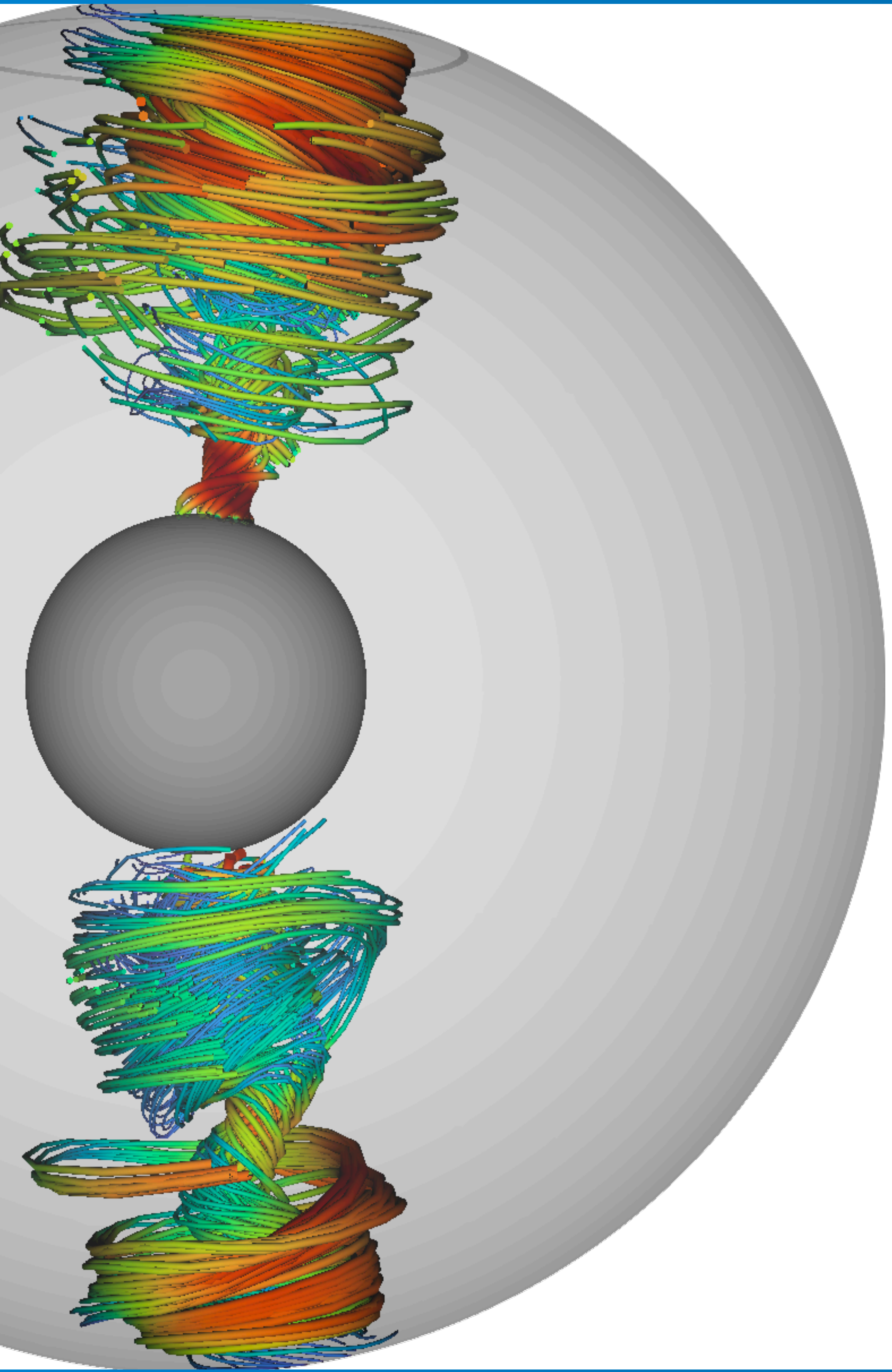


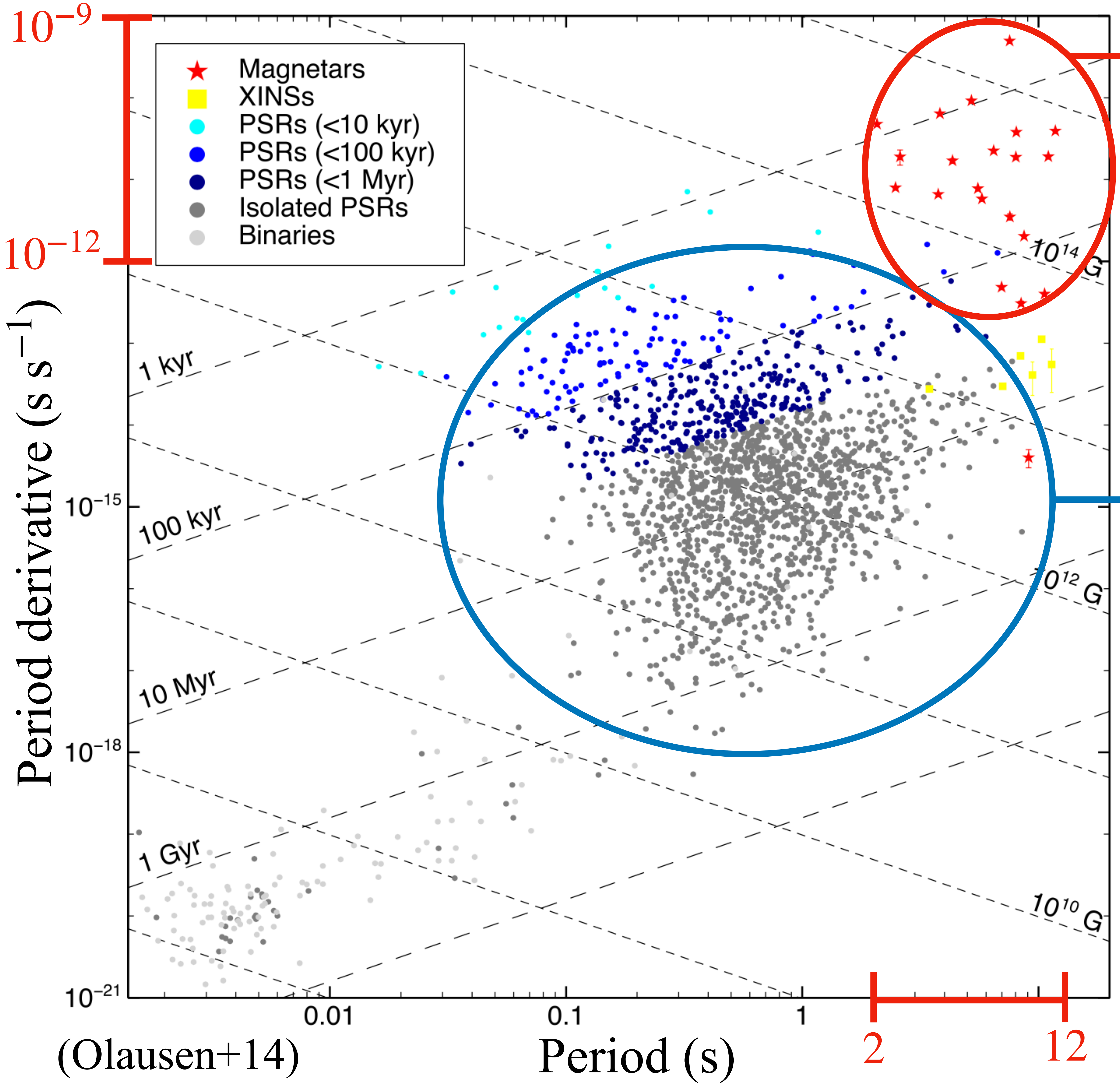
Impact of rotation on the Tayler-Spruit dynamo in proto-magnetars

Paul Barrère
(Département d'Astronomie,
Université de Genève)

Collaborators on this work:
J. Guilet (CEA, Saclay), R. Raynaud (CEA, Saclay),
A. Reboul-Salze (AEI, Potsdam),
H.-T. Janka (MPA, Garching),
A. Igoshev (Univ. of Leeds)

3rd October 2025

Magnetic dipole



(Olausen+14)

Dipole spin-down model

$$\boxed{B_{\rm dip} \propto \sqrt{P\dot{P}}}$$

Magnetars:

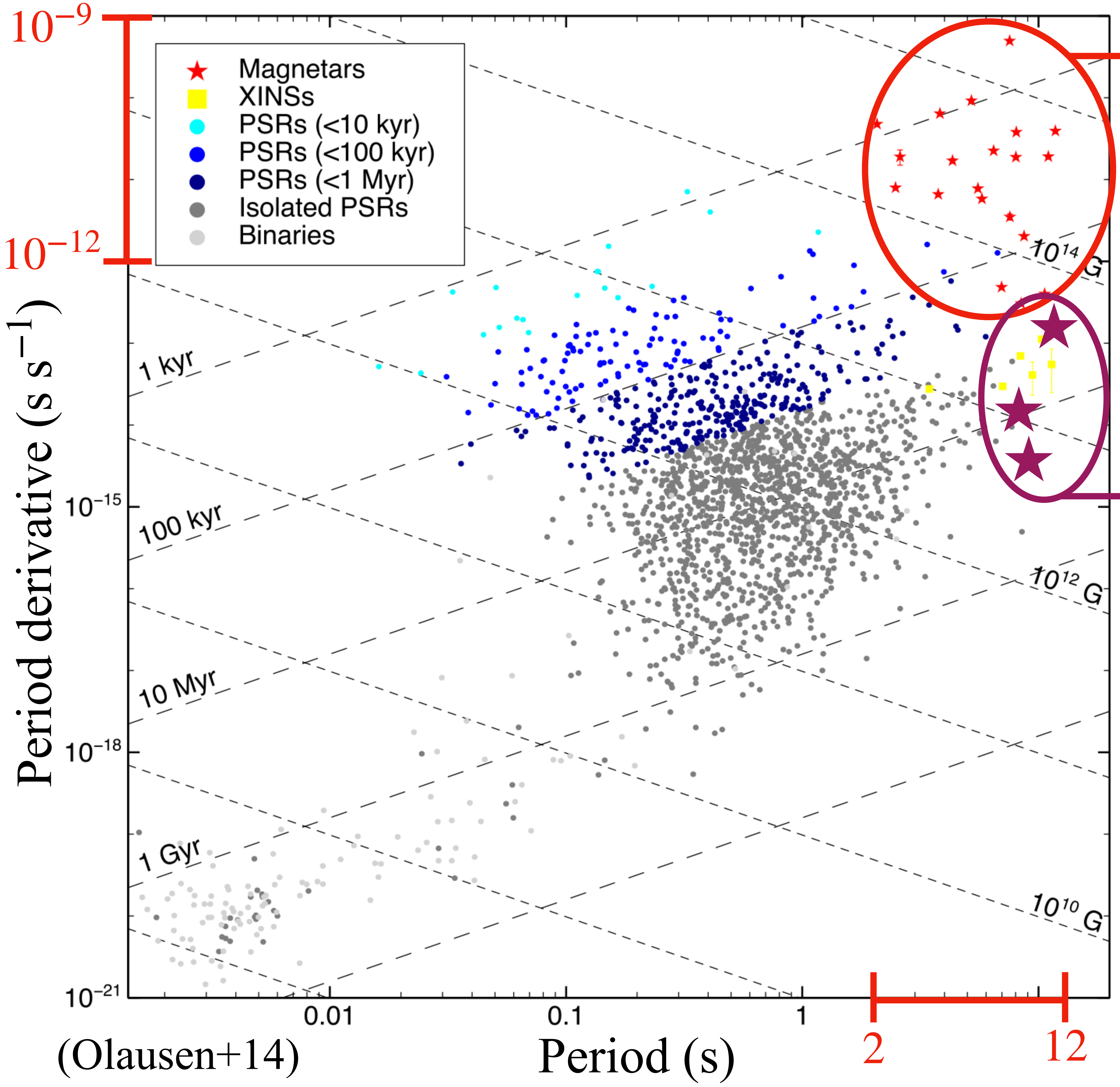
- 32 X-ray Galactic sources (Kaspi+17)
- 10 – 40 % of newborn neutron stars (Kouveliotou+94, Benjamini+19)
- 10 associated with supernovae remnant

$$\boxed{B_{\rm dip} \sim 10^{14} - 10^{15}\,{\rm G}}$$

Pulsars

$$\boxed{B_{\rm dip} \sim 10^{11} - 10^{13}\,{\rm G}}$$

Low-B_{dip} magnetars



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Low-B_{dip} magnetars (Rea+10,+12,+14)

$$B_{\mathrm{dip}} \in [6 \times 10^{12}, 4.1 \times 10^{13}]\,\mathrm{G}$$

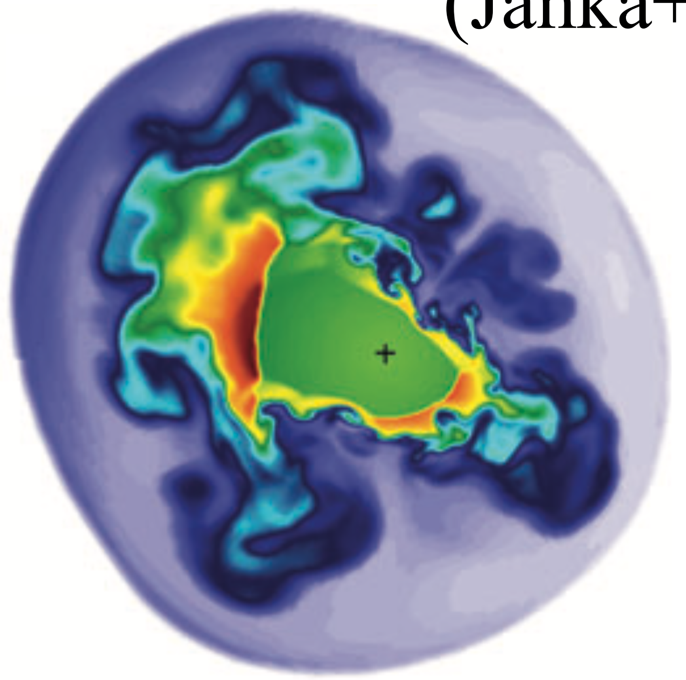
Dissipation of strong non-dipolar fields

- Proton cyclotron absorption lines in X-ray spectra (Tiengo+13, Rodríguez Castillo+16) → $B_{\mathrm{non-dip}} \sim 100 B_{\mathrm{dip}}$
- Phase modulation in the pulsed signal (Makishima+14, 16, 19, 21) → $B_{\mathrm{tor}} \sim 10^{16}\,\mathrm{G}$

Central engine of extreme explosions

Classical SNe

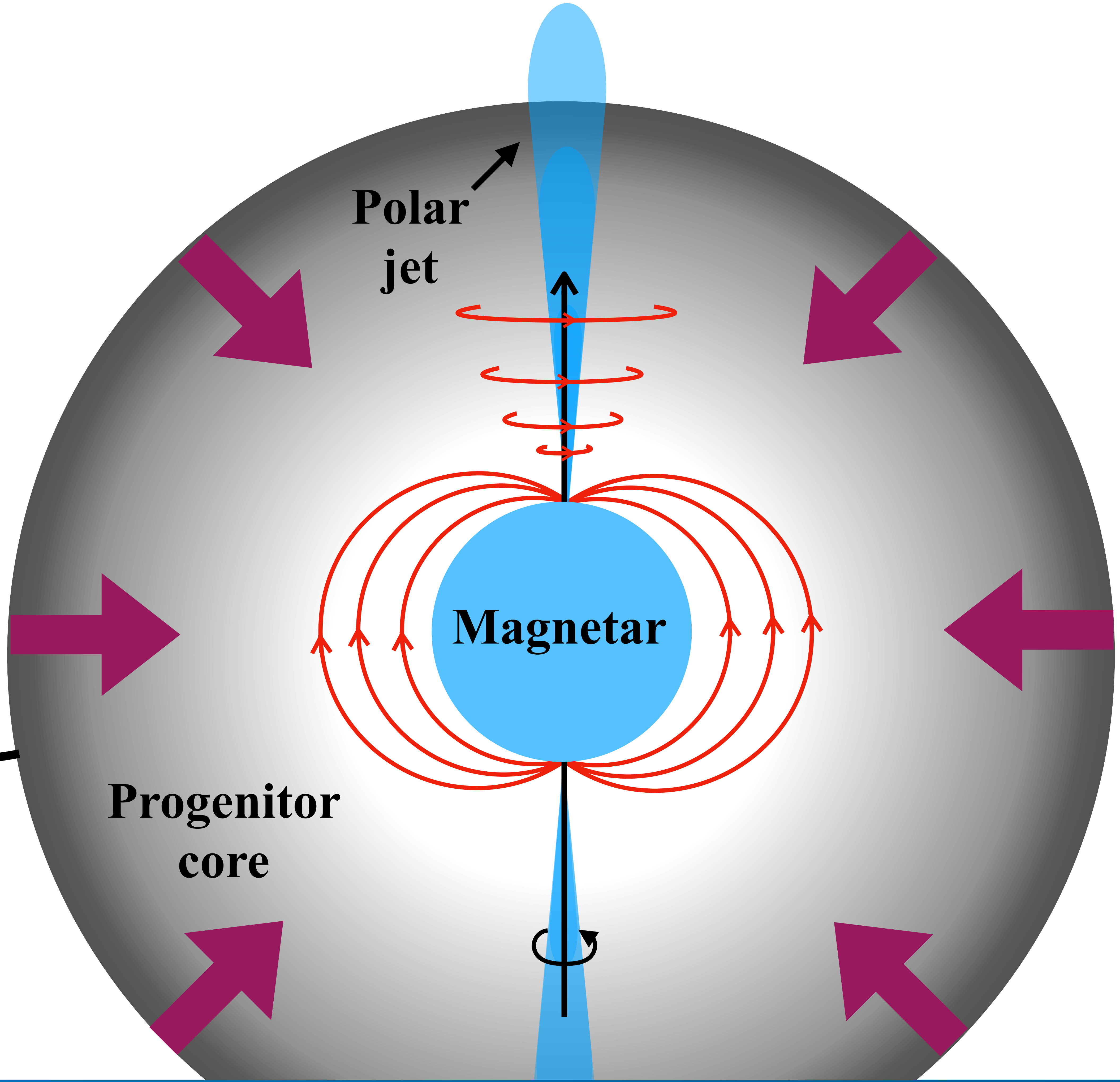
(Janka+12)



« Weak » magnetic fields
$B_{\rm dip} \lesssim 10^{14}$ G

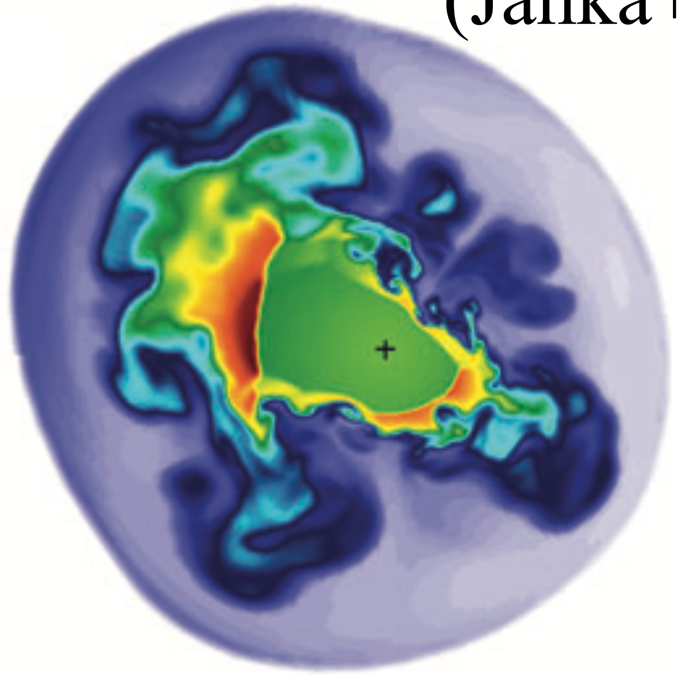
« Slow » rotations
$P \gtrsim 5$ ms

Observation of magnetars associated with a SN remnant
(Vink+06)



Classical SNe

(Janka+12)



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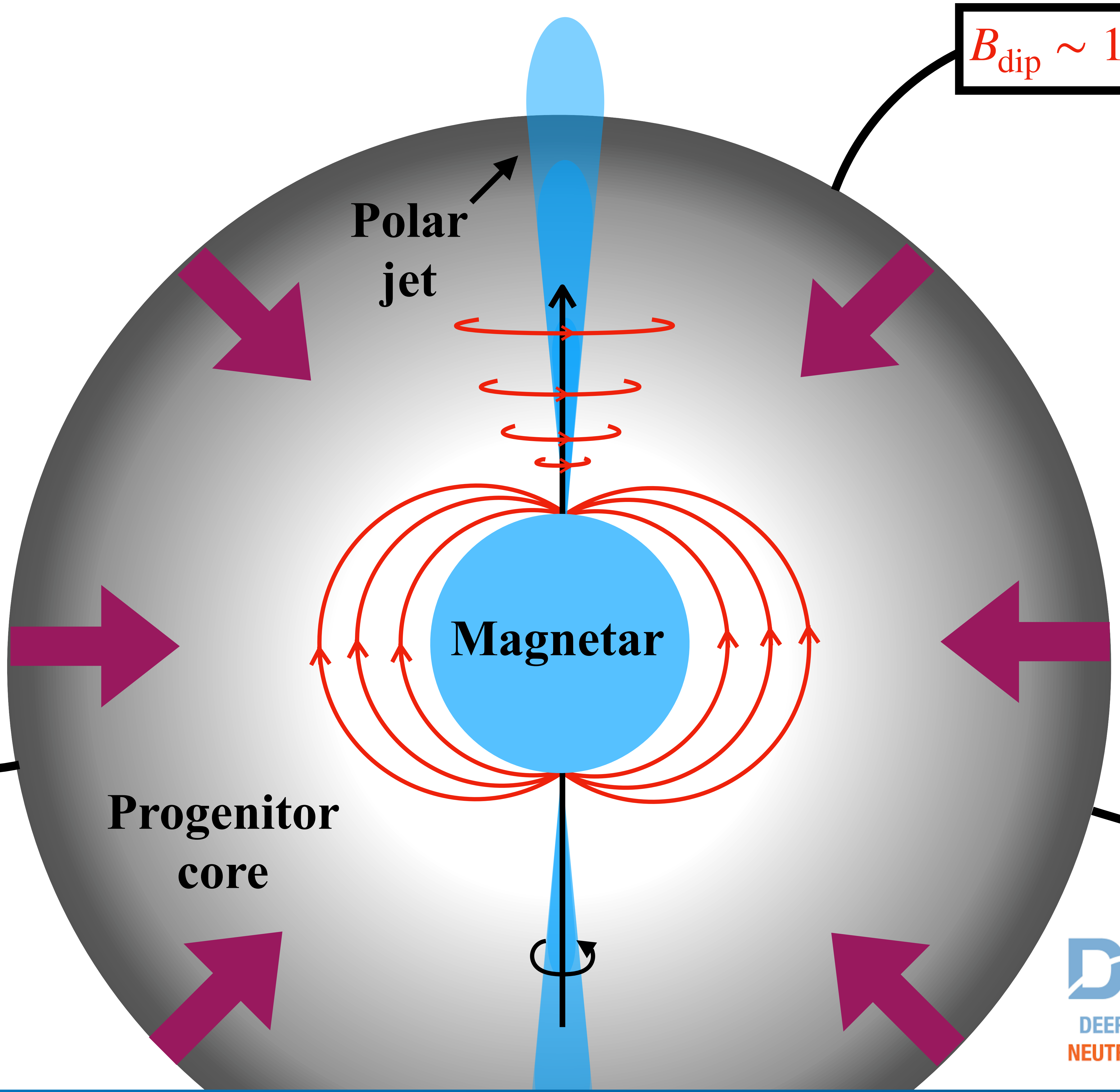
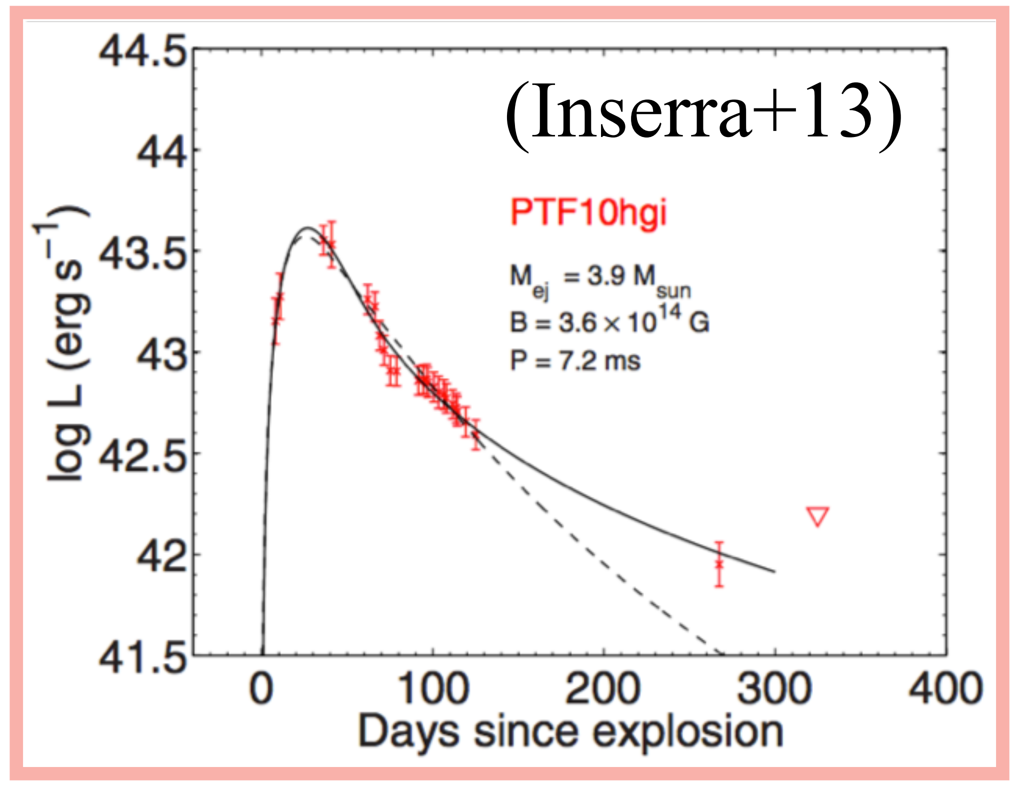


$P \lesssim 5\,$ms

$B_{\rm dip} \sim 10^{14}\,$G

Super luminous SNe



Hypernovae
Sometimes associated to LGRBs

$P \sim 1\,$ms

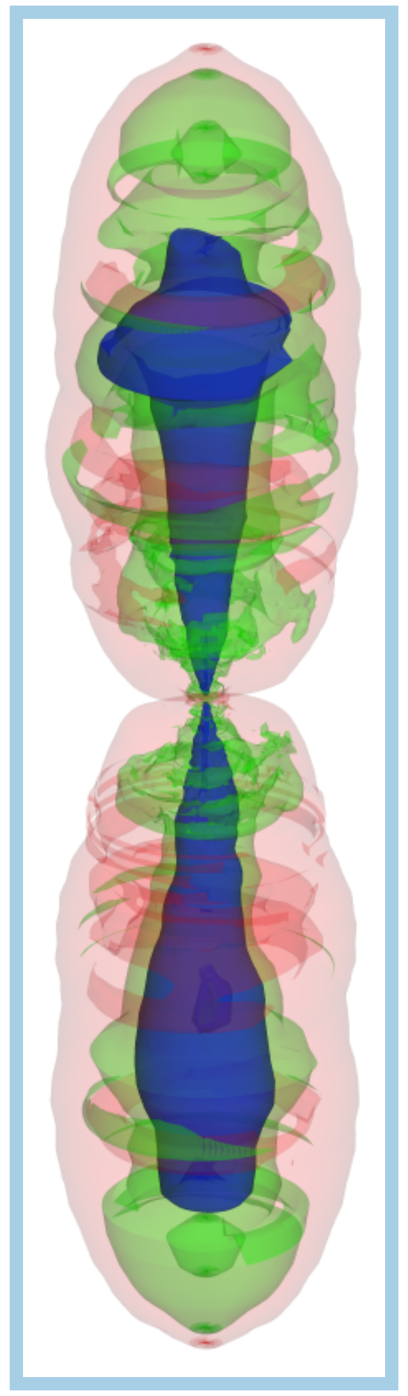
$B_{\rm dip} \sim 10^{15}\,$G

Einstein Telescope
/ NL / BE / D /

SVOM

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

(Bugli+21)

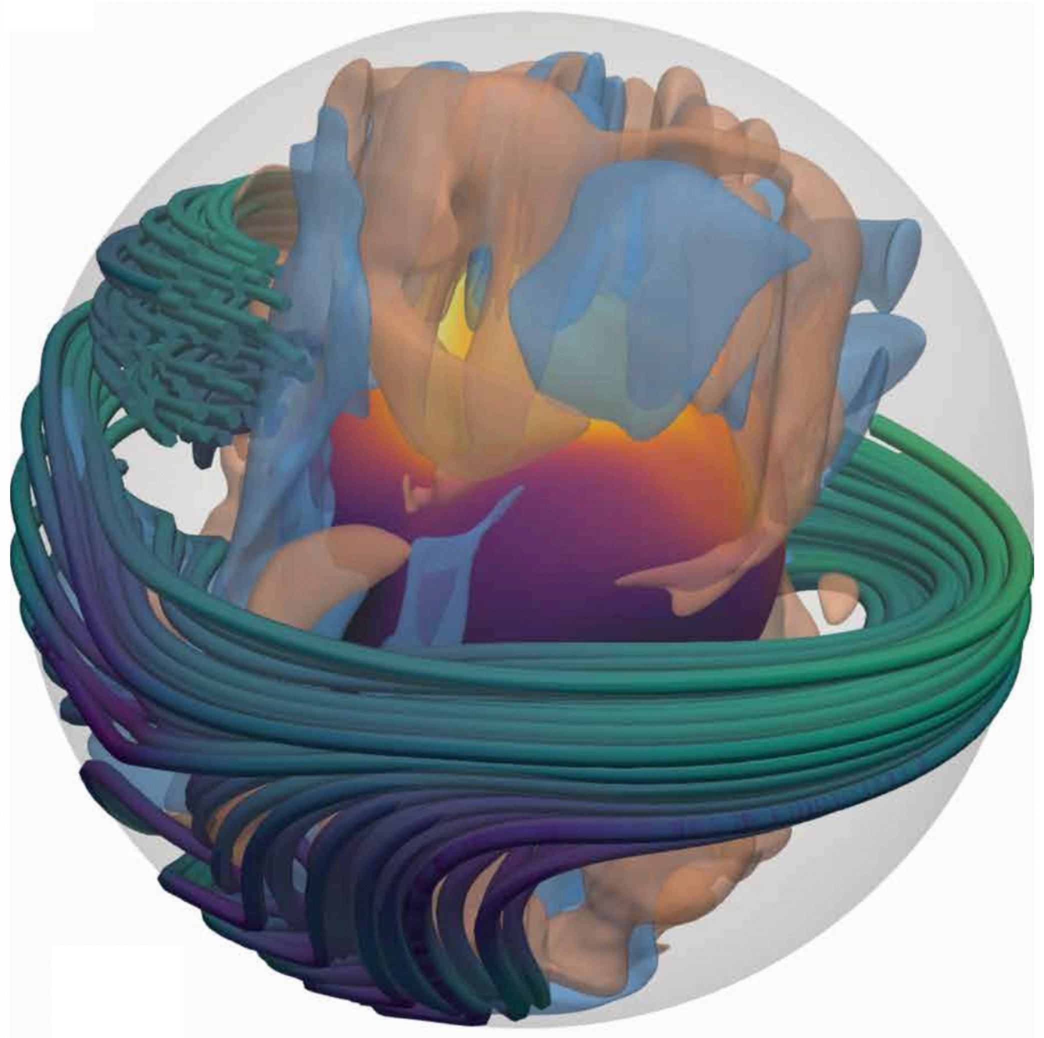


Diversity of formation scenarios

- Magnetic flux conservation during the core collapse
  - Ferrario+06
  - Hu+09
  - Makarenko+21
- Chiral magnetic instability
  - Dehman & Pons 24
- Precession movements at the end of the PNS stage
  - Lander 21
- Binary neutron star mergers
  - Schneider+19

In-situ amplification via dynamo action in a hot PNS

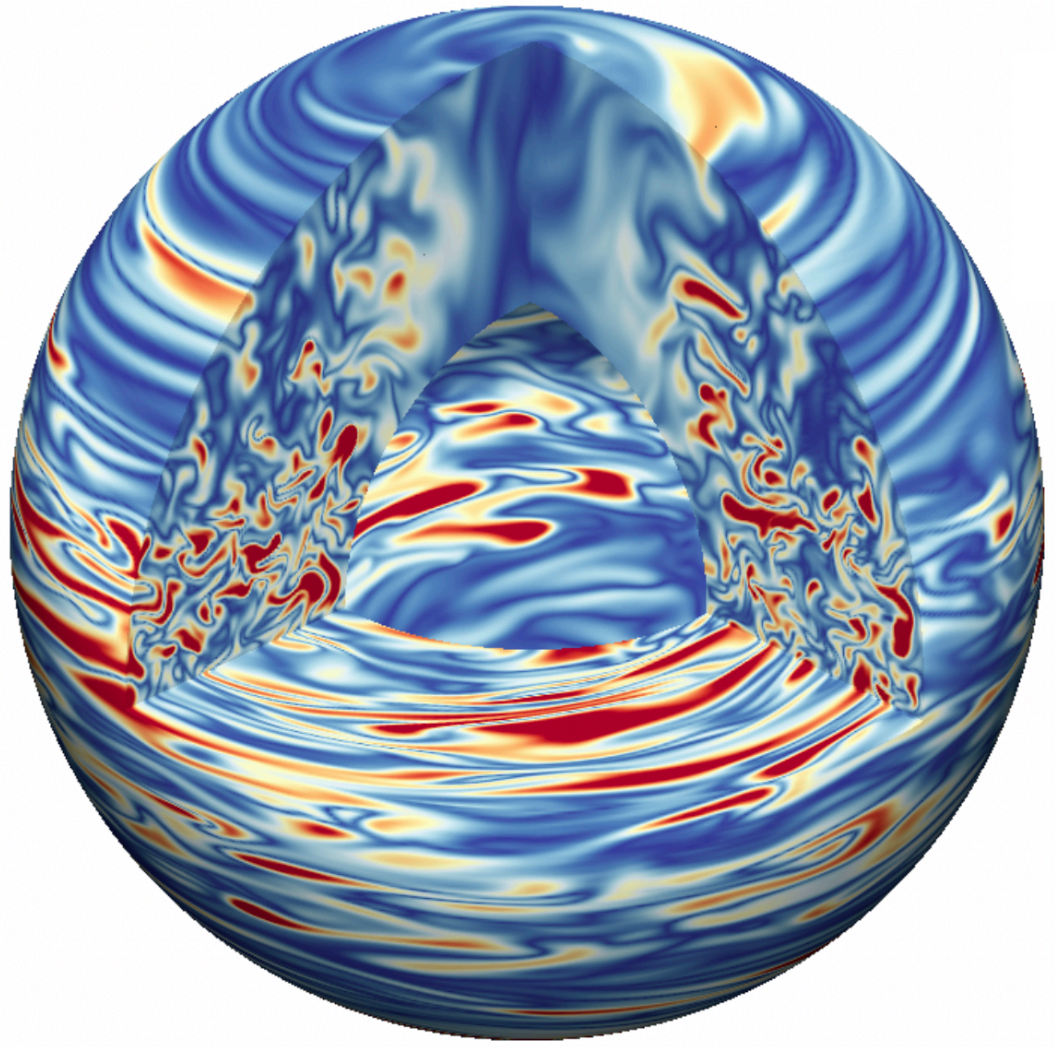
Convective dynamo



Convective zone lasting for ~ 10 s

- Raynaud+20,+22
- Masada+22

Magnetorotational instability



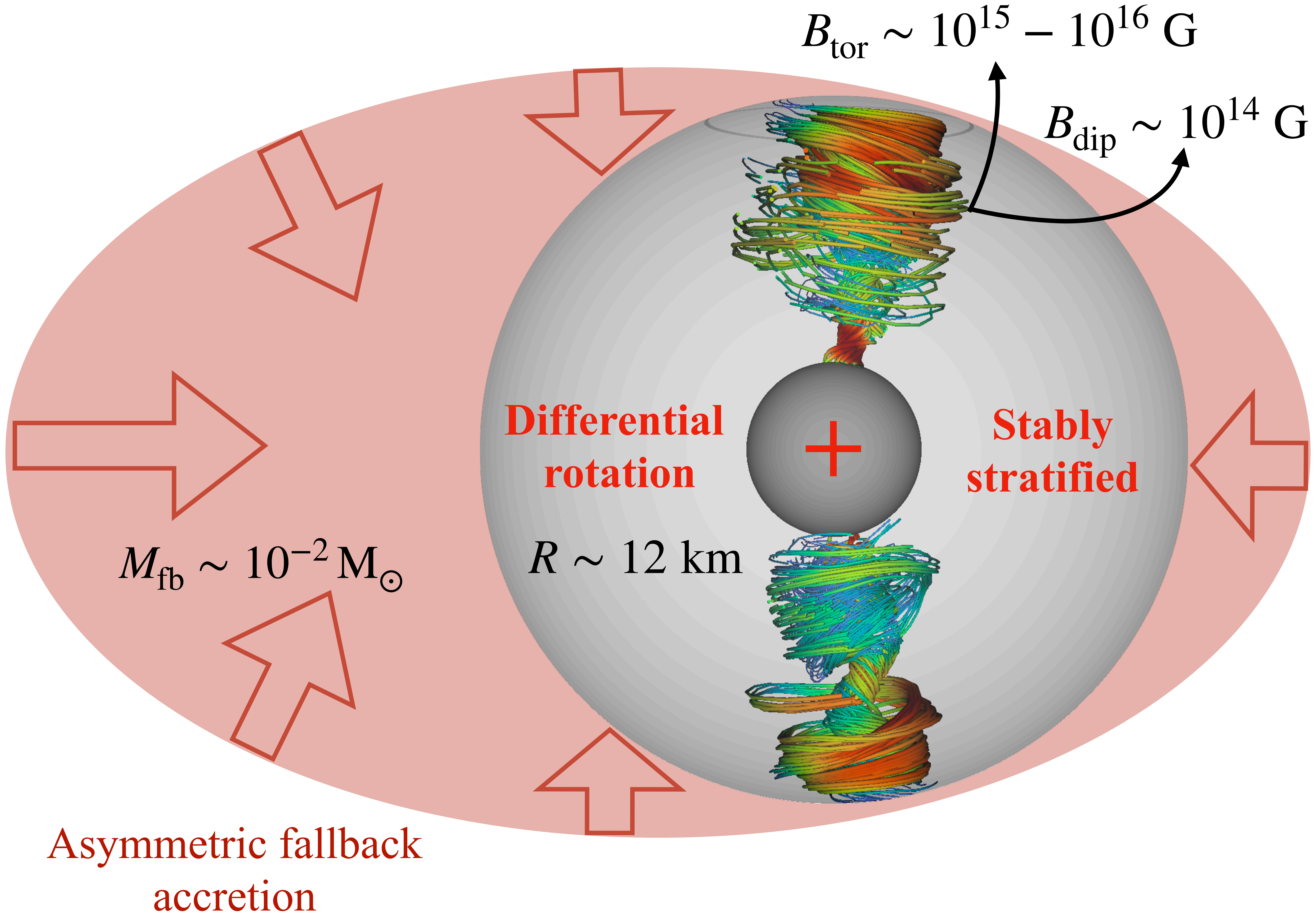
Stably stratified zone & differential rotation

- Reboul-Salze+21, 22
- Guilet+15, 23
- Rembiasz+13,+16a,b
- Obergaulinger+09

+ : Supported by 3D numerical simulations
Fast rotation + strong magnetic field $\Longrightarrow$ Magnetorotational explosions

– : Most magnetars certainly born in standard supernovae $\Longrightarrow$ Initial period $P_0 > 5$ ms
Need a fast rotating progenitor core $\Longrightarrow$ Large enough fraction to form all magnetars ?

New magnetar formation scenario

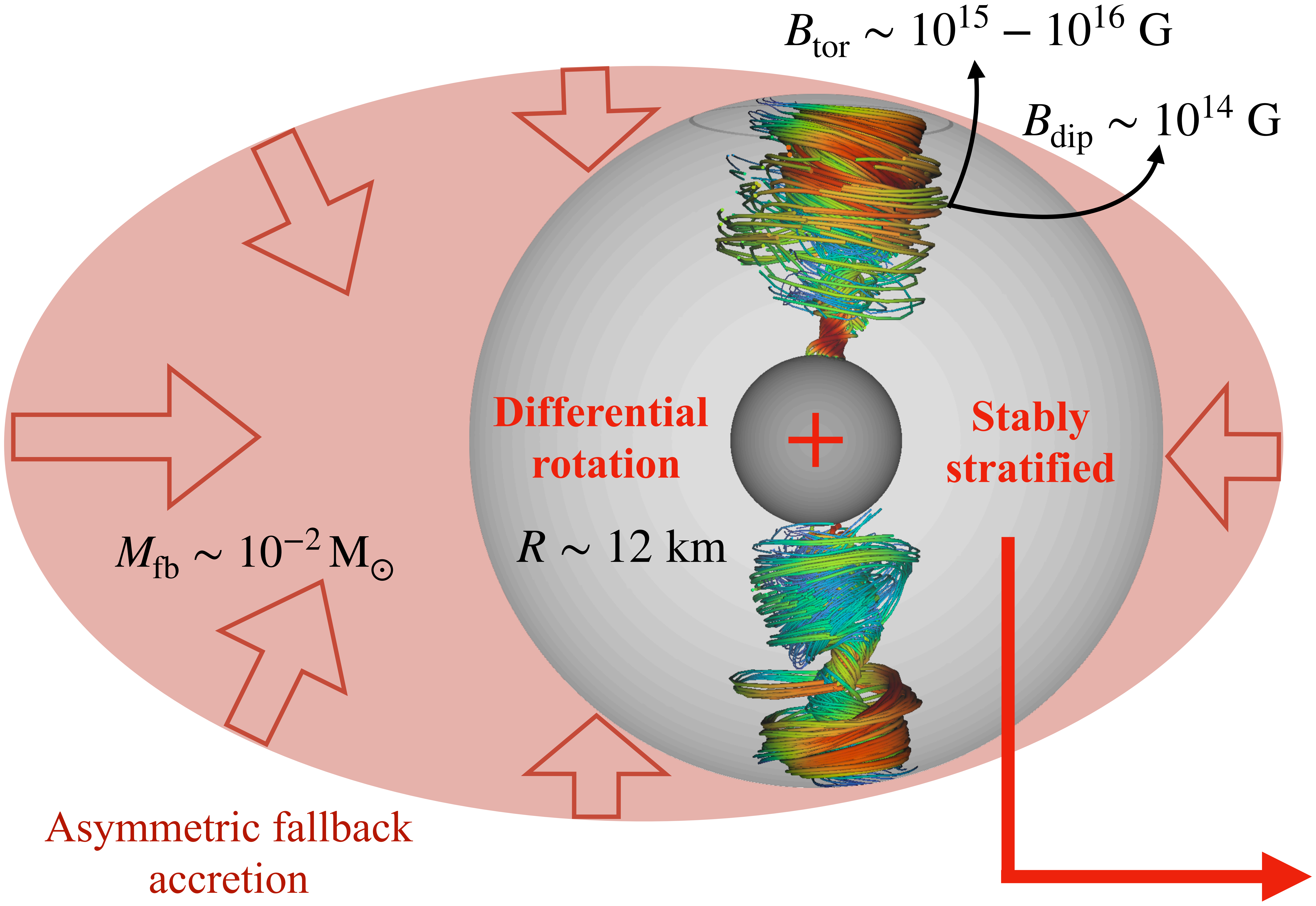


Fallback in 3D CCSN simulations

- *Fallback* = matter that remains gravitationally bound during the explosion
- starts **~10 s** after the core bounce
- $M_{fallback} \in [10^{-4}, 10^{-1}]\ M_\odot$
- lasts from minutes to hours
- Potential to spin up the proto-neutron star up to break up

(Chan+20, Janka+22)

New magnetar formation scenario



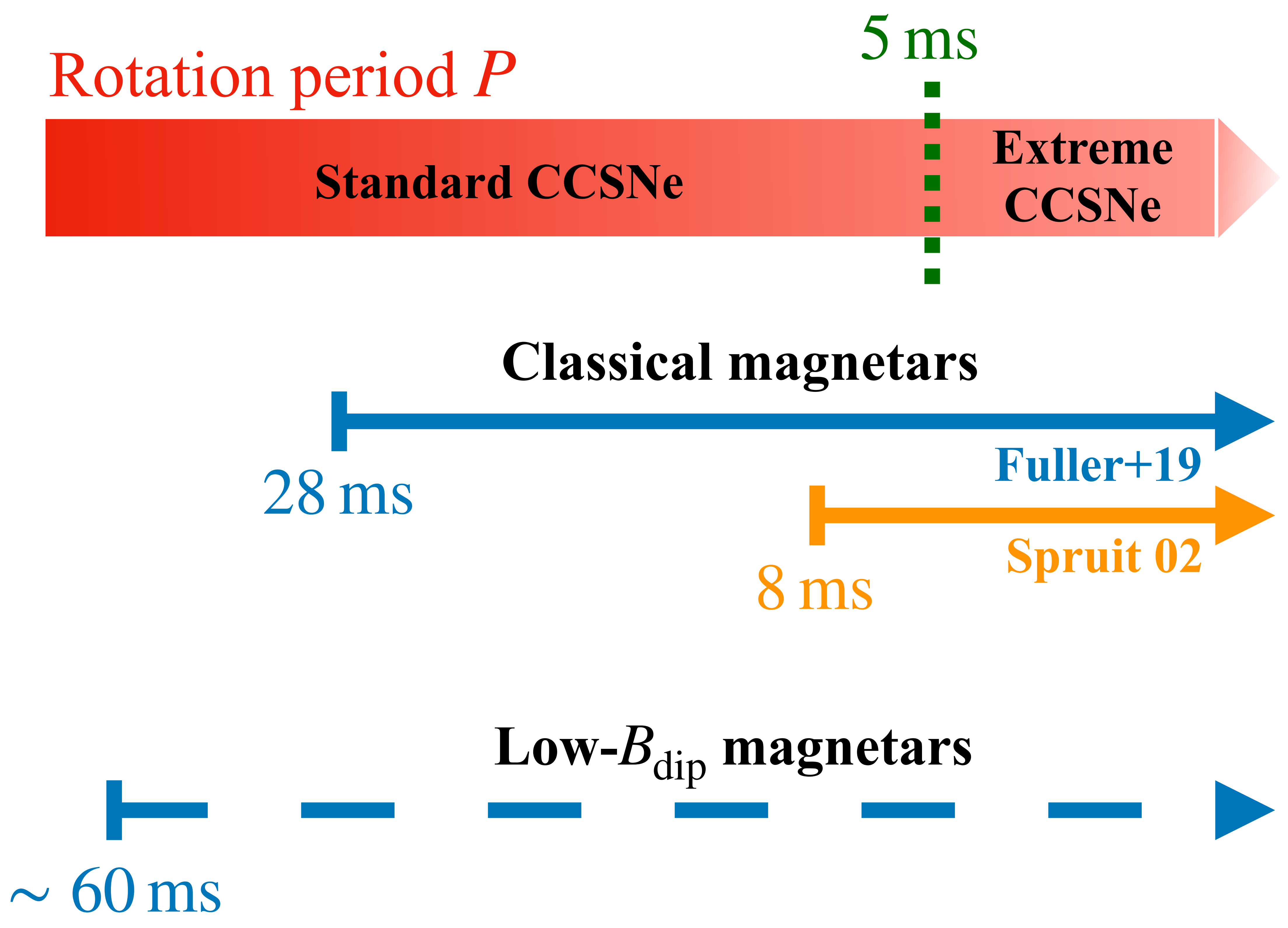
Crucial for stellar physics

- **Angular momentum transport** in radiative zones
- **Only** 2 analytical studies
  ➡ Spruit 02 & Fuller+19
  ➡ different predictions for the saturation
- First numerical studies are **very new**
  ➡ Petitdemange+23, **Barrère+23**

= **"Tayler-Spruit" dynamo ?**

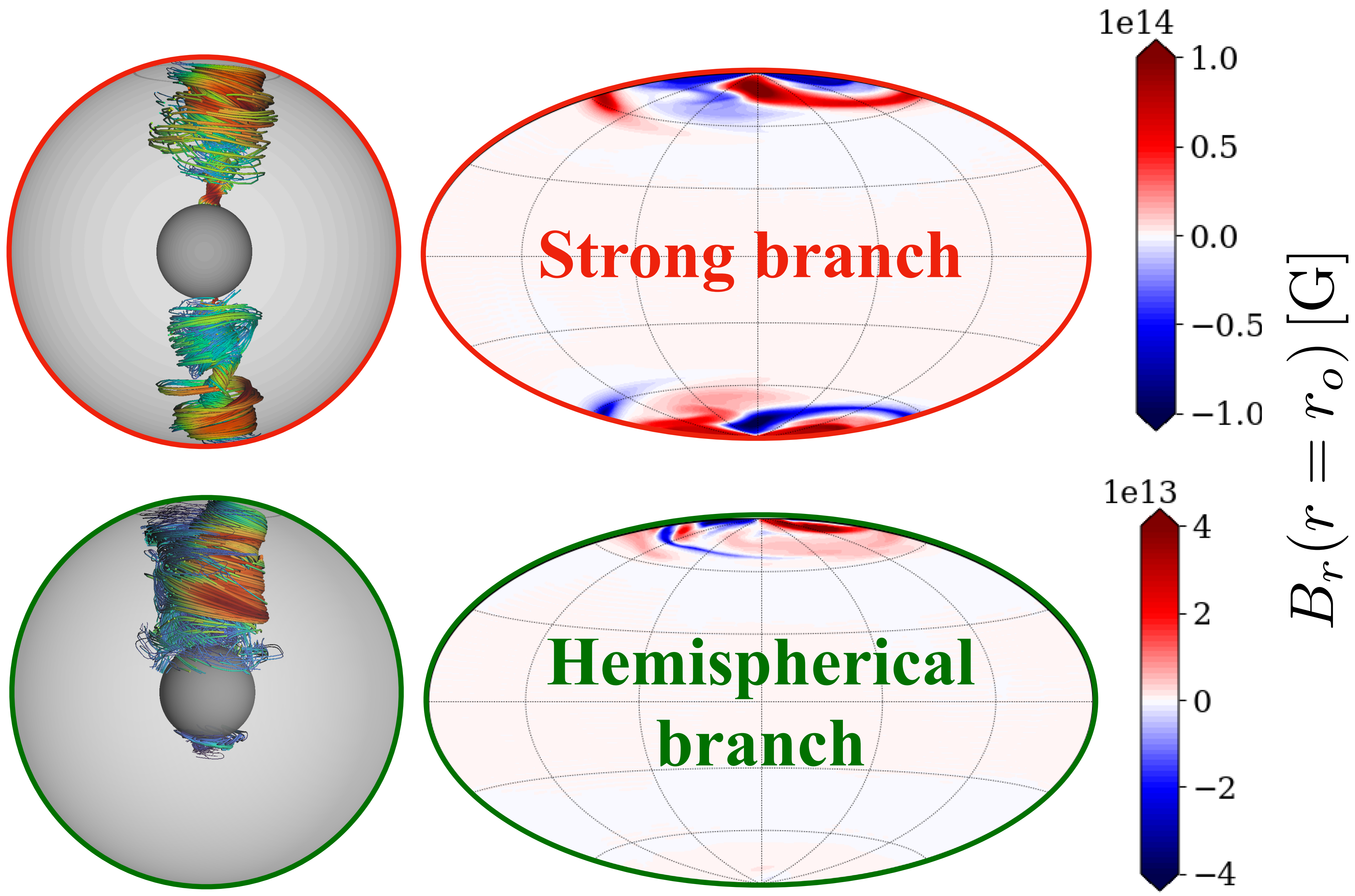
Proof of concept

One zone model (Barrère+22)



Simplistic 0D model + Dynamo elusive in 3D simulations
$\Longrightarrow$ 3D simulations needed to capture B geometry

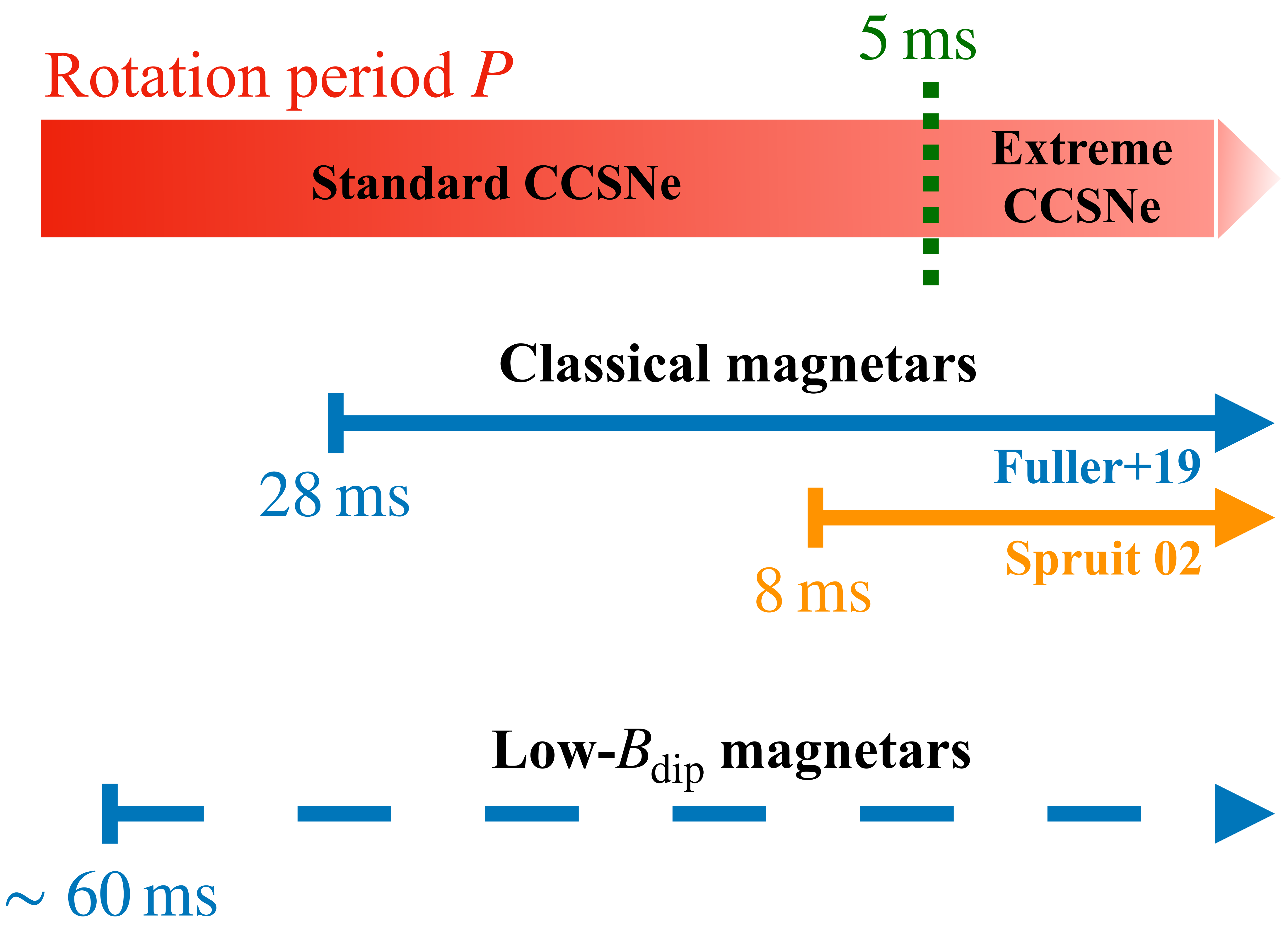
First numerical simulations (Barrère+23)



Fixed rotation $\Longrightarrow$ Parametric study varying rotation is required to test the limits of Barrère+22

Proof of concept

One zone model (Barrère+22)



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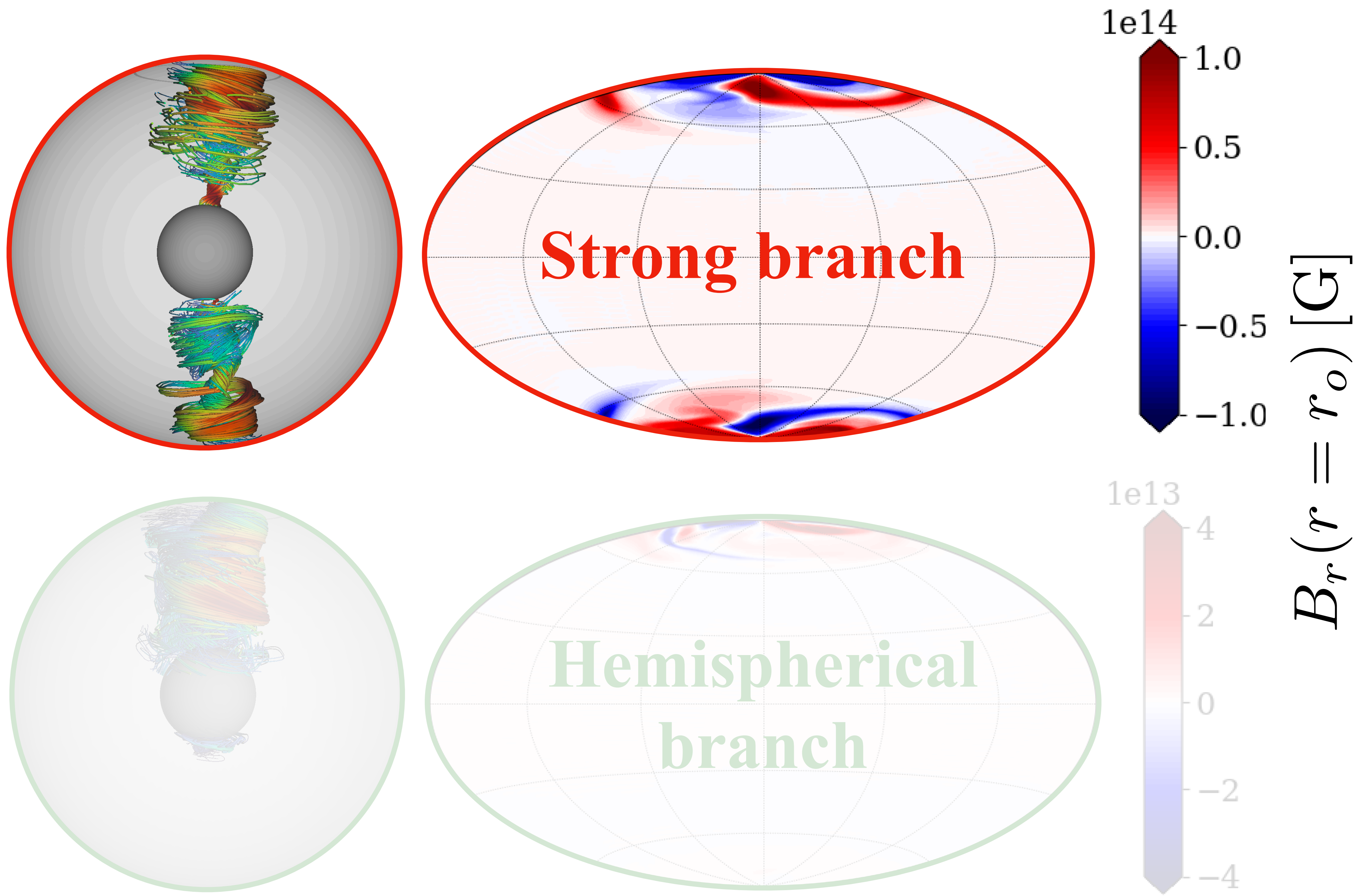
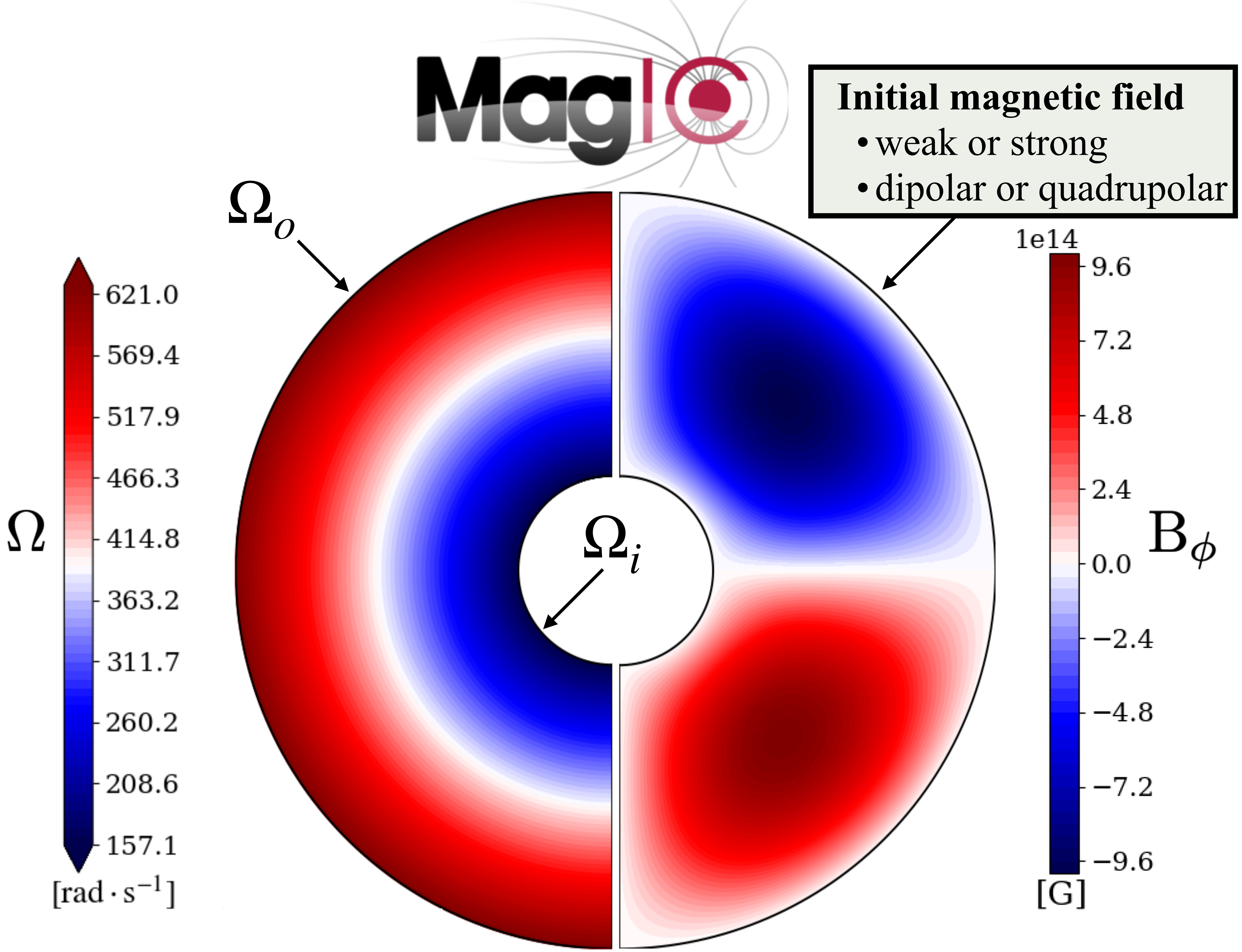


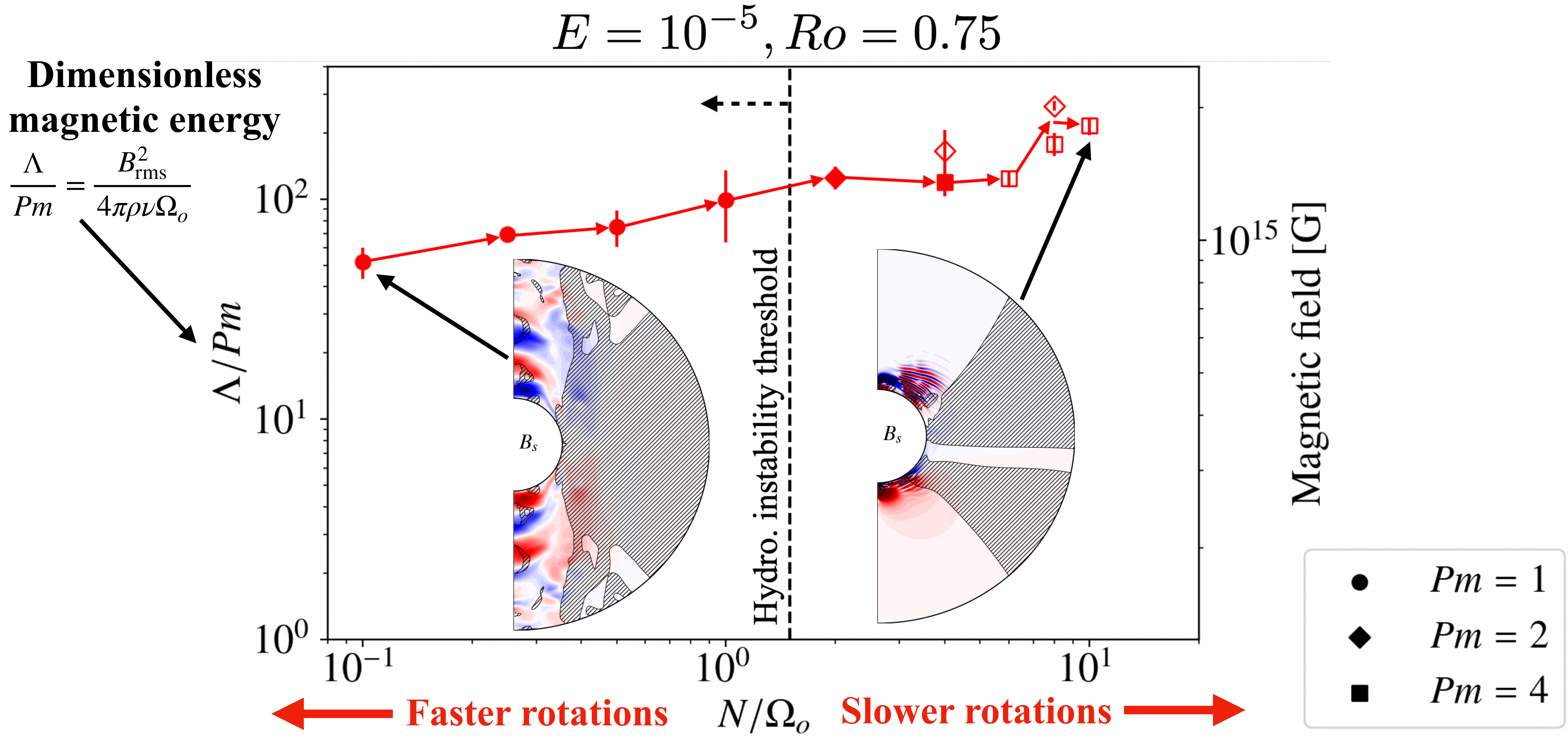
Fixed rotation $\Longrightarrow$ Parametric study varying rotation is required to test the limits of Barrère+22

Numerical setup

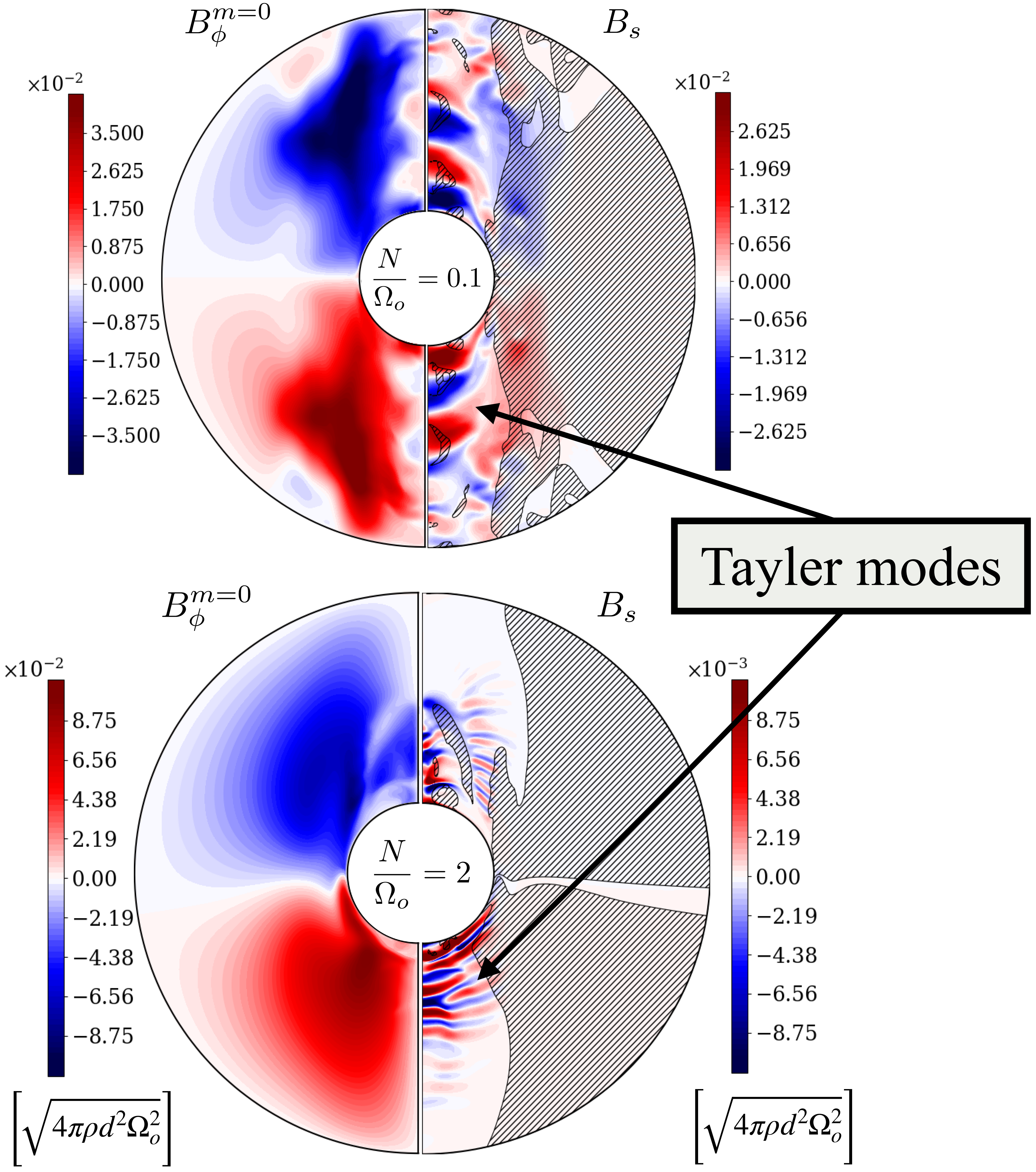
- **Neutron star** $\sim 10\,\mathrm{s}$ post-bounce
  $M \sim 1.4\ \mathrm{M}_\odot$
  $r_o = 12$ km
- **Constant density** (Boussinesq approx.)
  $\rho = 4 \times 10^{14}\,\mathrm{g\,cm^{-3}}$
- **Diffusivities**
  $Pr = \nu/\kappa = 0.1 \gtrsim 10^{-2}$
  $Pm = \nu/\eta \in [1, 4] \ll 10^{4}$
- **Stably stratified**
  $N/\Omega_o \in [0.1, 10]$
- **Spherical Couette** flow
  Positive shear $\Omega_o > \Omega_i$
  Rossby number $Ro = 1 - \Omega_i/\Omega_o$
  $Ro \in [0.125,\ 1.2]$

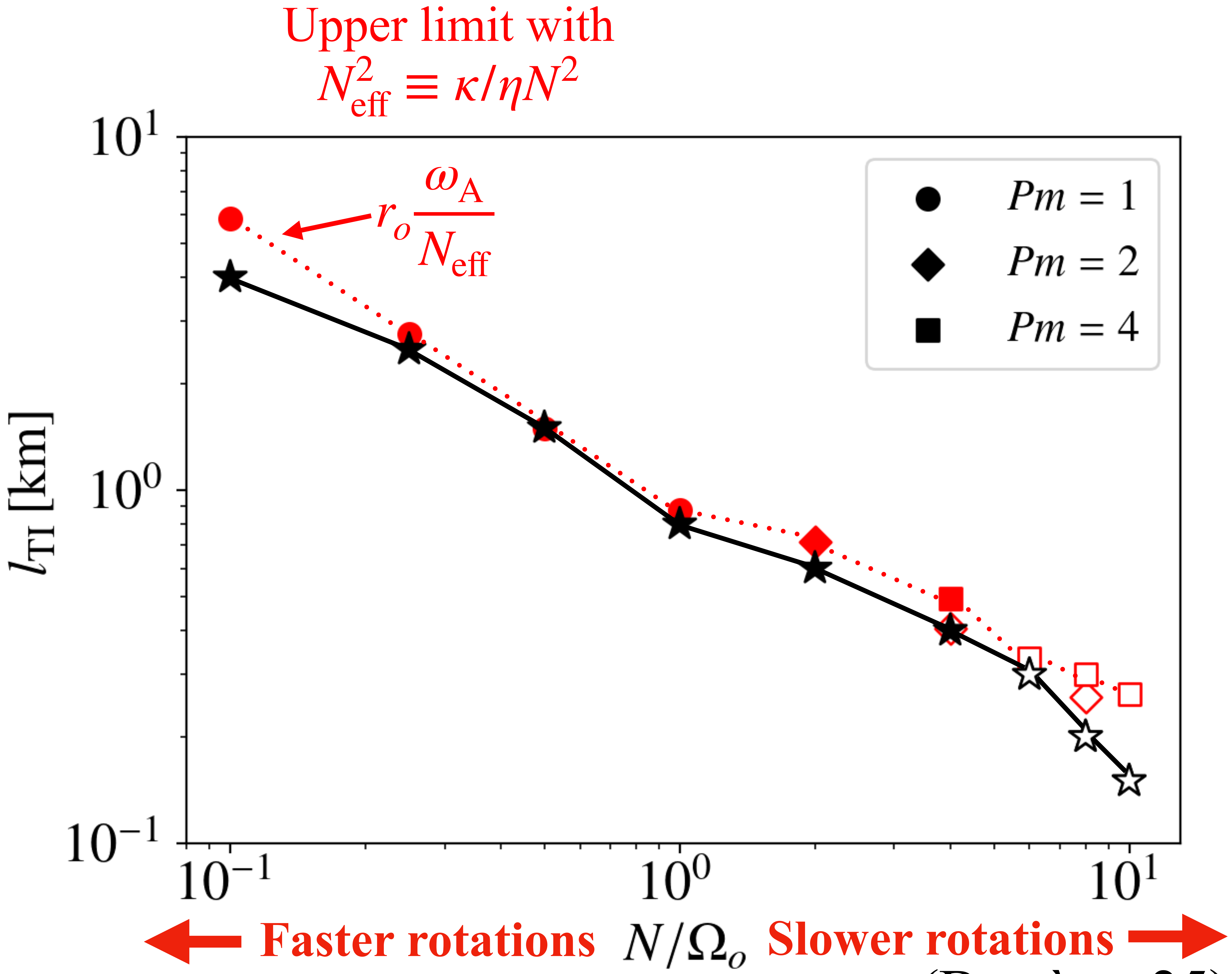


Bifurcation diagram



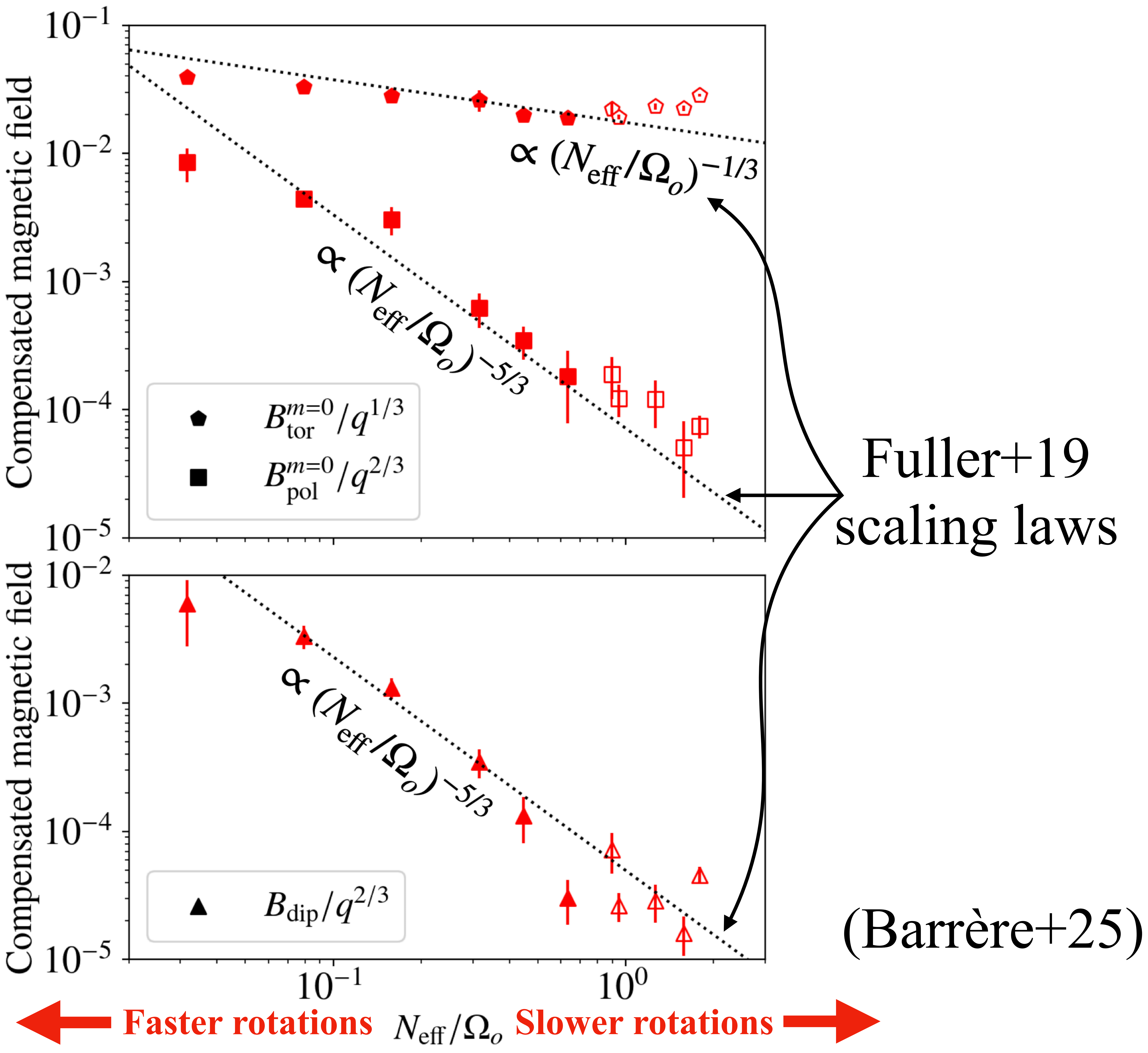
Impact on Tayler modes





(Barrère+25)

Scaling laws



(Barrère+25)

Parametrisation

Dimensionless normalisation factor

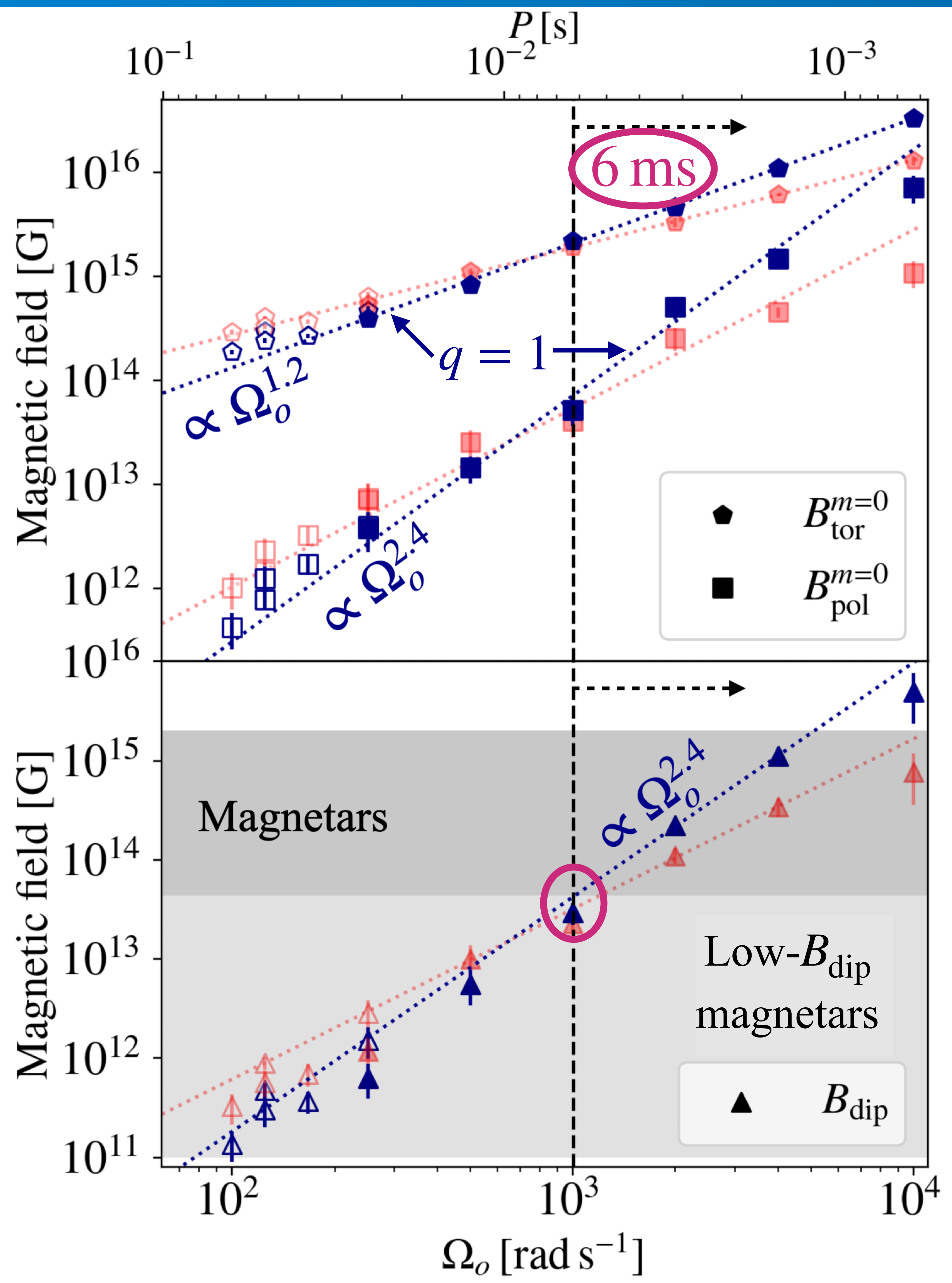
$$B_{\text{tor}}^{m=0} = \boxed{\alpha} \sqrt{4\pi\rho r_o^2}\,\Omega_o \left(\frac{q\Omega_o}{N_{\text{eff}}}\right)^{1/3}$$

$\alpha \sim 0.01$

in our simulations

$\alpha \sim 0.25 - 1$

Calibrated on asteroseismology
in sub-/red giants
(Fuller+19,+23,Eggenberger+19)



Impose $N = 1000\,\mathrm{s}^{-1}$

Rotation period P

5 ms

Standard CCSNe

Extreme CCSNe

Classical magnetars

28 ms

One-zone model ***(Barrère+22)***

6 ms **3D simulations** ***(Barrère+25)***

Low-$B_{\rm dip}$ magnetars ($B_{\rm tor}^{m=0} > 10^{14}$ G)

$\gtrsim$ 60 ms

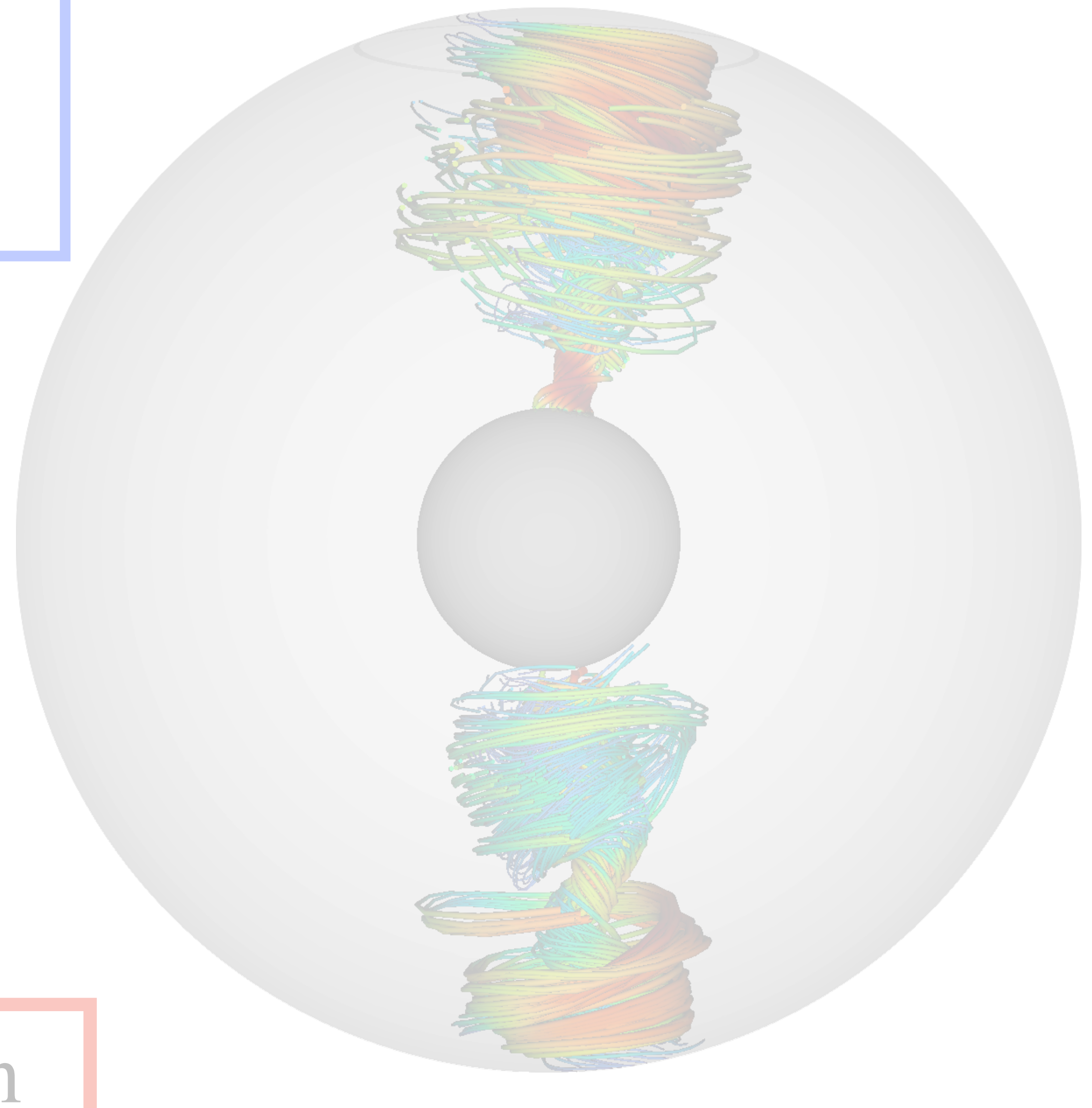
(Barrère+25)

Magnetothermal evolution

Collaboration with
A. Igoshev (Leeds)

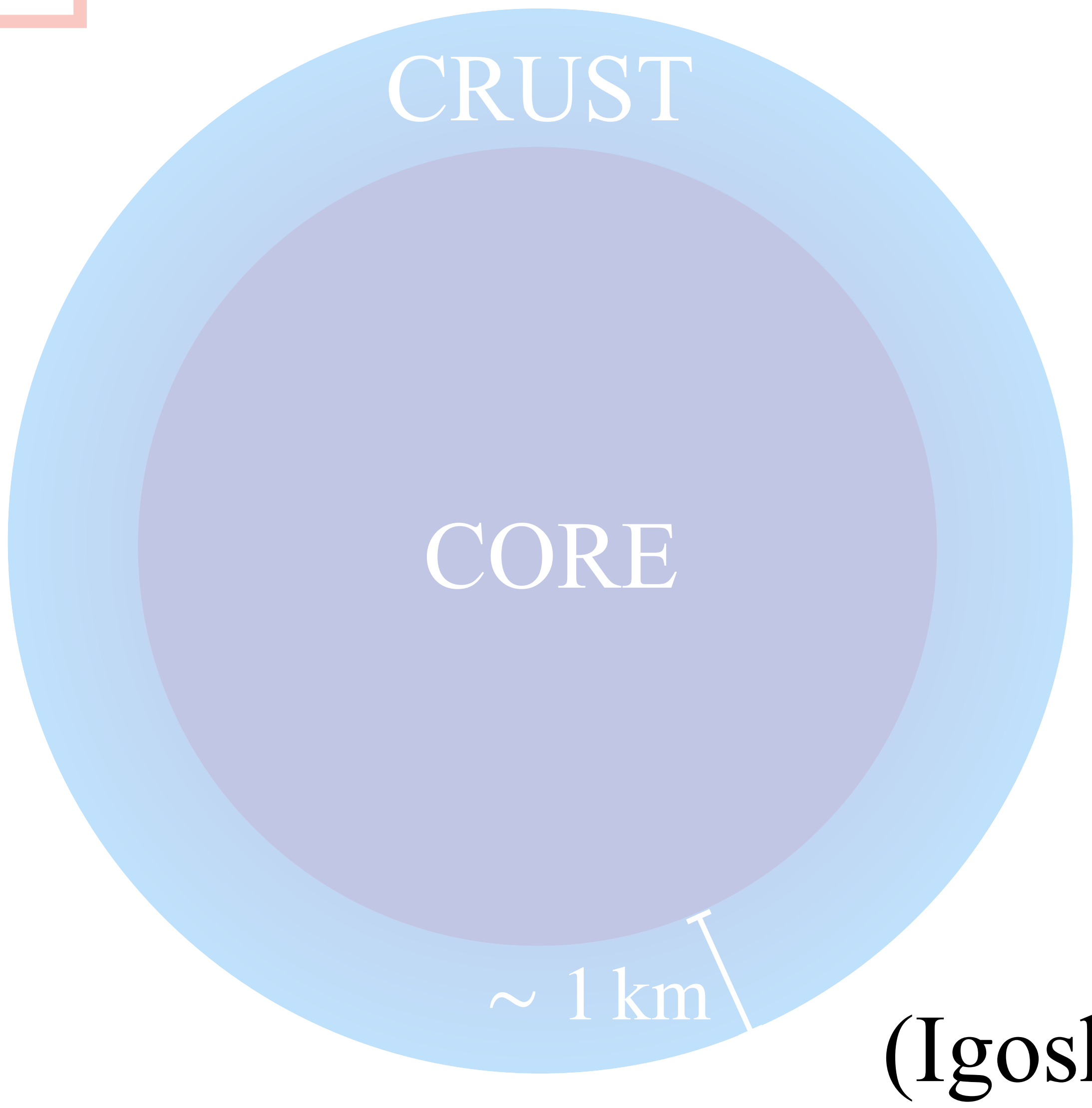
Low-B_{dip}
magnetars ?

PNS model



Input B-field in an
evolved NS structure

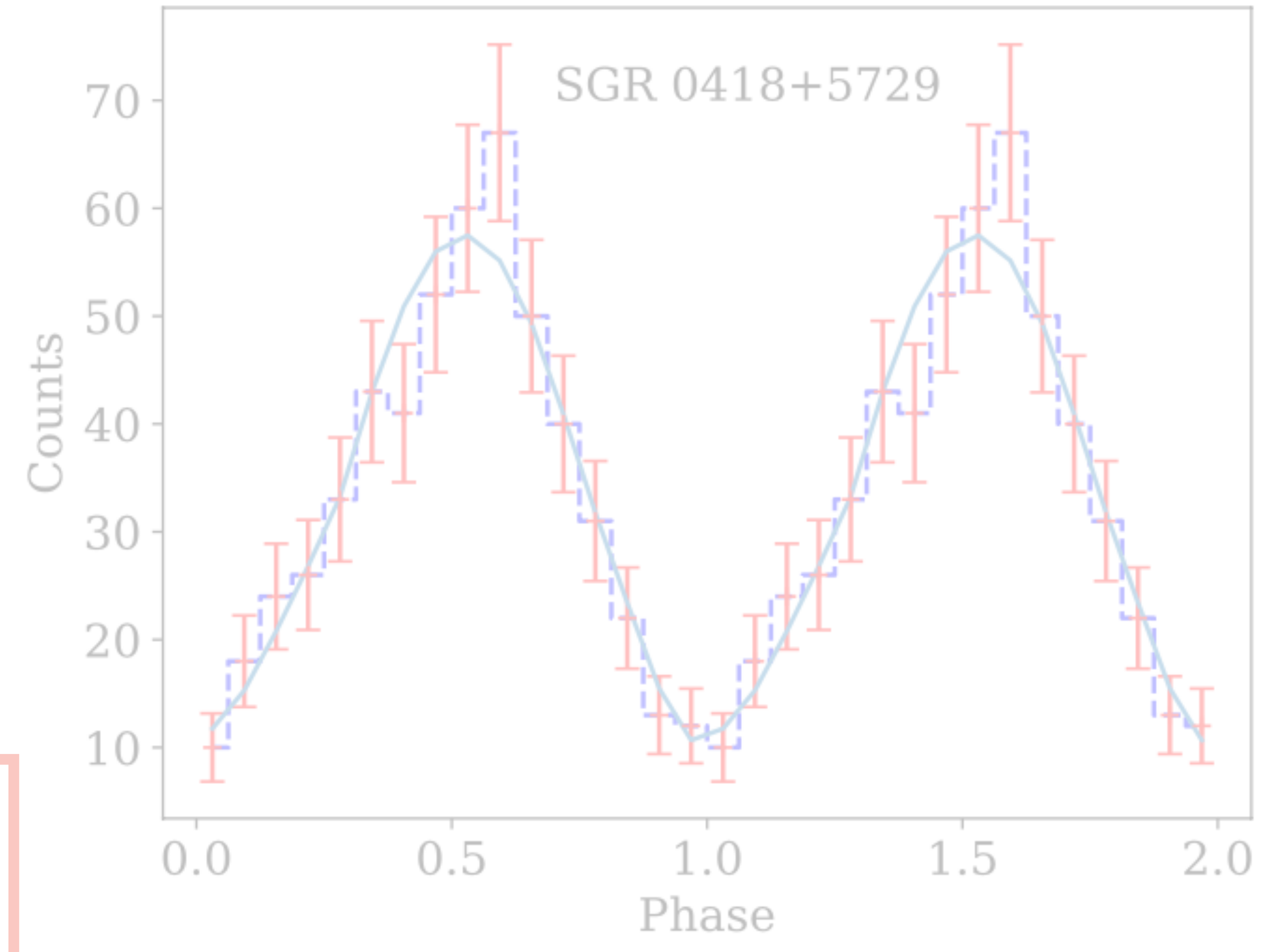
Evolved NS model

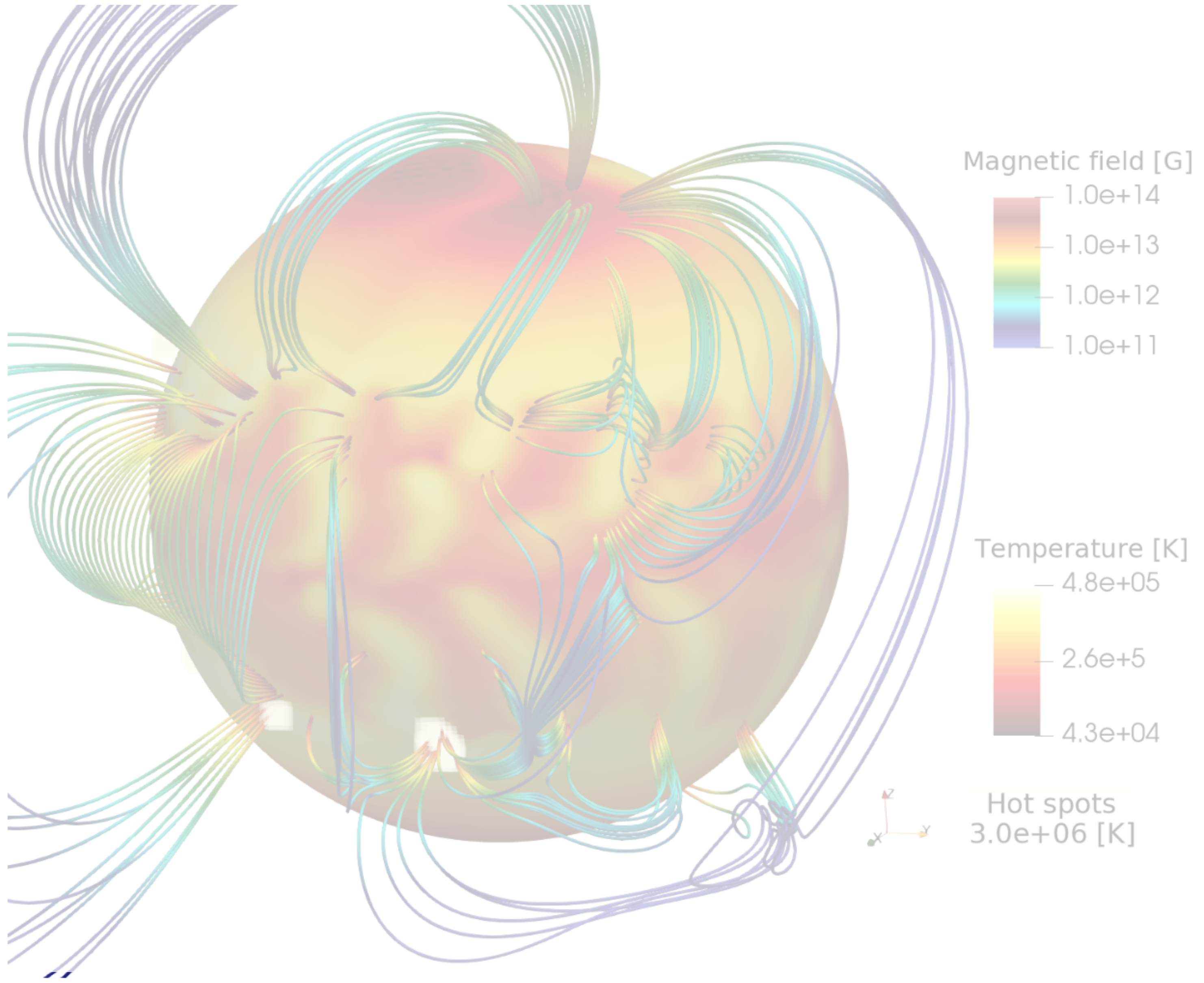


Coupled evolution of
B-field and temperature

…rature gives
…ay emission
…tensity

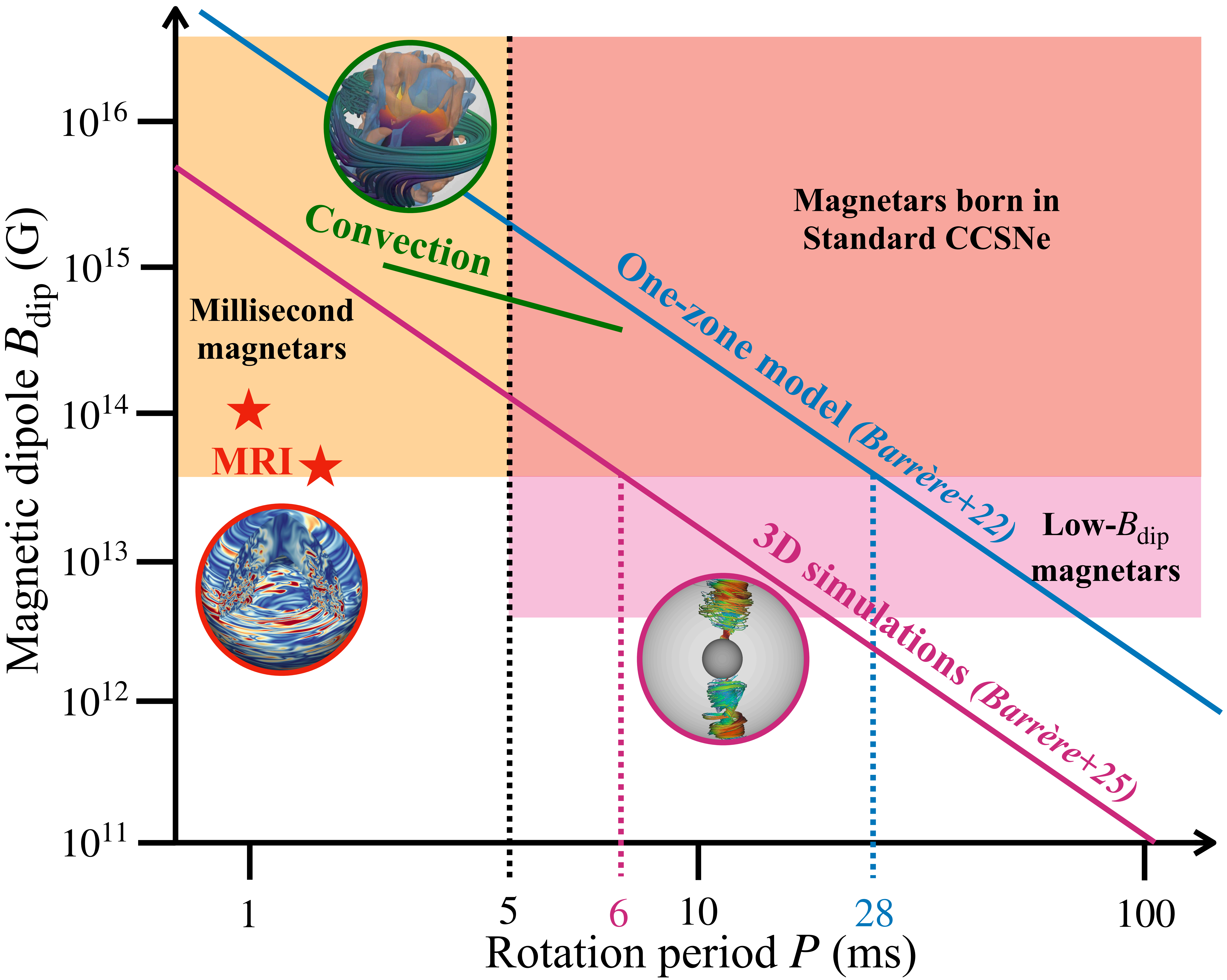
See the next talk by R. Raynaud





(Igoshev, Barrère+, *Nature Astronomy*, 2025)

General conclusions



Wide impact:
- Magnetar formation
- Stellar physics
- Dynamo theory

Possible improvements:
- Toward larger magnetic Prandtl numbers
  ⟶ More realistic diffusivities
  ⟶ Impact on the large-scale magnetic fields
- Realistic reference state (anelastic)
  ⟶ *Collaboration J. Novak*
- Evolving reference state
  ⟶ Relaxation of the magnetic field
  ⟶ Require new implementations