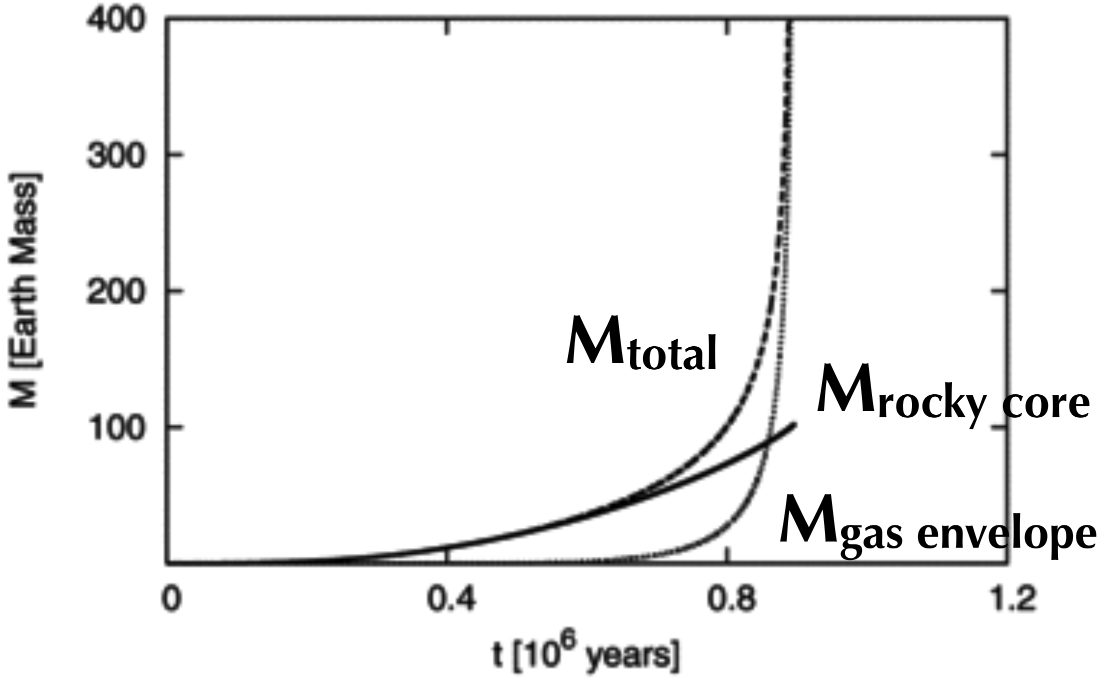
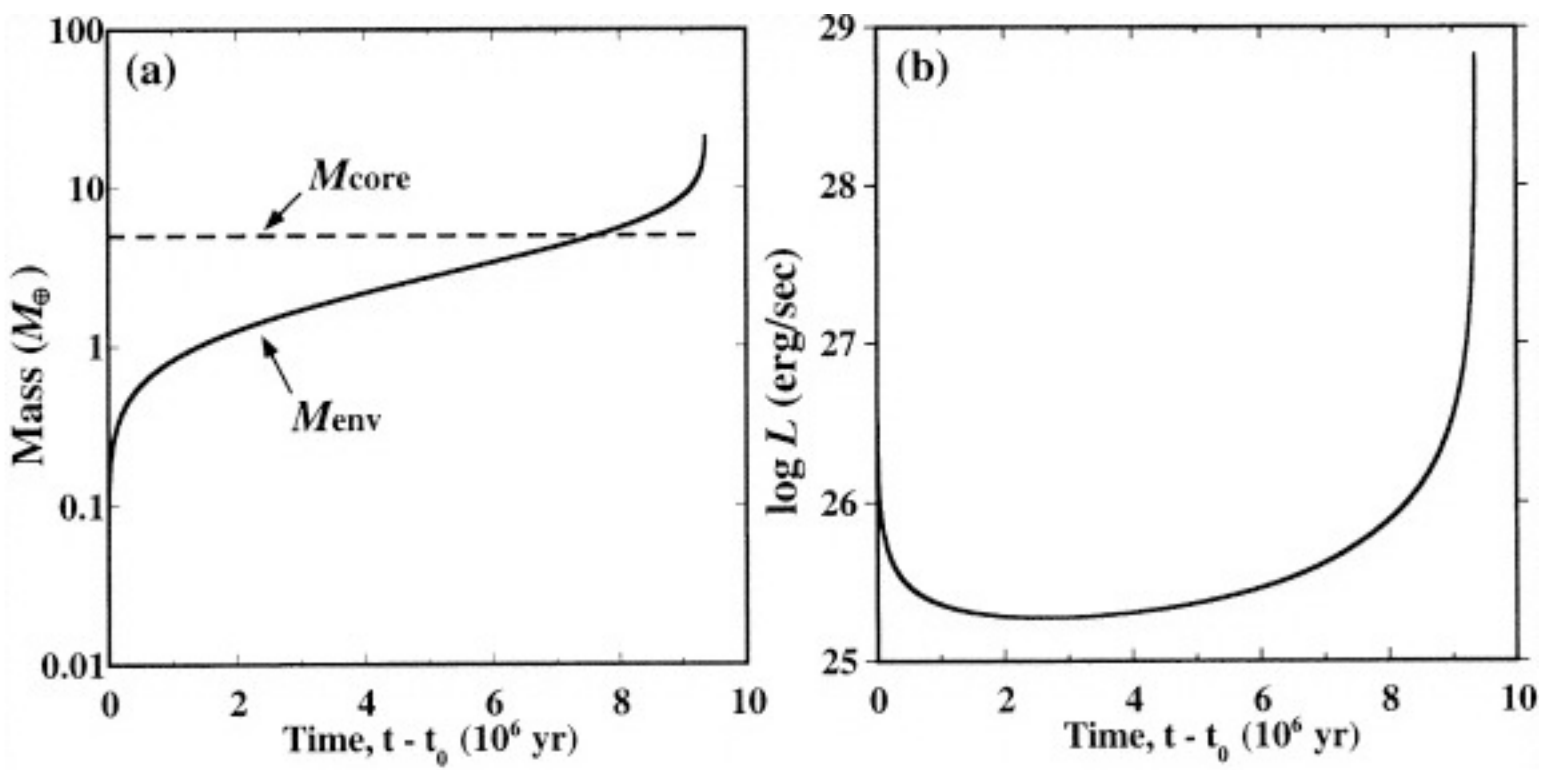
Giant planet formation

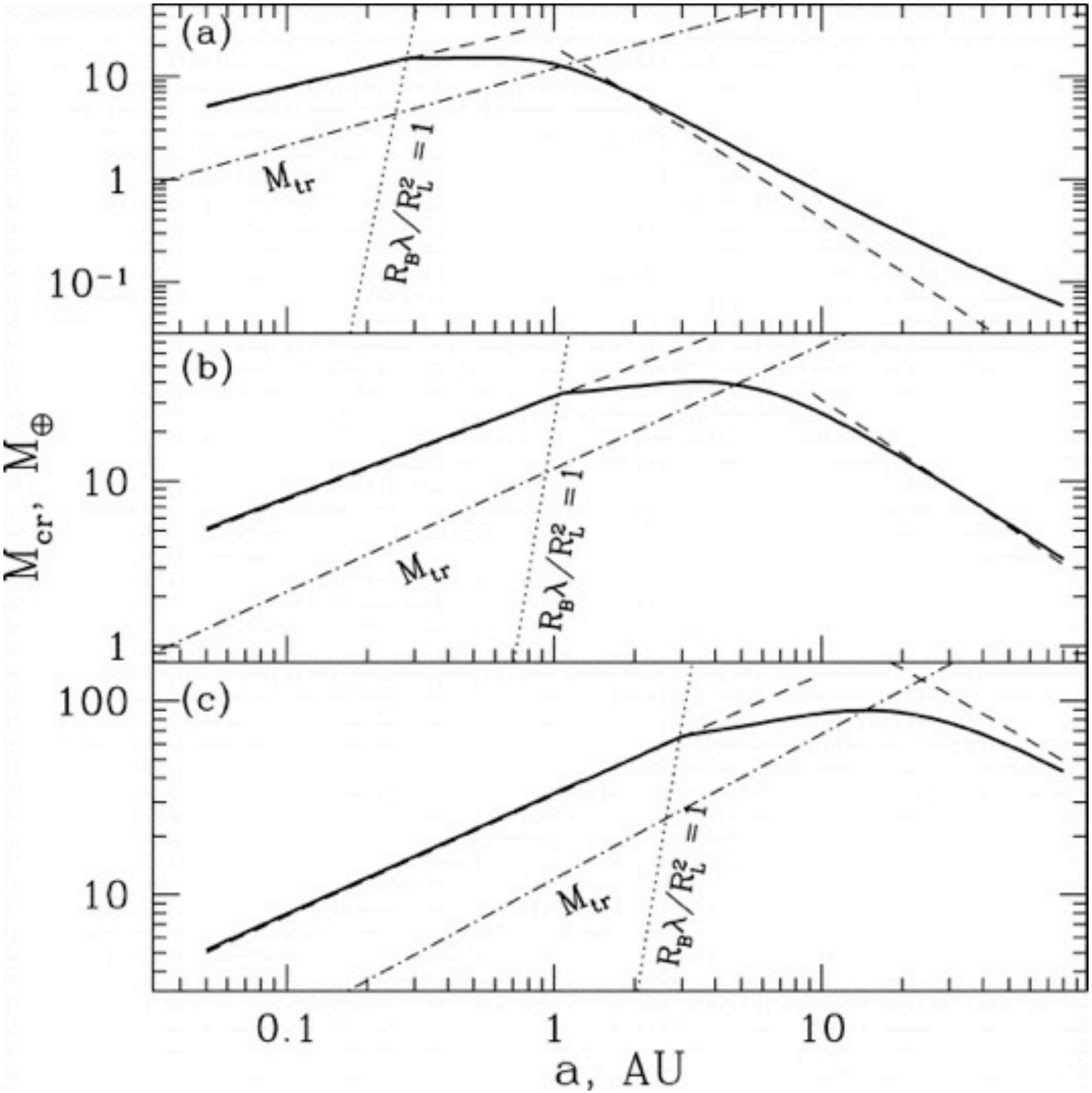
Core accretion
= core nucleation
= core instability
= “bottom-up”

Runaway gas accretion when
$M_{envelope} \sim M_{core}$



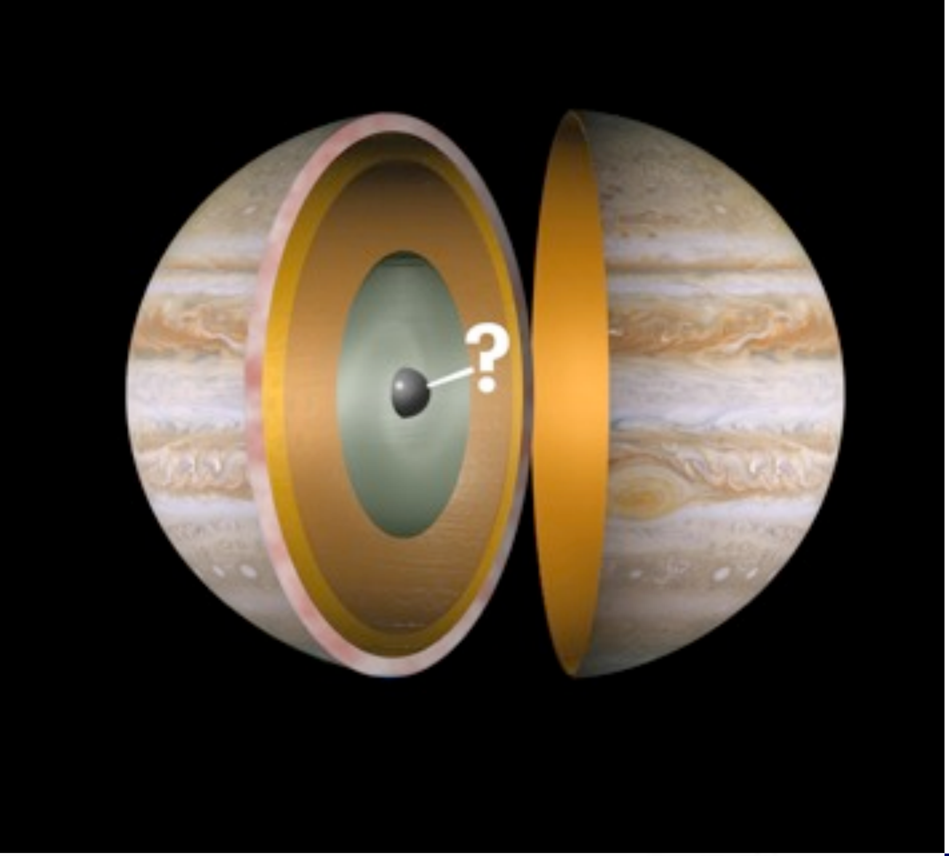


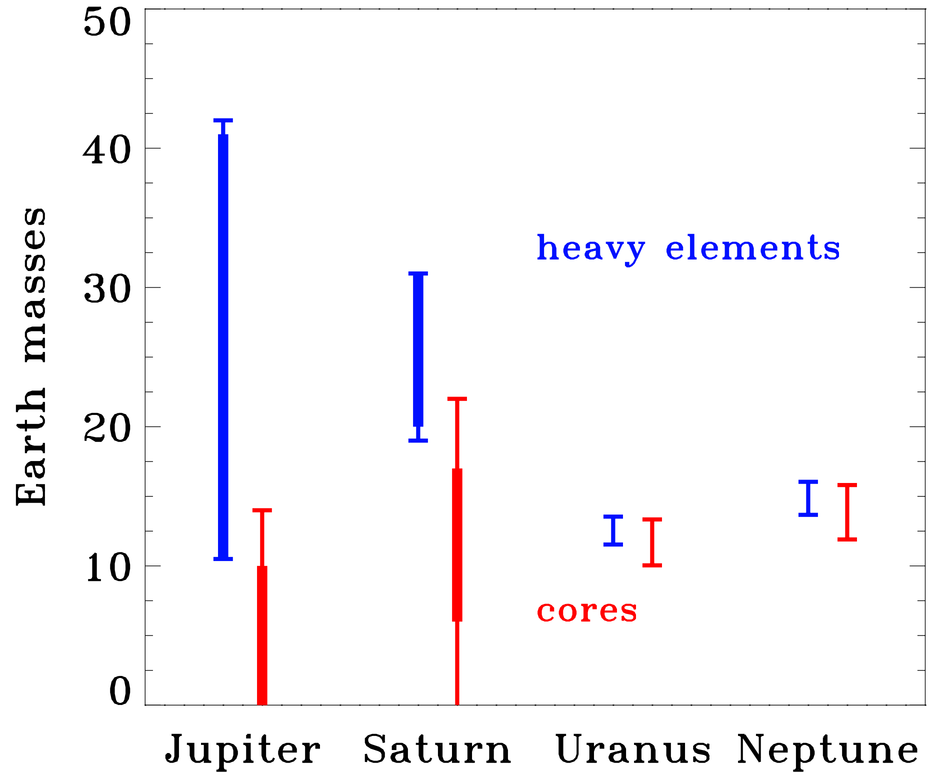
Miguel & Brunini 08

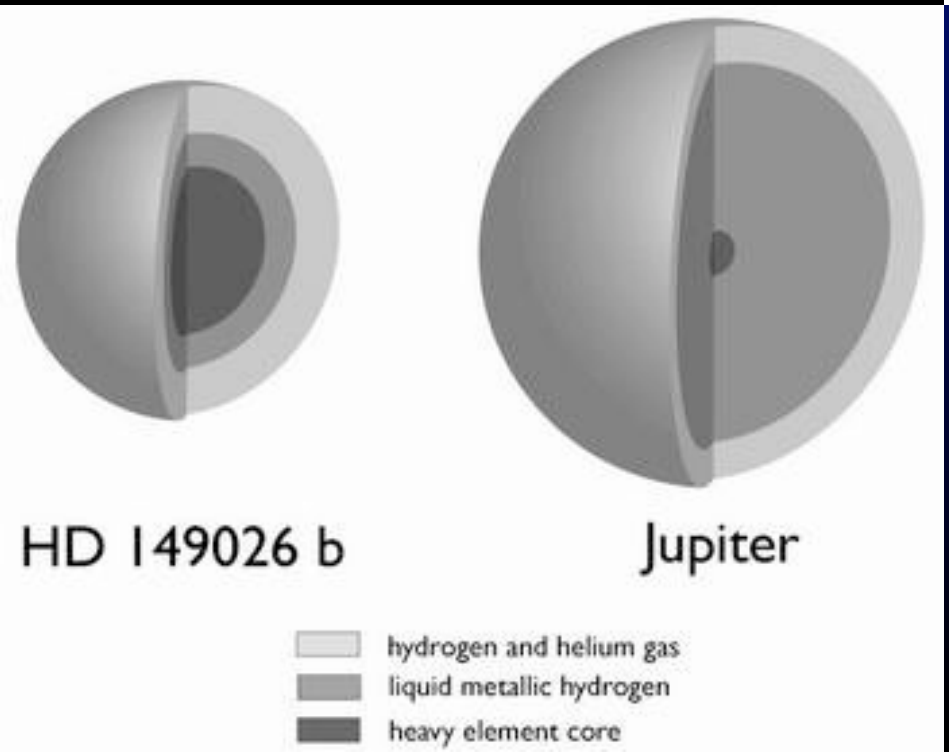


Critical core masses for various accretion rates

Rafikov 2006







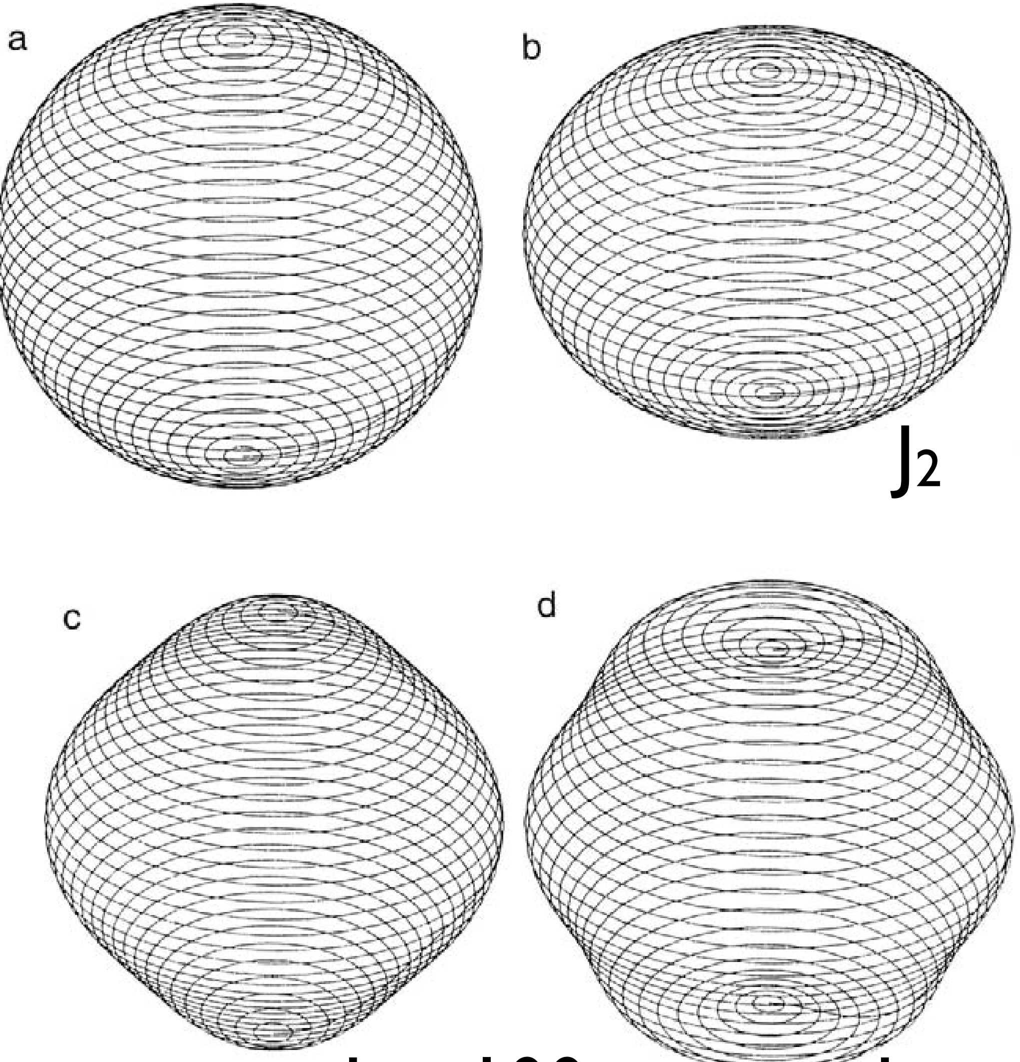
Core or No Core?

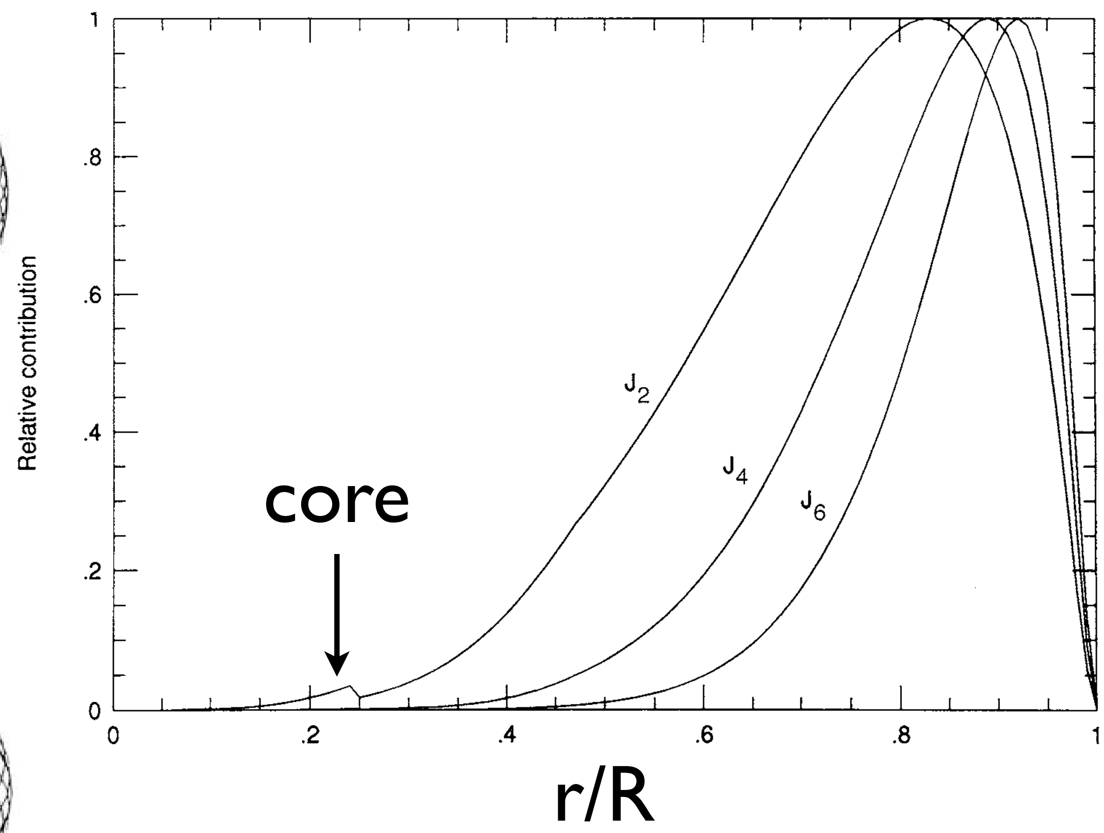
$M, R, J_2, J_4, J_6, \ldots$

$+ P(\rho)$

+ hydrostatic equilibrium (w/rotation)

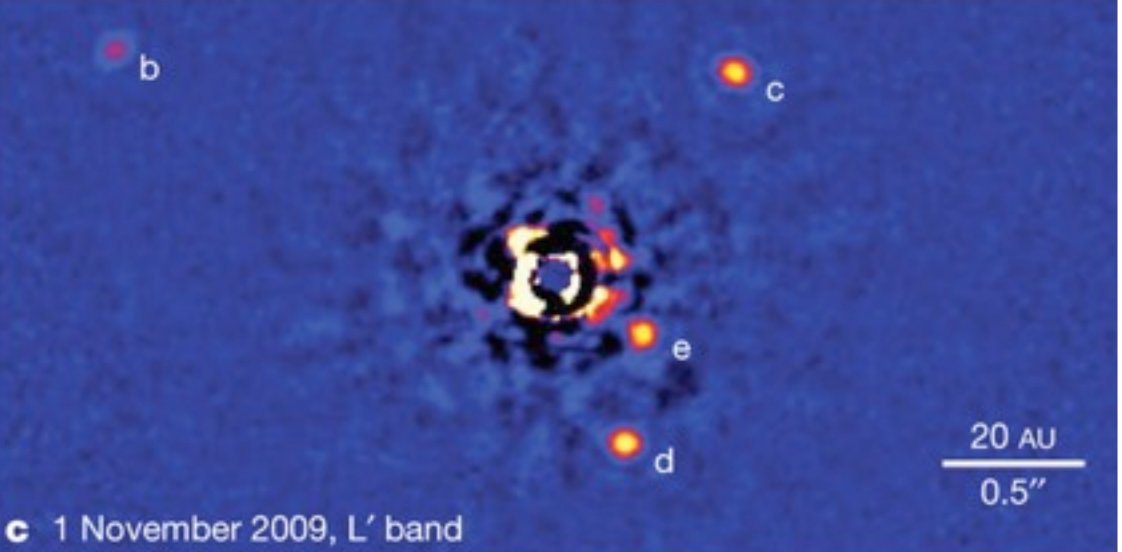
$\Rightarrow \rho(r)$



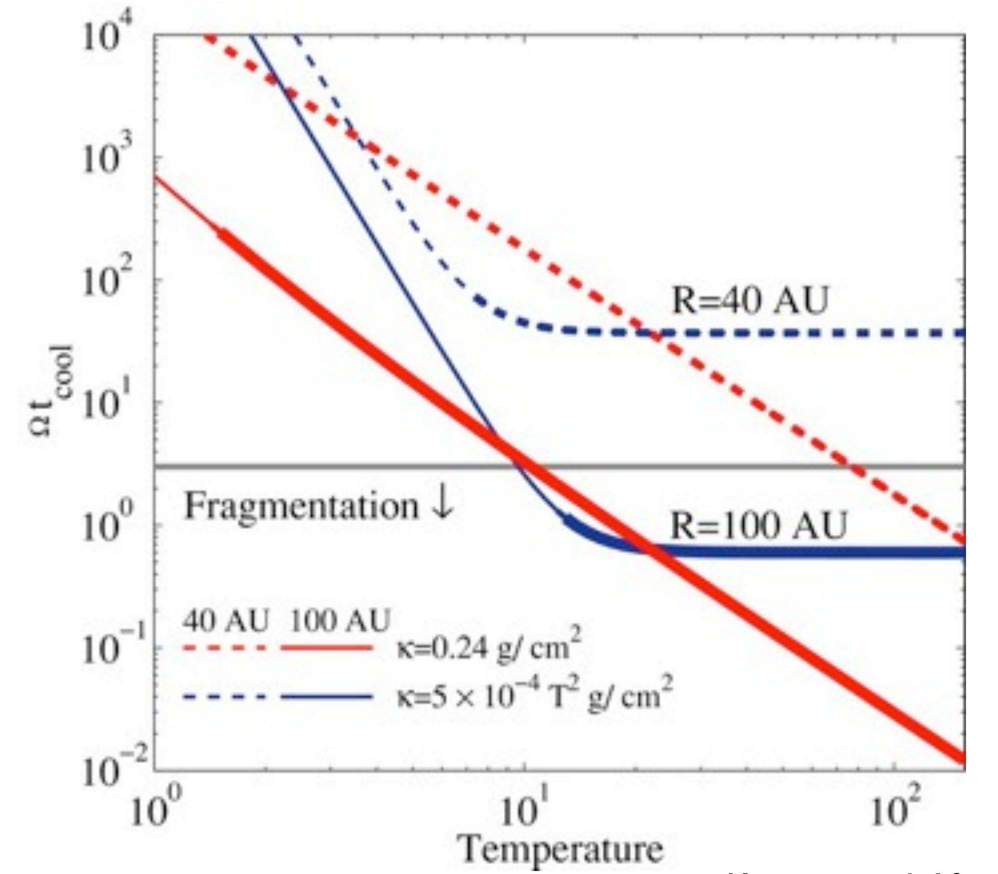


Relative contribution to gravitational harmonics in Saturn

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



Giant planet formation by gravitational fragmentation
= gravitational instability
= "top-down"



Kratter et al. 10

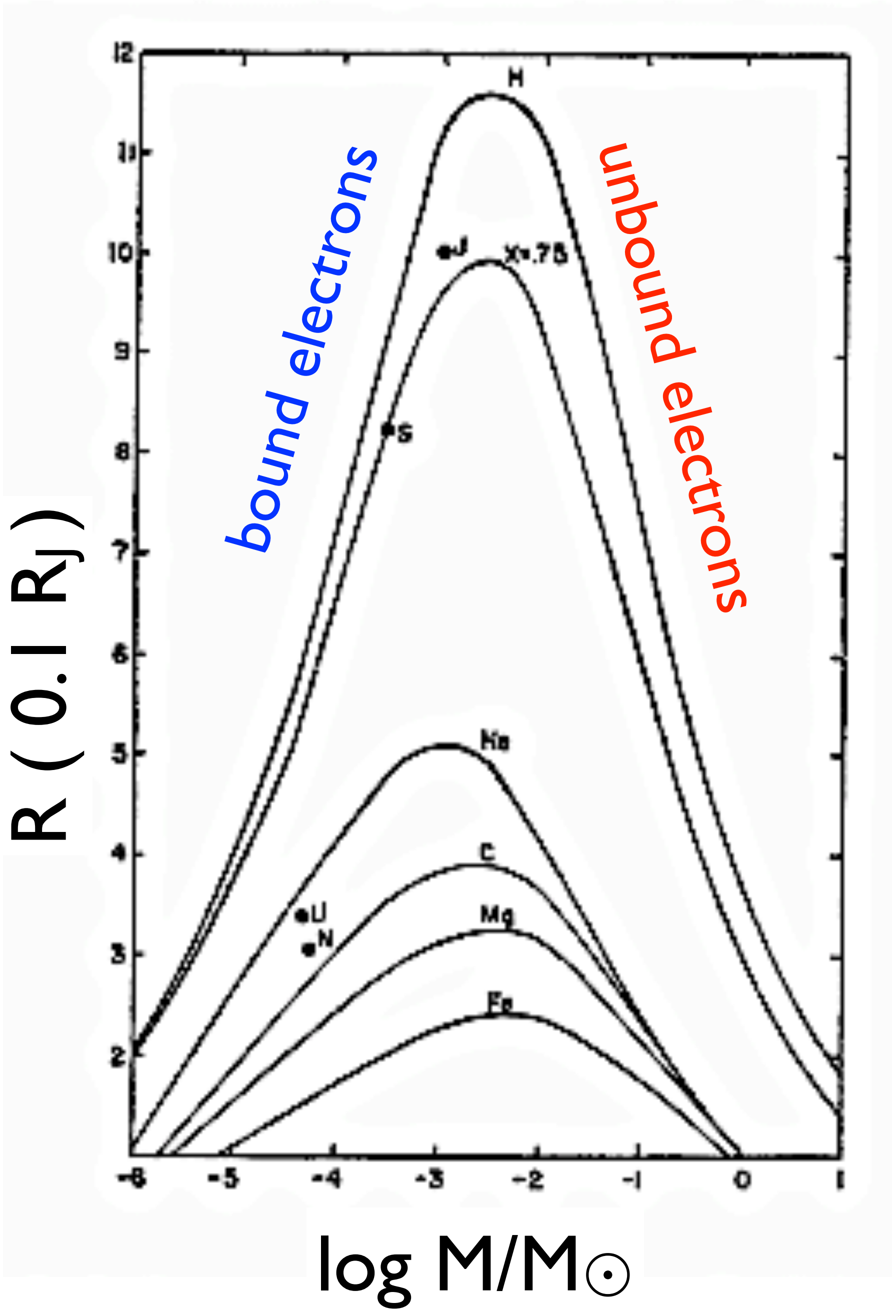
Requirements: Q ~ 1 and $t_{cool} < \Omega^{-1}$

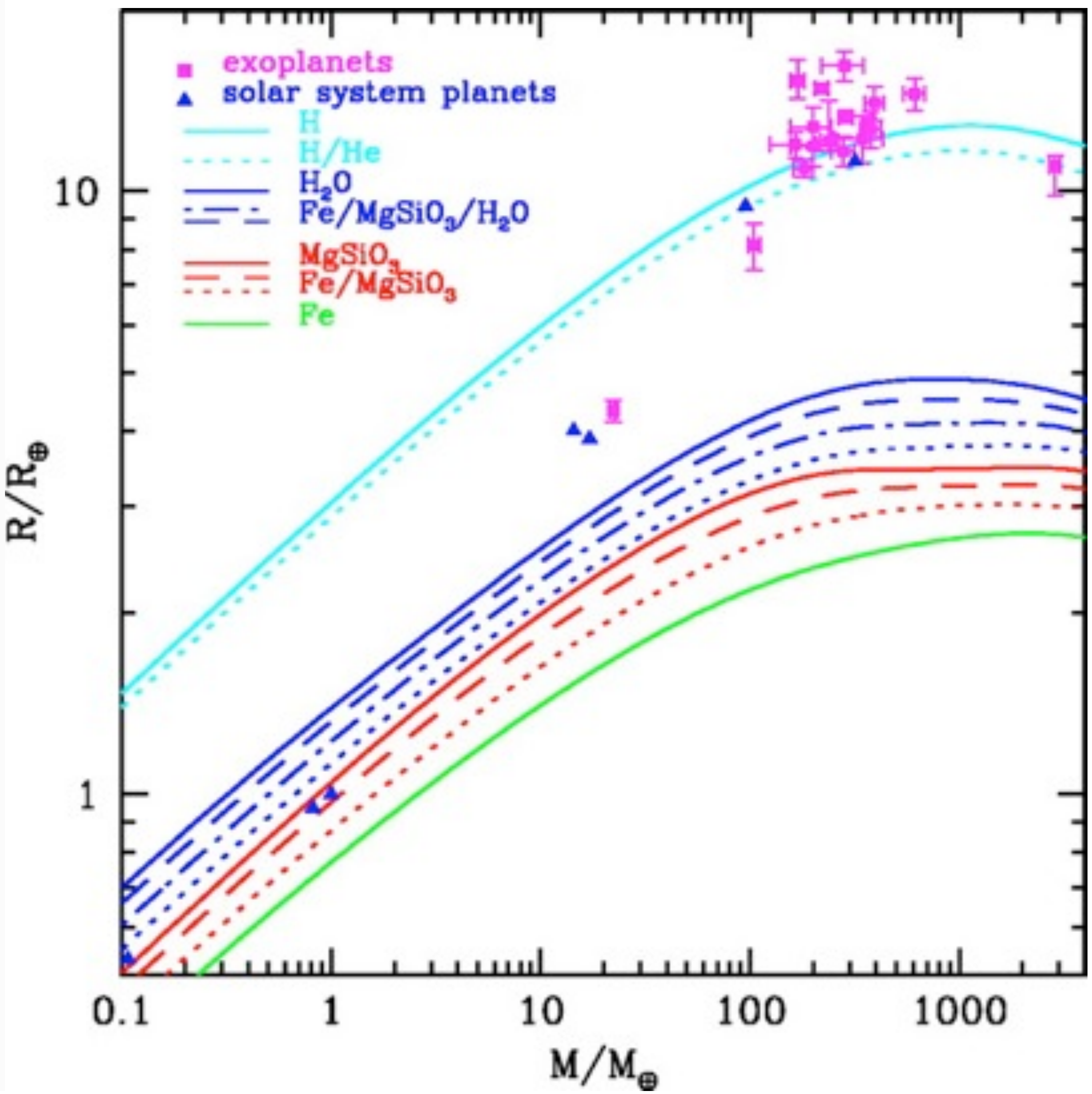
Could be met at large distance > 70 AU

Uncertainties include
- disk temperature
- mass infall rate from surrounding natal envelope
- final planet masses

More easily fragments into brown dwarfs than planets

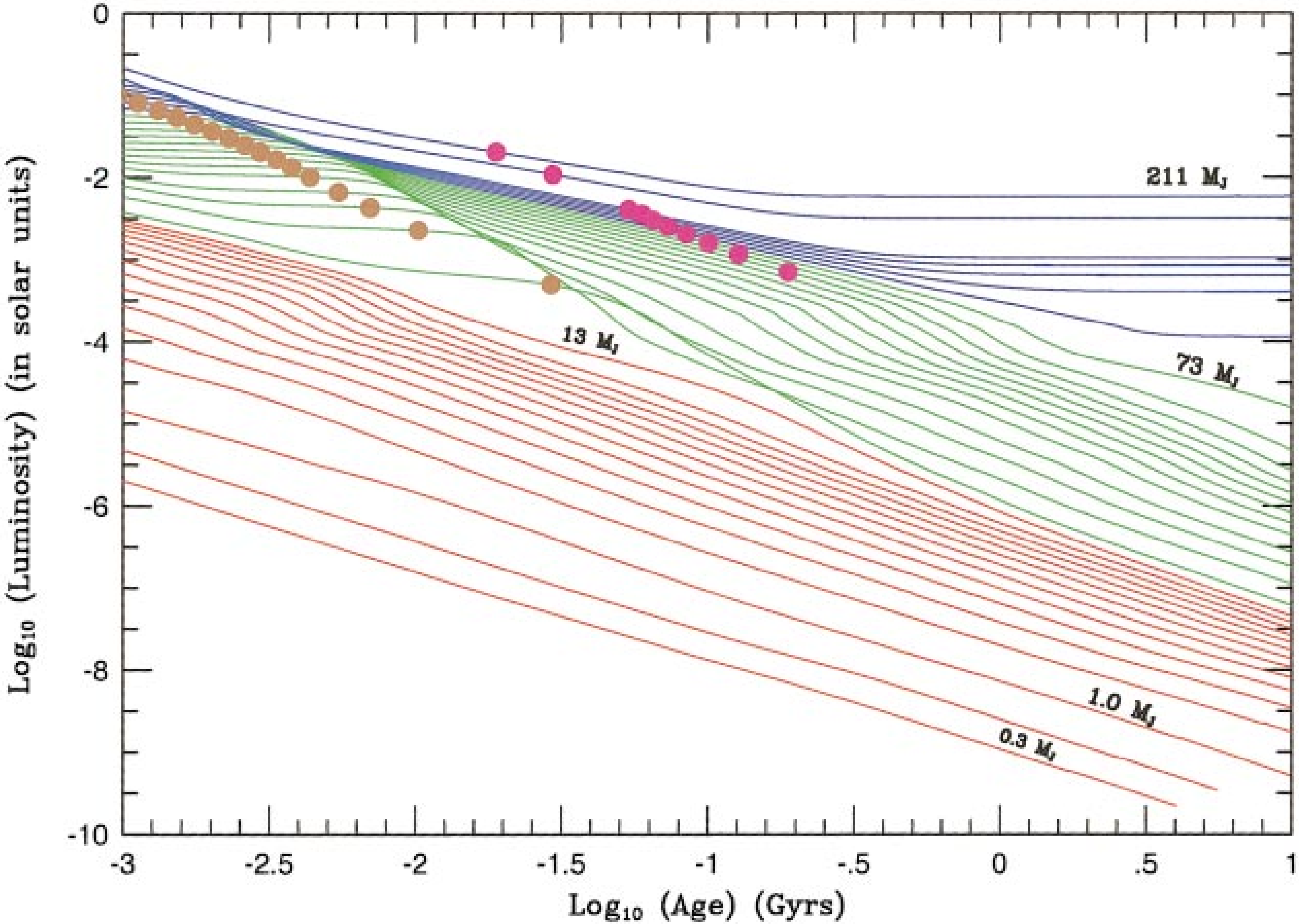
Degeneracy pressure



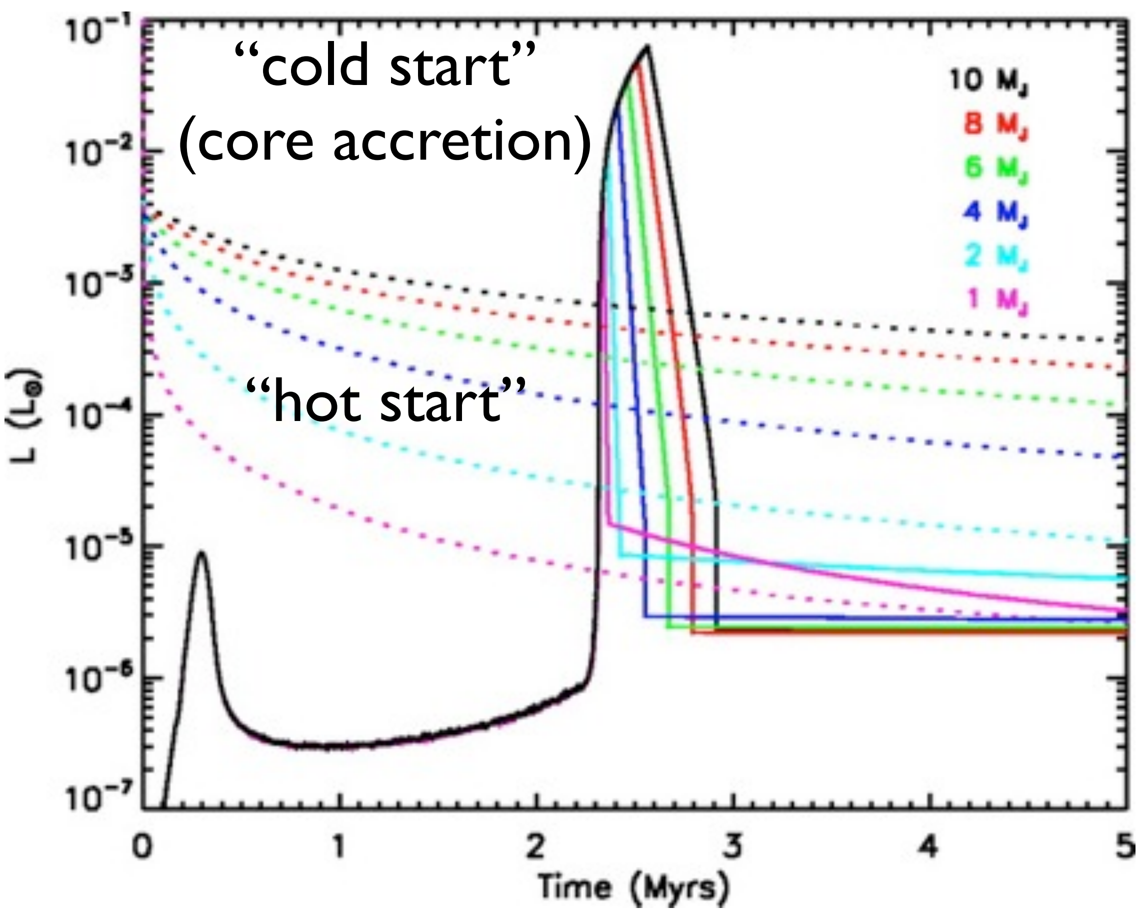


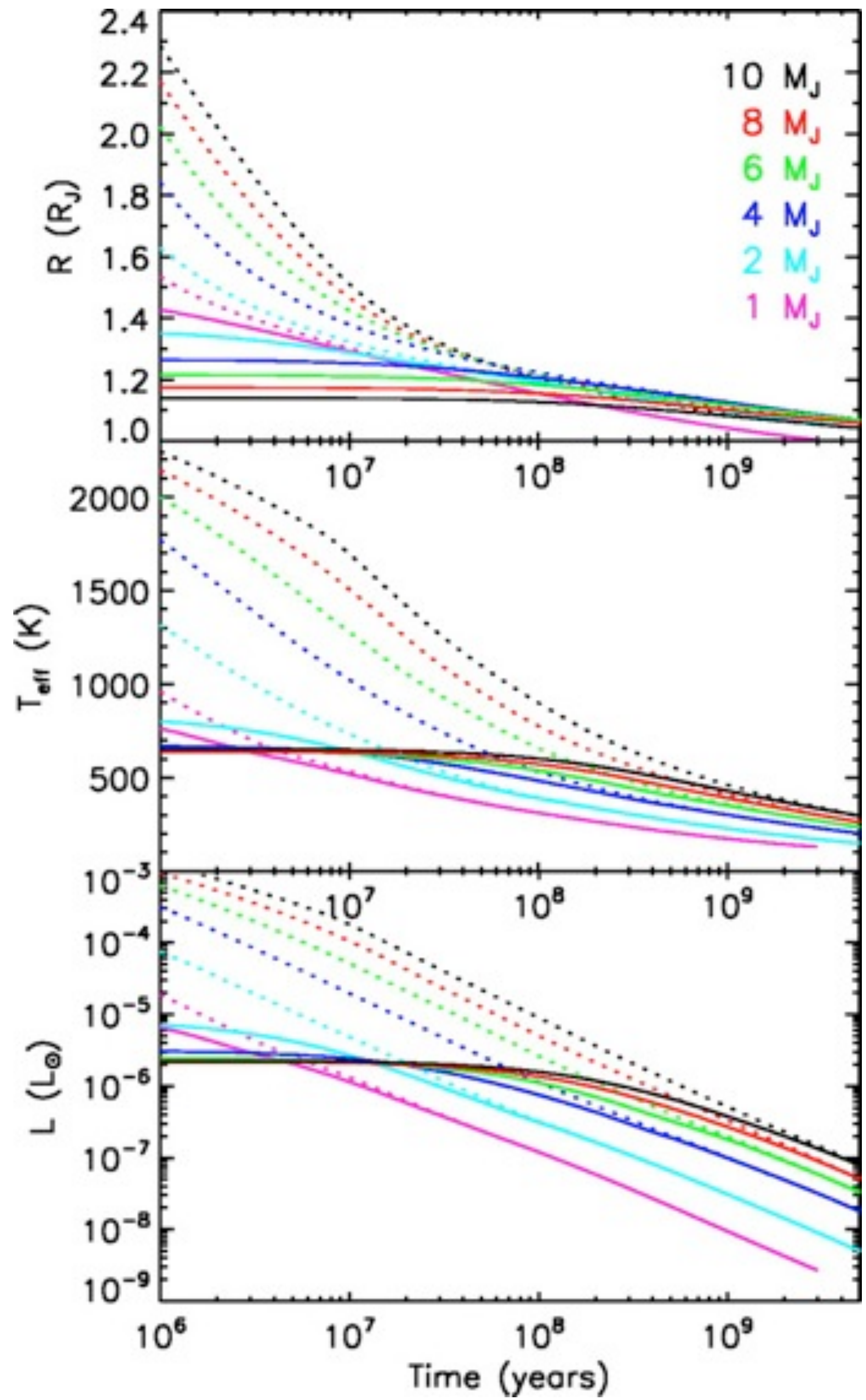
The new spectral classes
O B A F G K M L T

Cooling curves (standard "hot start")

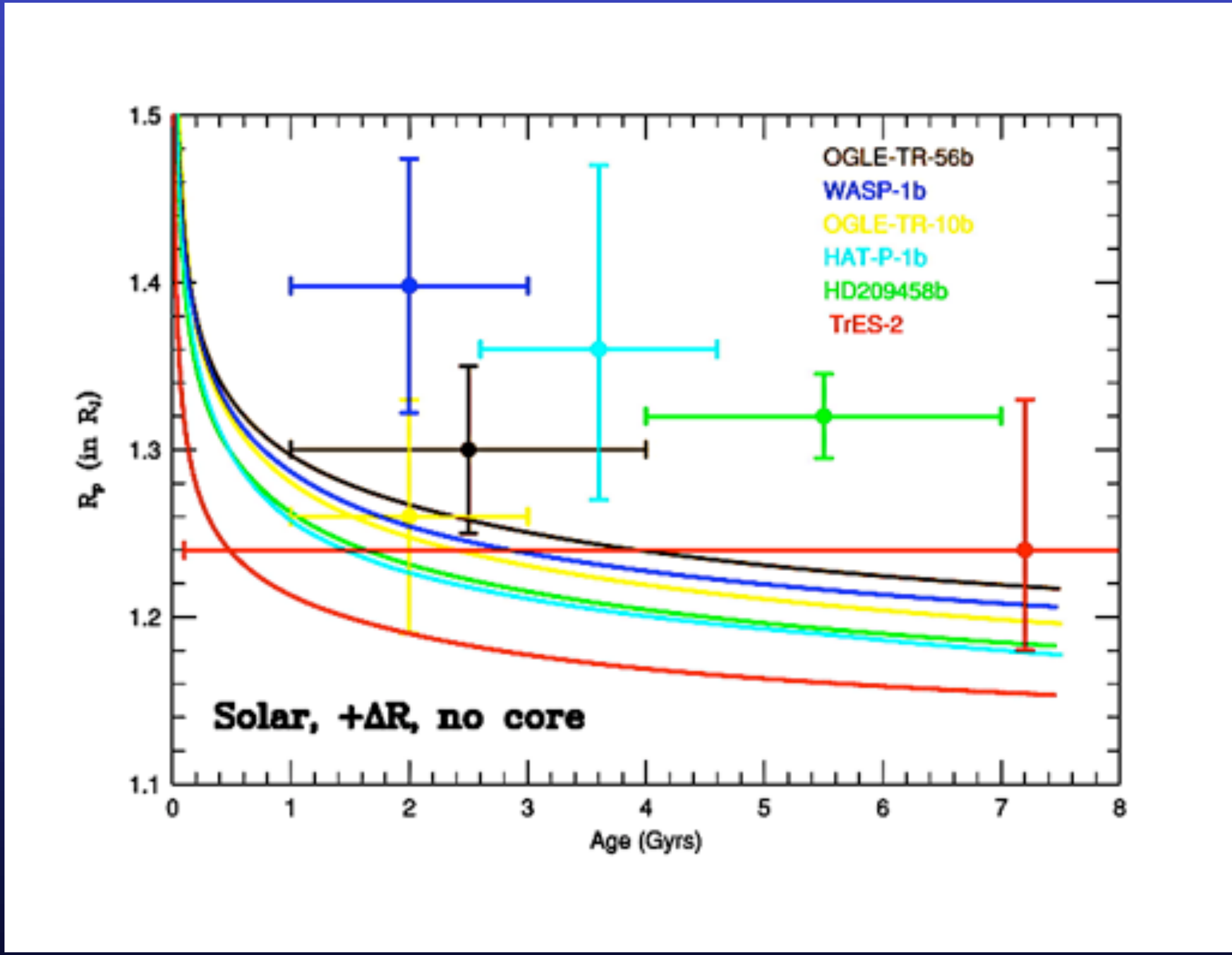


Early evolution uncertain





Hot Jupiters are inflated

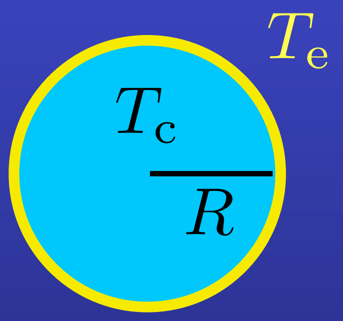


Transit radii > Theoretical radii

Burrows et al. 2007

How much = How long ago

Radiative cooling: $L = \sigma T_{\mathrm{e}}^4 4\pi R^2 = -Nk\dfrac{dT_{\mathrm{c}}}{dt}$



Not completely degenerate: $R \sim R_{\mathrm{J}}\left(1 + \dfrac{kT_{\mathrm{c}}}{\epsilon_{\mathrm{F}}}\right)$

Isentrope: $s_{\mathrm{e}}(T_{\mathrm{e}}, P_{\mathrm{e}} \sim g/\kappa_{\mathrm{e}}) = s_{\mathrm{c}}(T_{\mathrm{c}}, P_{\mathrm{c}} \sim GM^2/R^4)$

3 equations in 3 unknowns $T_{\mathrm{e}}, T_{\mathrm{c}}, R$ ➡

$$L \propto t^{-24/17}$$

$$T_{\mathrm{c}} \propto t^{-7/17}$$

$$R \uparrow T_{\mathrm{c}} \uparrow t \downarrow L \uparrow$$

using more accurate analytic formulae from Burrows & Liebert 93

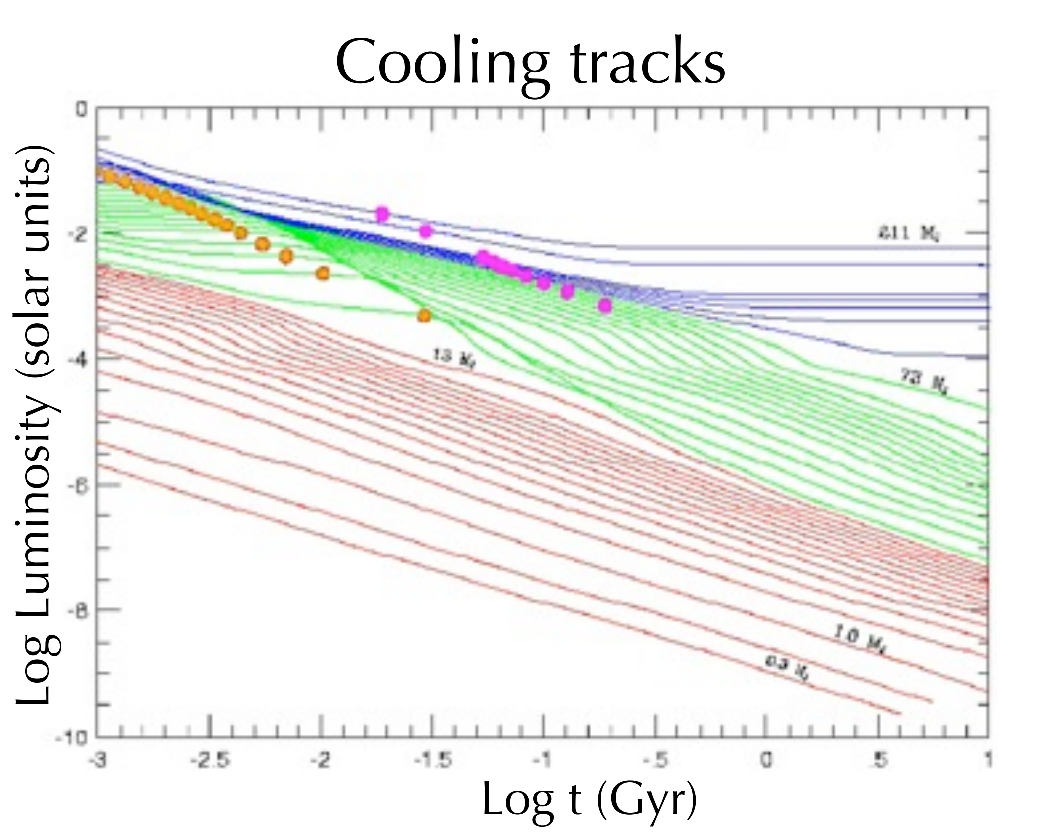
to increase R by 30% ,

$t \sim 2 \times 10^7$ yr

$L \sim 2 \times 10^{26}$ erg/s

vs. numerical $L \sim 6 \times 10^{26}$ erg/s

Burrows et al. 07



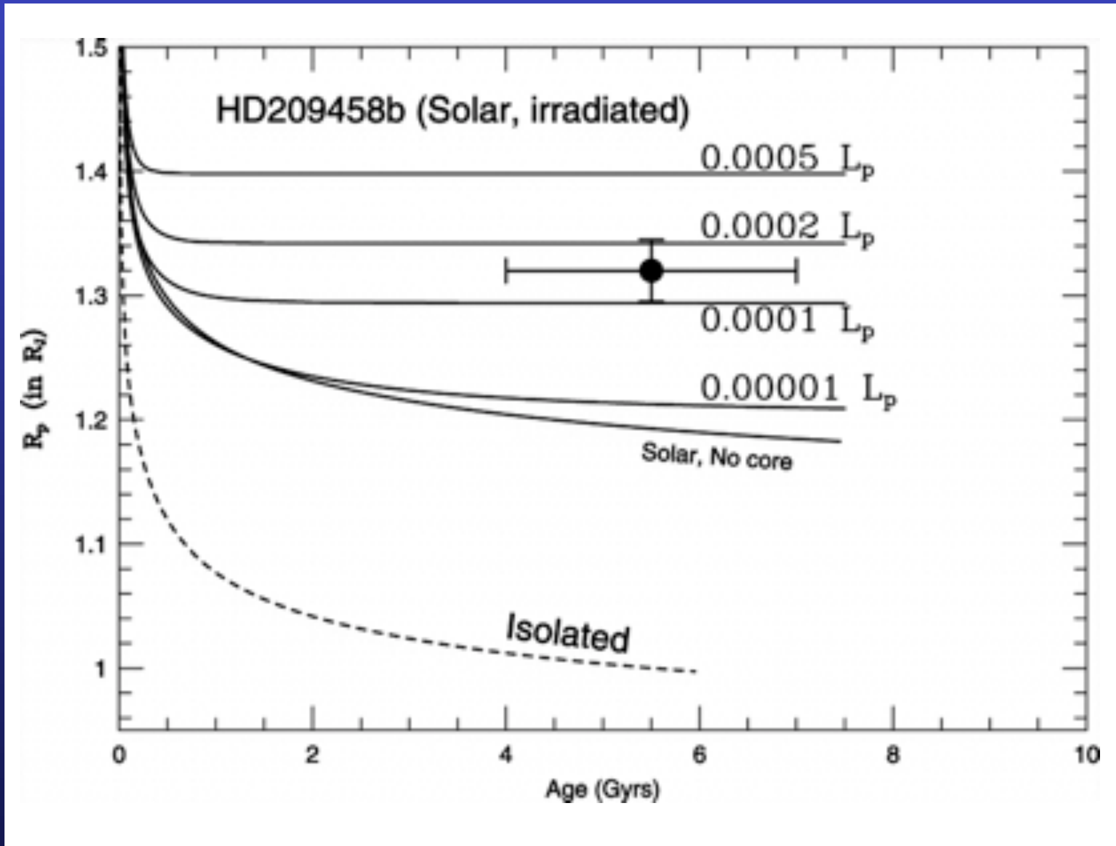
"Easy" problem

Compare required L
6 x 10^{26} erg/s

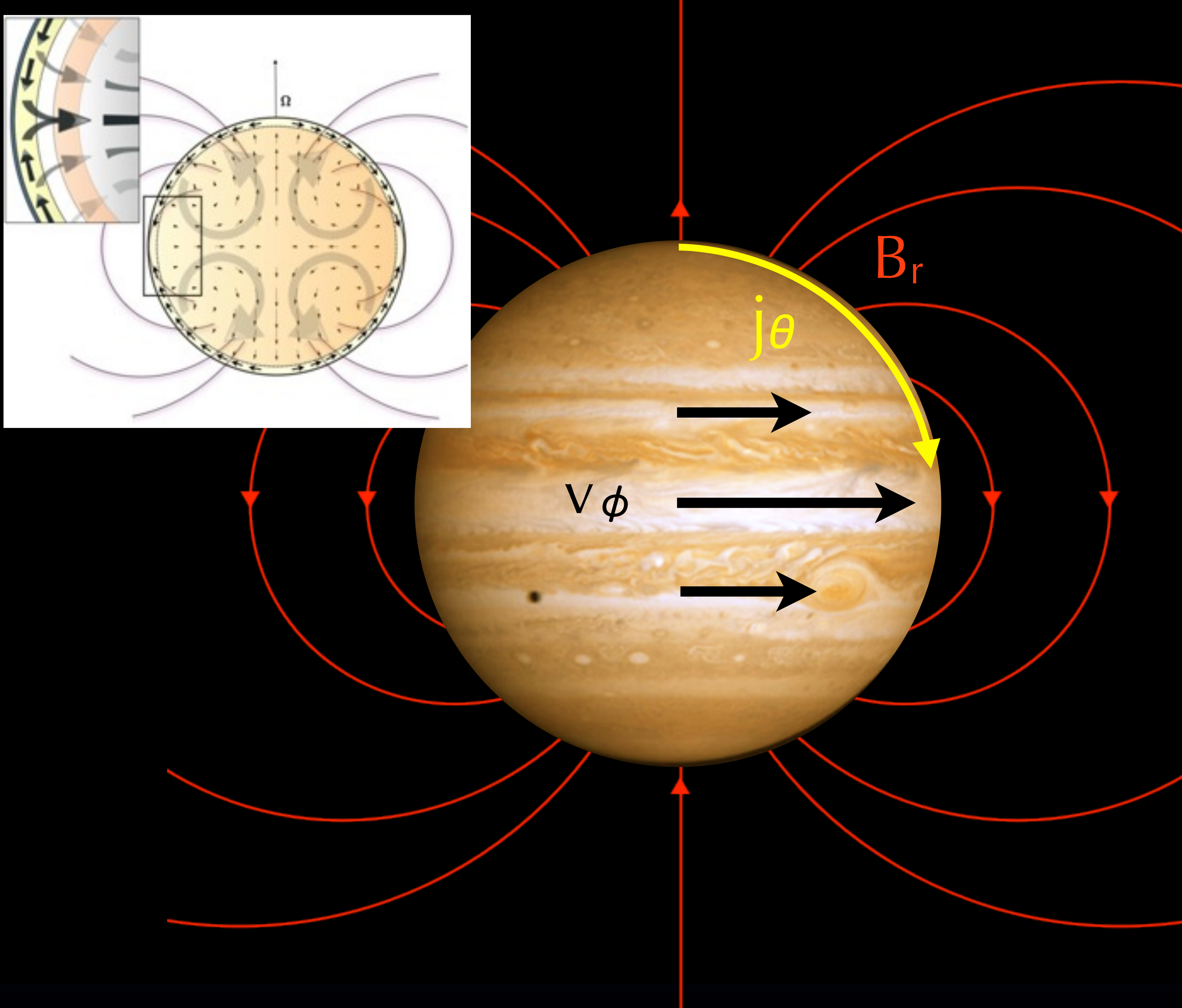
to

Incident L

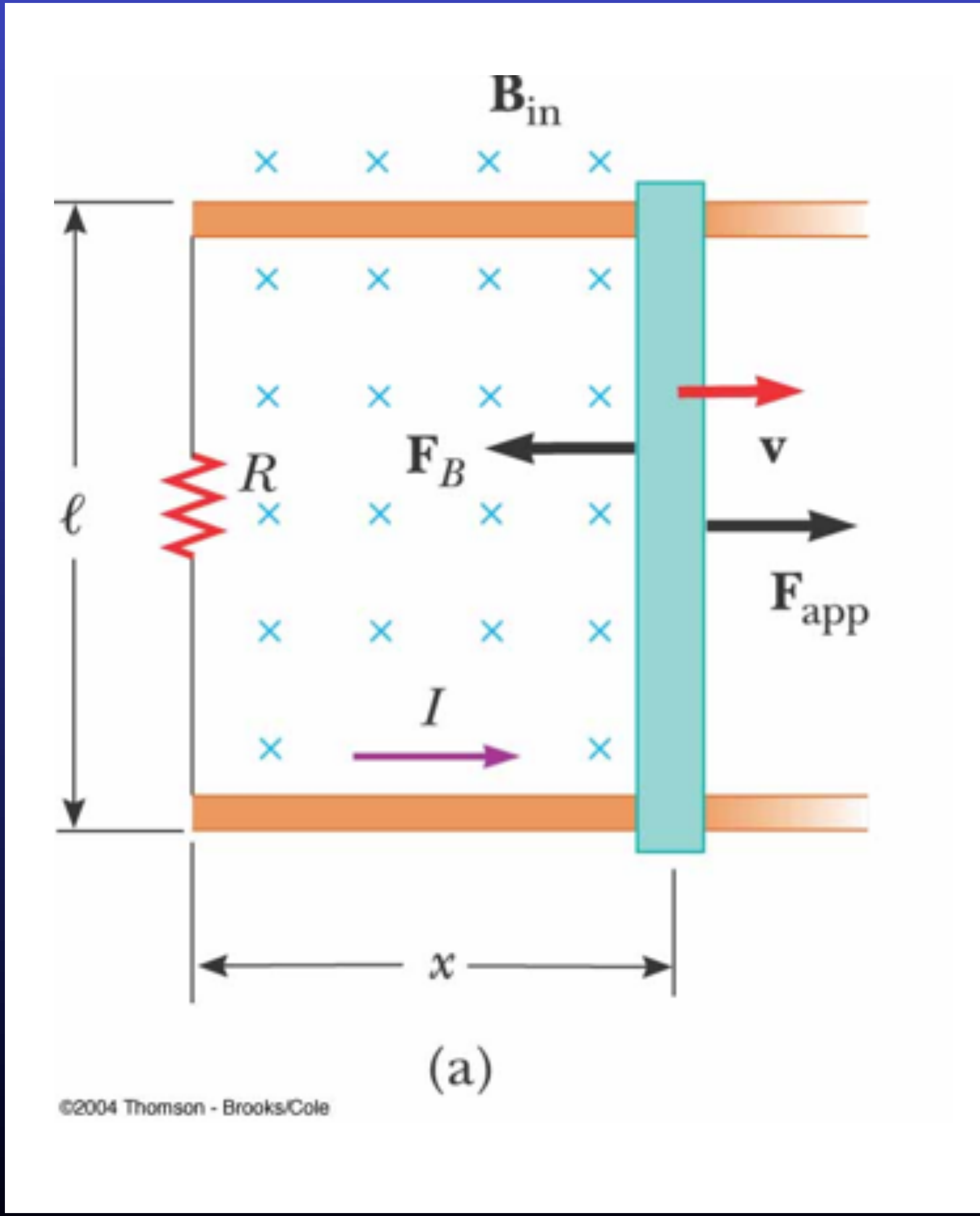
$$\frac{L_*}{4\pi a^2}\pi R_{\rm p}^2 A \sim 3 \times 10^{29}\ {\rm erg/s}$$



Even "easier": When planet is irradiated,
actual required L ~ 4 x 10^{25} erg/s


Ω
Br
jθ
V ϕ

Induced Current ⇒ Ohmic Power



$$\mathbf{F} = \frac{q}{c}\mathbf{v} \times \mathbf{B}$$

$$\varepsilon_{\text{emf}} = W/q = F\ell/q$$

$$I = \varepsilon_{\text{emf}}/R = \varepsilon_{\text{emf}}\frac{\sigma A}{\ell}$$

$$\text{Ohmic } P = I\varepsilon_{\text{emf}} = \frac{v^2 B^2 \sigma \ell A}{c^2}$$

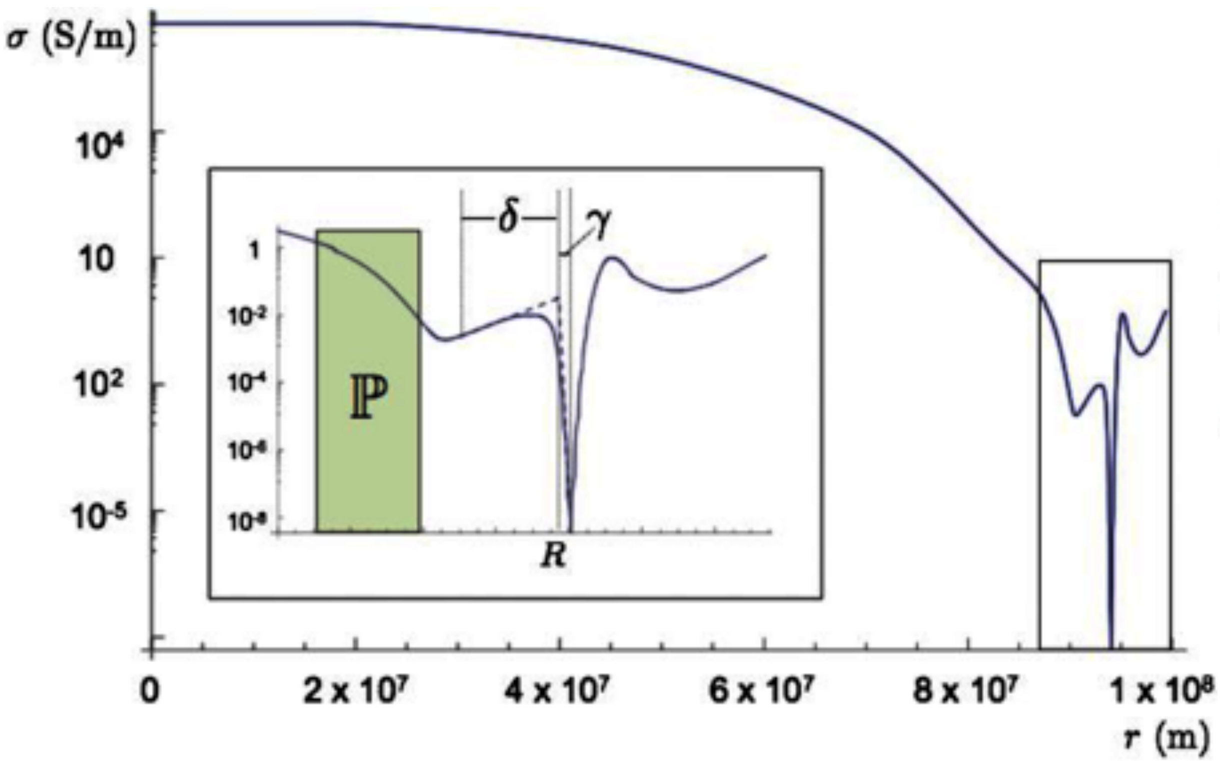
$$P = I^2 R$$

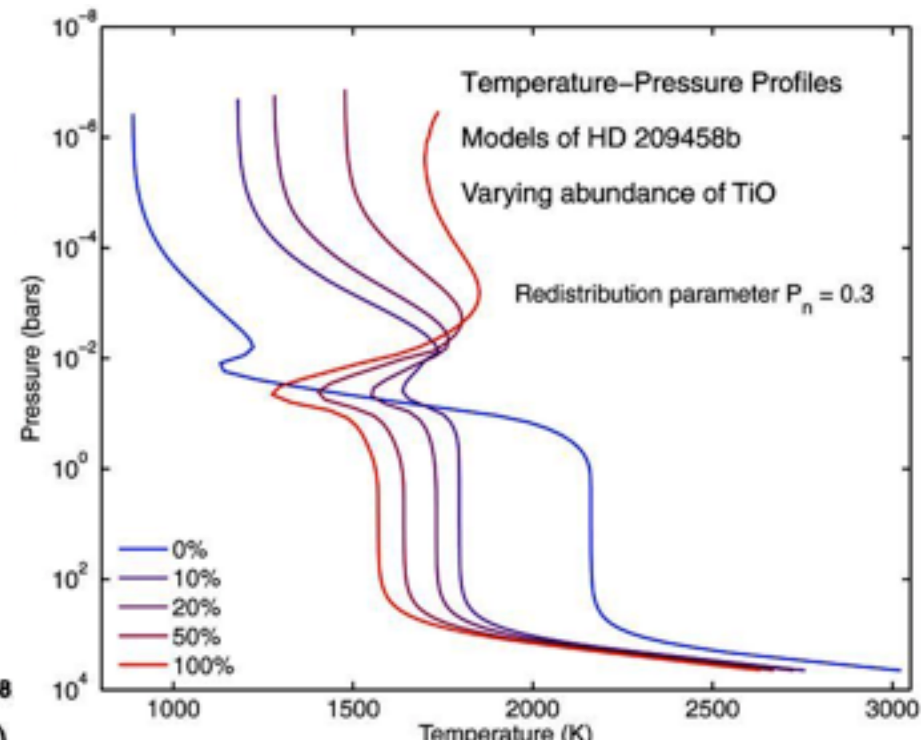
$$P = \int\int\int \frac{j^2}{\sigma}\, dV$$

$$\mathbf{j} = \sigma \mathbf{f} = \sigma\left(\frac{\mathbf{v}}{c} \times \mathbf{B} + \mathbf{E}\right)$$

copper 6e7 S/m
drinking water 0.0005 to 0.05 S/m

Planetary conductivity

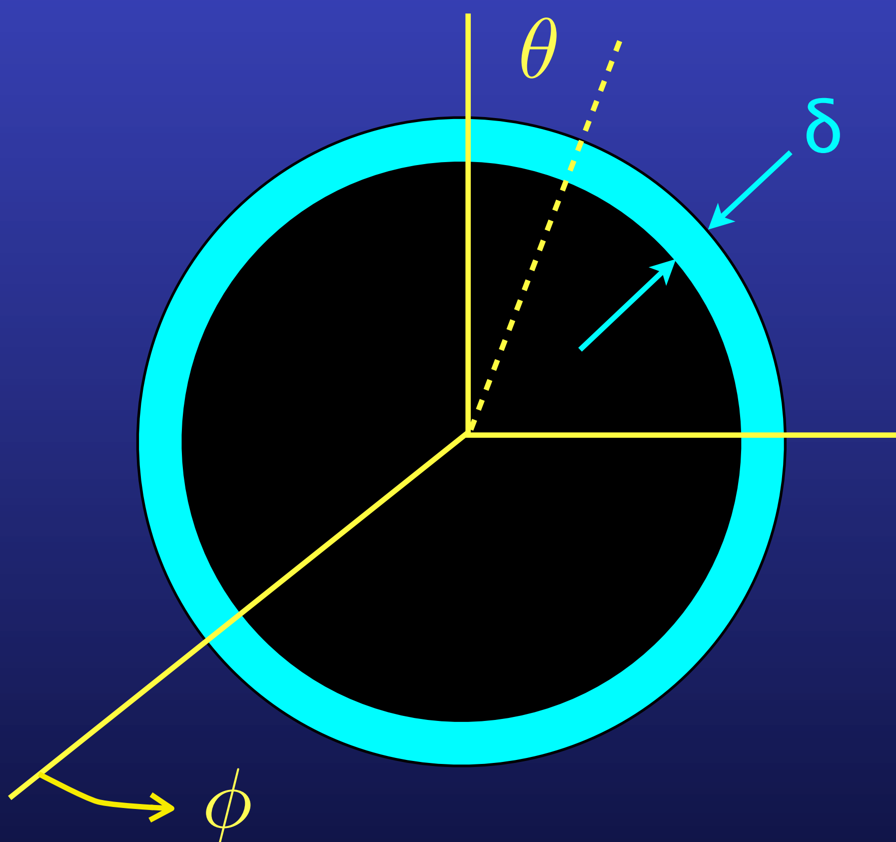


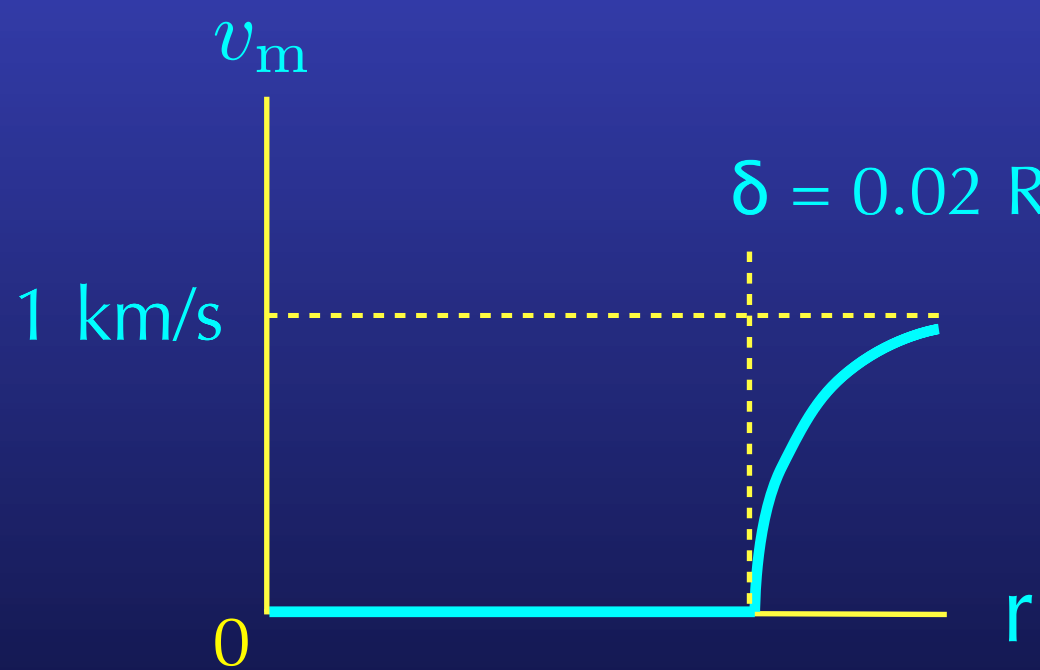


Batygin & Stevenson 10, Spiegel et al. 09

$$\mathbf{j} = \sigma \mathbf{f} = \sigma \left(\frac{\mathbf{v}}{c} \times \mathbf{B} + \mathbf{E} \right)$$

delta ~ 2.3e8 cm (R ~ 1.05e10)

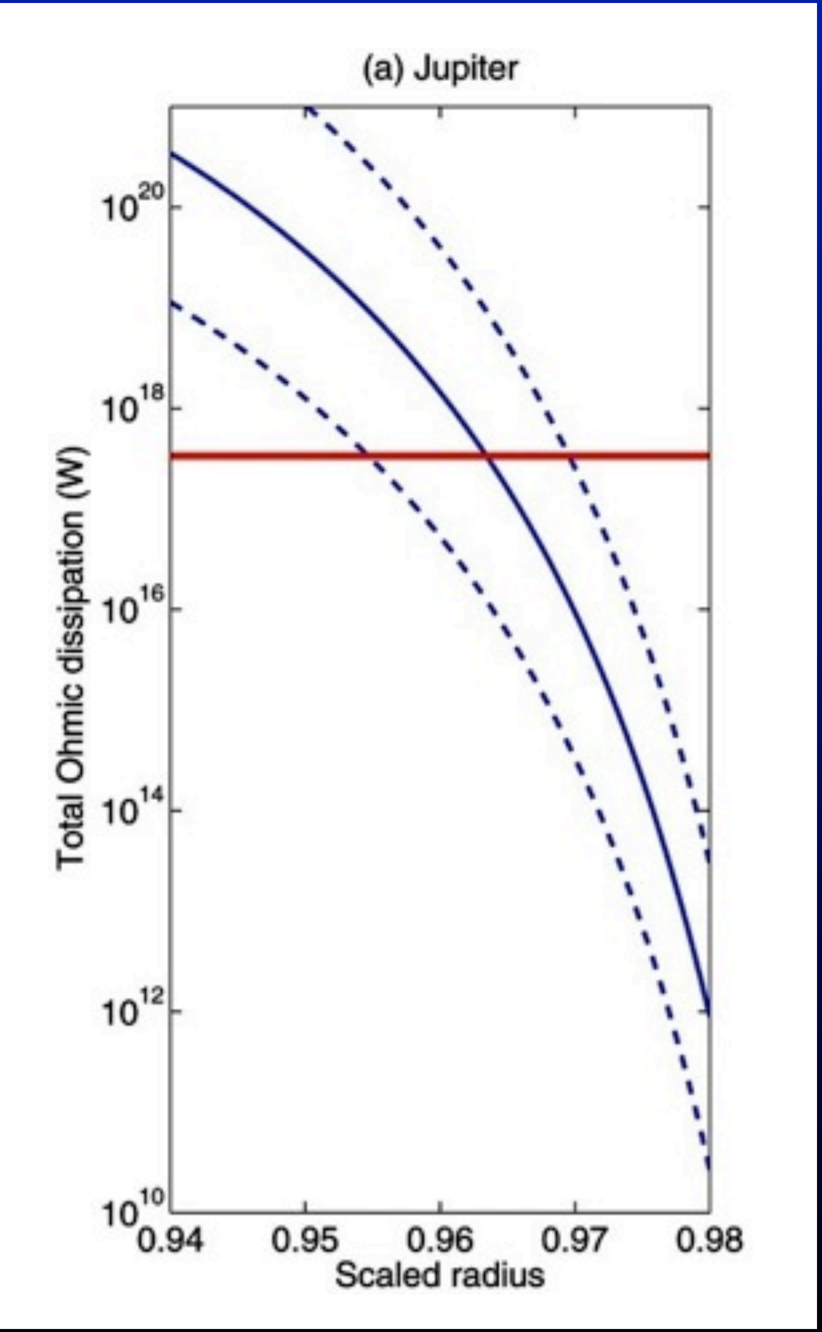




$$\mathbf{v}(r, \theta) = v_{\rm m} \sin \theta \, \hat{\phi}$$

$$f \frac{L_*}{4\pi a^2} \pi R^2 \sim \frac{\frac{1}{2} \rho v^2 4\pi R^2 h}{R/v} \Rightarrow v^3 \propto L_*/a^2$$

Differential rotation may only be skin deep



If winds extend too deep,
Ohmic power > internal luminosity

$\delta < 0.03R$ for Jupiter (maybe)

Also Taylor-Proudman theorem,
plus observed stability of B field,
enforces near solid-body rotation in
convective interior (maybe)
[$P(\rho) \Rightarrow$ v constant on cylinders]

Liu, Goldreich, & Stevenson 08
see also critique by Glatzmaier 08

$$\mathbf{j} = \sigma \mathbf{f} = \sigma \left(\frac{\mathbf{v}}{c} \times \mathbf{B} + \mathbf{E} \right)$$

Assume B(R) = 10 G [cf. Jupiter B(R) = 4.2 G]

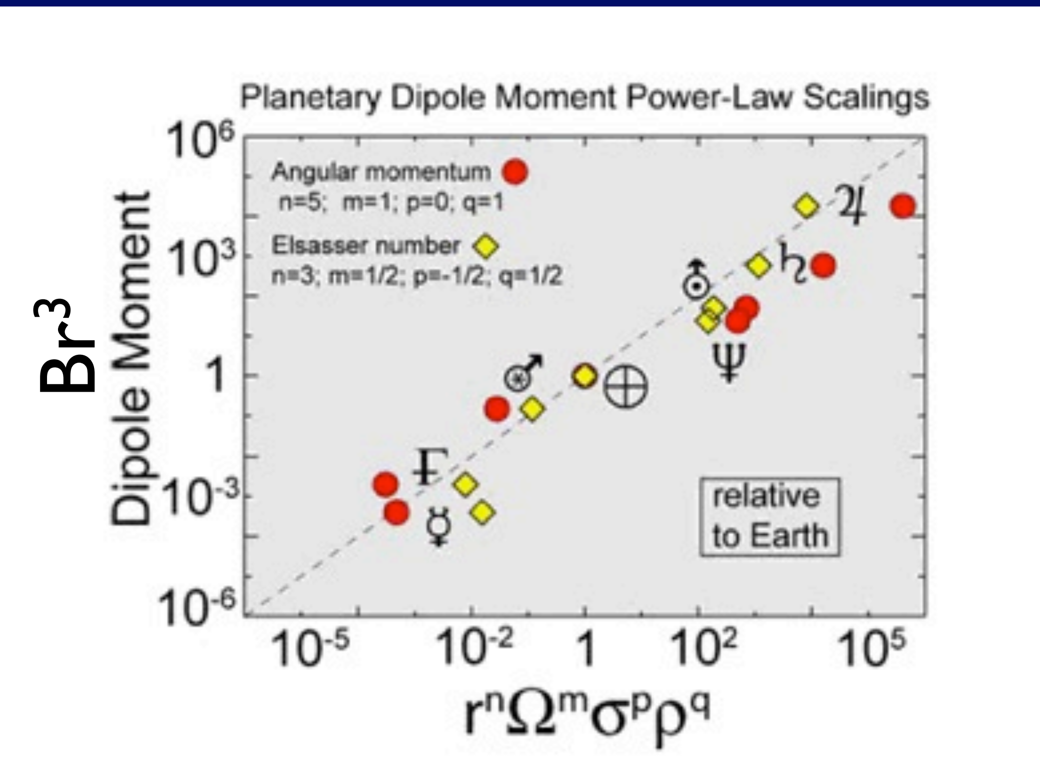
$$\text{Elsasser Number} = \frac{\mathcal{O}(\mathbf{j} \times \mathbf{B})/c}{\mathcal{O}(2\rho\mathbf{\Omega} \times \mathbf{v})} \propto \frac{\sigma B^2}{\rho\Omega}$$

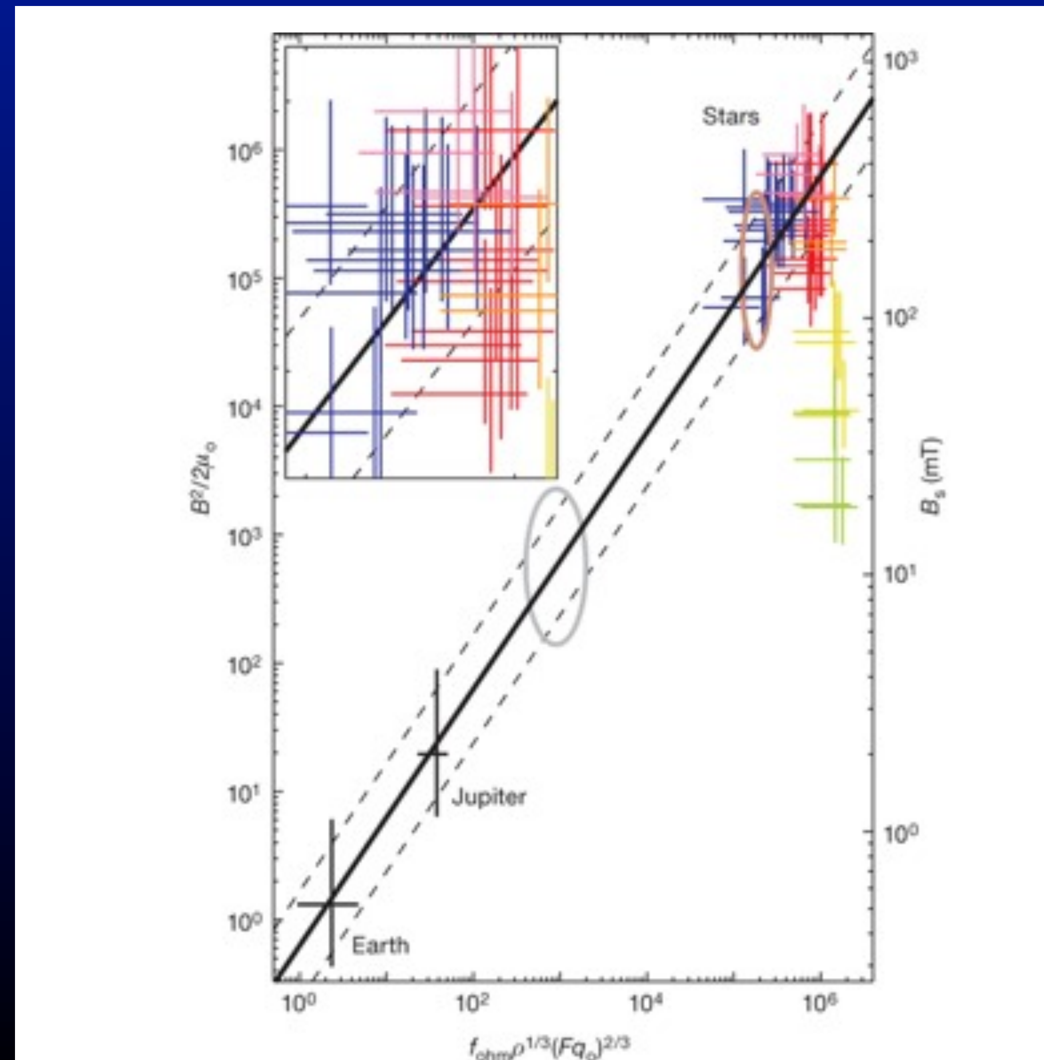
$$\text{Elsasser Number} \sim 1 \Rightarrow B^2 \propto \rho\Omega/\sigma$$

To reproduce assumed B,
assume surface dynamo different from Jupiter

$$\text{Energy flux scaling}: \; B^2 \propto \rho^{1/3} q^{2/3}$$

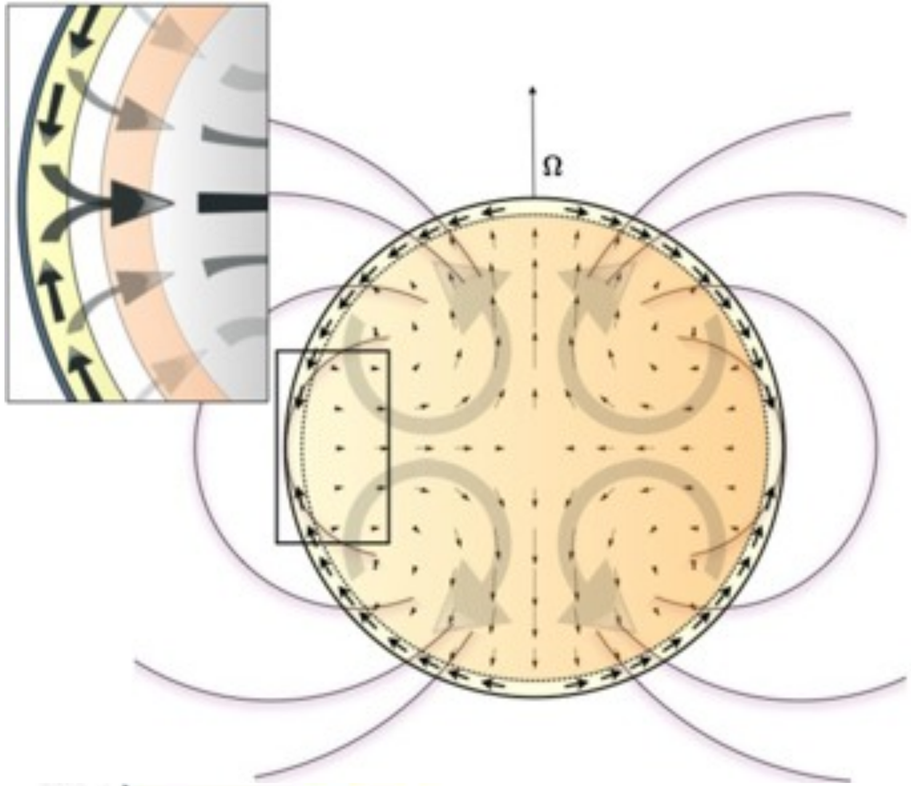
$$\text{Internal flux } q \text{ for Hot Jupiter} \sim 10^2\, q \text{ for Jupiter}$$

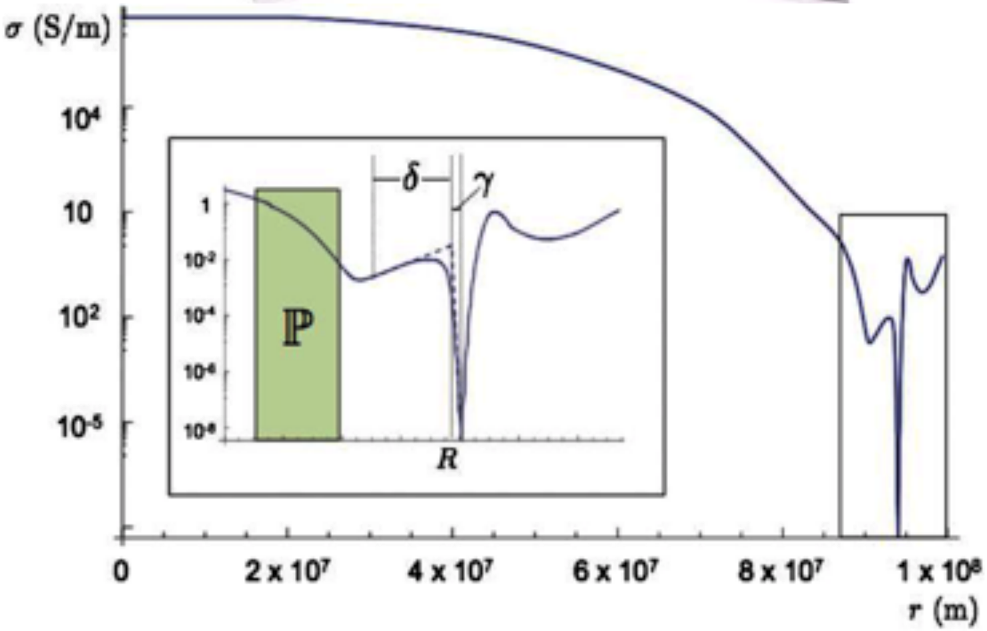




Christensen, Holzwarth, & Reiners 2009

Atmospheric Power





$$\mathbf{j} = \sigma \mathbf{f} = \sigma \left(\frac{\mathbf{v}}{c} \times \mathbf{B} + \mathbf{E} \right)$$

$$\sim \sigma \frac{\mathbf{v}}{c} \times \mathbf{B}$$

$$P = \int \int \int \frac{j^2}{\sigma} dV$$

$$\sim \frac{\sigma v^2 B^2}{c^2} 4\pi R^2 \delta$$

$$\sim 8 \times 10^{27} \mathrm{erg/s}$$

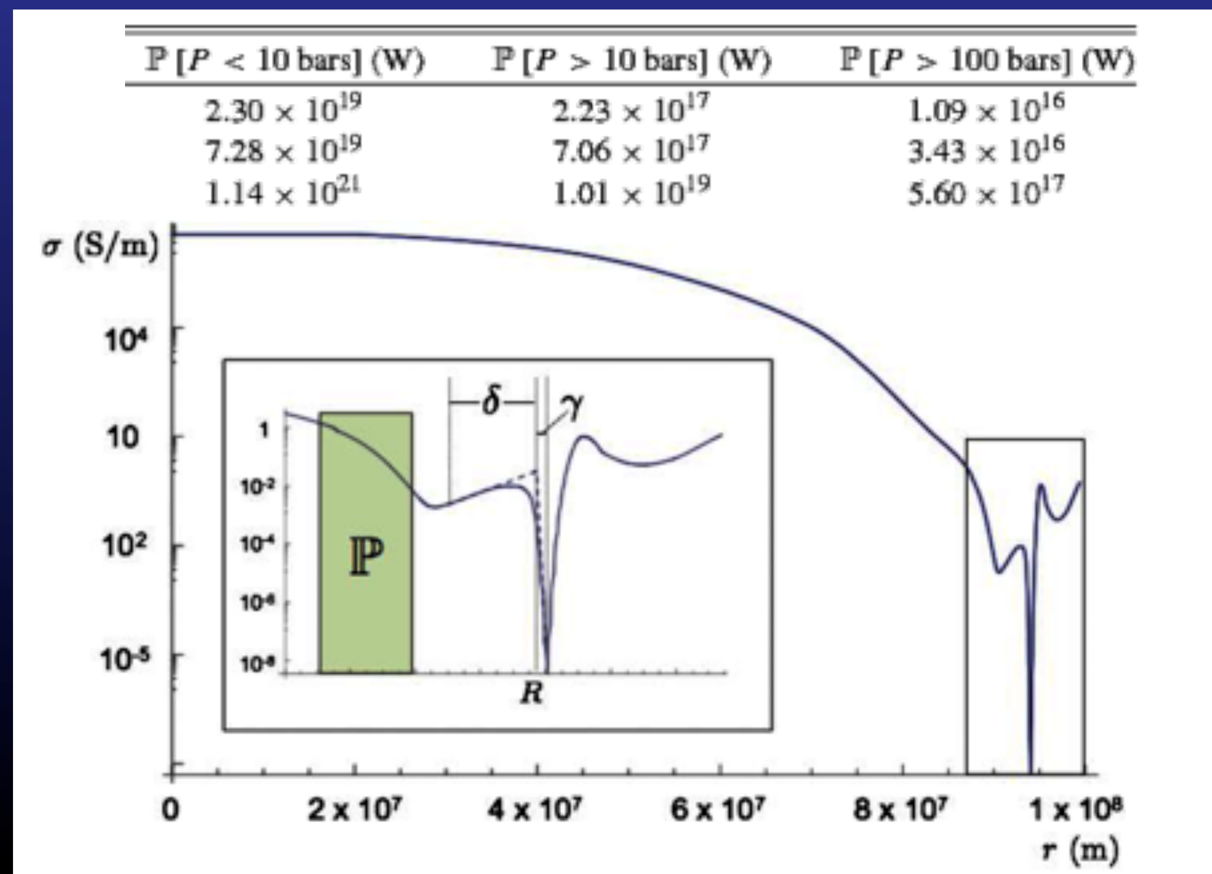
Planet	Y	$T_{\rm iso}$ (K)	Z (×solar)	$\mathbb{P}$ [P < 10 bars] (W)
HD209458b	0.24	1400	1	2.30×10^{19}
HD209458b	0.24	1400	10	7.28×10^{19}
HD209458b	0.24	1700	1	1.14×10^{21}

Power at Radiative-Convective (RC) Boundary

$$P_{\rm RC} = \int\int\int \frac{j^2}{\sigma}\, dV$$

$$\sim \frac{j^2}{\sigma_{\rm RC}} 2\pi R \times \delta\delta_{\rm RC}$$

$$\sim P \frac{\sigma}{\sigma_{\rm RC}} \frac{\delta_{\rm RC}}{R} \sim 1 \times 10^{25} {\rm erg/s}$$



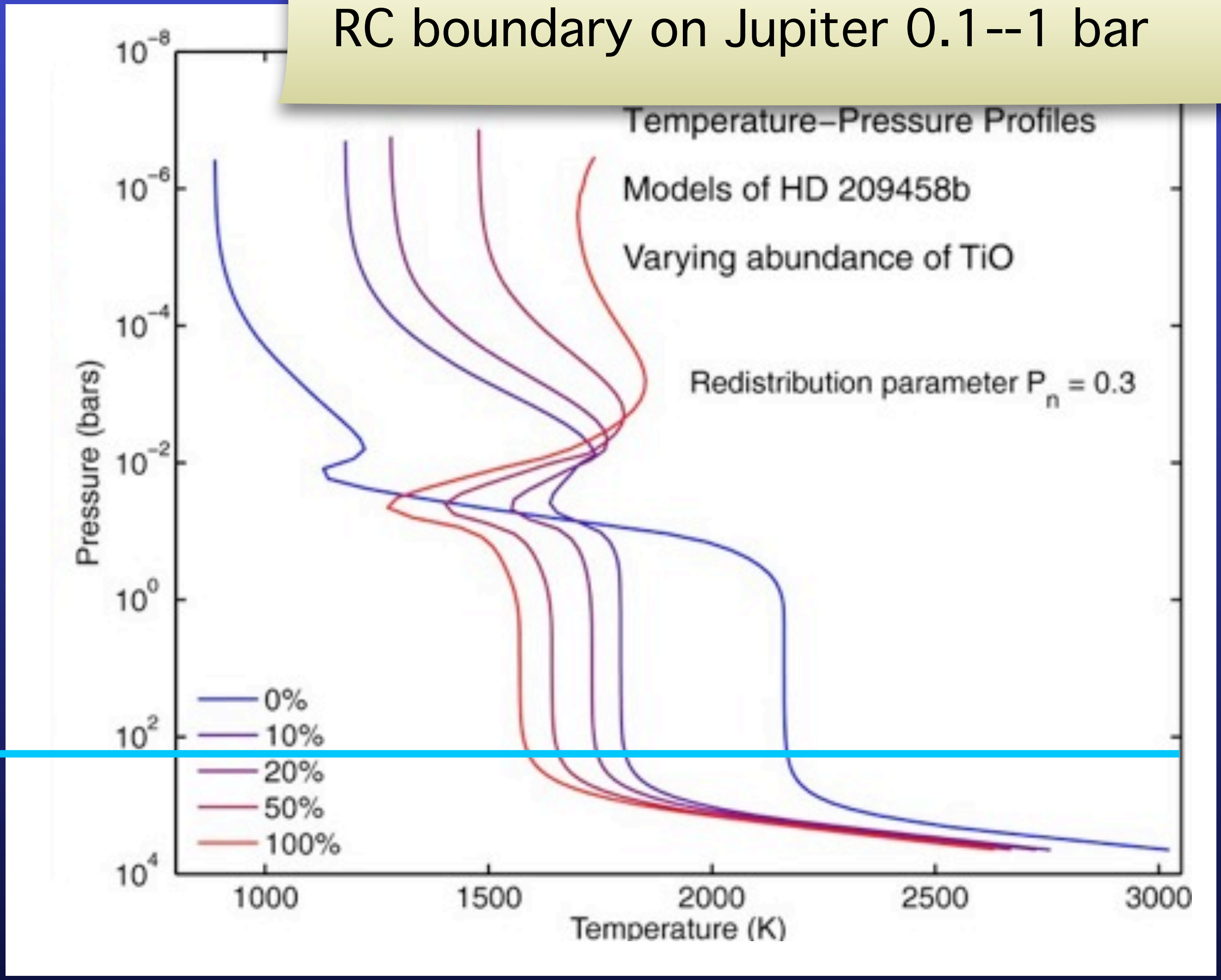
$\mathbb{P}\,[P < 10$ bars] (W)	$\mathbb{P}\,[P > 10$ bars] (W)	$\mathbb{P}\,[P > 100$ bars] (W)
2.30×10^{19}	2.23×10^{17}	1.09×10^{16}
7.28×10^{19}	7.06×10^{17}	3.43×10^{16}
1.14×10^{21}	1.01×10^{19}	5.60×10^{17}

How much extra power and where?

RC boundary on Jupiter 0.1--1 bar

Where : convective interior

Radiative-convective (RC) boundary



$$\text{Specific entropy } s = s_{\rm RC} \approx s_{\rm core}$$

$$\Rightarrow R(s, M)$$

Spiegel, Silverio, and Burrows 2009