Structure of Giant Planets

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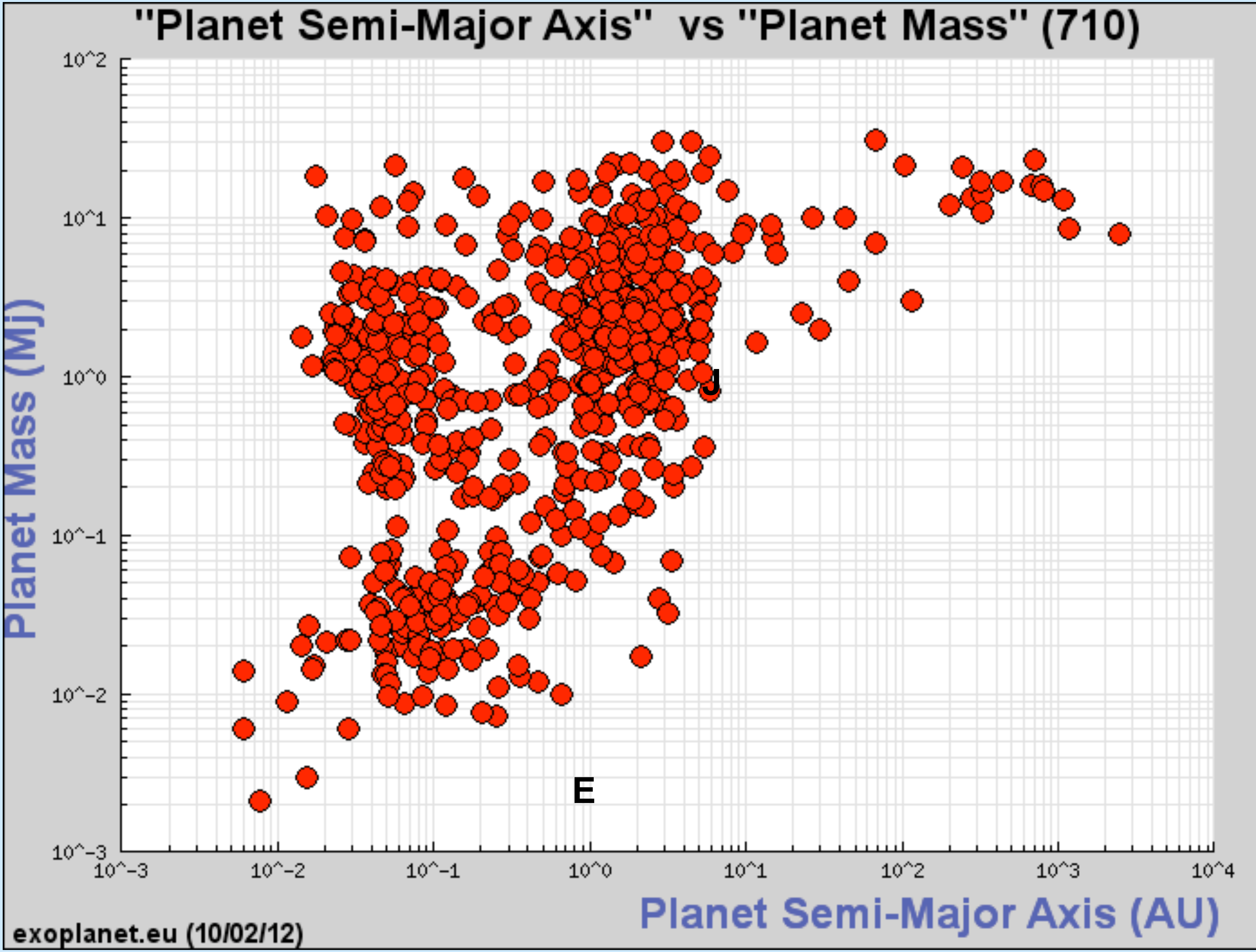
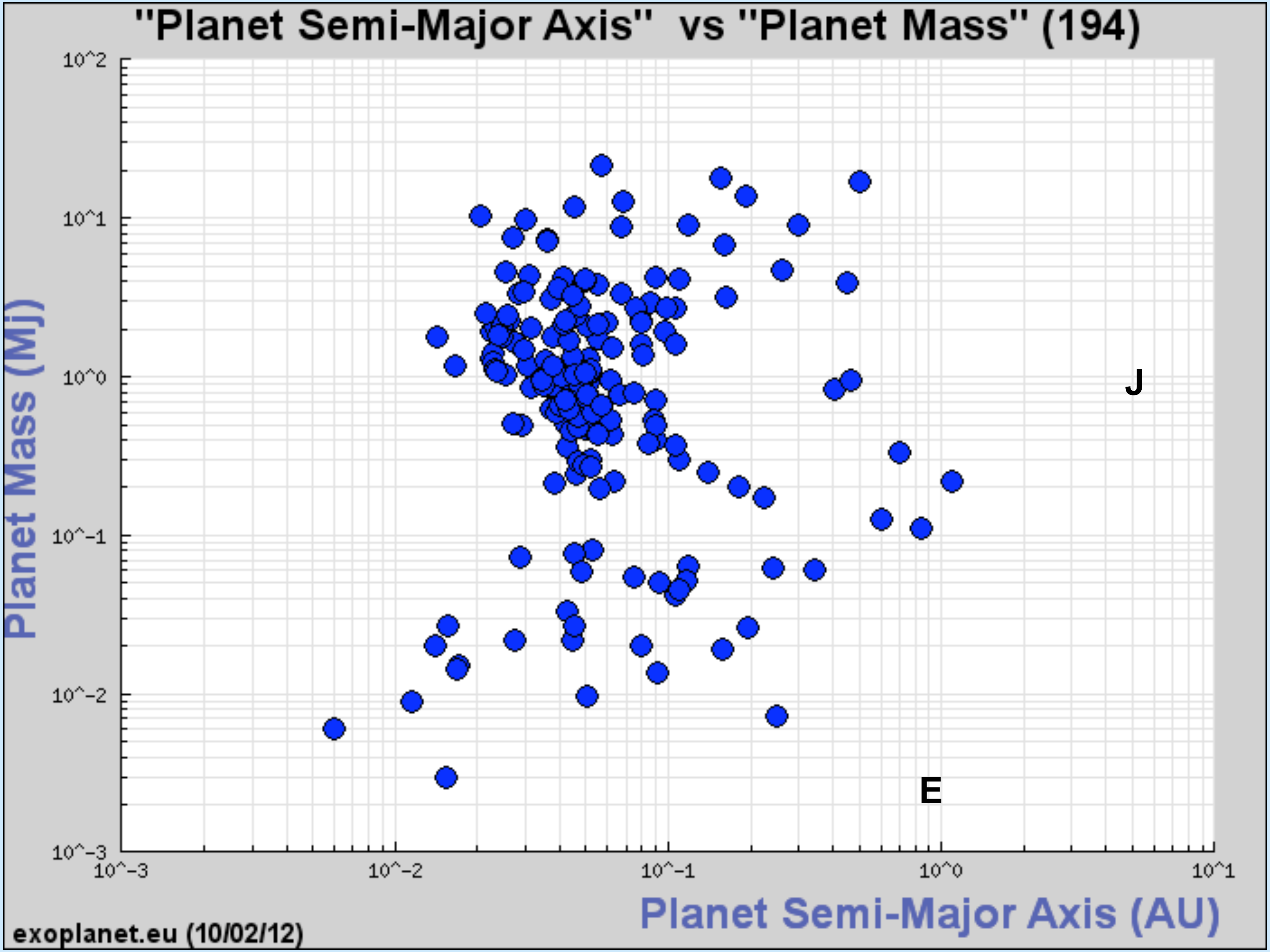
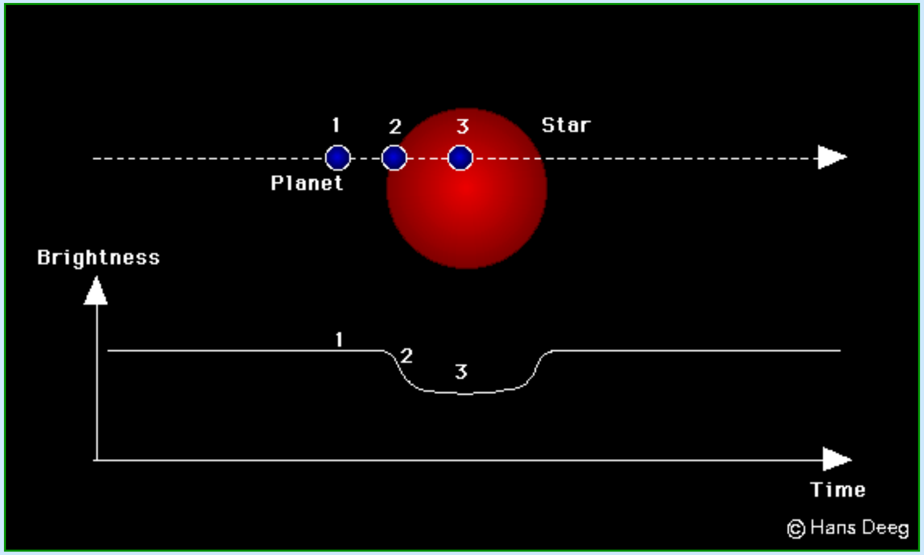
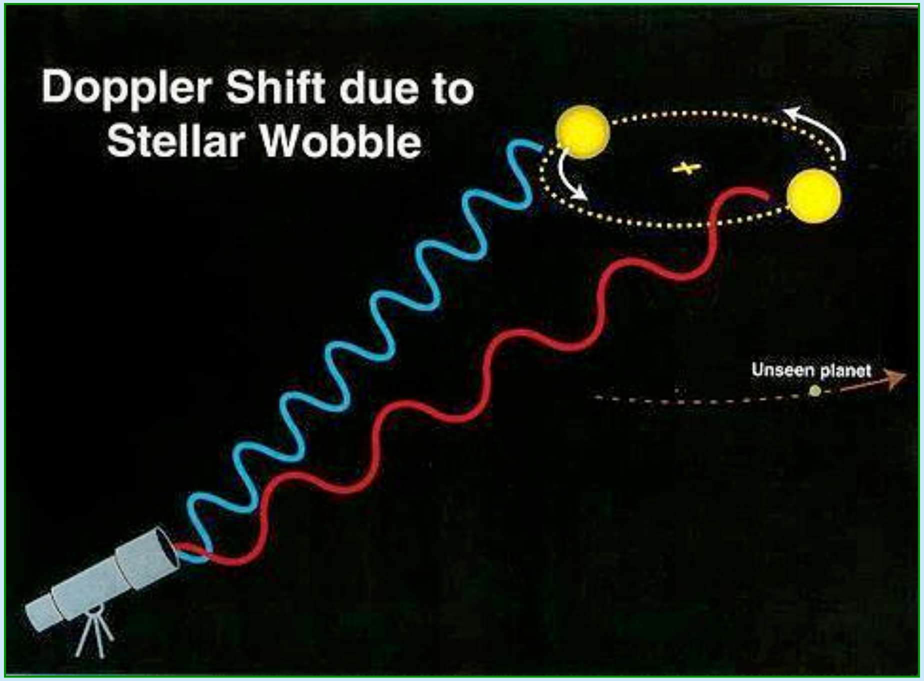

"Planet Semi-Major Axis" vs "Planet Mass" (710)
10^2
10^1
10^0
10^-1
10^-2
10^-3
Planet Mass (Mj)
J
E
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
Planet Semi-Major Axis (AU)
exoplanet.eu (10/02/12)


"Planet Semi-Major Axis" vs "Planet Mass" (194)
10^2
10^1
10^0
10^-1
10^-2
10^-3
Planet Mass (Mj)
10^-3
10^-2
10^-1
10^0
10^1
Planet Semi-Major Axis (AU)
J
E
exoplanet.eu (10/02/12)

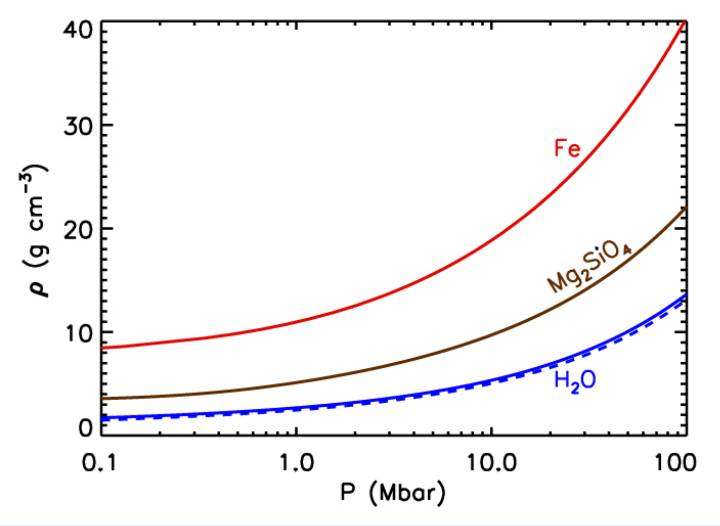
Transiting Planets, Large and Small

- Around 200 planets have now been seen to transit their parent stars, with measured masses
  - 180+ "hot Jupiters"
  - 10+ "super Earths"
- Combination of planet radius and mass yield density --> composition
- Strong bias towards finding mass/large planets on short-period orbits

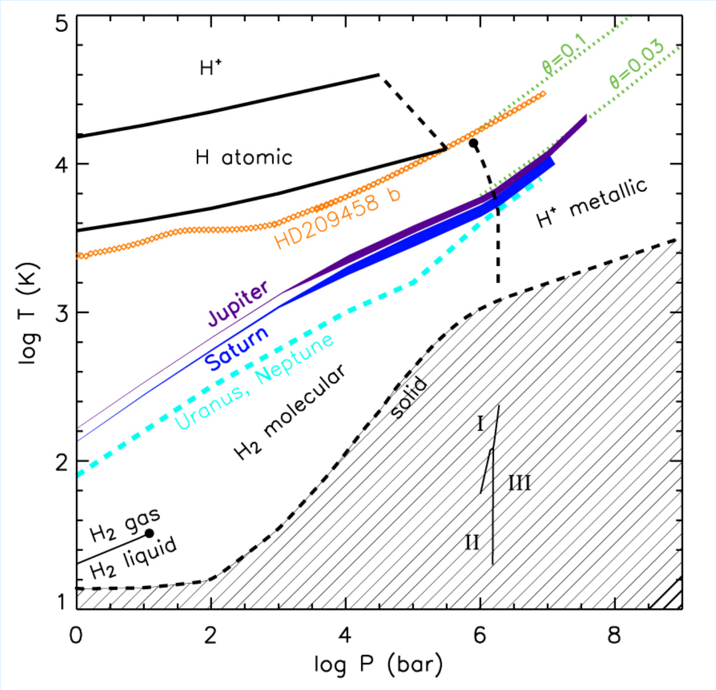


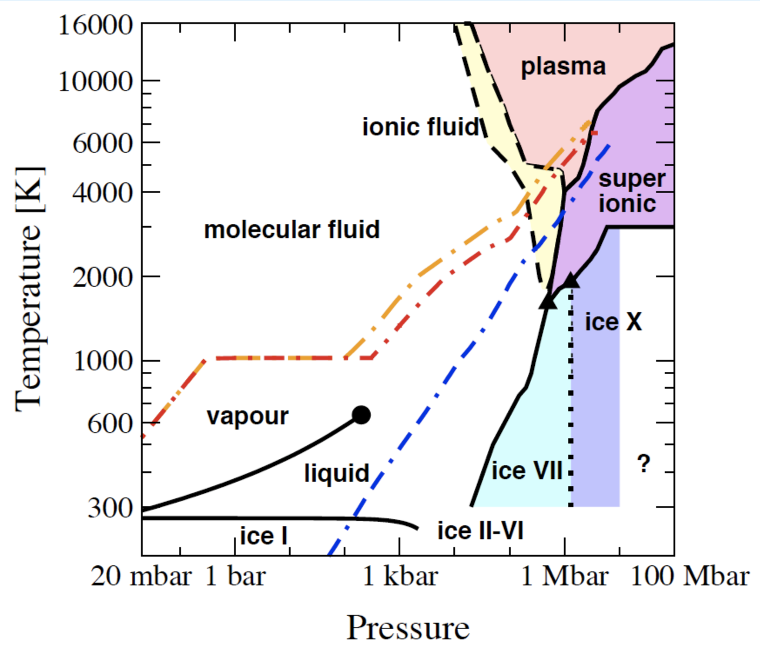


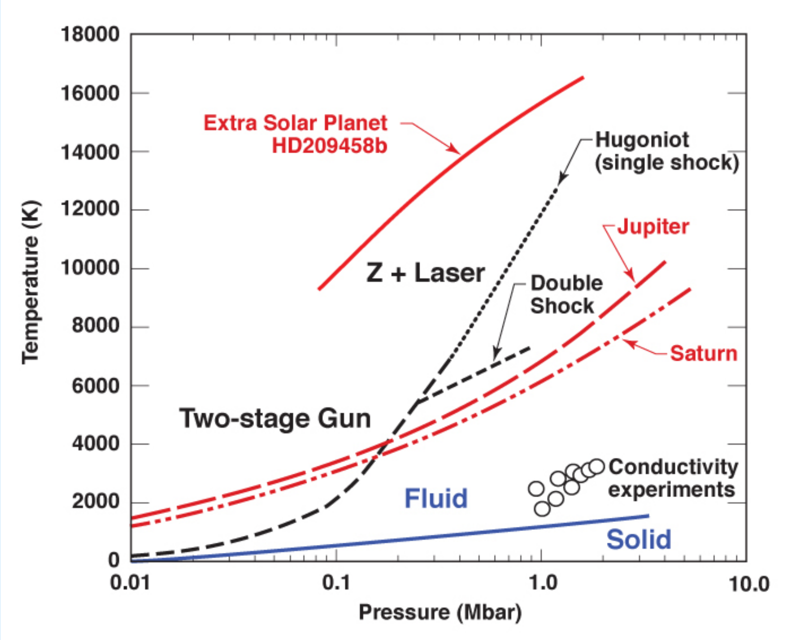
Equations of State of Planetary Materials



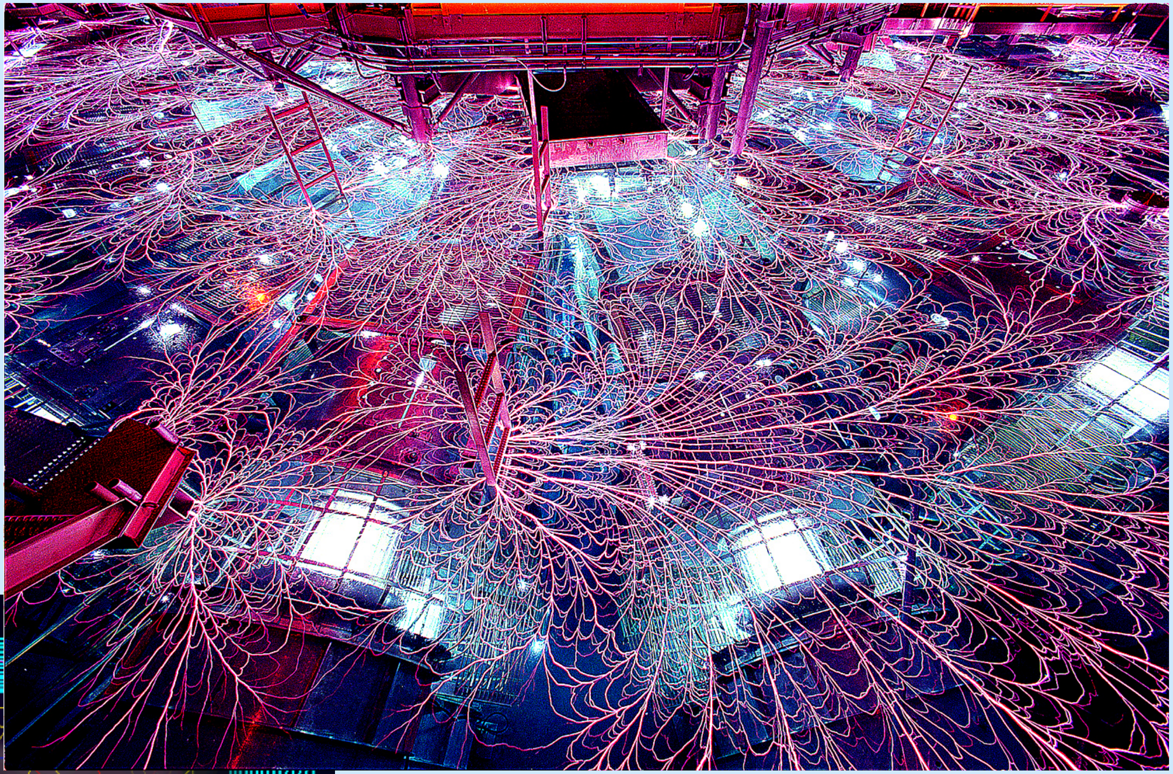
Giant planets are mostly liquid metallic hydrogen



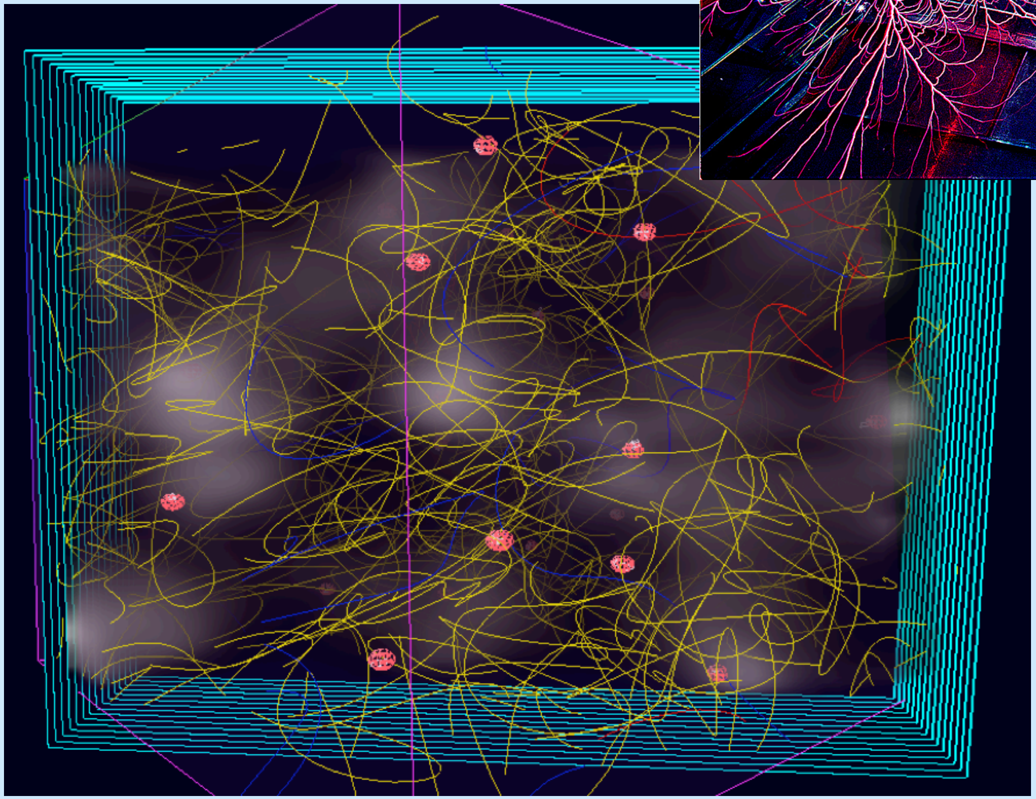




EOS at High Pressure: Obtaining Data



Sandia National Laboratory Z Machine



First principles direct simulations of matter

Giant Planet Evolution and Contraction: Key Ideas and Assumptions

- Giant planets are warm, fluid, and fully convective
- Convection is efficient and leads to an essentially adiabatic temperature gradient
    - H/He envelope is homogeneous and well mixed
    - Heavy element core is distinct from H/He envelope

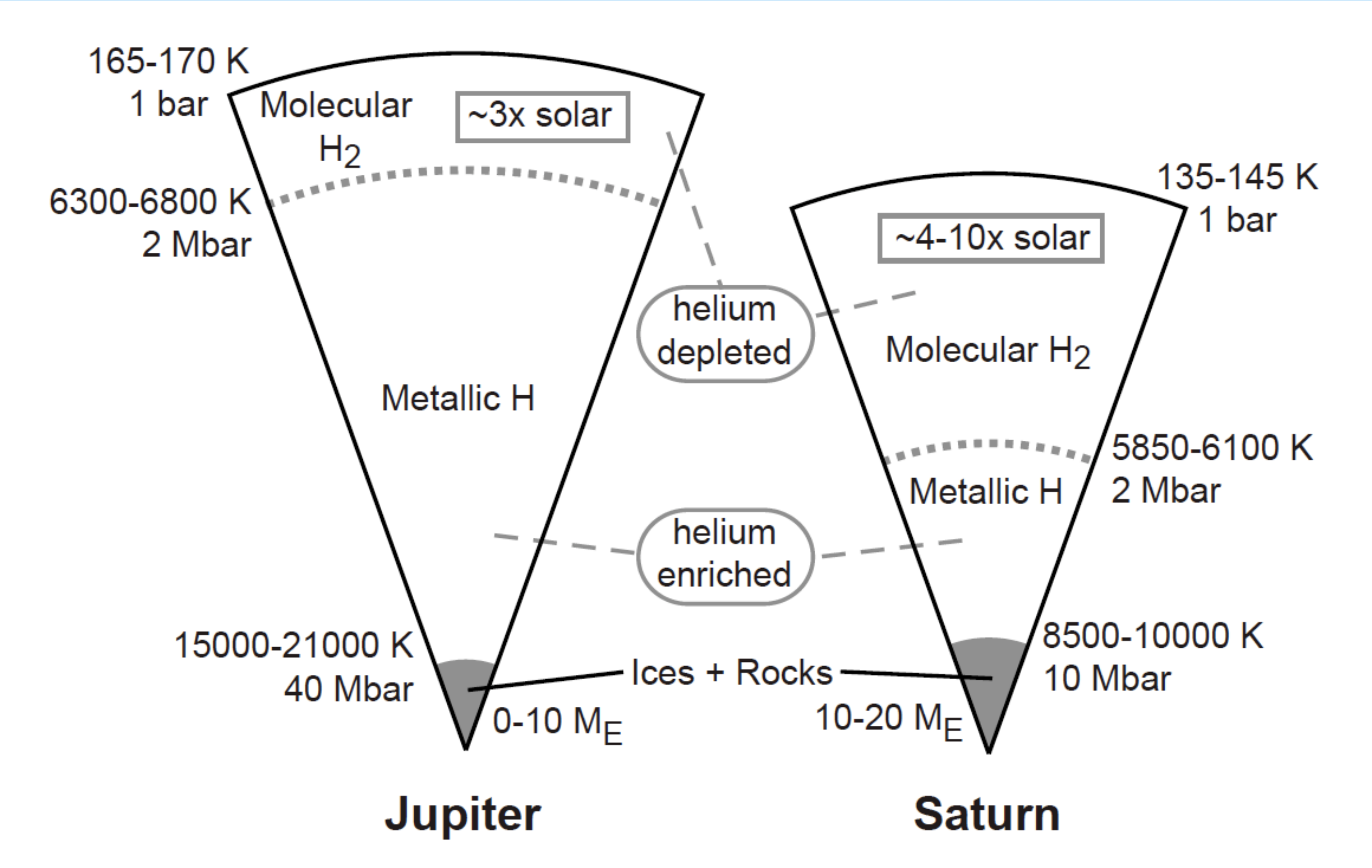
- It is the radiative atmosphere that is the bottleneck for interior cooling and contraction (atmosphere models are much more important here than in stellar evolution)

- One "planet-wide average" pressure-temperature profile serves as the upper boundary condition at a given age (no day/night difference)

- A Gyr ages, the vast majority of a giant planet's thermal energy is remnant energy from its formation (the big collapse) still working it's way out. There is little contraction at Gyr ages

How well does this work in our Solar System?

Our Gas Giant Prototypes: Jupiter and Saturn

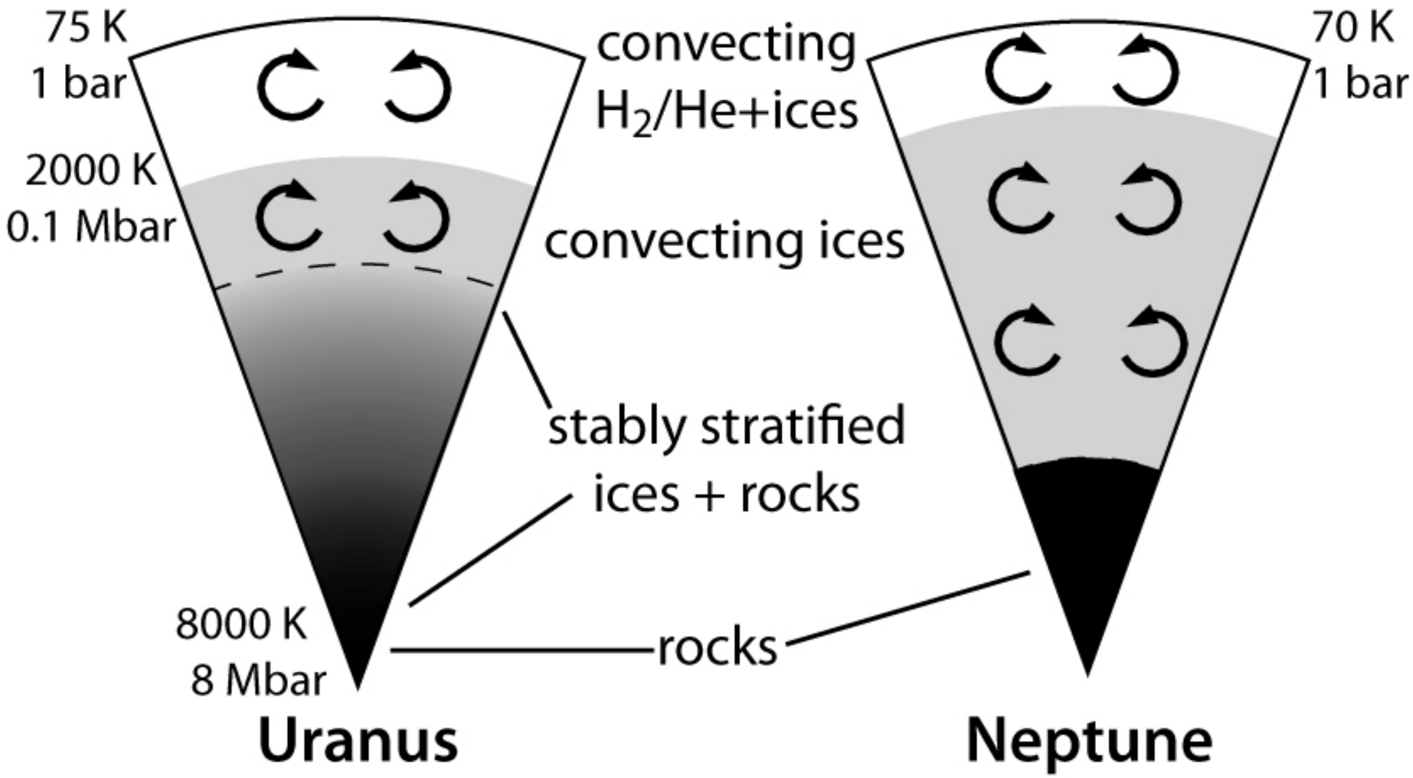


Fortney, Baraffe, & Militzer (2010)

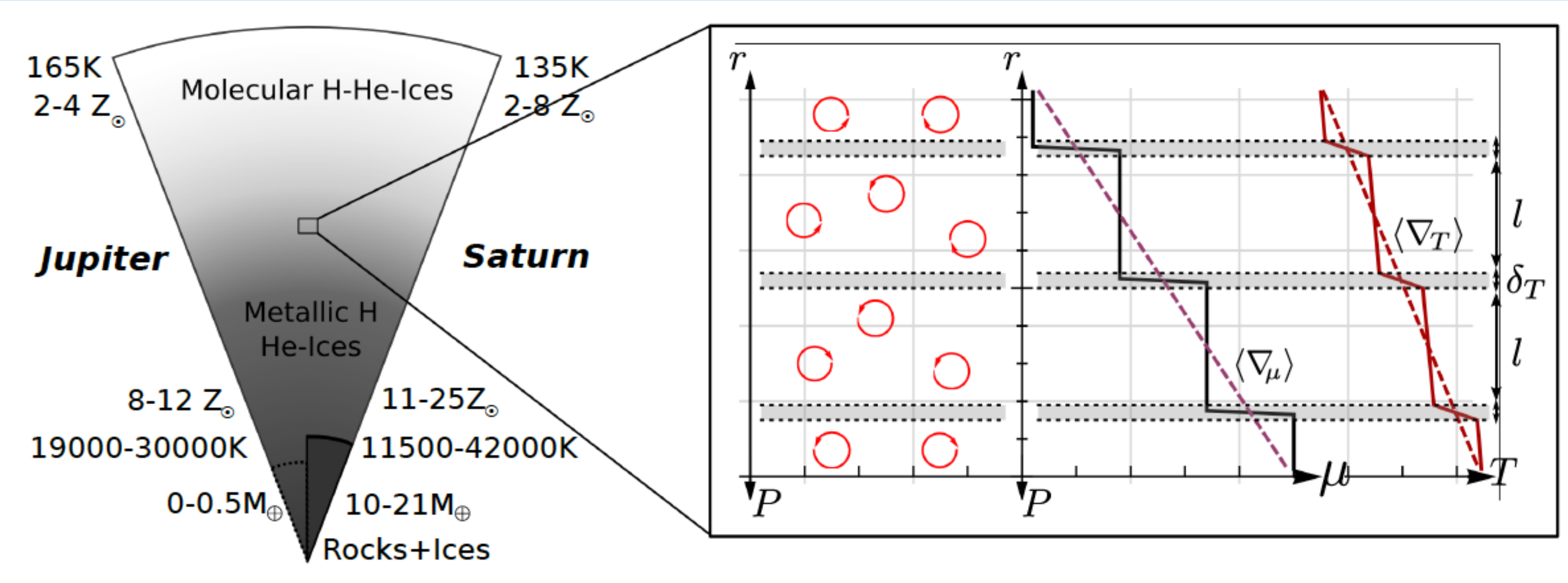
5-25% Heavy Elements by Mass

Our Ice Giant Prototypes: Uranus and Neptune

80-90% Heavy Elements by Mass

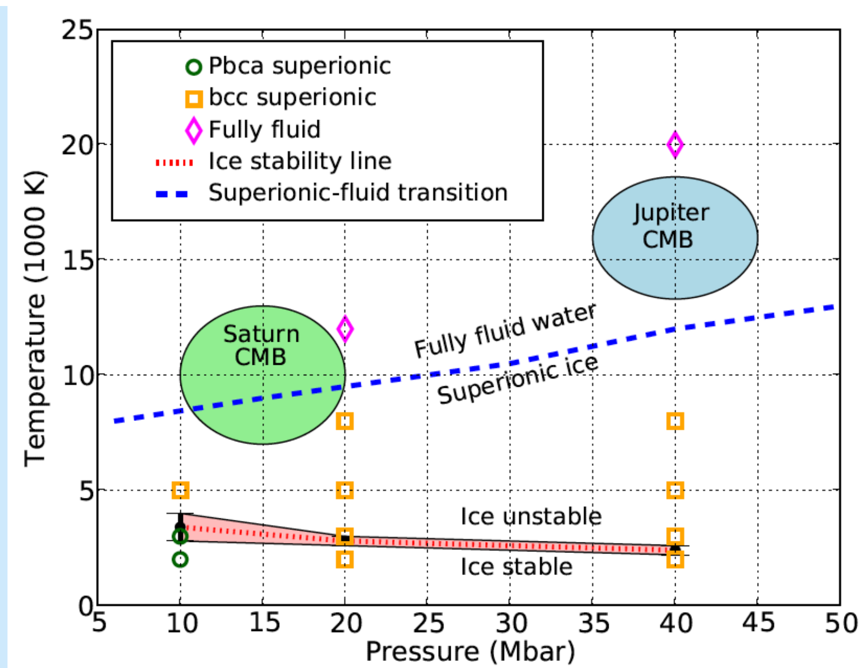


Fortney, Baraffe, & Militzer (2010)



Leconte & Chabrier (2012)

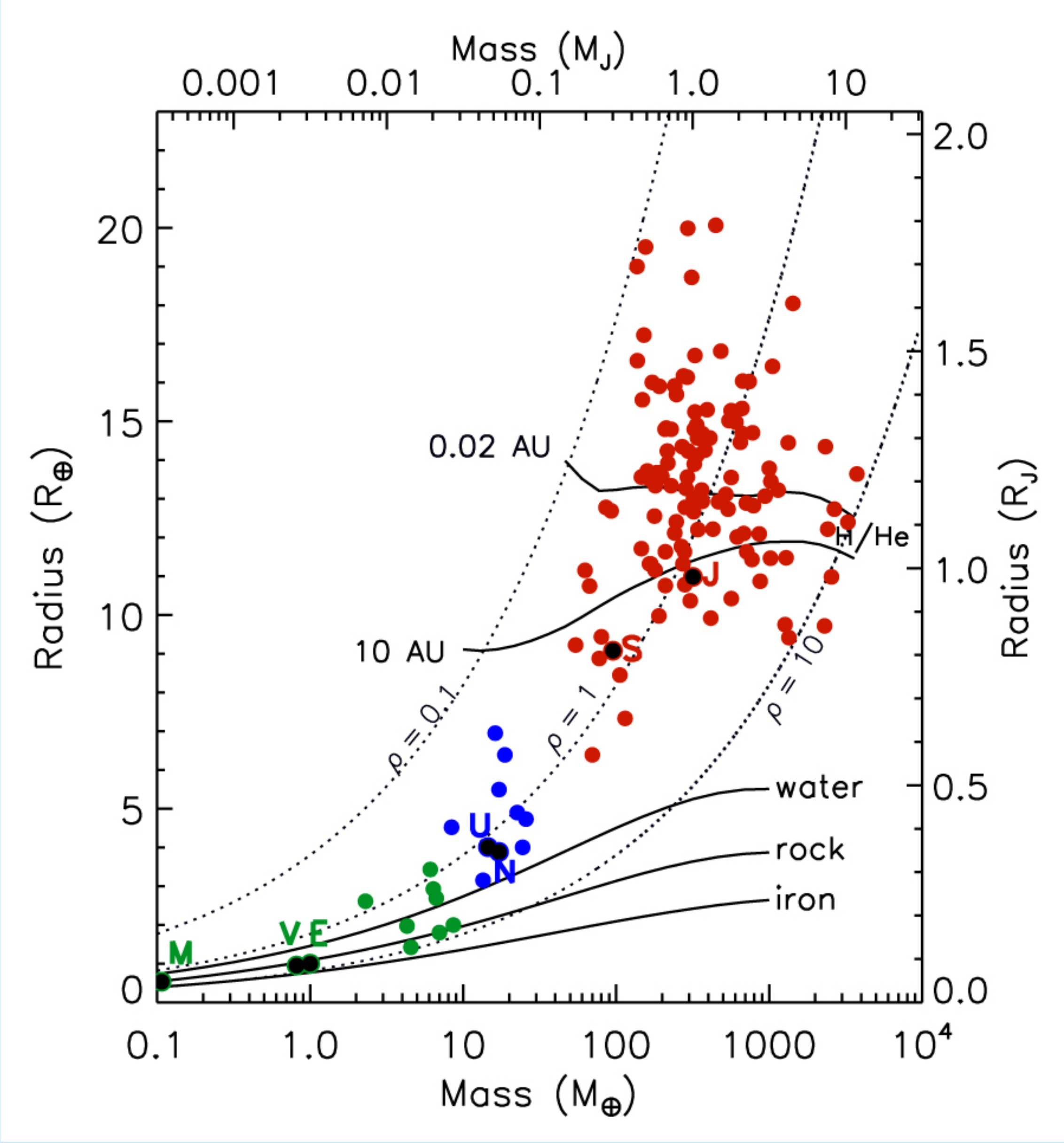
Giant Planets May Not be as Simple as We Would Hope Them to Be



Wilson & Militzer (2011)

There is an incredibly diversity of worlds

- We can also **characterize** these planets, not just find them



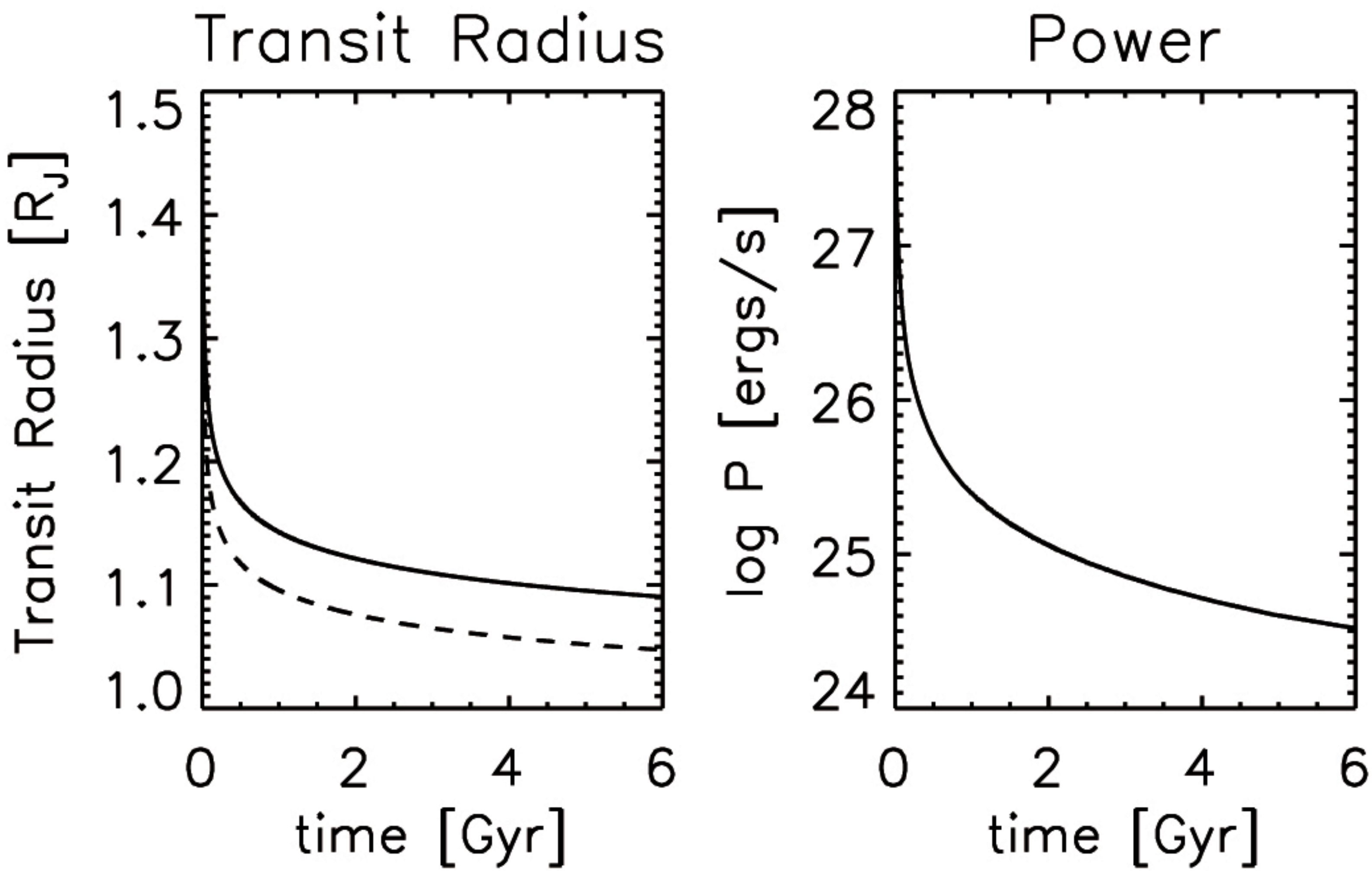
The shear number of discoveries opens up the prospect of understanding gas giants (Jupiter-like), ice giants (Neptune-like) and lower mass planets as classes of astrophysical objects

What are these planets made of?

What is their interior structure?

How do they compare to Jupiter and Saturn?

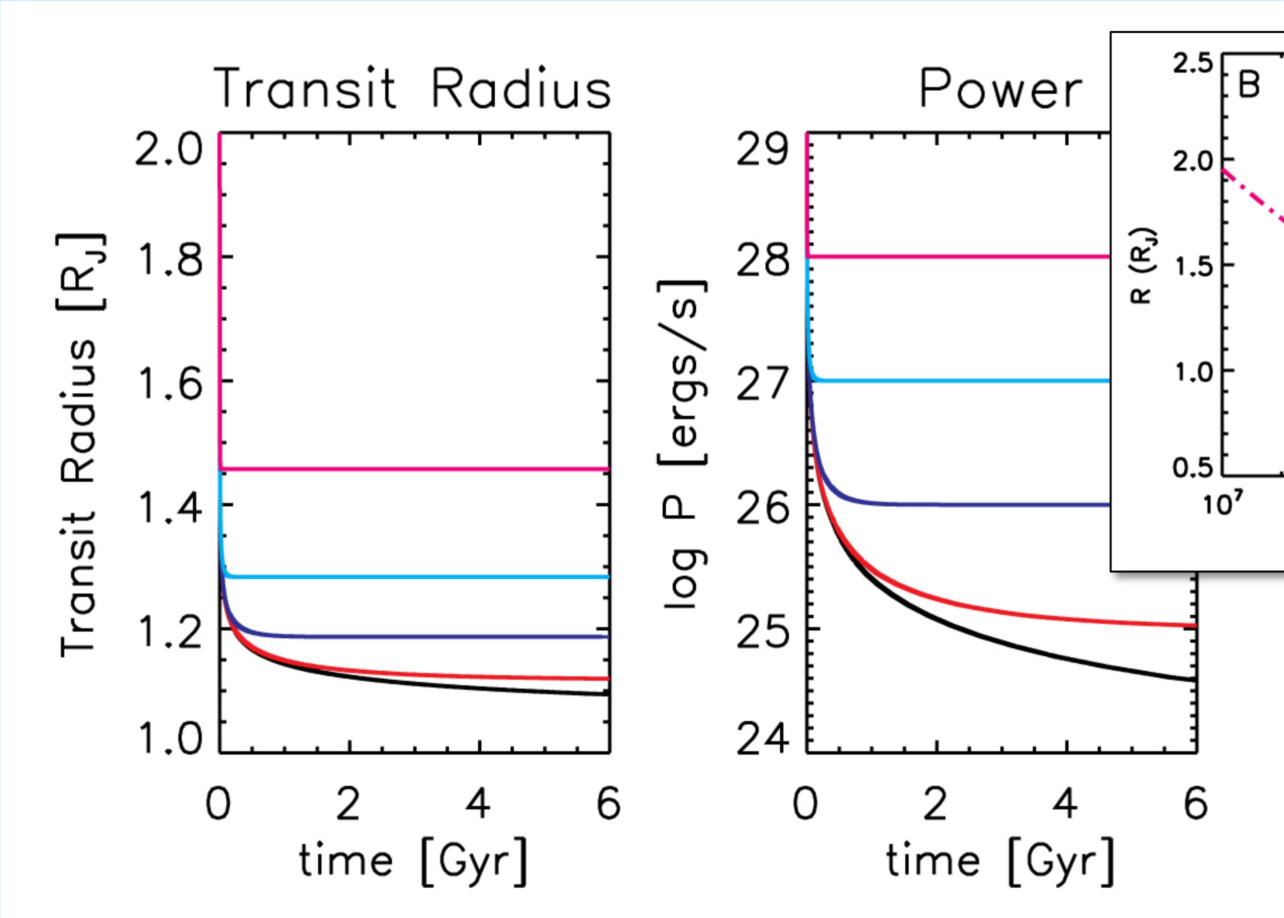
Building a Model, I: Standard Cooling and Contraction

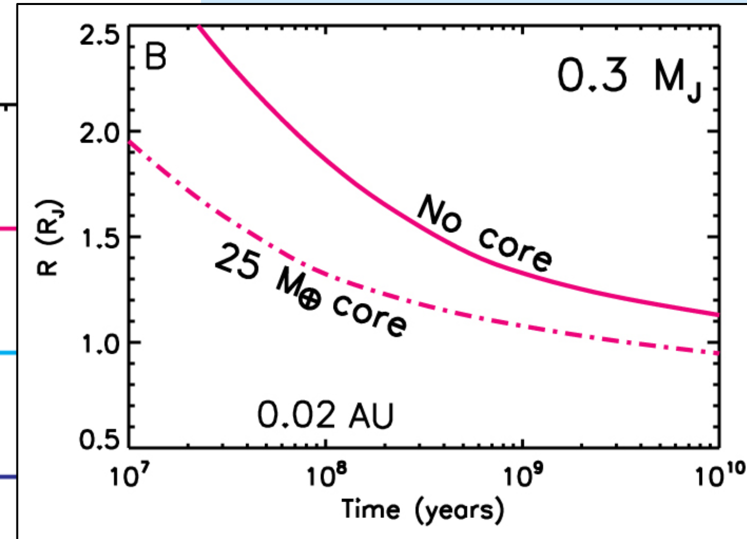


Miller, Fortney, & Jackson (2009)

1 M_J planet with a 10 M_E core, at 0.05 AU from the Sun

Additional Power Inflates Radii, Heavy Elements Shrink Radii

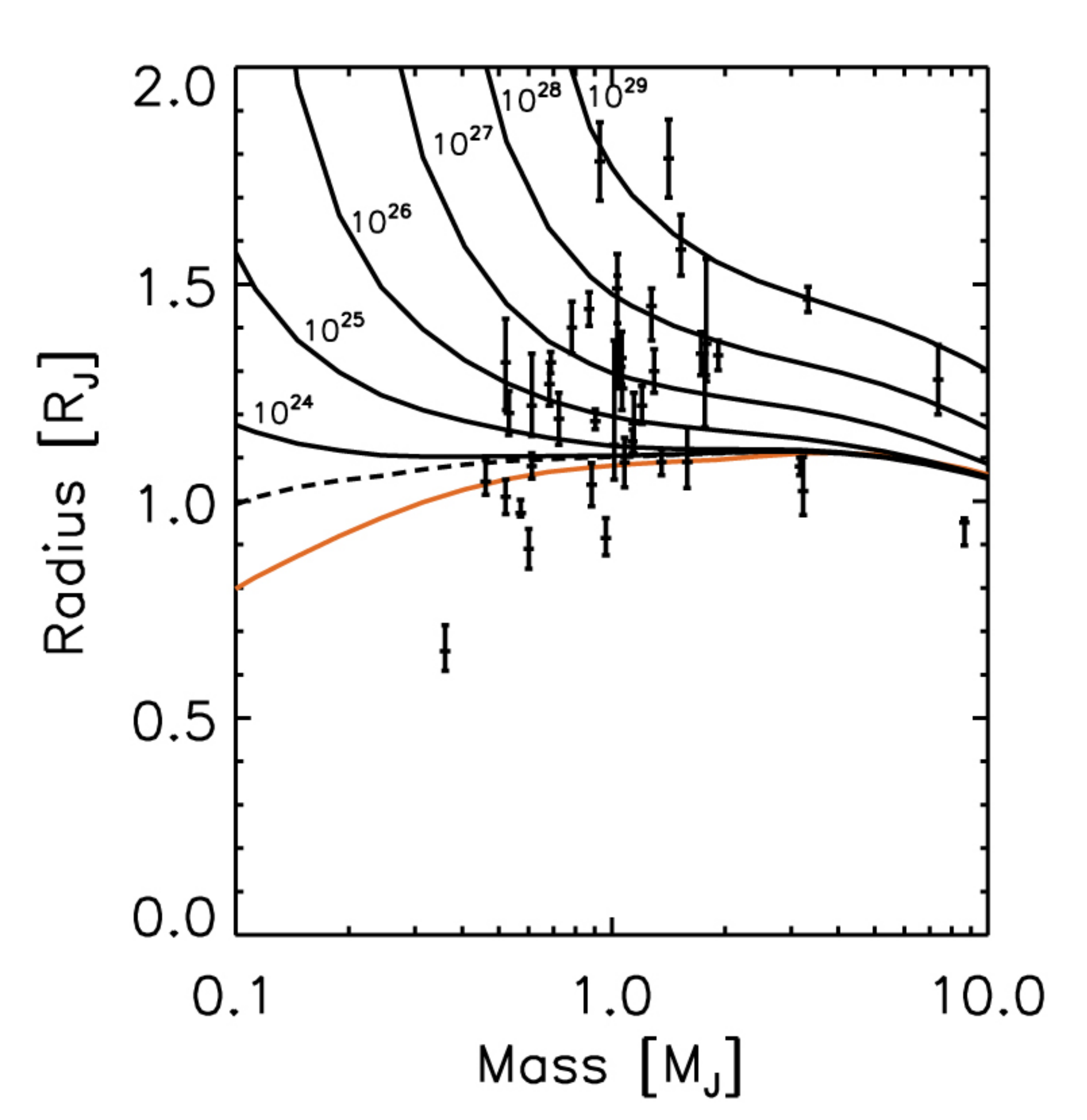




Miller, Fortney, & Jackson (2009)

For a given inflated hot Jupiter, we are blind to its composition, since we do not know the magnitude of the additional power source

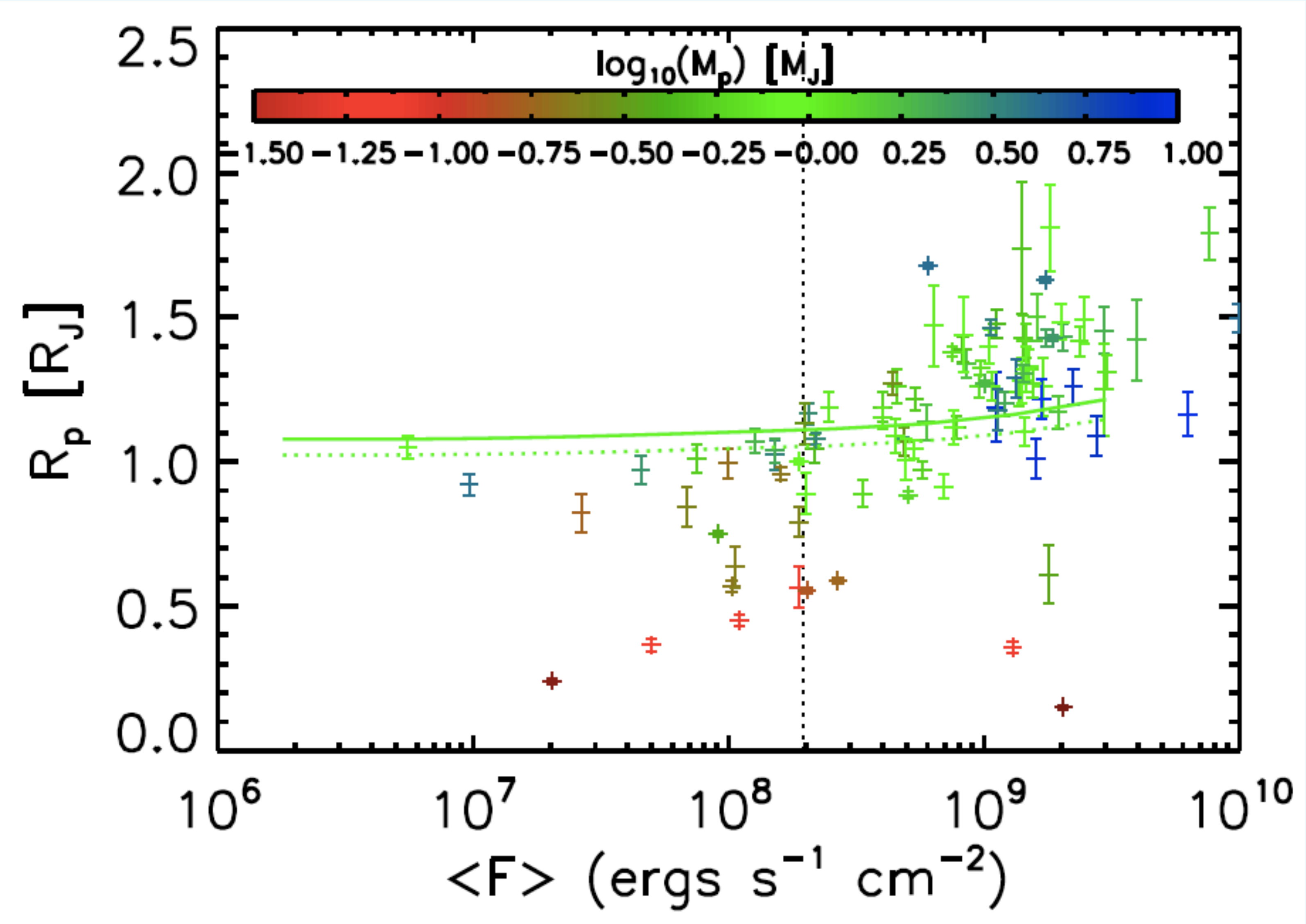
Building a Model, II: Additional Interior Power



Miller, Fortney, & Jackson (2009)

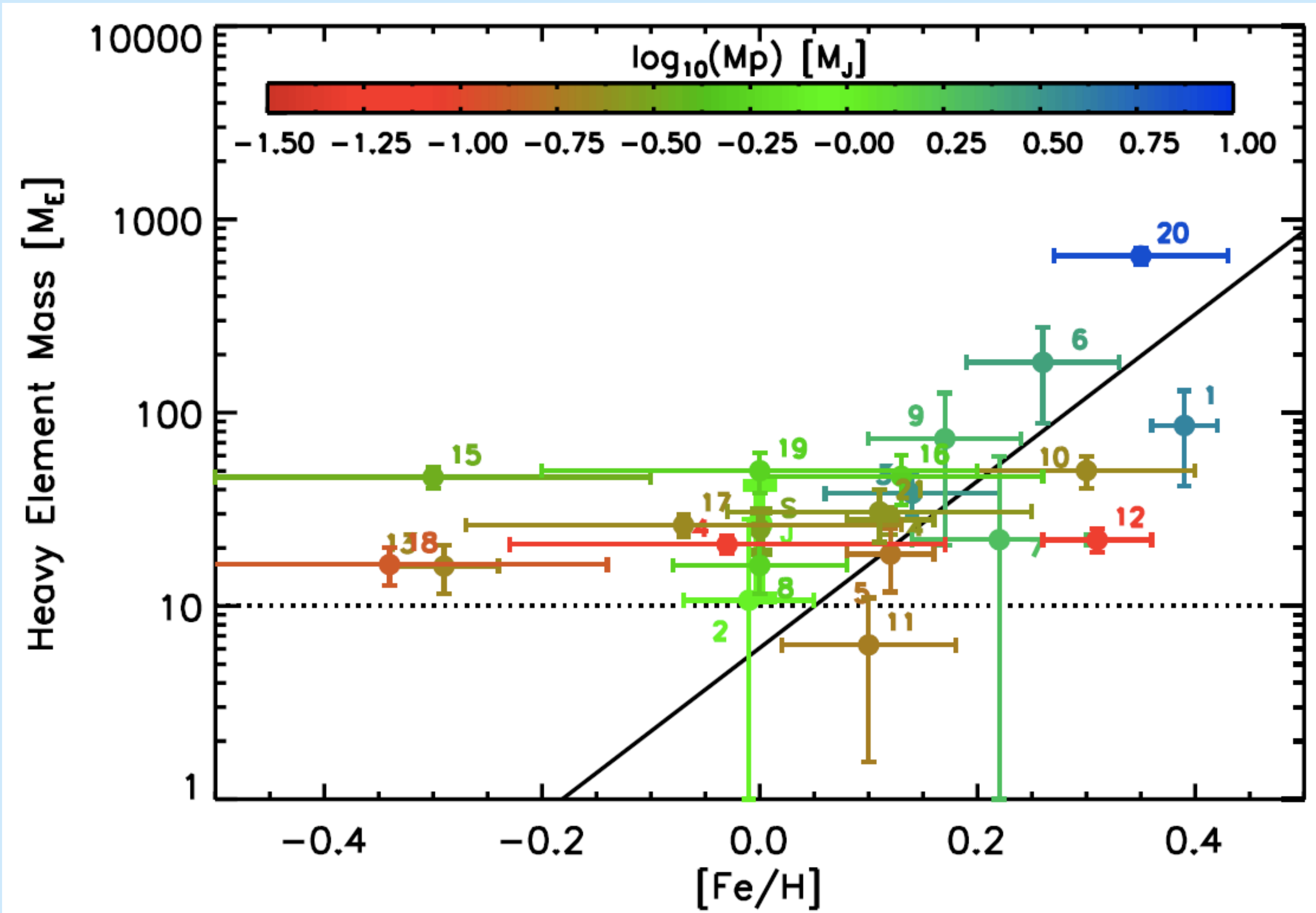
- Lower mass planets more easily influenced by a given magnitude of power source
- Power levels are generally small compared to Irradiation from the parent star ~10^{29} erg/s
- 1% "rule of thumb" for giant planet inflation is a pretty poor rule, generally

There is an emerging population of cool planets with no radius anomaly



Miller & Fortney (2011)

A strong correlation between star and planet abundances

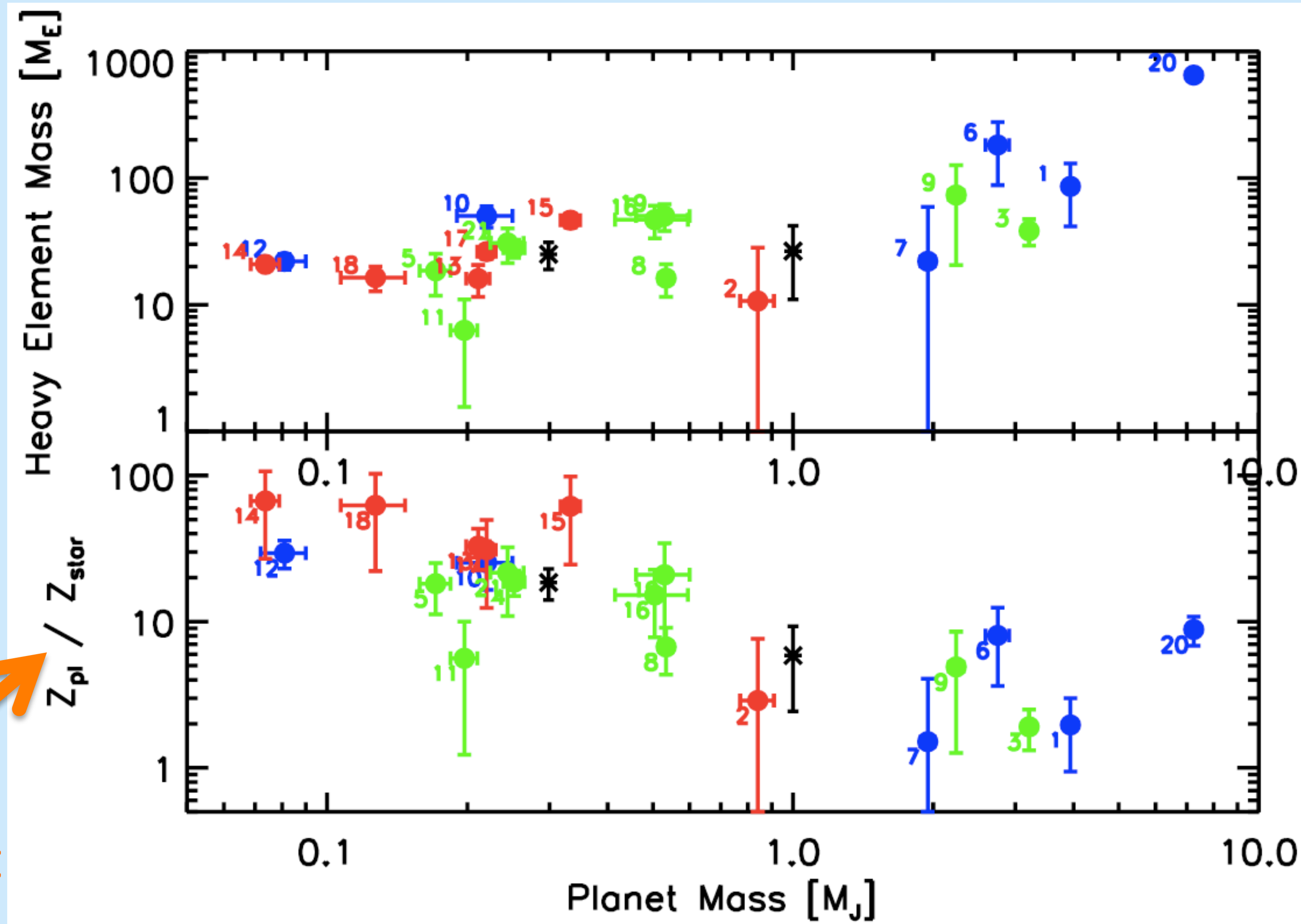


See also Guillot et al. (2006) & Burrows et al. (2007)

Miller & Fortney (2011)

- Exoplanetary Heavy Element Enrichment Fits Solar System Patterns
- A quasi-uniform super-solar enrichment above ~ 1 M_J

[Fe/H]<0.0
0.0≤[Fe/H]<0.2
0.2≤[Fe/H]<0.4

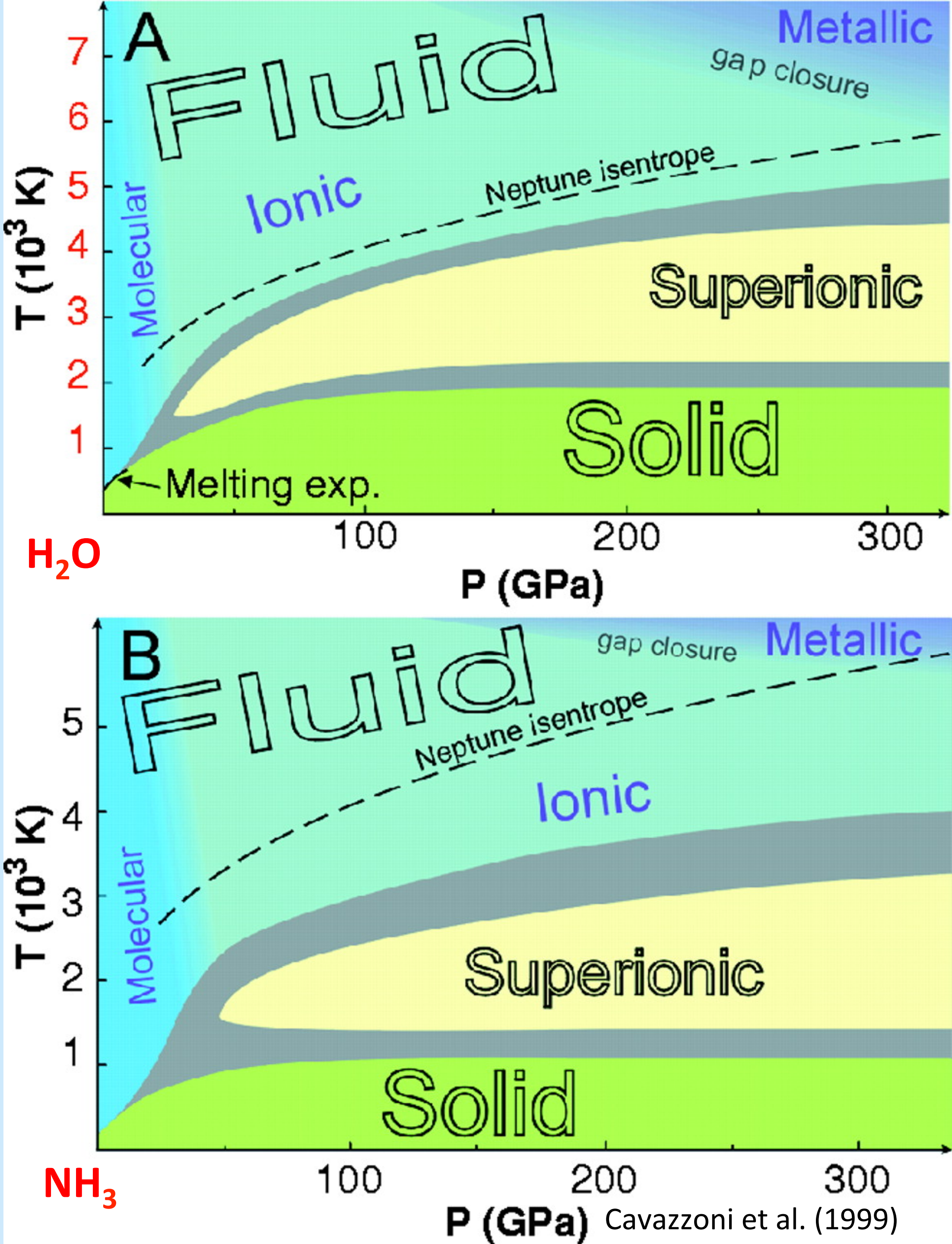


Enrichment Factor

Miller & Fortney (2011)

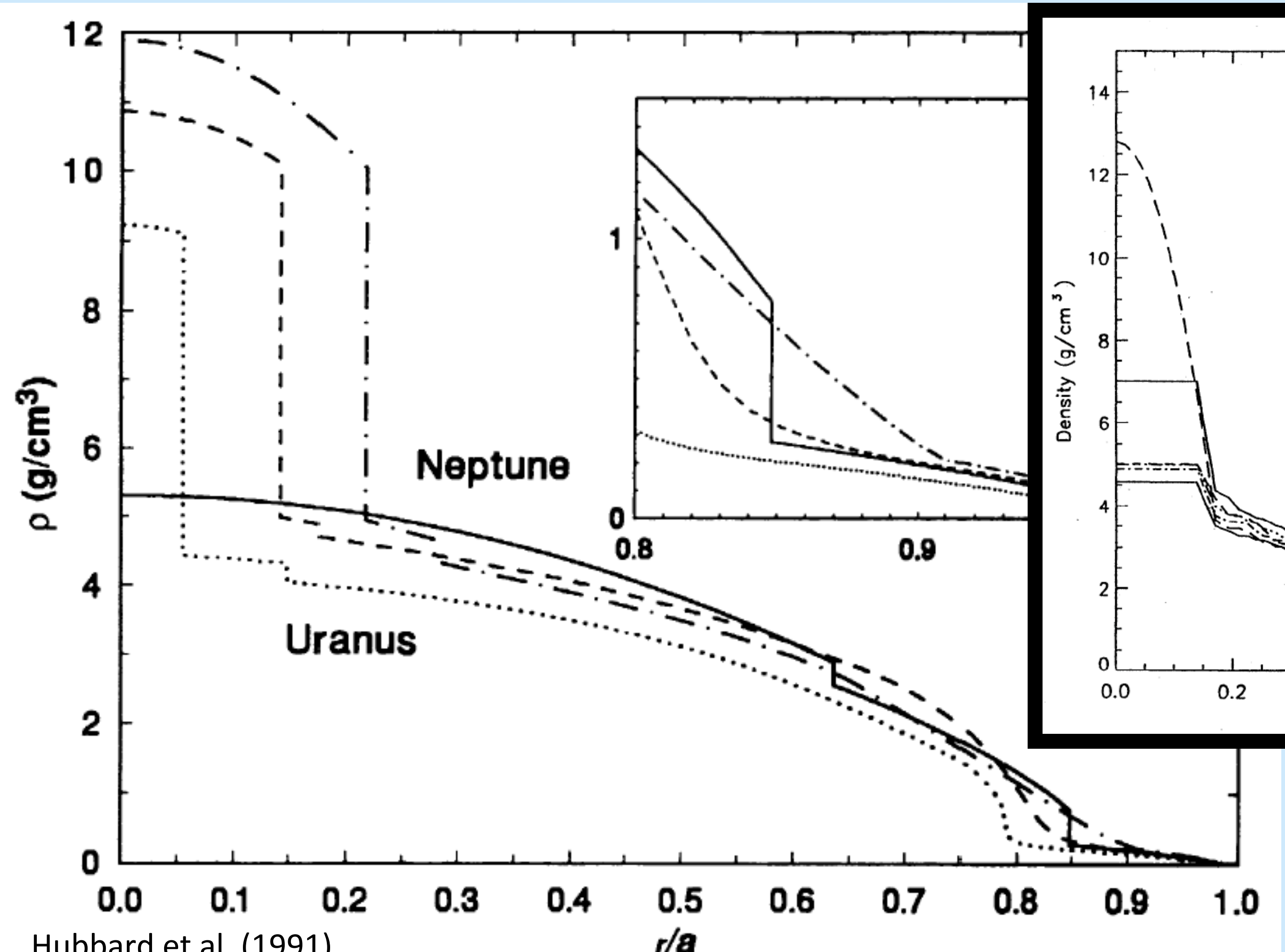
Is the ice in Neptune-class planets solid?

- No.
- All evidence for Uranus/ Neptune indicates that their interiors are predominantly fluid
  - A fluid “sea” of partially dissociated fluid H_2O, NH_3, and CH_4
  - This is backed up by models of dynamo-generated magnetic field
  - Experiments by Nellis et al. on water and “synthetic Uranus” mixtures

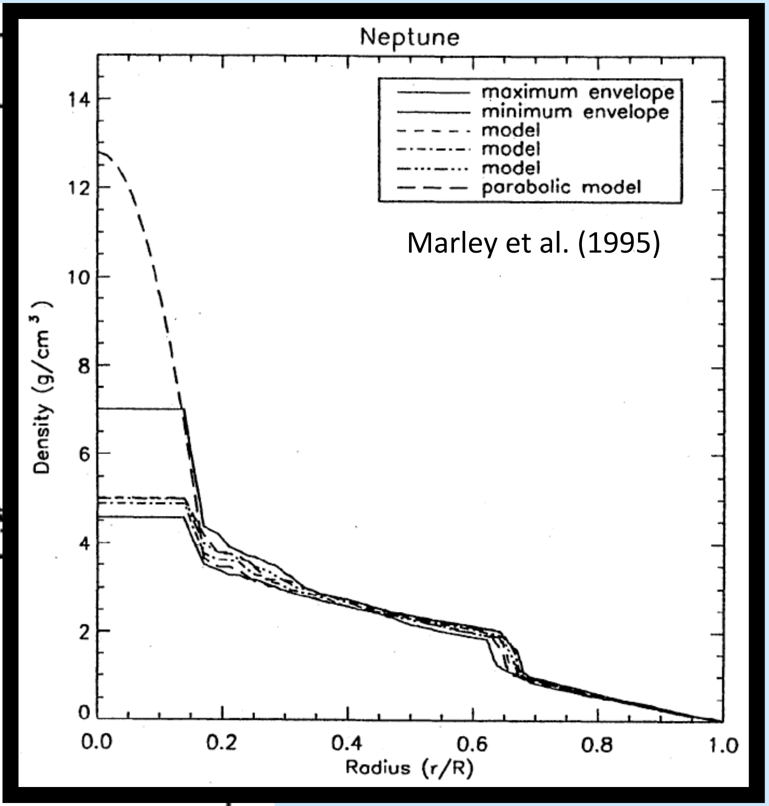


Cavazzoni et al. (1999)

Uncertainties in Understanding the Interiors of Uranus and Neptune



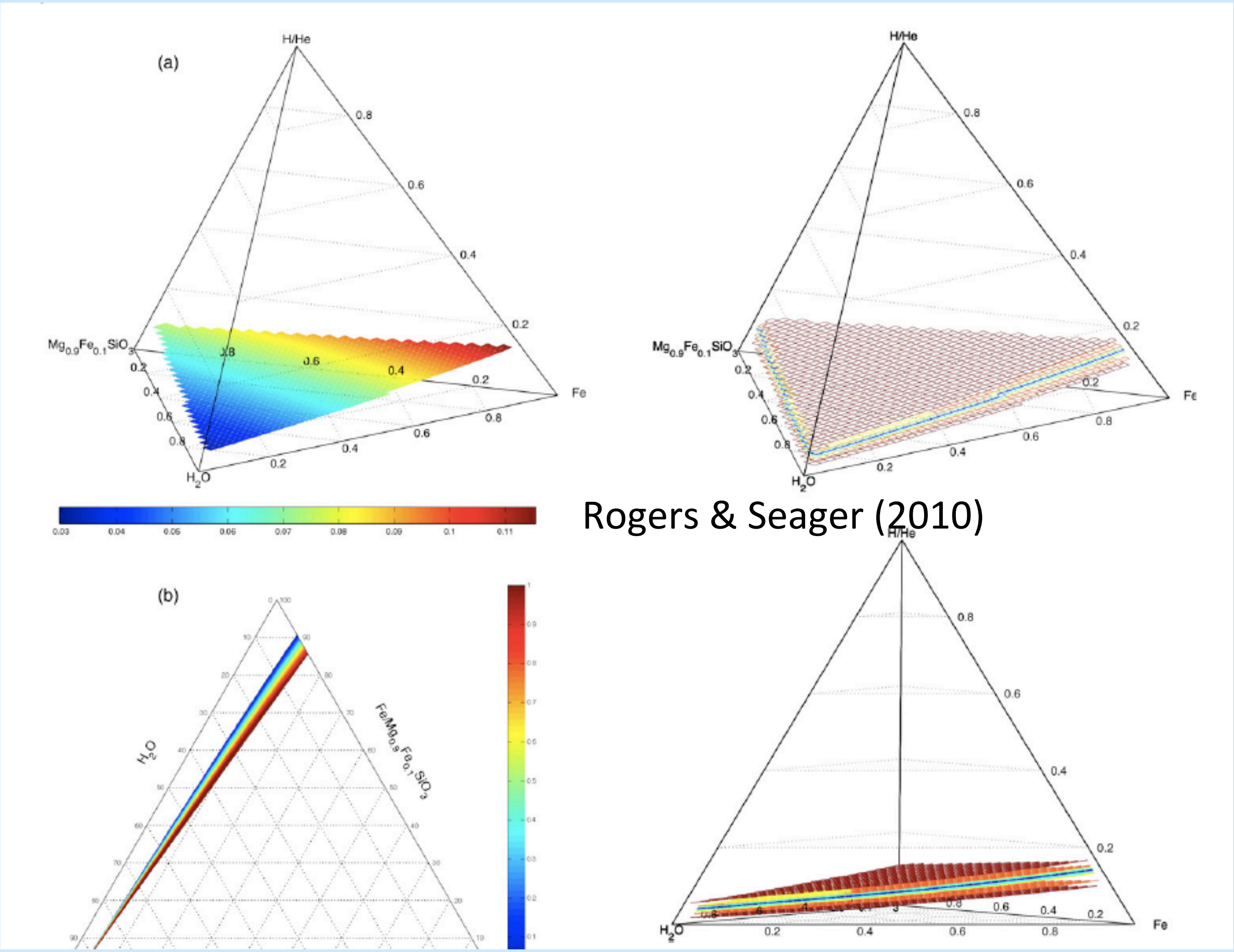
Hubbard et al. (1991)



Marley et al. (1995)

Uranus and Neptune DO NOT have 3 well-defined layers!

“Exo-Neptunes” Make it Even Worse



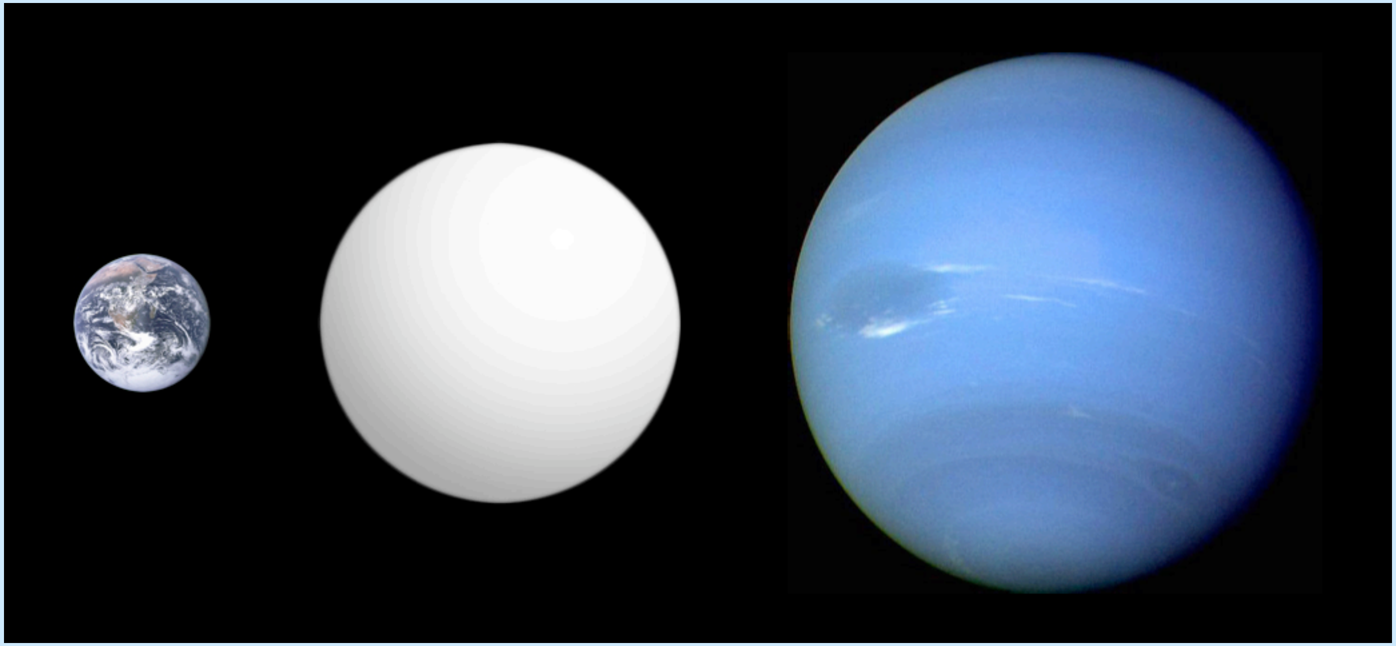
Rogers & Seager (2010)

But as we know from Uranus and Neptune, it is actually worse than this

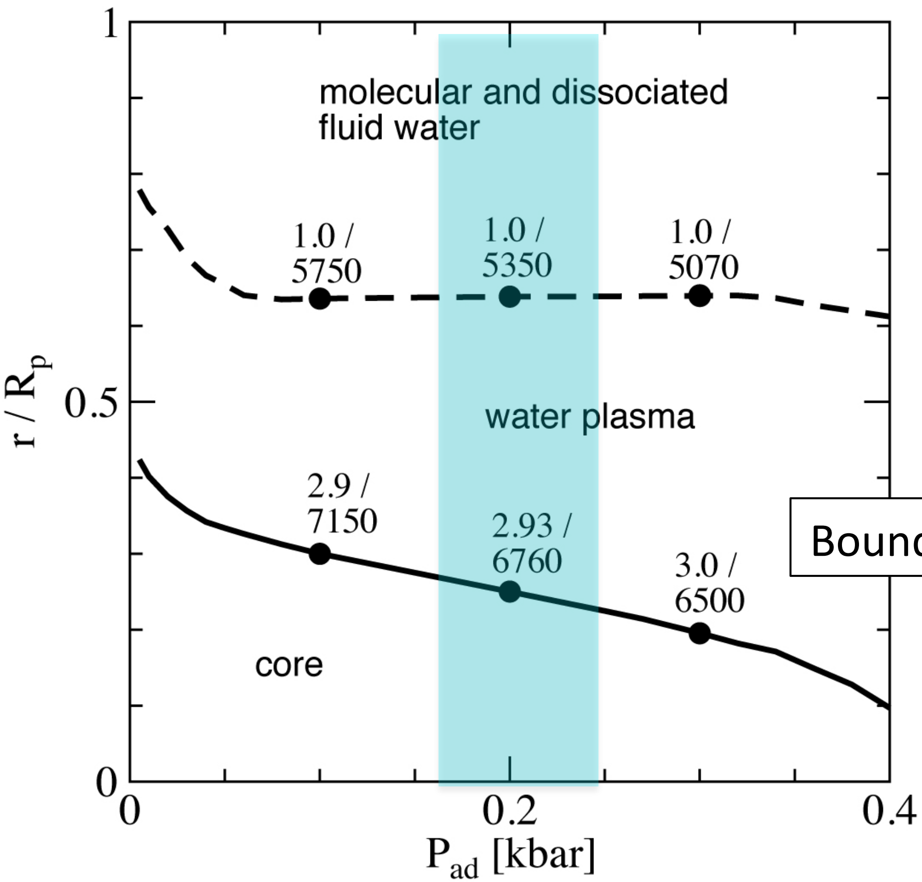
What is the Nature of the Planet's Atmosphere and Interior?

- Mass-Radius leads to degenerate solutions:
    - Mostly water with a small rocky core
        - A "failed" giant planet core?
    - Lower ice/rock ratio, with a H/He envelope
        - A mini Neptune?

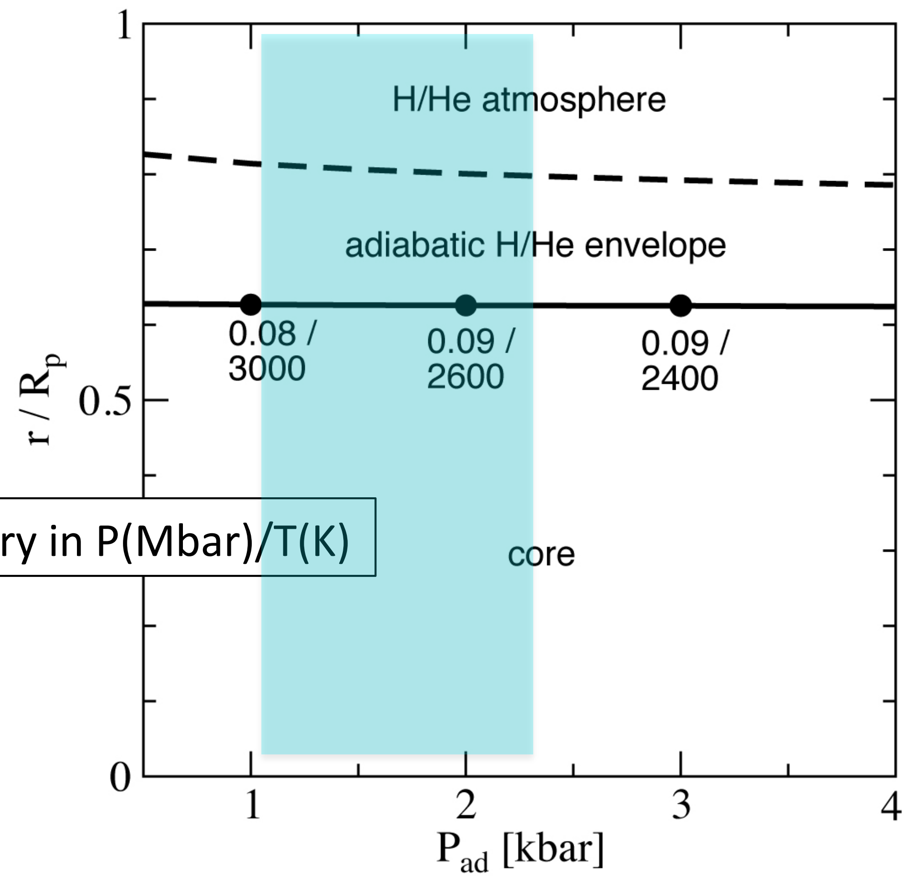
What is the cooling history and interior state of these two kinds of models?



Water World Model

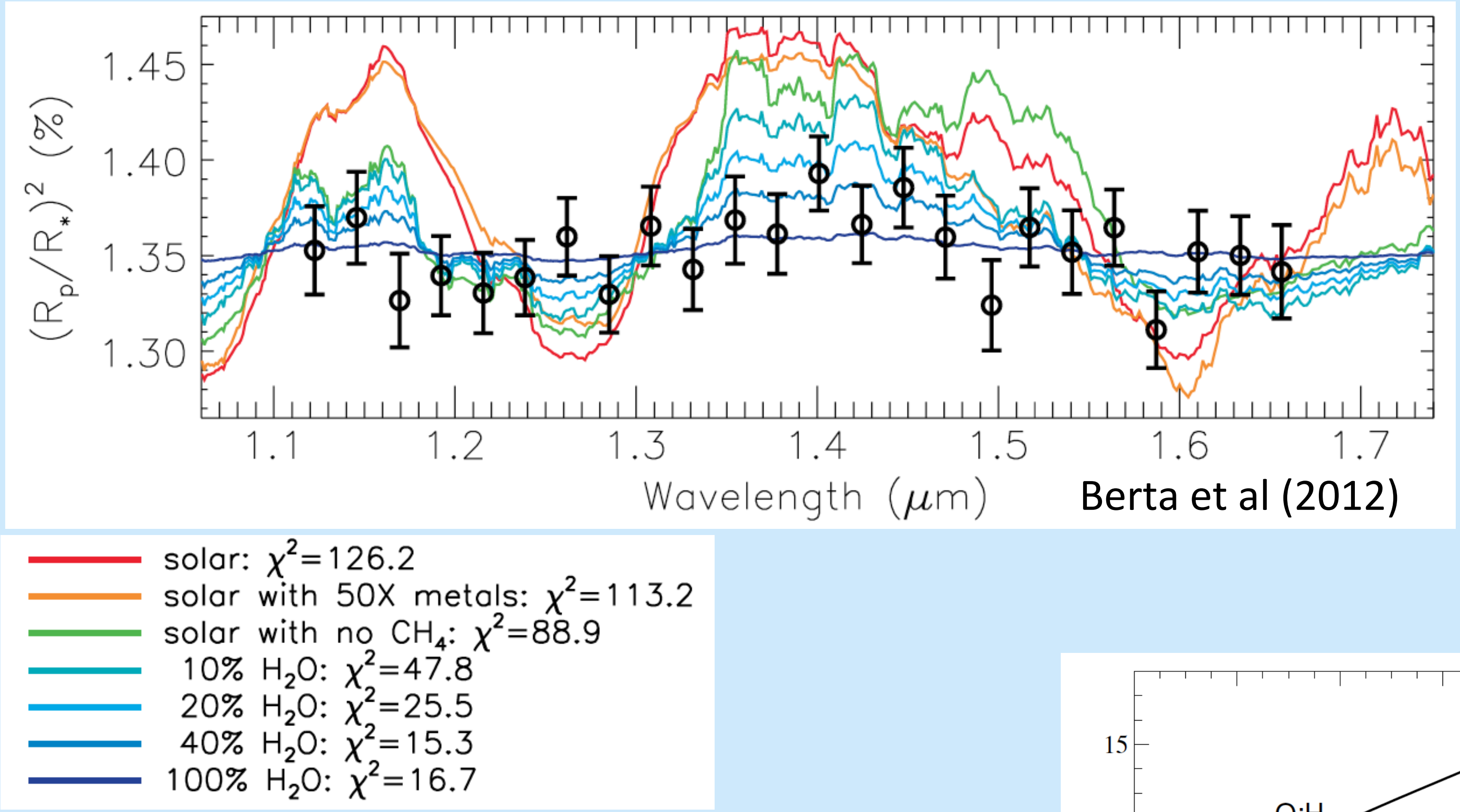


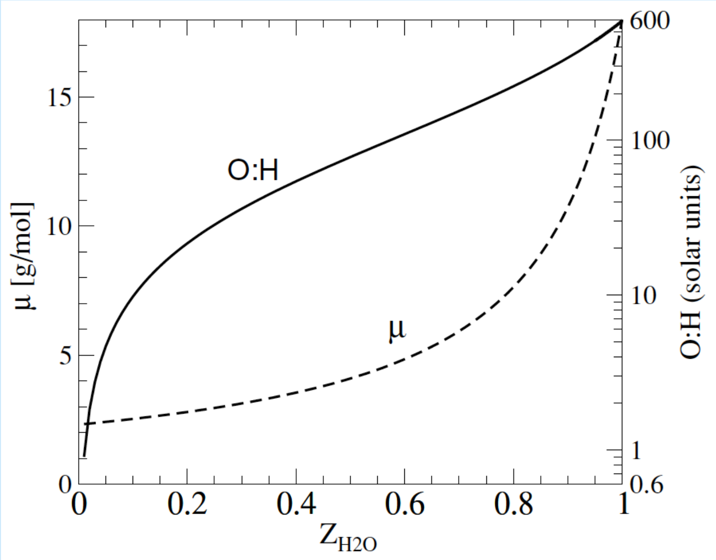
Mini Rocky Neptune Model

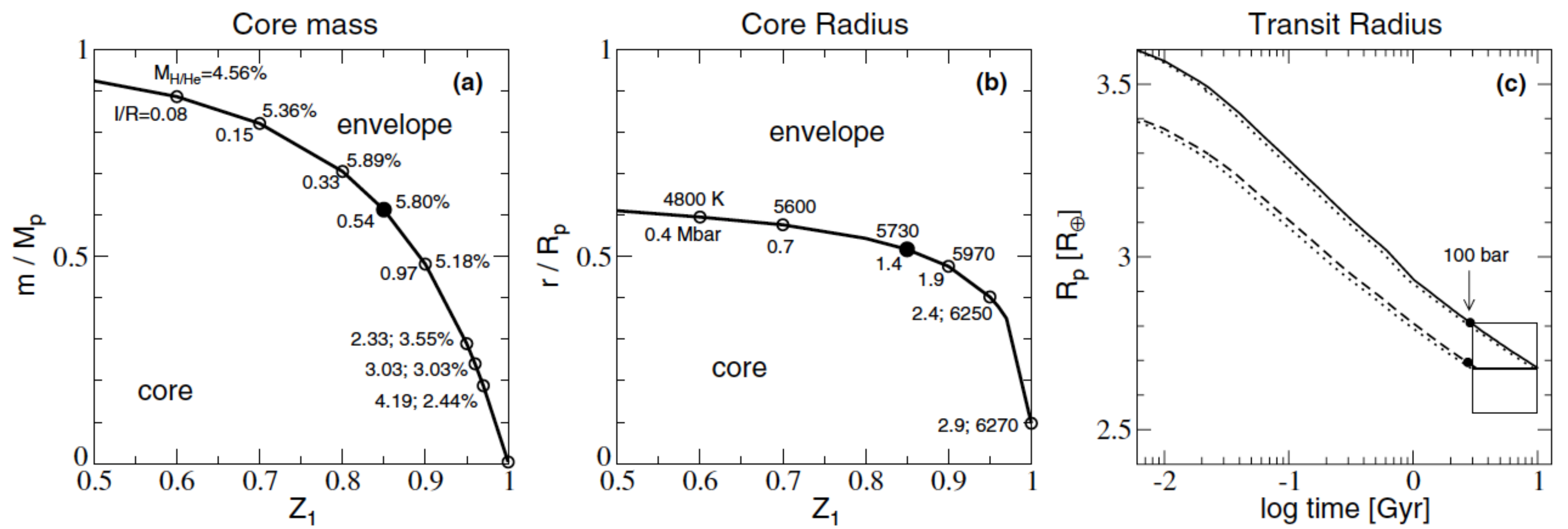


Boundary in P(Mbar)/T(K)

GJ1214b Atmospheric Transmission



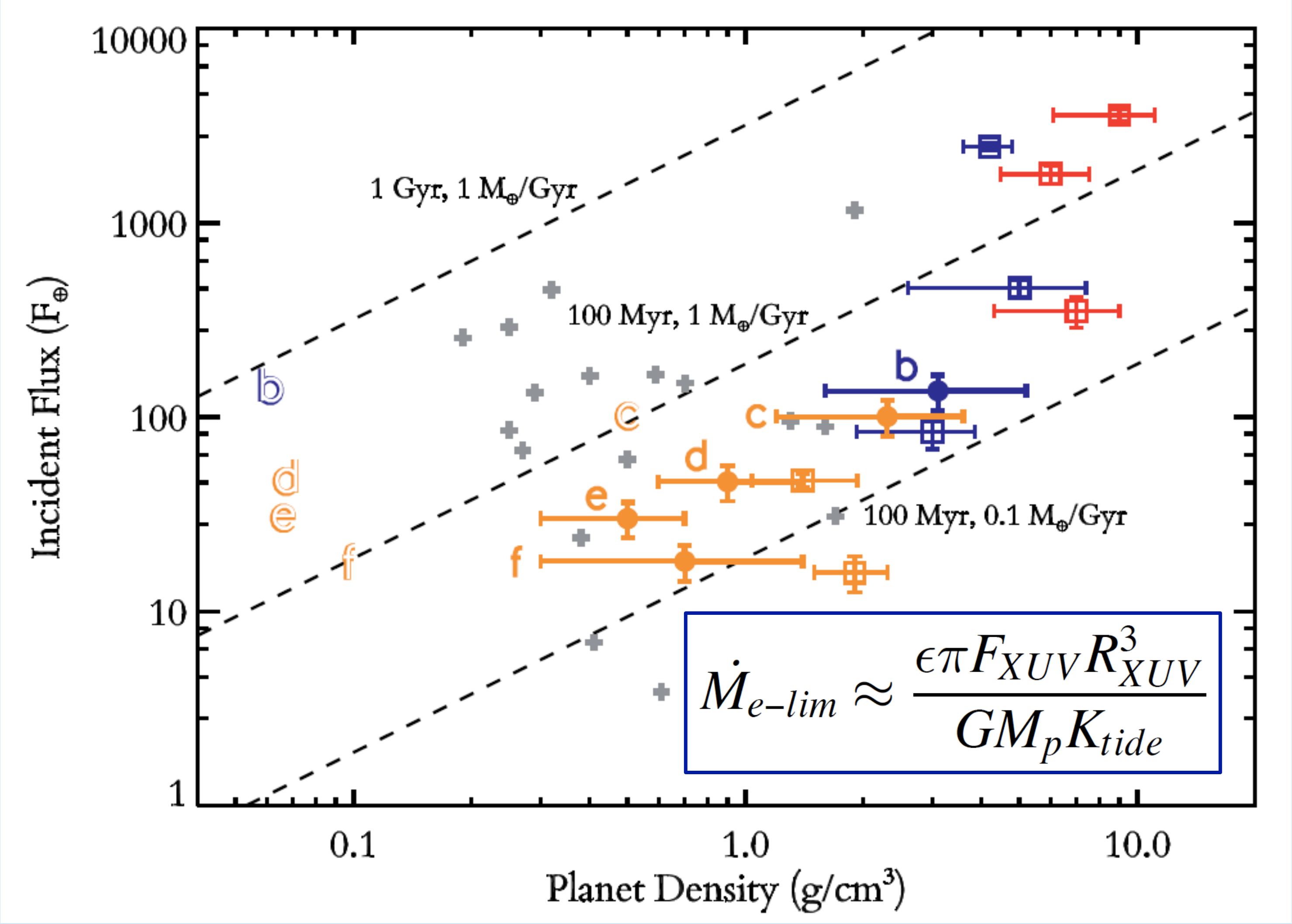




Nettelmann, Fortney, et al. (2011)

Perhaps the most sensible GJ 1214b models are those that are the most like Uranus and Neptune, with a small rocky core thick envelope of H/He dramatically enhanced in water (+other "ices").

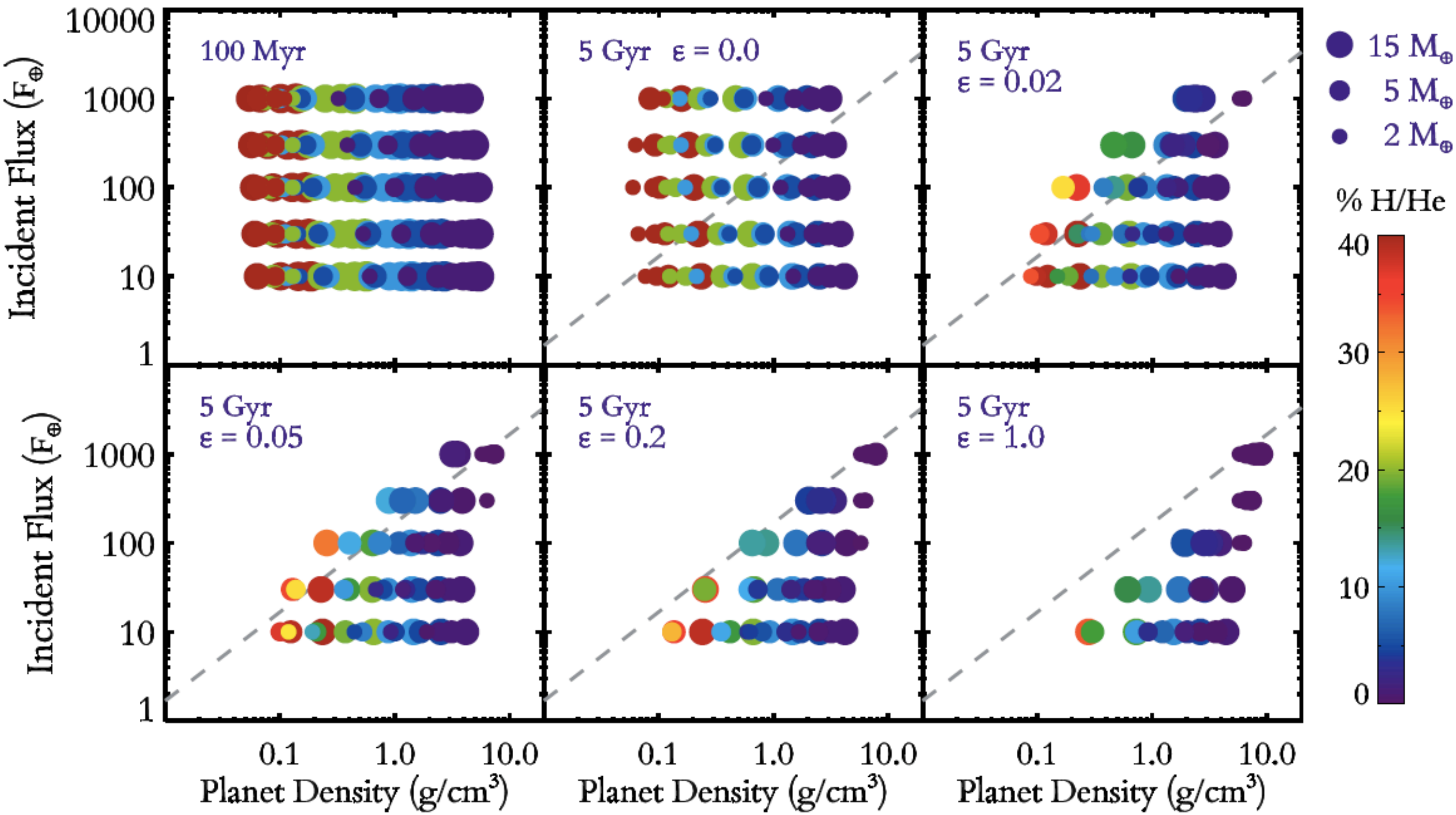
Kepler-11: A System Sculpted by Mass Loss?



- Kepler-11 and other low-mass planets on the density vs. flux plane

Lopez, Fortney, & Miller, ArXiv:1205.0010

Reproducing the Trend with Thermal/Radius Evolution + Mass Loss



Lopez, Fortney, & Miller, ArXiv:1205.0010

Conclusions

- A measurement of mass-radius yields important information about the structure of a gas giants
- It appears on all gas giant are enhanced in metals compared to their parent stars
- Tidal heating may have been important for systems at young ages, but generally not today
- The hottest planets have the largest radii
- No strong conensus yet on radius inflation mechanism, but it is clearly correlated with incident flux

- GJ1214b is likely a small cousin to Uranus and Neptune
- Low-mass low-density planets are quite common
    - Atmospheric mass loss can sculpt the populations of planets we see today