The physics governing magnetic field evolution in magnetars

MATINS
MAgneto-Thermal evolution of Isolated Neutron Stars

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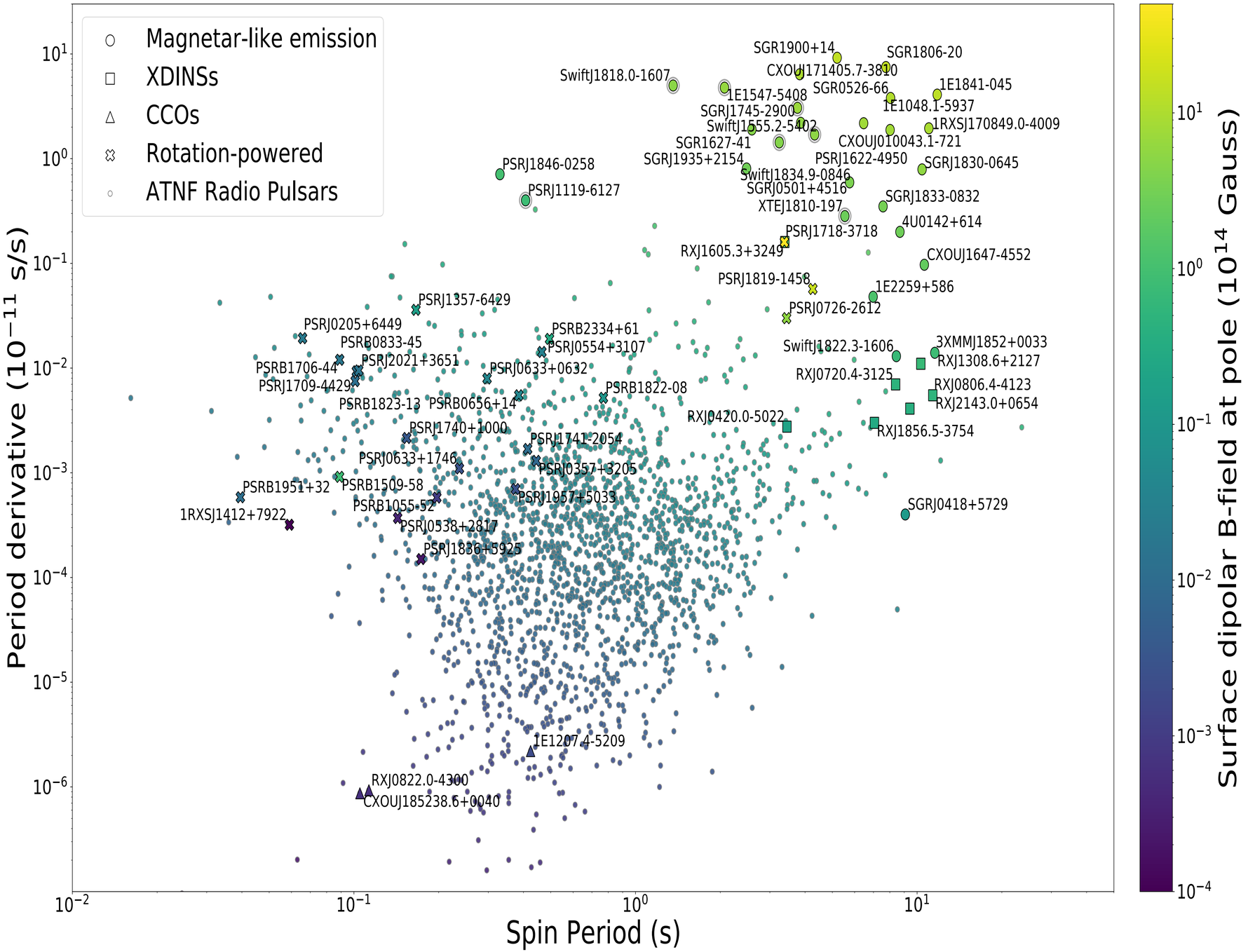
P-Pdot diagram for isolated neutron stars



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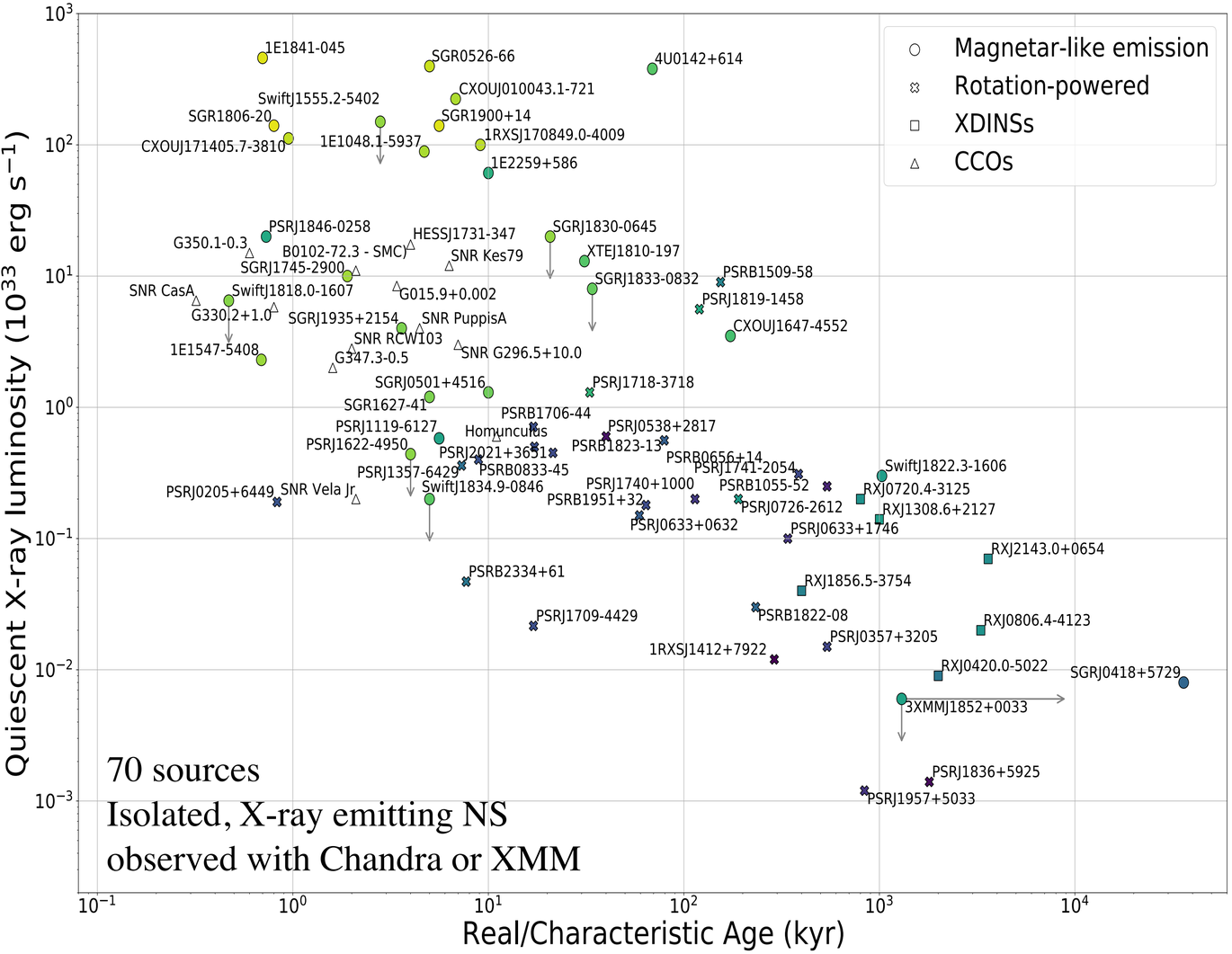
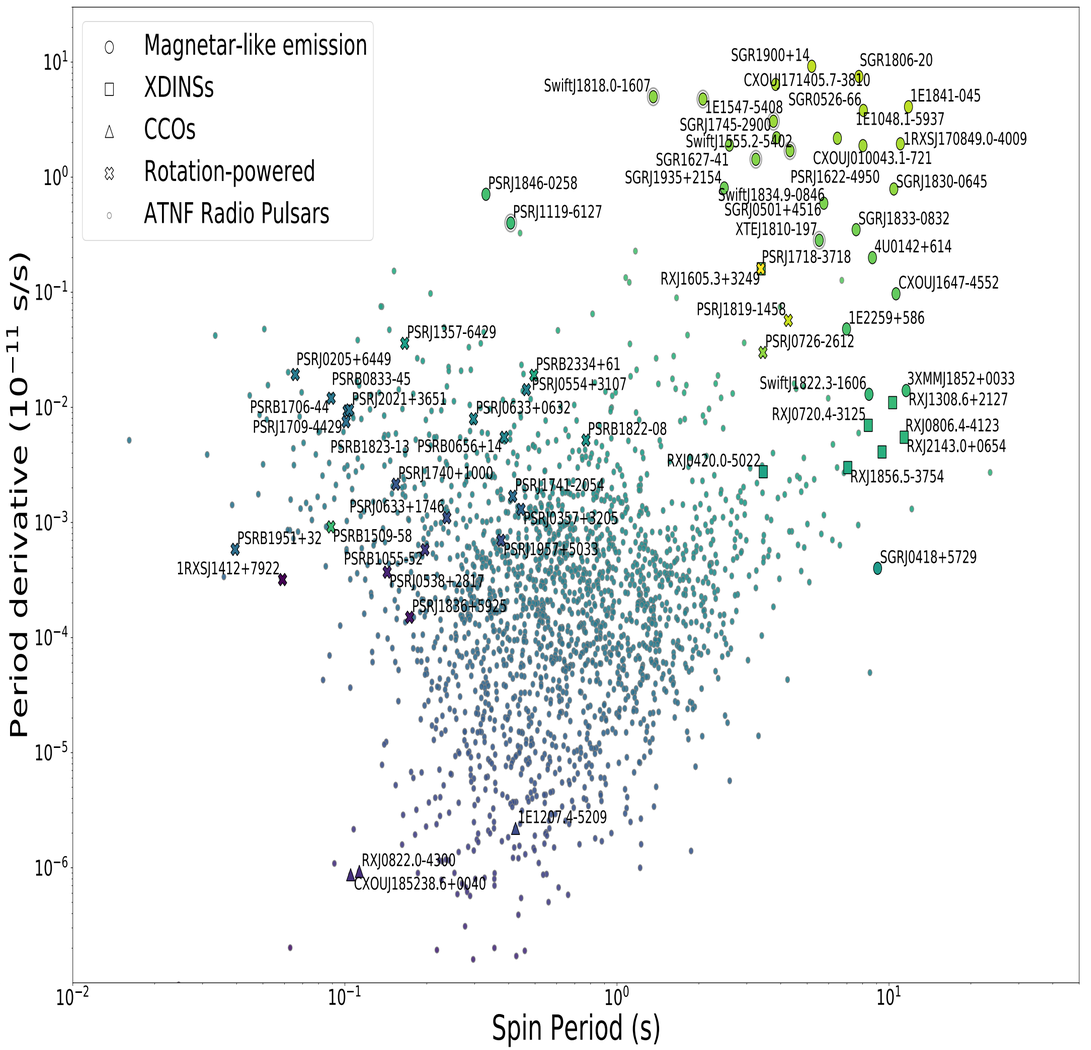
Observations: thermal X-ray luminosity, real age, P and Pdot





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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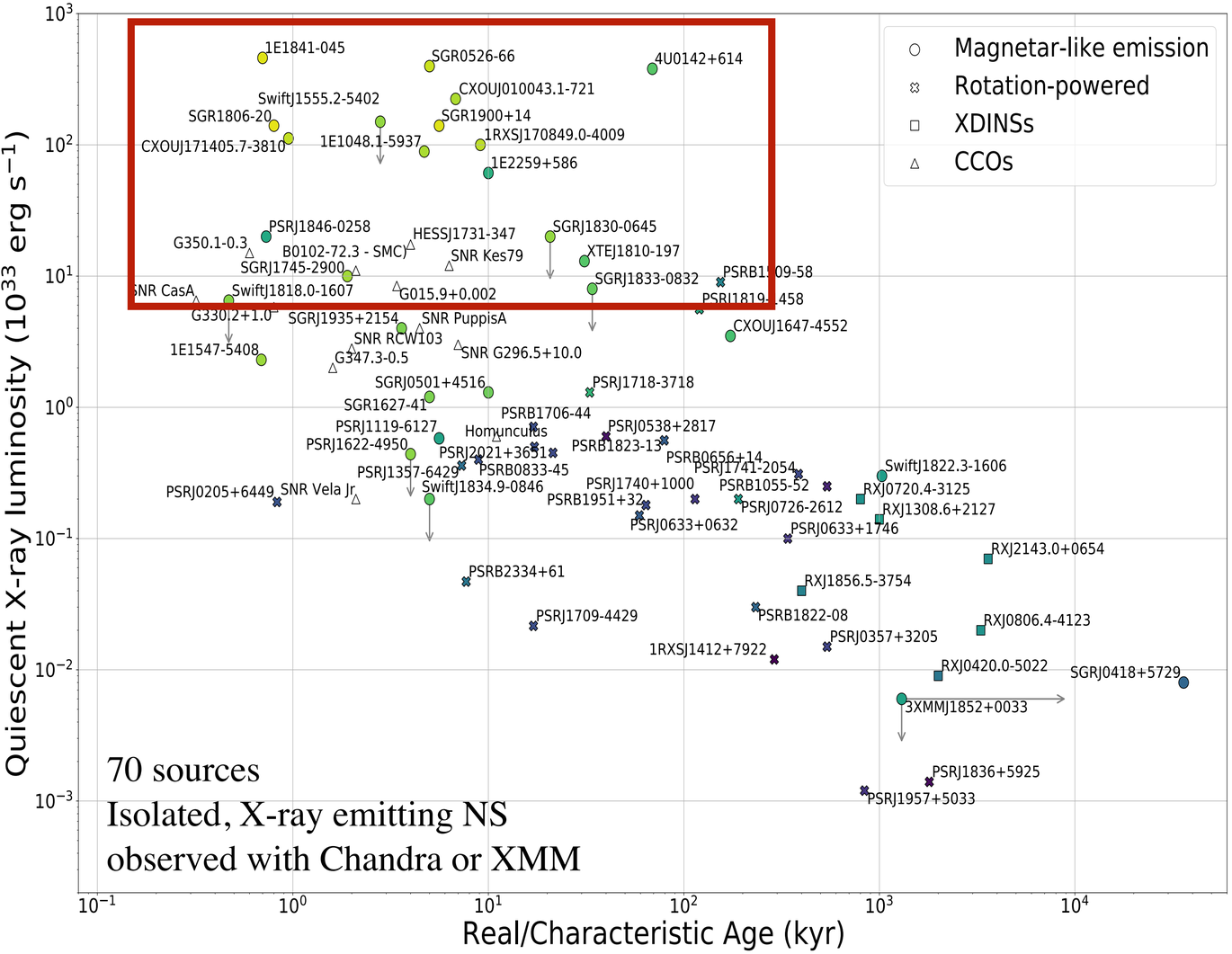
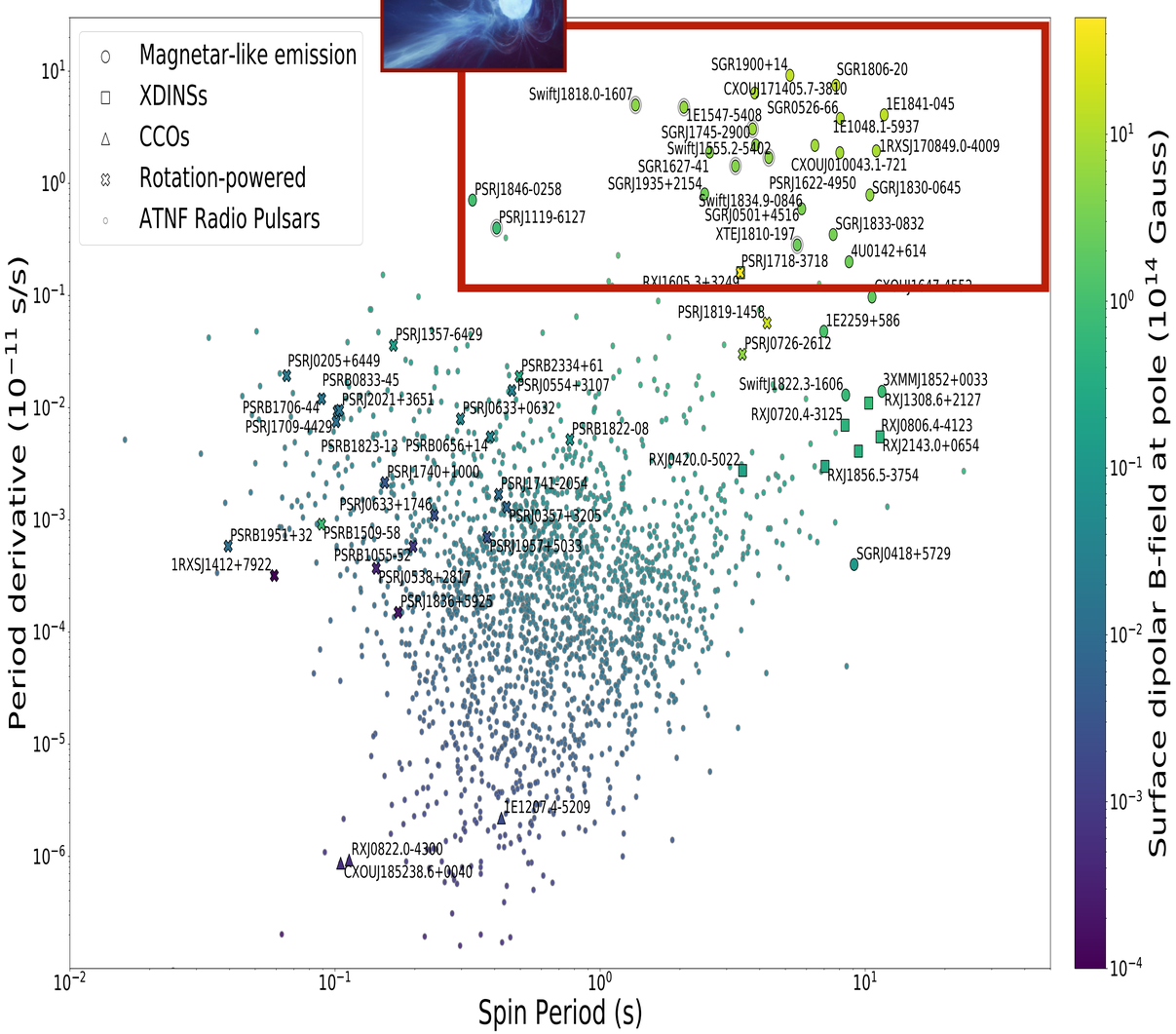
Observations: Magnetars





- Bright X-rays sources: $L_x \sim 10^{34}\ldots10^{36}$ erg/s
- Powered by magnetic field dissipation ($B_{\rm avg} \approx 10^{15}\ldots10^{16}$ G)
- Young objects ($t \lesssim 10$ kyr).
- Characterised by outbursts and flares
- Slow rotator ($P \sim 1\ldots12$ s).

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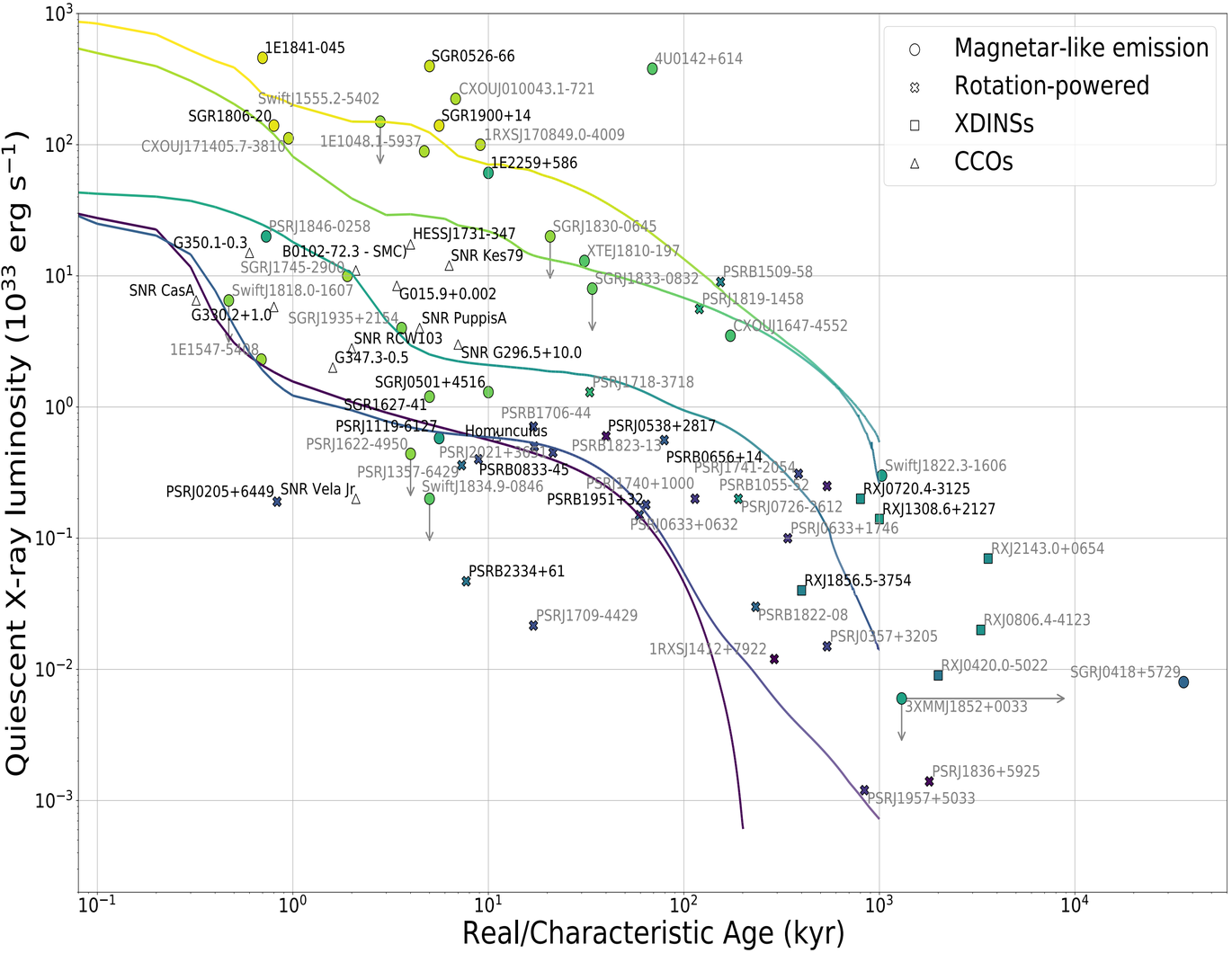
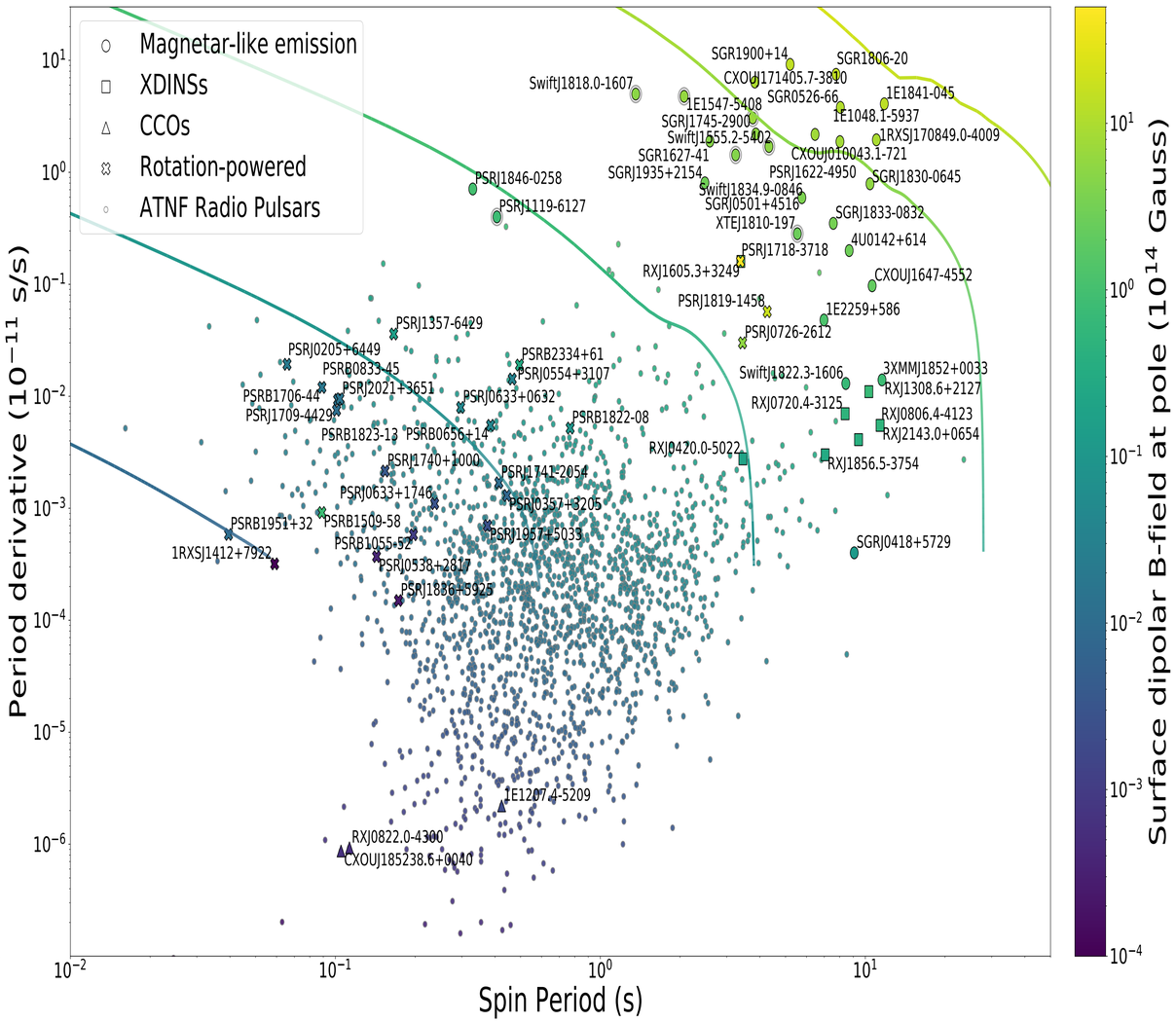
Why we need 3D magneto-thermal models?





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

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

"New 3D code MATINS"

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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***

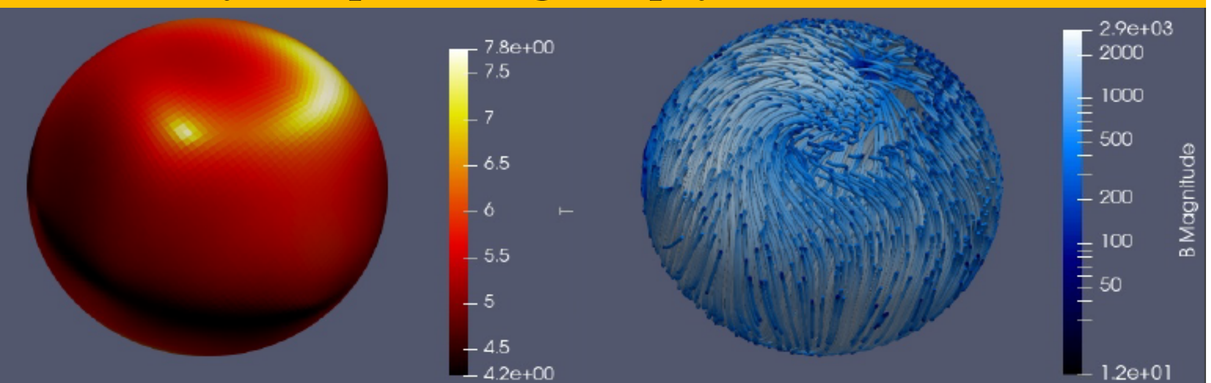
Dehman *& Pons 2025, PRR* (DOI: ***10.1103/rhv5-nd4v***): ***Chiral magnetic effect***

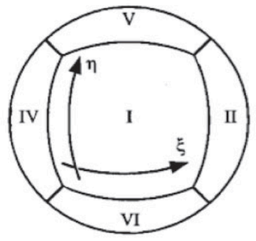
What's better than 2D (Viganò et al. 2021):

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

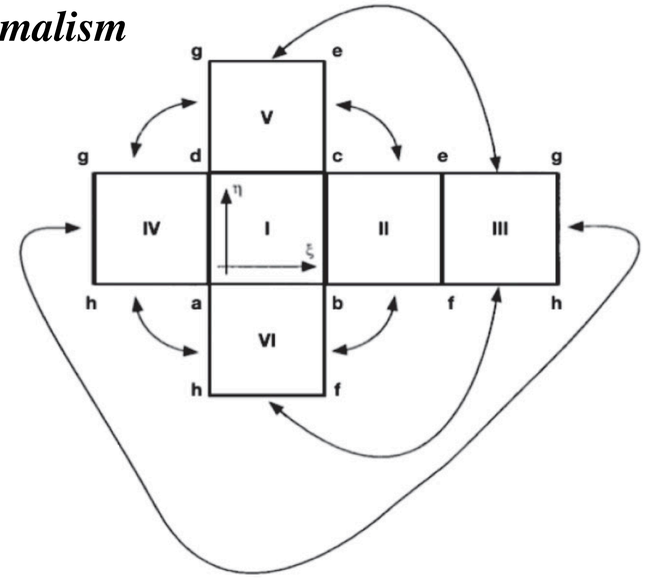
Advance obtained:

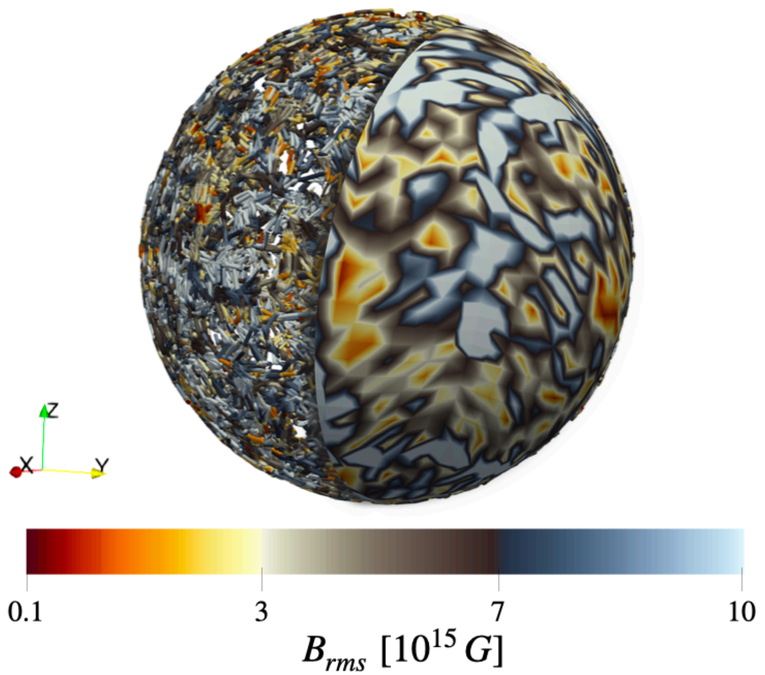
- **Realistic 3D evolution and topology, appearance of hotspots**
- **State-of-the-art microphysics, various masses and EOSs, with realistic structure obtained by solving the TOV equation.**
- **Numerical scheme to better capture non-linear dynamics**
- **General relativistic correction**
- **State of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





cubed sphere





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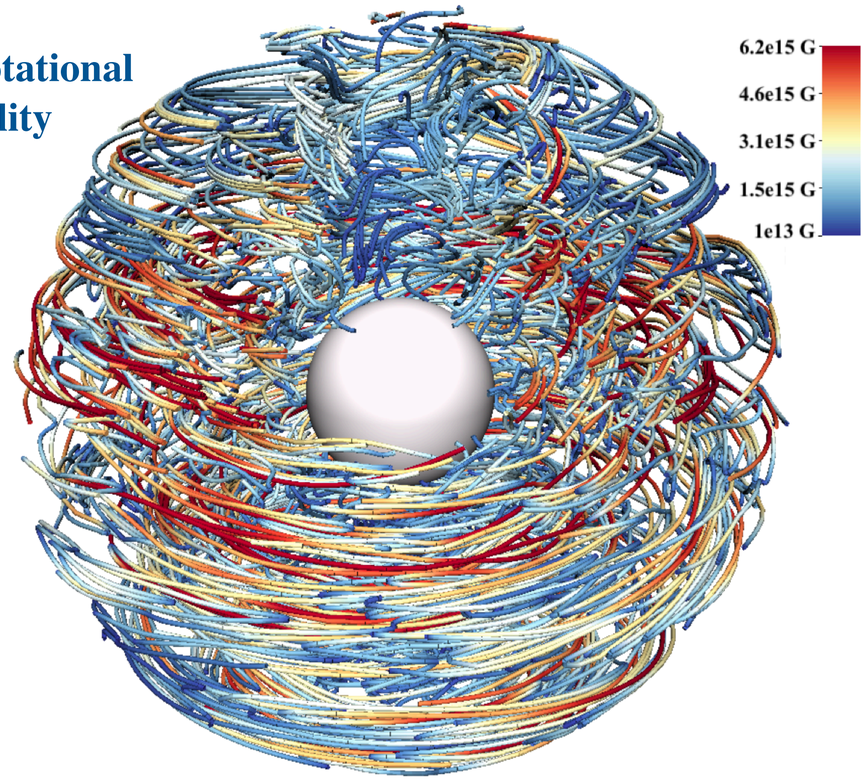
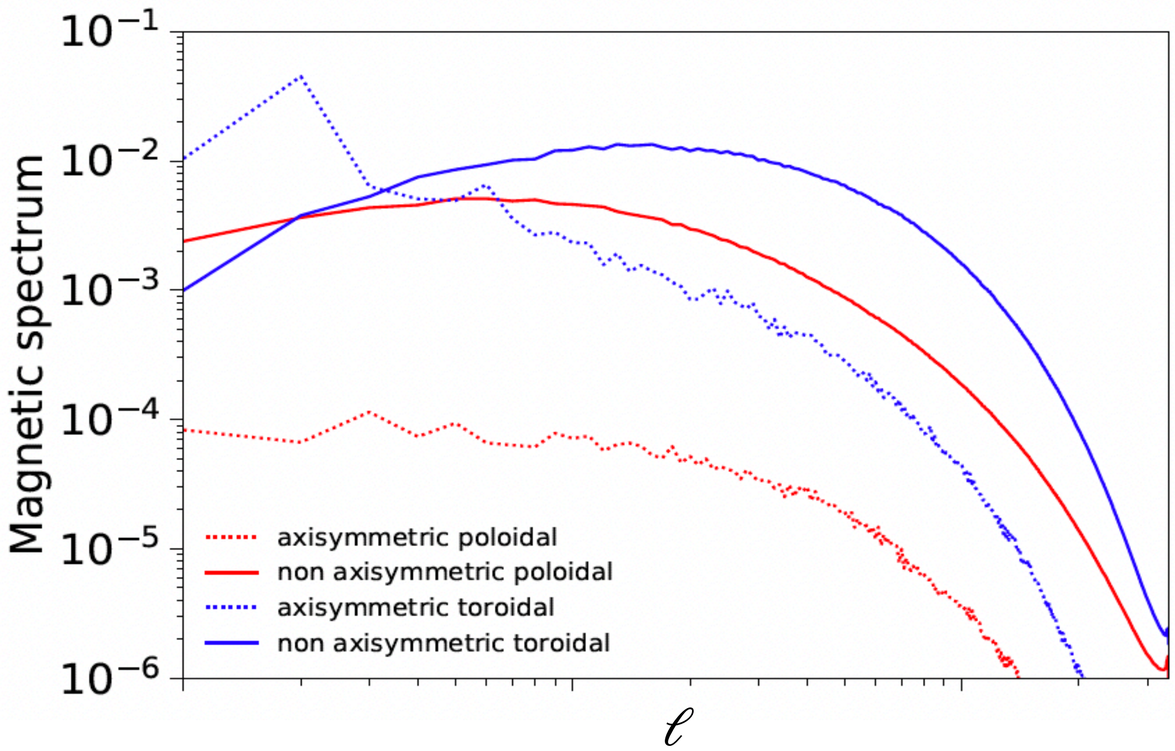
Magnetic field at birth: Magnetic spectrum after core-collapse

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!

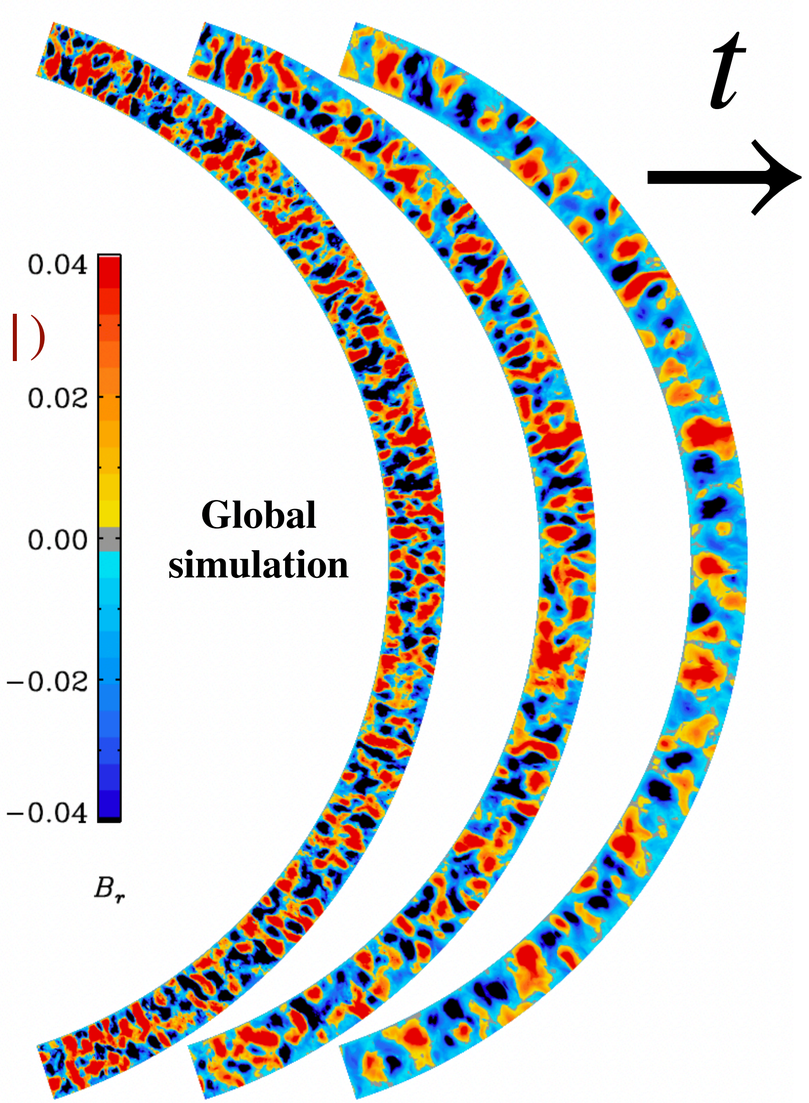
Energy transferred from small to large-scale multipoles.
Not observed in previous neutron star simulation studies.
Extreme aspect ratio (1:30)—thin crust— limits the inverse cascade.

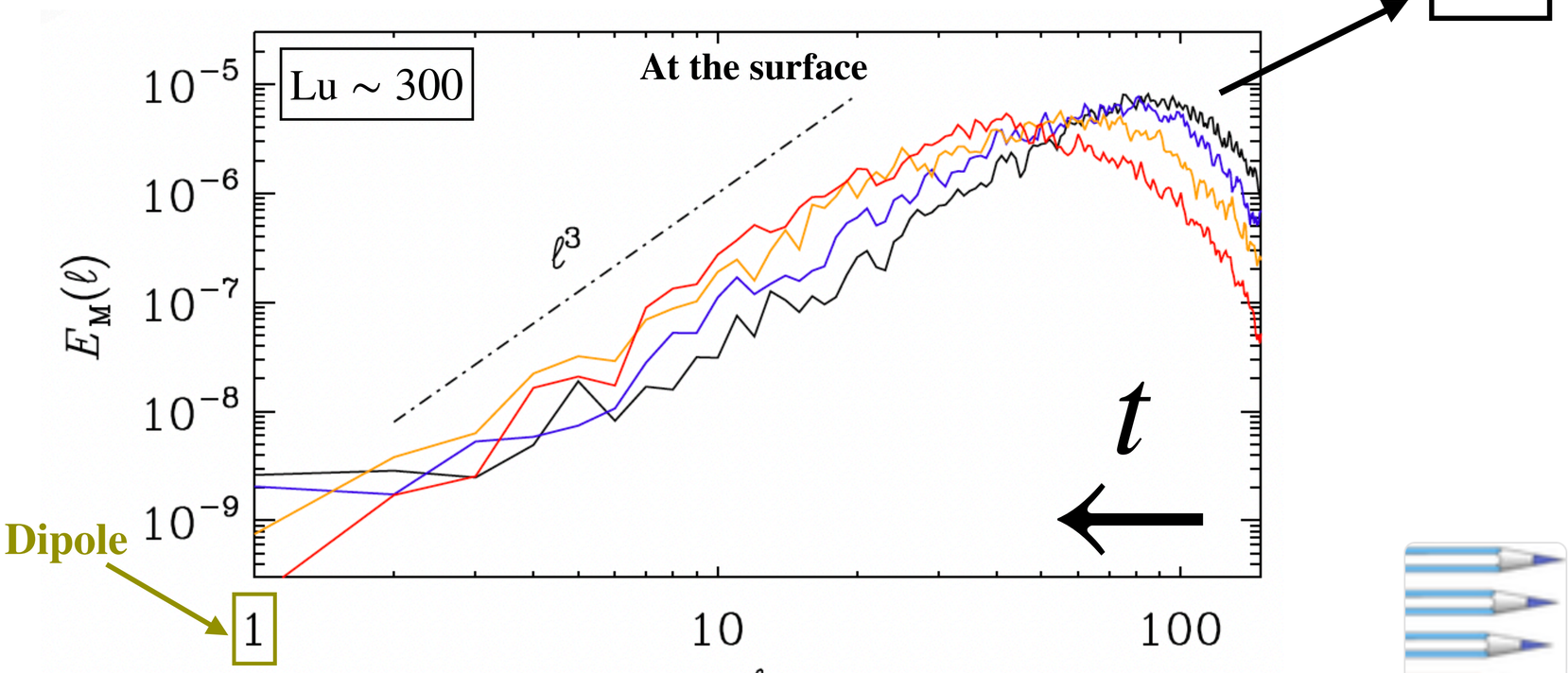
Maximally helical
(e.g., positive helicity):

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

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

$$|\boldsymbol{k}| \le \max(|\boldsymbol{p}|, |\boldsymbol{q}|)$$





[Dehman & Brandenburg 2025, A&A]

Pencil Code

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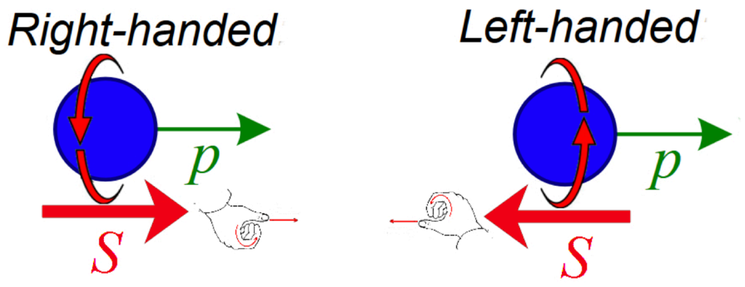
Chiral Anomaly



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

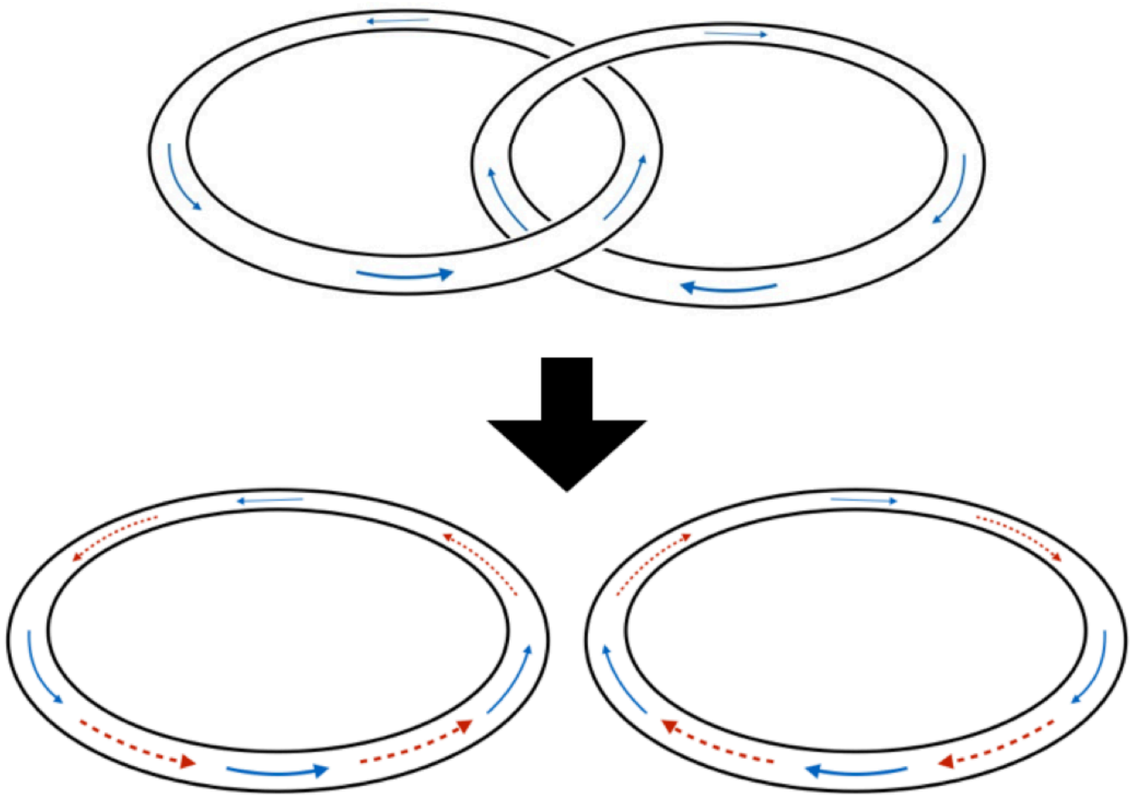


Image credit: Y. Hirono

[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)**
- **Magnetic helicity quantify the topological stability**

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

— Chiral Anomaly —

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

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

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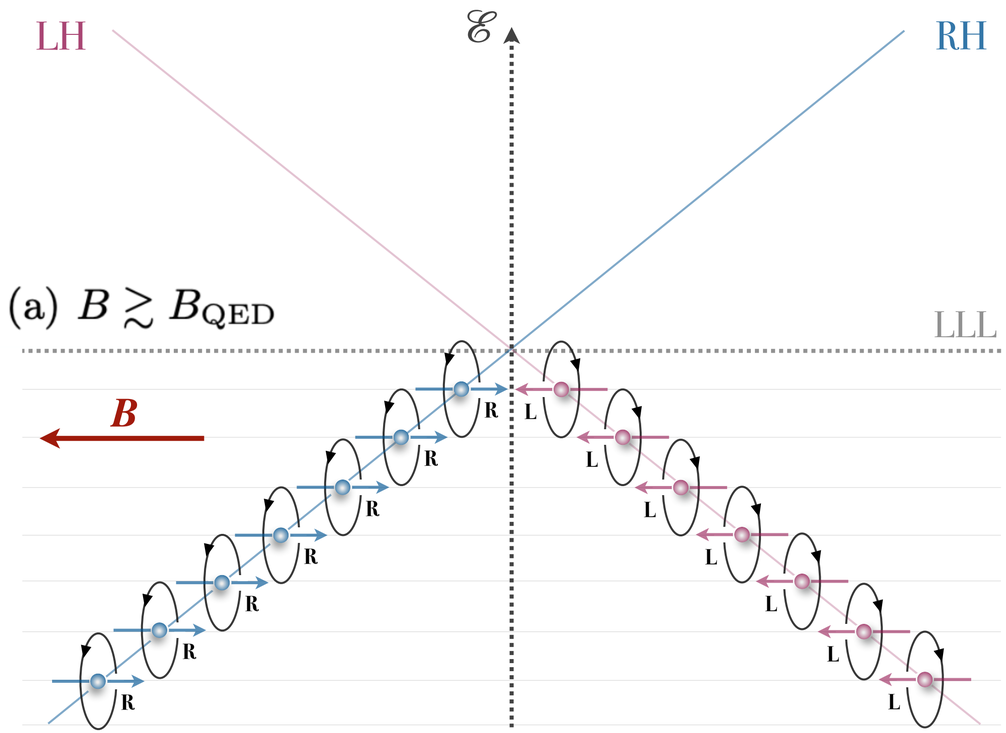

[Dehman 2026, arXiv: 2605.08068]

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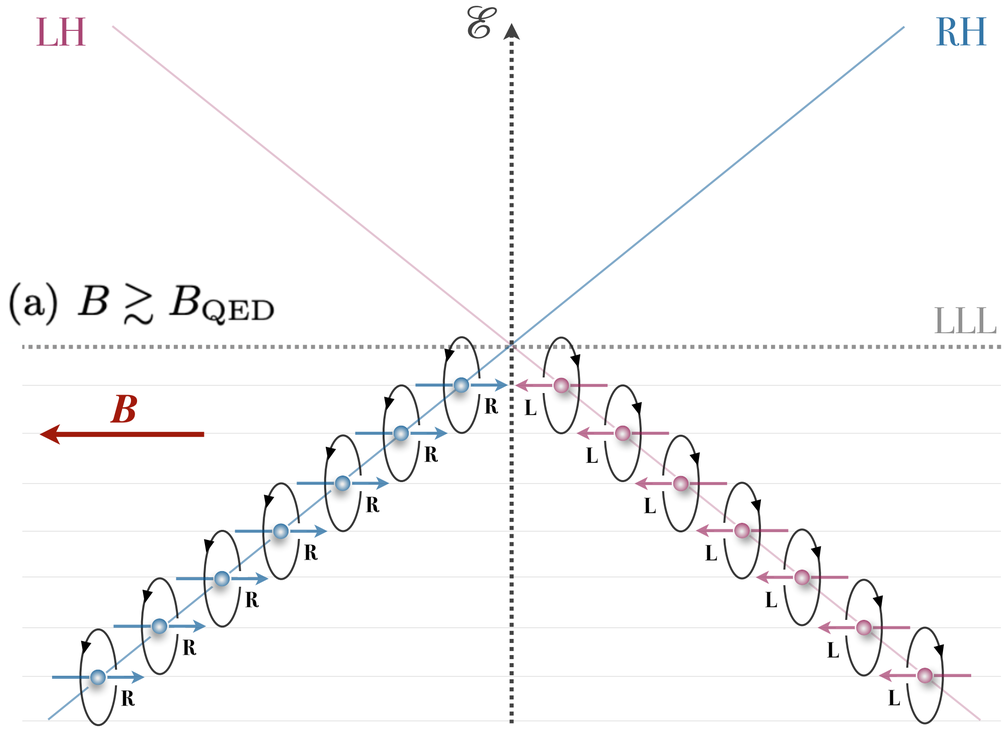

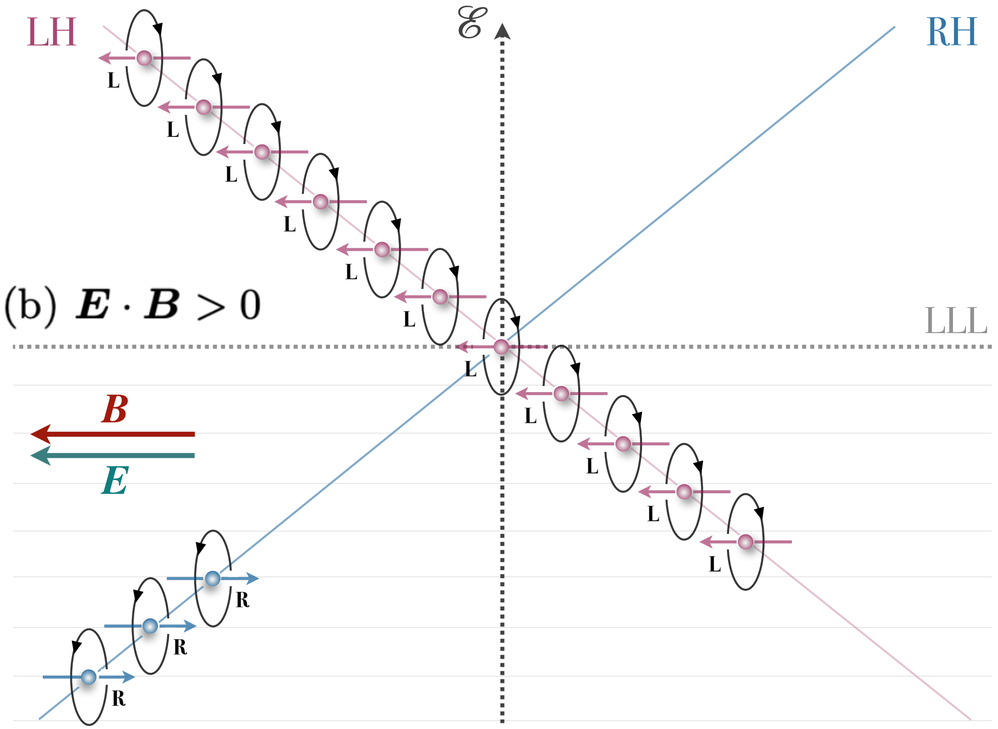

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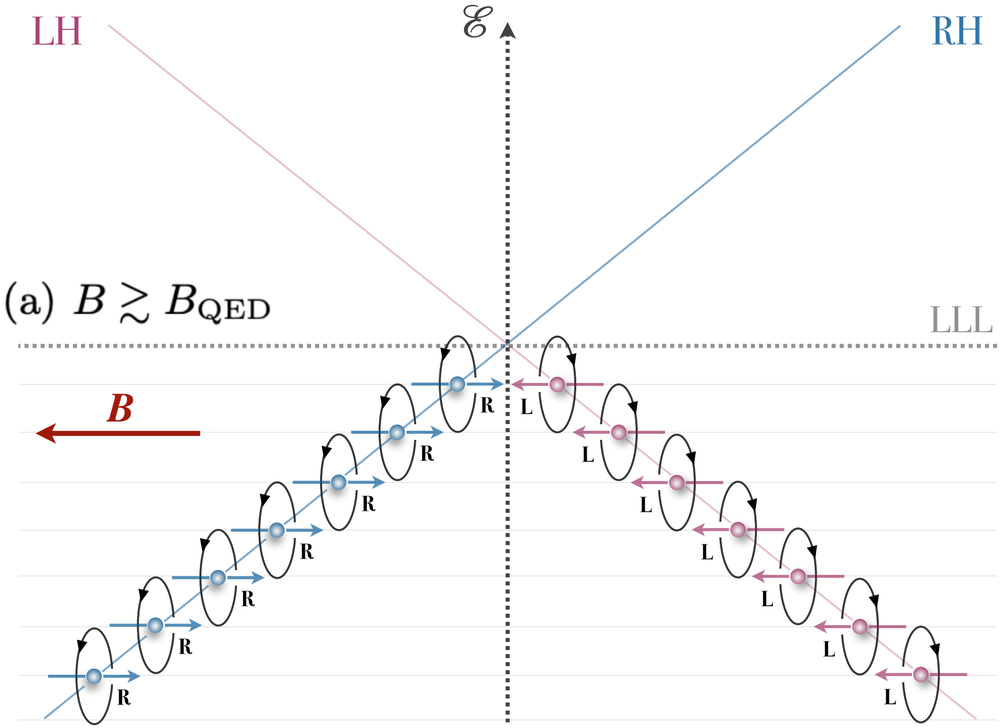

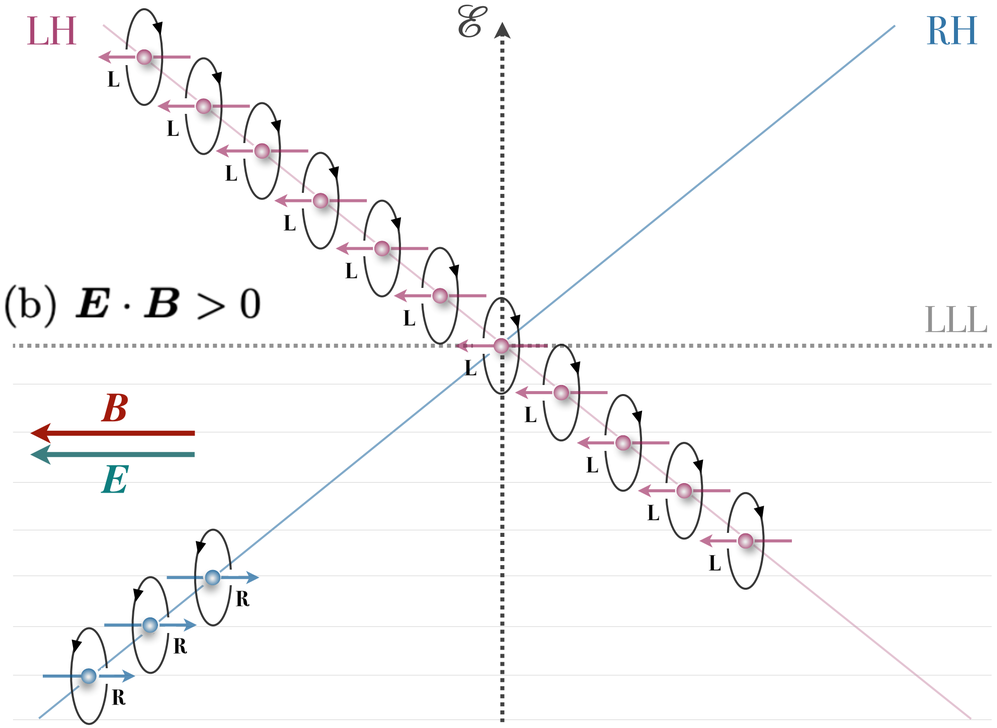

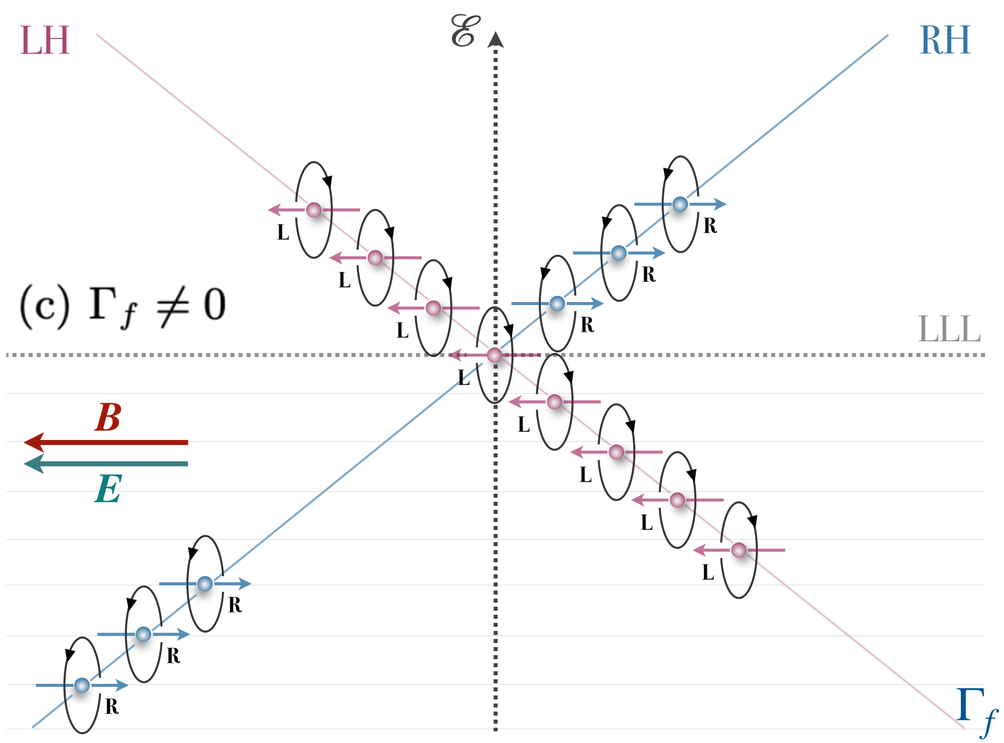

[Dehman 2026, arXiv: 2605.08068]

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

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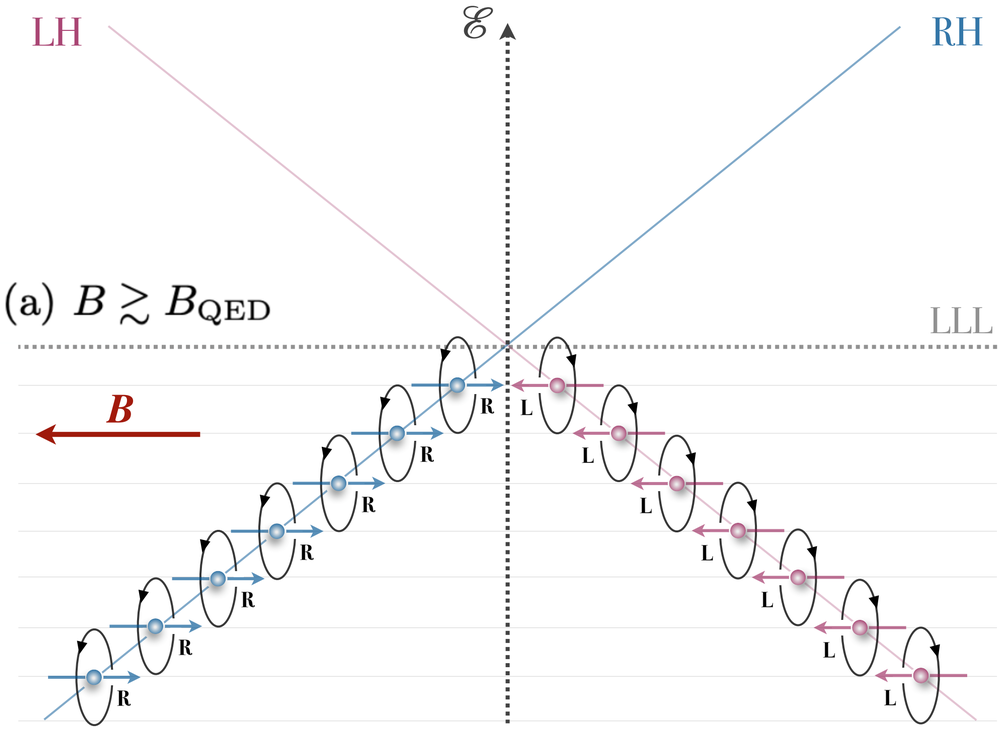

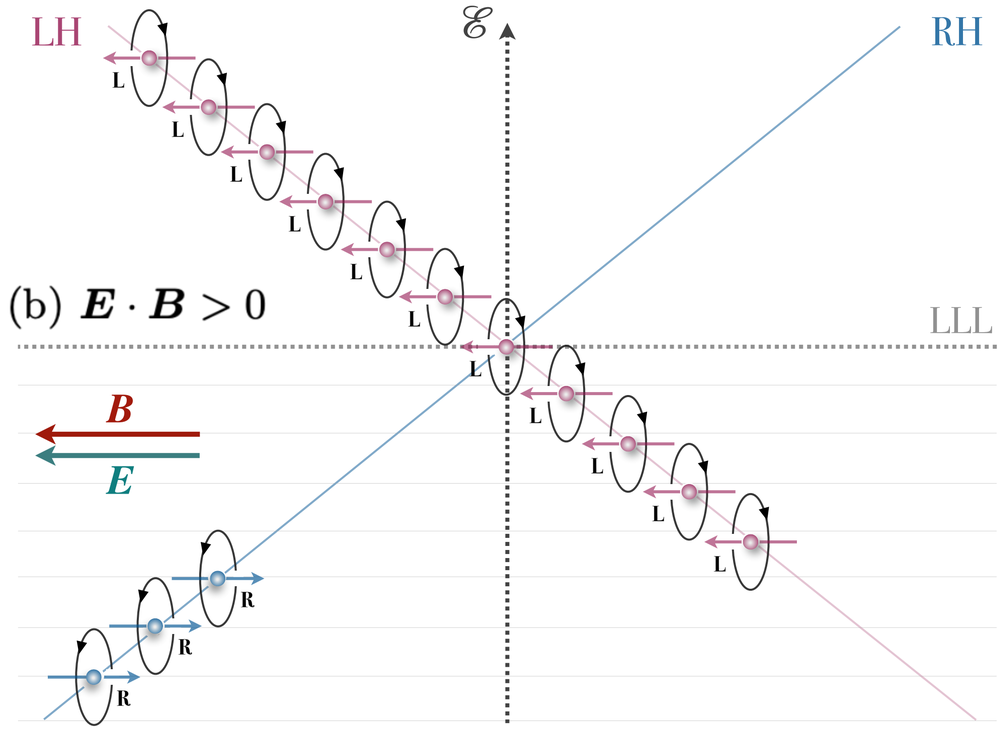

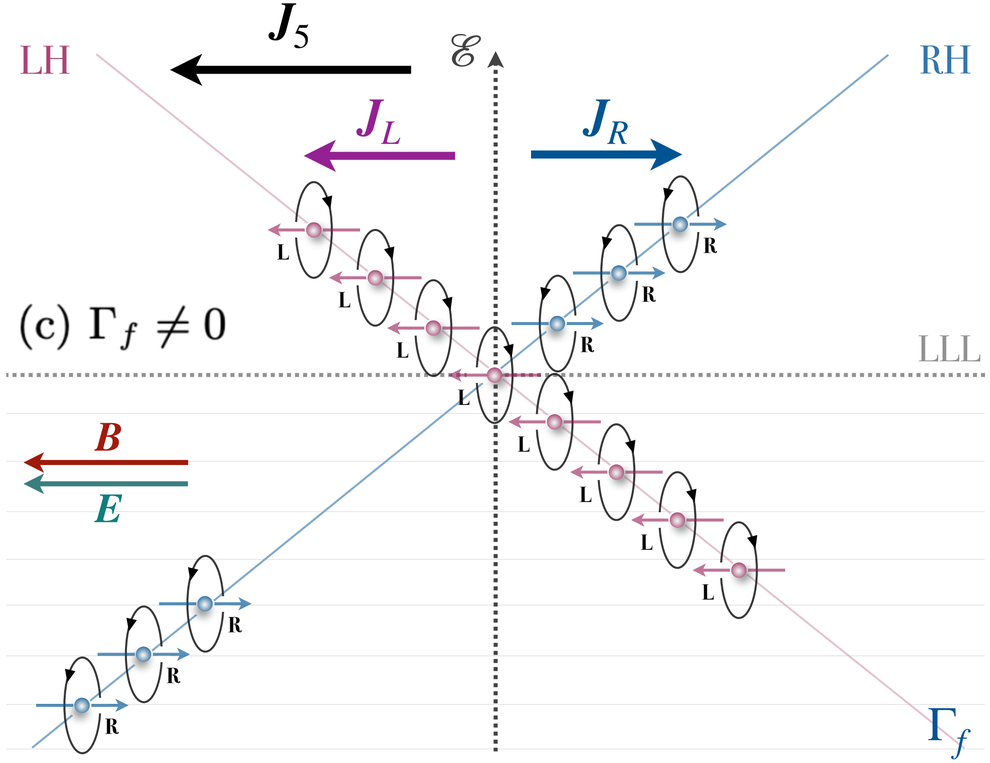

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$$\boldsymbol{J}_5 = \boldsymbol{J}_R + \boldsymbol{J}_L = \frac{\alpha}{\pi\hbar}\boldsymbol{B}(\mu_R - \mu_L) = \frac{\alpha\mu_5}{\pi\hbar}\boldsymbol{B}$$

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

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

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

[Dehman & Pons 2025, PRR]

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

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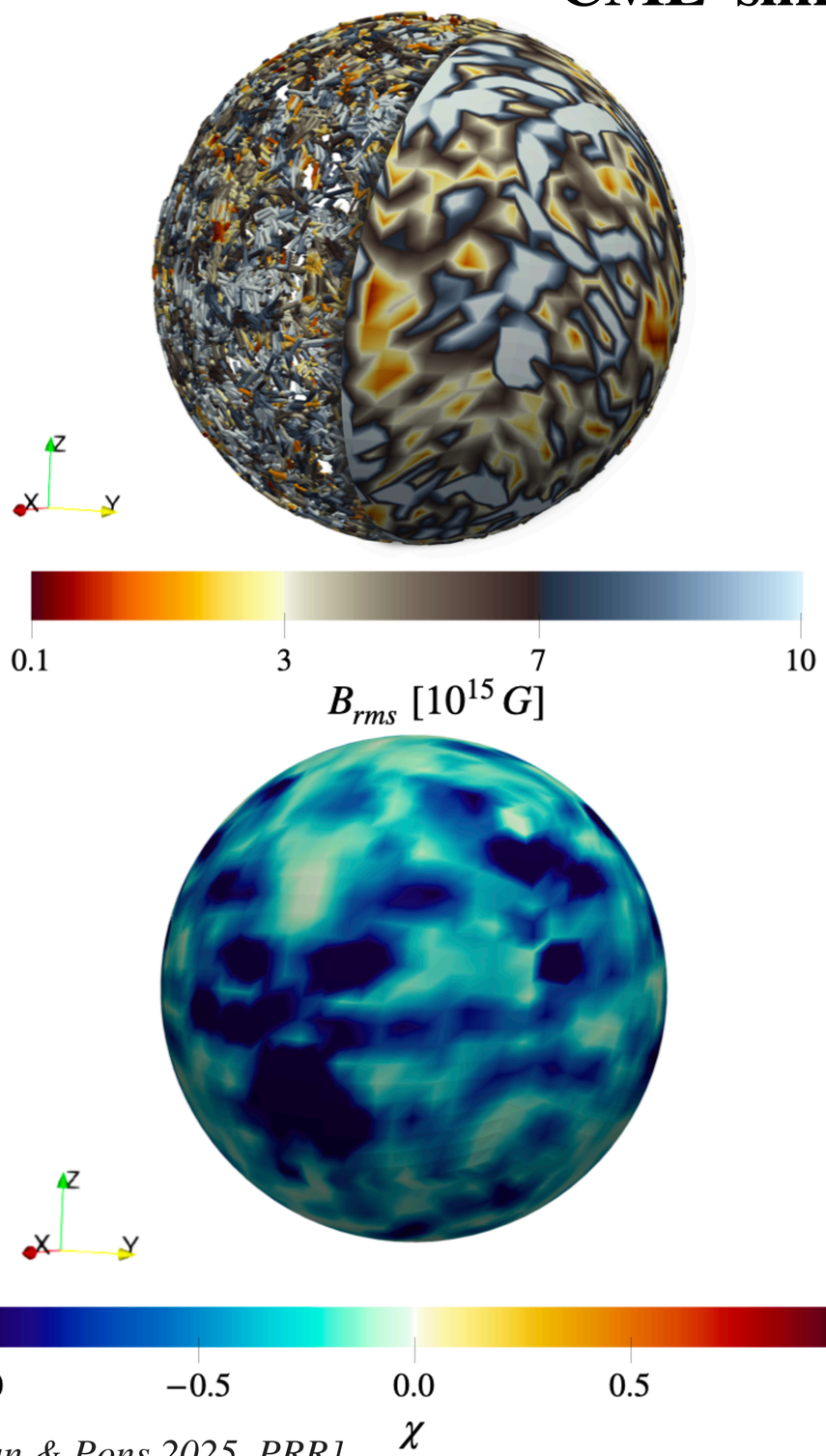
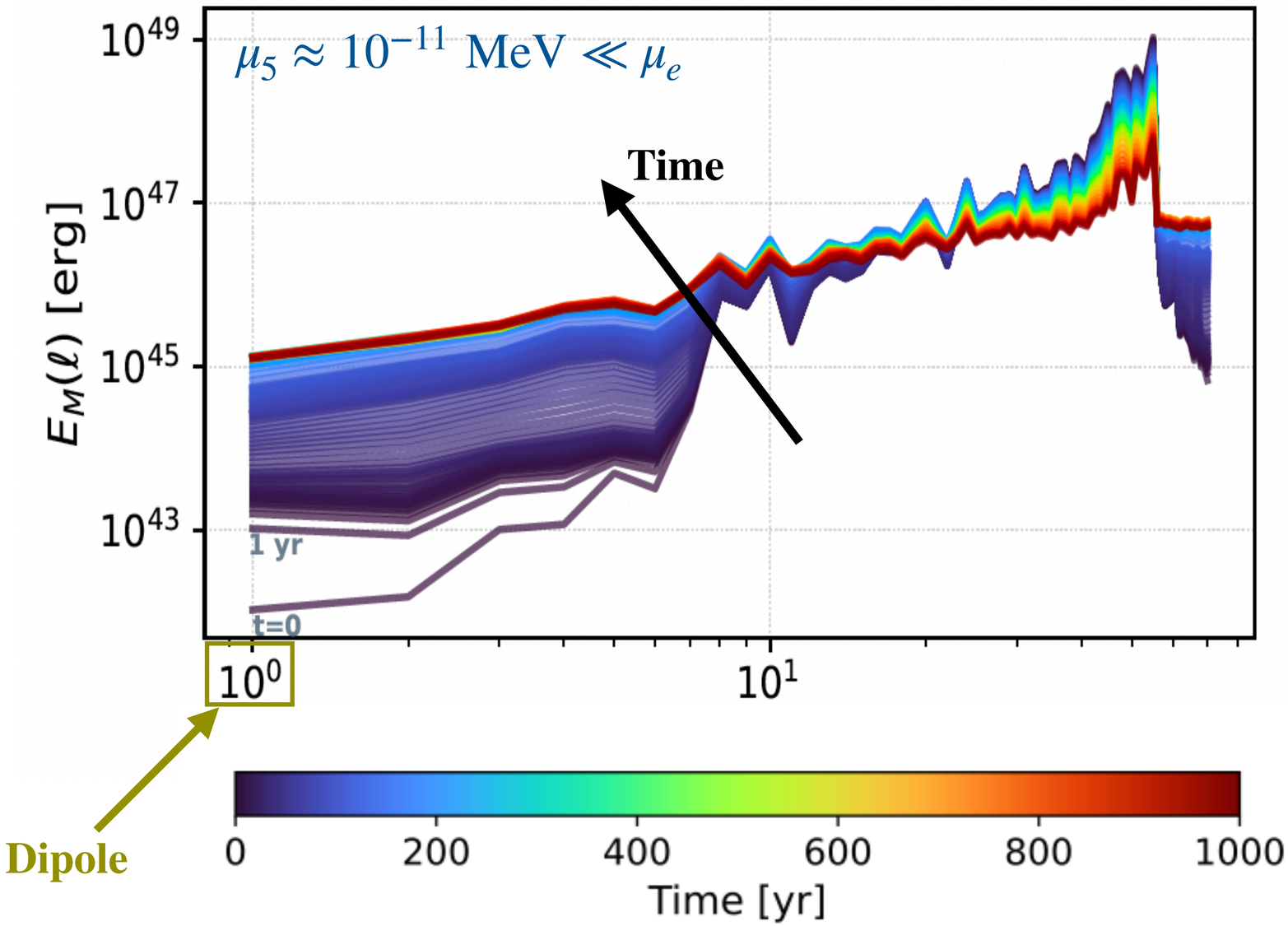
CME simulations — net magnetic helicity



[Dehman & Pons 2025, PRR]



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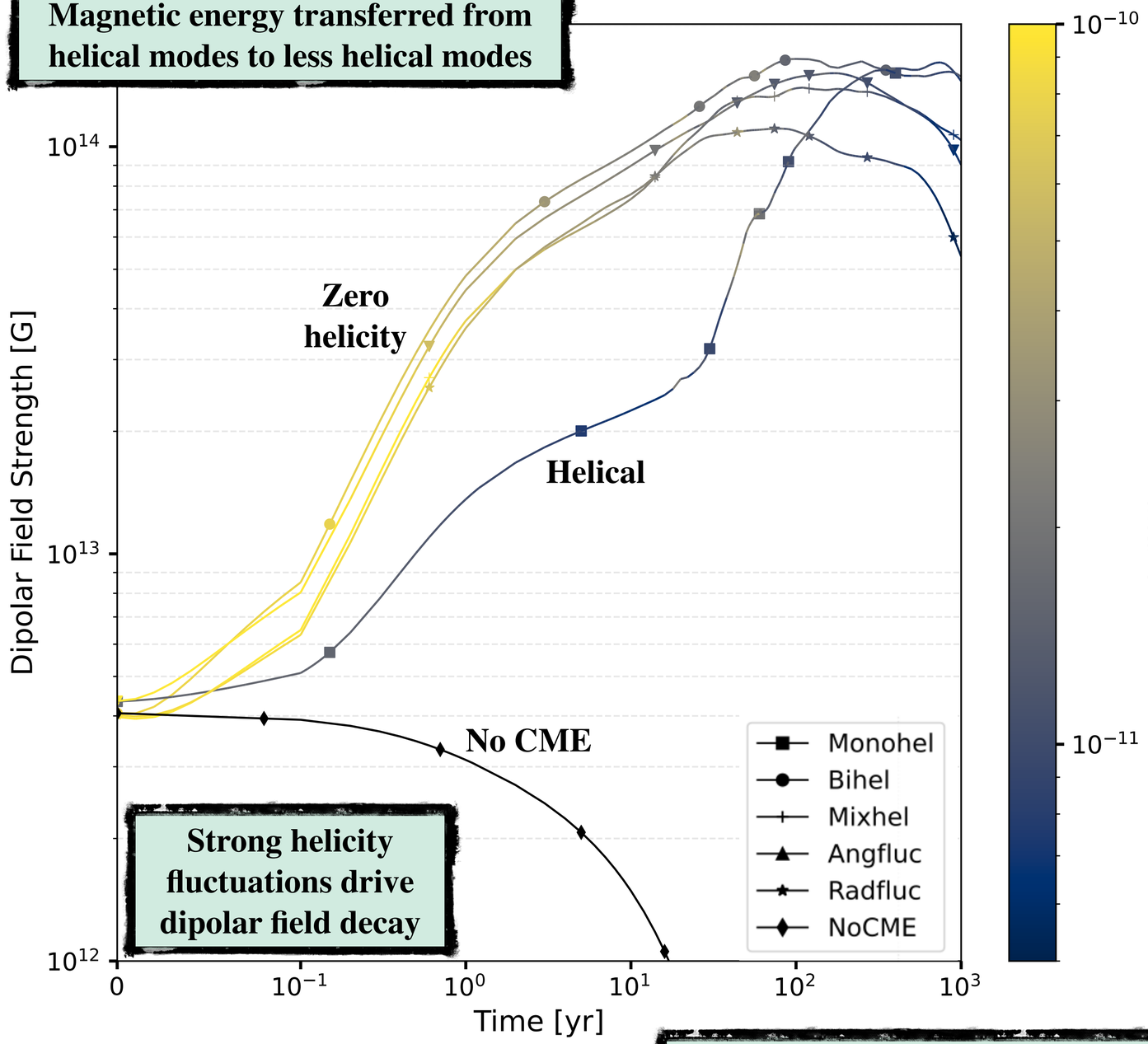
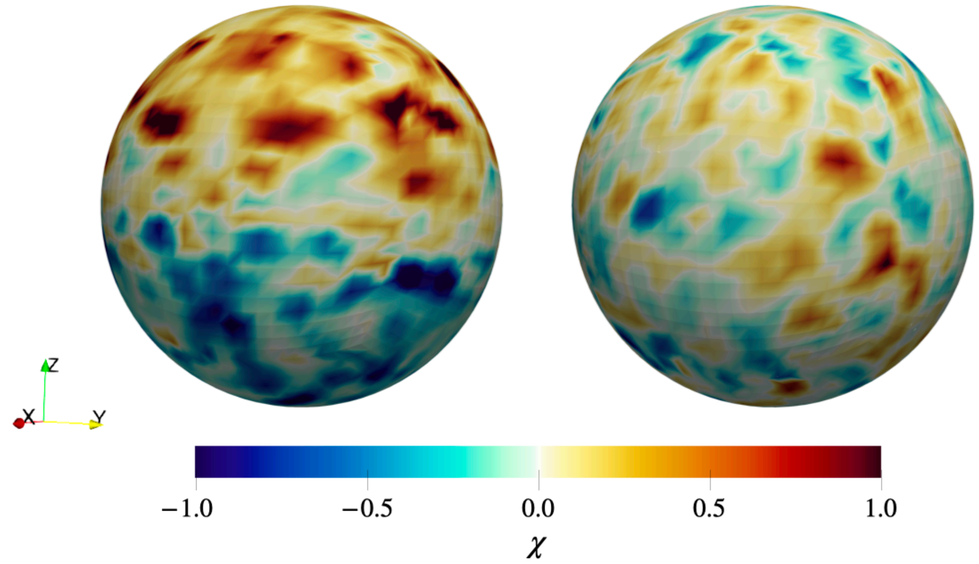
CME simulations — vanishing helicity

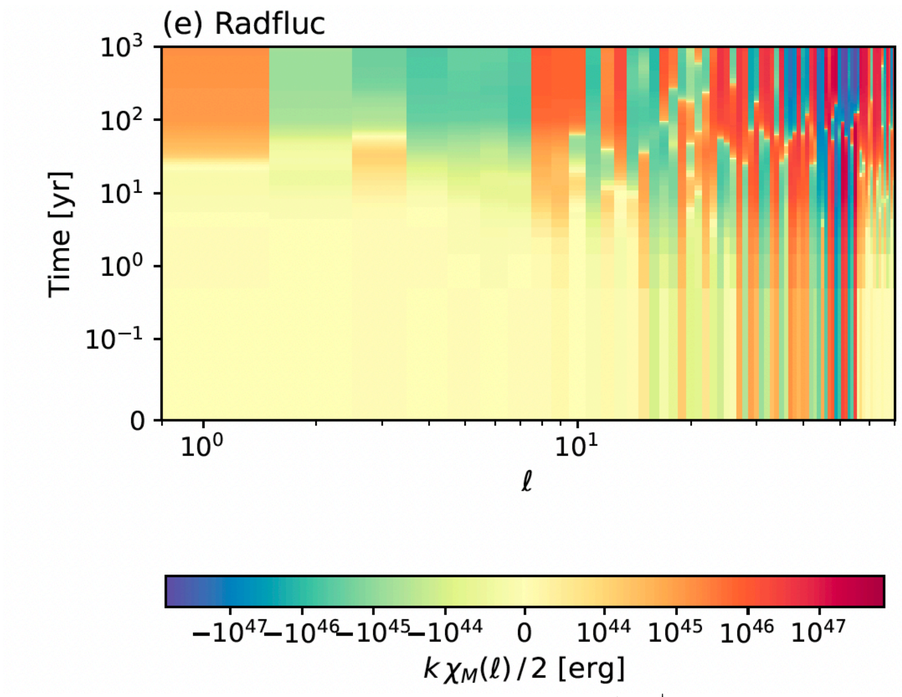
Onset of CMI is governed by $|\mu_5^{\max}|$

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, arXiv: 2605.08068]

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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 $\sim 10^{14}\ldots10^{15}$ G.

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

Hall cascade, Inverse Hall cascade, outburst, etc.

Origin of magnetic field in 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.

NewAthena: will not measure internal magnetic fields directly, but it may provide the strongest observational constraints yet on the hidden magnetic structures that govern neutron-star evolution.

➡ Resolve multipolar surface magnetic fields beyond the spin-down dipole.

➡ Constrain hidden internal (toroidal) magnetic-field components through thermal mapping.

➡ Measure the impact of magnetic-field decay on neutron-star heating and evolution.

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