Jitter Radiation for GRB Prompt Emission

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GRB Radiation Mechanism

- Fireball model: optical thin relativistic electrons accelerated by internal/external shock: Synchrotron

- Optical thick: thermal component

Synchrotron versus Jitter

- Relativistic electrons radiation in ordered magnetic field (external, homogenous & steady):

Synchrotron

- Relativistic electrons radiation in random and small-scale magnetic field:

Jitter

Synchrotron vs Jitter

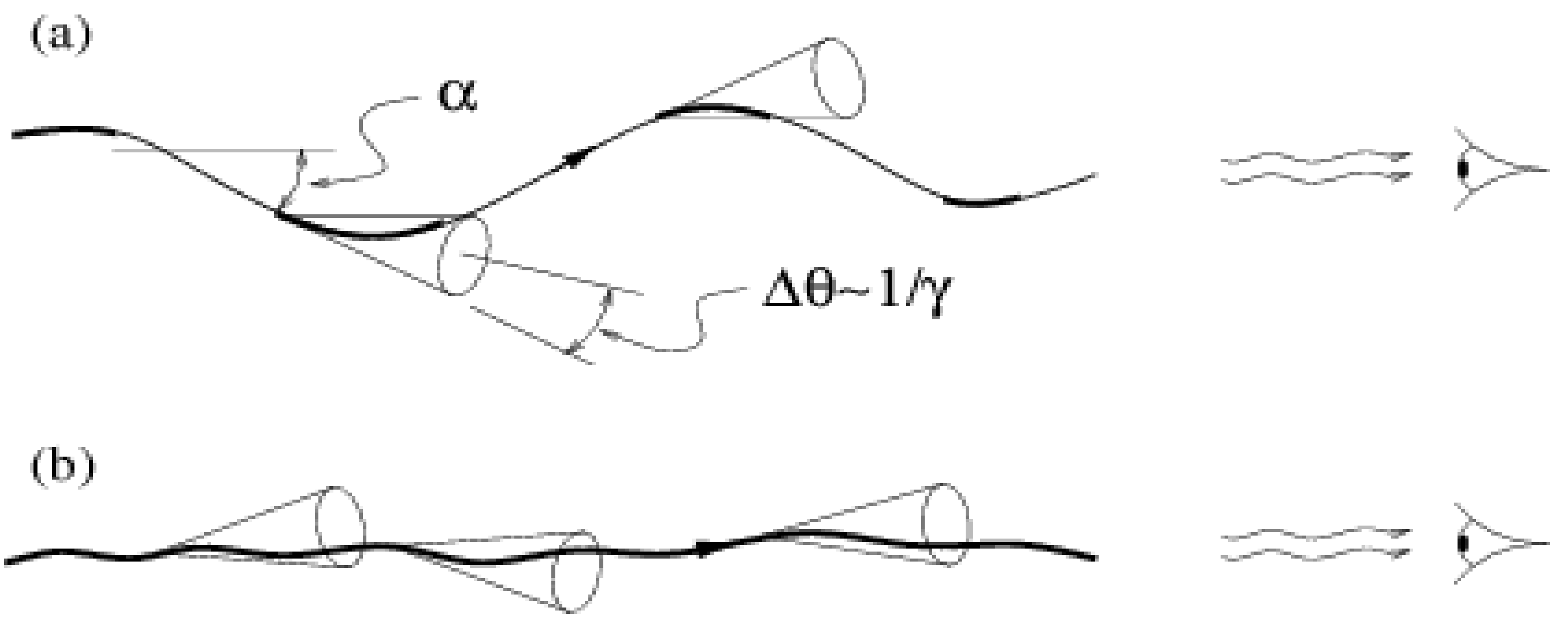


FIG. 1.— Emission from various points along particle's trajectory; (a) — $\alpha \gg \Delta\theta$, emission from selected parts (bold portions) of the trajectory is seen by an observer, (b) — $\alpha \ll \Delta\theta$, emission from the entire trajectory is observed.

Jitter Regime

- Radiation by a single relativistic particle in small scale magnetic field (Landau & Lifshitz 1971):

$$I_\omega = \frac{2\pi e^2}{c^3} \int_{1/2\gamma_*^2}^{\infty} \left(\frac{\omega}{\omega'}\right)^2 \left|w_{\omega'}\right|^2 \left(1 - \frac{\omega}{\omega'\gamma_*^2} + \frac{\omega^2}{2\omega'^2\gamma_*^4}\right) d\left(\frac{\omega'}{\omega}\right)$$

$$I_\omega = \frac{e^4}{m^2c^3\gamma^2} \int_{1/2\gamma_*^2}^{\infty} d\left(\frac{\omega'}{\omega}\right)\left(\frac{\omega}{\omega'}\right)^2 \left(1 - \frac{\omega}{\omega'\gamma_*^2} + \frac{\omega^2}{2\omega'^2\gamma_*^4}\right) \int dq_0\, dq\, \delta(\omega' - q_0 + qv) K(q) \delta(q_0 - q_0(q))$$

$$\gamma_*^{-2} = \gamma^{-2} + \omega_{pe}^2 / \omega^2 \qquad \omega' = (\omega/2)(\gamma^{-2} + \theta^2 + \omega_{pe}^2 / \omega^2)$$

$$q_0 = \gamma^2 cq(1 \pm \sqrt{1 - 4\omega_{pe}^2 / \gamma c^2 q^2} / 2)^{1/2}$$

Magnetic Field

- Different magnetic field origin and topology (Weibel instability or turbulence)
- Different jitter radiation features

Turbulence

- Stochastic spectrum

$$\langle B^2 \rangle = \int_{k_v}^{k_0} F(k)\,dk$$

$$F(k) \propto k^{-\alpha}$$

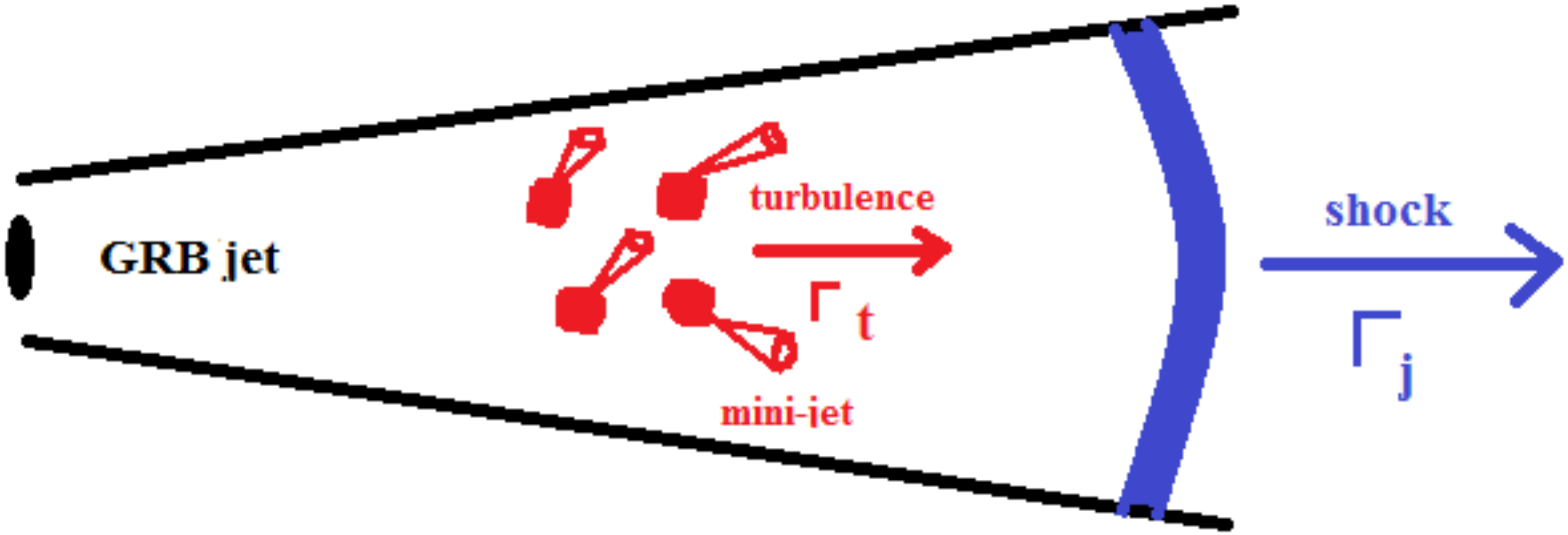
$$k_v \propto l_{eddy}^{-1} \propto (R/\Gamma_{sh}\gamma_t)^{-1}$$

High Frequency Spectrum

- Jitter spectrum: power-law with a index determined by turbulent feature

$$I_{\omega} \propto \omega^{-\alpha+1}$$

Jet-in-Jet Scenario



Electron Energy Distribution

- DSA: power-law distribution
- DSA + turbulence: power-law + Maxwellian

$$N(\gamma) = c\gamma^2 \exp(-\gamma / \Theta) / 2\Theta^3$$

$$N(\gamma) = c[\gamma_{nth}^2 \exp(-\gamma_{nth} / \Theta) / 2\Theta^3](\gamma / \gamma_{nth})^{-p}$$

$$\Theta = kT / m_e c^2$$

Acceleration/Cooling Timescale

$$t_{acc} = 1.4\times 10^{-12}\left(\frac{E}{MeV}\right)^{2}\left(\frac{B}{1.2\times 10^{6}G}\right)^{-2}\left(\frac{L}{1.0\times 10^{10}cm}\right)^{-1}\left(\frac{U}{0.1c}\right)^{-1}s$$

$$t_{cool} = 3.0\times 10^{-8}\left(\frac{\gamma}{1.8\times 10^{4}}\right)^{-1}\left(\frac{B}{1.2\times 10^{6}G}\right)^{-2}s$$

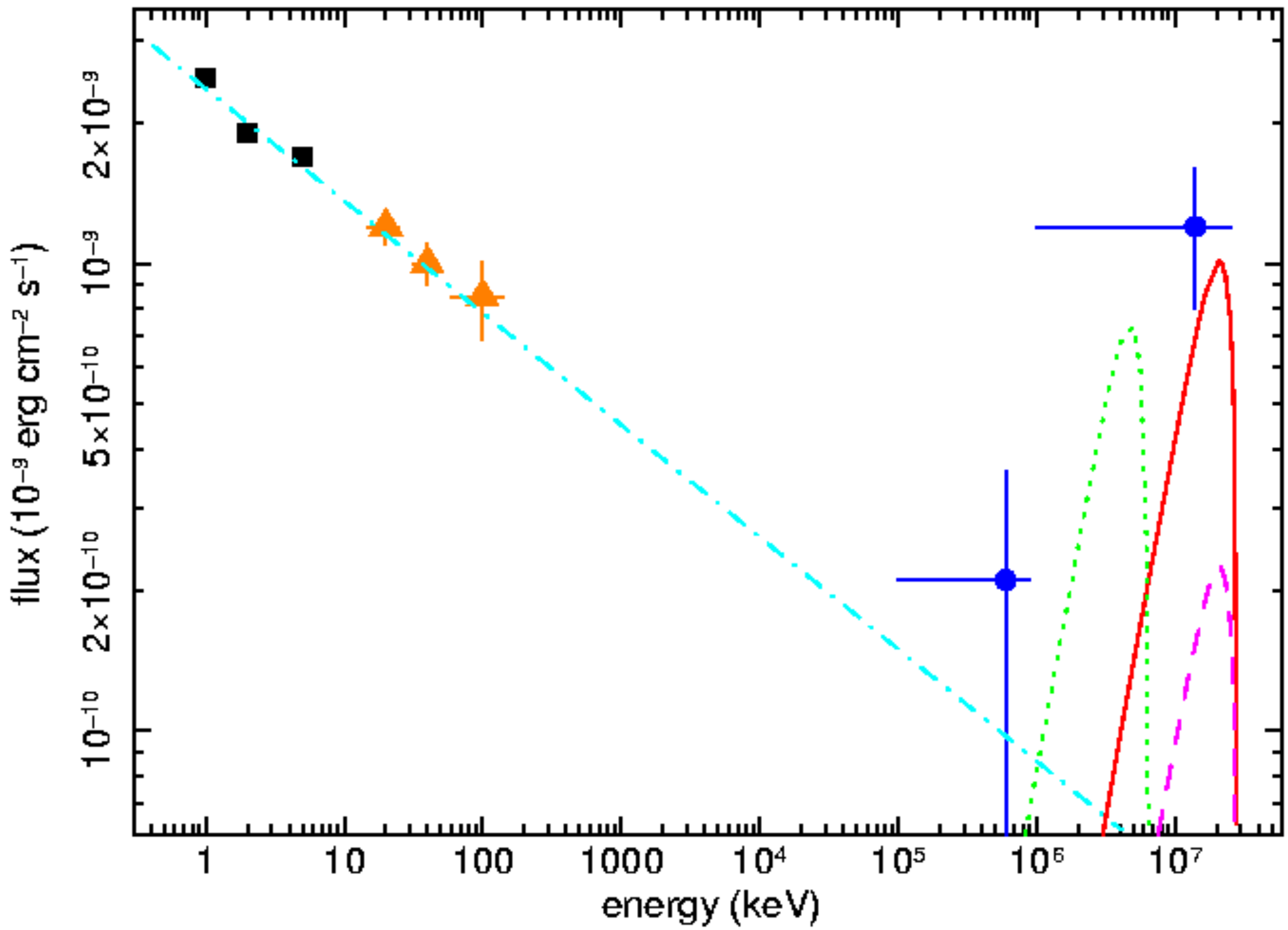
- Very short-timescale variabilities shown in GRB prompt lightcurves

Jitter self-Compton

- Synchrotron self-Compton (SSC)
- Jitter self-Compton (JSC)

- Fermi GBM & LAT observation

GRB 100728A

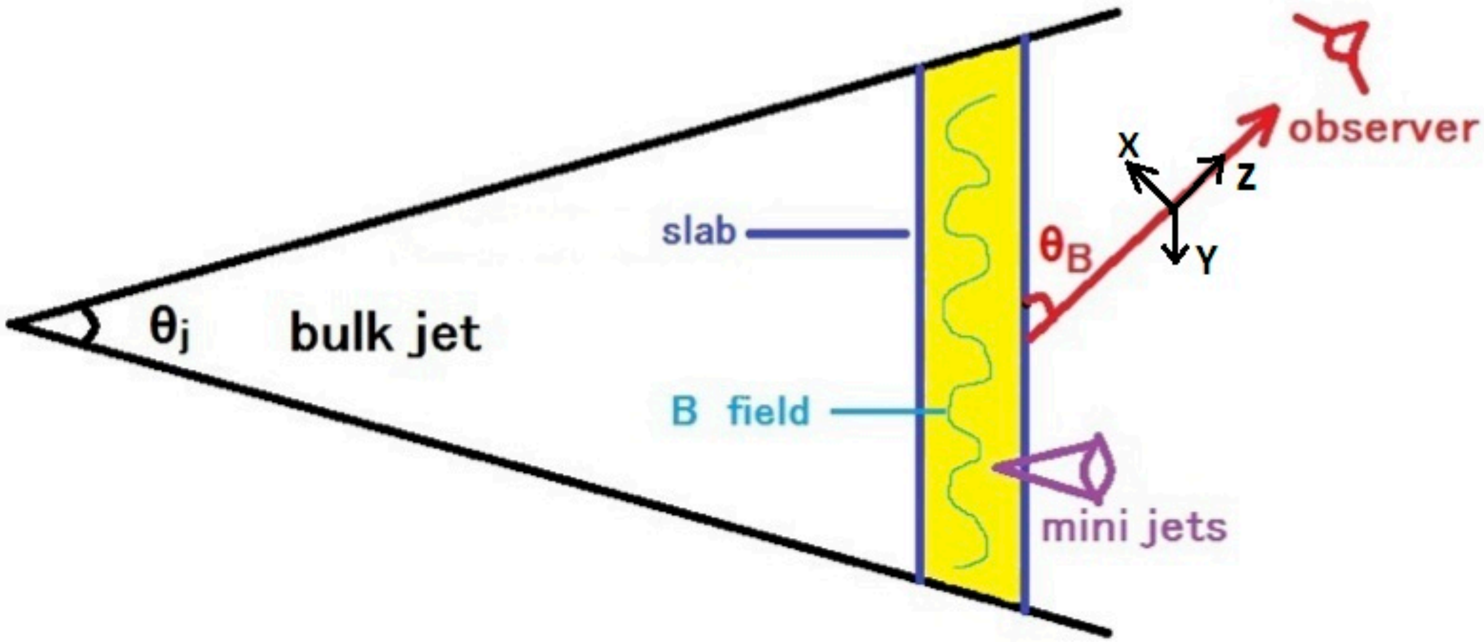


flux (10^{-9} erg cm^{-2} s^{-1})
energy (keV)
2×10^{-9}
10^{-9}
5×10^{-10}
2×10^{-10}
10^{-10}
1
10
100
1000
10^4
10^5
10^6
10^7

High-energy Polarization Observation

- RHESSI: GRB 021206 80 percent
- INTEGRAL: GRB 041219A 98 percent, 63 percent
- IKAROS: GRB 100826A 27 percent
  GRB 110301A 70 percent
  GRB 110721A 84 percent

Magnetic Slab & Jet-in-Jet



B-field Configuration

- Topology of magnetic field is important for Jitter radiation and polarization

$$I_\omega \propto B^2$$

- Geometry of GRB ejecta: jet & mini-jet structure

$$\vartheta_j = \alpha / \Gamma_j \quad \Gamma = 2\Gamma_j \Gamma_t / \alpha^2$$

B-field Topology

- Compressed magnetic slab

  Laing (1980, 2002)

$$B_x = B_0 \cos\phi \sin\vartheta_B, B_y = B_0 \sin\phi, B_z = B_0 \cos\phi \cos\vartheta_B$$

$$B = B_0 (\cos^2\phi \sin^2\vartheta_B + \sin^2\phi)^{1/2}$$

Stokes Parameters

$$I = C\int_0^{2\pi} (\cos^2\phi \sin^2\vartheta_B + \sin^2\phi)\,d\phi$$

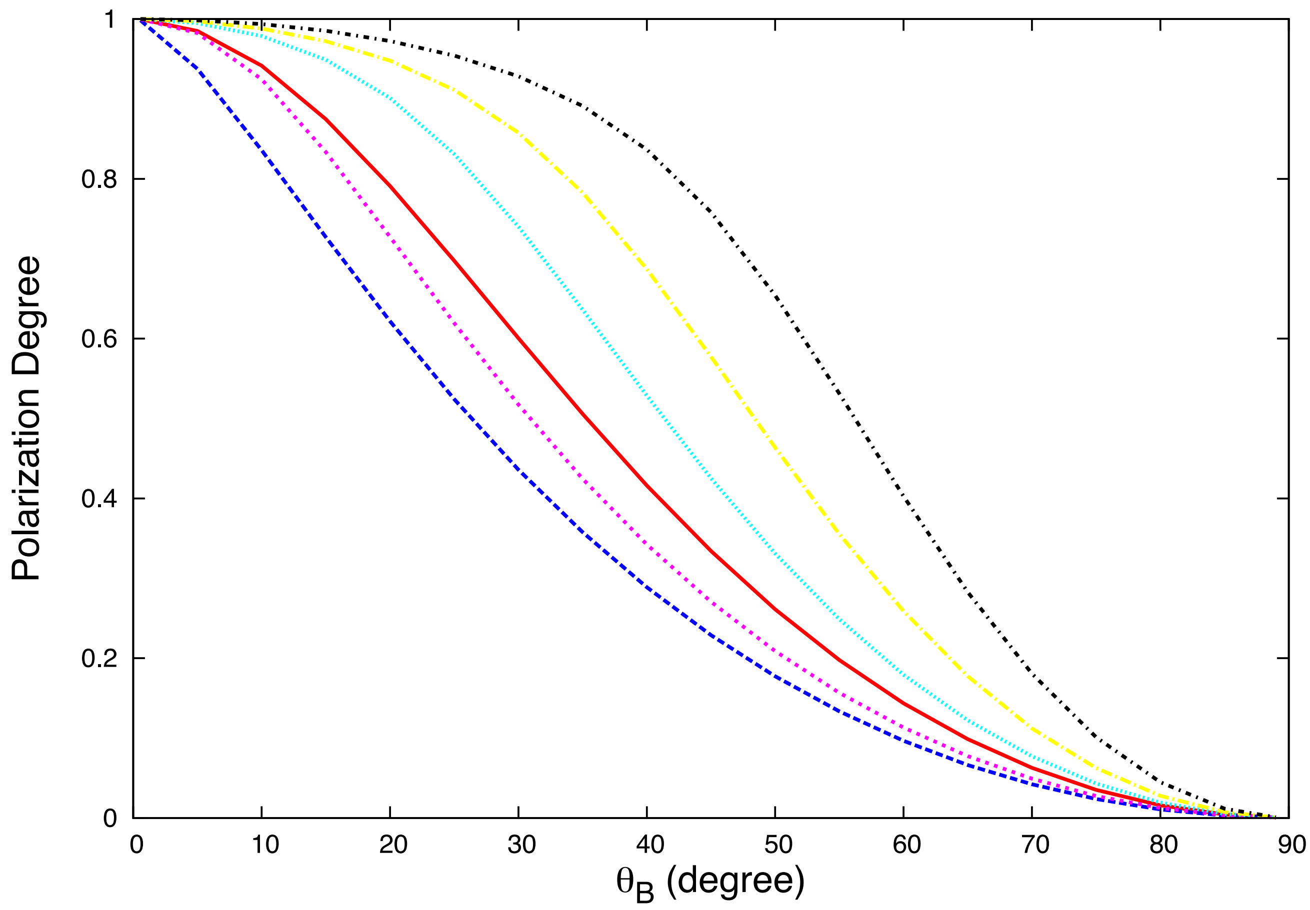
$$Q = -C\int_0^{2\pi} (\cos^2\phi \sin^2\vartheta_B - \sin^2\phi)\,d\phi$$

$$U = 0 \qquad V = 0$$

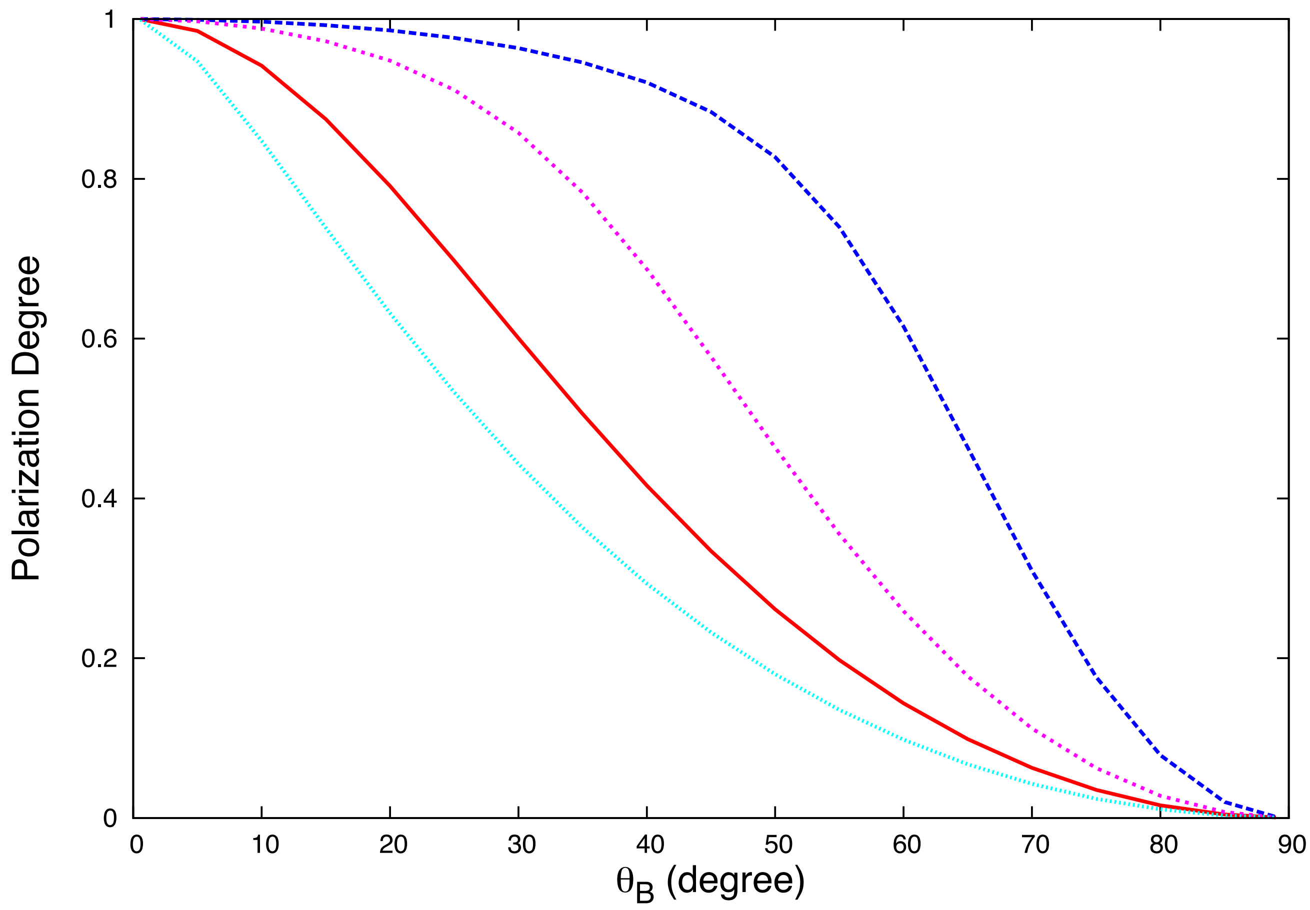
Jitter Polarization

- **Jitter polarization is only determined by the magnetic field configuration**

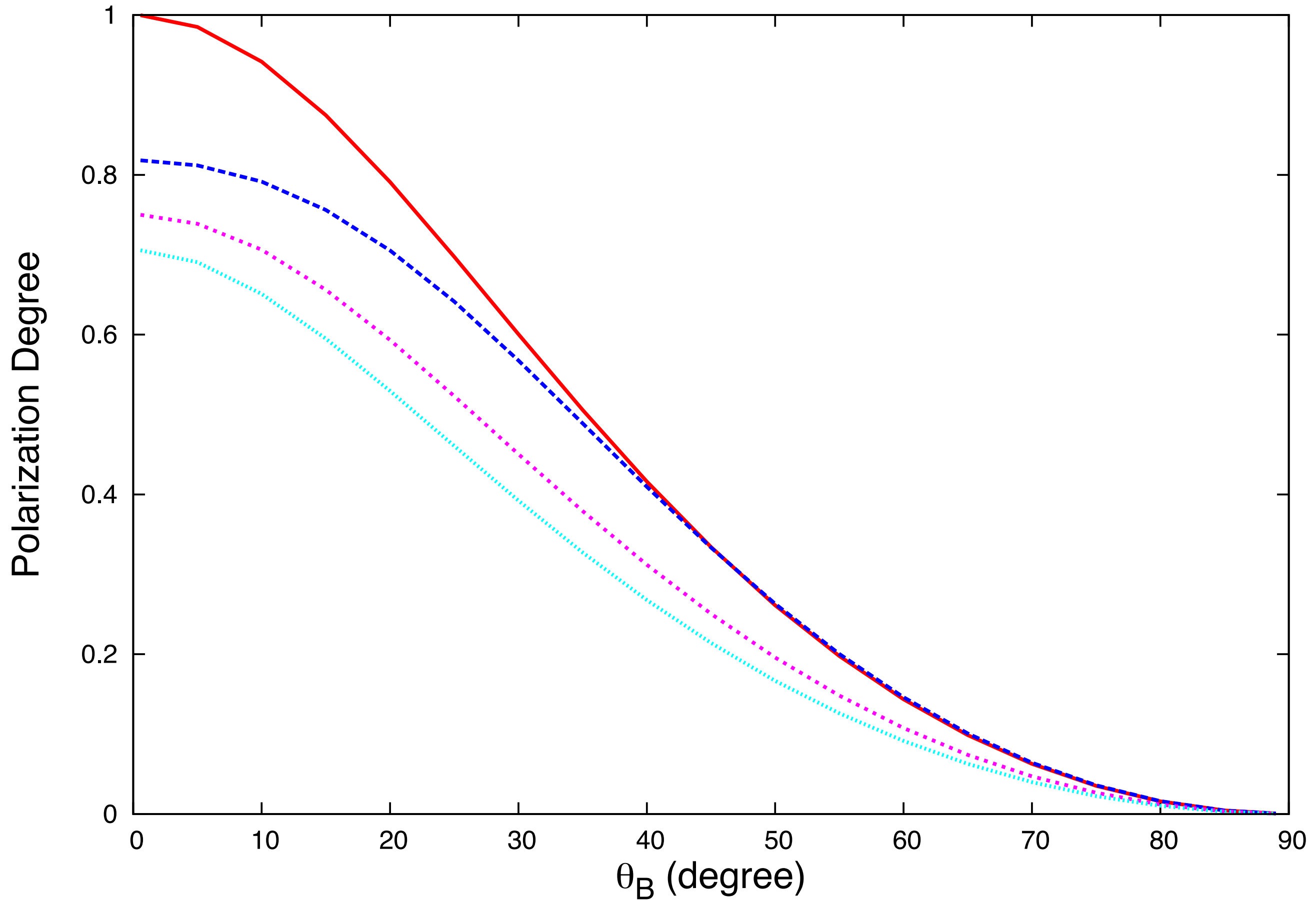
Jitter vs Synchrotron (single electron: radiation Frequency 1000,500,250,50,1keV)



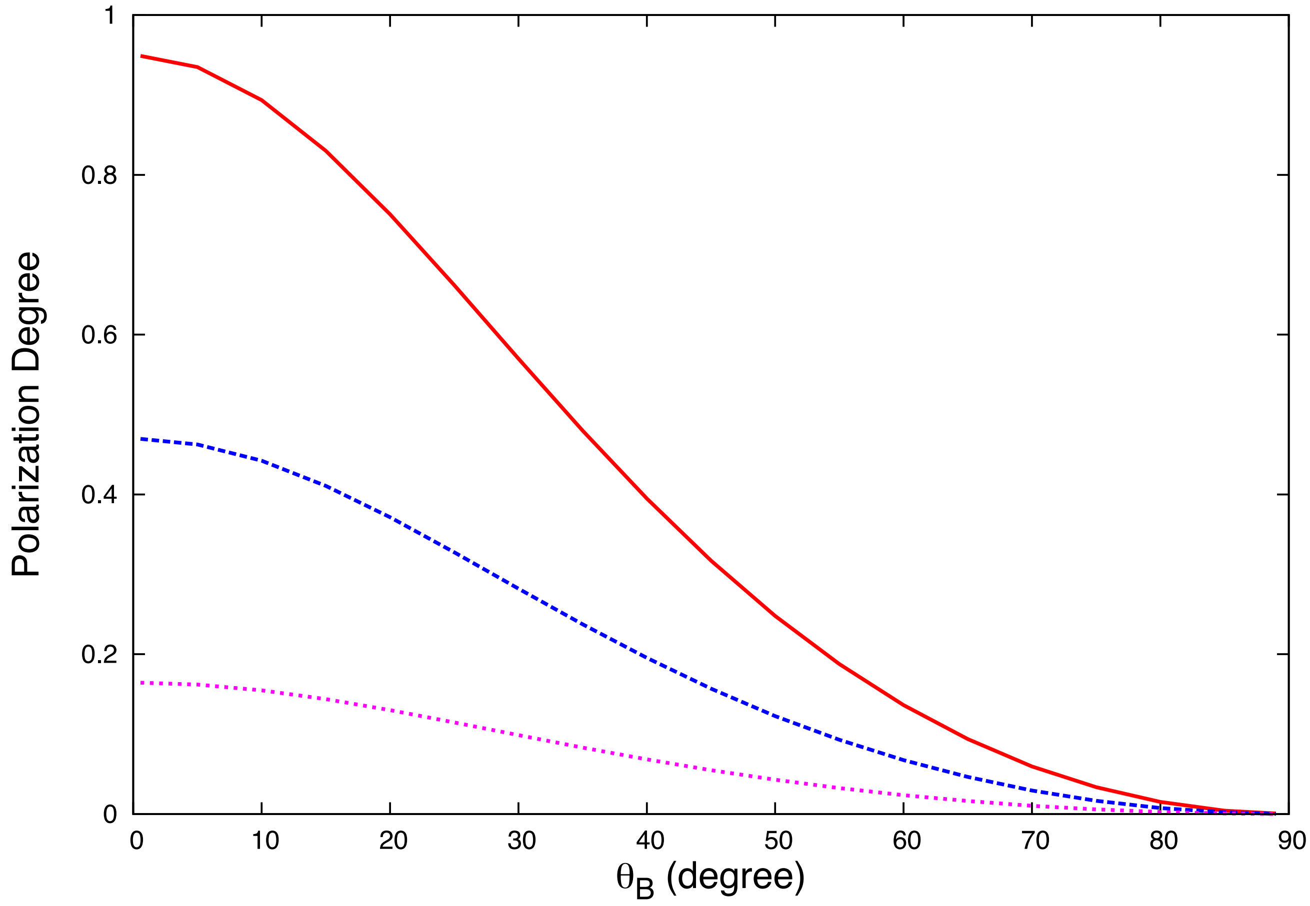
Jitter vs Synchrotron (single electron: electron Lorentz factor 500,10^3,10^4)



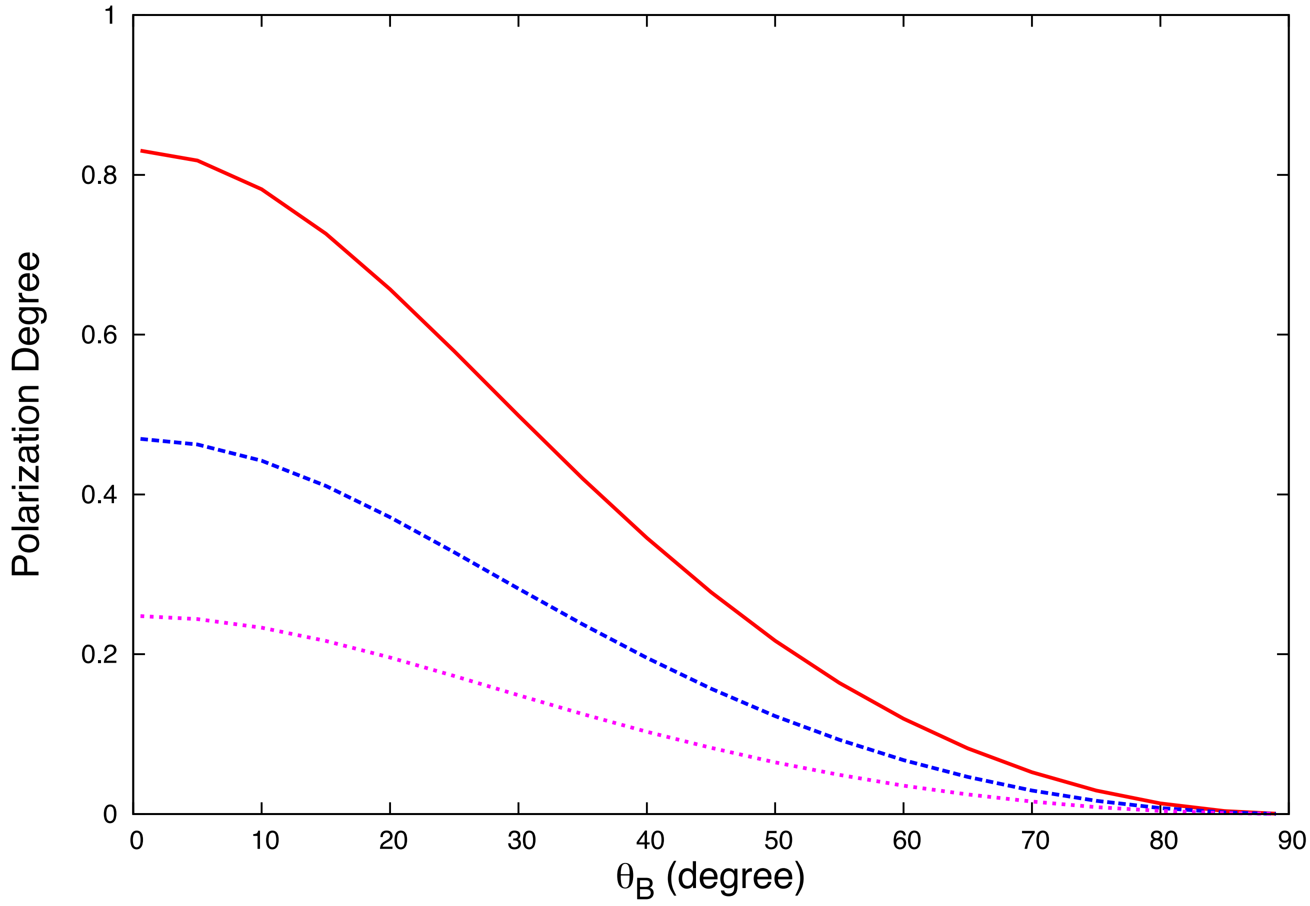
Jitter vs Synchrotron (gross electron radiation: radiation frequency 2.0,1.0,0.6)



Jitter Radiation: off-axis effect 1.55,1.3,1.0



Jitter Radiation: bulk Lorentz factor 85,100,120



Conclusion

- Random and small-scale magnetic field generated by turbulence
- Jitter radiation spectral index independent on electron energy distribution
- JSC to reproduce GRB GeV-emission
- High-degree polarization obtained for a given magnetic field configuration
- Mini-jets in a bulk Jet-structure are considered

Developments

- Medvedev 1999,2000,2006,2011 Fleishman 1985,2006,2010, Kelner 2013
- Hededal 2005, Sinori 2009, Nishikawa 2011, Teraki 2011
- Mao & Wang 2007,2011,2012,2013
- Schekochihin 2004,2007,2009

Length Scale

$$\omega_{pe} = \left(\frac{4\pi e^2 n}{\Gamma_{sh} m_e}\right)^{1/2}$$

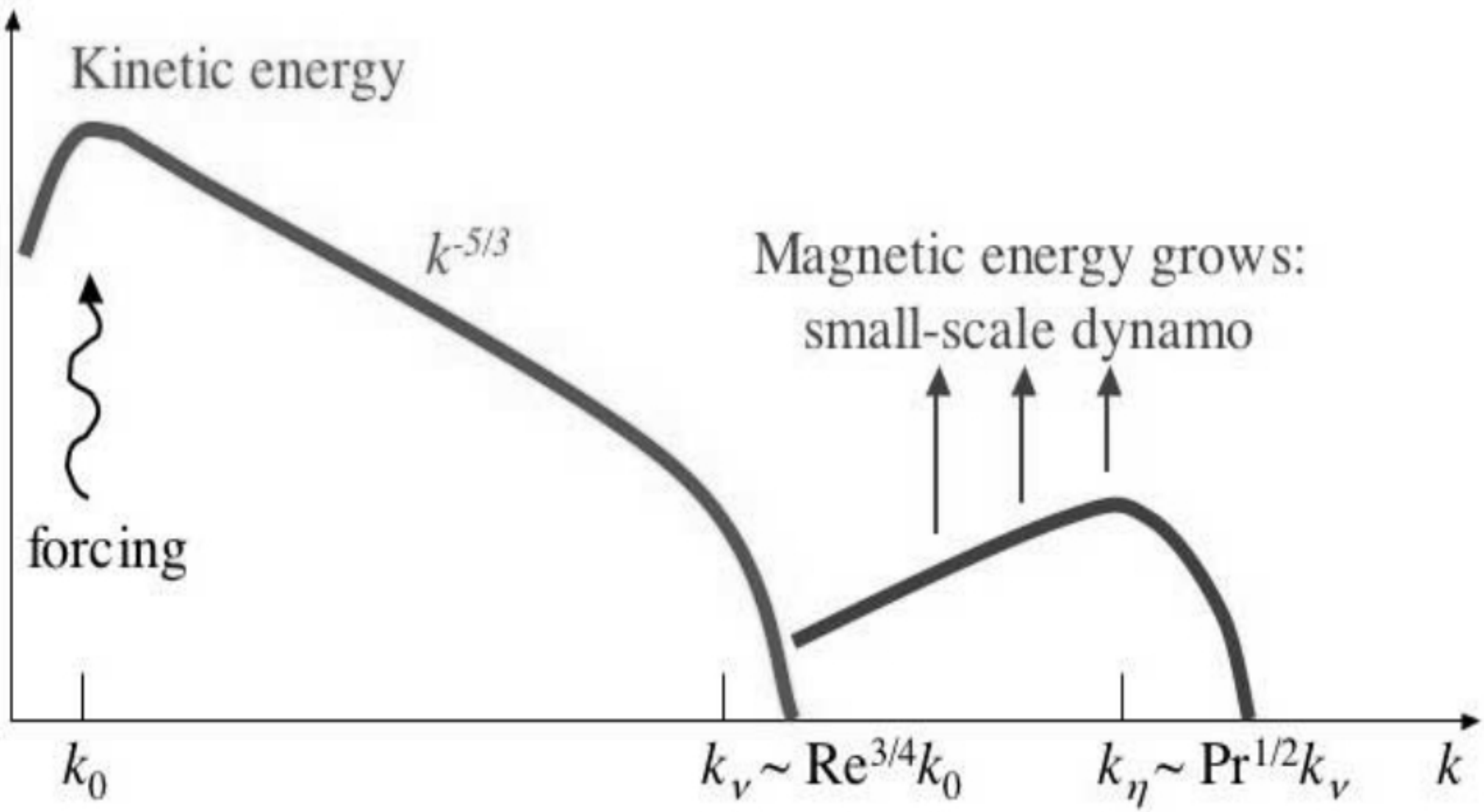
$$l_{col} \sim l_{skin} = c/\omega_{pe} = 30.6 \times \left(\frac{n}{3\times 10^{10}\, cm^{-3}}\right)^{-1/2} \left(\frac{\Gamma_{sh}}{100}\right)^{1/2} cm$$

$$r_L = \frac{\gamma m_e c^2}{eB} = 30.8 \times \left(\frac{\gamma}{2.2\times 10^{4}}\right)\left(\frac{B}{1.2\times 10^{6}\, G}\right)^{-1} cm$$

$$\theta = eBl_{col} / \gamma m_e c^2 < 1$$

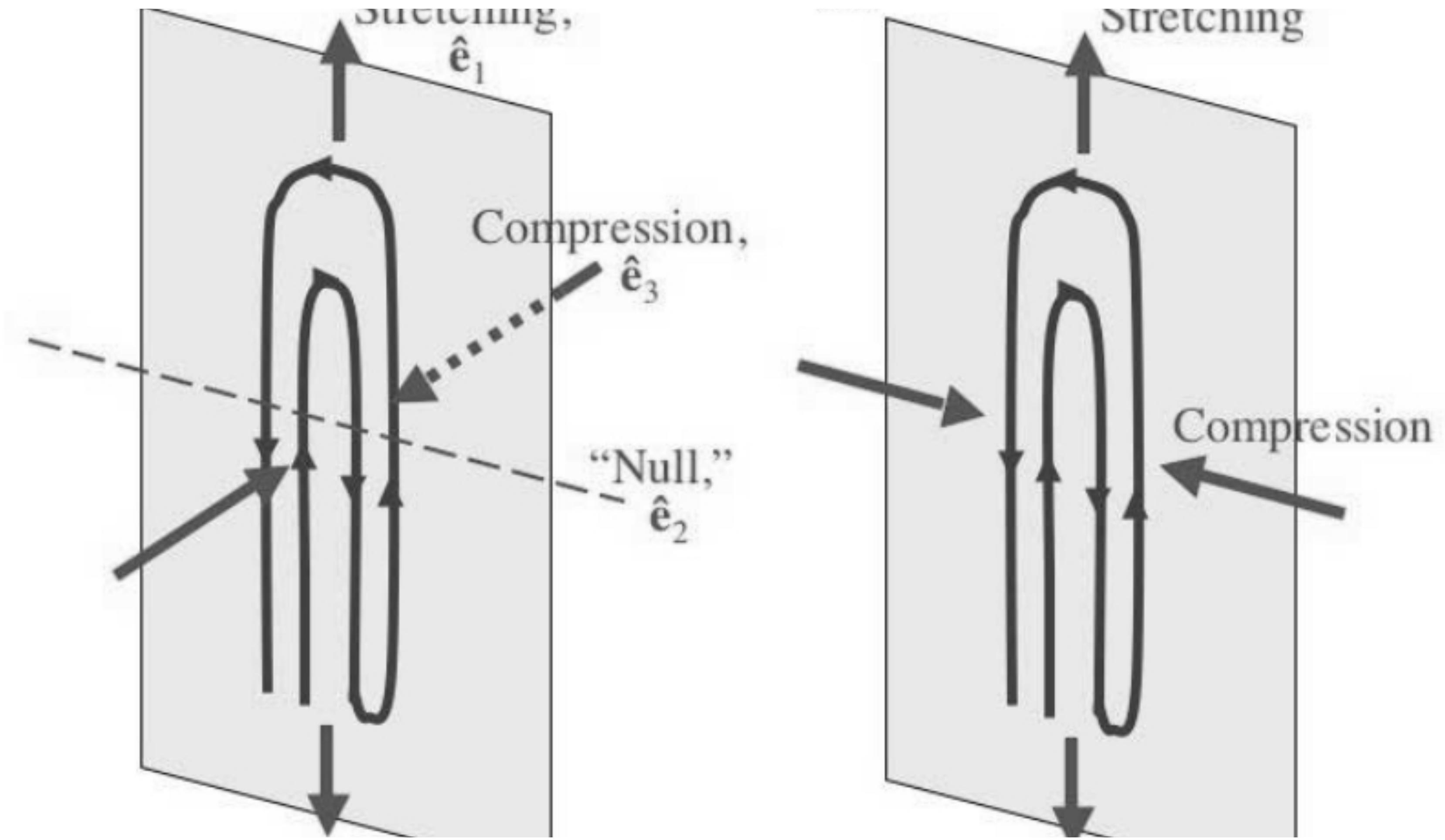
$$K = eBl_{col} / m_e c^2$$

Small-scale ?



Kinetic energy
$k^{-5/3}$
Magnetic energy grows:
small-scale dynamo
forcing
k_0
$k_\nu \sim Re^{3/4} k_0$
$k_\eta \sim Pr^{1/2} k_\nu$
k

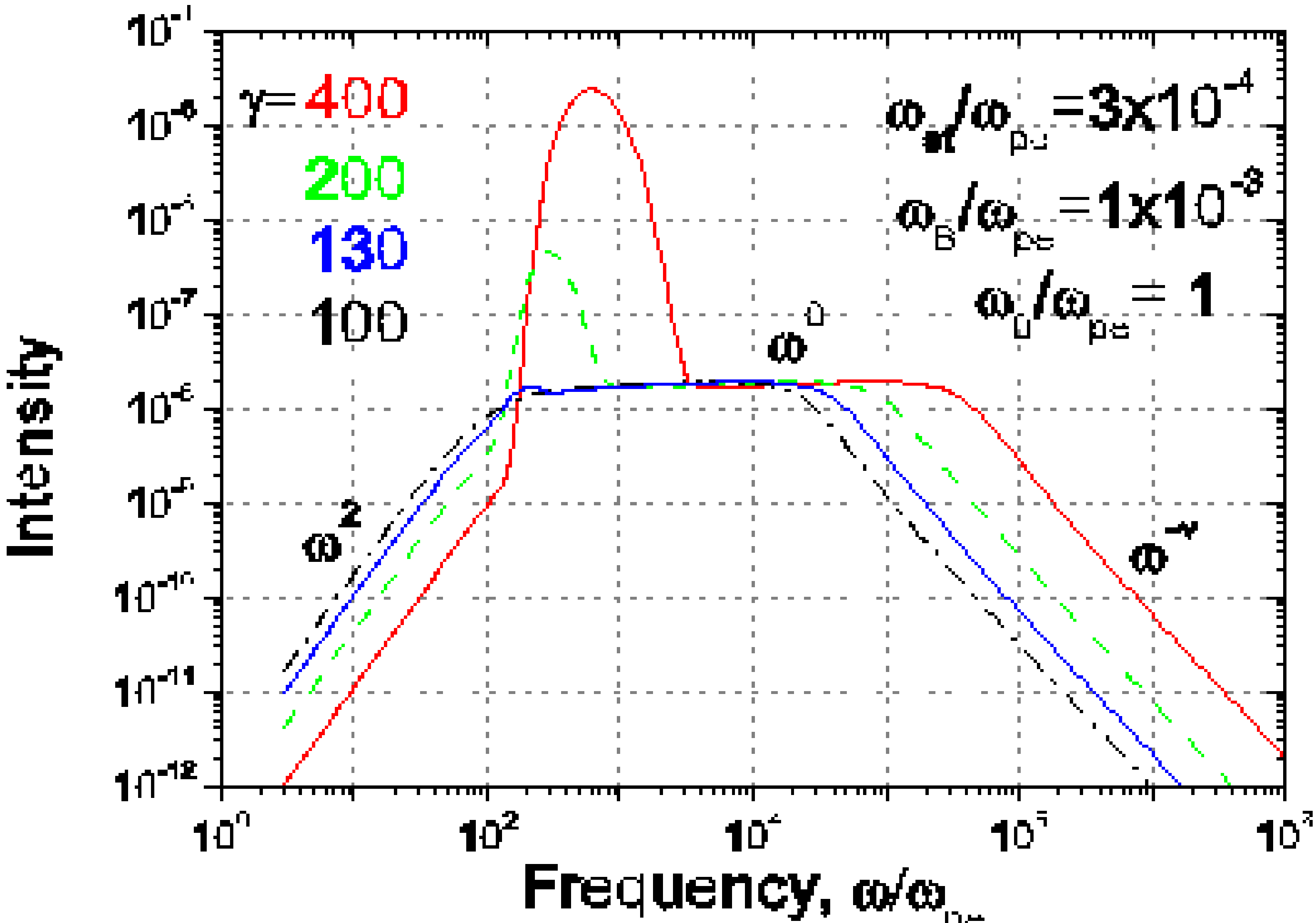
Magnetic Diffusion



Future Exploration

- Electron trajectory approximated as a rough straight line?
- Small-scale Magnetic features?
- Small-scale dynamo?
- Hydro/MHD or plasma physics?
- Astrophysical applications …

Jitter Spectrum



Acceleration

$$\langle \gamma \rangle = \varepsilon_e \Gamma m_p / m_e = 3.6 \times 10^4$$

$$\gamma_{\max} = eB / k_\upsilon mc^2 = 1.1 \times 10^{12}$$

$$E = 4.7 \times 10^{14} \left(\frac{\gamma}{1.8 \times 10^4}\right)^{-1/2} \left(\frac{L}{1.0 \times 10^{10} cm}\right)^{1/2} \left(\frac{U}{0.1c}\right) eV$$