Impact of chiral effects on core-collapse supernova dynamics

2026 ASROC Oral Presentation

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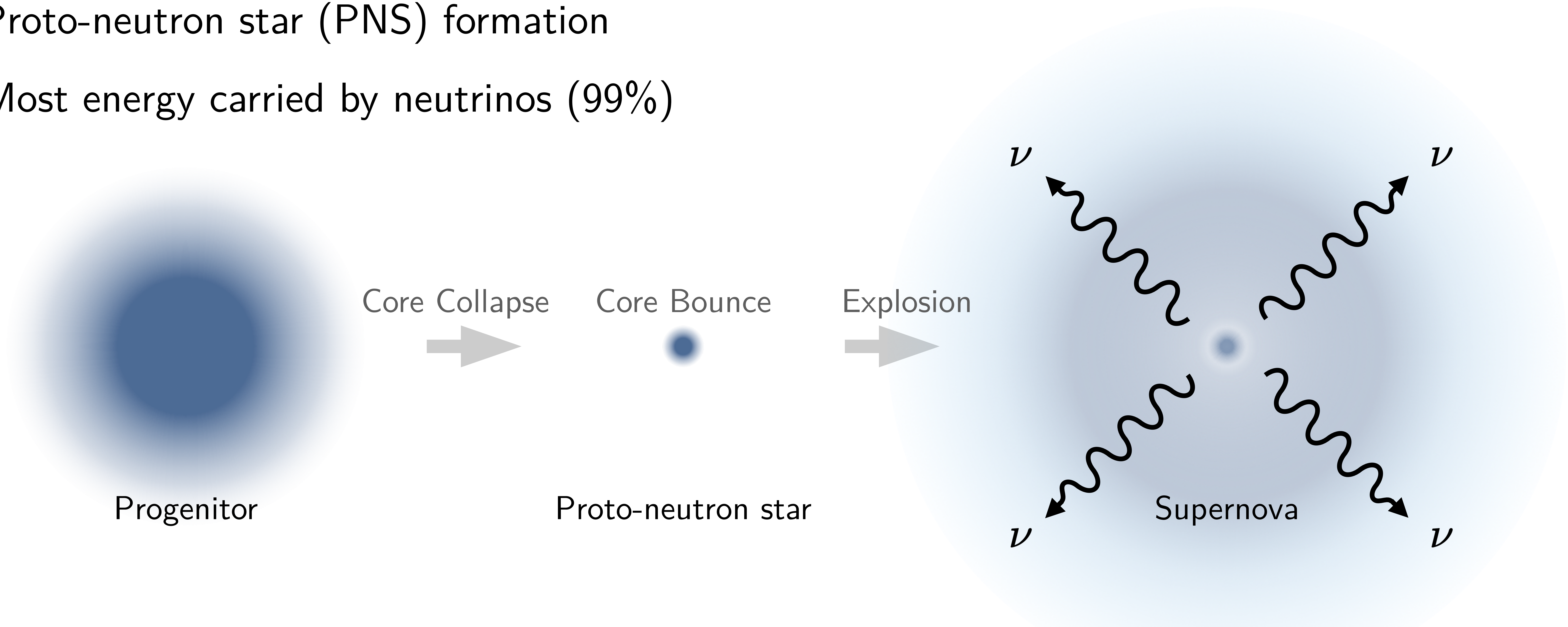
Introduction

Core Collapse Supernovae

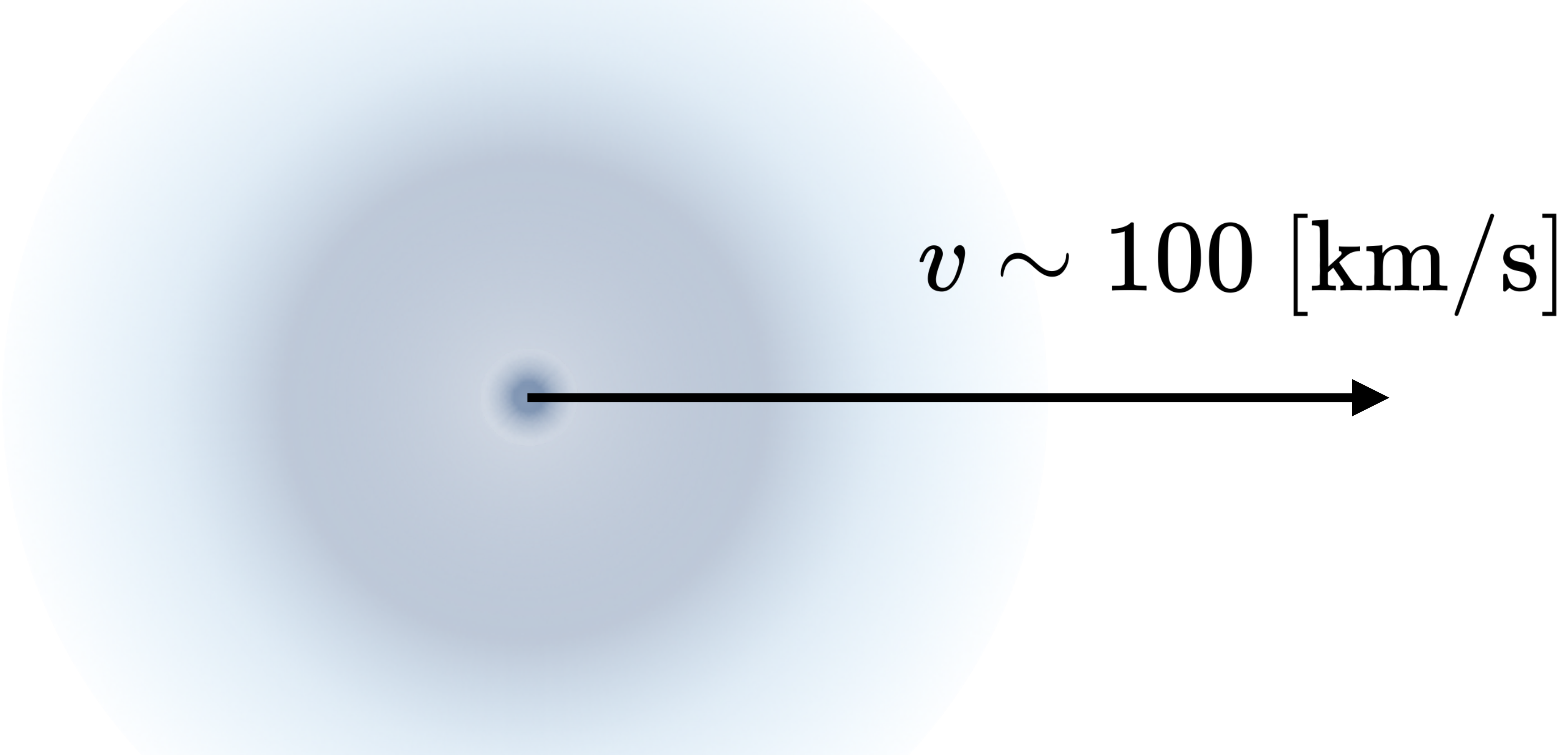
- Massive stars end $\rightarrow$ Core-Collapse Supernovae (CCSNe)
- Proto-neutron star (PNS) formation
- Most energy carried by neutrinos (99%)

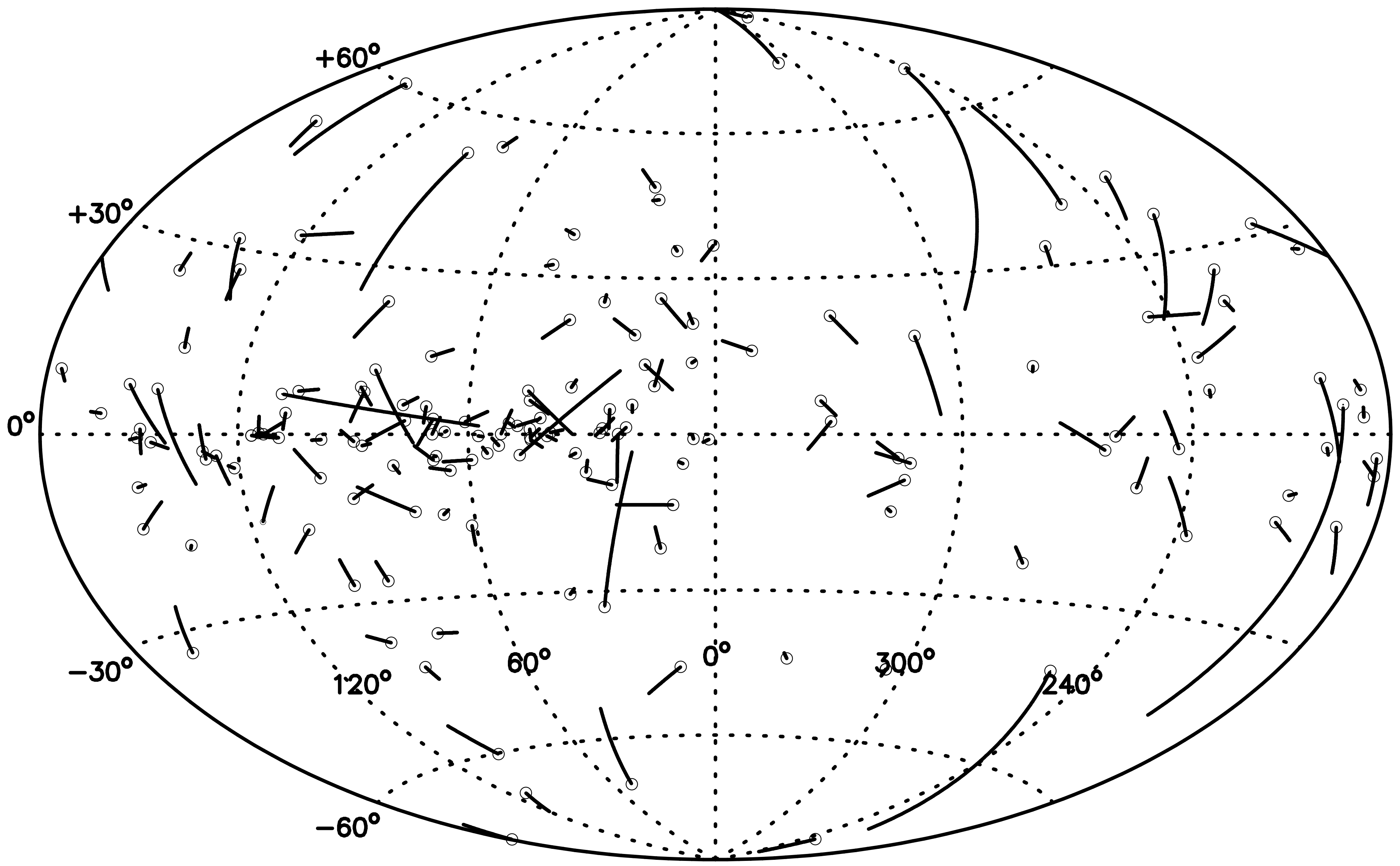


Introduction

Pulsar Kicks

- Neutron stars : move very fast after birth
- Observed velocities $\approx 100 \sim 1000$ km/s
- CCSNe $\rightarrow$ asymmetric explosions





Hobbs et al. (2005)

Hobbs et al., "A statistical study of 233 pulsar proper motions," MNRAS 360, 974 (2005).

Introduction

Chiral Neutrino Transport

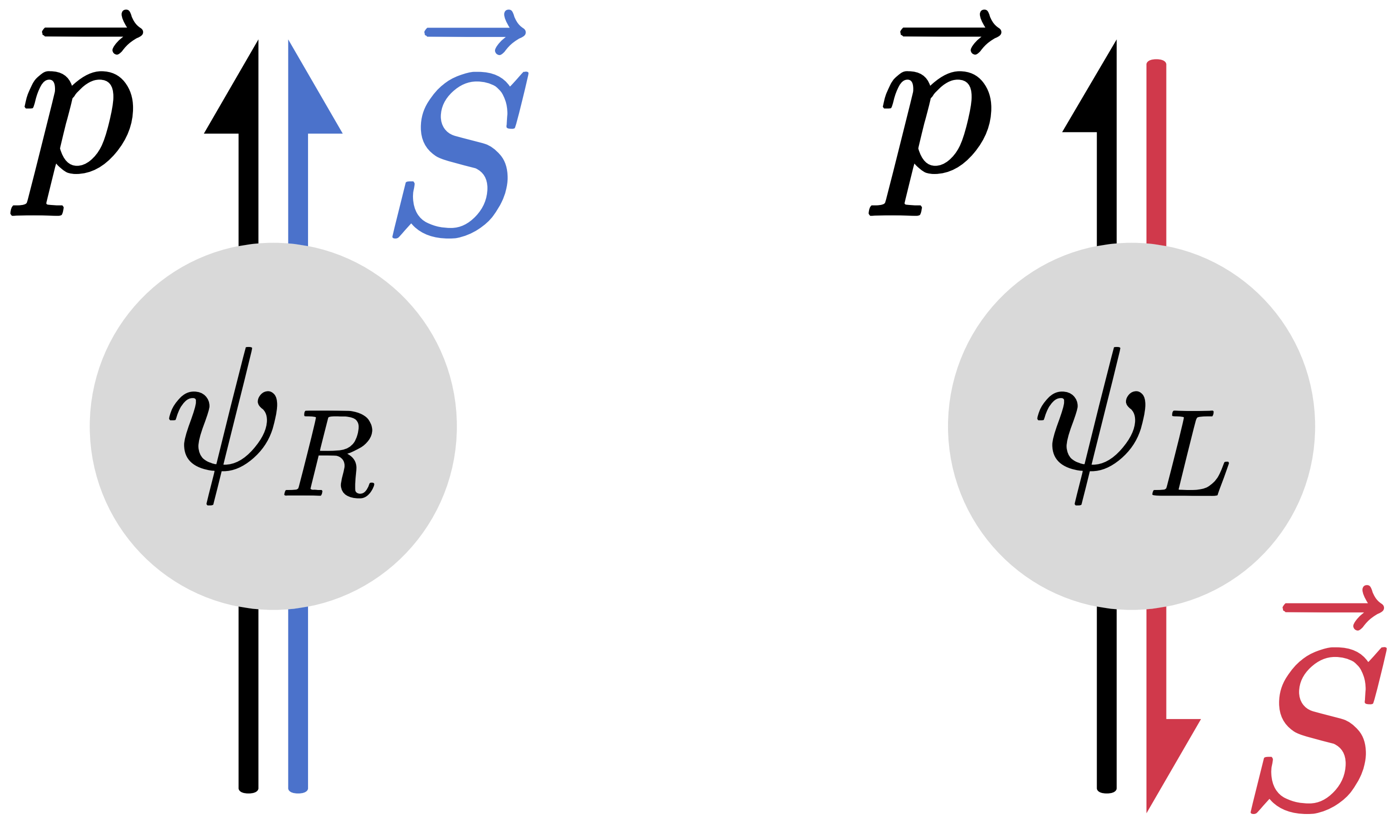
- Conventional: neutrinos $\rightarrow$ classical particles
- Neutrinos are left-handed
- Parity violation in weak interaction
- Neutrino transport $\rightarrow$ asymmetric momentum (Yamamoto & Yang 2020, 2021)

Can chiral neutrino transport affect CCSN dynamics
and contribute to pulsar kicks?

Physics Background

Chirality & Helicity

- Massless particles : ''Chirality'' $\sim$ ''Helicity''
- Spin aligned with momentum : right-handed
- Spin opposite to momentum : left-handed



Physics Background

Chiral Source Term

- Near-equilibrium chiral correction
- By Di-Lun Yang and Naoki Yamamoto: $\delta T^{\mu i}_{\mathrm{rad}} \propto (\boldsymbol{\nabla} \cdot \boldsymbol{v})\, B^i$
- Source Term for simulation:

$$\partial_\mu T^{\mu i}_{\mathrm{rad}} \approx -\frac{e\hbar^2}{72\pi M c\, G_{\mathrm{F}}^2 \left(g_{\mathrm{V}}^2 + g_{\mathrm{A}}^2\right)} \frac{e^{2(\mu_{\mathrm{n}}-\mu_{\mathrm{p}})/(k_B T)}}{n_{\mathrm{n}} - n_{\mathrm{p}}} \mu_\nu \left(B^i \left(\boldsymbol{\nabla} \cdot \boldsymbol{v}\right)^2 + \left(\boldsymbol{\nabla} \cdot \boldsymbol{v}\right) \left(\boldsymbol{B} \cdot \boldsymbol{\nabla}\right) v^i + \left(\boldsymbol{\nabla} \cdot \boldsymbol{v}\right) \partial_0 B^i\right)$$

Yamamoto, N., & Yang, D.-L. (2020), ''Chiral Radiation Transport Theory of Neutrinos'', *The Astrophysical Journal*, **895**(1), 56.
Yamamoto, N., & Yang, D.-L. (2021), ''Magnetic field induced neutrino chiral transport near equilibrium'', *Physical Review D*, **104**, 123019.

Method

Simulation Setup

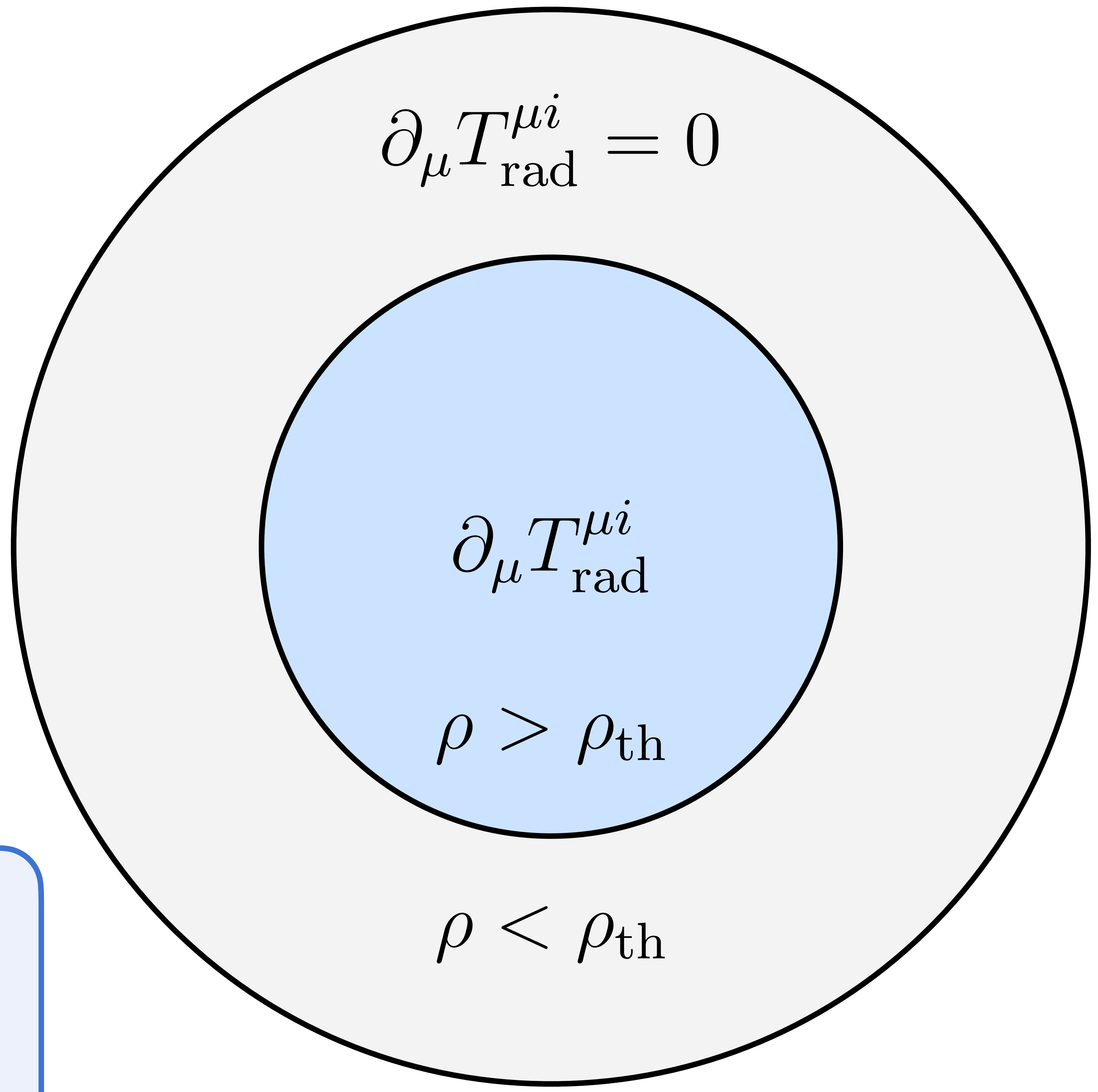
- 2D axisymmetric CCSN simulations
- FLASH MHD + IDSA neutrino transport (Pan et al. 2018, 2021)
- EoS : SFHo (Steiner et al. 2013)
- progenitor : $40\mathrm{M}_{\odot}$ solar metallicity (Woosley and Heger 2027)
- Momentum equation $\rightarrow$ add chiral source term

$$\frac{\partial(\rho v^i)}{\partial t} + \Big(\text{transport terms}\cdots\Big) = \partial_\mu T^{\mu i}_{\text{rad}} + \Big(\text{other source terms}\cdots\Big)$$

Method

Simulation Initial Setup

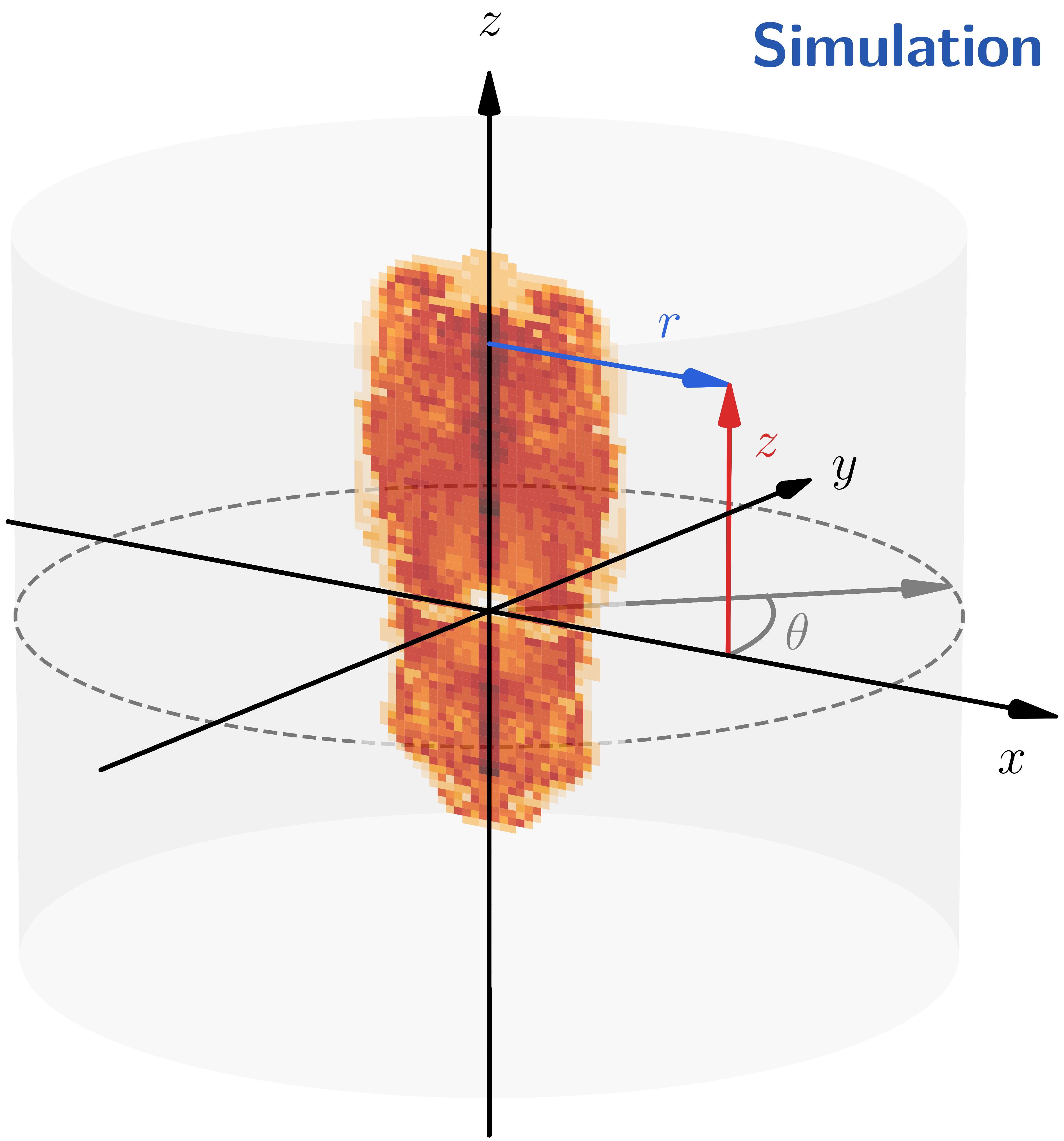
- Magnetic field : $B_0 = 10^{12}, 10^{13}$ G
- Rotation : $\Omega_0 = 0.5$ rad/s
- Density threshold : $\rho_{\rm th} = 10^{10} \sim 10^{11}$ g/cm^3
- Chiral Scale Factor : $\times 1$ and $\times 10$



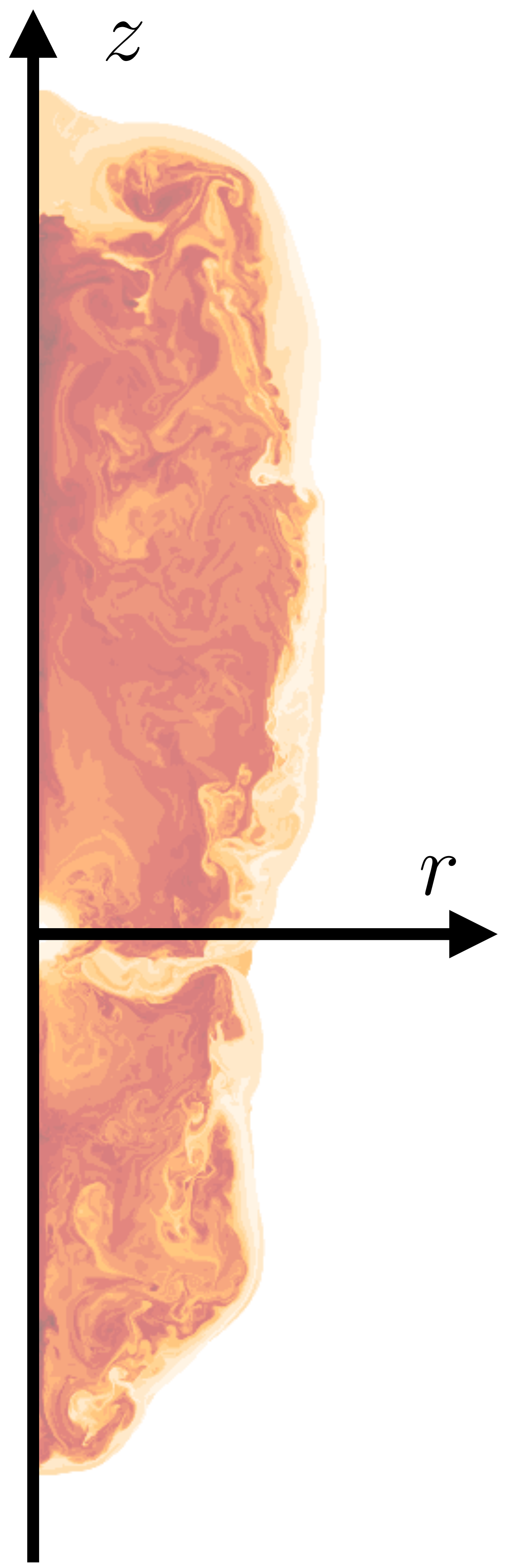
Test whether enhanced chiral effects can modify CCSN dynamics or produce kick-like asymmetry.

Method

Simulation Coordinate



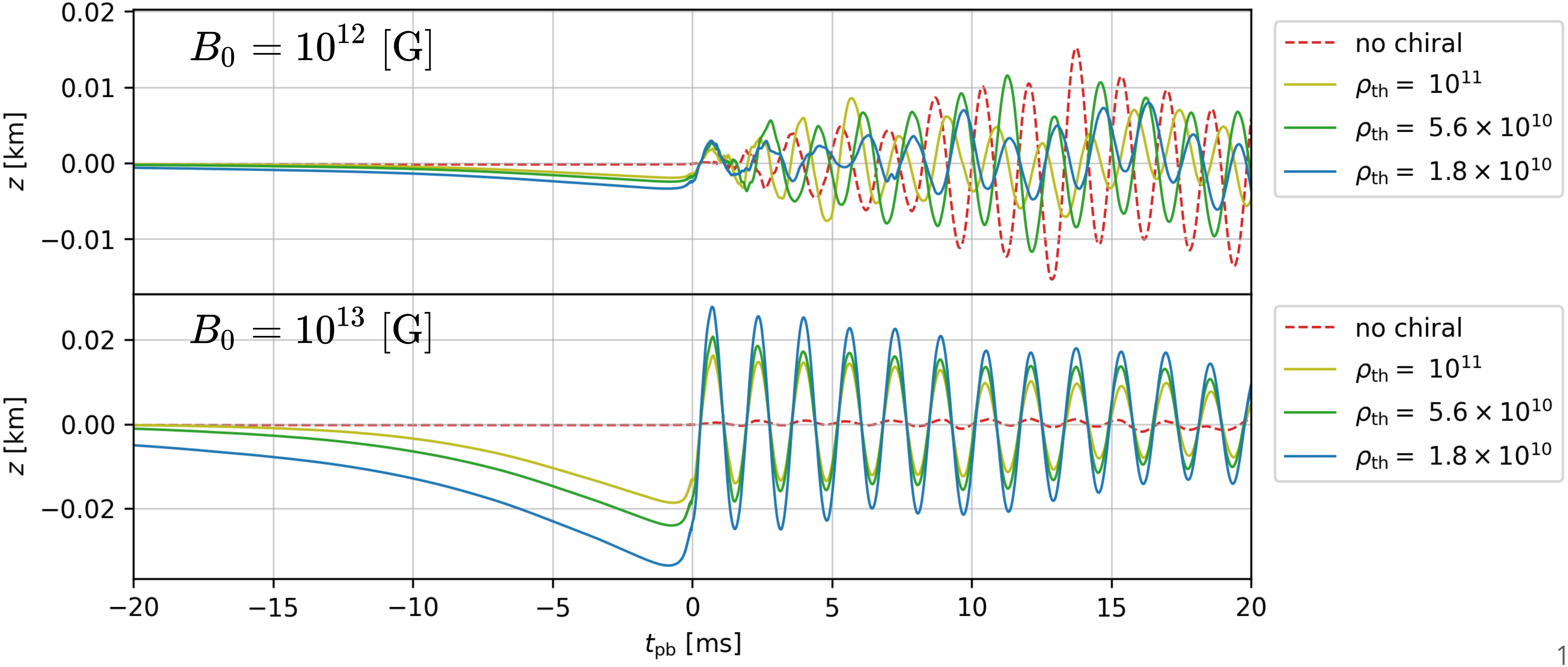
Simulation Coordinate 3D



Simulation Coordinate 2D

Results

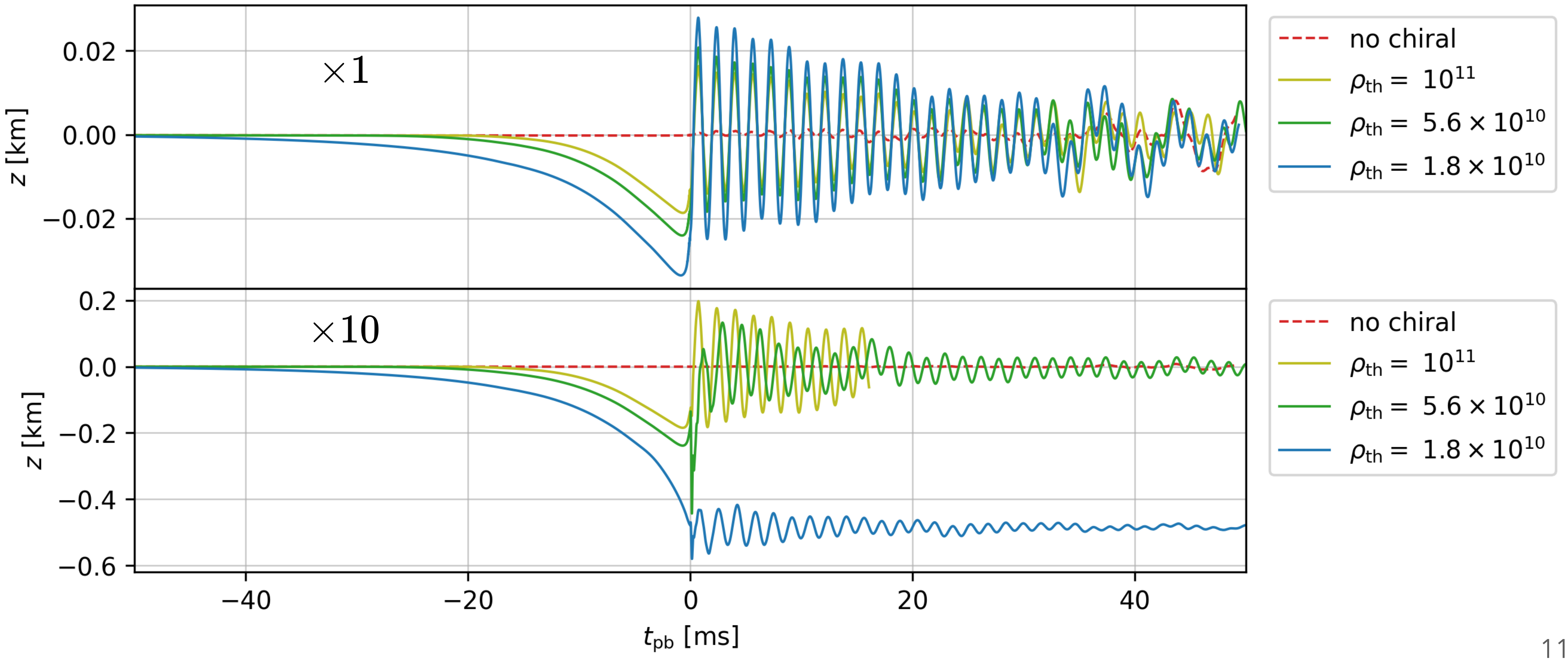
PNS position for unscaled Chiral Effect



Results

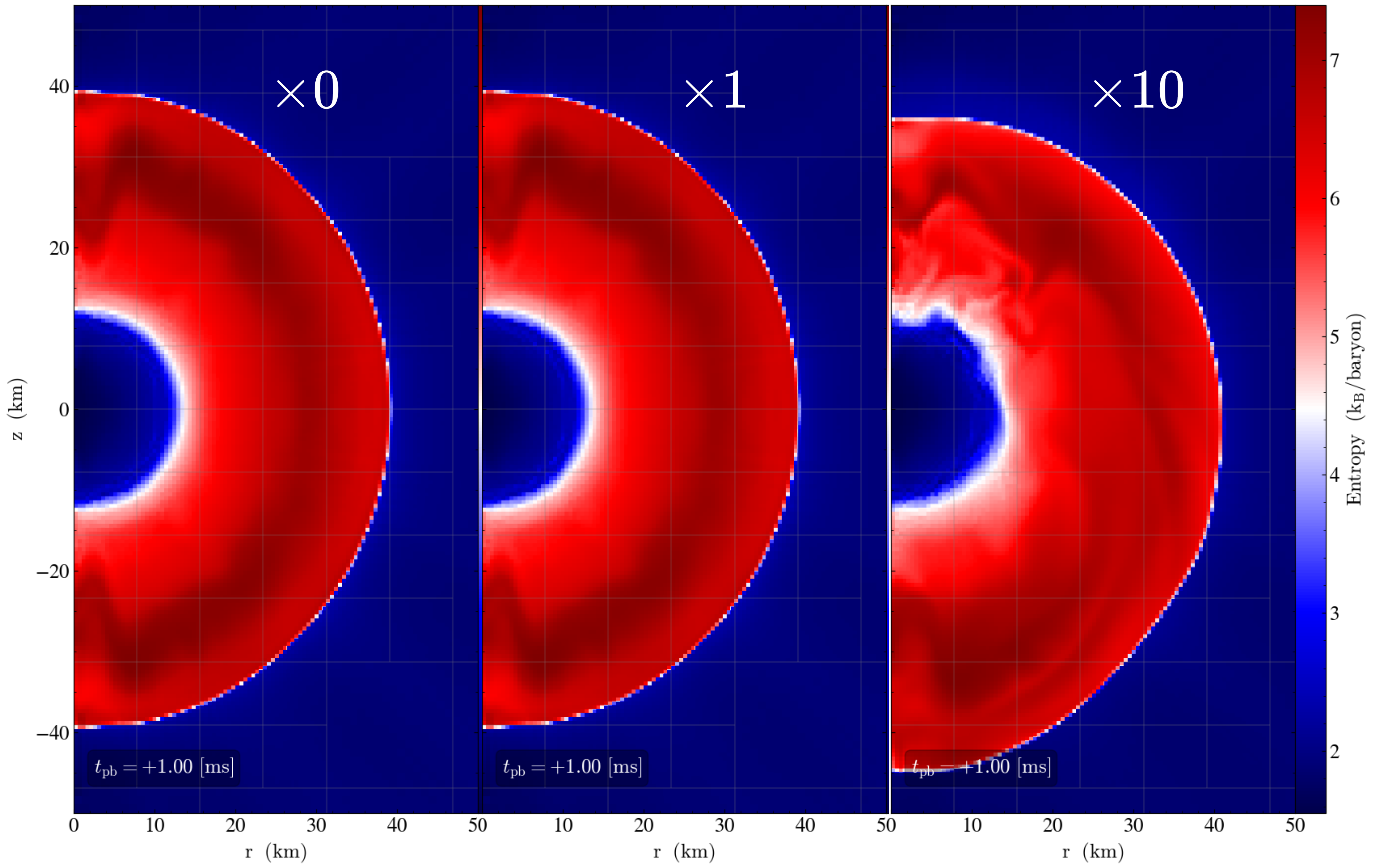
$B_0 = 10^{13}$ [G]

PNS position for scaled Chiral Effect



Results

Entropy Morphology



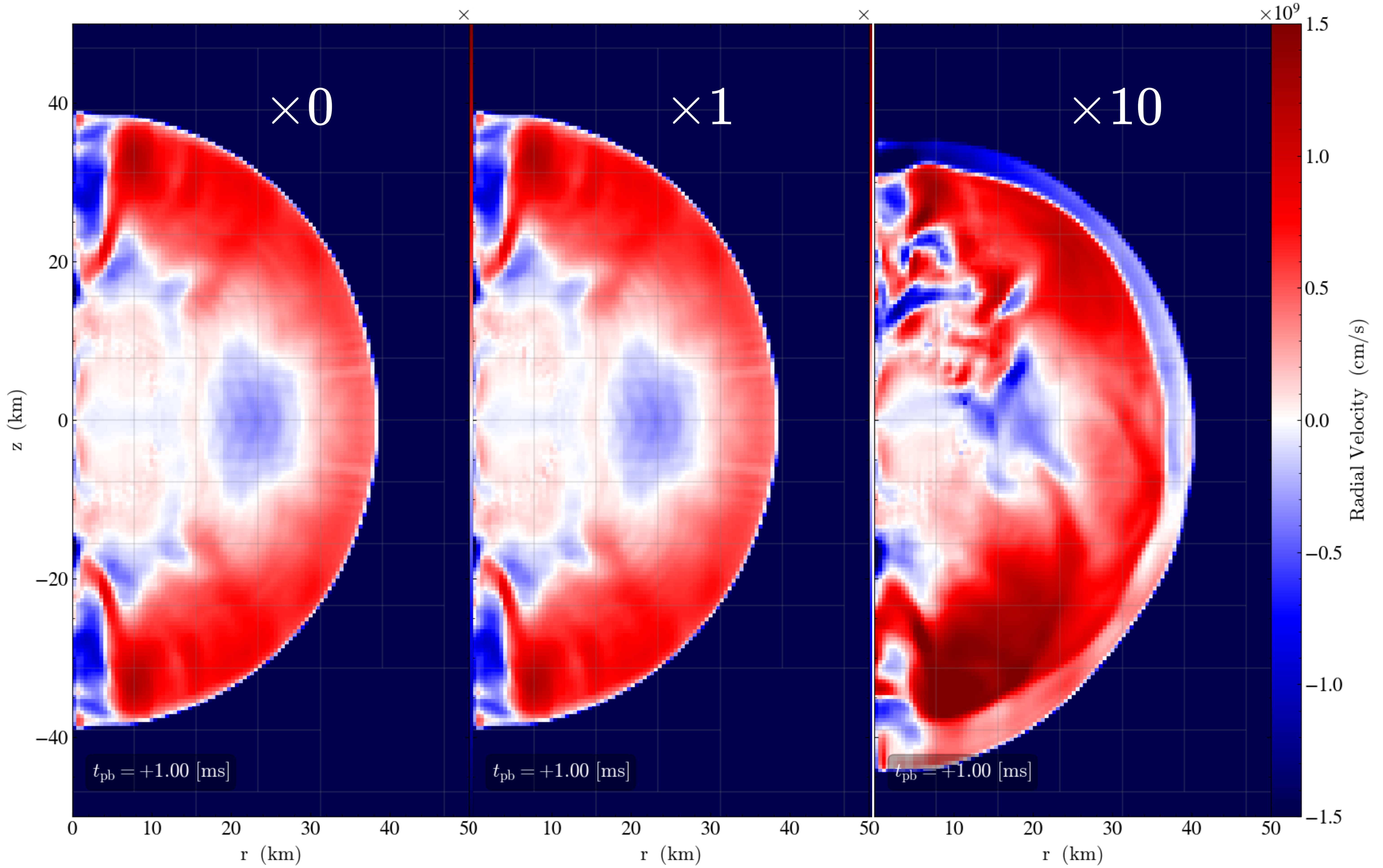
$B_0 = 10^{13}$ [G]

$\rho_{\rm th} = 5.6 \times 10^{10}$ [g/cm^3]

$t_{\rm pb} \approx 1$ [ms]

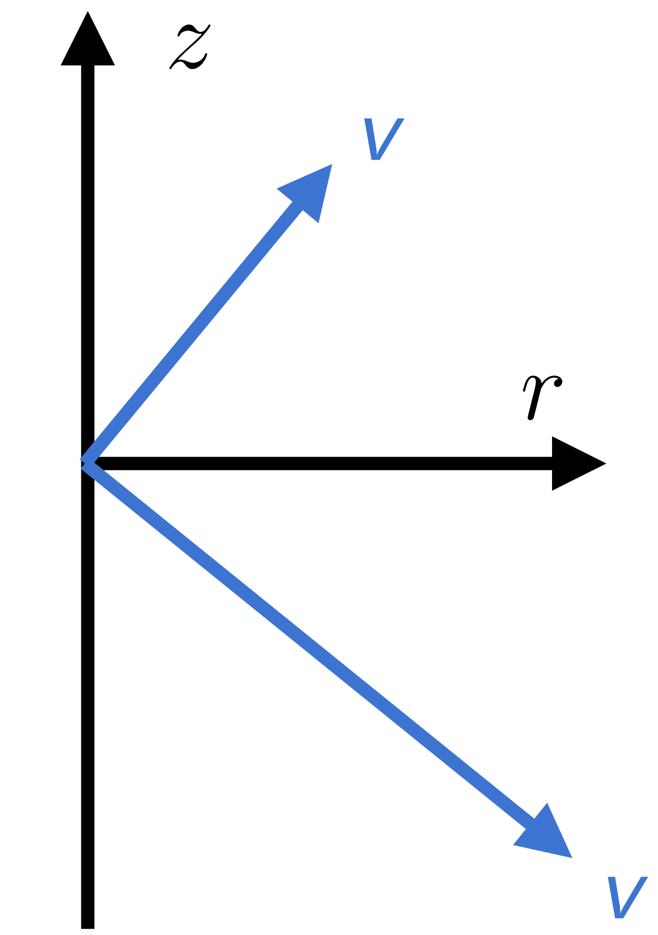
Results

Radial Velocity Morphology



$$B_0 = 10^{13}\ [\mathrm{G}]$$

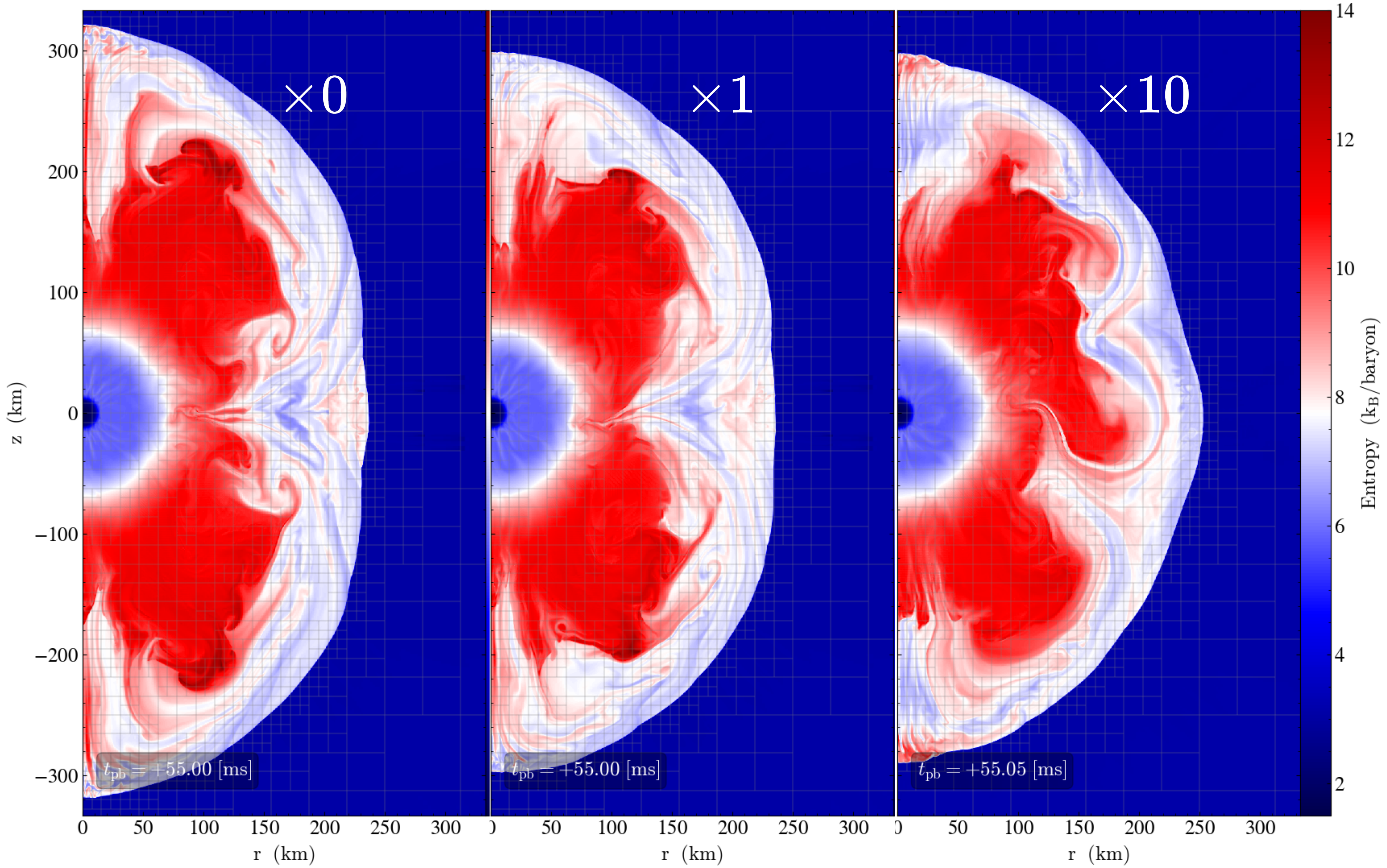
$$\rho_{\mathrm{th}} = 5.6 \times 10^{10}\ [\mathrm{g/cm^3}]$$



$$t_{\mathrm{pb}} \approx 1\ [\mathrm{ms}]$$

Results

Entropy Morphology



$B_0 = 10^{13}$ [G]

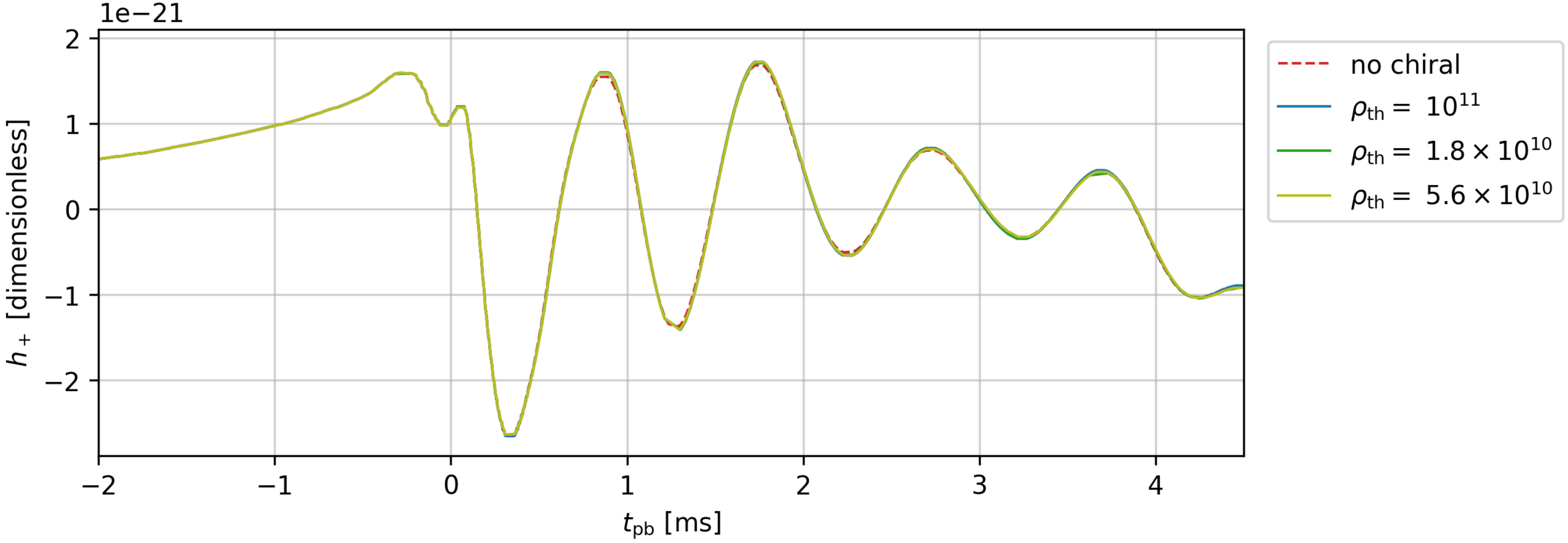
$\rho_{th} = 5.6 \times 10^{10}$ [g/cm^3]

$t_{pb} \approx 55$ [ms]

Results

Gravitational Wave Polarization for unscaled Chiral Effect

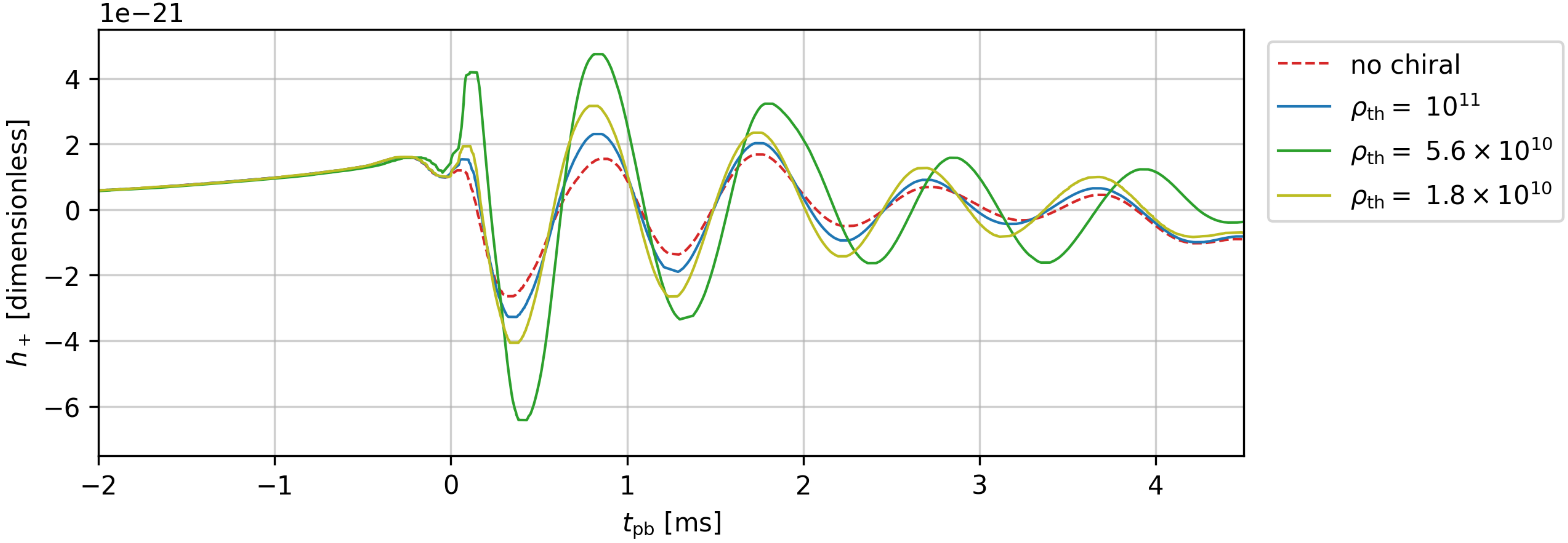
$$B_0 = 10^{13}\ [\mathrm{G}]$$



Results

Gravitational Wave Polarization for scaled 10 Chiral Effect

$$B_0 = 10^{13}\ [\mathrm{G}]$$



Summary & Outlook

- Chiral effects coupled into 2D CCSN simulations
- Original chiral effect $\rightarrow$ small impact on dynamics
- Enhanced ($\times 10$) chiral coupling produces:
  - PNS center displacement and oscillations
  - More asymmetric morphology
  - Stronger GW emission and frequency change
- Scaled-up chiral effects may enhance CCSN asymmetry
- Future work:
  - Include additional terms beyond current approximation
  - Explore stronger chiral effects

Thank you!

Backup Slides

Chiral Source Term

In CGS-Gaussian:

$$[\mathrm{g/cm^2/s^2}] \;—\; \partial_\mu T^{\mu i}_{\mathrm{rad}} \approx \frac{|e|h^2}{288\pi^3 c^2}\,\frac{1}{MG_\mathrm{F}^2\left(g_\mathrm{V}^2+3g_\mathrm{A}^2\right)}\,\frac{e^{2(\mu_\mathrm{n}-\mu_\mathrm{p})/(k_B T)}}{n_\mathrm{n}-n_\mathrm{p}}\,\mu_\nu \times \left(B^i(\boldsymbol{\nabla}\cdot\boldsymbol{v})^2 + (\boldsymbol{\nabla}\cdot\boldsymbol{v})\,(\boldsymbol{B}\cdot\boldsymbol{\nabla})\,v^i + (\boldsymbol{\nabla}\cdot\boldsymbol{v})\;\partial_0 B^i\right)$$

$k_B \approx 1.38065\times10^{-16}$ [erg/K]

$h \approx 6.62607\times10^{-27}$ [g · cm^2/s]

$e \approx 4.80320\times10^{-10}$ [esu]

$c \approx 2.99792\times10^{10}$ [cm/s]

$M \approx 1$ [amu] $\approx 1.66054\times10^{-24}$ [g]

$G_\mathrm{F} \approx 1.43585\times10^{-49}$ [erg · cm^3]

$g_\mathrm{V} = 1$

$g_\mathrm{A} = 1.27$

$\mu_{\mathrm{n,CGS}}$ [erg] $= \mu_{\mathrm{n,EoS}}$ [MeV] $\cdot\, 6.24151\times10^5$ [erg/MeV]

$\mu_{\mathrm{p,CGS}}$ [erg] $= \mu_{\mathrm{p,EoS}}$ [MeV] $\cdot\, 6.24151\times10^5$ [erg/MeV]

T_{CGS} [K]

$\mu_{\nu,\mathrm{CGS}}$ [erg] $= \mu_{\nu,\mathrm{EoS}}$ [MeV] $\cdot\, 6.24151\times10^5$ [erg/MeV]

v_{CGS} [cm/s]

$n_{\mathrm{p,CGS}}$ [1/cm^3]

$n_{\mathrm{n,CGS}}$ [1/cm^3]

$\partial_{i,\mathrm{CGS}}$ [1/cm]

B_{CGS} [Gauss]

Simulation Equations

in one of step

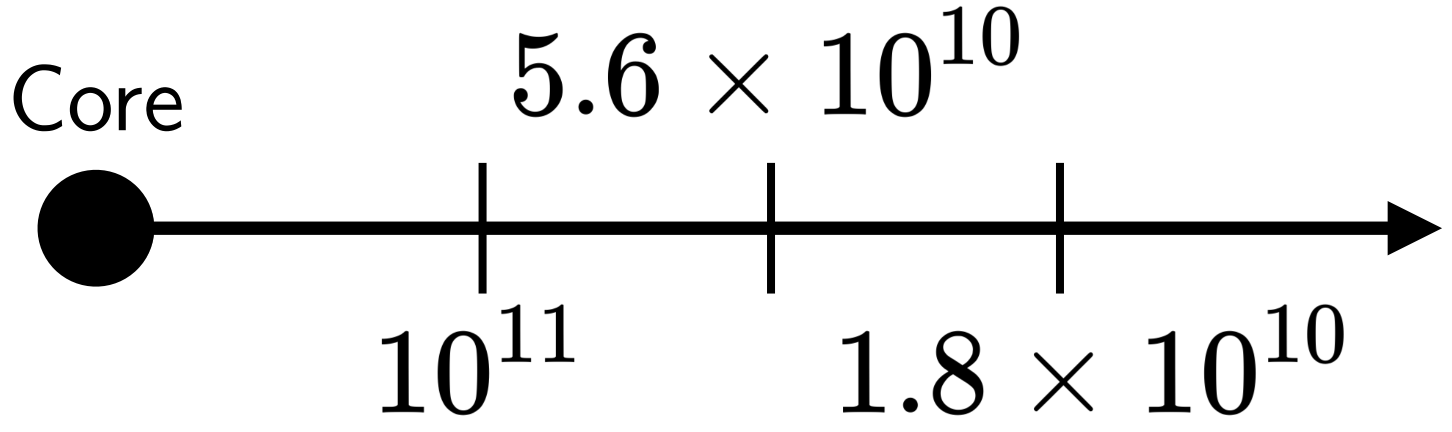
$$\partial_0 \left(\rho v^i\right) + \partial_j \left(\rho v^j v^i - B^i B^j + \delta^{ji}\left(P + \frac{B^2}{2}\right)\right) = -\partial_\mu (\Pi^{\mu i} + T^{\mu i}_{\mathrm{rad}}),$$

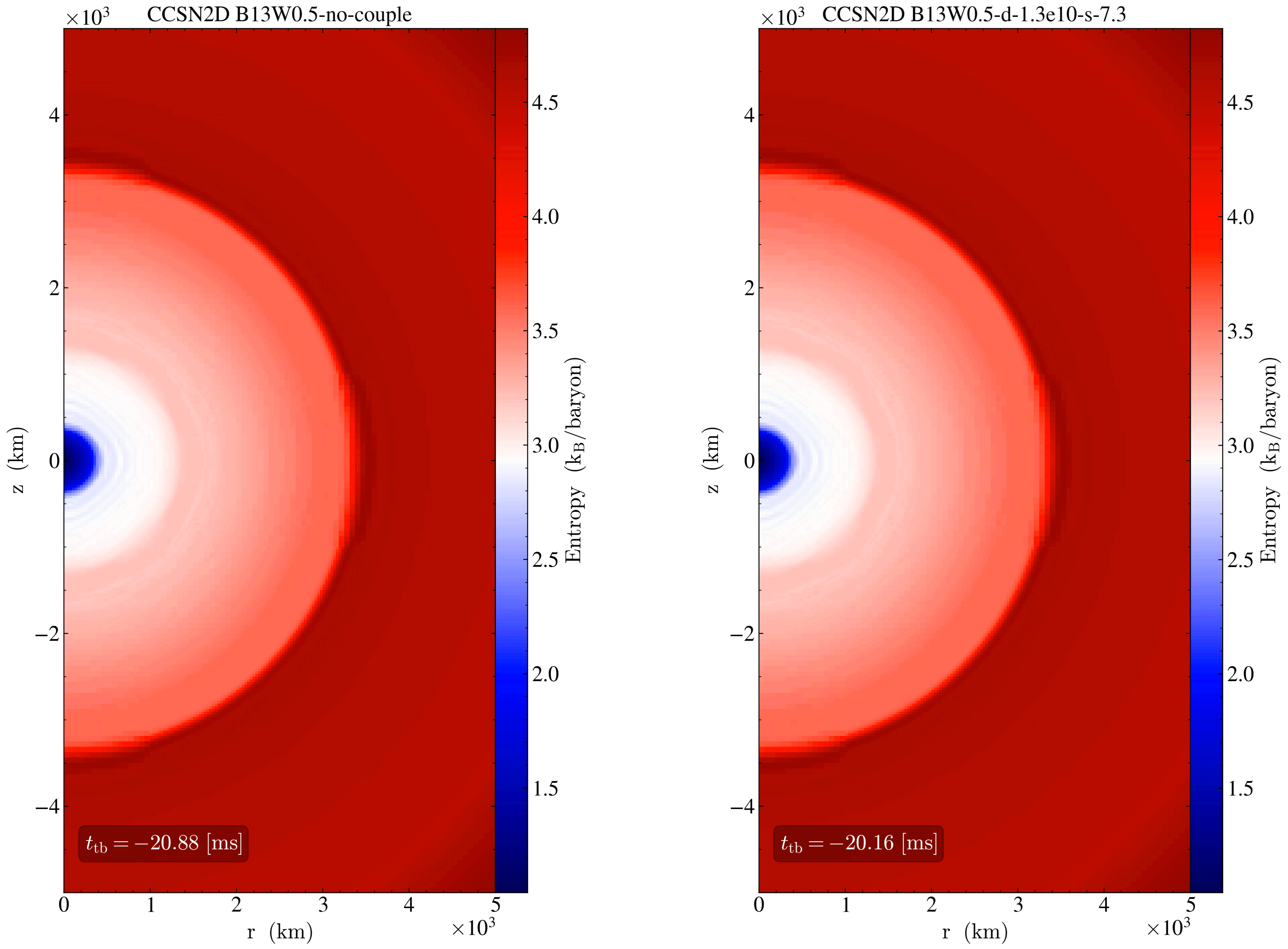
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B}) + \nabla \left(p + \frac{\boldsymbol{B}^2}{2}\right) = \nabla \cdot \boldsymbol{\tau}$$

Euler Approximation

$$\frac{\partial(\rho v^i)'}{\partial t} = -\partial_\mu T^{\mu i}_{\mathrm{rad}} \longrightarrow \frac{(\rho v^i)'_{n+1} - (\rho v^i)'_n}{\delta t} \approx -\partial_\mu T^{\mu i}_{\mathrm{rad}} \longrightarrow (\rho v^i)'_{n+1} \approx (\rho v^i)'_n - \delta t \times \partial_\mu T^{\mu i}_{\mathrm{rad}}$$

$$v^i \to v^i + \frac{\delta t}{\rho}(-\partial_\mu T^{\mu i}_{\mathrm{rad}})$$


Core
5.6×10^{10}
10^{11}
1.8×10^{10}



CCSN2D B13W0.5-no-couple
CCSN2D B13W0.5-d-1.3e10-s-7.3
×10^3
z (km)
r (km)
Entropy (k_B/baryon)
$t_{tb} = -20.88$ [ms]
$t_{tb} = -20.16$ [ms]