Impact of chiral effects on core-collapse supernova dynamics

2025 ASROC Annual Meeting

Chang-Mao Yang[1], Kuo-Chuan Pan[1,2], Di-Lun Yang[3]

[1]*Department of Physics, National Tsing Hua University, Hsinchu, 30013, Taiwan*
[2]*Institute of Astronomy, National Tsing Hua University, Hsinchu, 30013, Taiwan*
[3]*Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan*

Abstract:

Chiral effects induced by quantum anomalies, such as the chiral magnetic effect, are expected to influence the dynamics of core-collapse supernovae (CCSN). These effects arise in strong magnetic fields and rapid flows, which are common in supernova cores. In this project, we investigate the potential impact of chiral neutrino radiation transport in CCSN, focusing on contributions from neutrinos near equilibrium. We use an approximate formula for the chiral corrections to the neutrino radiation energy-momentum tensor $\partial_\mu T^{\mu i}_{\rm rad}$ from the work of Yamamoto & Yang (2021). We investigate the potential contributions from these chiral corrections on self-consistent 2D CCSN simulations with neutrino transport. We find that some of the chiral correction terms can significantly contribute to momentum changes and, therefore, can have a crucial impact on the dynamics of the proto-neutron star around the core bounce. This effect might be one of the origins of the pulsar kick.

Introduction:

Core-collapse supernovae (CCSNe) involve strong magnetic fields and rapid flows, where neutrino transport plays a key role in the explosion dynamics. While conventional schemes such as IDSA transport include neutrino-matter interactions, they do not account for the chirality of neutrinos, which is required by the Standard Model. Recent work by Yamamoto and Yang (2021) introduced a chiral radiation transport theory that incorporates quantum anomalies, leading to additional momentum source terms in the neutrino energy-momentum tensor.

In this study, we adopt the analytic expression derived for the near-equilibrium regime and apply it in post-processing to 2D FLASH + IDSA simulations. We find that, under strong magnetic fields, the resulting chiral source terms can be comparable to the background momentum evolution. These results indicate that chiral effects may play a non-negligible role in CCSNe. This mechanism could also contribute to the origin of pulsar kicks, whose typical birth velocities are observed to be around 400 km/s (Hobbs et al. 2005).

Methods:

We perform 2D axisymmetric simulations using the FLASH MHD code in cylindrical coordinates (r, z) with IDSA neutrino transport.

- **Equation of state**: SFHo (Steiner et al. 2013).
- **Progenitors**: $40\,M_\odot$, solar metallicity (Woosley & Heger 2007).
- **Magnetic field configuration**: Adjusting vector potential

$$(A_r, A_\theta, A_\varphi) = \left(0, 0, \frac{1}{2}\, r\, B_{\varphi,0}\left(\frac{r_0^3}{r_0^3 + r^3}\right)\right),$$

  with $r_0 = 10^8$ cm, following Jardine, Powell & Muller, 2021.
- **Parameter space**: Initial magnetic field strength $B_{\varphi,0}$ and rotation ω_0.

model	$B_{\varphi,0}$ [G]	ω_0 [rad/s]
B12_W1.0	10^{12}	1.0
B12_W0.5	10^{12}	0.5
B12_W0.4	10^{12}	0.4
B12_W0.3	10^{12}	0.3
B12_W0.2	10^{12}	0.2
B11_W0.5	10^{11}	0.5
B10_W0.5	10^{10}	0.5
B9_W0.5	10^{9}	0.5
B8_W0.5	10^{8}	0.5

We adopt the near-equilibrium formula from Yamamoto & Yang (2021) for the chiral correction to neutrino momentum transport. In natural units $(\hbar = c = k_B = 1)$ and with the electric charge e absorbed into $\boldsymbol{B}$, the correction takes the form

$$\partial_\mu T^{\mu i}_{\rm rad} \approx -\frac{1}{72\pi M G_{\rm F}^2 (g_{\rm V}^2 + g_{\rm A}^2)} \frac{e^{2(\mu_{\rm n}-\mu_{\rm p})/T}}{n_{\rm n} - n_{\rm p}} (\boldsymbol{\nabla}\cdot\boldsymbol{v})\, \mu_\nu \left[B^i (\boldsymbol{\nabla}\cdot\boldsymbol{v}) + (\boldsymbol{B}\cdot\boldsymbol{\nabla})\, v^i + \partial_t B^i\right],$$

where M is the nucleon mass, $G_{\rm F}$ is the Fermi constant, and $g_{\rm V,A}$ are the nucleon vector and axial-vector couplings. Here, $\rm n$ and $\rm p$ denote neutron and proton, respectively. This term is computed in **post-processing** from simulation outputs:

- Velocity v^i, magnetic field B^i, number densities $n_{\rm n}, n_{\rm p}$ and temperature T.
- Chemical potentials $\mu_{\rm n}, \mu_{\rm p}$ interpolated from EoS table.
- Neutrino chemical potential $\mu_\nu \approx \mu_{\rm p} + \mu_{\rm e} - \mu_{\rm n}$ under β-equilibrium assumption.

We quantify the significance of chiral momentum input via

1. Density-weighted ratio of chiral source and momentum evolution

$$\frac{\langle \partial_\mu T^{\mu i}_{\rm rad}\rangle}{\langle \partial_t(\rho v^i)\rangle}, \quad \langle A\rangle \equiv \frac{\int_{\mathbb{S}^3} \rho A\, \mathrm{d}\vec{r}}{\int_{\mathbb{S}^3} \rho\, \mathrm{d}\vec{r}},$$

   where $\mathbb{S}^3$ is the whole simulation space.

2. Approximating kick velocity contribution from the chiral source term using

$$v_i^{\rm (chiral)} \approx \int \frac{\int_{\mathbb{S}^3(M_{\rm enc})} \partial_\mu T^{\mu i}_{\rm rad}\, \mathrm{d}\vec{r}}{\int_{\mathbb{S}^3(M_{\rm enc})} \rho\, \mathrm{d}\vec{r}}\, \mathrm{d}t\,.$$

   where $\mathbb{S}^3(M_{\rm enc})$ denotes the region with enclosed mass $M_{\rm enc}$. We sample 1.0-1.5 $M_{\rm PNS}$, where $M_{\rm PNS}$ is determined at the end of simulation $\rho > 10^{11}\,{\rm g/cm^3}$. Integration is over the full simulation time.

Figures:

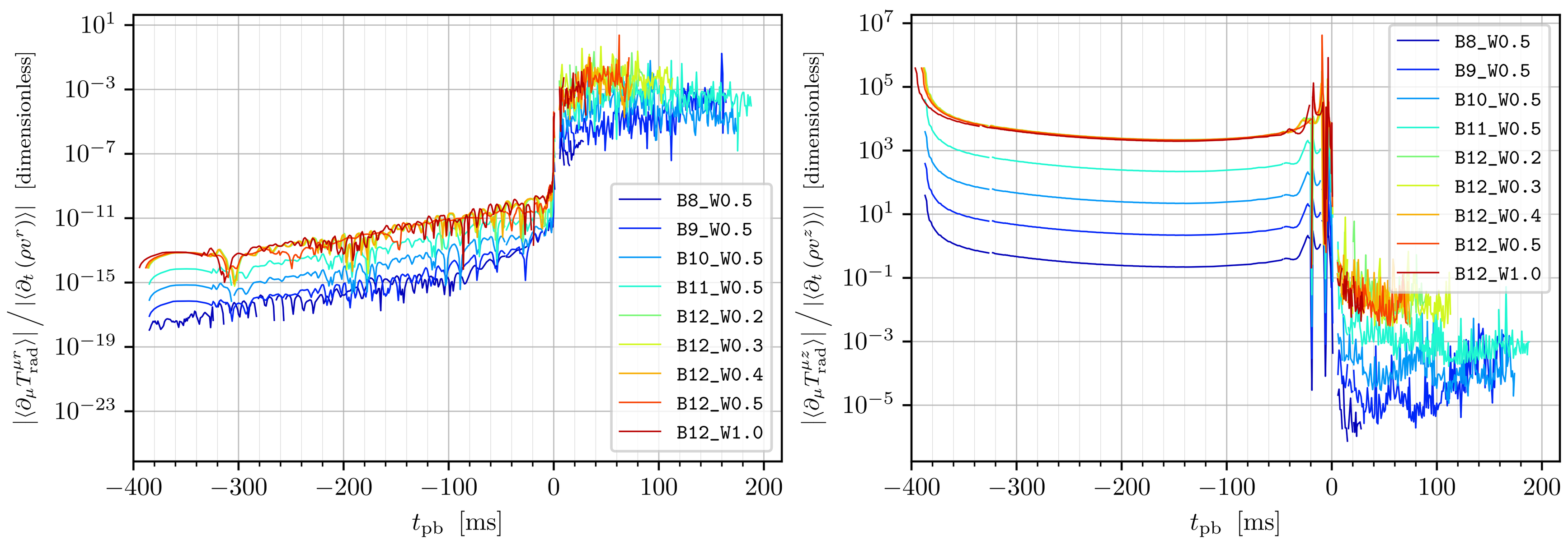

Figure 1. Time evolution of the magnitude ratio between the chiral source term $\partial_\mu T^{\mu i}_{\rm rad}$ and the momentum change $\partial_t(\rho v^i)$, for the radial (left) and axial (right) directions. The ratio is dimensionless, omitting signs to emphasize relative strength.

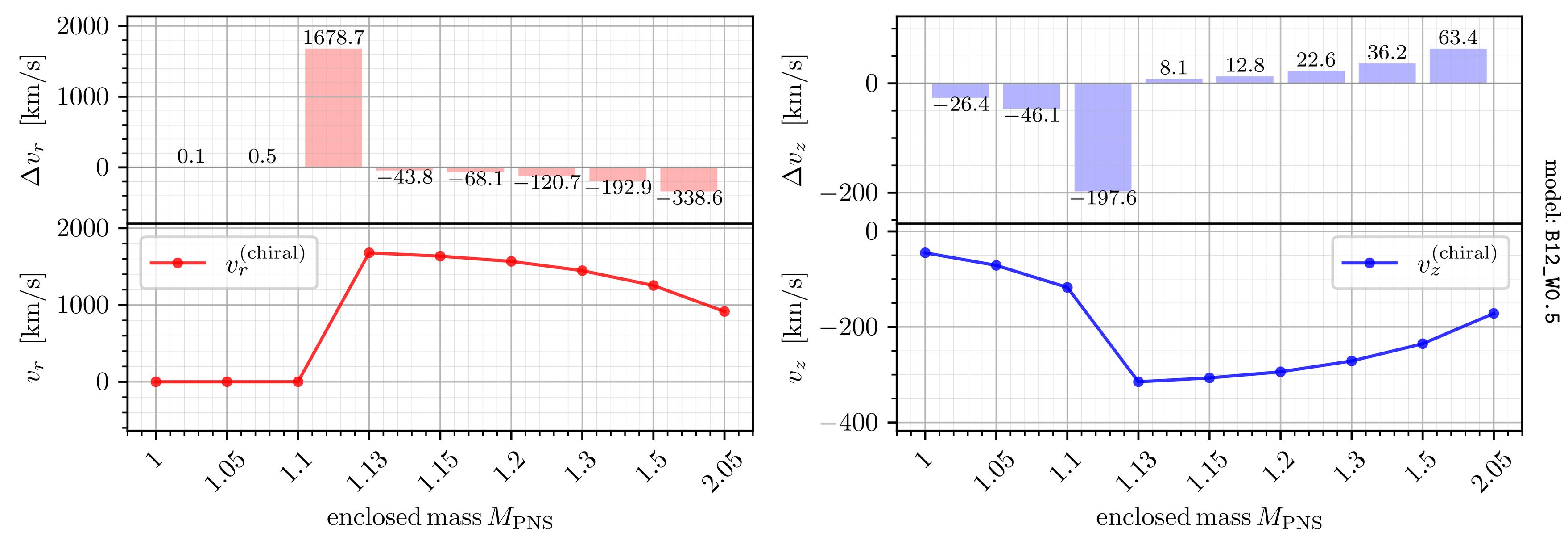

Figure 2. Final chiral kick velocity vs. enclosed mass (bottom), and incremental contribution from each shell (top), for radial (left) and axial (right) directions. Velocities are from time integration; bars show differences between mass layers.

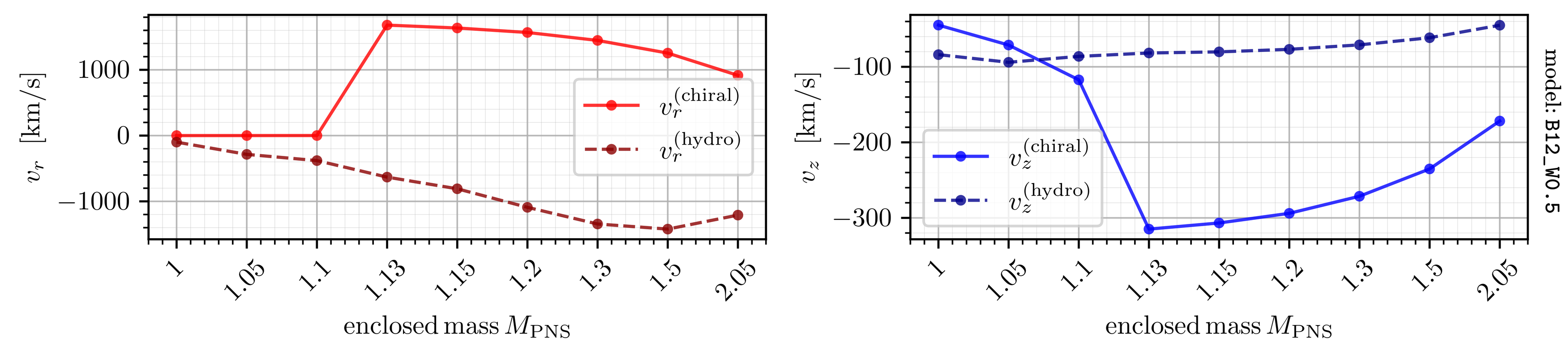

Figure 3. Final chiral kick velocity and hydrodynamic velocity vs. enclosed mass, for radial (left) and axial (right) directions. Hydrodynamic velocities are density-weighted averages $\langle v_i\rangle$ at the end of simulation.

Results:

- The chiral-to-momentum ratio is large in the z-direction before bounce and decreases afterward, while in the r-direction it starts small but grows post-bounce. Chiral effects in both directions become important at different stages.
- The ratio grows with magnetic field strength $B_{\varphi,0}$, but is insensitive to rotation ω_0.
- Both radial and axial kicks build up primarily in the 1.1-1.13 $M_{\rm PNS}$ shell, suggesting that chiral asymmetry is strongest in this region.
- Outer layers suppress the chiral kick in both directions.
- Despite smaller ratios, the final $v_r^{\rm (chiral)}$ reaches $\sim 10^3$ km/s, comparable in magnitude to hydro velocities, but opposite in sign.
- In the z-direction, $v_z^{\rm (chiral)}$ reaches 100-300 km/s and aligns with hydro, potentially explaining observed pulsar kicks.

Future Work:

Implement chiral source term into FLASH+IDSA for self-consistent feedback.

Reference:

[1] Yamamoto, N., & Yang, D.-L. (2020), "Chiral Radiation Transport Theory of Neutrinos", *The Astrophysical Journal*, **895**(1), 56.
[2] Yamamoto, N., & Yang, D.-L. (2021), "Magnetic field induced neutrino chiral transport near equilibrium", *Physical Review D*, **104**, 123019.
[3] Pan, K.-C., Liebendörfer, M., Couch, S. M., & Thielemann, F.-K. (2021), "Stellar mass black hole formation and multimessenger signals from three-dimensional rotating core-collapse supernova simulations". *The Astrophysical Journal*, **914**(2), 140.