The puzzle of low-density super-Earths

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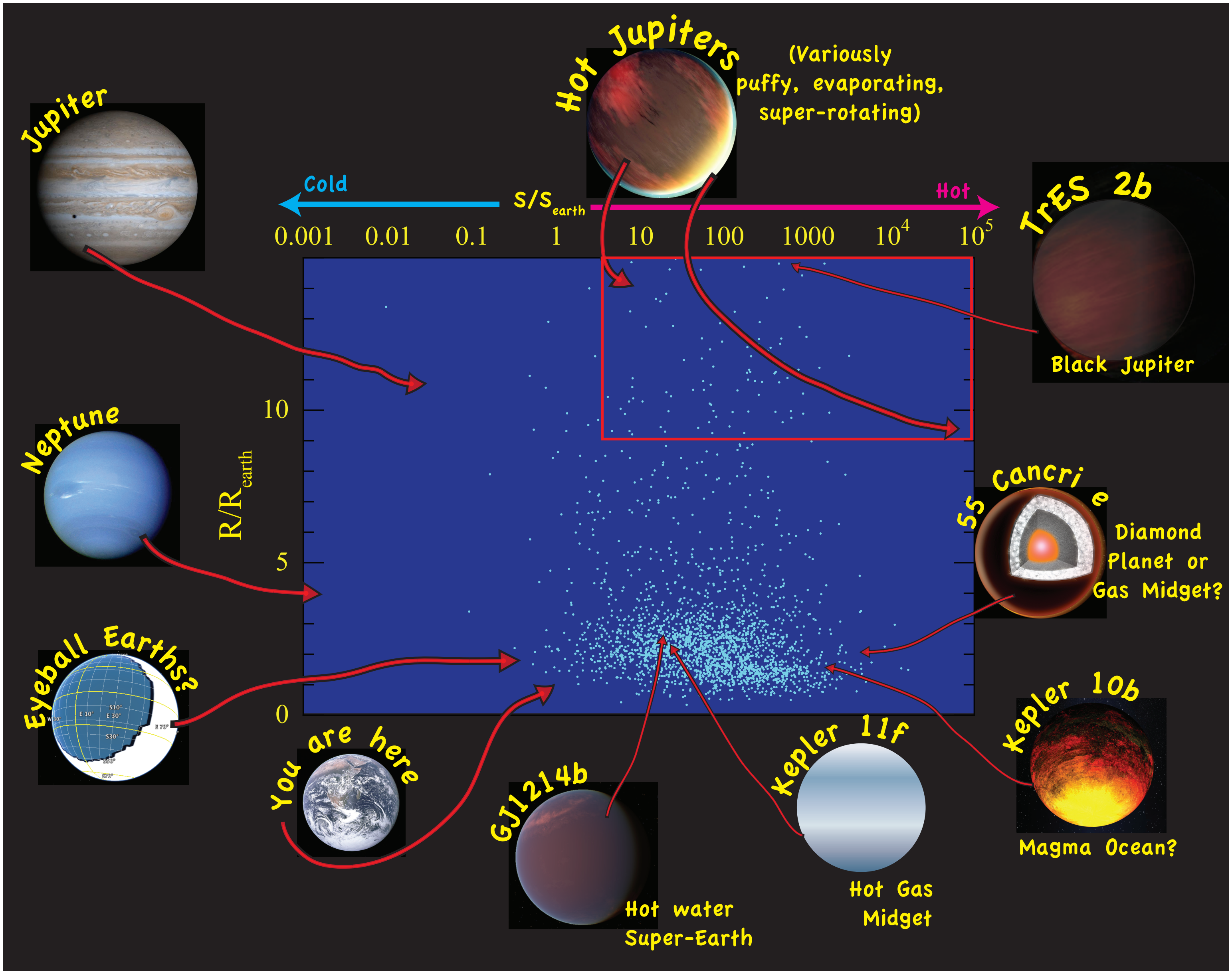
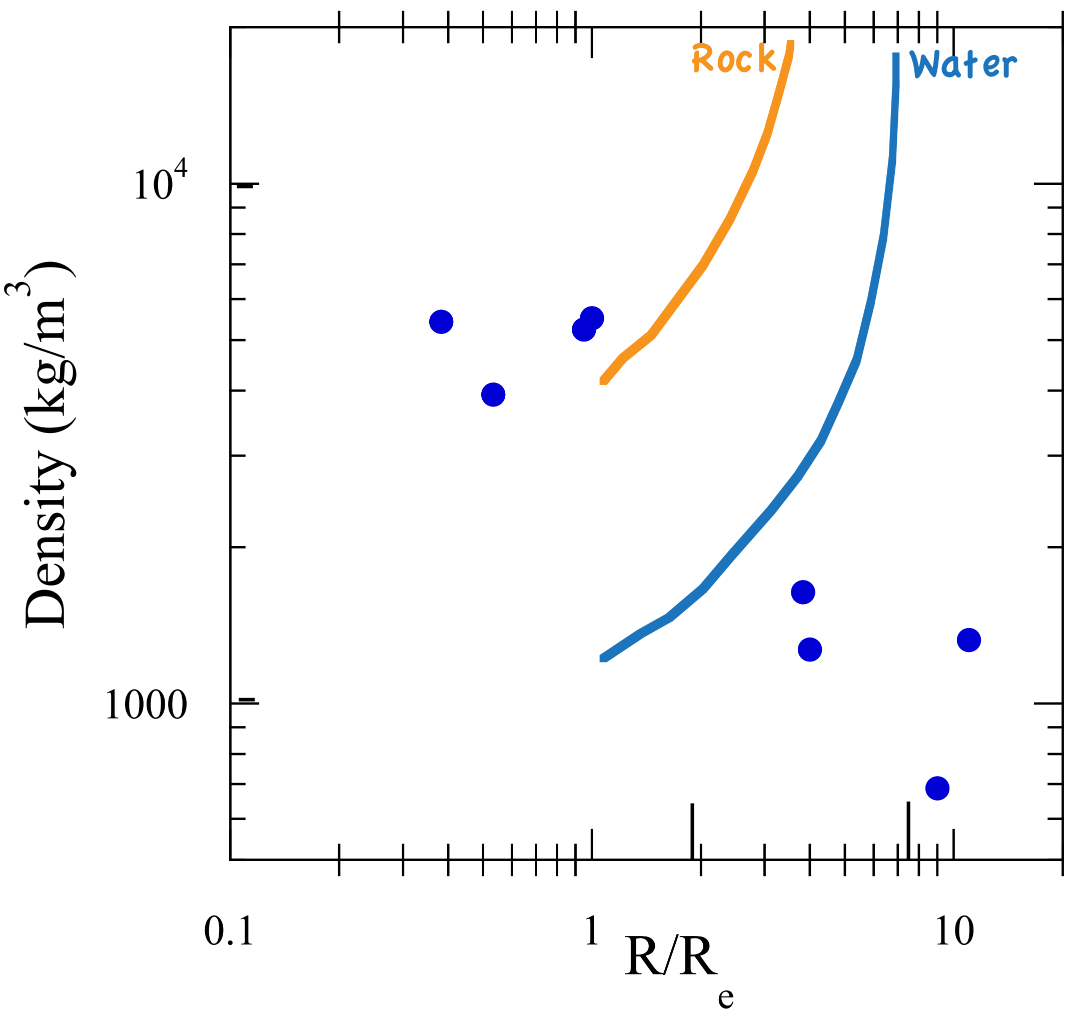
The University of Chicago

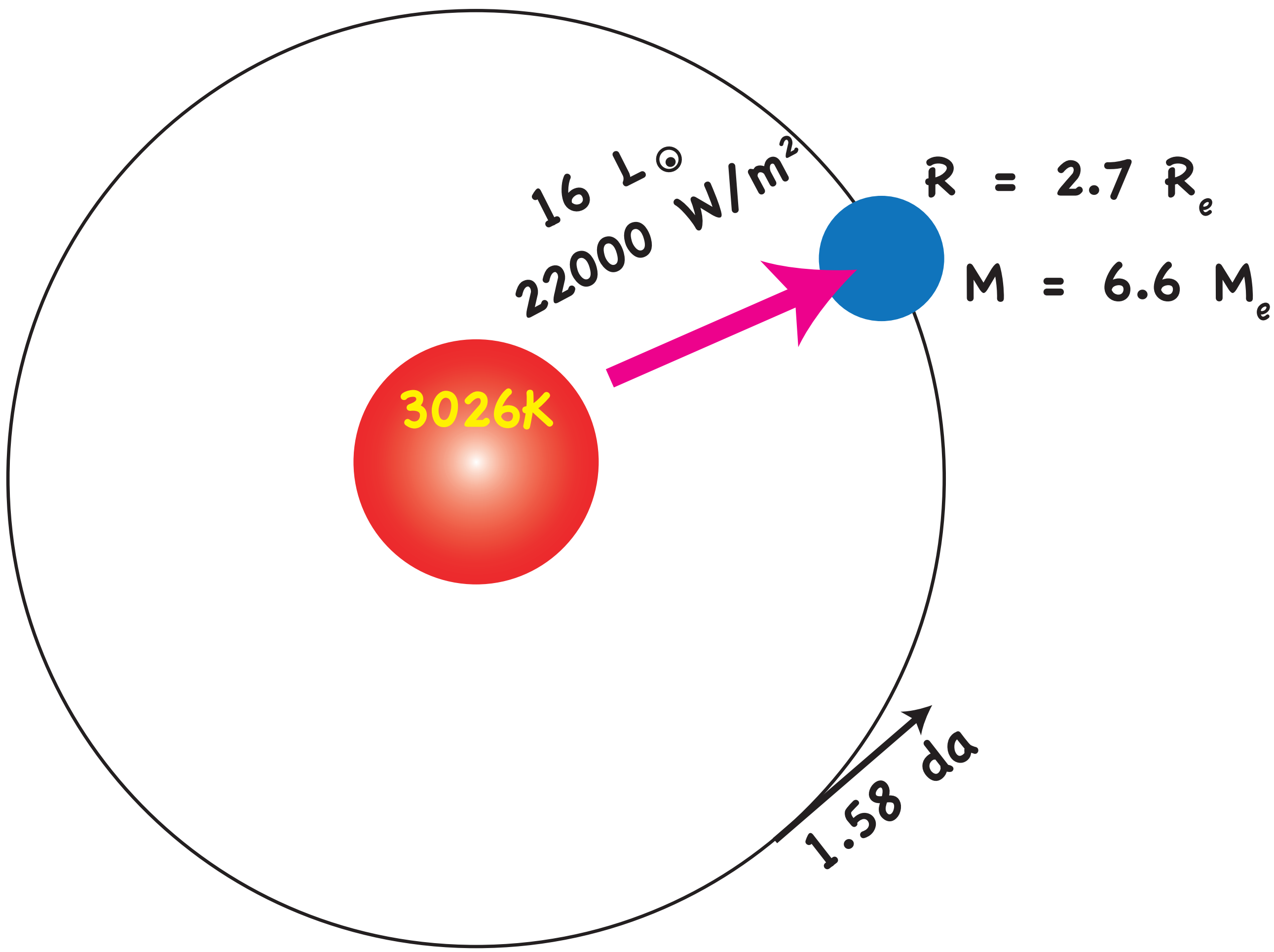


Pierrehumbert 2013, *Nature Geoscience*, doi:10.1038/ngeo1711

The Solar System



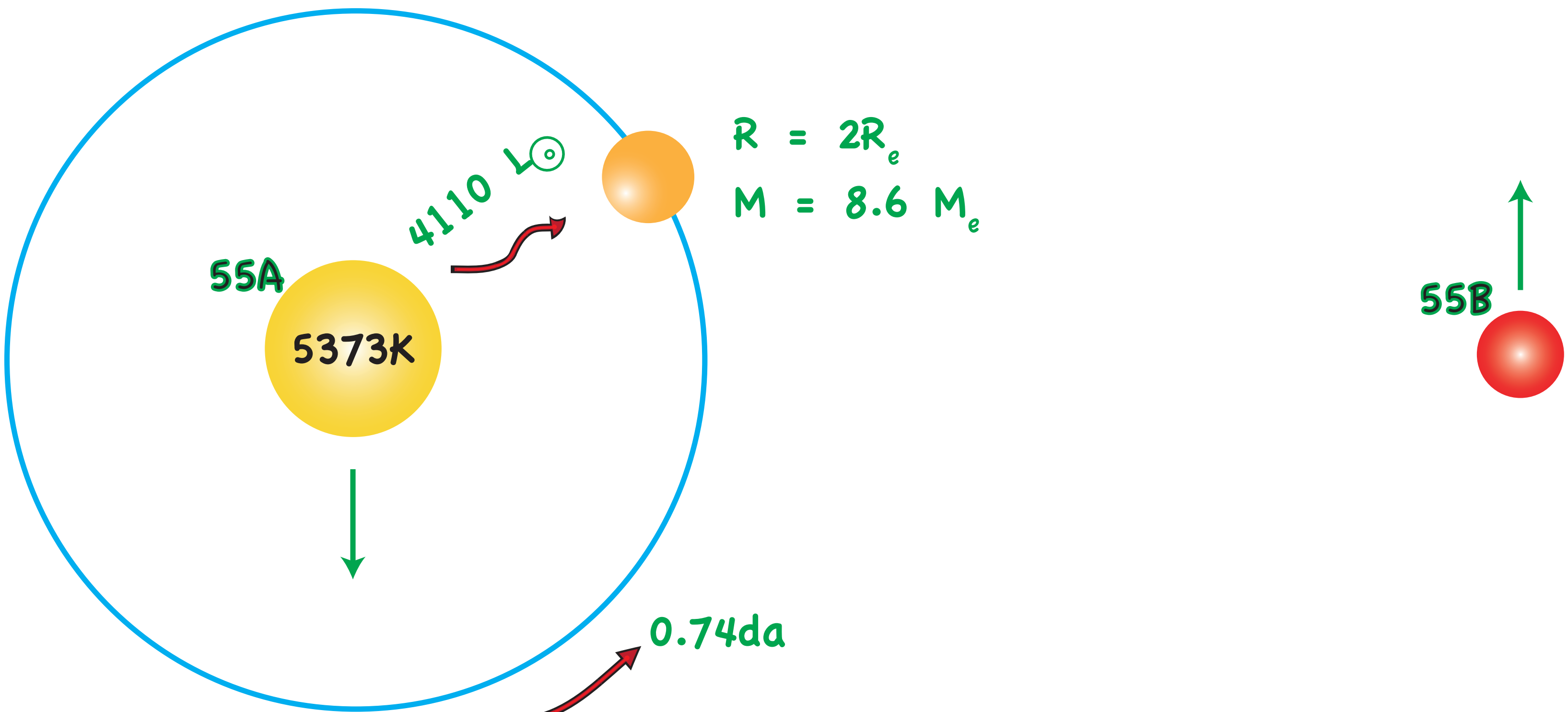
The case of GJ1214b



$\rho = 1900 \mathrm{kg/m}^3$

Detected by transit, with RV follow-up.

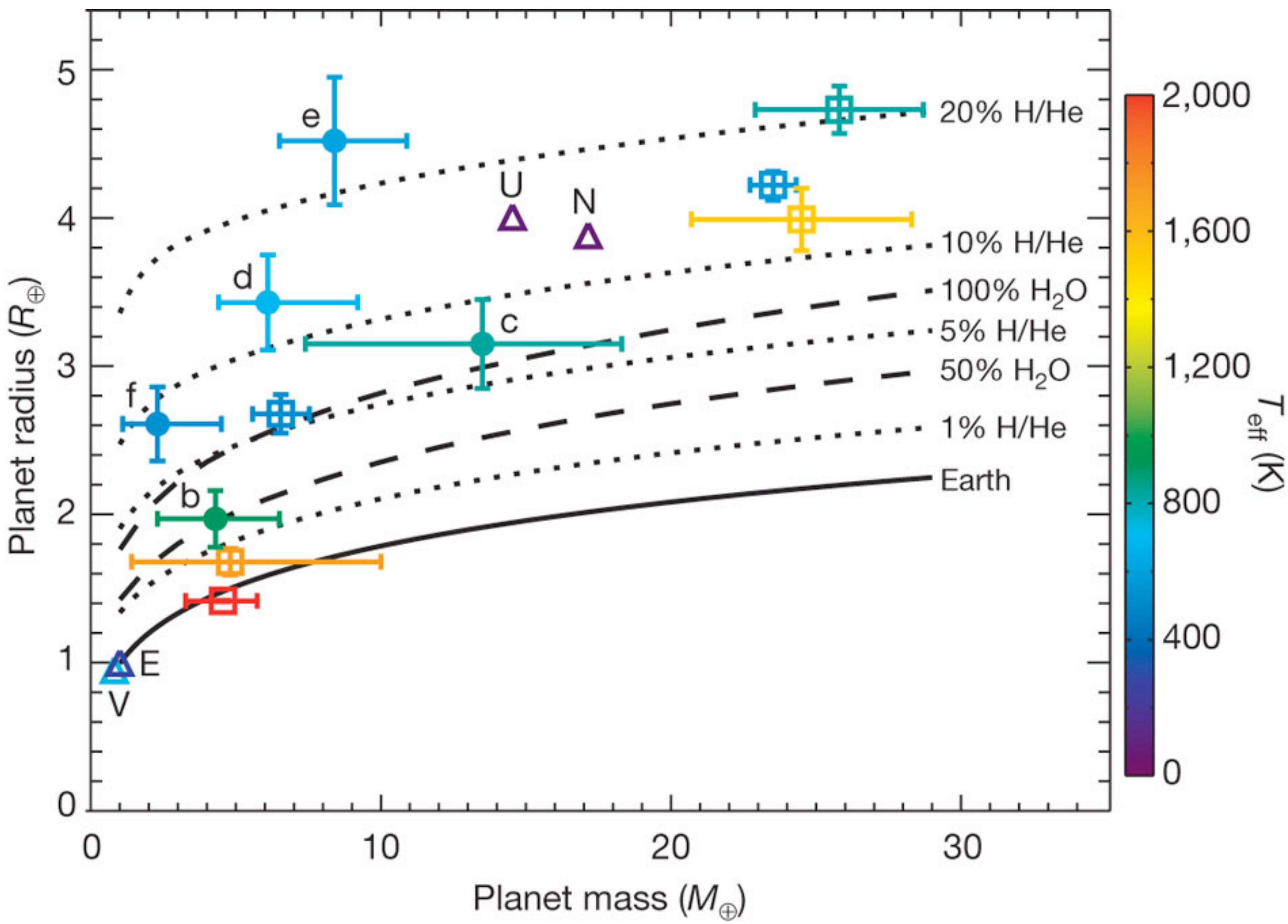
The case of 55 Cancri-e



$\rho = 5900\text{kg}/\text{m}^3$

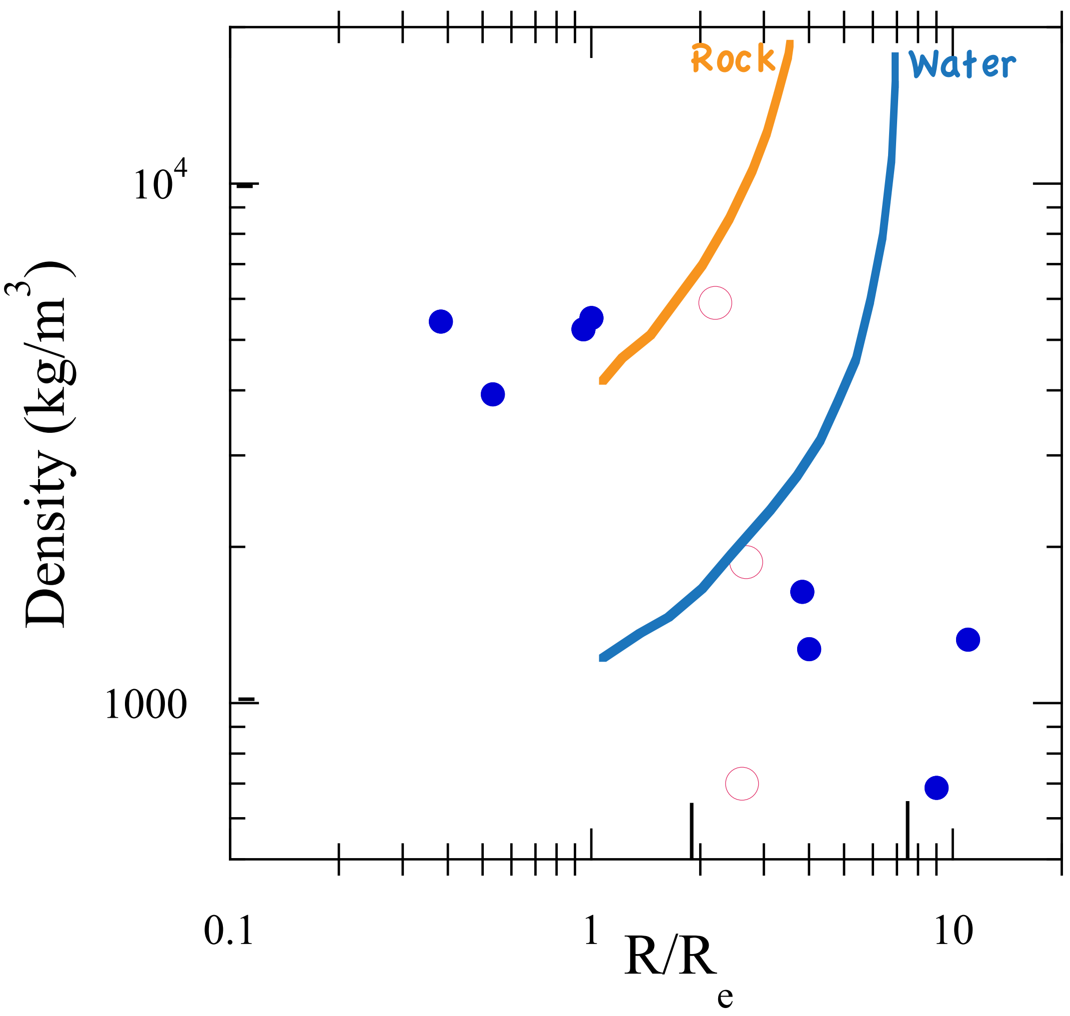
Transiting multi-planet system

The Kepler 11 system

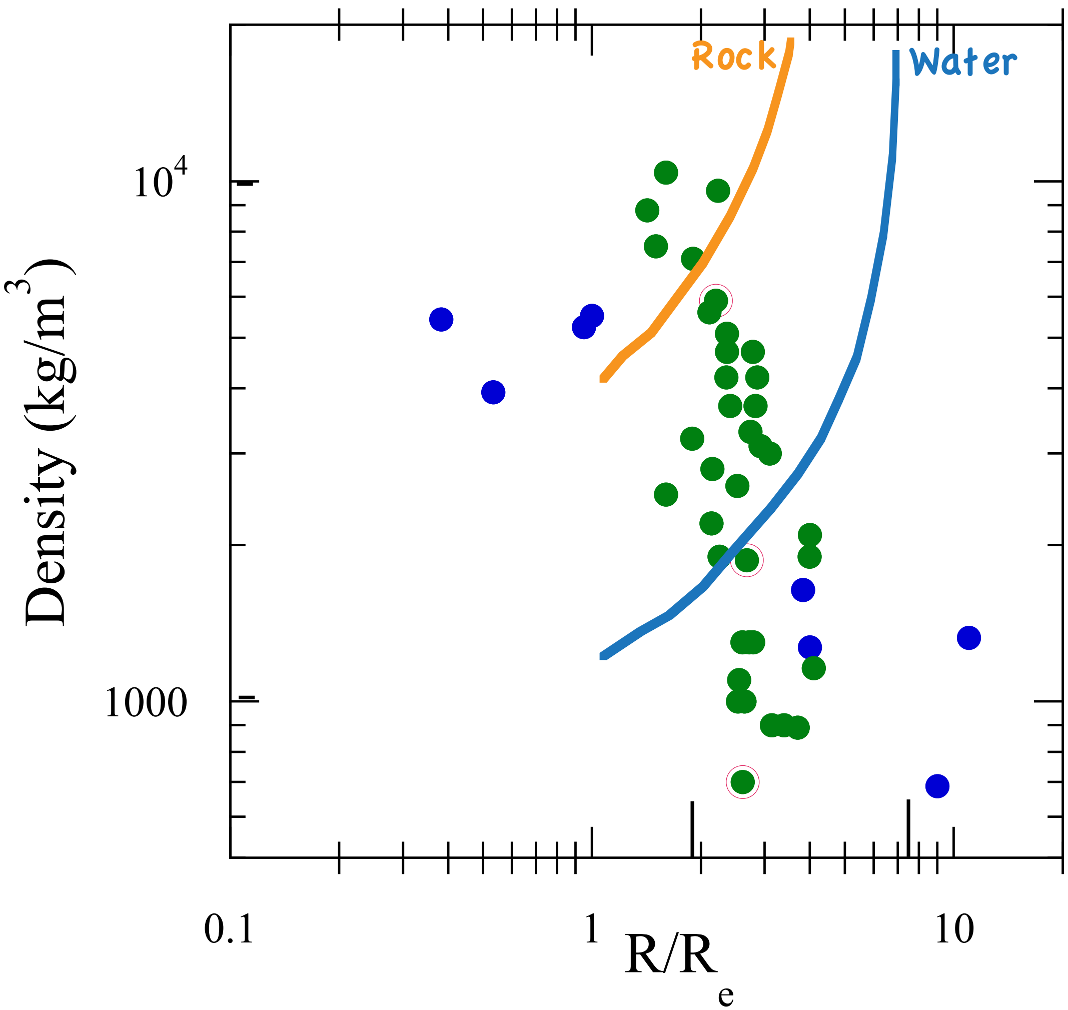


Lissauer *et al* 2011, *Nature*,doi:10.1038/nature09760

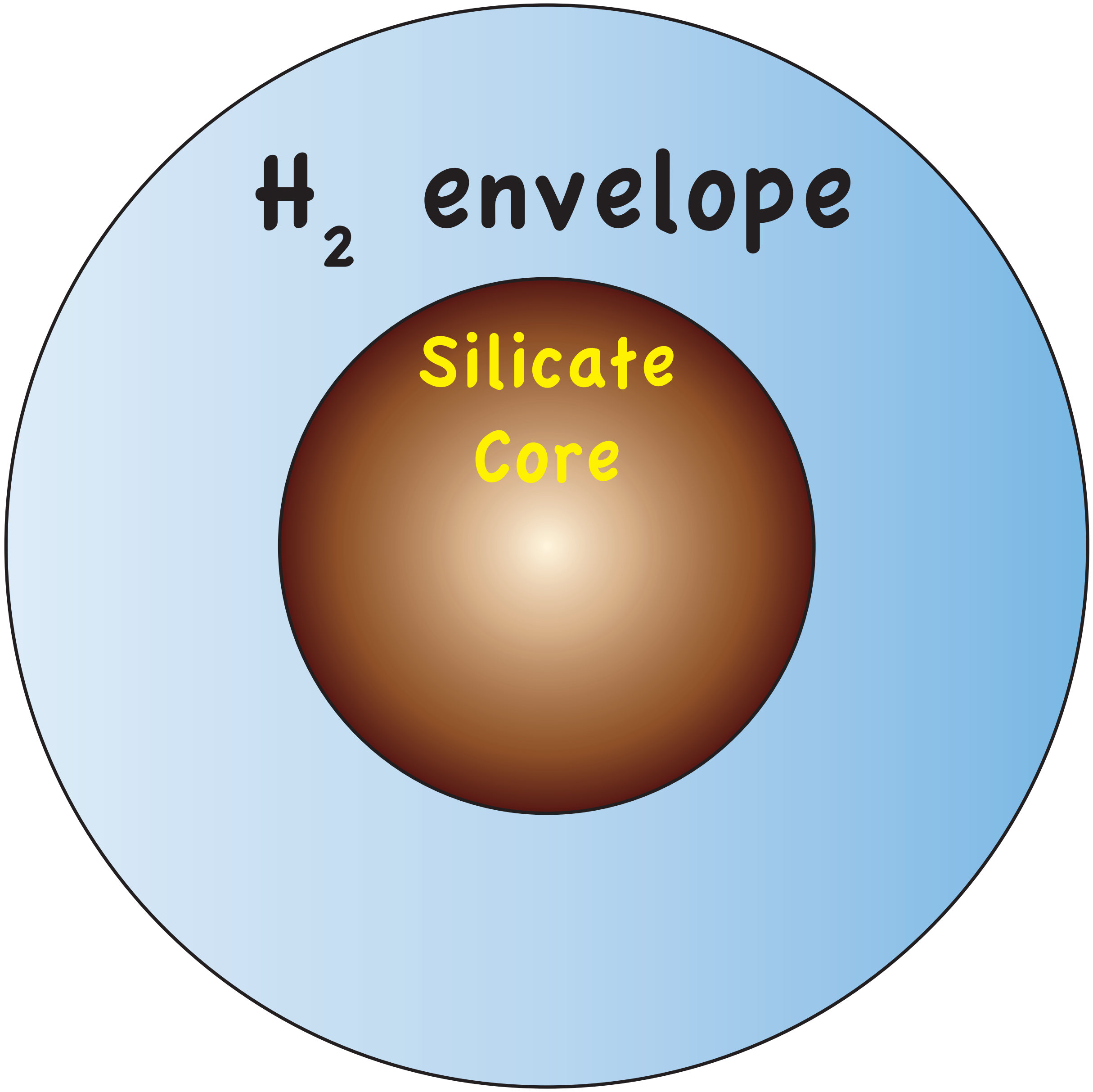
Our Planets so far



All planets with $R < 4R_e$, incl. Lithwick 2012 transit pairs



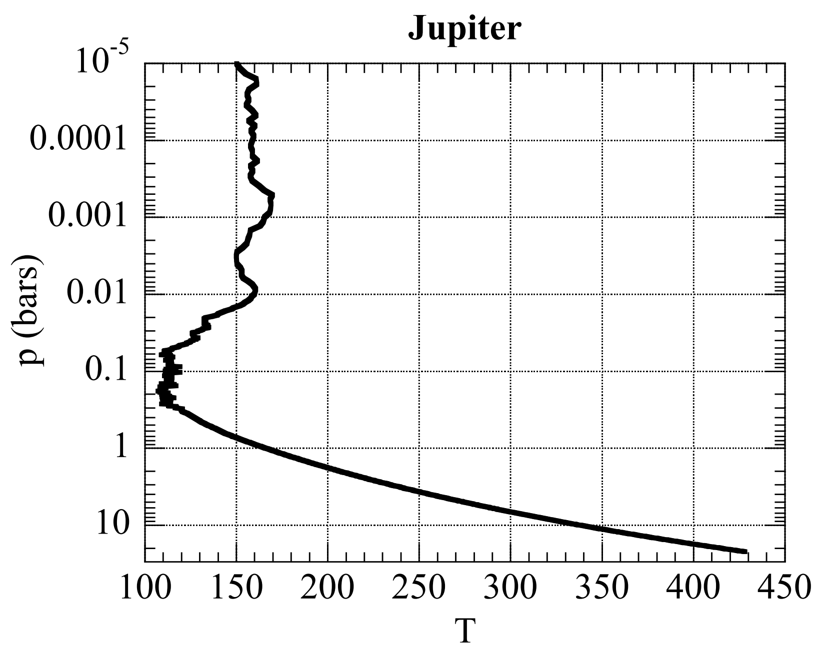
Model 1: Rocky (Silicate) core with H_2/He envelope



A connection to the extended habitable zone

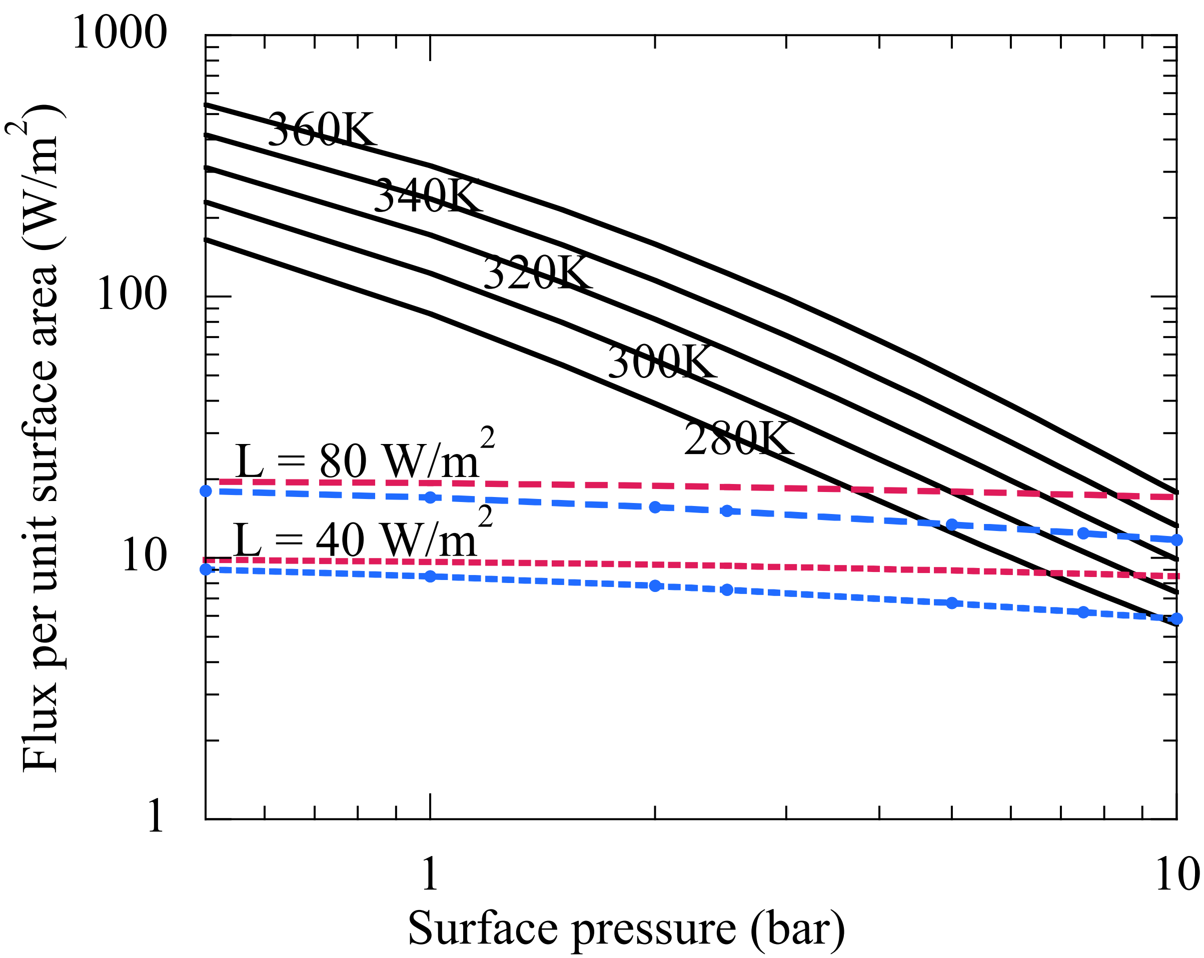
- If even these hot Super-Earths can retain an H_2 envelope
- ... then further out, it should be even easier to retain a massive envelope
- But in sufficient quantities H_2 is a good greenhouse gas
- ... and it doesn't condense as easily as CO_2

Small, rocky Jupiters?



Water-habitable at 5 bars, 2.4g_e!

Top-of-Atmosphere Energy Balance for a Hydrogen World



Pierrehumbert and Gaidos, *Ap. J. Lett.* doi:10.1088/2041-8205/734/1/L13

H_2-assisted greenhouse on Early Earth?

Science 4 January 2013:
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REPORT

Hydrogen-Nitrogen Greenhouse Warming in Earth's Early Atmosphere

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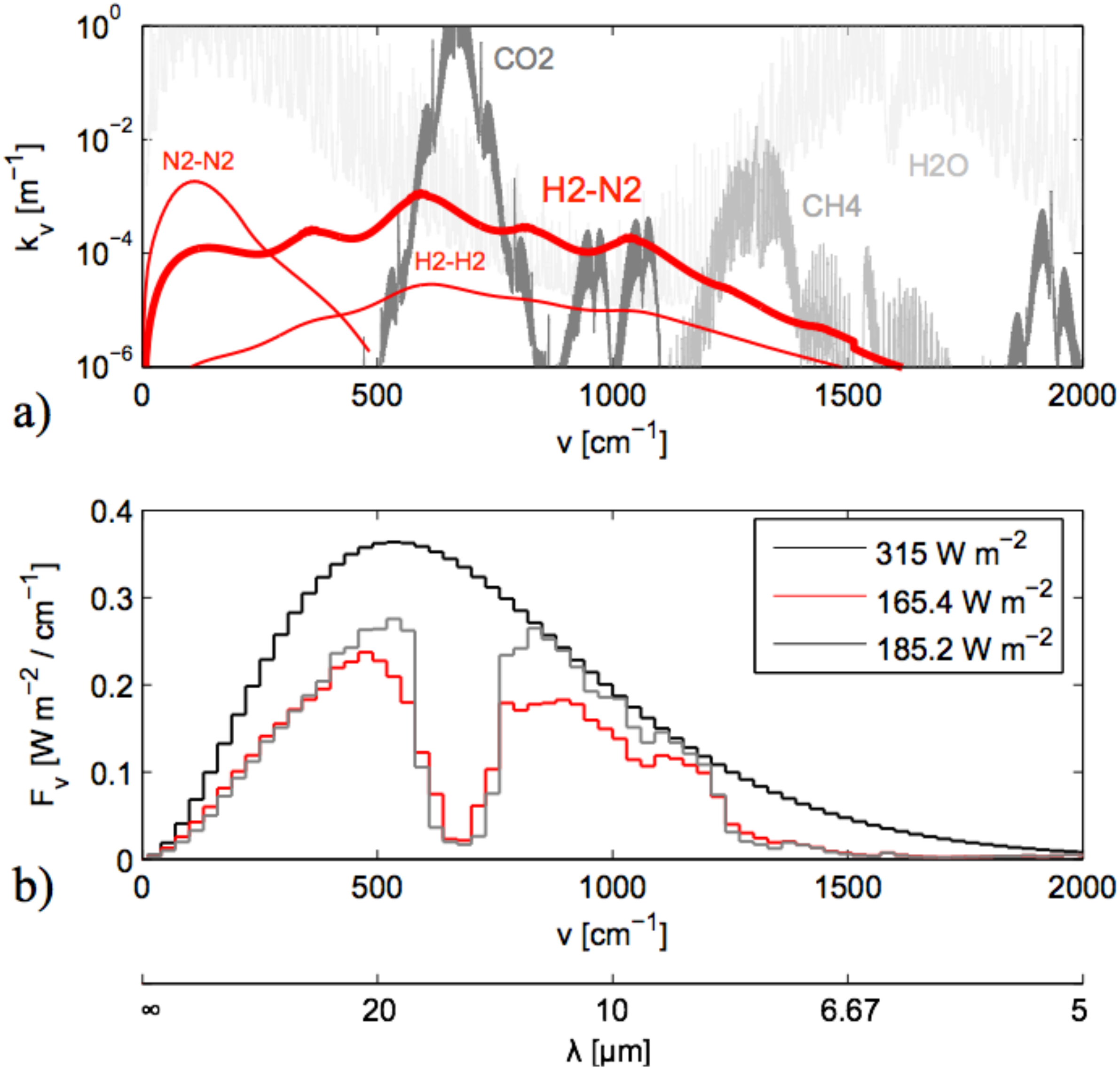
ABSTRACT

Understanding how Earth has sustained surface liquid water throughout its history remains a key challenge, given that the Sun's luminosity was much lower in the past. Here we show that with an

H_2-assisted greenhouse on Early Earth?



Even Early Mars may be able to retain H_2 in climatically significant quantities

A CO_2-H_2 Greenhouse for Early Mars

Ramses M. Ramirez[i,iii,v], Ravi Kopparapu[i,iii,v], Michael E. Zugger[ii,v], Tyler D. Robinson[iv,v], Richard Freedman[vi], and James F. Kasting[i,iii,v]

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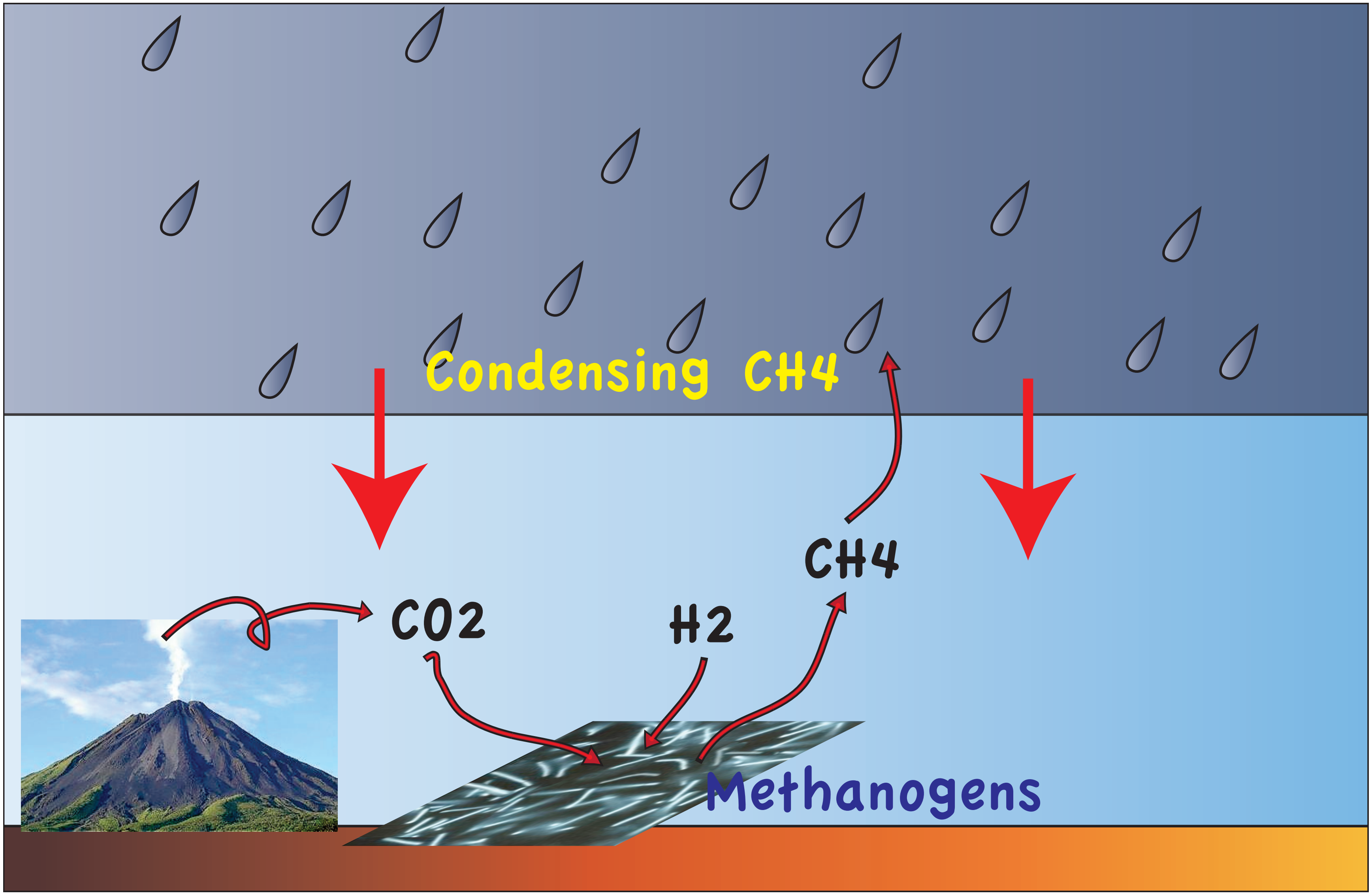
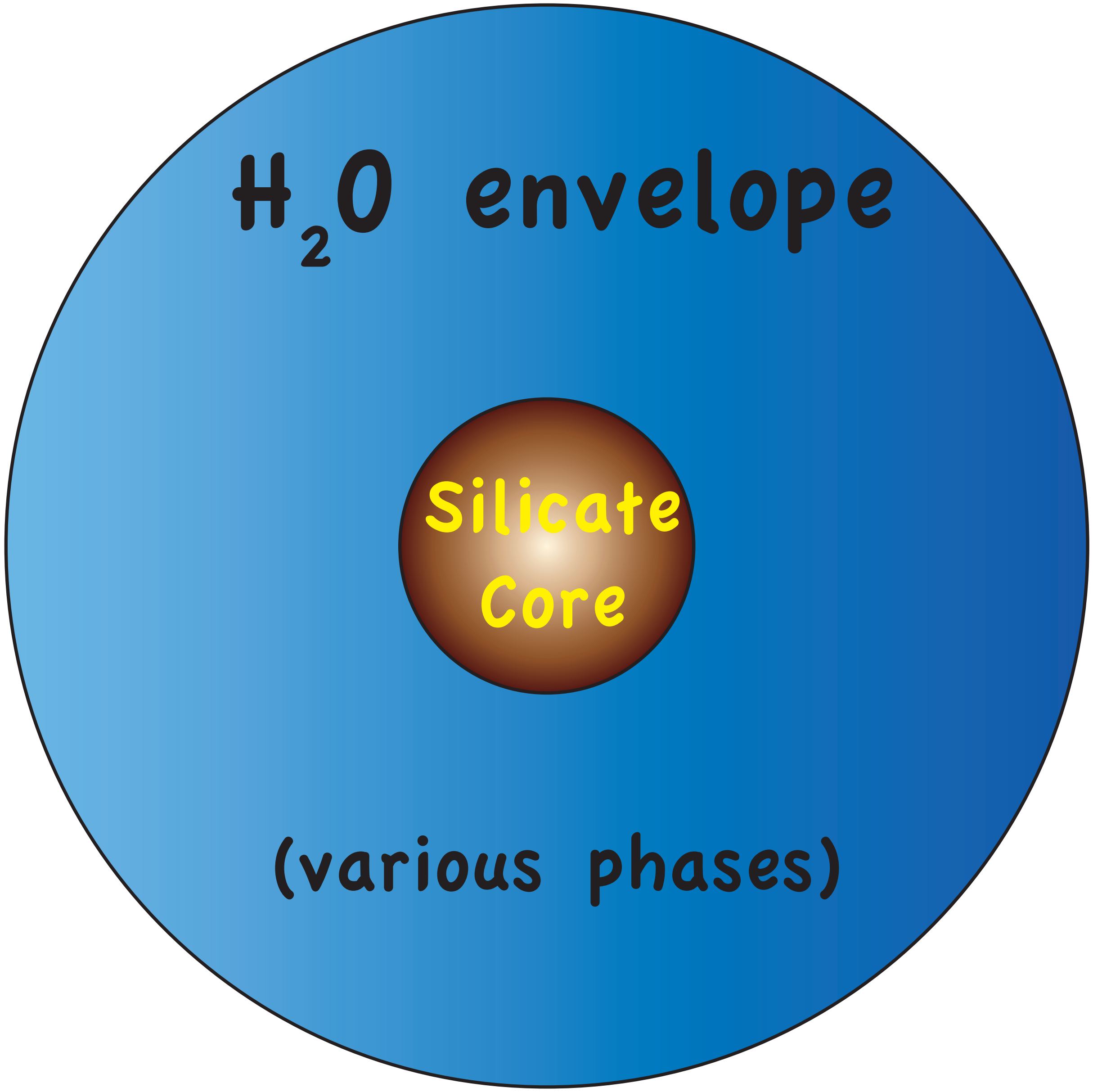
[v] NASA Astrobiology Institute Virtual Planetary Laboratory
[vi] SETI Institute, Mountain View, CA 94043/NASA Ames Research Center, Moffett Field, CA, 94035

Extended HZ Habitable only if uninhabited?



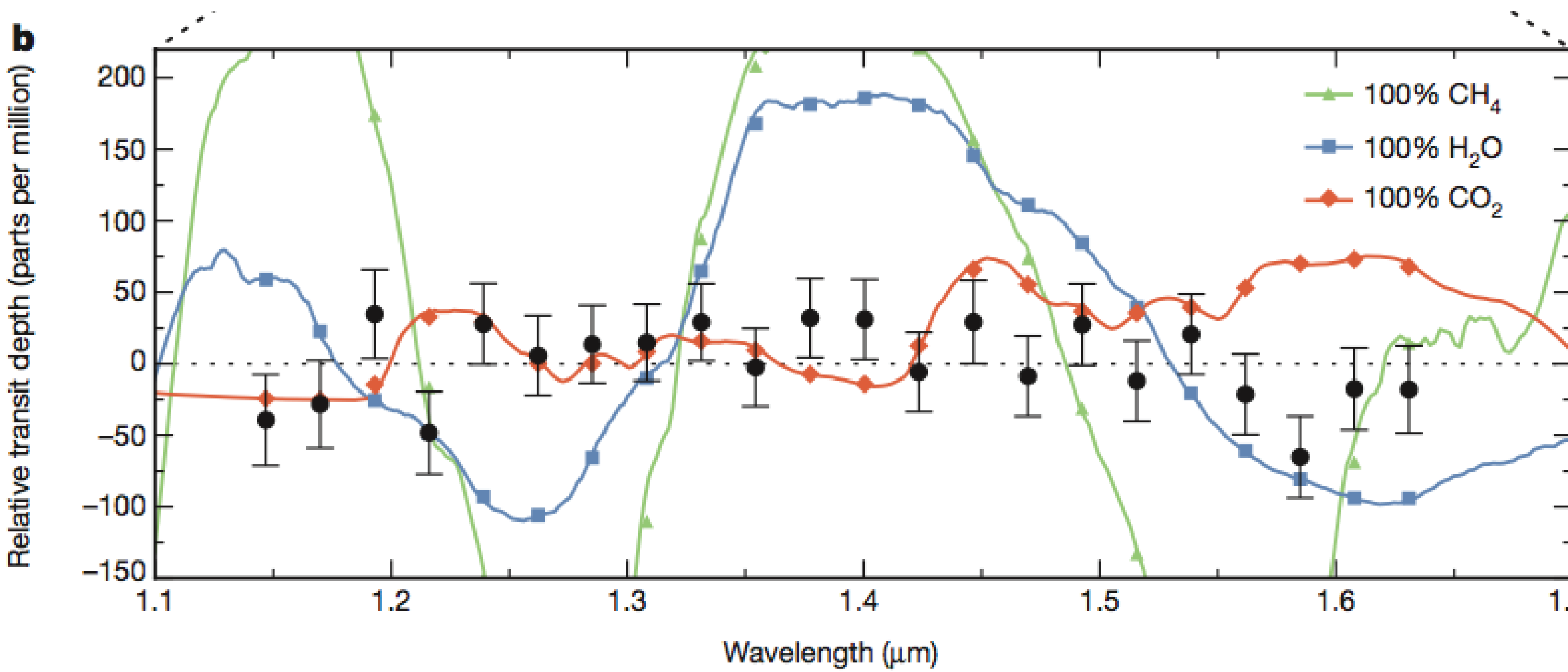
Model 2: Rocky (Silicate) core with H_2O envelope



What kind of thing is GJ1214b?

- Transit depth vs wavelength $\rightarrow$
  - no H_2 envelope (Bean, et al.)
  - *unless masked by high, optically thick clouds*
- Water-world has been a leading candidate
  But Kreidberg et al. *Nature* 2013 rule out
  cloud free pure water vapor atmosphere.
- High temperature $\rightarrow$
  - supercritical fluid, no liquid ocean interface,
  - probably no high-pressure ice mantle

Kreidberg et al 2013 rule out pure-CO_2 cloud-free atmosphere...



... but not by much

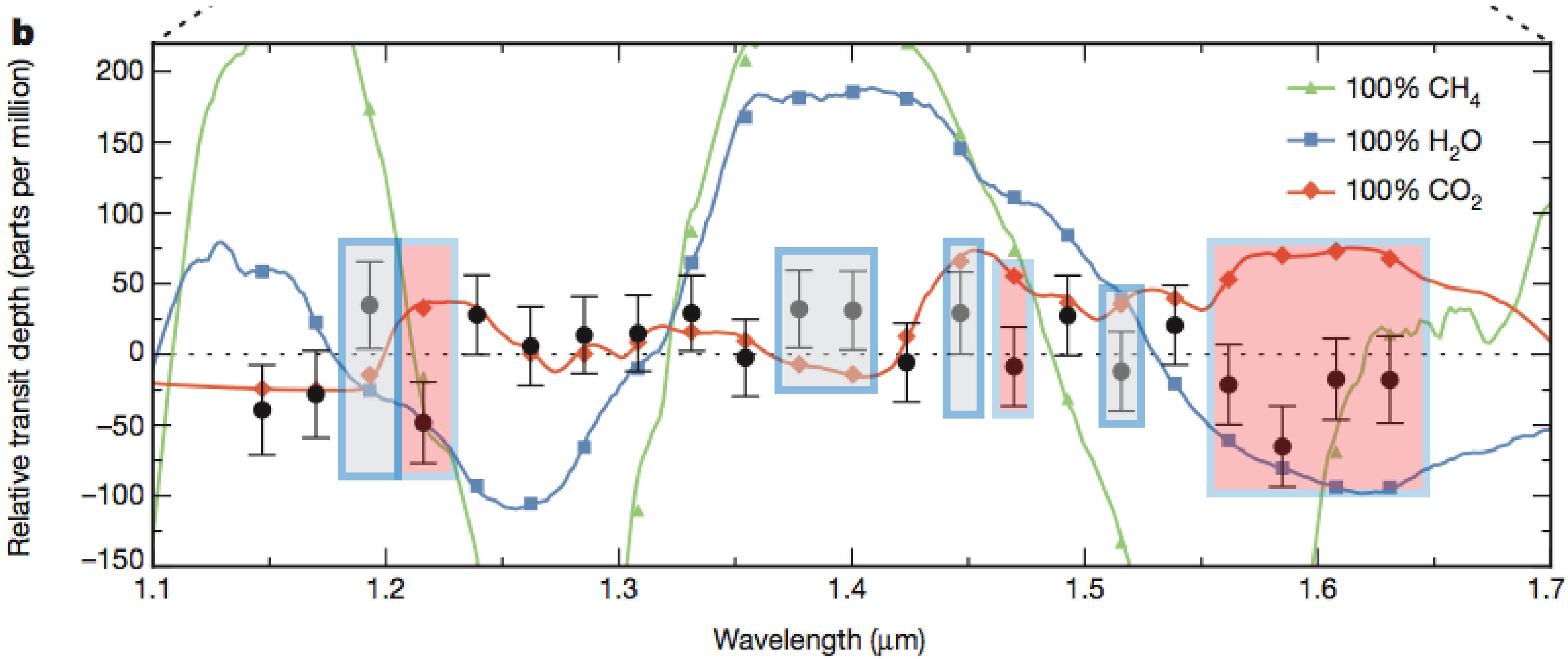
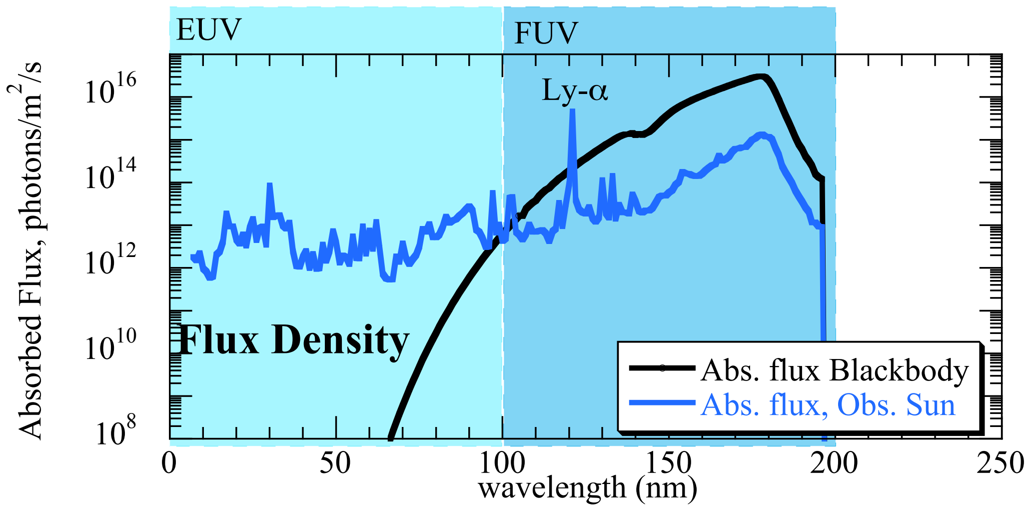
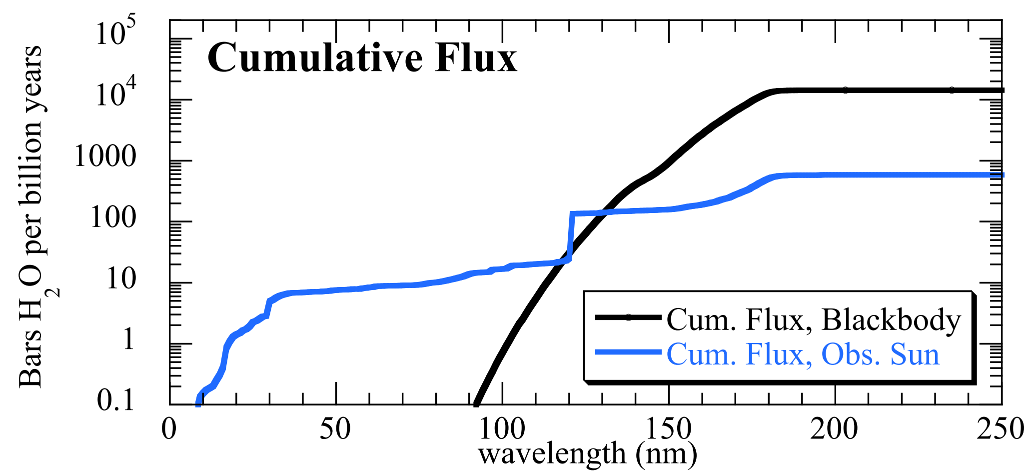


Photo-evaporation and hydrogen stripping

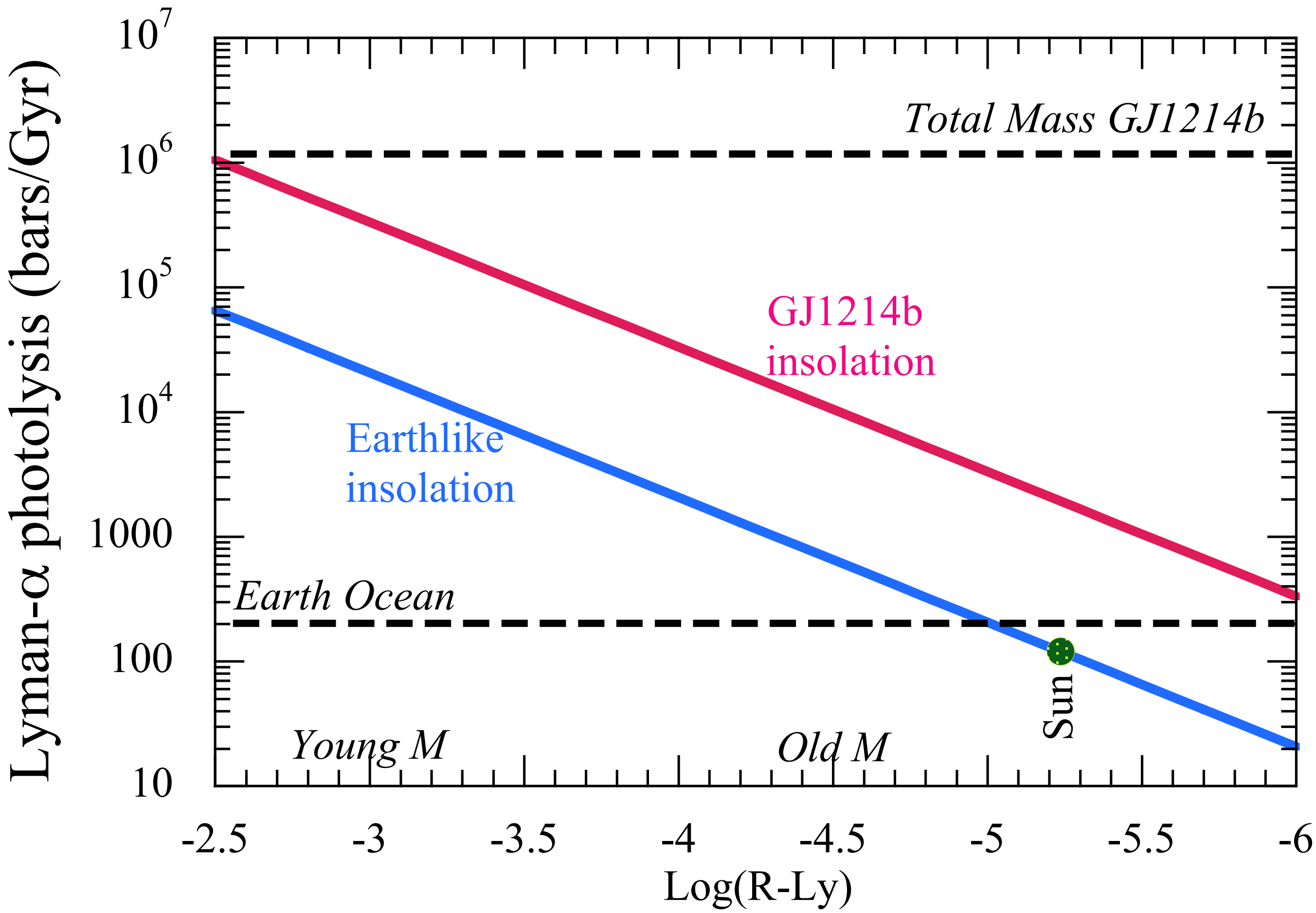
- Work in collaboration with Jamie Lloyd, Cornell (incl. ”Super Venus” concept)
- For M-stars, close-in planets like GJ1214b are subject to H-stripping due to EUV and XUV in pre Main-Sequence and young Main-Sequence stage
- It doesn’t matter much what molecule is the H carrier, since there are enough Ly-α photons to photolyze the whole atmosphere
- At present, GJ1214 doesn’t emit detectable Ly-α, so probably not much photchemistry/escape going on currently, and no opportunity to detect escape using Ly-α transits observations

G star photon flux absorbed by H_2O

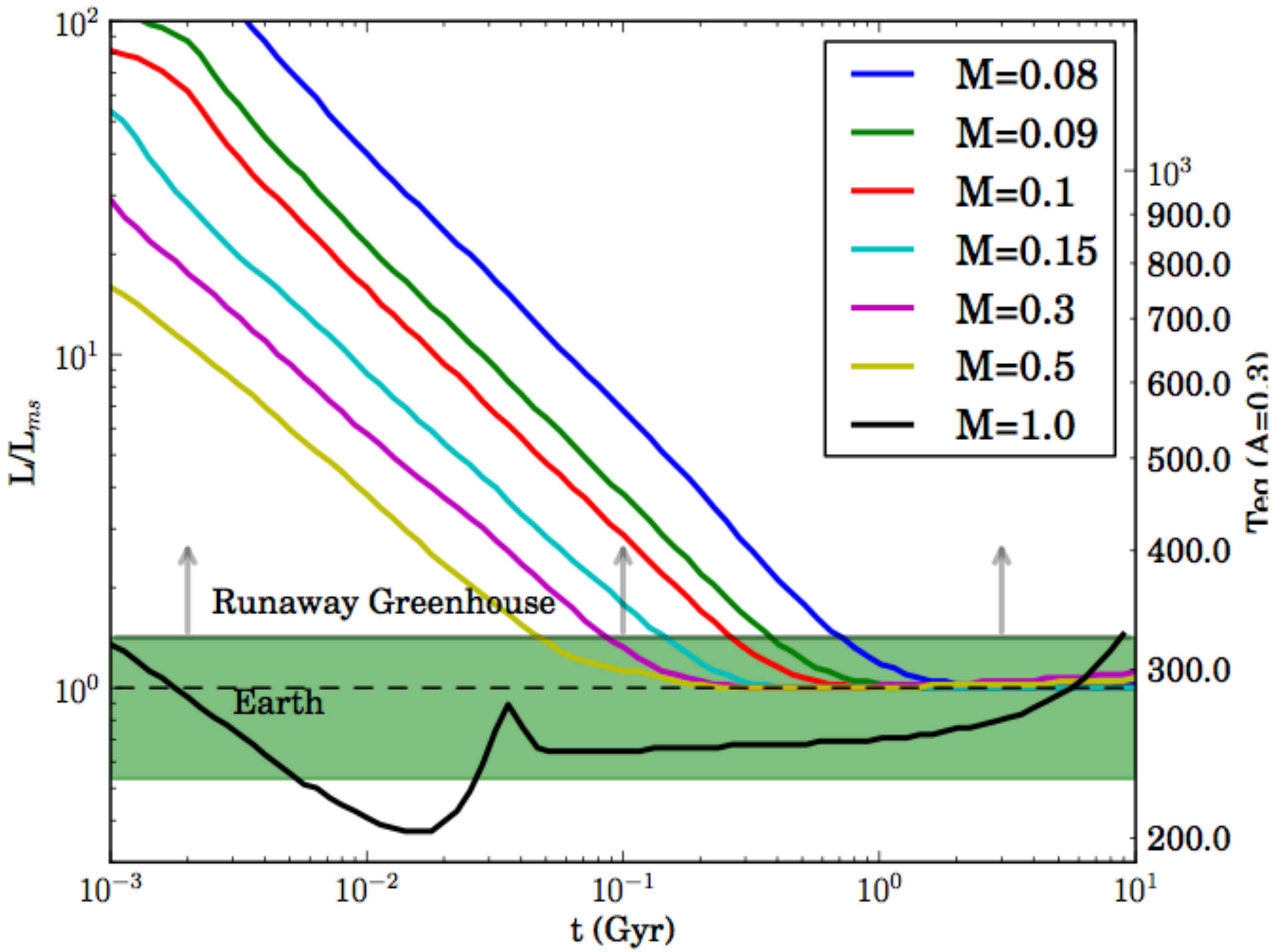




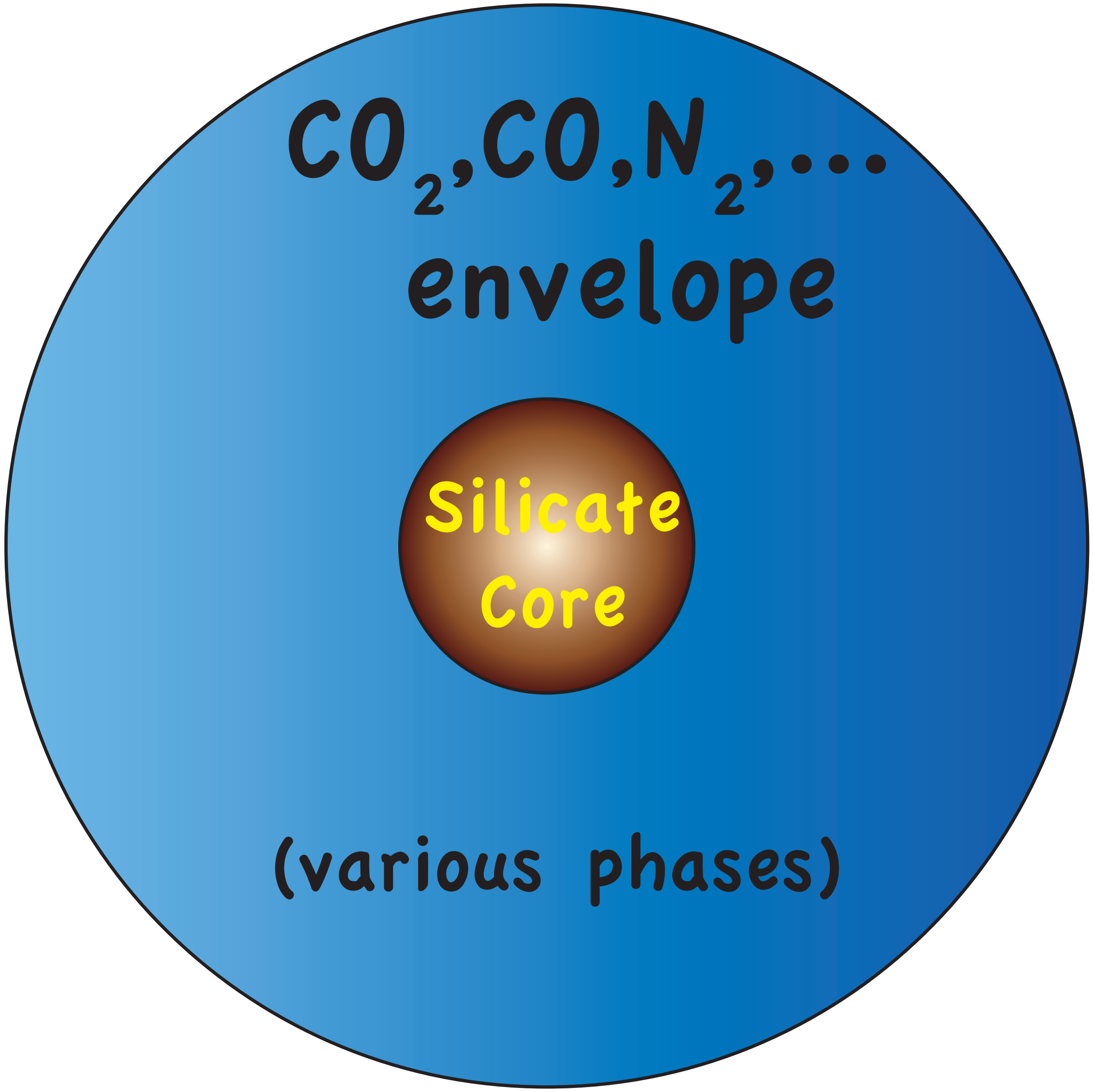
For M stars, H_2O photolysis dominated by Ly-α



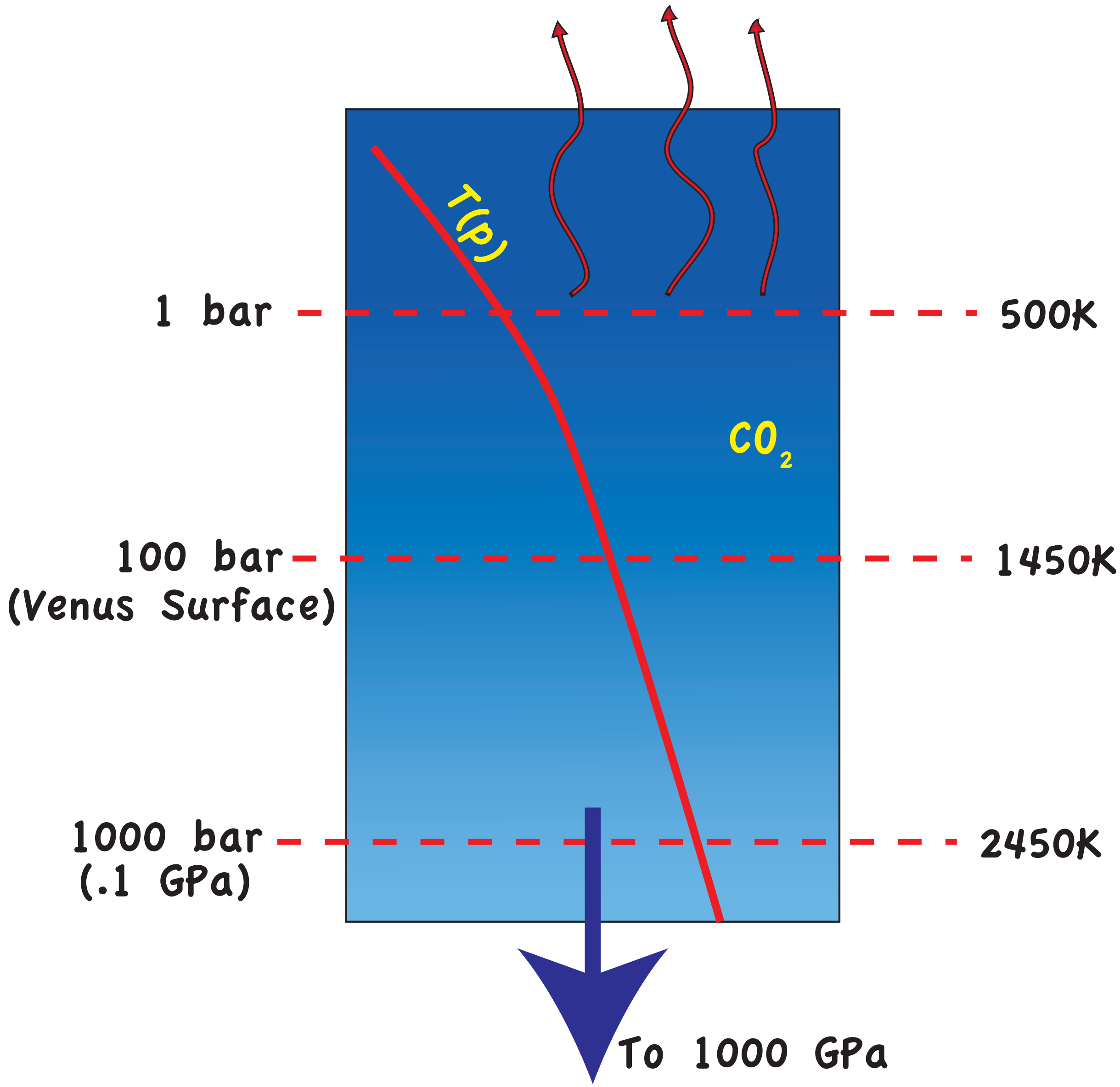
For M stars, high "radiation dose" in long pre main-sequence



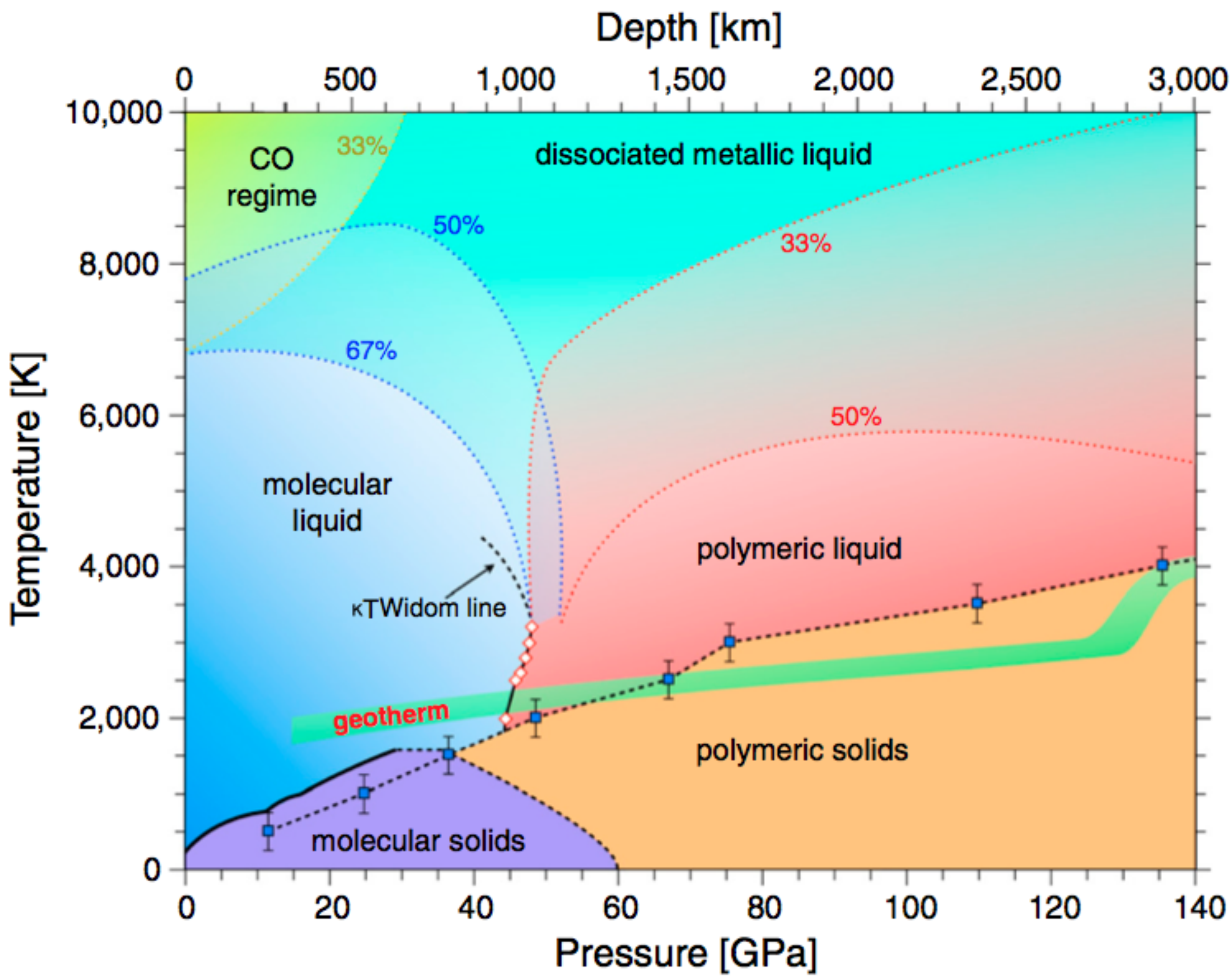
Model 3: Rocky (Silicate) core with H-depleted fluid envelope



GJ1214b as a CO_2 world (a Super-Duper Venus!)

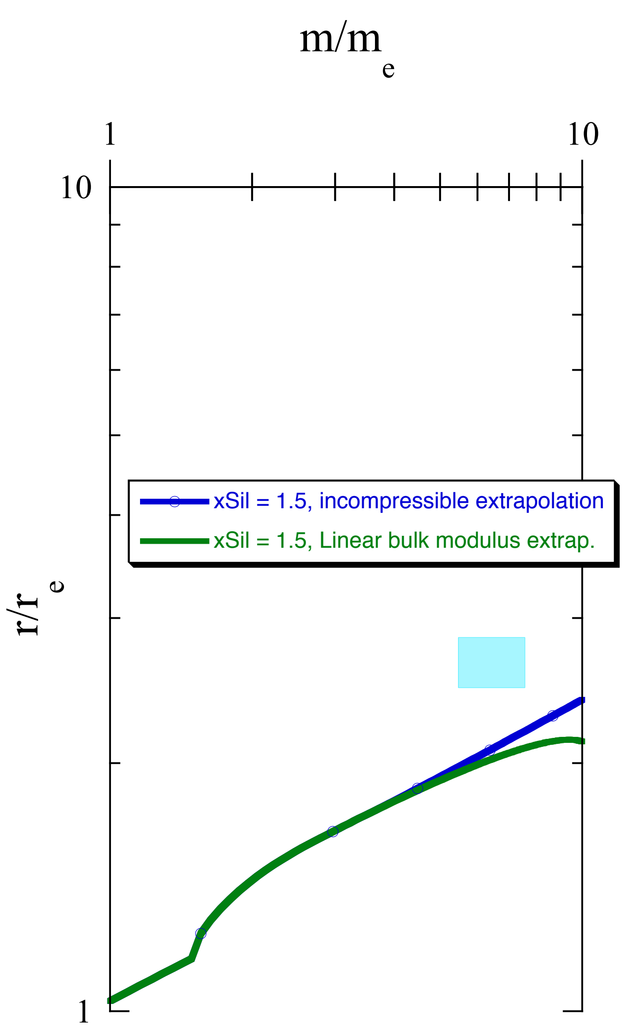


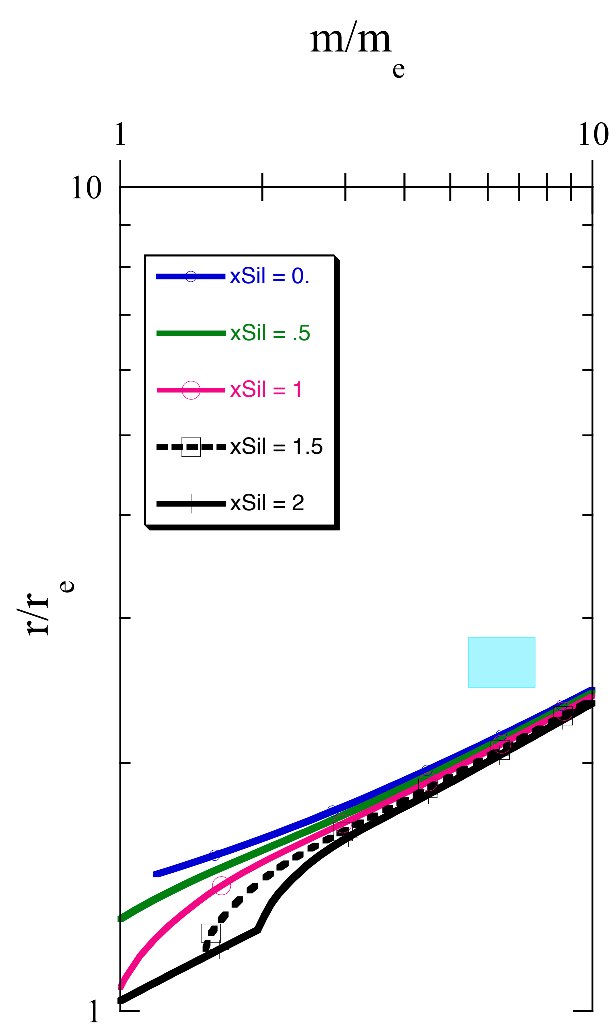
The CO_2 phase diagram (Boates, PNAS 2012)



GJ1214b too hot to have a CO_2 ice mantle, but cooler planets might.

Mass-radius relation for CO_2 worlds



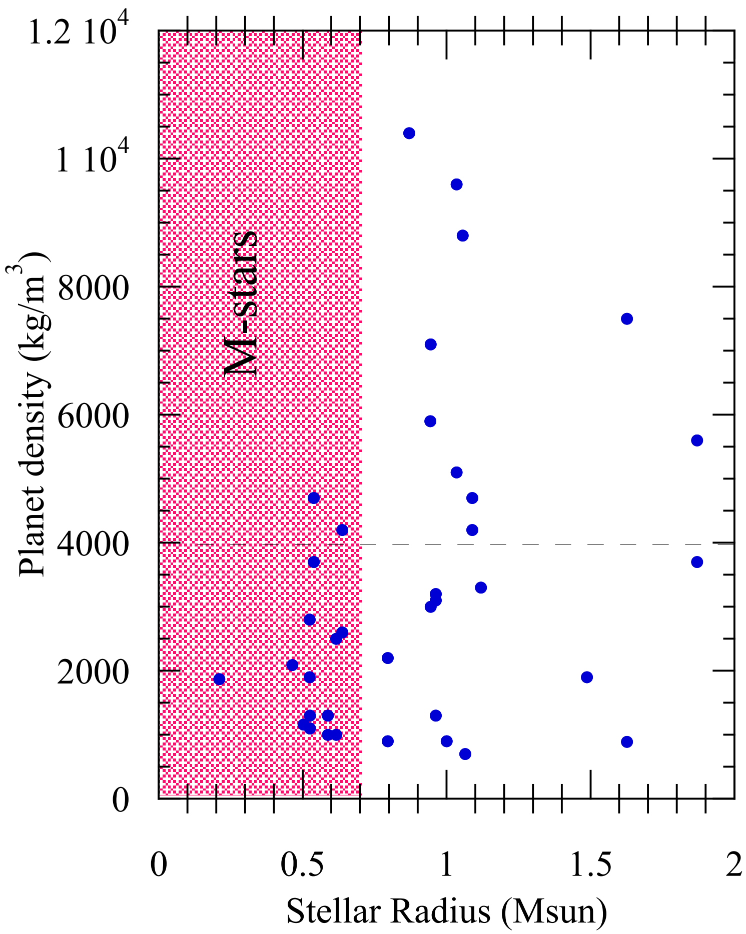


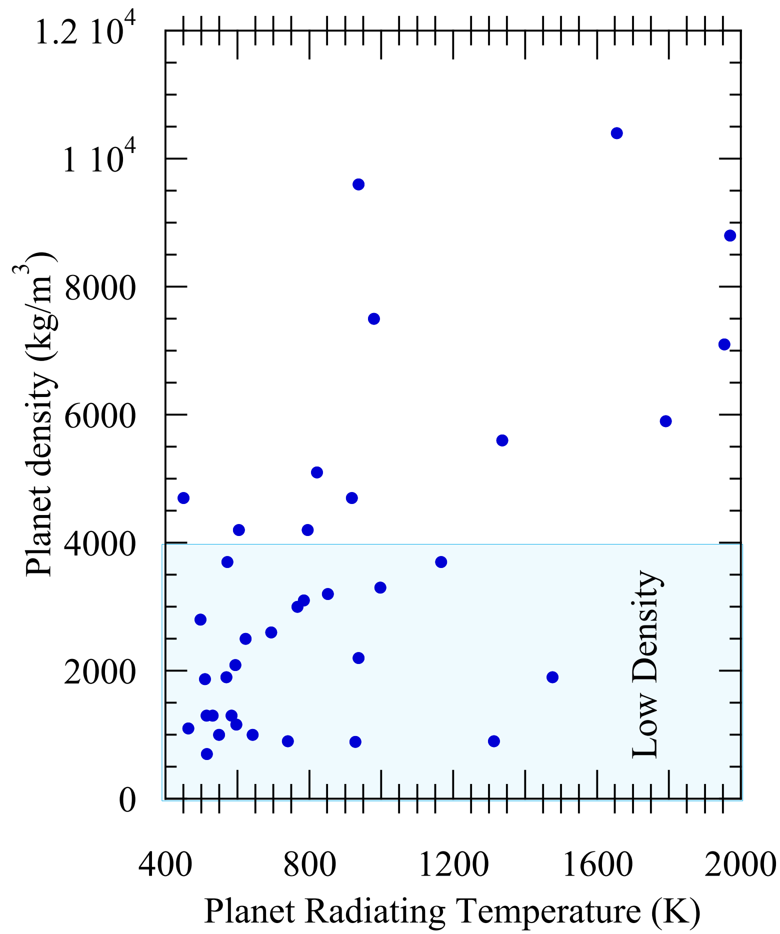
Adiabatic $T(p)$, extrapolated Boates EOS

CO_2 worlds appear too dense for GJ1214b, but...

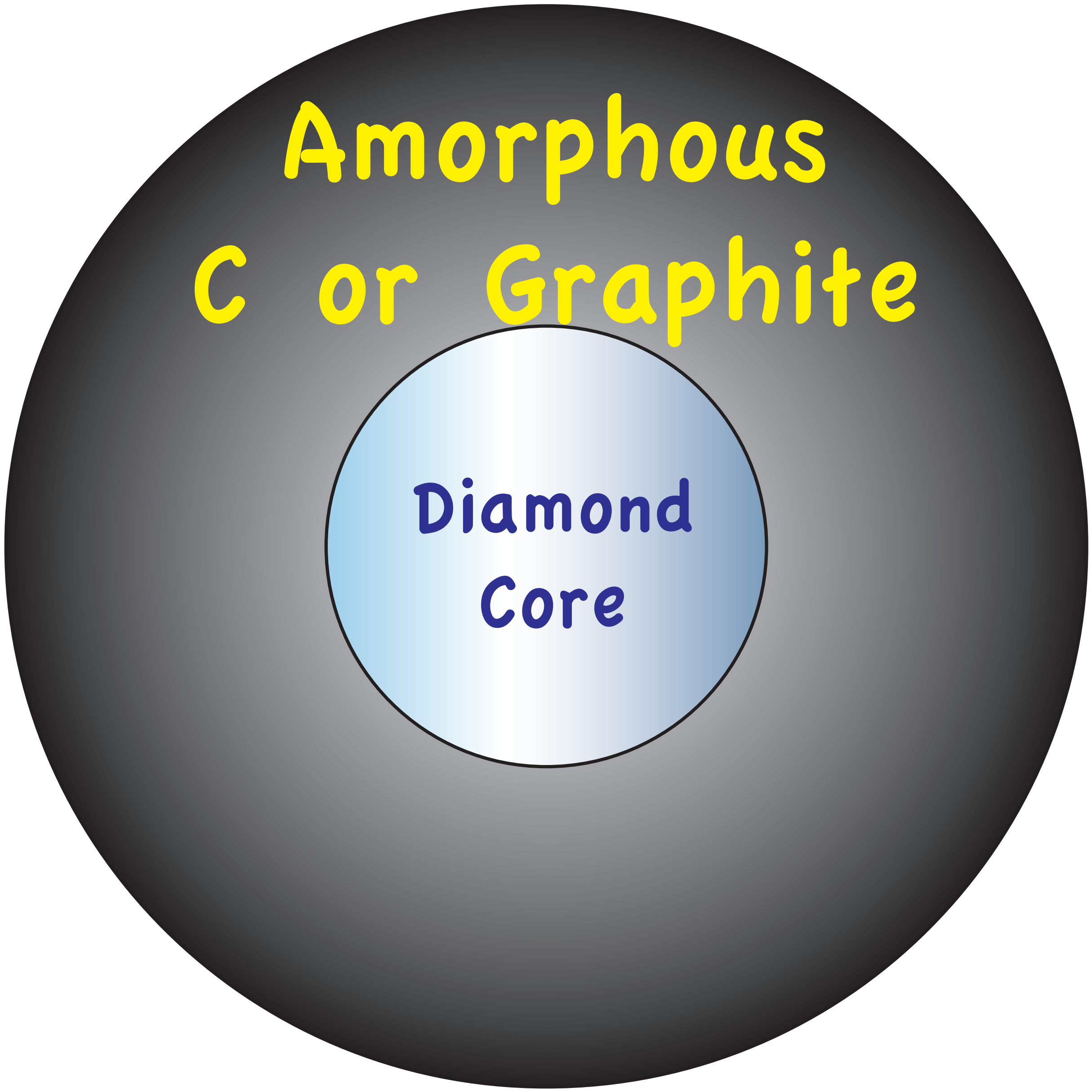
- There is a lot of guesswork in the EOS, and state of development of theory for fluid EOS seems primitive.
- Latest molecular dynamic results (Swift, ApJ) indicate H_2O is also too dense

Hot planets and M-star planets can have low density



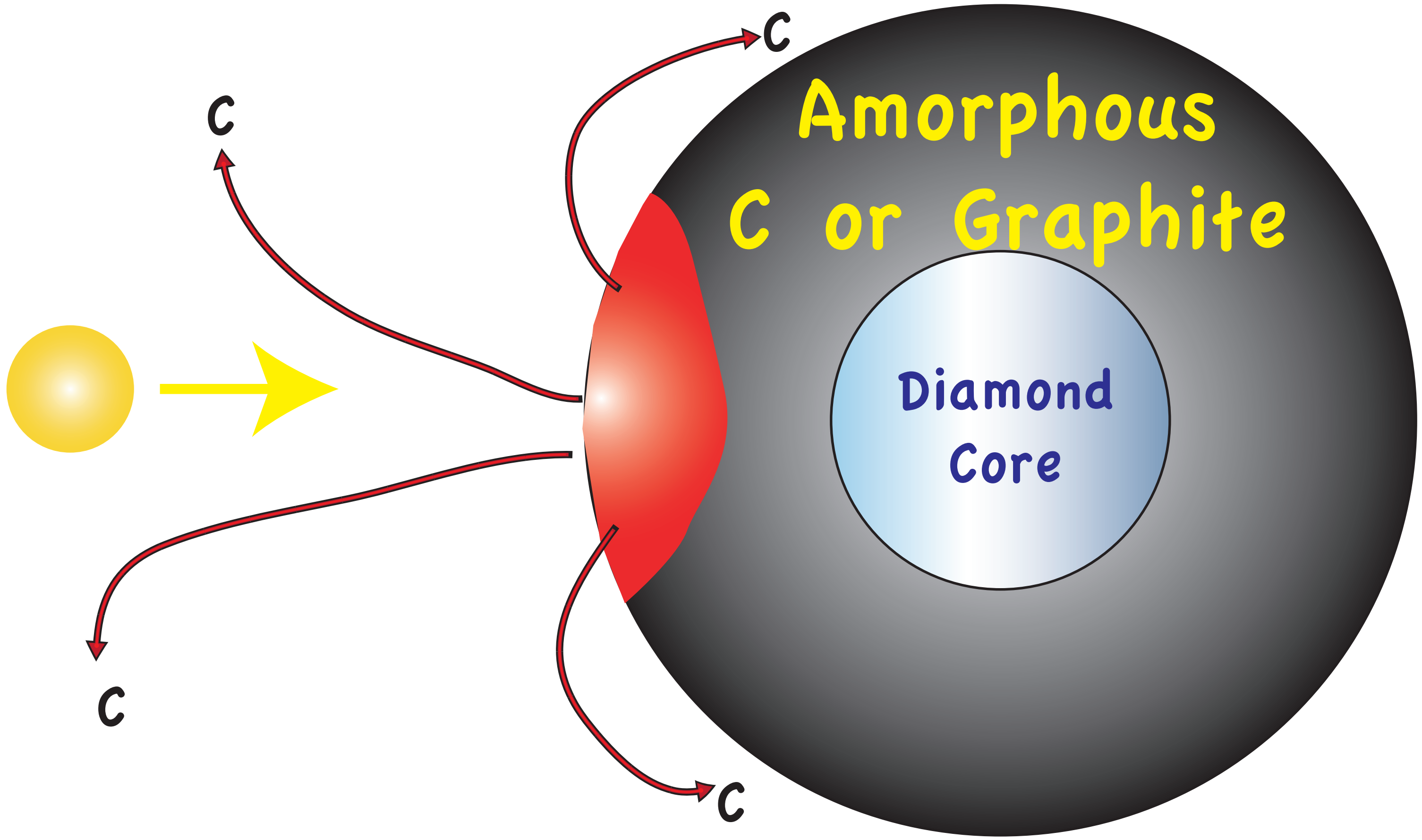


Model 4: Carbon worlds

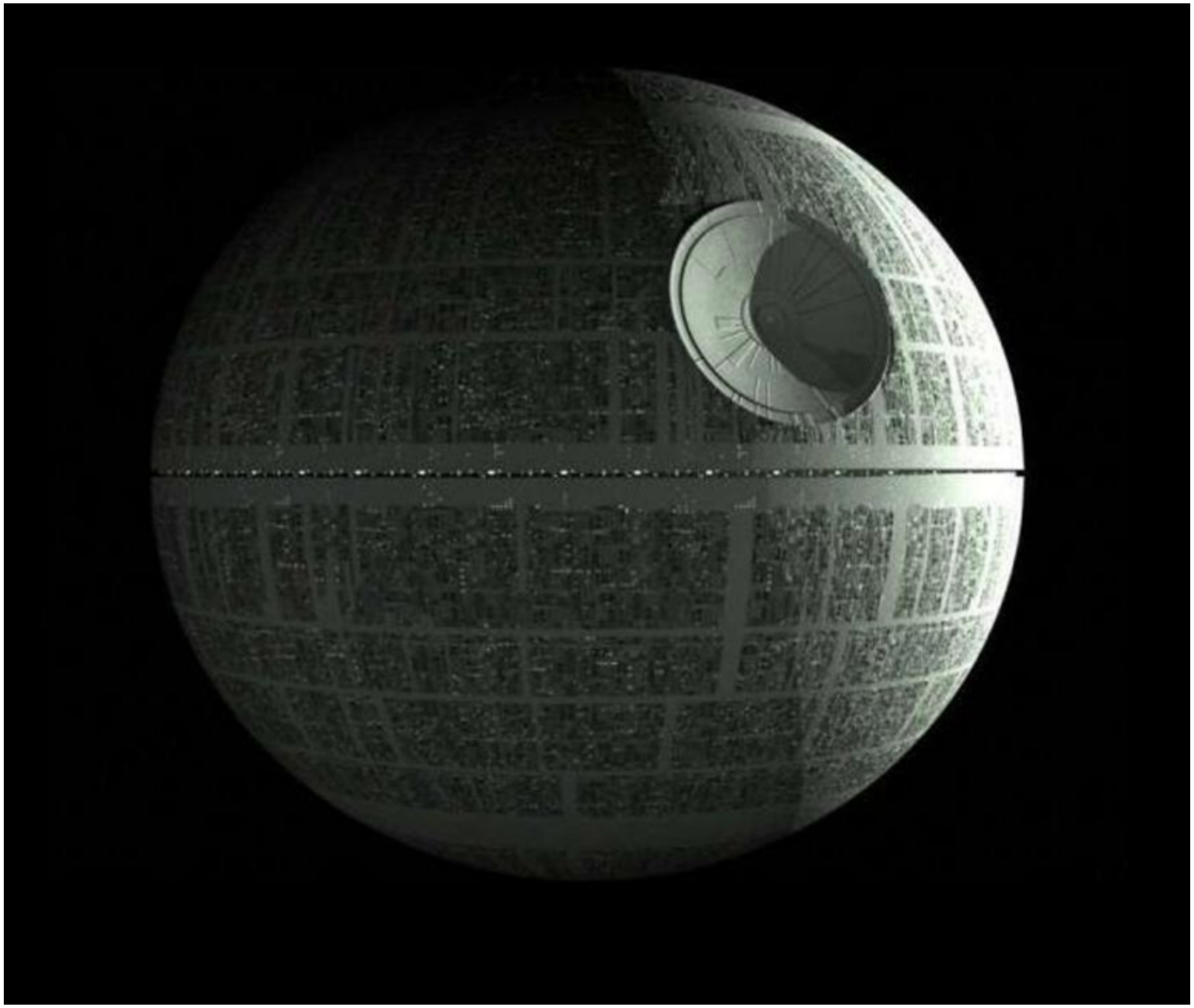


What kind of thing is 55 Cancri e ?

- This star puts out Lyman -α
- H escape would give extended atmosphere, deep Lyman-α transit
- ... but this is not seen, so H_2 envelope unlikely
- H_2O envelope also unlikely,
  because photolysis would lead to H escape
- Alternate composition: (mostly) Solid carbon-rich planet
- Liquid carbon ocean at substellar point,
  carbon vapor atmosphere (escaping?)
- But it could have a hydrogen-poor volatile envelope (e.g. CO_2)


C
C
Amorphous
C or Graphite
Diamond
Core
C
C

Model 5: Spherical hollow space habitat



e.g. the *Death Star*

Low-density Super-Earths raise interesting questions about ...

- Delivery of volatiles
- Planetary formation and migration
- Retention of atmospheres (esp. for hot cases)
- Thermal and compositional structure
- Relation of escape flux (potentially observable) to composition of the planet

Conclusions

- There are many Super-Earths with a volatile envelope (H_2, CO_2, H_2O, maybe others) making up a substantial fraction of the total mass of the planet.
- The hot low-density M-star worlds are our best evidence that M-star planets can retain volatiles. (Presently, our only evidence).
- For an M dwarf, H_2O photolysis likely dominated by Lyman-α, and typical fluxes can provide enough H to sustain energy limited escape.
- But we need more actual UV (esp E/XUV and FUV) observations of M dwarfs. validity of scaling laws vs. absolute bolometric luminosity?
- Hot close-orbit M-star planets were likely stripped of H during pre main-sequence and early main-sequence stage. But how to explain very low density objects? Did we just get lucky enough to see photo-evaporating Jupiters before they are all gone?
- Spectral confirmation of carbon rich (CO_2 worlds) vs worlds retaining H_2 envelopes is important.

- We need better CO_2 equation of state data out to 1000 GPa, at temperatures of 10000K and lower. Molecular dynamics simulations can do it, but evidently haven't been done in this range. Also possibilities for diamond anvil experiments. Shock wave experiments require extrapolation to temperatures far below the Hugoniot.