30th Anniversary of the Rencontres du Vietnam
"Windows on the Universe" in Quy Nhon, Vietnam on Aug. 11, 2023

The Detection and the Surface Mapping of a Terrestrial Planet in a Habitable zone

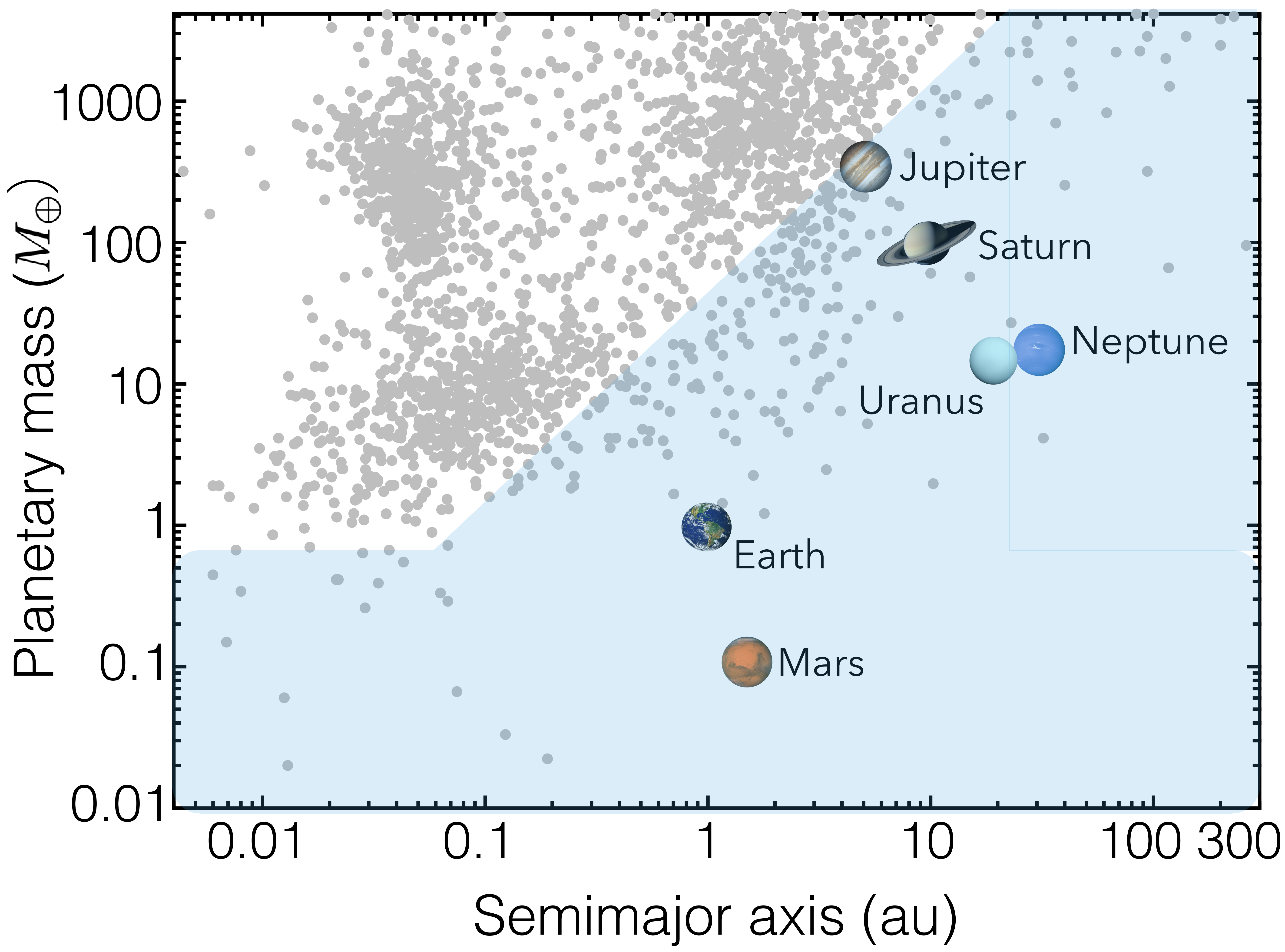
Yasunori Hori

Astrobiology Center
National Astronomical Observatory of Japan

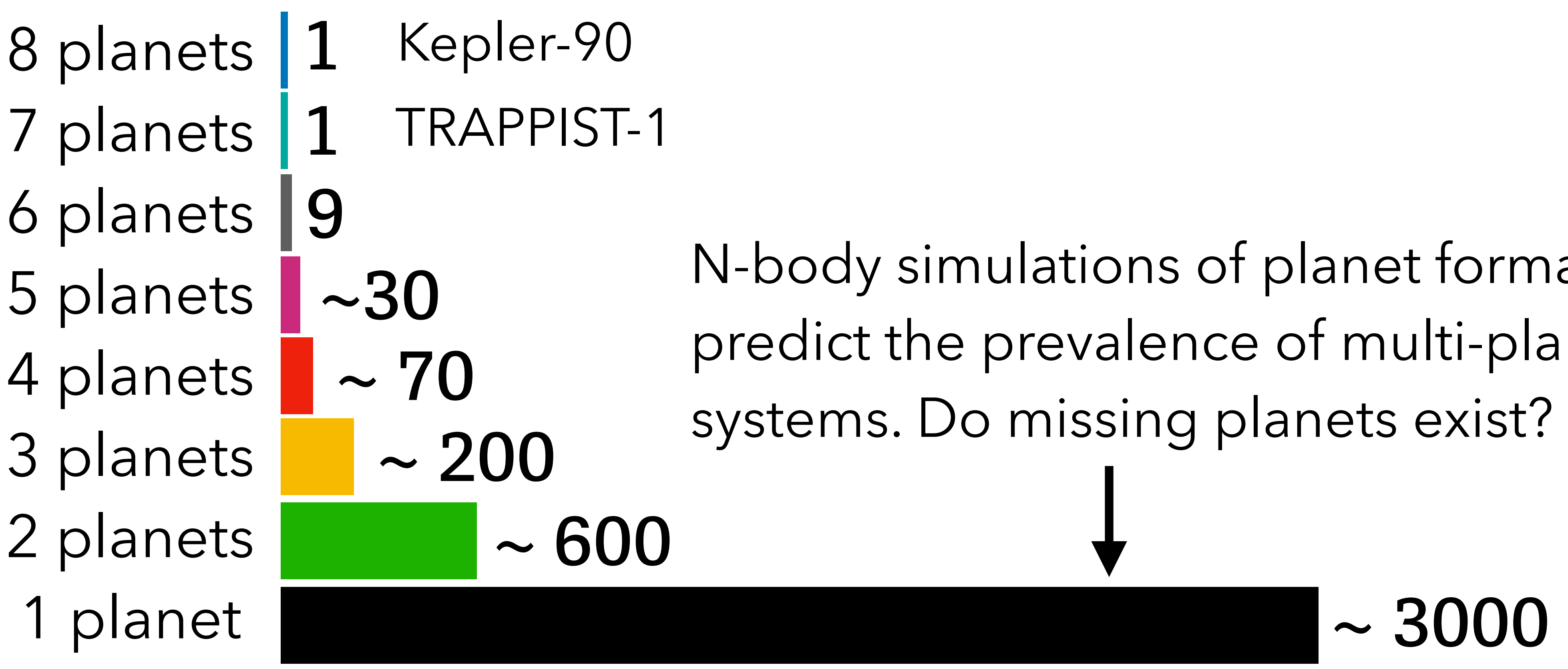

30%
GAS GIANT
The size of Saturn or Jupiter (the largest planet in our solar system), or many times bigger. They can be hotter than some stars!
4%
TERRESTRIAL
Small, rocky planets. Around the size of our home planet, or a little smaller.
35%
NEPTUNE-LIKE
Similar in size to Neptune and Uranus. They can be ice giants, or much warmer. “Warm” Neptunes are more rare.
31%
SUPER-EARTH
Planets in this size range between Earth and Neptune don’t exist in our solar system. Super-Earths, a reference to larger size, might be rocky worlds like Earth, while mini-Neptunes are likely shrouded in puffy atmospheres.
5000+
PLANETS FOUND

The Solar System in the Exoplanet Population

Are the solar system-like planets special or common?



Multiplicity

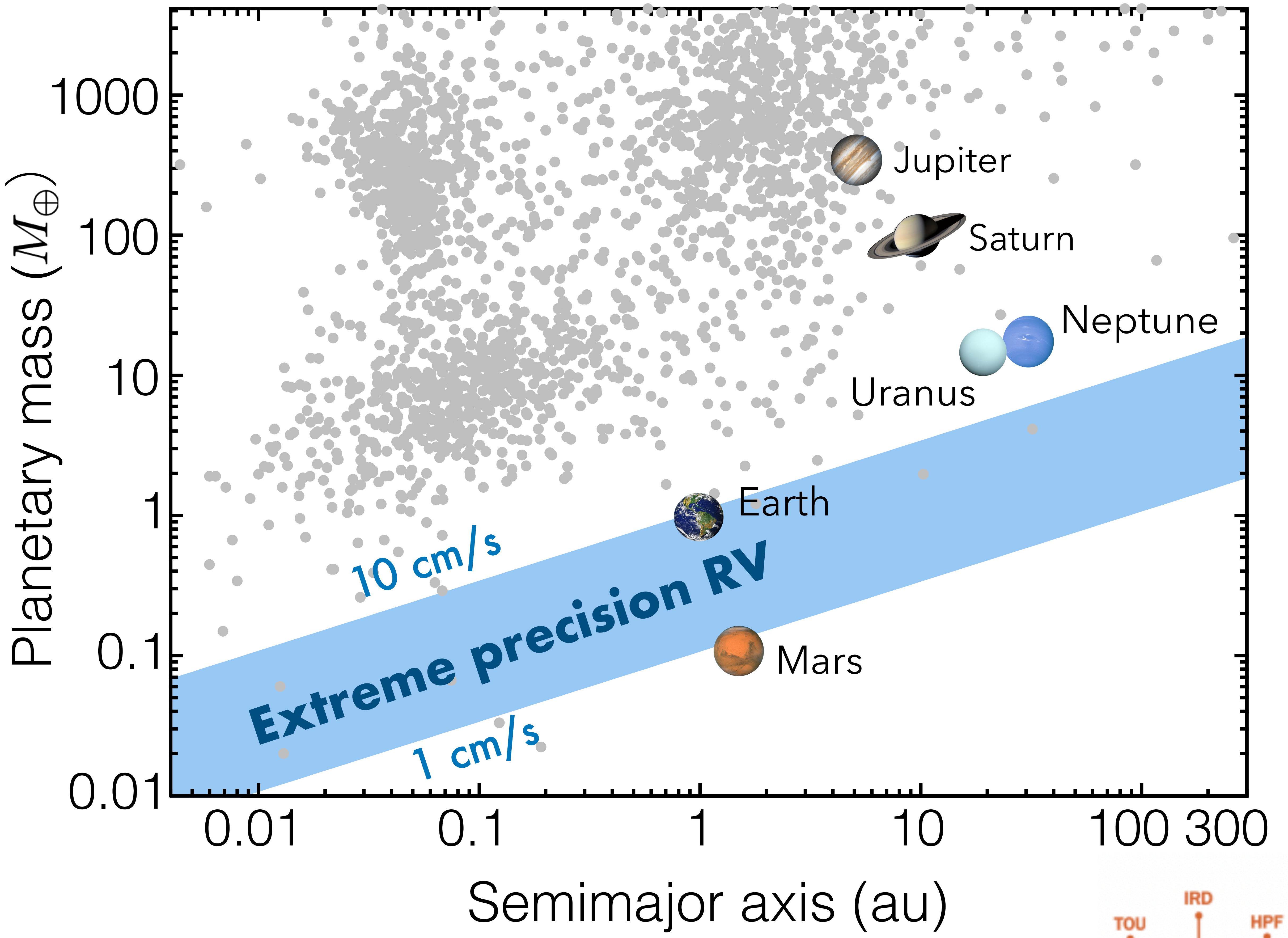


N-body simulations of planet formation predict the prevalence of multi-planet systems. Do missing planets exist?

Earth-mass habitable planet candidates
around low-mass stars (K- and M-type ones)

(e.g) Proxima Centauri (Anglada-Escuda *et al.* 2016)
TRAPPIST-1 (Gillon *et al.* 2016;2017)
Teegarden's Star (Zechmeister *et al.* 2019)
GJ 1002 (Suárez Mascareño *et al.* 2023)
Wolf 1069 (Kossakowski *et al.* 2023)

Planet Surveys Toward the Discovery of "ExoEarths"



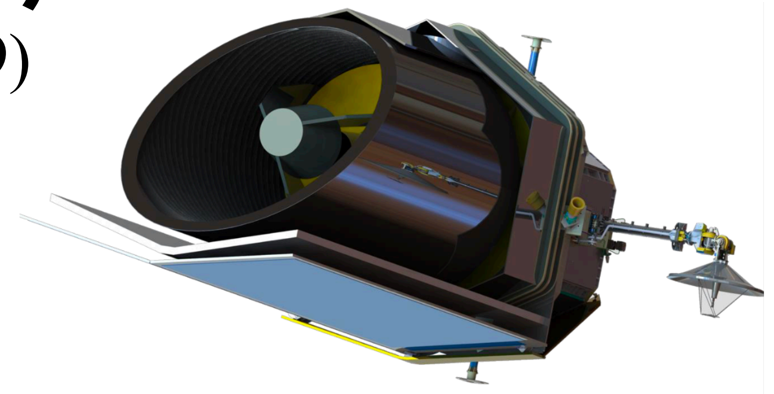
Ground-based Extreme Precision RV (~10 cm/s)

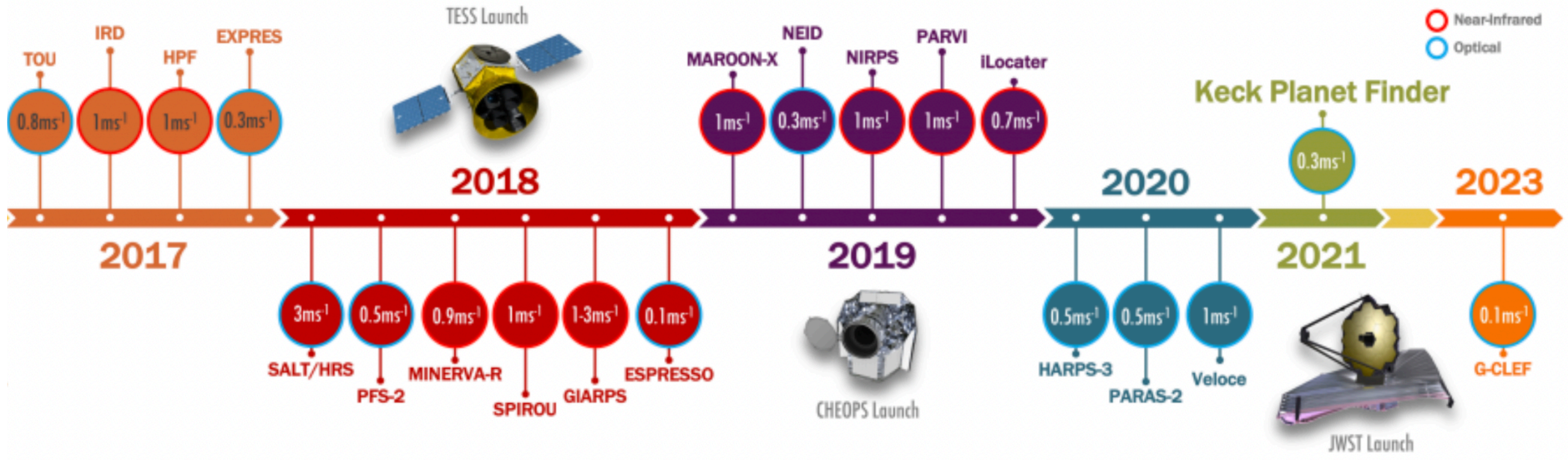
(e.g. Crass *et al*. 2021)

Understanding of stellar jitters (e.g. spots, granulation, & oscillations)
Removal of telluric contamination → photon noise limit

(e.g.) HARPS, ESPRESSO (VLT) (Pepe *et al*. 2013)
EXPRES (LDT) (Jurgenson *et al*. 2016)
NEID (WIYN) (Schwab *et al*. 2016)
Keck Planet Finder (Gibson *et al*. 2016)

→ **EarthFinder (~cm/s, 2032?)**
(Plavchan *et al*. 2019)

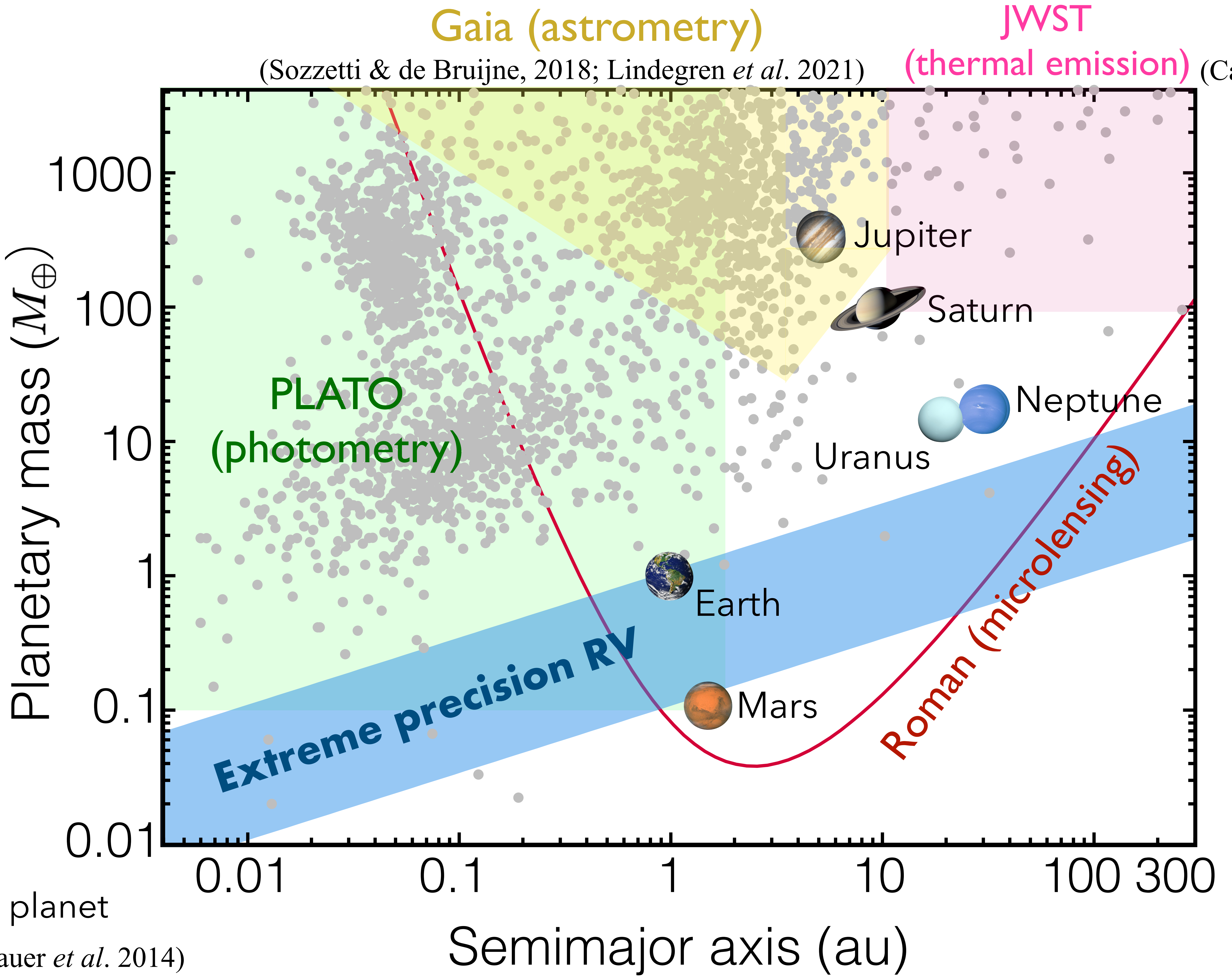




Space-based Planet Surveys in the Late 2020s

Gaia, JWST, and Roman CGI

Saturn-mass or more massive gas giants beyond a few au.



PLATO (2026)

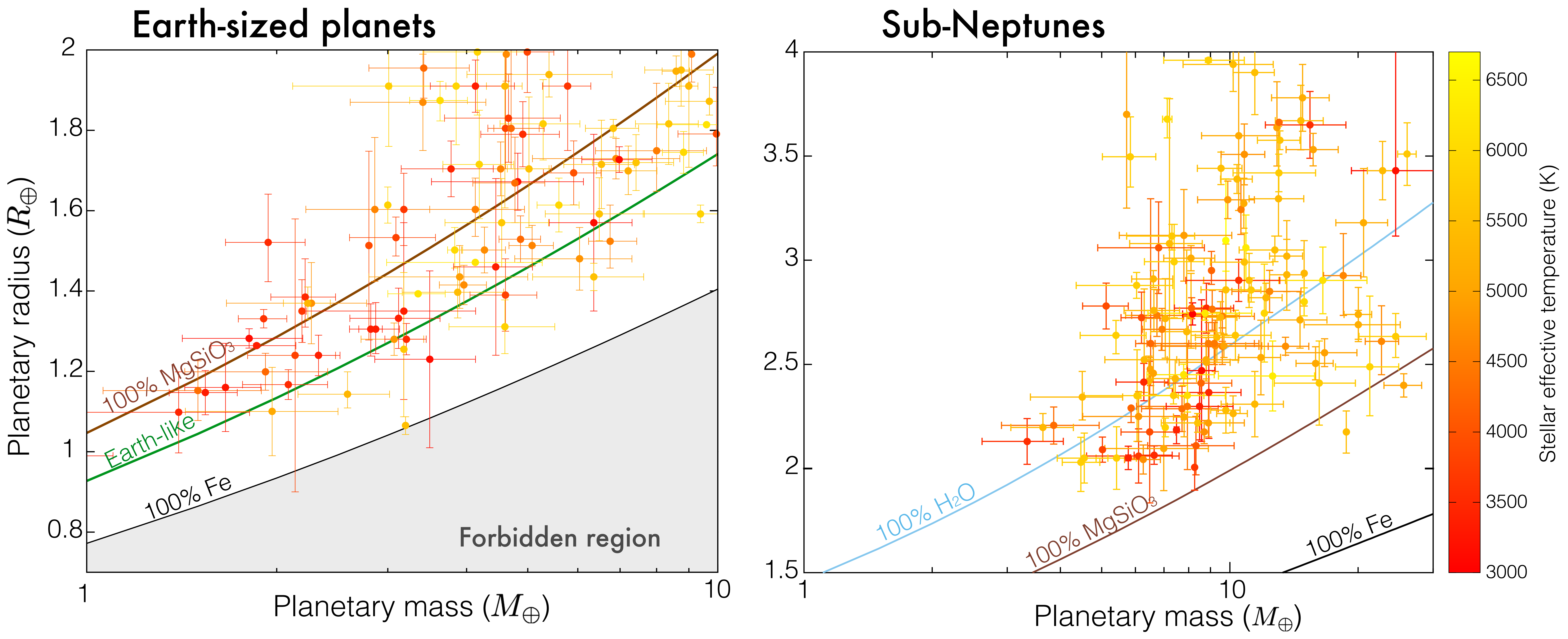
An Earth-sized habitable planet around a Sun-like star (Rauer *et al.* 2014)

Nancy Roman Telescope (2027)

(e.g. Penny *et al.* 2019)

Mars- and Earth-mass planet at ~1 au around M dwarfs and Sun-like stars .

Bulk Compositions of Earth-sized Planets and Sub-Neptunes



The interiors of Earth-sized planets show a variety of rocky compositions. (e.g.) Mg(Si)/Fe

(cf) The atmosphere of an ultra-short period planet provides a clue to exploring mantle/core compositions.

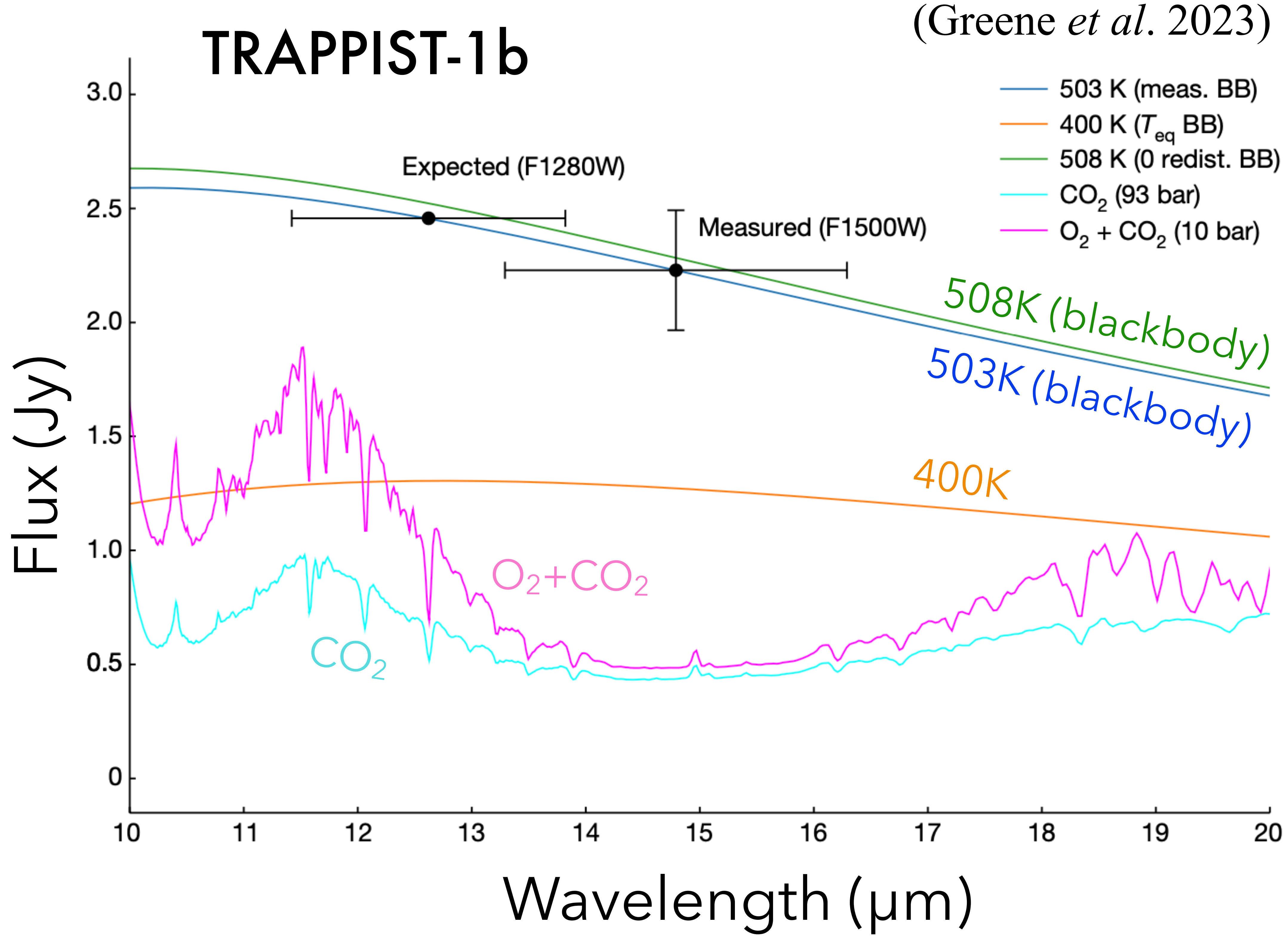
Many of sub-Neptunes are likely to have atmospheres and be water-worlds.

(e.g.) Detection of H_2O in the atmosphere of HAT-P-11b and K2-18b

(Fraine *et al*. 2014; Tsiaras *et al*. 2019)

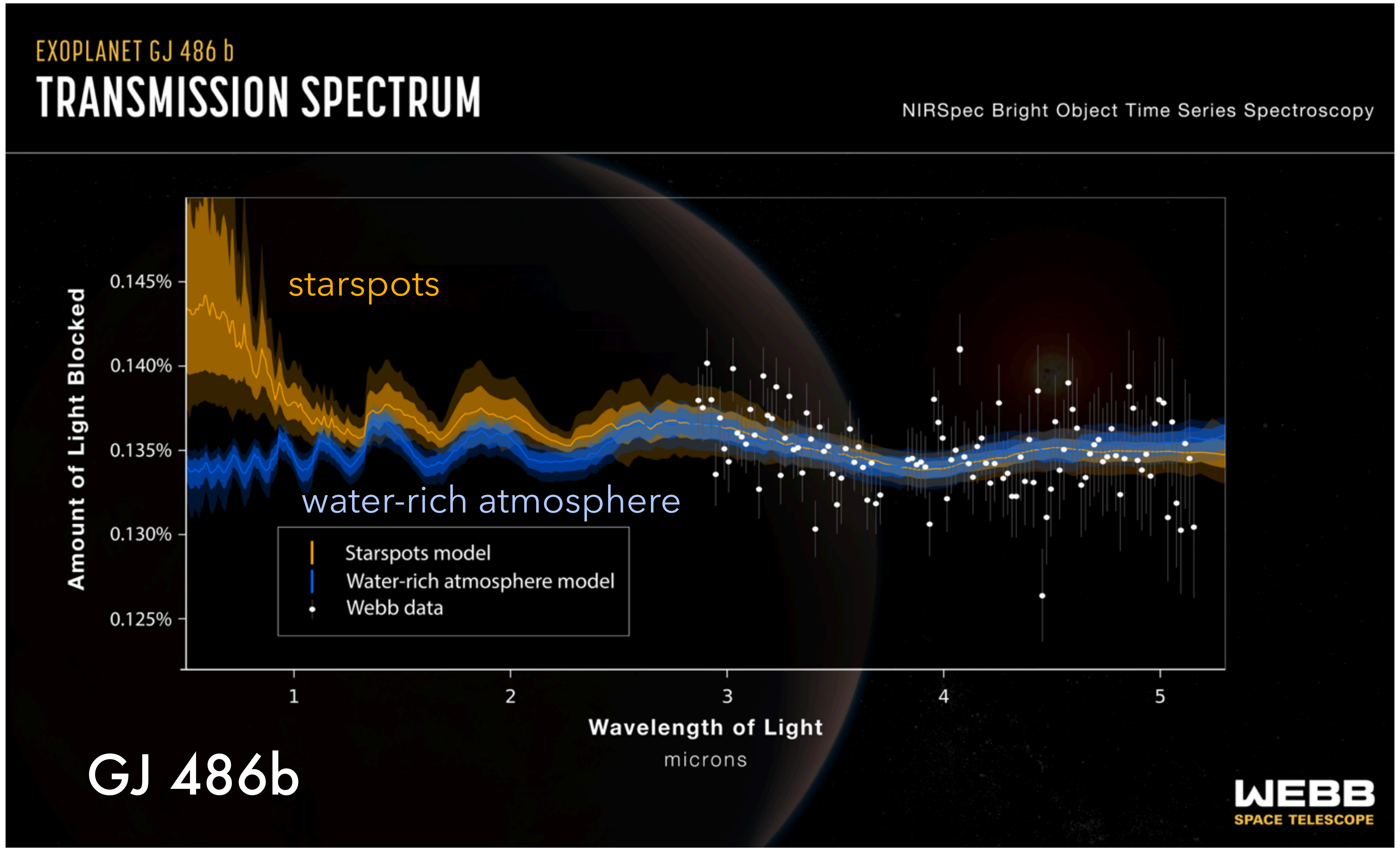
JWST Observations of Earth-sized Planets around a Nearby Star

(Greene *et al.* 2023)



TRAPPIST-1b may have no atmosphere?

(Moran *et al.* 2023)



Water-rich atmosphere of GJ 486b with 1.3 times Earth-radii

New Era Toward Characterization of Habitable Planets

Detection of habitable Earth-sized planets around a Sun-like star from PLATO and EPRV Observations

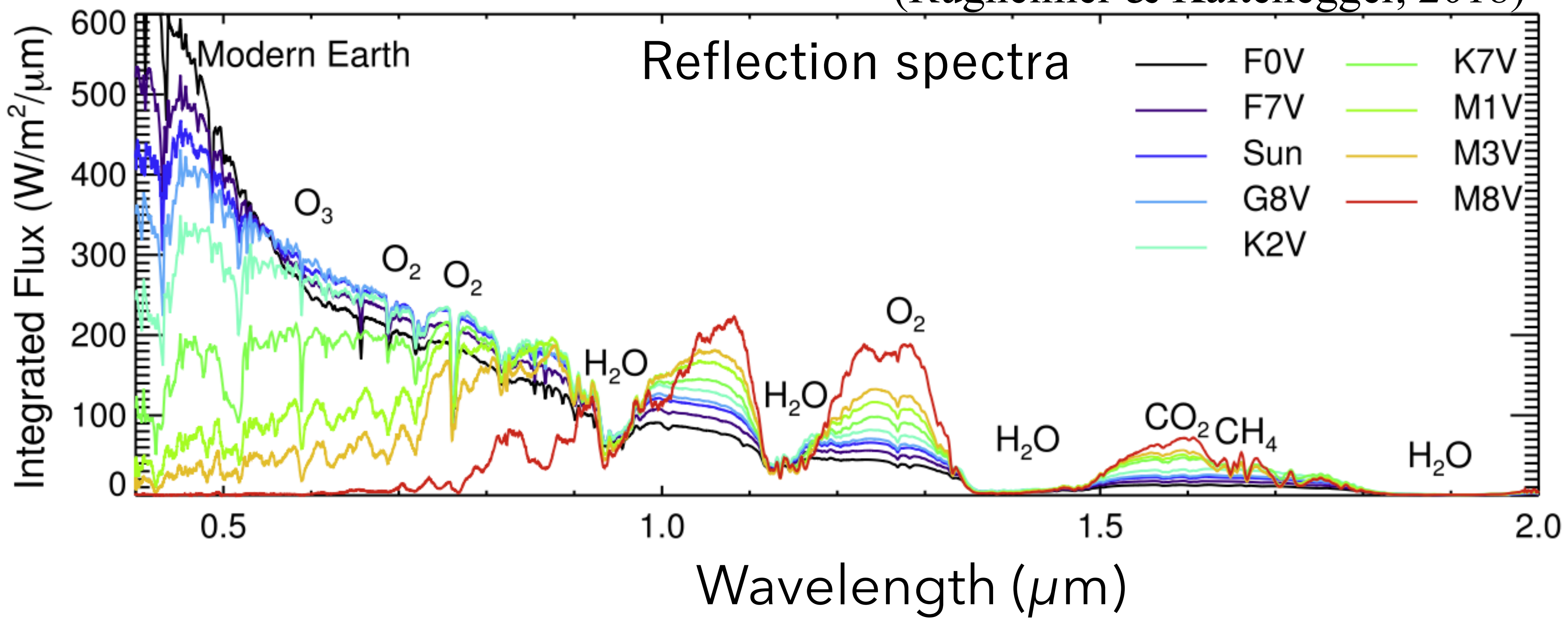
2020s	JWST (e.g. NIR Spec, MIRI)
2030s	ESA/Ariel 30m-class ground-based telescopes (E-ELT, TMT, GMT) (e.g. IRIS, MODHIS for TMT)
2040s	6m-class space telescope (LUVEx)

↓

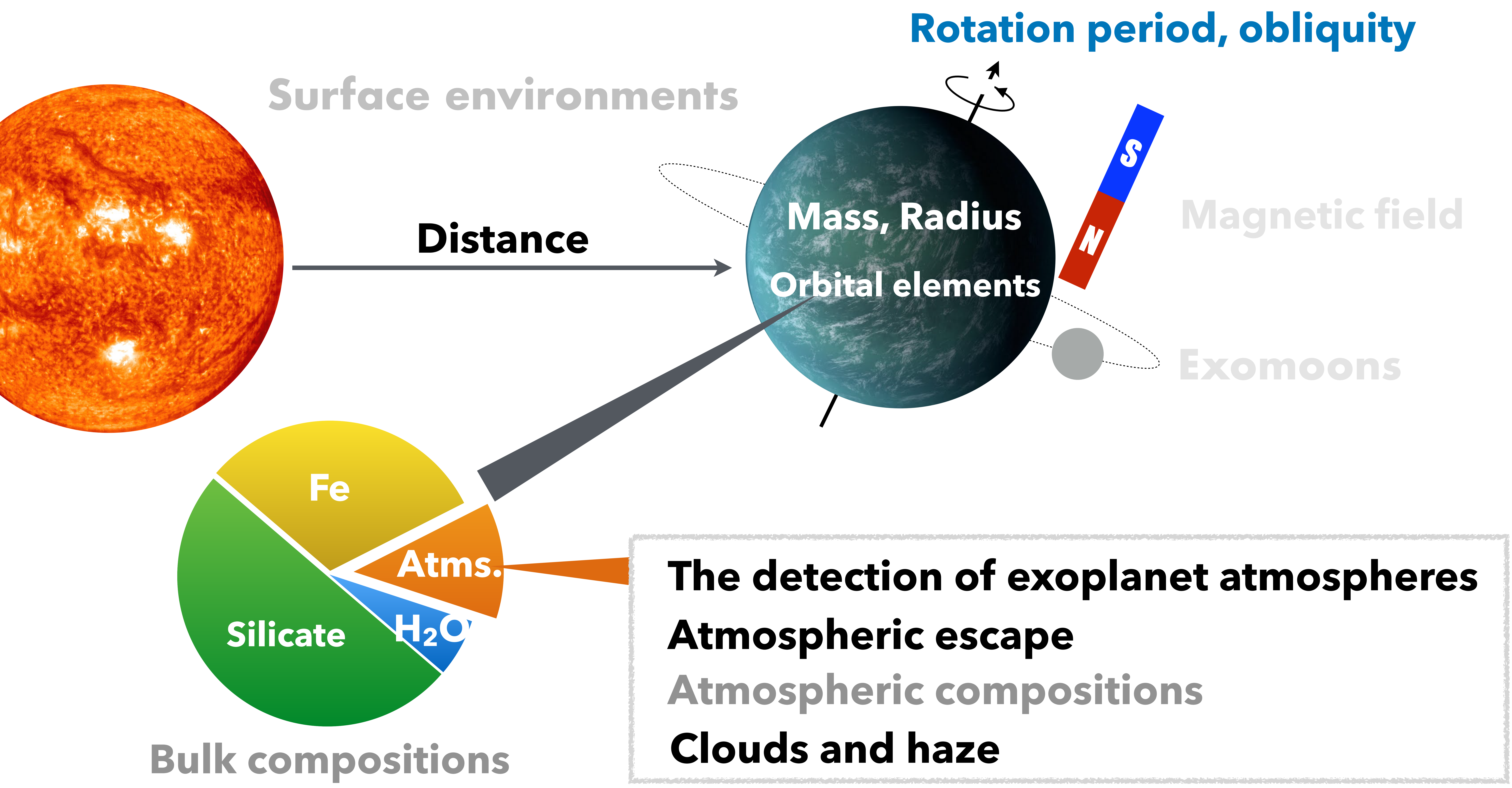
H_2O	liquid water on the surface	
O_2, O_3 CH_4 N_2O	biosignature	abiotic oxygen (false positives) photodissociation of H_2O, CO (cf) O_2 excess : O_2-O_2 CIA
H_2S, SO_2, CO_2	Volcanic activity	H_2SO_4, S_8 produced by photochemical reactions

(Kaltenegger *et al.*2010; Hu *et al.*2013; Misra *et al.*2015; Hu *et al.* 2013; Loftus *et al.*2019)

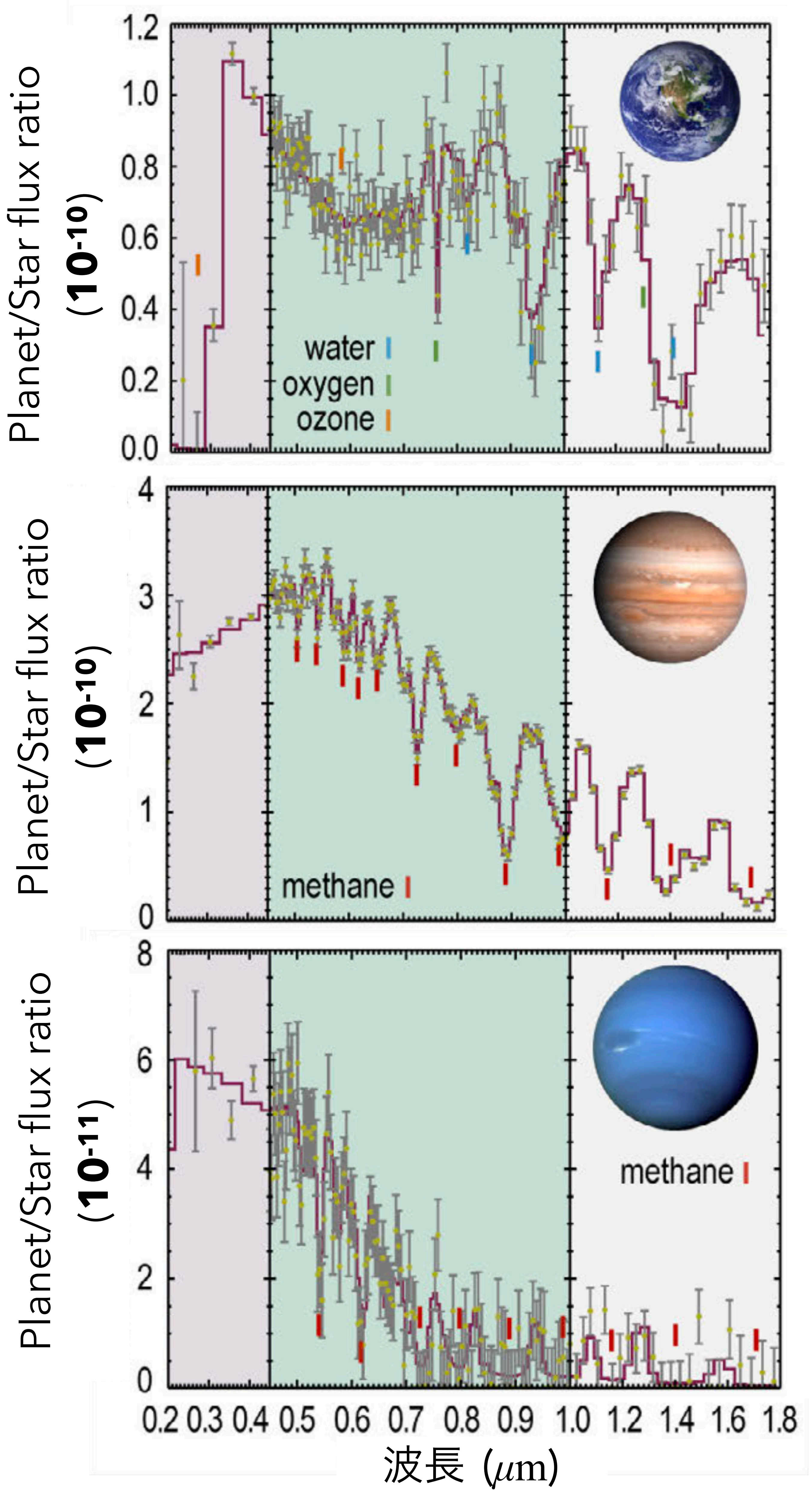
(Rugheimer & Kaltenegger, 2018)



Current Status of Exoplanet Characterization



Imaging of "Earth 2.0" in Reflection Spectra



The flux ratio of reflection light from a planet to stellar light (a Sun-like star at 10 pc) is

10^{-10} (**0.1"**) for Earth, **10^{-9}** (**0.5"**) for Jupiter, **10^{-11}** (**3"**) for Neptune.

Detectability of Reflection Light from Exoplanets

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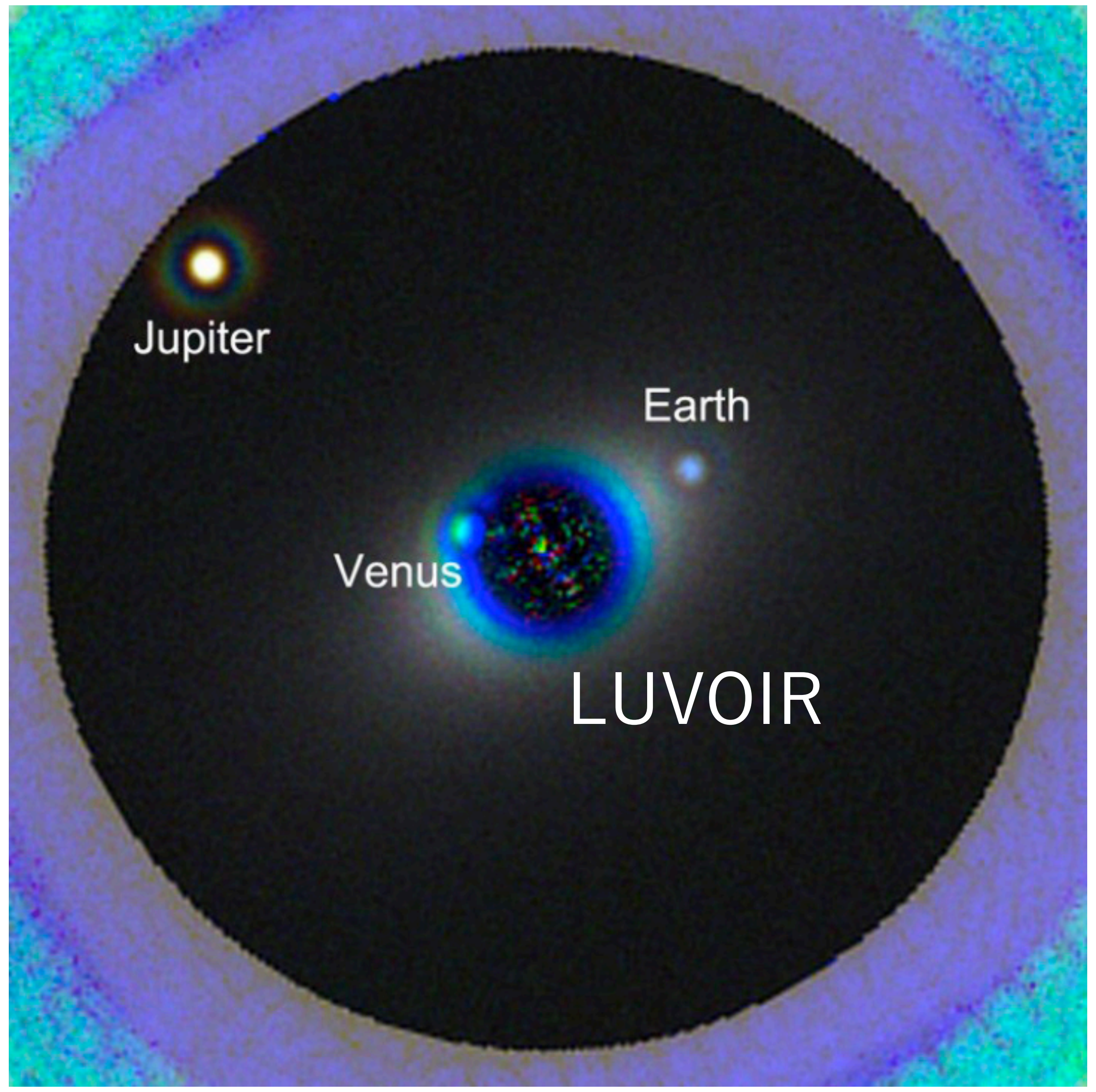
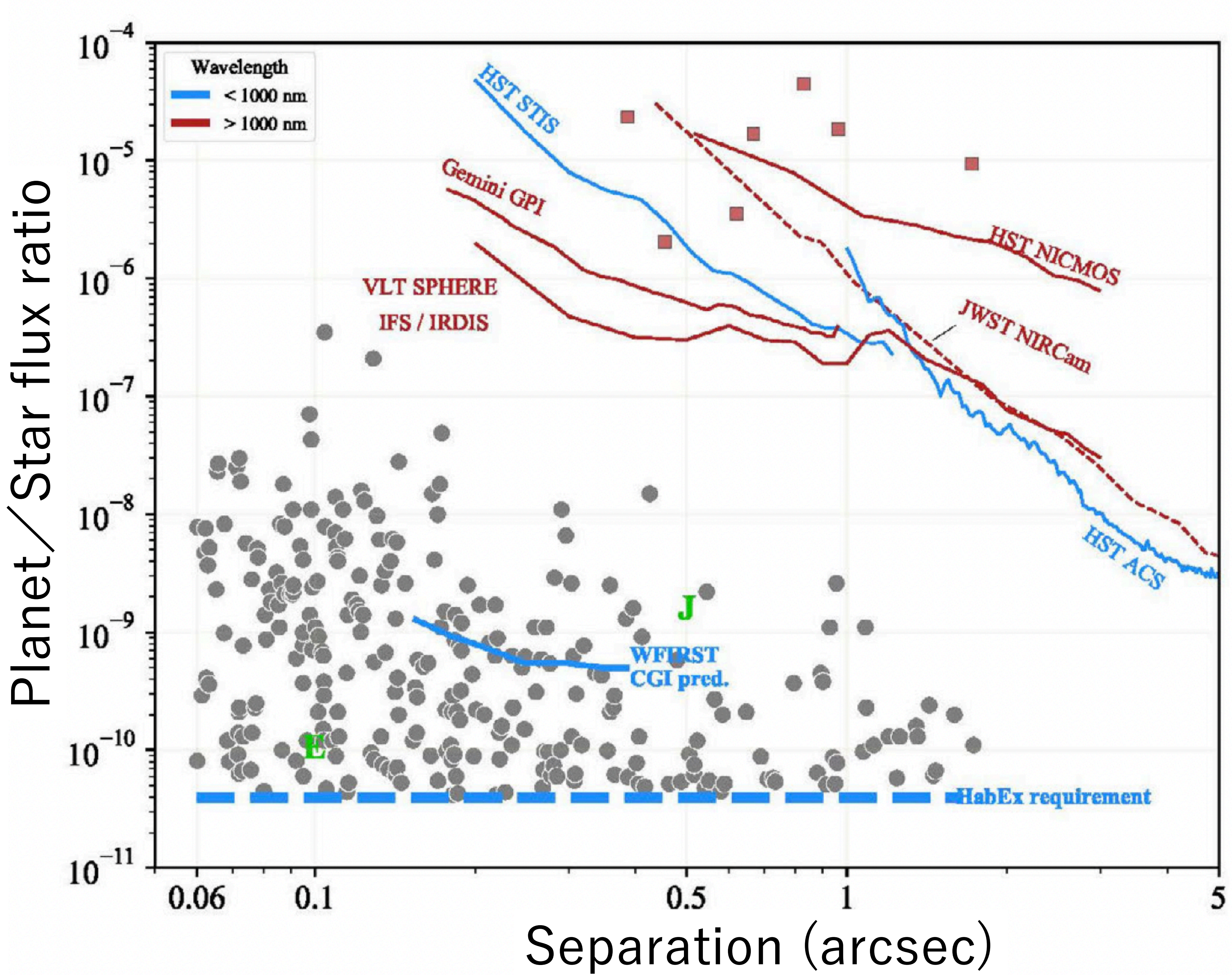




10m-class telescope + Extreme AO (SCExAO/Subaru, SPHERE/VLT, GPI/Gemini)

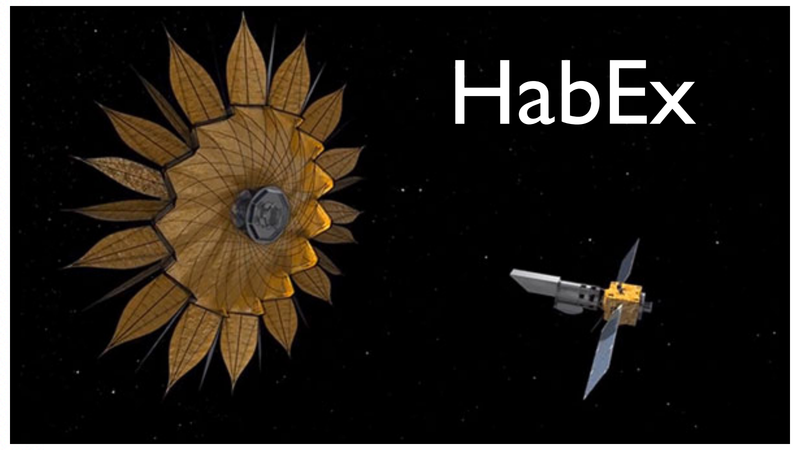
Detection limit ~10^{-6} (0.2″)

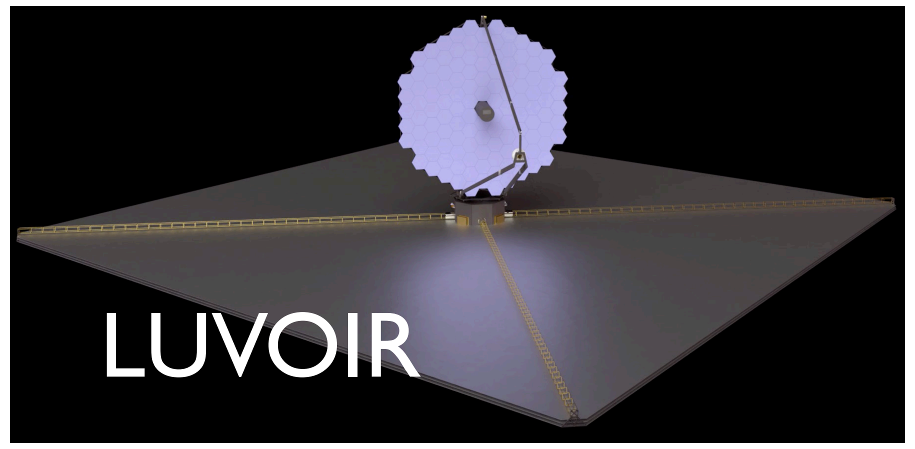
Roman space telescope (CGI)

Detection limit ~10^{-9} (~0.2″)

LUVEx

Detection limit ~10^{-10} (≲0.1″)





TMT/PSI (Planets System Imager)

Detection limit ~10^{-8} (~0.01″)

Next-generation space telescope – a habitable planet around a nearby Sun-like star

30m-class telescope – a habitable planet around a nearby M dwarf

What Should We Detect as a Sign of Life?

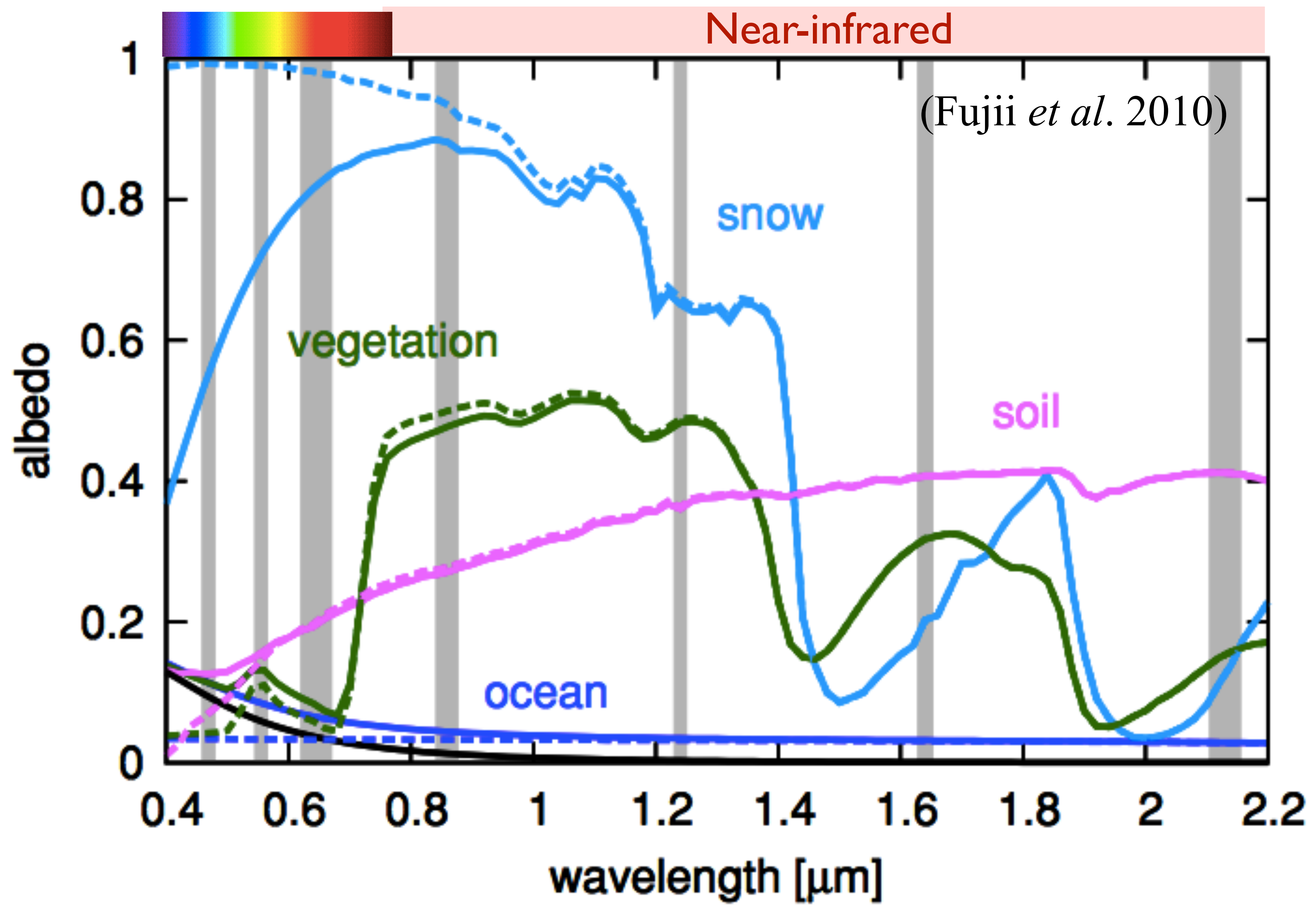
A standard(?) sequence from simple molecules to protocell entity

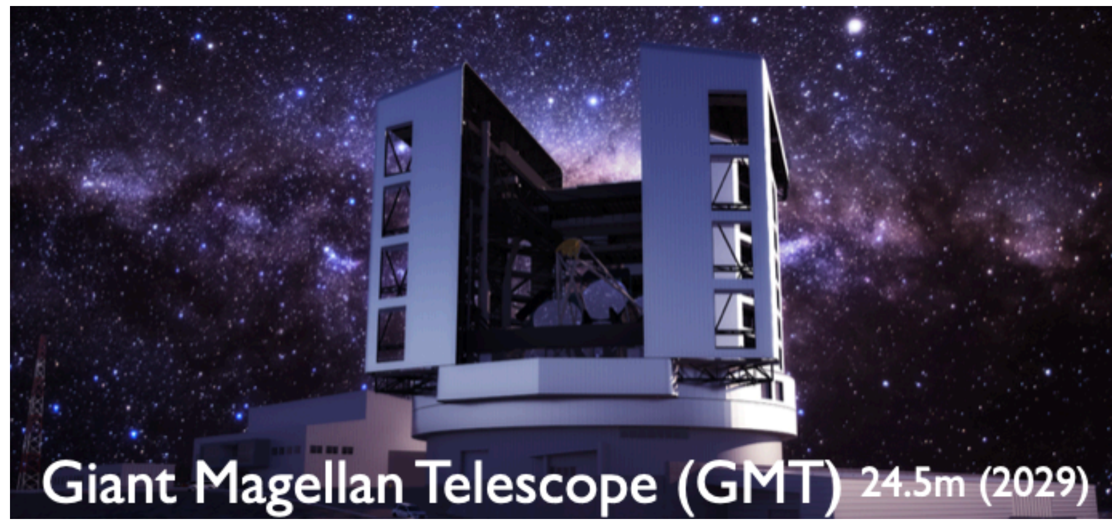
The compelling evidence for life on an Earth-like planet is to detect **several long-chain proteins** simultaneously.

Anatomy of ExoEarths Using Reflection light

What kind of information can we extract from reflection spectra of exoEarths?

- **Surface mapping** (e.g. land, ocean, cloud)
- Atmosphere (e.g. CO_2, H_2O, O_2, T-P profile)
- **Rotation** (period, obliquity)
- **Vegetation**





The Surface Mapping of ExoEarths

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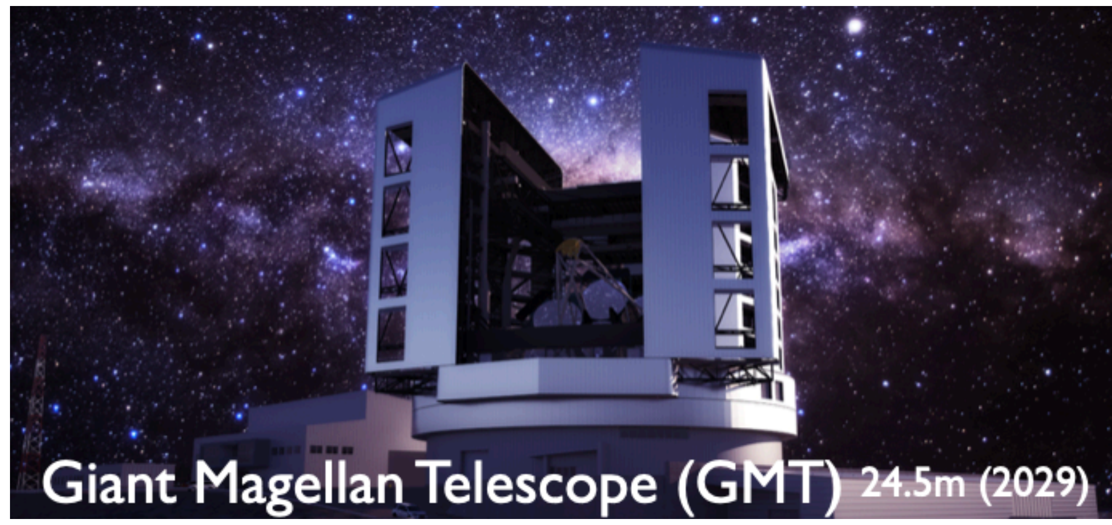
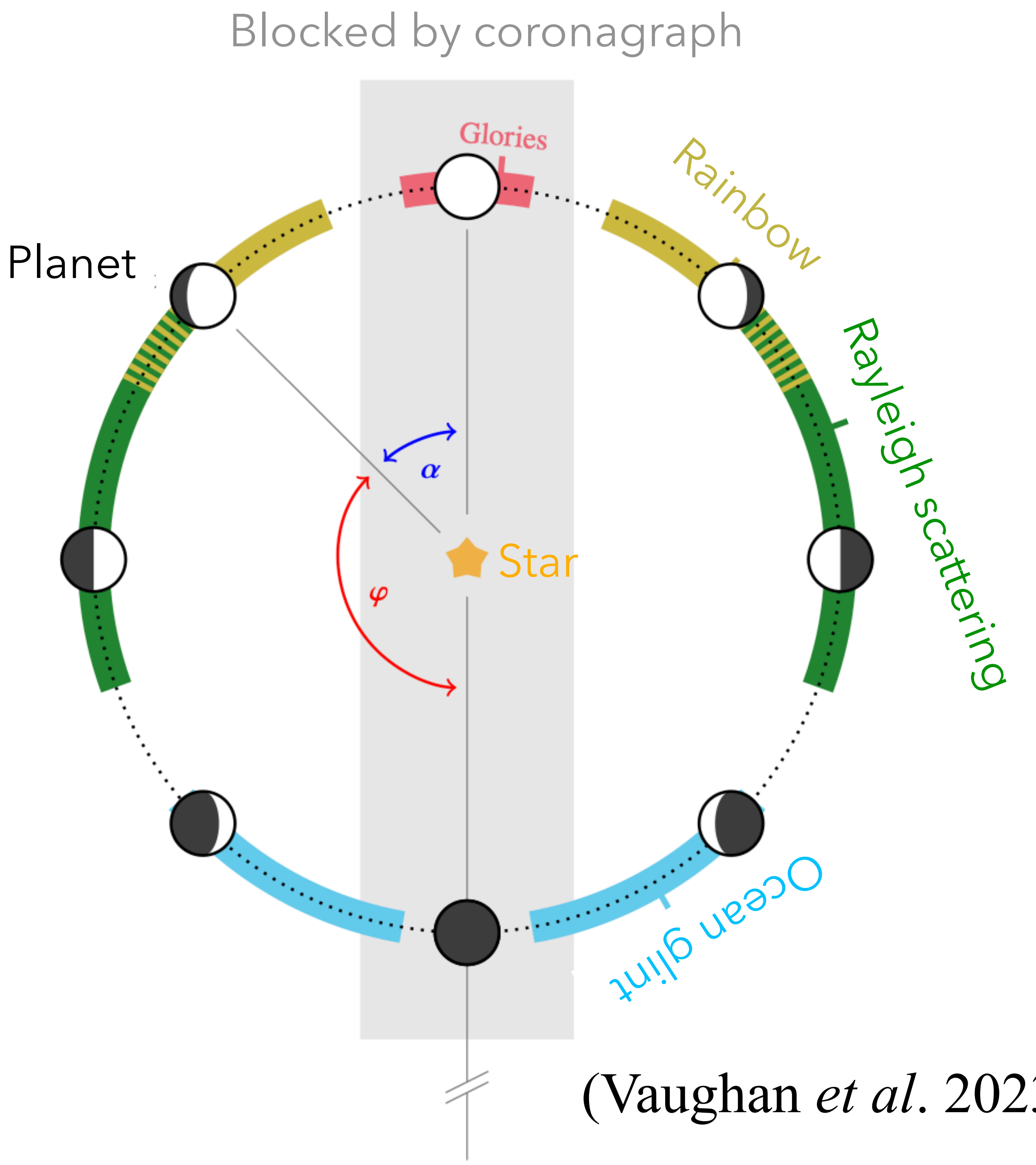
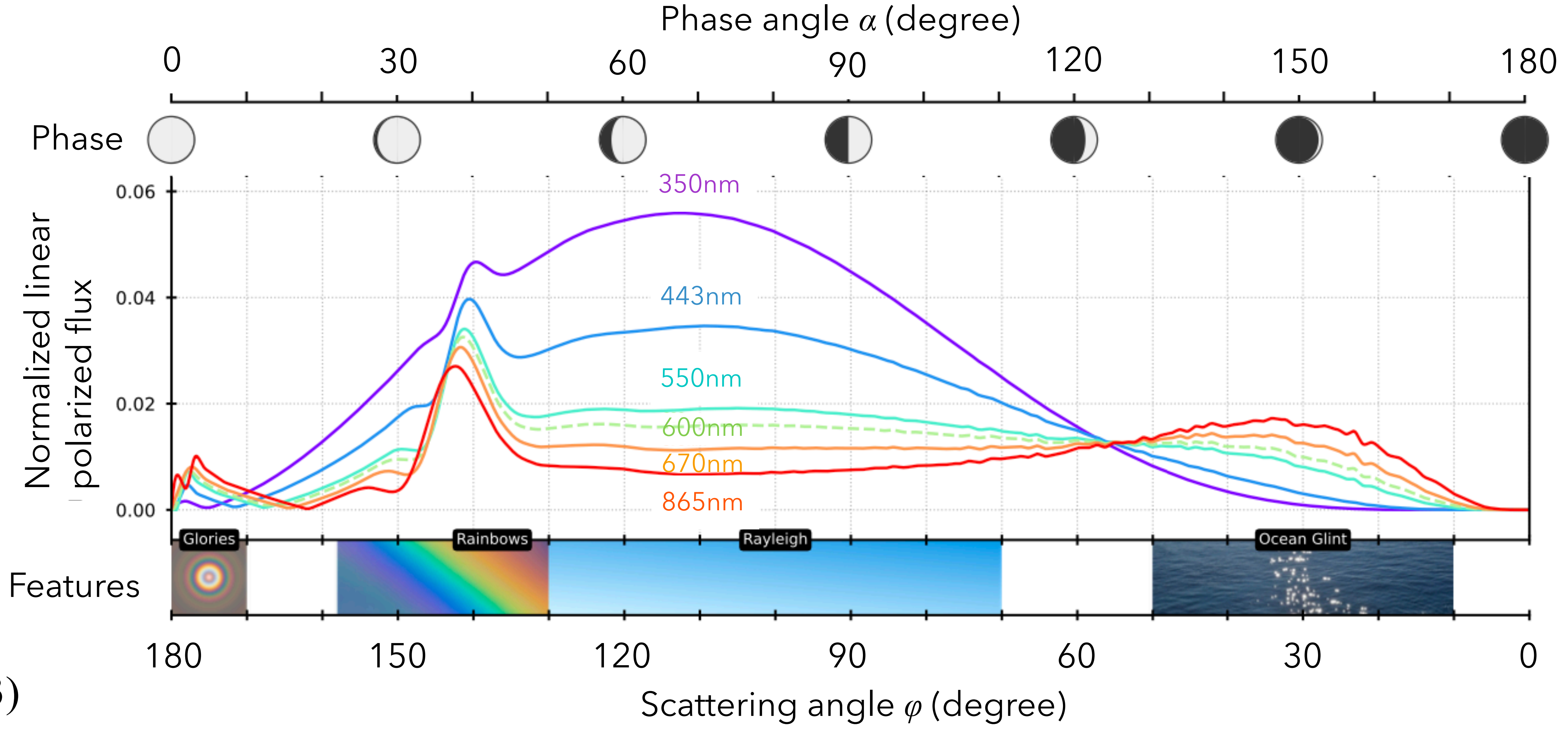




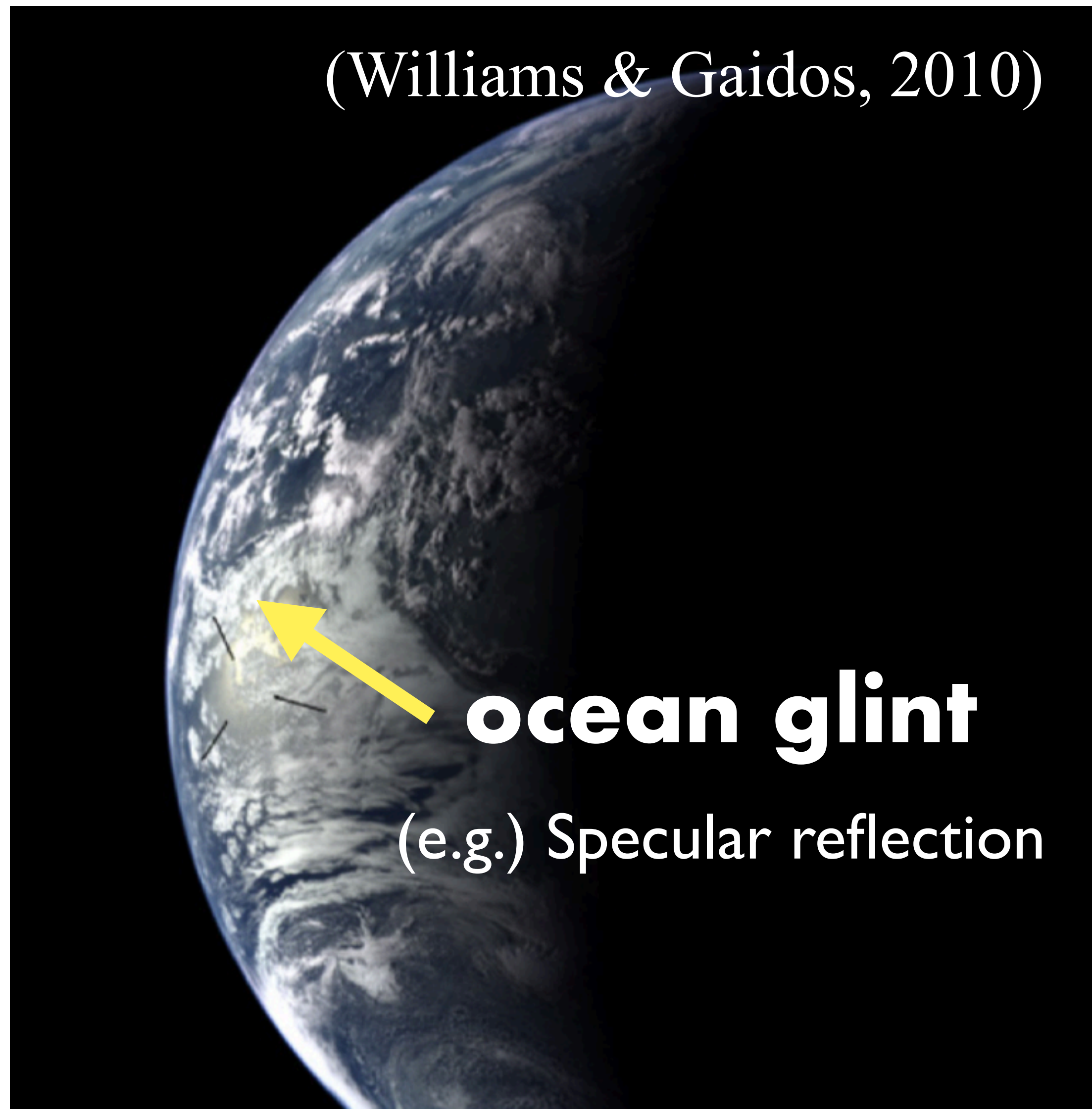
(Vaughan *et al.* 2023)

Polarization can be used for detecting a rainbow and clouds

(Karalidi *et al.* 2011; 2012)



(Williams & Gaidos, 2010)



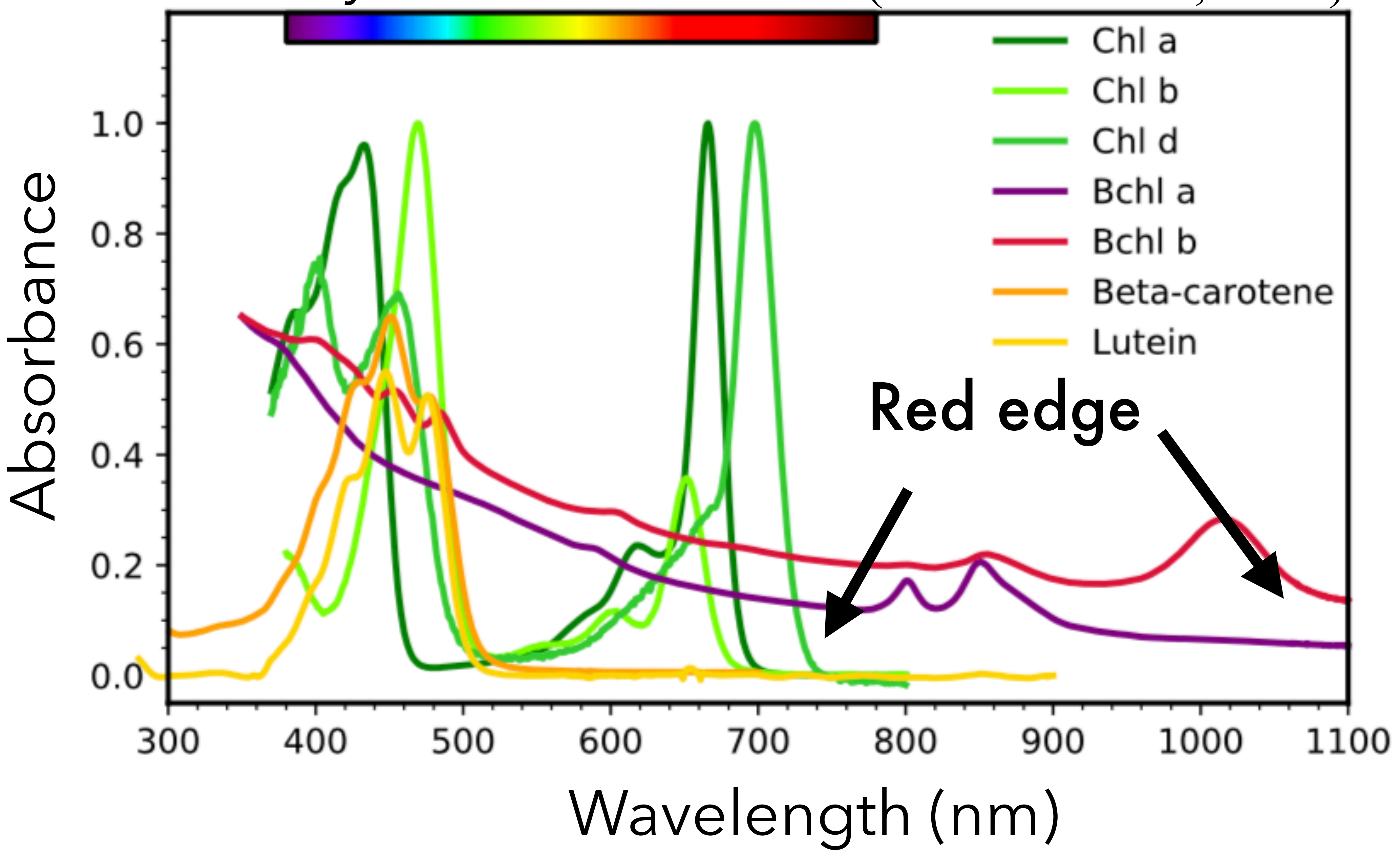
A Hint of Vegetation on ExoEarths

1) "Red edge"

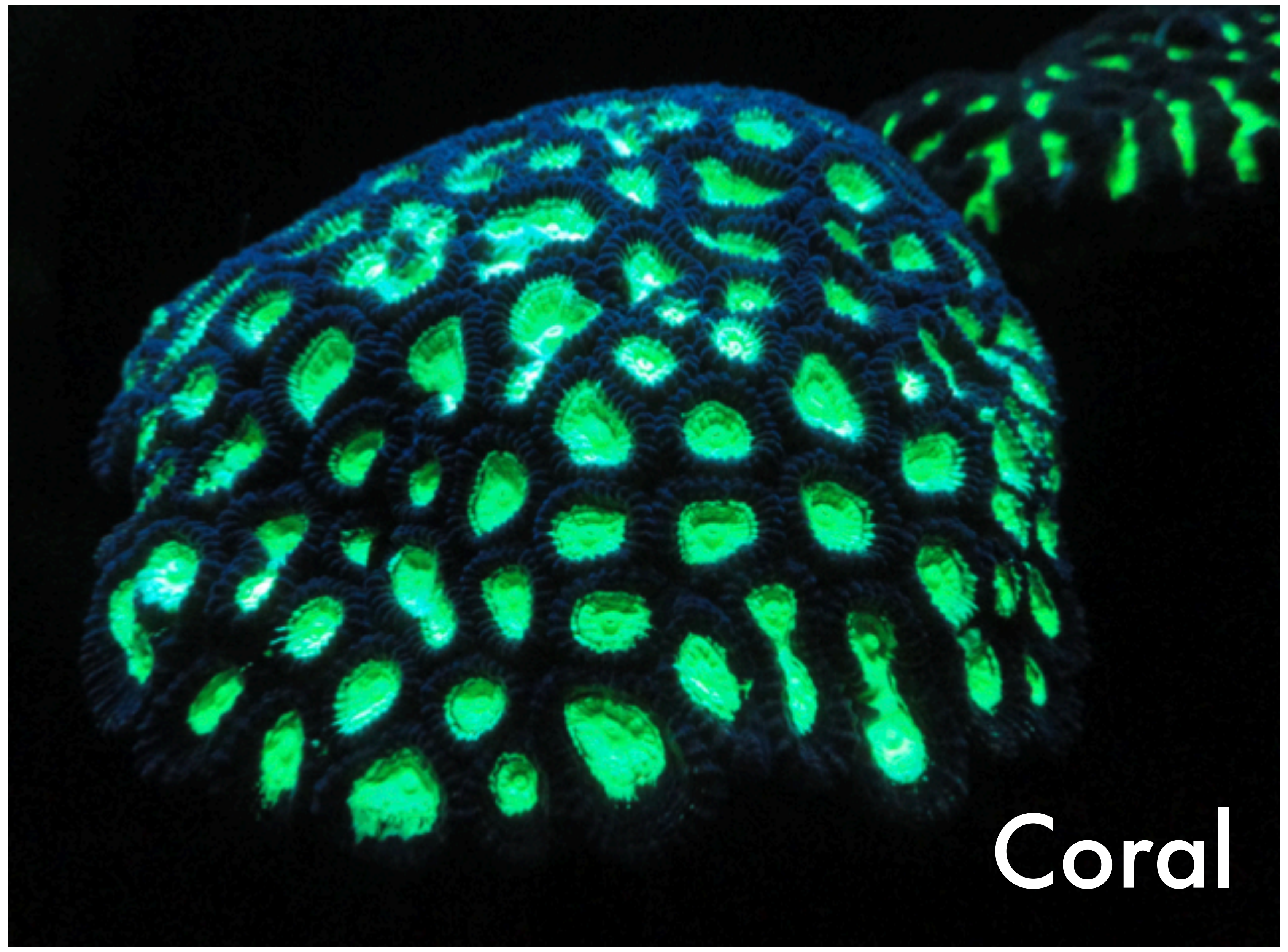
A sudden rise in reflectance appears near
680nm - 730nm for chlorophyll (Chl) a, b and
1-1.1μm for bacteriochlorophyll (Bchl) b

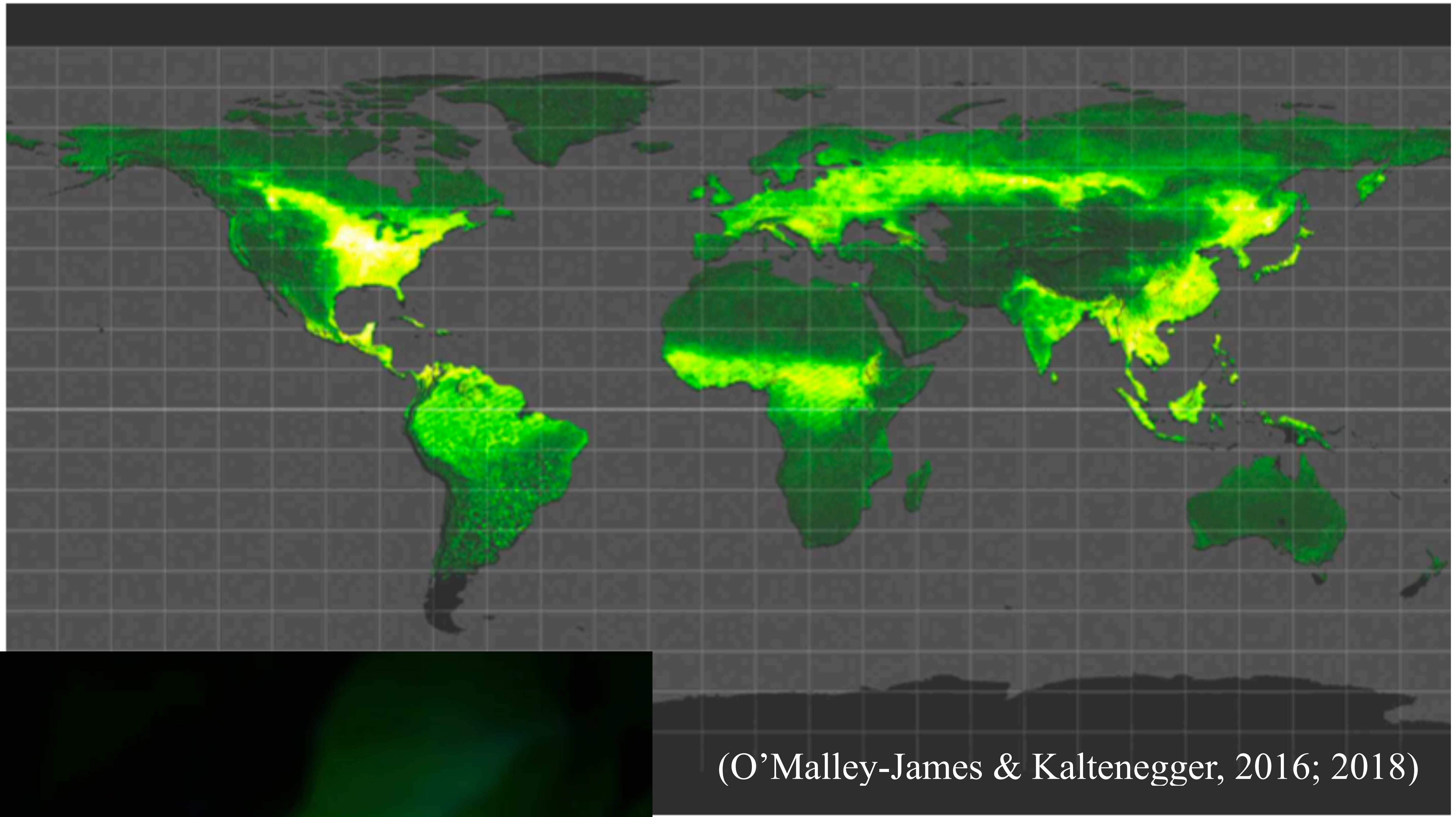
(cf) Oxygenic photosynthesis (Chlorophyll)
(e.g.) cyanobacteria – CO_2+H_2O
Anoxygenic photosynthesis (Bacteriochlorophyll)
(e.g.) purple bacteria, green sulfur bacteria – CO_2+H_2S

Photosynthesis on Earth (Schwieterman, 2018)



Biofluorescence from Vegetation





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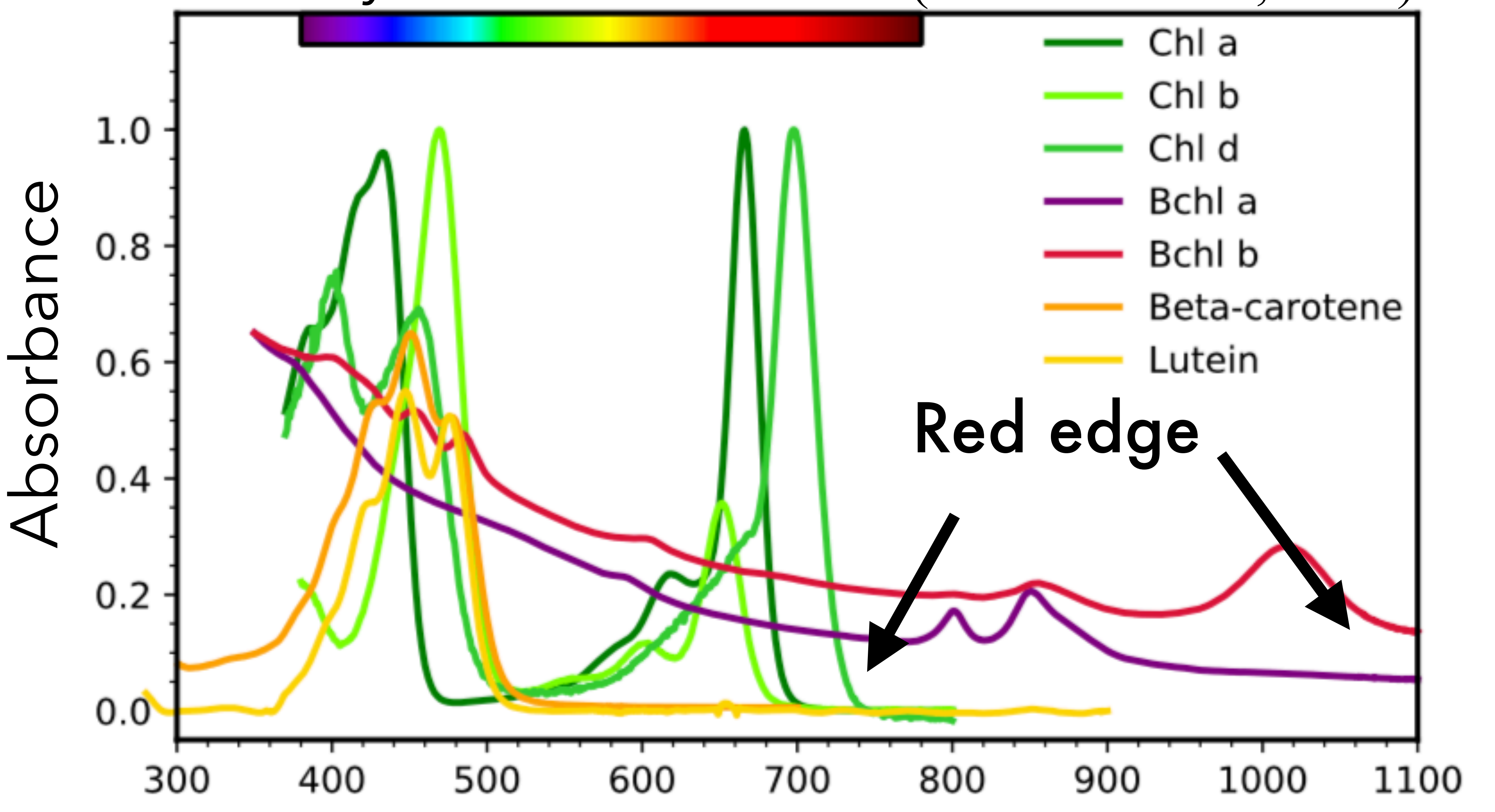
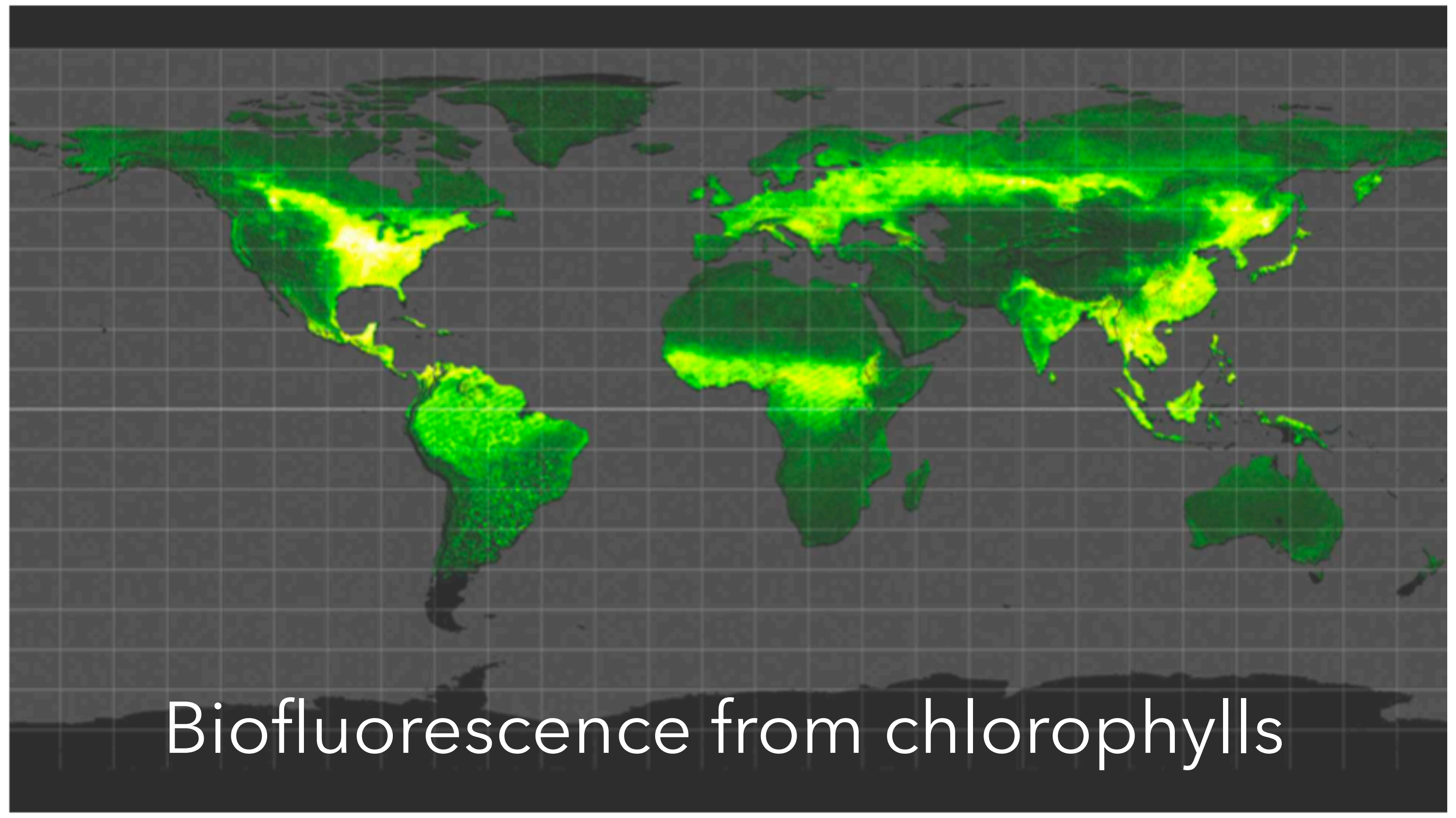
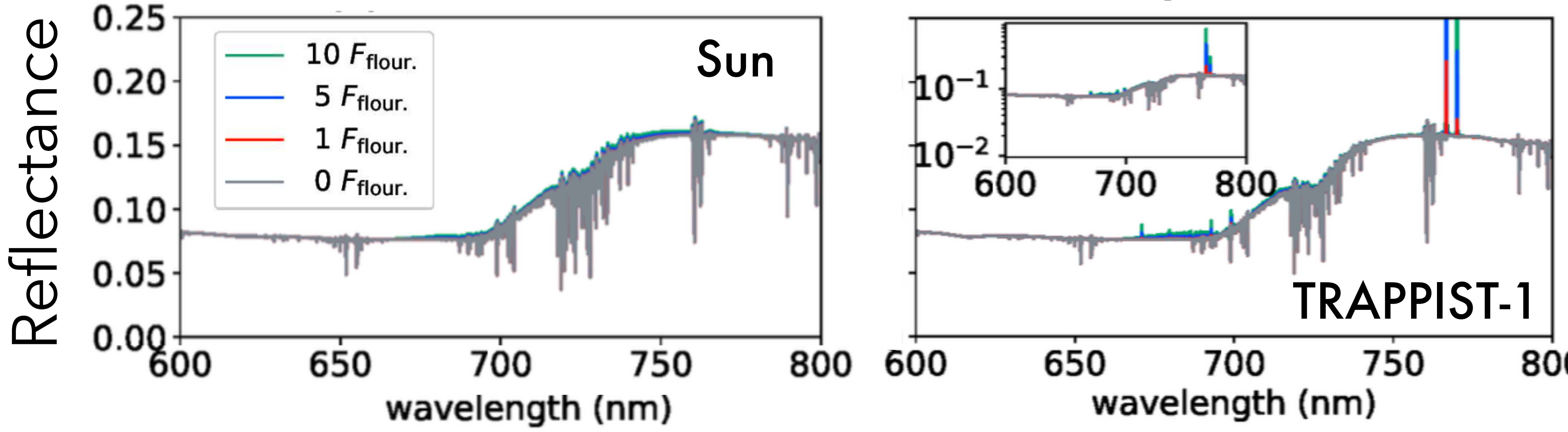


2) **Biofluorescence** (O'Malley-James & Kaltenegger, 2016; 2018)



Reflectance from an Earth-like planet



(Komatsu, YH *et al.* 2023)

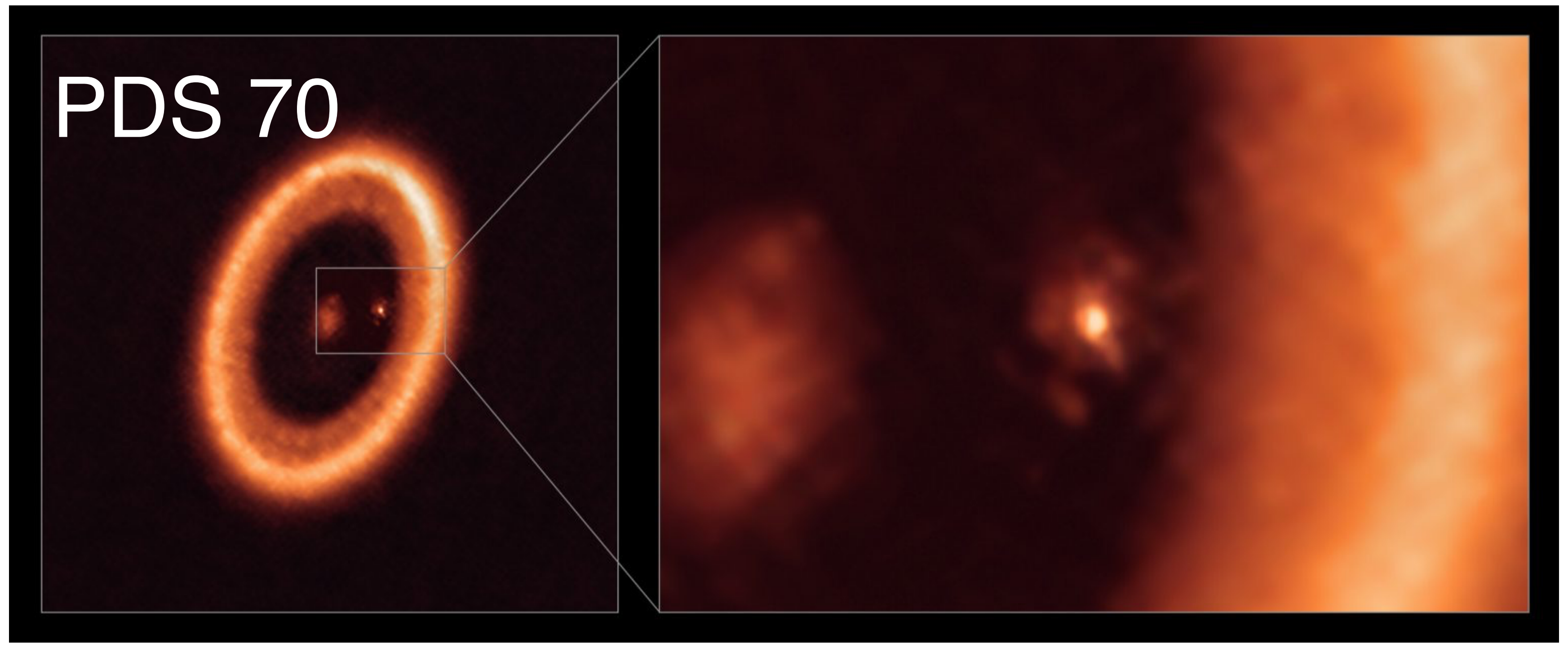
Further Characterization of Exoplanets

Universality of an Exomoon around Planets

Satellites exist around Earth, Mars and all the giant planets in the solar system.

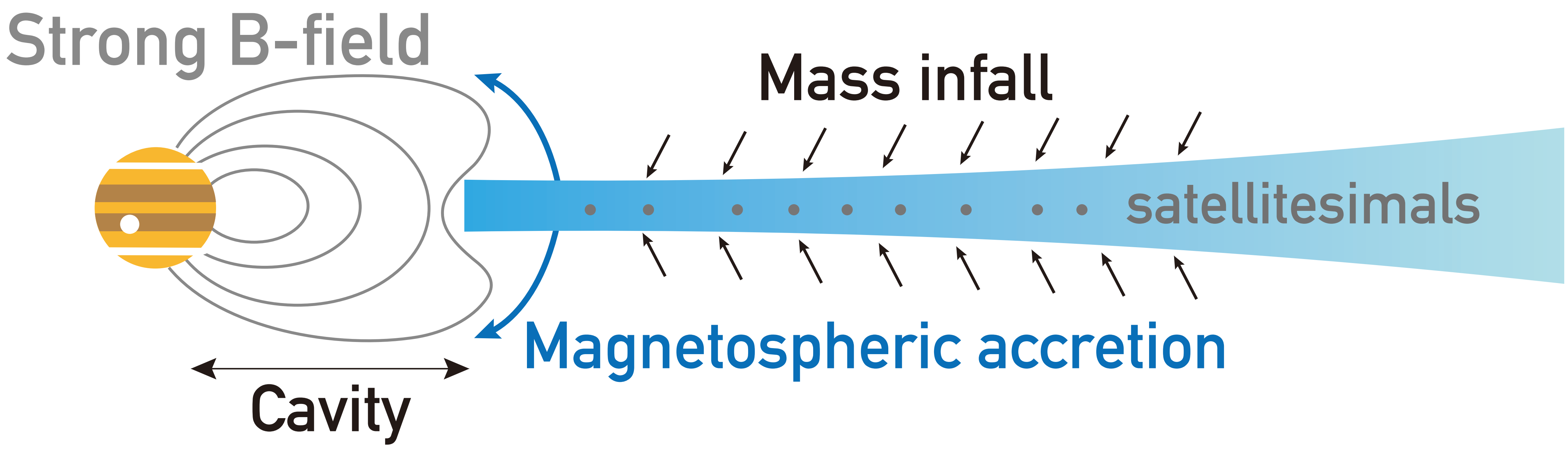
Formation processes:

a) solid accretion in a circumplanetary disk around a gas giant

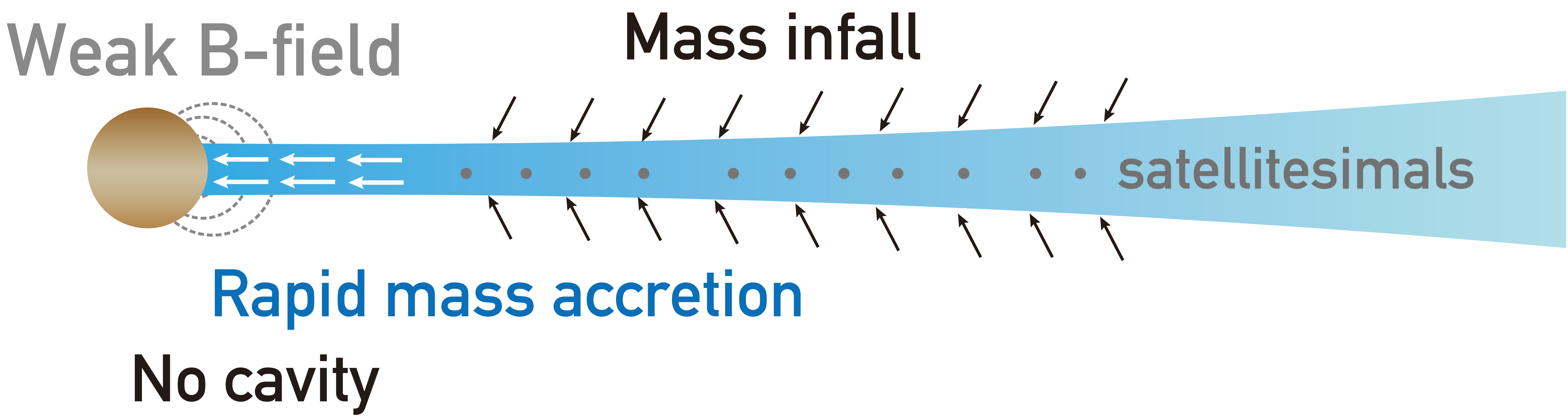


(e.g. Wagner *et al.* 2018; Haffert *et al.* 2019; Isella *et al.* 2019; Benisty *et al.* 2021)

Jupiter or More Massive Exoplanets



Saturn-mass Exoplanets



The system of multiple large satellites around a massive gas giant

(Fujii, Ogihara, & YH, *submitted*)

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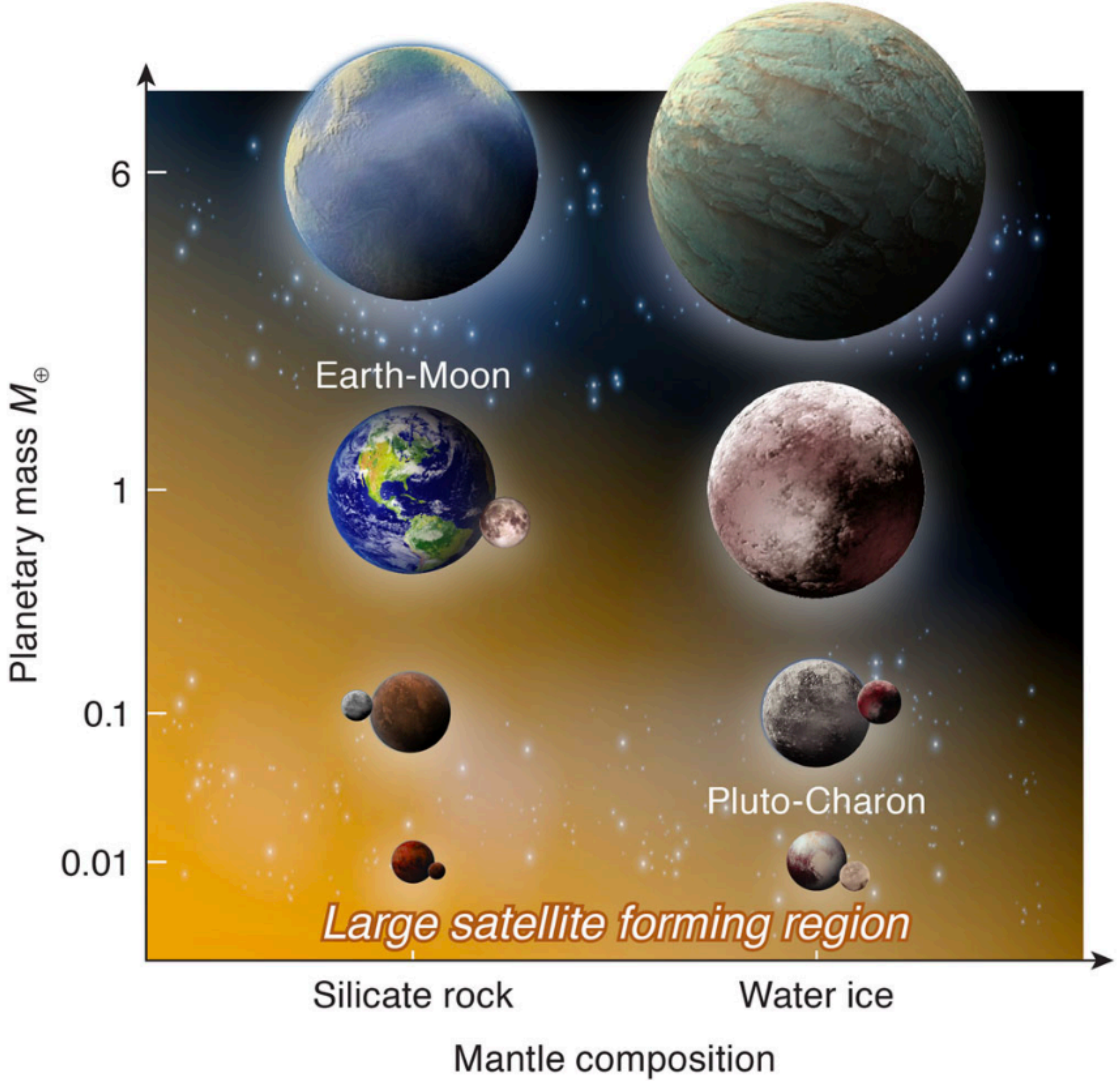
– The system of multiple large satellites around a massive gas giant

(Fujii, Ogihara, & YH, *submitted*)

b) giant impact on a planet or gravitational capture of large body

– moon formation around a rocky planet with < 6 Earth-mass or an icy planet with < Earth-mass (Nakajima *et al*. 2022)

(e.g. Wagner *et al*. 2018; Haffert *et al*. 2019;



Recent theoretical studies of moon formation predict the existence of moons around a gas giant and a low-mass rocky/icy planet

Toward the Detection of Exomoons

The detection of an exomoon is **true** or **false?**

Kepler-1708b-i (Super-Earth + Jupiter@1.64 au) (Kipping *et al.*, 2022)

Kepler-1625b-i (Neptune + Jupiter-sized@0.98 au) (Teachey & Kipping, 2018; Kipping, 2020)

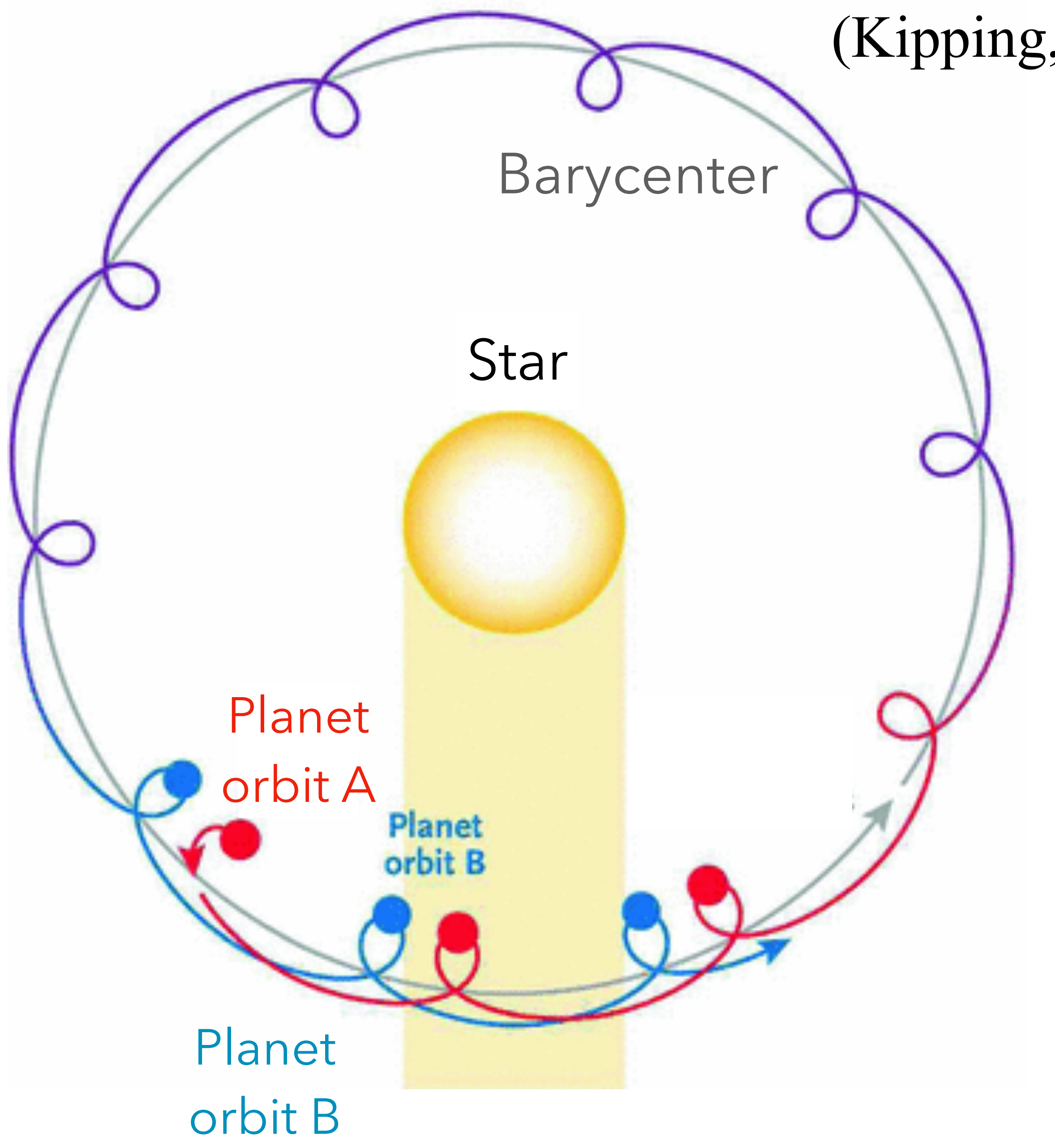
But no evidence? (Heller *et al*. 2019; Kreidberg *et al*. 2019)

A binary planet rather than an exomoon?

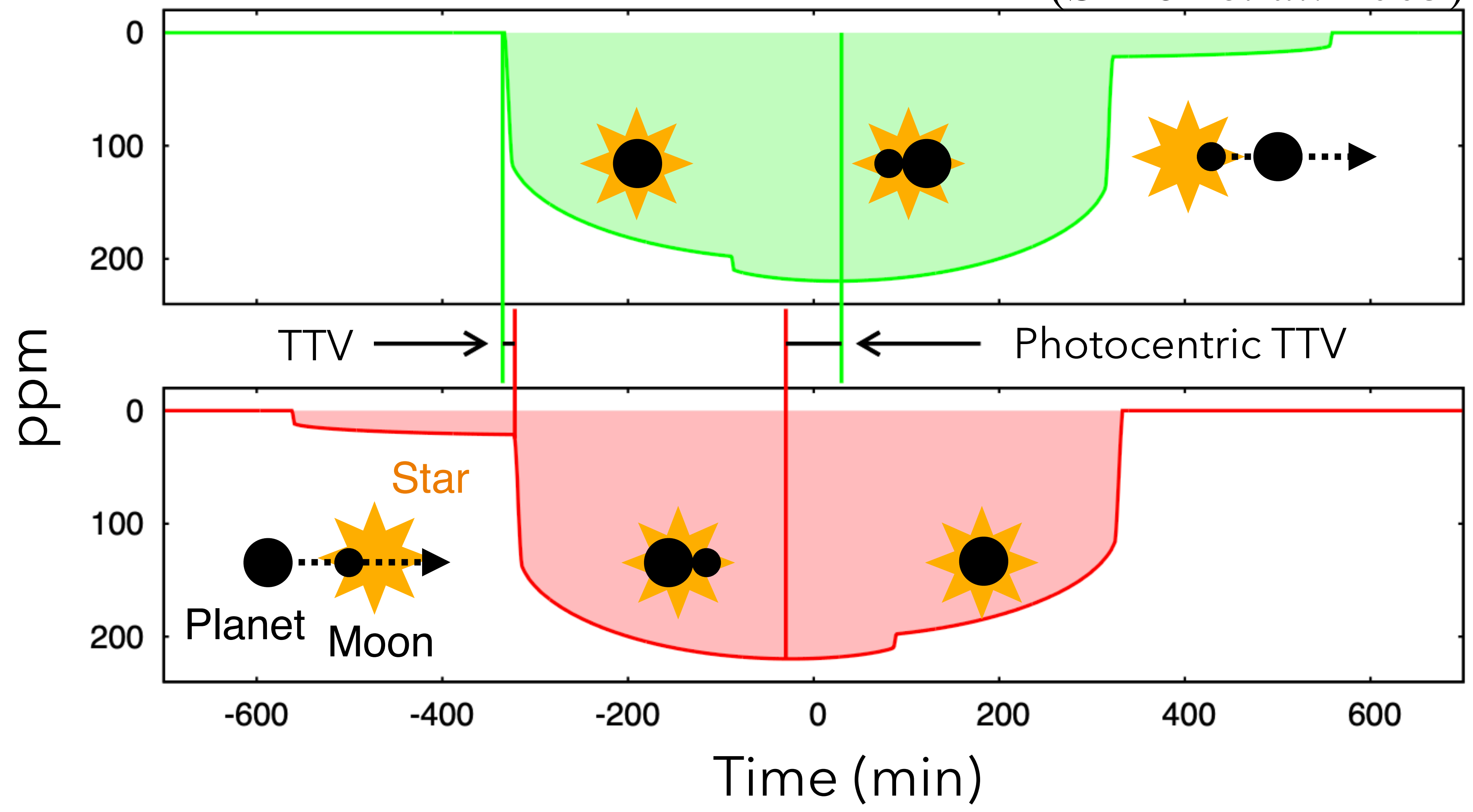
$$\Delta t_{\rm TTV} \sim 36\chi \left(\frac{M_{\rm moon}}{M_\oplus}\right)\left(\frac{M_{\rm P}}{M_{\rm Jup}}\right)^{-2/3}\left(\frac{M_\star}{M_\odot}\right)^{-1/3}\left(\frac{P_{\rm p}}{1\ {\rm yr}}\right) f(e_{\rm p}, e_{\rm moon}, \bar{\omega}_{\rm p}, \bar{\omega}_{\rm p})\ {\rm mins}$$

$$a_{\rm moon} = \chi r_{\rm Hill}$$

(Kipping, 2009)



(Simon *et al*. 2005)



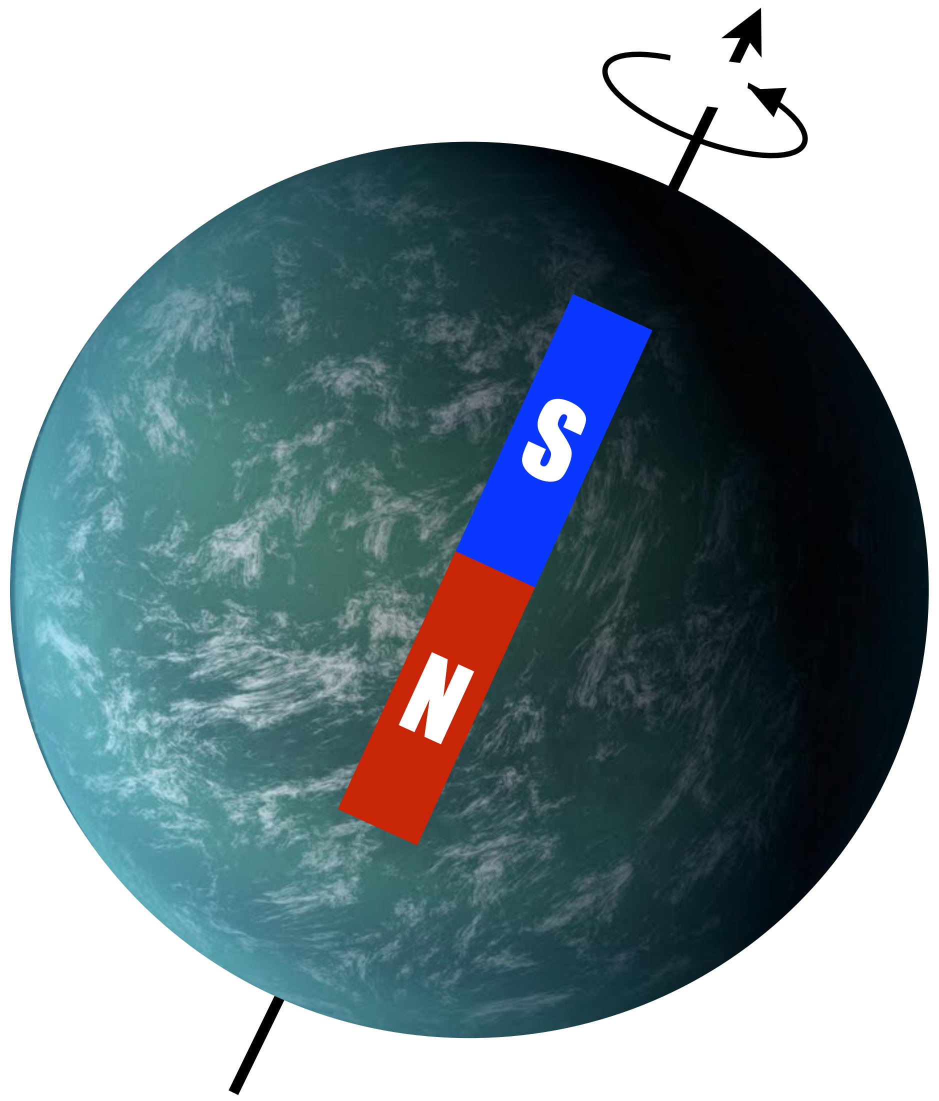
$$\frac{\Delta t_{\rm TDV}}{\Delta t_{\rm TTV}} \sim \frac{2\pi\sqrt{3}}{\chi^{3/2}}\frac{T_{\rm transit}}{P_{\rm p}}$$

i) Transit Timing Variation of a planet (**TTV**)

ii) Transit Duration Variation (**TDV**)

(Sartoretti & Schneider, 1999; Szabo *et al*. 2006; Simon *et al*. 2007; Kipping, 2009)

Planetary Magnetic Fields Are Common



Planetary magnetic fields (***B***) are generated by convective motions in an electrically conducting fluid, the so-called planetary dynamos.

A dynamo-driven ***B*** seems to be common among various types of planets.

- Earth-mass planets or fast-rotating low-mass super-Earths (e.g. Gaidos *et al*. 2011; Tachinami *et al*. 2011; Zuluaga *et al*. 2011)
- Giant planets (Yadav & Thorgren, 2017; YH, 2021)

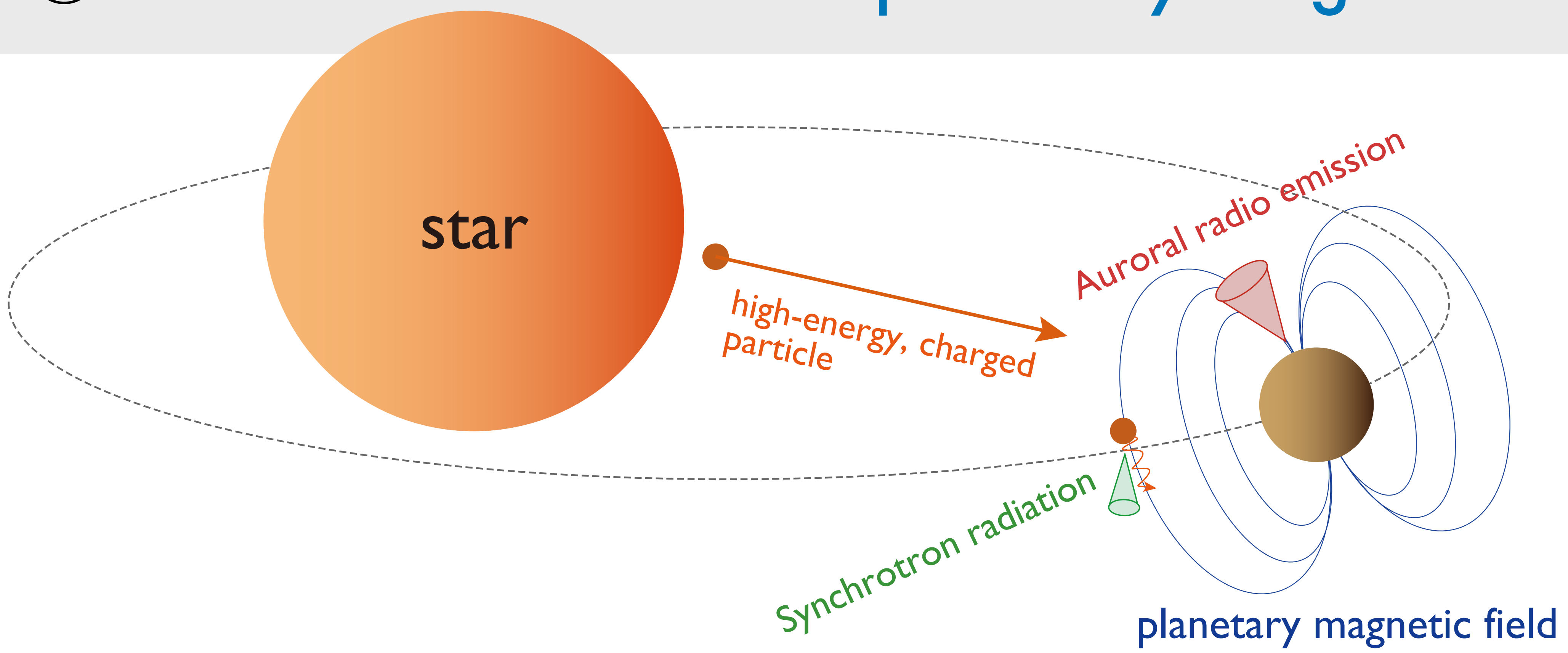
If ice giants have a low mass fraction of atmosphere, its mass should be less than several times Earth-mass. (Tian & Stanley, 2013)

(e.g.) Mercury, Earth, Jupiter, Saturn, Uranus, Neptune, and possibly, Ganymede

How Do We Detect Planetary Magnetic Fields?

① Interactions between a planetary magnetic field and high-energy, charged particles coming from a host star

(e.g. Grieβmeier *et al*. 2005; 2007)



(a) Synchrotron radiation

Emissions from accelerated electrons in a magnetic field

(b) Auroral radio emission

The cyclotron radiation from electrons moving along the magnetic field of a planet is attributed to the electron- cyclotron maser instability.

② Polarization in spectral lines in a magnetic field (e.g.) He I triplet lines escaping from a close-in planet

(Oklopčić & Hirata, 2018; Oklopčić *et al*. 2020)

- B < 1kG : atomic-level linear/circular polarization
  split of the atomic energy levels in multi-substates

Tentative detection? of circularly-polarized emissions from τ Boötis at LOFAR (14-21MHz) (Turner *et al*. 2021)

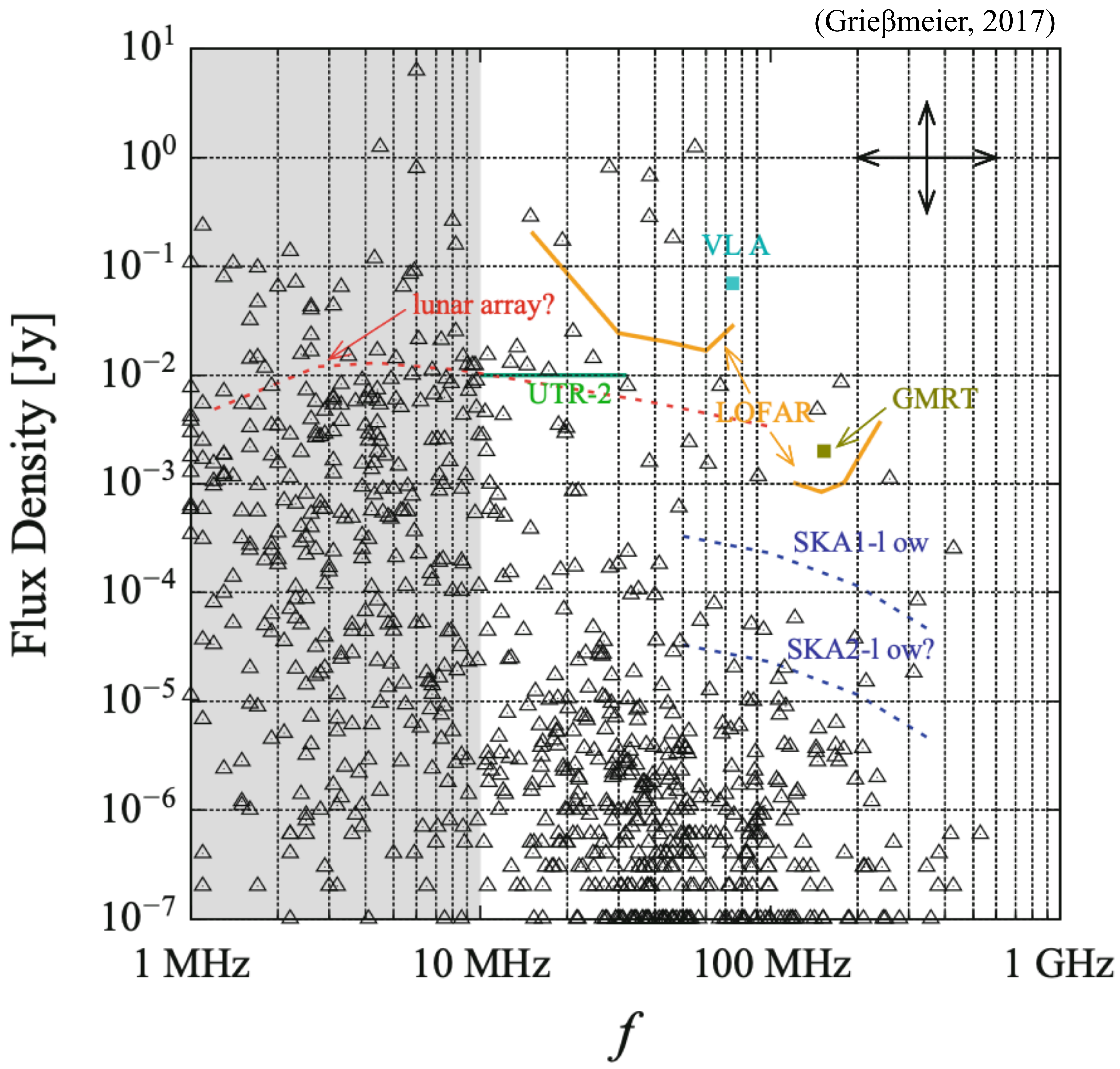
③ Star-Planet Interactions (SPIs) (e.g. Cuntz *et al*. 2000; Shkolnik *et al*. 2003; 2005; Saur et al. 2013; Lanza, 2013)

The Ca II K flux variations of HD 179949, HD189733, τ Boötis, and υ Andromedae are correlated with orbital periods of their hot Jupiters (Cauley *et al*. 2019)

④ The behavior of gases escaping from a planet

A magnetotail of HI and CII gas flowing out from HAT-P-11b (Ben-Jaffel *et al*. 2022)

Expected Flux Density of Radio Emissions from Planets



Cyclotron frequency: f

$$f = \frac{eB}{2\pi m_e c} \sim 2.8 \left(\frac{B}{1\,\mathrm{G}}\right) \mathrm{MHz}$$

m_e : electron mass
c : light speed
e : elementary charge

(cf) Plasma frequency $f_{\mathrm{pe}} = \sqrt{\frac{n_{\mathrm{e}} e^2}{2\pi m_{\mathrm{e}}}} \sim 8.98\,\mathrm{MHz}$

Planetary magnetic field (B) v.s Radio emission power (P_{rad})

(e.g. Grieβmeier *et al*.2005)

$$P_{\mathrm{rad}} \propto B^{2/3} n_0^{2/3} v^{7/3} a^{-4/3}$$

a : semimajor axis of a planet
v, n_0 : velocity and number density of charged particles from a star

Radio flux density observed on the Earth (Φ)

$$\Phi \sim \frac{P_{\mathrm{rad}}}{\Omega d^2 \Delta f} \propto B^{-1/3} n_0^{2/3} v^{7/3} a^{-4/3} d^{-2} R_{\mathrm{p}}^2$$

d : distance from Earth, R_{p} : planetary radius
Ω : solid angle of a beam, Δf : band width

Summary

The perspective of planet searches in the late 2020s and early 2030.

- Extreme precision RVs and the PLATO will reveal the population of Earth-sized planets in a HZ around a Sunlike star.
- The Roman space telescope will preferentially find Mars- and Earth-sized planets around an M dwarf.
- The Gaia and JWST can explore the distribution of gas giants more massive than Saturn beyond 1au.
- Near-infrared RVs have the potential of detecting planets orbiting a young star (10-100Myr).

↓

Comprehensive understanding of the formation and orbital evolution of planetary systems
The occurrence rate of a habitable Earth-sized planet and solar system-like planetary systems

A new era of 30m-class telescopes and LUVEx

- Imaging "Earth" and "Jupiter" around a nearby Sun-like star and an M dwarf.
- Information of detailed atmospheric compositions, surface environment such as ocean and vegetation, rotation properties of Earth-mass planets (and larger ones).
- The discovery of exomoons

↓

Comparative studies on atmospheric compositions and geological evolution of terrestrial planets