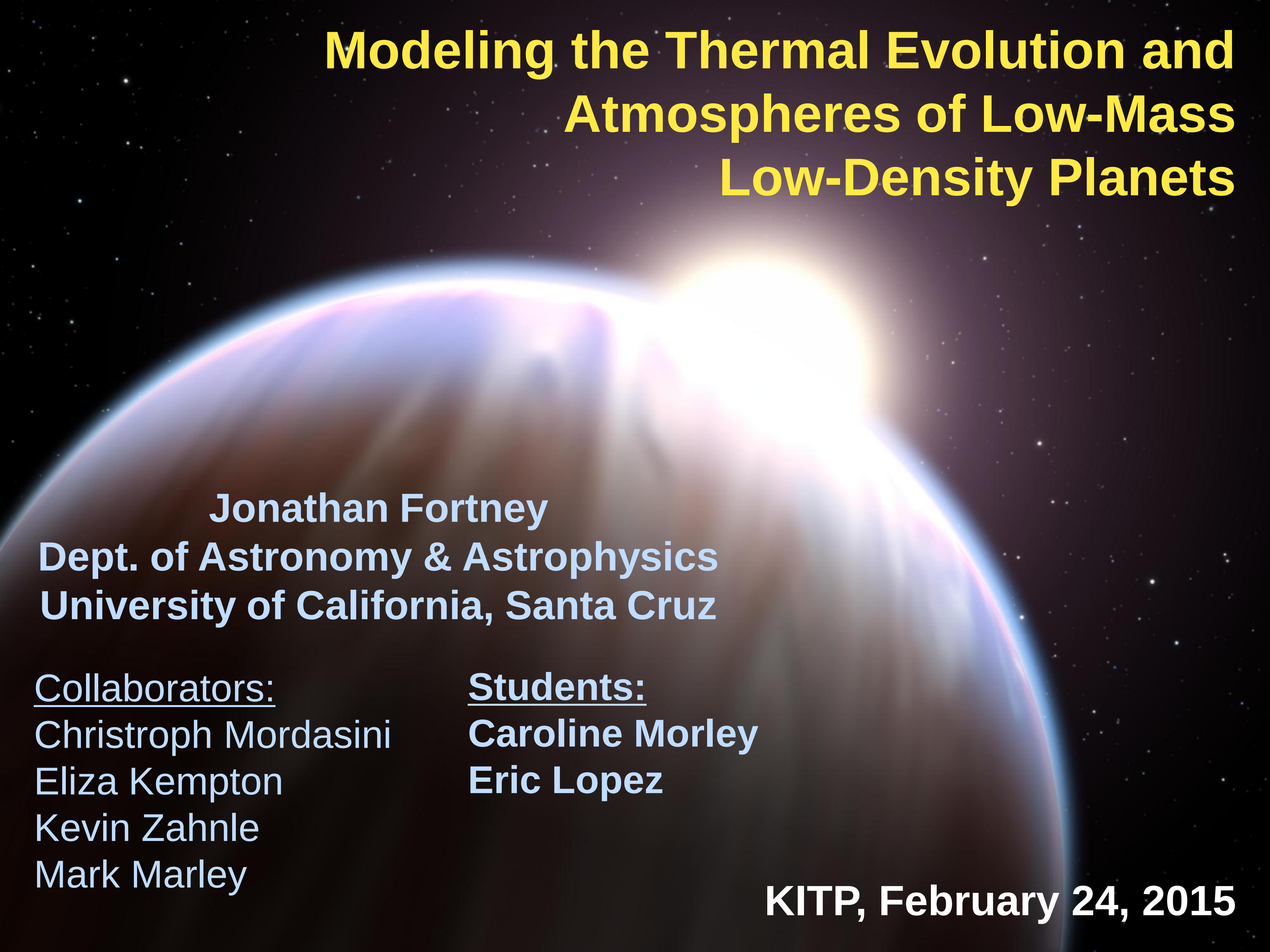

Modeling the Thermal Evolution and Atmospheres of Low-Mass Low-Density Planets

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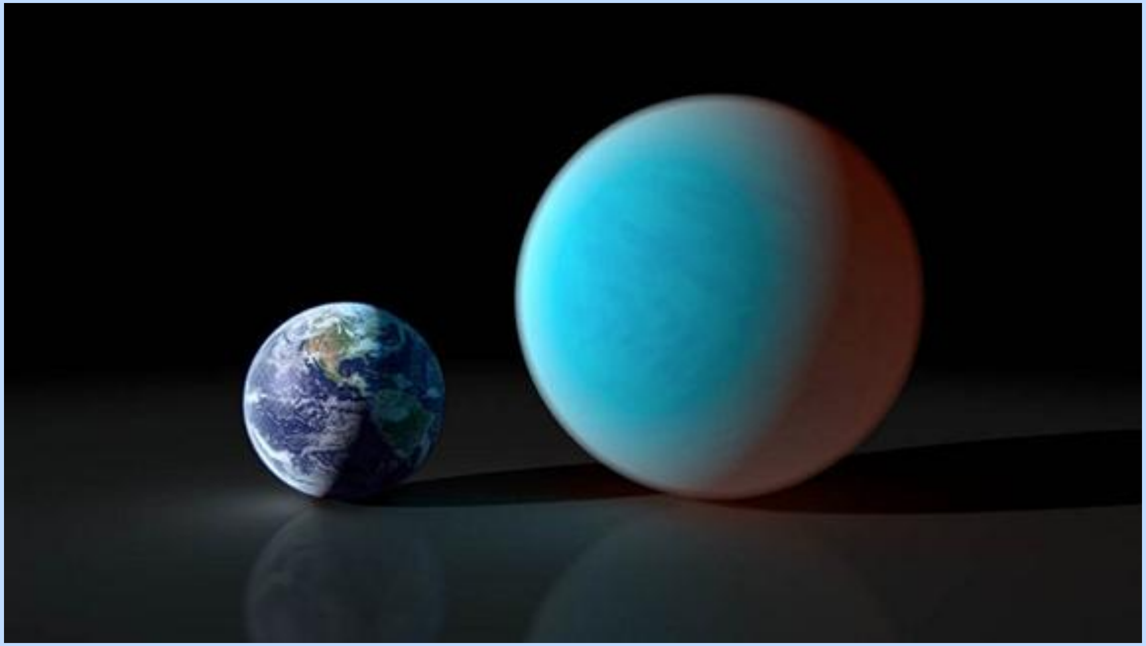
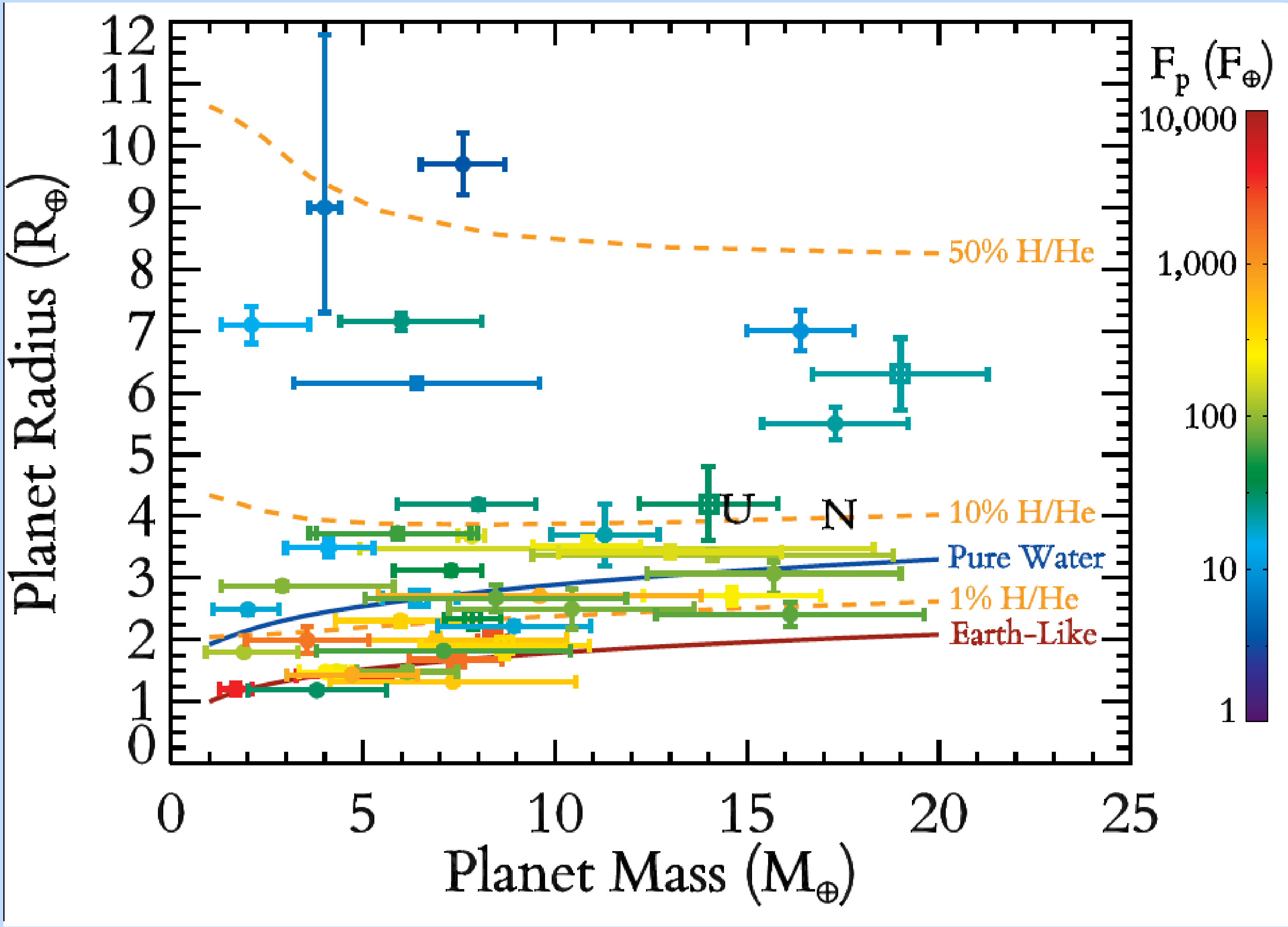
KITP, February 24, 2015

- <u>1st part of the talk:</u> 1st order composition information (fraction of planet’s mass that is H/He) for low-mass low-density (LMLD) planets from thermal evolution modeling, plus the role of evaporative hydrodynamic mass loss



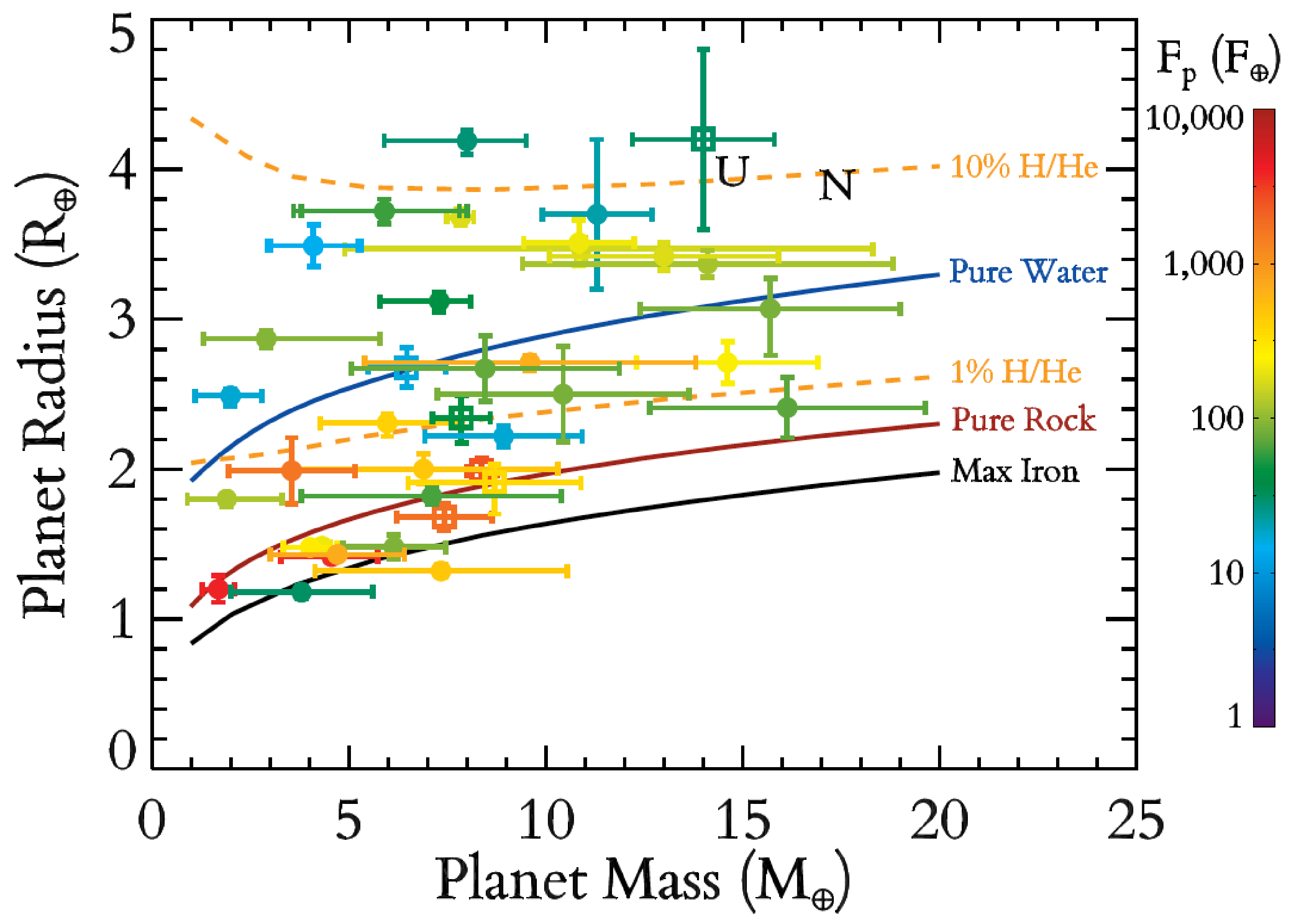
- <u>2nd part of the talk:</u> Towards 2nd order composition information from the spectra of the atmospheres of LMLD planets (looking for molecules), the problems that arise, and how to possibly circumvent them

Low-Mass Low-Density Planets



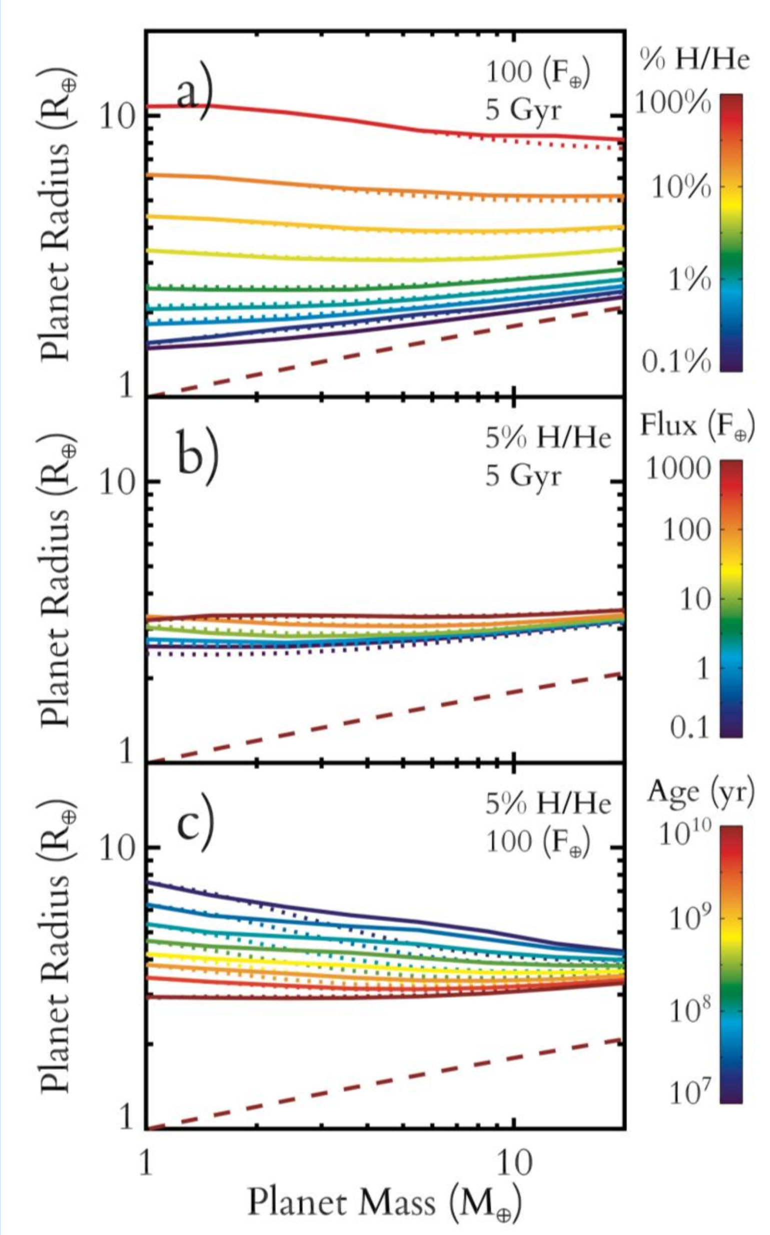
Courtesy of Eric Lopez

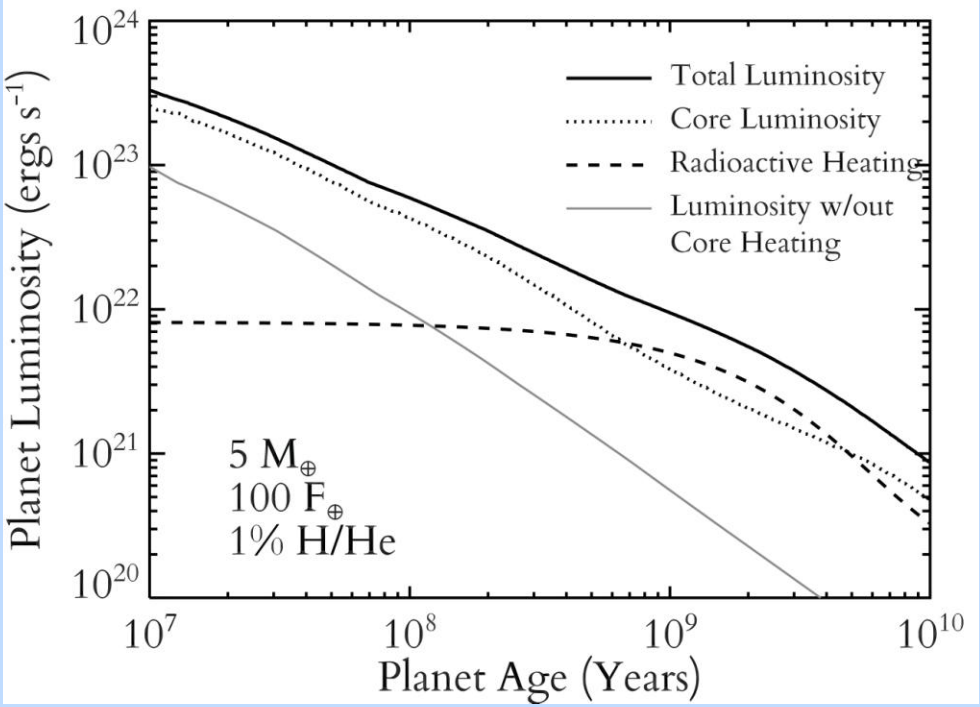
Low-Mass Low-Density Planets



Courtesy of Eric Lopez

Thermal Evolution of LMLD Planets

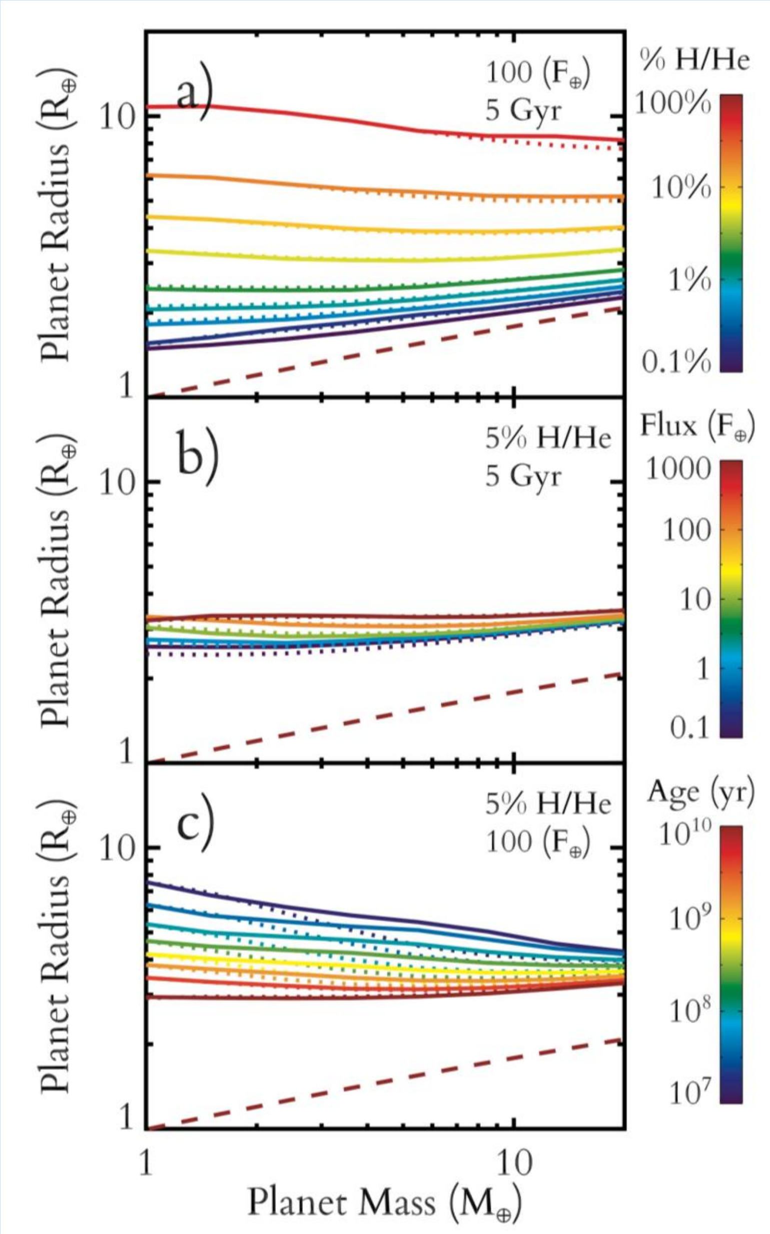




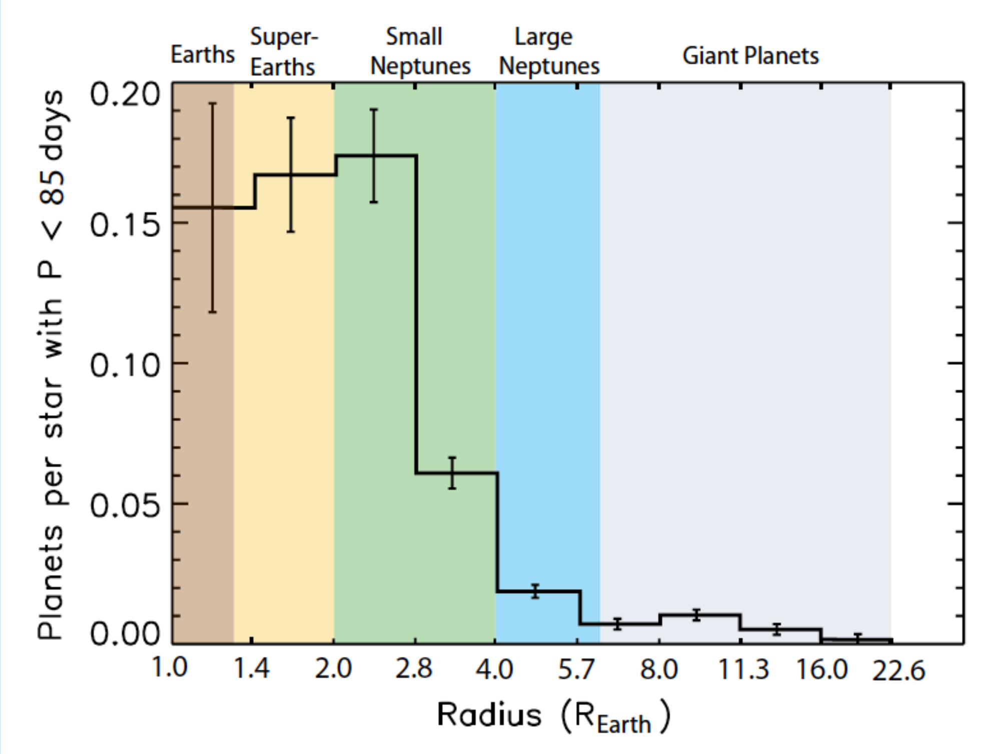
$$\int_{M_{\rm core}}^{M_{\rm p}} dm \frac{T\,dS}{dt} = -L_{\rm int} + L_{\rm radio} - c_{\rm v} M_{\rm core} \frac{dT_{\rm core}}{dt}$$

- 1st order composition: what fraction of planet’s mass is H/He envelope?
- Relatively flat mass-radius relation suggests one can constrain mass fraction of H/He without mass measurements

Radius as a Proxy for Composition

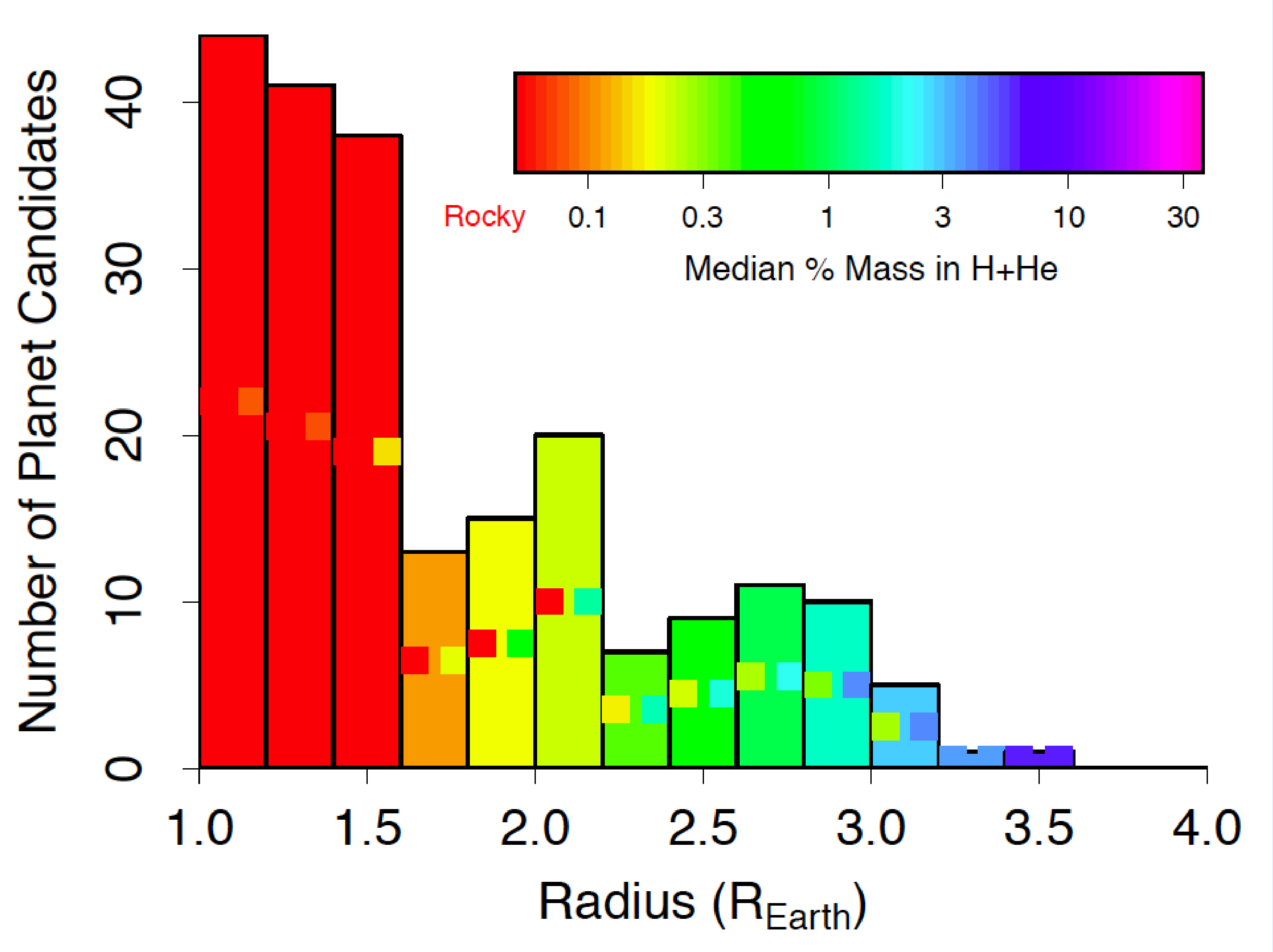


Lopez & Fortney (2014)

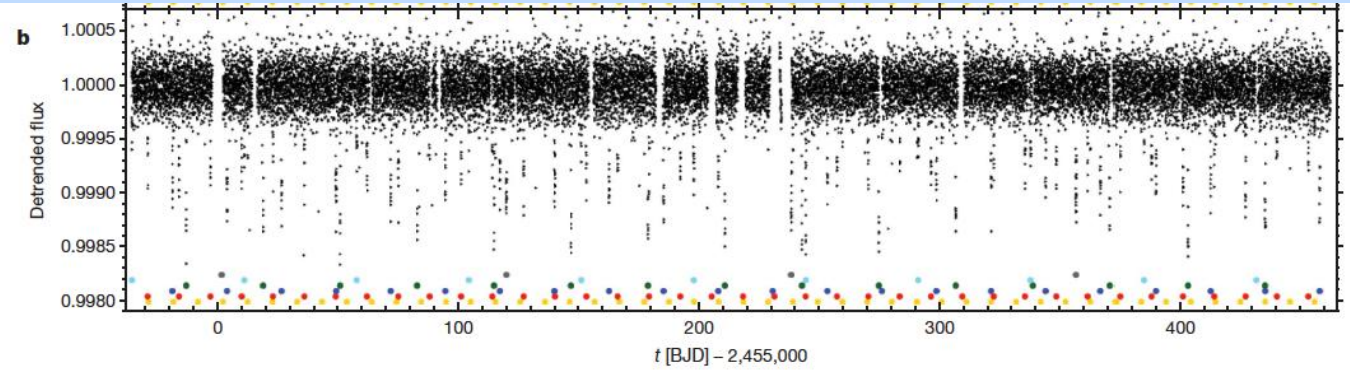


Fressin et al. (2013)

Implementing Radius as a Proxy for Composition



Wolfgang & Lopez (2014), Kepler planets within 0.15 AU



A closely packed system of low-mass, low-density planets transiting Kepler-11

Jack J. Lissauer[1], Daniel C. Fabrycky[2], Eric B. Ford[3], William J. Borucki[1], Francois Fressin[4], Geoffrey W. Marcy[5], Jerome A. Orosz[6], Jason F. Rowe[7], Guillermo Torres[4], William F. Welsh[6], Natalie M. Batalha[8], Stephen T. Bryson[1], Lars A. Buchhave[9], Douglas A. Caldwell[7], Joshua A. Carter[4], David Charbonneau[4], Jessie L. Christiansen[7], William D. Cochran[10], Jean-Michel Desert[4], Edward W. Dunham[11], Michael N. Fanelli[12], Jonathan J. Fortney[2], Thomas N. Gautier III[13], John C. Geary[4], Ronald L. Gilliland[14], Michael R. Haas[1], Jennifer R. Hall[15], Matthew J. Holman[4], David G. Koch[1], David W. Latham[4], Eric Lopez[2], Sean McCauliff[15], Neil Miller[2], Robert C. Morehead[3], Elisa V. Quintana[7], Darin Ragozzine[4], Dimitar Sasselov[4], Donald R. Short[6] & Jason H. Steffen[16]

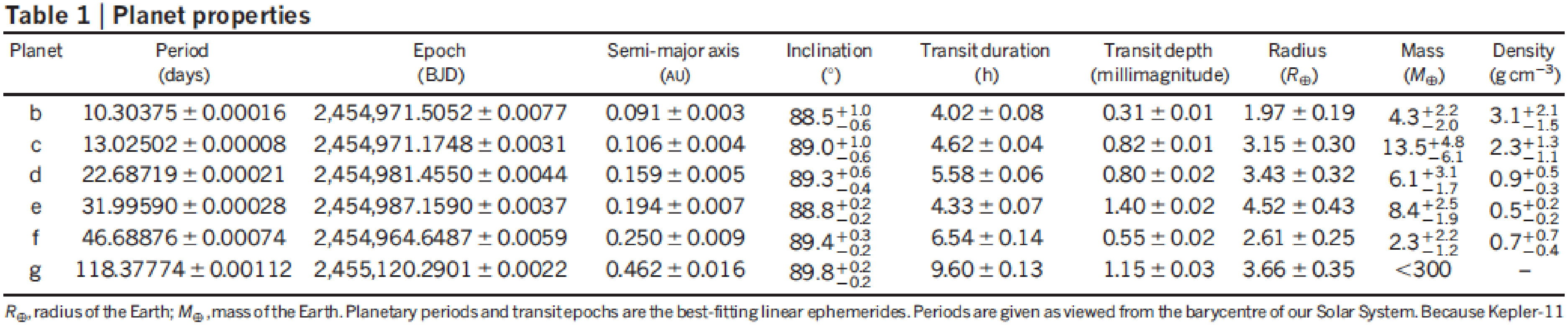
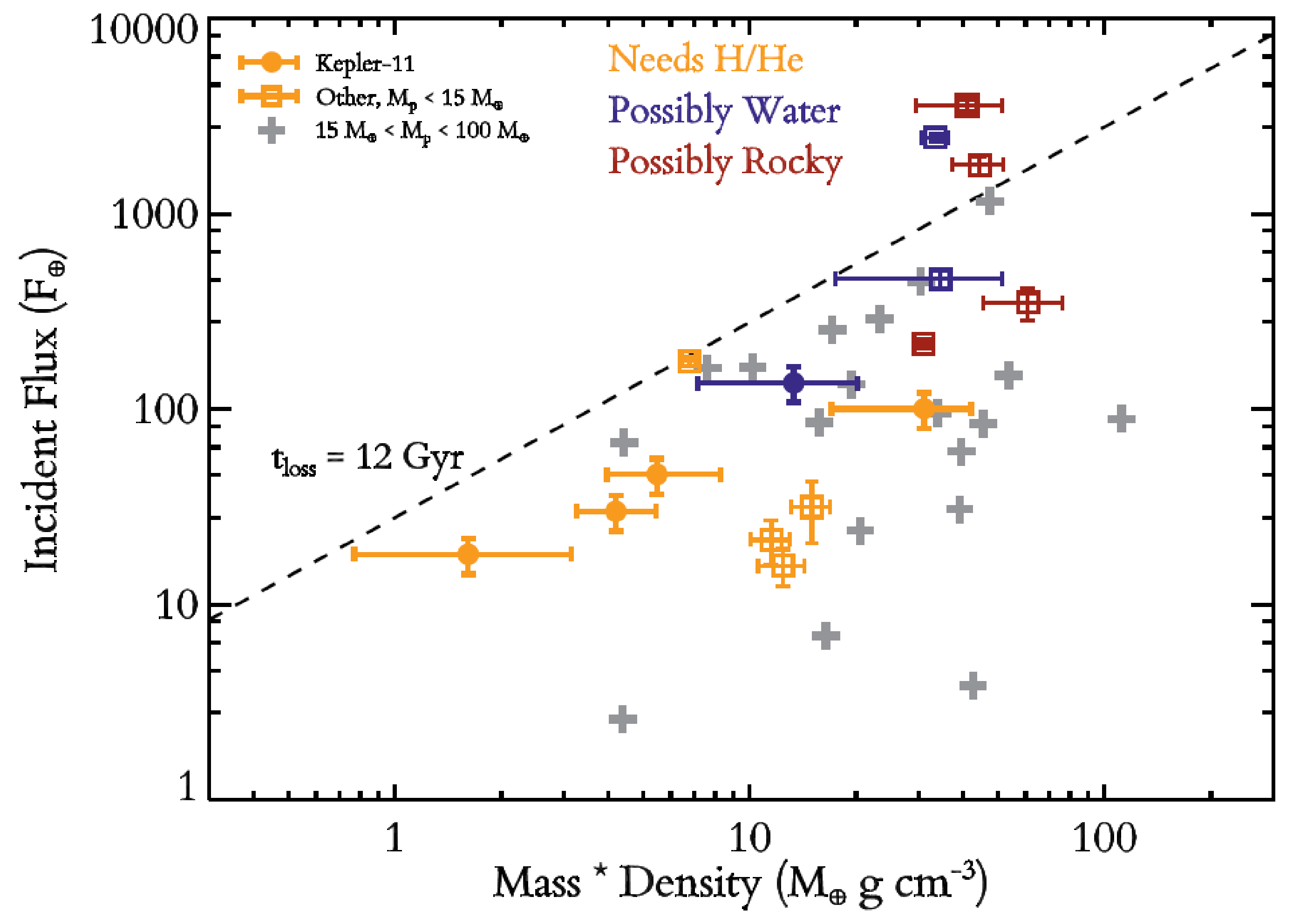


Table 1 | Planet properties

Planet	Period (days)	Epoch (BJD)	Semi-major axis (AU)	Inclination (°)	Transit duration (h)	Transit depth (millimagnitude)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g cm^{-3})
b	10.30375 ± 0.00016	2,454,971.5052 ± 0.0077	0.091 ± 0.003	$88.5^{+1.0}_{-0.6}$	4.02 ± 0.08	0.31 ± 0.01	1.97 ± 0.19	$4.3^{+2.2}_{-2.0}$	$3.1^{+2.1}_{-1.5}$
c	13.02502 ± 0.00008	2,454,971.1748 ± 0.0031	0.106 ± 0.004	$89.0^{+1.0}_{-0.6}$	4.62 ± 0.04	0.82 ± 0.01	3.15 ± 0.30	$13.5^{+4.8}_{-6.1}$	$2.3^{+1.3}_{-1.1}$
d	22.68719 ± 0.00021	2,454,981.4550 ± 0.0044	0.159 ± 0.005	$89.3^{+0.6}_{-0.4}$	5.58 ± 0.06	0.80 ± 0.02	3.43 ± 0.32	$6.1^{+3.1}_{-1.7}$	$0.9^{+0.5}_{-0.3}$
e	31.99590 ± 0.00028	2,454,987.1590 ± 0.0037	0.194 ± 0.007	$88.8^{+0.2}_{-0.2}$	4.33 ± 0.07	1.40 ± 0.02	4.52 ± 0.43	$8.4^{+2.5}_{-1.9}$	$0.5^{+0.2}_{-0.2}$
f	46.68876 ± 0.00074	2,454,964.6487 ± 0.0059	0.250 ± 0.009	$89.4^{+0.3}_{-0.2}$	6.54 ± 0.14	0.55 ± 0.02	2.61 ± 0.25	$2.3^{+2.2}_{-1.2}$	$0.7^{+0.7}_{-0.4}$
g	118.37774 ± 0.00112	2,455,120.2901 ± 0.0022	0.462 ± 0.016	$89.8^{+0.2}_{-0.2}$	9.60 ± 0.13	1.15 ± 0.03	3.66 ± 0.35	<300	–

$R_\oplus$, radius of the Earth; $M_\oplus$, mass of the Earth. Planetary periods and transit epochs are the best-fitting linear ephemerides. Periods are given as viewed from the barycentre of our Solar System. Because Kepler-11

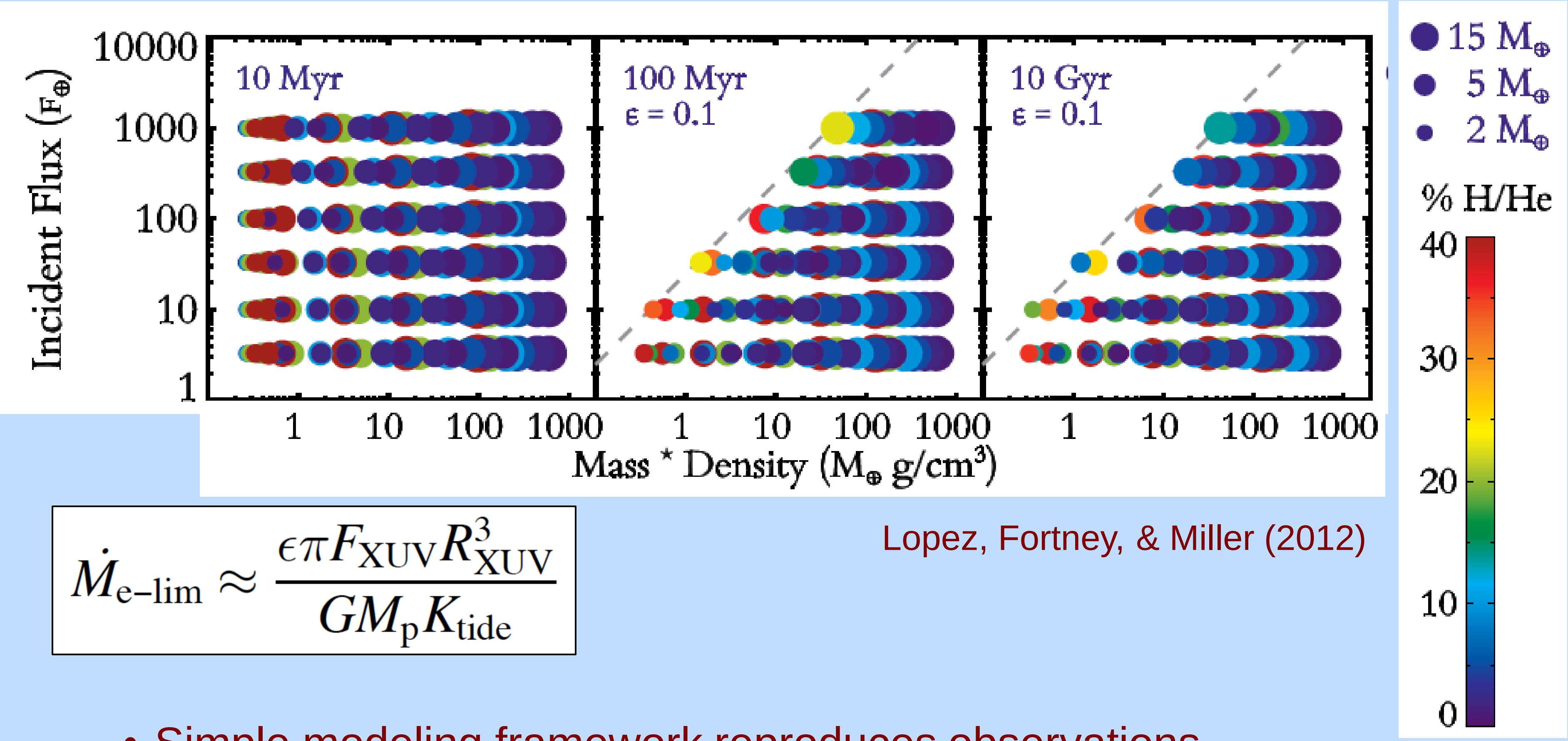
Sculpted by Atmospheric Mass Loss



$$\dot{M}_{\mathrm{e-lim}} \approx \frac{\epsilon \pi F_{\mathrm{XUV}} R^3_{\mathrm{XUV}}}{G M_{\mathrm{p}} K_{\mathrm{tide}}}$$

Lopez, Fortney, & Miller (2012)

Sculpted by Atmospheric Mass Loss

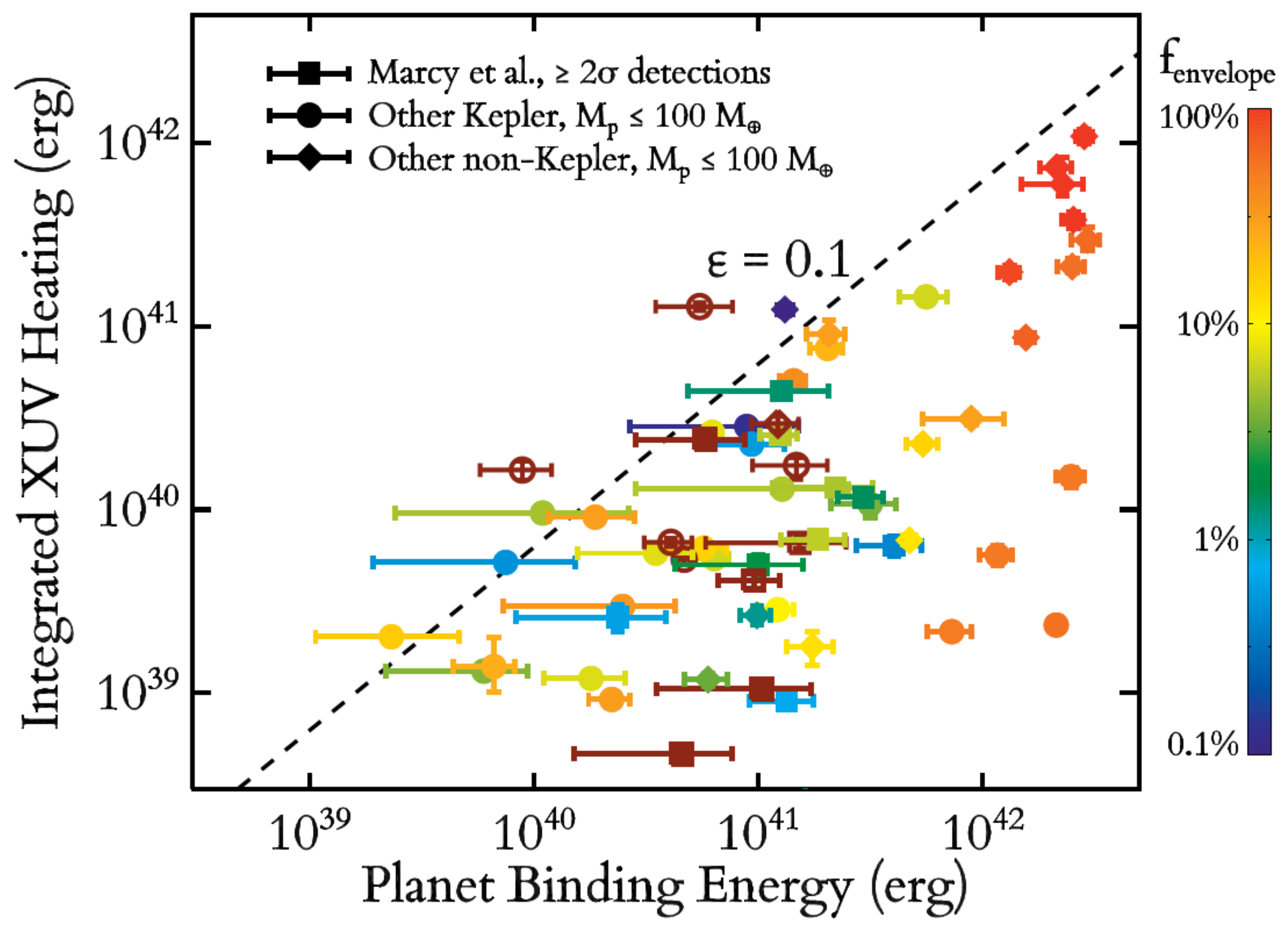


$$\dot{M}_{\mathrm{e-lim}} \approx \frac{\epsilon \pi F_{\mathrm{XUV}} R^3_{\mathrm{XUV}}}{G M_{\mathrm{p}} K_{\mathrm{tide}}}$$

Lopez, Fortney, & Miller (2012)

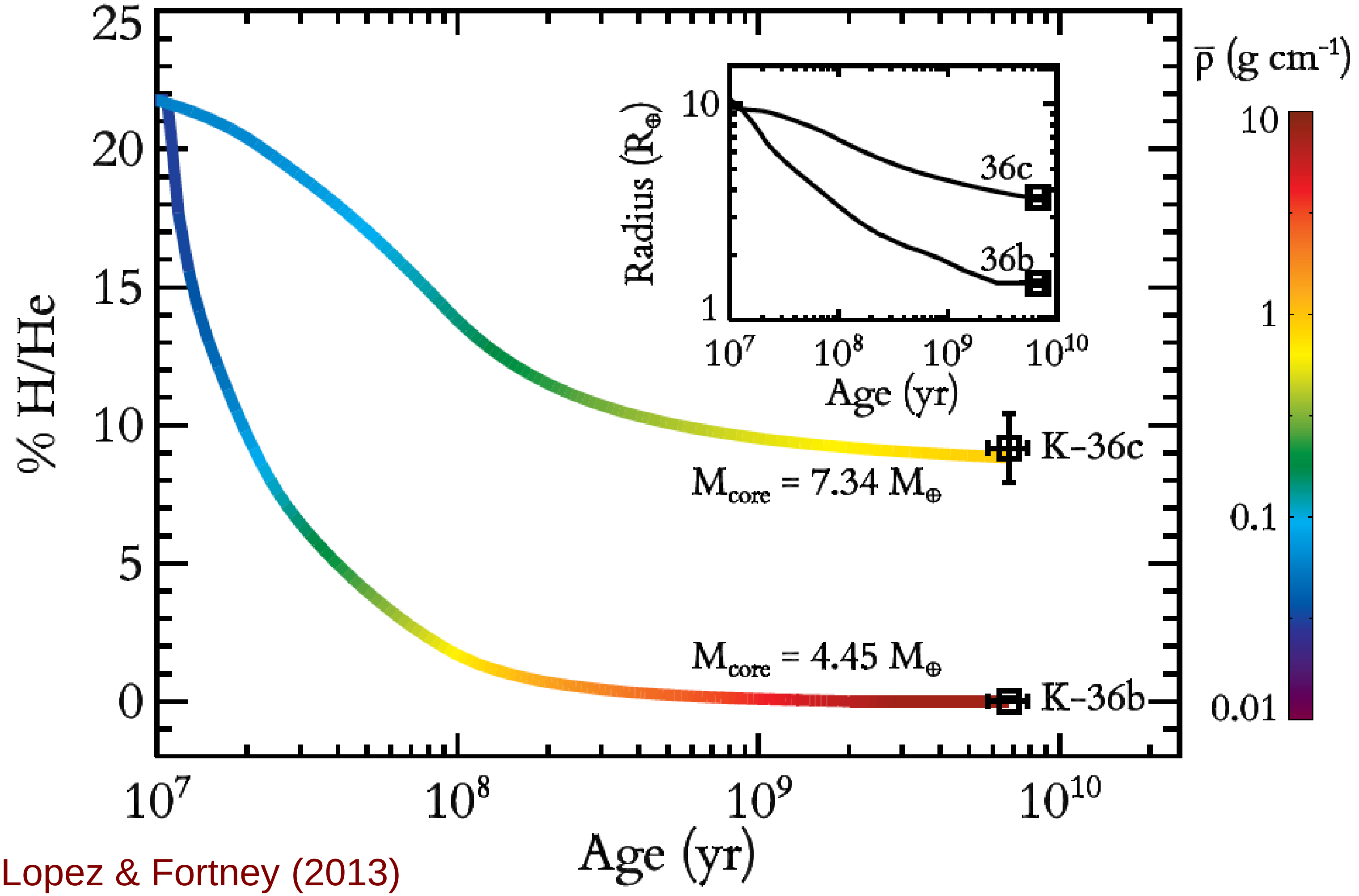
- Simple modeling framework reproduces observations
- Large XUV fluxes at young ages and large radii leads to most mass loss within first 100 Myr
- We are likely seeing a remnant population

Sculpted by Atmospheric Mass Loss



Updated from Lopez & Fortney (2014), courtesy Eric Lopez

Thermal Evolution of LMLD Planets with Mass Loss



Lopez & Fortney (2013)

- Thermal evolution with mass loss due to UV-driven evaporation
- Can transform the very nature of planets

LMLD Evolution Findings

- LMLD planets can undergo significant radius evolution over time, in particular at young ages. This, plus high XUV fluxes lead to mass loss

- Evidence for mass loss, reproduced by a simple couple evolution + mass loss model, looks very strong

- At Gyr+ ages, radius is mostly insensitive to mass, which can be exploited to constrain H/He mass fraction for a large number of planets (See Wolfgang & Lopez, 2015)

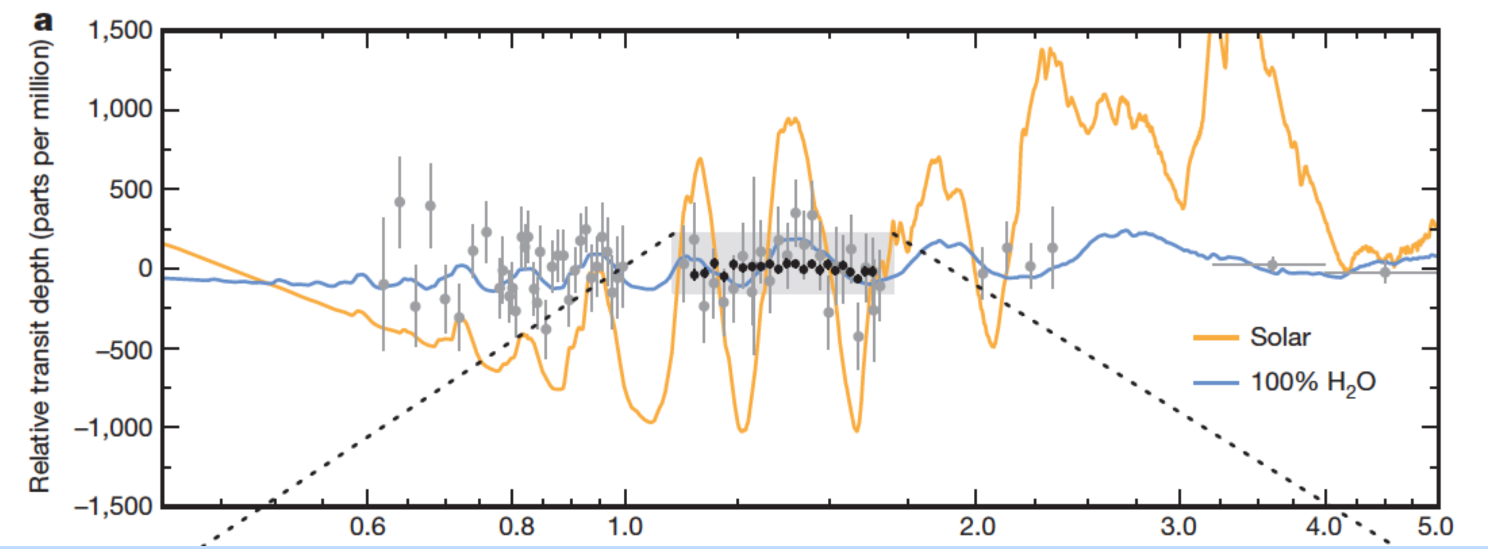
- Offshoot of this work (Luger et al. 2015): Transformation of 1-2 M_{Earth} LMLD planets into evaporated cores in M dwarf habitable zones

Atmospheres

- Apparently huge numbers of these relatively close-in planets have H-dominated envelopes of ~1-10% (or more) in mass

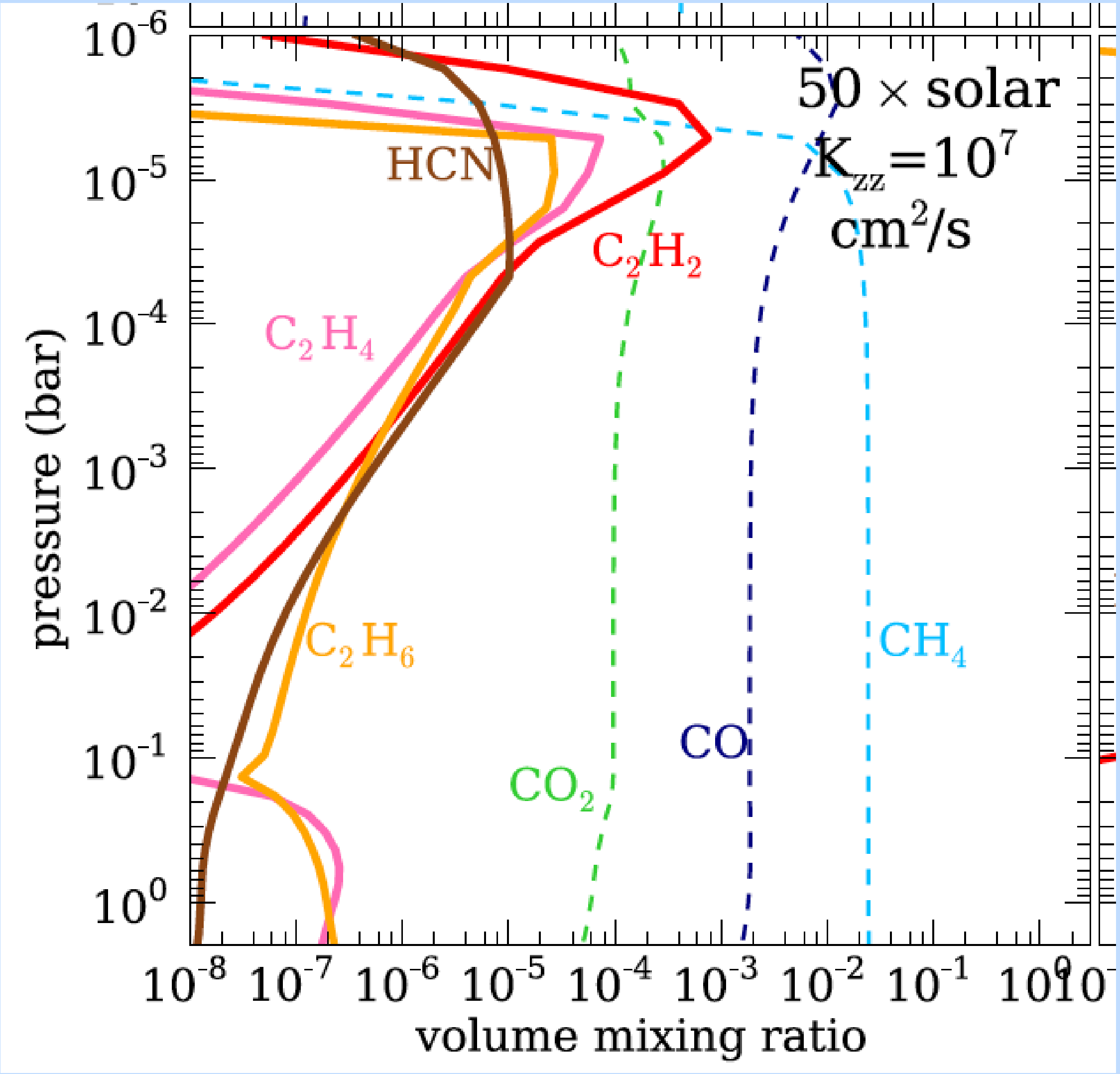
- These envelopes provide visible atmospheres that provide us significant opportunity to learn about about the planets

- These atmospheres are remnants of volatile materials accreted for the nebula, + an outgassed component (?)



Kreidberg et al. (2014a)

Breakdown of CH_4 by stellar UV leads to haze formation on Jupiter, Saturn, Uranus, Neptune, and Titan



Models for planet GJ 1214b

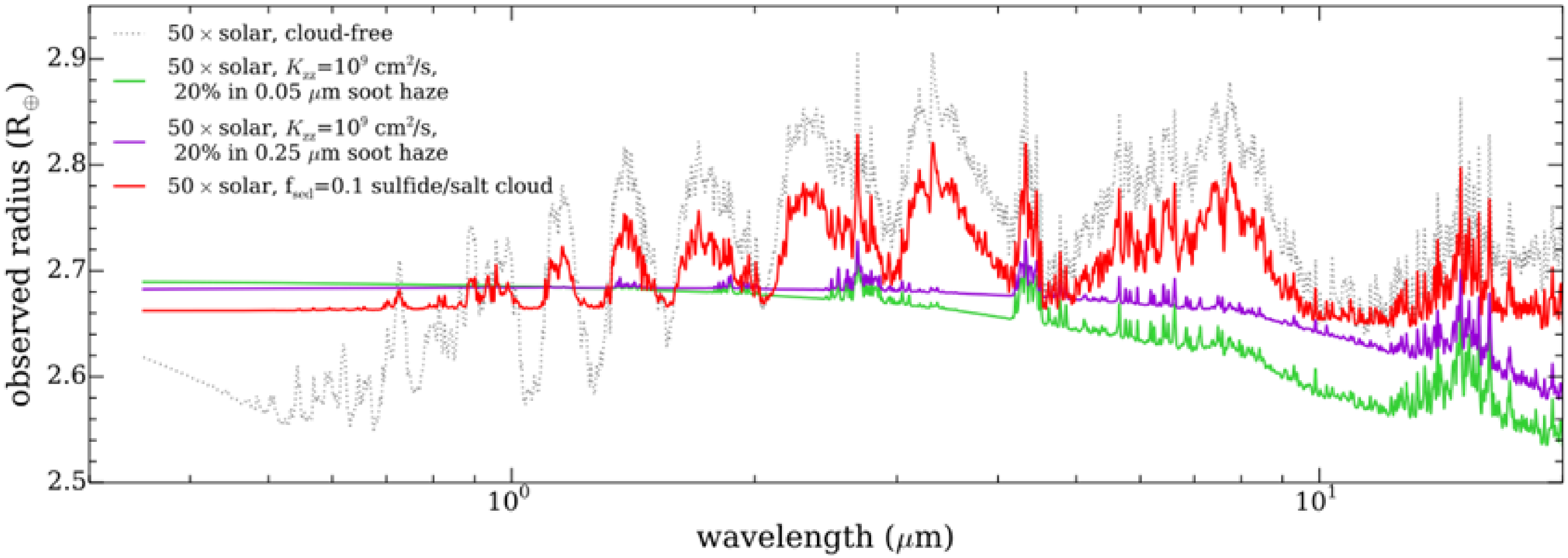
Morley, Fortney, et al. (2013)

Towards Better Characterization of Exoplanet Composition

- This is hard
- Compared to solar system scientists, exoplanetary astronomers are not a patient people

- If transmission spectra are mostly flat (Heather Knutson’s talk), well, then what else can we do?
- We’re looking to other viewing geometries besides transmission
  - Thermal Emission
  - Reflection

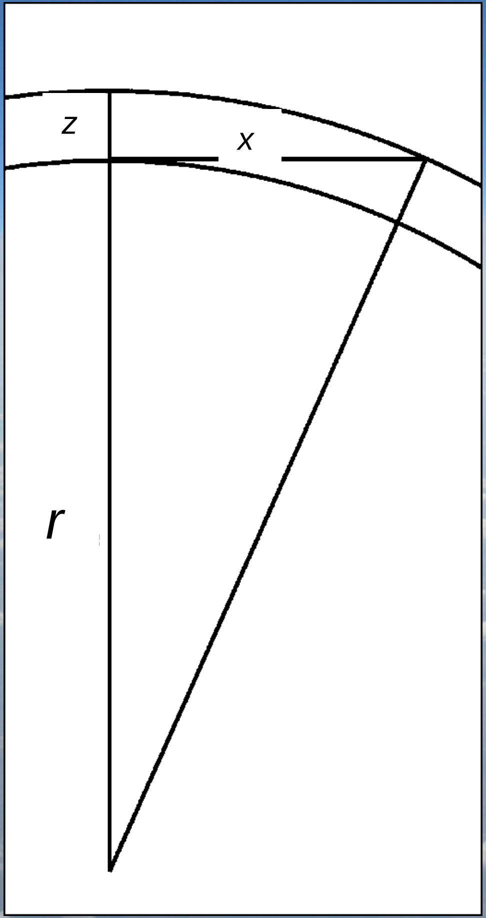
GJ 1214b as an example: Thick high-altitude soot haze from photochemistry can flatten transmission spectrum



What do truly flat transmission spectra look like at other viewing geometries?

(preliminary results: Morley & Fortney, in prep)

The Conundrum of 2015: How do we best characterize extremely cloudy atmospheres?



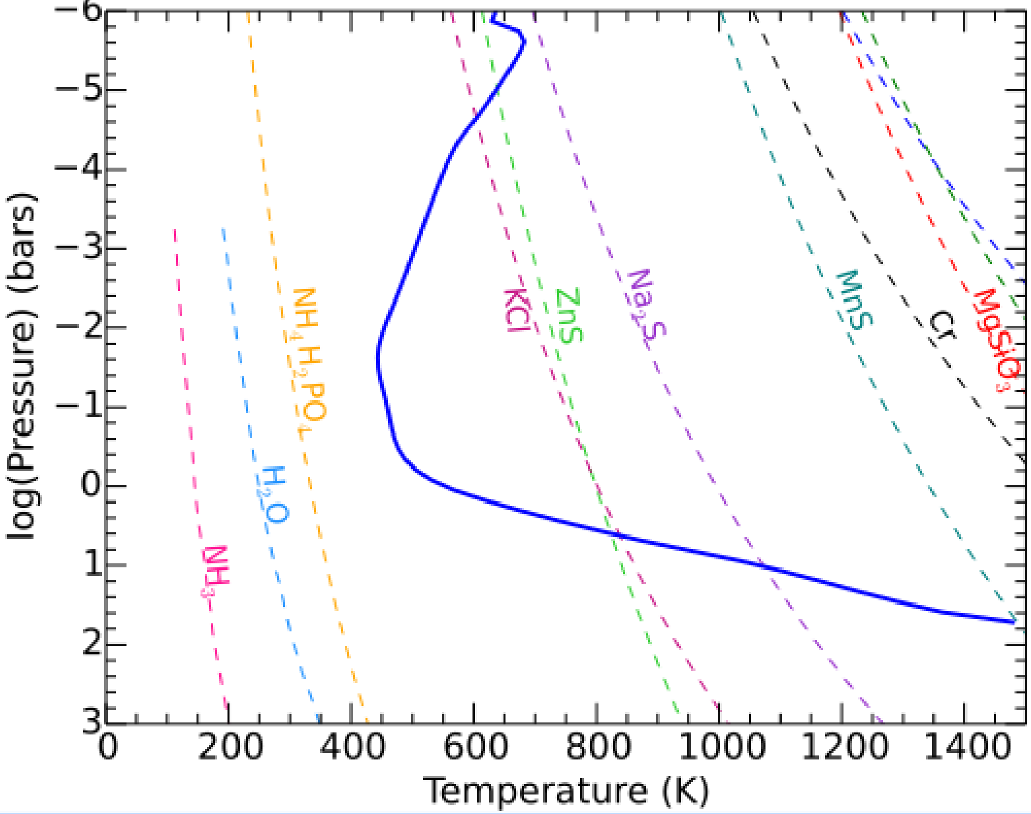
$$\frac{\tau_{\mathrm{H}}}{\tau_{\mathrm{V}}} = \sqrt{\frac{2\pi a}{H}}$$

Ratio is ~25 for GJ 1214b

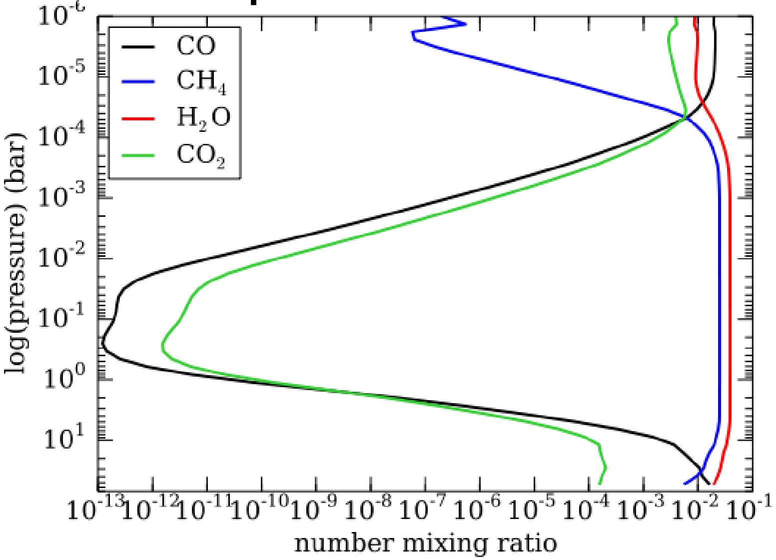
- Transmission spectroscopy samples relatively long path lengths, making clouds more important (Fortney, 2005)
- Thermal emission *may* be more favorable, due to optically thinner clouds
- Planets are relatively “cool” so best bet is probably thermal emission with JWST in the mid IR, where planets are brighter and clouds less opaque

Like our 4 solar system giant planets, and Titan, high-altitude photochemical hazes drive temperature inversions.

haze creates temperature inversion

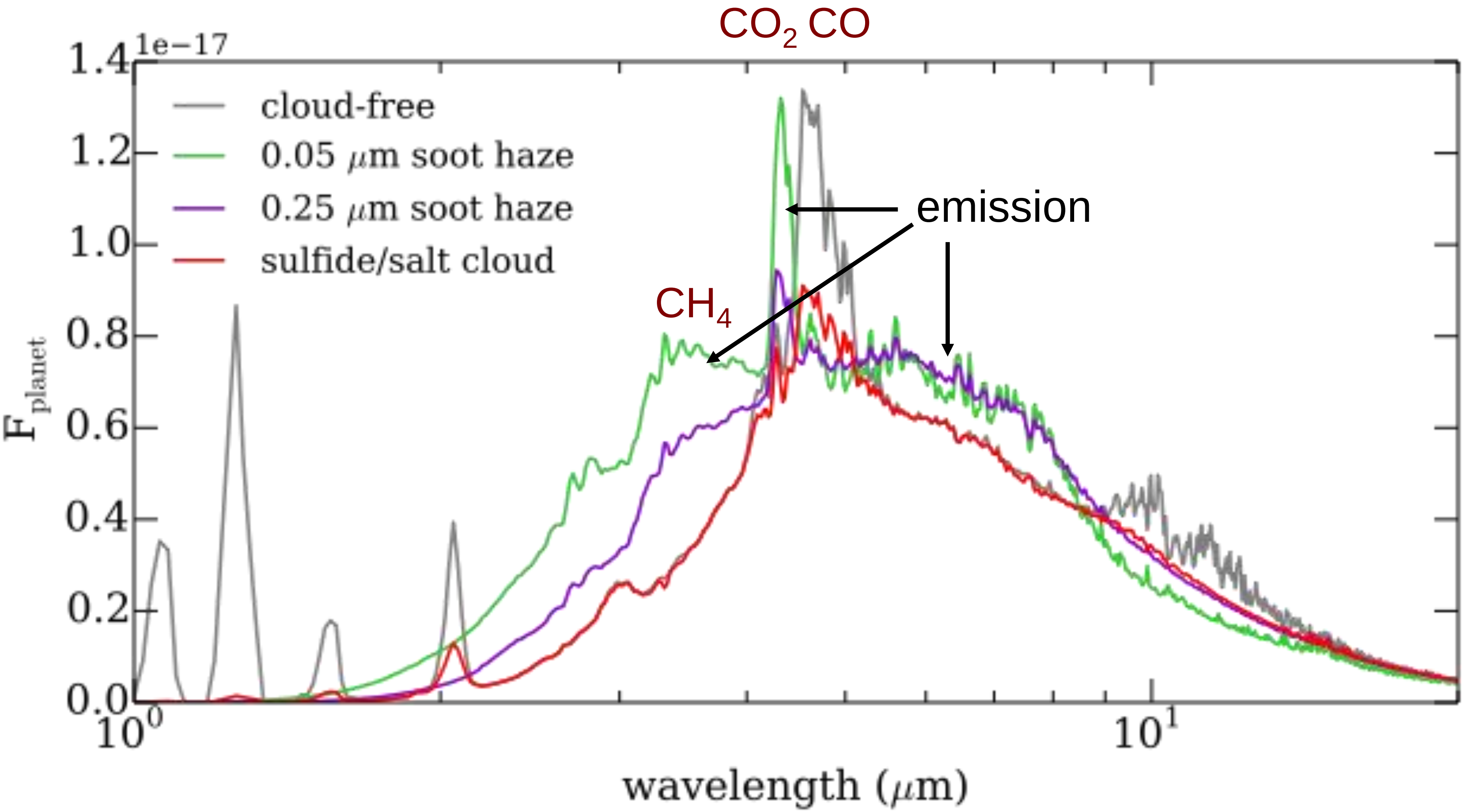


CO dominates high in atmosphere



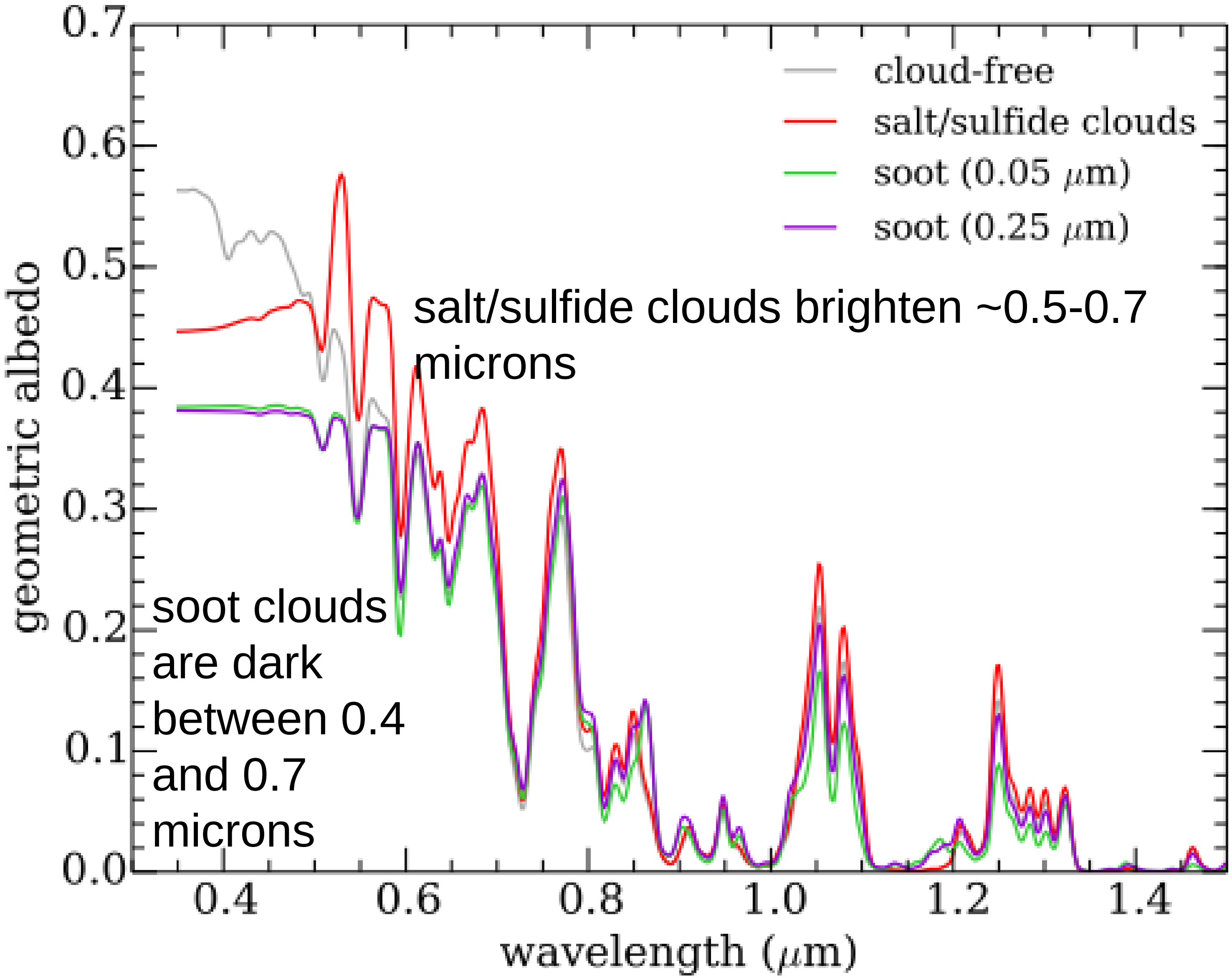
(preliminary results)

High-altitude hazes cause a **temperature inversion** whic creates **emission features**.



(preliminary results: Morley & Fortney, in prep)

Soots and salts/sulfides create different reflection spectra

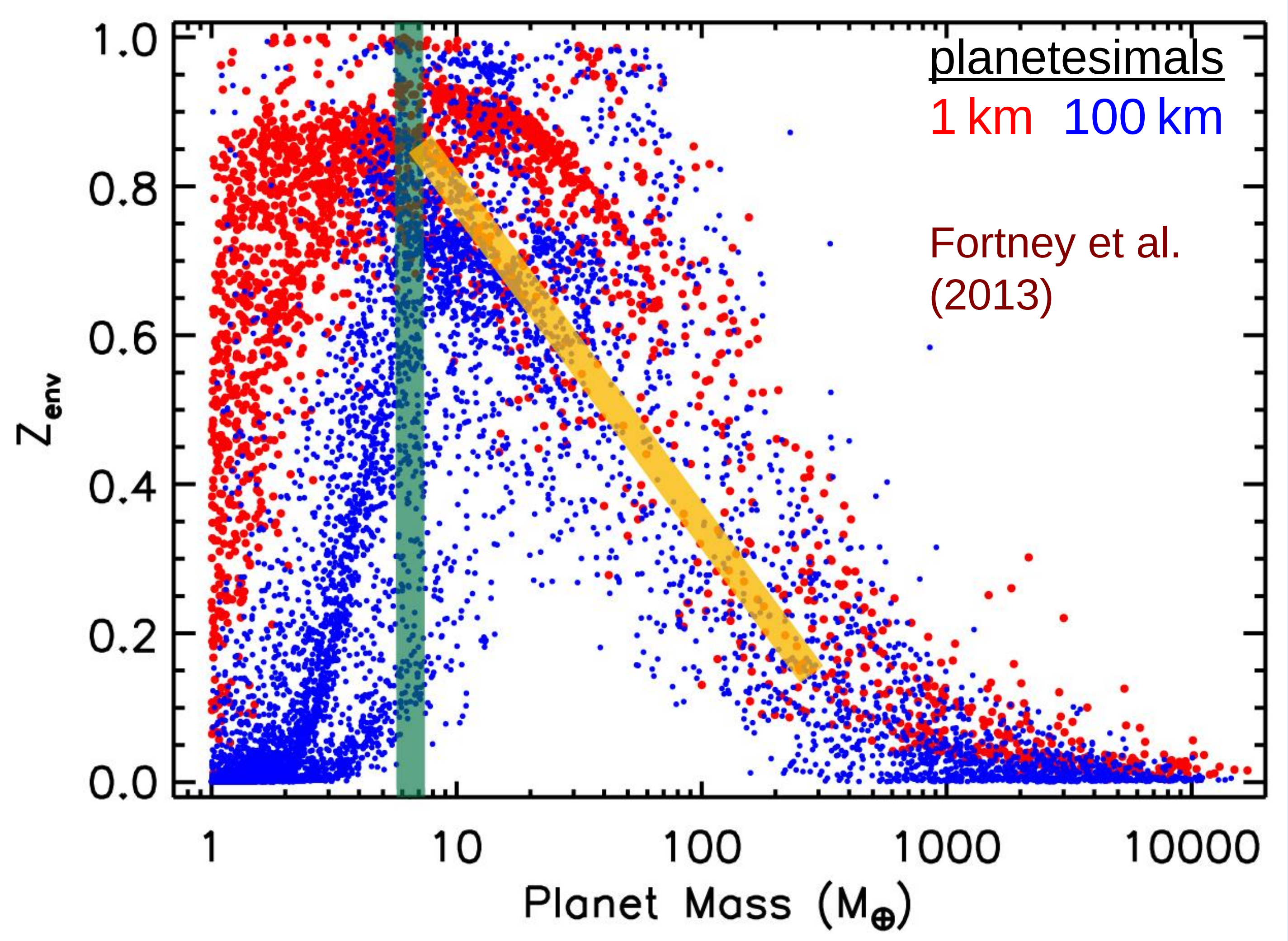


salt/sulfide clouds brighten ~0.5-0.7 microns

soot clouds are dark between 0.4 and 0.7 microns

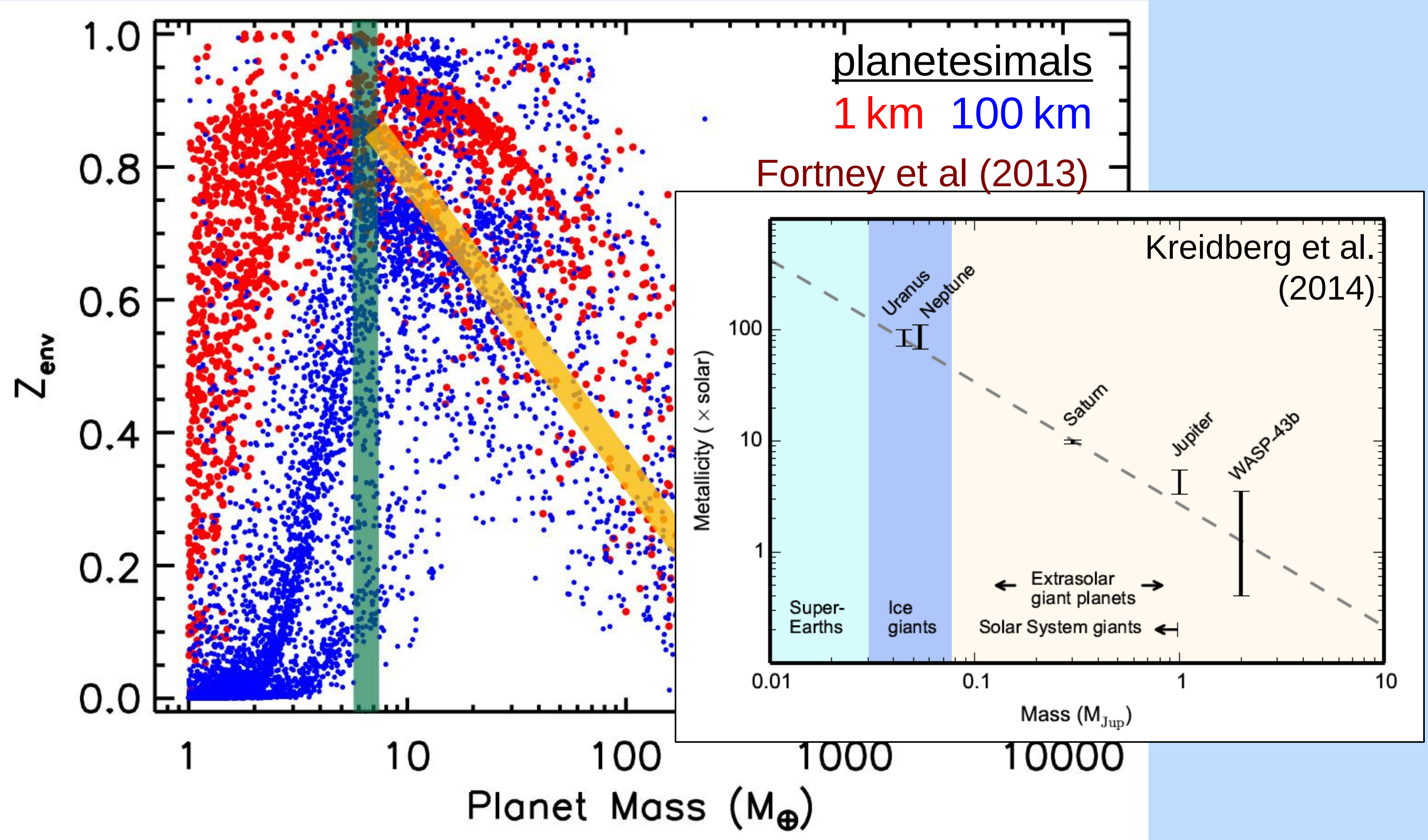
(preliminary results)

Thinking more about composition: 5000 Planets from "Population Synthesis"



- Models from Mordasini et al. (2012a,b)
- Low mass planets from 5-15 M_{earth} may have quite high Z_{env}

Very Metal-Rich Atmospheres May be the Rule

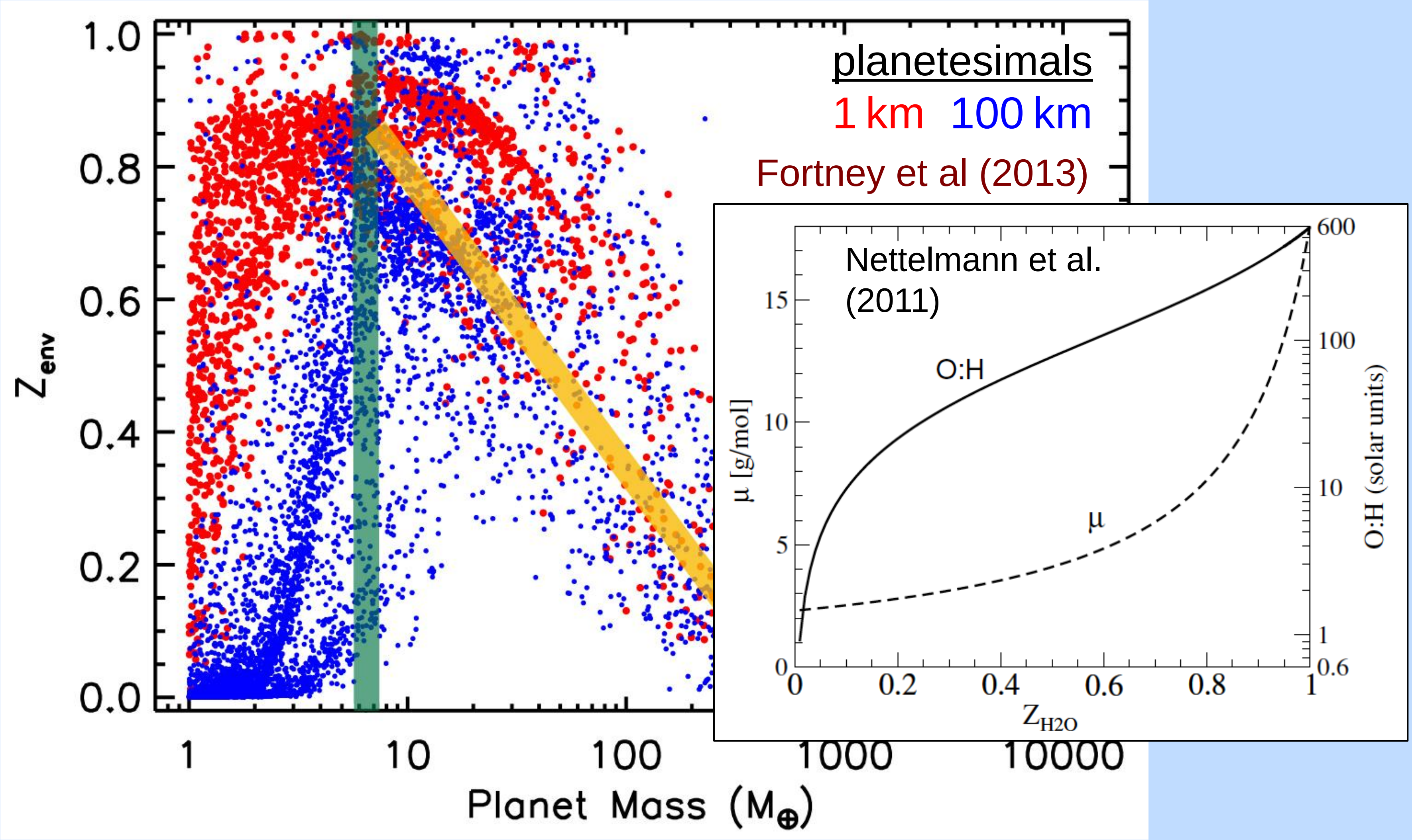


Fortney et al (2013)

Kreidberg et al. (2014)

- A wide diversity in metal enrichments?
- High Z_{env} making <u>abundant material for clouds</u>?

Very Metal-Rich Atmospheres May be the Rule



- A wide diversity in metal enrichments?
- High Z_{env} making <u>abundant material for clouds</u>?

Conclusions I

- We can model the thermal evolution of LMLD planets within a simple model that probably captures most behavior
  - Models should be tied to mass-loss models to understanding current (and past) composition
  - We can get 1st order composition information: The fraction of the planet's mass that is H/He envelope
  - Remnant cores can tell us about the composition of the material below H/He envelopes

- Planets are cool, which leads to condensation, and clouds
  - We're trying to think about ways to better characterize the atmospheres of LMLD planets, in thermal emission and reflection, for 2nd order composition information
  - Thermal emission appears promising
  - I'm sorry but it might take some patience

Conclusions II

- In my opinion we need to think a lot more about what we'd learn, and what it would mean, when we can measure atmospheric abundances
  - Accreted atmospheres
    - What solids do you accrete as a function of orbital separation?
    - What solids do you accrete in multiplanet vs. single systems? (Does the pot get stirred?)
    - Mostly rocky, mostly icy?
    - Caron-rich or poor?
  - How important is outgassing for mostly rocky planets with H-dominated atmospheres?