On the shoulders of giants, Torino

Long-term evolution of giant planets magnetism

Daniele Viganò & Albert Elias-López (Leiden Univ.)

25 March 2026

A&A, 696, A161 (2025)

Planetary dynamos in evolving cold gas giants

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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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A&A, 701, A8 (2025)

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

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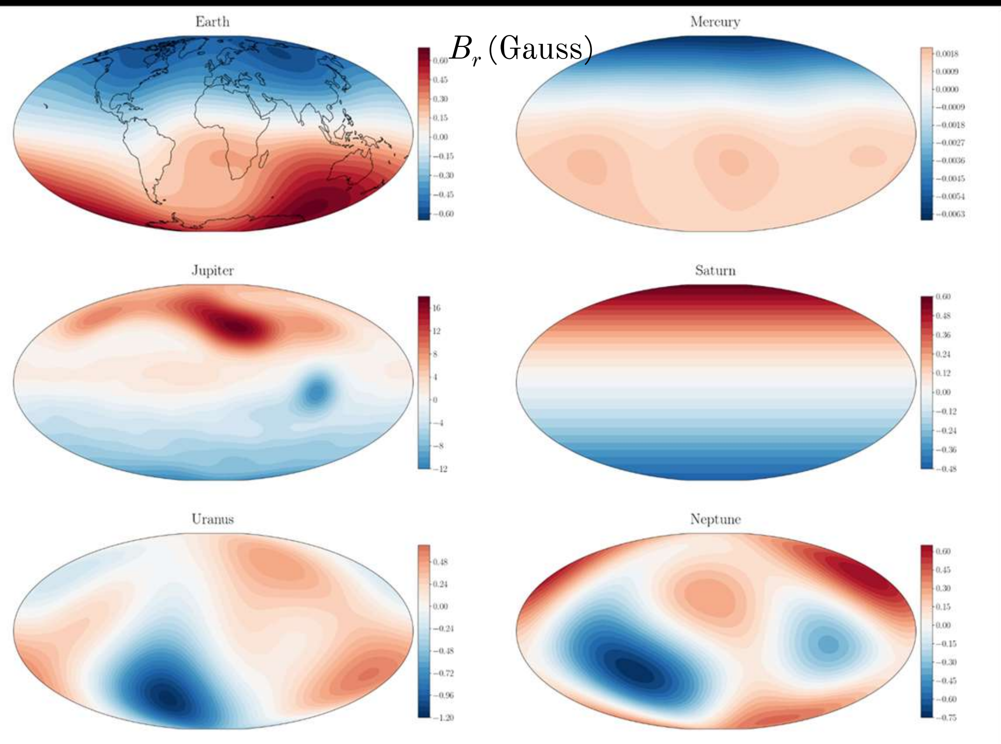
Magnetic fields in the solar system



Earth	Yes
Moon	Past
Jupiter	Yes
Saturn	Yes
Uranus	Yes
Neptune	Yes
Venus	No?
Mars	Past
Mercury	Yes
Ganymede	Yes
Other moons	No?
Exoplanets	???

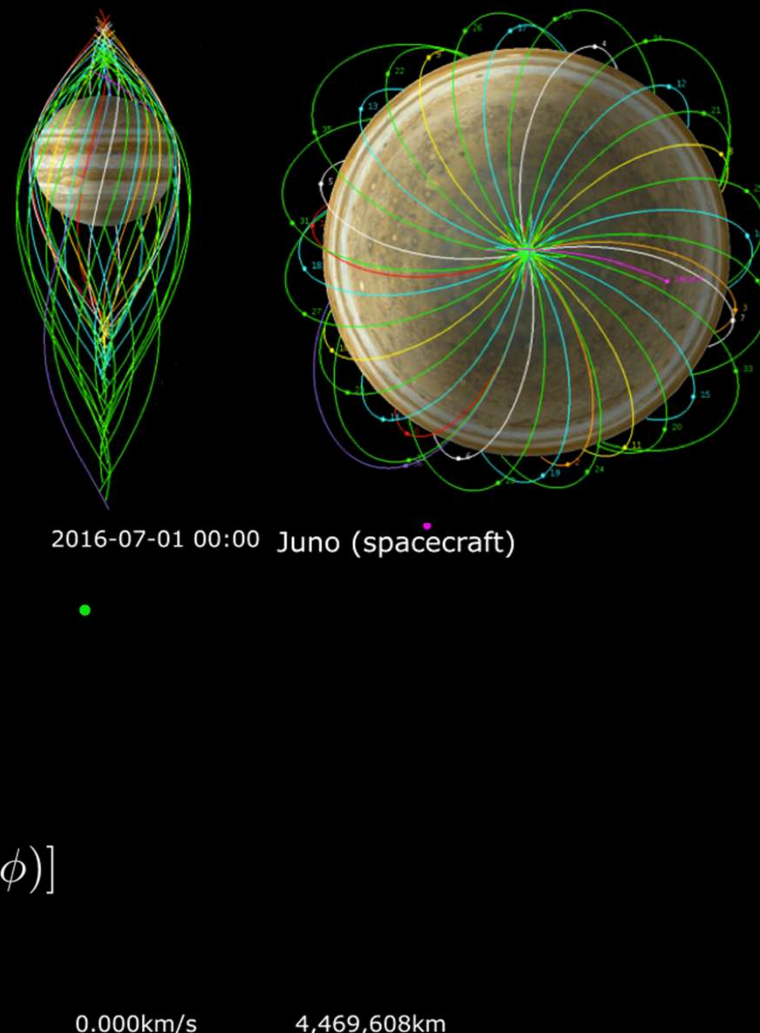
1. Magnetic fields in planets arise from rapid rotation and thermal convection, which is related to formation, accretion and differentiation.

2. Planetary magnetism is known only for Solar planets, so that validation of scaling laws (e.g., with mass) is still pending. Radio emission searches ongoing

Measurement characteristics

Measurements within 7 R_J, 64 samples/s, magnetic field between $1\cdot10^3$-$4\cdot10^6$ nT

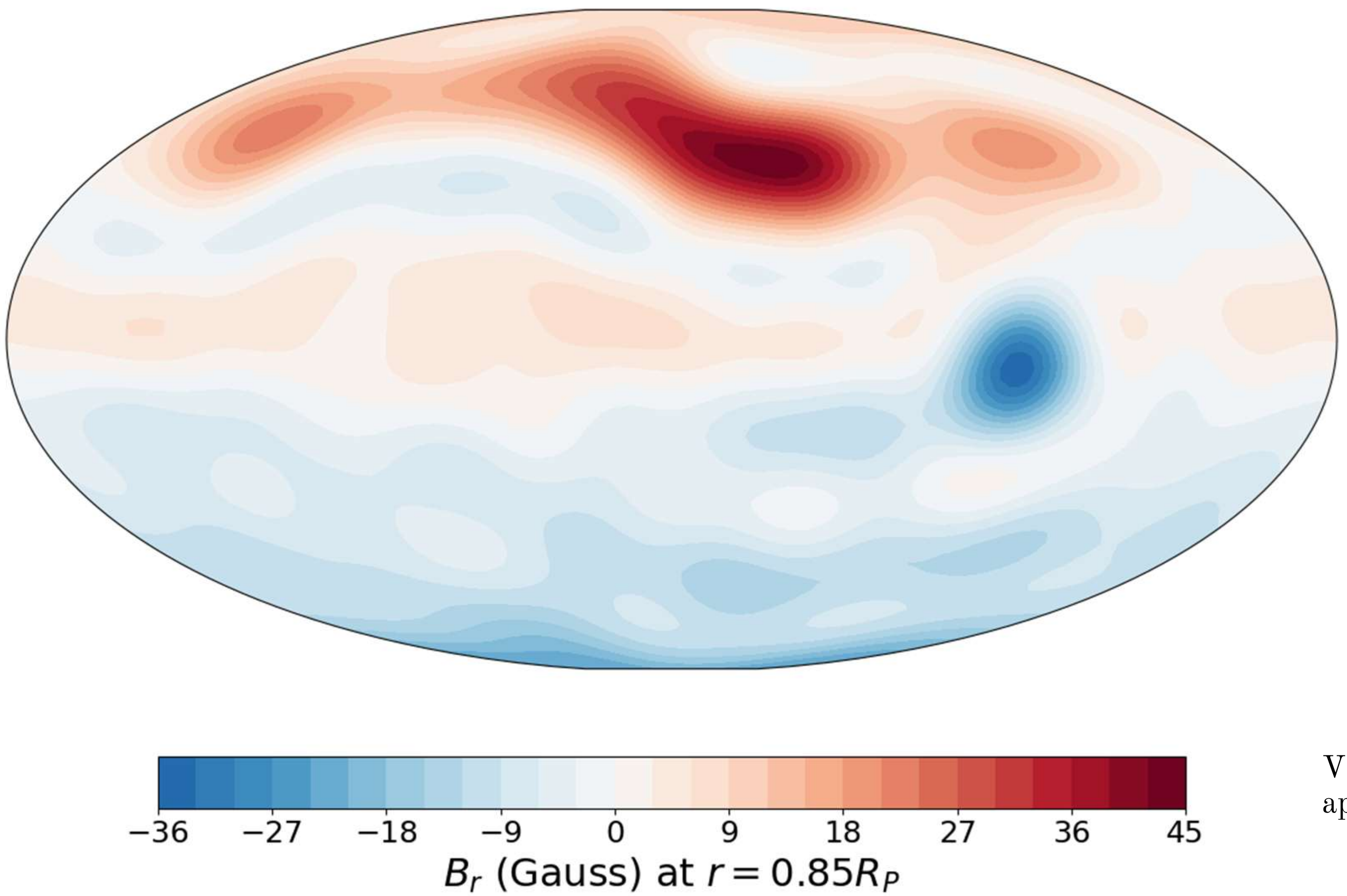
Obtain the set of g's and h's that define a scalar magnetic potential (only in current-free areas!!!).



$$\boldsymbol{B} = -\nabla V$$

$$V = a \sum_{n=1}^{n_{max}} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^{n} P_n^m(cos\theta)\left[g_n^m cos(m\phi) + h_n^m sin(m\phi)\right]$$

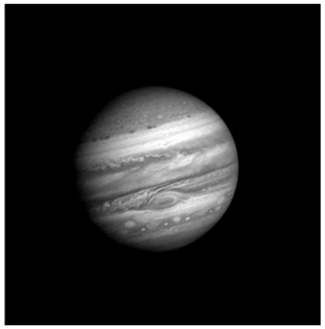
Jupiter magnetic field



At the planetary surface |B| ~ 12 G (Earth is ~ 0.5G), at the the dynamo surface |B| ~ 30 - 40 G

Mostly dipolar but shows an equatorial pole (not connected with the atmospheric Great Red Spot).

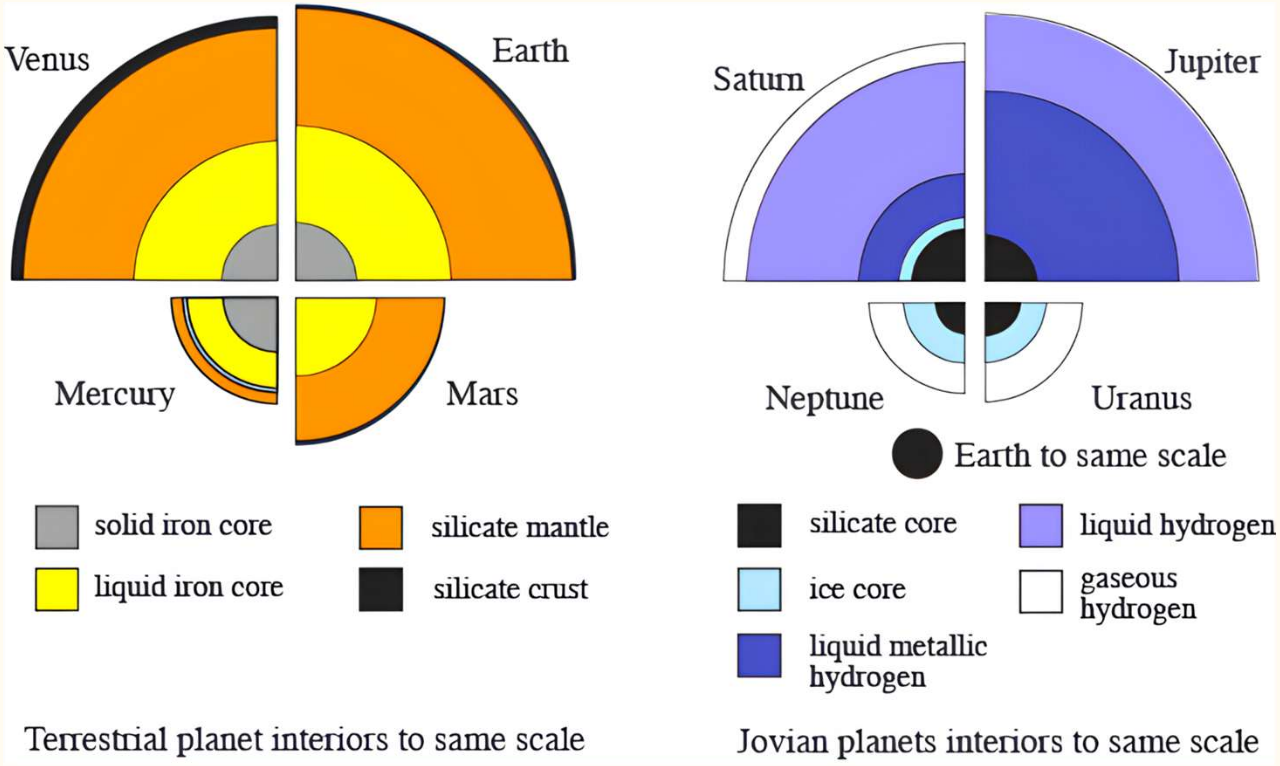
Voyager 1 approach



Planetary missions

Mercury	MESSENGER mission	Toepfer et al. EPS 2021, Toepfer et al. Ann. Geo 2022
Earth	IGRF	New model every 5 years
Jupiter	Juno mission	Connerney et al. GRL 2018, Connerney et al. GRL 2021
Ganymede	Juno and Galileo spacecrafts	Weber et al. GRL 2022
Saturn	Cassini mission	Cao et al. 2023
Uranus	Voyager 2	Ness et al. 1989
Neptune	Voyager 2	Connerney et al. 1987

Conductive layers of planets



Planetary magnetic fields must be dynamo generated, as they would have decayed by magnetic diffusion:

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

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

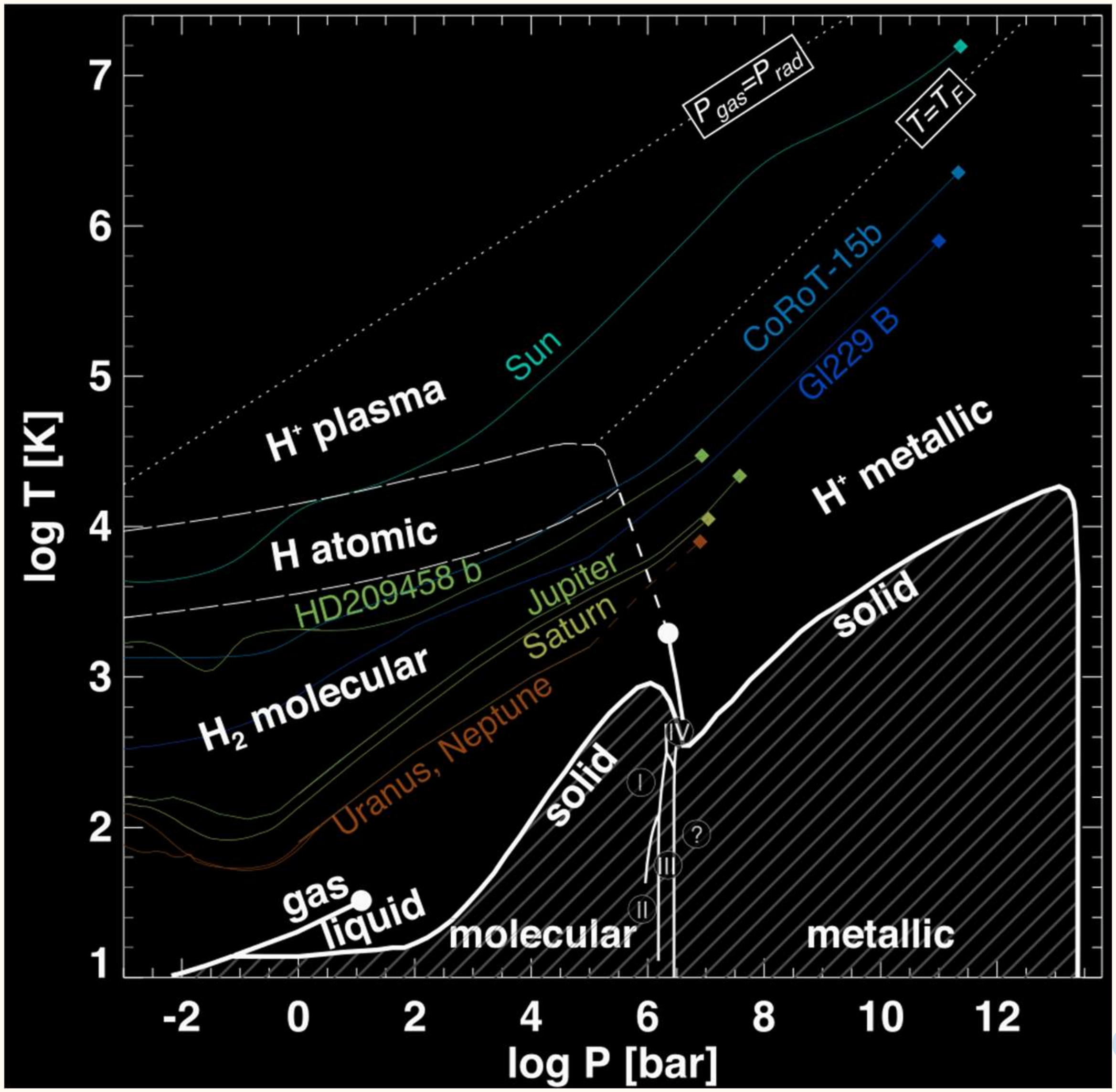
Diffusive timescales:

- 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.**

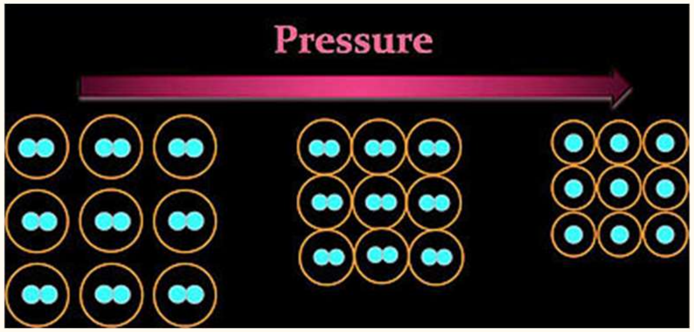
Hydrogen phase diagram

Dense hydrogen where molecules dissociate and share electrons. Theoretical prediction by Wigner and Huntington in 1935, now is reproduced in the lab.



Guillot & Gautier, 2015

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



Non-dimensionalized 3D MHD in a spherical shell

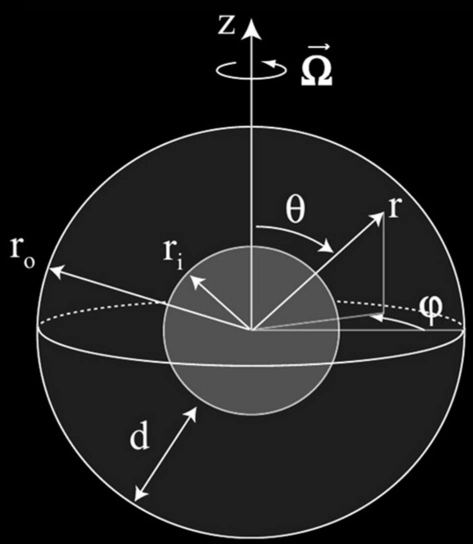
$$\nabla \cdot (\tilde{\rho}\mathbf{u}) = 0, \quad \text{Continuity equation}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\nabla\left(\frac{p'}{\tilde{\rho}}\right) - \frac{2}{E}\mathbf{e_z}\times\mathbf{u} - \frac{Ra}{Pr}\tilde{g}\tilde{\alpha}\tilde{T}\,s'\,\mathbf{e_r} + \frac{1}{Pm_i\,E\,\tilde{\rho}}(\nabla\times\mathbf{B})\times\mathbf{B} + \frac{1}{\tilde{\rho}}\nabla\cdot\mathbf{S}, \quad \text{Momentum equation}$$

$$\tilde{\rho}\tilde{T}\left(\frac{\partial s'}{\partial t} + \mathbf{u}\cdot\nabla s'\right) = \frac{1}{Pr}\nabla\cdot\left(\tilde{\rho}\tilde{T}\nabla s'\right) + \frac{Pr\,Di}{Ra}(Q_\nu + Q_\lambda), \quad \text{Entropy equation}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla}\times(\mathbf{u}\times\mathbf{B}) - \frac{1}{Pm}\boldsymbol{\nabla}\times\left(\tilde{\lambda}(r)\boldsymbol{\nabla}\times\mathbf{B}\right), \quad \text{Induction equation}$$

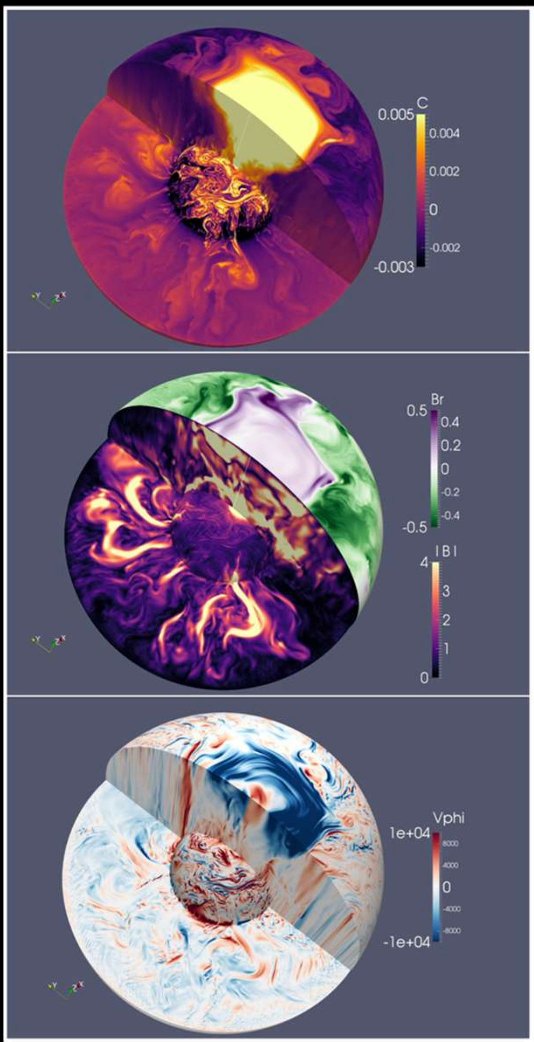
$$\nabla\cdot\mathbf{B} = 0,$$



$$E = \frac{\nu}{\Omega d^2}, \quad Ra = \frac{\alpha_o g_o T_o d^3 \Delta s}{c_p \nu \kappa}, \quad Pr = \frac{\nu}{\kappa}, \quad Pm = \frac{\nu}{\lambda_i}.$$

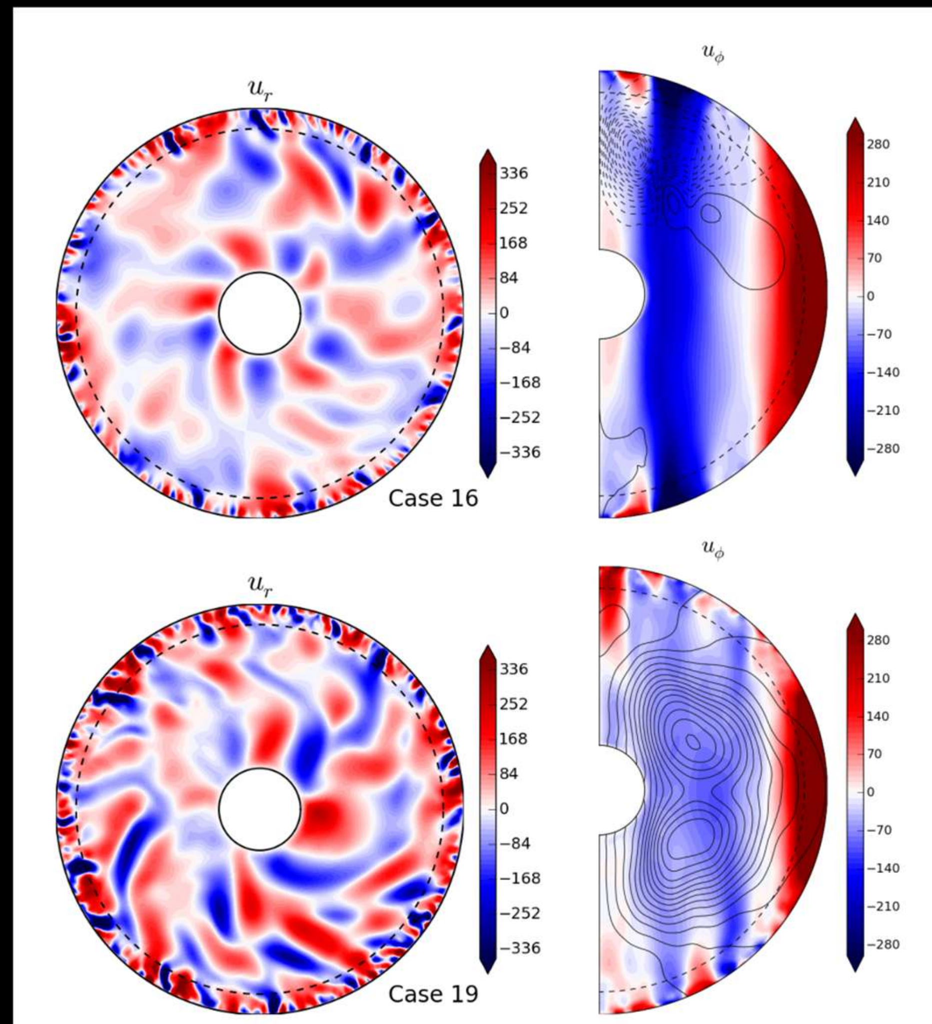
Non-dimensionalized equations with the Ekman, Rayleigh and Prandtl numbers

Non-dimensionalized 3D MHD in a spherical shell



Schaeffer et al 2017

Duarte et al., 2017



Problem!

$$E = \frac{\nu}{\Omega d^2}\ , \quad Ra = \frac{\alpha_o g_o T_o d^3 \Delta s}{c_p \nu \kappa}\ , \quad Pr = \frac{\nu}{\kappa}\ , \quad Pm = \frac{\nu}{\lambda_i}\ .$$

The available computational parameter space is order of magnitudes away from the physical one.

Parameter	Earth	Jupiter	Models
Ra	$\sim 10^6\ Ra_{crit}$	10^{31}	1-50 Ra_{crit}
E	$3 \cdot 10^{-15}$	10^{-18}	10^{-4}-10^{-10}
Pr	0.1 - 10	10^{-2}-1	10^{-2}-10^{3}
Pm	$2 \cdot 10^{-6}$	10^{-6}	10^{-1}-10^{3}

Scaling law between number of points and Ekman: $N^3 \propto E^{-3/2}$

When E decreases by 10, each direction needs 3.16x more points (about 30x in total).

As timesteps get shorter the total computation timestep increases by 100.

Planetary dynamos scaling laws (Christensen et al 2009)

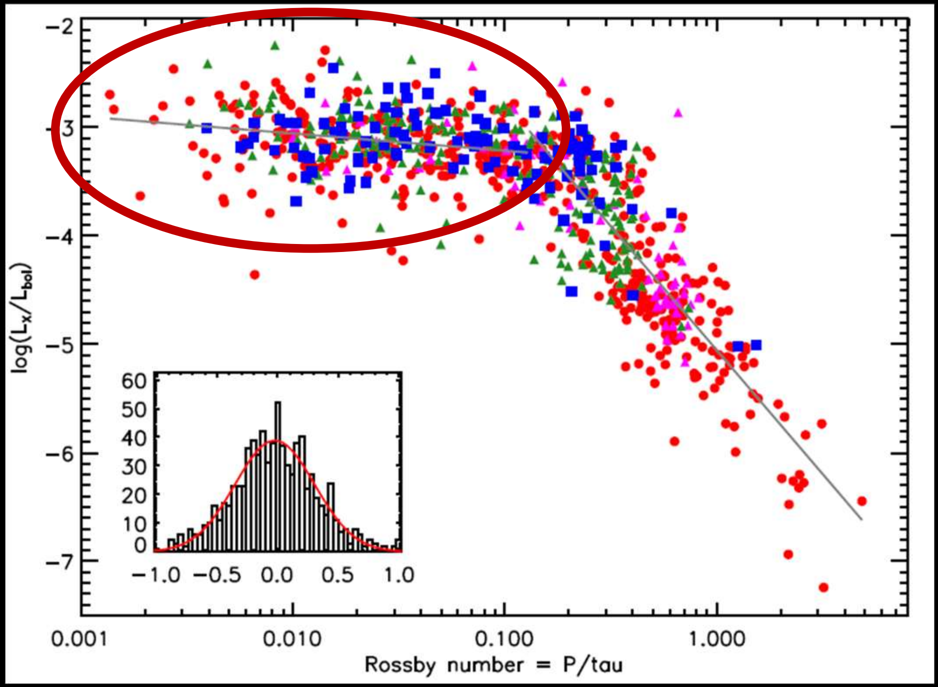
$$Ro = \frac{u_{rms}}{\Omega d} = \frac{\tau_{rot}}{\tau_{turn}}$$

In the fast rotator regime (Ro<0.12) and deep convection, B saturates:

magnetic energy is dictated not by rotation by the **buoyant power (heat flux q_c,** i.e. intrinsic luminosity)

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

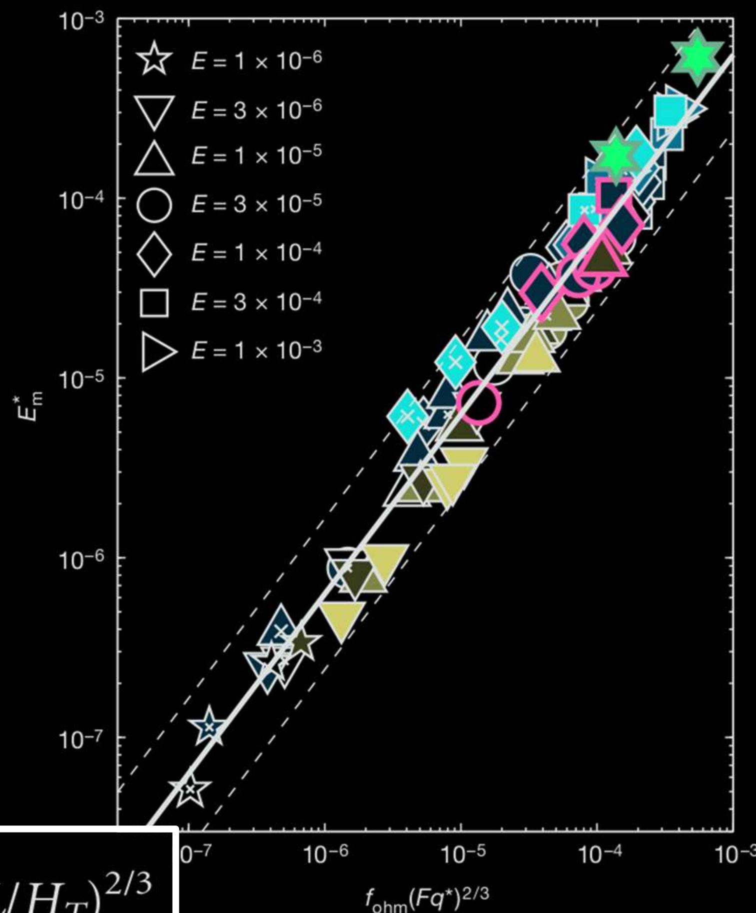
Scaling laws: Stellar magnetic fields as a function of Ro

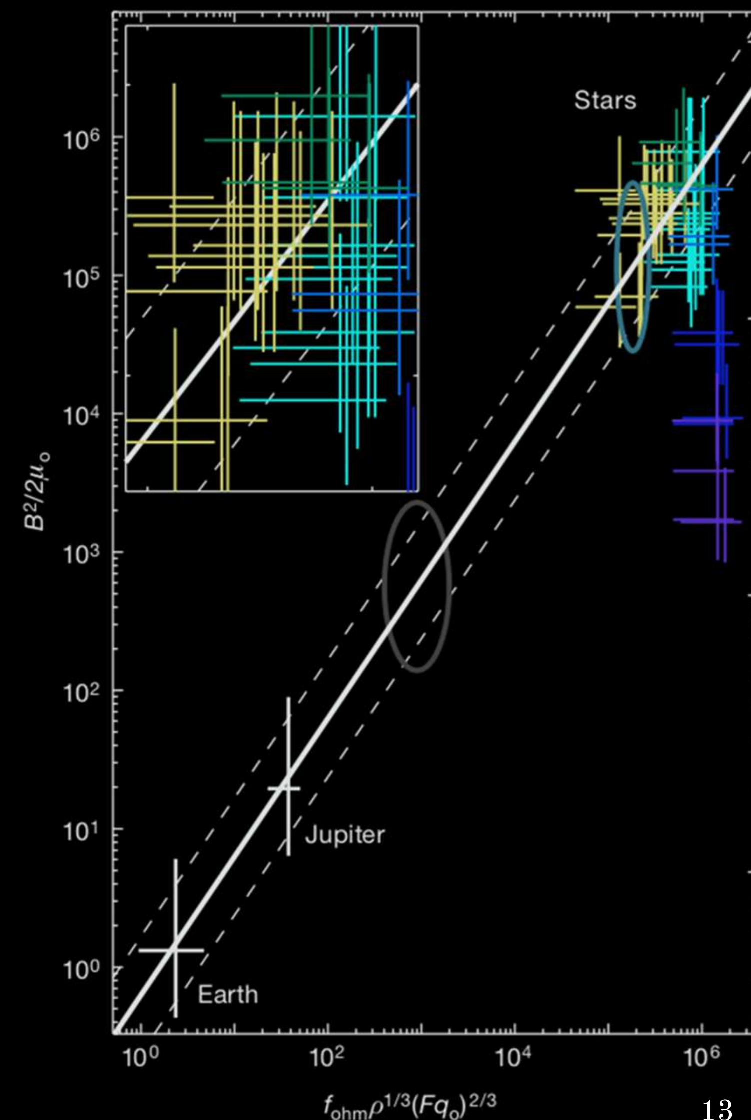


Reiners et al. 2014

Planetary dynamos scaling laws (Christensen et al 2009)

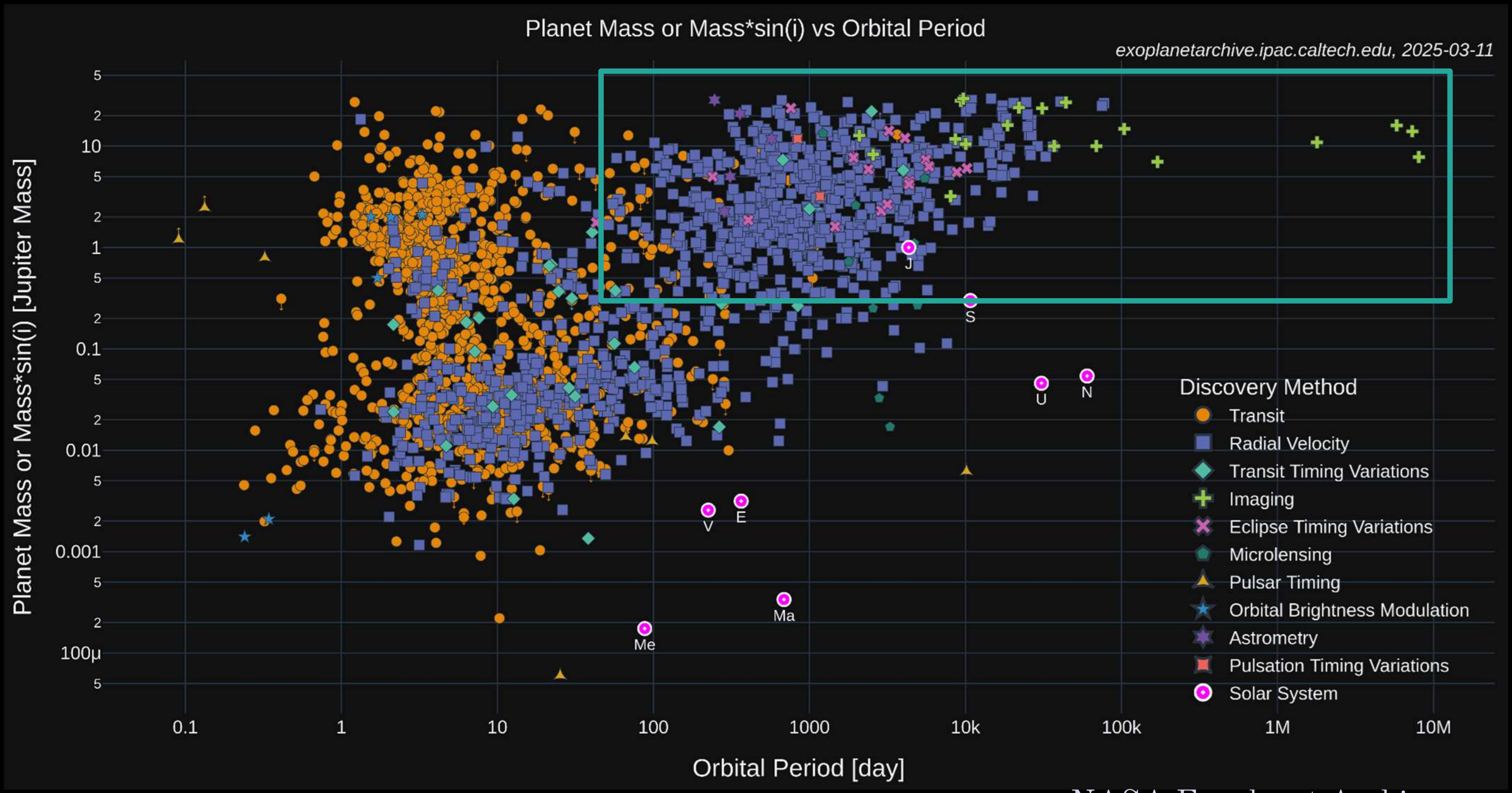
The scaling law surprisingly works for Earth, Jupiter and M dwarfs. It seems to fail for slow rotators, for not fully convective stars/planets, and (more unclearly) for brown dwarfs.





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

B expectations for the exoplanet cold giant population



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Long term evolution of B had only been addressed with scaling laws

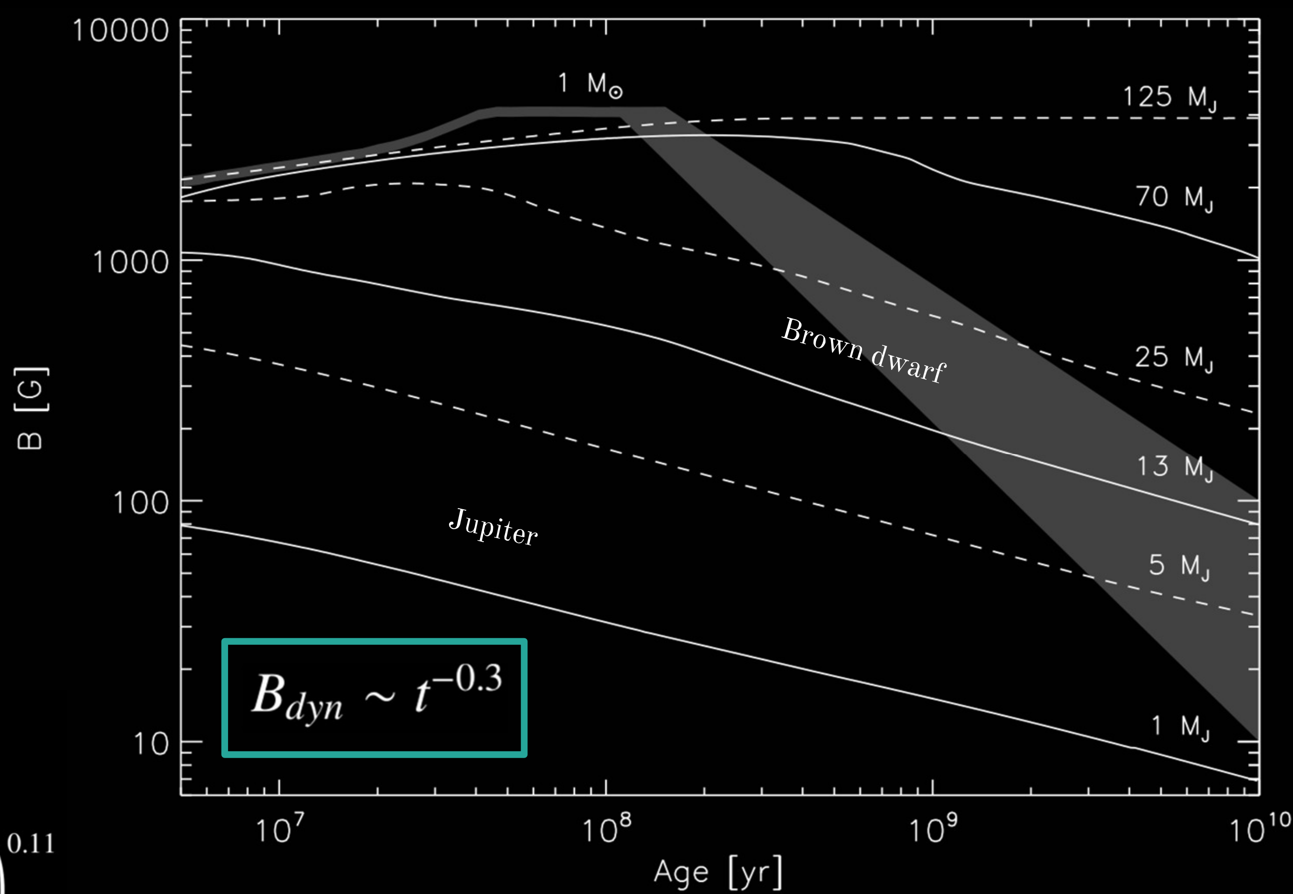
Reiners & Christensen 2009 simplified the scaling law with simple observables to give the B_{rms} at the dynamo surface:

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

Reiners & Christensen 2010 joined the scaling law with analytical evolutionary tracks from Burrows et al 2001.

$$L \sim 4\cdot 10^5 L_\odot \left(\frac{1Gy}{t}\right)^{1.3}\left(\frac{M}{0.05M_\odot}\right)^{2.64},$$

$$R \sim 6.7\cdot 10^4 km \left(\frac{10^5\ \mathrm{cm\,s^{-2}}}{g}\right)^{0.18}\left(\frac{T_{eff}}{1000K}\right)^{0.11}$$

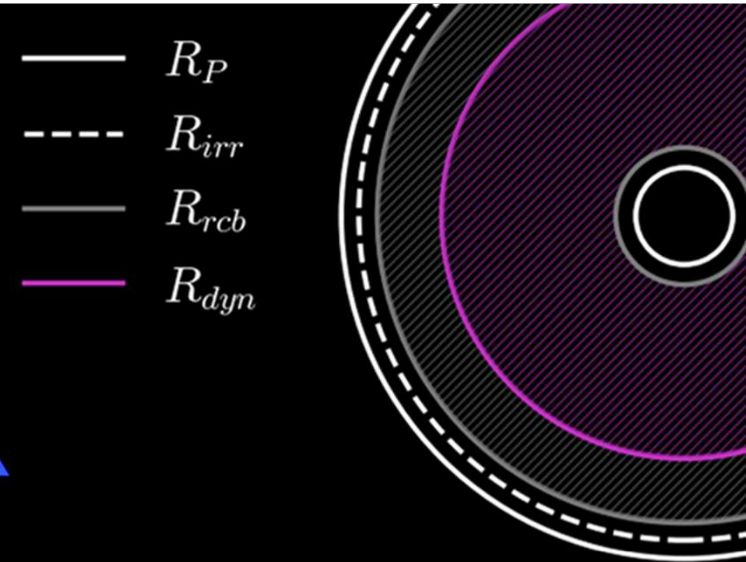


Planetary dynamos at different evolutionary times

1. Evolve a 1D **non/mild-irradiated gas giant** (~Gyr).
2. Implement the profiles in a 3D MHD code.
3. Evolve the anelastic MHD eqs. reaching a dynamo solution (~Kyr).
4. Repeat the process from step 2 for different ages.

Cooling (evolutionary) times ~ 10-100 Myr

Convection turnover time ~ 1-5 years.



MESA

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

General structure:

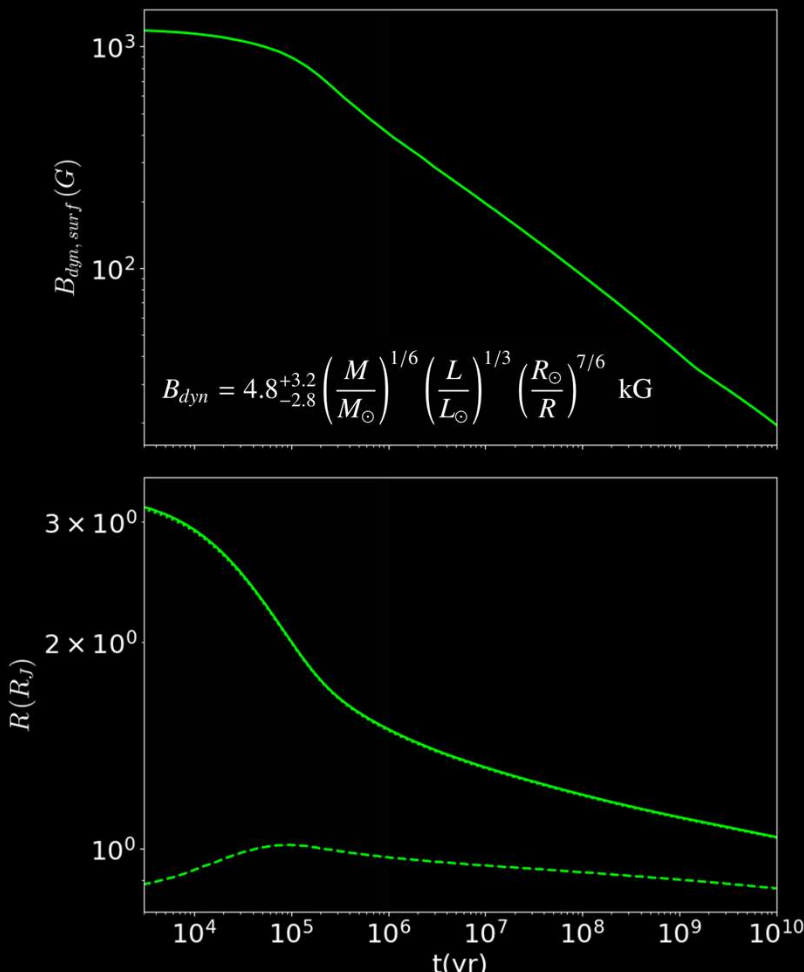
Irradiated layer

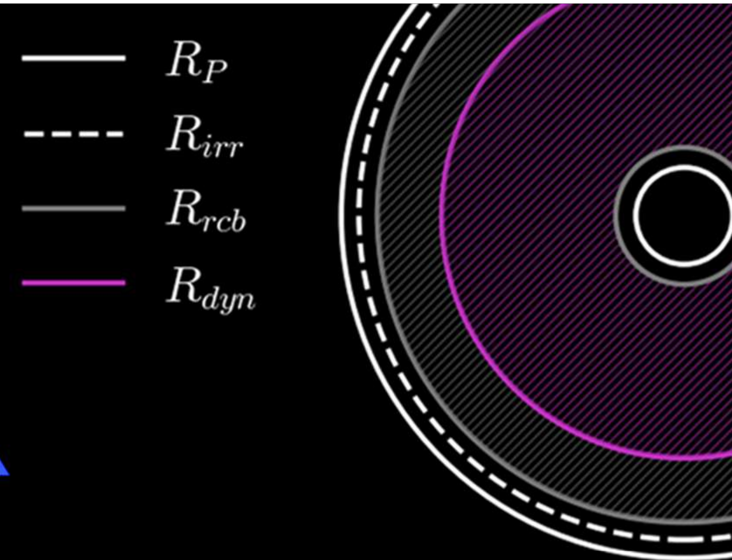
Stratified layer

Convective interior

Dynamo region (P>1 Mbar)

Planetary dynamos at different evolutionary times





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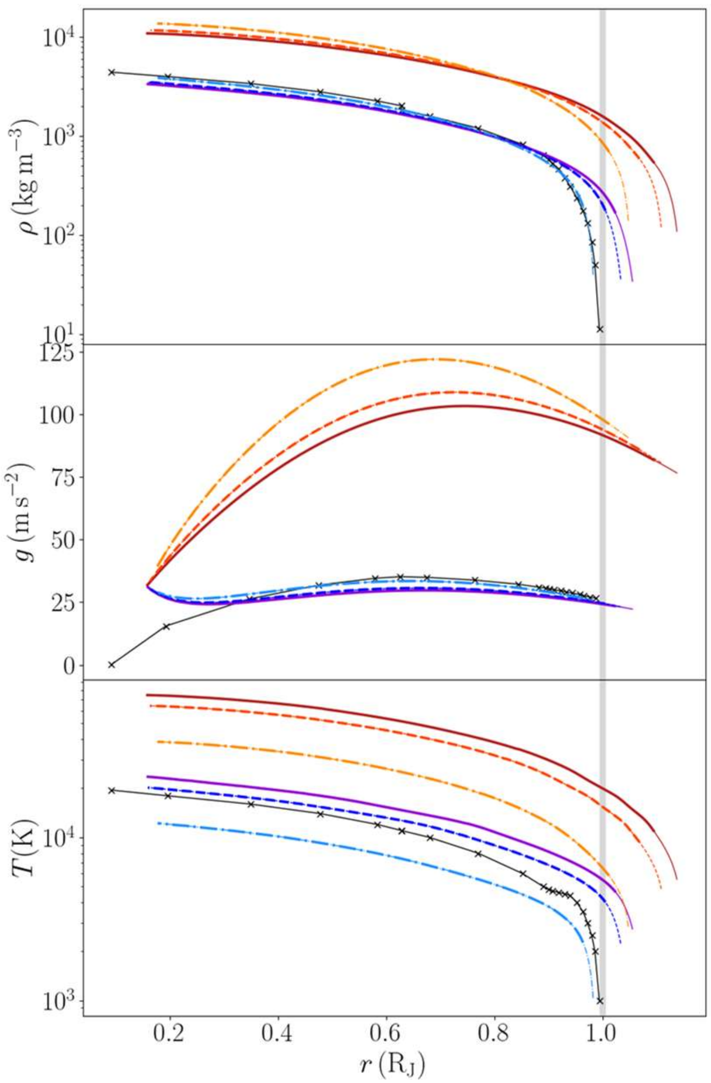
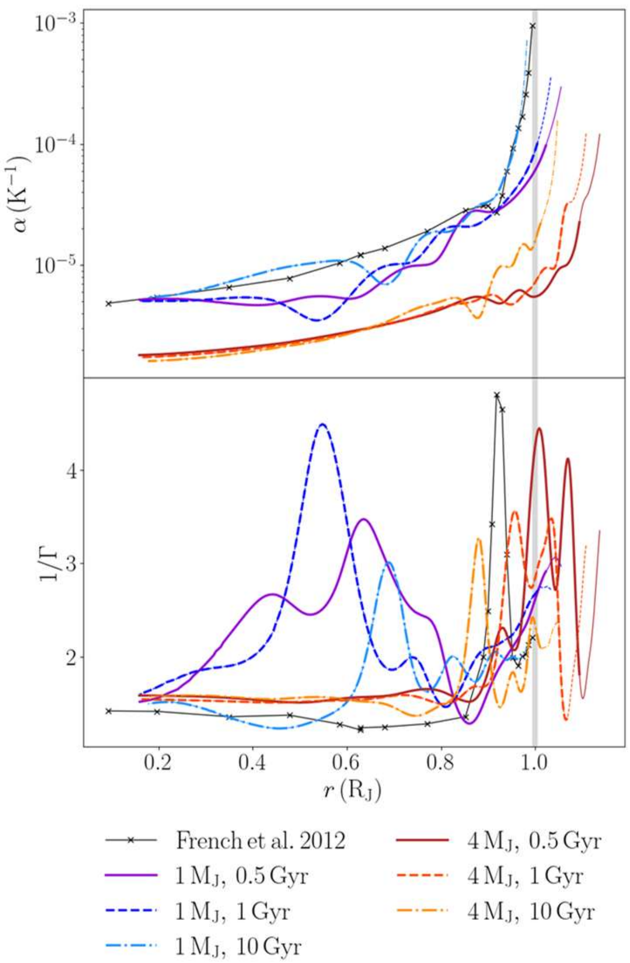


Radial dependencies: MESA 1D profiles

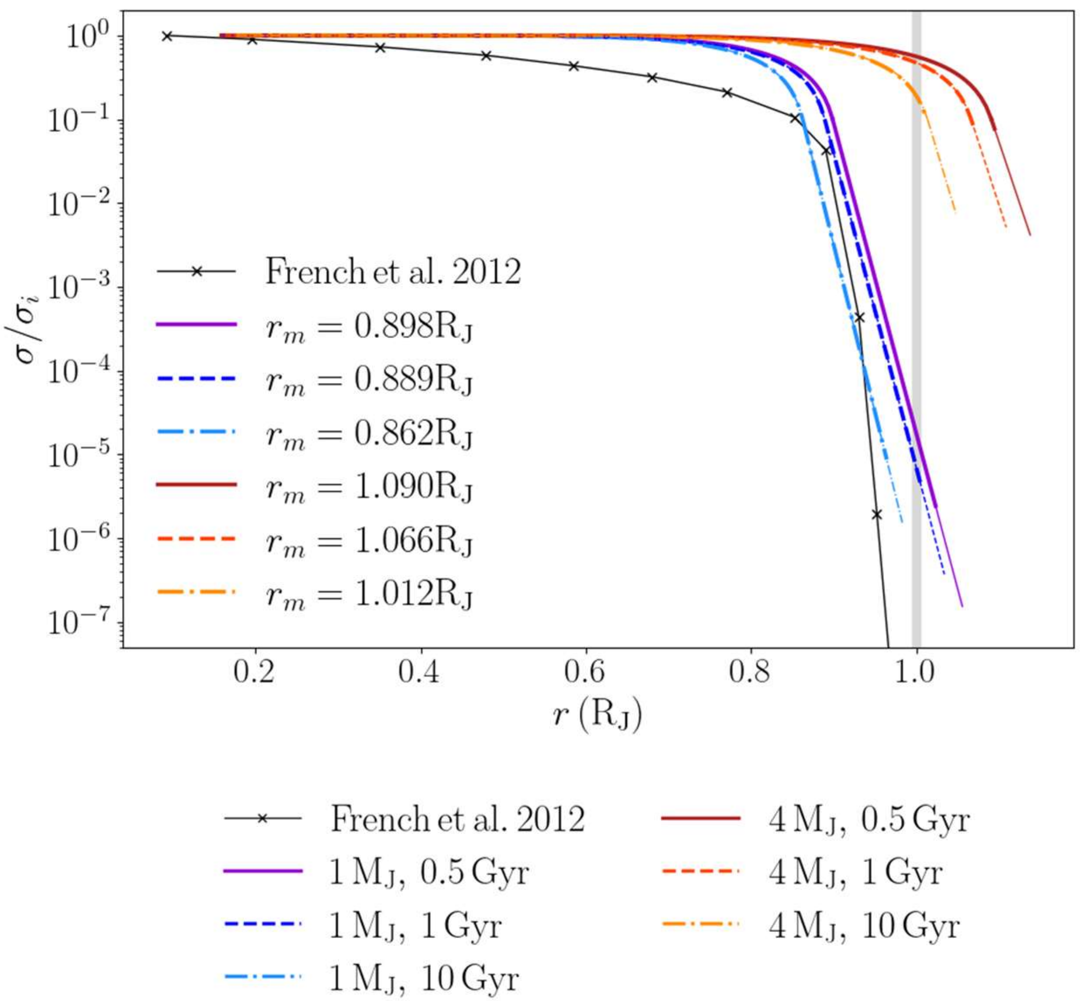


We cut the profiles and make sure that the region is fully convective.

ρ, g and T are smooth, but not the compressibility coefficient and Grüneisen parameter.

$$\big(\rho(r), T(r), g(r)\big) = \sum_{n=0}^{20} \big(\rho_n, T_n, g_n\big) r^n$$

$$\big(\alpha(r), \Gamma(r)\big) = \sum_{n=0}^{150} \big(\alpha_n, \Gamma_n\big) r^n$$



Radial dependencies: conductivity profiles

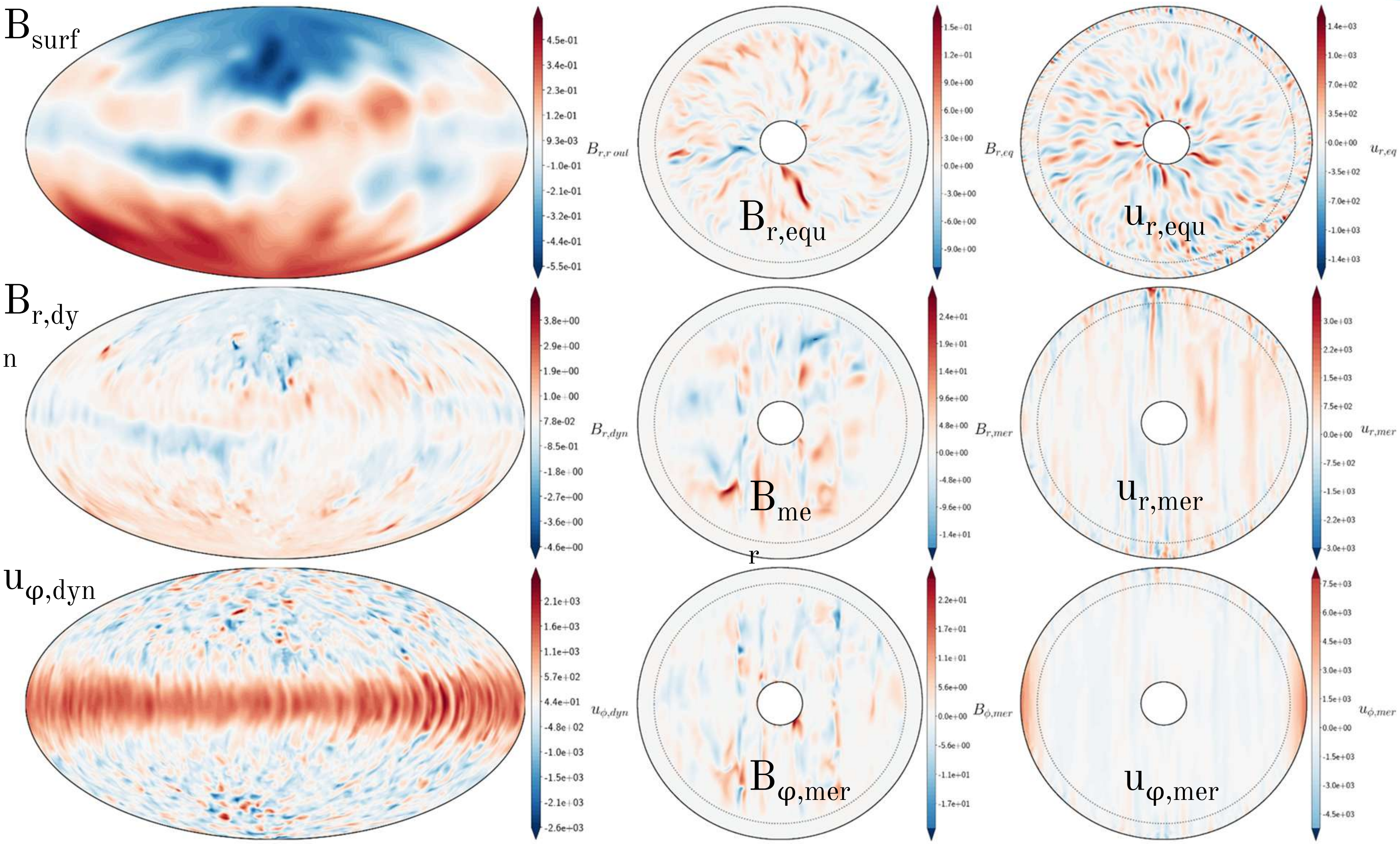
Magnetic diffusivity is only radial dependence that does NOT directly come from MESA.

$$\frac{1}{\tilde{\lambda}(r)} = \tilde{\sigma}(r) = \begin{cases} 1 + (\tilde{\sigma}_m - 1)\left(\frac{r - r_i}{r_m - r_i}\right)^{-a} & r < r_m, \\ \tilde{\sigma}_m e^{-a\left(\frac{r - r_m}{r_m - r_i}\right)\frac{\tilde{\sigma}_m - 1}{\tilde{\sigma}_m}} & r \geq r_m. \end{cases}$$

Gómez-Pérez et al 2010 introduced a function of outer decaying conductivity.

r_m is chosen as the radius where P = 1 Mbar, mimicking the appearance of metallic hydrogen. **This is different for every model.**

3D general saturated solution example: $1M_J$ 1 Gyr model



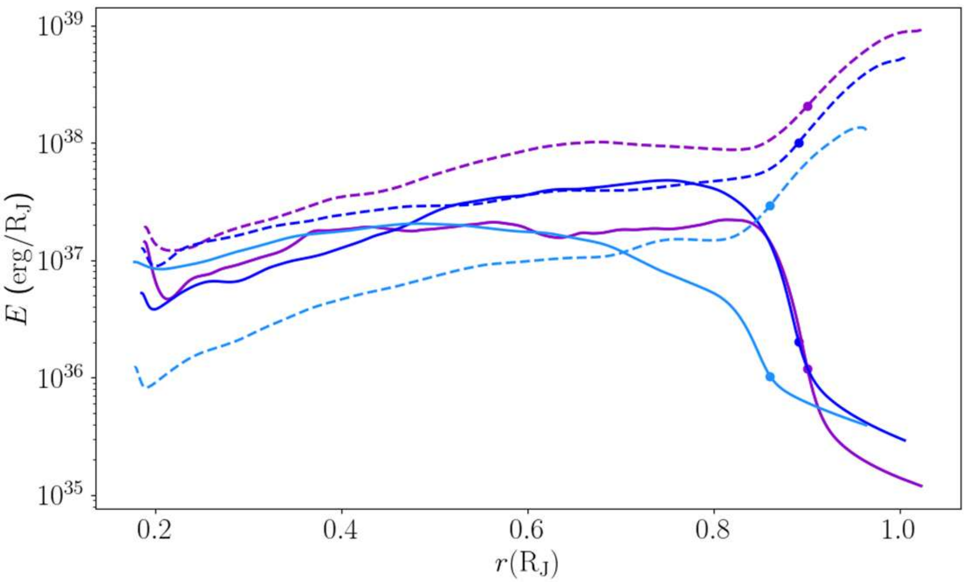
https://github.com/magic-sph/magic

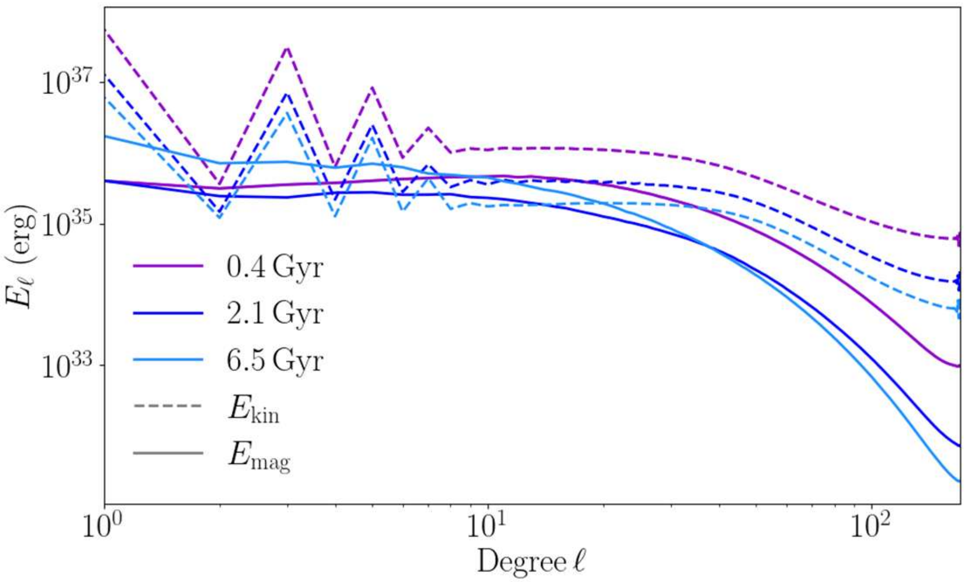
- Dipolar

- Magnetic field is contained within the **conductive volume.**

- Meridional slices show **columnar structures**.

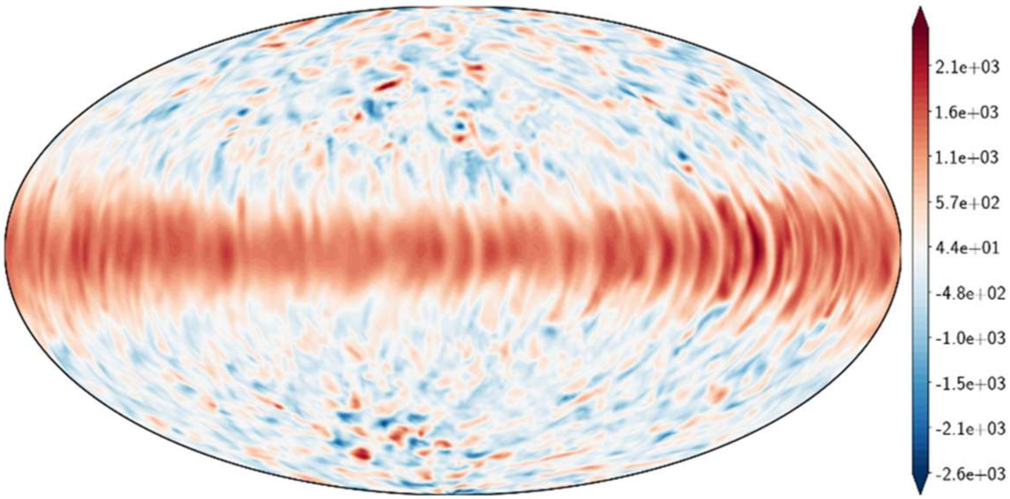
- There is one big **equatorial jet**.





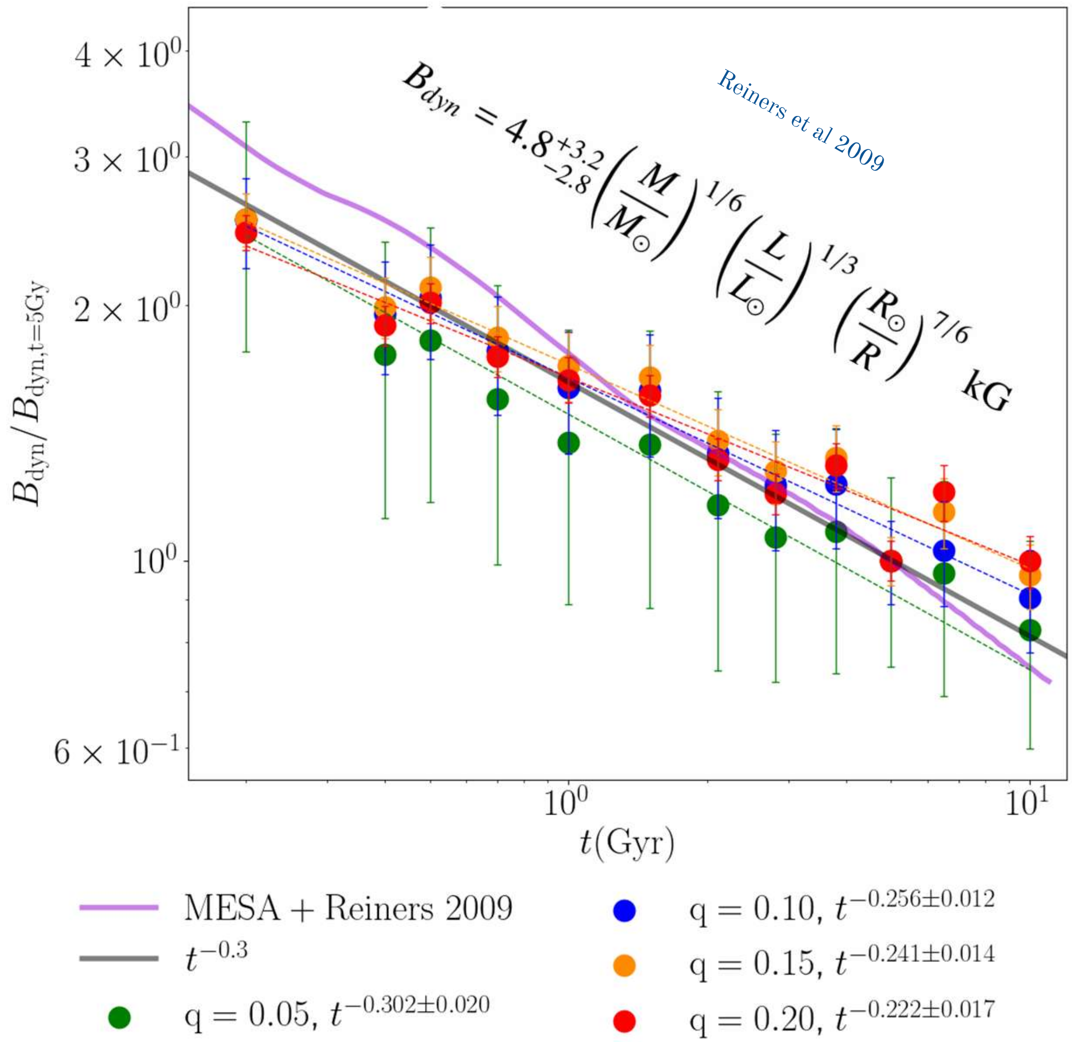
Energy distributions

- Jet dominates in kinetic energy (odd l's)
- Conductivity regions dictates where B drops (Duarte et al 2013)
- Equipartition is approximately reached in the inner regions



We define the dynamo radius as r_m

$$\frac{1}{\tilde{\lambda}(r)} = \tilde{\sigma}(r) = \begin{cases} 1 + (\tilde{\sigma}_m - 1)\left(\dfrac{r - r_i}{r_m - r_i}\right)^{-a} & r < r_m, \\ \tilde{\sigma}_m e^{-a\left(\frac{r-r_m}{r_m-r_i}\right)\frac{\tilde{\sigma}_m - 1}{\tilde{\sigma}_m}} & r \geq r_m. \end{cases}$$



Comparison with scaling laws

$$E_{mag,dyn}(q) = \frac{1}{r_m - r'_m}\int_{r'_m}^{r_m} E_{mag}(r)dr$$

$$r'_m(q) = (\chi_m - q)r_o$$

$$B_{dyn}(q) = \sqrt{2\mu_0 E_{mag,dyn}(q)/MV}$$

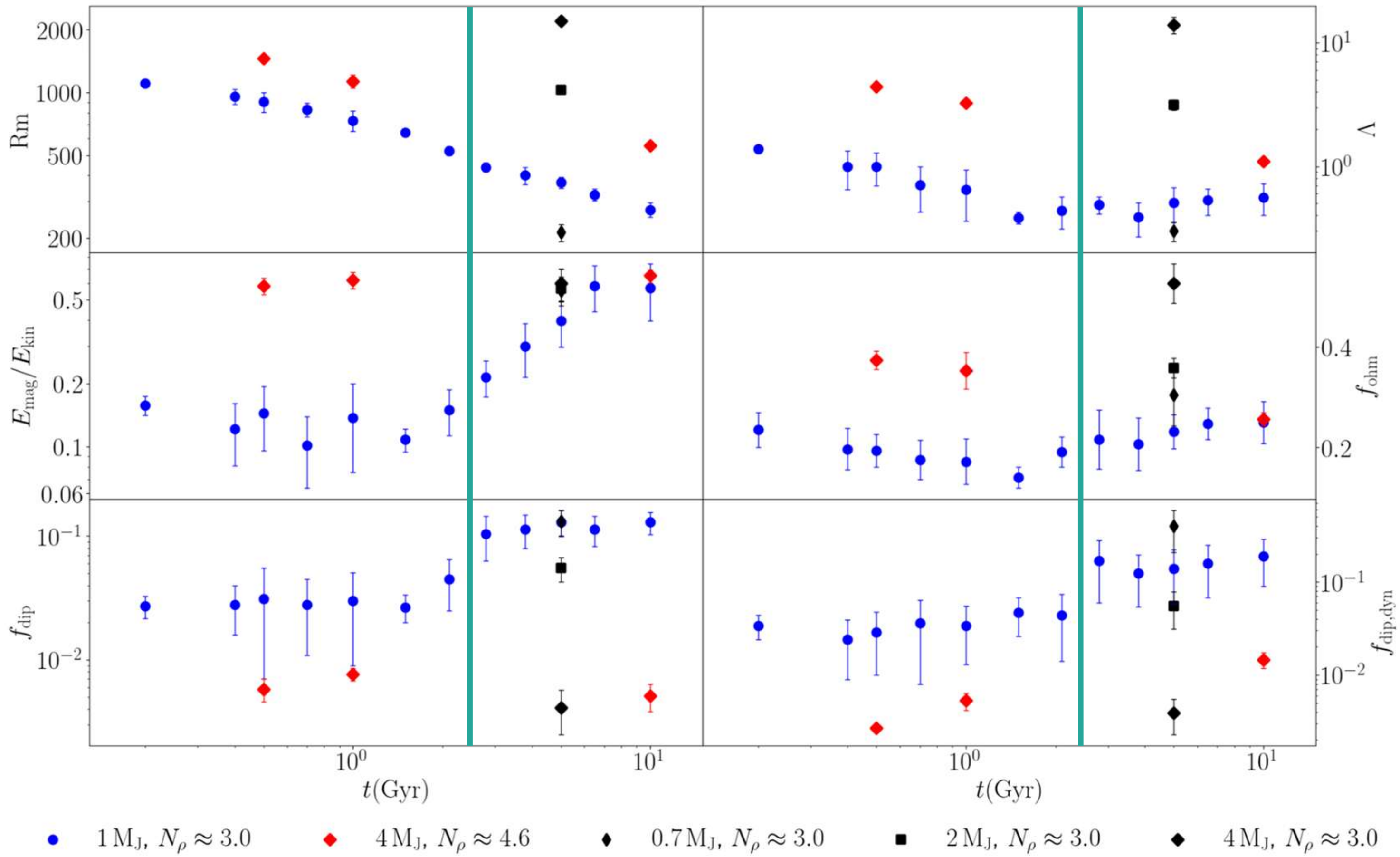
- Agreement with scaling laws (sanity check)
- Does not depend much on how thick is the integration shell around dynamo surface

Evolutionary changes: dimensionless numbers

Magnetic Reynolds number

Equipartition level

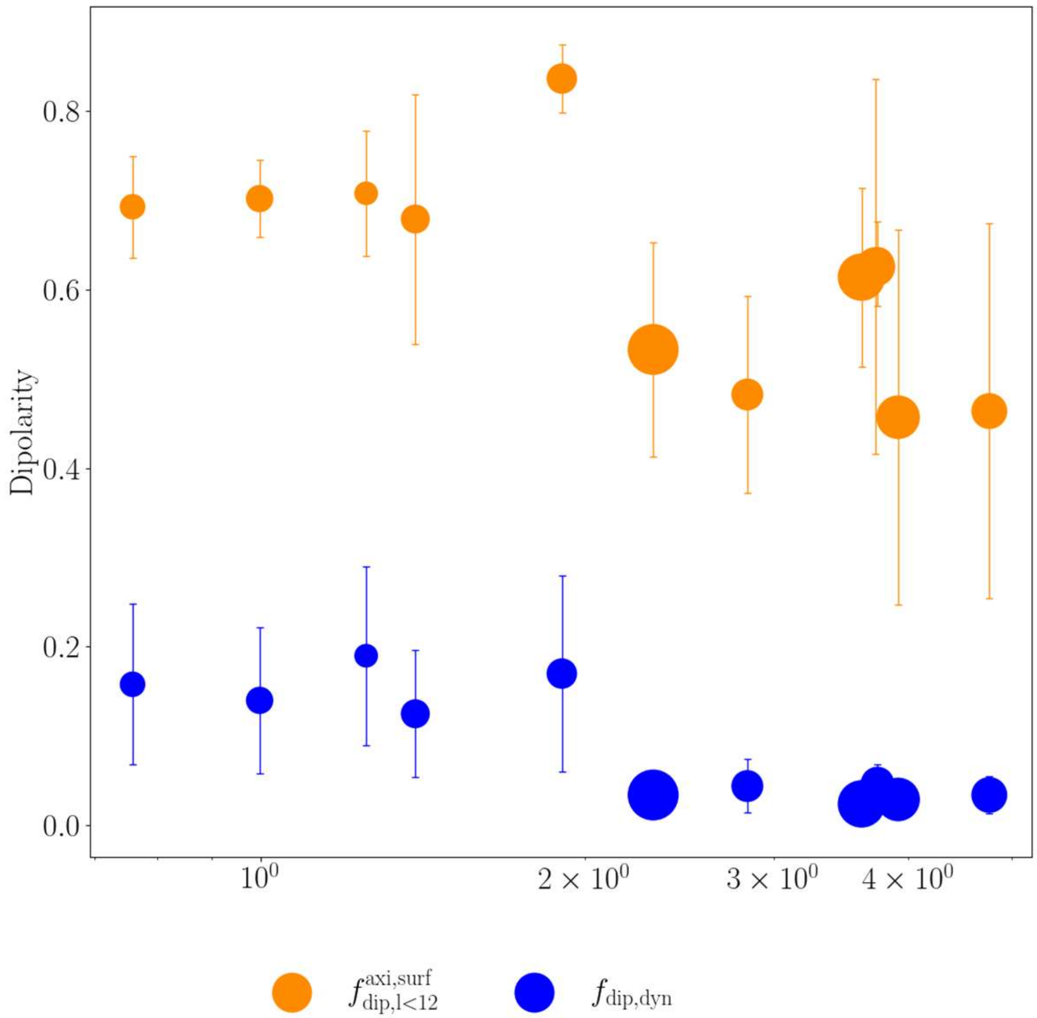
Total dipolar fraction



Elsasser number (proxy to B field)

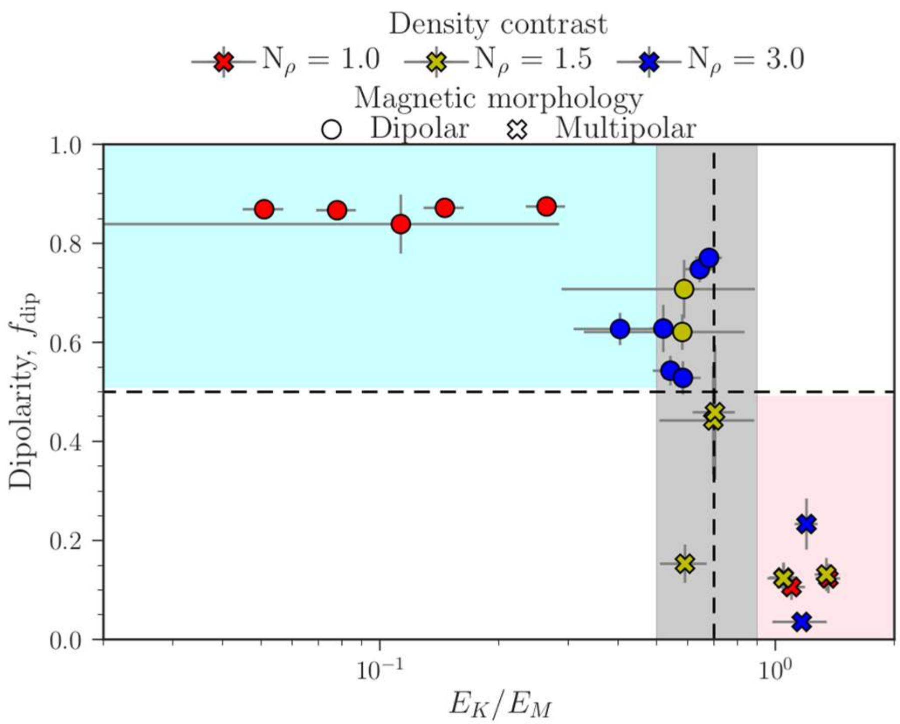
Ohmic dissipation fraction

Dipolar fraction at r_{dyn}

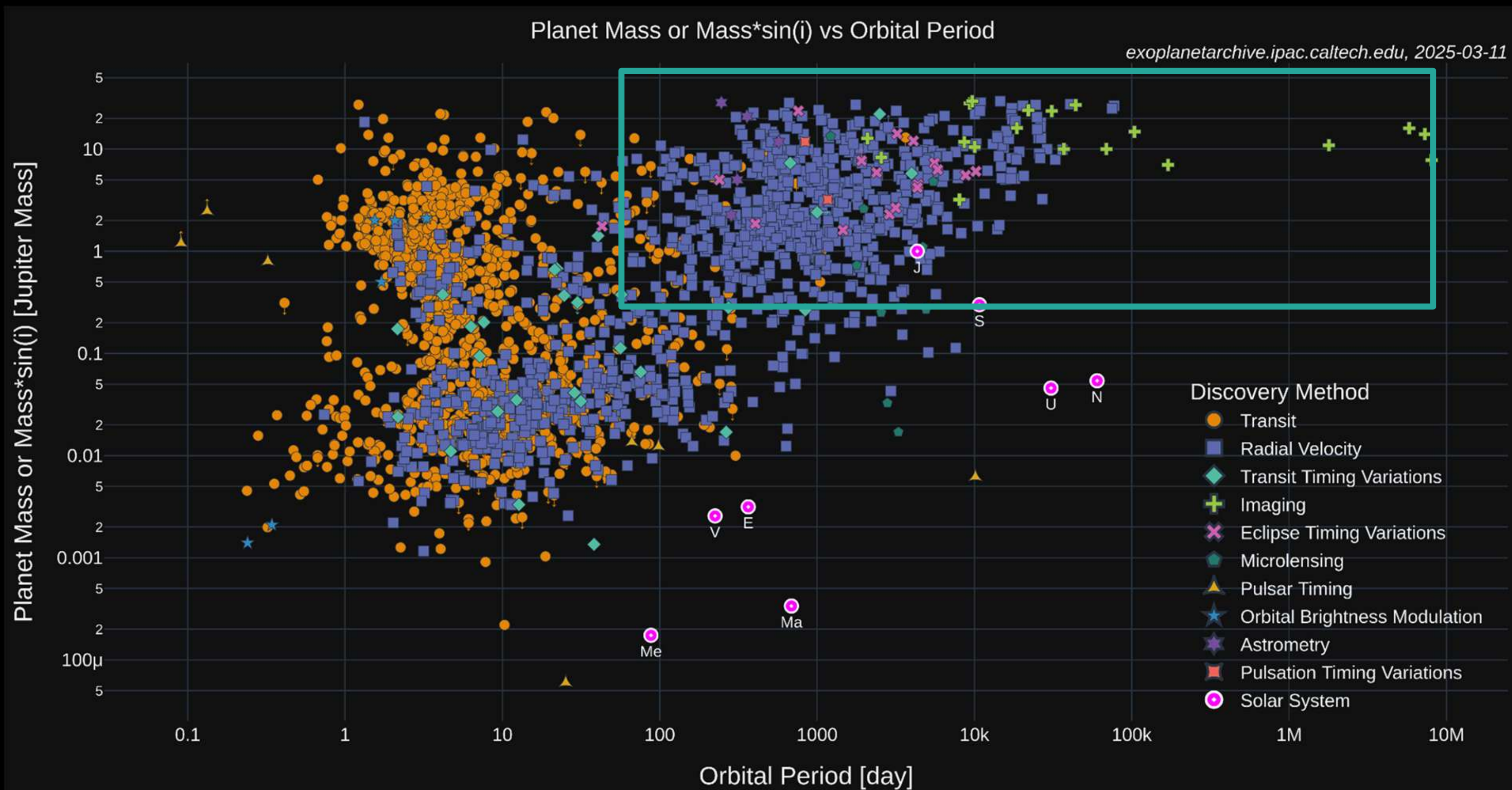


Multipolar to dipolar transition

Similar anelastic simulations: Zaire et al 2022. They have thinner radial shells (stellar dynamos), transition from dipolar to multipolar.



Application to Cold Jupiter Population



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650 CJ confirmed candidates should follow this evolutionary path.

Under 10 pc, there are only 4 candidates:

~ 0.6 Gyr

Eps. Eridani b

> 5 Gyr

Gliese 832b

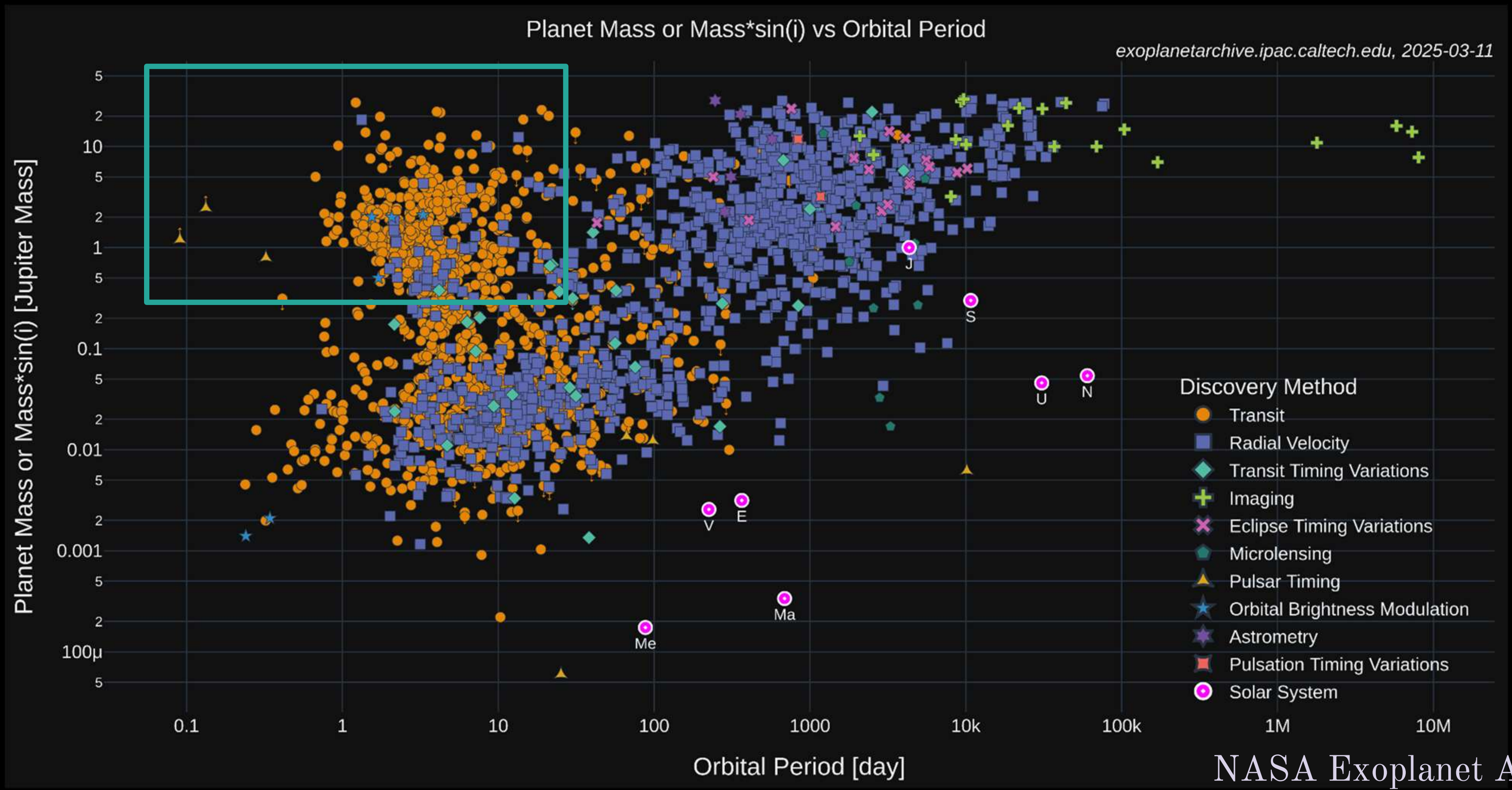
HD 219134h

GJ 3512b

Hot Jupiters

Gas giants ($0.3\ M_J < M_P < 13\ M_J$)

Highly irradiated, tidally locked ("slow" rotation)



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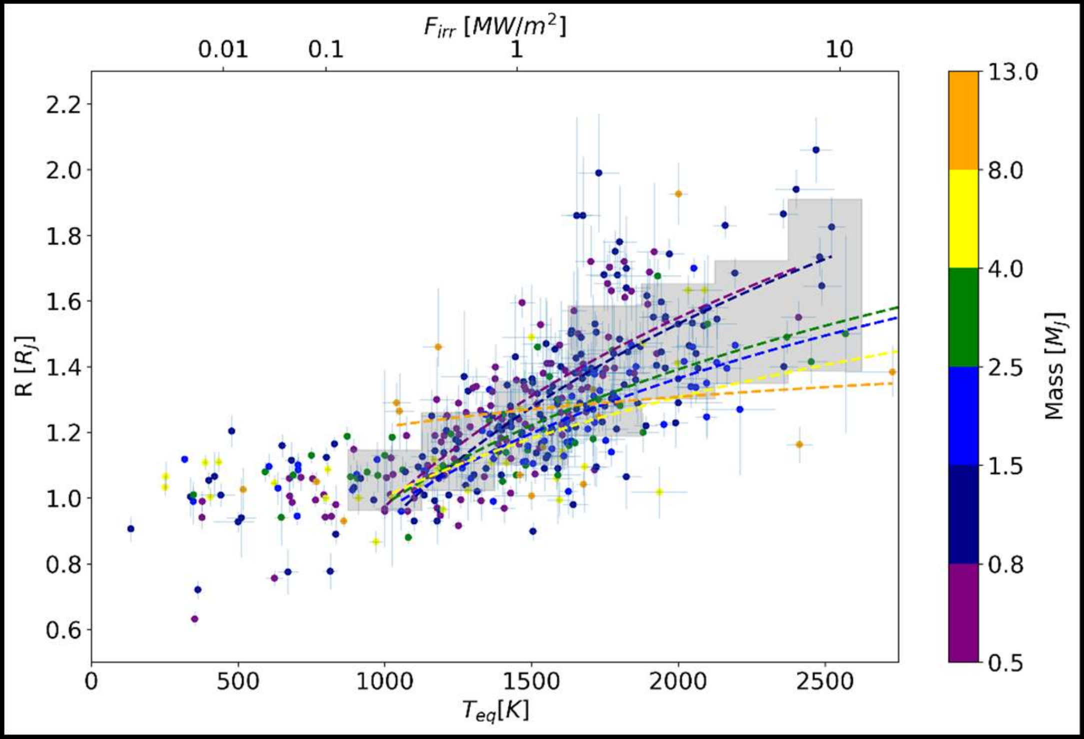
Hot Jupiters



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

Highly inflated, with a clear correlation with irradiation (equilibrium temperature).

Irradiation and/or delayed cooling (e.g., higher opacities) cannot explain the observed values

Additional heat is required, Ohmic or tidal dissipation are the main candidates.

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Hot Jupiter dynamos at different radial distances (fluxes)

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

MESA

Heuristic function which allow theoretical radii fitting the data (Thorngren & Fortney 2018)

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

$$\epsilon = \frac{Q_{\mathrm{dep}}}{\pi R^2 F_{\mathrm{irr}}} \qquad Q_{\mathrm{dep}} = \int_M \epsilon_{\mathrm{heat}}\;\mathrm{d}m$$

With this we can explore:

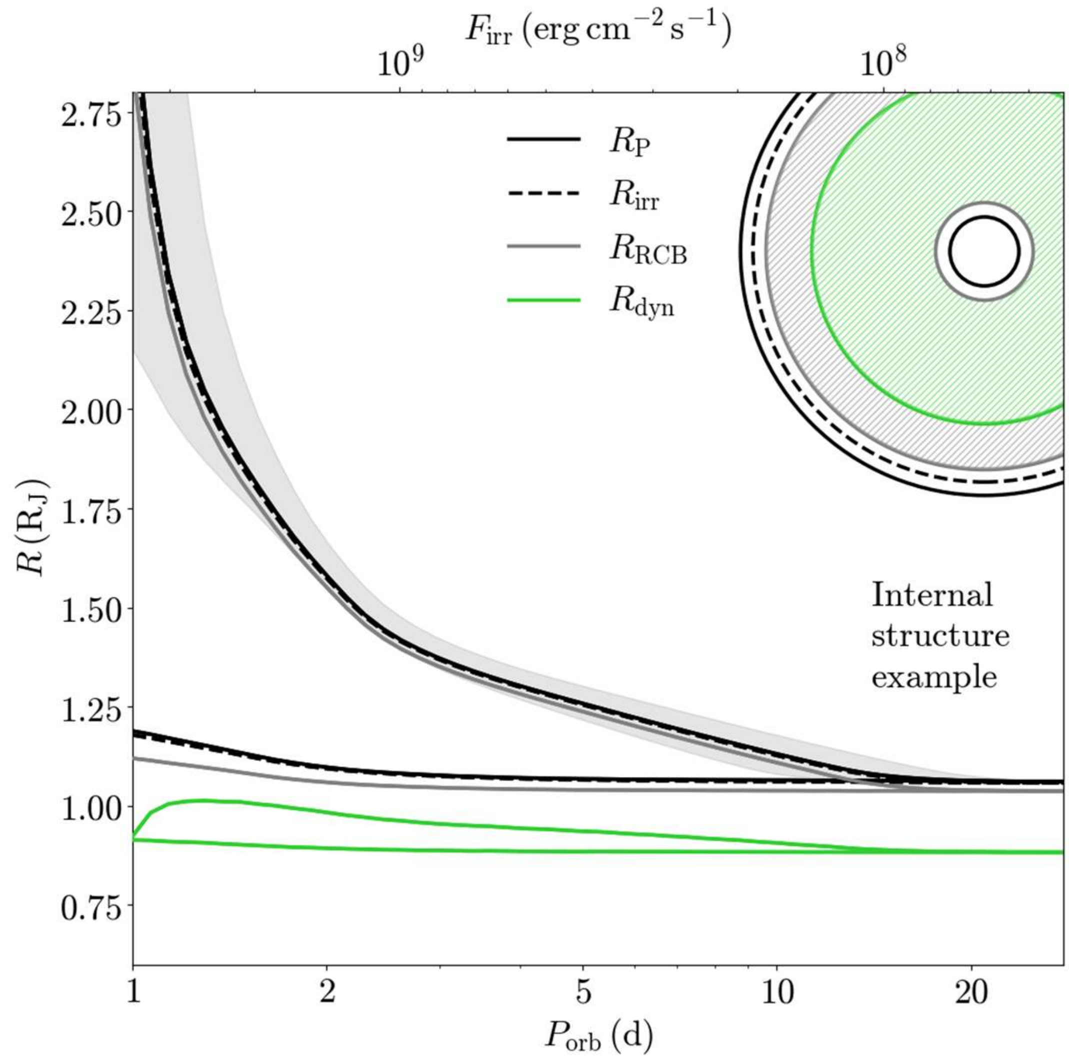
1. How do the interior dynamics of HJ change as a function of orbital separation & inflation (e.g. Rossby number)
2. How magnetic field predictions are influenced?

Inflated radius & structure

The extra heat allows the cooling to slow down, keeping the interior warmer, and enlarging the envelope.

It also pushes outward (few bars) the radiative-convective boundary, which otherwise tends to be pushed inward (up to kbar) by strong irradiation.

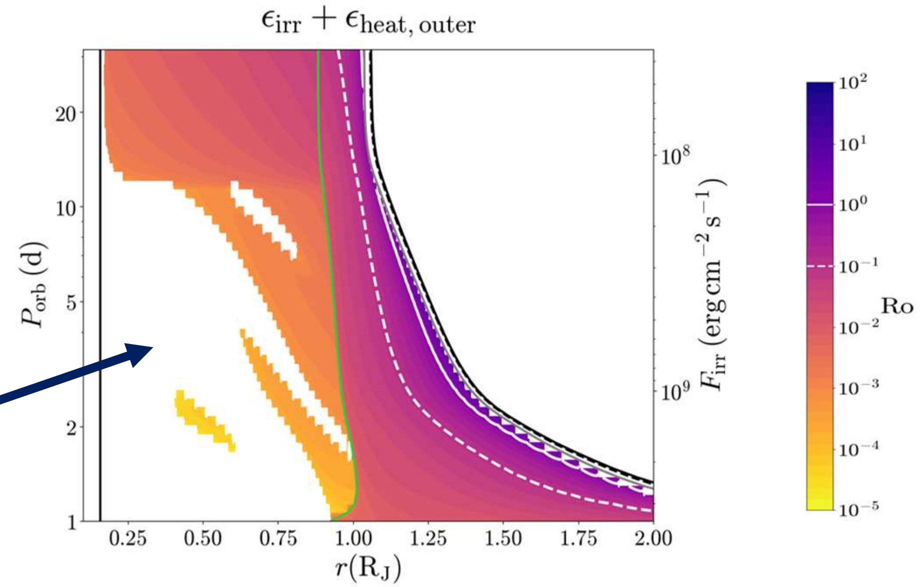
There is a large difference between the metallic hydrogen region (dynamo region R_{dyn}) and the surface.



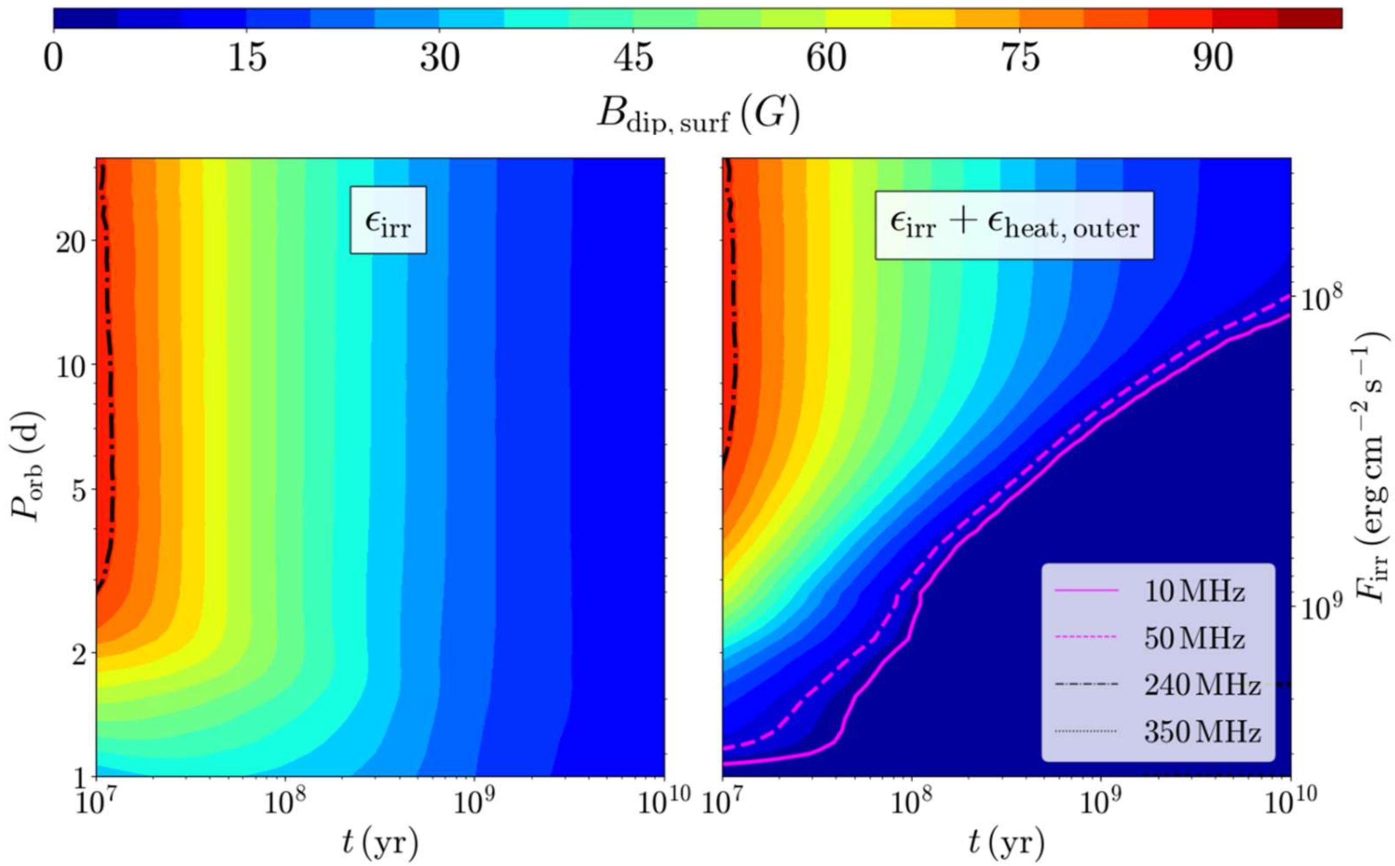
Additional heat kills convection!

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

Convection disappears or it's strongly reduced, due to the additional heat placed in the outer regions



Magnetic field dipole strength at the planetary surface



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

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

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

WRAPPING UP:

Cold Jupiters:

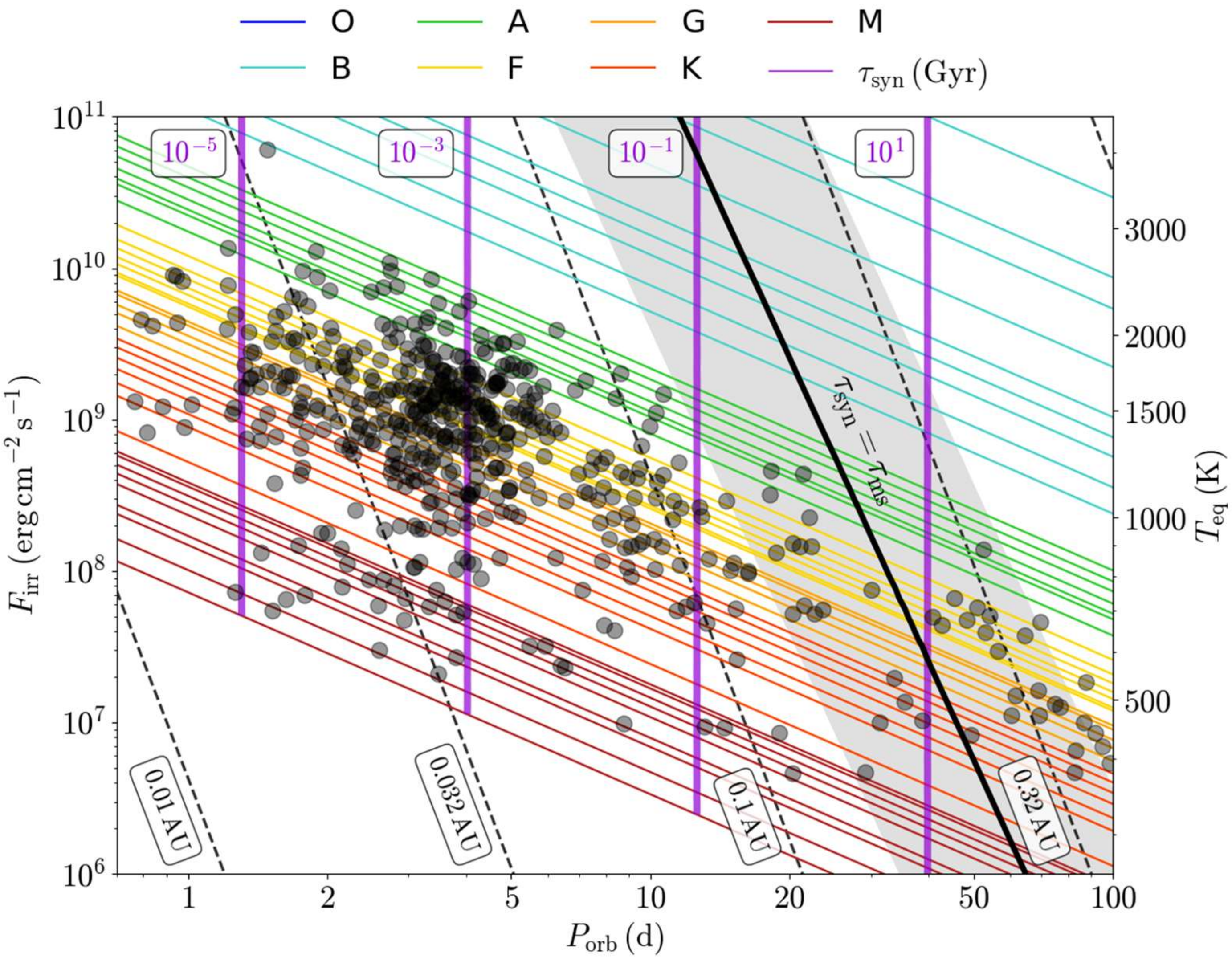
- Magnetic fields slowly decay in time.
- Possible transition from multipolar to dipolar.
- **We need observational validation of magnetic scaling laws (radio emission)**

Hot Jupiters:

- Fast rotators despite tidal lock: magnetic field should be set by heat flux
- Heat deposition necessary to explain radius inflation suppresses the convection, leading to **low (gauss at most) magnetic-fields prediction.**

...and for rocky planets?

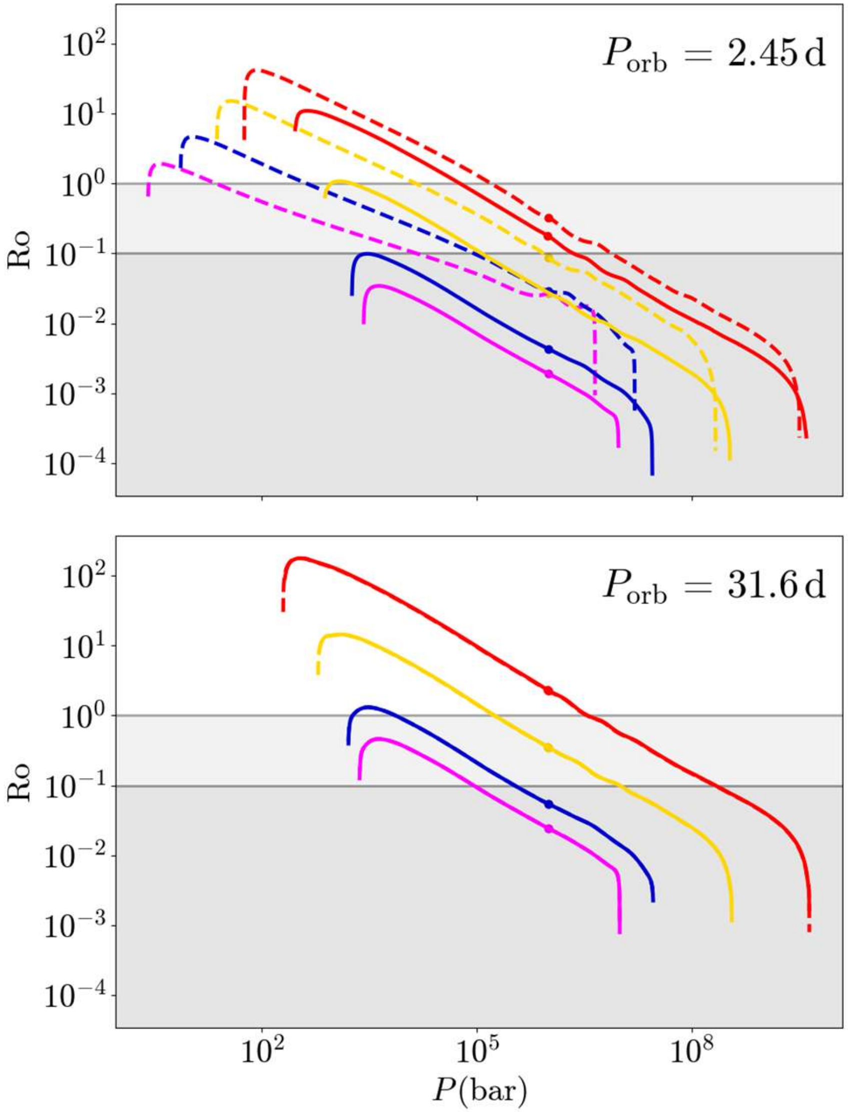
- By constraining gas giant magnetism models observationally (radio, star-planet interaction...), we can validate or not scaling laws which are supposed to hold for magnetic rocky planets as well
- Atmospheric features could give hints on having Earth-like (plate tectonics & dynamo) or Venus-like (stagnant lid) structure and magnetism



Series example: 1 M_J planet with 1 $M_\odot$ G2 host star

$T = 5800.0$ K
$L_\odot = 1.000$ Lsun
$\tau_{\mathrm{ms}} = 10.00$ Gyr

a(AU)	P(d)	F(c.g.s.)	τ_{syn}(Gy)
0.0180	0.88	$4.23\cdot10^9$	1.89e-06
0.0252	1.47	$2.14\cdot10^9$	1.63e-05
0.0355	2.45	$1.08\cdot10^9$	1.33e-04
0.0500	4.08	$5.47\cdot10^8$	1.07e-03
0.0703	6.81	$2.77\cdot10^8$	8.41e-03
0.0989	11.4	$1.40\cdot10^8$	6.59e-02
0.139	19.0	$7.06\cdot10^7$	5.13e-01
0.195	31.6	$3.57\cdot10^7$	3.99



Ro dependence on planetary mass: inflation vs no inflation

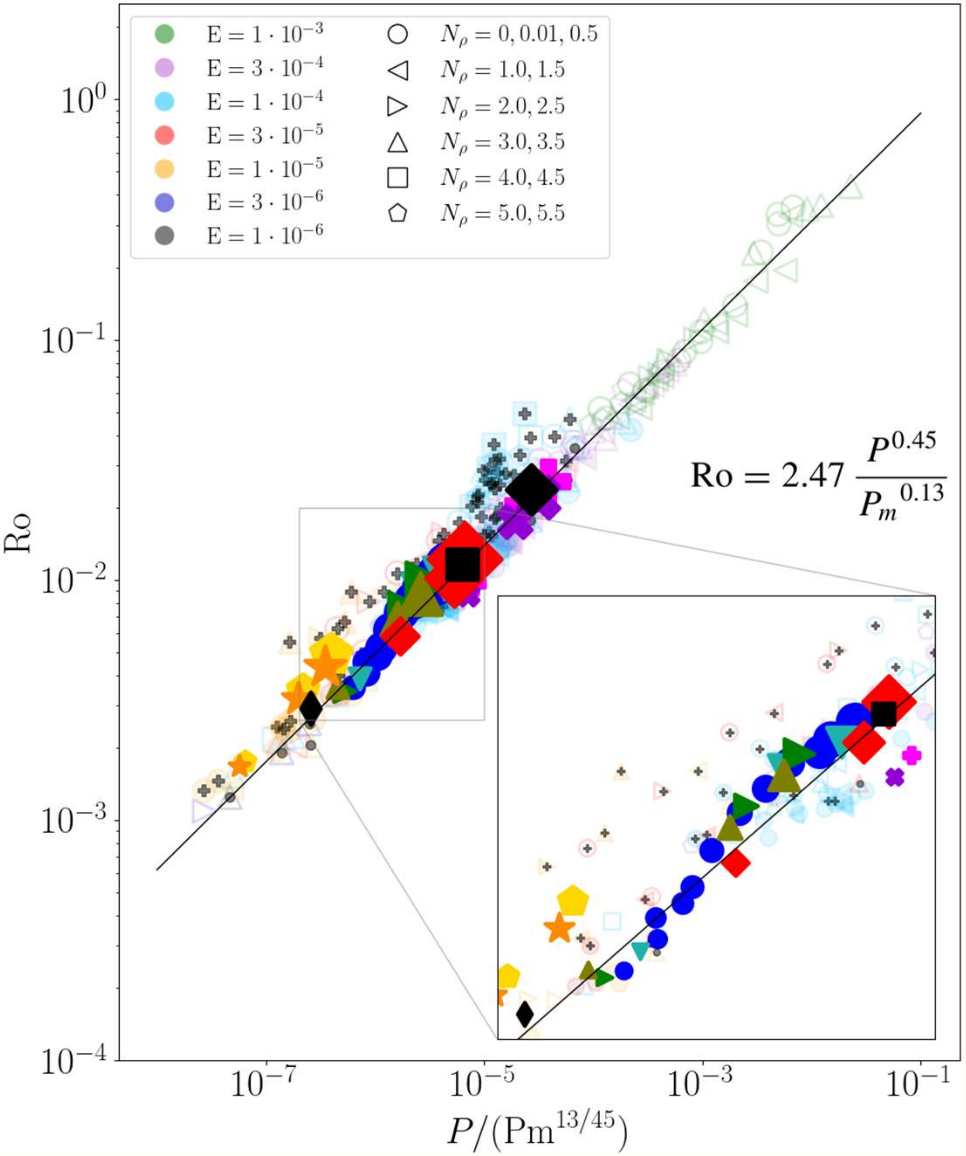
As the planetary mass increases, inflation effects become minimal. Lowest Ro are recovered for massive long period planets (but still tidally locked). Only 3 candidates for $\mathrm{M_P}>4\mathrm{M_J}$ and 15 d $<$ P $<$ 40 d:

GJ 86 b: 15.8 d, 4.4 $\mathrm{M_J}$, 10.8 pc, Stassun et al 2017

HD 72892 b: 39.4 d, 5.5 $\mathrm{M_J}$, 69.7 pc, Feng et al 2022

TIC 393818343 b: 16.2 d, 4.3 $\mathrm{M_J}$, 93.7 pc, Sgro et al 2024

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



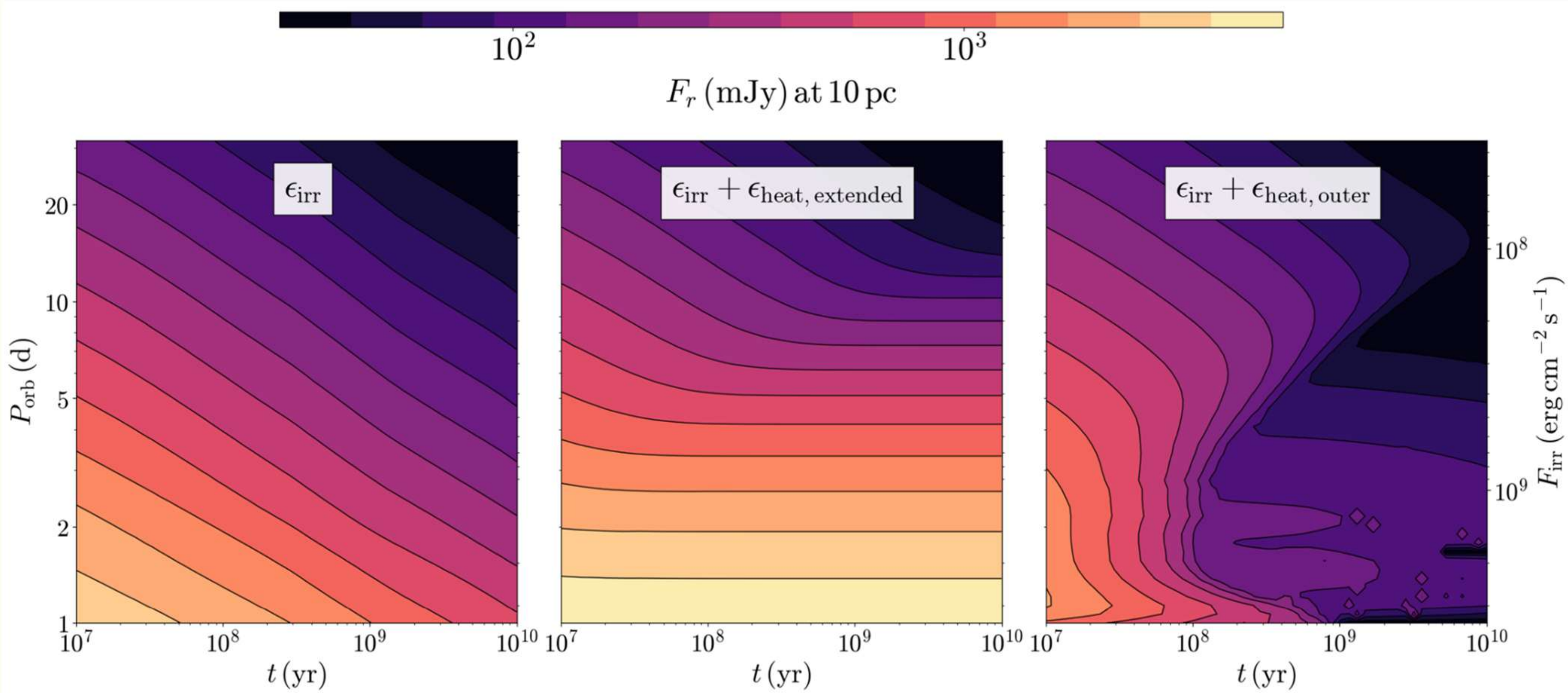
Scaling laws Yadav et al 2013: Rossby number

$$Ro = \frac{Rm\, E}{Pm} \qquad Rm = \overline{\frac{1}{V}\int_{r_i}^{r_o} \frac{\sqrt{\|\mathbf{u}^2\|}}{\tilde{\lambda}} r^2 dr}$$

Theoretical prediction: force balance argument leads to an exponent slightly larger than 0.4 (Aubert et al. 2001; Davidson 2013; Starchenko & Jones 2002).

Force balance: Quasi-geostrophic balance (Coriolis and pressure forces) at the largest scales, followed by an ageostrophic magneto-Archimedean-Coriolis balance (MAC).

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

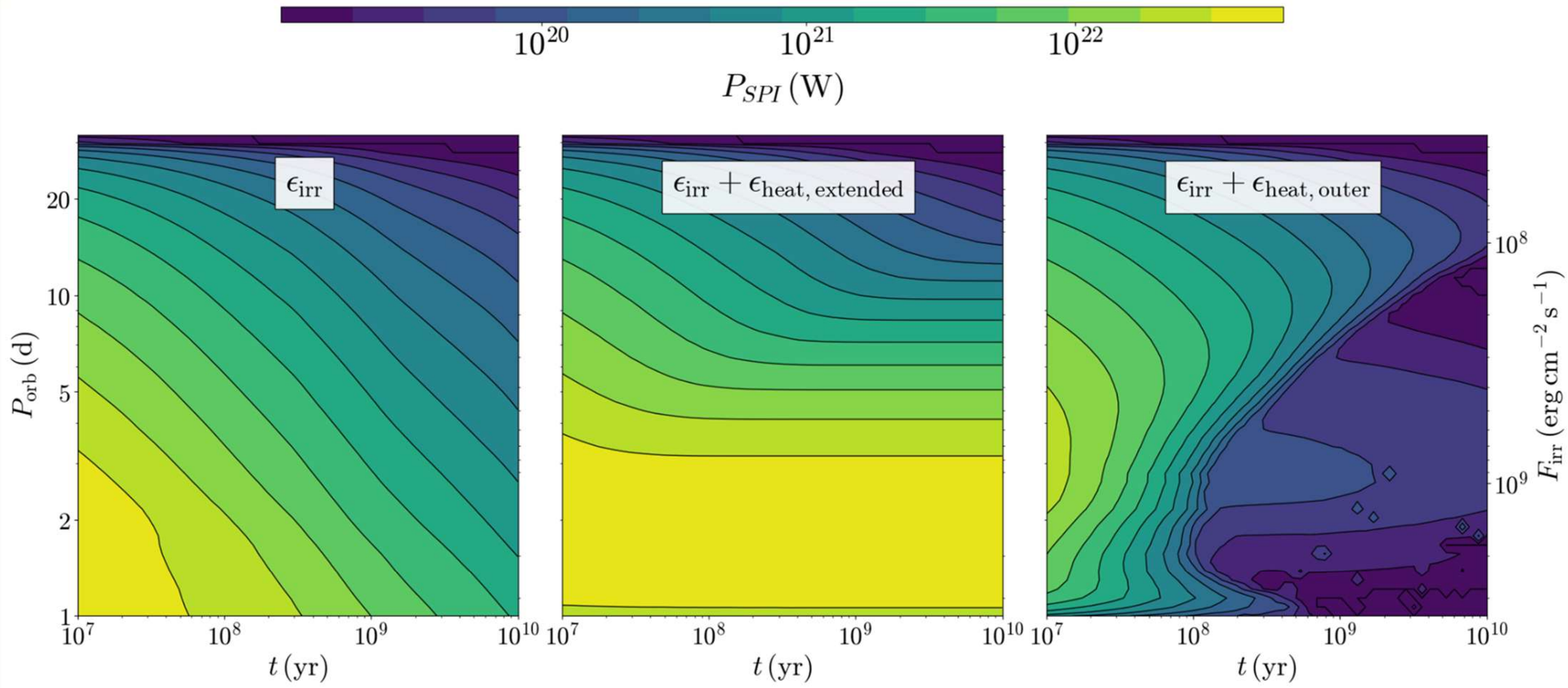


$$P_r \propto \dot{M}_\star^{2/3} M_{dip}^{2/3} a^{-4/3} V_W^{5/3}$$

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

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

Observational consequences: SPI power, from star (Lanza 2013)



$$P_{SPI} \simeq \frac{2\pi}{\mu_o} f_{AP} \, R_P^2 \, B_{dip,pole}^2 \, v_{rel},$$

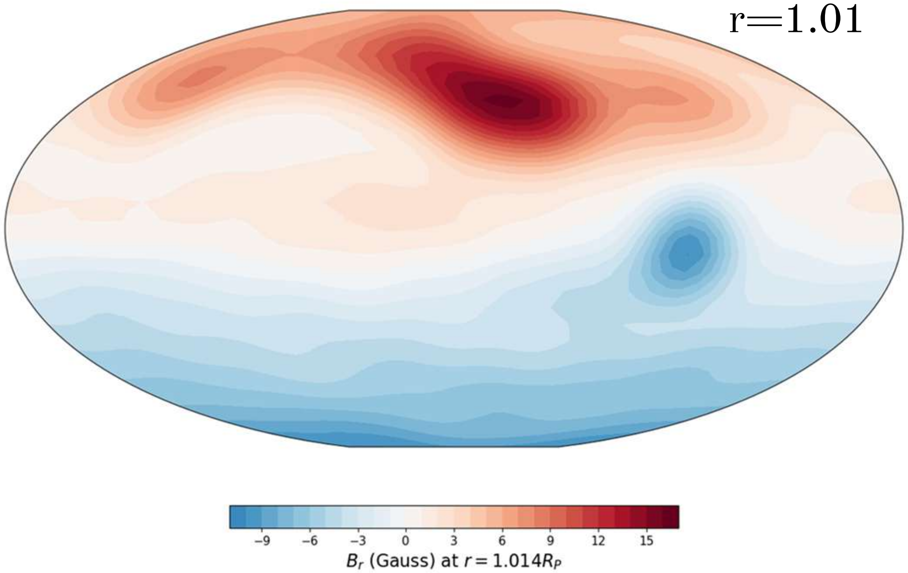
$$f_{AP} = 1 - \left(1 - \frac{3\xi^{1/3}}{2+\xi}\right)$$

$$\xi \; = \; B_\star(a)/B_{dip}$$

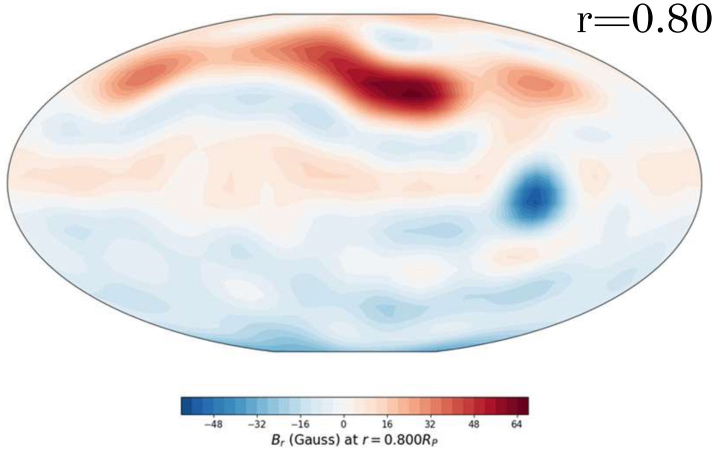
Downward continuation: Jupiter

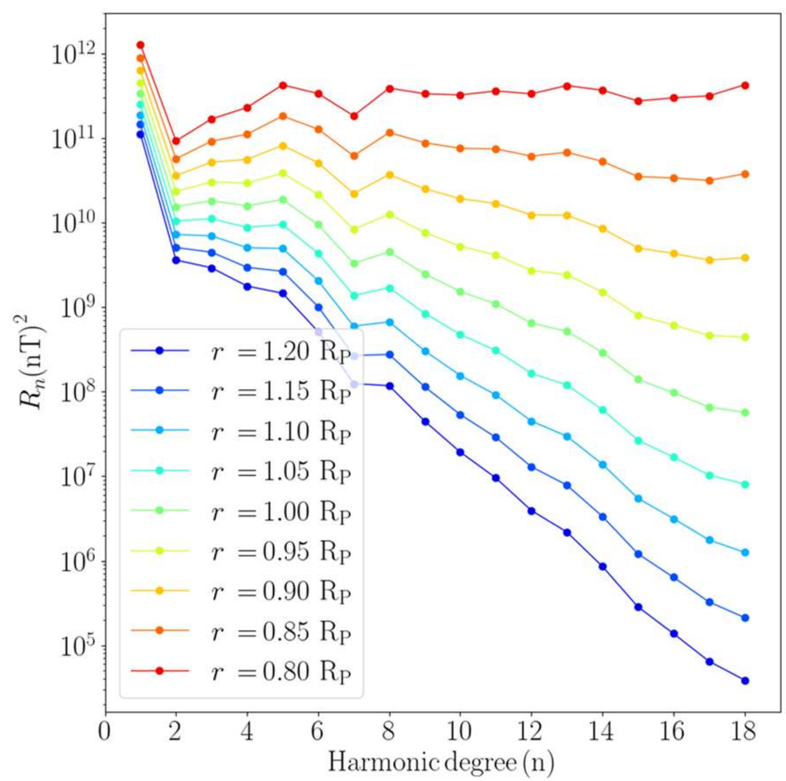
The order of magnitude is at the radius of which pressure is expected to reach metallization (Tsang & Jones 2020)

r=1.01

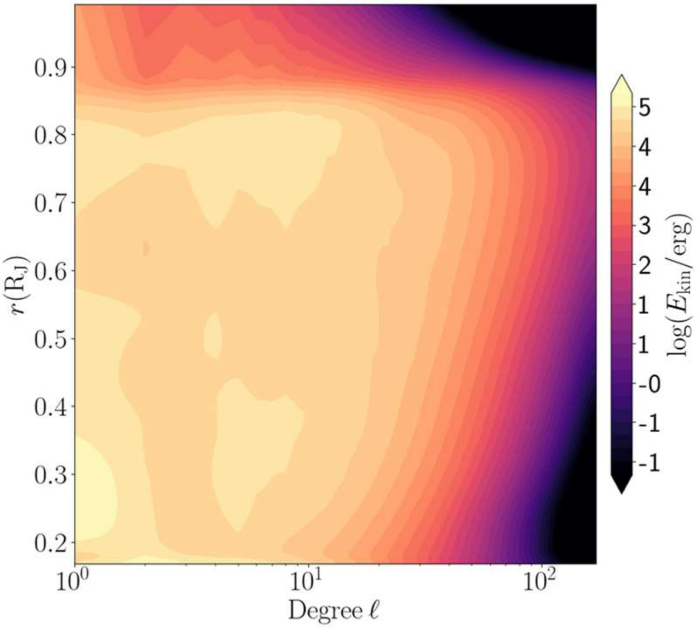


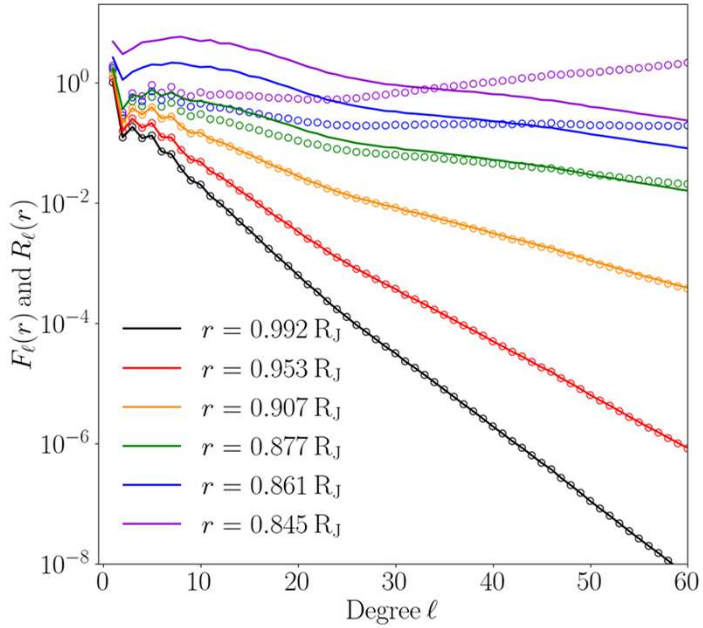
r=0.80

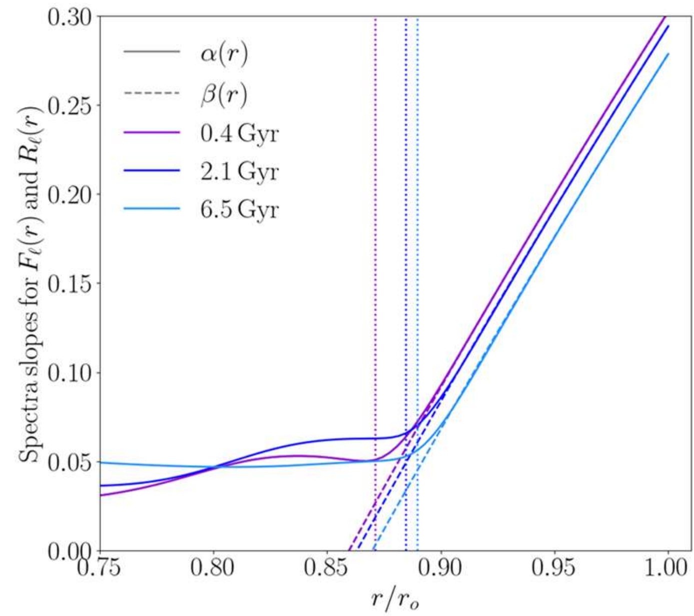




We can get a working definition of the dynamo surface







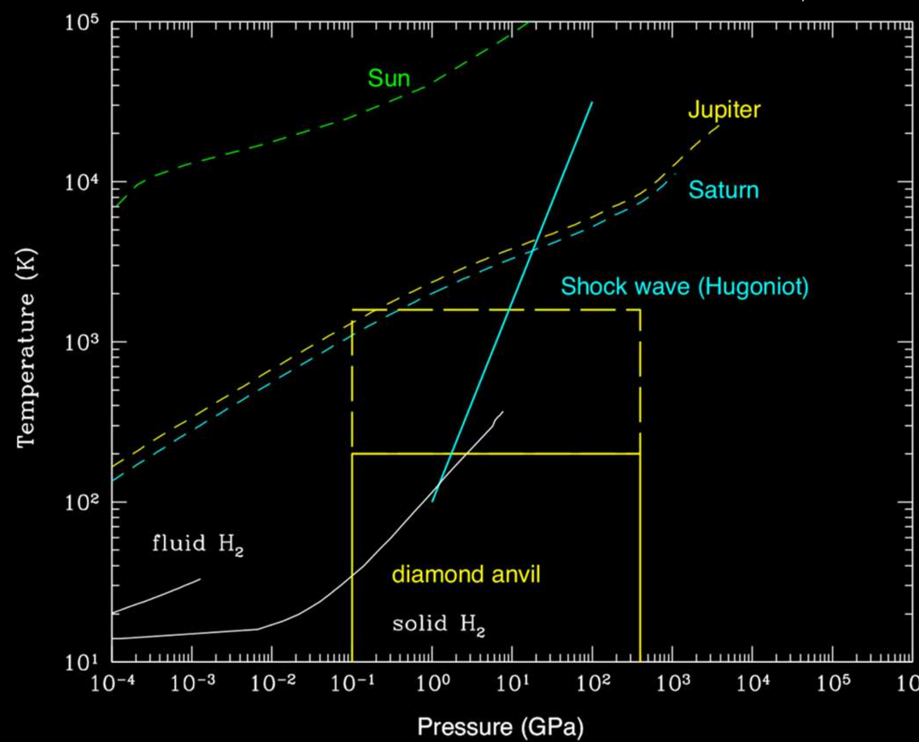
Calculate the slope of magnetic spectra from the outside by downward continuation, and see when it differs (Tsang & Jones 2020)

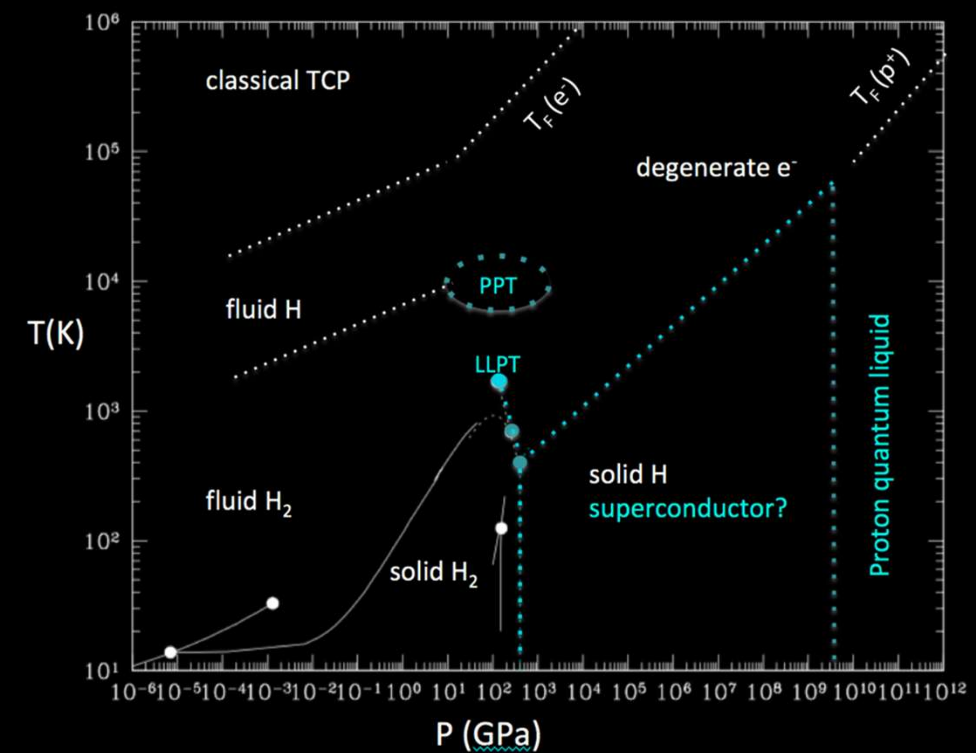
We recover values similar to r_m, so we take this as the working definition.

$$\frac{1}{\tilde{\lambda}(r)} = \tilde{\sigma}(r) = \begin{cases} 1 + (\tilde{\sigma}_m - 1)\left(\dfrac{r - r_i}{r_m - r_i}\right)^{-a} & r < r_m, \\ \tilde{\sigma}_m e^{-a\left(\frac{r - r_m}{r_m - r_i}\right)\frac{\tilde{\sigma}_m - 1}{\tilde{\sigma}_m}} & r \geq r_m. \end{cases}$$

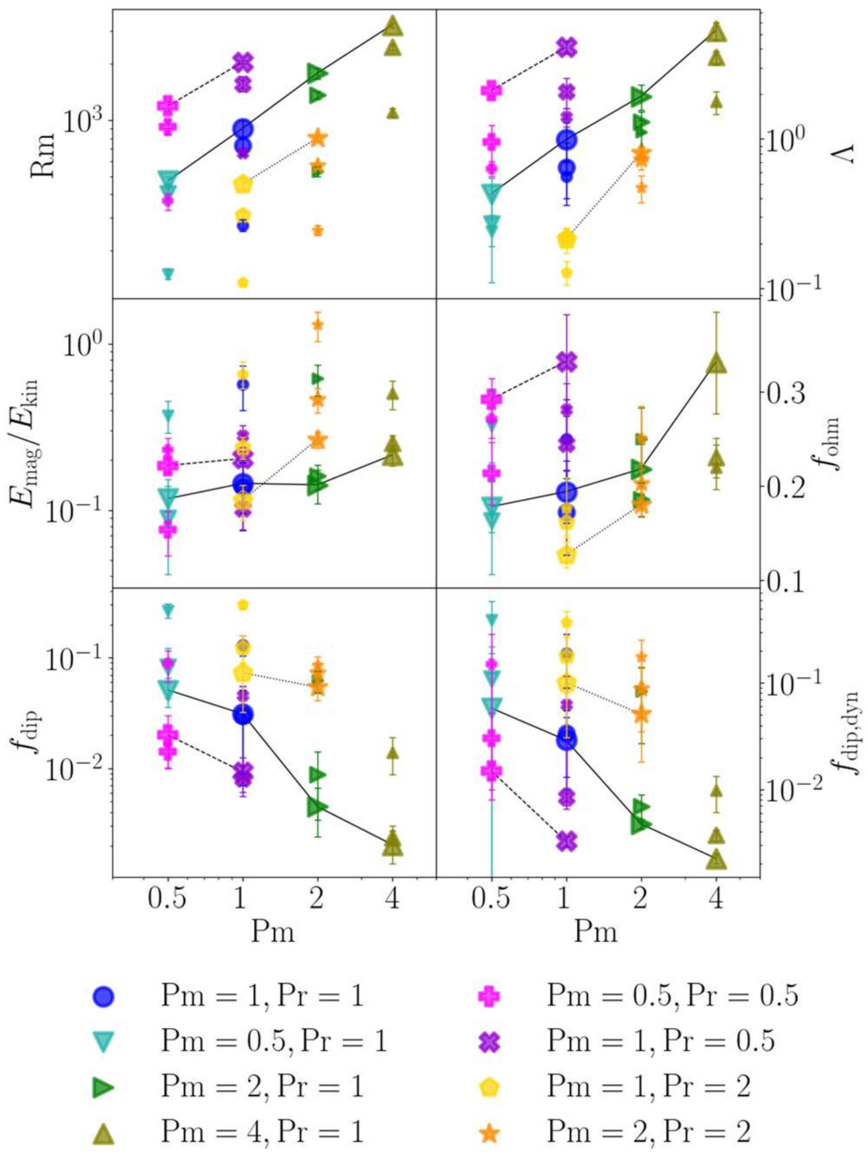
Hydrogen phase diagram

Bonitz et al, 2024: benchmark of dense hydrogen simulations (including PIMC, path integral Monte Carlo, and DFT, density functional theory)



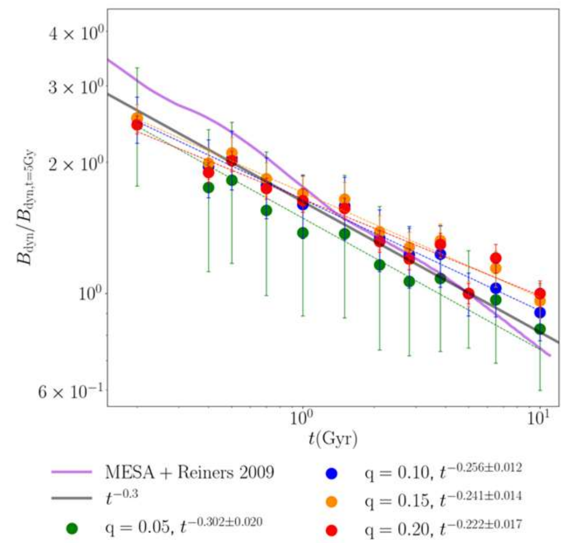


Metallic hydrogen starts at around 1 Mbar (or 100 GPa)



Evolutionary changes: different Prandtl numbers

- 0.5, 1 and 10 Gyr models
- Changing Pm and Pr does not change the trend in time.
- We still see multipolar to dipolar transitions
- Using time Pr(t) and Pm(t) could slightly change the evolutionary trends

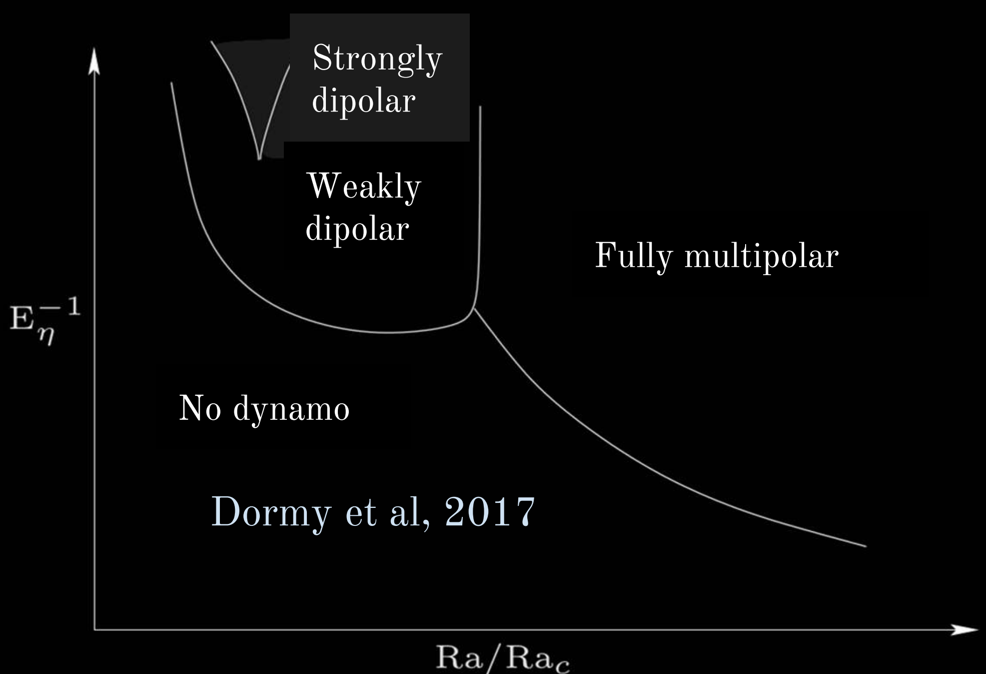


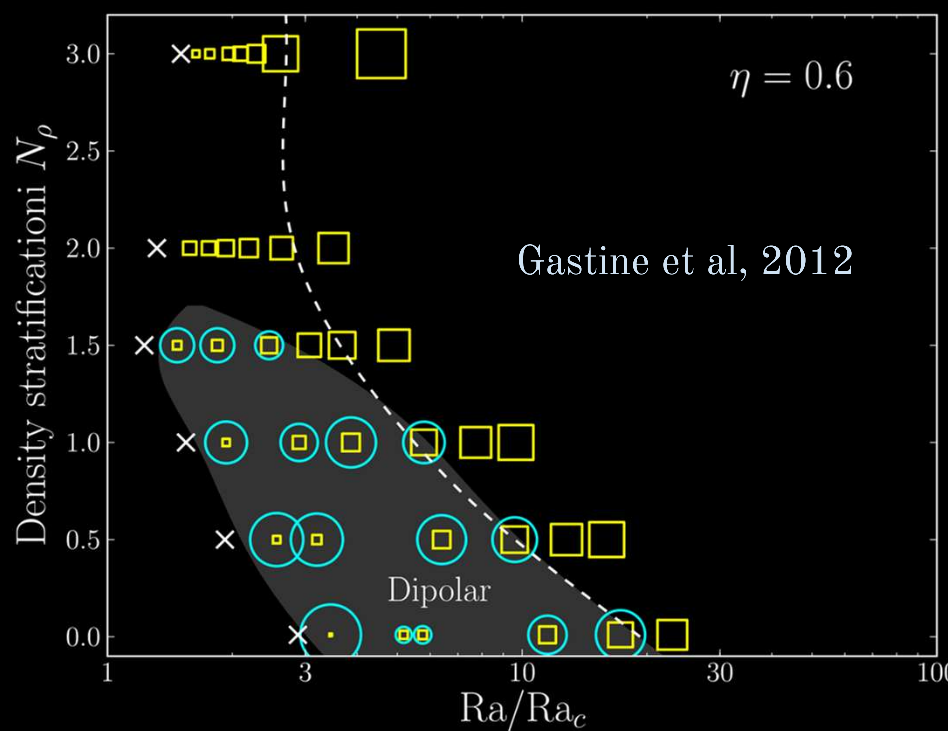
Dipolarity in simulations

Dipole dominated solutions are harder to get with density stratification.

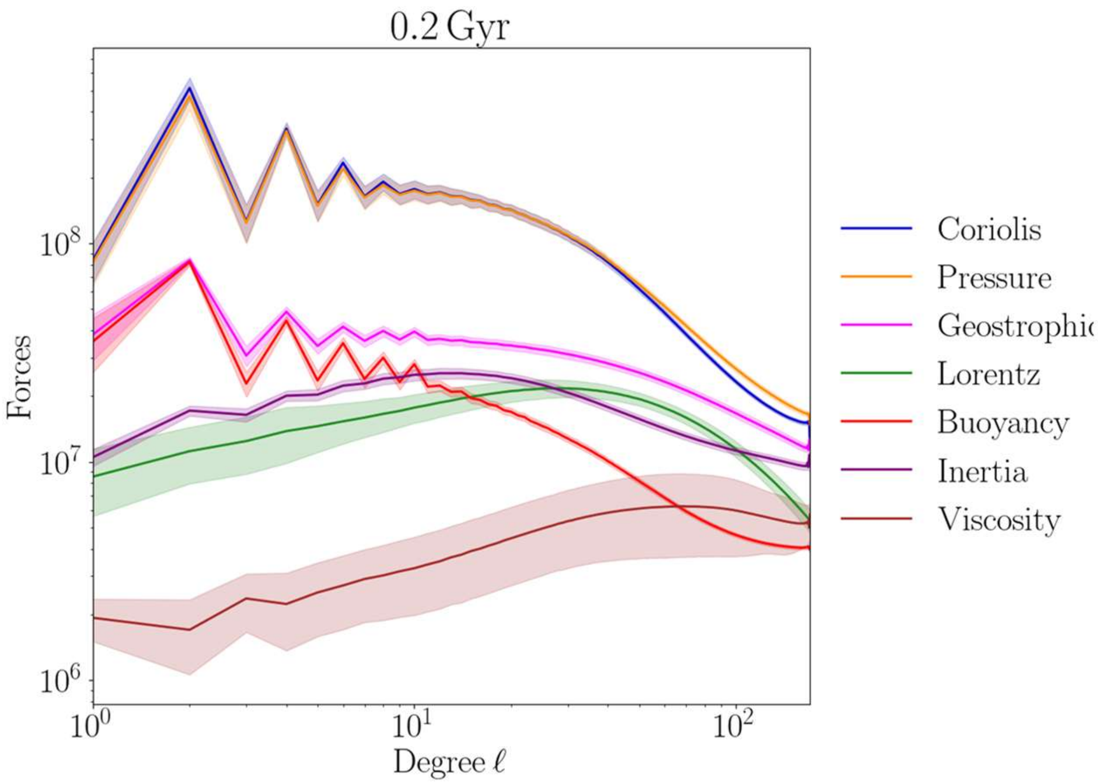
A transition from multipolar to dipolar is expected if the Rayleigh number is decreased.

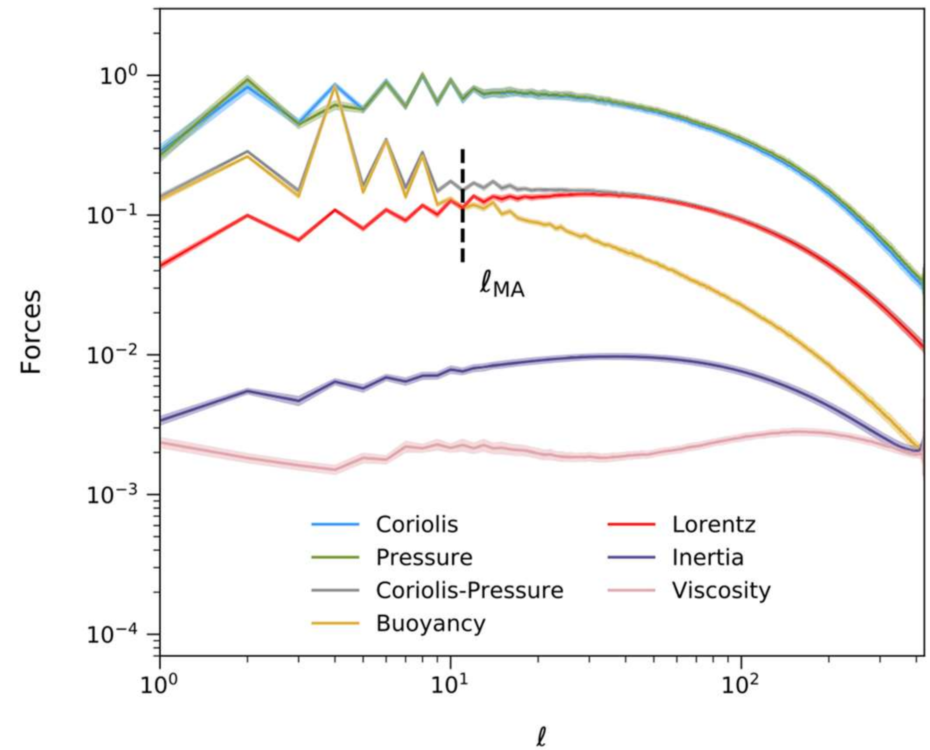
From Jupiter and Saturn, real gas giant dynamos are expected to be dipolar (at least a later stages)





Force balances

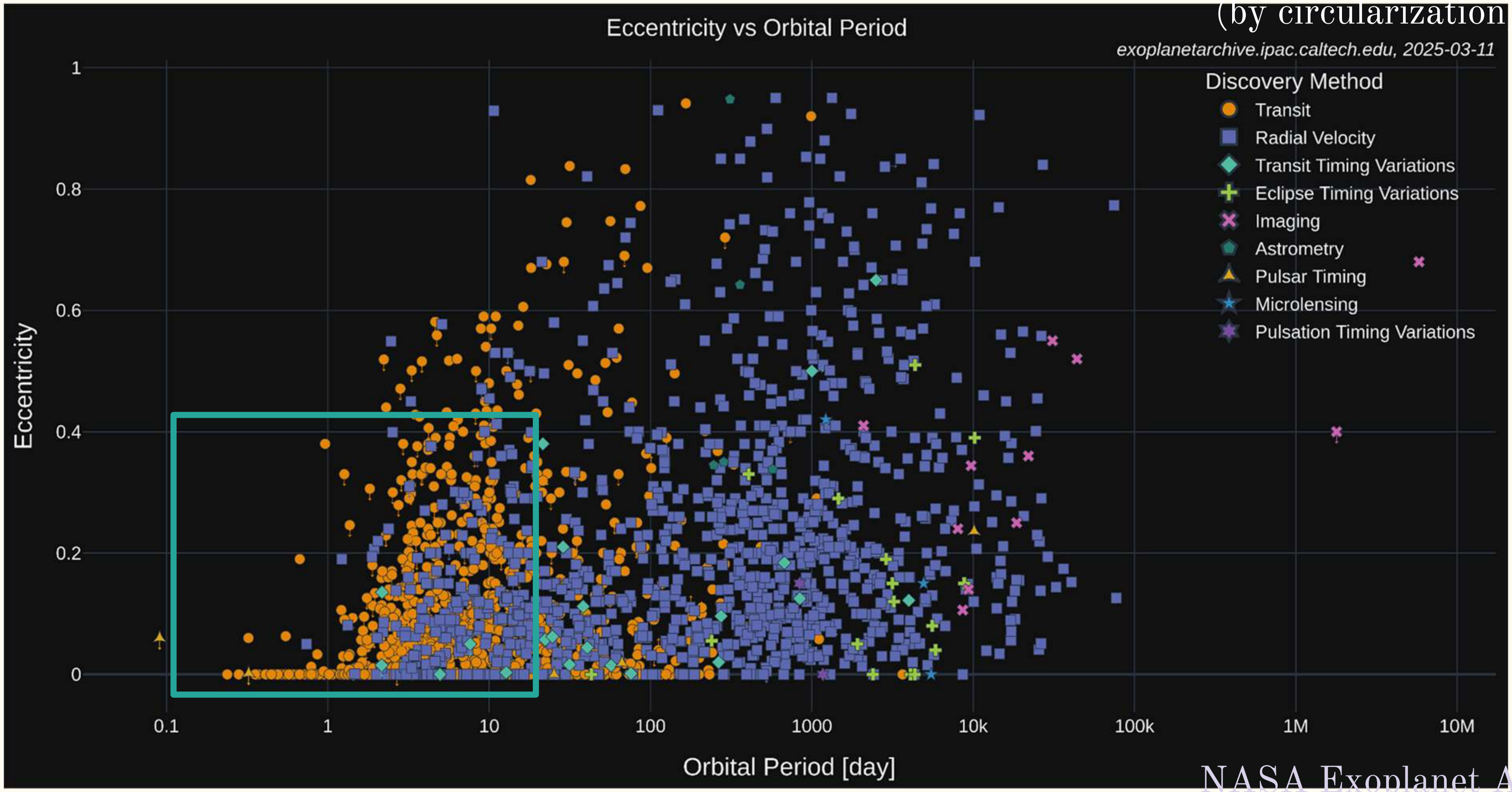




Hot Jupiters

Gas giants ($0.3\ M_J < M_P < 13\ M_J$)

Tidally locked and low eccentricity (by circularization)



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