Linking proto-neutron star Tayler-Spruit dynamos to low-field magnetars

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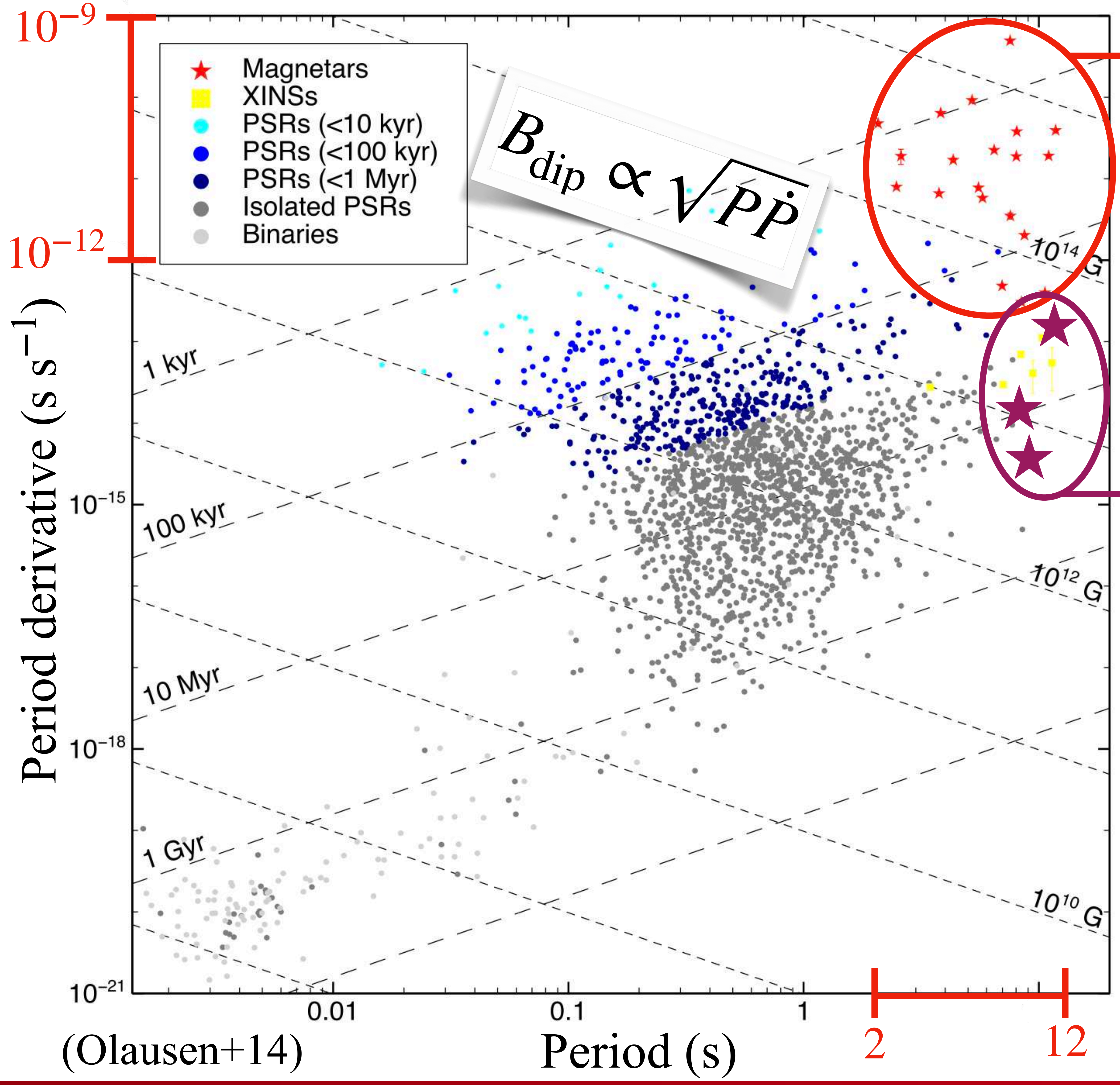
Low-field magnetars : an oxymoron ?



(Olausen+14)

Magnetars

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

- ~30 X-ray Galactic sources (Kaspi+17)
- 10-40 % of newborn neutron stars (Kouveliotou+94, Benjamini+19)

Low-B_{dip} magnetars

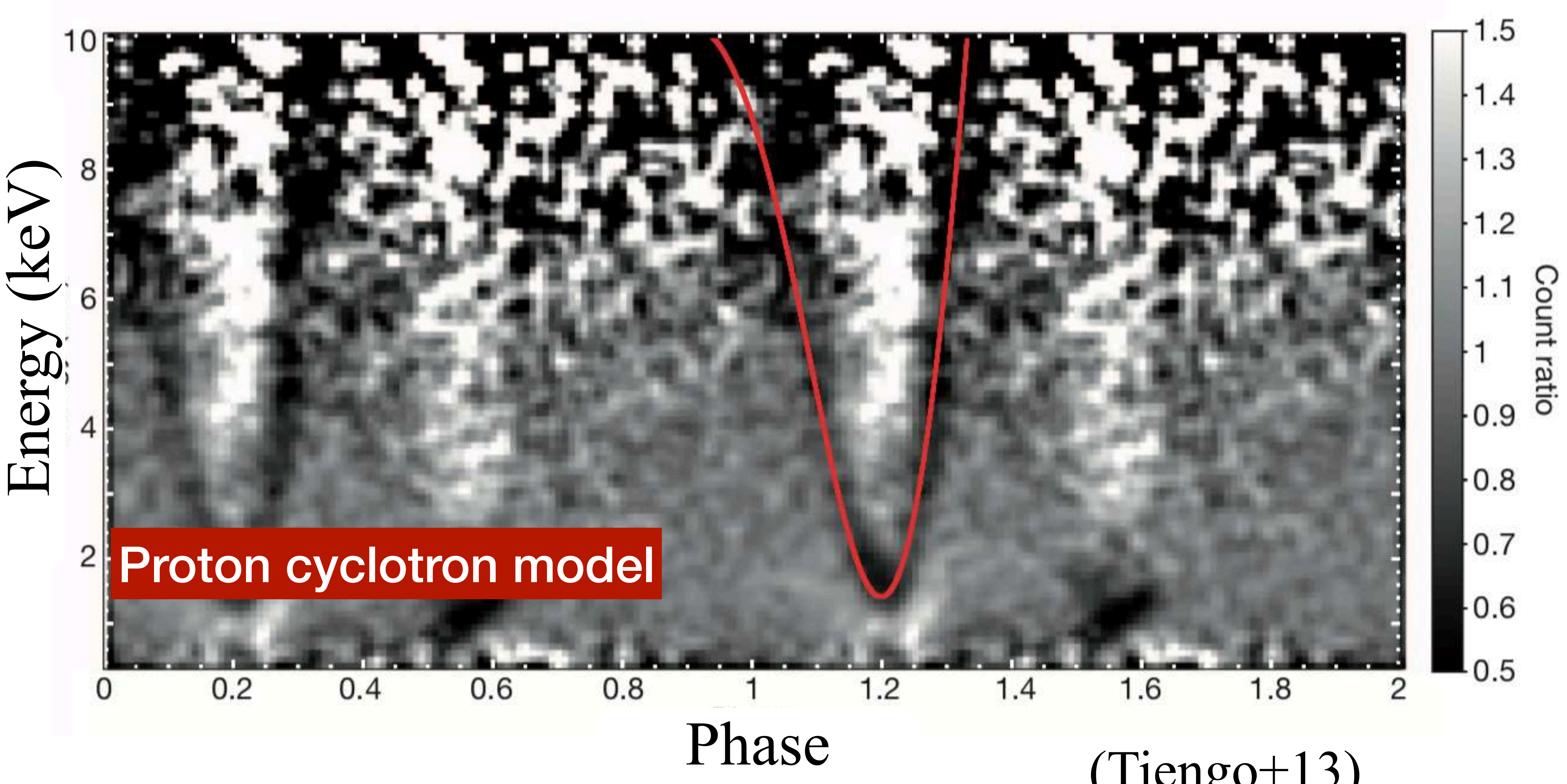
$B_{dip} \sim 10^{12} - 10^{13}$ G

- 5 objects with **weaker dipole field**
- X-ray magnetar-like activity, with bursts and outbursts **magnetically powered**
- Thermal emission from small **hotspot**(s) with size < 1km (Guillot+15 - SGR 0418+5729)

van der Horst+10, Rea+10,12,14

Small-scale versus large-scale magnetic field

Variable absorption feature in X-ray burst/outburst spectrum



(Tiengo+13)

$$B_{\rm non-dip} \sim \text{few} \times 10^{14} - \text{few} \times 10^{15}\,\text{G}$$

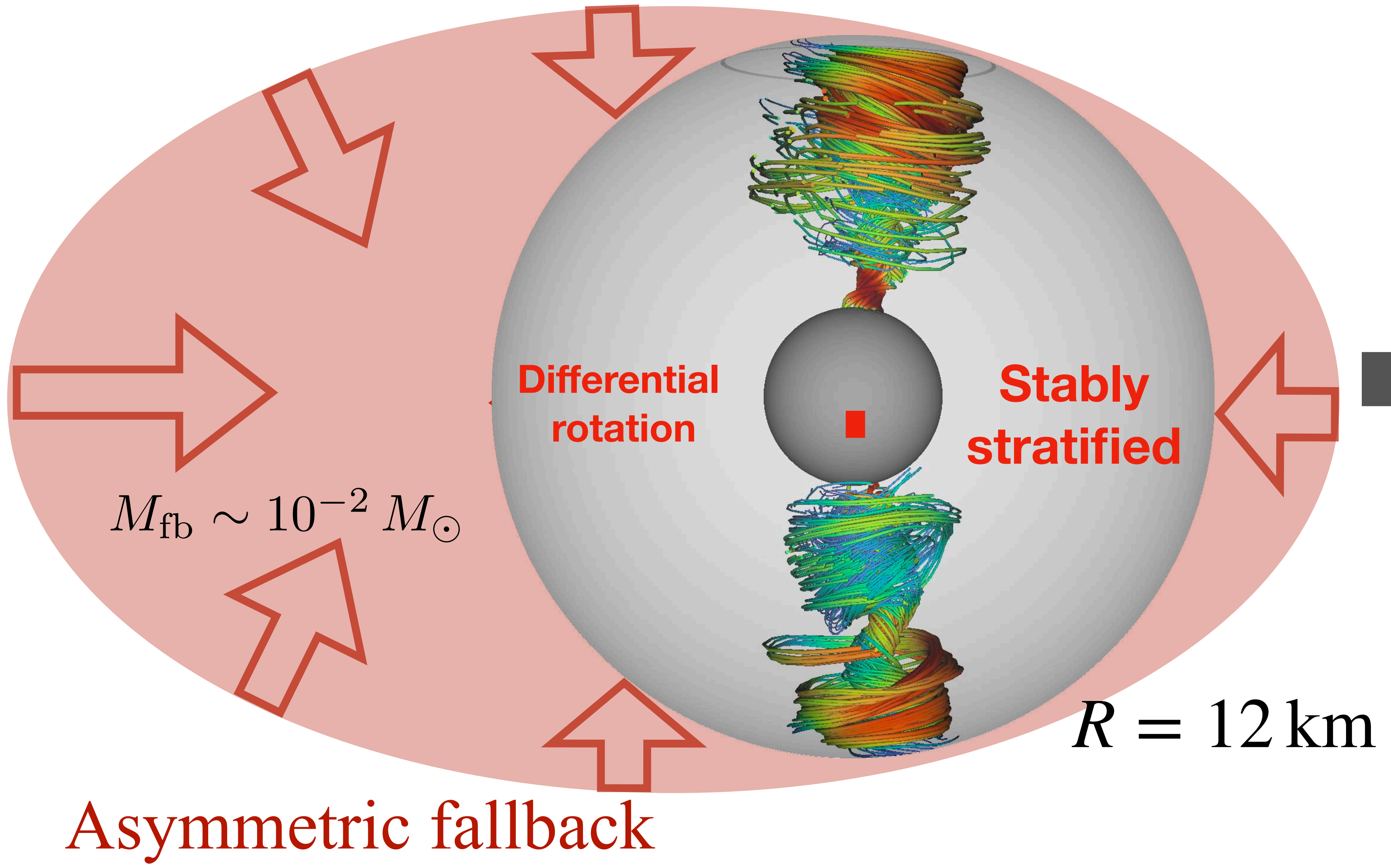
Low-field magnetars

$$B_{\rm small-scale} \gtrsim [10 - 10^2] \times B_{\rm dip}$$

(Tiengo+13, Rodríguez Castillo+16)

From proto-NS to NS simulations

Proto-neutron star

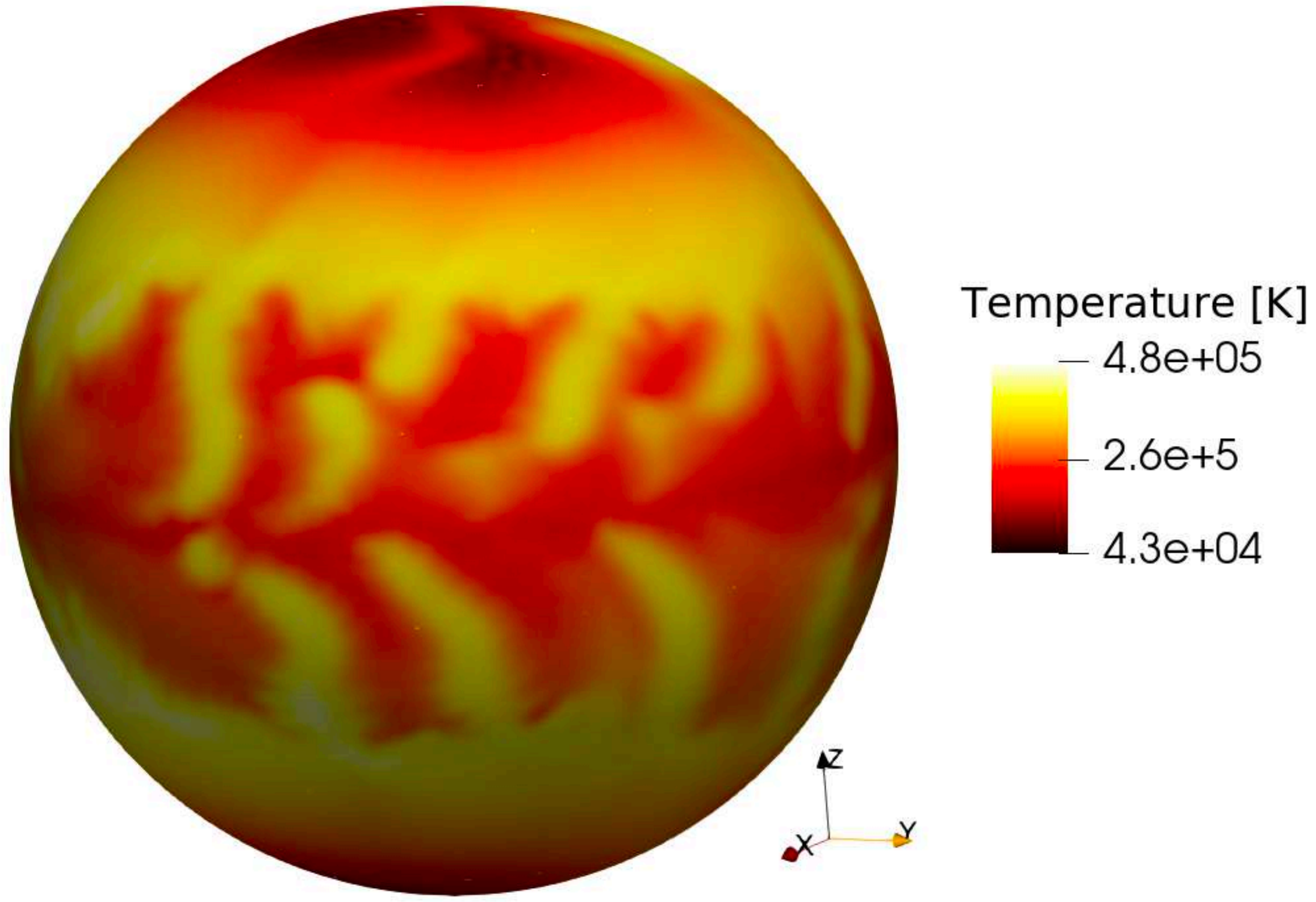


Crust formation

$\tau \sim \mathrm{min} - \mathrm{months}$

Not modelled

Neutron star



- age : ~ 10 s (after core-bounce)
- Rotation period : $\sim 10\,\mathrm{ms}$
- **Fluid => *MHD* simulation**
- Dynamo simulation over ~ 10 s

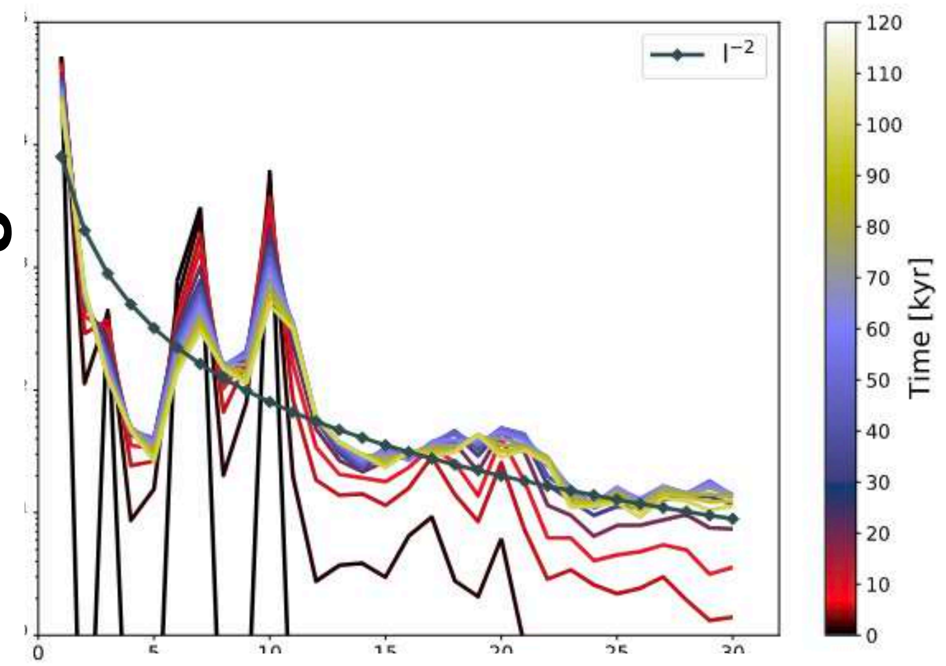
- age : 200 kyr (snapshot)
- Rotation period : $\sim 10\,\mathrm{s}$
- **Solid crust => *e-MHD* simulation**
- Cooling simulation over ~ 1 Myr

Long term cooling: magneto-thermal evolution

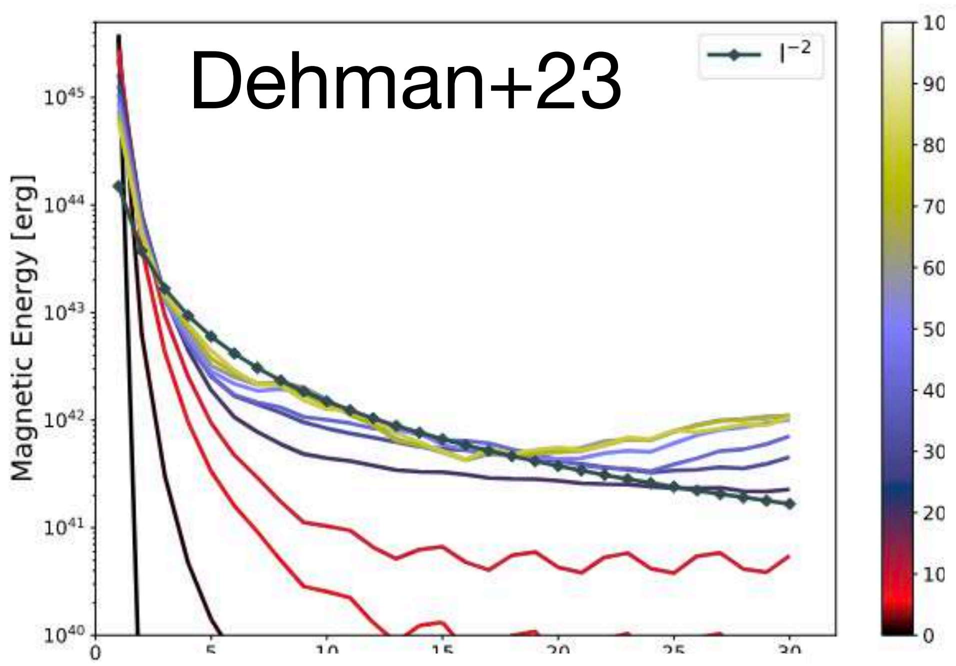
Neutron star crust

- ions are fixed ; currents generated by the flow of electrons
- Ohmic dissipation $\tau_\eta = \frac{R^2}{\eta}$
- Hall drift $\tau_H = \frac{4\pi n_0 e R^2}{c B_0}$
- $Ha = \tau_\eta / \tau_H \gg 1$
- Hall cascade partially keep B field structure

Emag



Harmonic degree



Harmonic degree

Time

Magnetic induction

Grandis+2020

$$\frac{\partial \vec{B}}{\partial t} = \underbrace{Se \nabla \left(\frac{1}{\mu}\right) \times \nabla T^2}_{\ll 1} + \underbrace{Ha \nabla \times \left[\frac{1}{\mu^3} \vec{B} \times (\nabla \times \vec{B})\right]}_{\text{Hall term}} \underbrace{- \nabla \times \left[\frac{1}{\mu^2} \nabla \times \vec{B}\right]}_{\text{Diffusion term}}$$

Thermal diffusion

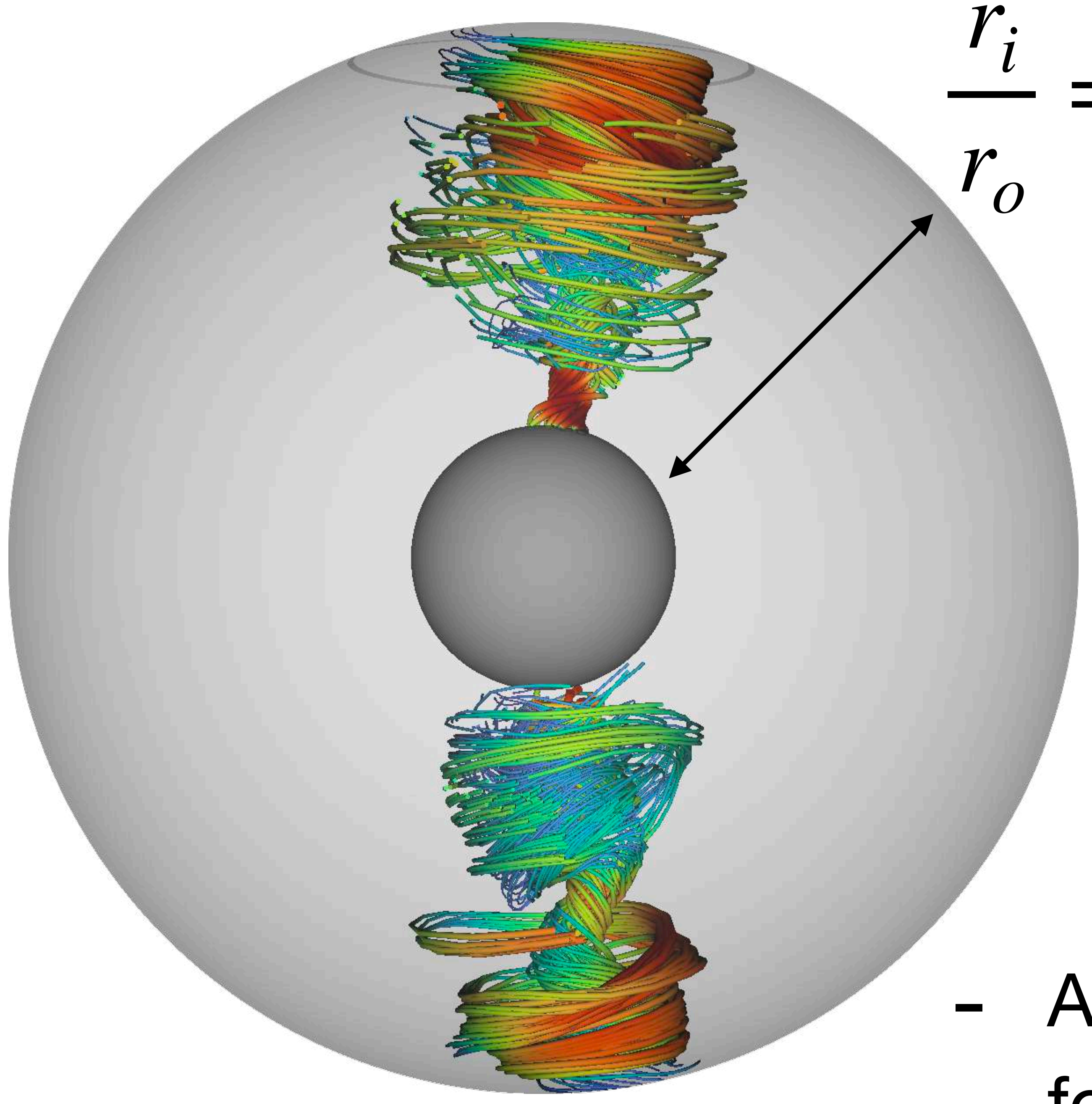
$$\frac{1}{Ro} \frac{C_v}{T} \frac{\partial T^2}{\partial t} = \underbrace{\nabla \cdot (\mu^2 \hat{\chi}(B) \cdot \nabla T^2)}_{\text{Heat flux}} + \underbrace{\frac{Pe}{Se} \frac{|\nabla \times \vec{B}|^2}{\mu^2}}_{\text{Ohmic heating}} + \underbrace{Pe \mu (\nabla \times B) \cdot \nabla \left(\frac{T^2}{\mu^2}\right)}_{\ll 1}$$

Anisotropic heat transport : $\hat{\chi}(B) = \frac{\delta_{ij} + \text{Ha}\, B_i B_j / \mu^2 - \text{Ha}\, \epsilon_{ijk} B_k / \mu}{1 + \text{Ha}^2 |\vec{B}|^2 / \mu^2}$,

> reduced heat flow in the direction orthogonal to B field lines

Implementing a PNS dynamo state as an initial condition

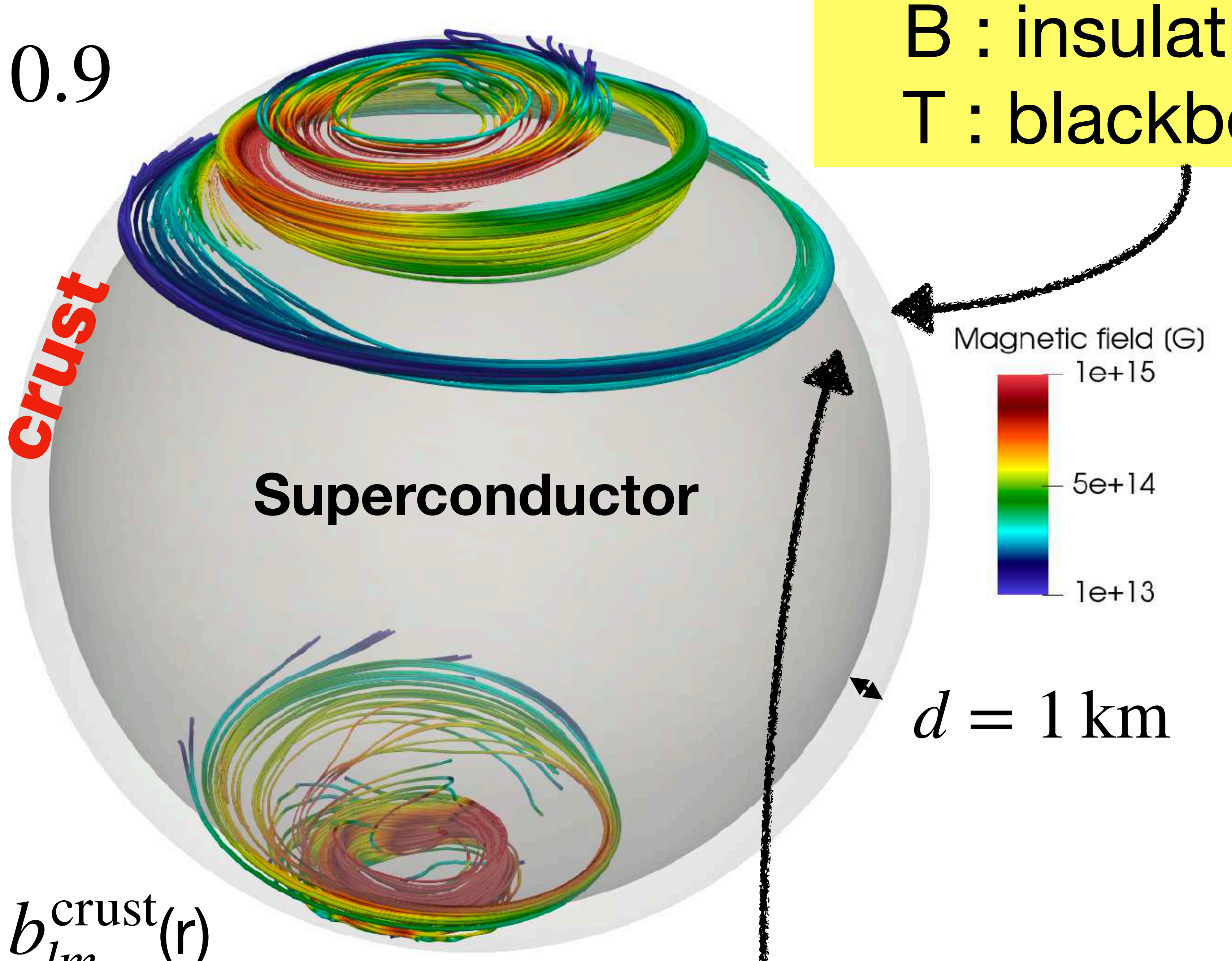
Tayler-Spruit dynamo



$\frac{r_i}{r_o} = 0.25$

Neutron star crust

$\frac{r_i}{r_o} = 0.9$



$d = 1\,\text{km}$

Outer boundary
B : insulating b. c.
T : blackbody emission

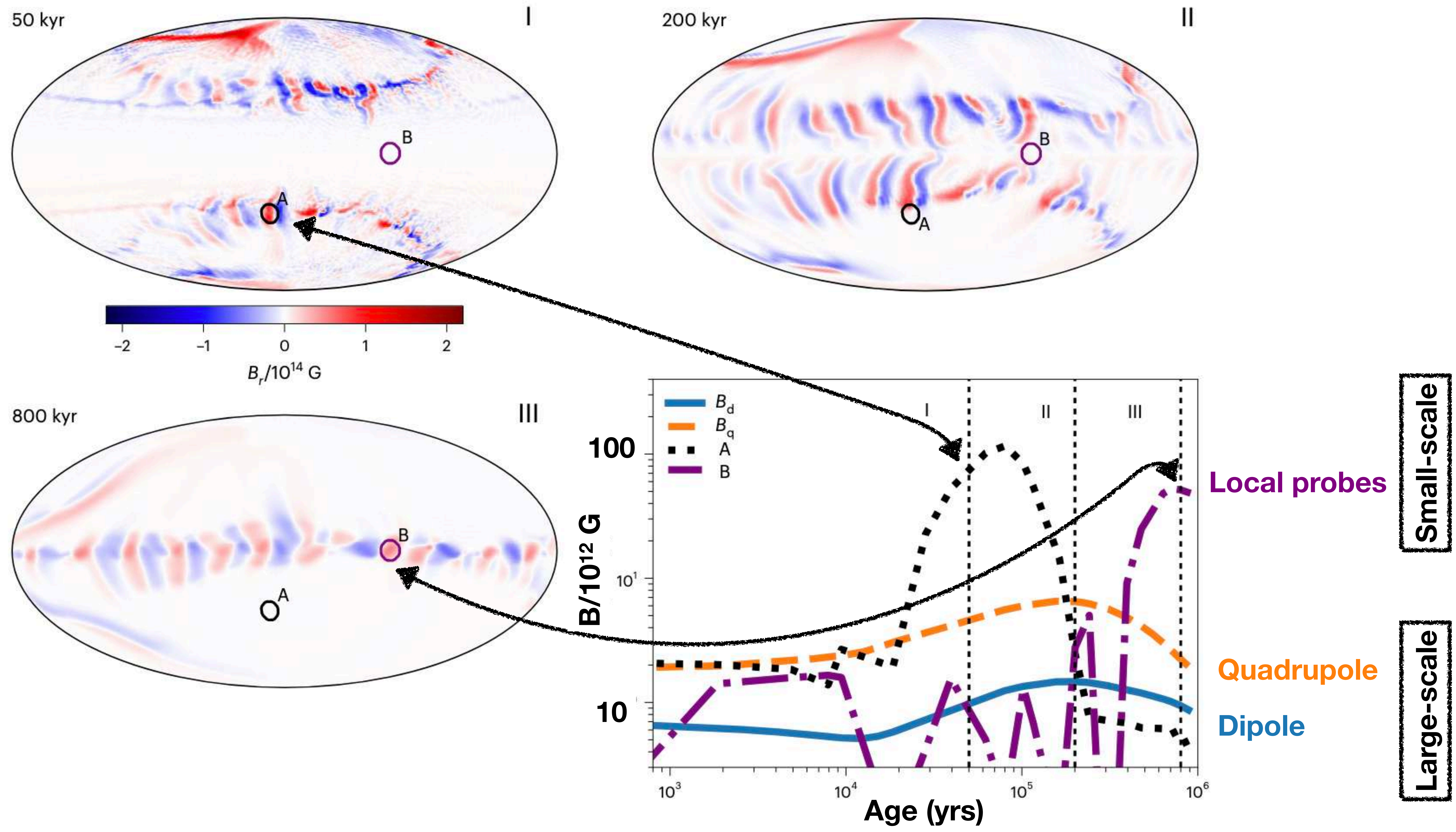
Inner boundary
B : Meissner condition
T : no flux $\partial_r T = 0$

Method

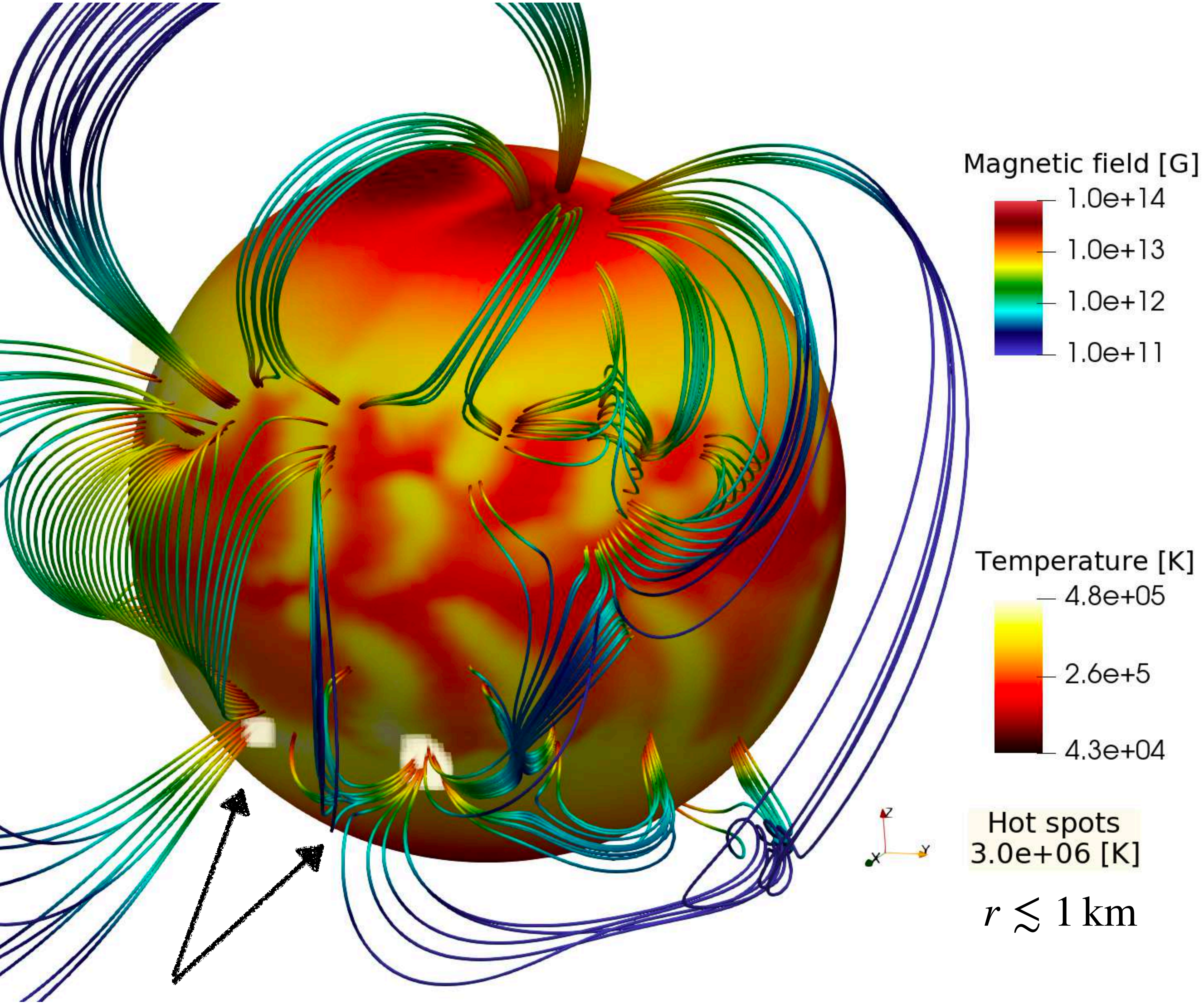
- Assume a polynomial expansion for the poloidal and toroidal potentials b_{lm}^{crust}(r)
- Determine the coefficients by matching the boundary conditions and imposing $b_{lm}^{\text{crust}}(r*) = b_{lm}^{\text{PNS}}(r*), \forall l \leq 30$ at $r* = [0.93 r_0, 0.96 r_o, r_0]$

Magnetic field evolution up to 800 kyr

$B_r(r_0)$



External magnetic field at 200 kyr



$r \lesssim 1\,\mathrm{km}$

- B field creates large T variations
- Footpoints with $B_r > 10^{13}$ G could produce hot spots heated by magnetospheric currents
=> X-ray light curve modulation

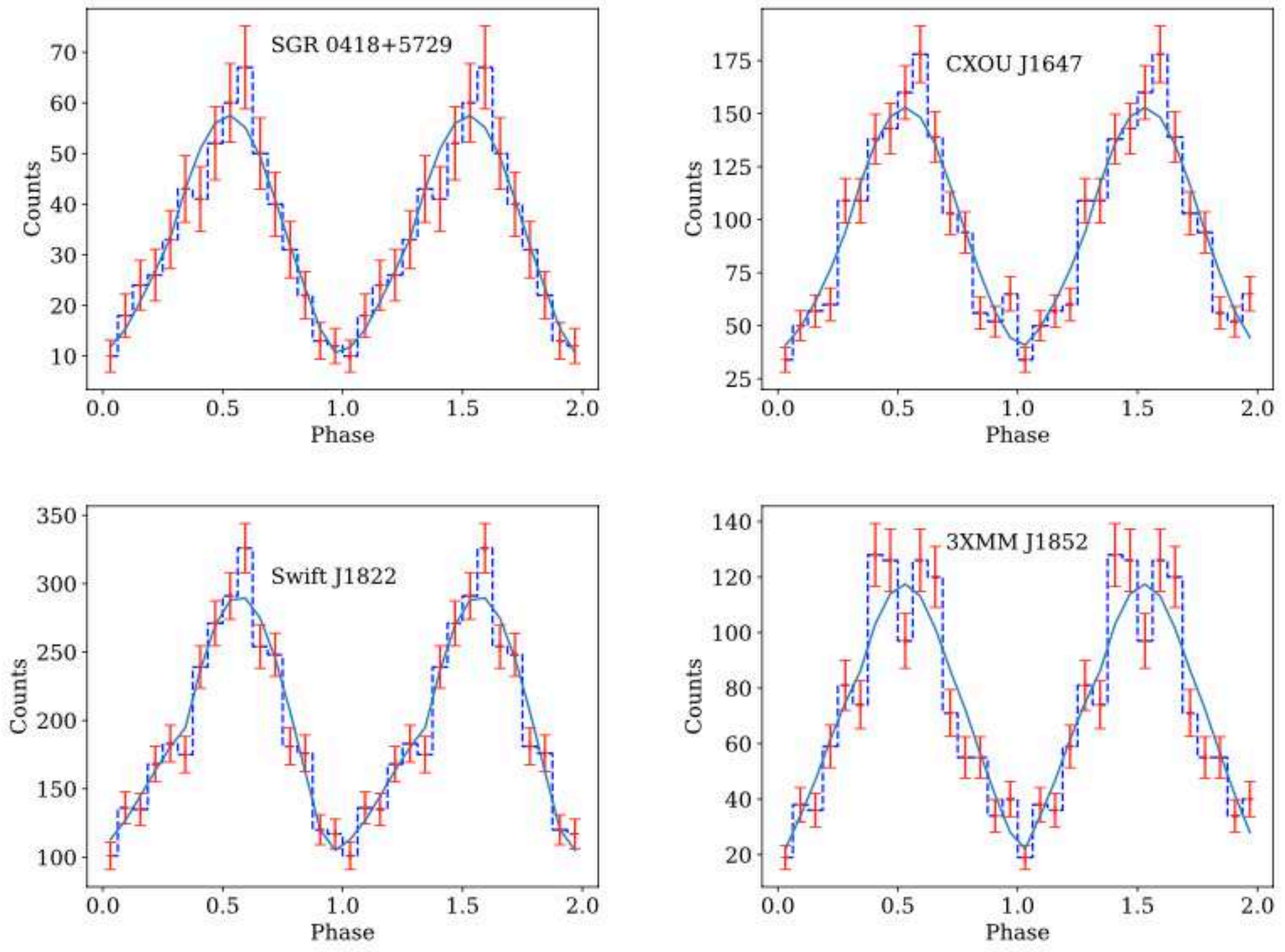


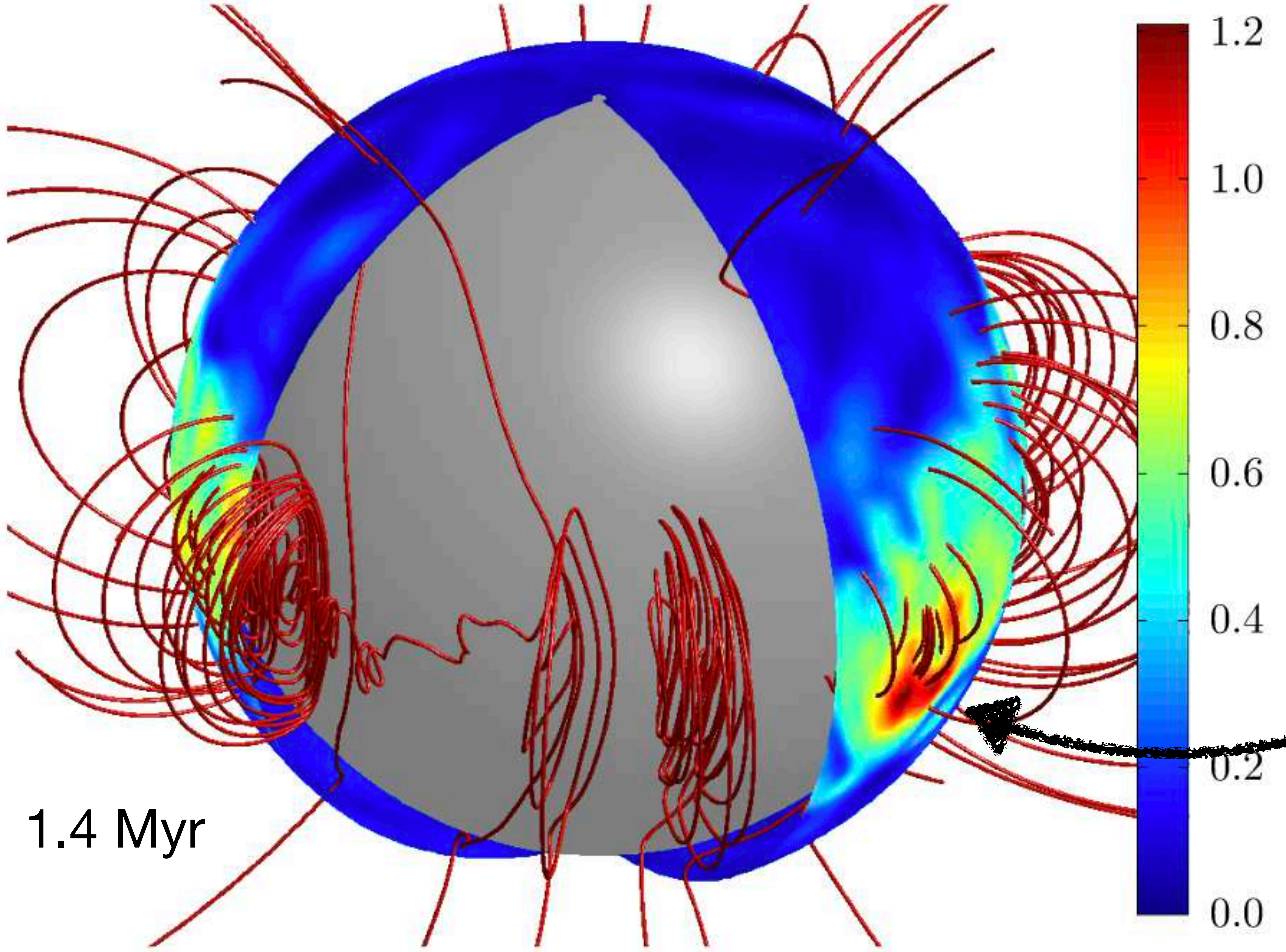
Figure 10: Observed soft X-ray lightcurves in the range of 0.3-2 keV for low-field magnetars in the quiescent state and the best fits (solid blue line). It is assumed that emission is produced by hot spots formed at the places with radial magnetic field exceeding 7×10^{13} G.

Crustal magnetic stresses

Initial B : dipole

Initial B : Tayler-Spruit dynamo

Wood+15

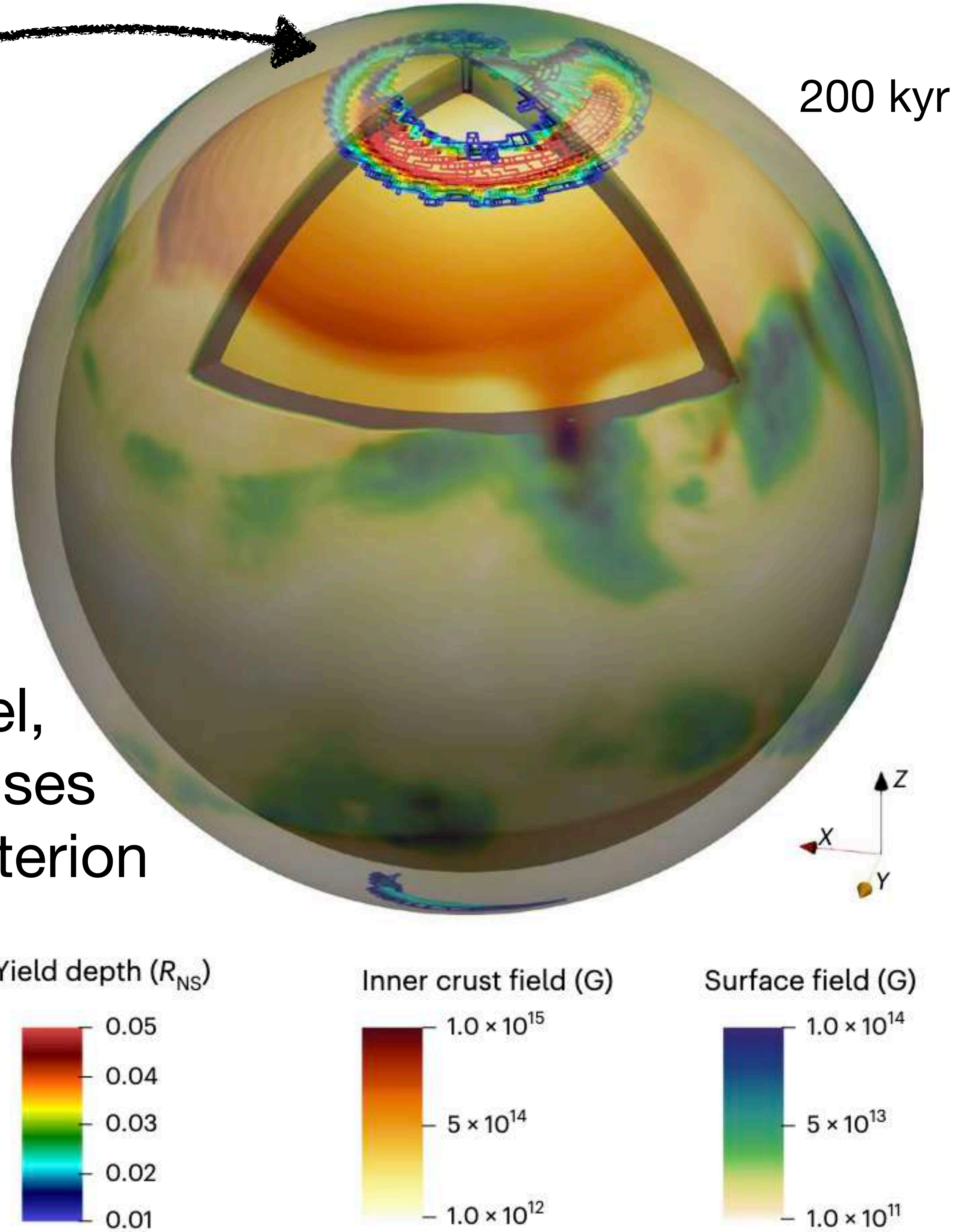


1.4 Myr

FIG. 5 (color online). Lines of the magnetic field generated by currents in the crust. The coloring indicates the ratio of magnetic pressure to breaking stress at the surface of the crust. A portion of the surface has been cut away to show field lines inside the crust, whose lower boundary is the gray sphere.

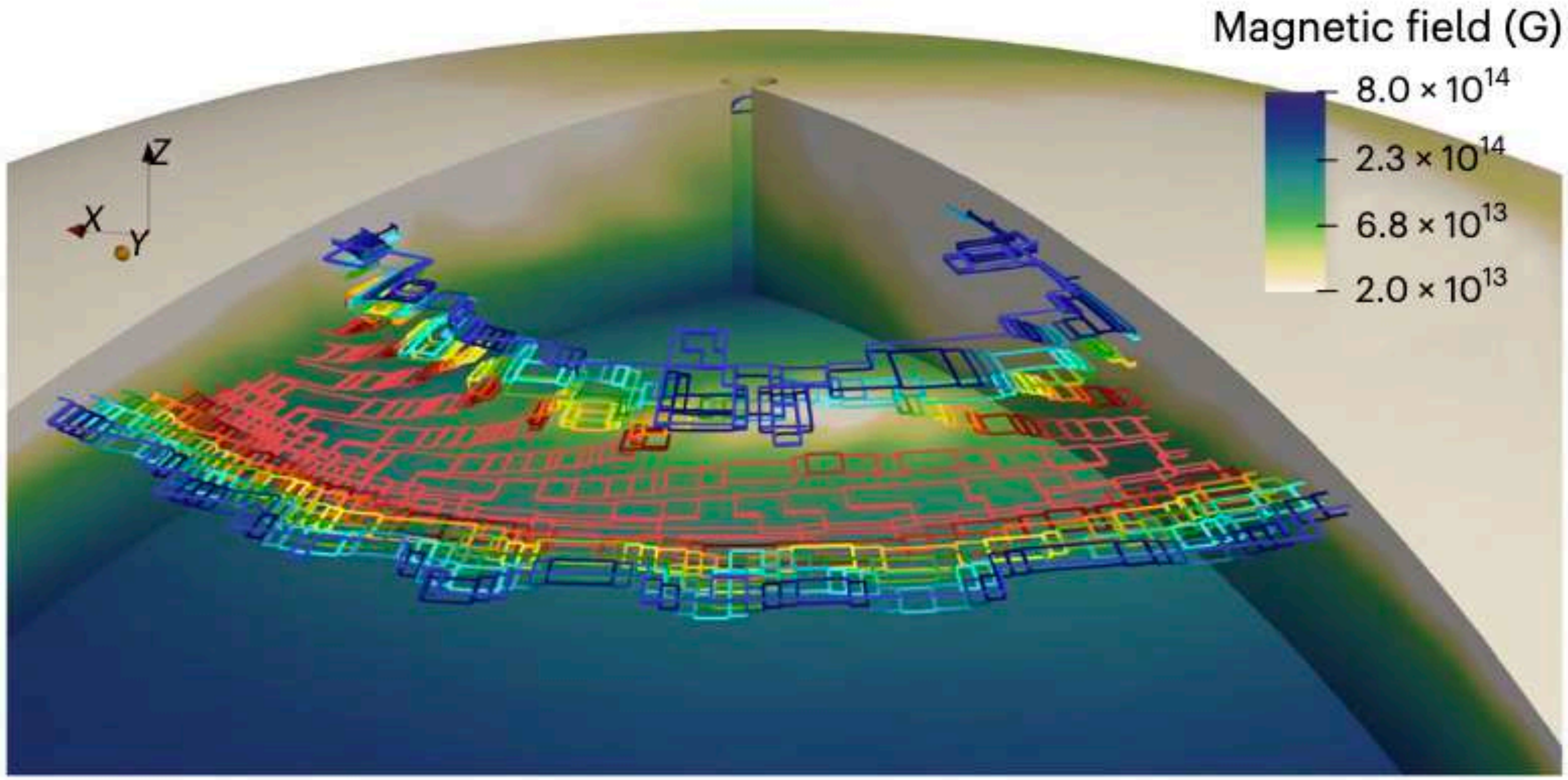
Crust yielding regions

200 kyr



Lander+19 model, based on von Mises crust yielding criterion
Lander+15,19

Powering magnetar X-ray activity



Energy release in crustal failure (Thompson+95)

$$E_{\mathrm{out}} \lesssim 2 \times 10^{39}\ \mathrm{erg} \left(\frac{l}{1\ \mathrm{km}}\right)^2 \left(\frac{|B|}{2 \times 10^{14}\ \mathrm{G}}\right)^2$$

Low-field magnetar observations

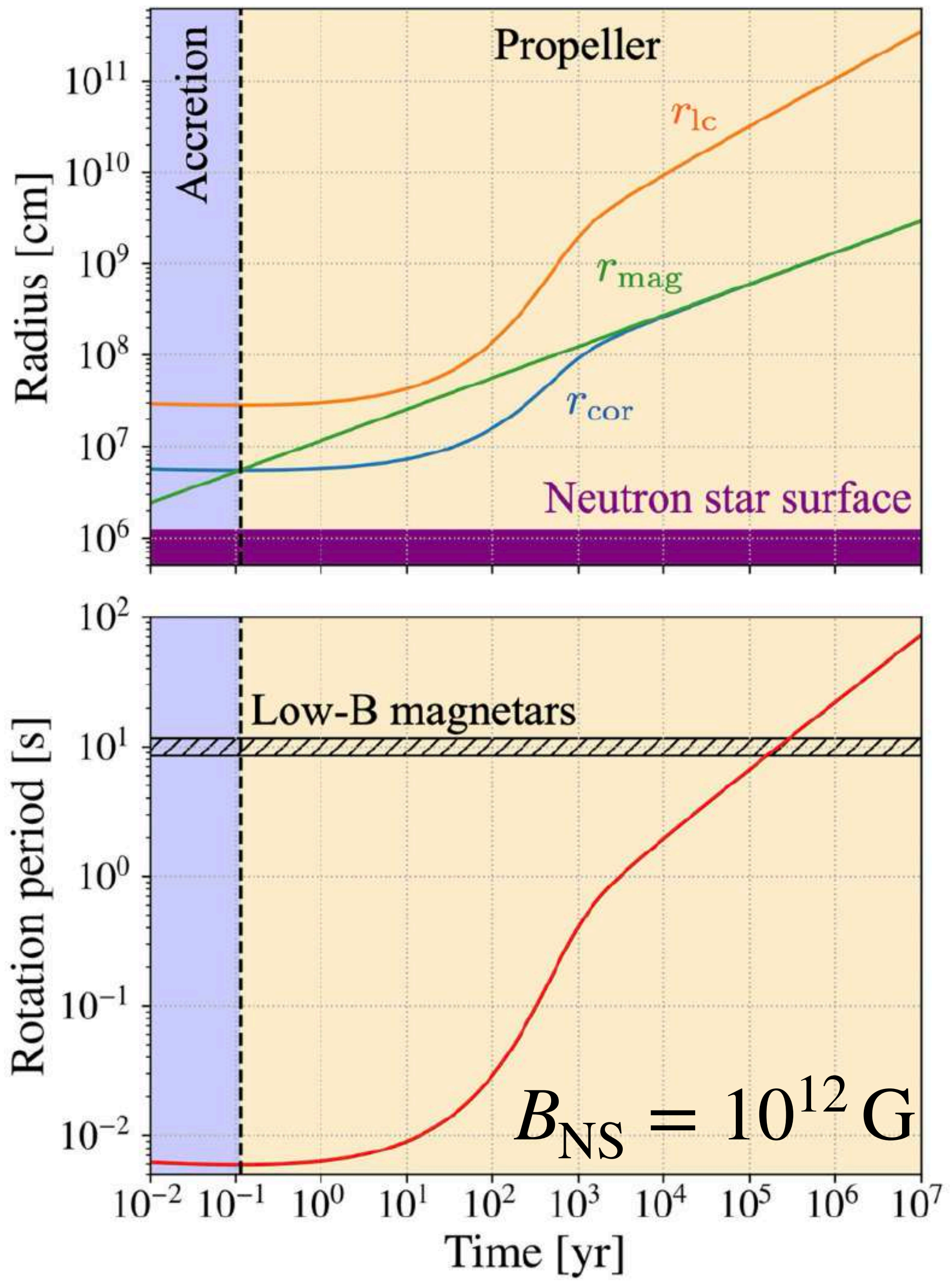
$E_{\mathrm{burst}} \sim 10^{37}\ \mathrm{erg}$ (Muno+07)

Spin down

Tayler-Spruit dynamo invoke CCSN fallback
=> rotational evolution controlled by interaction
with a fallback disc ($M \sim 0.01 M_{\odot}$)

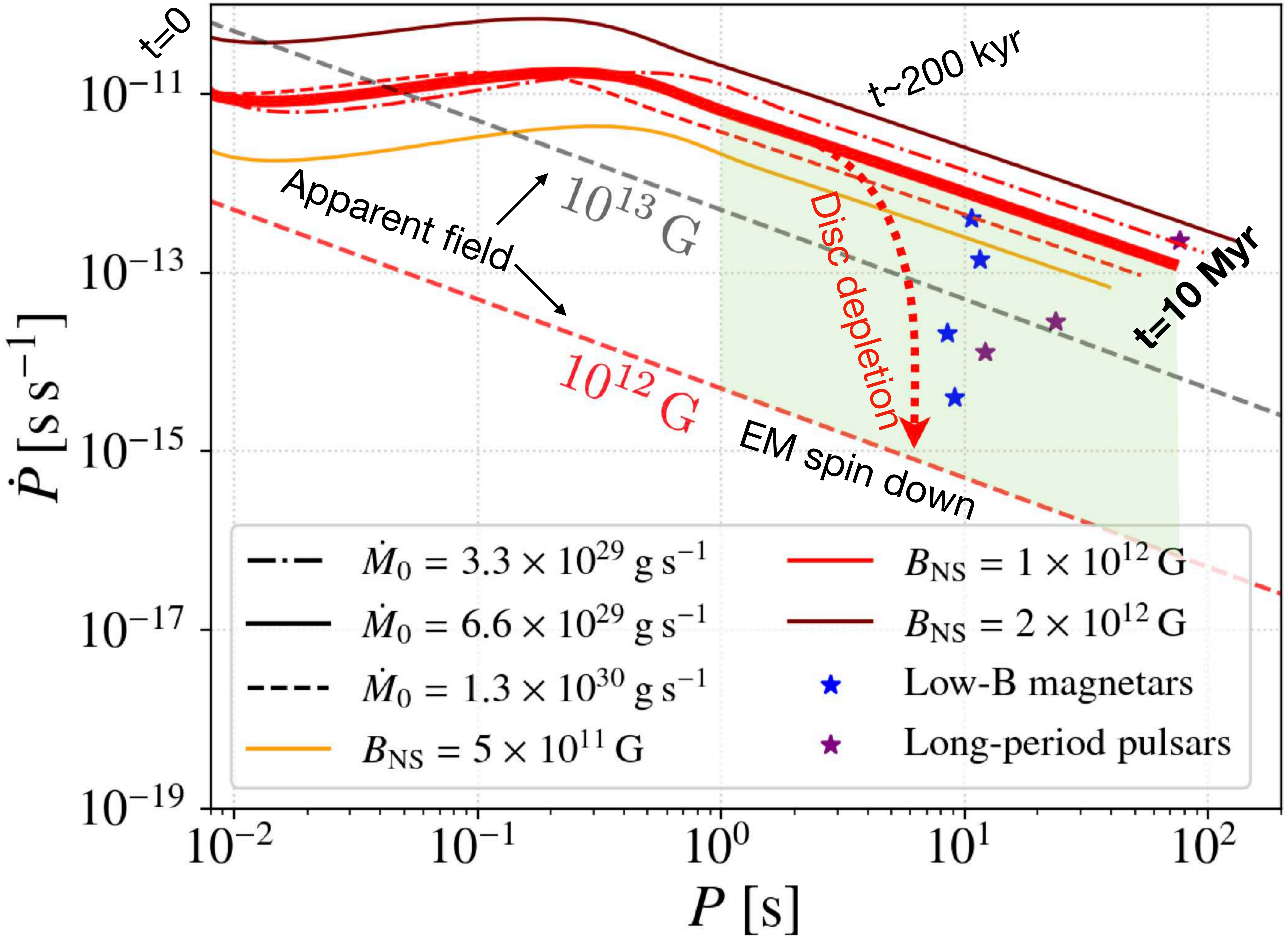
$$I_{\rm NS}\dot{\Omega}_{\rm NS} = N_{\rm acc} + N_{\rm dip}$$ (Ronchi+22)

Accretion torque — Electromagnetic torque



Propeller regime
=> NS spin dow

$P(t \sim 200\,{\rm kyr}) \approx 10\,{\rm s}$



Conclusions

Successfull proof-of-concept

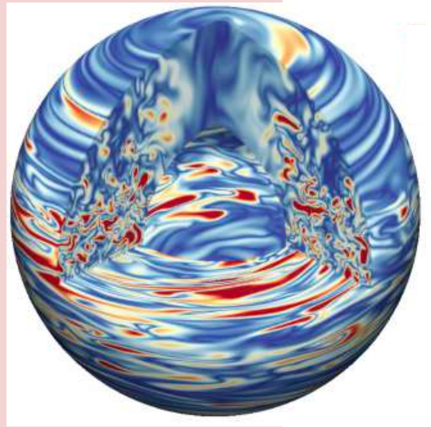
- Weak dipole field
- Strong small-scale fields
  => large surface temperature variation
  => formation of hotspots by magnetospheric currents
- Magnetically induced crustal failures
  => energy reservoir of X-ray burst
- Efficient spin-down in propeller regime

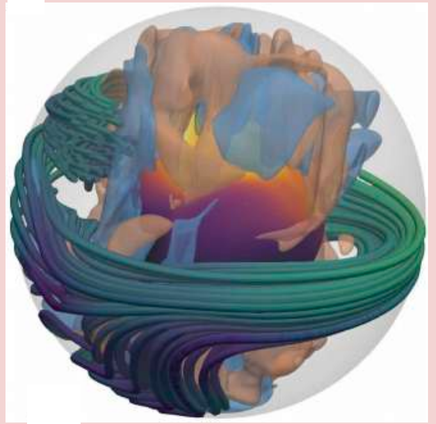
References

- Igoshev et al., Nat Astr., 2024
- Barrère et al., MNRAS, 2023, 2025

Perspectives: from PNS to NS

- Test several initial conditions with the Tayler-Spruit dynamo model (*WIP*)
- Investigate other dynamo scenario
  => MRI ?
  => convective dynamo ?





- Coupling with relativistic magnetosphere simulations (Mahlmann+23) :
  => magnetosphere dynamics
- Below the crust : global models including neutron star core (Igoshev+23)

Magnetar formation scenarios

Fossil field

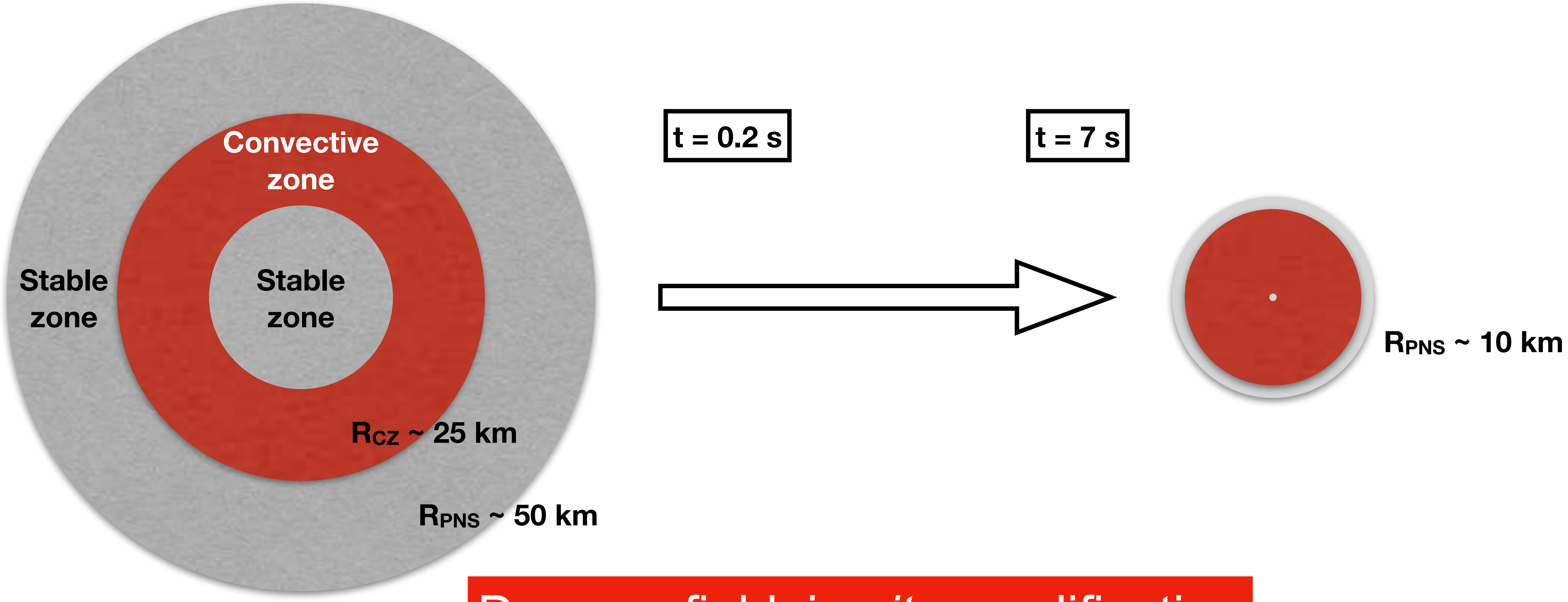
- Amplification factor

$$\left(\frac{r_{\rm core} \sim 10^3 \text{ km}}{r_{NS} \sim 10 \text{ km}}\right)^2 \sim 10^4$$

$$\Longrightarrow \quad B_{\rm core} \sim 10^{11} \text{ G}$$

- magnetic massive stars (10%) formed by stellar mergers ? (Schneider+19)

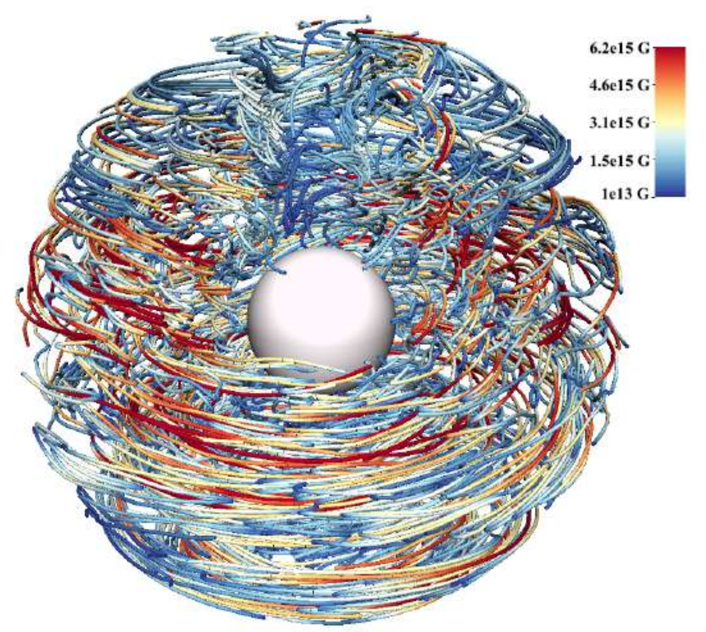
- Magnetisation of stellar cores ?
- Millisecond magnetars ?
- Unlikely to simultaneously reproduce pulsar and magnetar populations (Makarenko+21)



Dynamo field: *in situ* amplification

Outer stably stratified zone & differential rotation

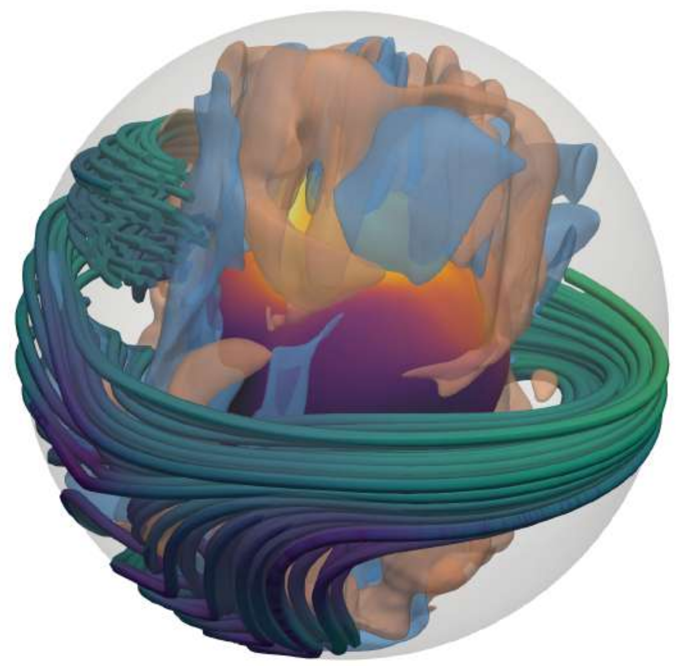
Magneto Rotational Instability



Reboul-Salze+21,22

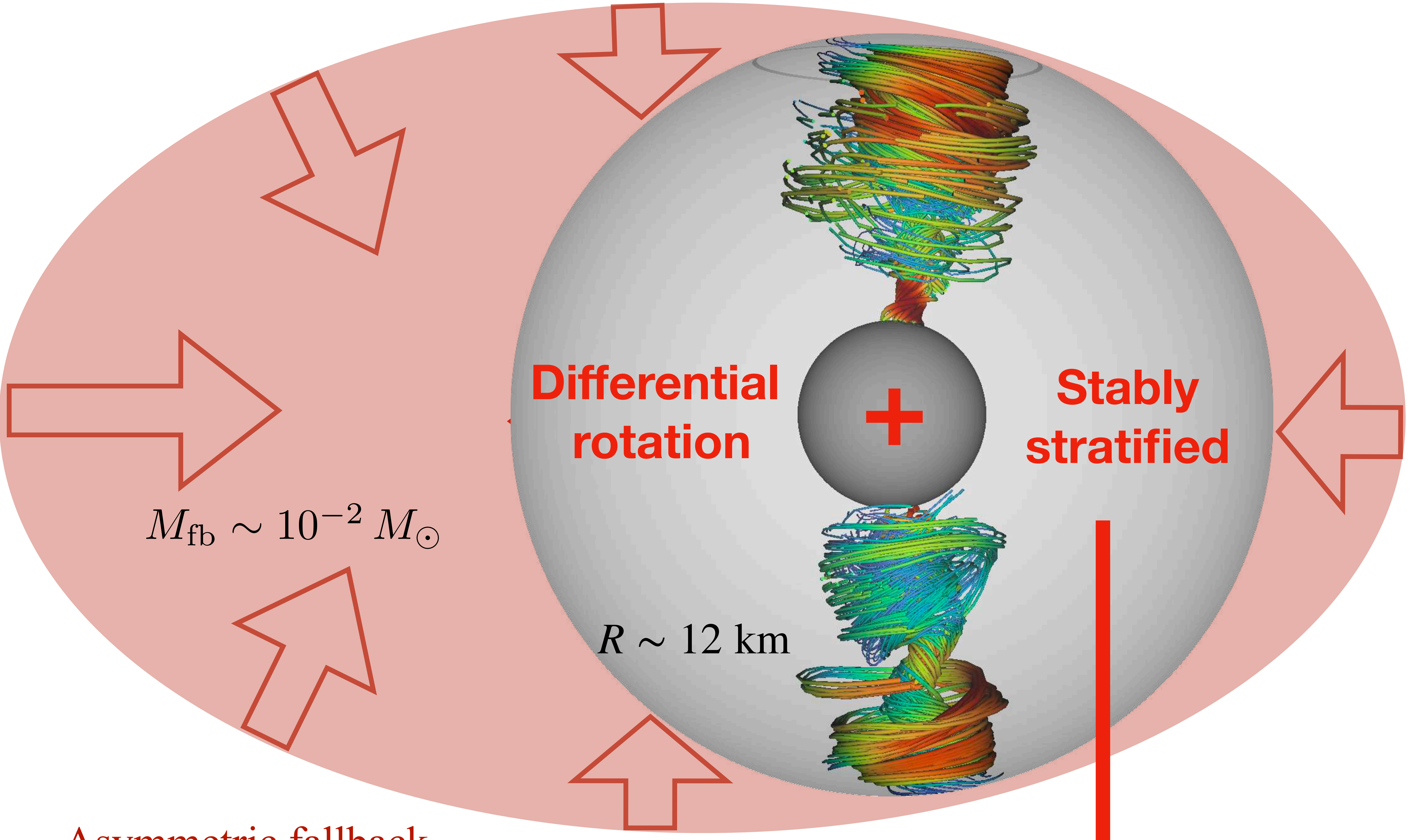
Convection lasting for ~10 s

Convective dynamo



Raynaud+20,22

New scenario: proto-neutron star spun up by supernova fallback



Asymmetric fallback accretion

Fallback in 3D CCSN simulations

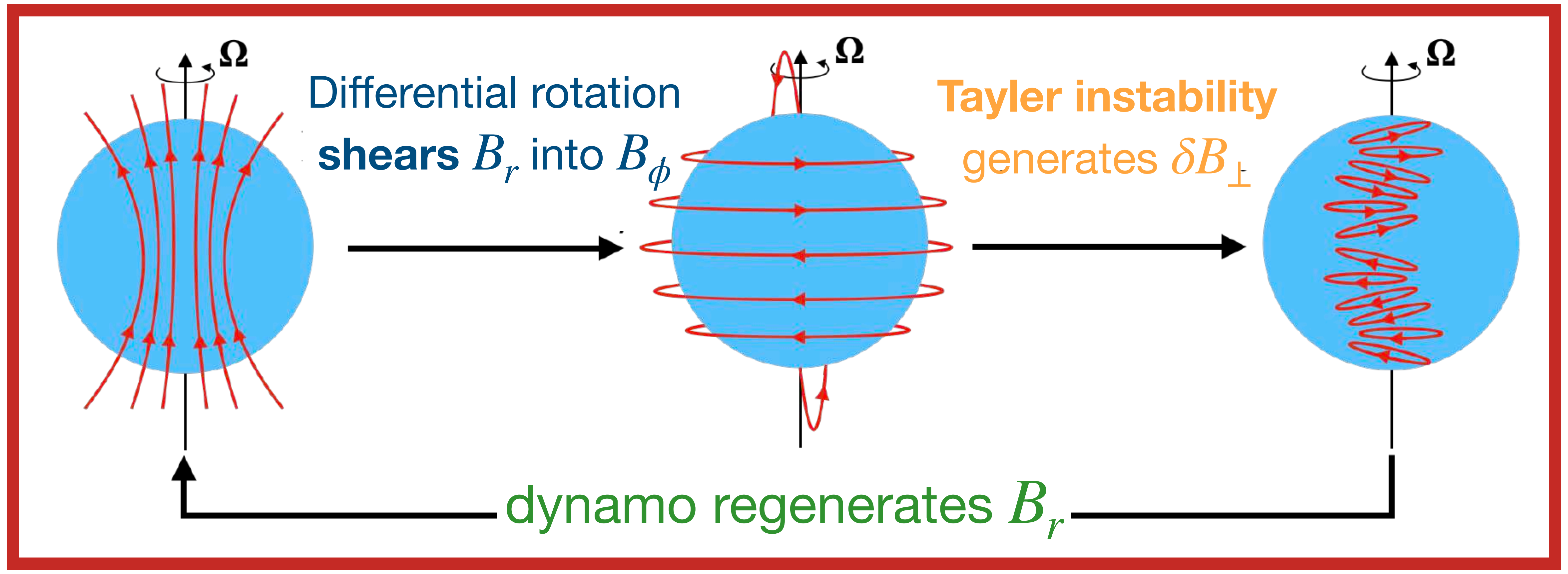
- *Fallback* = matter that remains gravitationally bound
- starts **~10 s** after the core bounce
- $M_{\rm fallback} \in [10^{-4}, 10^{-1}]\, M_\odot$
- lasts from minutes to hours
- Potential to spin up the proto-neutron star up to break up

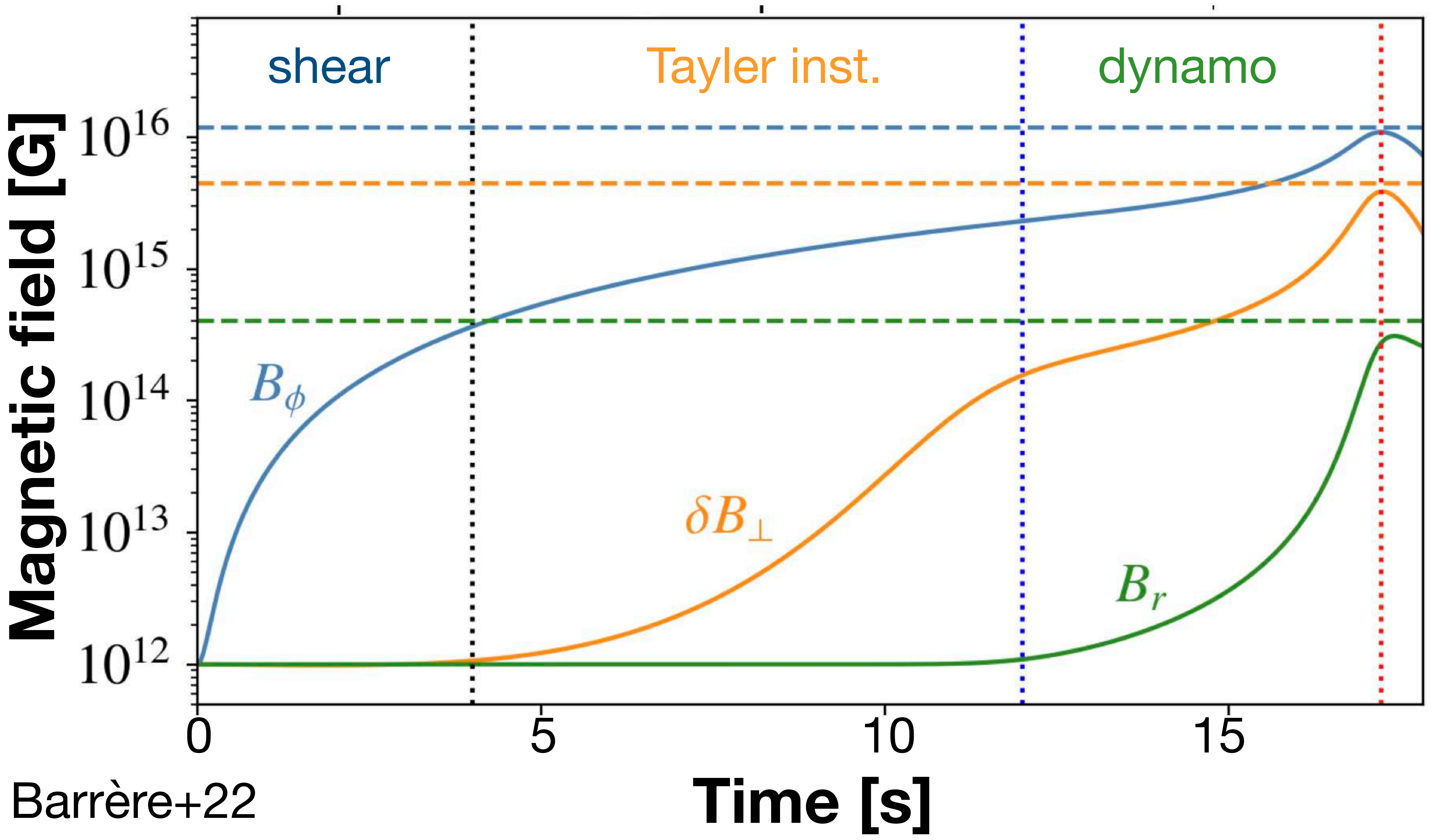
(Chan+20, Janka+22)

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

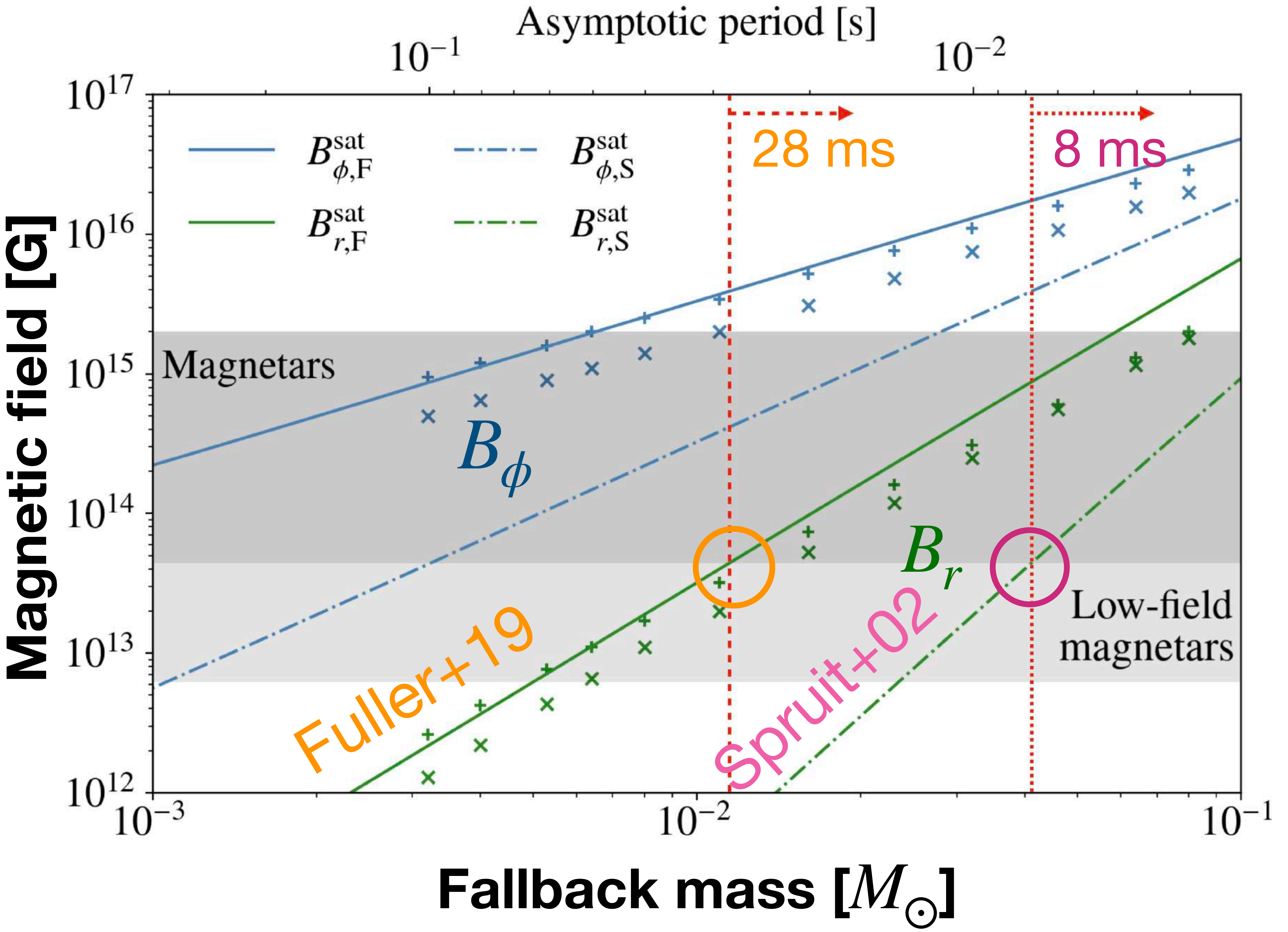
Proof of concept: one zone model

Tayler-Spruit dynamo loop (Spruit+02, Fuller+19)





Barrère+22

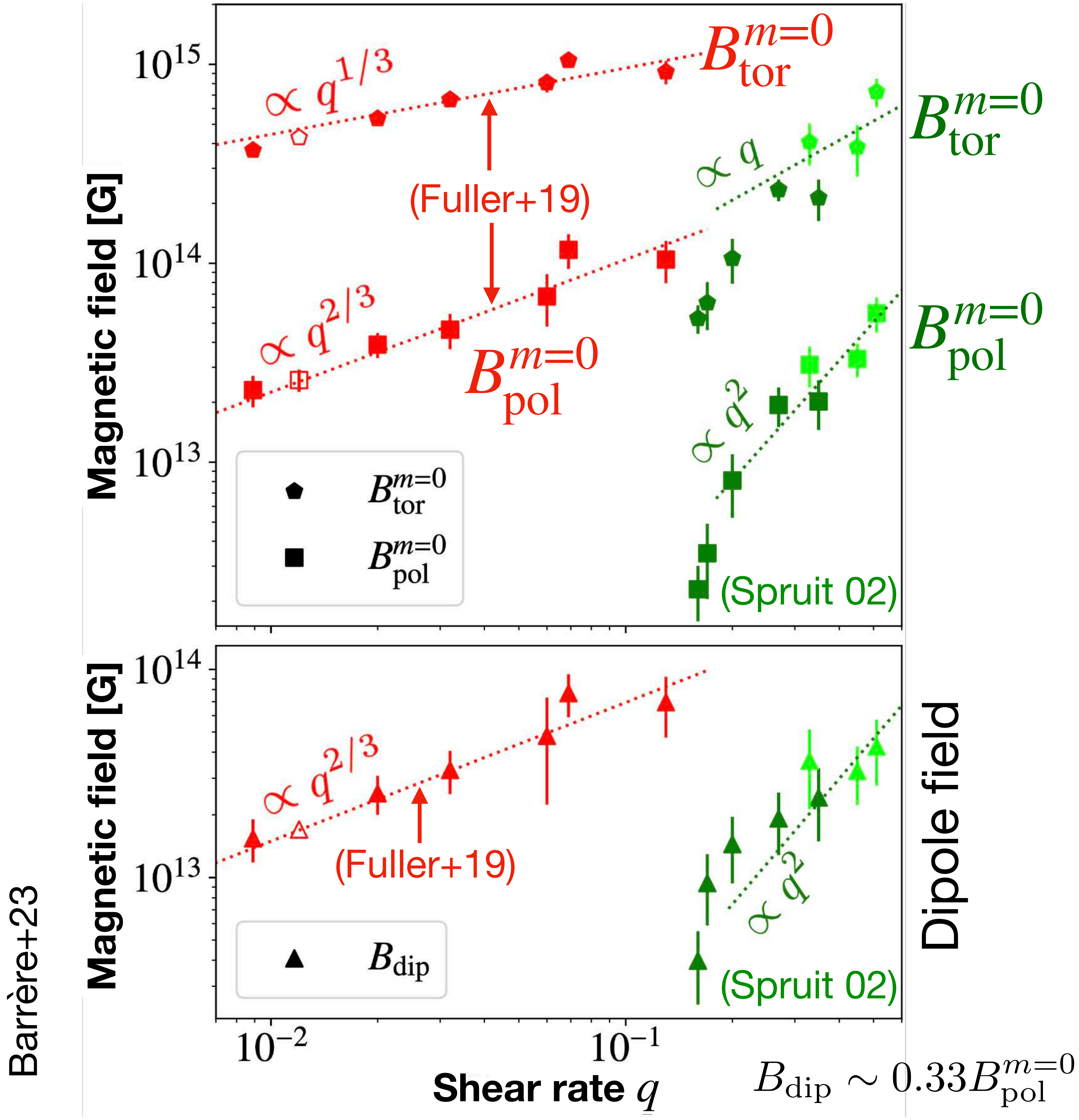


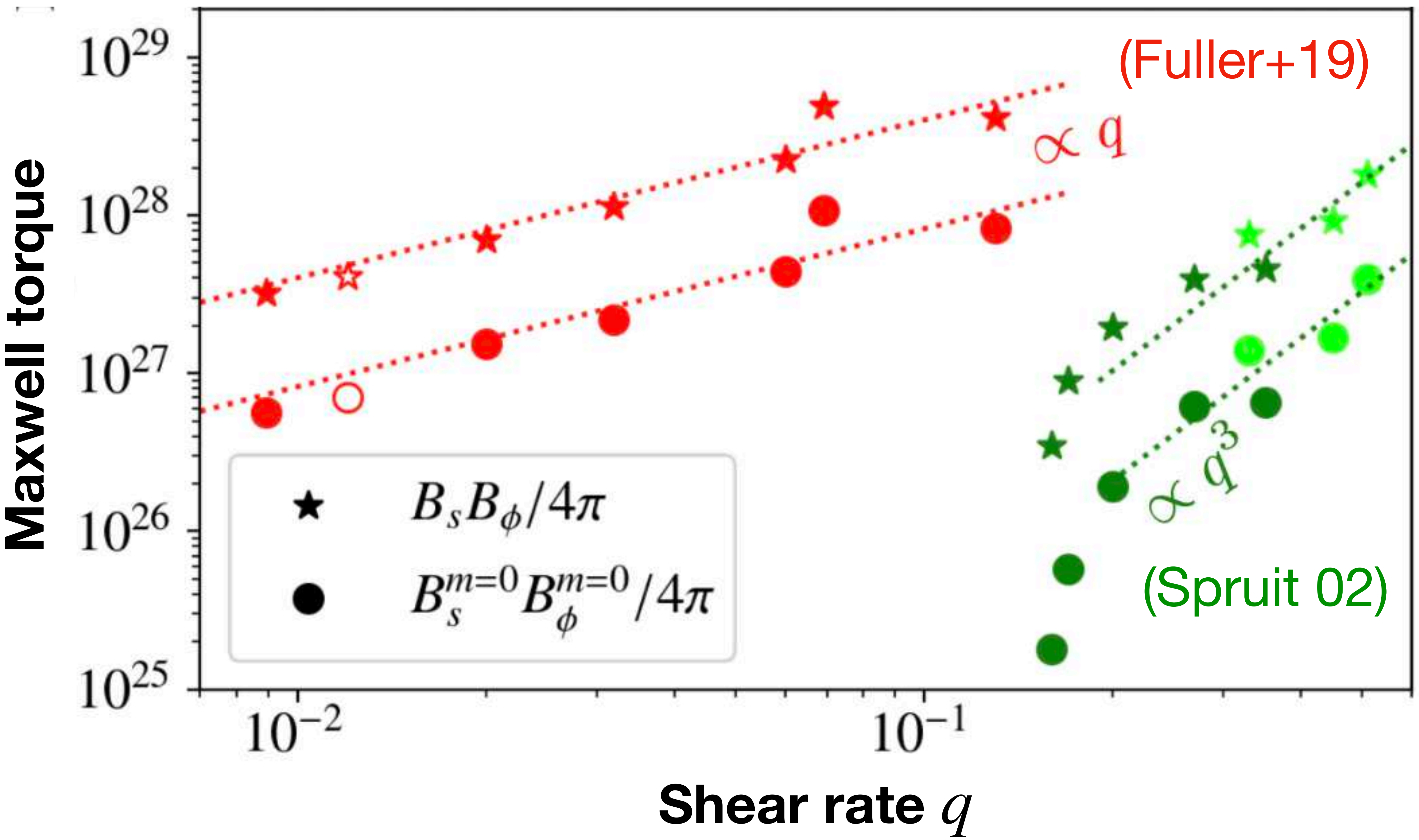
- $B_\phi \gg B_r > 4.4 \times 10^{13}$ G
  $\Longrightarrow \; M_{\mathrm{fallback}} \geq [1.1 - 4] \times 10^{-2} M_\odot$
- $15\ \mathrm{s} < \tau_{\mathrm{sat}} < 30\ \mathrm{s}$

Bifurcation diagram + magnetic field topology

$\Lambda = B_{\rm rms}^2/(4\pi\rho\eta\Omega_o)$

Barrère+23





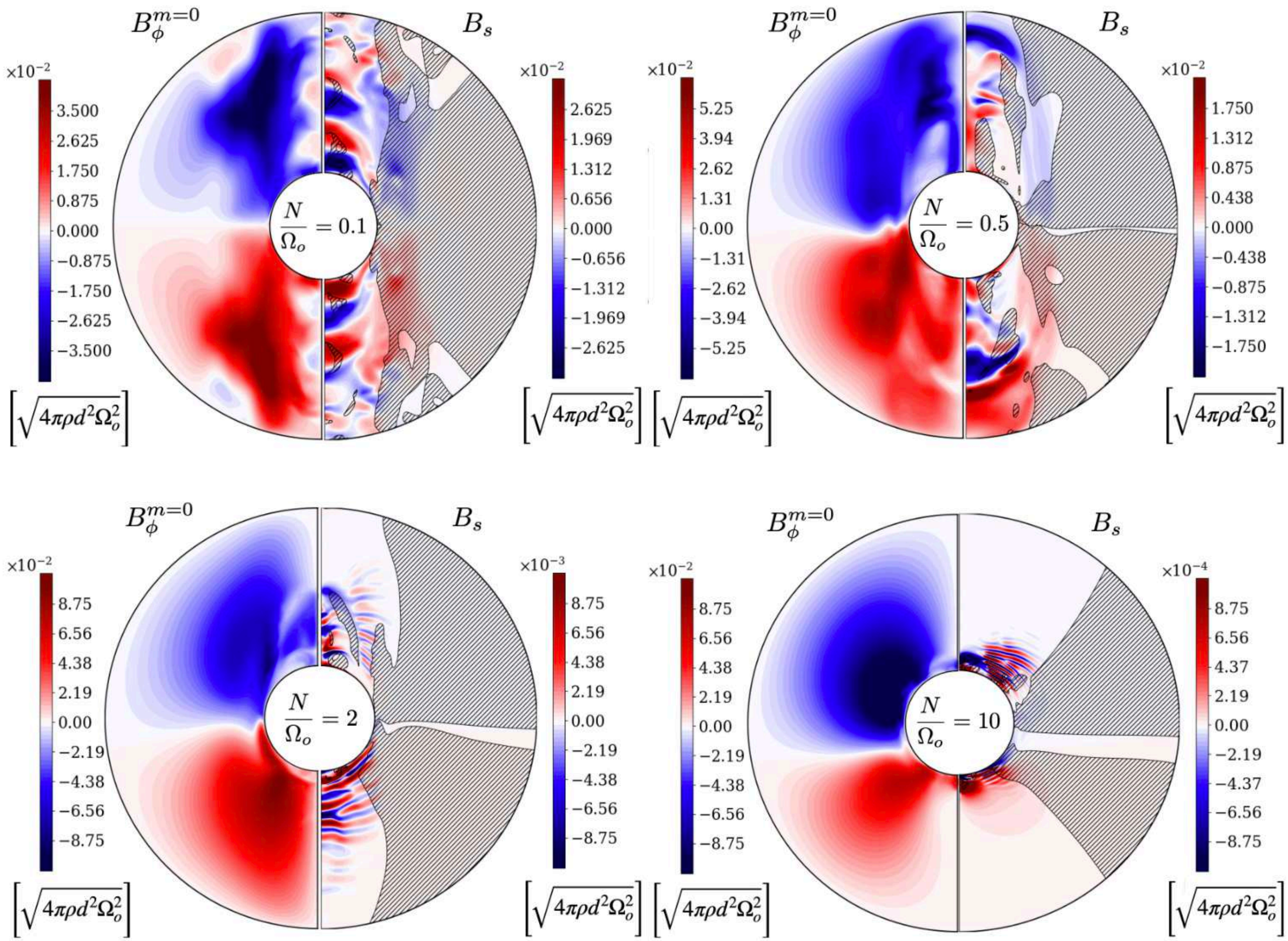
Theory

$\omega_A \ll \Omega \ll N$

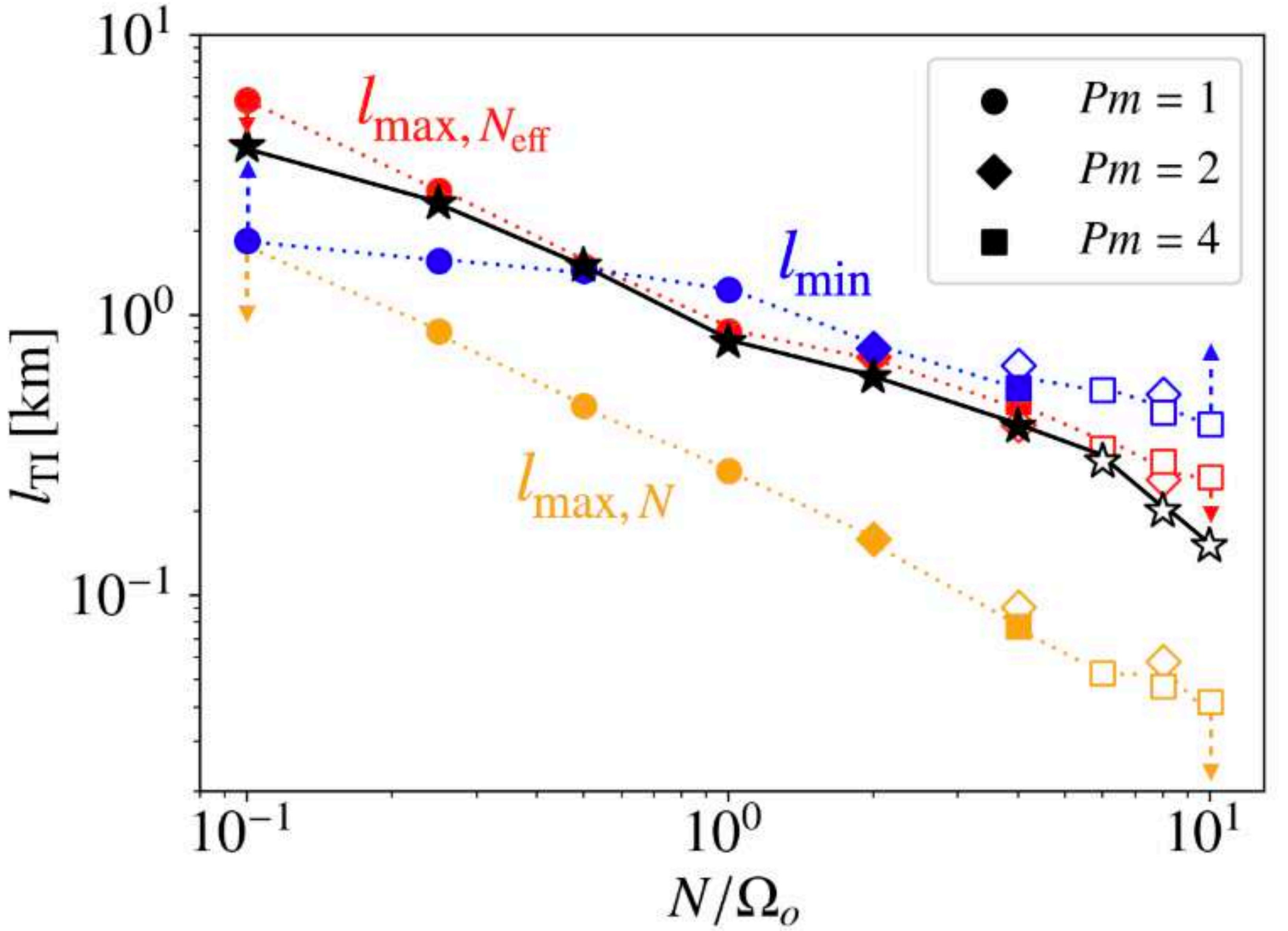
Simulations

$\frac{\omega_A}{\Omega} \lesssim 0.02$ **but** $\frac{N}{\Omega} = 0.1$

Impact of the stratification on the dipole branch

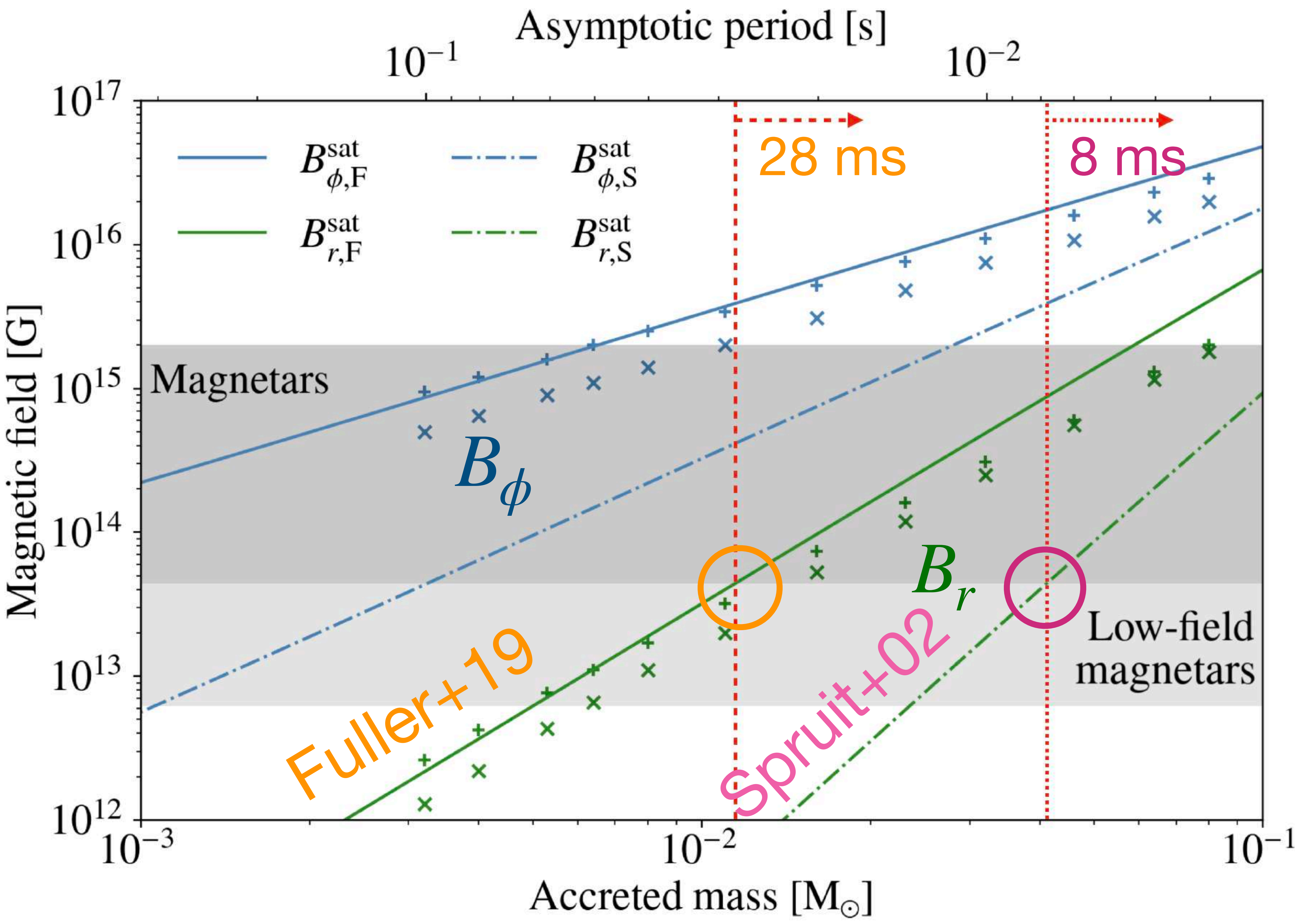


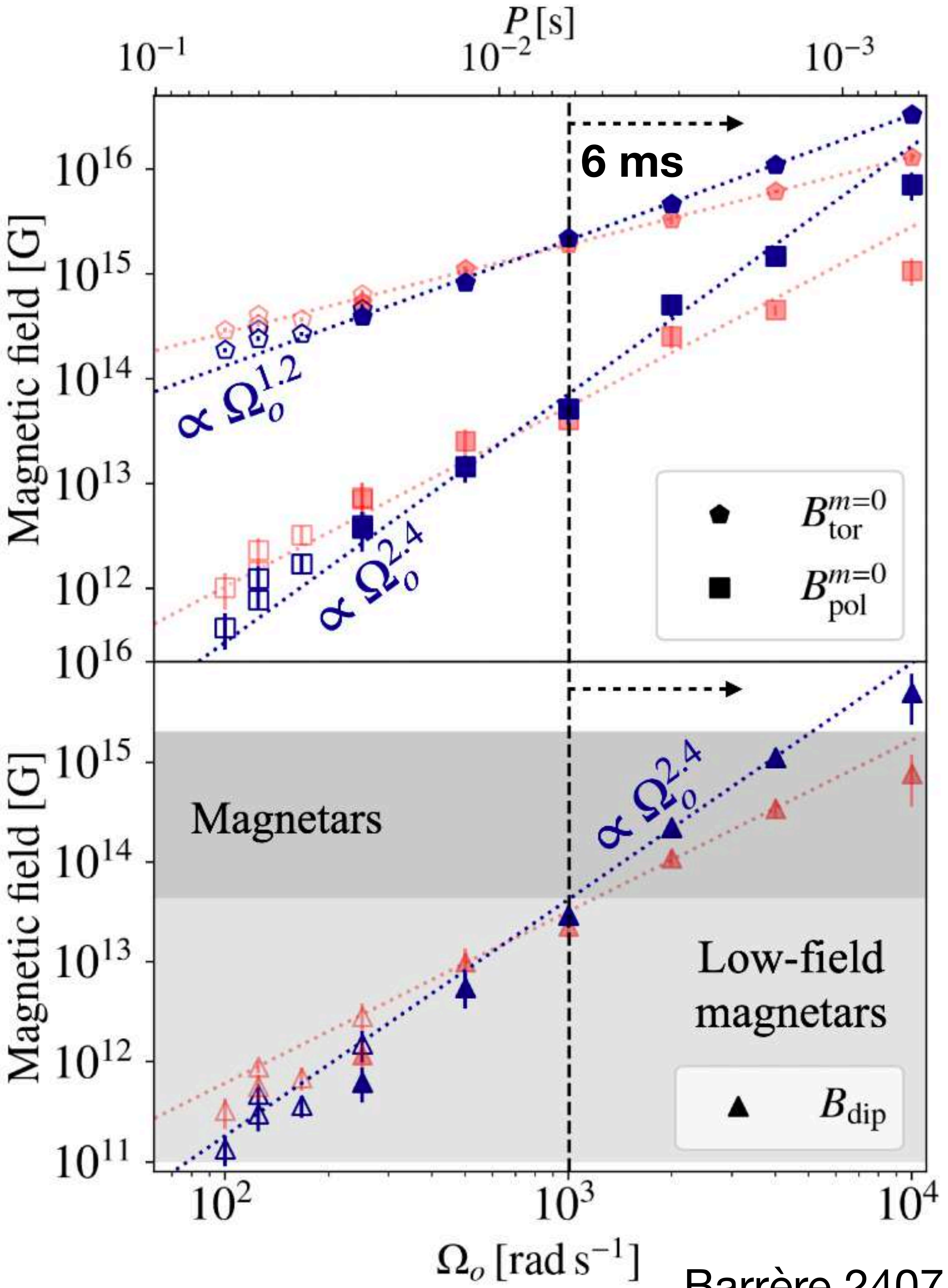
Instability length scale: measure vs theoretical bounds



Barrère 2407.01775v1

1D vs 3D model





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Appendix: fallback properties

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Janka, Wongwathanarat, & Kramer