Tayler-Spruit dynamo and formation of low-B magnetars

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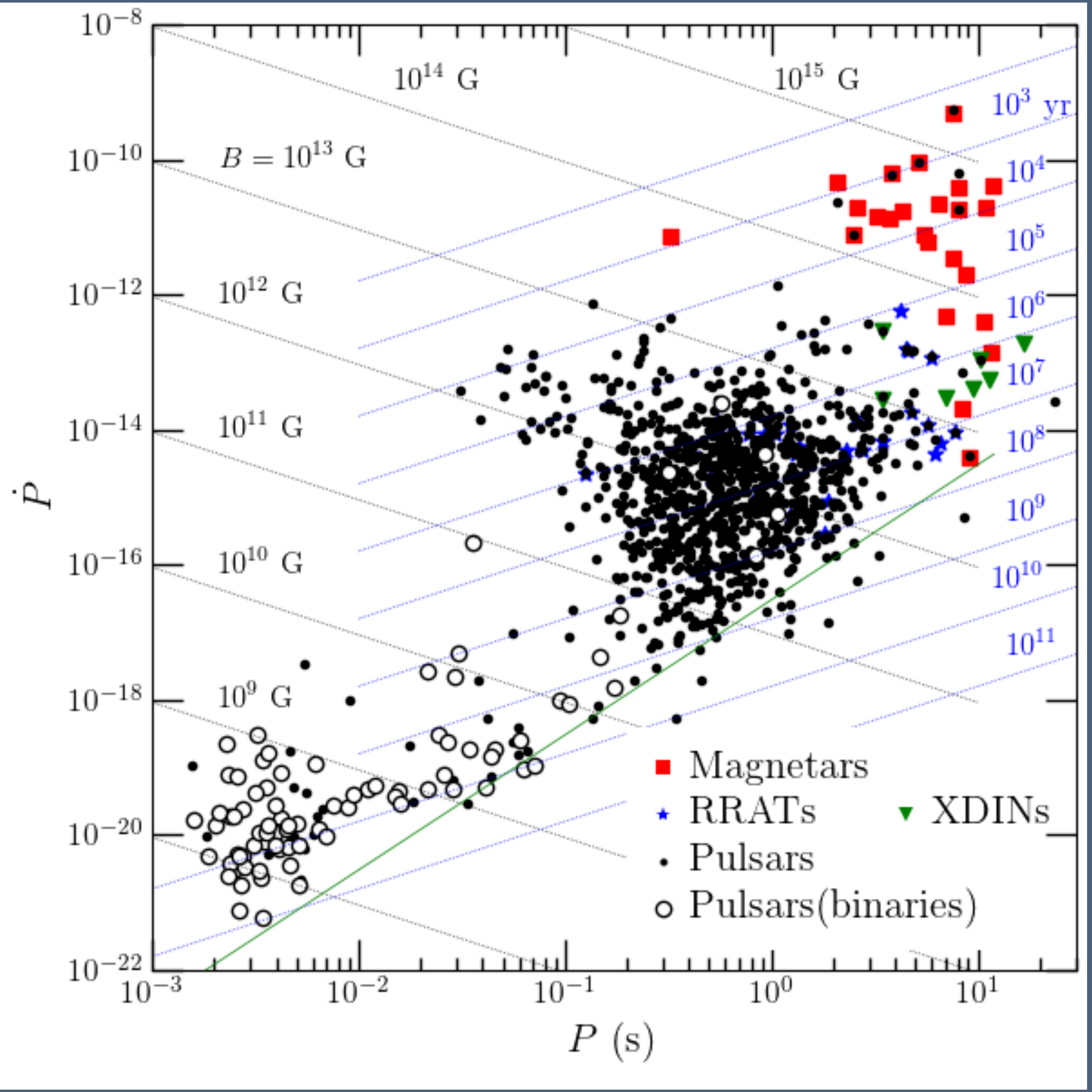
Science and Technology Facilities Council

DiRAC High Performance Computing Facility

Magnetars

Low-B magnetars

- Magnetars show a range of transient X-ray behaviour including X-ray bursts, outbursts and giant flares.
- Quiescent X-ray emission as well as X-ray transients are attributed to extreme magnetic fields $B > 10^{14}$ G, see e.g. review Kaspi & Beloborodov (2017).
- Some magnetars have small spin-down magnetic fields $\lesssim 10^{13}$ G, but still show bursts and outburst. These are named low-B magnetars (van der Horst+2010, Rea+2010,2012,2014)



http://neutronstars.utk.edu

Formation of strong magnetic fields

- Dynamo could be caused by proton-neutron star convection (Thompson & Duncan 1993; Raynaud+2020), magnetorotational instability (Reboul-Salze+2021,2022).
- New mechanism is the Tayler-Spruit dynamo (Spruit 2002; Barrère+2022,2023).

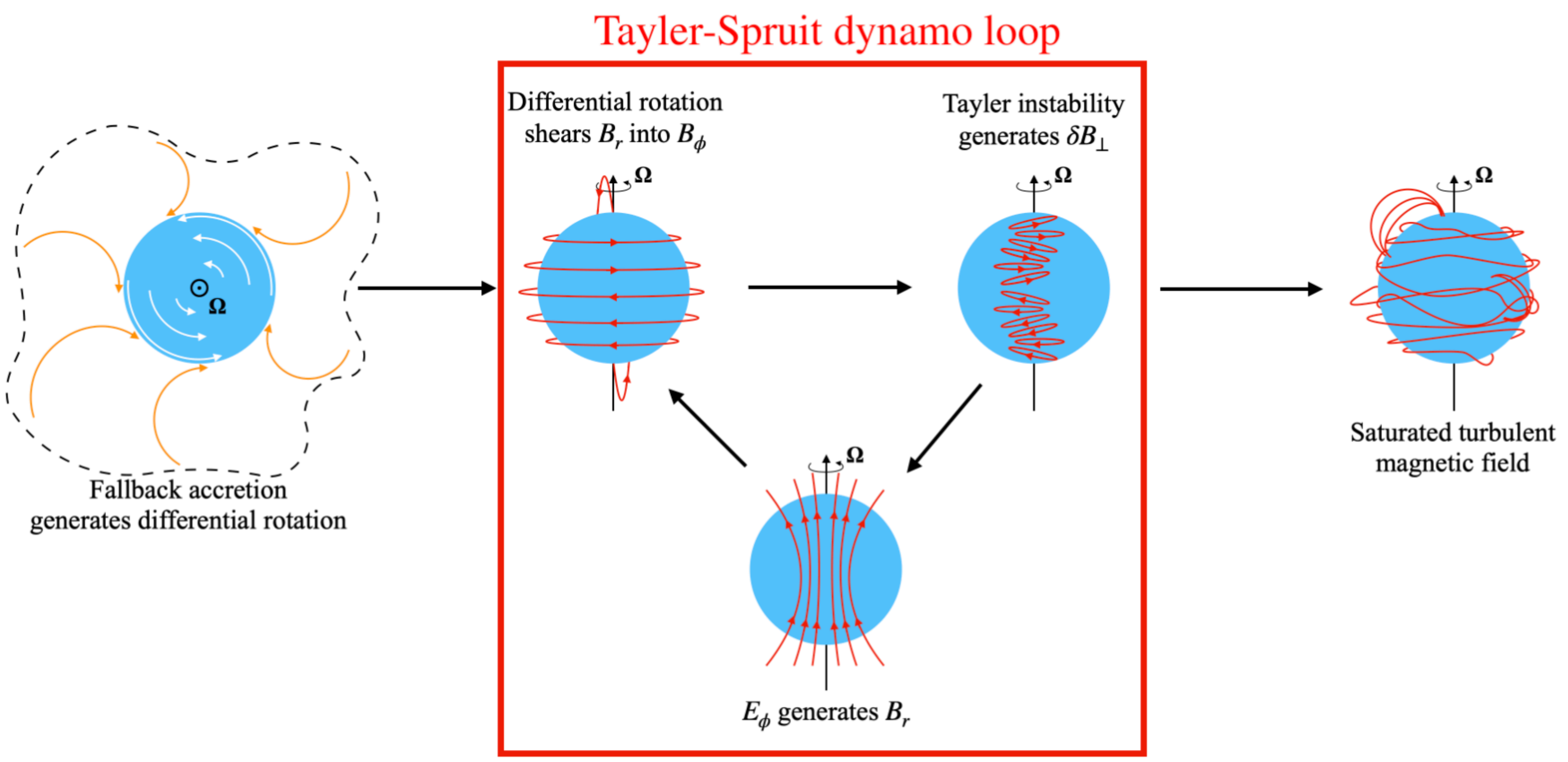
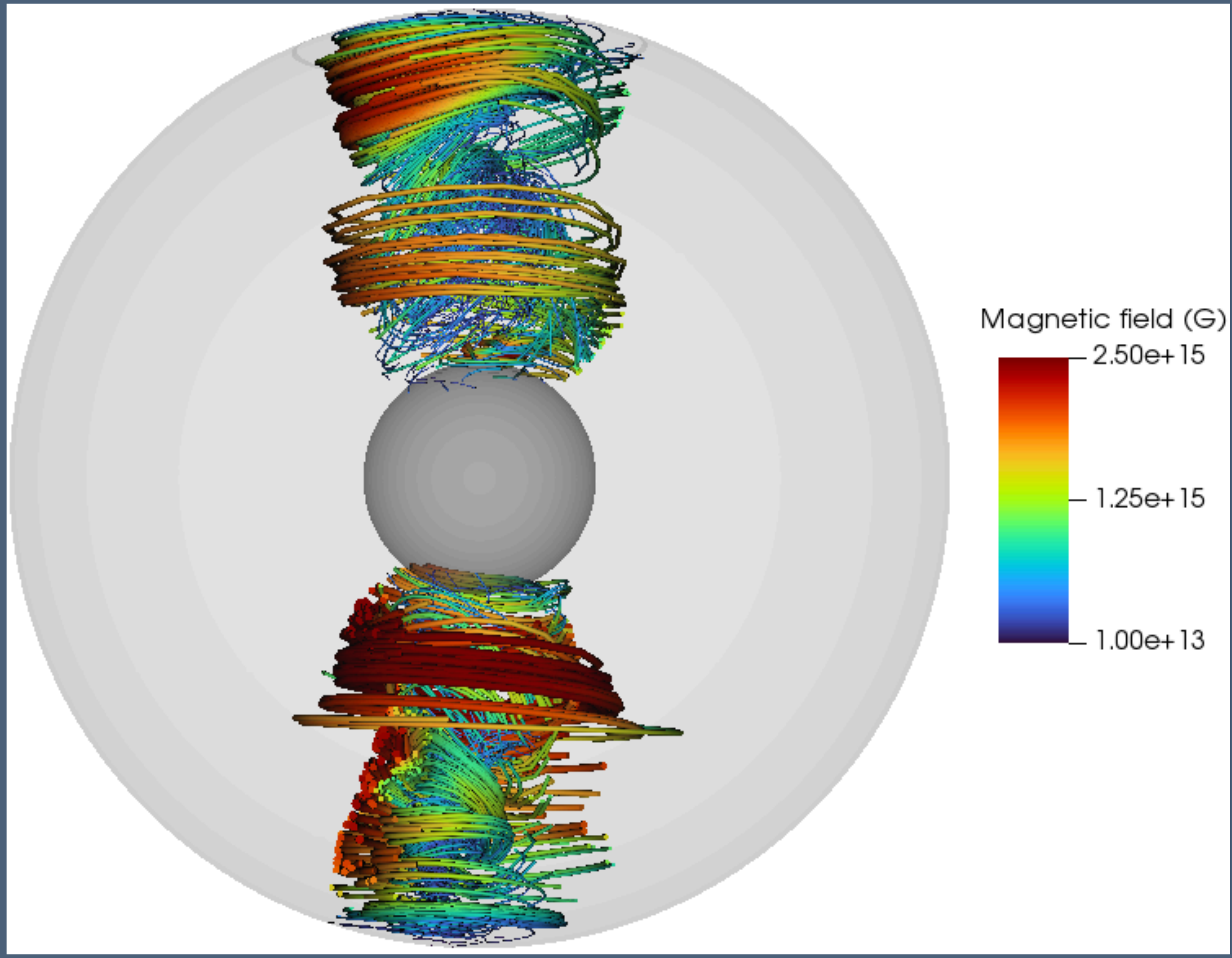


Fig. 1. Schematic representation of the different stages of our magnetar formation scenario. The dashed line encloses the region of the fallback (orange arrows). Red and white lines represent the magnetic field lines and fluid motions, respectively. $\boldsymbol{\Omega}$ and E_ϕ stand for the angular rotation frequency and the azimuthal component of the electromotive force, respectively. B_ϕ and B_r are the axisymmetric azimuthal and radial magnetic fields, and $\delta B_\perp$ is the non-axisymmetric perpendicular magnetic field.

Barrère, Guiltet, Reboul-Salze, Raynaud & Janka (2022)

Tayler-Spruit dynamo for proto-NS



MHD simulations

Barrère, Guiltet, Raynaud & Reboul-Salze (2023)

Magneto-thermal evolution of neutron stars

PARODY code

- We use the modified PARODY code to solve two equations simultaneously using the spectral decomposition for angular variables and finite difference scheme for radial direction.

- The equations are solved in a spherical shell which represents the neutron star crust. The shell extends for approximately 1 km in depth.

$$\frac{\partial \vec{B}}{\partial t} = Se\,\nabla\left(\frac{1}{\mu}\right) \times \nabla T^2 + Ha\nabla \times \left[\frac{1}{\mu^3}\vec{B} \times (\nabla \times \vec{B})\right] - \nabla \times \left[\frac{1}{\mu^2}\nabla \times \vec{B}\right]$$

Magnetic induction

$$\frac{1}{Ro}\frac{C_v}{T}\frac{\partial T^2}{\partial t} = \nabla \cdot (\mu^2 \hat{\chi} \cdot \nabla T^2) + \frac{Pe}{Se}\frac{|\nabla \times \vec{B}|^2}{\mu^2} + Pe\mu(\nabla \times B) \cdot \nabla\left(\frac{T^2}{\mu^2}\right)$$

Thermal diffusion

De Grandis et al. (2020)

Igoshev et al. (2021), Nature Astronomy

Igoshev et al. (2021), ApJ

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Biermann battery | Hall term | Ohmic term

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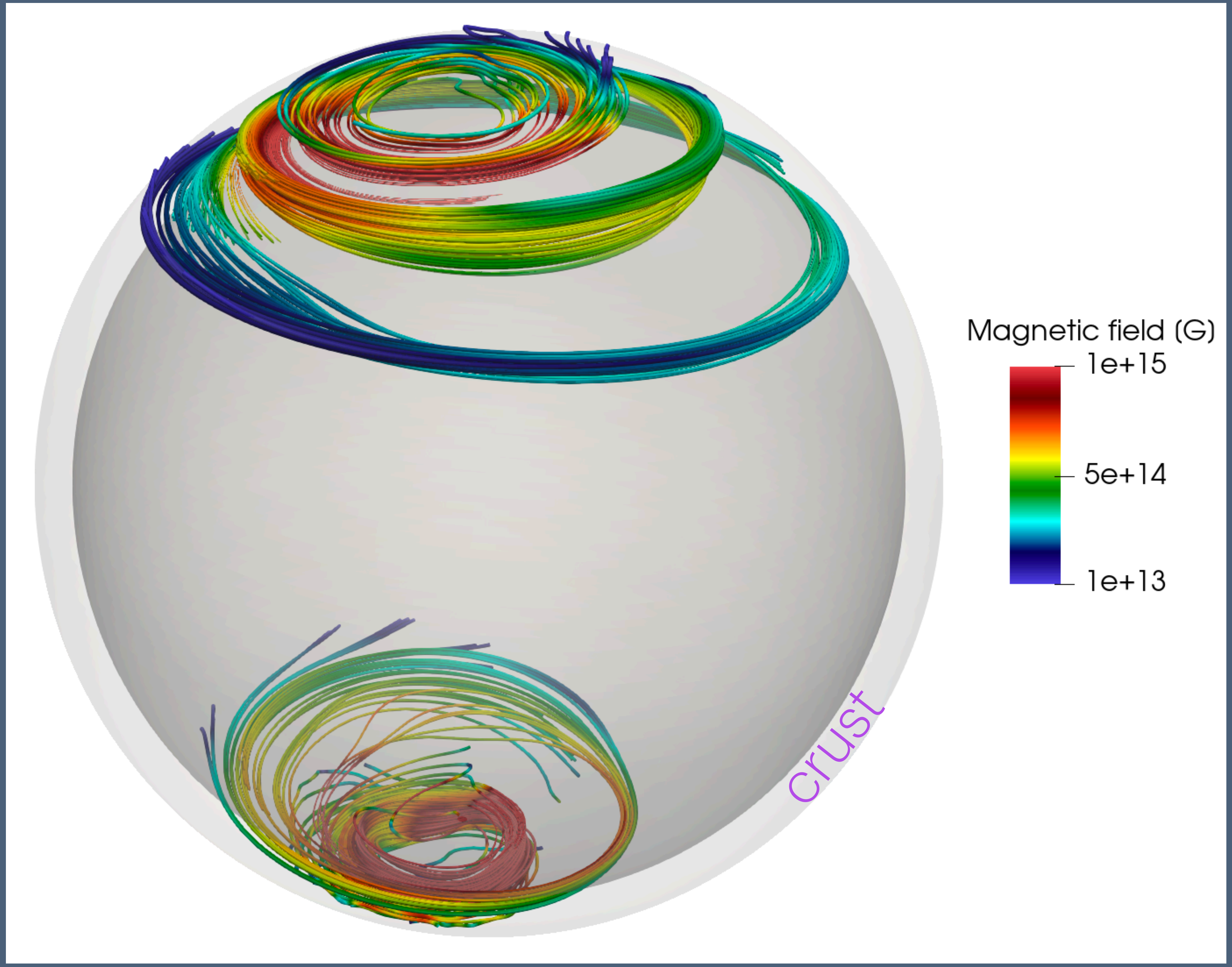
Thermal diffusion

Thermal diffusion

Initial and boundary condition

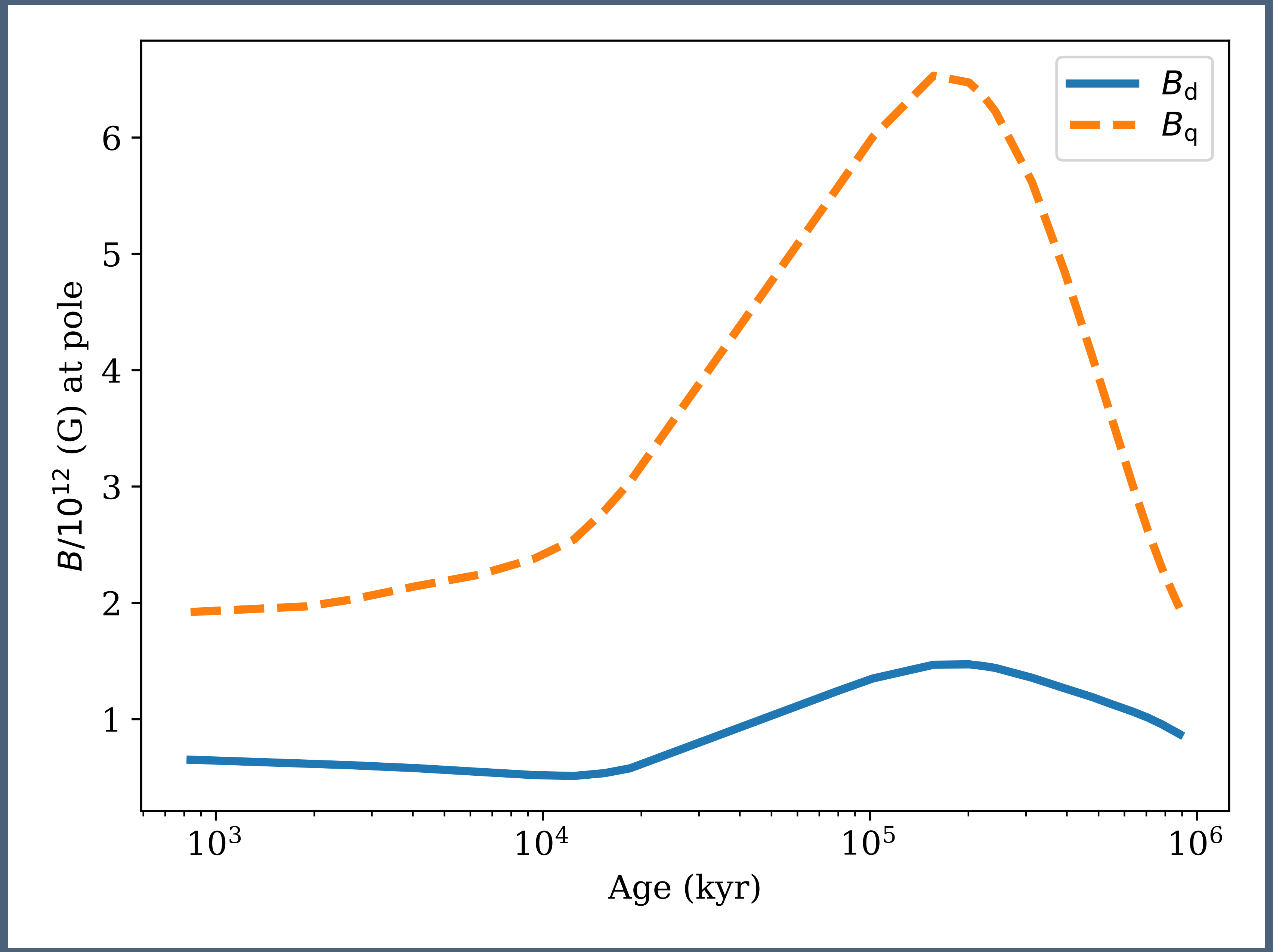
- Upper boundary condition:
  - $\nabla \times B = 0$ Force-free
  - $\frac{\pi^2 k_B^2}{6e^2}\vec{r} \cdot \hat{\chi} \cdot \nabla T_b^2 = \sigma_B T_s^4$ where $\left(\frac{T_s}{10^6}\right)^2 = \left(\frac{T_b}{10^8}\right)$
    Blackbody emission from the atmosphere
- Lower boundary condition
  - $B_r = 0$ the Meissner condition
  - $\frac{\partial T}{\partial t} = 0$ no cooling

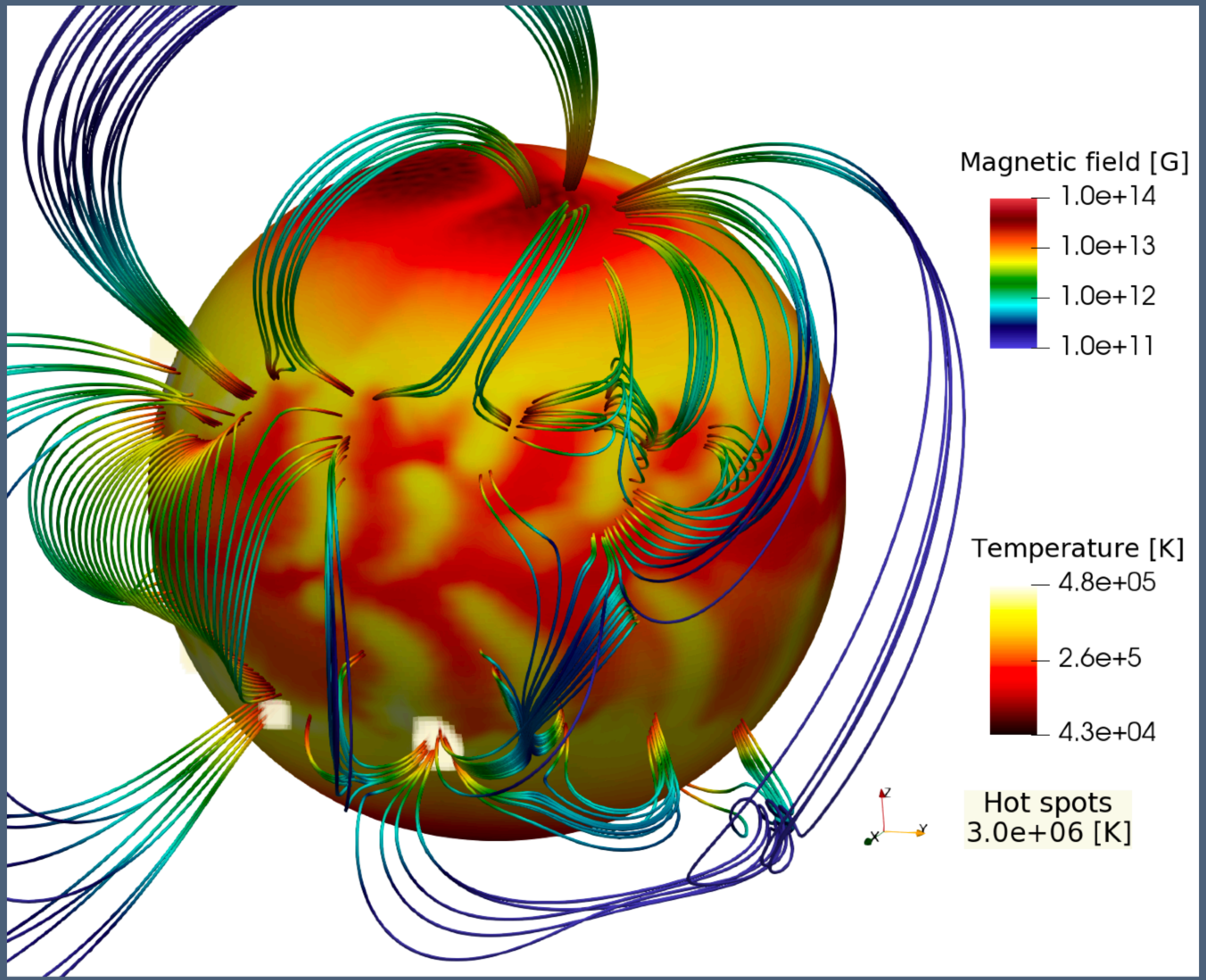


External magnetic field

Age 200 kyr

- Magnetic field structure is dominated by small scale fields. A system of magnetic arcs is formed.
- Magnetic field strength at the footpoints of individual arcs reaches 10^{14} G, the dipolar field stays low $\approx 10^{12}$ G.
- Hot regions are large and have insufficient temperature to be detected as quiescent emission.
- Surface can be heated by magnetospheric currents $\vec{J} = \vec{\nabla} \times \vec{B}$, force-free condition $\vec{\nabla} \times \vec{B} = \mu \vec{B}$ which means $J_r \propto B_r$. Regions with the strongest radial magnetic field can be heated by magnetospheric currents. Detailed future modelling is necessary.





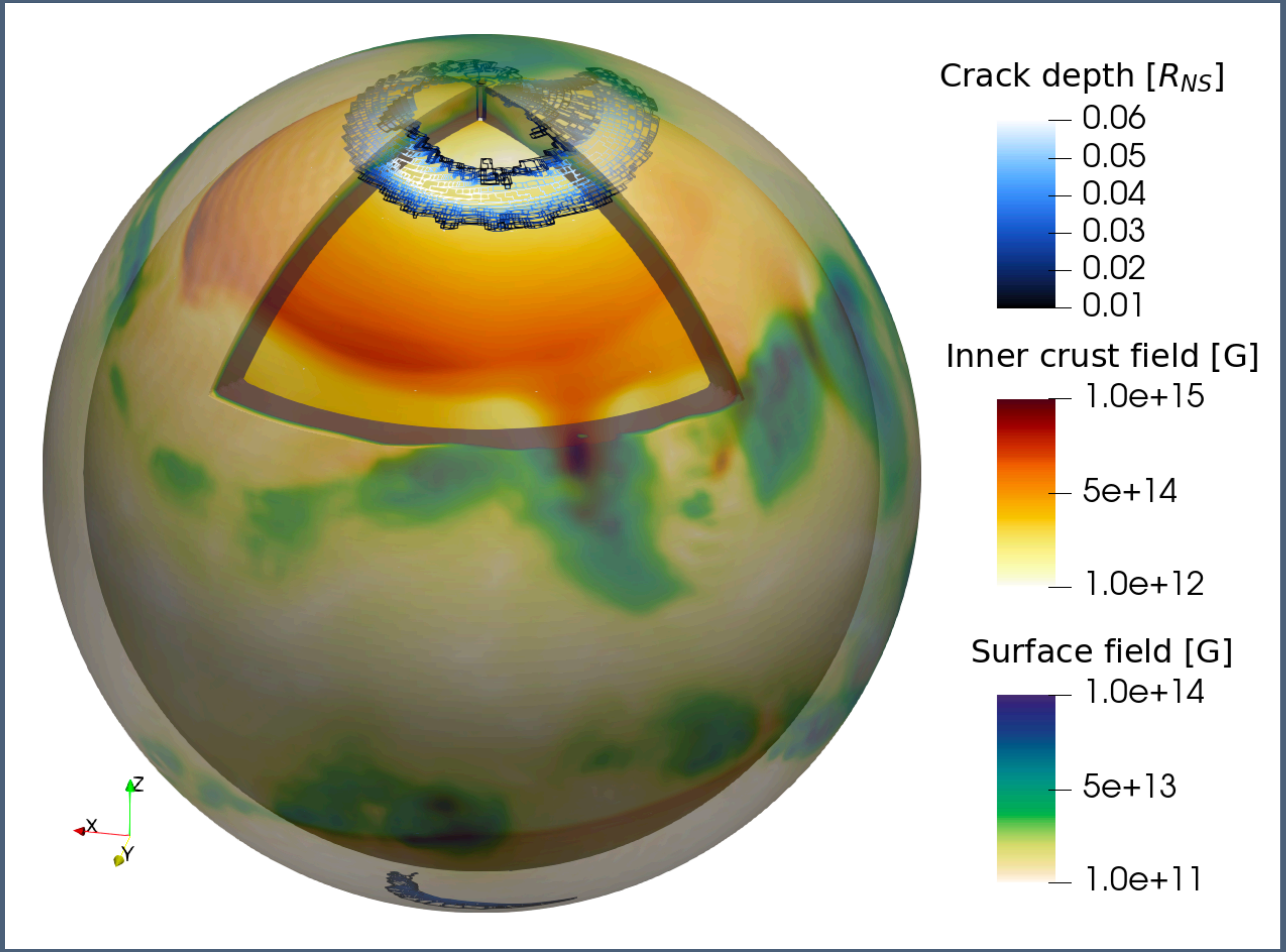
Mahlmann talk yesterday

Is it a magnetar?

Crust yielding criterion

- Crust will fail near the original magnetic pole and can trigger outbursts similar to magnetar outburst with energies up to 2×10^{39} erg.

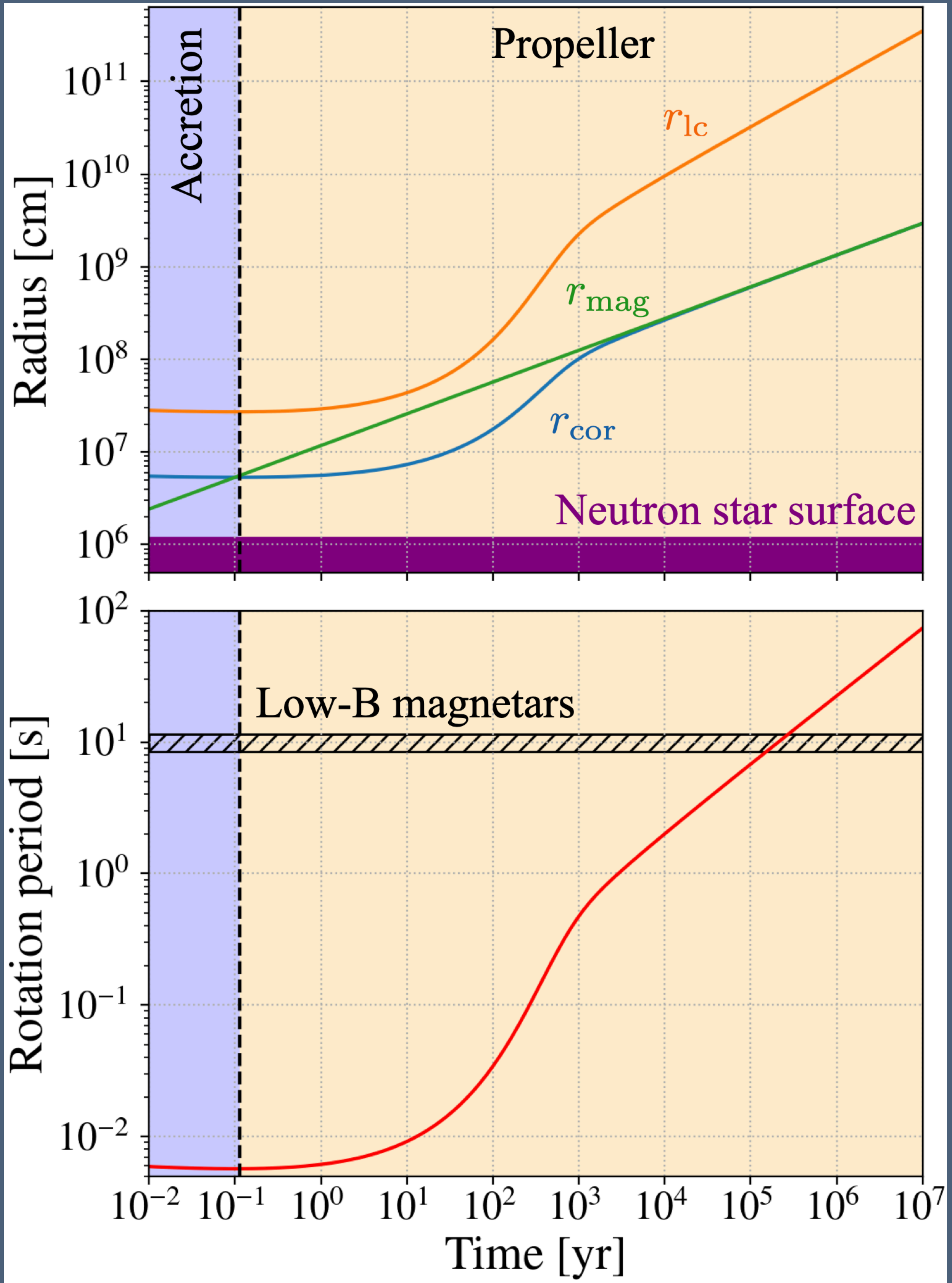
Lander & Gourgouliatos (2019) model



Spin period

Fallback disk

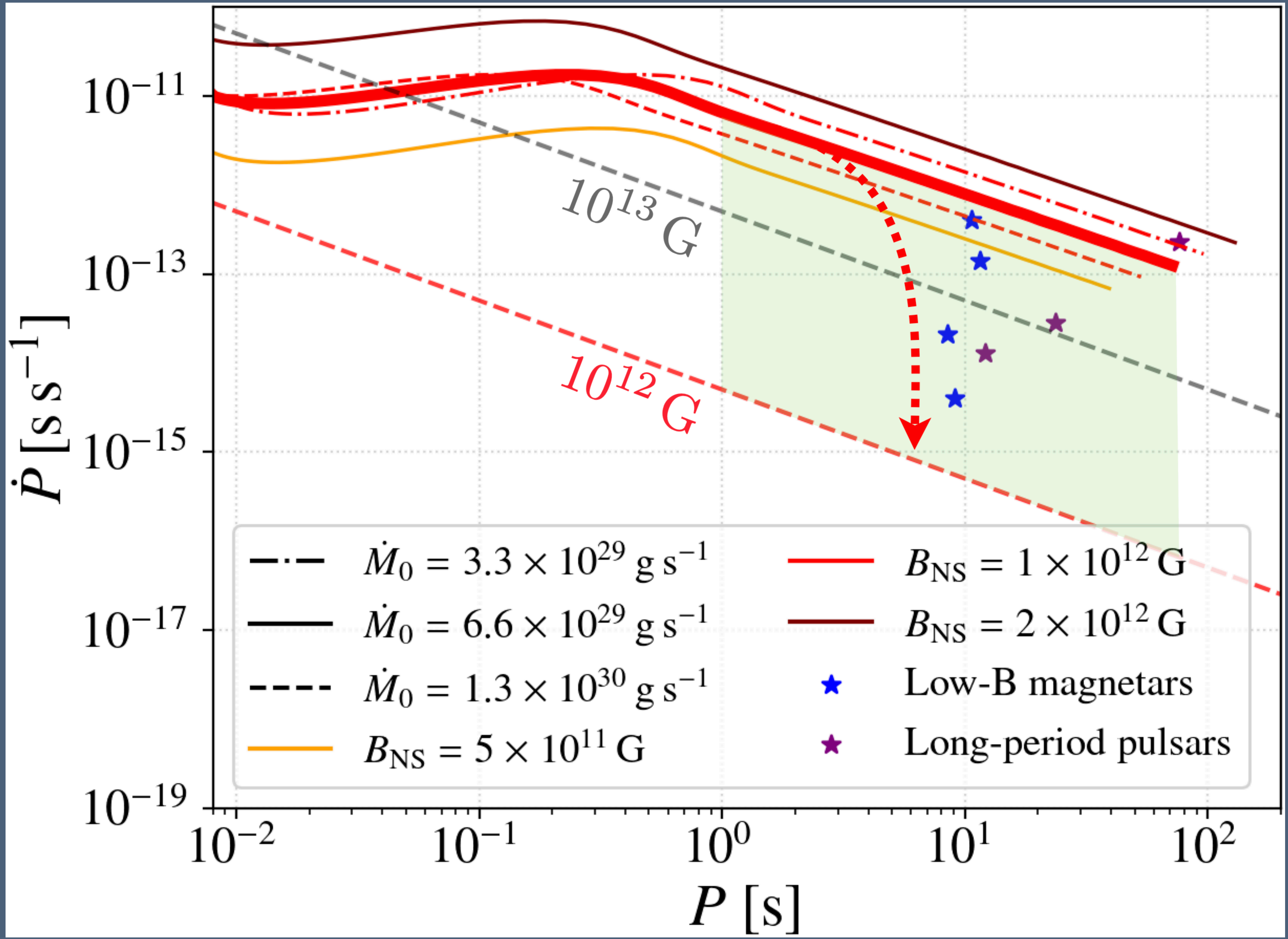
- Long periods > 1sec cannot be reached using the dipolar braking.
- Tayler-Spruit dynamo requires significant fallback accretion to operate.
- If fallback continues, it will decelerate neutron star in the propeller regime. The neutron star reaches spin periods ~ 10 sec by 200 kyr.
- Simulations based on Gompertz et al. (2014) and Ronchi, Rea, Graber et al. (2022) but with $\dot{M}_0 = 6.5 \times 10^{29}$ g/s based on TS dynamo simulations.



Spin period

Fallback disk

- The period derivative depends on the state of the fallback disk. If the fallback disk is partially (completely) depleted, the period derivative is closer to magnetospheric spin-down.
- At older ages these objects could turn into long-period pulsars.



Summary and future work

- Tayler-Spruit dynamo creates magnetic field configuration with strong toroidal magnetic field and weak poloidal surface fields.

- These configurations do form strong surface radial magnetic fields, but these do not merge and form instead separate footpoints similar to solar physics.

- Magnetic field evolution could trigger crust yielding and magnetar outbursts.

- Objects are very similar to low-B magnetars.

- These findings suggest two distinct formation channels for classical and low-field magnetars, potentially linked to different dynamo mechanisms.

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- These findings suggest two distinct formation channels for classical and low-field magnetars, potentially linked to different dynamo mechanisms.

New research group at Newcastle University

PhD (UK) and postdoc positions planned to be advertised in 6-8 months around November/December 2024

Stay tuned or contact me for more details:

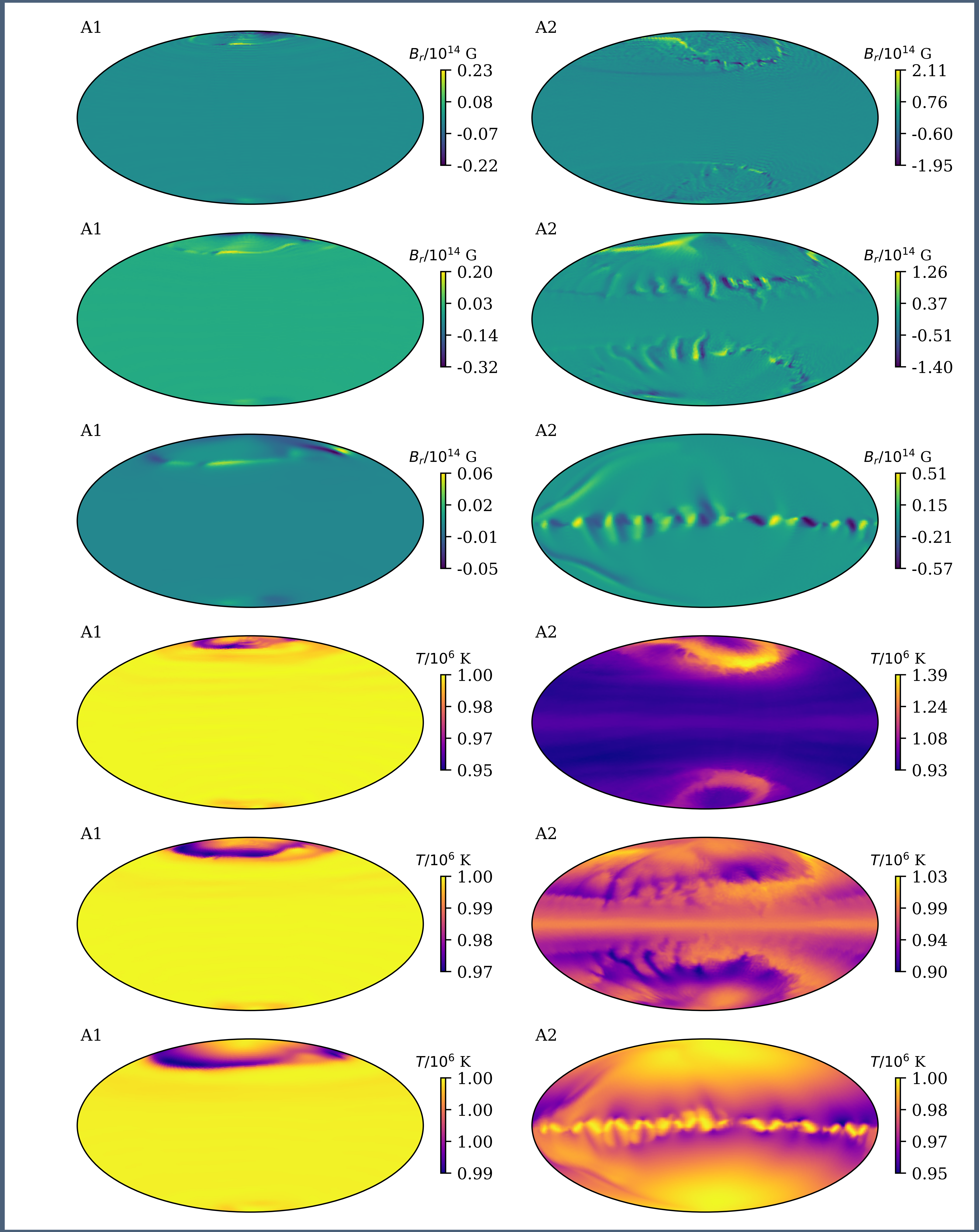
ignotur@gmail.com

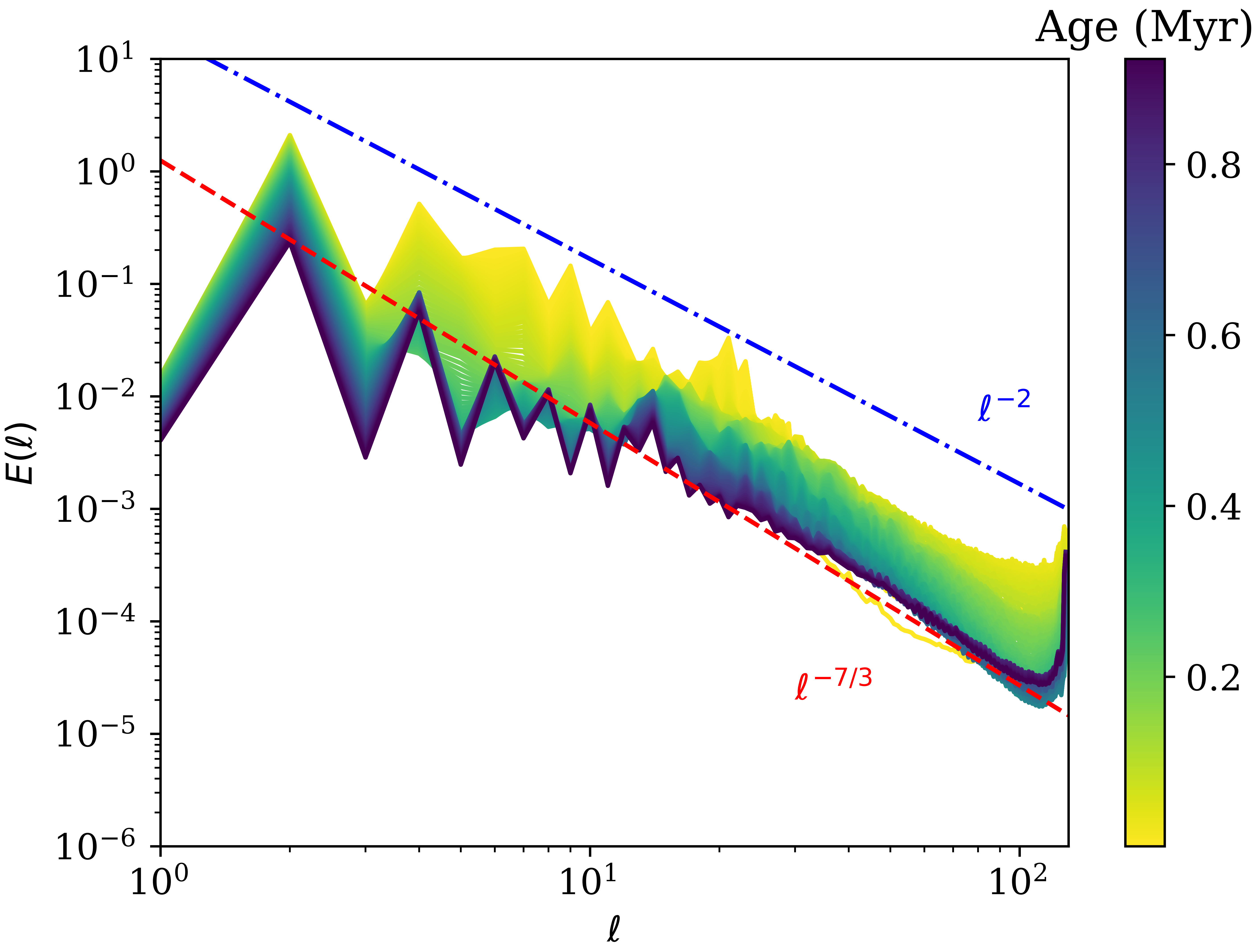
Thank you for your attention!

10 kyr

50 kyr

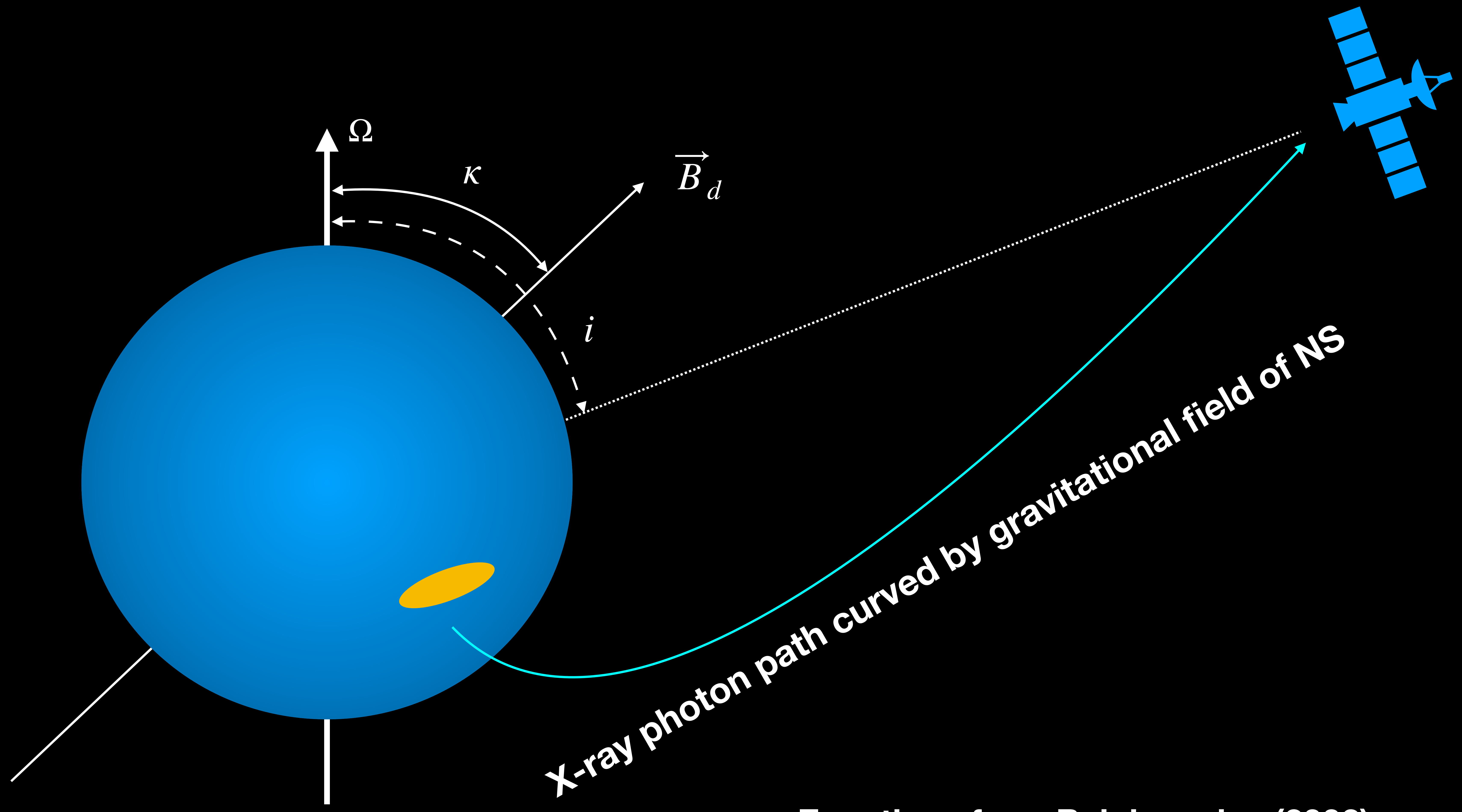
1000 kyr





Age (Myr)
0.8
0.6
0.4
0.2
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$E(\ell)$
10^{0}
10^{1}
10^{2}
ℓ
ℓ^{-2}
$\ell^{-7/3}$

Orientation of NS and light curve



Equations from Beloborodov (2002)

https://github.com/ignotur/magpies

Magpies package is coming