Rossby number, convection suppression, and magnetism in inflated hot Jupiters

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Layers of Understanding
Heidelberg
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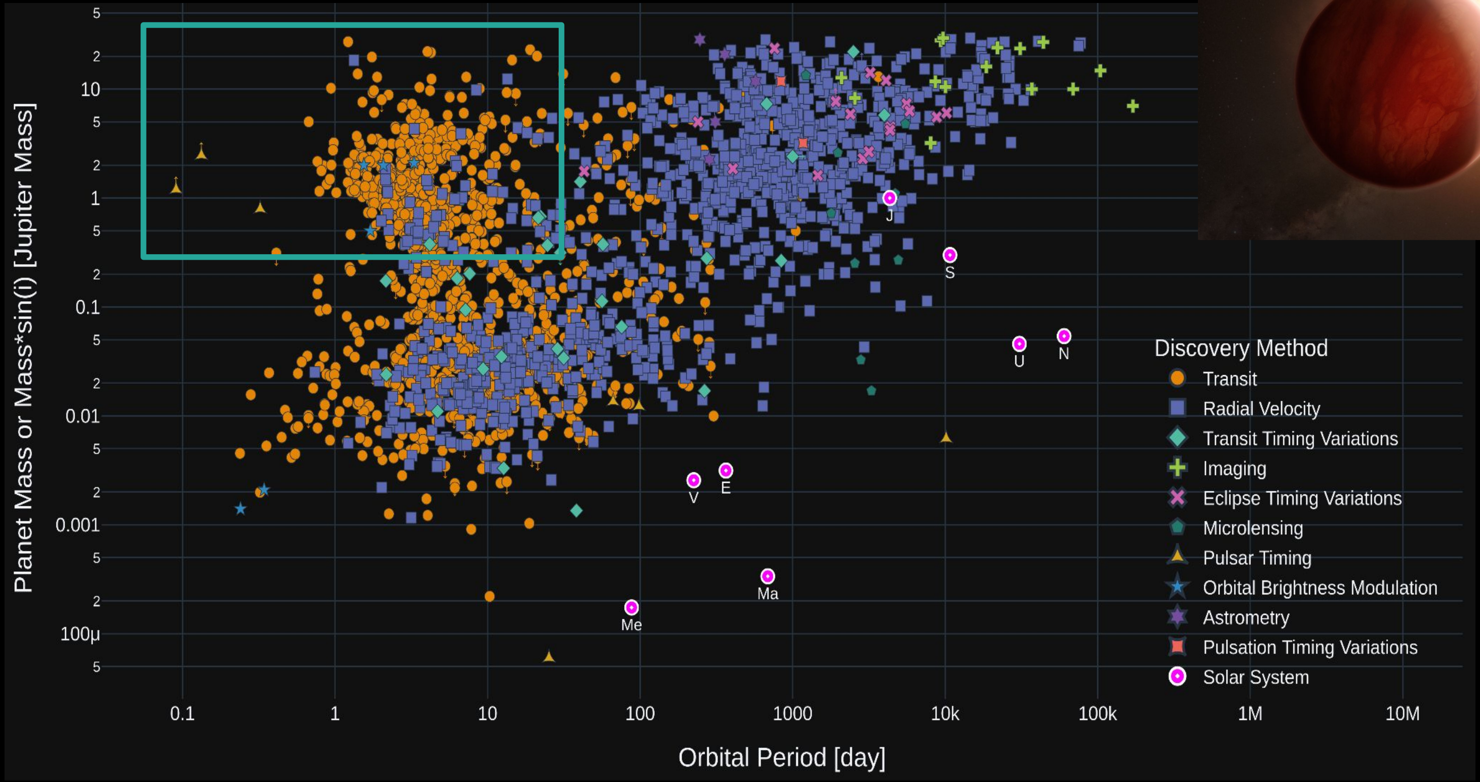
Daniele Viganò, Aline Vidotto, Matteo Cantiello, Fabio del Sordo, Simranpreet Kaur, Simon Andres Szabel, Emily Sandford, Clàudia Soriano, Paul Cristofari

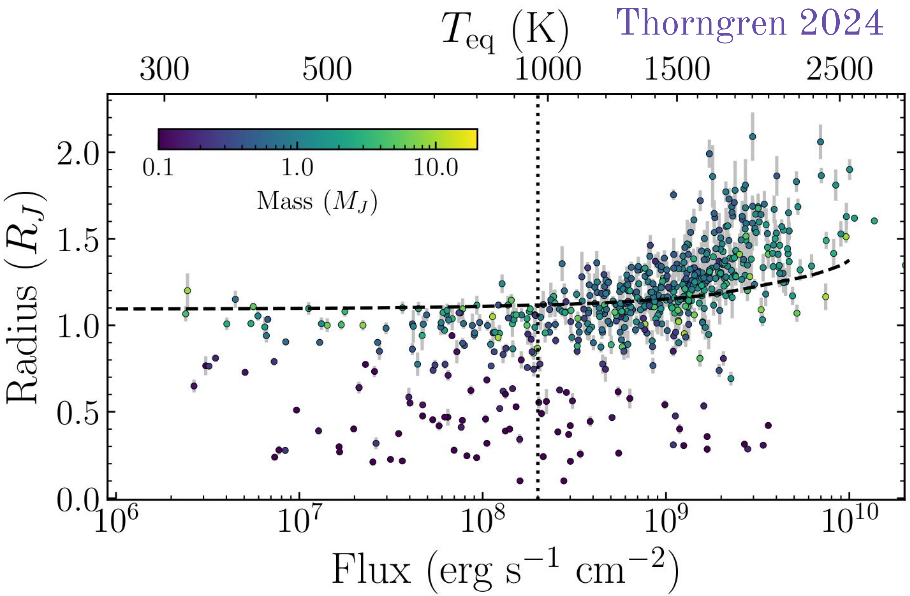
Hot Jupiters

NASA Exoplanet Archive



- Highly irradiated
- Tidally locked
- Low eccentricities

Hot Jupiter inflation dilemma



Irradiated models cannot reach the observed inflated radii of HJs (even playing with M_{core}, Z, opacities, etc.).

Inflation is correlated with received irradiated stellar flux.

Heating efficiency

$$\epsilon = \frac{Q_{\rm dep}}{\pi R^2 F_{\rm irr}}$$

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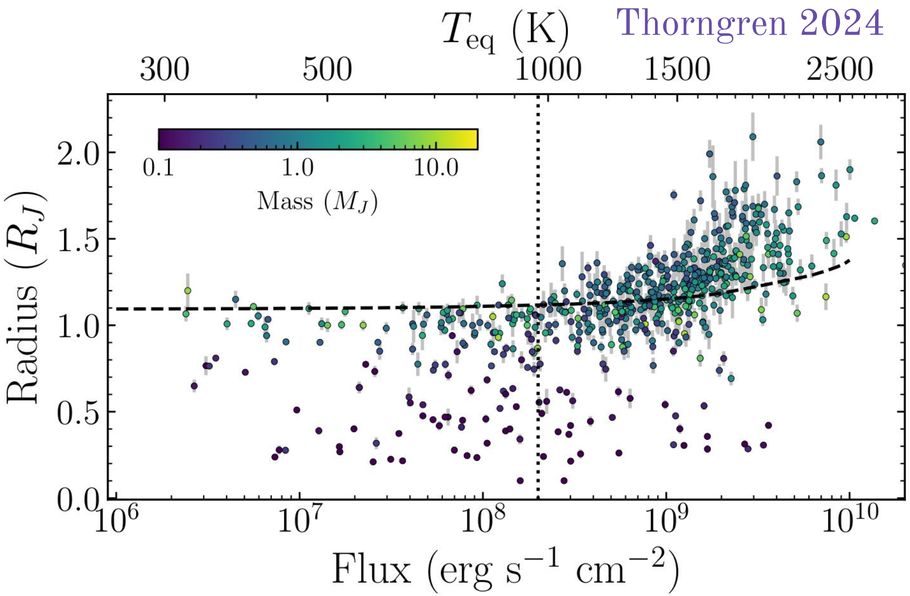

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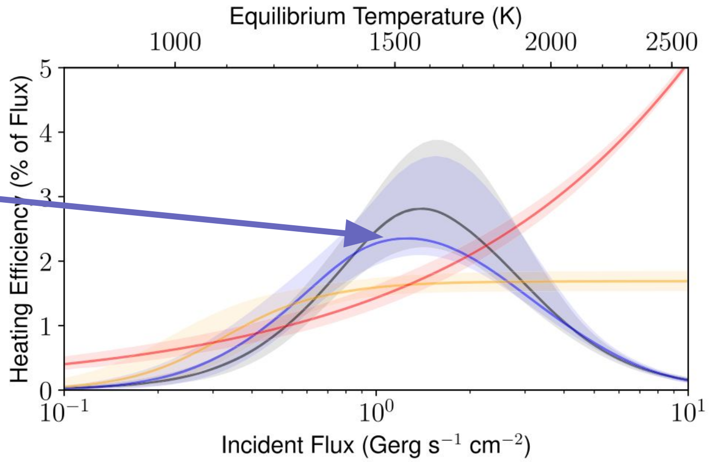
Heating efficiency $$\epsilon = \frac{Q_{\rm dep}}{\pi R^2 F_{\rm irr}}$$

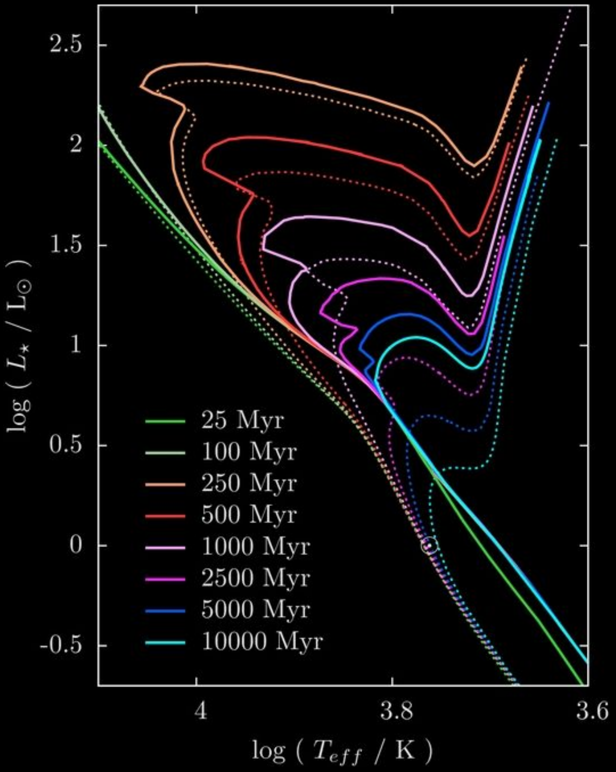
$$\epsilon = \left(2.37^{+1.3}_{-0.26}\,\%\right) \exp\left[-\frac{\left(\log_{10}(F_{\rm irr}/F_0) - 0.14^{+0.060}_{-0.069}\right)^2}{2\cdot\left(0.37^{+0.038}_{-0.059}\right)^2}\right]$$



Bayesian analysis with HJ populations: Thorngren & Fortney 2018 (also Sarkis et al 2021)

Elias-López et al 2025: inflated HJ interior models

MESA



Solve the numerical stellar structure equation (1D stellar):

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

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

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

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

Constant in mass below the RCB

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$$\epsilon = \frac{Q_{\rm dep}}{\pi R^2 F_{\rm irr}} \qquad Q_{\rm dep} = \int_M \epsilon_{\rm heat}\ dm$$

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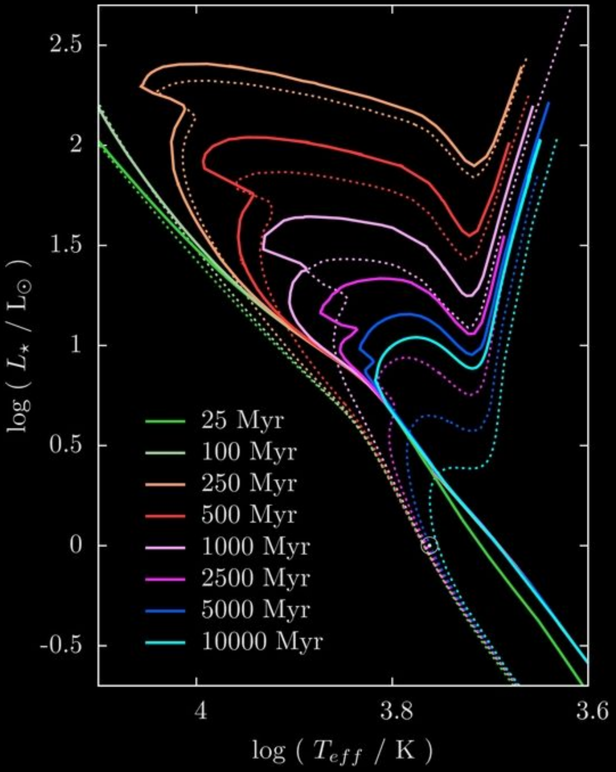

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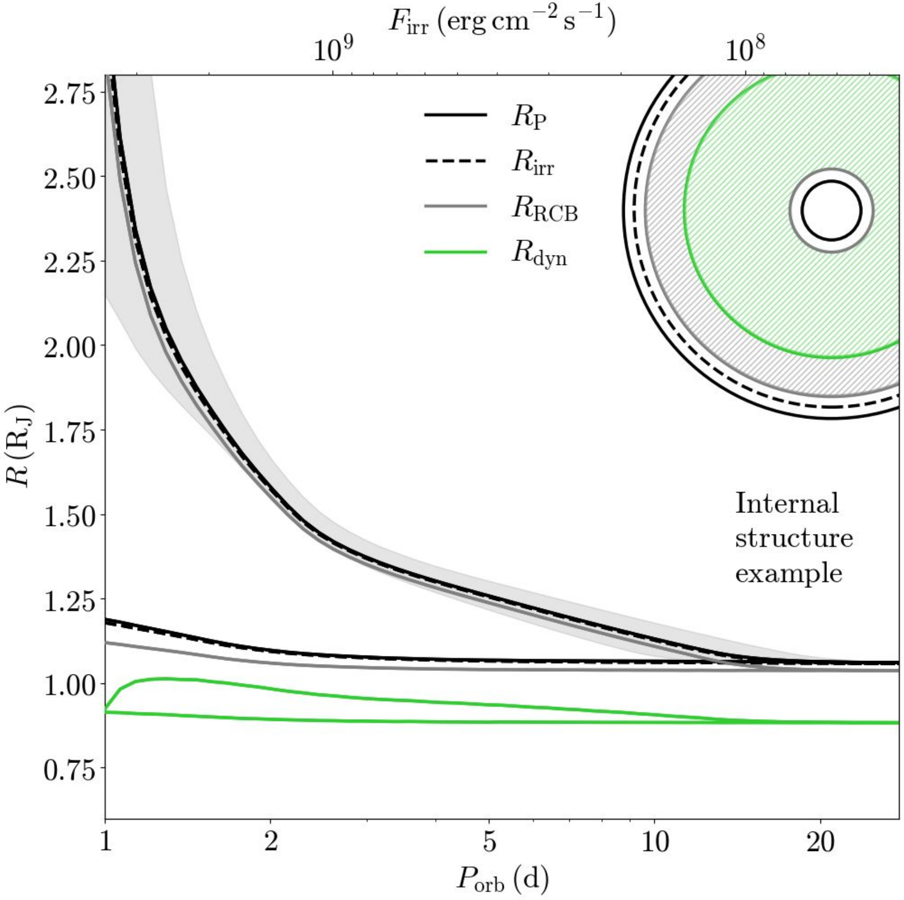
Questions:

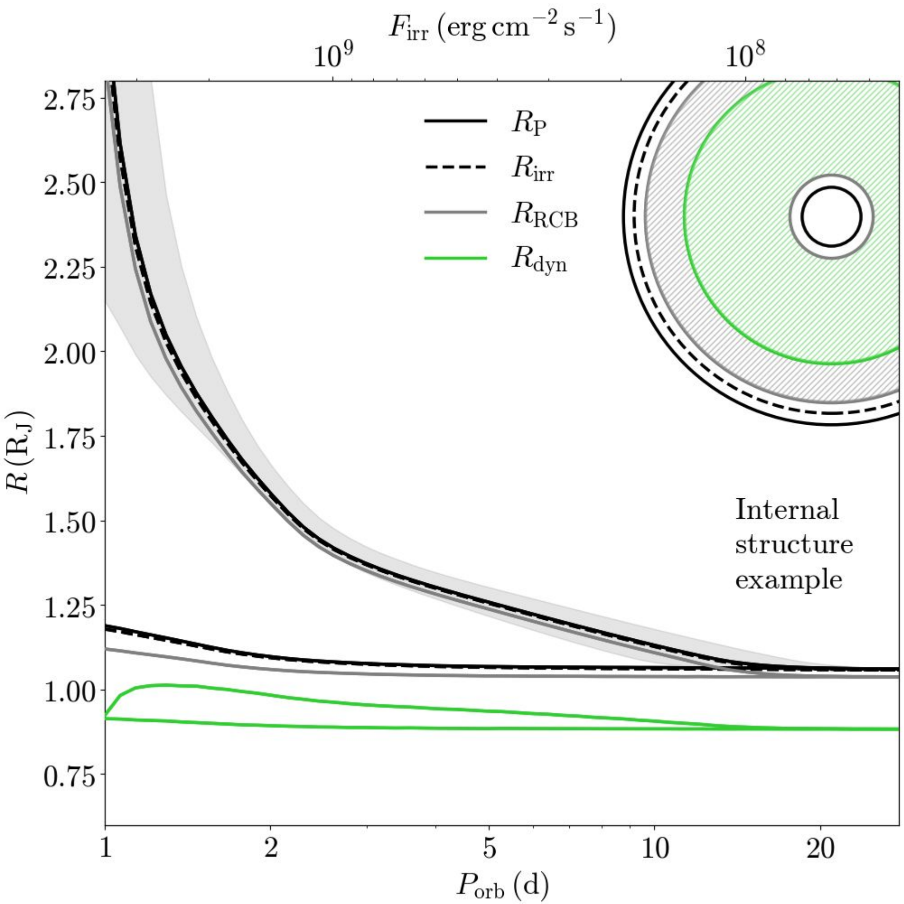
1. How do interior quantites of HJ change as a function of orbital separation? (specifically, the Rossby number)
2. How does this influence the magnetic field predictions its observational consequences?

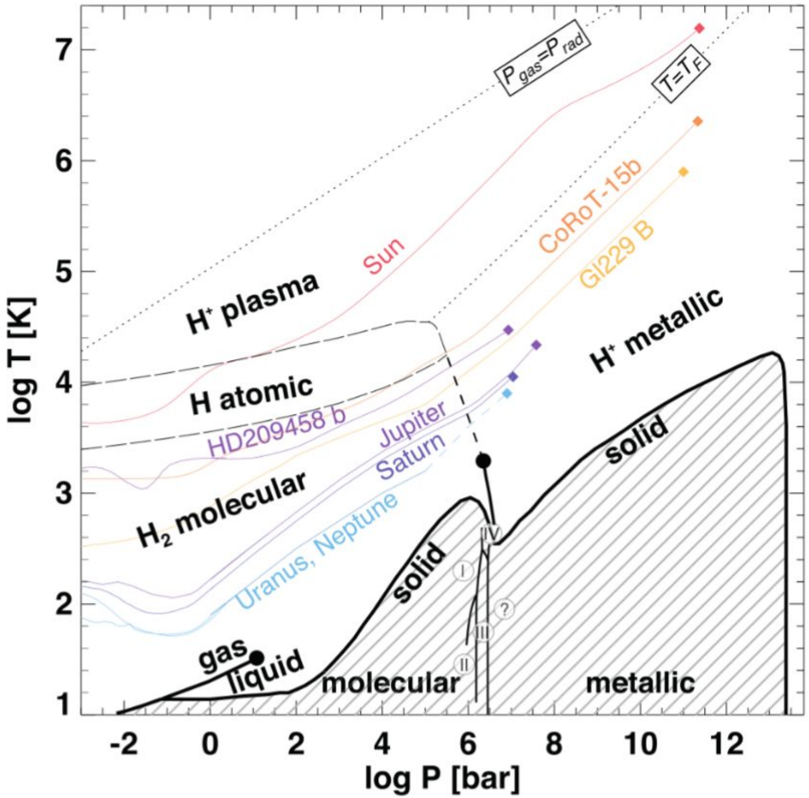
1 M_J planet around 1 $M_\odot$ star at 5 Gyr



1 M_J planet around 1 $M_\odot$ star at 5 Gyr

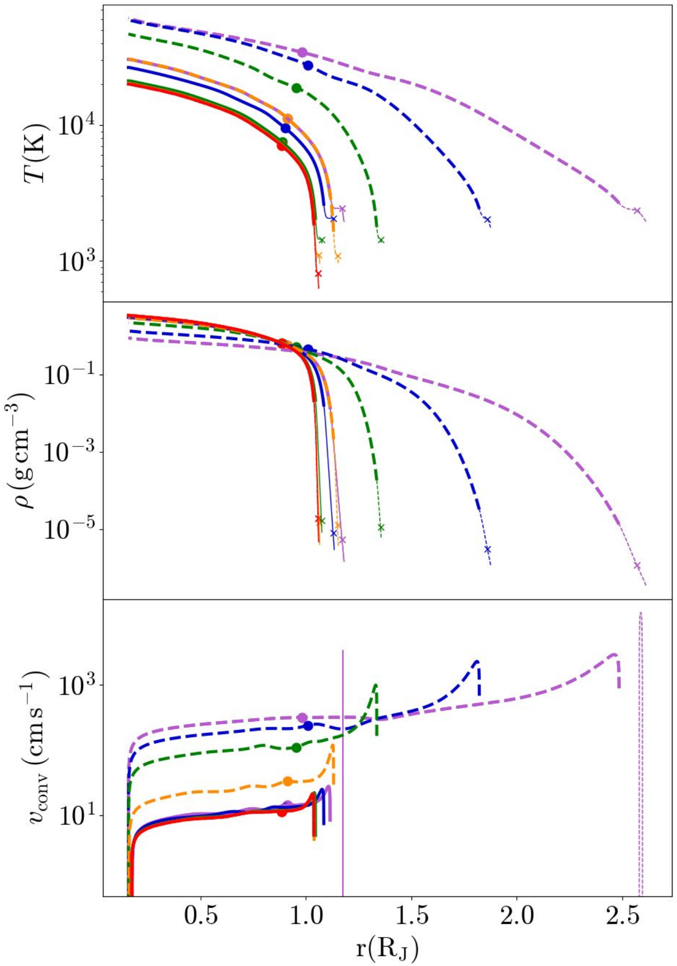
Guillot & Gautier 2015

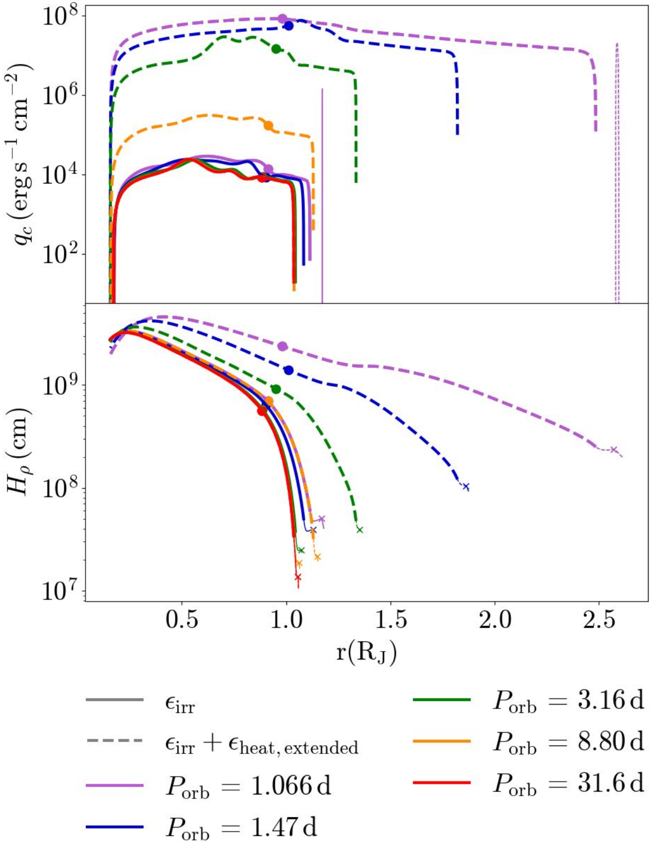




Assumption: Metallic hydrogen starts at around 1 Mbar (or 100 GPa)

Radial profiles at 5 Gyr





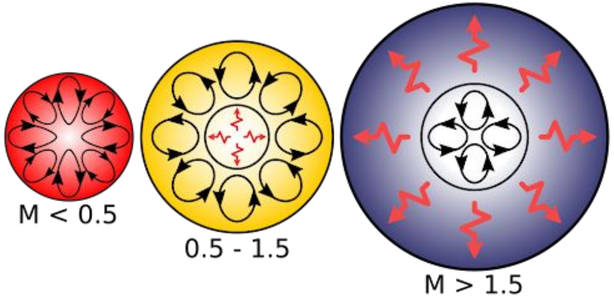
$$q_c = \frac{2\,c_P\,T\,\rho^2\,v_{conv}^3}{P\,\delta}$$

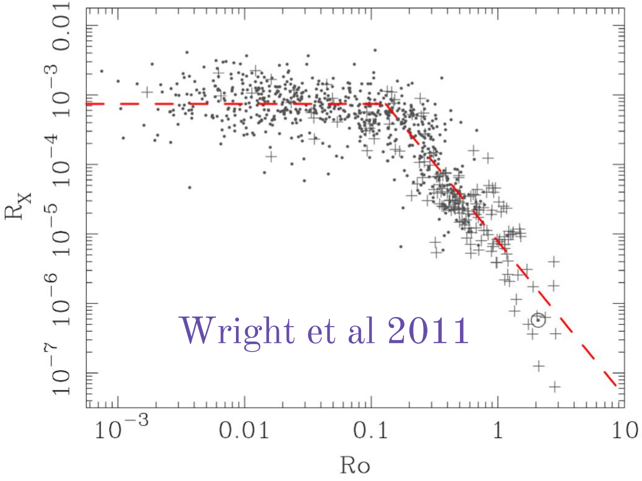
$$\delta = -(\partial \ln \rho / \partial \ln T)_P$$

Interior profiles will be used for Ro and B_{rms} estimates

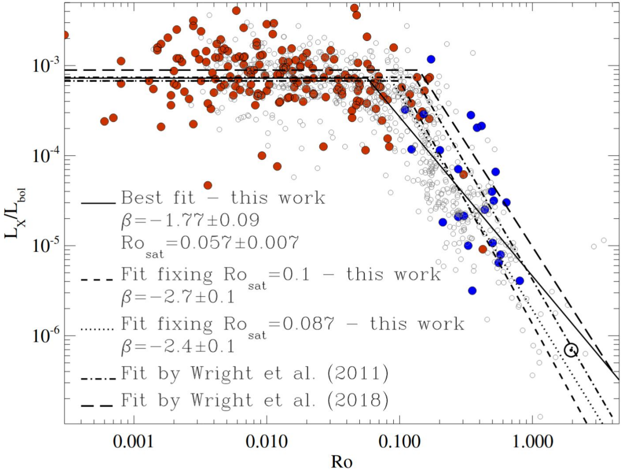
Magnetic scaling laws

The Rossby number defines two limits in stellar X ray luminosities (and therefore magnetic activity)





Landin et al 2023



Rossby number regimes

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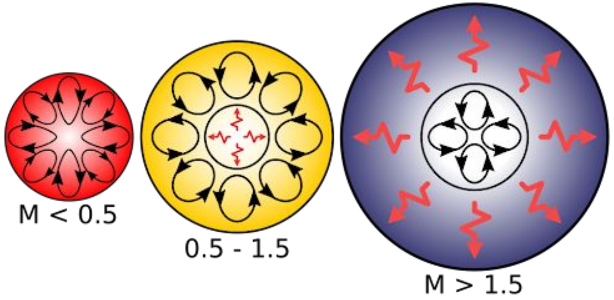
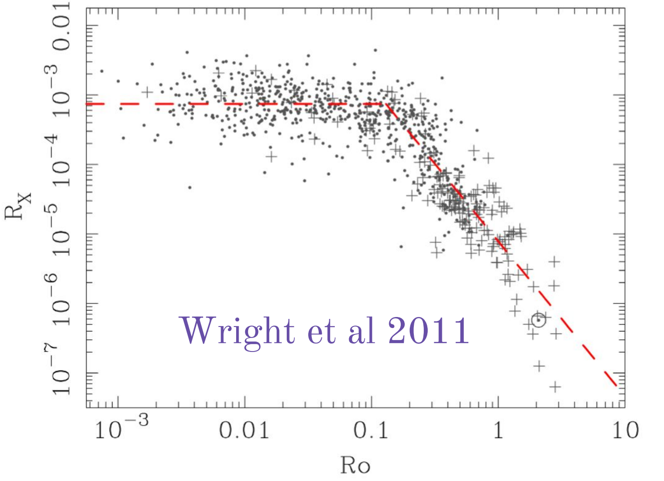


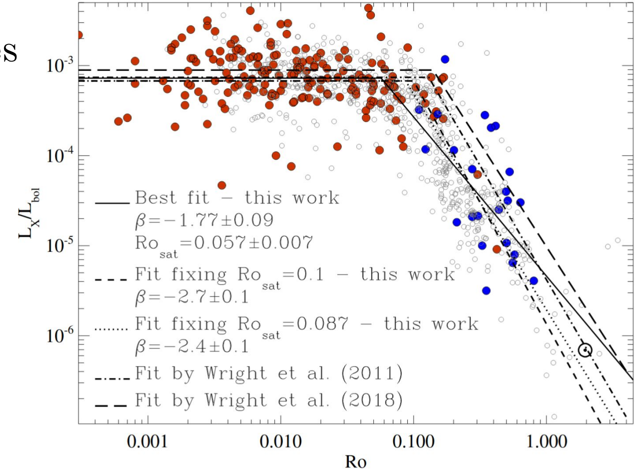


$$Ro = \frac{u_{rms}}{\Omega d} = \frac{\tau_{rot}}{\tau_{turn}}$$

Slow rotator regime ($Ro<0.12$): magnetic field strength is dependant on rotation rate

Fast rotator regime ($Ro<0.12$): dynamo saturates

Landin et al 2023



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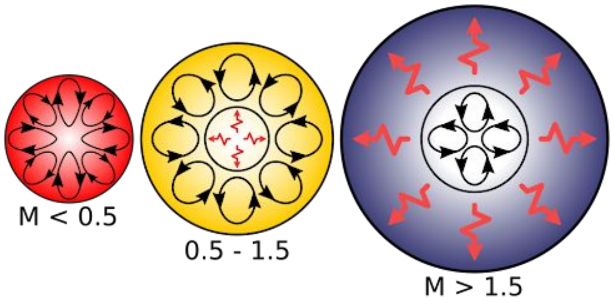

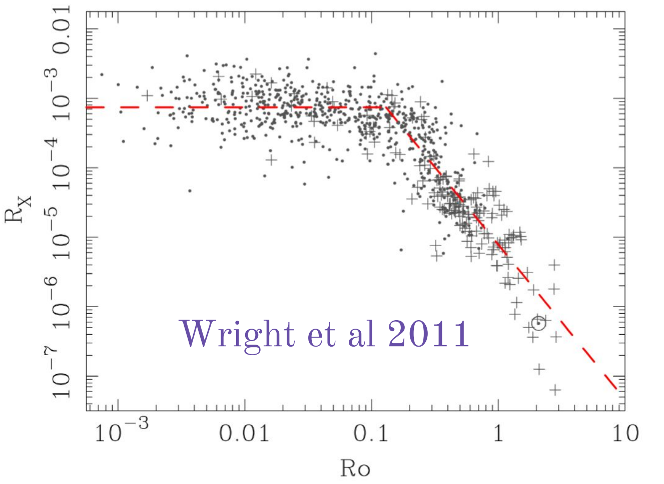

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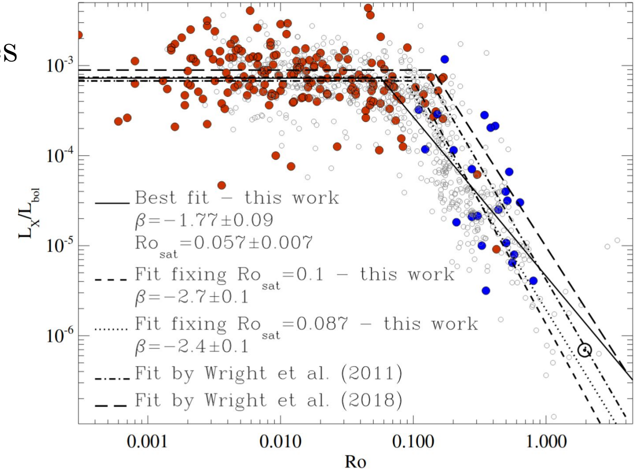
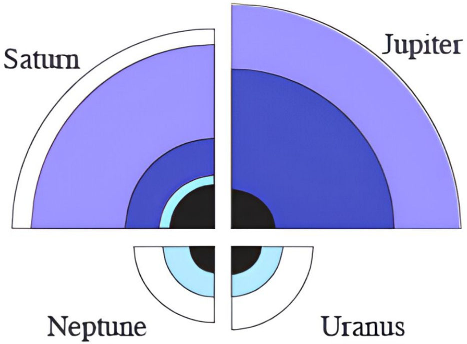


Planets usually lie in the fast rotator regime (Jupiter and Saturn do). Are also HJs there?

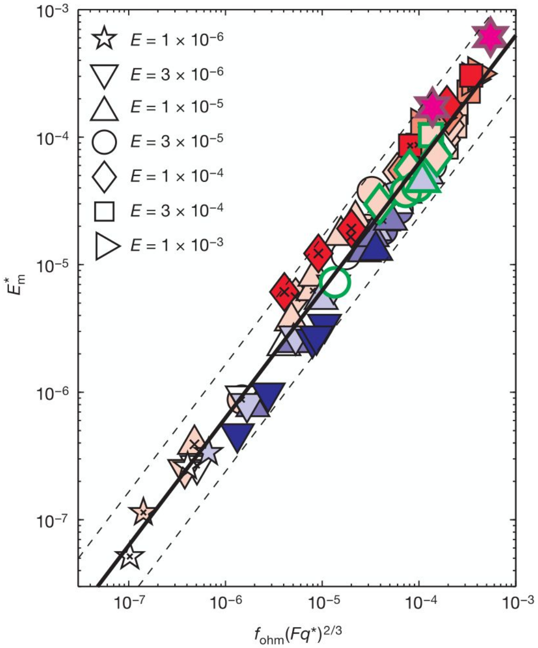


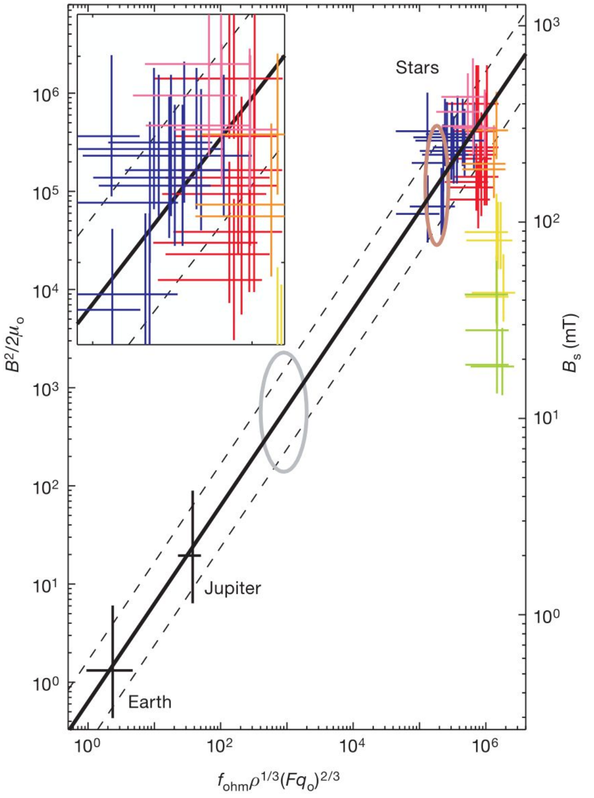
Scaling laws (Christensen et al 2006 & 2009)

In the fast rotator regime (Ro<0.12) **magnetic energy** is dictated by the **buoyant power**, (convective thermal luminosity):

$$B^2/(2\mu_o) \propto f_{ohm}\rho^{1/3}(q_c L/H_T)^{2/3}$$

The full scaling law can be expressed as a radial integral:





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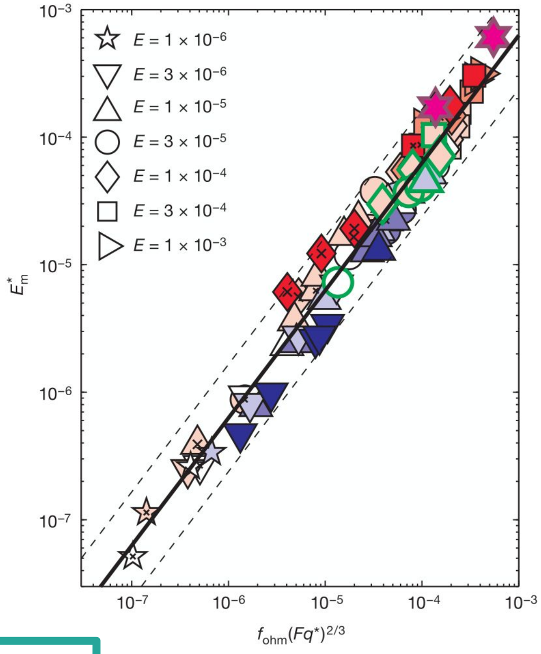

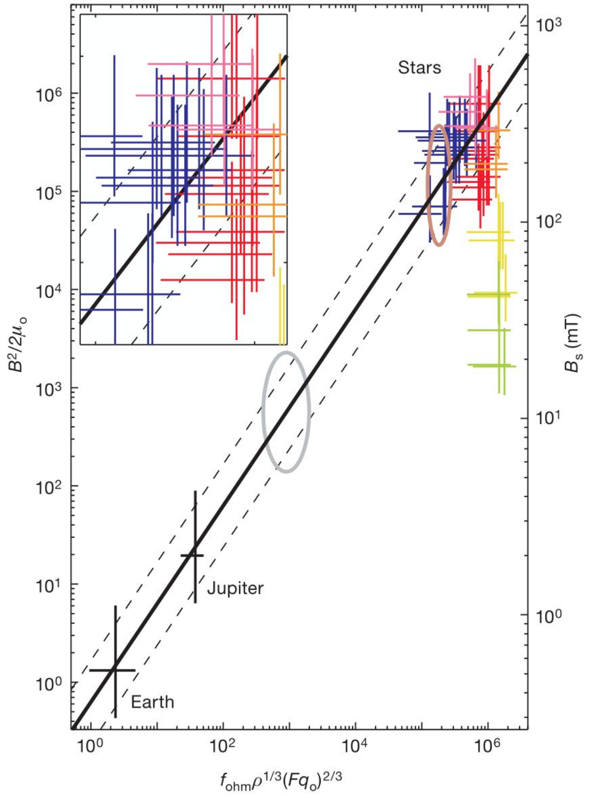

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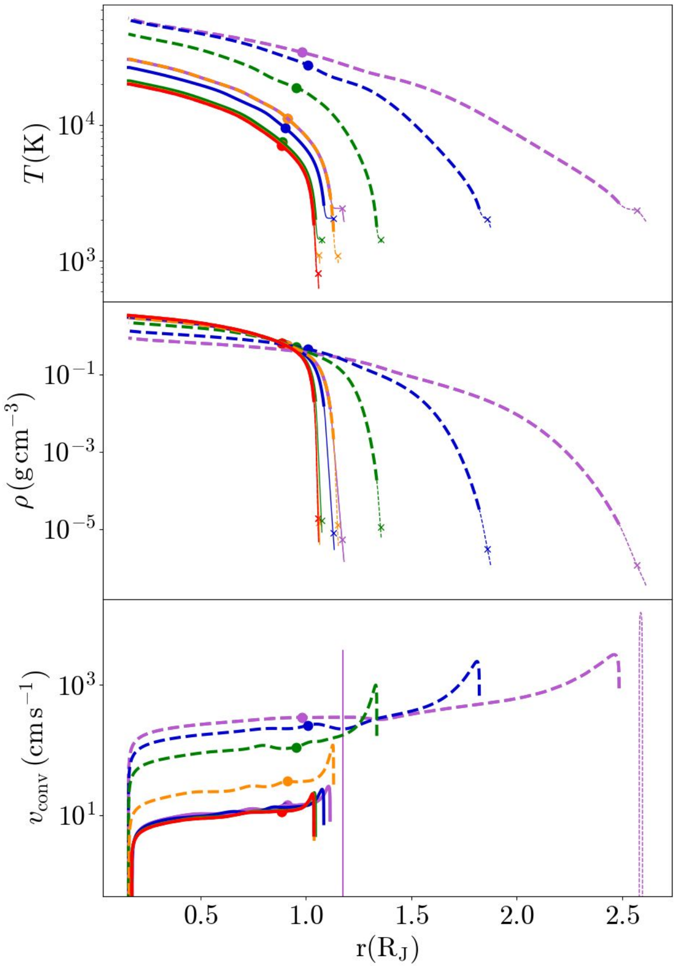
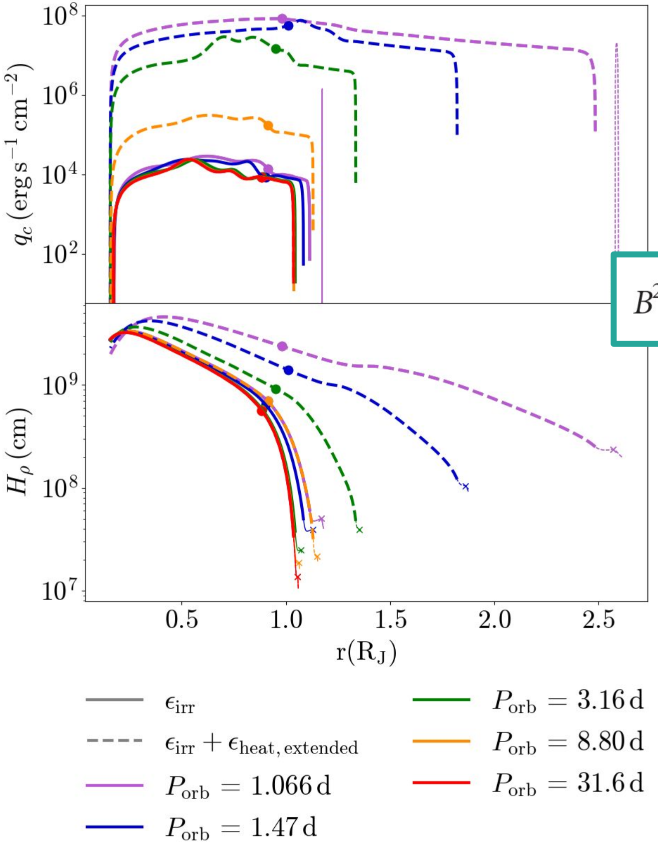
$$F^{2/3} = \frac{1}{V}\int_{R_{\rm core}}^{R_{\rm dyn}} \left(\frac{q_c(r)}{q_0}\frac{L(r)}{H_T(r)}\right)^{2/3} \left(\frac{\rho(r)}{\langle \rho \rangle}\right)^{1/3} 4\pi r^2\, dr$$

$$B_{\rm dyn} = 4.8^{+3.2}_{-2.8} \left(\frac{M}{M_\odot}\right)^{1/6} \left(\frac{L}{L_\odot}\right)^{1/3} \left(\frac{R_\odot}{R}\right)^{7/6} \text{kG}$$

Reiners et al 2009

Radial profiles at 5 Gyr





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$$Ro = \frac{u_{rms}}{\Omega d} = \frac{\tau_{rot}}{\tau_{turn}}$$

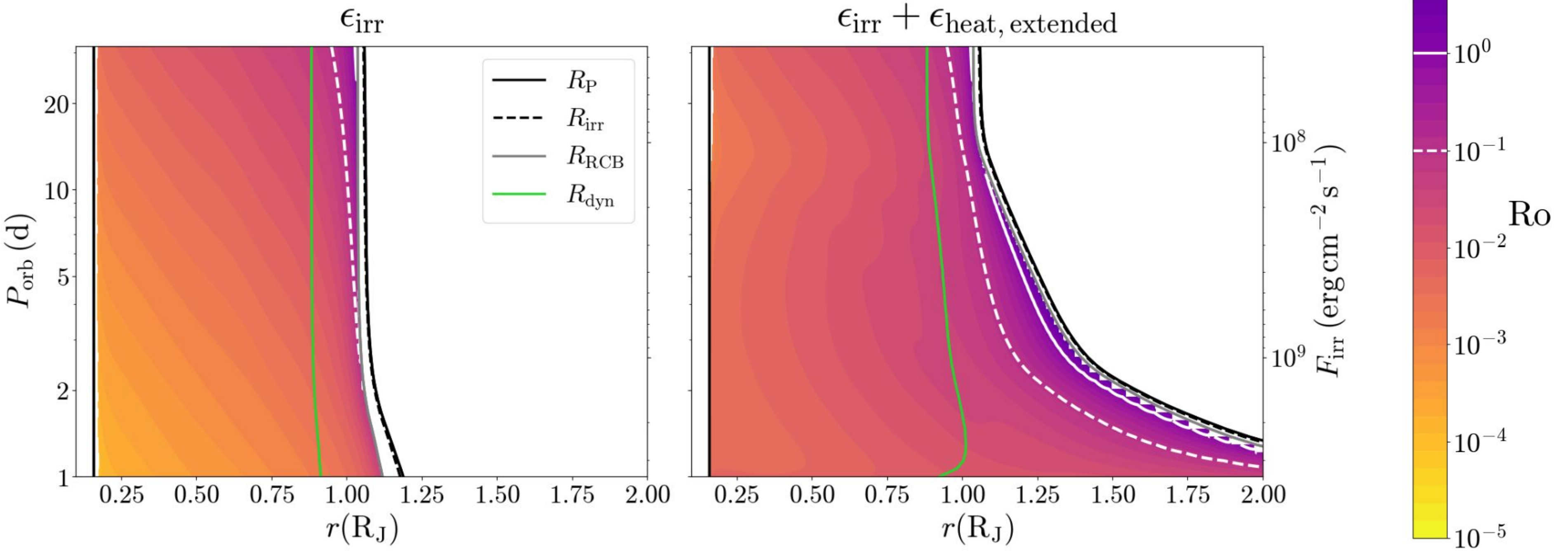
$$\mathrm{Ro}(r) = \frac{\tau_{rot} v_{conv}(r)}{H_\rho(r)}$$

Rossby number dependence on orbital distance and planetary depth

$$\mathrm{Ro}(r) = \frac{\tau_{rot} v_{conv}(r)}{H_\rho(r)}$$

- Slow rotator regime (Ro<0.1)
- Fast rotator regime (Ro<0.1)

Inflation increases Ro, but not enough to reach a slow rotator regime (1 M_J planet).



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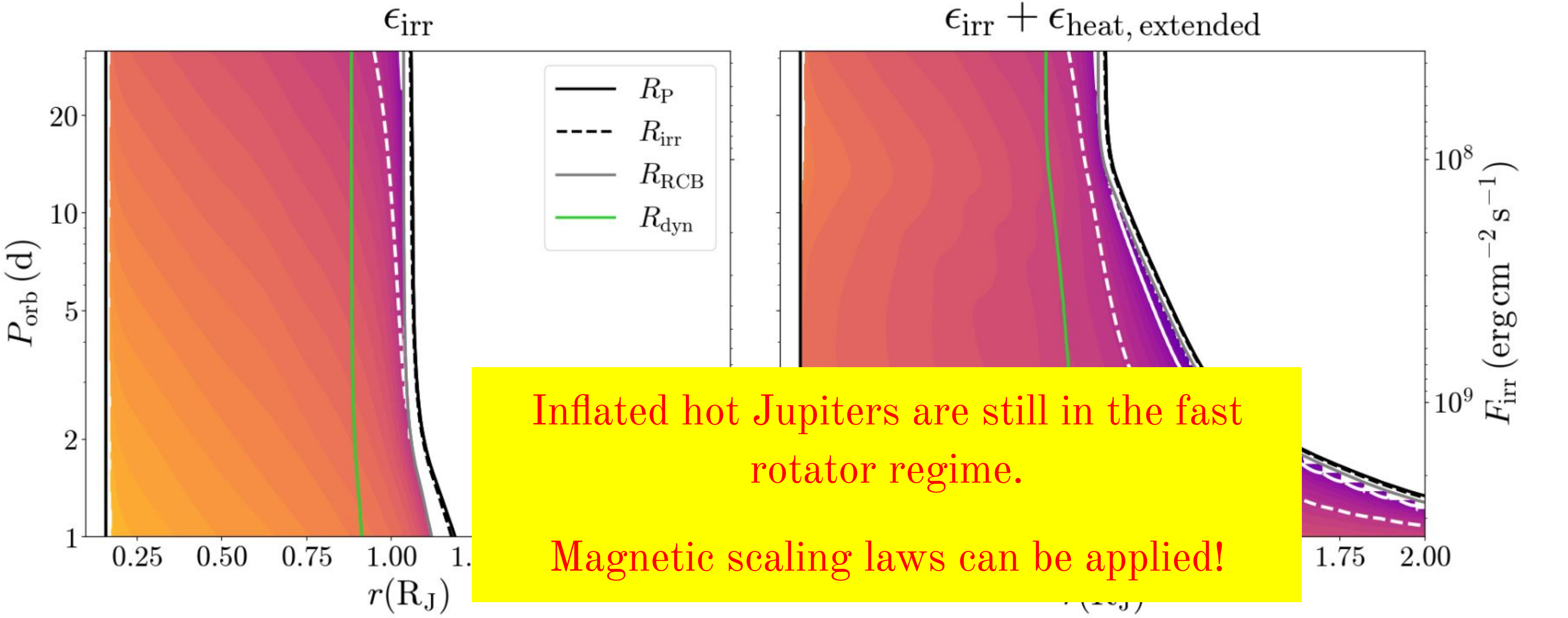
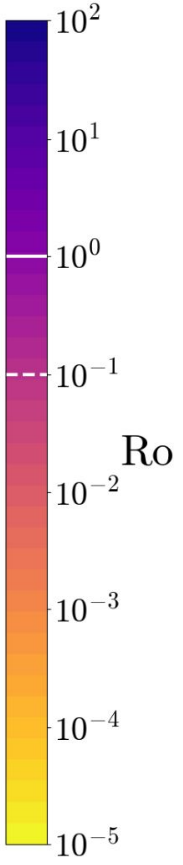
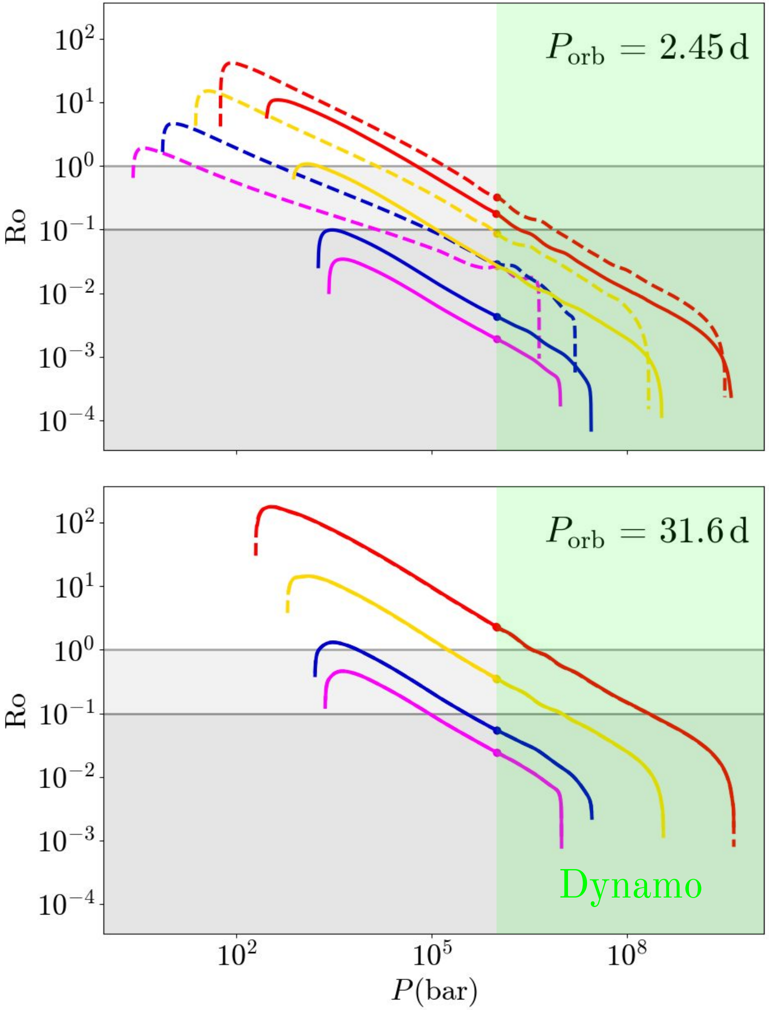




Inflated hot Jupiters are still in the fast rotator regime.

Magnetic scaling laws can be applied!



Ro dependence on planetary mass

As the planetary mass increases, inflation effects become minimal. Lowest Ro are recovered for massive long period planets (but still tidally locked).

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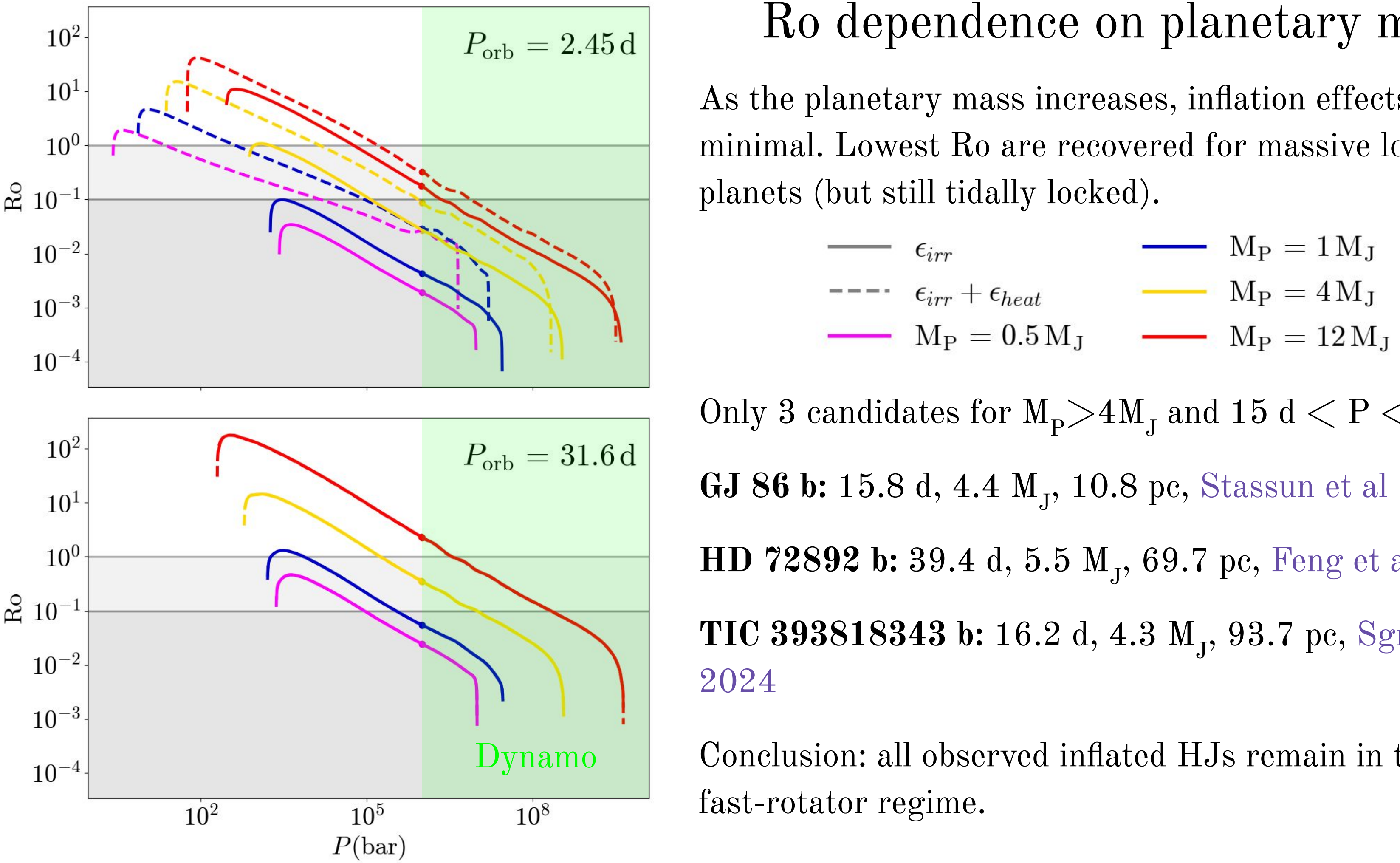

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Only 3 candidates for $M_P > 4 M_J$ and 15 d $<$ P $<$ 40 d:

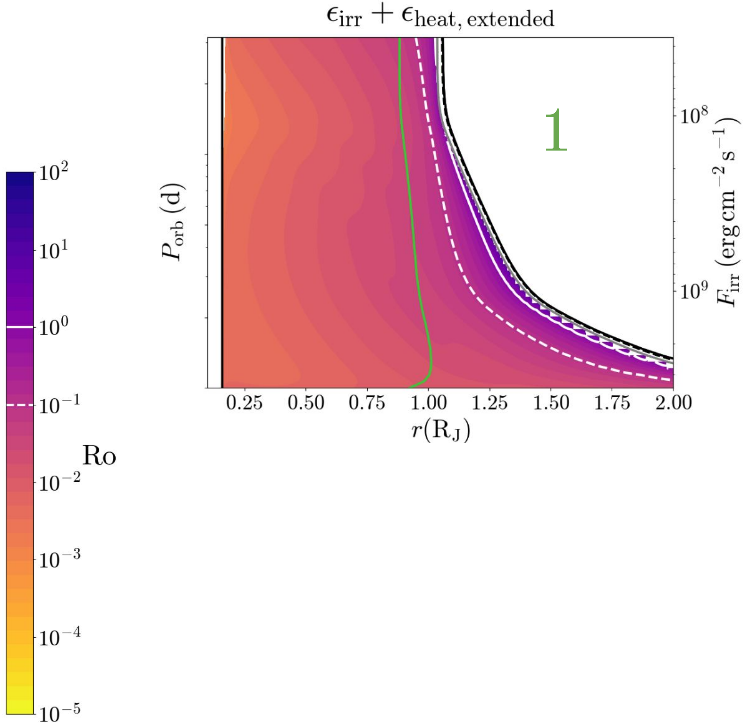
GJ 86 b: 15.8 d, 4.4 M_J, 10.8 pc, Stassun et al 2017

HD 72892 b: 39.4 d, 5.5 M_J, 69.7 pc, Feng et al 2022

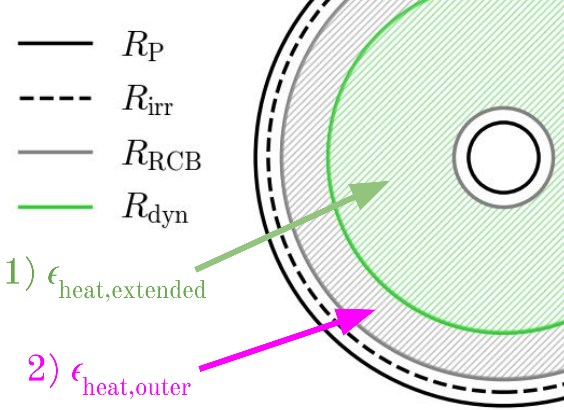
TIC 393818343 b: 16.2 d, 4.3 M_J, 93.7 pc, Sgro et al 2024

Conclusion: all observed inflated HJs remain in the fast-rotator regime.

Different heating injections



Where should be the heat applied? We consider only two extreme cases, all below the R_{dyn} or above R_{dyn}.



Most heat deposition models (ohmic, tidal and atmospheric) happens in the outermost layers.

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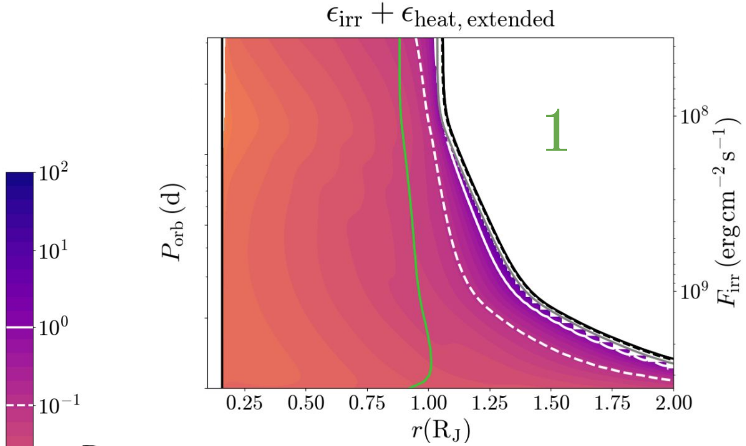

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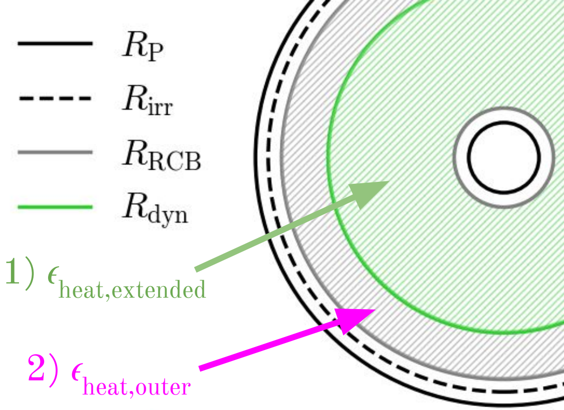

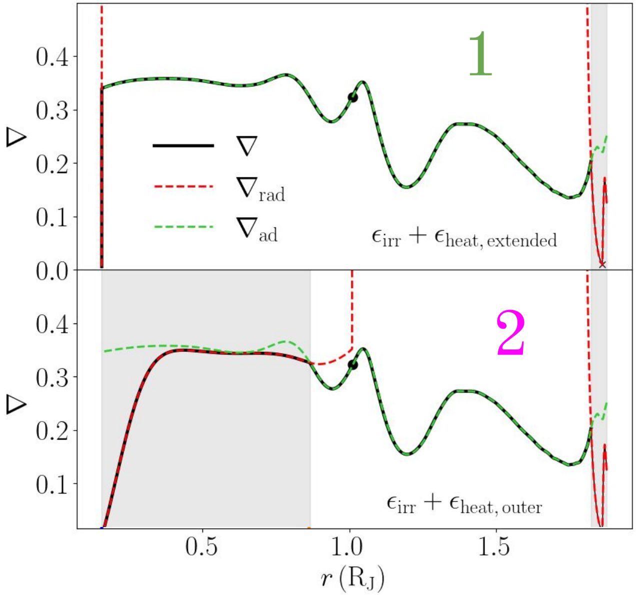

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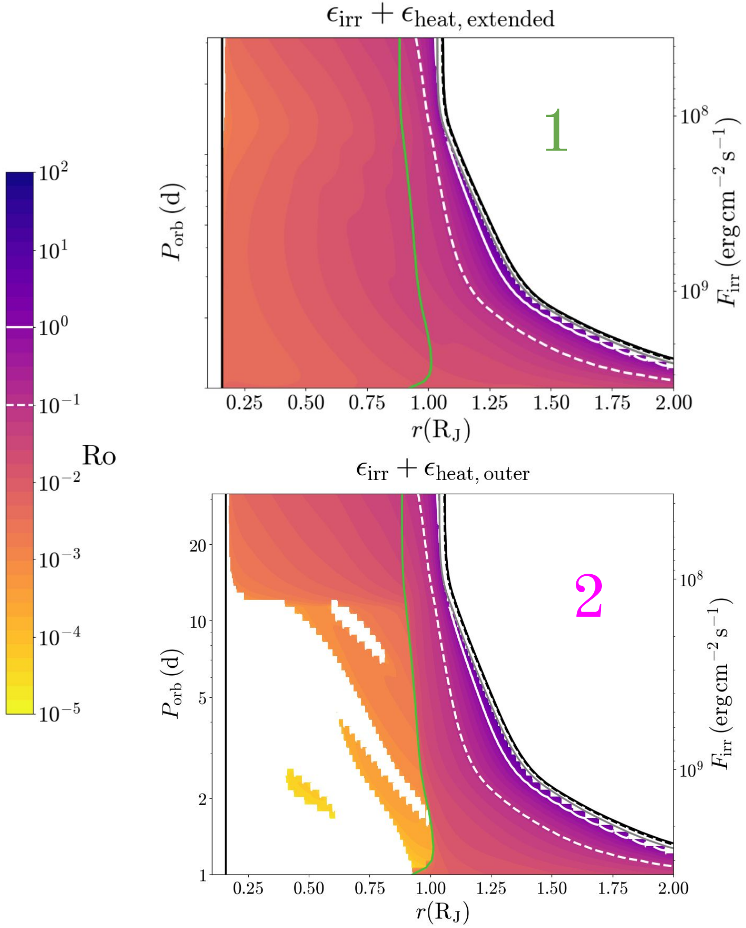
Rossby number with injection above dynamo



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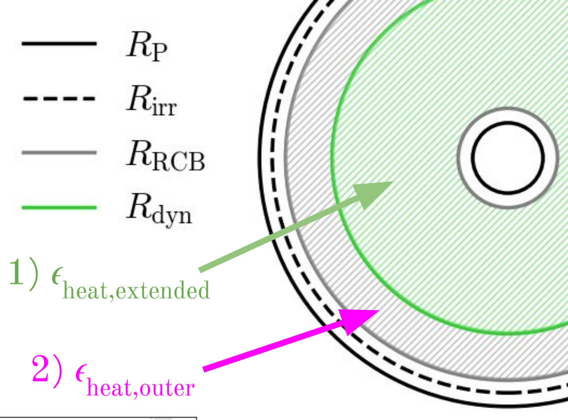

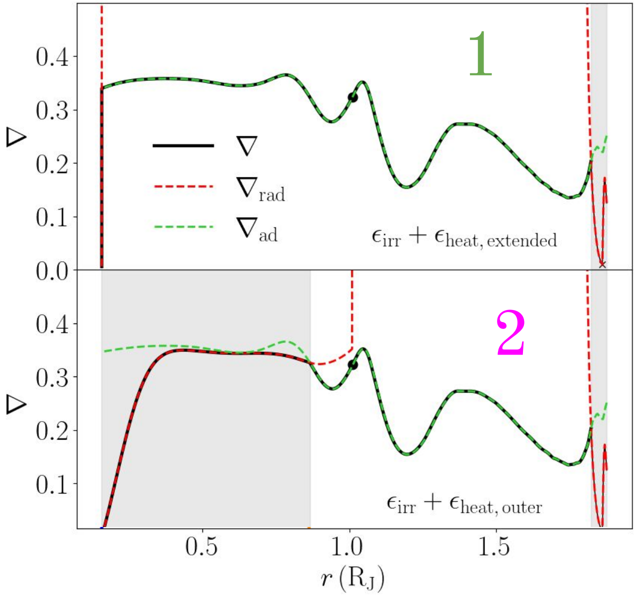

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Magnetic field estimates
(for $P_{orb} = 2.5$ days, $F_{irr} = 10^9$ erg cm^{-2} s^{-1})

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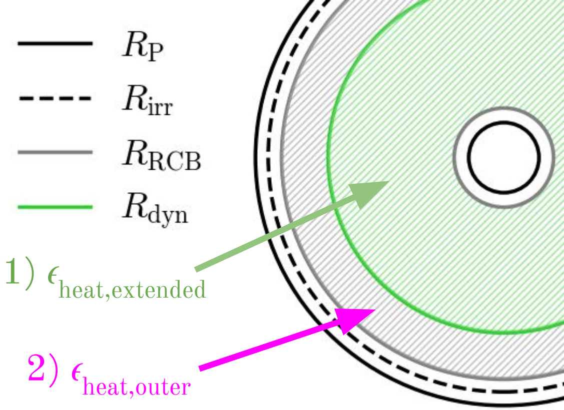
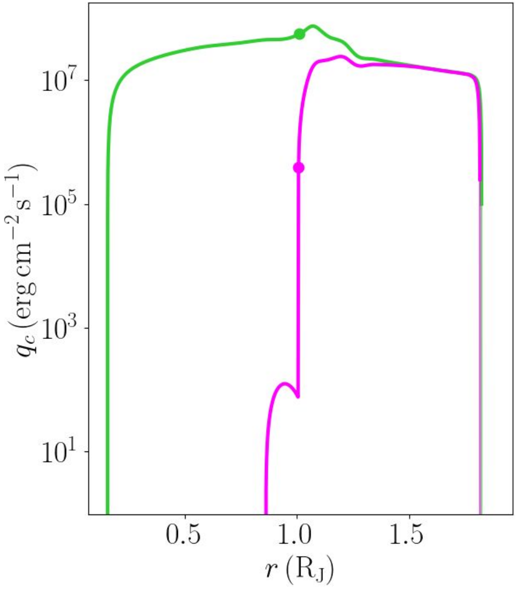
The two types of heating with maximize and minimize the integrated flux in the dynamo region.





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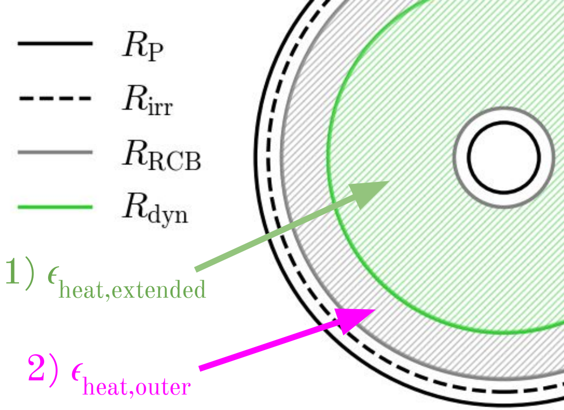
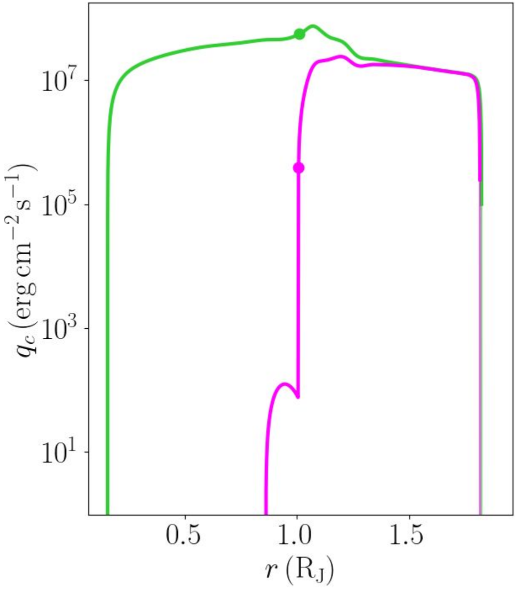
$B_{\rm rms,dyn}$	~800 G	~10 G
$B_{\rm dip,surf}$	~100 G	~2 G

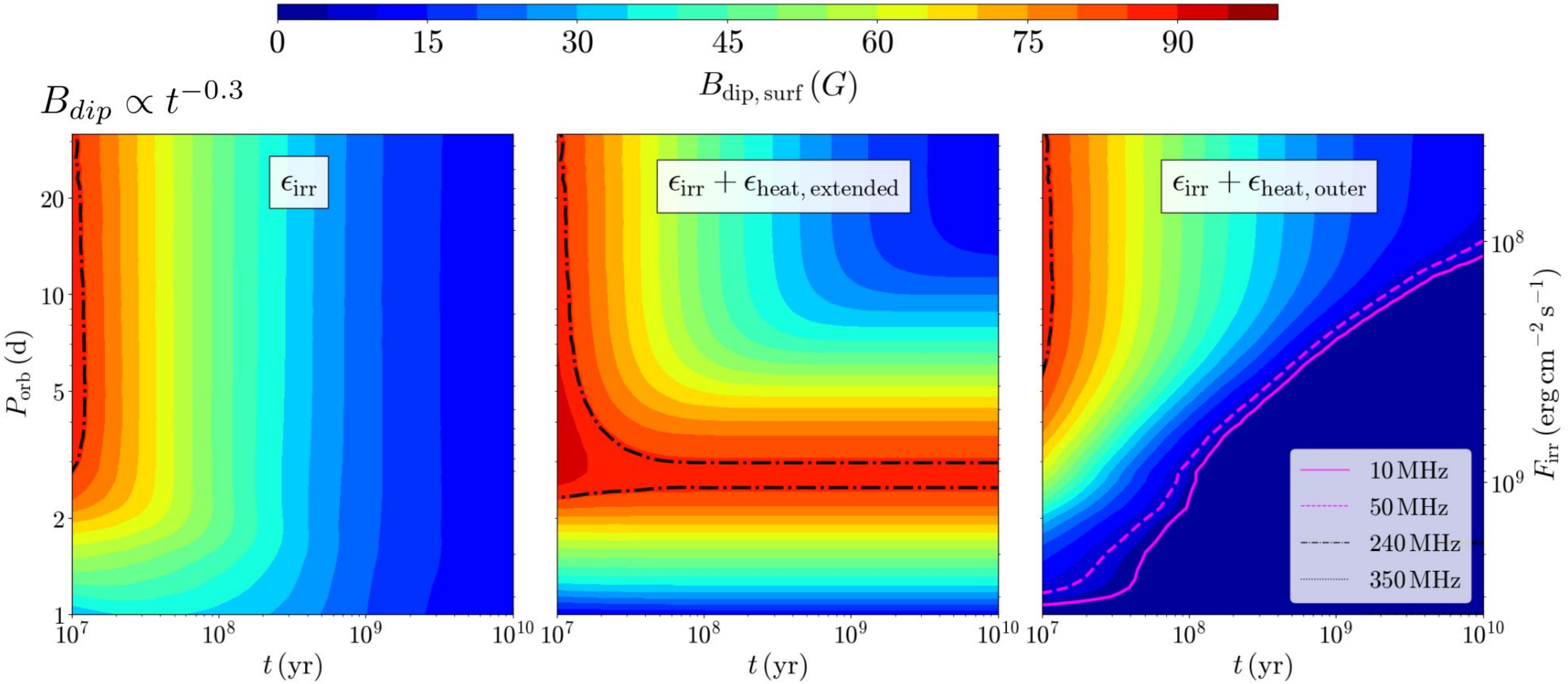
$$B_{\rm dip,surf} = \frac{1}{2\sqrt{2}}\left(\frac{R_{\rm dyn}}{R_{\rm P}}\right)^3 B_{\rm dyn}$$





Magnetic field dipole strength at the planetary surface

$B_{dip} \propto t^{-0.3}$



Conclusions

Rossby number regime, convection suppression, and dynamo-generated magnetism in inflated hot Jupiters. Elias-López, A., Cantiello, M., Viganò, D., Del Sordo, F., accepted in APJ on July 2025.

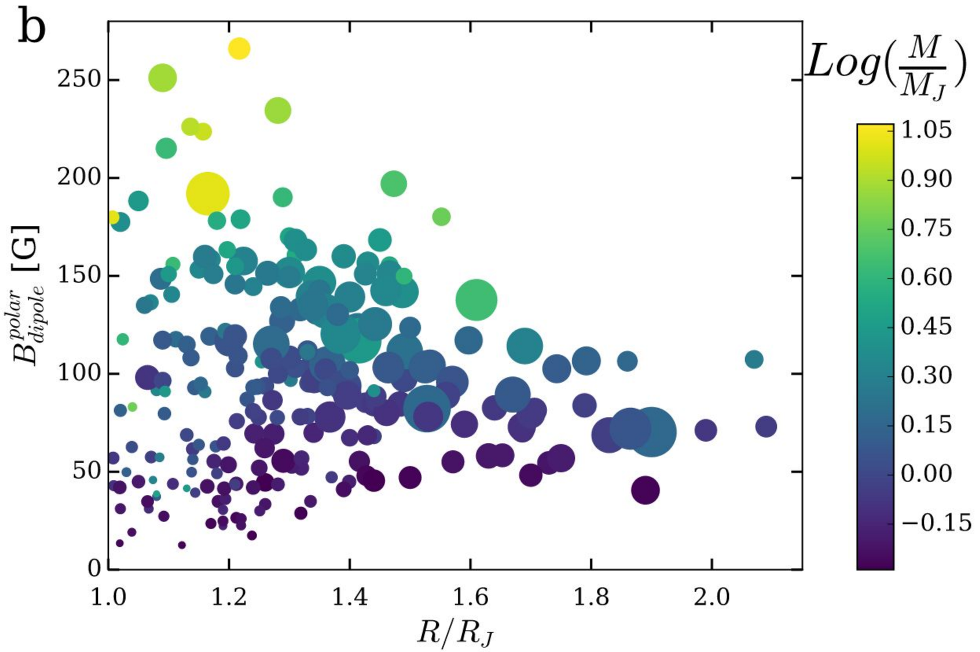
- HJs interiors are in the fast-rotator regime.
- Distant ($P > 15$ days but tidally locked) and massive planets ($M > 4\ M_J$) lie in the slow-rotator regime (only 3 candidates).
- Heating injection above the dynamo leads to a convective shut-down and lowers the magnetic-fields prediction.
- SPI and radio estimates become much smaller with outer heat injection, possibly compatible with the current lack of observations.

To do:

- Do this results change when other codes are used?
- Which other effects could vary B_{rms}? SSLs, diffuse core, chemical gradients, etc...

Individual magnetic field predictions for HJ (very optimistic)

Yadav & Thorngren 2017



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

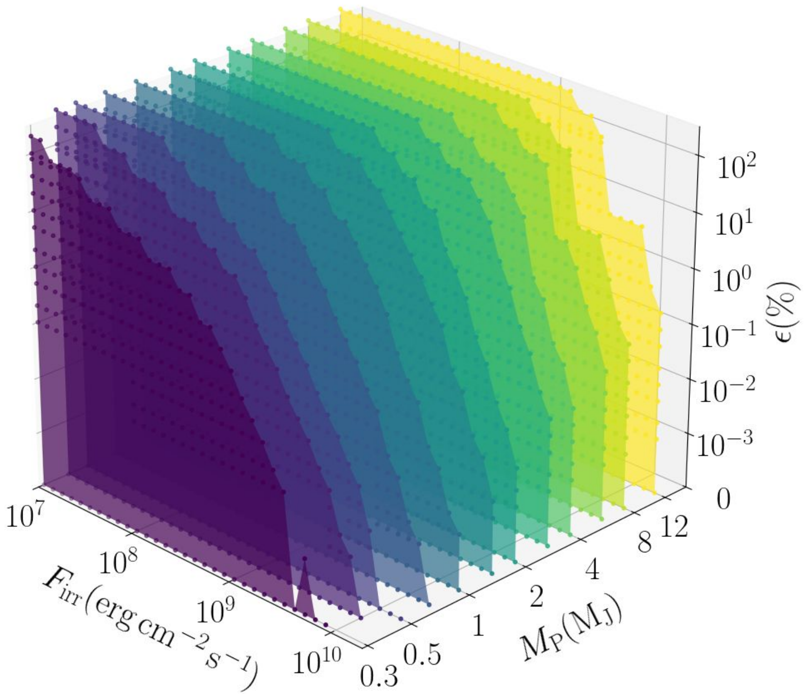
$$F^{2/3} = \frac{1}{V}\int_{r_i}^{R}\left(\frac{q_c(r)}{q_0}\frac{L(r)}{H_T(r)}\right)^{2/3}\left(\frac{\rho(r)}{\langle\rho\rangle}\right)^{1/3} 4\pi r^2\, dr$$

Reiners et al 2009

$$B_{\rm dyn} = 4.8^{+3.2}_{-2.8}\left(\frac{M}{M_\odot}\right)^{1/6}\left(\frac{L}{L_\odot}\right)^{1/3}\left(\frac{R_\odot}{R}\right)^{7/6} \text{kG}$$

$$\epsilon\pi R_P^2 F_{\rm irr}$$

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



HJ grid of models and interpolator

Elias-López et al 2026 (in prep)

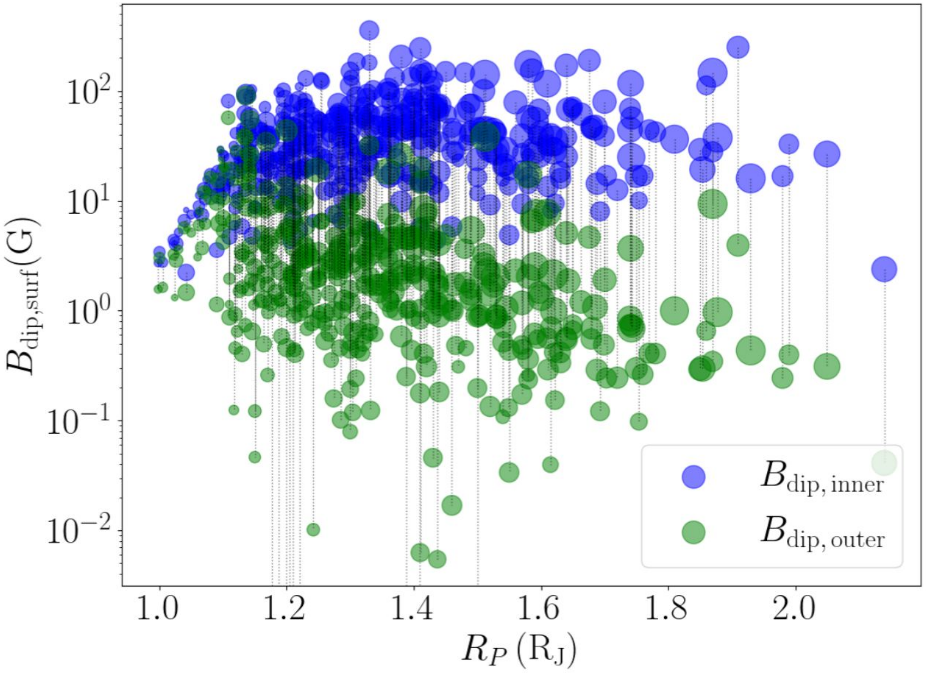
$$\text{MESA}(F_{irr}, M_P, \epsilon_{heat}) \xrightarrow{\text{Evolve}} R_P, B_{rms,dyn}, B_{surf,dip}$$

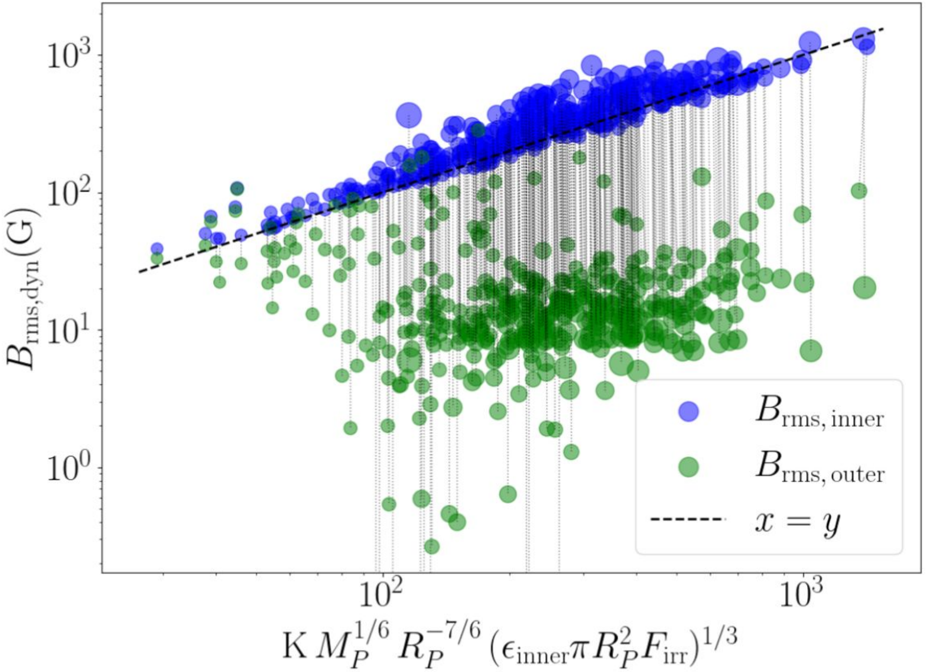
(assuming 10 M_E core and $Z_{env} = 0.02$)

$$\mathcal{I}_{\epsilon_{heat}}(F_{irr,obs}, M_{P,obs}, R_{P,obs}) \rightarrow \epsilon_{heat}$$
$$\mathcal{I}_{B_{rms,dyn}}(F_{irr,obs}, M_{P,obs}, R_{P,obs}) \rightarrow B_{rms,dyn}$$
$$\mathcal{I}_{B_{surf,dip}}(F_{irr,obs}, M_{P,obs}, R_{P,obs}) \rightarrow B_{surf,dip}$$

Planet	M (M_J)	R (R_J)	F_{irr} (erg cm^{-2} s^{-1})	ϵ (%)	$B_{dip,inner}$	$B_{dip,outer}$	$B_{dip,irr}$
KELT-12 b	0.950	1.780	$2.381\cdot10^9$	0.95%	727 G	7.04 G	72.7 G
TOI-3807 b	1.040	1.650	$1.661\cdot10^9$	2.54%	860 G	8.29 G	72.4 G
WASP-190 b	1.000	1.150	$1.199\cdot10^9$	0.010%	122 G	14.1 G	68.5 G

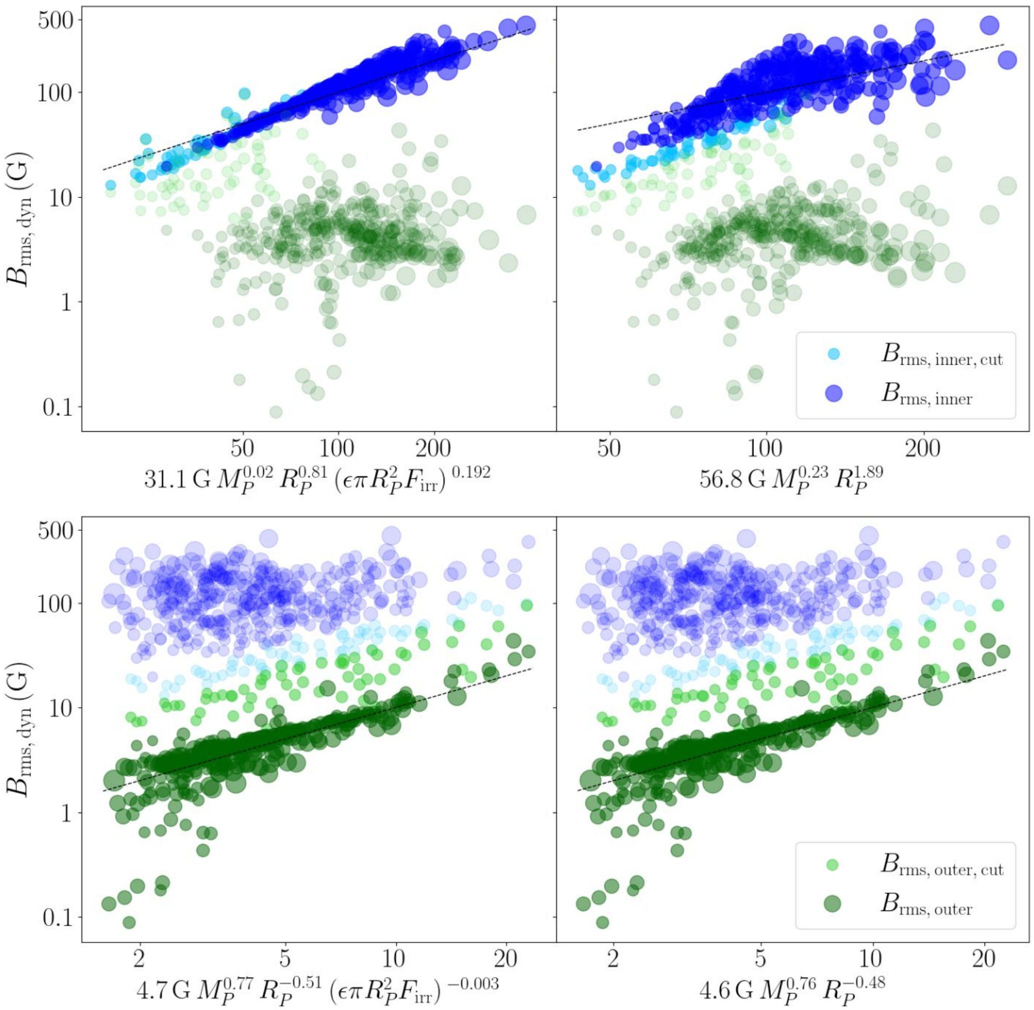
HJ magnetic field predictions





Both populations give vastly distinct estimates (100 times less typically).

The optimistic model agrees with previous scaling laws.



Inflated HJ magnetic scaling laws

We are trying to derive simple scaling laws that can give optimistic and pesimistic estimates to observers.

Future observation will tell which model is closer to reality.

We are also exploring the B dependance on other variables: Z, EoS, α_{MLT}, etc.

Conclusions

Rossby number regime, convection suppression, and dynamo-generated magnetism in inflated hot Jupiters. Elias-López, A., Cantiello, M., Viganò, D., Del Sordo, F., accepted in APJ on July 2025.

Revised Hot Jupiter magnetic field predictions. Elias-López, A., Vidotto, M., Viganò, D, (in prep.)

- HJs interiors are in the fast-rotator regime.
- Distant ($P > 15$ days but tidally locked) and massive planets ($M > 4\ M_J$) lie in the slow-rotator regime (only 3 candidates).
- Heating injection above the dynamo leads to a convective shut-down and lowers the magnetic-fields prediction.
- SPI and radio estimates become much smaller with outer heat injection, possibly compatible with the current lack of observations.
- With individual HJ magnetic field predictions, future ECMI/SPI detections can help constrain their interiors.

To do:

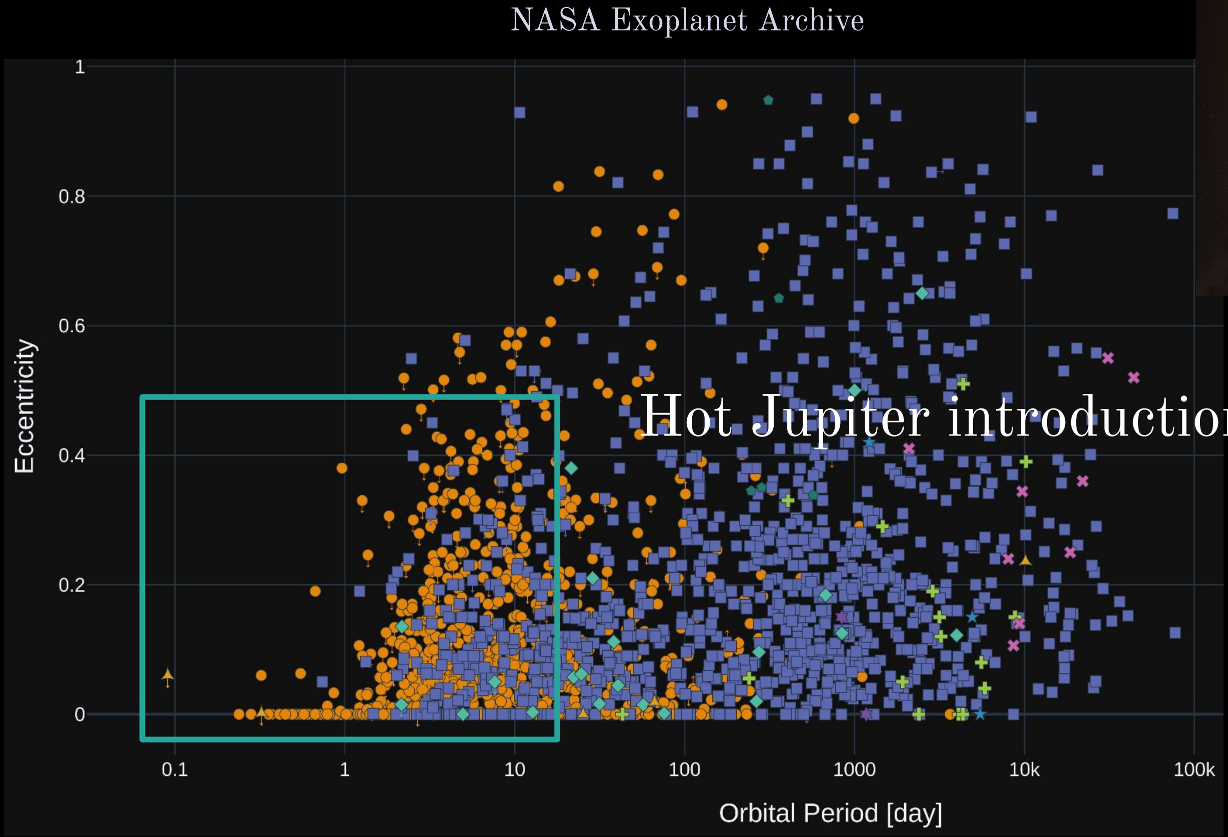
- Do this results change when other codes are used?
- Which other effects could vary B_{rms}? SSLs, diffuse core, chemical gradients, etc...

Summary

1. Hot Jupiter introduction
2. Evolutionary MESA models
3. Results: Rossby number and magnetic field predictions
4. Magnetic field predictions and observational consequences
5. Conclusions

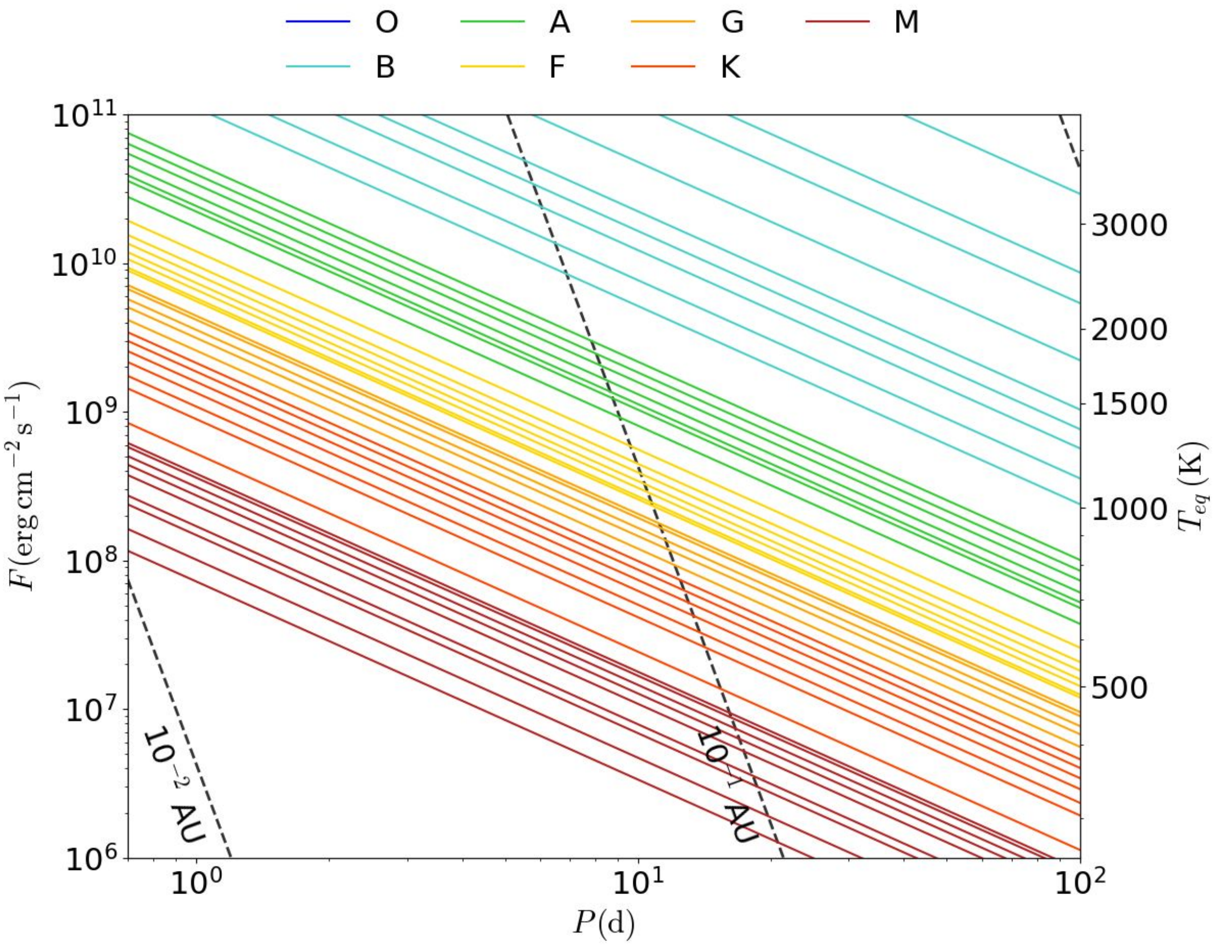
Extra slides

Hot Jupiter introduction



- Gas giants ($M_P < 13\ M_J$)
- Highly irradiated
- Tidally locked and low eccentricity (by circularization)

Gas giant stellar fluxes



Flux for each type of star as a function of orbital period:

$$L_{\star,SB} = 4\pi\sigma R_\star^2 T_\star^4$$

$$F_\star = \frac{L_\star}{4\pi d^2}$$

Equilibrium temperature is related to the flux arriving at the planetary surface and its albedo:

$$T_{eq} = \left(\frac{L_\star(1 - A_B)}{16\pi\sigma d^2}\right)^{1/4} =$$

$$= (1 - A_B)^{1/4}\left(\frac{R_\star}{2d}\right)^{1/2} T_\star$$

Hot Jupiter occurrence rate (Gan et al 2022)

Table 3
Summary of Occurrence Rates of Hot Jupiters from Other Works

Work	f_{occ}(%)	Stellar Type	Method	Definition of Hot Jupiters
Endl et al. (2006)	<1.27	M	RV	$M_p \sin i \sim 1\ M_J$, a < 1 au
Gould et al. (2006)	$0.31^{+0.43}_{-0.18}$	FGKM	Transit	$1 \leqslant R_p \leqslant 1.25\ R_J$, $3 \leqslant P_b \leqslant 5$ days
Cumming et al. (2008)	1.5 ± 0.6	FGK	RV	$M_p \sin i > 0.3\ M_J$, $P_b < 11.5$ days
Mayor et al. (2011)	0.89 ± 0.36	FGKM	RV	$M_p \sin i > 50\ M_\oplus$, $P_b < 11$ days
Wright et al. (2012)	1.20 ± 0.38	FGK	RV	$M_p \sin i > 0.1\ M_J$, $P_b < 10$ days
Howard et al. (2012)	0.4 ± 0.1	GK	Transit	$8 \leqslant R_p \leqslant 32\ R_\oplus$, $P_b < 10$ days
Fressin et al. (2013)	0.43 ± 0.05	FGKM	Transit	$6 \leqslant R_p \leqslant 22\ R_\oplus$, $0.8 \leqslant P_b \leqslant 10$ days
Kovács et al. (2013)	<1.7%–2.0	M	Transit	$R_p \sim 1.0\ R_J$, $0.8 \leqslant P_b \leqslant 10$ days
Masuda & Winn (2017)	$0.43^{+0.07}_{-0.06}$	FGK	Transit	$0.8 \leqslant R_p \leqslant 2\ R_J$, $P_b < 10$ days
Petigura et al. (2018)	$0.57^{+0.14}_{-0.12}$	FGK	Transit	$8 \leqslant R_p \leqslant 24\ R_\oplus$, $1 \leqslant P_b \leqslant 10$ days
Zhou et al. (2019) [a]	0.26 ± 0.11	A	Transit	$0.8 \leqslant R_p \leqslant 2.5\ R_J$, $0.9 \leqslant P_b \leqslant 10$ days
Zhou et al. (2019)	0.43 ± 0.15	F	Transit	$0.8 \leqslant R_p \leqslant 2.5\ R_J$, $0.9 \leqslant P_b \leqslant 10$ days
Zhou et al. (2019)	0.71 ± 0.31	G	Transit	$0.8 \leqslant R_p \leqslant 2.5\ R_J$, $0.9 \leqslant P_b \leqslant 10$ days
Wittenmyer et al. (2020)	$0.84^{+0.70}_{-0.20}$	FGK	RV	$M_p \sin i > 0.3\ M_J$, $1 \leqslant P_b \leqslant 10$ days
Sabotta et al. (2021)	<3	M	RV	$100 < M_p < 1000\ M_\oplus$, $P_b < 10$ days
Zhu (2022)	2.8 ± 0.8	FGK	RV	$M_p \sin i > 0.3\ M_J$, $a \leqslant 0.1$ au
Beleznay & Kunimoto (2022) [b]	0.29 ± 0.05	A	Transit	$0.8 \leqslant R_p \leqslant 2.5\ R_J$, $0.9 \leqslant P_b \leqslant 10$ days
Beleznay & Kunimoto (2022)	0.36 ± 0.06	F	Transit	$0.8 \leqslant R_p \leqslant 2.5\ R_J$, $0.9 \leqslant P_b \leqslant 10$ days
Beleznay & Kunimoto (2022)	0.55 ± 0.14	G	Transit	$0.8 \leqslant R_p \leqslant 2.5\ R_J$, $0.9 \leqslant P_b \leqslant 10$ days
This work	0.27 ± 0.09	M	Transit	$7\ R_\oplus \leqslant R_p \leqslant 2\ R_J$, $0.8 \leqslant P_b \leqslant 10$ days

The rate is very uncertain with significant differences between works. Note different methods and different definitions of HJ.

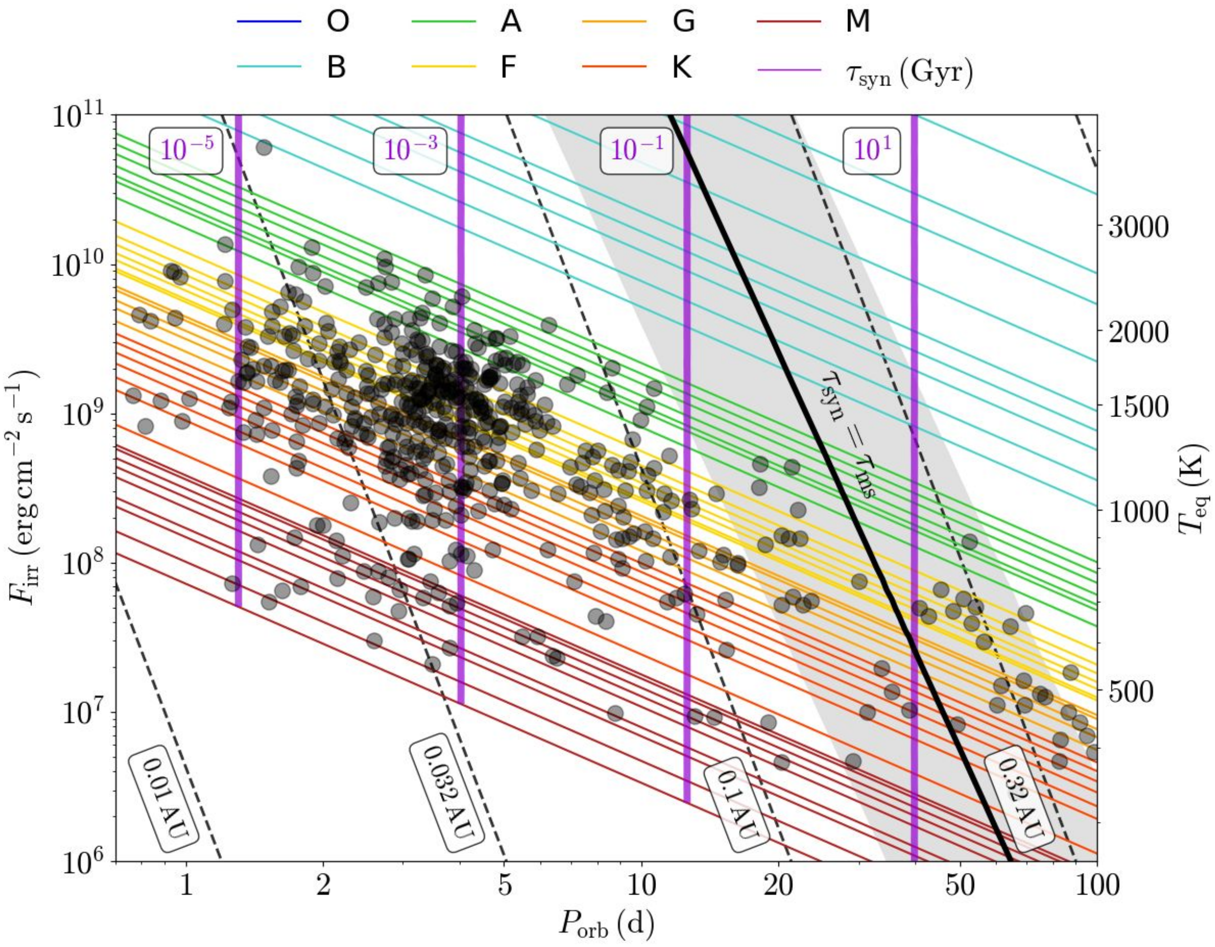
M stars seem to have less HJs.

F G K have the highest rate with a peak at G stars

A stars have a lower rate

No rate at higher mass stars

Synchronization timescales



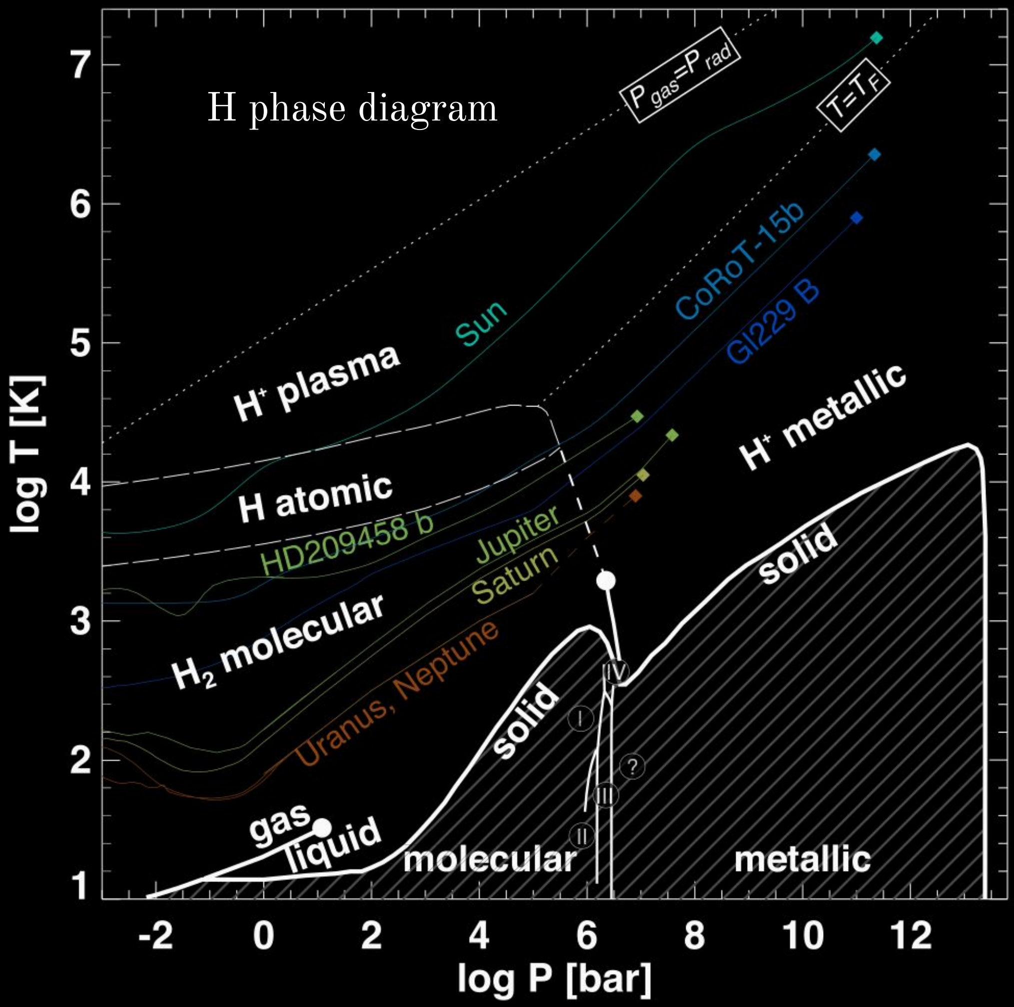
From Goldreich & Soter 1996 and Hubbard 1984 we can get values for the tidal locking timescales:

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

$$= \frac{G\alpha}{36\pi^4}\frac{M_P Q'_P P^4}{R_P^3}\Delta\omega$$

where $\alpha = \frac{I}{M_P R_P^2}$, $Q'_P = \frac{3Q_P}{2k_{2,P}}$.

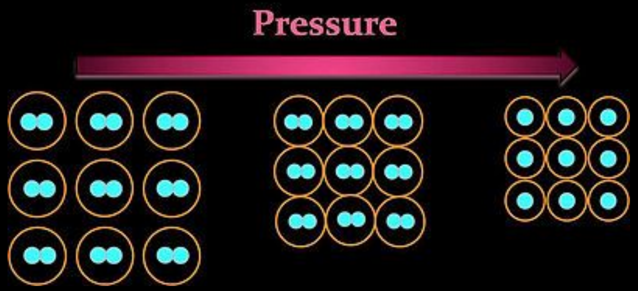
(assuming circular orbits, zero obliquity, no migration and no evaporation)



Metallic hydrogen

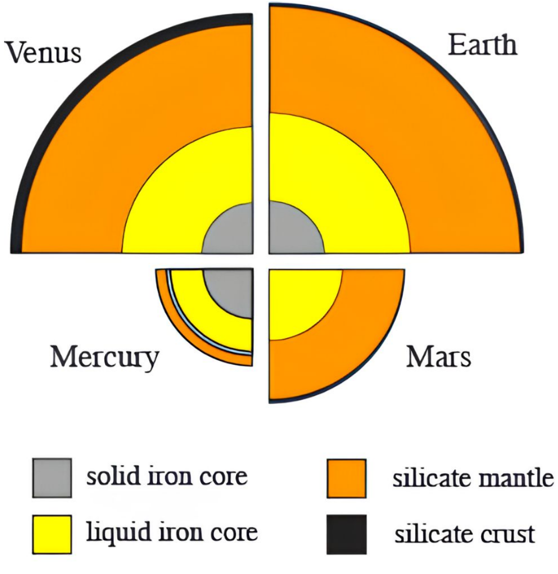
Phase hydrogen in which it behaves like an electrical conductor. Theoretical prediction by Wigner and Huntington in 1935, now is reproduced in the lab.

Metallic hydrogen starts at around 1 Mbar (or 100 GPa)

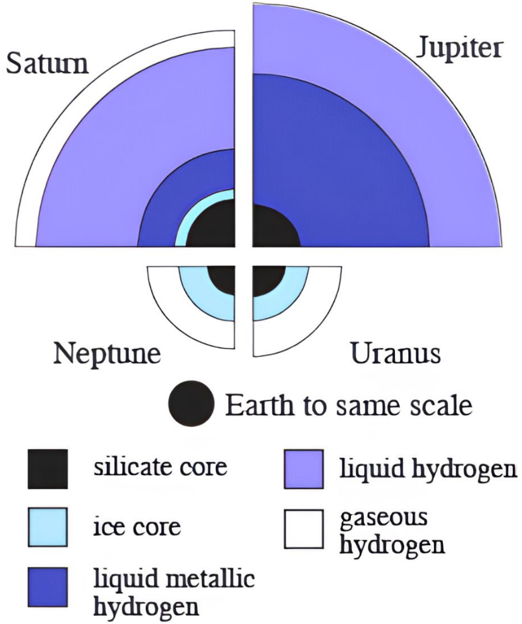


Guillot & Gautier, 2015

Conductive layers of planets



Terrestrial planet interiors to same scale



Jovian planets interiors to same scale

Planetary magnetic fields are dynamo generated:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \longrightarrow$$

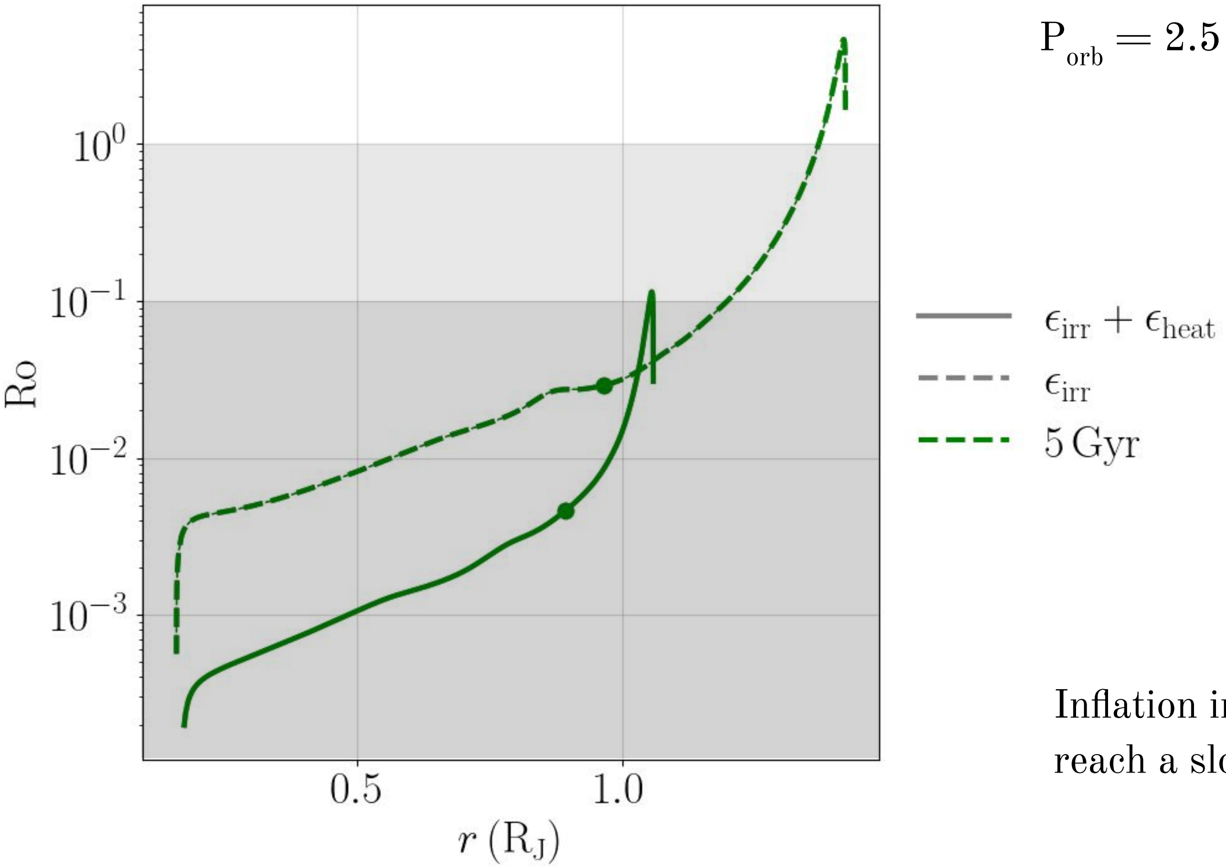
$$\longrightarrow \frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} \longrightarrow \tau_d = \frac{L^2}{\eta}$$

Diffusive limit of the induction equation

- Earth: 10^4-10^5 yr
- Jupiter: 10^5-10^6 yr

Their interiors must have regions with are both **conductive** and **convective**. The nature of the convective region is different between planets: **molten metal**, **salty oceans** or **metallic hydrogen.**

Rossby number as a function of planetary depth



$P_{orb} = 2.5$ days, $F_{irr} = 10^9$ erg cm^{-2} s^{-1}

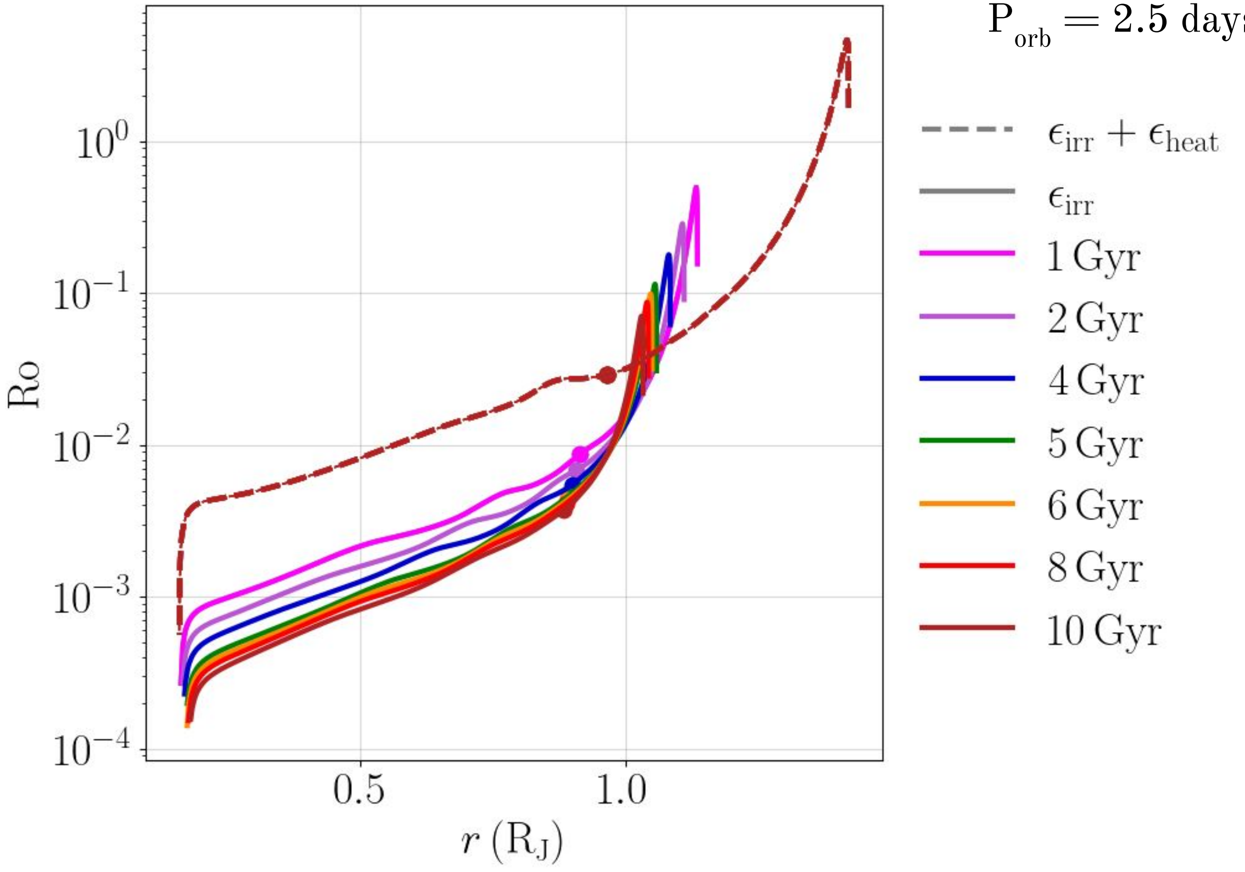
$$\mathrm{Ro}(r) = \frac{\tau_{rot} v_{conv}(r)}{H_\rho(r)}$$

- Ro<1: Coriolis forces dominate over convective forces
- Slow rotator regime (Ro<0.1)
- Fast rotator regime (Ro<0.1)

Inflation increases Ro, but not enough to reach a slow rotator regime (1 M_J planet).

Rossby number evolution

$P_{orb} = 2.5$ days, $F_{irr} = 10^9$ erg cm^{-2} s^{-1}

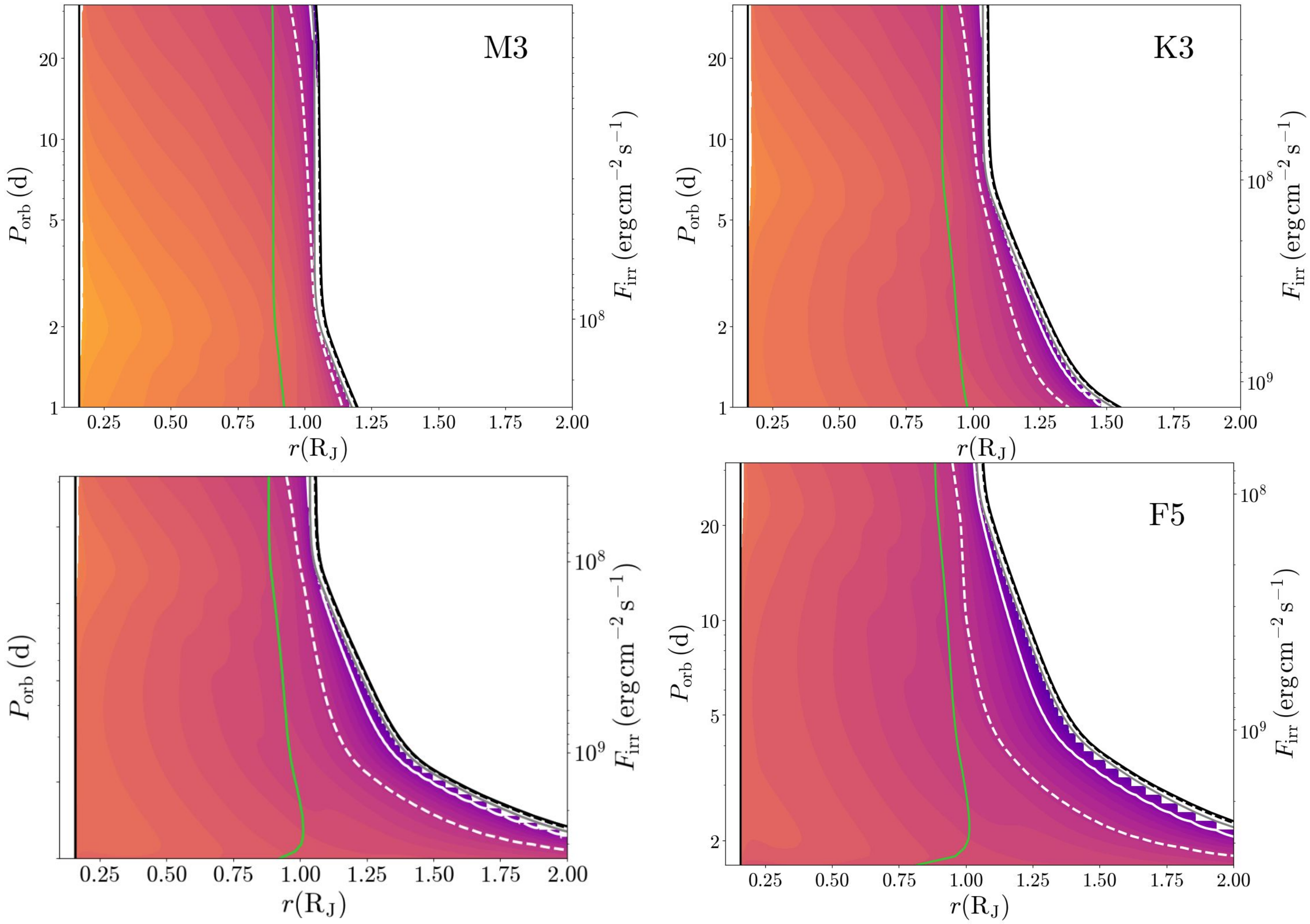


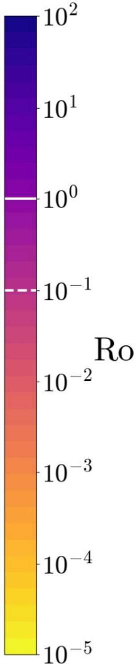
$$\mathrm{Ro}(r) = \frac{\tau_{rot} v_{conv}(r)}{H_\rho(r)}$$

Ro<1: Coriolis forces dominate over convective forces

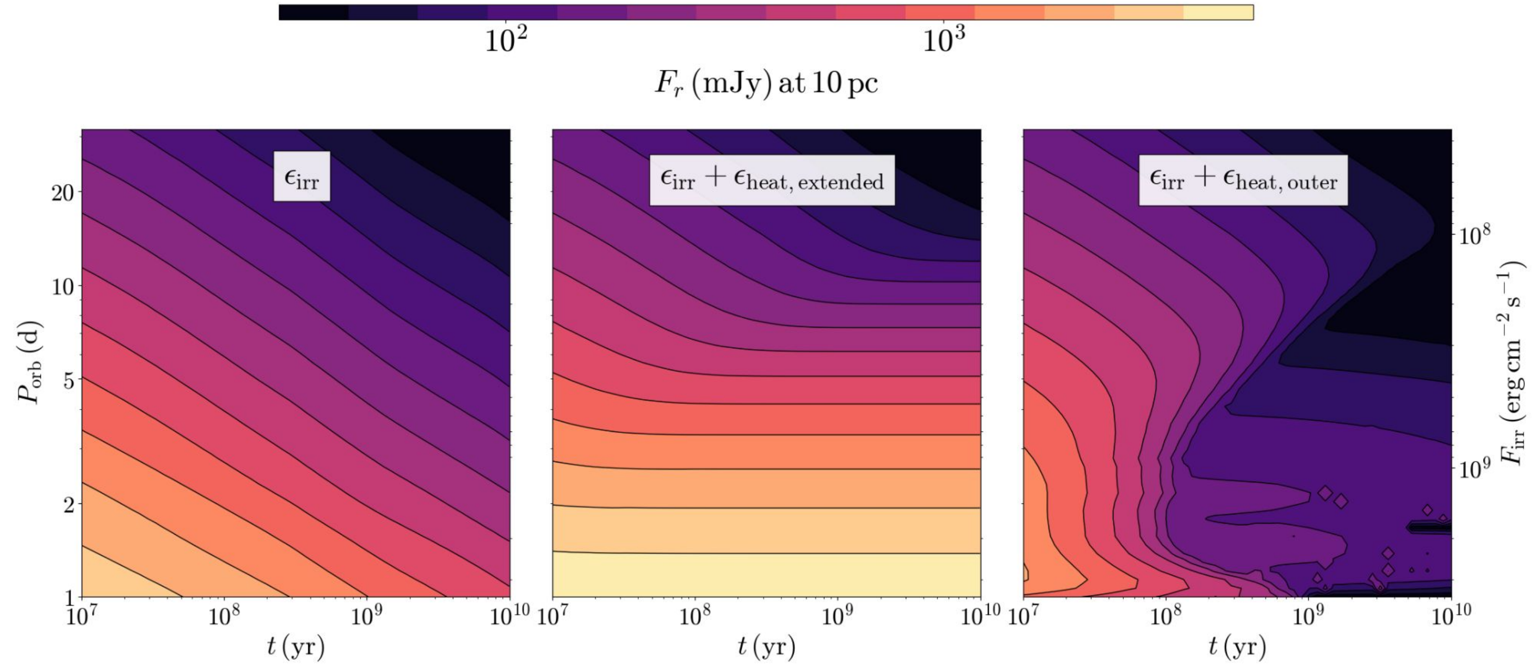
Inflation increases Ro, but not enough to reach a slow rotator regime (1 M_J planet).

Rossby number dependence stellar type





Observational consequences: ECM radio emission, from planet (Stevens 2005)



$$P_r \propto \dot{M}_\star^{2/3} M_{dip}^{2/3} a^{-4/3} V_W^{5/3}$$

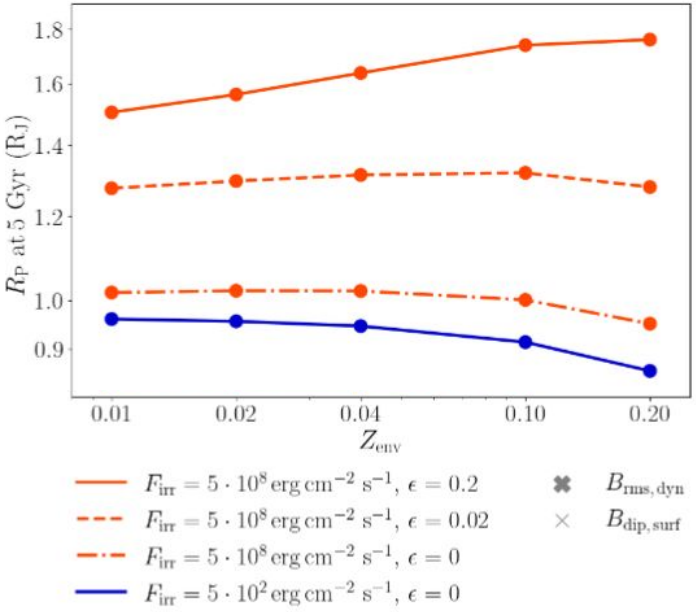
Bode's law

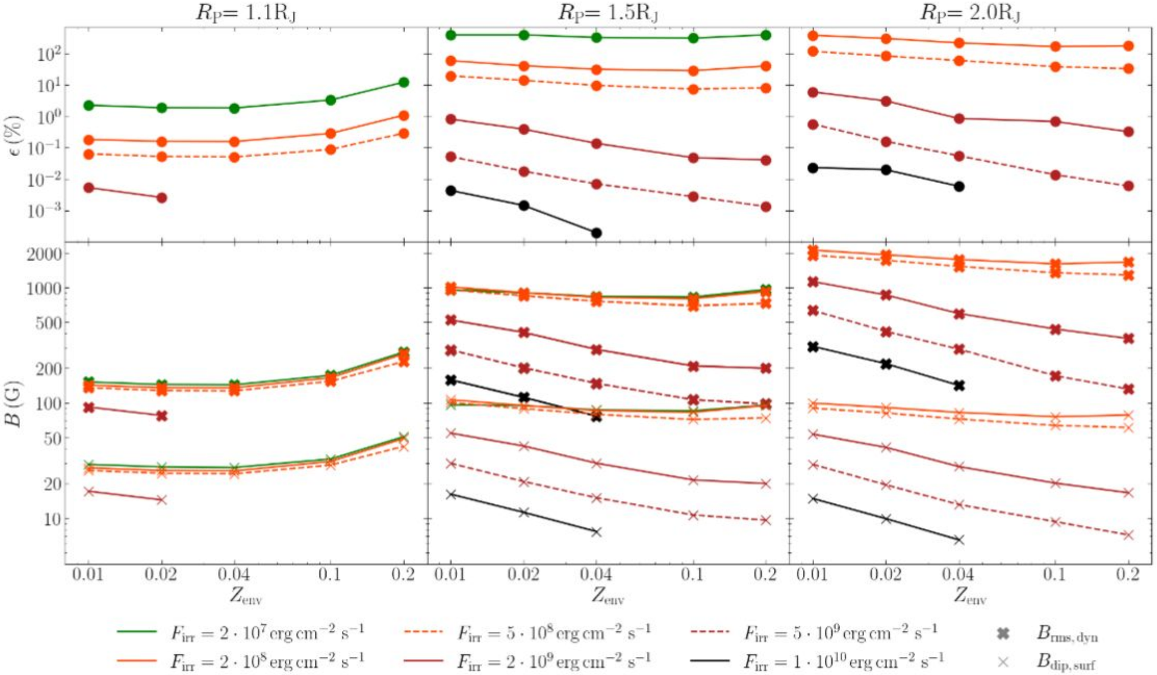
$$P_r = 2.35 \cdot 10^{-2}\,\mathrm{mJy} \cdot \left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{2/3} \cdot \left(\frac{M_{dip}}{M_{dip,J}}\right)^{2/3} \cdot \left(\frac{a}{5\,\mathrm{AU}}\right)^{-4/3} \cdot \left(\frac{V_W}{400\,\mathrm{km\,s^{-1}}}\right)^{5/3} \cdot \left(\frac{d}{10\,\mathrm{pc}}\right)^{-2}$$

This models are very optimistic and do not account for time variability and beaming.

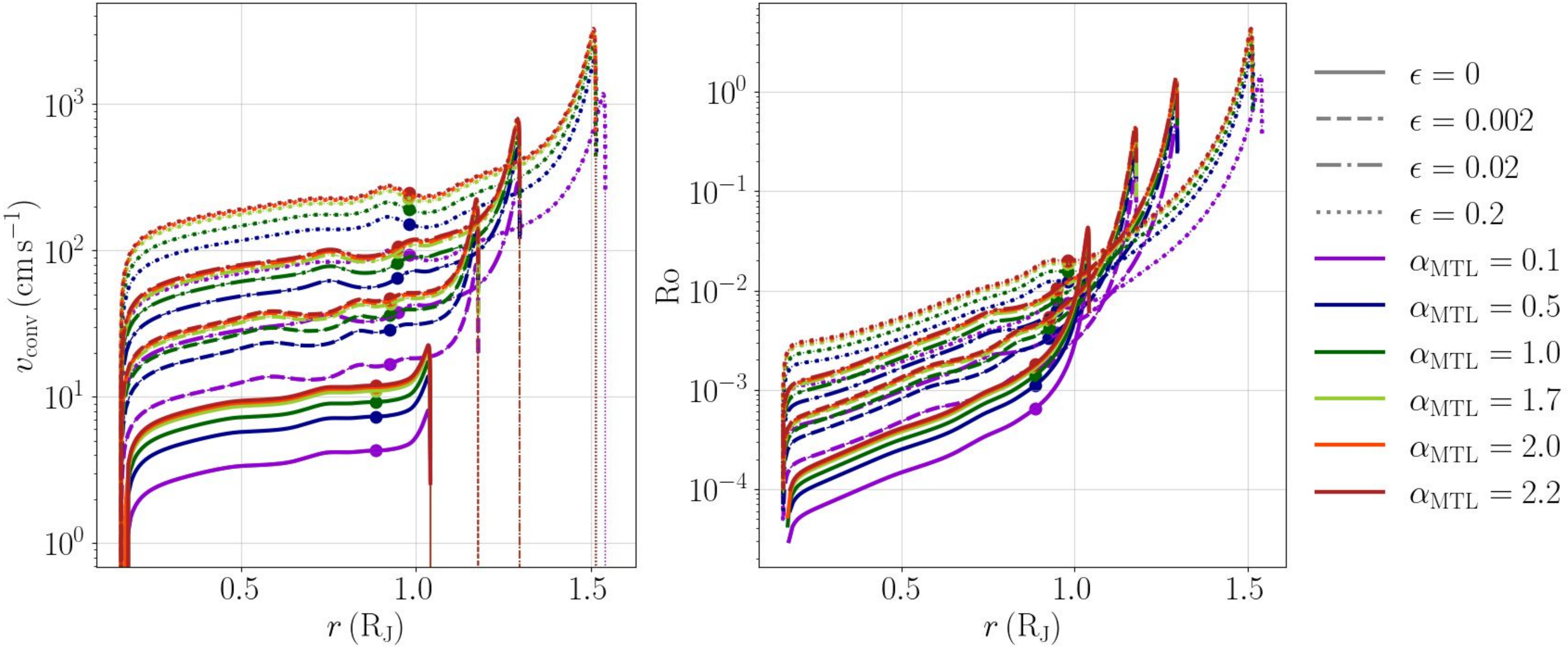
Dependance on metalliciy

There is a complex Z, ϵ degeneracy: for planets with high ϵ, increasing Z increases radius.

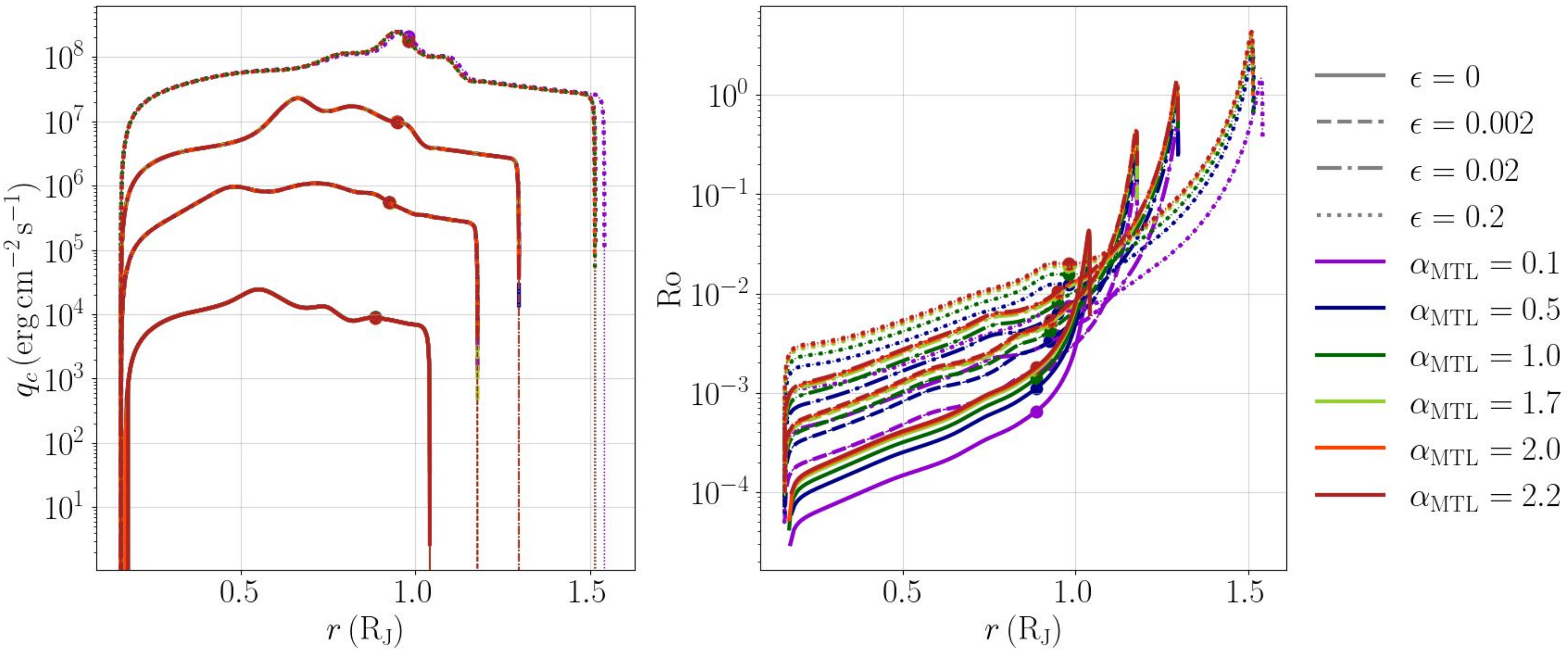




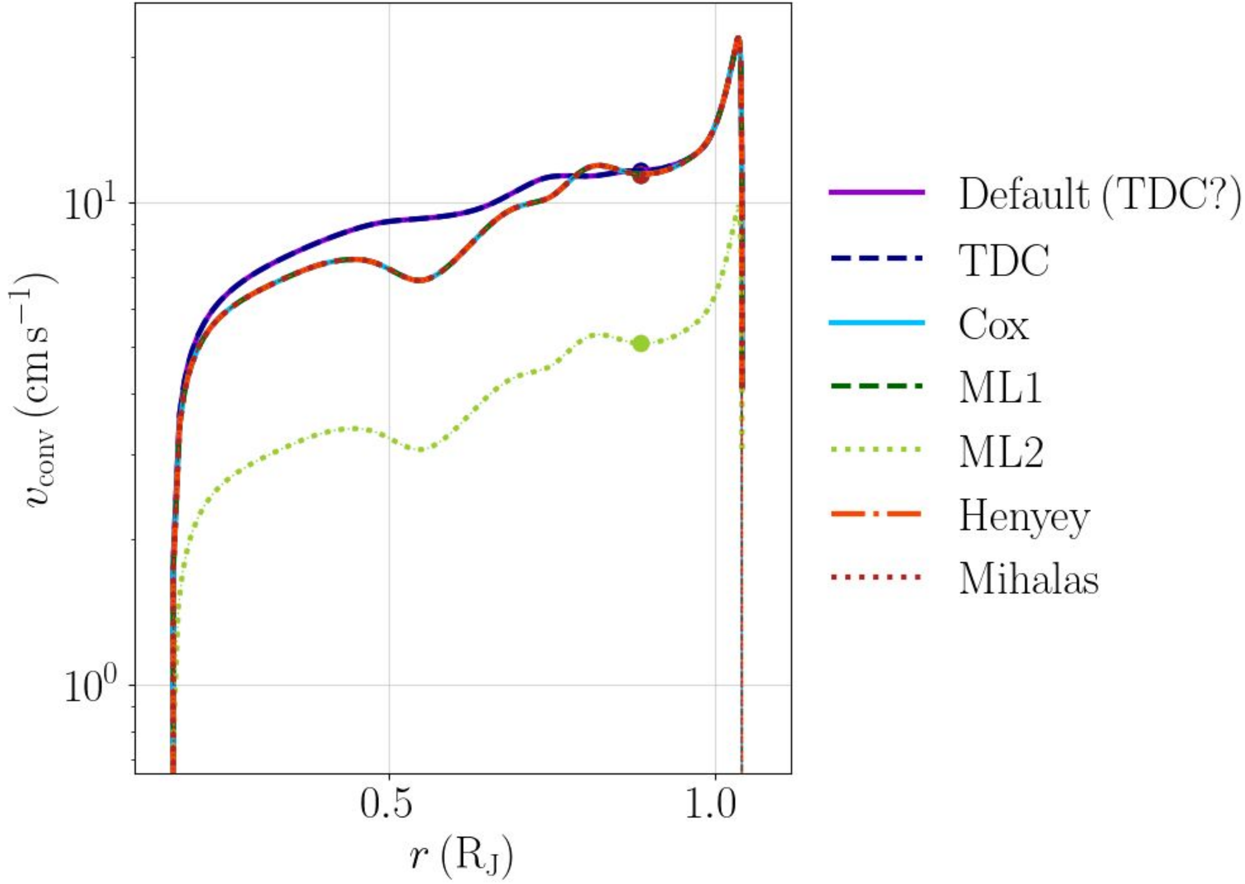
Dependance on α_{MLT}



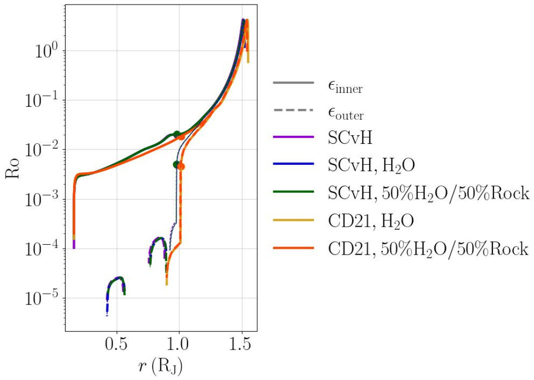
Dependance on α_{MLT}



Dependance on α_{MLT}



Are there really this is similar? Maybe MESA variables are not working or these MLT schemes are no longer working (outdated maybe?)



Dependance on EoS