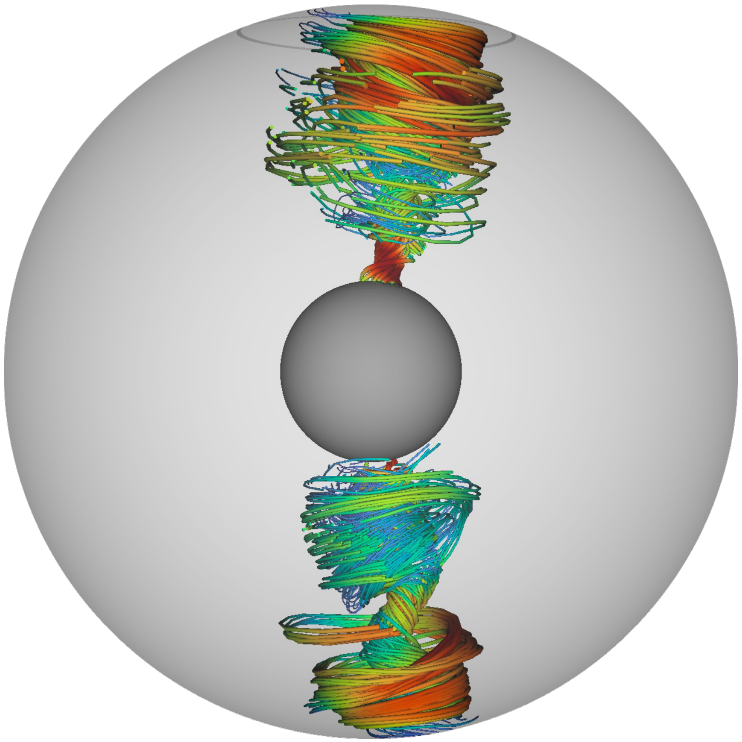
Magnetar formation from Tayler-Spruit dynamo in protoneutron stars



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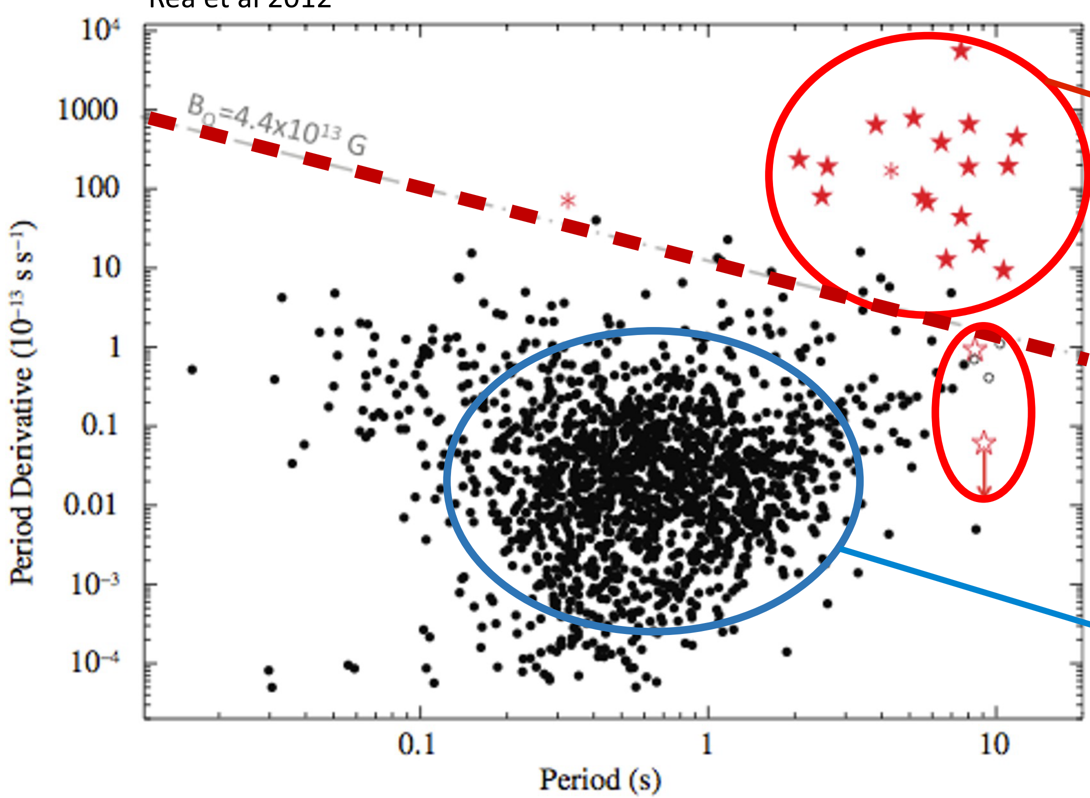
cea SACLAY

Magnetars: the most intense known magnetic fields

Rea et al 2012



$$B_{\rm dip} \propto \sqrt{P\dot{P}} \sim 10^{14} - 10^{15}\,{\rm G}$$

Magnetars

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

Strong dipole magnetic field:

$B \sim 10^{14} - 10^{15}$ G

Pulsars

$B \sim 10^{12} - 10^{13}$ G

Galactic magnetars: observational constraints

30 magnetars in Galaxy and magellanic clouds

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

Indications of stronger multipolar/toroidal field

Young: typically $10^4 - 10^5$ years

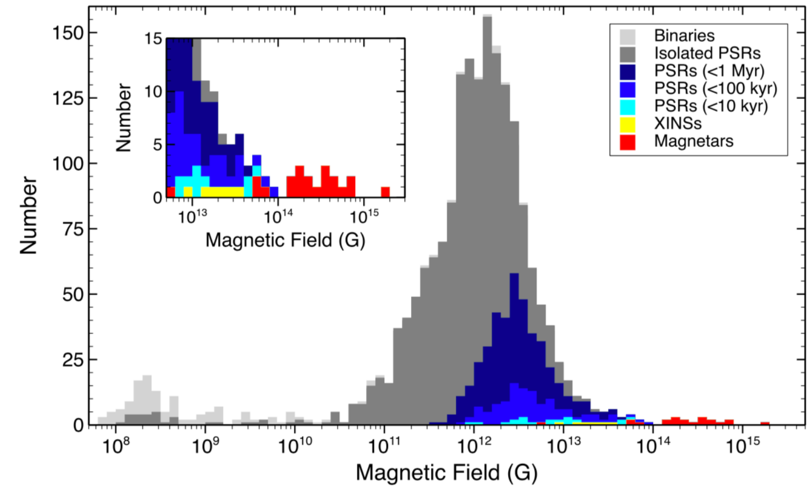
Birth rate : ~10-50 % of core-collapse SNe/neutron star birth

Slow rotation P ~1 - 10 s

-> But rotation at birth unknown

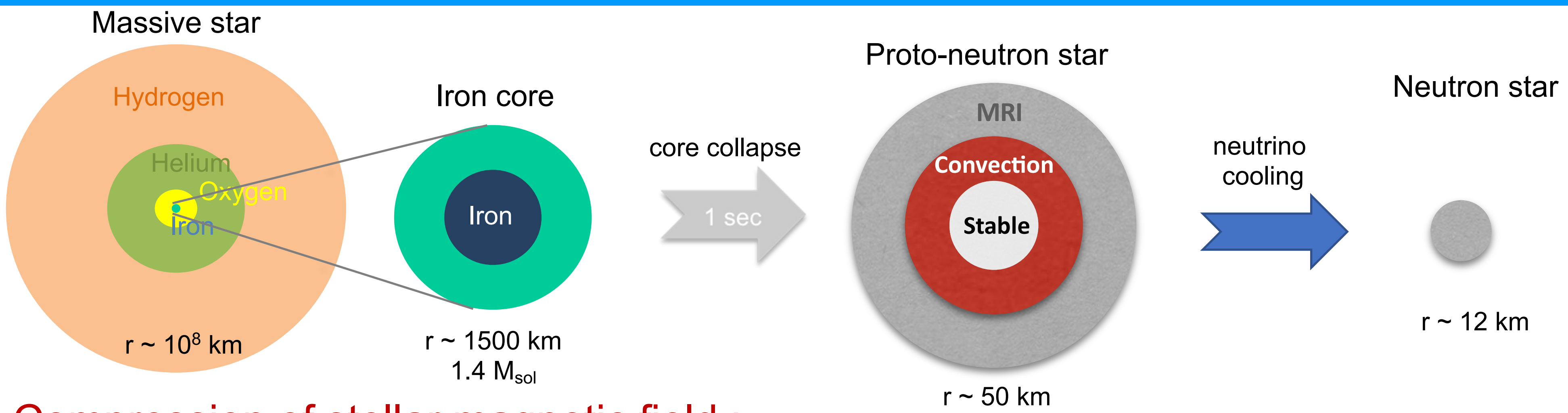
~10 magnetars associated to a supernova remnants

=> Normal explosion kinetic energy => P > 5 ms



Olausen & Kaspi 2014

Different scenarios for magnetar formation



Compression of stellar magnetic field :

Amplification by a few ~10^4 during core collapse

Very magnetised stars on surface (B >1 kG) : also need a 10^{10}-10^{11} G in the iron core

Protoneutron star dynamos

Magnetorotational instability

Similar to accretion disks

Reboul-Salze+ 22, Guilet+ 22

Convective dynamo

Similar to planetary & stellar dynamos

Raynaud+20, 22, Verma+26, Masada+22

Tayler-Spruit dynamo

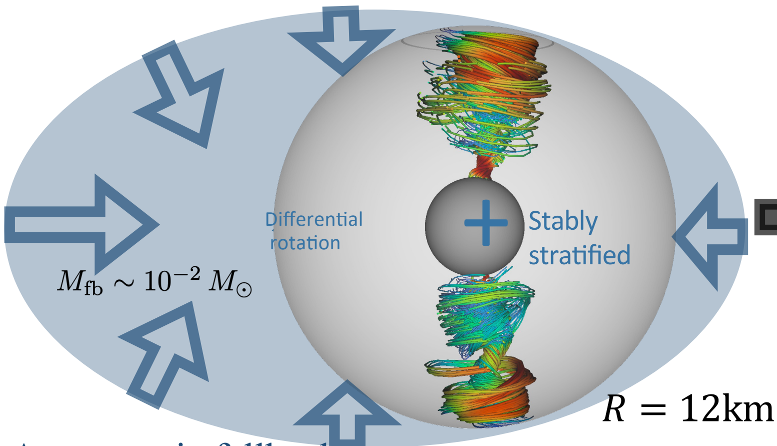
Similar to stellar radiative zones

Barrère+ 22, 23, 25, 26

Chiral magnetic instability, Dehman & Pons 2024

From proto-NS to NS simulations

Proto-neutron star



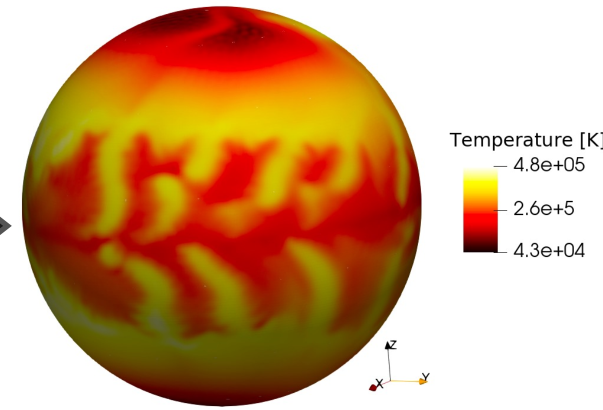
Asymmetric fallback accretion

Crust formation

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

Not modelled

Neutron star



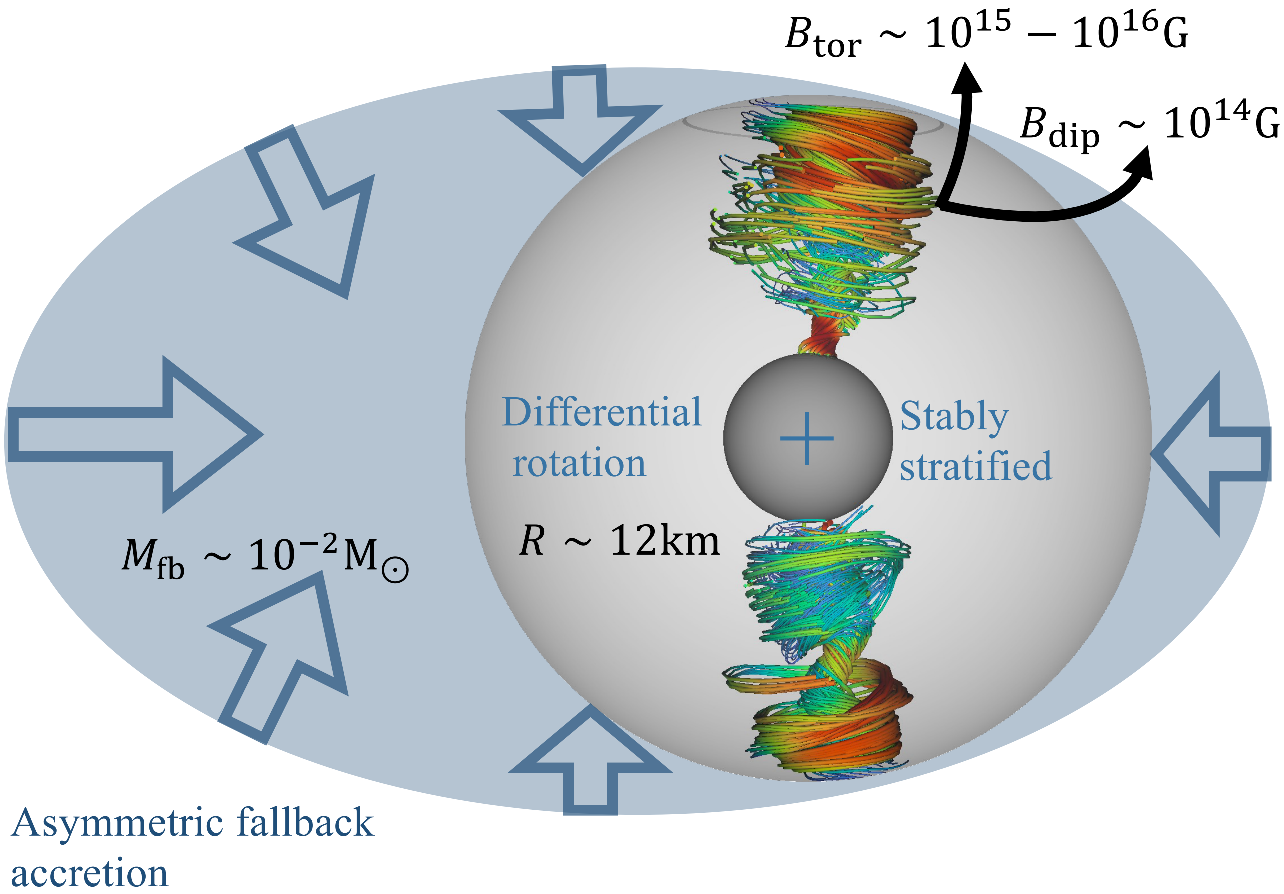
- age : ~ 10 s (after core-bounce)
- Rotation period : $\sim$ 10ms
- **Fluid => *MHD* simulation**
- Dynamo simulation over ~ 10 s

Barrère+ 22, 23, 25, 26

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

Igoshev+25

Tayler-Spruit dynamo: a new magnetar formation scenario

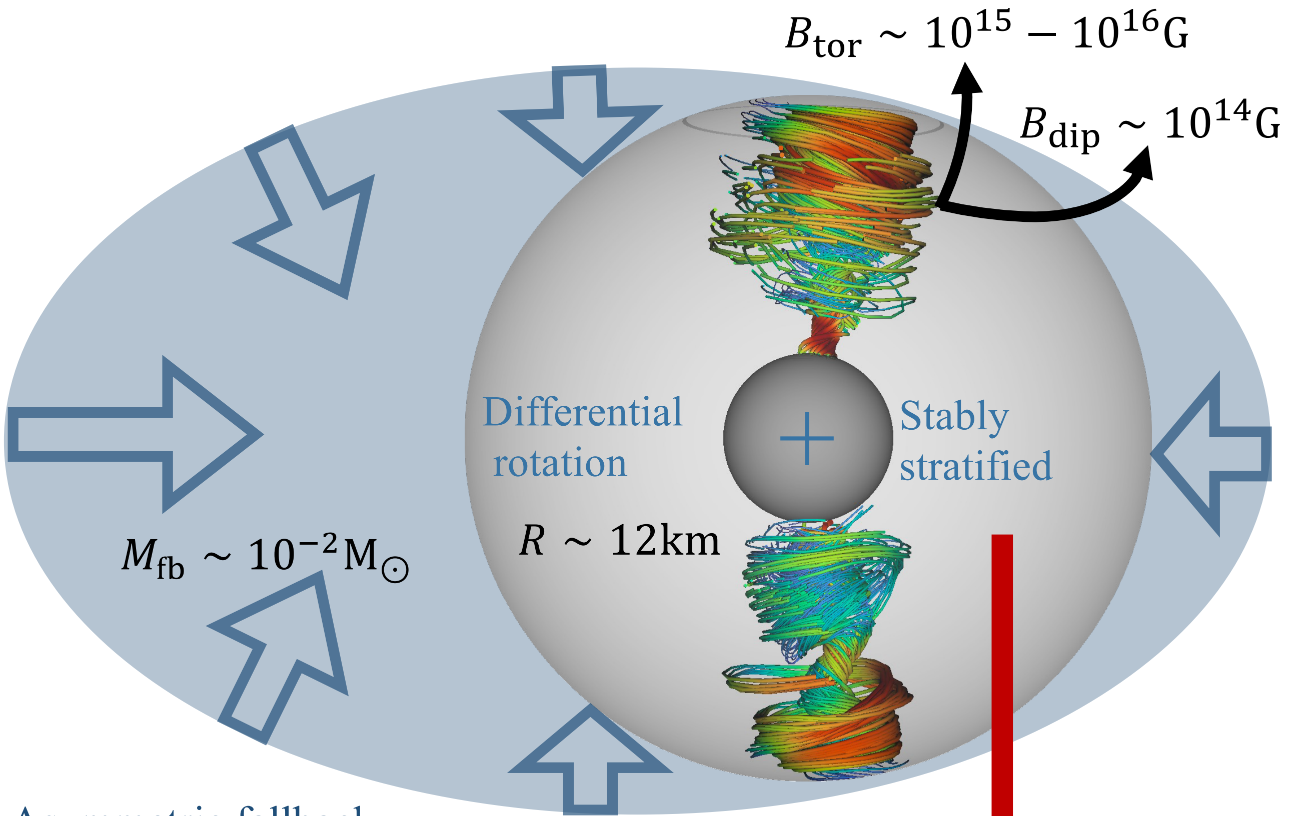


Fallback in 3D CCSN simulations

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

(Chan+20, Janka+22)

Tayler-Spruit dynamo: a new magnetar formation scenario



Asymmetric fallback accretion

Crucial for stellar physics

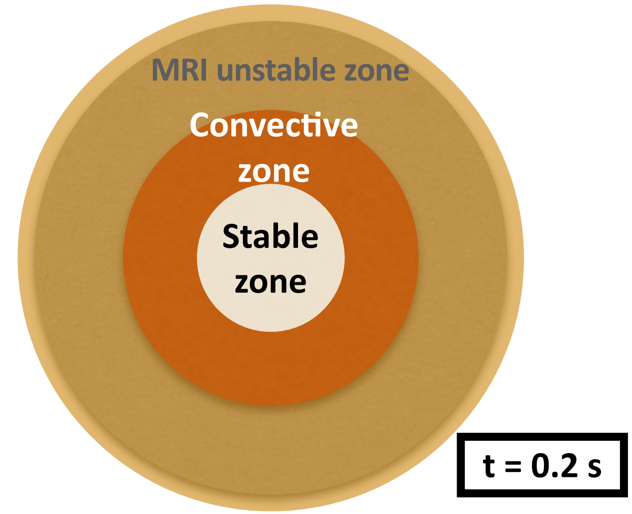
- **Angular momentum transport** in radiative zones
- **Only** 2 analytical studies
  ➡ Spruit 02 & Fuller+19
  ➡ different predictions for the saturation
- First numerical studies are **very new**
  ➡ Petitdemange+23, **Barrère+23**

= "Tayler-Spruit" dynamo ?

Modelling protoneutron star dynamo with the MagIC code

MagIC (Wicht+02, Gastine+12)

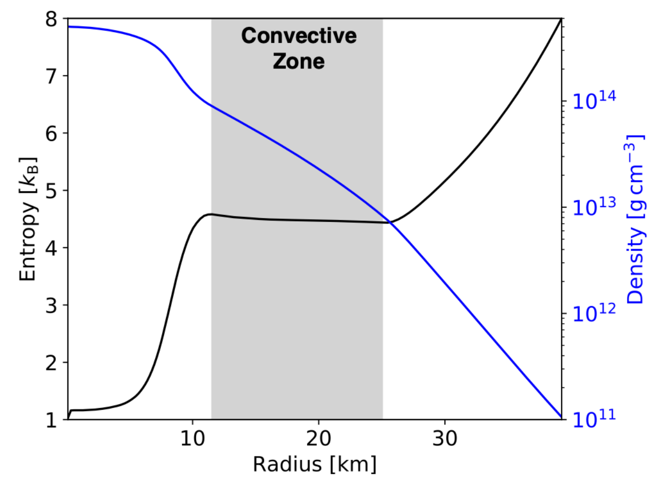
Protoneutron star structure



Pseudo-spectral numerical method in spherical geometry

Physical assumptions:

- Classical MHD equations, (pseudo-)Newtonian gravity
- Anelastic or Boussinesq approximation (sound proof)
- Ultra-high density equation of state

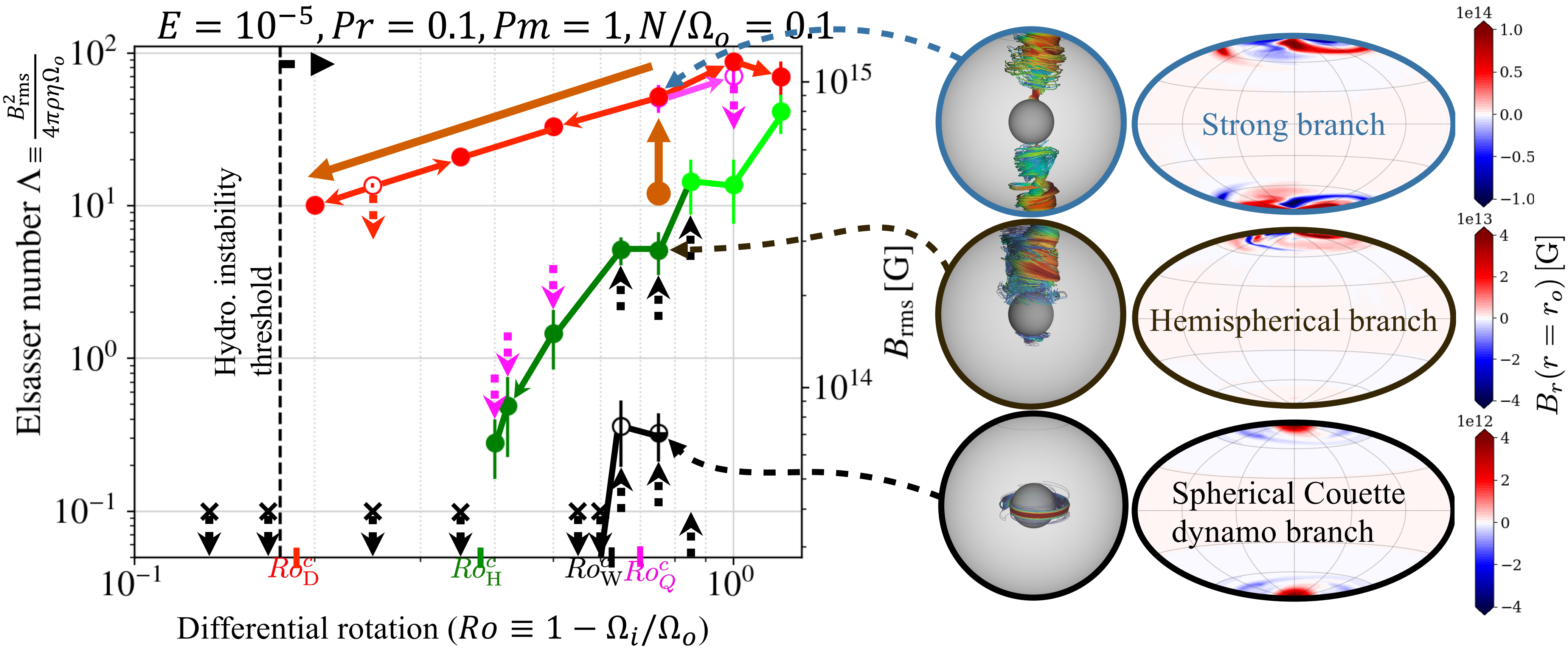


Ekman number : $E = \frac{\nu}{\Omega d^2} = 10^{-5} - 10^{-3} > 10^{-4} - 10^{-8}$

Rayleigh number : $E = \frac{N^2 d^4}{\nu \kappa} = 10^6 - 10^7 < 10^8 - 10^{12}$

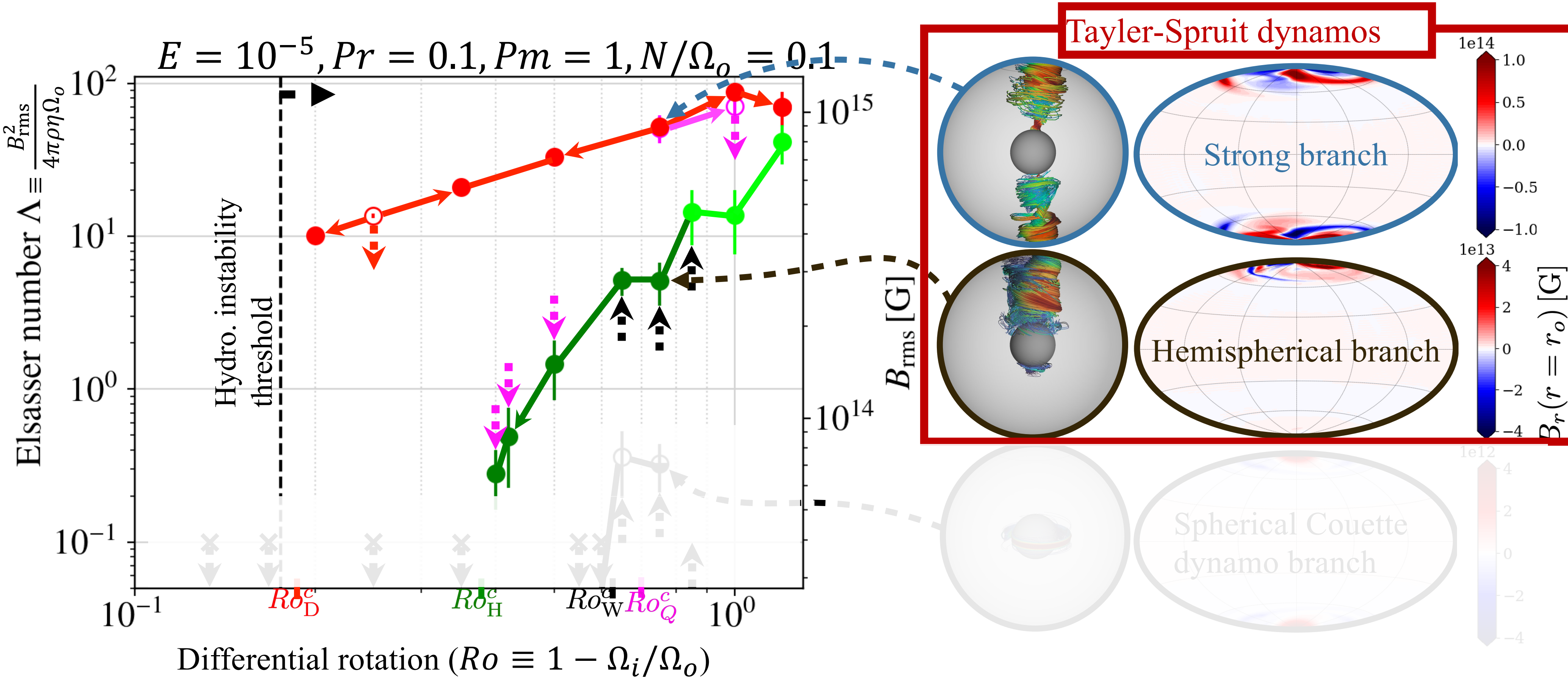
Magnetic Prandtl number : $Pm = \nu/\eta \in [1,16] \ll 10^{12}$

Different dynamo branches



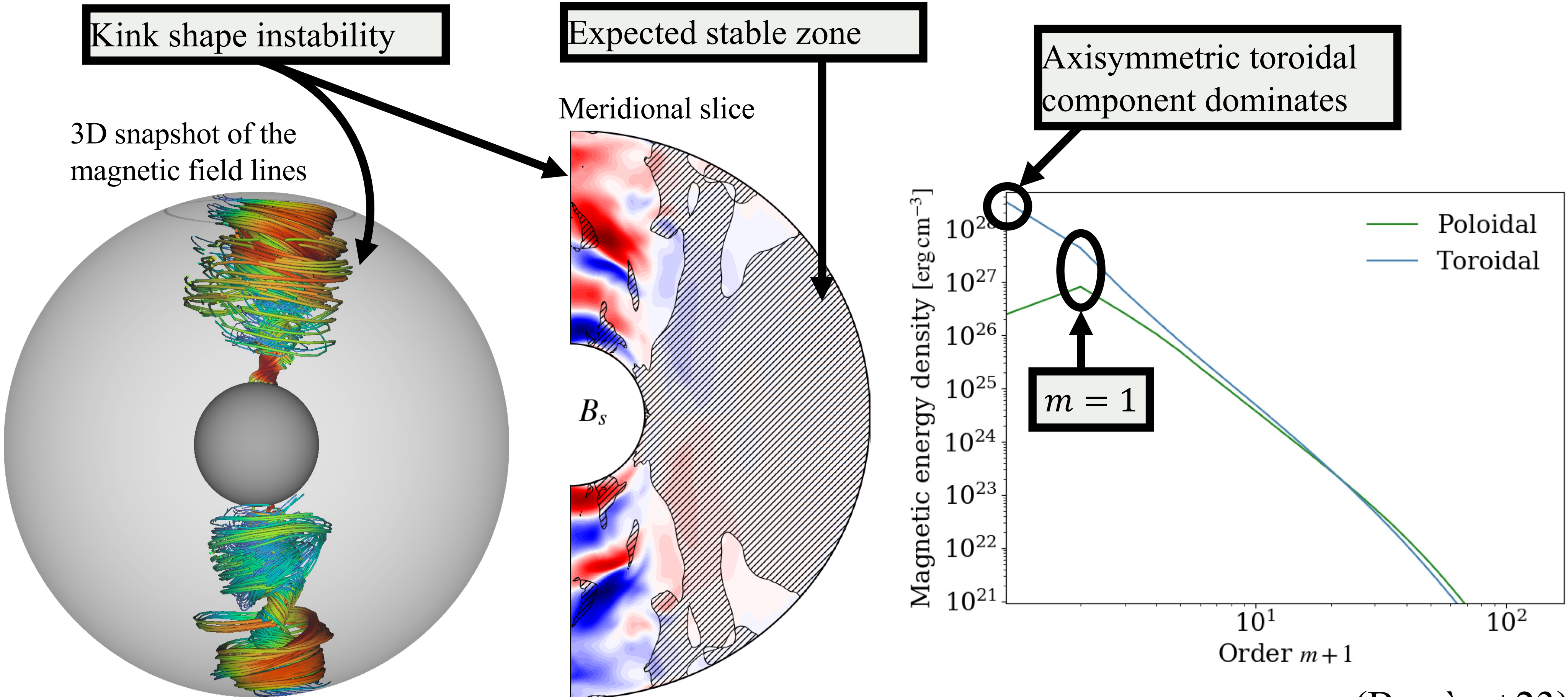
(Barrère+23)

Different dynamo branches

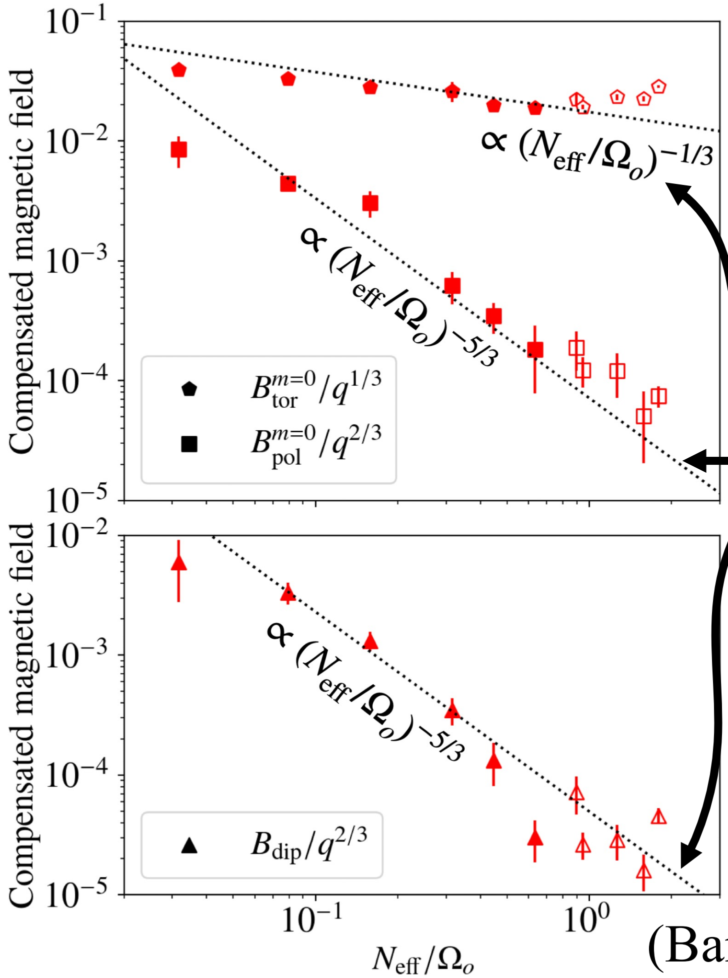


(Barrère+23)

Magnetic field structure



(Barrère+23)



Fuller+19 scaling laws

(Barrère+25)

Parametrisation

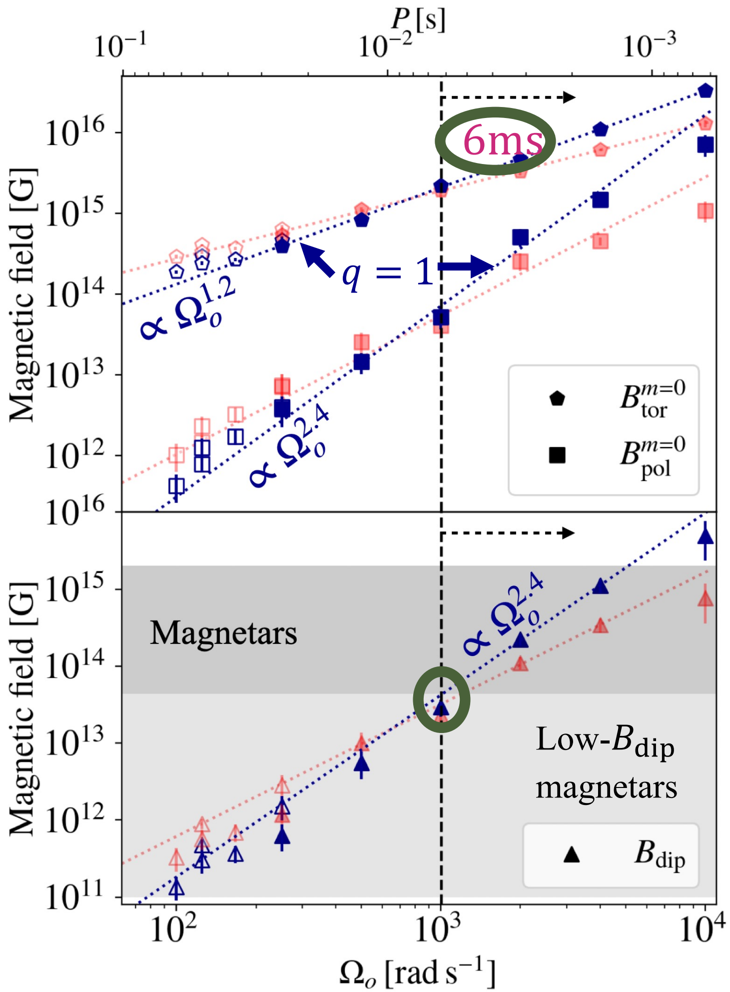
Dimensionless normalisation factor

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

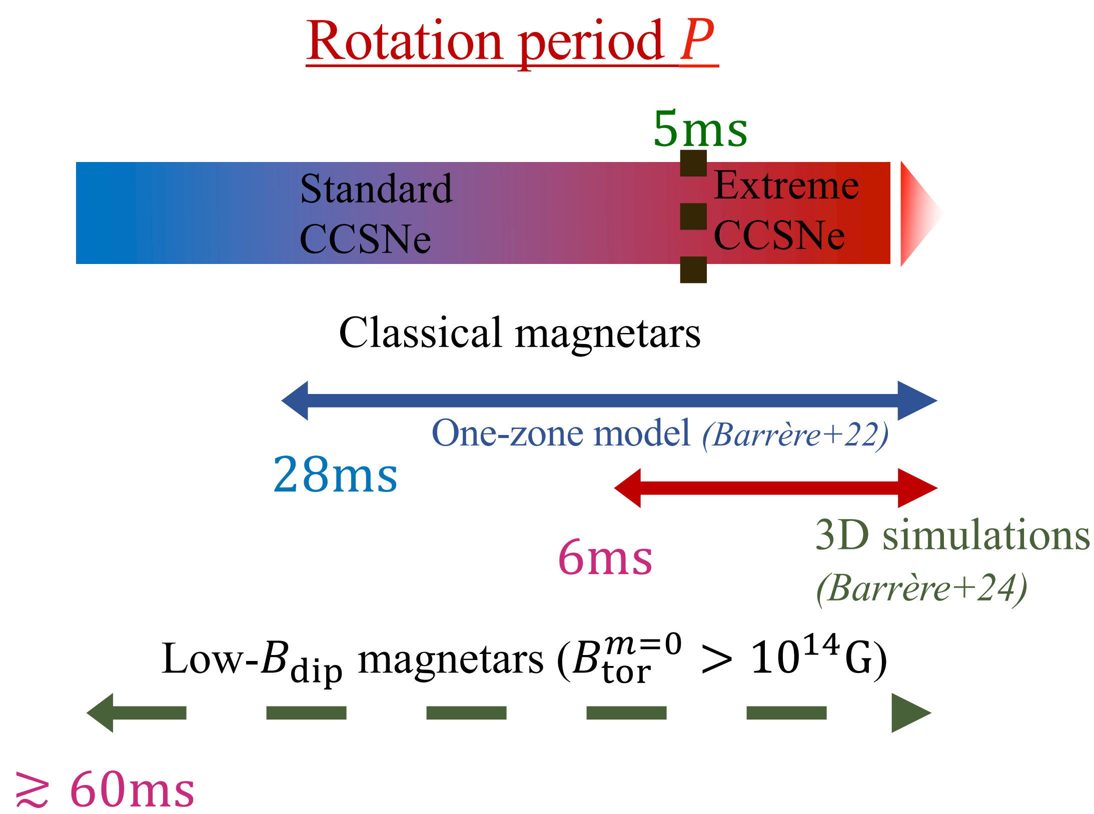
$\alpha \sim 0.01$
in our simulations

$\alpha \sim 0.25 - 1$
Calibrated on asteroseismology in sub-/red giants (Fuller+19,+23,Eggenberger+19)

Application to magnetar formation



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

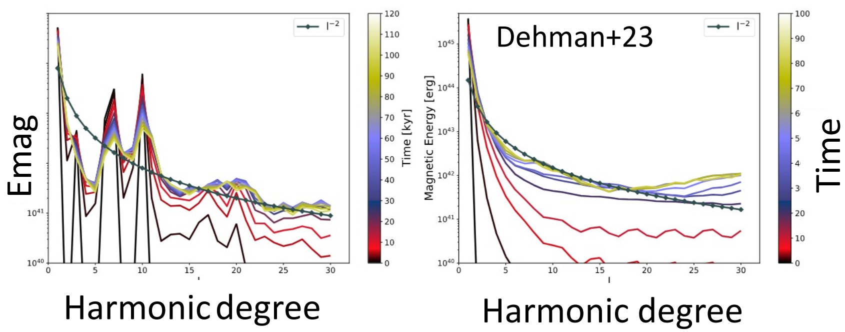


(Barrère+25)

Long term evolution: 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



Grandis+2020

Magnetic induction

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

Thermal diffusion

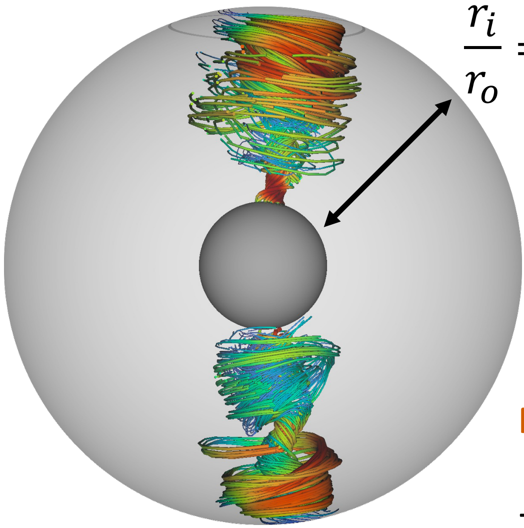
$$\frac{1}{Ro}\frac{C_v}{T}\frac{\partial T^2}{\partial t} = \underbrace{\nabla\cdot(\mu^2\hat{\chi}(B)\cdot\nabla T^2)}_{\text{Heat flux}} + \underbrace{\frac{Pe}{Se}\frac{|\nabla\times\vec{B}|^2}{\mu^2}}_{\text{Ohmic heating}} + \underbrace{Pe\mu(\nabla\times B)\cdot\nabla\left(\frac{T^2}{\mu^2}\right)}_{\ll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

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

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

Implementing a PNS dynamo state as an initial condition

Tayler-Spruit dynamo

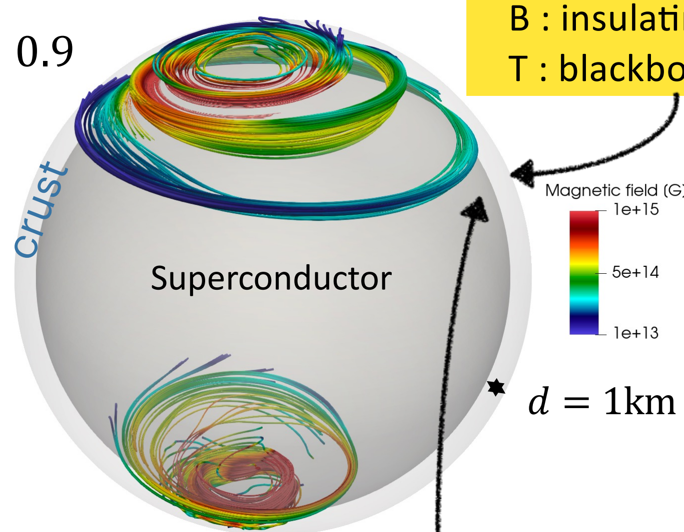


$\frac{r_i}{r_o} = 0.25$

Simulation from
Barrère+ 23

Neutron star crust

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



$d = 1\text{km}$

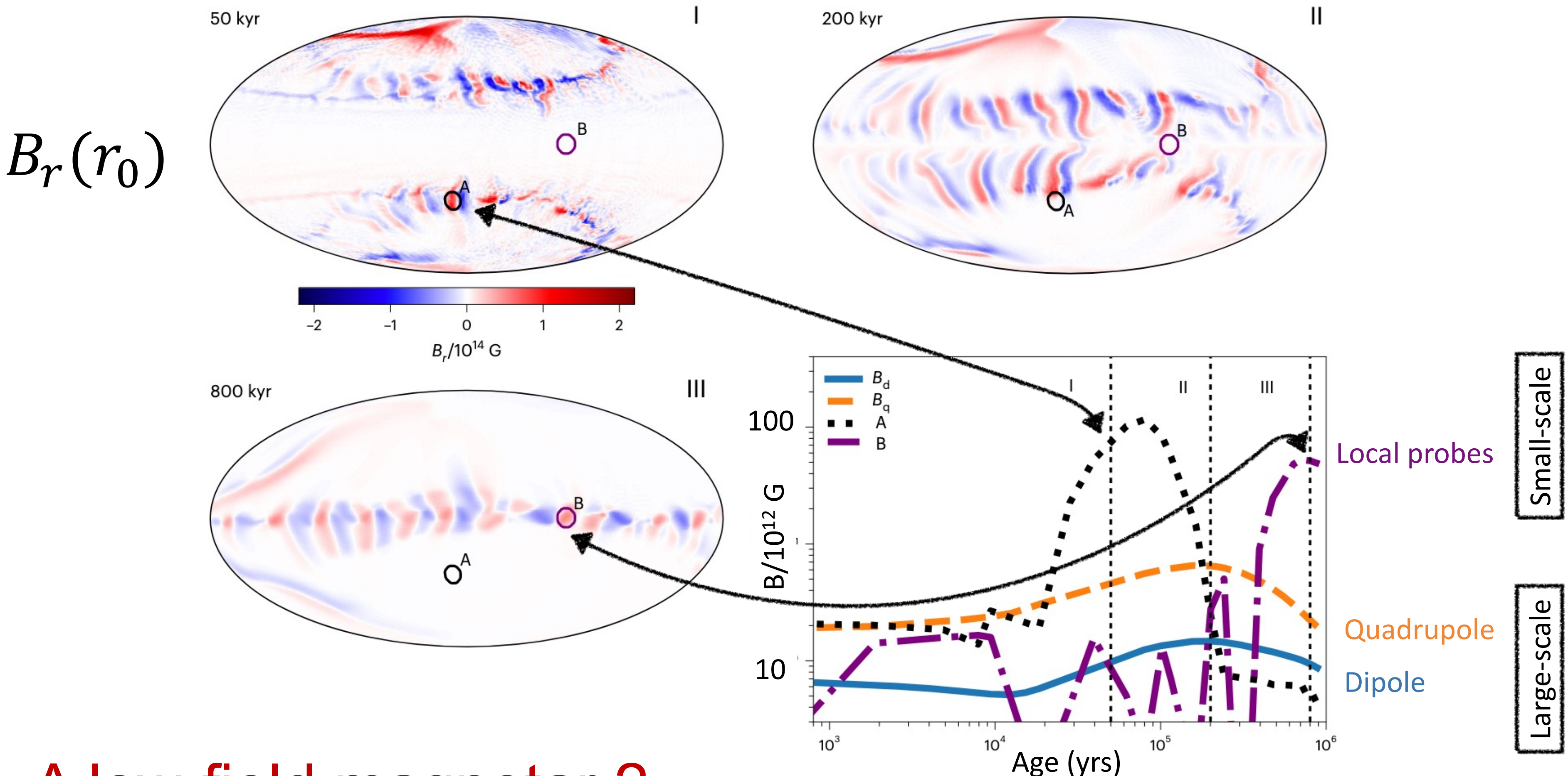
Outer boundary
B : insulating b. c.
T : blackbody emission

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

Method

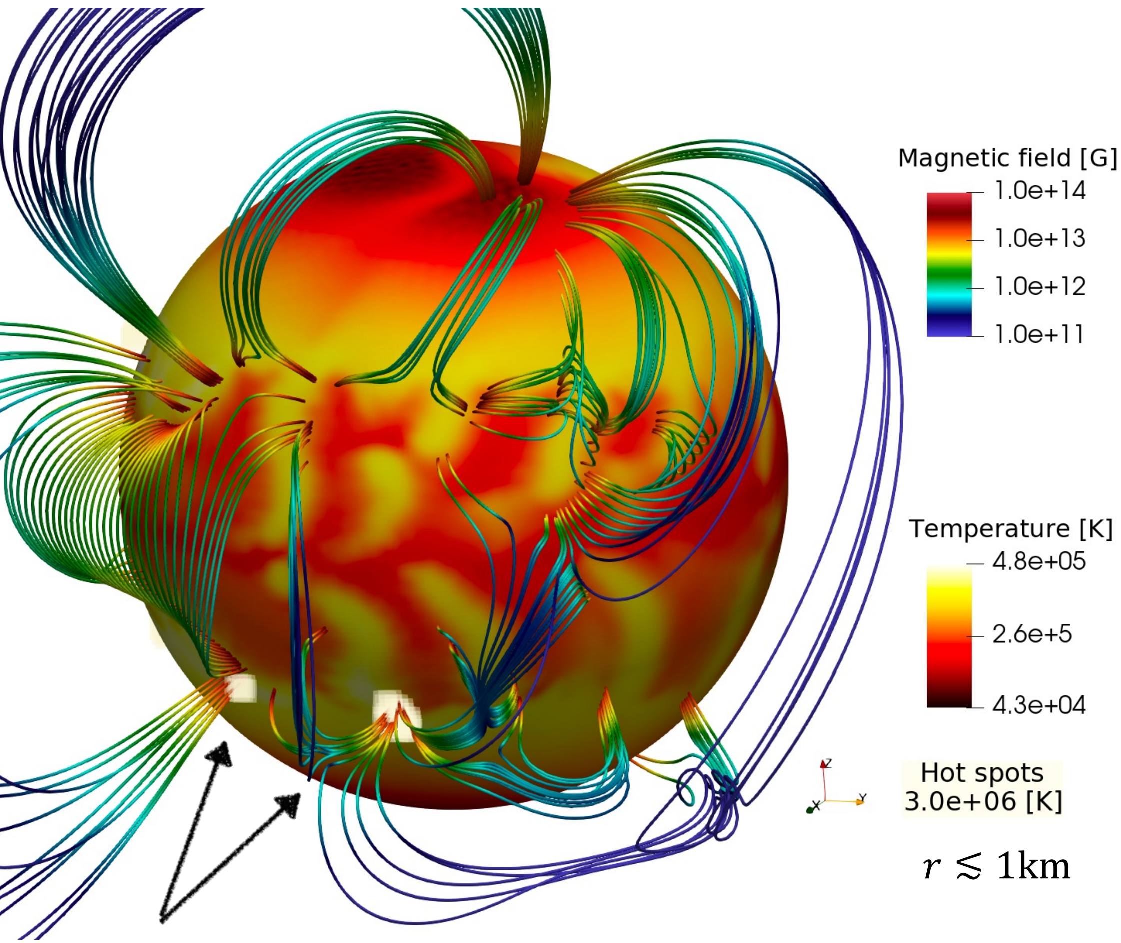
- Assume a polynomial expansion for the poloidal and toroidal potentials b_{lm}^{crust}(r)
- Determine the coefficients by matching the boundary conditions and imposing $b_{lm}^{\text{crust}}(r*) = b_{lm}^{\text{PNS}}(r*), \forall l \leq 30$ at $r* = [0.93r_0, 0.96r_o, r_0]$

Magnetic field long term evolution



A low-field magnetar ?

External magnetic field at 200 kyr



B field creates large T variations

Footpoints with $B_r > 10^{13}\text{G}$ could produce hot spots heated by magnetospheric currents
=> X-ray light curve modulation

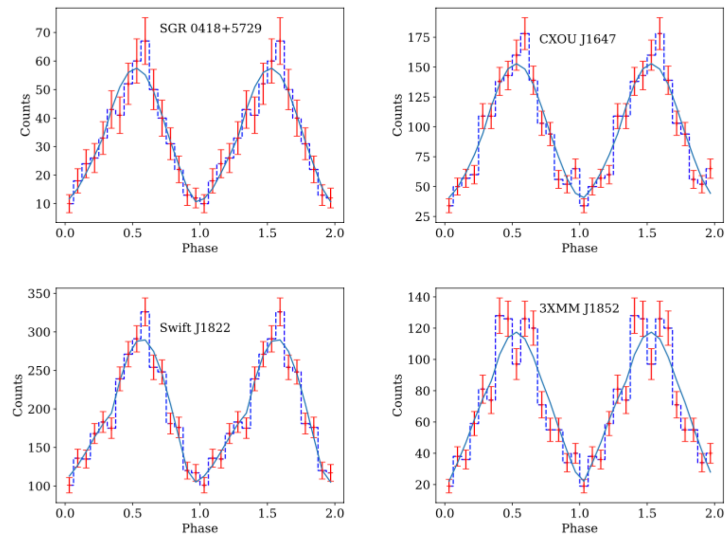


Figure 10: Observed soft X-ray lightcurves in the range of 0.3-2 keV for low-field magnetars in the quiescent state and the best fits (solid blue line). It is assumed that emission is produced by hot spots formed at the places with radial magnetic field exceeding 7×10^{13} G.

Crustal magnetic stresses

Initial B : dipole

Initial B : Tayler-Spruit dynamo

Wood+15

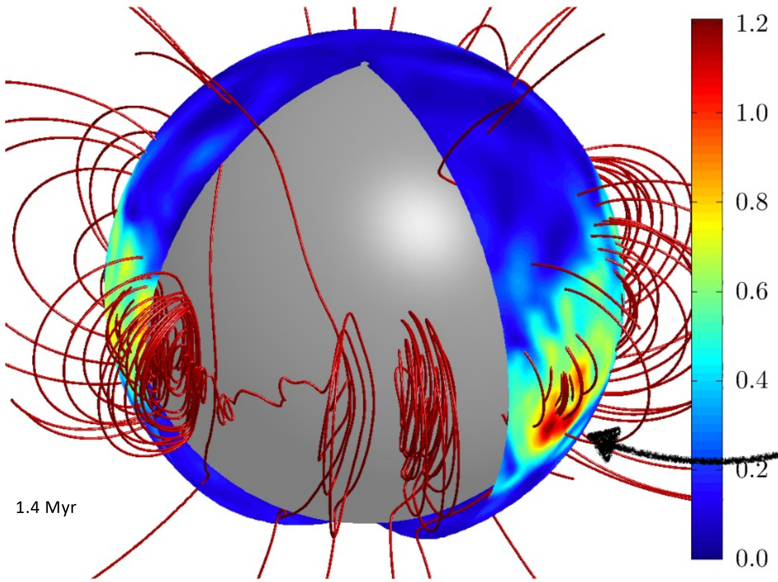
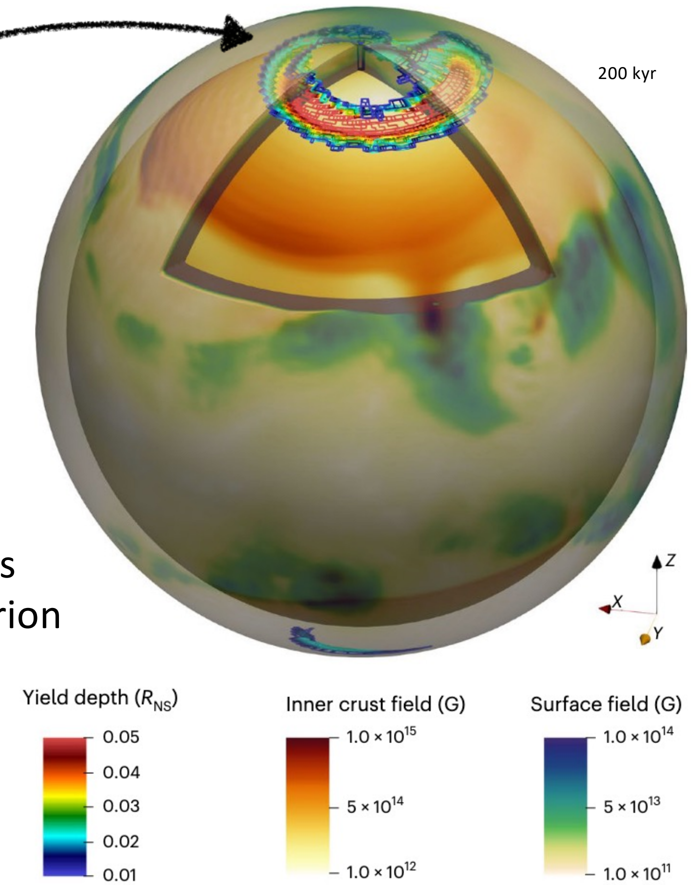


FIG. 5 (color online). Lines of the magnetic field generated by currents in the crust. The coloring indicates the ratio of magnetic pressure to breaking stress at the surface of the crust. A portion of the surface has been cut away to show field lines inside the crust, whose lower boundary is the gray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

Crust yielding regions

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

Lander+15,19

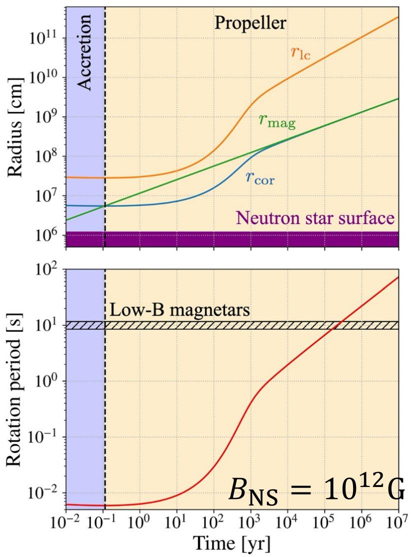


Spin down

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

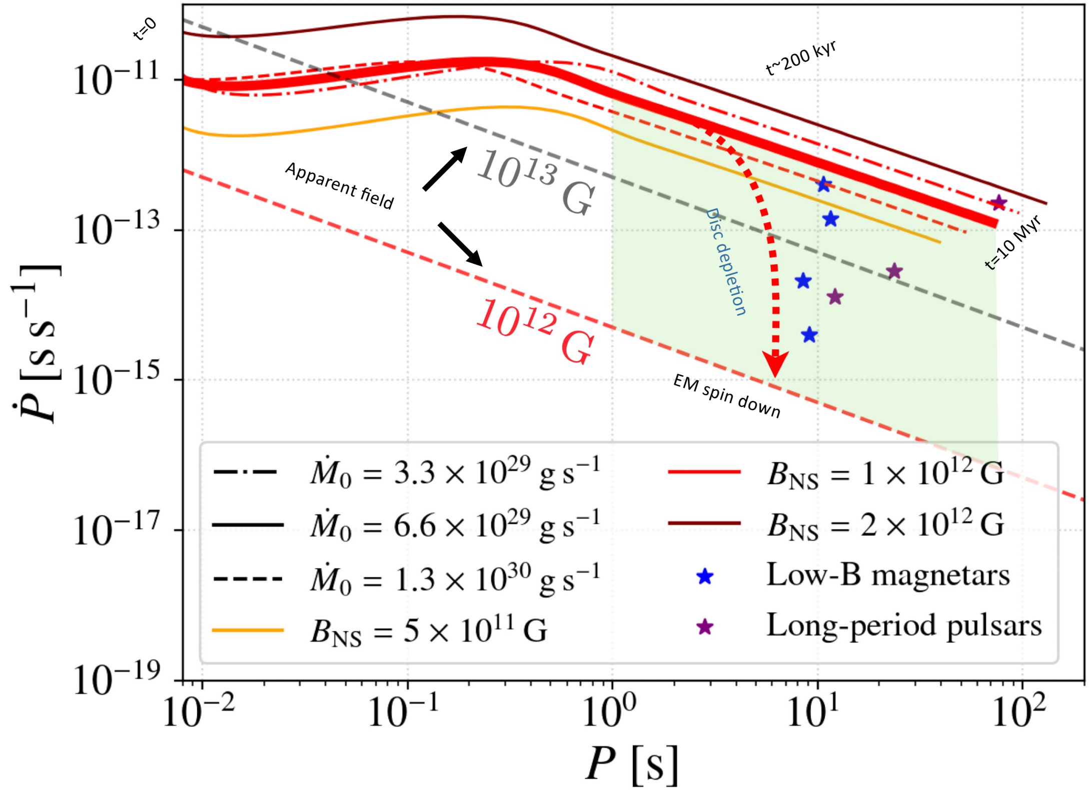
$$I_{NS}\dot{\Omega}_{NS} = N_{acc} + N_{dip}$$ (Ronchi+22)

Accretion torque — Electromagnetic torque



Propeller regime
=> NS spin dow

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



Conclusions

From Tayler Spruit dynamo…

Classical magnetar possible for fast rotation (P < 6 ms)
=> tension with observational constraints

Strong azimutal B field: could explain low-field magnetar

3D geometry : concentrated near pole

Scaling consistent with theoretical predictions (Fuller+19) but with a small normalisation factor

Perspectives

- Realistic PNS structure
- Large magnetic Prandl number (Pm)

...to long term evolution

First proof of concept

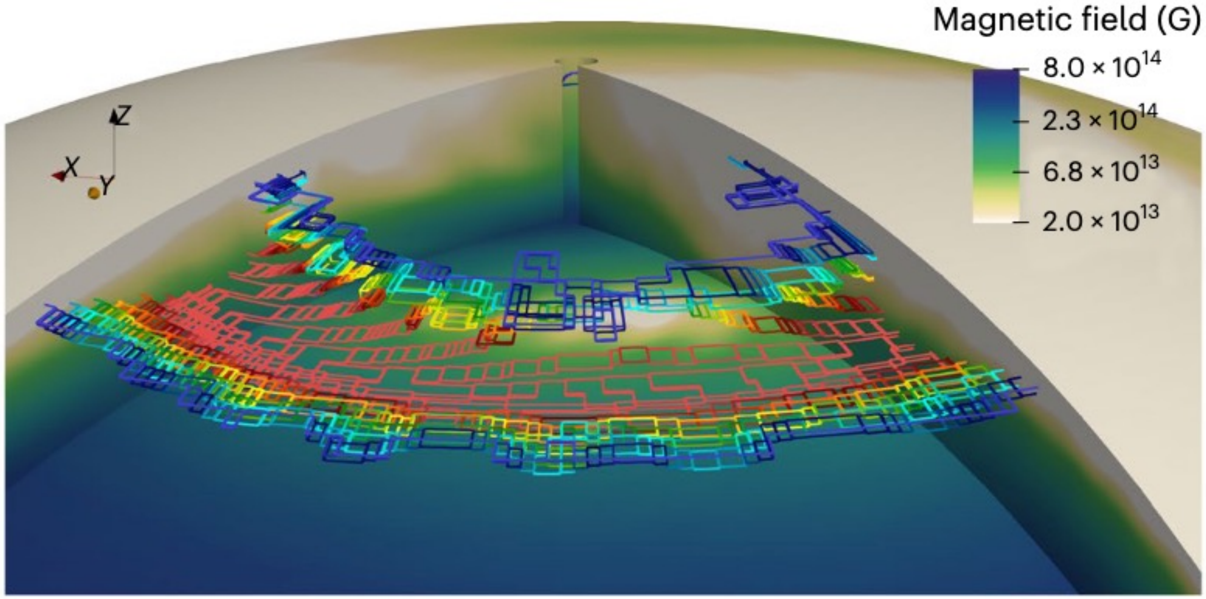
Consistent with low-field magnetar:
- low dipole but locally strong B field
- crust yield
- slow rotation reproduced

Perspectives

- Different dynamo initial conditions
- Better mapping from dynamo to crust : magnetic relaxation
- Below the crust : global models including neutron star core (Igoshev+23)
  Talk by Nicolas Moraga on Friday

Questions ?

Powering magnetar X-ray activity



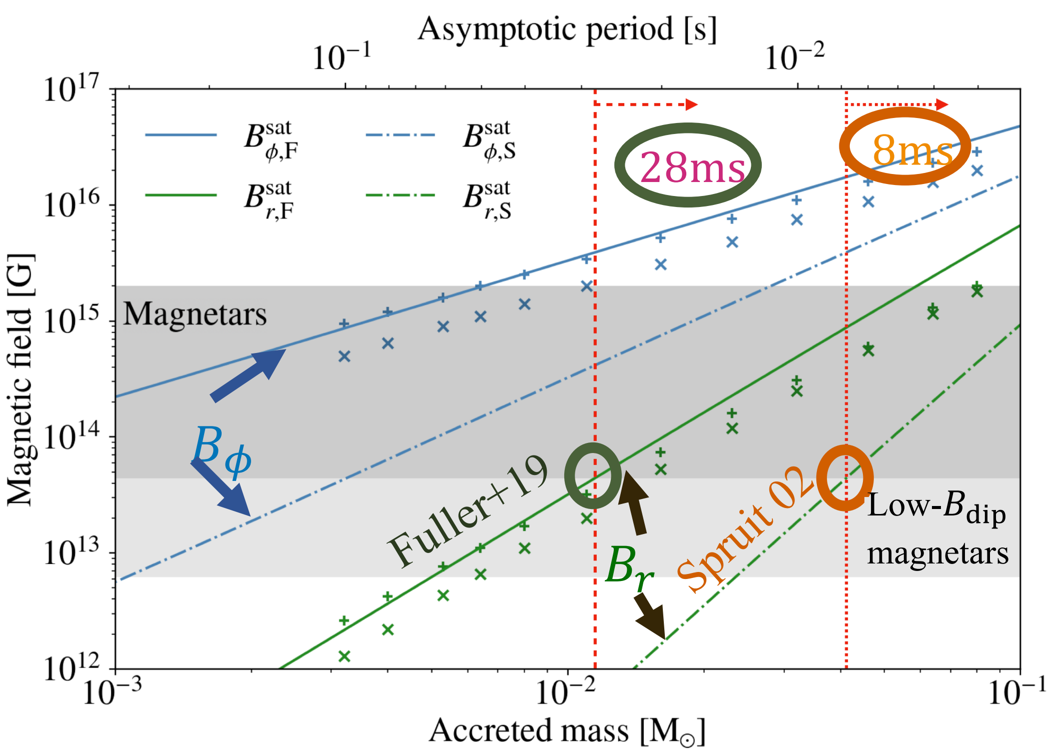
Energy release in crustal failure (Thompson+95)

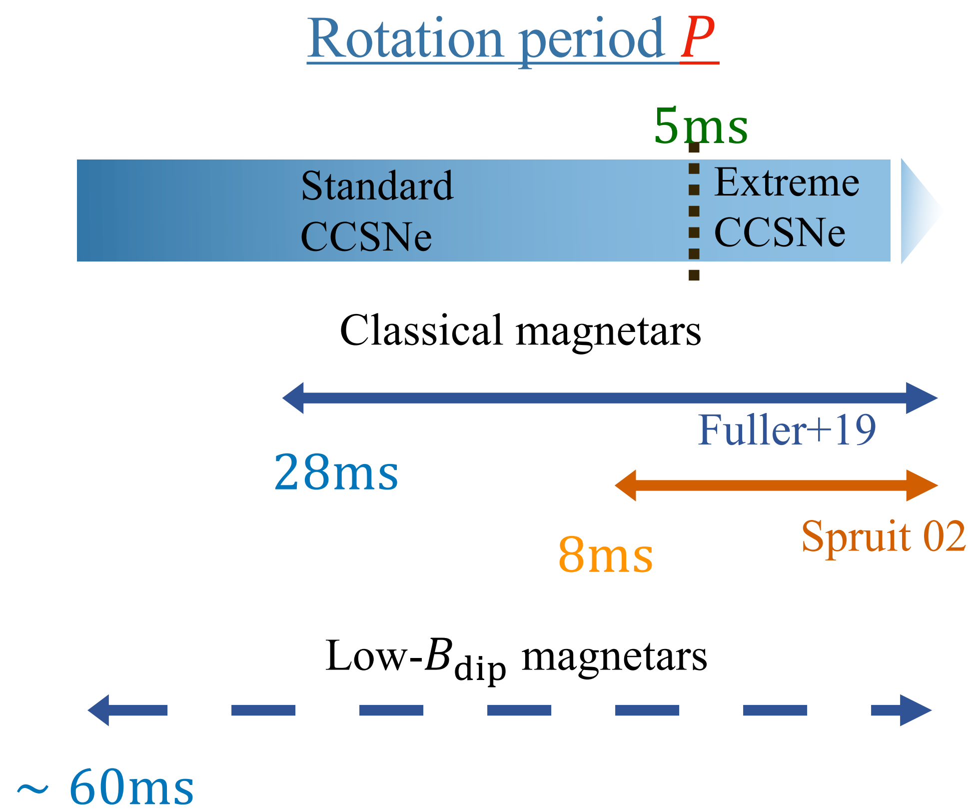
$$E_{\rm out} \lesssim 2{\times}10^{39}{\rm erg}\left(\frac{l}{1{\rm km}}\right)^2\left(\frac{|B|}{2{\times}10^{14}{\rm G}}\right)^2$$

Low-field magnetar observations

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

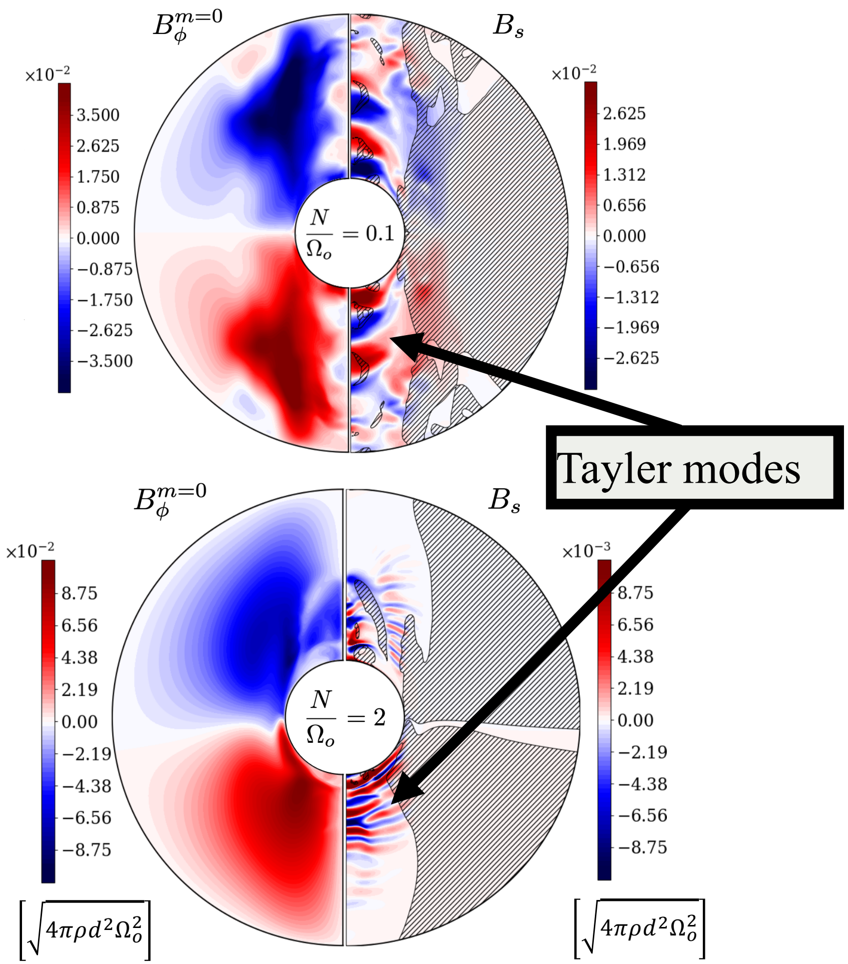
Proof of concept: one-zone model

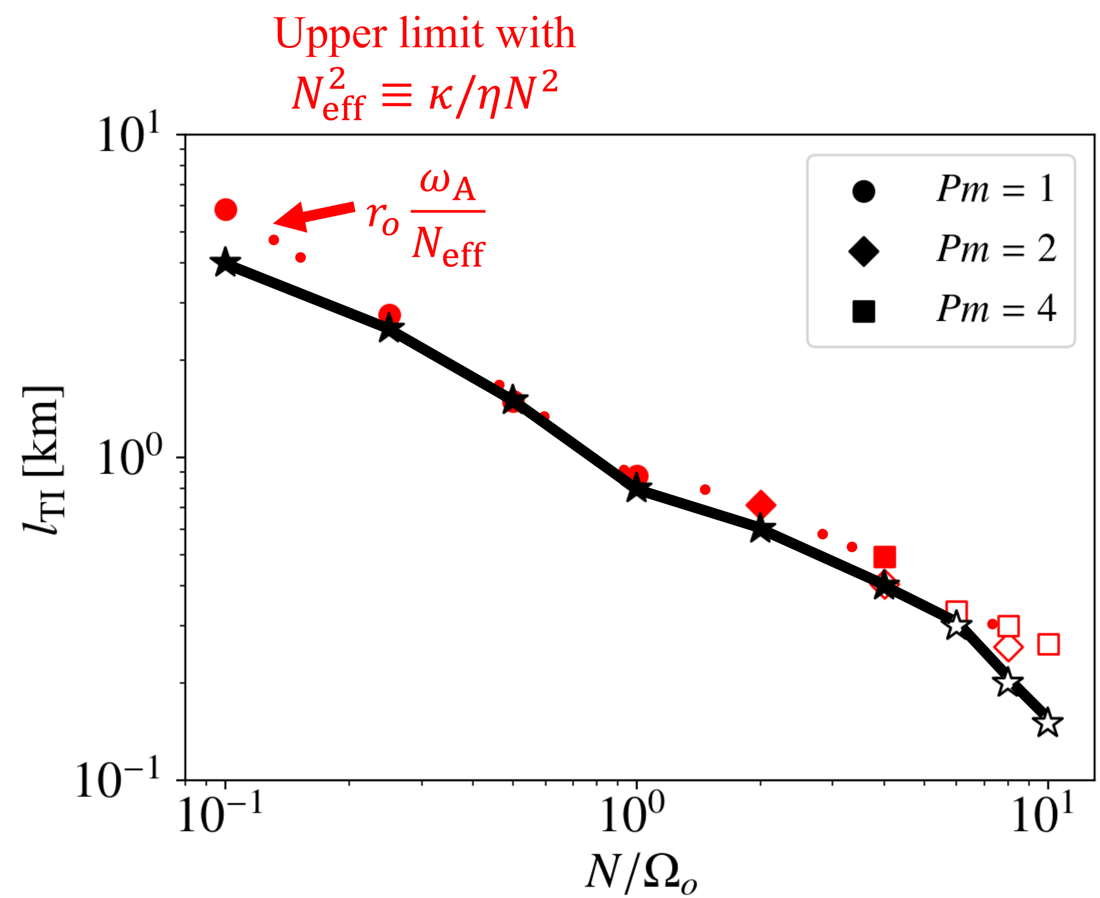




(Barrère+22)

Impact of stratification on Tayler modes





(Barrère+24)