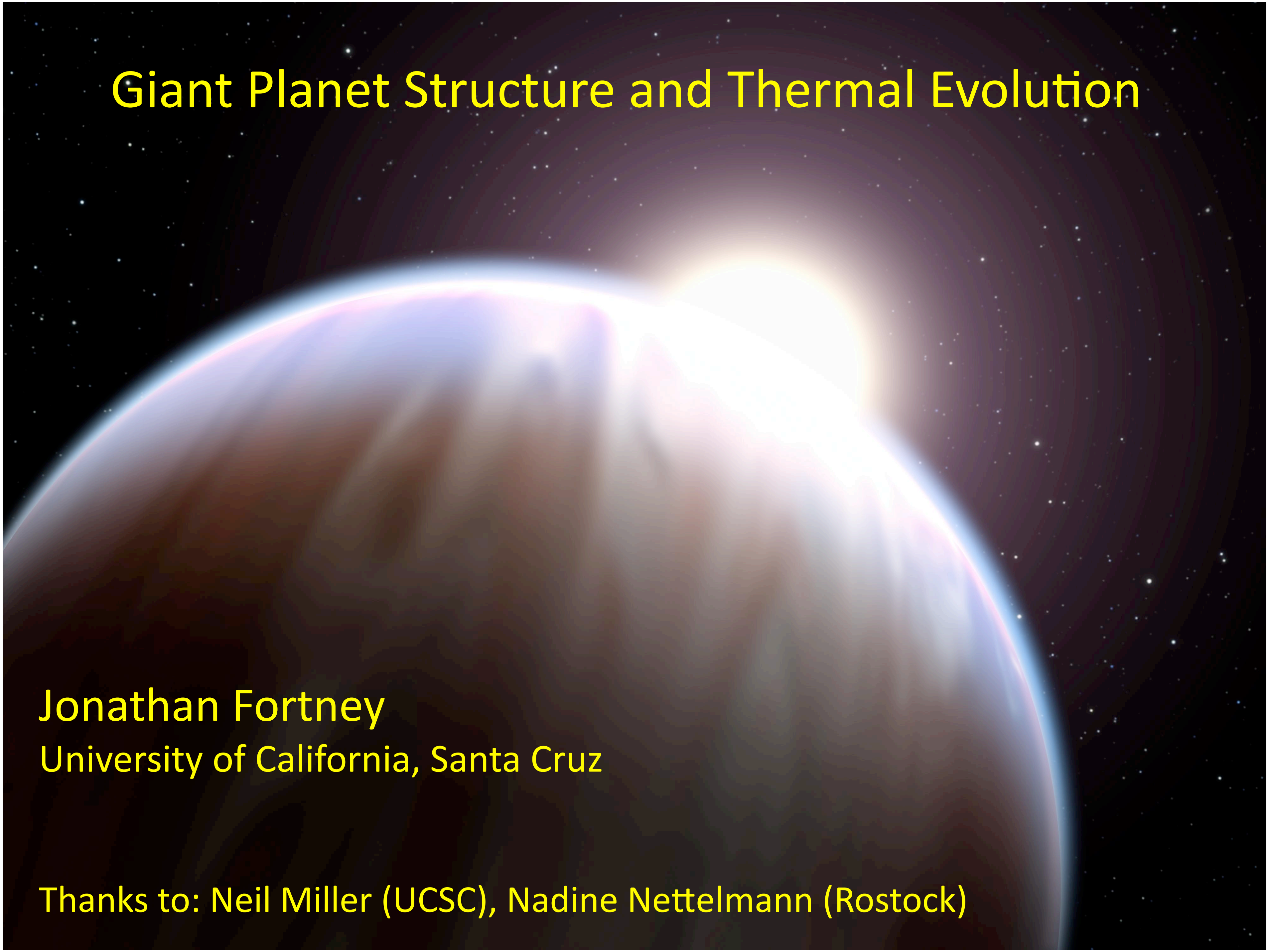
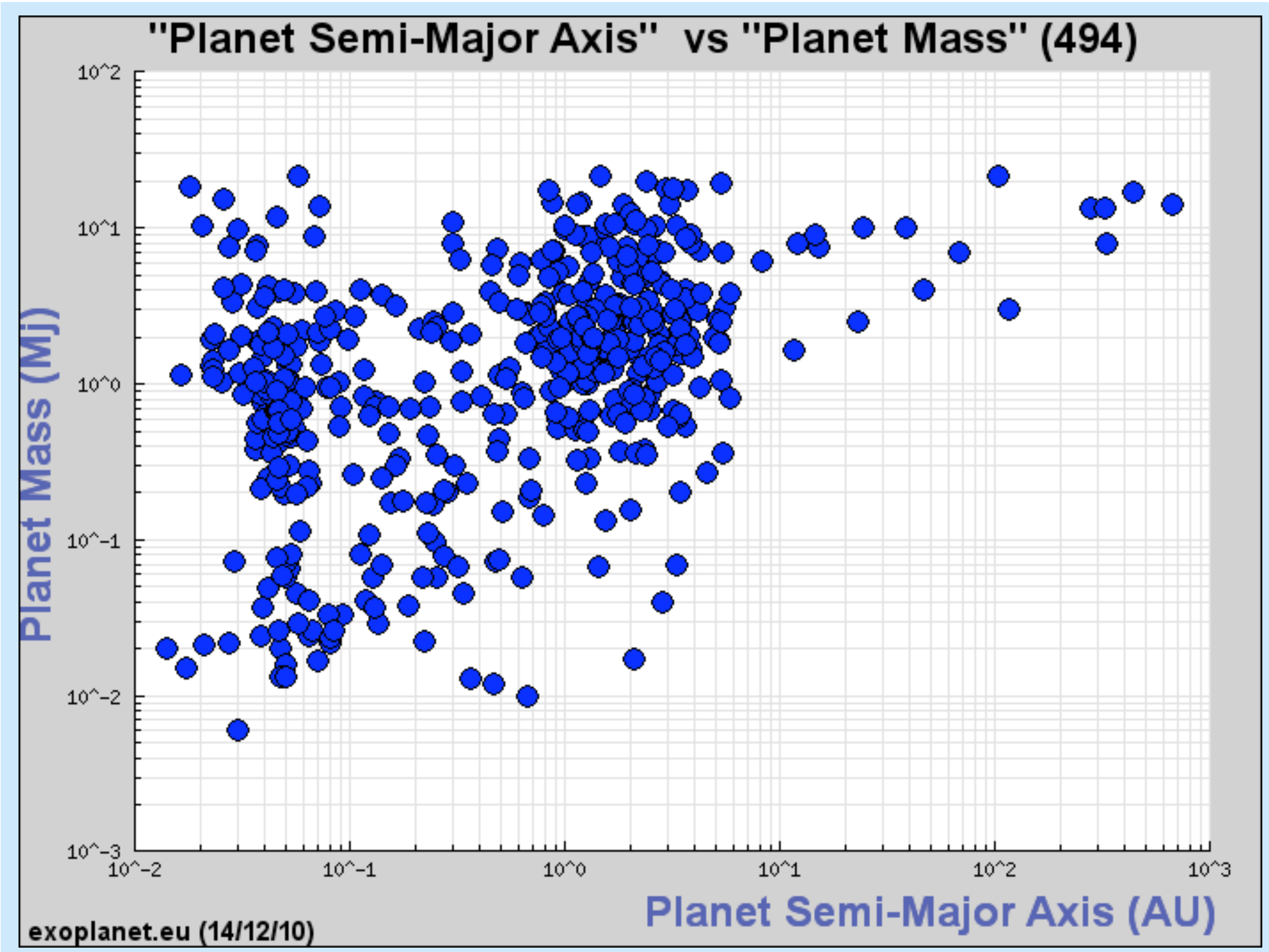


Giant Planet Structure and Thermal Evolution

Jonathan Fortney
University of California, Santa Cruz

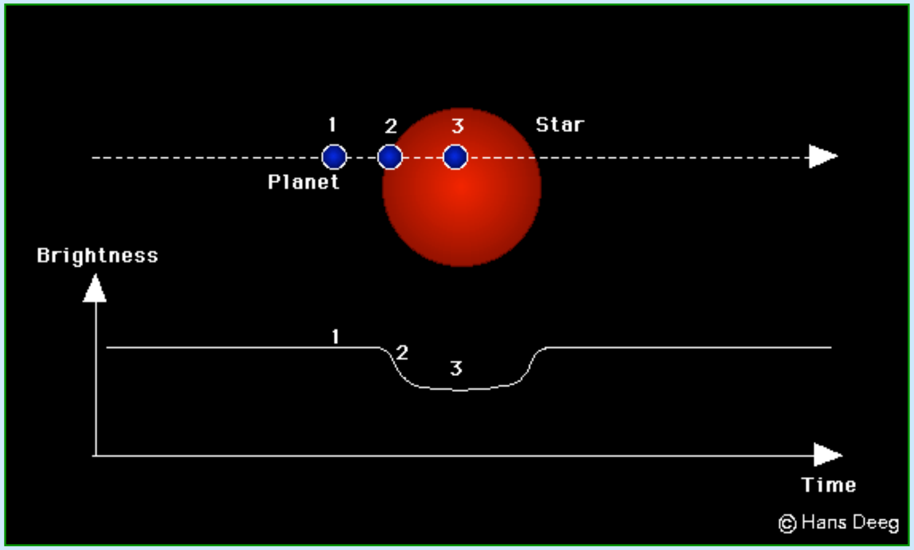
Thanks to: Neil Miller (UCSC), Nadine Nettelmann (Rostock)

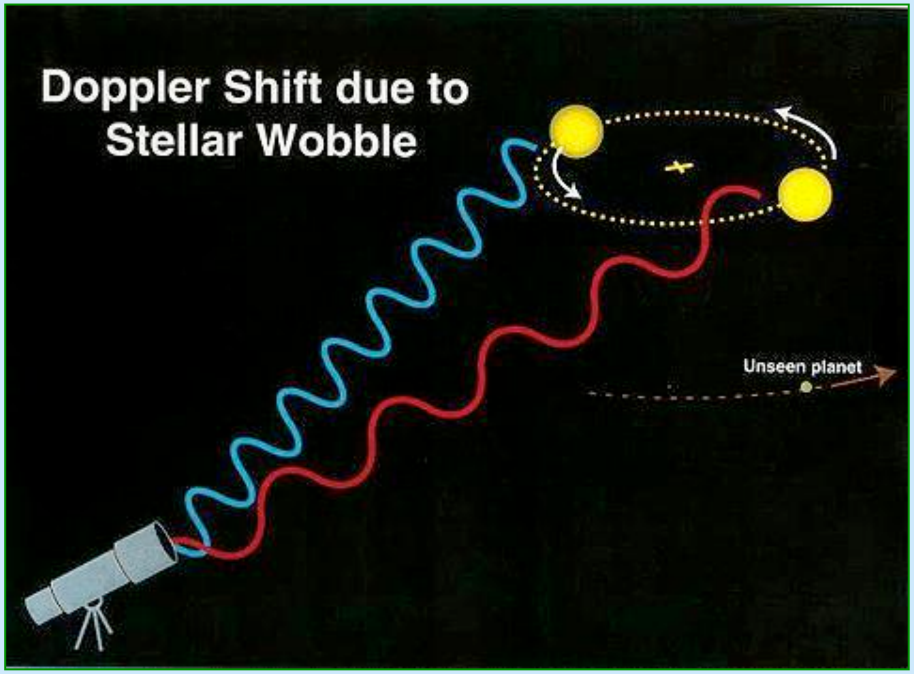


"Planet Semi-Major Axis" vs "Planet Mass" (494)
Planet Mass (Mj)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
Planet Semi-Major Axis (AU)
exoplanet.eu (14/12/10)

Transiting Planets, Large and Small

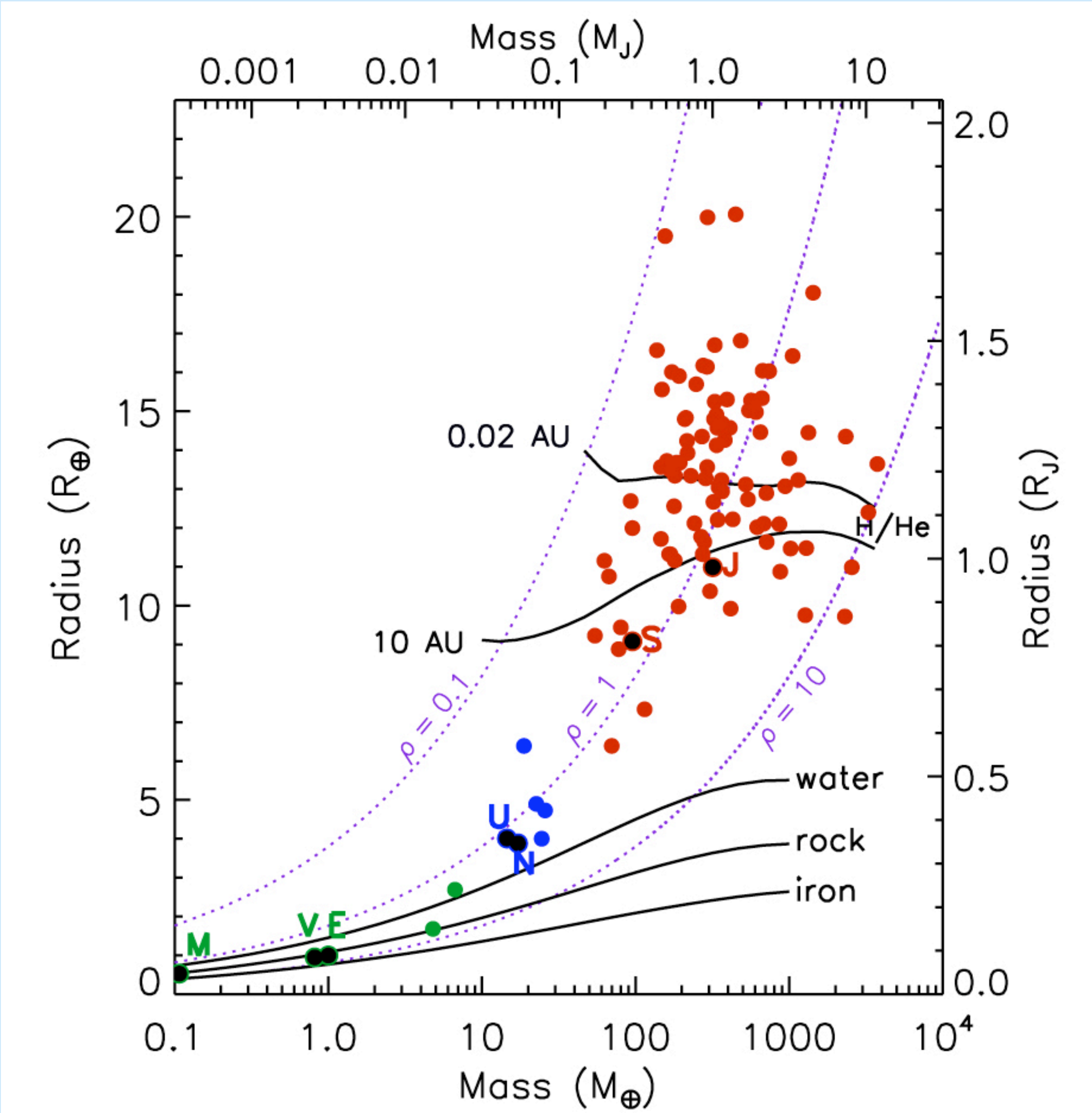
- 100 planets have now been seen to transit their parent stars
  - 94 “hot Jupiters”
  - 4 “hot Neptunes”
  - 2 “super Earths”
- Combination of planet radius and mass yield density --> composition
- Strong bias towards finding mass/large planets on short-period orbits





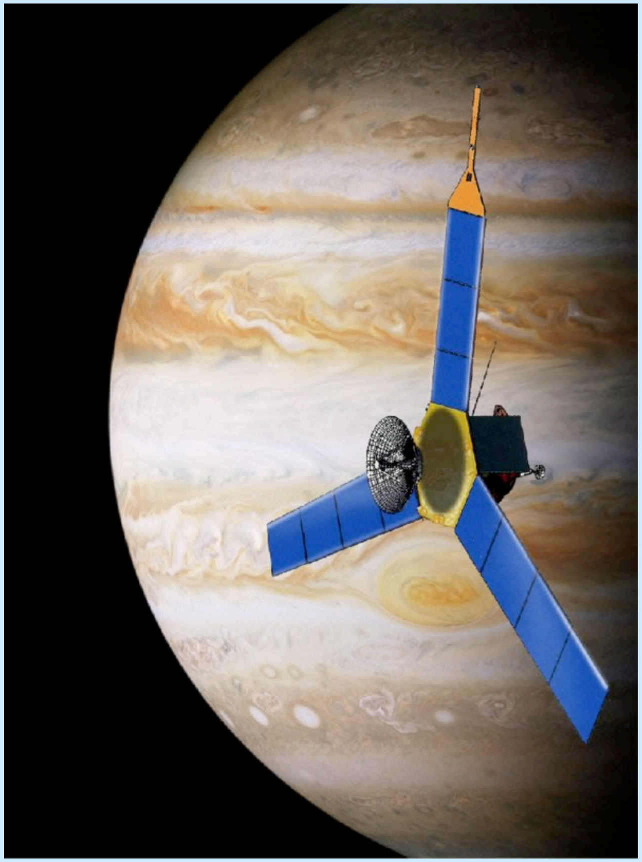
There is an incredibly diversity of worlds

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



The Big Questions and How We Try to Answer Them, I

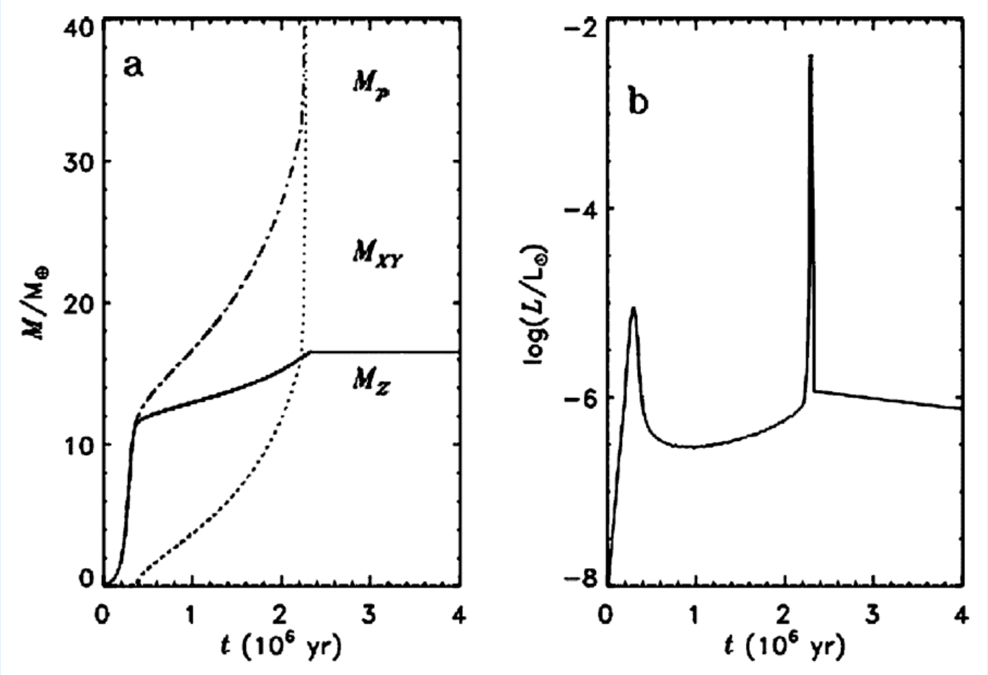
- What is the **composition** of giant planets?
- What is the **core mass**?
- How do atmospheric **abundances** relate to interior abundances?
- What is the "**metallicity**" and the **ice/rock** ratio?
- How does **composition** vary from Neptune-like planets (ice giants) to Jupiter-like planets (gas giants)?



- Bulk composition comes from mass and radius—can be observed for solar system planets and exoplanets
- Gravity field yields constraints on density profile—achieved via solar system space missions
- Atmospheric abundances are most reliably achieved by entry probes, can also be determined via spectroscopy, for solar system planets or exoplanets

The Big Questions and How We Try to Answer Them, II

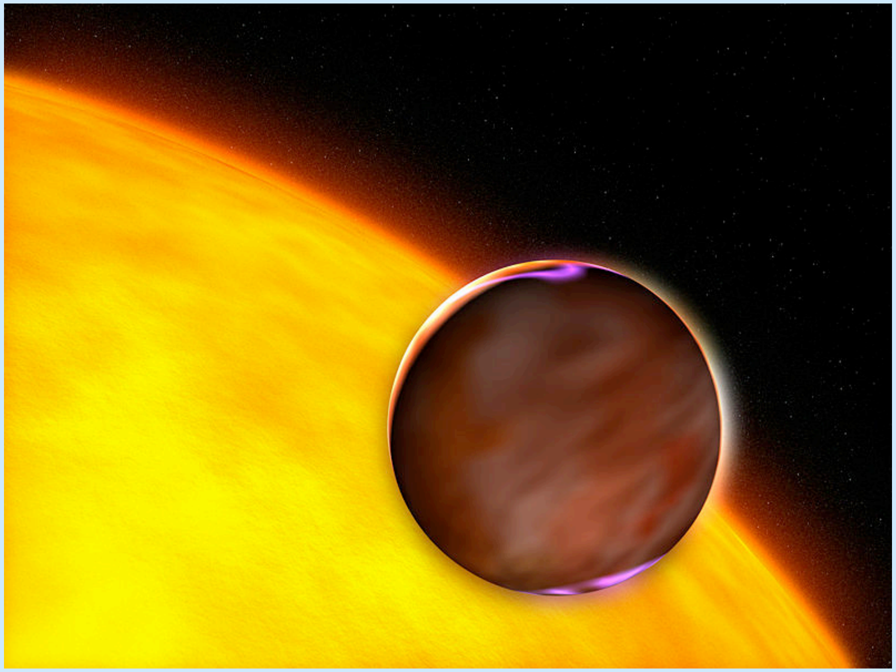
- How do giant planets form?
- Is there one **formation mechanism** or two?
- If two, what are the **observables** that discriminate between them?
- How does the disk **environment** affect final planet properties?



- A lot of computer time and ink get used: models and models
- For the solar system planets, gravity field + atmospheric abundances allow for quantitative analysis of the core accretion process

- Radial Velocity (RV) + plus transit observations allow for measurements of planet frequency is a function of mass, which can be compared to population synthesis models

The Big Questions and How We Try to Answer Them, III



- How does intense **stellar insolation** affect planetary evolution?
- How good is our **input physics**?
- Are we **missing input** physics?
- Can we understand giant planets as a class of **astrophysical objects**?

- We can study mass vs. radius vs. time vs. insolation via transits

- We can probe planetary interiors via dynamic shock experiments and via first-principles calculations

- Beyond the solar system, we can observe planets at Myr ages, Gyrs ages, at 0.01 AU and 100 AU, from Neptune-class to Brown Dwarfs

The Low-Mass Star Giant Planet Connection

Early 1960s: Discovery of fully convective Hayashi Phase

1963: Theoretical Discovery of Brown Dwarfs by Hayashi & Nakano (1963) and Kumar (1963)

1966: Low, observing at 20 μm, finds that Jupiter has an internal energy source (emits more 20 μm flux than it receives from the Sun)

1968: Hubbard shows that neither conductive nor radiative transport can bring the observed flux throughout Jupiter's interior the surface, implying the planet's interior is warm (10^4 K) fluid, and convective, not cold and solid [Also Zharkov & Trubitsyn in USSR]

EVOLUTION OF PROTOSTARS[1]

BY CHUSHIRO HAYASHI

Department of Physics, Kyoto University, Kyoto, Japan

Evolution of Stars of Small Masses in the Pre-Main-Sequence Stages

Chushiro Hayashi and Takenori Nakano

Department of Nuclear Science, Kyoto University, Kyoto

(Received June 12, 1963)

THE STRUCTURE OF STARS OF VERY LOW MASS

SHIV S. KUMAR*

NASA Goddard Space Flight Center, Institute for Space Studies, New York 27, N.Y.

Received October 20, 1962; revised November 27, 1962

Observations of Venus, Jupiter, and Saturn at λ20 μ. FRANK J. LOW, *University of Arizona.*—The first observations of the planets at 20 μ were reported by Low (*Lowell Obs. Bull.* **128**, 184, 1965).

THERMAL STRUCTURE OF JUPITER*

W. B. HUBBARD

California Institute of Technology, Pasadena, California

Received August 14, 1967; revised November 24, 1967

Our Planetary Materials

Hydrogen and Helium

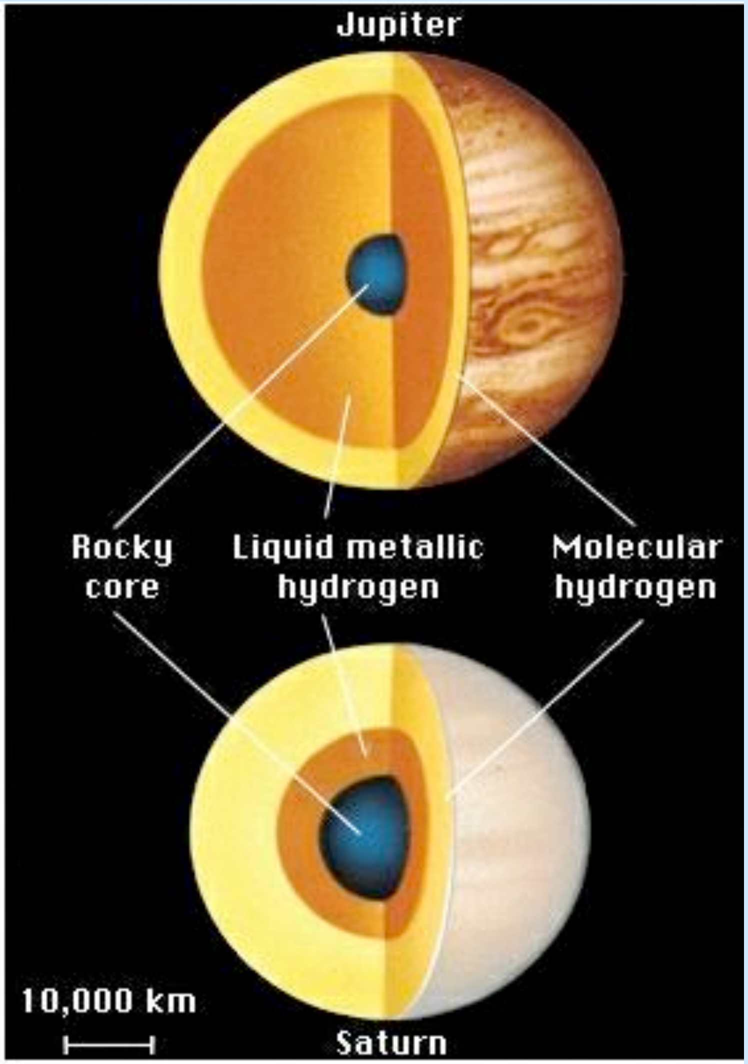
- Not really gas
- Dense H fluid transitions from molecular to metallic state
- Strongly coupled dense H+ plasma with mostly neutral He

Planetary Ices

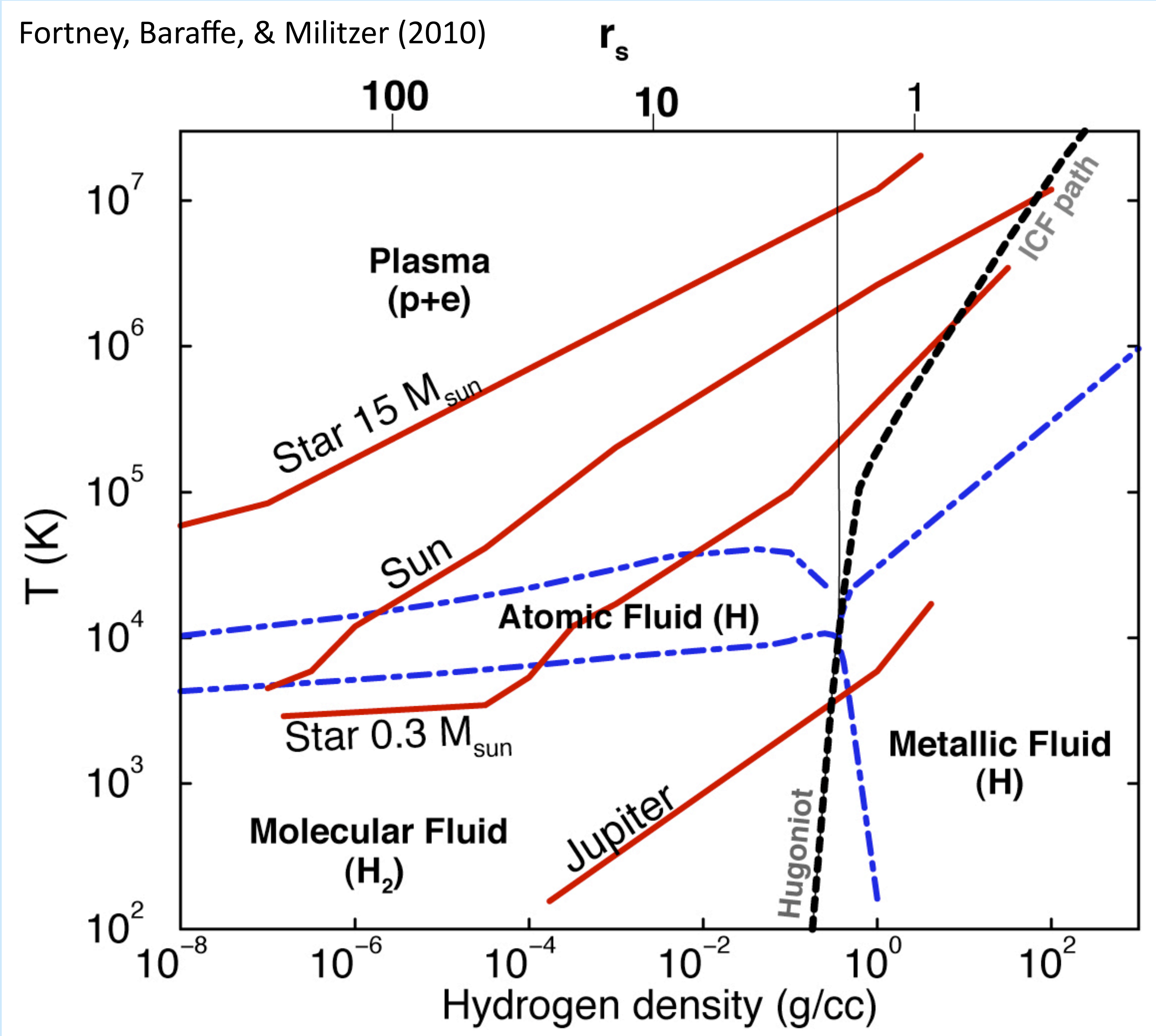
- Not really ice
- Dense fluid of H_2O, CH_4, NH_3, not necessarily in intact molecules

Rocks

- Includes rocks (Mg/Si dominated) and iron
- At boundary between solid and liquid



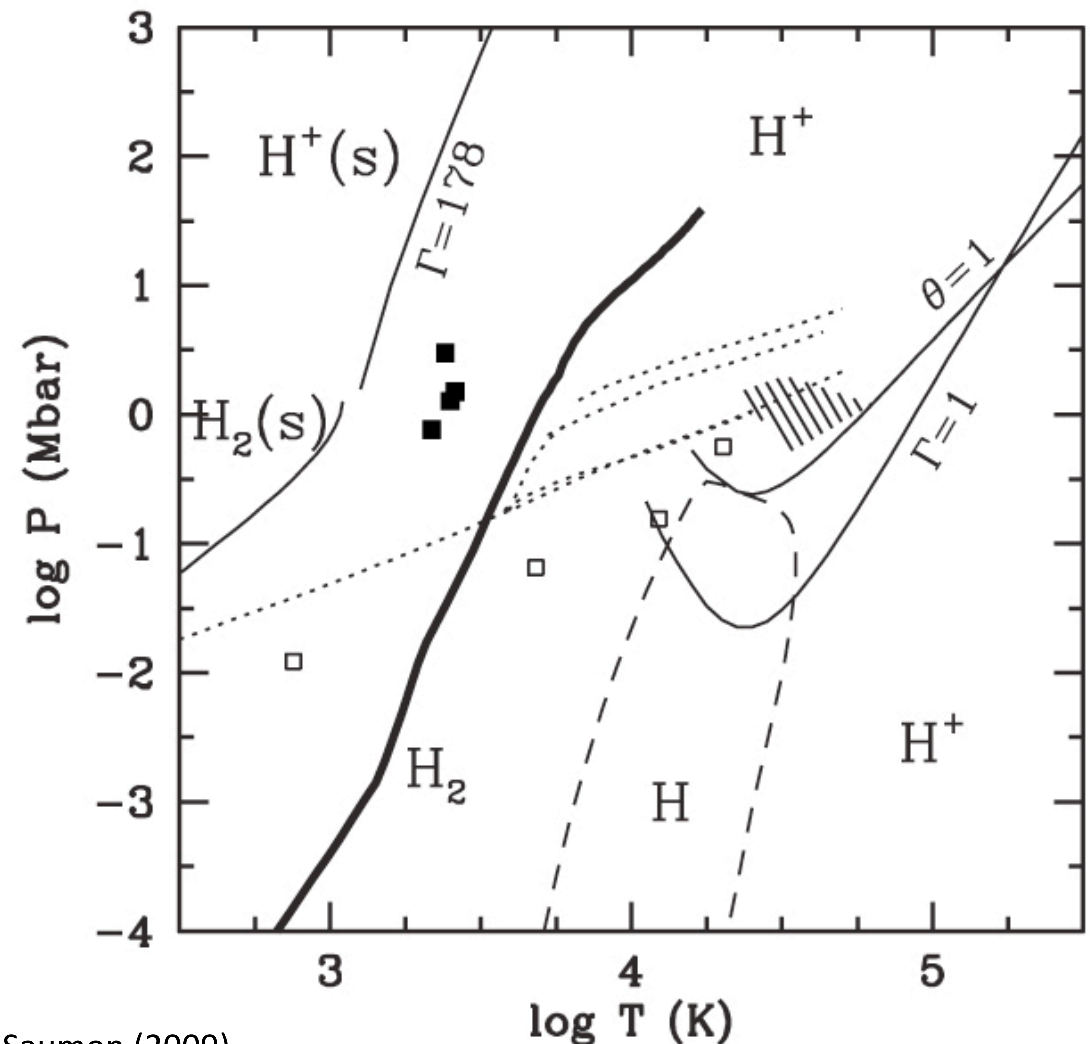
Hydrogen Phase Diagram



H in fluid plasma phase (liquid metal)

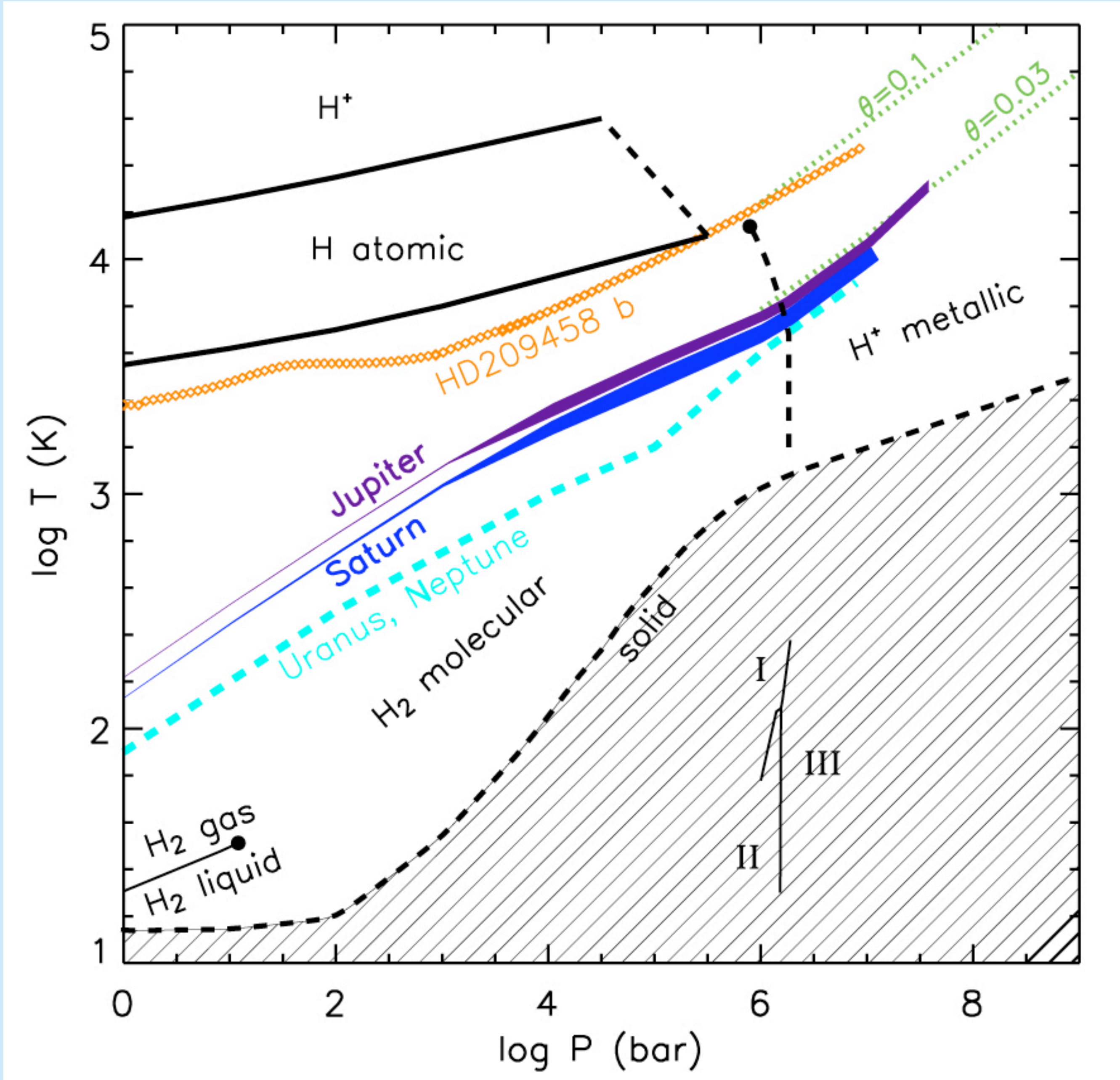
Plasmas is strongly coupled
$\Gamma = e^2/ak_bT$

Plasma is degenerate
$\theta = T/T_F$



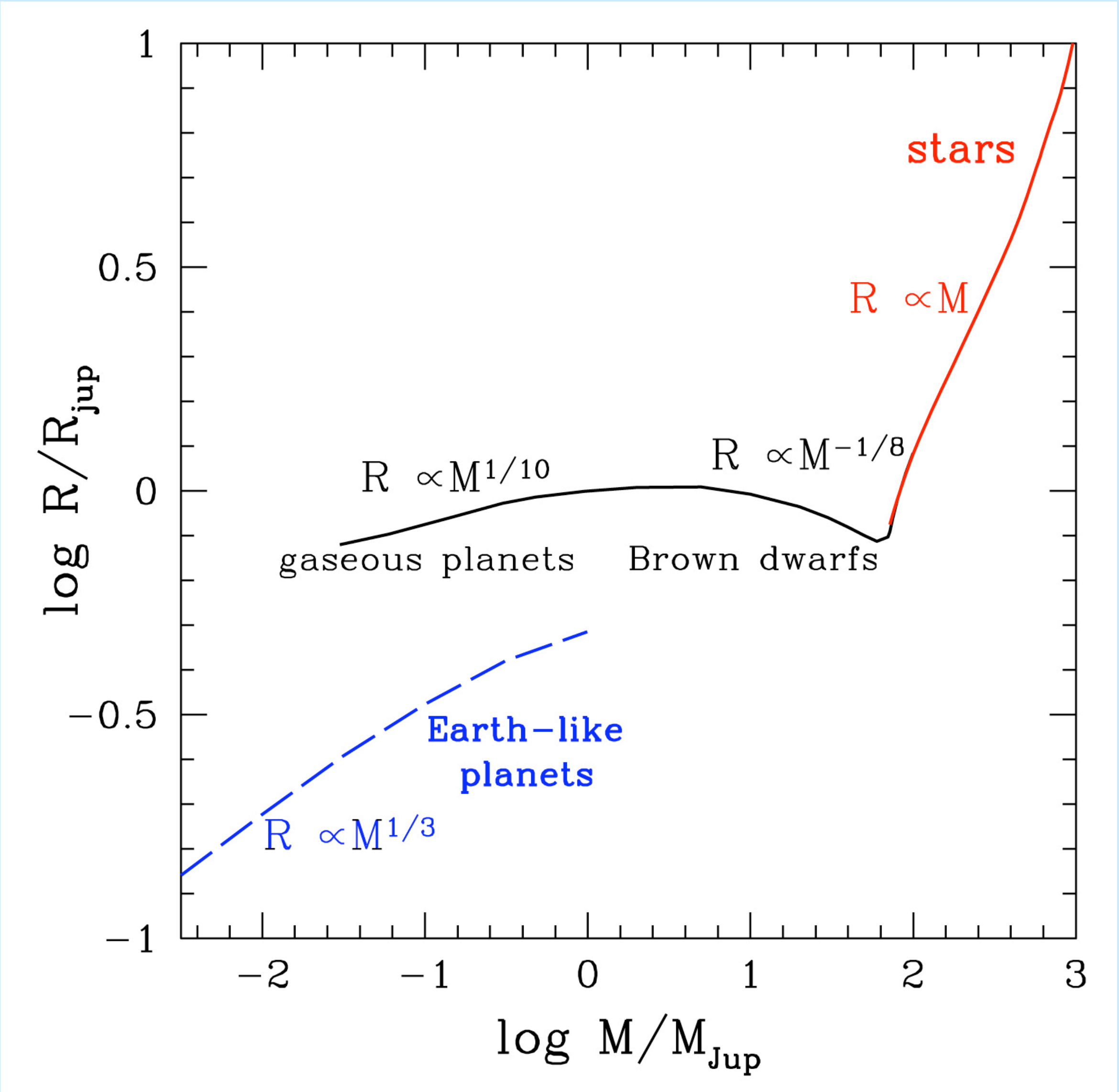
Saumon (2009)

$$\Gamma = \frac{e^2}{ak_BT} \sim 20\text{–}30, \qquad \theta = \frac{T}{T_F} \sim 0.02,$$



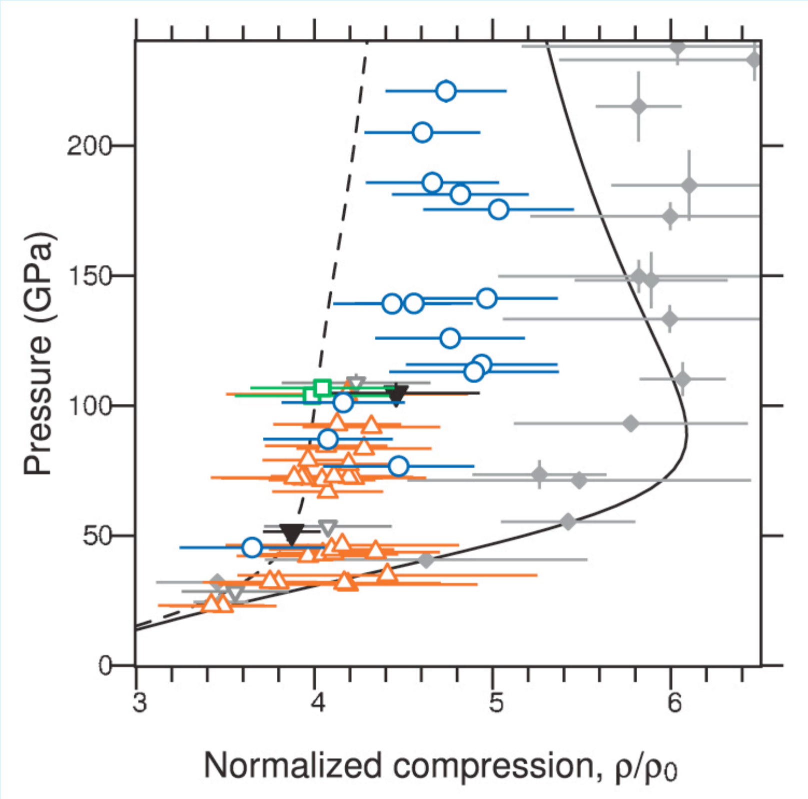
Guillot (2005)

Coulomb Repulsion + Degeneracy Leads to Radius nearly independent of Mass

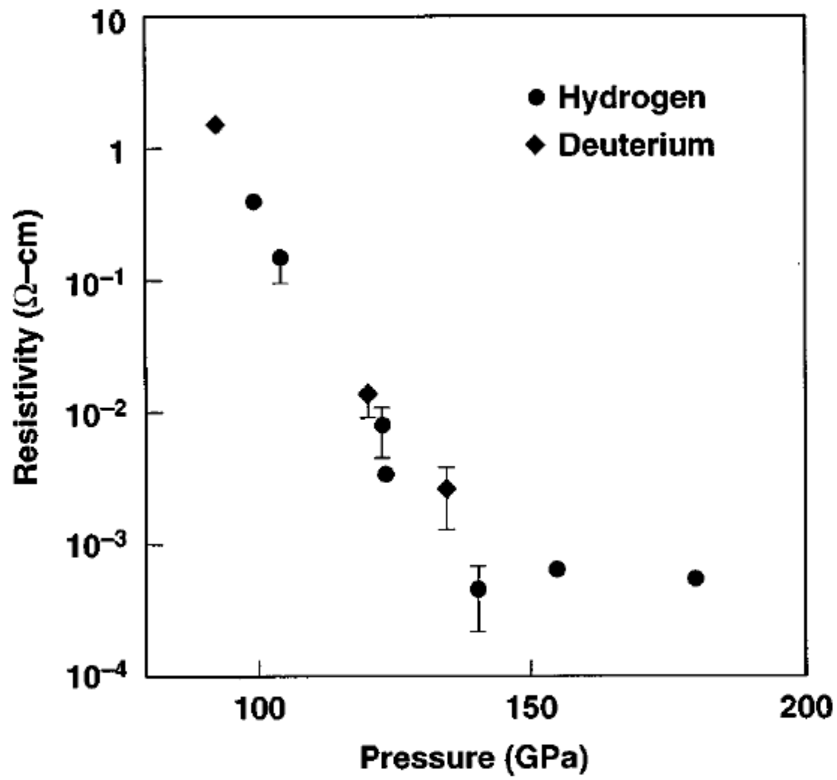


Shock Experiments

- Pressure-density
- Temperatures
- Conductivies

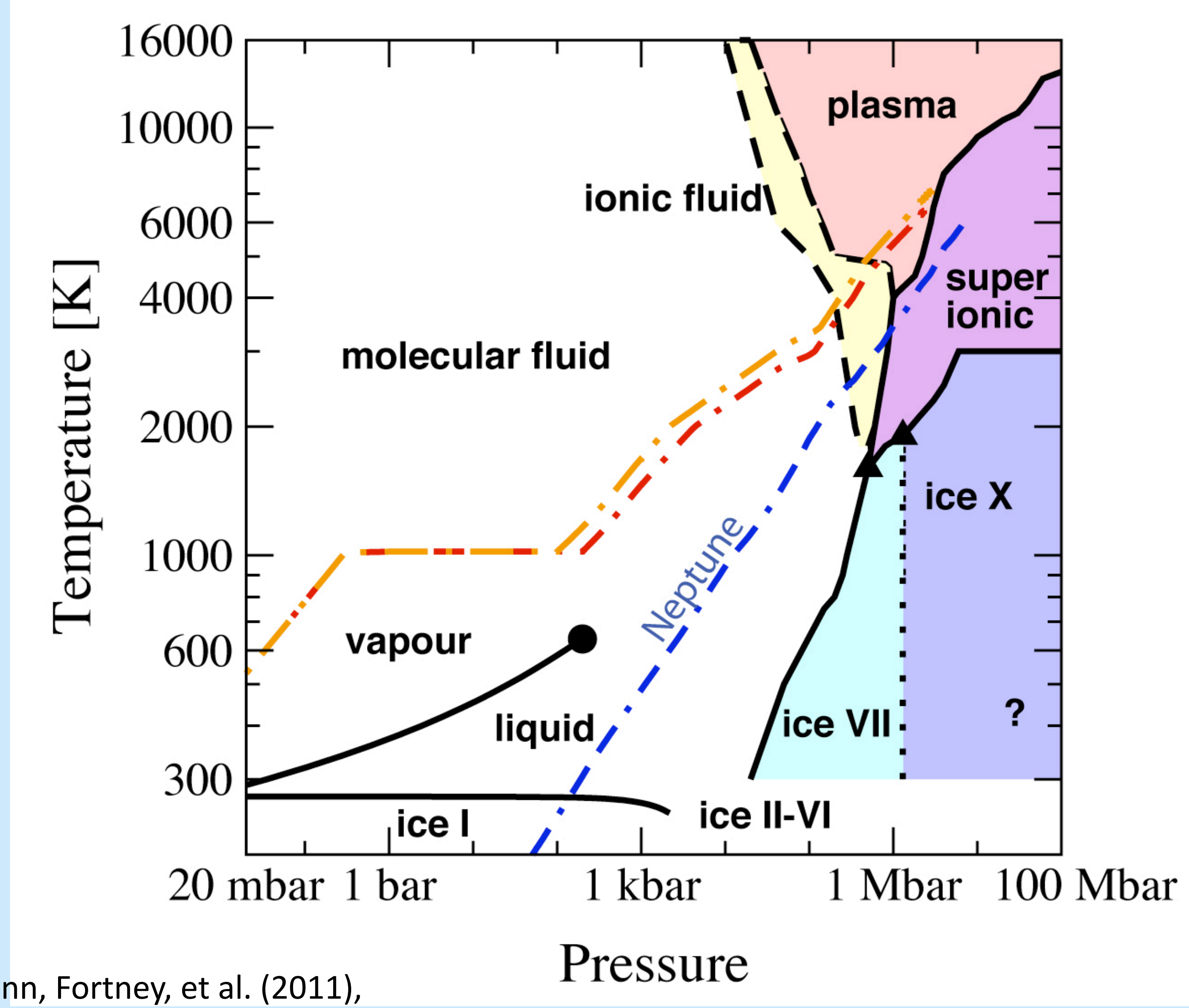


Hicks et al. (2009)



Nellis et al. (2009)

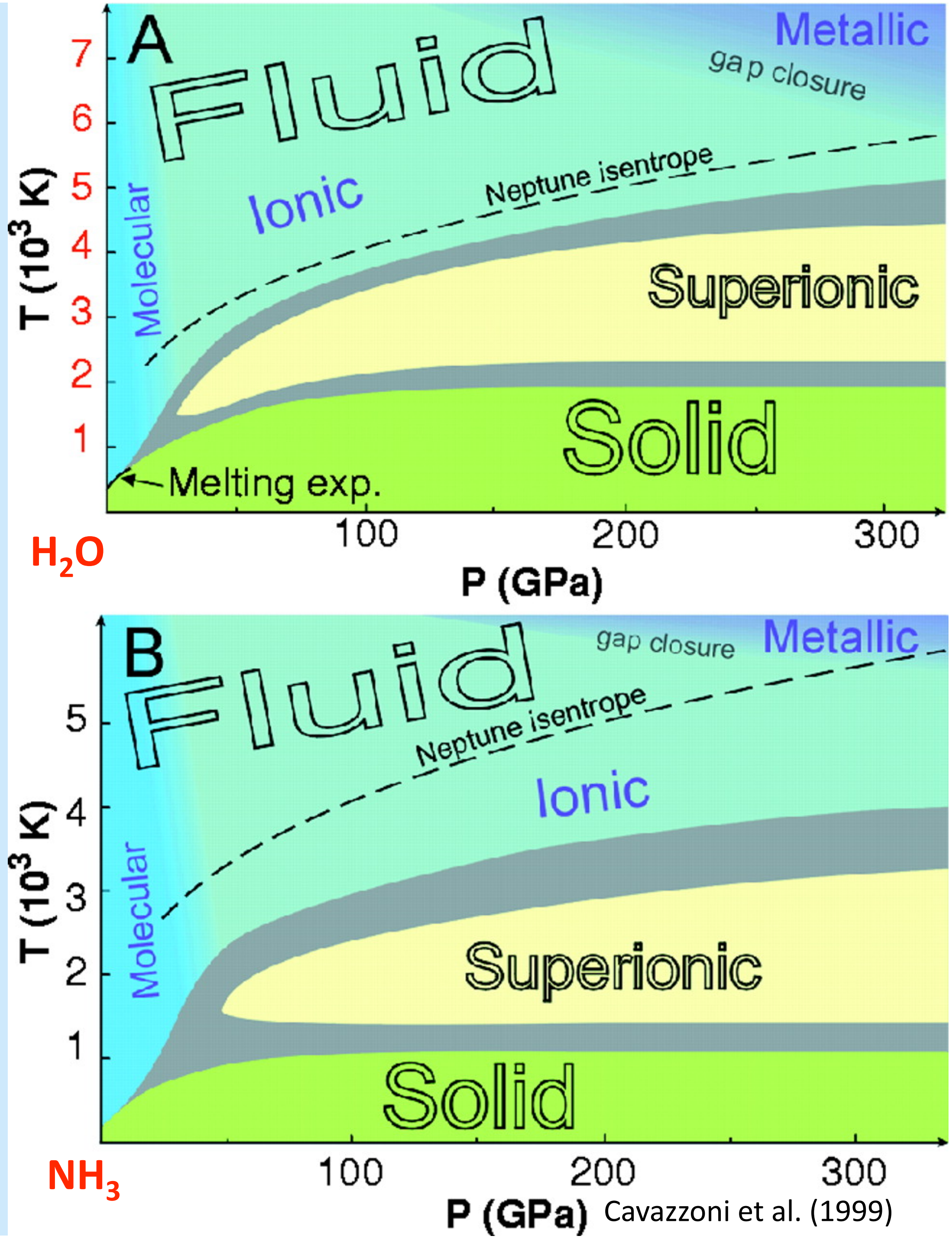
Water Phase Diagram



Nettelmann, Fortney, et al. (2011),
after French et al. (2008)

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)

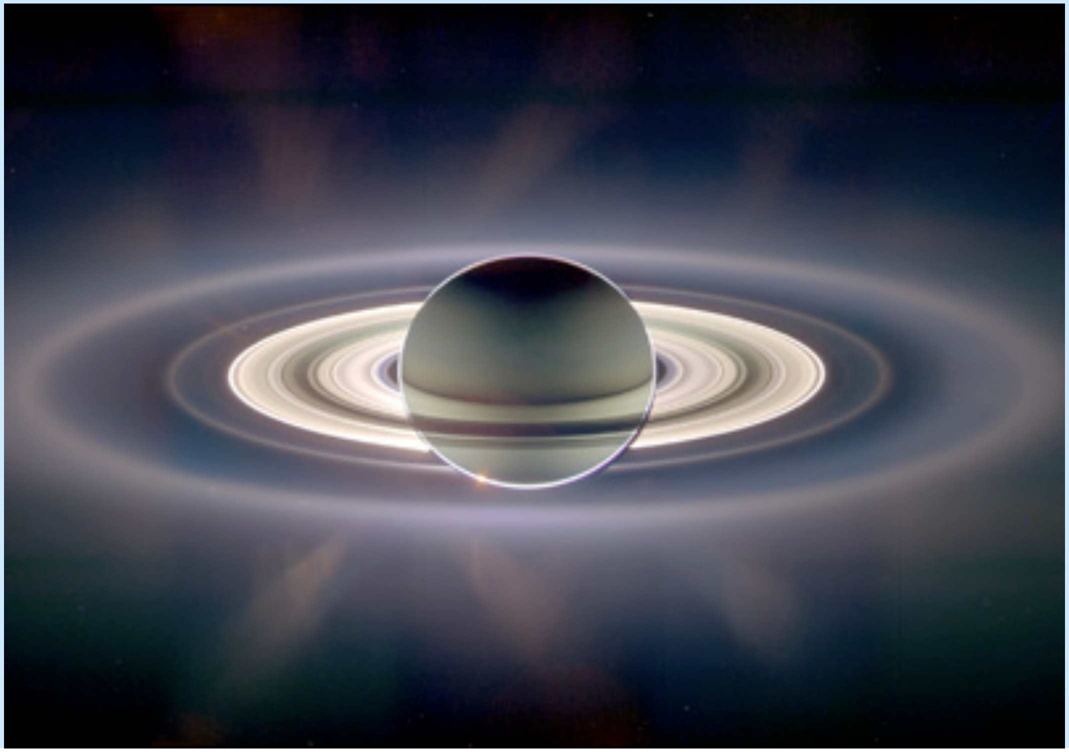
Giant Planet Evolution: The Basic Equations

$$
\begin{aligned}
\frac{\partial P}{\partial r} &= -\rho g \\
\frac{\partial T}{\partial r} &= \frac{\partial P}{\partial r}\frac{T}{P}\nabla_T. \\
\frac{\partial m}{\partial r} &= 4\pi r^2 \rho. \\
\frac{\partial L}{\partial r} &= 4\pi r^2 \rho \left(\dot{\epsilon} - T\frac{\partial S}{\partial t}\right)
\end{aligned}
$$

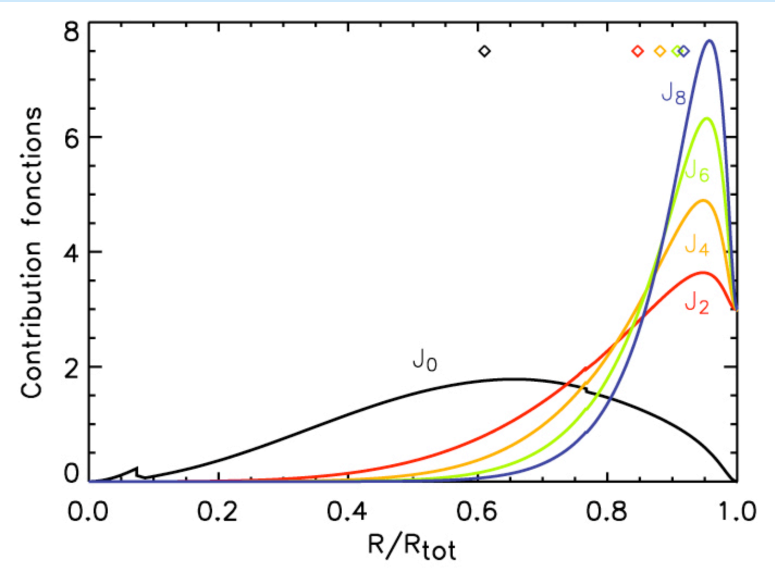
The same as for stars!

The Solar System's Giant Planets

- Known precisely: Mass, Radius, Age, T_{eff}
- Known well: Gravity Field, Magnetic Field, 1-bar temperature, Albedo
- Data quality scales inversely with distance, especially due to the *Galileo Orbiter, Galileo Entry Probe,* and *Cassini* Missions
- No planned Uranus and Neptune Orbiters

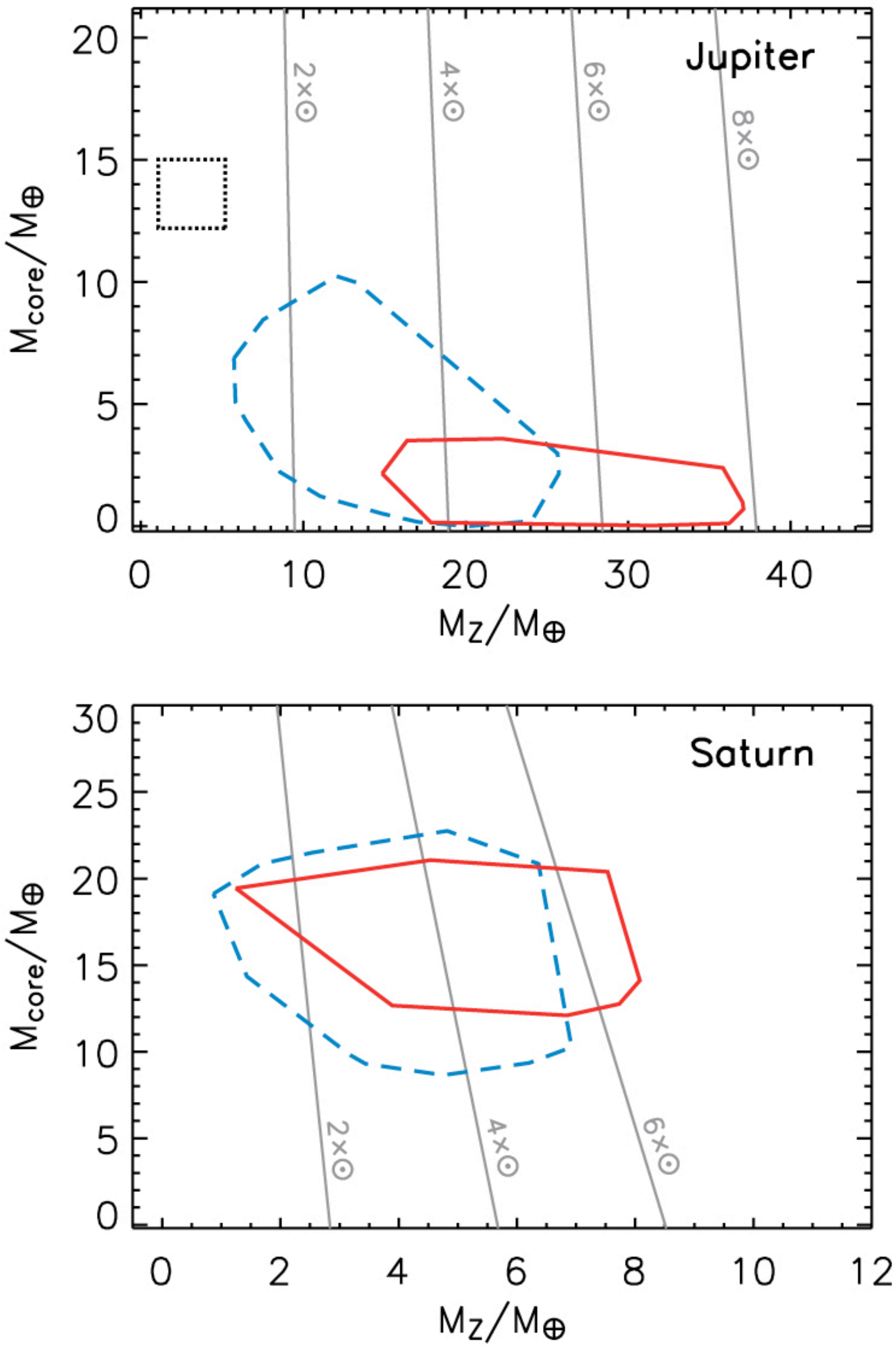


Jupiter and Saturn: Current Interior

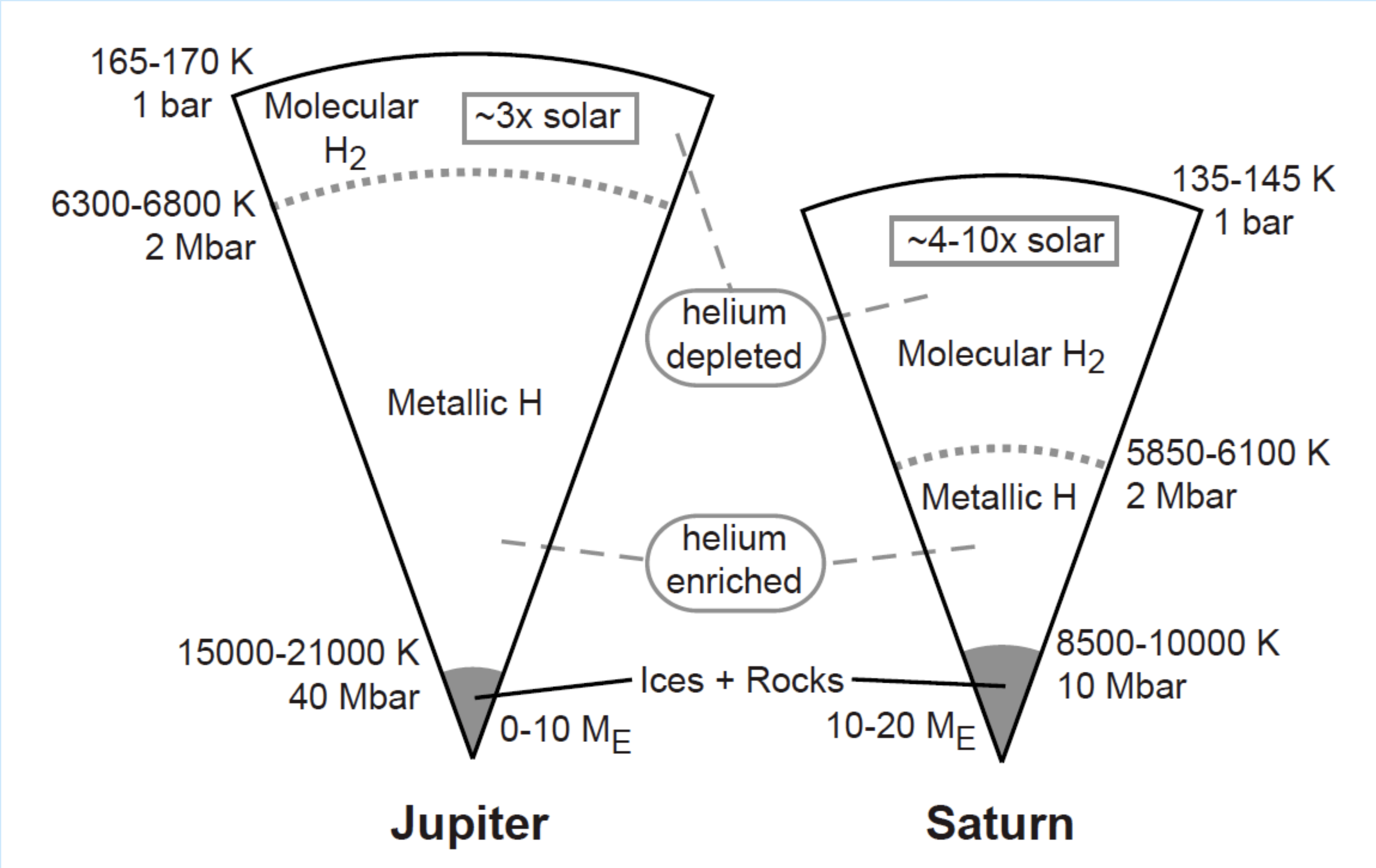


$$V_{\mathrm{grav}} = \frac{GM}{r}\left[1 - \sum_{\mathrm{n}=1}^{\infty}\left(\frac{a}{r}\right)^{2\mathrm{n}} J_{2\mathrm{n}} P_{2\mathrm{n}}(cos\theta)\right]$$

$$J_{2\mathrm{n}} = -\frac{1}{Ma^{2\mathrm{n}}}\int\int\int \rho(r,\theta) r^{2\mathrm{n}} P_{2\mathrm{n}}(cos\theta)dv,$$

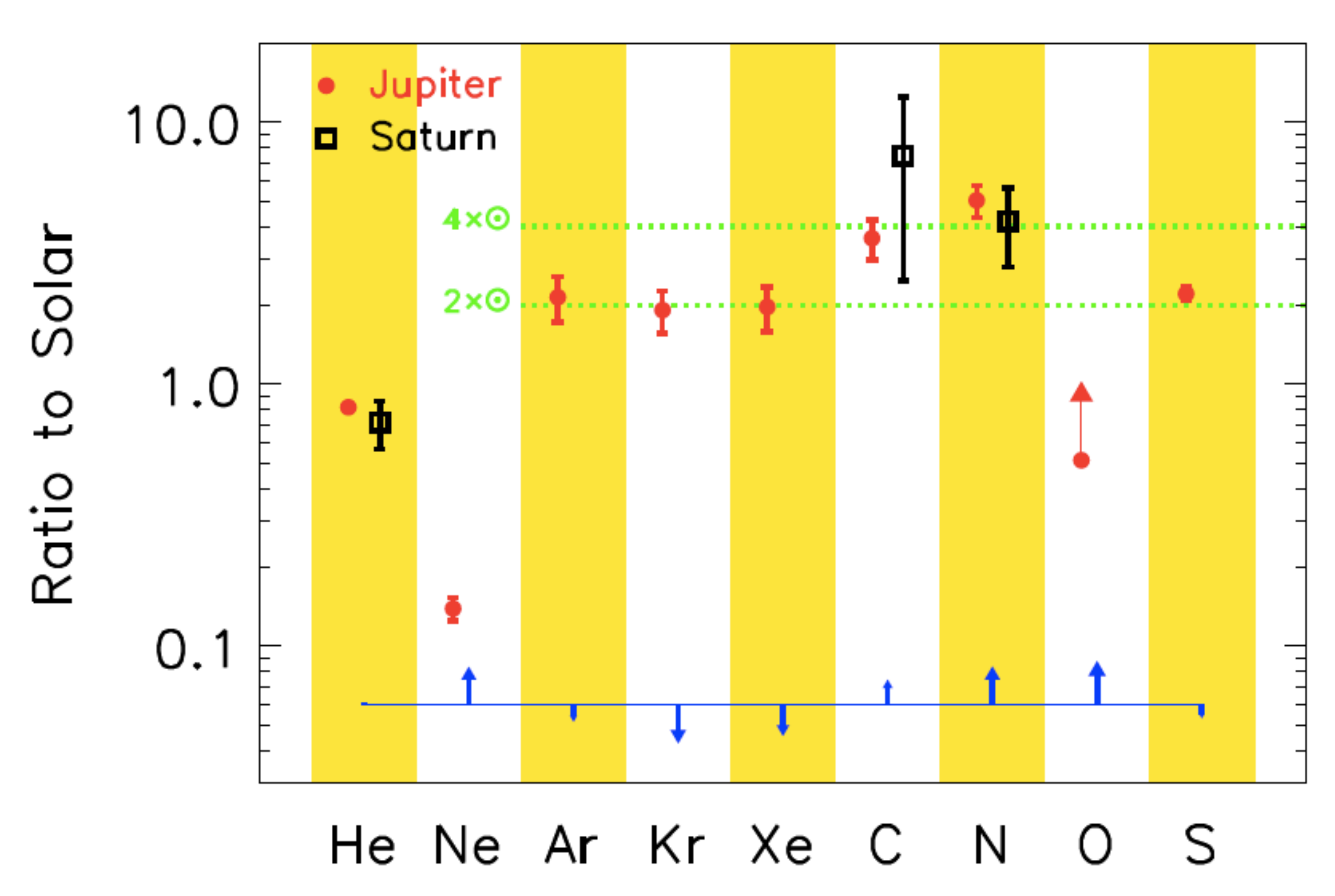


Schematic View of Jupiter and Saturn



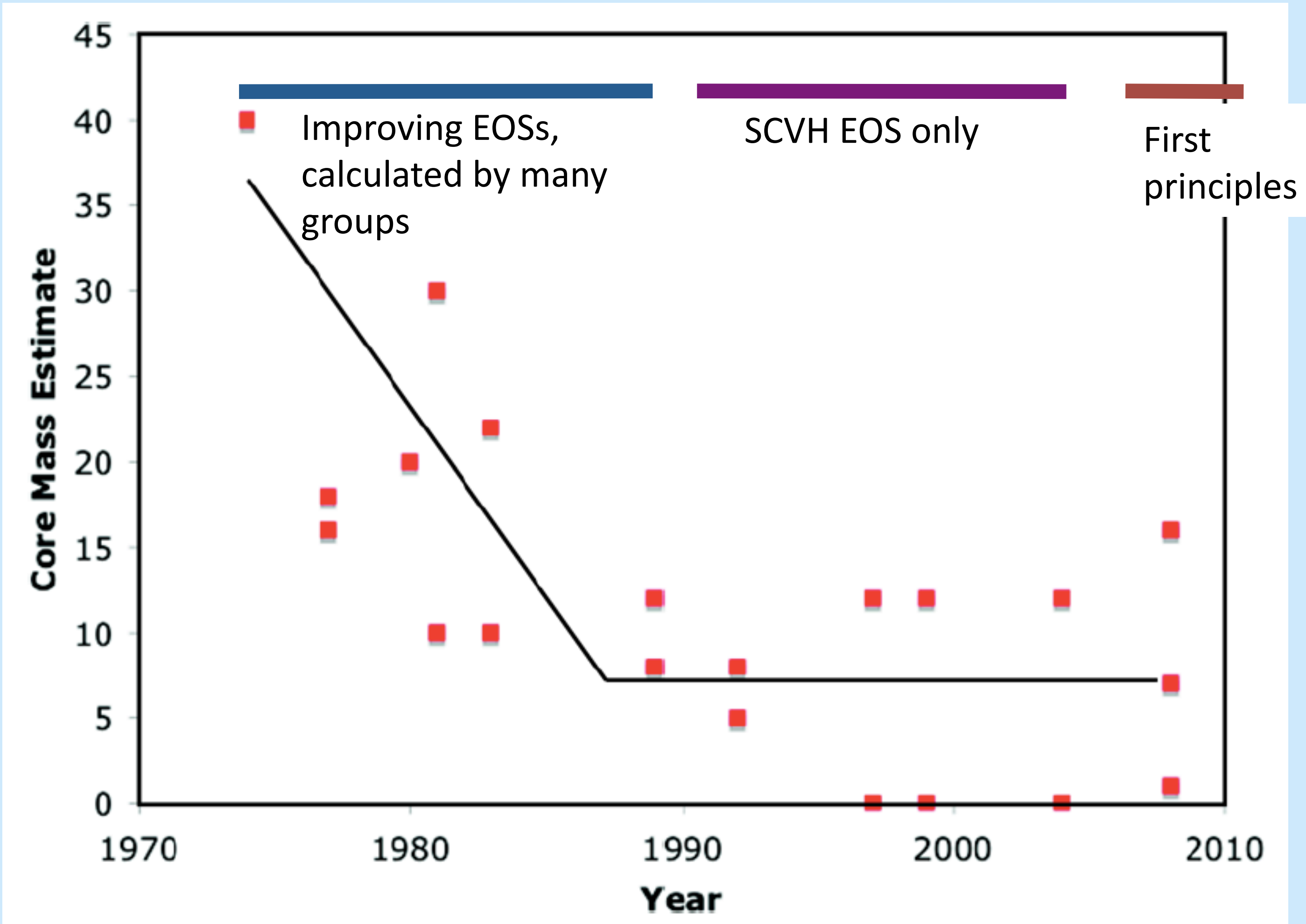
Fortney, Baraffe, & Militzer (2010)

Envelope Abundances for Jupiter and Saturn



"Solar" is Lodders (2003)

Evolution of Calculations of Jupiter's Core Mass



Fortney & Nettelmann (2010)

The Three Temperatures

T_{eff}=temperature of a blackbody that would emit the same bolometric flux are the planet
This includes intrinsic flux as well as absorbed & re-radiated stellar flux

T_{int}=T_{eff} in the absence of stellar flux

T_{eq}= T_{eff} in the absence of an interior energy source – set only by absorbed flux

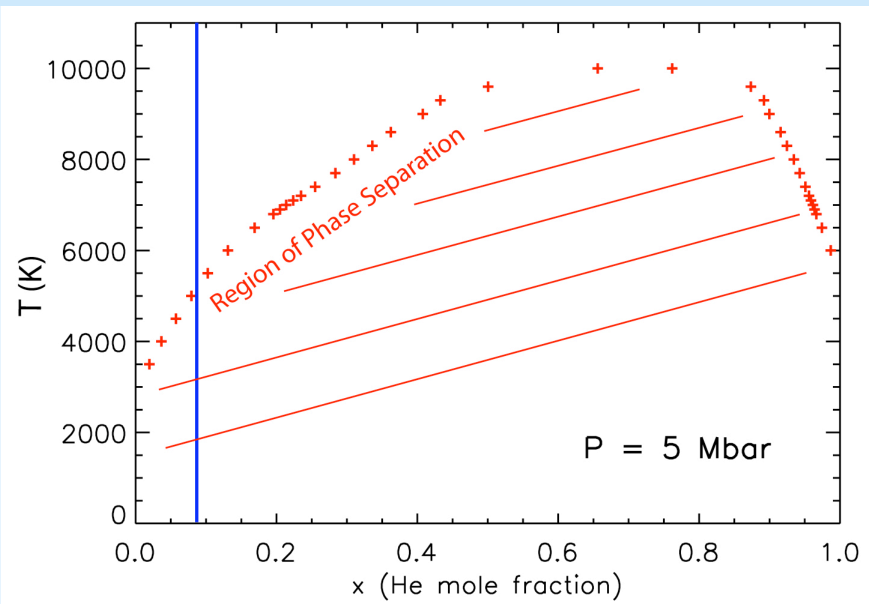
$$T_{\mathrm{eq}}^4 = f(1-A)L_*/(16\pi\sigma d^2)$$

$T_{eq}^4 + T_{int}^4 = T_{eff}^4$

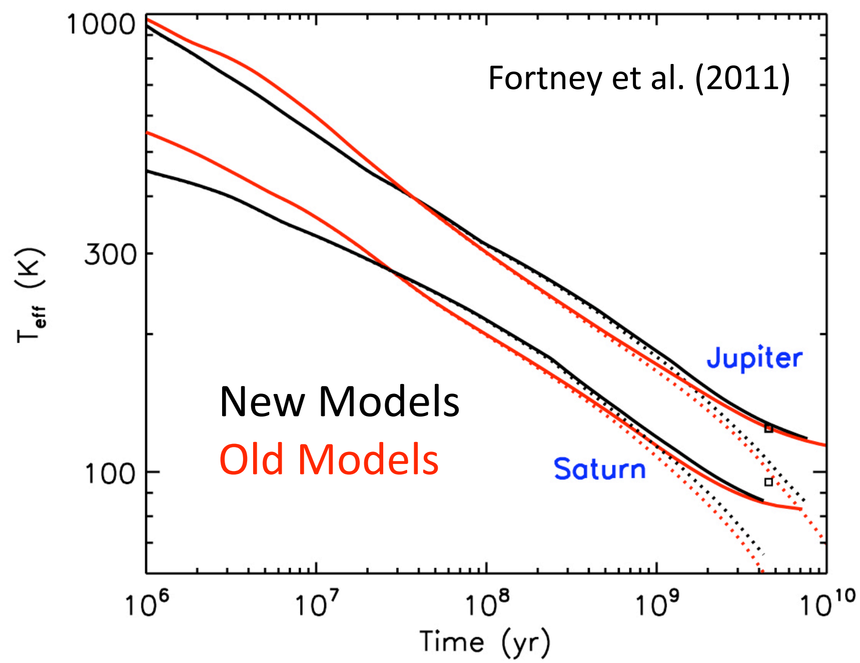
Jupiter and Saturn: Thermal Evolution

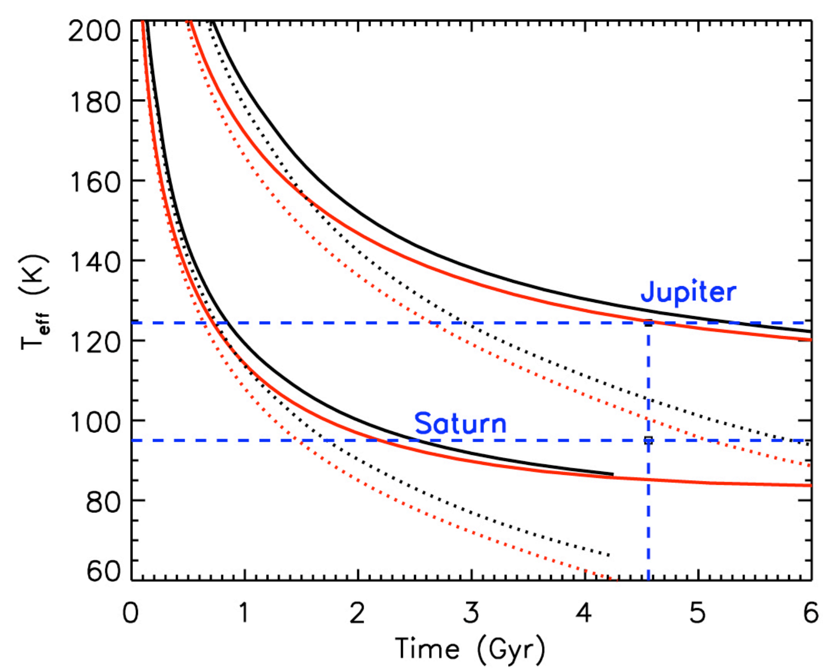
- Cooling models reproduce Jupiter's current T_{eff} reasonably well, given uncertainties in input physics

- Saturn is far warmer than these same models predict
- H/He phase separation is thought to be Saturn's additional energy source

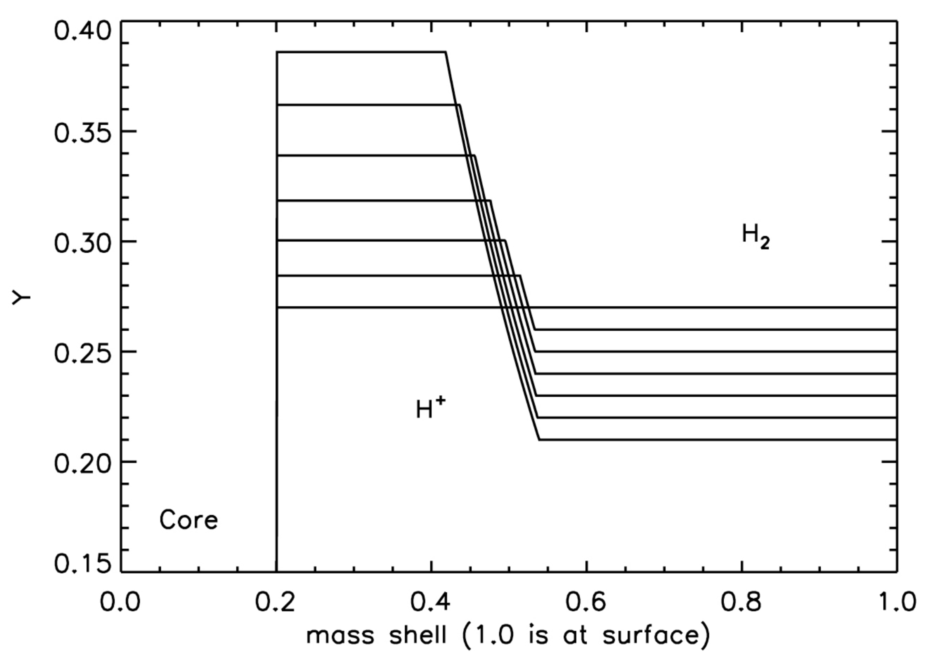


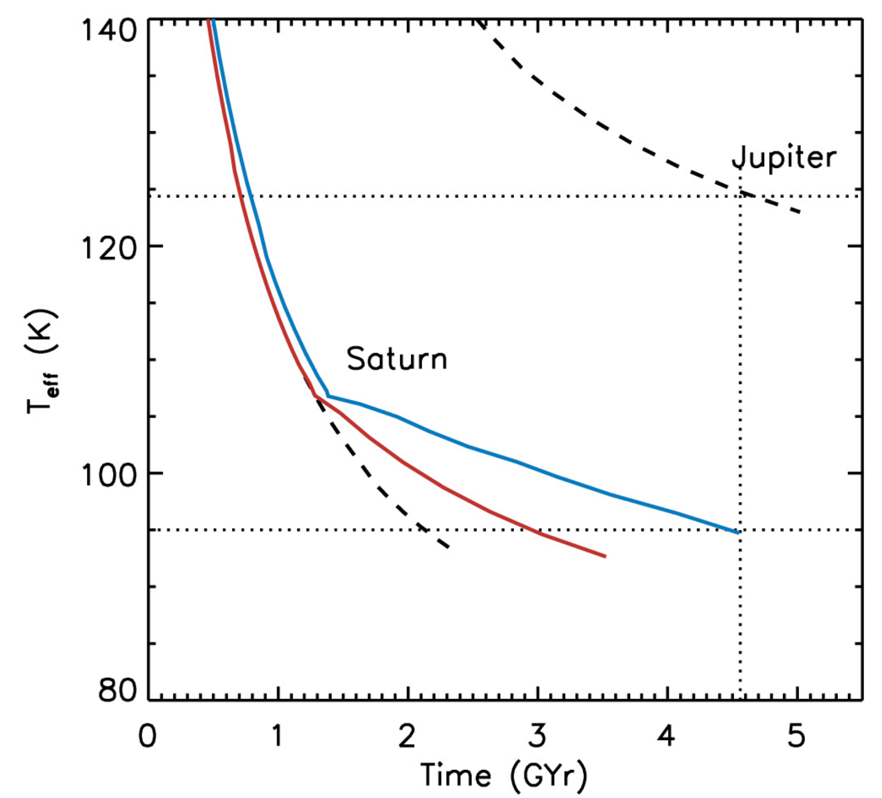
Hubbard & DeWitt (1985)





Jupiter and Saturn: Inhomogeneous Evolution



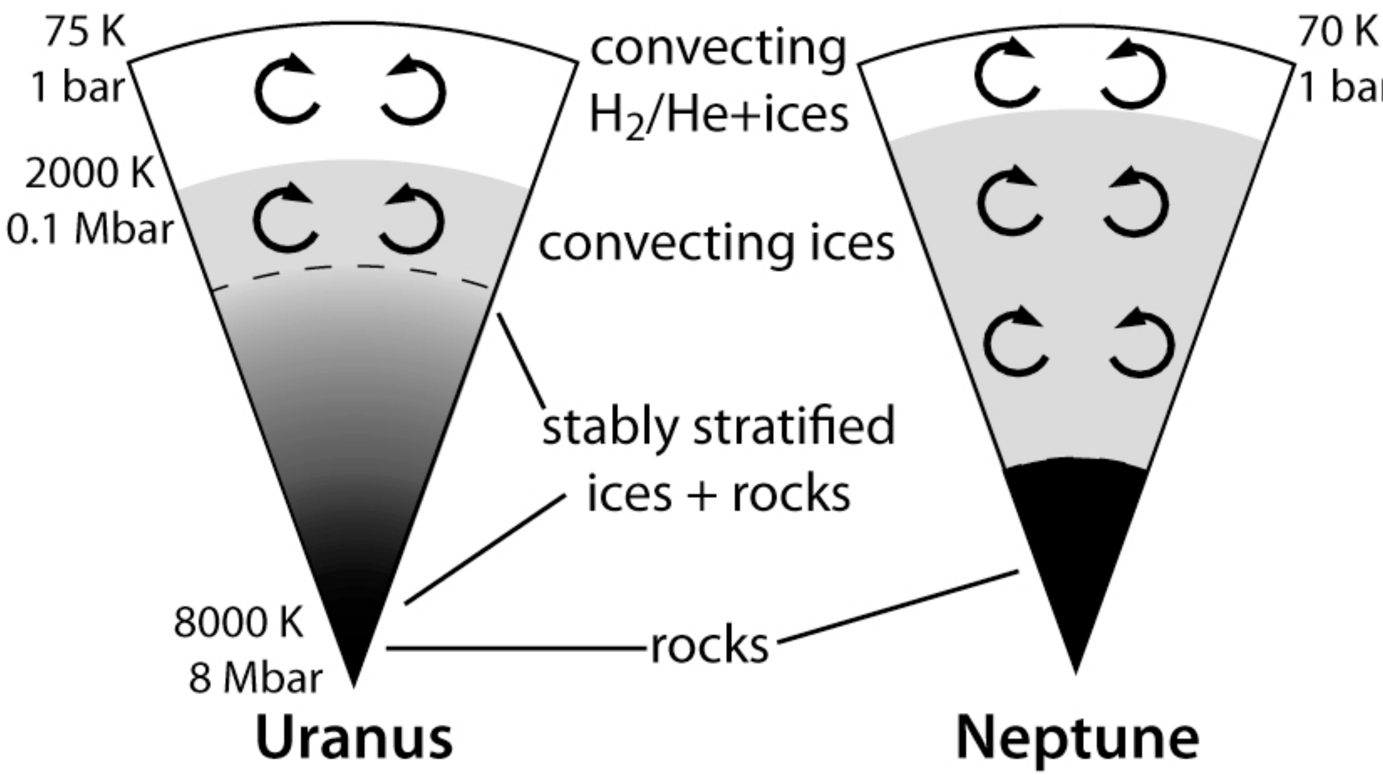


Fortney & Hubbard (2003, 2004)

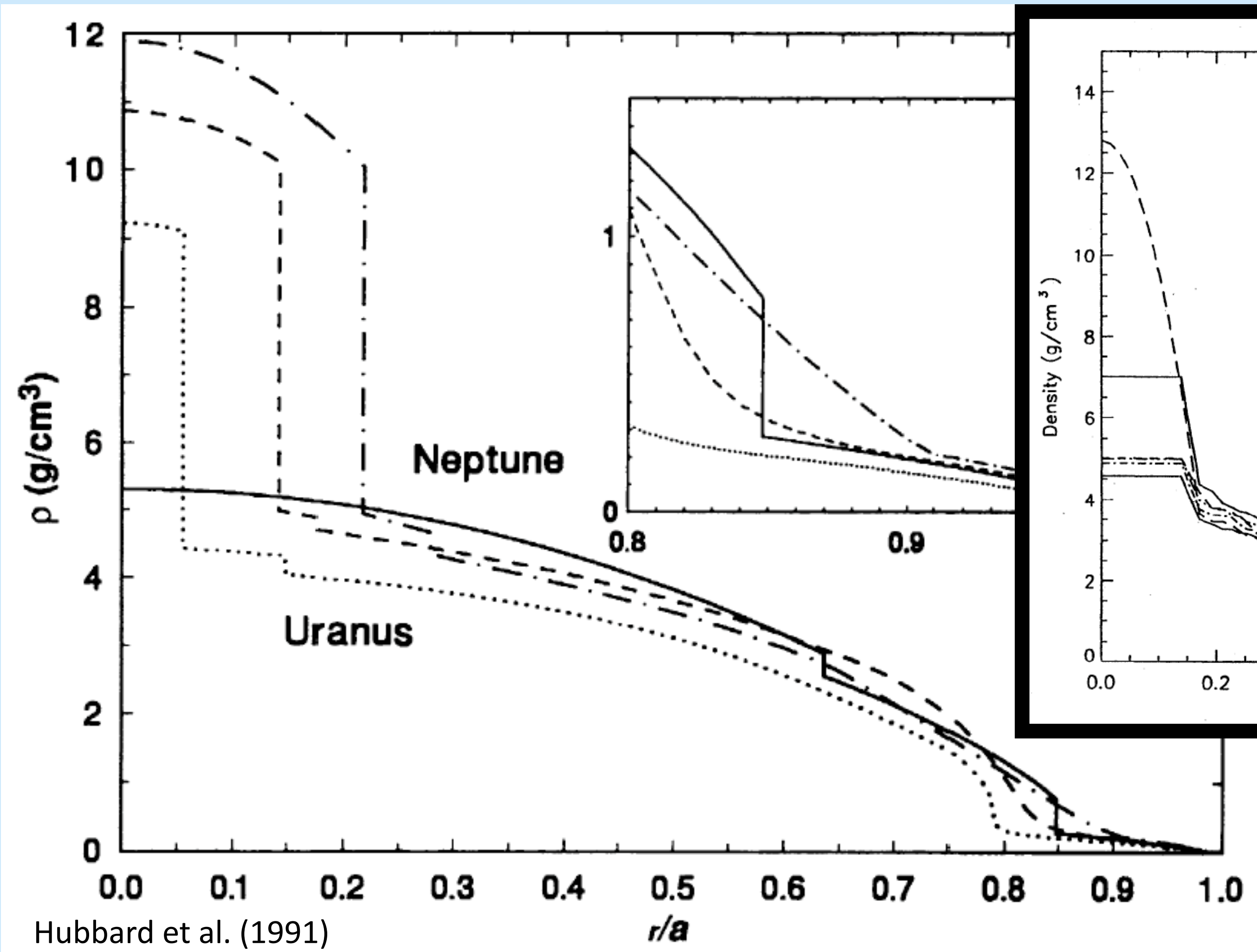
$Y_{protosolar}$=0.275 ± 0.01 (helioseismo)
$Y_{Jupiter}$= 0.238 ± 0.005 (probe)
Y_{Saturn}= 0.18-0.25 (spectra)

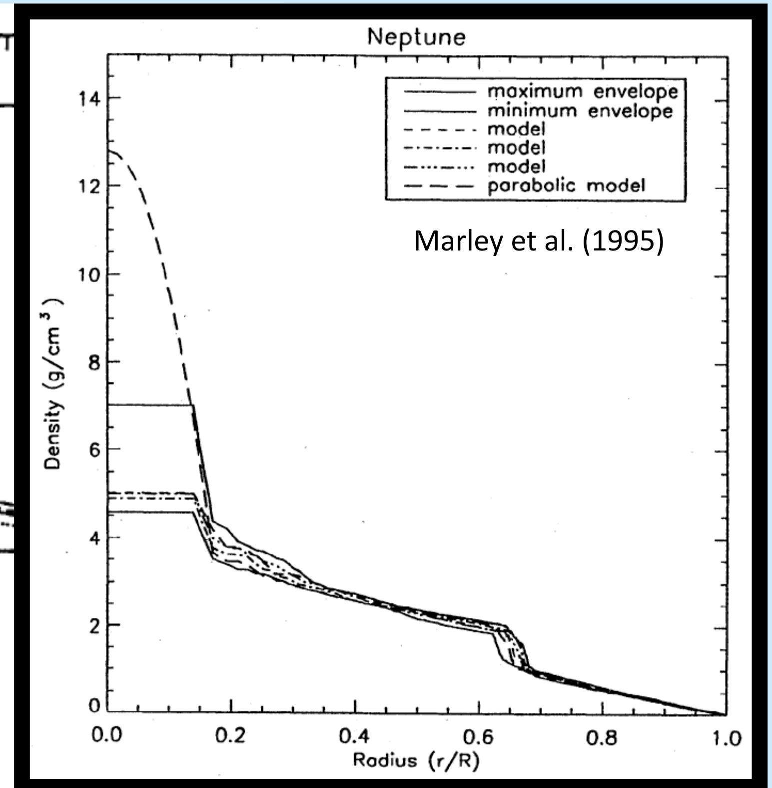
Including He differentiation is essential to the next generation of Jupiter and Saturn cooling models, but many details (phase diagram, effect of composition gradient are not well understood)

Uranus and Neptune: Current Interior



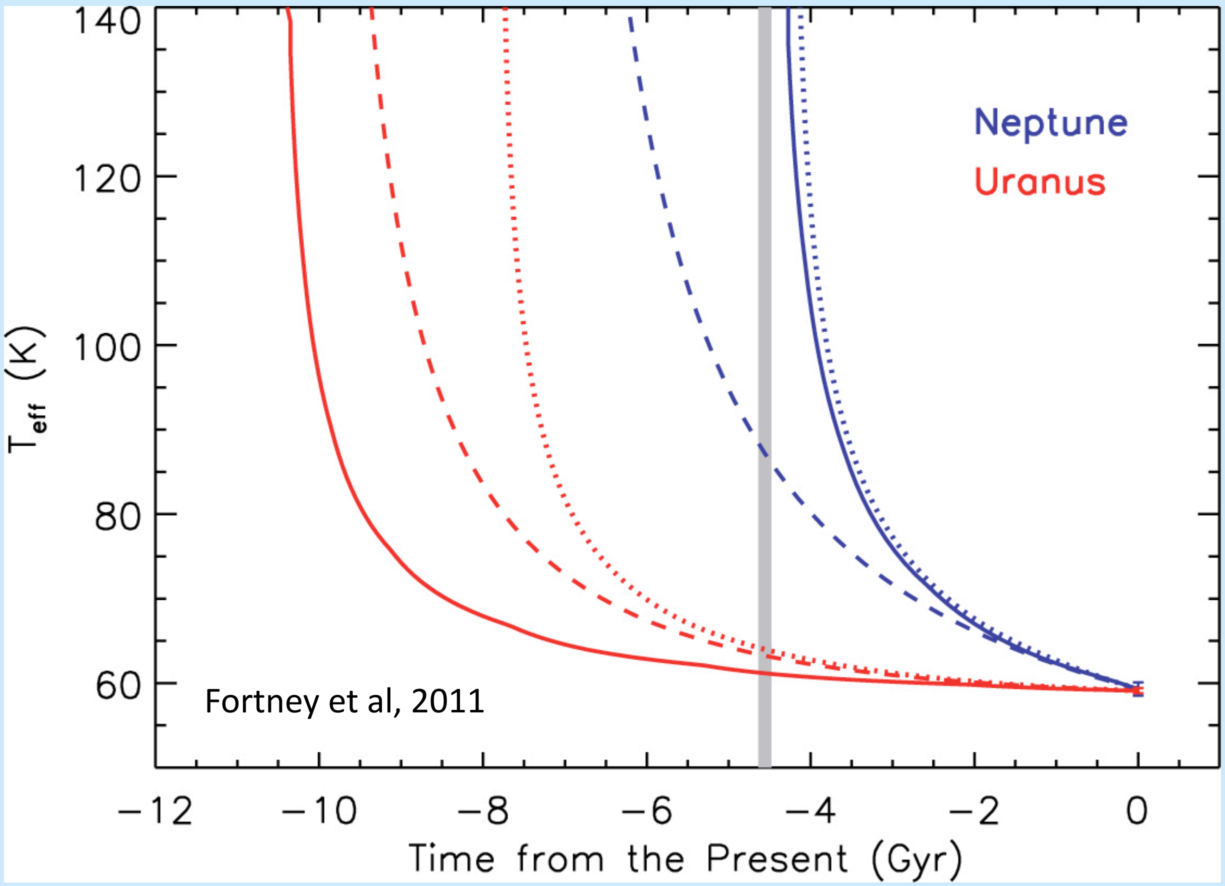
Uncertainties in Understanding the Interiors of Uranus and Neptune





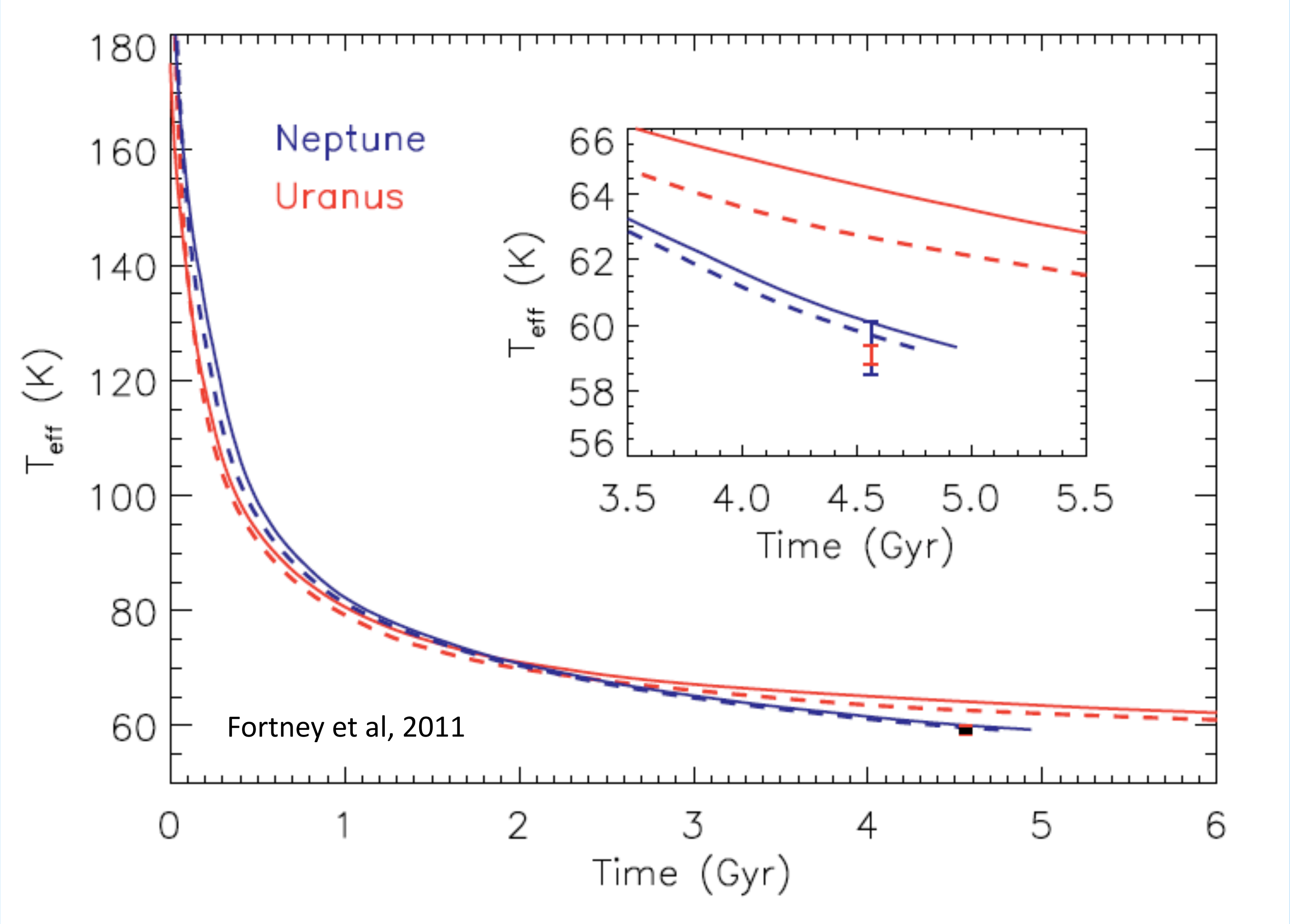
Uranus and Neptune DO NOT have 3 well-defined layers!

Uranus & Neptune: Dramatically revised high-pressure water EOS has an even larger impact than new atmospheres



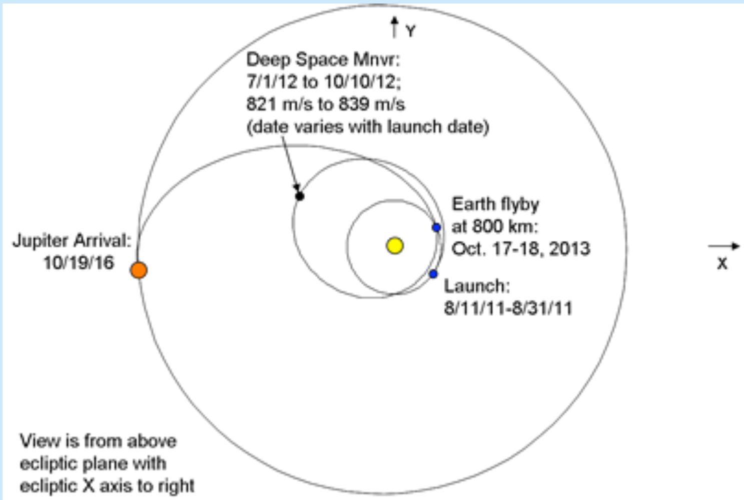
Simple Hubbard & MacFarlane (1980)-style 3 layer models: H/He, H_2O, rock

For the first time, Neptune models match measured T_{eff}



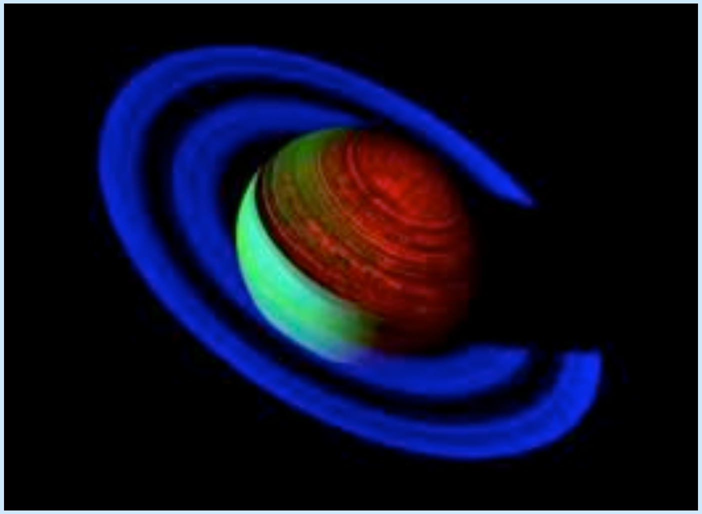
Gravity fields of both planets also matched (constrains current structure)

Juno at Jupiter, 2016



•Very high order gravity field and magnetic field observations
•Microwave spectroscopy of deep atmosphere to determine water and ammonia abundances

Cassini at Saturn, until 2017



•Extended-extended mission (XXM) will map gravity field before plunging into the atmosphere

Takeaway Message for the 4 Planets

Jupiter:

- Cooling models modestly overestimate T_{eff} at 4.5 Gyr
- Probably the current H EOS overestimates interior temperatures, which was already suggested by lab data
- Core mass still not well constrained

Saturn:

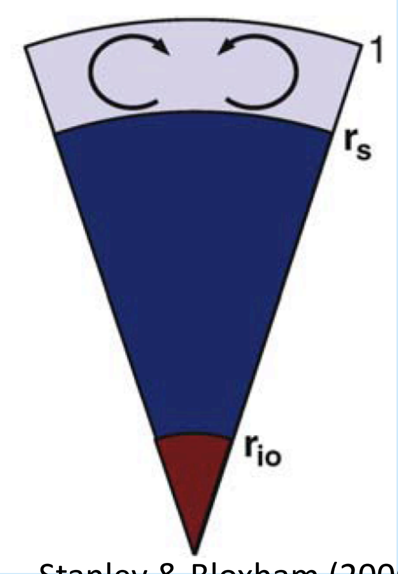
- Cooling models greatly underestimate T_{eff} at 4.5 Gyr
- He rain clearly still needed
- Core mass well constrained at 10-20 M_E

Uranus:

- Cooling models greatly overestimate T_{eff} at 4.5 Gyr
- Tiny interior flux still not well understood

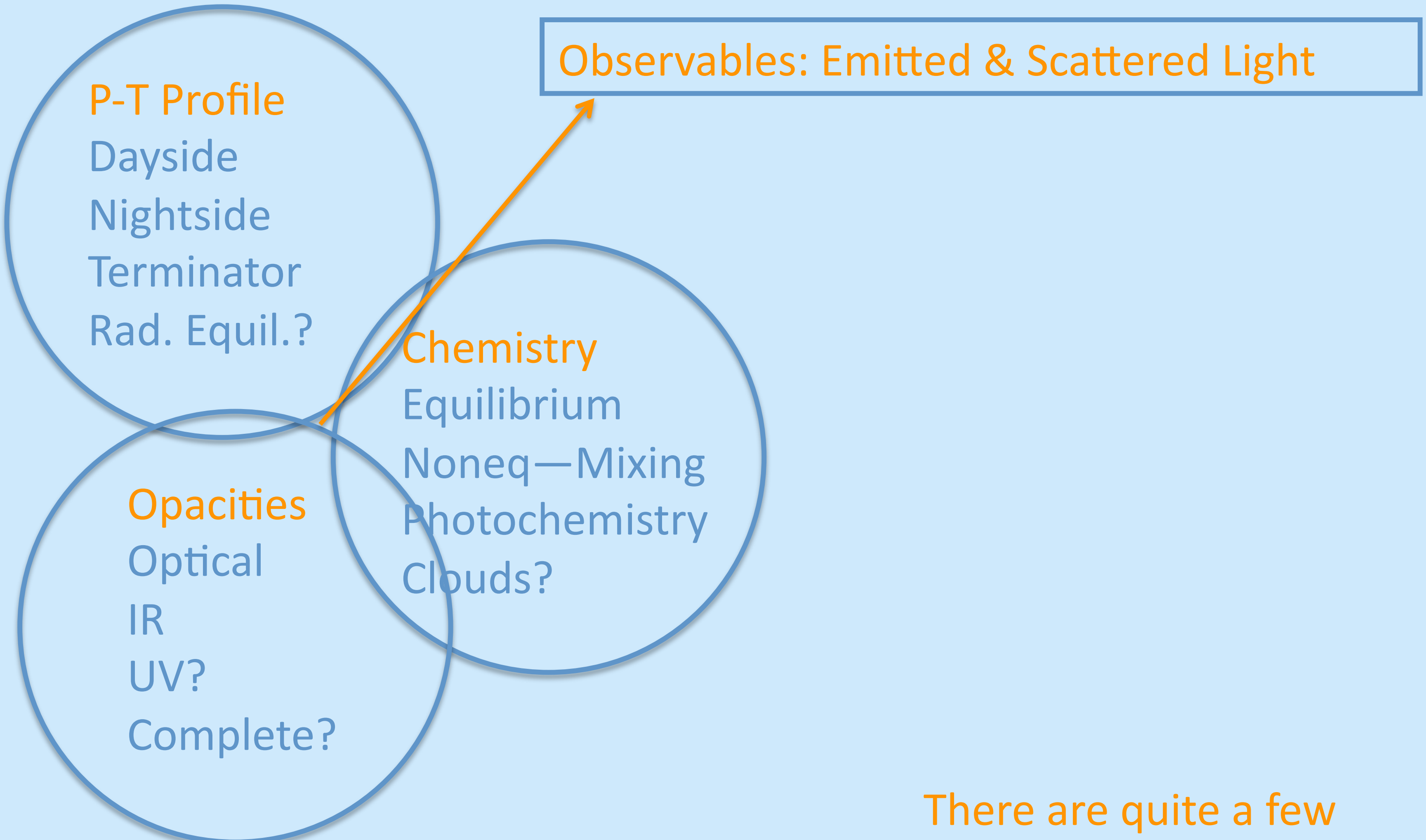
Neptune:

- Cooling models match T_{eff} at 4.5 Gyr
- One model can match gravity field and T_{eff}, for the first time
- Even more significant dichotomy with Uranus
- If entire H/He and water-rich envelopes are freely convecting, what impact on magnetic field generation?



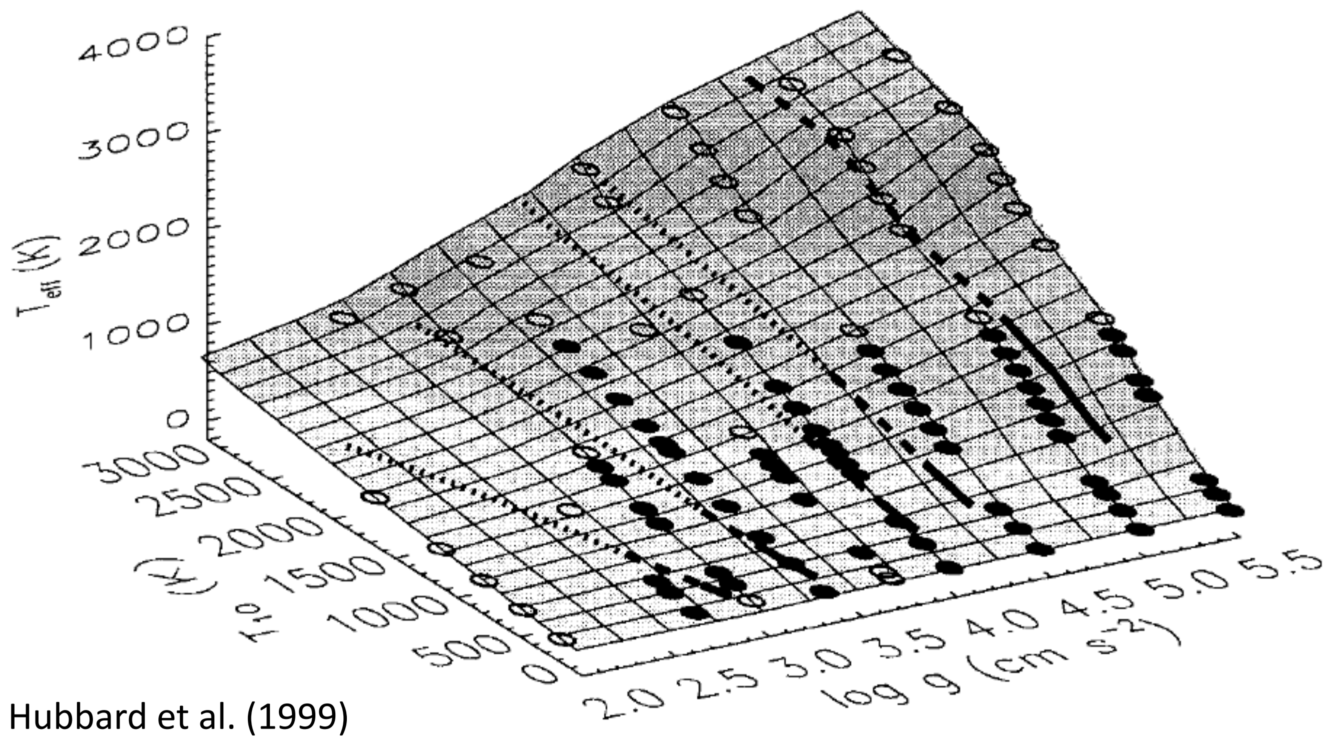
Stanley & Bloxham (2006)

Model Atmospheres



There are quite a few ways of doing this

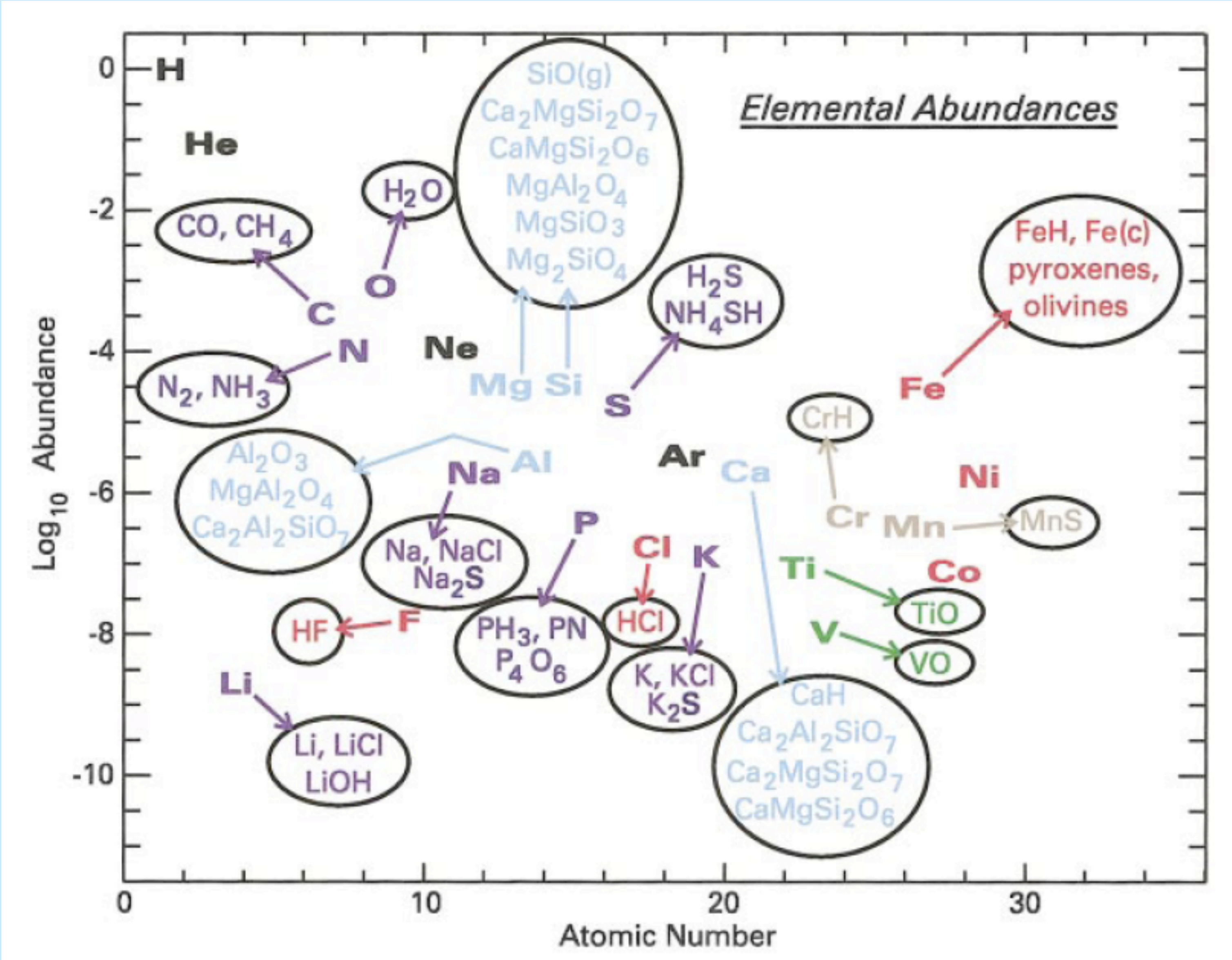
Model Atmosphere Grid Serves as Upper Boundary Condition

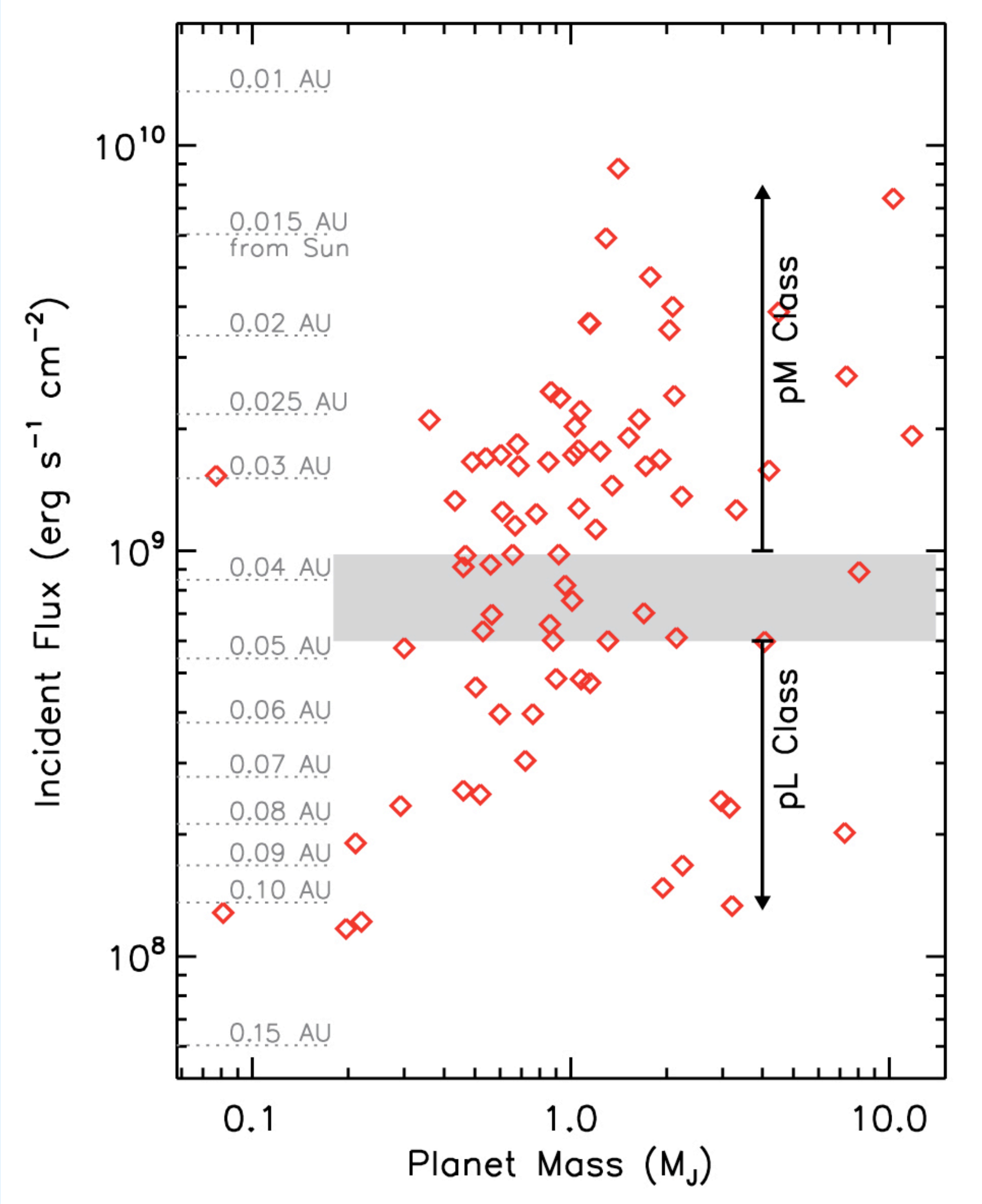


Hubbard et al. (1999)

- Radiative-convective atmosphere model yields *S* at atmosphere bottom, or *T* & *P* at tau=100
- Structure model gives a snapshot of log *g* and *S*, the atmosphere grid is interpolated to yield $T_{\rm eff}$

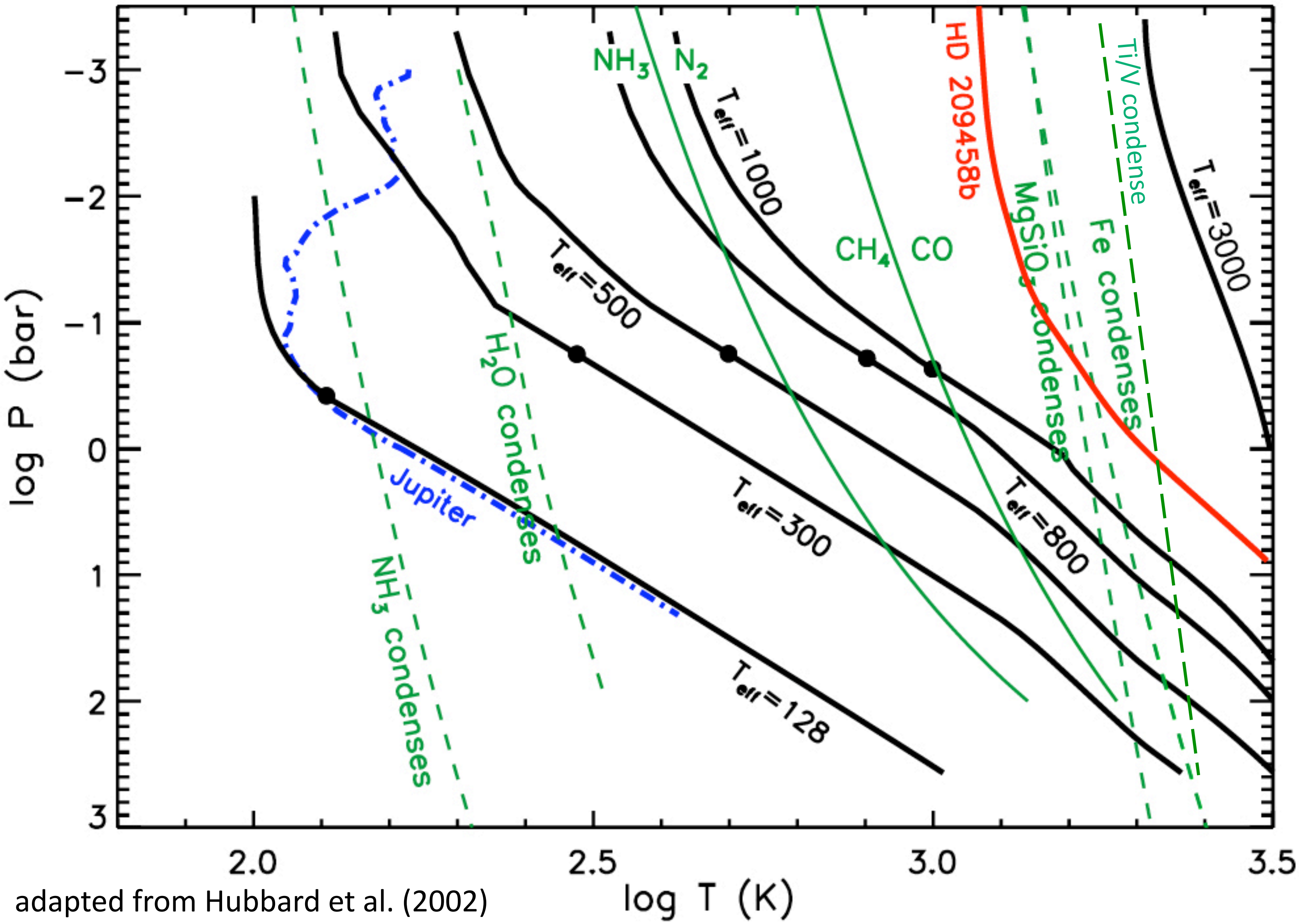
Atmospheres: Structure, Chemistry, Effect on Evolution





What is a "hot Jupiter"?

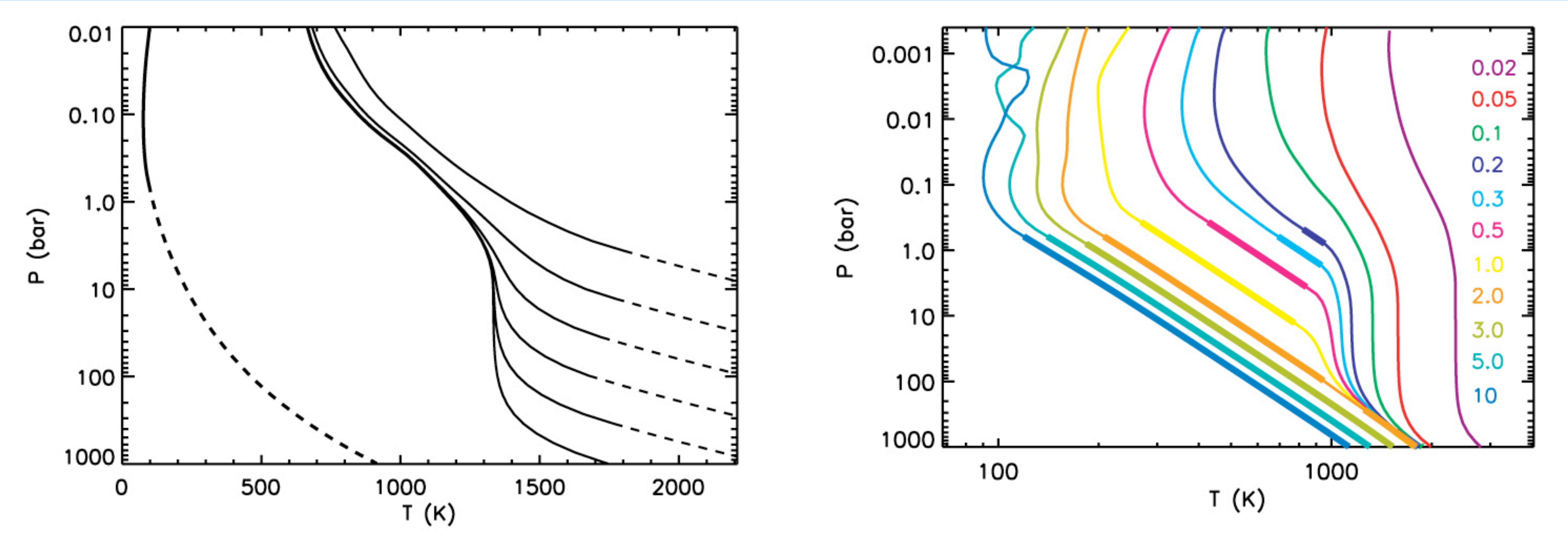
Diversity!



adapted from Hubbard et al. (2002)

Pressure-Temperature (*P-T*) profiles from Jupiter to a 3000K M dwarf star

Hot Jupiters: Fully Radiative Atmospheres

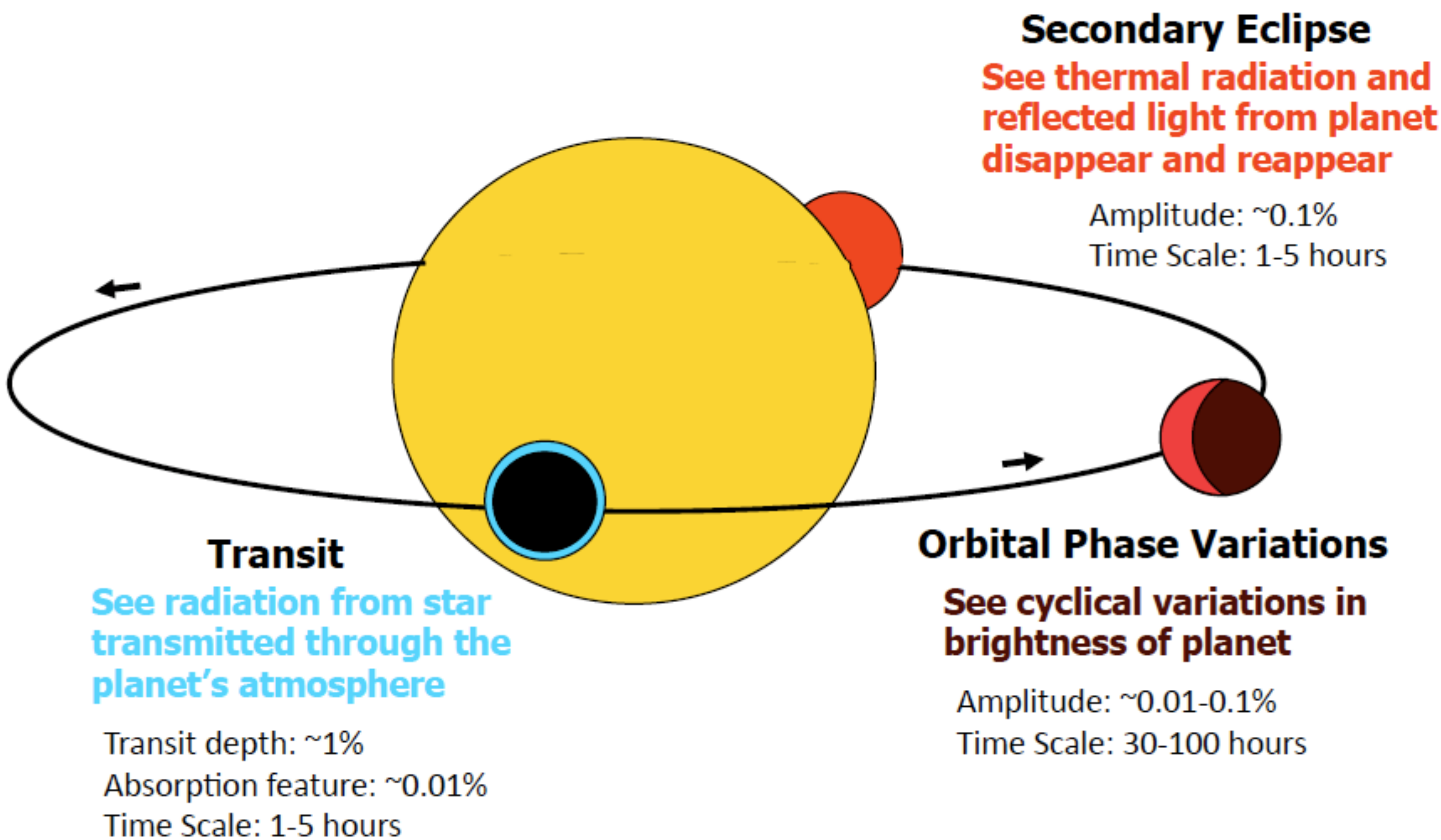


Fortney et al. (2007)

•Shallower atmospheric T-gradient leads to slower interior cooling, and larger radius at a given age

•Temperature structure evaluated analytically in the gray approximation by B. Hanson (2008) and T. Guillot (2011)

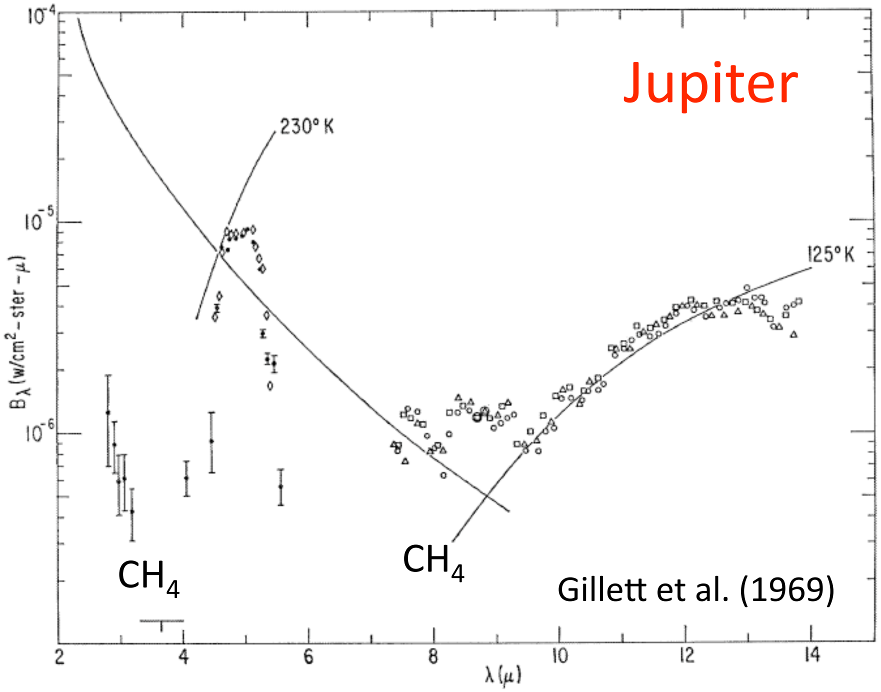
Methods for Characterizing the Atmospheres of Transiting Planets

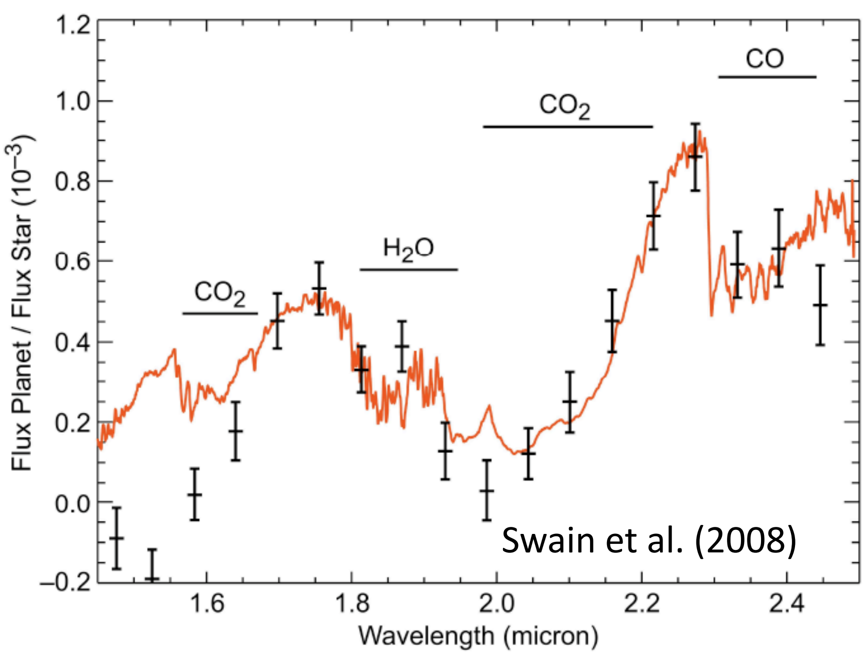


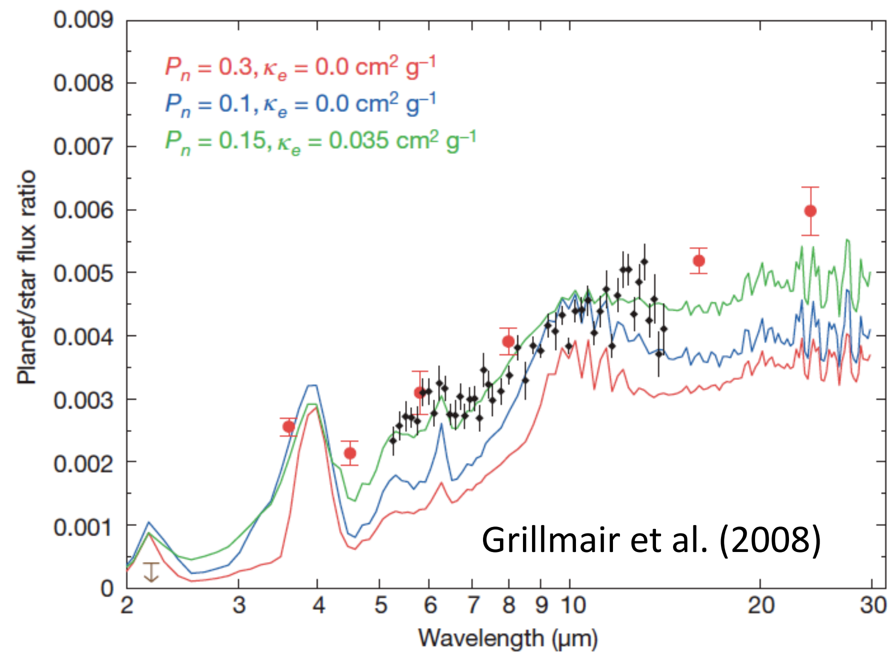
Spectroscopy of thermal infrared light emitted by the planets

- Jupiter, 1969
- HD 189733b, 2008

- For most transiting planets, spectra are difficult to obtain, so we can only measure the brightness in a few wide wavelength bands

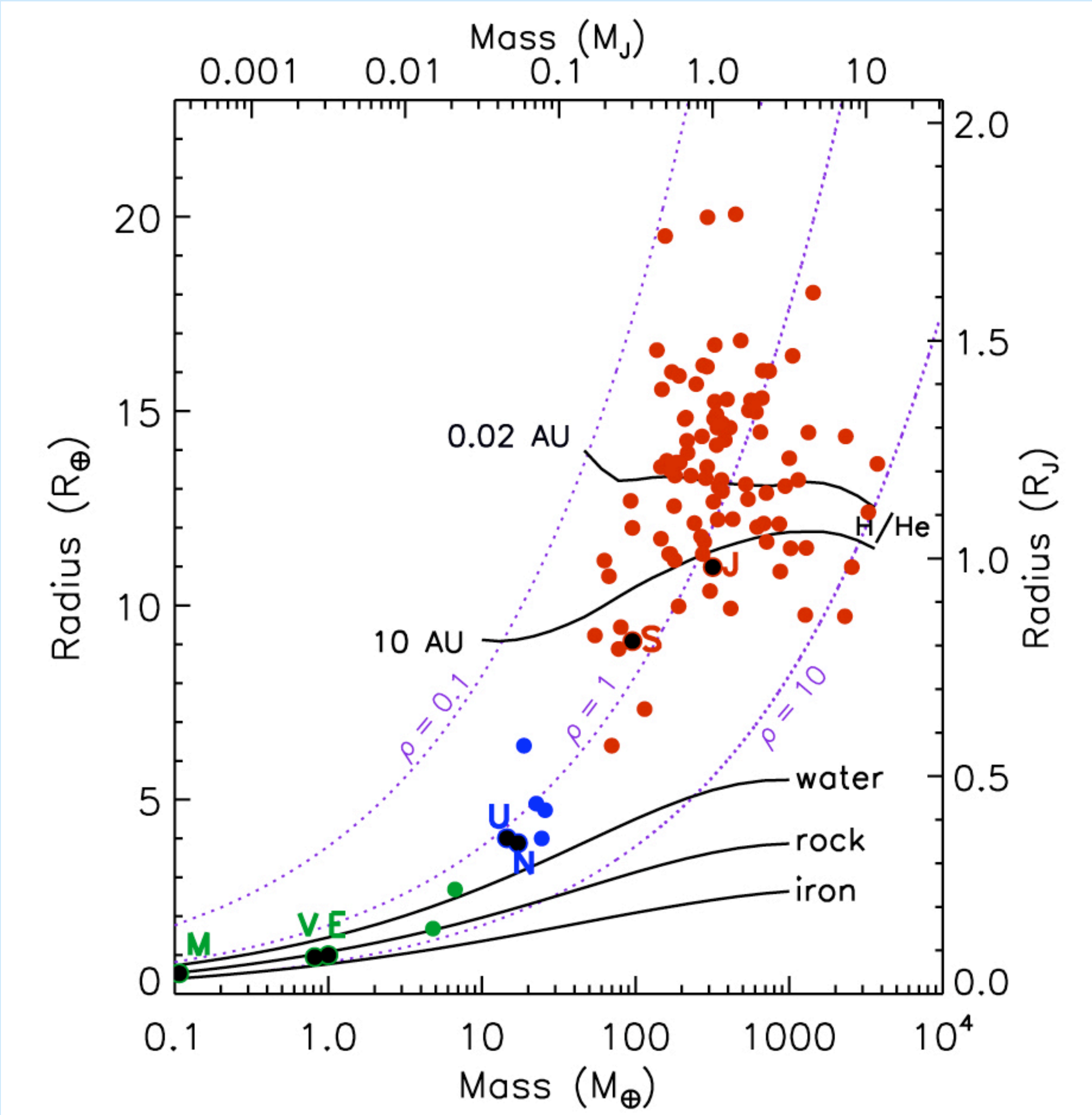


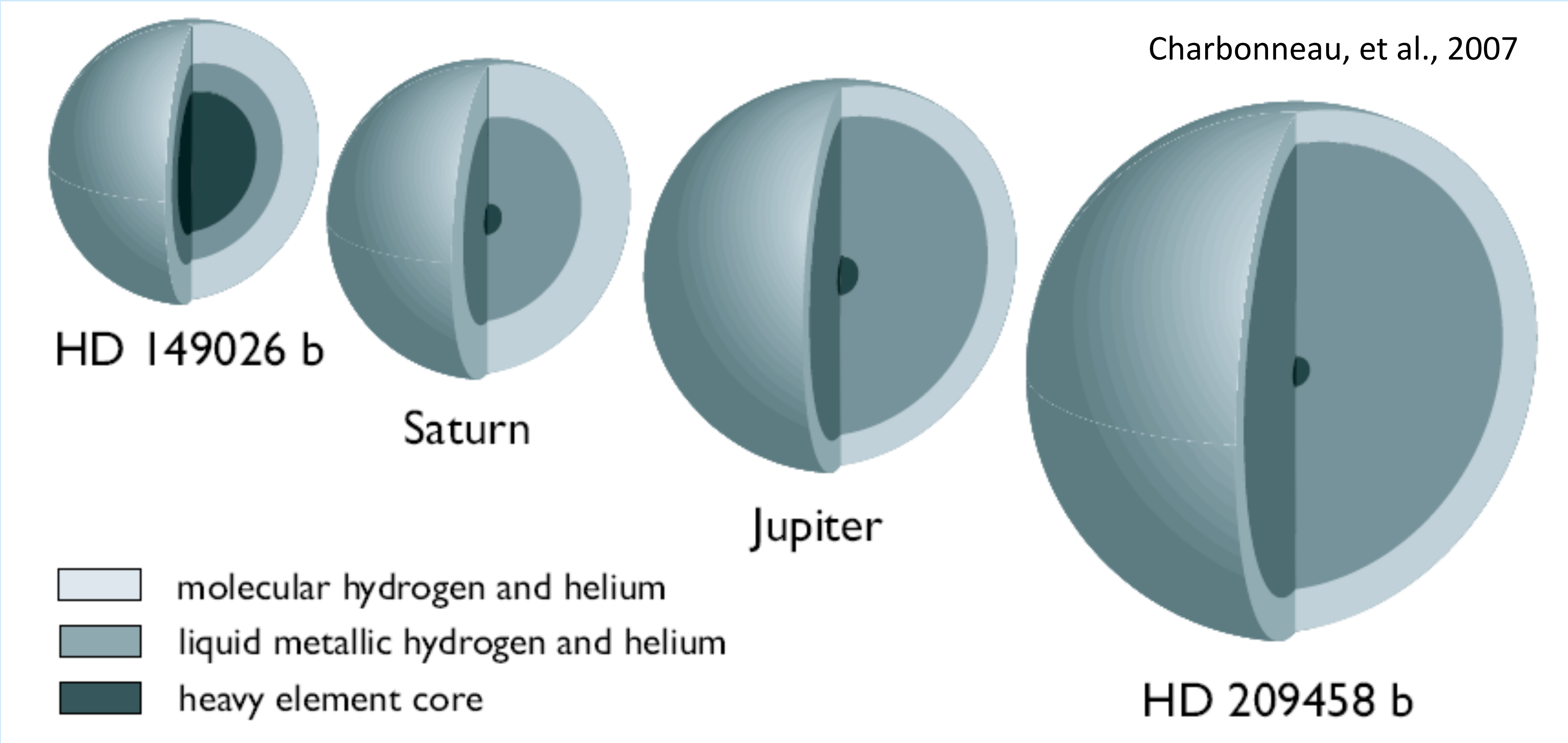




There is an incredibly diversity of worlds

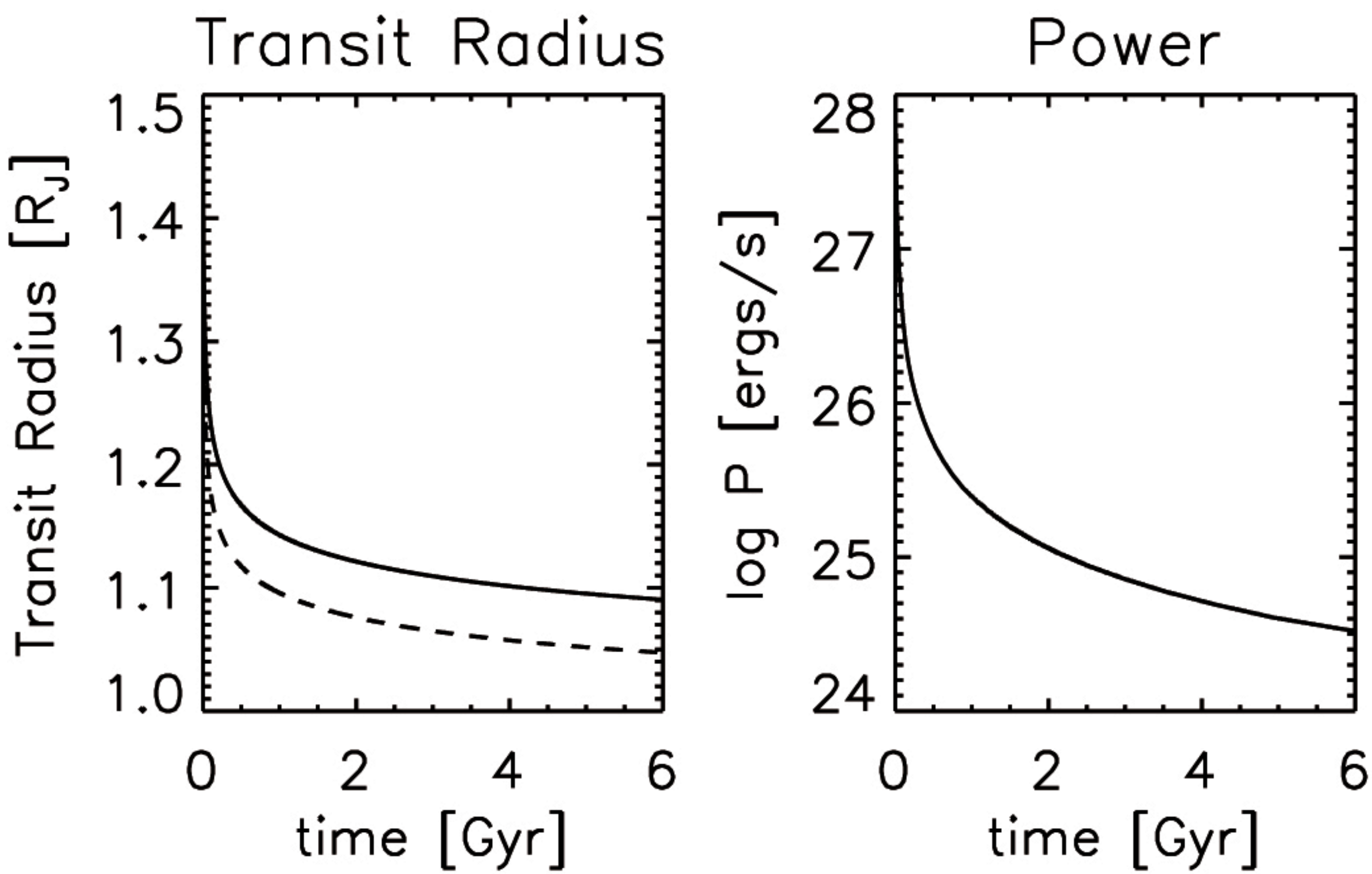
- We can also **characterize** these planets, not just find them





- There is considerable diversity amongst the known transiting planets
- Radii for planets of similar masses differ by a factor of two, which cannot happen for pure H/He objects

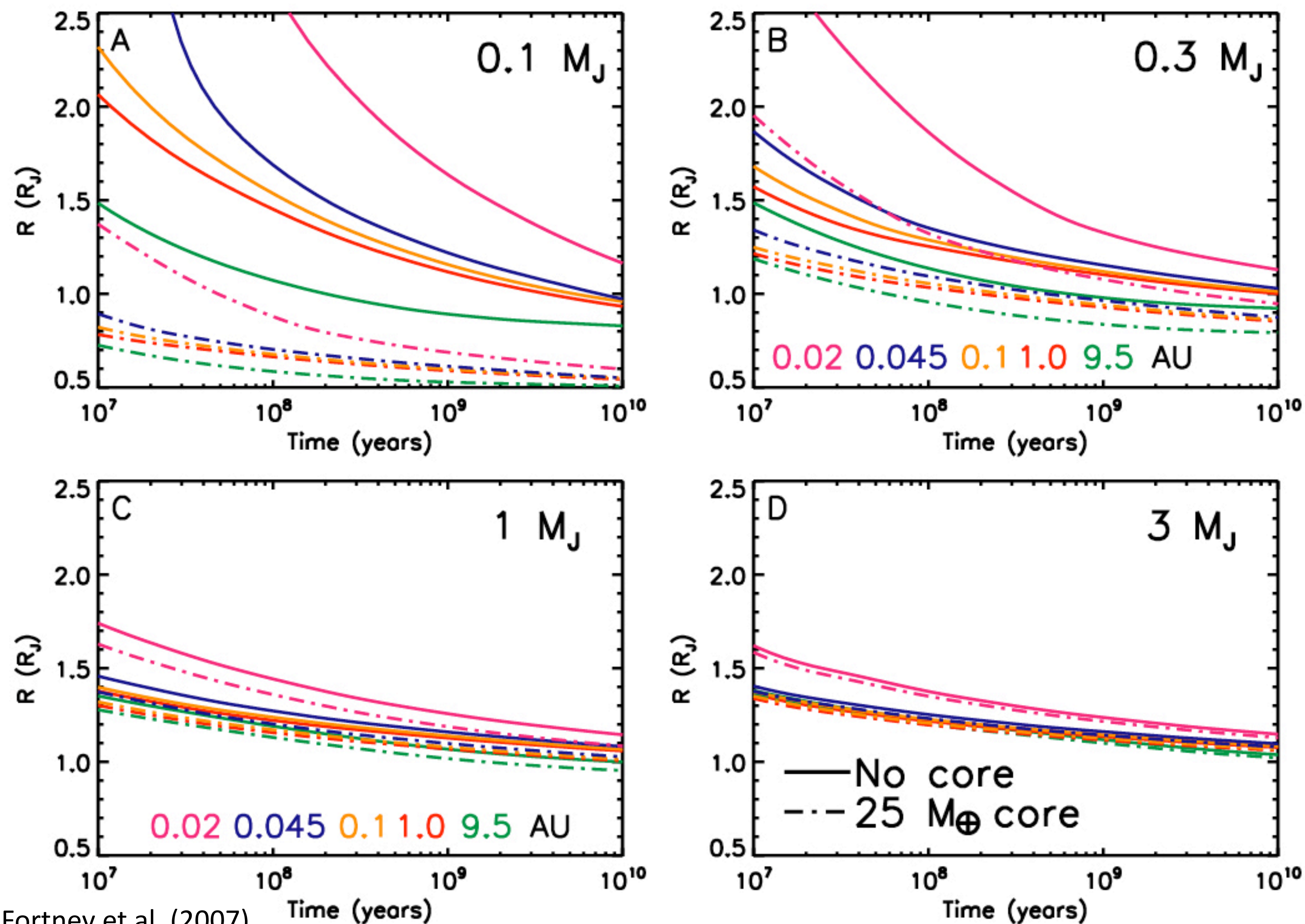
Building a Model, I: Standard Cooling and Contraction



Miller, Fortney, & Jackson (2009)

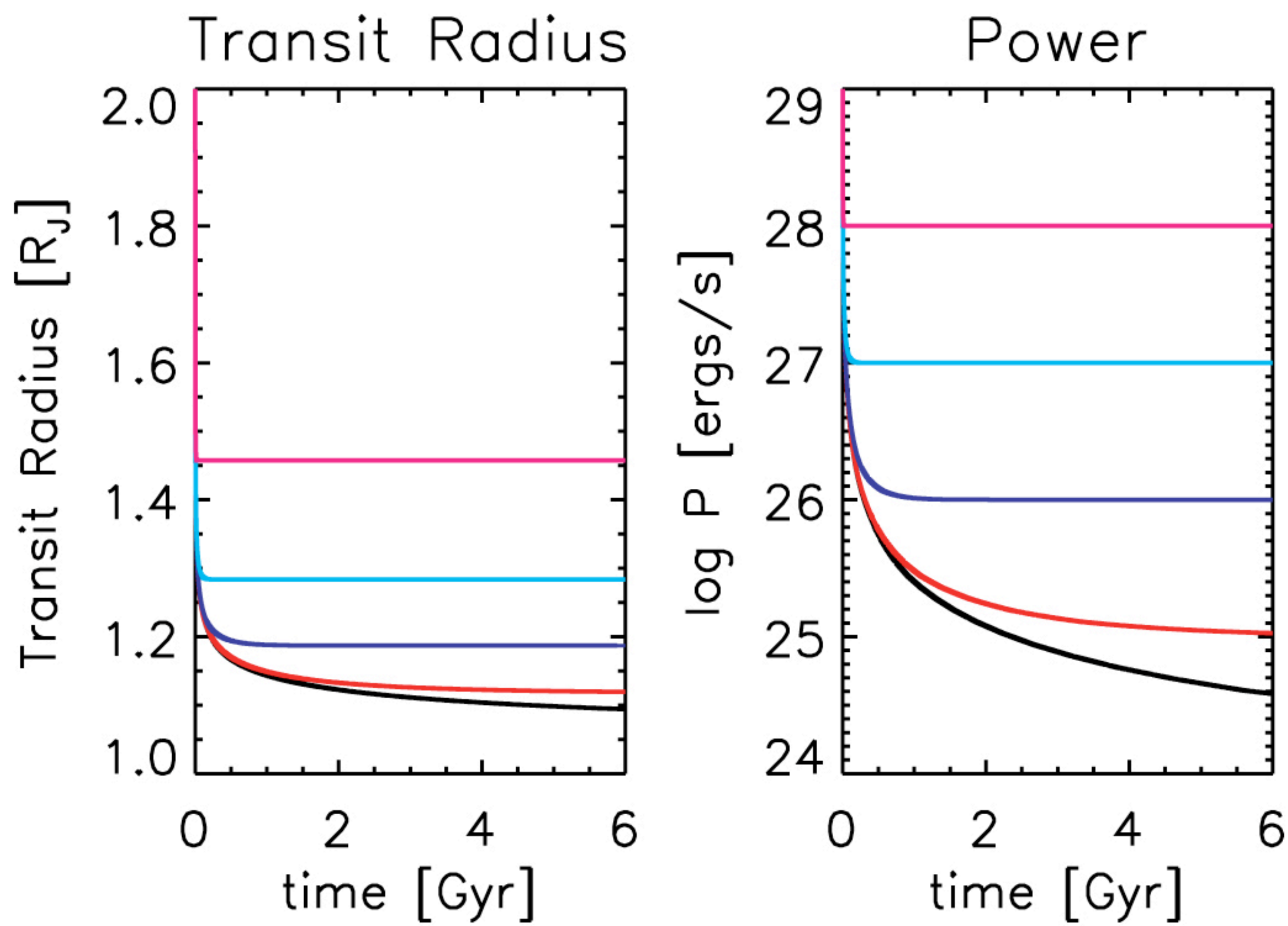
1 M_J planet with a 10 M_E core, at 0.05 AU from the Sun

At Gyr ages, ~1.3 R_J is the largest radius of a standard cooling model



Fortney et al. (2007)

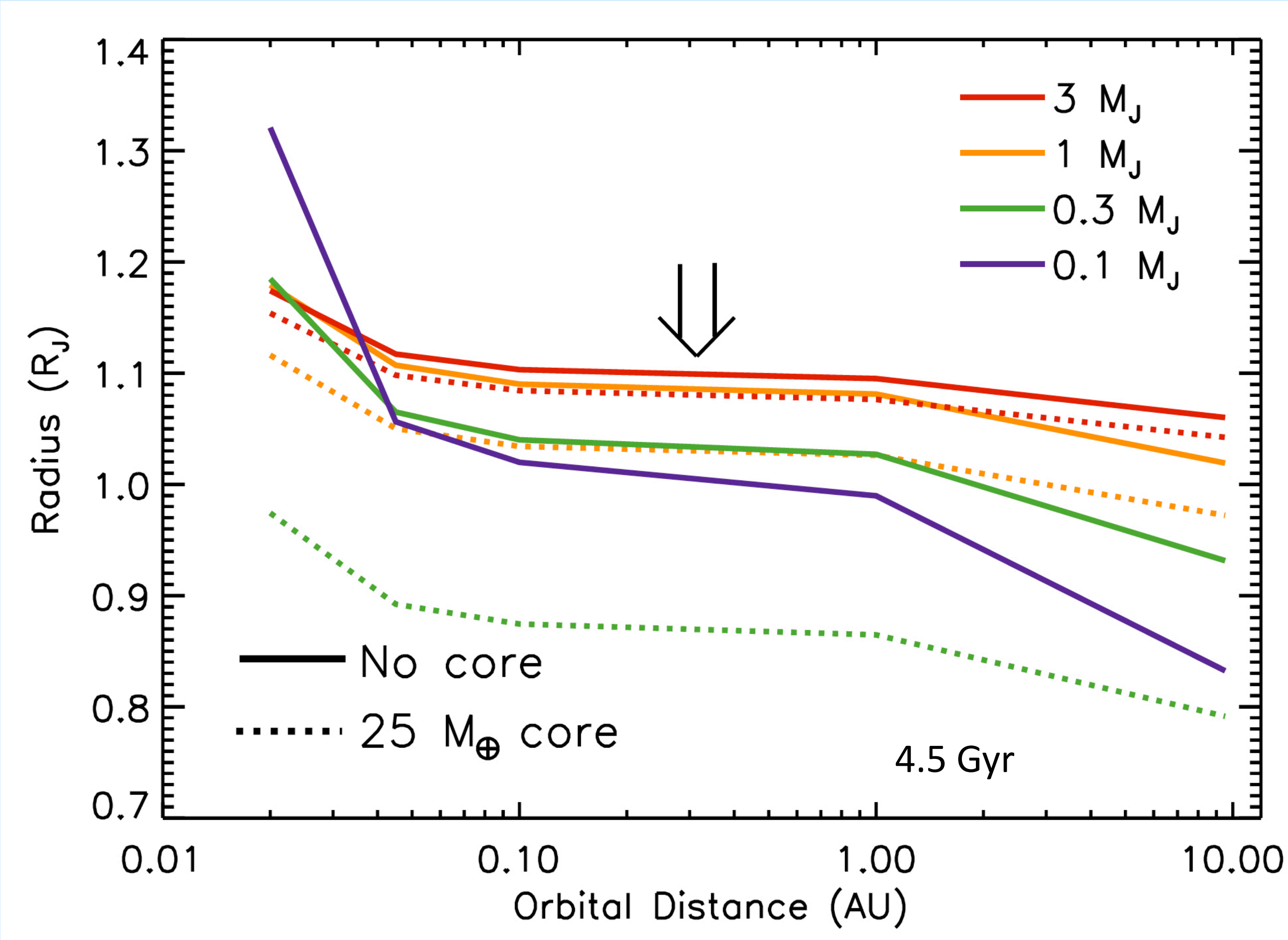
Building a Model, II: Additional Interior Power



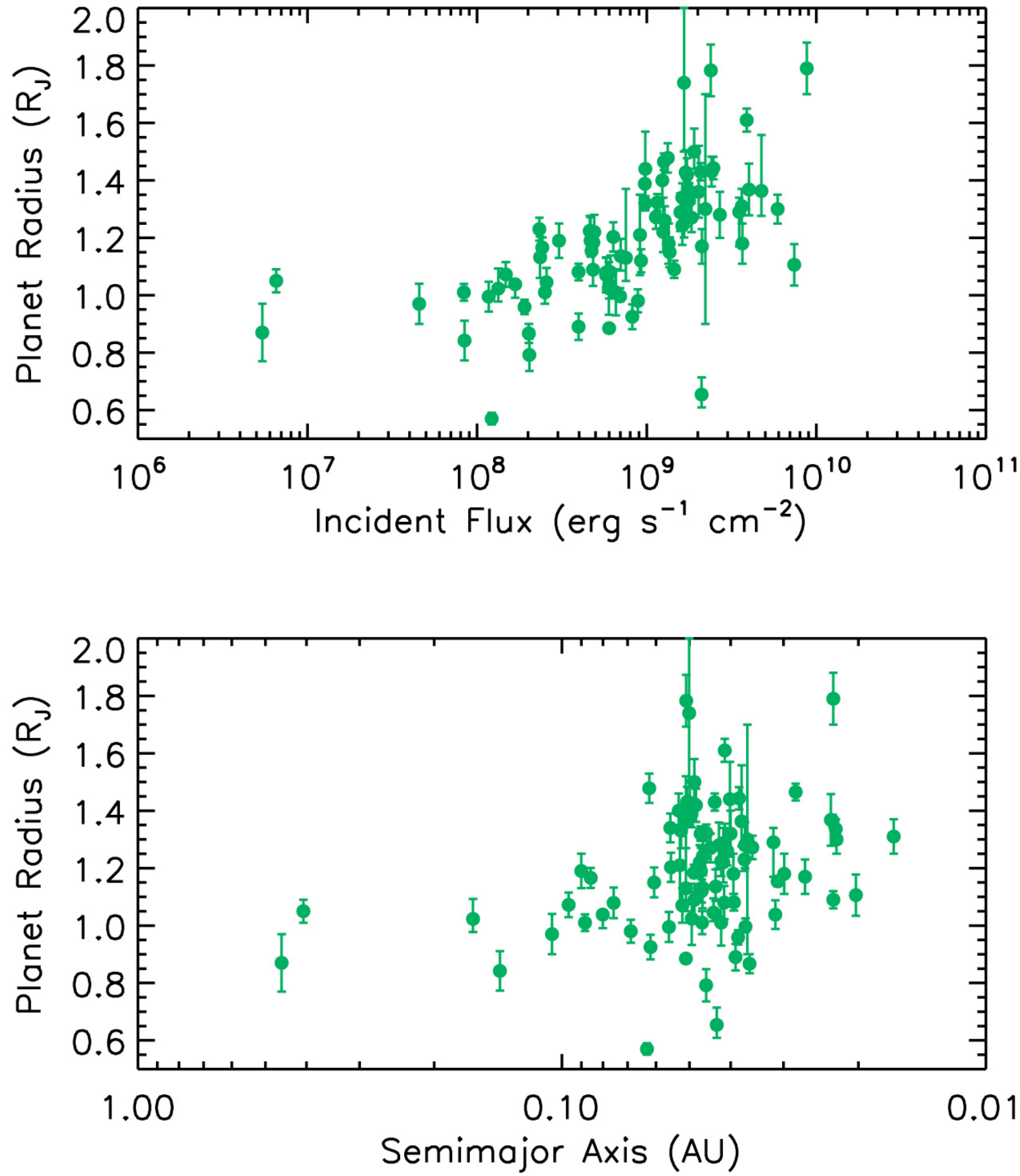
Miller, Fortney, & Jackson (2009)

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

Planet Radius vs. Irradiation Level



A trend is now clear: The largest radius planets are the hottest



Explaining Large Radii

An area of active research!

Evolution of "51 Pegasus b-like" planets

T. Guillot[1] and A. P. Showman[2]

ON THE TIDAL INFLATION OF SHORT-PERIOD EXTRASOLAR PLANETS[1]

PETER BODENHEIMER,[2] D. N. C. LIN,[2] AND R. A. MARDLING[2,3]

Received 2000 May 17; accepted 2000 October 11

OBLIQUITY TIDES ON HOT JUPITERS

JOSHUA N. WINN[1] AND MATTHEW J. HOLMAN
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Received 2005 May 13; accepted 2005 June 20; published 2005 July 15

The effect of evaporation on the evolution of close-in giant planets

I. Baraffe[1], F. Selsis[2], G. Chabrier[1], T. S. Barman[3], F. Allard[1], P. H. Hauschildt[4], and H. Lammer[5]

POSSIBLE SOLUTIONS TO THE RADIUS ANOMALIES OF TRANSITING GIANT PLANETS

A. BURROWS,[1] I. HUBENY,[1] J. BUDAJ,[1,2] AND W. B. HUBBARD[3]

Received 2006 December 22; accepted 2007 February 9

HEAT TRANSPORT IN GIANT (EXO)PLANETS: A NEW PERSPECTIVE

GILLES CHABRIER AND ISABELLE BARAFFE[1,2]

Received 2007 March 6; accepted 2007 March 28; published

TWO CLASSES OF HOT JUPITERS

BRAD M. S. HANSEN[1] AND TRAVIS BARMAN[2]

Received 2007 June 20; accepted 2007 August 23

TIDAL HEATING OF EXTRASOLAR PLANETS

BRIAN JACKSON, RICHARD GREENBERG, AND RORY BARNES
Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721

Received 2007 December 5; accepted 2008 February 12

INFLATING HOT JUPITERS WITH OHMIC DISSIPATION

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Received 2010 February 18; accepted 2010 March 23; published 2010 April

THERMAL TIDES IN FLUID EXTRASOLAR PLANETS

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[2] Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA; socrates@ias.edu

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CASSINI STATES WITH DISSIPATION: WHY OBLIQUITY TIDES CANNOT INFLATE HOT JUPITERS

DANIEL C. FABRYCKY, ERIC T. JOHNSON, AND JEREMY GOODMAN
Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544

Received 2007 March 16; accepted 2007 April 23

INFLATING AND DEFLATING HOT JUPITERS: COUPLED TIDAL AND THERMAL EVOLUTION OF KNOWN TRANSITING PLANETS

N. MILLER[1], J. J. FORTNEY[1], AND B. JACKSON[2]
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[2] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA; bjackson@lpl.arizona.edu

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COUPLED EVOLUTION WITH TIDES OF THE RADIUS AND ORBIT OF TRANSITING GIANT PLANETS: GENERAL RESULTS

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THE MECHANICAL GREENHOUSE: BURIAL OF HEAT BY TURBULENCE IN HOT JUPITER ATMOSPHERES

ANDREW N. YOUDIN[1] AND JONATHAN L. MITCHELL[2]
[1] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 3H8, Canada
[2] Department of Earth & Space Sciences and Department of Atmospheric and Oceanic Sciences, University of California Los Angeles, 595 Charles Young East Drive, Los Angeles, CA 90095-1567, USA

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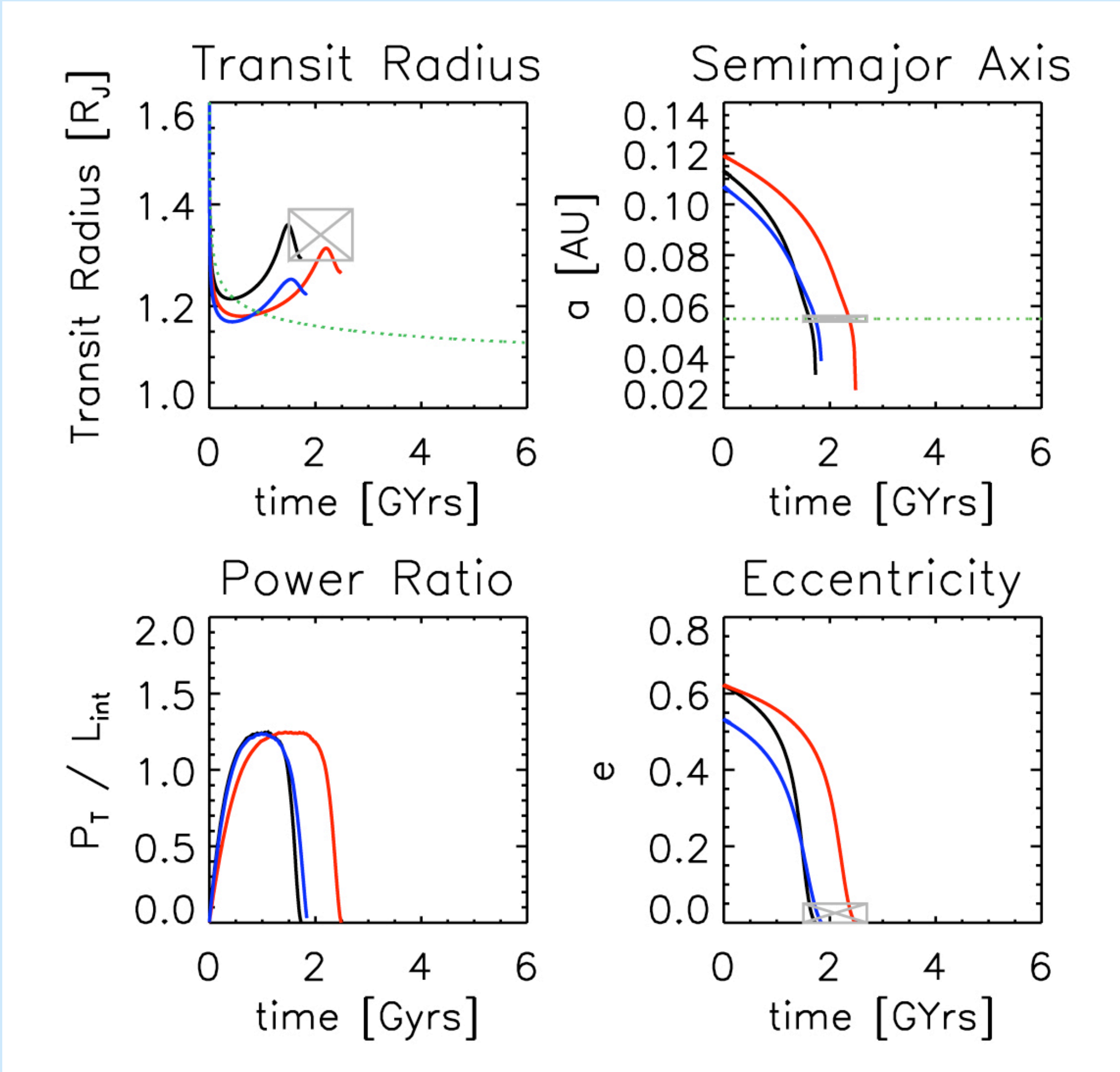
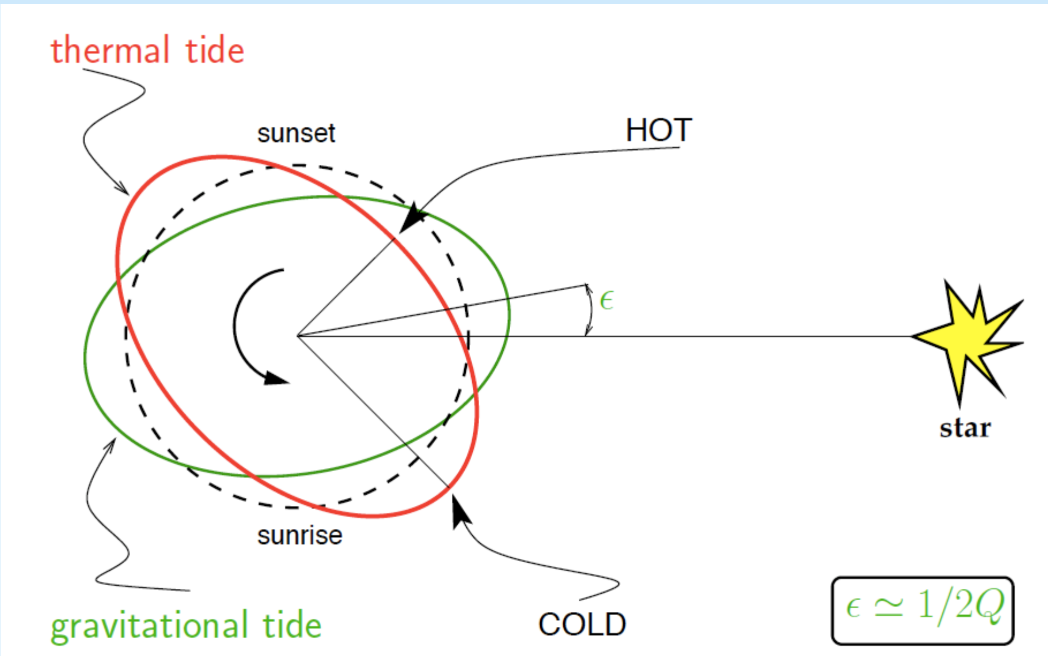
Example XO-4b: Inflated, Current e ≈ 0, but not well constrained



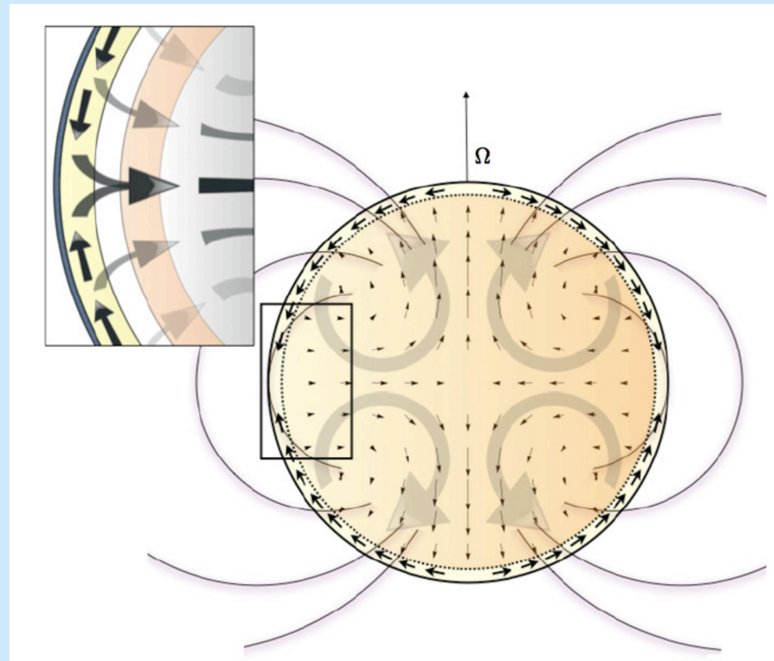
Explaining Large Radii: Two Recent Contenders

Thermal Tide



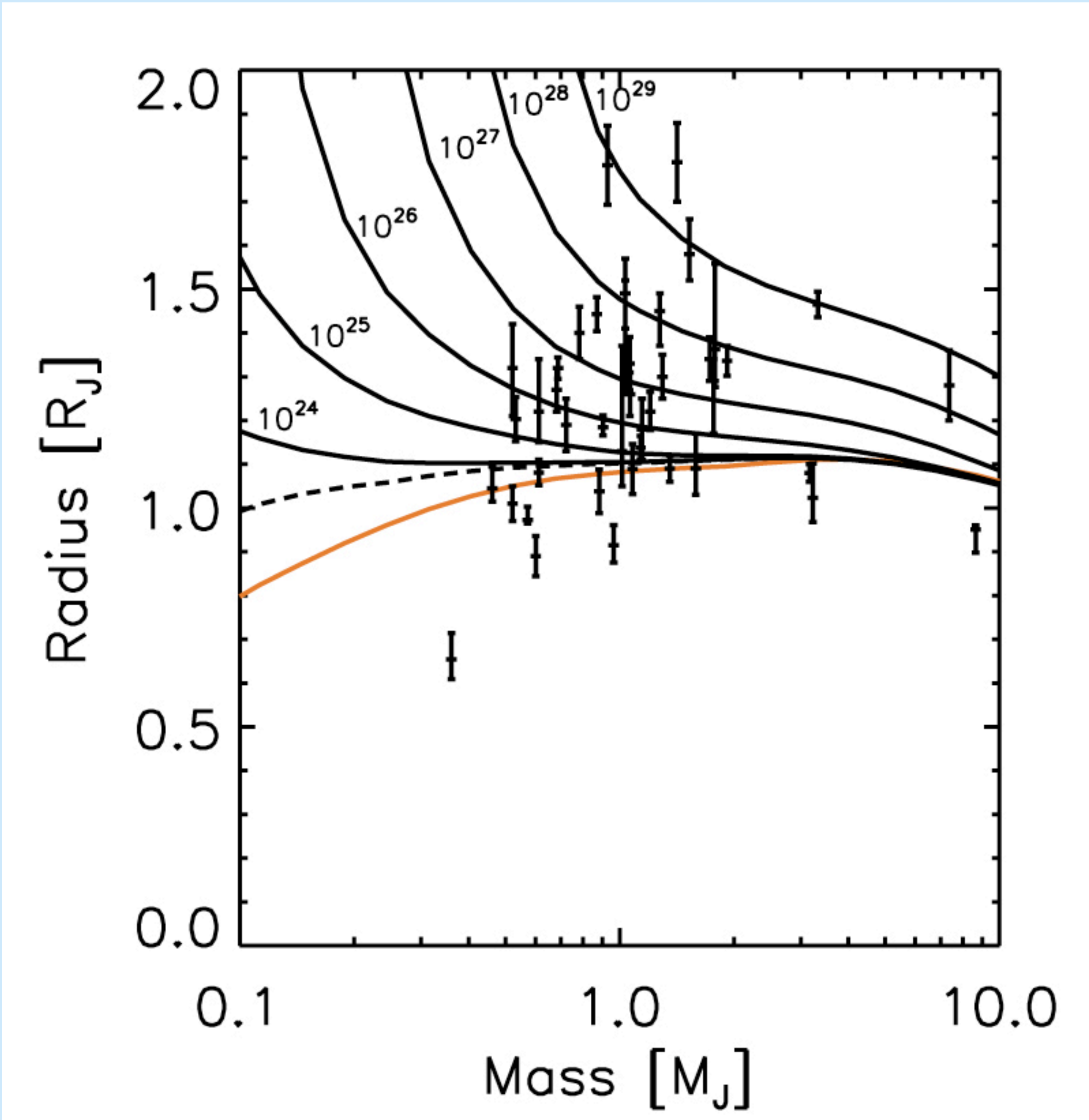
Arras & Socrates (2010)

Ohmic Dissipation



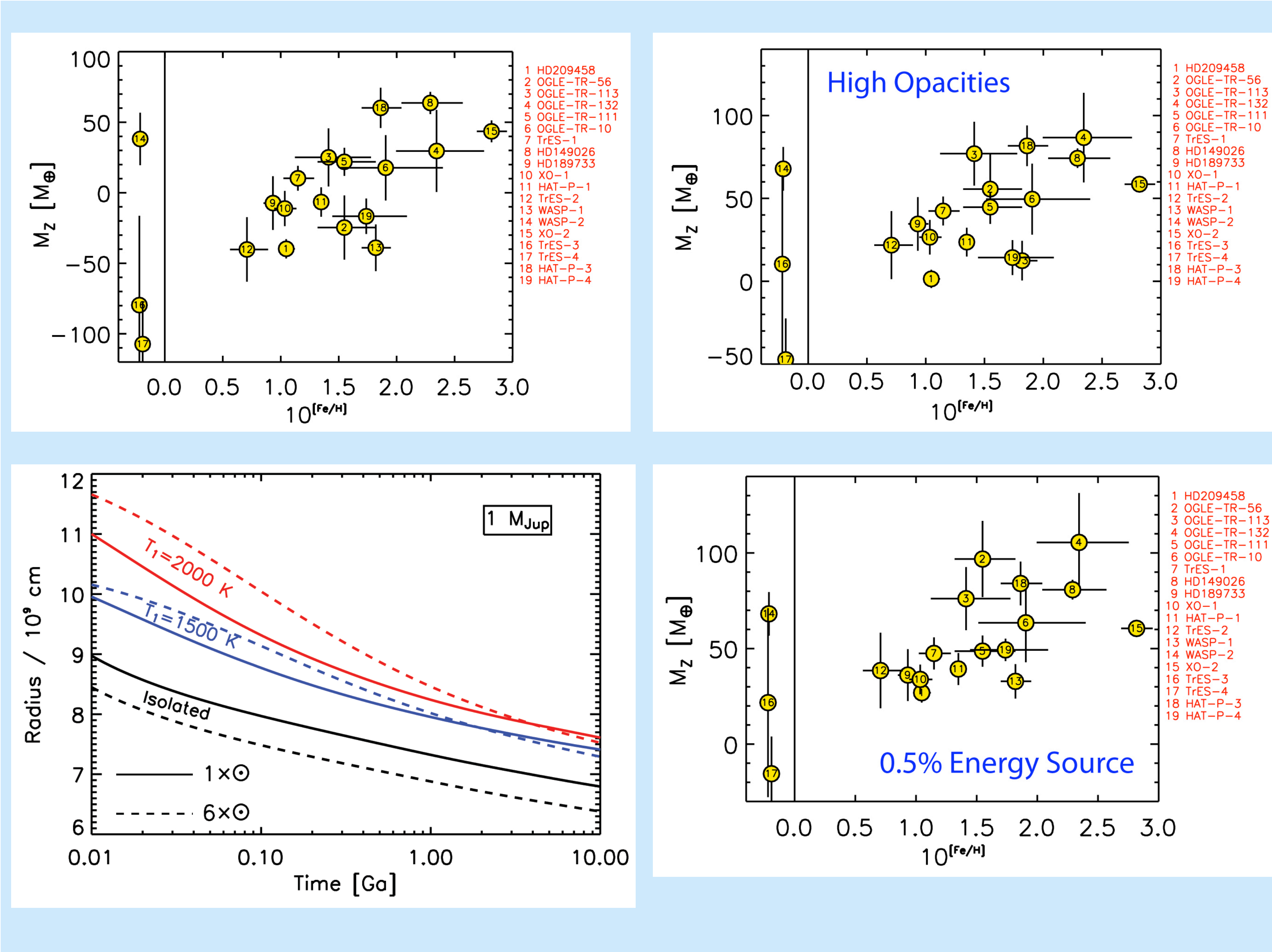
Batygin & Stevenson (2010)

Building a Model, II: Additional Interior Power



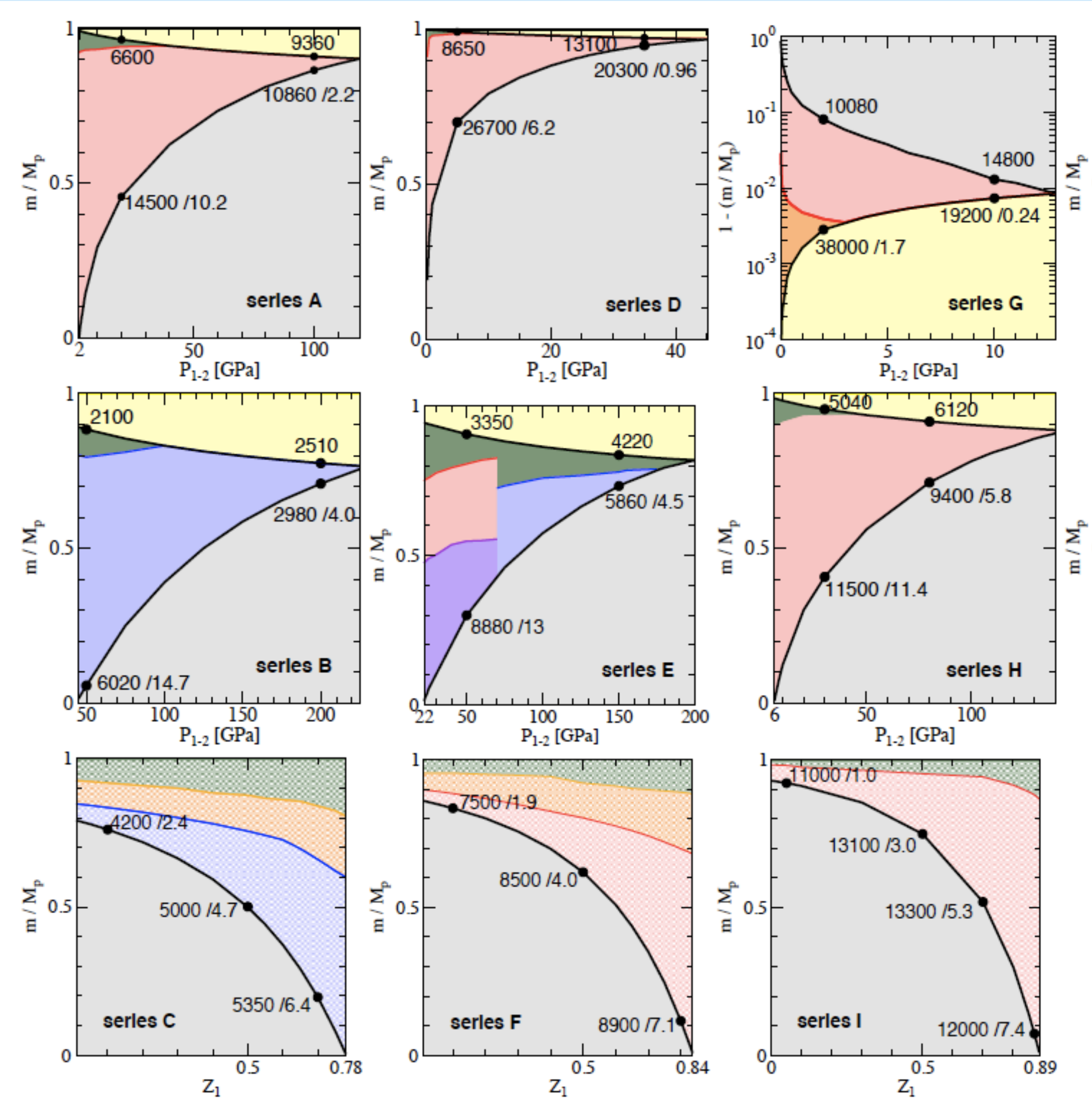
Miller, Fortney, & Jackson (2009)

- 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
- Transit radius effect only important at low gravity



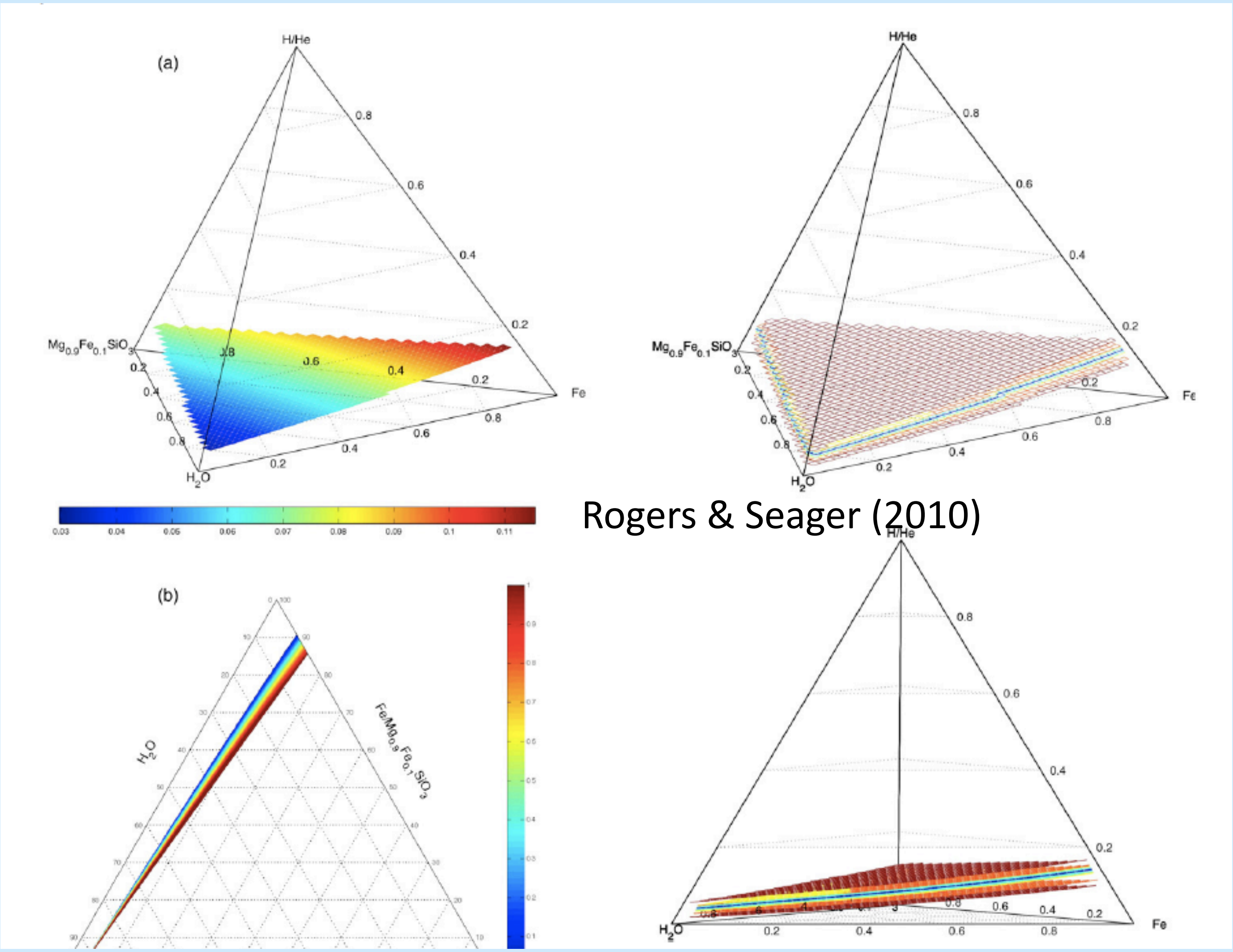
High Opacities
0.5% Energy Source
M_Z [$M_\oplus$]
$10^{[Fe/H]}$
1 HD209458
2 OGLE−TR−56
3 OGLE−TR−113
4 OGLE−TR−132
5 OGLE−TR−111
6 OGLE−TR−10
7 TrES−1
8 HD149026
9 HD189733
10 XO−1
11 HAT−P−1
12 TrES−2
13 WASP−1
14 WASP−2
15 XO−2
16 TrES−3
17 TrES−4
18 HAT−P−3
19 HAT−P−4
1 M_{Jup}
T_1=2000 K
T_1=1500 K
Isolated
1×⊙
6×⊙
Radius / 10^9 cm
Time [Ga]

Degeneracy: Many compositions yield the same mass/radius



Nettelmann et al. (2010)

“Exo-Neptunes” Make it Even Worse



Rogers & Seager (2010)

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

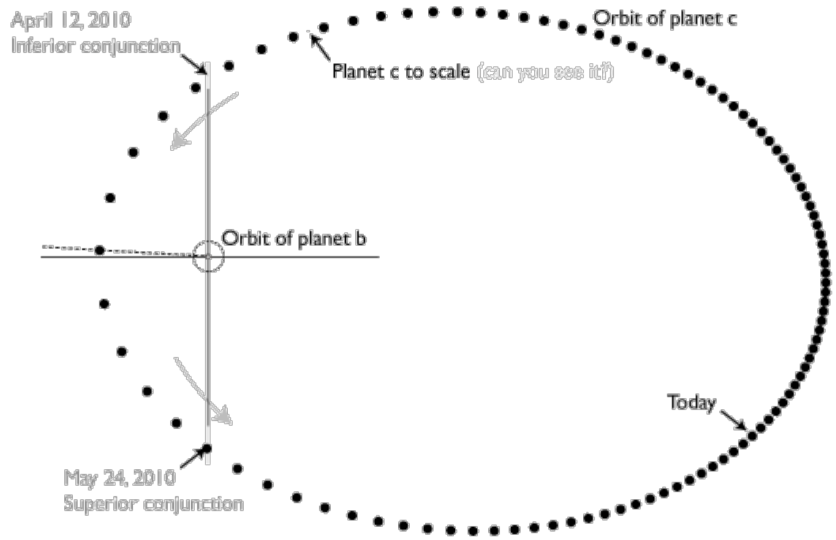
Transits in multi-planets systems: A path towards direct interior constraints: Tidal Love #, k_{2b}

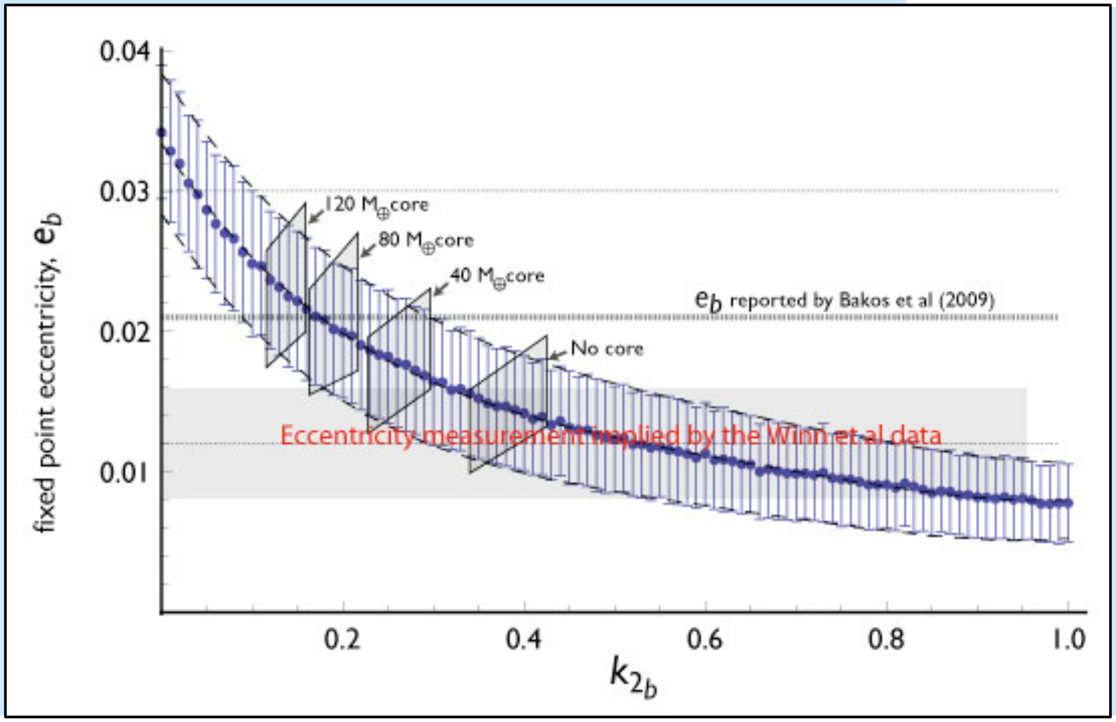
calculation of k_{2b} is straightforward (Sterne 1939),[3]

$$k_{2b} = \frac{3 - \eta_2(R_{\rm Pl})}{2 + \eta_2(R_{\rm Pl})}\,, \tag{13}$$

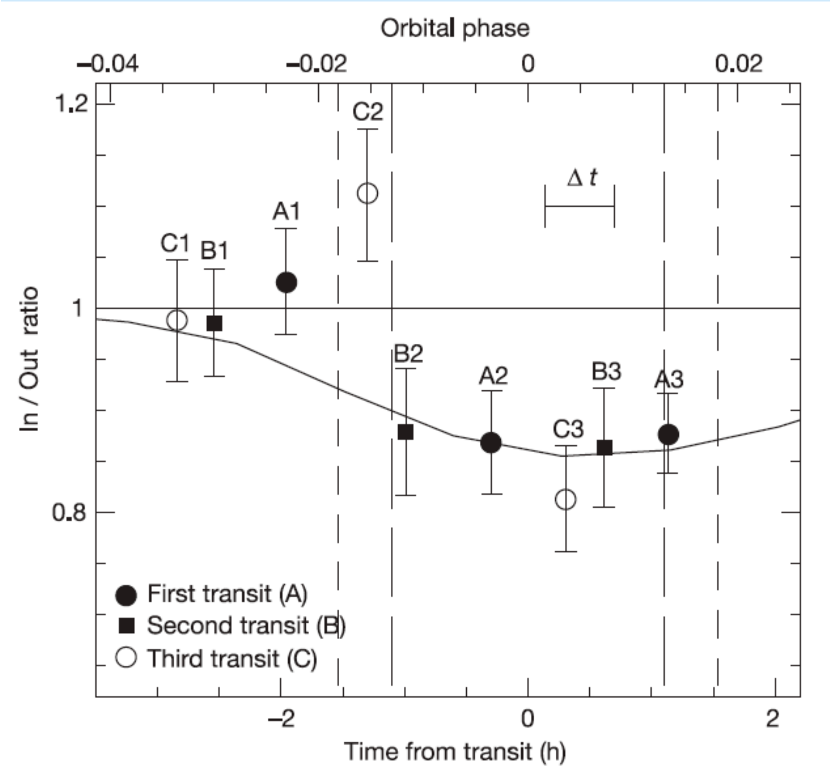
where $\eta_2(R_{\rm Pl})$ is obtained by integrating an ordinary differential equation for $\eta_2(r)$ radially outward from $\eta_2(0) = 0$,

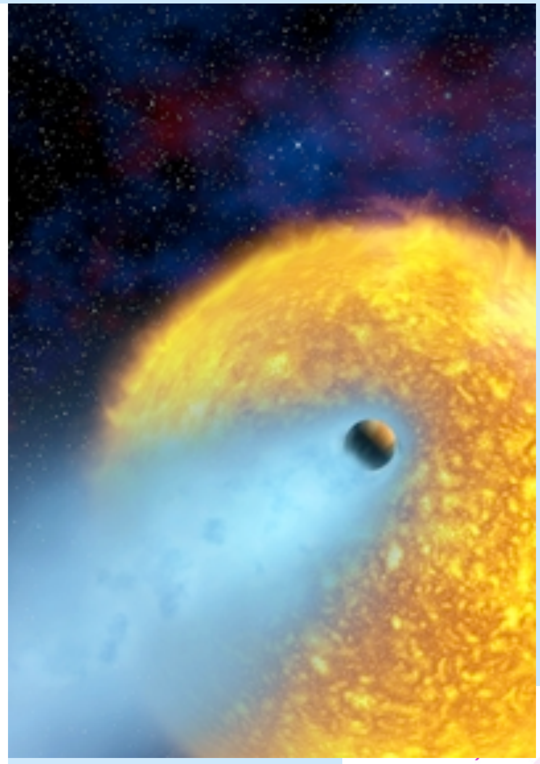
$$r\frac{d\eta_2}{dr} + \eta_2^2 - \eta_2 - 6 + \frac{6\rho}{\rho_m}(\eta_2 + 1) = 0\,, \tag{14}$$



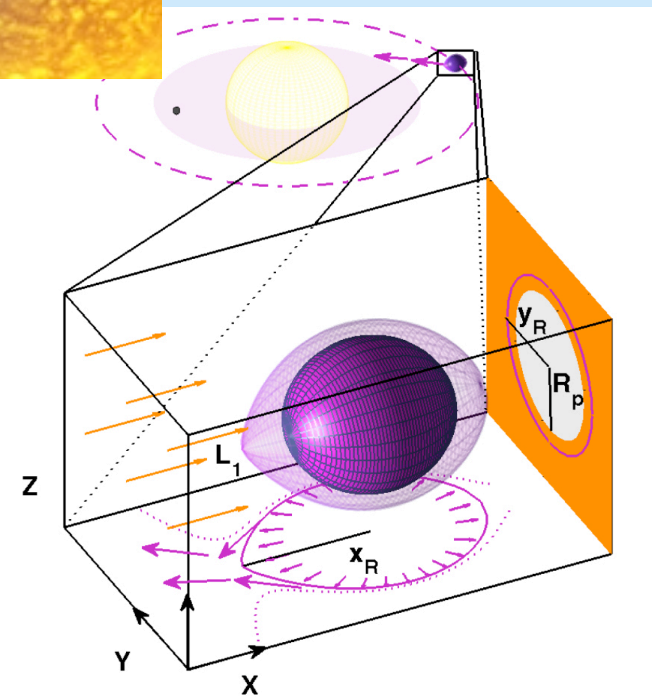


Wu & Goldreich (2005)
Batygin et al. (2009)



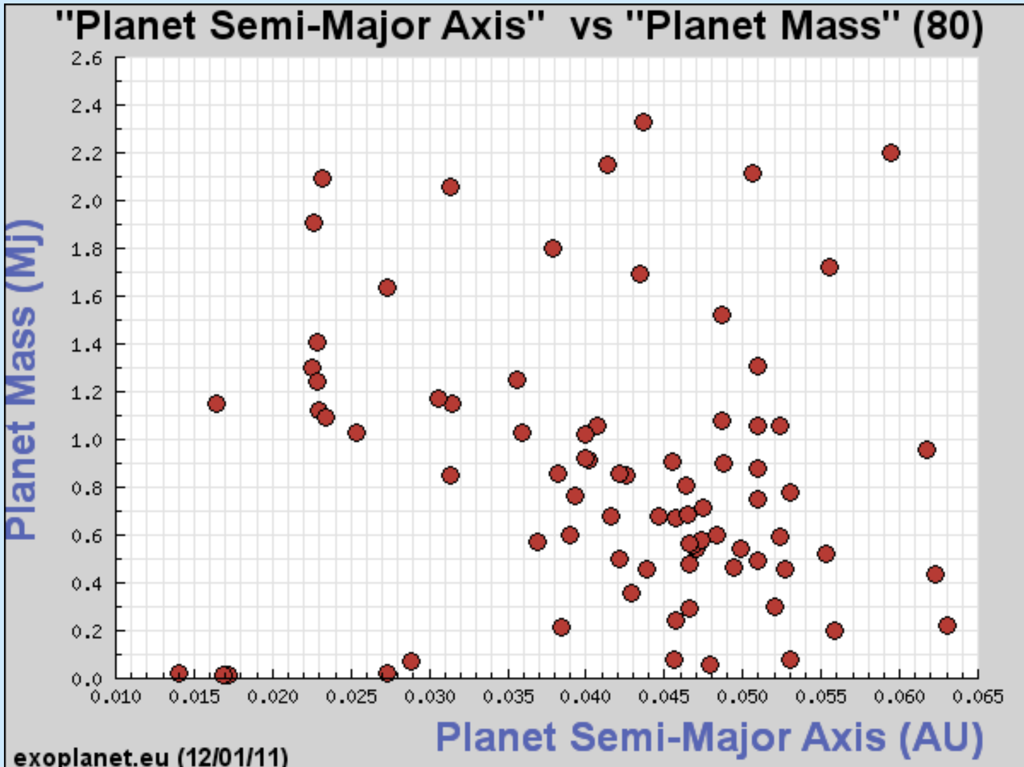


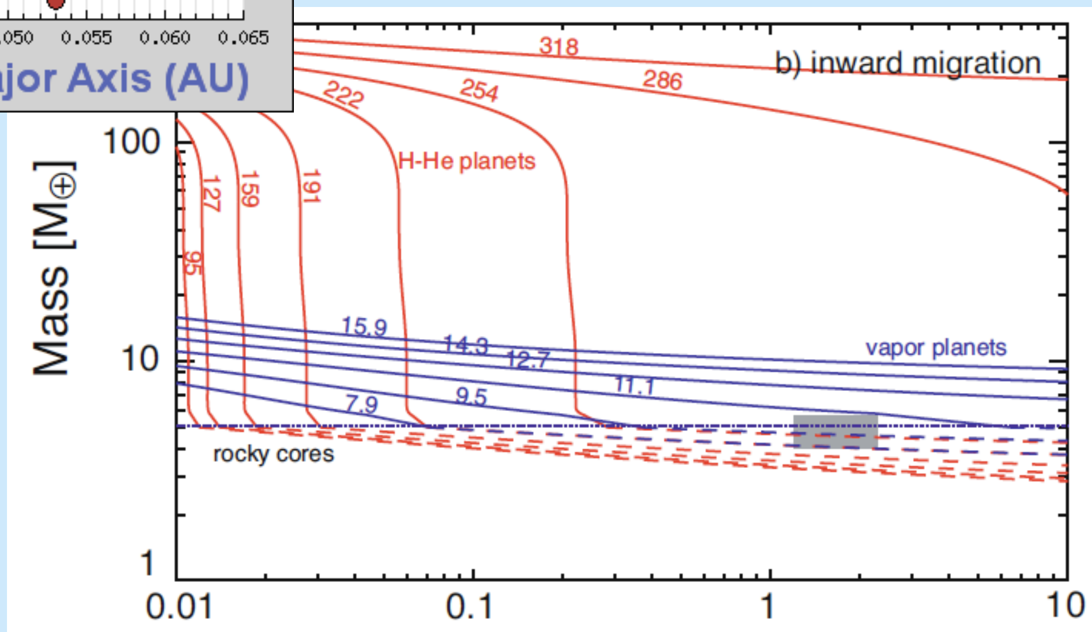
Ongoing Mass Loss



Vidal-Madjar et al. (2003): “evaporative” mass loss

- •Observed for ~3 planet but likely common to all hot Jupiters
- •Probably has little effect on evolution of Jupiter-class planets, but likely important for smaller Neptune-class planets

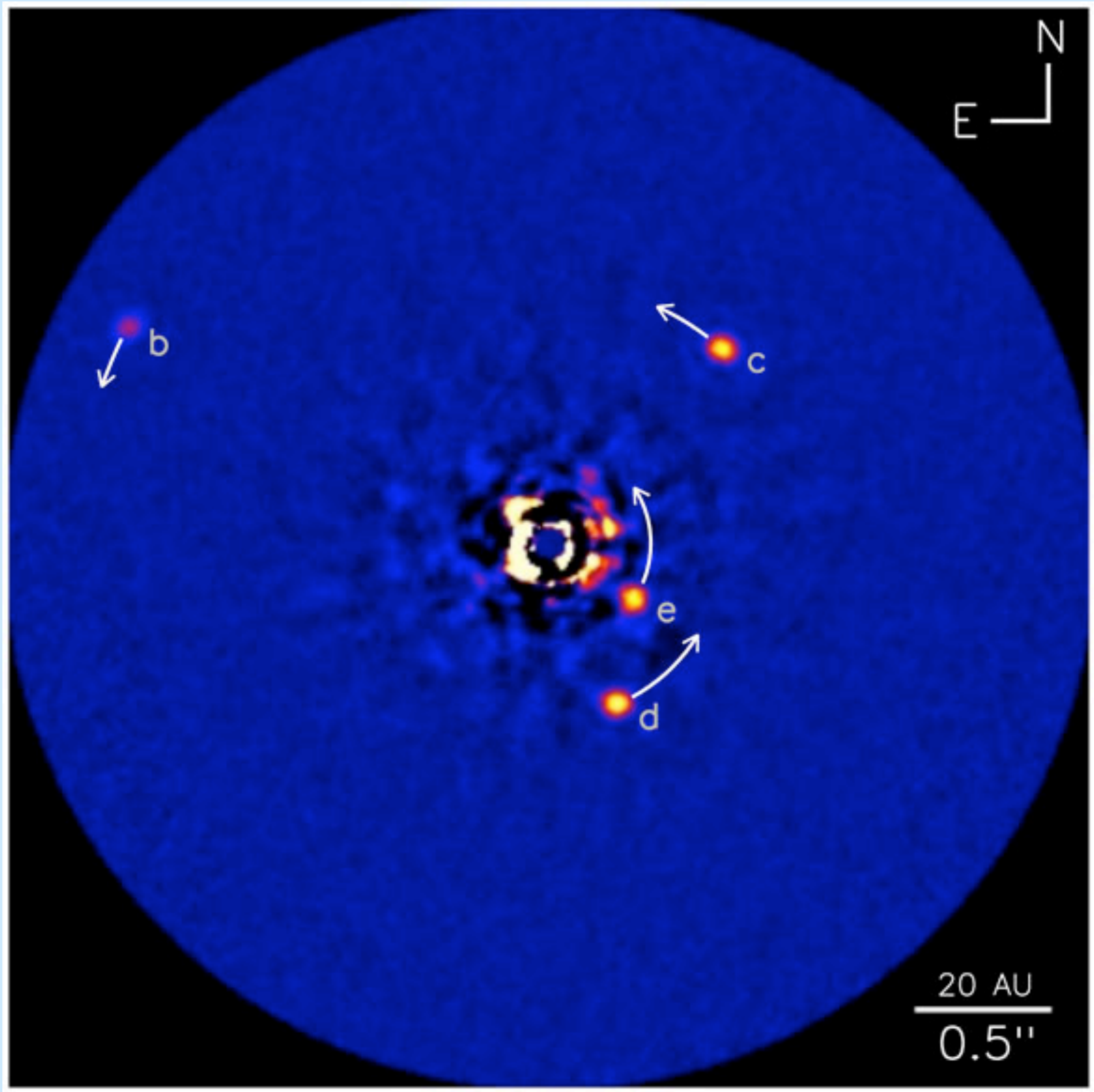




Valencia et al. (2010)

CoRoT-7b

Direct Imaging: Probes of Early Planet Evolution



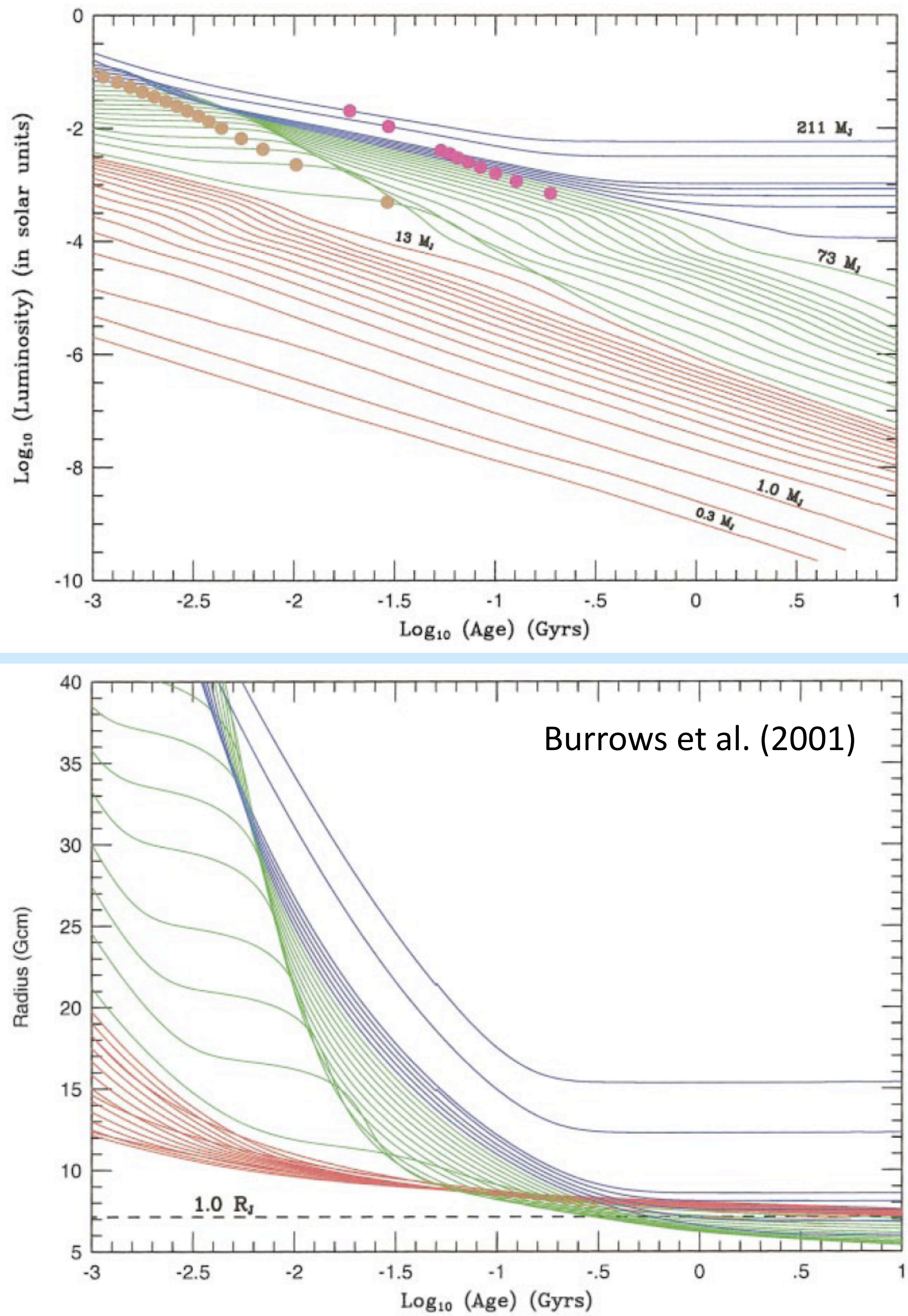
Marois et al. (2010)

Suites of Thermal Evolution Models for Planets and Brown Dwarfs

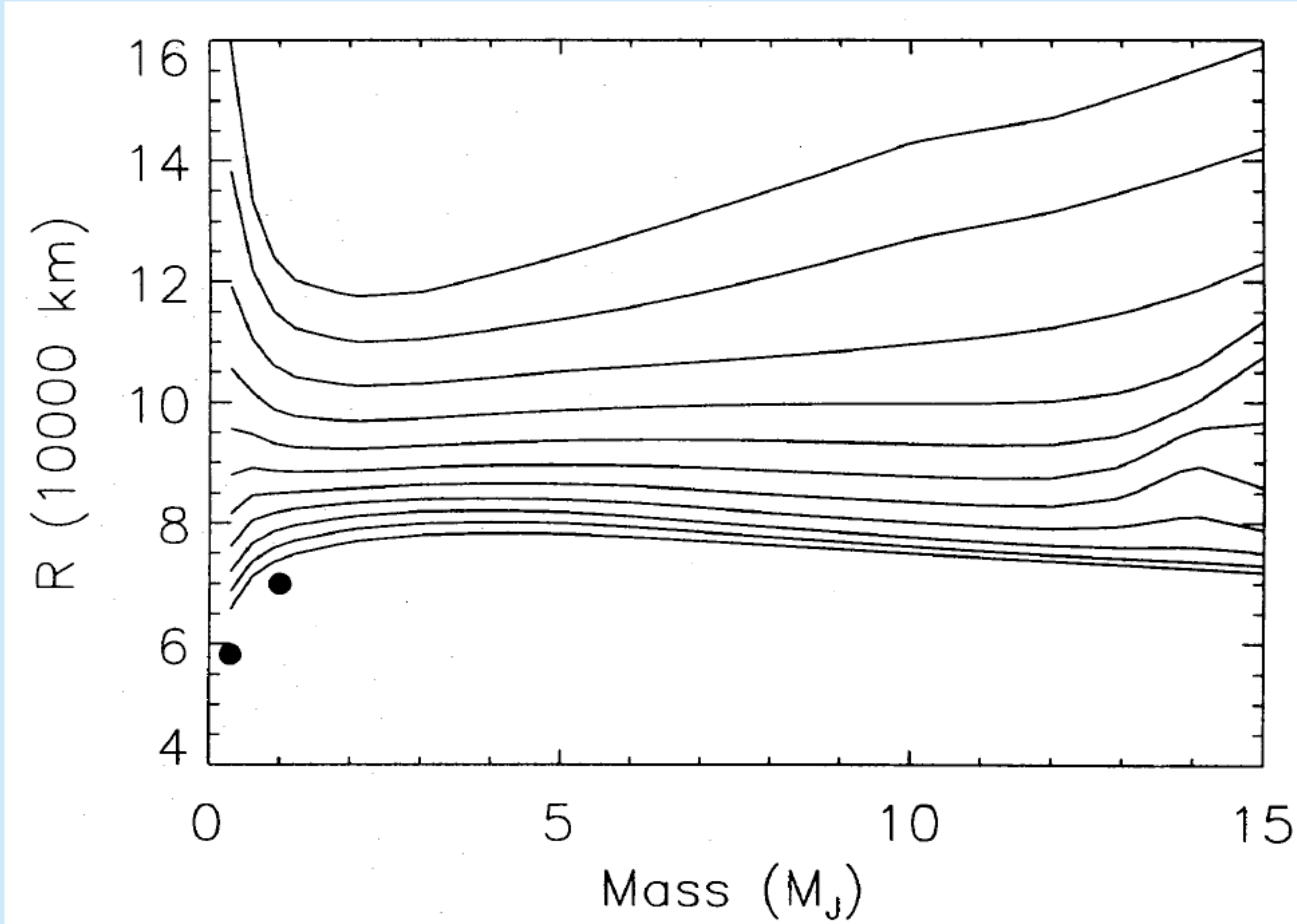
The standard references are:
Burrows et al. (1997)
Chabrier et al. (2000)
Baraffe et al. (2003)
Saumon & Marley (2008)

What assumption goes into the initial condition for these models, and are they correct?

Investigated in Marley, Fortney, et al. (2007)



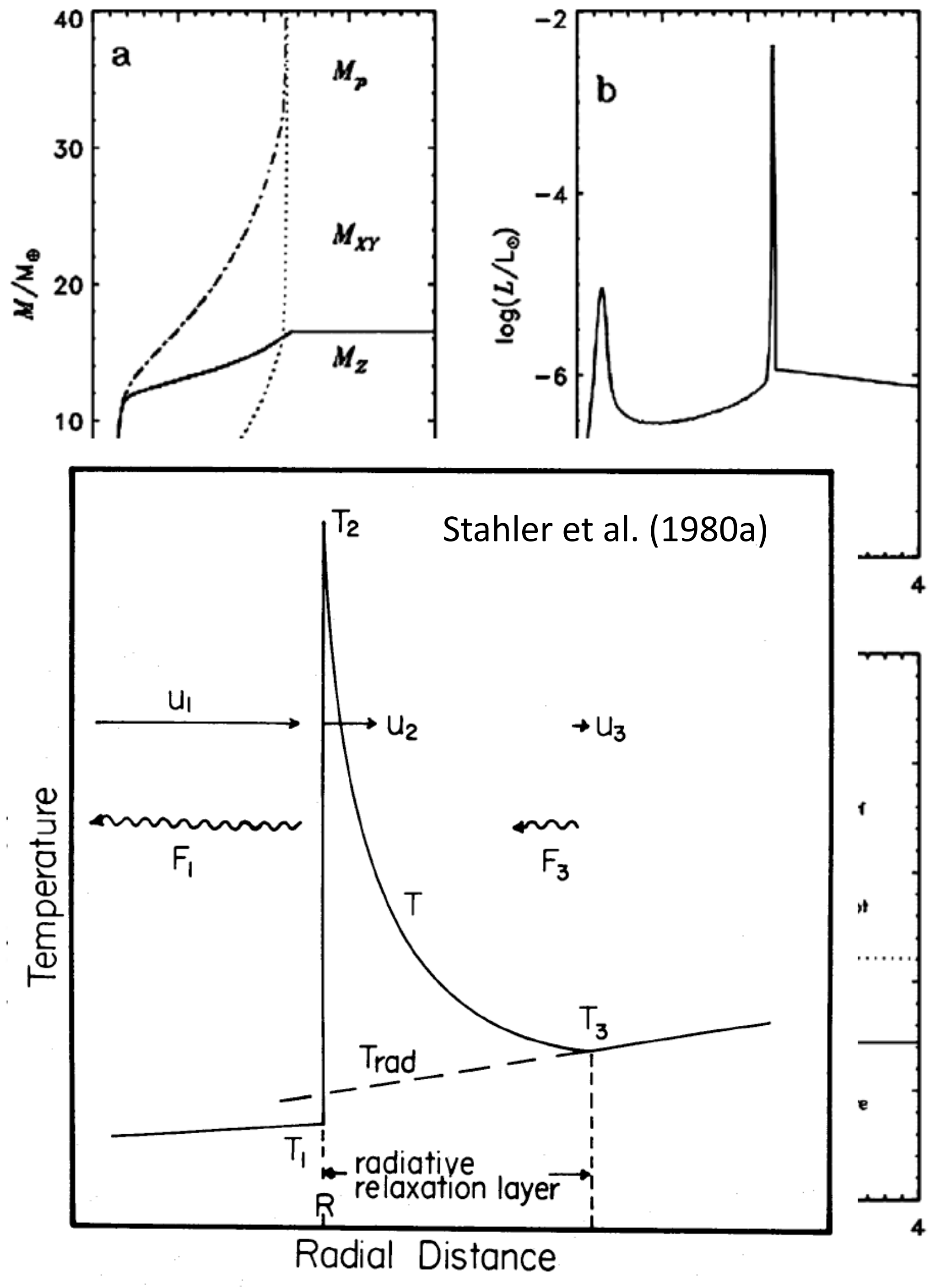
Saumon et al. (1996)



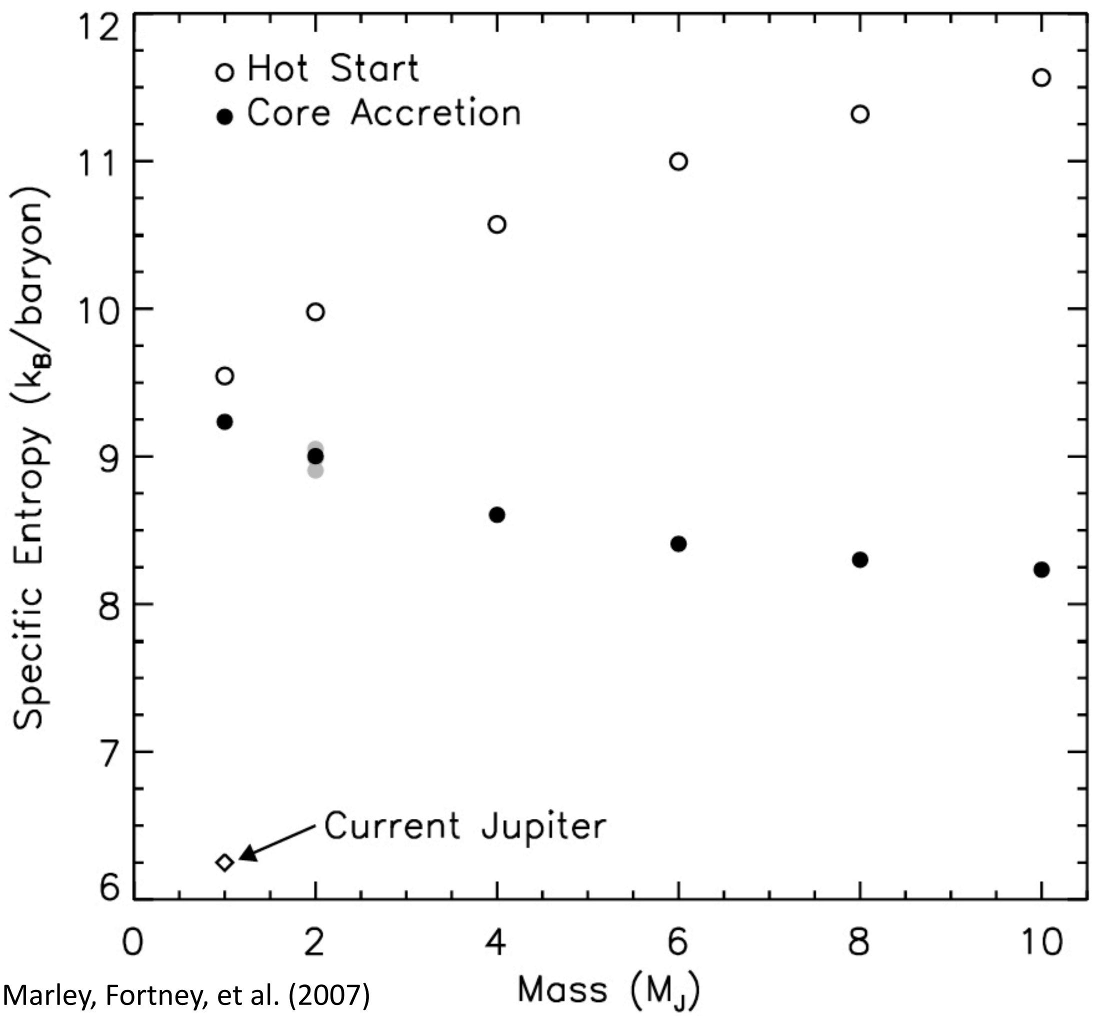
"Although all these calculations may reliably represent the degenerate cooling phase, they cannot be expected to provide accurate information on the first 10^5-10^8 years of evolution because of the artificiality of an initially adiabatic, homologously contracting state.
--Stevenson (1982)

Hubickyj, Bodenheimer, & Lissauer implementation of the core-accretion model

1. Planetesimals→core
2. Gas accretion rate grows and surpasses solid accretion rate
3. Runaway gas accretion
4. Limiting gas accretion→how fast can nebular gas be supplied? Gas arrives at a *shock interface*.
5. Accretion terminates→ isolation stage (cooling & contraction)



Post-Formation Entropy



Marley, Fortney, et al. (2007)

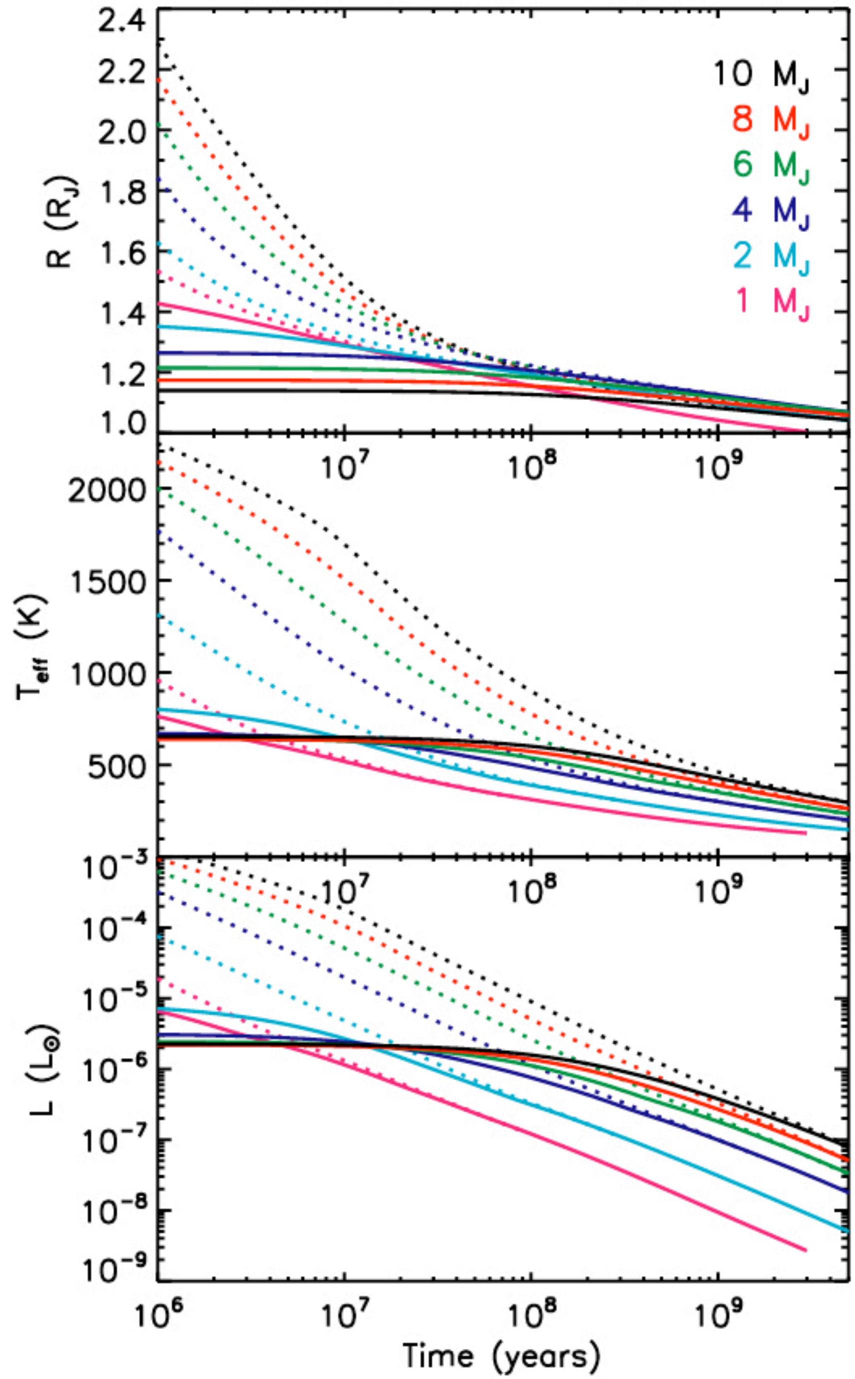
- Internal specific entropy 1 Myr after formation
- Entropy monotonically decreases with age
- Low post-formation entropy → small radii & low luminosity
- Quite dependent on the treatment of the accretion shock!
- At higher masses, a higher % of mass has passed through shock

1. Core-accretion planets are formed with significantly smaller entropy and radii

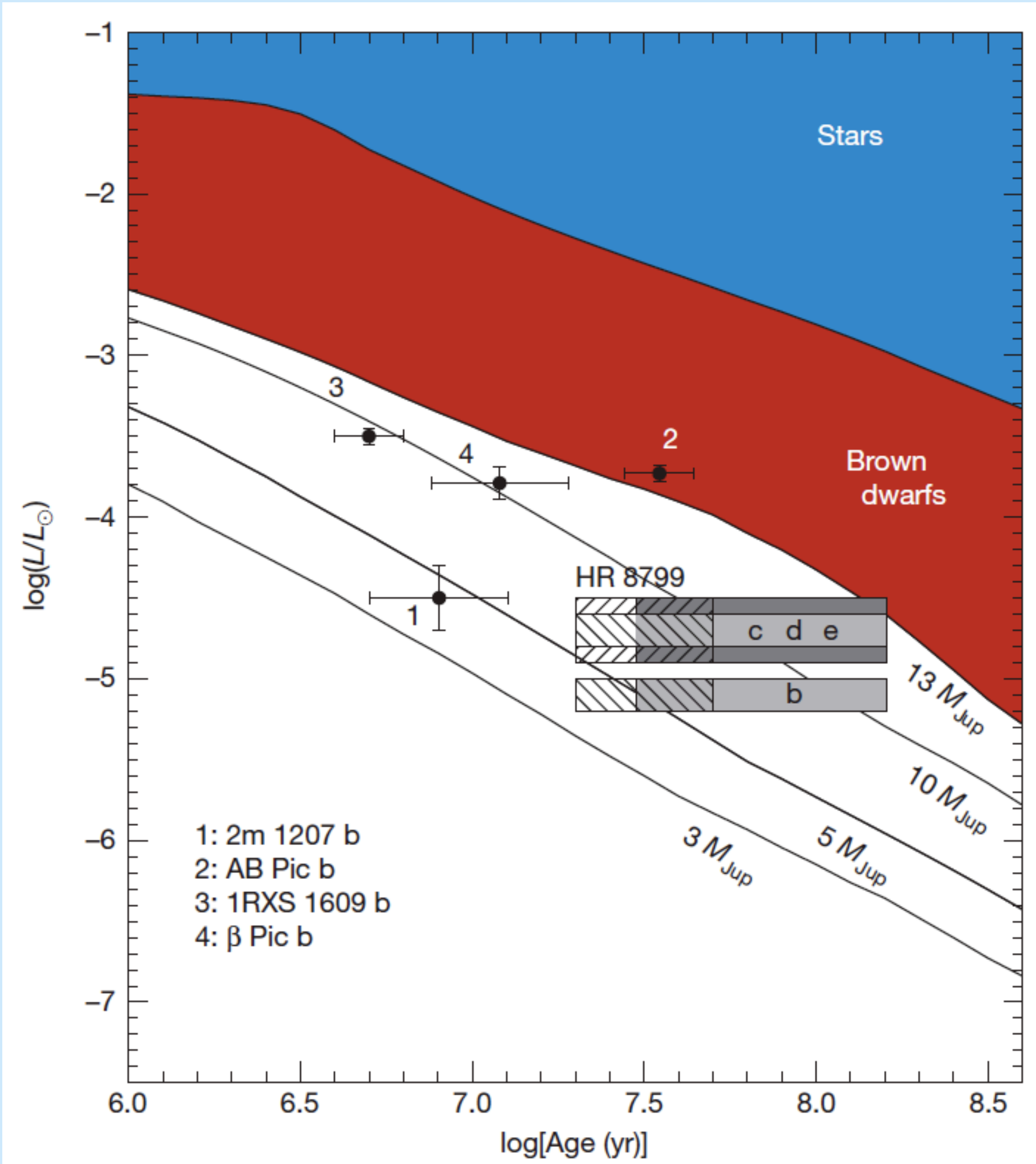
2. $t_{KH} \propto 1/LR \propto e^{-2.8S}$, meaning evolution is initially much slower for the core-accretion planets

3. Initial conditions are not forgotten in "a few million years," but rather, 10 million to 1 billion.

4. Initial T_{eff} values cluster around 600-800 K



The HR 8799 system



If these planets did form by core accretion, then perhaps the "hot start" is closer to reality

Starting in late 2011, the Gemini Planet Imager (GPI) on Gemini South and SPHERE on the VLT, specially designed "extreme AO" instruments, should image 100-400 additional giant planets

Conclusions

- The field is going from 4 objects to hundreds, and then thousands
- A measurement of mass-radius yields important information about the structure of a gas giants
- Mass-radius tells us less about about the structure of Neptune-class planets, broadly defined
- Work is progressing on understanding the visible atmosphere
- No clear winner yet regarding what is inflating the planets, but emerging trends will help to clarify this issue