XI International Conference on New Frontiers in Physics

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Conference venue: OAC conference center, Kolymbari, Crete, Greece. The conference will take place in Crete in physical form, however participation is also possible via internet
Europe/Athens timezone

Chiral effects from non-equilibrium left-handed neutrinos in core-collapse supernovae

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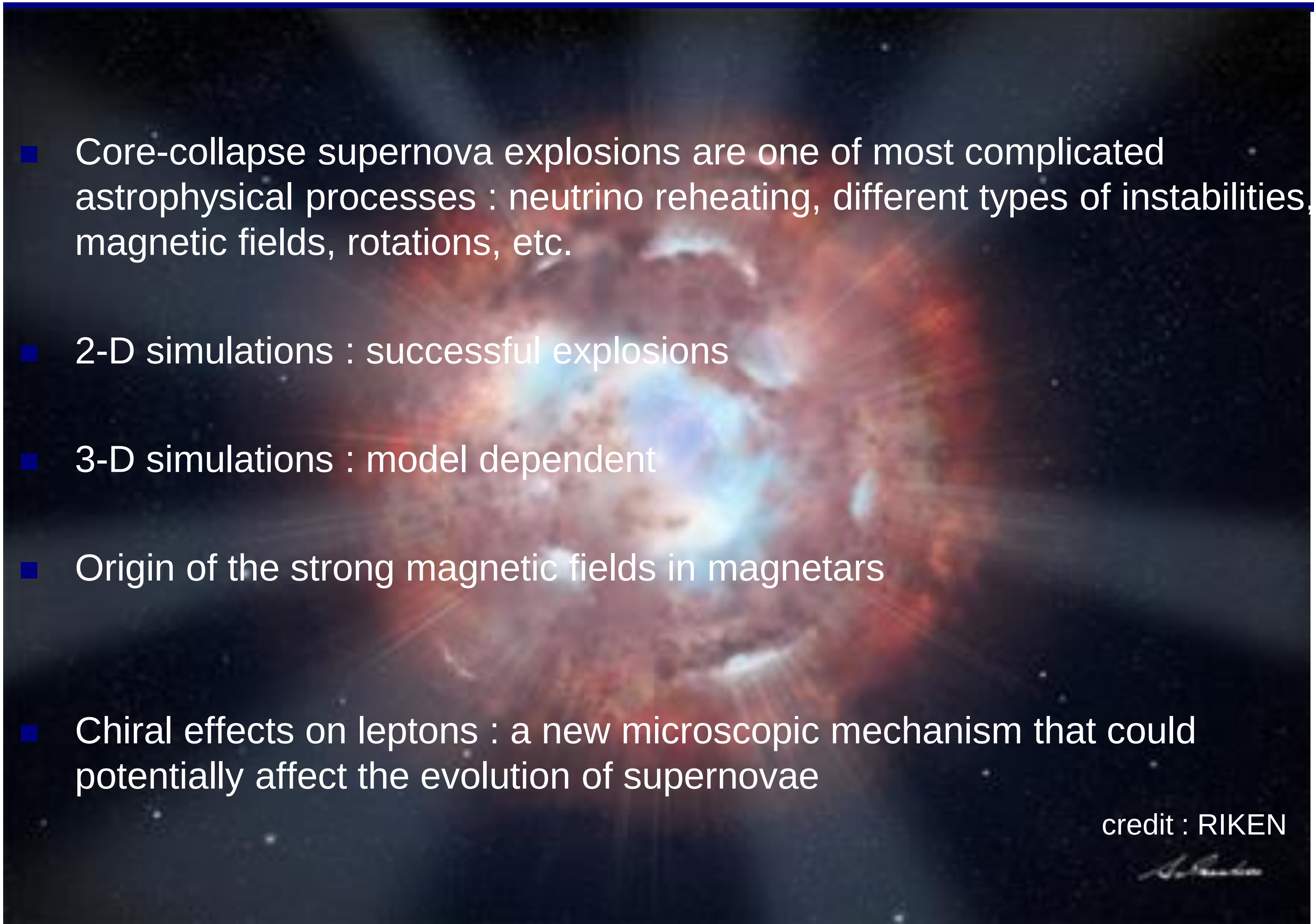
Core-collapse supernovae (CCSN)



- Core-collapse supernova explosions are one of most complicated astrophysical processes : neutrino reheating, different types of instabilities, magnetic fields, rotations, etc.

- 2-D simulations : successful explosions

- 3-D simulations : model dependent

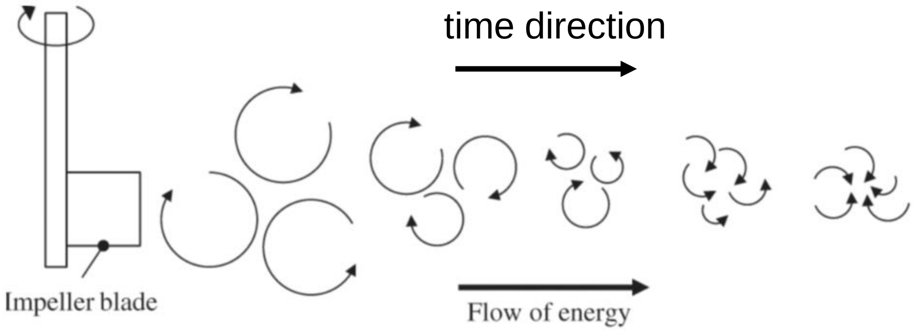
- Origin of the strong magnetic fields in magnetars

- Chiral effects on leptons : a new microscopic mechanism that could potentially affect the evolution of supernovae

credit : RIKEN

Direct & inverse energy cascades

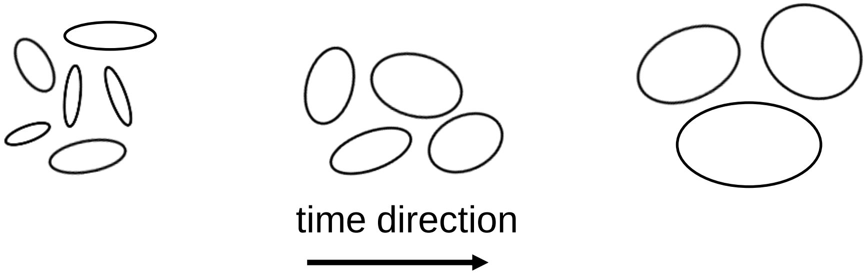
- Intuitively, why is the 3D system more difficult to achieve explosion?
- Turbulence in 3D : direct energy cascade (difficult to explode)



https://doi.org/10.1515/htmp-2016-0043

Kolmogorov 1941

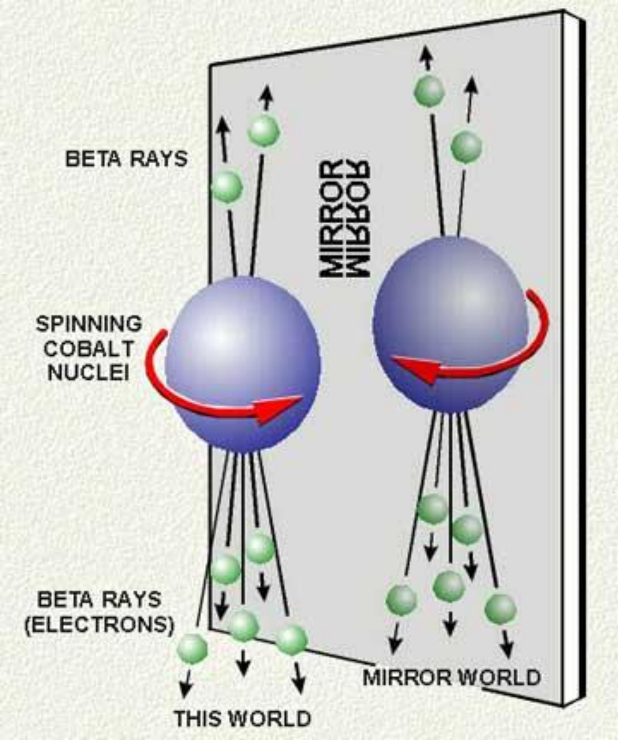
- Turbulence in 2D : inverse energy cascade (easier to explode)



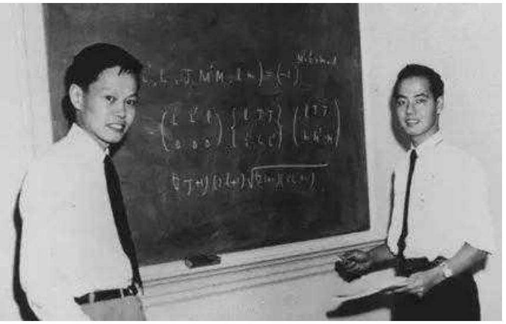
Kraichnan, Leith, Batchelor
1967-1969

- Chiral effects in 3D : inverse cascade

Parity violation & weak interaction



http://physics.nist.gov/GenInt/Parity/cover.html]



Lee & Yang

Wu, 1956

- Global parity violation in weak interaction
- Weak-interaction processes between leptons and nucleons are ubiquitous in CCSN.
- What will be the transport properties for (massless) chiral fermions under parity (chirality) violation?

Chiral anomaly and helicity conservation

- Chiral anomaly : $\partial_\mu J_5^\mu = \frac{\mathbf{E}\cdot\mathbf{B}}{2\pi^2}$ (for approximated massless fermions)

S. Adler, J. Bell, R. Jackiw, 69
K. Fujikawa, 79

- Helicity conservation : $\frac{\mathrm{d}H_{\mathrm{tot}}}{\mathrm{d}t} = 0\,, \quad H_{\mathrm{tot}} \equiv N_{5,\mathrm{eff}} + \frac{H_{\mathrm{mag}}}{4\pi^2}\,,$

$$N_{5,\mathrm{eff}} \equiv \int \mathrm{d}^3x\; n_{5,\mathrm{eff}}\,, \quad H_{\mathrm{mag}} \equiv \int \mathrm{d}^3x\; \boldsymbol{A}\cdot\boldsymbol{B}$$

exchange btw the “effective” axial charge & magnetic helicity

- Chiral magnetic effect (CME) : $J^\mu = \xi_B B^\mu\,, \quad \xi_B = \frac{\mu_5}{2\pi^2}\,. \quad (\mu_5 = \mu_R - \mu_L)$

A. Vilenkin, PRD 22, 3080 (1980)

K. Fukushima, D. Kharzeev, H. Warringa, PRD78, 074033 (2008)

Chiral plasma instability

- Anomalous Maxwell's eq. : $\partial_t \boldsymbol{B} = -\boldsymbol{\nabla} \times \boldsymbol{E}, \quad \boldsymbol{\nabla} \times B = \eta^{-1}\boldsymbol{E} + \boxed{\xi_B \boldsymbol{B}}.$

CME

$$\Rightarrow \frac{\partial \boldsymbol{B}}{\partial t} = \boxed{\eta \boldsymbol{\nabla}^2 \boldsymbol{B}} + \boxed{\eta\, \boldsymbol{\nabla} \times (\xi_B \boldsymbol{B})}$$

diffusion CME (instability)

- Chiral plasma instability (CPI) : $\delta \boldsymbol{B} \propto \mathrm{e}^{\sigma t + \mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$ ($\sigma > 0$: an unstable mode of magnetic fields)

M. Joyce and M. E. Shaposhnikov, PRL **79**, 1193 (1997).

Y. Akamatsu and N. Yamamoto, PRL 111, 052002 (2013).

$$\sigma = \eta k(\xi_B - k)$$

(for small k, long wavelength)

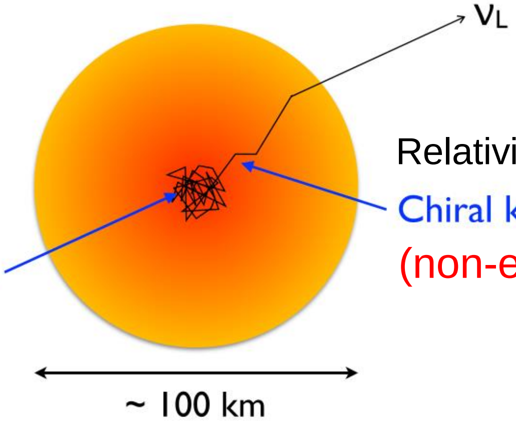
❖ σ becomes maximum when $k = \xi_B/2 \equiv k_{\mathrm{CPI}}$

$$\Rightarrow \tau_{\mathrm{CPI}} = \frac{4}{\eta \xi_B^2}$$

Chiral radiation hydrodynamics

- Matter (e, N) in equilibrium + radiation (ν) out of equilibrium

S. W. Bruenn, Astrophys. Jl. Suppl. 58 (1985) 771.



Magneto-hydro

Chiral hydro

(equilibrium)

Relativistic kinetic theory

Chiral kinetic theory

(non-equilibrium)

(CKT) : quantum kinetic theory incorporating chiral anomaly & spin-orbit int.

N. Yamamoto, DY, APJ 895 (2020) 1, 56.
Review : K. Kamada, N. Yamamoto, DY, arXiv:2207.09184

- Near the core : ChMHD (e, N, ν)
- Away from the core : ChMHD (e, N) + chiral kinetic theory (ν) ⟹ chiral radiation hydrodynamics

$$\boxed{\nabla_\mu T^{\mu\nu}_{\rm rad}} + \boxed{\nabla_\mu T^{\mu\nu}_{\rm mat}} = 0$$

(neutrinos) (electrons, nucleons : equilibrium)

Neutrino flux driven by magnetic fields

- Considering neutrinos near equilibrium with the neutrino absorption on nucleons $\nu_{\rm L}^{\rm e}(q) + {\rm n}(k) \rightleftharpoons {\rm e}_{\rm L}(q') + {\rm p}(k')$:

N. Yamamoto & DY, PRD 104, 123019 (2021)

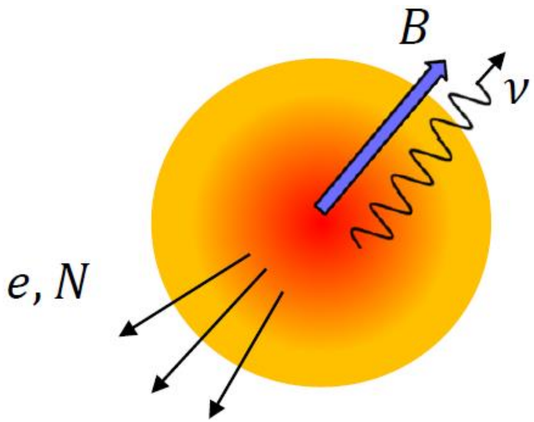
$$\Delta j_\nu^i = -\kappa(\boldsymbol{\nabla}\cdot\boldsymbol{v})B^i,$$
$$\Delta T_\nu^{i0} = \mu_\nu \Delta j_\nu^i.$$

$$\kappa = \frac{1}{72\pi M G_{\rm F}^2(g_{\rm V}^2 + 3g_{\rm A}^2)}\,\frac{{\rm e}^{2\beta(\mu_{\rm n}-\mu_{\rm p})}}{n_{\rm n}-n_{\rm p}}$$

- The momentum kick from neutrinos : $\Delta T_{\rm e}^{i0} = -\Delta T_\nu^{i0}, \quad \Delta T_{\rm e}^{i0} = \mu_{\rm e}\Delta j_{\rm e}^i$

⇨ $\Delta J_{\rm e}^i = \xi_B B^i,$ (effective CME)

$$\xi_B = -\kappa(\boldsymbol{\nabla}\cdot\boldsymbol{v})\frac{\mu_\nu}{\mu_{\rm e}}.$$



Taking $n_{\rm n} - n_{\rm p} \sim 0.1\,{\rm fm}^{-3}$, $\mu_{\rm n} - \mu_{\rm p} \sim 100\,{\rm MeV}$, $\mu_\nu \sim \mu_{\rm e} \sim 100\,{\rm MeV}$, $T \sim 10\,{\rm MeV}$, $L \sim 10\,{\rm km}$, $|\boldsymbol{v}| \sim 0.01$, we have $\boxed{\xi_B \sim 10\,{\rm MeV},}$ (approx. upper bound)

Chiral magnetohydrodynamics

- Chiral magetohydrodynamics (MHD) equations:

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0\,, \tag{17}$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \boldsymbol{\nabla} \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \left(P + \frac{B^2}{2}\right)\mathbf{I}\right] = \boldsymbol{S}\,, \tag{18}$$

$$\begin{aligned} \frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \frac{1}{\Gamma - 1}P + \frac{B^2}{2}\right) + \boldsymbol{\nabla} \cdot \Bigg[\left(\frac{1}{2}\rho v^2 + \frac{\Gamma}{\Gamma - 1}P\right)\boldsymbol{v} \\ + \boldsymbol{E} \times \boldsymbol{B}\Bigg] = -\boldsymbol{S} \cdot \boldsymbol{v} - \Delta \boldsymbol{J} \cdot \boldsymbol{E}\,, \end{aligned} \tag{19}$$

$$\boxed{\begin{aligned} \frac{\partial \boldsymbol{B}}{\partial t} &= \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \boldsymbol{\nabla}^2 \boldsymbol{B} + \eta\, \boldsymbol{\nabla} \times (\xi_B \boldsymbol{B})\,, & (20) \\ \frac{\partial n_{5,\mathrm{eff}}}{\partial t} &= \frac{1}{2\pi^2}\boldsymbol{E} \cdot \boldsymbol{B}\,, & (21) \end{aligned}}$$

$$\boldsymbol{S} = \rho\nu \boldsymbol{\nabla}^2 \boldsymbol{v} + \frac{1}{3}\rho\nu \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{v})$$

J. Matsumoto, N. Yamamoto, DY, PRD 105 (2022) 12, 123029

See also Y. Masada, K. Kotake, T. Takiwaki, and N. Yamamoto, PRD 98, 083018 (2018)

Time evolution of the magnetic field

- Numerical simulations :

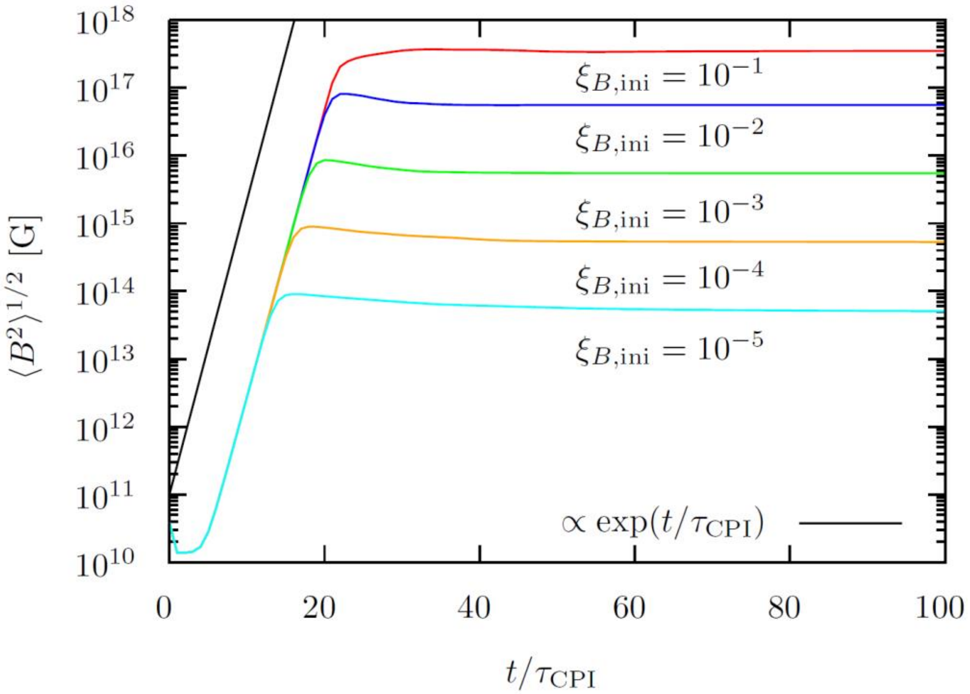
resistivity : $\eta = 1$ viscosity : $\nu = 0.01$

in the units of $100\,\mathrm{MeV} = 1$

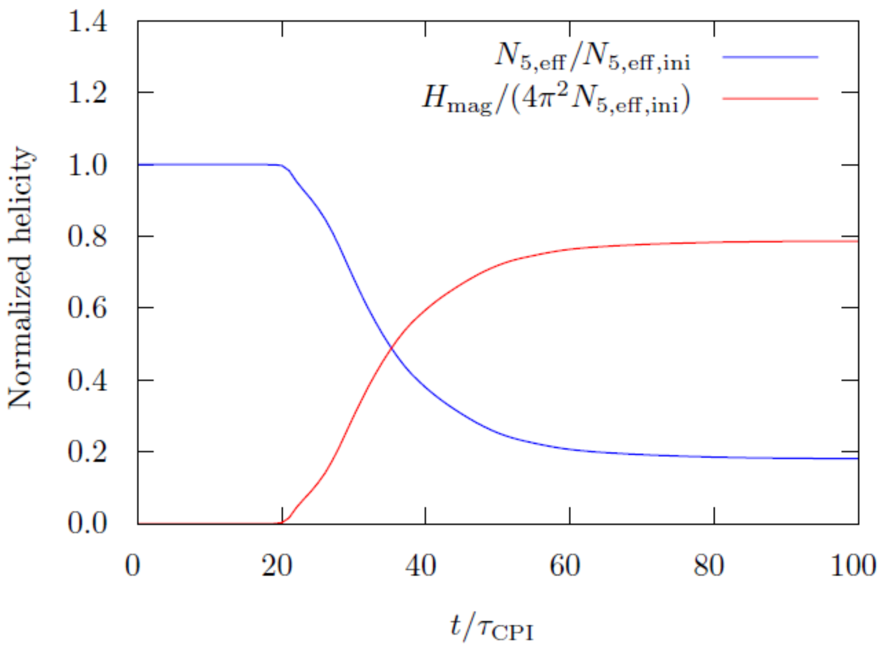
J. Matsumoto, N. Yamamoto, DY, PRD 105 (2022) 12, 123029

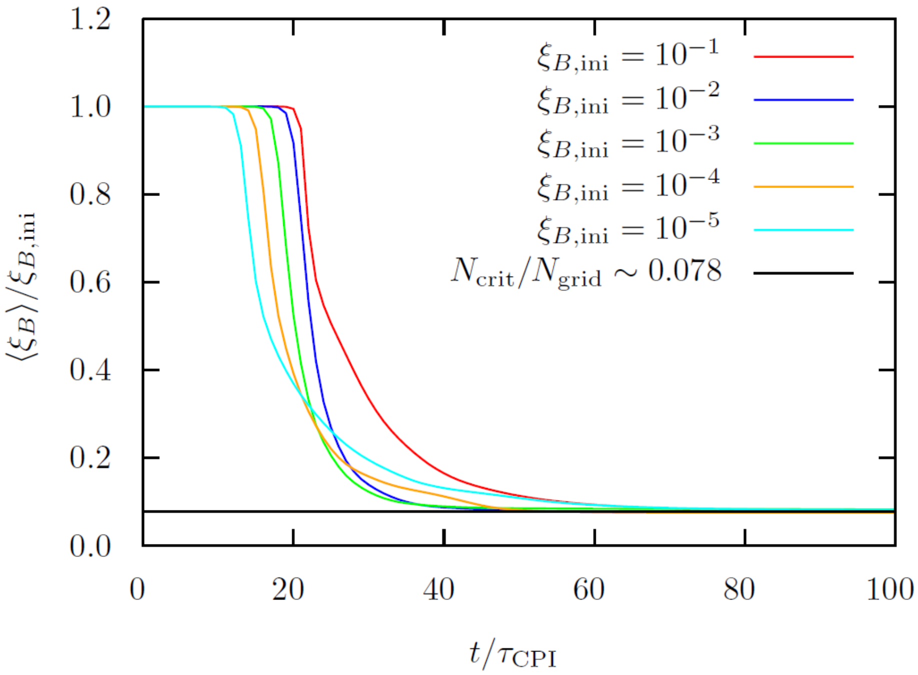
TABLE I. Summary of the simulation runs.

Name	L	$\xi_{B,\mathrm{ini}}$	τ_{CPI}
Model 1	8×10^2	10^{-1}	4×10^2
Model 2	8×10^3	10^{-2}	4×10^4
Model 3	8×10^4	10^{-3}	4×10^6
Model 4	8×10^5	10^{-4}	4×10^8
Model 5	8×10^6	10^{-5}	4×10^{10}



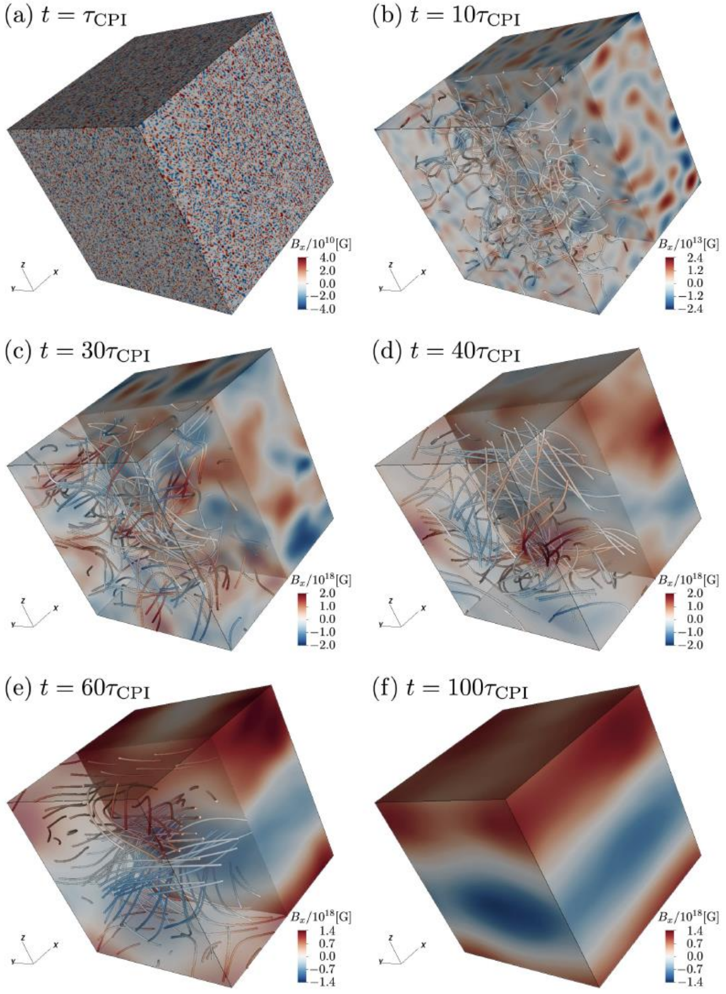
Helicity evolution





Inverse cascade

- Inverse cascade

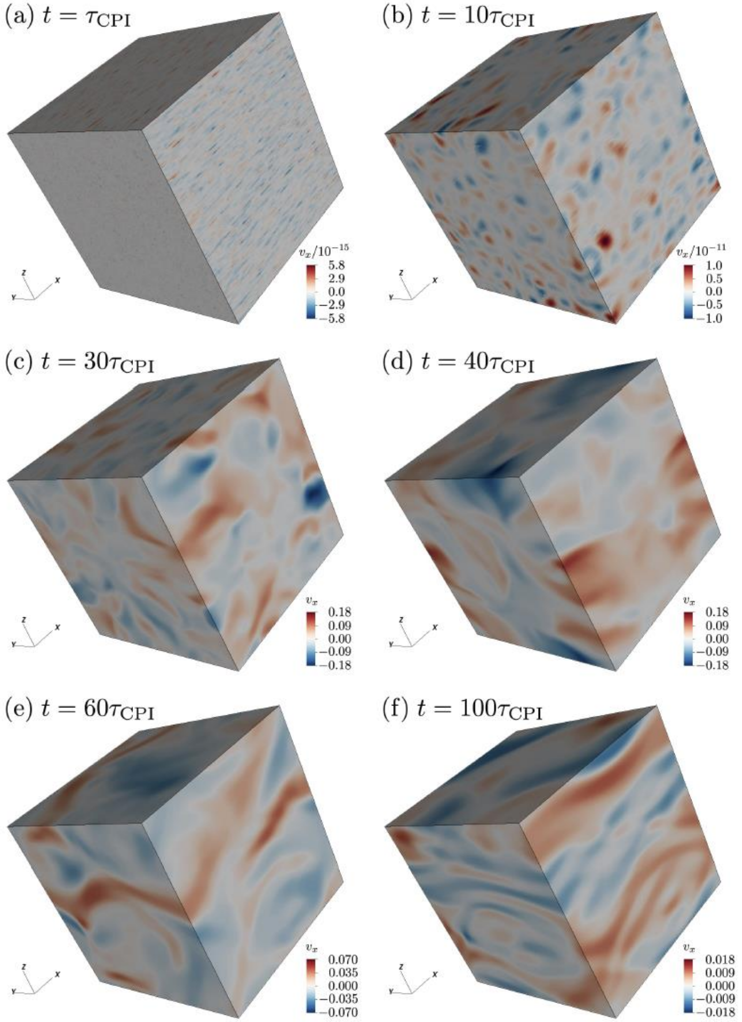


(a) $t = \tau_{\rm CPI}$ (b) $t = 10\tau_{\rm CPI}$

(c) $t = 30\tau_{\rm CPI}$ (d) $t = 40\tau_{\rm CPI}$

(e) $t = 60\tau_{\rm CPI}$ (f) $t = 100\tau_{\rm CPI}$

magnetic field



(a) $t = \tau_{\rm CPI}$ (b) $t = 10\tau_{\rm CPI}$

(c) $t = 30\tau_{\rm CPI}$ (d) $t = 40\tau_{\rm CPI}$

(e) $t = 60\tau_{\rm CPI}$ (f) $t = 100\tau_{\rm CPI}$

fluid velocity

Conclusions & outlook

- ✓ The chiral effect for leptons due to “parity violation” could qualitatively affect the supernova evolution.

- ✓ Back-reaction on the matter sector from the magnetic-field induced neutrino flux could genrate an “effective CME”, which further results in the “CPI”.

- ✓ The evolution of matter dictated by chiral MHD follows the “inverse cascade” led by CPI and generates to a “strong and stable magnetic field” in late times.

(Review : K. Kamada, N. Yamamoto, DY, arXiv:2207.09184)

- ❖ It is important to perform the chiral MHD simulations with the CME conductivity depending on the fluid-velocity gradient.

- ❖ More importantly, the back-reaction of chiral effects from “out-of-equilibrium” neutrinos should be included.

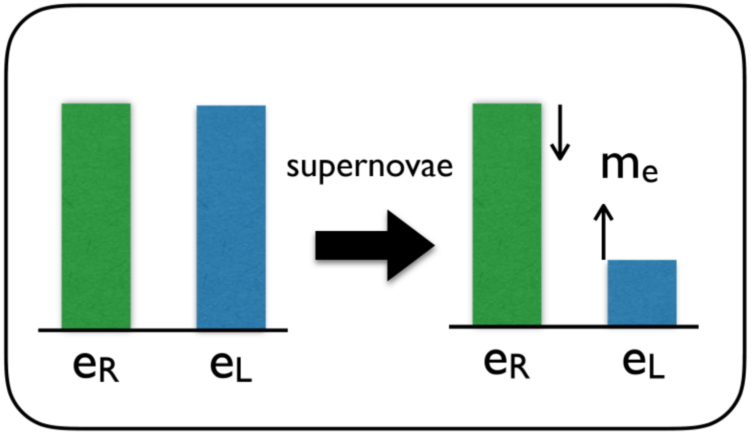
Thank you!

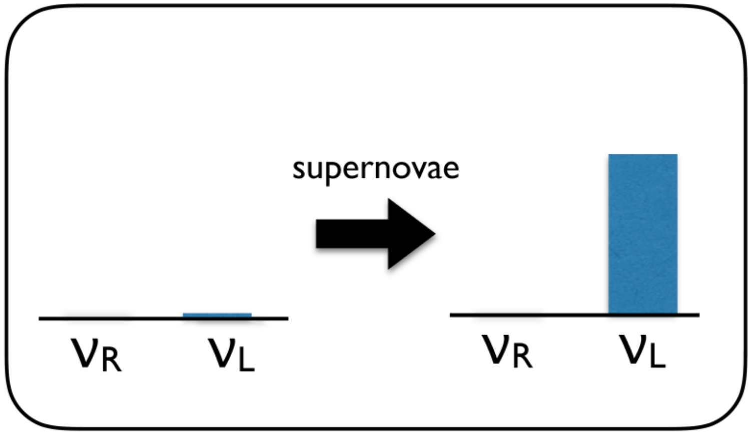
Intrinsic chiral imbalance

- Electron capture process in supernovae :

an innate lefthander

$$p + \underline{e^{\mathrm{L}}} \to n + \boxed{\nu_e^{\mathrm{L}}}$$





N. Yamamoto's talk at the workshop on recent developments in chiral matter and topology, NTU, Taiwan, 18

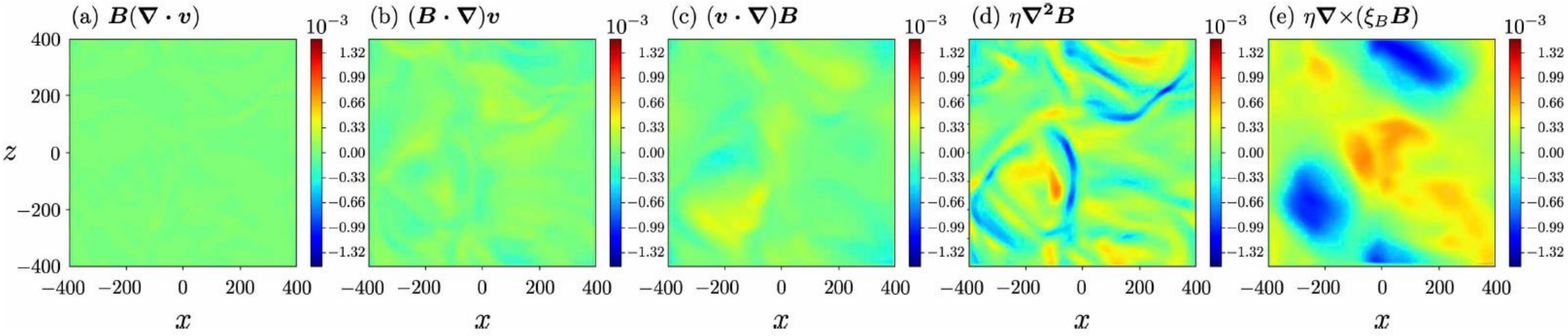
- Back-reaction from non-equilibrium neutrinos.

Dominance of the CPI

- Anatomy of the induction equation :

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \boldsymbol{\nabla}^2 \boldsymbol{B} + \eta\, \boldsymbol{\nabla} \times (\xi_B \boldsymbol{B}) \ ,$$

$$\boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) = \boldsymbol{B}(\boldsymbol{\nabla} \cdot \boldsymbol{v}) + (\boldsymbol{B} \cdot \boldsymbol{\nabla})\boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{B}$$



- CPI dominates under the condition : $|\boldsymbol{v}| \ll \eta|\xi_B|$