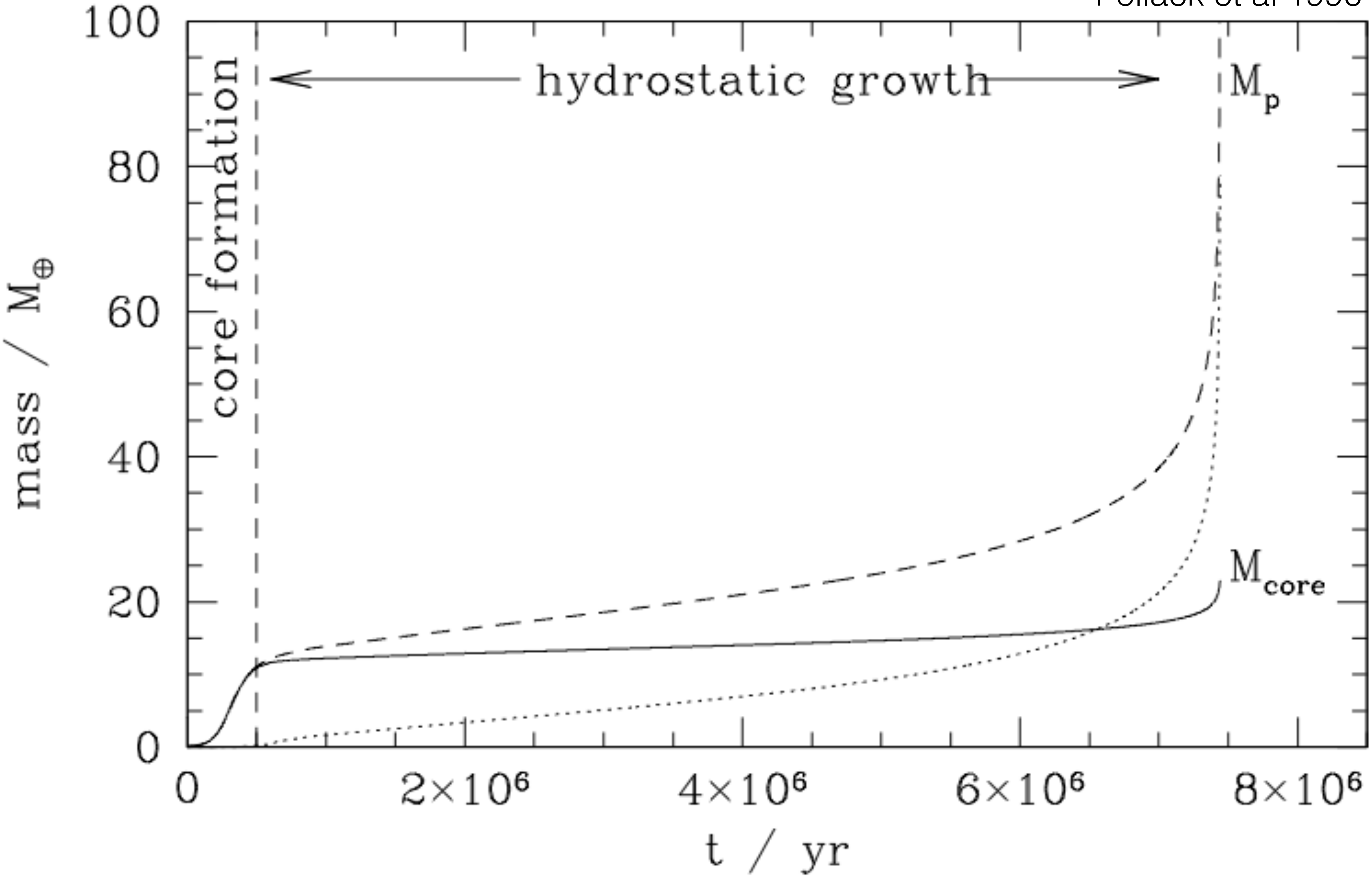
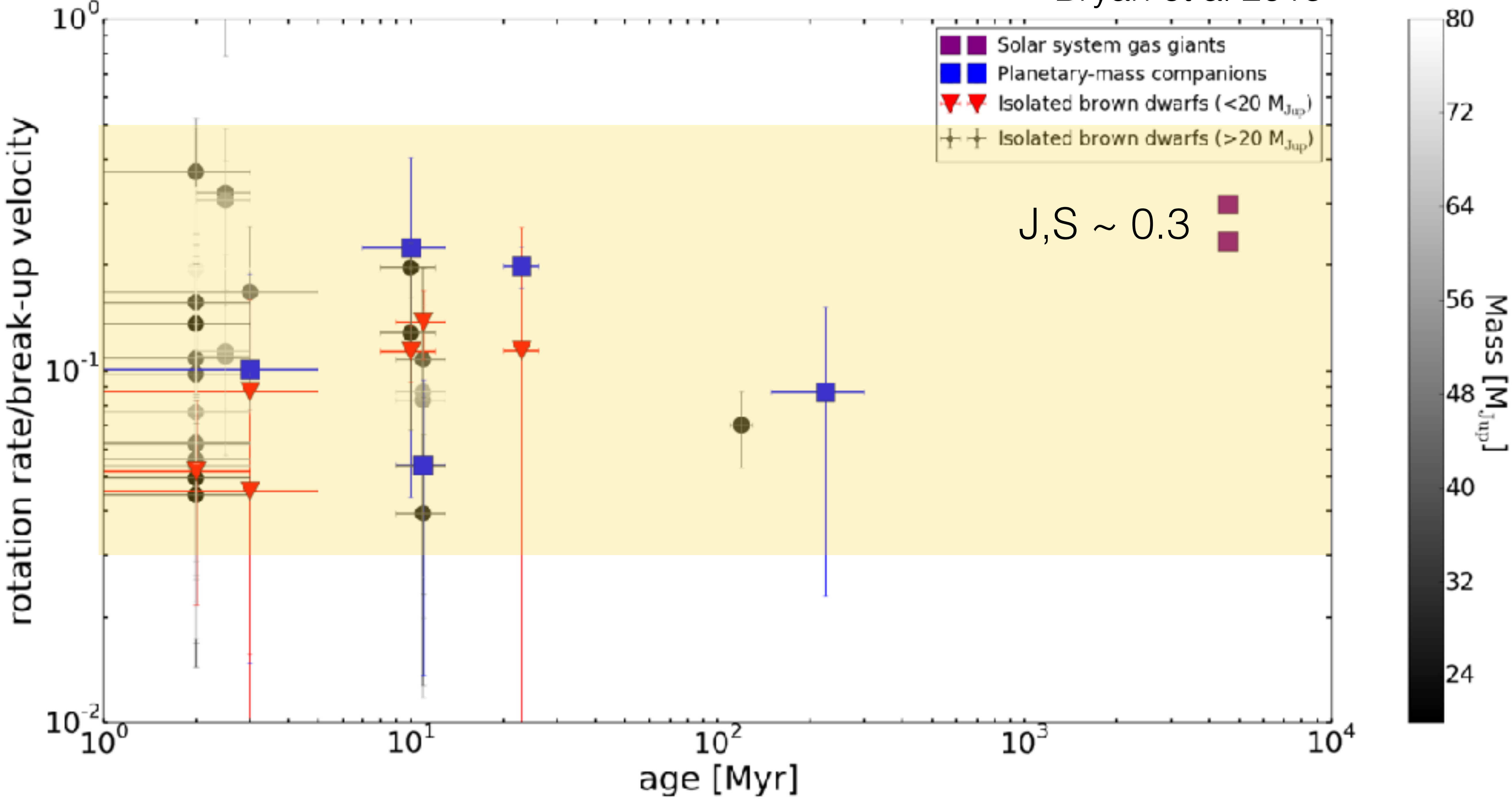
Konstantin Batygin
Caltech

Giant Planet Formation

Pollack et al 1996



Bryan et al 2018



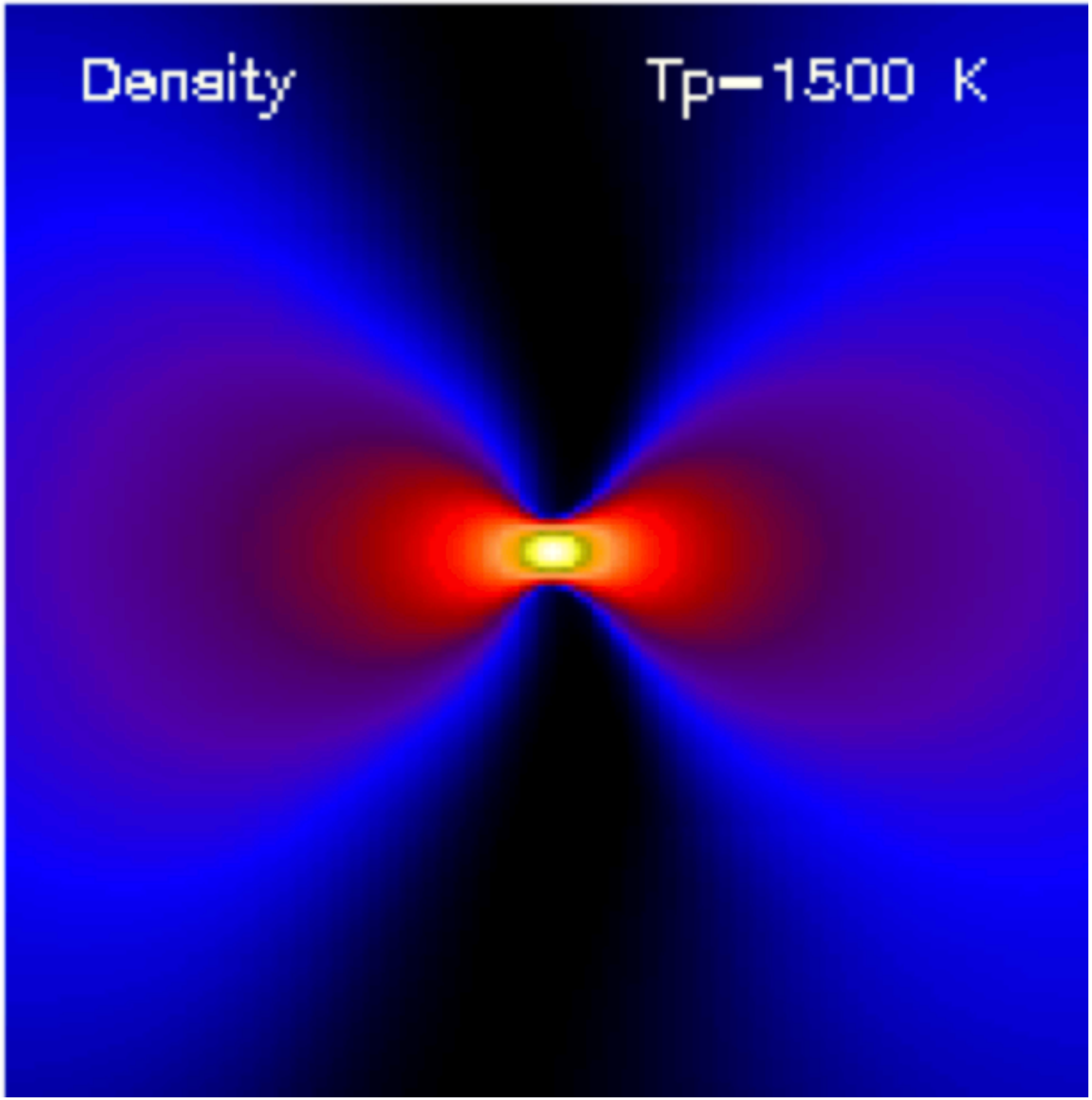
No clear trend of rotation rate with age…

Naively, runaway accretion should lead to near-breakup rotation. Gravitational contraction makes it even worse.

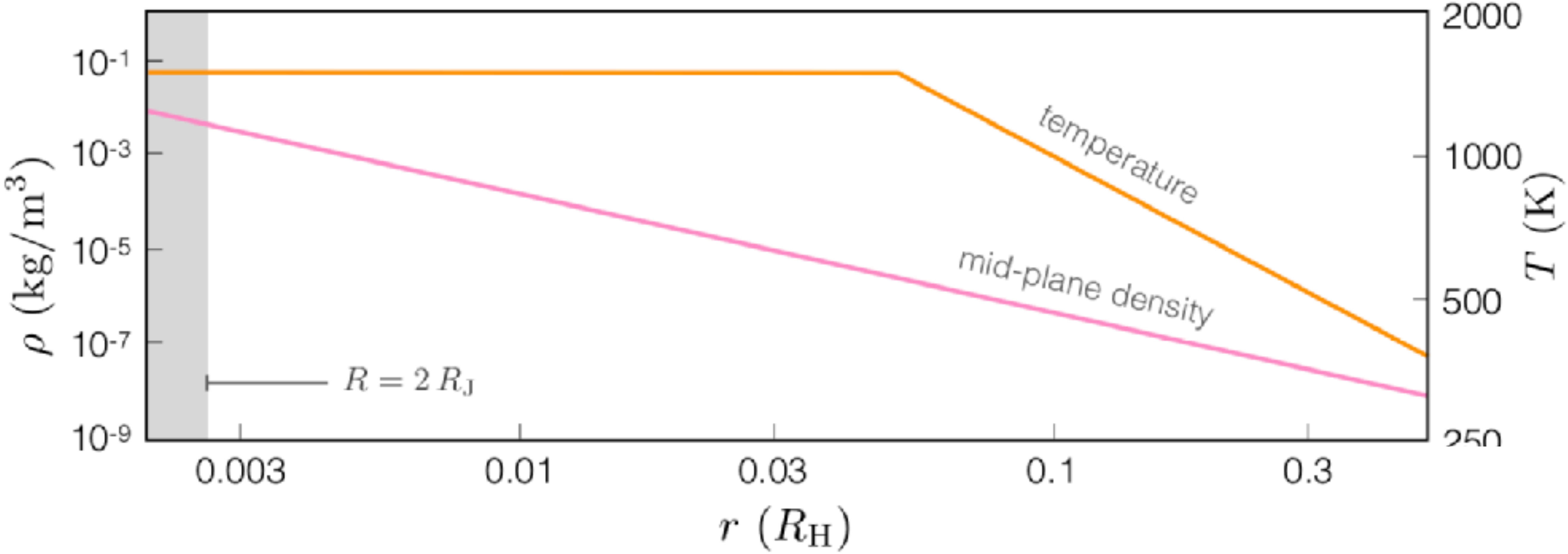
Significantly sub-breakup rotation is the rule not the exception.

Regulation mechanism seems independent of mass and age. Probably operates during infancy.

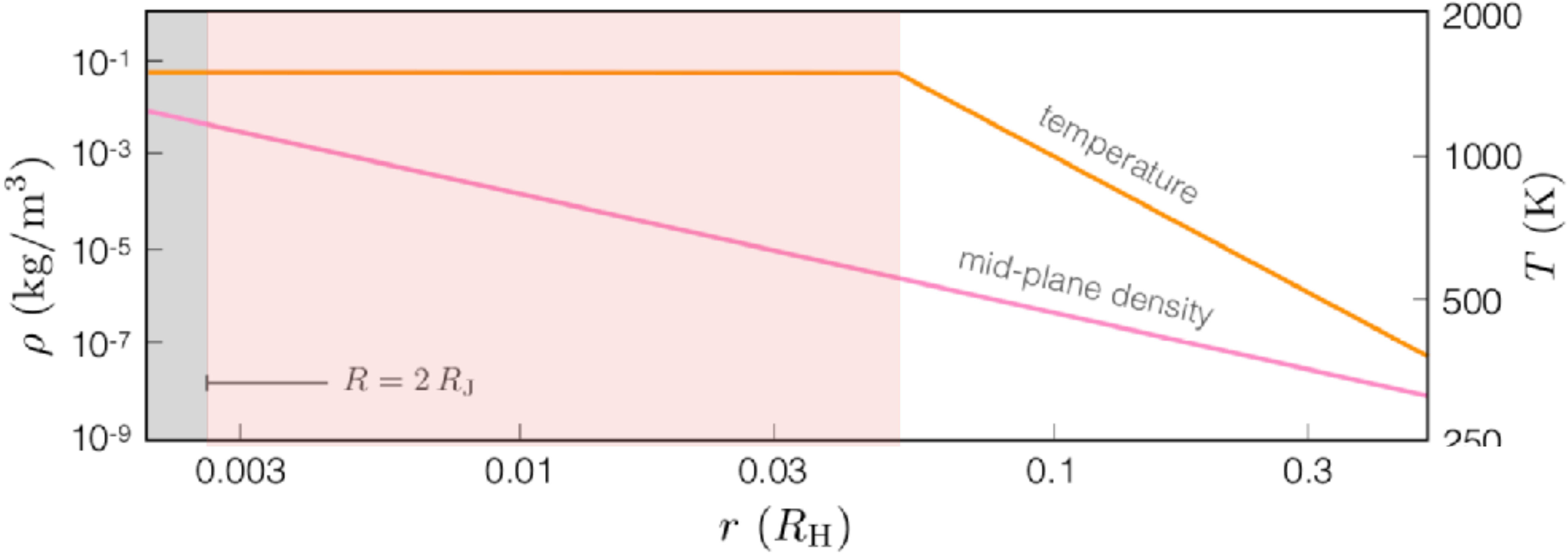
A possible solution: look at an earlier epoch i.e. the runaway accretion phase itself



Szulagyi et al 2016



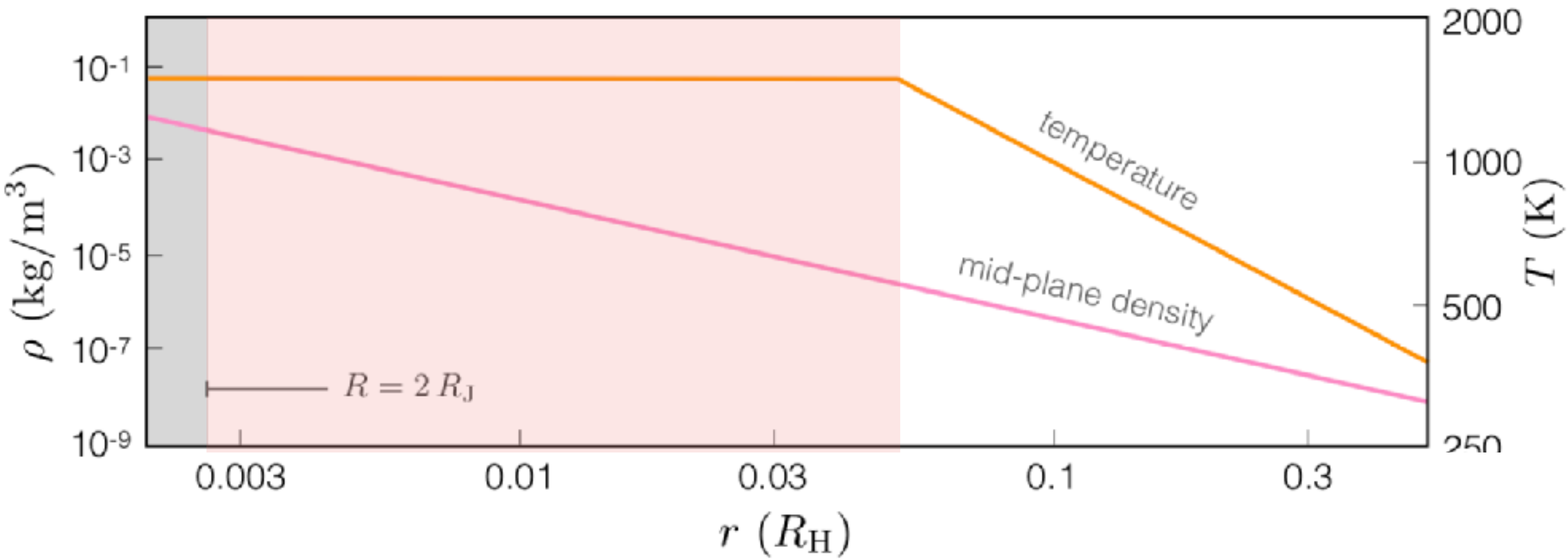
10-1
10-3
10-5
10-7
10-9
ρ (kg/m3)
2000
1000
500
250
T (K)
temperature
mid-plane density
R = 2 RJ
0.003
0.01
0.03
0.1
0.3
r (RH)



thermal ionization:

$$\frac{n_i^+ \, n_e}{n_i - n_i^+} = \left(\frac{m_e \, k_\mathrm{b} \, T}{2\pi \, \hbar^2} \right)^{3/2} \exp\left(- I_i / k_\mathrm{b} \, T \right)$$

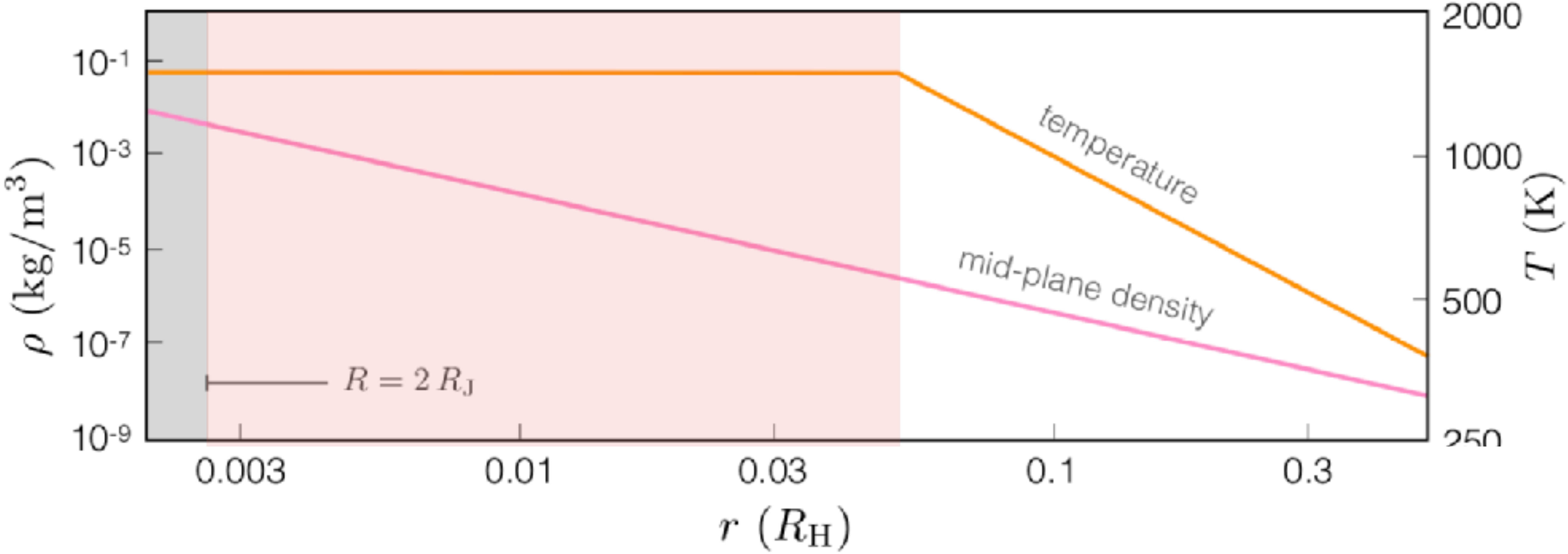
ionization fraction ~ 0.1 - 1 ppm in the inner disk



electrical conductivity:

$$\sigma = \frac{n_e}{n_n} \frac{e^2}{m_e\, \mathcal{A}_c} \sqrt{\frac{\pi\, m_e}{8\, k_b\, T}} \sim 0.1 \text{ S/m}$$

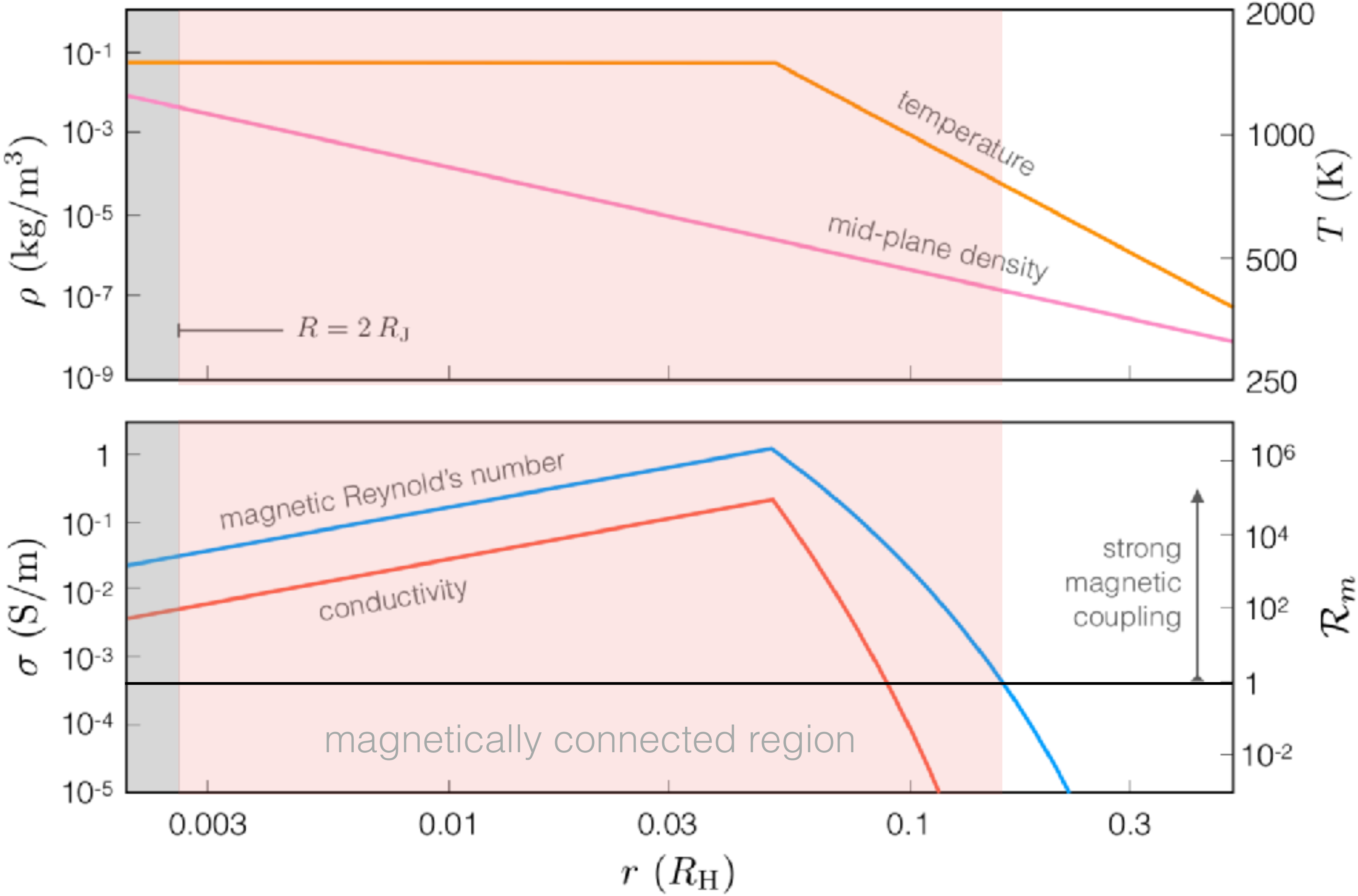
for comparison: salty water has a conductivity of ~ 1 S/m



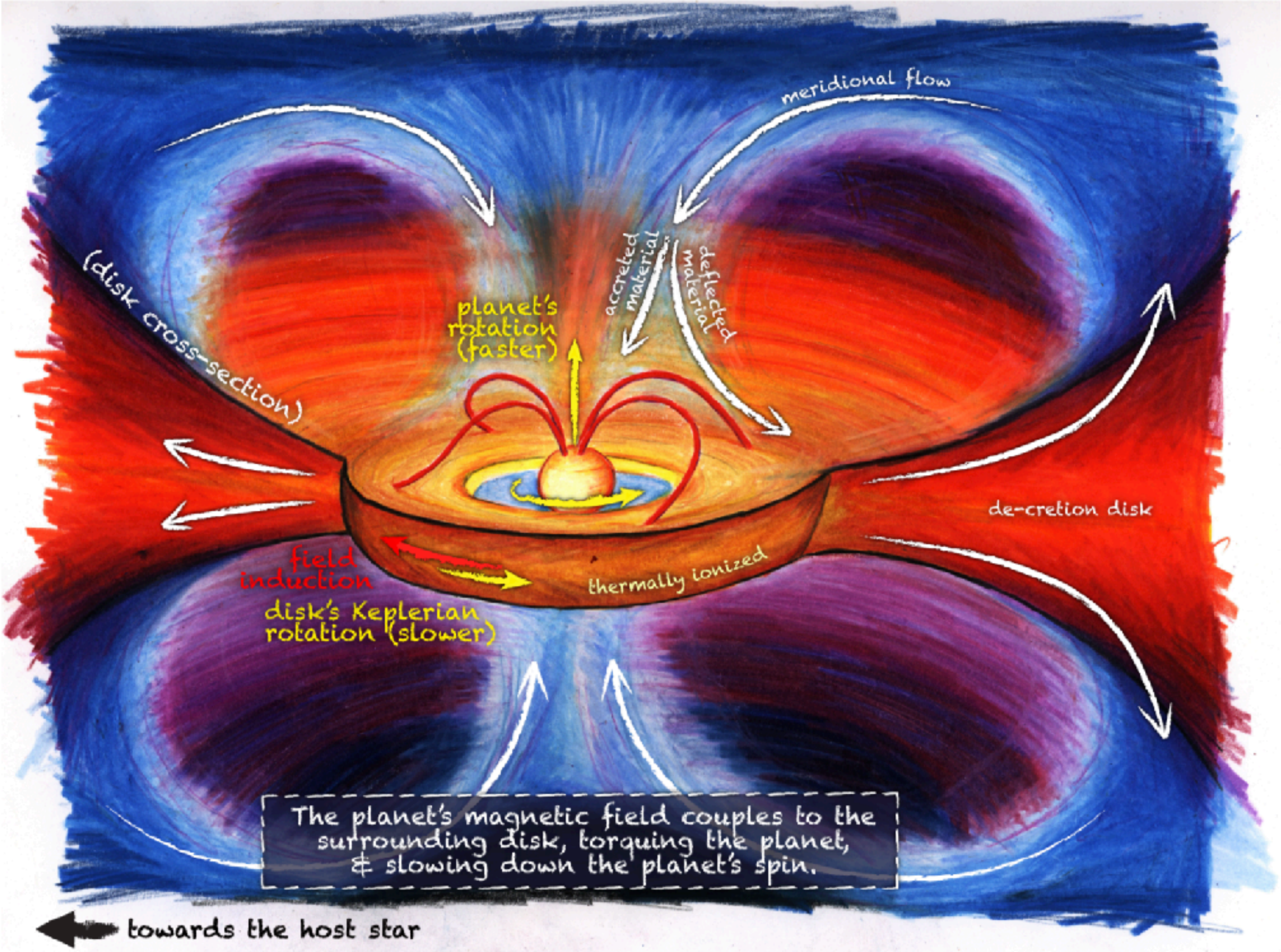
magnetic Reynold's number

$$\mathcal{R}_m = \frac{v_{\rm kep}\, h}{\eta} = \mu_0\, \sigma\, r \sqrt{\frac{k_{\rm b}\, T}{\mu}}$$ ~ infinity

diffusive effects are not important for induction!



10-1
10-3
10-5
10-7
10-9
ρ (kg/m^3)
2000
1000
500
250
T (K)
temperature
mid-plane density
$R = 2\,R_J$
1
10-1
10-2
10-3
10-4
10-5
σ (S/m)
10^6
10^4
10^2
1
10-2
$\mathcal{R}_m$
magnetic Reynold's number
conductivity
strong
magnetic
coupling
magnetically connected region
0.003
0.01
0.03
0.1
0.3
r (R_H)


meridional flow
accreted material
deflected material
planet's rotation (faster)
(disk cross-section)
de-cretion disk
field induction
thermally ionized
disk's Keplerian rotation (slower)
The planet's magnetic field couples to the surrounding disk, torquing the planet, & slowing down the planet's spin.
towards the host star

Letter | Published: 08 January 2009

Energy flux determines magnetic field strength of planets and stars

Ulrich R. Christensen, Volkmar Holzwarth & Ansgar Reiners

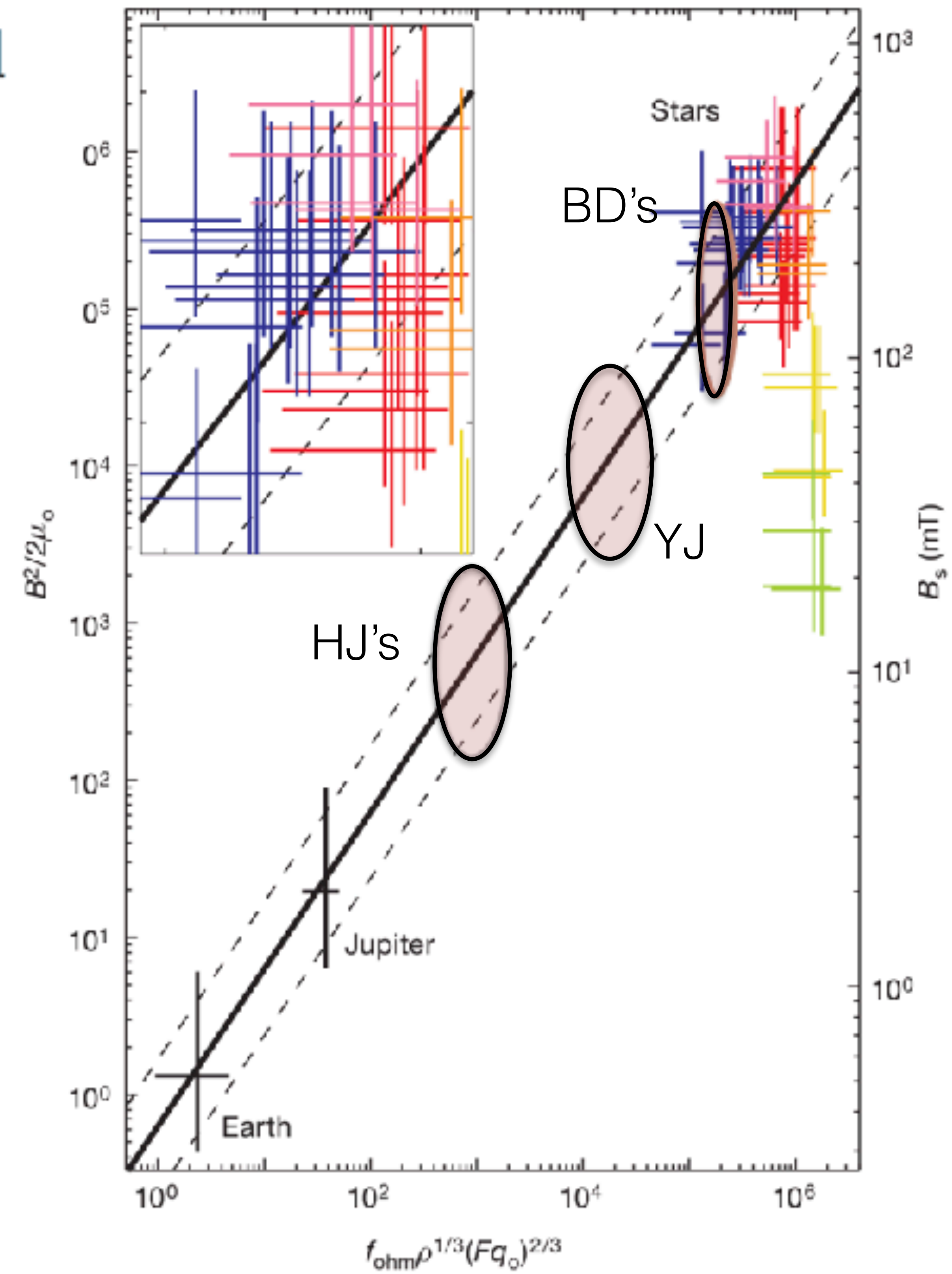
Nature **457**, 167–169 (08 January 2009) | Download Citation

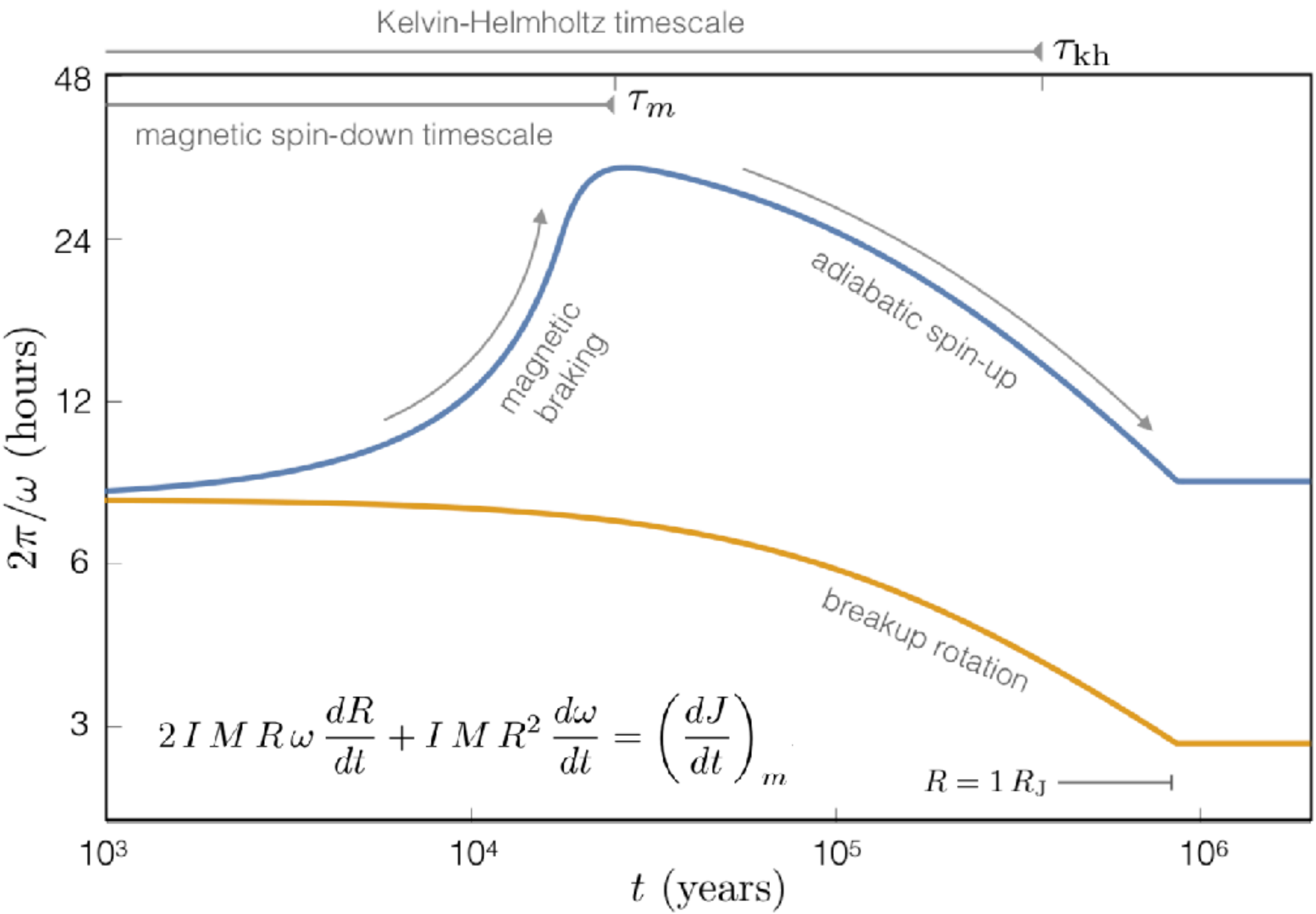
~1 ~10^{-4} solar

$$\langle B^2\rangle/2\mu_0 = c\, f_{\rm ohm}\, \langle\rho\rangle^{1/3}\, (F\, q)^{2/3}$$

$$\sim \langle\rho\rangle\, v_{\rm conv}^2$$

B ~ <*B*> / 3.5 ~ 500 Gauss




Kelvin-Helmholtz timescale
$\tau_{\rm kh}$
τ_m
magnetic spin-down timescale
magnetic braking
adiabatic spin-up
breakup rotation
$2\,I\,M\,R\,\omega\,\frac{dR}{dt} + I\,M\,R^2\,\frac{d\omega}{dt} = \left(\frac{dJ}{dt}\right)_m$
$R = 1\,R_{\rm J}$
48
24
12
6
3
$2\pi/\omega$ (hours)
10^3
10^4
10^5
10^6
t (years)

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On the Terminal Rotation Rates of Giant Planets

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