Modelling some aspects of stellar magnetism with MagIC

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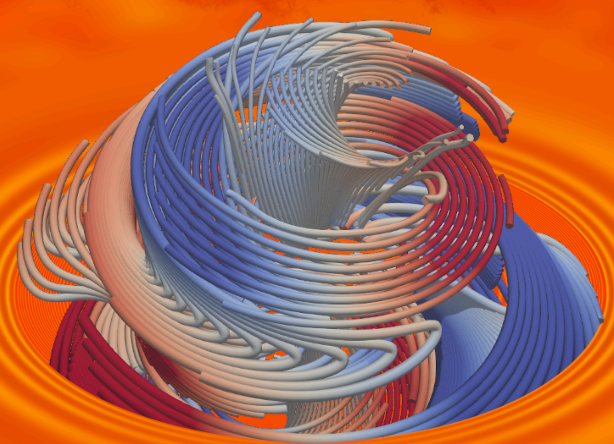
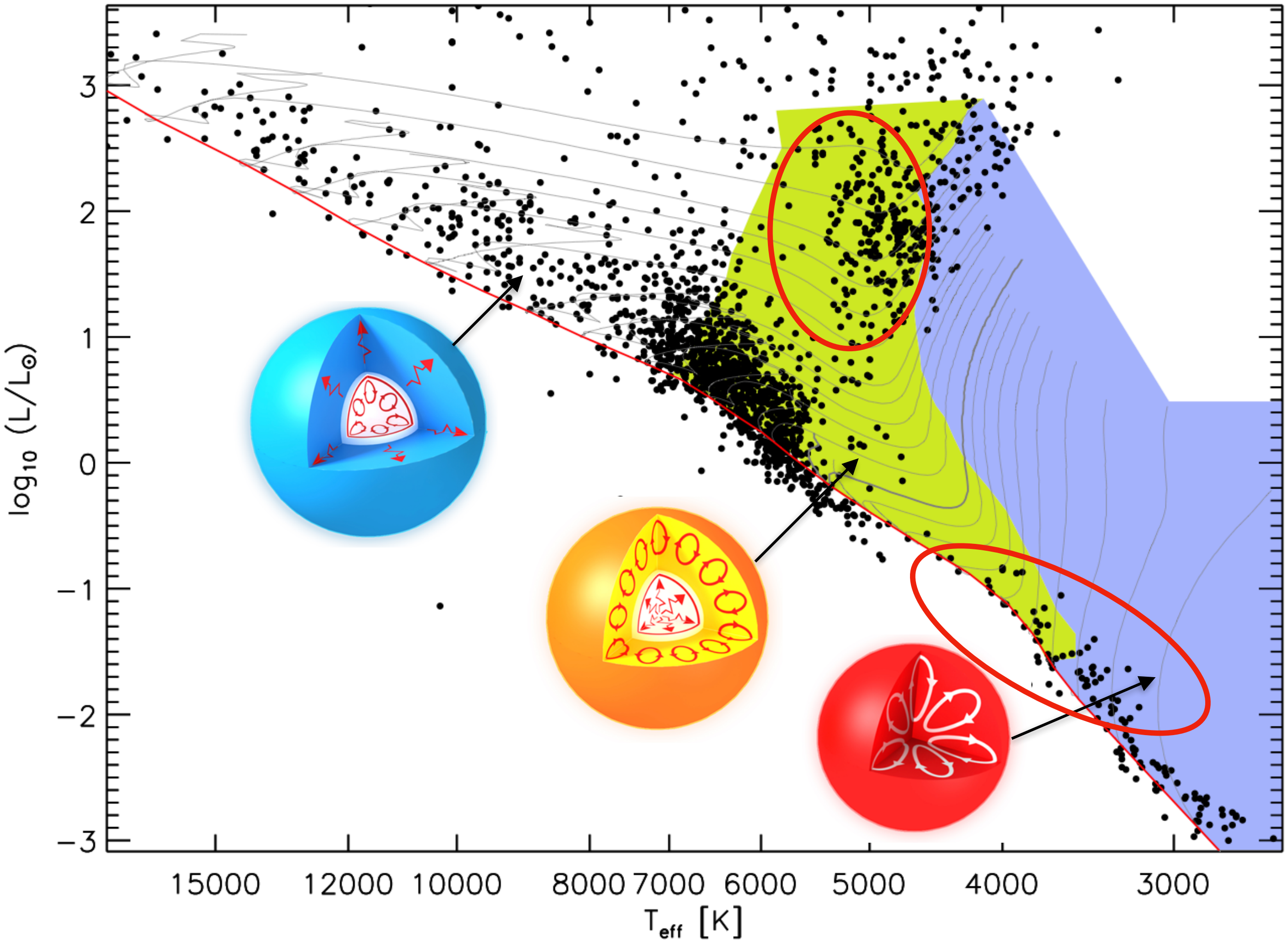


Grenoble, December 2025

Credit: J. Ballot, IRAP

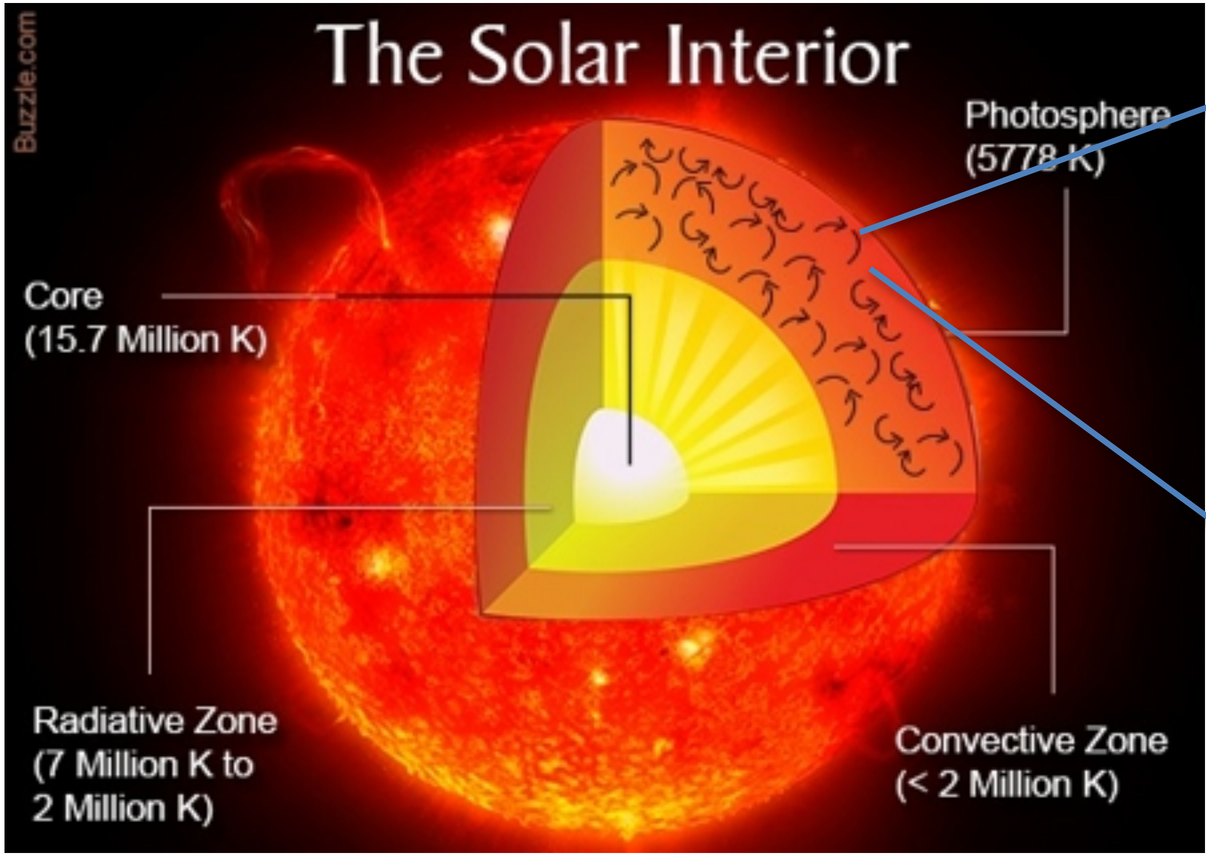
Internal structure of stars



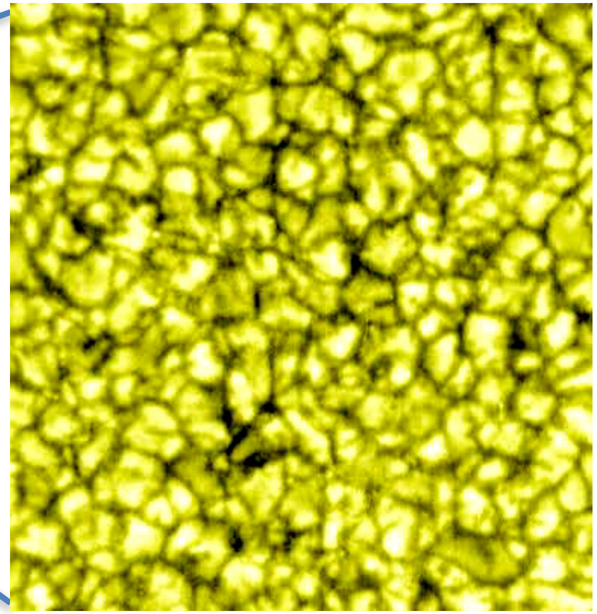
Focus in this presentation on:

- ✓ Convective envelopes of cool stars
- ✓ Radiative cores of red giant stars

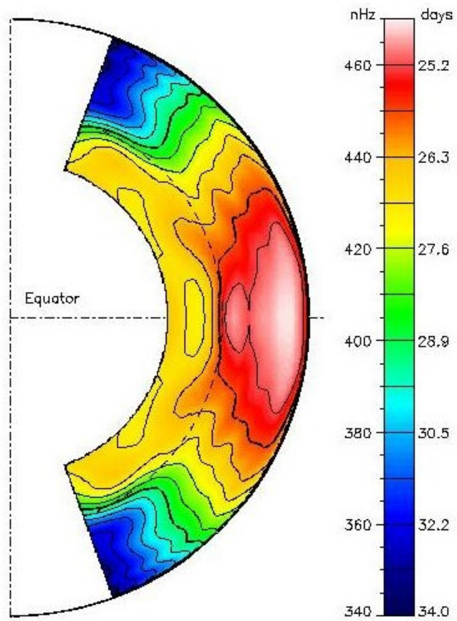
Solar interior and plasma flows



- ❑ Granulation (surface convection)

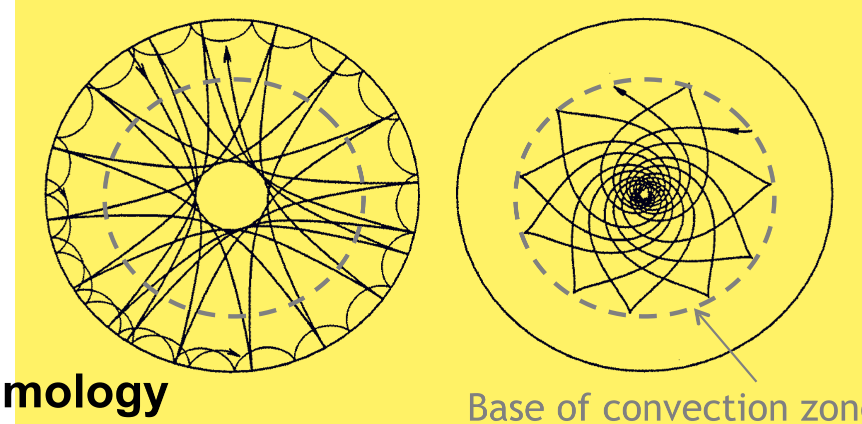


- ❑ Rotation



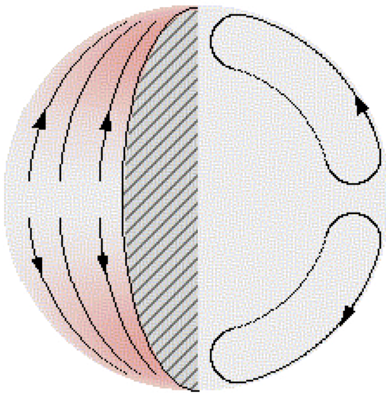
Schou et al. 98

Acoustic waves   Gravity waves



Helioseismology

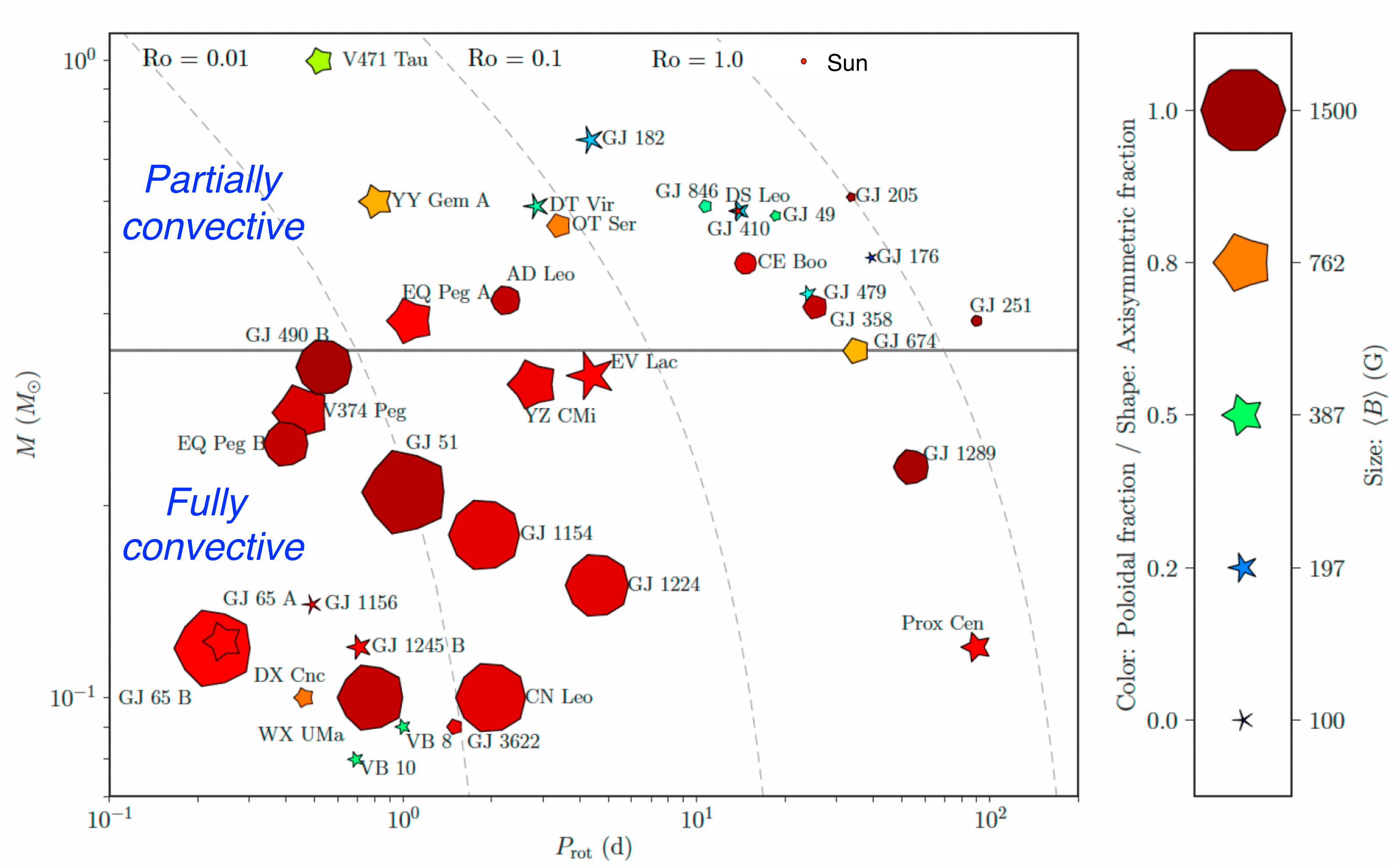
- ❑ Meridional flow



Gizon et al. 2020

Magnetic fields in cool stars (M dwarfs)

Morin, Donati et al. (2008-2011)
Moutou et al. (2017)
Kochukhov & Shulyak (2019)
Klein et al. (2021)
Kochukhov (2021)
Zaire PhD thesis (2022)

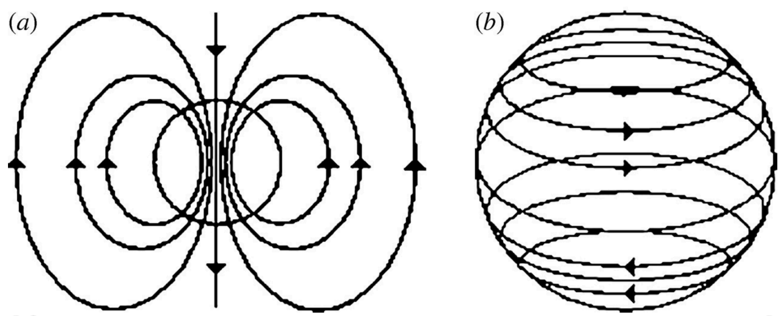


Rossby number

$$Ro = P_{rot}/\tau_c$$

- Mostly multipolar $M_\odot > 0.35$ for and/or $Ro < 0.1$
- Mostly dipolar for $M_\odot < 0.35$ and/or $Ro > 0.1$

Poloidal Toroidal



What controls the magnetic topology of cool stars?

Anelastic MHD simulations

- Anelastic equations: filtering out sound waves to avoid untractably small time steps: very efficient and accurate for stellar interiors!

$$\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\vec{\nabla}\vec{u}\right) = -\vec{\nabla}\left(\frac{p'}{\tilde{\rho}}\right) - \frac{2}{E}\vec{e_z}\times\vec{u} + \frac{Ra}{Pr}\tilde{g}\, s'\,\vec{e_r} + \frac{Ra_\xi}{Sc}\tilde{g}\,\xi'\,\vec{e_r} + \frac{1}{Pm\,E\,\tilde{\rho}}\left(\vec{\nabla}\times\vec{B}\right)\times\vec{B} + \frac{1}{\tilde{\rho}}\vec{\nabla}\cdot\mathsf{S},$$

$$\vec{\nabla}\cdot\tilde{\rho}\vec{u} = 0,$$

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

$$\tilde{\rho}\left(\frac{\partial \xi'}{\partial t} + \vec{u}\cdot\vec{\nabla}\xi'\right) = \frac{1}{Sc}\vec{\nabla}\cdot\left(\kappa_\xi(r)\tilde{\rho}\vec{\nabla}\xi'\right)$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times\left(\vec{u}\times\vec{B}\right) - \frac{1}{Pm}\vec{\nabla}\times\left(\lambda(r)\,\vec{\nabla}\times\vec{B}\right),$$

$$\tilde{\rho}\tilde{T}\left(\frac{\partial s'}{\partial t} + \vec{u}\cdot\vec{\nabla}s'\right) = \frac{1}{Pr}\vec{\nabla}\cdot\left(\kappa(r)\tilde{\rho}\tilde{T}\vec{\nabla}s'\right) + \frac{Pr\,Di}{Ra}\Phi_\nu + \frac{Pr\,Di}{Pm^2\,E\,Ra}\lambda(r)\left(\vec{\nabla}\times\vec{B}\right)^2,$$

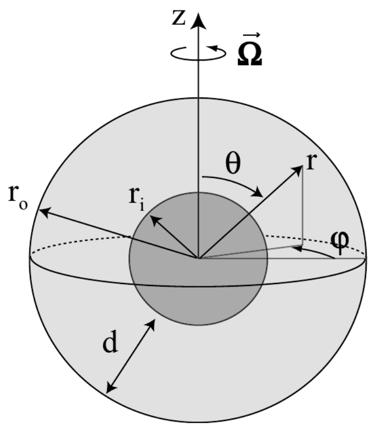
- Dimensionless control parameters

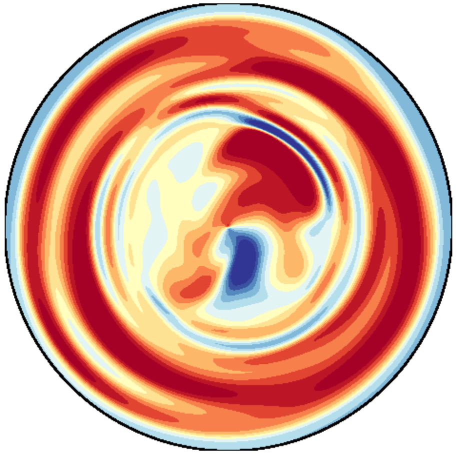
$$E = \frac{\nu}{\Omega d^2},\qquad Ra = \frac{\alpha_o g_o T_o d^3 \Delta s}{c_p \kappa_o \nu_o},\qquad Pr = \frac{\nu_o}{\kappa_o},\qquad Pm = \frac{\nu_o}{\lambda_i}.$$

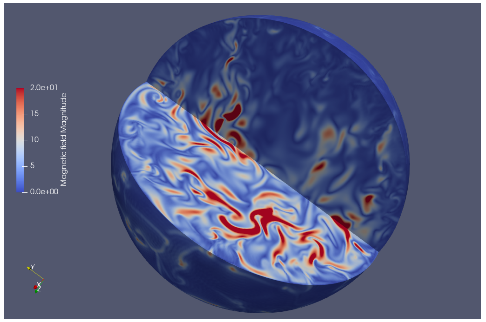
Viscosity/Coriolis | *Buoyancy/Dissipation* | *Viscosity/Thermal diff* | *Viscosity/Mag diff*

The MagIC code

❑ Geometry and numerical method





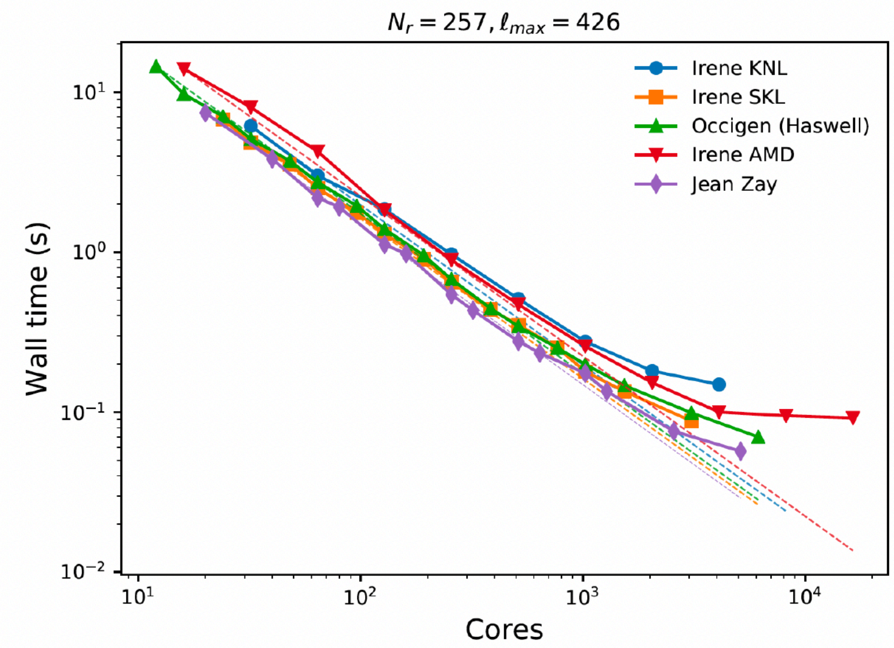


Wicht 2002, Gastine & Wicht 2012

- Boussinesq/anelastic MHD equations
- Pseudo-spectral code: spherical harmonics in θ, ϕ (use of SHTns) Chebyshev or FD in r
- Several IMEX time stepping methods (here CNAB2 method)
- Full sphere setup now
- Freely available on Github: https://magic-sph.github.io/

❑ Parallelisation and scaling

- Hybrid MPI/OpenMP parallelisation
- Runs on regional and national centers
- Scales up to several thousands of CPUs
- No GPU version yet

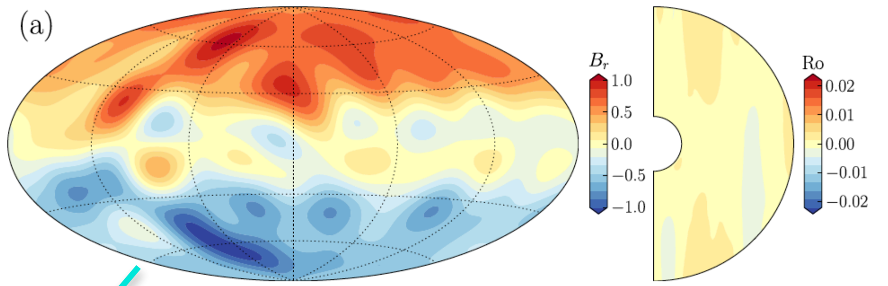


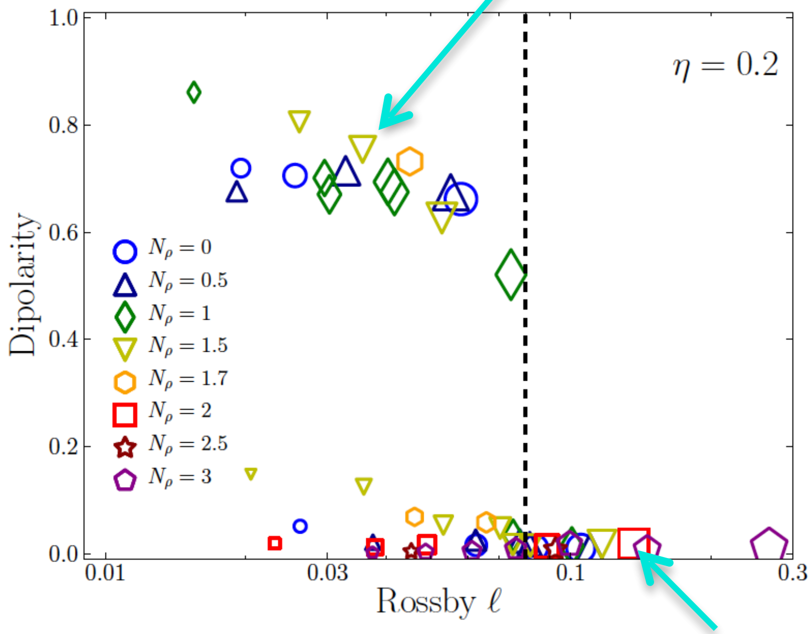
Magnetic topology in cool stars: influence of the Rossby number

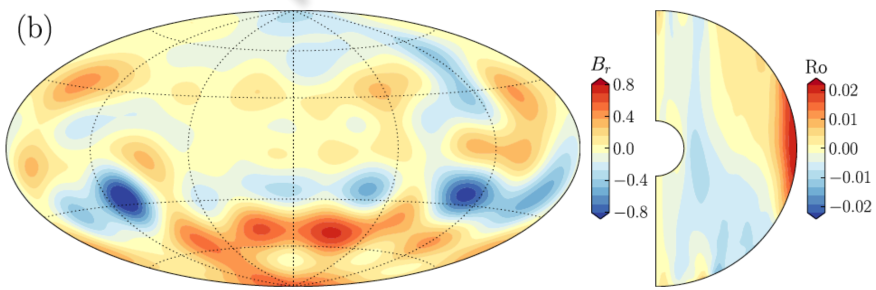
- ❑ Change in Rossby
  Ro=inertia/Coriolis
  (also seen in planetary dynamos: Christensen & Aubert 2006)

  - Small Ro:
    Ordering role of Coriolis=dipolar
    (no role of shear)

  - Large Ro:
    Inertia becomes dominant=multipolar
    (important role of shear)







Gastine et al. (2012, 2013)
Raynaud et al. (2015)
Petitdemange (2018)

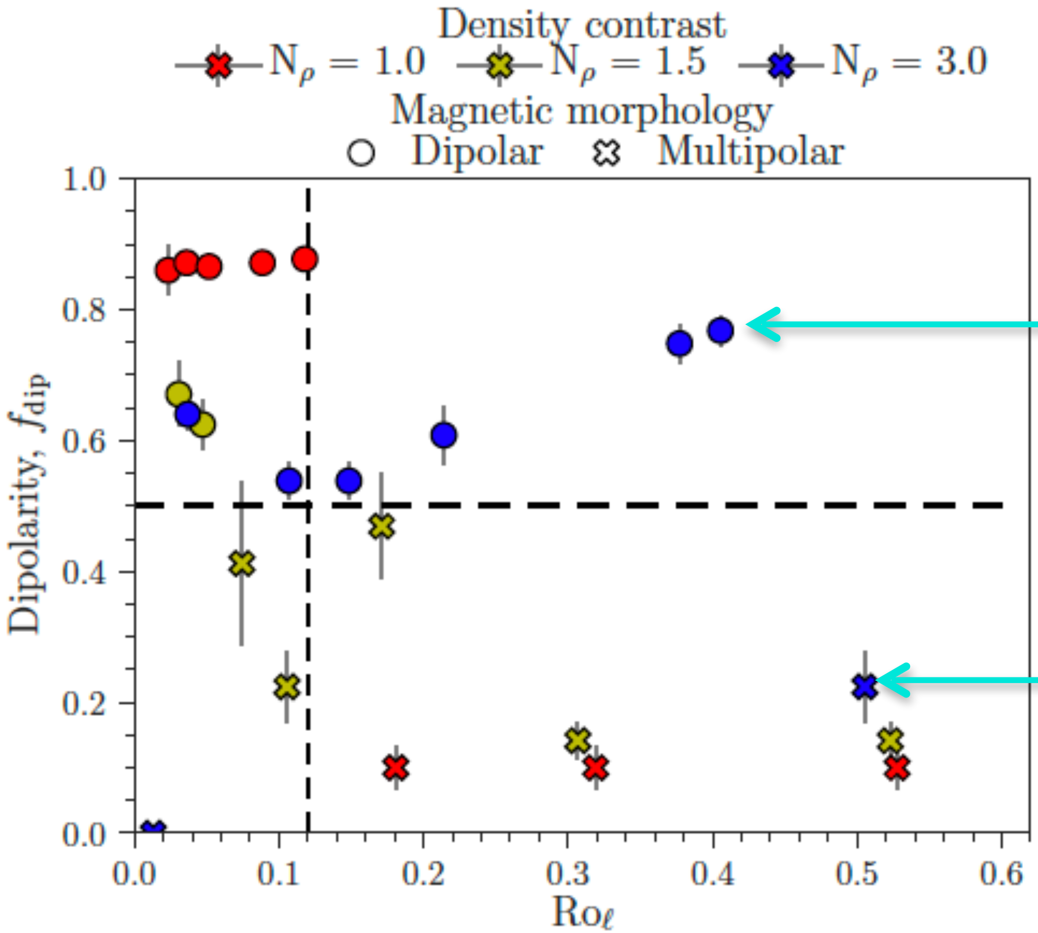
- ❑ Strong stratification leads to multipolar fields ? $N_\rho = \ln(\rho_i/\rho_o)$
  Yadav et al. 2015, 2016

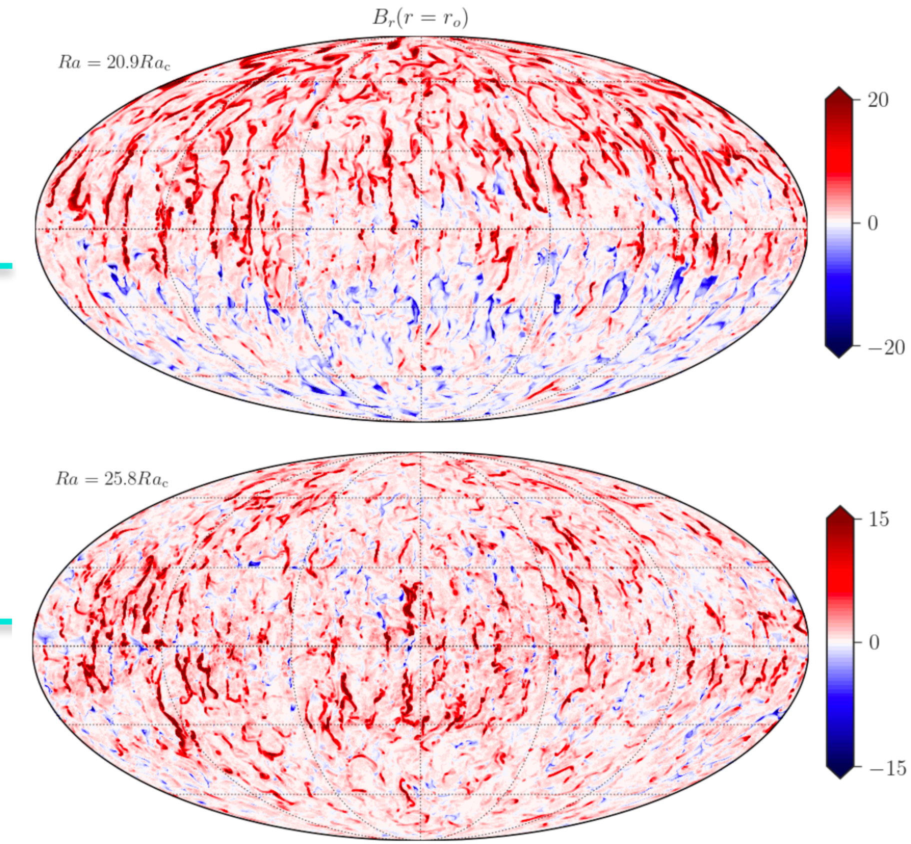
Magnetic topology: influence of the Rossby number?

Zaire, Jouve et al. 2022

MagIC Code
(pseudo-spectral 3D MHD)
Wicht 2002, Gastine & Wicht 2012

- With more turbulent simulations with stronger role of Lorentz force on dynamics (Pm=5), dipole seems to survive at high Ro and high Nrho.

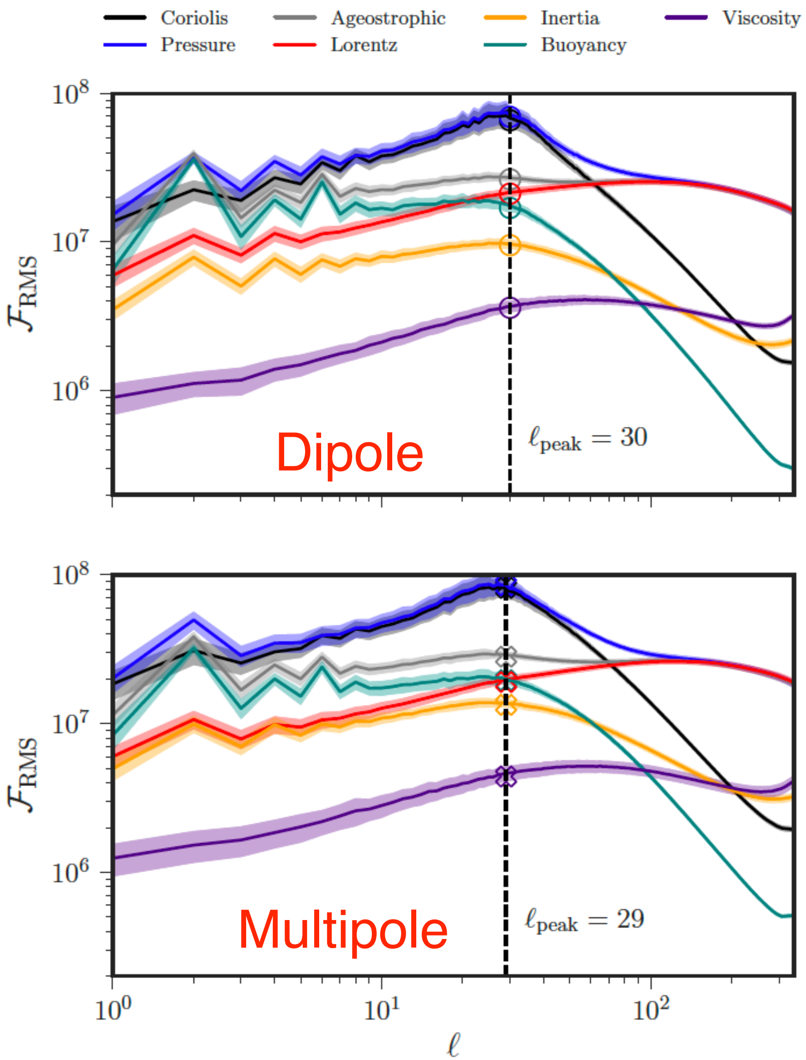




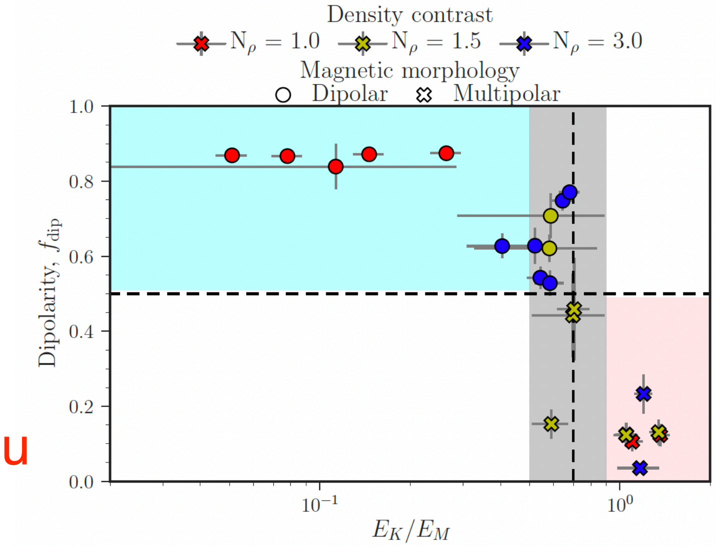
Magnetic topology: influence of the Rossby number?

- Need to look at new force balance (Schwaiger et al. 2019)
- The ratio of inertia to Lorentz forces (instead of inertia to Coriolis) seems to be a better indicator of dipolarity => ratio of kinetic to magnetic energies as a proxy

  First seen in Boussinesq calculations of Menu et al. 2020 and then Tassin et al. 2021

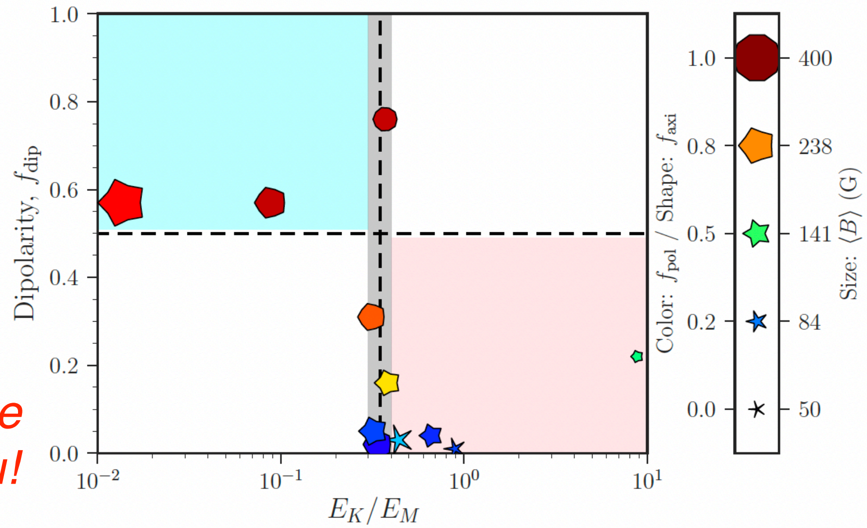


Simu



Obs

More to come with SPIRou!

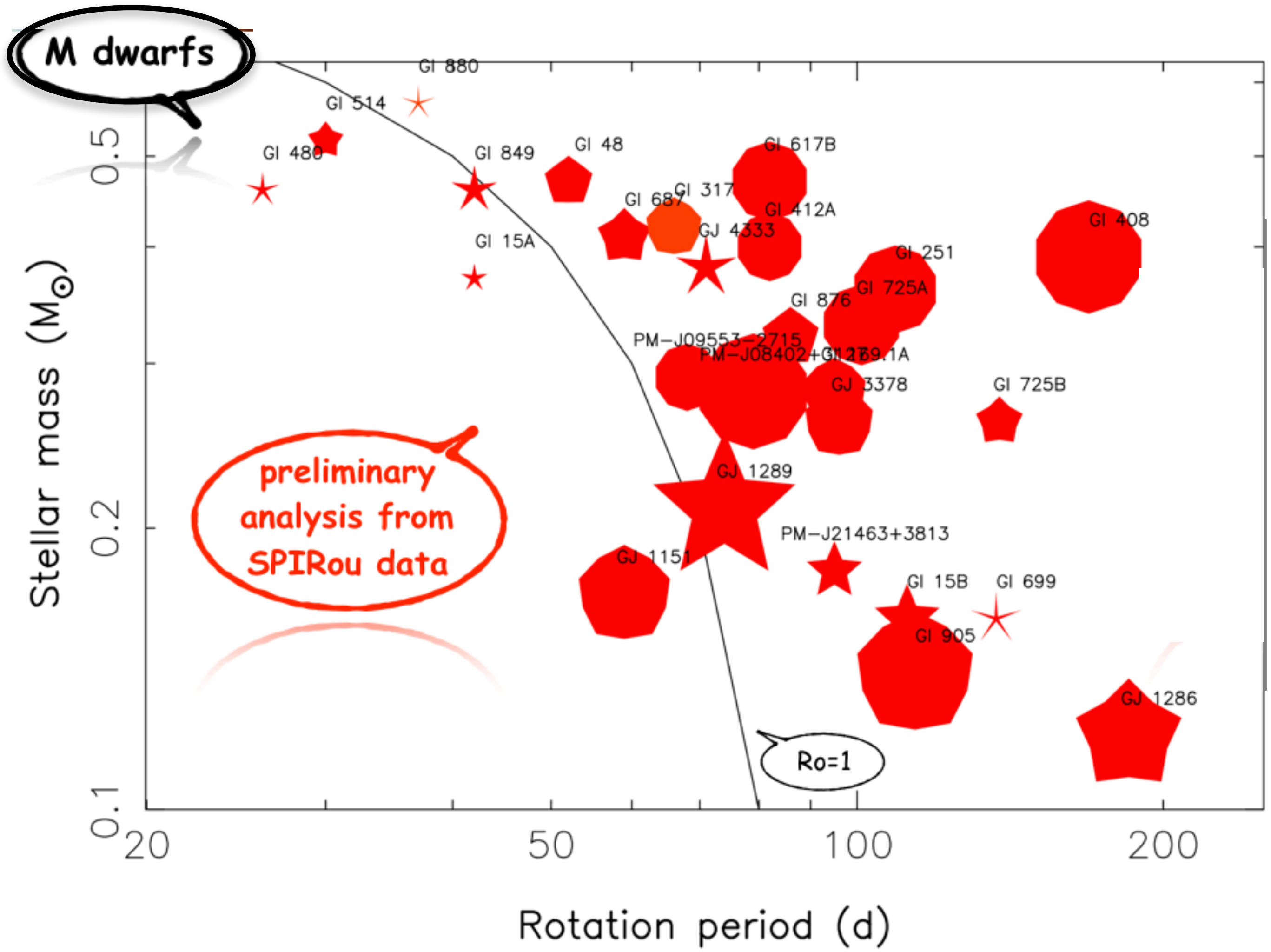


Magnetic topology: influence of the Rossby number?

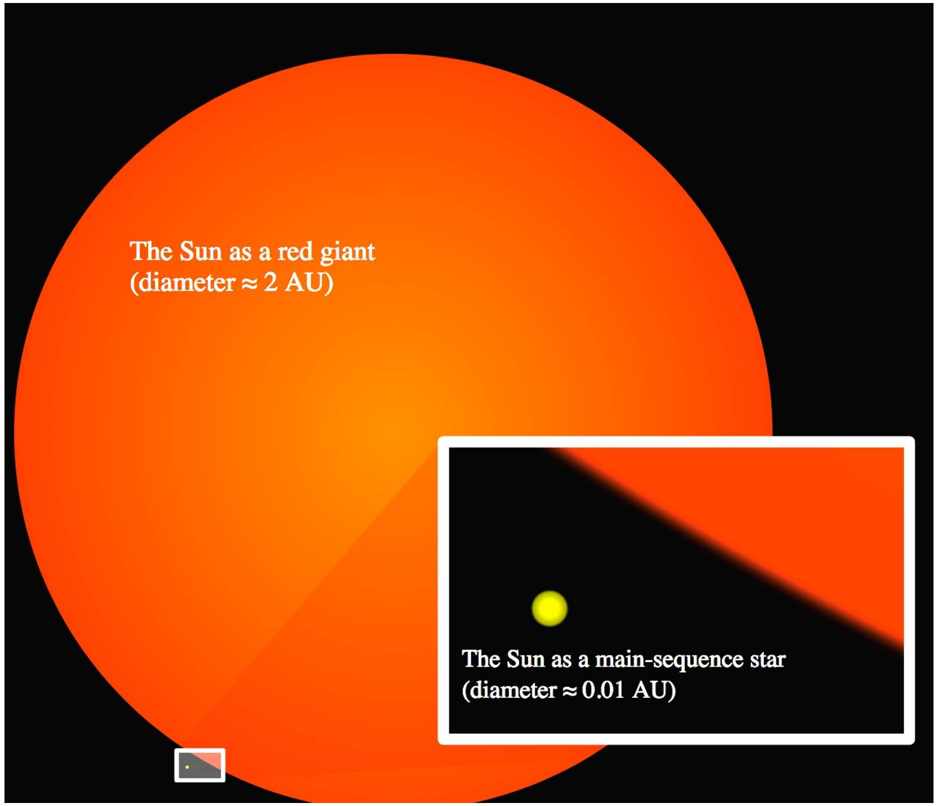
- New SPIRou results

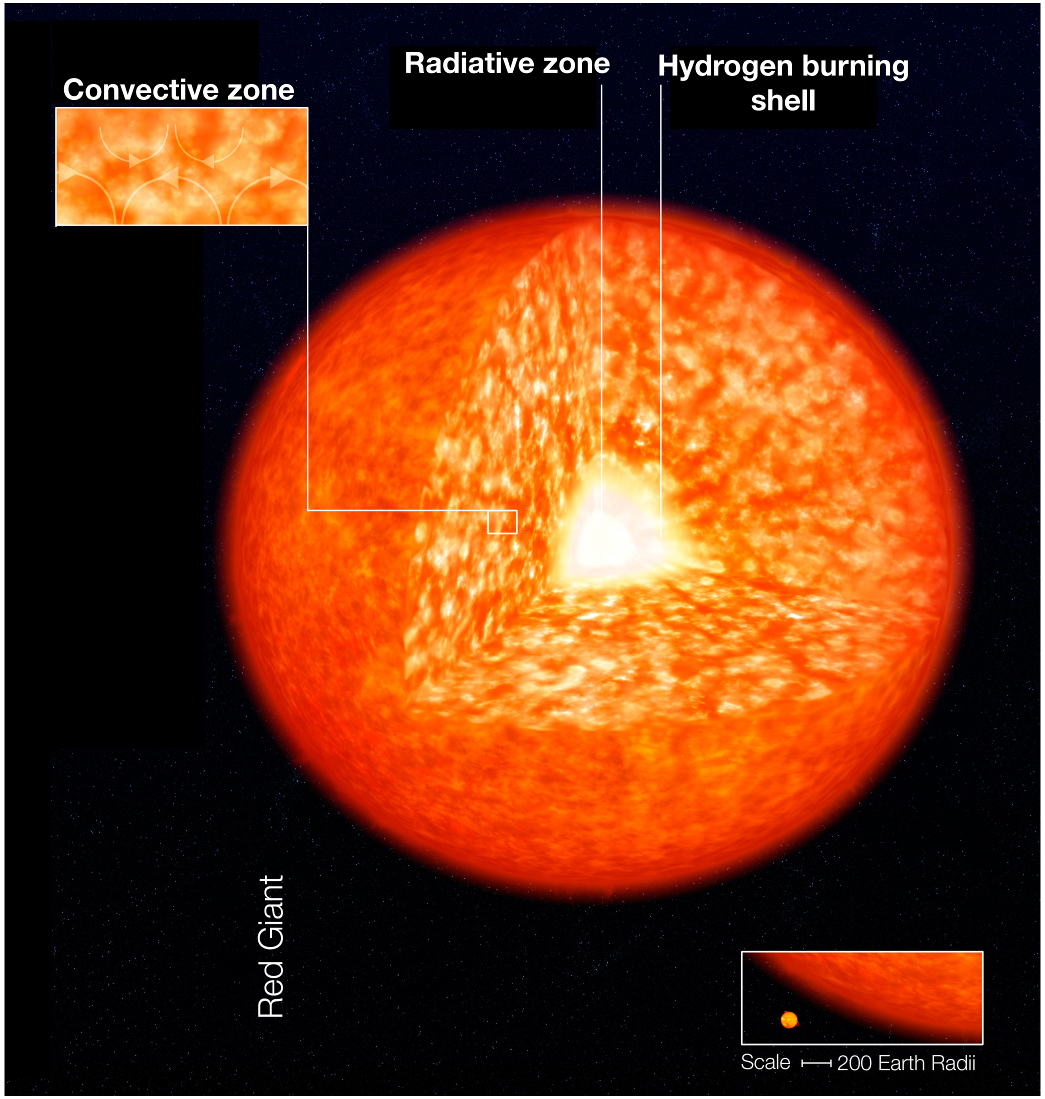
  Donati et al. (not published yet)
  Lehmann et al. 2024, See et al. 2025

- 50 weakly active M dwarfs monitored for 7 semesters (2019-2022)
- Some polarity reversals (cycles?)
- Large-scale fields even for slow rotators (i.e. large Rossby numbers)



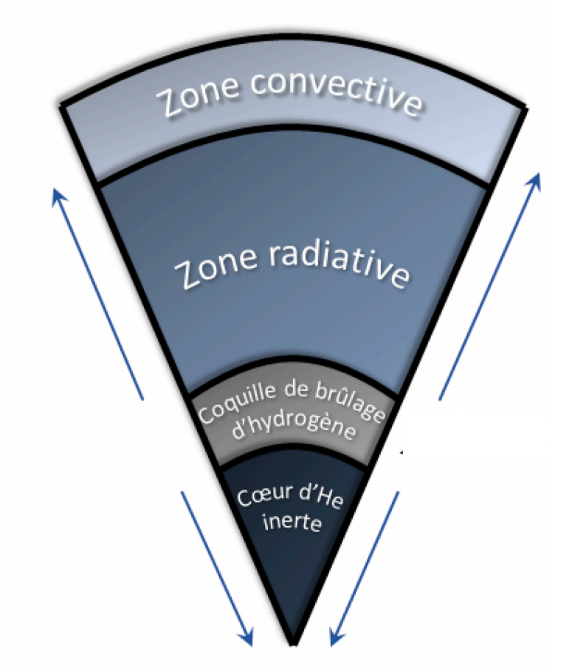
Red giant stars

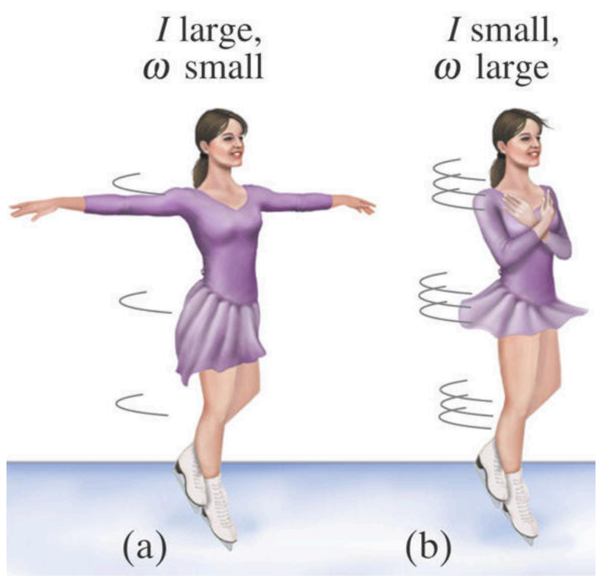


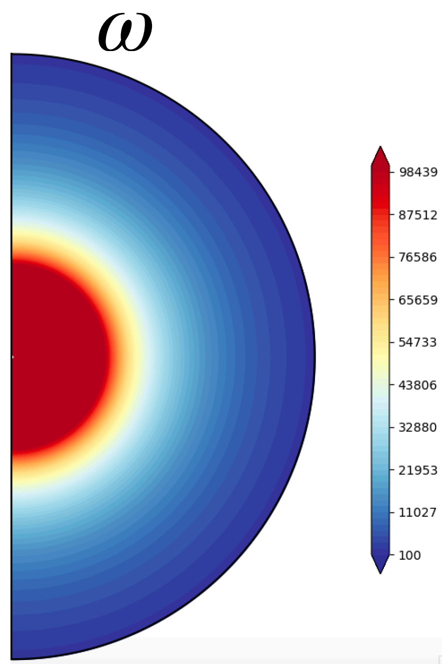


What do we know about them: their core rotates much slower than predicted

- Core contraction => spin-up







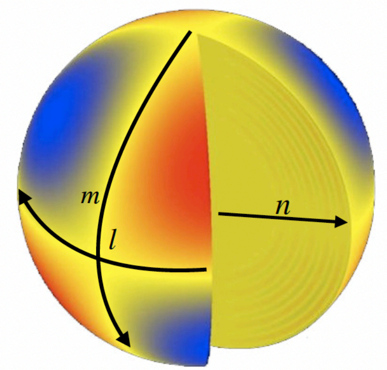
- But strong constrains by asteroseismology:
  - For young sub-giants: evidence for quasi-solid body rotation (Deheuvels et al. 2020)
  - For more evolved sub-giants: Core spin-up and envelope spin-down with $\Omega_c \approx 5 - 15\ \Omega_{env}$ (e.g. Deheuvels et al. 2014)
  - For red giants: Ω_c remains constant despite contraction (Gehan et al. 2018)

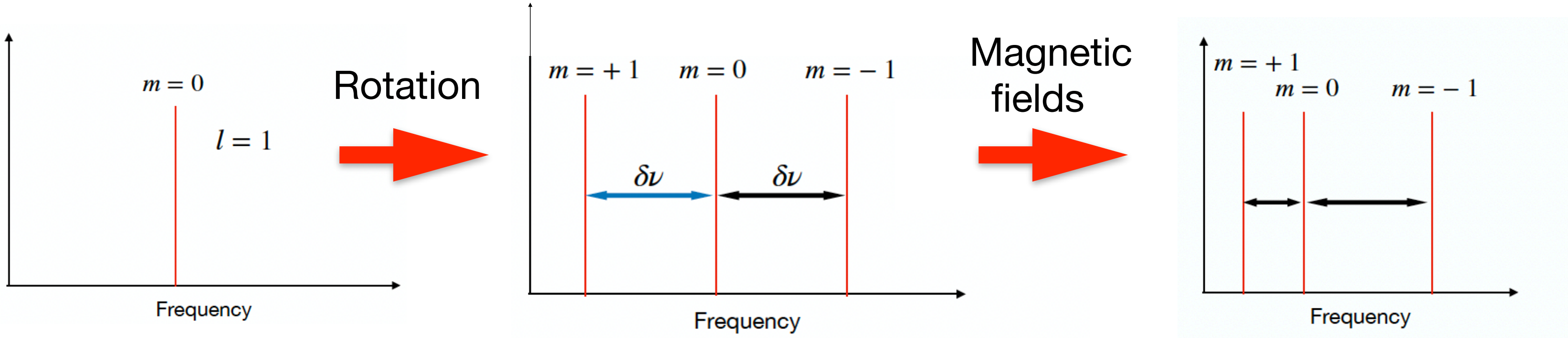
=> An efficient process at play to redistribute angular momentum at least during young sub-giant and red giant phases: **without magnetic fields, all models have failed so far**

What do we know about them: strong magnetic fields are present in their cores!

- Recent discovery of fields of 100kG and more in the core of red giants

ANR Beaming (PI S. Deheuvels): Li et al. 2022, Nature, Deheuvels et al. 2023, Li et al. 2023

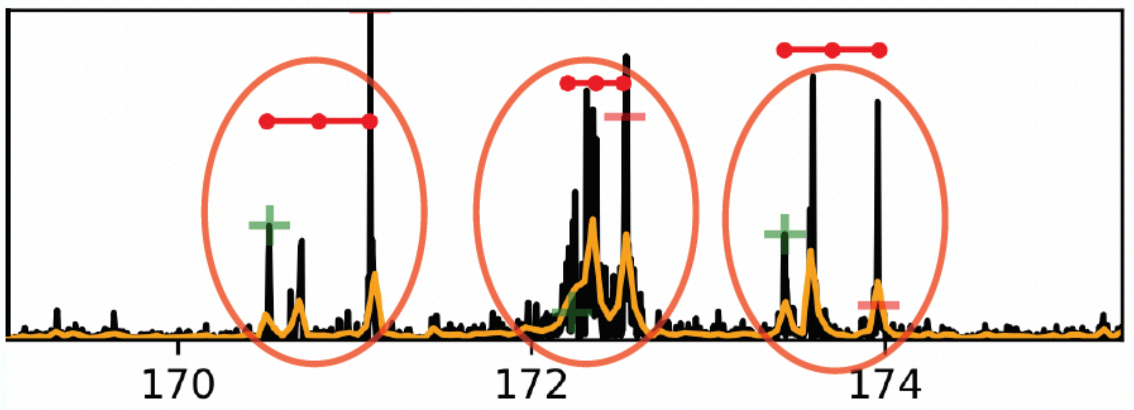




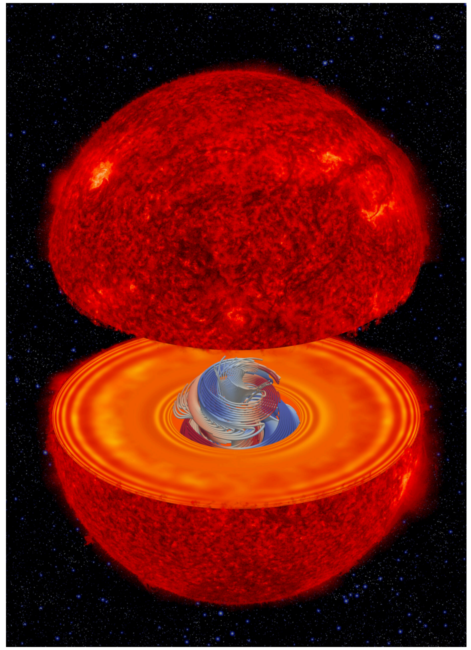
Symmetric multiplet

Positive or negative asymmetry

Observed magnetic splitting



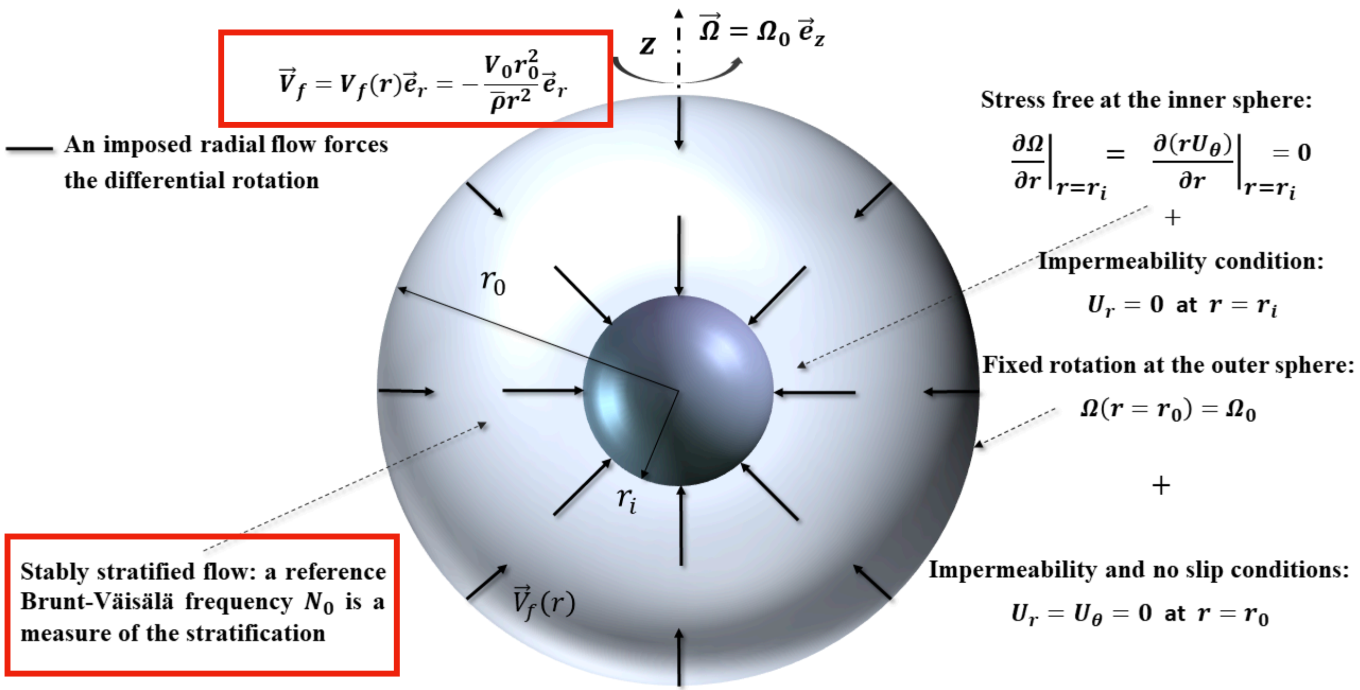
Positive asymmetric splittings



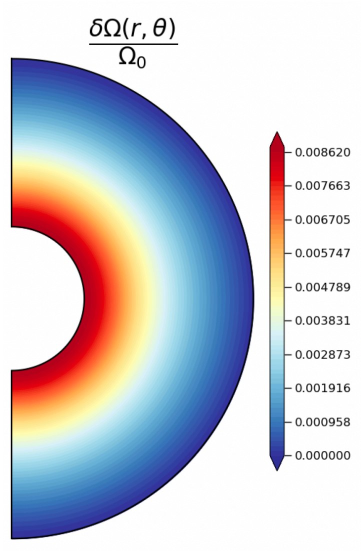
Can magnetic fields help at solving the AM problem in red giants?

2D Boussinesq/anelastic MHD simulations of a contracting RZ

- Fluid (+ mag field) contained in a contracting zone with stable stratification.



Gouhier et al. 2022, 2023



- Without magnetic fields, a radial differential rotation is established when N_0 is large (as expected)

- With an initial magnetic field?

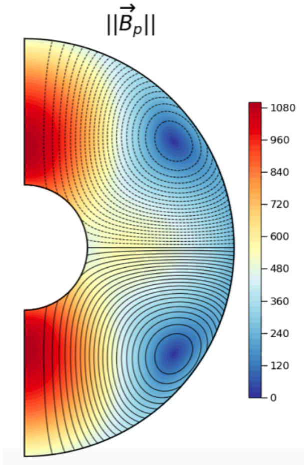
Alfvén time-scale: $\tau_{Ap} = \frac{\sqrt{4\pi\rho}\, r_o}{B_p}$

In stars (and in the simulations), the Alfvén time-scale is small compared to the contraction time-scale $\tau_c = r_o / V_0$

Magnetic tension + magnetorotational instability

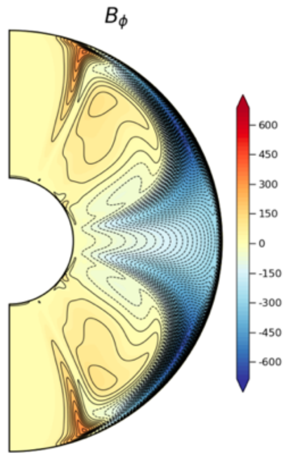
- Initial poloidal field, production of toroidal field, shaping of differential rotation by magnetic tension

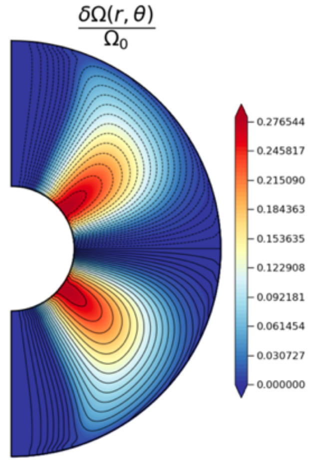
Initial quadrupolar field



+ contraction (i.e. forcing of DR on long timescales)

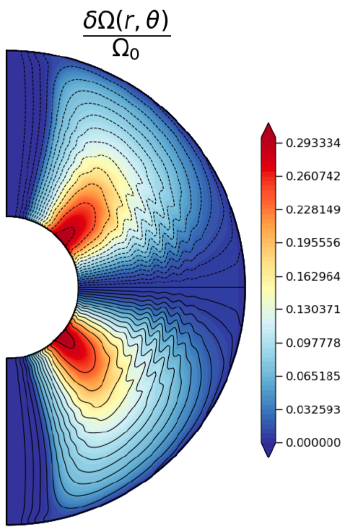
=>

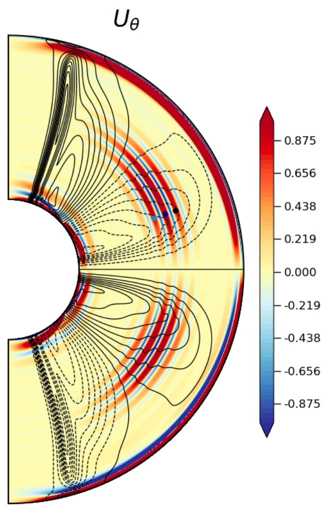


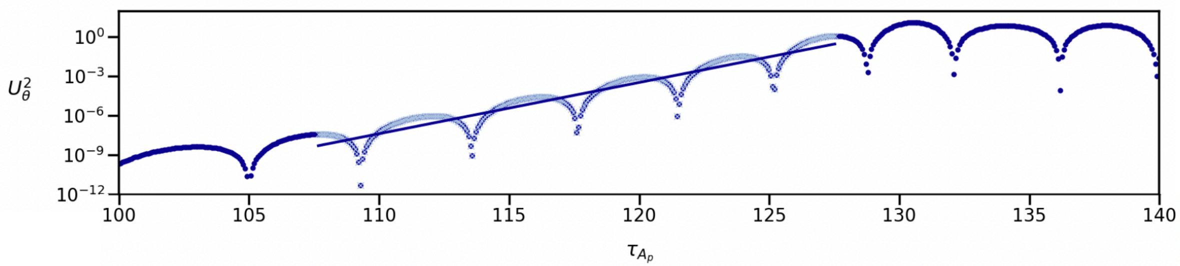


- An instability sets in if field not too strong: in strongly stratified cases, MRI may be triggered on latitudinal gradients of Ω, with elongated structures in horizontal directions

Axisym-metric MRI



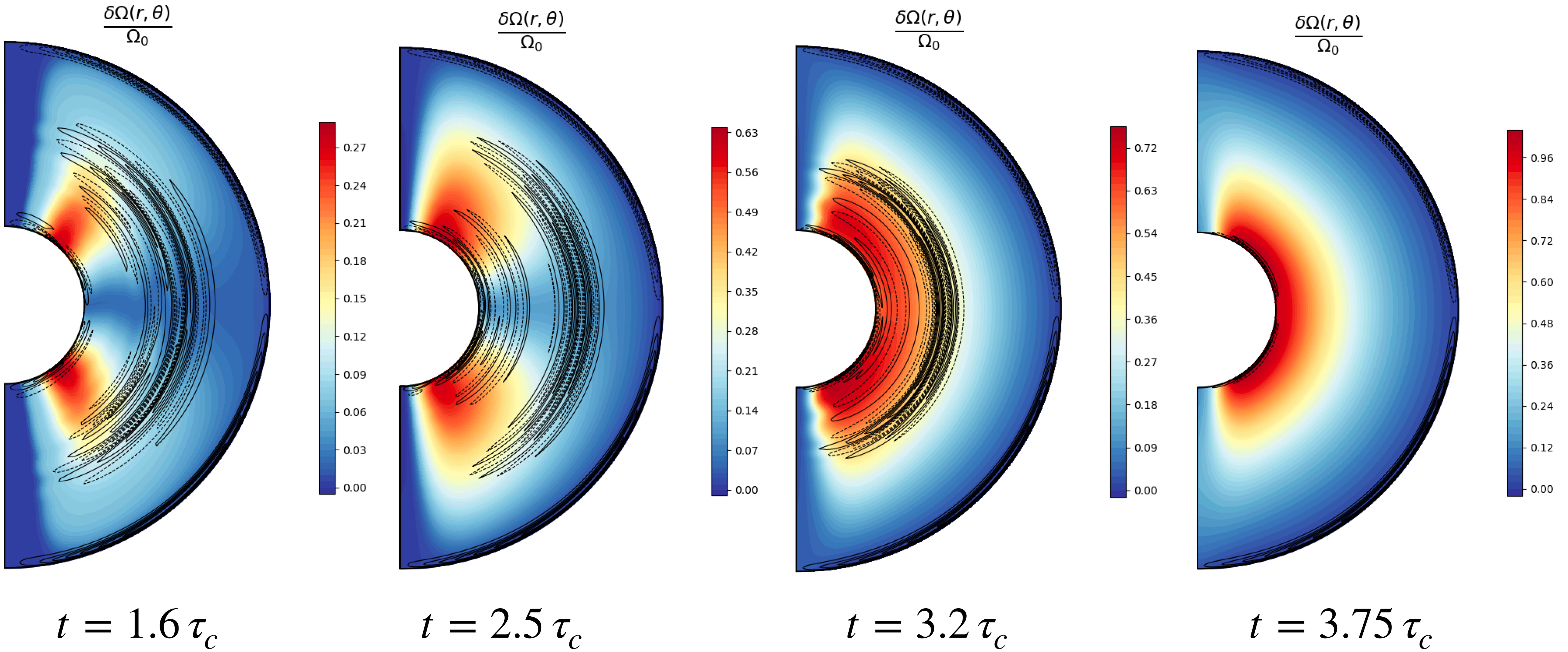




Development of the instability

- Non-linear development of the instability:

  Meridional flow with strong v_θ + dissipation drastically reconfigure flow and field



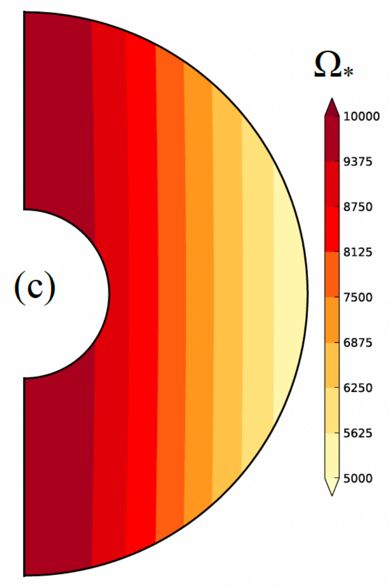
- Scenario for AM evolution in red giant stars:
  - 1. Large-scale magnetic field imposes a low level of differential rotation during 1 or 2 τ_c

    => young sub-giants with quasi-solid body rotation
  - 2. MRI destroys the large-scale field: differential rotation builds up freely

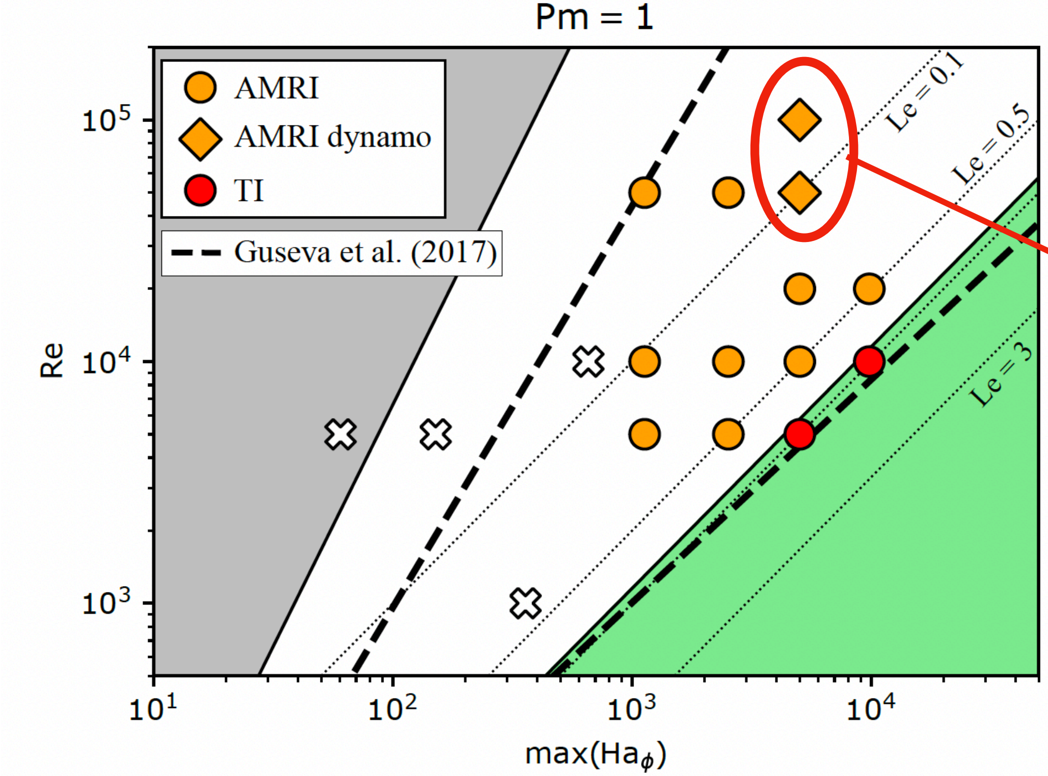
    => measured diff. rot on more evolved sub giants
  - 3. Another efficient transport spins-down the core of red giants: non-axi instabilities?

Dynamo action based on magneto-rotational instability

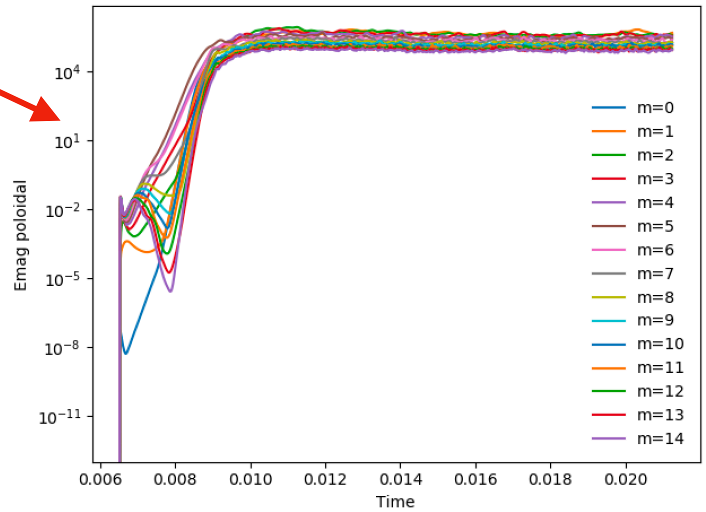
- ❑ Local shearing box calculations showed MRI dynamo in accretion disk context (review by Rincon et al. 2019)
- ❑ Global geometry: Volumetric forcing of differential rotation (Meduri et al. 2024) or Taylor-Couette flows (Guseva et al. 2017)
  Reynolds number $Re = \Omega_0 d^2/\nu$
- ❑ Purely toroidal field
  $Ha_\phi = B_\phi d/\sqrt{4\pi\rho\nu\eta}$
- ❑ A variety of behaviours

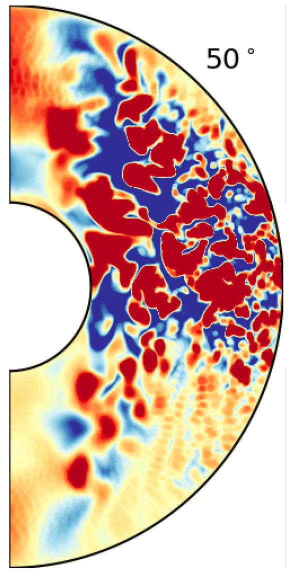


Meduri et al. 2024



✓ Dynamo action !

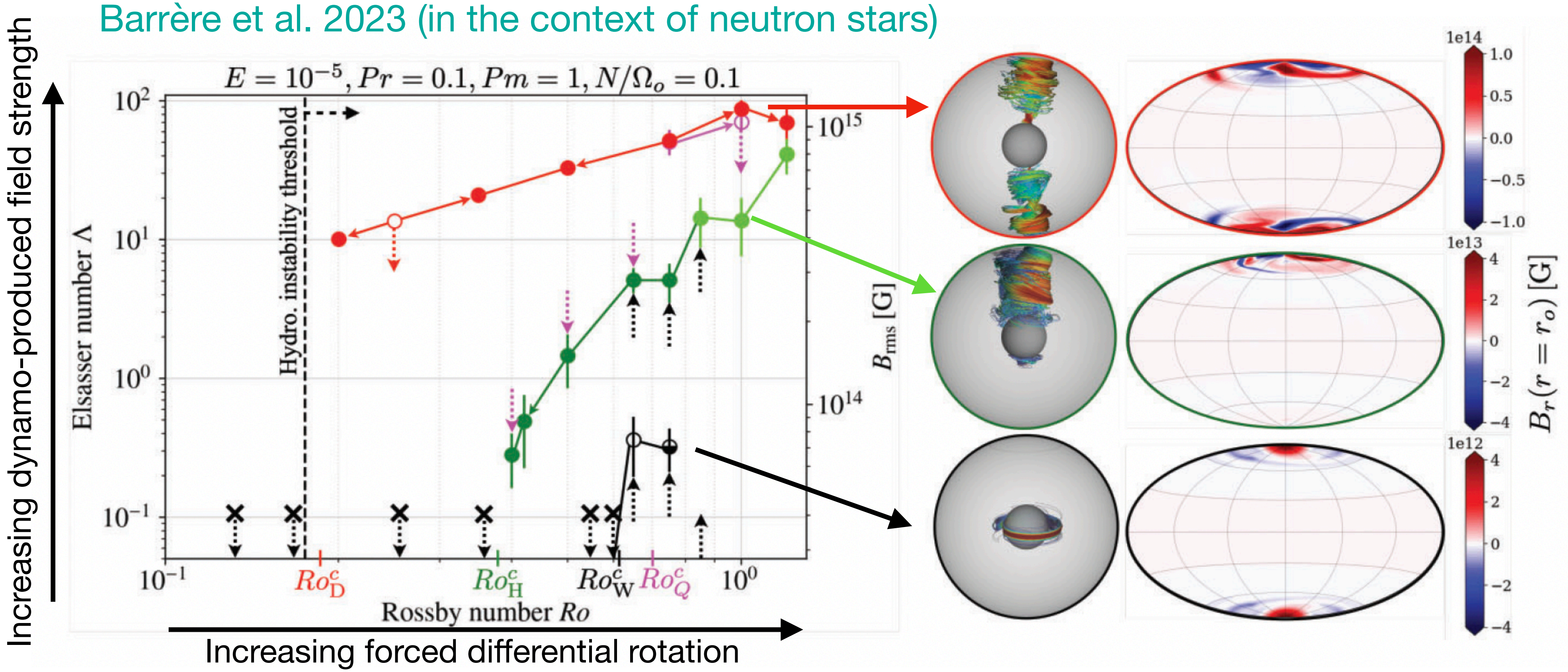




Dynamo action based on Tayler instability

Previous debates and calculations on TI dynamos: Spruit 2002, Braithwaite 2006, Zahn et al. 2007
New developments: Petitdemange et al. 2023, Barrère et al. 2023, 2024

Barrère et al. 2023 (in the context of neutron stars)

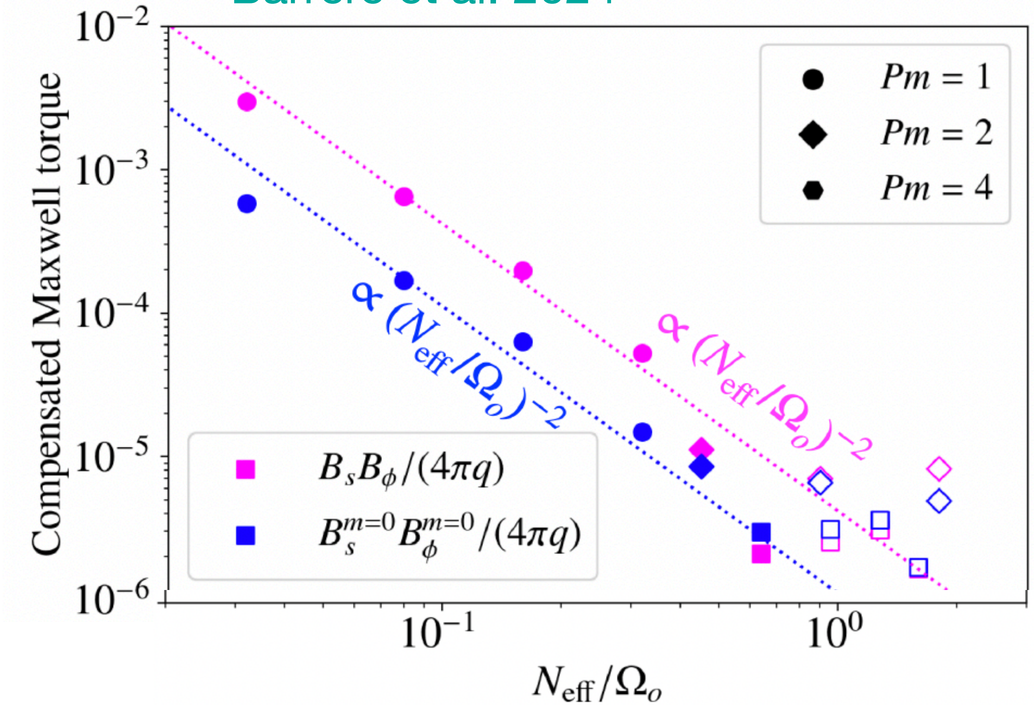


❑ Subcritical dynamos with 2 branches: hemispherical and dipolar
❑ Found by first triggering a kinematic dynamo which brings magnetic energy above the TI threshold
❑ Strong stabilising effect of stratification

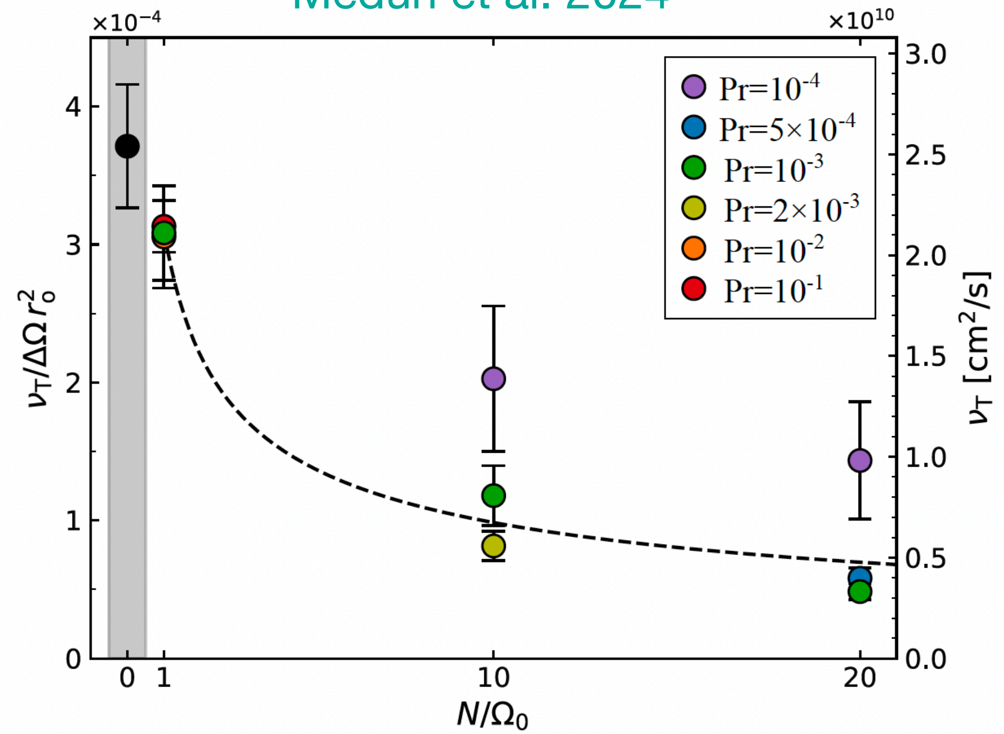
Angular momentum transport by MRI and TI dynamos (effect of stable stratification)

Maxwell stress
$$-\overline{B_r' B_\phi'} = -\nu_T \, s \frac{\partial \overline{\Omega}}{\partial r}$$

Barrère et al. 2024



Meduri et al. 2024



- ❑ Maxwell stresses dominate the transport in both cases
- ❑ Scaling with stratification different (possibly $N/\Omega^{-1/2}$ for MRI and N/Ω^{-2} for TI): possible comparisons to theoretical predictions (Spruit 1999, 2002, Fuller et al. 2019)
- ❑ Application to angular momentum (and chemical mixing) in stars?

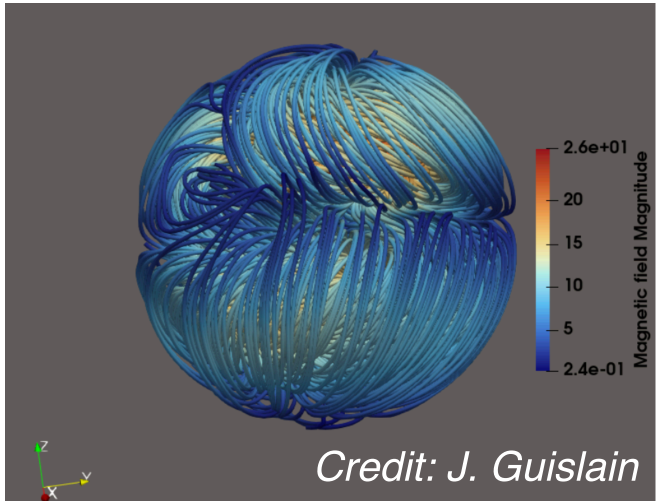
Conclusions/open questions

- Dynamo models of fully convective stars:

  - Change of geometry with Rossby number (or with internal structure?)
  - Studying force balances in detail is necessary
  - How do dipoles resist strong stratifications? Need more realistic parameters and full sphere simulations (Marti et al. 2014, Brown et al. 2020)?

- Stellar radiative zones:

  - Strong magnetic fields exist in stellar radiative zones (origin in RGS? Thesis of J. Guislain)
  - MRI unstable fields if latitudinal differential rotation
  - Possibly strong implications for angular momentum



  - Radiative zone dynamo? (talks by A. Reboul-Salze, P. Barrère)
  - Angular momentum transport by non-axisymmetric instabilities? Local simulations with SNOOPY (Jouve et al. in prep)

- More to come with SPIRou, PLATO, SolO, PSP,… and more and more efficient codes