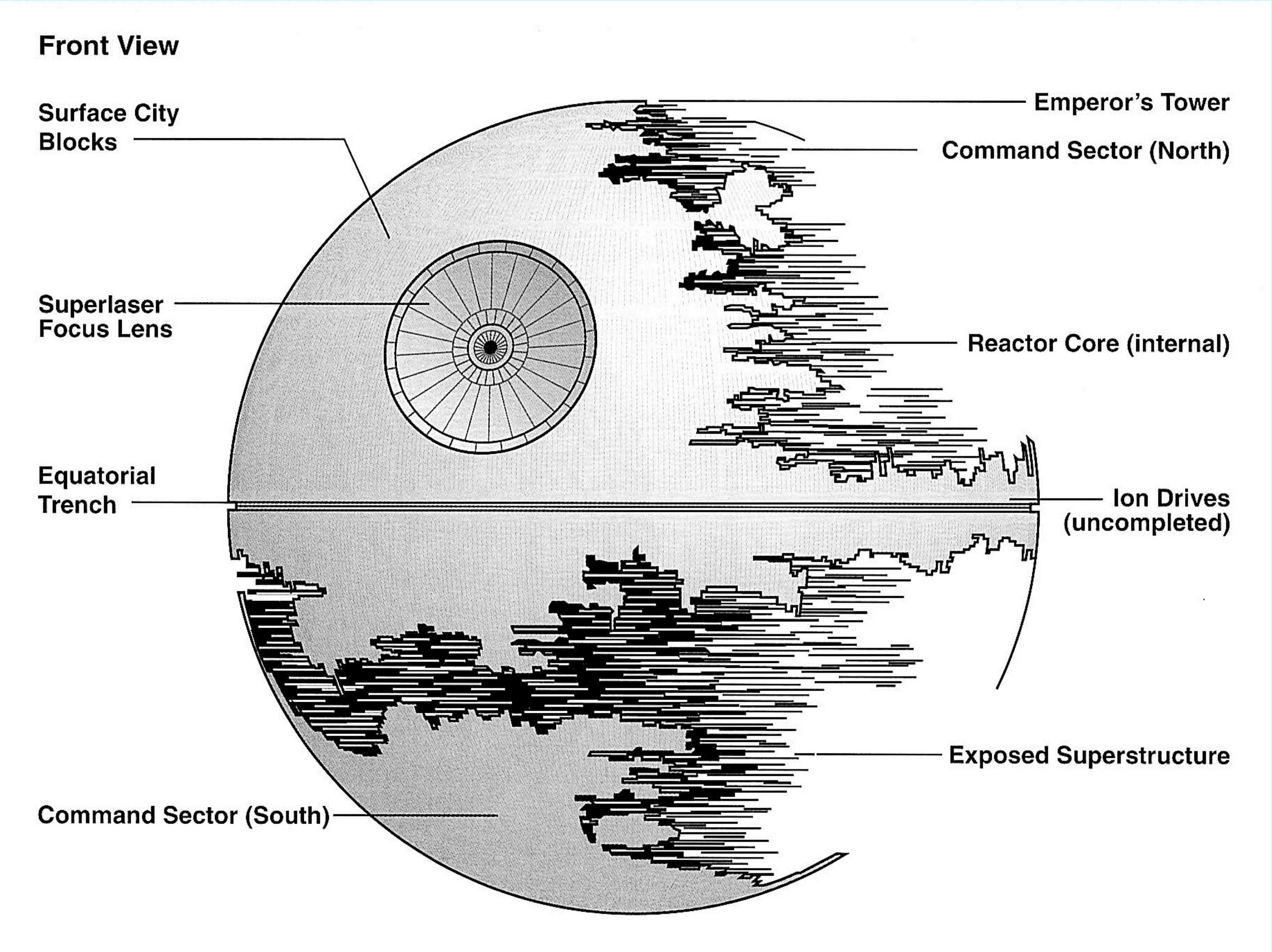
The Interior Structure of Planets



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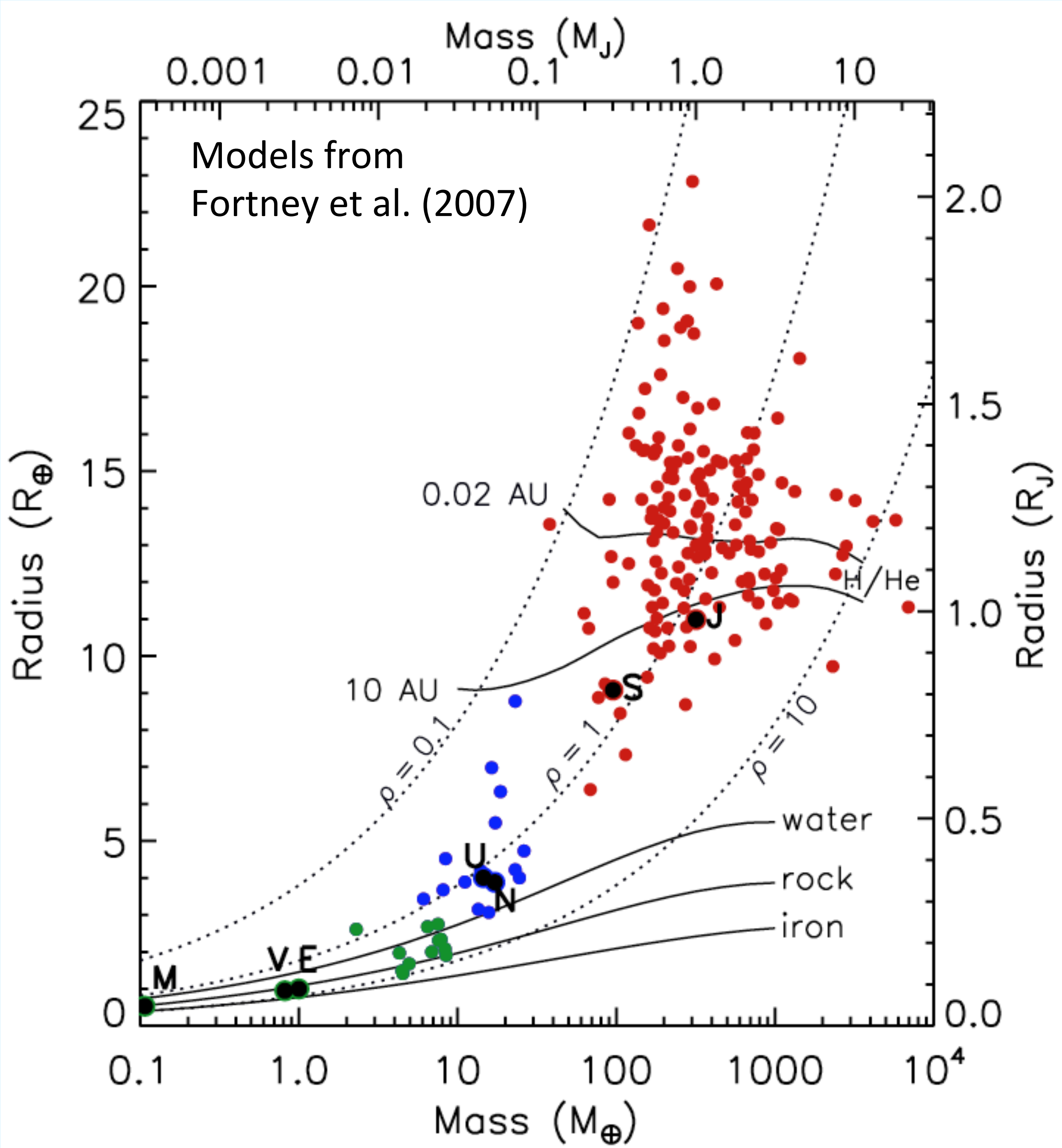
University of California, Santa Cruz

Christophe Sotin
JPL, Pasadena

http://m100group.files.wordpress.com/2012/05/deathstarii_egvv.jpg

Main Themes

- New era of EOS calculations & lab work
- The Solar System: We now have the ability to test the validity of long-held working assumptions
- Status of understanding Hot Jupiter radius anomaly
- Connecting stellar and planetary metallicity
- Neptunes, Sub-Neptunes, and Super Earths: Composition and Evaporation
- Iron in Rocky Planets



Fast Moving Field

Since PPV, we've gone from around 7 transiting planets to over 200 with mass measurements

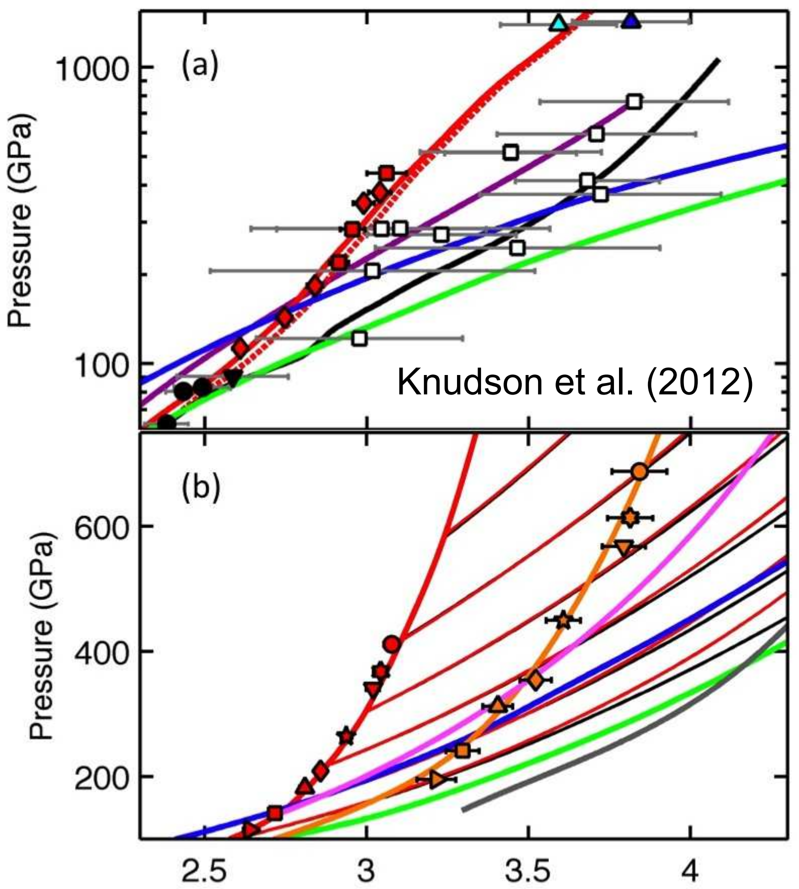
The promise of transiting planets:

What are these planets made of?

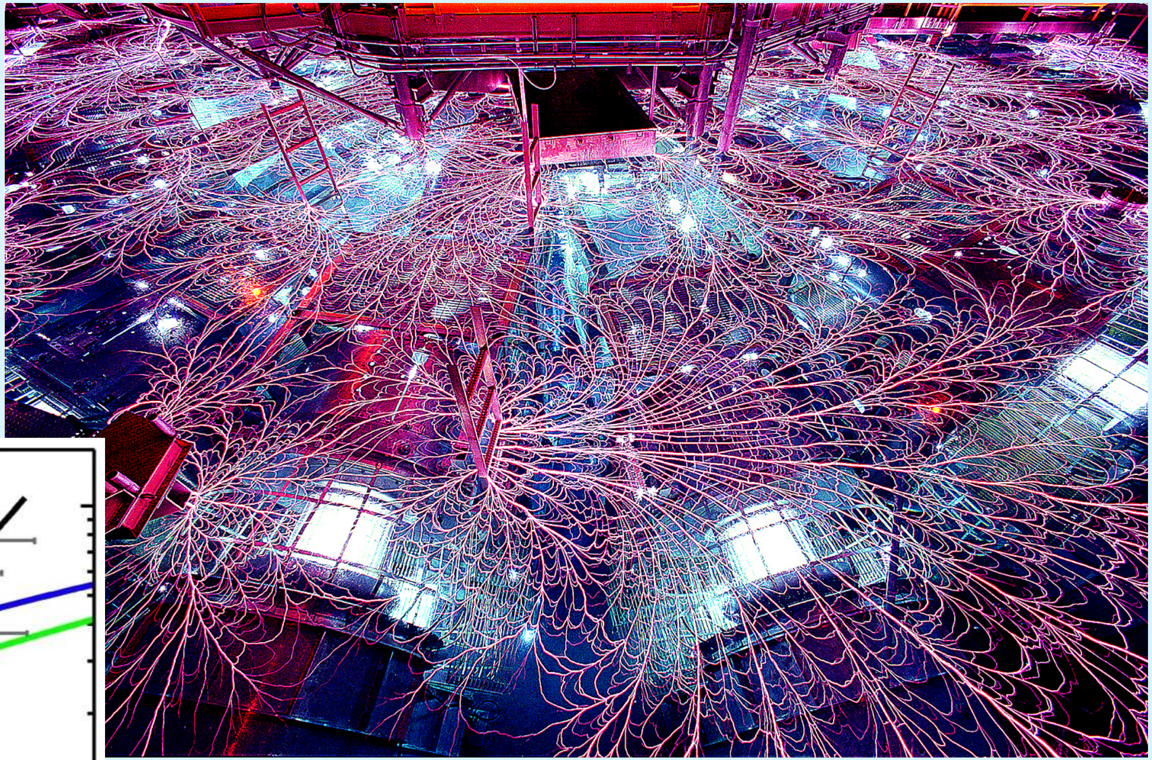
How do they compare to our Solar System's planets?

We can address that, but we've also got other problems like inflated radii

EOS at High Pressure: New Calculations and Precise Measurements



PRL v108, 091102

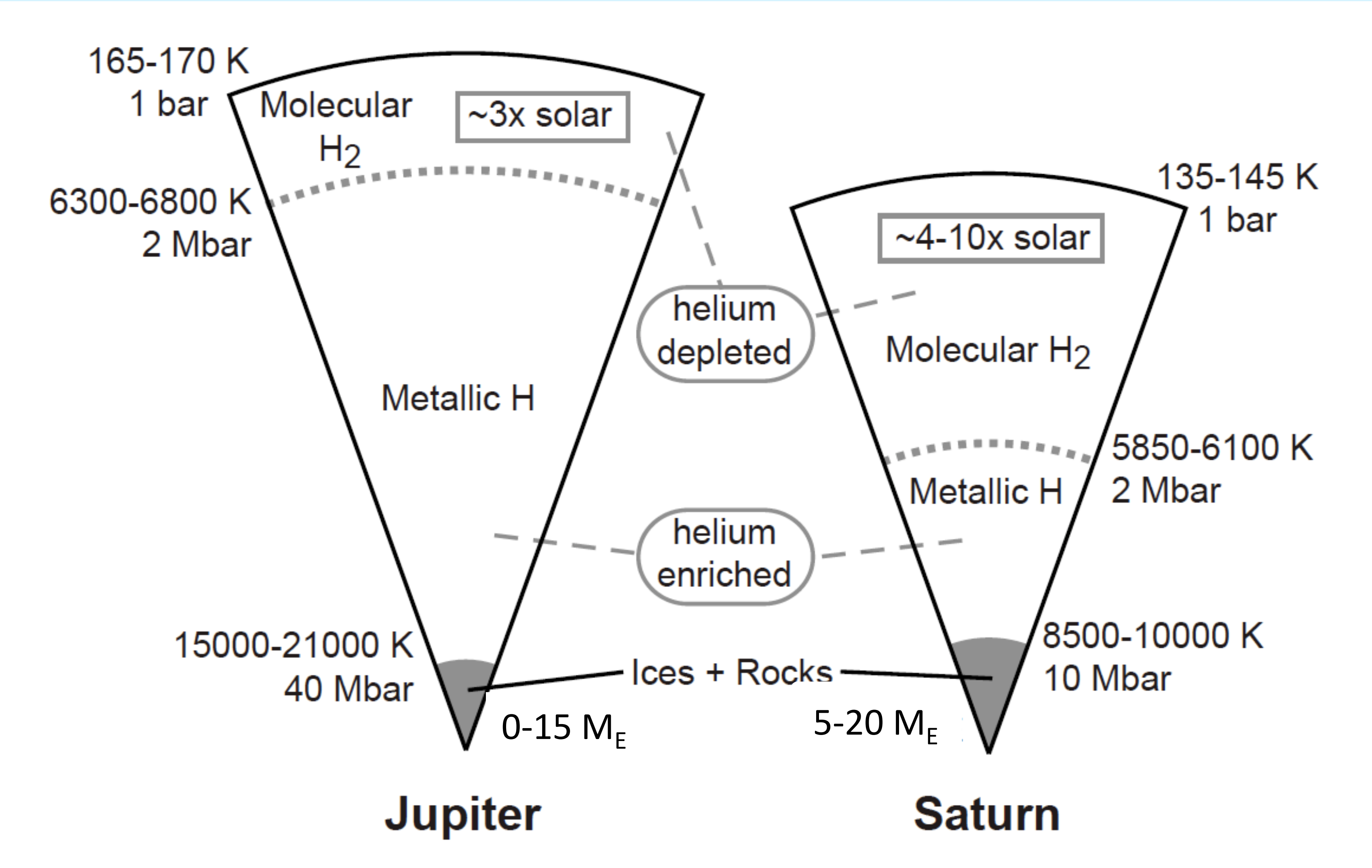


Sandia National Laboratory Z Machine

- After many decades of effort, we are now in an era of detailed first-principles calculations of the equation of state (EOS)
- Precision EOS measurements are also now available

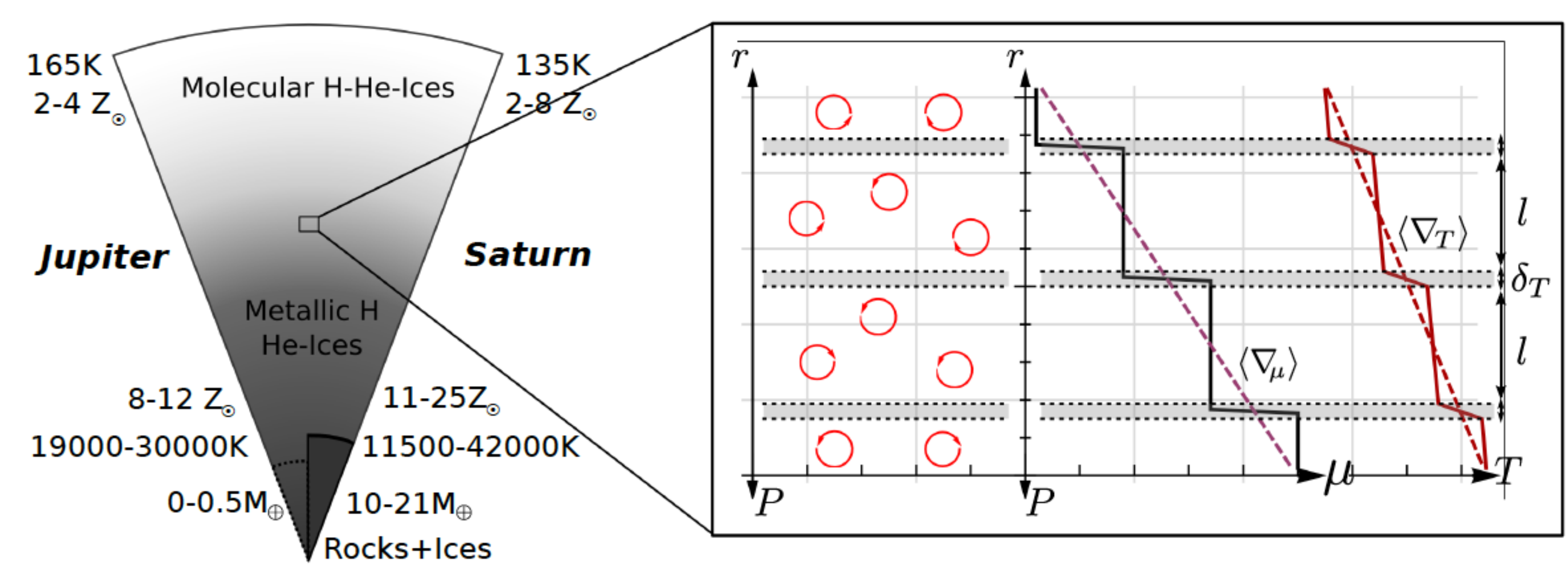
French et al. (2009) water EOS

Our Gas Giant Prototypes: Jupiter and Saturn



5-25% Heavy Elements by Mass

Fortney, Baraffe, & Militzer (2010) “Exoplanets” book, Arizona Space Science Series



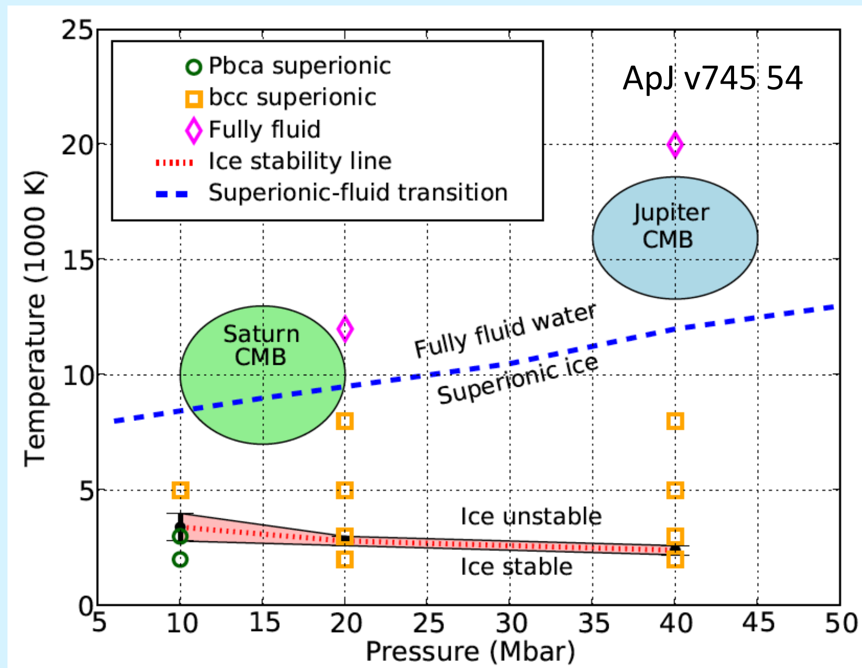
Leconte & Chabrier (2012), A&A v540, A20
based in part on 3D simulations of Garaud & collaborators

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

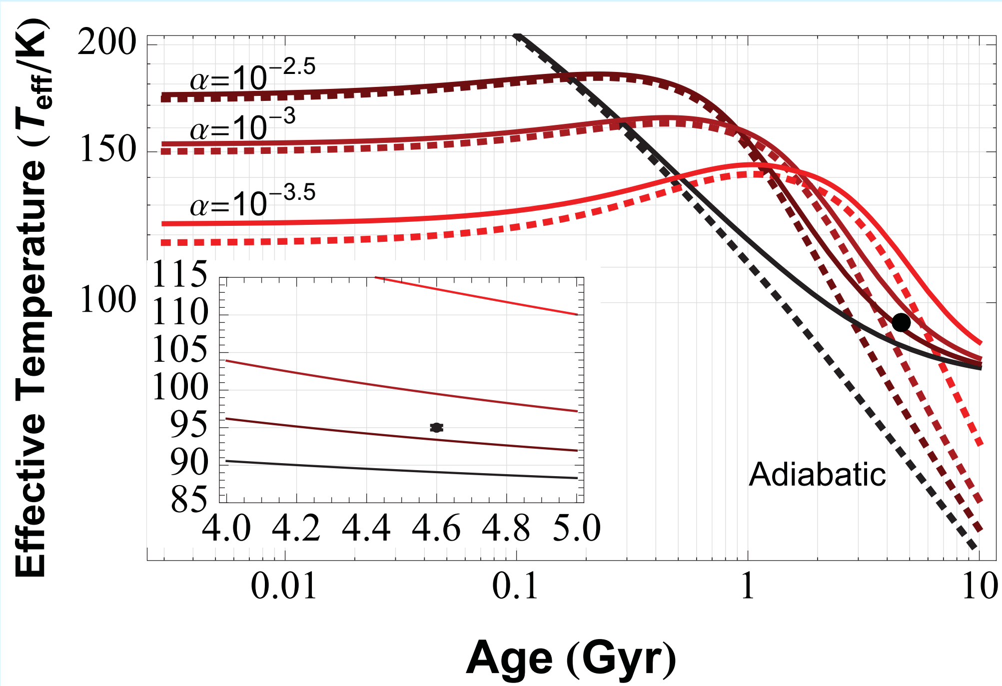
The assumptions of fully convective interiors and distinct heavy element cores can now be examined

(See also Stevenson 1982, 1985)

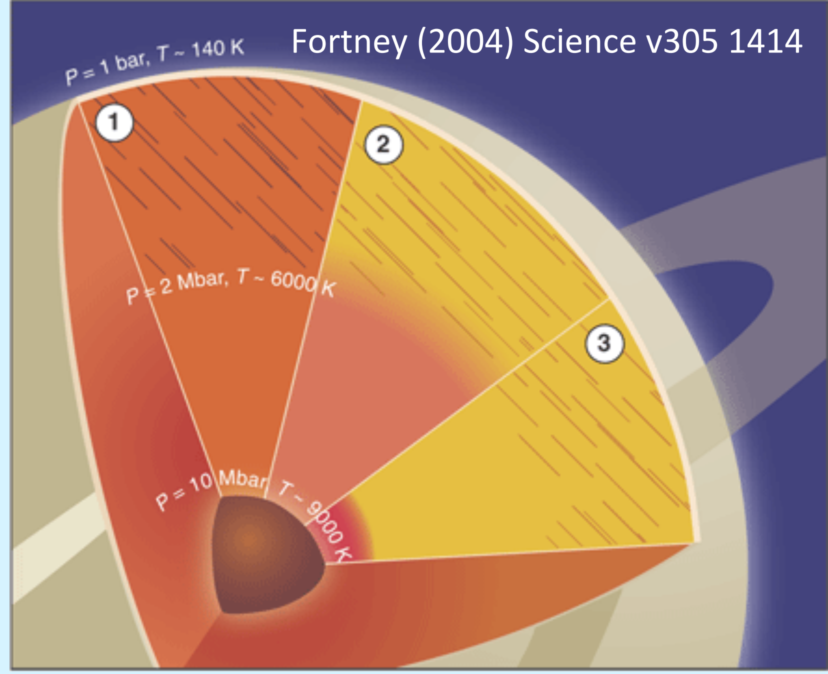
Wilson & Militzer (2012)

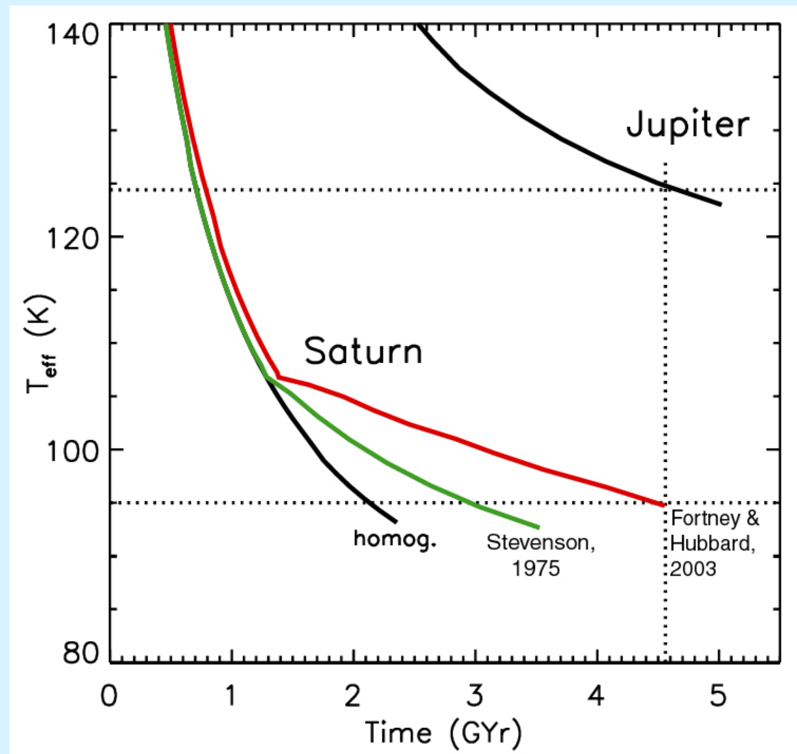


Evolutionary Histories with Composition Gradients can be Complex

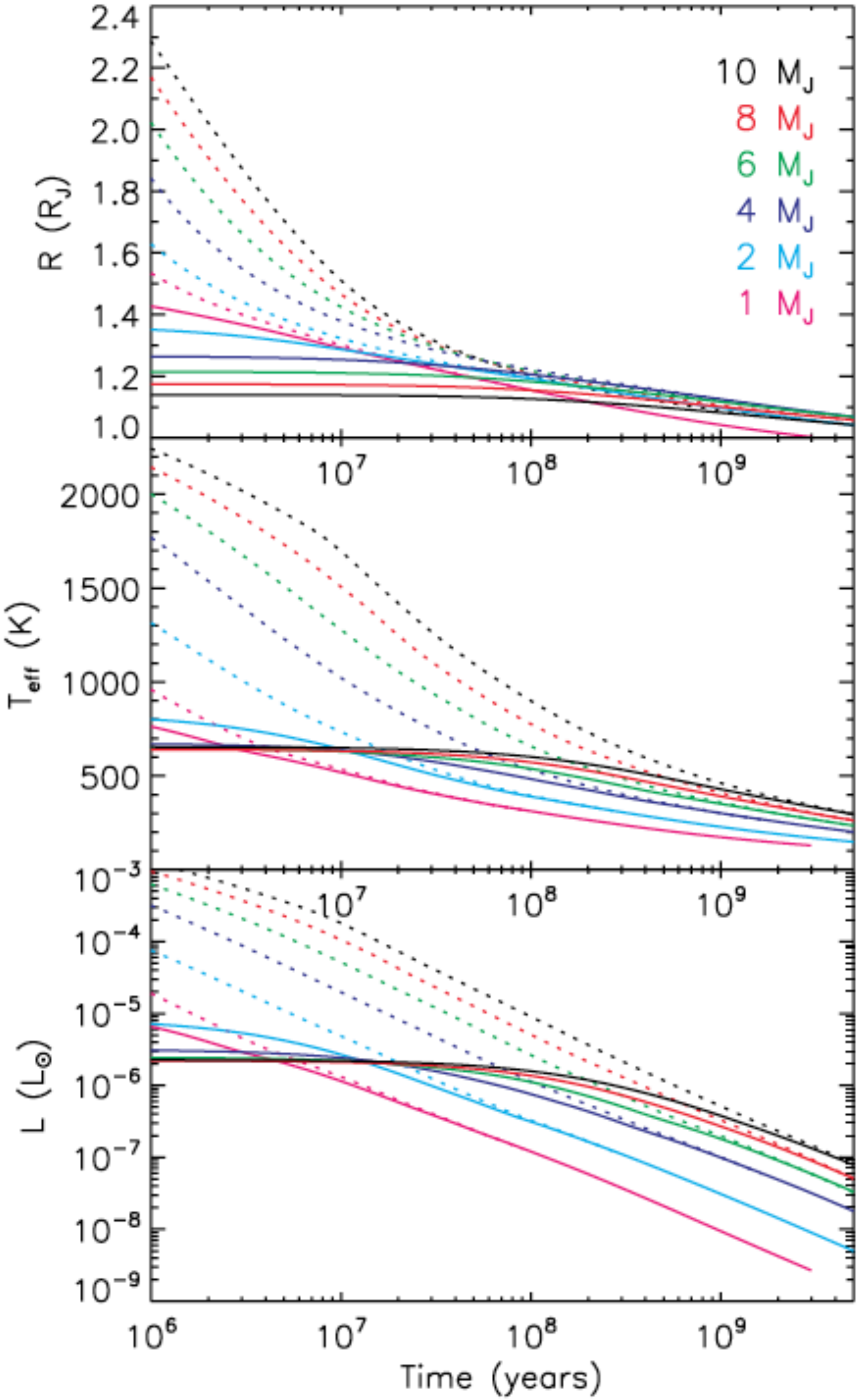


Leconte & Chabrier (2013) Nat Geo v6 347





Anomalously large T_{eff} of Saturn could be due to helium rain, or altered cooling due to composition gradients, or both



We Need a Better Understanding of Giant Planet Initial Conditions

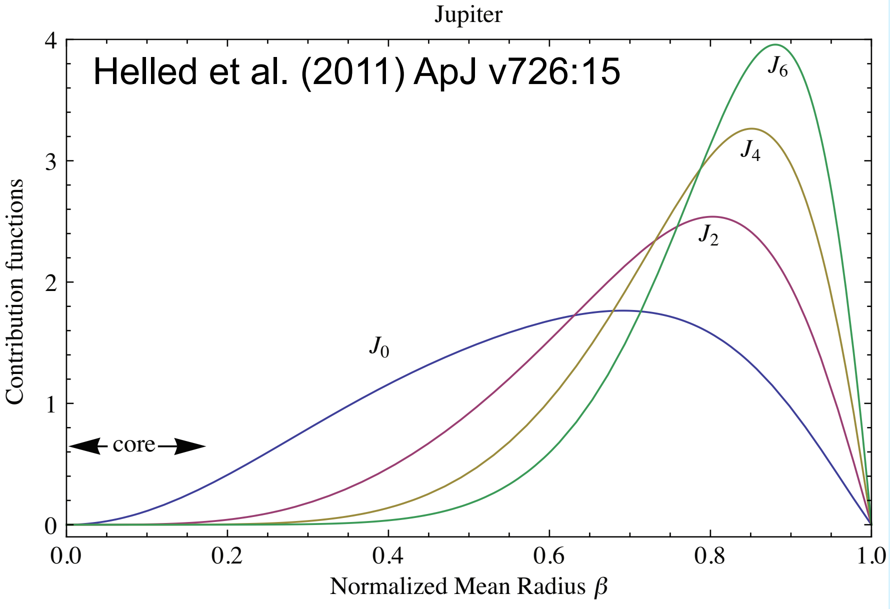
Early thermal evolution of giant planets is strongly dependent on the treatment of accretion, as well as the presence of composition gradients

A variety of new surveys will achieve 10^{-6} to 10^{-7} contrast to find dozens of planets (based on MC modeling of the frequency of long-term RV trends) to better understand these early ages

Figure from Marley et al. (2007) ApJ v655:541
See also Fortney et al. (2008), Spiegel & Burrows (2012), Mordansini (2013), Marleau & Cumming (2013)

A Giant Planets Interiors Mission: Juno at Jupiter, 2016-17

- Are observed surface flows representative of internal differential rotation?
    - Detailed constraints on the planet's gravity field
- What is the abundance of water and ammonia at 100 bars, well below the cloud decks (potentially representative of entire H/He envelope)
- Detailed mapping of the dynamo-generated 3D magnetic field
- Constraints on heavy element core
    - Lense-Thirring Effect may yield moment of inertia
    - Tides raised on Jupiter by Io may yield k_2 Love number



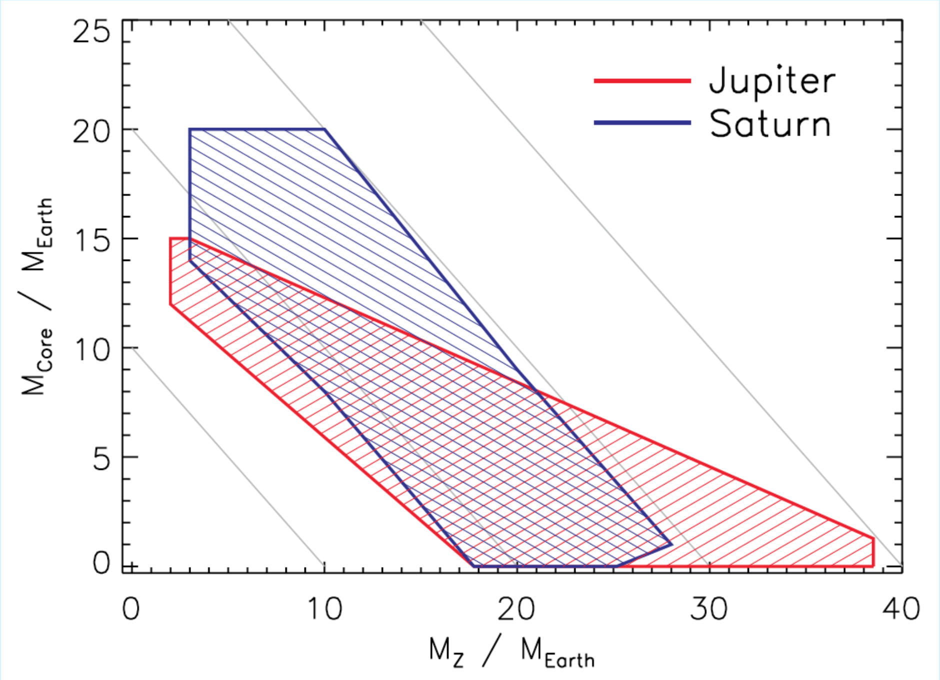
Main investigators publishing in this area: Y. Kaspi, R. Helled, W. Hubbard, G. Schubert

$$V_{\mathrm{ext}}(r, \cos\theta) = \frac{GM}{r}\left[1 - \sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{2n} J_{2n} P_{2n}(\cos\theta)\right],$$

Metal-Enrichment of Giant Planets

Given our renewed appreciation of the **difficulty to ascertain the current core masses**, and our lack of knowledge of the **relation between any current core mass and initial core mass**, it makes more sense to really just think about **the total heavy element enrichment** in giant planets

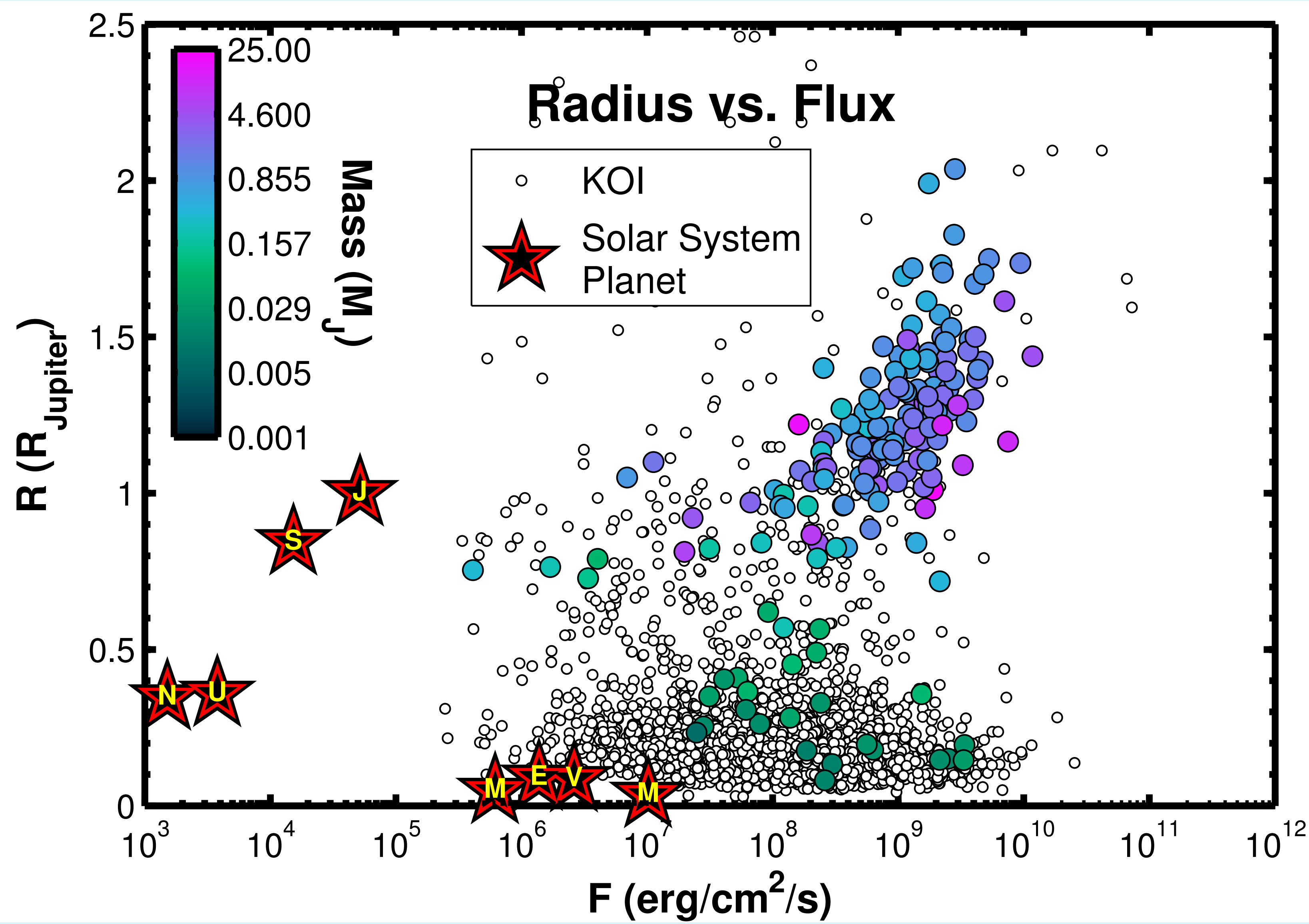
This isn't really a huge problem, since this total enrichment is the only thing we'll be able to measure for the vast majority of transiting planets



Current constraints for Jupiter and Saturn from adiabatic interior models, similar to what is used for all exoplanet models.

Jupiter: 3x to 8x solar
Saturn: 12x to 21x solar

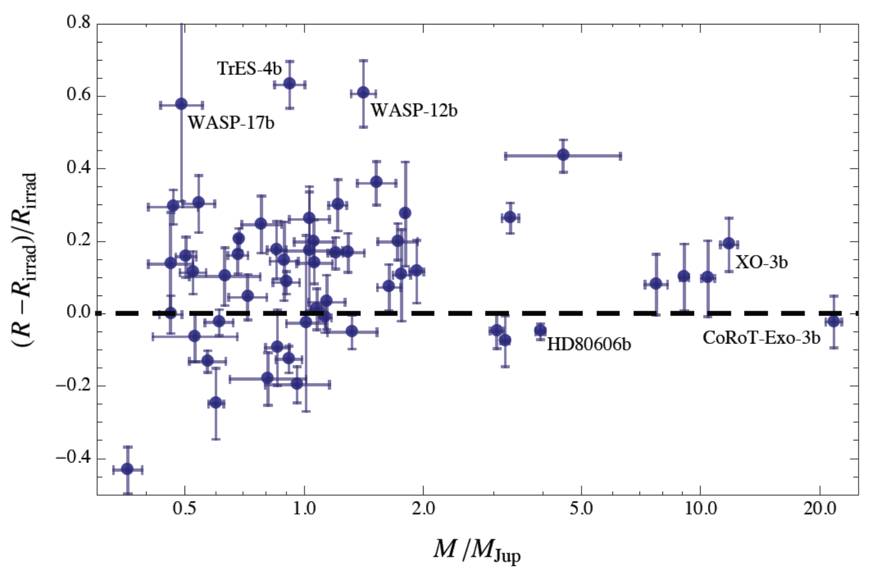
Strong relation between Radius and Incident Flux



Spiegel et al. (2013, in prep)

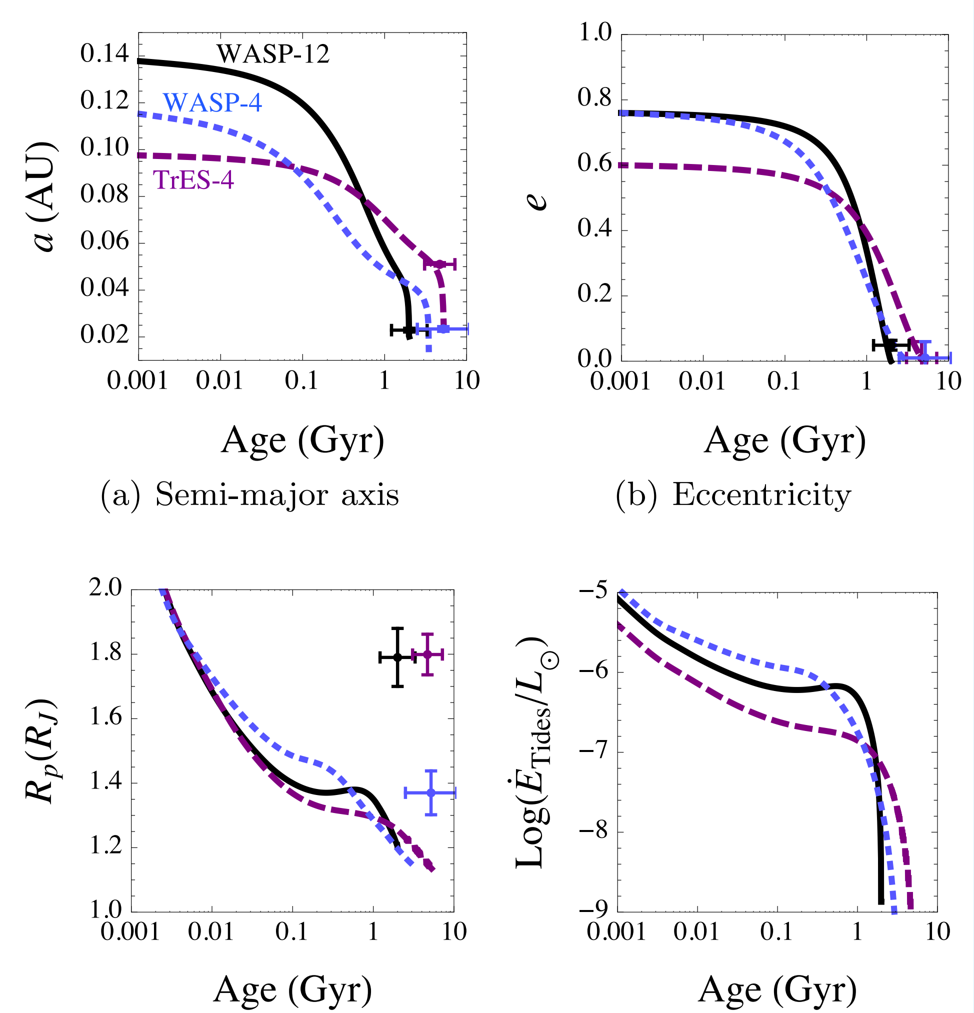
Three classes of explanations for large planets

- **Energy comes from the star**
  - 0.1-1% of incident energy must makes its way near to or below into the radiative-convective boundary at 100+ bars (e.g. Showman & Guillot, 2002)
  - Readily explains strong correlation with incident flux
  - What is the mechanism for energy conversion/deposition?
- **Energy comes from the planetary orbit**
  - Tidal energy deposition
  - Works well but is a short-lived effect
  - Cannot be the universal mechanism
- **Delayed/stalled contraction**
  - High atmospheric opacities stall cooling, a bit (Burrows et al. 2007)
  - Interior composition gradients can stall cooling (Chabrier & Baraffe 2007)
  - Cannot be the universal mechanism



Leconte et al. (2010) A&A v516:A64

Tidal Inflation: Not the Universal Mechanism



(a) Semi-major axis
(b) Eccentricity
(c) Planetary radius
(d) Tidal energy dissipation

Many papers on this topic over the past 10 years (e.g., Bodenheimer et al. 2000, Jackson et al. 2008, Ibgui & Burrows 2009, Miller et al. 2009), gradually moving to better and more complete tidal models (e.g. Leconte et al. 2010)

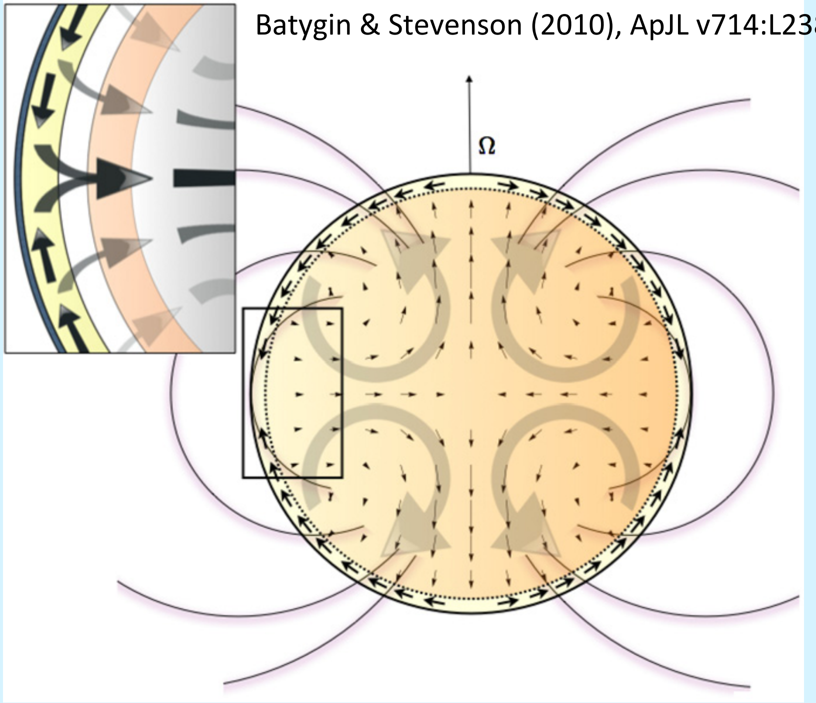
Attractive mechanism, and likely effects most planets if hot Jupiters commonly start on eccentric orbits

Tidal inflation of planet is a short-lived phenomenon that can inflate radii at young ages but is not the universal radius inflation mechanism at Gyr ages

Leconte et al. (2010) A&A v516: A64

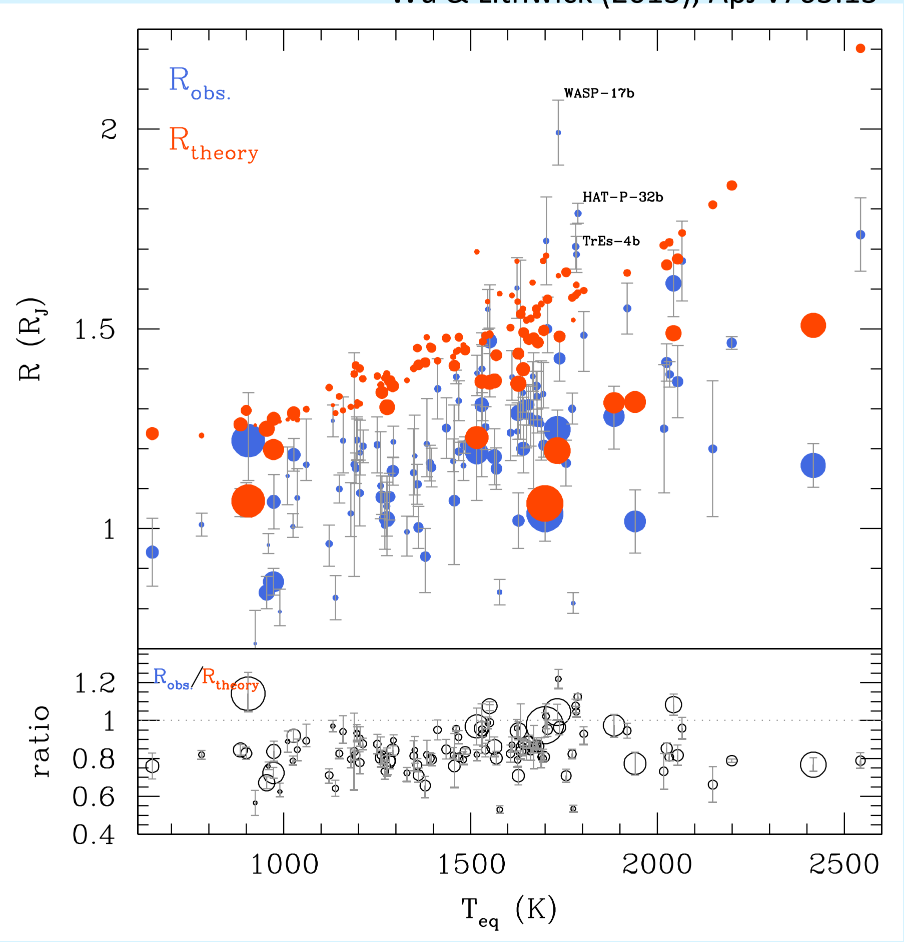
A Contender: Ohmic Dissipation

Batygin & Stevenson (2010), ApJL v714:L238



Batygin & Stevenson (2010)
Perna et al. (2010a,b)
Batygin et al. (2011)
Huang & Cumming (2012)
Wu & Lithwick (2013)
Rauscher & Menou (2013)
Spiegel & Burrows (2013)

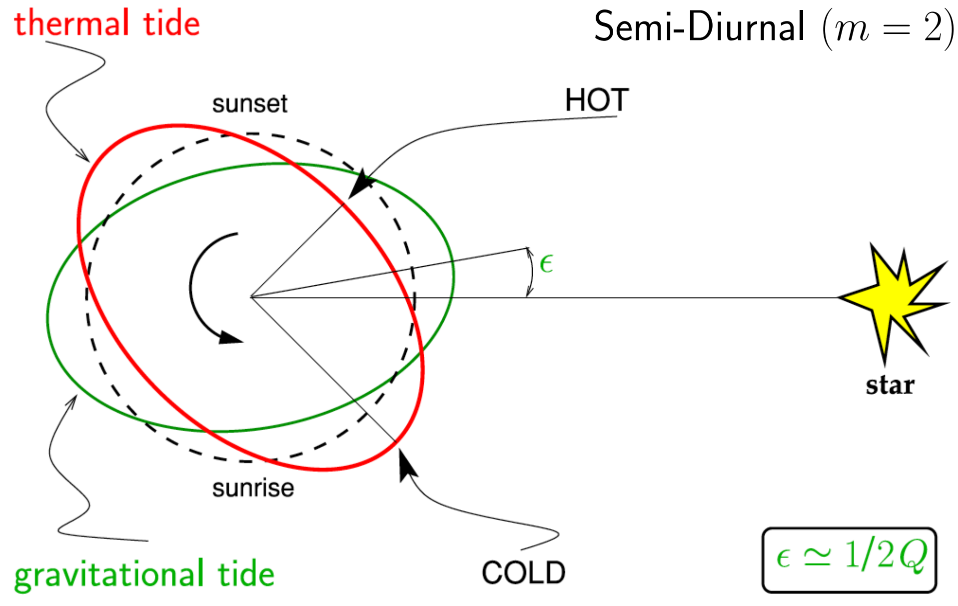
Wu & Lithwick (2013), ApJ v763:13



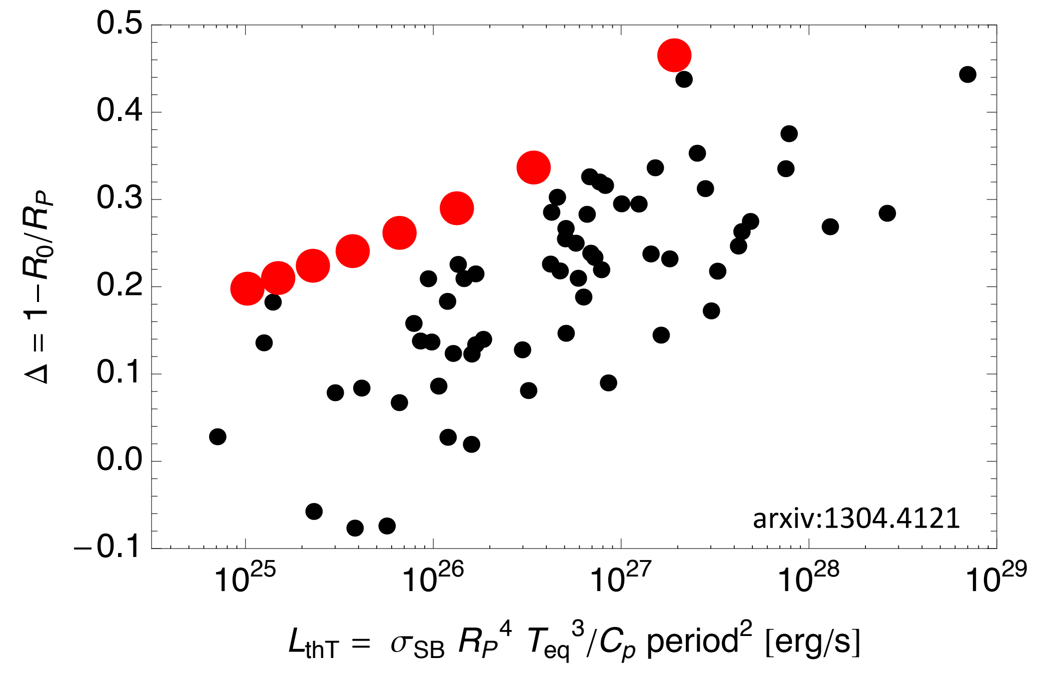
- Thermally ionized alkalis advected in the weather layer due to fast winds
- Creates **B**-field distinct from internally-generated dynamo **B**-field
- Associated induced current **J** driven into deep atmosphere or into planet's interior
- Ohmically dissipated, with power ~$\mathbf{J}^2/\sigma$

A Contender: Thermal Tides

- Thermal tides generally occur on planets due to finite thermal inertia of the atmosphere
- Peak temperature delayed from peak heating (afternoon hotter than noon)
- Stellar pull on thermal tidal bulge acts to speed up planetary rotation
- Gravitational planetary tidal bulge is in steady-state opposition to this thermal tidal buldge
- Planet obtains permanent non-synchronous spin and energy source
- Outcome: A tidal mechanism where the energy source is the stellar irradiation

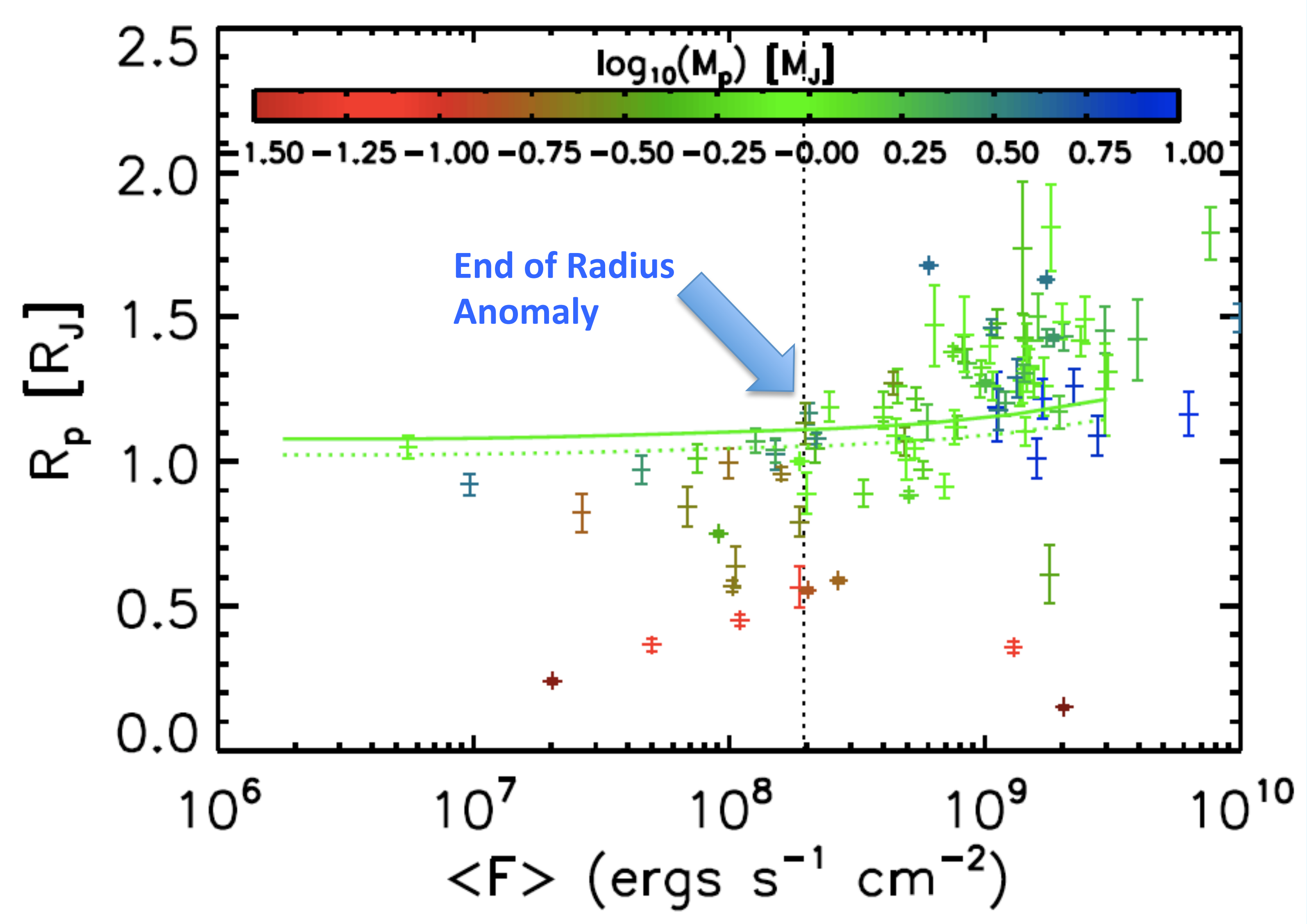


Arras & Socrates (2010) ApJ v714:1



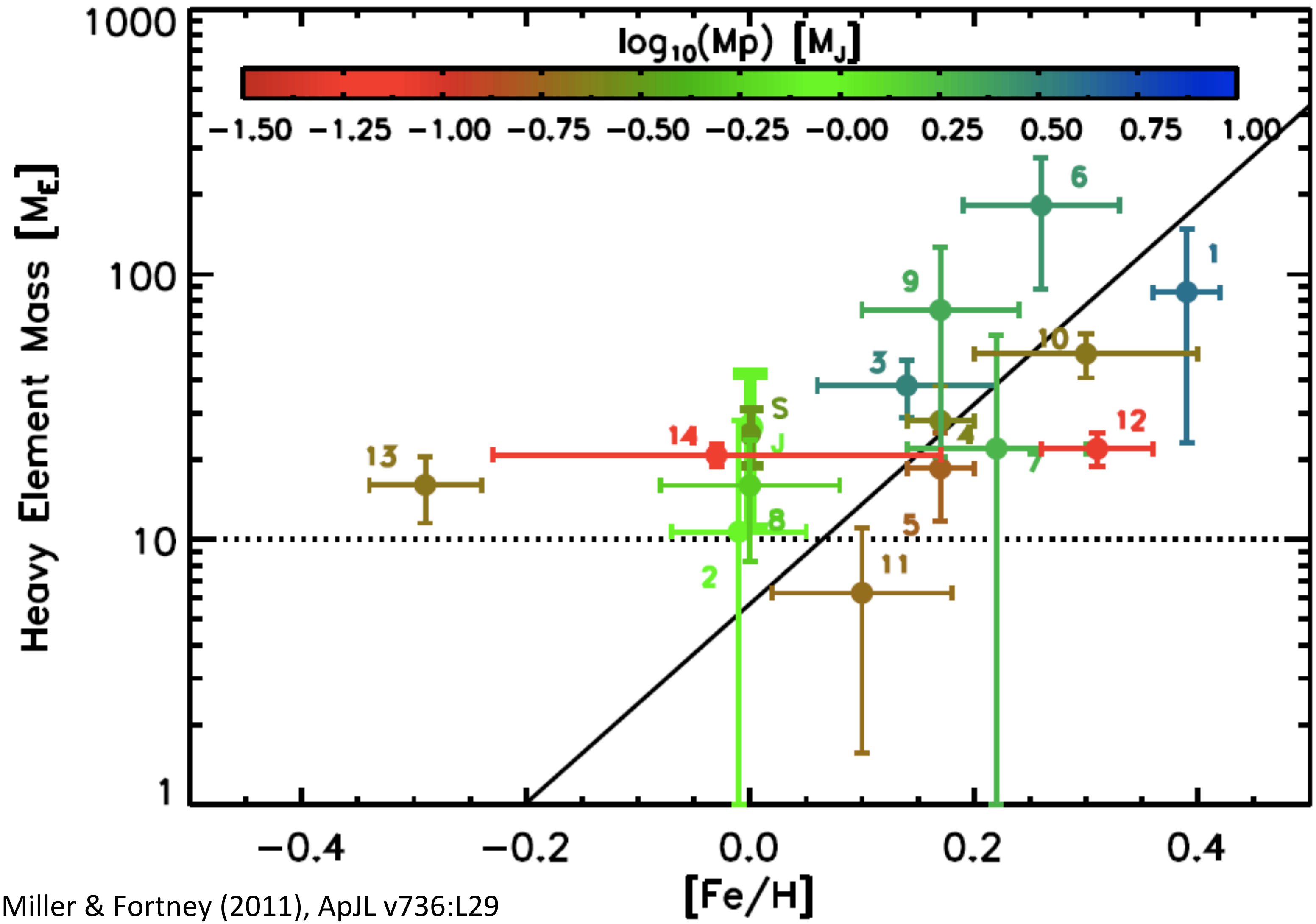
Socrates (2013) arxiv:1304:4121

There is an emerging population of planets with no radius anomaly



Miller & Fortney (2011), ApJL v736:L29

A strong correlation between star and planet abundances



Miller & Fortney (2011), ApJL v736:L29

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

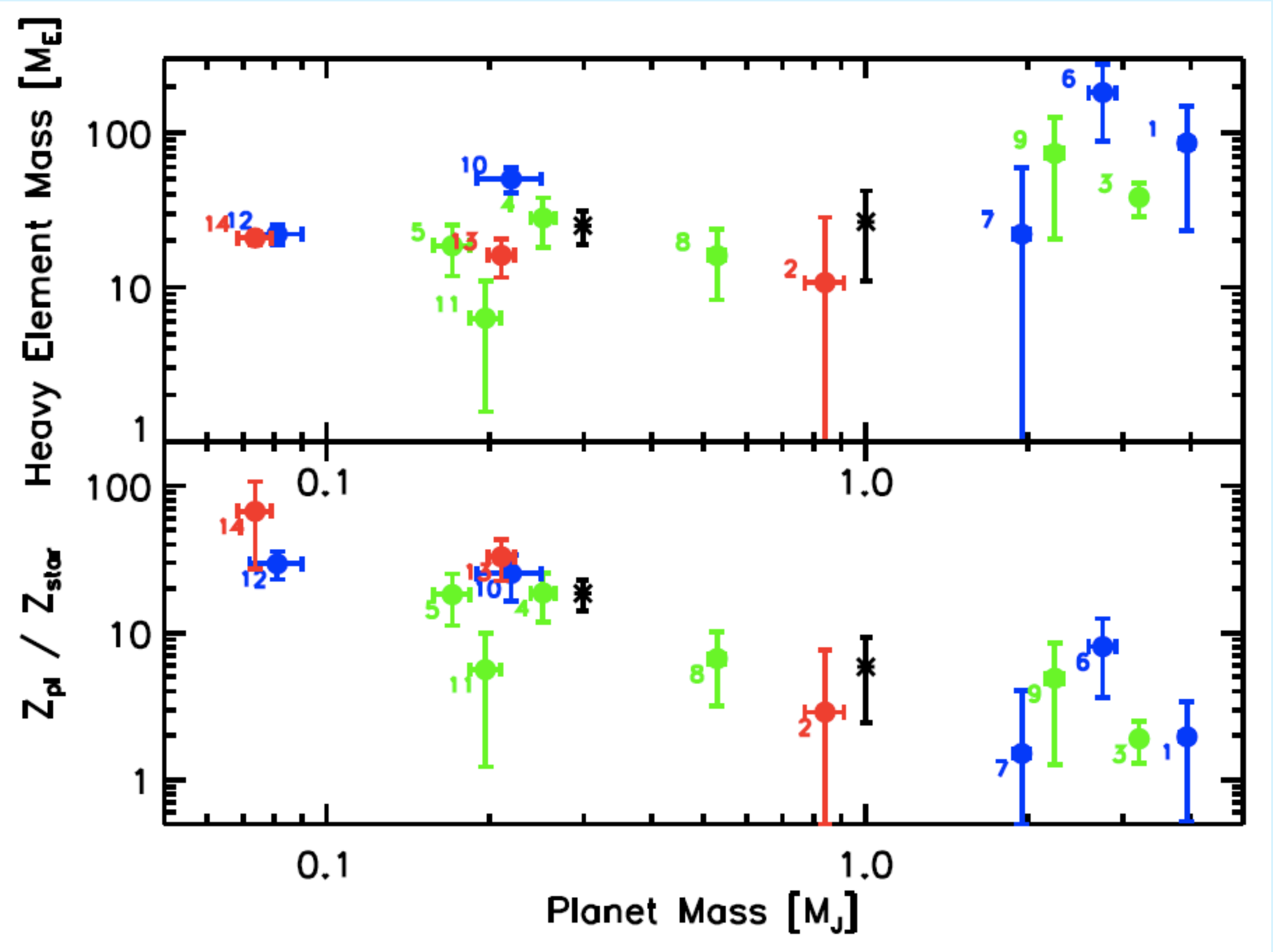
$$\log M_Z = (0.75 \pm 0.07) + (3.76 \pm 0.35)[\mathrm{Fe/H}]$$

Studying Giant Planets Compositions for Classes of Planets

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

Would this plot differ when using stellar [Si/H] or [O/H] rather than [Fe/H]?

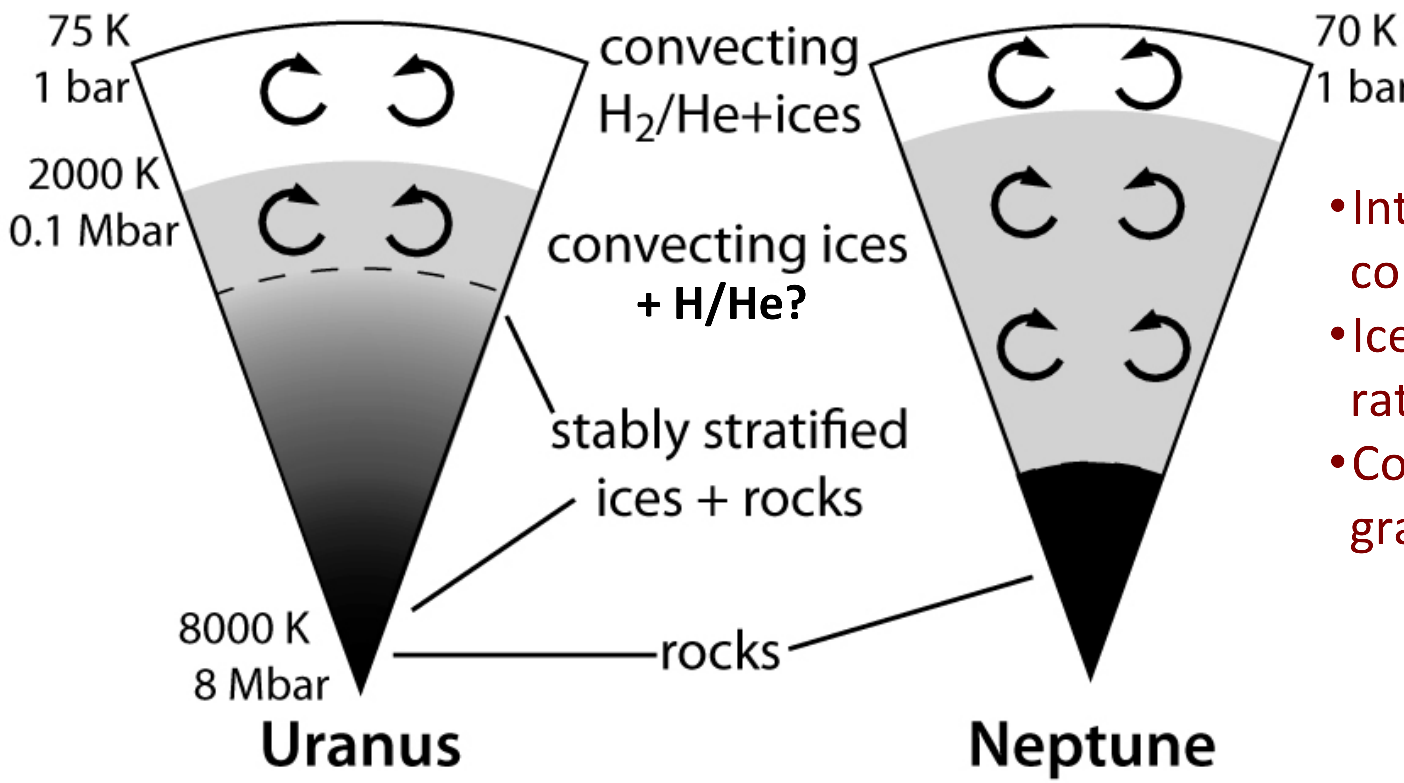
2011 sample size was only 15 planets, but the sample is now approaching 30



Miller & Fortney (2011) ApJL v736:L29

Our Ice Giant Prototypes: Uranus and Neptune

80-90% Heavy Elements by Mass



- Interior convection?
- Ice/rock ratio?
- Composition gradients?

Fortney, Baraffe, & Militzer (2010)
"Exoplanets" book, Arizona Space Science Series

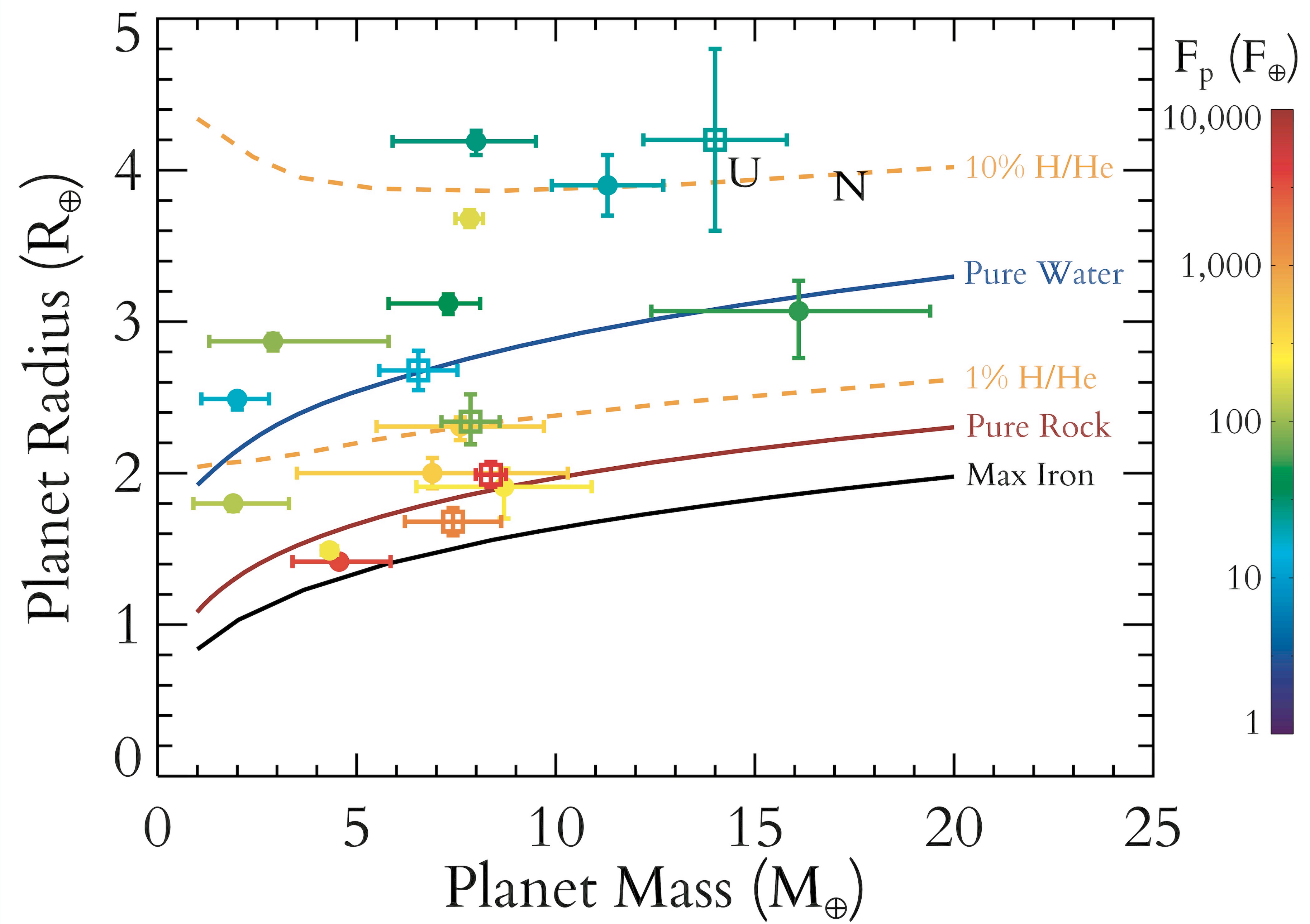


Figure from Eric Lopez, UC Santa Cruz

Low Mass Low Density Planets

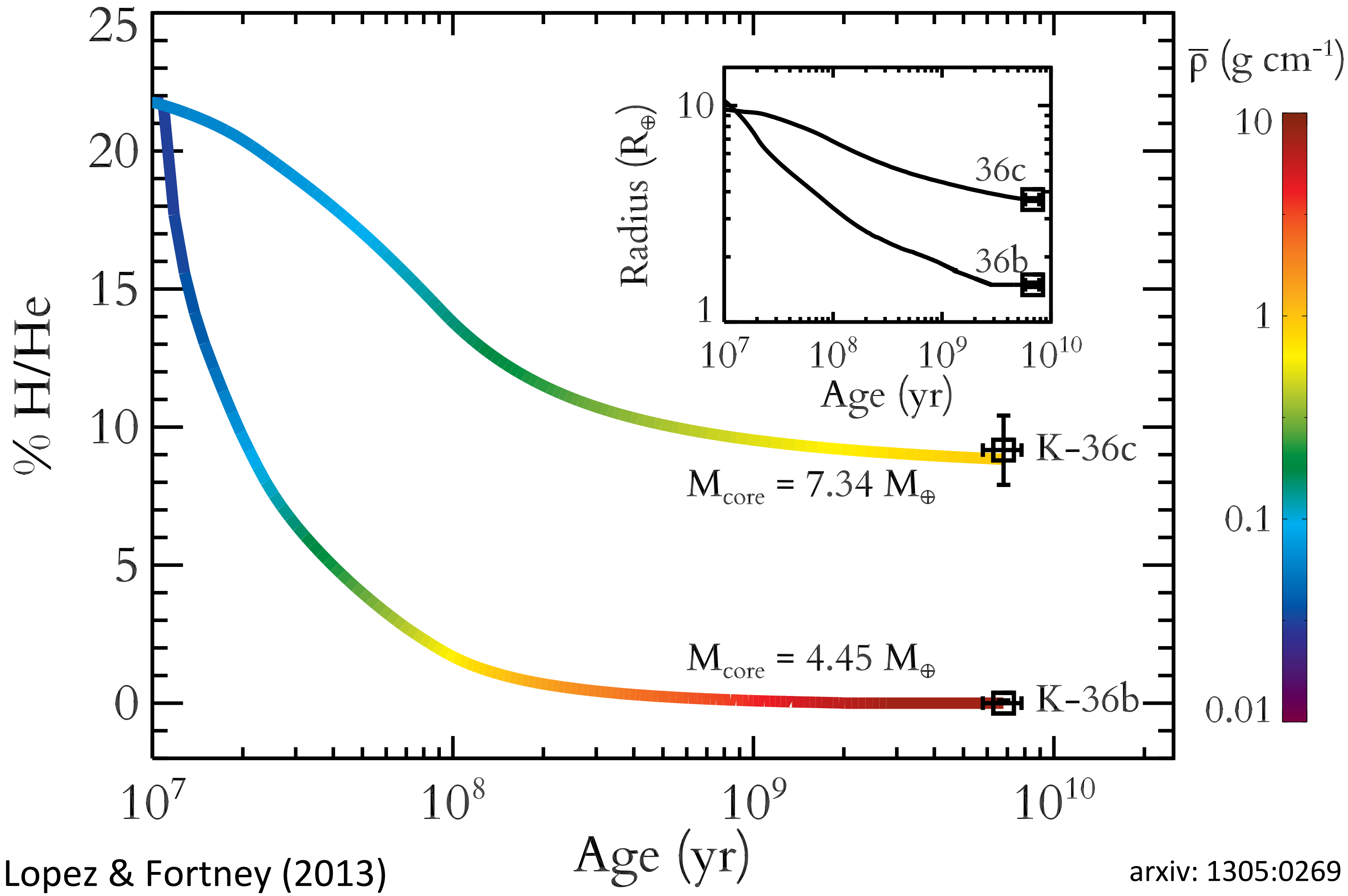
- H-dominated atmospheres may be accreted from the nebula or a few % my mass could outgassed from the interior (Elkins-Tanton & Seager, 2008; Rogers & Seager, 2010)

- While H-envelope evaporative mass loss has little effect on hot Jupiter structural evolution, can dramatically effect LMLD planets

- What is the main component of the heavier elements below H-dominated envelope? Rocks? Water? (Where did they form?)

- Are the H-dominated envelopes extremely metal-enriched? What are the observational diagnostics?

LMLD Planets: What Are They and Where Do They Form?



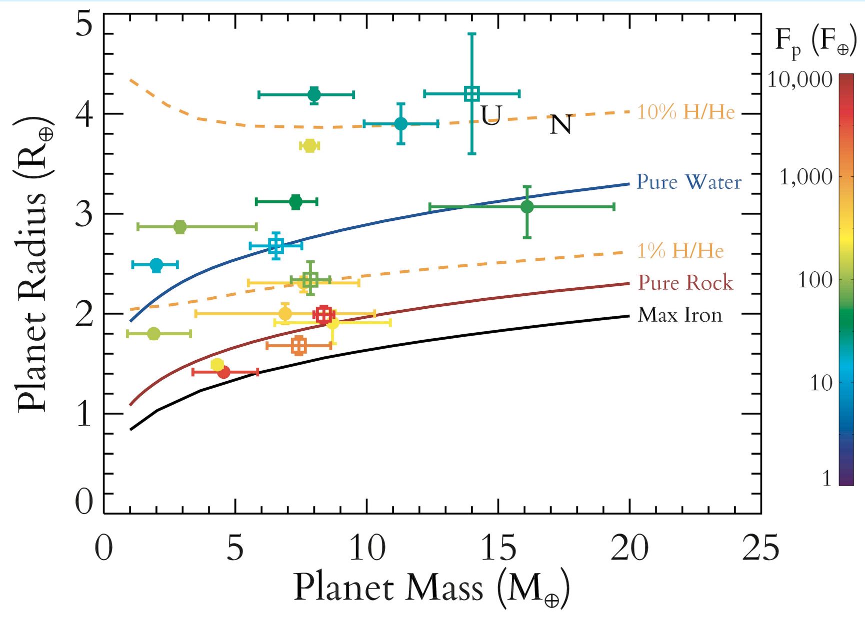
Lopez & Fortney (2013)

arxiv: 1305:0269

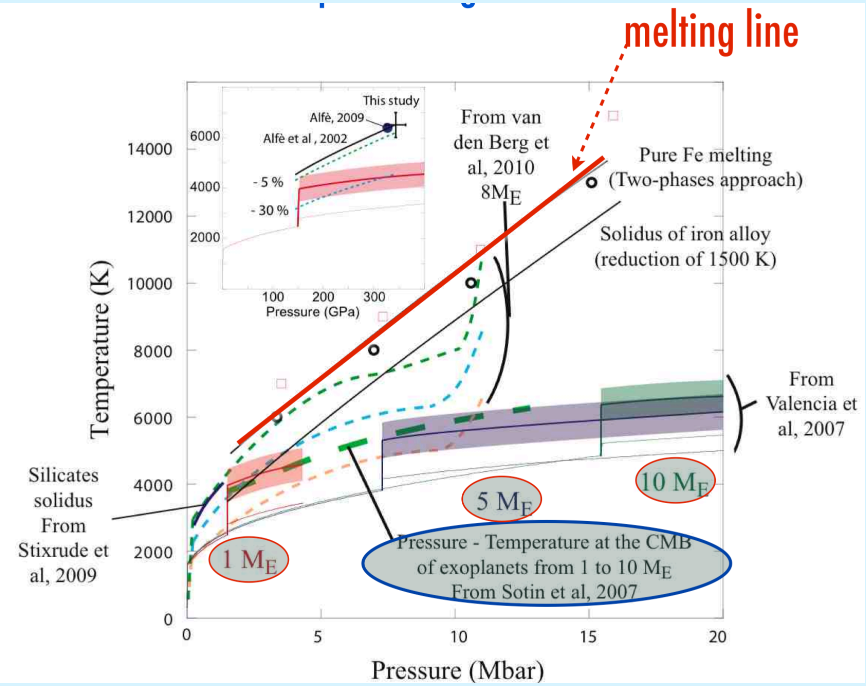
Populations of planets that have lost their H/He envelopes may show us what resides beneath

A Few Comments on Rocky Planets

- It has been suggest that Mercury's high iron/rock ratio could be condensation/segregation effects present at high temperature
  - Testable with modestly larger populations of rocky planets with with accurate M and R measurements



- Rocky Super-Earths may lack dynamos because the phase diagram of Fe shows that $T_{core} < T_{melt}$ for high pressure iron, above ~ 2 M_{Earth}



Morard, Bouchet, Mazevet, Valencia, Guyot, EPSL (2013), submitted

Main Points

- New era of EOS modeling and experiments: H, He, water/ices, rock, iron
    - Allows for breakthroughs in the solar system without new planet observations
- Constraints on distribution of heavy elements within solar system giant planets depends on model assumptions
- Transiting Gas Giants
    - No consensus on hot Jupiter radius inflation, but the mechanism(s) must be based on level of incident flux
    - Giant planet metal enrichment similar to Jupiter and Saturn
- Neptunes and below
    - Degeneracy in composition, ice/rock ratio, etc.
    - Evaporation effects with important especially for smallest planets
- For rocky planets, some fairly simple, yet important questions, can already be understood
- Keep Finding Planets: TESS, CHEOPS, ground-based transits, imaging