Universitat d'Alacant

GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN

GENERALITAT VALENCIANA
Conselleria de Educación, Cultura, Universidades y Empleo

The Interior Physics of Neutron Stars: Magnetic and Thermal Evolution

MATINS
MAgneto-Thermal evolution of Isolated Neutron Stars

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Nuclear Physics in Astrophysics XII

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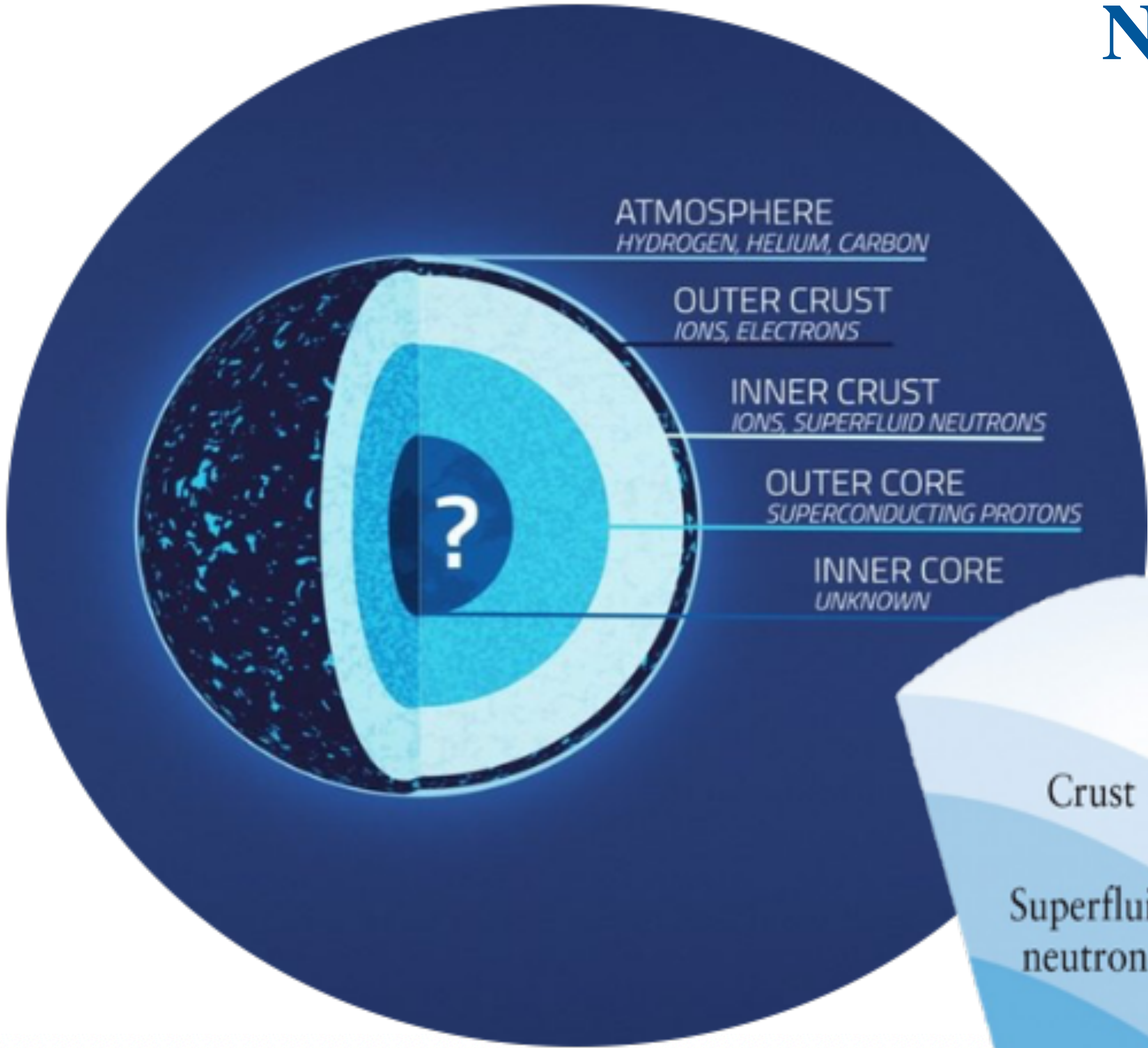
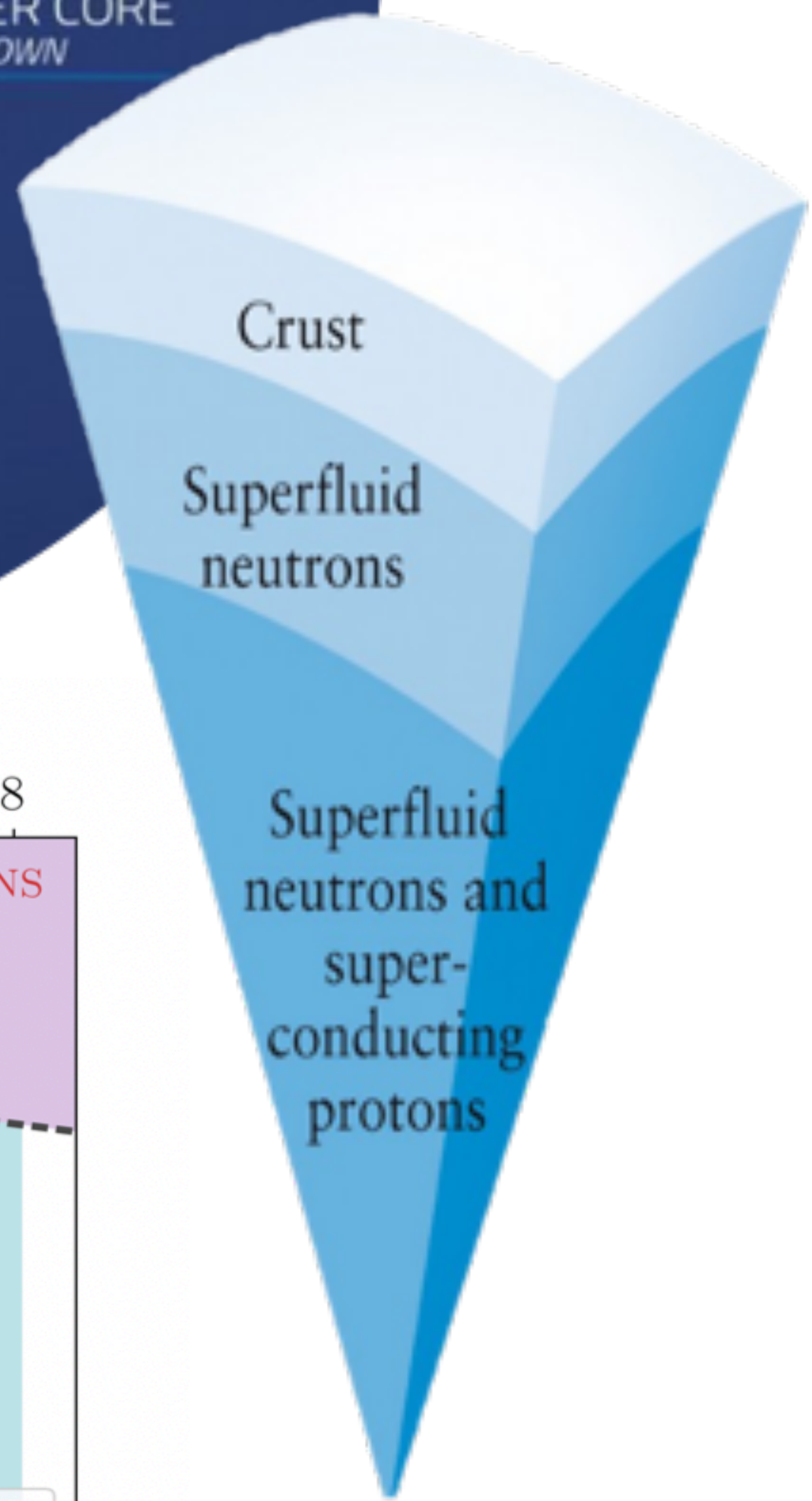
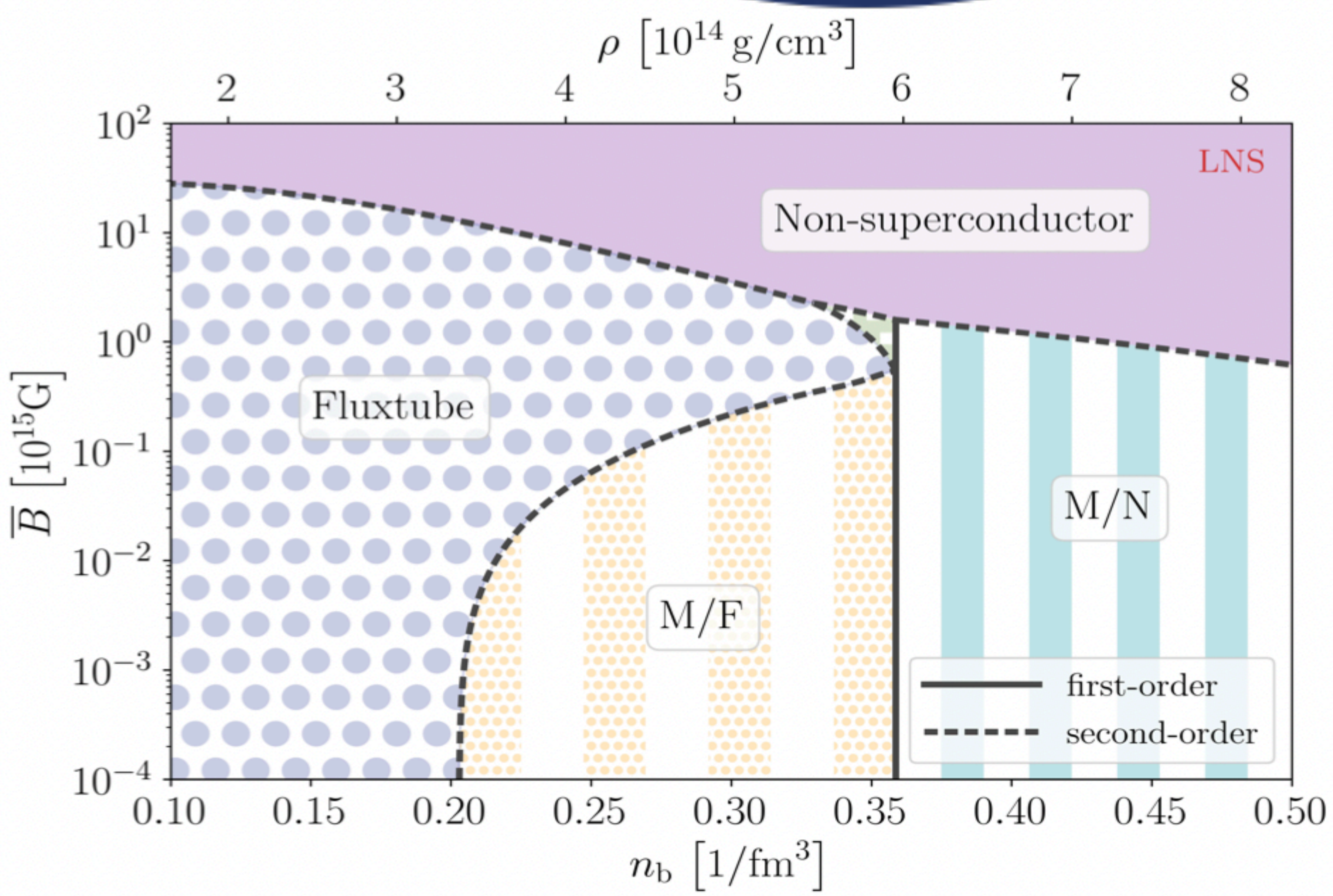
Neutron stars

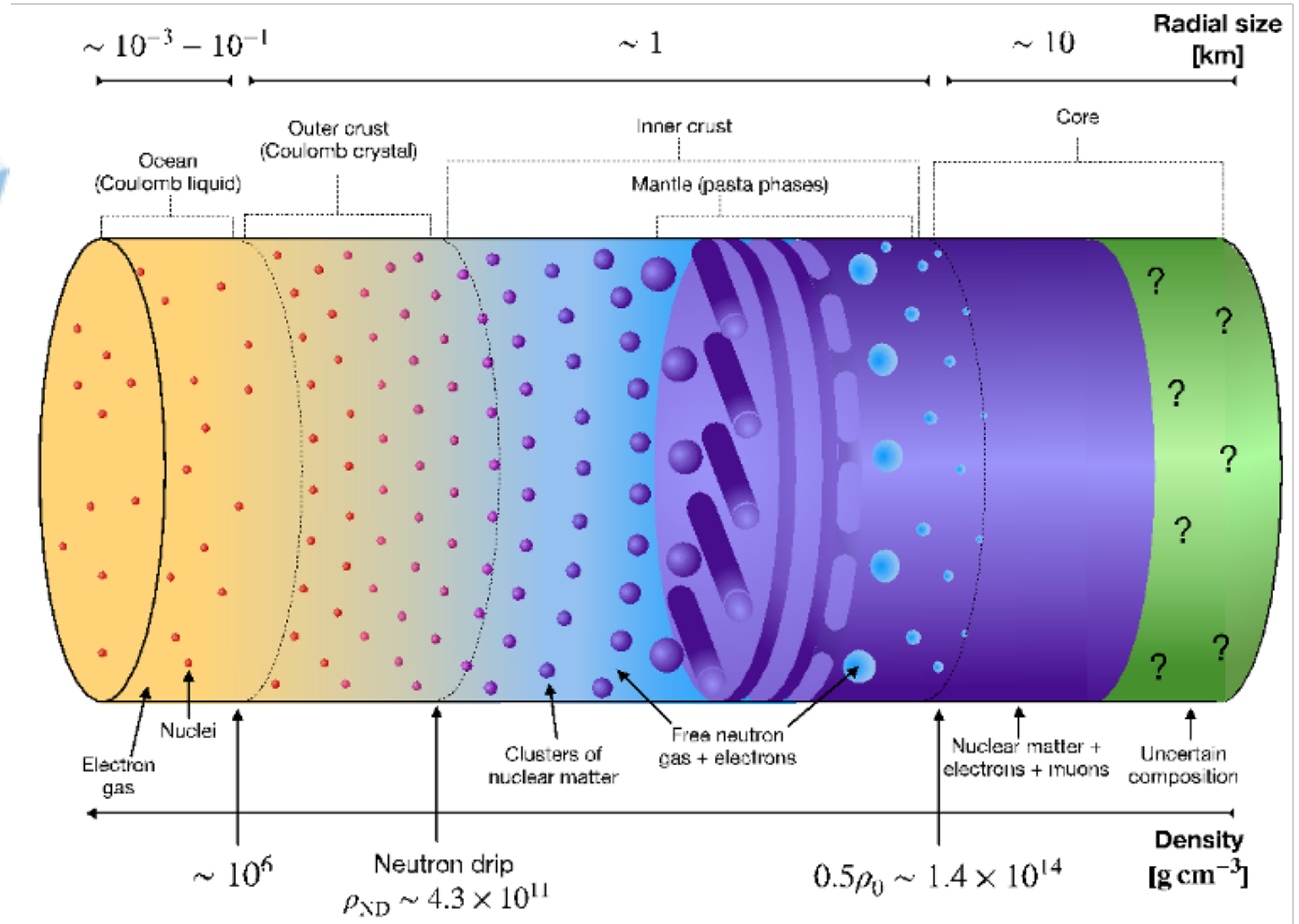
Neutron stars form in core-collapse supernovae, pass through a proto–neutron star (PNS) phase, and settle into compact objects with typical masses ≈ 1.4 $M_\odot$ and radii ≈ 10 – 12 km.







[Wood et al. 2022]



[Ascenzi, Graber & Rea, 2024]

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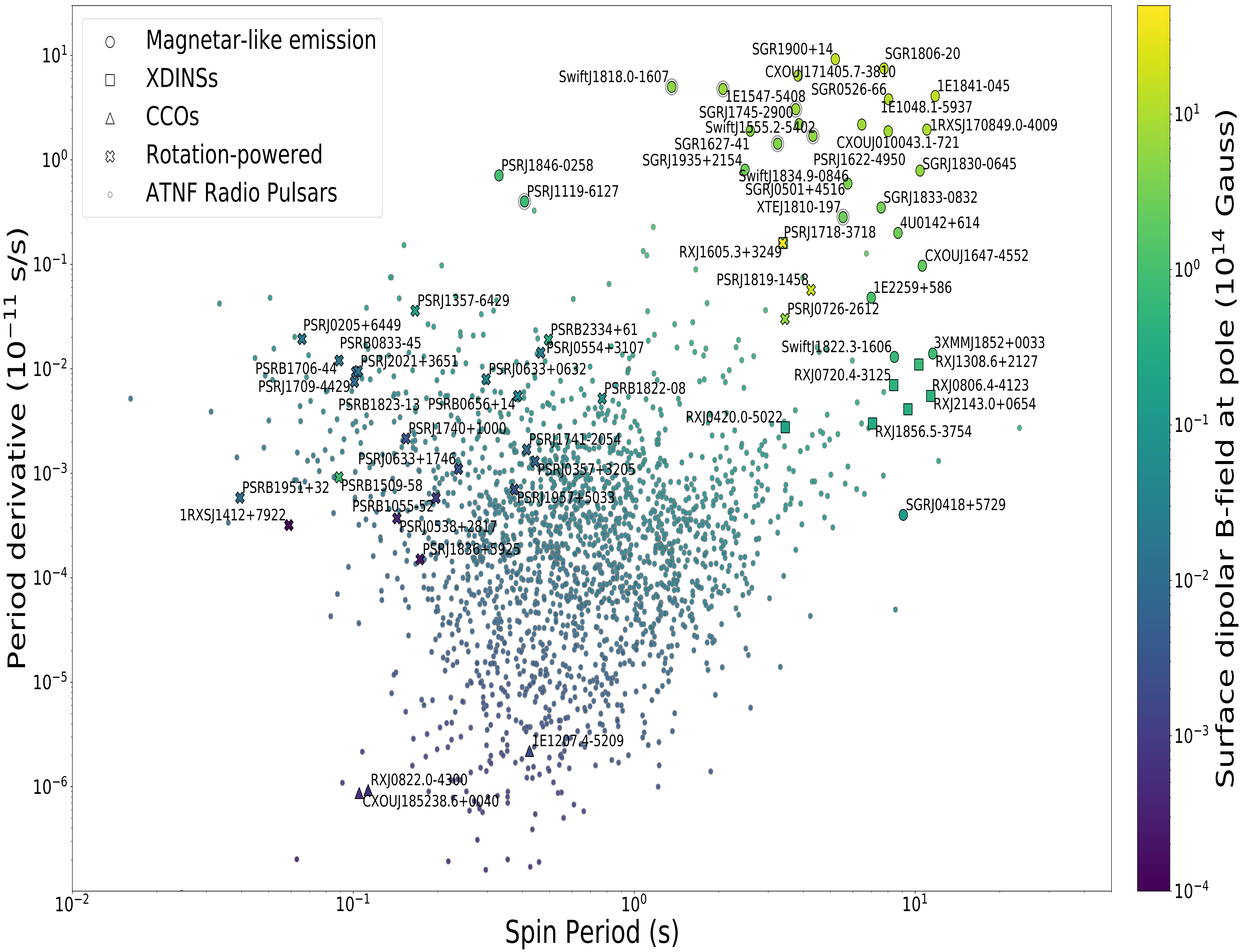
P-Pdot diagram for isolated neutron stars



Neutron stars form are observed across the electromagnetic spectrum

Dipolar magnetic field at the pole of the star:

$$B_{dip} = 6.4 \times 10^{19} \sqrt{P\dot{P}}$$

Characteristic age:

$$\tau_c = \frac{P}{2\dot{P}}$$

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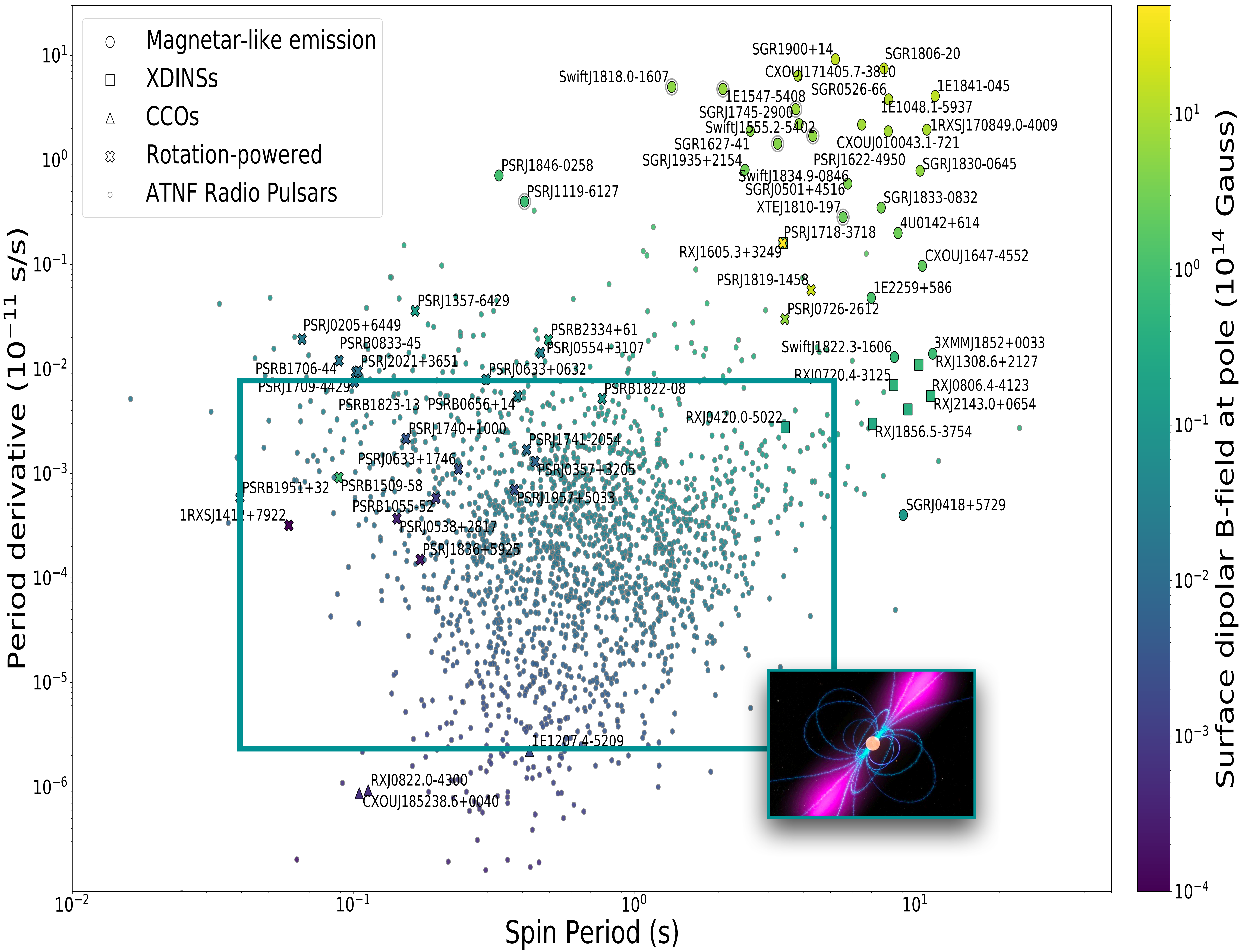
P-Pdot diagram for isolated neutron stars



Rotational-Powered Pulsars

Powered by rotational energy. Typically emitting in radio.

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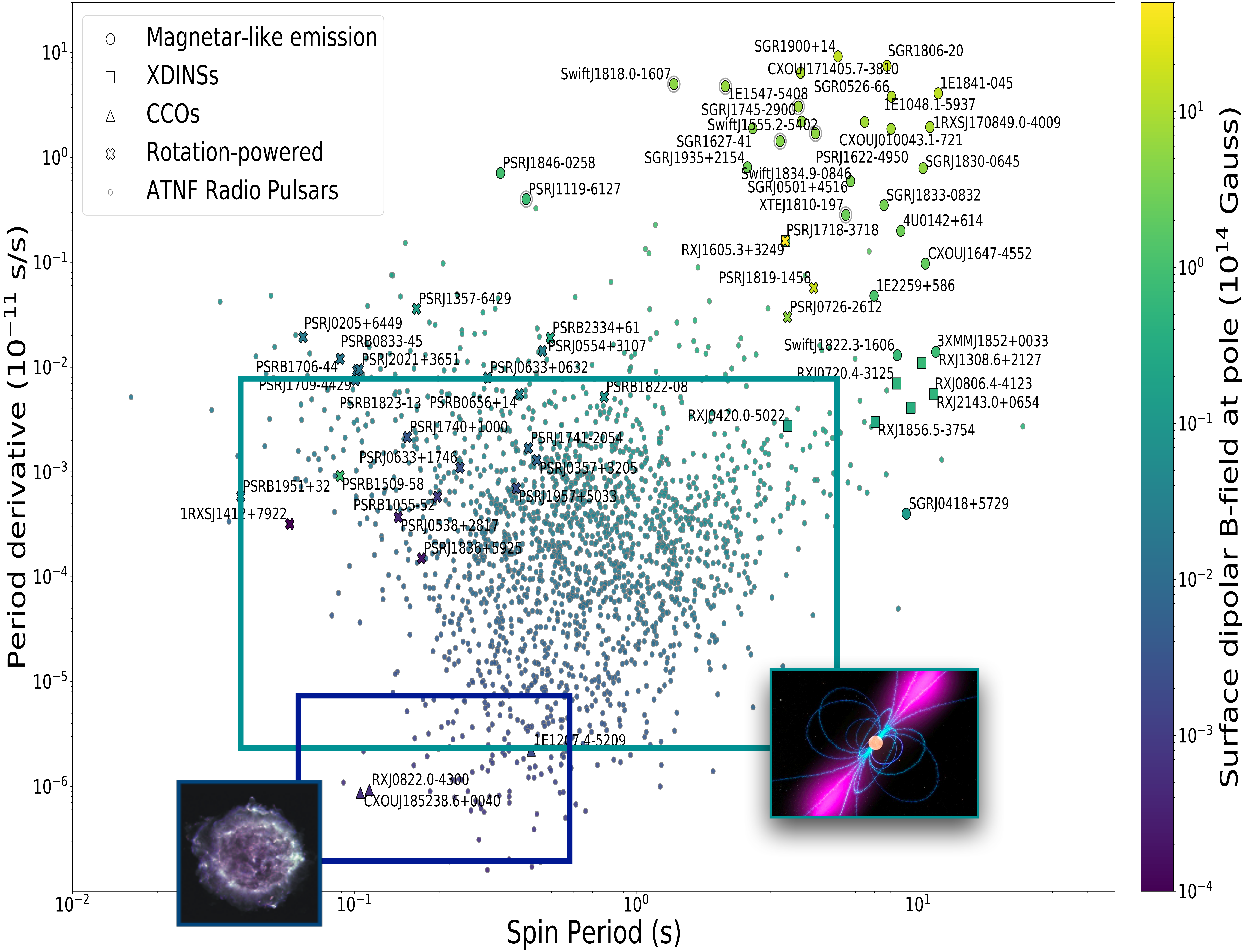
P-Pdot diagram for isolated neutron stars



Central Compact Objects

Powered by magnetic energy. Young with bright SNRs. Typically emitting in X-rays

Rotational-Powered Pulsars

Powered by rotational energy. Typically emitting in radio.

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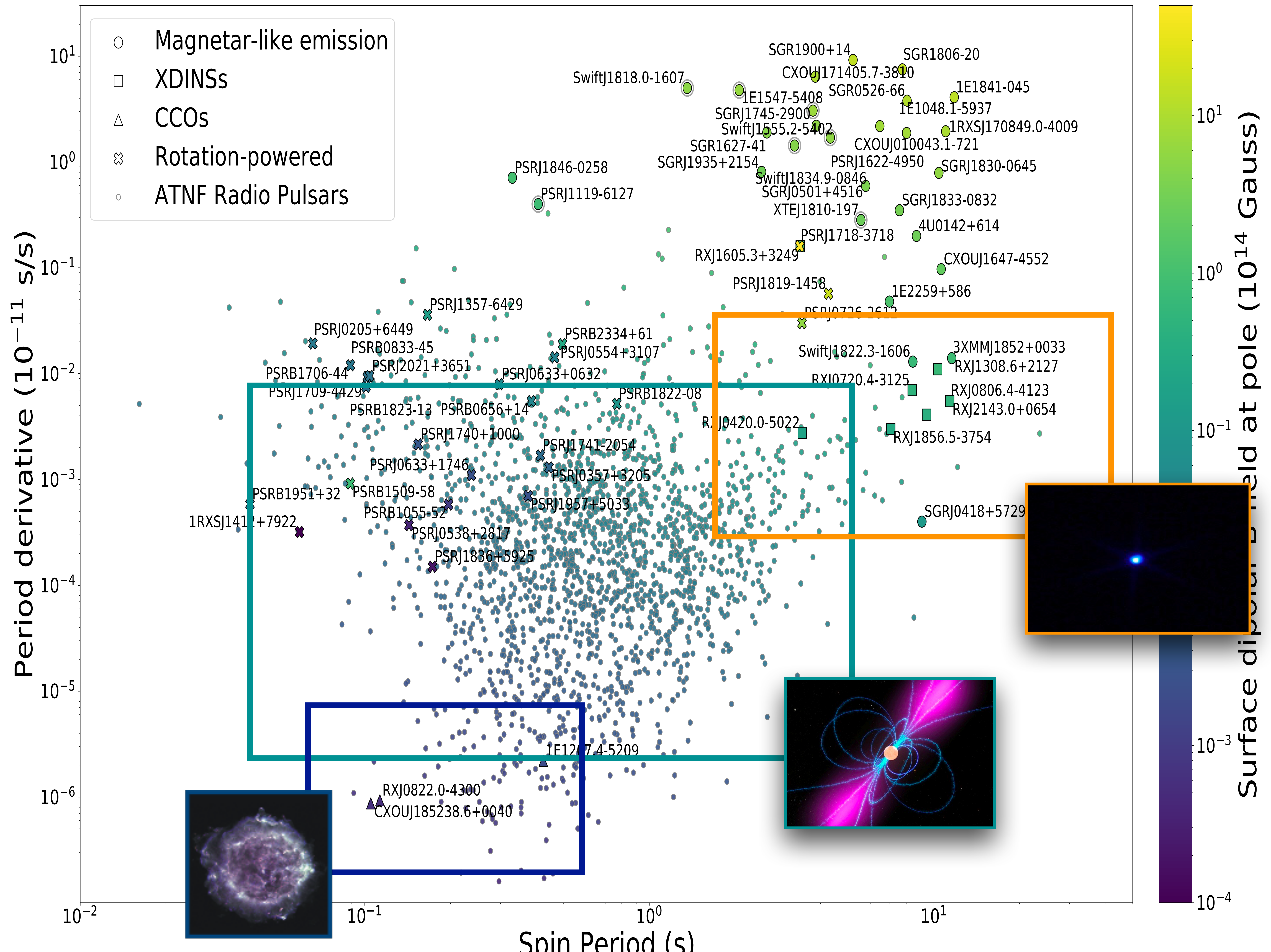
P-Pdot diagram for isolated neutron stars



X-ray Dim Isolated Neutron Stars

Powered by magnetic energy. Old, almost pure blackbodies. Typically emitting in X-rays

Central Compact Objects

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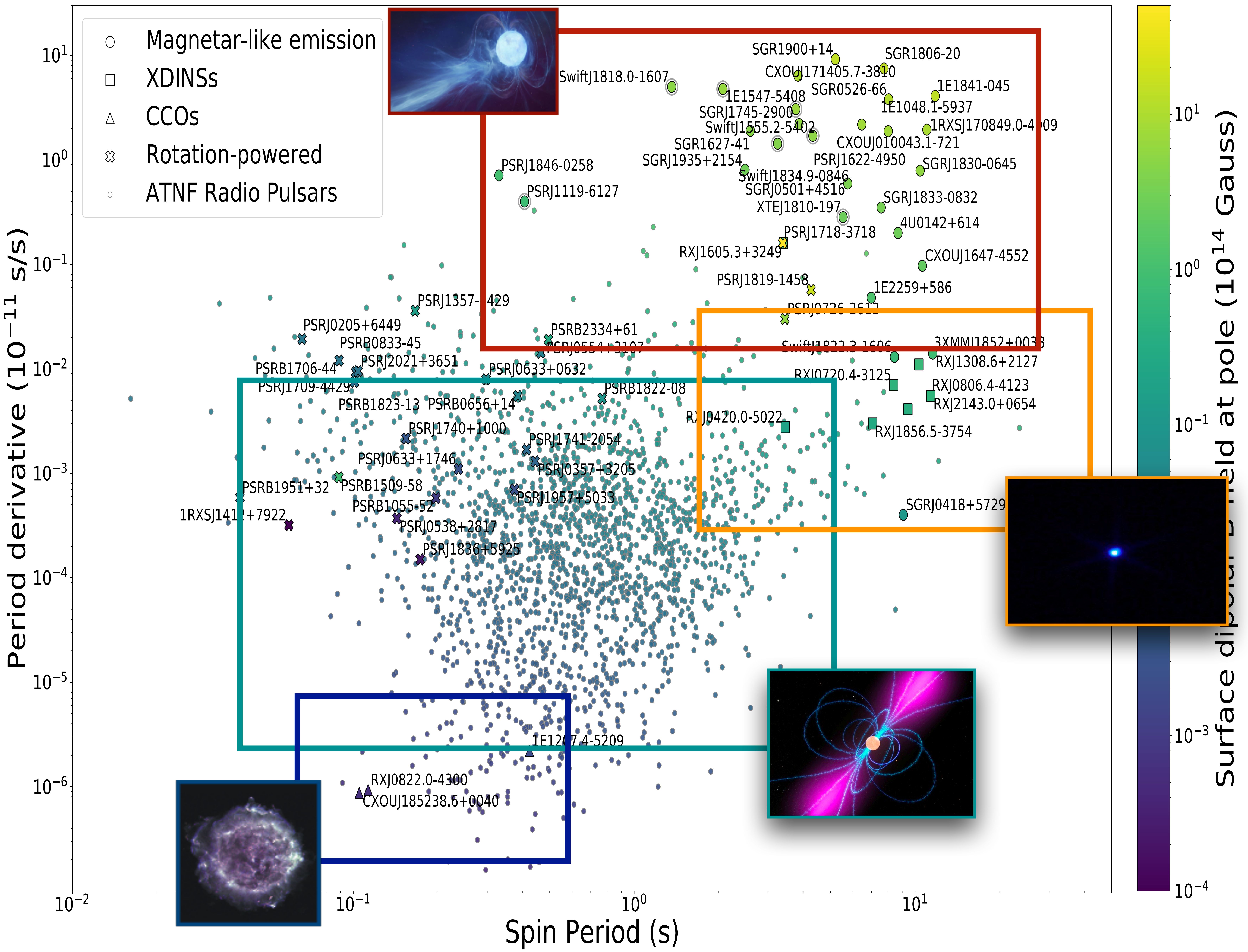
P-Pdot diagram for isolated neutron stars



Magnetars

Powered by magnetic energy.
Characterised by outbursts and flares.
Typically emitting in X-rays

X-ray Dim Isolated Neutron Stars

Powered by magnetic energy. Old, almost pure blackbodies. Typically emitting in X-rays

Central Compact Objects

Powered by magnetic energy. Young with bright SNRs. Typically emitting in X-rays

Rotational-Powered Pulsars

Powered by rotational energy. Typically emitting in radio.

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Observations: thermal X-ray luminosity, real age, P and Pdot

Four independent measured parameters.

"Need for coupled magneto-thermal simulations to explain the luminosity and the evolution path of different isolated neutron stars" — [Viganò et al. 2013].

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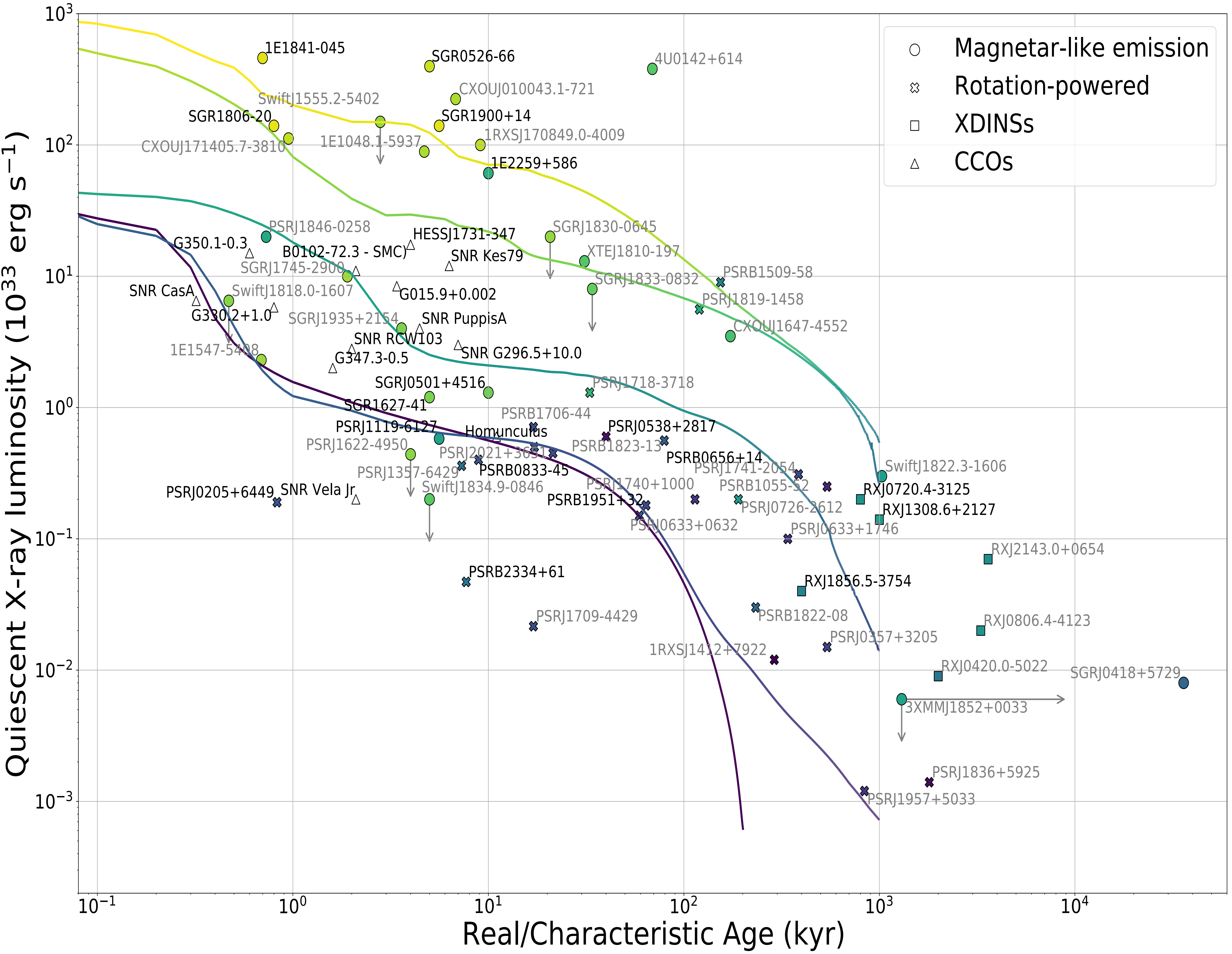
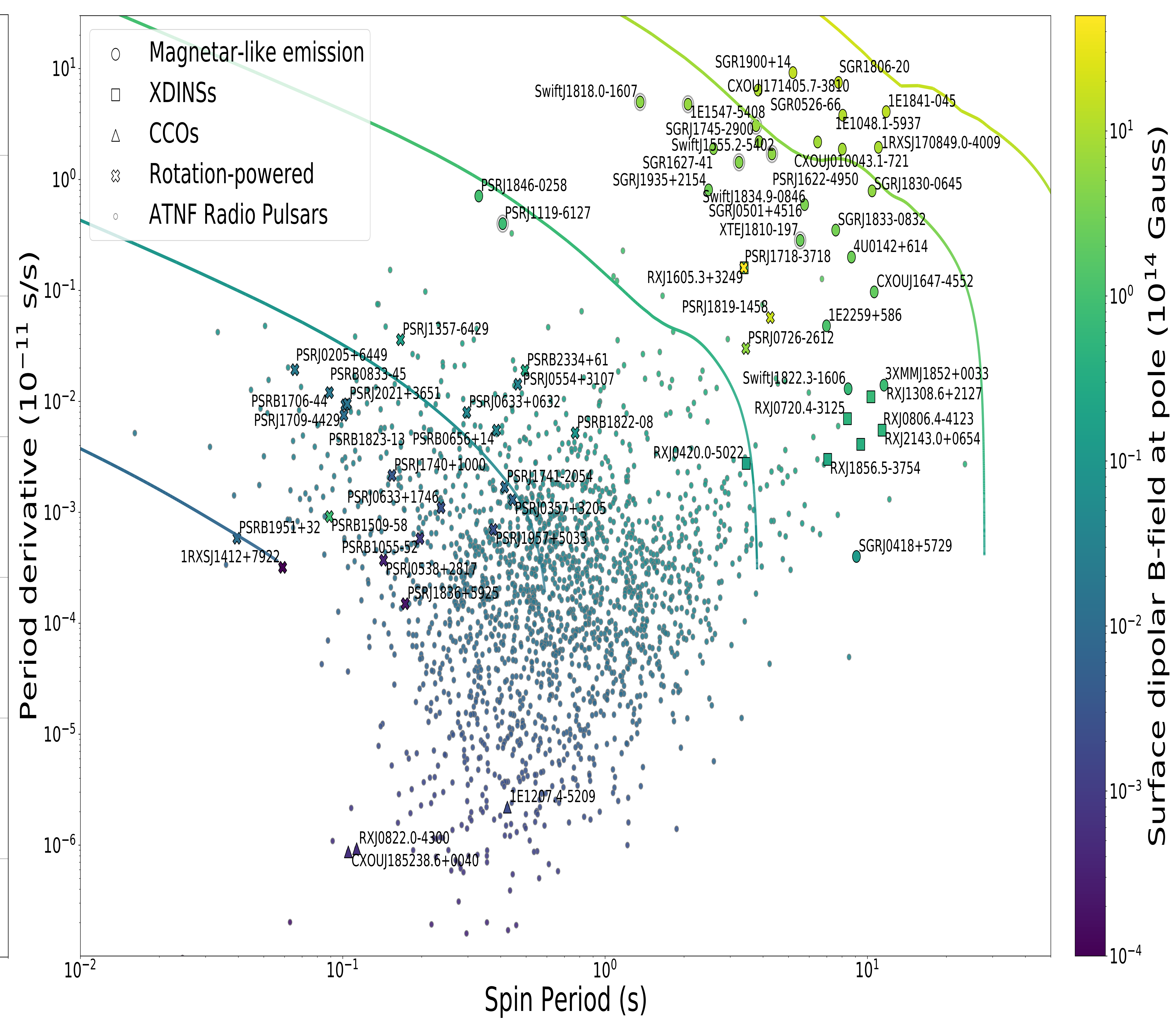
Why we need 3D magneto-thermal models?





- Realistic magnetic topology: complex and non-axisymmetric
- The need to model cooling curves, that depend on the 3d configuration

"New 3D code MATINS"

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[Dehman, Marino, Kovlakas, Rea et al., in prep.]

Neutron star model & Cooling

The structure is provided by the TOV equations which solve the hydrostatic equilibrium assuming a static interior Schwarzschild metric

Cold matter EOS + central pressure: star structure & composition (fixed)

Thermal evolution:

$$c_V(T)\frac{\partial\left(Te^{\nu}\right)}{\partial t} = \vec{\nabla}\cdot(e^{\nu}\hat{\kappa}\cdot\vec{\nabla}(e^{\nu}T)) + e^{2\nu}(Q_J - Q_\nu)$$

Ingredients:

- Heat capacity $C_V(\rho, T)$: main contribution by neutrons in the core
- **Thermal conductivity** $\boldsymbol{\kappa}(\rho, T, \boldsymbol{B})$ very large (star core rapidly isothermal), dominated by electrons, becomes **anisotropic** in presence of magnetic field
- Neutrino emissivity $Q_\nu(\rho, T, \boldsymbol{B})$
- Sources of internal heat Q_j: nuclear reactions, **Ohmic dissipation**, accretion…
- Hydrostatic equilibrium models of envelope (i.e., liquid outermost 100 m), that due to its stronger gradients of density and temperature has much faster timescales than the interior
- Emission model (atmosphere, blackbody, condensed surface...)

[Potekhin et al. 2015, review]
[Pons, Dehman, Viganò 2026, Living Review]

http://www.ioffe.ru/astro/conduct/
https://compose.obspm.fr/

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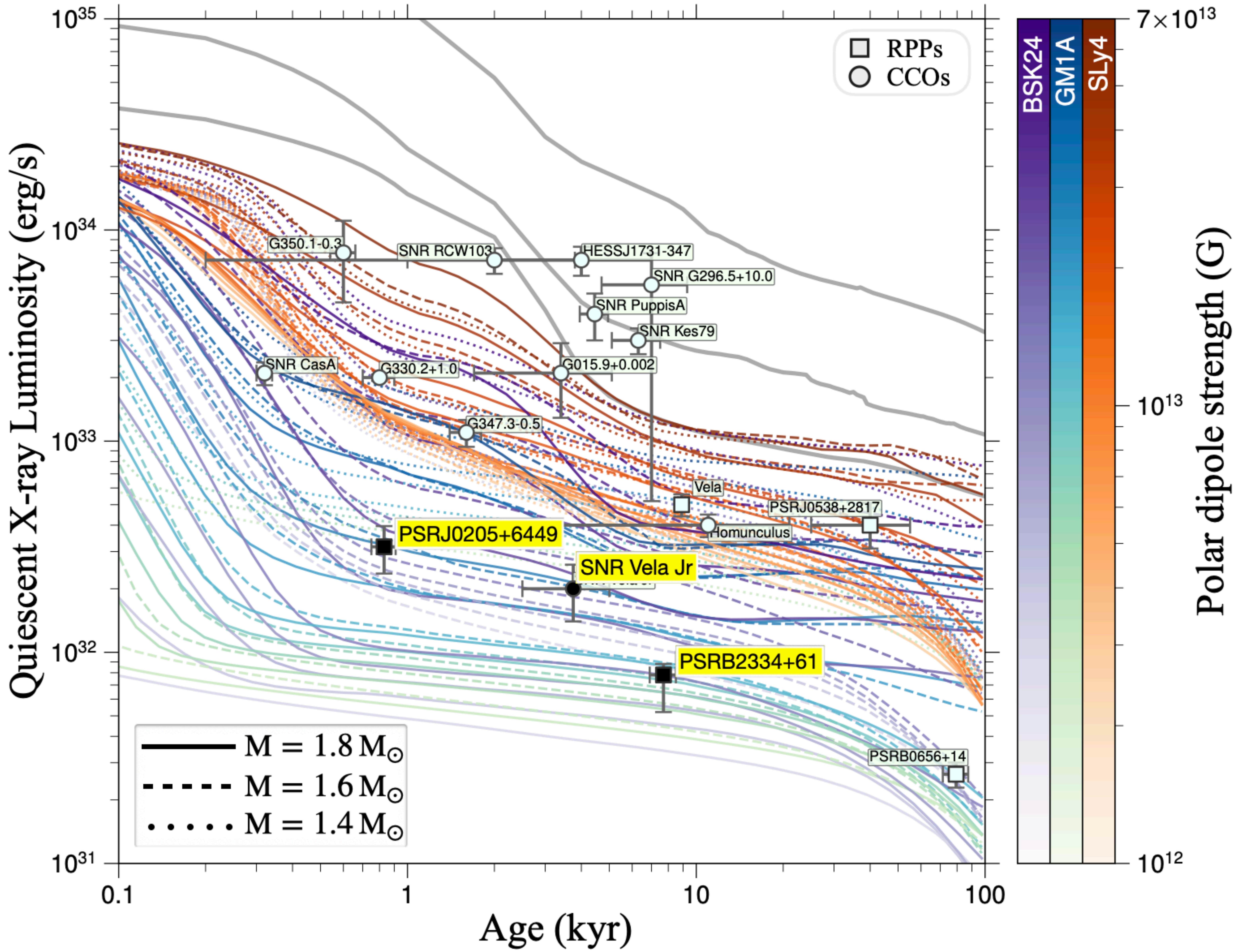
Enhanced cooling and constraining nuclear EoS

This marks the first direct measurement of enhanced cooling. Magneto-thermal simulation and machine learning techniques were used to understand this finding.

A suitable EoS should elucidate both exceptionally bright objects like magnetars (Joule heating) and extremely faint objects at young ages.

Taking into account a simplified meta-modeling approach (Margueron et al., 2018), the excluded range is estimated to encompass approximately 75% of the proposed nuclear EoSs.



[Anzuini, Melatos, Dehman et al. 2021, MNRAS]
[Anzuini, Melatos, Dehman et al. 2022, MNRAS]
GM1A — with hyperons in the core

[Marino, Dehman, Kovlakas, Rea et al. 2024, Nature Astronomy]

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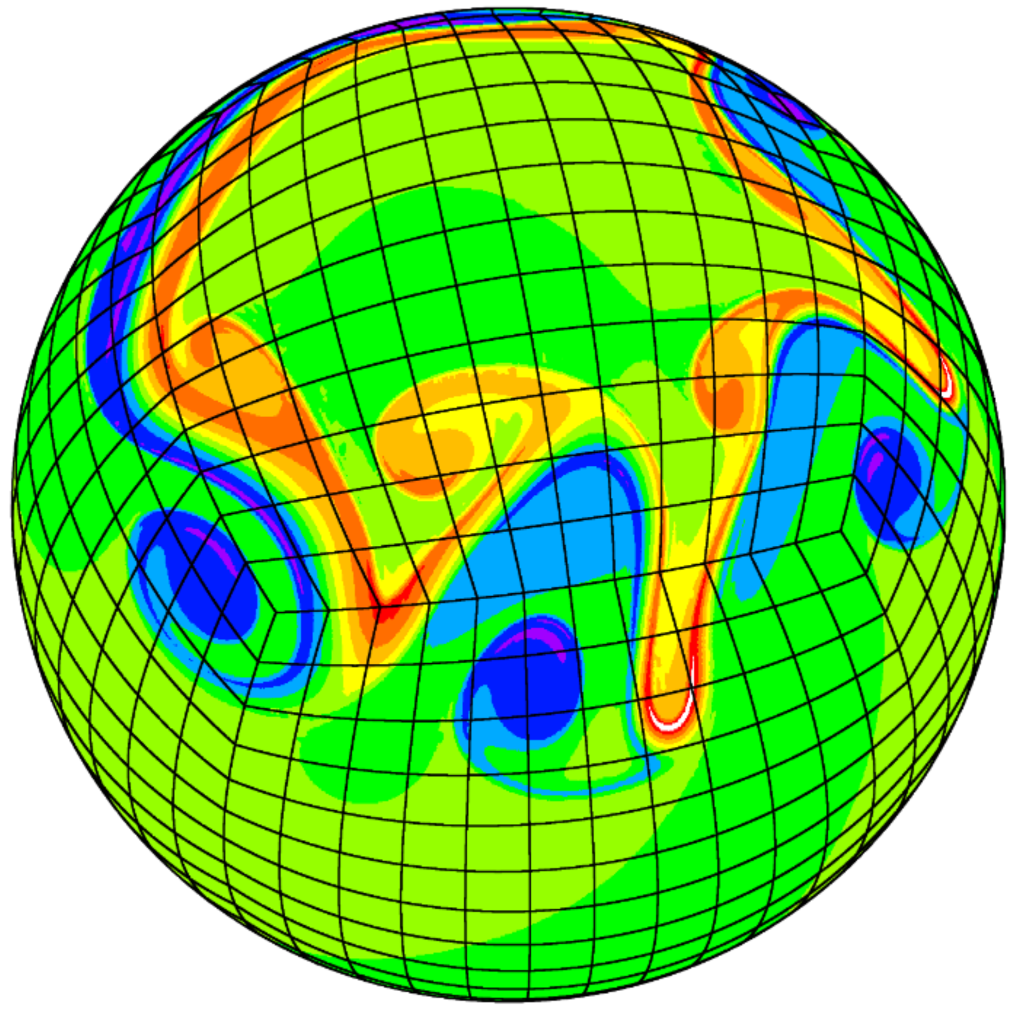
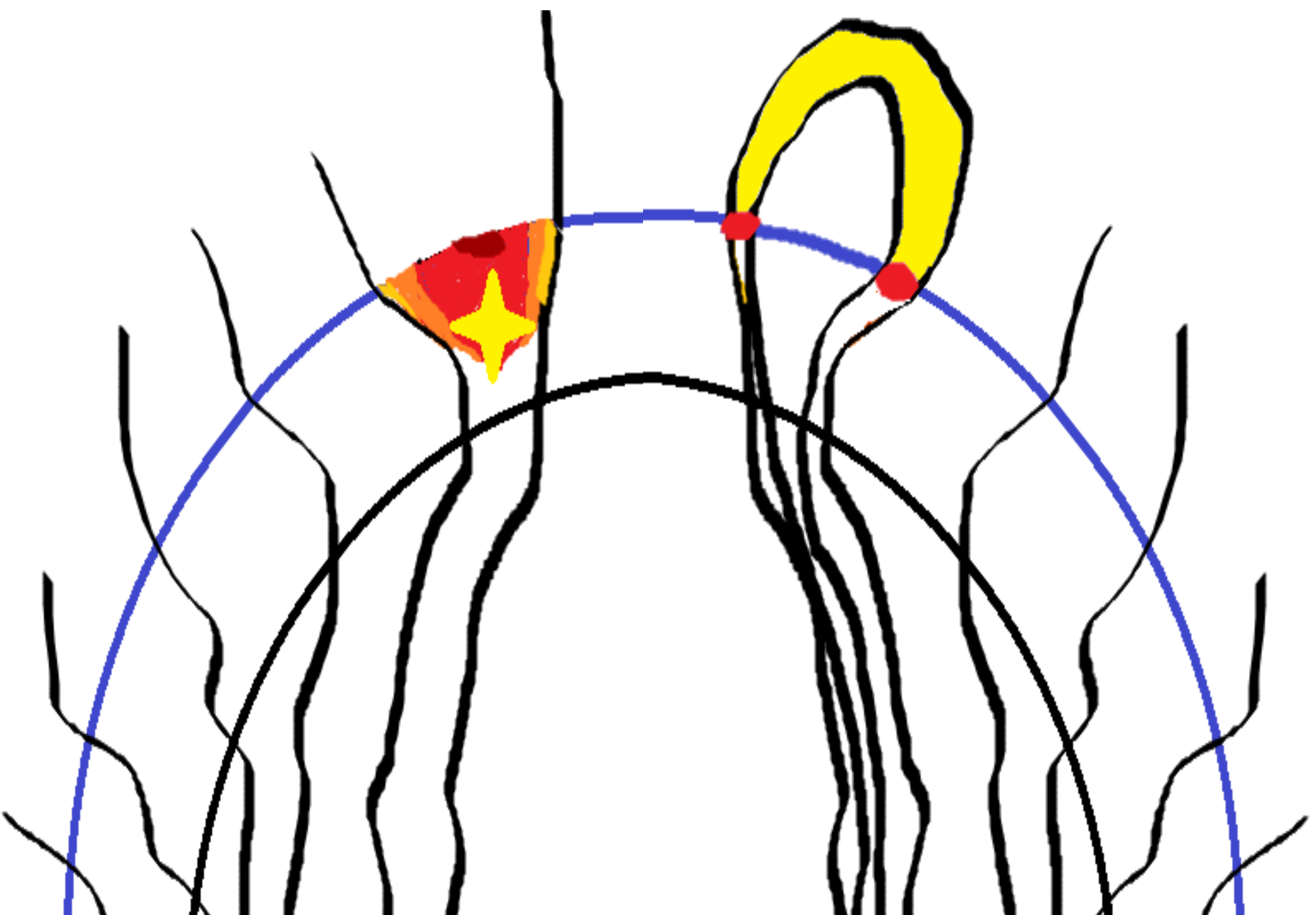


Magnetic Field

Evolution



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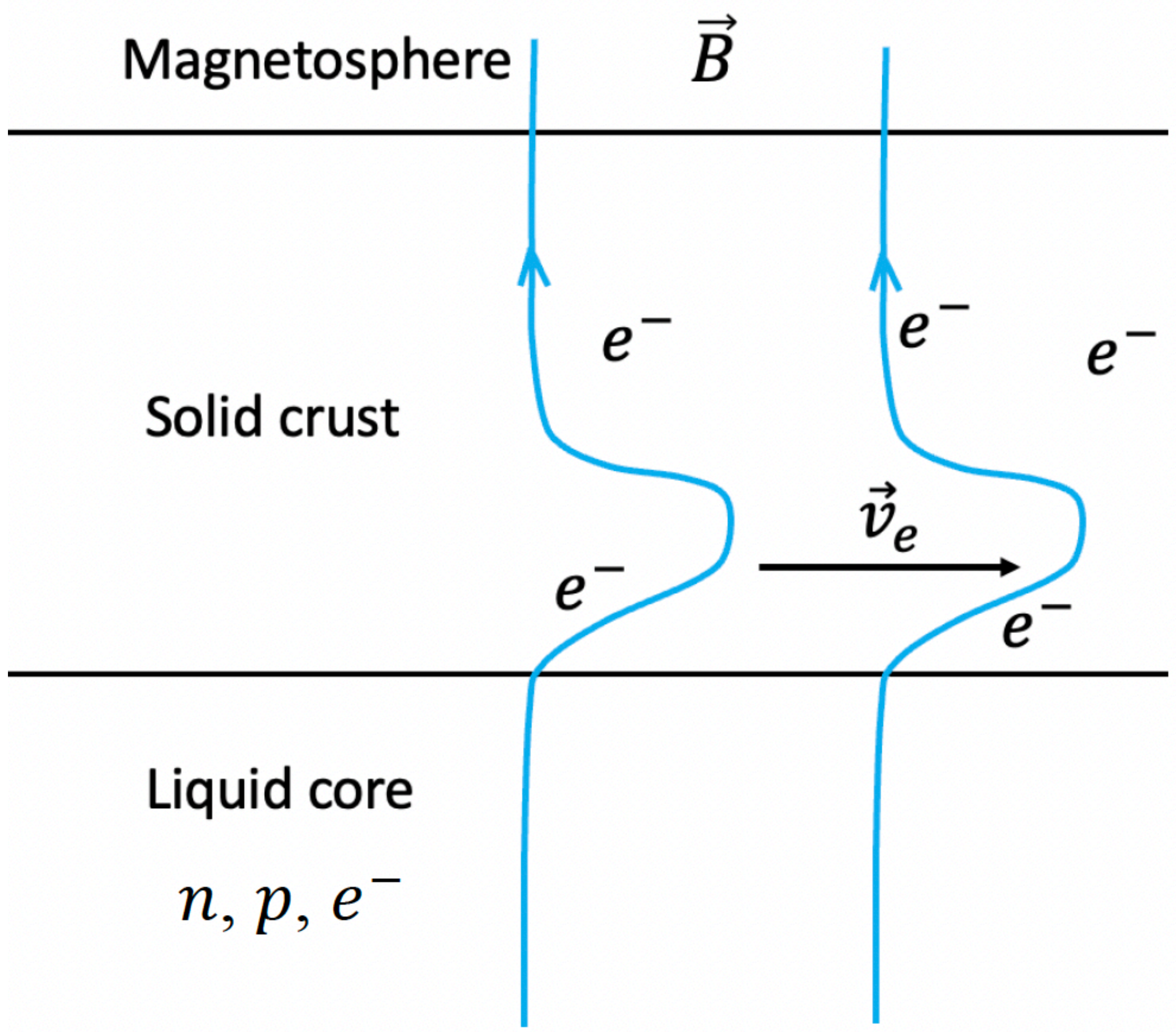
Magnetic field evolution in the crust

- **Neutron star interior:** complex multi-fluid system.
- **Crust:** solidifies early; nuclei mobility is limited; conductivity governed by electrons.
- **Core:** remains a full multi-fluid on long timescales.
- **Limit:** eMHD used in the **crust of a neutron star**



$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \left[\eta \nabla \times \boldsymbol{B} - \eta k_5 \boldsymbol{B} + f_h (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}\right]$$

$$\left(\eta = \frac{c^2}{4\pi\sigma_e}; \qquad k_5 = \frac{4\alpha\mu_5}{\hbar c}; \qquad f_h = \frac{c}{4\pi e n_e}\right)$$

Ohmic term $\propto \left(\eta \nabla \times \boldsymbol{B}\right)$**:** the magnetic diffusivity is sensitive to temperature evolution and electron density (strong radial gradients).

Chiral term $\propto \left(\eta k_5 \boldsymbol{B}\right)$**:** It redistributes magnetic energy among different magnetic spatial scales.

Hall term $\propto \left(f_h (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}\right)$**:** It naturally creates magnetic discontinuity and transfers energy between different scales.

$$k_5 = \frac{(\nabla \times \boldsymbol{B}) \cdot \boldsymbol{B}}{\frac{\mu_e^2}{8\pi\alpha^2 \eta (\hbar c)} \Gamma_f + B^2} = \frac{(\nabla \times \boldsymbol{B}) \cdot \boldsymbol{B}}{\left(\frac{2\mu_e^2}{m_e^2 c^4}\right) \frac{B_{\rm QED}^2}{3\pi} + B^2}$$

Perfect conductor B.C. at the crust-core interface (Meissner/type-I) and potential B.C. at the surface.

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[Pons, Dehman, Viganò 2026, Living Review] *[Dehman & Pons 2025, PRR]*

MATINS the brand new 3D code

— Open Access: https://github.com/ice-csic-astroexotic/MATINS —

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \left[\eta \nabla \times (e^{\nu}\boldsymbol{B}) - \eta k_5 \boldsymbol{B} + f_h \nabla \times (e^{\nu}\boldsymbol{B}) \times \boldsymbol{B}\right] \qquad c_V(T)\frac{\partial\left(Te^{\nu}\right)}{\partial t} = \vec{\nabla}\cdot(e^{\nu}\hat{\kappa}\cdot\vec{\nabla}(e^{\nu}T)) + e^{2\nu}(Q_J - Q_{\nu})$$

Dehman**, Viganò, Pons & Rea 2023, MNRAS* (DOI: **10.1093/mnras/stac2761**): ***Cubed-sphere grid + Magnetic formalism

Dehman**, Viganò, Ascenzi, Pons & Rea 2023, MNRAS* (DOI: ***10.1093/mnras/stad1773): **First *3D magneto-thermal simulation***

*Ascenzi, Viganò, **Dehman**, Pons & Rea, Perna 2024, MNRAS* (DOI: ***10.1093/mnras/stae1749***): ***Thermal formalism***

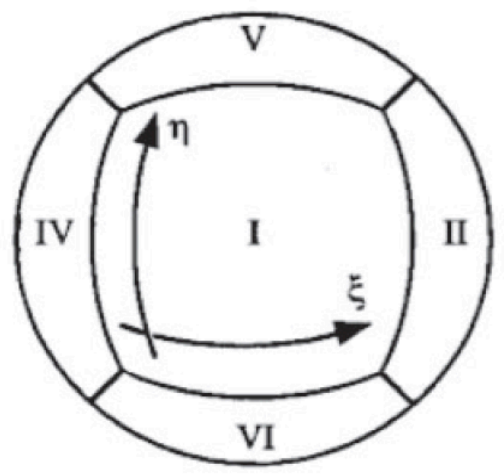
Dehman** & Pons 2025, PRR* (DOI: ***10.1103/rhv5-nd4v): ***Chiral magnetic effect***

What's better than 2D (Viganò et al. 2021):

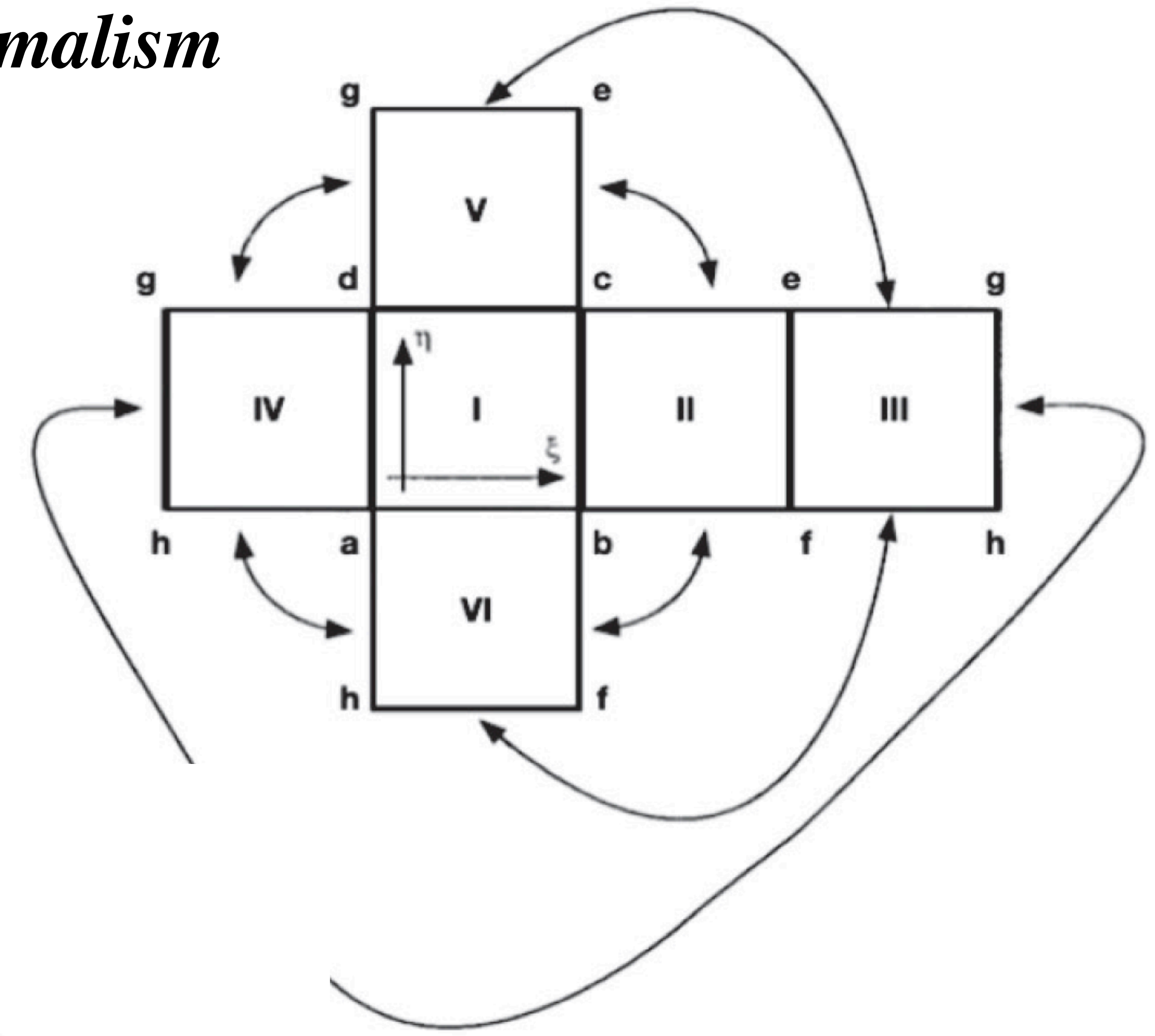
- Simulation of 3D magnetic modes, hotspots, and light curves
- Better documentation, **use of novel coordinates (cubed-sphere)**
- Optimization and use of OpenMP

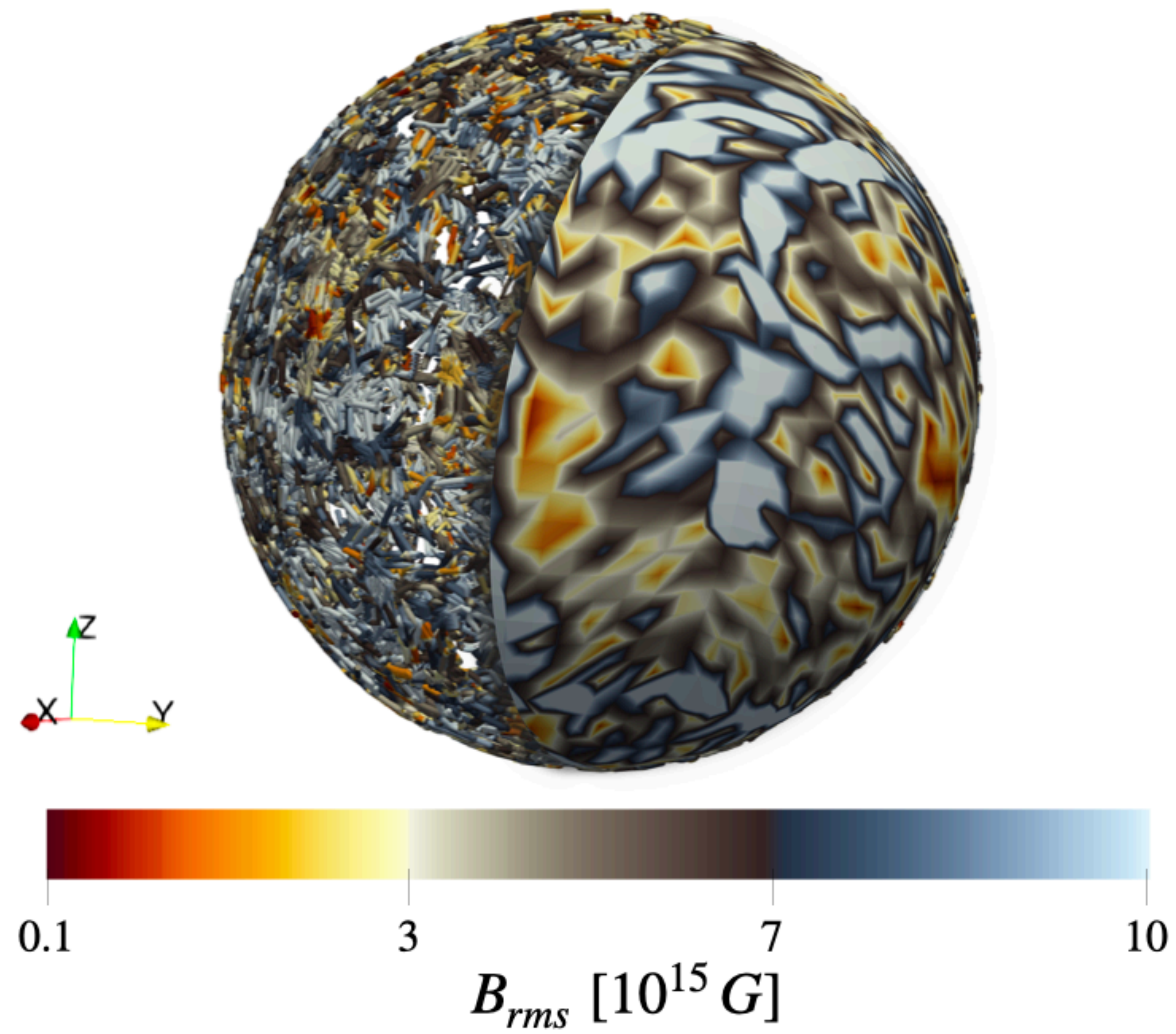
Advance obtained:

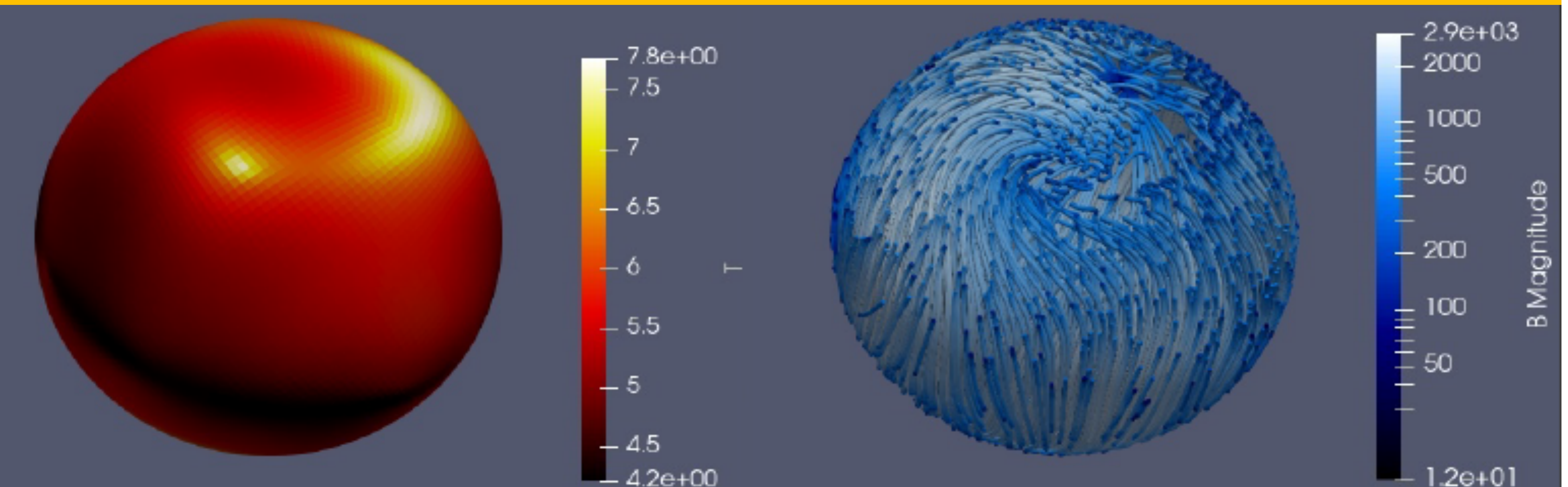
- **Realistic 3D evolution and topology, appearance of hotspots**
- **State-of-the-art microphysics, various masses and EOSs, with realistic structure obtained by solving the TOV equation.**
- **Numerical scheme to better capture non-linear dynamics**
- **General relativistic correction**
- **State of art envelope model**
- **Flexibility in implementing new physics**



cubed sphere







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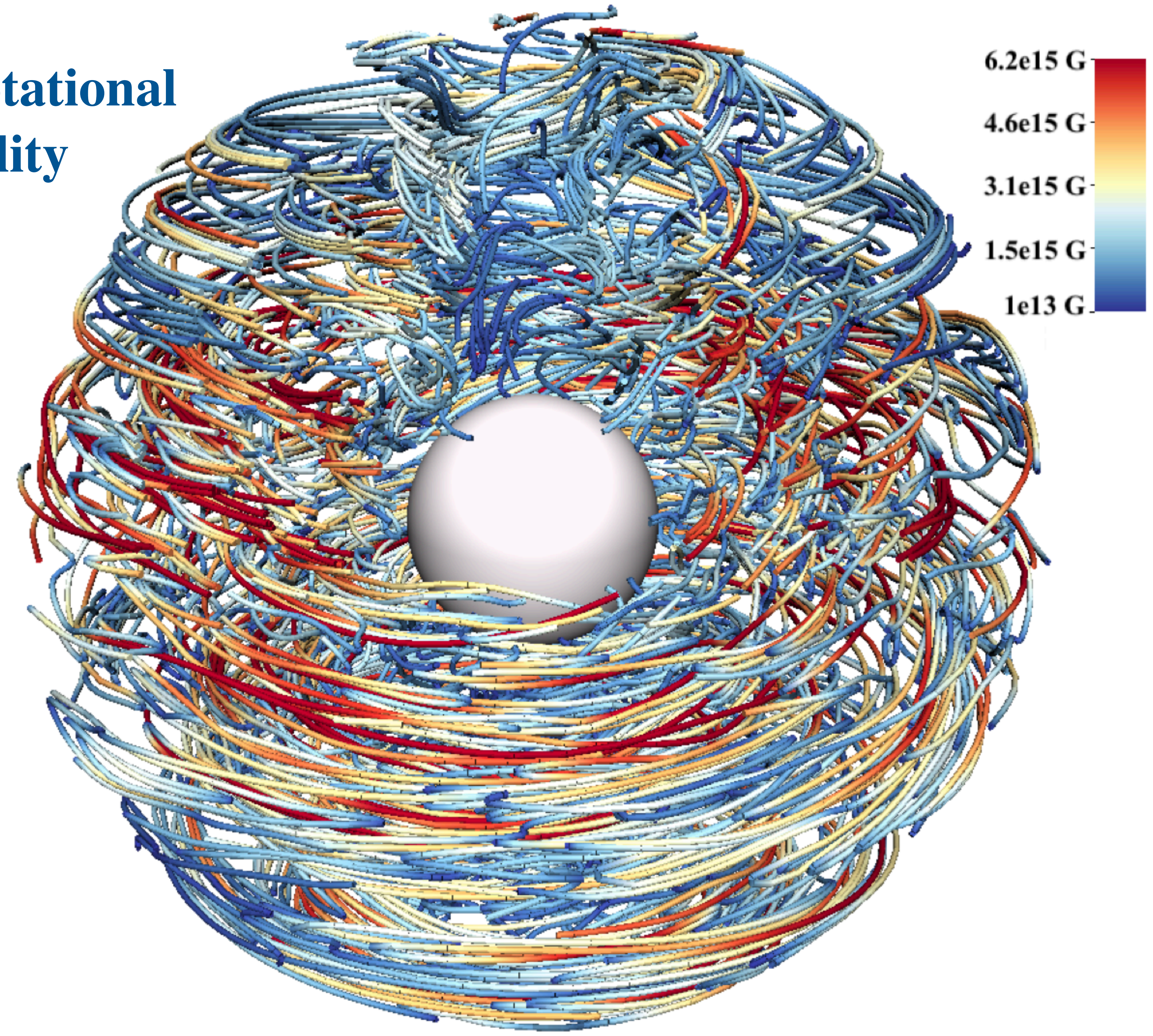
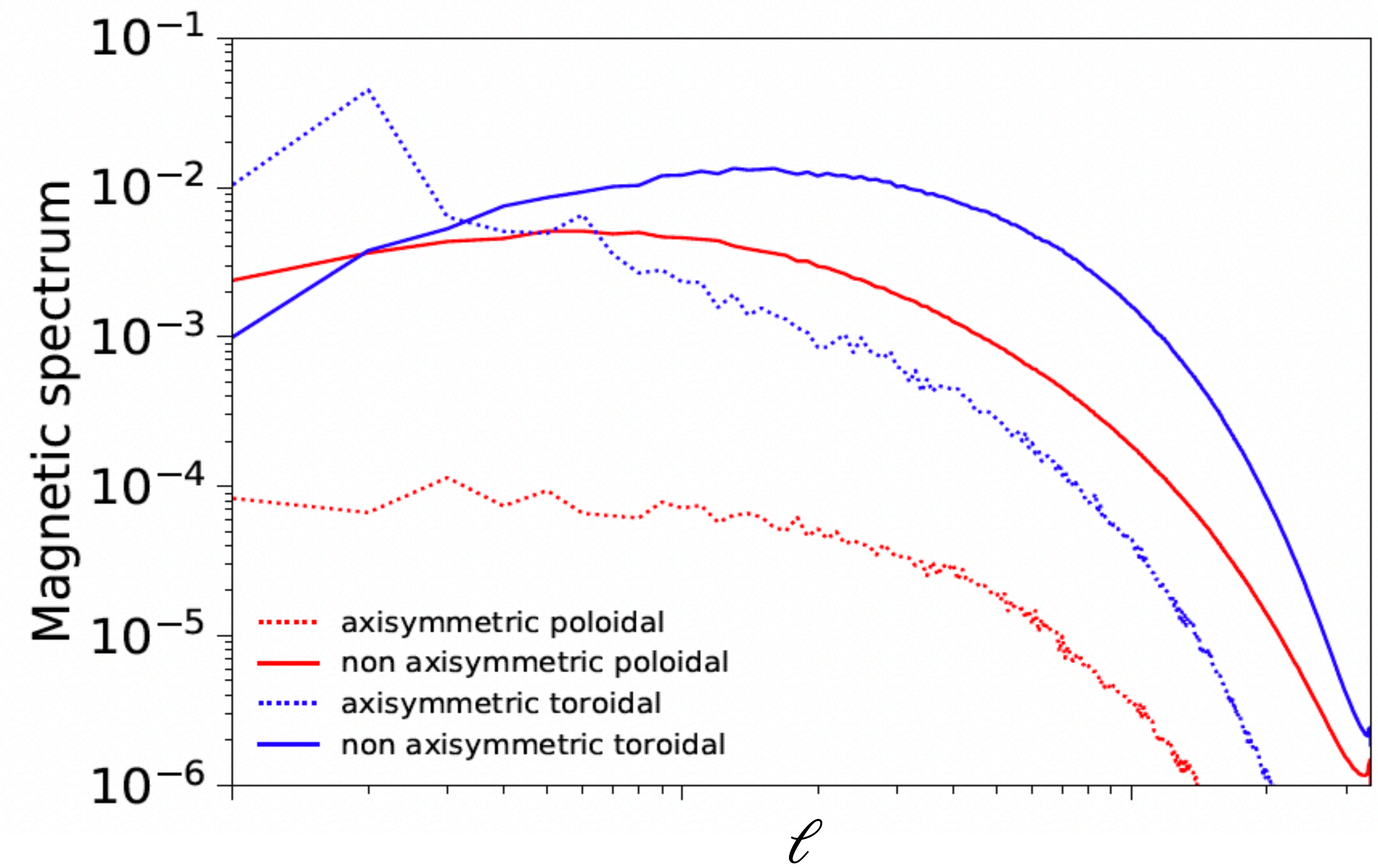
Magnetic field at birth: Magnetic spectrum after core-collapse

Magneto-rotational instability





Magnetic energy is distributed across a broad range of scales.

Toroidal axisymmetric quadrupole and non-axisymmetric components dominate.

Dipolar field accounts for less than 5% of the total magnetic energy ($\approx 10^{12}$ G).

From post-collapse to neutron star phase, plenty of MHD timescales to approach an equilibrium, with dynamo still going on and at the same time dissipating the smallest scales.

But how does a strong dipole of 10^{14} G form in magnetars, leading to their long spin periods?

[Reboul-Salze et al. 2022]
[Dehman et al. 2023c]
} **Magneto-rotational instability**

[Barrère et al. 2025]
[Igoshev et al. 2025]
} **Taylor-Spruit dynamo**

Candidates to explain CCOs, low field magnetars → **Weak dipolar component (order of 10^{12} G)**

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Hall-driven inverse cascade in neutron star crusts

Initial field:

Helical magnetic field.
Random initial field peaking at $\ell_0 \sim 100$.
Causal spectrum as used in the cosmological context.
Correct aspect ratio of the NS crust.

Inverse Cascade occurs!

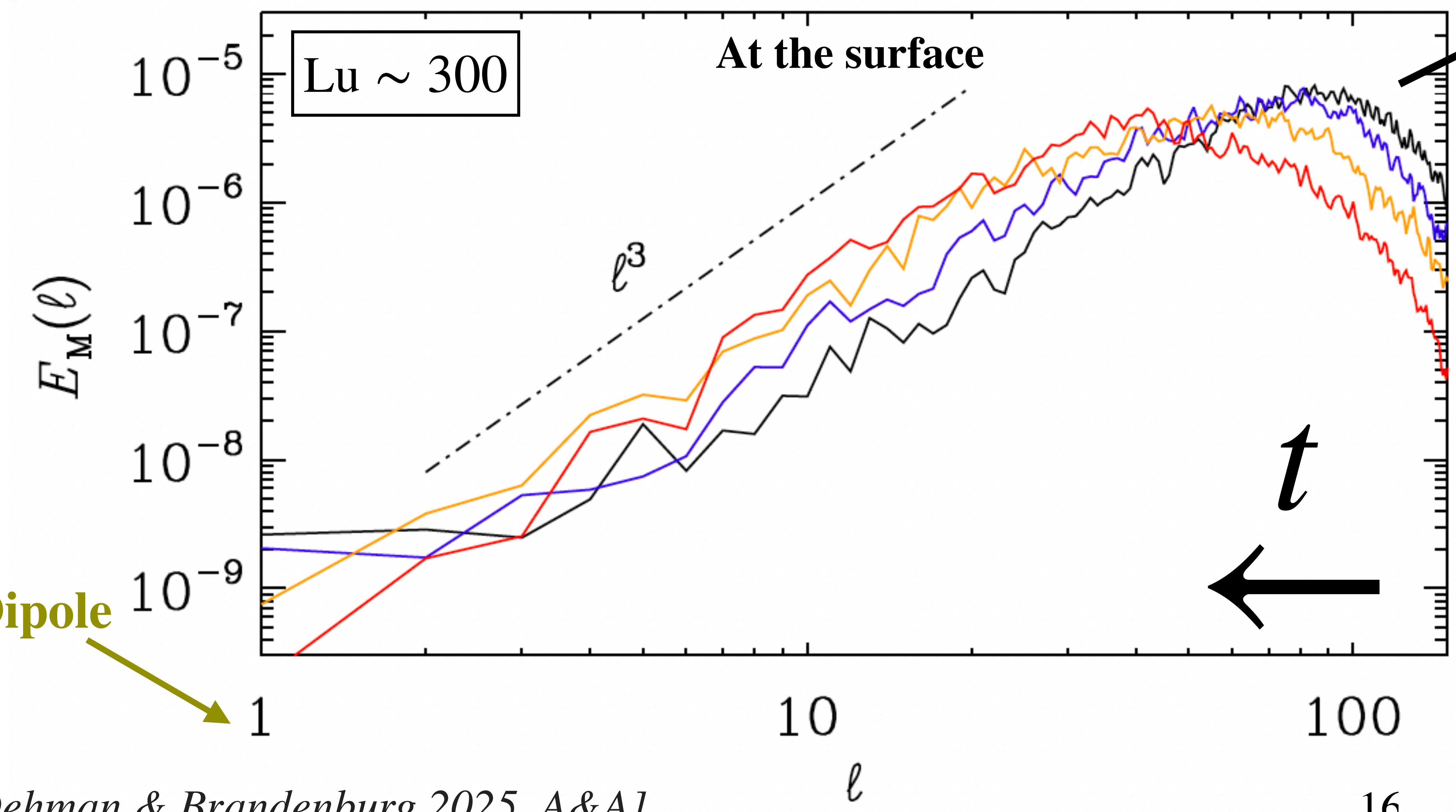
Energy transferred from small to large-scale multipoles.
Not observed in previous neutron star simulation studies.
Extreme aspect ratio (1:30)—thin crust— limits the inverse cascade.

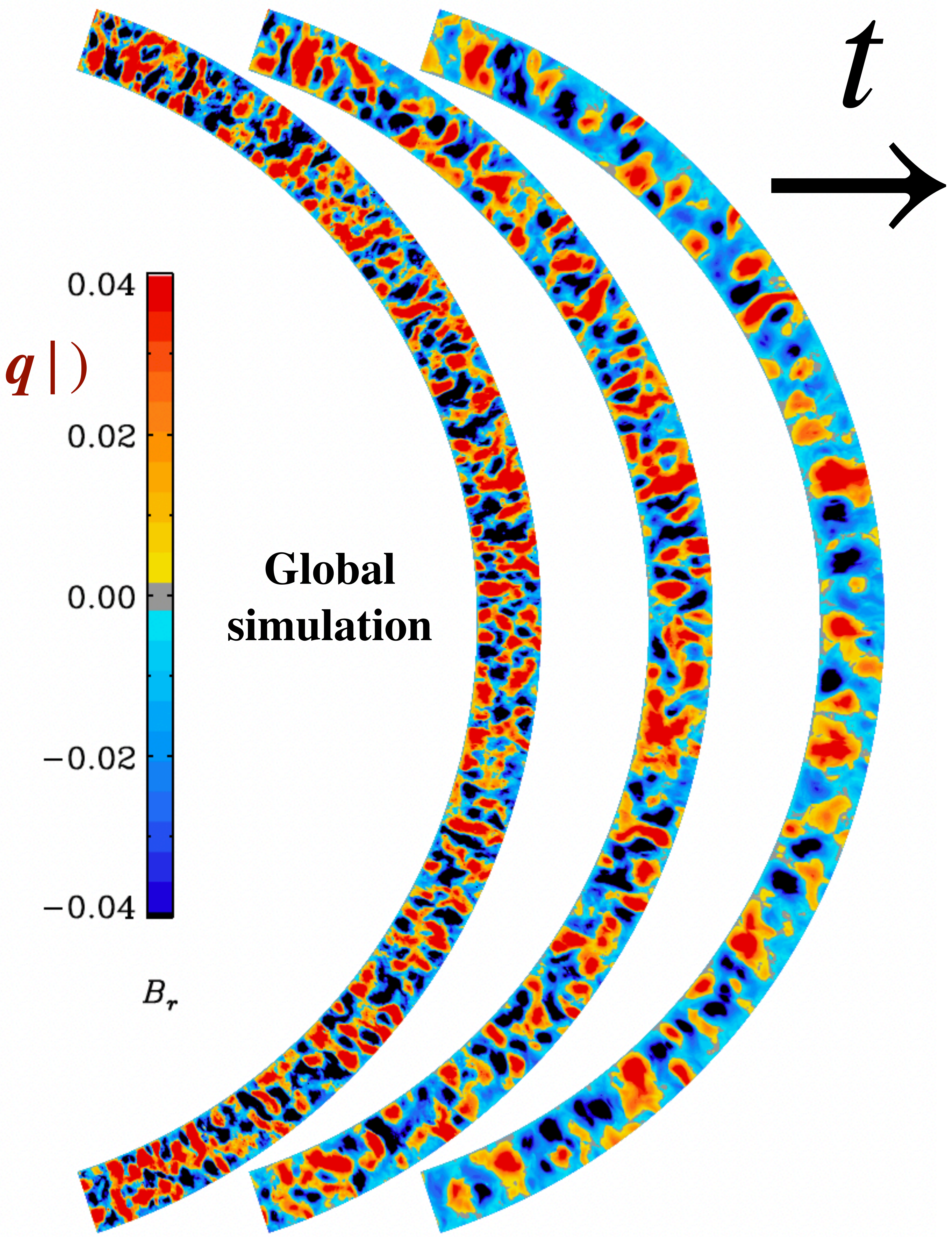
Maximally helical (e.g., positive helicity):

$$\boldsymbol{k} = \boldsymbol{p} + \boldsymbol{q}$$

$k|H_M(k)|/2E_M(k) \leq 1$
$H_M = 2E_M(k)/k$

$$|\boldsymbol{k}| \leq \max\left(|\boldsymbol{p}|, |\boldsymbol{q}|\right)$$





Pencil Code

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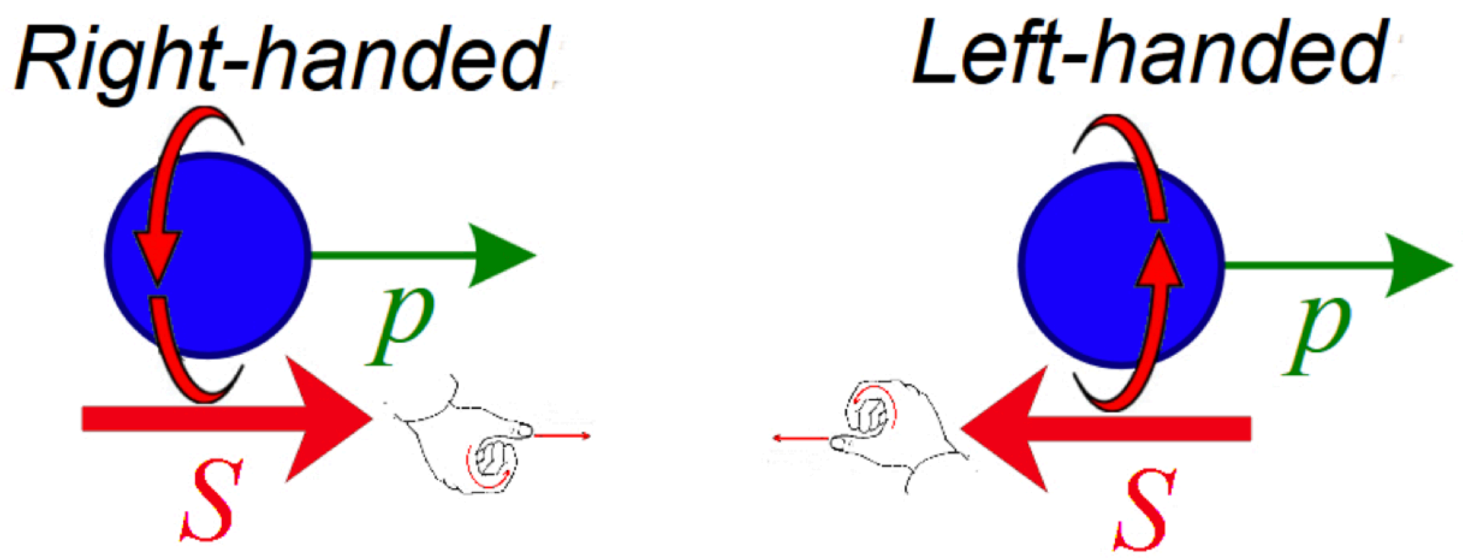
[Dehman & Brandenburg 2025, A&A]

Chiral Anomaly



A particle is moving with momentum p represented by the green arrow.

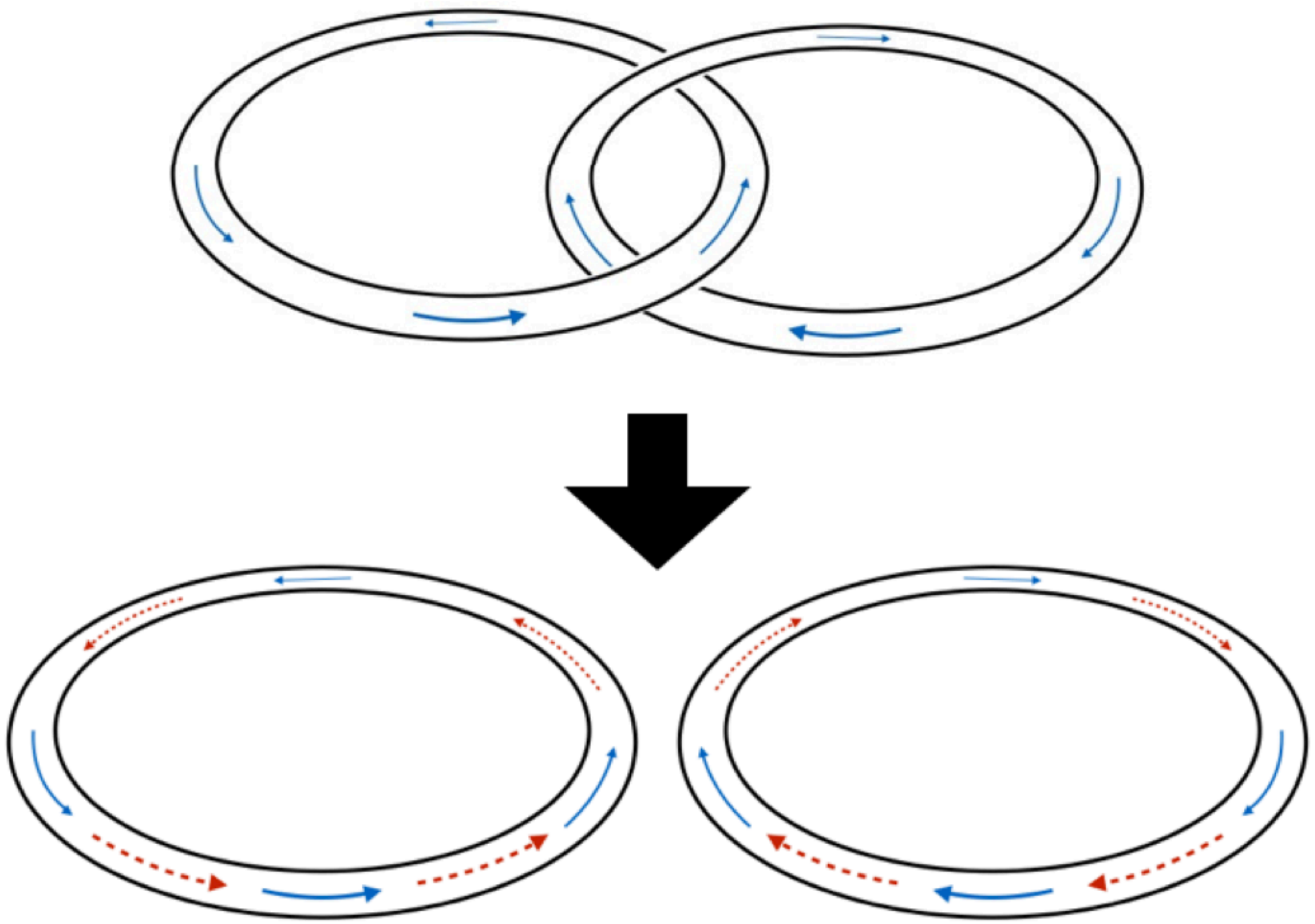


Image credit: Y. Hirono

[Boyarsky et al. 2012]

— Particle Chirality —

The chirality of a particle is the projection of the spin along the direction of movement:

- right-handed if it is parallel to the movement;
- left-handed otherwise.

— Magnetic Helicity —

- Pure poloidal & toroidal components are unstable
- Both components are necessary for the stability (linked structures)
- <u>Magnetic helicity quantify the topological stability</u>

$$\frac{\partial\left(\boldsymbol{A}\cdot\boldsymbol{B}\right)}{\partial t} = \boxed{-2c\boldsymbol{E}\cdot\boldsymbol{B}} - c\nabla\cdot\left(\boldsymbol{E}\times\boldsymbol{A}\right)$$

— Chiral Anomaly —

- Changes in magnetic helicity create or destroy chiral asymmetry (vice versa).
- Chiral electric current induced along field lines

$$\frac{\partial n_5}{\partial t} = \boxed{\frac{2\alpha}{\pi\hbar}\boldsymbol{E}\cdot\boldsymbol{B}} - n_5\Gamma_f$$

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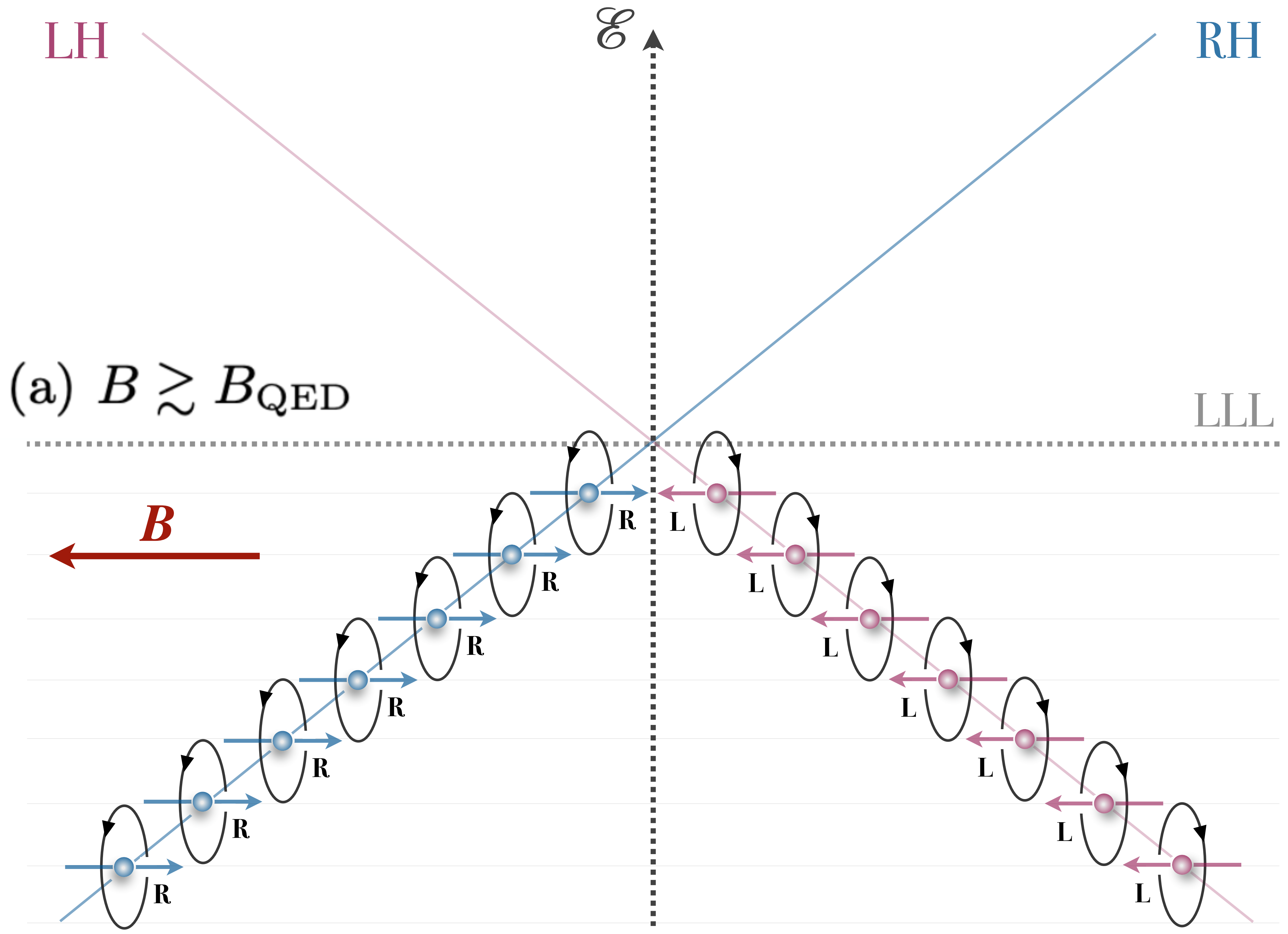

[Dehman 2026, PRD]

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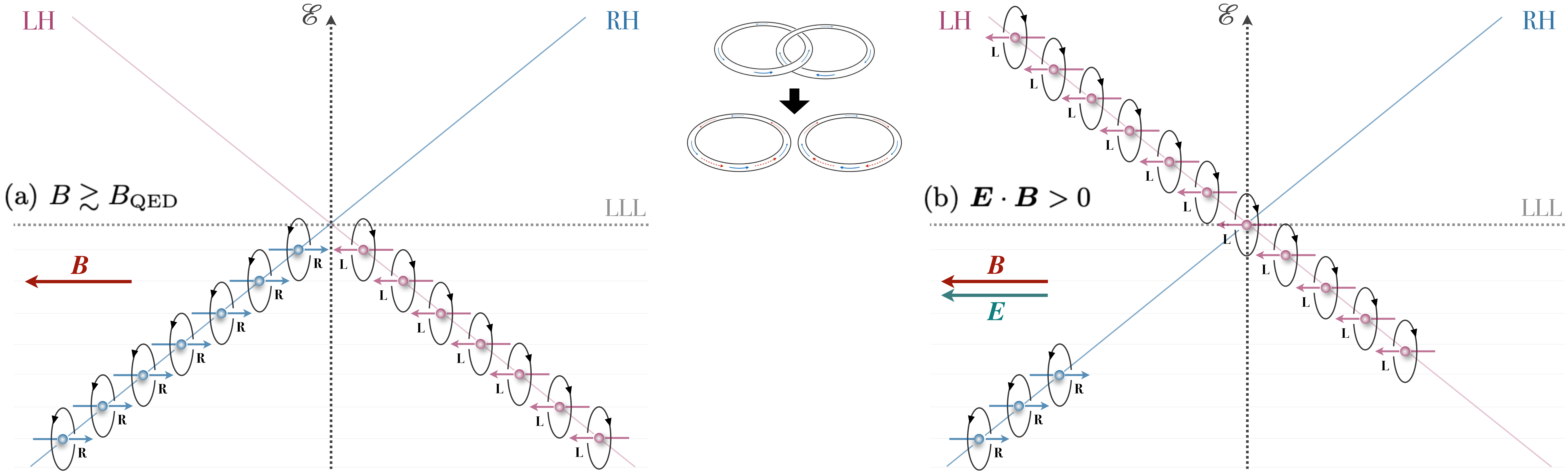

[Dehman 2026, PRD]

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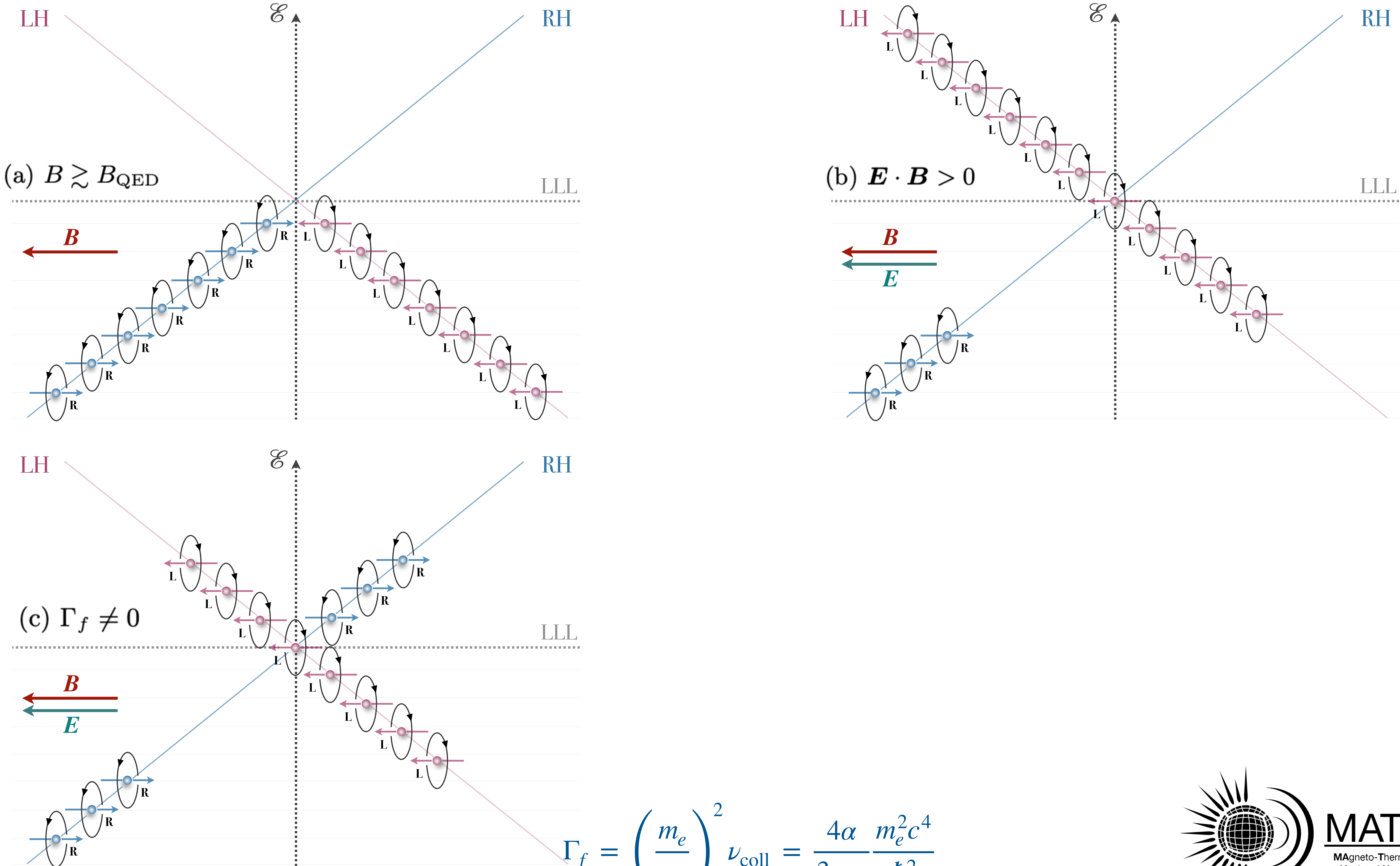
MAgneto-**T**hermal evolution of **I**solated **N**eutron **S**tars



$$\Gamma_f = \left(\frac{m_e}{\mu_e}\right)^2 \nu_{\rm coll} = \frac{4\alpha}{3\pi\sigma_e}\frac{m_e^2 c^4}{\hbar^2}$$

[Dehman 2026, PRD]

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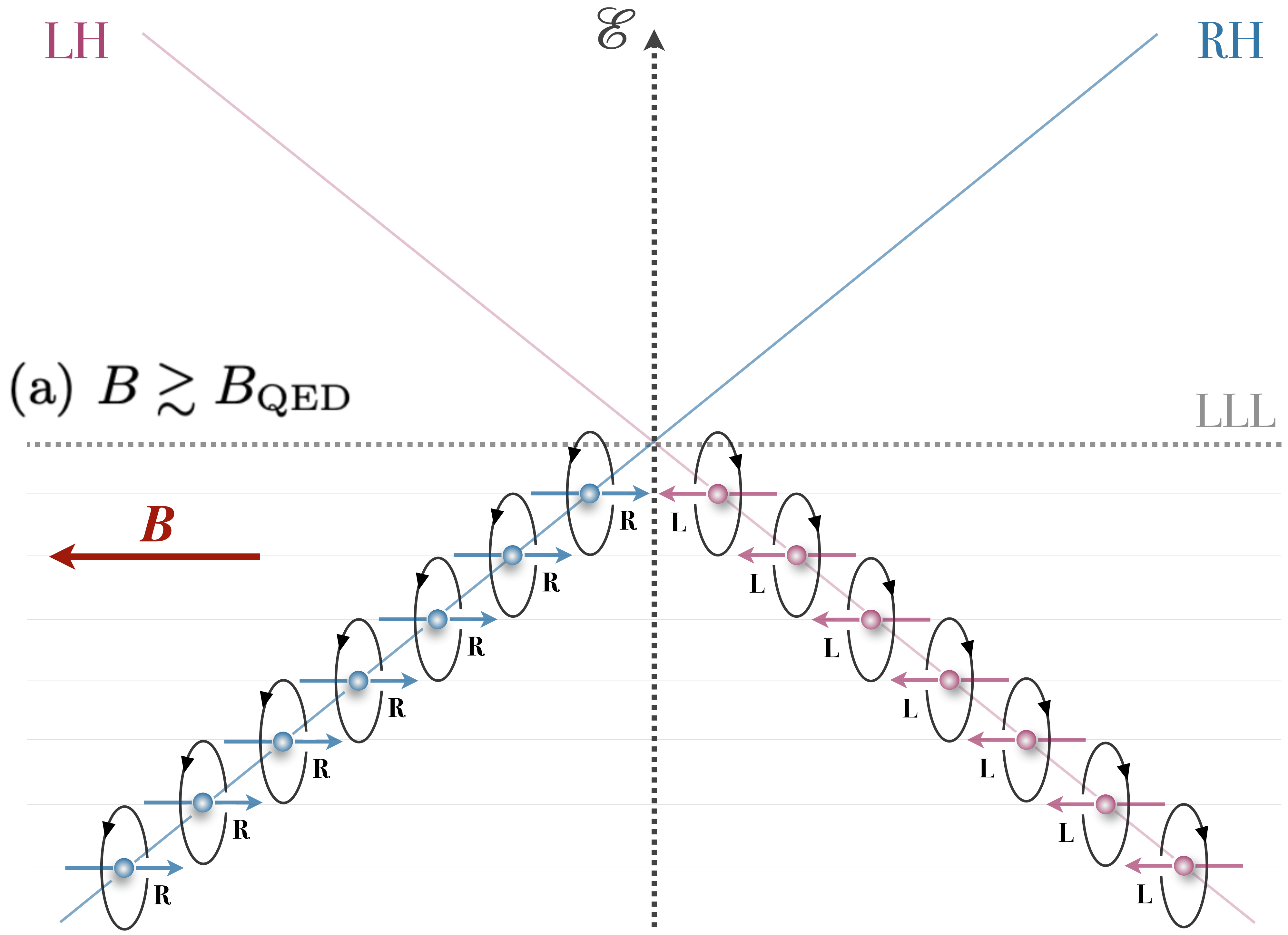
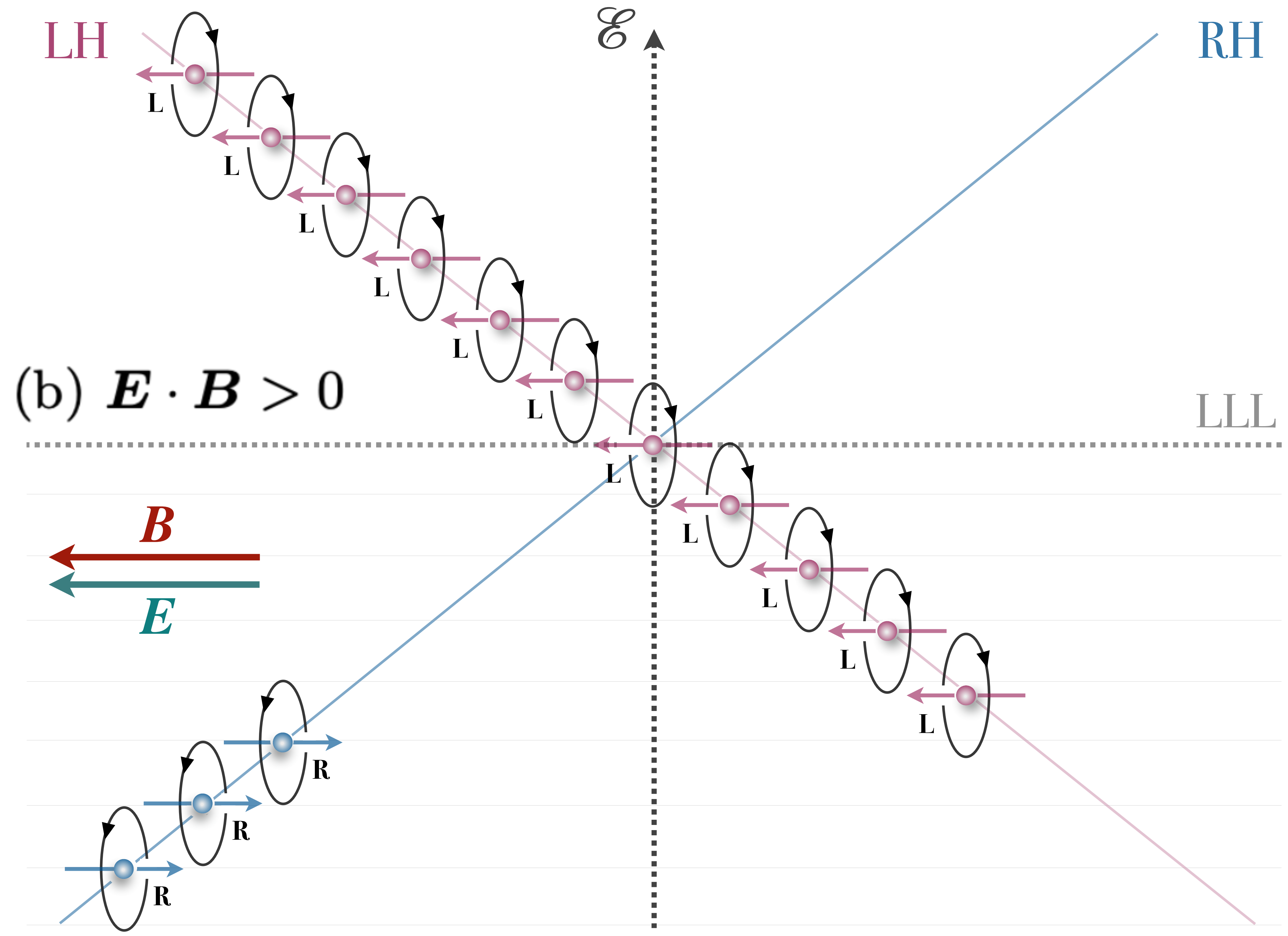
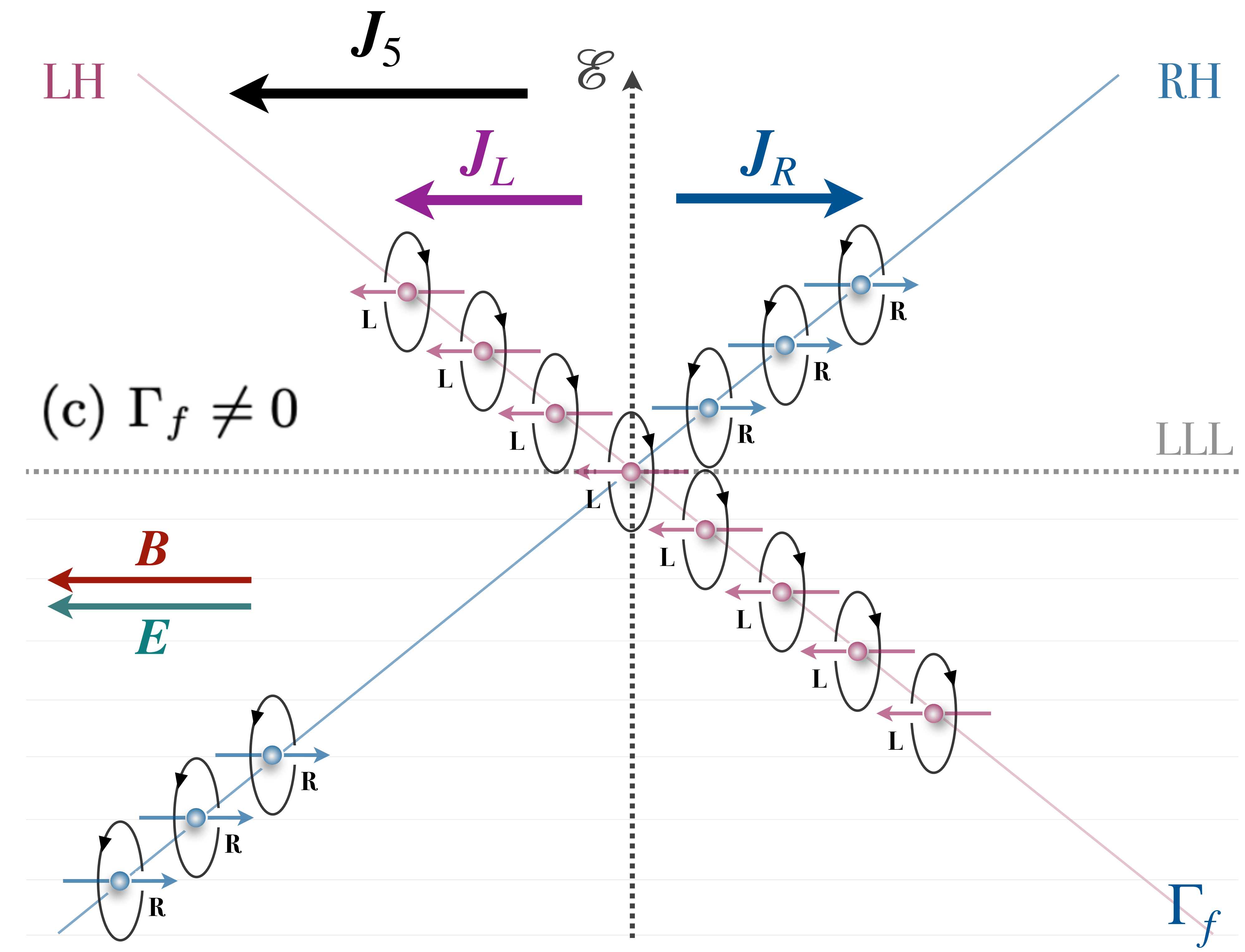




$$\boldsymbol{J}_5 = \boldsymbol{J}_R + \boldsymbol{J}_L = \frac{\alpha}{\pi\hbar}\boldsymbol{B}(\mu_R - \mu_L) = \frac{\alpha\mu_5}{\pi\hbar}\boldsymbol{B}$$

$$|\mu_5| \approx 10^{-12}\ldots10^{-11}\ \text{MeV} \ll \mu_e = 10\ldots100\ \text{MeV}$$



$$\boldsymbol{J} = \frac{c}{4\pi}(\nabla\times\boldsymbol{B}) = \sigma_e\boldsymbol{E} + \boldsymbol{J}_5$$

$$\frac{\partial\boldsymbol{B}}{\partial t} = -\nabla\times\left[\eta\nabla\times\boldsymbol{B} - \eta k_5\boldsymbol{B} + f_h(\nabla\times\boldsymbol{B})\times\boldsymbol{B}\right]$$

[Dehman & Pons 2025, PRR]

$$\Gamma_f = \left(\frac{m_e}{\mu_e}\right)^2 \nu_{\rm coll} = \frac{4\alpha}{3\pi\sigma_e}\frac{m_e^2c^4}{\hbar^2}$$

[Dehman 2026, PRD]

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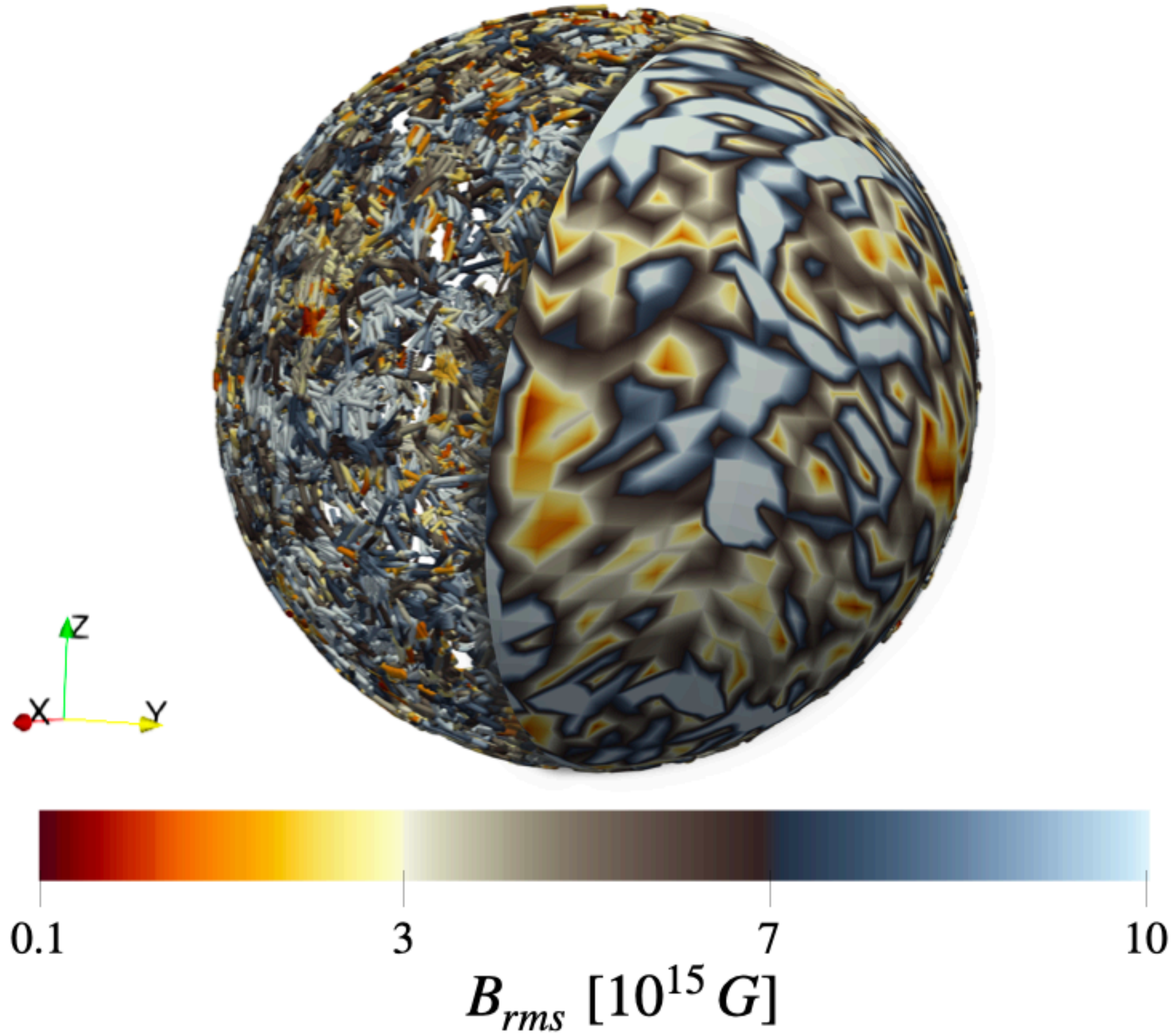
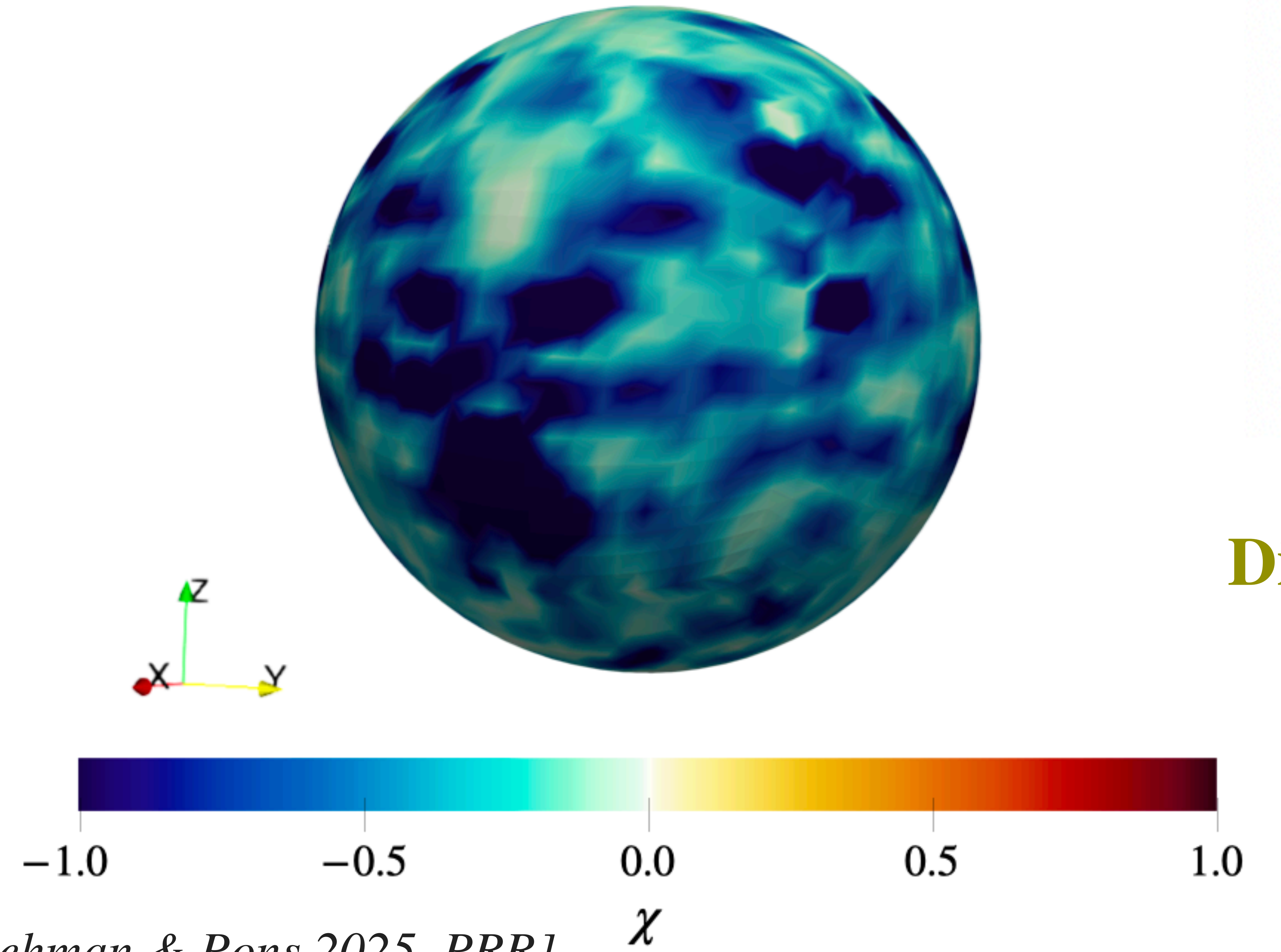
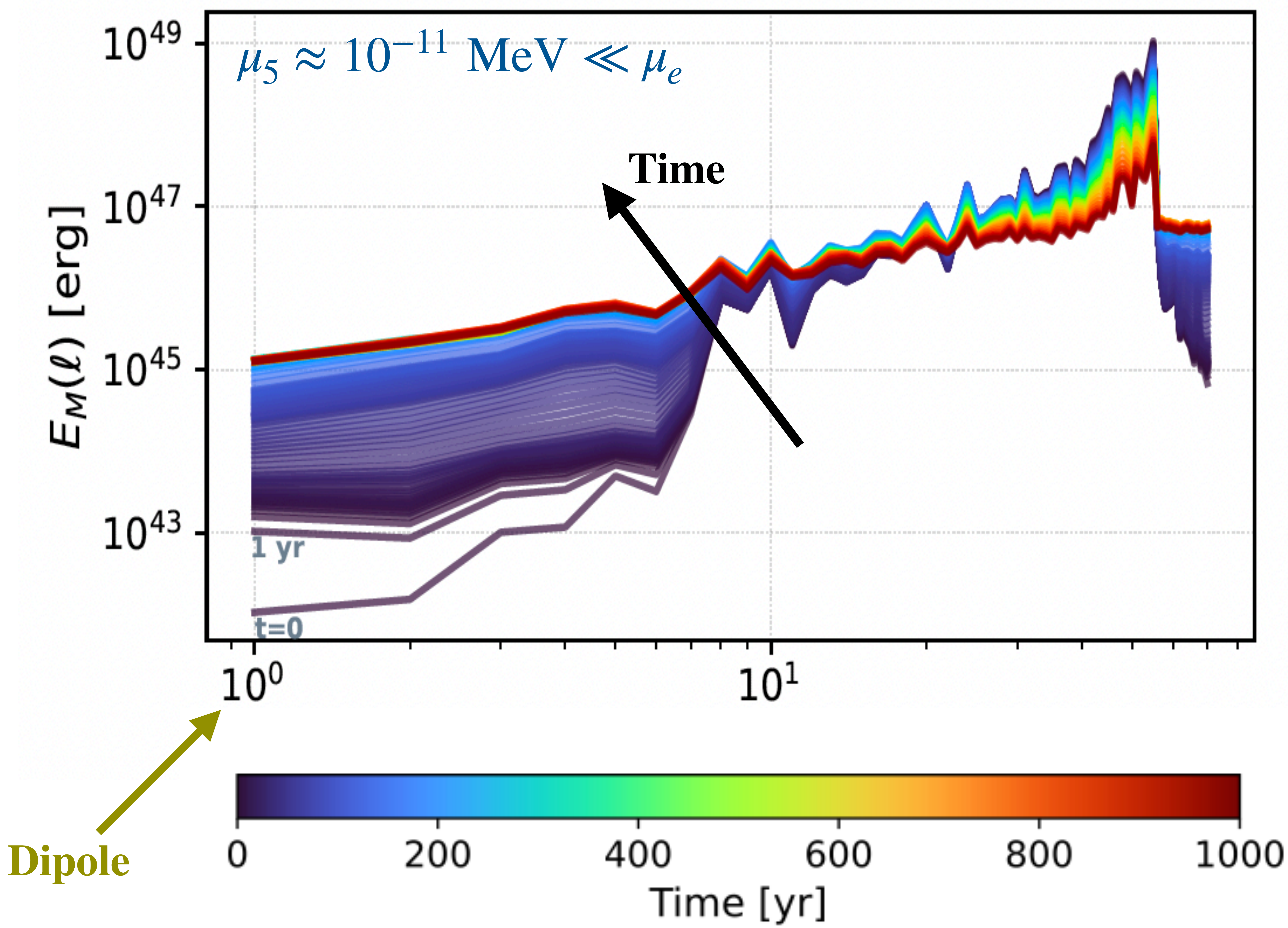
CME simulations — net magnetic helicity







[Dehman & Pons 2025, PRR]

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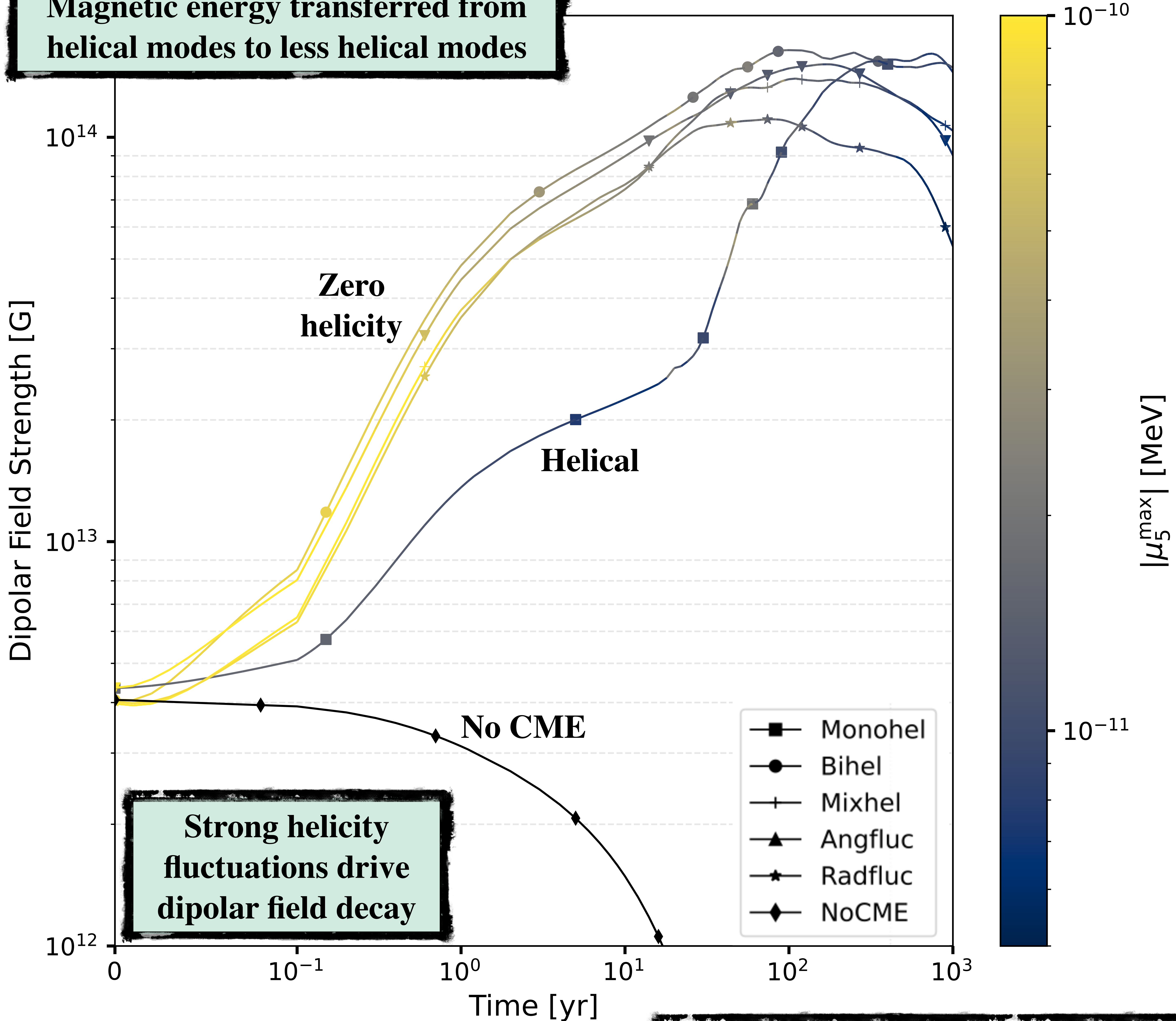
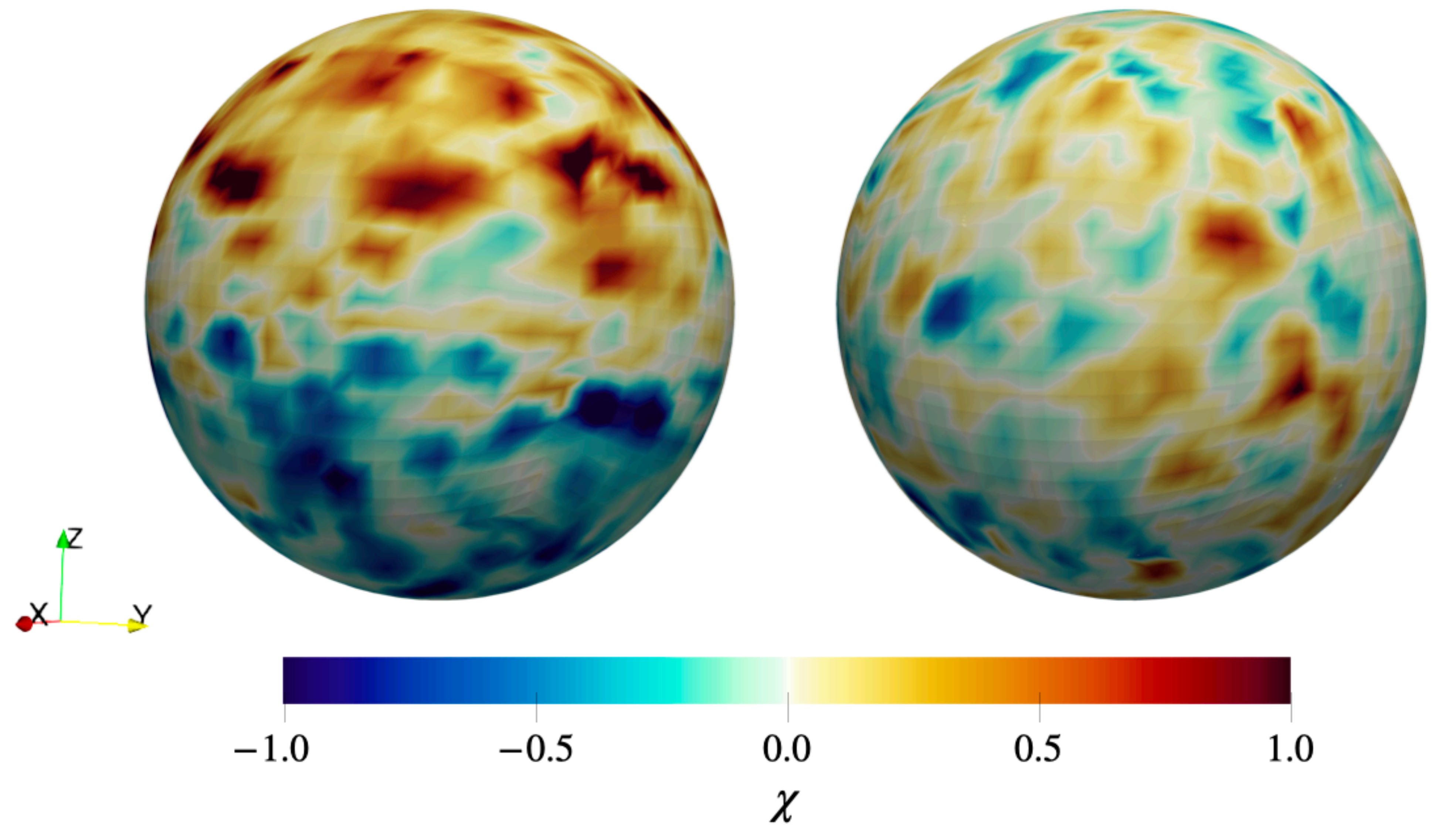
CME simulations — vanishing helicity

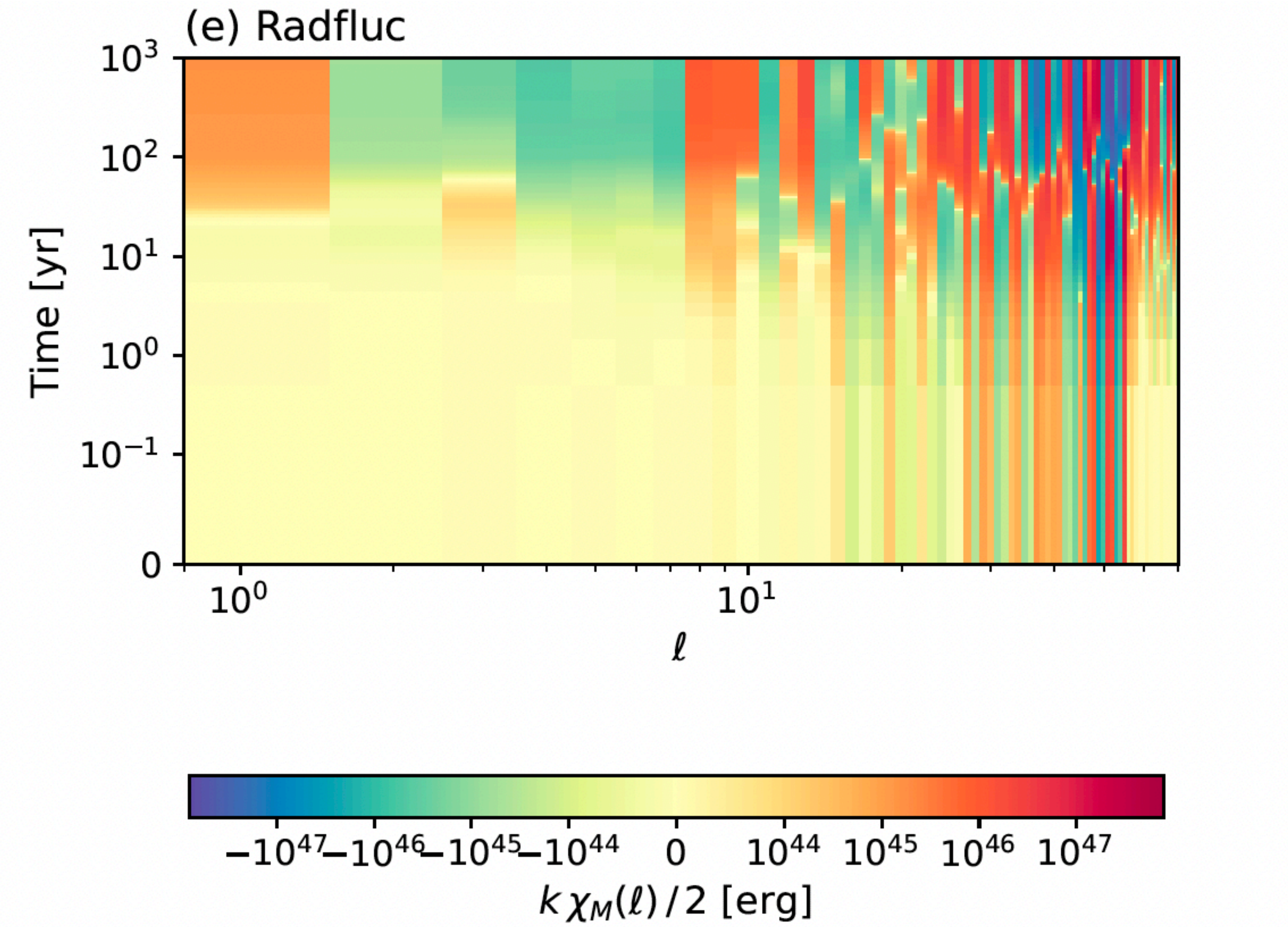
Onset of CMI is governed by $|\mu_5^{max}|$

Magnetic energy transferred from helical modes to less helical modes



Strong helicity fluctuations drive dipolar field decay





CME provides a possible explanation for magnetar formation

At birth: need initial field (small scales) + helicity distribution

[Dehman 2026, PRD]

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Summary & Conclusion:

MATINS: a new 3D code for magneto-thermal evolution of isolated neutron stars, enabling self-consistent Myr-scale evolution linking magnetic fields to X-ray emission, spin-down, and magnetar activity.

Long-term evolution (10^6 yr) with a strong magnetic field $\sim 10^{14} \ldots 10^{15}$ G.

Proper treatments of microphysics, envelope models, axial singularity, field structure, temperature, etc.

Hall cascade, Inverse Hall cascade, outburst, etc.

Neutron star cooling:

- Careful microphysics treatment, including superfluid and superconducting gap effects, is essential for neutron-star cooling models.
- Nuclear EOSs must activate enhanced cooling in order to explain the observations of faint yet young neutron stars.

Magnetic field in neutron stars and magnetars:

- Dynamo simulations in core-collapse simulations and proto-neutron stars.
- Inverse cascade in neutron star
- **Chiral anomaly at the origin of magnetars large scale magnetic field.**

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MAgneto-Thermal evolution of Isolated Neutron Stars