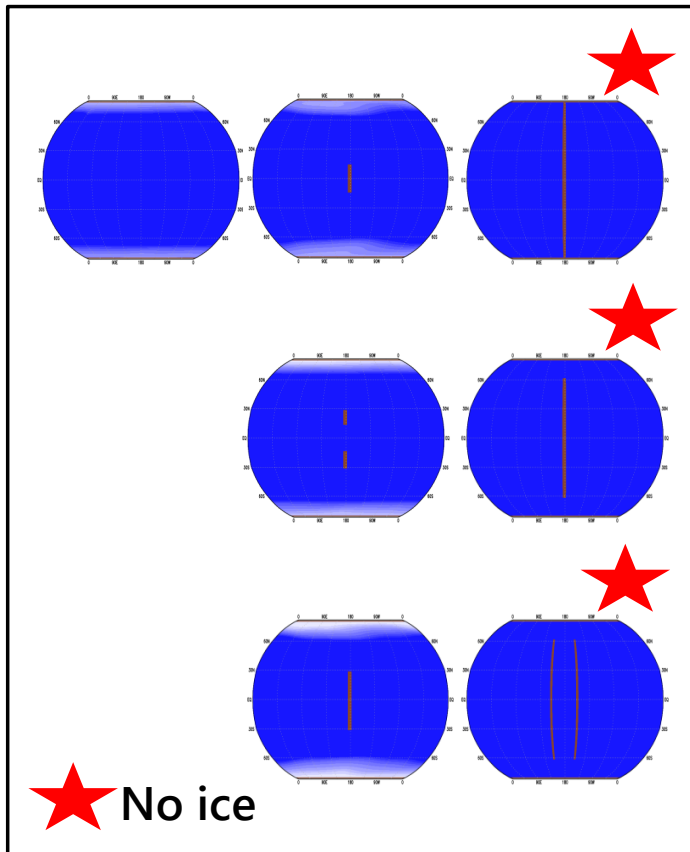


Results: Sea Ice Distribution

Small continent

Low-latitude land area

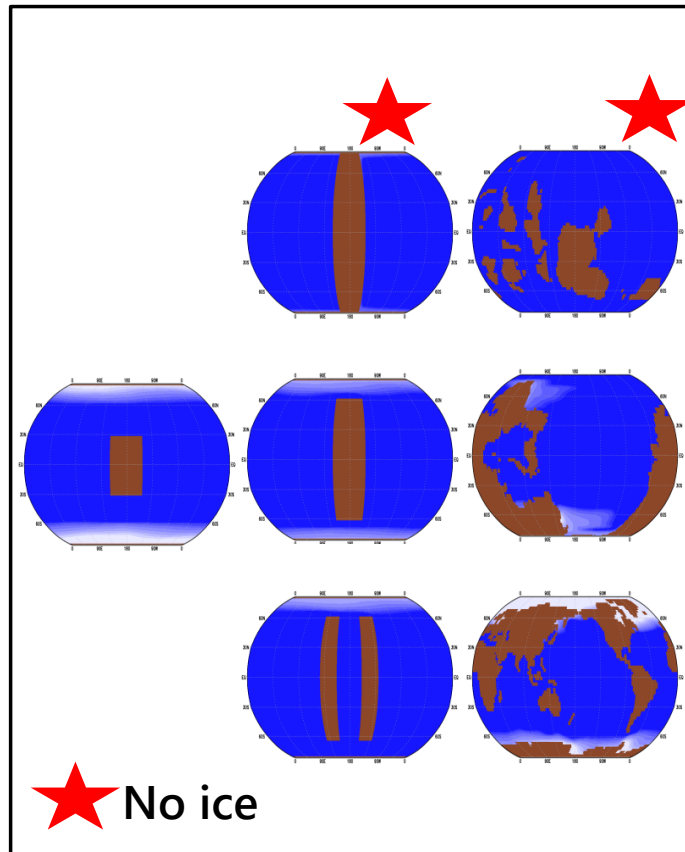
less than 50% of the modern value



Middle continent

Low-latitude land area

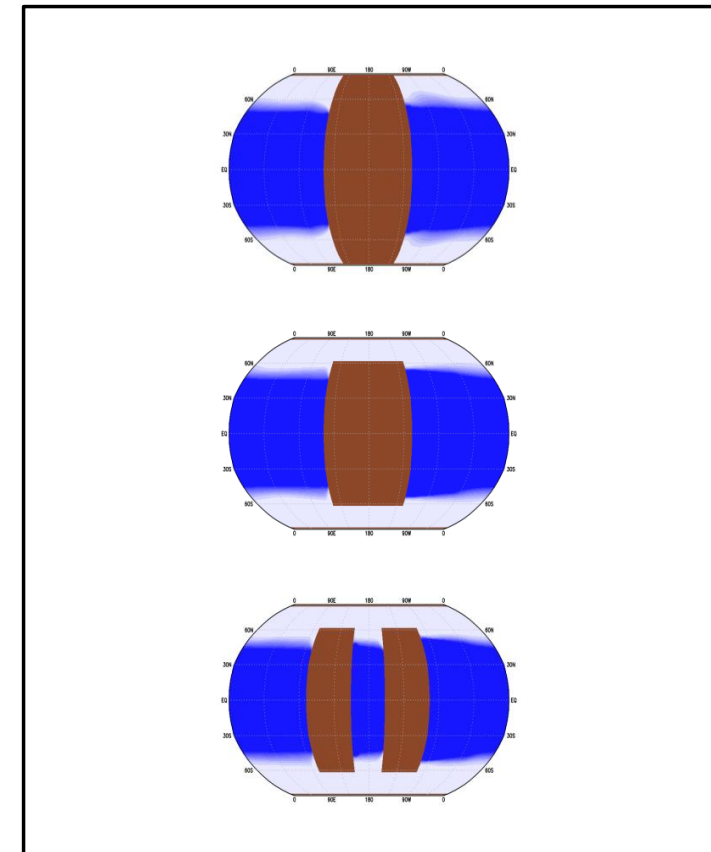
from the modern value to 50%



Large continent

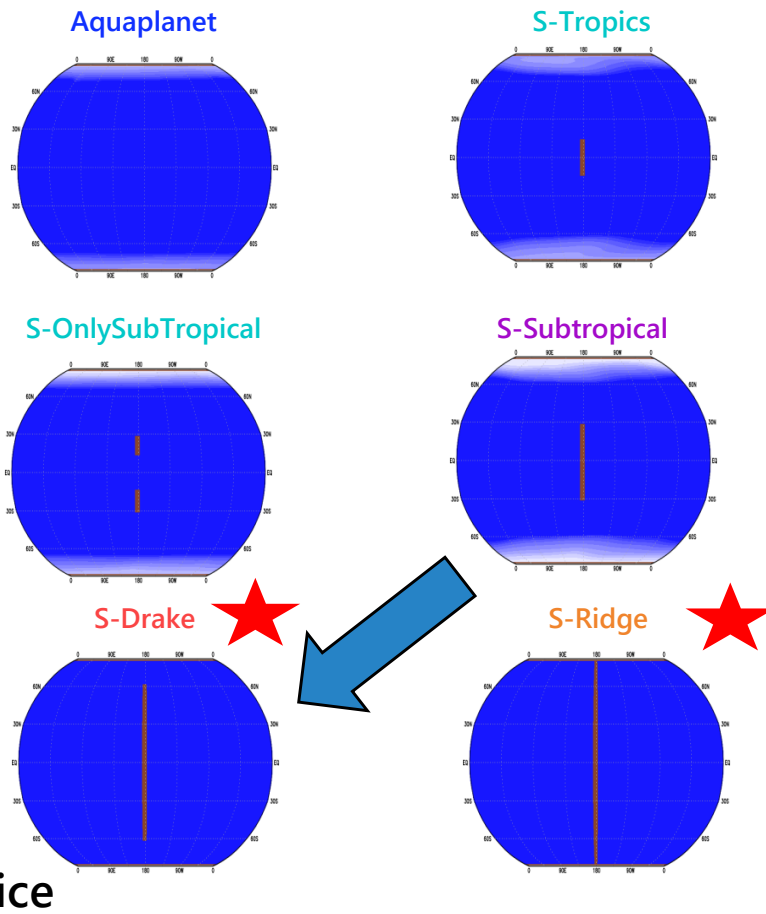
Low-latitude land area

more than the modern value

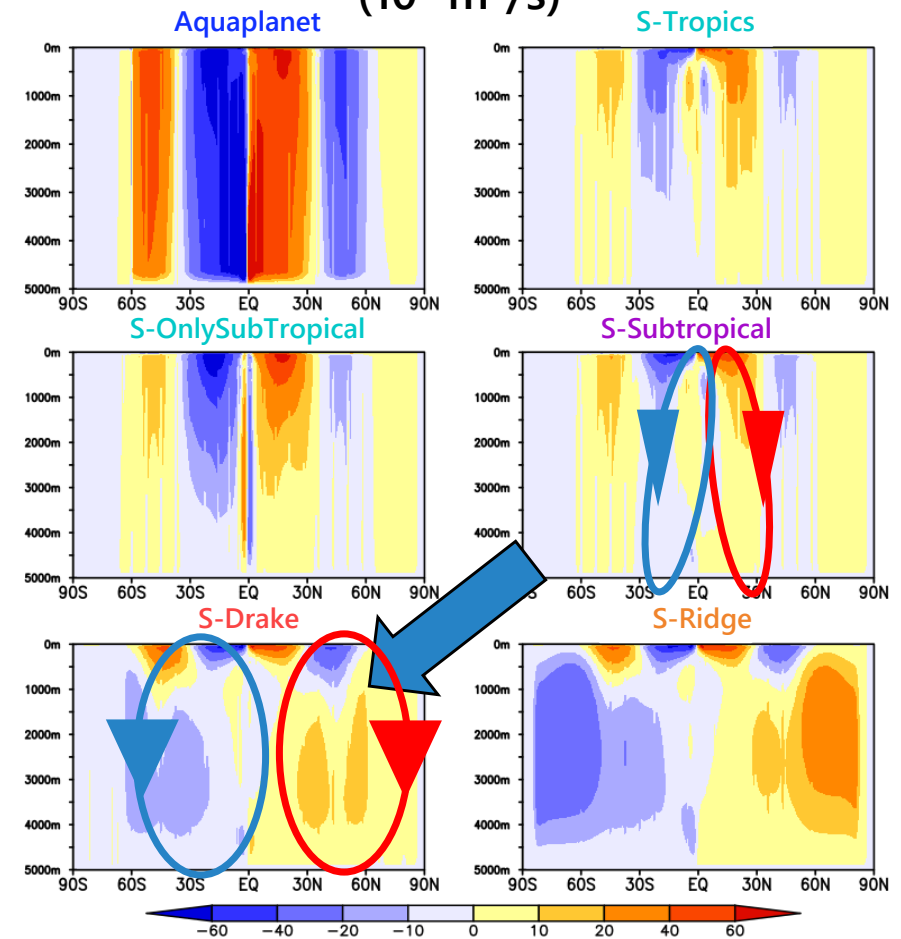


Results: Ocean Circulation Variability to Continental Distributions

Sea ice concentration

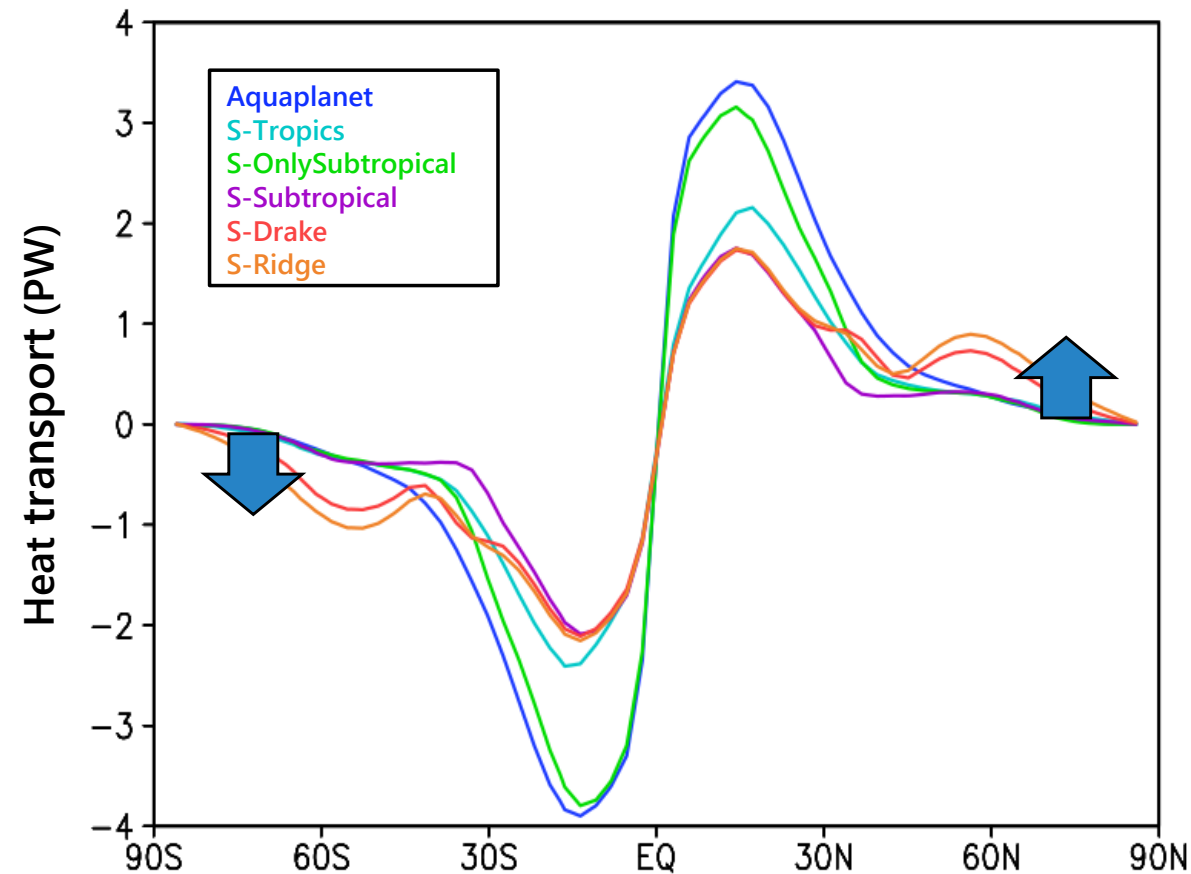


Ocean meridional stream function ($10^6 \text{ m}^3/\text{s}$)

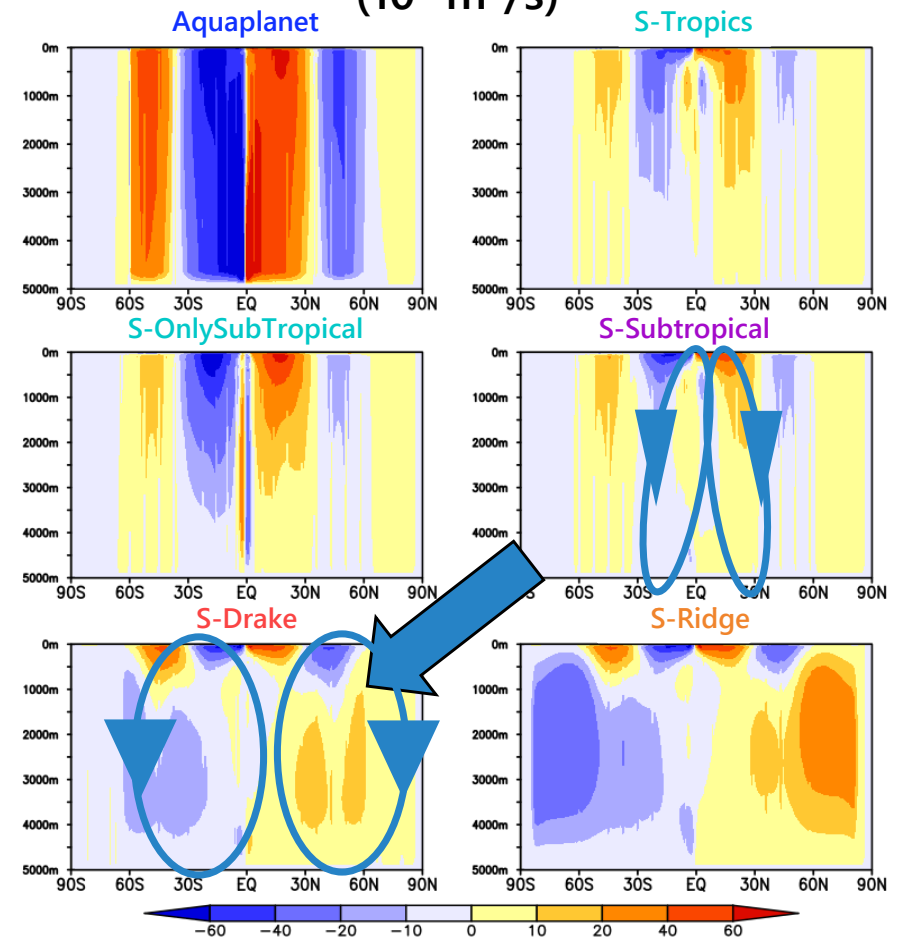


Results: Ocean Circulation Variability to Continental Distributions

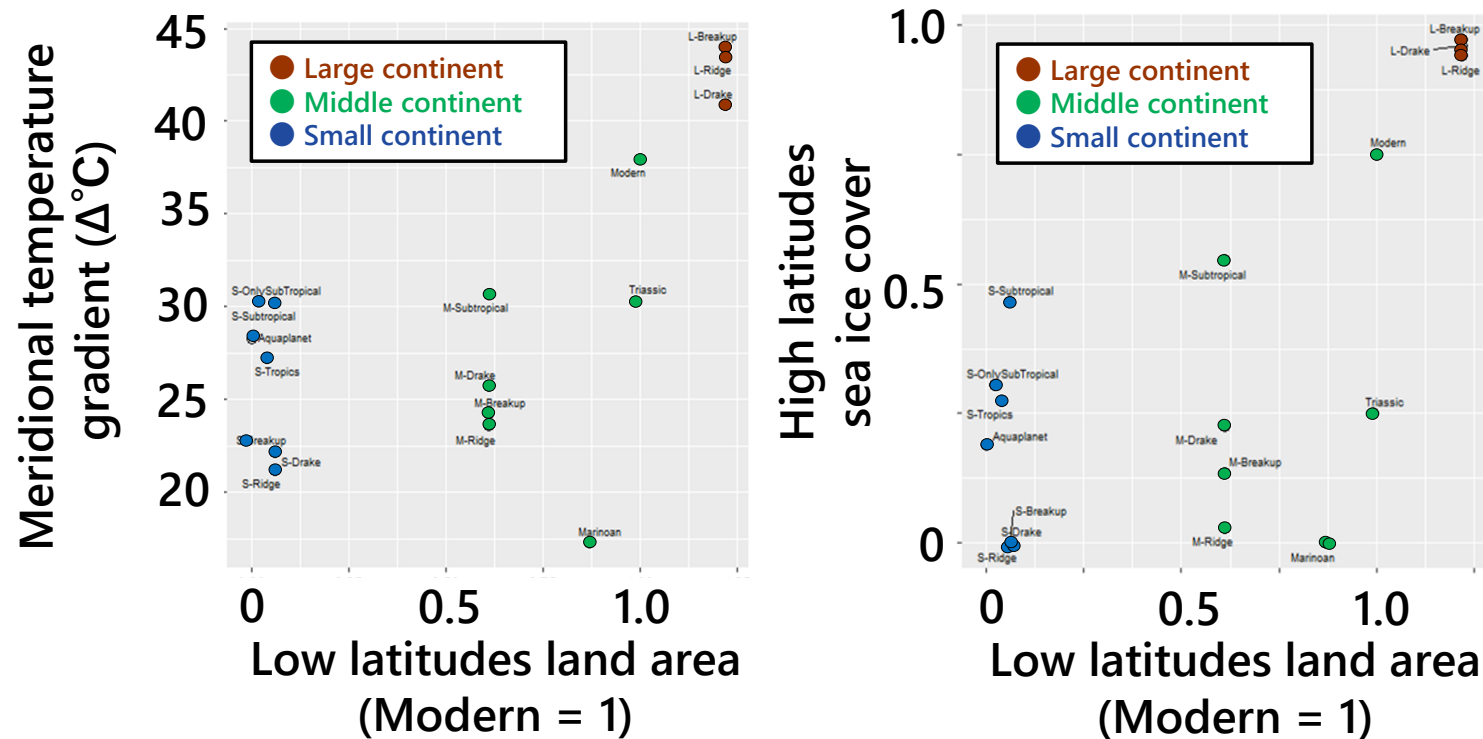
Ocean northward heat transport (PW)



Ocean meridional stream function ($10^6 \text{ m}^3/\text{s}$)

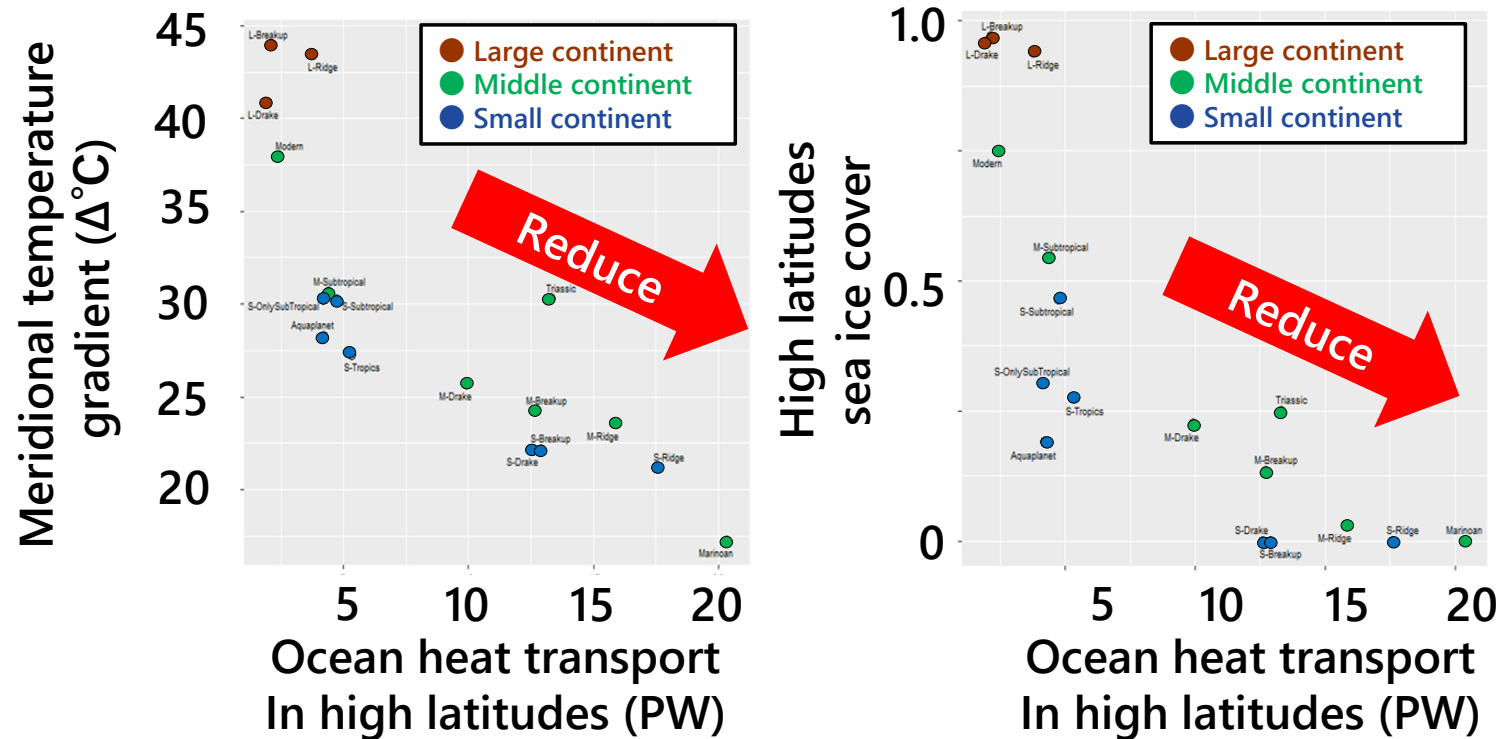


Results: Influence of Continental Size on Polar Climate



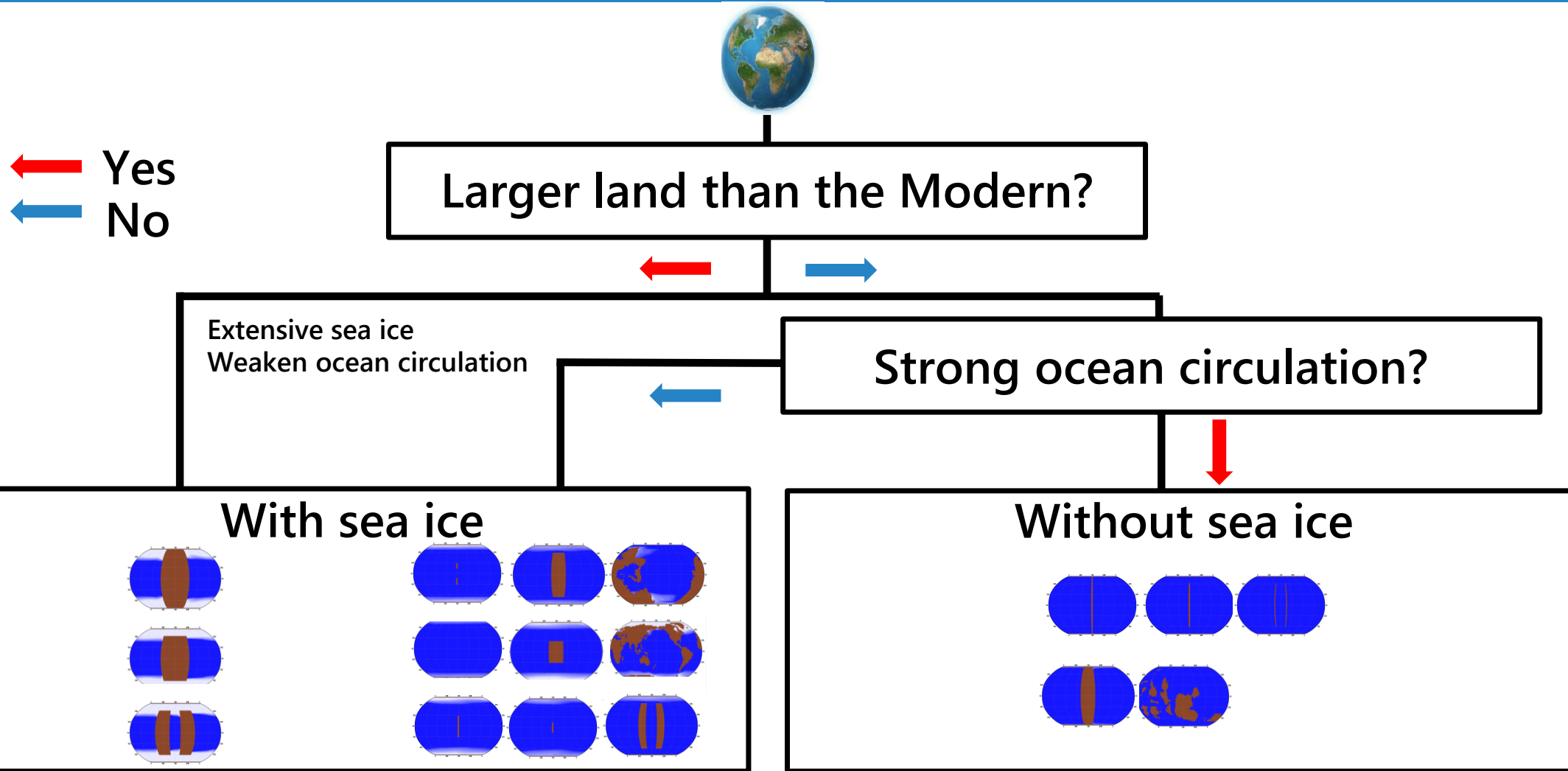
Continental size is not the dominant factor in polar climate diversity

Results: Influence of Ocean Circulation on Polar Climate



Ocean heat transport controls polar climate, except under large continent conditions

Climate Classification of the Simulated Earth-like Planets



Summary in This Study

1: To what extent do changes in continental configuration affect ice conditions on exo-terrestrial planets?

>The continental changes can shift planetary ice conditions from ice-free to extensive high-latitude sea ice

>Even with little change in continental area, high-latitude sea ice coverage can vary by 50%

2: What are the dominant processes through which changes in continental configuration influence ice conditions on exo-terrestrial planets?

>Controlled primarily by ocean circulation under limited land, whereas extensive continents favor widespread ice conditions.

Information about surface ice conditions might provide insights into ocean circulation on Earth-like exoplanets

Long-Term Water Redistribution and Observable Habitability on a Tidally Locked Terrestrial Planet

Arihiro Kamada¹, Takanori Kodama¹, and Takeshi Kuroda²

¹ Earth-Life Science Institute, Institute of Science Tokyo; ² Graduate School of Science, Tohoku University

Lead author: Arihiro Kamada

Abstract:

The long-term habitability of a tidally locked terrestrial planet hinges on atmospheric circulation and the redistribution of water between the atmosphere, oceans, rivers, groundwater, and ice sheets. We simulated an idealized TRAPPIST-1e-like planet with a dayside ocean and nightside land using a coupled global climate and water-cycle model over a period of approximately 10,000 years. We varied the geothermal heat flux from 150 to 500 mW m⁻², and up to 5,000 mW m⁻² in additional cases. With a geothermal heat flux of 150–500 mW/m², which is a realistic range for TRAPPIST-1e, the process of evaporation transfers water from the ocean on the dayside to the nightside, where an ice sheet thicker than 1 km develops. Higher geothermal heat flux within this range enhances subglacial melting and river flow; however, the returned water evaporates before it can replenish the dayside ocean. A stable dayside ocean and a vigorous atmospheric water cycle only appear when the geothermal heat flux reaches approximately 3,000 mW m⁻², which is far above current estimates for TRAPPIST-1e. These results demonstrate that observable habitability hinges on the long-term redistribution of water through a coupled system, and that the presence of weak atmospheric water vapor, sparse clouds, or an absence of an exposed ocean does not necessarily preclude the existence of liquid water stored beneath nightside ice.

Science Case Summary

On a tidally locked planet, water can evaporate from the dayside, fall as snow on the nightside, and become trapped in a thick ice sheet. This means that an initially wet planet may gradually lose its visible ocean. Our simulations suggest that the geothermal heat flux on TRAPPIST-1e is insufficient to return enough meltwater to the dayside, although liquid water may persist beneath the nightside ice and sustain rivers. This is important for HWO because the presence of little water vapor, few clouds or no visible ocean would not prove that a rocky planet is dry in isolation; observations must be interpreted alongside the planetary long-term water redistribution.

Long-Term Water Redistribution and Observable Habitability on a Tidally Locked Terrestrial Planet

Arihiro Kamada¹,

Takanori Kodama¹, and Takeshi Kuroda²

¹ Earth-Life Science Institute, Institute of Science Tokyo

² Graduate School of Science, Tohoku University

arihiro.kamada@elsi.jp

Exoplanet Discovery & TRAPPIST-1

- To date, **more than 6,000 exoplanets have been discovered in our neighborhood** (NASA Exoplanet Archive), and many of them are orbiting around M-dwarf stars under **tidally-locked condition**.
- The TRAPPIST-1 system, located about 40 ly away is a fascinating discovery in the search for habitable exoplanets, which consists of seven Earth-sized planets orbiting an ultra-cool dwarf star (Gillon et al., 2017).
- The inner three planets, TRAPPIST-1b, c, and d, are on the inner edge of the habitable zone and may have experienced water loss due to a runaway greenhouse effect, and the outer planets, TRAPPIST-1f, g, and h, could be in a snowball state due to their position and low geothermal heat flux.

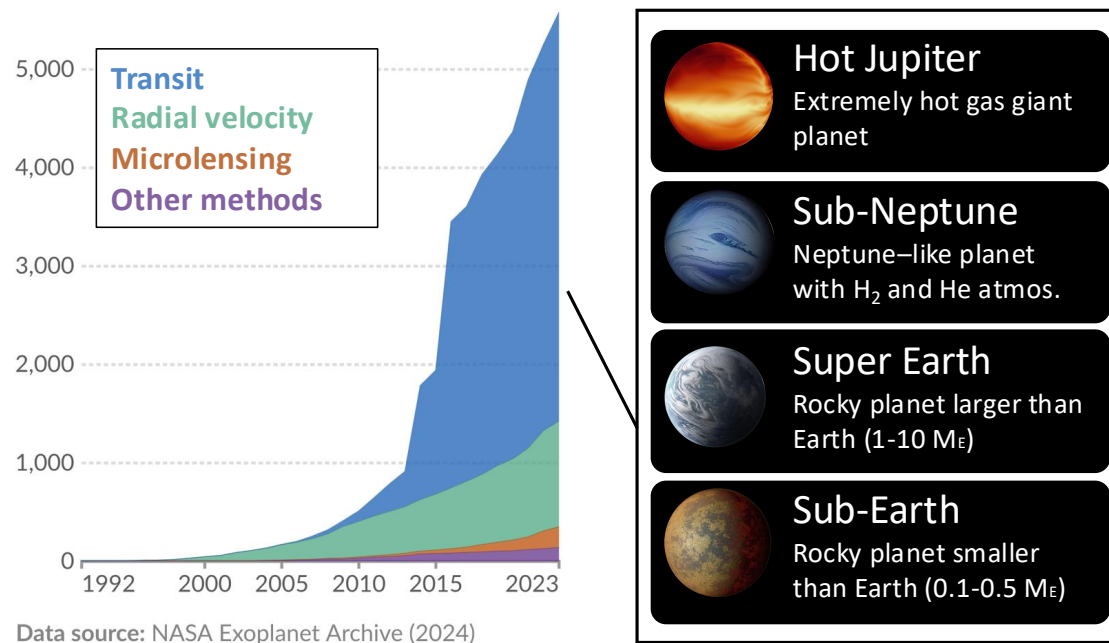


Fig. Number of confirmed exoplanets, and types of exoplanets

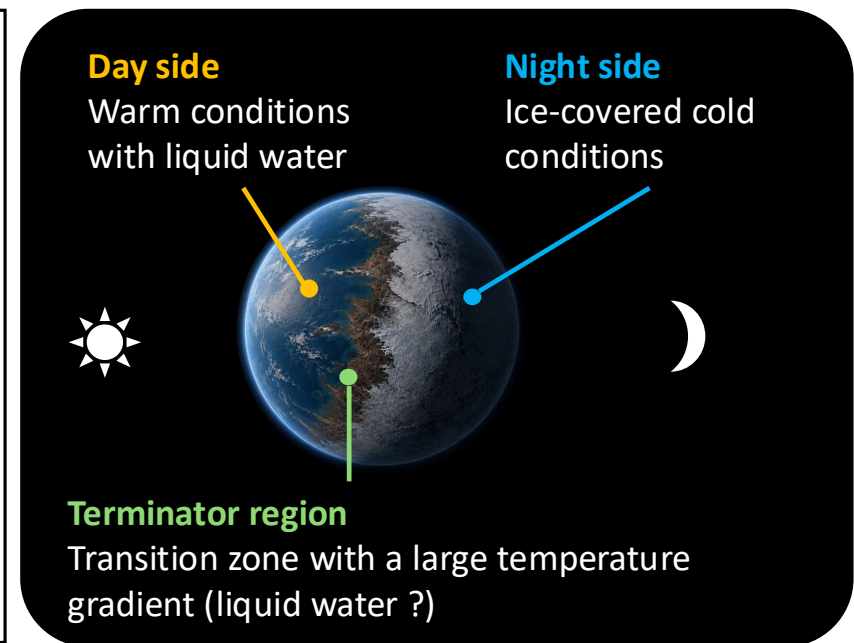


Fig. Illustration of tidally locked TRAPPIST-1e.

TRAPPIST-1e is key target for understanding tidally locked rocky planets in the habitable zone and is one of the most promising candidates for habitability.

Previous TRAPPIST-1e GCM Studies

- In the **Trappist Habitable Atmosphere Intercomparison (THAI) project** (Fauchez et al., 2020), several different GCMs (ExoCAM, LMD-G, ROCKE-3D, and UM) simulate the climate of TRAPPIST-1e to provide a reference for evaluating TRAPPIST-1e climate prediction.
- According to Sergeev et al. (2022) for aqua planet condition (Hab1 & Hab2),
 - For Hab1 (1 bar of N_2 + 400 ppm of CO_2), the global mean temperature is approximately 240-250 K. There is a significant temperature gradient between day and nightside due to inactive energy cycle.
 - For Hab2 (1 bar of CO_2), the global mean temperature is around 270-290 K, and there is a small temperature difference between dayside and nightside, and active day/night energy cycle.

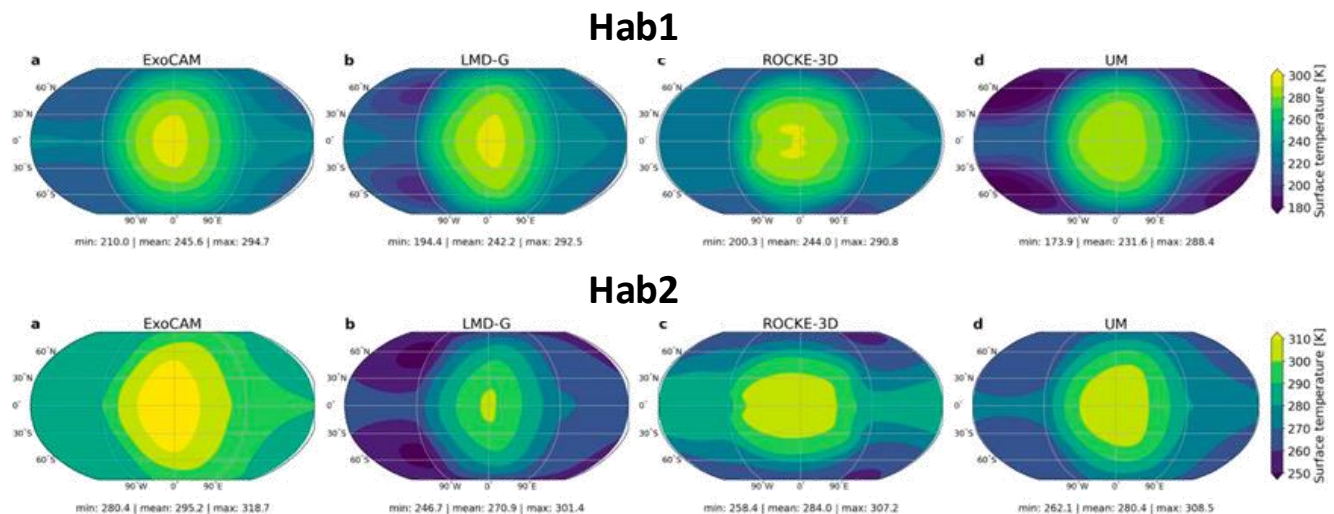
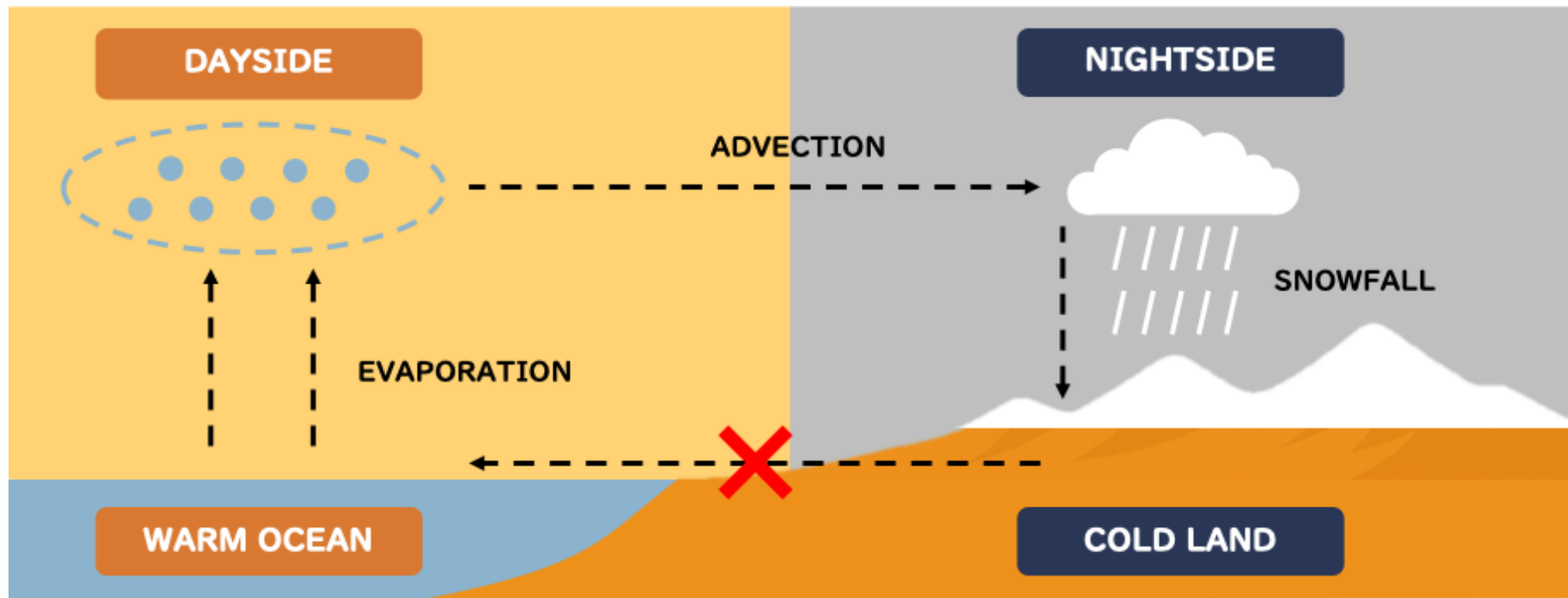


Fig. Time-mean surface temperature (K) for Hab1 and Hab2 cases [Sergeev et al., 2022].

Previous TRAPPIST-1e GCMs have mainly focused on atmospheric circulation, clouds, precipitation, surface temperature, and surface liquid water distribution.

Water Cycle on Tidally-locked Planets EARTH-LIFE SCIENCE INSTITUTE

- Such previous GCM studies for tidally-locked rocky planets have led to the idea that **if TRAPPIST-1e has dayside ocean and nightside land, all the water on the dayside evaporates and is finally transported to nightside and accumulated.**



What level of geothermal heat flux is needed to maintain an active water cycle on TRAPPIST-1e, despite the dayside evaporation and night side snow accumulation?



To understand such global water cycle, it is necessary to consider the full water cycle between atmosphere, ocean and land surface, including river and ice sheet.

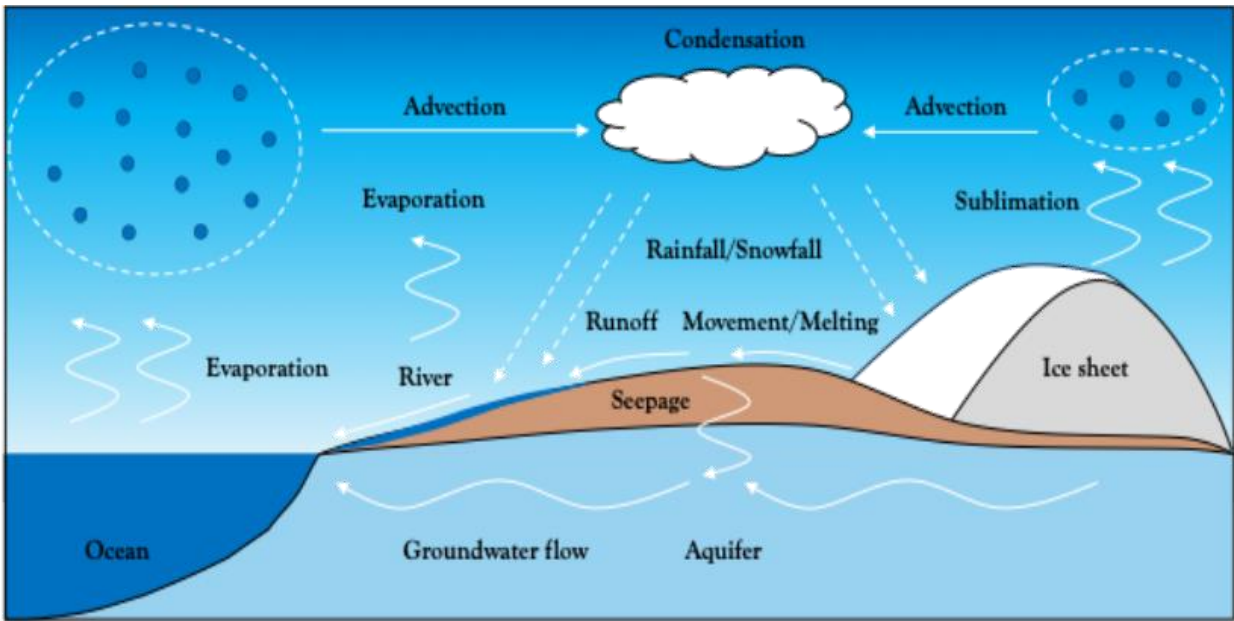


Fig. A schematic diagram of the water cycle in the coupled global climate model.

Table. The model settings in this study.

Parameter	Value
Star and spectrum	2600 K BT-Settl with Fe/H = 0
Semimajor axis	0.02925 au
Orbital periods	6.1 days
Obliquity	0
Eccentricity	0
Insolation	879.0 W/m ²
Planet radius	5868 km
Gravity	8.01 m s ⁻²
Atmosphere	1 bar N ₂ + 400 ppm CO ₂
Resolution	T21 x L28 (~80 km)

Atmosphere

- Circulation
- Condensation
- Rainfall/snowfall
- Radiative transfer
- Diffusion

Ocean

- Slab ocean (100m)
- Energy balance
- Water evaporation
- Sea ice formation
- Sea level adjustment

River

- Energy balance
- River routing
- Water evaporation
- River ice formation
- River inflow to ocean

Groundwater

- Energy balance
- Saturate flow
- Unsaturated flow
- Freeze/thaw cycle
- Recharge/discharge

Ice sheet

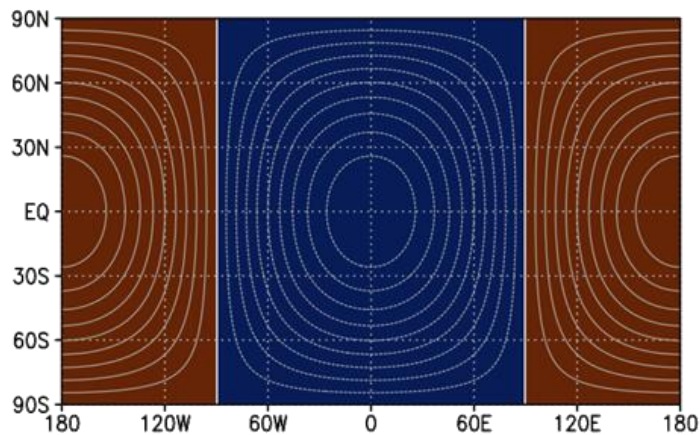
- Energy balance
- Temperate ice flow
- Cold ice deformation
- Subglacial melting
- Isostasy

The model fully couples the global water cycle between atmosphere, ocean, rivers, groundwater, and ice sheets, and calculates over a period of ~ 10⁴ years.

Global climate and water cycle model

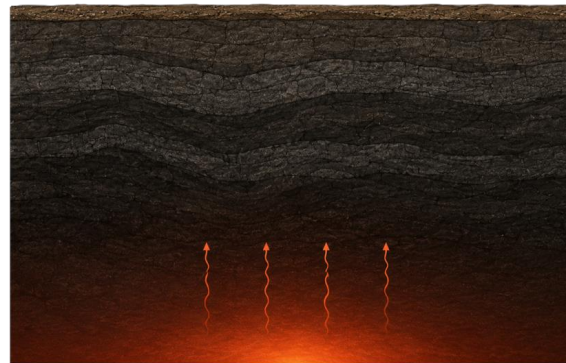
Topography

Dayside ocean / nightside land
-1000 m ~ +1000 m topography

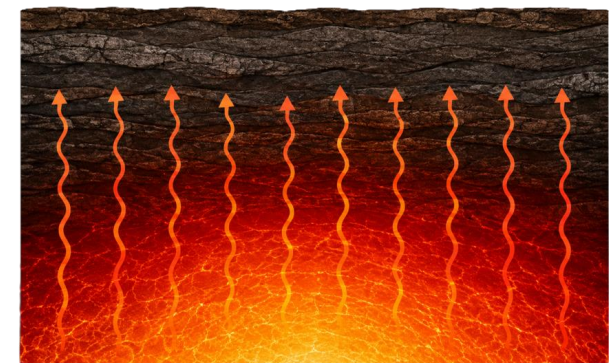


Geothermal heat flux (GHF)

1 Low GHF (150 mW/m²)

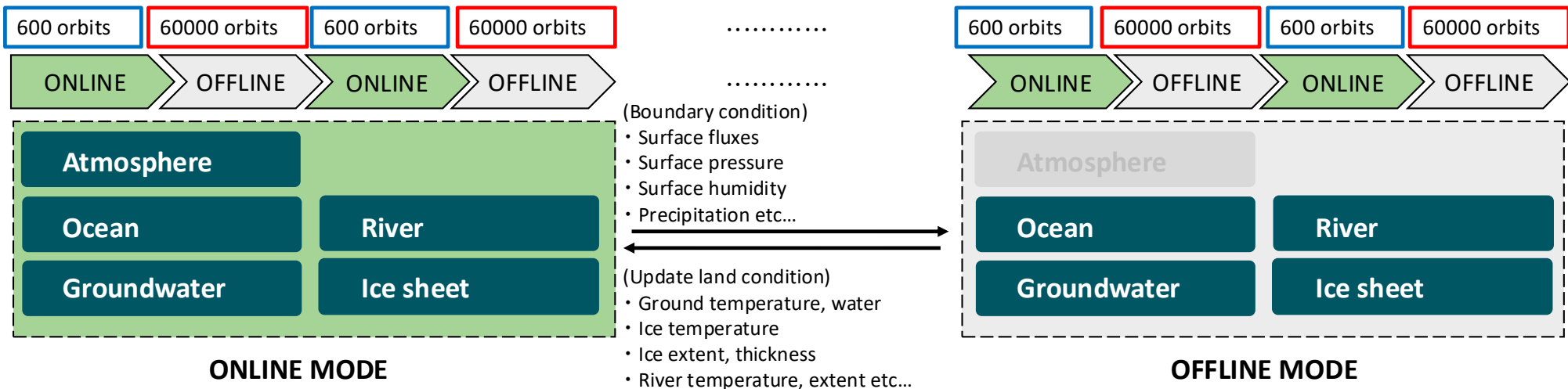


2 High GHF (500 mW/m²)



※130-510 mW/m² [Bolmont et al., 2026]

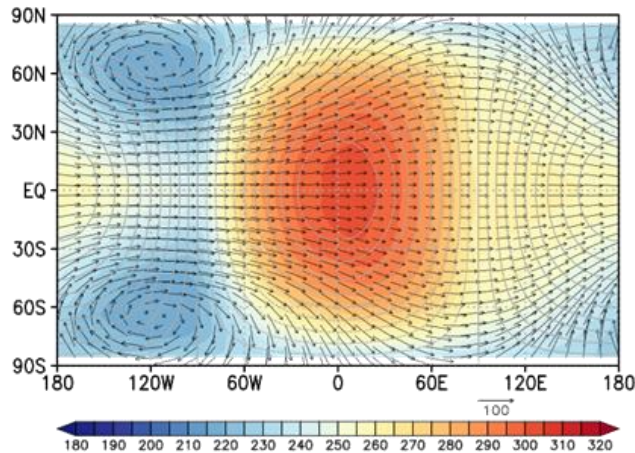
Time integration scheme for 10000 yr calculation



Atmospheric conditions (~0 yr)

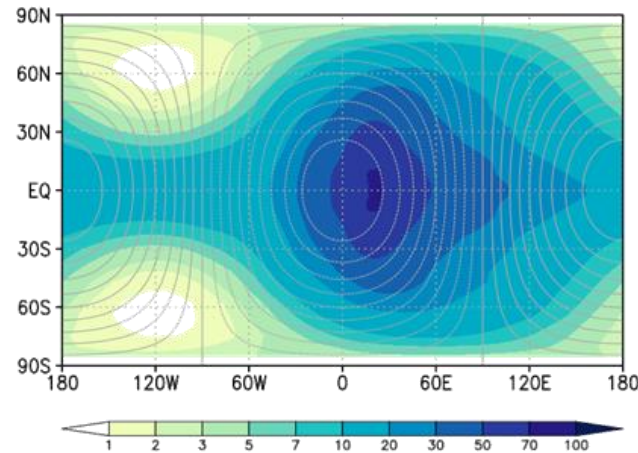
GHF of 150 mW/m²

Temperature [K] and wind [m/s]



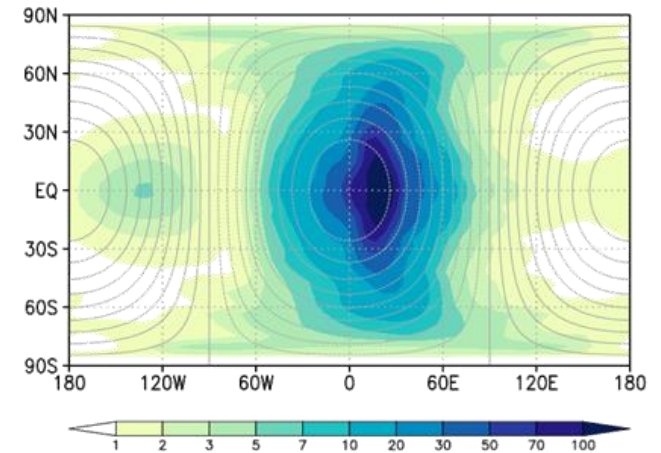
Min: 215 | Mean: 260 | Max: 302 (K)

Water vapor column [mm]



Min: 0.7 | Mean: 19.4 | Max: 71.4 (mm)

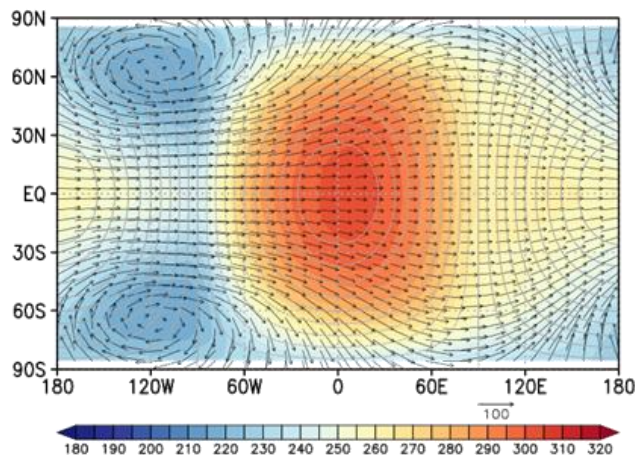
Water cloud column [$\times 10^{-5}$ m]



Min: 0.5 | Mean: 9.4 | Max: 151 ($\times 10^{-5}$ m)

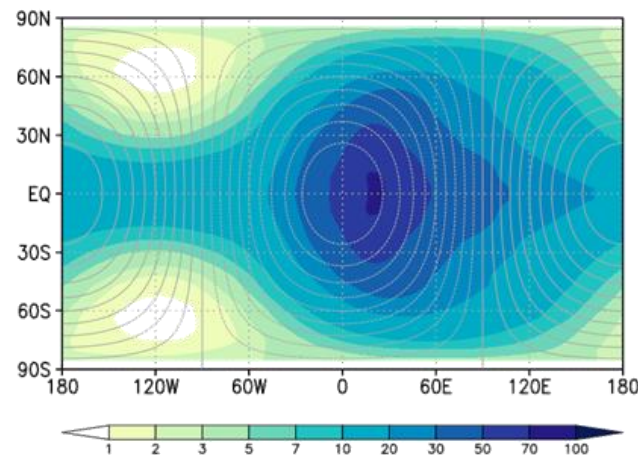
GHF of 500 mW/m²

Temperature [K] and wind [m/s]



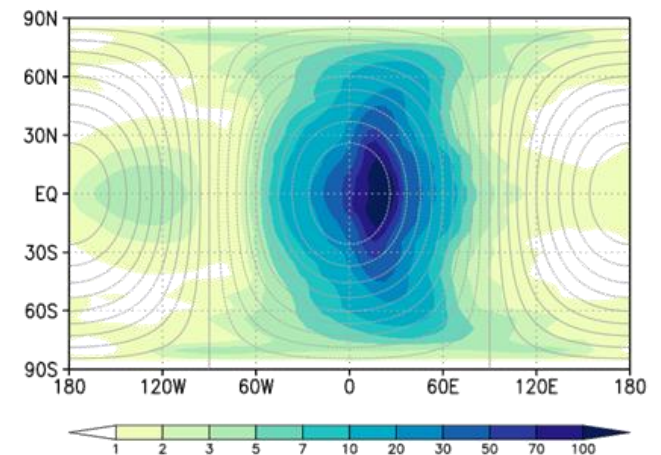
Min: 215 | Mean: 261 | Max: 302 (K)

Water vapor column [mm]



Min: 0.7 | Mean: 19.7 | Max: 71.6 (mm)

Water cloud column [$\times 10^{-5}$ m]

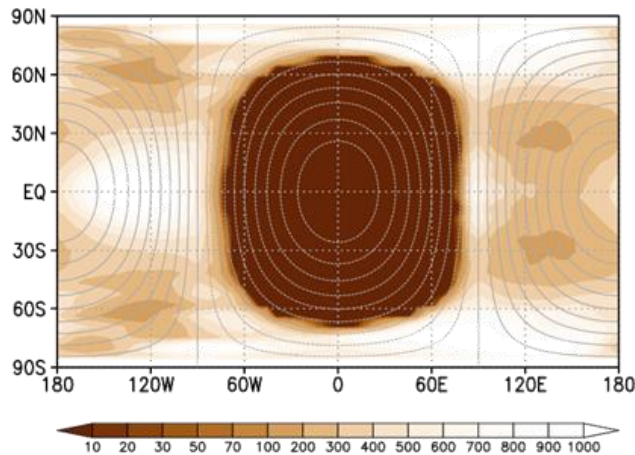


Min: 0.6 | Mean: 9.4 | Max: 152 ($\times 10^{-5}$ m)

Ice sheet/River (~10000 yr)

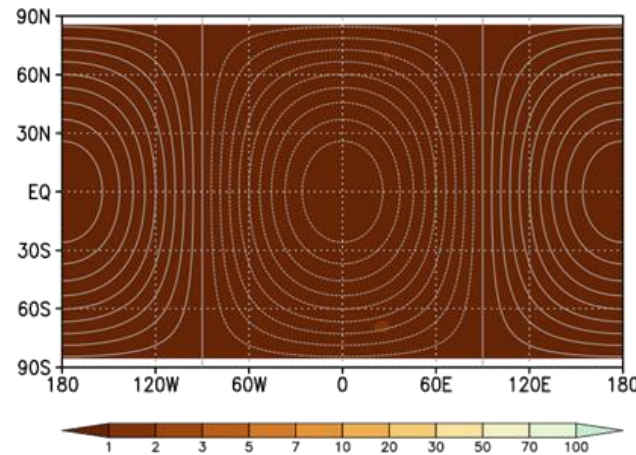
GHF of 150 mW/m²

Ice sheet thickness [m]



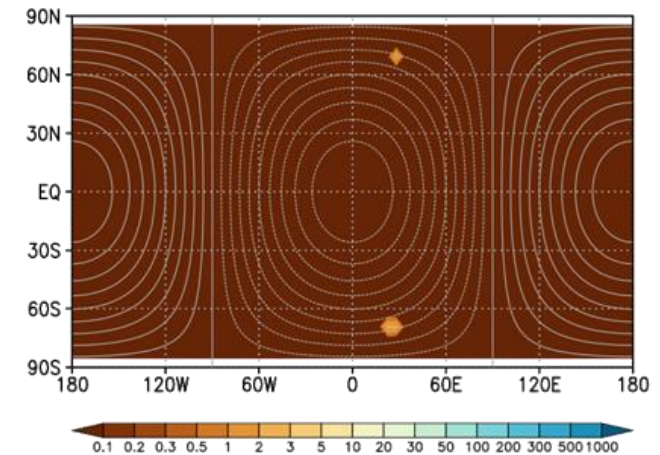
Min: 0.0 | Max: 1440 (m)

Annual subglacial melting [mm/yr]



Min: 0.0 | Mean: 0.0 | Max: 2.1 (mm/yr)

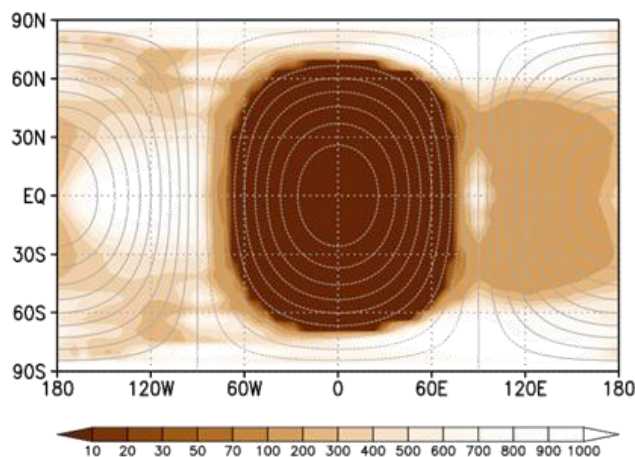
River discharge [mm/yr]



Min: 0.0 | Mean: 0.0 | Max: 2.3 (mm/yr)

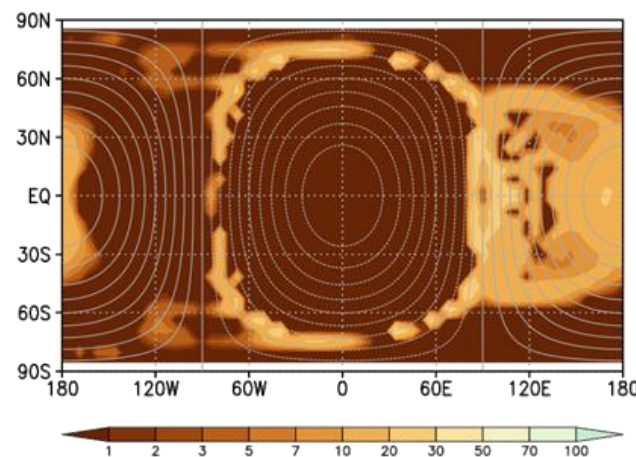
GHF of 500 mW/m²

Ice sheet thickness [m]



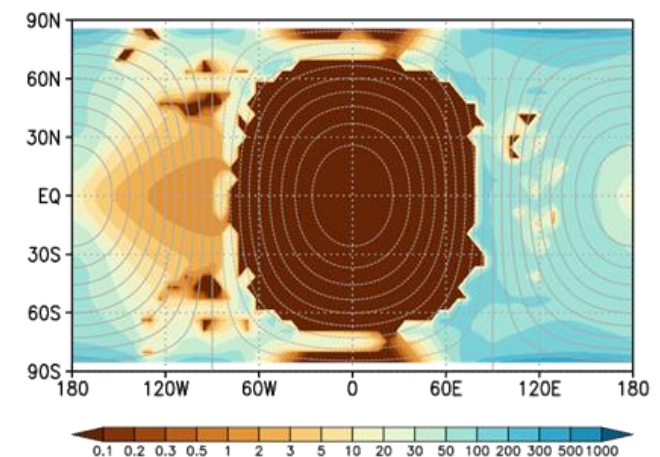
Min: 0.0 | Max: 1630 (m)

Annual subglacial melting [mm/yr]



Min: 0.0 | Mean: 3.7 | Max: 35.1 (mm/yr)

River discharge [mm/yr]

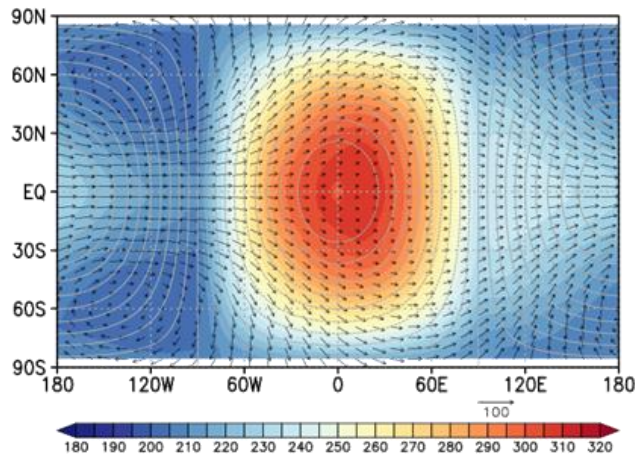


Min: 0.0 | Mean: 26.3 | Max: 413 (mm/yr)

Atmospheric conditions (~10000 yr)

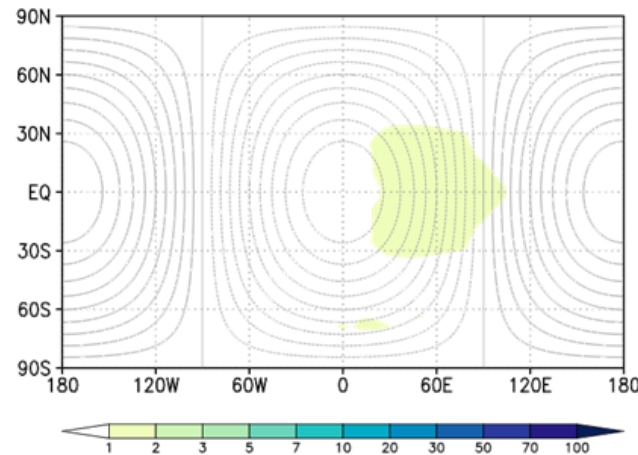
GHF of 150 mW/m²

Temperature [K] and wind [m/s]



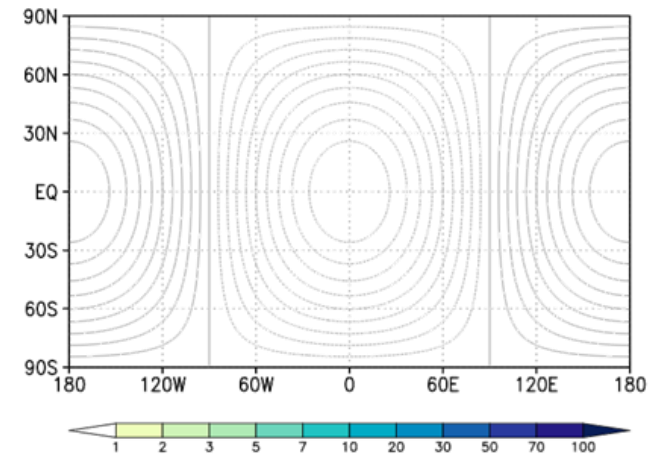
Min: 200 | Mean: 243 | Max: 310 (K)

Water vapor column [$\times 10^{-3}$ m]



Min: 0.3 | Mean: 0.7 | Max: 1.3 ($\times 10^{-3}$ m)

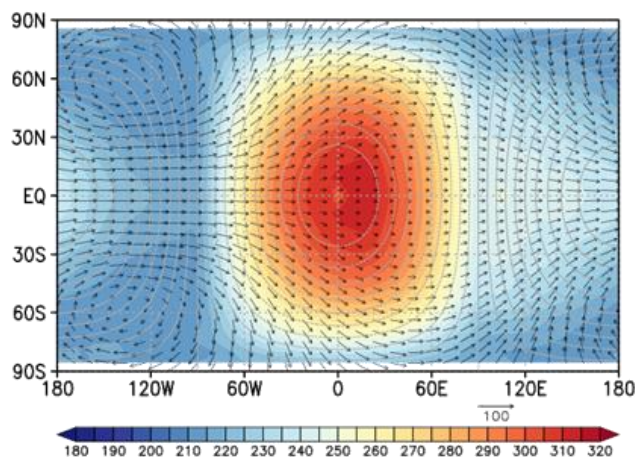
Water cloud column [$\times 10^{-5}$ m]



Min: 0.0 | Mean: 0.2 | Max: 0.9 ($\times 10^{-5}$ m)

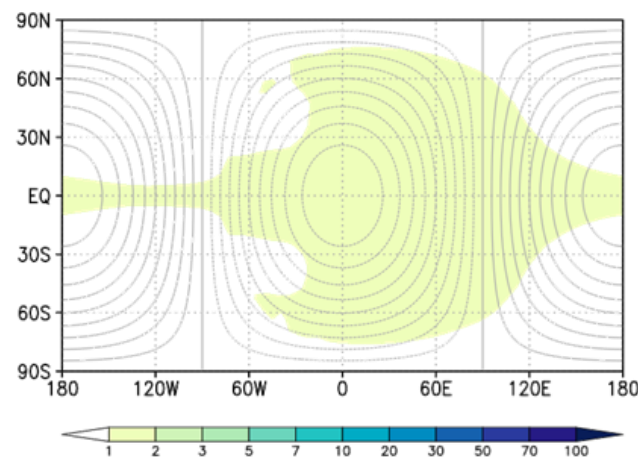
GHF of 500 mW/m²

Temperature [K] and wind [m/s]



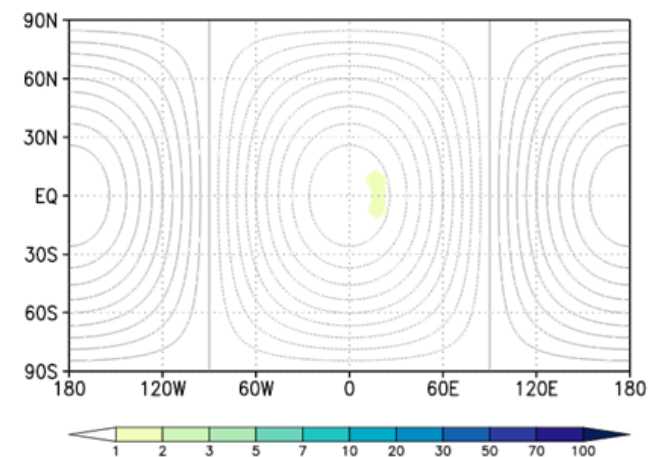
Min: 211 | Mean: 248 | Max: 312 (K)

Water vapor column [$\times 10^{-3}$ m]



Min: 0.4 | Mean: 1.0 | Max: 1.9 ($\times 10^{-3}$ m)

Water cloud column [$\times 10^{-5}$ m]

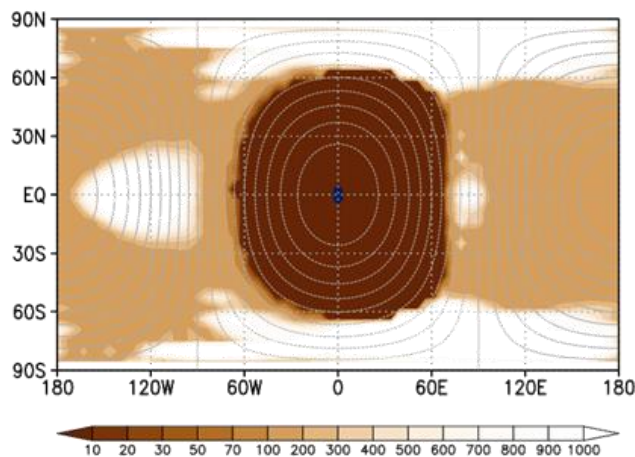


Min: 0.0 | Mean: 0.3 | Max: 1.4 ($\times 10^{-5}$ m)

Effect of geothermal heat flux

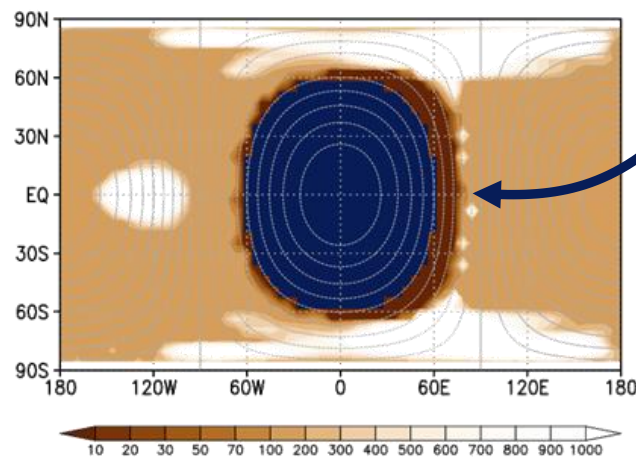
Ice sheet thickness [m]

GHF = 2000 mW/m²



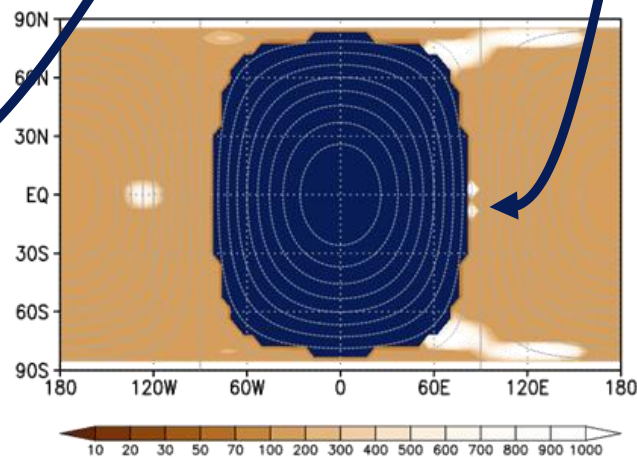
Min: 0.0 | Max: 2890 (m)

GHF = 3000 mW/m²



Min: 0.0 | Max: 2820 (m)

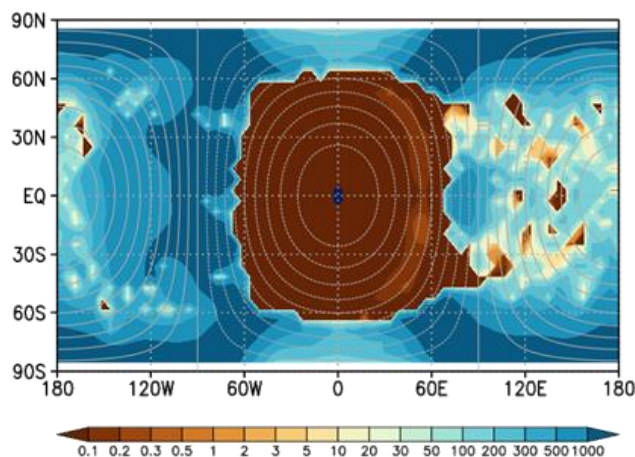
GHF = 5000 mW/m²



Min: 0.0 | Max: 1600 (m)

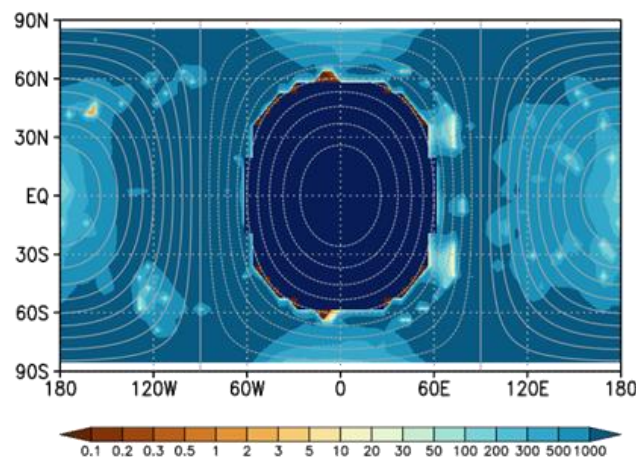
River discharge [mm/yr]

GHF = 2000 mW/m²



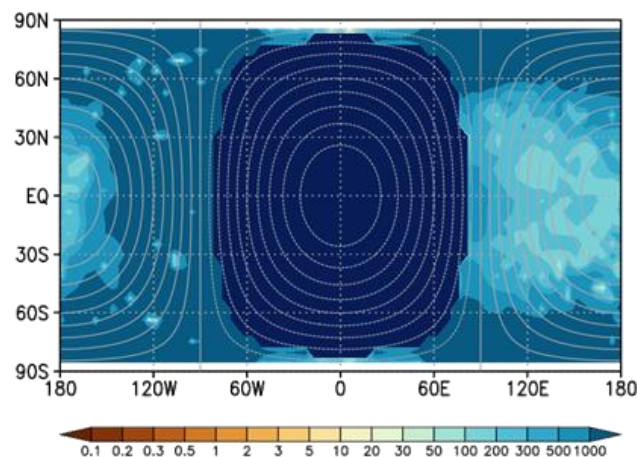
Min: 0 | Mean: 394 | Max: 5900 (mm/yr)

GHF = 3000 mW/m²



Min: 0 | Mean: 1000 | Max: 12700 (mm/yr)

GHF = 5000 mW/m²



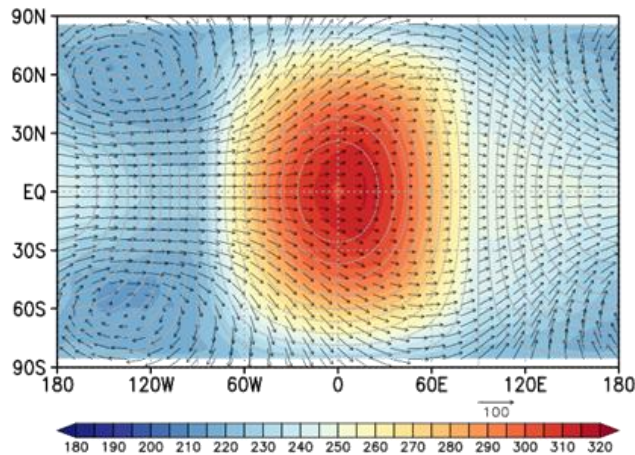
Min: 0 | Mean: 753 | Max: 14900 (mm/yr)

OCEAN

Effect of geothermal heat flux

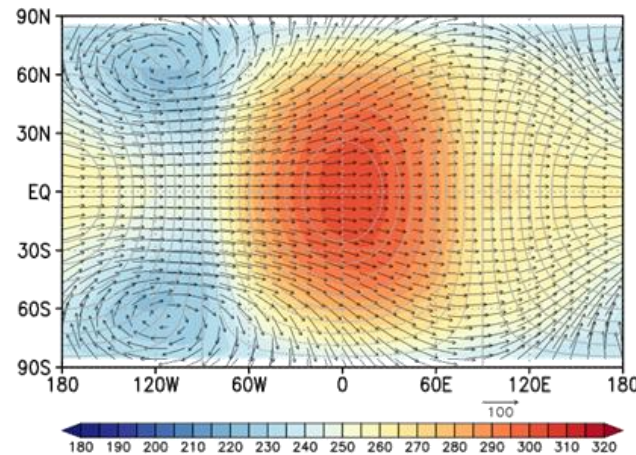
Temperature [K] and wind [m/s]

GHF = 2000 mW/m²



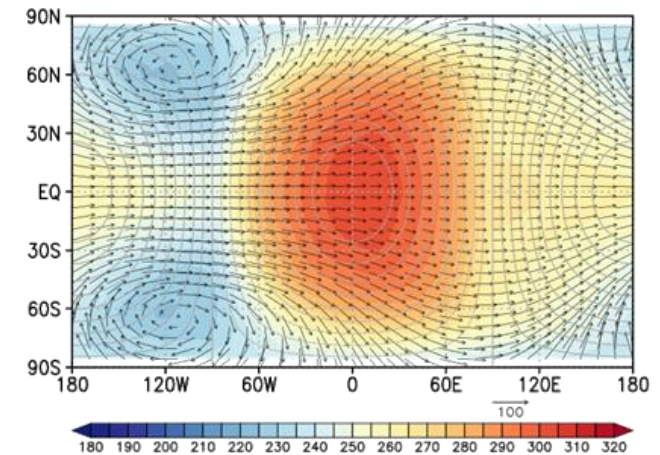
Min: 211 | Mean: 253 | Max: 315 (K)

GHF = 3000 mW/m²



Min: 223 | Mean: 264 | Max: 303 (K)

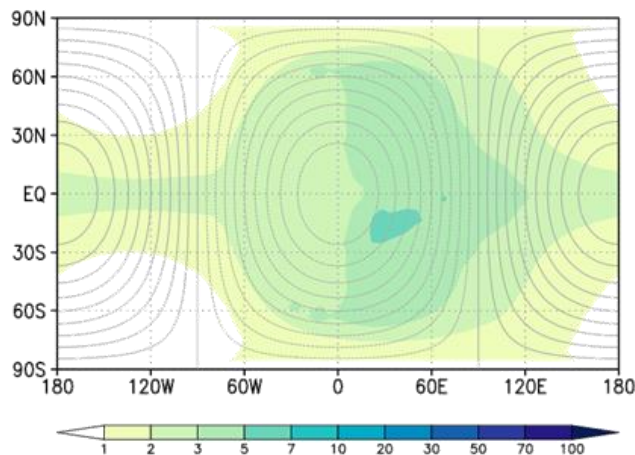
GHF = 5000 mW/m²



Min: 223 | Mean: 264 | Max: 303 (K)

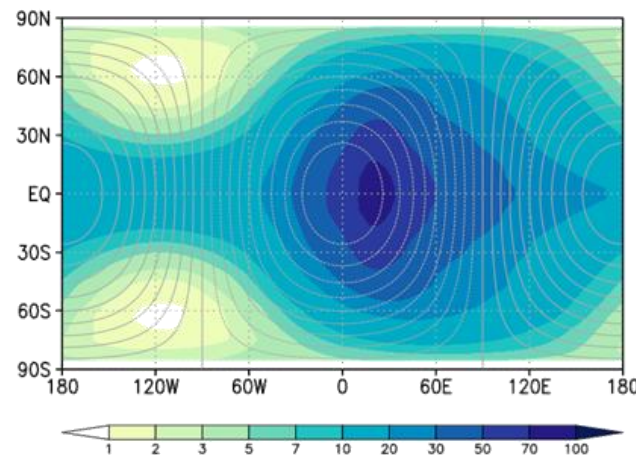
Water vapor column [mm]

GHF = 2000 mW/m²



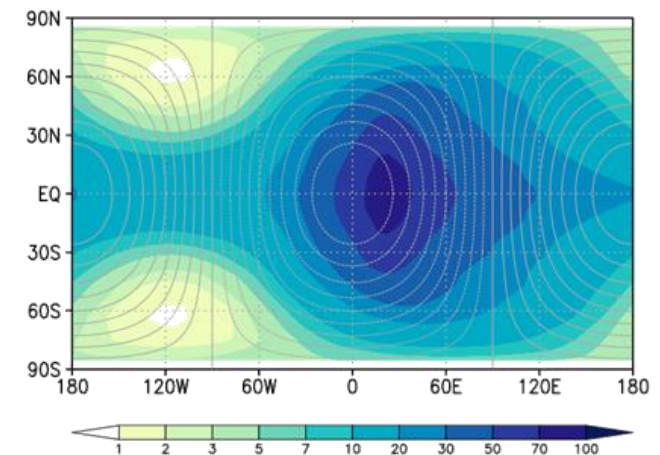
Min: 0.4 | Mean: 2.2 | Max: 5.2 (mm)

GHF = 3000 mW/m²



Min: 0.8 | Mean: 21.0 | Max: 75.4 (mm)

GHF = 5000 mW/m²

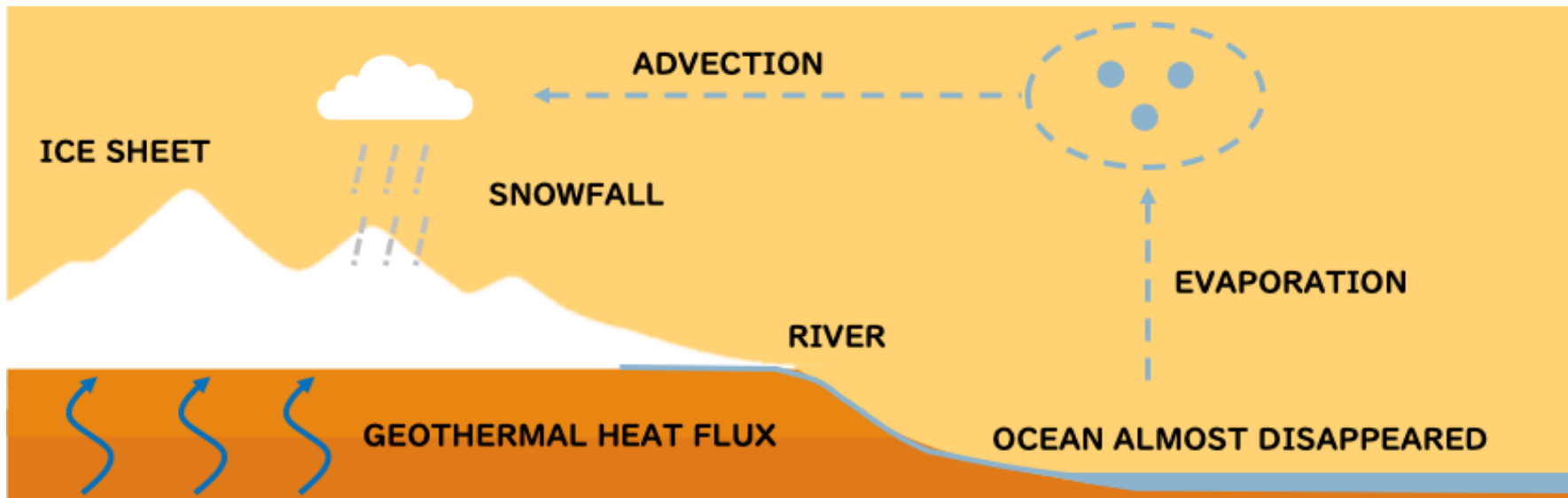


Min: 0.9 | Mean: 22.3 | Max: 78.5 (mm)

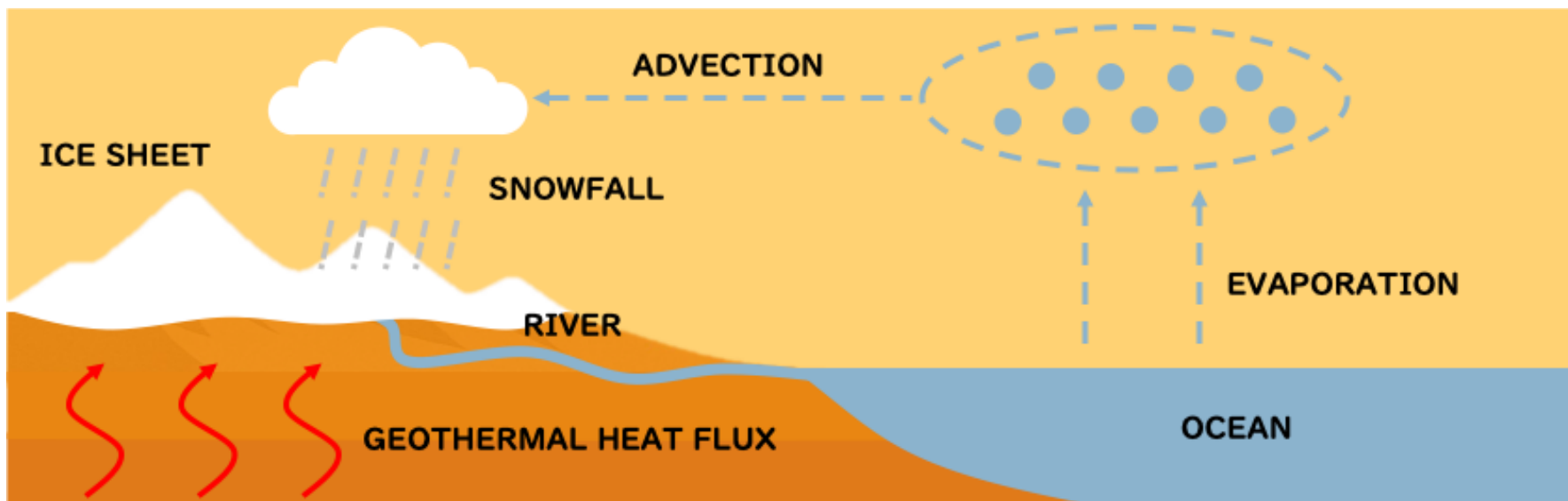
Water Cycle on Tidally-locked Planets EARTH-LIFE SCIENCE INSTITUTE

Weak geothermal heat flux

Geothermal heat flux $\ll 3000 \text{ mW/m}^2$

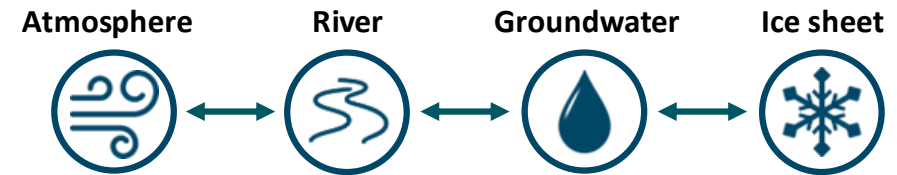


Strong geothermal heat flux



Summary

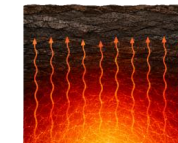
- 1** We applied a coupled global climate, river, groundwater, and ice sheet model to TRAPPIST-1e simulations.



- 2** Geothermal heat change nightside water cycle:
150 mW/m²: Little meltwater and rivers.
500 mW/m²: Much meltwater creates rivers.



Geothermal heat
flux of 150
mW/m²



Geothermal
heat flux of
500 mW/m²

- 3** Geothermal heat control global water cycle:
GHF << 3000 mW/m²: Losing dayside ocean.
GHF > 3000 mW/m²: Maintaining dayside ocean.



Geothermal heat
flux << 3000
mW/m²



Geothermal heat
flux > 3000
mW/m²

- ✓ TRAPPIST-1e might not be able to maintain dayside ocean assuming realistic GHF when initial global water mass is relatively small (A GHF of over 3,000 mW/m² is required, but this is 6 times the maximum estimated GHF of TRAPPIST-1e).
- ✓ Long-term habitability for tidally-locked planet should be evaluated as coupled redistribution of water among atmos., ocean, river, groundwater, and ice sheet.
- ✓ Although HWO's observational targets are planets orbiting around G-type stars, the absence of clouds or water vapor, or the lack of oceans, does not necessarily mean that liquid water cannot exist on a planet (subglacial water).

The Detectability of Escaping Atmosphere from Terrestrial Exoplanets in Runaway Greenhouse State by Ultraviolet Transit Spectroscopy

Lead author: Ryuga Kato

Abstract: Water-rich terrestrial planets orbiting inside the inner edge of the habitable zone are expected to be in a runaway greenhouse state. In a runaway greenhouse state, the surface oceans evaporate entirely, leading to the formation of a water-vapor atmosphere. Hydrogen and oxygen atoms produced by the photodissociation of water vapor are expected to undergo hydrodynamic escape. The shape of transmission spectra reflects the upper-atmospheric structure, providing direct insights into the atmospheric mass-loss rate and outflow velocity. Therefore, the Habitable Worlds Observatory (HWO) is expected to constrain the atmospheric compositions of terrestrial planets and enhance our understanding of their water loss processes through ultraviolet transit spectroscopy.

Studies of close-in gas giants predict that upper-atmospheric structure depends on the intensities of stellar emission lines and XUV (X-ray and extreme-ultraviolet) radiation. Understanding the upper-atmospheric structure is essential for assessing detectability. However, theoretical studies of the upper-atmospheric structure in the ultraviolet (UV) environments around the habitable zone are scarce, and our understanding remains insufficient. Therefore, investigating the upper-atmospheric structure of terrestrial planets under various UV environments is necessary for future observational missions.

In this study, we performed upper-atmospheric simulations using a three-dimensional particle model, assuming hypothetical Earth-mass and Earth-radius planets with water-vapor atmospheres orbiting sub-solar-mass stars. In these simulations, we examined a range of orbits from the runaway greenhouse limit to 20 times the Earth's insolation. Our model considers stellar and planetary gravity, radiation pressure, and photoionization. Even in the environment most favorable for increasing the line-of-sight velocity, the resulting velocity is still insufficient to avoid ISM absorption. Our results reveal that hydrogen atoms are detectable under most conditions if the system radial velocity is < -20 km/s. For oxygen atoms, favorable targets include planets orbiting either small stars, which produce large transit depths, or near-solar-mass stars, where smaller transit depths are compensated by strong stellar emission. In this presentation, we will discuss detectability and upper-atmospheric structures under various ultraviolet environments.

Science Case Summary

The upper atmospheres of runaway-greenhouse terrestrial planets are detectable across diverse environments. Ly- α detection requires a system radial velocity of < -20 km/s to avoid ISM absorption. O I detection is promising around both M and K stars, as bright stellar emission could compensate for smaller transit depths.

The Detectability of Escaping Atmosphere from Terrestrial Exoplanets in Runaway Greenhouse State by Ultraviolet Transit Spectroscopy

Presenter: Ryuga Kato (Ph.D. Student) 

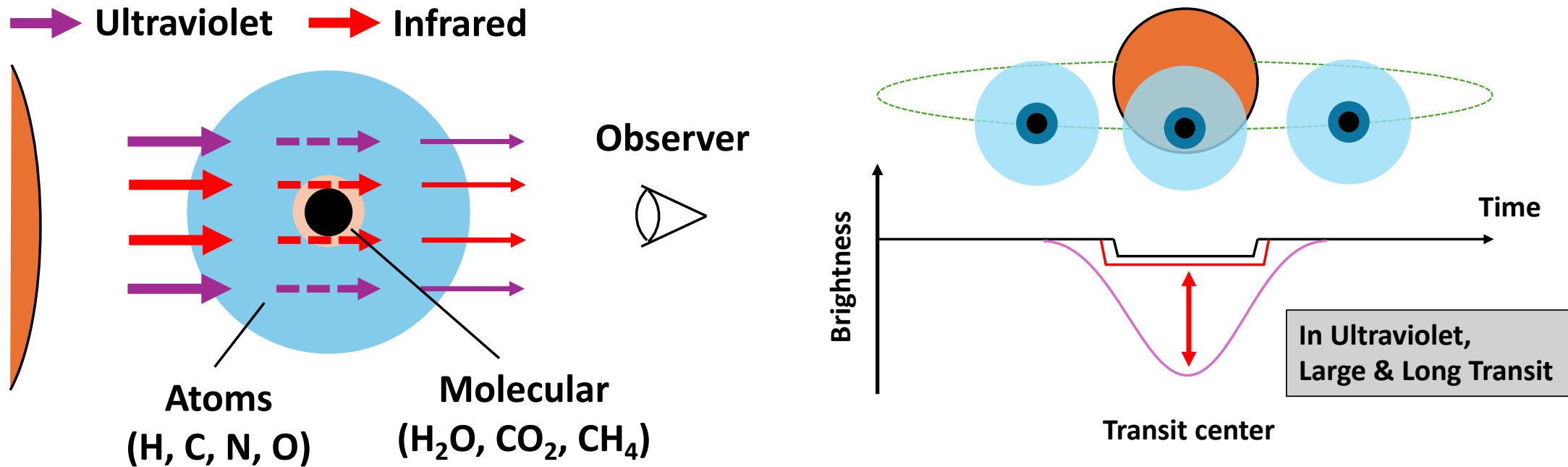
Collaborators: ¹Akifumi Nakayama², Shingo Kameda¹

¹Rikkyo University, ²Earth-Life Science Institute (ELSI)

JAXA ISAS Sagamihara campus | 16 July 2026

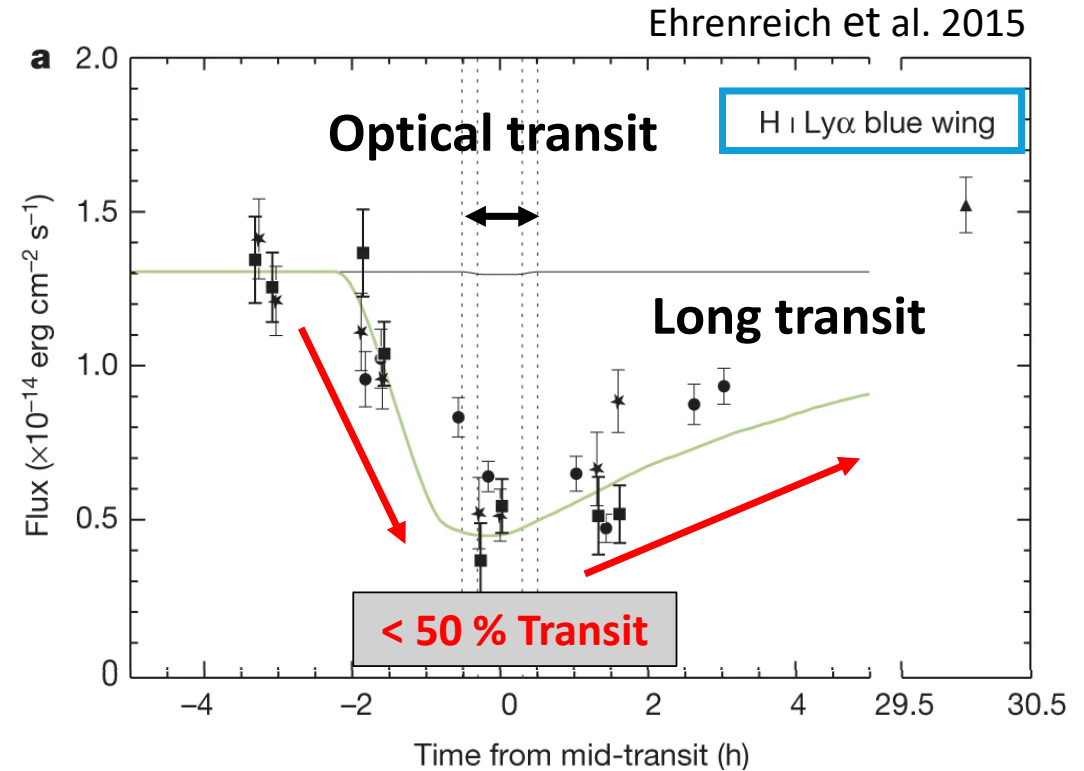
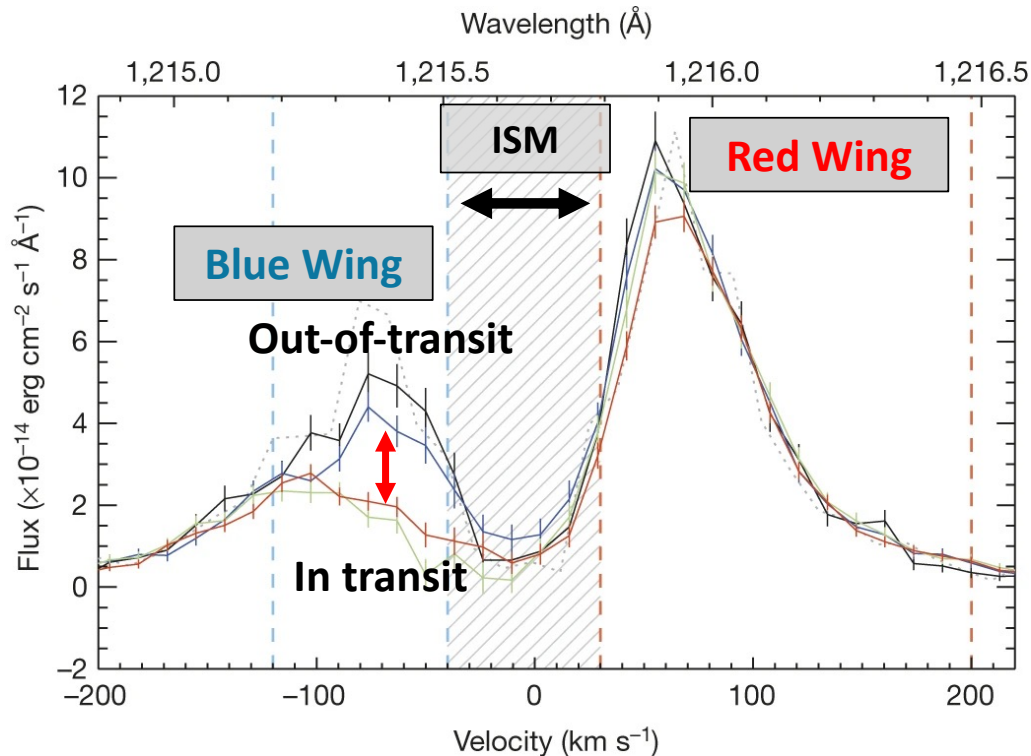
Introduction: Atmospheric Observation of Exoplanets

Transit spectroscopy provides atmospheric composition and temperature.



UV transit observations provide direct insight into atmospheric evolution!

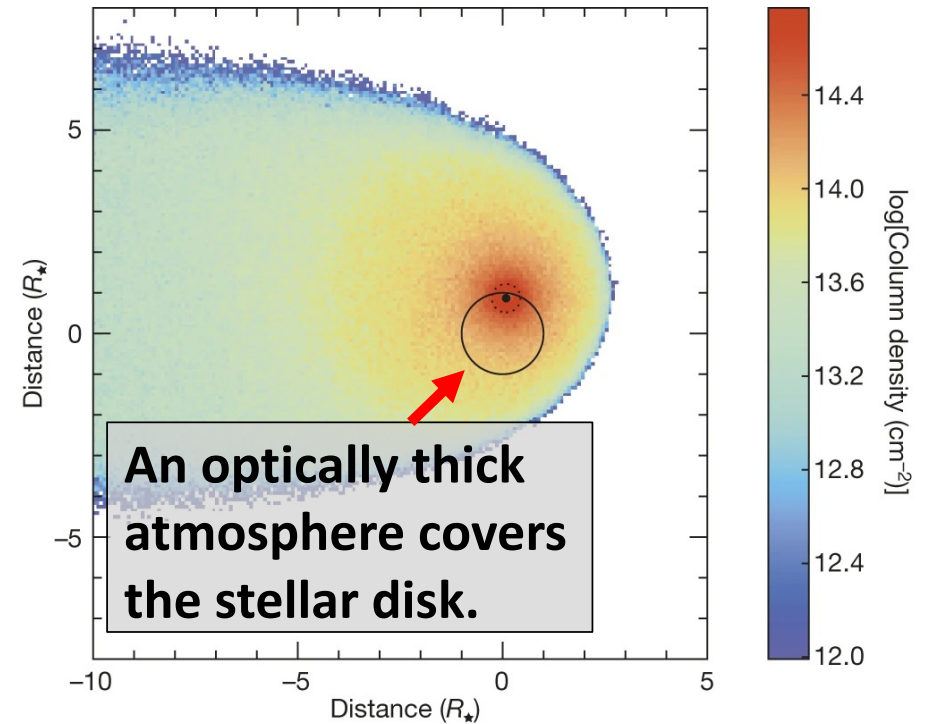
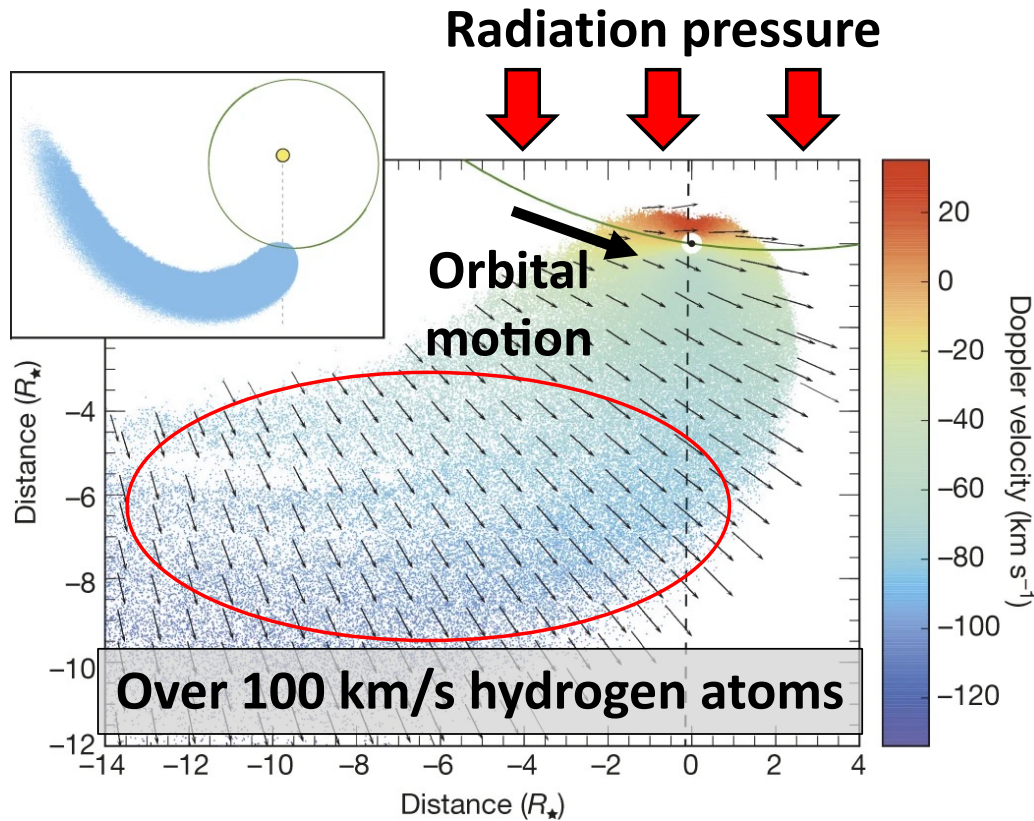
Introduction: Detection of Hydrogen Cloud in Gas Giants



The Ly- α line core is covered by the absorption of the interstellar stellar medium (ISM)

➡ Absorptions by the planetary atmosphere are **detectable only in the line wings**.

Introduction: Upper Atmospheric Structure



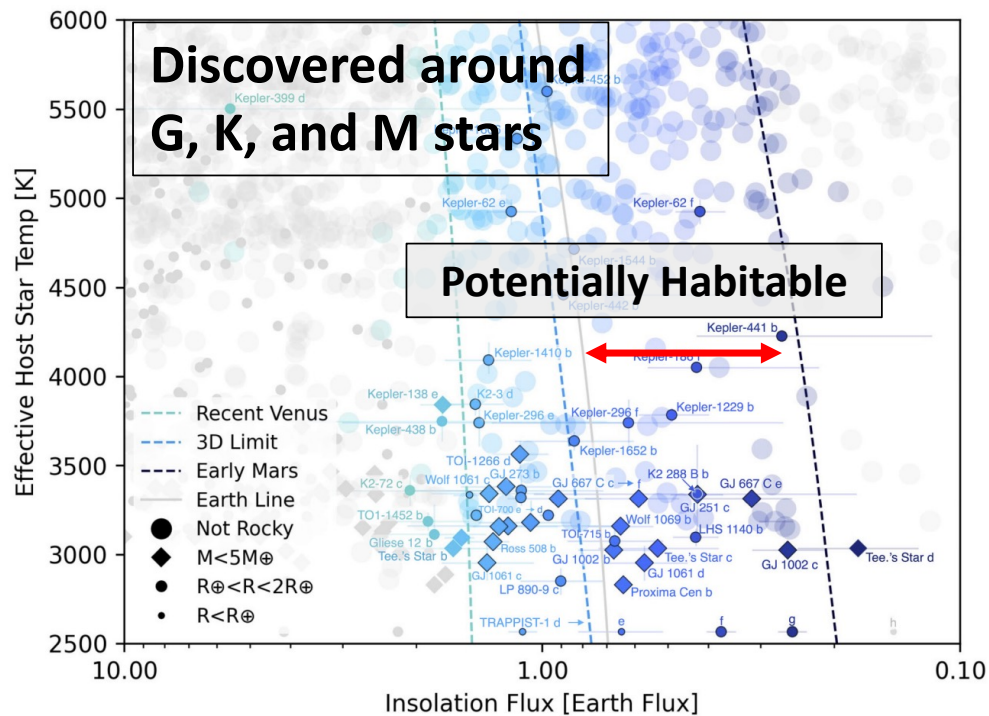
Ehrenreich et al. 2015

Line-of-sight velocity & column density are important for detectability

➡ These factors depend on **the intensity of ultraviolet radiation**

Introduction: Terrestrial Exoplanets Exploration

Many terrestrial exoplanets have been discovered around the habitable zone.



Bohl+ 2026

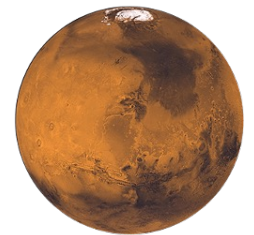
In our solar system,
planetary surface environments are different.



$T_{\text{surf}}: 750 \text{ K}$
Main
composition: CO_2



$T_{\text{surf}}: 300 \text{ K}$
Main
composition: N_2, O_2

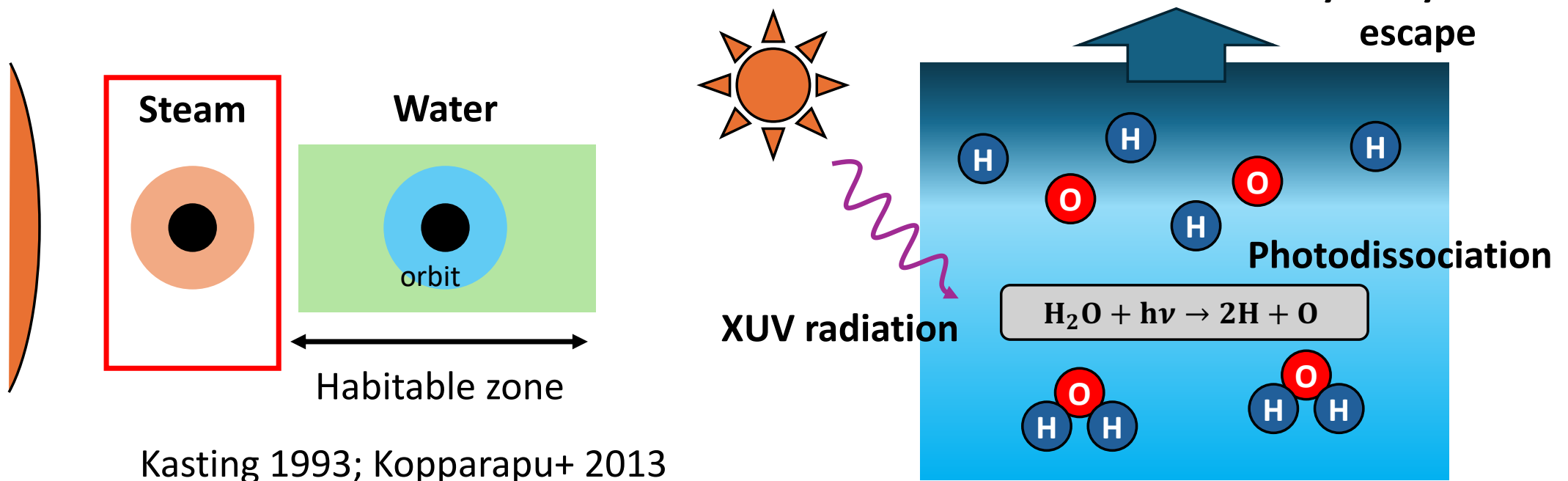


$T_{\text{surf}}: 250 \text{ K (day)}$
Main
composition: CO_2

Do they have atmospheres and liquid water on surface like current Earth ?

Introduction: Water Vapor Atmosphere

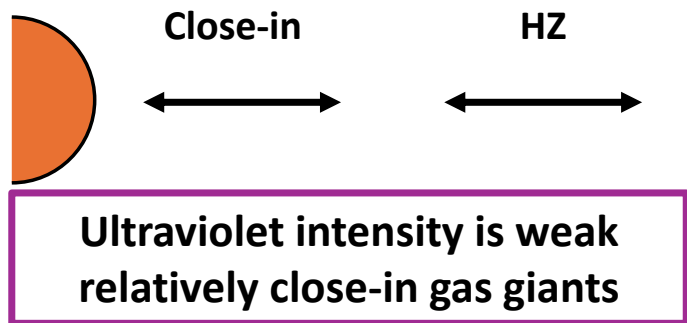
Terrestrial planets in a runaway greenhouse state



- ✓ Understanding **the water loss process** on terrestrial planets
- ✓ **Large transit depth** even Earth-sized planets

Introduction: Purpose of This Study

Are upper atmospheres detectable by the Habitable Worlds Observatory?



Hydrogen atmosphere

⇒ Mass loss rate is completely hydrogen.

H₂O atmosphere

$$\Rightarrow \dot{M}_H = \frac{2}{18} \dot{M}_{\text{tot}}, \quad \dot{M}_O = \frac{16}{18} \dot{M}_{\text{tot}}$$

Most of the mass loss rate will be Oxygen.

The escaping atmospheric composition is very different



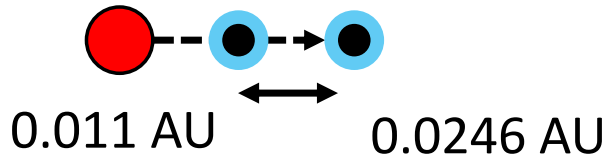
We investigate

- The upper atmospheric **structure** and **transit depth** escaping from terrestrial exoplanets in a runaway greenhouse state.
- **Detectability of hydrogen and oxygen atoms** via transit observations by the HWO.

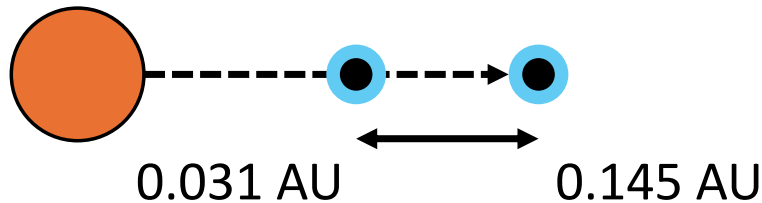
Method: Simulation Overview

$F_{\oplus}$: Current Earth insolation

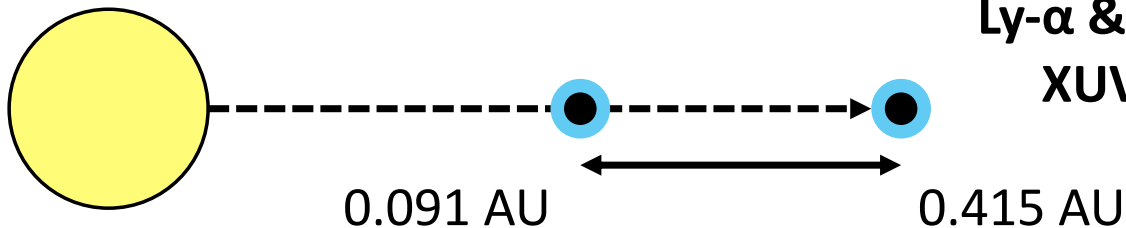
TRAPPIST-1: $0.09M_{\odot}$, $0.12R_{\odot}$



GJ163: $0.4M_{\odot}$, $0.4R_{\odot}$



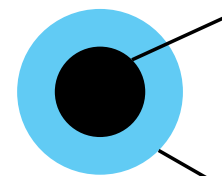
HD85512: $0.69M_{\odot}$, $0.69R_{\odot}$



- Planetary orbit

Inner Orbit: $20F_{\oplus}$ - equivalent (~ 580 K)

Outer Orbit: Runaway greenhouse limit (RGL)



Earth mass, Earth radius

Atmospheric Temperature: 10000 K

Composition: $2H + O$

Hydrodynamic escape

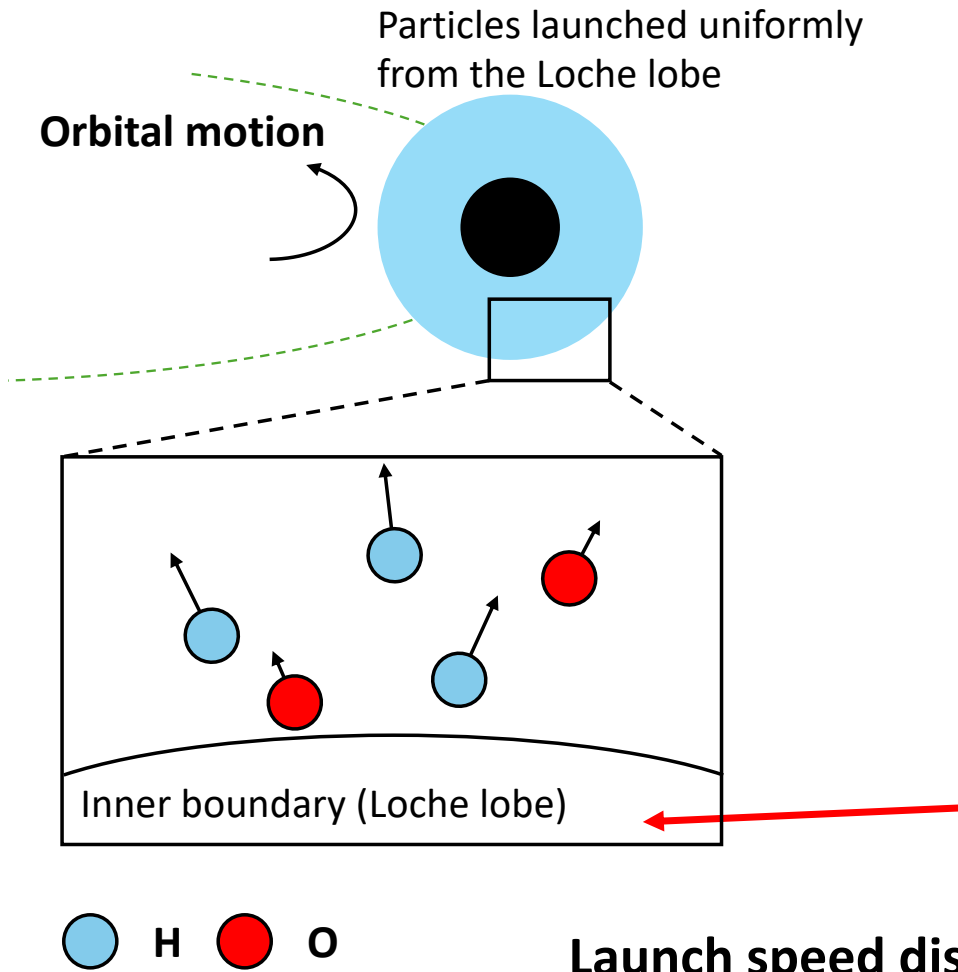
- Luminosity of

Ly- α & O I: TRAPPIST-1 < GJ163 < HD85512

XUV: HD85512 < GJ163 < TRAPPIST-1

Method: 3D Upper Atmosphere Model

We used a 3D Monte Carlo particle model based on Bourrier et al. 2013.



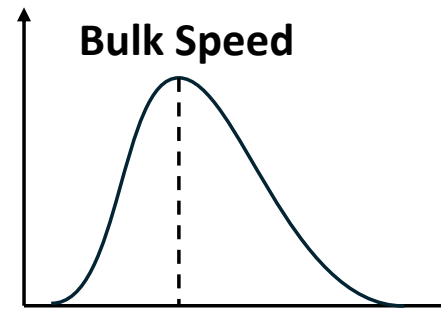
✓ Dynamics

Stellar and Planetary Gravity, Radiation Pressure

$$\frac{d^2\vec{r}}{dt^2} = -\frac{GM_S}{|\vec{r}|^3}\vec{r} - \frac{GM_P}{|\vec{r} - \vec{r}_P|^3}(\vec{r} - \vec{r}_P) - F_{\text{rad}}\frac{\vec{r}}{|\vec{r}|}$$

✓ Ionization (Photoionization)

$$n = n_0 \exp\left(-\frac{t}{t_{\text{ion}}}\right)$$



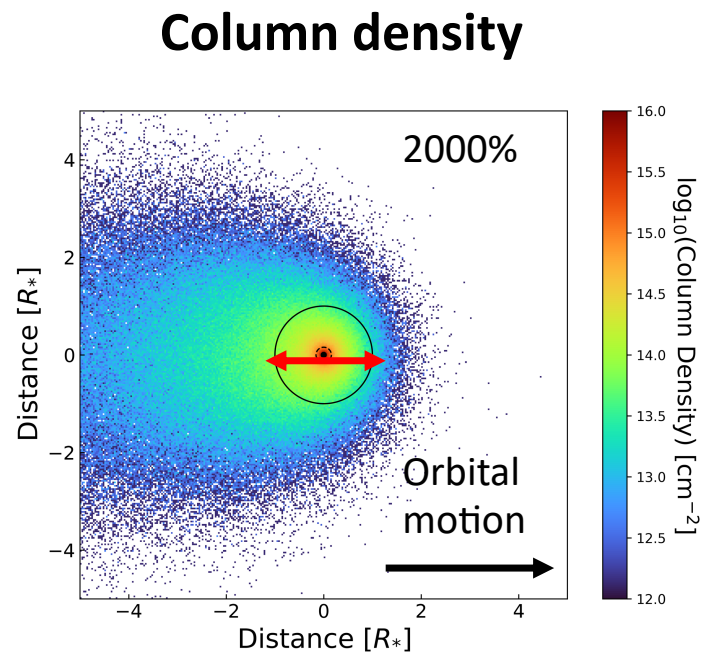
Bulk Speed + Maxwellian

✓ **Mass loss rate:**
energy-limit ($\eta = 0.1$)

Launch speed distribution is the same in all simulations

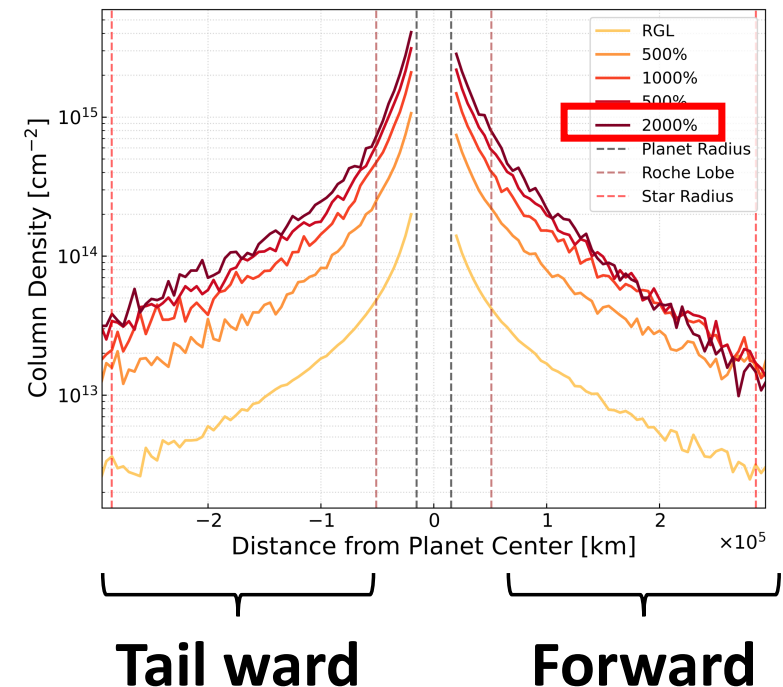
Results: Column Density Distributions

Comparison of column density distributions in each orbit (GJ163)



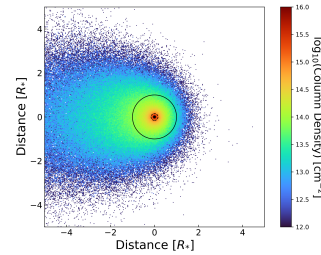
Average column density
in a vertical direction of 5 pixels

Plot of column density in the horizontal
direction of the left figure.

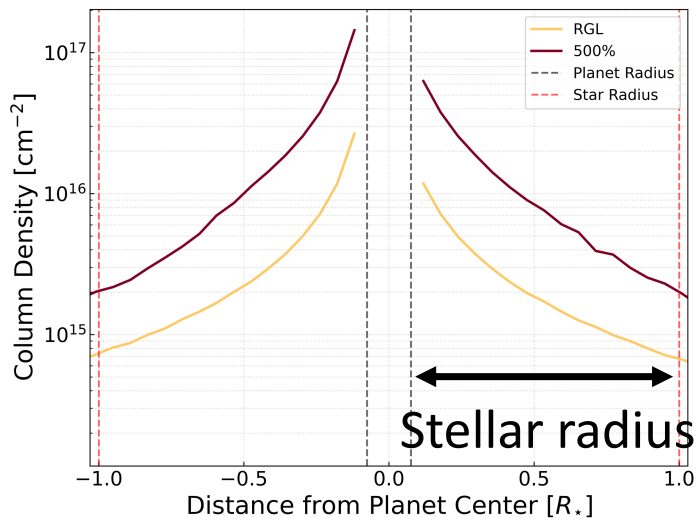


Results: Column Density Distributions (Hydrogen)

Column density distribution of hydrogen atoms in the transit center

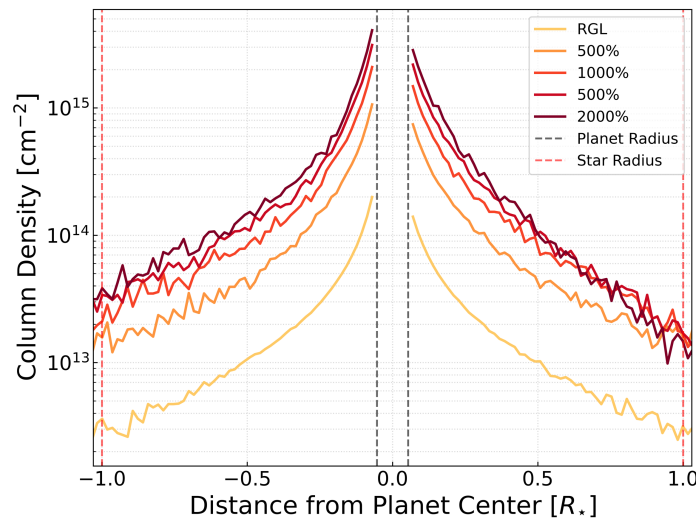


TRAPPIST-1



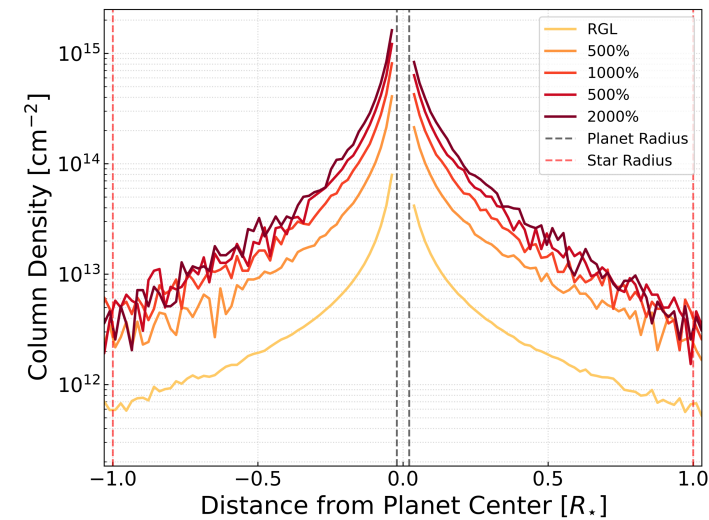
540 – 2980 XUV

GJ163



15 – 320 XUV

HD85512



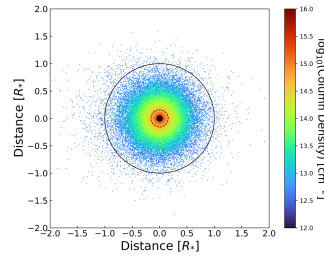
4 – 85 XUV

Star dependence: **TRAPPIST-1 > GJ163 > HD85512** (XUV Intensity Order)

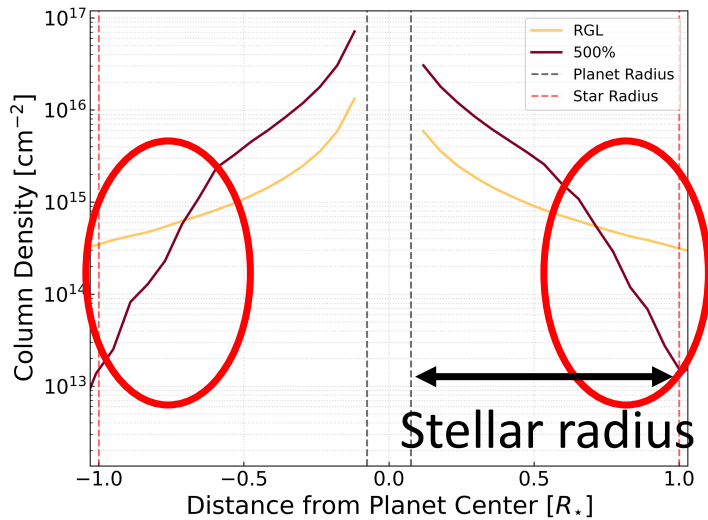
Orbit dependence: The column density increases as the radiation intensity increases.

Results: Column Density Distributions (Oxygen)

Column density distribution of oxygen atoms in the transit center

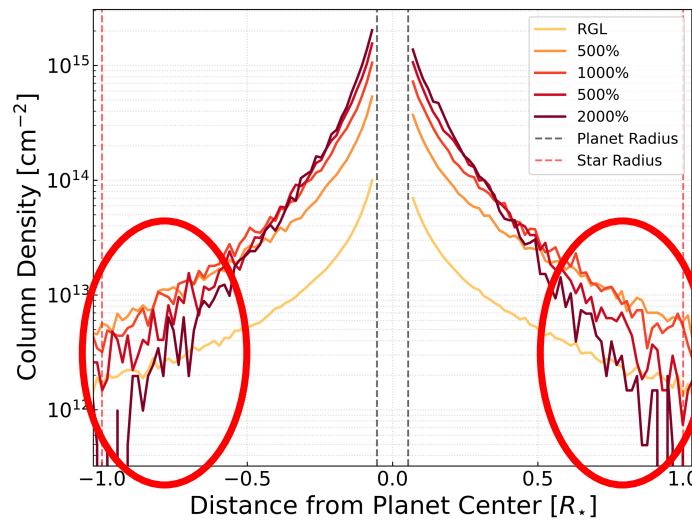


TRAPPIST-1



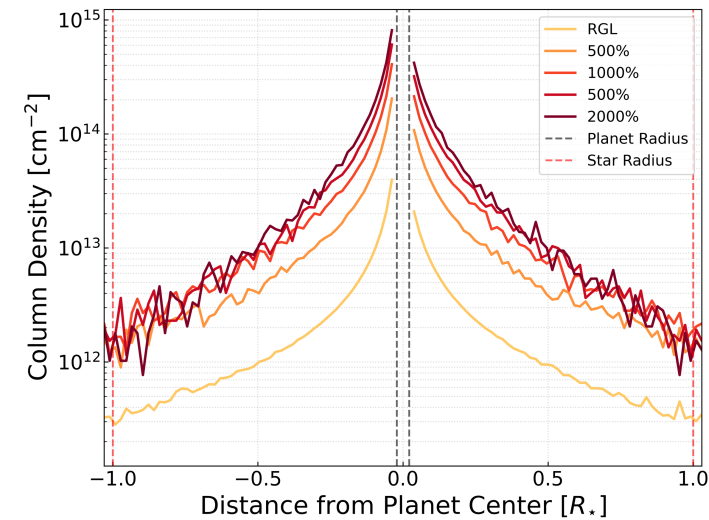
540 – 2980 XUV

GJ163



15 – 320 XUV

HD85512



4 – 85 XUV

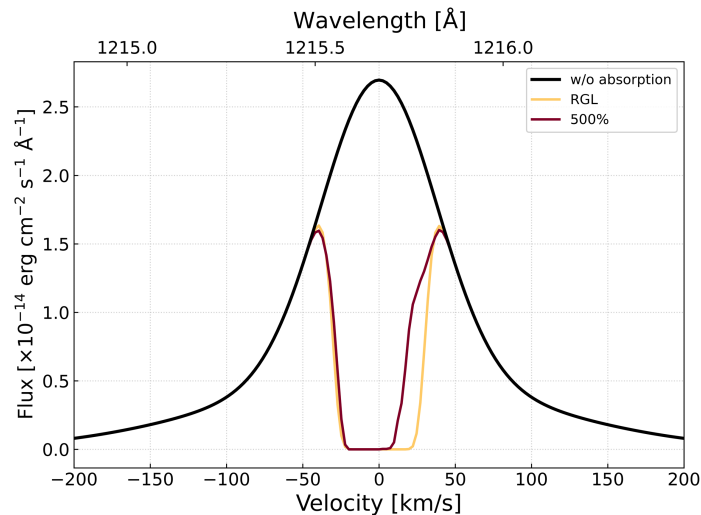
Oxygen atoms have a larger photoionization cross section than hydrogen atoms

➡ The column density decreases more rapidly with distance from the planet (100 XUV <)

Results: Transmission Spectrum (Ly- α 1216Å)

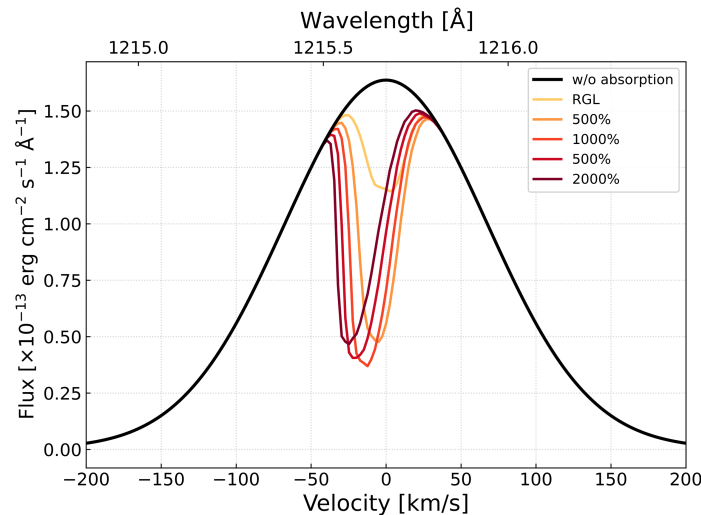
Ly- α transmission spectrum at transit center

TRAPPIST-1



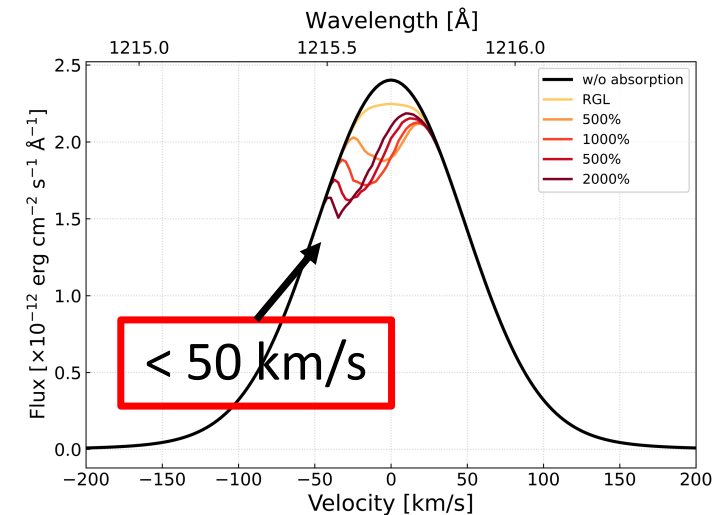
540 – 2980 XUV

GJ163



15 – 320 XUV

HD85512



4 – 85 XUV

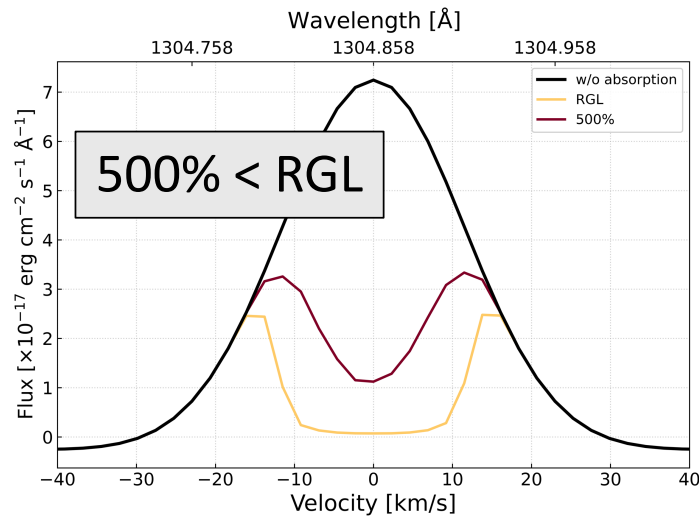
Ly- α intensity: **TRAPPIST-1** < **GJ163** < **HD85512**

➡ Even under the conditions most favorable for particle acceleration (HD85512@2000%), the line-of-sight velocity is **< 50 km/s** (within ISM absorption effect)

Results: Transmission Spectrum (O I 1305Å)

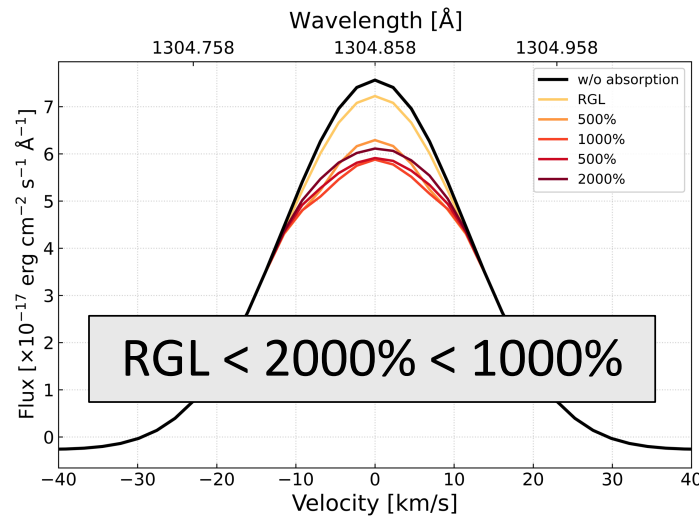
O I transmission spectrum at transit center

TRAPPIST-1



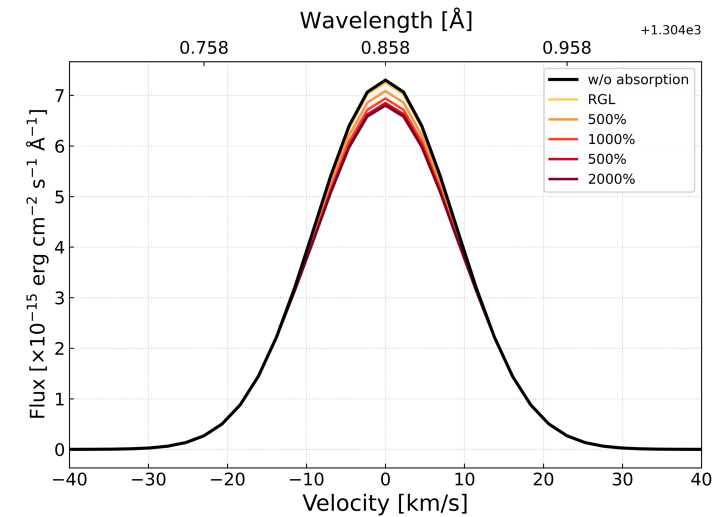
540 – 2980 XUV

GJ163



15 – 320 XUV

HD85512



4 – 85 XUV

The column density decreases more rapidly with distance from the planet ($100 \text{ XUV} <$)

➡ The coverage fraction decreases, leading to a smaller transit depth

Discussion: Detectability by the HWO Observations

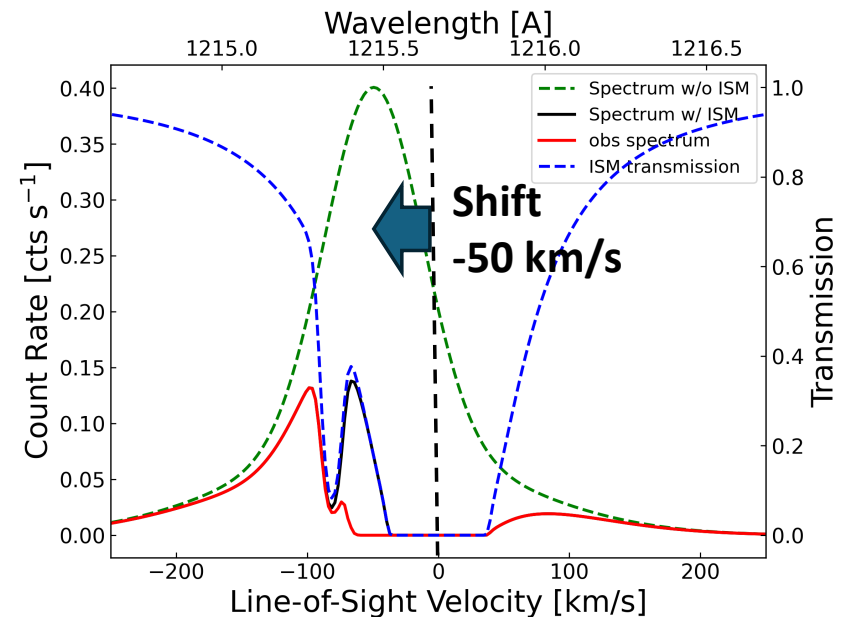
Based on the simulation results...

To detect Ly- α transits, it is necessary to avoid the ISM based on **the stellar system's radial velocity**.



We estimated the observation time required to detect these at the 3σ level, assuming various radial velocities for different stellar systems.

Examples of the star with a radial velocity of -50 km/s
(Similar to the actual TRAPPIST-1)



Discussion: Estimation of Observational Time by HWO

Ly-a (TRAPPIST-1 like)

Rad Vel	-50 km/s	-40 km/s	-30 km/s	-20 km/s	-10 km/s
RGL	27 s	50 s	182 s	1534 s	74000 s
500 %	28 s	51 s	187 s	1619 s	64000 s

O I

RGL	1566 s
500 %	7162 s

Transit duration

9968.9 s
6512.9 s

Ly-a (GJ163 like)

Rad Vel	-50 km/s	-40 km/s	-30 km/s	-20 km/s	-10 km/s
RGL	261 s	1094 s	12000 s	5.2×10^5	1.5×10^8 s
500 %	31 s	105 s	935 s	5.4×10^5	1.8×10^8 s
1000 %	20 s	44 s	230 s	5251 s	3.3×10^6 s
1500 %	12 s	16 s	43 s	274 s	1.9×10^5 s
2000 %	31 s	32 s	81 s	498 s	1.9×10^5 s

O I

RGL	1.5×10^6 s
500 %	1.2×10^5 s
1000 %	90000 s
1500 %	7400 s
2000 %	1.5×10^5 s

Transit duration

11780.7 s
7740.6 s
6511.6 s
5878.1 s
5473.4 s

Assumption: 6-m Telescope (three mirrors) + HRS (Collimator + Echelle + Cross disperser + tapered MCP)

Discussion: Estimation of Observational Time by HWO

Ly-a (HD85512 like)

Rad Vel	-50 km/s	-40 km/s	-30 km/s	-20 km/s	-10 km/s
RGL	382 s	1523 s	1.5×10^4 s	5.9×10^5 s	1.2×10^7 s
500 %	24 s	75 s	563 s	2.4×10^4 s	1.3×10^7 s
1000 %	12 s	23 s	98 s	1254 s	4.2×10^5 s
1500 %	12 s	15 s	43 s	247 s	1.0×10^4 s
2000 %	14 s	16 s	30 s	126 s	1588 s

O I

RGL	5.5×10^5 s
500 %	2.9×10^4 s
1000 %	1.1×10^4 s
1500 %	7389 s
2000 %	6395 s

Transit
duration

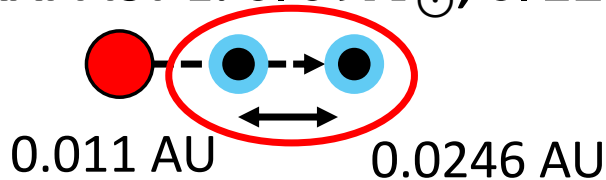
25408 s
16861 s
14183 s
12816 s
11923 s

- ✓ Hydrogen atoms could be detected under most conditions if the stellar system has a radial velocity of **< -20 km/s**.
- ✓ Oxygen atoms could be detected around **small stars** (a large transit depth) and **relatively inner orbits of near-solar-mass stars** (bright emission lines).

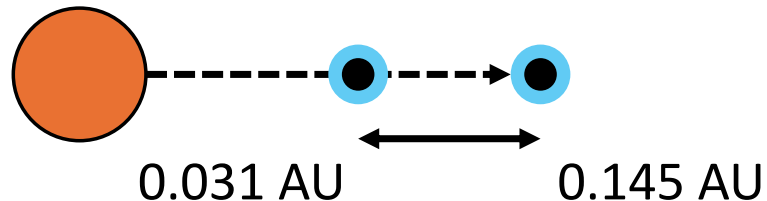
Assumption: 6-m Telescope (three mirrors) + HRS (Collimator + Echelle + Cross disperser + tapered MCP)

Summary

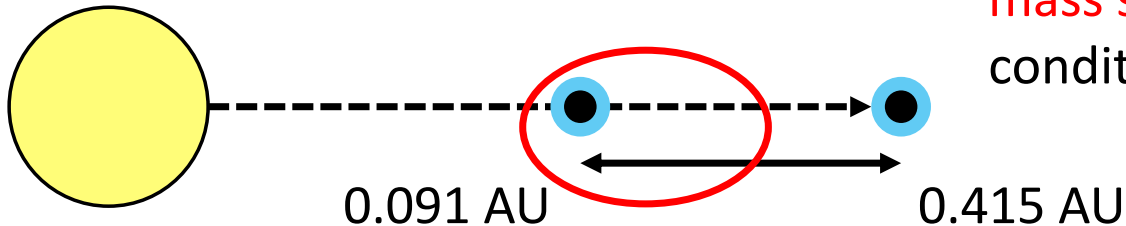
TRAPPIST-1: $0.09M_{\odot}$, $0.12R_{\odot}$



GJ163: $0.4M_{\odot}$, $0.4R_{\odot}$



HD85512: $0.69M_{\odot}$, $0.69R_{\odot}$



We simulated the upper atmosphere of terrestrial exoplanets in a runaway greenhouse state.

Ly- α transits:

- In many conditions, it is detectable if the stellar system's velocity is < -20 km/s.

O I Transit:

- A high XUV environment around **small active stars** and **relative inner orbit of near-solar-mass stars with bright emission lines** are good conditions.

Presenter: Vigneshwaran Krishnamurthy, Tohoku University

Title: Exoplanet atmospheres and escape in the HWO era: What JWST is teaching us

Lead author: Vigneshwaran Krishnamurthy

Abstract: The James Webb Space Telescope (JWST) has ushered in a new era of exoplanet atmospheric characterization, providing unprecedented insights into the compositions, structures, and evolution of planetary atmospheres. In this talk, I will discuss recent advances in our understanding of atmospheric escape and primordial atmospheres of sub-Neptunes and mini-Neptunes, highlighting what JWST observations have revealed about these planets and the key questions that remain. I will explore how atmospheric escape shapes planetary evolution, the challenges of interpreting transmission spectra in the presence of stellar heterogeneity, and the implications for the habitability of temperate planets retaining H/He envelopes. Finally, I will discuss how future UV–visible–near-infrared observations with next-generation facilities, such as the Habitable Worlds Observatory (HWO), will enable simultaneous studies of atmospheric chemistry, escape, and stellar activity, providing a comprehensive picture of planetary evolution and habitability.

Science Case Summary:

Understanding how planetary atmospheres form, evolve, and escape is essential for interpreting the diversity of exoplanets and identifying worlds that may be habitable. This work directly supports the scientific goals of the Astro2020 Decadal Survey and the Habitable Worlds Observatory by providing the physical framework needed to characterize potentially habitable planets, understand their host stars, and place Earth in the broader context of planetary systems.



Exoplanet atmospheres and escape in the HWO era: What JWST is teaching us

Vigneshwaran Krishnamurthy

クリシュナムルティ ヴィグニシュワラン

Specially Appointed Assistant Professor
Planetary System Formation (Obs.) Group,
Astronomical Institute, Tohoku University

Work in collaboration with

Charles Cadieux, Mahesh Herath, Jared Splinter, Dhvani Doshi, Louis-Philippe Coulombe, Nicolas Cowan,
René Doyon, Vincent Yarov, Sylvie Beaulieu, Teruyuki Hirano, John Livingston
and new collaborators!

Artwork by: Angel P. Geego (WASP-107b)

High-resolution Ultraviolet-to-Near-Infrared Characterization of Exoplanet Atmospheres with HWO

Patricio E. Cubillos,^{1,2} Matteo Brogi,^{2,3} Antonio García Muñoz,⁴ Luca Fossati,¹ Jasmina Blečić,^{5,6} Sudeshna Boro Saikia,⁷ Vincent Bourrier,⁸ Jose A. Caballero,⁹ Juan Cabrera,¹⁰ Andrea Chiavassa,¹¹ Andrzej Fludracc,¹² Leonardos Gkouvelis,¹³ John Lee Grenfell,¹⁰ Manuel Guedelcc,⁷ Gopal Hazracc,¹⁴ Alvaro Labianoc,¹⁵ Monika Lendl,⁸ Donna Rodgers-Lee,¹⁶ Arnaud Salvador,¹⁰ Ilane Schroetter,¹⁷ Antoine Strugarek,⁴ Benjamin Taysum,¹⁰ Aline Vidotto,¹⁸ and Thomas G. Wilson¹⁹

Exoplanet Atmospheric Escape Observations with the Habitable Worlds Observatory

Leonardo A. Dos Santos^{1,2} and Eric D. Lopez^{3,4}

¹Space Telescope Science Institute, Baltimore, Maryland, USA;

ldsantos@stsci.edu

²Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland, USA

³NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

⁴GSFC Sellers Exoplanet Environments Collaboration, NASA GSFC, Greenbelt, Maryland, USA

Table 2: Requirements for combined UV, optical, and NIR observations of exoplanet atmospheres and escape (GB: ground-based high-resolution telescopes; OIR: optical plus NIR wavelengths).

Observation	State of the Art	Incremental Progress	Substantial Progress	Major Progress
Spectral range (nm)	81–360 (UV, HST) 350–2500 (OIR, GB)	150–1100	120–1700	100–2500
Mirror size (m)	2.5 (UV, HST) 8.0 (OIR, ESO/VLT)	4.0	7.0	15.0
Spectral resolving power	$\geq 115,000$ (echelle spectrographs)	60,000	100,000	>100,000
Wavelength stability	5 km s ⁻¹ (UV) 10 cm s ⁻¹ (optical) 10 m s ⁻¹ (NIR)	10 m s ⁻¹	1 m s ⁻¹	< 1 m s ⁻¹
Stokes parameters	I (UV) I, Q, U, V (OIR)	I	I and Q	I, Q, U, and V
Telluric contamination	No (UV) Yes (OIR)	No	No	No
UV to NIR simultaneity	No	No	Yes	Yes

Table 2: Requirements for detecting atmospheric escape in exoplanets with HWO.

Obs. Requirement	State of the Art	Incremental Progress	Substantial Progress	Major Progress
Effective area	680 cm ²	6 800 cm ²	73 100 cm ²	130 000 cm ²
Wavelength range	100 – 300 nm	100 – 300 nm	100 – 300 nm	100 – 300 nm
Spectral resolving power	$R \sim 114\,000$	$R > 15\,000$	$R > 45\,000$	$R > 45\,000$
Detector dynamic range	136 cts s ⁻¹ px ⁻¹	500 cts s ⁻¹ px ⁻¹	1 000 cts s ⁻¹ px ⁻¹	10 000 cts s ⁻¹ px ⁻¹

Example: Pollux Instrument (Neiner et al. 2026)

0.1 – 1.8 microns
R ~ 70,000 – 100,000
Spectropolarimetry

No worry
about
clouds!!

No worry
about Earth's
geocorona

No tellurics !!



Escape

Primordial atmosphere

Why escape is something
needed to study?

Markers

Atmosphere

Carbon chemistry

Formation and evolution

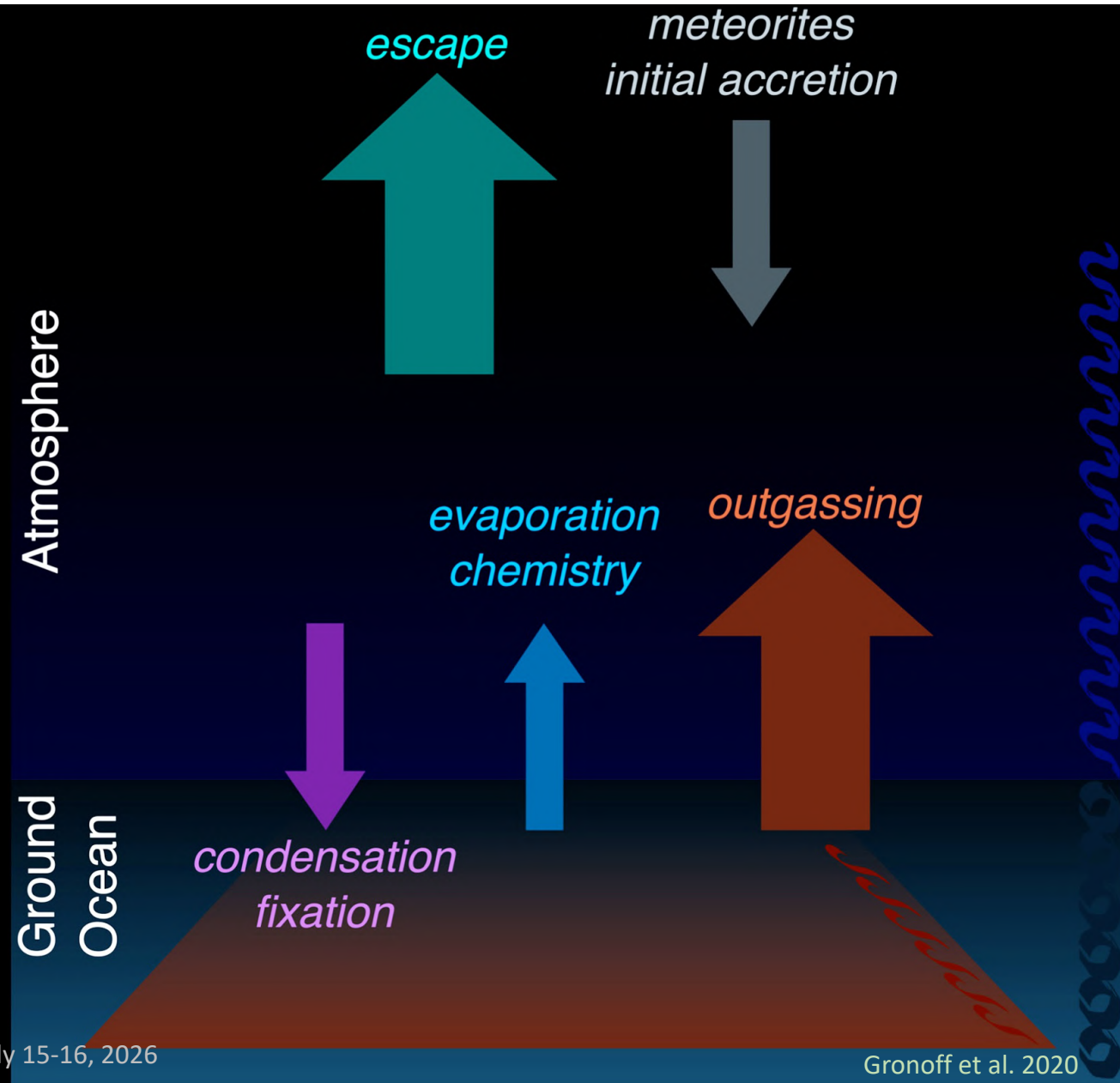
Star

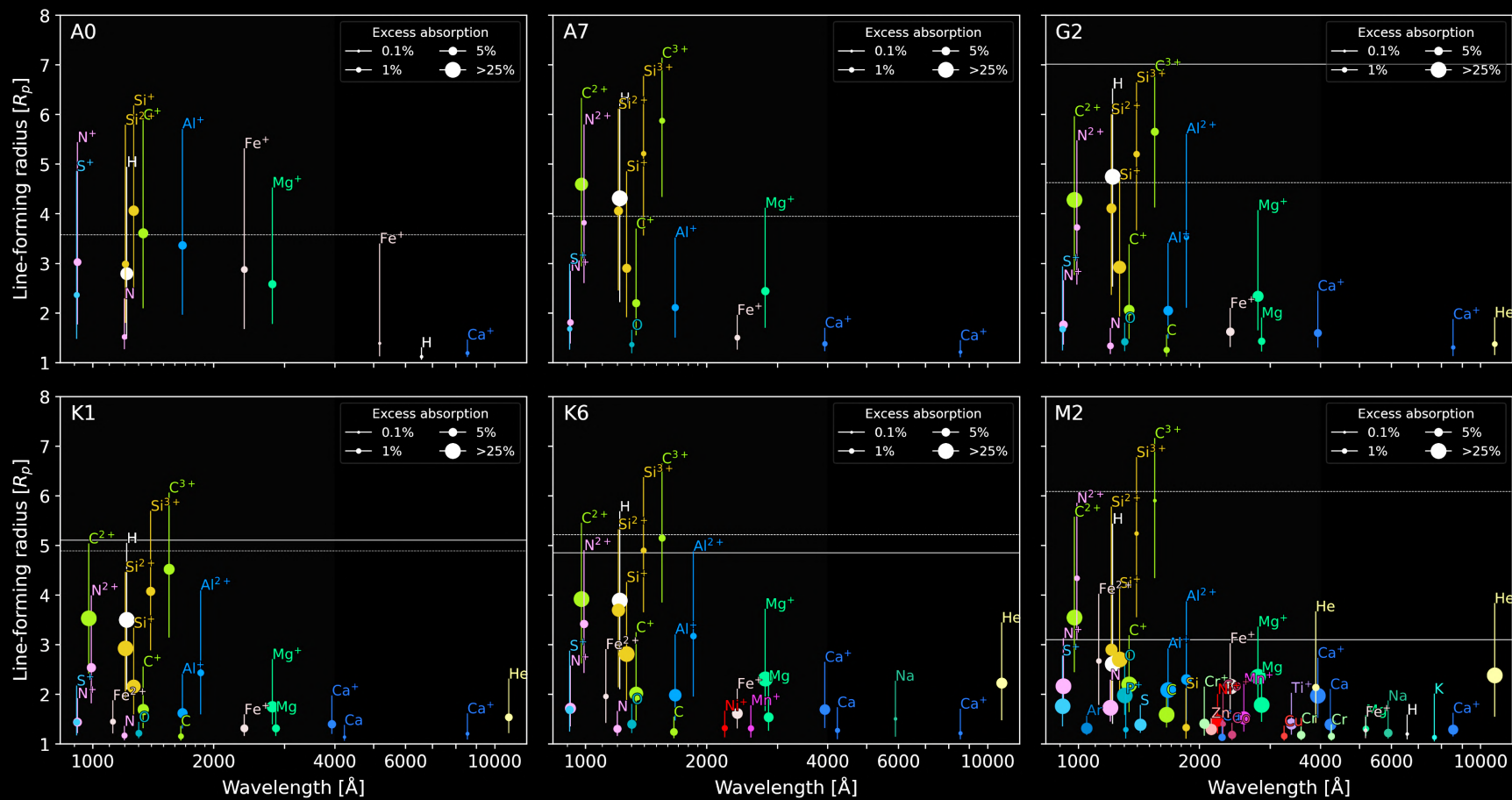
TLSE

Multi-planet system

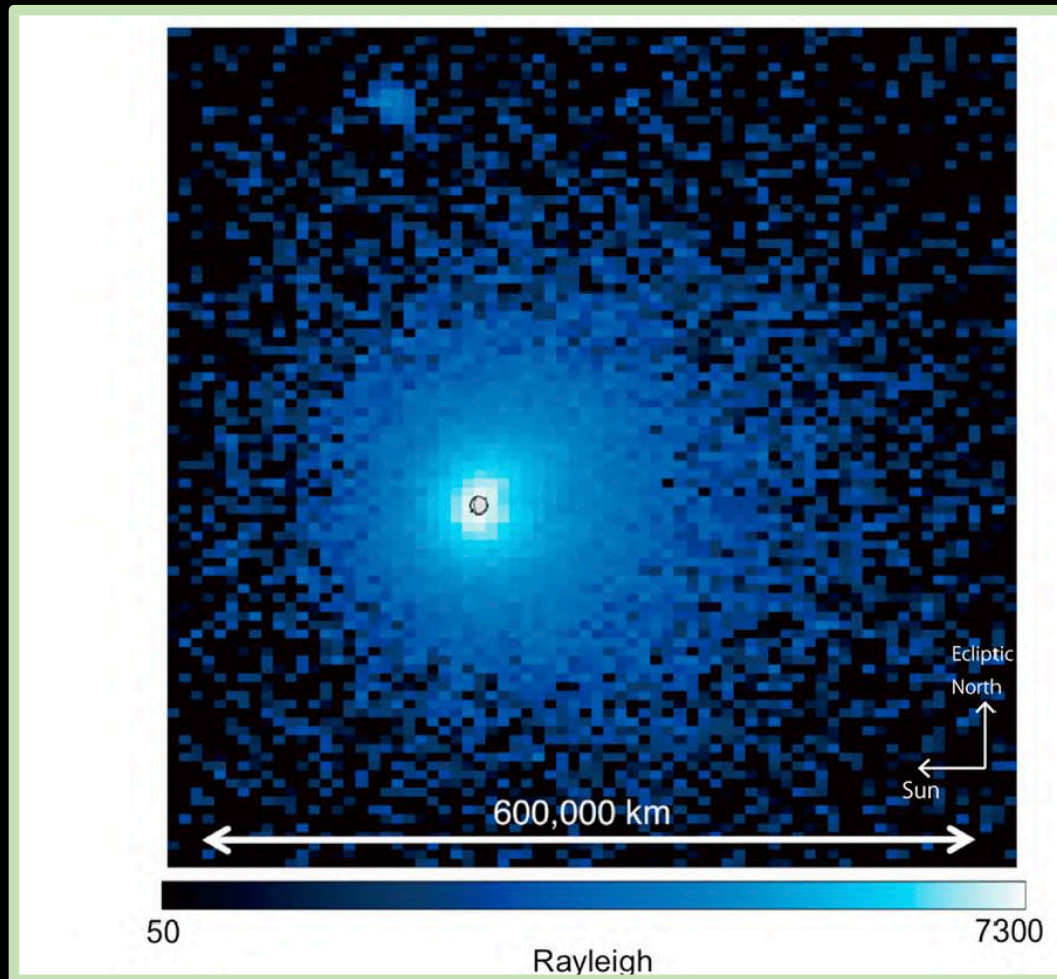
Atmospheric evolution

Physical processes



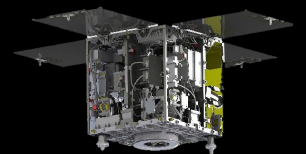


Linssen & Oklopčić 2023



Neutral Hydrogen
Geocorona of Earth

5.8×10^7 atoms/cm²/s



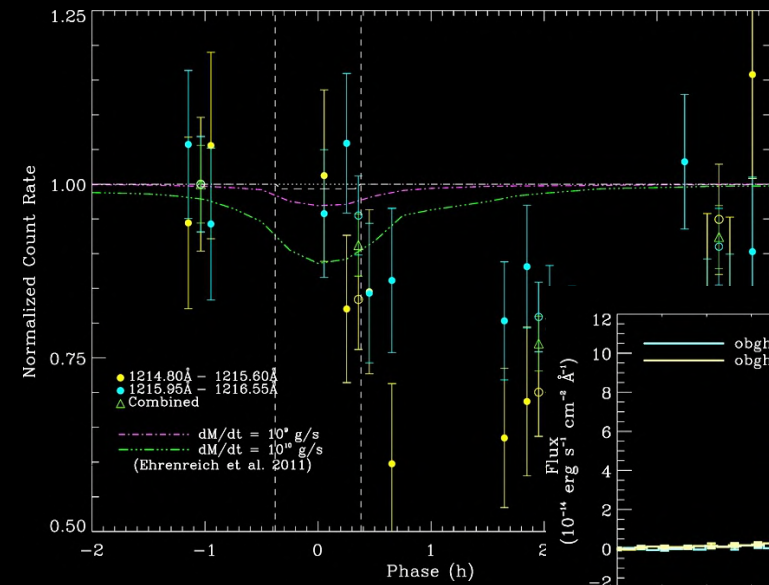
Kameda et al. 2017
(PROCYON spacecraft)

Lyman-alpha



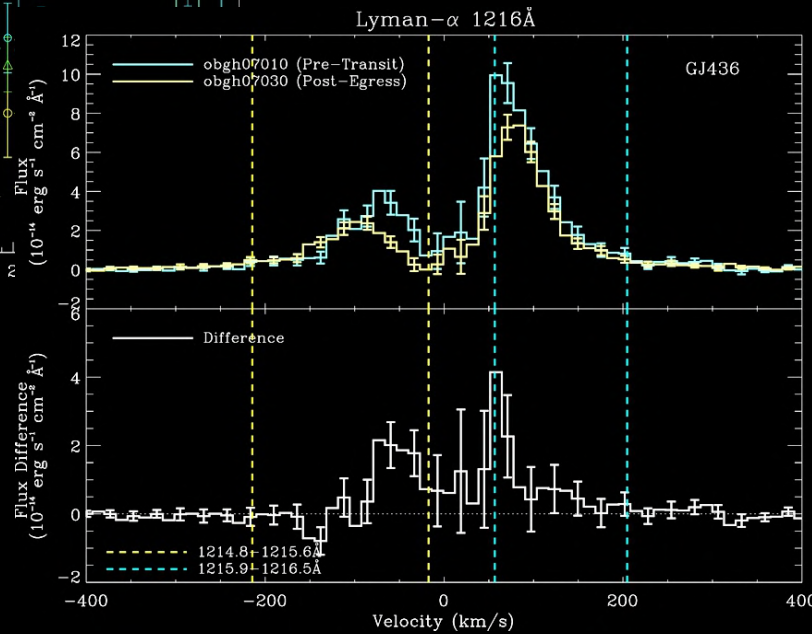
HST/STIS

GJ 436 b (Ehrenreich et al. 2011,
Kulow et al. 2014)

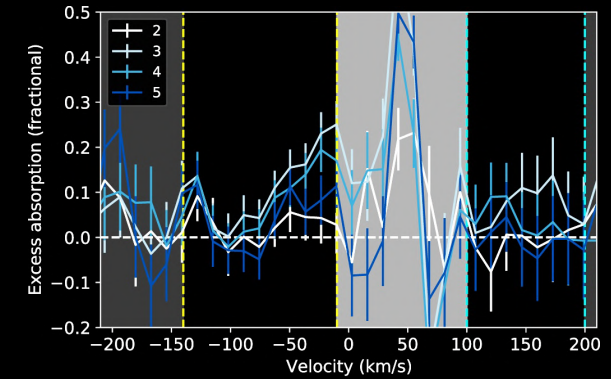


$R = 4.33 R_{\oplus}$
 $P = 2.64$ day

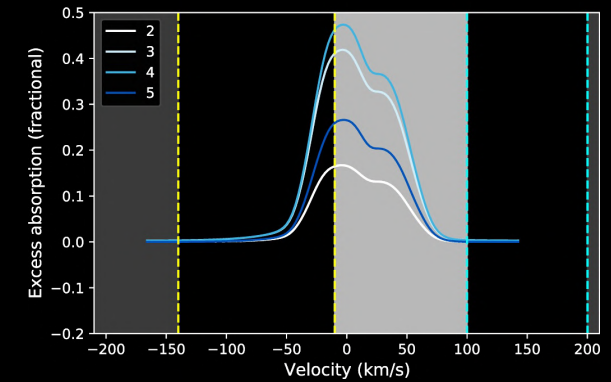
Distance: 31 ly
Age: 7.4 Gyr



HD 63433 c (Zhang et al. 2022)



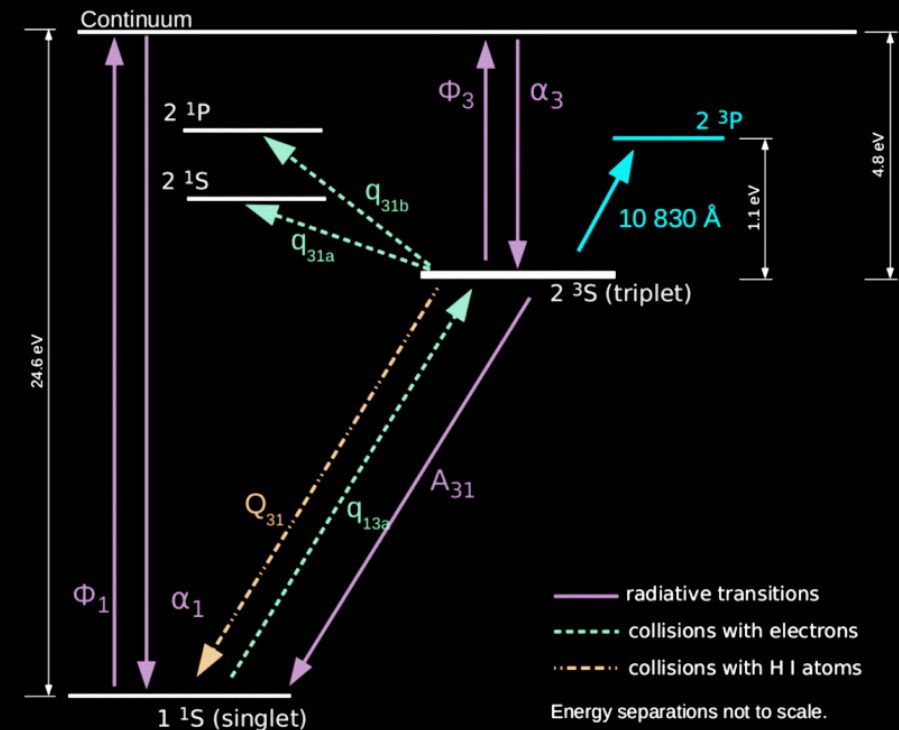
$R = 2.67 R_{\oplus}$
 $P = 20.5$ day



Distance: 75 ly
Age: 440 Myr

Helium I triplet at 10830 Å

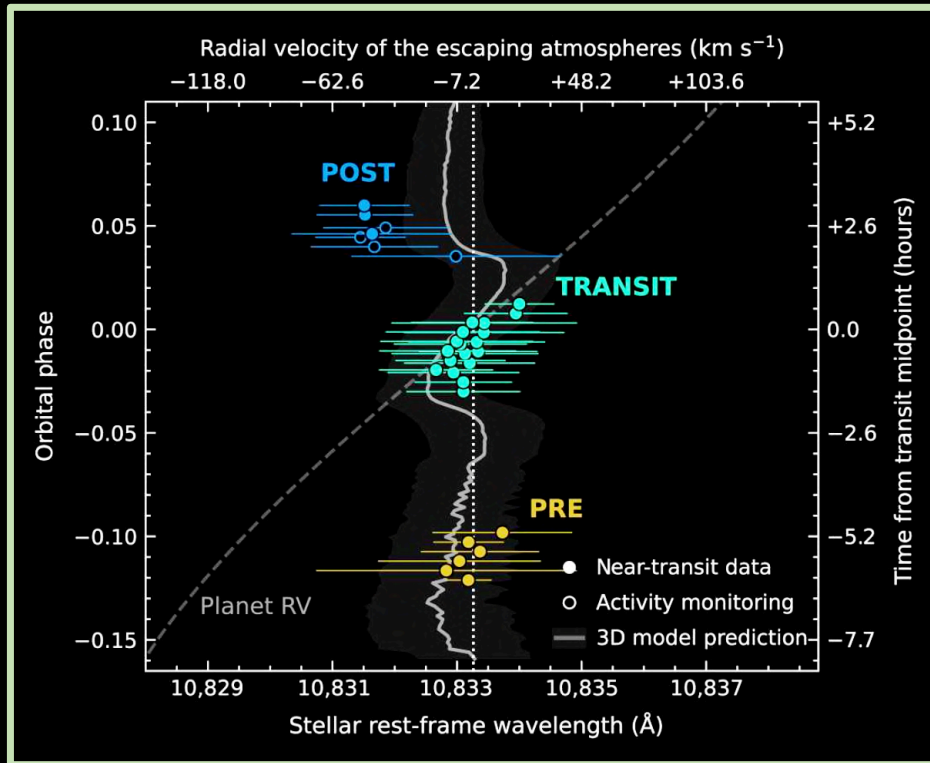
- EUV stellar radiation (< 50.4 nm) photoionizes neutral He atoms.
- Recombination at the planet's upper atmosphere is efficient for singlet states.
- Recombination cascade halts at 2^3S for triplet states without a rapid decay path.
- Higher XUV/mid-UV ratio is ideal.



(Oklopčić & Hirata, 2018)



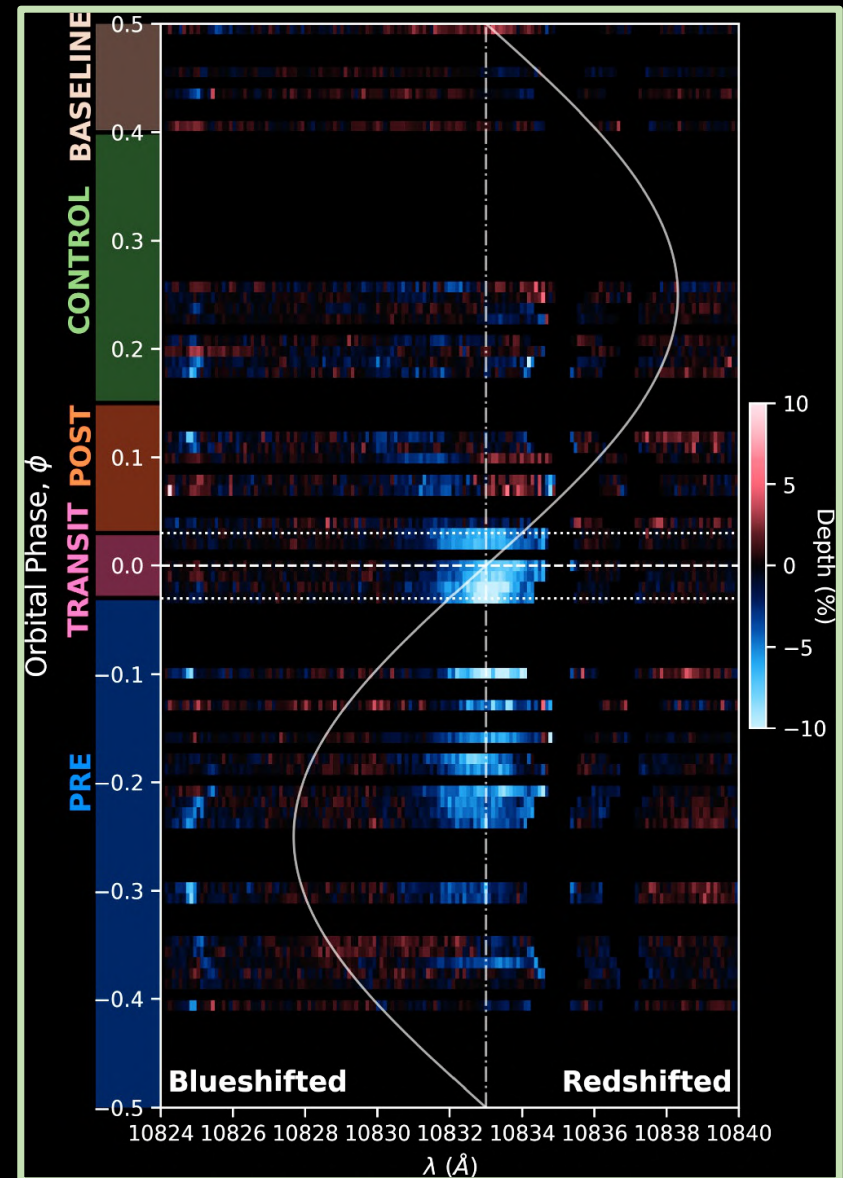
Stitched multi-night spectra HPF/HET



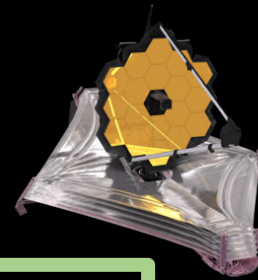
Zhang et al. 2023

Gully-Santiago et al. 2024

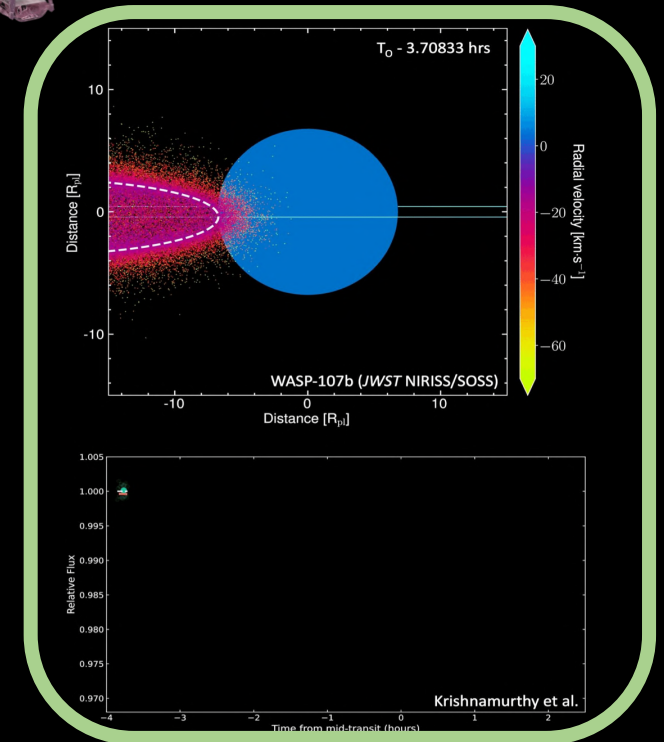
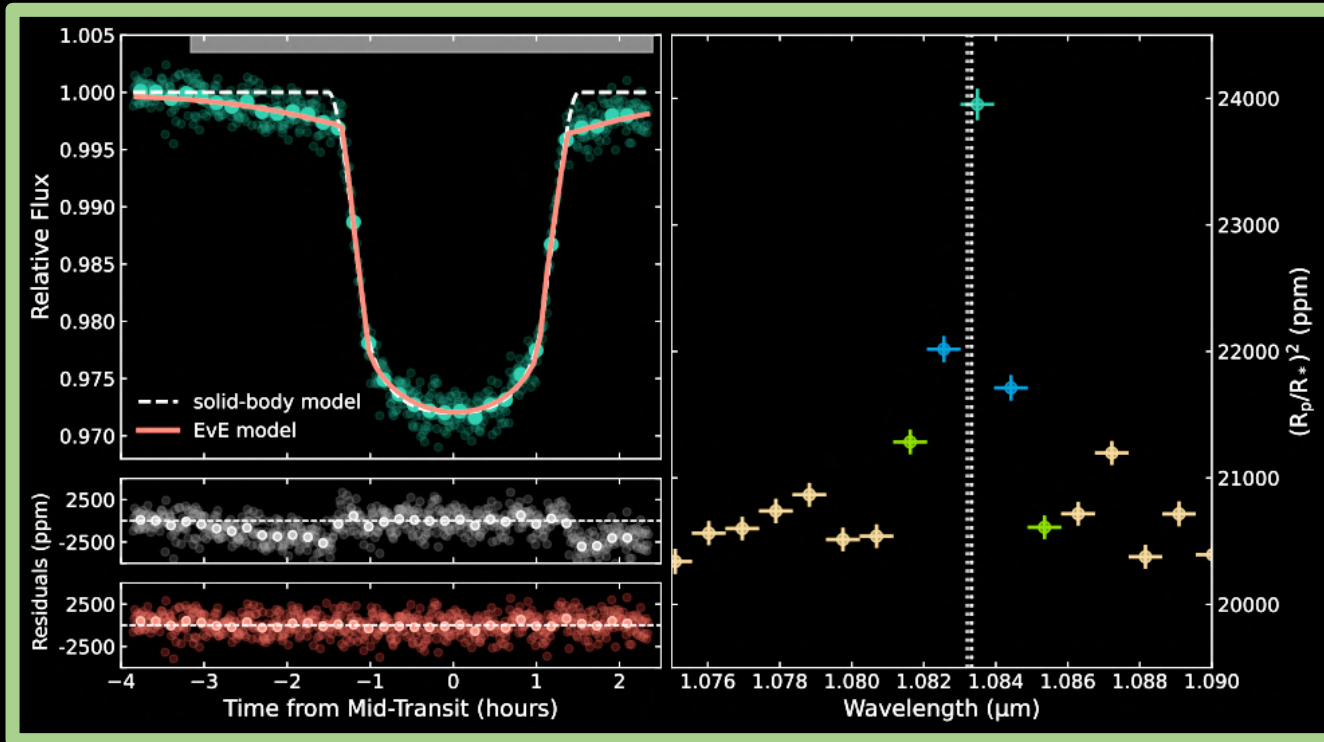
Vigneshwaran Krishnamurthy | HWO Japan Science Workshop 2 | July 15-16, 2026

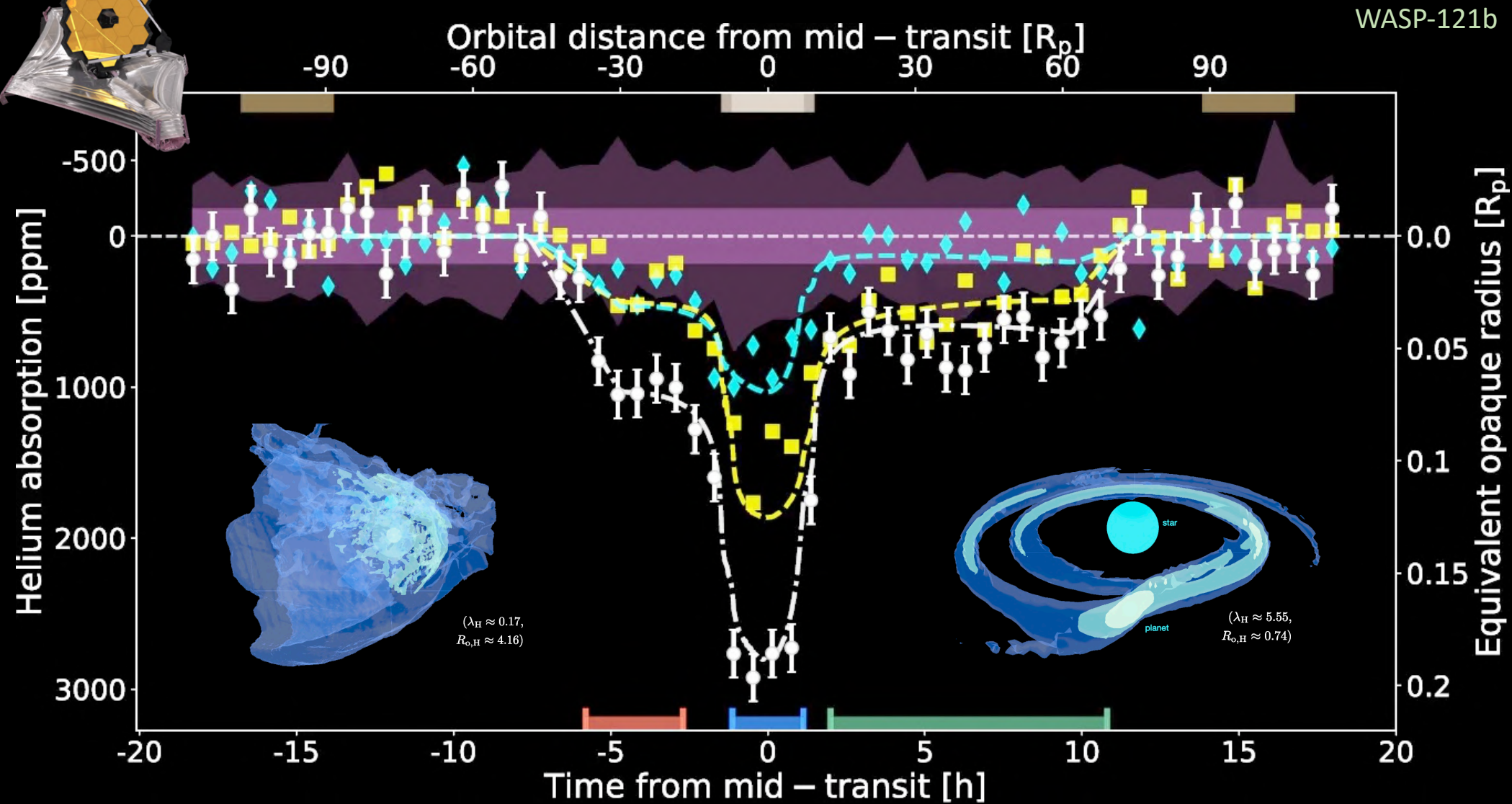
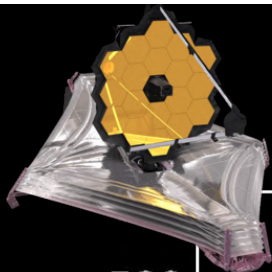


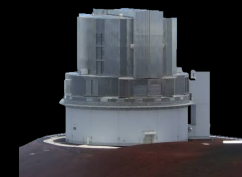
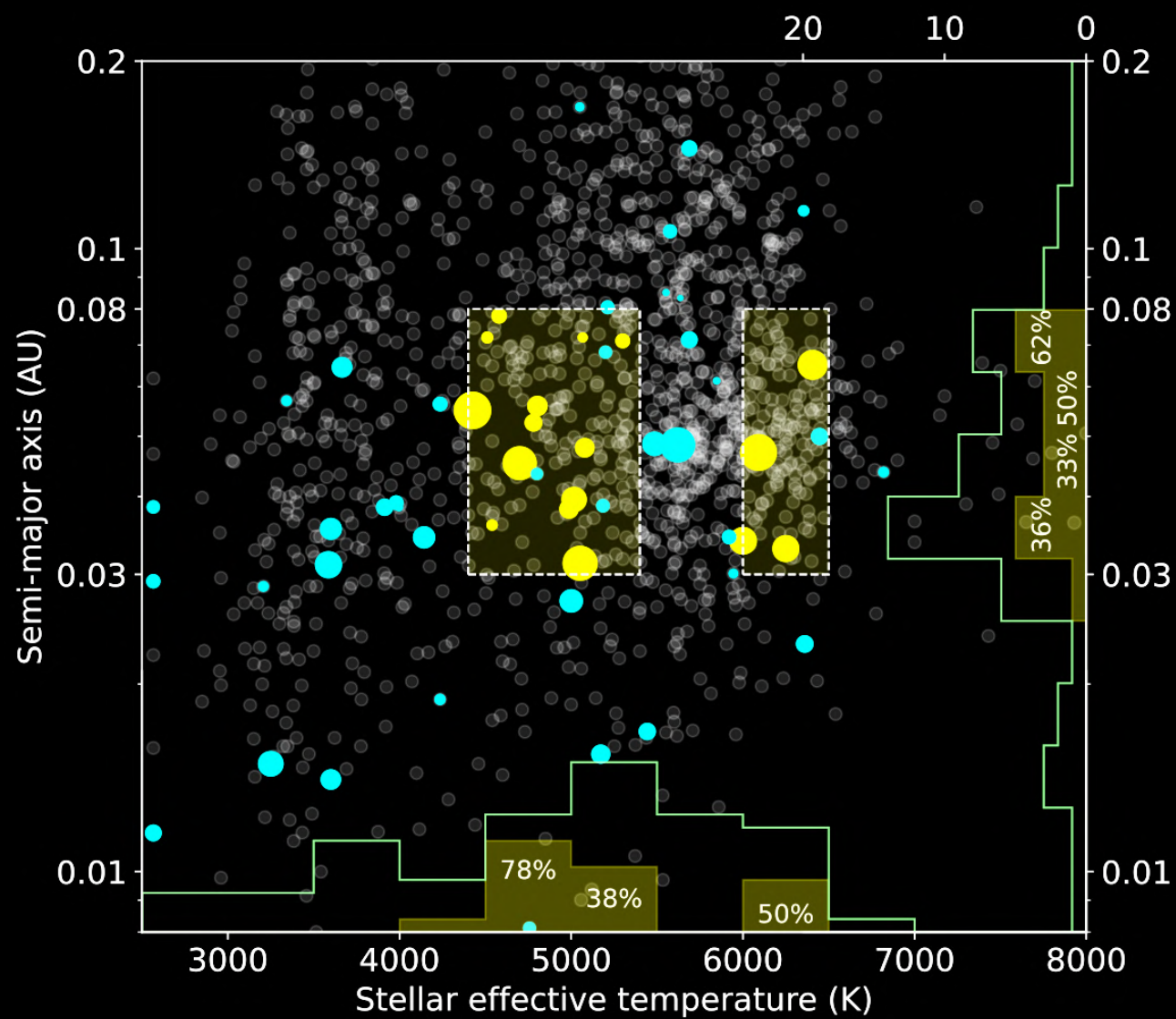
WASP-107b



Radius: $0.96 \pm 0.03 R_J$
 Mass: $\sim 30 M_{\oplus}$
 Age: 3.4 Gyr
 Period: 5.72 days
 eccentricity > 0







Bimodal distribution!

A gap in host star effective temperature

Colder regions?

How expansive are the primordial atmosphere?

Are we looking at the star variations or planetary signals?

With the presence of H/He atmosphere, how does the habitability affect?

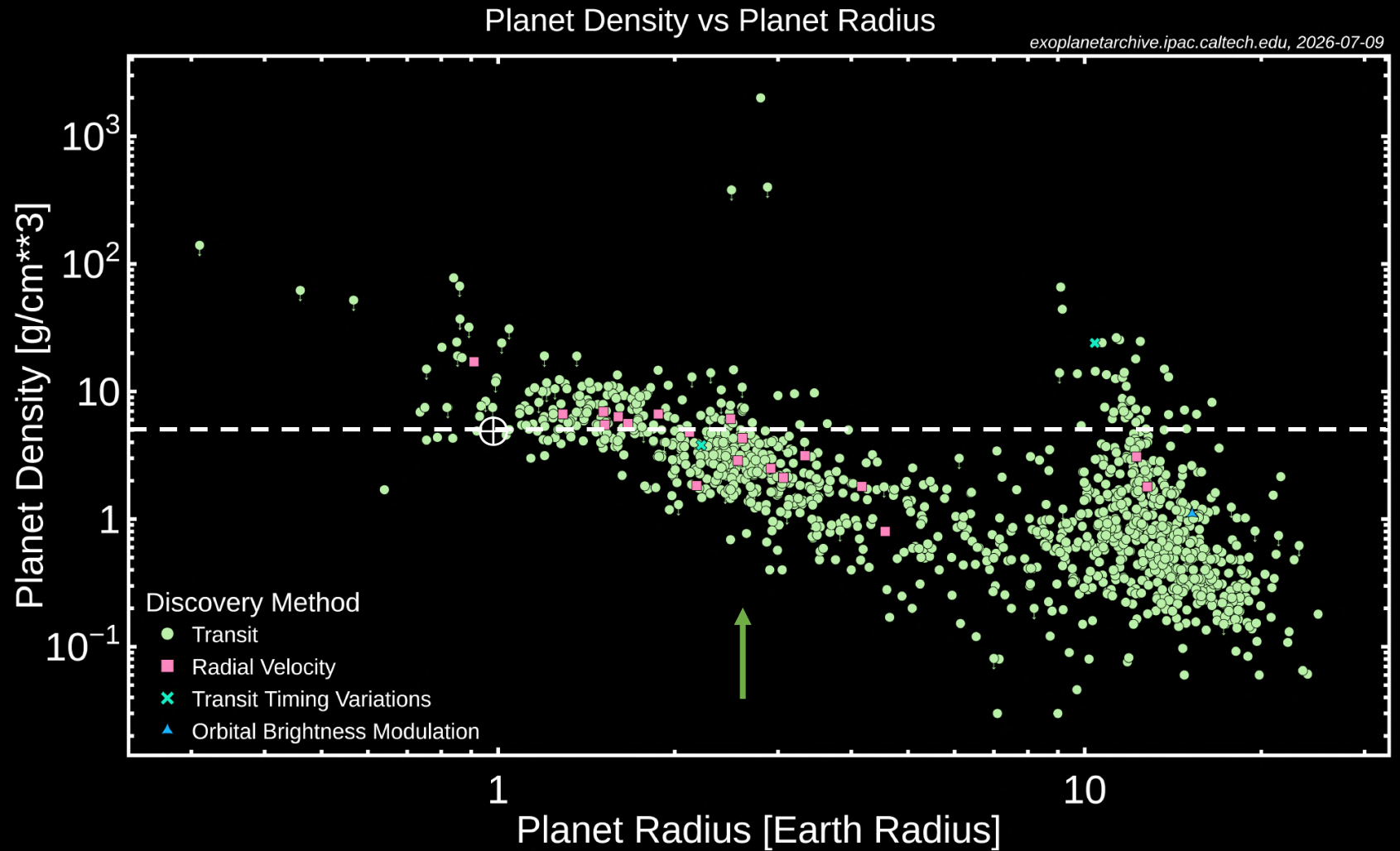
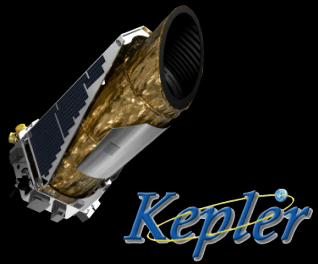
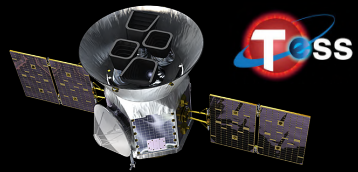
Hycean planets



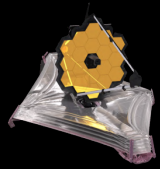
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Photo credit: N. Madhusudhan

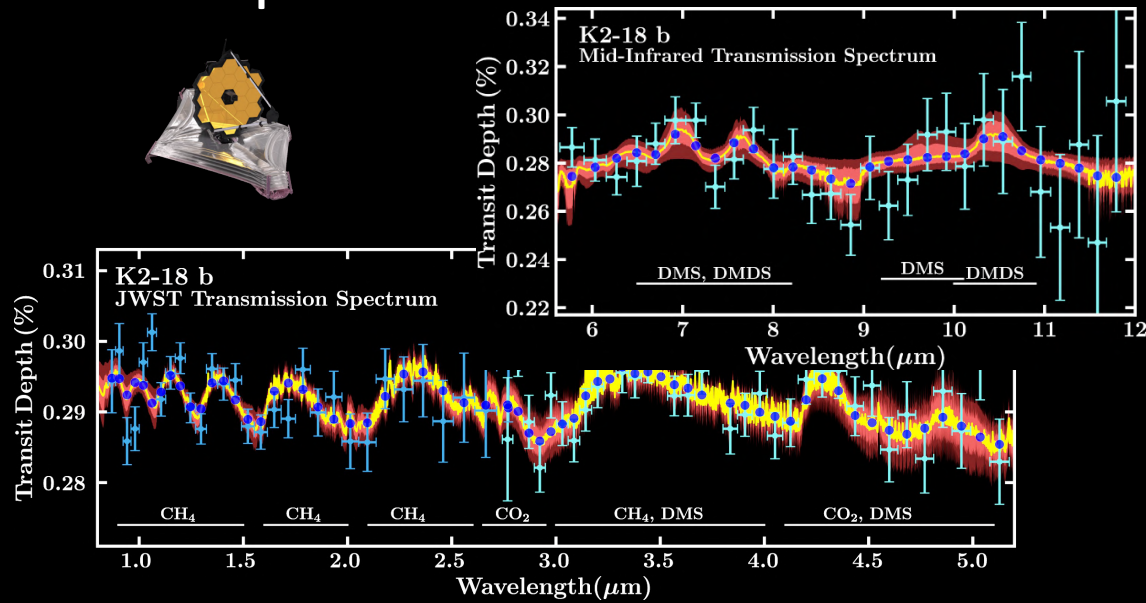
Sub-Neptunes



Sub-Neptunes

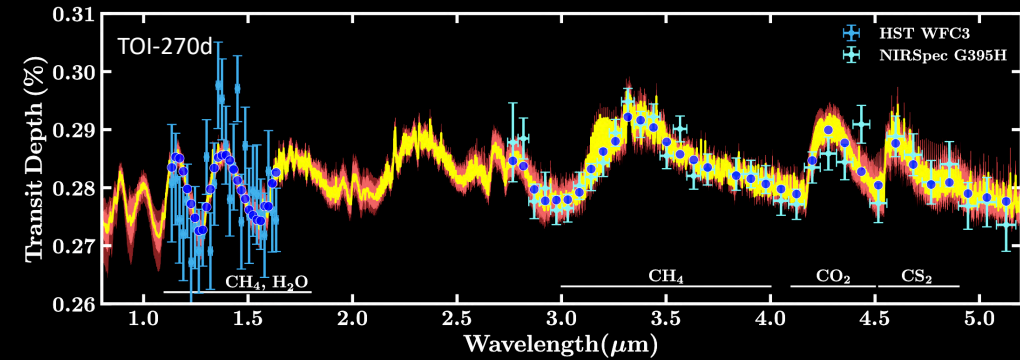


Madhusudhan et al. 2026

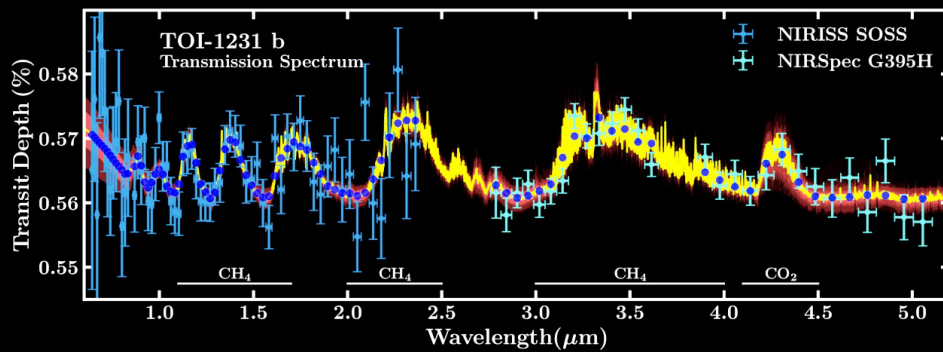


Temperate sub-Neptunes (300– 500 K)

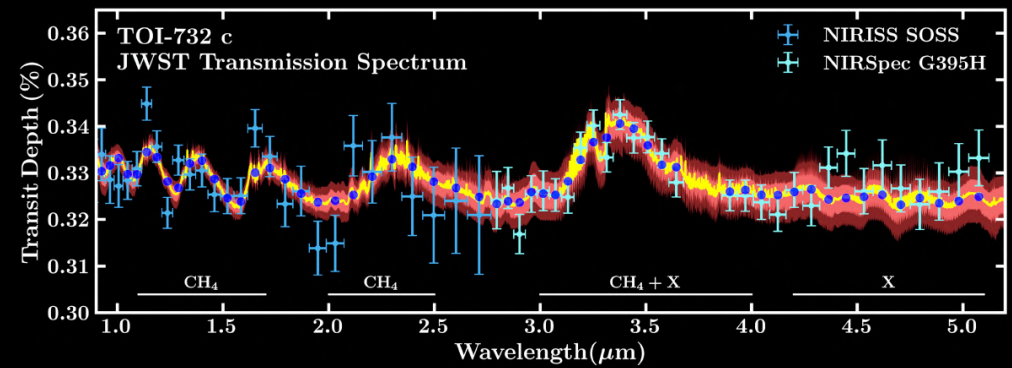
Holmberg & Madhusudhan 2023

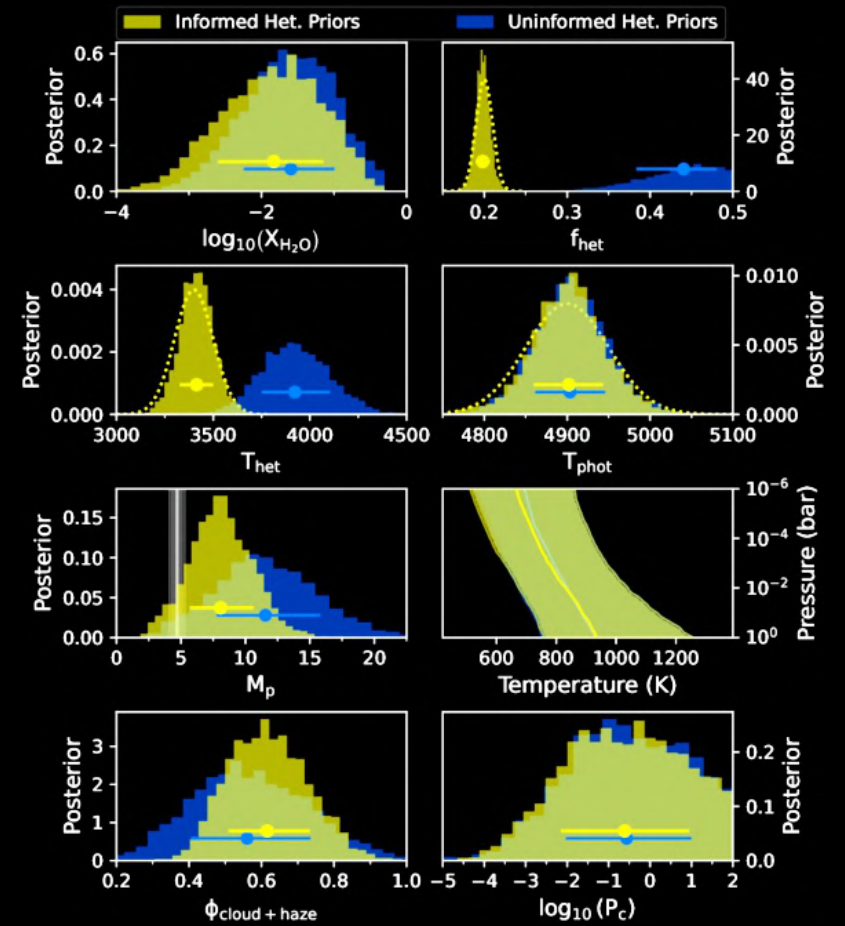
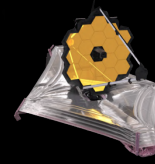
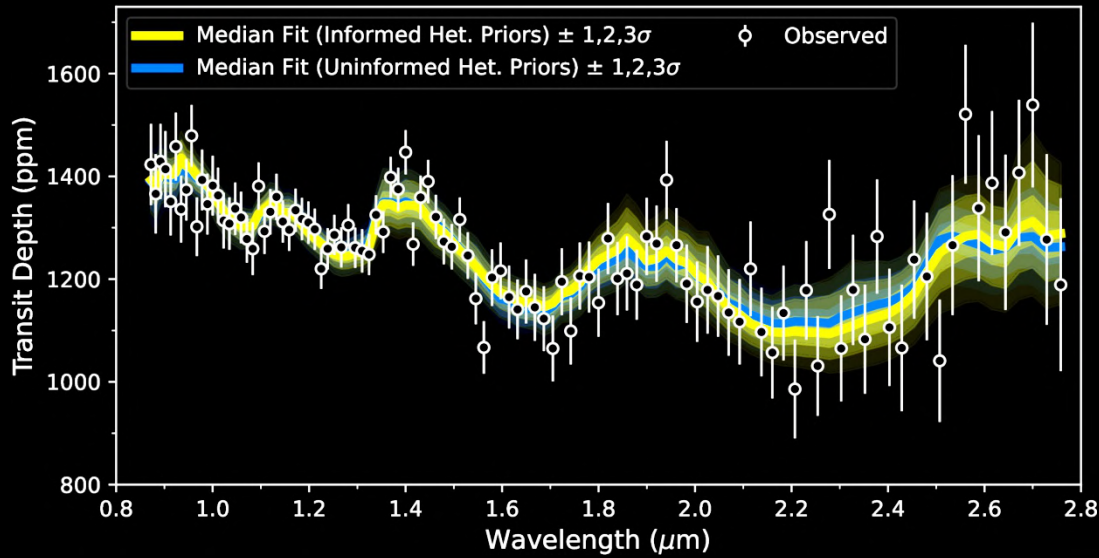


Sarkar et al. 2026



Rigby et al. 2025





Parameter	Units	Value (Informed)	(Uninformed)
Chemistry			
$\log_{10}(X_{\text{H}_2\text{O}})$	...	$-1.83^{+0.68}_{-0.77}$	$-1.59^{+0.60}_{-0.65}$
$\log_{10}(X_{\text{CH}_4})$	...	$-8.38^{+2.36}_{-2.20}$	$-8.45^{+2.22}_{-2.24}$
$\log_{10}(X_{\text{NH}_3})$	...	$-8.30^{+2.48}_{-2.28}$	$-8.43^{+2.26}_{-2.20}$
$\log_{10}(X_{\text{HCN}})$	...	$-8.01^{+2.60}_{-2.47}$	$-7.83^{+2.57}_{-2.54}$
$\log_{10}(X_{\text{CO}})$	...	$-7.05^{+3.08}_{-2.97}$	$-7.15^{+3.09}_{-2.97}$
$\log_{10}(X_{\text{CO}_2})$	...	$-7.35^{+2.81}_{-2.89}$	$-7.12^{+2.96}_{-2.90}$

V 1298c
 $R = 5.08 \pm 0.37 R_{\oplus}$
 $M = 4.7 \pm 0.6 M_{\oplus}$
 (Livingston et al. 2026)

P - T Profile

T_0 K 625^{+181}_{-153} 650^{+176}_{-158}

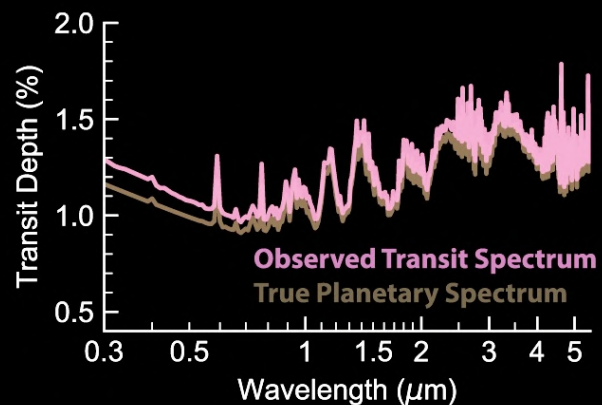
Murphy et al.. 2026

Carbon and Oxygen chemistry in the HZ planets in one go!

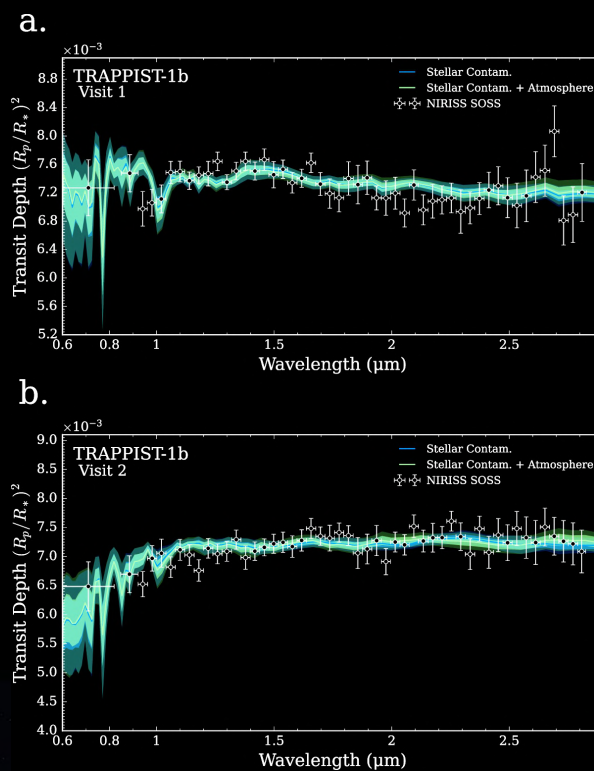
Cloud-Haze chemistry; day-night variations

Possible biosignatures;
vegetation signature (?)

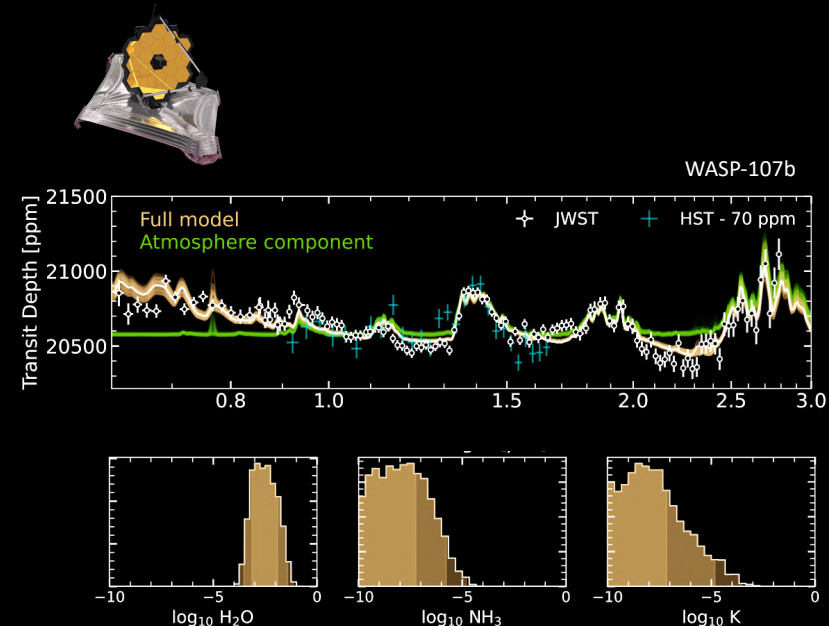
System architecture; formation and migration history



Rackham, Apai & Giampapa 2018



Lim et al. 2023



Krishnamurthy et al. 2025



Understand stellar heterogeneity

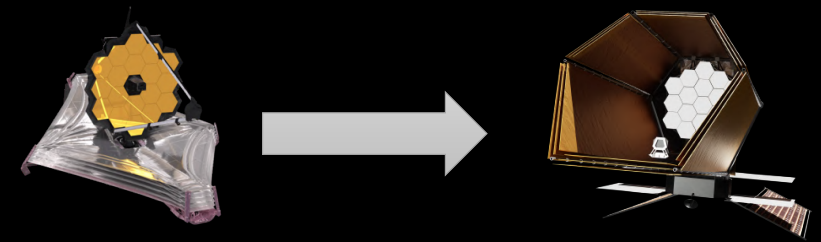
Multi-planet 'peas in a pod' system – good target for star characterization

Strong impact on habitability

UV-Vis-NIR Simultaneous Spectroscopy is necessary for atmospheric characterization

So we can get.....

- Understand the atmospheric evolution better
- Complete C- and O- chemistry in the planet's atmosphere
- Understand the star better



Future ultraviolet space telescope mission LAPYUTA

Lead author: Fuminori Tsuchiya

Abstract:

Life-Environmentology, Astronomy, and Planetary Ultraviolet Telescope Assembly (LAPYUTA) is a future ultraviolet (UV) space telescope selected as a candidate for JAXA's M-class mission, with its launch planned for the early 2030s. LAPYUTA has four primary objectives: (1) investigating the upper atmospheres of solar system planets, (2) characterizing the atmospheres of exoplanets in and around the habitable zone, (3) revealing the structures of present-day galaxies, and (4) understanding the synthesis processes of heavy elements through observations of neutron star mergers.

The key to addressing these scientific goals is measuring the physical states of hydrogen, oxygen, and carbon. These elements are ubiquitous in the universe and crucial for understanding the structure and evolution of the cosmos across various spatial scales—from planets to stars and galaxies. UV spectroscopy and imaging are optimal for measuring these physical states.

To achieve these goals, LAPYUTA will perform spectroscopic and imaging observations in the far-ultraviolet (FUV) spectral range (110–190 nm) with a large effective area ($> 300\text{cm}^2$) and a high spatial resolution (0.1 arcsec). The mission payload consists of a Cassegrain telescope with a 60-cm aperture primary mirror and three focal plane instruments: a medium-dispersion spectrograph (MRS), a high-dispersion spectrograph (HRS), and a UV slit imager (UVSI). To achieve a large effective area and high angular resolution, we are developing three key technologies: UV mirror deposition, a large high-precision detector, and a pointing disturbance correction system, while also studying the structural concept of the telescope. Furthermore, some of these key technologies will serve as stepping stones for future participation in the Habitable Worlds Observatory (HWO).

Science Case Summary

The LAPYUTA project aims to study the following: (1) the time-variable aspects of the atmospheres of Solar System bodies; (2) the atmospheres of exoplanets; (3) the structure of present-day galaxies; (4) the synthesis processes of heavy elements.

Future ultraviolet space telescope mission LAPYUTA

**Fuminori Tsuchiya¹, Go Murakami², Atsushi Yamazaki², Shingo Kameda³, Masato Kagitani¹, Kazuo Yoshioka⁴, Ryoichi Koga⁵, Jun Kimura⁶, Tomoki Kimura⁷, Chihiro Tao⁸, Kei Masunaga⁹, Shotaro Sakai¹, Akifumi Nakayama³, Masahiro Ikoma¹⁰, Norio Narita⁴, Masami Ouchi^{4,10}, Masaomi Tanaka¹, Masaki Kuwabara³, Shin Toriumi², Yuta Notsu¹¹, Kosuke Namekata¹²
LAPYUTA JAXA pre-project team*

1. Tohoku Univ., 2. ISAS/JAXA, 3. Rikkyo Univ., 4. The Univ. Tokyo, 5. Nagoya City Univ., 6. Osaka Univ., 7. Tokyo Univ. Science, 8. NICT, 9. Yamagata Univ., 10. NAOJ, 11. Colorado Univ., 12. Kyoto Univ.

- Science goals & objectives
- Instrument
- Sensitivity
- Key technologies
- Toward HWO

- Current status
 - One of JAXA M-class candidates
 - Down selection will be planned
- Target launch year
 - Early 2030s

LAPYUTA Science goals & objectives

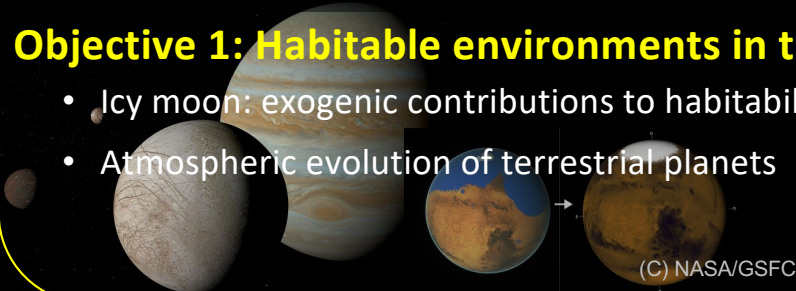
Goal1: habitable environments in the universe

Elements for the habitable environment

Hydrogen, Oxygen, Carbon → Advantage of UV spectroscopy

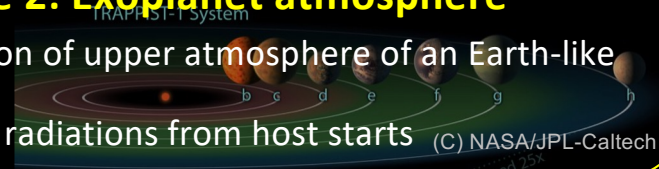
Objective 1: Habitable environments in the solar system

- Icy moon: exogenic contributions to habitability
- Atmospheric evolution of terrestrial planets



Objective 2: Exoplanet atmosphere

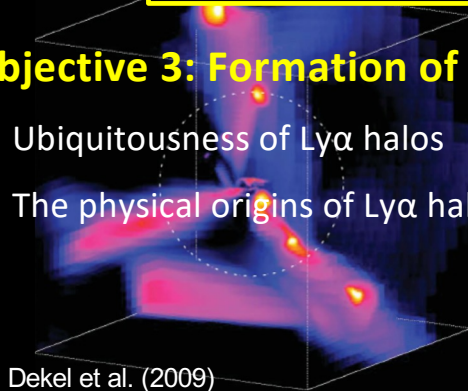
- First detection of upper atmosphere of an Earth-like exoplanet
- High energy radiations from host stars



Goal2: the origin of matter and space in the universe

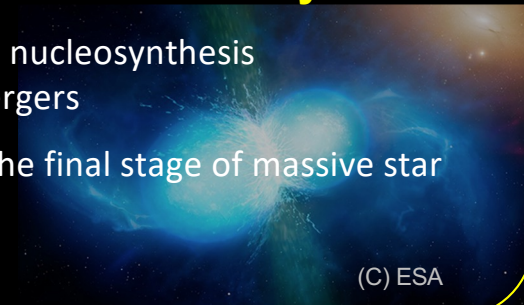
Objective 3: Formation of present-day galaxy

- Ubiquitousness of Ly α halos
- The physical origins of Ly α halos (the Cold Streams)



Objective 4: Origin of the heavy element

- The heavy element nucleosynthesis by neutron star mergers
- Understanding of the final stage of massive star evolution



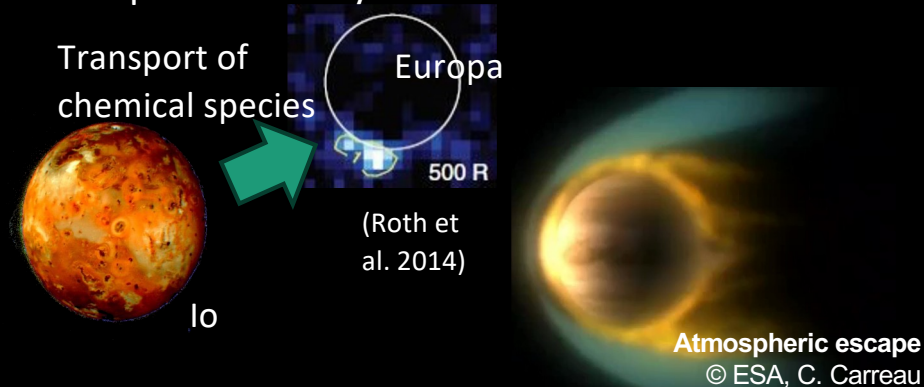
UV astronomy

Science Investigations(habitable environments in the universe)

[1-1] Icy moons of giant planets: a second habitable environment

Potential exogenic contributions

- Transport of chemical species from Io
- Production of oxidants by hot plasma irradiation
- Tidal process on icy moons

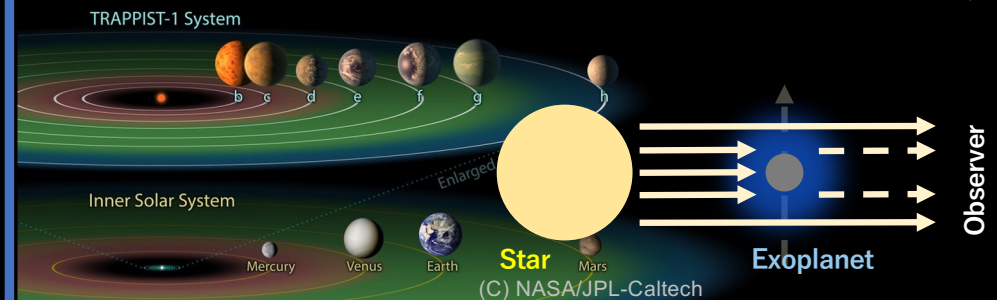


[1-2] Atmospheric escape of Venus & Mars: Atmospheric evolution

Global observations of H, O, and C

Ongoing atmospheric escape
& response to Sun and atmospheric variability

[2] Exoplanetary Atmospheres: Planets in the habitable zone Earth-like?



Transit observation with Ultraviolet Spectroscopy: Detection of upper atmosphere of terrestrial planets

- (1) First detection of expanded upper atmospheres (**O**, **C**)
→ Discovery of habitable planet candidates
- (2) First detection of a large outflow atmosphere (**H**)
→ understanding of planetary evolution (runaway greenhouse, etc.)
- (3) High-energy radiation from central stars (stellar flares, CME, etc.)
→ understanding of direct effects on atmospheres

Target : Planet around M-type star to be discovered by preceding missions (JASMINE, ARIEL, large groundbased telescope, etc)

Science Investigations(origin of matter and space in the universe)

[3] Formation of present-day galaxy

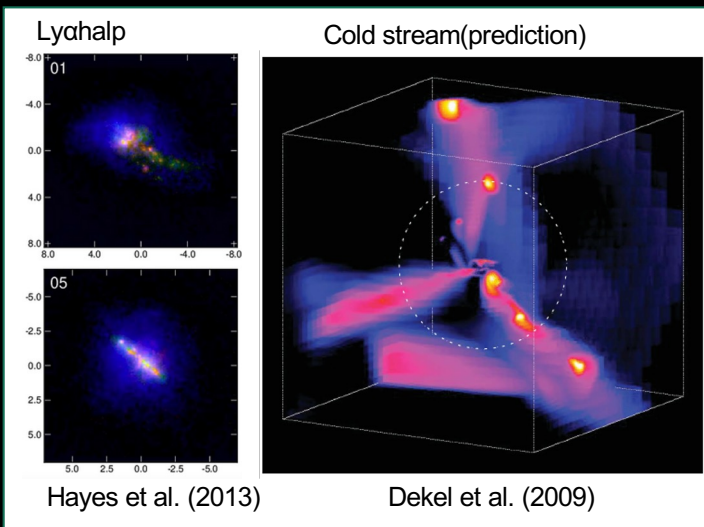
Ubiquitousness of the Galactic Ly α Halo

- Presence of the Ly α halo in galaxies today?

Large-Scale Structure of the Universe

~First Detection of "Cold Streams" in Galaxies

- Physical origin of the galactic Ly α halo.
- Basic structure of the material around galaxies.
- Verification of the galaxy formation process.
- Obtain ultraviolet atlas of galaxies.

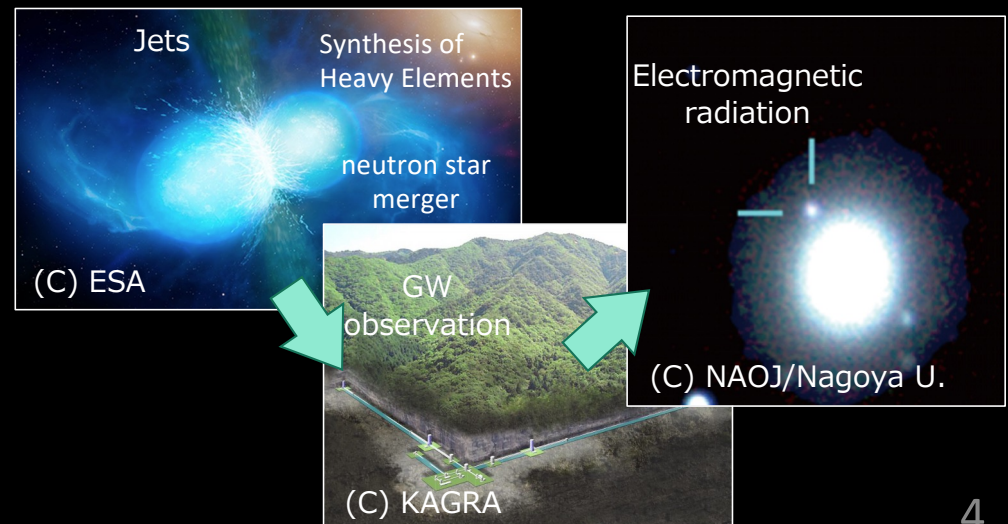


[4] Origin of The heavy element

Era of "Multi-messenger Astronomy"

Observation of total spectral distribution of the radiation and its time evolution from neutron star mergers (within 3 hours from discovery)

- Understanding the Origin of Heavy Elements
- Overall Picture of the Synthesis of Heavy Elements



Instruments : Specification



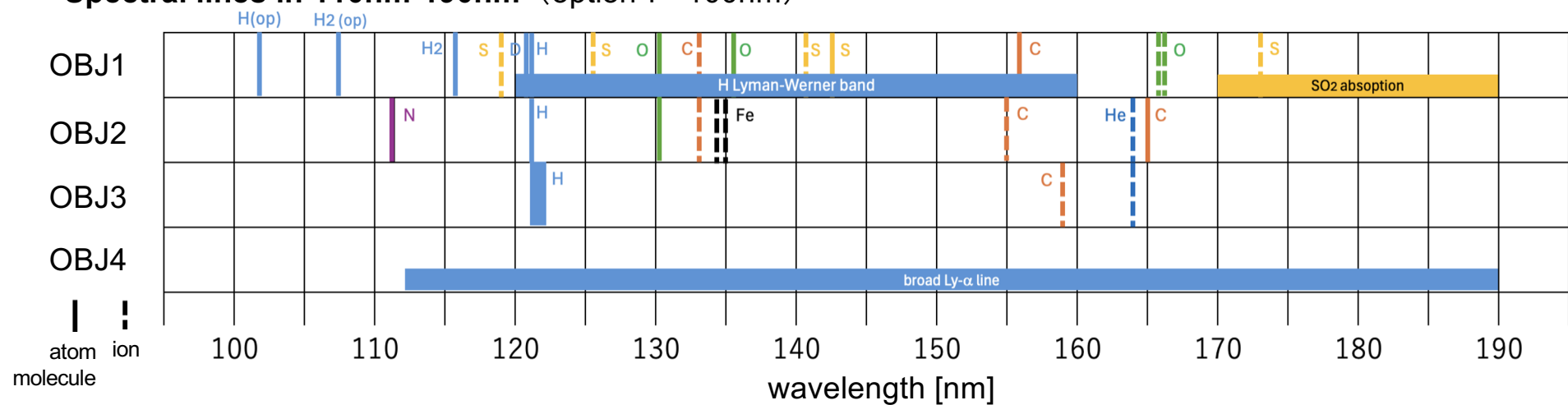
Spectrograph data

	Mid-dispersion	High-dispersion
• FOV	100 arcsec	13.5 arcsec
• Spectral range	110-190 nm	110–170nm
• Spatial resolution	0.1 arcsec	0.6 arcsec
• Spectral resolution	0.02 nm (6,500)	0.003 nm (43,000)

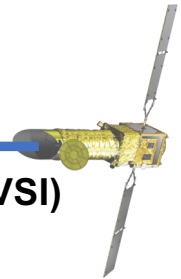
Imaging data

- FOV : **180 arcsec**
- Spectral range : 110-190 nm
- Six bands selectable with filter wheel
- Spatial resolution : **0.2 arcsec**

Spectral lines in 110nm-190nm (option : >100nm)



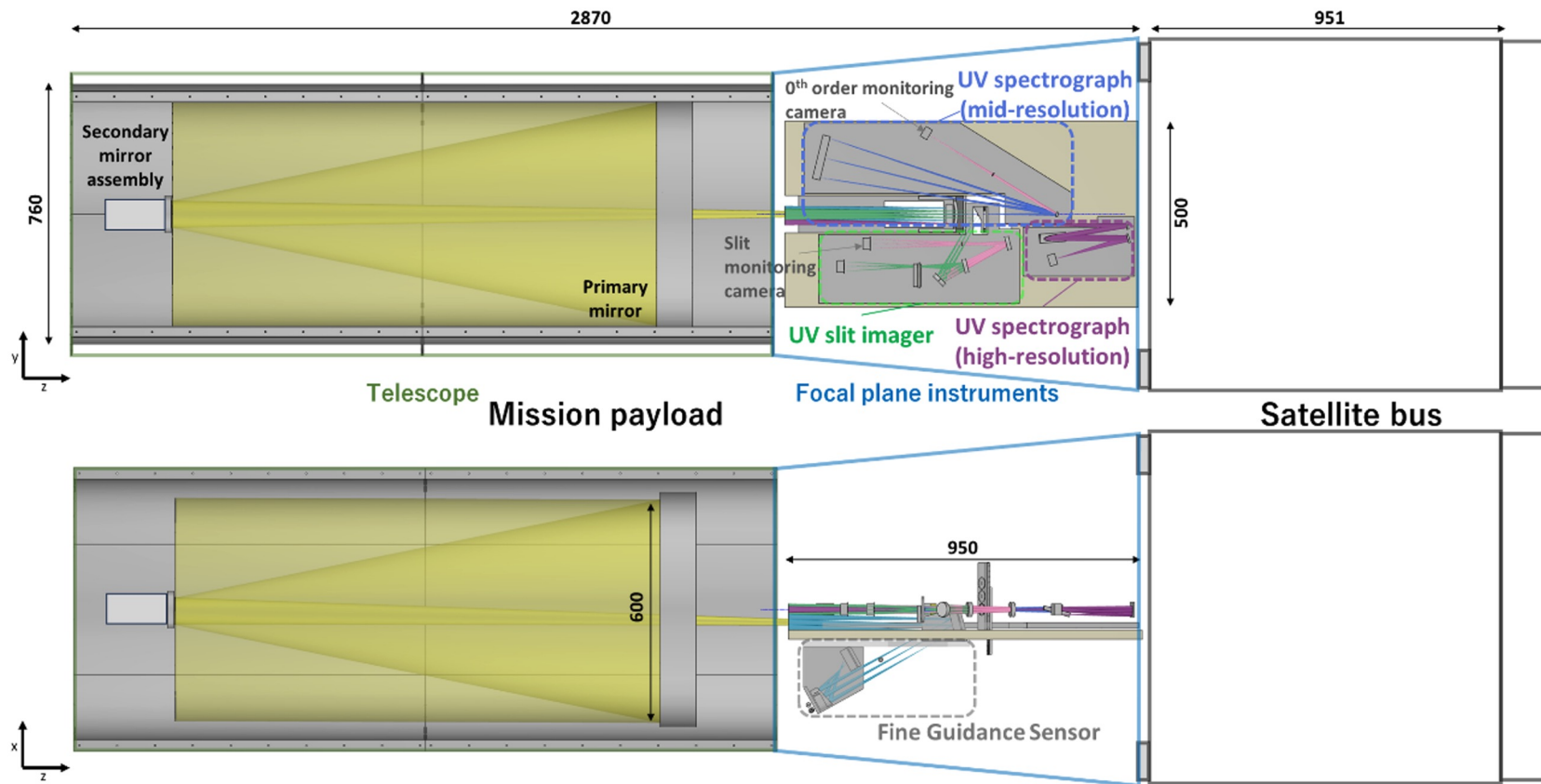
Instruments : Telescope + three instruments



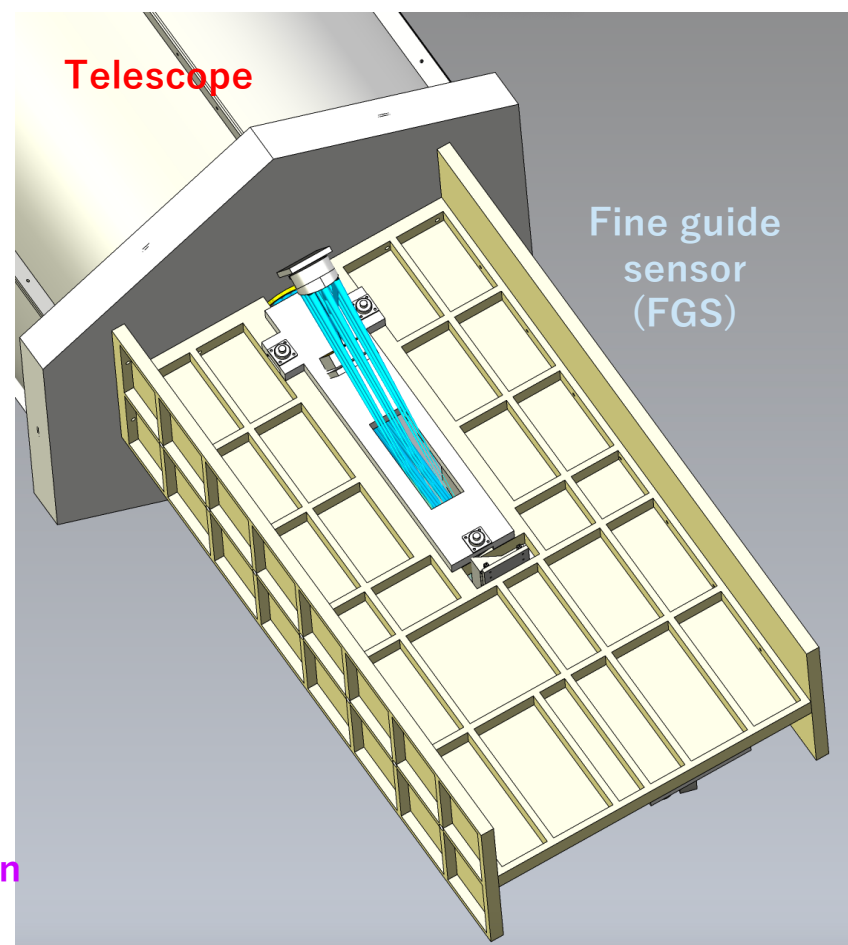
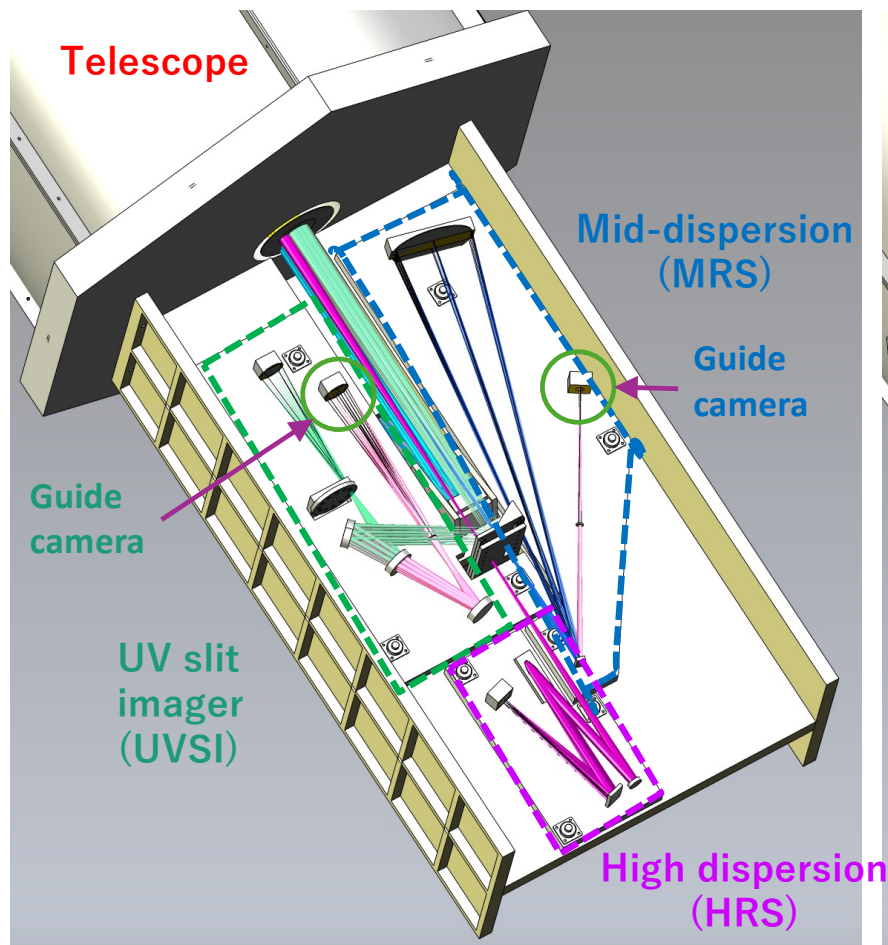
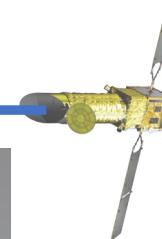
Mission payload:

A telescope + focal plane instruments

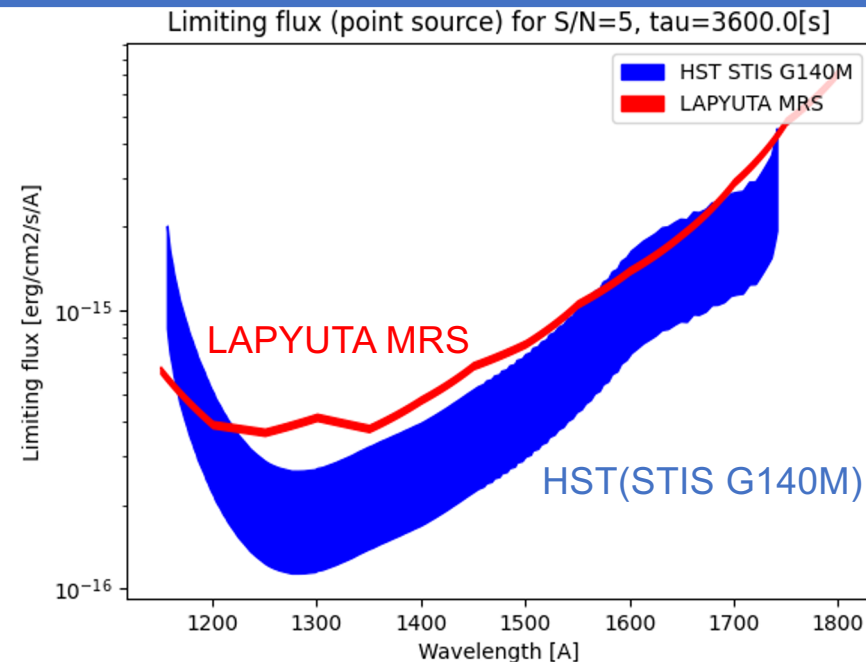
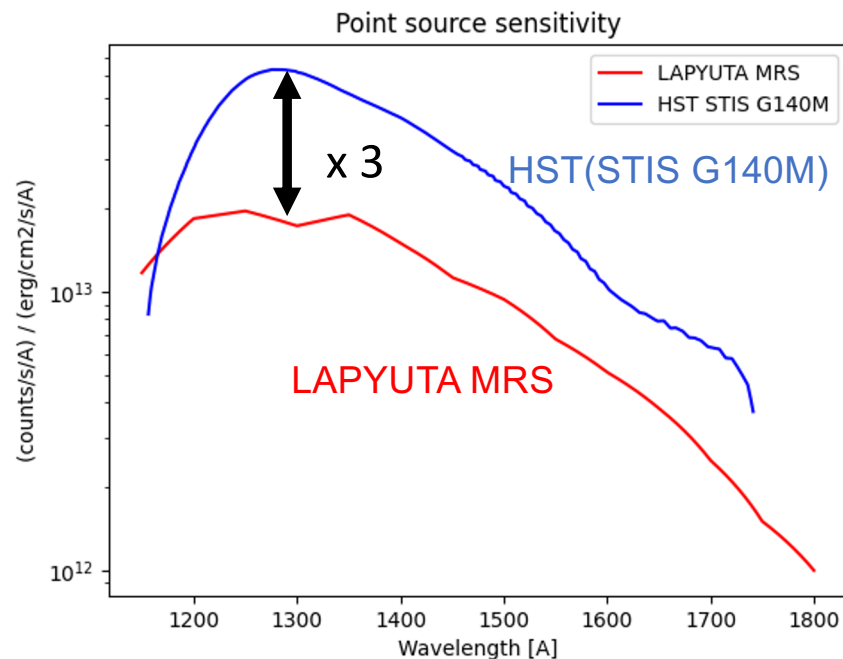
- Mid-resolution spectrograph (MRS)
- High-resolution spectrograph (HRS)
- UV slit imager (UVSI)



Instruments : Focal plane instruments



Instruments : Sensitivity (vs. HST)



HST(STIS G140M) vs. LAPYUTA(MRS)

- Primary mirror diameter
HST: 2.4m, LAPYUTA: 0.6m (x1/16)
- Throughput
HST (STIS G140M): 2%, LAPYUTA (MRS): 12% (x 6)

Comparable with the current HST/STIS performance

- Dark noise
 - HST/STIS 1.1 – 96 counts/s/cm²
(STIS Instrument Handbook)
 - LAPYUTA 0.7 – 11 counts /s/cm²
(Hisaki heritage)

Key technologies



1. MCP detector for UV

High efficiency: **funnel-type MCP**

Large format (120 x 30 mm/8k x 2k)

--- **A prototype (80 x 80mm) has been developed and is now under evaluation**

High dynamic range and resolution: **CMOS readout**

2. Mirror coating & grating

UV mirror coating

Base line: Al + MgF₂ / **90% at 130 nm achieved !**

Other coatings: Al + MgF₂ + XeF

Toroidal blazed holographic grating ~50% at 130 nm achieved

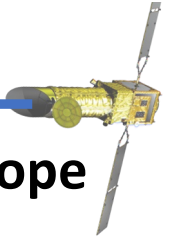
3. Pointing fluctuation cancelling system

Concept of pointing cancellation system

"Electronical image stabilization" onboard the mission system

- High-speed imaging of visible light & detection of UV photons
- Correction of the UV photon positions with reference to the centroid of the visible image.

Sciences & technologies toward HWO



**Habitable Worlds Observatory : a 6-m class UV/VIS/near-IR space telescope
(NASA)**

Engineering participation to HWO

based on technologies developed for LAPYUTA

High sensitive detector

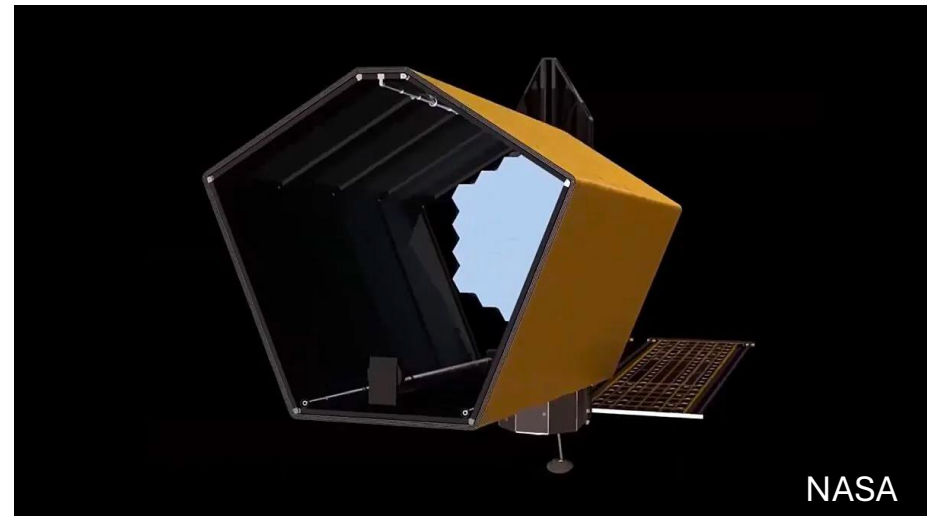
High reflectance mirror coating

Scientific participation to HWO

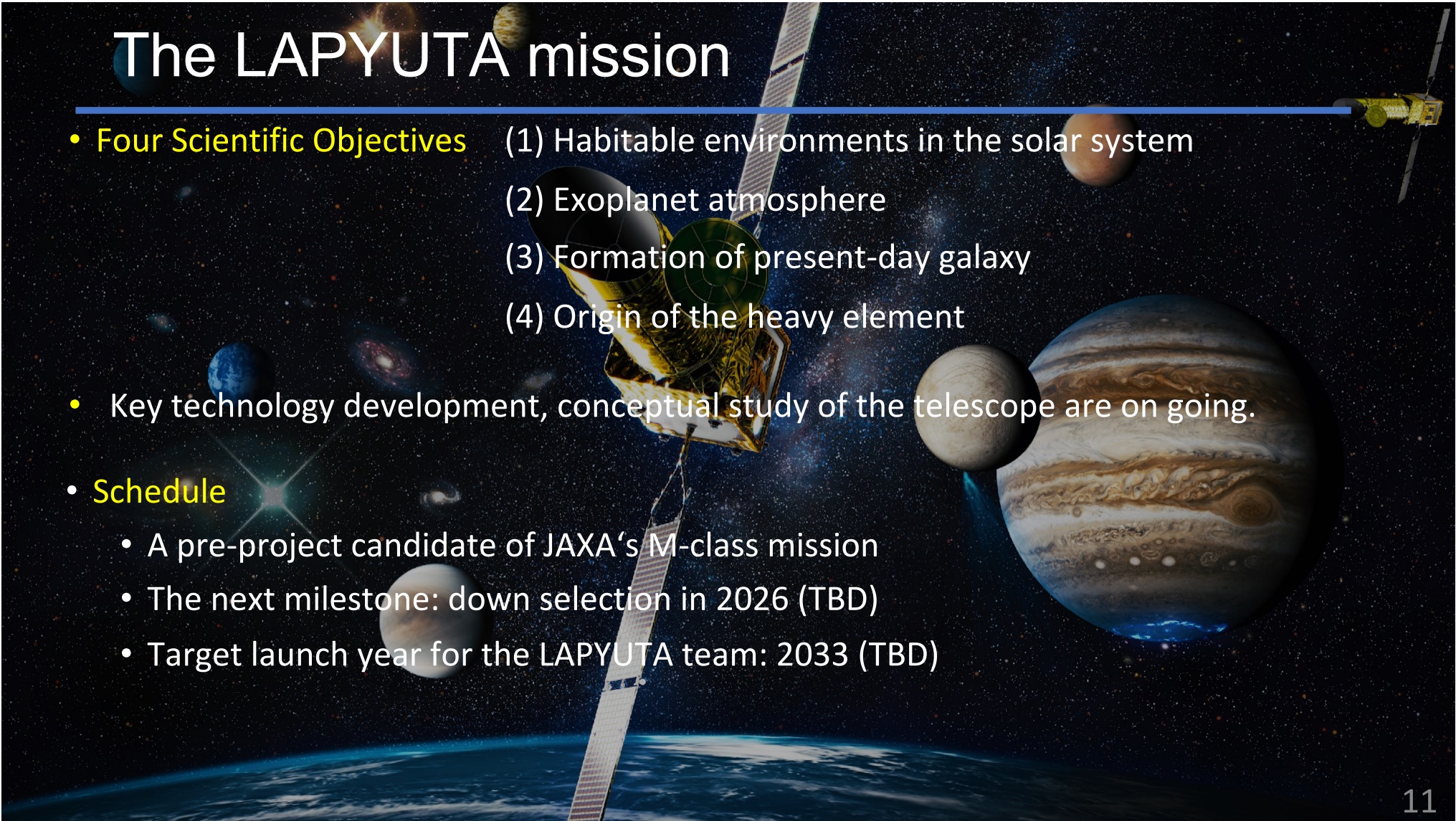
LAPYUTA could be a path finder to HWO

LAPYUTA will open a public observation slot 1-2 months/year

Proposals of UV observation are welcome.



The LAPYUTA mission



- **Four Scientific Objectives**
 - (1) Habitable environments in the solar system
 - (2) Exoplanet atmosphere
 - (3) Formation of present-day galaxy
 - (4) Origin of the heavy element
- Key technology development, conceptual study of the telescope are on going.
- **Schedule**
 - A pre-project candidate of JAXA's M-class mission
 - The next milestone: down selection in 2026 (TBD)
 - Target launch year for the LAPYUTA team: 2033 (TBD)

Electron-impact C I 156.1 nm emission as a probe of Martian ionospheric variability

Shotaro Sakai¹, Justin Deighan², Hiromu Nakagawa³, Fuminori Tsuchiya⁴, Kei Masunaga⁵, David L. Mitchell⁶, Mehdi Benna^{7,8}, Nicholas M. Schneider², Naoki Terada³, Sonal K. Jain², Majd Mayyasi⁹, Christian Mazelle¹⁰, Robert J. Lillis⁶, Shannon M. Curry², Kanako Seki¹¹

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2: Laboratory for Atmospheric and Space Physics, University of Colorado Boulder

3: Department of Geophysics, Graduate School of Science, Tohoku University

4: Planetary Plasma and Atmospheric Research Center, Graduate School of Science, Tohoku University

5: Institute of Arts and Sciences, Yamagata University

6: Space Sciences Laboratory, University of California, Berkeley

7: Center for Space Sciences and Technology, University of Maryland, Baltimore County

8: Solar System Exploration Division, NASA Goddard Space Flight Center

9: Center for Space Physics, Boston University

10: University of Toulouse, CNES, CNRS, IRAP(, Toulouse, France)

11: Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo

Lead author: Shotaro Sakai

Abstract

It is widely believed that Mars had a warm and humid climate more than 4 billion years ago, as it maintained a thick atmosphere and sustained liquid water. In contrast, present-day Mars has only a thin atmosphere, and no liquid water remains on its surface. This indicates that Mars has undergone significant atmospheric escape into space and associated atmospheric evolution over the past 4.6 billion years. A key process in understanding this evolution is the escape of carbon dioxide (CO₂) and carbon monoxide (CO), the dominant components of the Martian atmosphere. These gases escape not only as molecules but also as carbon (C) and oxygen (O) atoms or, particularly in the upper atmosphere, as ions through dissociative ionization. This suggests that carbon is a useful tracer of thermospheric CO₂ and CO variation, as well as ionospheric variability on Mars. Sakai et al. (2024) investigated the emission mechanisms of C II 133.5 nm and found that C II emission is driven by both dissociative ionization and electron impact ionization of CO₂ and CO in the lower ionosphere. Their findings suggest that C II emission may not serve as a tracer of ionospheric variability but rather as an indicator of variability in the Martian thermosphere, where CO₂ and CO dominate.

In contrast, C I emission has the potential to be a more direct tracer of Martian ionospheric variability. Lo et al. (2022) demonstrated that C I 156.1 nm emission is primarily driven by electron impact below an altitude of 140 km, where the emission is most intense. This suggests that suprathermal electrons associated with the ionosphere may play a key role in determining this emission. Gérard et al. (2026) further showed that electron impacts with both CO₂ and CO contribute significantly to C I 156.1 nm emission. The present study aims to elucidate the relationship between suprathermal electrons and C I 156.1 nm emission. Furthermore, an investigation is conducted into whether C I emission can serve as a diagnostic tool for ionospheric variability by estimating electron flux from the intensity of C I emission.

For this analysis, data from Solar Wind Electron Analyzer (SWEA) and Neutral Gas and Ion Mass Spectrometer (NGIMS) onboard the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft were used, focusing on deep dip campaigns #2 (17 – 22 April 2015), #8 (16 – 23 October

2017), and #9 (14 – 30 April 2018) as well as the aerobraking campaign (12 February – 29 March 2019). The results have indicated that C I 156 nm emission is proportional to the integrated electron flux, particularly in the energy range of 25 – 400 eV, and the CO₂ density rather than to altitude. In contrast, Imaging Ultraviolet Spectrograph (IUVS) onboard MAVEN has observed C I emission brightness approximately one order of magnitude greater than that inferred from in-situ observations. Even when observations are made at the same altitude, differences in CO₂ density can alter the relative contributions of multiple C I emission processes; therefore, the brightness observed by IUVS may be higher than that observed in situ. Electron impact on CO can contribute up to about 30% of the C I emission relative to that produced by electron impact on CO₂. However, at altitudes where CO₂ density exceeds 10¹⁰ cm⁻³, electron-impact C I emission remains dominant, indicating that this emission can serve as a tracer of suprathermal electrons in the Martian ionosphere.

References:

- Gérard, J. C., Soret, L., Hubert, B., Lillis, R., Jain, S., & Deighan, J. (2026). Far ultraviolet carbon emissions in the Mars aurora: Brightness, intensity ratios and seasonal dependence. *Icarus*, 448, 116919. <https://doi.org/10.1016/j.icarus.2025.116919>
- Lo, D. Y., Yelle, R. V., Deighan, J. I., Jain, S. K., Evans, J. S., Stevens, M. H., et al. (2022). MAVEN/IUVS observations of C I 156.1 nm and 165.7 nm dayglow: Direct detection of carbon and implications on photochemical escape. *Icarus*, 371, 114664. <https://doi.org/10.1016/j.icarus.2021.114664>
- Sakai, S., Nakagawa, H., Deighan, J., Jain, S. K., Masunaga, K., Tsuchiya, F., et al. (2024). C⁺ 133.5 nm emission mechanisms on Mars revealed by the MAVEN observations. *Ap. J.*, 977:226. <https://doi.org/10.3847/1538-4357/ad8e35>

More than 4 billion years ago, Mars is thought to have had a warm climate, a thick atmosphere, and liquid water on its surface. Today, however, Mars has a very thin atmosphere, indicating that much of its atmosphere has escaped into space over time. Understanding how this atmospheric loss occurred is essential for revealing how Mars evolved from a potentially habitable planet into the cold and dry world seen today.

This study investigates ultraviolet emissions from carbon atoms in the Martian upper atmosphere using observations from the MAVEN spacecraft. Previous studies suggested that emissions from ionized carbon mainly reflect variations in the neutral upper atmosphere rather than changes in the ionosphere. In contrast, neutral carbon emissions may provide a more direct way to trace energetic electrons in the Martian ionosphere. We analyzed measurements obtained during multiple deep atmospheric observation campaigns and examined the relationship between carbon emissions, electron flux, and atmospheric density.

The results show that carbon emission at 156.1 nm is strongly correlated with suprathermal electron flux, particularly for electrons with energies between 25 and 400 eV, as well as with carbon dioxide density. Although carbon monoxide also contributes to the emission, carbon dioxide remains the dominant source in most regions of the Martian upper atmosphere. These findings indicate that carbon emission can serve as a diagnostic tool for investigating ionospheric variability and energetic electron activity on Mars. This approach may help improve our understanding of atmospheric escape processes and the long-term evolution of the Martian atmosphere.



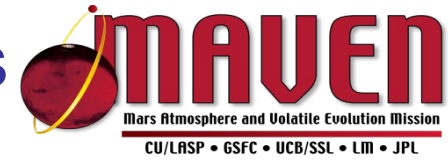
HWO Japan Science Workshop 2,
JAXA/ISAS, 16 July 2026

Electron-impact C I 156.1 nm emission as a probe of Martian ionospheric variability

*Shotaro Sakai¹, J. Deighan², H. Nakagawa³, F. Tsuchiya³, K. Masunaga⁴, D. L. Mitchell⁵,
M. Benna^{6,7}, N. M. Schneider², N. Terada³, S. K. Jain², M. Mayyasi⁸, C. Mazelle^{9,10},
R. J. Lillis⁵, S. M. Curry², K. Seki¹¹*

*1: Keio University SFC, 2: LASP, University of Colorado Boulder, 3: Tohoku University, 4: Yamagata University,
5: SSL, University of California, Berkeley, 6: CSST, University of Maryland, 7: NASA GSFC, 8: CSP, Boston University,
9: UPS-OMP, Université de Toulouse, 10: CNRS, IRAP, 11: University of Tokyo*

UV observations and atmospheric escape on Mars

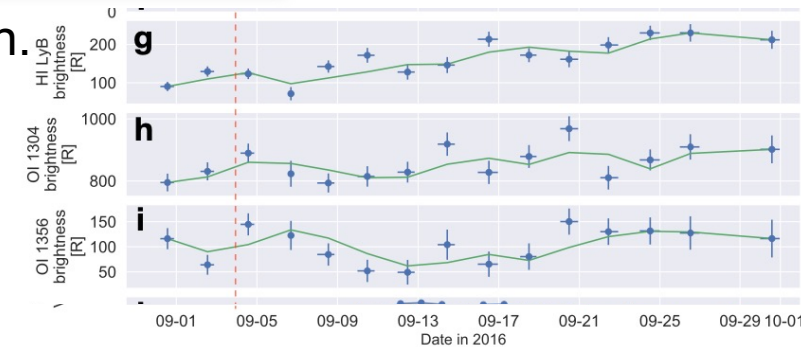


UV observation: Investigating the upper atmospheric distribution.

- Associated with the atmospheric escape.
- Suitable for looking at the internal/external effects.

Effects of dust storms and solar events on the H and O distribution from Hisaki (Masunaga+, 2020, 2022).

- Global H and O observations

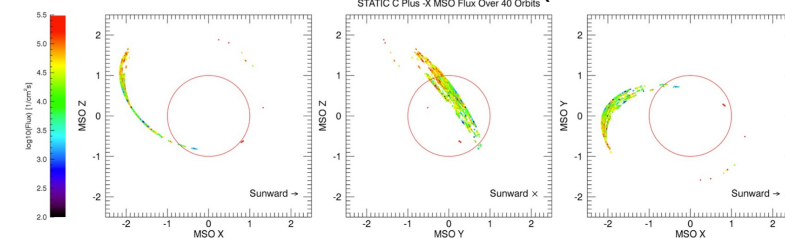


H and O brightness observed by Hisaki (Masunaga+, 2022, dev.)

Martian (& Venusian) atmosphere: CO₂ (and CO), so **C is also important!**

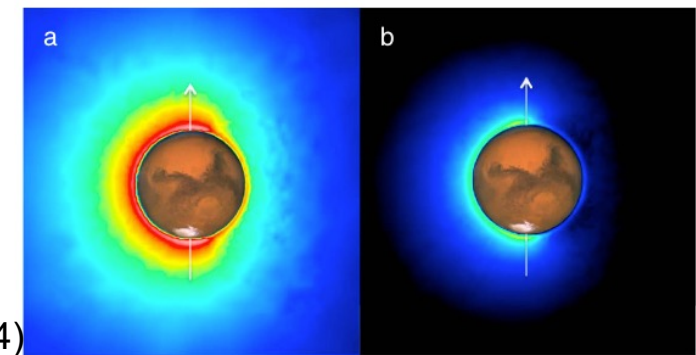
- Exists as C⁺ and C in the upper atmosphere.
 - Limited C⁺ observations by MAVEN/STATIC (Pickett+, 2022; Hanley+, 2024).
 - C corona by modeling (e.g., Lee+, 2014)
- Global C observations have just started or not yet been done.

C⁺ flux (Pickett+, 2022)



Our motivation is to investigate the ionospheric and thermospheric variability from global C observations.

C corona (Lee+, 2014)

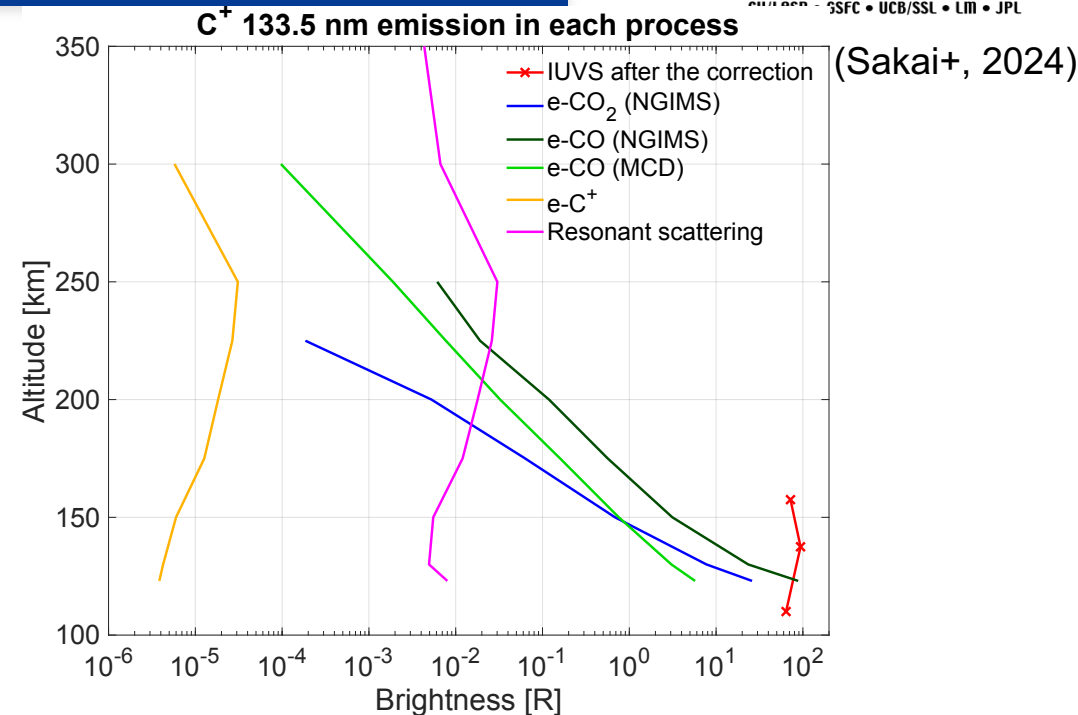


What is the dominant mechanism of C II emission?



Dominant processes of C II (C^+) emission

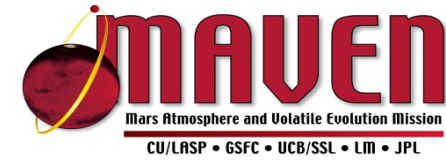
- Large CO density case (NGIMS)
 - $h < 150$ km: DI/PI and EI
 - 82% DI/PI, 18% EI
 - $150 < h < 175$ km: DI/PI
- Small CO density case (MCD-LMD)
 - $h < \sim 200$ km: DI/PI



C II emission as the ionospheric tracer on Mars?

- C II emission mostly comes from DI/PI of CO_2 and CO and partially from EI.
 - It only reflects the variation of CO_2 and CO in the thermosphere.
- It is also difficult to figure out the suprathermal electron distribution associated with EI because of the small contribution of EI to emission.
 - **C II emission cannot be a tracer of ionospheric variation.**

Can we use C I emission as a tracer?

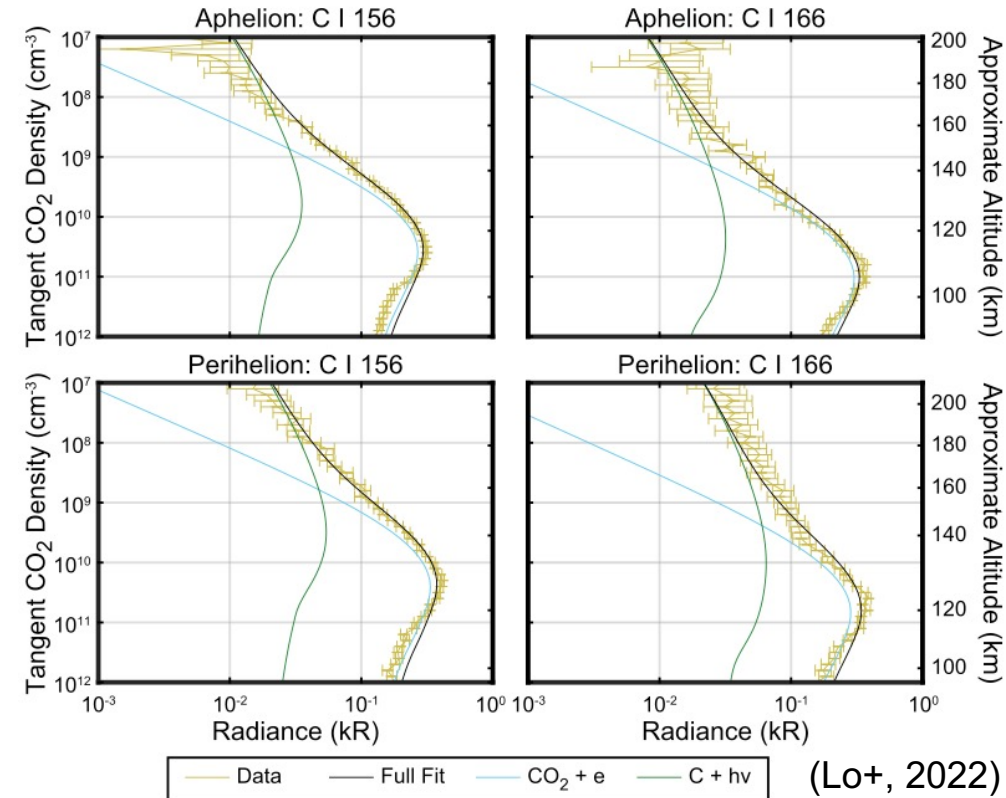


C I emission is a candidate for an ionospheric tracer because EI dominates the emission (Lo+, 2022)

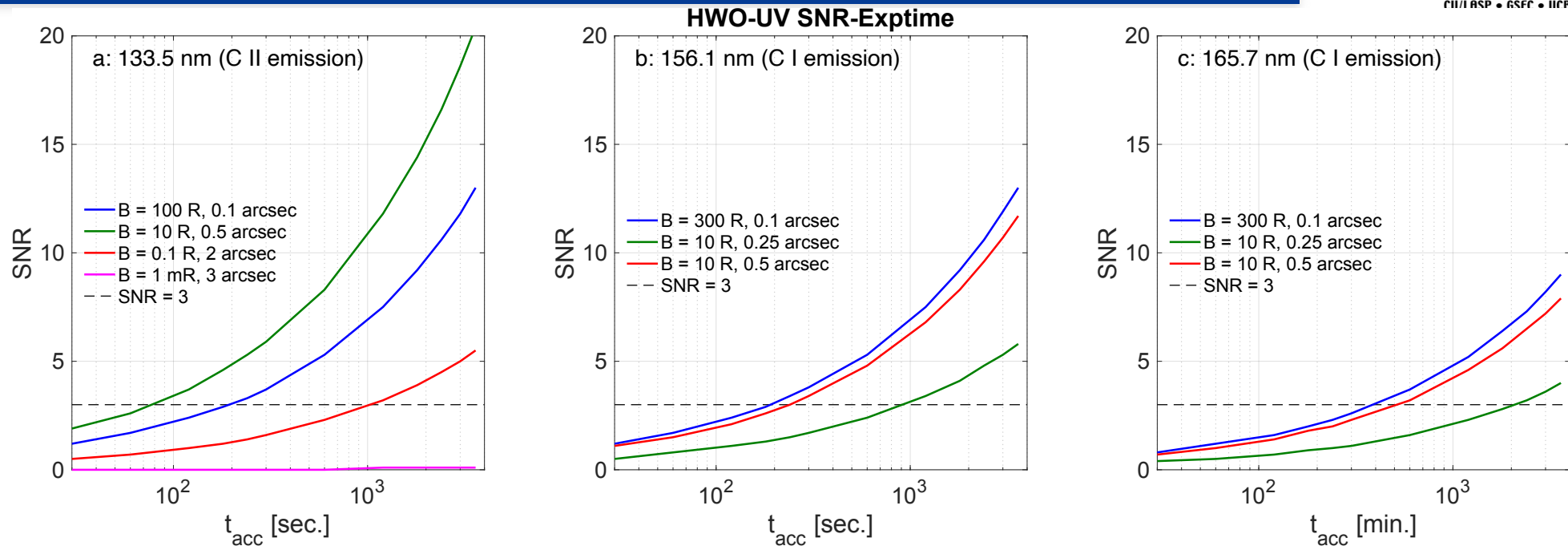
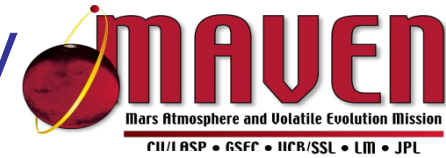
→ **Both C I and C II emissions are important for understanding the variability of the ionosphere and thermosphere at Mars.**

C I emission processes?

- EI with CO₂ is dominant at low altitudes around 130 km, particularly in 156.1 nm emission.



Feasibility study of C I & C II emissions for HWO-UV



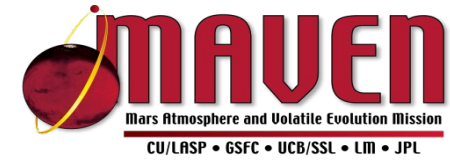
Mars: 20 arcsec

- 0.1 arcsec ~ 35 km
- 0.5 arcsec ~ 175 km
- 1 arcsec ~ 350 km

Venus: 25 arcsec

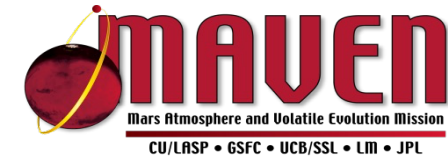
- 0.1 arcsec ~ 50 km
- 0.5 arcsec ~ 250 km
- 1 arcsec ~ 500 km

Summary



- C II emission cannot be an ionospheric tracer
 - C II emission mostly comes from DI/PI of CO₂ and CO and partially from EI.
 - It is also difficult to figure out the suprathermal electron distribution associated with EI because of the small contribution of EI to emission.
 - C I emission (maximum) by electron impact estimation from SWEA and NGIMS
 - DD2: ~300 R (at 135 km), DD8 & DD9: ~100 R (at ~125 km), DD4 & DD7: 10 – 20 R (at ~130 km)
 - C I emission can be a candidate for an ionospheric tracer on the dayside.
 - EI dominates the emission and correlates with integrated electron flux (25 – 400 eV).
 - Comparison with IUVS observations
 - Brightness from IUVS observations is much greater than the brightness estimated from SWEA and NGIMS observations.
 - Other emission processes, such as resonant scattering, can be contaminated at higher altitudes.
- The C I 156.1 nm emission can serve as a tracer of suprathermal electrons in CO₂-rich regions of the Martian lower ionosphere on the dayside.

References



- Avakyan, S. V., Il'in, R. N., Lavrov, V. M., & Ogurtsov, G. N. (1998). *Collision Processes and Excitation of UV Emission from Planetary Atmospheric Gases: A Handbook of Cross Sections*. Amsterdam, Netherlands: Gordon and Breach Science Publishers.
- Lee, Y., Combi, M. R., Tennishev, V., & Bougher, S. W. (2014). Hot carbon corona in Mars' upper thermosphere and exosphere: 1. Mechanisms and structure of the hot corona for low solar activity at equinox. *Journal of Geophysical Research: Planets*, 119, 905-924. <https://doi.org/10.1002/2013JE004552>
- Lillis, R. J., Deighan, J., Fox, J. L., Bougher, S. W., Lee, Y., Combi, M. R., et al. (2017). Photochemical escape of oxygen from Mars: First results from MAVEN in situ data. *Journal of Geophysical Research: Space Physics*, 122, 3815-3836. <https://doi.org/10.1002/2016JA023525>
- Lo, D. Y., Yelle, R. V., Lillis, R. J., & Deighan, J. I. (2021). Carbon photochemical escape rates from the modern Mars atmosphere. *Icarus*, 360, 114371. <https://doi.org/10.1016/j.icarus.2021.114371>
- Lo, D. Y., Yelle, R. V., Deighan, J. I., Jain, S. K., Evans, J. S., Stevens, M. H., et al. (2022). MAVEN/IUVS observations of C I 156.1 nm and 165.7 nm dayglow: Direct detection of carbon and implications on photochemical escape. *Icarus*, 371, 114664. <https://doi.org/10.1016/j.icarus.2021.114664>.
- Masunaga, K., Yoshioka, K., Chaffin, M. S., Deighan, J., Jain, S. K., Schneider, N. M., et al. (2020). Martian oxygen and hydrogen upper atmospheres responding to solar and dust storm drivers: Hisaki space telescope observations. *Journal of Geophysical Research: Space Physics*, 125, e2020JE006500. <https://doi.org/10.1029/2020JE006500>
- Masunaga, K., Terada, N., Yoshida, N., Nakamura, Y., Kuroda, T., Yoshioka, K., et al. (2022). Alternate oscillations of Martian hydrogen and oxygen upper atmospheres during a major dust storm. *Nature Communications*, 13, 6609. <https://doi.org/10.1038/s41467-022-34224-6>
- McClintock, W. E., Schneider, N. M., Holsclaw, G. M., Hoskins, A. C., Stewart, I., Deighan, J., et al. (2015). The Imaging UltraViolet Spectrograph (IUVS) for the MAVEN mission. *Space Science Reviews*, 195, 75-124. <https://doi.org/10.1007/s11214-014-0098-7>
- Pickett, N. B., McFadden, J. P., Fowler, C. M., Hanley, H. G., & Benna, M. (2022). Carbon ion fluxes at Mars: First results of tailward flows from MAVEN-STATIC. *Journal of Geophysical Research: Space Physics*, 127, e2021JA029635. <https://doi.org/10.1029/2021JA029635>
- Tsuchiya, F., Murakami, G., Yamazaki, A., Kameda, S., Kimura, T., Koga, R., et al. (2024). Overview of the LAPYUTA mission (Life-environmentology, Astronomy, and Planetary Ultraviolet Telescope Assembly). *Proceedings of SPIE 13093, Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray*, 130930I. <https://doi.org/10.1117/12.3017298>

From Roman to Habitable Worlds: Science Planning for the Future of Exoplanet and Disk Imaging

Lead author: Masayuki Kuzuhara

Abstract: The primary goal of the Habitable Worlds Observatory (HWO) is to detect light from habitable planets and characterize their surfaces, enabling the search for biosignatures. The Roman Space Telescope, scheduled to be launched this summer, will demonstrate the high-contrast imaging technologies necessary to image habitable planets with HWO. In parallel with these technology demonstrations, the Roman Coronagraph mission will maximize its scientific return. The Roman Coronagraph instrument will be capable of detecting objects with flux ratios below $1\text{E-}07$ at visible wavelengths. With this unprecedented contrast performance, the mission will observe known self-luminous planets and brown dwarfs, debris disks, and exozodiacal dust. In addition, the mission will attempt to achieve contrasts of $1\text{E-}08$ to $1\text{E-}09$ in order to detect, for the first time, starlight reflected by Jovian planets. In this talk, we will present the latest science planning for the Roman Coronagraph mission. We will also discuss the limitations of the Roman Coronagraph's performance. In the future, HWO will provide the capabilities needed to address science cases beyond the reach of the Roman Coronagraph. We therefore present preliminary HWO science cases that build upon and extend the science enabled by Roman.

Science Case Summary

With the Roman Coronagraph, achieving contrast levels better than $1\text{E-}08$ will be possible only for a limited number of targets. In addition, the Roman Coronagraph is not well suited for observations of stellar hosts fainter than $V = 6$ mag. Therefore, full-scale characterization of reflected light from giant planets will be a major scientific focus for HWO, especially with infrared and ultraviolet coronagraphic capabilities. Furthermore, self-luminous giant planets in star-forming regions will be excellent targets for HWO, as these regions are typically located at distances beyond 100 pc. Finally, measurements of the obliquities of giant planets and brown dwarfs with HWO and ELT will be highly valuable, potentially enabling the discovery and characterization of an exo-Uranus.



From Roman to Habitable Worlds: Science Planning for the Future of Exoplanet and Disk Imaging

M. Kuzuhara (ABC/NAOJ)

The slides in this talk is the version created by editing the slides of Schuyler Wolff (Univ. of Arizona) in the Spirit of the Lyot 2026



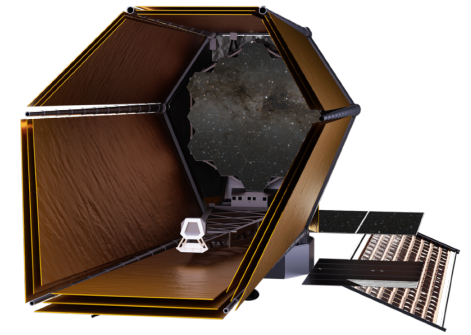
Roman Coronagraph as a Science TestBed Toward the HWO Coronagraph



Roman



HWO



Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

- First detection of reflected light from **Jovian** planet, etc

- First detection of reflected light from **Earth-like** planet, etc

- Development of items that are necessary for the success of the project
- We can learn what we need to prepare for HWO from Roman



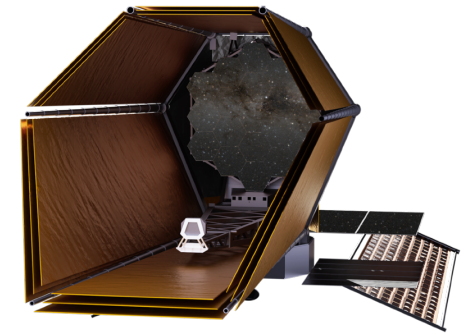
Roman Coronagraph as a Science TestBed Toward the HWO Coronagraph



Roman



HWO



Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

- First detection of reflected light from **Jovian** planet, etc

- First detection of reflected light from **Earth-like** planet, etc

Roman is a testbed for sciences of HWO as well

Observation Planning Team in Community Participation Program (CPP)



- CPP is planning observations, developing tools such as data reduction pipelines, preparing calibration methods, etc.
- Many members with various backgrounds are working in the observation planning team led by Schuyler Wolff (entire CCP lead by V. Bailey and S. Wolff)
- MK (for companions) and Toshiyuki Mizuki (for disks) are contributing to the observation planning from JAXA



Roman Coronagraph Mission Observing Strategy

- Baseline: 2200hr (90 days) during first 18mo of Mission
- Top priority: achieve Technology Requirement
 - Flux ratio of 10^{-7} on a $V \sim 5$ star in Band 1 (575 nm)
- As time/resources allow, push performance limits and commission additional observing modes
- Prioritize scientifically-interesting targets when possible
 - Roman data has no proprietary period
- Planing observations during the first 6mo was finished

Observation Plans Benefit From Community Input



Community Input

- Jan. 2025 Community Interest Survey
- Summer 2025 White Paper (WP) Call (N~80)
- Gap-filling WP from CPP



Observation
Programs

Observation Plans Benefit From Community Input



Community Input

Many suggestions for detecting reflected lights from Jovian planets

- Jan. 2025 Community Interest Survey
- Summer 2025 White Paper (WP) Call (N~80)



Observation Programs

- Gap-filling WP from CPP



Early Observation Plans and High Priorities

- Note
 - Available targets can change depending on some undecided restrictions
- We will first test the required contrast performance (10^{-7} in Band 1 = 575 nm) with moderate contrast test system: likely HIP 71618 B
- High Impact Science Goals:
 - Reflected light planets: ups And d, Eps Eri b, +
 - Debris Disks and exozodi observations: Eps Eri, eta Crv, HR 4796
- Technology Demonstration beyond TTR5



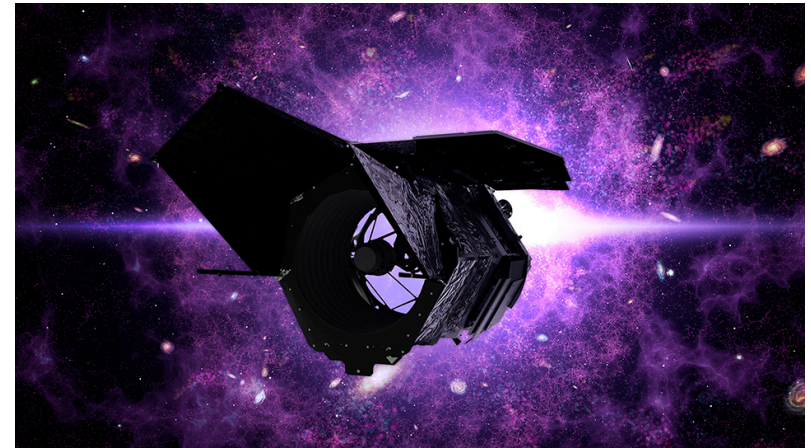
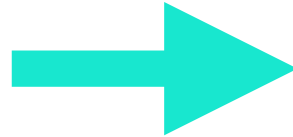
Subaru Contributions to the Roman Coronagraph



Credit: NAOJ, SExAO Team



SExAO: extreme adaptive optics
CHARIS: Integral Field Unit (IFU) Spectrograph



Credit: GSFC/SVC

**We contribute to the Roman Coronagraph
via the Subaru intensive survey**

PI. T. Currie/Deputy PI. M. Kuzuhara

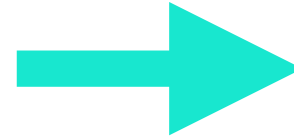


Subaru Contributions to the Roman Coronagraph

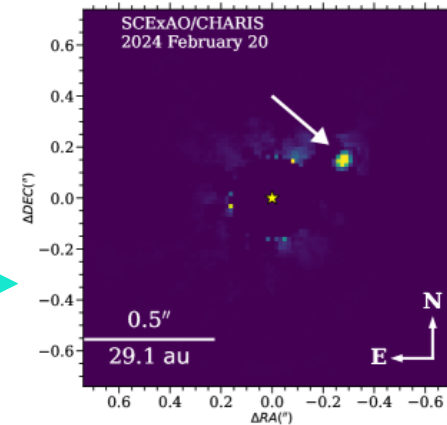


Credit: NAOJ, SCEAO Team

SCEAO: extreme adaptive optics
CHARIS: Integral Field Unit (IFU) Spectrograph

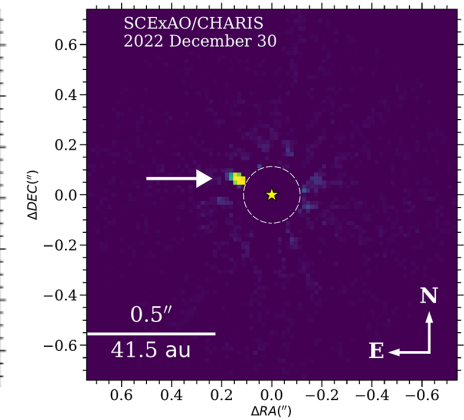


HIP 71618 B



El Morsy et al. 2025

HIP 54515 b



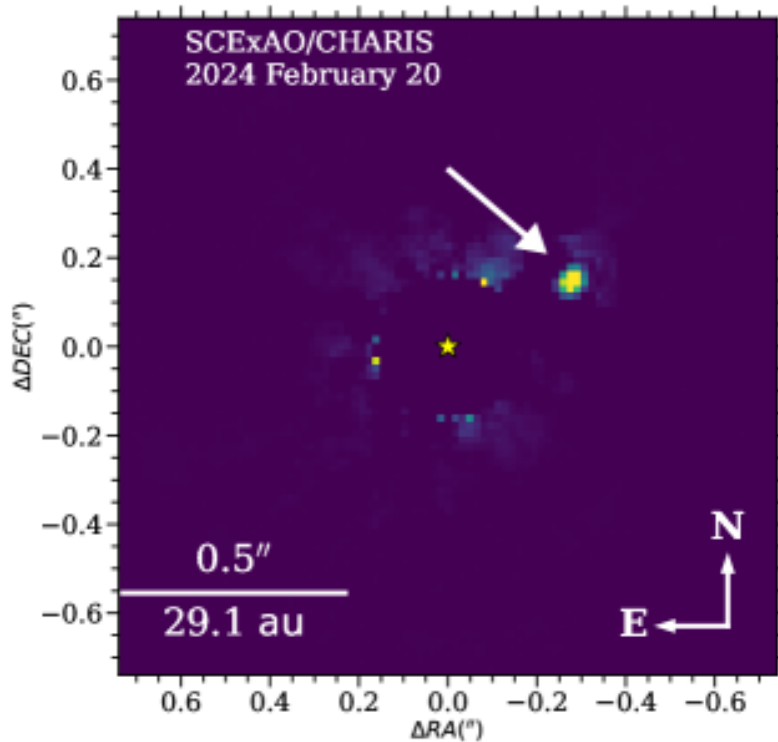
Currie+Li et al. 2025

**We contribute to the Roman Coronagraph
via the Subaru intensive survey**

PI. T. Currie/Deputy PI. M. Kuzuhara



HIP 71618 B from the Subaru/SCExAO Intensive Program

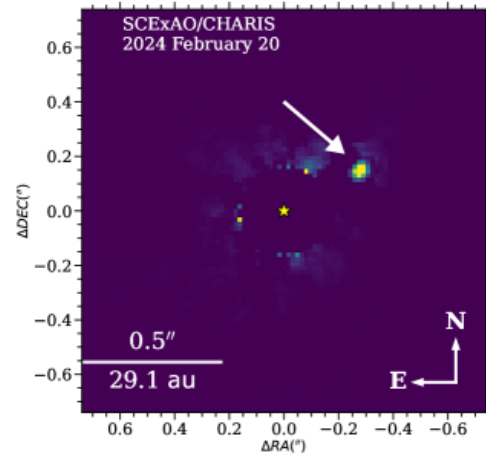


El Morsy et al. 2025

- SCExAO/CHARIS Intensive Program is now ongoing to search for substellar companions (Pl. T. Currie/Deputy Pl. M. Kuzuhara)
- One of the big motivations is to supply a target for the Roman Coronagraph mission
- HIP 71618 B, discovered by this survey, will be (most-likely) observed as a primary tech. demo. target

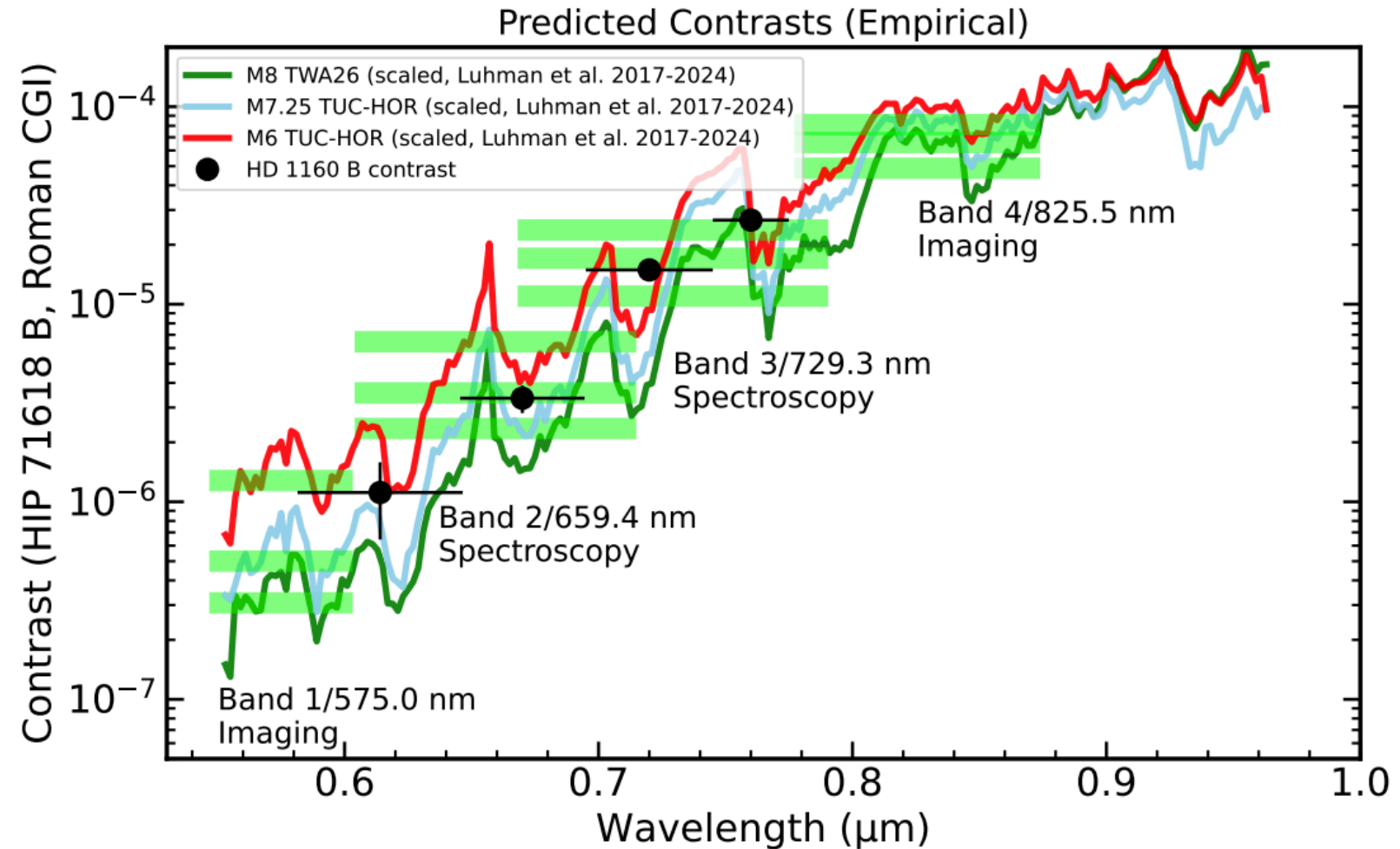


HIP 71618 B from the Subaru/SCEXAO Intensive Program

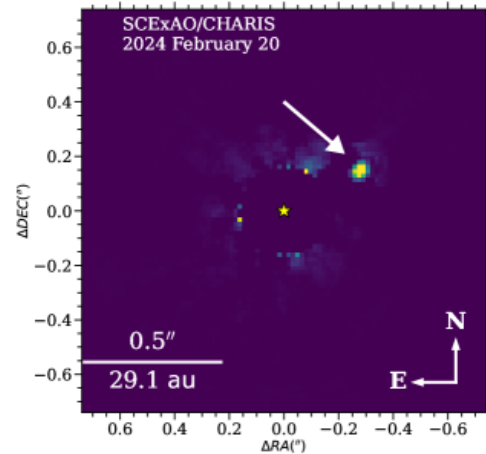


HIP 71618 B:
A self-luminous
high-mass brown
dwarf candidate

El Morsy et al. 2025

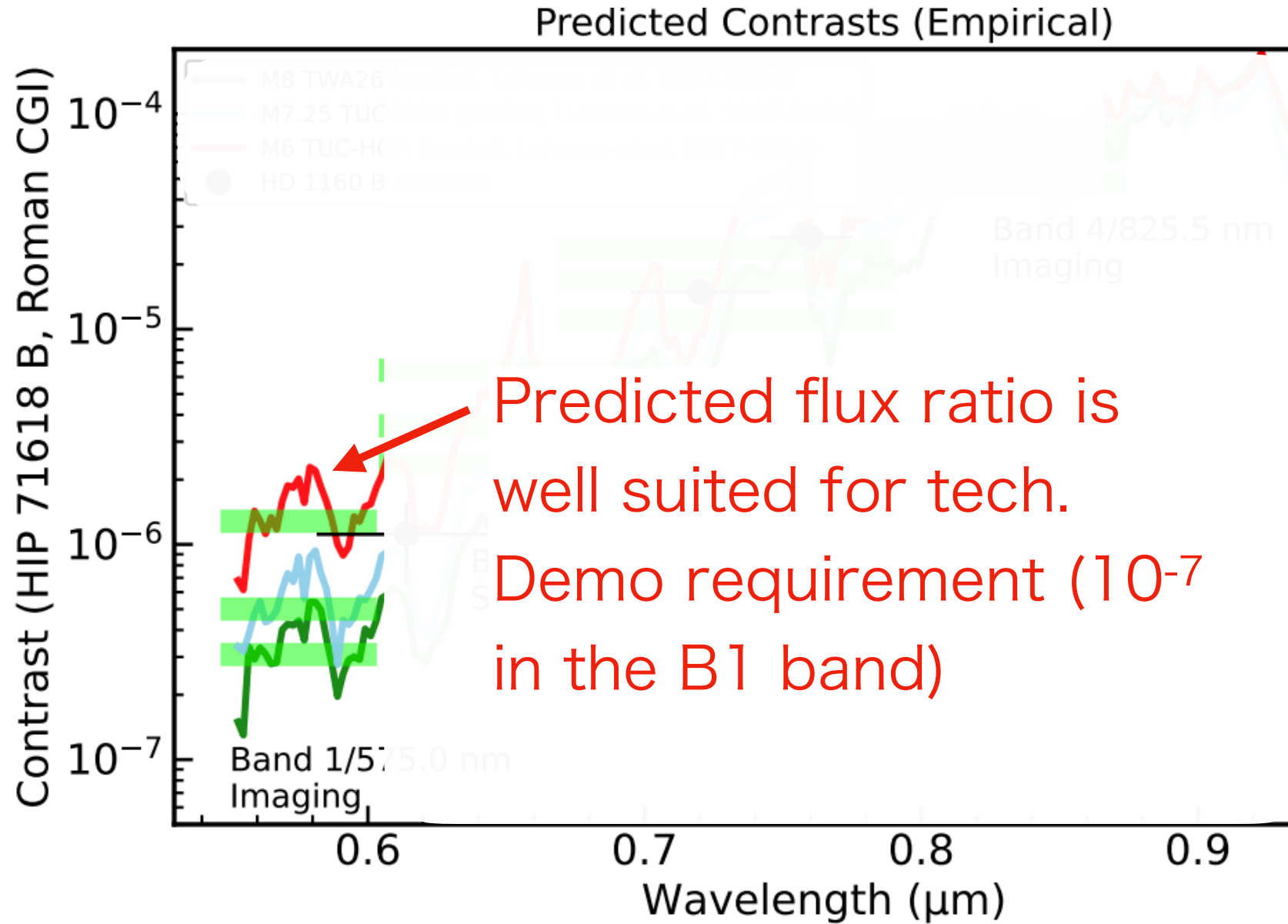


HIP 71618 B



HIP 71618 B:
A self-luminous
high-mass brown
dwarf candidate

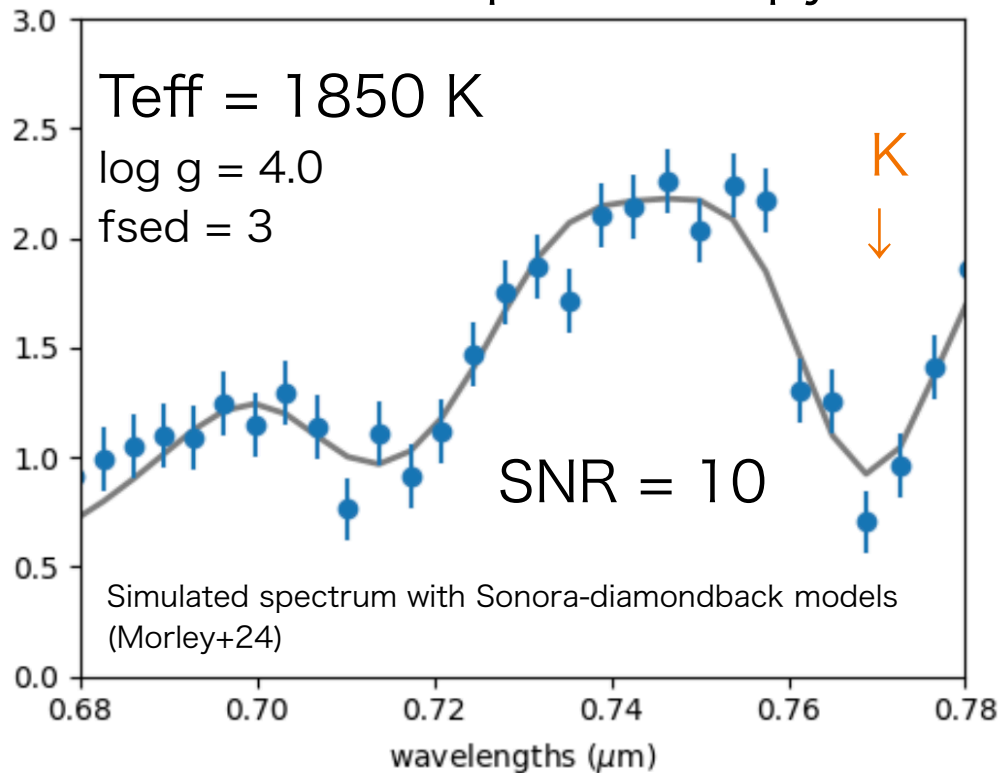
El Morsy et al. 2025



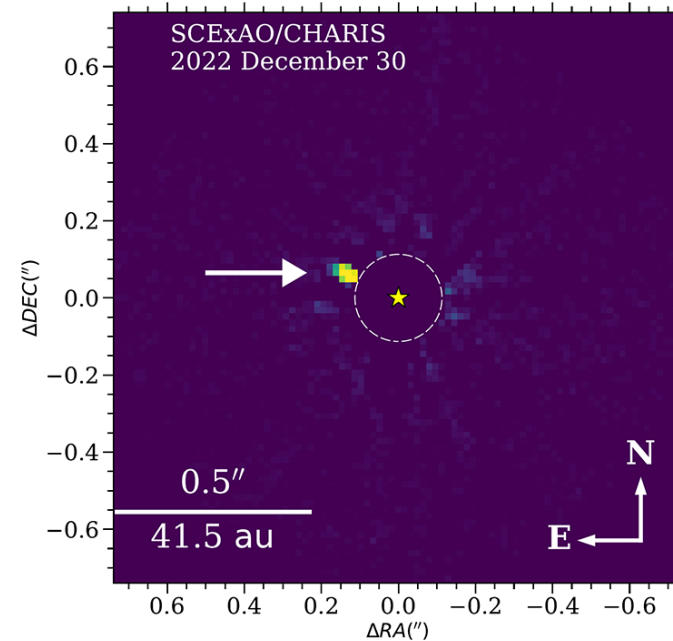


HIP 54515 b as a spectroscopy target

B3 mode spectroscopy



- HIP 54515 b: Mass = $18 (+8, -5) M_{\text{Jup}}$



Currie+Li et al. 2026

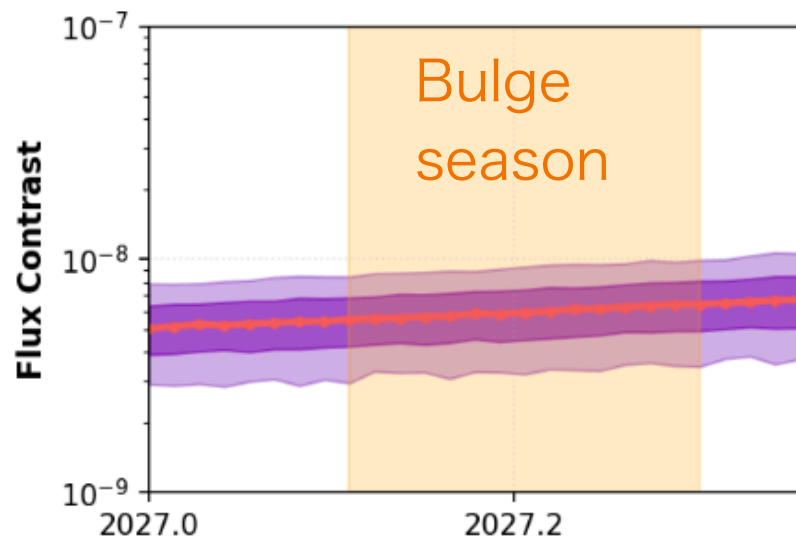


Imaging of Reflected Light Planets

ups And d HLC B1

- ups And d: $M_p \sin i = 4 M_{\text{Jup}}$ at $a = 2.5$ au
(Wright+2009)

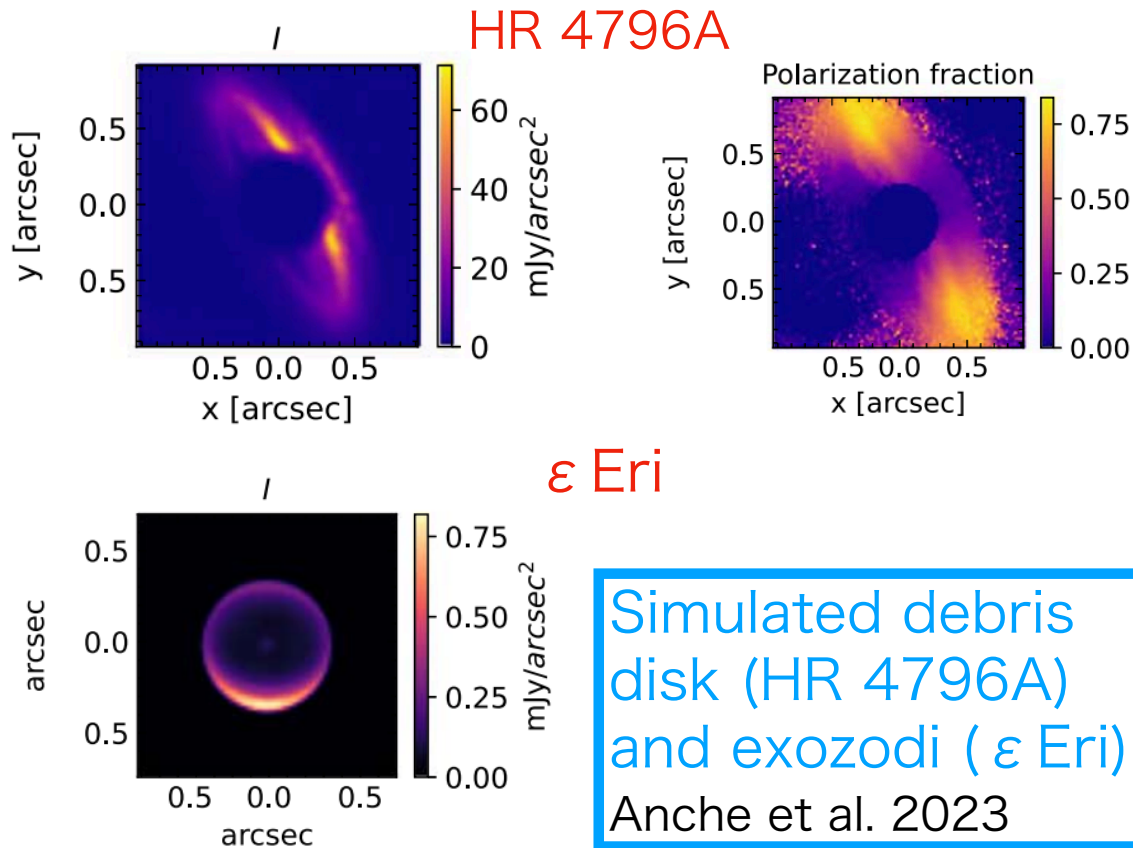
→ predicted separation = 0.15-0.20 arcsec



Courtesy of C. Do O, E. Bogat, A. Vigan

- Necessary performance better than 10^{-8}
- Detection of reflected light from ups And d may be possible assuming an optimistic performance (note that total wall clock time is much longer)
- Another high-priority target is Eps Eri

Some Ideas of Disk Imaging

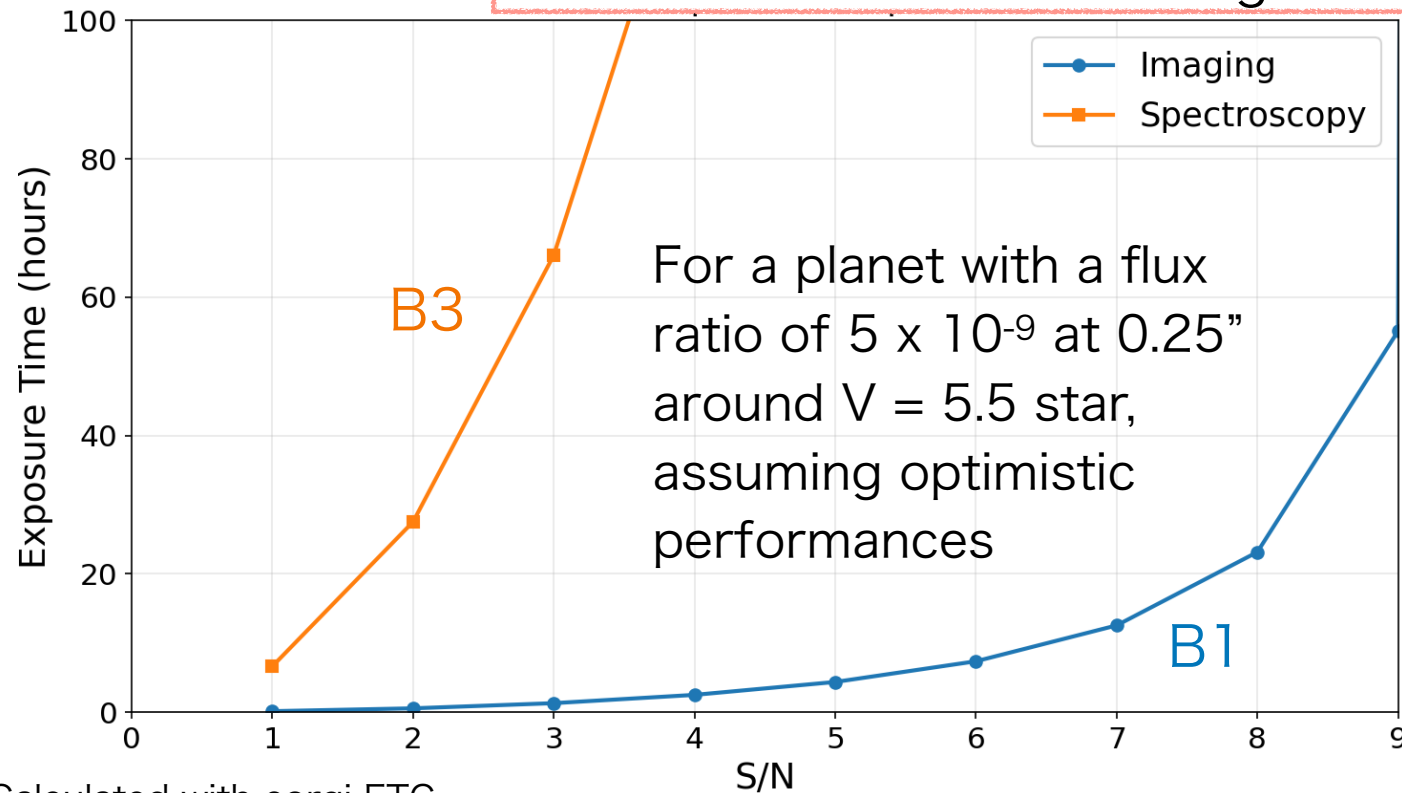


- Observation of the debris disk around HR 4796A to understand its extended structure and the polarimetry performance
- Imaging of exozodiacal dusts



Limitation of the Roman Coronagraph

Observation of Reflected-Light Planets

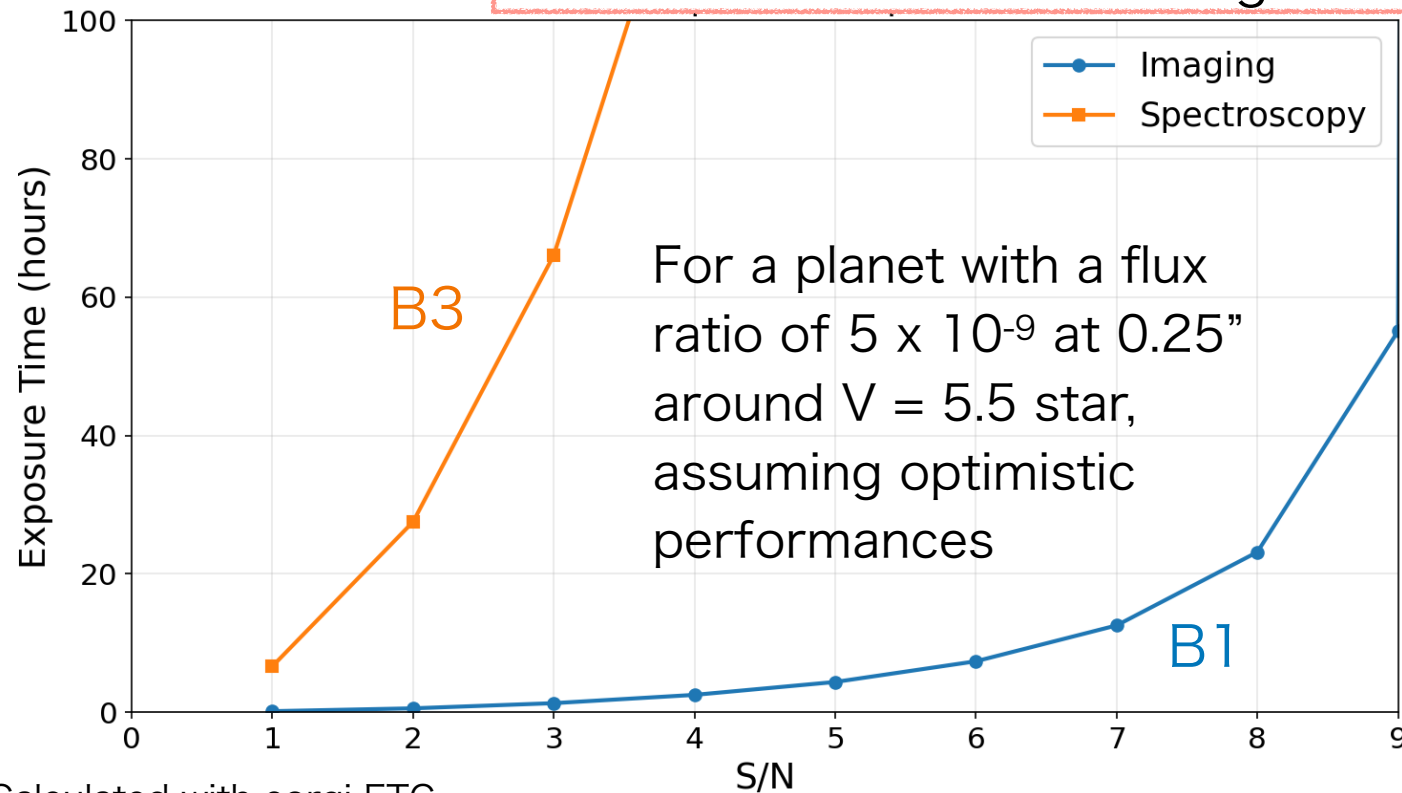


Calculated with corgi ETC



Limitation of the Roman Coronagraph

Observation of Reflected-Light Planets



Calculated with corgi ETC

- Possible for limited targets
- High quality characterization (e.g., high-SNR photometry or spectroscopy) of a reflected-light planet is still challenging

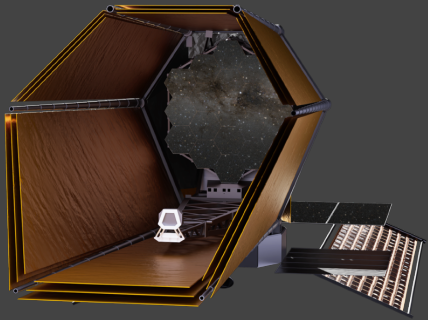
Pass the baton from Roman to HWO: Potential Science Cases (Preliminary)



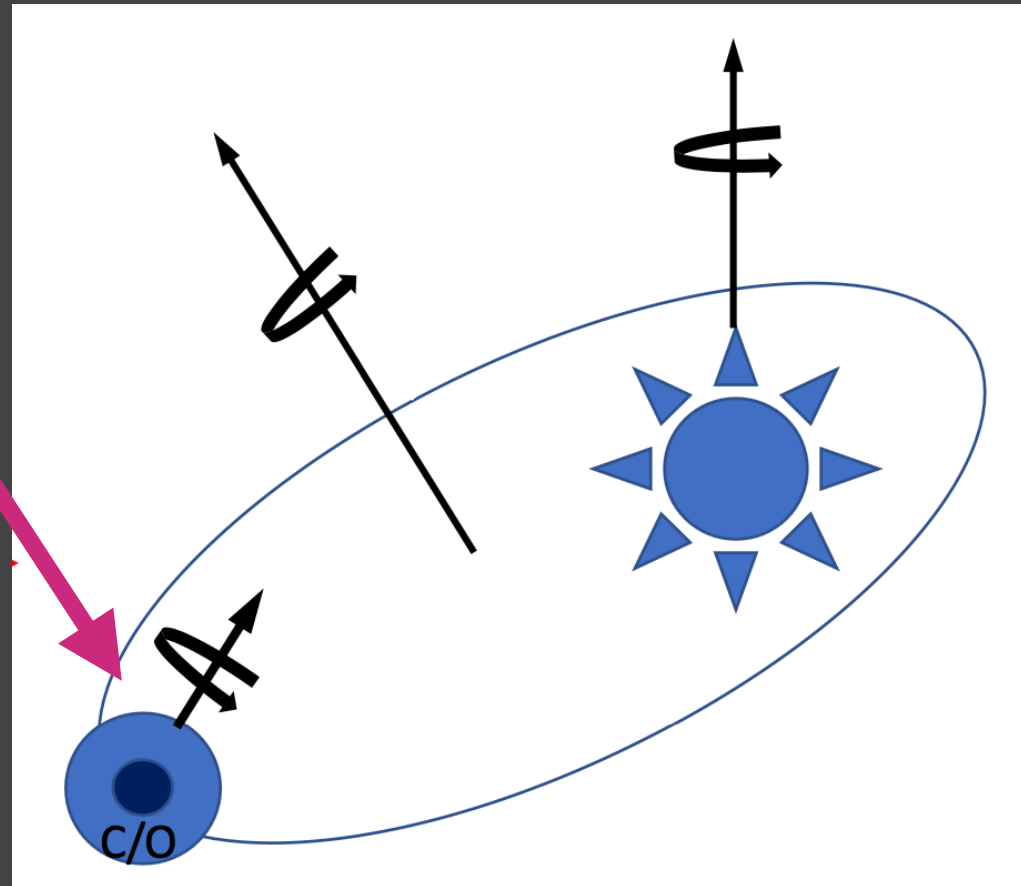
- **Full-scale characterization of reflected light from giant planets** will be feasible with HWO
- In particular, **infrared/UV coronagraph imaging** helps characterizations due to the absence of this capability in Roman
- **Stars with $V > 6$** are not well suited for Roman, but **suitable for HWO**
→ e.g.,) (self-luminous) giant planets in star-forming regions (NIR ← ELT; i.e. synergy)
- Obliquity study? ← personal interest

Measuring Obliquity of Wide-Orbit Planets

HWO

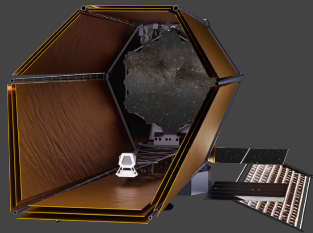


Credit: NASA's Goddard Space
Flight Center Conceptual Image
Lab



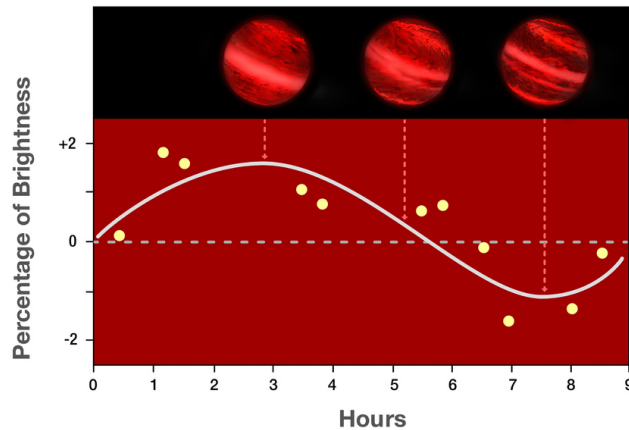
Measuring Obliquity of Wide-Orbit Planets

Measuring rotation period
from light curve with HWO



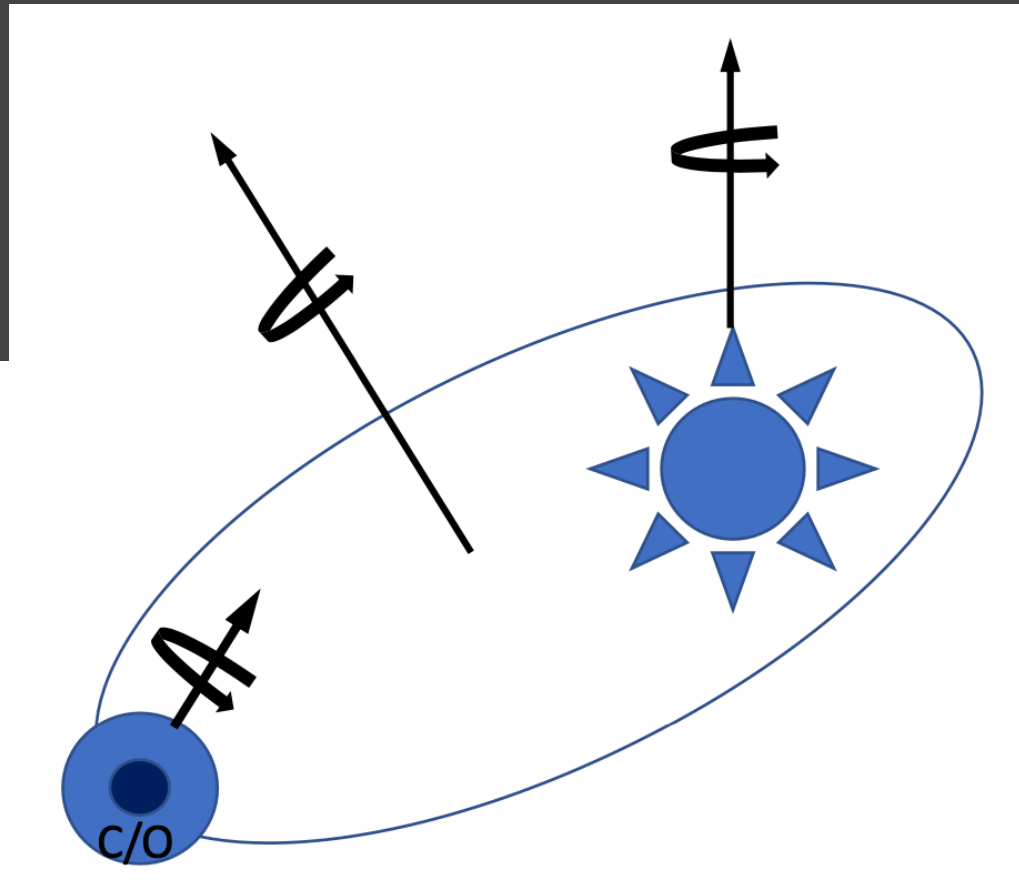
Credit: NASA's Goddard Space Flight Center
Conceptual Image Lab

Light Curve of Rotation of Super-Jupiter 2M1207b



Zhou et al. 2016

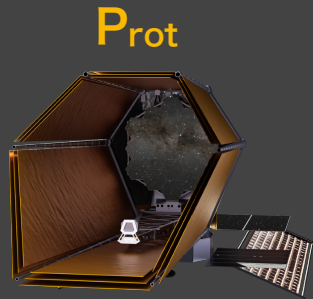
STScI • 2016-05



Credit for the left-bottom figure: NASA, ESA, Y. Zhou (University of Arizona), and P. Jeffries (STScI)

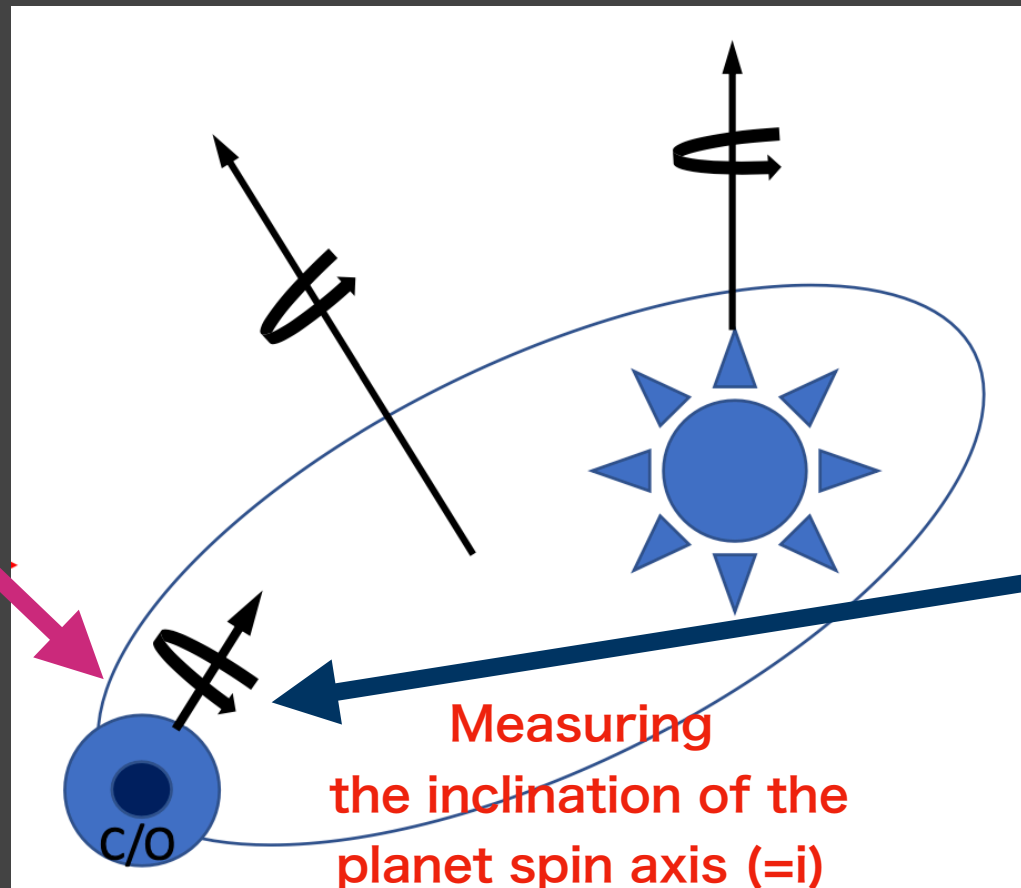
Measuring Obliquity of Wide-Orbit Planets

Measuring rotation
period from light curve



Credit: NASA's Goddard Space Flight Center
Conceptual Image Lab

$$V = 2\pi R / P_{rot}$$



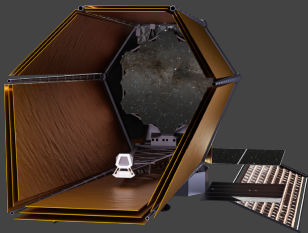
Credit: NAOJ

Measuring
 $V \sin i$ (projected
rotation velocity)
via high-reso
spectroscopy

Measuring Obliquity of Wide-Orbit Planets

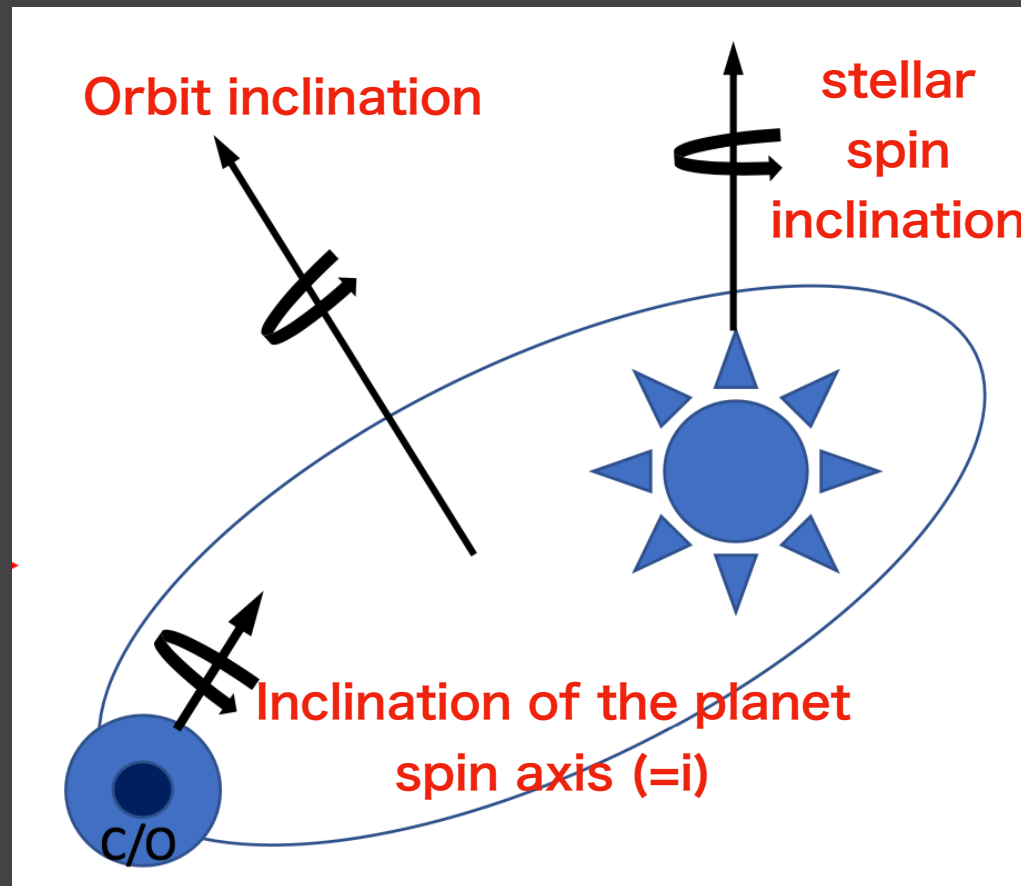
Obliquity can be constrained

Rotation period from
light curve, P_{rot}



Credit: NASA's Goddard Space Flight Center
Conceptual Image Lab

Demonstration with
Roman may be
possible for some
high-mass objects



$V \sin i$

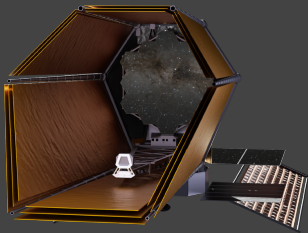


Credit: NAOJ

Measuring Obliqu

Obliqu

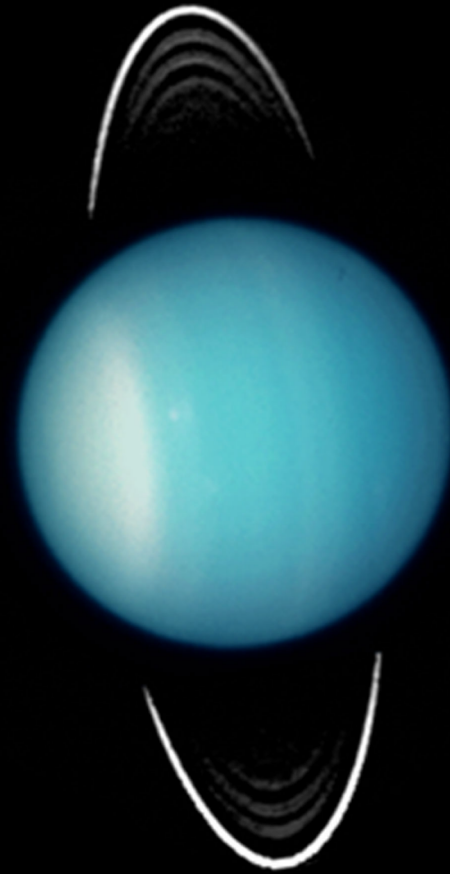
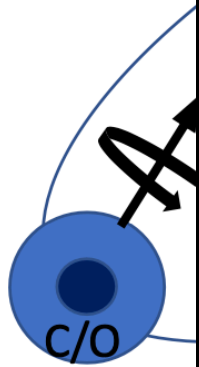
Rotation period from
light curve, P_{rot}



Credit: NASA's Goddard Space Flight Center
Conceptual Image Lab

Demonstration with
Roman may be
possible for some
high-mass objects

Orbit in



Let's find exo-
Uranus

bit Planets

ellar
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$V \sin i$



Credit: NAOJ

Credit:
NASA, ESA, and M. Showalter (SETI Institute)

Summary and Messages



- Roman will be launched soon to perform technology demonstration observations and gain lessons for space-based high-contrast imaging, which are critical for imaging Earth-like planets.
- The targets for the first six months have been selected, including self-luminous giant planets (contributed by Subaru), reflected-light planets, debris disks, and exozodiacal dust.
- The baton will be passed from Roman to HWO to carry out full-scale science.
- High-contrast imaging is compatible with both disk science and planetary science.
- You are welcome to the CPP

Final Discussion Summary

SOC Questions (blue) & Attendees Responses (black)

- 1. Strengthening collaboration between the science and instrumentation communities

What interactions are currently missing?

More workshops/meetings such as this would be highly valuable

Ensuring a clear communication path from the community to the HWO-J team

How can science priorities better guide instrument development?

We firstly need to ensure more science cases from diverse science communities, then perhaps follow the path used in the USA for START/CSIT

How should scientists and instrument teams work together towards HWO?

New mechanisms may be needed in NAOJ or a voluntary group?

ISAS project post-docs. Current only for coronagraph development position, broadening the topics would be useful

Establishing the JAXA-HWO fellowship program would be very exciting

- 2. Building a Japanese HWO community and organizational framework

What kind of community structures and what actions should be taken over the next few years?

Town meetings/talks and webinars to update and ensure full knowledge of HWO status, timeline, progress

Workshop w many participants from diverse fields (possibly to be held this fall?). This would be an invitation only (incentive) meeting for attracting early career researchers. Letting them submit some writing after the meeting.

Incentives are needed: JWST proposal for the HWO preparatory category, proceedings, papers, grant opportunities, linking to USA/EU, etc.

Webpage showing key people and materials (incl. slides) in JAXA and NAOJ-ABC sites, improved communication and dissemination of information is important.