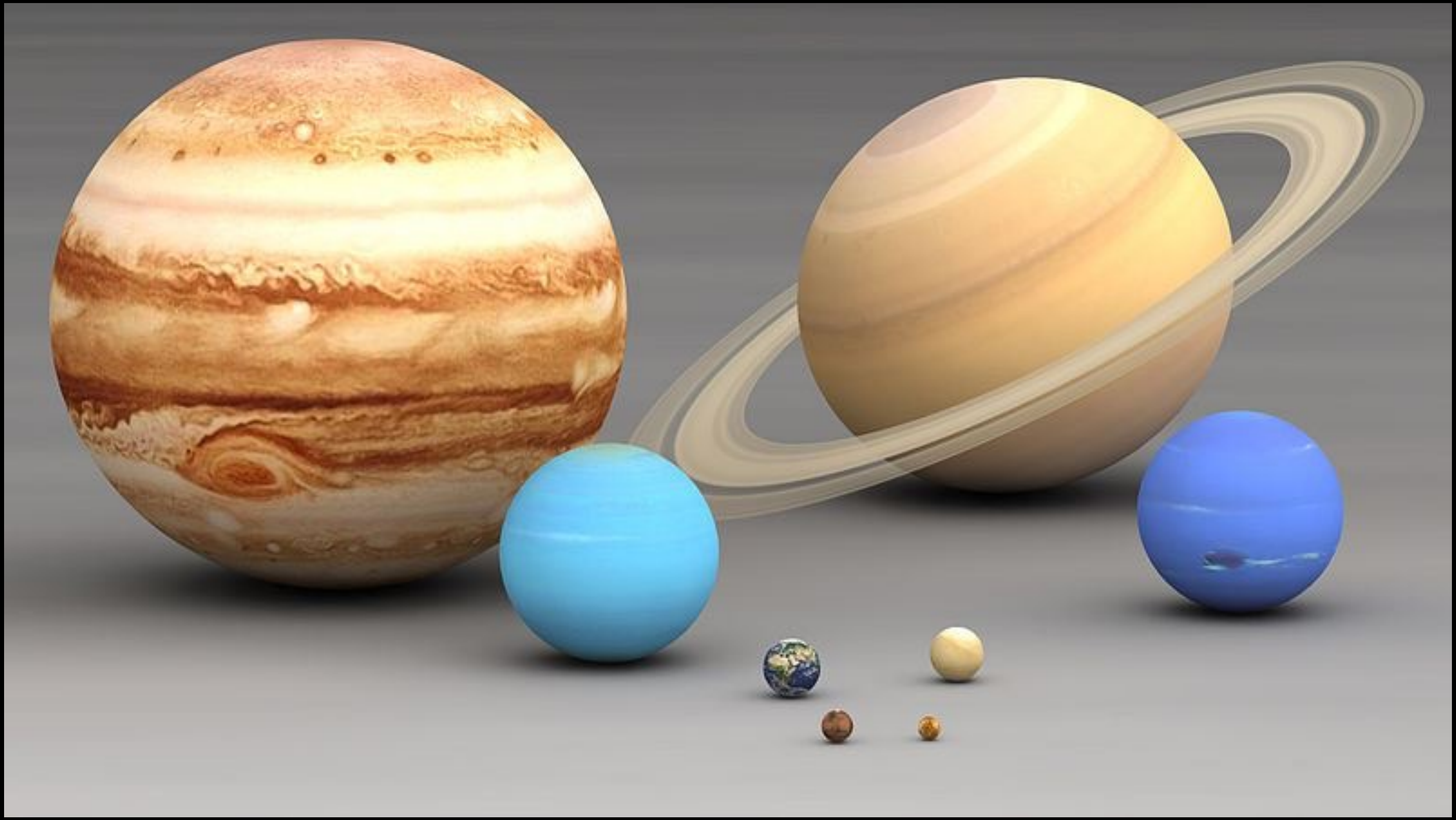
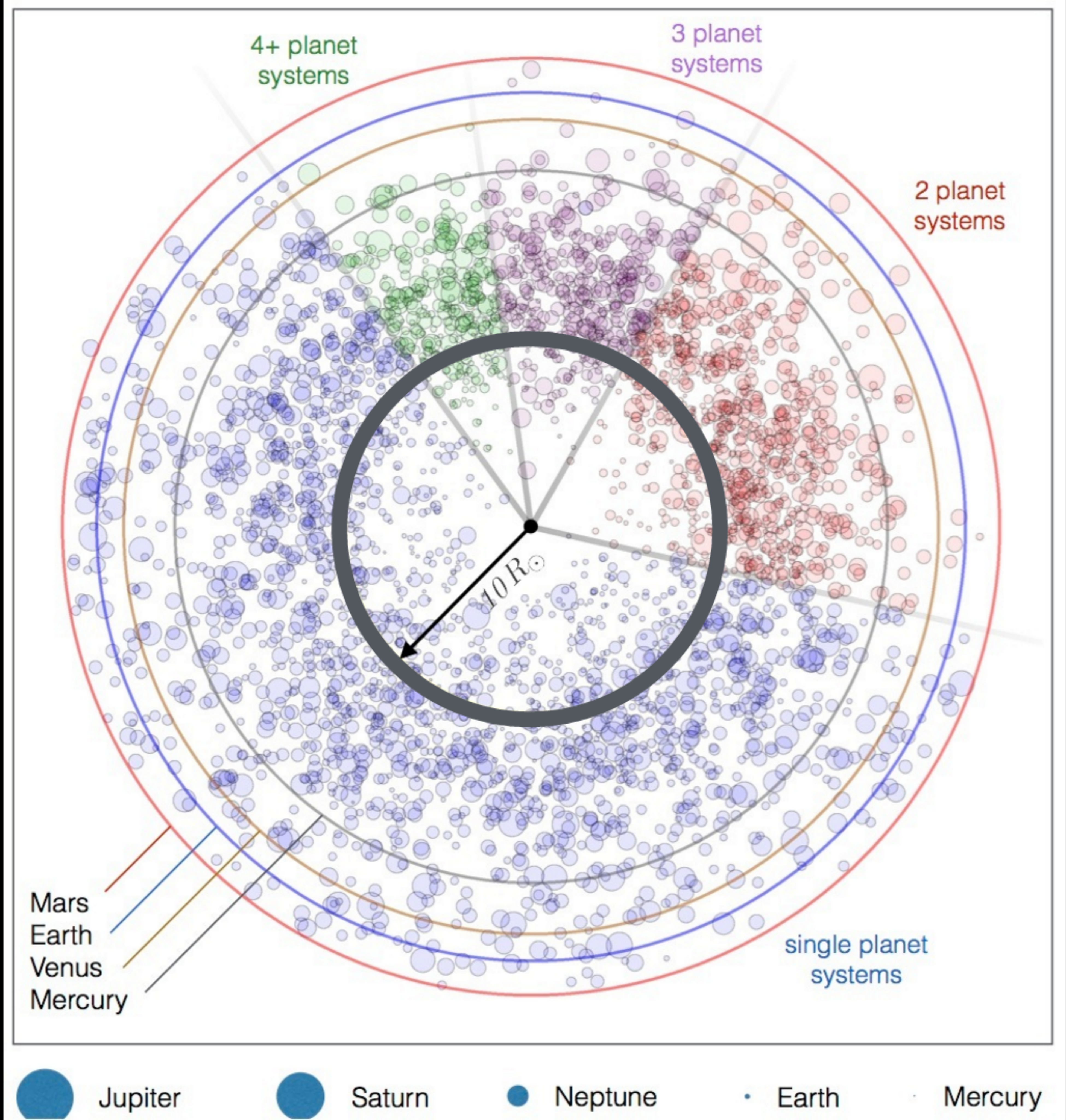
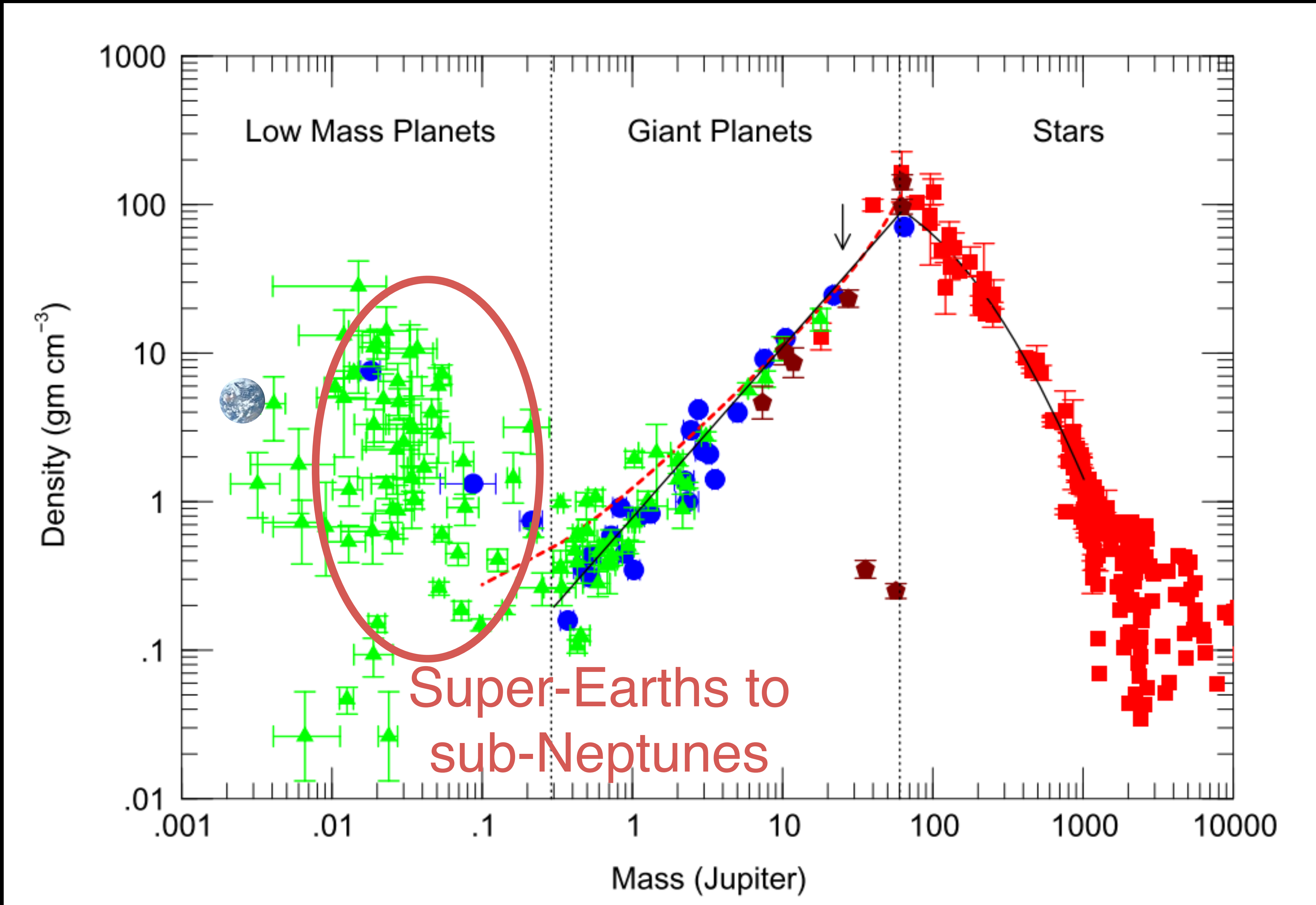
(A very brief) Intro to Exoplanet Science with LUVOIR

Mark Marley & Vikki Meadows

Michael Carroll

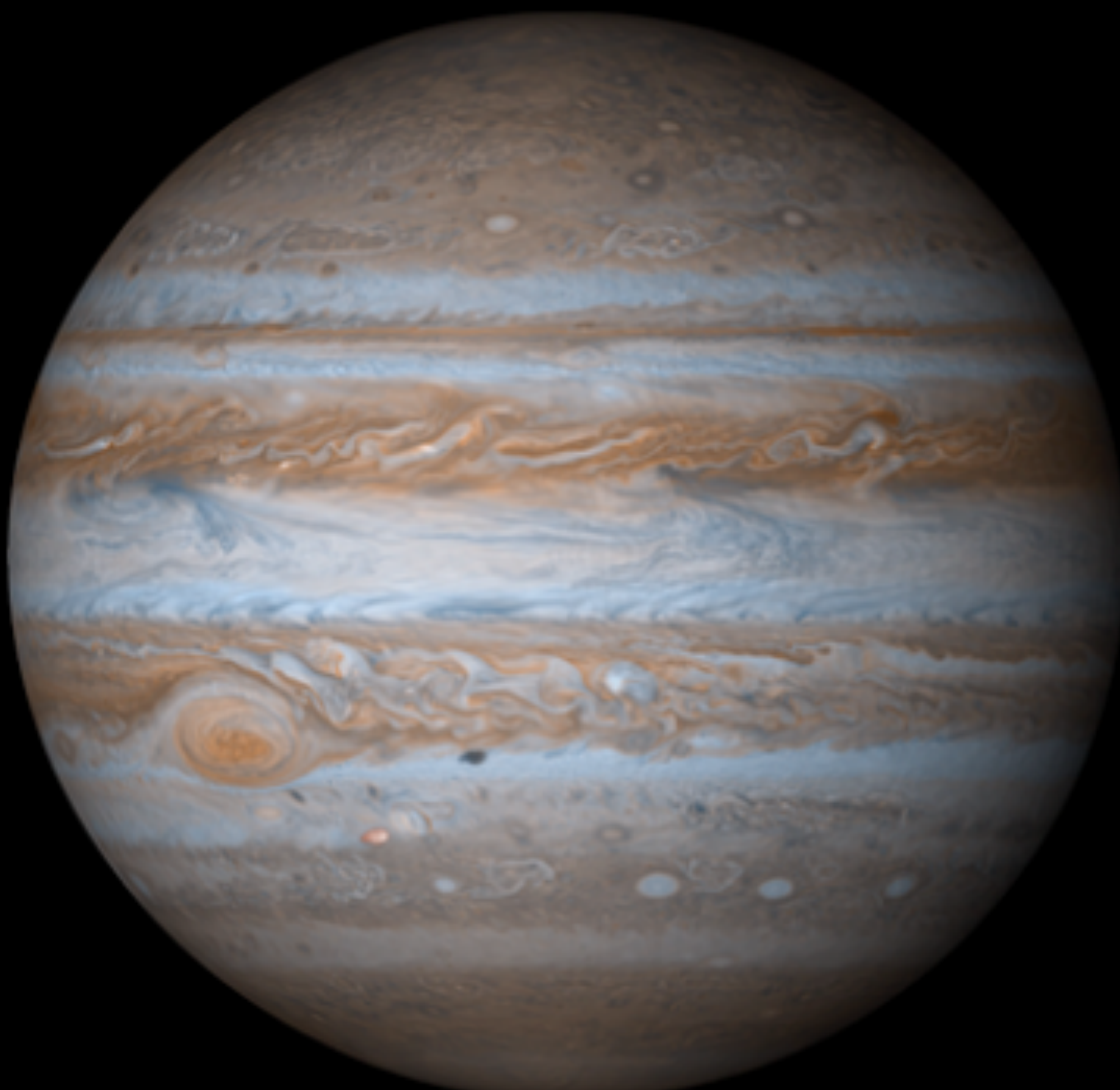



4+ planet systems
3 planet systems
2 planet systems
single planet systems
$10 R_\odot$
Mars
Earth
Venus
Mercury
Jupiter
Saturn
Neptune
Earth
Mercury



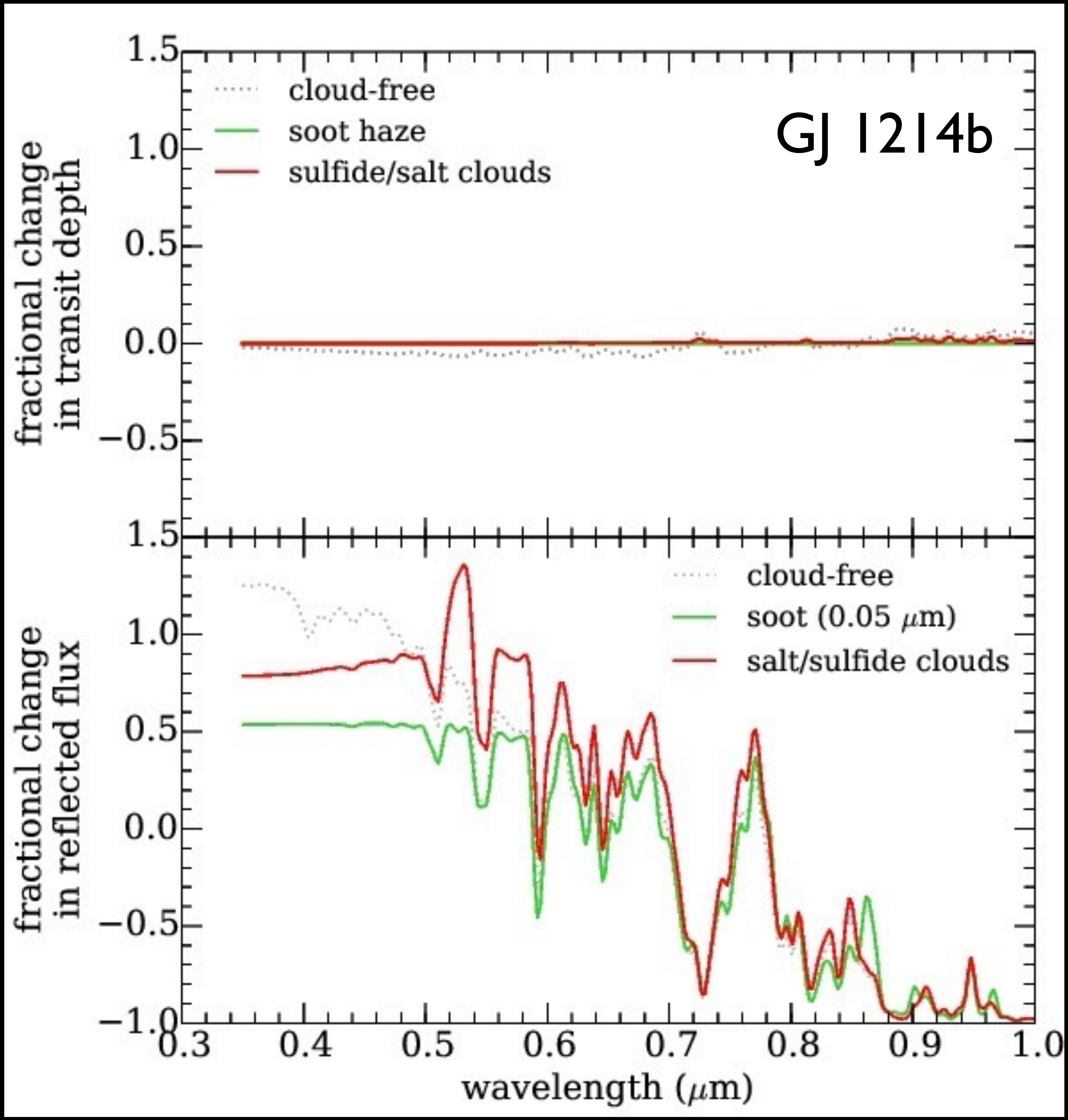
Hatzes & Rauer (2015)

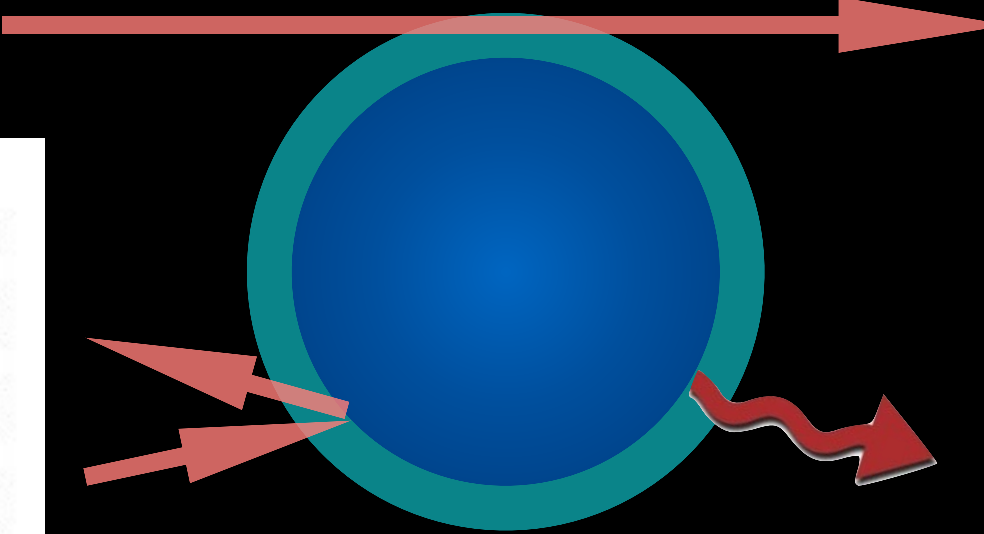
Direct Imaging Science is Distinctive



Kepler, RV, microlensing primarily reveal planetary system architectures. Direct imaging isolates & detects light directly from the planet.

What about Transit Spectroscopy?

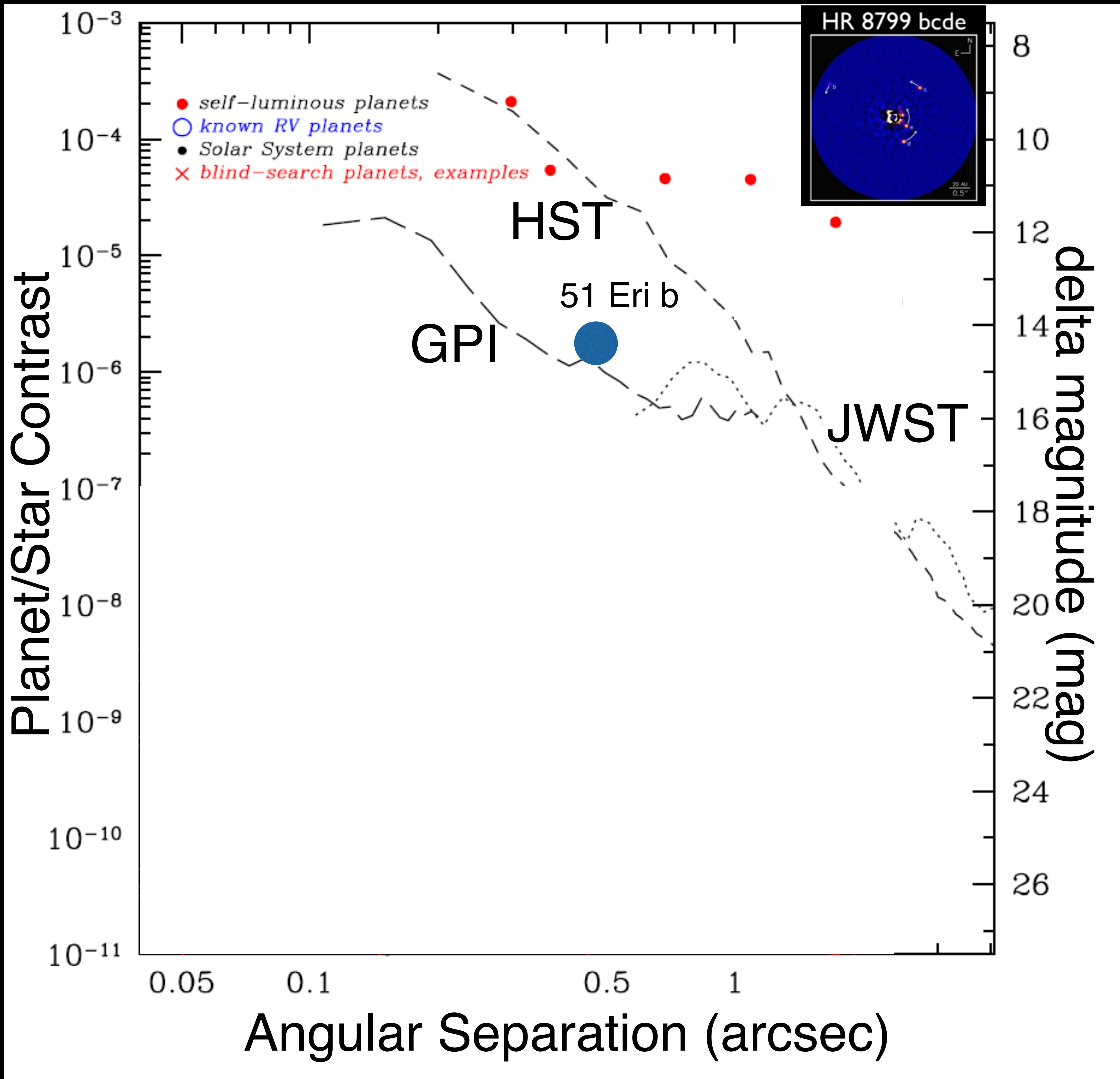




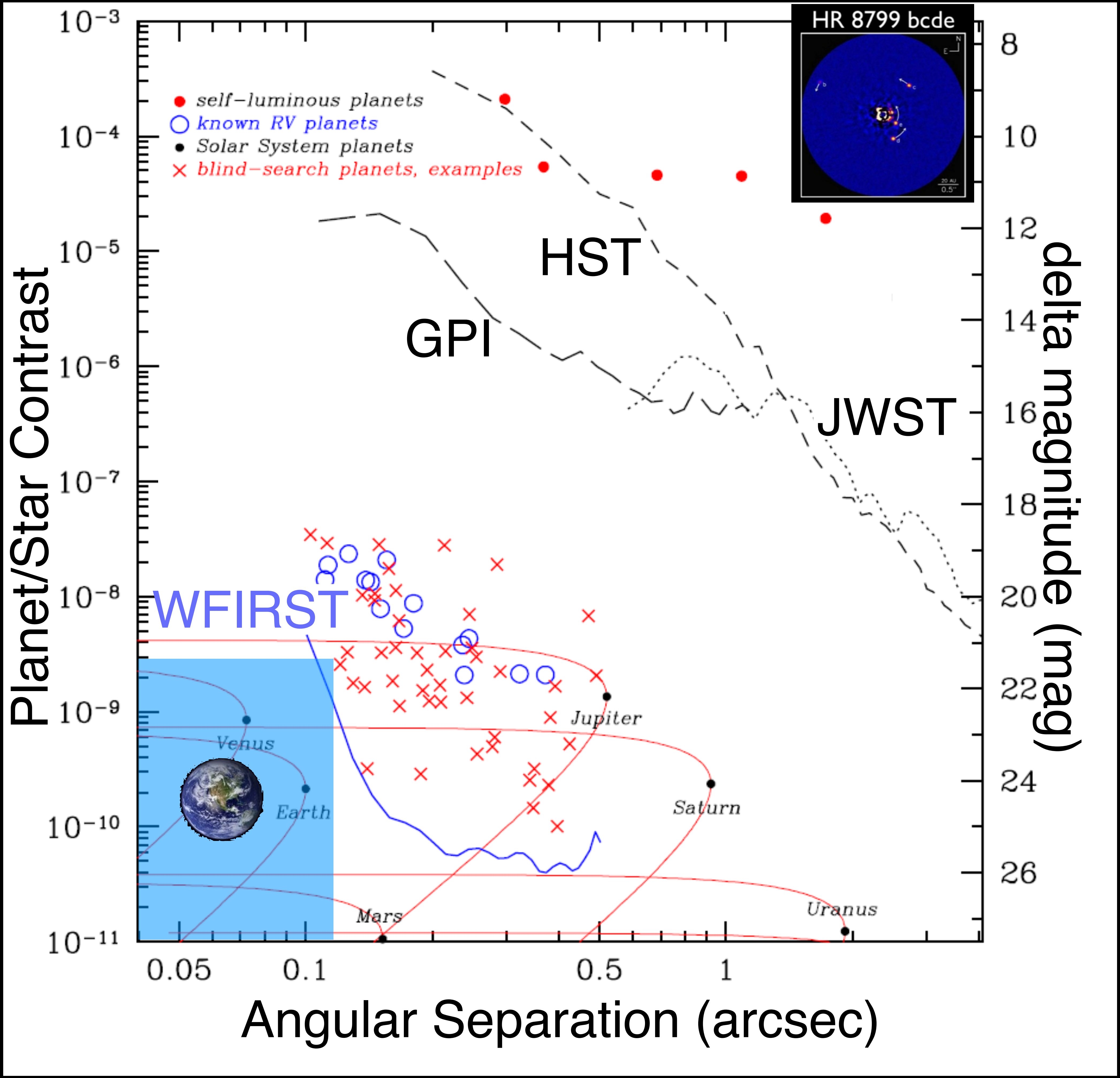
Upper vs. deep atmosphere

Atmosphere features are more readily detected by imaging than by transits

Model spectra by Caroline Morley



HR 8799 bcde
self−luminous planets
known RV planets
Solar System planets
blind−search planets, examples
HST
51 Eri b
GPI
JWST
Planet/Star Contrast
delta magnitude (mag)
Angular Separation (arcsec)



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Cool giants have distinct atmospheric physics/chemistry from hot transiting planets

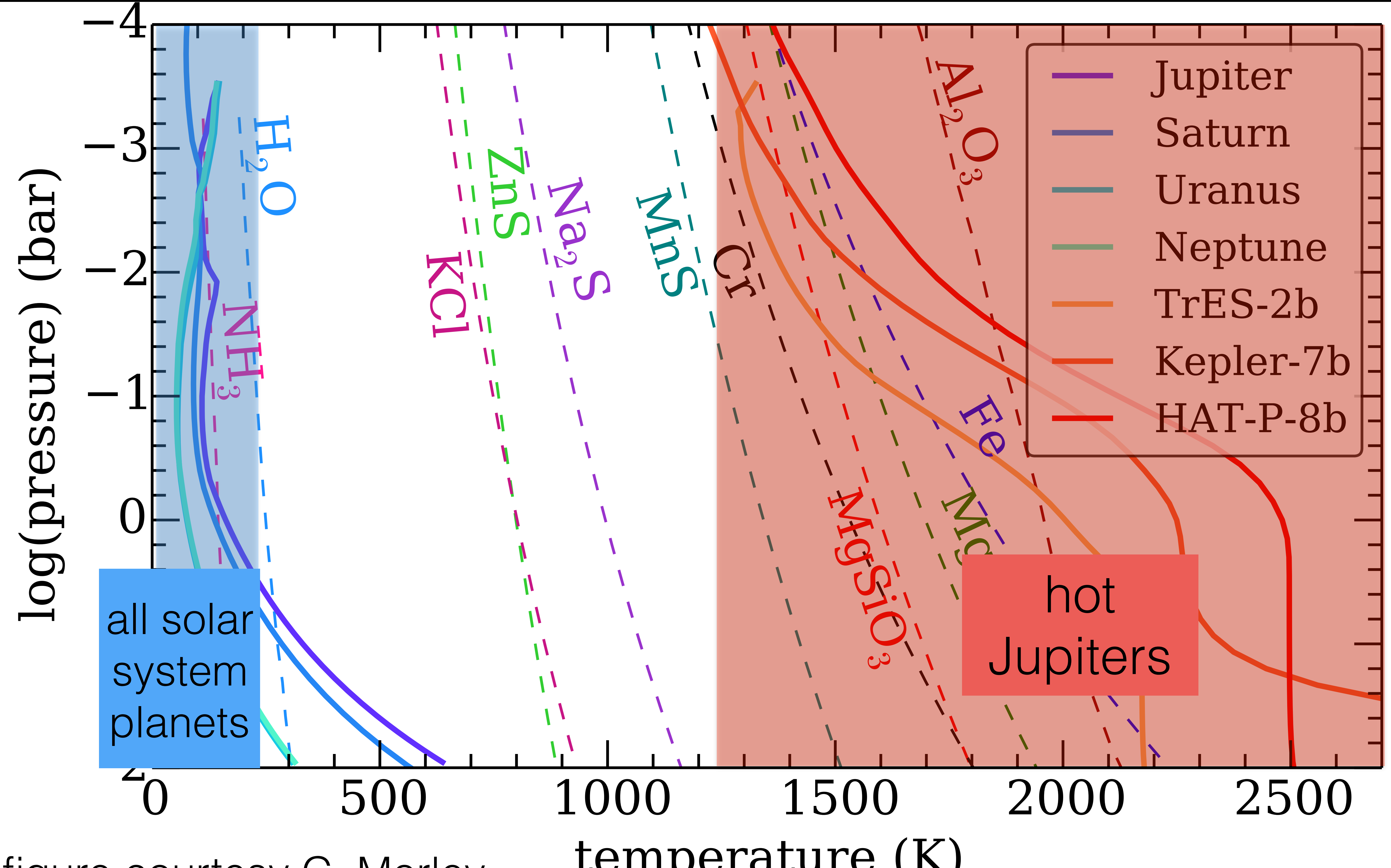
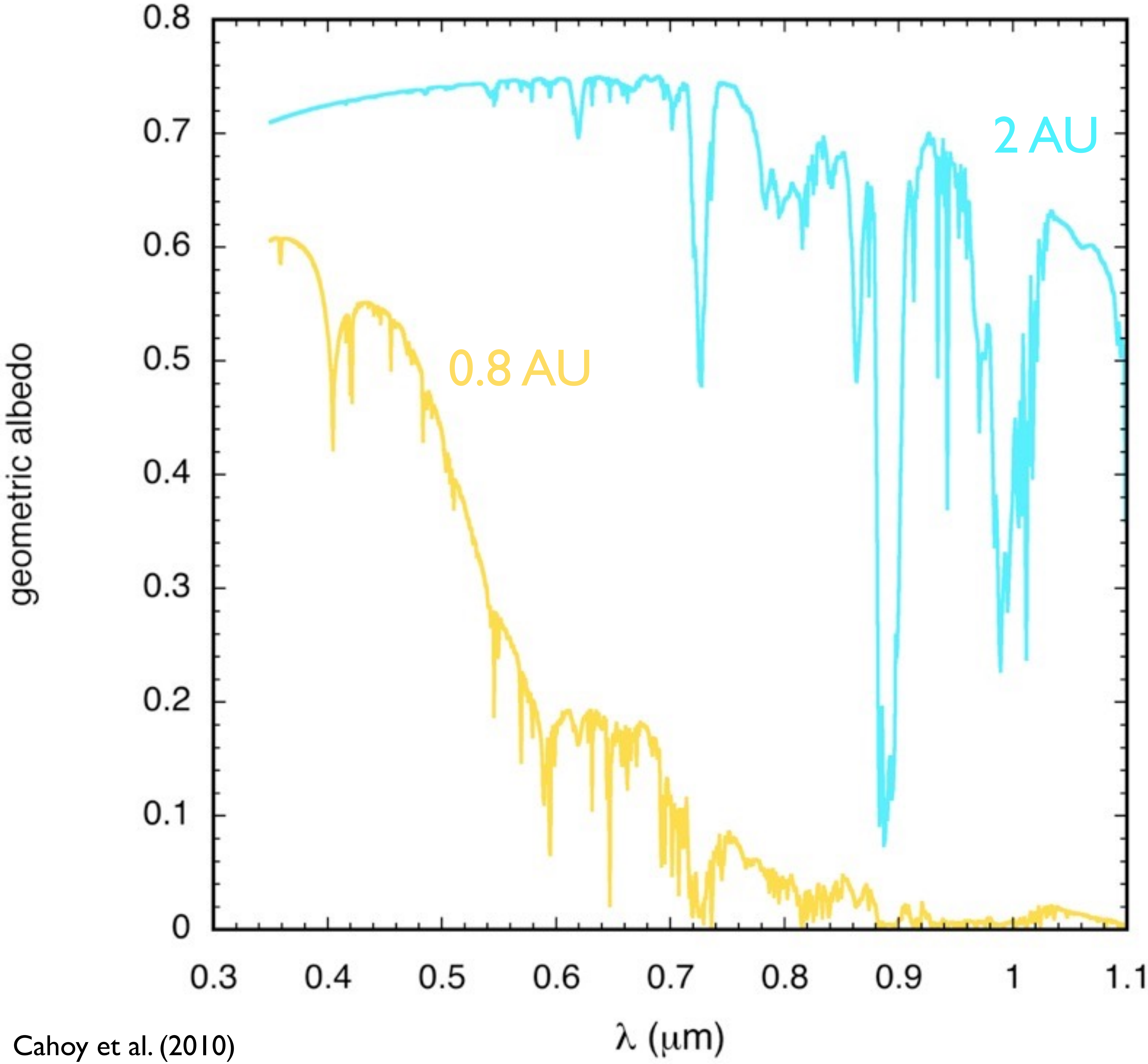


figure courtesy C. Morley

Example: Diversity of Jupiters

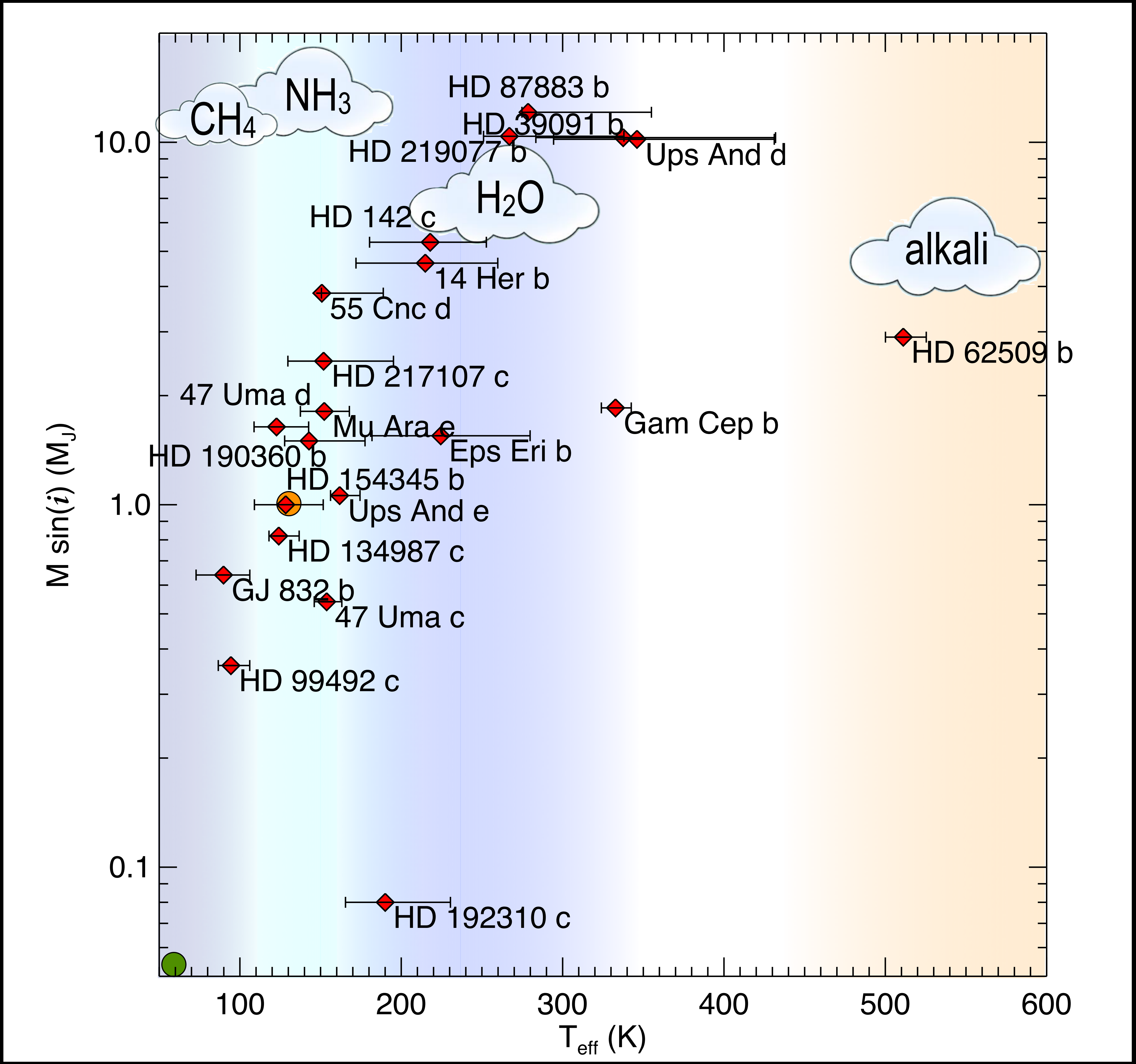
Color and albedo are functions of type and depth of clouds.

Clouds depend on BOTH internal heat flow (mass, age) and incident flux.

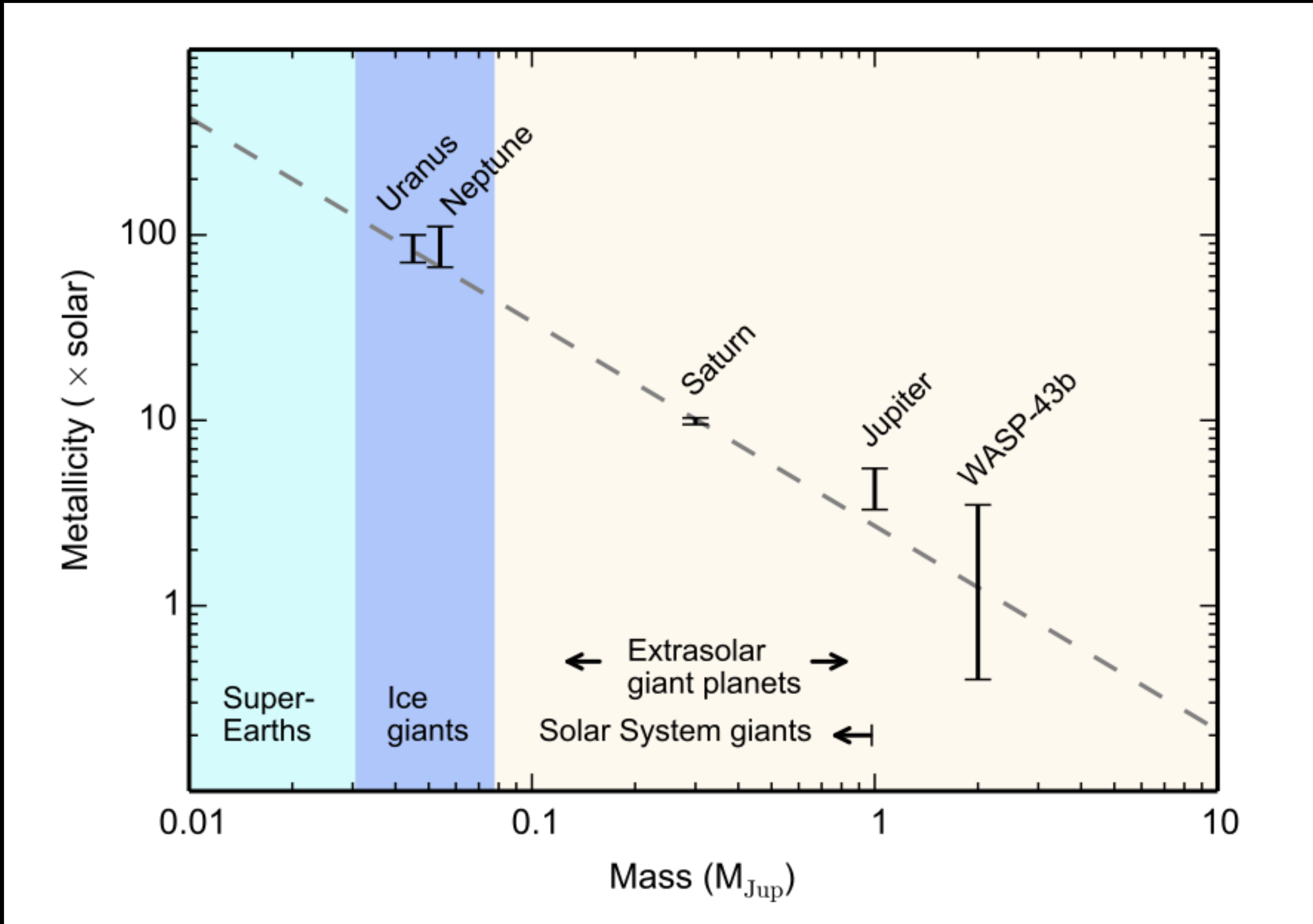


Cahoy et al. (2010)

Favorable RV Planets for Direct Imaging w/ 2.4-m telescope



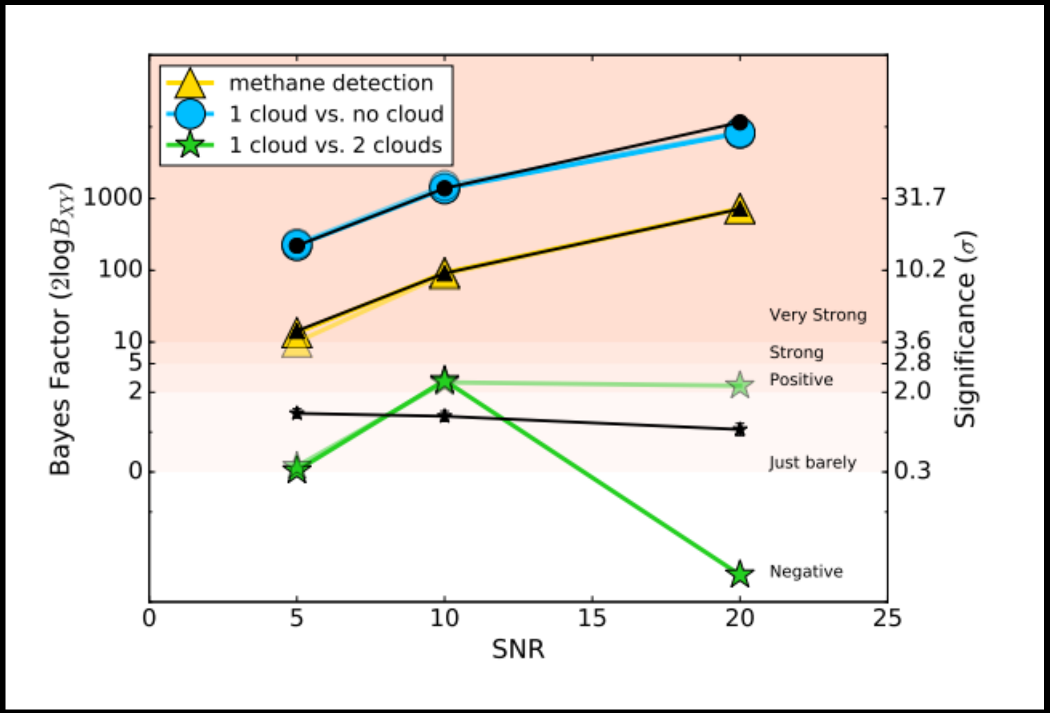
Marley+ 2014



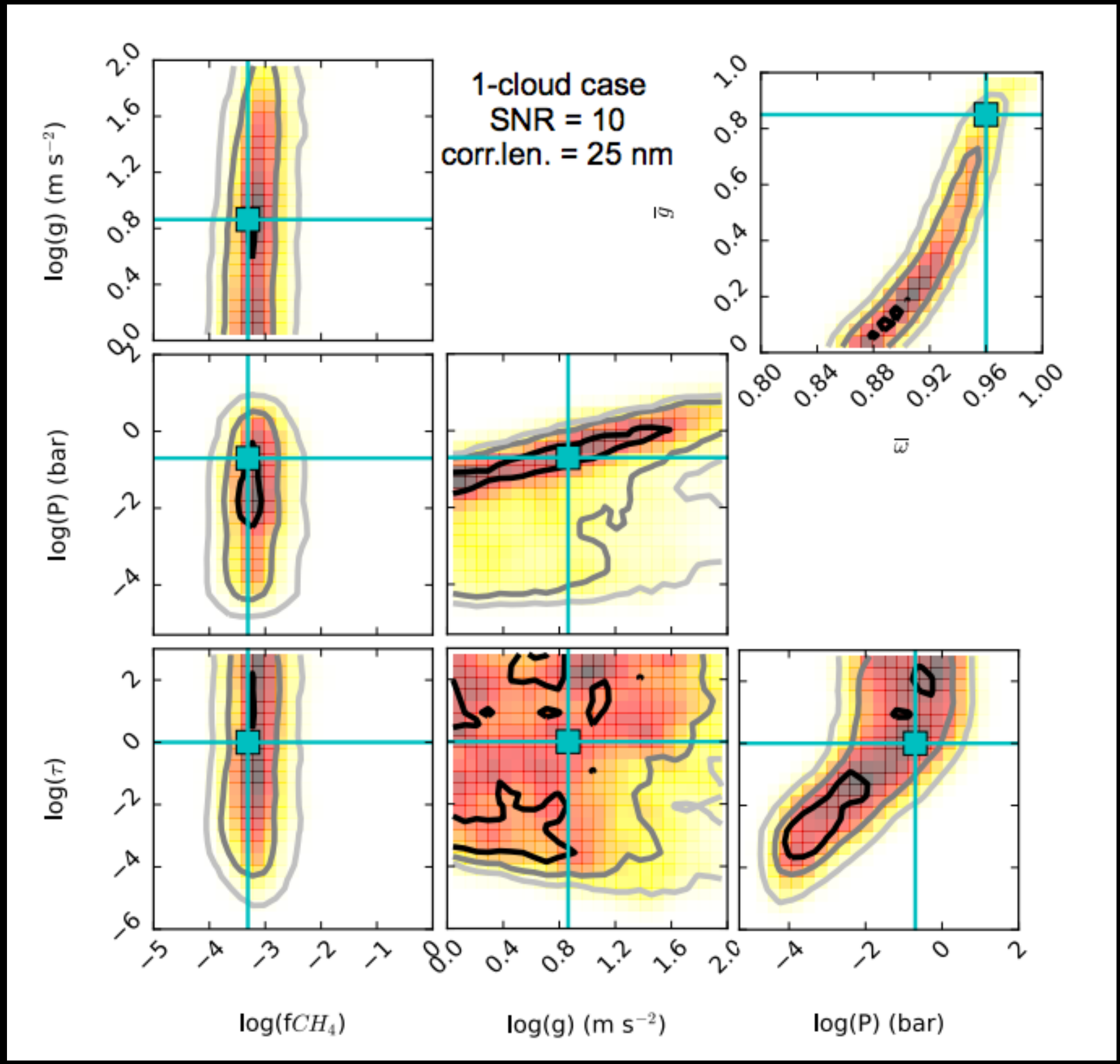
Kreidberg+ 2014

Won’t WFIRST Do All This?

- Coronagraph Instrument is technology demonstrator for high contrast imaging
- Only 2.4-m telescope, 1 year for coronagraph
- Very Limited targets w/spectra



Lupu et al. (2016)



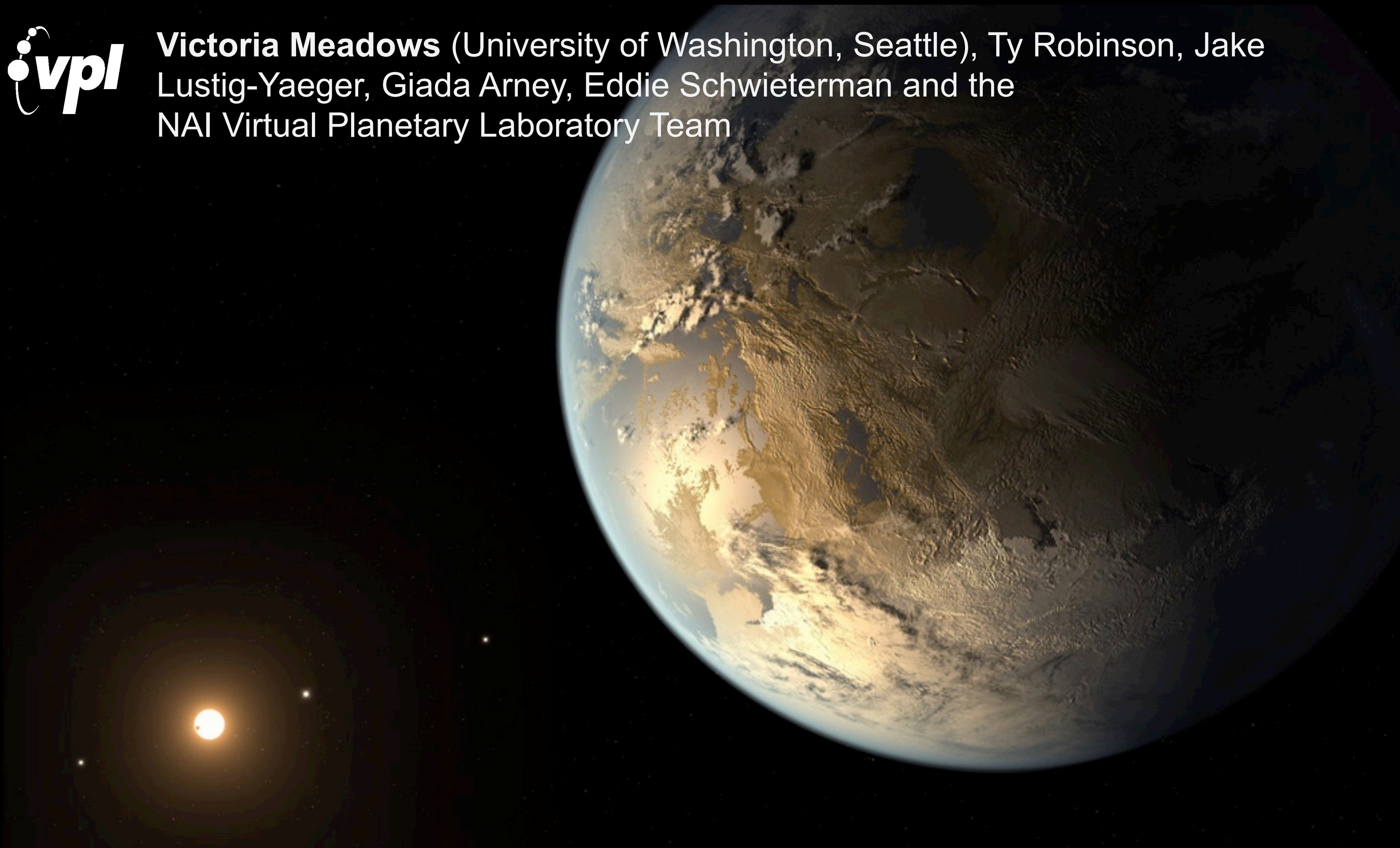
Diverse Exoplanet Science

- Characterize all possible planets
  - provides context for habitable planets
  - need to understand systems holistically incl. near misses
- Nature of super Earths/sub-Neptunes
- Giant planets
  - easier, outstanding spectroscopy targets (OWA requirement)
  - laboratories for clouds, photochemistry, formation, stellar influence, etc.

Terrestrial Exoplanets With LUVOIR

…or why we need a large, space-based telescope beyond JWST.

Victoria Meadows (University of Washington, Seattle), Ty Robinson, Jake Lustig-Yaeger, Giada Arney, Eddie Schwieterman and the NAI Virtual Planetary Laboratory Team



Comparative Planetology

Are we weird?

Mathias Pederson

The Search for Life Elsewhere

Are we alone?

A Big Telescope for Small Planets

- Comparative Planetology
  - What is the nature of their surfaces and atmospheres?
  - How are super-Earths and mini-Neptunes related to each other, and to other planets in our Solar System?
  - What can these planets tell us about terrestrial planetary processes in different physical and chemical regimes?
  - Can abiotic planetary processes mimic biosignatures?

- The Search for Life Beyond the Solar System
  - What are the characteristics of HZ planets?
  - Are they habitable?
  - Do they exhibit signs of life?
  - With a meaningful statistical sample, what is the prevalence of habitable and inhabited planets in our Galaxy?

JWST, WFIRST, ELTs provide initial opportunities on a few targets

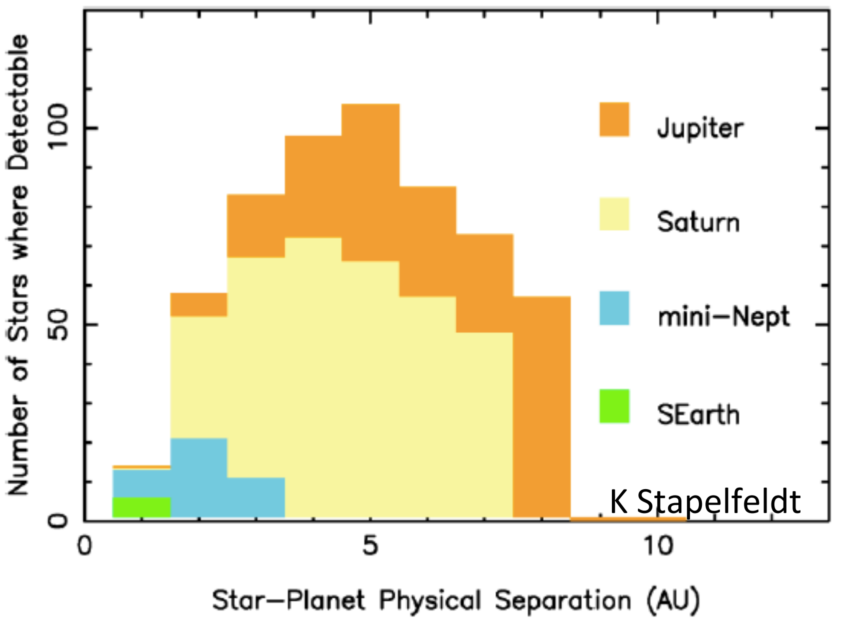
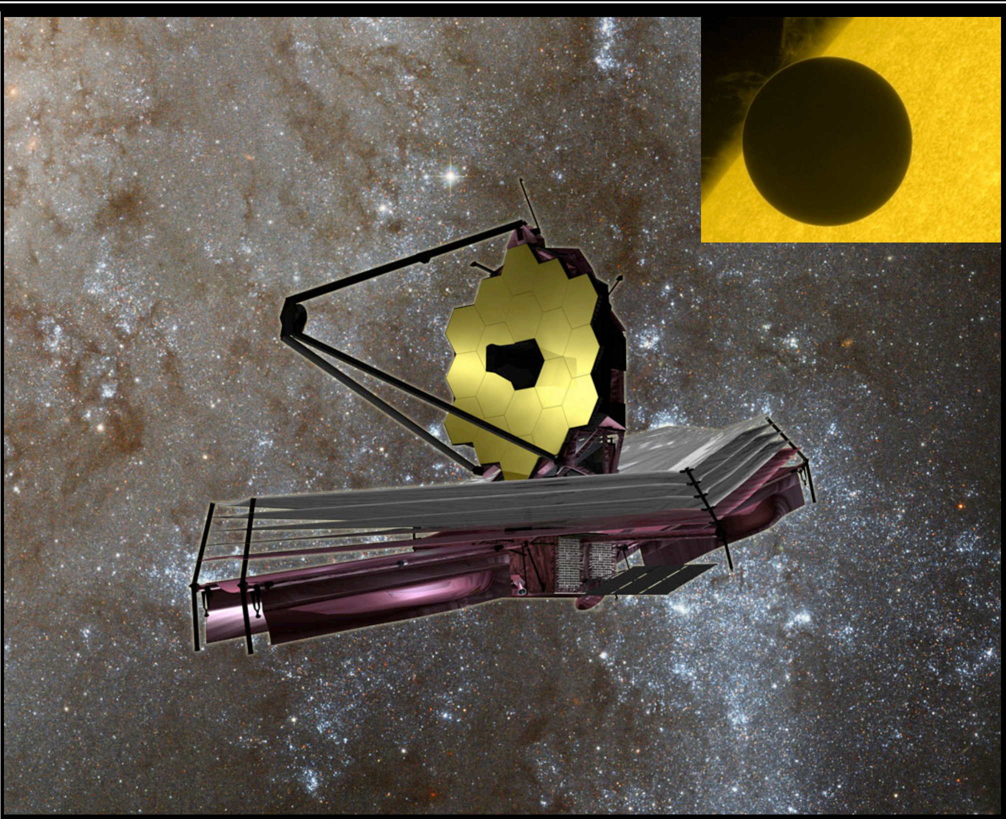


Figure 3. Number of nearby stars amenable to WFIRST photometric detection of super-Earths (green) and mini -Neptunes (blue) at S/N 7 with 1 day of V band integration. The simulation uses the hybrid Lyot coronagraph PSF and mask information, and requires the planet semi-major axis to be > 1.15 times the IWA, equivalent to detecting the planet within ±30° of elongation. This provides 33% completeness in a single observation.



For JWST, WFIRST, the number of targets accessible will be small:
JWST may obtain spectra of 1-3 HZ terrestrials orbiting M dwarfs.
ELT direct imaging could access ~ 12 late M dwarfs, not all will have HZ planet
WFIRST could detect ~5 super-Earths around F and G dwarfs with 1-2 spectra

Small Planets with WFIRST

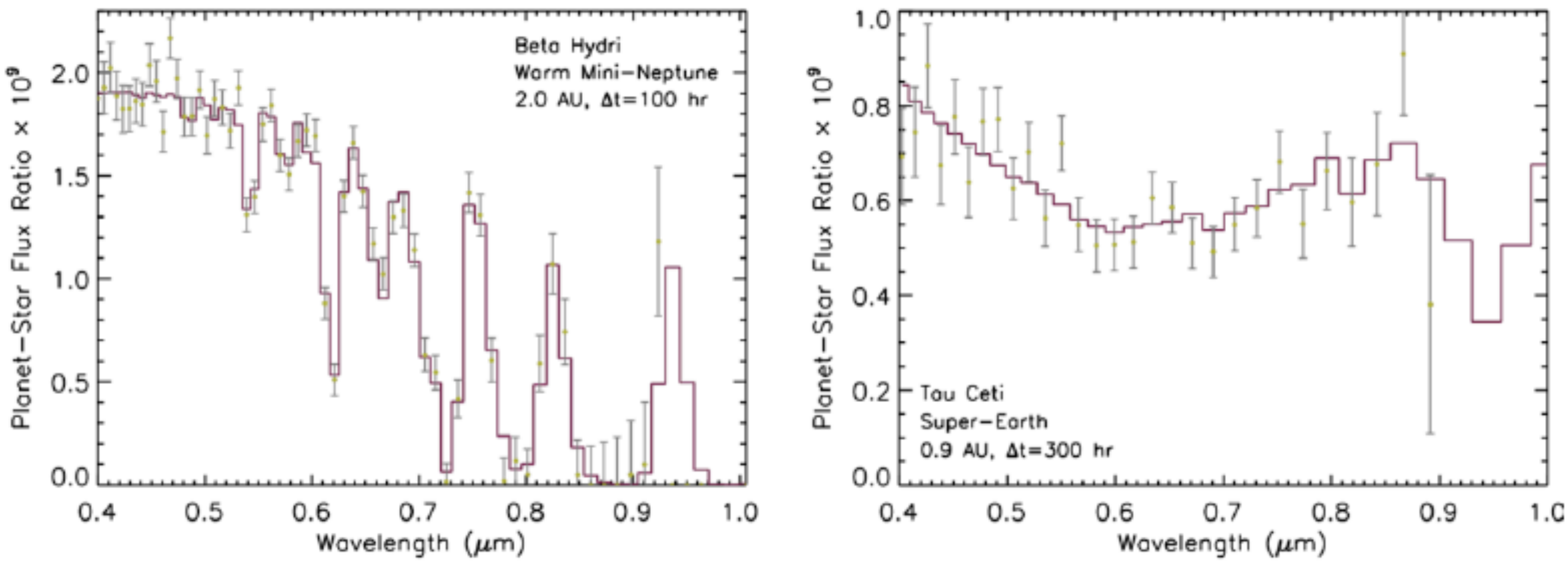
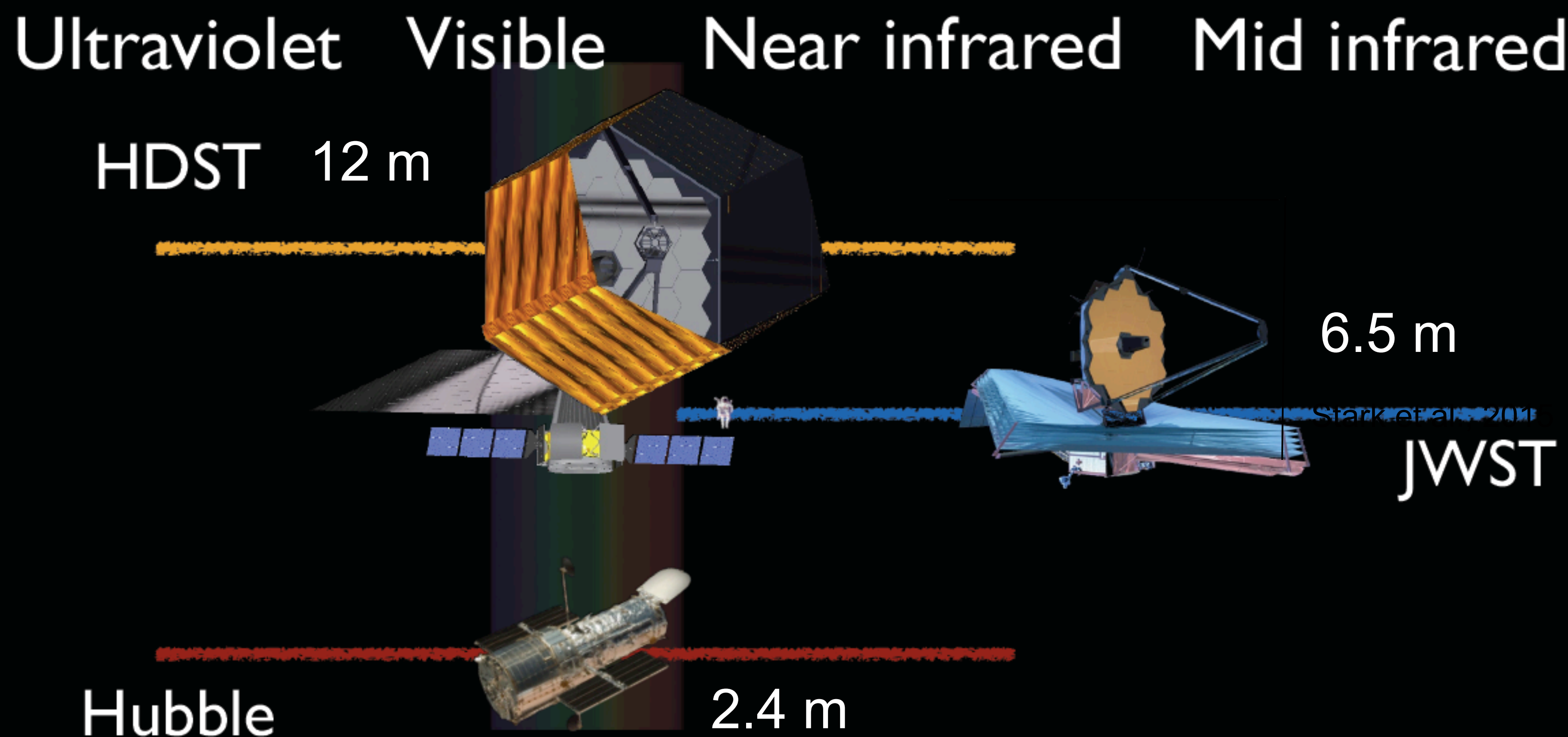


Figure 4. Preliminary simulations of observations taken with WFIRST AFTA-C for a mini-Neptune orbiting Beta Hydri whose spectrum is dominated by CH_4 absorption (left) and a super-Earth in the HZ of Tau Ceti (right) with a spectrum dominated by Rayleigh scattering and ozone and water absorption. The exposure times per 10% band given in the respective plots. Note that the super-Earth-analog has been degraded to R∼35, losing sensitivity to the oxygen A-Band. These simulations show that spectroscopic observations of 300 hrs or more could be used produce high S/N spectra of super-Earths and mini-Neptunes.

Meadows et al., WFIRST SIT proposal
Figures by Ty Robinson

LUVOIR will be able to observe *tens* of HZ Earths

LUVOIR should be able to directly image tens of Earth-sized planets in the Habitable Zone.



Dalcanton et al., 2015

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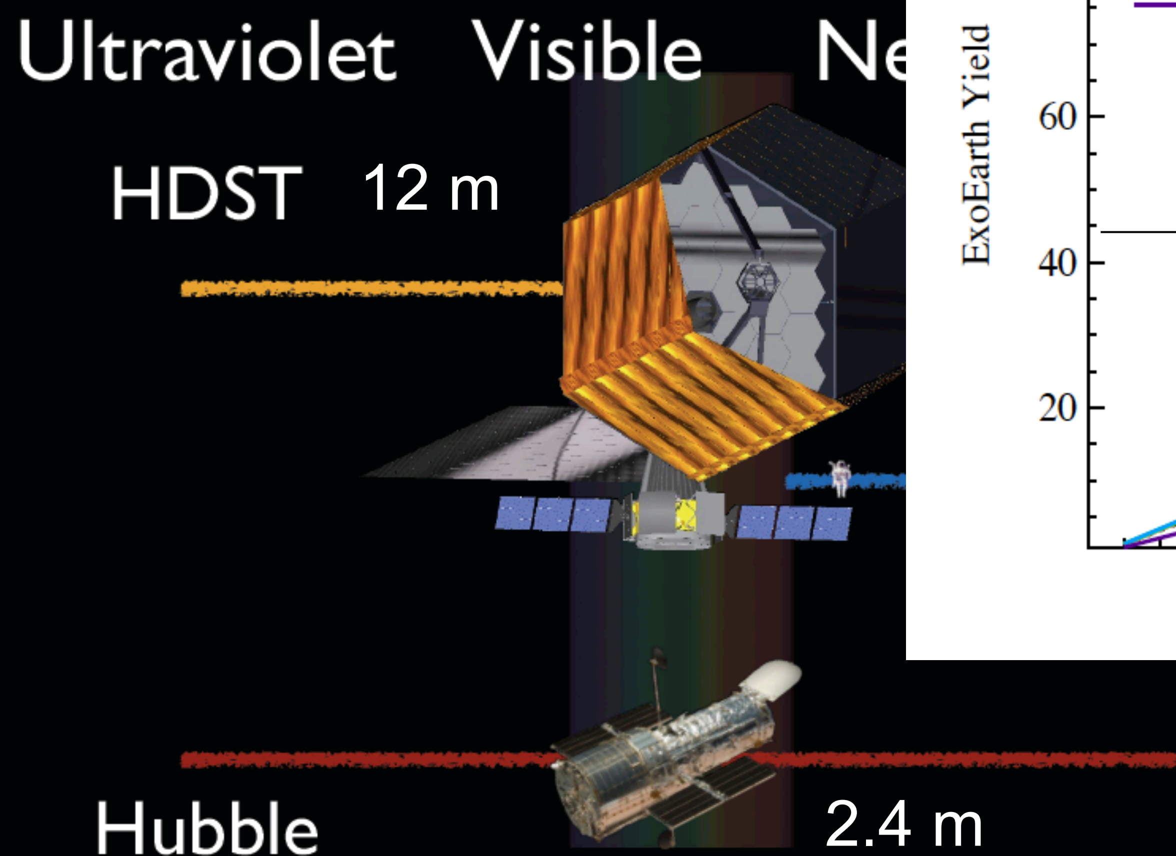
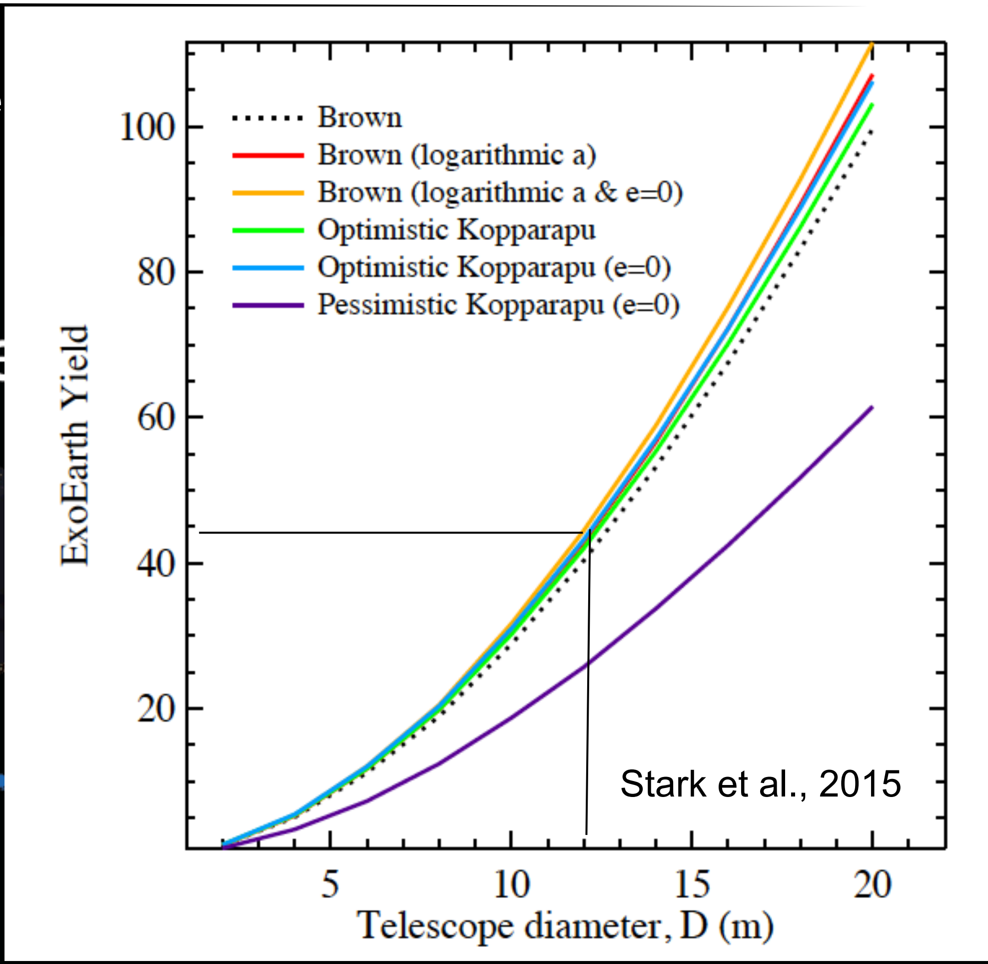




Dalcanton et al., 2015

LUVOIR will access planets orbiting a broad range of stellar types

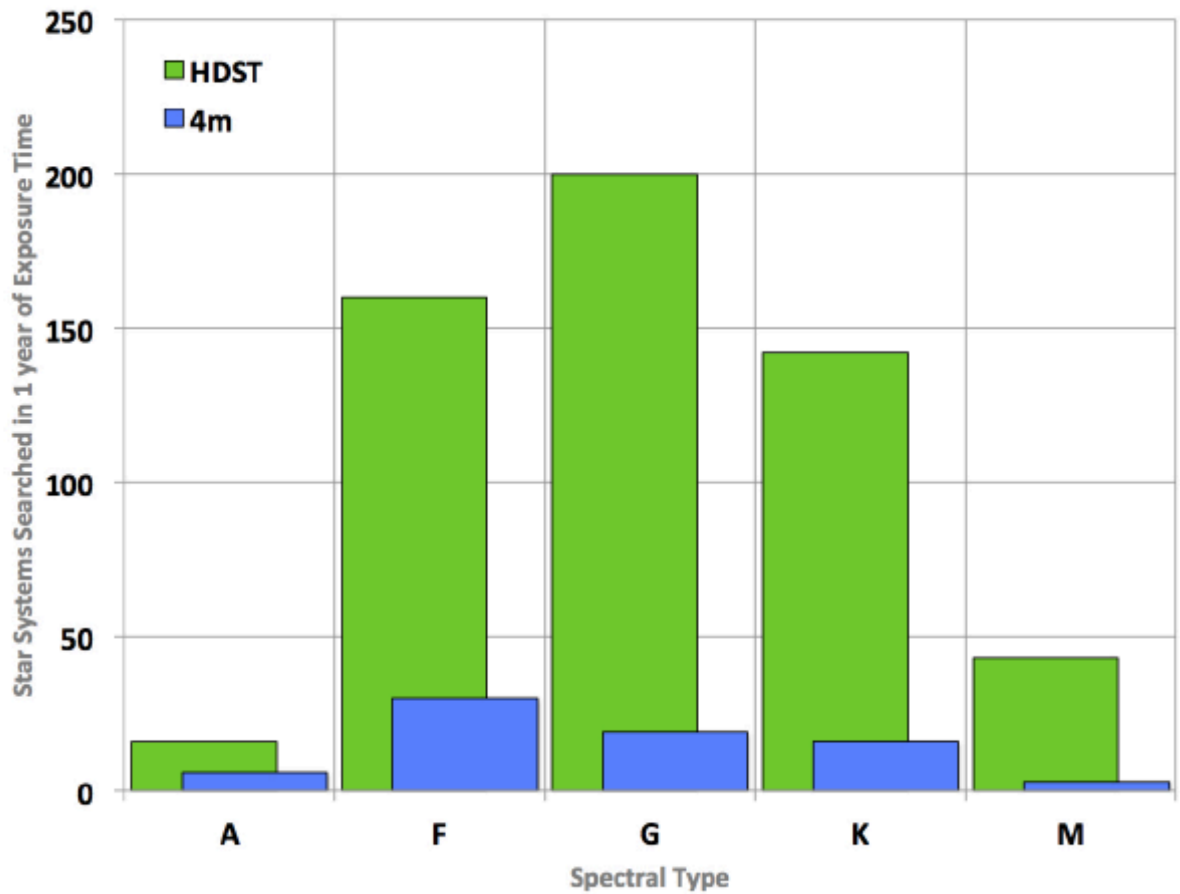
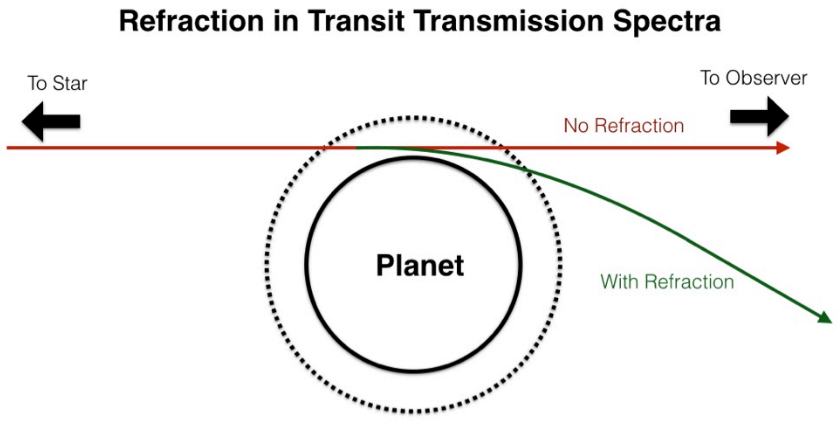
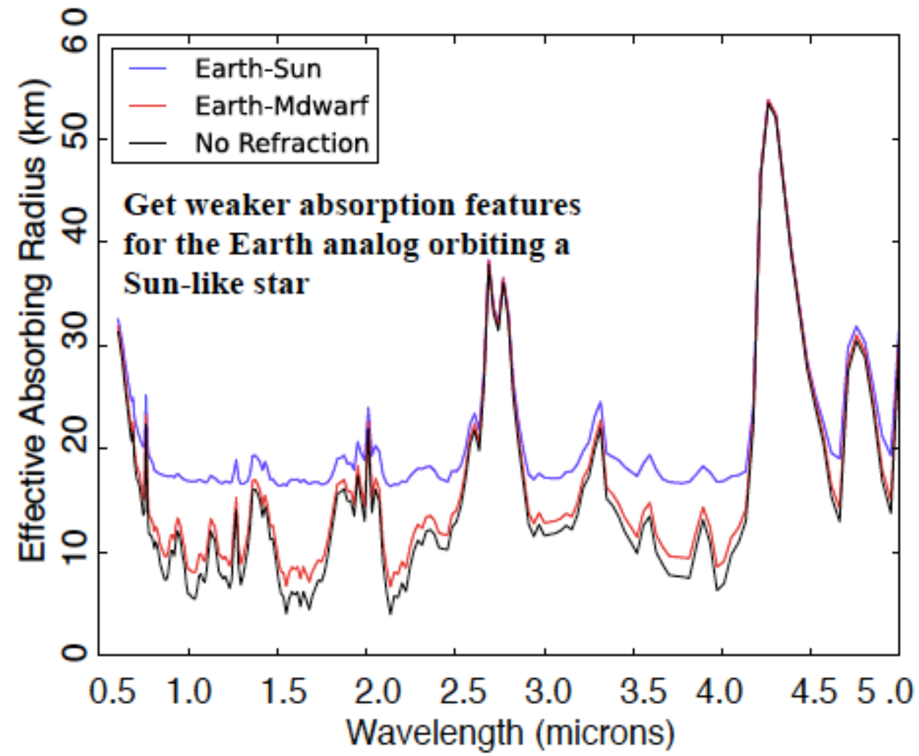


Fig. 1.— The distribution of stellar spectral types in the design reference mission (DRM) for a 12 m *HDST* (green) and for a 4 m exoplanet mission (blue). The histograms show the number of stars in each spectral type surveyed with a survey integration time of 1 year (which includes spectroscopic characterization of Earth-like planets). *HDST* surveys a total of 561 stars. The 4 m space telescope surveys 74 stars. The Stark et al. (2015) altruistic yield optimization algorithm is used in these DRMs.

Refraction Limits Altitudes Probed in Transmission



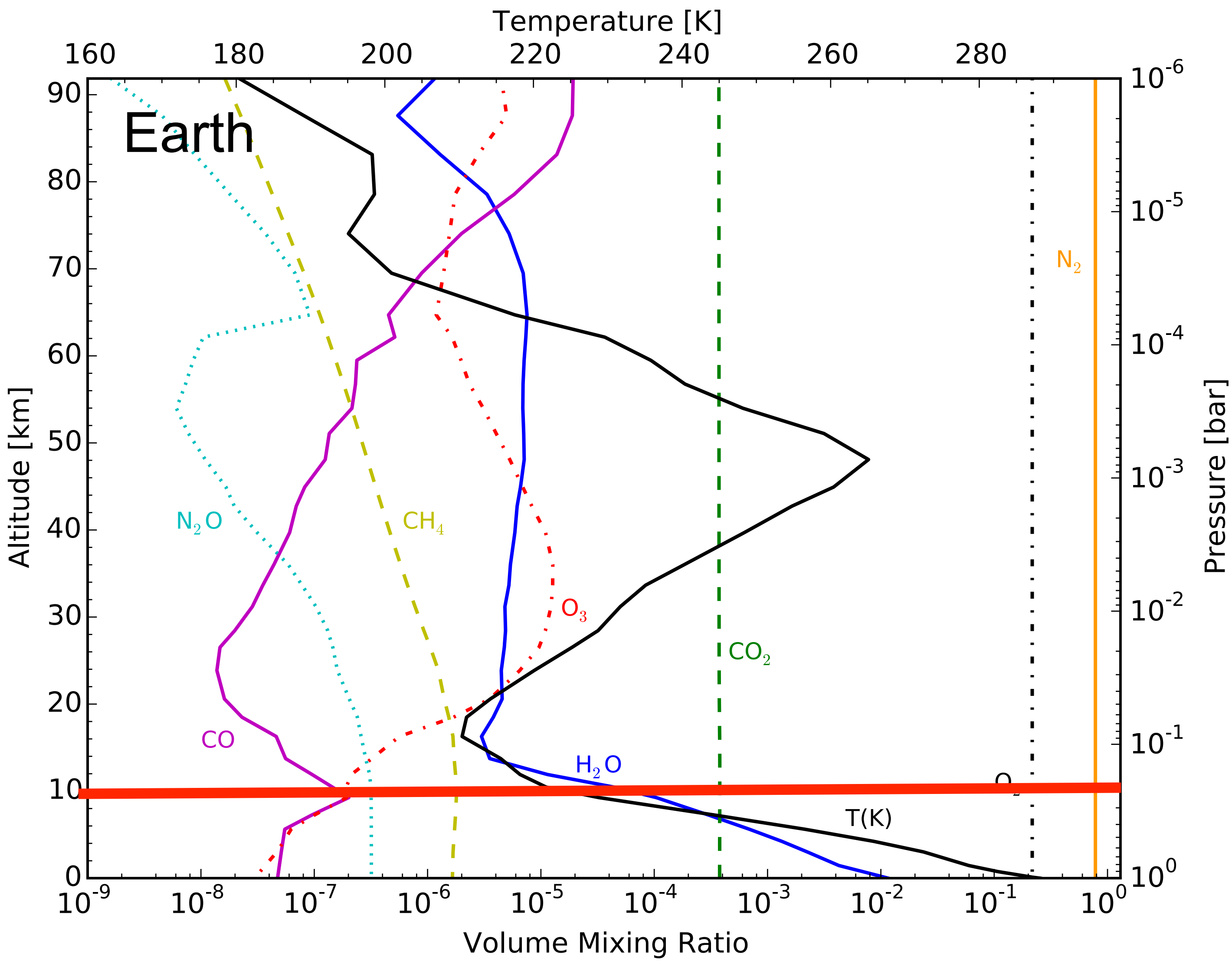
Misra et al., 2014



- Transmission spectra - from JWST or the ground – cannot observe the planetary surface
- For every planet/star system there will be a maximum pressure (or minimum atmospheric altitude) that can be probed.
- Can probe deeper for planets in M dwarf habitable zones (but still limited to 8-10km) Habitable planets orbiting Sun-like stars are not accessible.

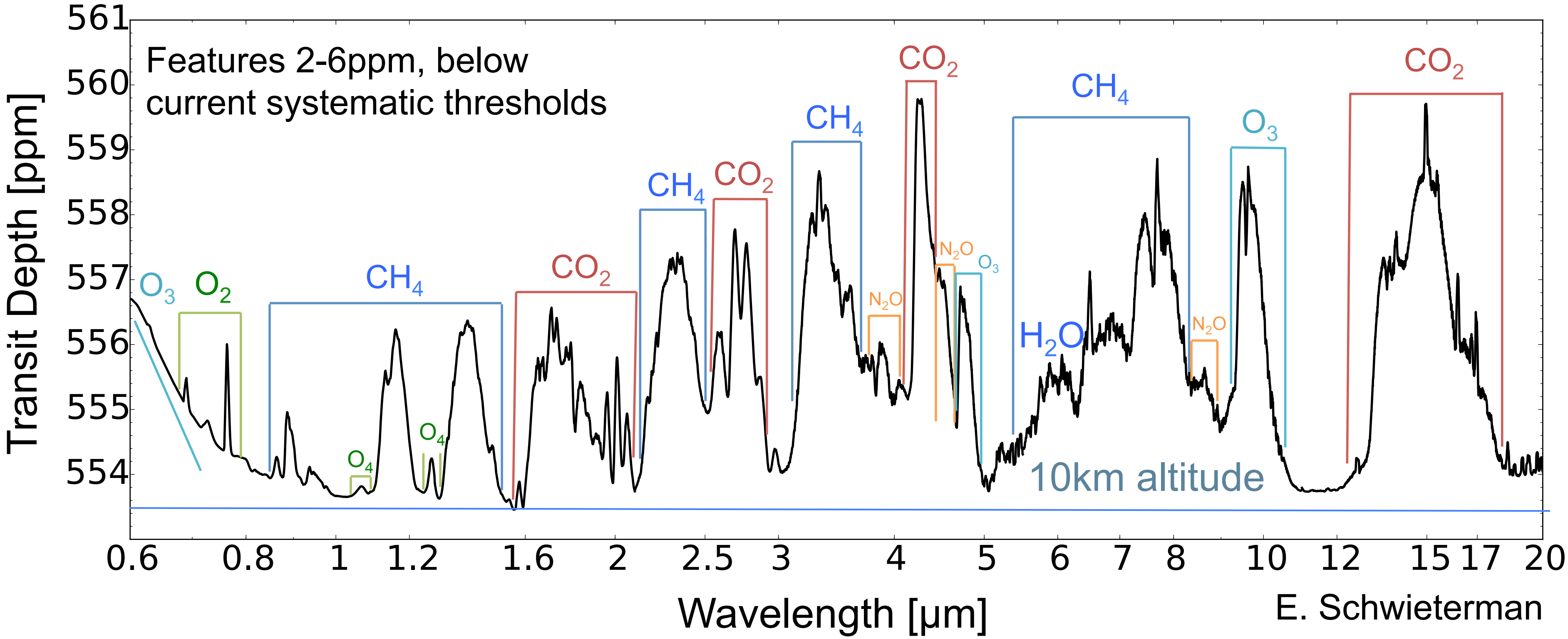
Garcia-Muñoz et al., 2012; Misra, Meadows and Crisp., 2014; Bertremieux & Kaltenegger, 2013, 2014

Habitable terrestrials have dry stratospheres
H_2O difficult to detect in transmission!



…a wet stratosphere indicates a planet in crisis!

Self-Consistent Earth orbiting an M3.5V seen in transmission

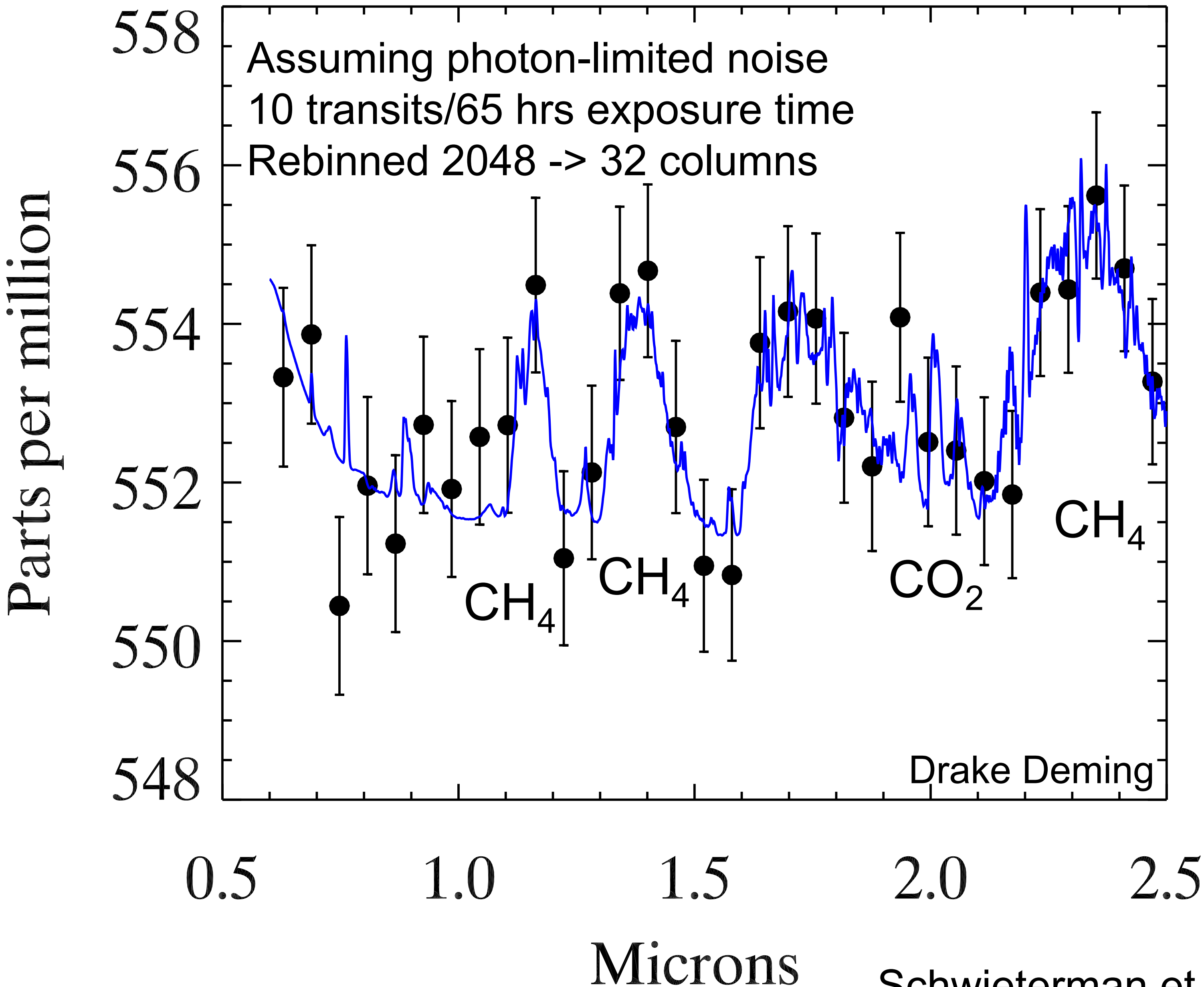


Spectrum of *self-consistent* Earth around an M3.5V from Segura et al., 2005. Transmission model (includes refraction) from Misra et al., 2014.

Water vapor is not seen at shorter wavelengths as the much weaker signal is swamped by CH_4 at 1.1 and 1.4um!

Identifying terrestrial planets with water vapor will be challenging in transmission

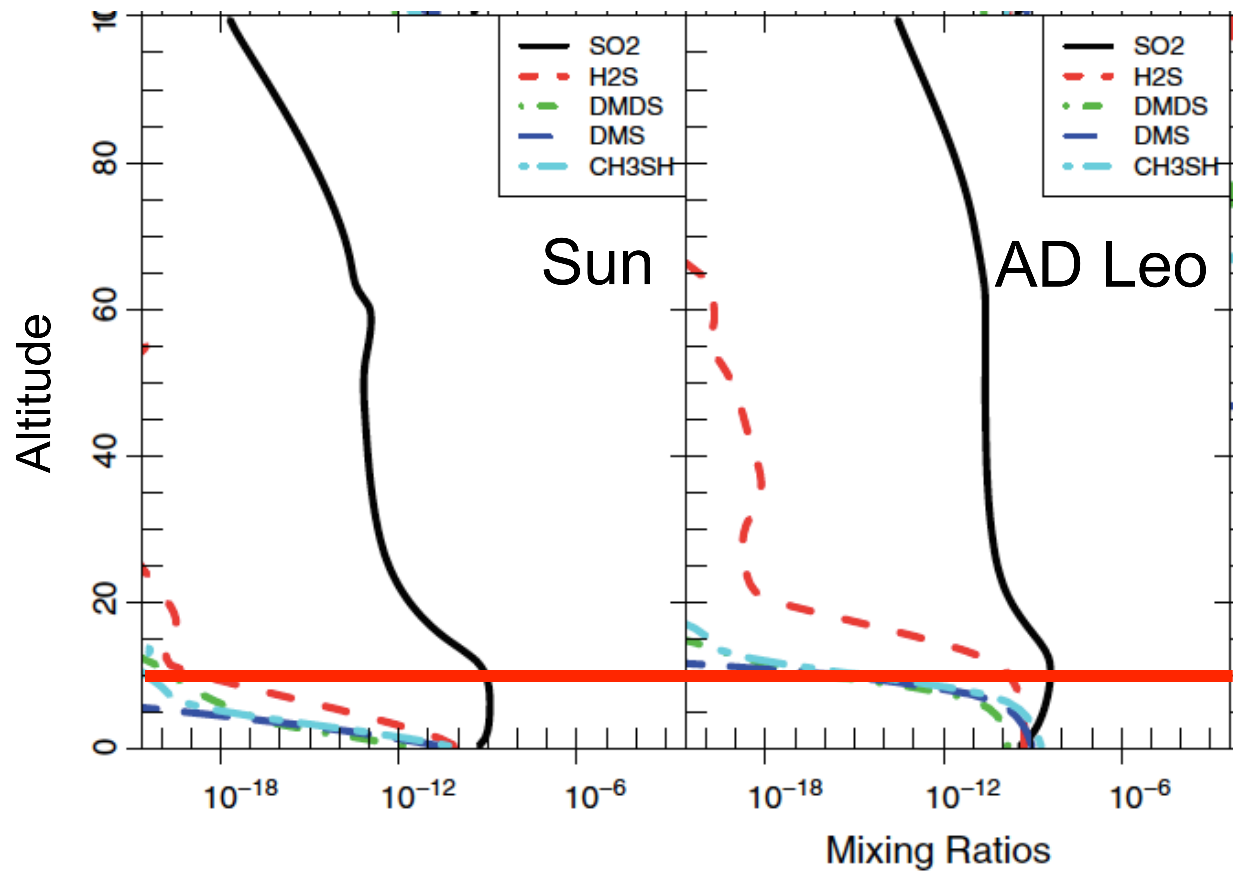
Simulated JWST/NIRISS Spectrum of M3.5V Earth



Schwieterman et al., 2016

Many (non-O_2) biosignatures will be confined to the deep atmosphere
Transmission cannot probe there.

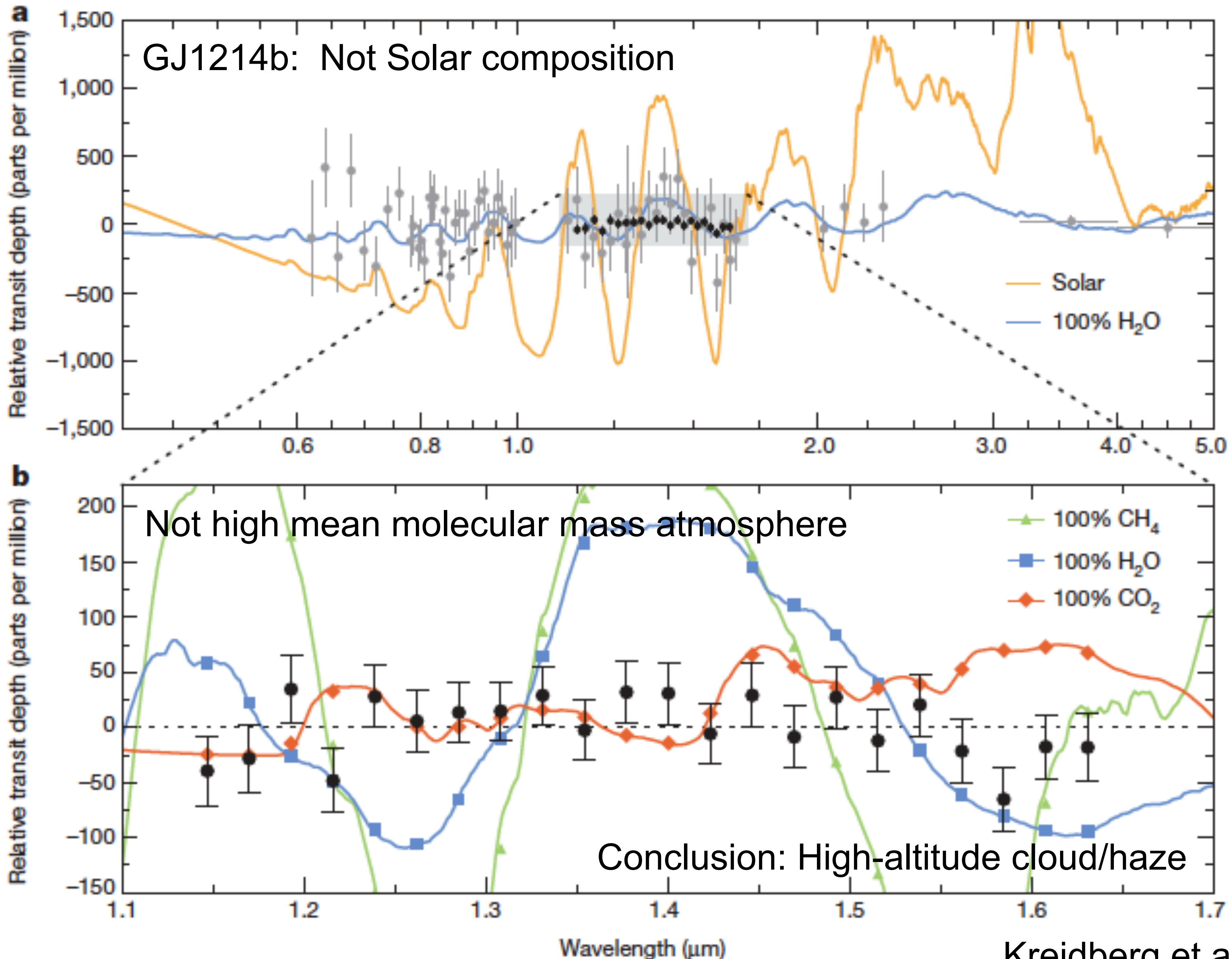
Early Earth with a sulfur-dominated biosphere



Domagal-Goldman et al., 2011

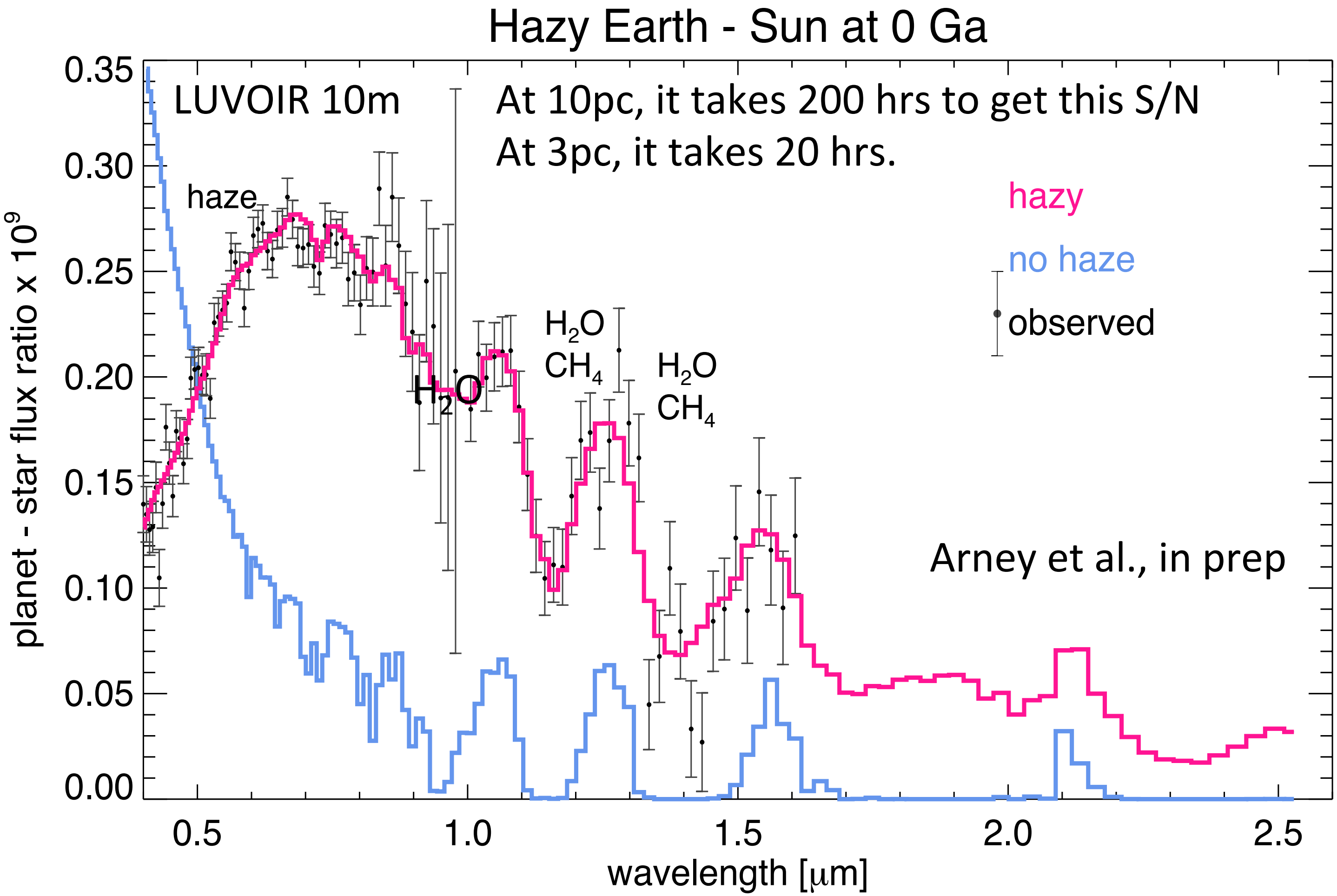
- Exotic biosignature molecules that are more susceptible to UV radiation will be less abundant and found in the lower troposphere only - may not be accessible to transmission.
- Many of these molecules also have their strongest features in the MIR.

Haze can severely limit transmission spectra



Kreidberg et al., 2014

Haze is not as big an issue for direct imaging

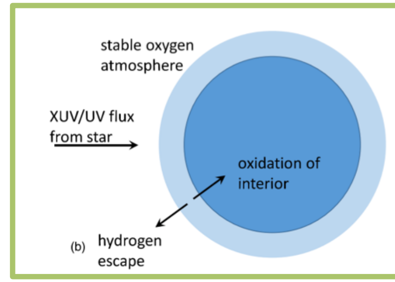


Thin haze still allows access to the deeper atmosphere, including detection of tropospheric water vapor, even at visible wavelengths.

LUVOIR targets will orbit earlier type stars as well as M dwarfs
Susceptible to fewer biosignature false positive mechanisms

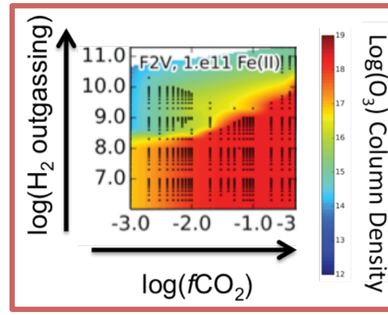
1. H Escape from Thin N-Depleted Atmospheres
(Wordsworth & Pierrehumbert 2014)

Direct Imaging - F, G, K, M Dwarfs



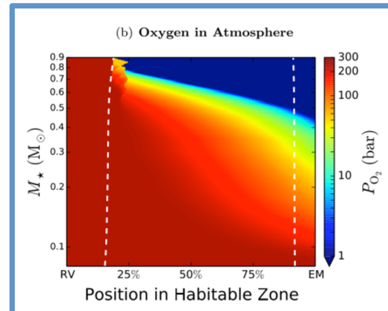
2. Photochemical Production of O_2/O_3 (Domagal-Goldman et al.; Tian et al., 2014, Harman et al., 2015)

Transmission - M Dwarfs



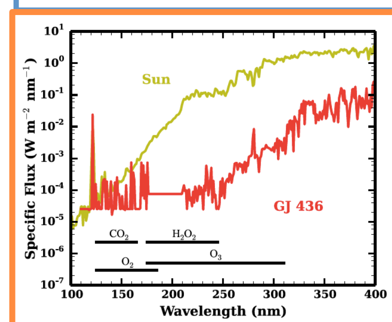
3. O_2-Dominated Post-Runaway Atmospheres from XUV-driven H Loss (Luger & Barnes 2014)

Transmission - M Dwarfs



4. CO_2 Photolysis in Dessicated Atmospheres
(Gao, Hu, Robinson, Li, Yung, 2015)

Transmission - M Dwarfs



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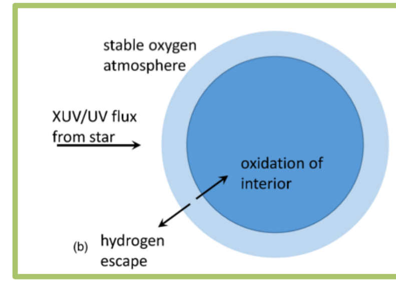
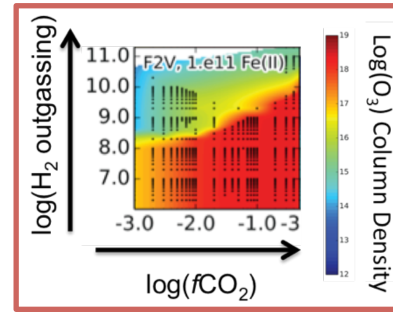


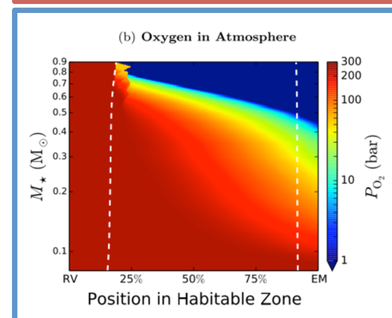
2. Photochemical Pro... of O_2/O_3 (Domagal-Goldman et al.; Ti... et al., 2015)

...sion - M Dwarfs



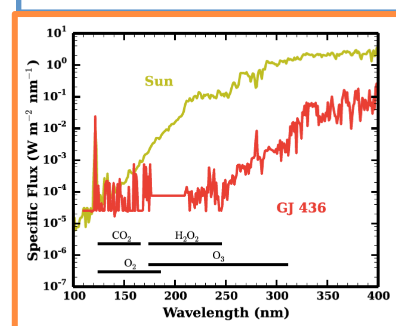
3. O_2-Do...ted ...unaway At...eres from XU... ...ven H ... (...er & Barn... ...4)

Trans... - M Dwarfs



4. CO_2 Pho... ...Dessicat... ...pheres
(Gao, Hu, Robins...

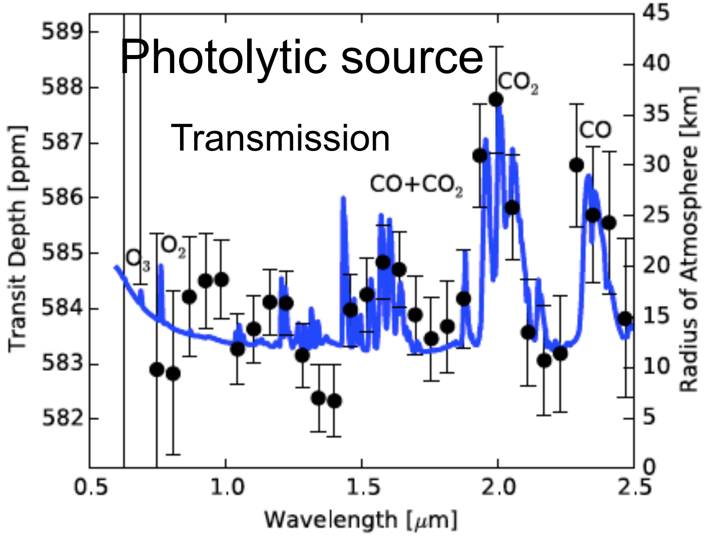
...ransmission - M Dwarfs

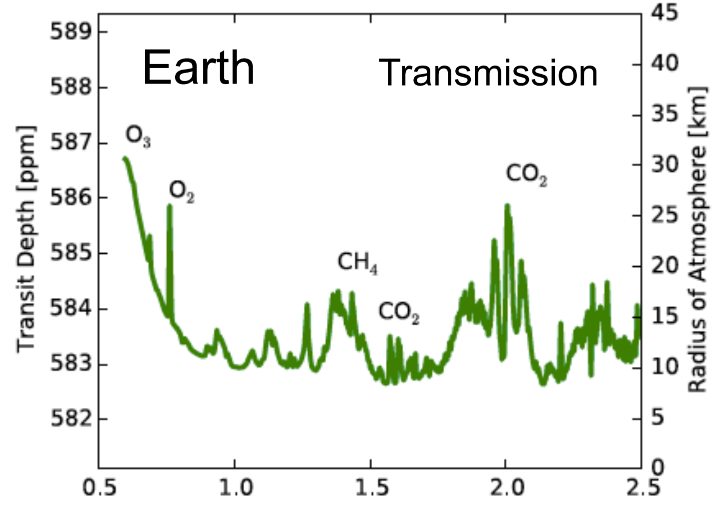


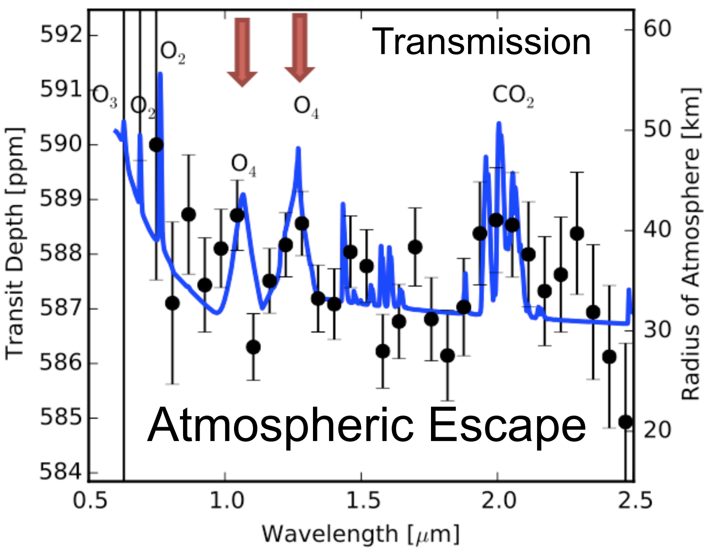
M Dwarfs Only

Abiotic O_2 generation can be identified…

if we have wavelength coverage in the visible to near-infrared.







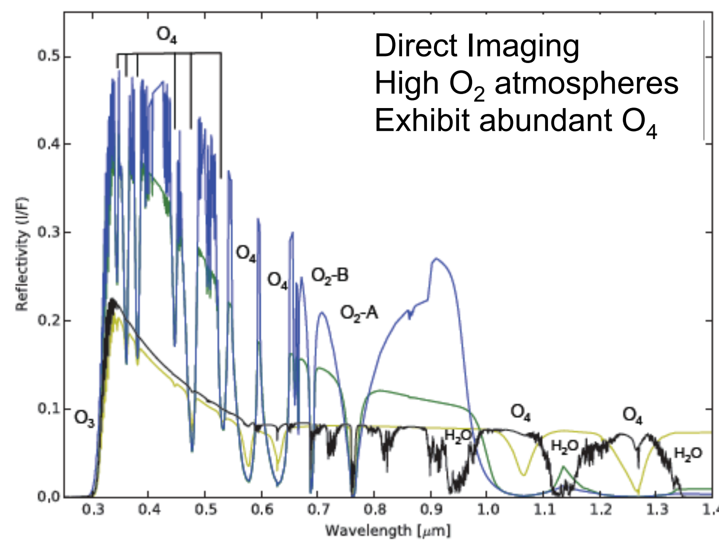
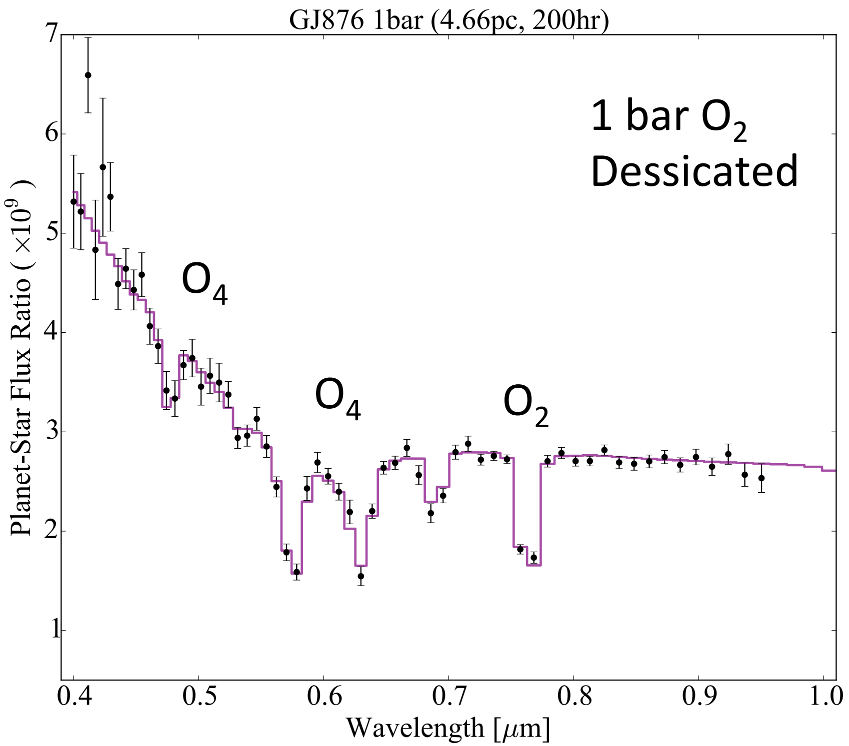
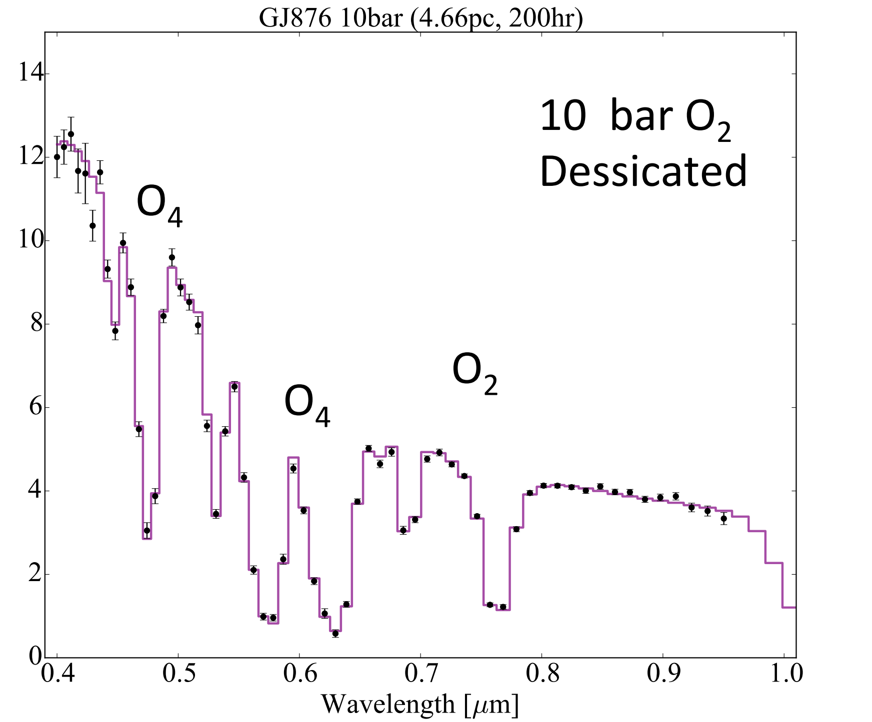


Figure 1. Synthetic reflectance spectra of 1, 10, and 100 bar high-O_2 atmospheres (yellow, green, and blue, respectively) with O_2 and O_4 bands identified. A comparable Earth spectrum is shown in black.

CO, CO_2, O_4 and CH_4 features can help reveal abiotic processes.

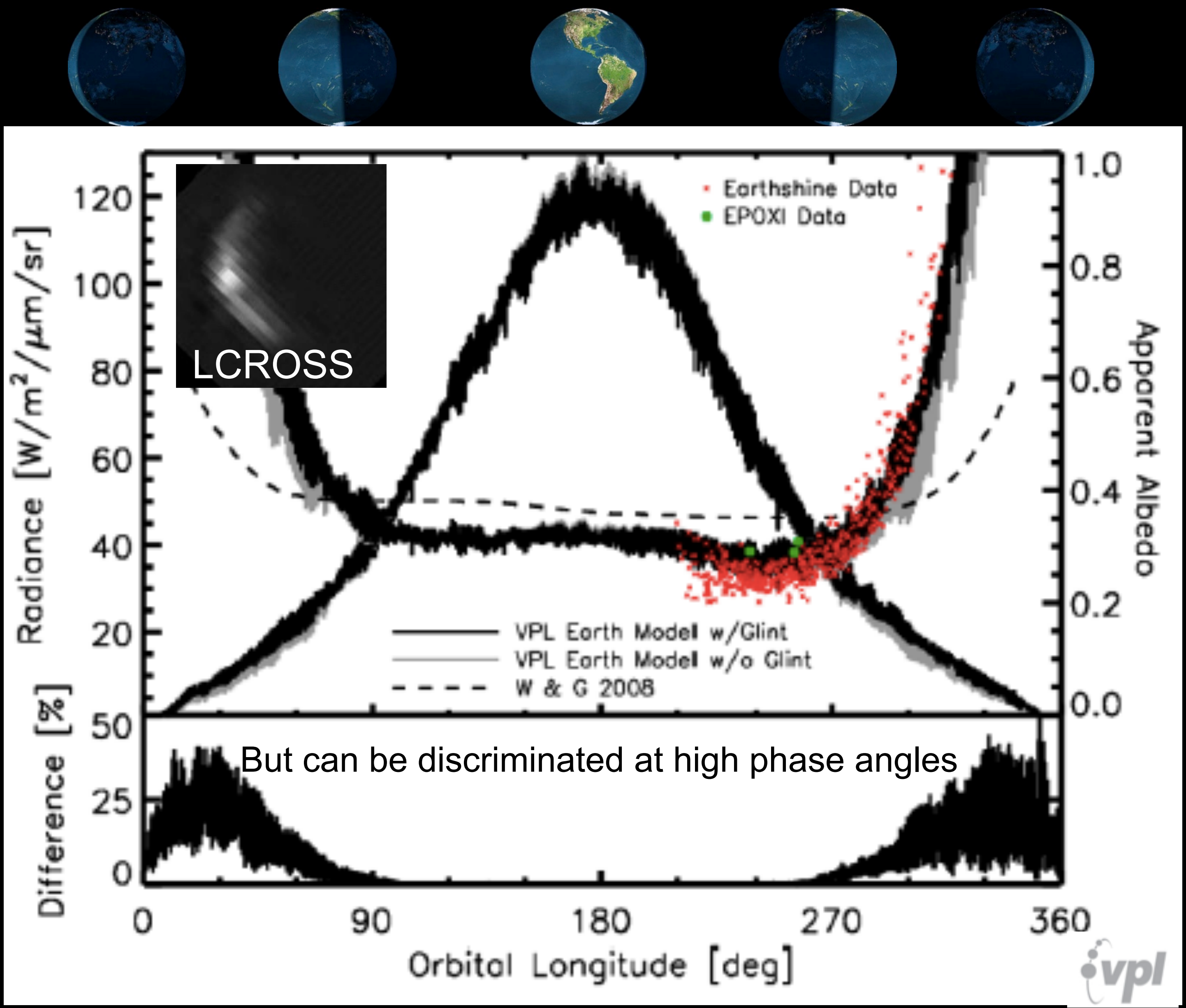
Visible O_4 bands may reveal O_2 from atmospheric loss





Jake Lustig-Yaeger, Eddie Schwieterman, Ty Robinson, Giada Arney

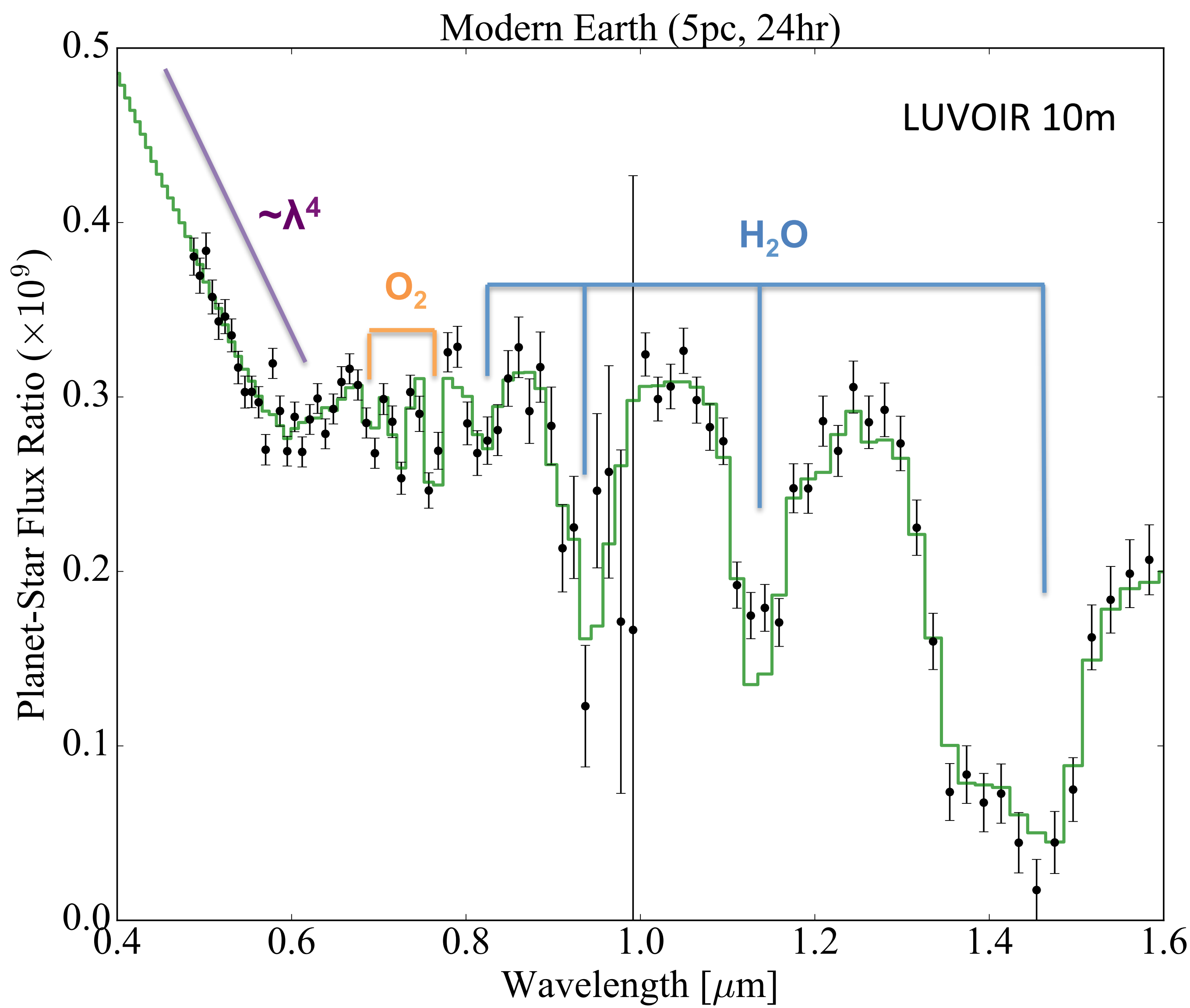
Phase Dependent Imaging of Terrestrials – Ocean Detection



But can be discriminated at high phase angles

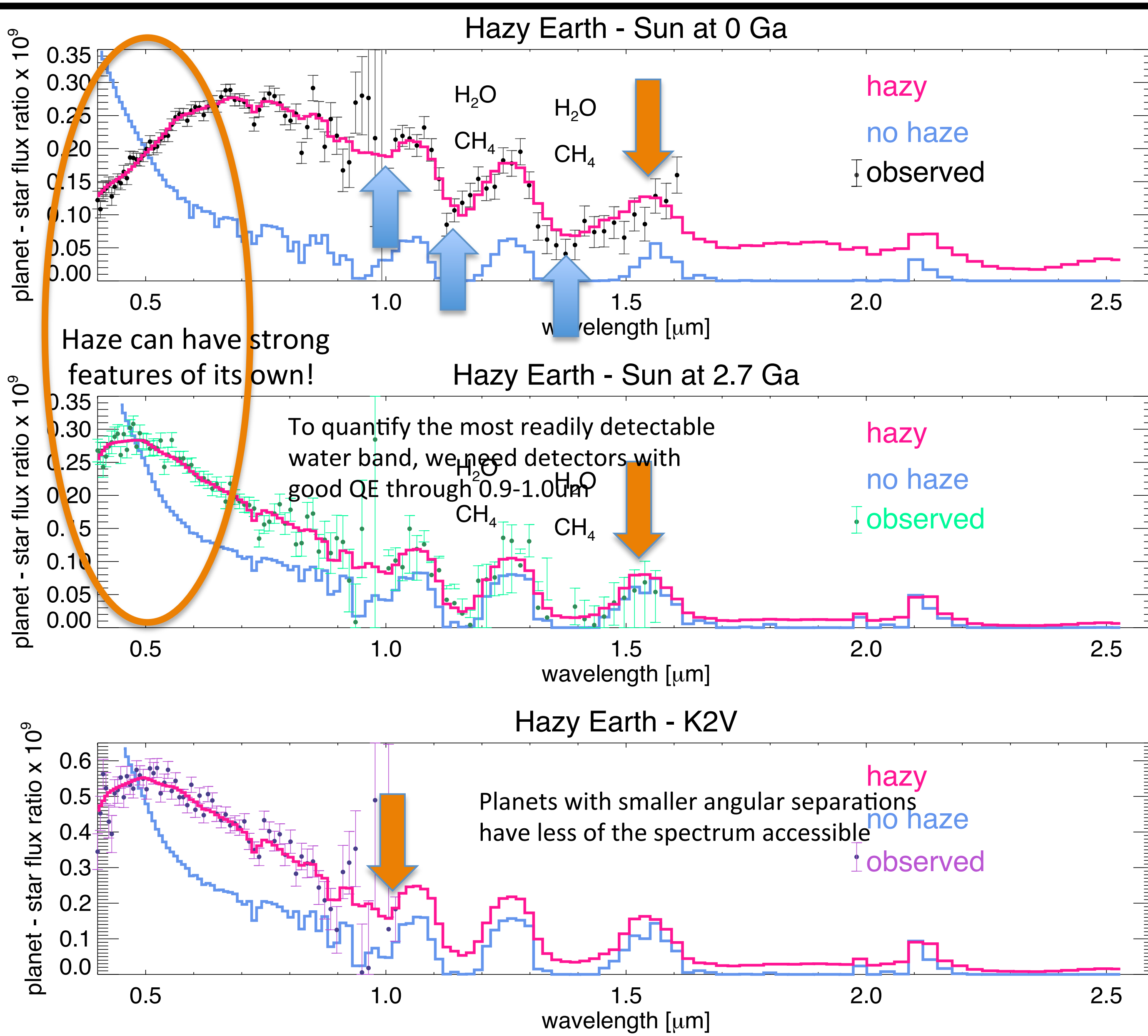
Robinson, Meadows, & Crisp (2010)

The Money Plot



Eddie Schwieterman, Jake Lustig-Yaeger, Ty Robinson, Giada Arney

Direct Imaging of Terrestrials – Some Issues



Arney et al., in prep

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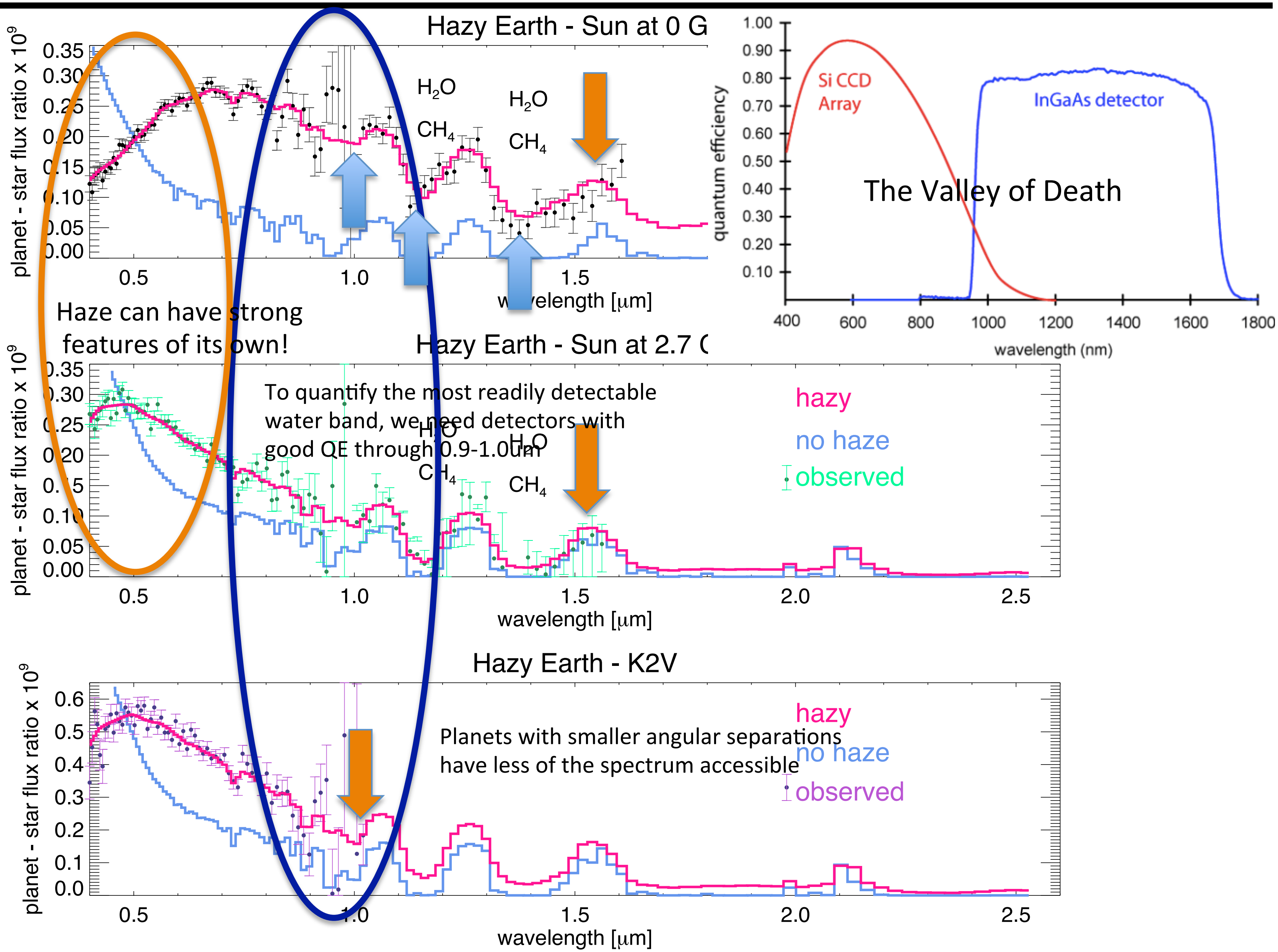
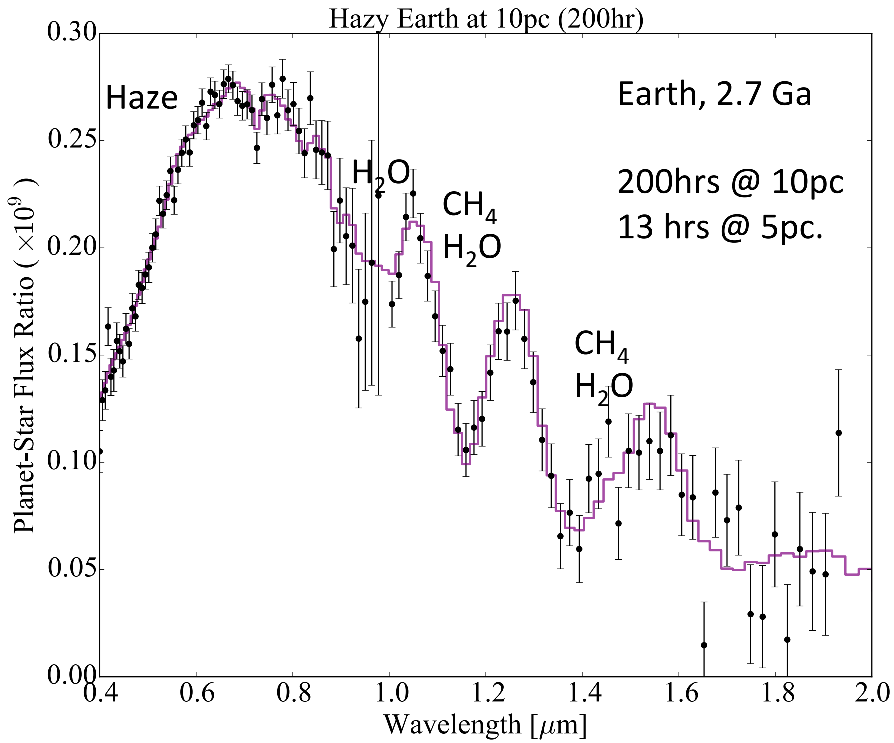
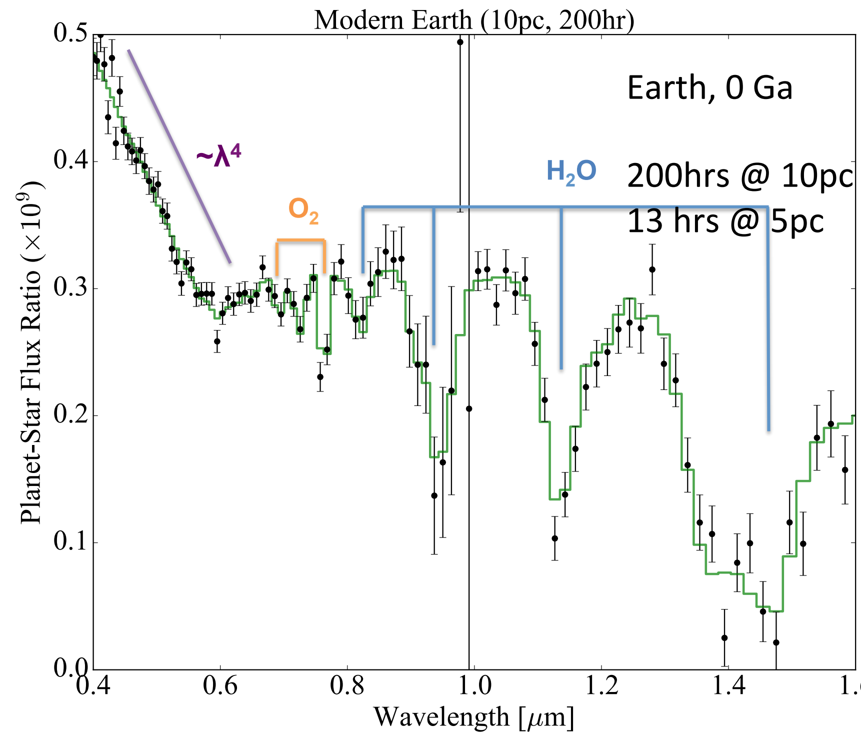


Arney et al., in prep

Long band-pass simultaneous nulling is *highly desirable*



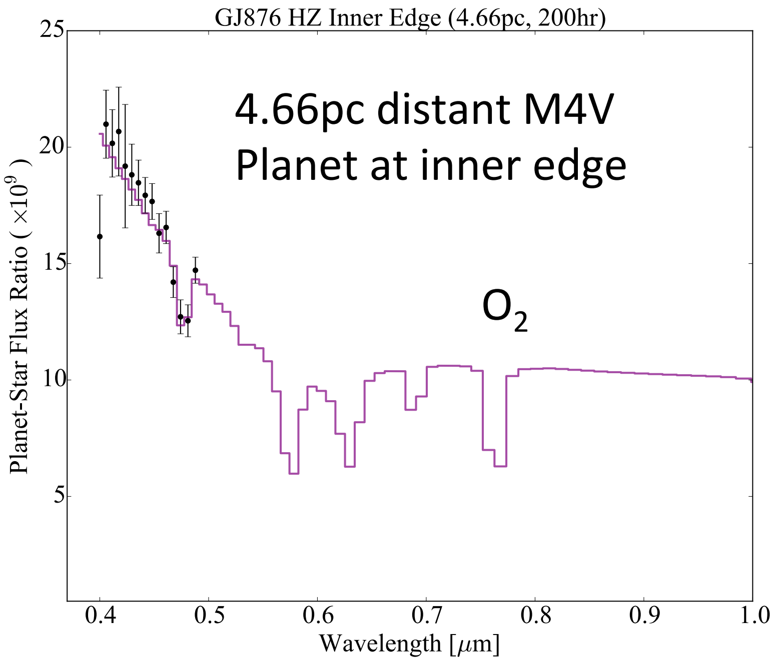


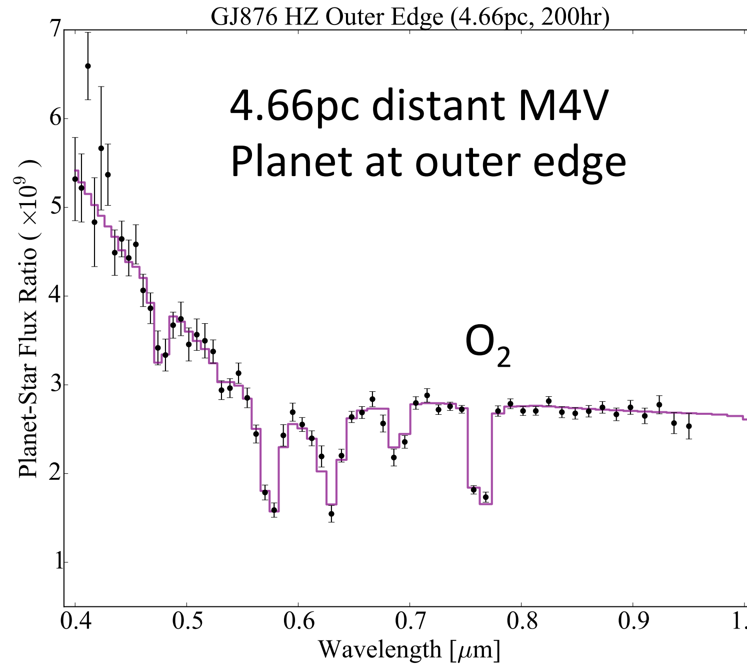
Jake Lustig-Yaeger, Eddie Schwieterman, Ty Robinson, Giada Arney

The 200 hrs here is PER BANDPASS. With, say, 4 nulling bandpasses spanning the wavelength range, this would be 800 hrs on target.
(*might need multiple coronagraphs!)

Being able to bin down spectral resolution on fainter targets will be crucial
– low to no noise detectors needed!

M Dwarf HZs may be accessible over limited wavelength





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This is great for comparative planetology as LUVOIR can access true Solar System analogs as well as some M dwarf planets.

Wavelength range accessibility also depends on position in the HZ!

LUVOIR will have unique capabilities

- Observations by upcoming missions, including JWST, WFIRST and ground-based telescopes will provide initial opportunities to study the atmospheres and surfaces of HZ terrestrials.
  - the number of targets accessible will be small (or possibly non-existent).
  - transmission spectroscopy cannot access the troposphere and surface, where most water, and a wider array of biosignatures may be present.
  - JWST and ELTs are limited to M dwarf planets, where possible false positives for biosignatures are potentially much higher.

- Direct imaging of a large number of HZ Terrestrials around A through M Dwarf stars with LUVOIR will:
  - Provide meaningful statistics on the fraction of worlds that are habitable and that support life
  - Allow access to the surfaces and entire atmospheric column for more detailed characterization of planetary systems, including those like our own.
  - Vastly improved capability to search for habitability and biosignatures.