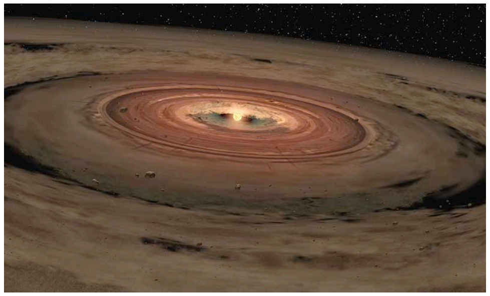
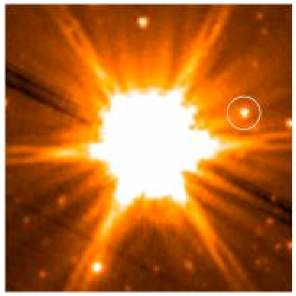
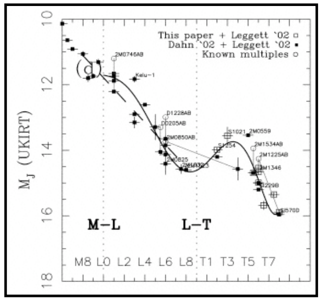
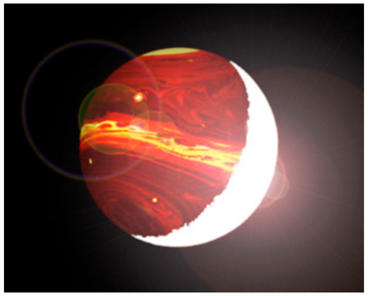
Research paper assignment

- Review of research that interests you, more focused than discussions in class
- Include references and figures
- Final format should be PDF (try LaTeX!)
- Concise! < 5000 words
- Steps:
  - Write down specific questions that interest you and **send them to us by March 21st** (next week)
  - On approval, search the literature (resources on webpage)
  - Refine outline, write paper - **first draft due April 25th**
  - After paper is reviewed, revise and **submit final draft by May 16**

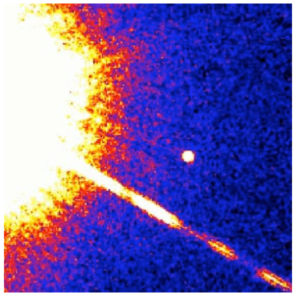
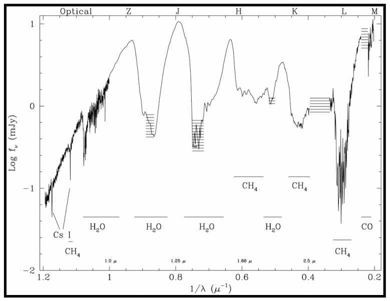
Full information on webpage: **http://web.mit.edu/8.972/www**

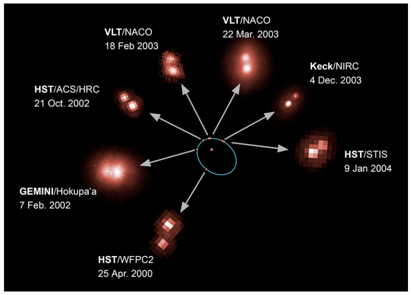




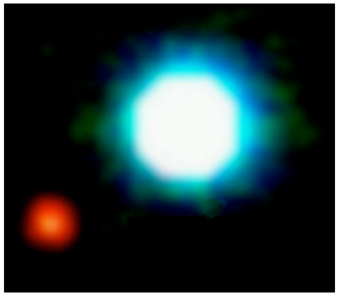


Lecture 6:

Interiors of Brown Dwarfs and Exoplanets





What is the state of matter inside a brown dwarf/exoplanet?

What determines the minimum mass for H fusion?

How does the interior state relate to the gross physical properties of brown dwarfs/exoplanets?

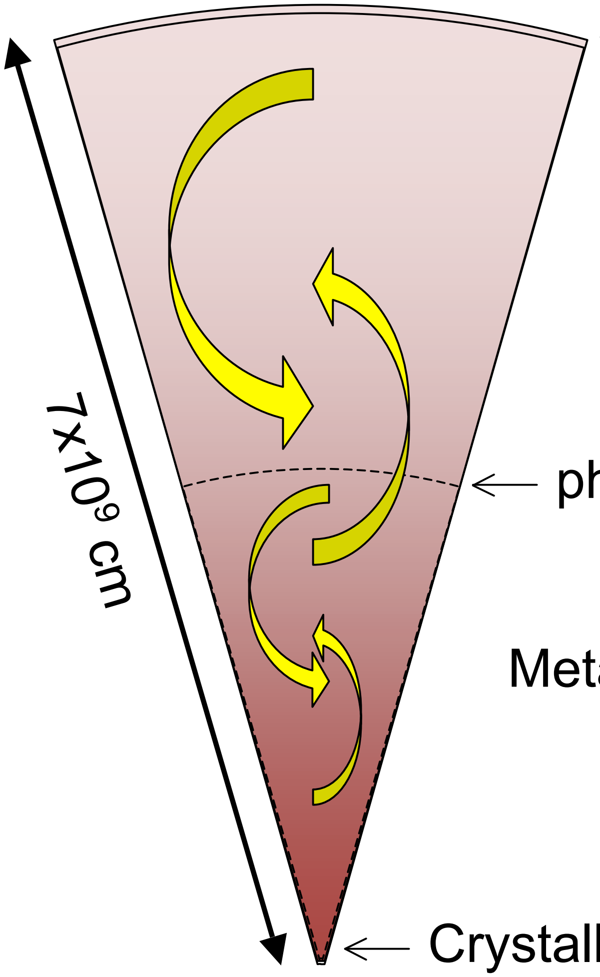
How do we model the evolution of a brown dwarf/exoplanet?

How do we check our interior models through observation?

	5 Myr BD	5 Gyr BD	5 Gyr Jupiter
Mass ($M_\odot$)	0.05	0.05	0.001
Radius ($R_\odot$)	0.6	0.09	0.11
g (cm/s^2)	$6x10^3$	$2x10^5$	$3x10^3$
ρ_c (g/cm^3)	4	600	3
P_c (Mbar)	50	10^5	10
T_c (°K)	10^6	10^6	$1.5x10^4$
ρ_{ph} (g/cm^3)	$3x10^{-6}$	10^{-4}	$6x10^{-6}$
P_{ph} (bar)	0.1	4	1
T_{eff} (°K)	3000	800	125
L ($L_\odot$)	$3x10^{-2}$	$3x10^{-6}$	10^{-9}

0.05 $M_\odot$ Brown dwarf at 5 Gyr

P ≈ 5 bar, T ≈ 1000 K, $\rho \approx 10^{-4}$ g/cc



7×10^{9} cm

← atmosphere (~10 km)

H_2 fluid

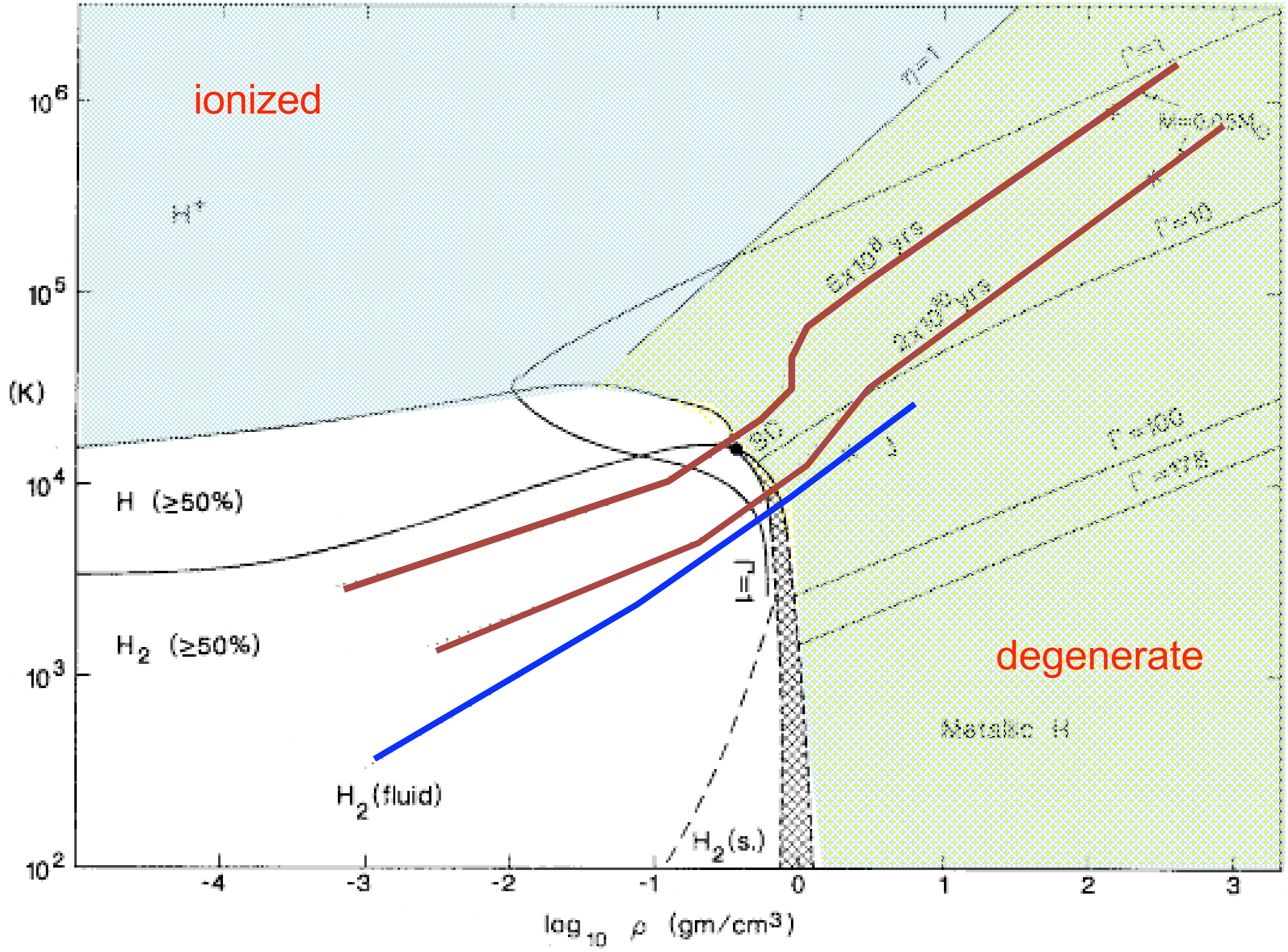
← phase change?

Metallic H

← Crystalline H?

P ≈ 10^{11} bar, T ≈ 10^{6} K, $\rho \approx 500$ g/cc

The state of Hydrogen



Burrows & Liebert (1993)

Bulk of substellar interior is…

- **Ionized H & He** via pressure ionization (ρ > 1 g/cc)
- **Partially degenerate electron gas**:

$$\eta \equiv \frac{kT_F}{kT} = \frac{1}{T}\frac{\hbar^2}{2m_e}\left(3\pi^2\frac{\rho}{\mu_e m_p}\right)^{\frac{2}{3}} \approx 3{\times}10^5\frac{\rho^{2/3}}{T} \approx 10$$

- **Strongly coupled plasma** due to coulomb forces

$$\Gamma \equiv \frac{Z^2e^2}{r_s kT} \approx 2.3{\times}10^5\rho^{1/3}T^{-1} \approx 1$$

- **Fully convective** - radiative opacity (primarily election scattering) is high for T > 10^4 K

Polytrope models

Kippenhahn & Weigert (1930s)

See Hansen & Kawaler “Stellar Interiors”

$$\frac{dP}{dr} = -\frac{GM(r)\rho}{r^2}$$ Hydrostatic equilibrium

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho$$ Continuity equation

$$\Rightarrow \frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2}{\rho}\frac{dP}{dr}\right) = -4\pi G\rho$$ **Poisson’s equation**

Polytrope models

$$\boxed{P = K\rho^{1+\frac{1}{n}}}$$

Equation of state (EOS)

Then, with some algebraic manipulation…

$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta}{d\xi}\right) = -\theta^n$$

Lane-Emden equation

With $\rho(r) = \rho_c\theta^n(r)$ and $r = \xi\sqrt{\frac{(1+n)P_c}{4\pi G\rho_c^2}}$

What is best polytrope?

$$P = K\rho^{1+\frac{1}{n}}$$

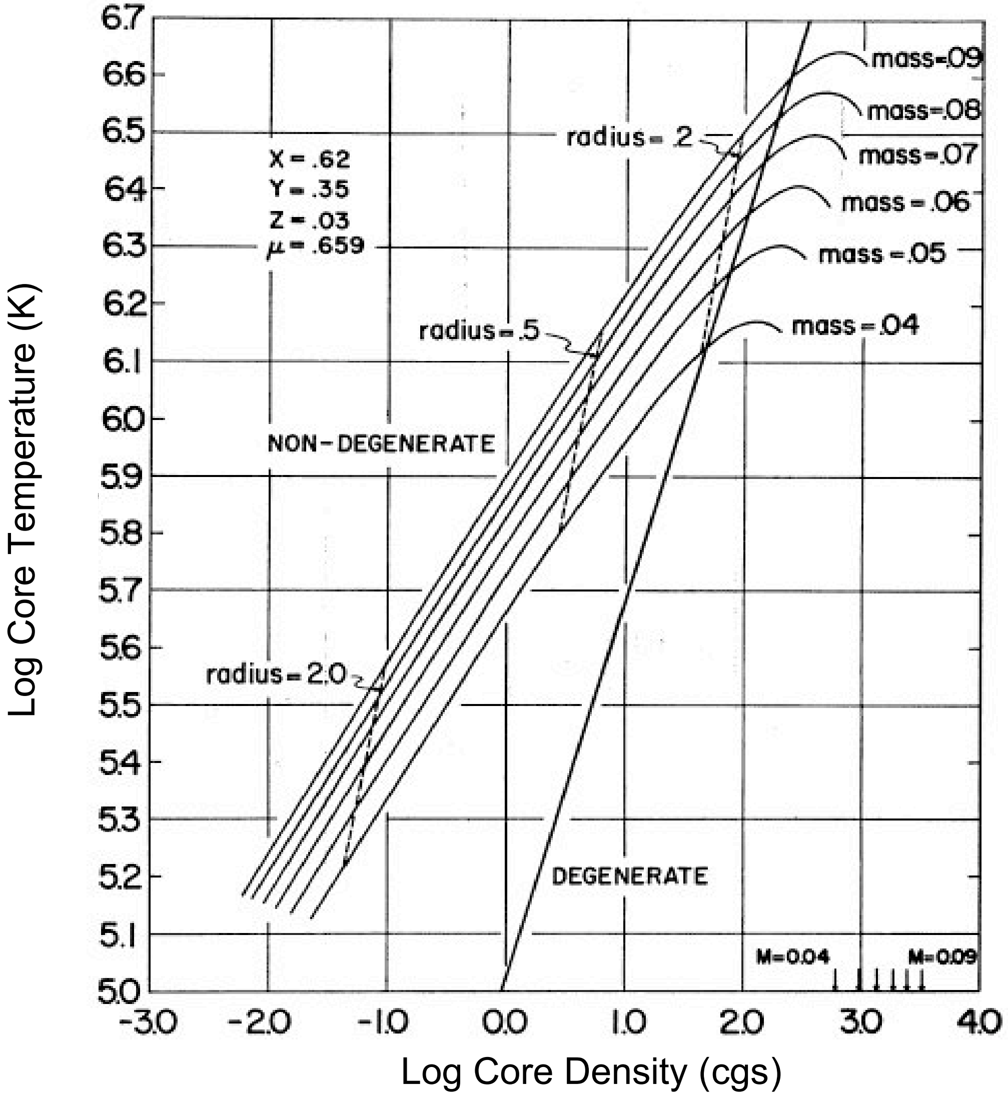
n = 1.5 - adiabatic ideal gas & degenerate gas

n = 1.0 - strongly coupled degenerate gas (appropriate for low mass, old brown dwarfs)

Scalings for n=1.5

$$\left\{\begin{aligned} \rho_c &\approx 6\langle\rho\rangle \propto M^2 \\ P_c &\approx 0.77\frac{GM^2}{R^4} \propto M^{10/3} \\ R &\approx 2.4\frac{K}{G}M^{-1/3} \propto M^{-1/3} \end{aligned}\right.$$

What sets the mass of a brown dwarf?



Kumar (1962, 1963); see also Hayashi & Nakano (1963)

The maximum core temperature as a function of mass can be determined by an appropriate polytrope model (e.g., Stevenson 1991) and must exceed the threshold for H fusion for a star.

Critical temperatures for fusion

PPI chain

$p + p \rightarrow d + e^{+} + \nu_e$ $T_{crit} \approx 3\text{x}10^6$ K, $M_{min} \approx 0.075\ M_\odot$

$p + d \rightarrow {}^3He + \gamma$ $T_{crit} \approx 5\text{x}10^5$ K, $M_{min} \approx 0.013\ M_\odot$

${}^3He + {}^3He \rightarrow {}^4He + 2p$ $T_{crit} \approx 6\text{x}10^6$ K, $M_{min} \approx 0.15\ M_\odot$

Li burning

(PPII chain)

${}^7Li + p \rightarrow {}^4He + {}^4He$ $T_{crit} \approx 2.5\text{x}10^6$ K, $M_{min} \approx 0.065\ M_\odot$

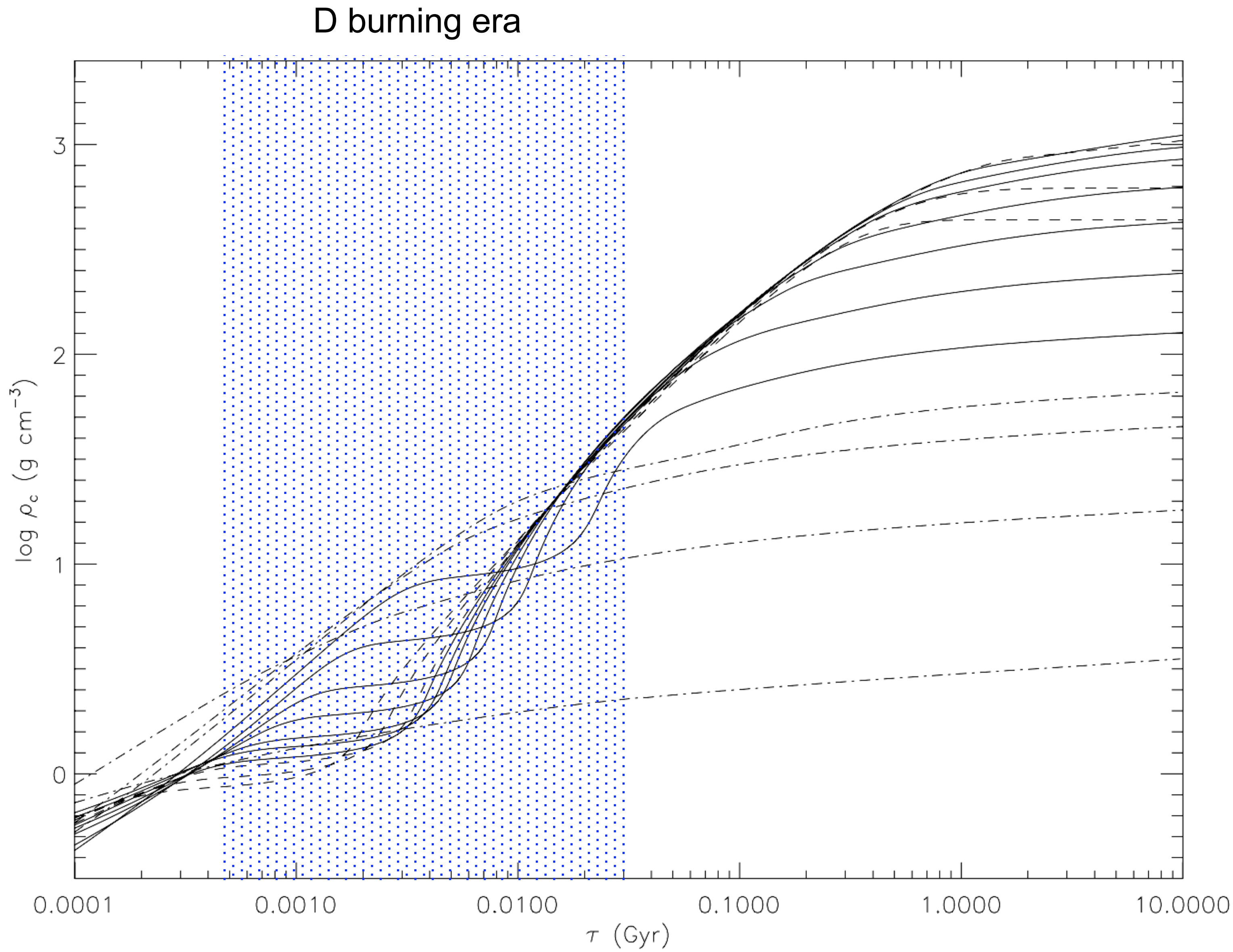
Evolution of a Brown Dwarf

Adiabatic P/ρ profile $\Rightarrow$ entropy (S) and degeneracy (η) are constant throughout interior*

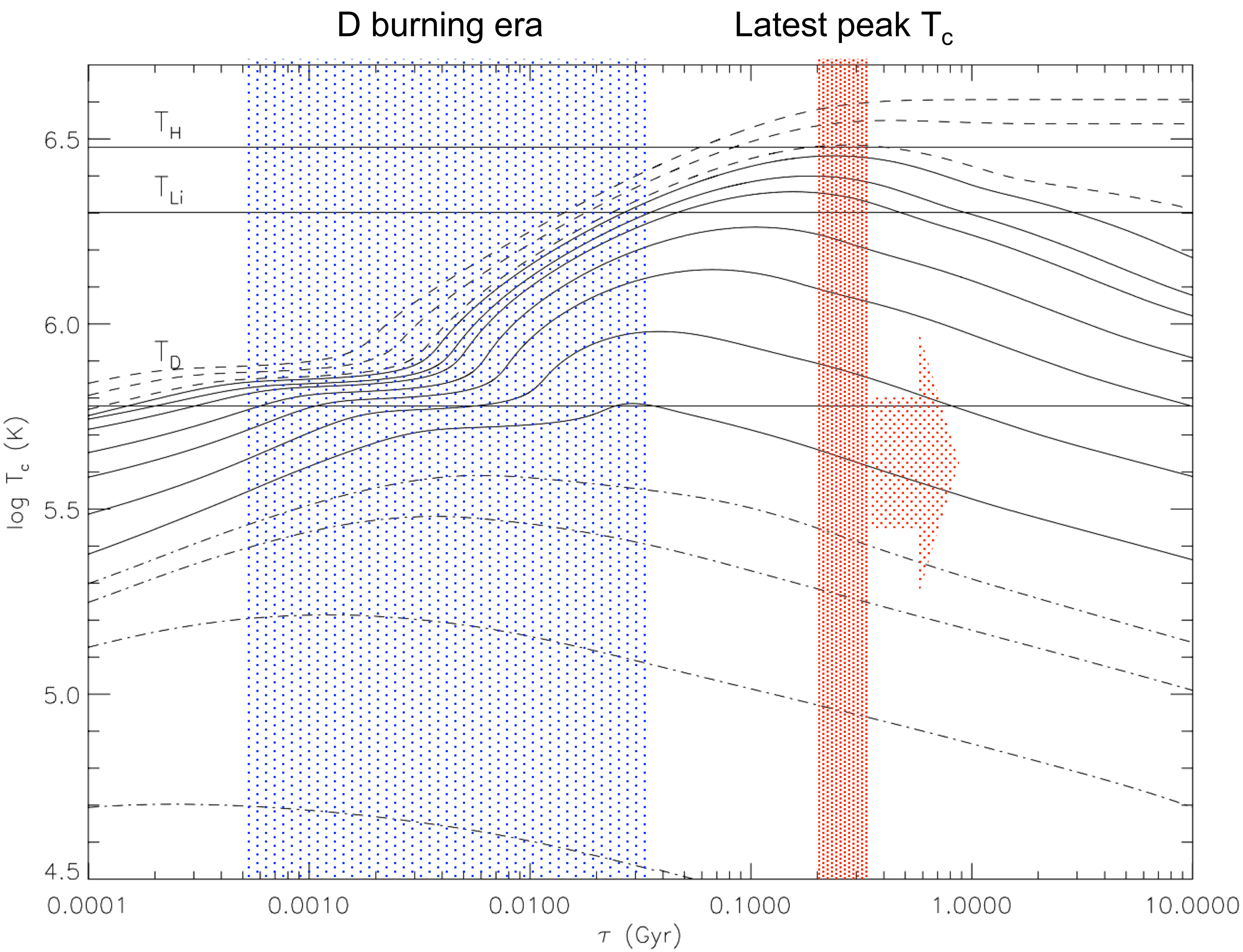
Evolution is dictated by decreasing S and increasing η

Entropy (energy content) lost ($-\frac{dS}{dt}\int TdM$) through radiation at photosphere ($L = 4\pi R^2\sigma T_e^4$) assuming entropy constant up to base of photosphere ($S_{interior} = S_{atm}$)

*Neglecting any phase transitions or a conductive core



Models from Burrows et al. (1997)



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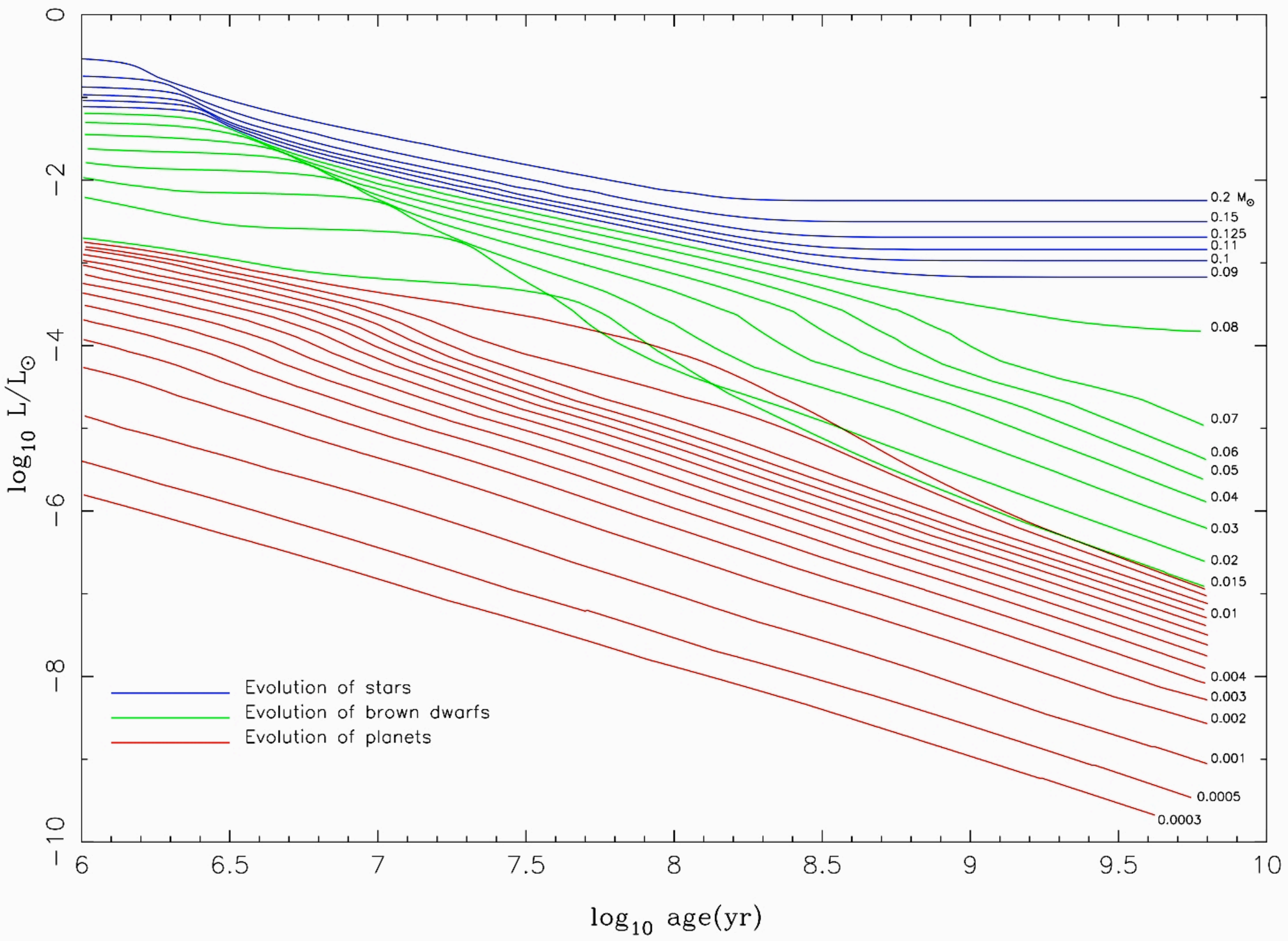

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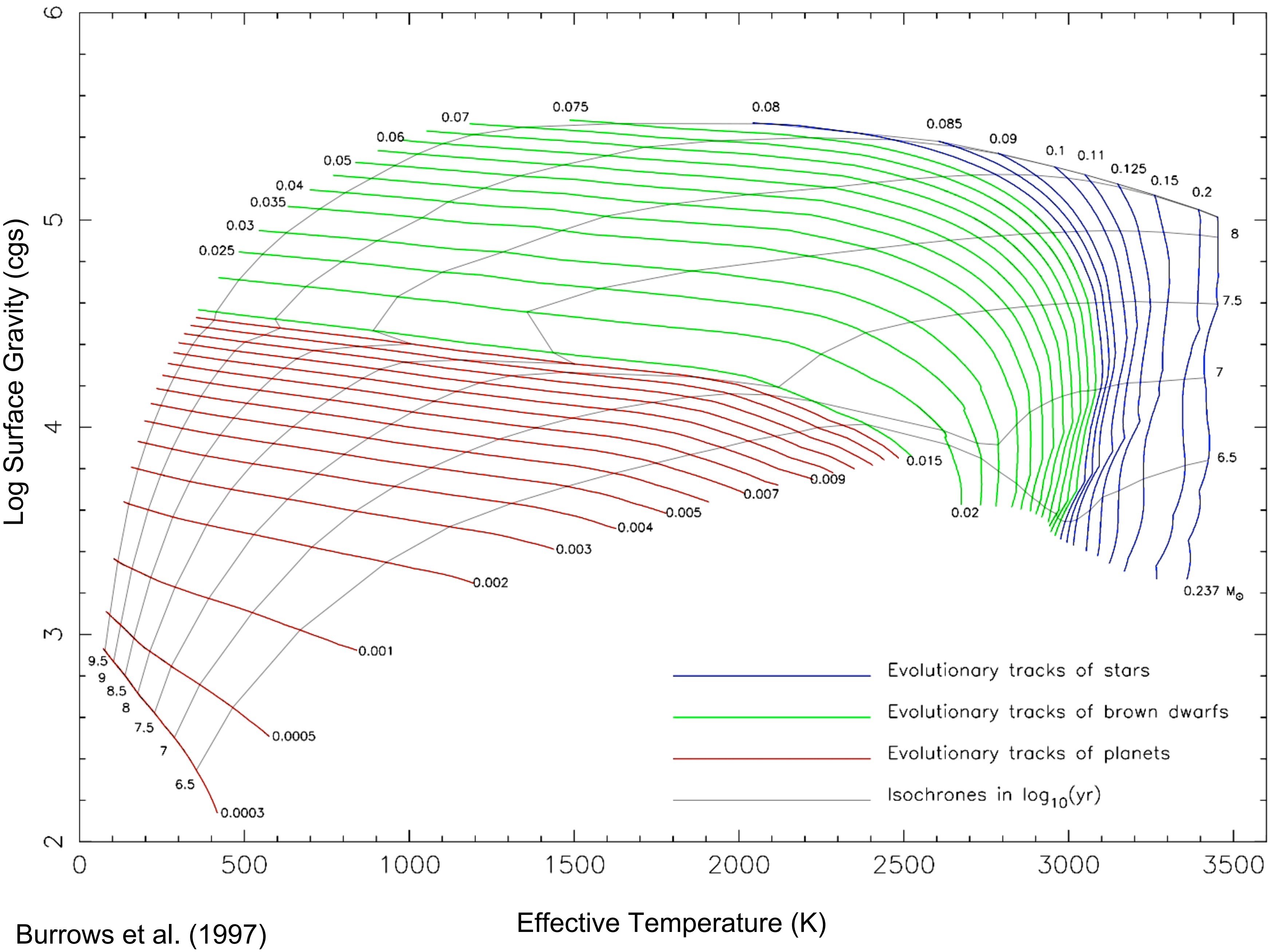
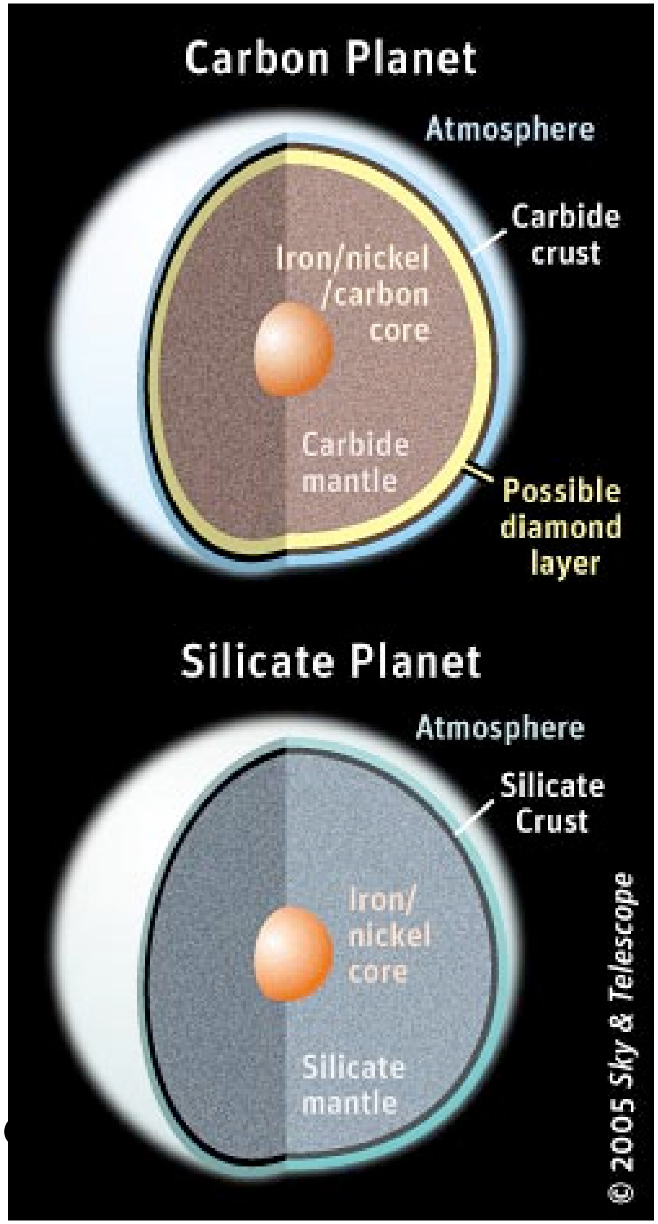


Burrows et al. (1997)

How do planetary interiors differ?

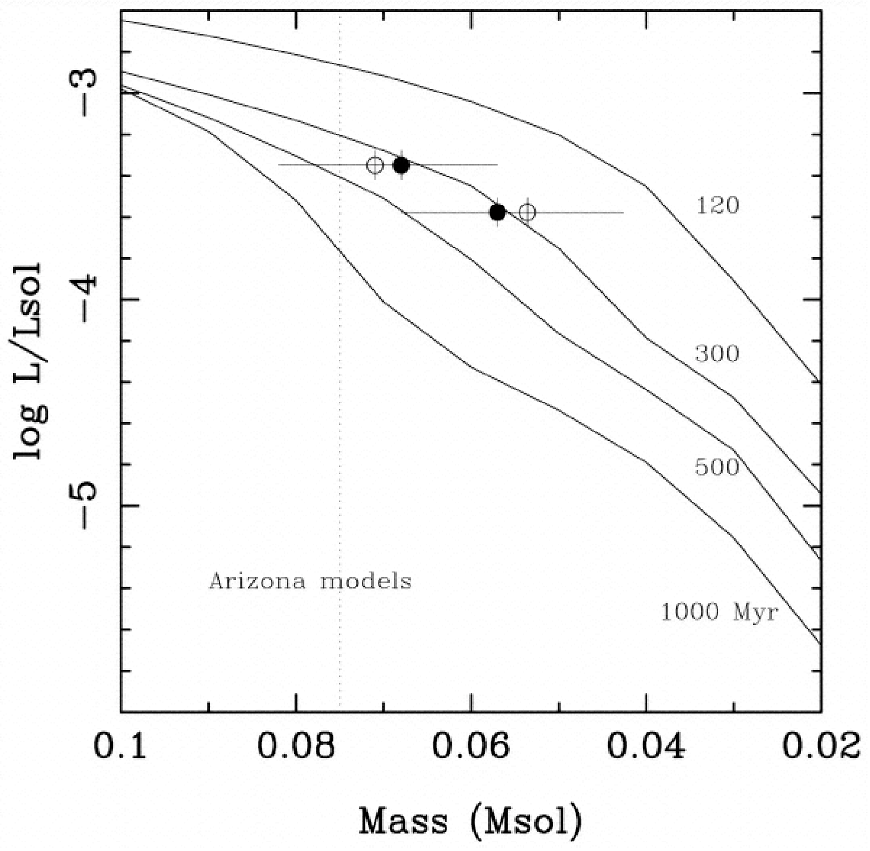
- Lower masses ⇒ lower P, T, ρ; different EOS?
- Irradiance of host star can affect evolution (hot Jupiters)
- Higher abundances of “metals” ⇒ rock, ice, heavy metals more abundant
- More complex structure
- Presence of (solid) core(s)



How do we test interior models?

For Brown Dwarfs:

Orbital Motion in Binaries with known ages and distances - compare mass/luminosity/age relations to empirically determined masses tests evolutionary theory (1+ systems)



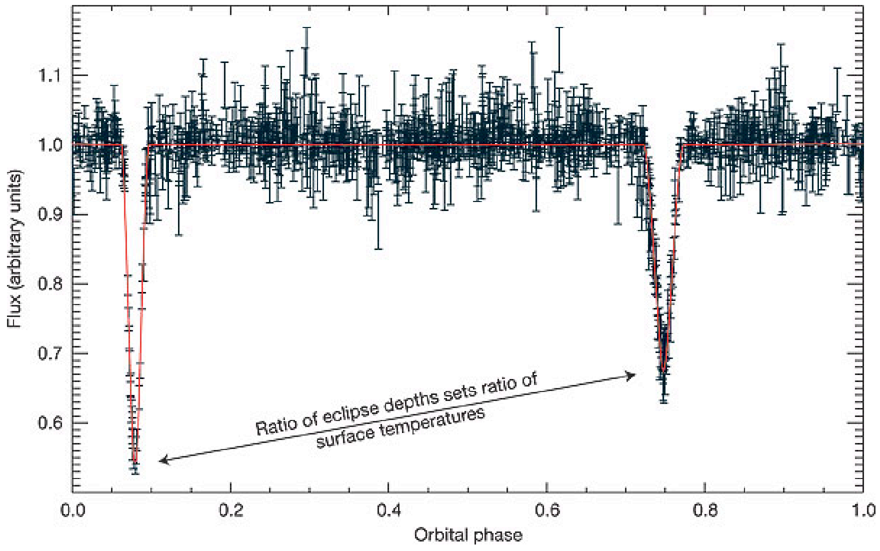
Gliese 569BC: Zapatero Osorio et al. (2004)

How do we test interior models?

For Brown Dwarfs:

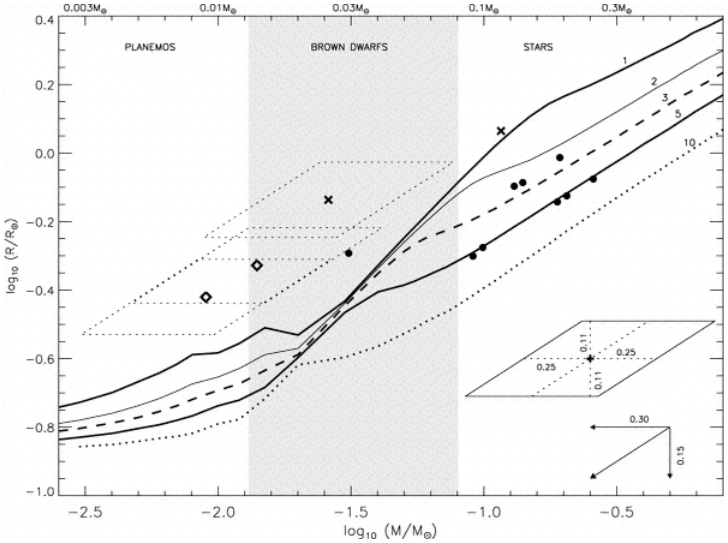
Orbital Motion in Binaries with known ages and distances -
compare mass/luminosity/age relations to empirically determined masses tests evolutionary theory (1+ systems)

Eclipsing Binaries -
radius measurements provide direct test of structure model (1 system)

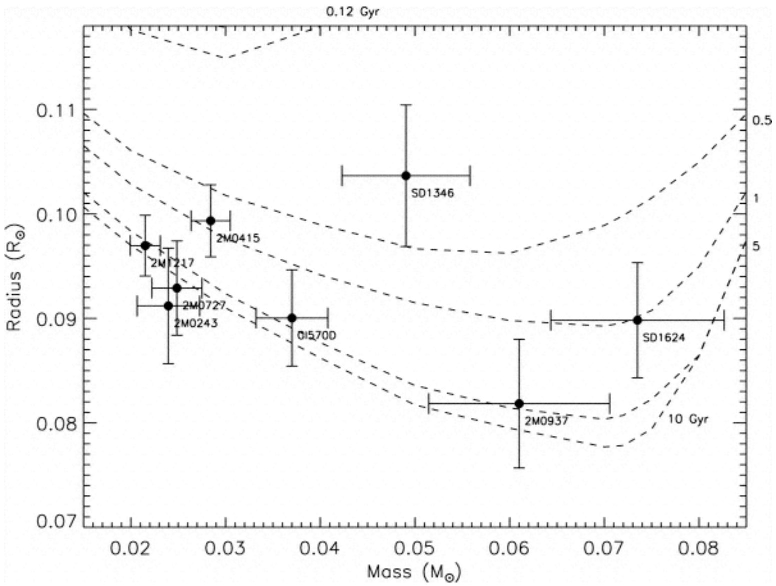


2MASS J0535–0546AB: Stassun et al. (2006)

Indirect techniques



Mohanty et al. (2004) - young brown dwarfs



Burgasser et al. (2006) - T dwarfs

Radius can be inferred from:

$$L_{bol} = 4\pi R^2 \sigma T_{eff}^4$$

Mass can be inferred from:

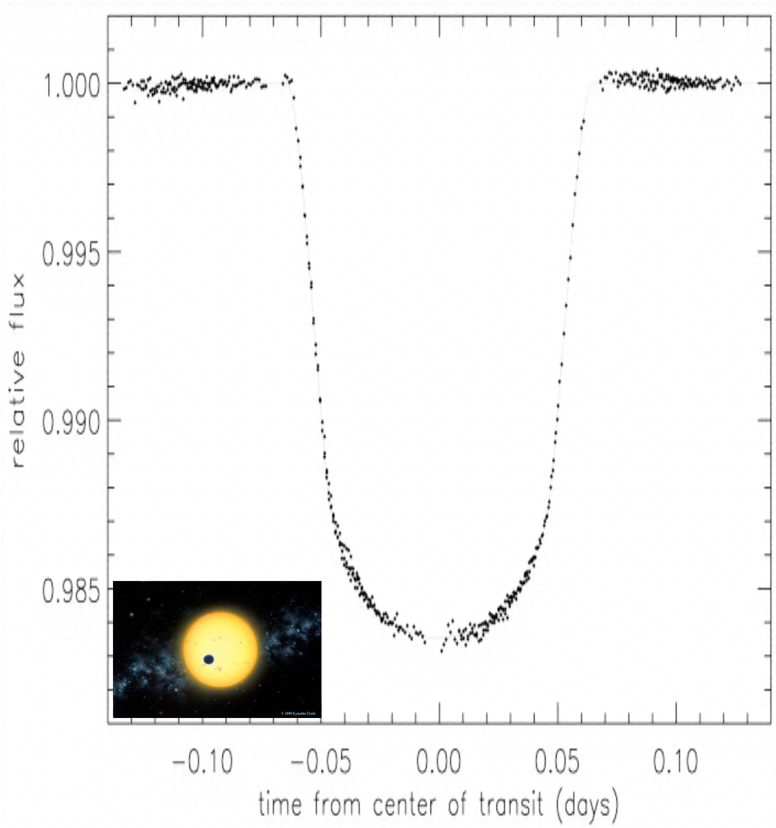
$$g = \frac{GM}{R^2}$$

⇒ Mass/radius relations can be (roughly) tested

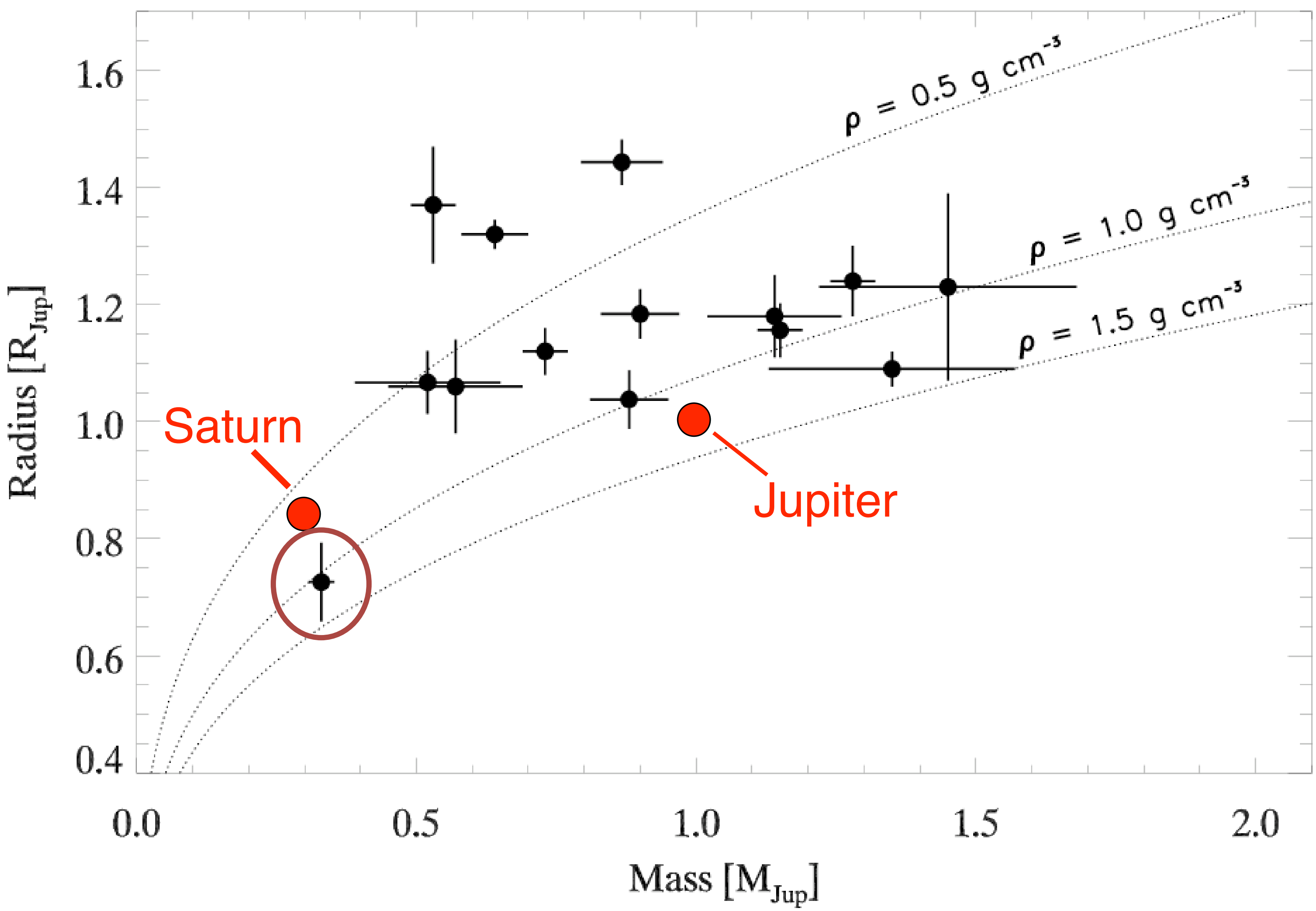
How do we test interior models?

For Planets:

Transiting planets provide radius (transit depth) and mass (radial velocities) to test structure models



HD 209458b: Brown et al. (2001)
based on HST data



ρ = 0.5 g cm⁻³
ρ = 1.0 g cm⁻³
ρ = 1.5 g cm⁻³
Saturn
Jupiter
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.0
0.5
1.0
1.5
2.0
Radius [R_Jup]
Mass [M_Jup]

The “Super-Neptune” HD 149026b

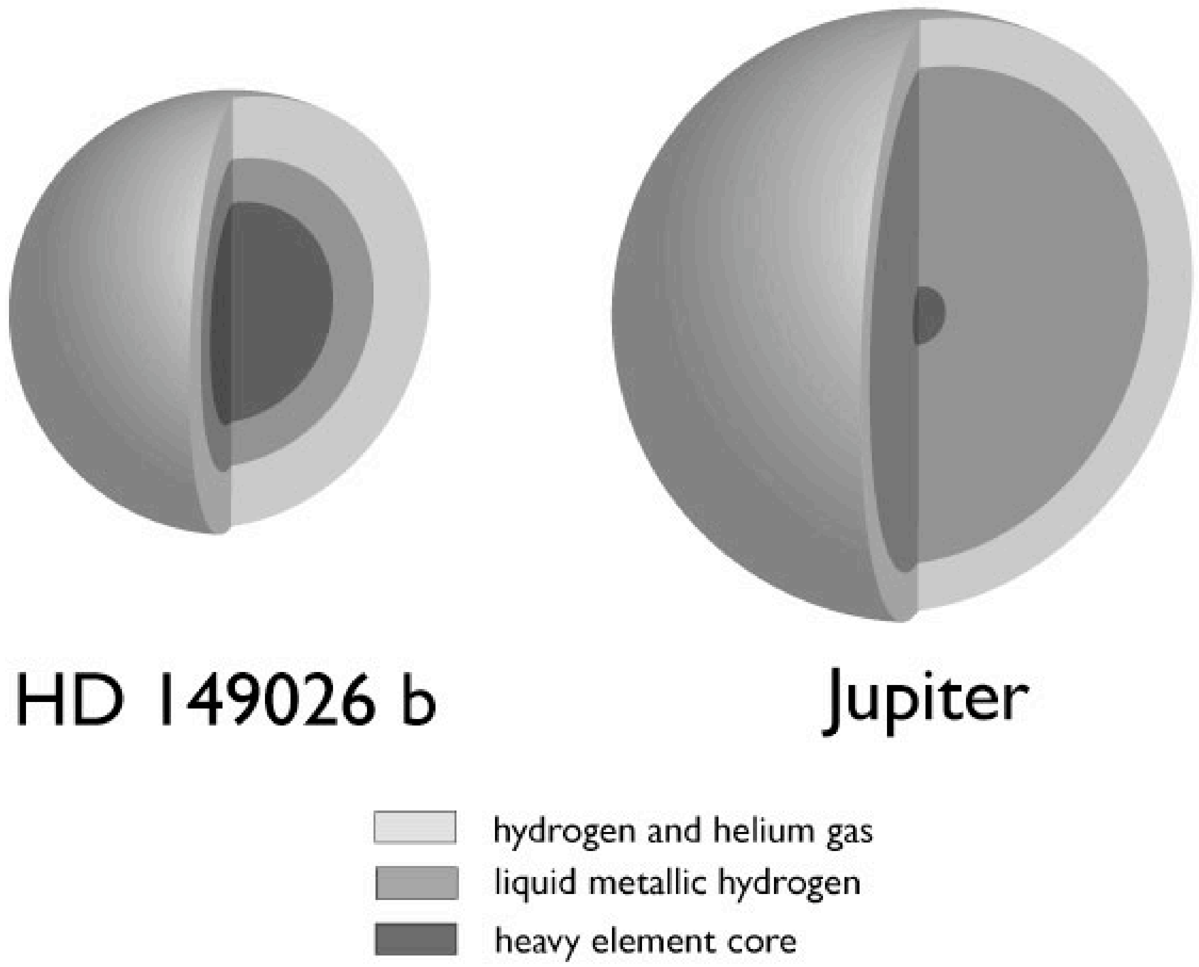
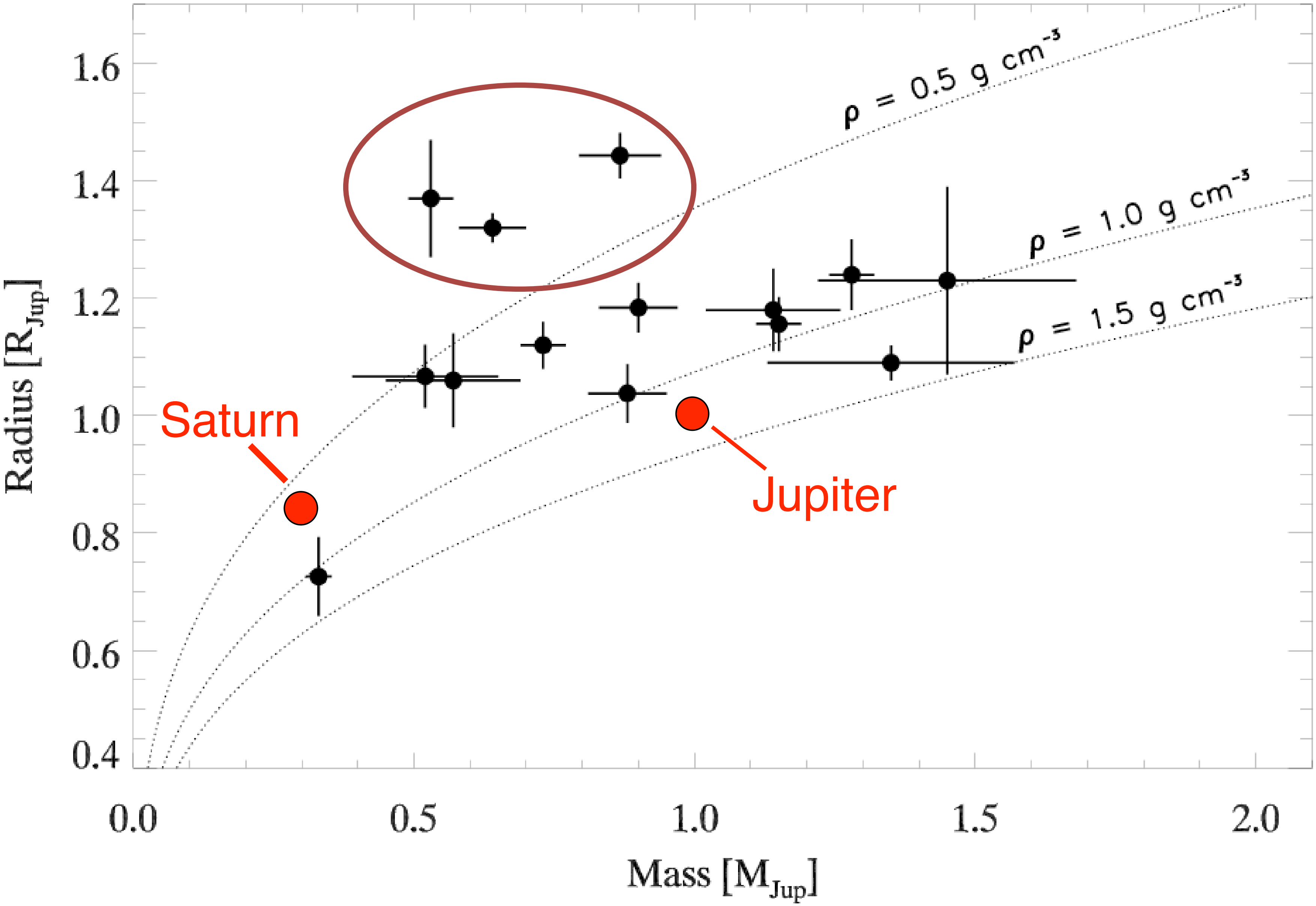
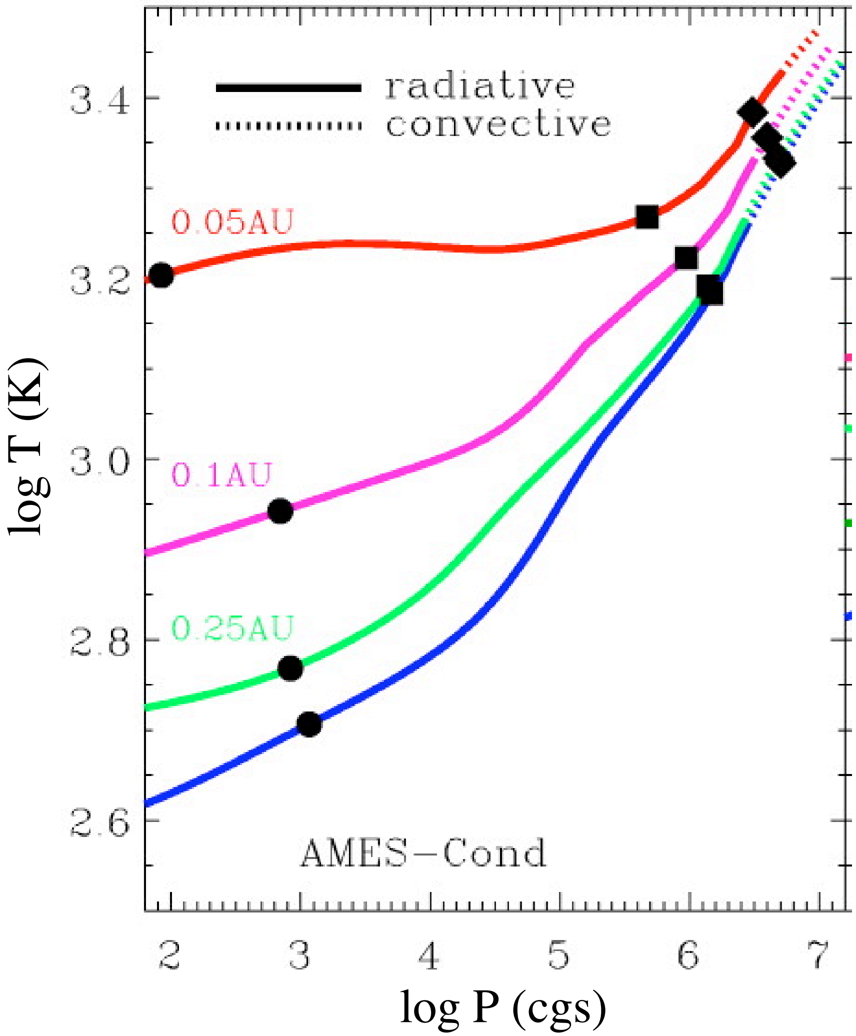


image courtesy G. Laughlin



Radius [R_{Jup}]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.0
0.5
1.0
1.5
2.0
Mass [M_{Jup}]
ρ = 0.5 g cm^{-3}
ρ = 1.0 g cm^{-3}
ρ = 1.5 g cm^{-3}
Saturn
Jupiter

Stellar Irradiation



Barman et al. (2004)

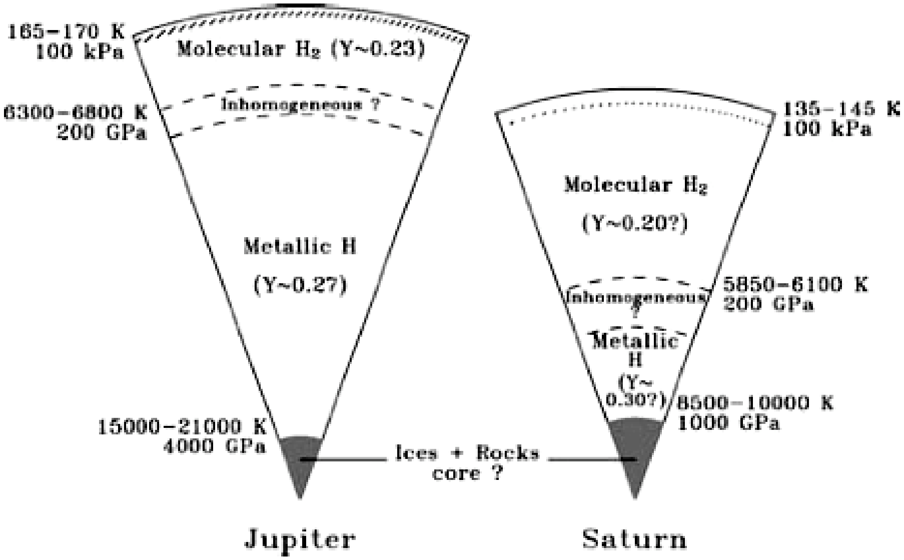
Energy deposited into the upper atmosphere by the host star changes its atmospheric T/P profile and creates a **deep upper radiative zone**.

Planet cannot release heat/entropy as effectively, unable to evolve in same manner as isolated planetary mass objects

Do Jupiter/Saturn have cores?

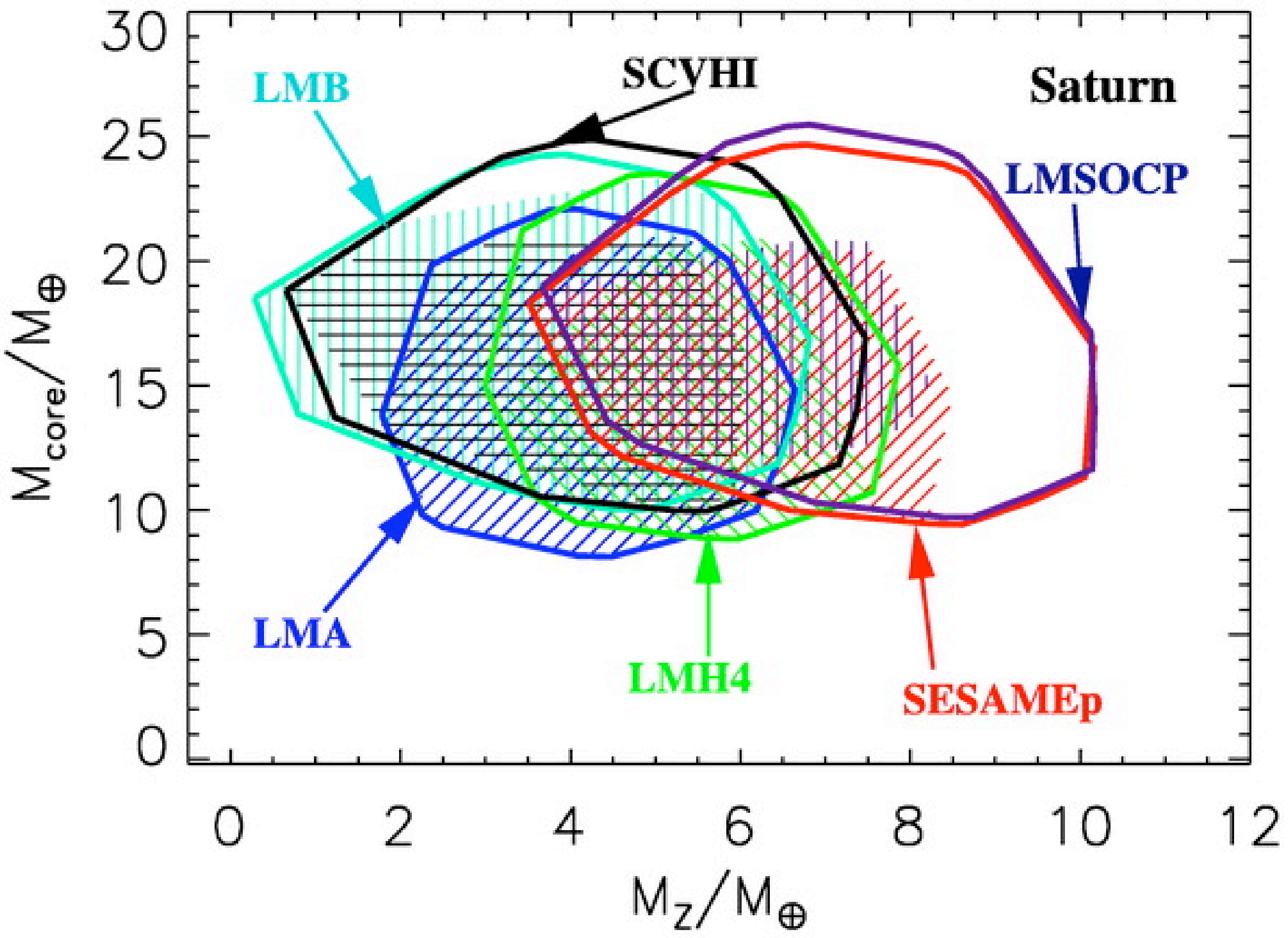
A core of 10-20 $M_\oplus$ is predicted by **core accretion models** (Pollack et al. 1996), while other mechanisms (e.g., **disk fragmentation**; Boss 2000) do not require them.

For solar planets we can search for evidence of cores using the observed mass (M), equatorial radius (R_e), rotational period (P) **and gravitational moments (J_2, J_4, …)** and appropriate models



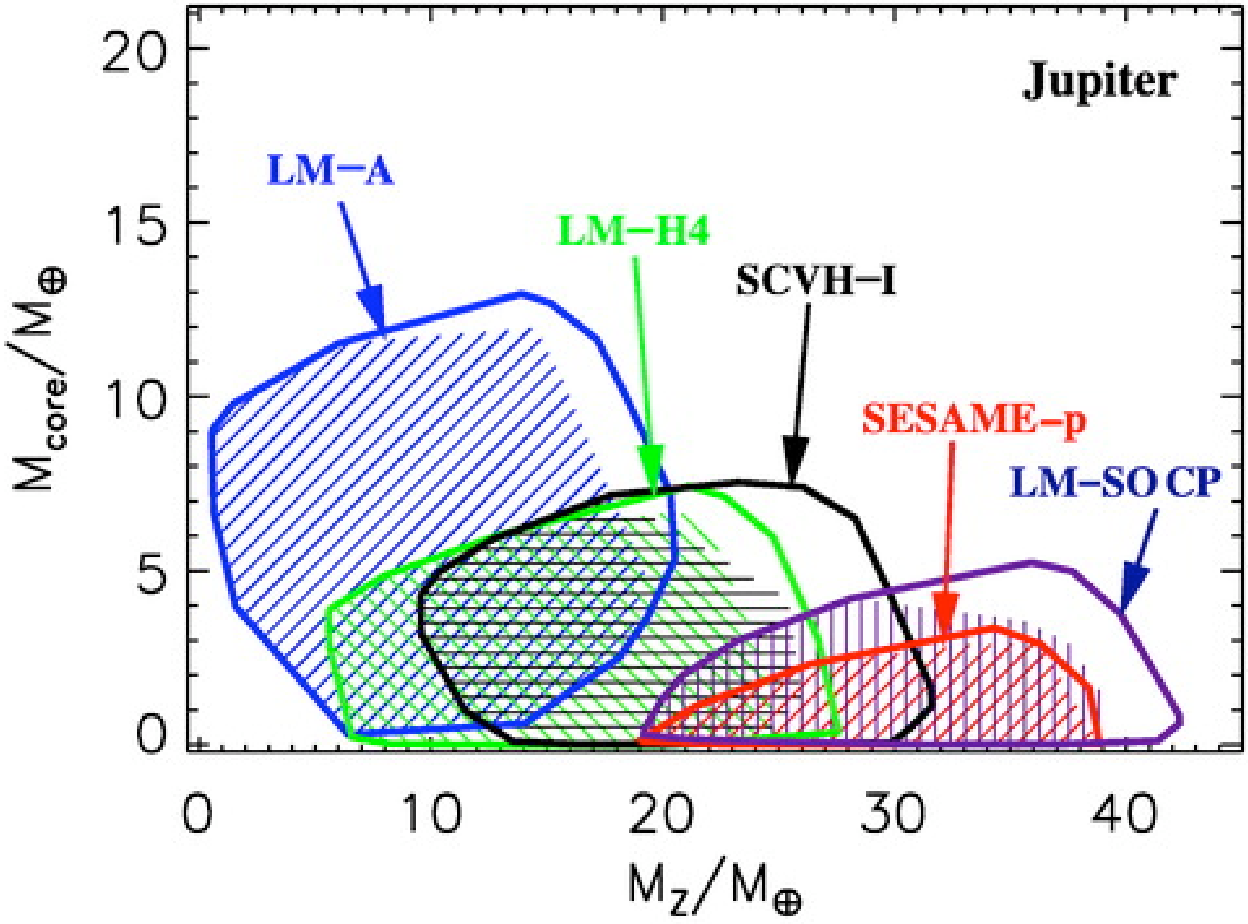
Guillot (2005)

Saturn: has a core



Saumon & Guillot (2004)

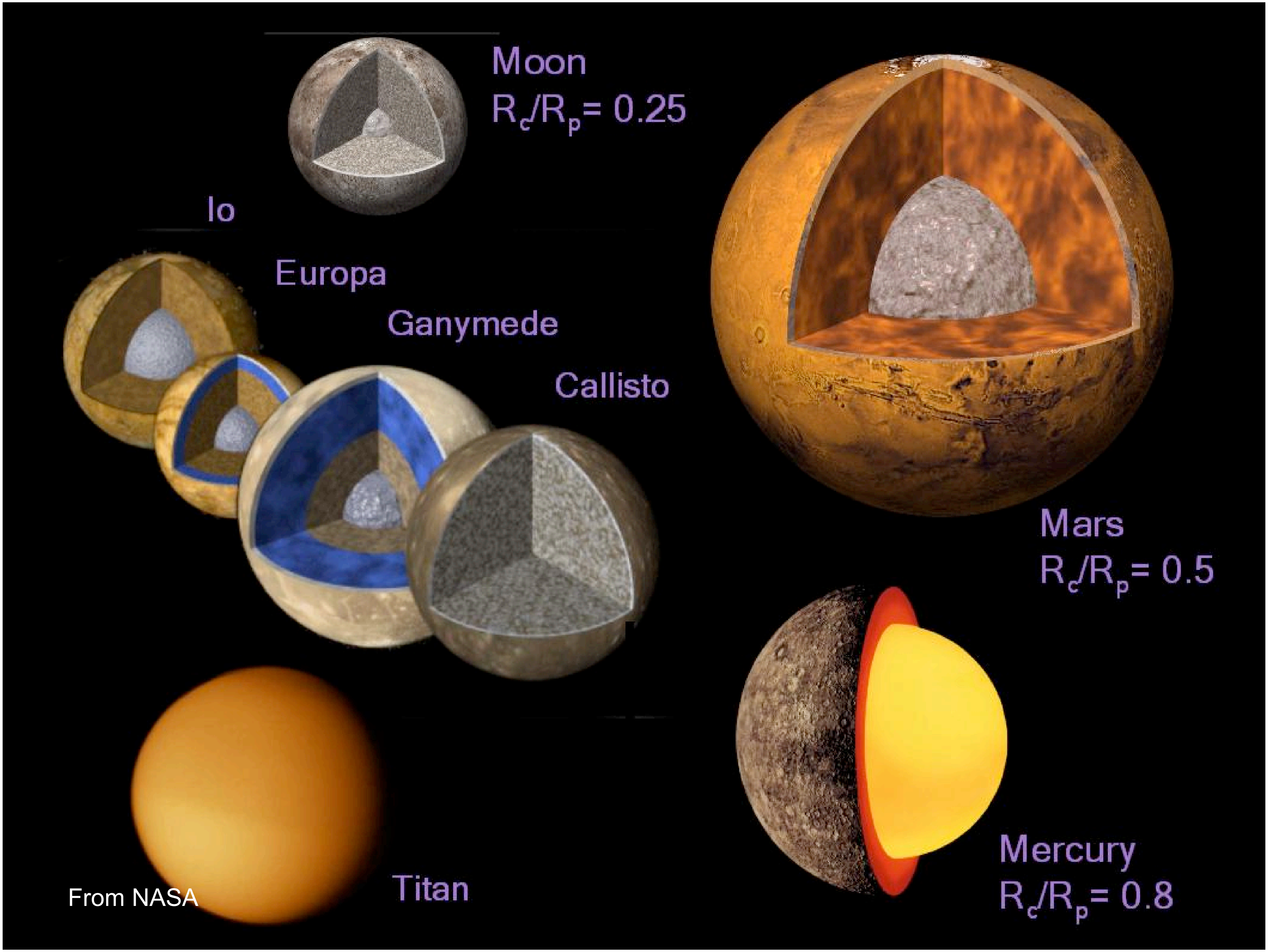
Jupiter has no core?



Saumon & Guillot (2004)

For Further Thought

1. How do we improve our understanding of the EOS in the interiors of planets and brown dwarfs?
2. How can make better empirical constraints on BD structure models?
3. Can we determine whether exoplanets have cores?
4. What other parameters might have an effect on the structure of a BD/planet (e.g., metallicity, magnetic fields, rotation)
5. What is the thermal evolution of a hot rotating Jupiter?


Moon
R_c/R_p= 0.25
Io
Europa
Ganymede
Callisto
Mars
R_c/R_p= 0.5
Mercury
R_c/R_p= 0.8
Titan

From NASA