HOT JUPITERS INFLATED RADII & MAGNETISM: COUPLING JETS, DYNAMO AND INDUCED FIELDS

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14th April 2026, Heidelberg, *Layers of understanding*

based on: Viganò et al. A&A 2025, Elias-López et al. ApJ 2025

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Inflated hot Jupiters: Inferring average atmospheric velocity via Ohmic models coupled with internal dynamo evolution

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Rossby Number Regime, Convection Suppression, and Dynamo-generated Magnetism in Inflated Hot Jupiters

Albert Elias-López, Matteo Cantiello, Daniele Viganò, Fabio Del Sordo, Simranpreet Kaur, and Clàudia Soriano-Guerrero

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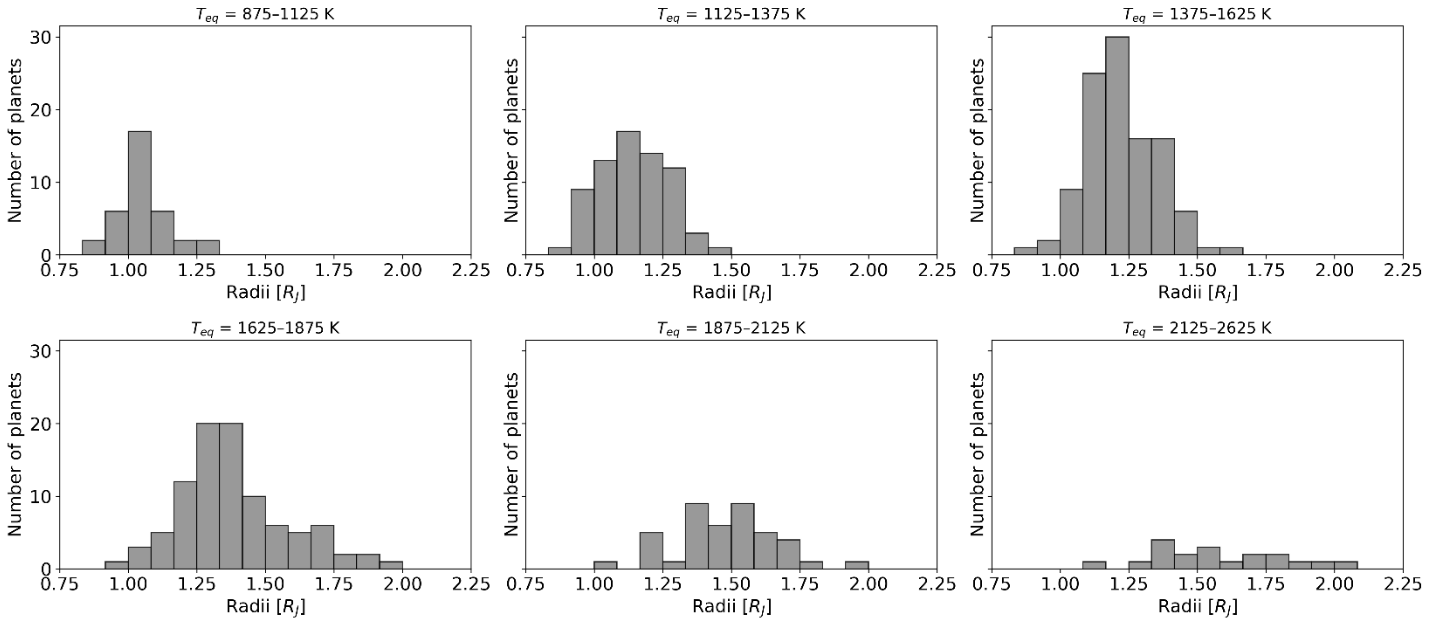
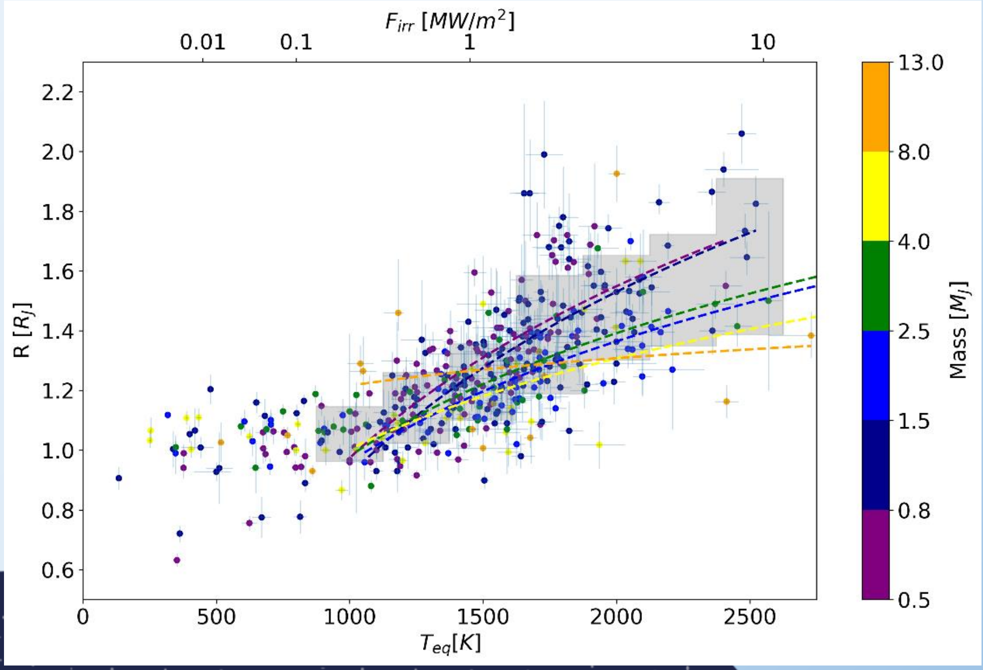
Hot Jupiters: inflated radii



[424 HJs with M=0.5-13 Mj, t>100 Myr, Viganò et al. 2025]



FACTS

Many HJs look "puffy"

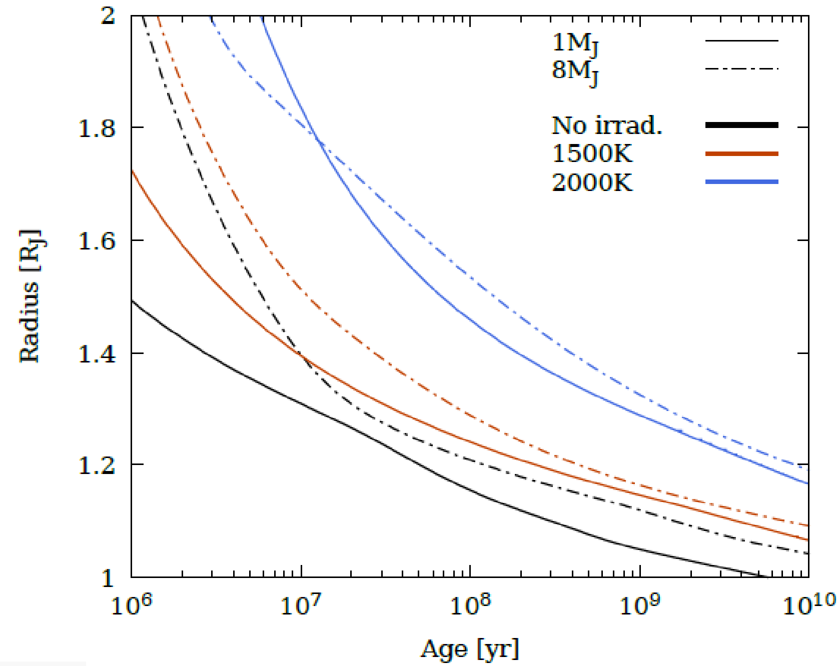
- A clear trend with irradiation is seen
- More massive planets inflate less

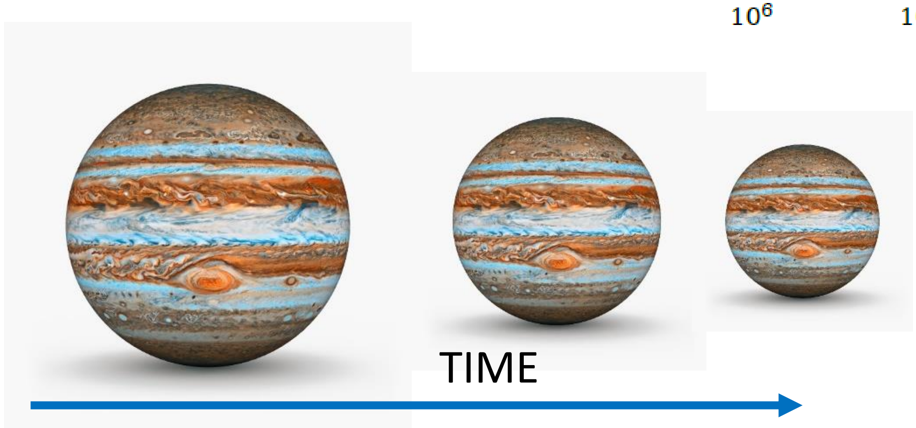
Cooling models

- Radius shrinking from initial values of several Rj happens in Myr
- Considering irradiation is not enough, it delays the shrinking, but it cannot provide more than about 1.3 Rj at Gyr ages.
- "delaying cooling" mechanisms (e.g. enhanced opacity) could explain moderate inflation only.

$$\frac{dm}{dr} = 4\pi r^2 \rho \ ,$$
$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4} \ ,$$
$$\frac{dL}{dm} = -T\frac{ds}{dt} + \epsilon_{irr} + \epsilon_{heat} \ ,$$
$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla \ ,$$

$$\nabla \equiv d\ln T / d\ln P$$





Hot Jupiter inflation radii: need for additional heat

There must be a temperature-dependence of the source heat to explain data.

Heating is usually parametrized by efficiency: $\varepsilon = Q_{heat}/L_{irr}$

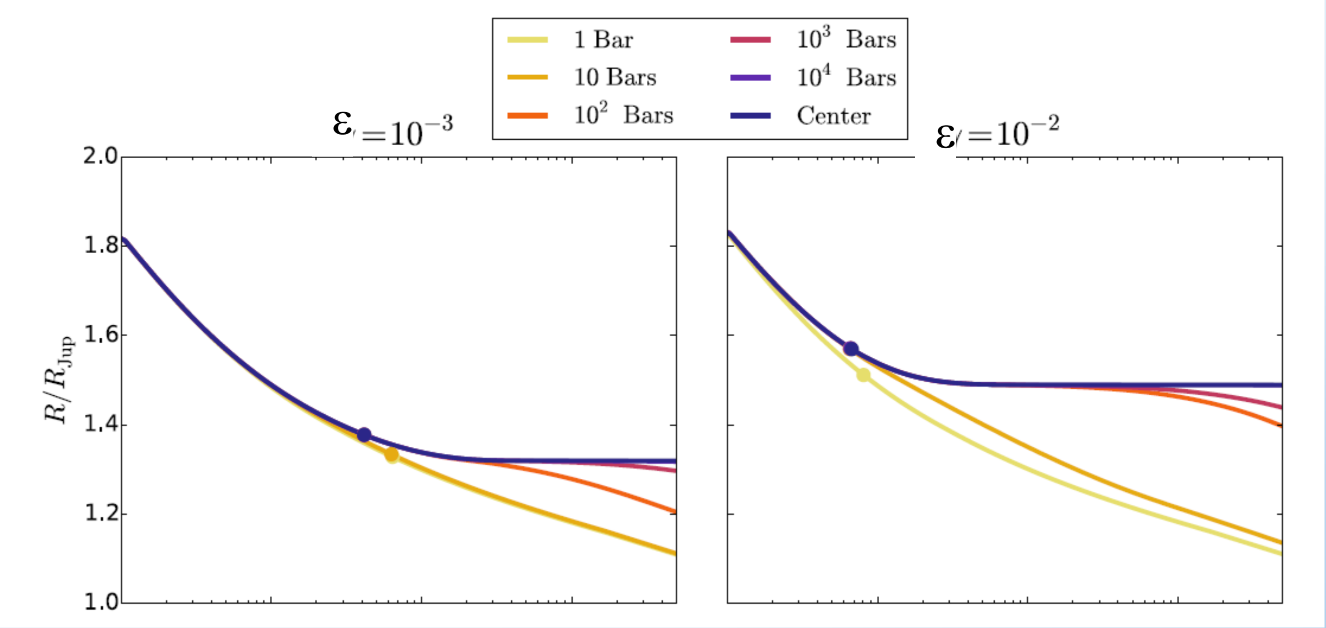
- additional heat with a few % of the irradiation flux is enough, efficiency peaking at around 1500-1700 K.
- the inflation is effective if the heat is put in the convective region
- with constant efficiency, a perfect balance between cooling and heating: plateaux

$$\frac{dm}{dr} = 4\pi r^2 \rho \ ,$$

$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4} \ ,$$

$$\frac{dL}{dm} = -T\frac{ds}{dt} + \epsilon_{irr} + \epsilon_{heat} \ ,$$

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla \ ,$$



[Komacek et al. 2017, Thonrgren & Fortney 2018]

$$\epsilon = \left(2.37^{+1.3}_{-0.26}\,\%\right) \exp\left[-\frac{\left(\log_{10}(F_{\rm irr}/F_0) - 0.14^{+0.060}_{-0.069}\right)^2}{2\cdot\left(0.37^{+0.038}_{-0.059}\right)^2}\right]$$

Hot Jupiter inflation radii: which heating mechanisms?

- Tidal effects due to eccentricity (Bodenheimer et al. 2001)
- Turbulent dragged inside and dissipation of kinetic energy (Youdin & Mitchell 2010).
- **Ohmic dissipation** (Batygin et al. 2010, Perna et al. 2010), for which the deposition of the heat is external

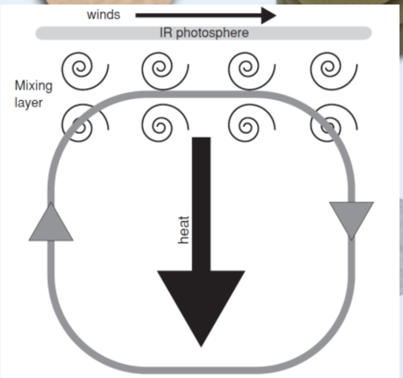


Figure 1. Schematic of the mechanical greenhouse effect to inflate hot Jupiters. A downward flux of heat (large black arrow) is driven by turbulence in the convectively stable "mixing layer" and deposited in the deep interior.

$$\epsilon_j = \frac{Q_j}{\rho} = \frac{J^2}{\sigma\,\rho}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho\ ,$$

$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}\ ,$$

$$\frac{dL}{dm} = -T\frac{ds}{dt} + \epsilon_{irr} + \epsilon_{heat}\ ,$$

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla\ ,$$

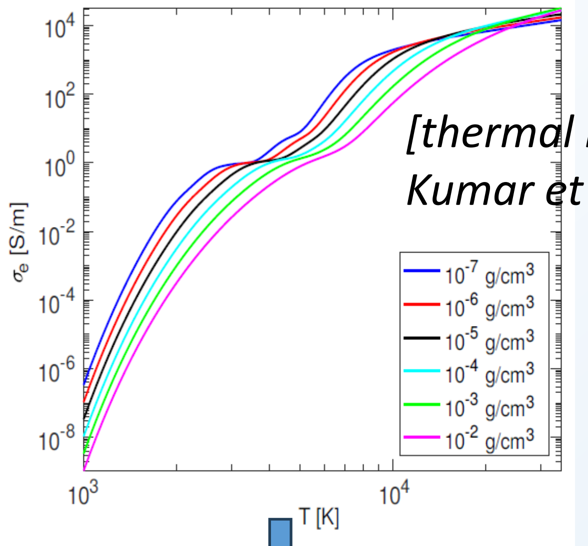
$$\nabla \equiv d\ln T/d\ln P$$

We need to prescribe:

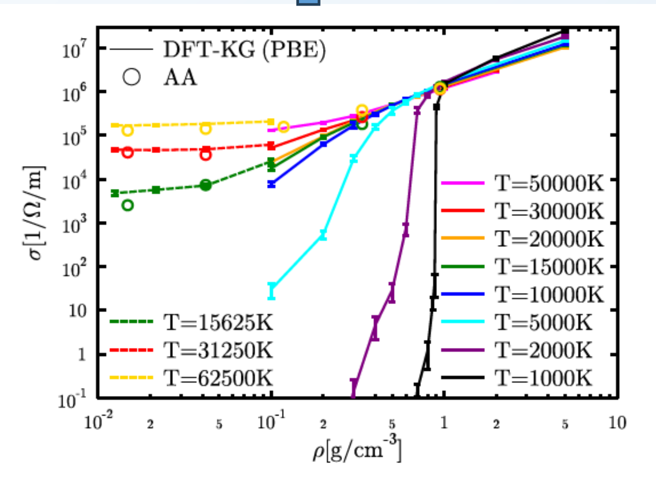
1. **Conductivity profile**
2. **Current distribution**

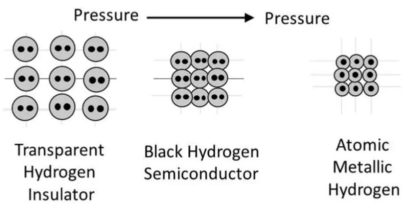
Full Ohmic model: conductivity profiles

[Viganò et al. 2025]



[thermal ionization Kumar et al. 2021]





[pressure ionization Bonitz et al. 2024]

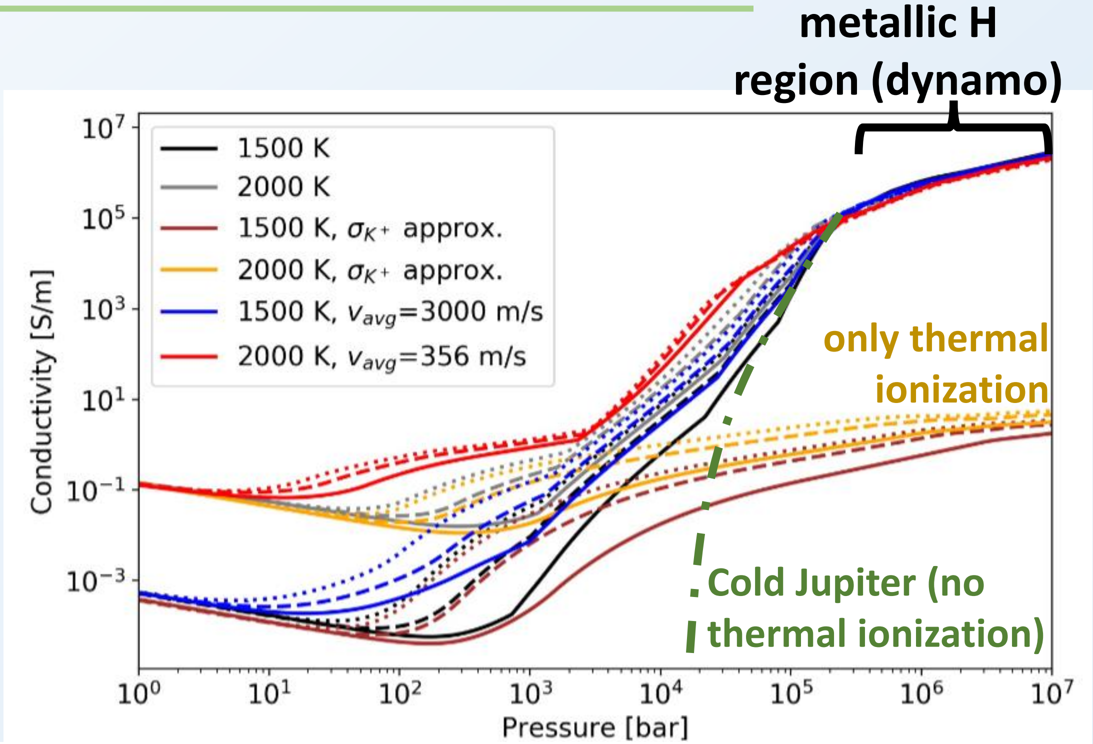
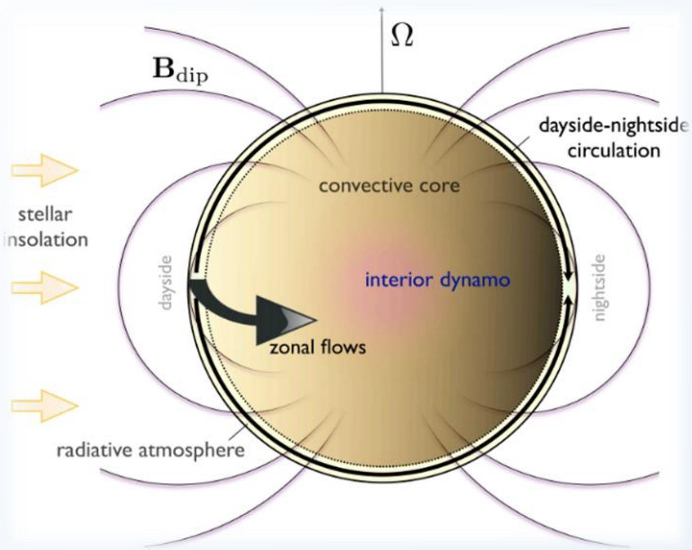
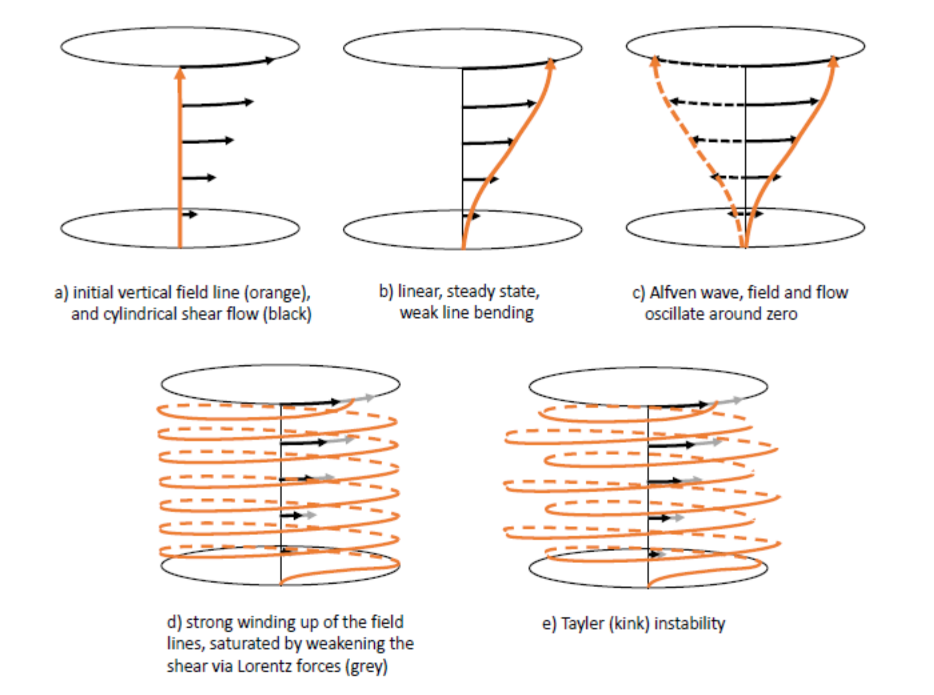


Fig. 2. Electrical conductivity σ as a function of pressure for different planetary models. We show ages of $t \simeq 0.4$ (dots), 1.1 (dashes), and 5 Gyr (solid lines), for a planet with $M = 1\ M_j$, showing two cases $T_{eq} = 1500, 2000$ K, without (black, grey) and with Ohmic heating, parameter $v_{avg} = 3000$ and 356 m/s, respectively (blue, red). We also

Ohmic dissipation in HJs: winding & induced currents



[Batygin et al. 2013]



[Dietrich et al. 2022]

The supersonic thermal jets, since the material is ionized, induce currents, i.e., atmospheric magnetic fields, which twists and amplifies the one generated inside. This induction involve also the deeper layers.

Induced currents

$$\frac{dB_{\text{ind}}}{dt} = \nabla \times \left(v \times B - \frac{J}{\sigma} \right) = 0$$

$$J = \sigma(v \times B - \nabla\Phi) ,$$

and imposing the continuity equation $\nabla \cdot J = 0$, so that

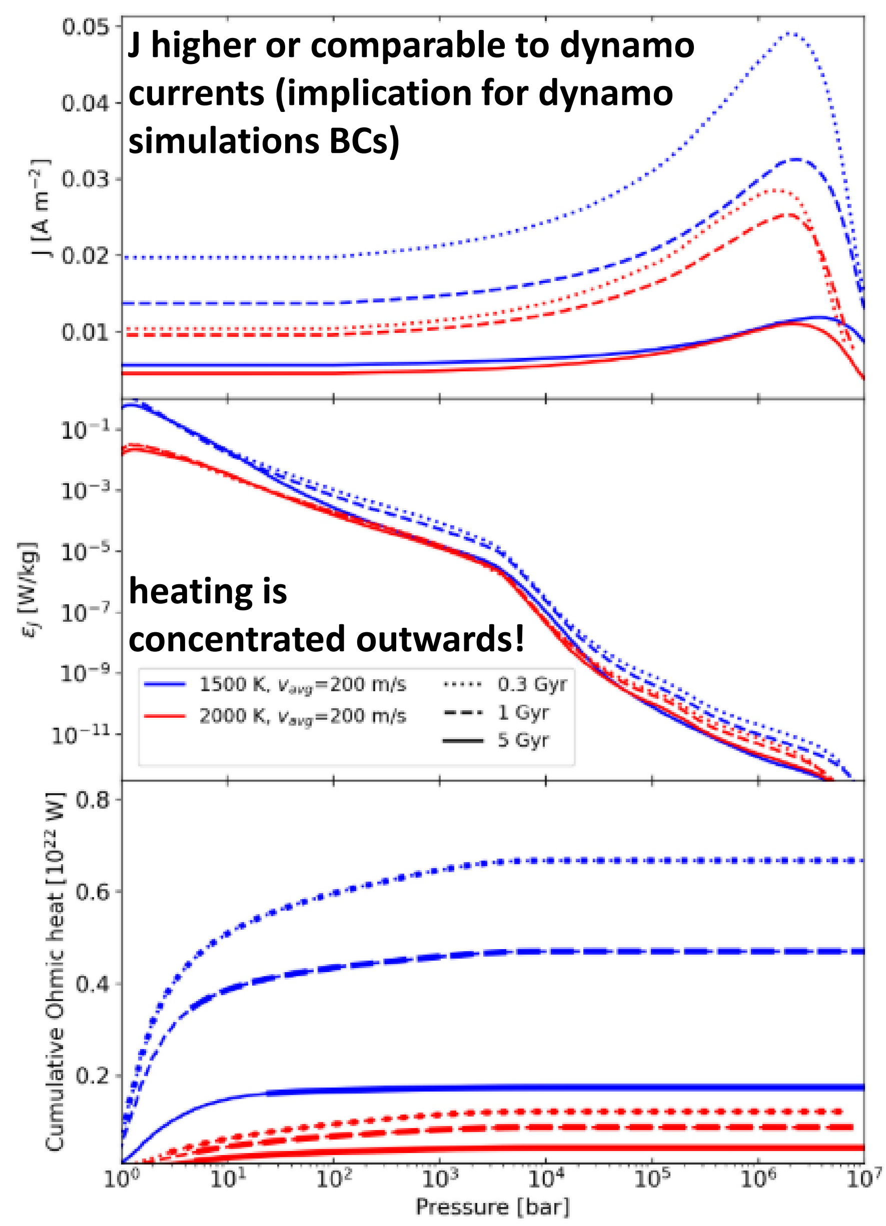
$$\sigma\nabla^2\Phi + \nabla\sigma \cdot \nabla\Phi = \nabla \cdot [\sigma(v \times B)] .$$

Obtain J(r) in the v=0 region (p>10 bar) for a given **conductivity and internal B geometry.** We use a normalization of the atmospheric current in the atmosphere (p<10 bar):

$$J(p < p_{atm})(t) = \sigma_{atm}(t) v_{avg} B_{bkg}(t)$$

The heat is mostly in the outer convective regions (similar results found by Batygin et al. 2010, 2011, and others).

[Viganò et al. 2025]



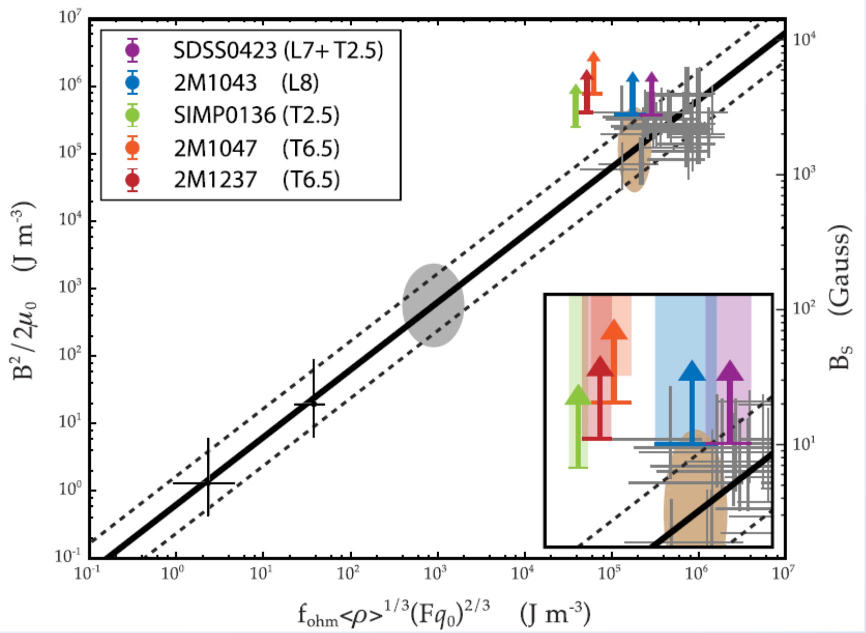
Coupling with dynamo scaling laws

Based on numerical simulations of dynamo, and on observations of Jupiter, Earth and low-mass (fully convective) fast-rotating stars (**see Albert Elias-López talk**):

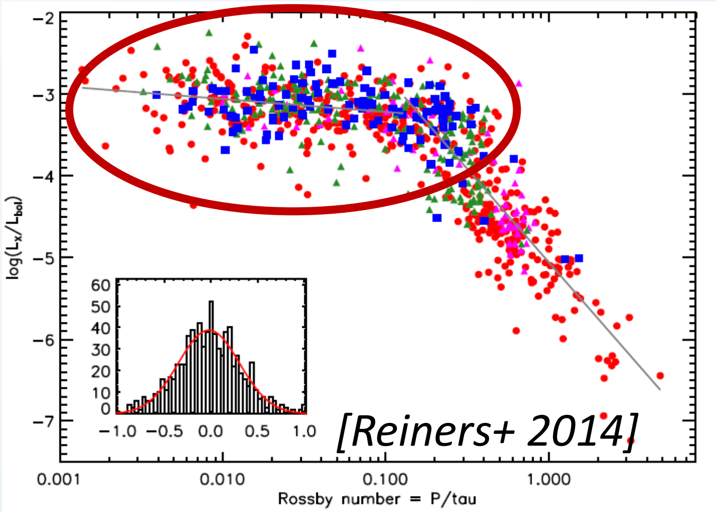
$$\frac{\langle B^2 \rangle}{2\mu_0} = c\, f_{ohm}\, \langle \rho \rangle^{1/3}\, (F\, q_o)^{2/3}\,.$$

$$F^{2/3} = \frac{1}{V} \int_{r_i}^{R_{dyn}} \left(\frac{q_c(r)}{q_0} \frac{L(r)}{H_T(r)} \right)^{2/3} \left(\frac{\rho(r)}{\langle \rho \rangle} \right)^{1/3} 4\pi r^2\, dr$$

[Christensen et al. 2009]



[Kao+ 2019]



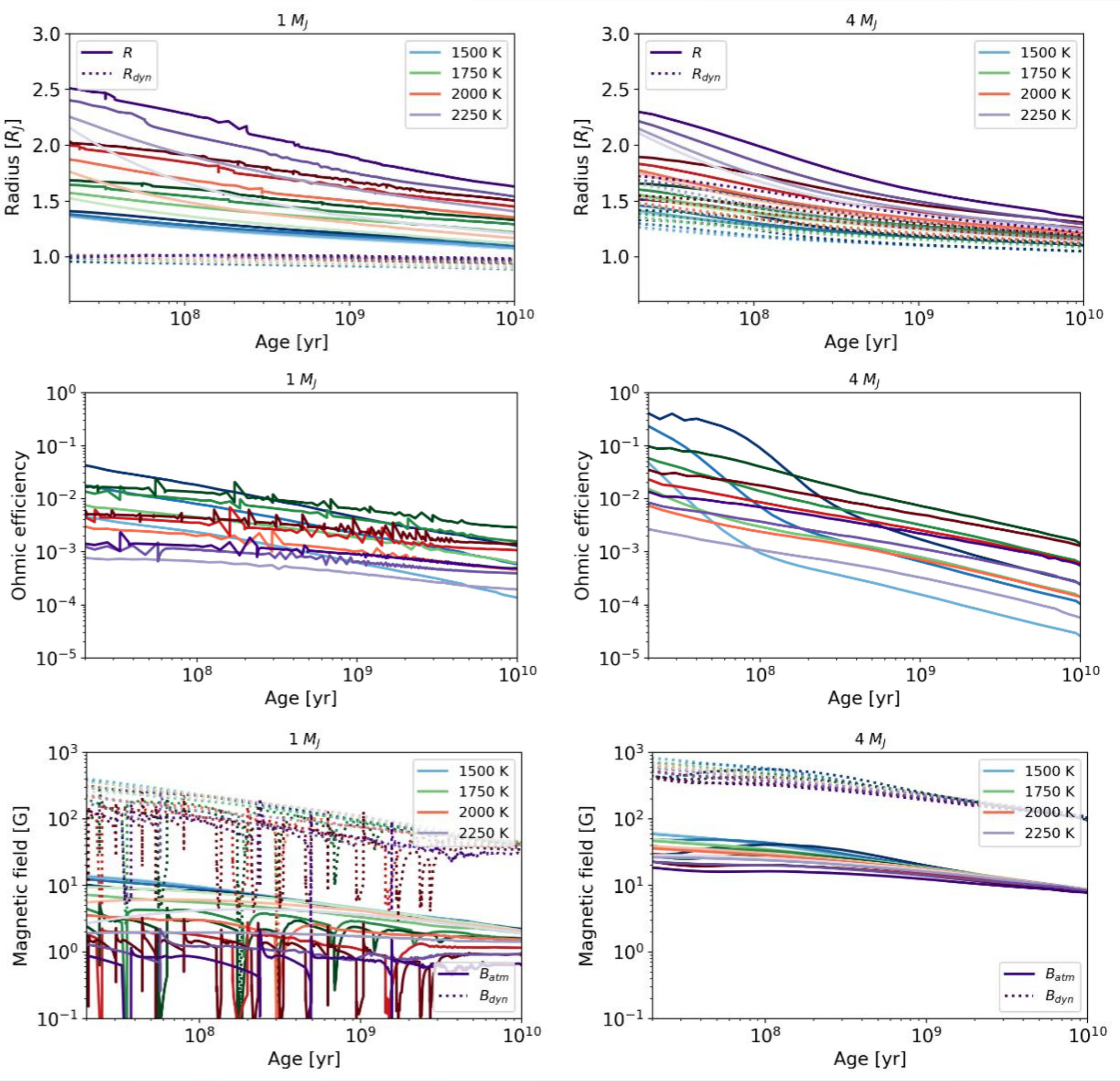
[Reiners+ 2014]

$$J(p < p_{atm})(t) = \sigma_{atm}(t)\, v_{avg}\, B_{bkg}(t)$$

We use the dynamo field as background field at the surface (accounting for the scaling with radius)

the average velocity is the only free parameter for our Ohmic model. We assume it constant (to be improved)

Evolutionary models results



Radius of dynamo region doesn't change much. It's the envelope being inflated.

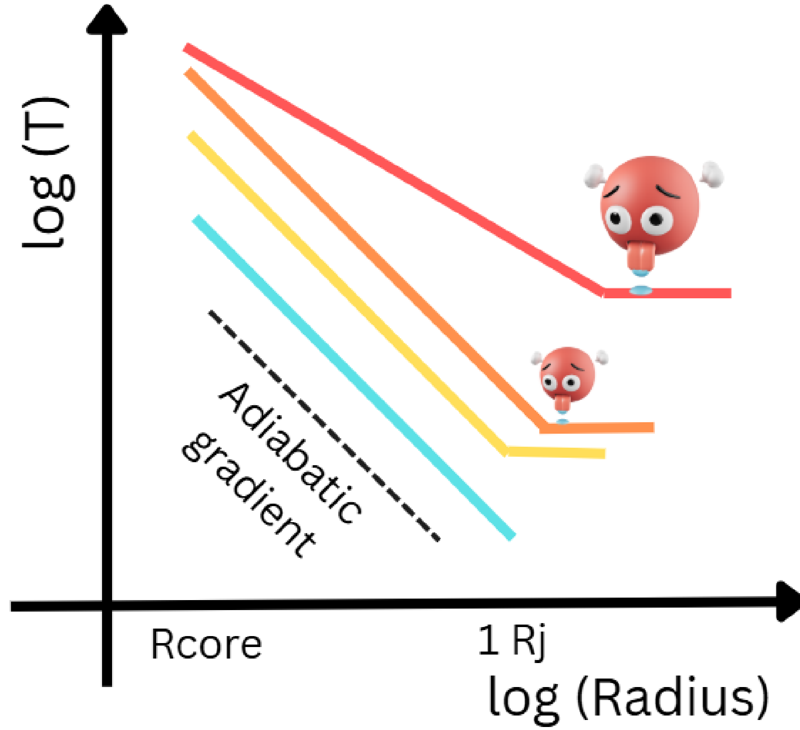
Ohmic efficiencies decrease in time (due to decrease of B), so the radius doesn't stall.

B of HJs might be only in the range of Jupiter (< 10 G), unless they are very massive: winds can be maintained at km/s levels (detectable!)

[Viganò et al. 2025]

Effects on the structure

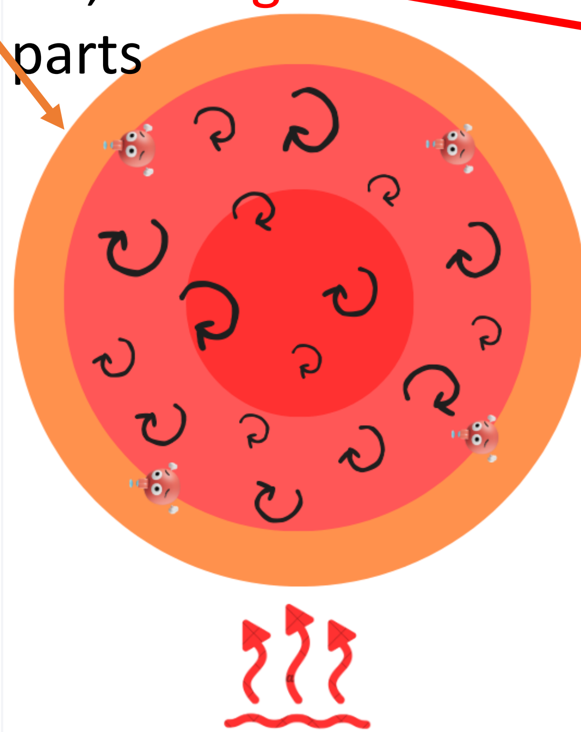
Cold Jupiter

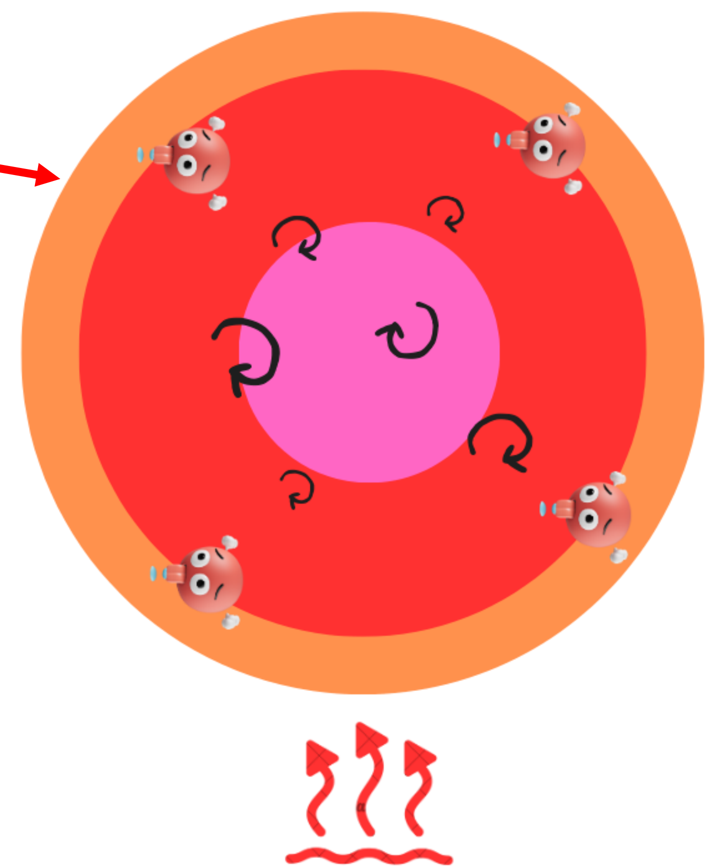


Similar killing convections by keeping the outer layers too hot: Venus (stagnant lid), Io (tidal heating)?

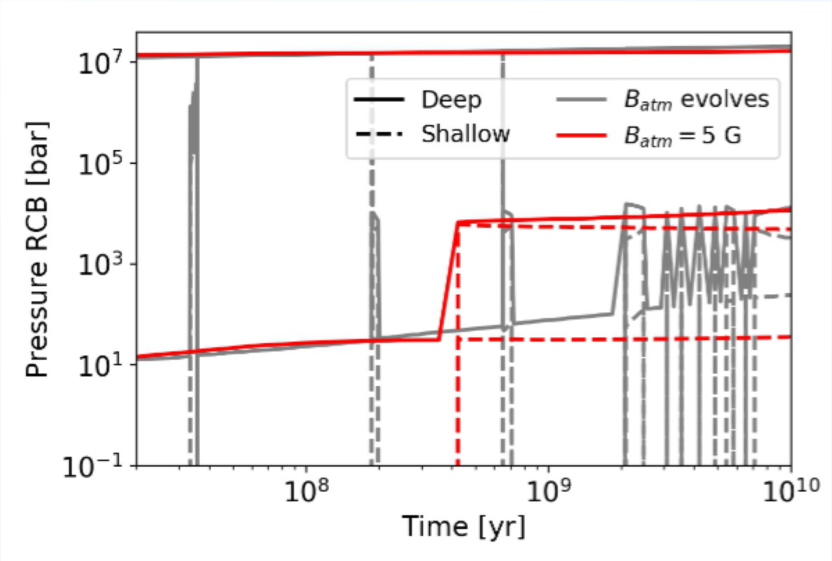
Temperature gradient softens: convection (and dynamo) suppressed

Hot Jupiters with: no, moderate, strong internal heating in the outer parts

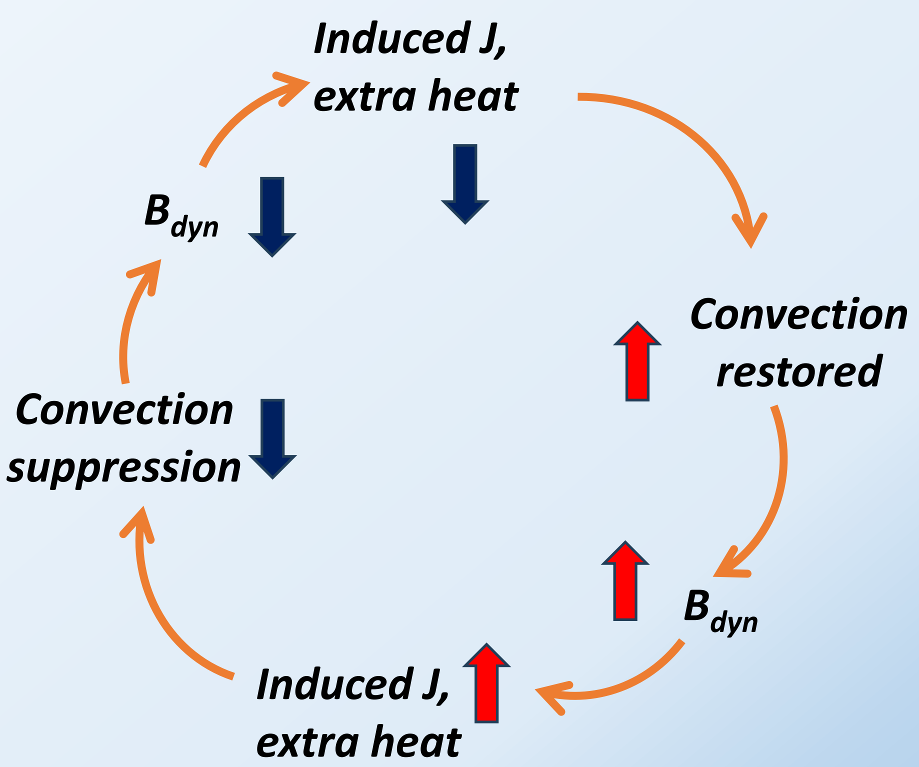




Feedback dynamo-atmospheric field: cycles?



$$J(p < p_{atm})(t) = \sigma_{atm}(t) v_{avg} B_{bkg}(t)$$



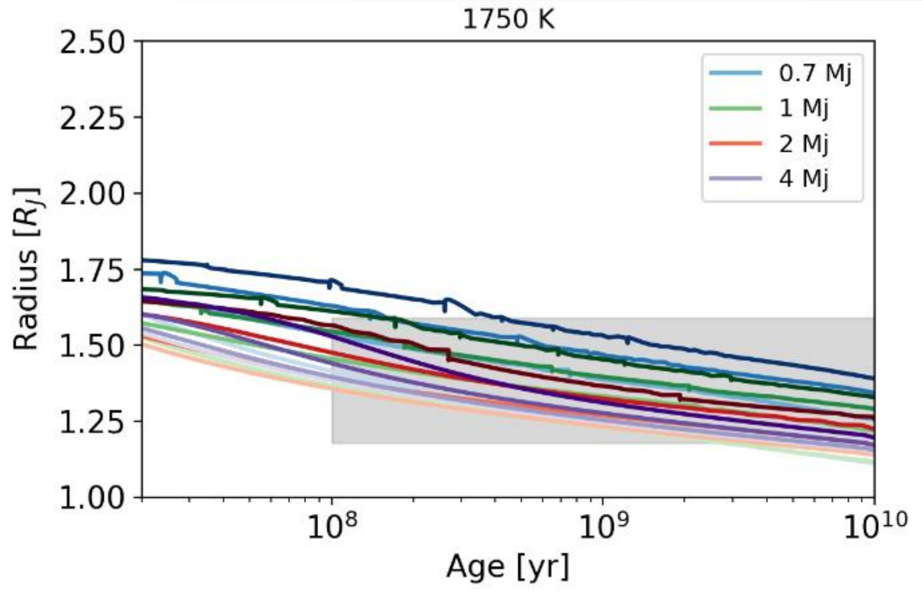
The timescales for these cycles are not assessable by the current code, but they are not purely numerical.

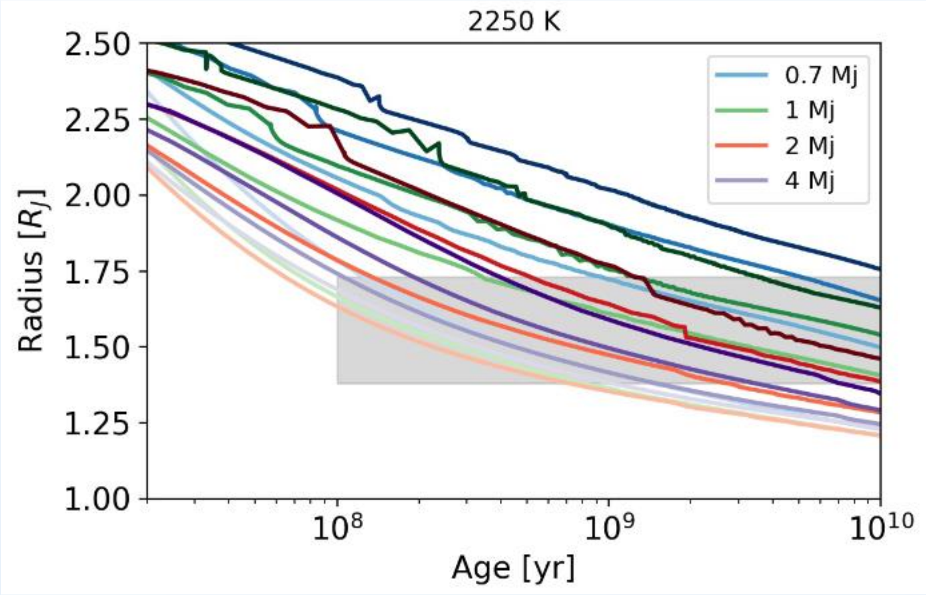
Caveat! Velocities should depend on B (magnetic drag) instead of constant could mitigate the effect

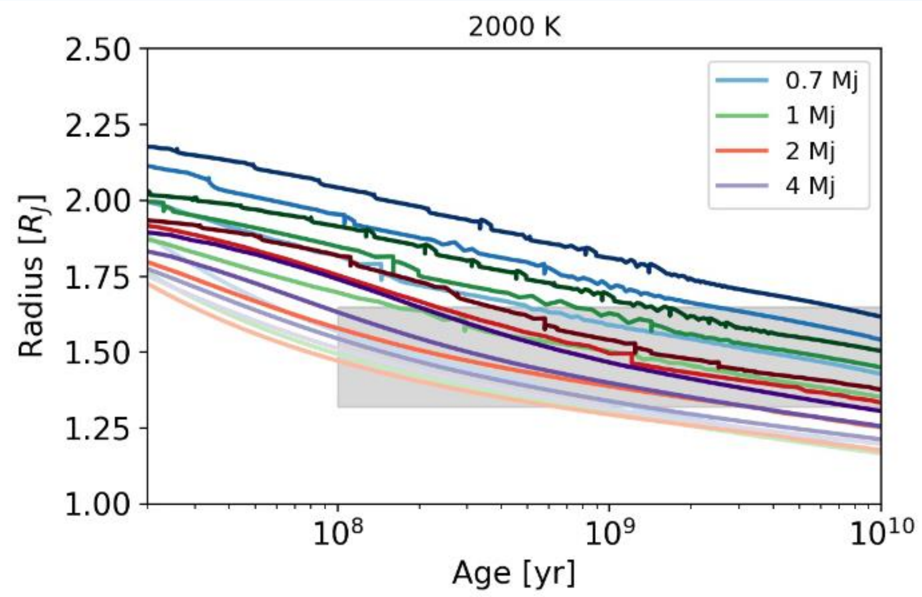
(IF v_{avg} constant!)

Results and comparison with data

[Viganò et al. 2025]







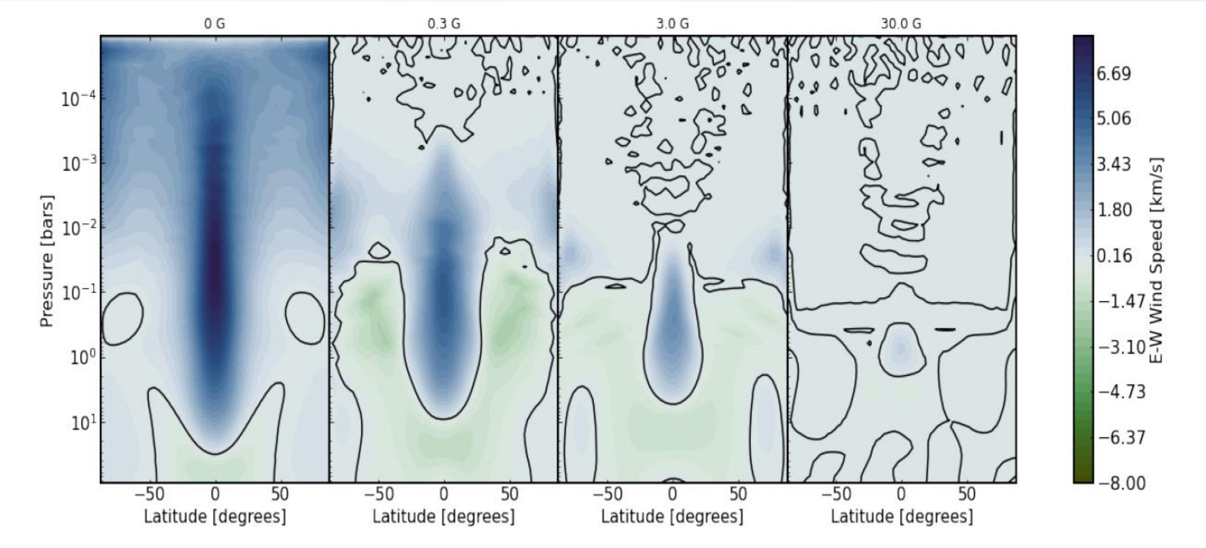
For T>1500 K, we need velocities up to:

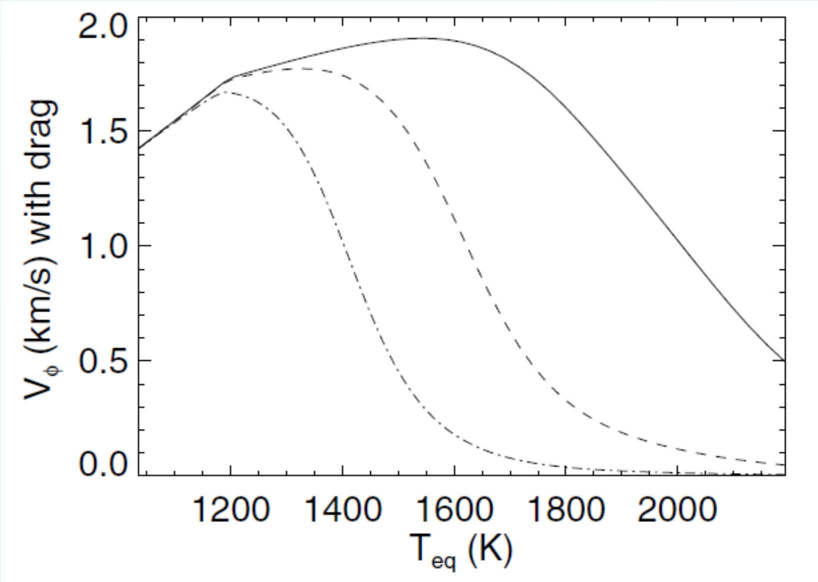
$$v_{\rm avg}^{\rm stab} \sim 3000 \frac{M_{\rm j}}{M} \left(\frac{1500\,{\rm K}}{T_{\rm eq}} \right)^6 \frac{\rm m}{\rm s}$$

Global circulation models: the magnetic drag

$$v_{\rm avg}^{\rm stab} \sim 3000 \frac{M_{\rm j}}{M} \left(\frac{1500\,{\rm K}}{T_{\rm eq}}\right)^6 \; \frac{\rm m}{\rm s}$$

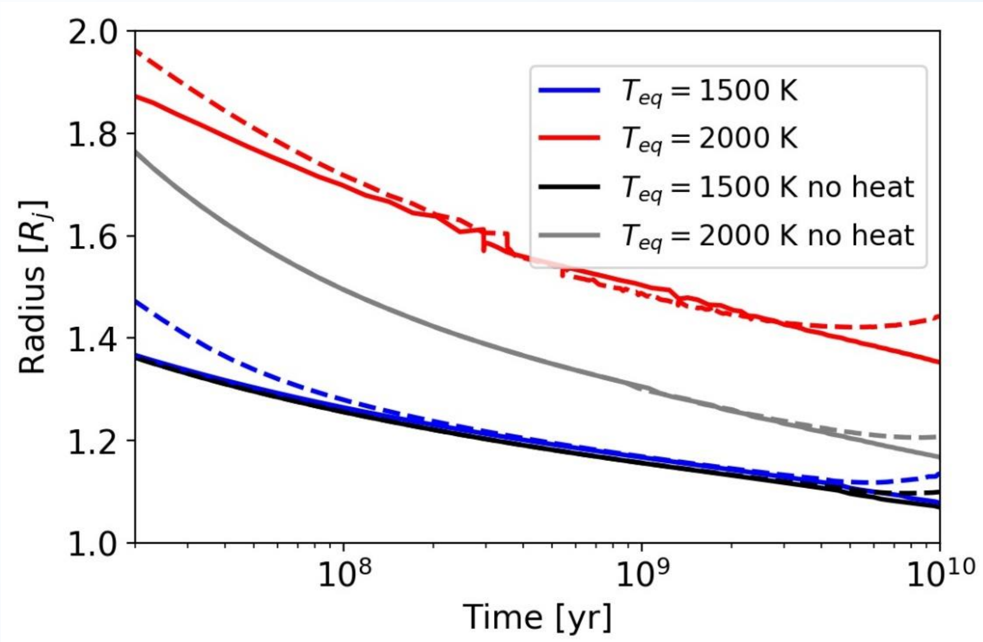
The inferred reduced velocities for higher fields (i.e. mass) is consistent with the magnetic drag effects on the winds: too strong induced fields backreact on the flow via Lorentz force and slow it down.

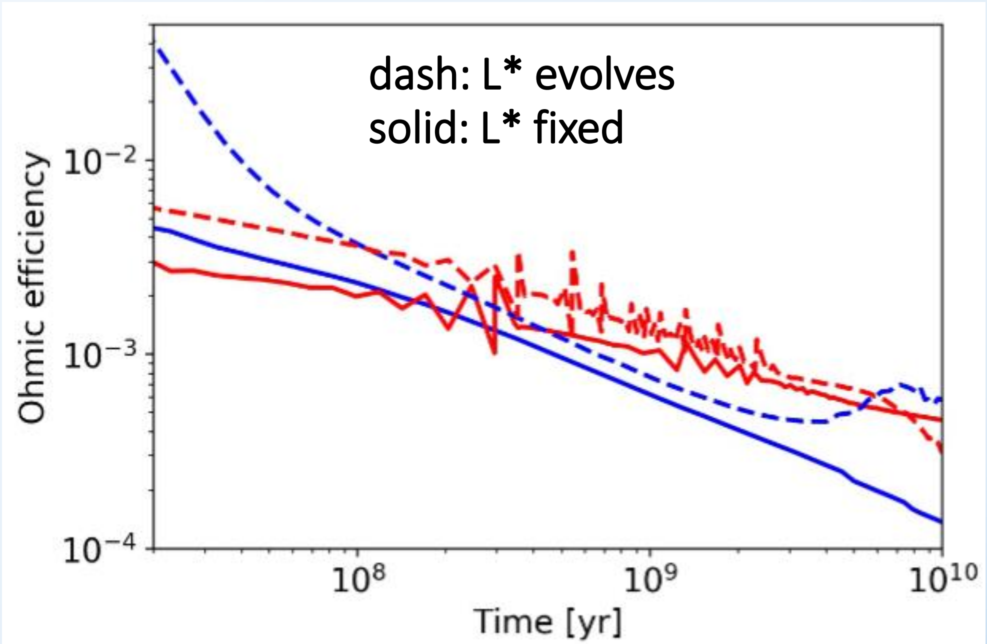




[Beltz et al. 2022, Menou 2012, see also Perna+2010, Batygin+ 2013 & more]

Evolving host star luminosity and re-inflation





Letting star luminosity L* to evolve can easily lead to re-inflation, due to the increased role of irradiation+heating.
A similar effect can be produced by secular orbital shrinking.

[Viganò et al. 2025]

1. Realistic Ohmic models coupled to dynamo evolution can lead to suppression of convection and B-field, except for massive planets: **Jupiter-like fields (G) at most!**
2. The coupling between the internal and atmospheric magnetic fields generally implies a decay in time of the Ohmic efficiency, but re-inflation can happen for evolving stellar luminosities.
3. The average atmospheric velocities we infer are in line with what expected (up to km/s) and decrease with higher irradiation and planetary mass (tens of m/s), compatible with to the effects of larger magnetic drag on winds.
4. **Observational consequences:**
   Good news for km/s winds in transmission spectroscopy!
   Bad news for radio emission: HJs might be not the best candidates.

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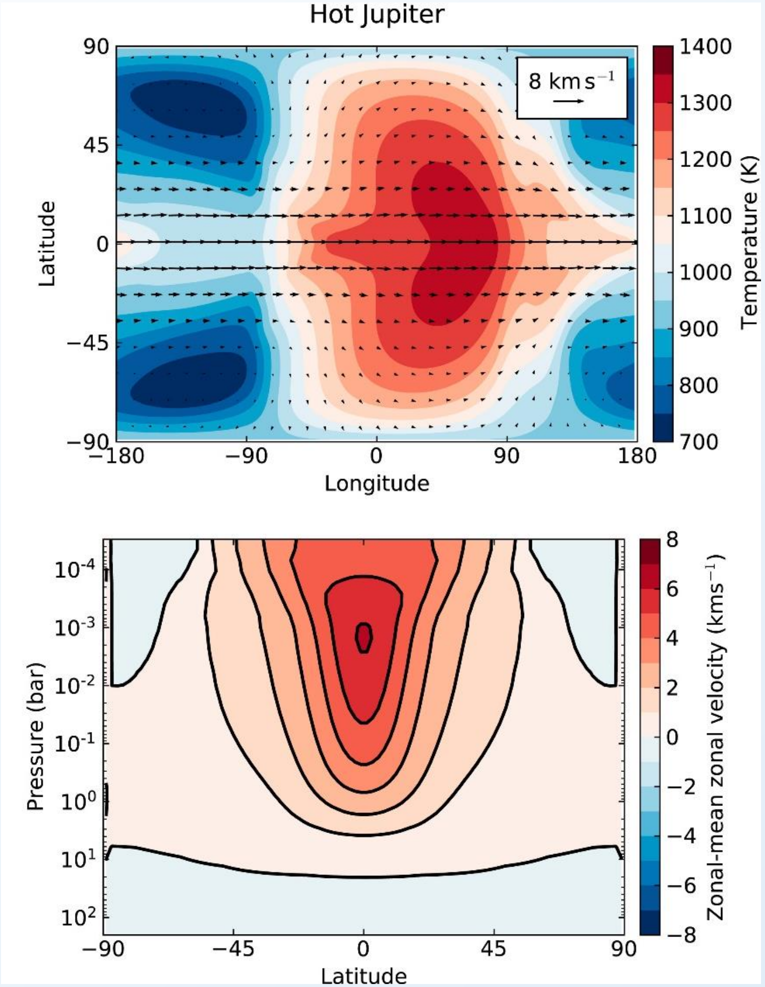
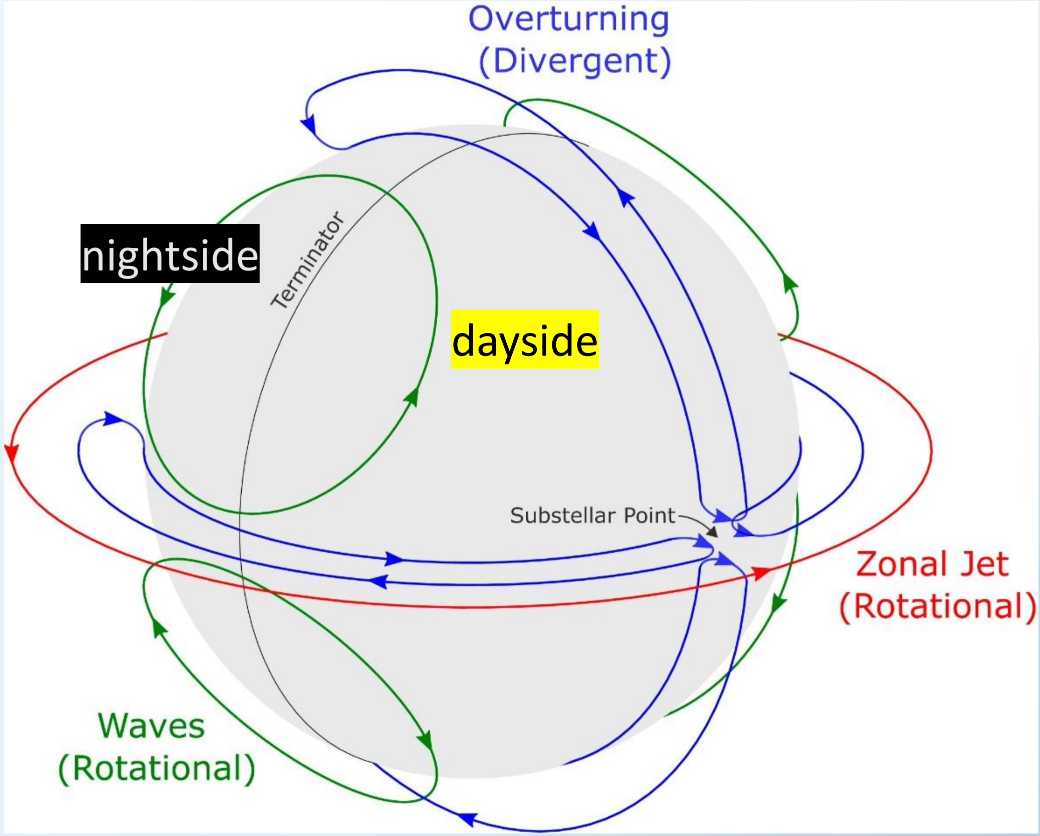
Hot Jupiters: thermally driven circulation

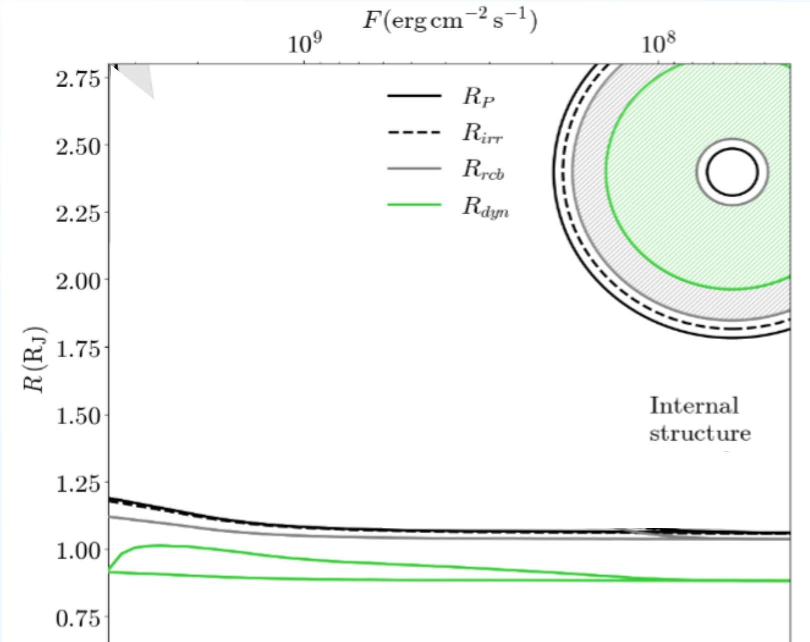
Tidal locking means having a permanent dayside and a nightside, with huge temperature differences. The thermal gradients drive winds in the outermost layers (atmosphere), with winds close or above the speed of sound (km/s)

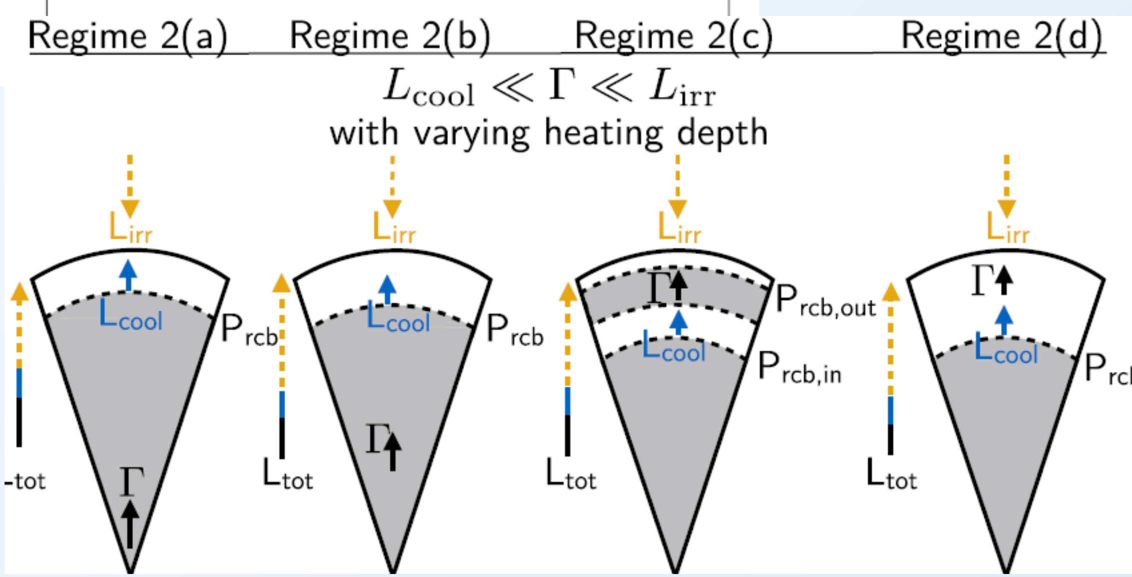




[Hammond and Lewis 2021]

Hot Jupiters: internal structure and cooling

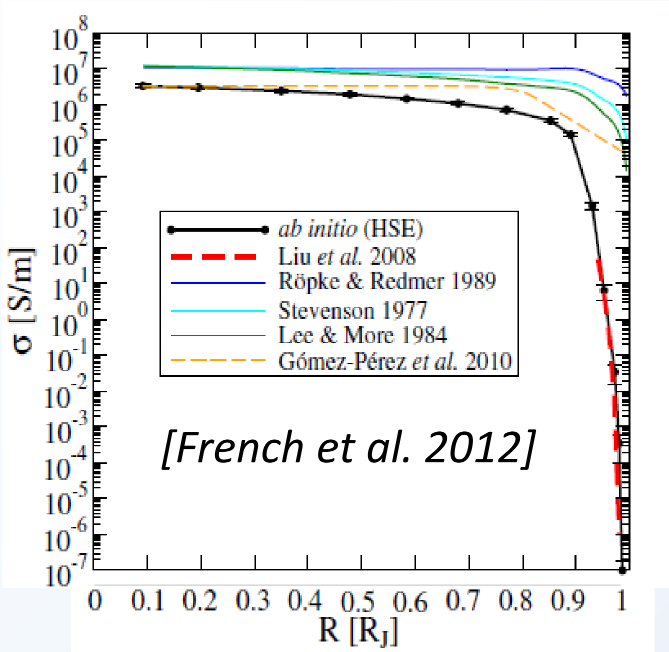


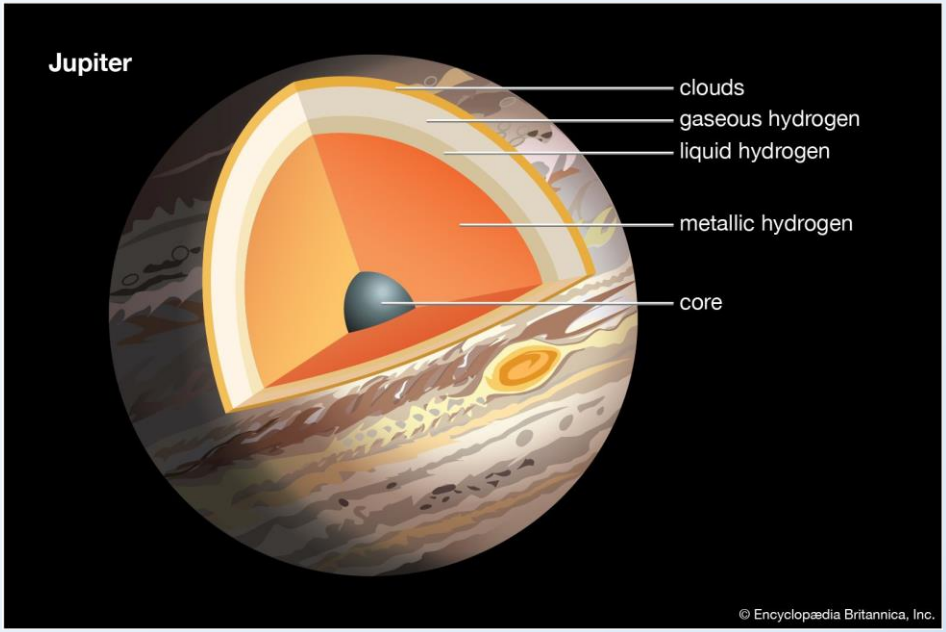


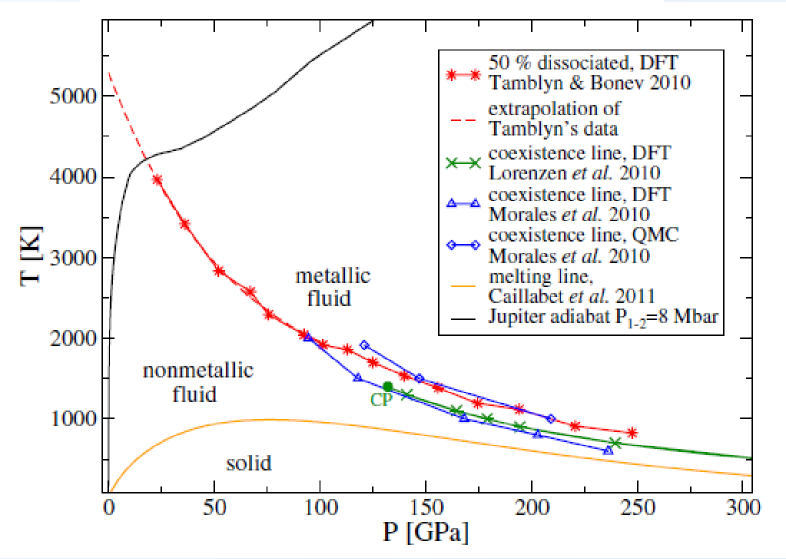
Almost entirely convective, except the inner core (if any) and the outermost, irradiated layers

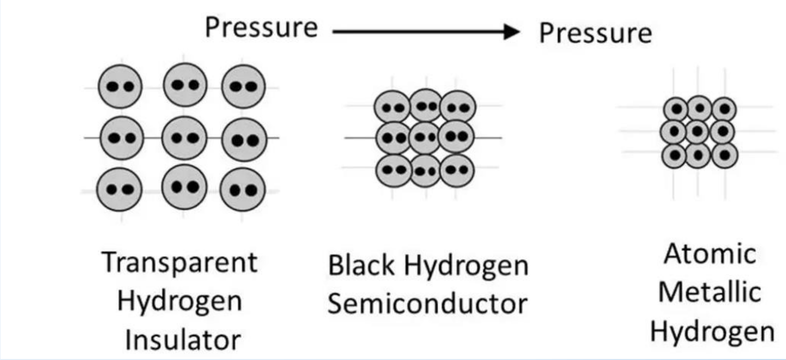
Regimes of heating and convection suppression [Komacek & Youdin 2017]

Conductivity: pressure-ionization









Recipes for convective quantities in MESA

$$\mathrm{Ro}(r) = \frac{P_{\rm orb}\, v_{\rm conv}(r)}{H_\rho(r)}$$

- density scale height $H_\rho(r) = P/\rho g$
- convective velocity comes from mixing length theory based on the model in Kuhfuss (1986), which reduces to the expression given by (Cox & Giuli 1968, chap. 14), in the limit of long time steps (seePaxton et al. (2011); Jermyn et al. (2023) for details).

- Convetive heat flux given by:

$$q_{\rm c} = \frac{2\, c_P\, T\ \ \rho^2\, v_{\rm conv}^3}{P\, \delta}$$

where $\delta = -(\partial \ln\rho / \partial \ln T)_P$.

- **Synchronization:**

$$\frac{d\omega}{dt} = \frac{9}{4}\frac{1}{\alpha Q'_P}\frac{GM_{\rm P}}{R_{\rm P}^3}\left(\frac{M_*}{M_{\rm P}}\right)^2\left(\frac{R_{\rm P}}{a}\right)^6 \quad (3)$$

$$\text{where} \quad \alpha = \frac{I}{M_{\rm P}R_{\rm P}^2} \quad , \quad Q'_{\rm P} = \frac{3Q_{\rm P}}{2k_{2,\rm P}} ,$$

$M_{\rm P}$ and $R_{\rm P}$ are the planetary mass and radius, respectively, I is the planetary moment of inertia, $Q_{\rm P}$ is the dissipation factor, $k_{2,\rm P}$ is the Love number of the planet and G is the gravitational constant (e.g. Goldreich & Soter 1966; Murray & Dermott 1999; Grießmeier et al. 2007). The synchronization timescale is then given by:

$$\tau_{\rm syn} \approx \frac{\Delta\omega}{d\omega/dt} = \frac{4}{9}\frac{d^6 I Q'_P \Delta\omega}{GM_*^2 R_{\rm P}^5} \simeq \frac{G\alpha}{36\pi^4}\frac{M_{\rm P}Q'_P P^4 \omega_i}{R_{\rm P}^3} , \quad (4)$$

where P is the orbital period, and $\Delta\omega = \omega_i - \omega_f \sim \omega_i$, since $\omega_i \gg \omega_f$, the difference between initial and final rotation. On the right panel of Fig. 1 we show in purple different lines of constant $\tau_{\rm syn}$ for a $M_{\rm P} = 1$ $\rm M_J$ planet, assuming $\alpha = 2/5$ (homogeneous sphere), $R_{\rm P} = 1.5$ $\rm R_J$, $Q'_P = 5 \cdot 10^5$ as in Grießmeier et al. (2007), and an initial spin period of 5 hours typical of known fast-rotating substellar objects, $\omega_i = (2\pi/5\ {\rm h})$, and conservatively larger