Atmospheric Properties of Warm Neptunes

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With considerable contributions from Laura Kreidberg, CfA

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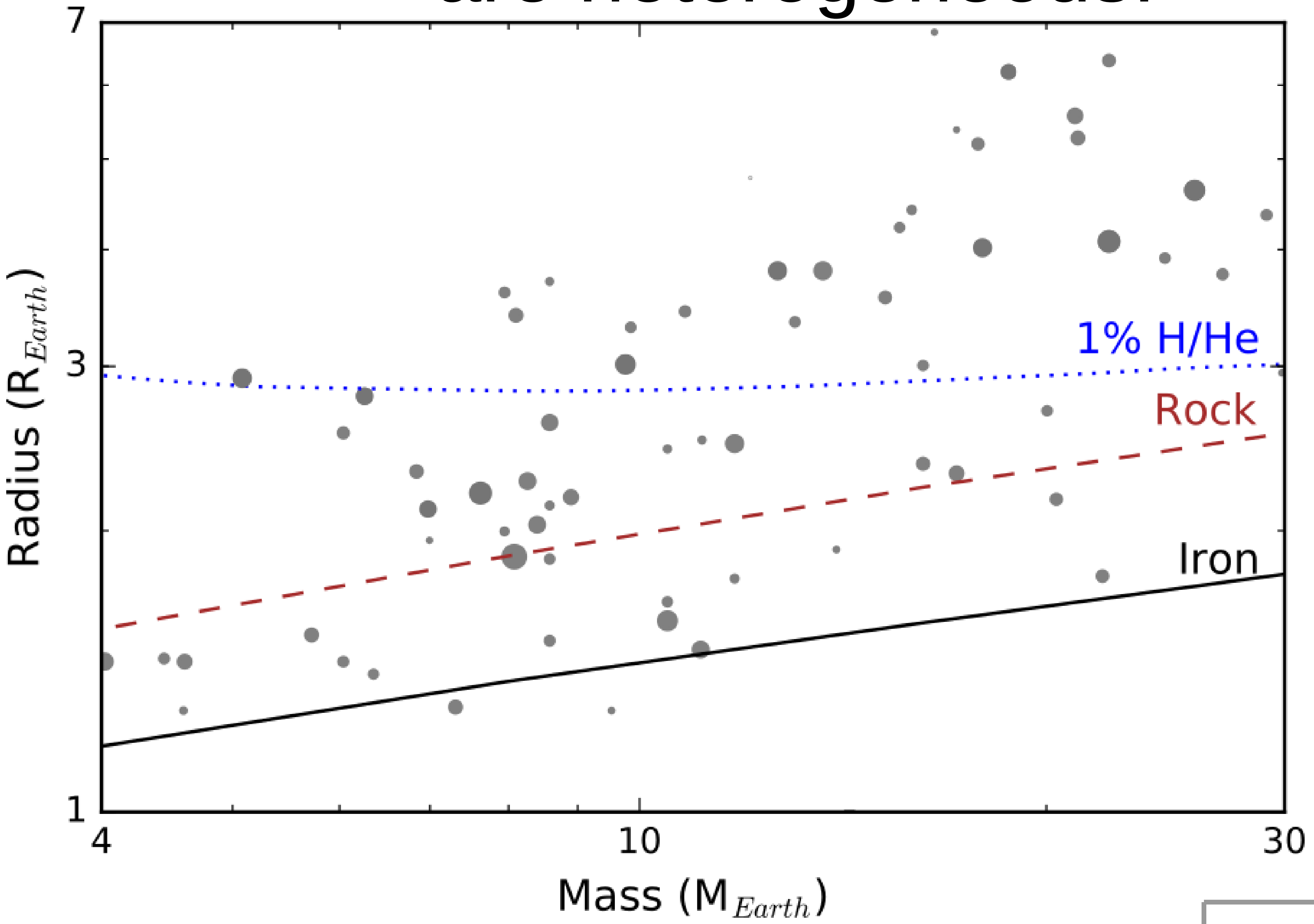
Institute of
Technology

Key take-home points:

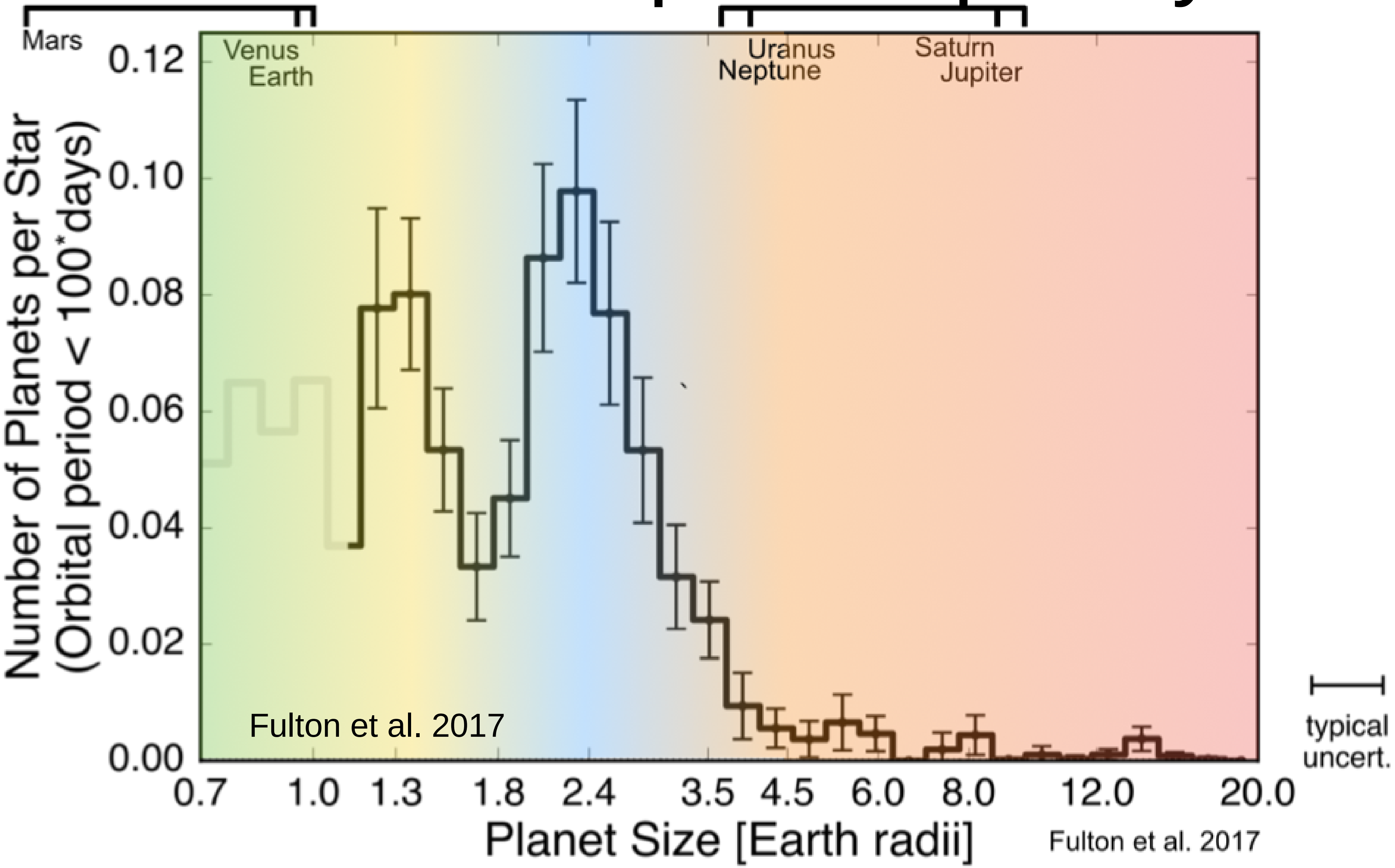
- Warm Neptunes' spectral amplitude may correlate with planet temperature and/or H/He mass fraction

- The current sample of low-mass planets with atmospheric measurements is still too small – but K2 is helping (and soon: TESS!)

Small, low-mass planets are heterogeneous:



Super-Earths and sub-Neptunes occur with ~equal frequency:



Fulton et al. 2017

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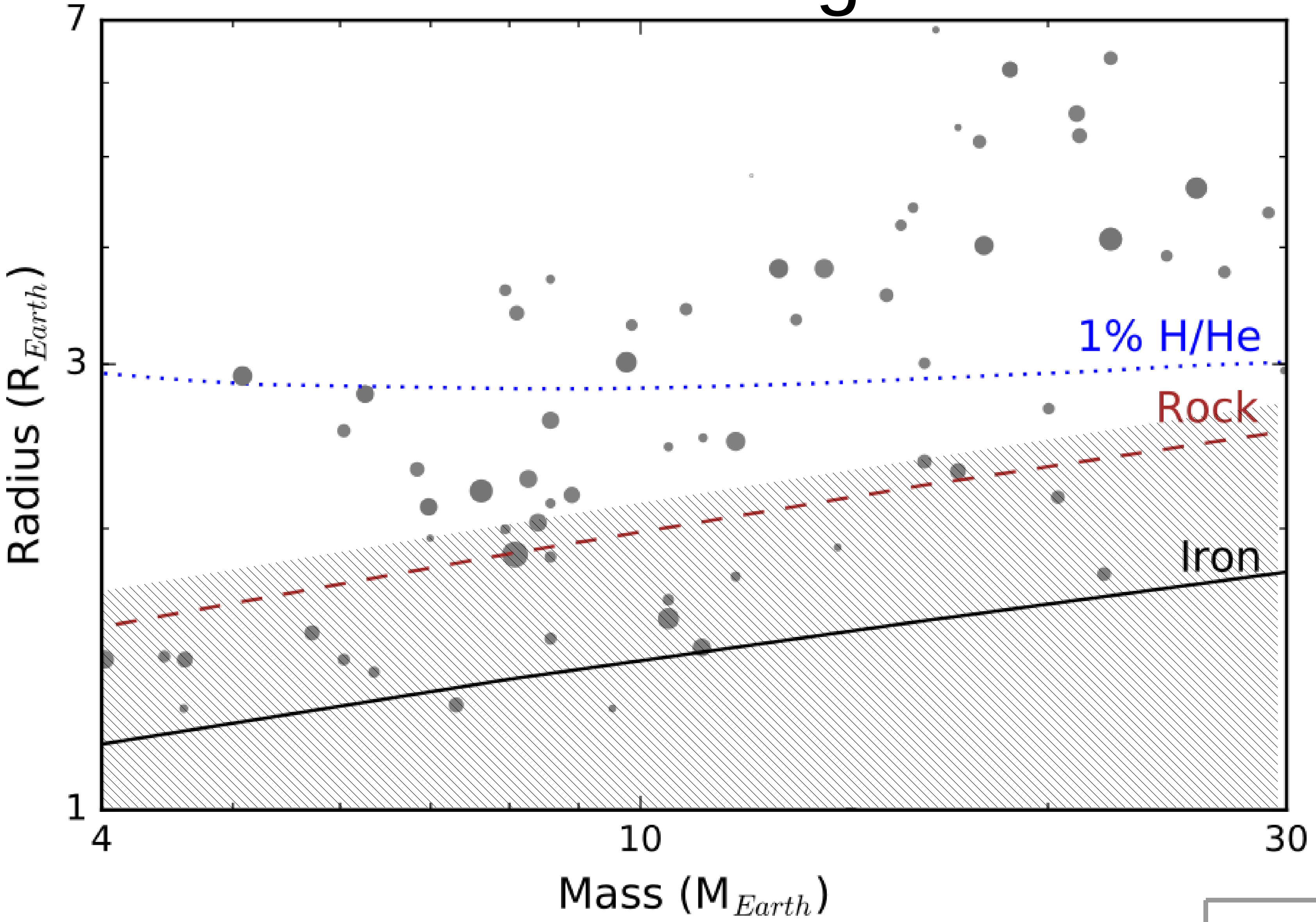
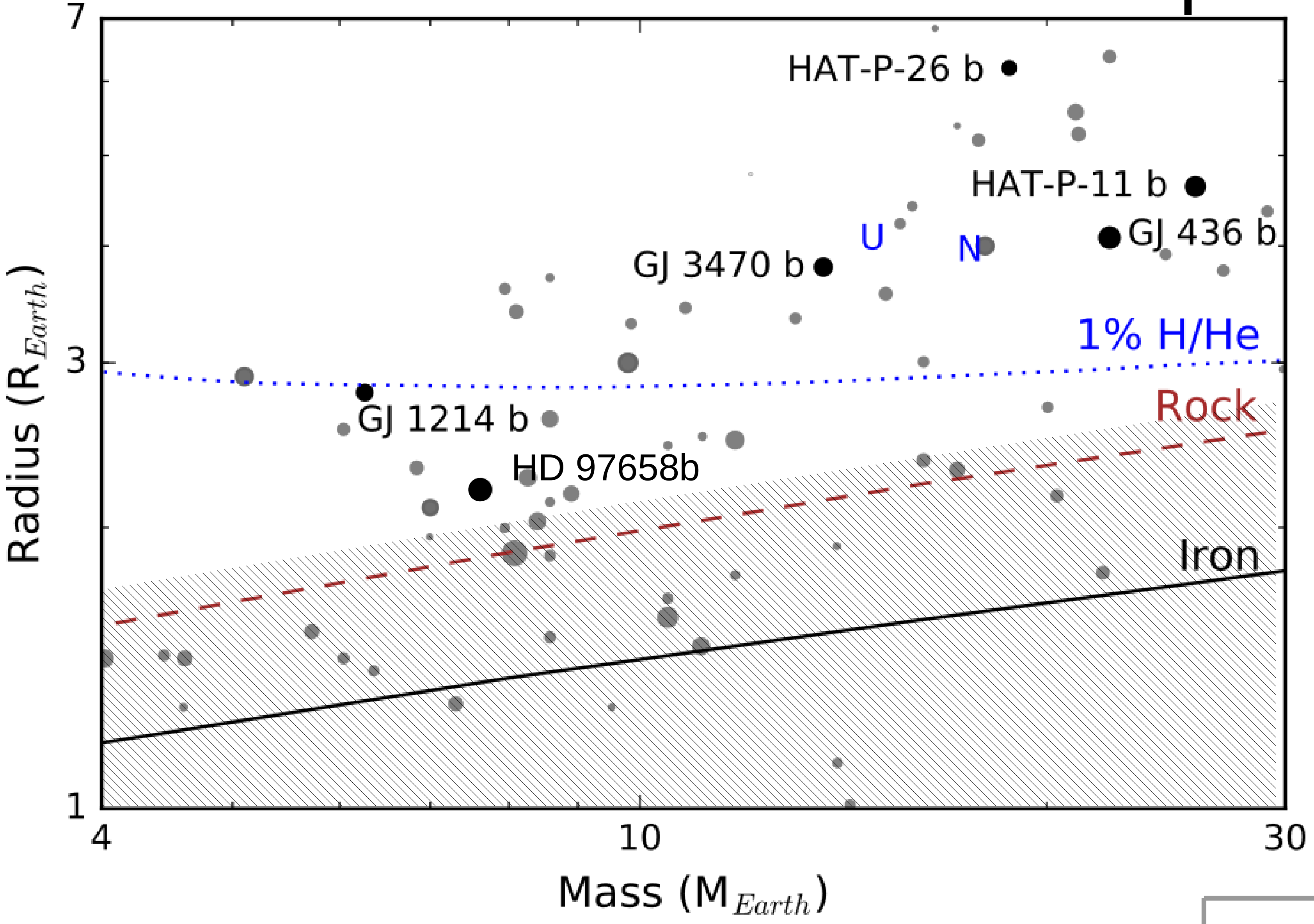
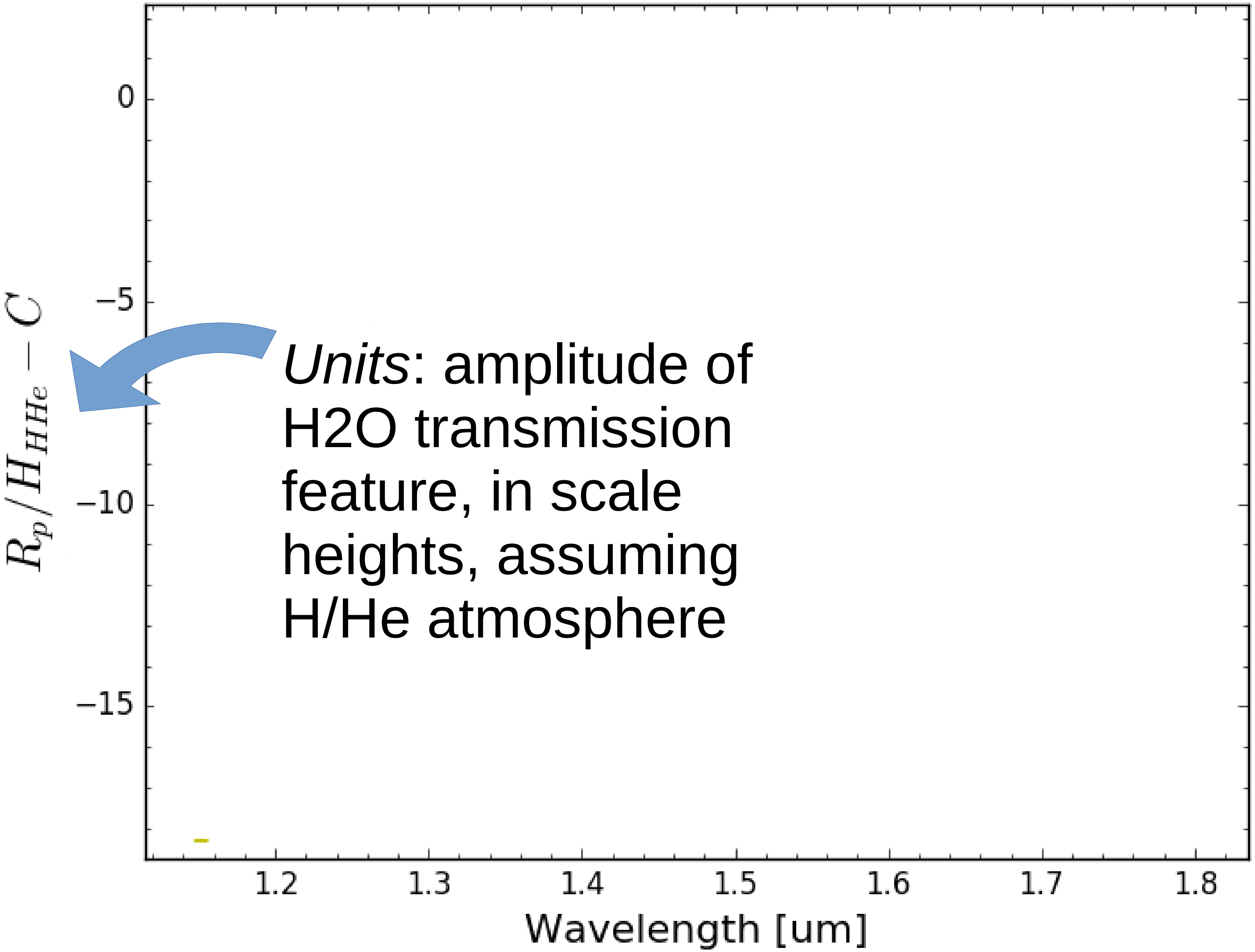


Atmospheric measurements have been made for six low-mass planets:



Transmission spectroscopy of six low-mass exoplanets:



Units: amplitude of H2O transmission feature, in scale heights, assuming H/He atmosphere

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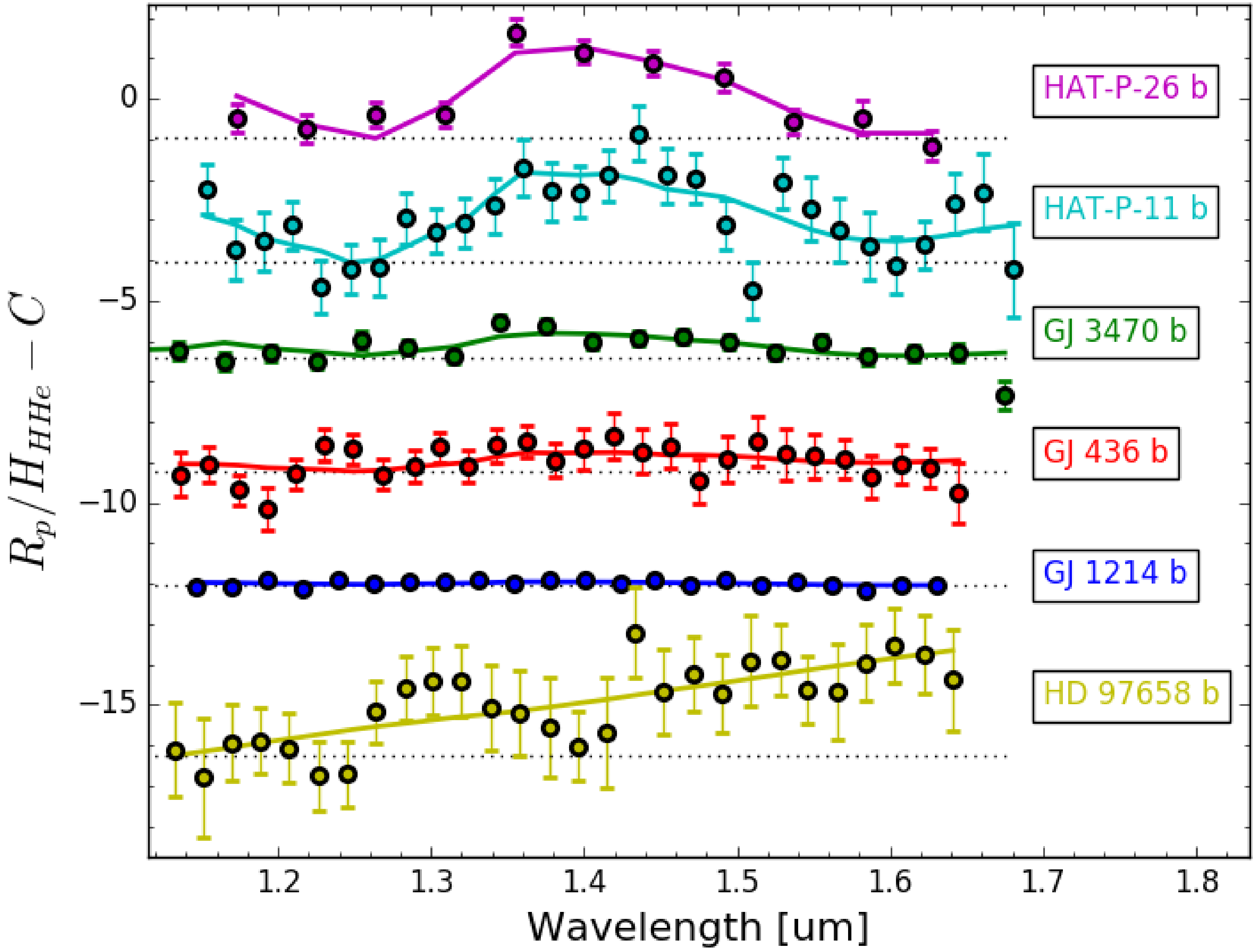

Wakeford et al. 2017

Fraine et al. 2014

Tsiaras et al. 2017

Knutson et al. 2014b

Kreidberg et al. 2014

Knutson et al. 2014a

Crossfield &
Kreidberg 2017

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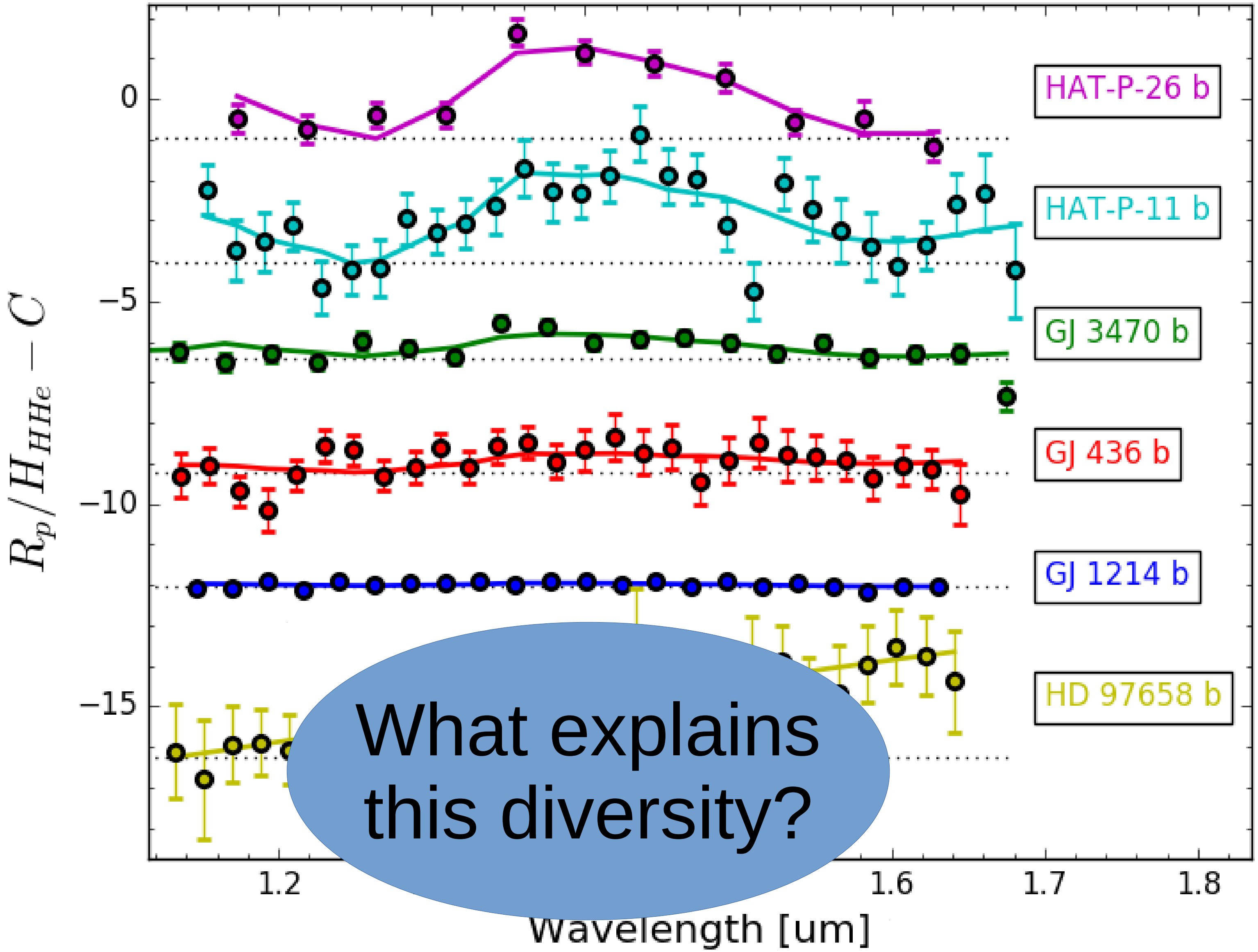

What explains this diversity?

Wakeford et al. 2017

Fraine et al. 2014

Tsiaras et al. 2017

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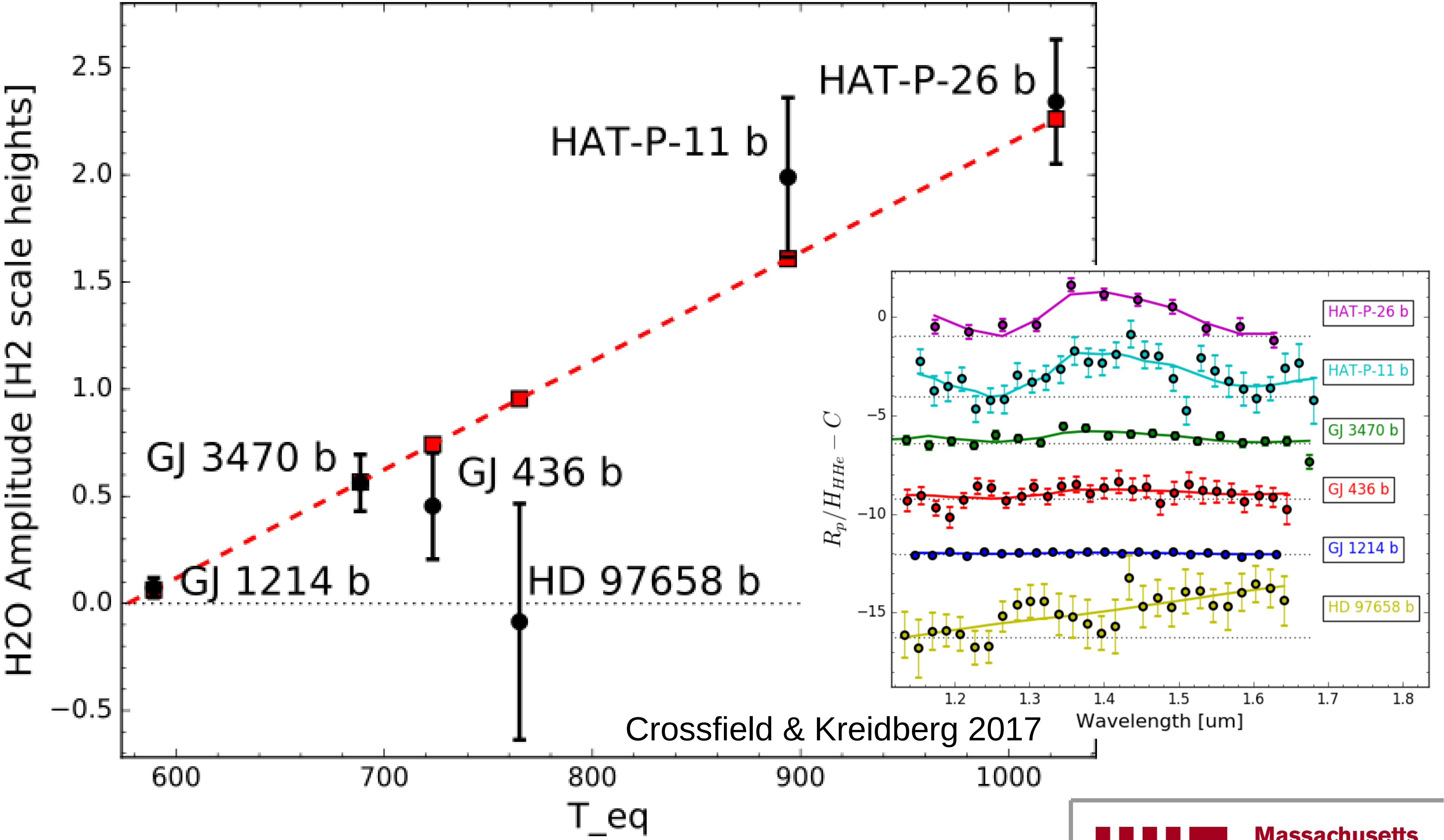
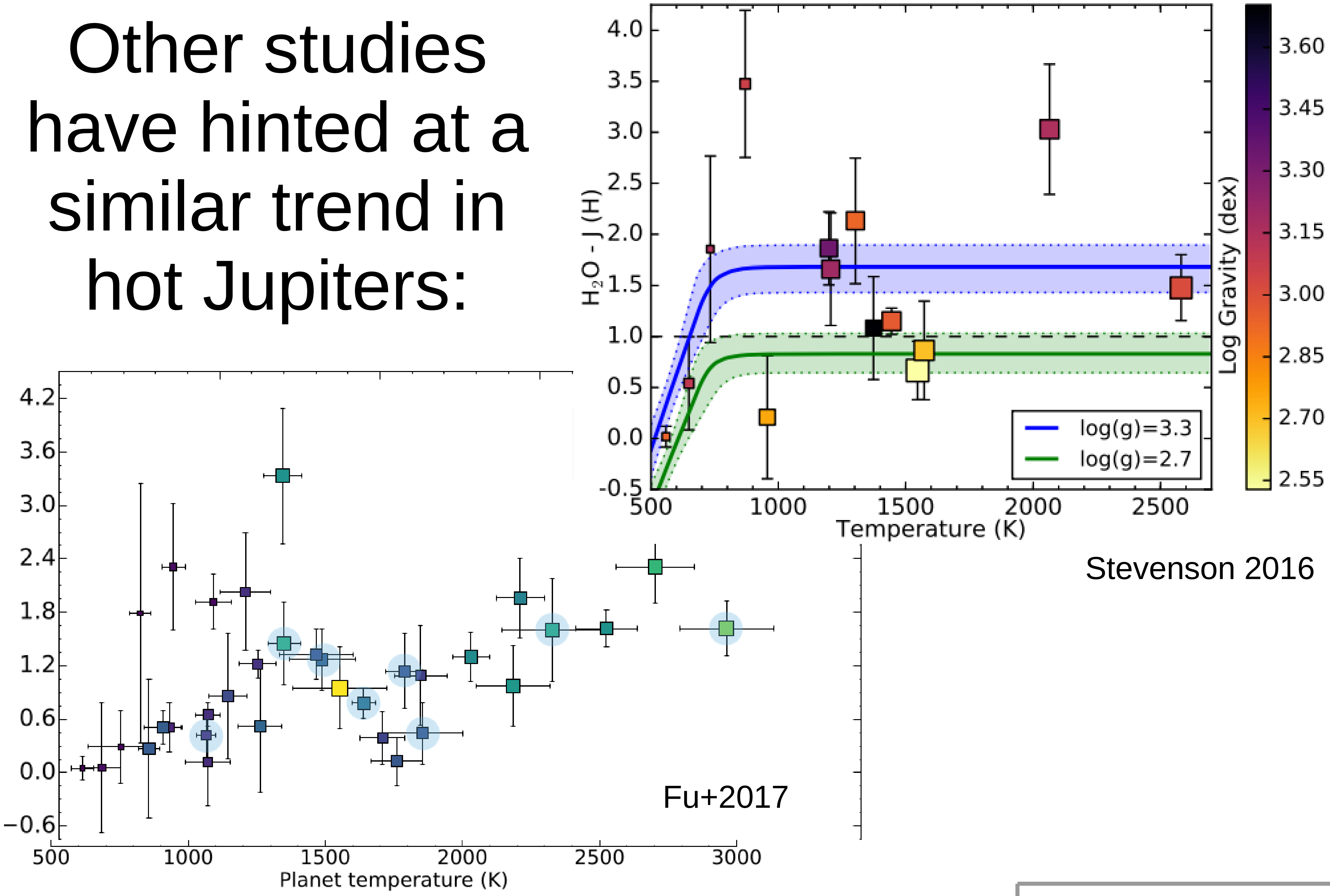
Crossfield & Kreidberg 2017

(1) For low-mass planets, transmission amplitude scales with equilibrium temperature:



Crossfield & Kreidberg 2017

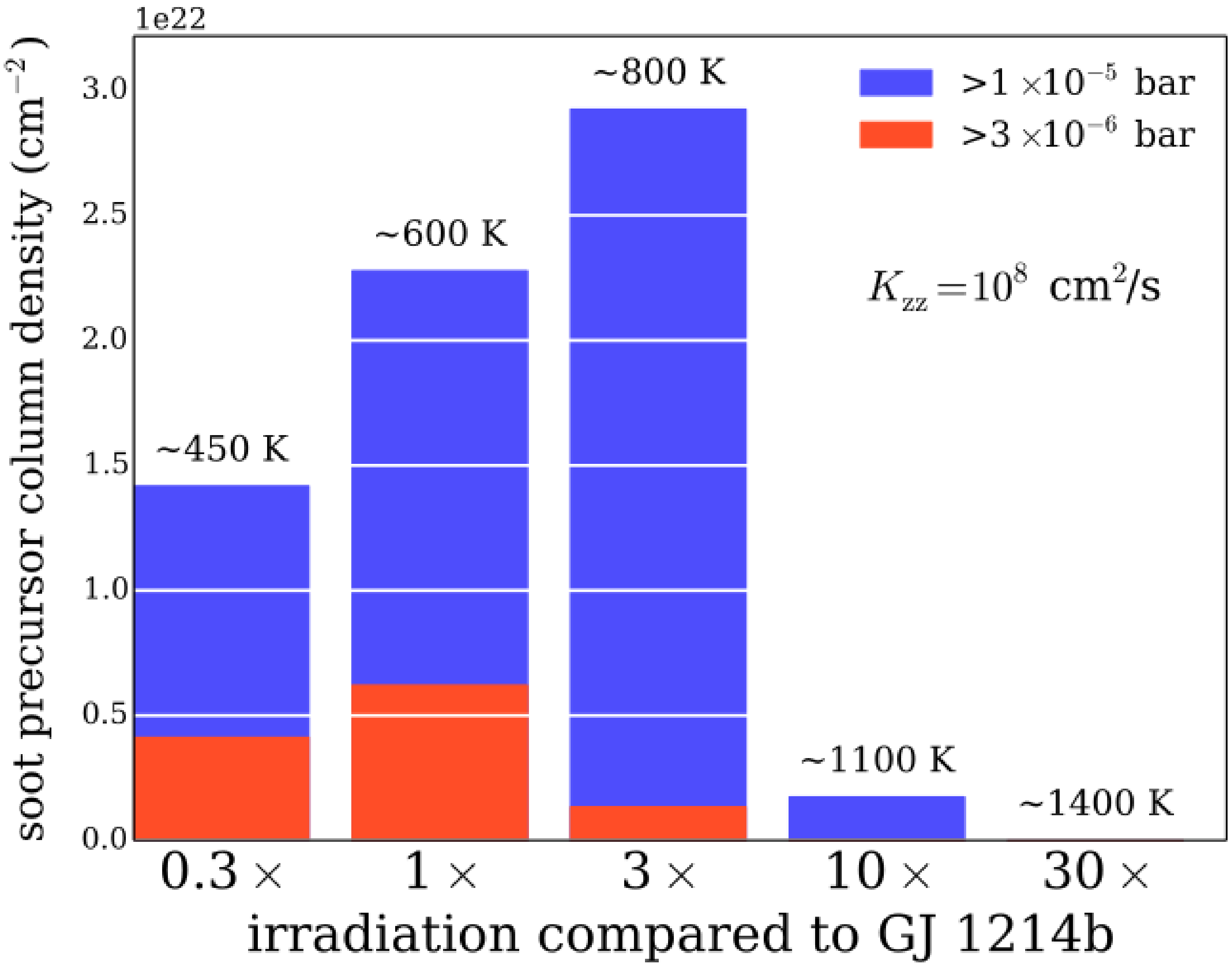
Other studies have hinted at a similar trend in hot Jupiters:



Stevenson 2016

Fu+2017

Are low-mass planets below 900 K covered in obscuring hazes?



Morley et al. 2015

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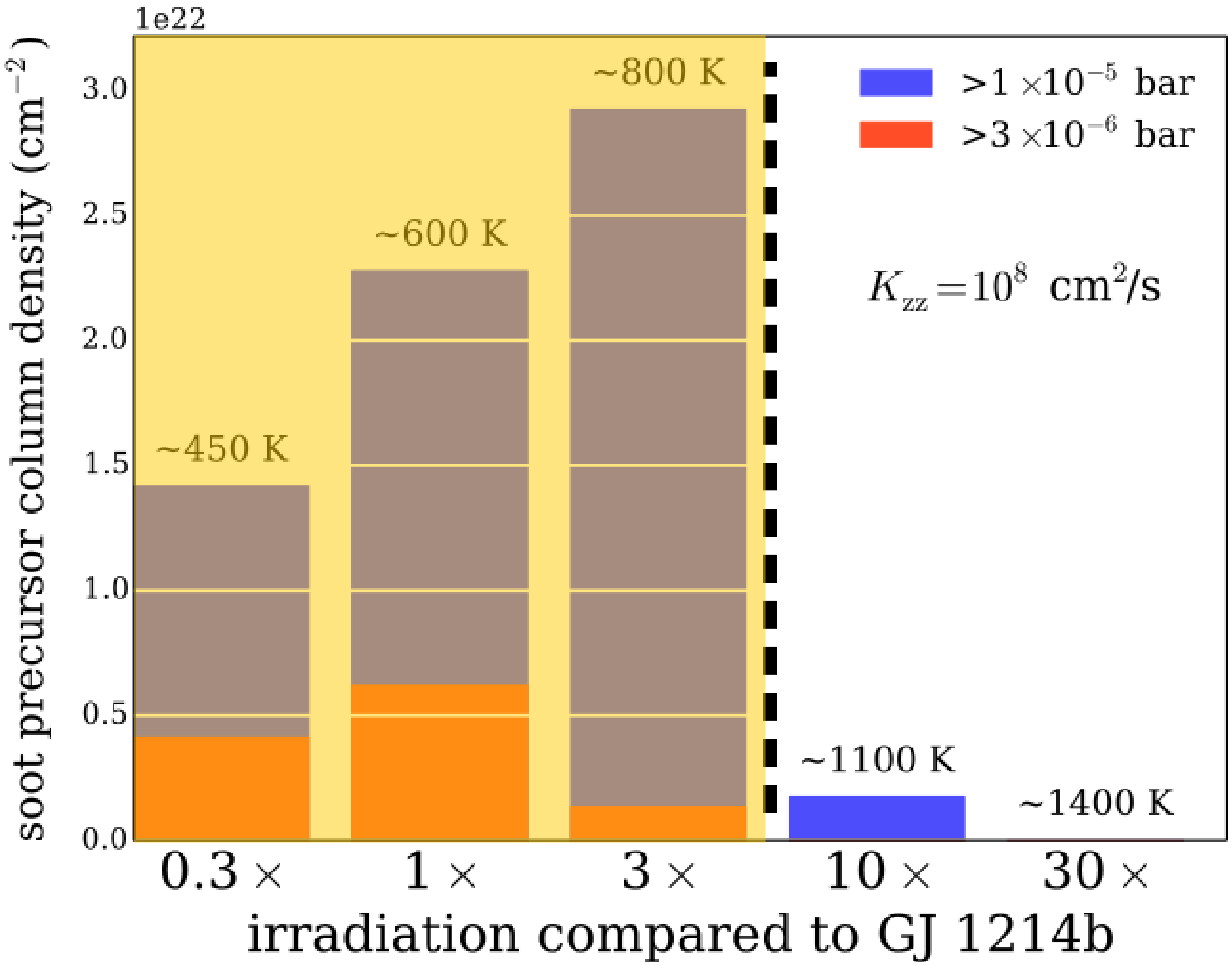
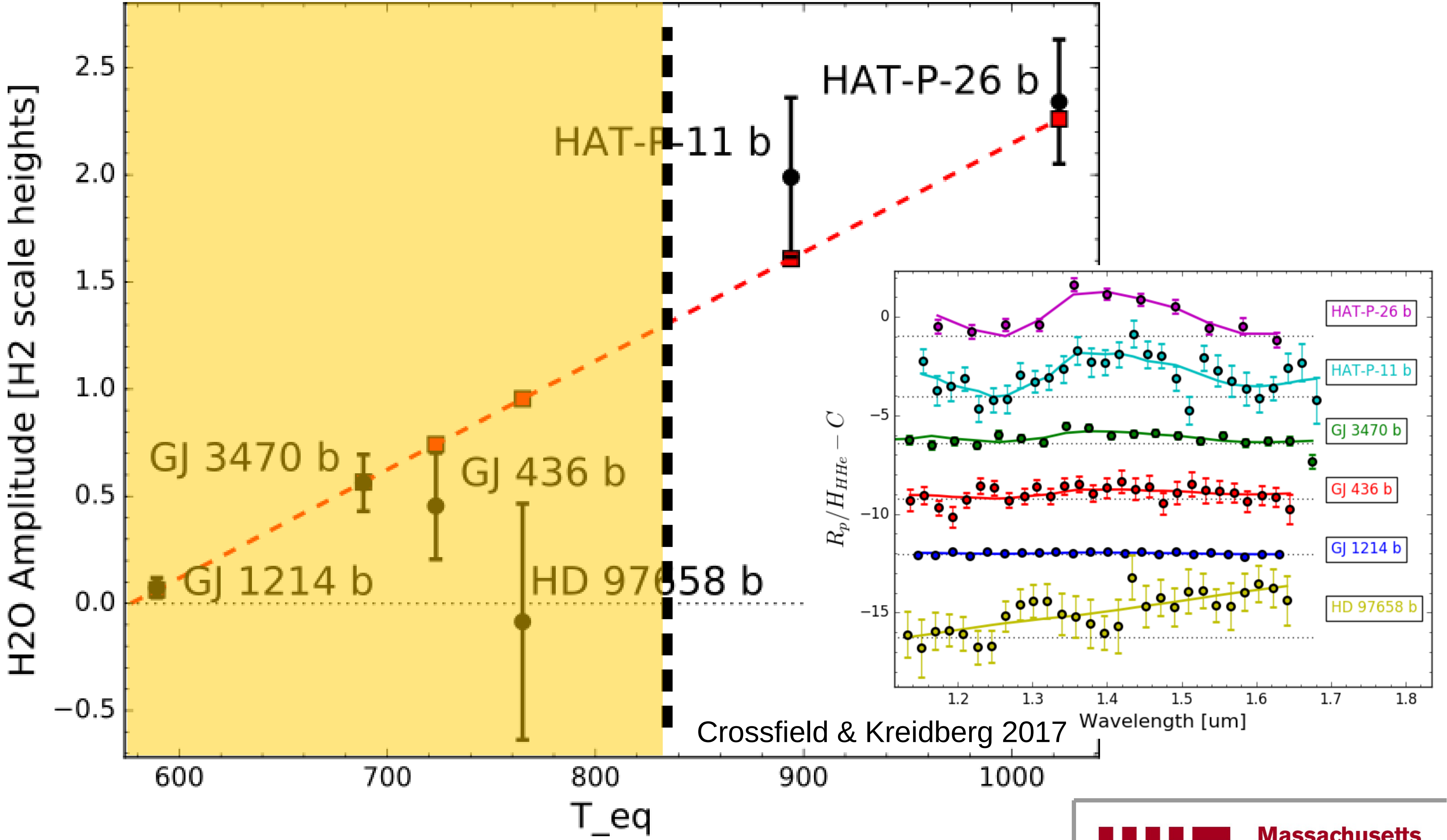


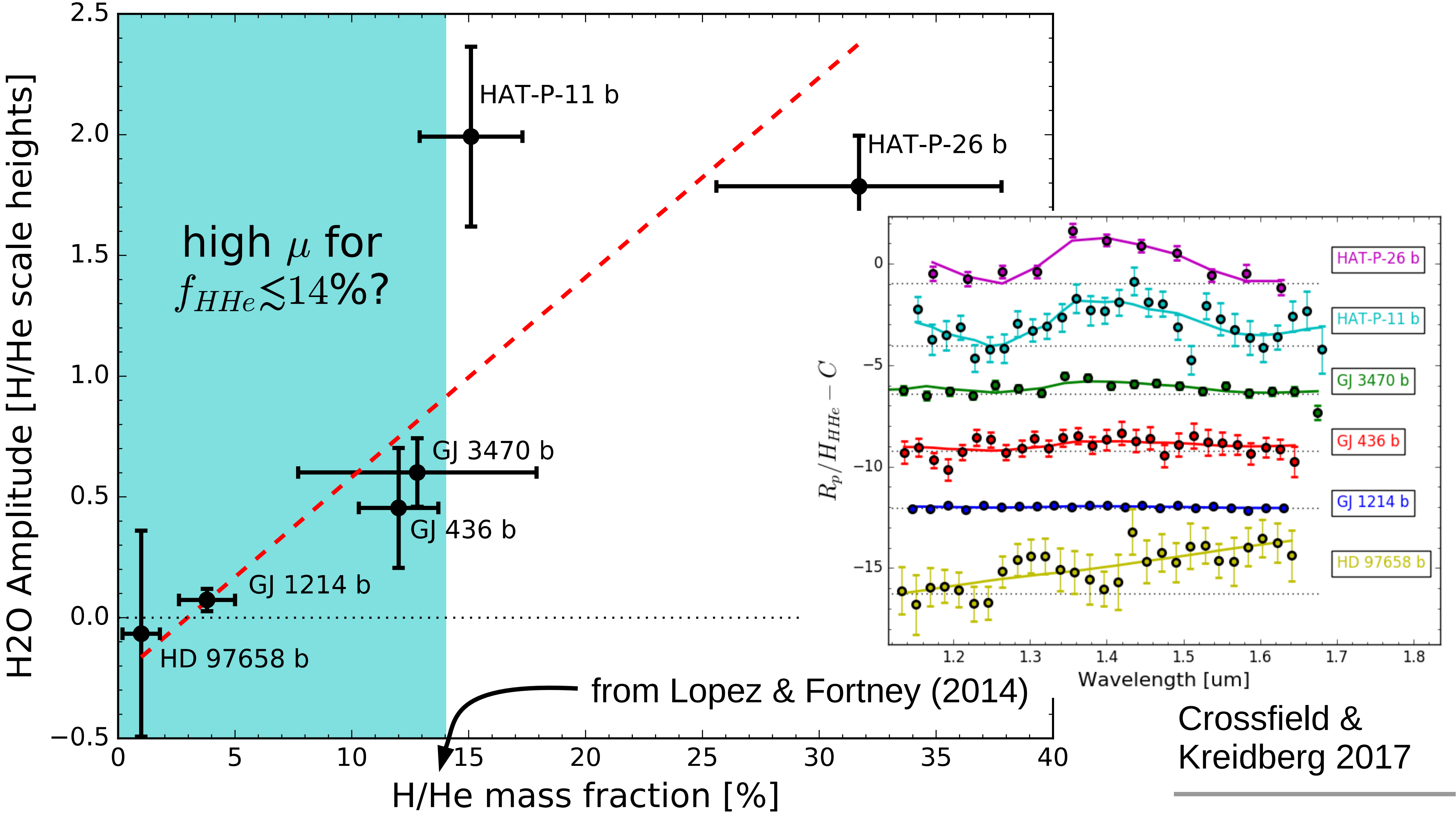
Morley et al. 2015

Maybe cooler planets are mostly hazy, while warmer planets are mostly clear:



Crossfield & Kreidberg 2017

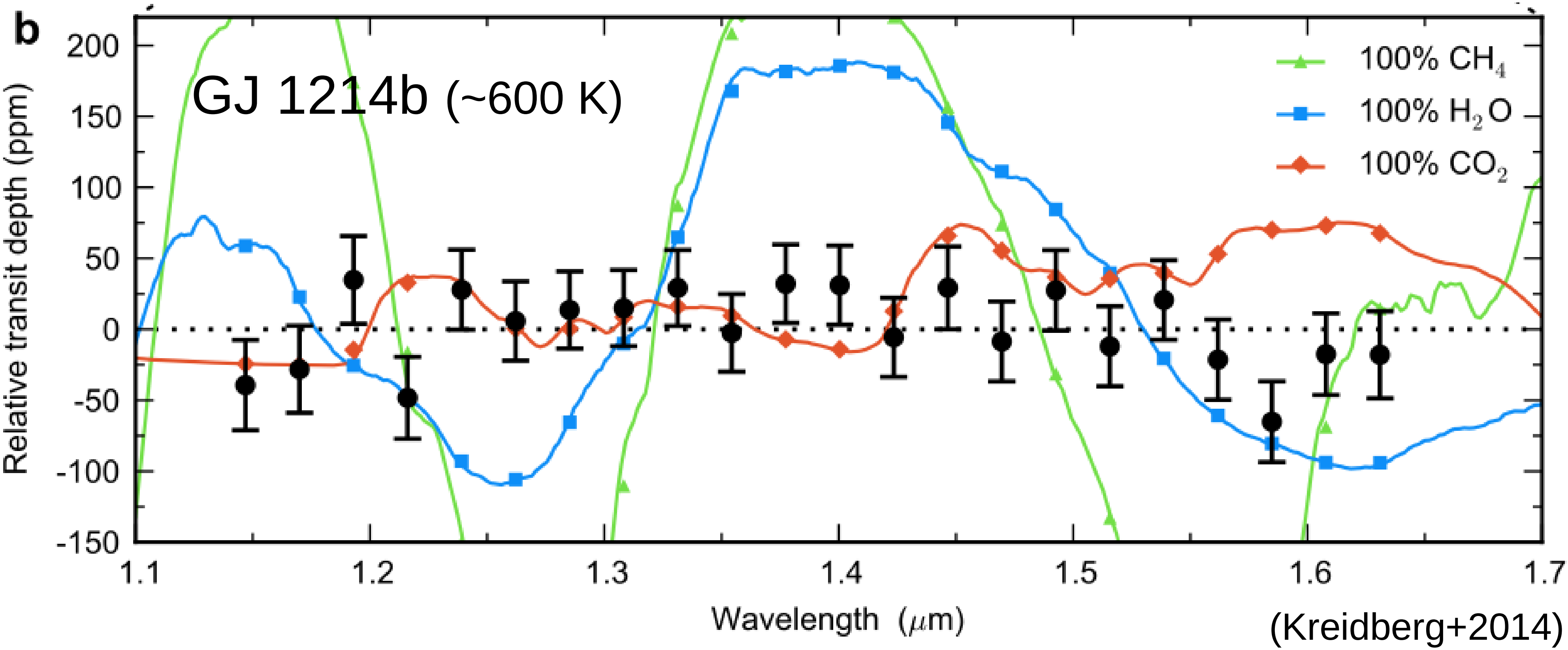
(2) For low-mass planets, transmission amplitude also scales with H/He mass fraction:



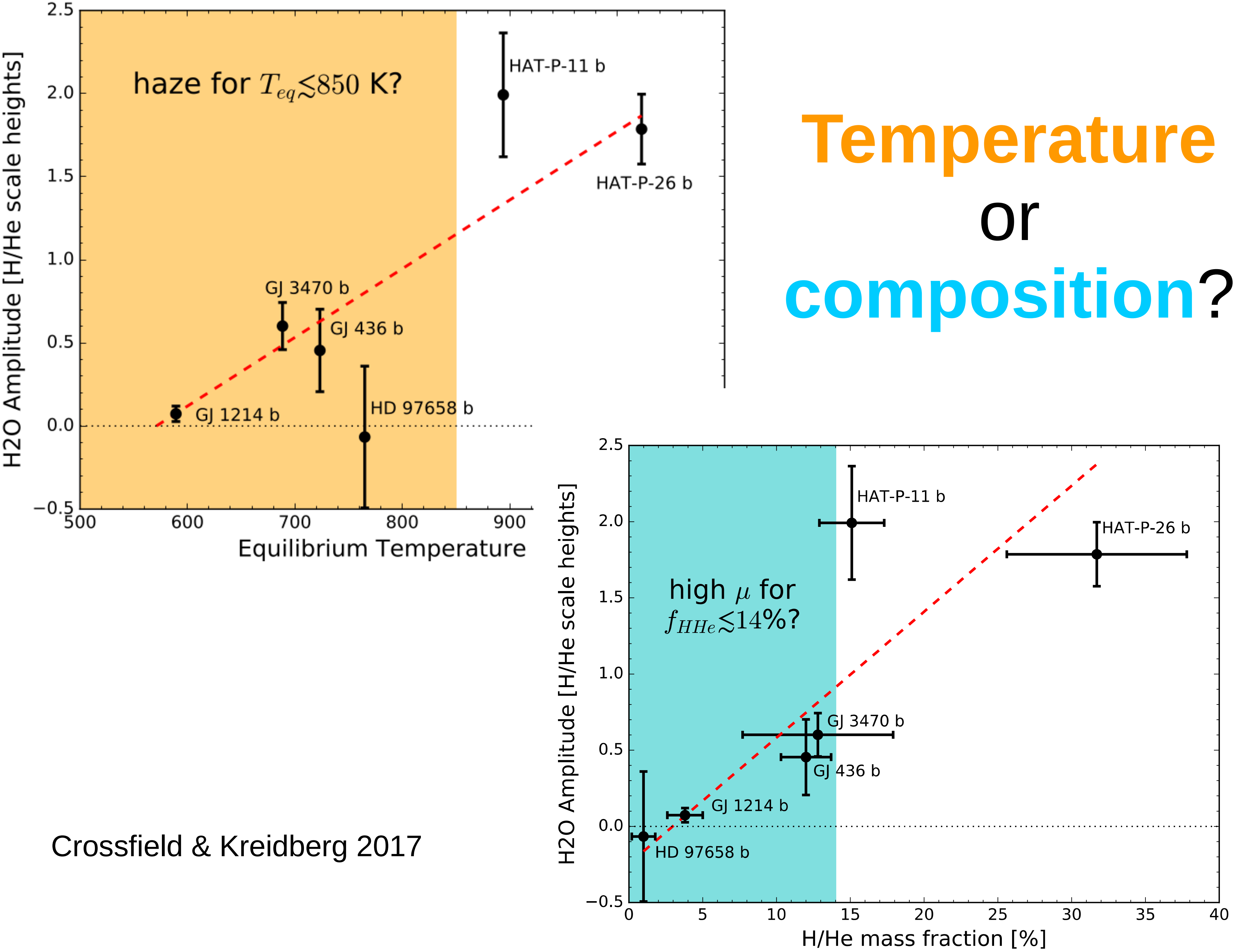
from Lopez & Fortney (2014)

Crossfield & Kreidberg 2017

BUT: GJ 1214b is too flat to be explained by metallicity alone:



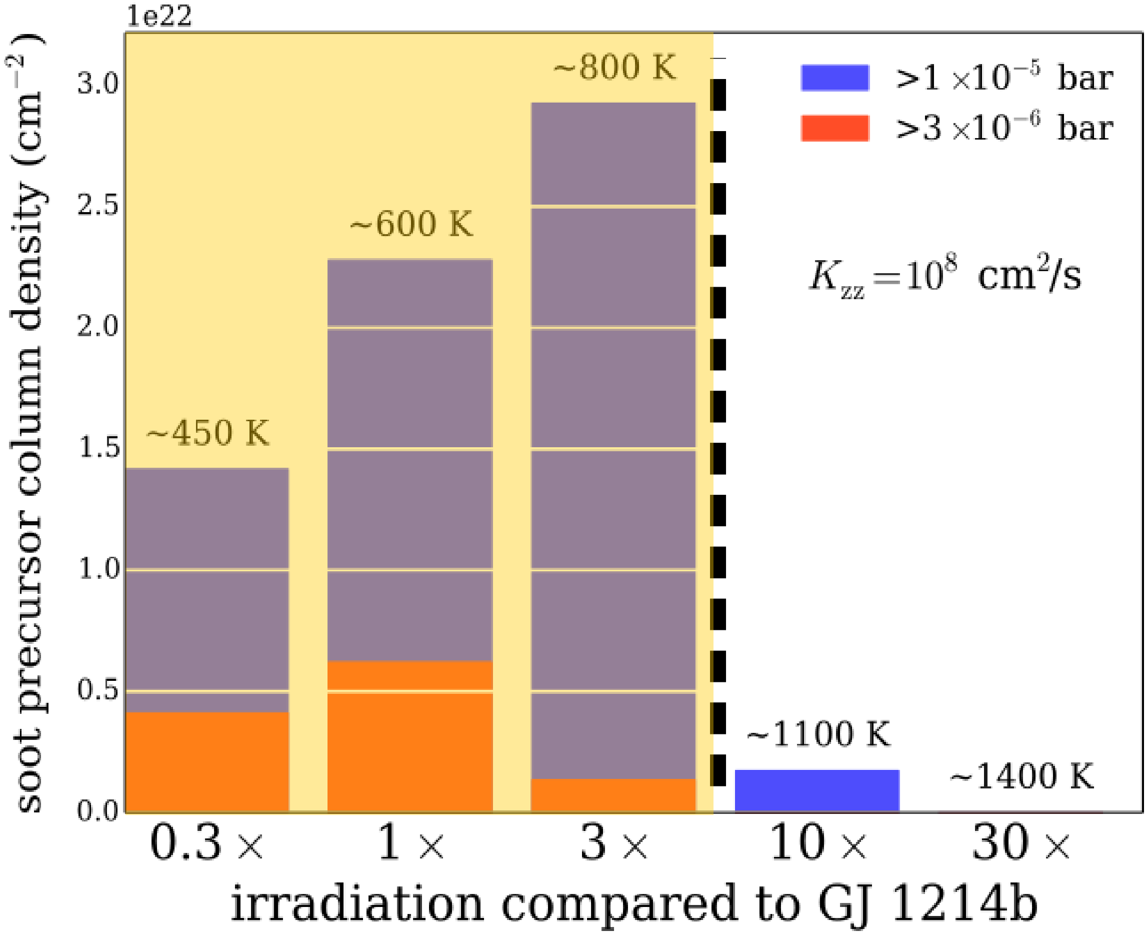
(Kreidberg+2014)

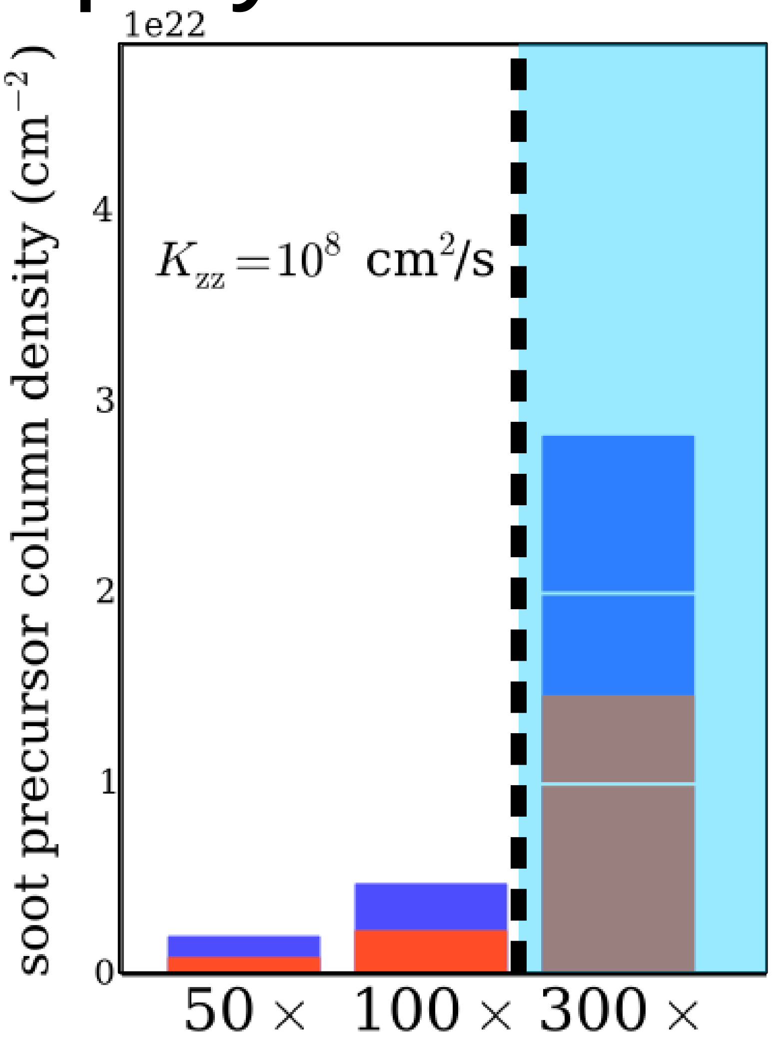


Temperature or **composition**?

Crossfield & Kreidberg 2017

Maybe both **temperature** *and* **metal enhancement** play a role:

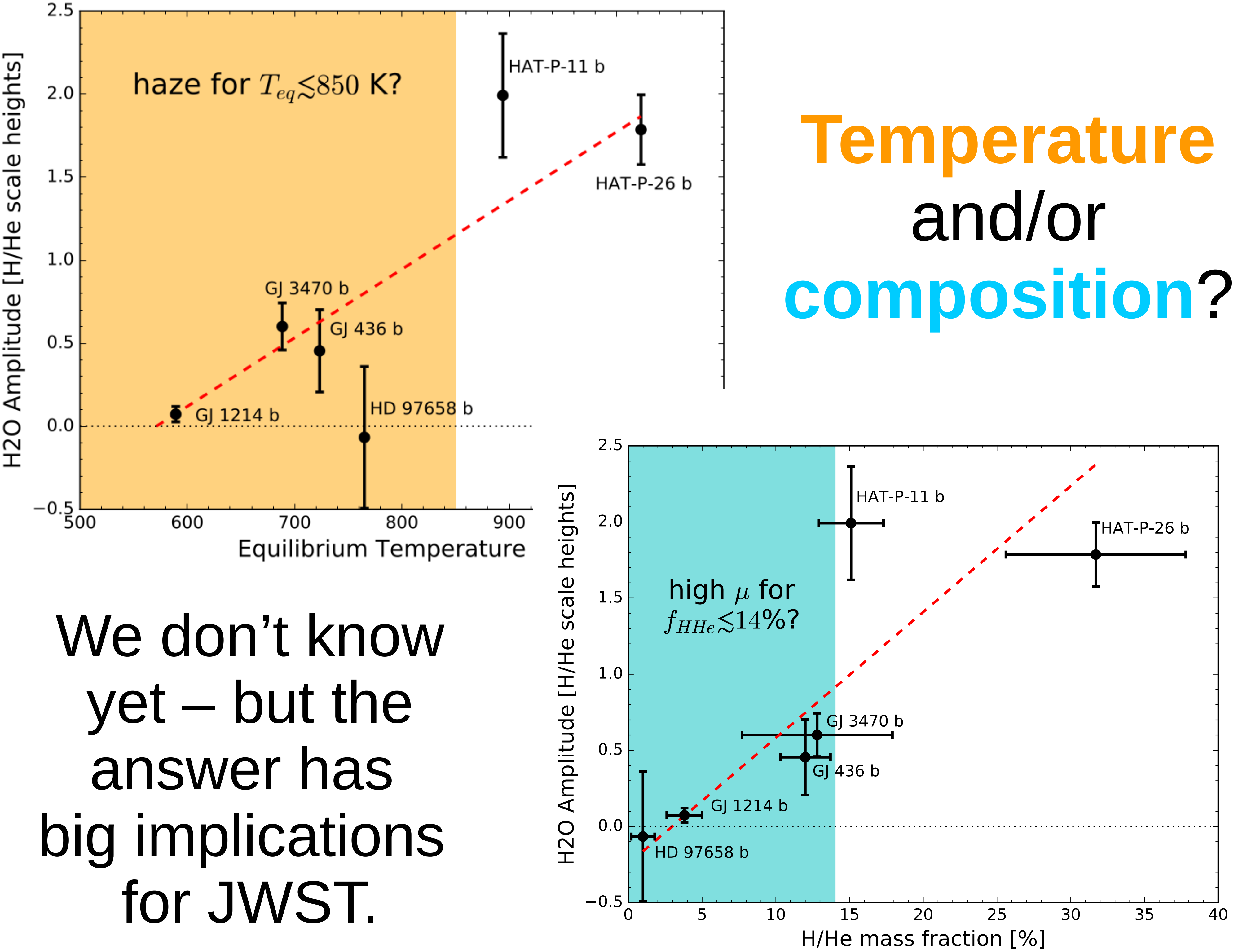




Metallicity (x Solar)

Morley et al. 2015

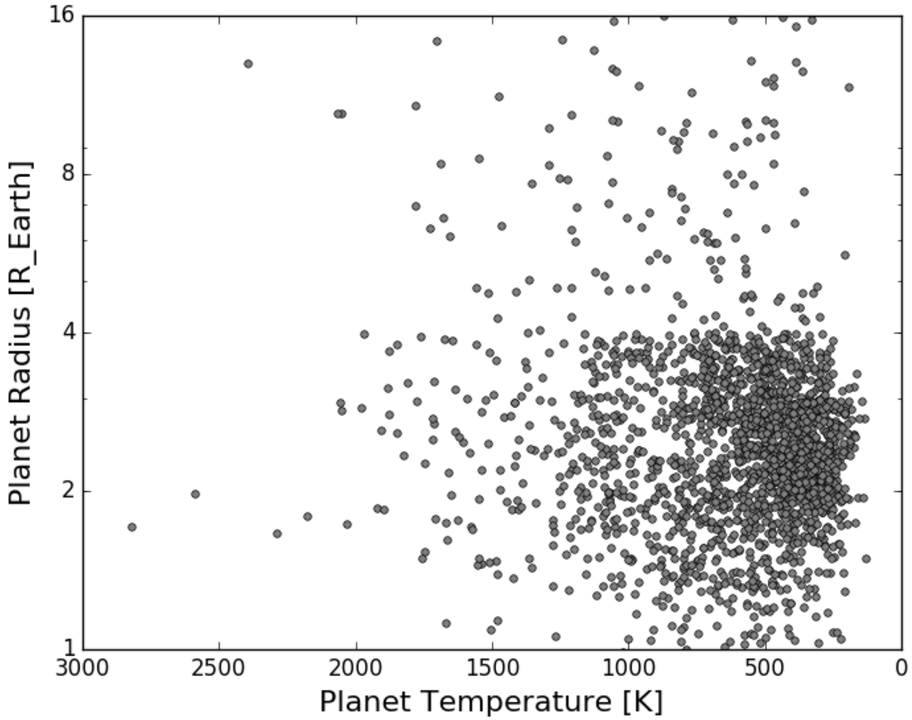
Temperature and/or **composition**?

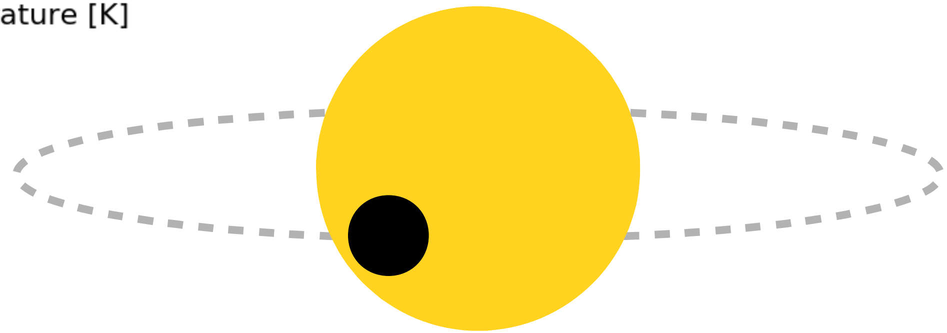


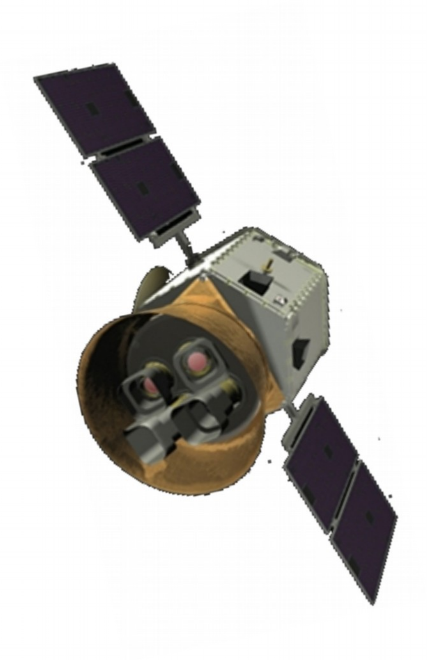
We don't know yet – but the answer has big implications for JWST.

TESS & JWST:

TESS simulated planet yield:
(Sullivan et al. 2015)







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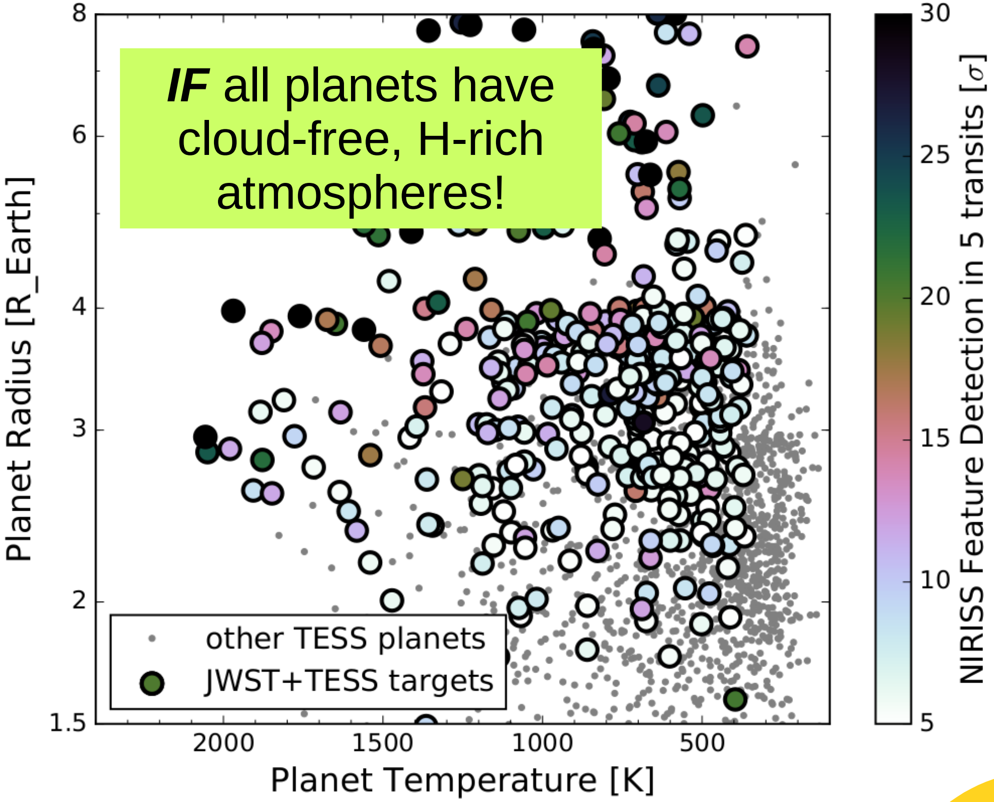
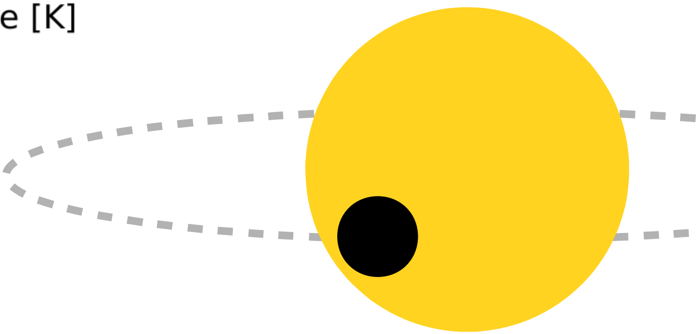

IF **all planets have cloud-free, H-rich atmospheres!**



How many TESS Neptunes could JWST characterize?

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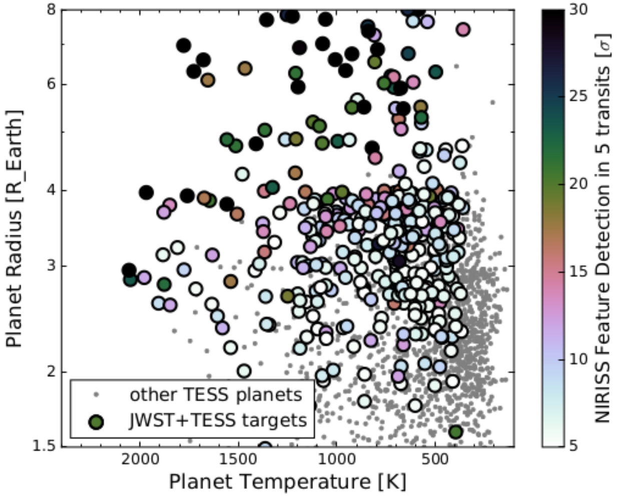

hundreds of Neptunes! :-)

(We require 5-sigma JWST/NIRISS detection with 5 transits)

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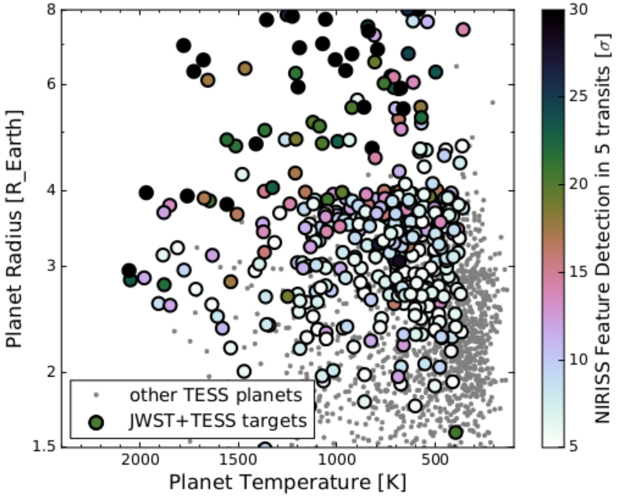

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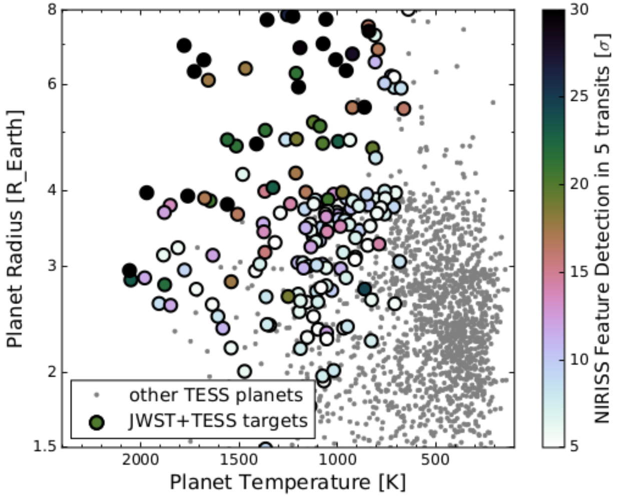

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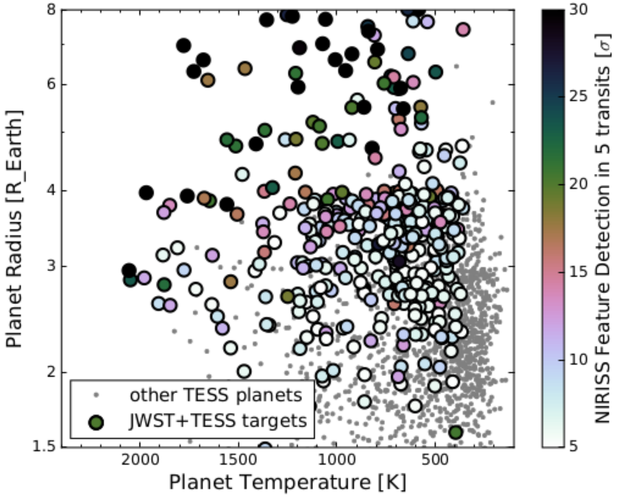

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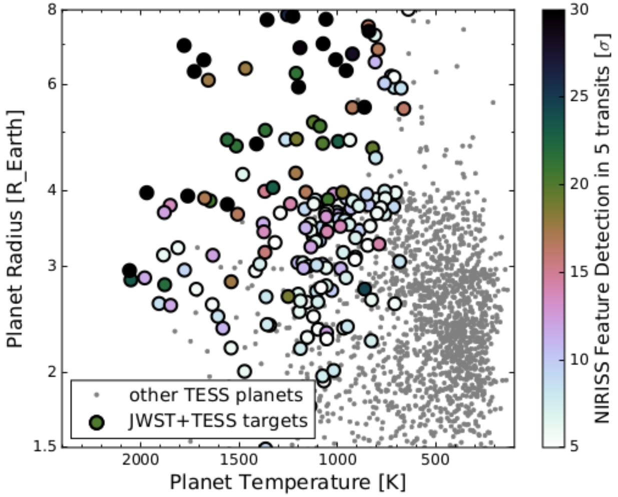
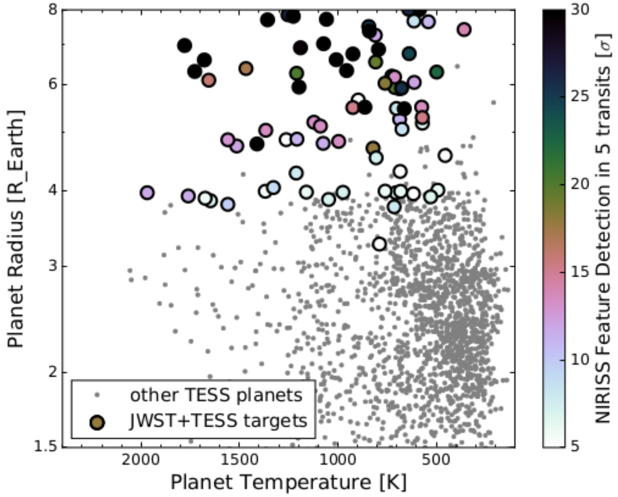


dozens of Neptunes! :-/

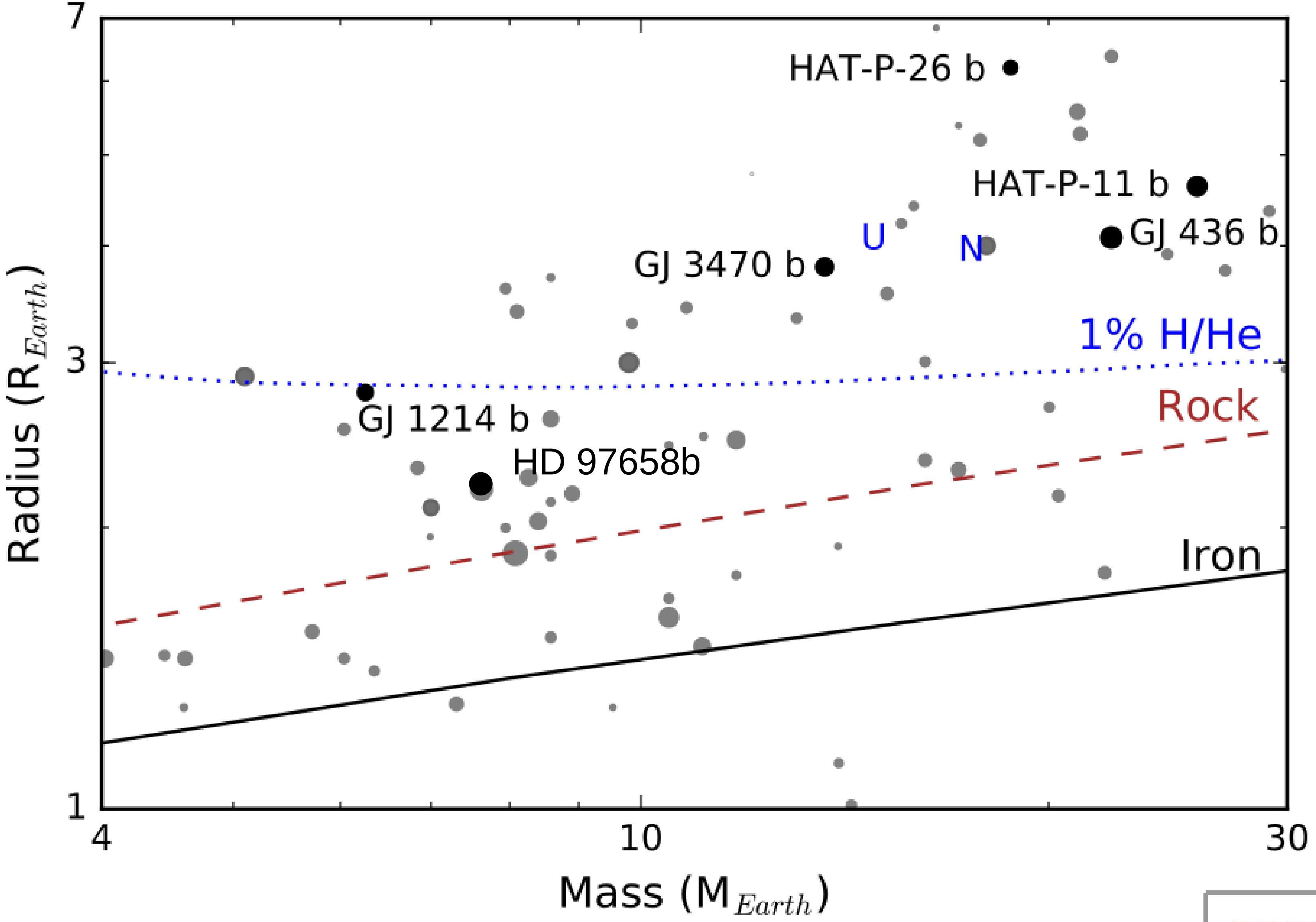
If atmospheric features scale with bulk composition:



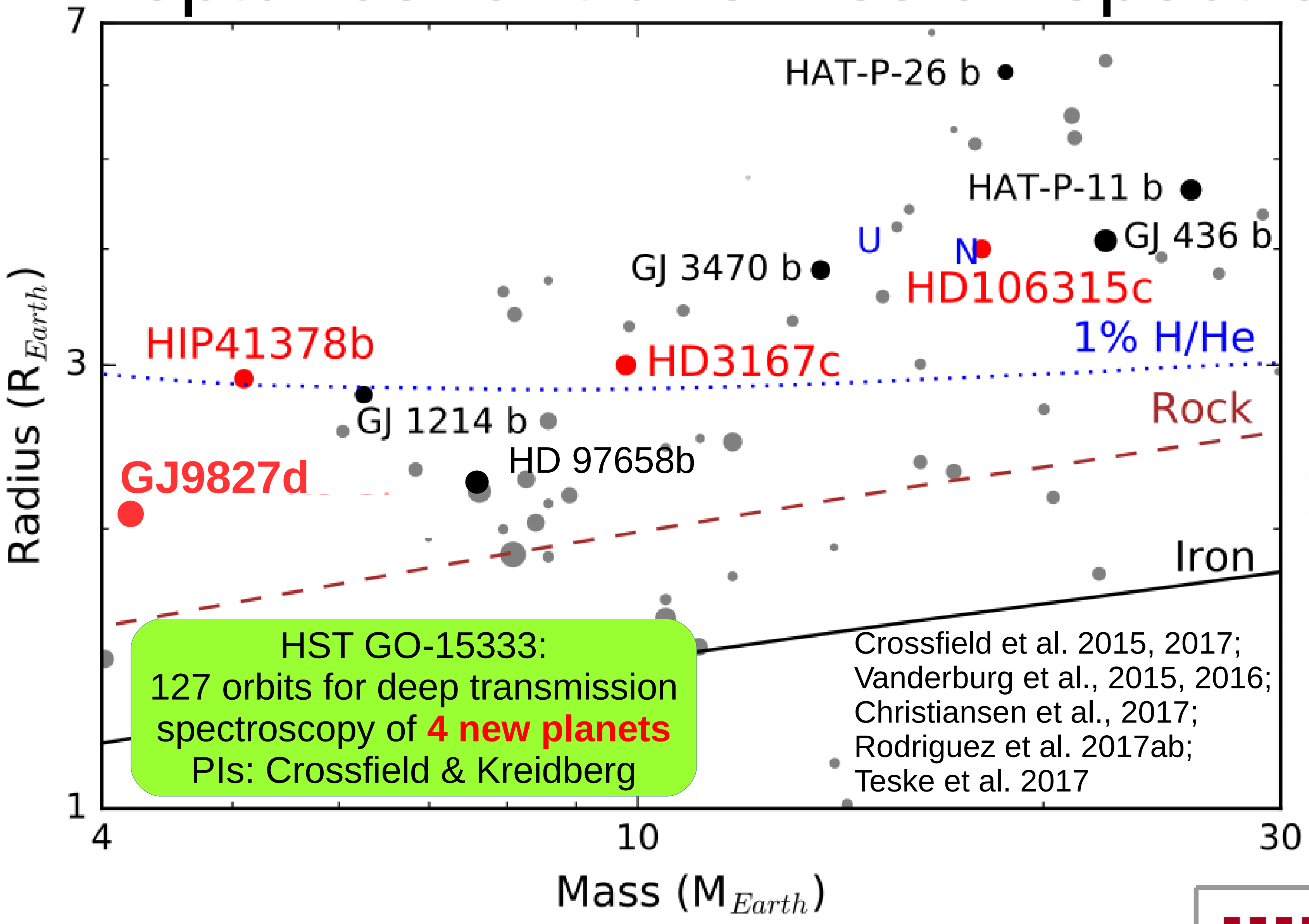
A few tens of Neptunes! :-(

(We require 5-sigma JWST/NIRISS detection with 5 transits)

Our current sample is too small to know whether Teq or H/He fraction plays a larger role:

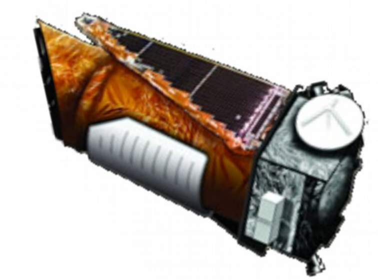


Luckily, K2 is already finding many new Neptunes for transmission spectroscopy:



HST GO-15333:
127 orbits for deep transmission spectroscopy of **4 new planets**
PIs: Crossfield & Kreidberg

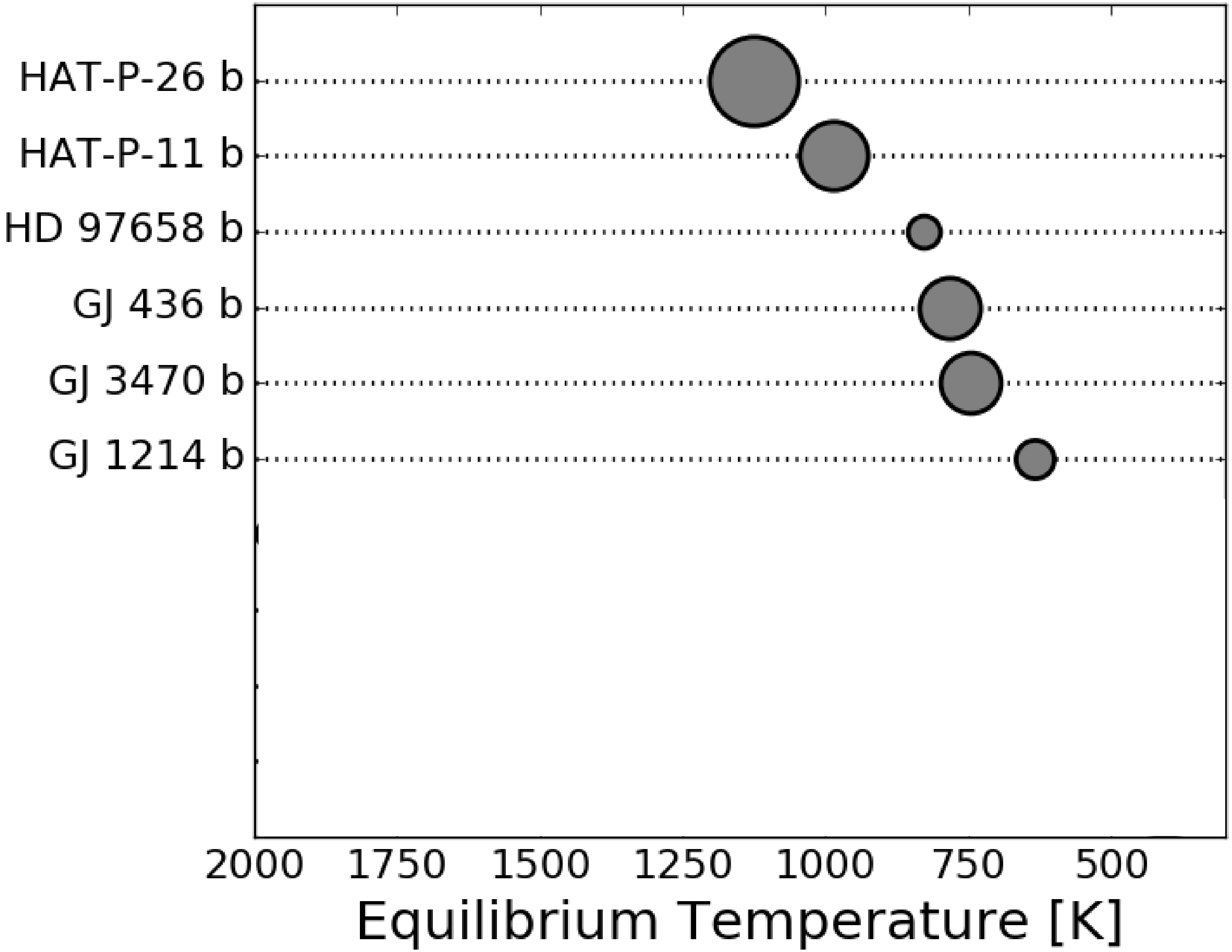
Crossfield et al. 2015, 2017;
Vanderburg et al., 2015, 2016;
Christiansen et al., 2017;
Rodriguez et al. 2017ab;
Teske et al. 2017



Conclusions:

- Transmission spectroscopy of warm Neptunes reveals possible trends with either:
  - Equilibrium temperature (haze/clouds?), *or*
  - Bulk H/He mass fraction (metal enhancement?)
- The current sample of sub-Neptunes is too small: luckily with K2 we are expanding the list of plausible targets.
- Next steps:
  - observe these new planets with HST!
  - prepare for TESS+JWST.

Multiplicity: a signpost of planet formation & migration?



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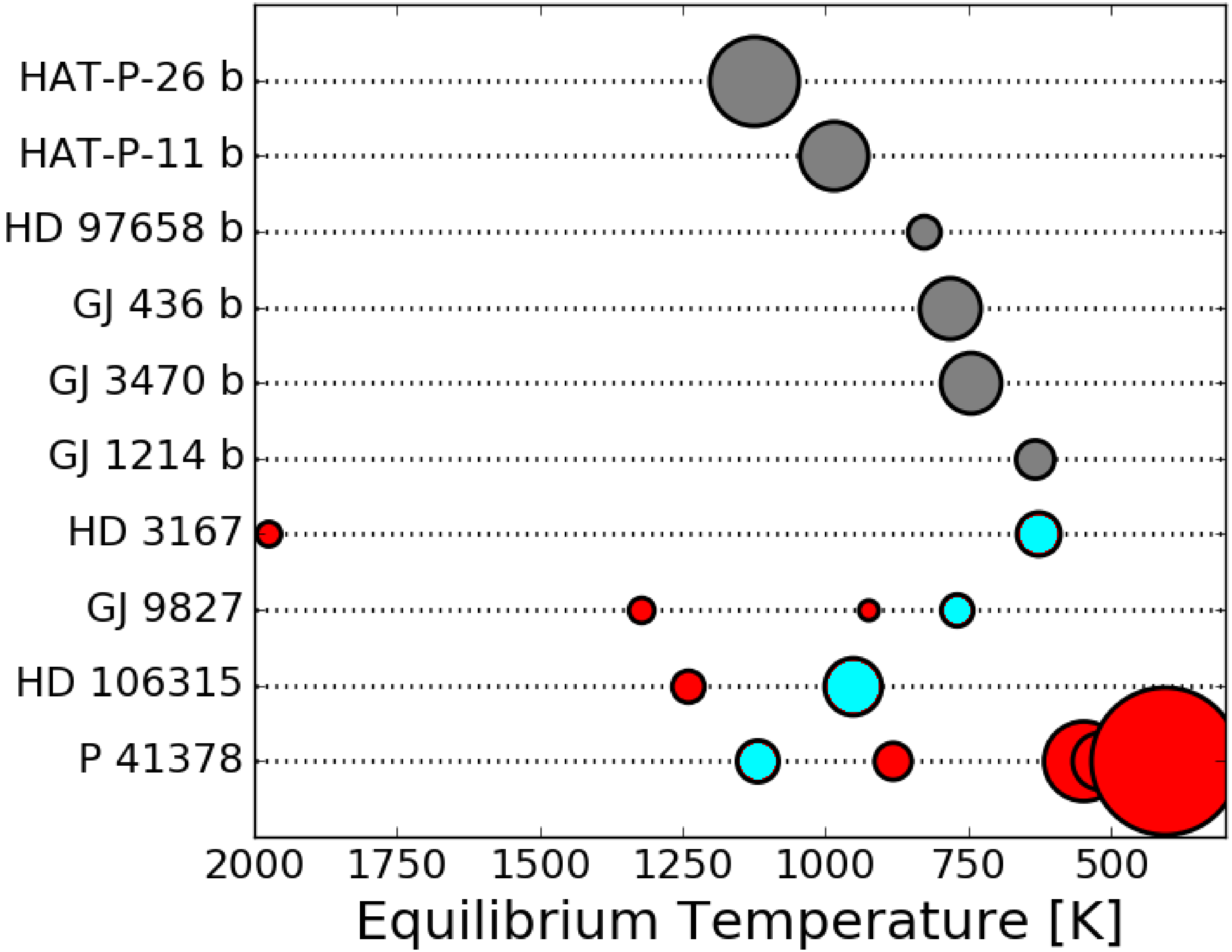
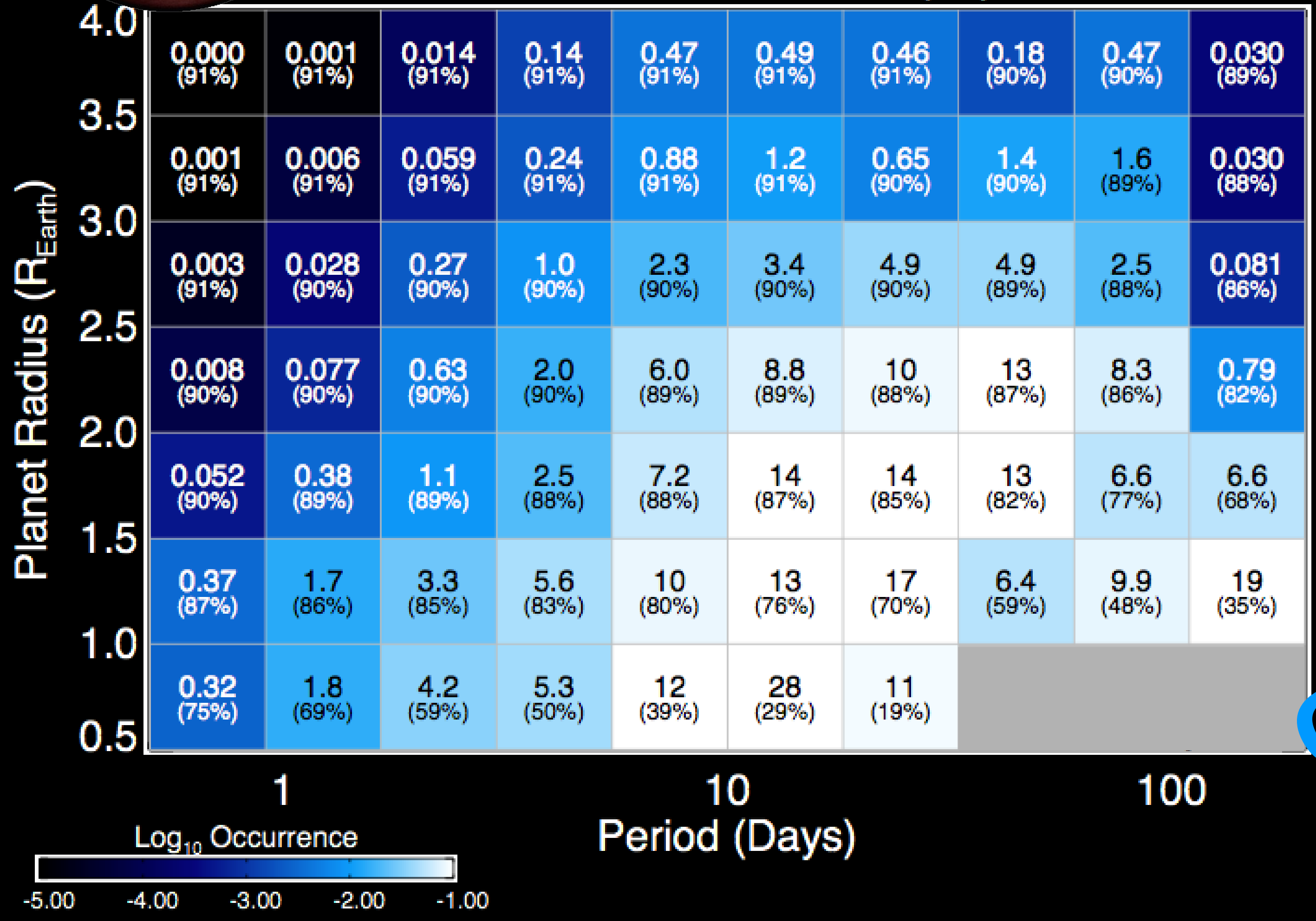


Small, Low-mass planets are extremely common:

(for both M stars & FGKs)

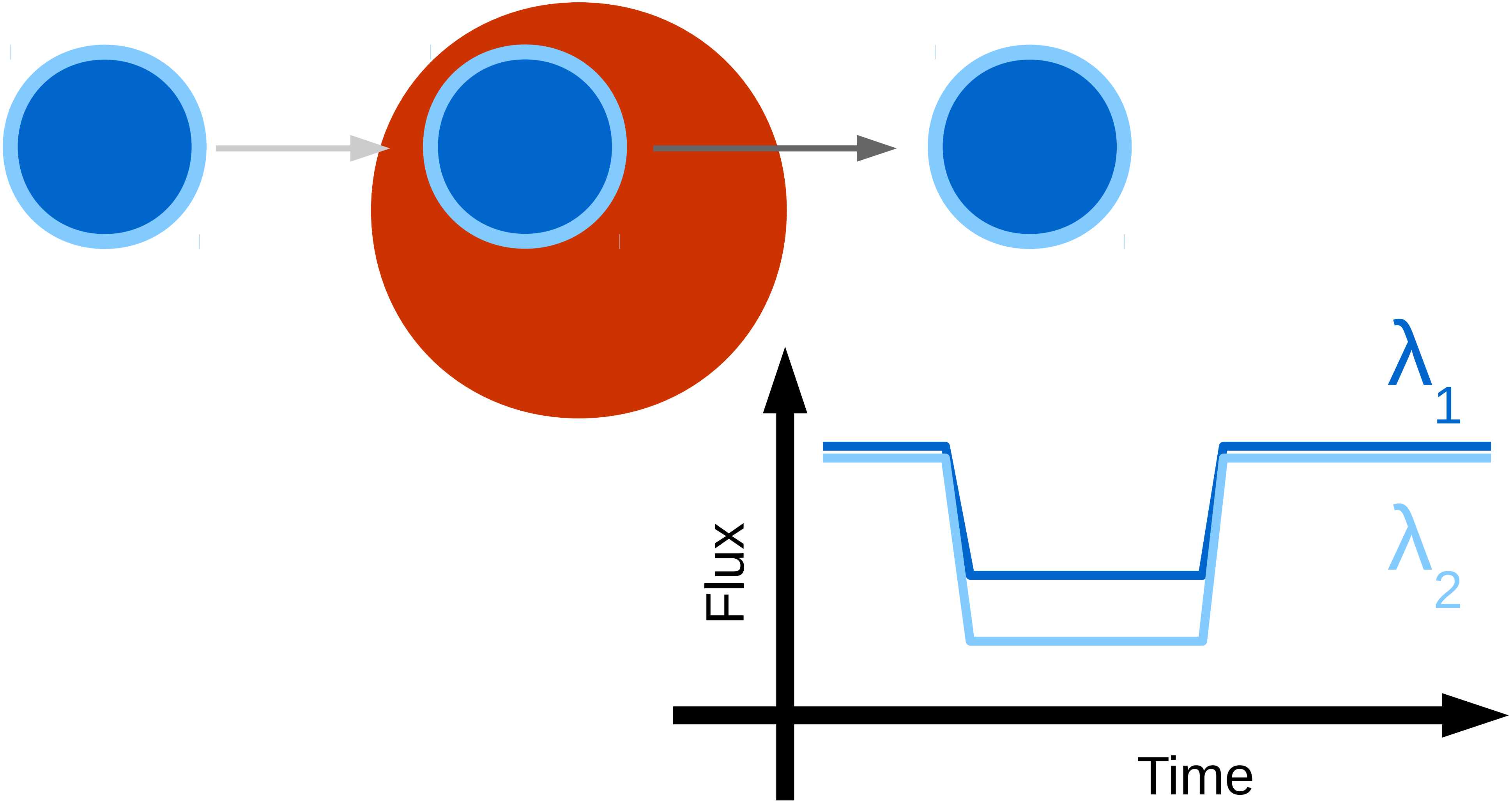
Planet Occurrence (%)



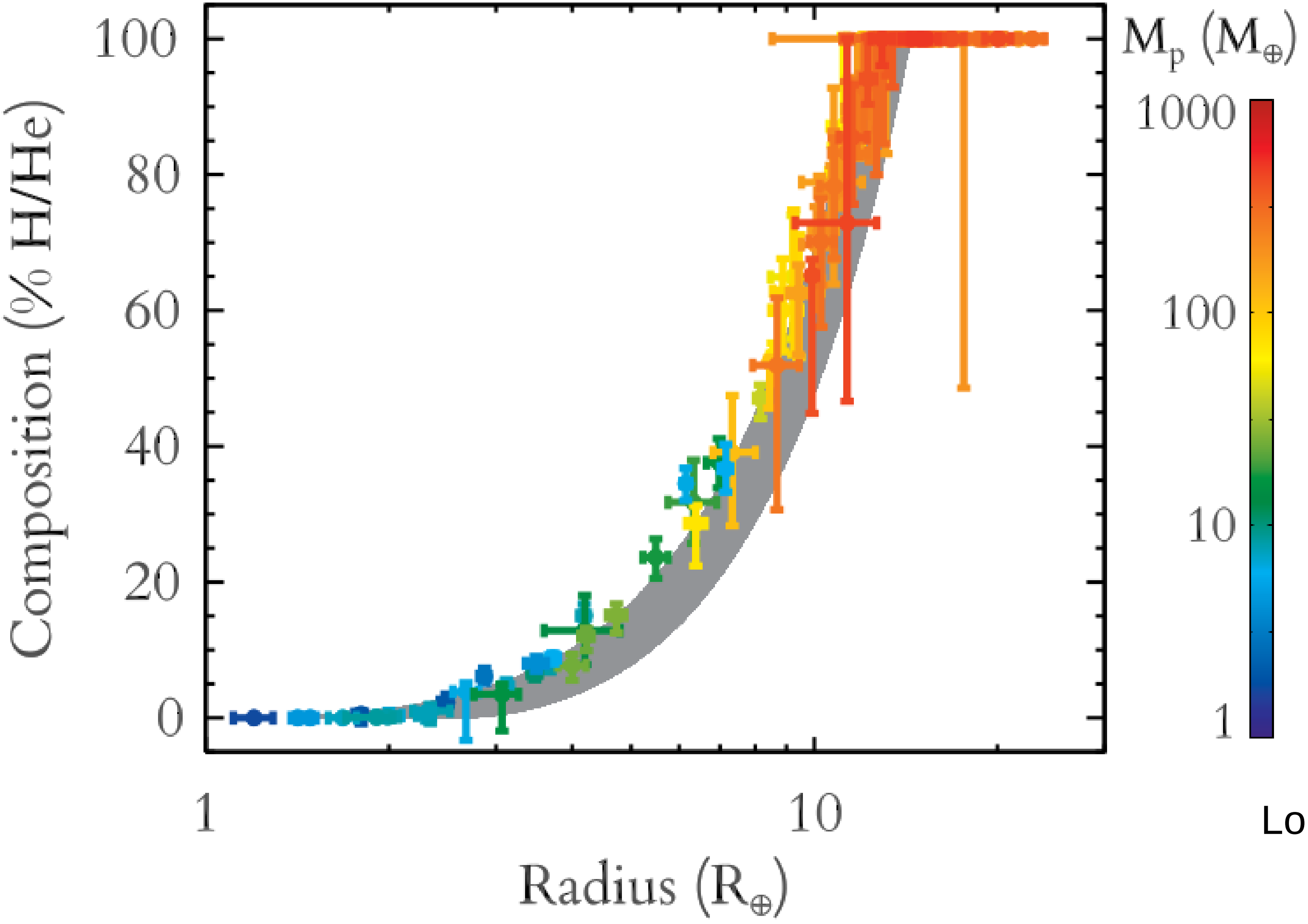
0.000 (91%)	0.001 (91%)	0.014 (91%)	0.14 (91%)	0.47 (91%)	0.49 (91%)	0.46 (91%)	0.18 (90%)	0.47 (90%)	0.030 (89%)
0.001 (91%)	0.006 (91%)	0.059 (91%)	0.24 (91%)	0.88 (91%)	1.2 (91%)	0.65 (90%)	1.4 (90%)	1.6 (89%)	0.030 (88%)
0.003 (91%)	0.028 (90%)	0.27 (90%)	1.0 (90%)	2.3 (90%)	3.4 (90%)	4.9 (90%)	4.9 (89%)	2.5 (88%)	0.081 (86%)
0.008 (90%)	0.077 (90%)	0.63 (90%)	2.0 (90%)	6.0 (89%)	8.8 (89%)	10 (88%)	13 (87%)	8.3 (86%)	0.79 (82%)
0.052 (90%)	0.38 (89%)	1.1 (89%)	2.5 (88%)	7.2 (88%)	14 (87%)	14 (85%)	13 (82%)	6.6 (77%)	6.6 (68%)
0.37 (87%)	1.7 (86%)	3.3 (85%)	5.6 (83%)	10 (80%)	13 (76%)	17 (70%)	6.4 (59%)	9.9 (48%)	19 (35%)
0.32 (75%)	1.8 (69%)	4.2 (59%)	5.3 (50%)	12 (39%)	28 (29%)	11 (19%)			

Dressing+2013, 2015,
Howard+2012

Transmission spectroscopy probes exo-atmospheric makeup:

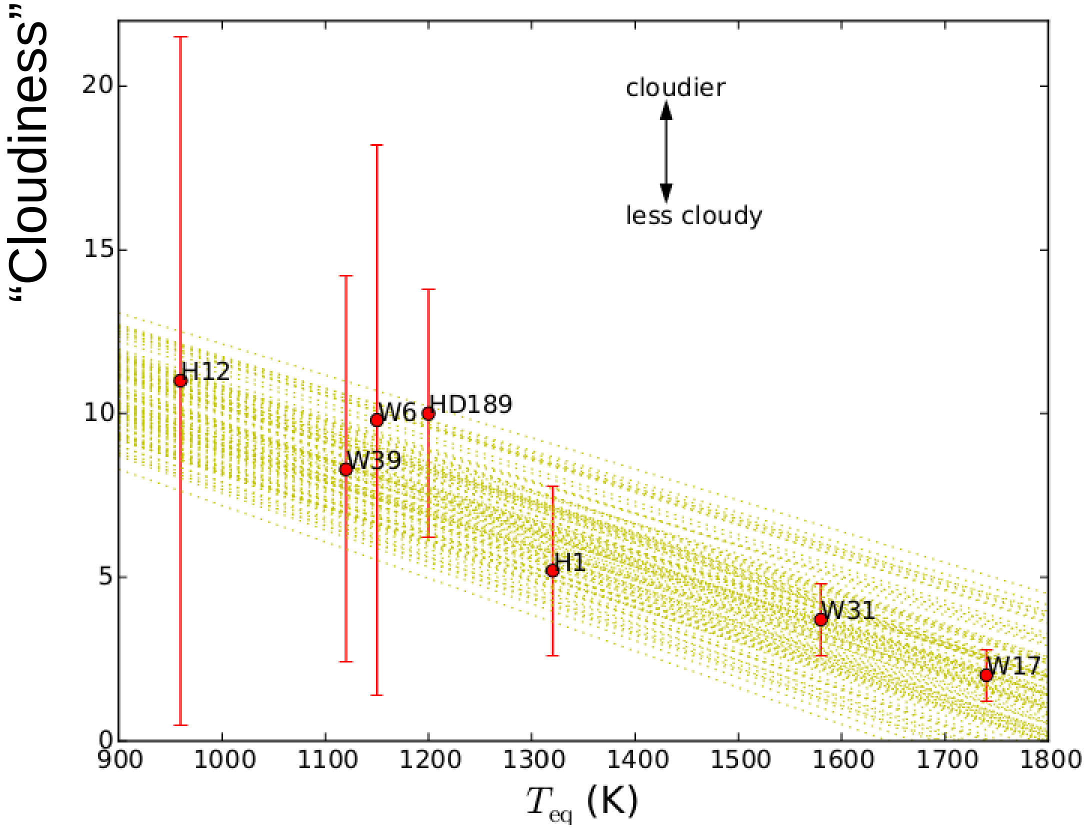


Radius is a proxy for composition for sub-Jovian planets:



Lopez & Fortney 2014

For hot Jupiters, irradiation (as Teq) may correlate with signal amplitude:



Heng 2016

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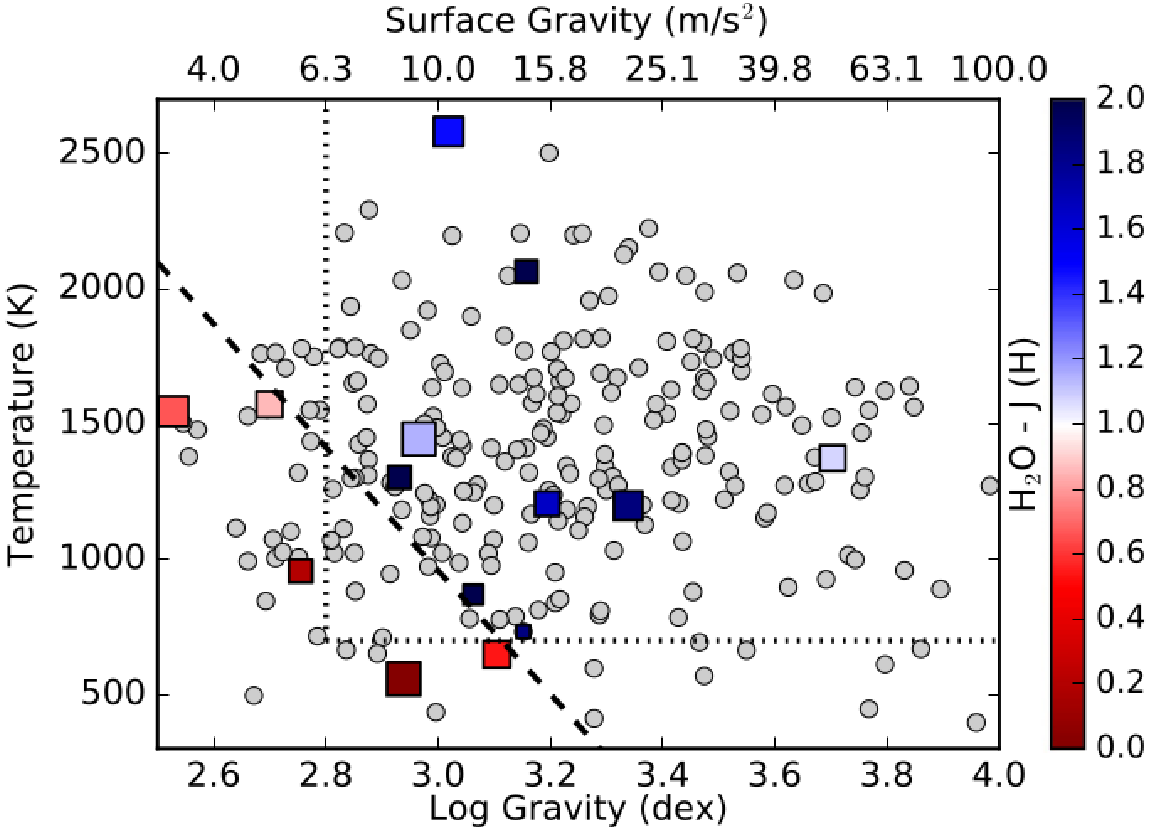
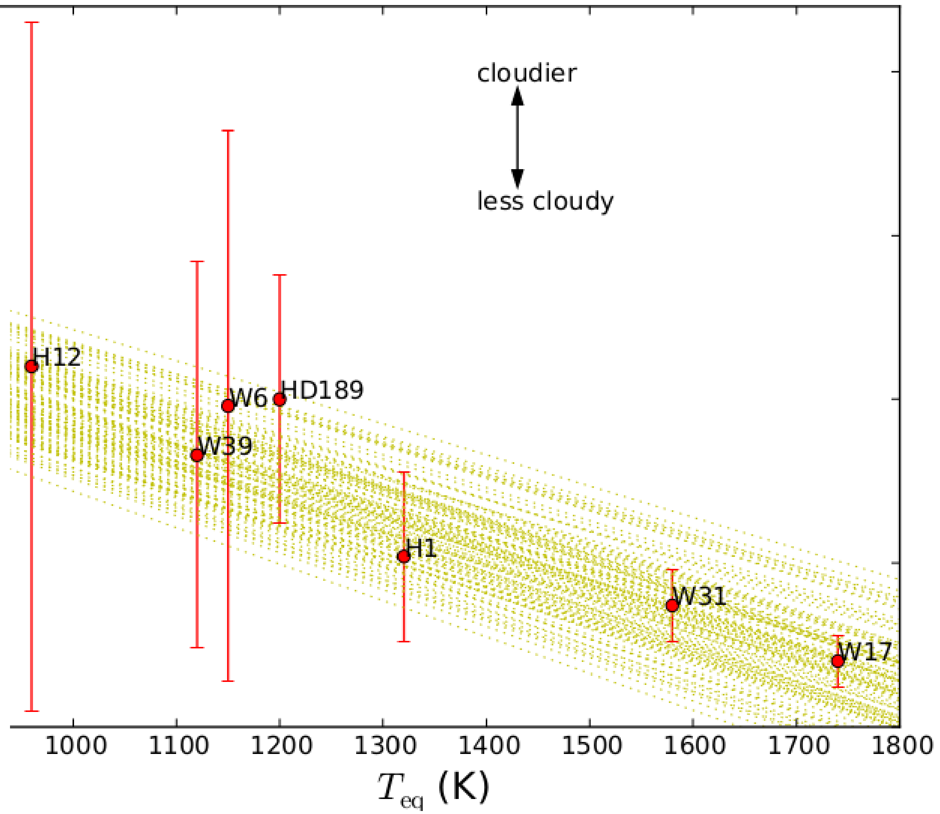


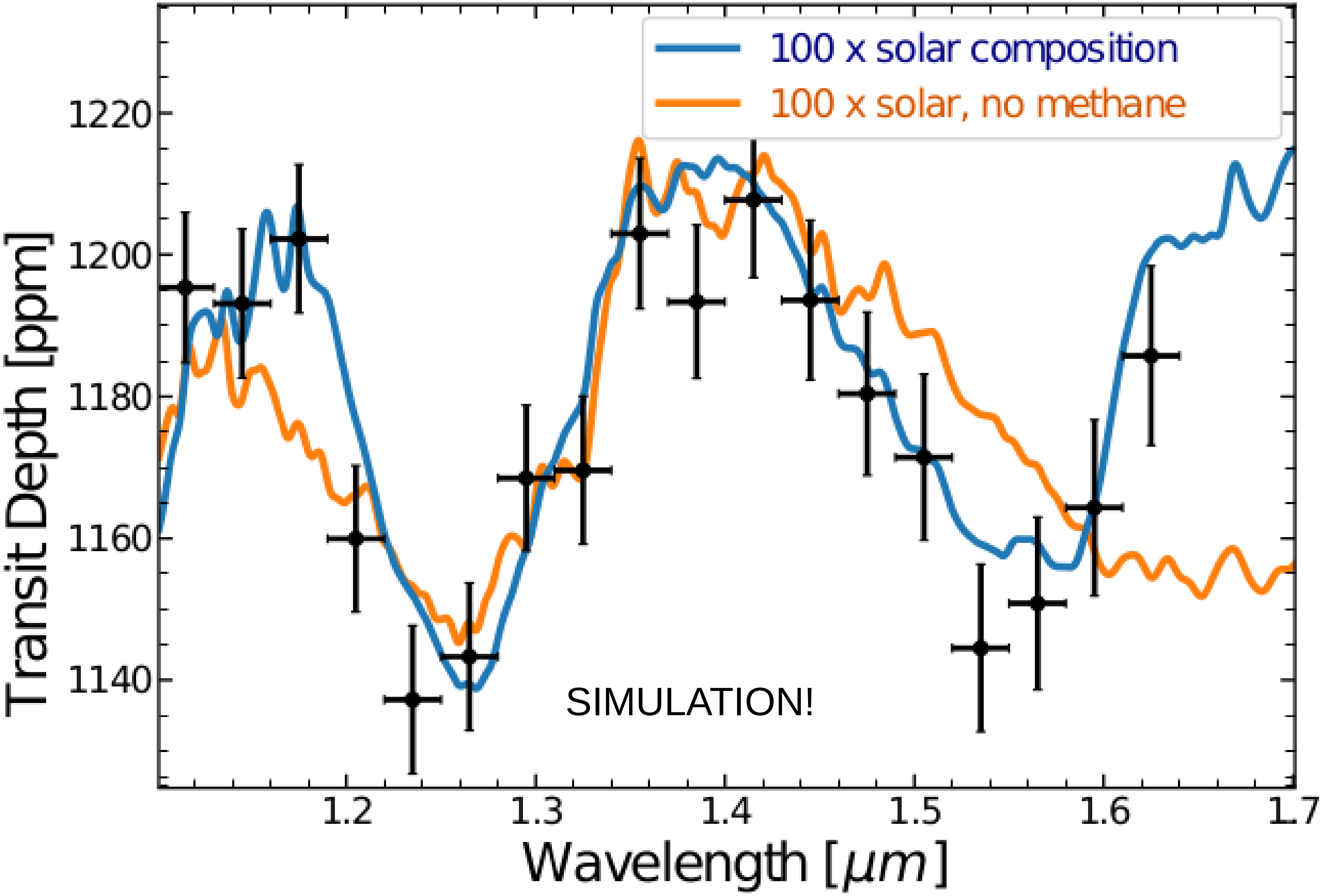
Stevenson 2016



Heng 2016

- TIC stellar parameters
- MC distribution of planets (R_p, P) (Kepler occurrence rates)
- Probabilistic distribution of M_p (Wolfgang et al. M/R relation)
- Likelihood of transit
- TESS transit S/N and detectability (S/N > X)
- Amplitude of transmission features
- Required JWST time to detect features
- Sort & prioritize

Example: WFC3 observations of HD3167c would measure H2O, CH4, metallicity, cloud level, etc. etc.



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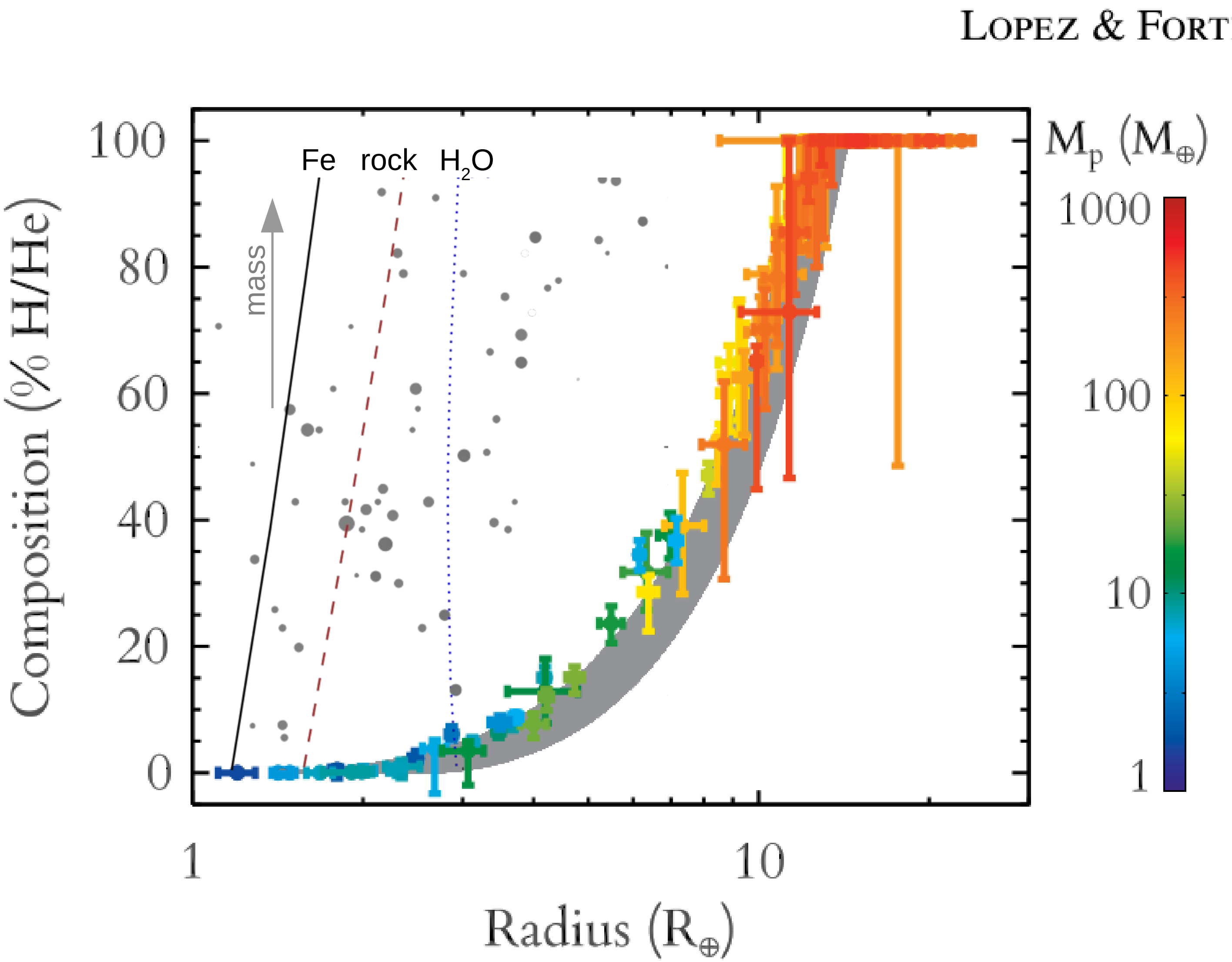
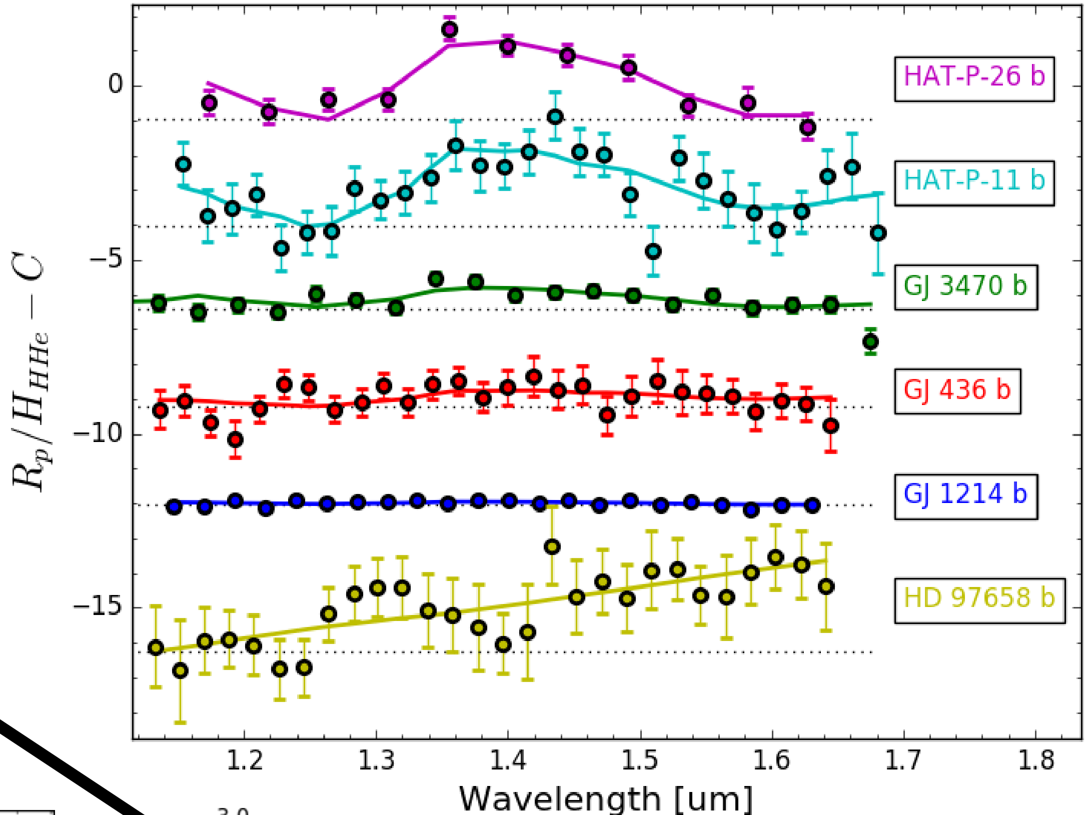
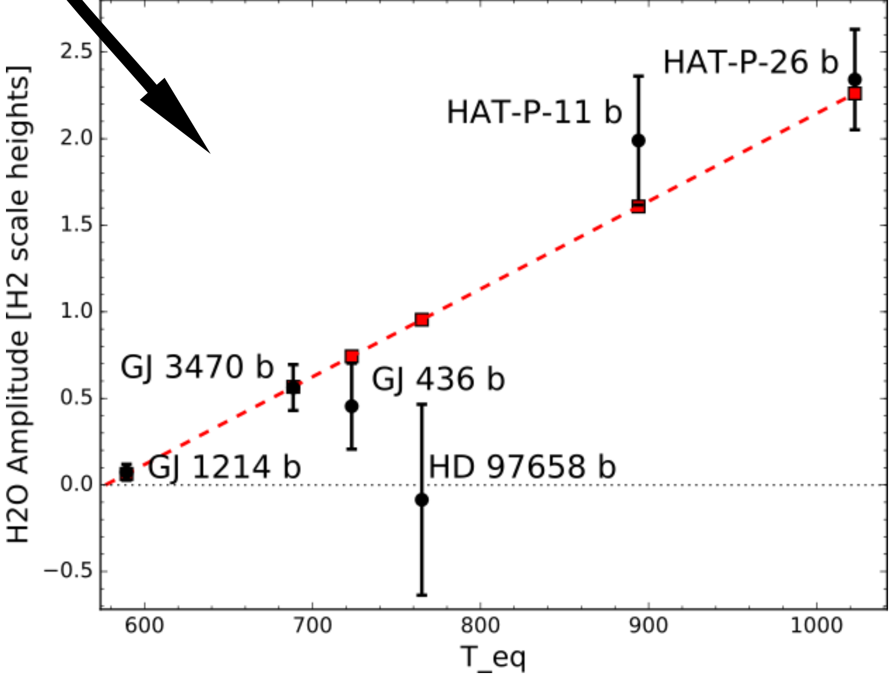
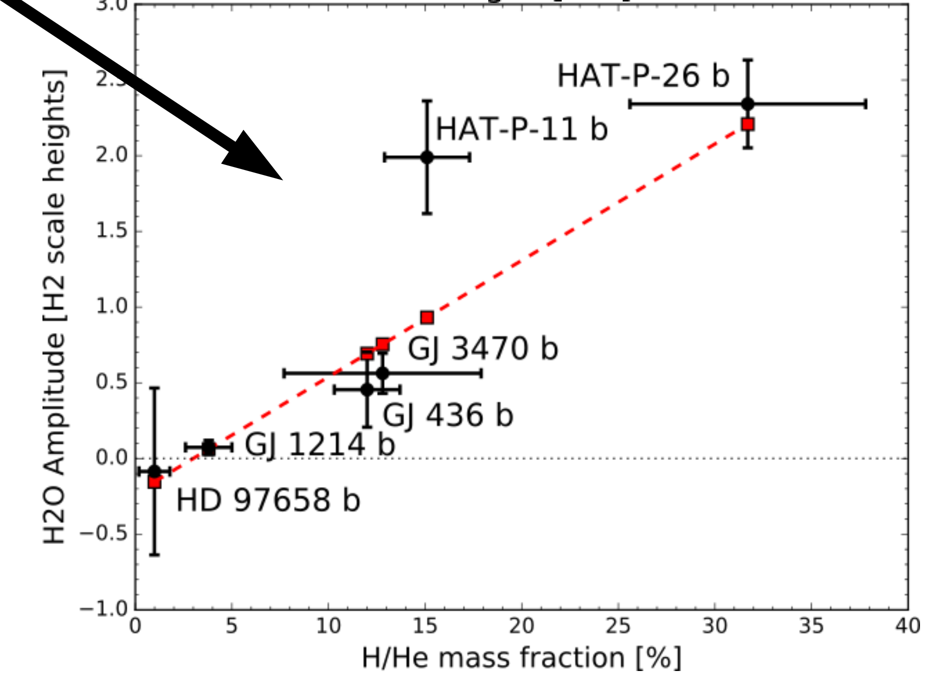


HST/WFC3 sub-Neptune transmission spectroscopy:

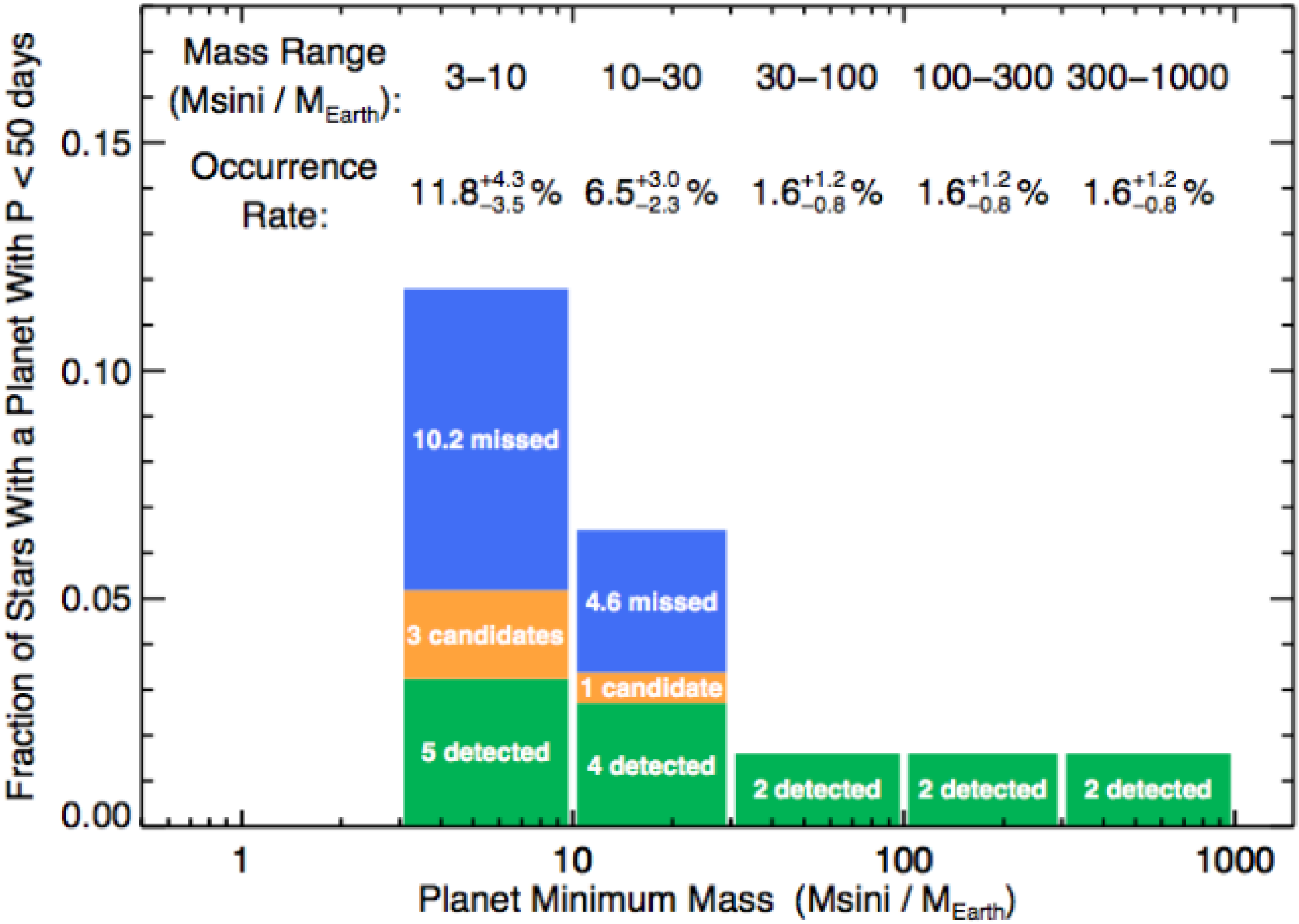
feature amplitude (*right*)
scales with
equilibrium temperature
or
bulk H/He fraction:





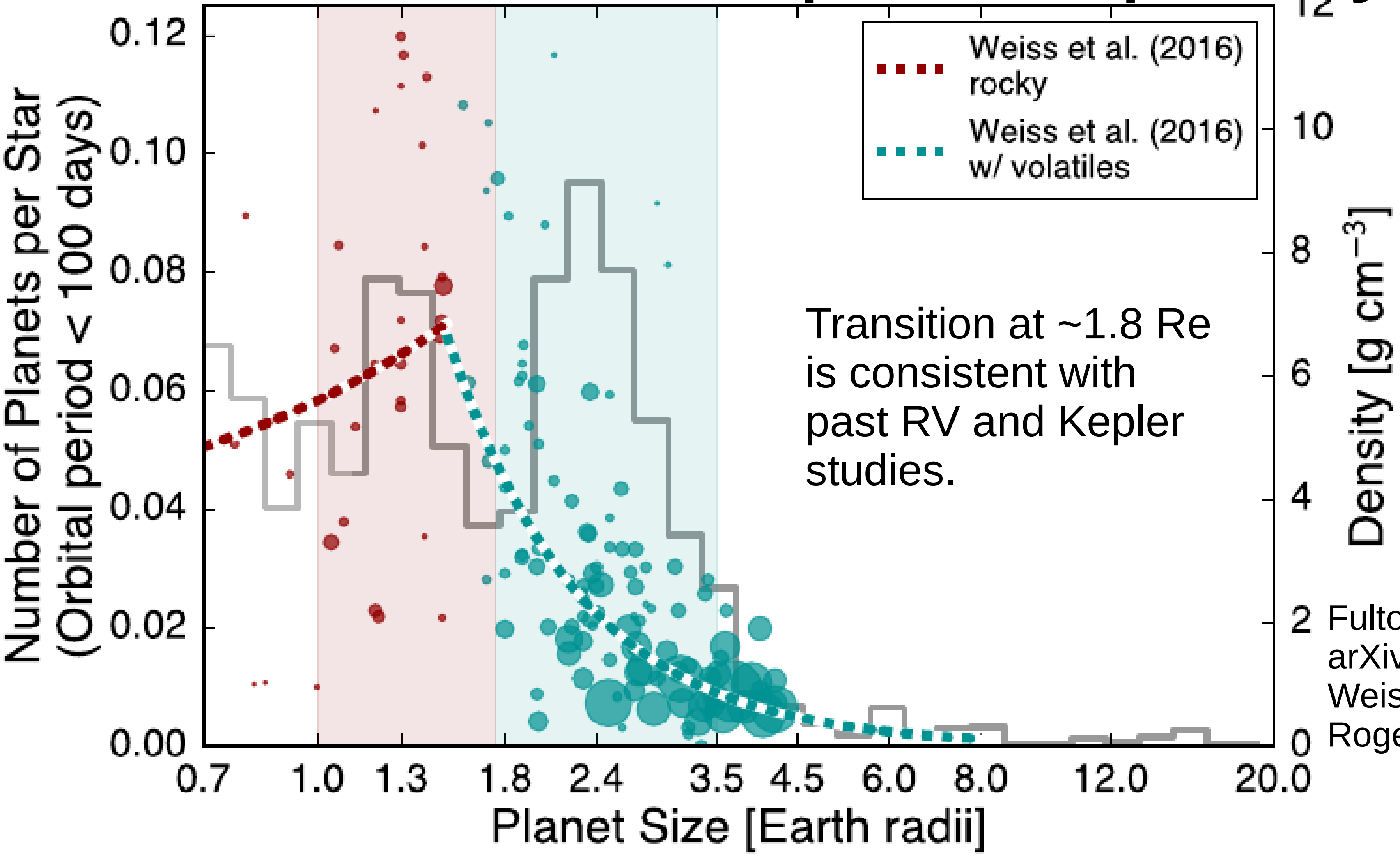


Low-mass planets are extremely common:



Howard et al. 2010

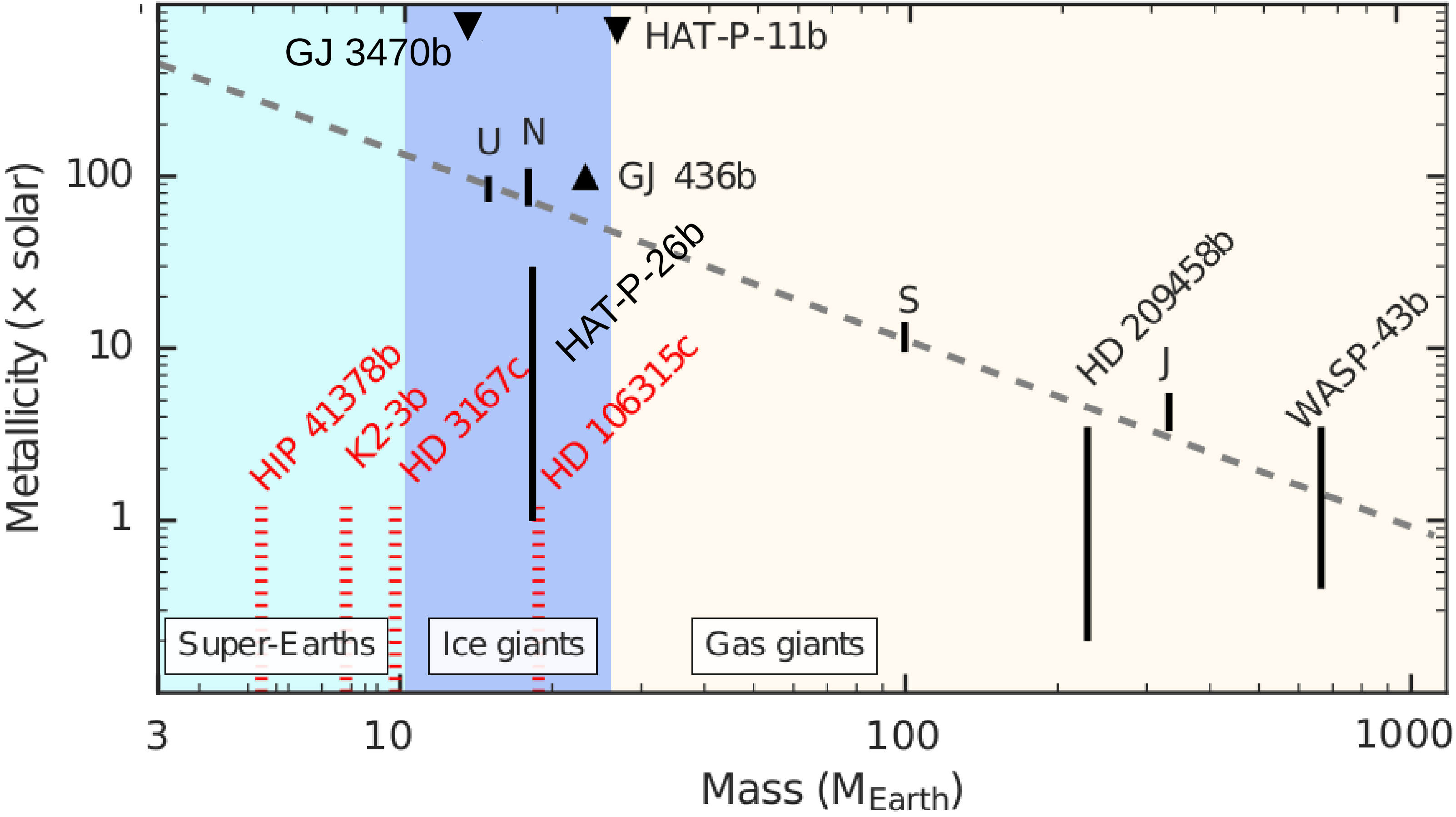
Super-Earths and sub-Neptunes occur with ~equal frequency:



Transition at ~1.8 Re is consistent with past RV and Kepler studies.

Fulton, Petigura, et al., arXiv:1703.10375; Weiss et al. (2016); Rogers et al. (2016)

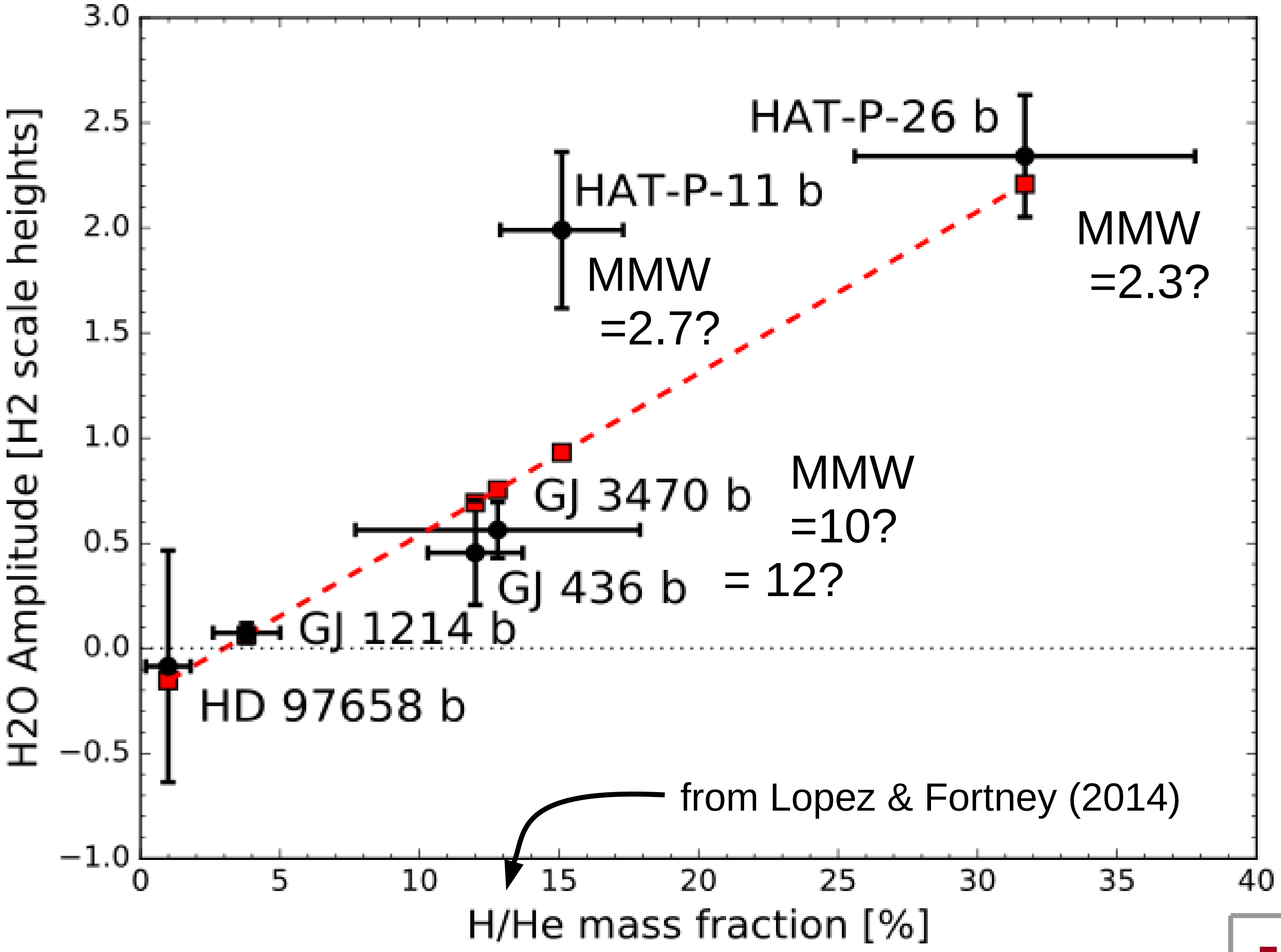
Scaling with H/He mass fraction seems analogous to the mass-metallicity relation:



from Kreidberg et al. (2015),
updated by L. Kreidberg;
GJ3470b from B. Benneke
(see next talk!)

(see also, e.g.,
Mordasini et al. 2016)

(2) Maybe atmospheric metallicity decreases with increasing H/He fraction



from Lopez & Fortney (2014)