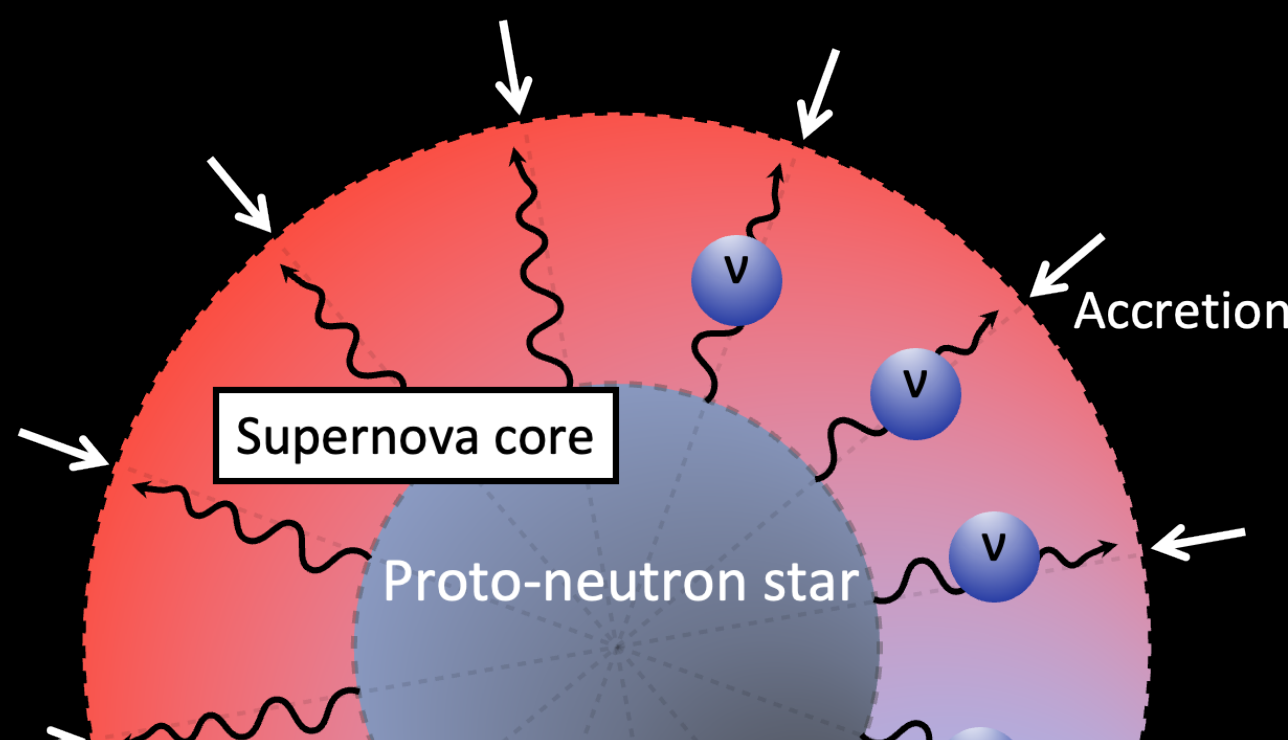
Parity violation of the weak interaction and supernovae

Naoki Yamamoto (Keio University)

Condensed Matter Physics of QCD 2024

Main message

- Key to explosion and neutron star formation: neutrino transport
- Microscopic process: weak interaction
- Conventional neutrino transport theory ignores parity violation
- This qualitatively modifies the dynamical evolution of supernovae



$$\mathrm{n} + \nu_{\mathrm{e}}^{\mathrm{L}} \leftrightarrow \mathrm{p} + \mathrm{e}^{\mathrm{L}}$$

Magnetars

- Neutrons stars with strong magnetic fields
- Surface magnetic field ~10^{15} G ("the strongest magnet")
- Origin of such a strong and stable magnetic field?

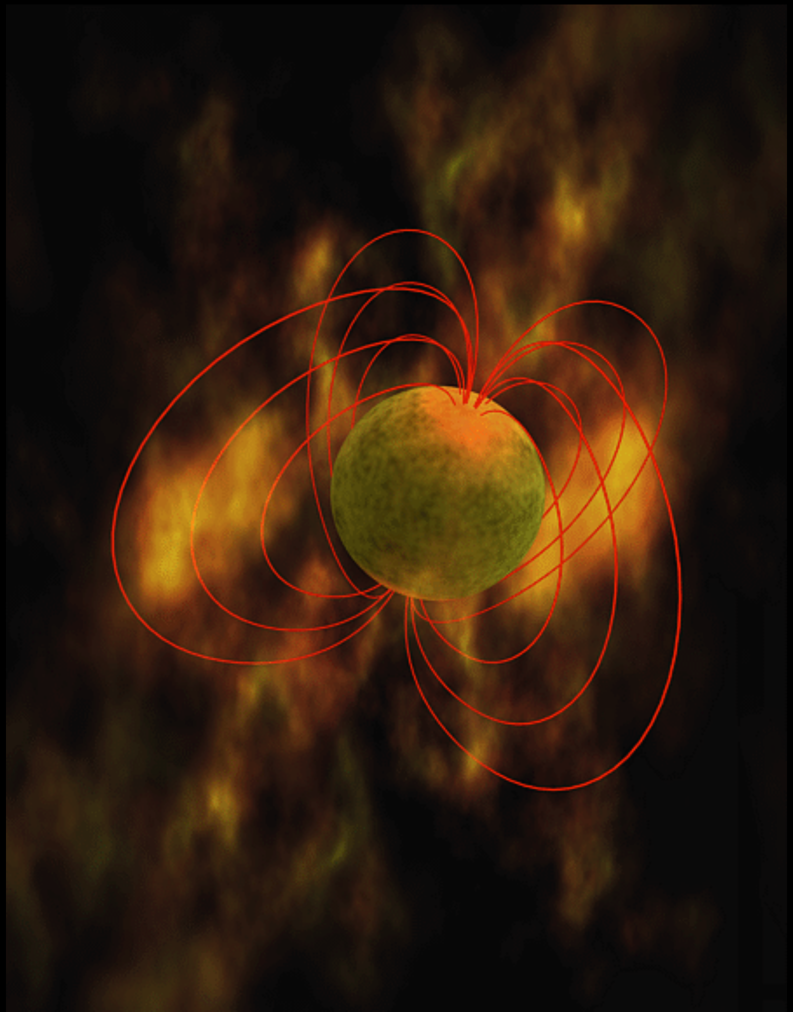
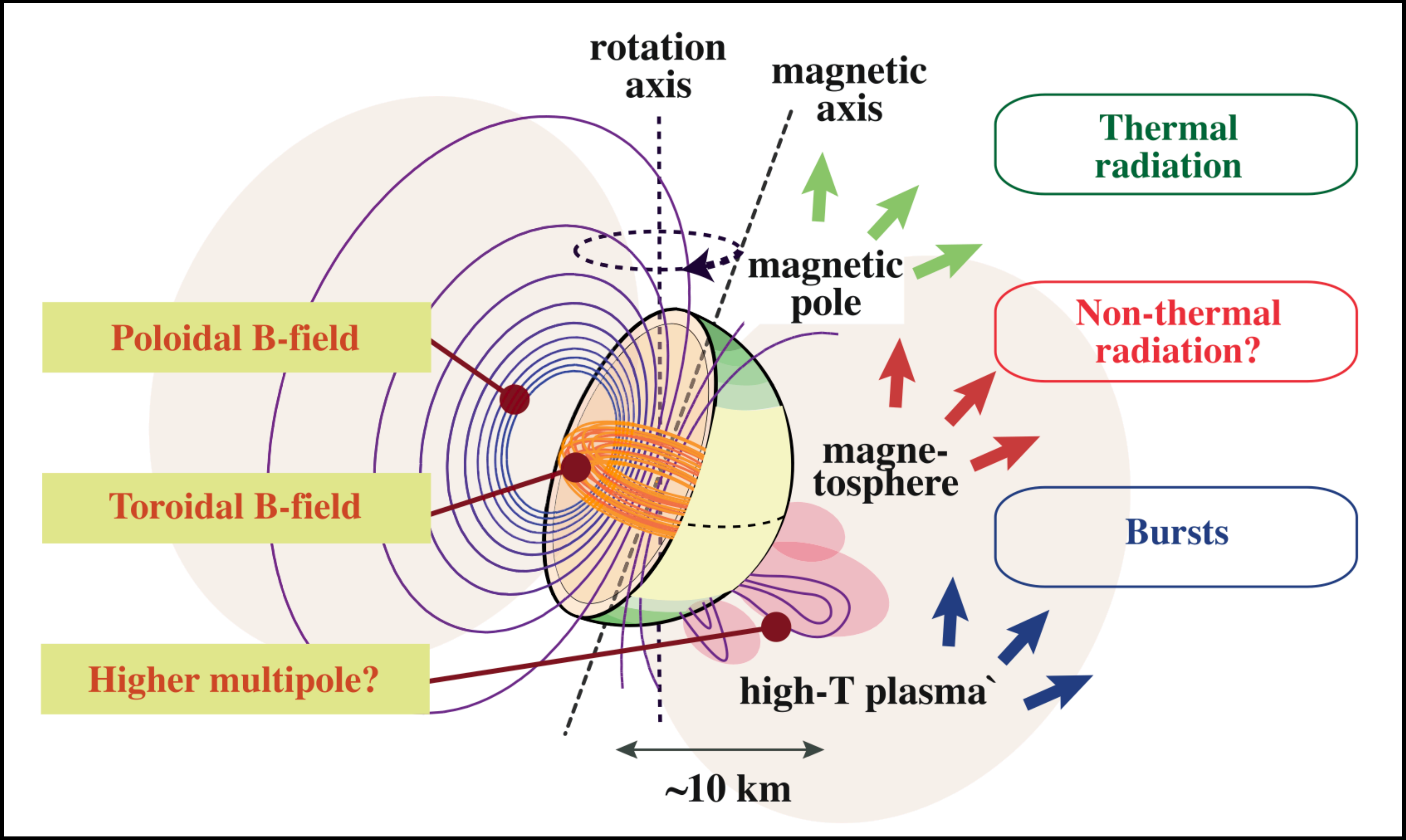


Illustration from Wikipedia

Poloidal and toroidal fields

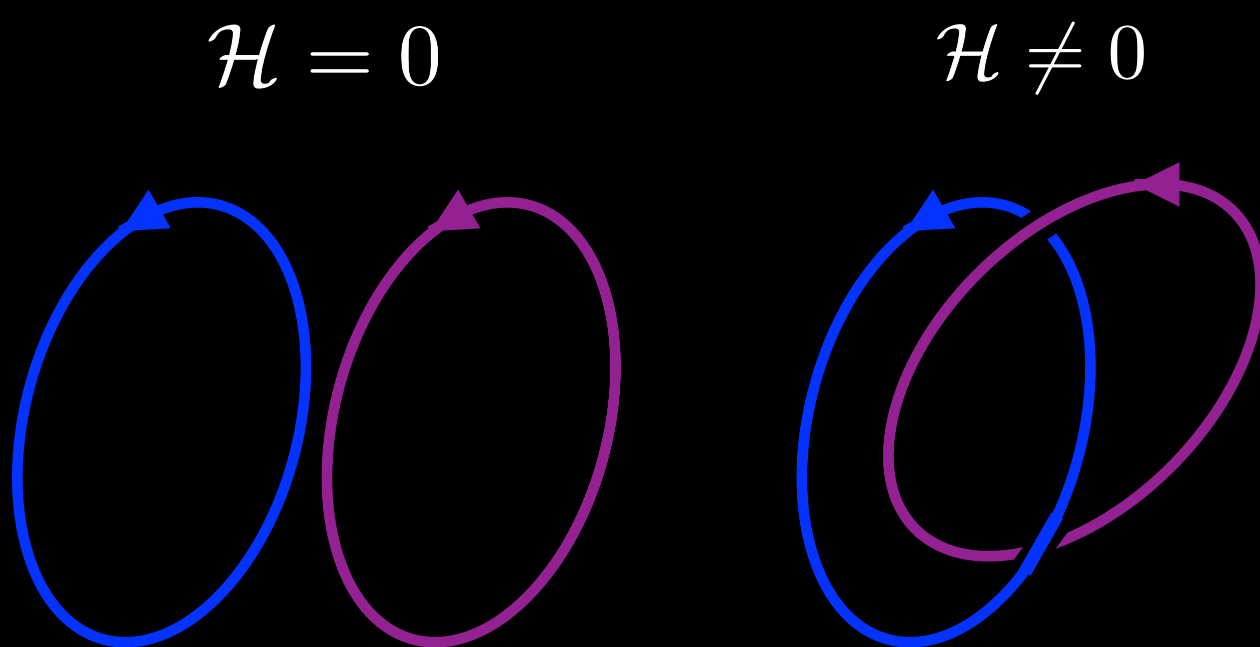
Purely poloidal or toroidal magnetic fields are unstable.



Enoto, Kisaka, Shibata (2019)

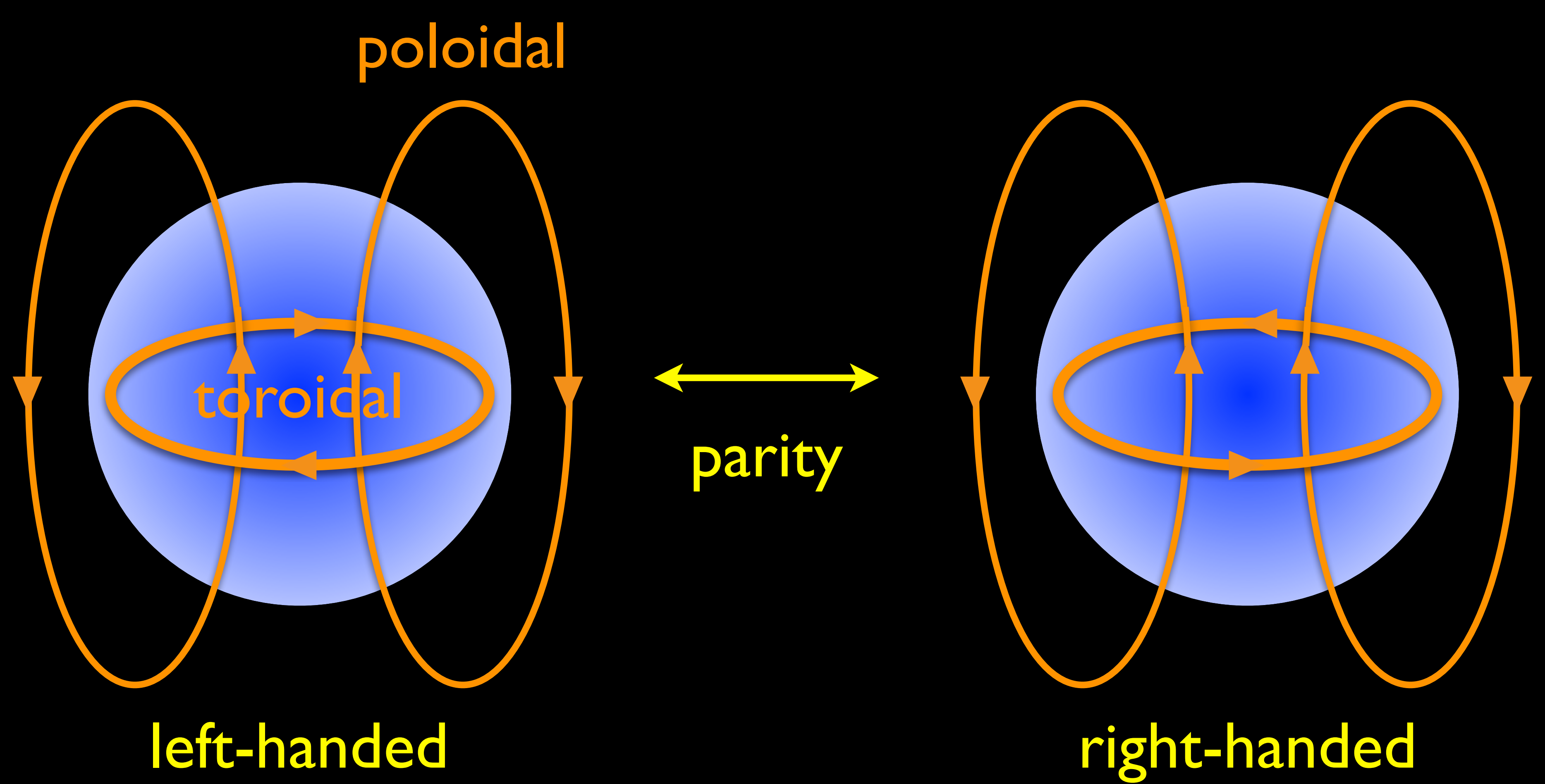
Magnetic helicity

- $\mathcal{H} = \int \mathrm{d}^3\boldsymbol{x}\boldsymbol{A} \cdot \boldsymbol{B}$: linking of magnetic fluxes (topological stability)



Magnetic helicity

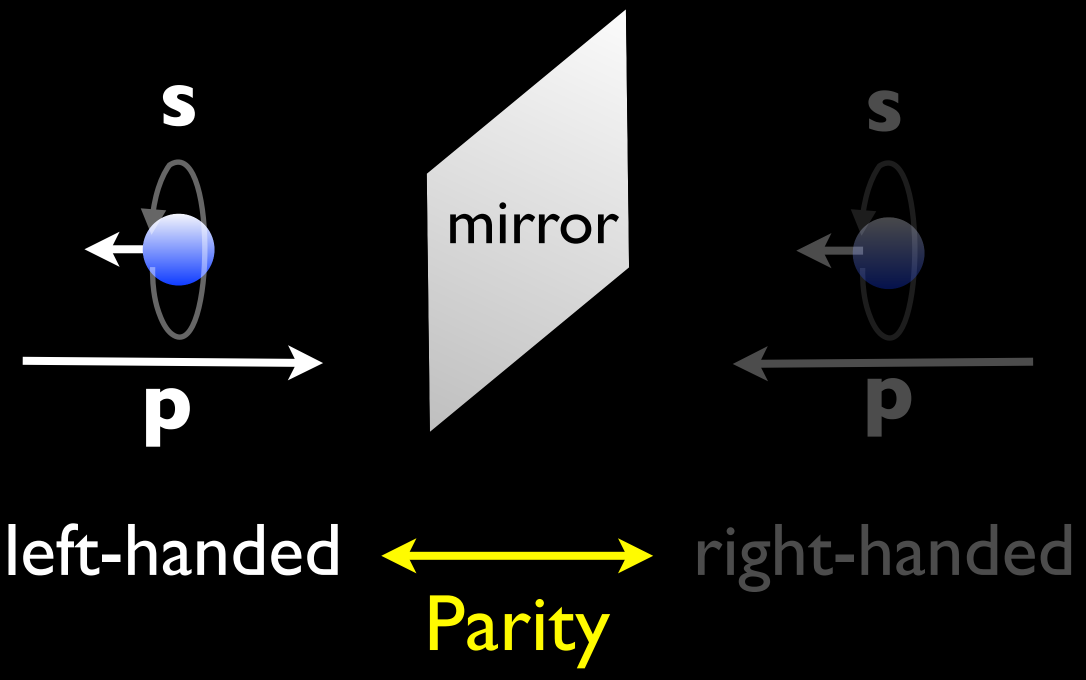
- $\mathcal{H} = \int \mathrm{d}^3 \boldsymbol{x} \boldsymbol{A} \cdot \boldsymbol{B}$: linking of magnetic fluxes (topological stability)
- Typically assumed as initial conditions, but its origin is unclear (how is parity-*odd* $\mathscr{H}$ generated from parity-*even* MHD?)



Effective theory for supernovae

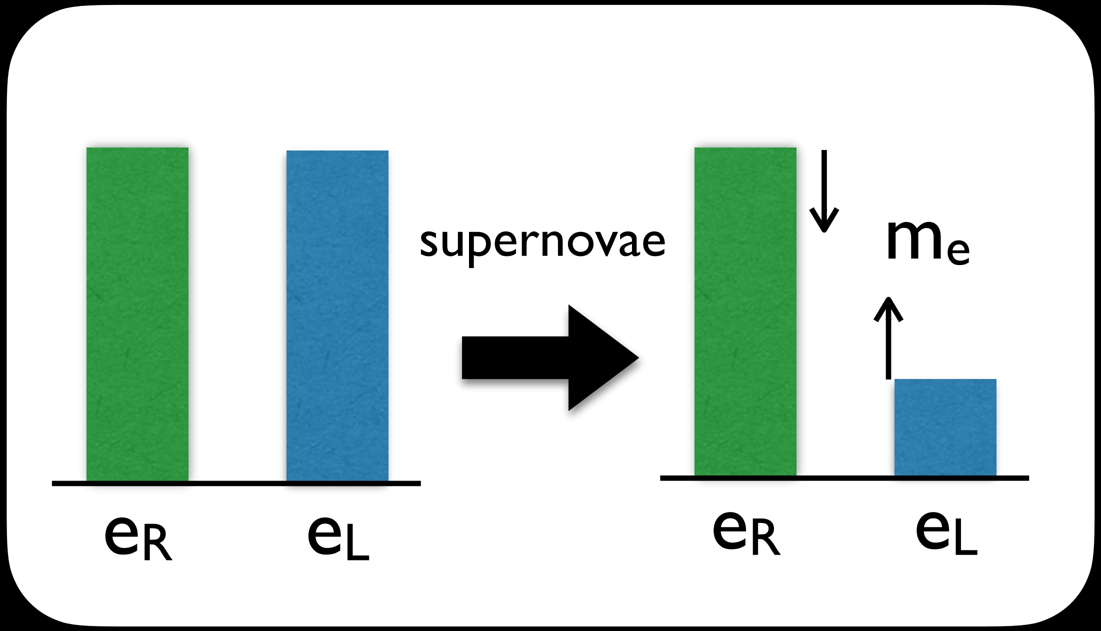
Problem w/ conventional theories

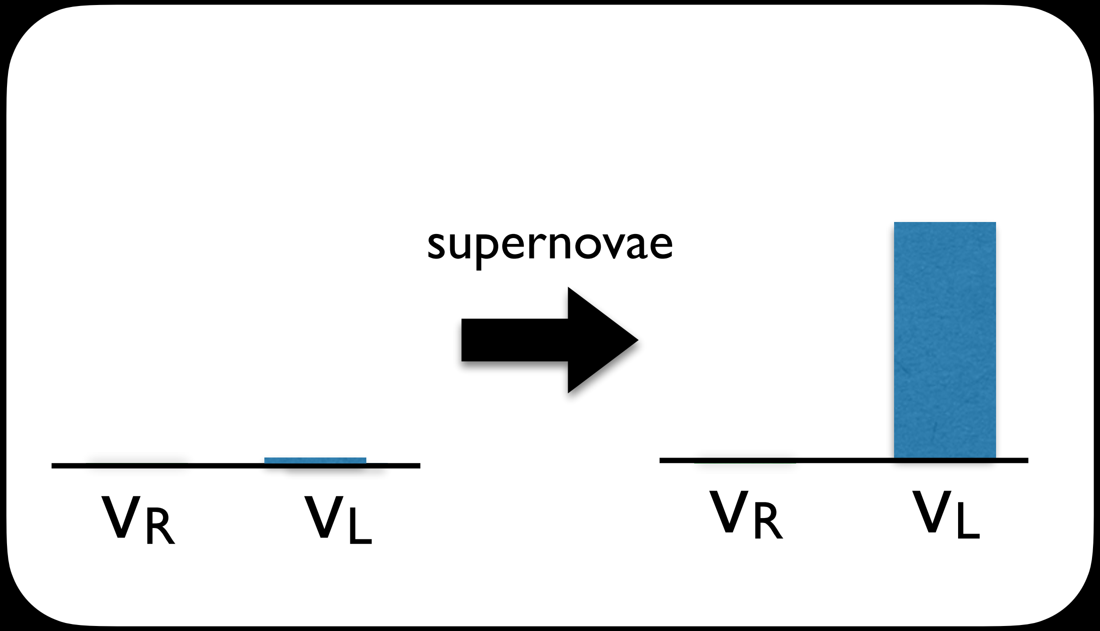
- Effective theory for supernovae: nonequilibrium kinetic theory for ν
- Conventional kinetic theory violates this basic tenet: 100 % parity violation by left-handedness



Supernova = Giant Parity Breaker

$$\mathrm{p} + \mathrm{e}^{\mathrm{L}} \rightarrow \mathrm{n} + \nu_{\mathrm{e}}{}^{\mathrm{L}}$$

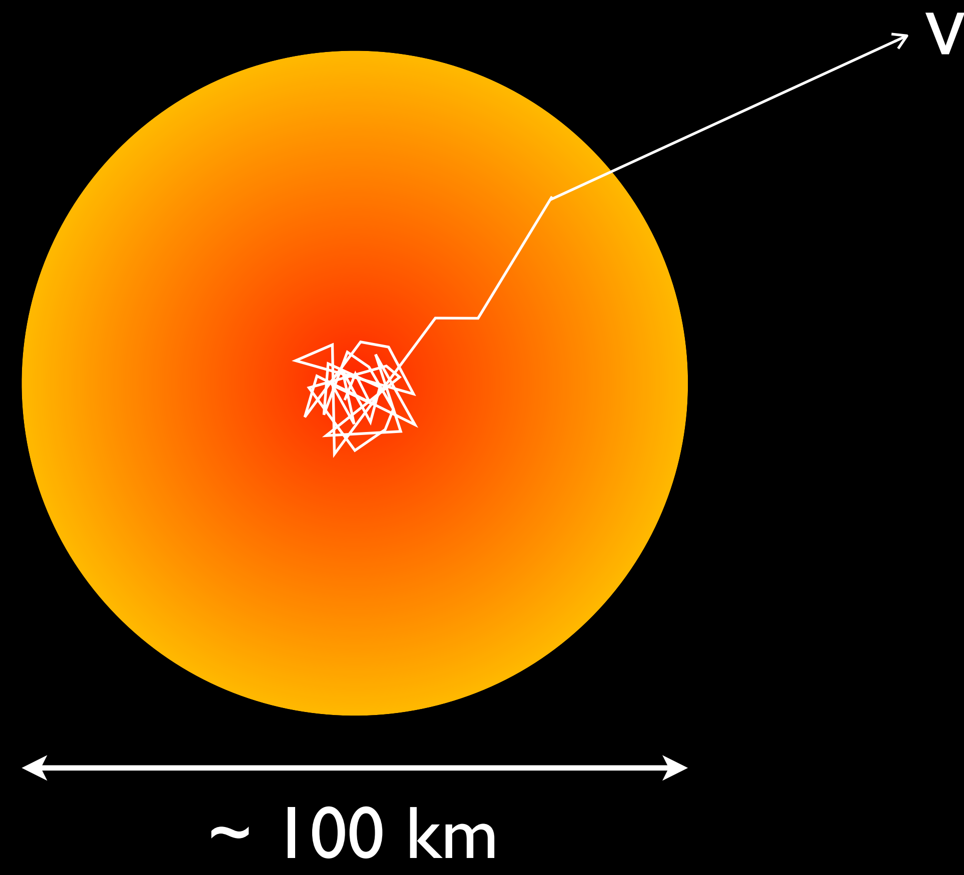




Ohnishi, Yamamoto (2014); Grabowska, Kaplan, Reddy (2015); Sigl, Leite (2016), …

Neutrino radiation transfer

$l_\nu \sim 1$ cm for $\rho_N \sim 10^{15}$ g/cm^3



$$\nabla_\alpha T^{\alpha\beta}_{\rm mat} = -\nabla_\alpha T^{\alpha\beta}_{\nu}$$

Stress tensor for matter (e, N)
(Hydrodynamics)

Stress tensor for ν
(Chiral kinetic theory)

From micro to macro

Micro | Standard Model of Particle Physics

↓ ← Systematic low-energy expansion

Nonequilibrium kinetic theory for ν

↓

Macro | Hydrodynamic evolution of core-collapse supernovae

From QFT to chiral kinetic theory

see, e.g., a review by Hidaka, Pu, Wang, Yang, PPNP (2022)

- Wigner function: $S^<(q,x) = \int_y \mathrm{e}^{-\mathrm{i}q\cdot y}\langle\psi^\dagger(x+y/2)\psi(x-y/2)\rangle \equiv \sigma^\mu \mathcal{L}^<_\mu$
- Equations of motion:

$$\mathcal{D}_\mu \mathcal{L}^{<\mu} = 0, \qquad \cdots(1)$$

$$q_\mu \mathcal{L}^{<\mu} = 0, \qquad \cdots(2)$$

$$\mathcal{D}_\mu \mathcal{L}^<_\nu - \mathcal{D}_\nu \mathcal{L}^<_\mu = -2\epsilon_{\mu\nu\rho\sigma} q^\rho \mathcal{L}^{<\sigma} \qquad \cdots(3)$$

where $\mathcal{D}_\mu \mathcal{L}^<_\nu \equiv \partial_\mu \mathcal{L}^<_\nu - \Sigma^<_\mu \mathcal{L}^>_\nu + \Sigma^>_\mu \mathcal{L}^<_\nu$

- Solution of (2), (3): $\mathcal{L}^{<\mu} = 2\pi\delta(q^2)\big(q^\mu - S^{\mu\nu}\mathcal{D}_\nu\big) f^<$

where $S^{\mu\nu} = \dfrac{\epsilon^{\mu\nu\alpha\beta} q_\alpha n_\beta}{2q\cdot n}$

- Inserting it into (1) → transport equation with collisions

$$J^\mu = 2\int_q \mathcal{L}^{<\mu}, \quad T^{\mu\nu} = \int_q (\mathcal{L}^{<\mu} q^\nu + \mathcal{L}^{<\nu} q^\mu)$$

Chiral radiation transport theory

Yamamoto, Yang, ApJ (2020)

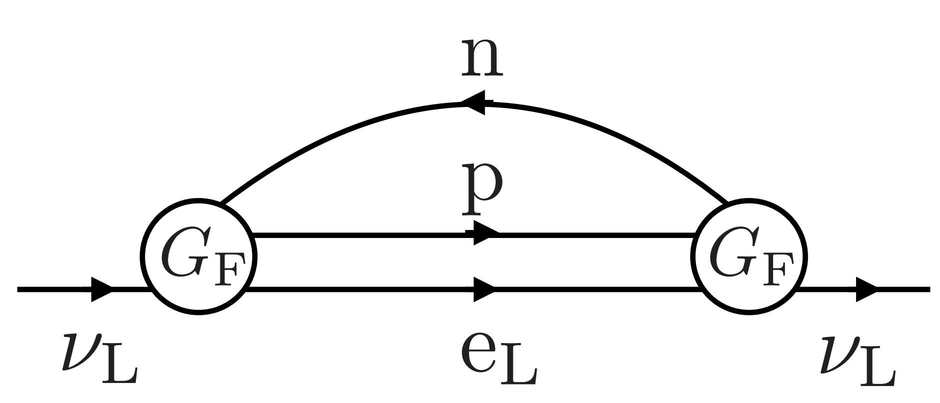
General Relativity + Standard Model + Nonequilibrium Field Theory

emission absorption

$$\left[q^\mu D_\mu - (D_\mu S^{\mu\nu})\partial_\nu + S^{\mu\nu} q^\rho R^\lambda_{\rho\mu\nu}\partial_{q\lambda}\right] f = (1-f)\Gamma^< - f\Gamma^>$$

$$D_\mu = \nabla_\mu - \Gamma^\lambda_{\mu\nu} q^\nu \partial_{q\lambda}, \quad \Gamma^{\lessgtr} = (q^\nu - D_\mu S^{\mu\nu})\,\Sigma^{\lessgtr}_\nu, \quad S^{\mu\nu} = \frac{\epsilon^{\mu\nu\alpha\beta} q_\alpha n_\beta}{2q\cdot n}$$

Example of the neutrino self-energy

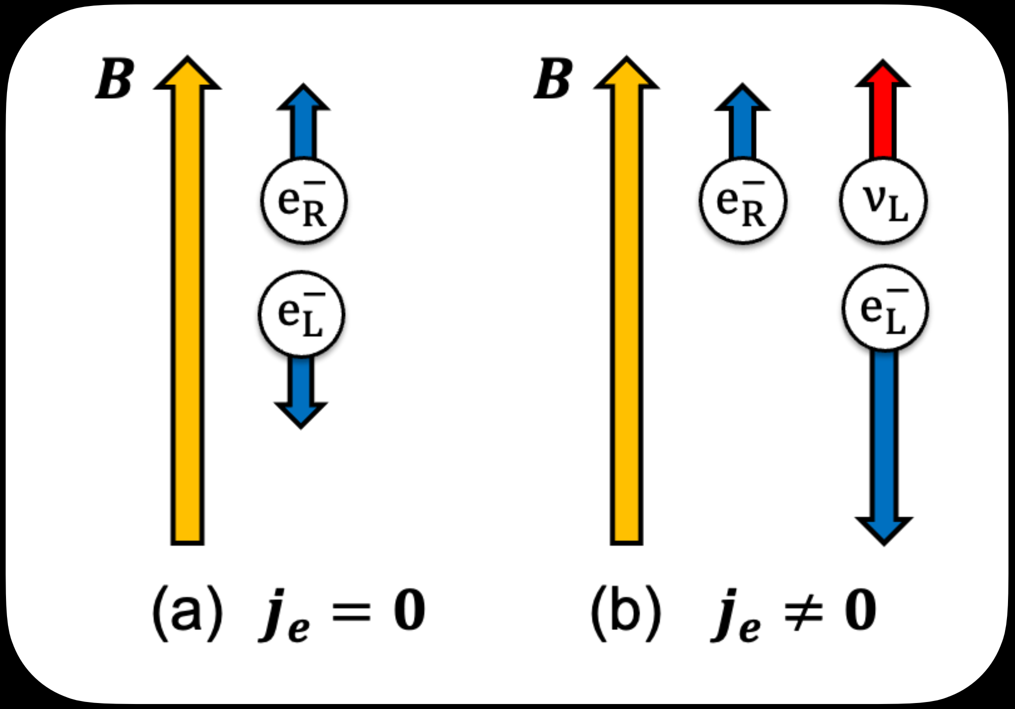


Back reaction of neutrinos

Yamamoto, Yang, PRL (2023)

$$\boldsymbol{j}_{\rm e} = \xi_B \boldsymbol{B}$$

Effective chiral magnetic effect
(without μ5)

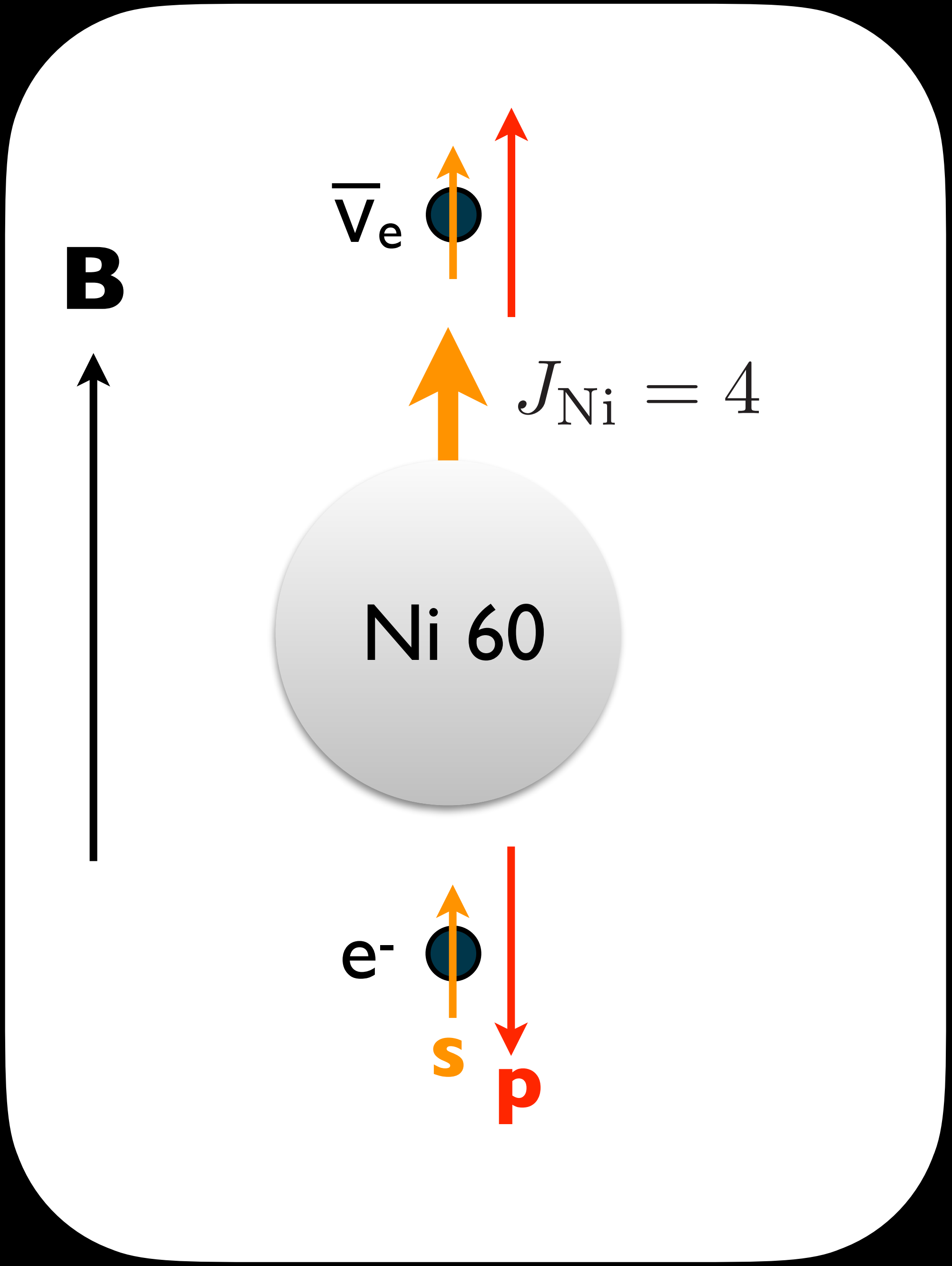


$$\dot{\xi}_B = \frac{1}{4\pi^3}(g_{\rm V}^2 + 3g_{\rm A}^2)G_{\rm F}^2(n_{\rm p} - n_{\rm n})\int_0^\infty p^2 {\rm d}p \left[\frac{\bar{f}_{\rm e}(1-f_\nu)}{1-{\rm e}^{\beta(\mu_{\rm n}-\mu_{\rm p})}} + \frac{(1-\bar{f}_{\rm e})f_\nu}{1-{\rm e}^{\beta(\mu_{\rm p}-\mu_{\rm n})}}\right] + ({\rm antiparticle's})$$

$|\xi_B^{\rm tot}| \sim 0.1\text{-}1\,{\rm MeV}$ at the gain region (where neutrino heating is efficient)

for $f_\nu(q_0),\ Y_{\rm e} \simeq 0.4,\ \rho \sim 10^{10}\,{\rm g\cdot cm^{-3}},\ T \sim 10^{11}\,{\rm K},\ \mu_{\rm n} - \mu_{\rm p} \simeq 3\,{\rm MeV},\ t \sim 0.1\,{\rm s}$

Wu experiment



Chien-Shiung Wu
Wu et al. (1957)

$J_{\mathrm{e},\nu} \propto B$: nonequilibrium many-body manifestation of the chiral effect

Applications

Local simulation for supernovae

Masada et al. (2018); Matsumoto et al. (2022)

Chiral magnetohydrodynamic (MHD) equations

$$\partial_t \rho + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0$$

$$\partial_t (\rho \boldsymbol{v}) + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v} \boldsymbol{v}) = -\boldsymbol{\nabla} P + \boldsymbol{J} \times \boldsymbol{B} + \text{(dissipation)}$$

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \boldsymbol{\nabla}^2 \boldsymbol{B} + \eta \boldsymbol{\nabla} \times \underline{(\xi_B \boldsymbol{B})}$$

$$\partial_t \mathcal{H}(\xi_B) = \frac{\eta}{2\pi^2} (\boldsymbol{\nabla} \times \boldsymbol{B} - \xi_B \boldsymbol{B}) \cdot \boldsymbol{B}$$

see also Rogachevskii et al. (2017), Brandenburg et al. (2017), Schober et al. (2018)

Chiral plasma instability

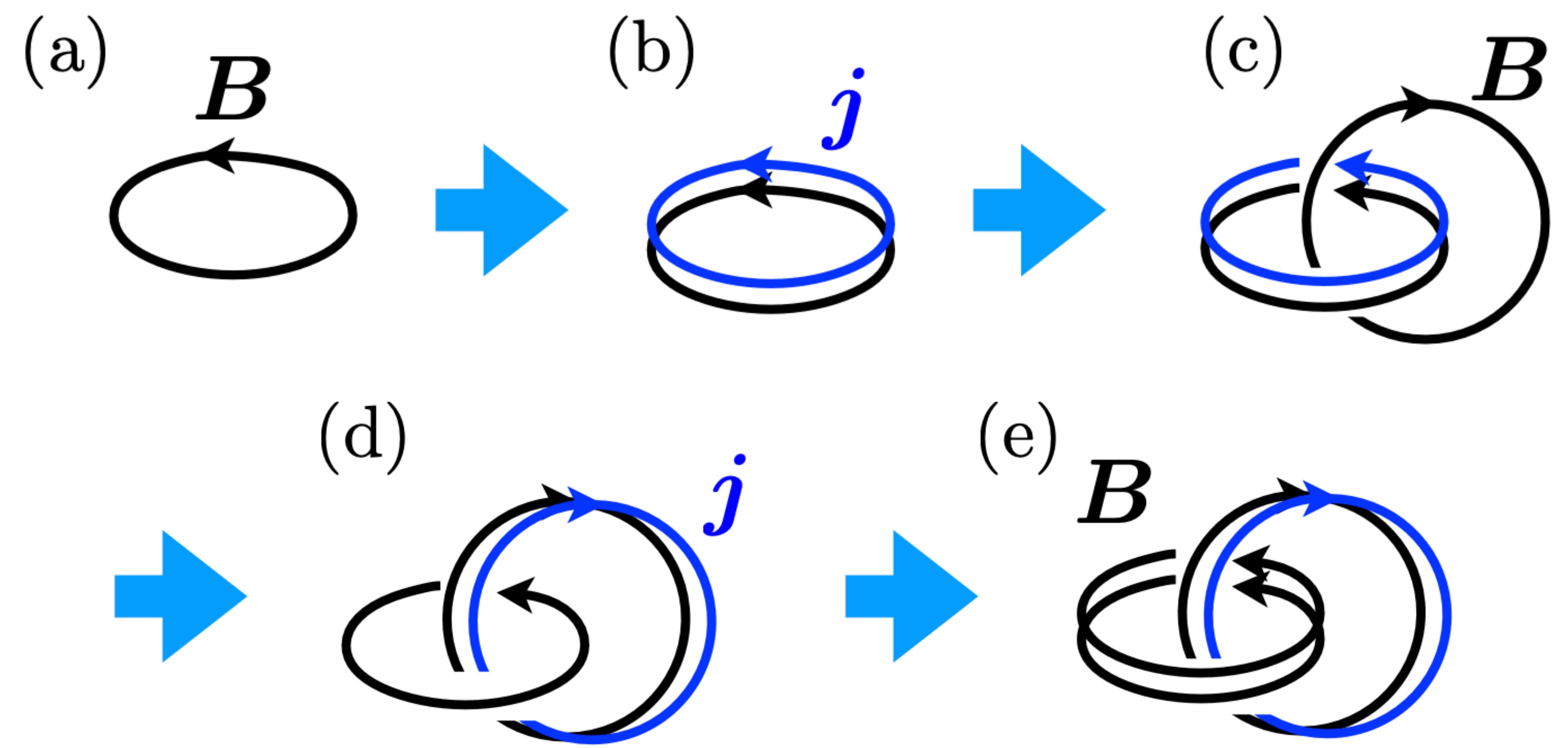


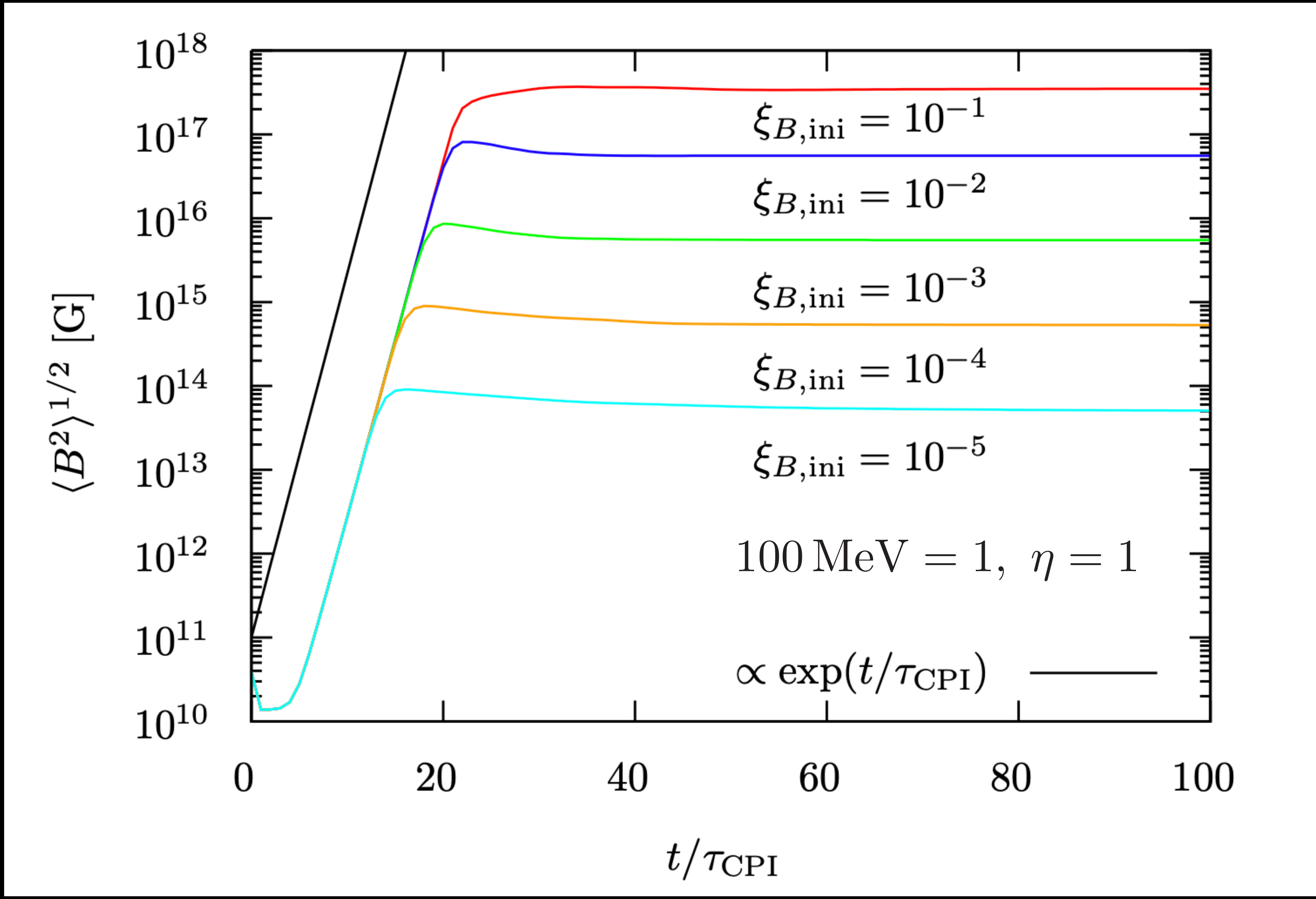
figure taken from arXiv:2305.01234

Positive feedback → Strong magnetic field with linking (helicity)

Akamatsu, Yamamoto (2013), Ohnishi, Yamamoto (2014), …

Time evolution of *B*

Matsumoto, Yamamoto, Yang, PRD (2022)

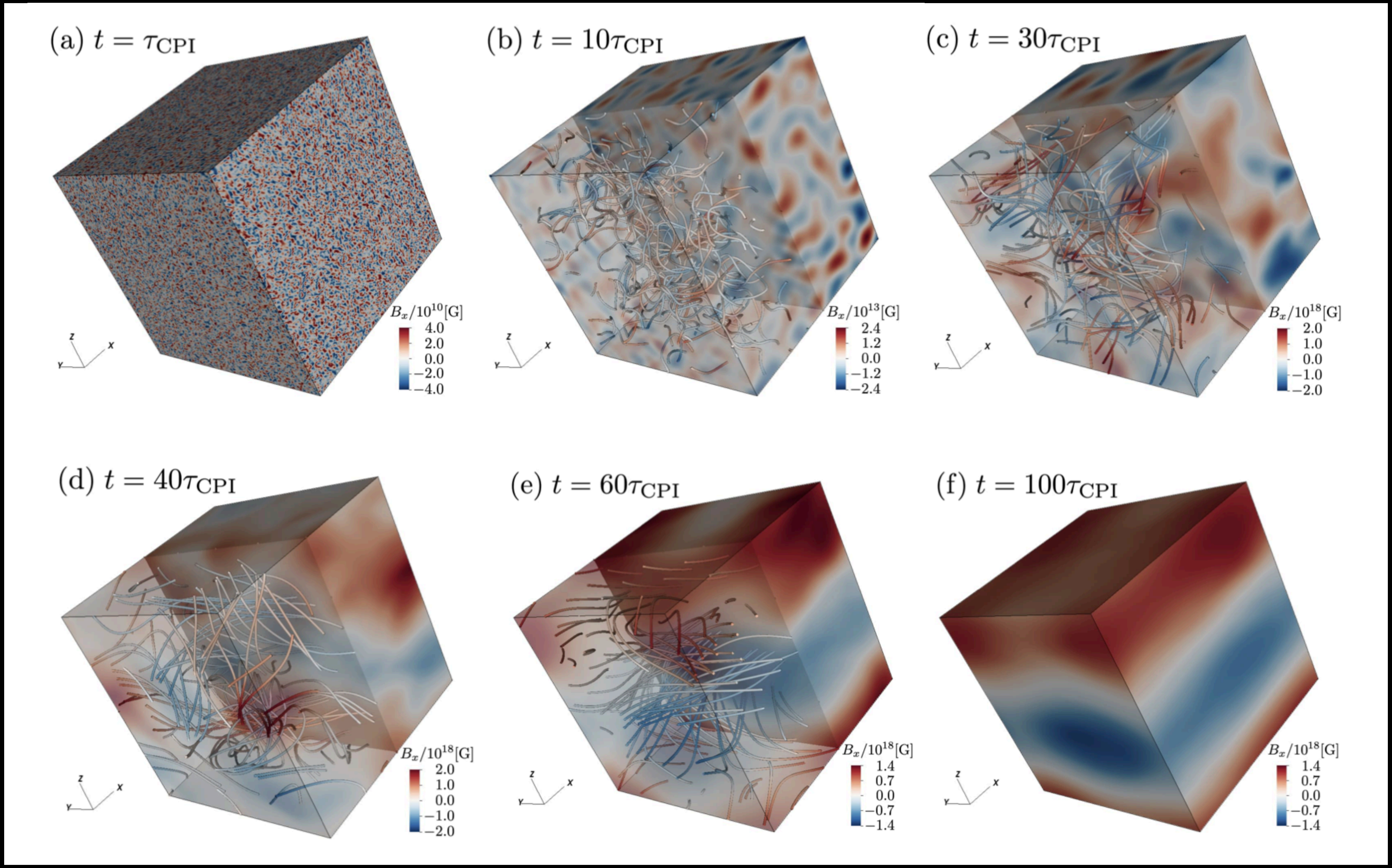


A possible new mechanism for magnetars

Time evolution of ***B***

$\xi_{B,\mathrm{ini}} = 10^{-1}$

Matsumoto, Yamamoto, Yang, PRD (2022)

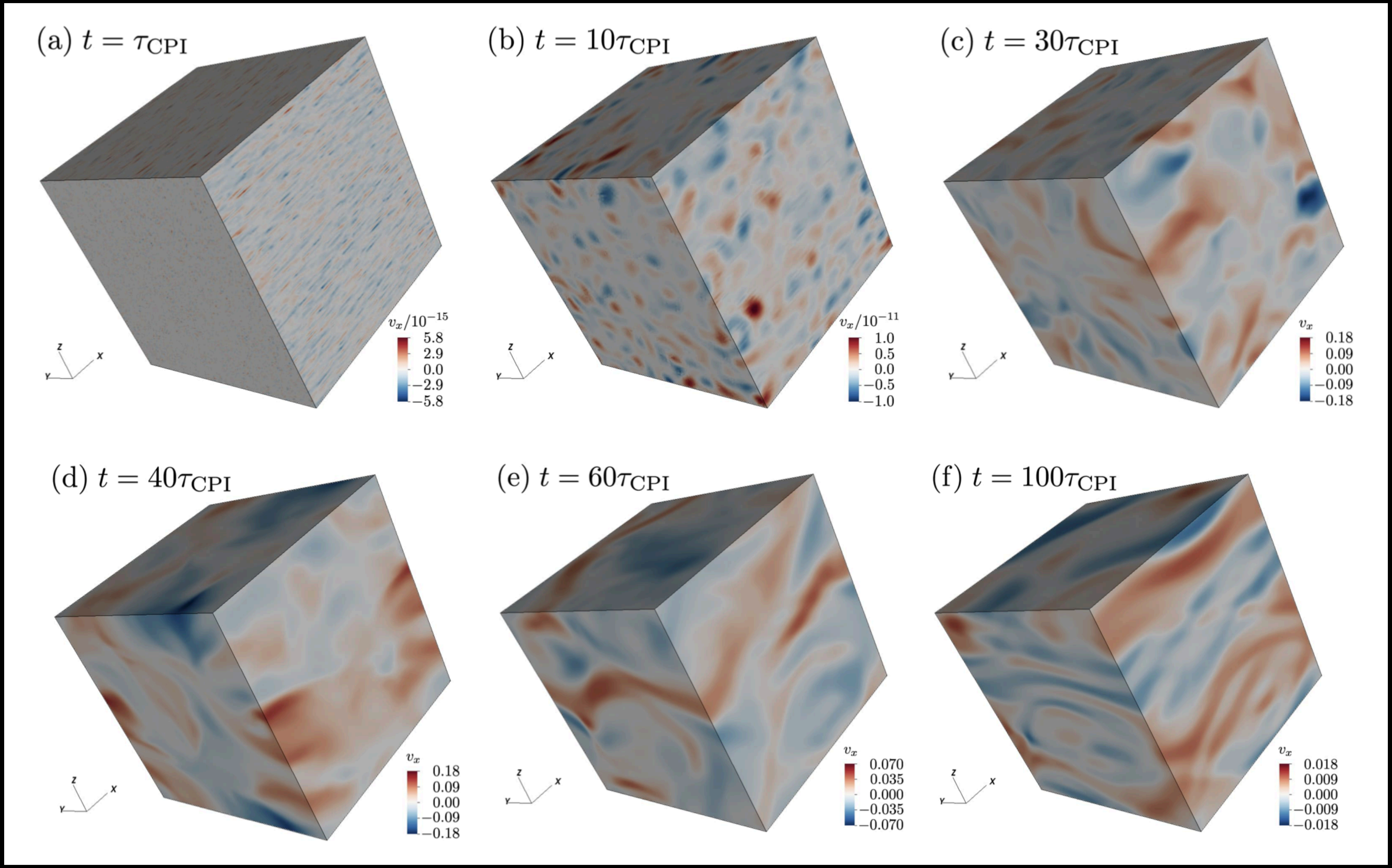


see also Brandenburg et al. (2017); Masada et al. (2018)

Time evolution of **v**

$\xi_{B,\mathrm{ini}} = 10^{-1}$

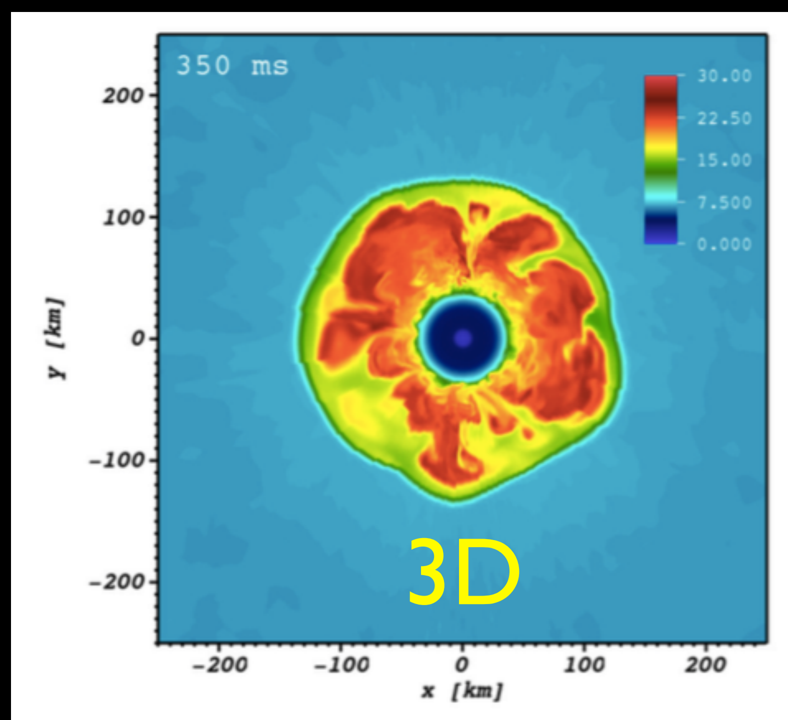
Matsumoto, Yamamoto, Yang, PRD (2022)



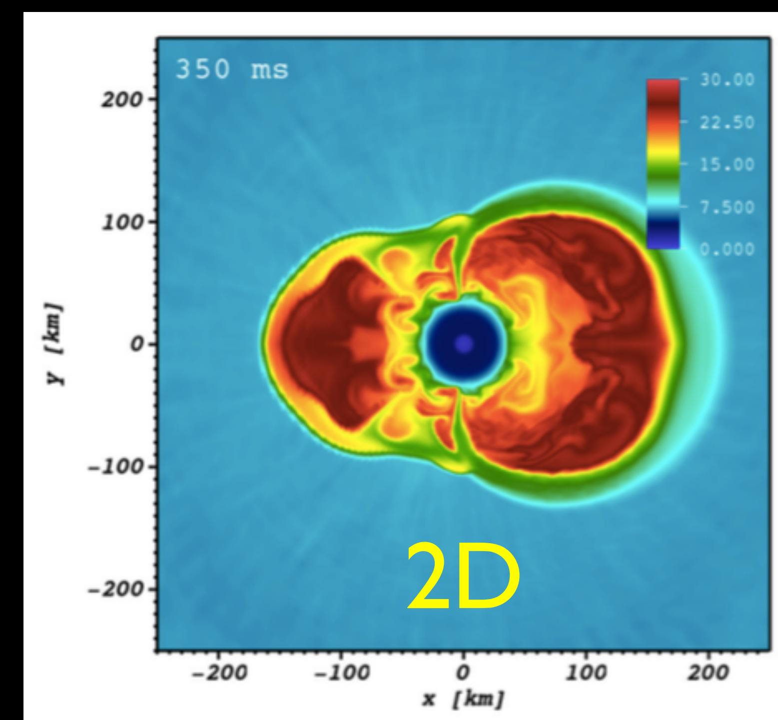
Chiral effects lead to inverse cascade, which may affect explosion dynamics

Turbulent cascade and explosion

Direct cascade (3D w/o chirality):
energy



Inverse cascade (2D):
energy & enstrophy



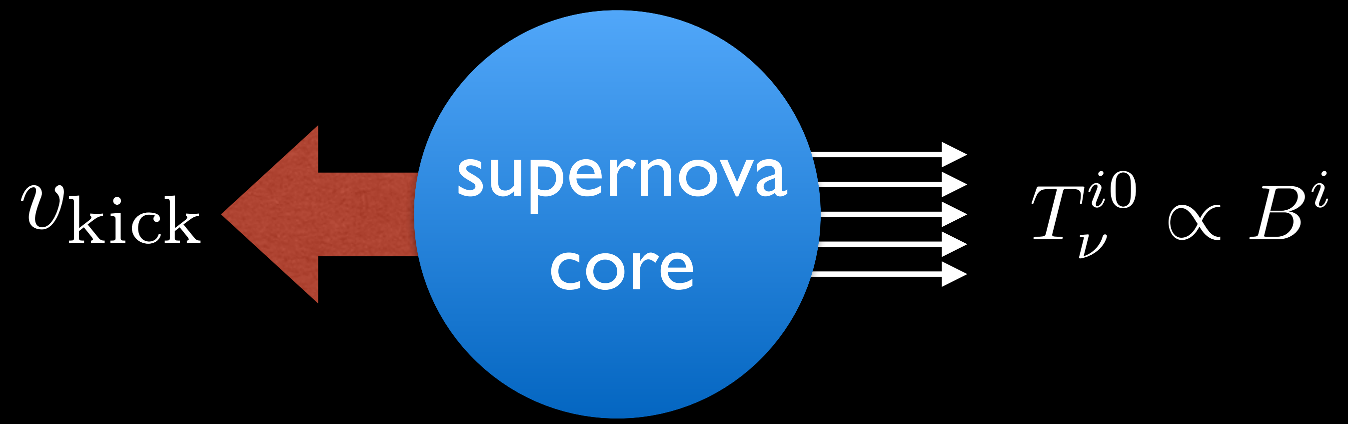
Hanke (2014)

Inverse cascade for 3D matter w/ chiral effects: energy & helicity

How does it affect the evolution of supernovae?

Pulsar kicks

- Neutron stars have typically high velocities ~ several 100 km/s.
- A mechanism: supernova core recoiled by the neutrino emission.



$$v_{\rm kick} \sim 100 \left(\frac{B}{10^{15}\ {\rm G}} \right) \ {\rm km/s}$$

Chugai (1984) + many; Yamamoto, Yang, PRD (2021); see also Fukushima, Yu, 2401.04568

Summary & Outlook

- Parity violation should be included in neutrino transport.
- Typical consequences: chiral plasma instability and inverse cascade
- Relevant to magnetars, pulsar kicks, explosion dynamics.
- Other chiral effects (e.g., chiral vortical effect, spin Hall effect)?
- Global simulations of chiral radiation hydro would be required.