What Do We Want to See? Water Worlds and Rocky Planet Atmospheres

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Sagan Workshop
Imaging Planets & Disks
July 25, 2014

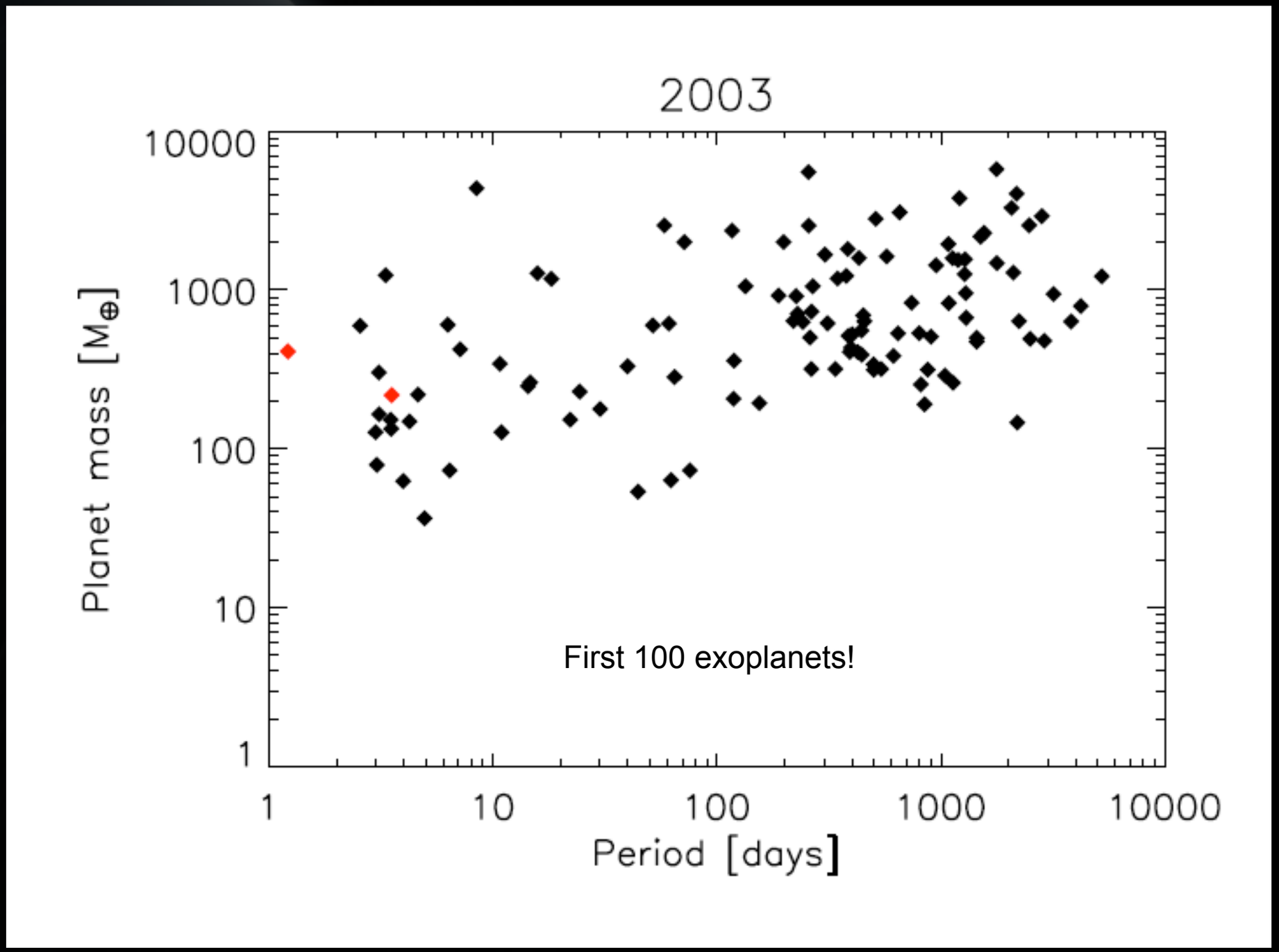
Image Credit: Paul A. Kempton

Outline

- Super-Earths – Their Formation and Their Interiors
- Super-Earths – Their Atmospheres (What have we seen so far?)
- Lessons learned for direct imaging

Improved observational equipment and techniques over the recent years have revealed a large population of low-mass exoplanets

- Radial Velocity
- Transit
- Microlensing
- Solar System



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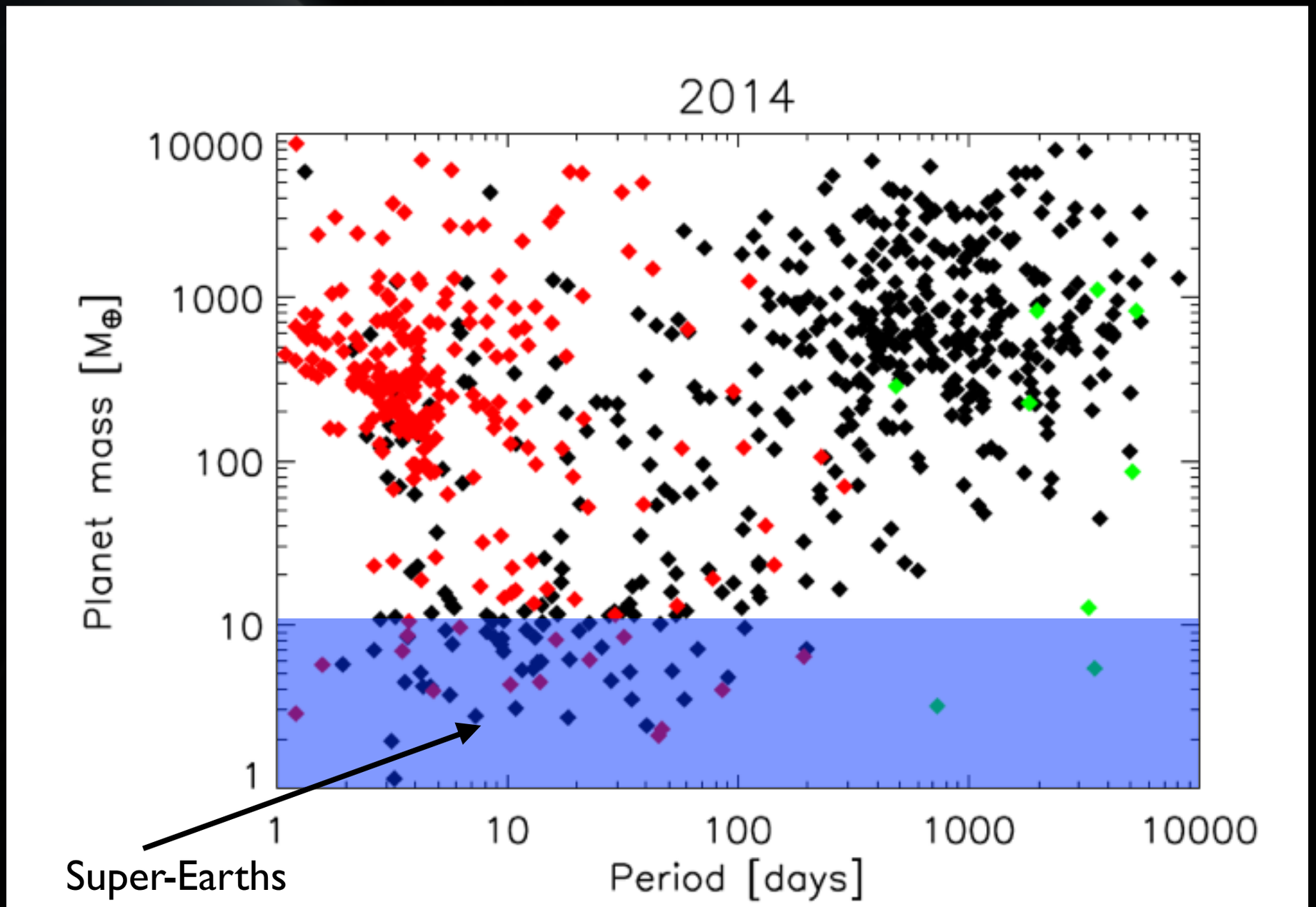
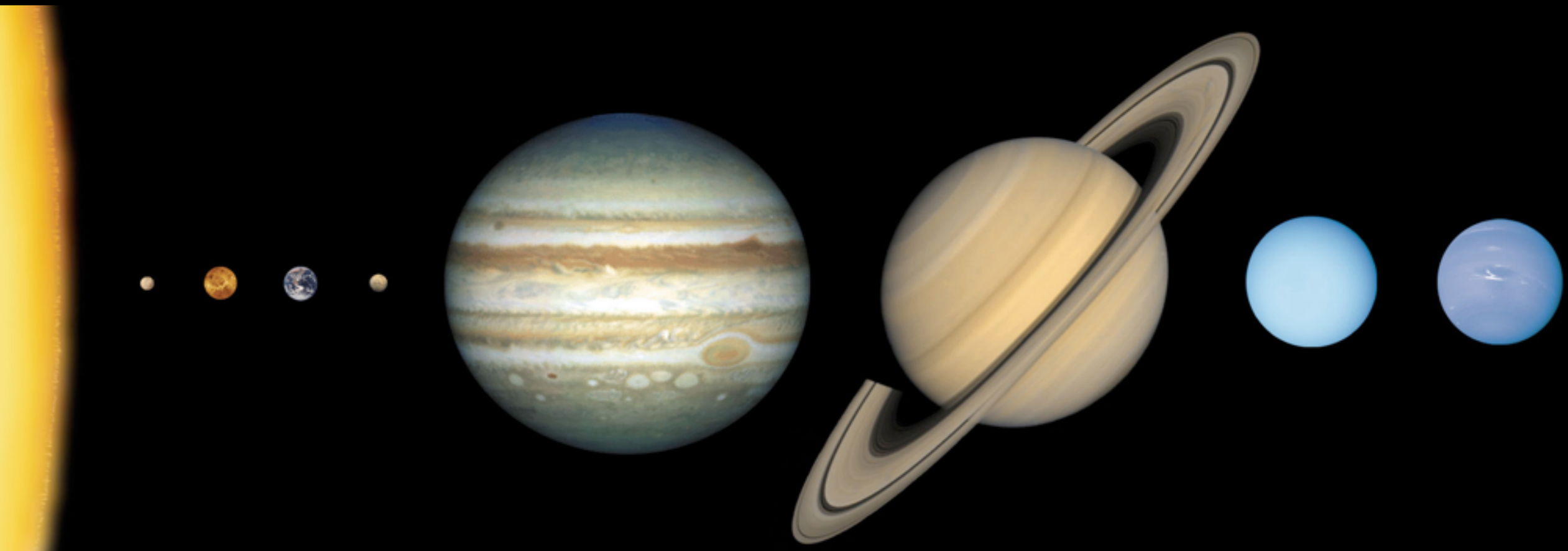


Super-Earths – Bridging the Gap



Super-Earths are a fundamentally new class of planets,
not present in our solar system

A more typical solar system, perhaps?

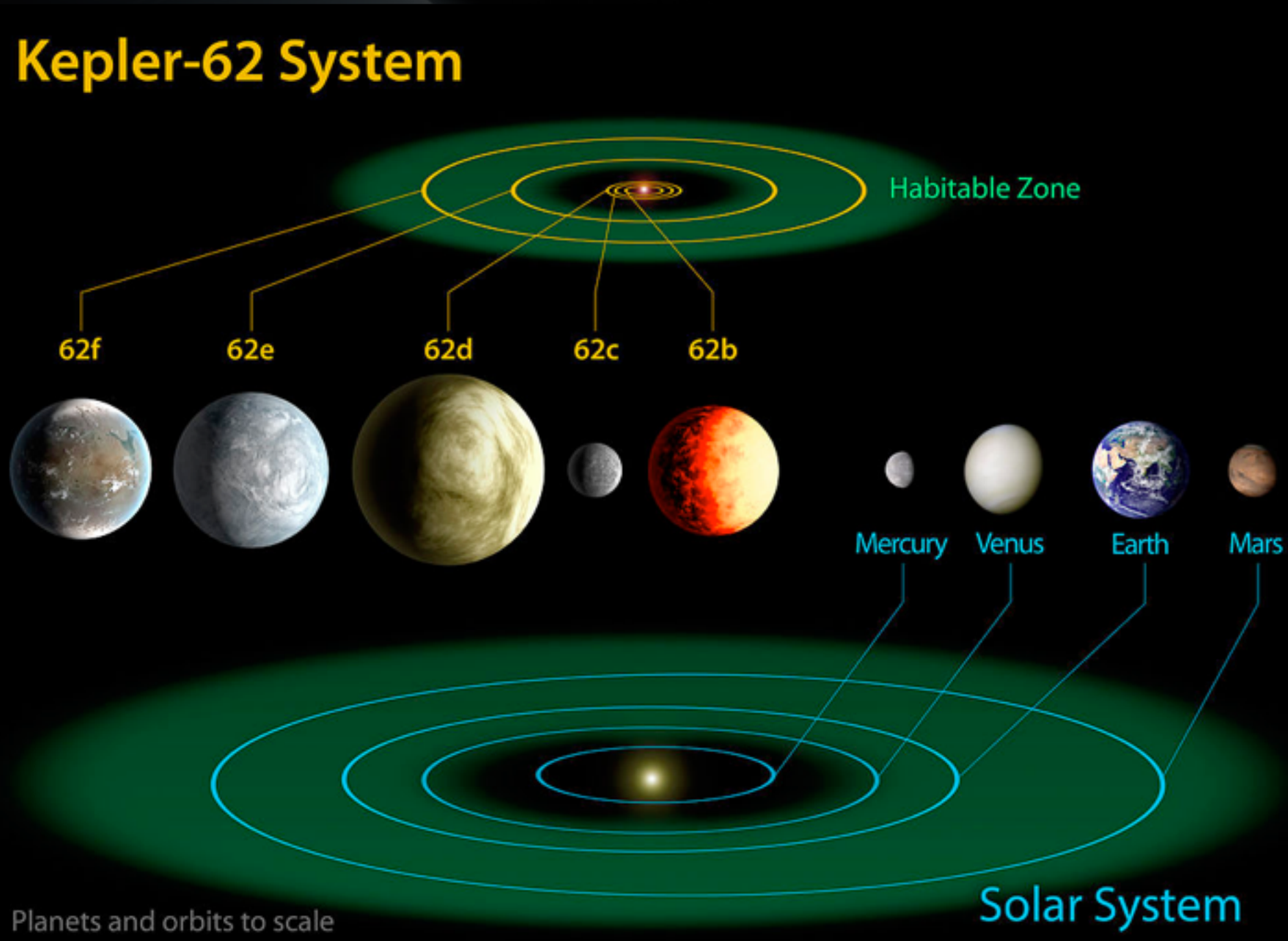
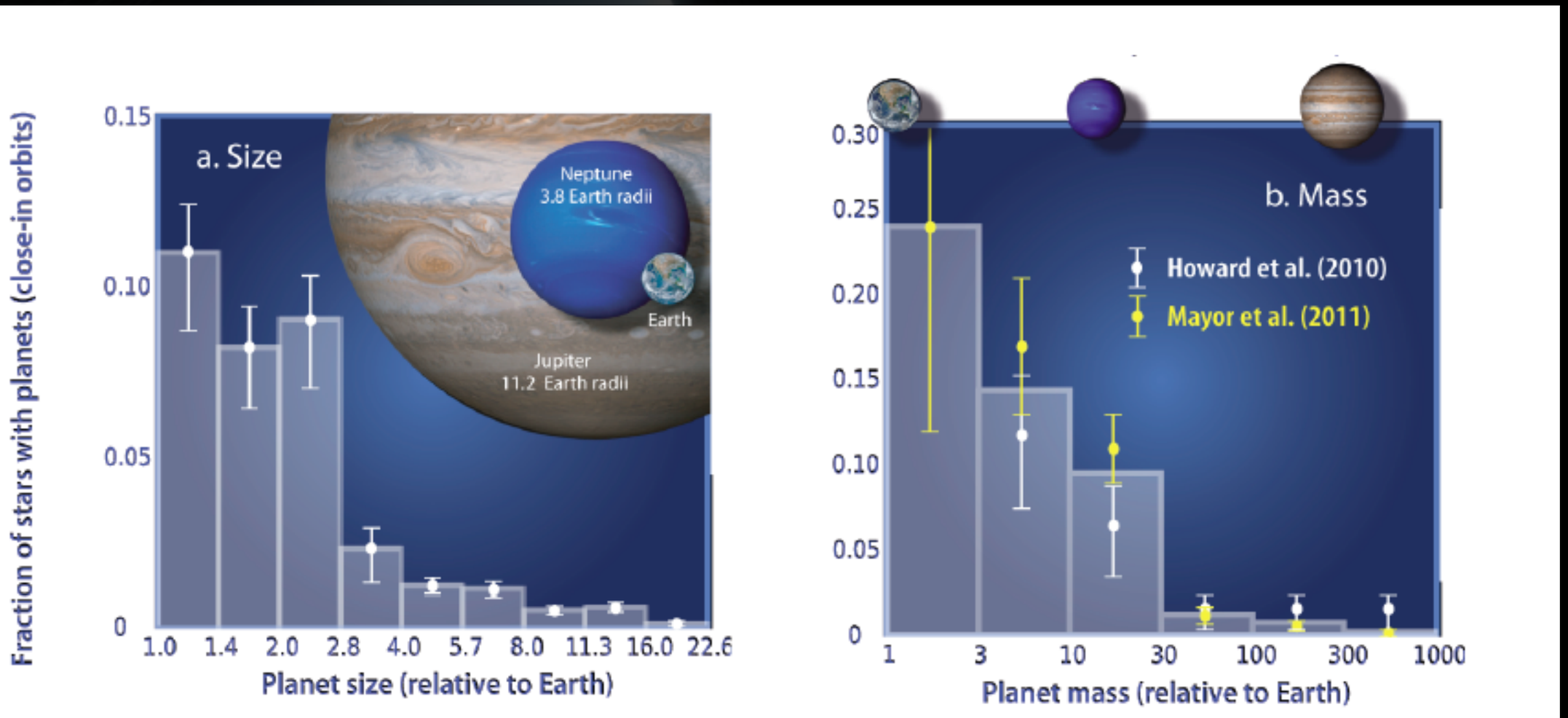


Image credit: NASA Ames/JPL-Caltech

"The most common class of planetary system detectable today consists of one or more planets approximately one to three times Earth's size orbiting within a fraction of the Earth-Sun distance." - Andrew Howard (*Science*, 2013)

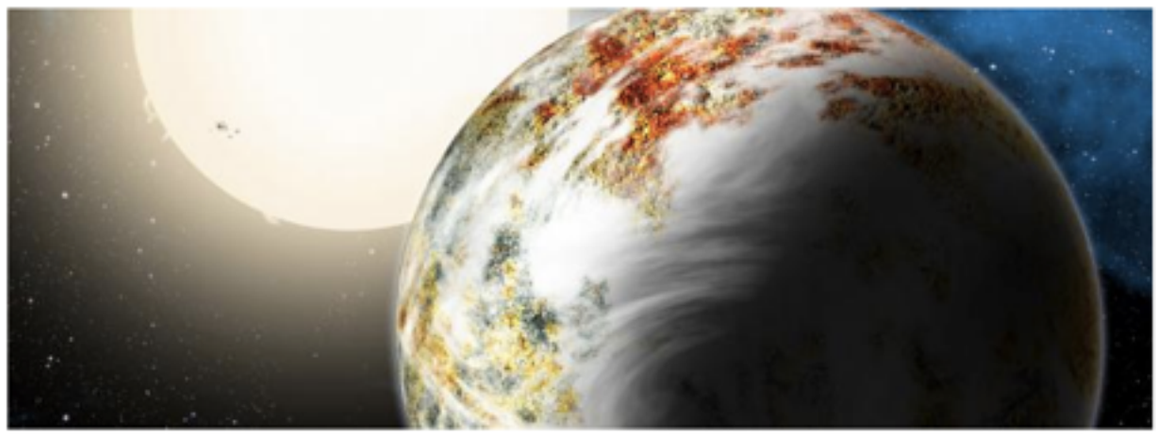


Howard, *Science*, 2013

The many names of super-Earth:

Astronomers Find a New Type of Planet: The "Mega-Earth"

Release No.: 2014-14
For Release: Monday, June 2, 2014 - 11:40am



Cambridge, MA - Astronomers announced today that they have discovered a new type of planet - a rocky world weighing 17 times as much as Earth. Theorists believed such a world couldn't form because anything so hefty would grab hydrogen gas as it grew and become a Jupiter-like gas giant. This planet, though, is all solids and much bigger

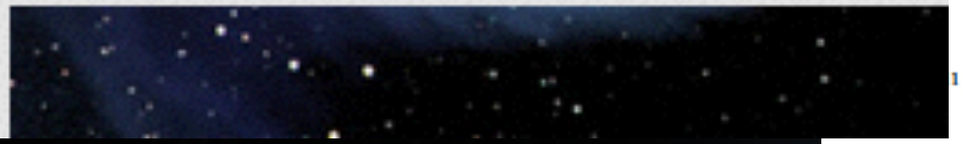
NEWS IN BRIEF EXOPLANETS, ASTRONOMY

Earth-mass planet resembles a mini-Neptune

Exoplanet 200 light-years away made mostly of gas, not rock

BY ANDREW GRANT 3:46PM, JANUARY 8, 2014

Hubble Discovers Waterworld Planet



POSSIBLE DISINTEGRATING SHORT-PERIOD SUPER-MERCURY ORBITING KIC 12557548

S. Rappaport[1], A. Levine[2], E. Chiang[3,4], I. El Mellah[1,5], J. Jenkins[6], B. Kalomeni[2,7,8], E. S. Kite[4,9], M. Kotson[1], L. Nelson[10], L. Rousseau-Nepton[11], and K. Tran[1]

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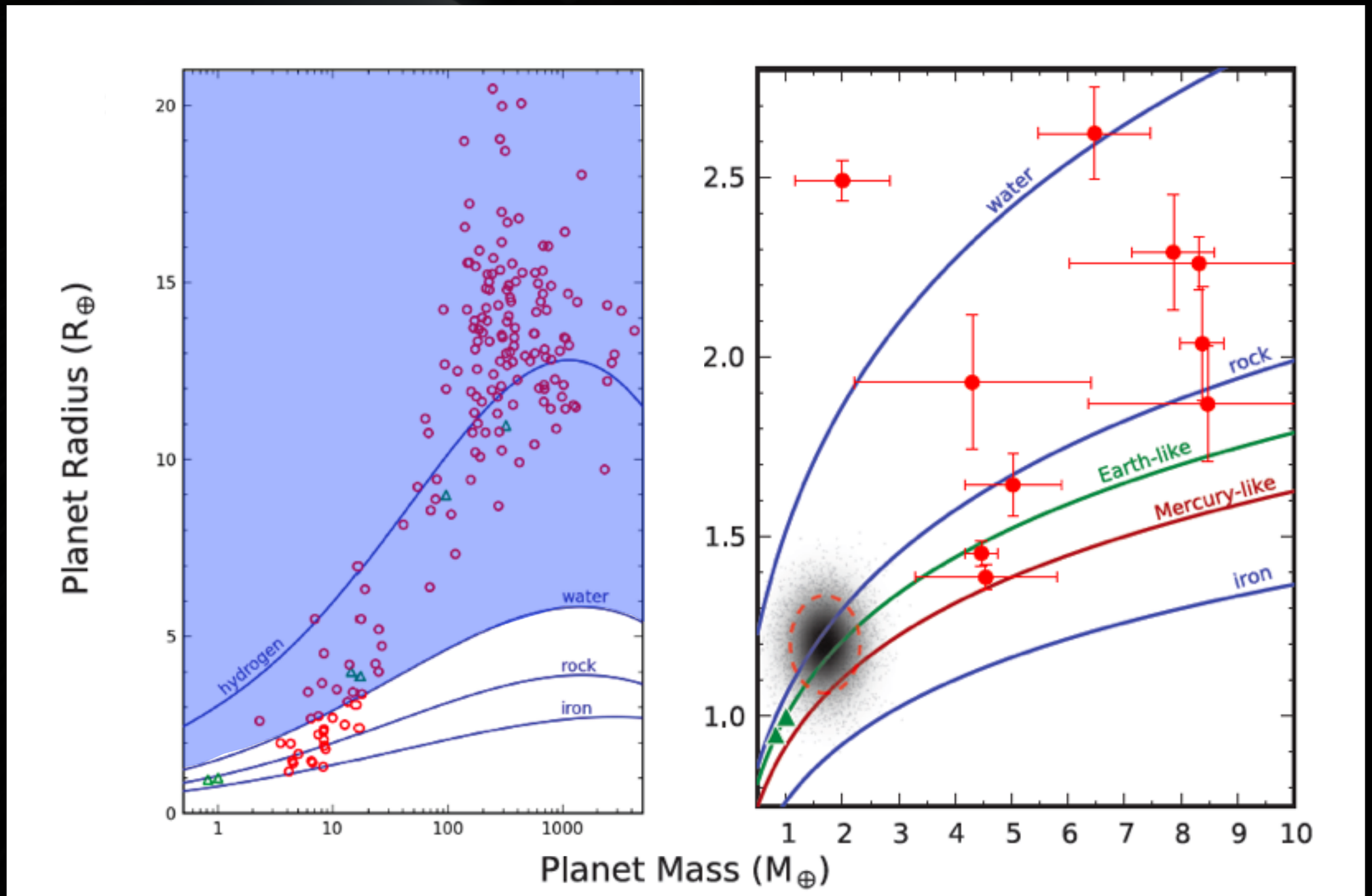
ABSTRACT

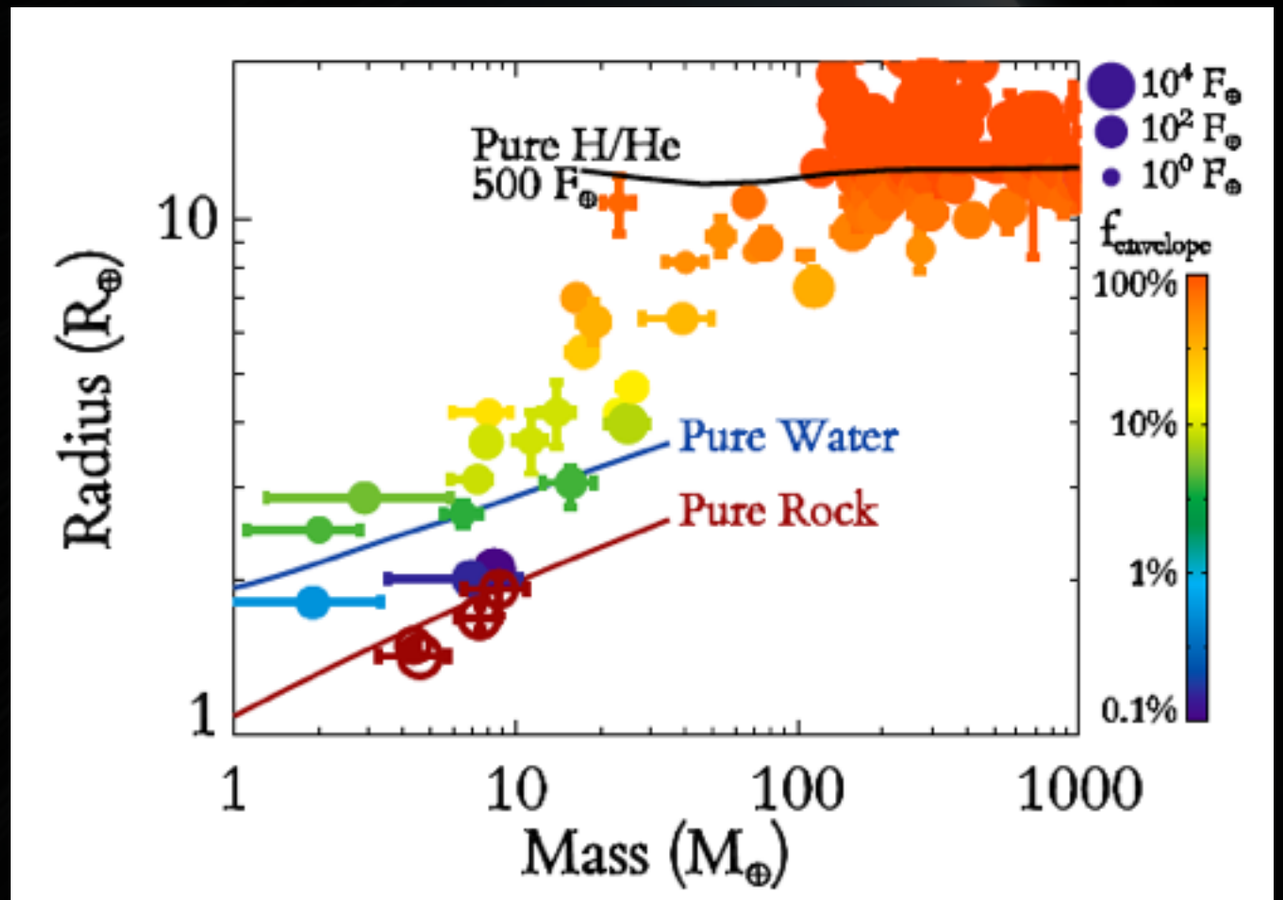
We report on the discovery of stellar occultations, observed with *Kepler*, which recur periodically at 15.685 hr intervals, but which vary in depth from a maximum of 1.3% to a minimum that can be less than 0.2%. The star that is apparently being occulted is KIC 12557548, a $V = 16$ mag K dwarf with $T_{\rm eff,s} \simeq 4400$ K. The out-of-occultation behavior shows no evidence for ellipsoidal light variations, indicating that the mass of the orbiting object is less than

Super-Earths have diverse bulk properties.

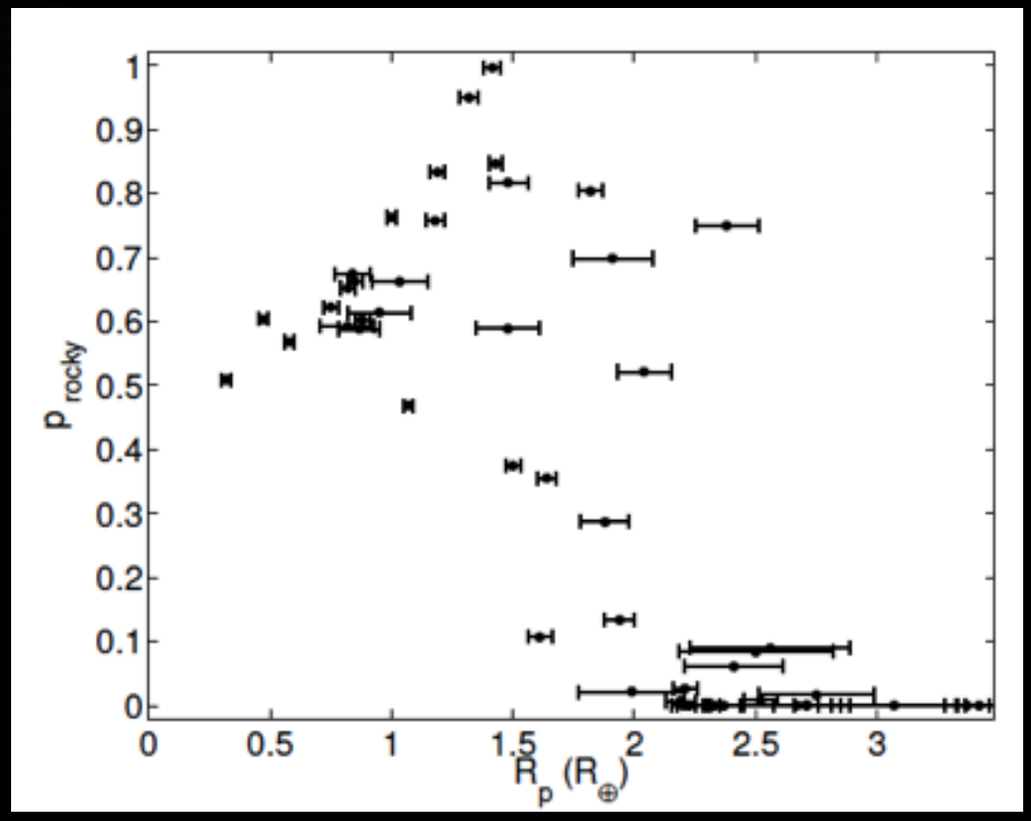


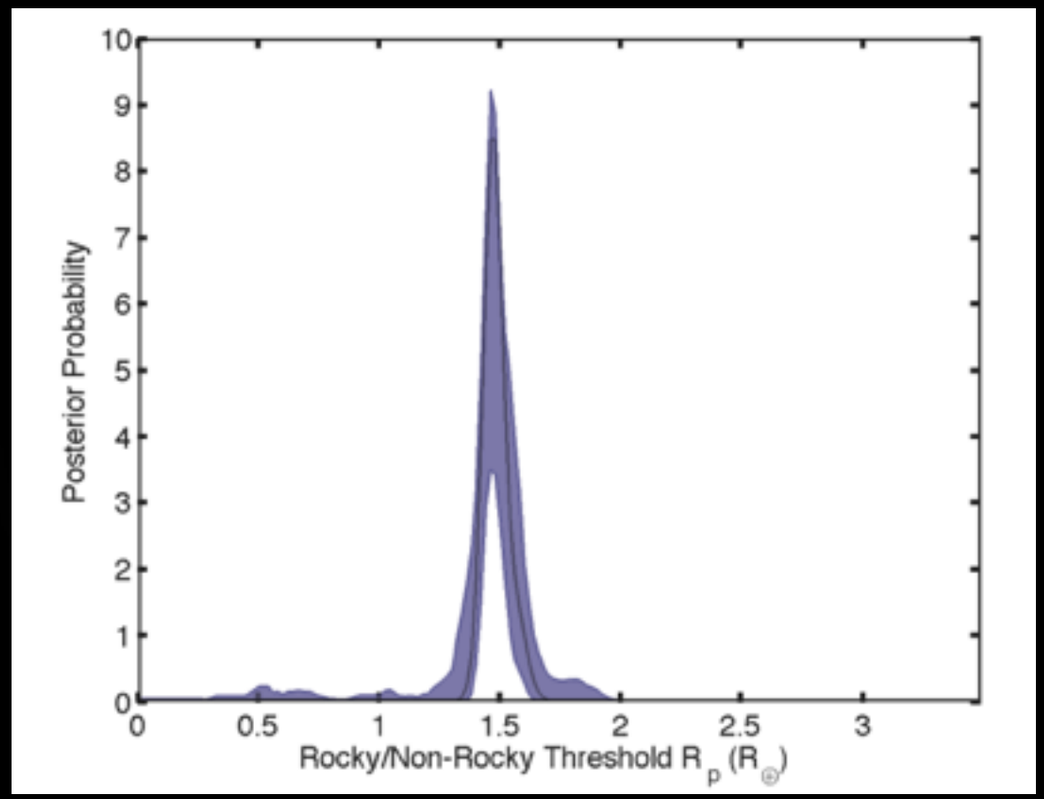
Howard et al., *Nature*, 2013

Transits are useful! Planet radius is a strong indicator of bulk composition.



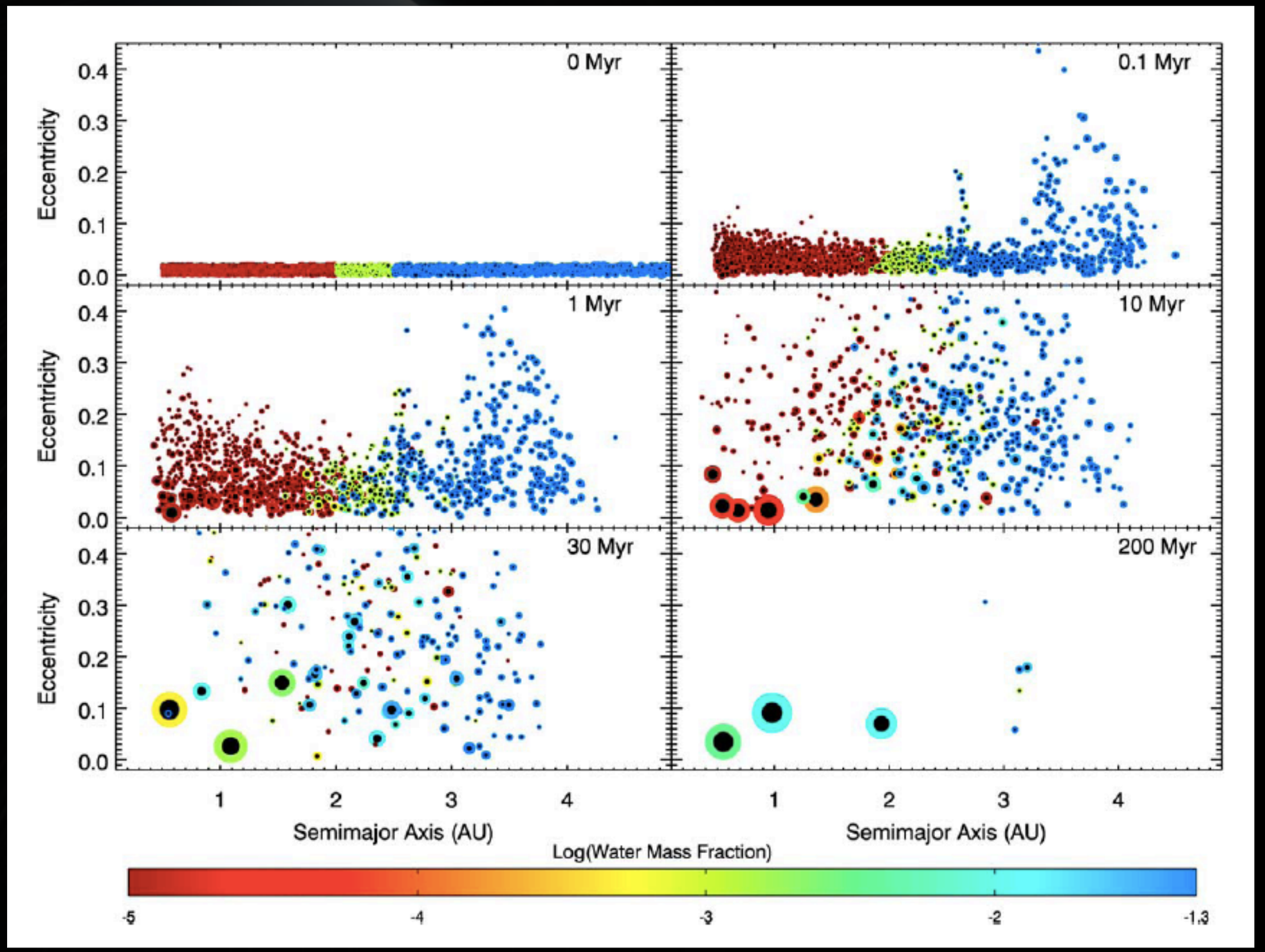
Lopez & Fortney, 2013 *arXiv 1311.0329*





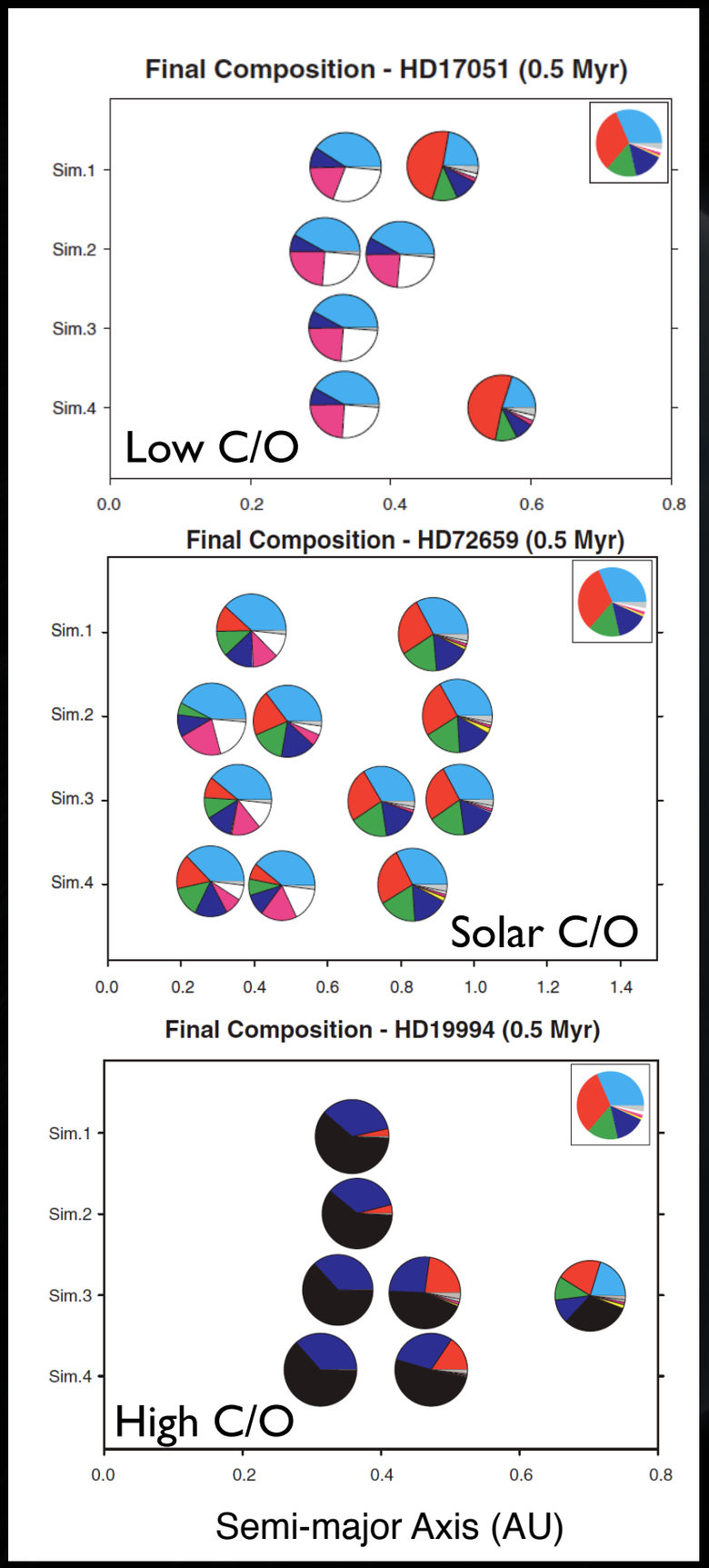
Rogers, 2014 *arXiv 1407.4457*

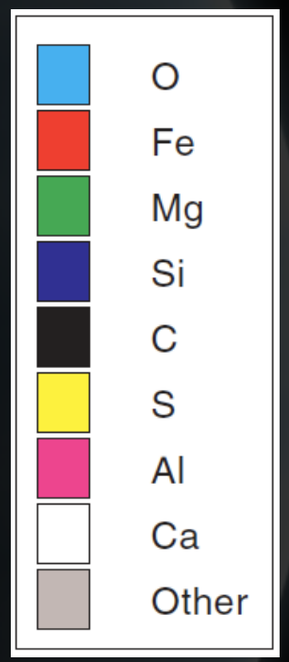
N-body simulations show possible formation pathways for water-rich super-Earths

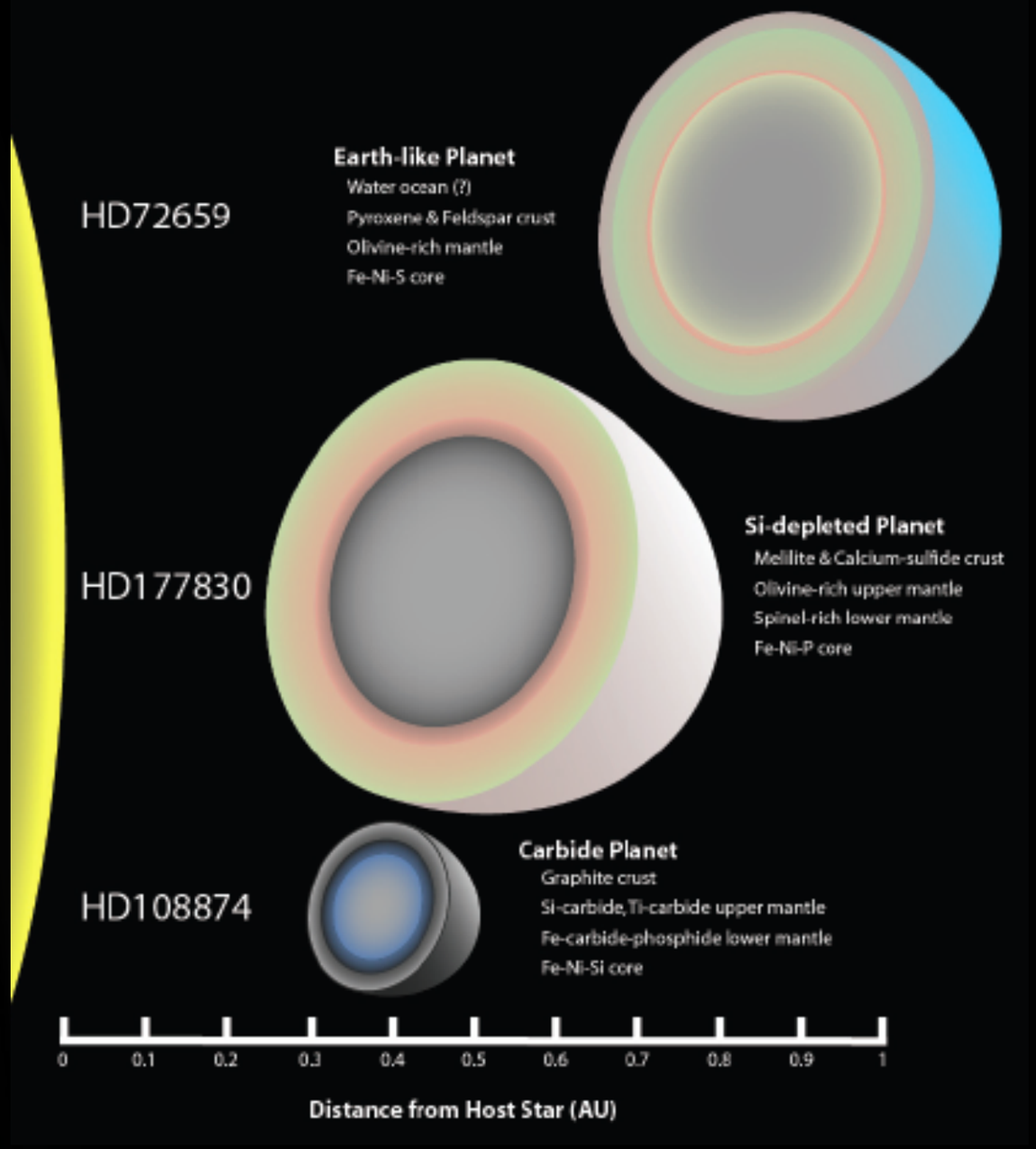


Raymond et al., *Icarus*, 2006

Planetary composition depends on stellar host abundances







Bond, O'Brien, Lauretta, *ApJ*, 2010

Secondary Atmospheres – Imagine the Possibilities...

PLANET FORMATION

EQUILIBRIUM CHEMISTRY

OUTGASSING OF VOLATILES

PHOTOCHEMISTRY

PLANET LOCATION

MASS LOSS

PLANET TEMPERATURE

COOLING HISTORY

PLANET SURFACE GRAVITY

CLUSTER ENVIRONMENT

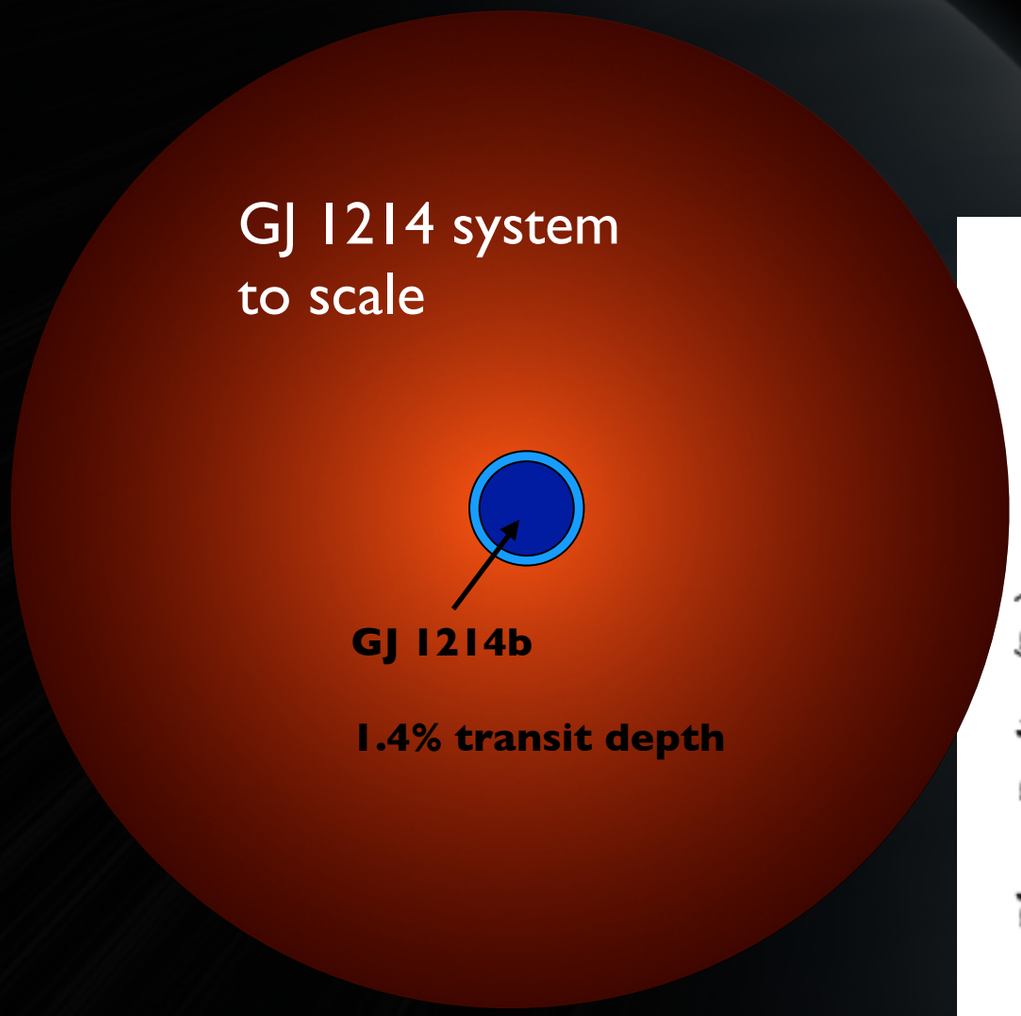
PLATE TECTONICS

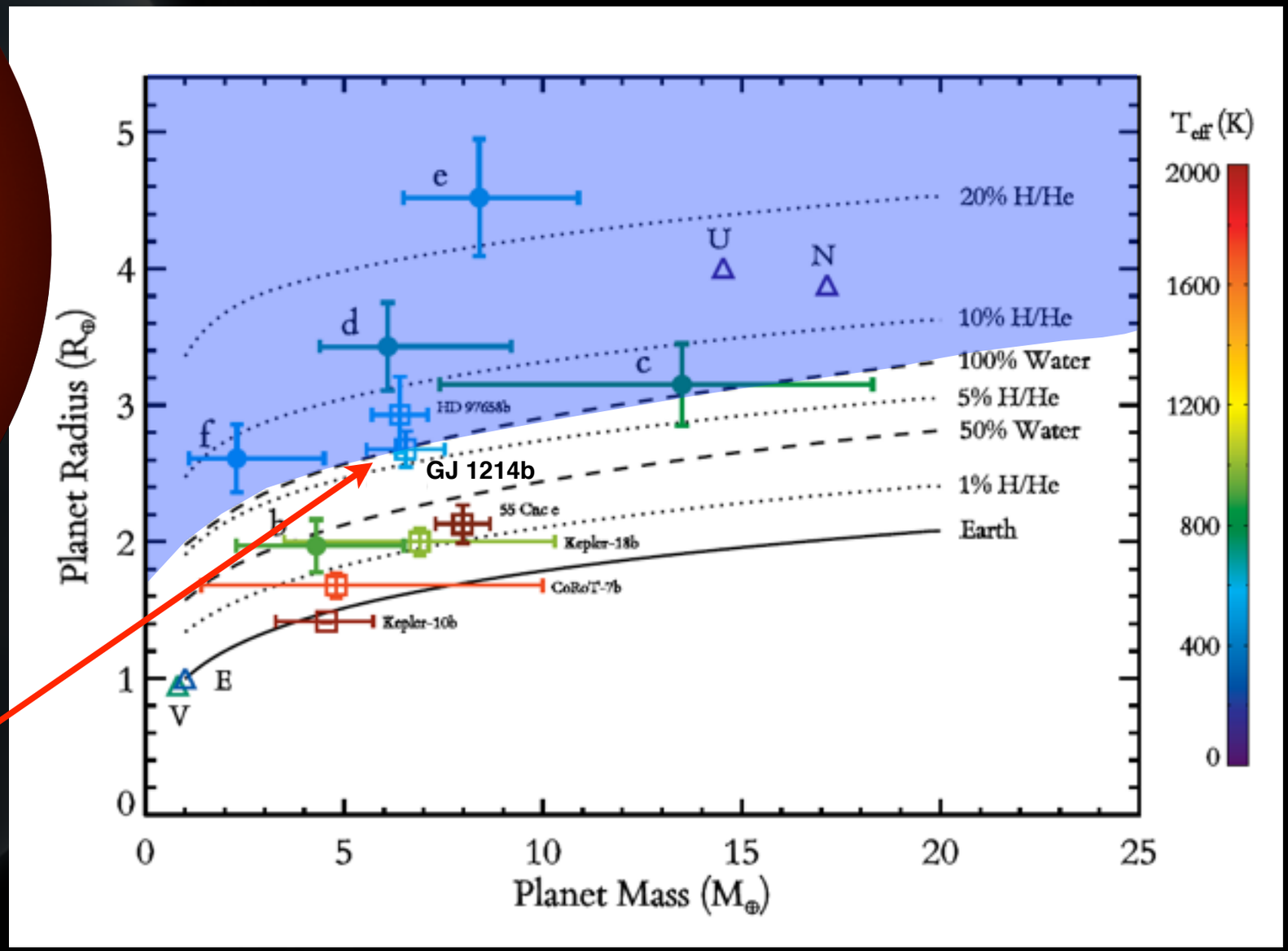
PARENT STAR SPECTRUM

PLANET MAGNETIC FIELD

GJ 1214b was the first transiting super-Earth for which atmospheric observations were possible

GJ 1214 system
to scale

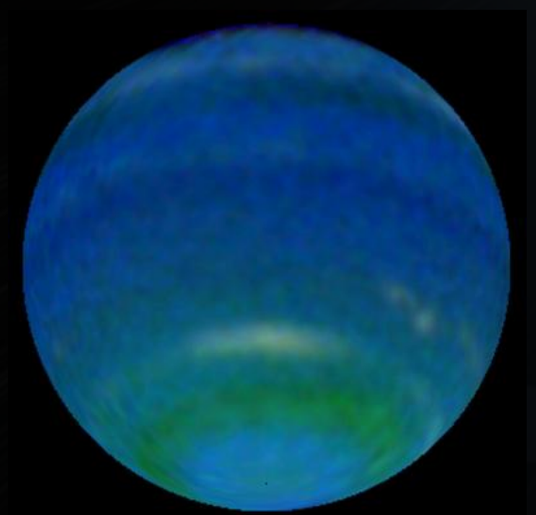




Planet is too big to be explained without the presence of a significant atmosphere!

Lissauer et al., *Nature*, 2011 (modified c/o E. Lopez)

The low bulk density of GJ 1214b informs us of its possible atmospheric composition



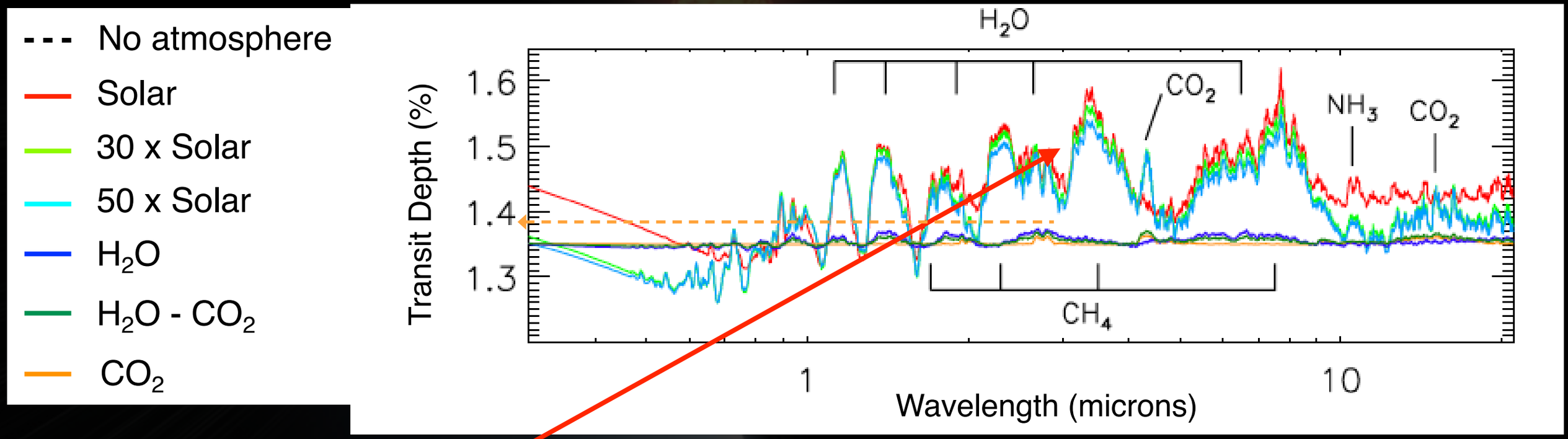
1. "Mini-Neptune" Scenario:

   Rock / ice interior + hydrogen-dominated atmosphere (mostly H_2+ trace H_2O, CH_4, etc.)

2. Water World Scenario:

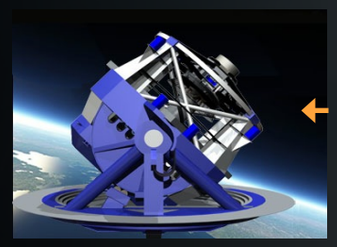
   Mostly H_2O - ice interior + steam atmosphere

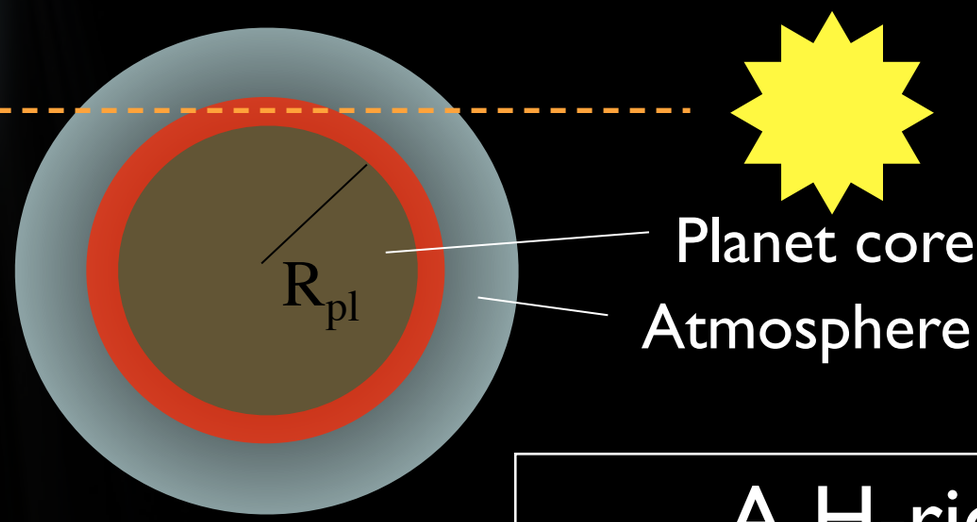
(Rogers & Seager, *ApJ*, 2010 + Nettelmann et al. 2011)



Miller-Ricci (Kempton) & Fortney, *ApJL* 2010

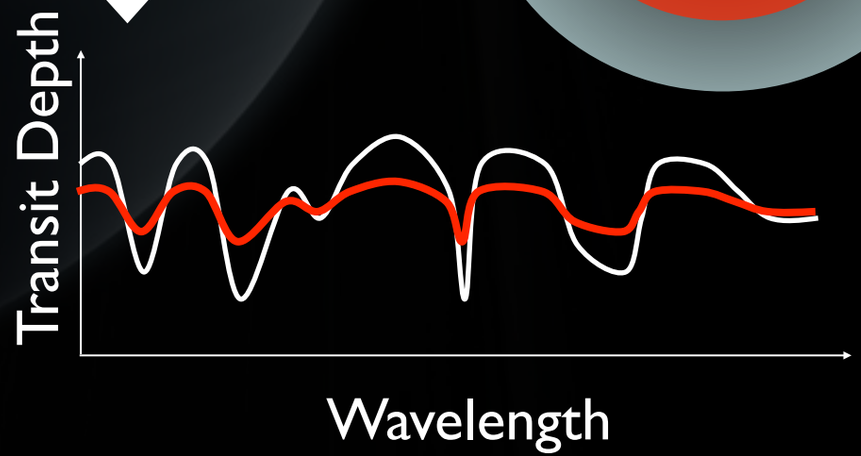
Signatures of 0.1 - 0.3% for H-rich atmospheres!





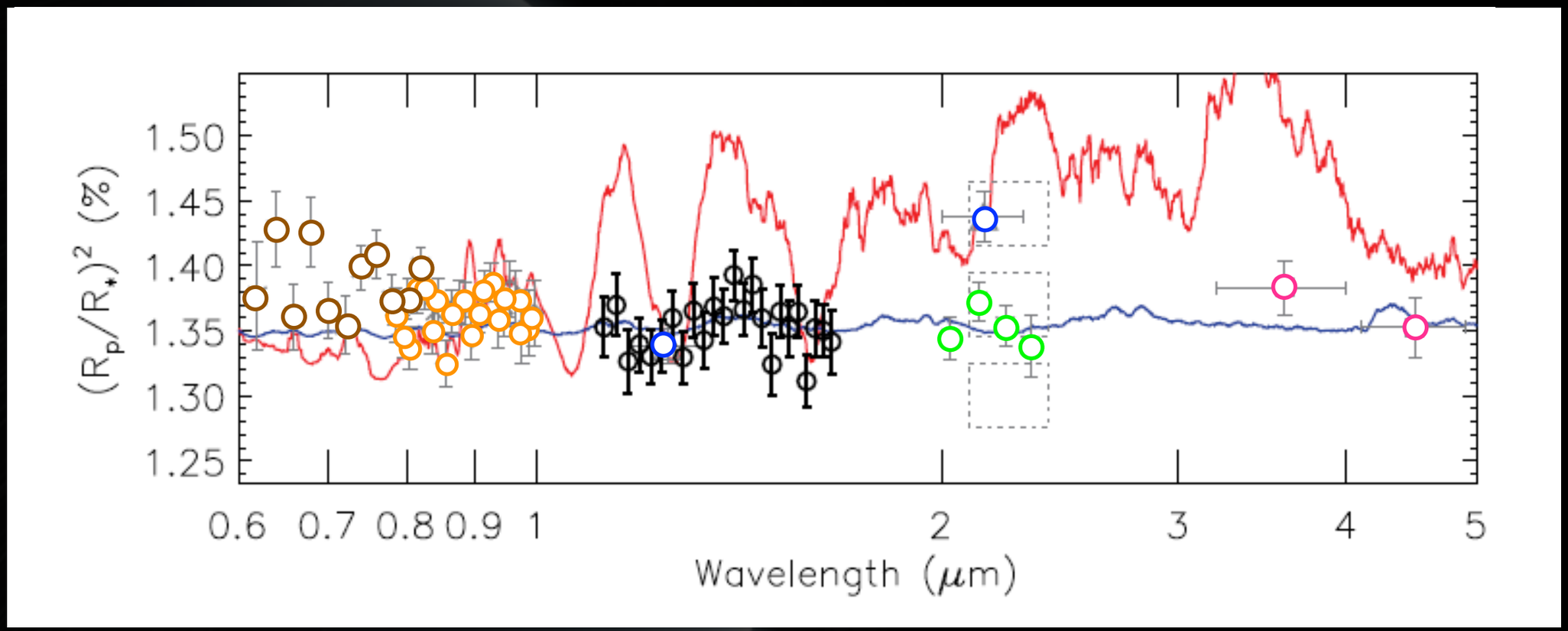
Scale height ($H = \frac{kT}{mg}$)

$\Delta_{depth} \sim 20H\ R_{pl} / R_*^2$



A H-rich atmosphere should have been easy to observe

...but a flat spectrum does not necessarily imply a high mean molecular weight atmosphere



Berta, Charbonneau, Désert, Kempton et al., *ApJ* 2012

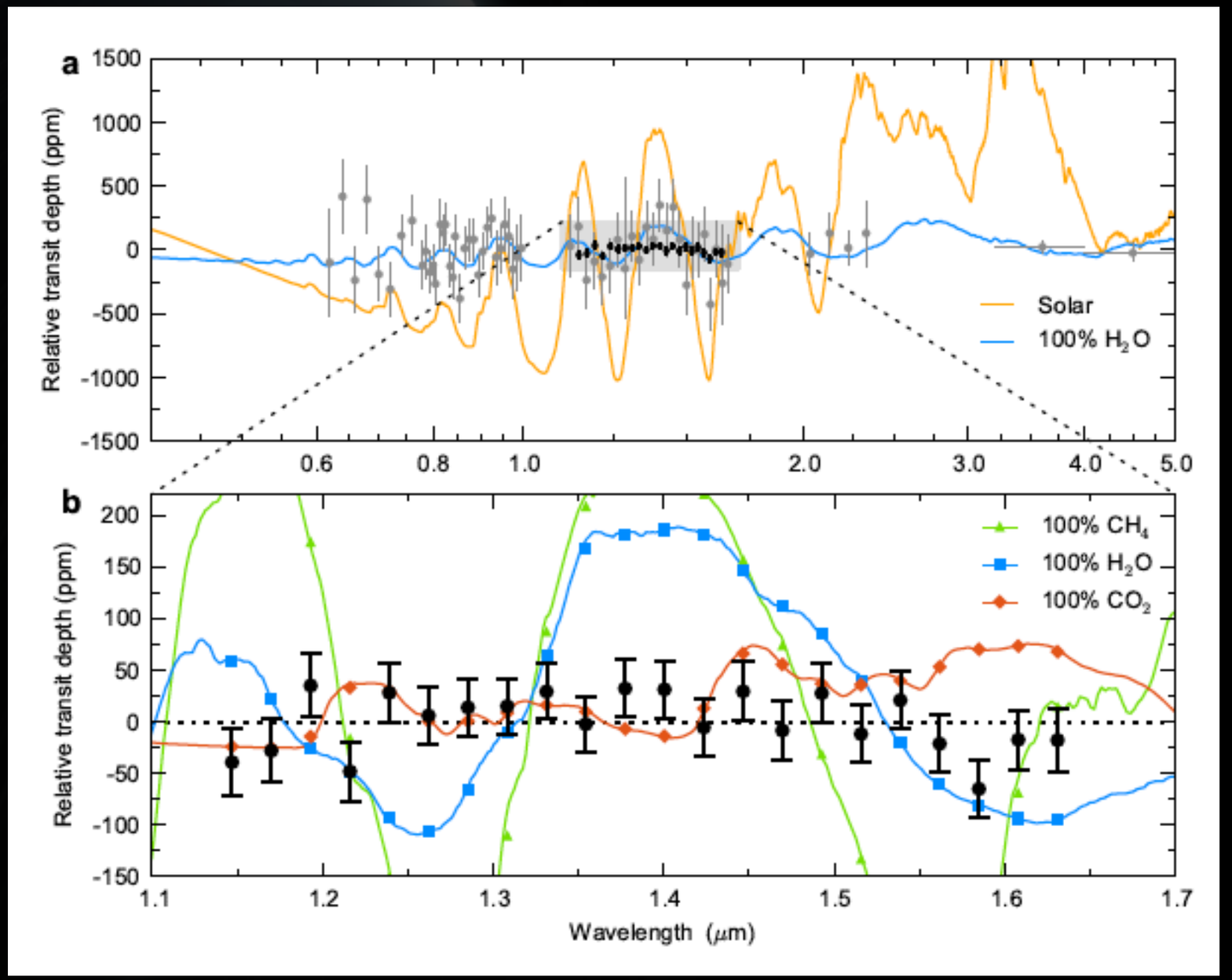
Solar Composition — 100% H_2O

VLT (Bean et al. 2011) VLT (Bean et al. 2010) WFC3 (Berta et al.) CFHT (Croll et al. 2011)

Magellan (Bean et al. 2011) Spitzer (Désert et al. 2011) ---- Keck (Crossfield et al. 2011)

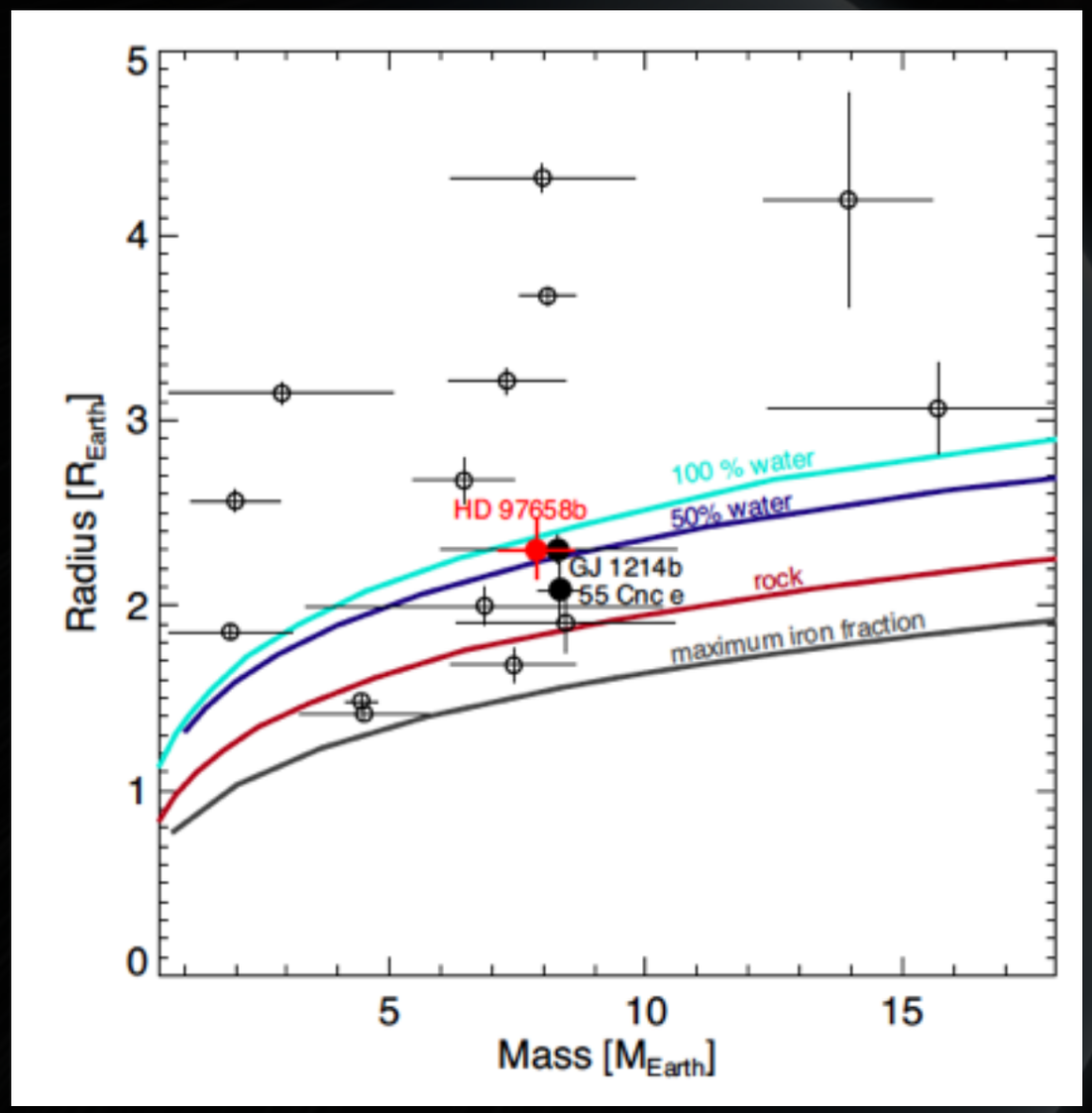
- H-rich composition ruled out at 8.2-σ confidence
- 10% water by volume (50% by mass) required to be within 1σ (m = 3.6)
- Alternative is high-altitude clouds or hazes

15 transits of WFC3 observations with HST reveal that clouds or hazes are the only explanation consistent with the data. The clouds must become optically thick at pressures < 0.1mbar

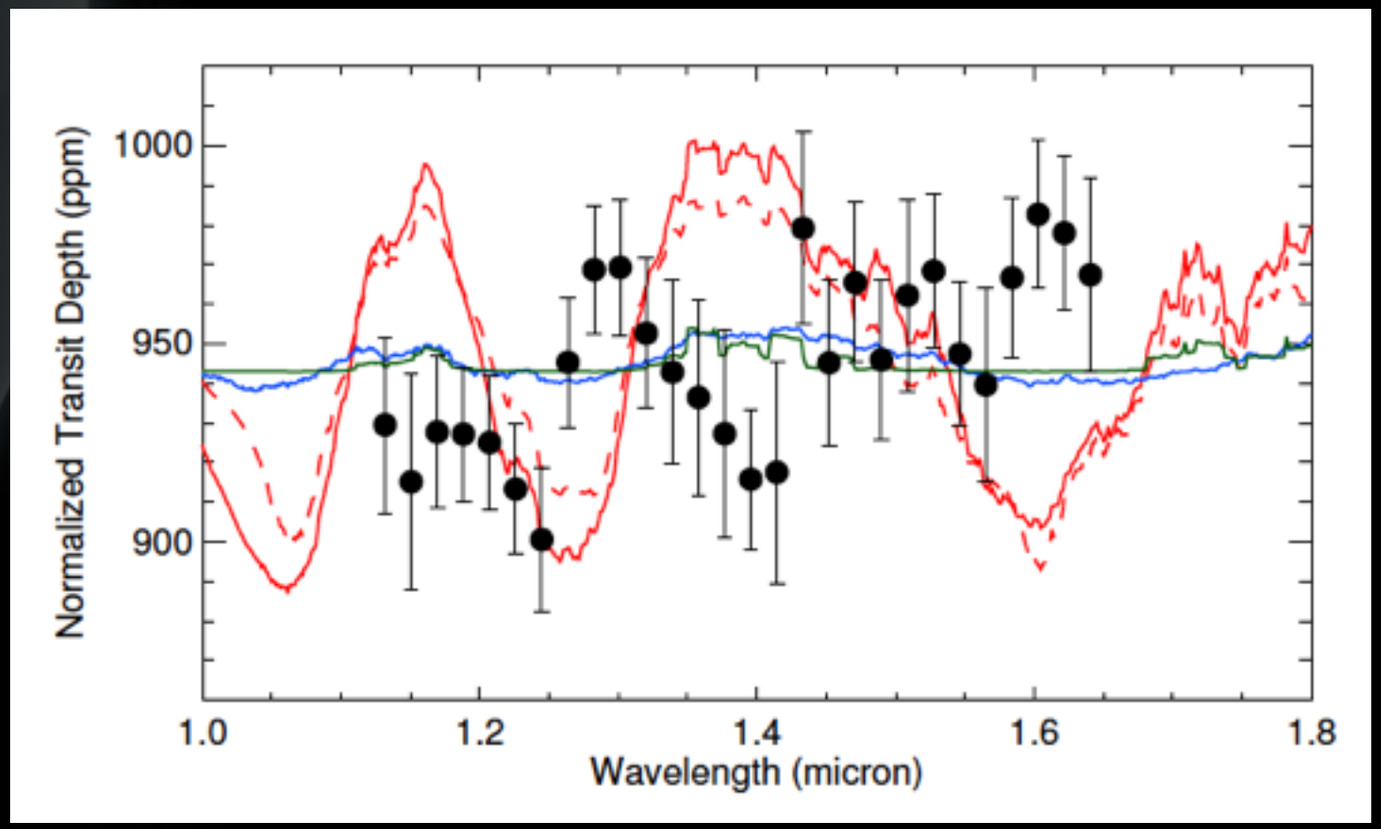


Kreidberg et al., *Nature* 2013

A second benchmark super-Earth HD 97658b also appears to have a flat transmission spectrum

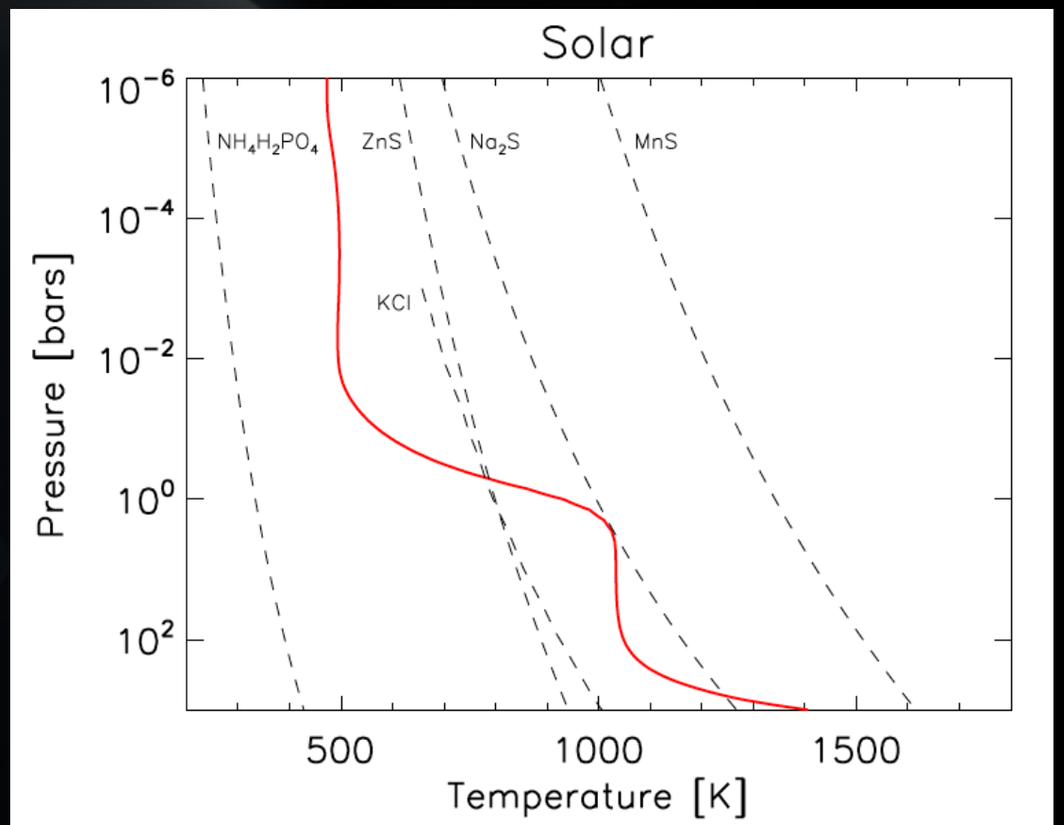


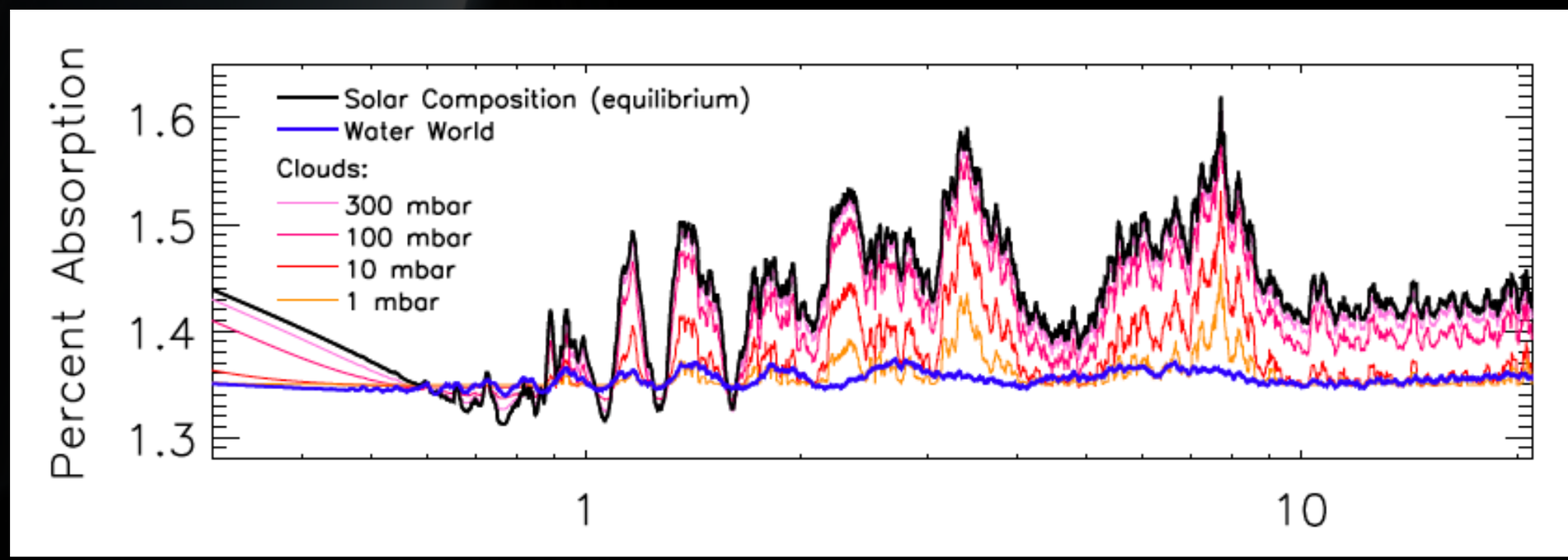
- M_{pl} = 7.9 $M_{\oplus}$
- R_{pl} = 2.3 $R_{\oplus}$
- ρ = 3.4 g/cm^3
- P = 9.49 days
- $T_{eq} \approx$ 700 K



Knutson et al., *ApJ*, *submitted*

The prevalence of clouds might seem unsurprising, but what are these clouds made of?



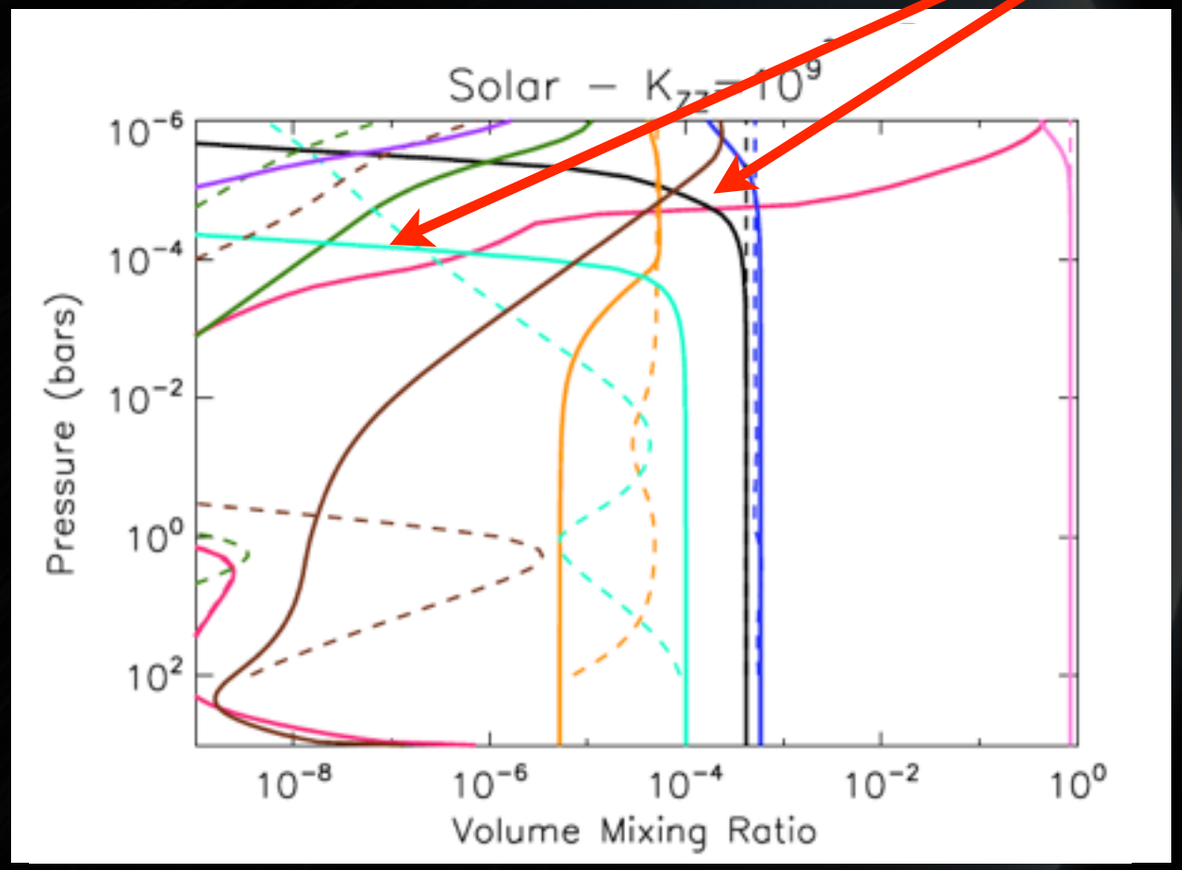


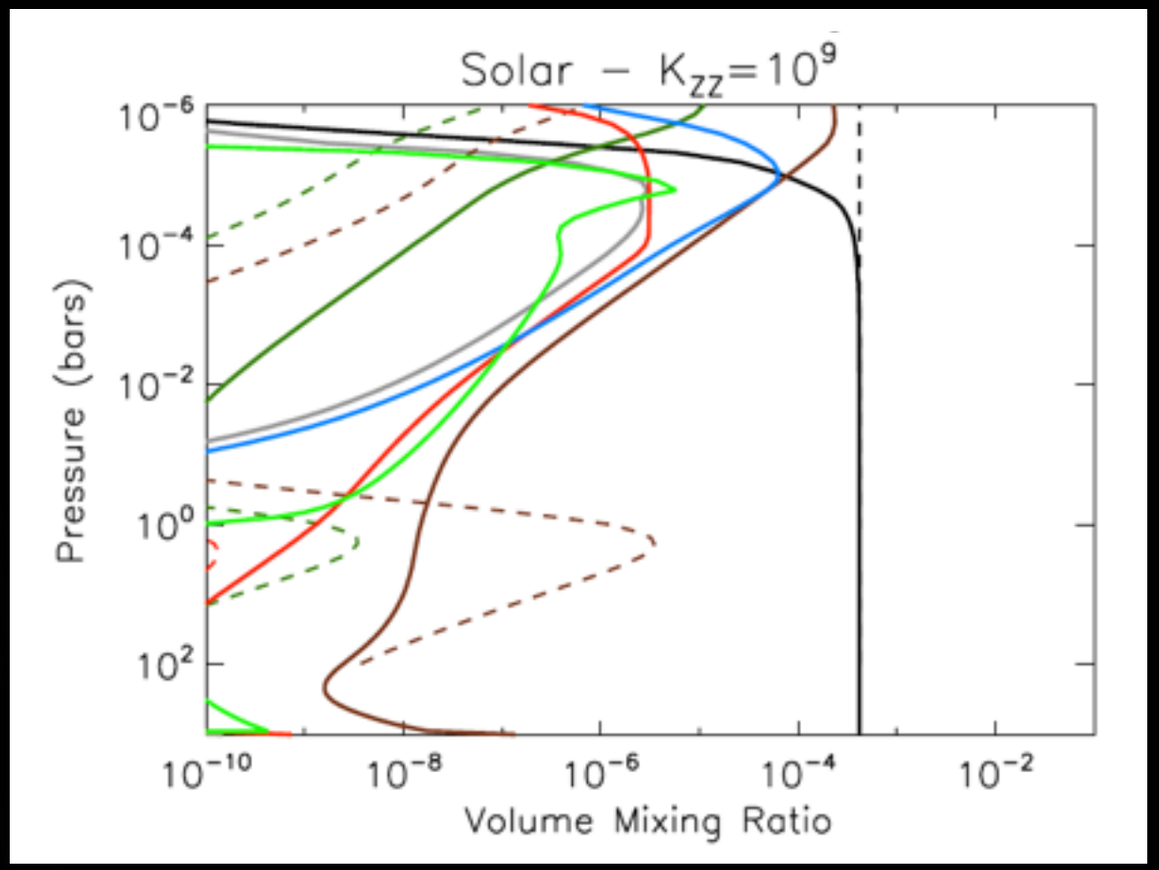
Hazes (perhaps those made of complex hydrocarbons) may be responsible for the flat transmission spectra

‘Major’ Species

Depletion of methane + ammonia via photodissociation

Carbon-Bearing Species





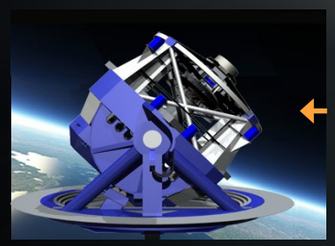
Miller-Ricci Kempton, Zahnle, Fortney, *ApJ* 2012

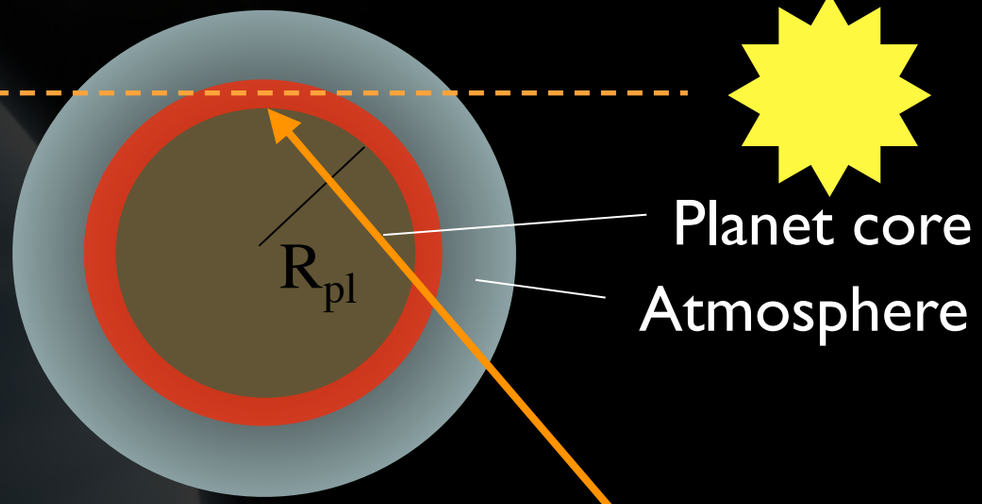
H_2 H_2O CH_4 NH_3 N_2 CO CO_2 H OH

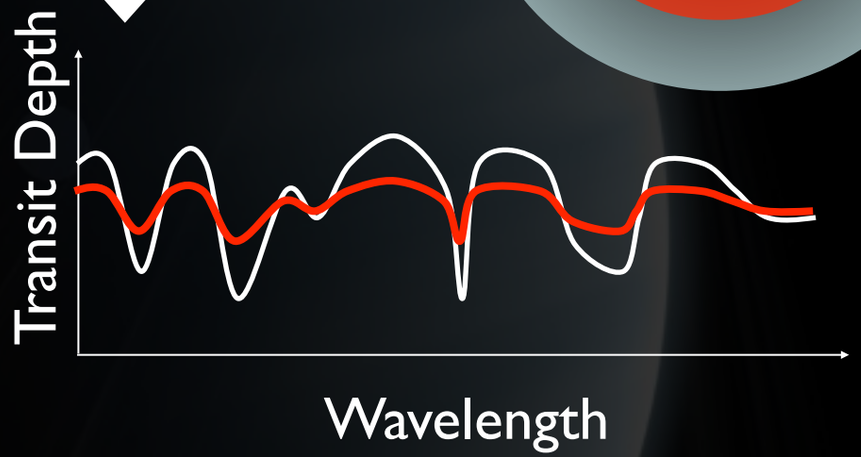
CH_4 C_2H_2 C_2H_4 C_2H_6 HCN CO CO_2

- - - - Equilibrium Abundances —— Photochemical Abundances

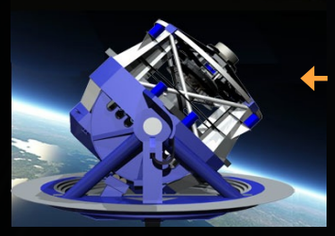
A reminder: Transmission spectra are not emission spectra

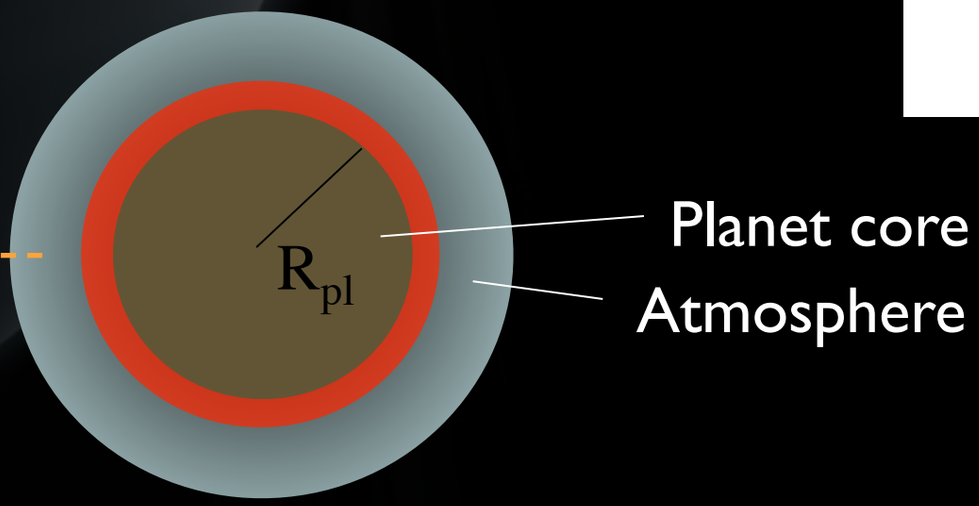






A longer light path through the atmosphere means a larger impact of clouds on transmission spectra. Also, terminator vs. dayside geometry could matter.





The challenges to direct imaging of super-Earths include very small planet / star contrast

Image credit: http://www.eso.org

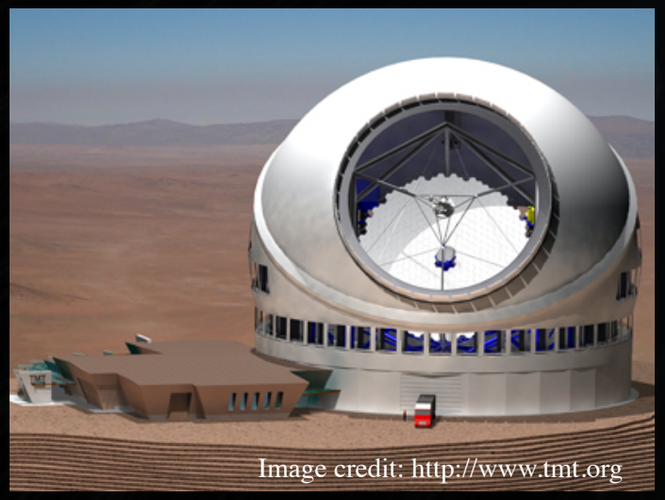
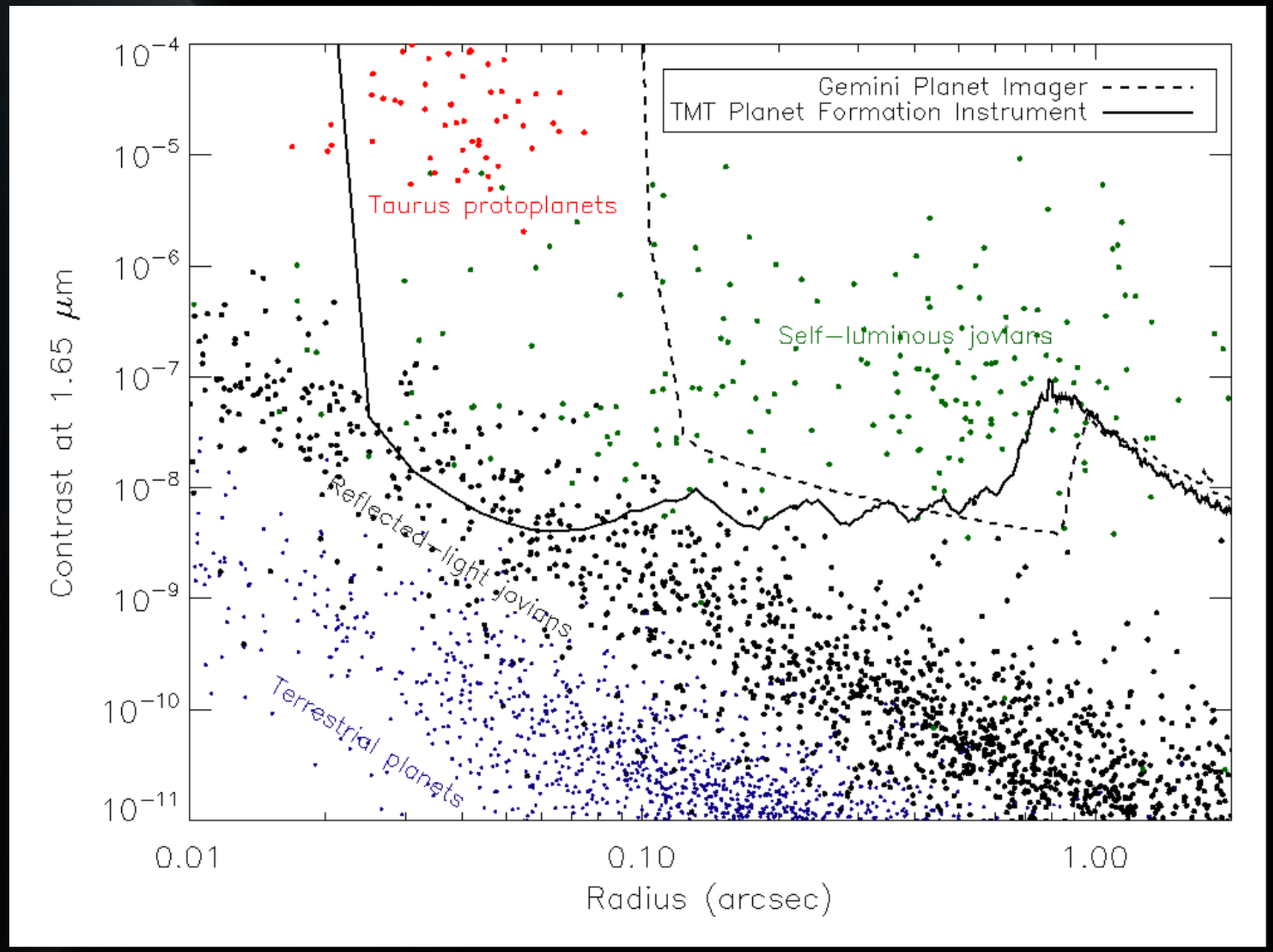


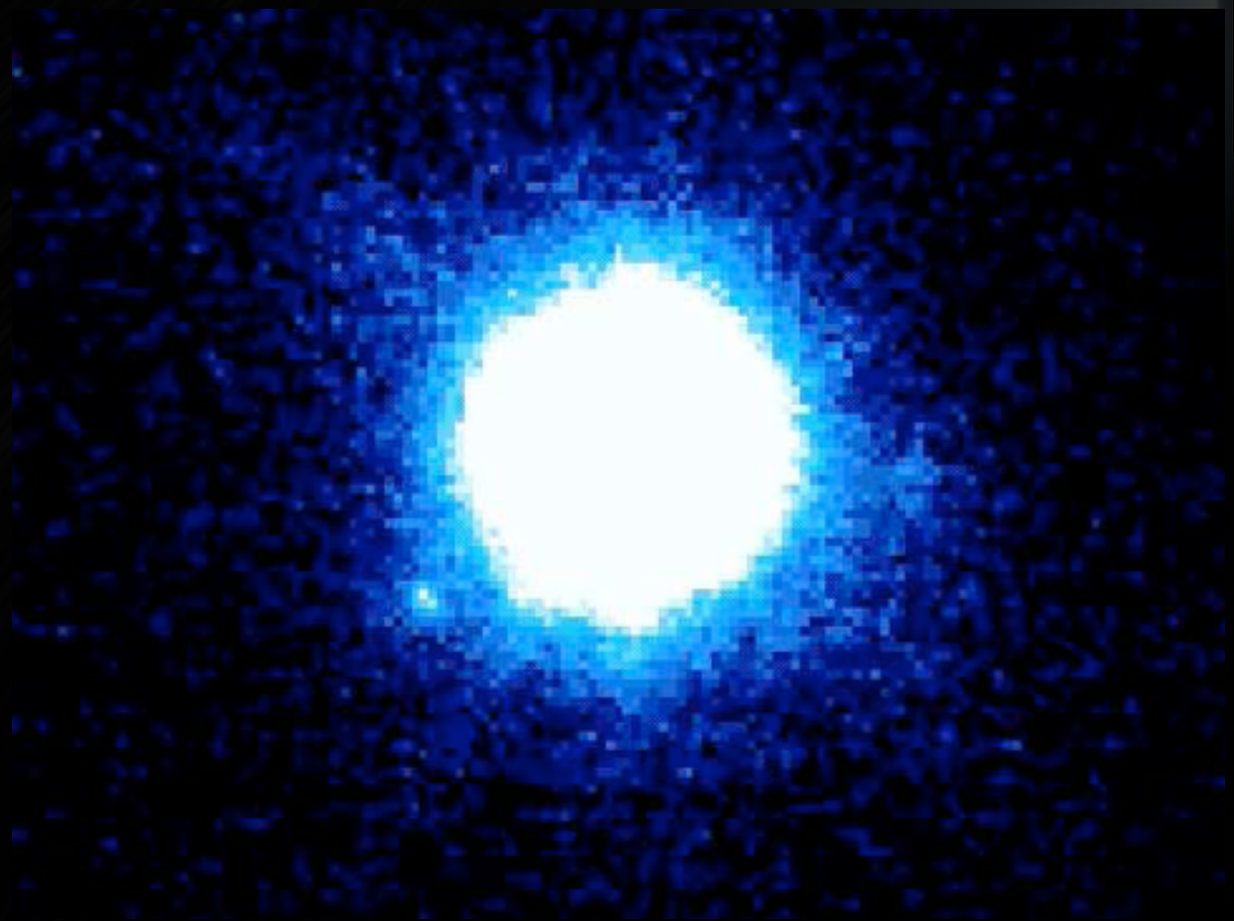
Image credit: http://www.tmt.org

Image credit: http://www.gmto.org



Macintosh et al., 2006

The curious case of 2M1217B might be explained as a terrestrial planet that recently experienced a large collision during its formation process



Accepted to ApJ Letters, 4 September 2007

An Improbable Solution to the Underluminosity of 2M1207B: A Hot Protoplanet Collision Afterglow

Eric E. Mamajek

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and

Michael R. Meyer

Steward Observatory, The University of Arizona, Tucson, AZ, 85721

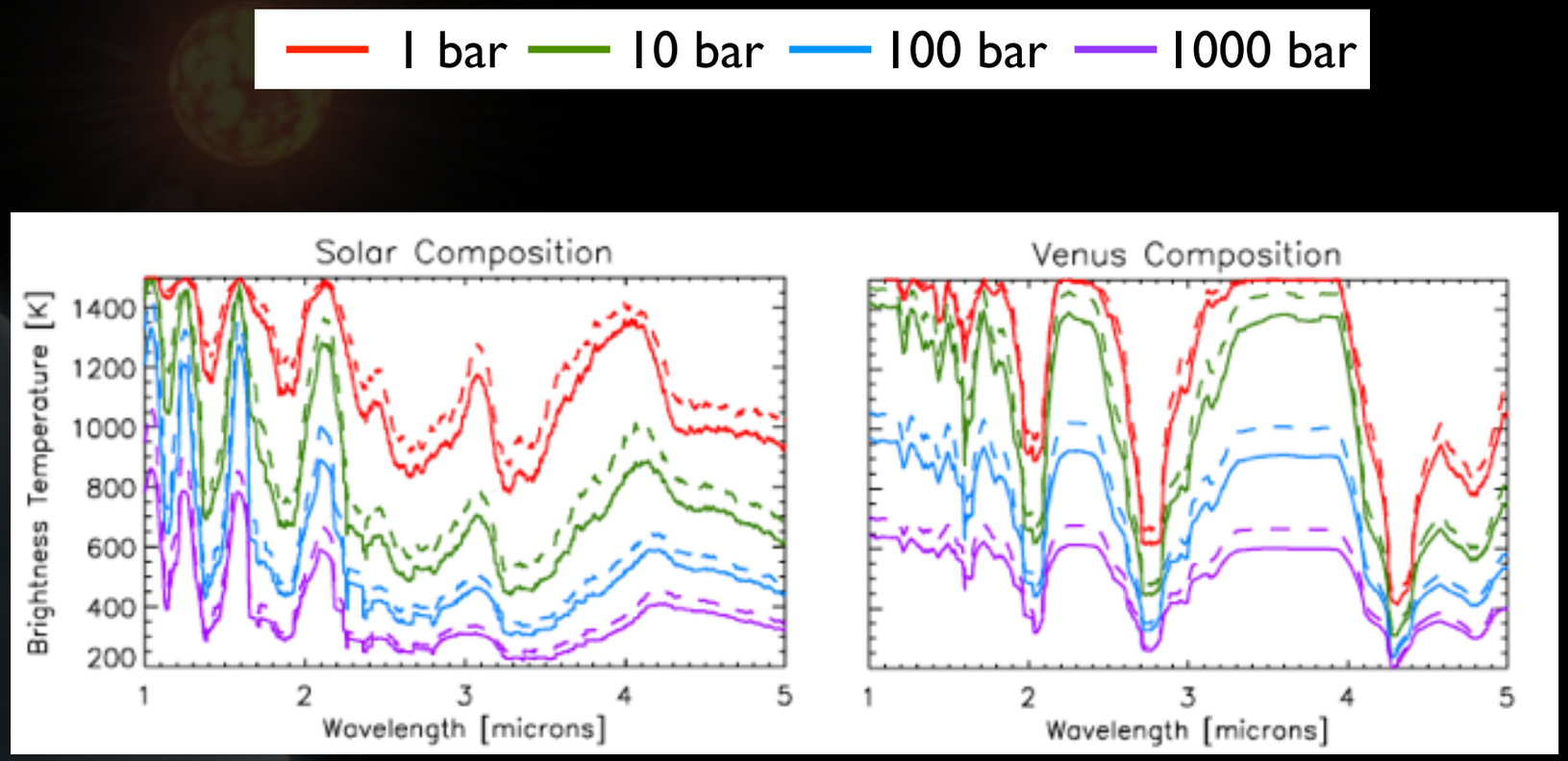
Some simple math for why you might want to look for protoplanet collision afterglows

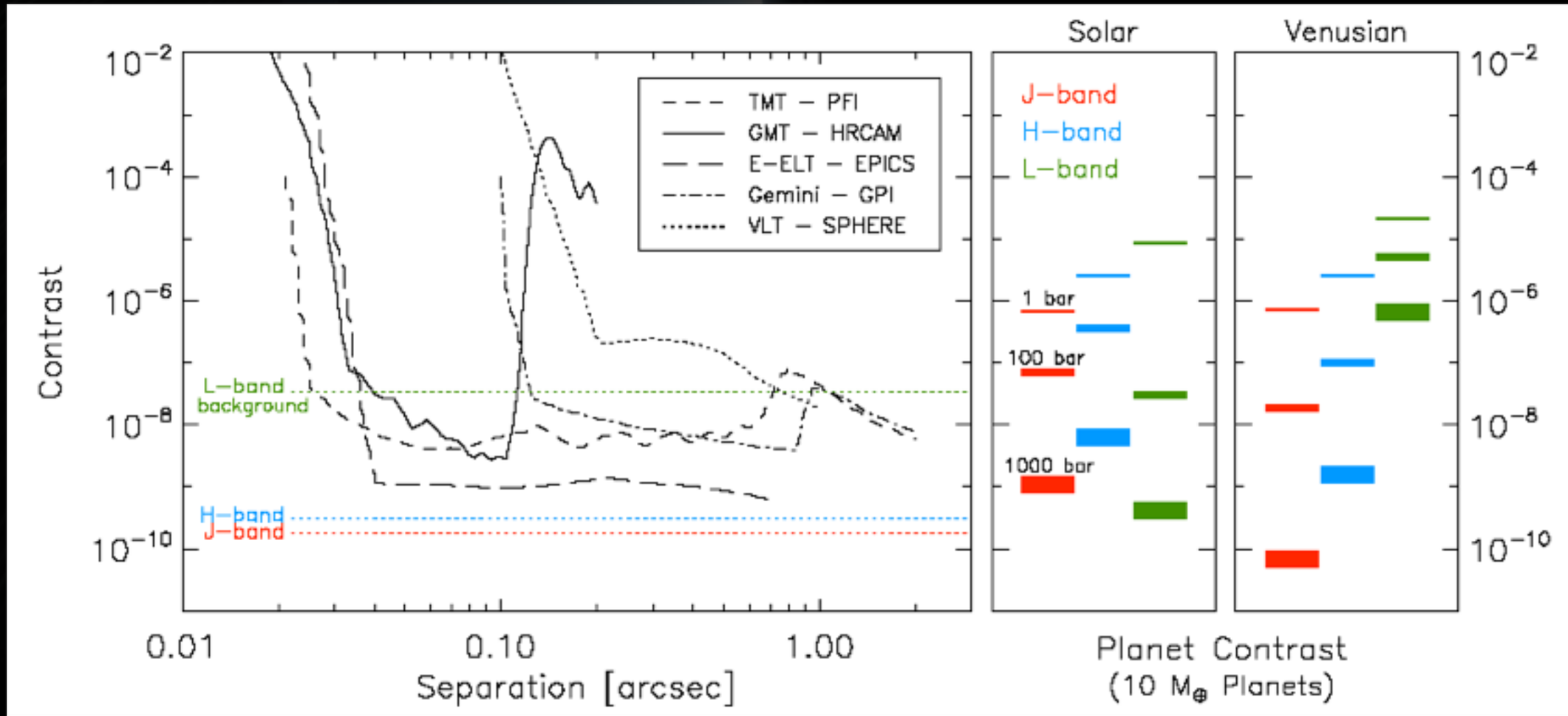
Surface temperature:
1,500-4,000 K
Cooling time in free space:
~100,000 yrs
Cooling time with a thick atmosphere:
~1-10 Myr

⟶

~10% of young stars with a hot super-Earth afterglow at a given time

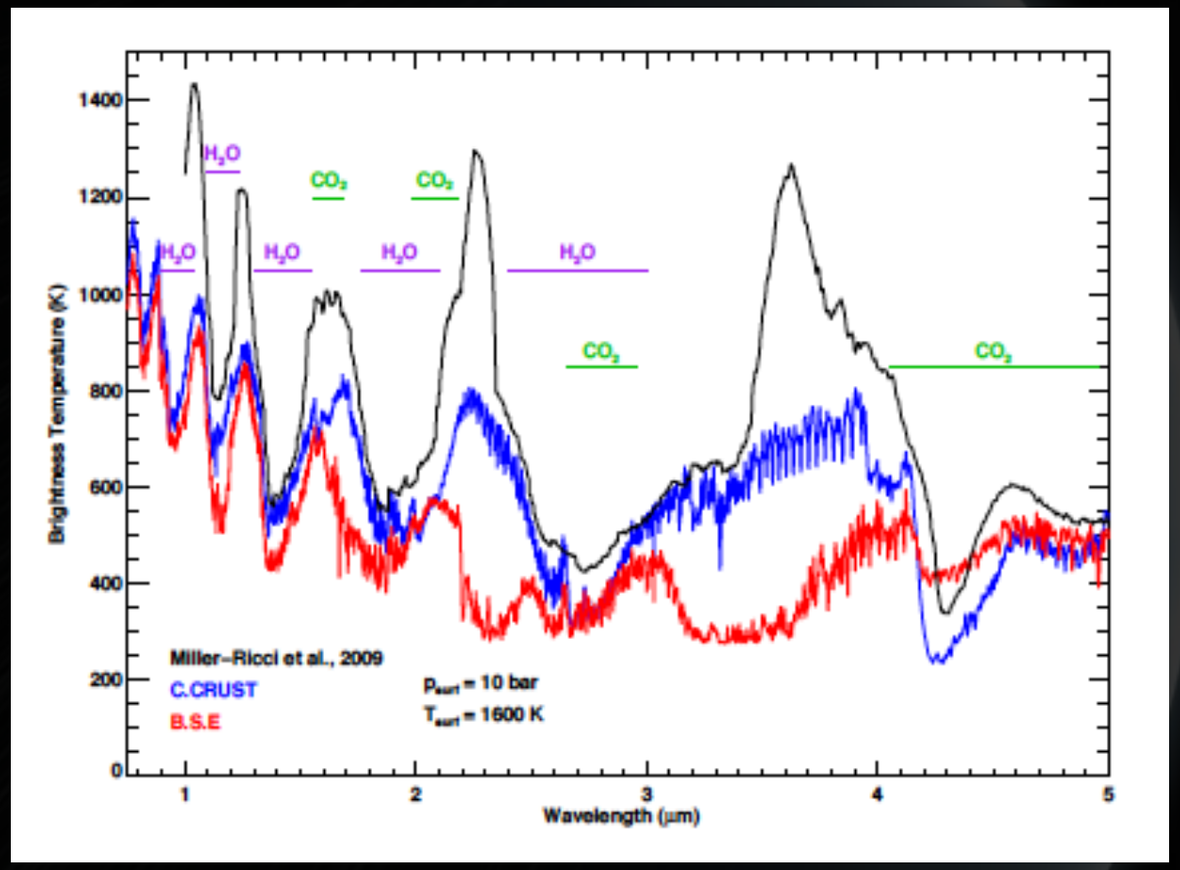
High contrasts are possible for protoplanet collision afterglows, but the details depend strongly on properties of the atmosphere.



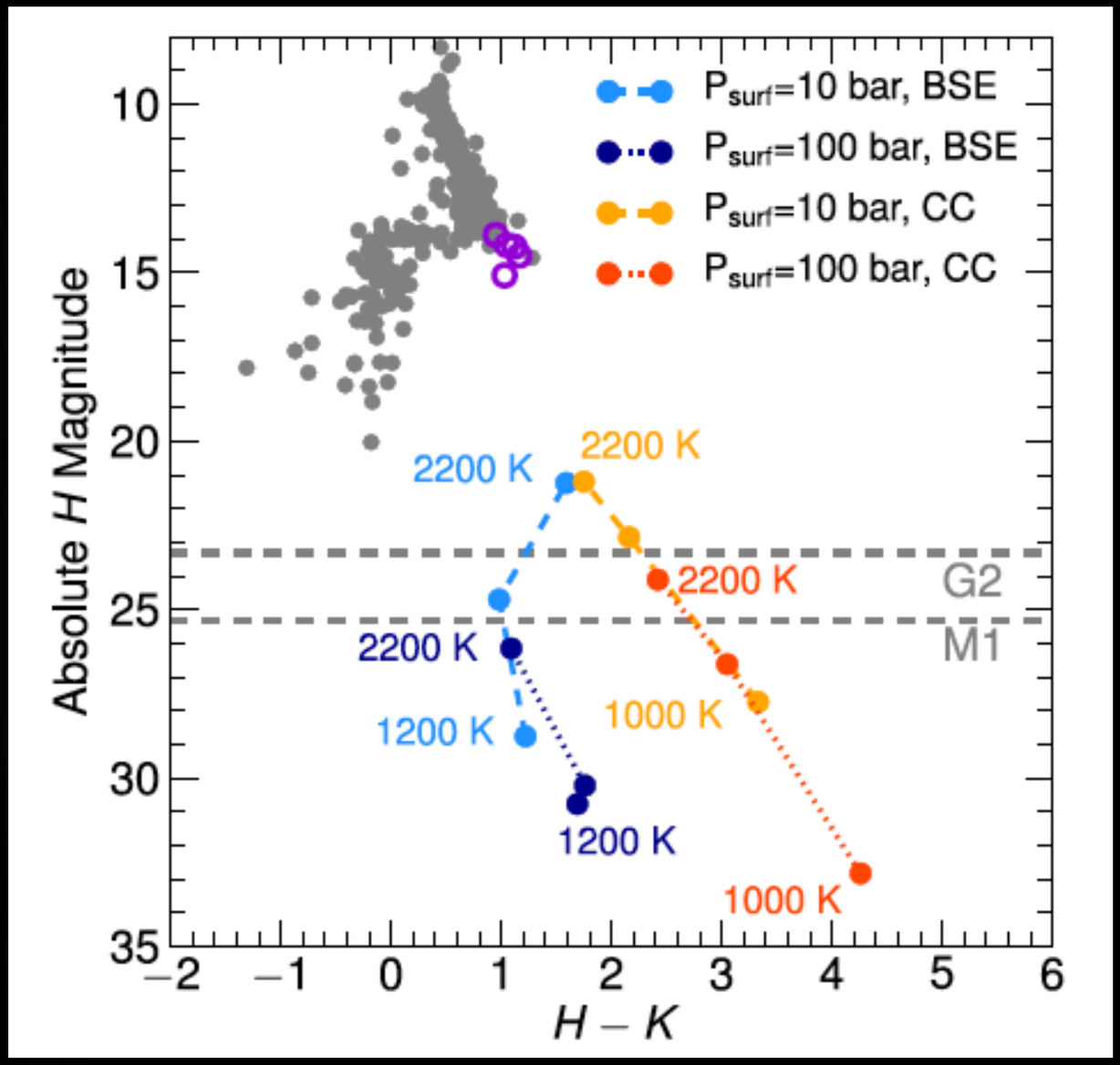


Miller-Ricci (Kempton) et al., 2009

Improved modeling and opacity data show direct detection will be somewhat more challenging and will require 30-m class telescopes to achieve.



Lupu et al., 2014



Outline (in Reverse)

- Lessons learned for direct imaging

- Super-Earths – Their Atmospheres (What have we seen so far?)

- Super-Earths – Their Formation and Their Interiors

Summary / Conclusions

- Super-Earths are planets that are have size and mass intermediate to Earth and Neptune
- There are no super-Earths in our solar system, but there appear to be many around nearby stars
- Super Earths are a highly diverse population of planets
- Interior models experience significant degeneracies, therefore observations of the planets' atmospheres are the best way to differentiate between different bulk compositions
- Direct imaging of super-Earths is extremely challenging because they are small and cool (do not retain heat from formation processes for more than 100 Myr typically)
- Best current prospects for imaging super-Earths comes during the process of collisional formation
- Future instrumentation (you guys!) will ultimately allow us to image terrestrial exoplanets