Electromagnetic wave spectrum from radiative cooling electrons in relativistic Alfvén wave

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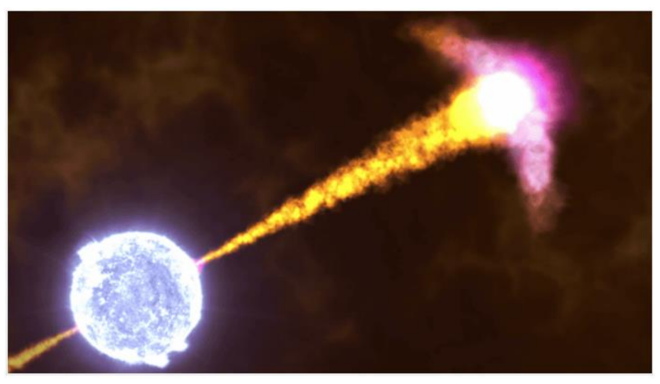
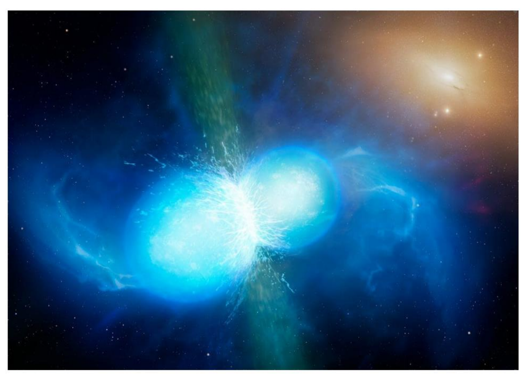
Introduction

Gamma Ray Bursts

The brightest explosions in the universe.

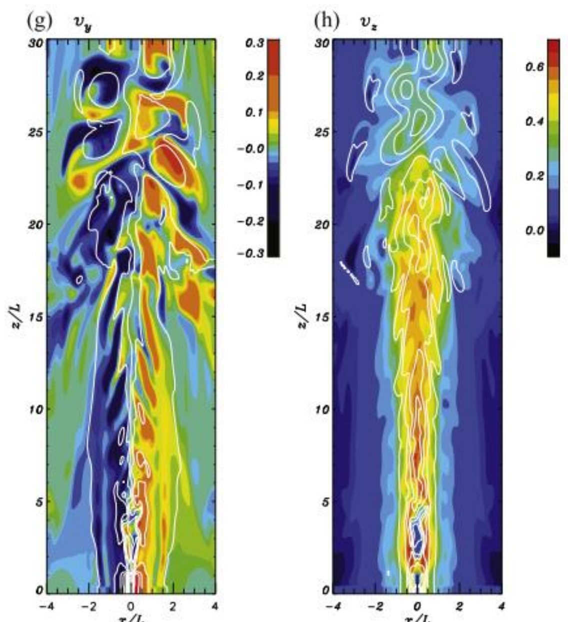


credit: NASA



credit: University of Warwick /Mark Garlick

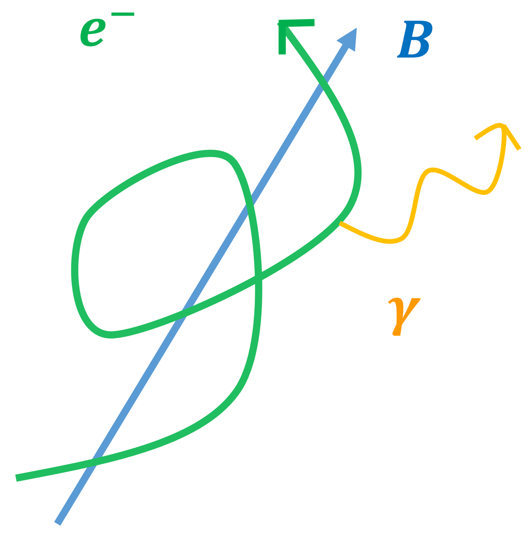
Relativistic turbulence in jet



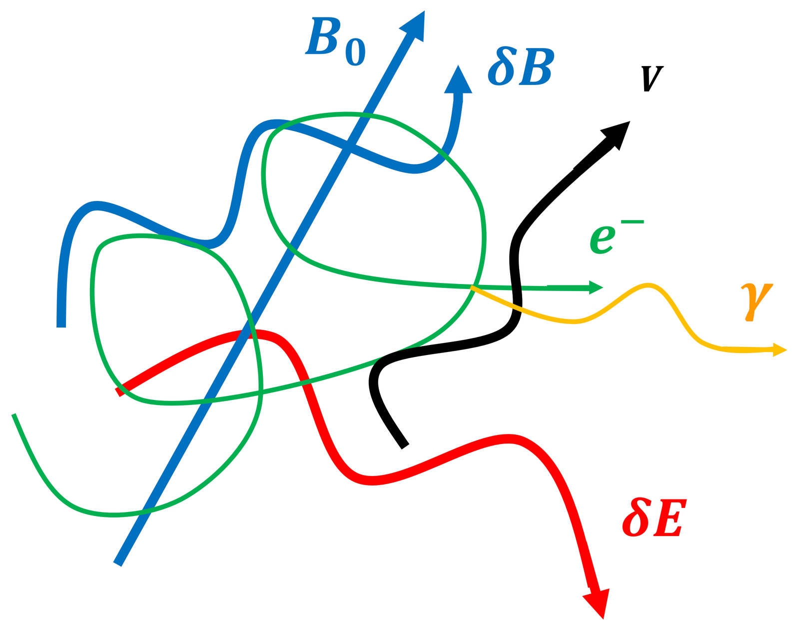
Singh et al. 2016

Motivation of this study

Synchrotron radiation in uniform magnetic field



Radiation in relativistic turbulence



Method

We consider relativistic Alfvén wave propagating in turbulence.

Fluid velocity is relativistic $V \sim c$

Alfvén velocity is relativistic $V_A \sim c$

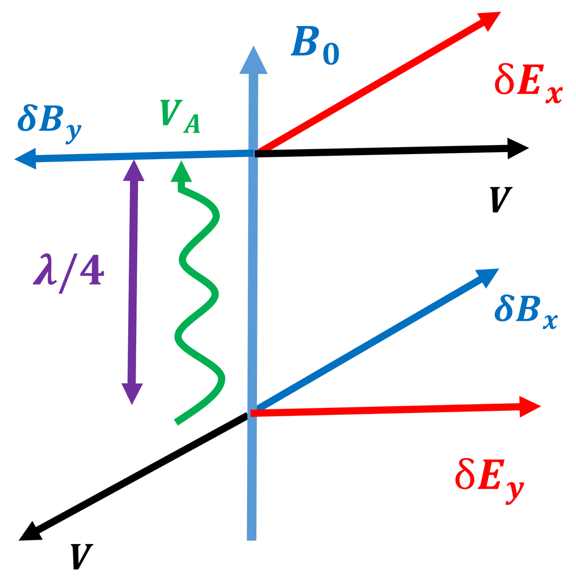
Electric field is comparable to magnetic field $\delta E \sim \delta B \sim B_0$

$$\delta B_x = -\left(\frac{V}{c}\right)\left(\frac{c}{V_A}\right) B_0 \cos\left(2\pi\frac{z}{\lambda} - \omega_A t\right),\quad \delta E_x = -\left(\frac{V}{c}\right) B_0 \sin\left(2\pi\frac{z}{\lambda} - \omega_A t\right),$$

$$\delta B_y = -\left(\frac{V}{c}\right)\left(\frac{c}{V_A}\right) B_0 \sin\left(2\pi\frac{z}{\lambda} - \omega_A t\right),\quad \delta E_y = \left(\frac{V}{c}\right) B_0 \cos\left(2\pi\frac{z}{\lambda} - \omega_A t\right),$$

$$B_z = B_0,\quad \delta E_z = 0$$

Circularly polarized Alfvén wave



- **electron trajectory**

$$\frac{d\gamma m v}{dt} = -eE - e\frac{v}{c} \times B$$

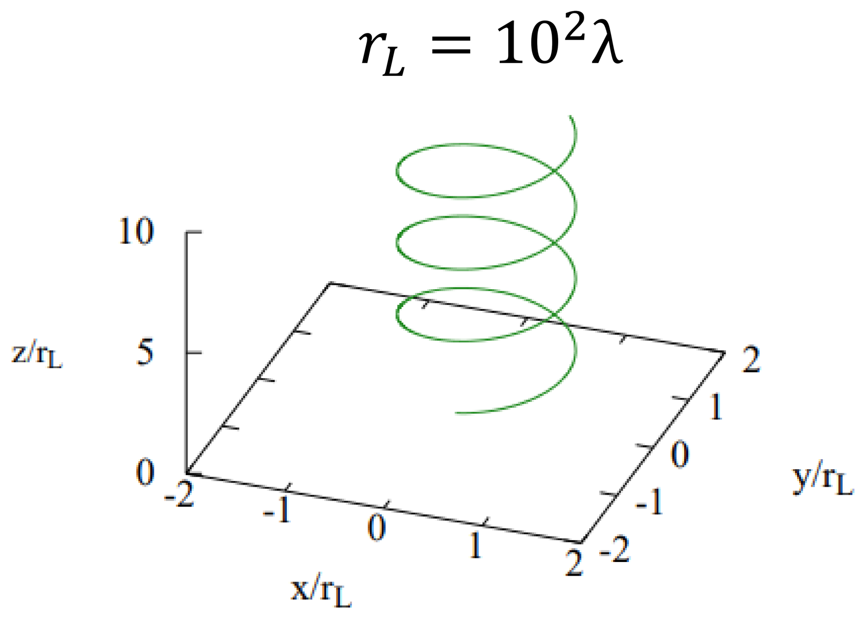
- **Radiation spectrum**

Fourier transform of electromagnetic wave of Liénard-Wiechart potential

$$\frac{dW}{d\omega} = \int d\Omega \frac{e^2}{4\pi^2 c^5}\left|\int \frac{n \times \left\{\left(n - \frac{v}{c}\right) \times \dot{a}\right\}}{\left(1 - n \cdot \frac{v}{c}\right)^2} exp\left[i\omega(t' - n \cdot x(t')/c)\right]dt'\right|^2$$

Result

Radiation from electron with $r_L \gg \lambda$



Electromagnetic field felt by electron

$$B_{eff} \approx |B_0 + \delta B + E|$$

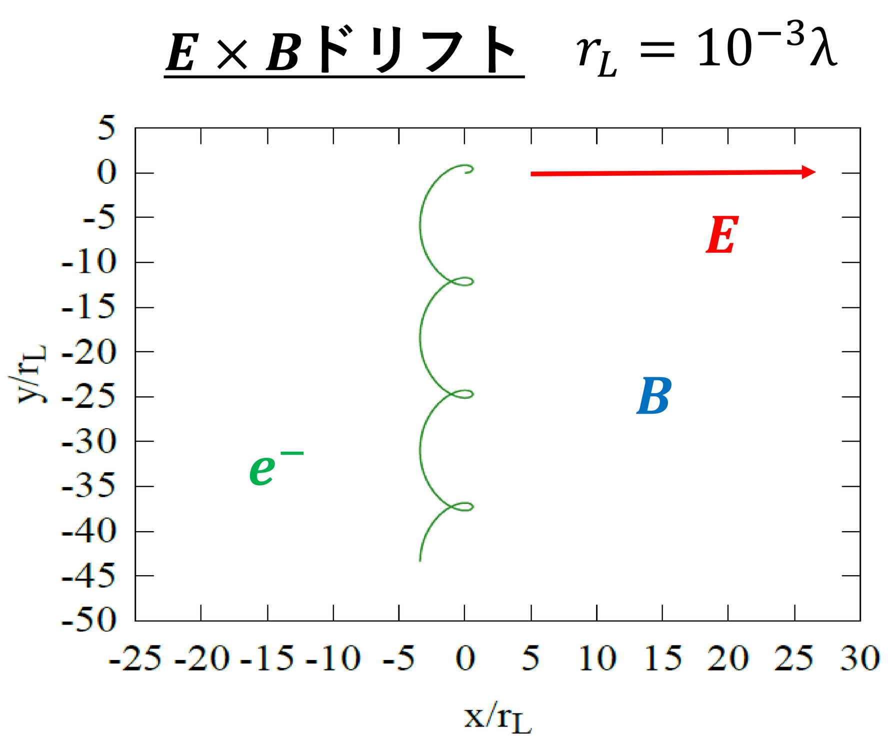
Typical frequency of emitted photons

$$\nu \approx \frac{3}{4\pi}\gamma^2 \frac{eB_{eff}}{m_e c}$$

Radiation power

$$P \approx \frac{4}{3}\gamma^2 \sigma_T c \frac{B_{eff}^2}{8\pi}$$

Radiation from electron with $r_L \ll \lambda$



$$\Gamma_{E\times B} \equiv \left(1 - \left(\frac{E}{B}\right)^2\right)^{-1/2} \approx \sqrt{2}$$

$$\gamma = \Gamma_{E\times B}\gamma' \quad B = \Gamma_{E\times B} B'$$

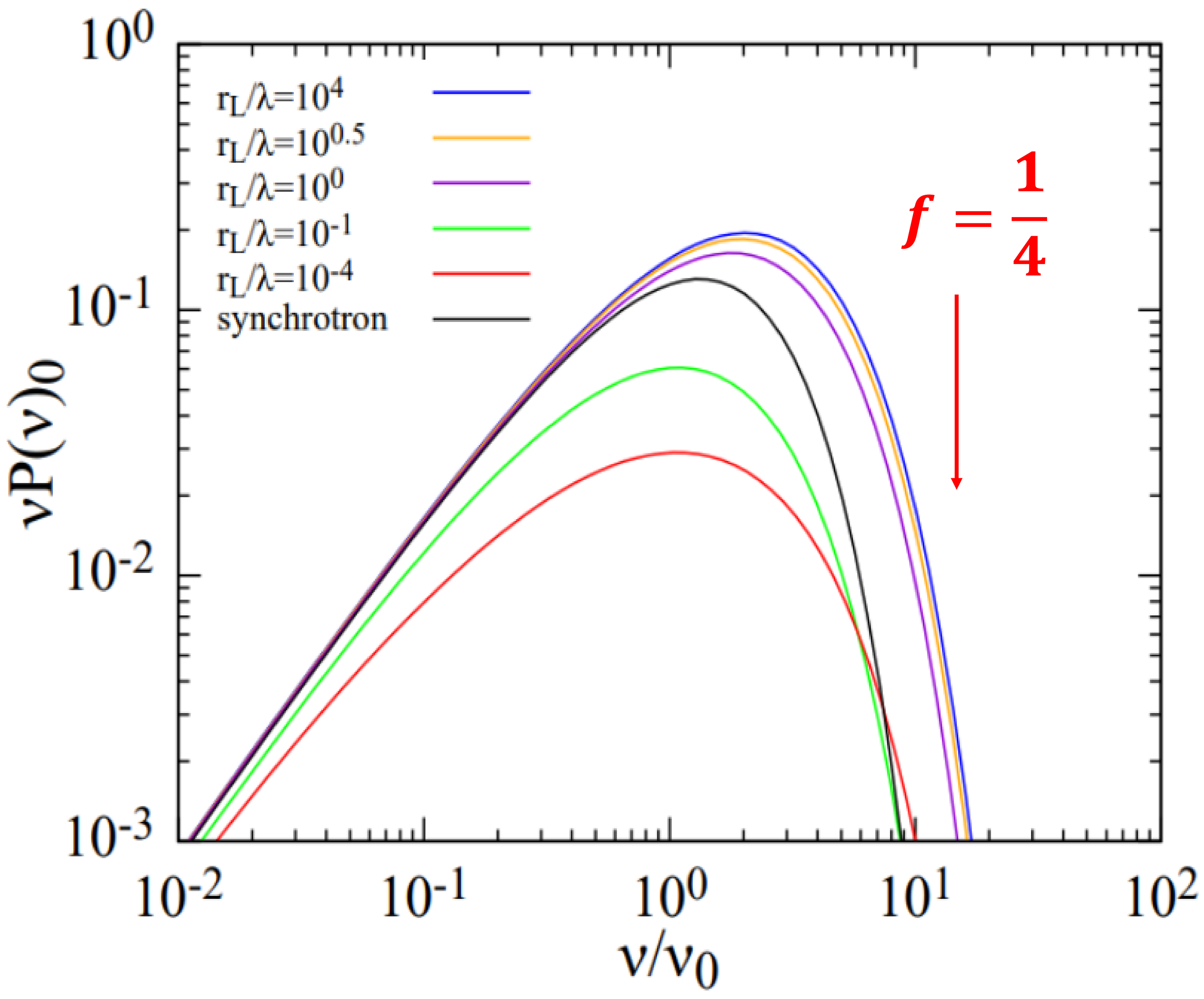
Typical frequency of emitted photons

$$\nu \approx \Gamma_{E\times B}\frac{3}{4\pi}\gamma'^2 \frac{eB'}{m_e} = \frac{3}{4\pi}\frac{1}{\Gamma_{E\times B}^2}\gamma^2\frac{eB}{m_e}$$

Radiation power

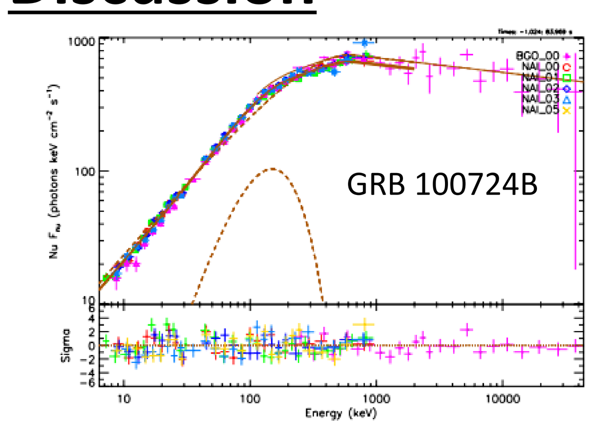
$$P \approx \frac{4}{3}c\sigma_T\gamma'^2\frac{B'^2}{8\pi} = \frac{1}{\Gamma_{E\times B}^4}\frac{4}{3}c\sigma_T\gamma^2\frac{B^2}{8\pi}$$

Radiation spectrum in relativistic Alfvén wave

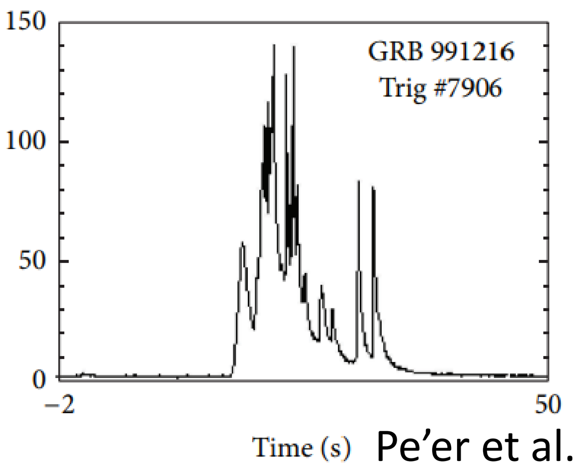


Radiation by Electrons with $r_L \ll \lambda$ is suppressed.

Discussion



Guiriec et al. 2011



Pe'er et al. 2015

$$E_{pk} = \Gamma_j \gamma_e^2 \frac{eB}{m_e c} = 1\text{MeV}$$

$$L_{pk} = f\Gamma_j^2 \frac{4}{3}\gamma_e^2 c\sigma_T \frac{B^2}{8\pi} N_e'(\gamma_e) 4\pi R^2 \frac{R}{\Gamma_j} = 10^{53}\text{erg/s}$$

$$L_B = 4\pi R^2 c\Gamma_j^2 \frac{B^2}{4\pi} = 10^{53}\text{erg/s}$$

$$t_p \approx \frac{R}{2c\Gamma_j^2} \approx 1\text{s}$$

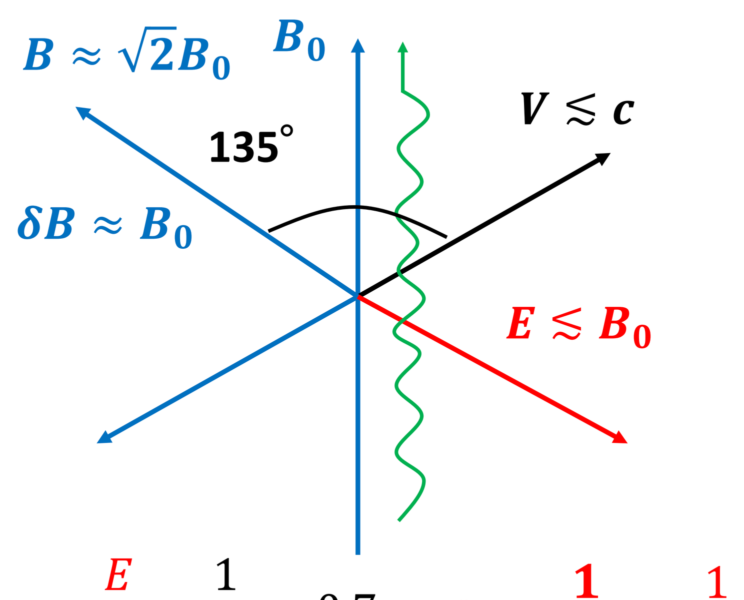
$\Gamma_j = 300$　$B = 1000\text{G}$

$N_e'(\gamma_e) = 10^3$　$R = 10^{16}\text{cm}$

$\gamma_e = 10^4$　$\sigma \equiv \frac{B^2}{4\pi\gamma_e N_e'(\gamma_e) m_e c^2} \approx 10^4 f$

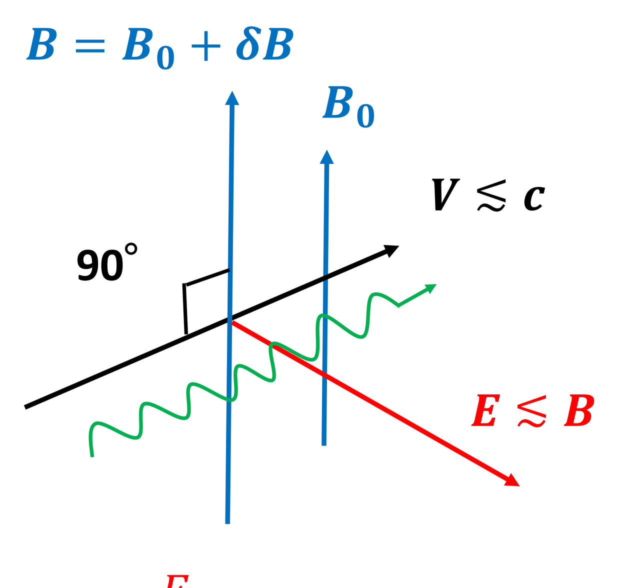
Ideal Magnetohydrodynamic electric field　$\frac{E}{B} = \frac{\left|-\frac{V}{c}\times B\right|}{B}$

Relativistic Alfvén wave



$\frac{E}{B} = \frac{1}{\sqrt{2}} \approx 0.7$　$f \approx \frac{1}{\Gamma_{E\times B}^4} \approx \frac{1}{4}$

Compressible wave



$\frac{E}{B} \lesssim 1$　$f \ll 1$

Future work

I would like to apply radiation in relativistic turbulence to gamma ray burst by doing magnetohydrodynamic simulation taking in to account compressible wave.