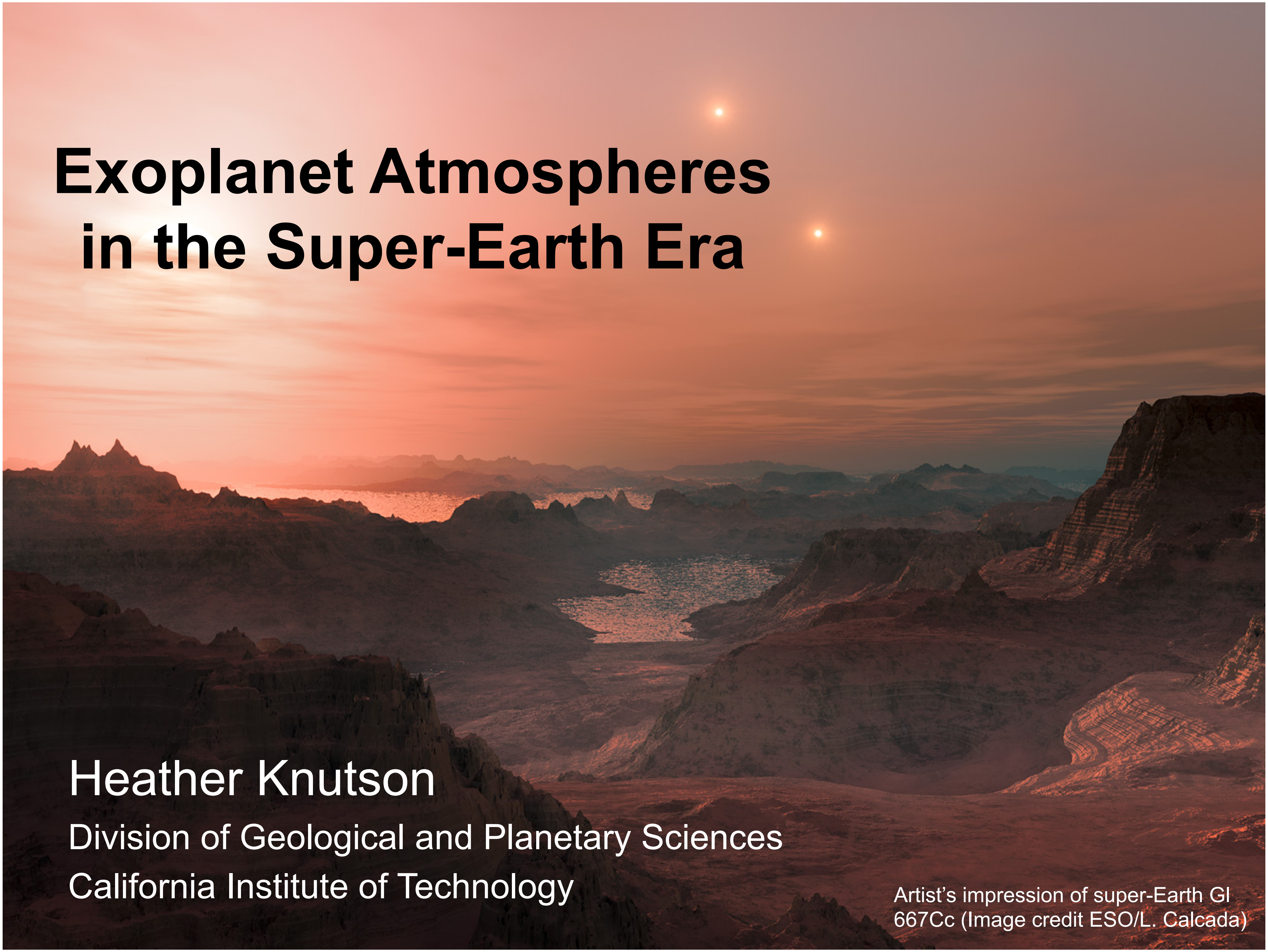

Exoplanet Atmospheres in the Super-Earth Era

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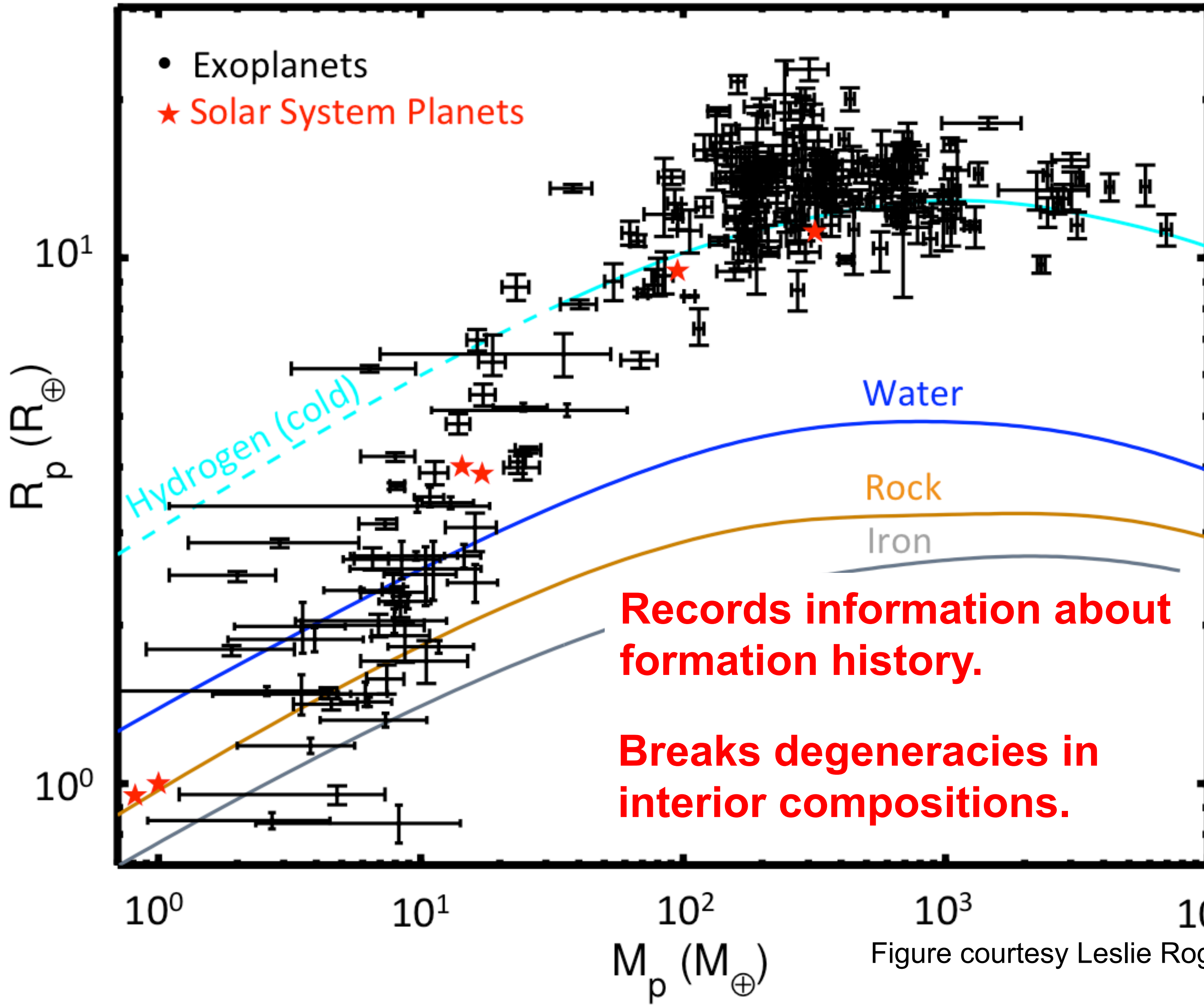
Division of Geological and Planetary Sciences

California Institute of Technology

Artist's impression of super-Earth Gl 667Cc (Image credit ESO/L. Calcada)

Why Study Small Planet Atmospheres?



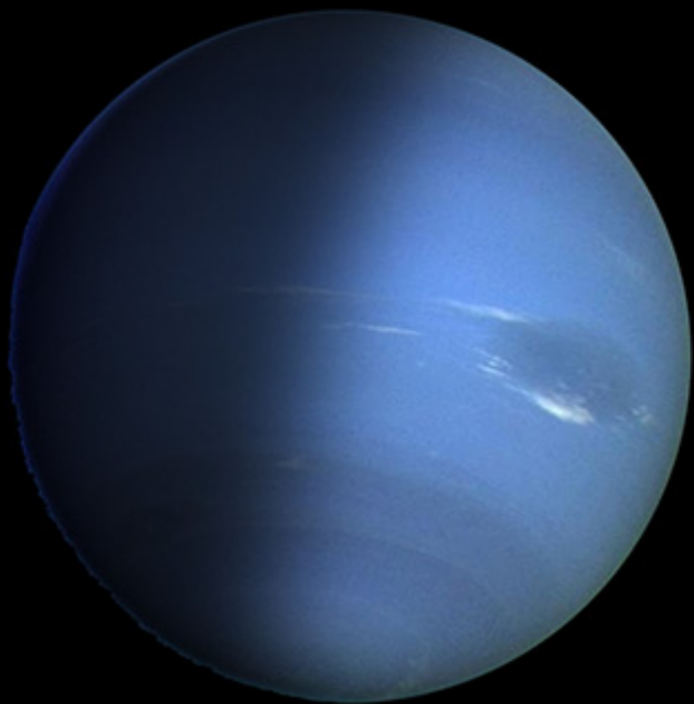
Records information about formation history.

Breaks degeneracies in interior compositions.

Figure courtesy Leslie Rogers

How Do Planets Acquire Their Atmospheres?

Gas Giants



Primordial: hydrogen-rich gas accreted directly from protoplanetary disk.

Super-Earths

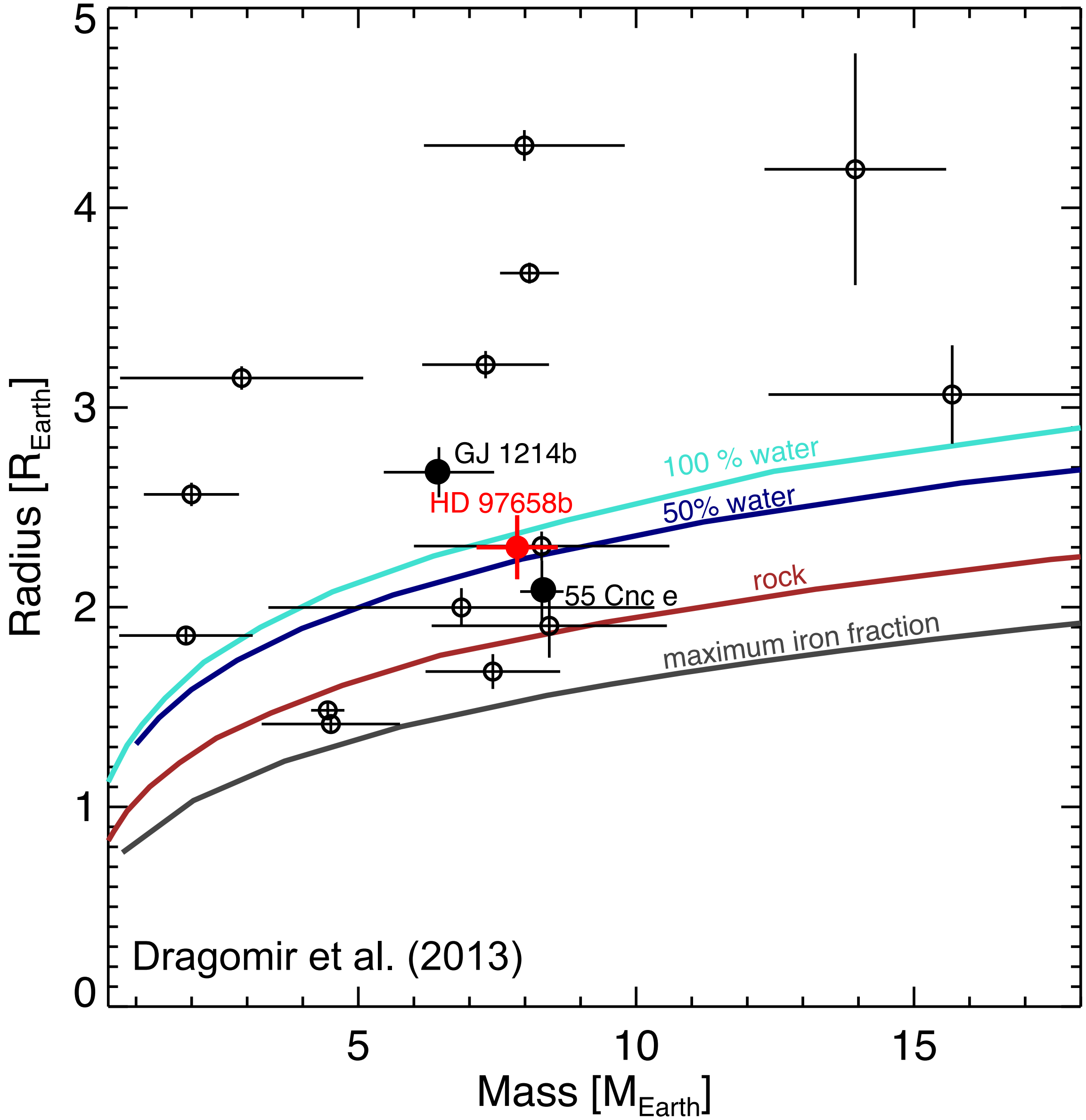
What happens at intermediate masses?

Terrestrial

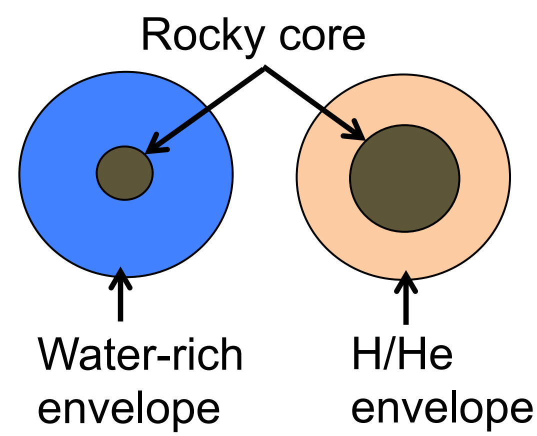
Outgassed: melting of solids releases gas into atmosphere.

Depletion of light elements

Breaking Degeneracies in Super-Earth Compositions



Caveat: the presence of thick atmospheres makes it difficult to **uniquely constrain** bulk compositions from mass and radius alone.

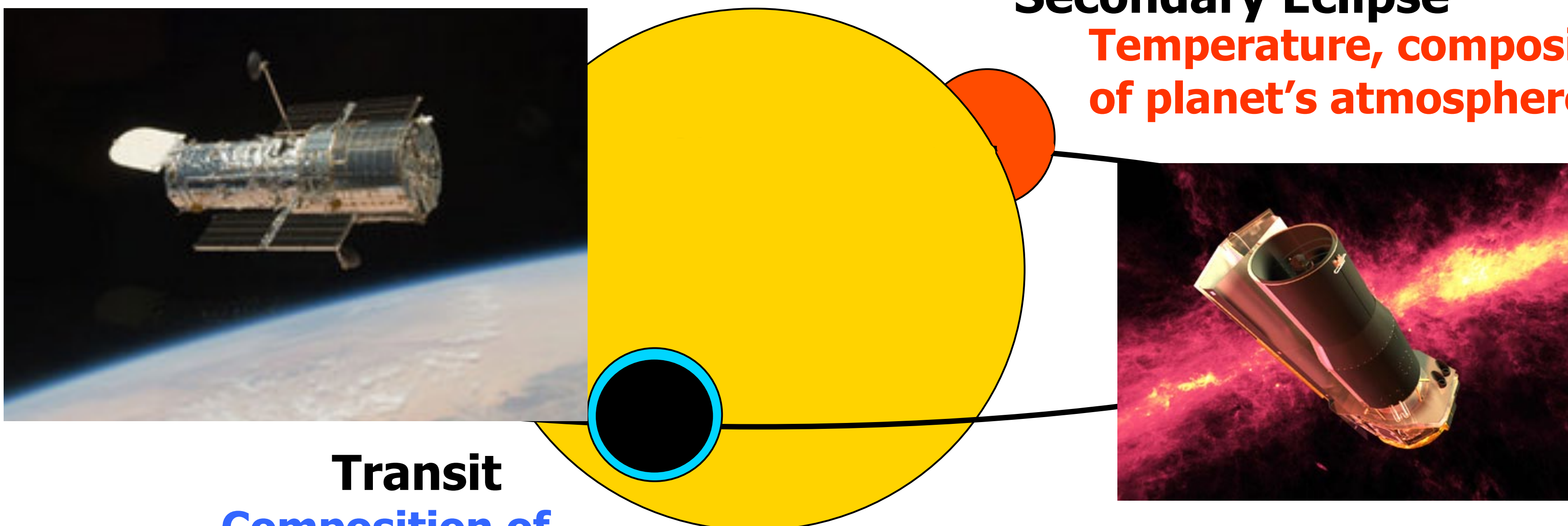


Water world (migrated from beyond ice line) **or rocky with a H/He envelope** (in situ formation)?

Transiting Planets as a Tool For Studying Planetary Atmospheres

Hubble Space Telescope
(Visible + near IR)

Secondary Eclipse
Temperature, composition of planet's atmosphere

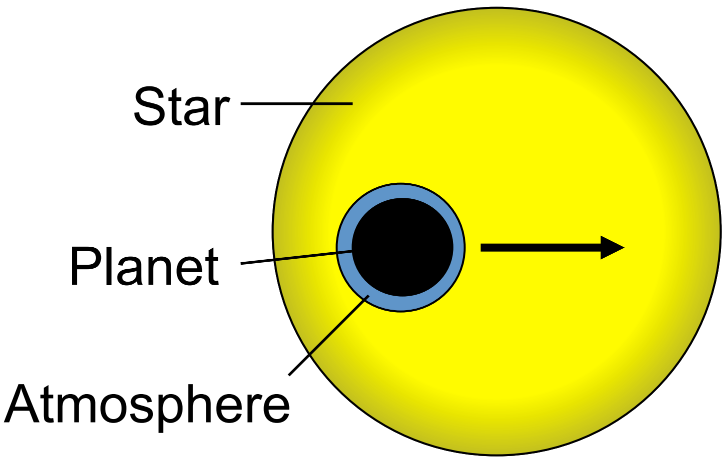


Transit
Composition of planet's atmosphere

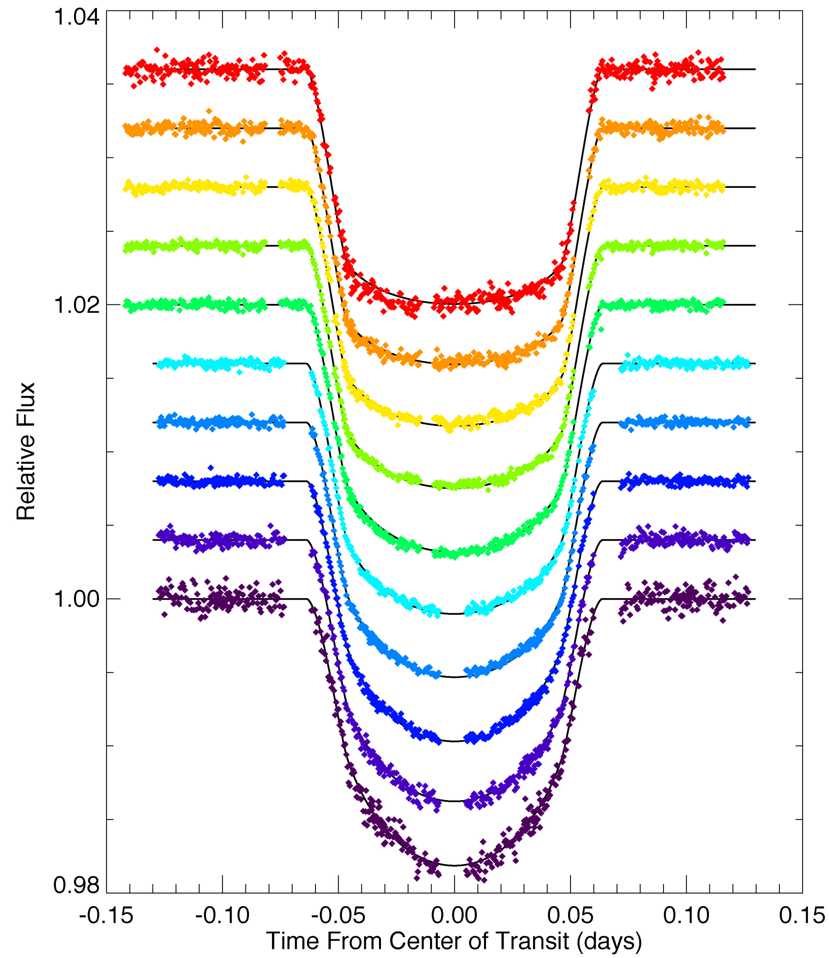
***Spitzer Space Telescope* (IR)**

If the planet is eclipsing, we can study the detailed properties of its atmosphere.

Transmission Spectroscopy as a Probe of Atmospheric Composition

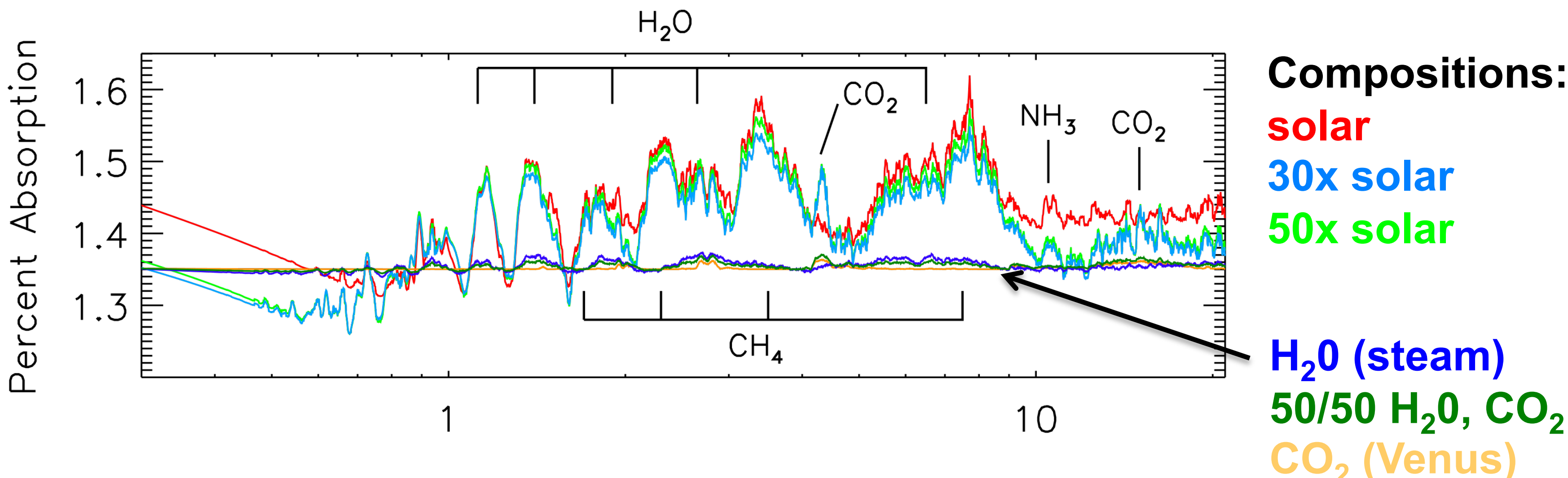


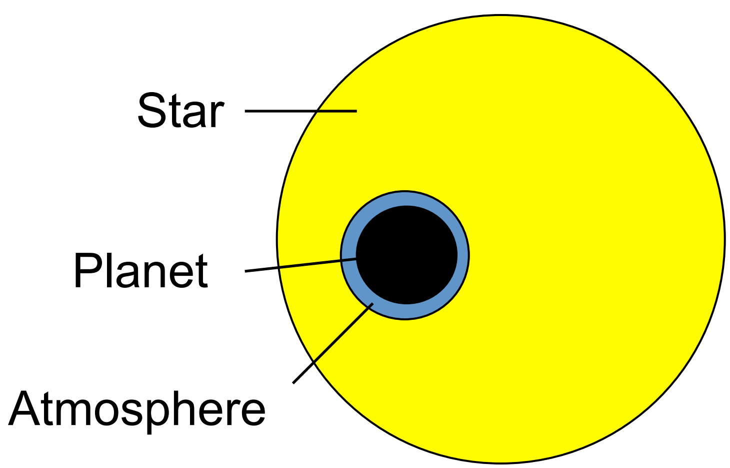
Wavelength-dependent transit depth tells us about composition of planet's atmosphere.



Hubble STIS transits of HD 209458b from 290-1030 nm (Knutson et al. 2007)

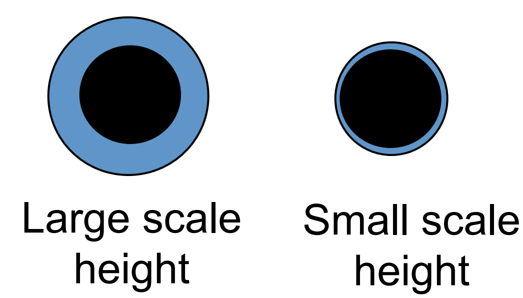
Constraining Atmospheric Hydrogen Fraction With Transmission Spectroscopy





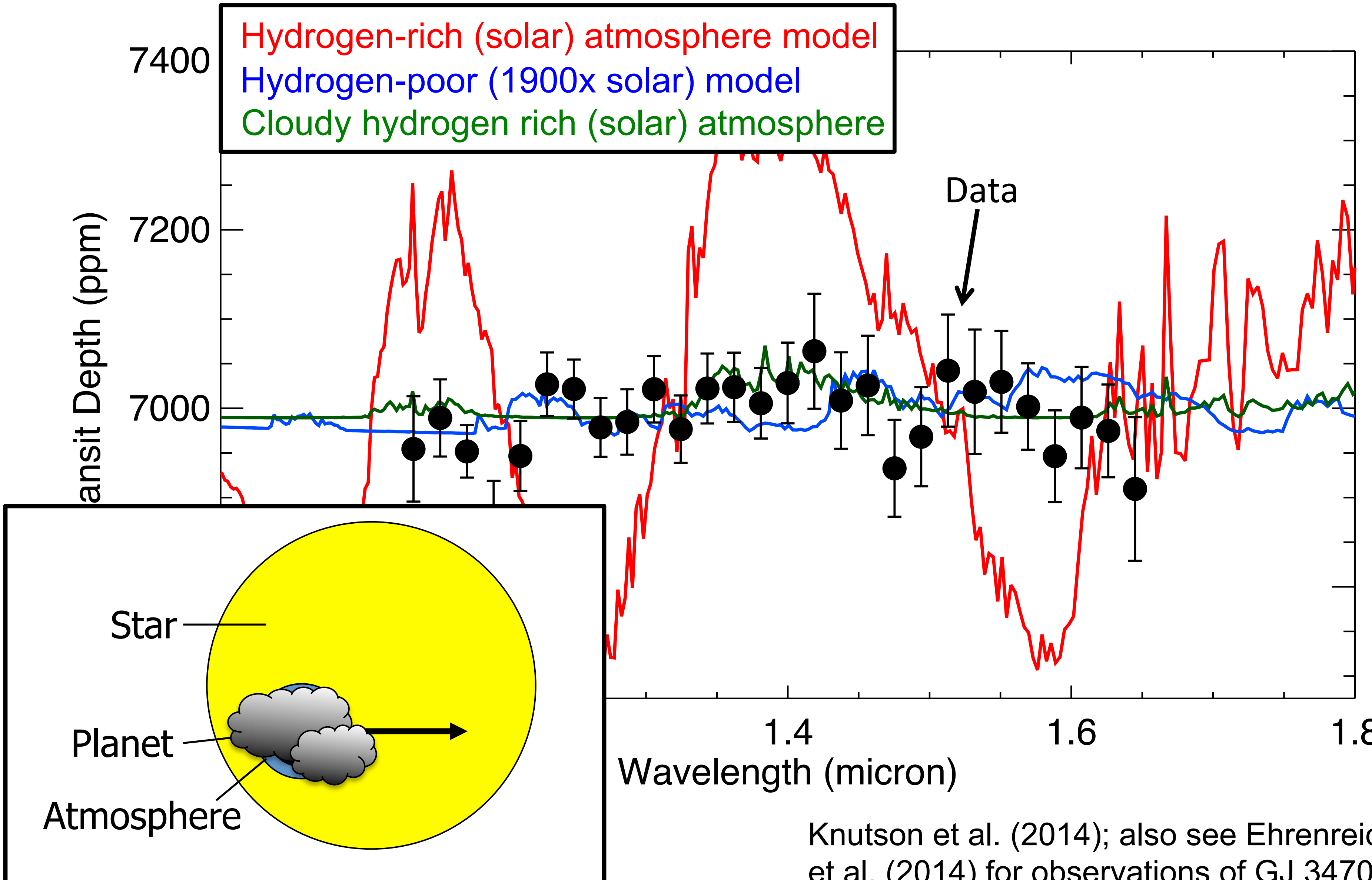
Scale Height

$$H = \frac{kT}{g\mu}$$



Miller-Ricci & Fortney (2010)

A *Hubble Space Telescope* Transmission Spectrum for Warm Neptune GJ 436b



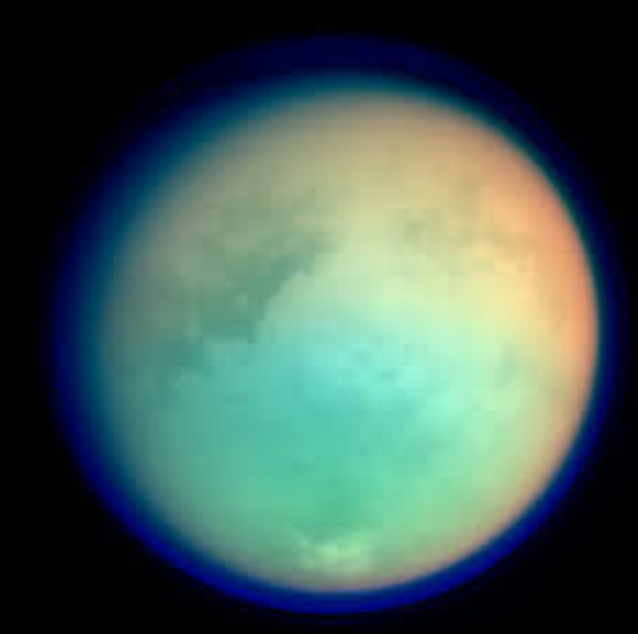
Knutson et al. (2014); also see Ehrenreich et al. (2014) for observations of GJ 3470b

What Might Form Clouds on GJ 436b?

Condensate clouds like
the Earth?

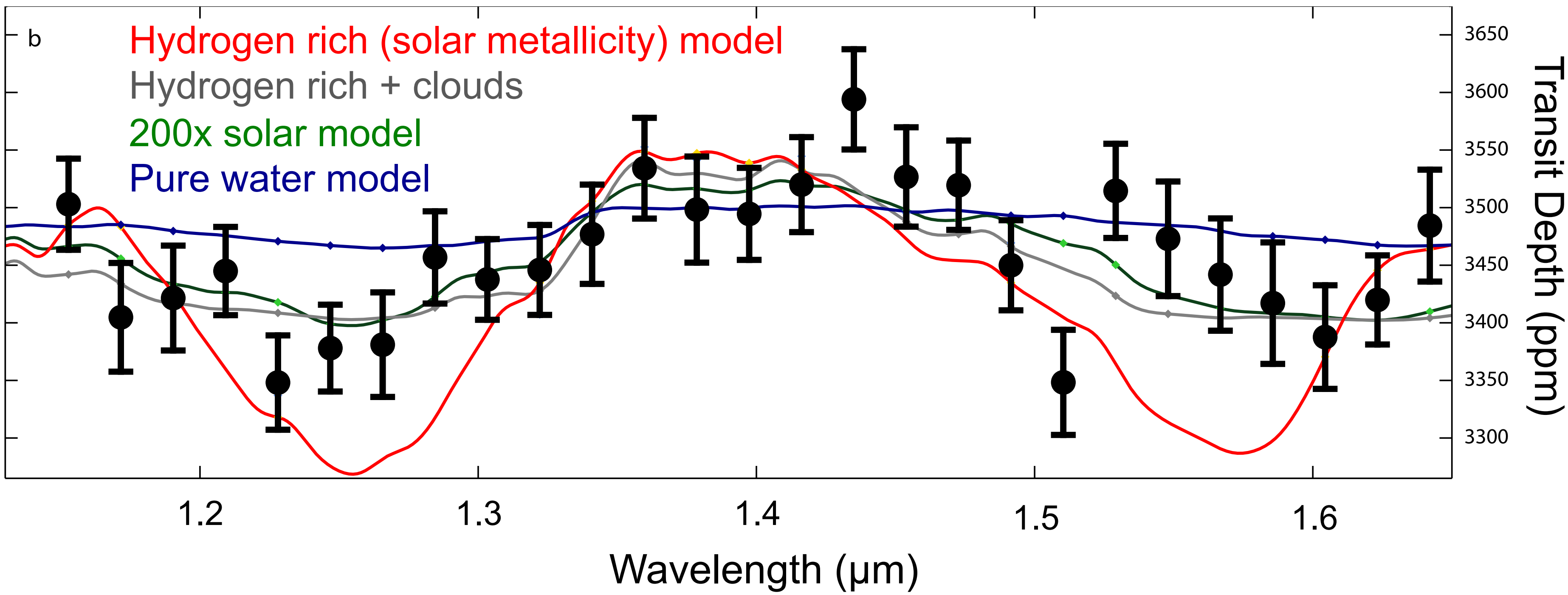
Zinc sulfide or potassium
chloride (Morley et al. 2013)

Photochemical hazes
like Titan?



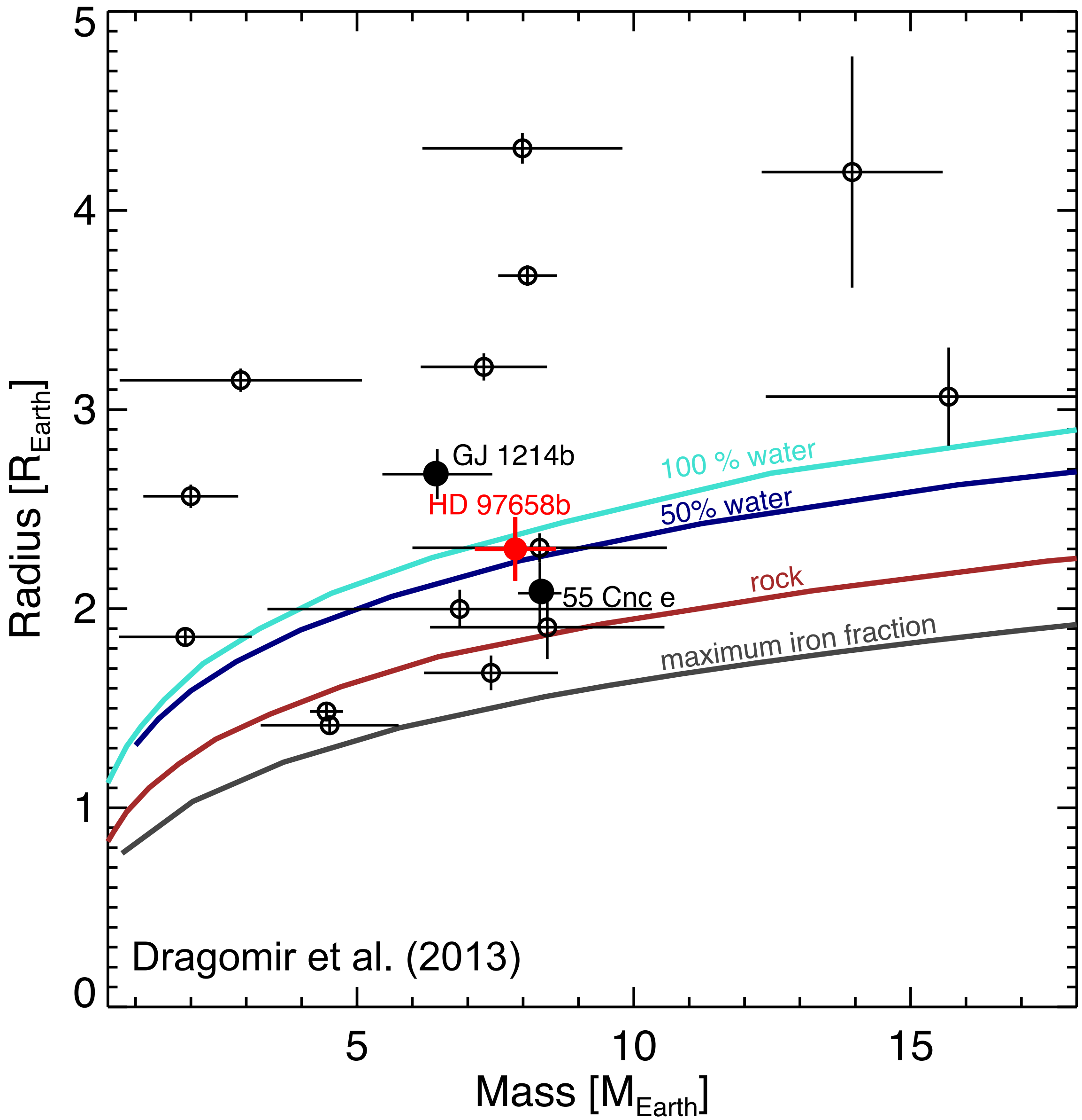
Photochemistry converts methane
to “soot” (long hydrocarbon chains)

(Relatively) Clear Skies and Water Vapor on Warm Neptune HAT-P-11b

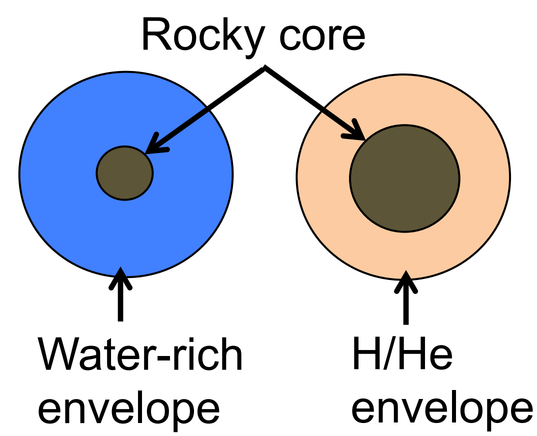


Detection of water absorption places **upper limit** on atmospheric metallicity (Fraine et al. 2014)

Next Up: Super-Earths

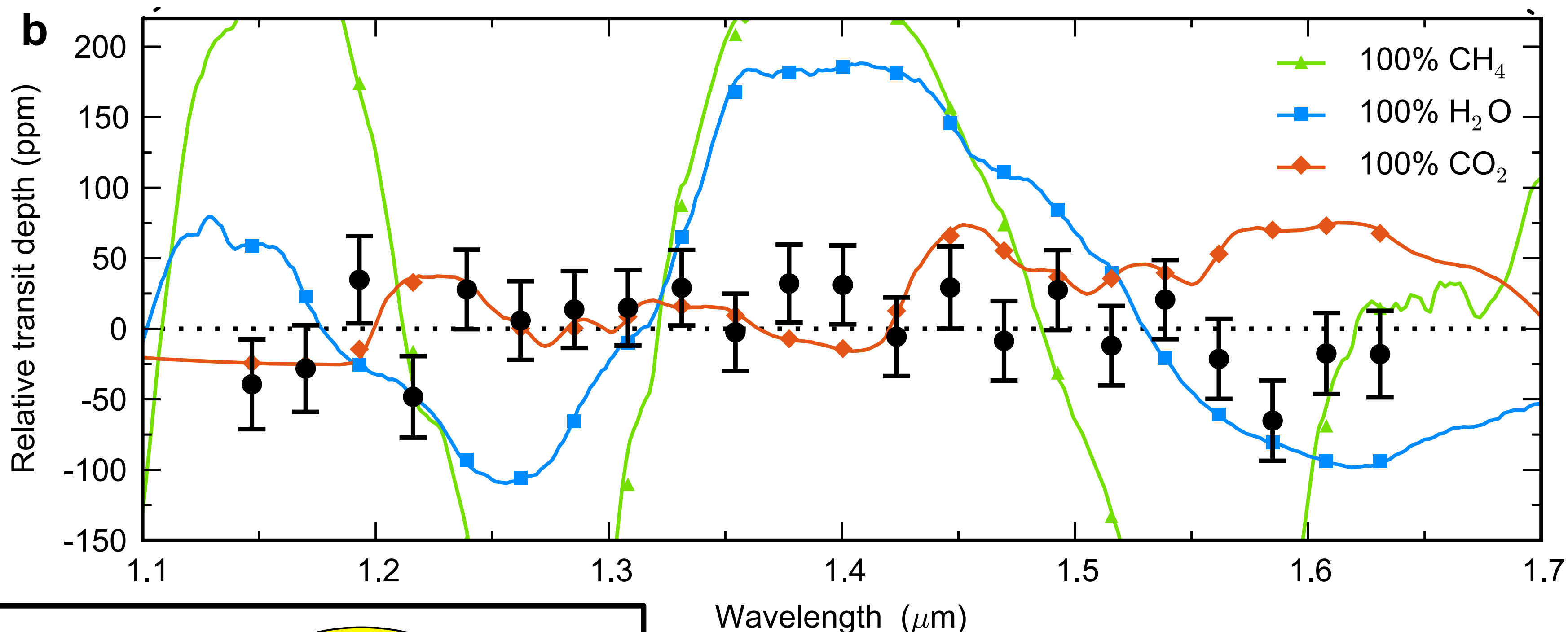


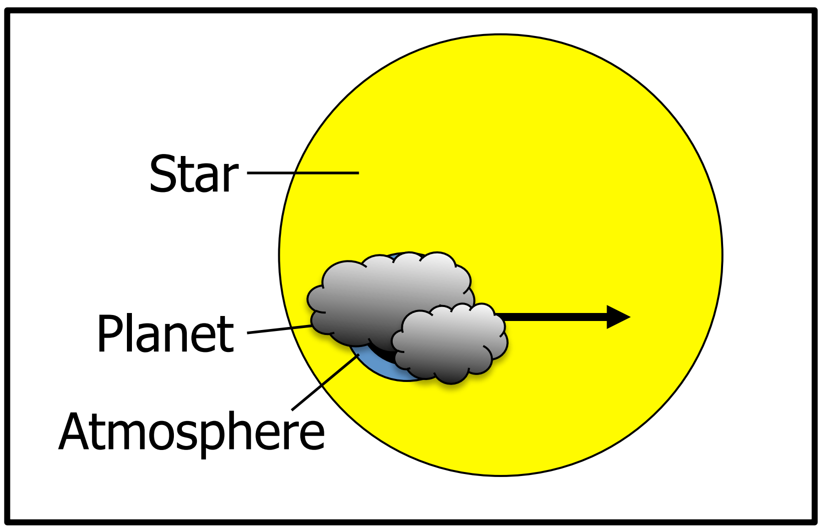
Caveat: the presence of thick atmospheres makes it difficult to **uniquely constrain** bulk compositions from mass and radius alone.



Water world (migrated from beyond ice line) **or rocky with a H/He envelope** (in situ formation)?

HST Observations of Super-Earth GJ 1214b

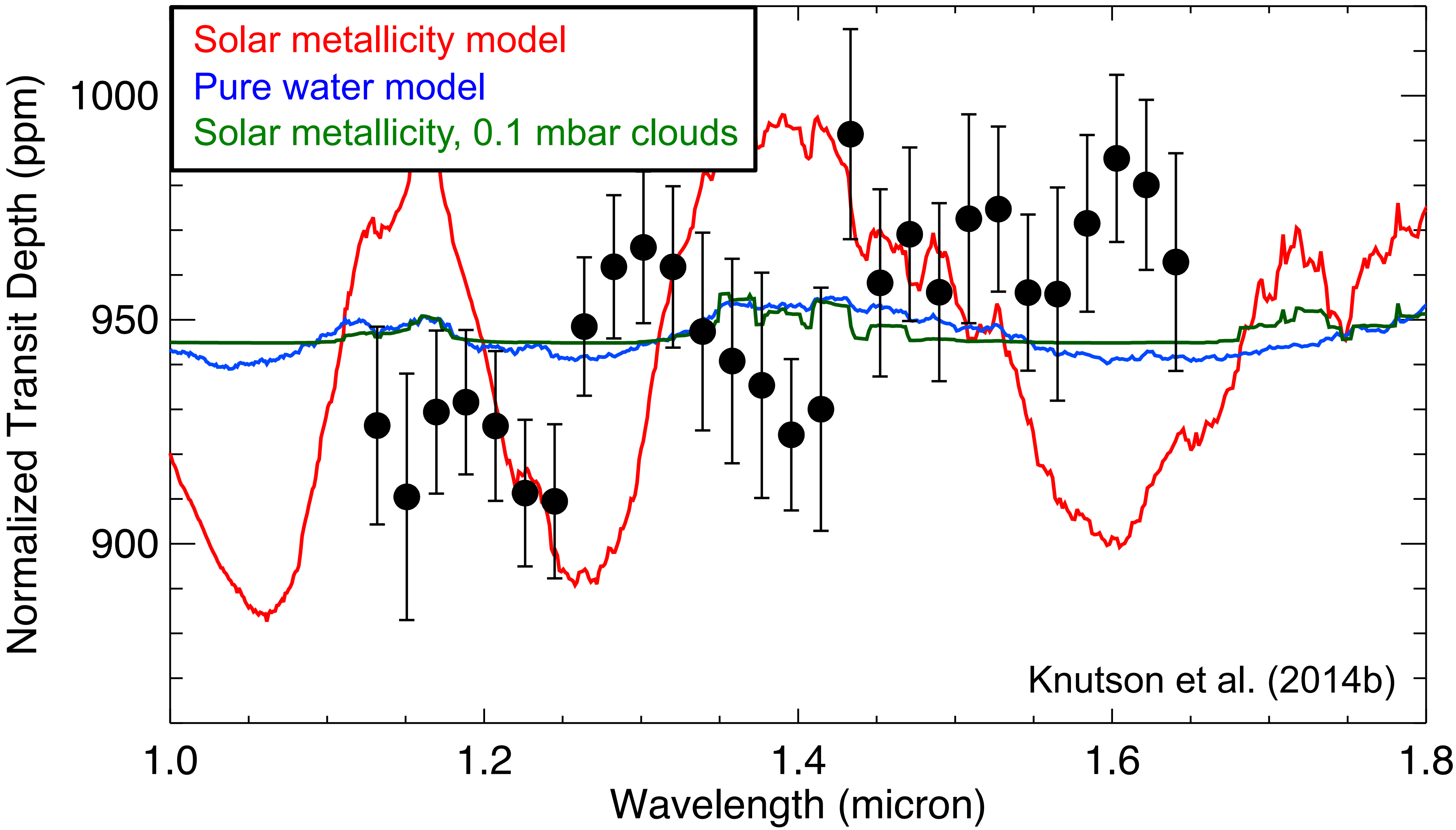




Even metal-rich atmospheres would have been detectible, planet **must have clouds** regardless of composition. Could have same composition as clouds on GJ 436b.

Kreidberg et al. (2014), Berta et al. (2012)

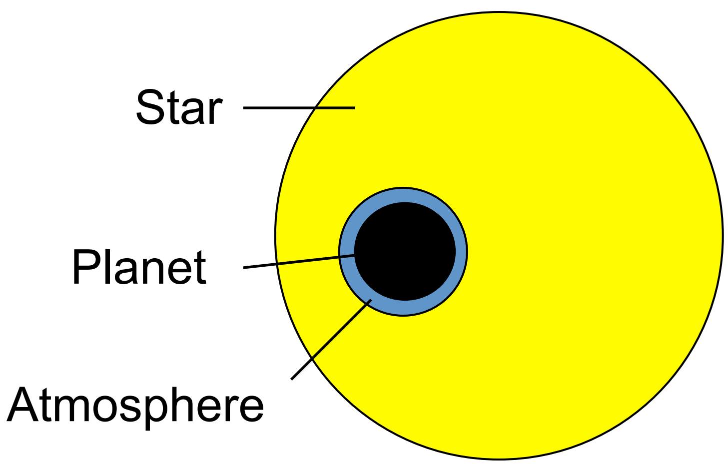
HST Observations of Super-Earth HD 97658b



New frontiers for HST: Precision of 20 ppm with two transits vs 30 ppm with 12 transits for GJ 1214b.

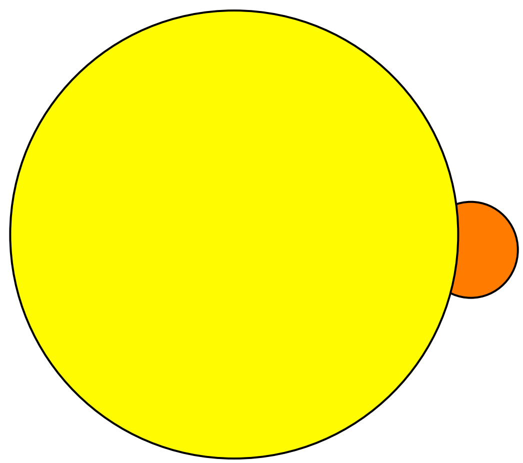
Exoplanet Meteorology: Optical Wavelengths Provide New Clues for Cloud Composition

Transmission spectroscopy can constrain **location and particle sizes** for cloud layers.



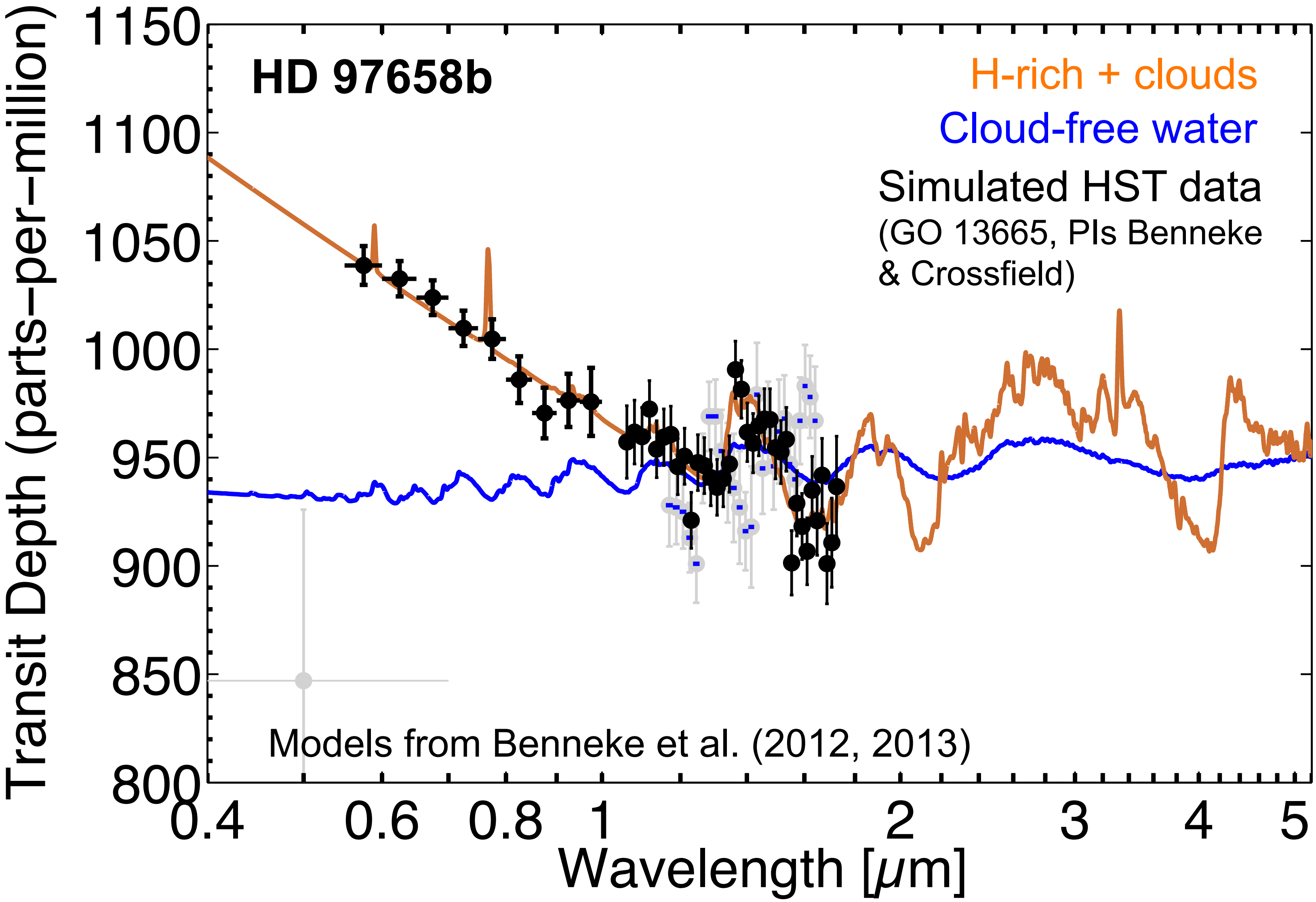
Wavelength dependence of scattering scales with particle size.

Measurements of secondary eclipse can constrain **cloud albedos.**

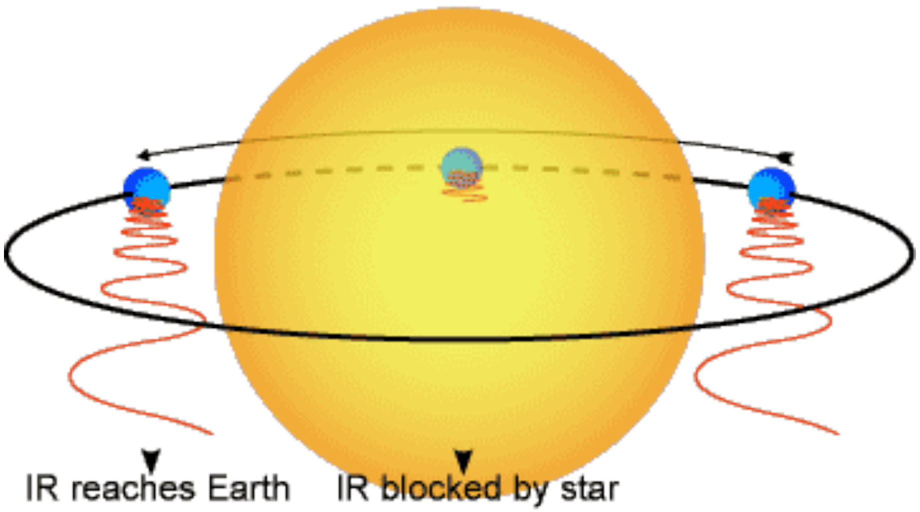


Reflected light “color” constrains composition of cloud particles.

Optical Spectroscopy Can Break Degeneracy Between Clouds and H-Poor Atmosphere for Super-Earths

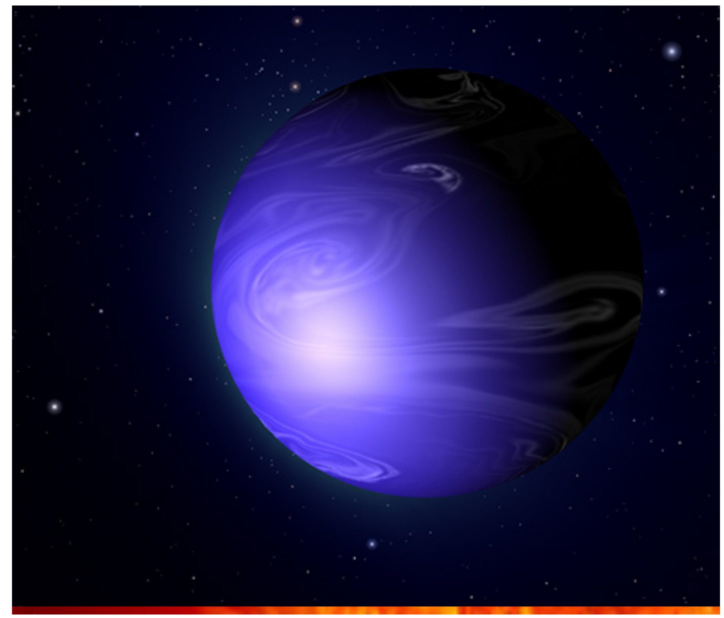


Proof of Concept for Albedo Measurements: Reflected Light Spectrum for a Hot Jupiter



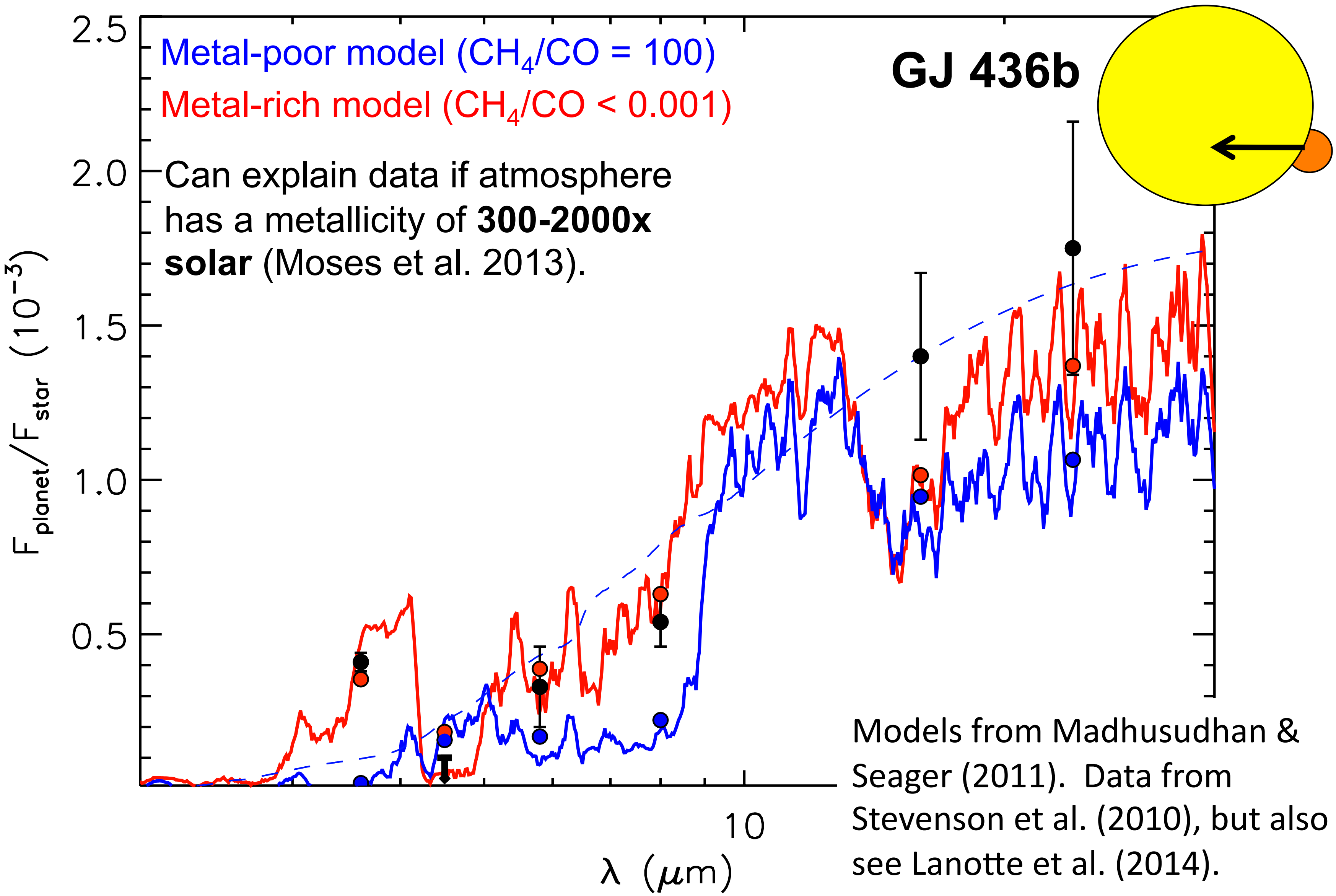
Measure secondary eclipse at optical wavelengths for hot Jupiter HD 189733 with HST/STIS.

HD 189733b is blue!



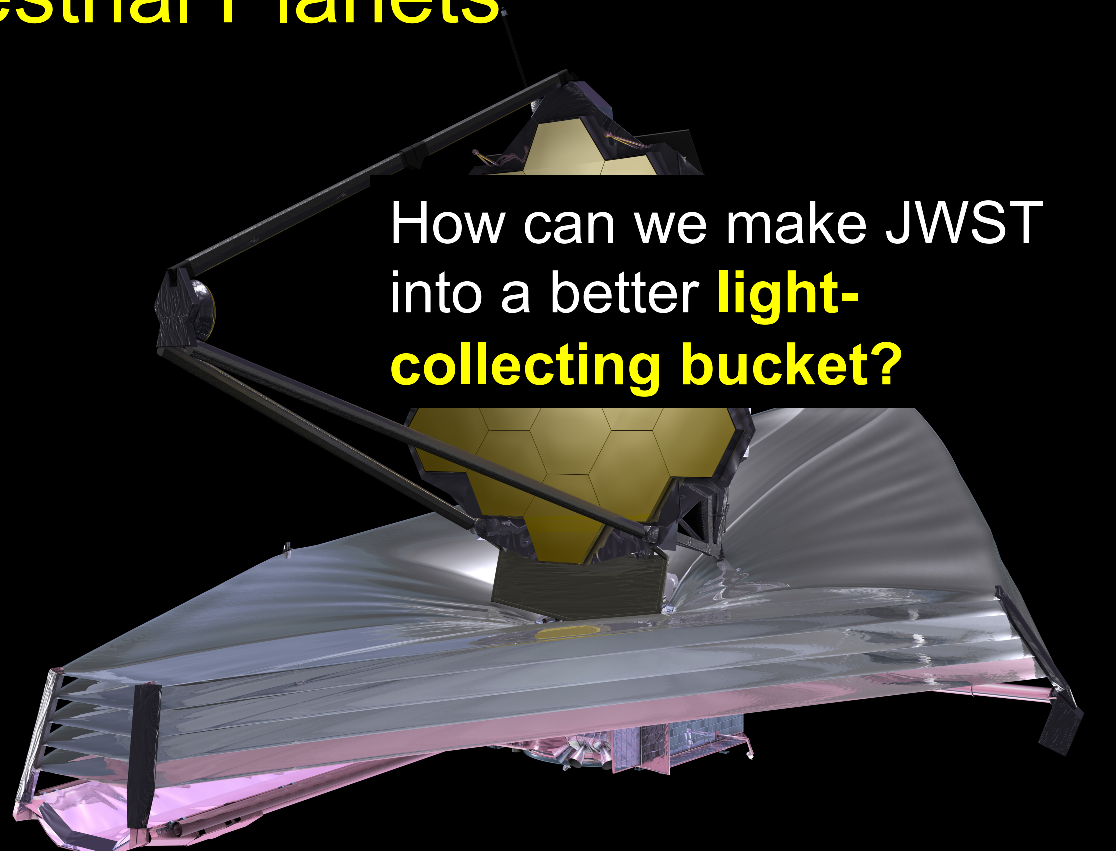
Albedo is largest at short wavelengths (Evans et al. 2013). This may be related to the **presence of clouds** (silicate?) detected via transmission spectroscopy.

Can we use emission spectroscopy to see through clouds at infrared wavelengths?



Models from Madhusudhan & Seager (2011). Data from Stevenson et al. (2010), but also see Lanotte et al. (2014).

Pushing Towards Atmosphere Studies of Terrestrial Planets

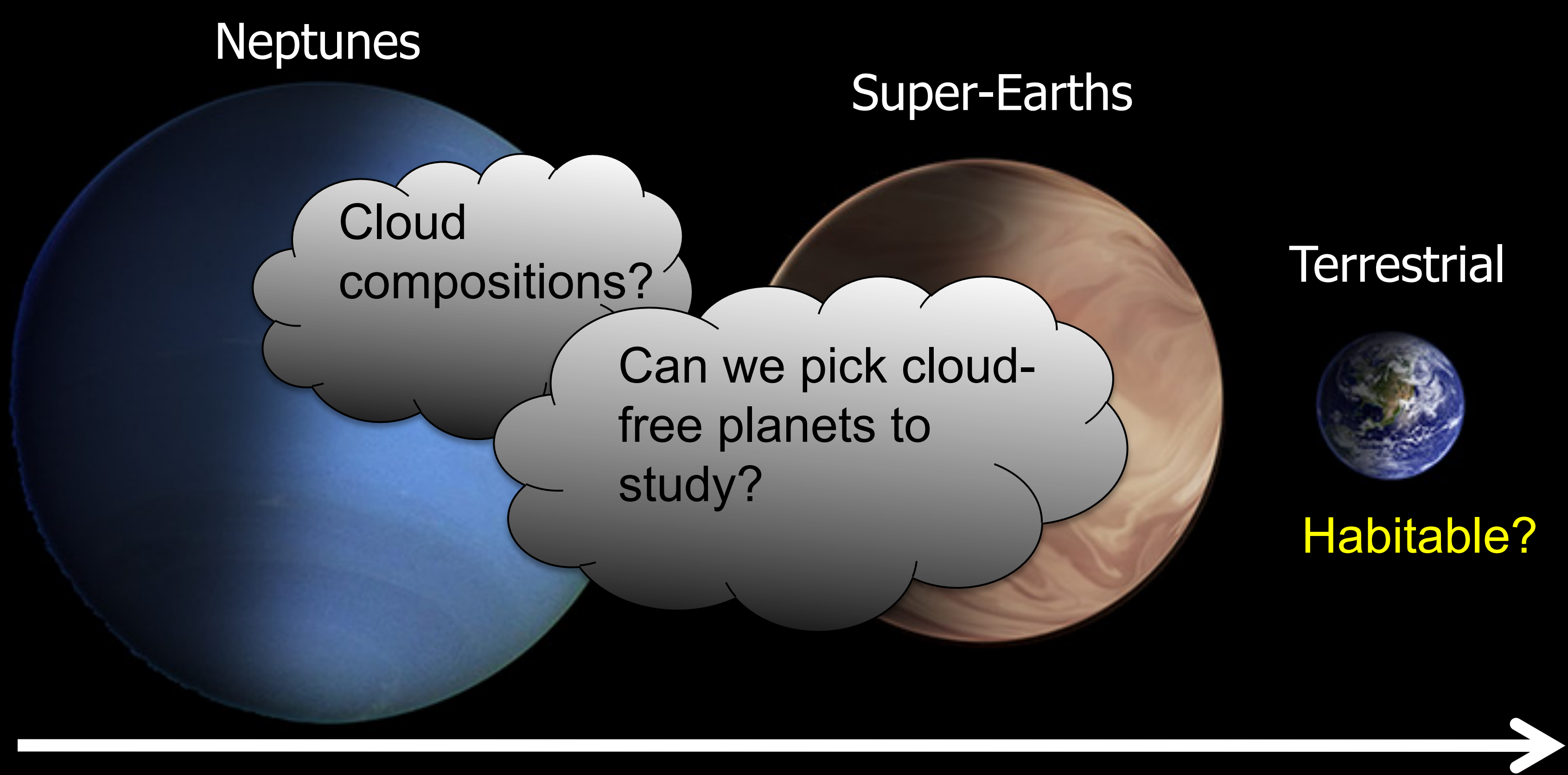


How can we make JWST into a better **light-collecting bucket?**

There are currently only a handf of small planets transiting bright, nearby stars. **K2** (now) and **TESS** (2017) will change this.

The **James Webb Space Telescope** (2018) will allow us to characterize even smaller and cooler planets (mainly around low-mass stars).

Conclusion: What Can We Learn From Atmosphere Studies of Small Planets?



Primordial or outgassed atmosphere? Loss of light elements?

Breaking degeneracies in interior composition. Formation in situ or beyond ice line?

Planets drawn to scale.