NAOJ Future Planning Symposium 2021: Thinking about Future Plans Across Wavelengths

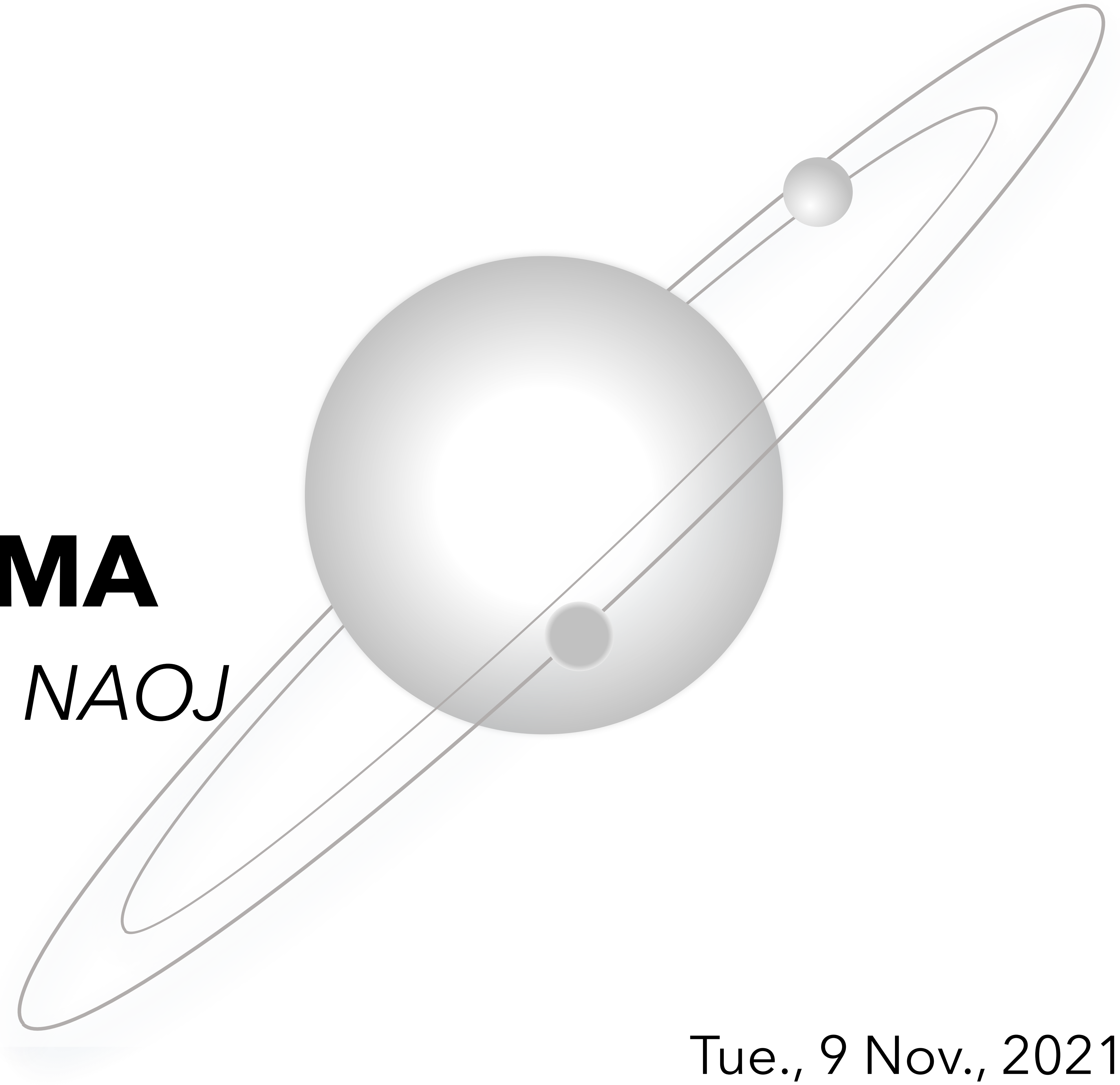
SG: Horizontal Axis 3 (Stars, Planetary System Formation, and Exoplanets)

Keynote talk on

Exoplanets

Masahiro IKOMA

Division of Science, NAOJ



Tue., 9 Nov., 2021

Key Questions

Are we alone?

To understand the "place" that we life occupy in the galactic context.

Diversity

- How diverse are planets and planetary systems?
- What fraction of planets or planetary systems resemble our own?

Formation & Evolution

- What brings about the diversity of planets and planetary systems?
- What is the critical factor in forming our Earth and Solar System?

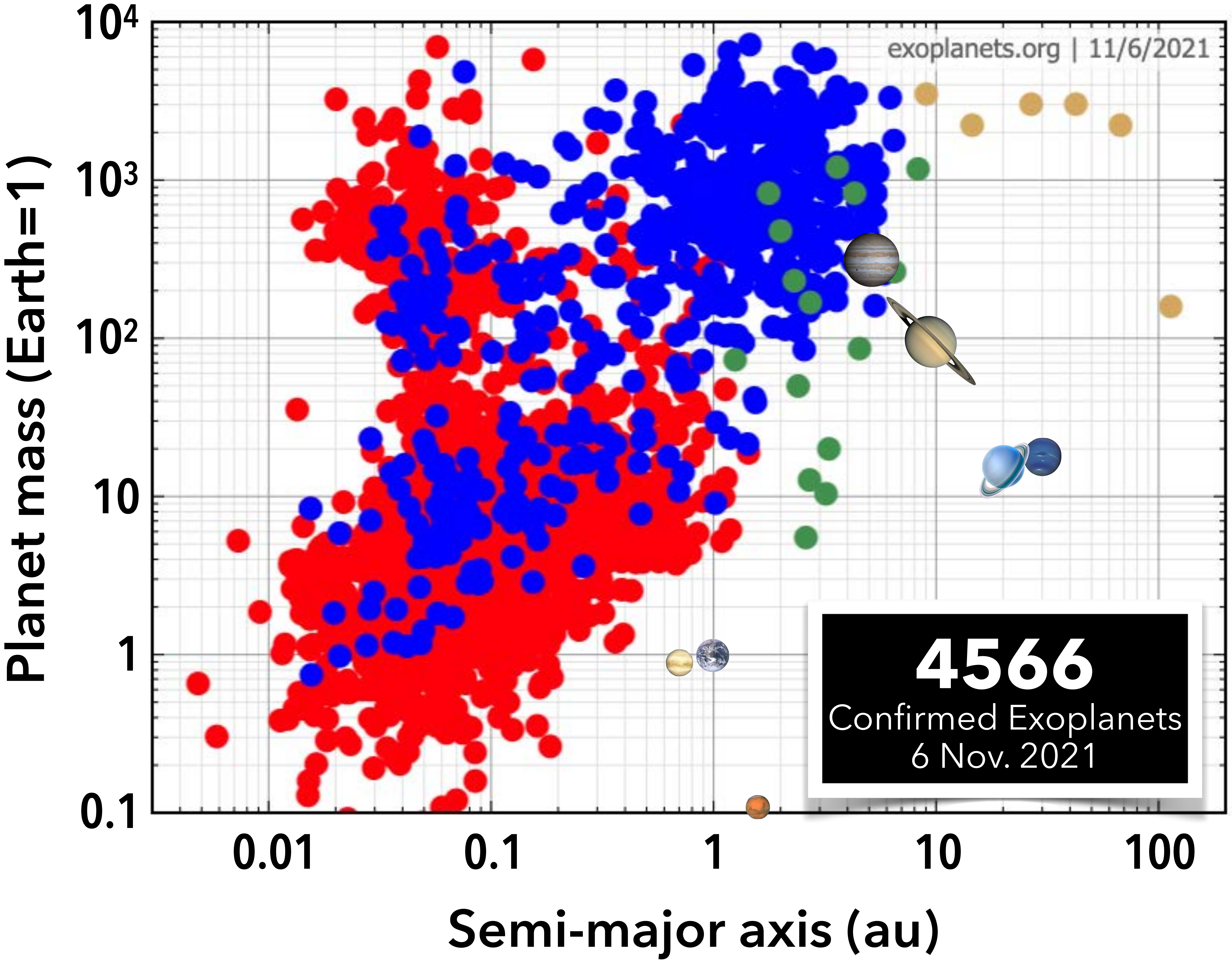
Habitability

- What are surface environments of rocky exoplanets like?
- How can rocky planets maintain stable, warm climates habitable to life?

Life

- How can we detect Earth-twins?
- How can we detect life on exoplanets?

Discovery Satus and Methods



Transit

- Detect apparent declines in stellar brightness during planetary transits
- Biased toward close-in planets

Radial Velocity

- Detect stellar wobbling
- Biased toward massive planets close to their host stars

Microlensing

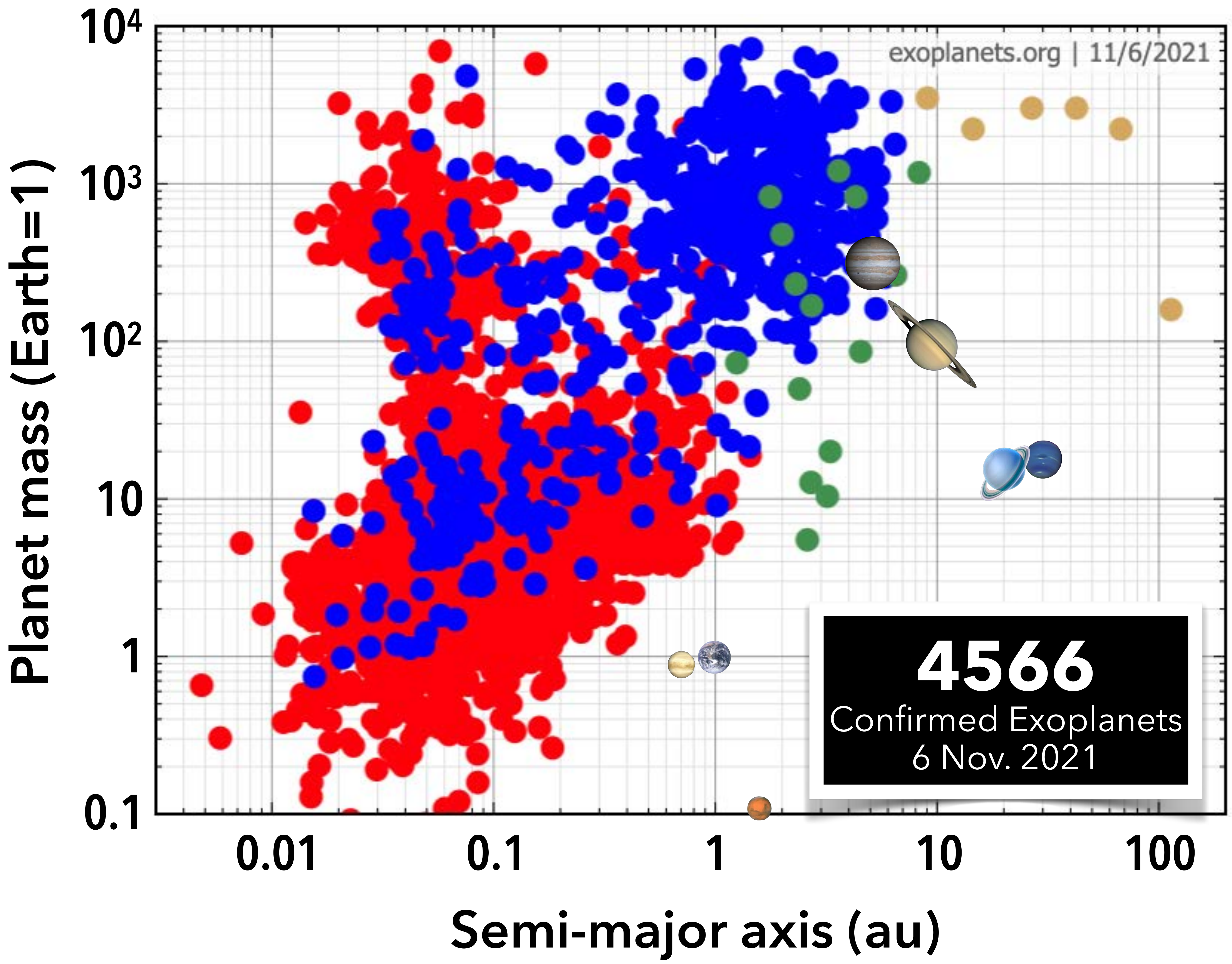
- Detect apparent brightening of the source star
- Biased toward planets orbiting in middle regions around their host stars

Direct Imaging

- Detect emission or reflection from planets directly
- Biased toward massive/large or young planets far from their host stars.

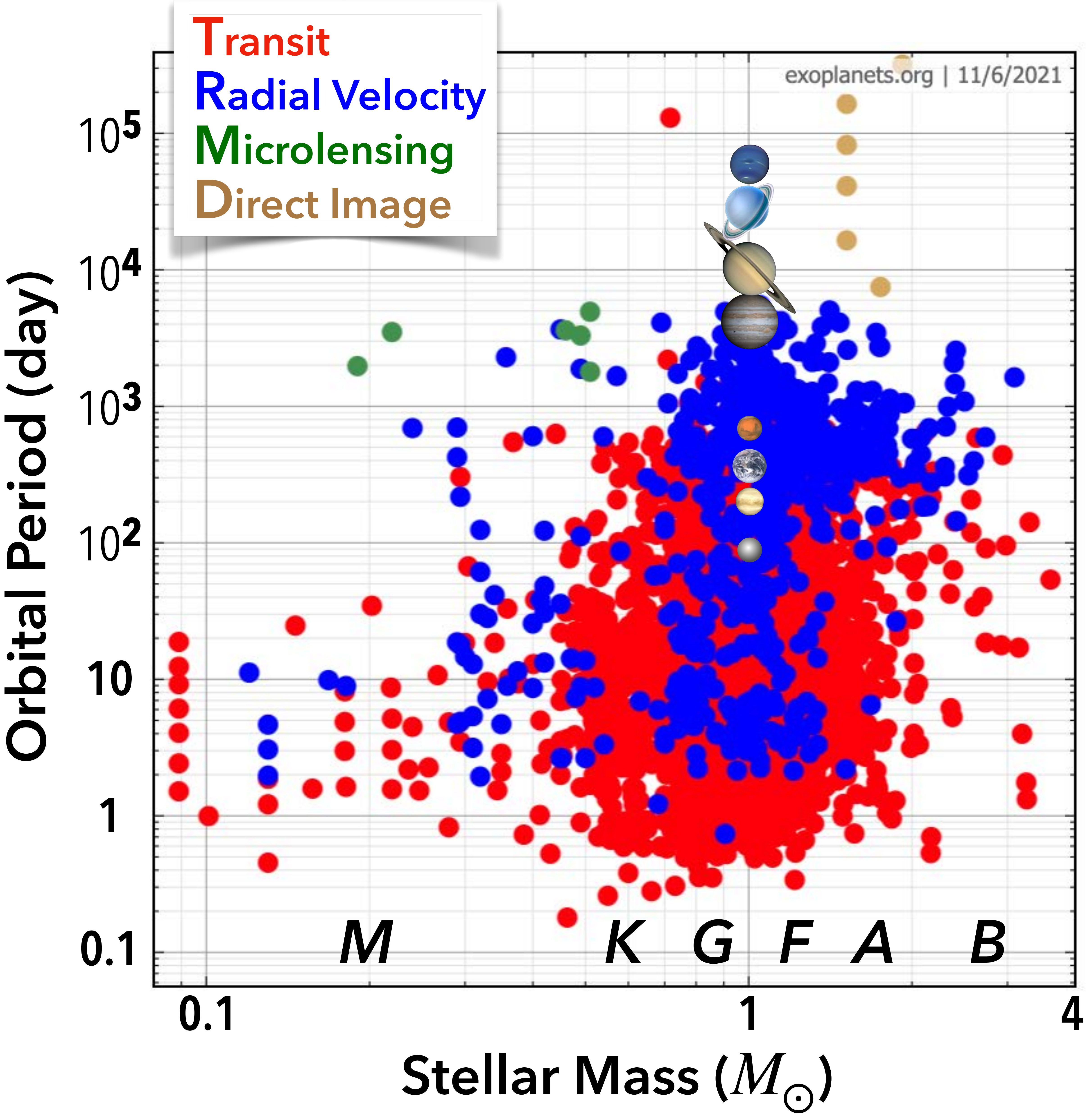

Japanese contribution to
Exoplanet Exploration
Image, UV-IR
LUVOIR-HabEX
Characterization of Earth-analogs
Biosignatures
Image, infra-red TMT
Characterization of Earth-analogs
Biosignatures
2040
2030
Transit, infra-red JASMINE
Survey for exoplanets around late M dwarfs
Ariel Transit, Infra-red, spectroscopy
Characterization of exoplanet atmospheres
+
Roman Microlensing, infra-red
Survey for long-period exoplanets
Doppler, infra-red
SAND
Survey for exoplanets around late M dwarfs
Microlensing, infra-red
PRIME
Survey for long-period exoplanets
WSO-UV Transit, Ultraviolet spectroscopy
Detection of Earth-analogs with extended atmospheres
2020
Dopper, Infra-red
Subaru-IRD
Survey for exoplanets around late M dwarfs
Spectroscopy
LUVOIR-HabEx
2040s
LAPYUTA
2030s
TMT, GMT
2030s
ELT
2027-
Ariel
2029-
WSO-UV
2025-
Subaru
VLT etc.
JWST
2021-
Hubble
UV
Vis
IR

Diversity of Planetary Systems



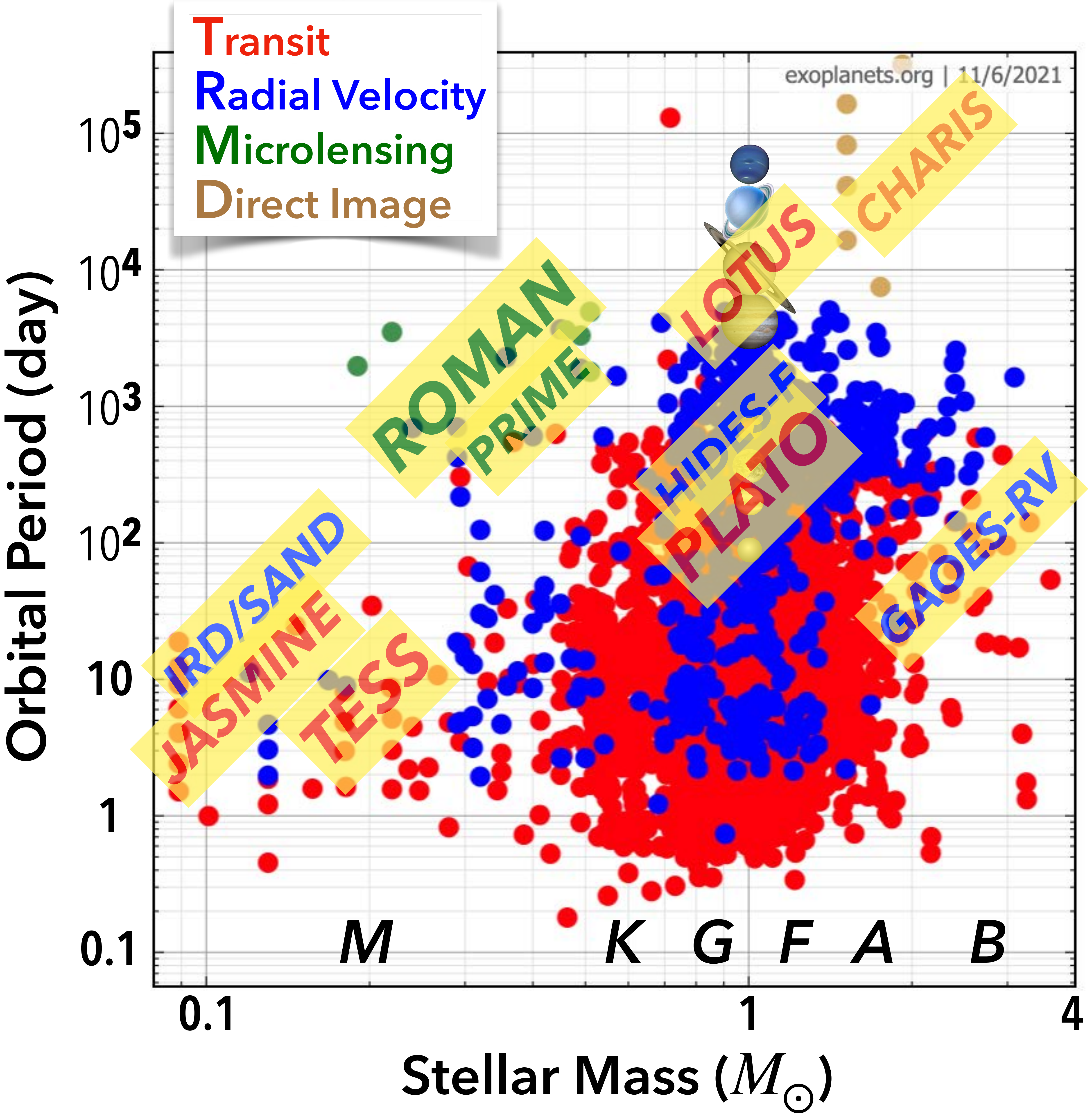
- Planets are **common** in the Galaxy.
  - At least, one planet per star.
- Planets are **diverse** in orbit and radius.
  - No solar-system analog has been discovered.
- The vast **majority** are planets larger than Earth but smaller than Neptune.
  - Confirmed for orbital periods < 100 days around FGK dwarfs (or Sun-like stars)
  - No such planet is found in the Solar System
- Gas giant planets like Jupiter are less common but not so rare.

Uncharted Territories



- Most of exoplanets detected so far are orbiting Sun-like stars.
  - $\lesssim 10^3$ days for transiting planets
  - $\lesssim 10^4$ days for RV planets
- Largely uncharted territories:
  - Around relatively late M dwarfs
  - Beyond Jupiter's orbit around Sun-like stars (FGK dwarfs)
  - Around $\gtrsim 2M_\odot$ stars

Ongoing and Near-future Projects for Finding Planets



Space

TESS (NASA) 2018-
… Earth-analogs orbiting mid M dwarfs

PLATO (ESA) 2026-
… Earth-analogs orbiting Sun-like stars

Roman (NASA) 2026-
… From sub-Earths to gas giants near and beyond the snowline mainly around M dwarfs

JASMINE (Japan) 2028-
… Earth-analogs orbiting late M dwarfs

LOTUS (Japan) 20xx- *… Solar-system analogs*

Ground (Japan)

IRD @ Subaru … Super-Earths orbiting late M dwarfs

PRIME @ SALT 2022-… Planets near & beyond snowlines

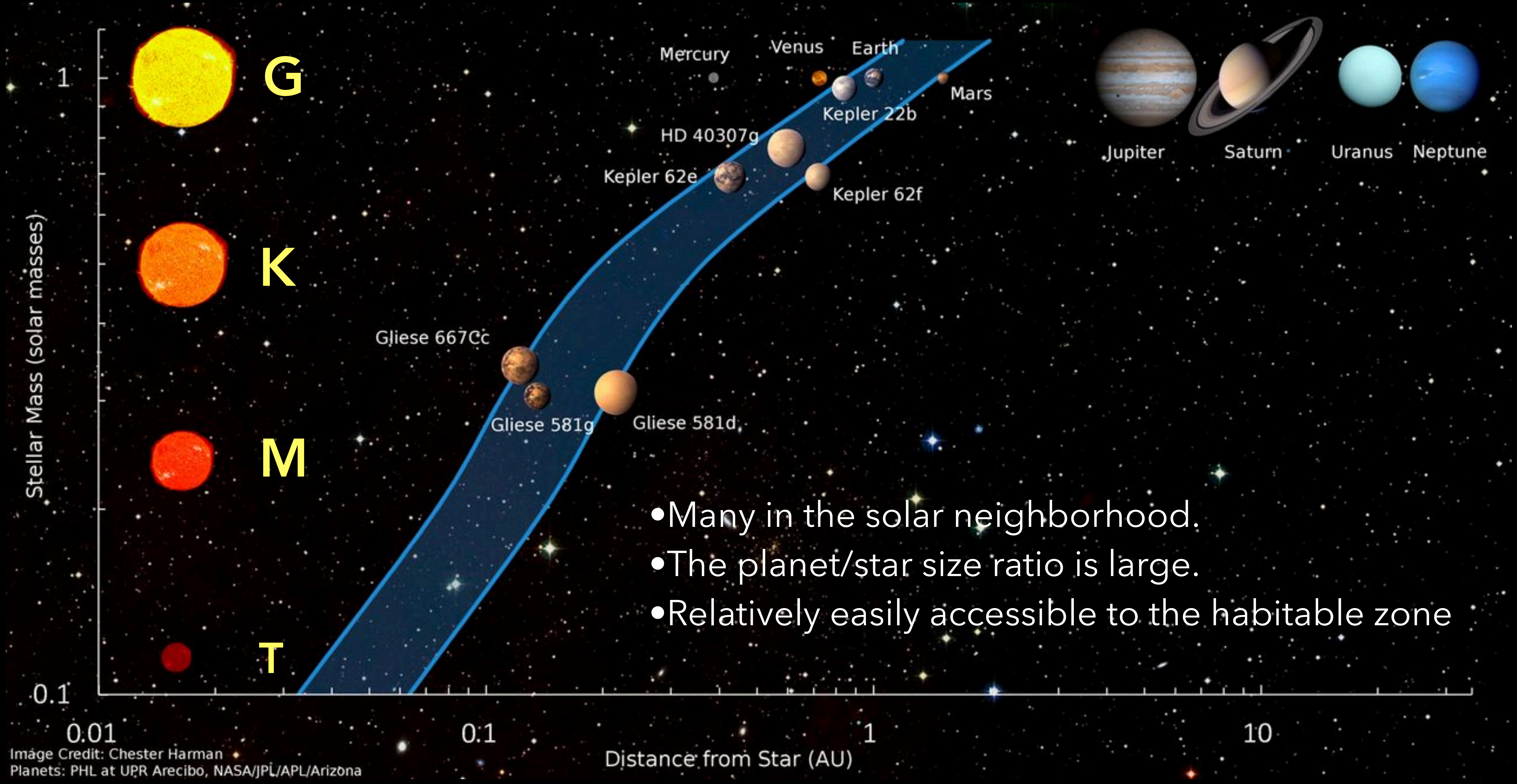
SAND @ SALT 2022(?)- … Super-Earths orbiting late M dwarfs

CHARIS @ Subaru … Young gas giants by direct imaging

HIDES-F @ Okayama188cm … Super-Earths orbiting Sun-like stars

GAOES-RV @ SEIMEI … Planets orbiting red giants of $> 2M_\odot$

Why M dwarfs?

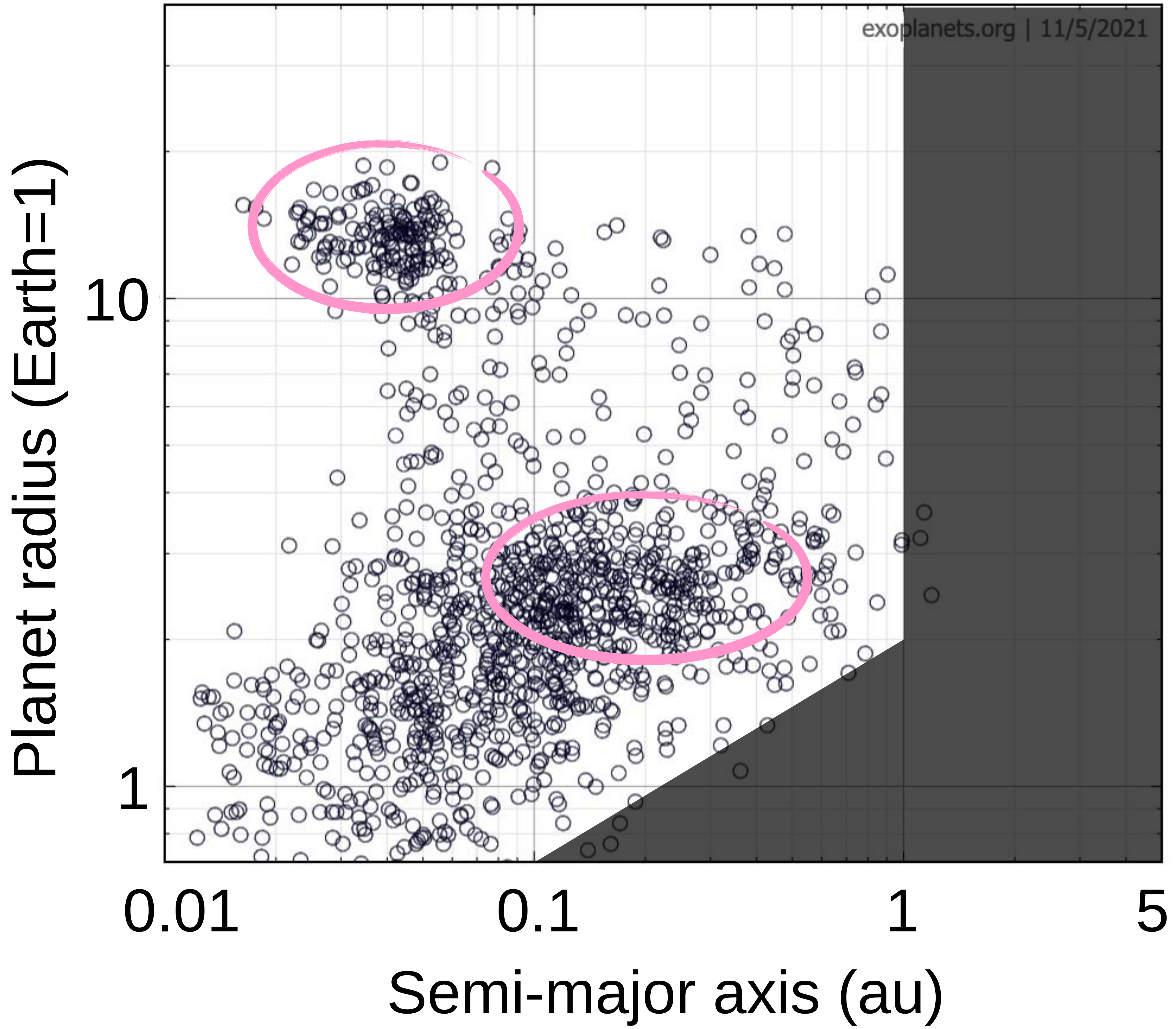


- Many in the solar neighborhood.
- The planet/star size ratio is large.
- Relatively easily accessible to the habitable zone

Planet Formation: Theory vs. Observation

Observed distribution of
planets orbiting FGK dwarfs

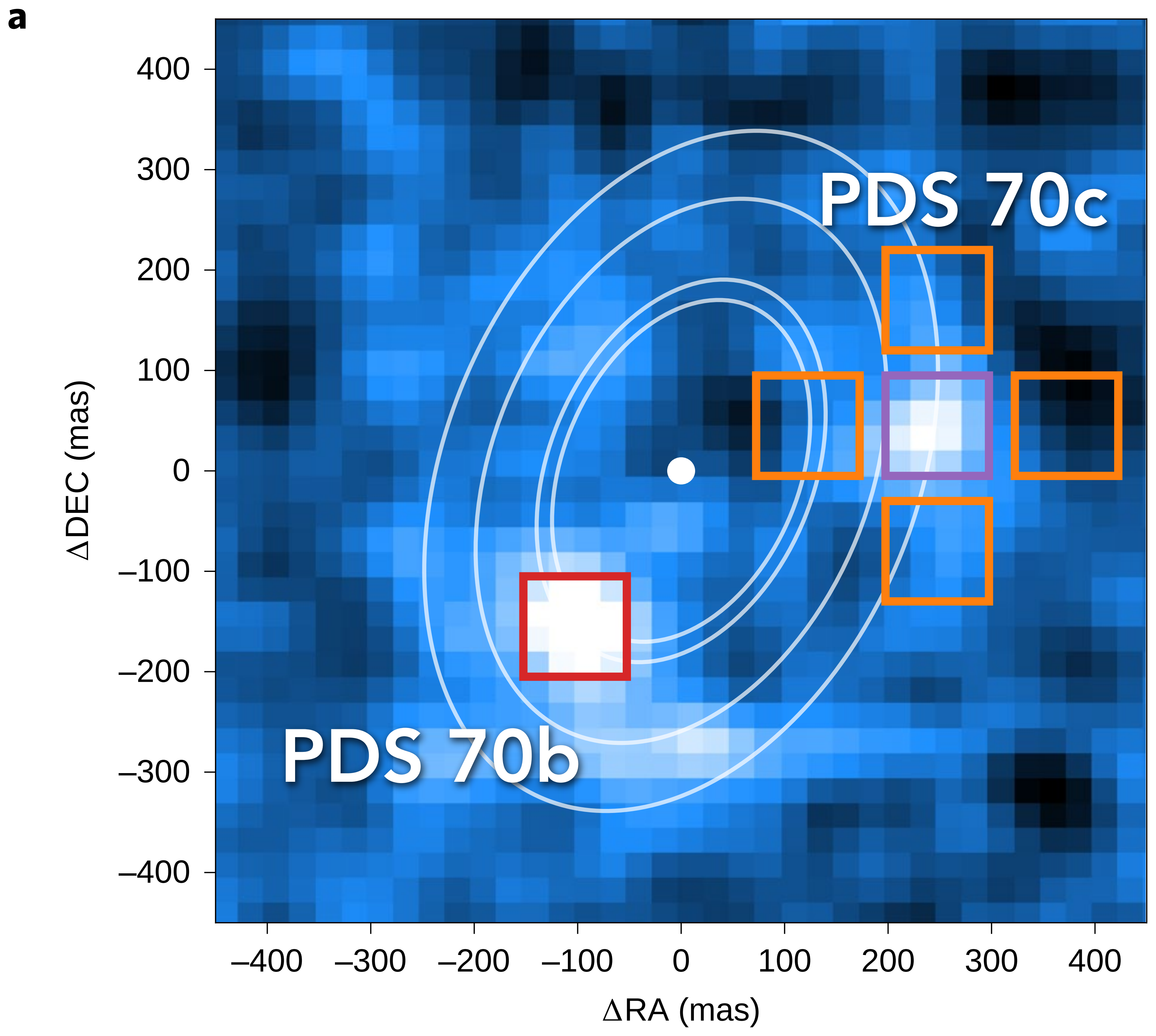
taken from exoplanets.org



- Close-in gas giants are predicted to be much less common than observed.
  - -The accumulation processes of solids and gas have been relatively well understood.
  - -The critical issues are to understand how solid materials are distributed in protoplanetary disks and how planetary cores migrate before runaway gas accretion.
- Predicted abundance of super-Earths/sub-Neptunes is inconsistent with the observed one.
  - ➡Lack in understanding of the accumulation and photo-evaporation of their atmospheres.
- Diversity in bulk composition is predicted.
  - ➡Bulk composition is useful in validating planet formation theories.

Observation of Growing Protoplanets

Observation of Hα emission from protoplanets

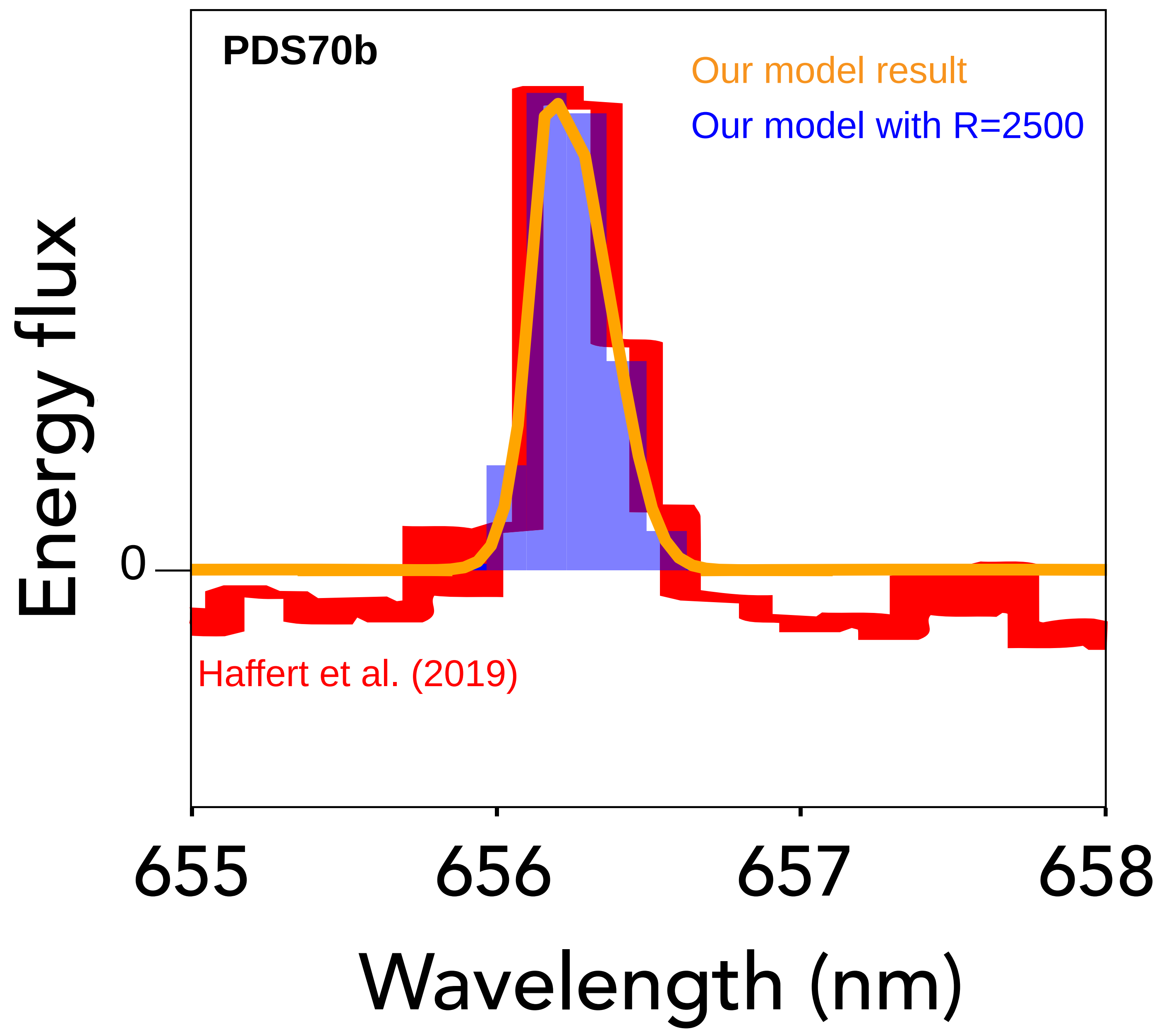


Haffert et al. (2019)

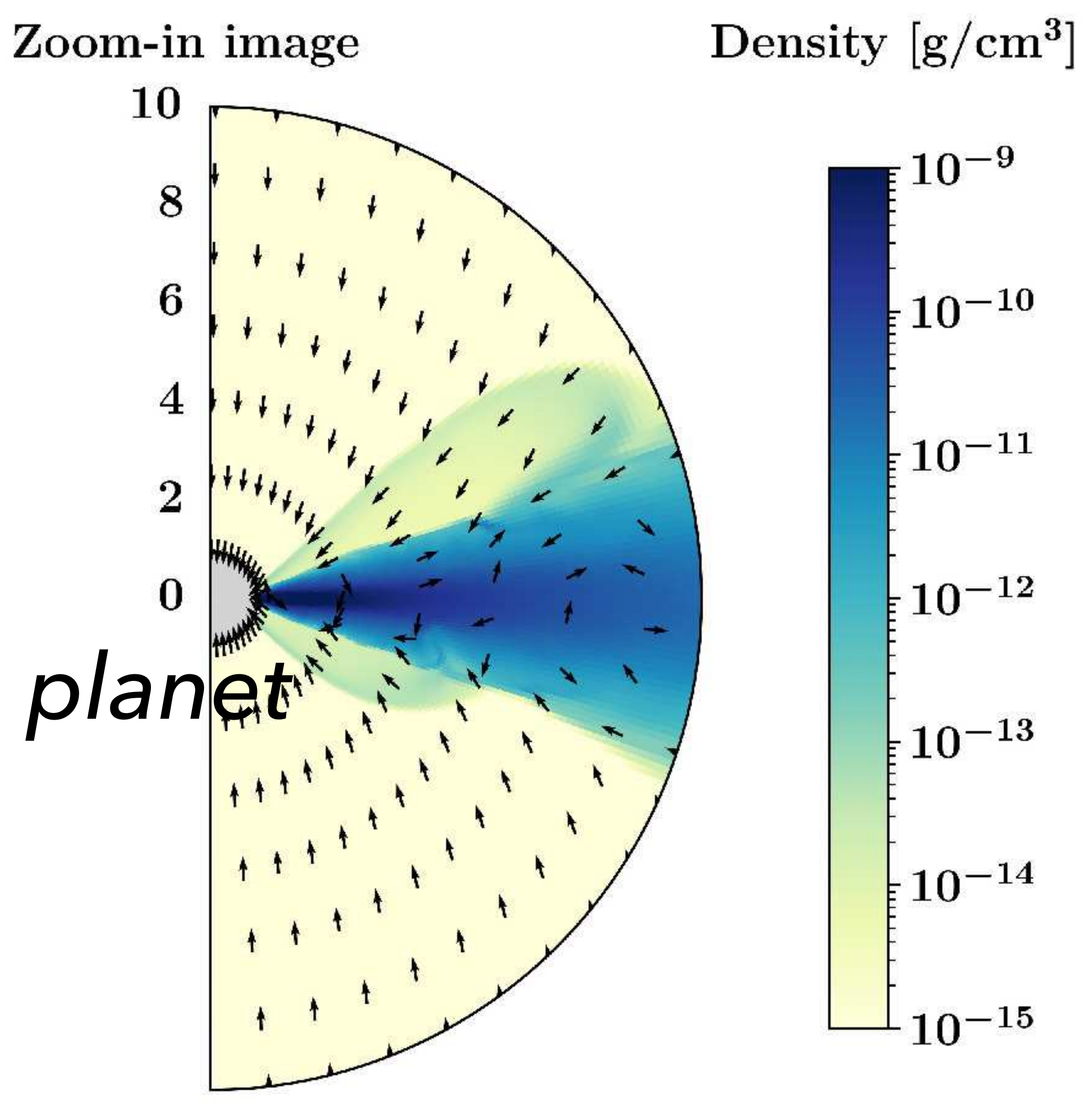
LTAO-HRSDI in MUSE@VLT

Theoretical prediction

Line profile
(Aoyama & Ikoma 2019)



Hydrodynamics
(Takasao, Aoyama & Ikoma 2021)

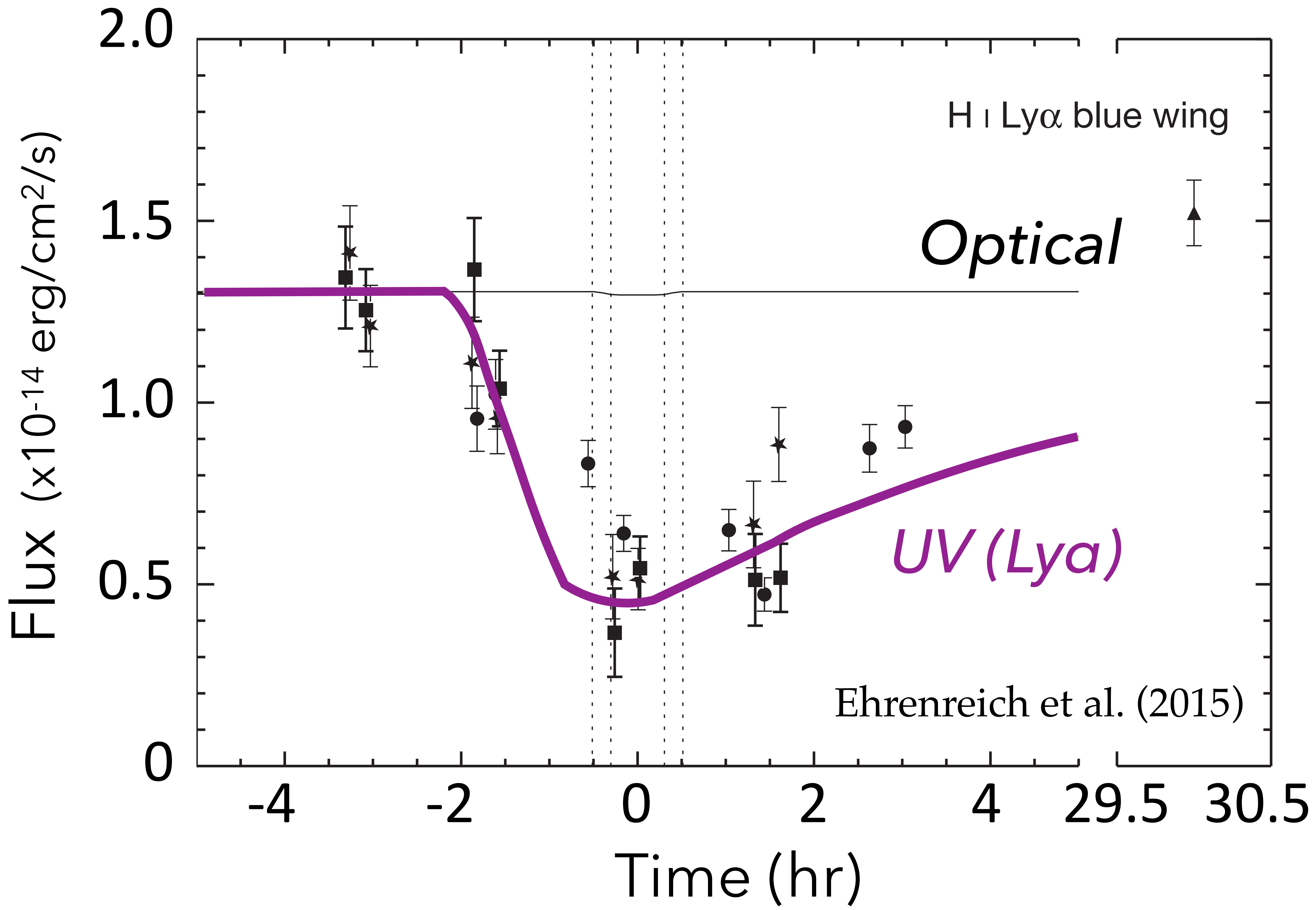


- The Hα emission comes from the shock-heated gas around the accreting protoplanets.
- Detection of Hα emission is useful in understanding where gas giant planets are formed in protoplanetary disks.

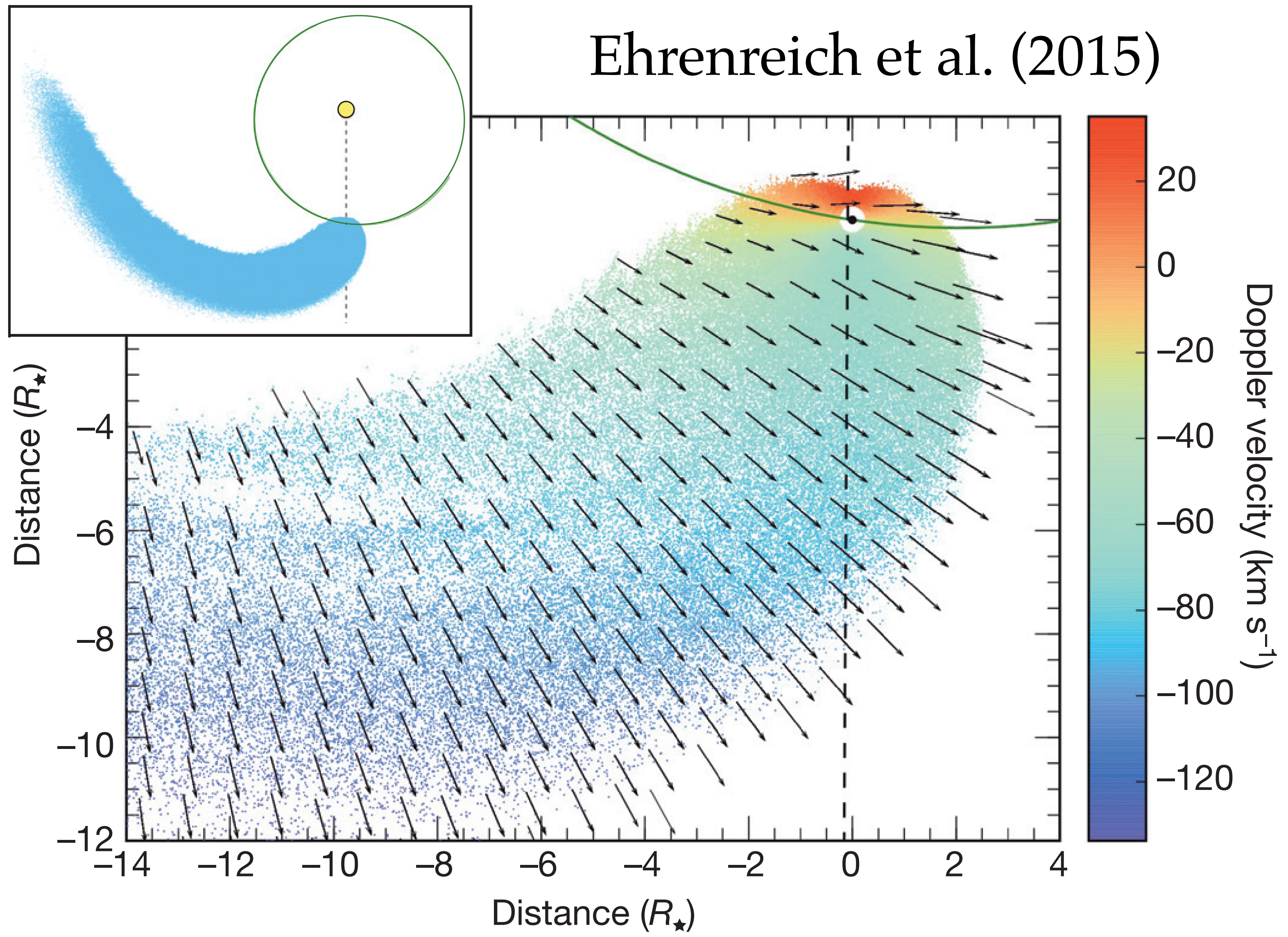
→ *Hα imaging with Subaru/SCExAO+VAMPIRES*
(Uyama et al. 2020)

Observation of Evaporating Atmospheres

Transit light curve for super-Earth GJ 436b taken with HST



Hydrodynamic simulation of atmospheric escape

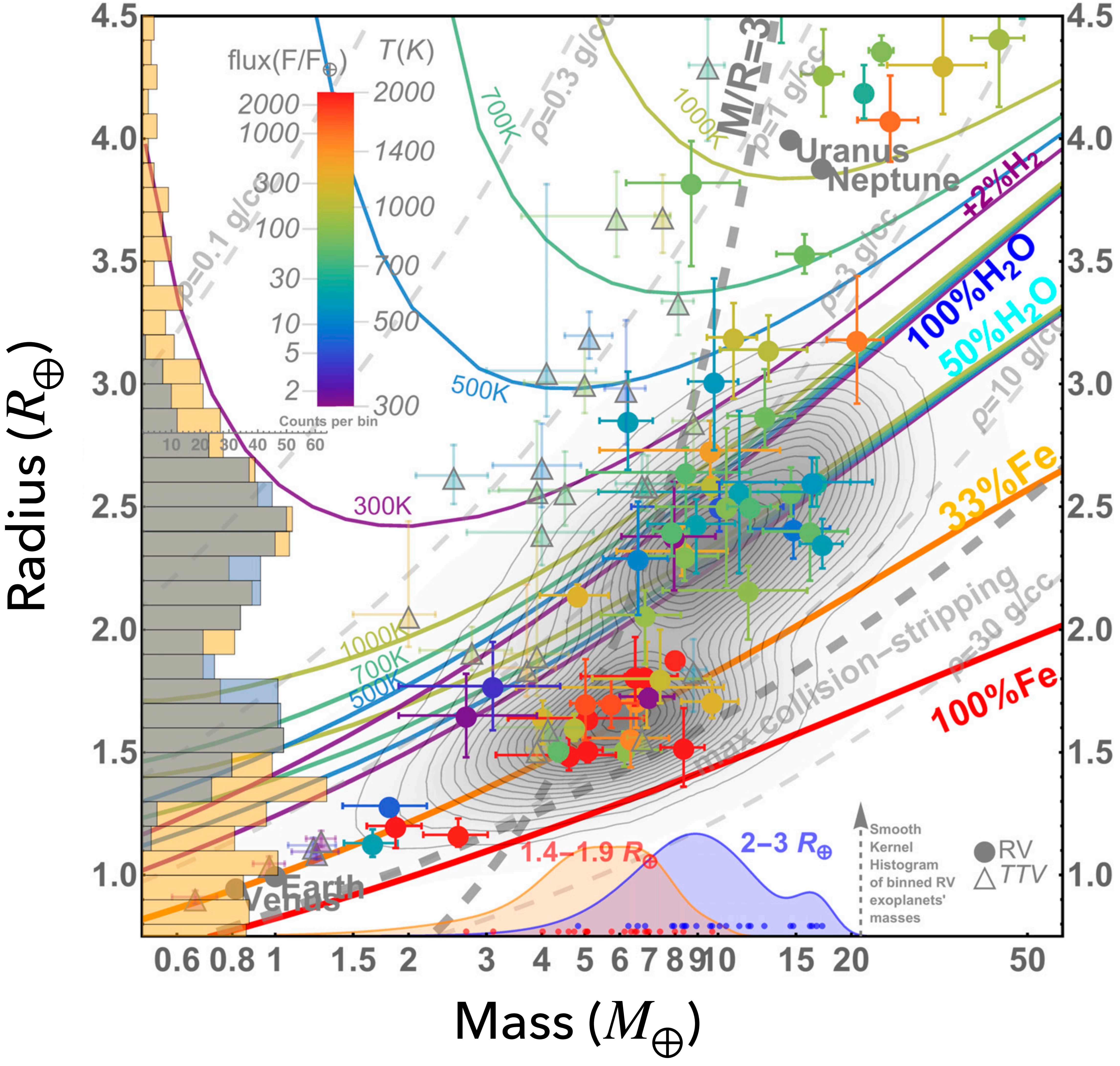


The Lya transit depth is > 50%,
whereas the optical one is only 0.7%.

- More samples are needed to better understand the photo-evaporation process of super-Earths.
- Only **WSO-UV** (and **LAPYUTA**) can perform UV observation in 2020s and 2030s, after the end of HST operation.

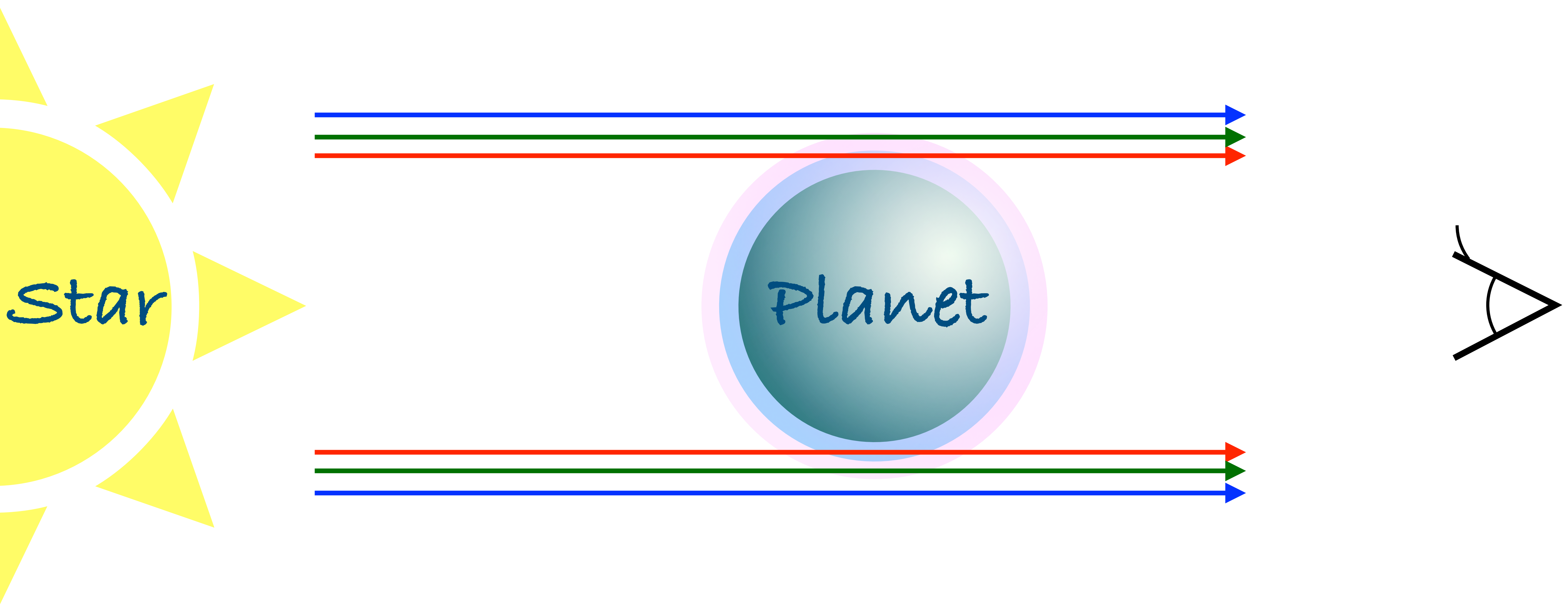
Mass vs. Radius

Zeng+ (2019, PNAS)

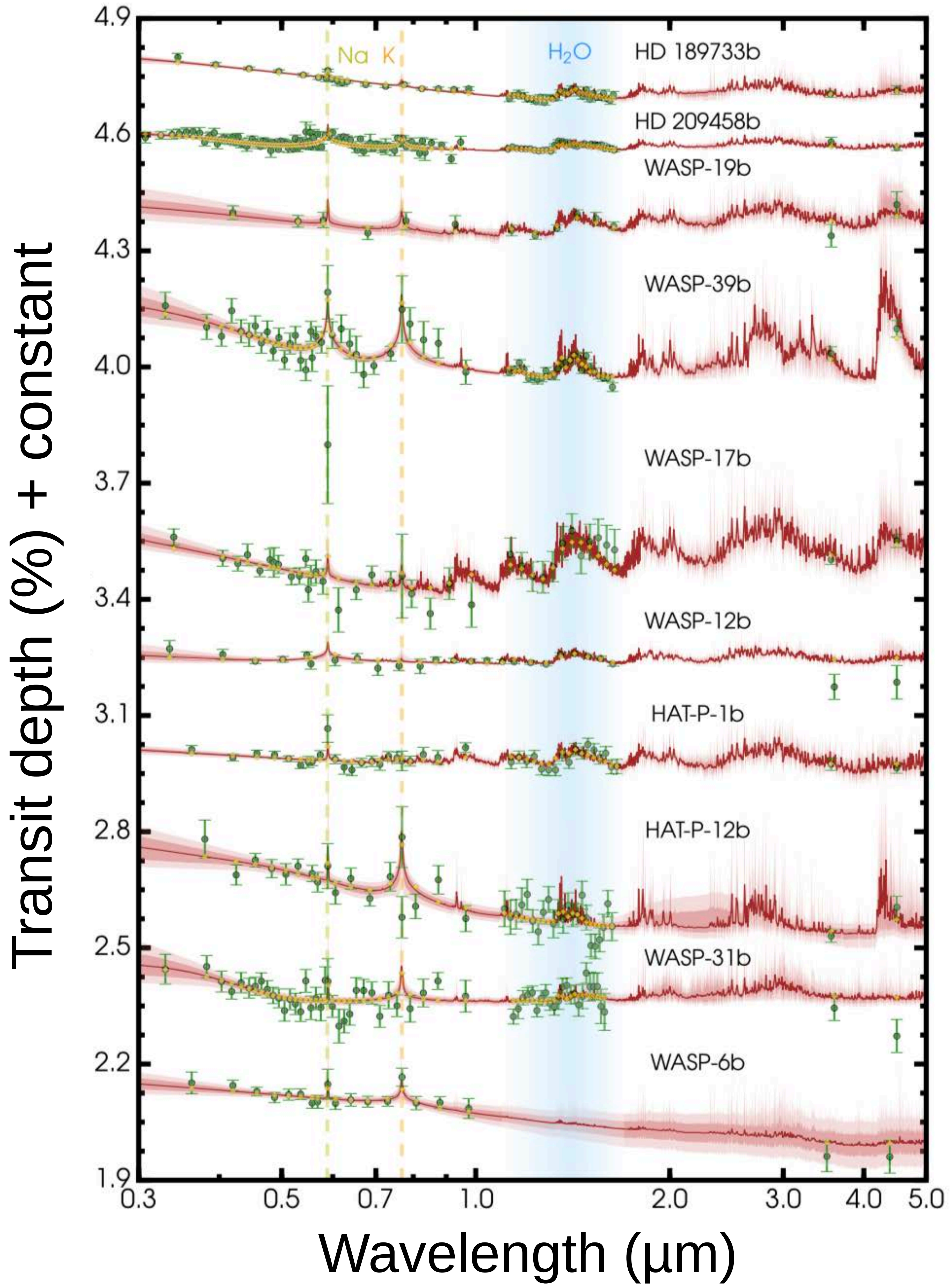


- Observed mass vs. radius relationships place **constraints to the bulk composition** of planets.
- Observationally, planets of the same mass have different radii, indicating **diversity in bulk composition**.
- Theoretically, planets with different bulk compositions have the same mass-radius relationship. → ***Degeneracy in bulk composition***

Observation of Planetary Atmospheres



- Multi-wavelength observations are useful in placing constraints to atmospheric composition.
- Telescopes & Instruments
  - Low-resolution … JWST, Ariel
  - High-resolution … Subaru/ IRD, TMT/PSI, MICHI



Pinhas et al. (2019)

Critical Issue: Linking Atmosphere to Interior of Super-Earths

Aqua-planets

having stable warm climates

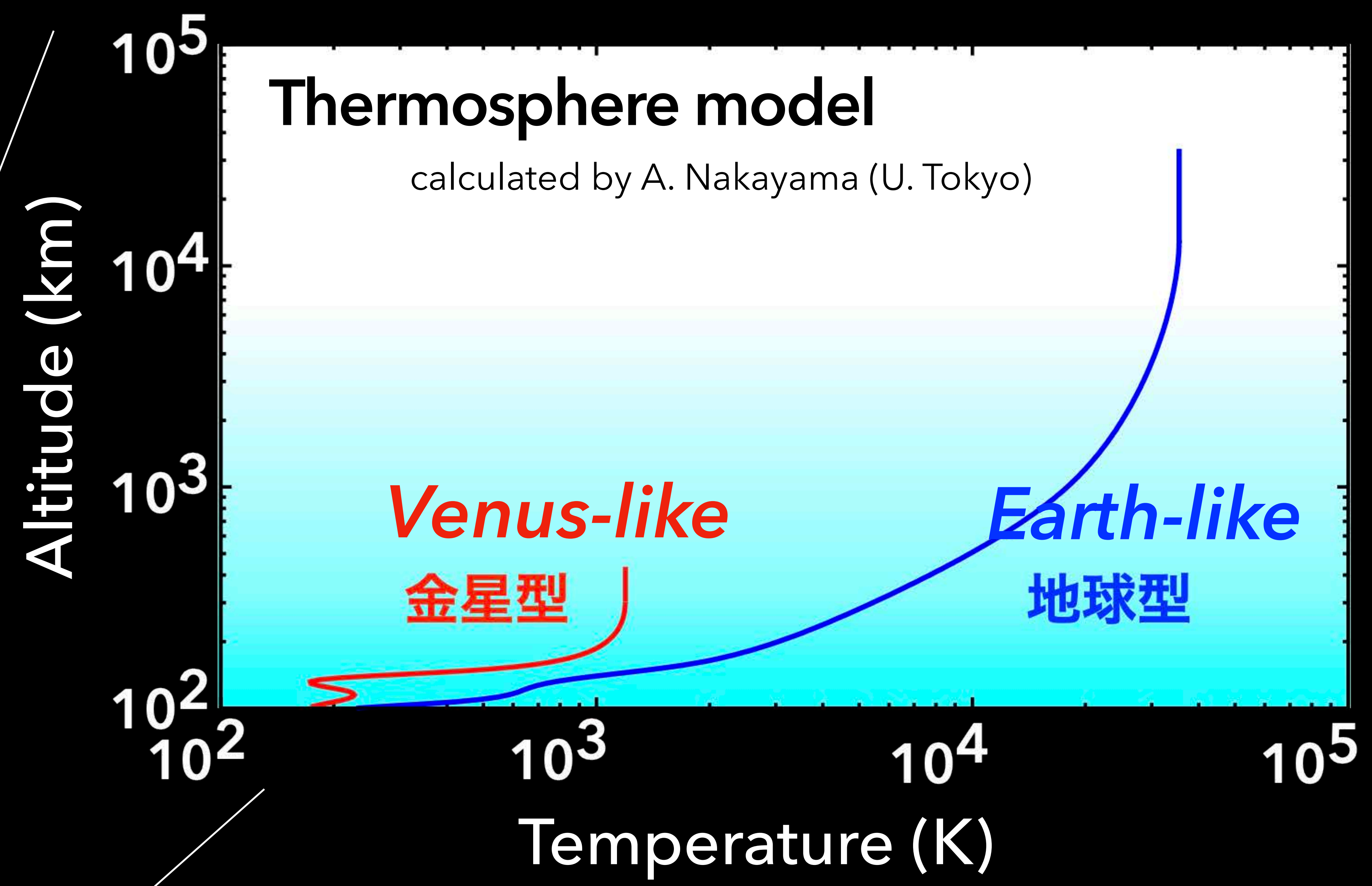
<u>Critical Issue:</u>

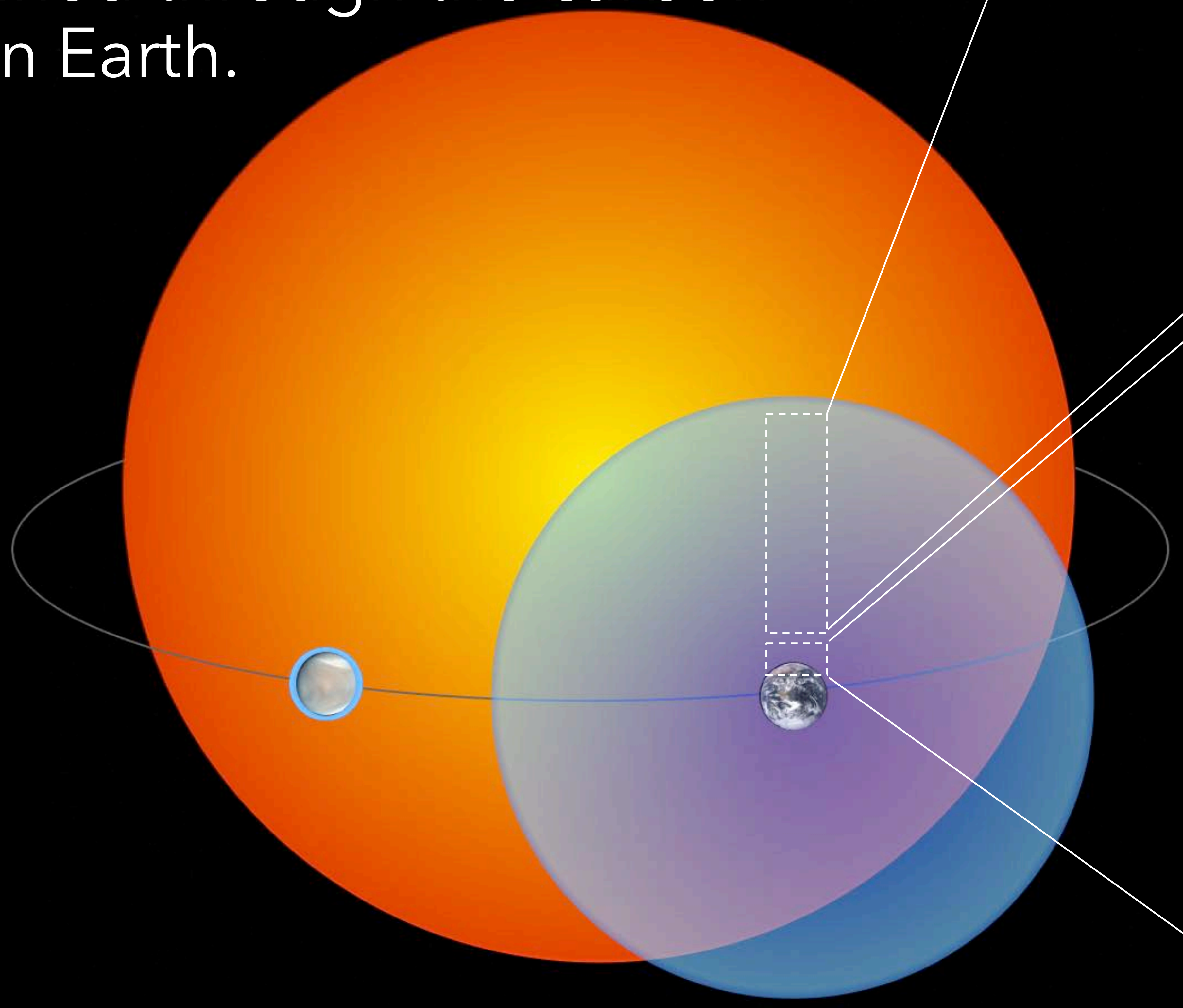
How can we detect such thin atmospheres?

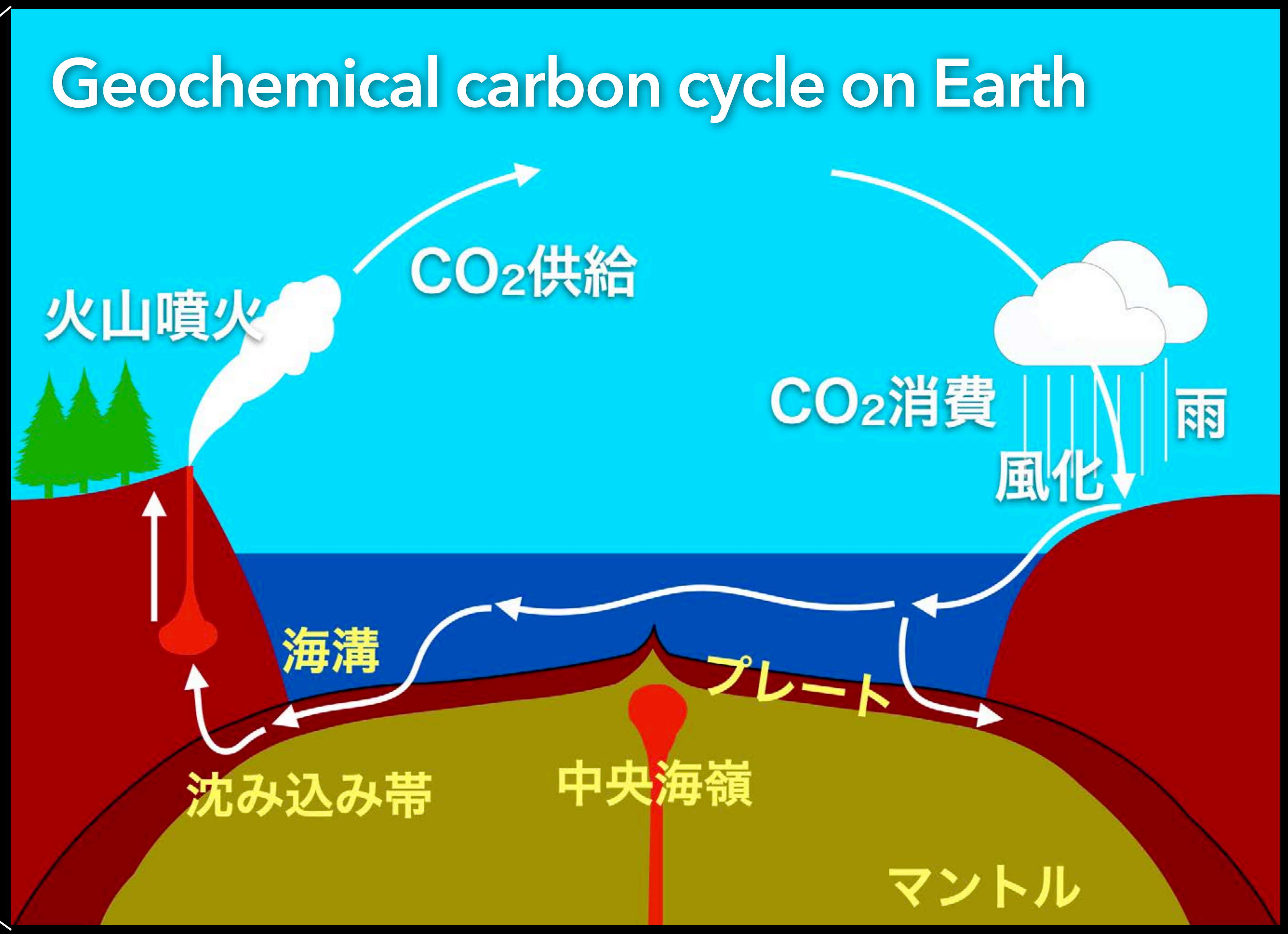
How can we know if the planet has warm climate?

Detecting Earth-analogs through upper atmospheres

- The UV irradiated thermosphere with small amounts of CO_2 is hot and extended.
- The small amount of CO_2 is maintained through the carbon cycle on Earth.

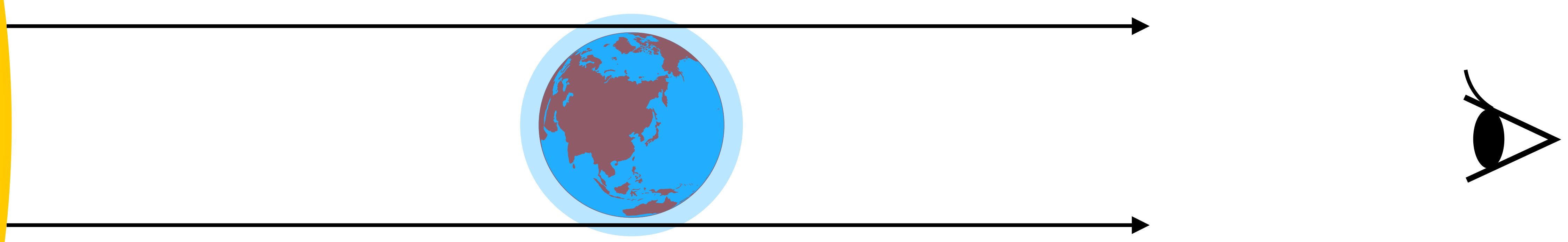




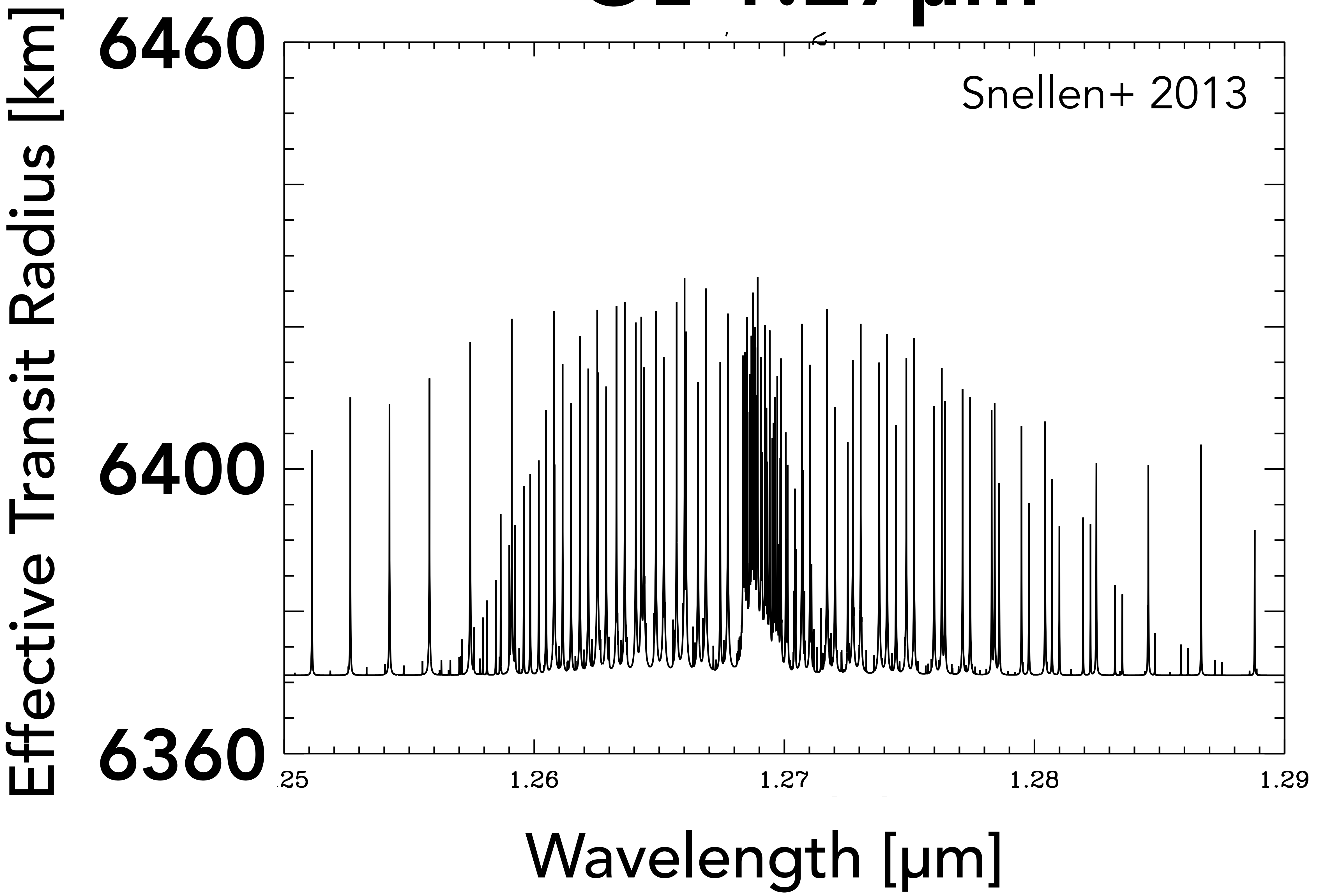


Search for Biosignatures

Transit Transmission



O_2 1.27μm



- Need for high resolution spectroscopic observations with ELT, TLT, and large space telescopes.
- Space missions in 2020s can provide good targets for such observations.

Summary

- The final goal of exoplanet sciences is to understand the place that we occupy in the galactic context. Toward it, we have been addressing issues regarding planetary diversity, formation/evolution, habitability, and life.
- A key issue is to look into the deep atmosphere and interior, and thereby to understand the planet formation, through multi-wavelength observations of upper parts of the atmosphere.
- To do so, we need to tackle the issue with a variety of approaches including astronomy-based and Earth/planetary-science-based ones.
- Japanese researchers have participated in a variety of large projects for exoplanet observations scheduled in 2020s.
- We will need to have synergetic collaborations among those projects to maximize the scientific achievements and for Japan to have a strategic advantage in this field in 2030s and beyond.