OHMIC INFLATION OF HOT JUPITERS

Daniele Viganò

[in collaboration with Albert Elias-López, Clàudia Soriano-Guerrero, M. Cantiello, F. del Sordo, R. Perna, S. Sengupta, S. Kaur, T. Akgün & more]

10th July 2025, Coimbra, *Detection and Dynamics of Exoplanets*

Viganò et al. 2025, submitted;
Elias-López et al. ApJ, 2025, arxiv:2507.05202

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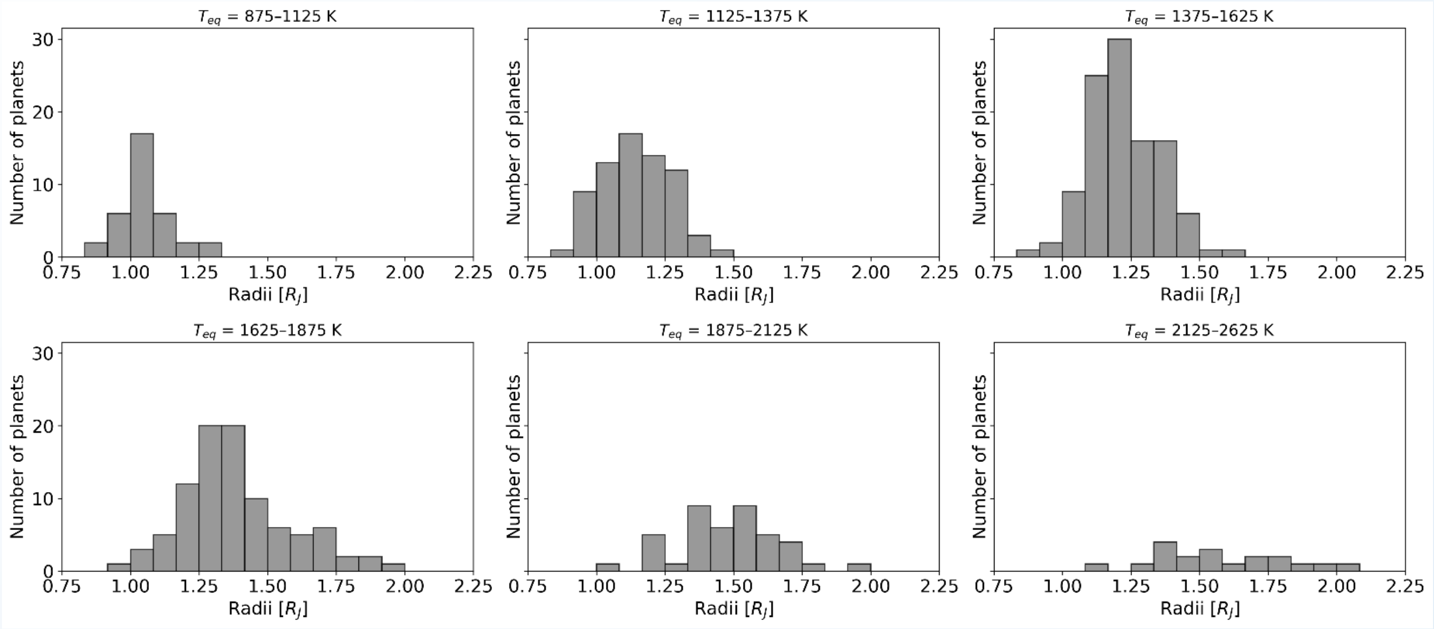
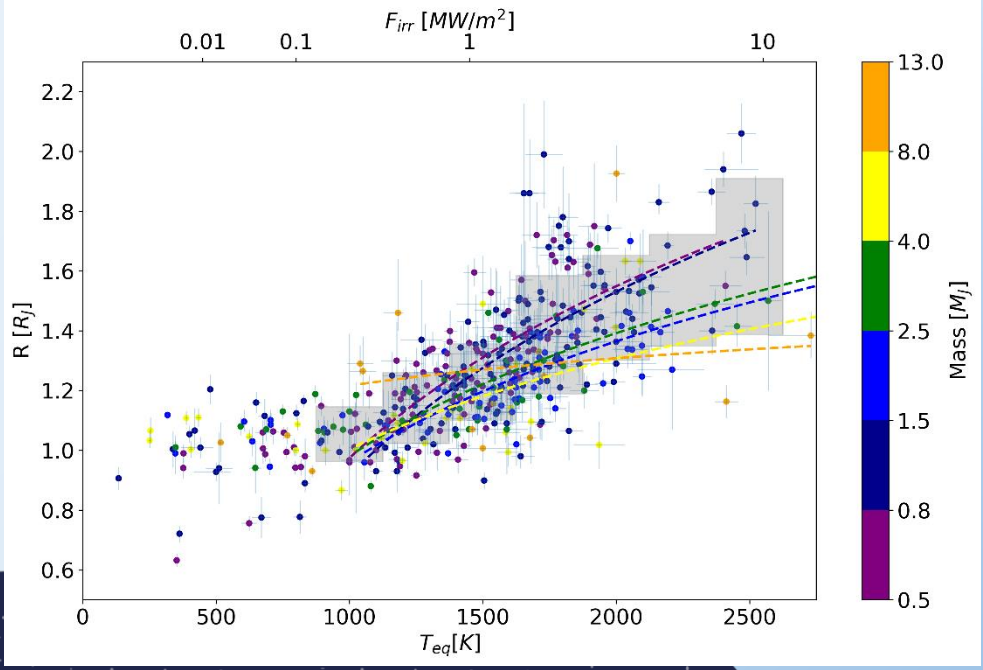
Hot Jupiters: inflated radii



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



FACTS

Many HJs look "puffy"

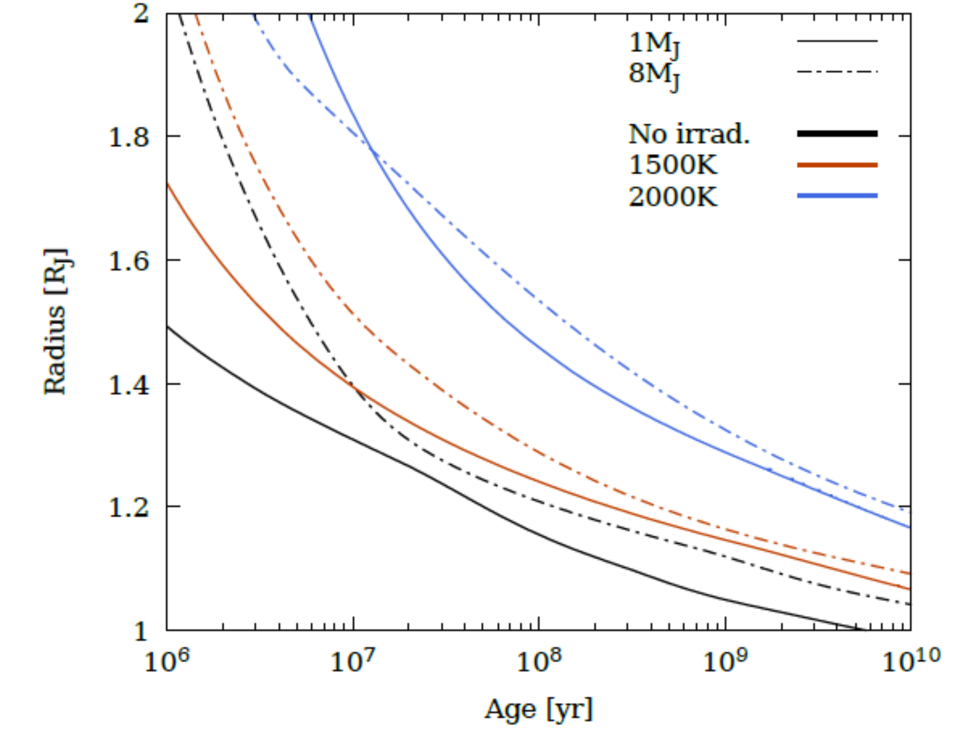
- A clear trend with irradiation is seen
- More massive planets inflate less

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.

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

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



[image credit: T. Akgün]

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: $\varepsilon = Q_{heat}/Lirr$

- 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

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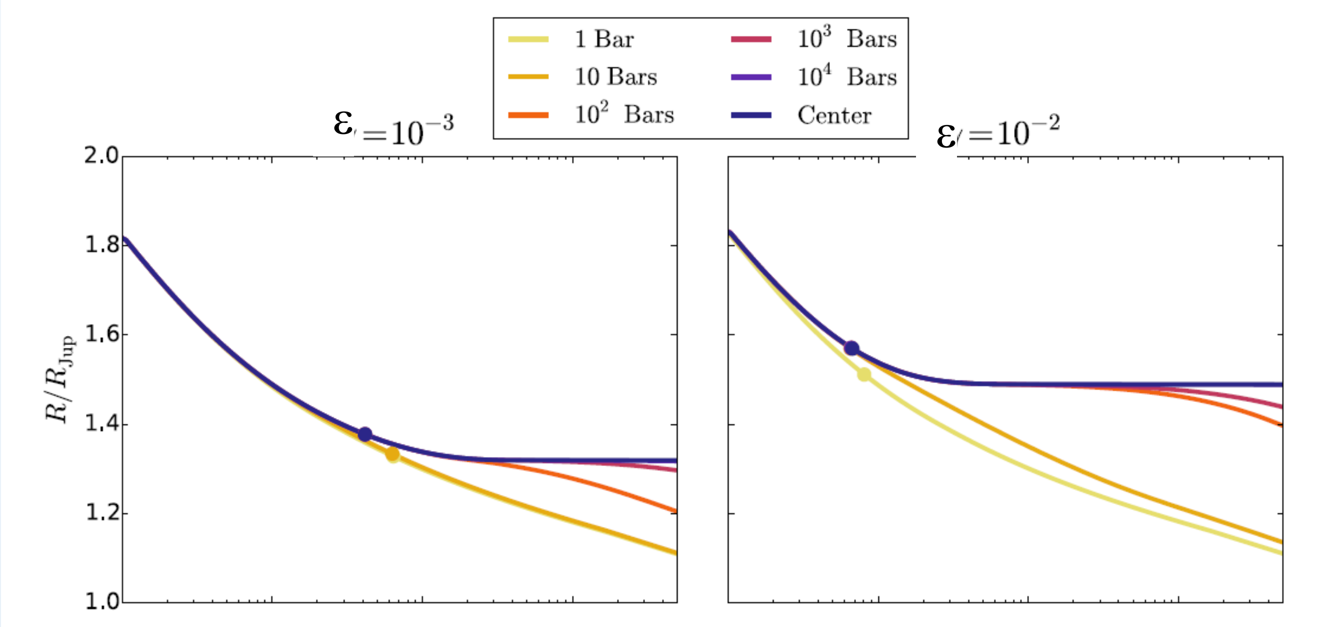


$$\epsilon = \left(2.37^{+1.3}_{-0.26}\%\right) \exp\left[-\frac{\left(\log_{10}(F_{\rm irr}/F_0) - 0.14^{+0.060}_{-0.069}\right)^2}{2\cdot\left(0.37^{+0.038}_{-0.059}\right)^2}\right]$$

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

Hot Jupiter inflation radii: which heating mechanisms?

- Tidal effects due to eccentricity (Bodenheimer et al. 2001, see **talk by K. Batygin**)
- Turbulent dragged inside and dissipation of kinetic energy (Youdin & Mitchell 2010).
- **Ohmic dissipation** (Batygin et al. 2010, Perna et al. 2010)

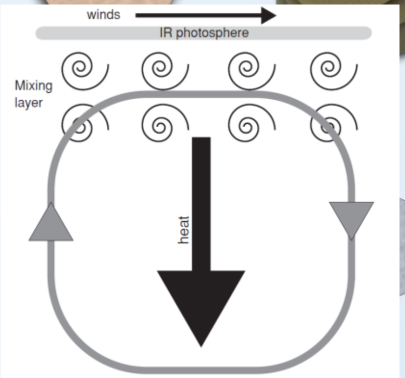


Figure 1. Schematic of the mechanical greenhouse effect to inflate hot Jupiters. A downward flux of heat (large black arrow) is driven by turbulence in the convectively stable "mixing layer" and deposited in the deep interior.

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

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

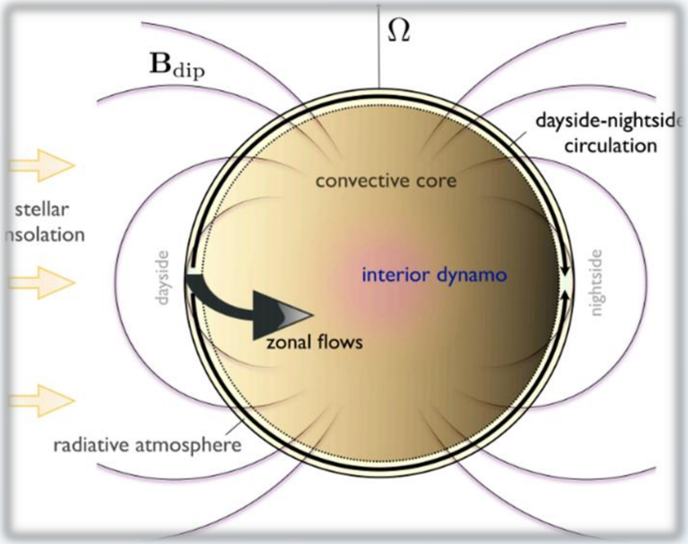
$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}\ ,$$

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

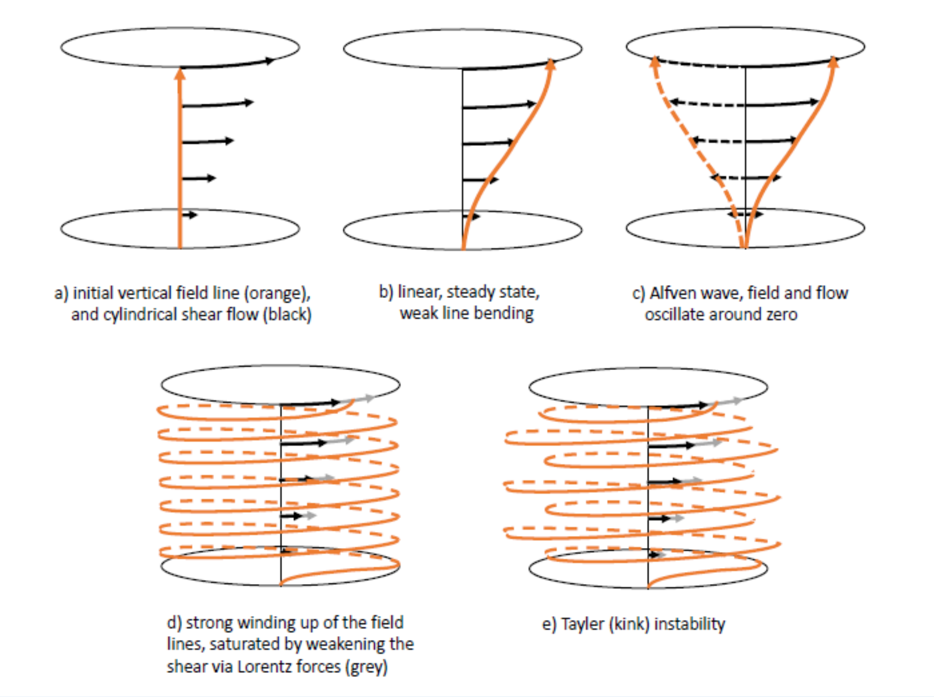
$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla\ ,$$

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

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. This induction involve also the deeper layers.

$$\frac{d\boldsymbol{B}}{dt} = \boldsymbol{\nabla} \times \left(\boldsymbol{v} \times \boldsymbol{B} - \frac{\boldsymbol{J}}{\sigma} \right) = 0$$

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

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

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

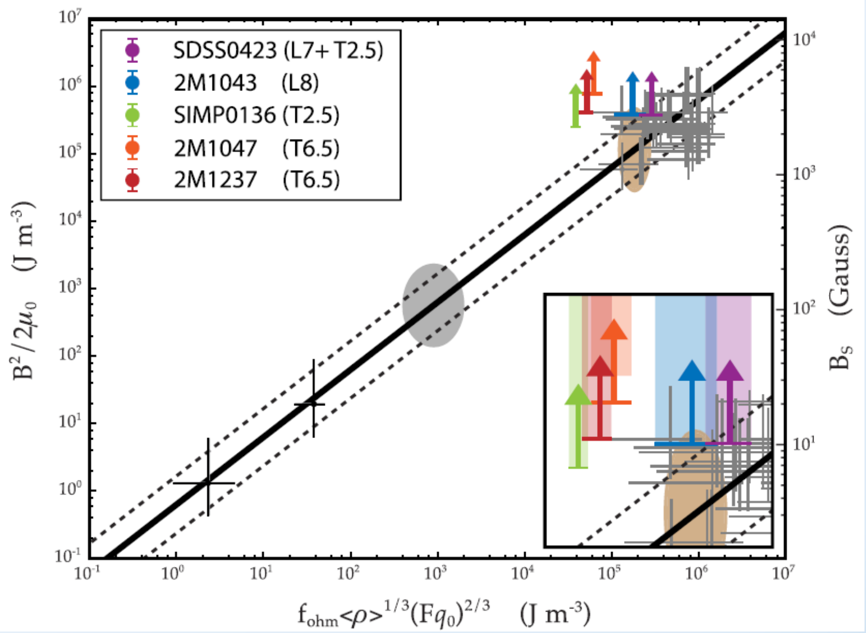
Dynamo scaling laws

Based on numerical simulations of dynamo, and on observations of Jupiter, Earth and low-mass (fully convective) fast-rotating stars:

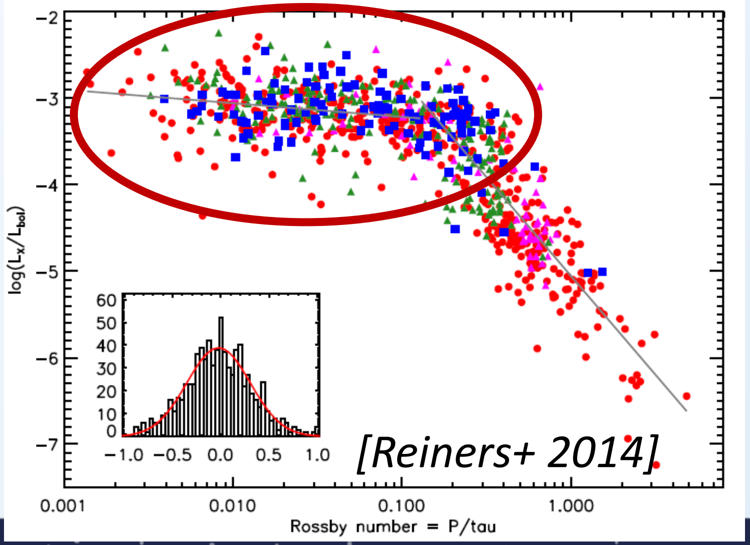
$$\frac{\langle B^2 \rangle}{2\mu_0} = c\, f_{ohm}\, \langle \rho \rangle^{1/3}\, (F\, q_o)^{2/3}\,.$$

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

[Christensen et al. 2009]



[Kao+ 2019]

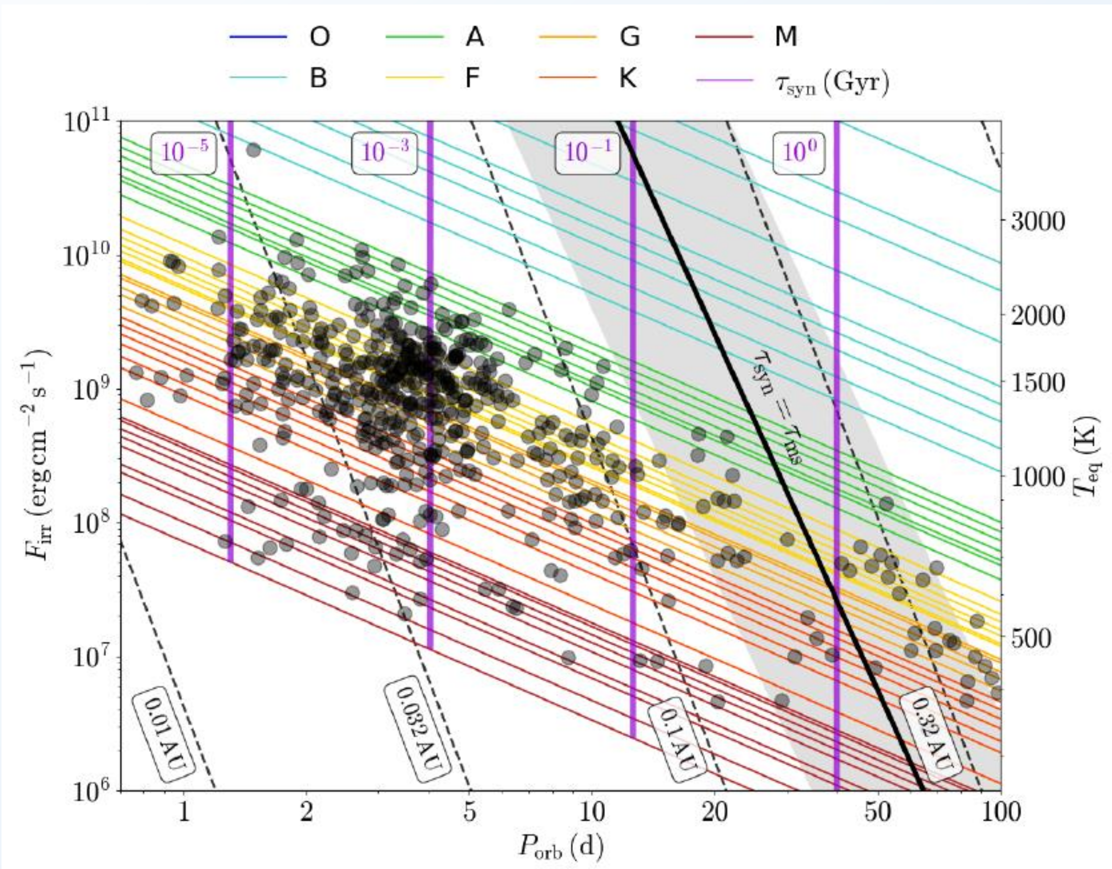


[Reiners+ 2014]

But… are we sure that we can apply this "fast-rotators" (Ro<0.1 in stars) scaling laws to HJ?

$$\mathrm{Ro} = P_{\mathrm{rot}} / \tau_{\mathrm{turn}}$$

Hot Jupiters: irradiation and tidal locking



[Elias-López et al. 2025, https://arxiv.org/abs/2507.05202]

$$\tau_{syn} \approx \frac{\Delta\omega}{d\omega/dt} = \frac{4}{9}\frac{d^6 I Q'_P \Delta\omega}{G M_*^2 R_P^5} = \frac{G\alpha}{36\pi^4}\frac{M_P Q'_P P^4 \omega_i}{R_P^3}$$

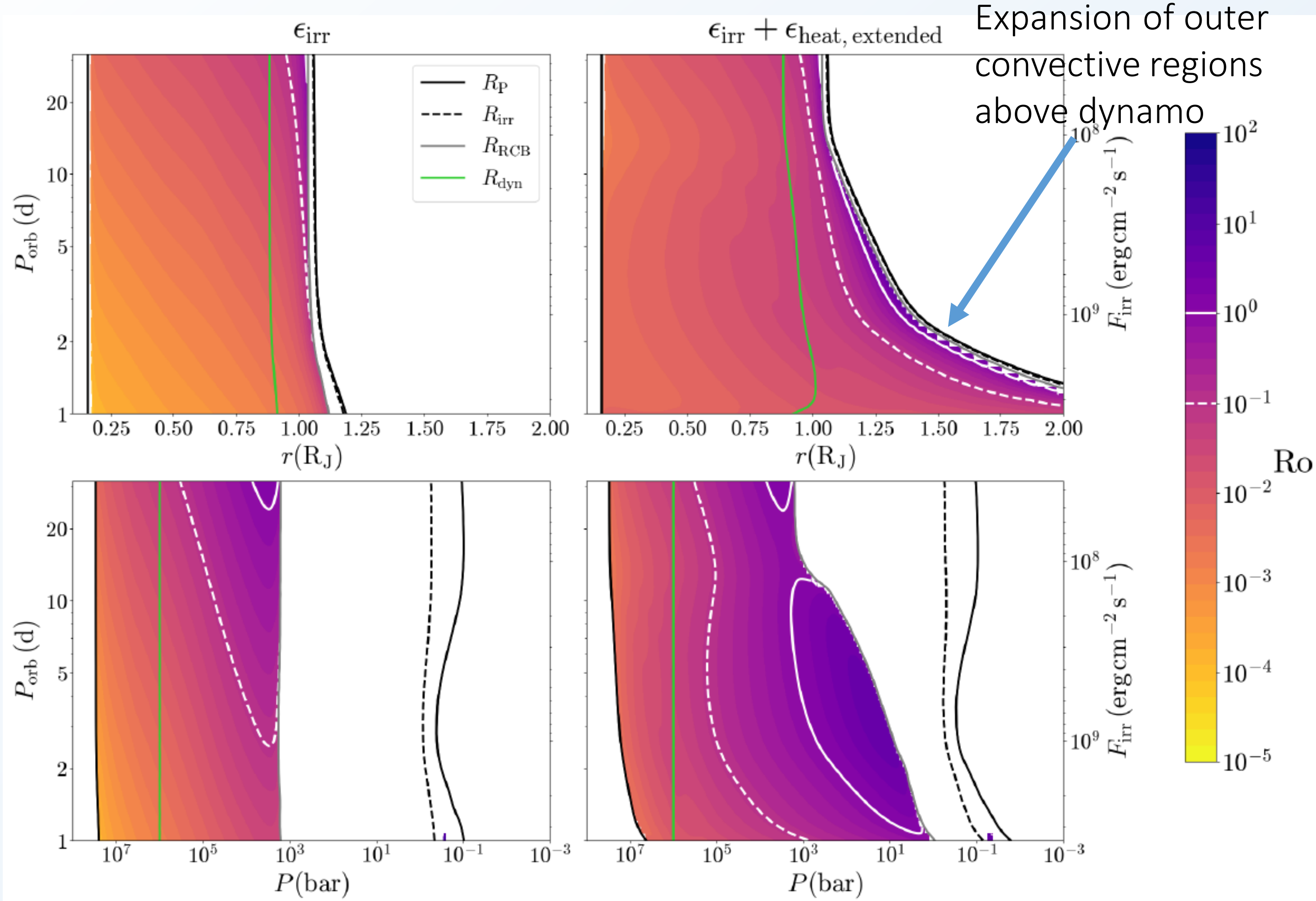
Short tidal locking timescales:

$$P_{rot} = P_{orb}$$

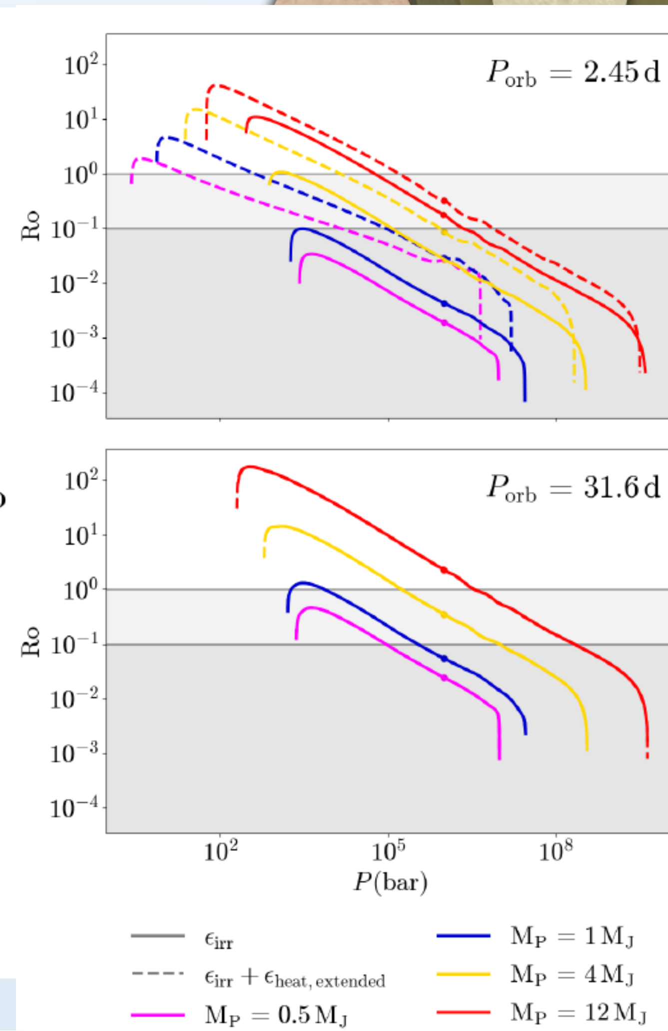
local turn over time from convective velocity (MLT) and scale height from thermodynamic profiles:

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

Hot Jupiters are "fast rotators"



Expansion of outer convective regions above dynamo



Irradiation only (no heat)

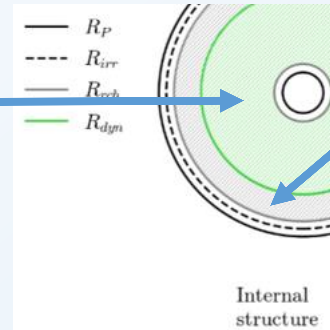
Thorngren 2018 for heat:

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

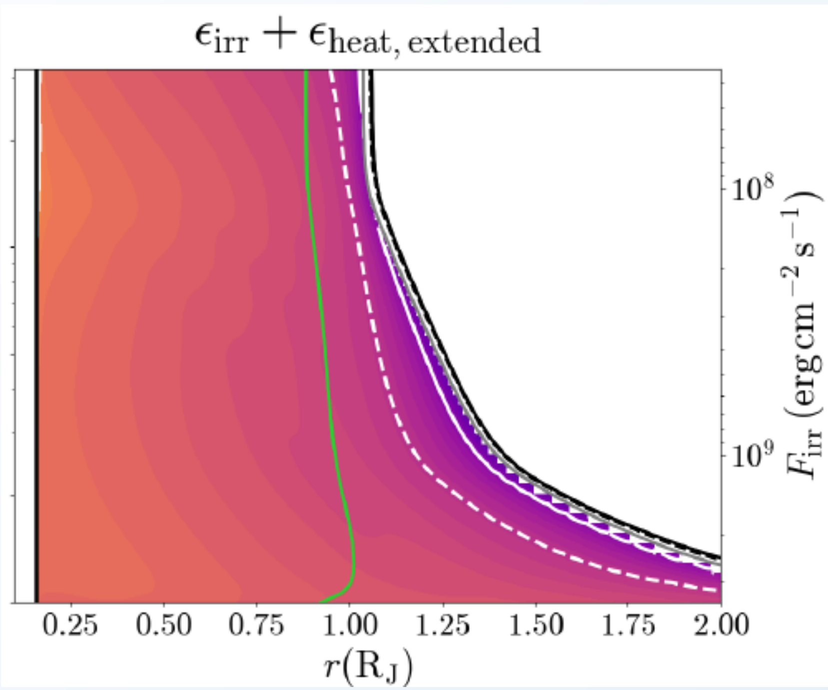
[Elias-López et al. 2025, https://arxiv.org/abs/2507.05202]

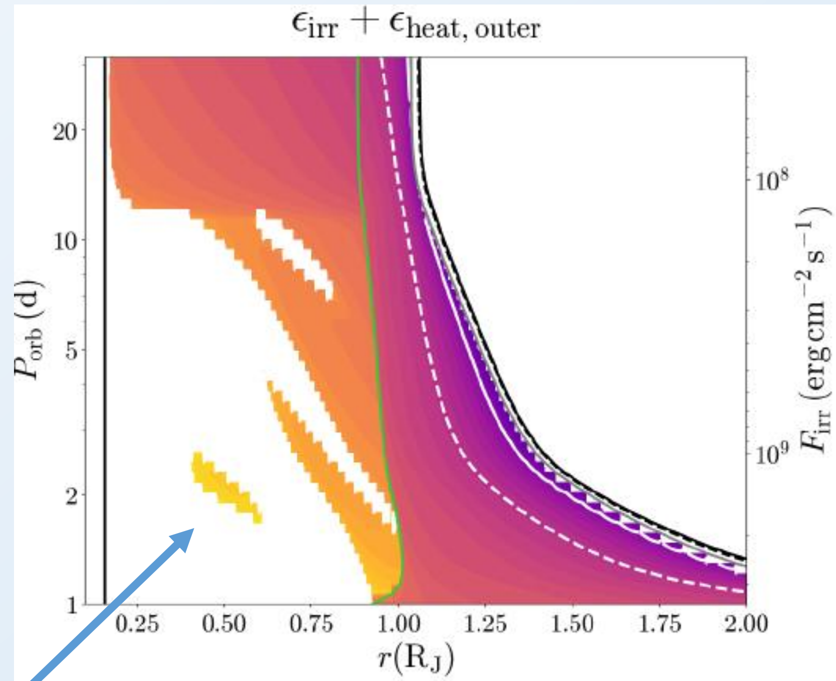
The role of heating in defining the convective regions

HEAT MOSTLY IN THE DYNAMO REGION



HEAT MOSTLY ABOVE THE DYNAMO REGION (Ohmic models)

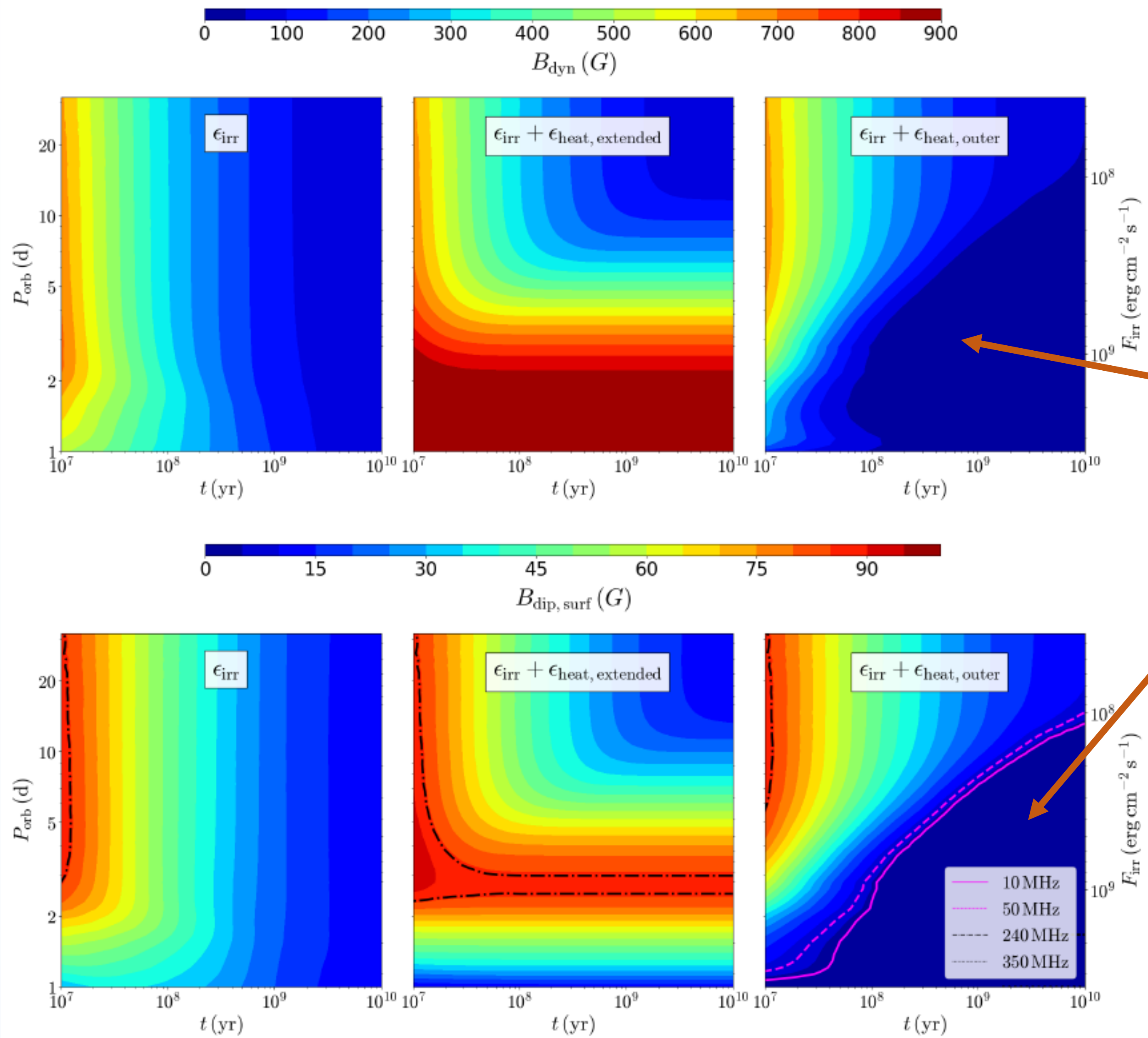




A lot of heat in the outer region lowers dT/dr below the convective threshold (white regions), although the overall structure is not much changed (outer layers are the ones to expand anyway). See also Komacek et al. 2017

[Elias-López et al. 2025, https://arxiv.org/abs/2507.05202]

The role of heating in defining the dynamo strength



Less convection =
Less internal field =
Less surface field =
Lower cyclotron freq.
frequency

$$\nu_c = 2.8 B \text{ [G] MHz}$$

(HJ are classical
targets for radio
emission searches)

Inflated HJ: higher
reduction of surface vs
dynamo field (large Rp)

$$B_{\rm dip,surf} = \frac{1}{2\sqrt{2}} \left(\frac{R_{\rm dyn}}{R_{\rm P}} \right)^3 B_{\rm dyn}$$

The role of heating in defining the radio/SPI power

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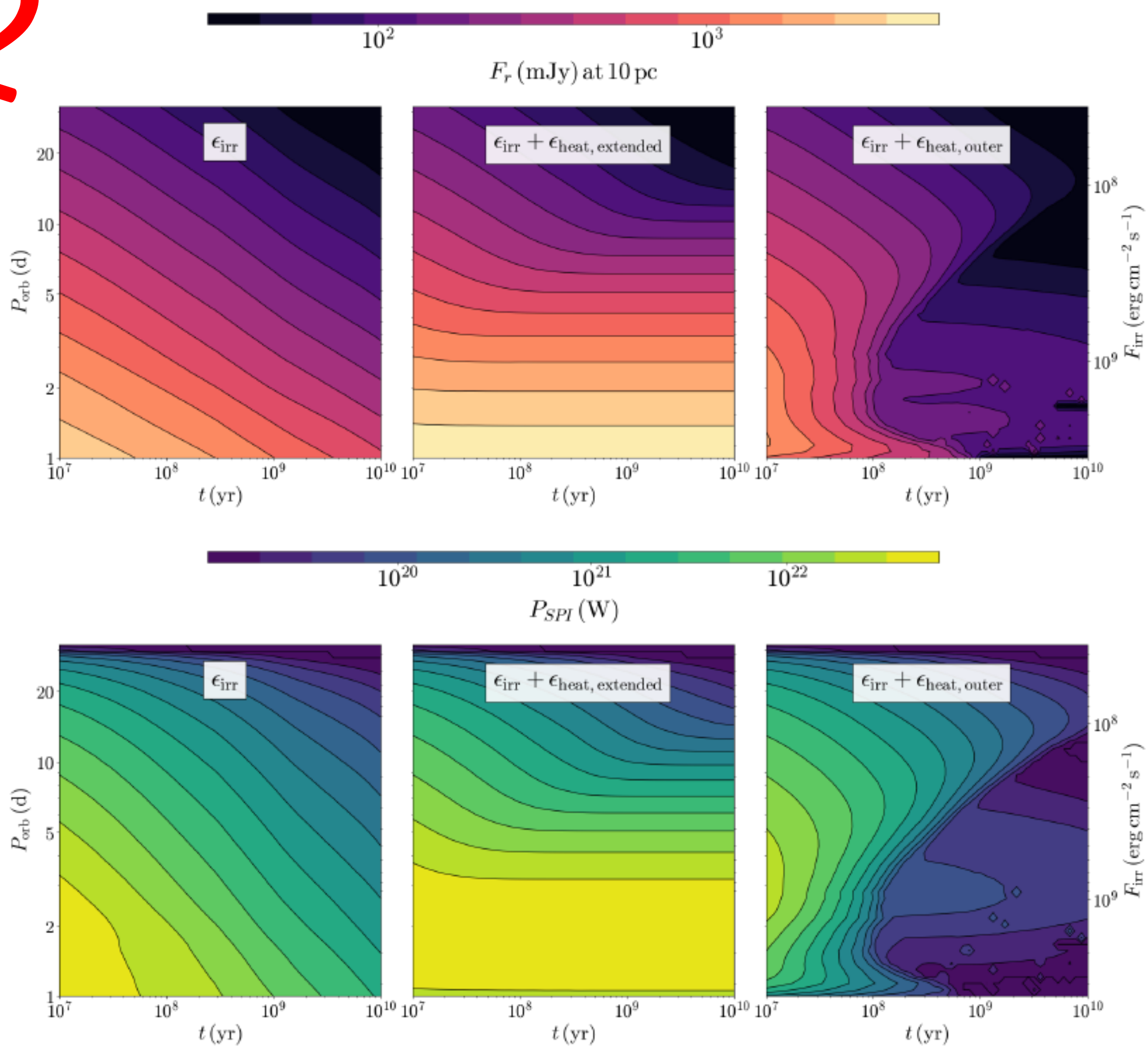


Figure 9. Estimates for Jovian-like coherent radio flux (top, for a 10 pc away HJ) and SPI available power (bottom), as a function of age and $P_{\rm orb}$, for the same models shown in Fig. 8.

Jupiter-like ECM radio flux from planet in (optimistic) emission models (Stevens et al. 2005)

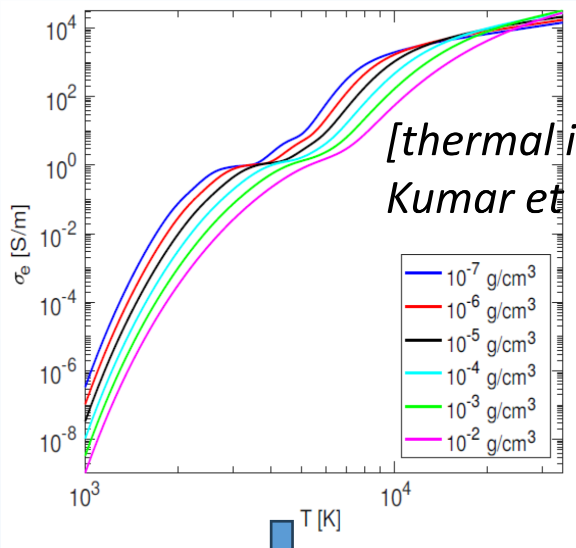
$$F_r = 2.35 \cdot 10^{-2}\,\mathrm{mJy} \cdot \left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{2/3} \cdot \left(\frac{M_{dip}}{M_{dip,J}}\right)^{2/3} \cdot \left(\frac{a}{5\,\mathrm{AU}}\right)^{-4/3} \cdot \left(\frac{V_W}{400\,\mathrm{km\,s^{-1}}}\right)^{5/3} \cdot \left(\frac{d}{10\,\mathrm{pc}}\right)^{-2}$$

Star-Planet Interaction energy budget (Lanza 2013), used for e.g. Cauley et al. 2019 about HJ magnetic field indirect measurement.

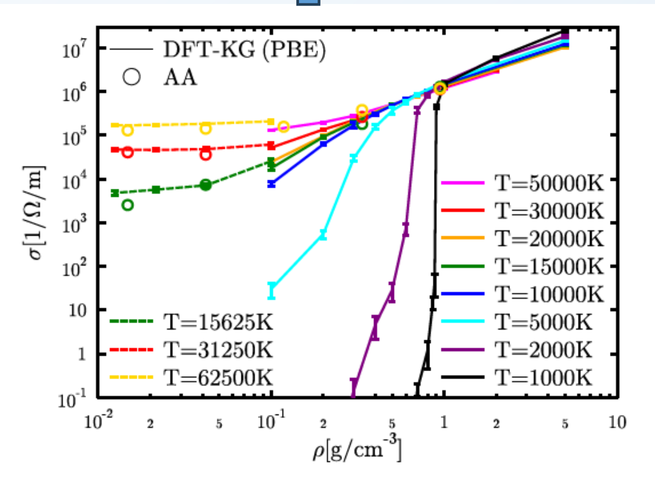
$$P_{\rm SPI} \simeq \frac{2\pi}{\mu_o} f_{\rm AP}\, R_{\rm P}^2\, (2B_{dip,surf})^2\, v_{\rm rel},$$

[Elias-López et al. 2025]

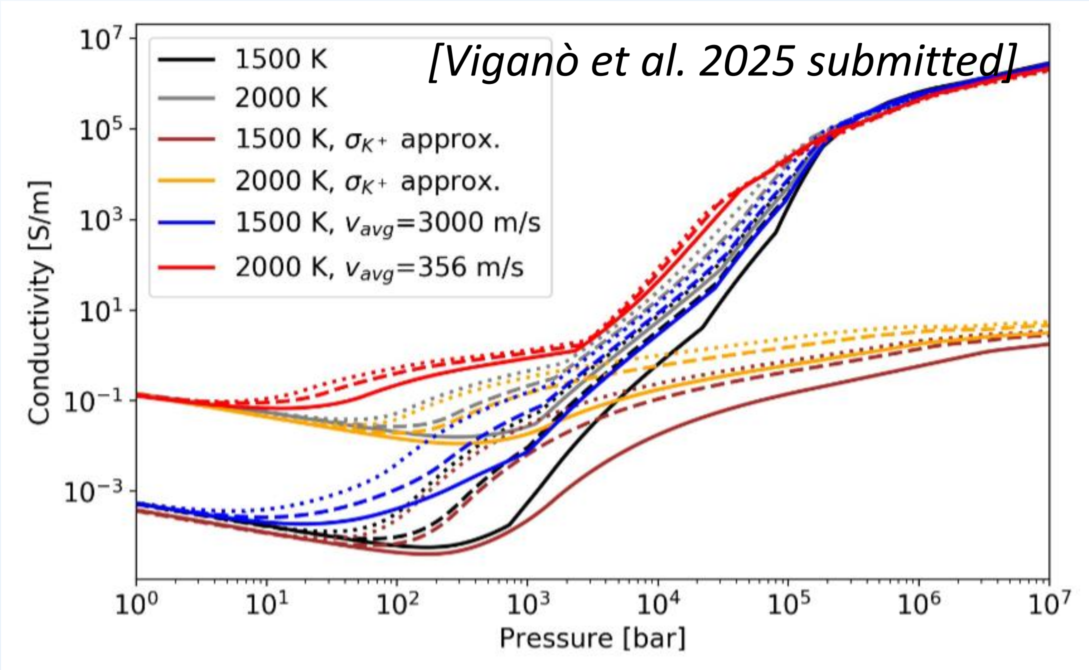
Full Ohmic model: conductivity profiles



[thermal ionization Kumar et al. 2021]

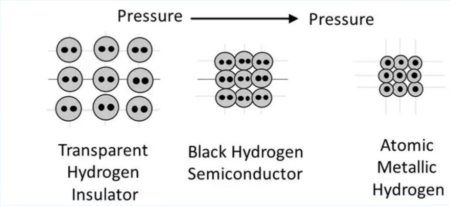


[pressure ionization Bonitz et al. 2024]



[Viganò et al. 2025 submitted]

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 $T_{\rm eq} = 1500, 2000$ K, without (black, grey) and with Ohmic heating, parameter $v_{\rm avg} = 3000$ and 356 m/s, respectively (blue, red). We also



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

Induced currents

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

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

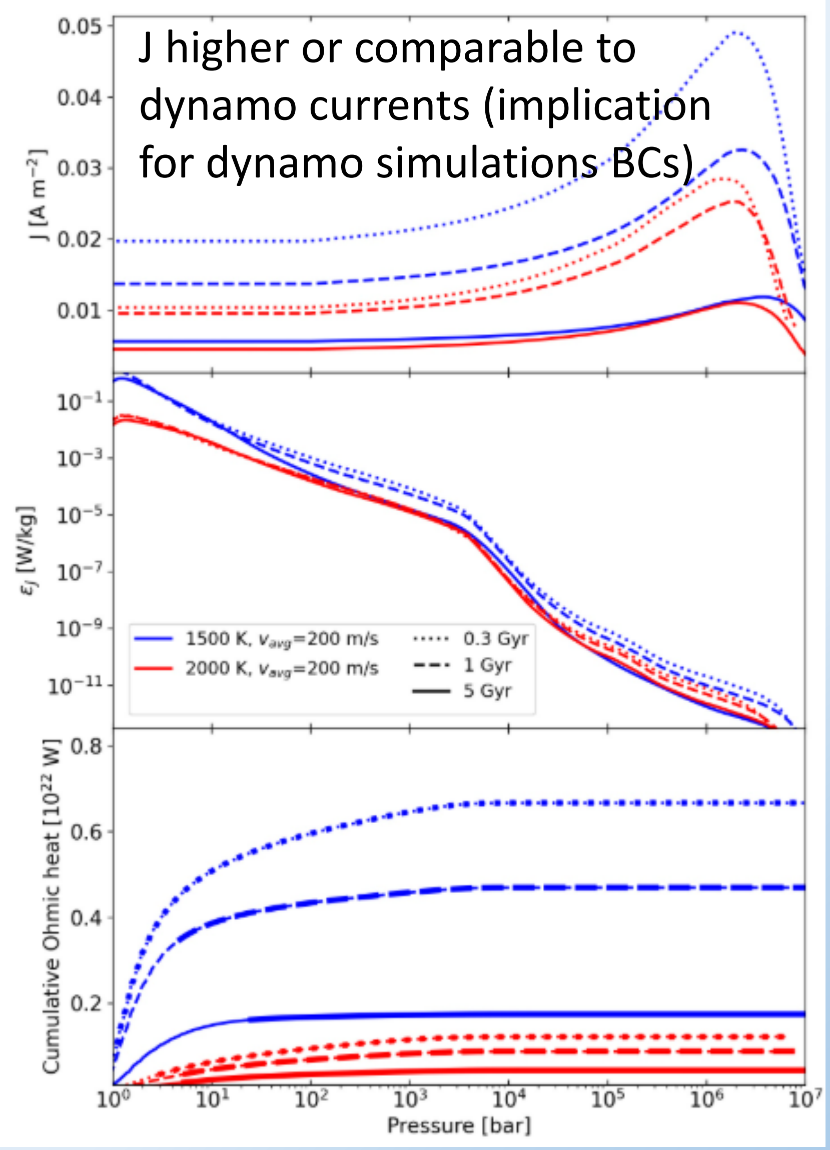
$$\sigma\nabla^2\Phi + \nabla\sigma \cdot \nabla\Phi = \nabla \cdot [\sigma(v \times B)]\,.$$

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 (10 bar):

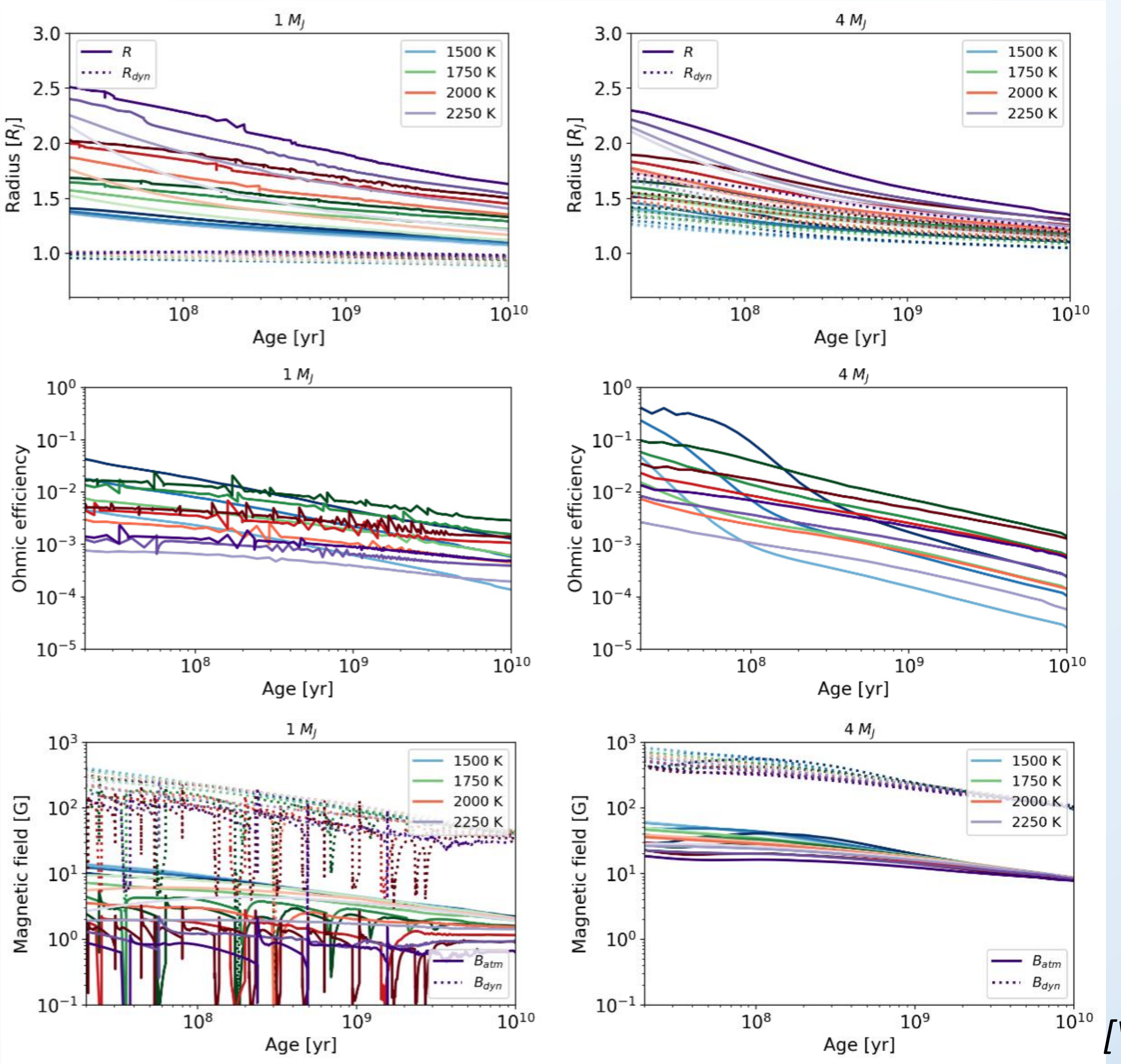
$$J(p < p_{atm})(t) = \sigma_{atm}(t) v_{avg} B_{bkg}(t)$$

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



[Viganò et al. 2025 submitted]

Evolutionary models results



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

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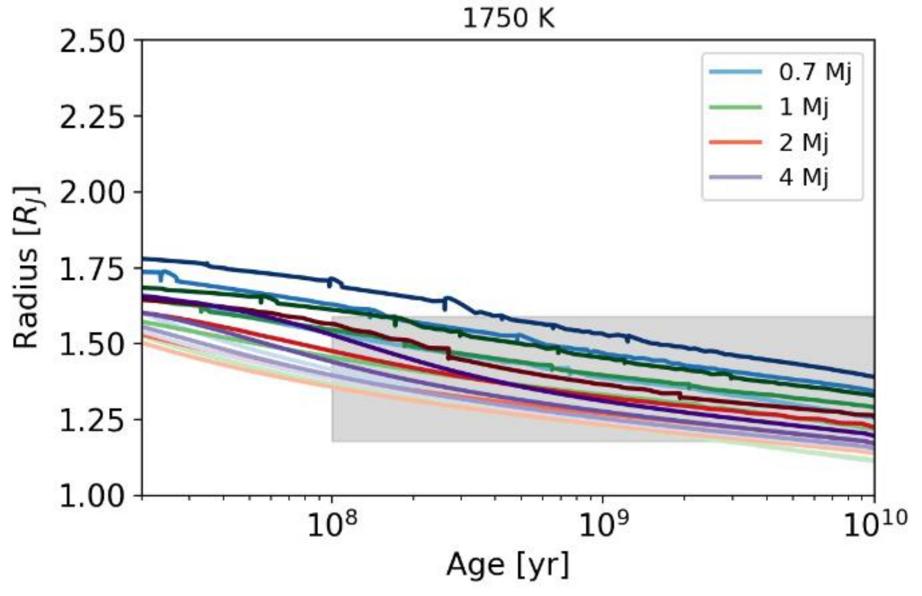
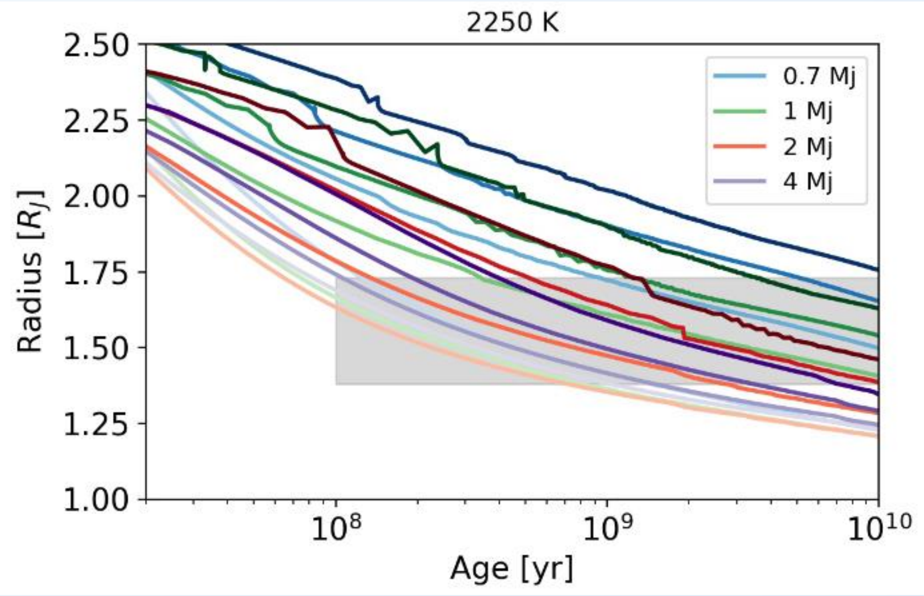
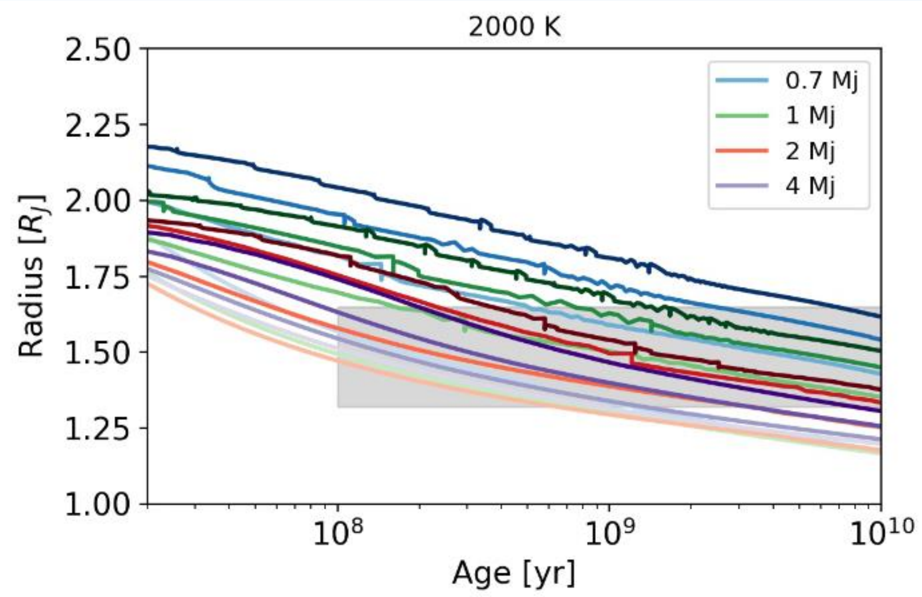
Contrarily to what commonly thought, B of HJs might be only in the range of Jupiter (< 10 G), unless they are very massive.

[Viganò et al. 2025 submitted]

Results and comparison with data







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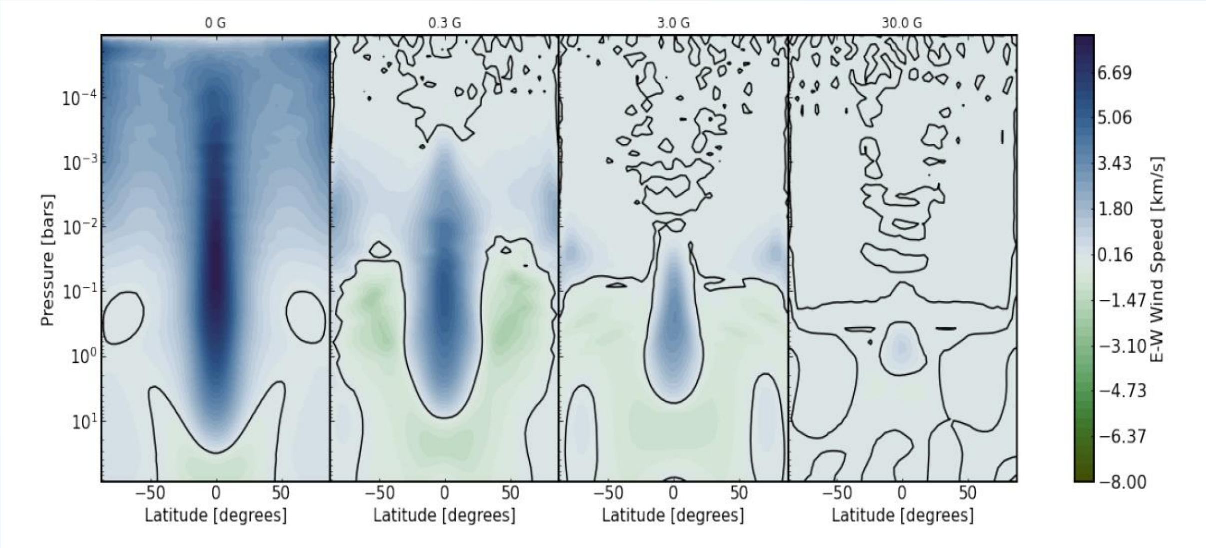
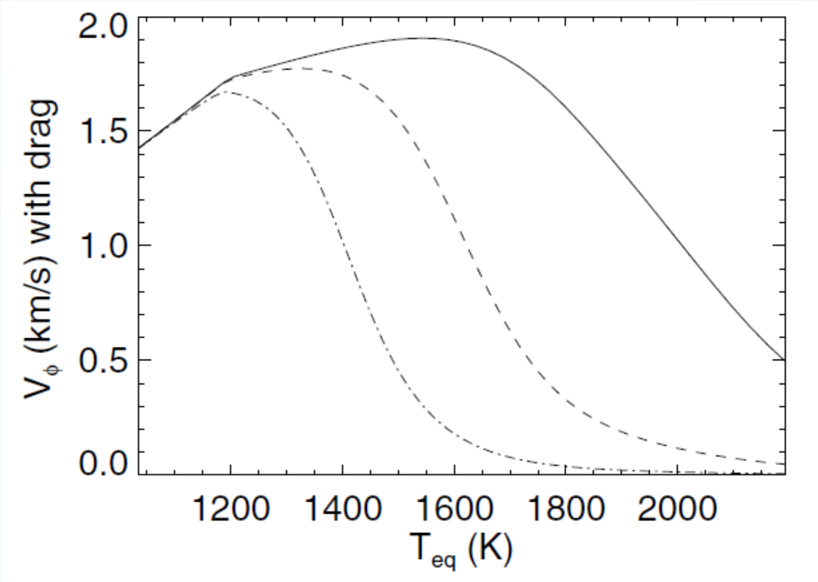
We need velocities of km/s for light, mildly irradiated (1500 K) planets, and much slower for heavier / highly irradiated HJs.

[Viganò et al. 2025 submitted]

Global circulation models: the magnetic drag

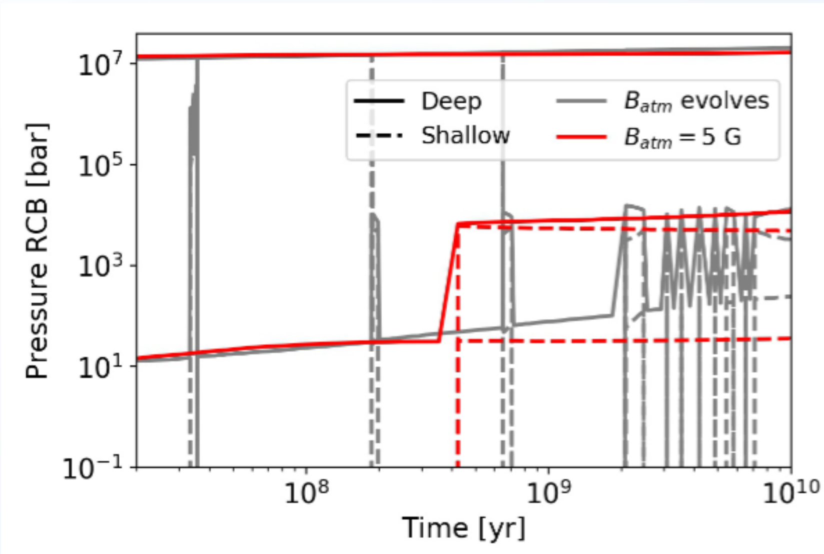
The inferred reduced velocities for higher fields (i.e. mass) is consistent with the magnetic drag effects on the winds.



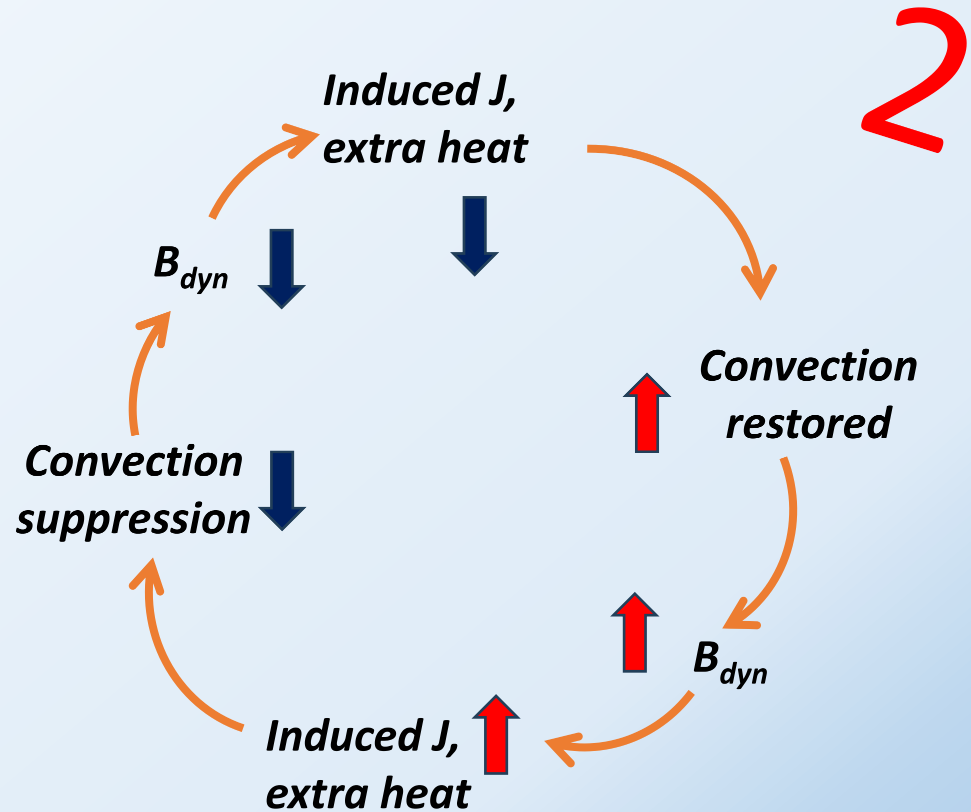


[Beltz et al. 2022, Menou 2012, see also Perna+2010, Batygin+ 2013 & more]

Feedback dynamo-atmospheric field: cycles?



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

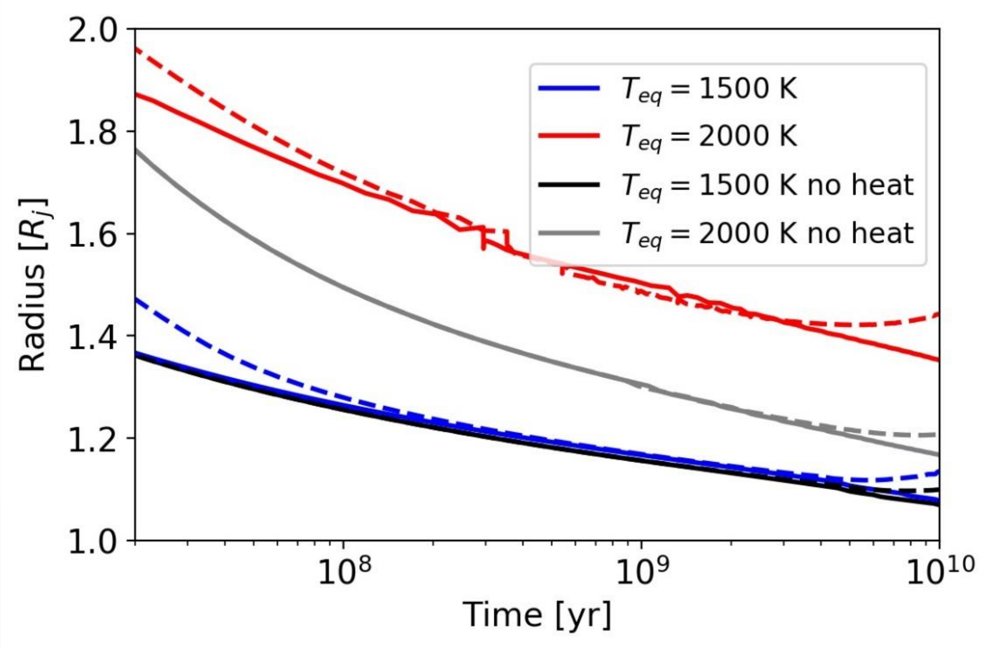


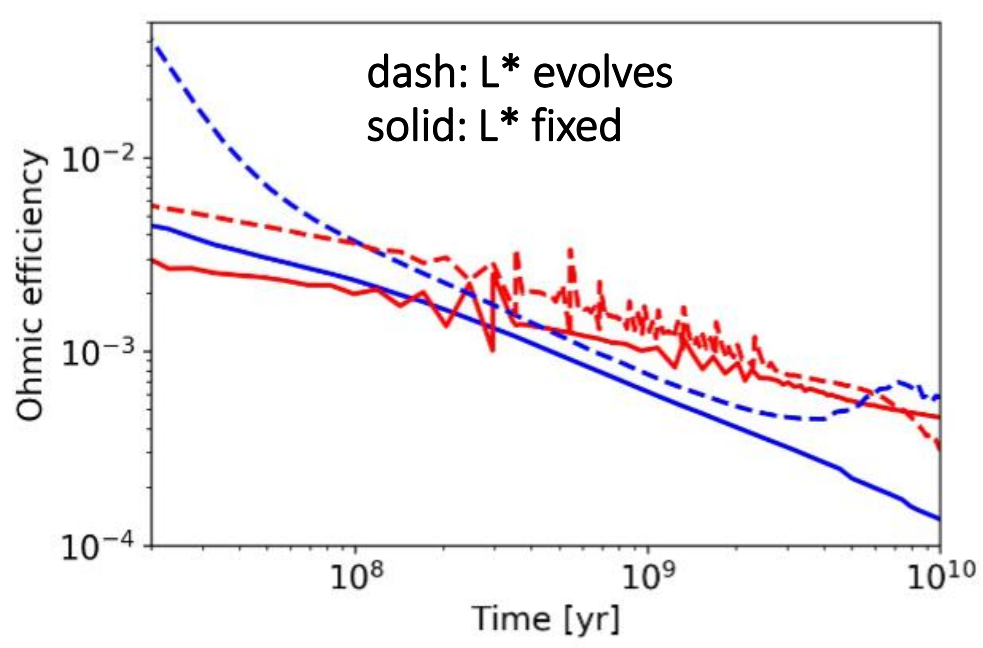
The timescales for these cycles are not assessable by the current code, but they are not purely numerical.

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

(IF v_{avg} constant!)

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 submitted]

1. **HJs are fast-rotators** (Rossby < 0.1): magnetic scaling laws relate convective flux-B.
2. Realistic Ohmic models can lead to suppression of convection and B-field (**radio/SPI detectability implications**), except for massive planets.
3. 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 L* (**collect observational evidence about re-inflation**).
4. 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 (any clear **observational trend mass - inferred velocities?**).

Next steps:

- **relax the constant velocity assumption**
- **population synthesis considering star luminosity variations**
- **explore the cyclic behaviour with short timescales**

OBRIGADO!

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