Magnetic and thermal evolution of neutron stars with superfluid and superconducting interiors

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MAgneto-Thermal evolution of Isolated Neutron Stars

June 24, 2026
Scales General Meeting
University of Coimbra, Portugal

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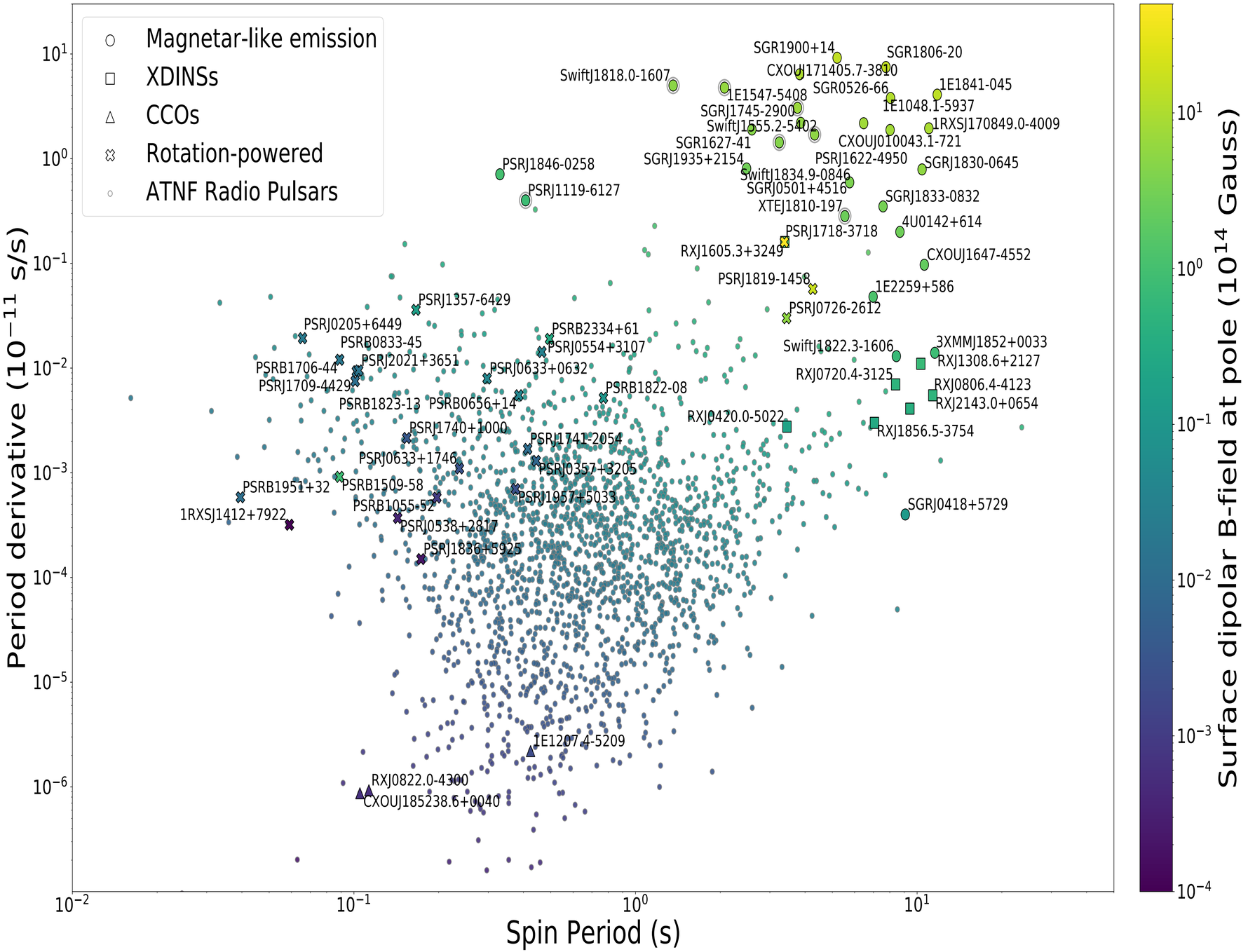
P-Pdot diagram for isolated neutron stars



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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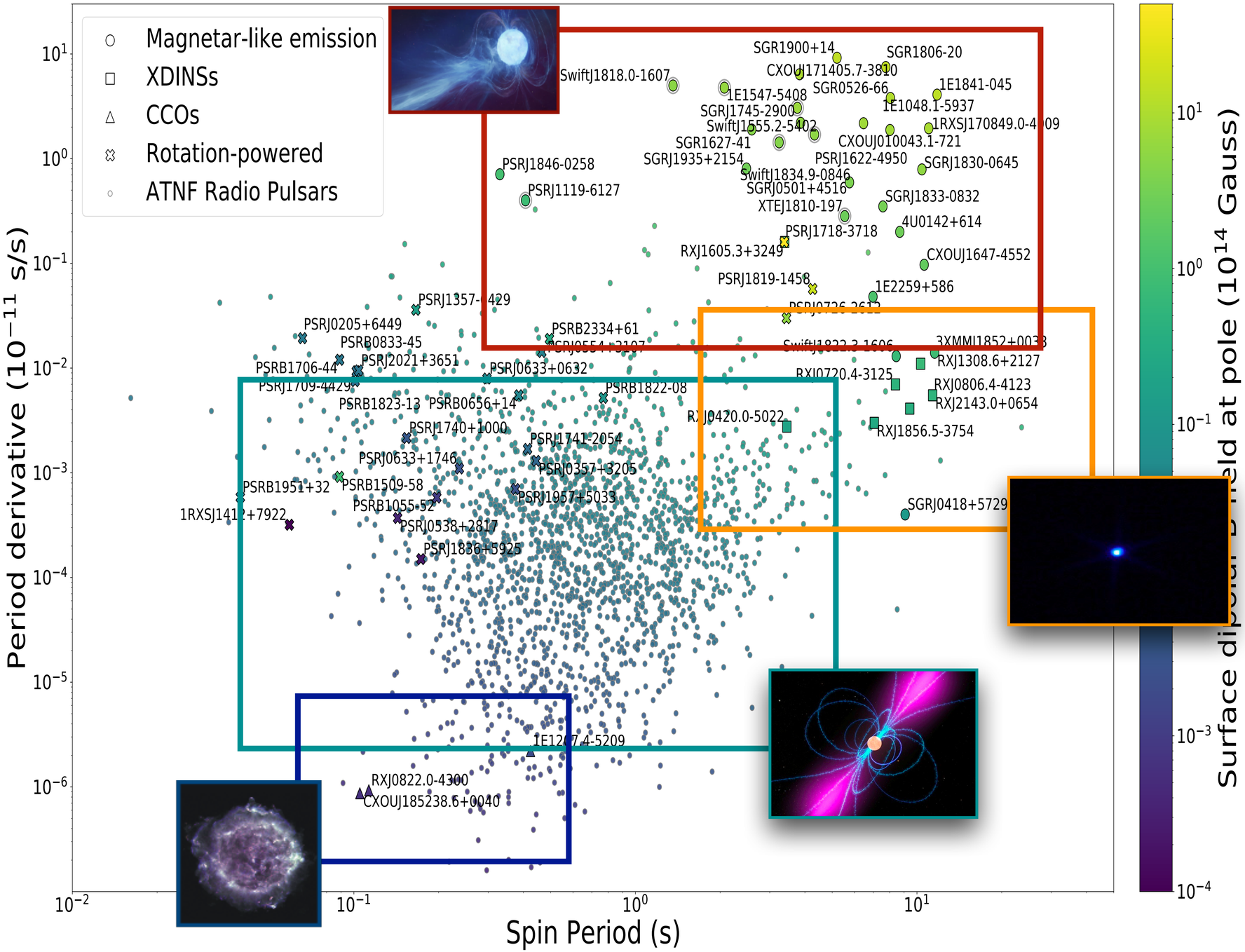
P-Pdot diagram for isolated neutron stars



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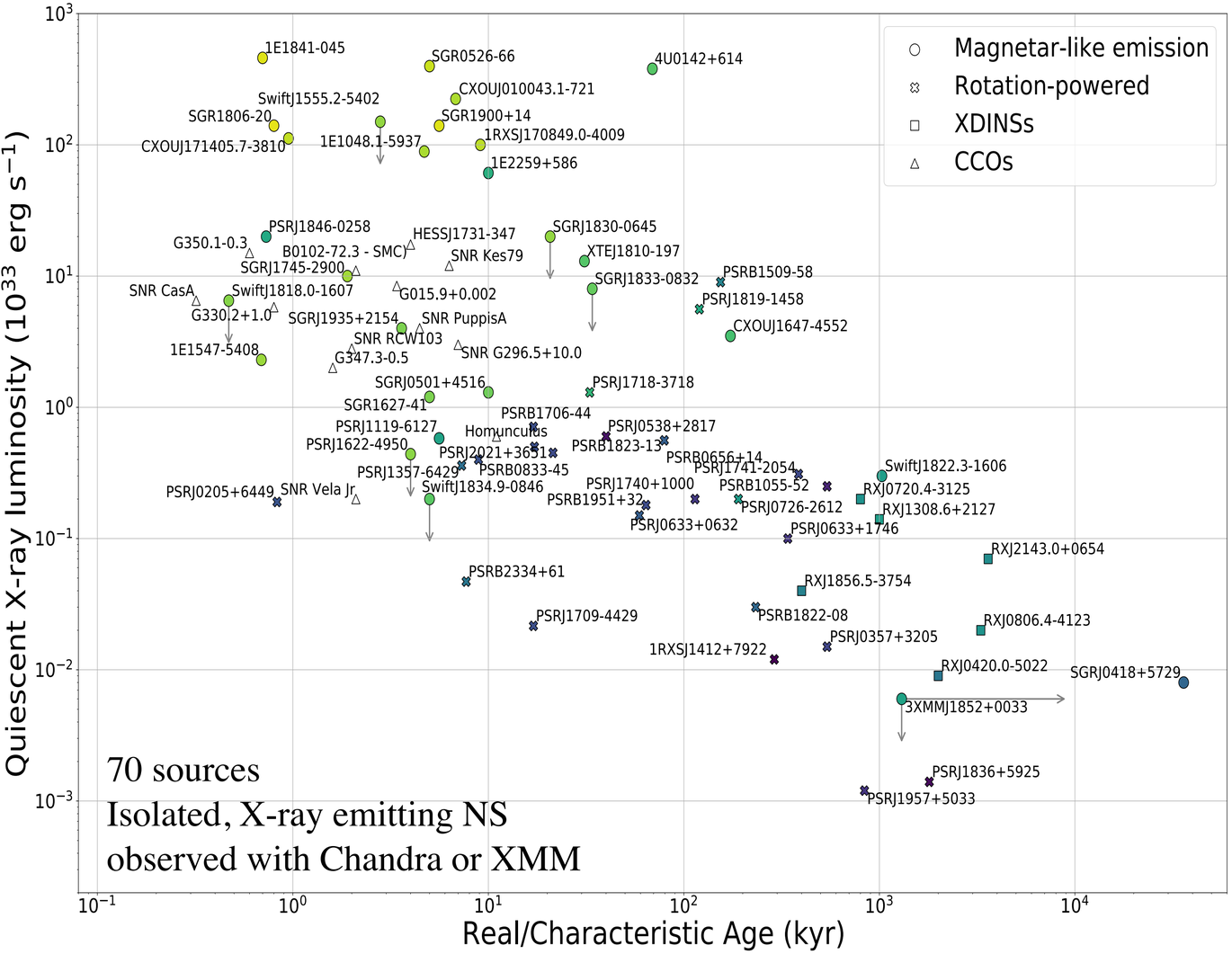
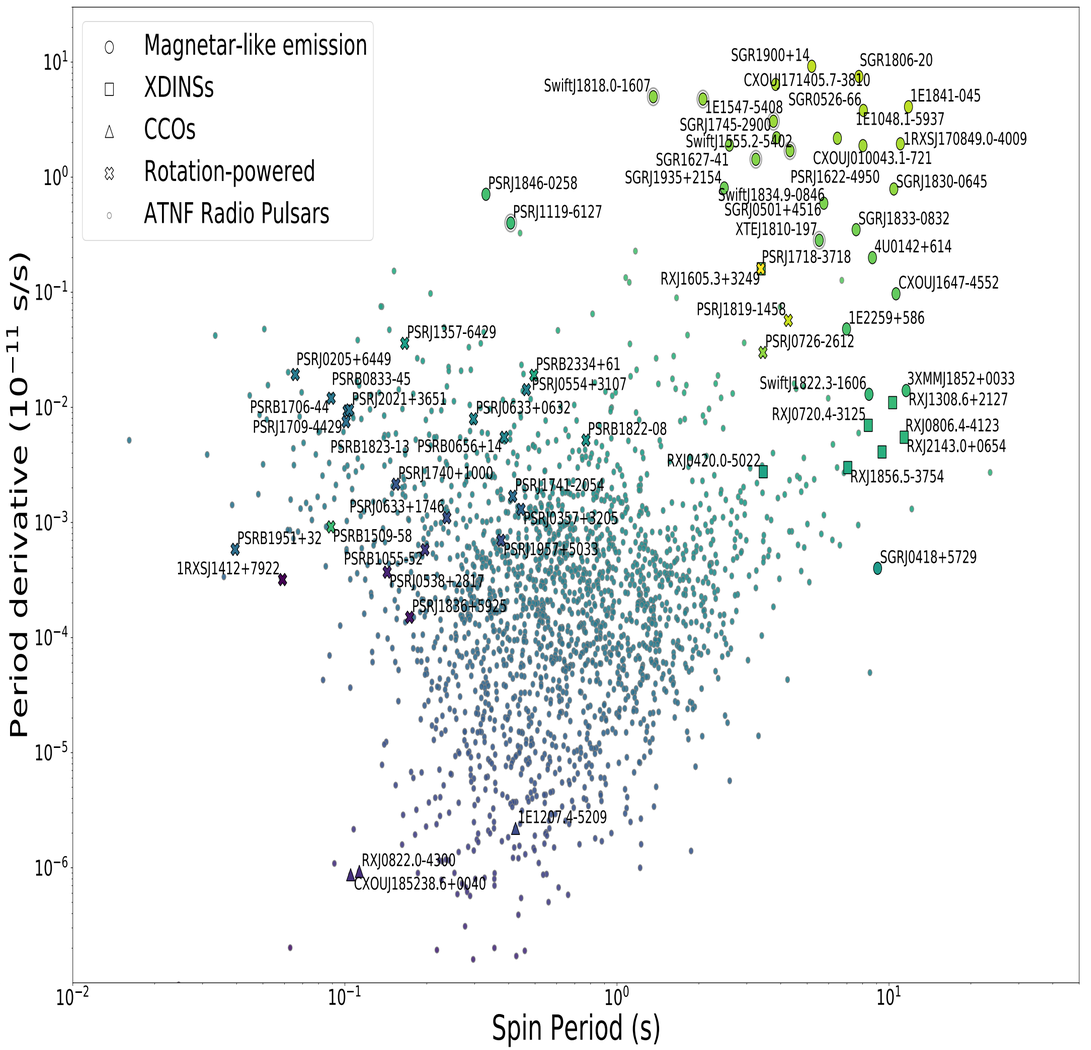
Observations: thermal X-ray luminosity, real age, P and Pdot





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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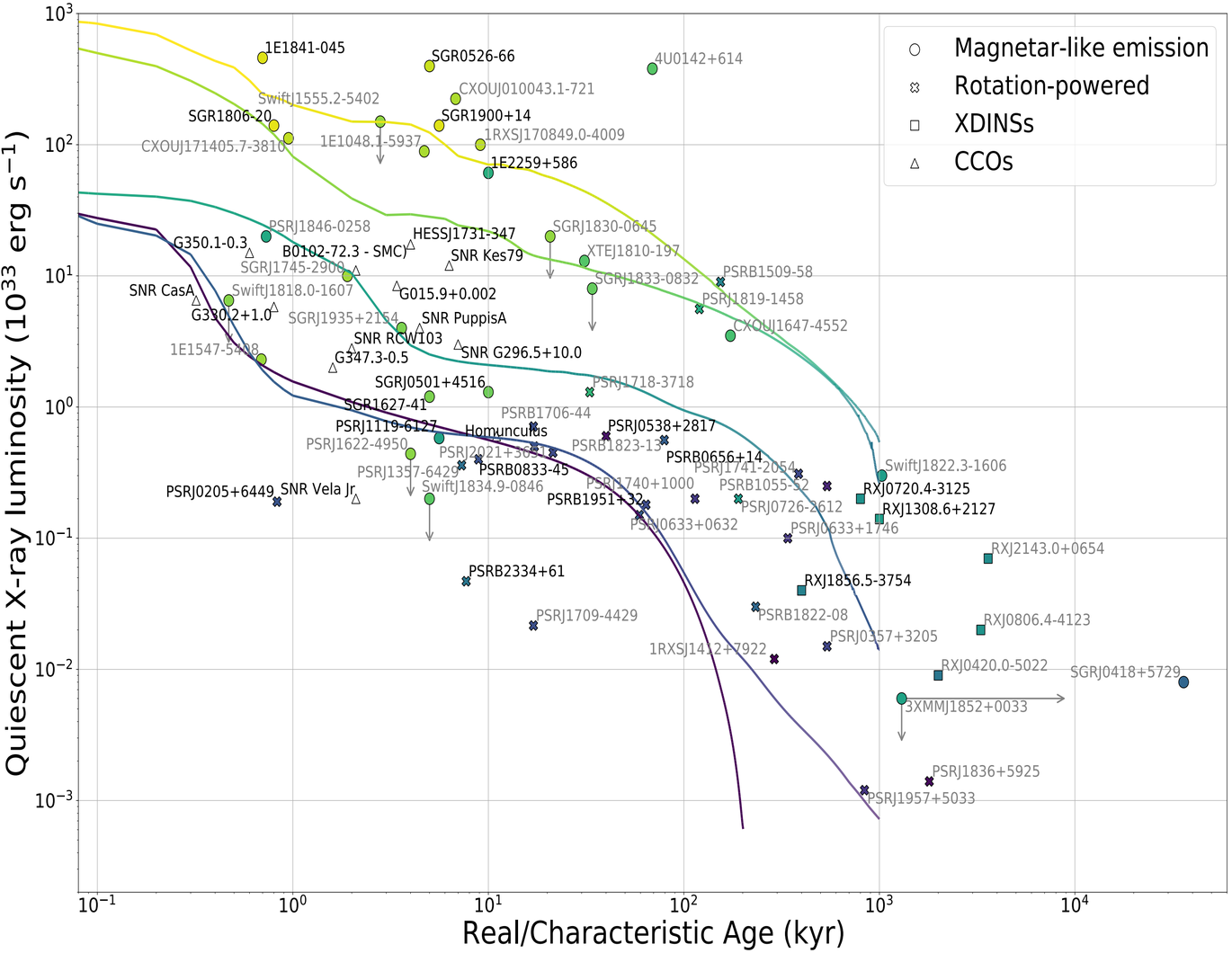
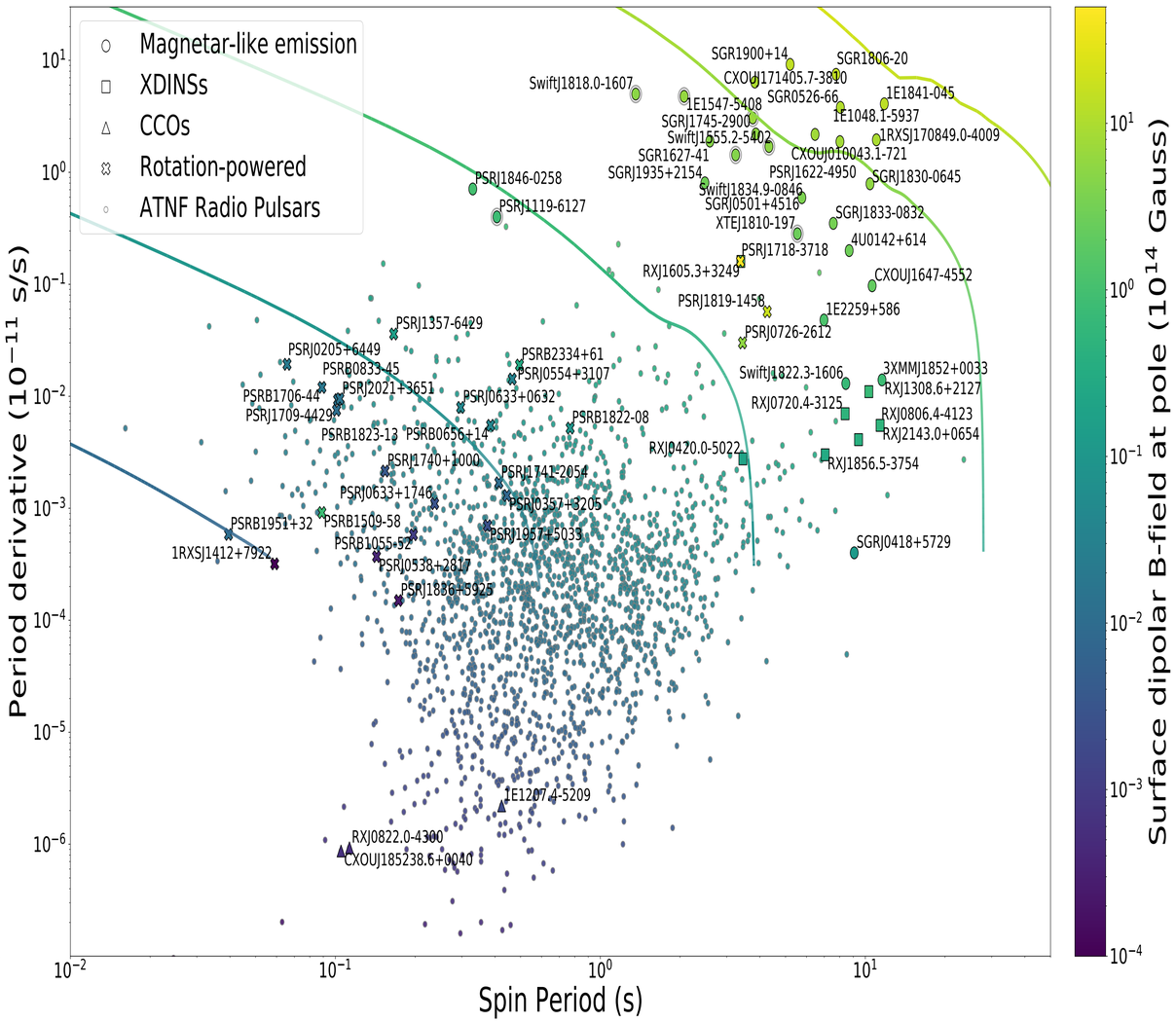
Why we need 3D magneto-thermal models?





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

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

"New 3D code MATINS"

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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:

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

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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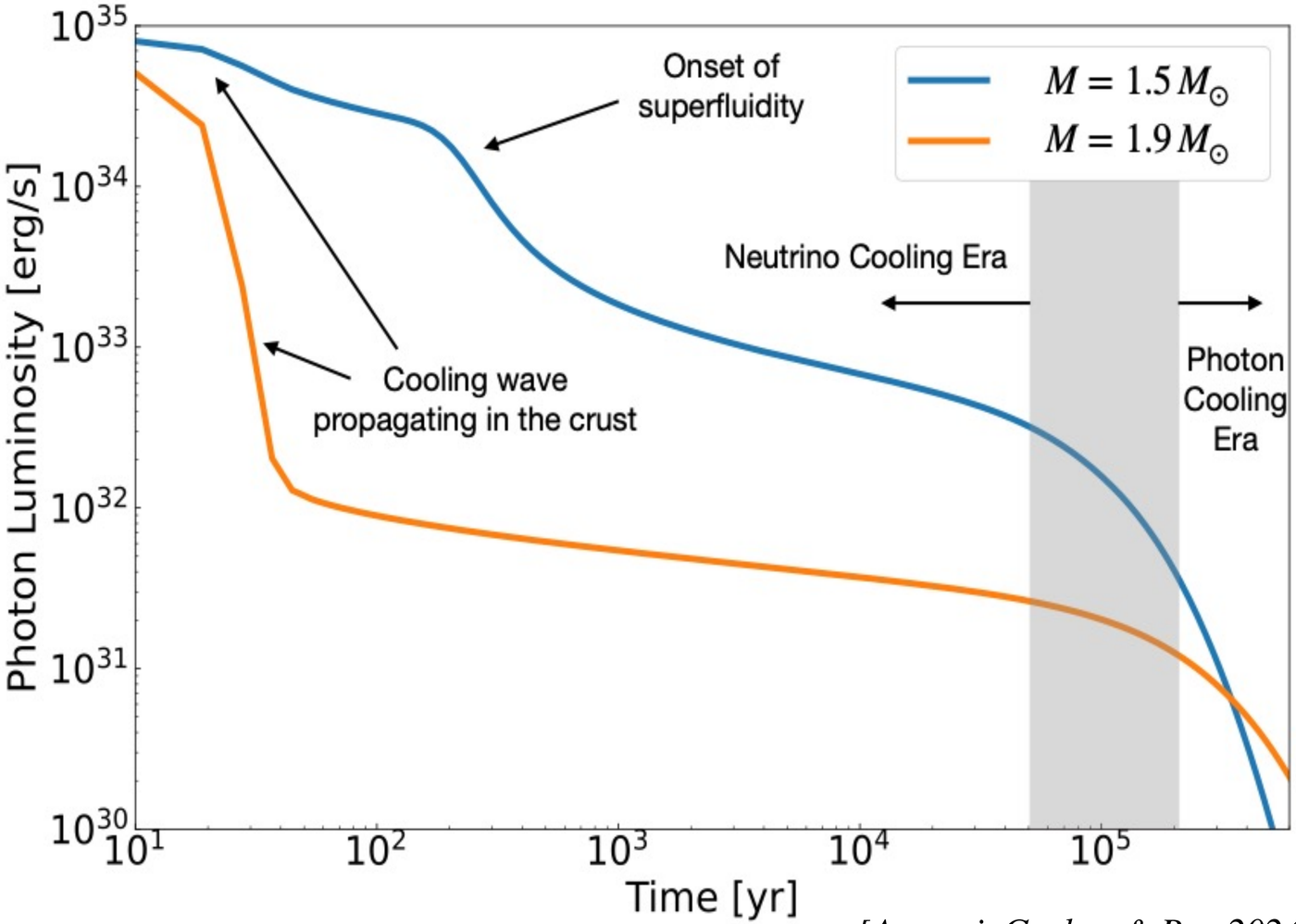
Cooling Model: Neutrino vs Photon Cooling Stages



[Ascenzi, Graber & Rea 2024]

Neutrino cooling dominates during the first 10-100 kyr: the star cools from inside.

Photon cooling dominates when the star is cold enough, so that neutrino production is much less efficient, and heat is mostly transferred to the surface and radiated.

Isolated neutron stars are X-ray bright because they are born hot, visible as thermal emitters.

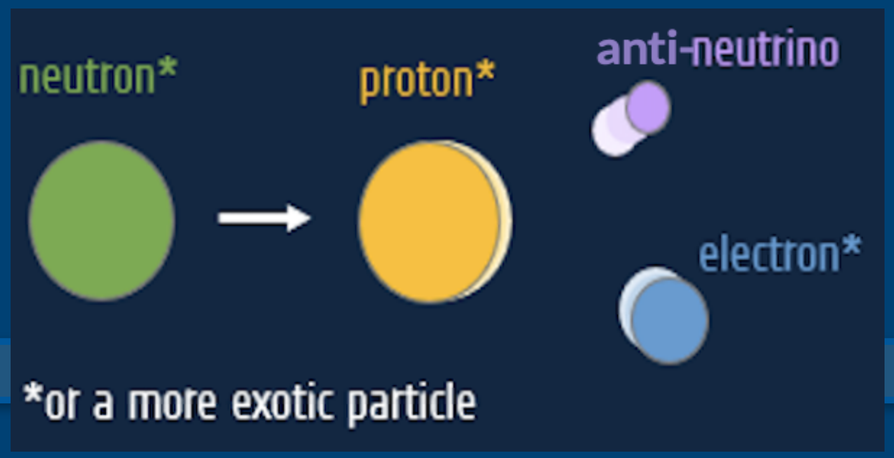
For magnetars at least, need for extra heating.

Neutrinos Reactions

Standard Cooling

+

Enhanced Cooling



Process	Q_ν [erg cm^{-3} s^{-1}]	Onset
Core		
Modified Urca (n-branch)		
$nn \to pne\bar{\nu}_e,\ pne \to nn\nu_e$	$8\times10^{21}\mathscr{R}_n^{MU} n_p^{1/3} T_9^8$	
Modified Urca (p-branch)		
$np \to ppe\bar{\nu}_e,\ ppe \to np\nu_e$	$8\times10^{21}\mathscr{R}_p^{MU} n_p^{1/3} T_9^8$	$Y_p^c = 0.01$
N-N bremstralung		
$nn \to nn\nu\bar{\nu}$	$7\times10^{19}\mathscr{R}^{nn} n_n^{1/3} T_9^8$	
$np \to np\nu\bar{\nu}$	$1\times10^{20}\mathscr{R}^{np} n_p^{1/3} T_9^8$	
$pp \to pp\nu\bar{\nu}$	$7\times10^{19}\mathscr{R}^{pp} n_p^{1/3} T_9^8$	
e-p Bremsstrahlung		
$ep \to ep\nu\bar{\nu}$	$2\times10^{17} n_B^{-2/3} T_9^8$	
Direct Urca		
$n \to pe\bar{\nu}_e,\ pe \to n\nu_e$	$4\times10^{27}\mathscr{R}^{DU} n_e^{1/3} T_9^6$	$Y_p^c = 0.11$
$n \to p\mu^-\bar{\nu}_\mu,\ p\mu^- \to n\nu_\mu$	$4\times10^{27}\mathscr{R}^{DU} n_\mu^{1/3} T_9^6$	$Y_p^c = 0.14$
Crust		
Pair annihilation		
$ee^+ \to \nu\bar{\nu}$	$9\times10^{20} F_{\rm pair}(n_e, n_{e^+})$	
Plasmon decay		
$\Gamma \to \nu + \bar{\nu}$	$1\times10^{20} I_{pl}(T, y_e)$	
e-nucleus Bremsstrahlung		
$e(A,Z) \to e(A,Z)\nu\bar{\nu}$	$3\times10^{12} L_{eN} Z \rho_0 n_e T_9^6$	
$N-N$ Bremsstrahlung		
$nn \to nn\nu\bar{\nu}$	$7\times10^{19} R^{nn} f_\nu n_n^{1/3} T_9^8$	
Core and crust		
Cooper Pair Breaking and Formation (CPBF)		
$\tilde{B}\tilde{B} \to \nu\bar{\nu}$	$1\times10^{21} n_N^{1/3} F_{A,B} T_9^7$	
Electron Synchrotron		
$e \xrightarrow{B} e\nu\bar{\nu}$	$9\times10^{14} S_{AB,BC} B_{13}^2 T_9^5$	

Impact of superfluidity and superconductivity on cooling

Different gap models strongly affect NS cooling, with the impact set by their height and width.
In the zero-temperature limit, BCS theory predicts that the energy gaps are proportional to the critical temperature.

For the singlet (isotropic) pairing:

$$k_b T_c \approx 0.5669\Delta,$$

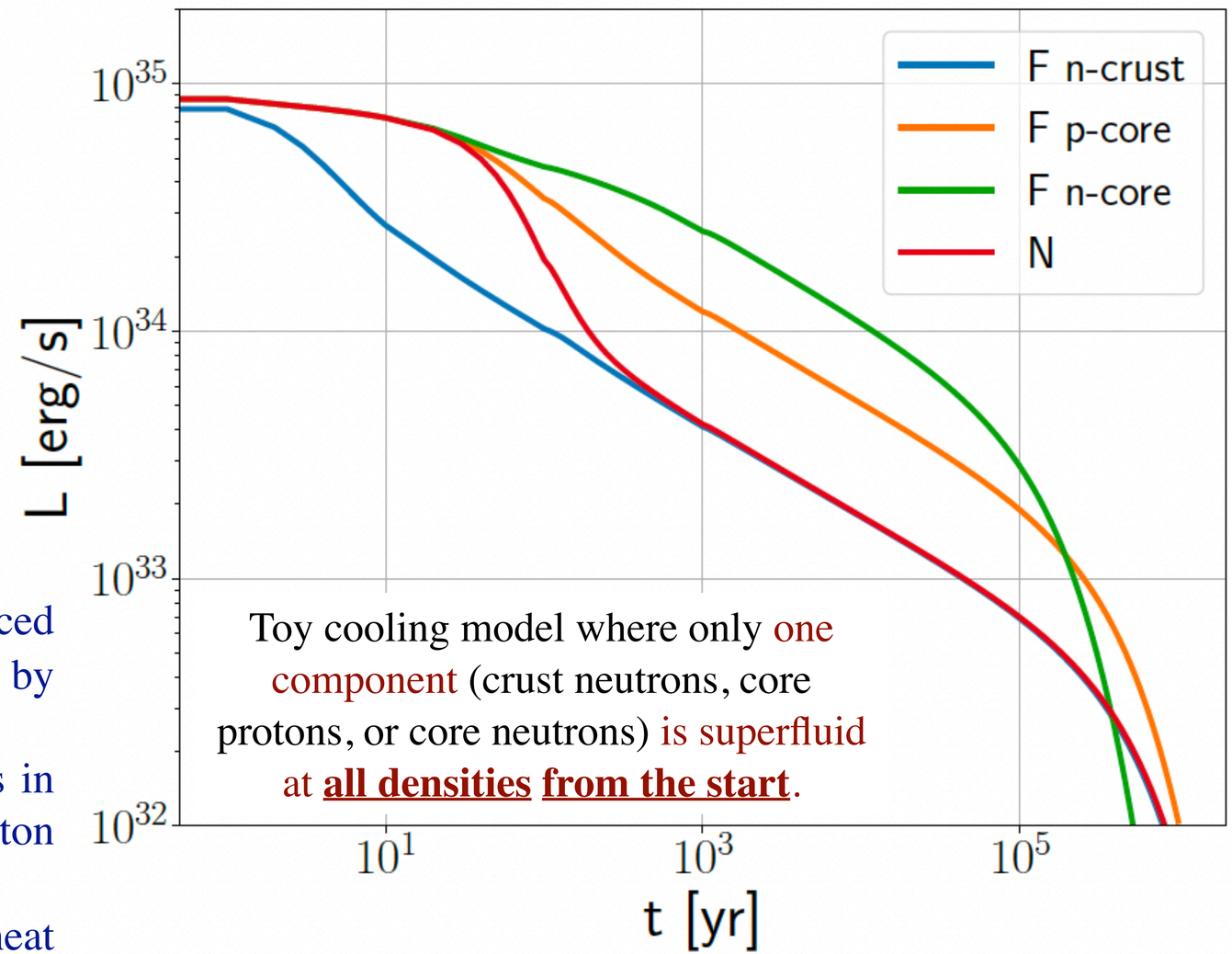
For the triplet (anisotropic) pairing

$$k_b T_c \approx 0.1887\Delta,$$

[Ho et al. 2015]

Higher critical temperature → earlier superfluidity;
Wider gap → larger volume where transport is affected.

1) Early Evolution: onset of superfluidity ($T \sim T_c$) → enhanced cooling from Cooper pair neutrino emission, mainly driven by crustal neutron superfluidity.
2) Mid evolution: suppression of standard neutrino processes in the core → slower cooling, driven by neutron and proton superfluidity in the core.
3) Late time: fully superfluid regime ($T \ll T_c$) → reduced heat capacity, so the star reacts faster to energy losses. Driven mainly by core neutron superfluidity.



Toy cooling model where only one component (crust neutrons, core protons, or core neutrons) is superfluid at **all densities from the start**.

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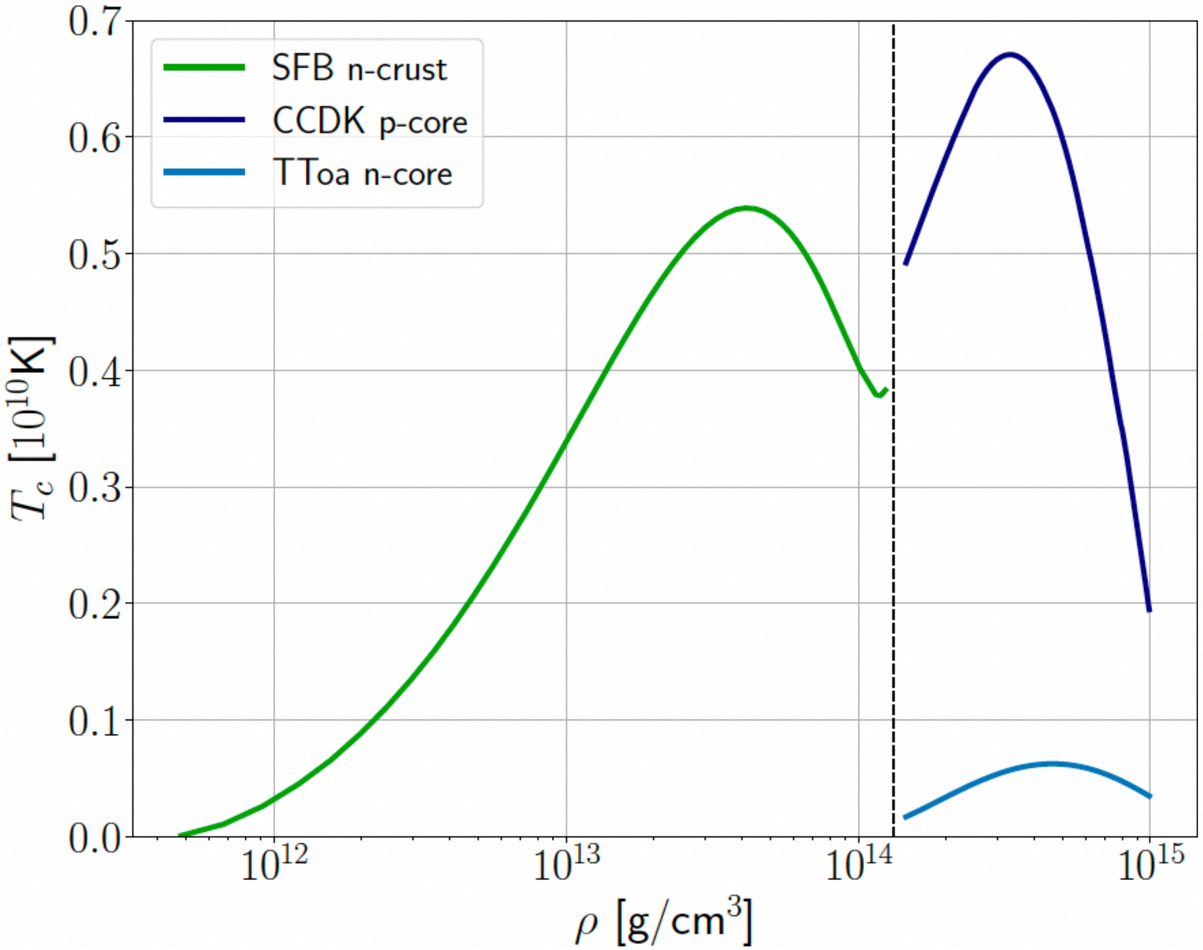
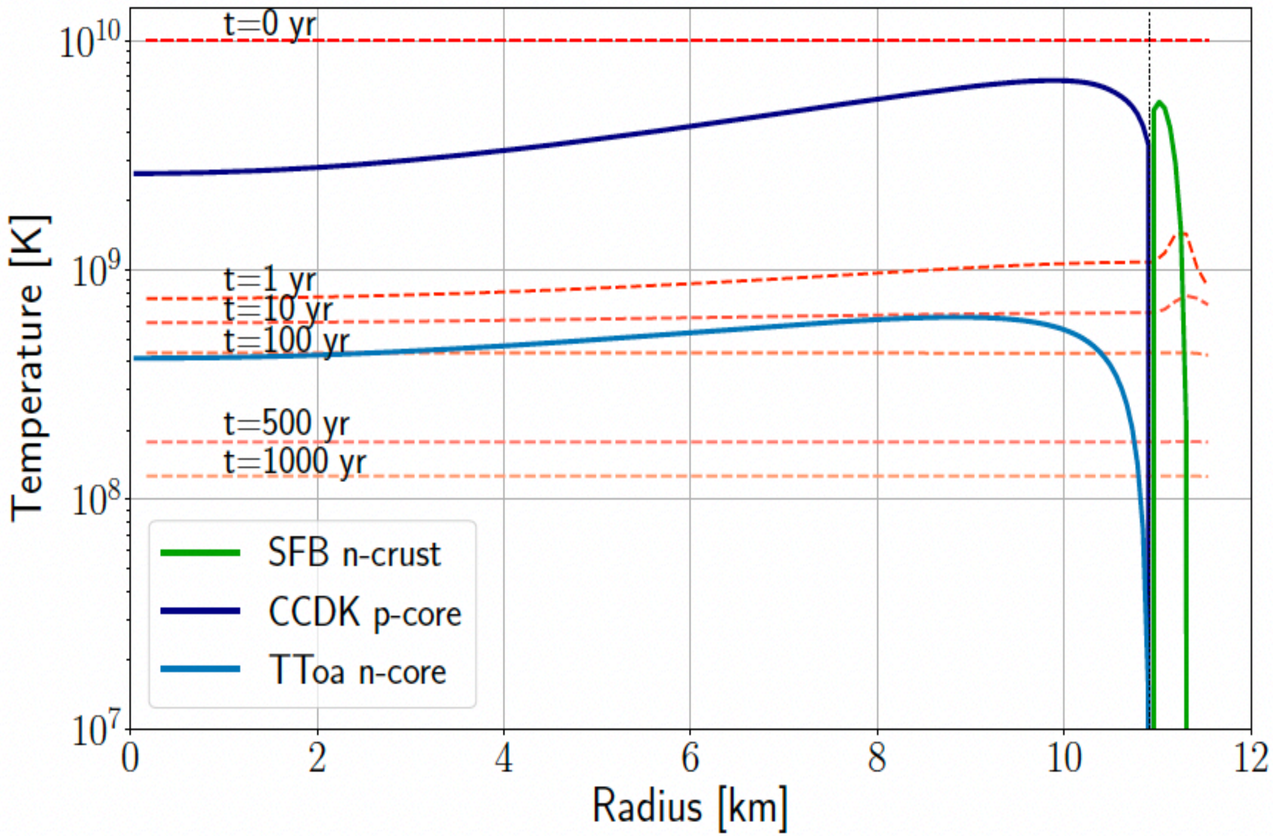
Gap models used in our current cooling models

SF081326: weak n-crust singlet gap (SFB); strong p-core singlet (CCDK); moderate n-core triplet (TToa).





SF081326 evolution:

- Superfluidity when T < T_c.
- Early (weeks–months): p-core + n-crust become superfluid.
- Later (~100 yrs): n-core becomes superfluid.
- ~100 yrs: star becomes isothermal (end of thermal relaxation).
- Core superfluid volume ≫ crust.

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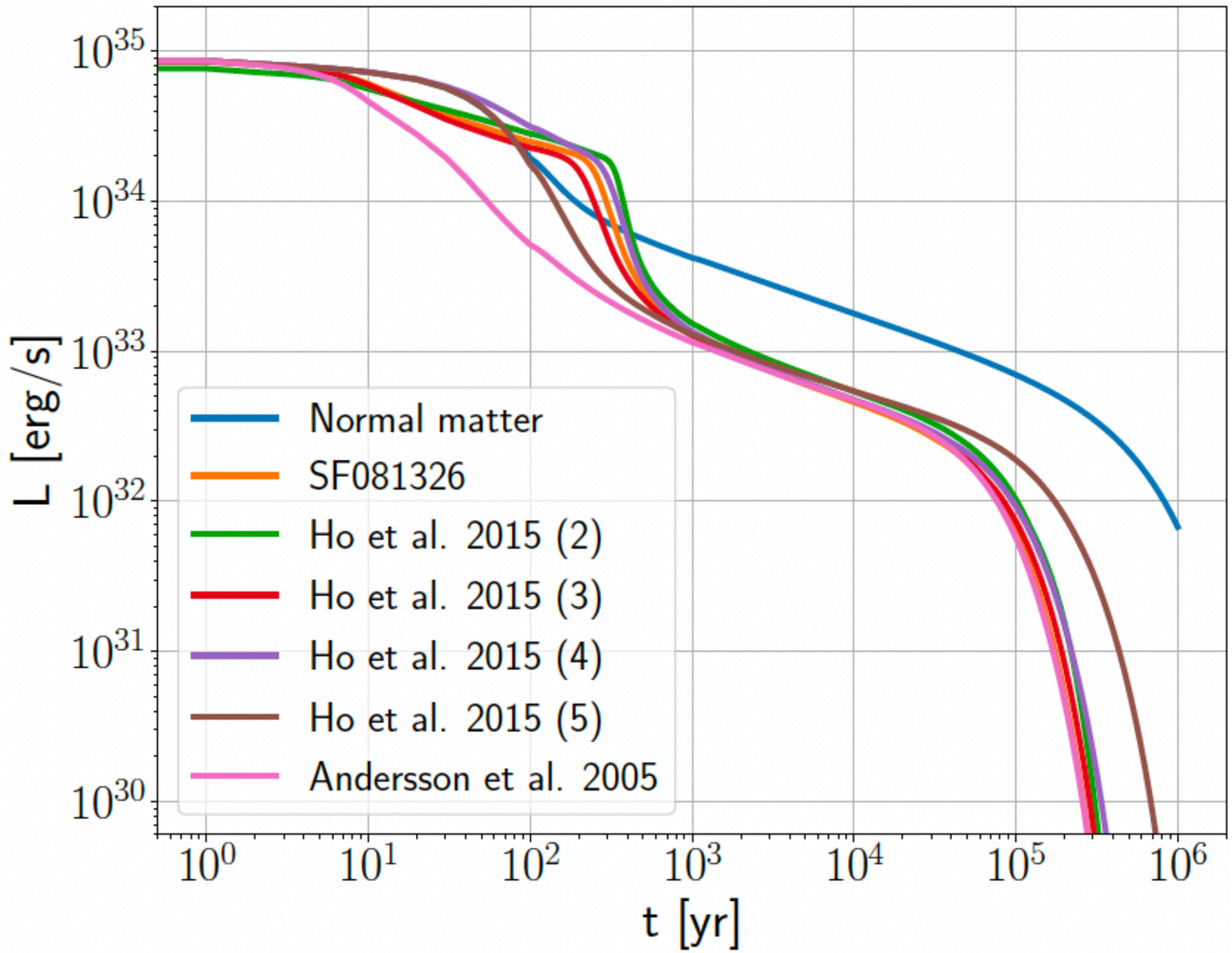
Impact of superfluidity and superconductivity on cooling

Realistic gaps are density-dependent; their height and shape (uncertain) set where superfluid transitions occur.

The stronger the pairing (larger gap Δ), the higher the temperature at which the system becomes superfluid/superconducting.

Real stars show overlapping superfluid transitions, with competing effects that evolve as the star cools.

Overall, superfluidity leads to faster cooling (BUT NOT enhanced cooling!) than normal matter.



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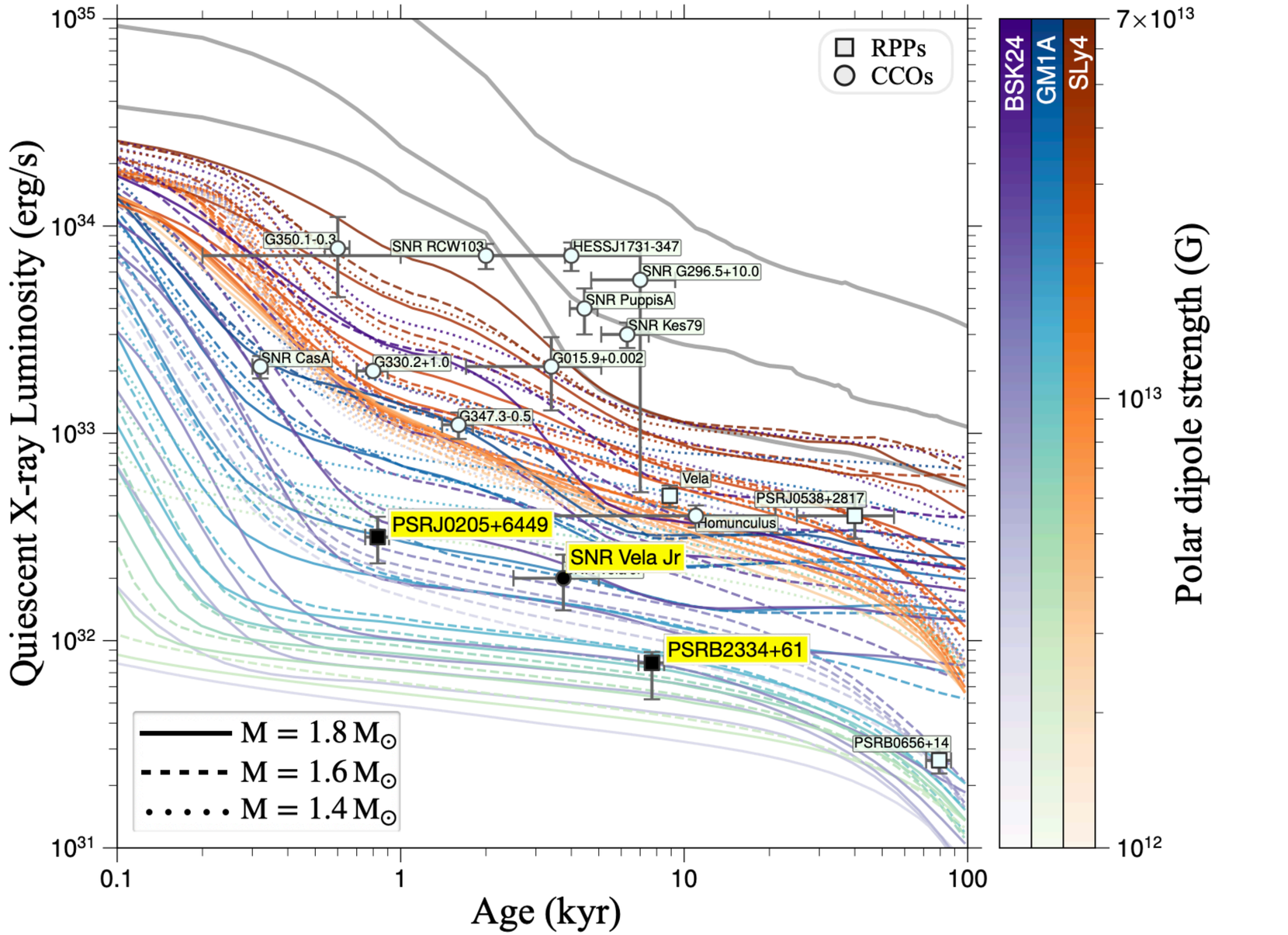
Enhanced cooling and constraining nuclear EoS

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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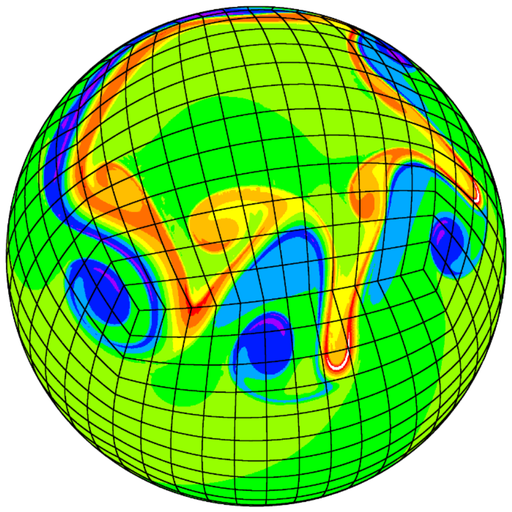
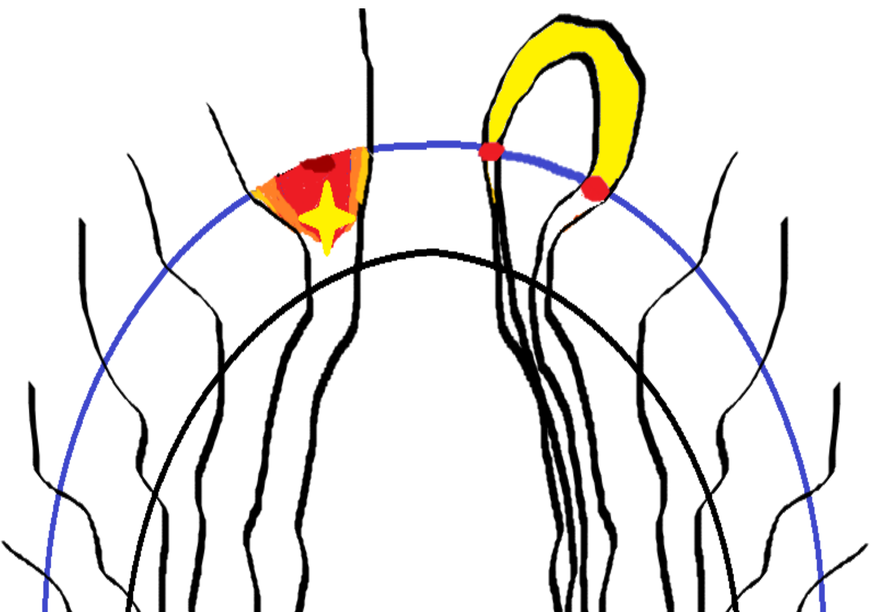


Magnetic Field

Evolution



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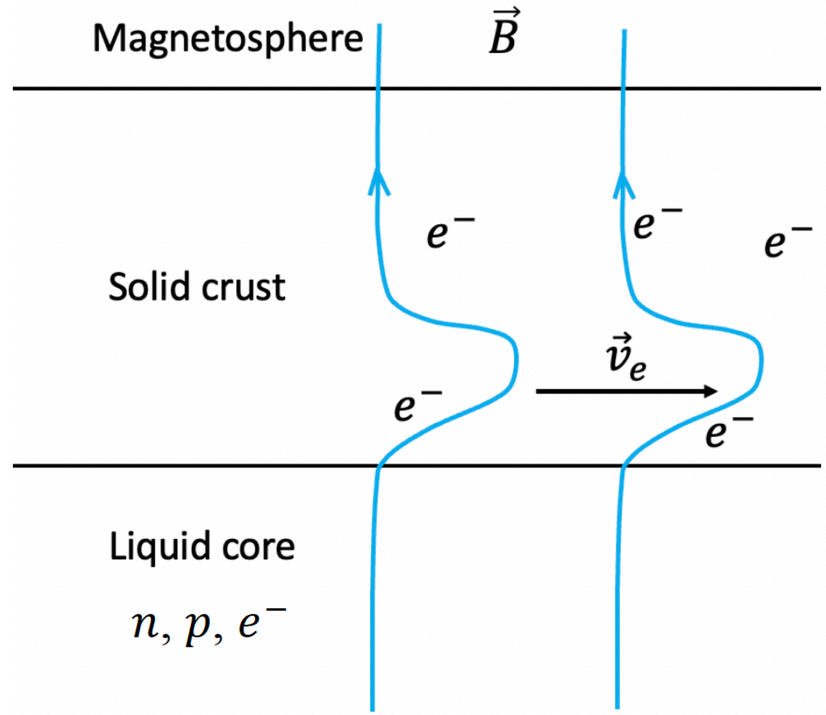
Magnetic field evolution in the crust

- **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.

[Pons, Dehman, Viganò 2026, Living Review]

[Dehman & Pons 2025, PRR]

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MATINS the brand new 3D code

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

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

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***

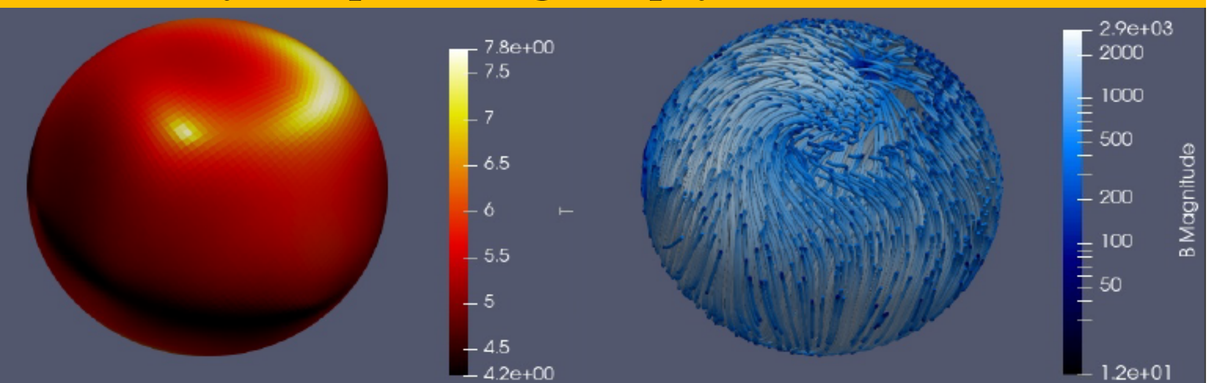
Dehman *& Pons 2025, PRR* (DOI: ***10.1103/rhv5-nd4v***): ***Chiral magnetic effect***

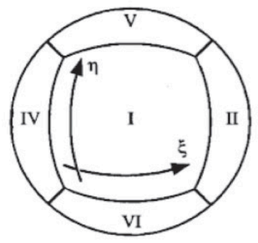
What's better than 2D (Viganò et al. 2021):

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

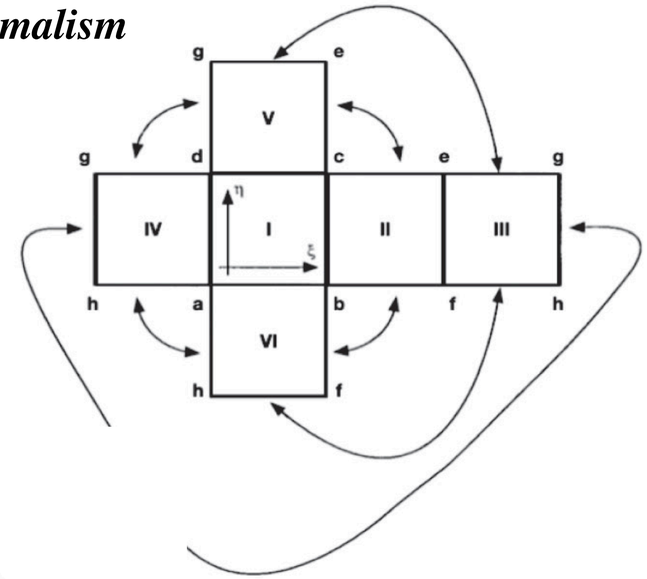
Advance obtained:

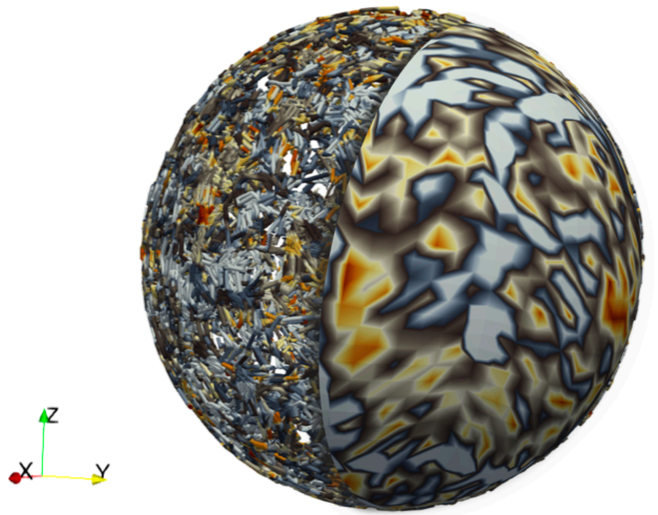
- **Realistic 3D evolution and topology, appearance of hotspots**
- **State-of-the-art microphysics, various masses and EOSs, with realistic structure obtained by solving the TOV equation.**
- **Numerical scheme to better capture non-linear dynamics**
- **General relativistic correction**
- **State of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





cubed sphere





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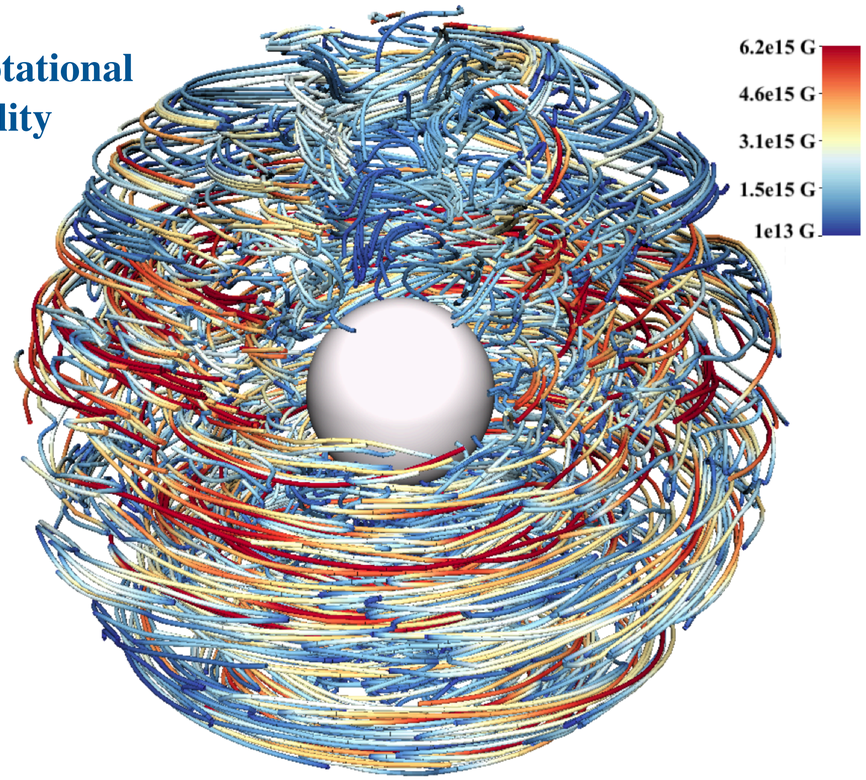
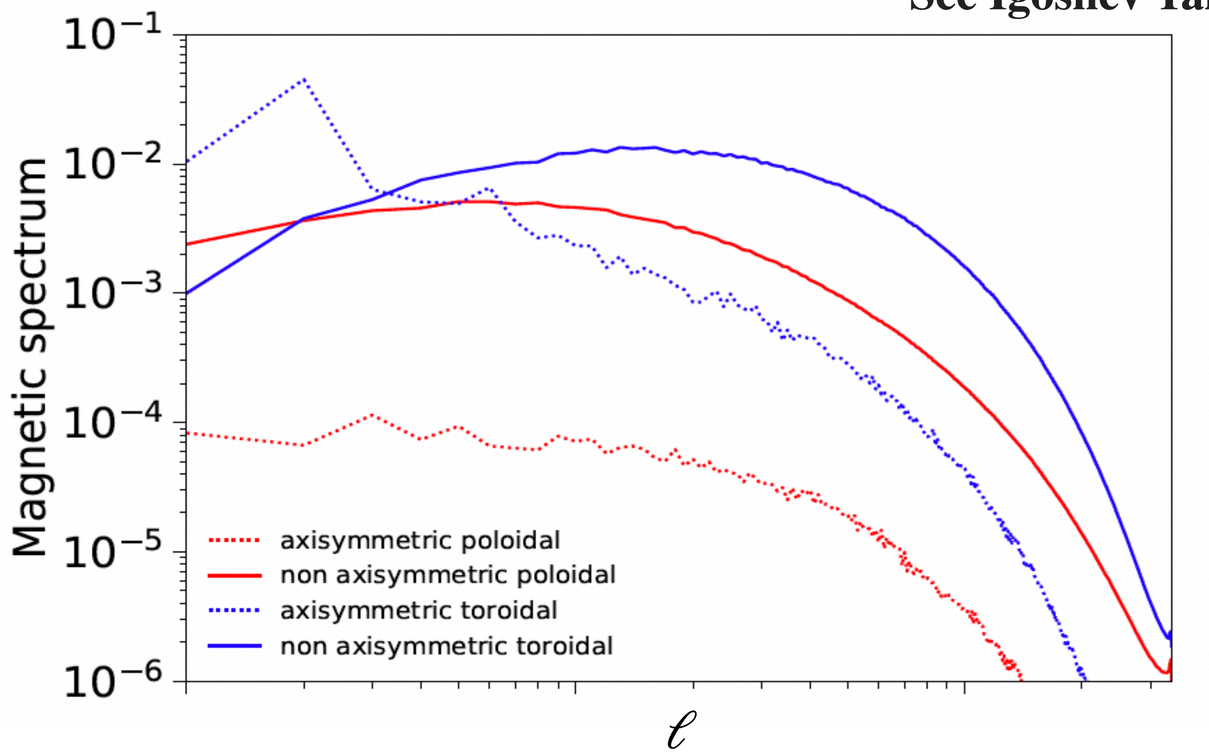
Magnetic field at birth: Magnetic spectrum after core-collapse

Magneto-rotational instability



See Igoshev Talk



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!

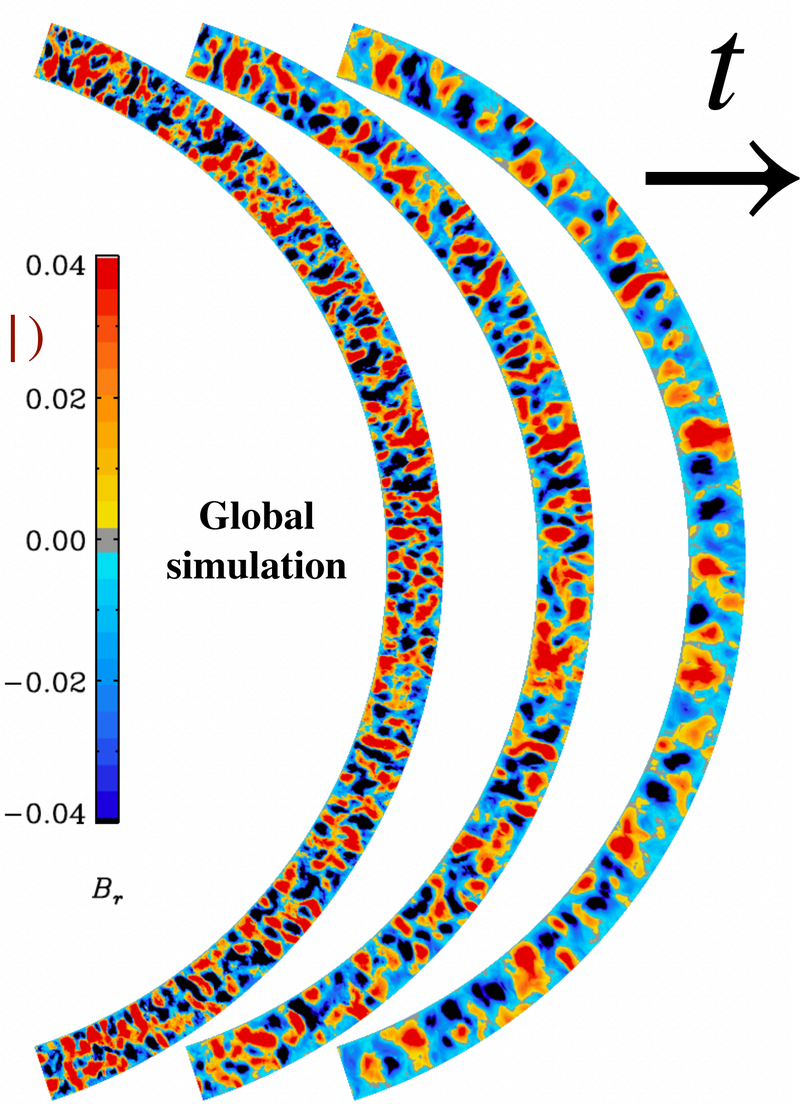
Energy transferred from small to large-scale multipoles.
Not observed in previous neutron star simulation studies.
Extreme aspect ratio (1:30)—thin crust— limits the inverse cascade.

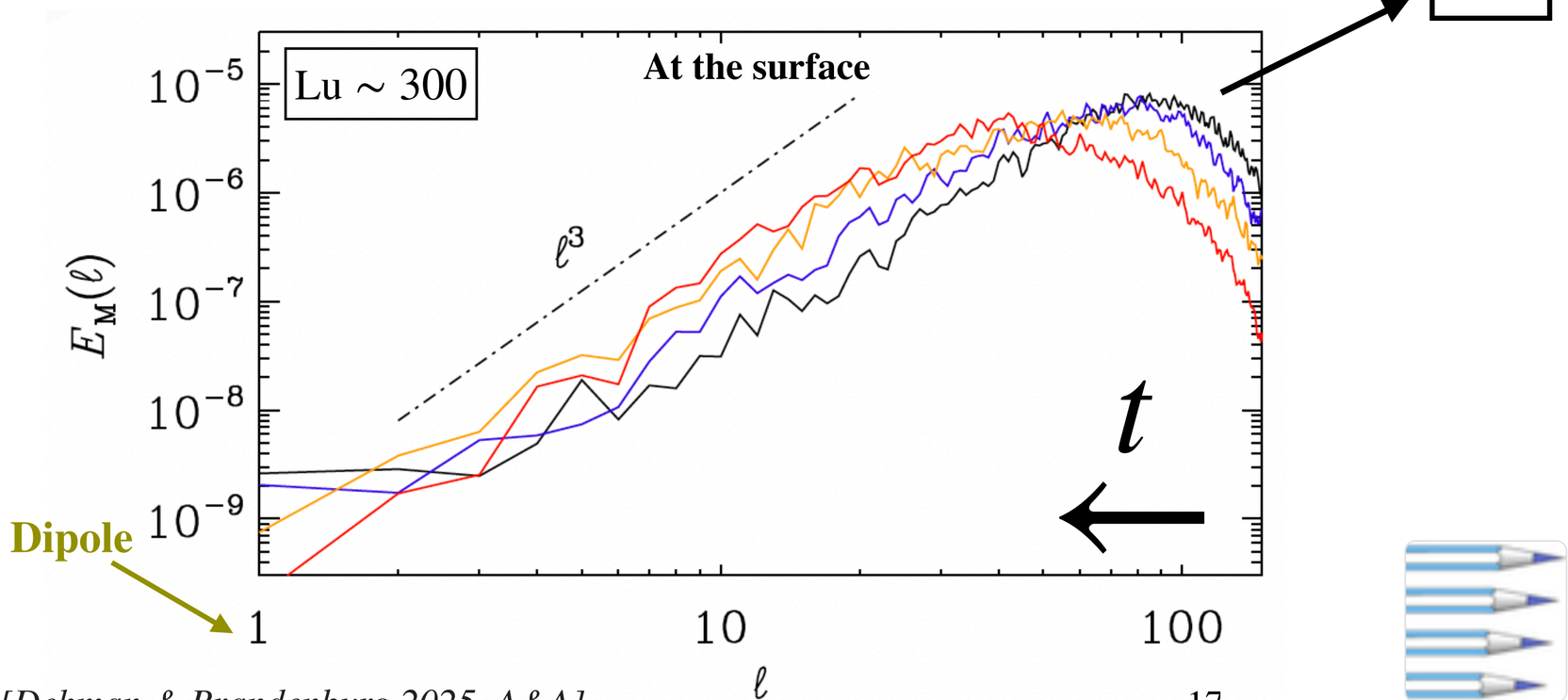
Maximally helical
(e.g., positive helicity):

$$k = p + q$$

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

$$|k| \le \max(|p|, |q|)$$





[Dehman & Brandenburg 2025, A&A]

Pencil Code

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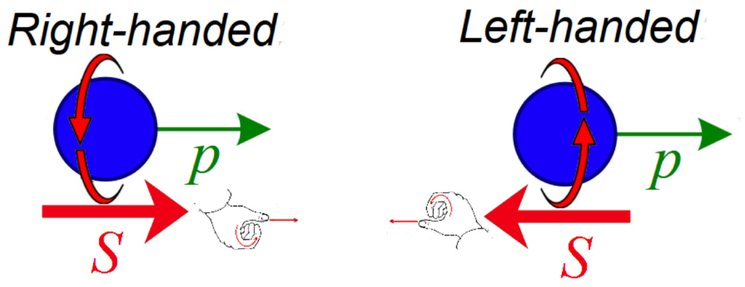
Chiral Anomaly



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

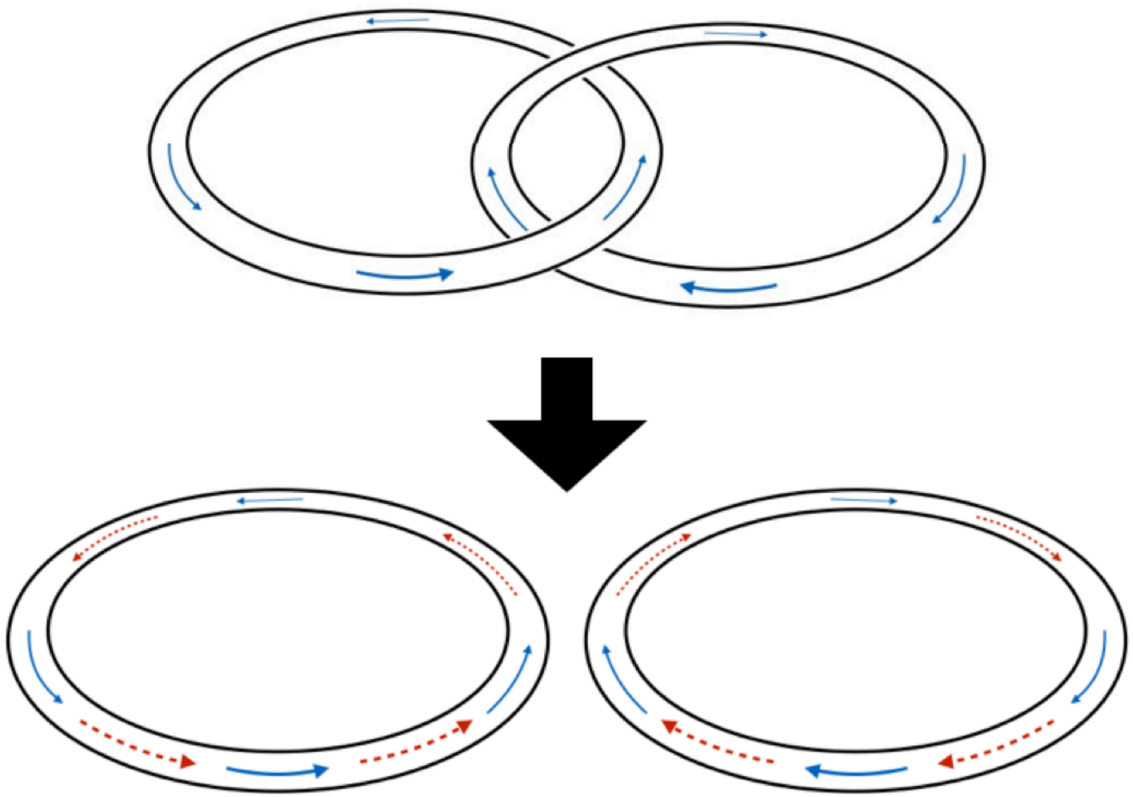


Image credit: Y. Hirono

[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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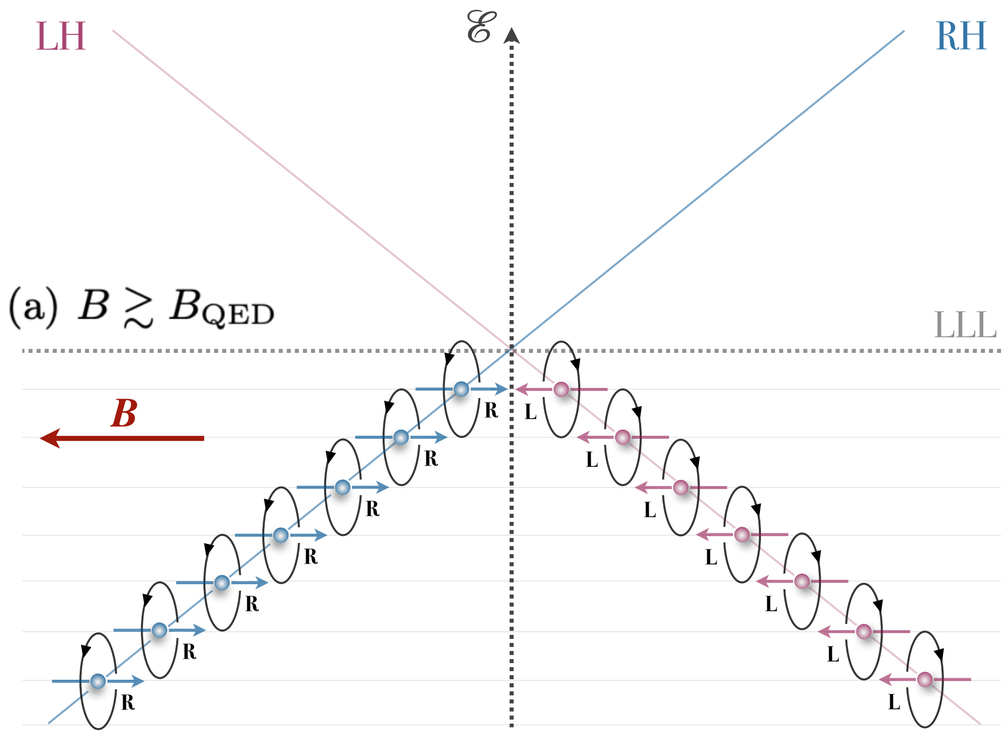
MAgneto-Thermal evolution of Isolated Neutron Stars



[Dehman 2026, arXiv: 2605.08068]

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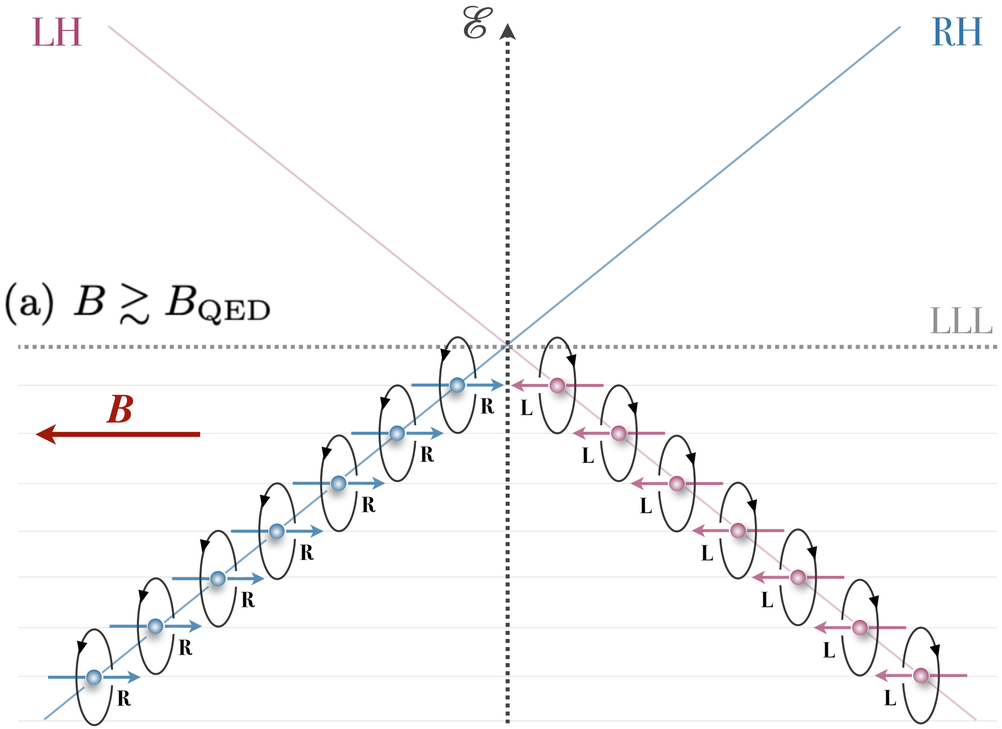
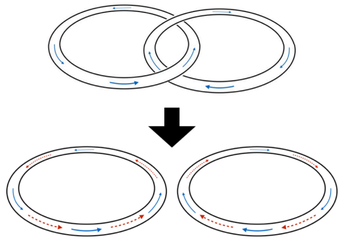
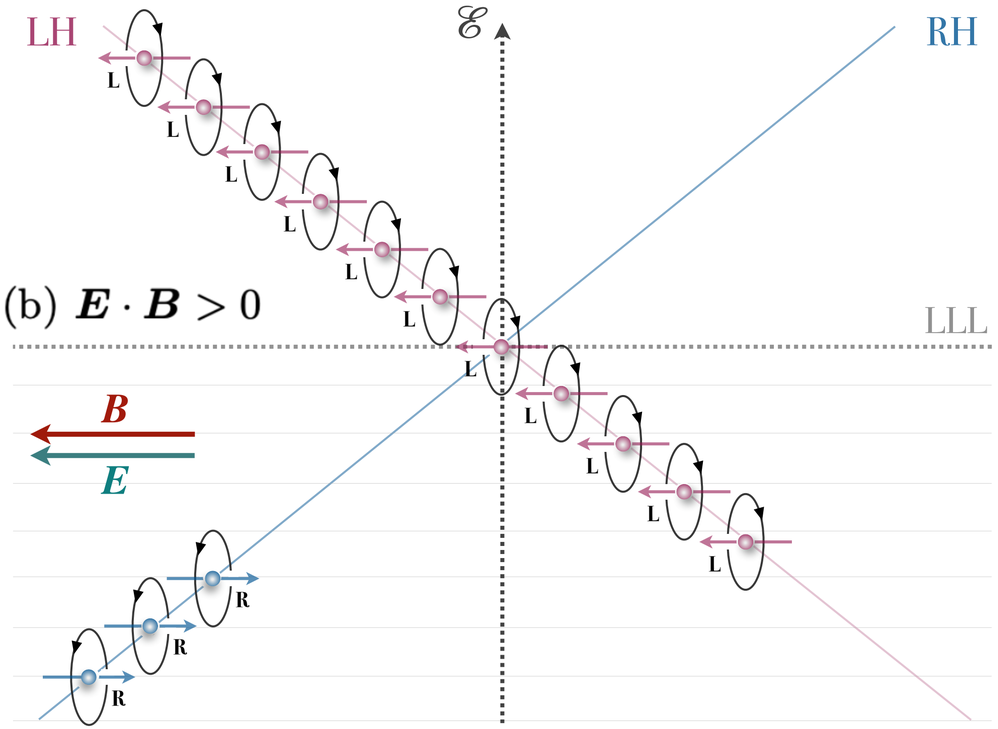
MAgneto-**T**hermal evolution
of **I**solated **N**eutron **S**tars







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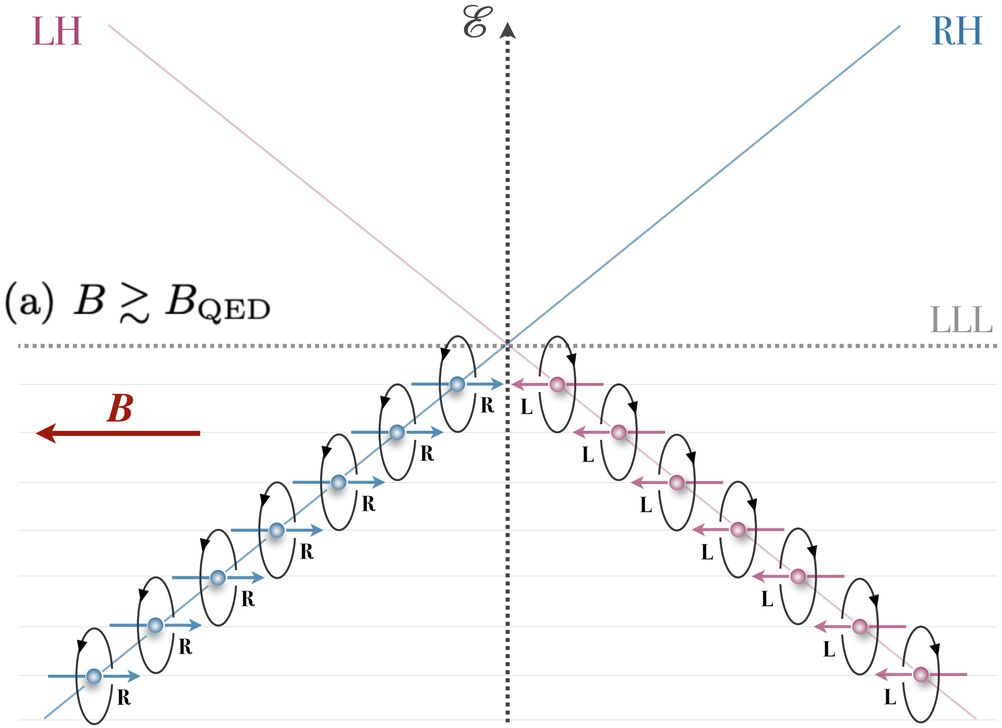

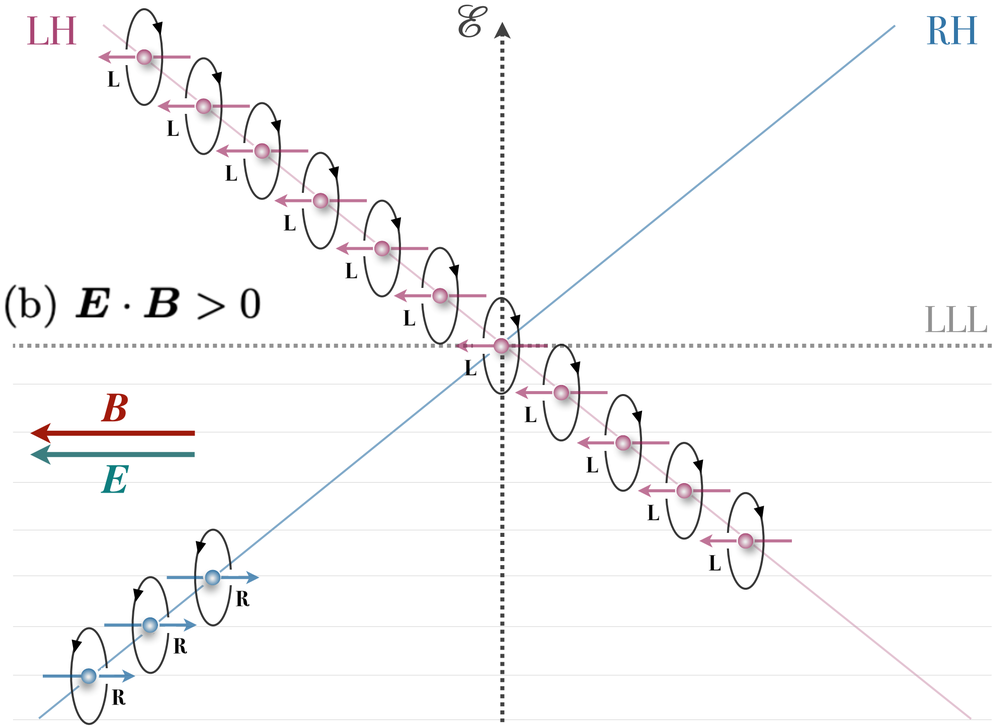

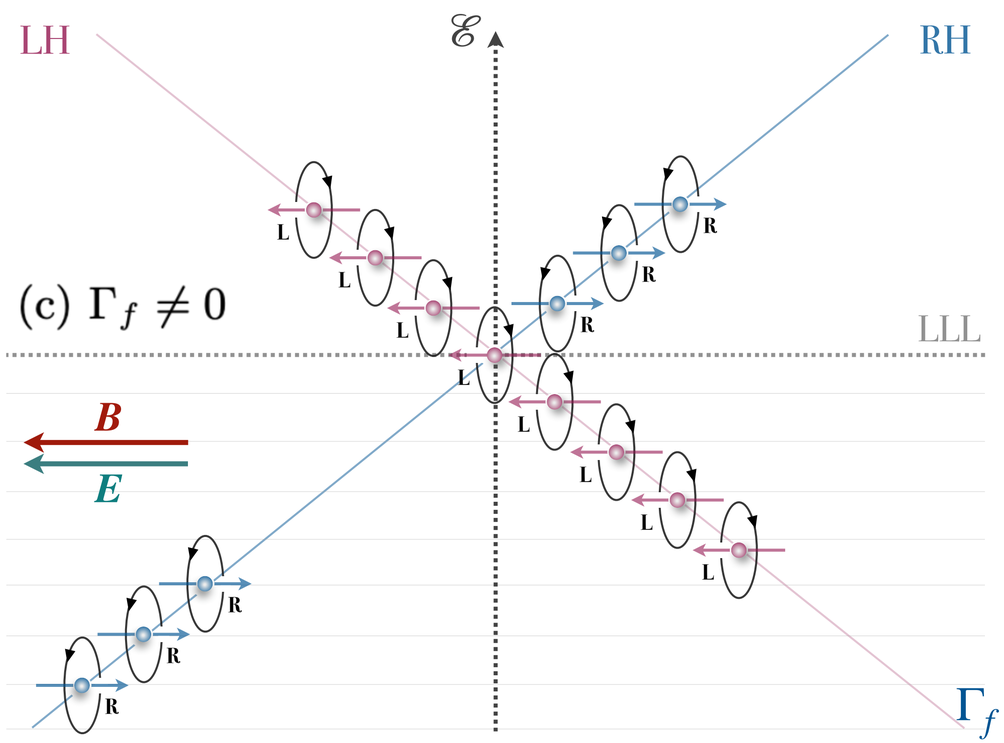

[Dehman 2026, arXiv: 2605.08068]

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

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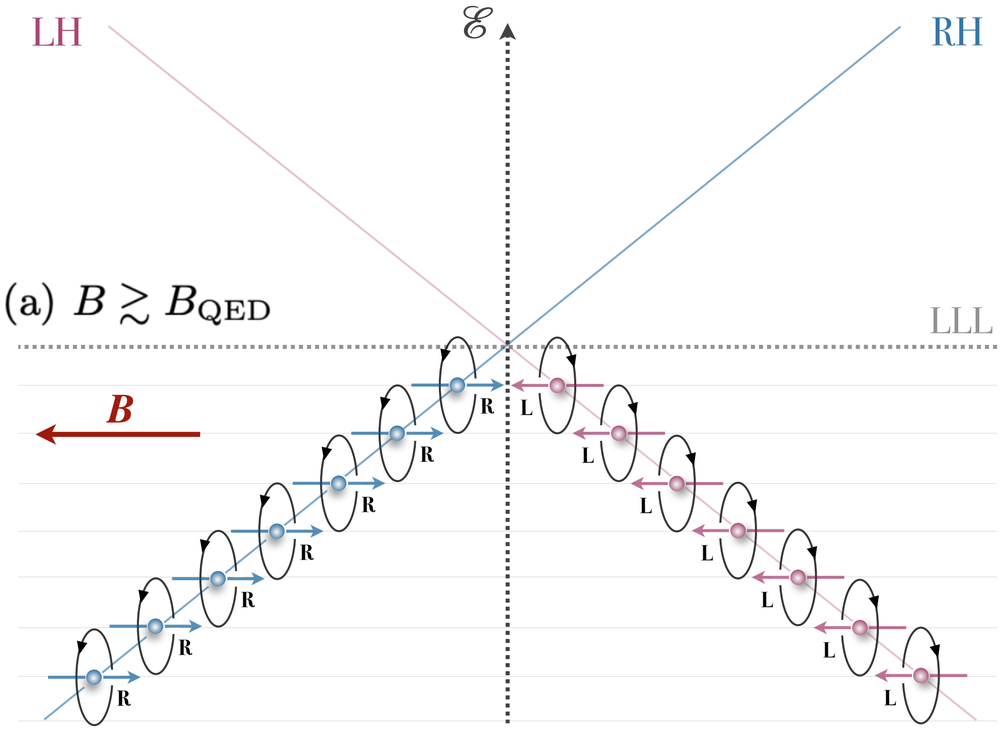

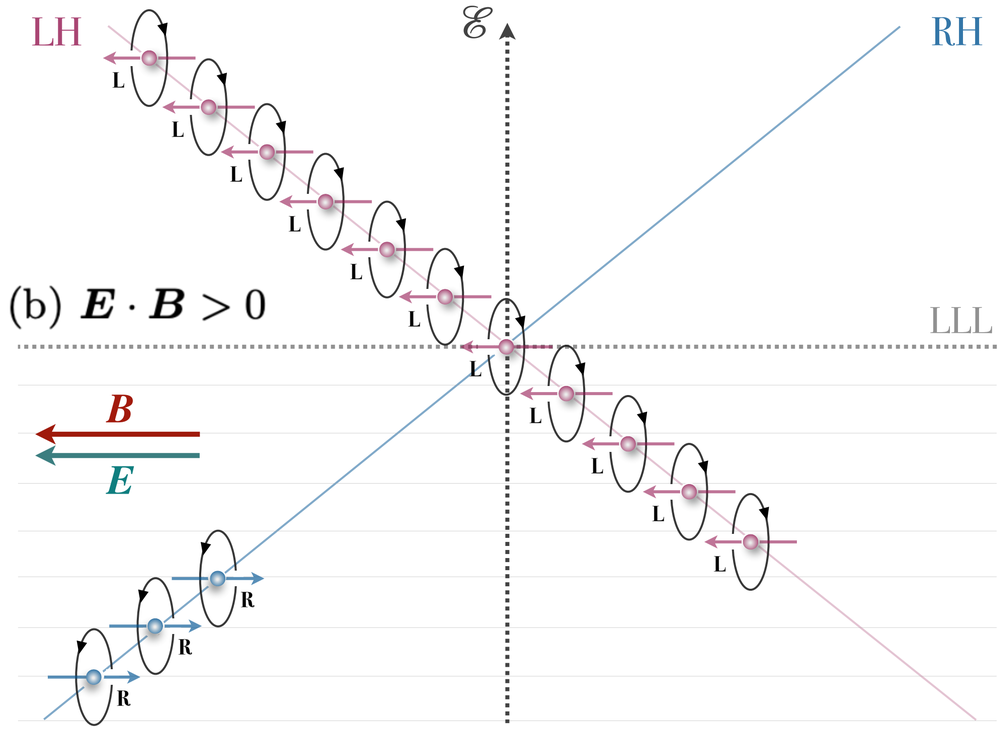

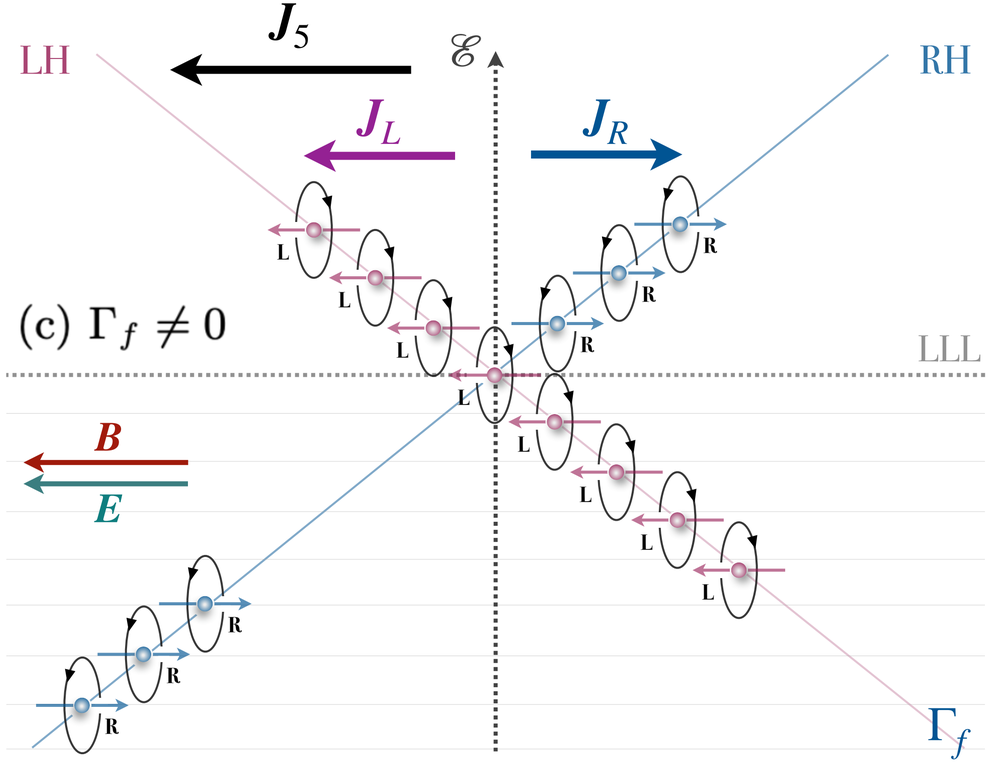

[Dehman 2026, arXiv: 2605.08068]

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

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

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

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

[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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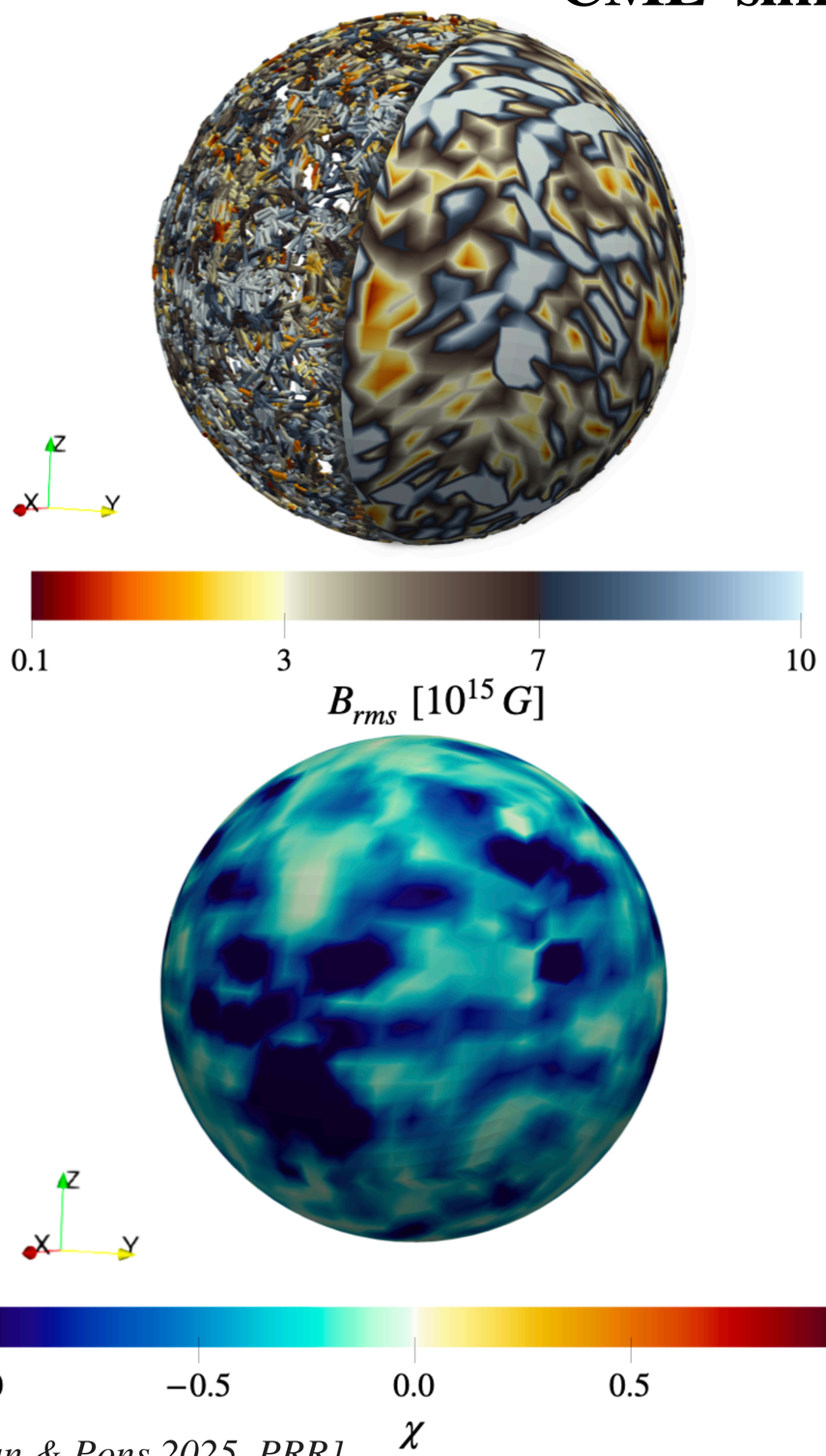
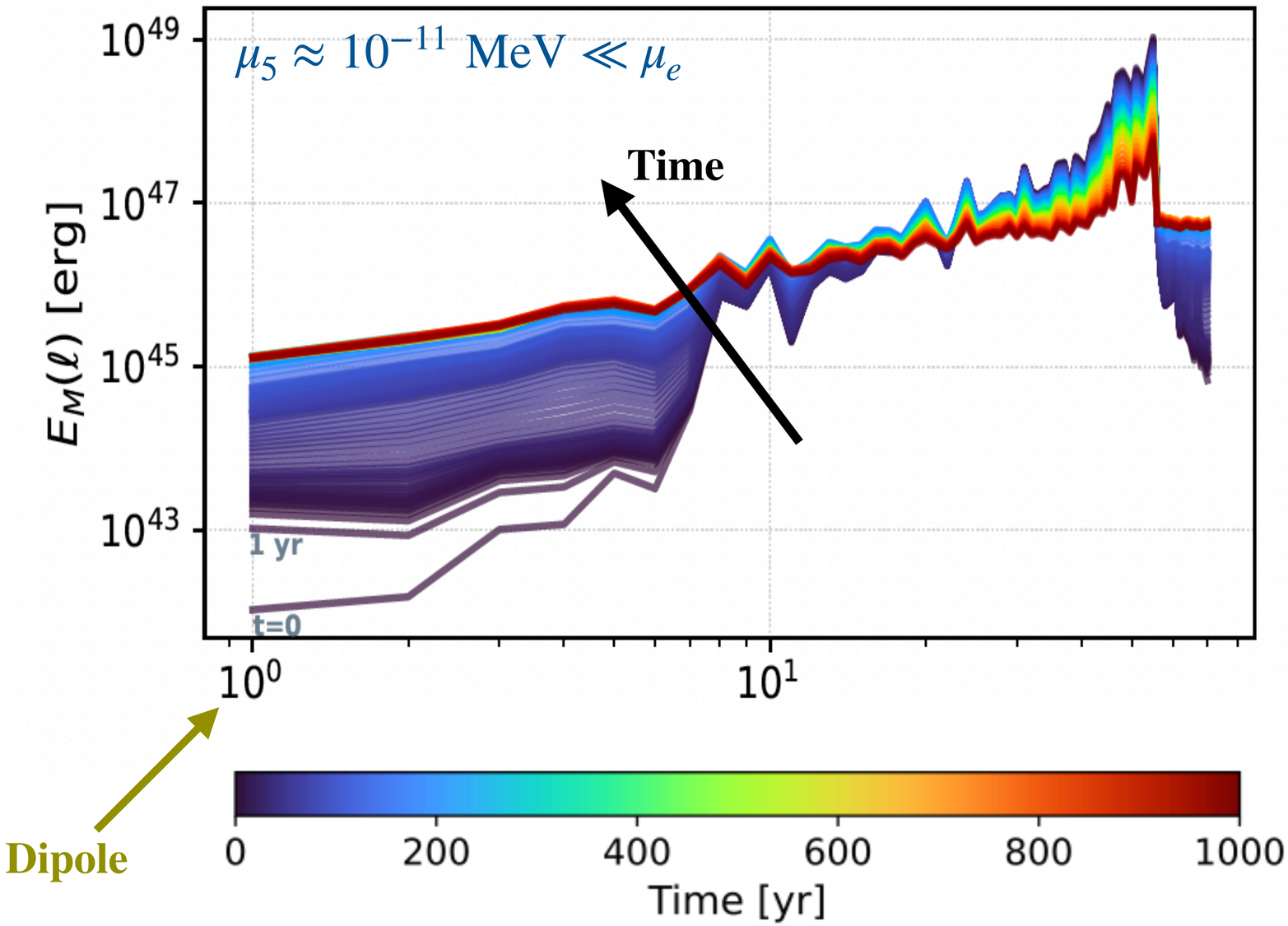
CME simulations — net magnetic helicity



[Dehman & Pons 2025, PRR]



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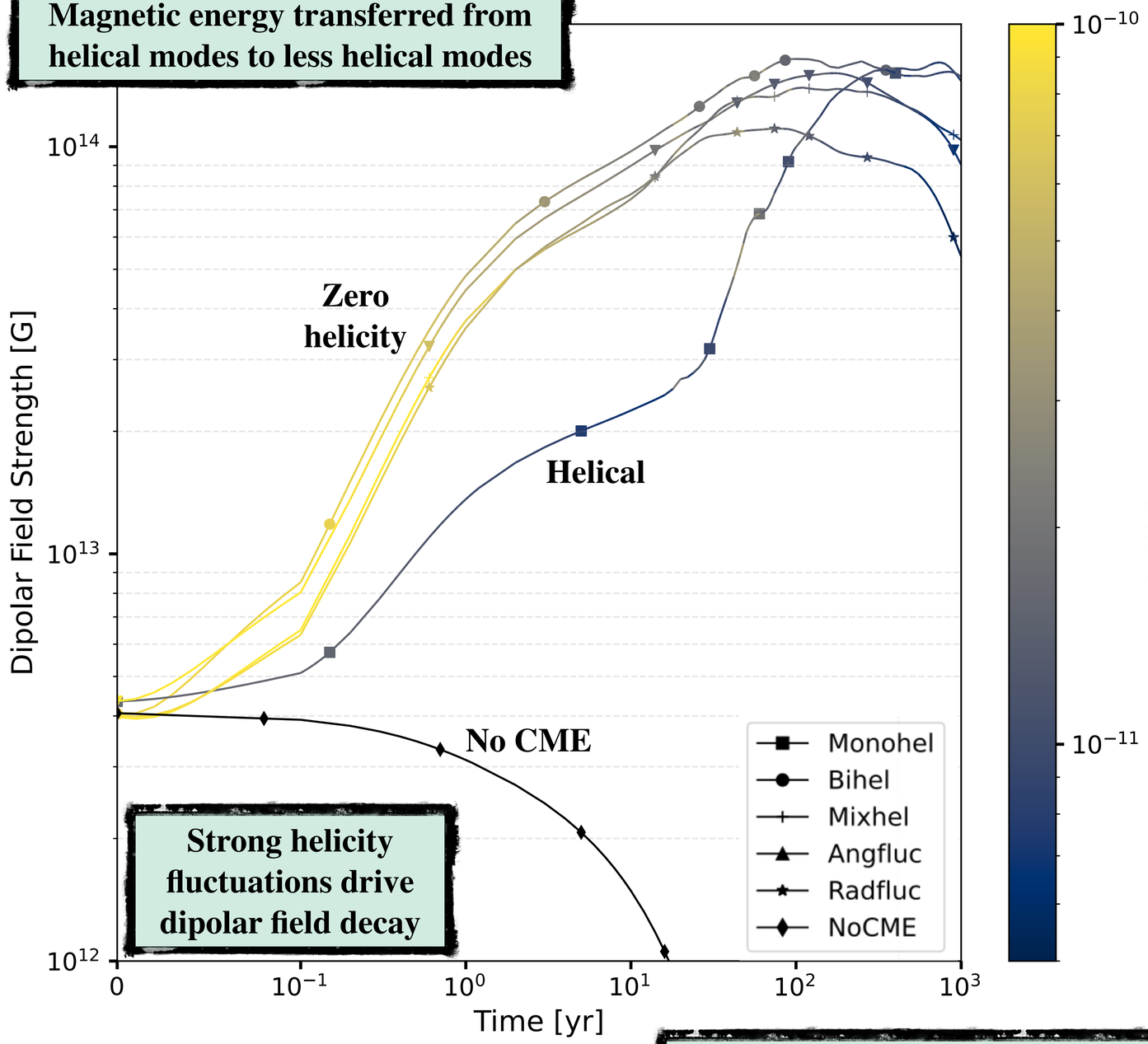
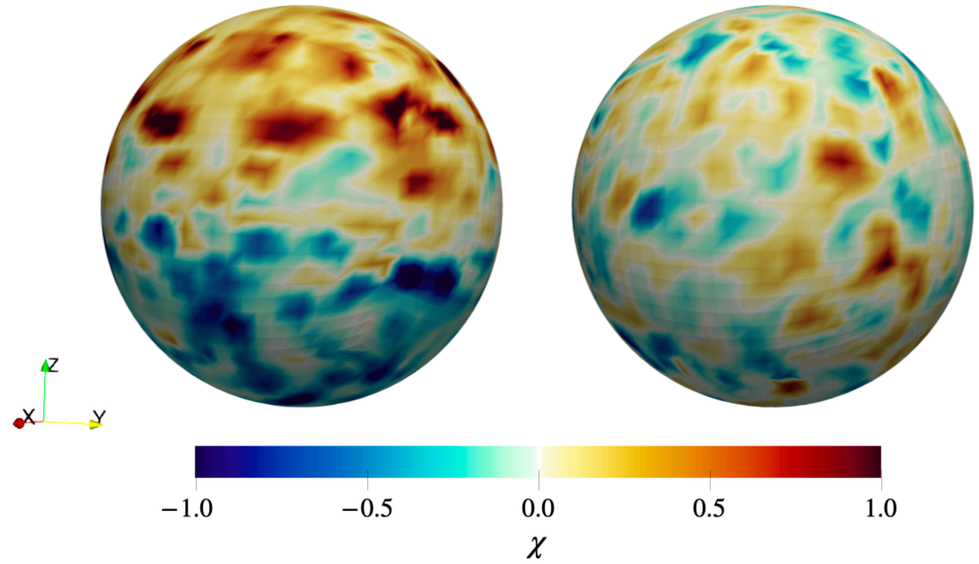
CME simulations — vanishing helicity

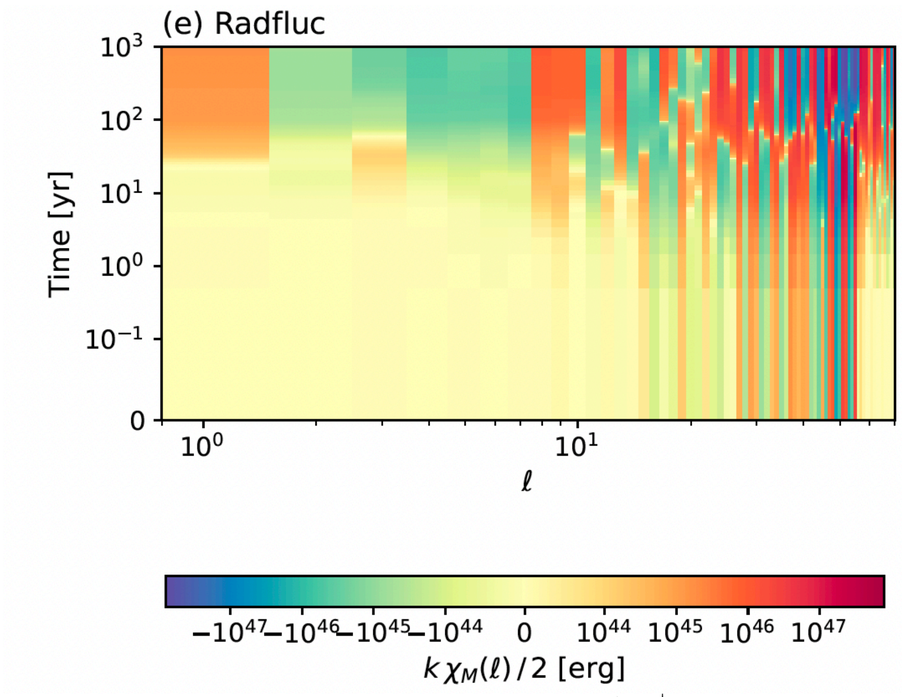
Onset of CMI is governed by $|\mu_5^{\max}|$

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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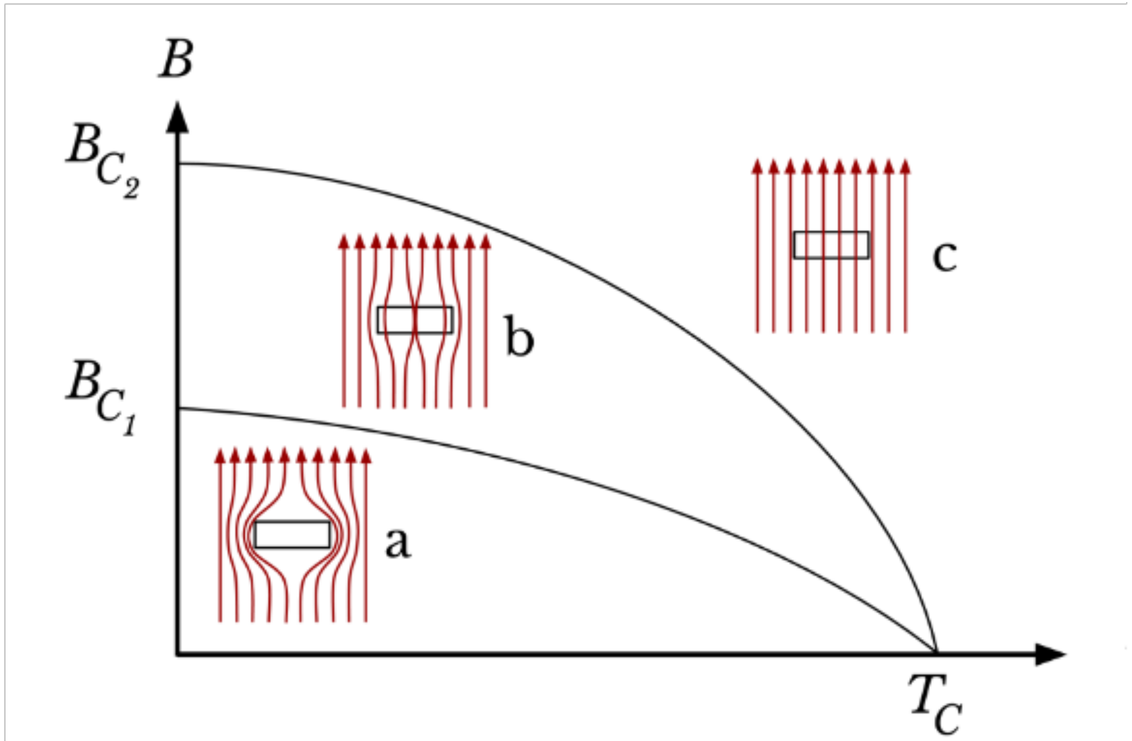
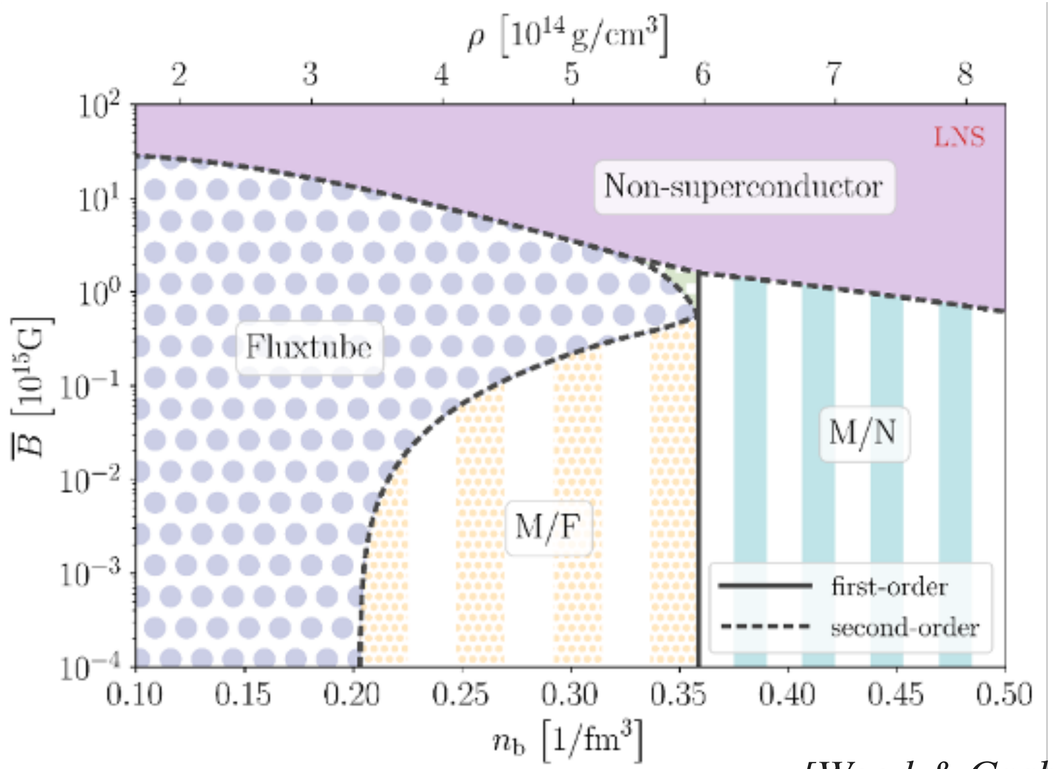
What physics is still missing?

Magnetic field evolution in the core





[Wood & Graber 2022]

In the core, physics is more complex. A mixture of neutrons, protons, electrons, muons (and others?) is expected: multi-fluid MHD —> ambipolar diffusion.

Moreover: superfluidity (neutrons) and superconductivity (protons) of type II (b), with the magnetic flux contained in tiny vortexes (fluxtubes); for lower B, Meissner effect (type I, (a)).

Multi-spatial/timescale problem extremely challenging! (Gusakov et al. 2020 for a review of the current debate, and Igoshev & Hollerbach 2022 for recent results –no SC, only ambipolar diffusion-).

How does type-II superconductivity affect field evolution in the core?

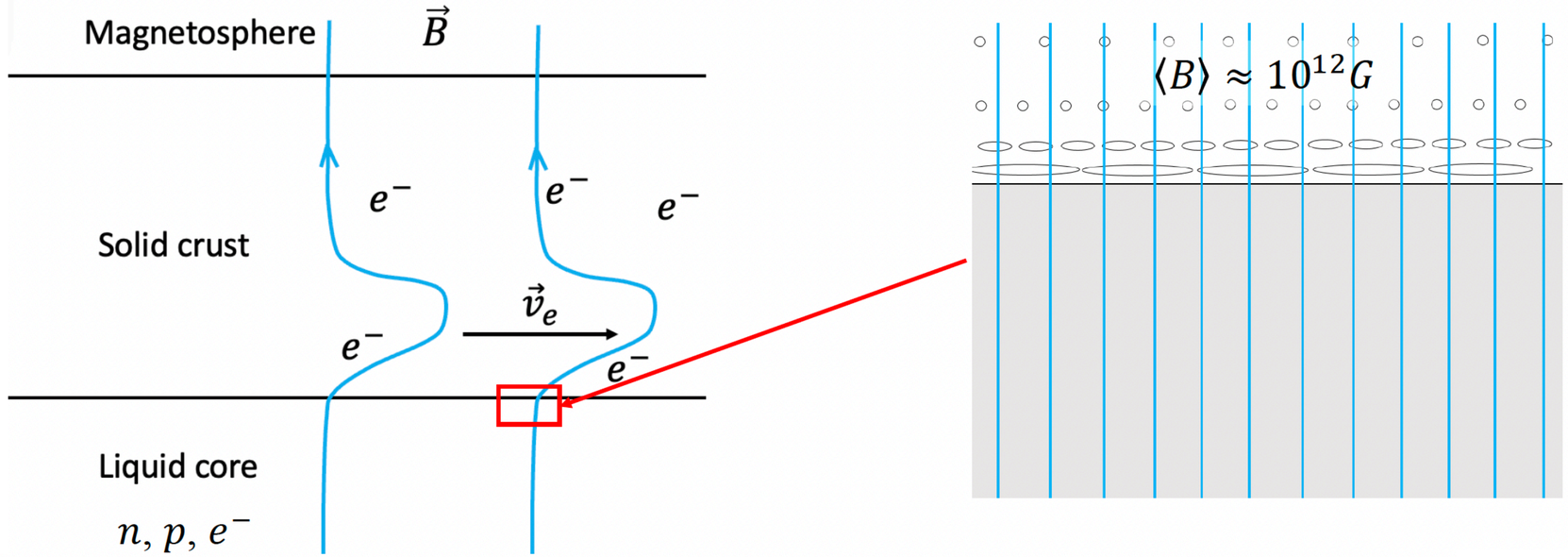
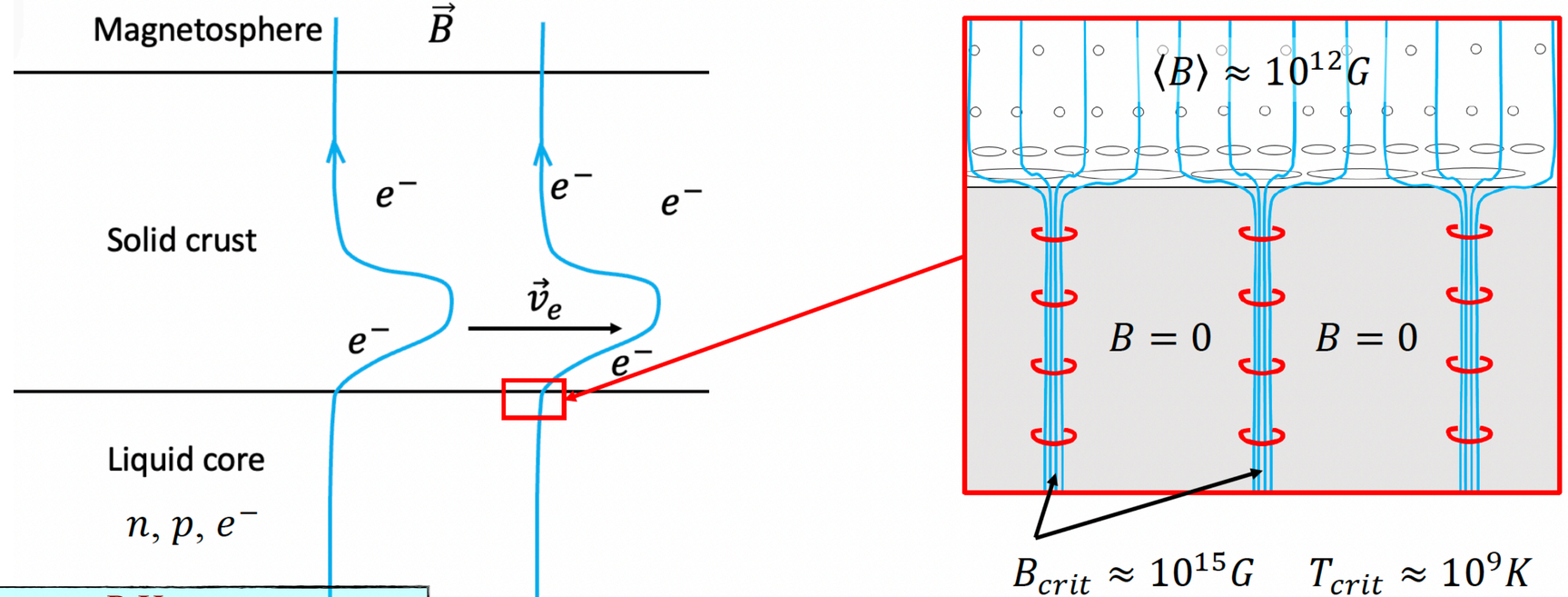


Image credit: Y. Levin

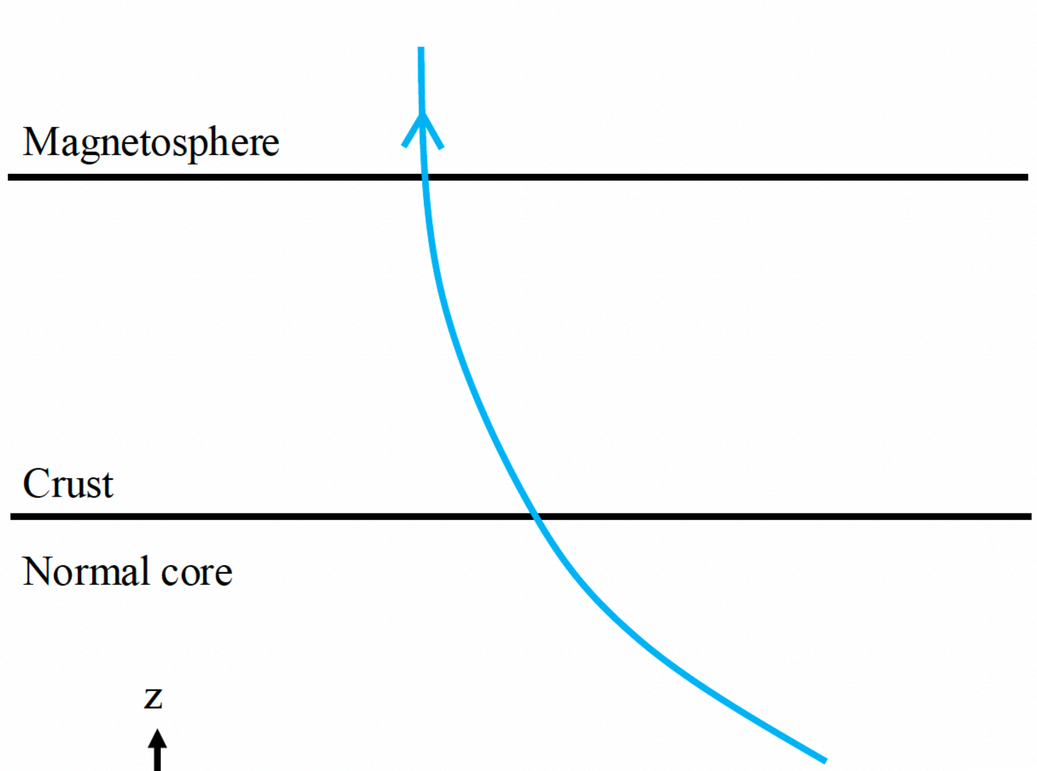
TYPE II SUPERCONDUCTOR



Maxwell Stress: $\frac{B_i B_j}{4\pi} \rightarrow \frac{B_i H_j}{4\pi}$ **1000x larger**

[Midgal 1959; Baym+1969; Akgun & Wasserman 2008]

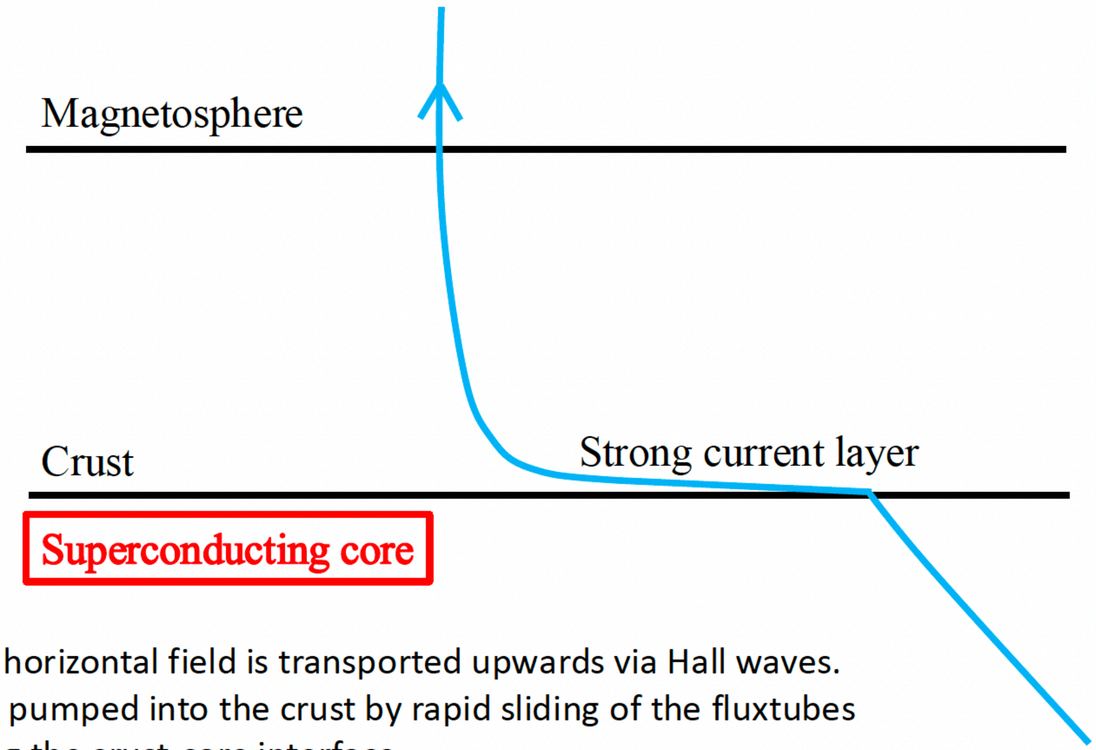
Hall-pulse launch at the crust-core interface



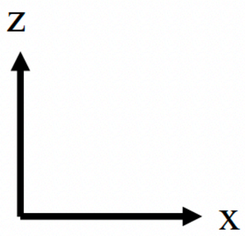
Matching conditions

$B_x(0^+) = B_x(0^-)$
$B_y(0^+) = B_y(0^-)$
$B_z(0^+) = B_z(0^-)$

Image credit: Y. Levin



The horizontal field is transported upwards via Hall waves.
It is pumped into the crust by rapid sliding of the fluxtubes along the crust-core interface.



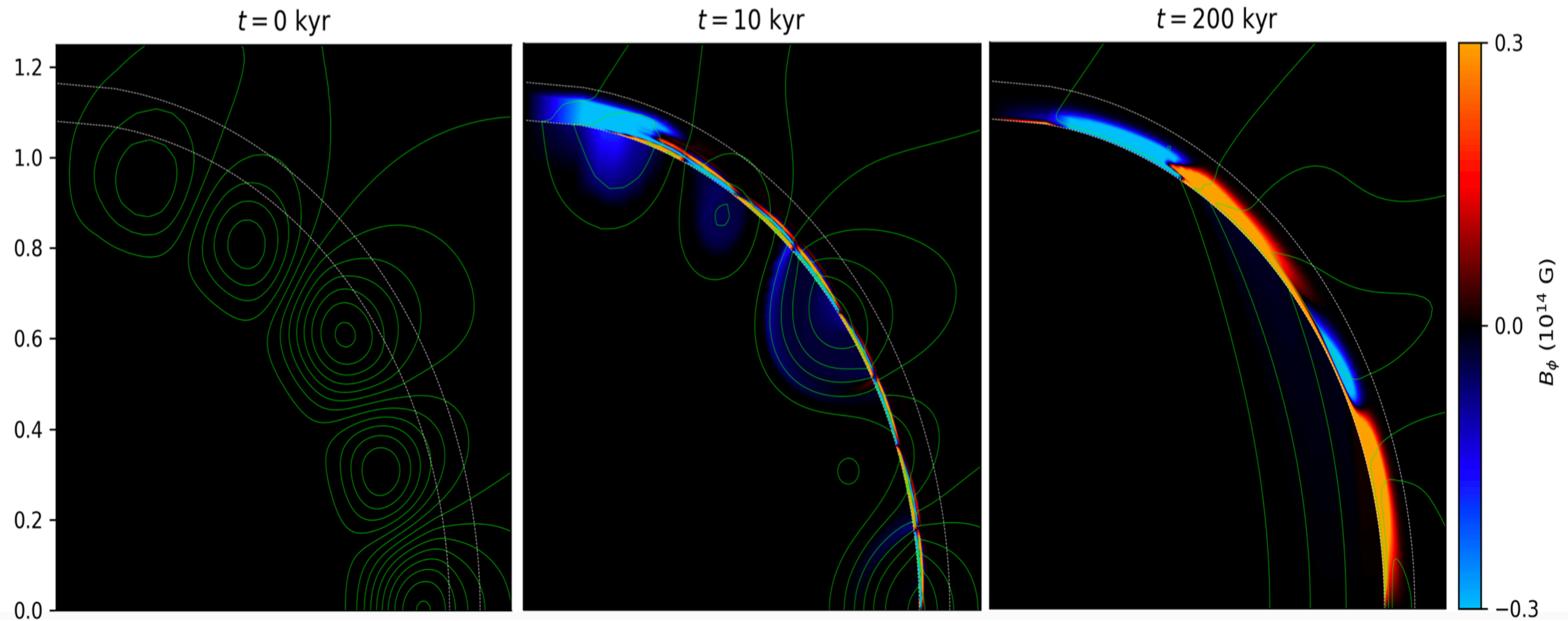
Matching conditions:
continuity of tangential Maxwell stress

$B_x(0^+) = H_x(0^-)$
$B_y(0^+) = H_y(0^-)$
$B_z(0^+) = B_z(0^-)$

[Akgun & Wasserman 2008]

Hall-pulse launch at the crust-core interface

— 2D simulations —



A potential candidate to explain variation in the braking index, crustal failures in the crusts of pulsars (low magnetic field with respect to magnetars).

[Bransgrove, Levin & Beloborodov 2025]

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.

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.**

Including superconductivity in magnetic field evolution is essential for realistic studies.

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