Primordial Magnetic Field from Chiral Plasma Instability with Sourcing

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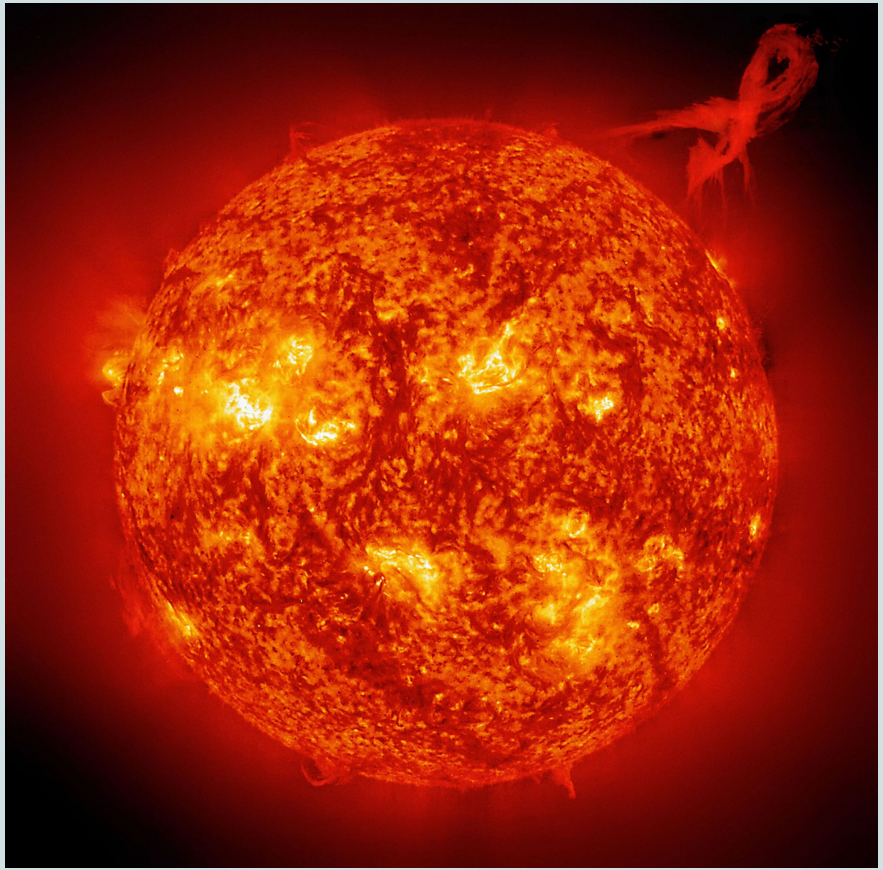


Credit: Extreme Ultraviolet Imaging Telescope onboard the Solar and Heliospheric Observatory

Motivation & The Big Picture

- **Observational Puzzles:** PMFs are a potential explanation for the observed galactic and intergalactic magnetic fields. [Durrer, R., & Neronov, A. 2013,]

- **Early Universe Probe:** They provide a unique window into the physics of the very early universe, potentially linked to baryogenesis, inflation, or phase transitions.

- **The Problem:** Generating fields of sufficient strength and coherence that survive until today is a major theoretical challenge.

Motivation & The Big Picture

- **Magnetic fields:** MicroG in galaxies, possible $10^{-15}\,\mathrm{G}$ in voids

[Durrer, R., & Neronov, A. 2013]

- **Origin still unclear:** There broadly are three classes
    - Inflationary magnetic field generation
    - Generation of magnetic fields during phase transitions
    - Magnetogenesis from second-order cosmological perturbations

The Chiral Plasma instability (CPI)

- $J_{\mathrm{CPI}} = c\tilde{\mu}_5 B$ [Vilenkin 1980]

- **CPI was shown to amplify helical B field** [Joyce & Shaposhnikov 1997]

- **Nonlinear evolution via χMHD simulations** [Rogachevskii et al. 2017, arXiv:1705.00378]
  [Brandenburg et al. 2017, arXiv:1707.03385]

The Chiral Plasma Instability

- **Foundation:** This research is continuation of previous work which established the CPI at 100 GeV and 1GeV [Brandenburg et al. 2017]

- **Chiral Asymmetry:** A net difference between right-handed and left-handed fermions in a plasma.

- **Chiral Magnetic Effect (CME):** This asymmetry sources a helical current parallel to an existing magnetic field.

$$J_{\mathrm{CPI}} = c\tilde{\mu}_5 B$$

- **The Instability:** This current amplifies the magnetic field, leading to an inverse cascade of energy to larger scales.

Our Model: Introducing a Source Term

$$\Gamma_R = \Gamma(\phi \to e_R^- + e_R^+ + X), \qquad \Gamma_L = \Gamma(\phi \to e_L^- + e_L^+ + \bar{X})$$

$$\Gamma_R = (1+\epsilon)\frac{\beta}{2}\Gamma_\phi, \qquad \Gamma_L = (1-\epsilon)\frac{\beta}{2}\Gamma_\phi$$

$$S_5(t_c) = (\Gamma_R - \Gamma_L) n_\phi(t_c) = \epsilon\beta\Gamma_\phi n_\phi(t_c)$$

$$S_5(t_c) = \epsilon\beta\Gamma_\phi \frac{\rho_{\rm rad}\Omega_\phi}{m_\phi c^2}\left(\frac{t_c}{\tau_\phi}\right)^{-3/2} e^{-\Gamma_\phi(t_c-\tau_\phi)}$$

$$S_5(t) = \bar{S}_5 \frac{t}{t_\phi} e^{-(t^2-t_\phi^2)/(2t_\phi^2)}$$

Our Model: Introducing a Source Term

$$\frac{\partial}{\partial t}\mathbf{A} = \mathbf{u} \times \mathbf{B} + \eta \left(\tilde{\mu}_5 \mathbf{B} - \frac{1}{c}\mathbf{J} \right)$$

$$\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \tilde{\mu}_5 = -\tilde{\mu}_5 \nabla \cdot \mathbf{u} + D_5 \nabla^2 \tilde{\mu}_5 - \lambda \eta \left(\tilde{\mu}_5 \mathbf{B} - \frac{1}{c}\mathbf{J} \right) \cdot \mathbf{B} - \Gamma_5 \tilde{\mu}_5 + \tilde{S}_5$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = 2\nabla \cdot (\rho \nu \mathbf{S}) - \frac{c^2}{4}\nabla \rho + \frac{1}{3}\mathbf{u} \nabla \cdot (\rho \mathbf{u}) + \frac{3c}{4}\mathbf{J} \times \mathbf{B} - \mathbf{u} \left[\frac{1}{c}\mathbf{u} \cdot (\mathbf{J} \times \mathbf{B}) + \frac{1}{c^2}\eta |\mathbf{J}|^2 \right]$$

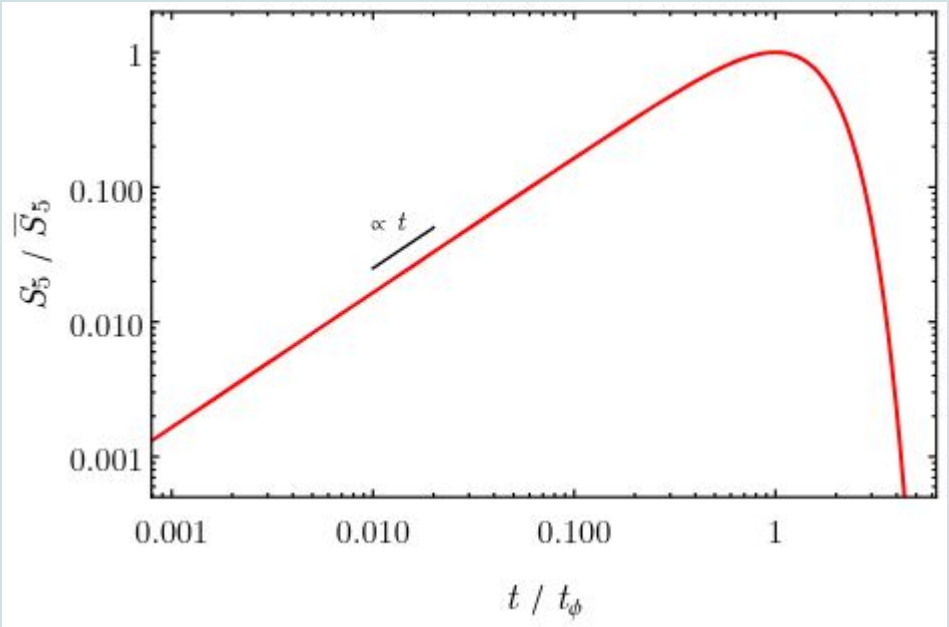
$$\frac{\partial}{\partial t}\rho = -\frac{4}{3}\rho \nabla \cdot \mathbf{u} - \frac{4}{3}\mathbf{u} \cdot \nabla \rho + \frac{1}{c}\mathbf{u} \cdot (\mathbf{J} \times \mathbf{B}) + \frac{1}{c^2}\eta |\mathbf{J}|^2$$

Our Model: Introducing a Source Term

$$\Gamma_R = (1+\epsilon)\frac{\beta}{2}\Gamma_\phi, \qquad \Gamma_L = (1-\epsilon)\frac{\beta}{2}\Gamma_\phi$$

$$S_5(t_c) = (\Gamma_R - \Gamma_L)n_\phi(t_c) = \epsilon\beta\Gamma_\phi n_\phi(t_c)$$

$$S_5(t) = \bar{S}_5 \frac{t}{t_\phi} e^{-(t^2-t_\phi^2)/(2t_\phi^2)}$$



Evolution of the chiral source with conformal time.

Pencil Code

Table 1: Fiducial background parameters (electroweak epoch).

Quantity	**Symbol**	**Physical Value**	**Comoving Value**
Plasma temperature	$T_{\rm phys,*}$	$100\,{\rm GeV}/k_B$	$7.8\times10^{-5}\,a_0\,{\rm eV}/k_B$
Scale factor	a_*	—	$7.8\times10^{-16}\,a_0$
Cosmic time	$t_{c,*}$	$2.3\times10^{-11}\,{\rm s}$	$6.0\times10^{4}/a_0$
Hubble length	$l_{\rm phys,*}$	$1.4\,{\rm cm}$	$1.8\times10^{15}/a_0\,{\rm cm}$
Hubble energy	$E_{\rm phys,*}$	$1.3\times10^{60}\,{\rm eV}$	$9.8\times10^{44}\,a_0\,{\rm eV}$

Table 2: Fiducial χMHD parameter estimates

Parameter	**Symbol**	**Fiducial Value**
Magnetic diffusivity	η	$\eta_* = 1.4\times10^{-18}\,l_*^2 t_*^{-1}$
Chiral diffusivity	D_5	$D_{5,*} = 1.4\times10^{-18}\,l_*^2 t_*^{-1}$
Kinematic viscosity	ν	$\nu_* = 1.4\times10^{-18}\,l_*^2 t_*^{-1}$
CME coupling	λ	$\lambda_* = 1.2\times10^{29}\,l_* E_*^{-1}$
Chirality erasure rate	Γ_5	$\Gamma_{5,*} = 8.0\times10^{2}\,t_*^{-1}$
Source amplitude	$\tilde{\tilde{S}}_5$	$\tilde{\tilde{S}}_{5,*} = 4.1\times10^{13}\,l_*^{-1} t_*^{-1}$
Source duration	t_ϕ	$t_{\phi,*} = 0.05\,t_*$

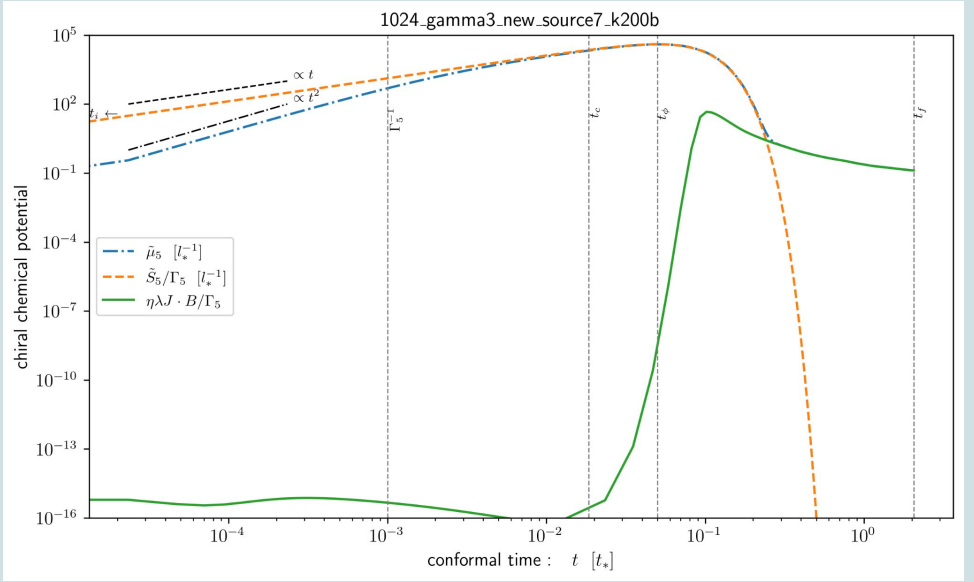
$$
\begin{aligned}
t_i &= 10^{-5}\,t_* \\
\boldsymbol{A}(\boldsymbol{x},t_i) &= \mathcal{N}(10^{-12}\,E_*^{1/2} l_*^{-1/2}) \\
\tilde{\mu}_5(\boldsymbol{x},t_i) &= 0 \\
\boldsymbol{u}(\boldsymbol{x},t_i) &= 0 \\
\rho(\boldsymbol{x},t_i) &= E_* l_*^{-3}\,.
\end{aligned}
$$

Results

$$\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\tilde{\mu}_5 = -\tilde{\mu}_5\nabla\cdot\mathbf{u} + D_5\nabla^2\tilde{\mu}_5 - \lambda\eta\left(\tilde{\mu}_5\mathbf{B} - \frac{1}{c}\mathbf{J}\right)\cdot\mathbf{B}$$
$$-\Gamma_5\tilde{\mu}_5 + \tilde{S}_5$$

$$t_i < t < \Gamma_5^{-1} \quad \propto t^2$$

$$\Gamma_5^{-1} < t < t_{\text{cross}}, \quad \propto t^1$$

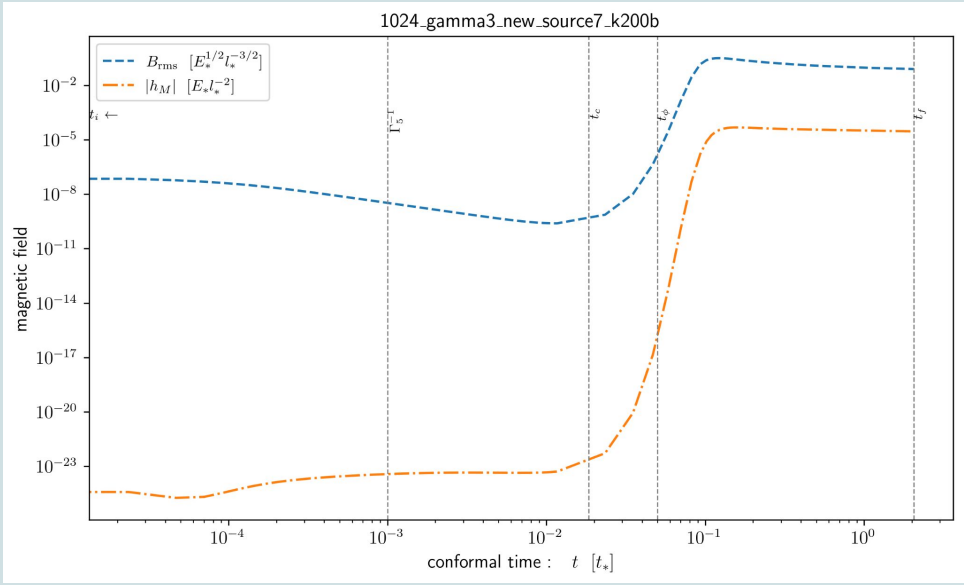


Evolution of volume averaged chiral asymmetry:

Results

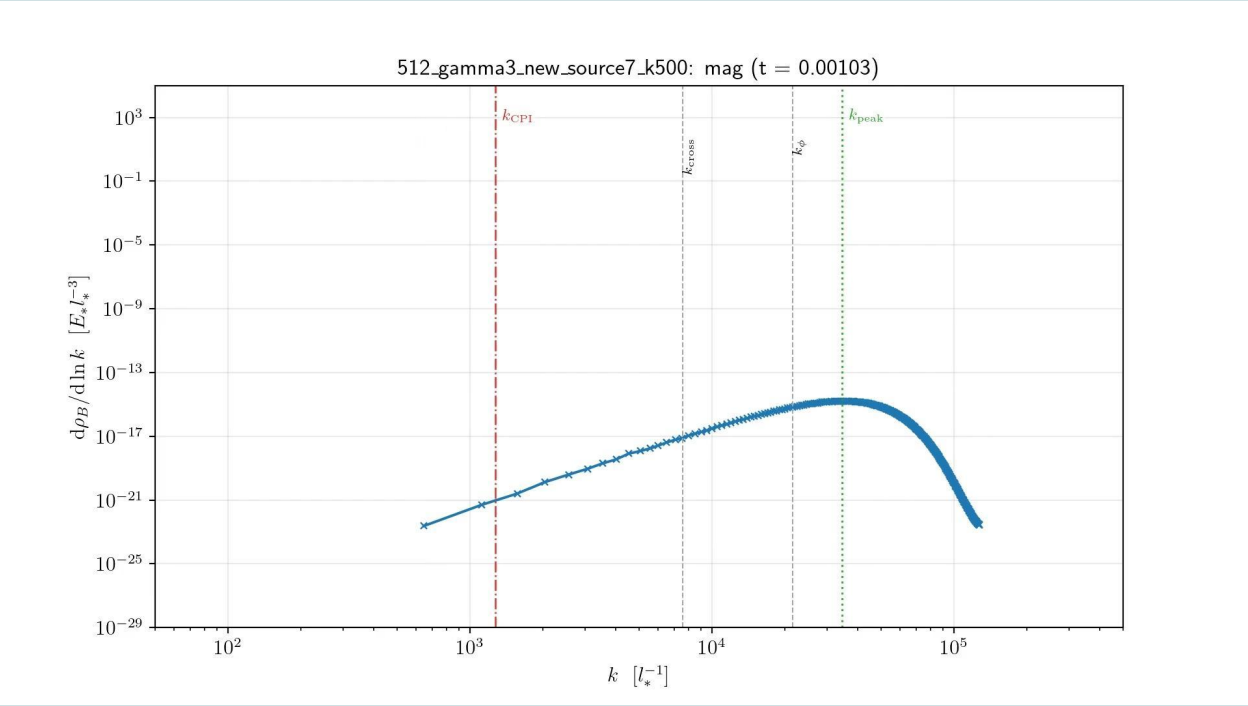
$$\partial_t A_{k,\pm} + (\eta |k|^2 \mp \eta \tilde{\mu}_5 |k|) A_{k,\pm} = 0$$

- mu =0 $A_{k,\pm} \propto \exp[-\eta |k|^2 t]$
- mu>0 $|k| < \tilde{\mu}_5$
- mu <0 $|k| < -\tilde{\mu}_5$



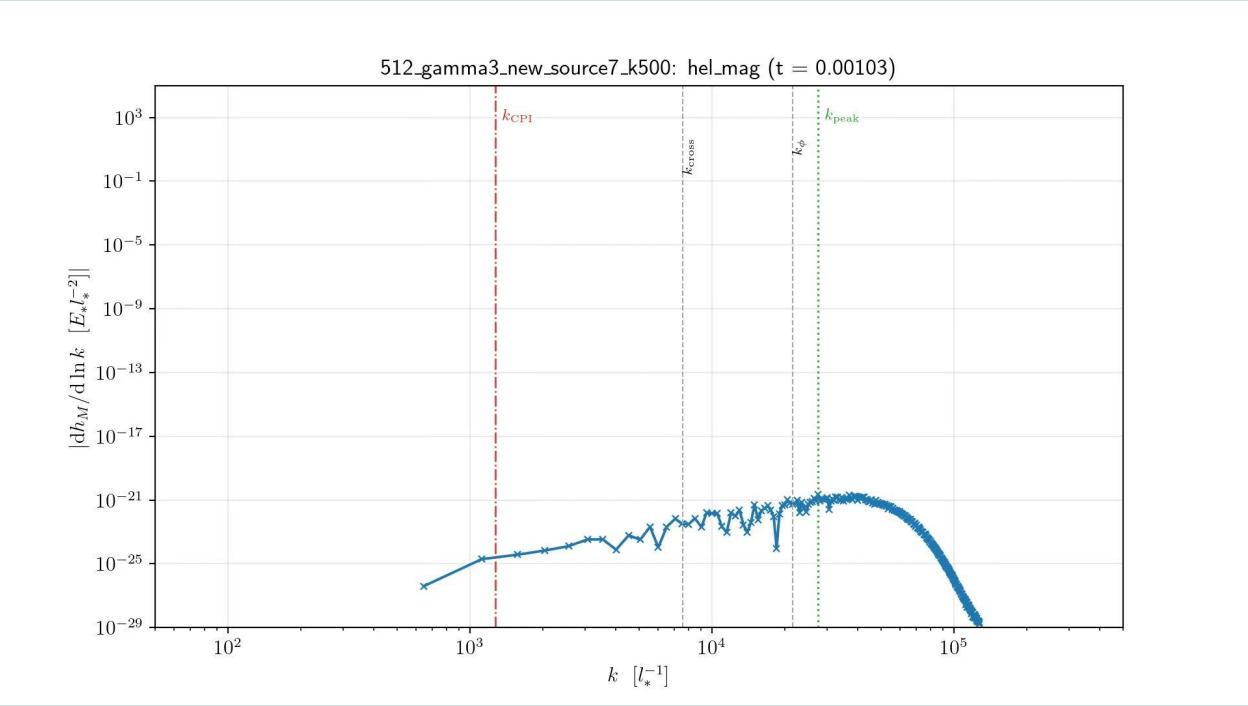
Evolution of magnetic field rms and volume averaged helicity.
*For units to match helicity needs to be multiplied by hiral feedback parameter

Results



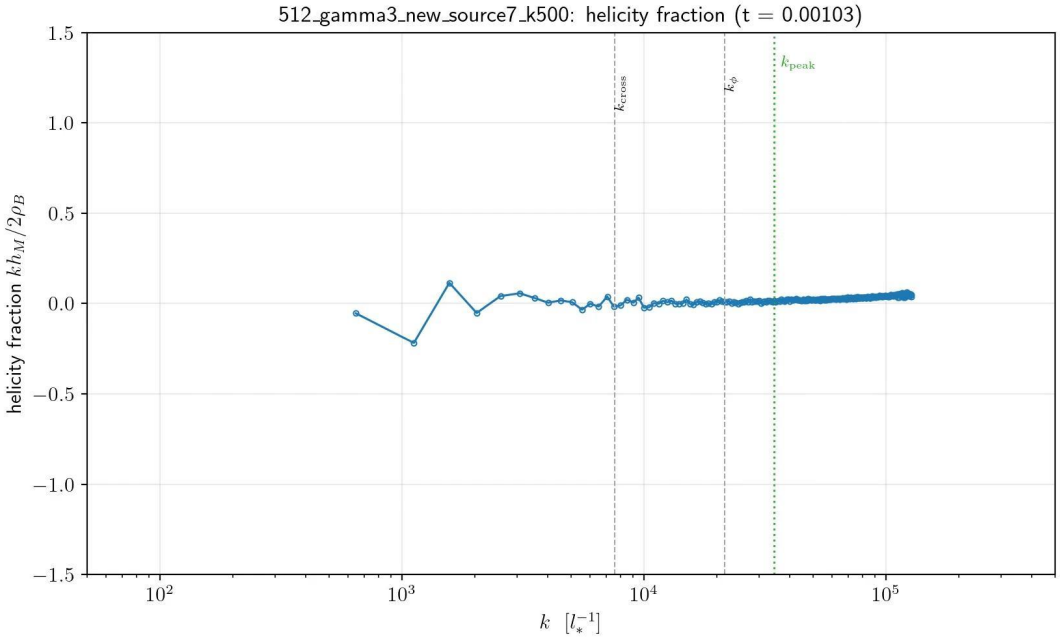
Evolution of comuving magnetic energy density spectrum

Results

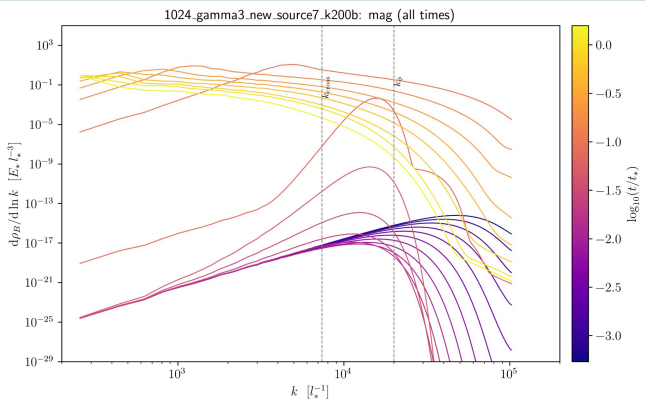


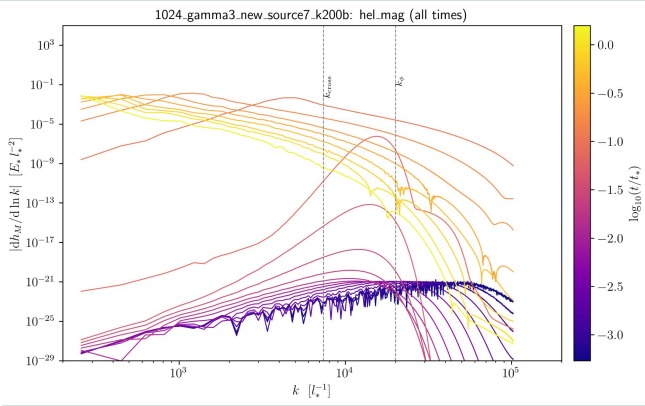
Evolution of comoving helicity energy density spectrum

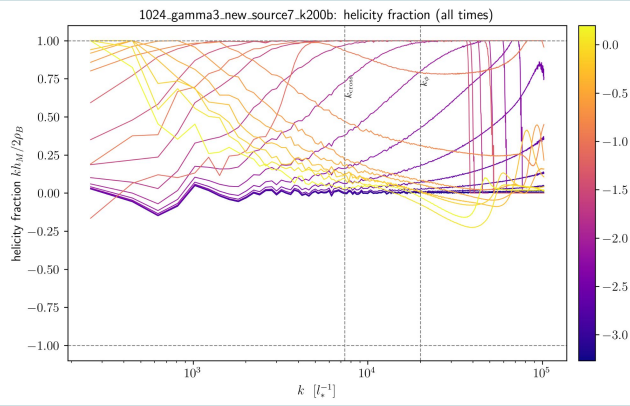
Results


512_gamma3_new_source7_k500: helicity fraction (t = 0.00103)
helicity fraction $kh_M/2\rho_B$
k $[l_*^{-1}]$
$k_{\rm cross}$
k_ϕ
$k_{\rm peak}$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
10^2
10^3
10^4
10^5

Results


1024_gamma3_new_source7_k200b: mag (all times)
$k_{\rm cross}$
k_ν
$\mathrm{d}\rho_B/\mathrm{d}\ln k\ \ [E_*\, l_*^{-3}]$
$k\ \ [l_*^{-1}]$
$\log_{10}(t/t_*)$


1024_gamma3_new_source7_k200b: hel_mag (all times)
$k_{\rm cross}$
k_ν
$|\mathrm{d}h_M/\mathrm{d}\ln k|\ \ [E_*\, l_*^{-2}]$
$k\ \ [l_*^{-1}]$
$\log_{10}(t/t_*)$


1024_gamma3_new_source7_k200b: helicity fraction (all times)
$k_{\rm cross}$
k_ν
helicity fraction $kh_M/2\rho_B$
$k\ \ [l_*^{-1}]$

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Thank you

Backup

Our Model: Introducing a Source Term

$$S_5(t_c) = (\Gamma_R - \Gamma_L) n_\phi(t_c) = \epsilon \beta \Gamma_\phi n_\phi(t_c)$$

$$t_c = \frac{a(\tau_\phi)^2 t^2}{4\tau_\phi} \qquad n_5 = \frac{k_B^2}{\hbar^3 c^3} \frac{\mu_5 T^2}{3}, \qquad \mu_5 = \frac{1}{4}(\mu_{e_R^-} + \mu_{e_R^+} - \mu_{e_L^-} - \mu_{e_L^+})$$

$$S_5(t_c) = \epsilon \beta \Gamma_\phi \frac{\rho_{\rm rad} \Omega_\phi}{m_\phi c^2} \left(\frac{t_c}{\tau_\phi}\right)^{-3/2} e^{-\Gamma_\phi (t_c - \tau_\phi)} \qquad \Omega_\phi = \frac{\rho_\phi(\tau_\phi)}{\rho_{\rm rad}(\tau_\phi)}$$

$$\frac{\partial n_5}{\partial t_c} = S_5(t_c) + \cdots \qquad S_5(t) = \bar{S}_5 \frac{t}{t_\phi} e^{-(t^2 - t_\phi^2)/(2t_\phi^2)}$$

$$\rho_\phi \simeq m_\phi c^2 n_\phi, \qquad \rho_{\rm rad} = \frac{\pi^2}{30} \frac{k_B^4}{\hbar^3 c^3} g_E T^4$$