Spectroastrometric detection of exomoons

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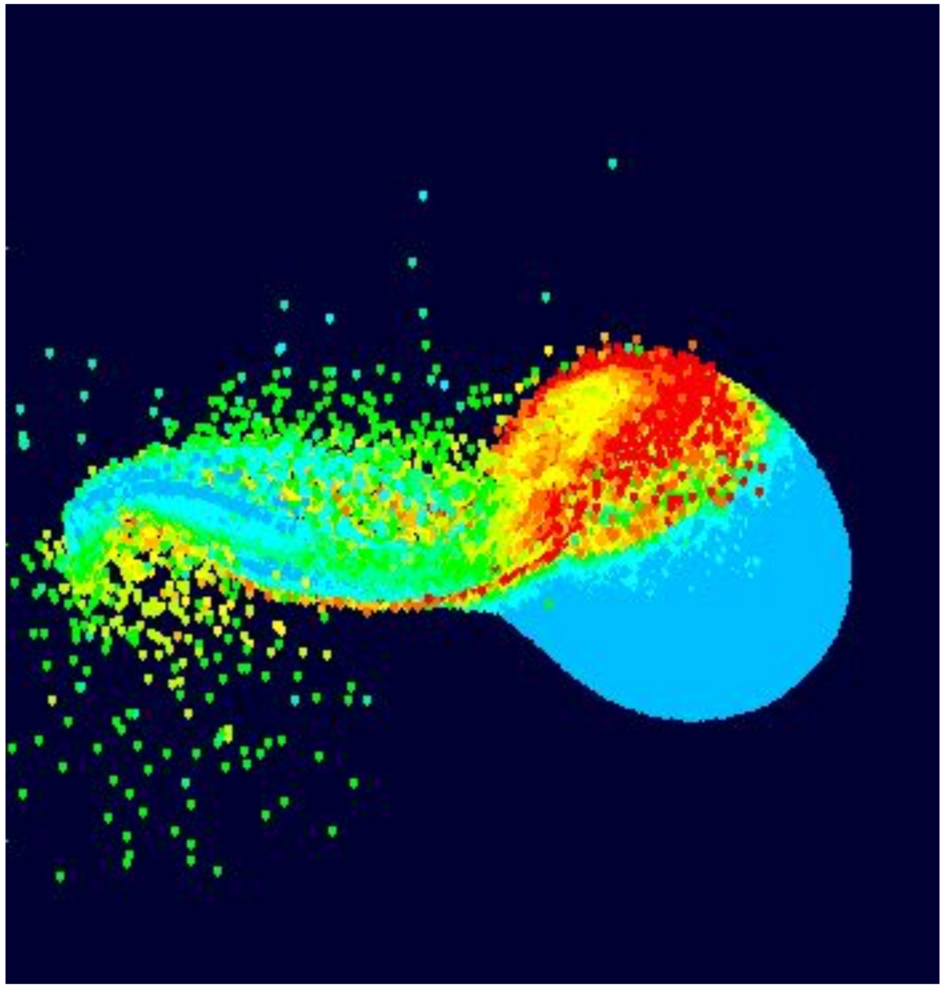
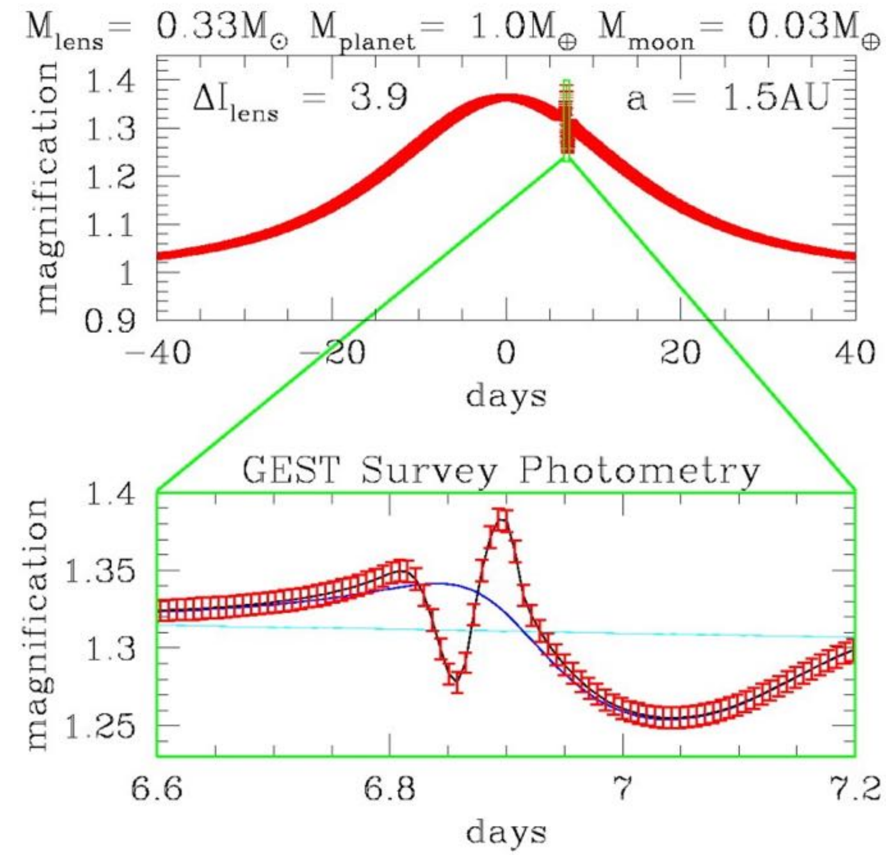
Exomoon formation

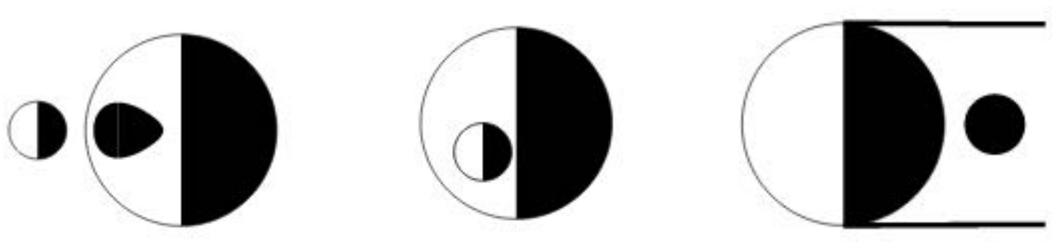
- Giant impact (e.g. Canap & Asphaug 2001)
- Disk formation (e.g. Heller et al. 2015)
- Yet unimagined mechanism(s)
- Planet + moon ≈ binary planet

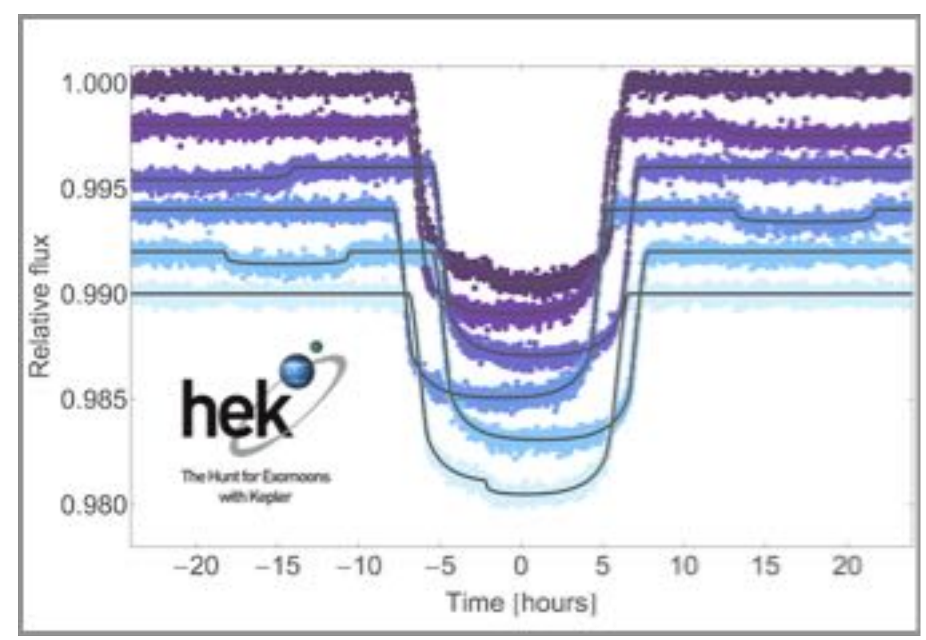


Exomoon detection

- Microlensing (Bennett & Rhie 2001)
- Transits: timing/duration variation, ‘shoulders’ (Kipping 2011; Heller 2014)
- Mutual events (Cabrera & Schneider 2007)
- Phase function/thermal IR (Robinson 2011)





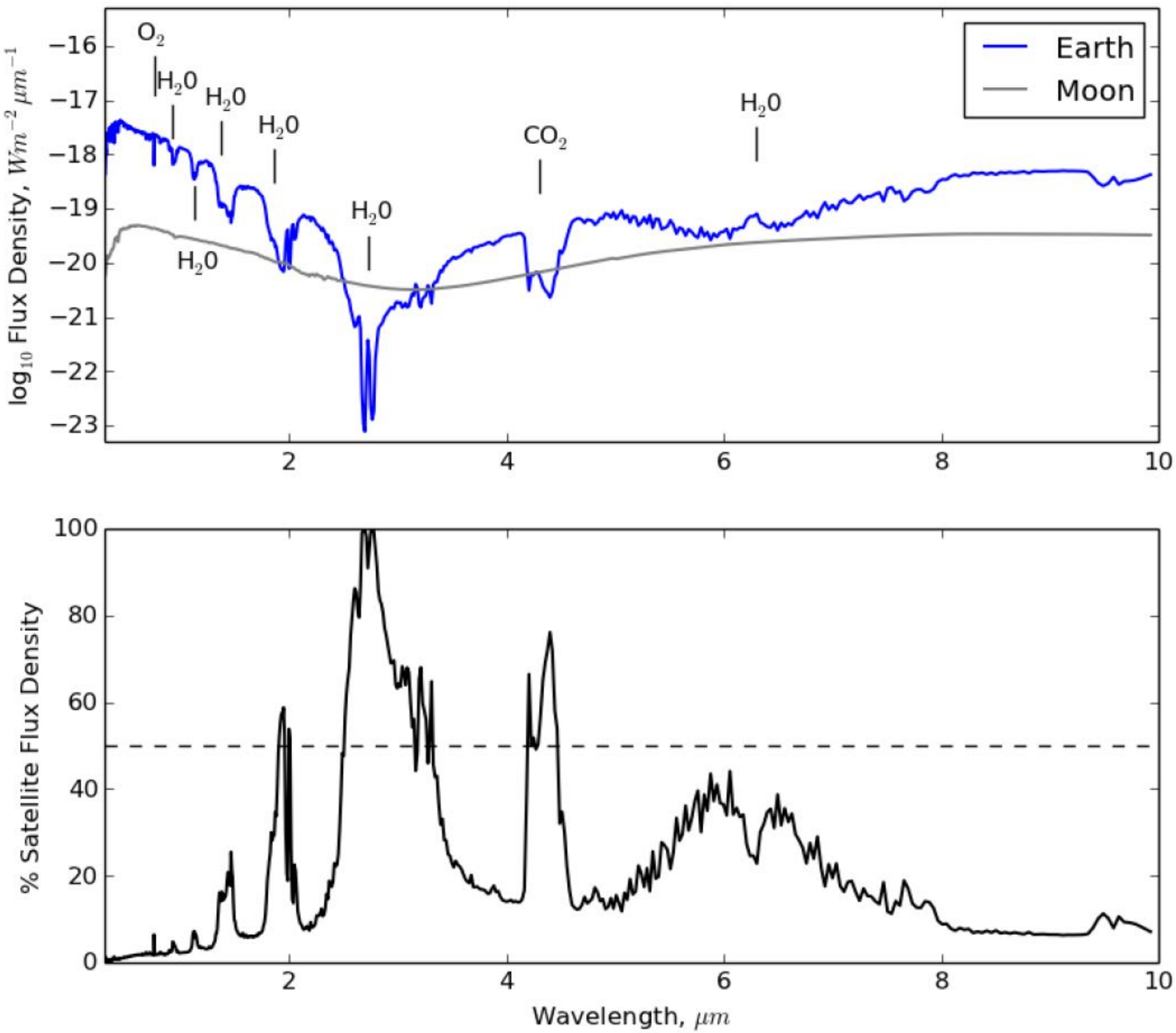


Exomoon characterization

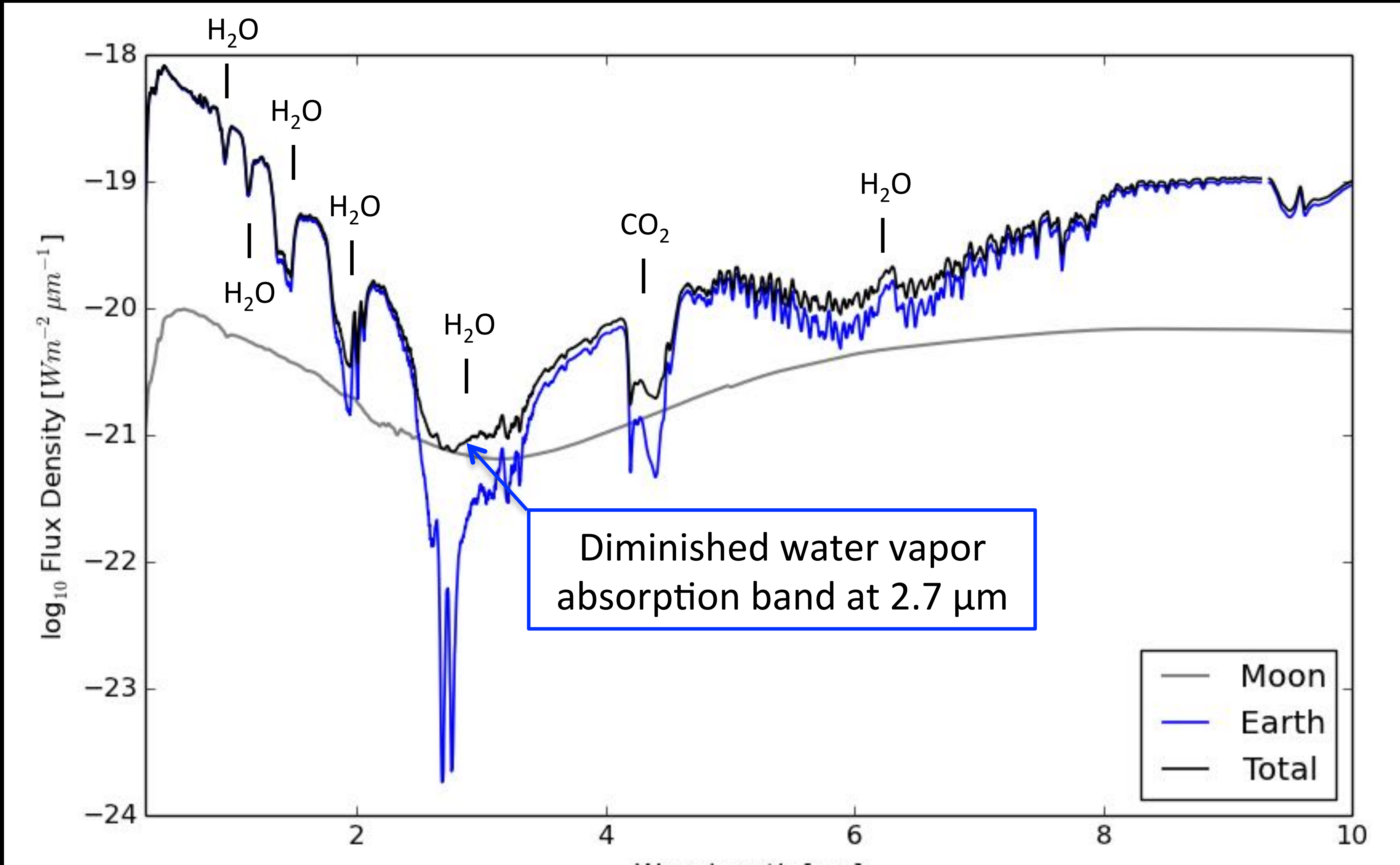
- Mass, radius
- Orbit about planet
- Spectrum: albedo? atmospheric composition?
- Disentangle spectrum of moon from planet
  - ➡ Biosignature false-positive: two equilibrium atmospheres of differing composition can appear as a single atmosphere in disequilibrium (Rein, Fuji & Spiegel 2014)

The Moon can outshine Earth

The Moon can outshine Earth



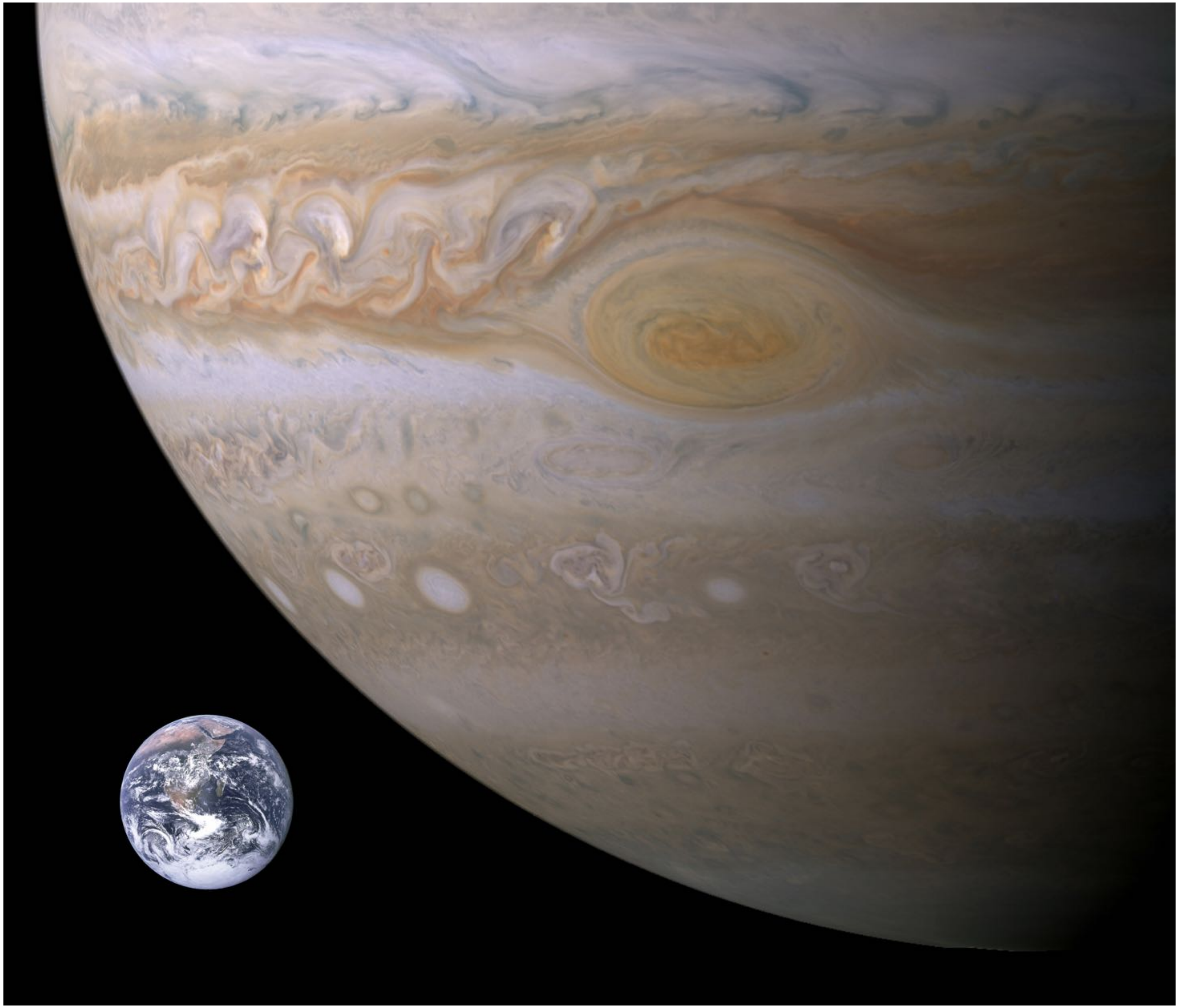
Example of Spectral Confusion



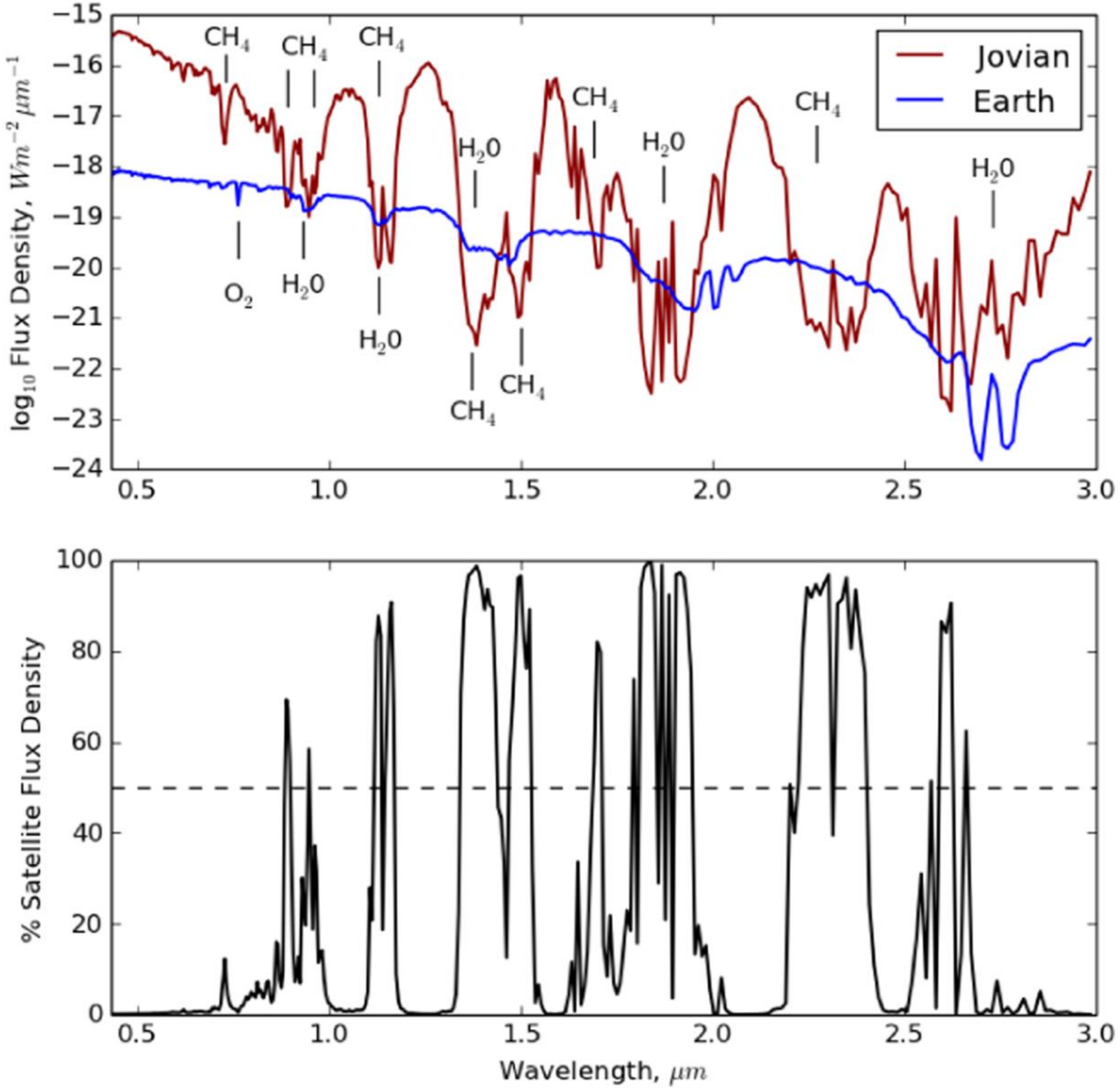
Robinson et al. 2011, Agol et al. 2015

The combined spectrum of the Earth and the Moon at 3 parsecs.
Cause unknown a priori. Clouds? Moon?

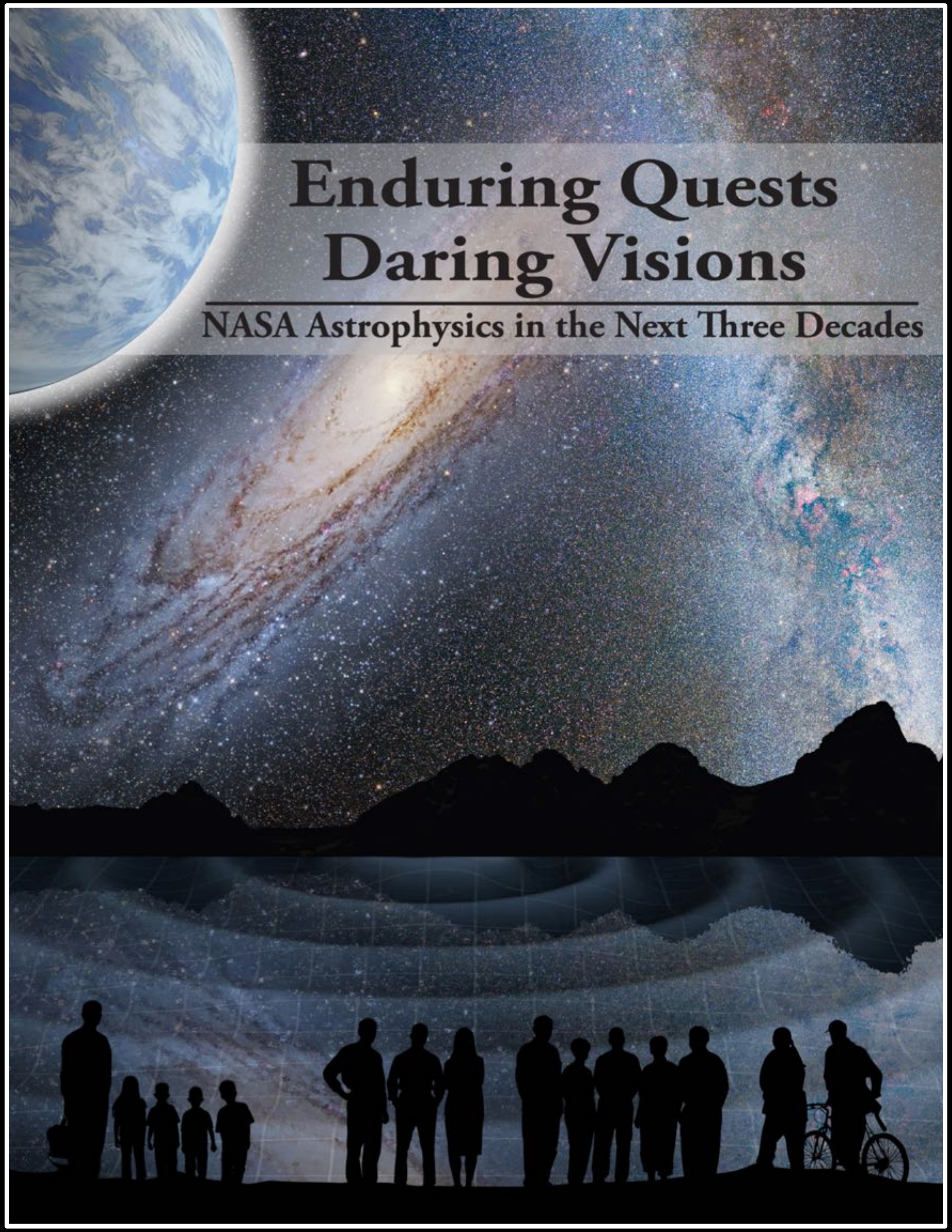
The Earth can outshine Jupiter

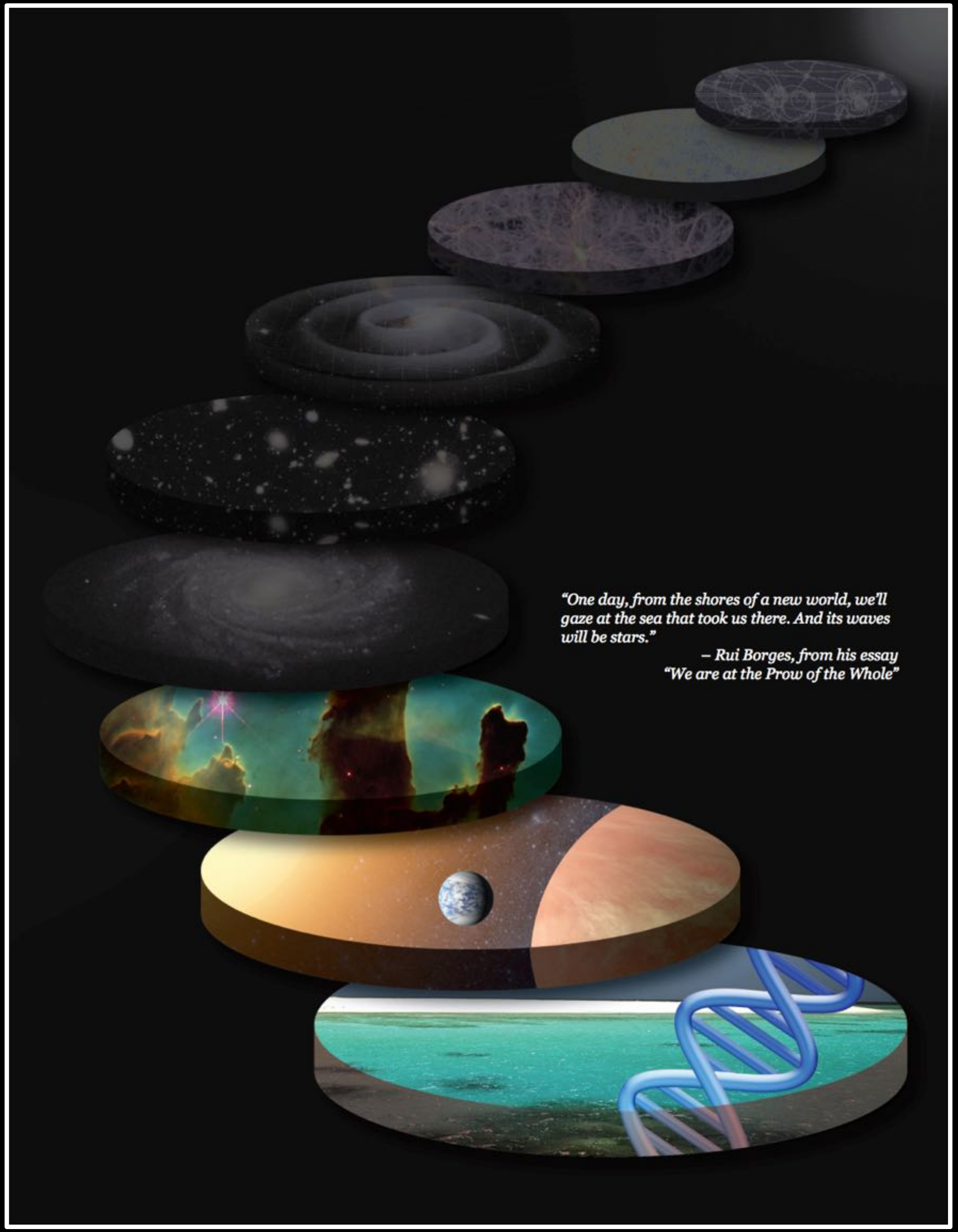


The Earth can outshine Jupiter



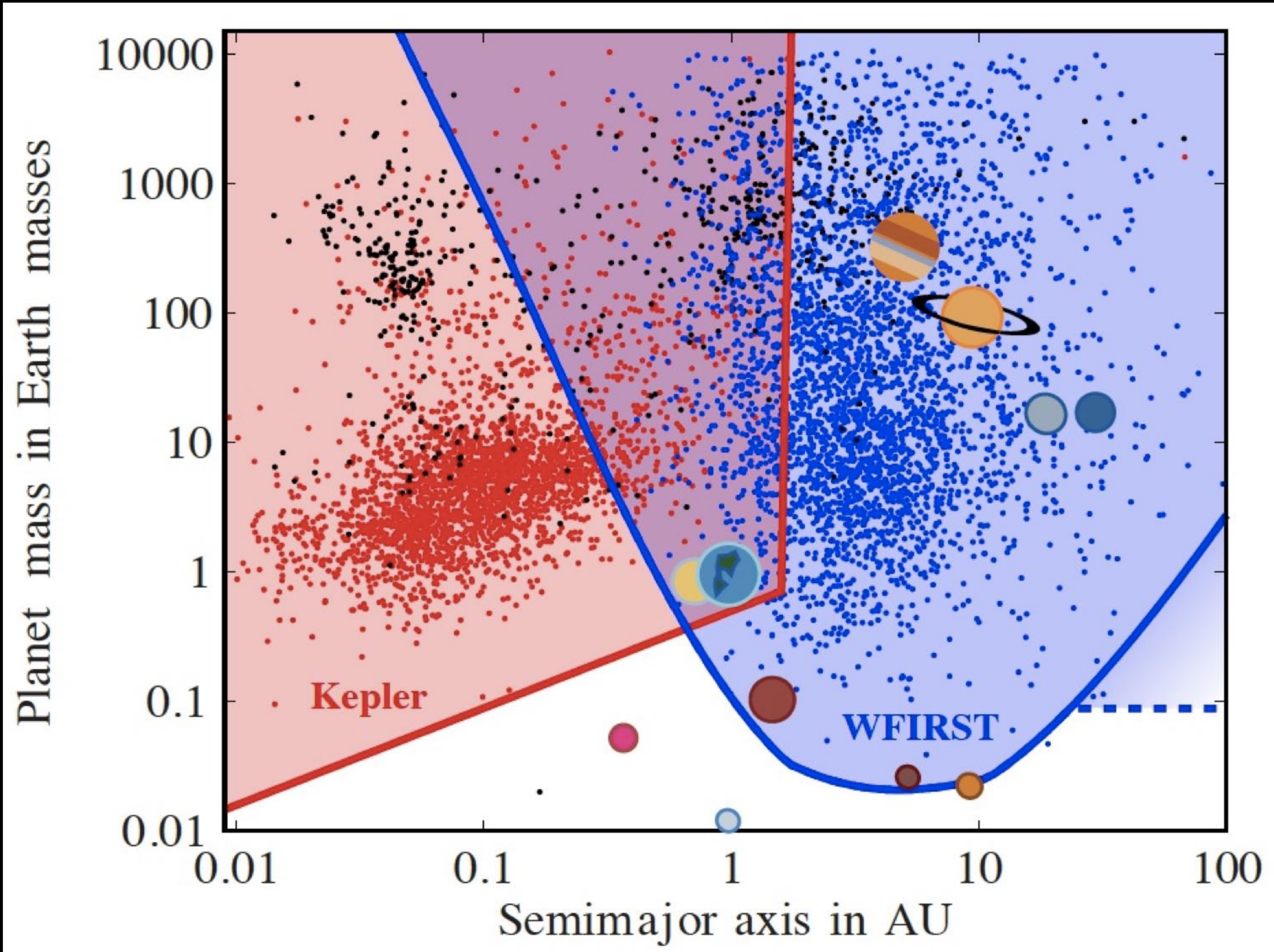
Are we Alone?





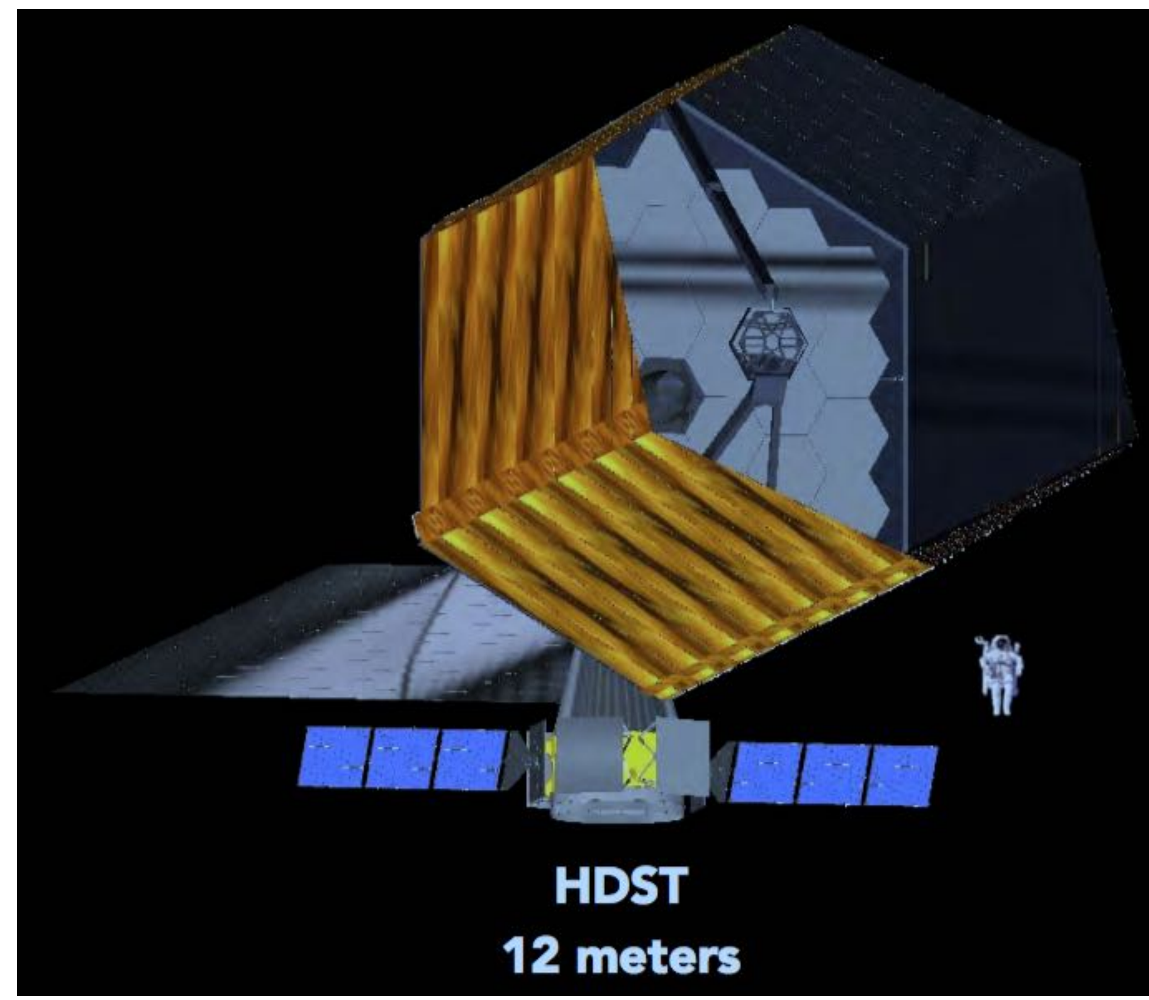
1.) The Exoplanet Zoo
2.) What are Exoplanets Like?
3.) The Search for Life

Kepler and *WFIRST*: a complete statistical census?

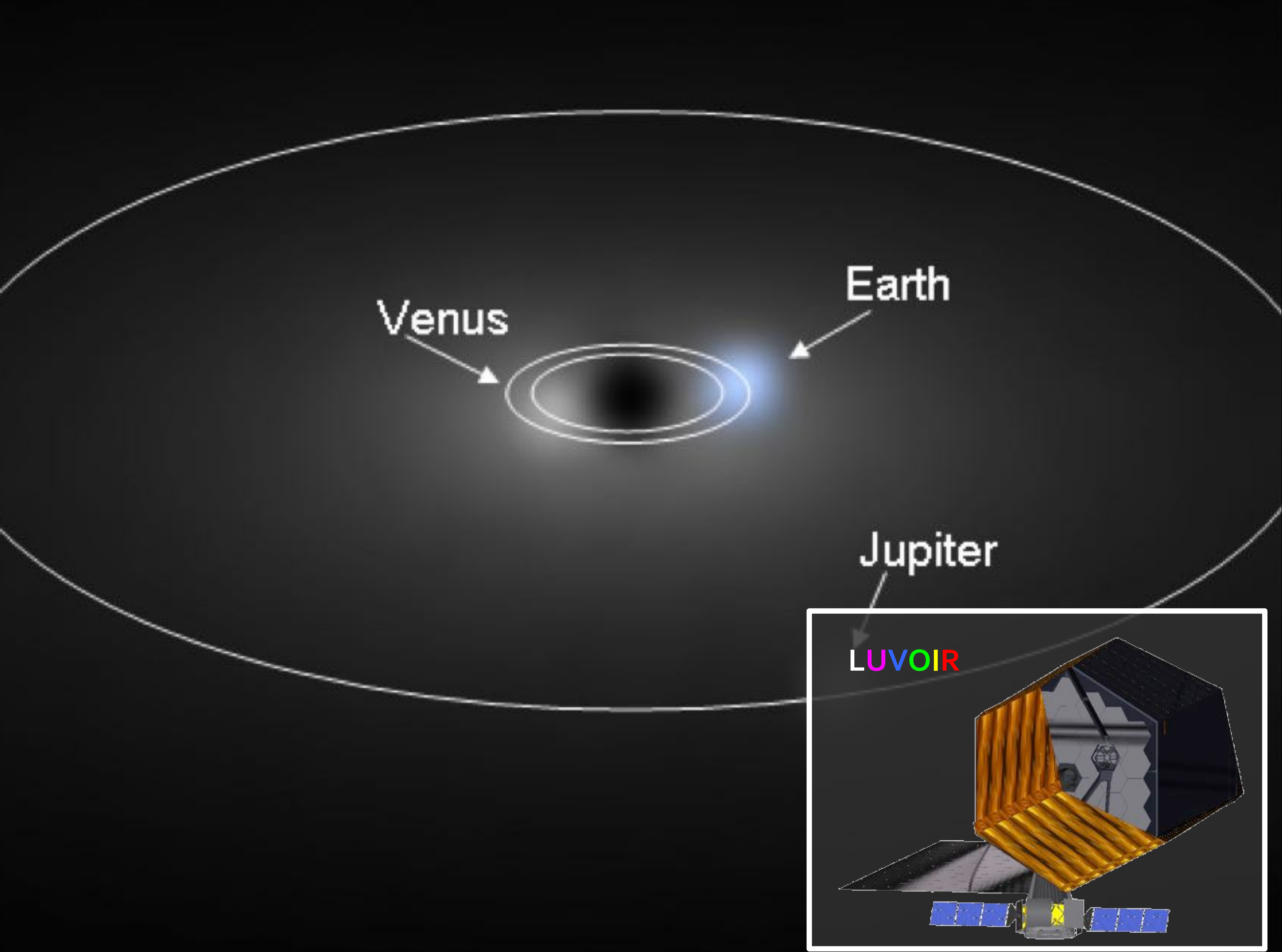


Characterizing planets with HDST/LUVOIR/ATLAST

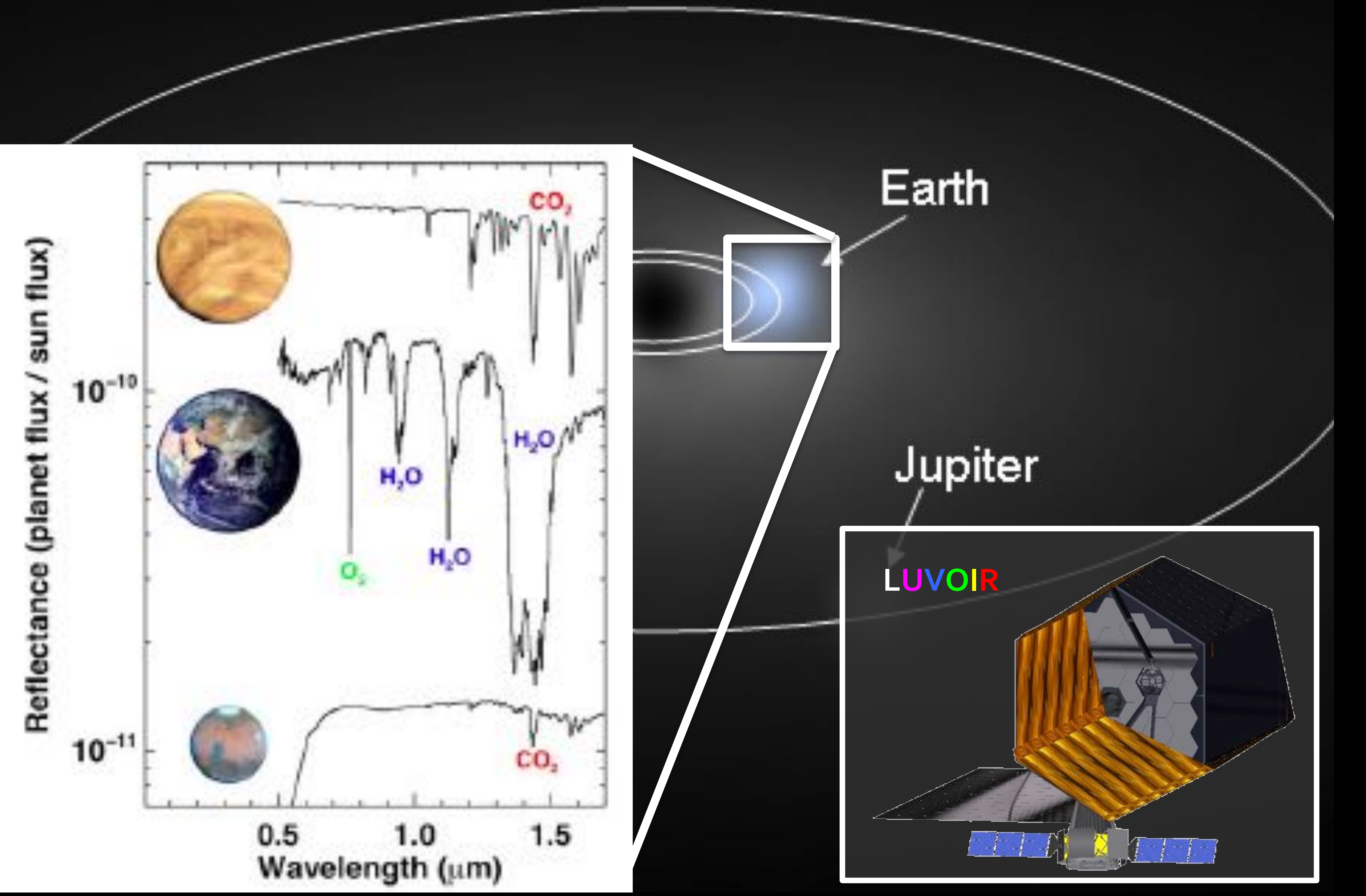
- Internal coronagraph: suppress starlight, image planet systems
- Main goal: spectroscopy, chemistry - ‘biosignatures’
- The *architecture* of planetary systems
- Temporal color variability - planet ‘mapping’
- Astrometric variations



(Kouveliotou, Agol et al. 2014; Dalcanton, Seager et al. 2015)


Venus
Earth
Jupiter
LUVOIR

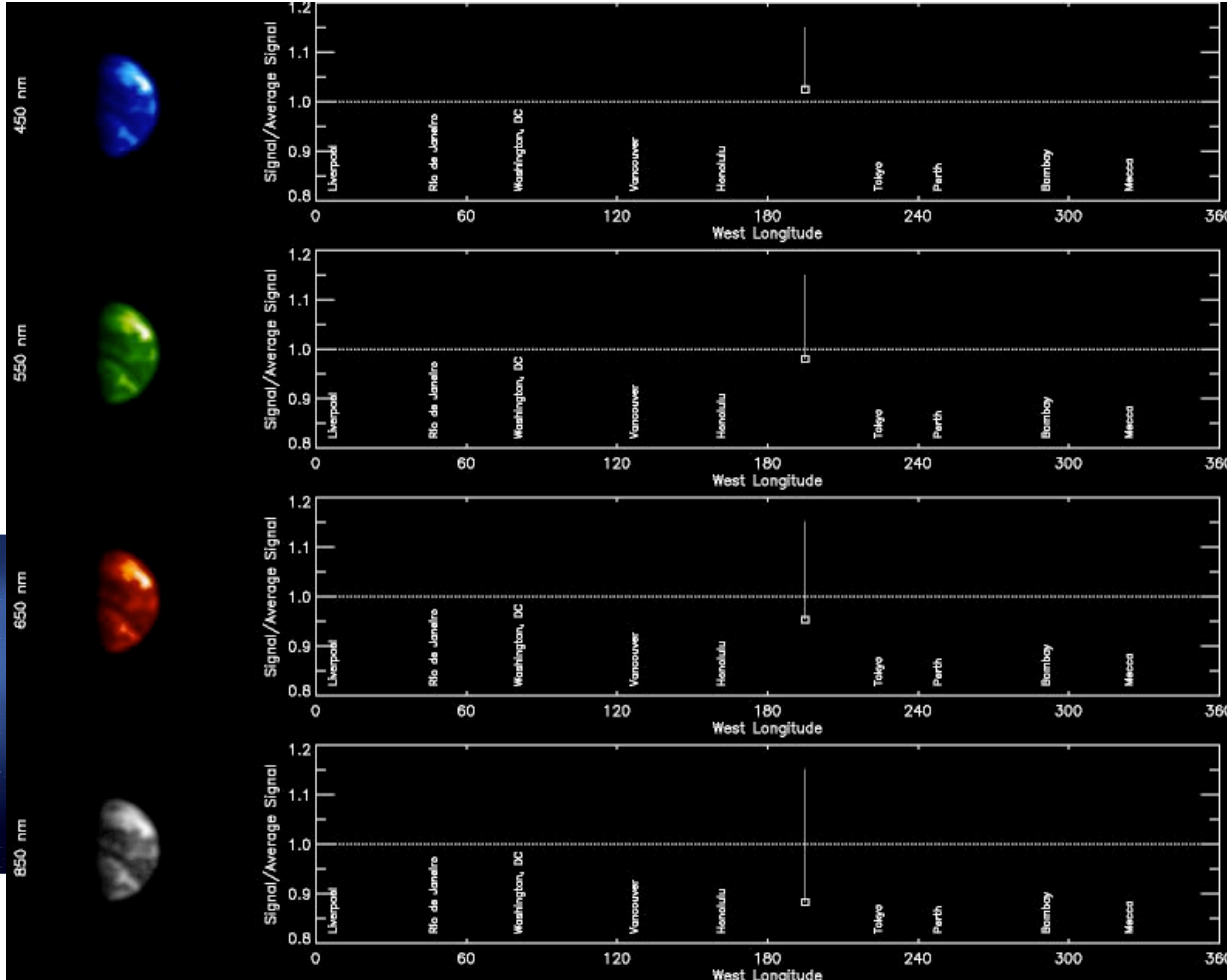
Spectra of “Pale Blue Dots” with LUVOIR Surveyor.



EPOXI* Earth observations

*Extrasolar Planet Observation and Deep Impact Extended Investigation

7 colors
5 days at different perspectives, phases, & seasons



‘Mapping’ an exoearth

EPOXI* Earth observation

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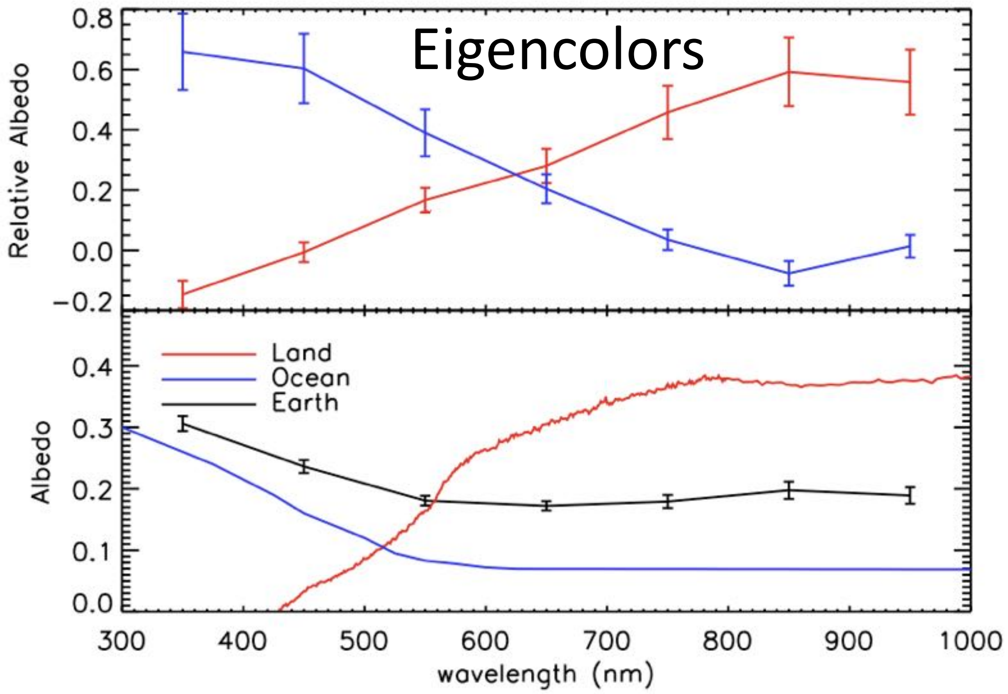
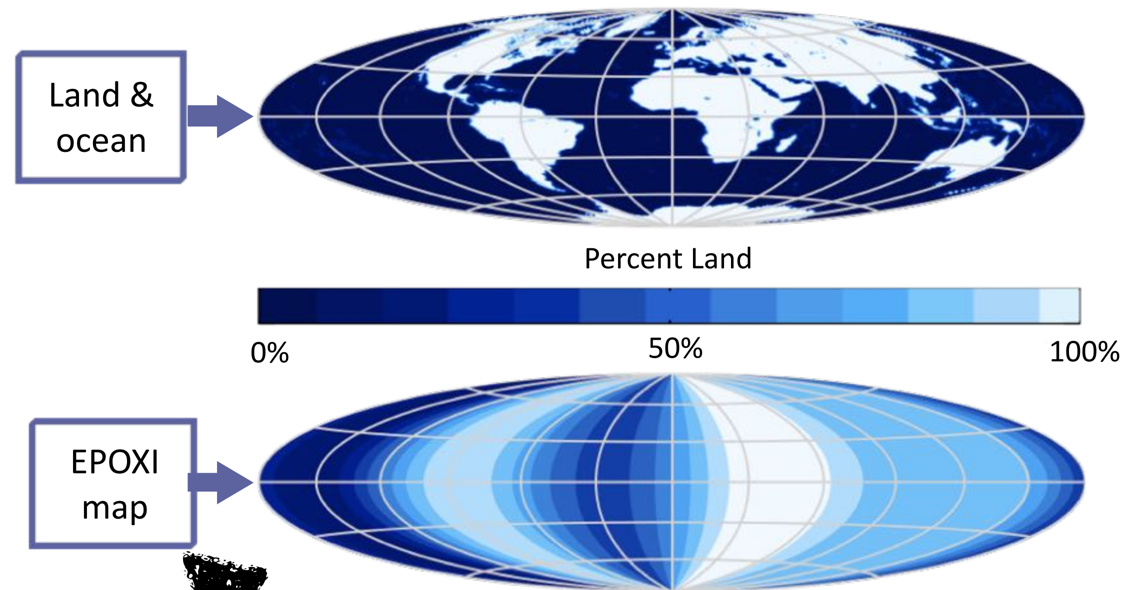
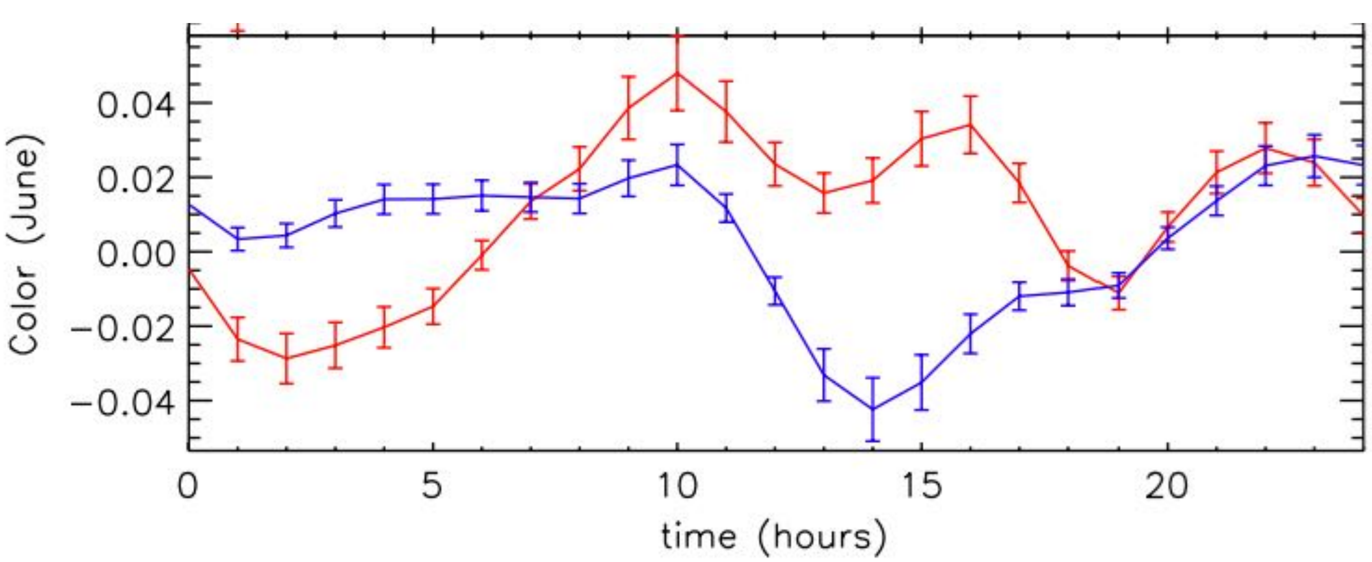


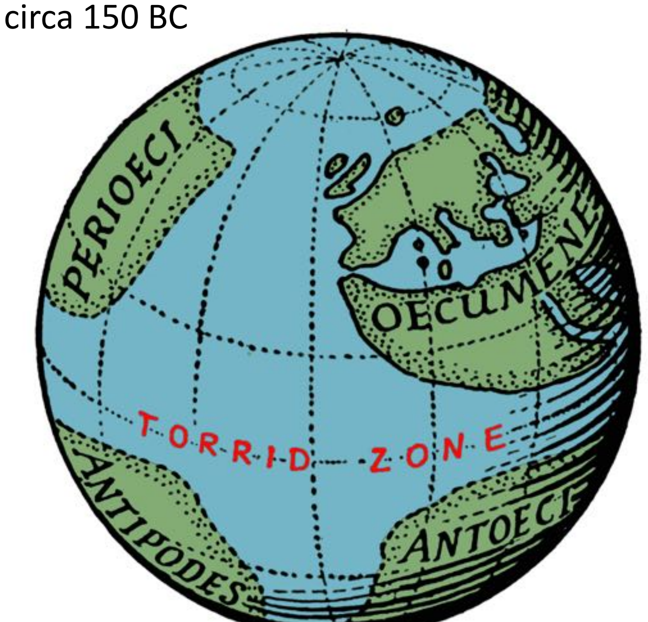


Cowan, Agol et al. (2009)

Time variation of eigencolors



Crates’ Globe circa 150 BC



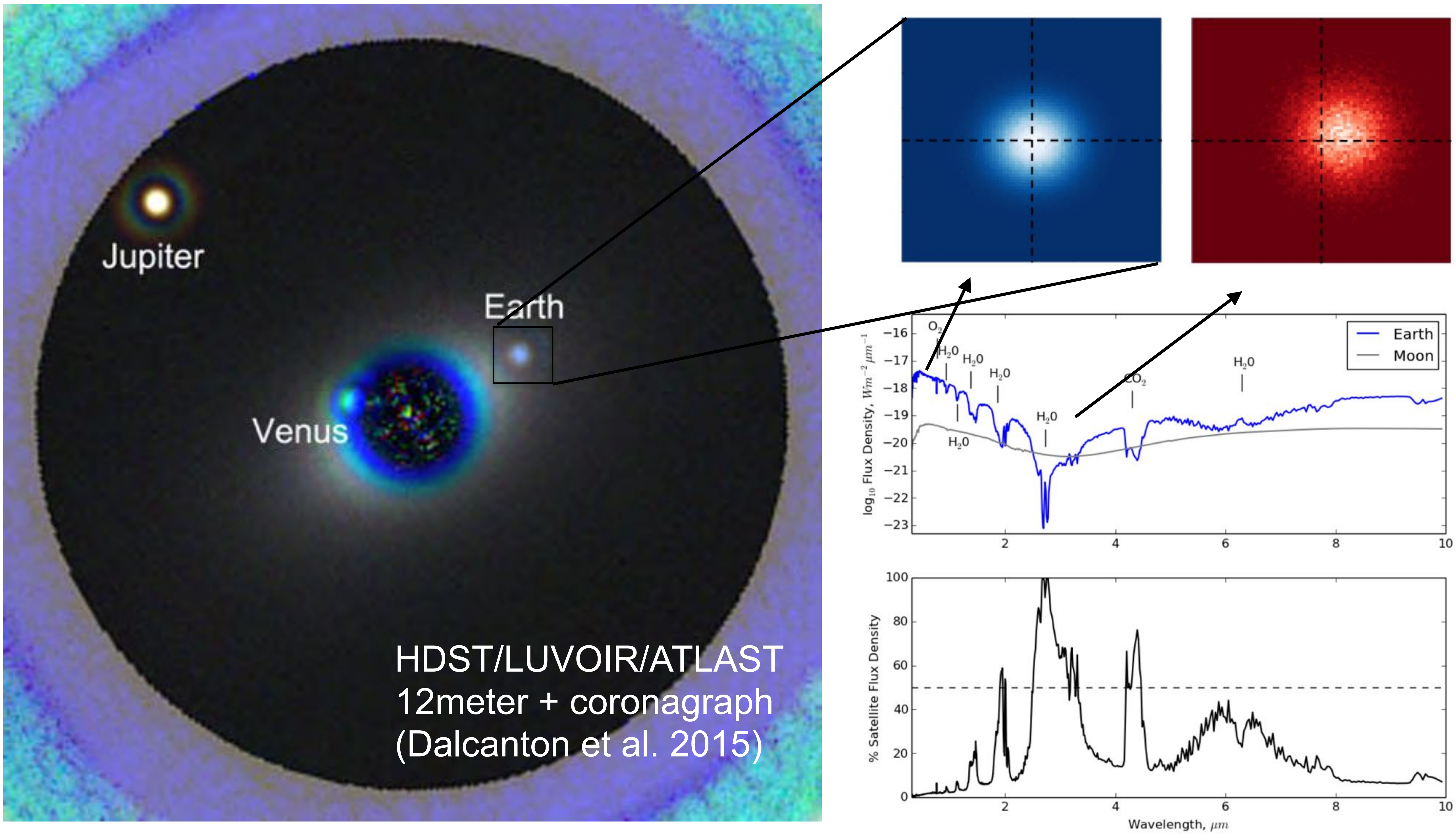
EPOXI* Earth observations

*Extrasolar Planet Observation and Deep Impact Extended Investigation

Astrometric signal

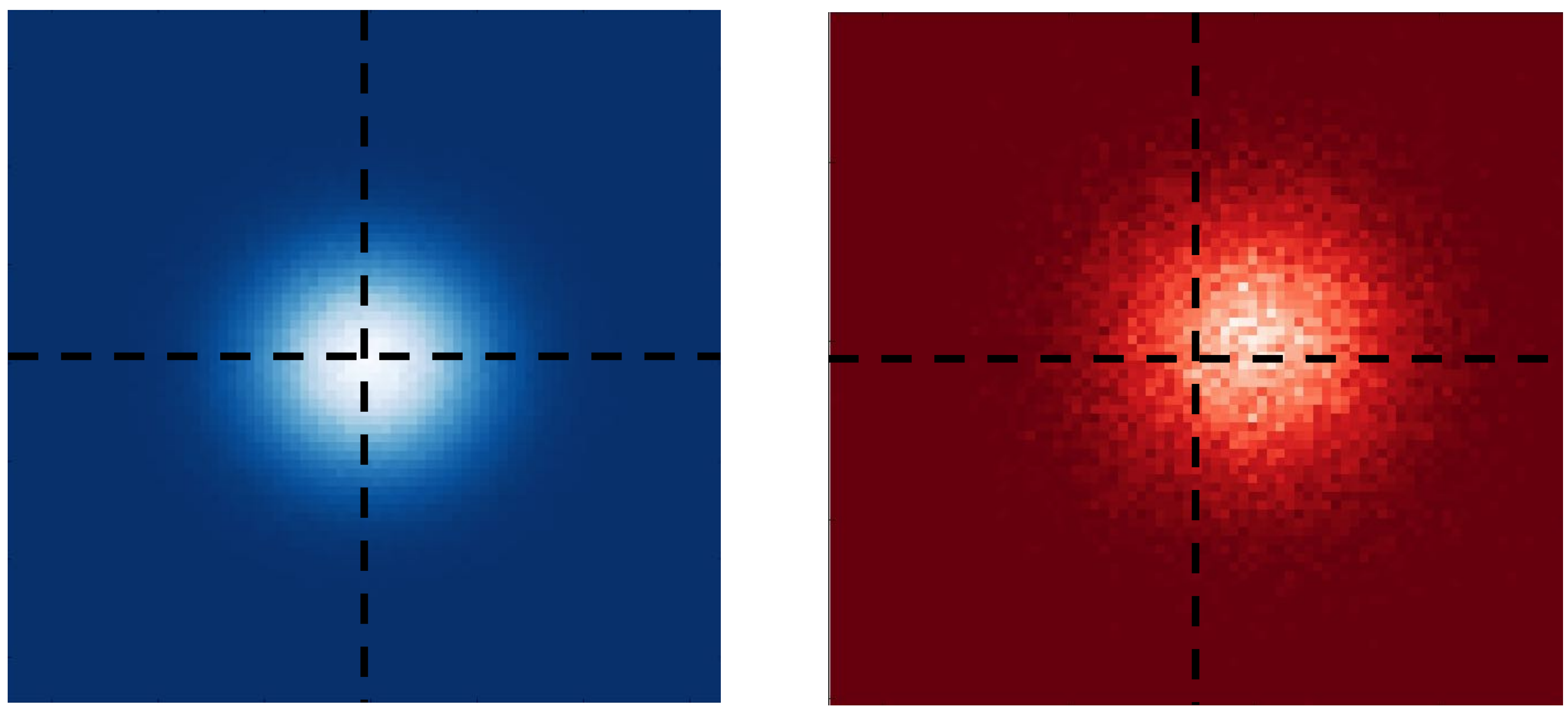
• Orbit of the Earth	~AU
• Non-uniform albedo of the Earth	$<R_\oplus$
• Center of mass of Earth-Moon	$\sim R_\oplus$
• Perturbations by other planets	$\sim R_\oplus$
• Offset to Moon	$\sim 60\ R_\oplus$
• $R_\oplus$/10 pc	~ 4μas

Spectroastrometric detection of exomoons (Agol, Jansen, Lacy, Robinson & Meadows 2015)



Modeling Spectroastrometric Signal

Signal: $|Centroid(\lambda_{planet}) - Centroid(\lambda_{moon})|$



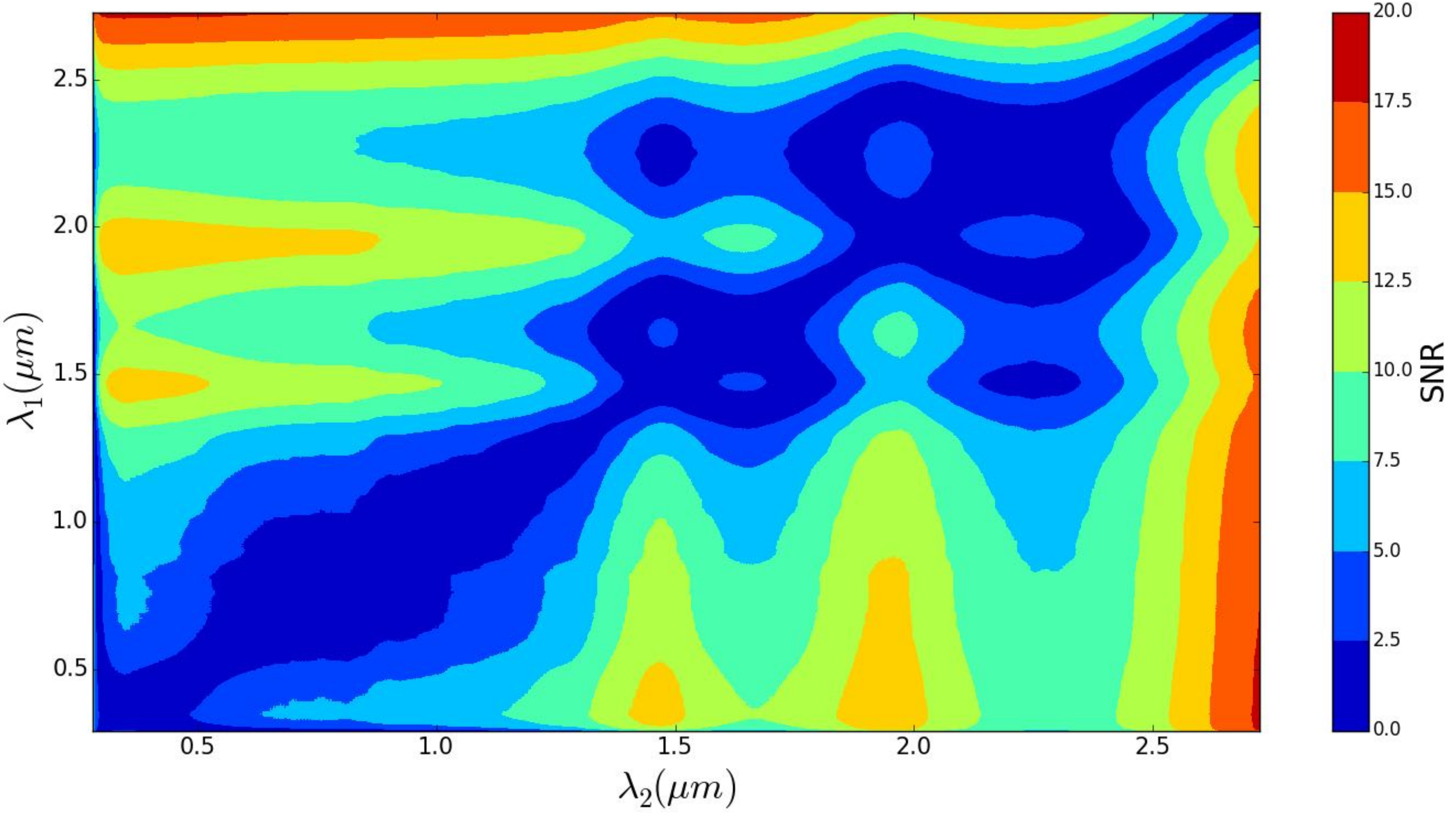
- Modelled direct images of Earth and Moon analog around α-Centauri
- Two Wavelengths of light: 0.35 μm on left and 2.69 μm on right
- Assumed 12 m space telescope with high definition coronagraphic capabilities and 24 hour exposure time– note we have used high sampling of psf for illustrative purposes

Parameters in signal to noise* ratio

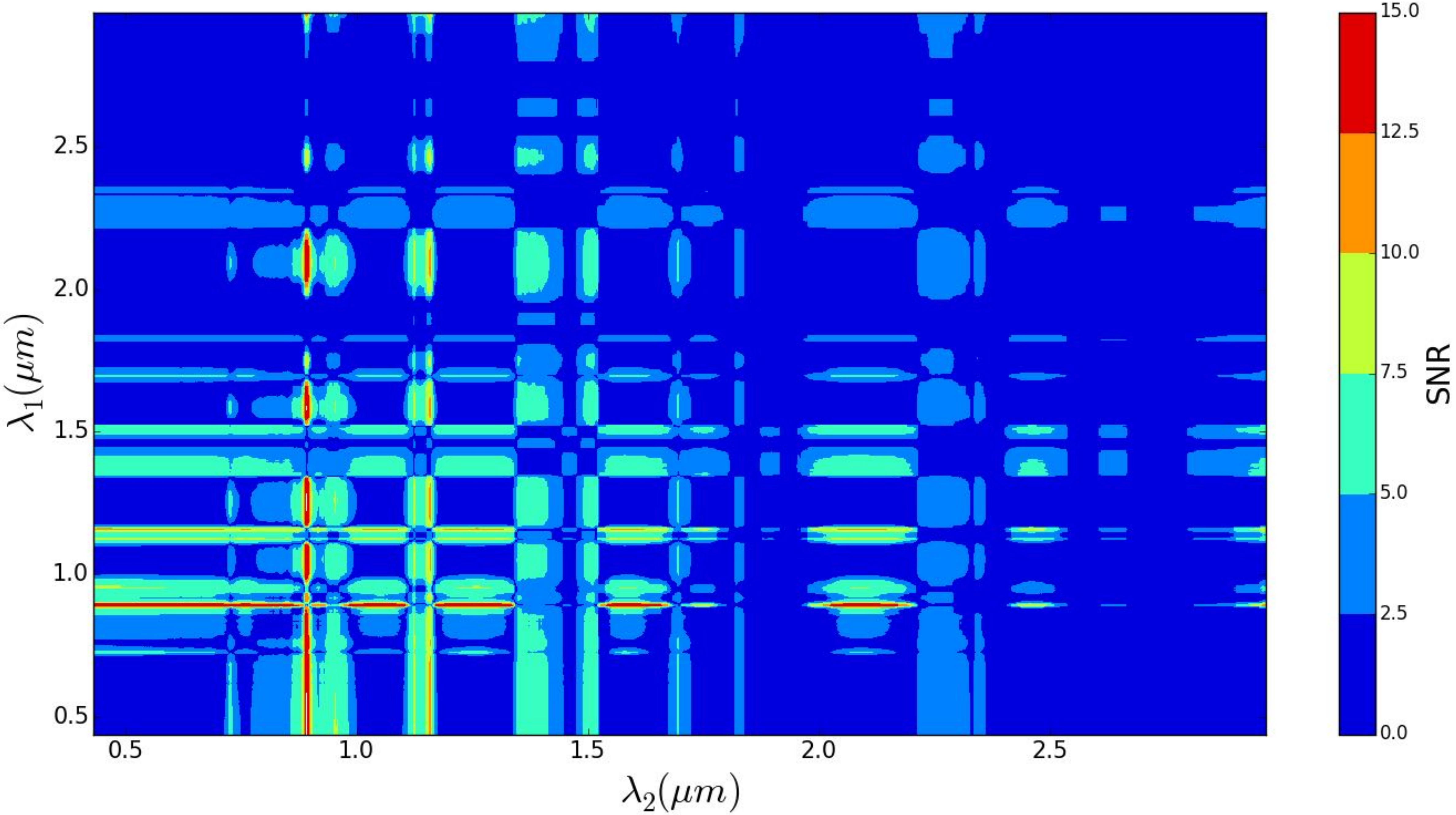
*assume noise dominated by photon counting and diffraction limit

- Exomoon and exoplanet **separation**
- **Distance** from observer (power of -2)
- Relative Fluxes of the two bodies & total flux – particularly the **moon**
- **Diameter** of telescope (power of 2)
- Exposure **time** (power of $-1/2$)

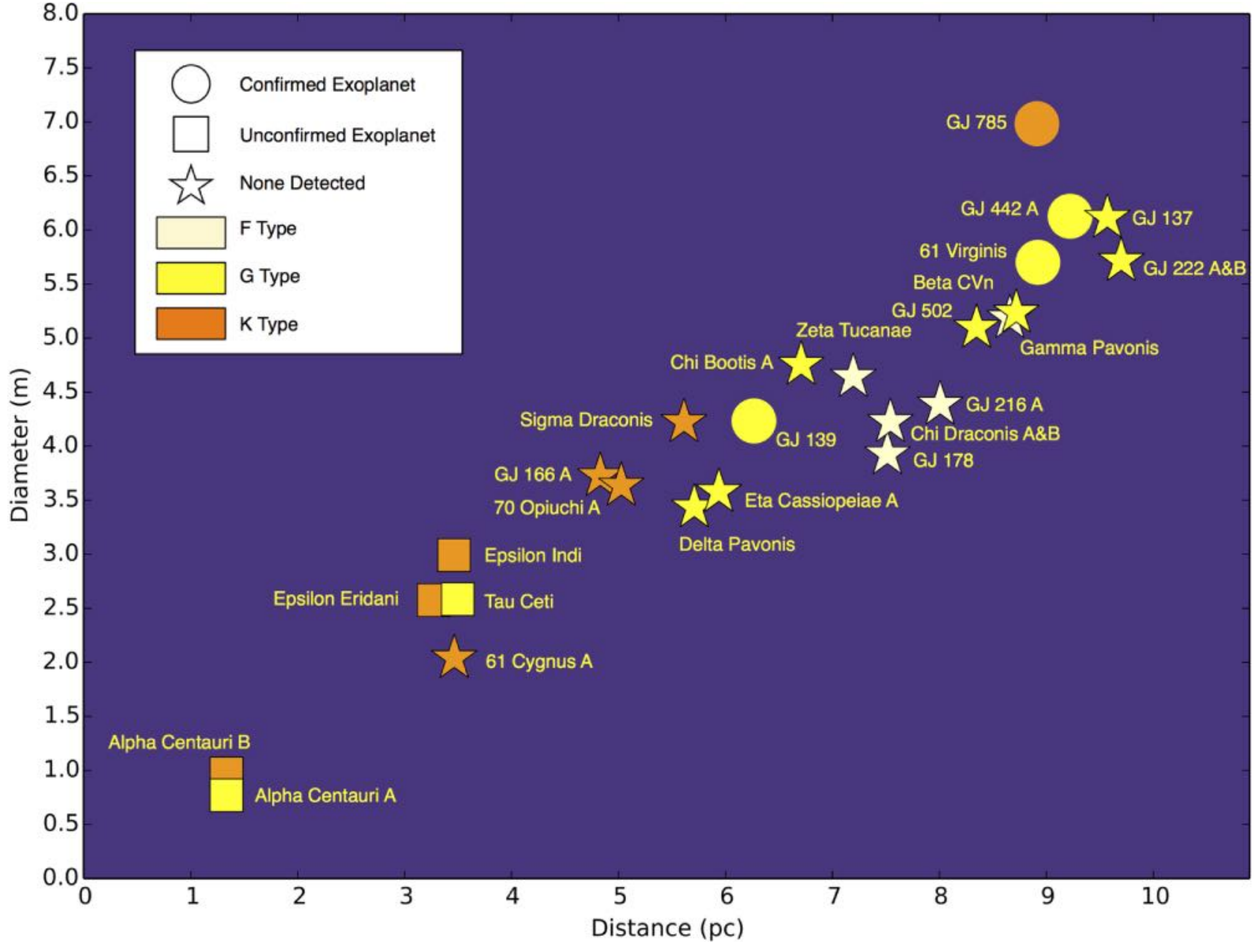
SNR for Earth & Moon Detection



SNR for Jovian & Earth Detection



S/N for HZ Jupiter/Earth



Spectroastrometry advantages

1). Planet & moon can be unresolved;

2). No reference source is required;

3). The orbital motion of the planet + moon drops out;

4). *Much* larger signal than planet centroid motion alone;

5). Repeats as moon orbits planet: unlikely to be covariant with systematic errors over a long period of time.

Spectral disentanglement

1). Identify wavelengths where Earth dominates & where Moon dominates;

2). Measure centroid as a function of wavelength (take out orbital motion for long-term integration);

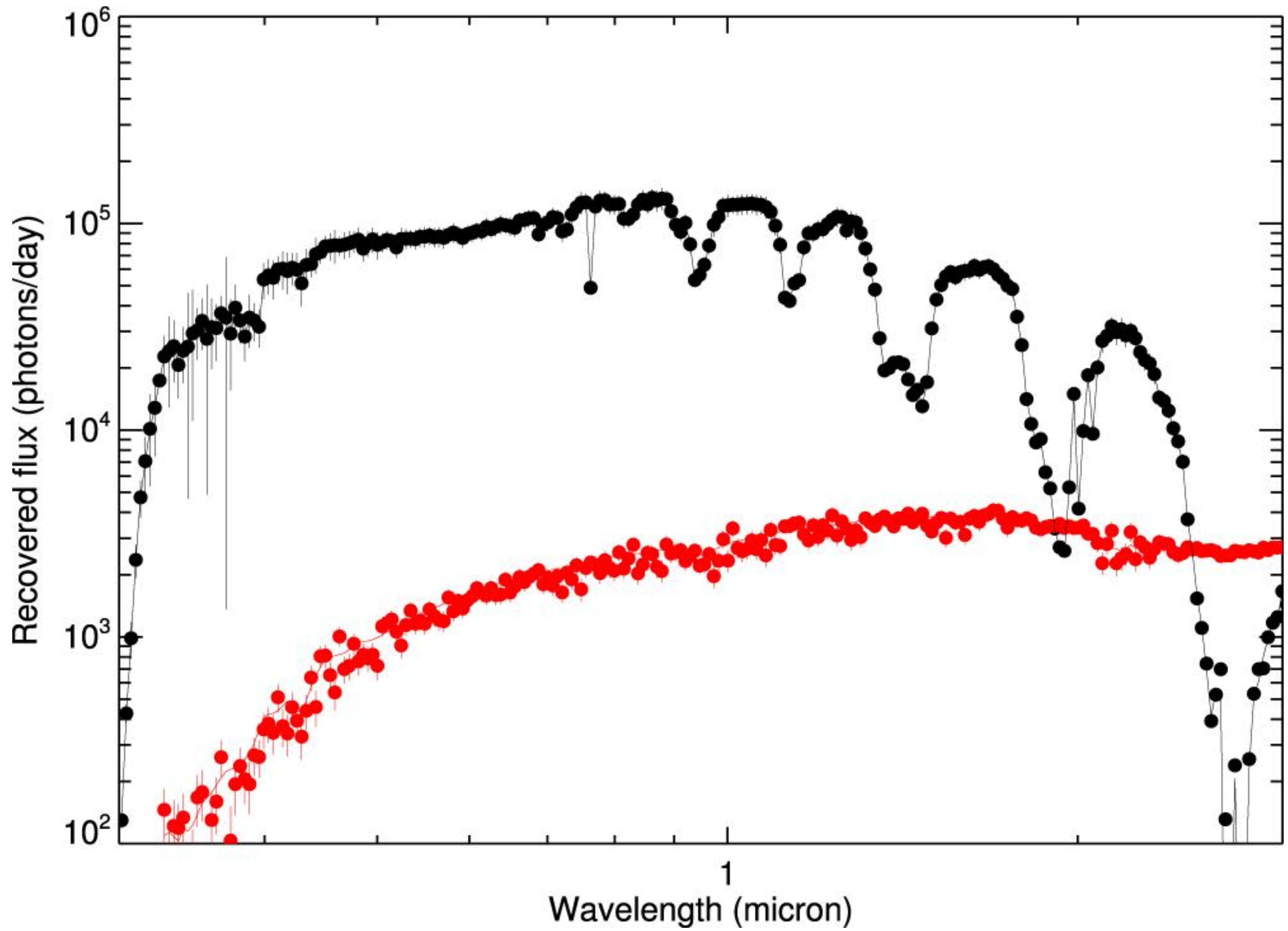
3). The fractional offset versus wavelength times the total flux gives the Moon’s spectrum.

Spectral disentanglement

Assumes: Earth-Moon twin at 1.3 pc (Alpha Centauri)

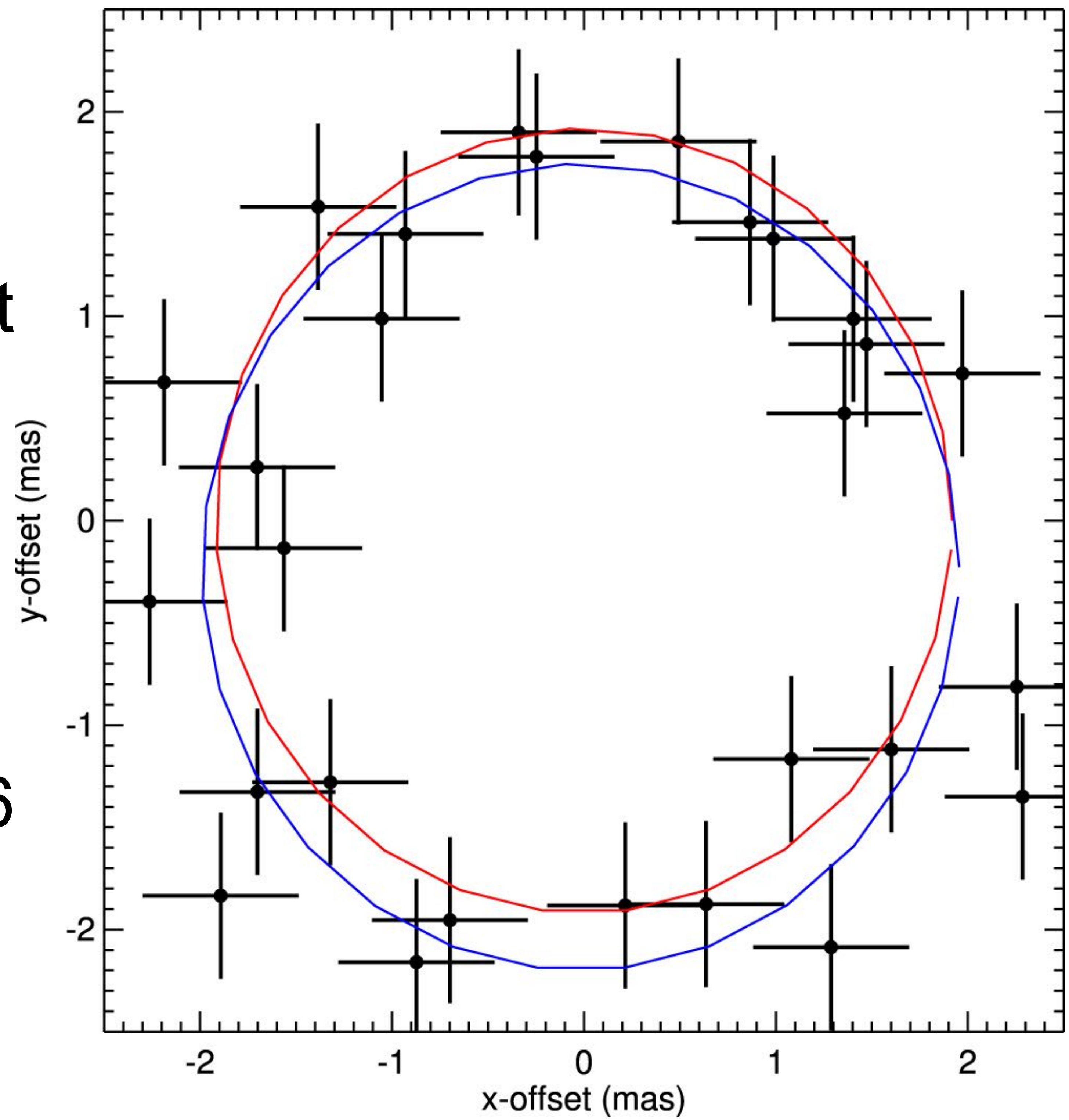
One month (!) integration; only photon-noise limited.

Extreme, idealized case!



Mass measurement

- Orbital motion of Moon with time gives orbital period;
- Spectroastrometric offset gives semi-major axis;
- Kepler's law gives sum of masses!
- Earth-Moon at 1.34 pc; centroid offset between 0.35 μm (Earth) and 2.76 μm (Moon);
- Poisson noise only: M=1.03±0.12 M♁.



Spectroastrometry requirements

1). Simultaneous spatial & spectral information: IFU? MKID?

2). Sufficient sampling of PSF;

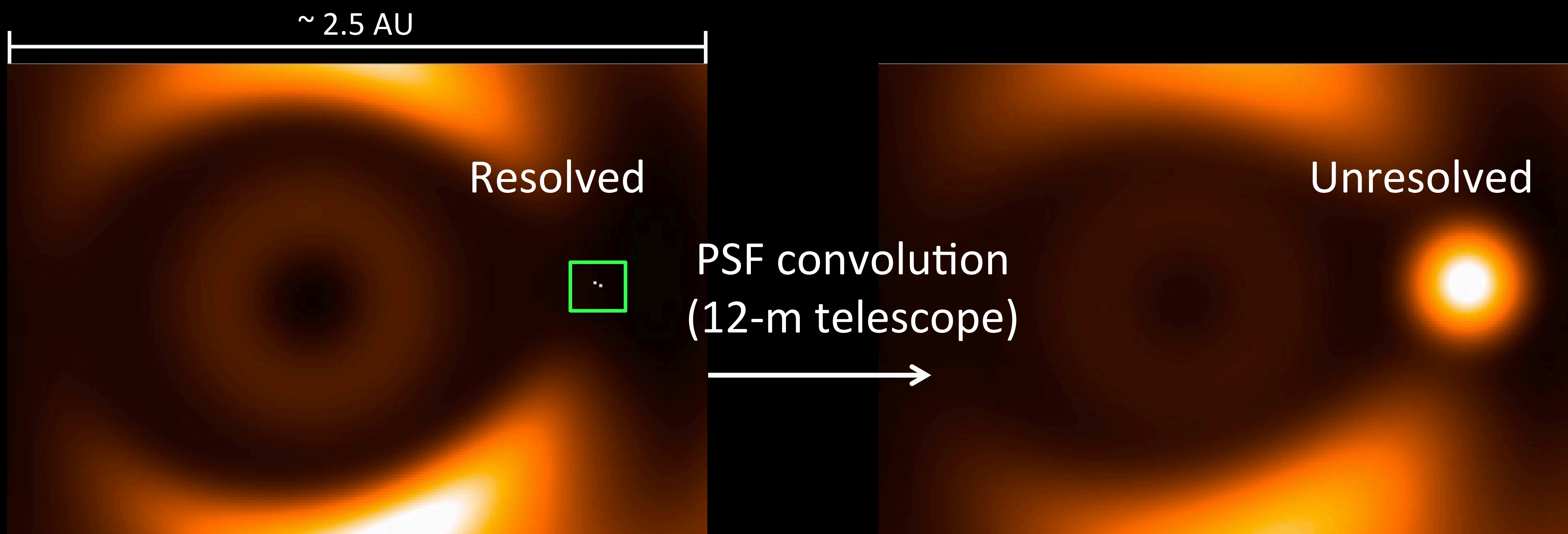
3). Precise control of PSF over range of longitudes;

4). Precise calibration of centroid over potentially ***wide*** range of wavelengths;

5). ~3 micron to cover water band;

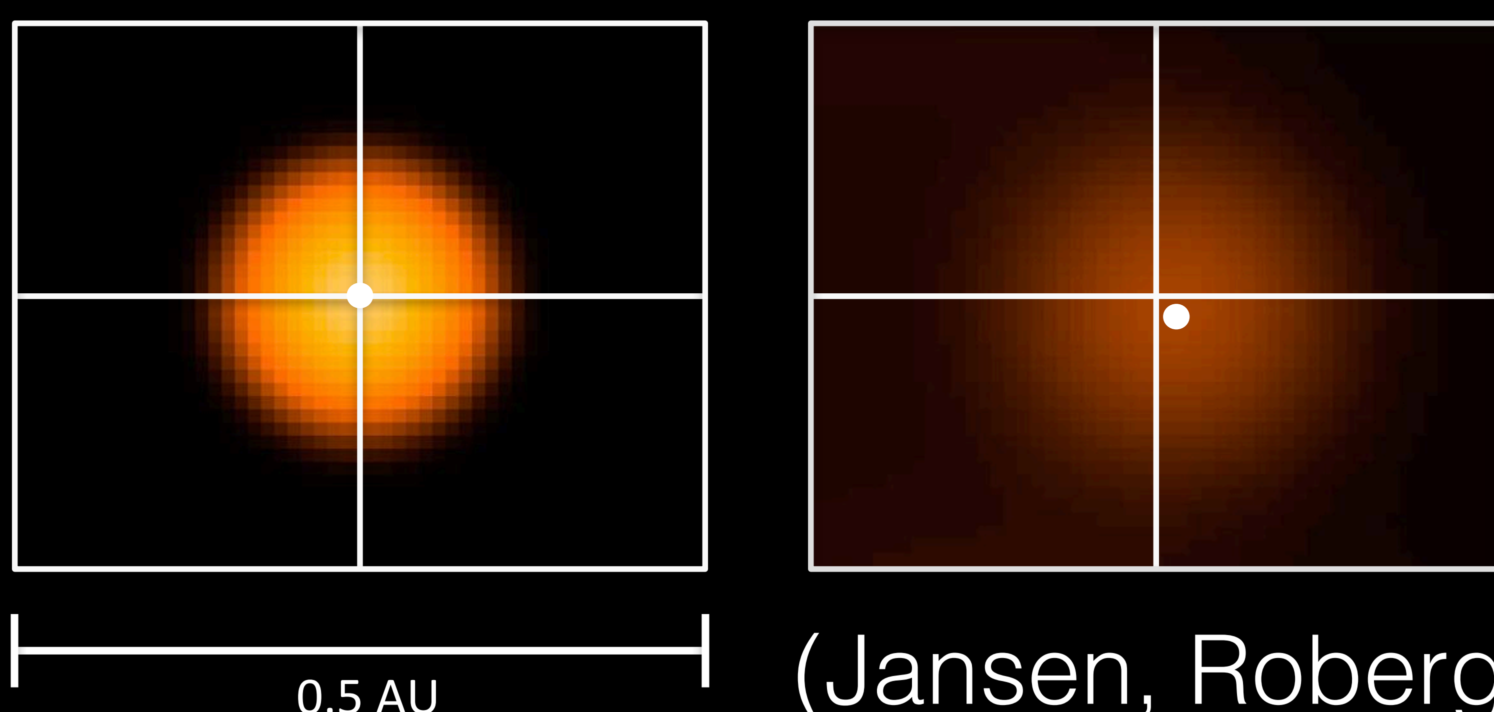
6). Higher contrast? Speckle control?

Preliminary Spectroastrometric Results



λ = 0.45 µm
(Jovian dominated)

λ = 0.89 µm
(moon dominated)



Presence of Earthlike moon produces centroid shift of 1.4 mas for system at 10 pc

(Jansen, Roberge, Stark, et al. in prep.)

Conclusions

- Spectroastrometry may be a means of detection & characterization binary planets/exomoons with direct imaging.
  - ➡ It may yield the moon's orbit & planet's mass.
  - ➡ It might allow for disentangling of spectra.
  - ➡ Forecast times of mutual events: measure size of planet/moon.
- More detailed study of the potential for this technique is warranted: effects of realistic noise model, exozodi, etc. (Haystacks!); different atmospheres, orbital configurations, stellar distances, multiple moons….