Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

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4th International Conference on Numerical Modeling of Space Plasma Flows
June 29th - July 3rd 2009, Chamonix , FRANCE

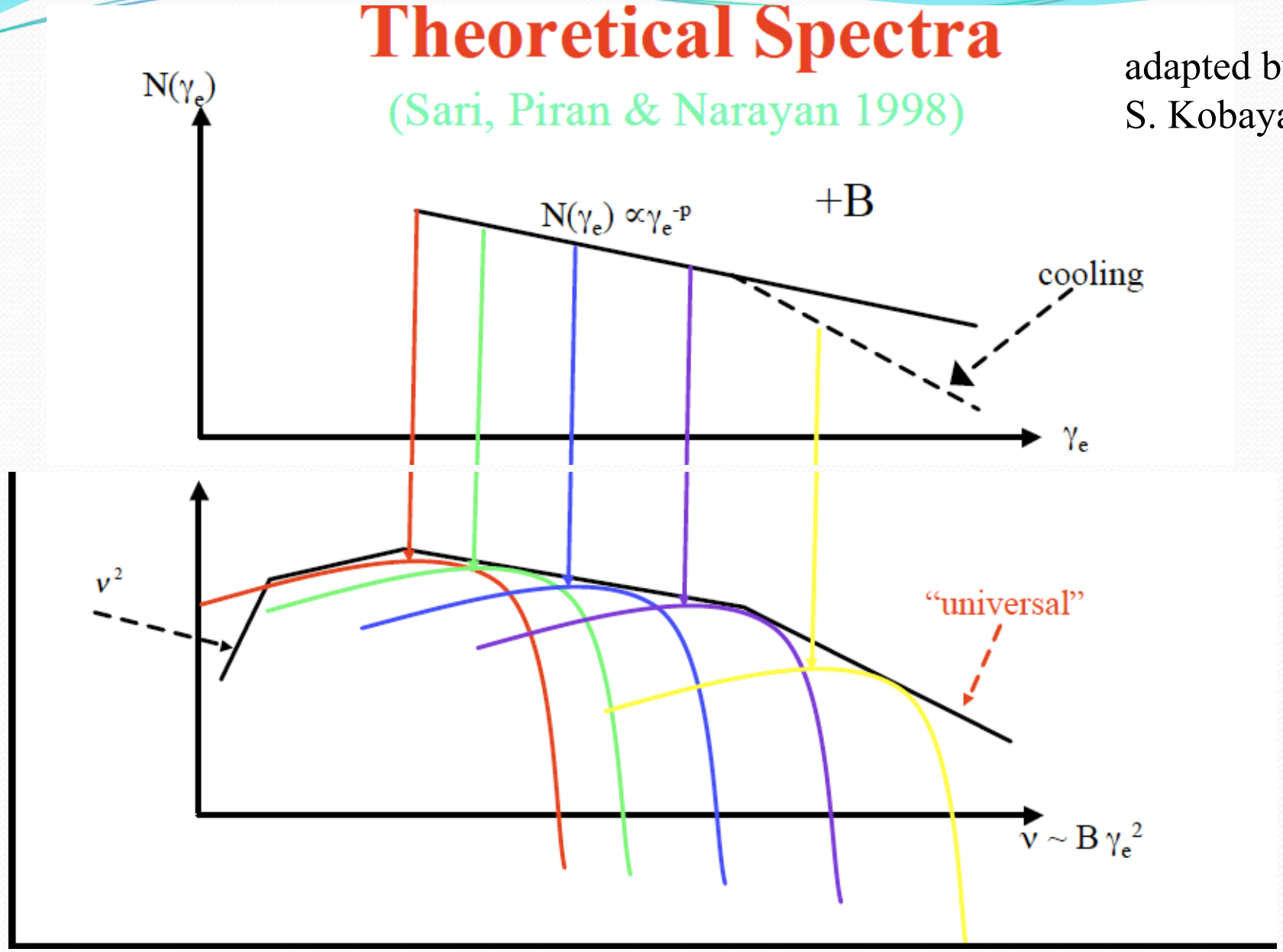
Outline of talk

- **Motivations**
- **Recent 3-D particle simulations of relativistic jets**
  * **$e^{\pm}$pair jet into $e^{\pm}$pair, γ= 15**
- **Radiation from two electrons**
- **New initial results of radiation from electrons based on particle trajectories**
- **Summary**
- **Future plans of our simulations of relativistic jets**

1. Present theory of Synchrotron radiation

- Fermi acceleration (Monte Carlo simulations are not self-consistent; particles are crossing at the shock surface many times and accelerated, the strength of turbulent magnetic fields are assumed), New simulations show Fermi acceleration (Spitkovsky 2008, Martins et al. 2009)
- The strength of magnetic fields is assumed based on the equipartition (magnetic field is similar to the thermal energy) (ε_B)
- The density of accelerated electrons are assumed by the power law ($F(\gamma) = \gamma^{-p}$; $p = 2.2$?) (ε_e)
- Synchrotron emission is calculated based on p and ε_B
- There are many assumptions in this calculation

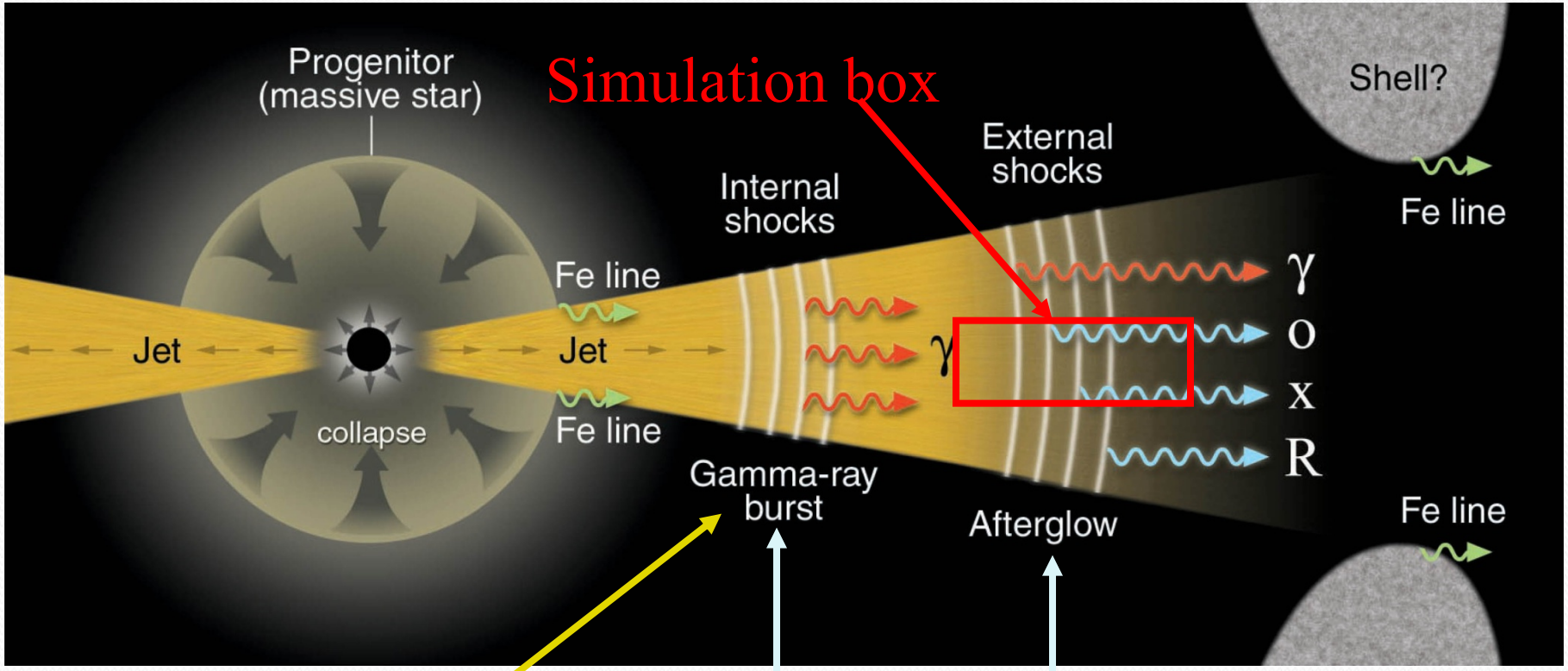
Synchrotron Emission: radiation from accelerated



adapted by
S. Kobayashi

Schematic GRB from a massive stellar progenitor

(Meszaros, Science 2001)



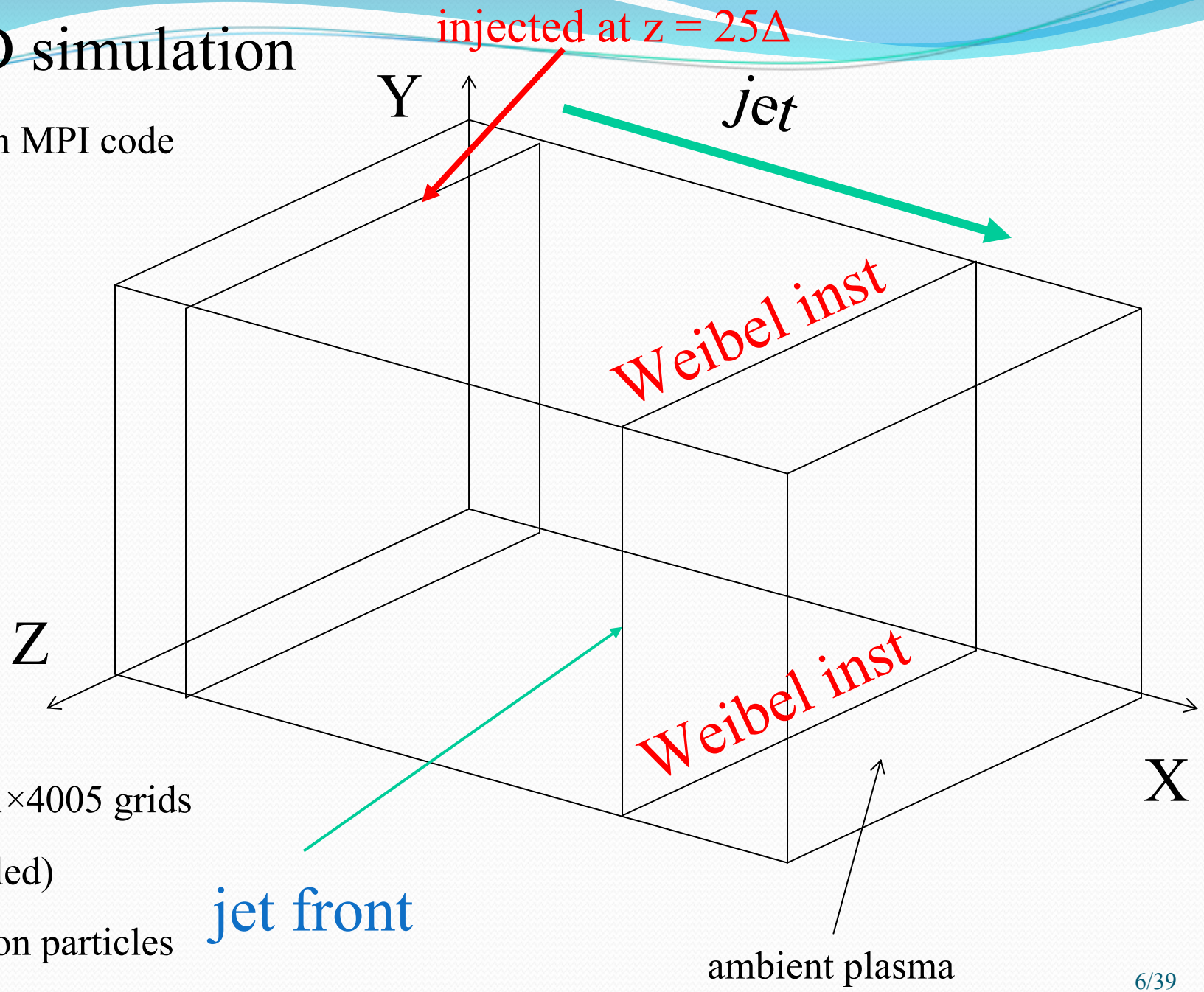
Prompt emission

Polarization ?

Accelerated particles emit waves at shocks

3-D simulation

with MPI code



131×131×4005 grids

(not scaled)

1.2 billion particles

Collisionless shock

Electric and magnetic fields created self-consistently by particle dynamics randomize particles

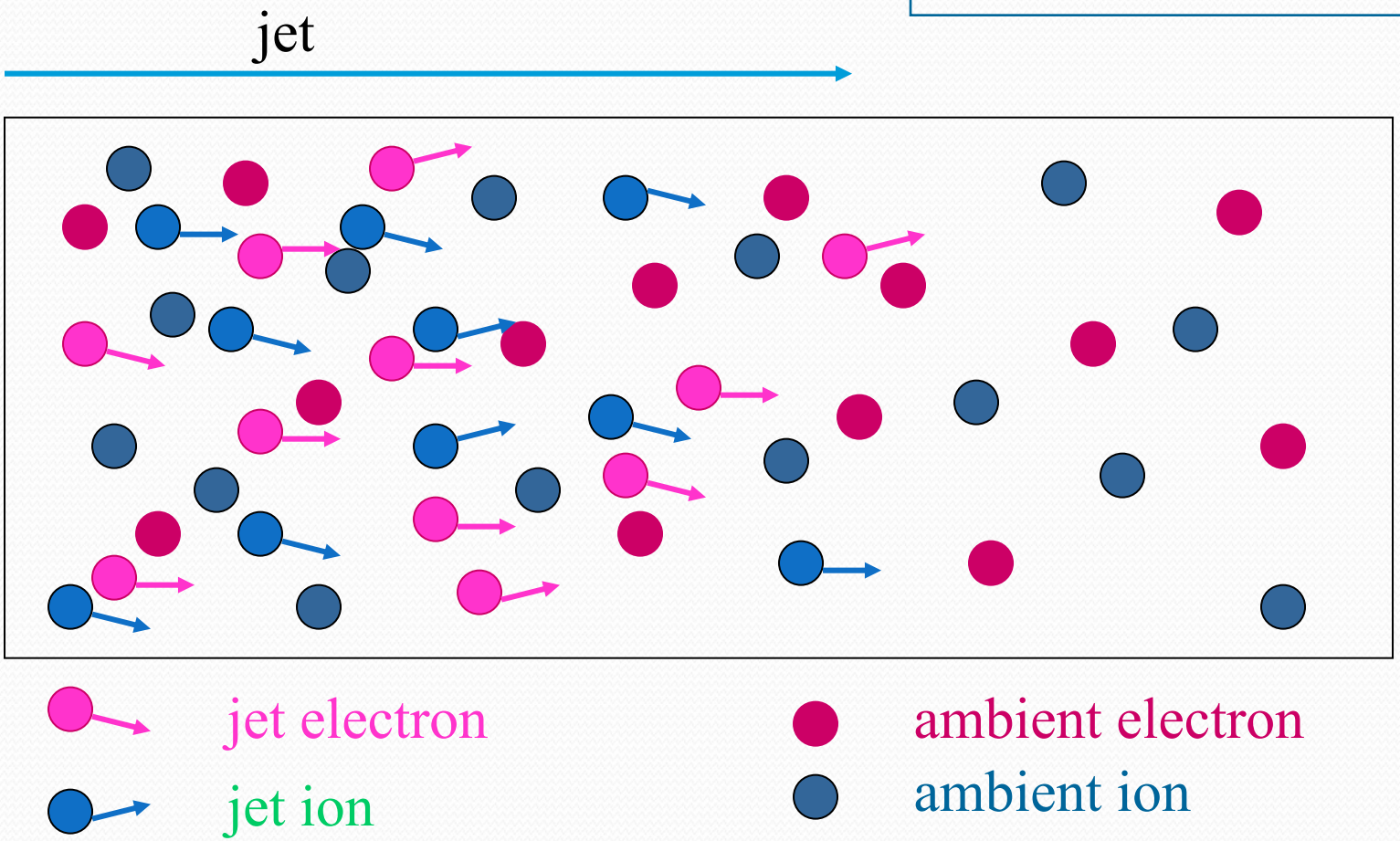
(Buneman 1993)

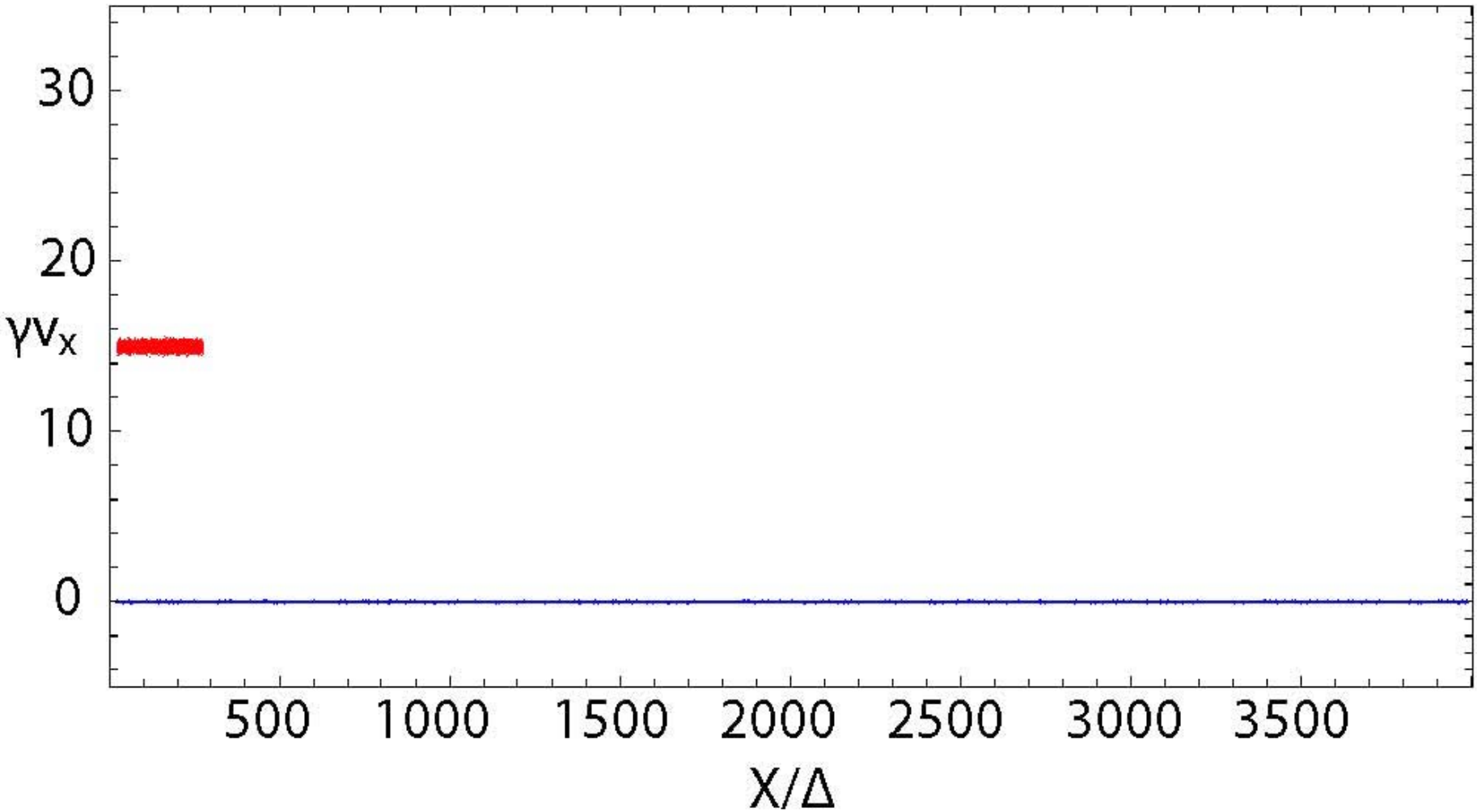
$$\partial B / \partial t = -\nabla \times E$$

$$\partial E / \partial t = \nabla \times B - J$$

$$dm_0 \gamma v / dt = q(E + v \times B)$$

$$\partial \rho / \partial t + \nabla \mathrm{g} J = 0$$



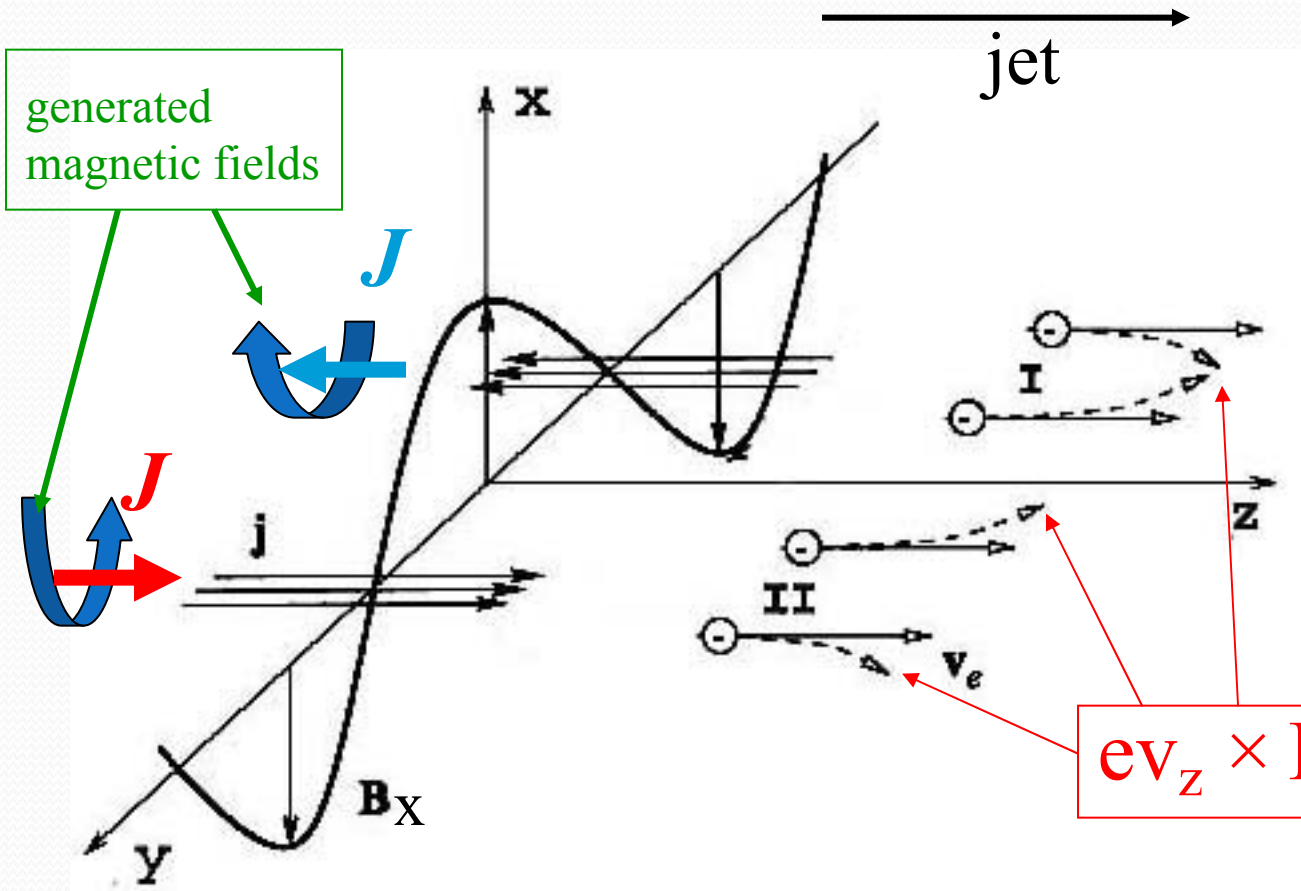


(Nishikawa et al. ApJ, 698, L10, 2009)

Weibel instability

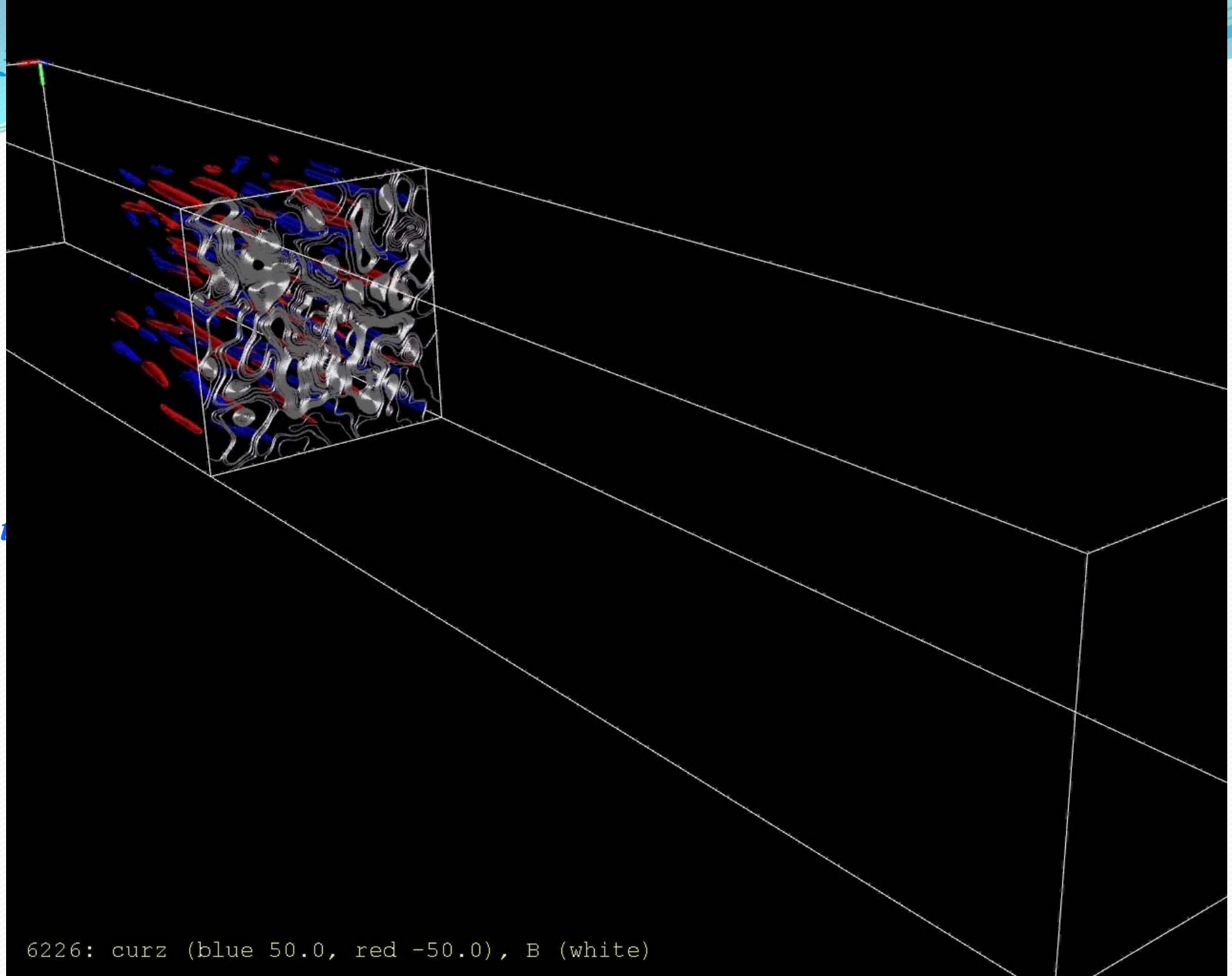
current filamentation

Time:
$\tau = \gamma_{sh}^{1/2}/\omega_{pe} \approx 21.5$ Length:
$\lambda = \gamma_{th}^{1/2} c/\omega_{pe} \approx 9.6\Delta$

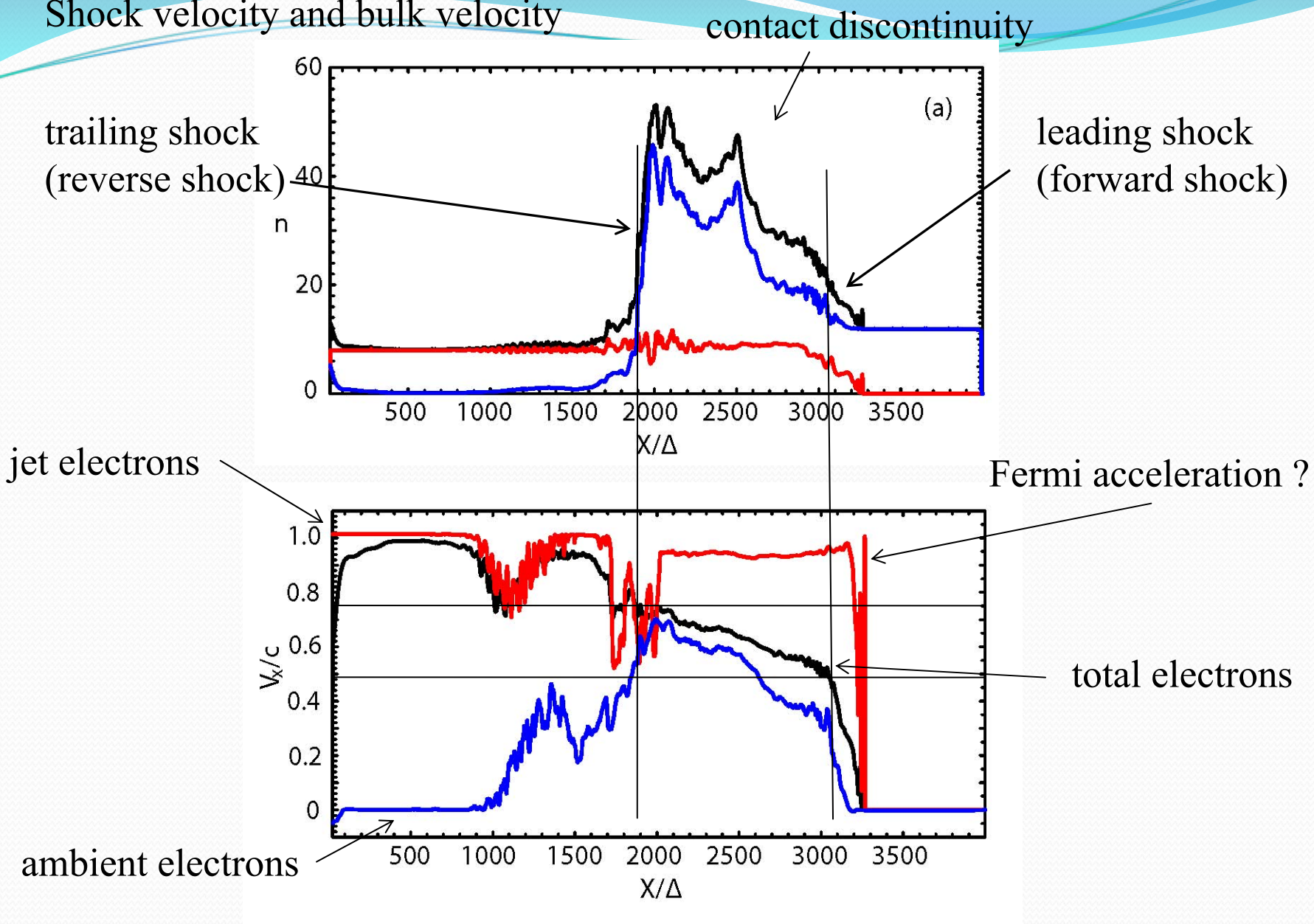


$ev_z \times B_x$ (electrons)

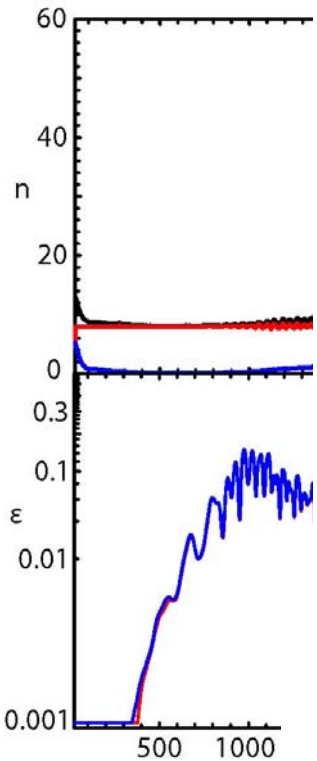
(Medvedev & Loeb, 1999, ApJ)

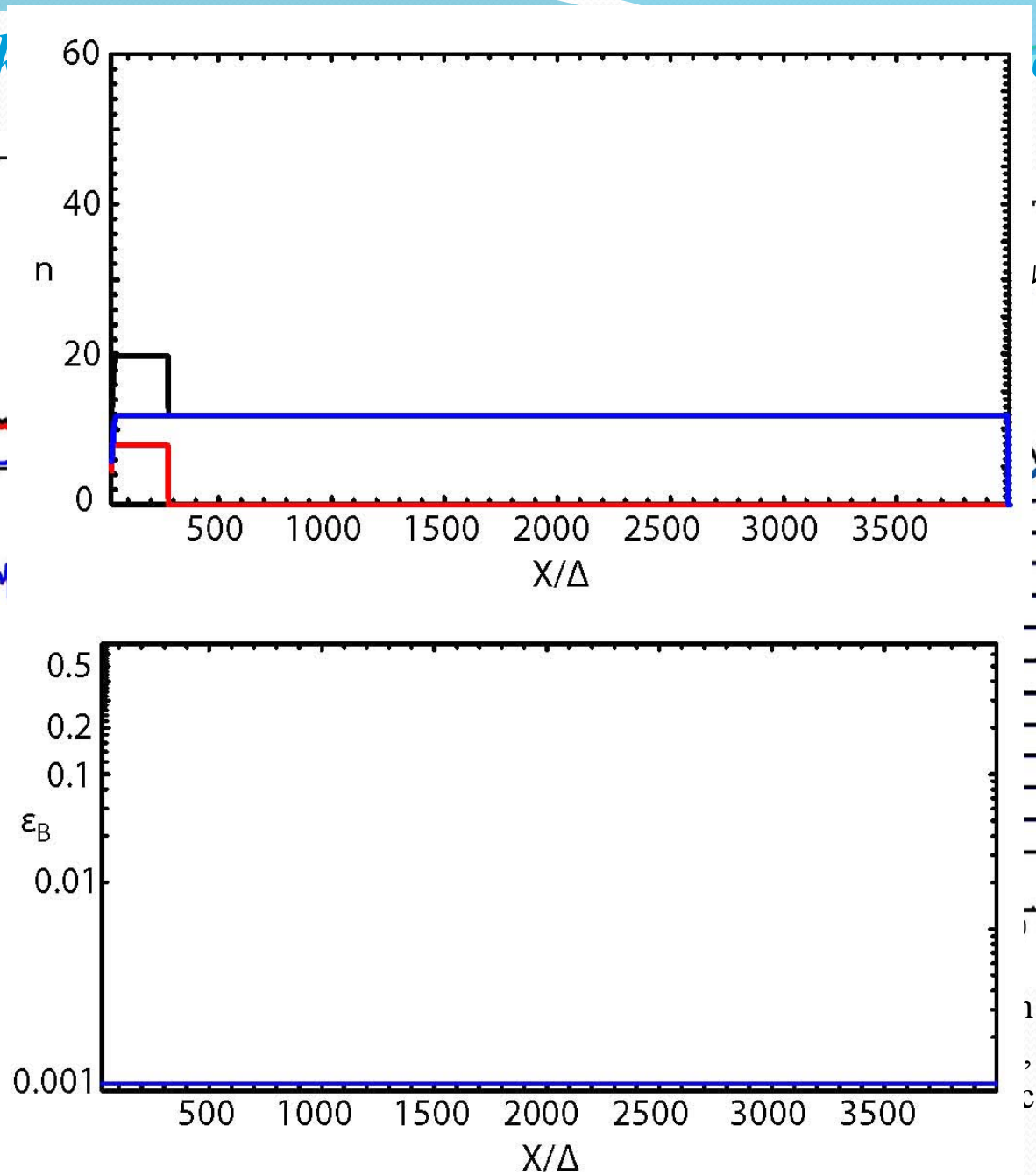

6226: curz (blue 50.0, red -50.0), B (white)

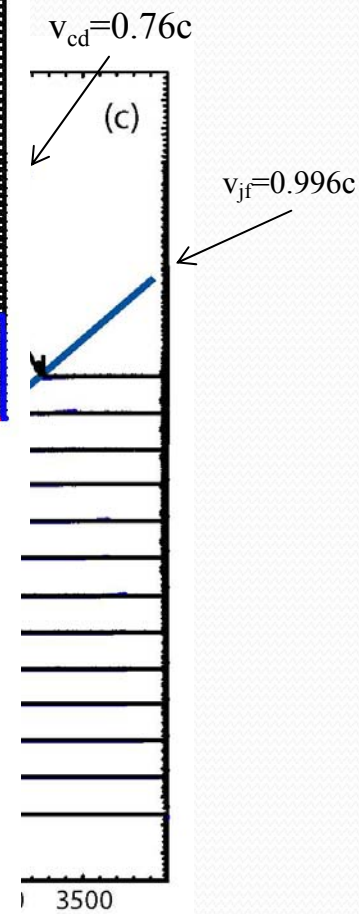
Shock velocity and bulk velocity



Shock ock







(a) electron dens
field energy (ε_B, ε_I
kinetic energy at t

n density.
, the predicted
c, and the

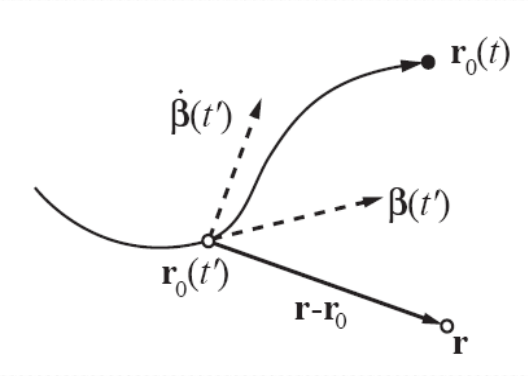
(Nishikawa et a

Radiation from particles in collisionless shock

To obtain a spectrum, "just" integrate:

$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 c q^2}{16\pi^3}\left|\int_{-\infty}^{\infty}\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^2}\,e^{i\omega(t'-\mathbf{n}\cdot\mathbf{r}_0(t')/c)}dt'\right|^2$$

where $\mathbf{r}_0$ is the position, $\boldsymbol{\beta}$ the velocity and $\dot{\boldsymbol{\beta}}$ the acceleration



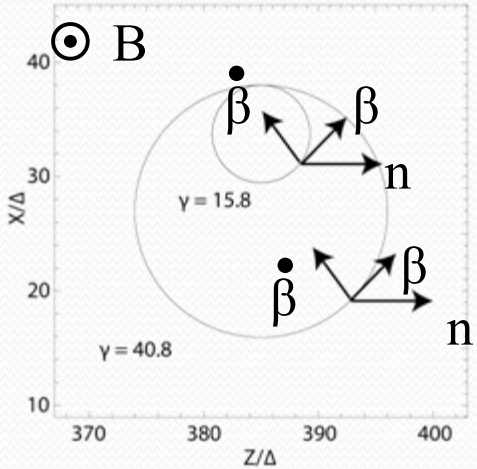
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

Hededal, Thesis 2005 (astro-ph/0506559)

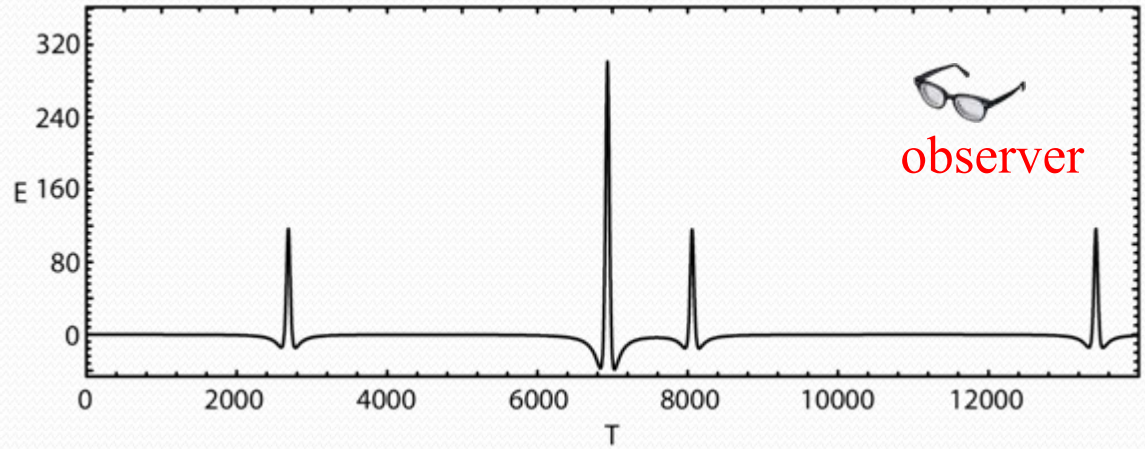
Nishikawa et al. 2008 (astro-ph/0802.2558)

Synchrotron radiation from gyrating electrons in a uniform magnetic field

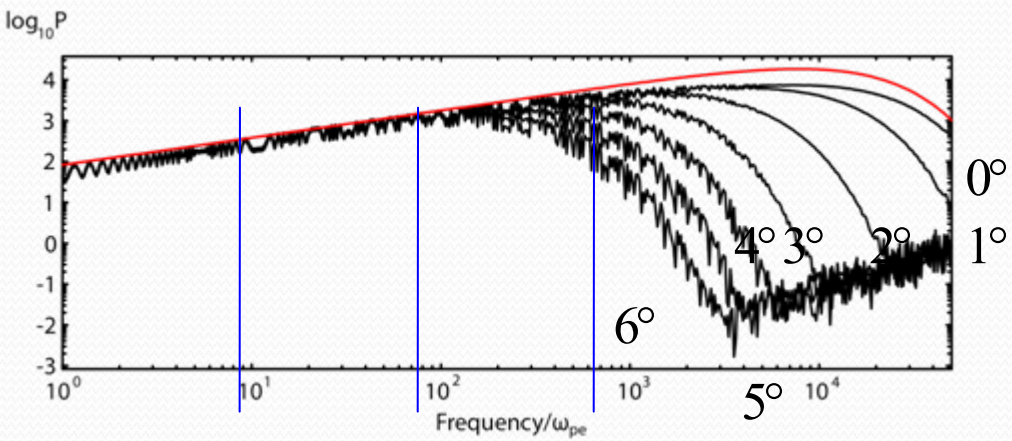
electron trajectories



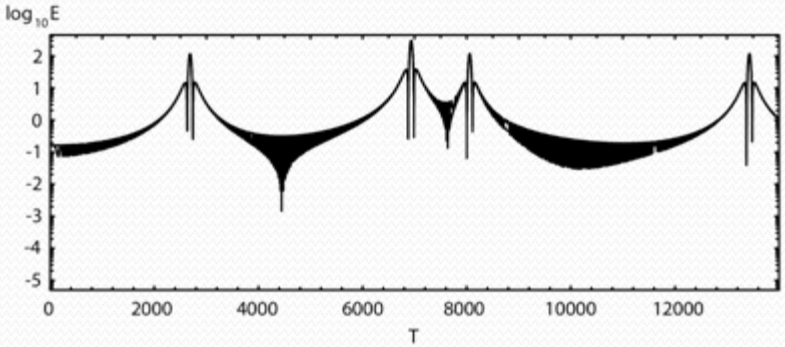
radiation electric field observed at long distance



spectra with different viewing angles



time evolution of three frequencies

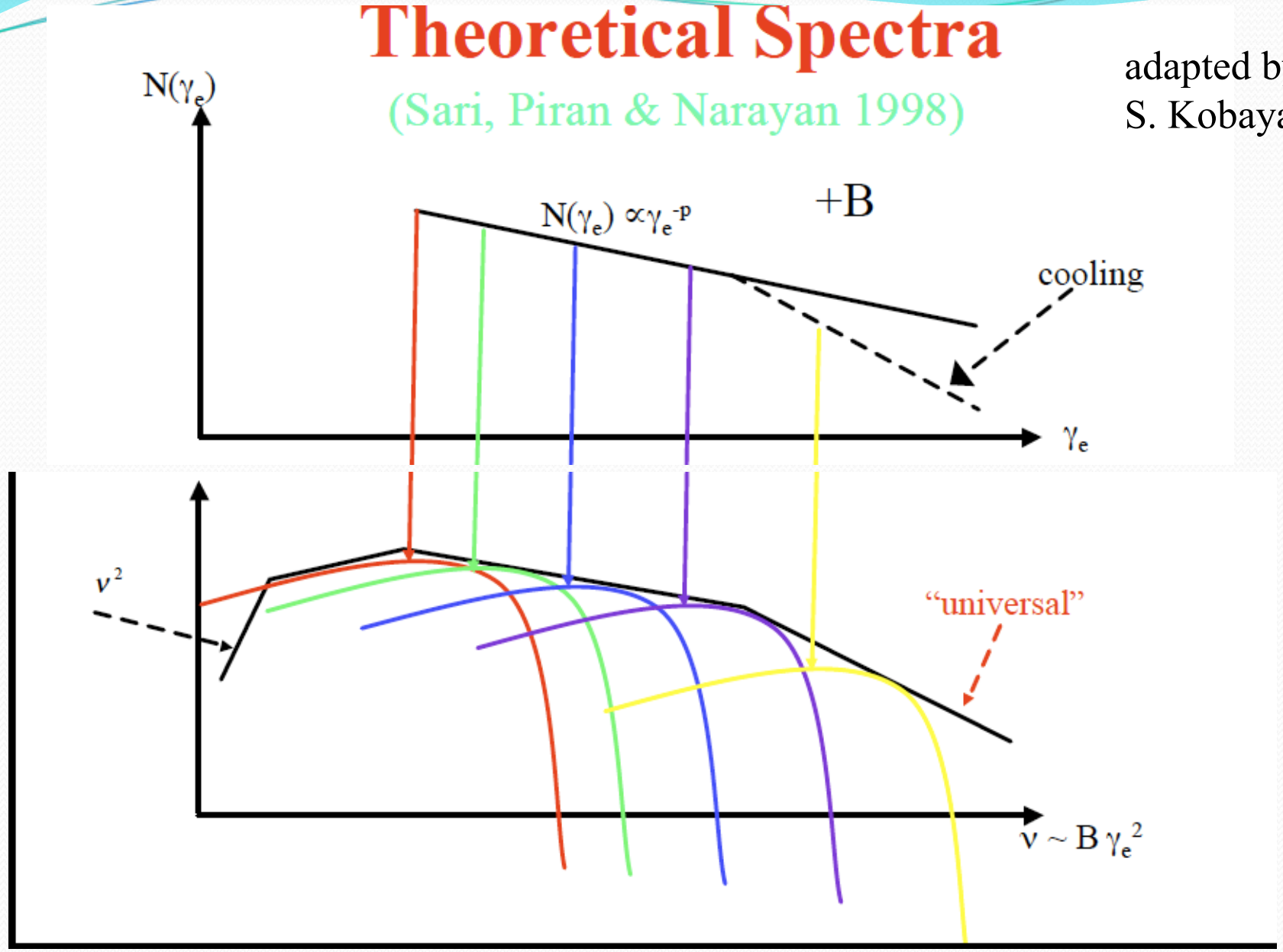


f/ω_{pe} = 8.5, 74.8, 654.

theoretical synchrotron spectrum

Rybicki, G. B., & Lightman, A. P. 1979, *Radiative Processes in Astrophysics, John Wiley & Sons, New York*

Synchrotron Emission: radiation from accelerated



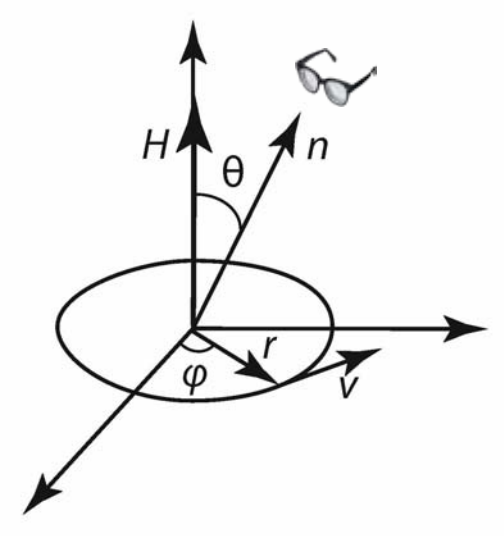
adapted by
S. Kobayashi

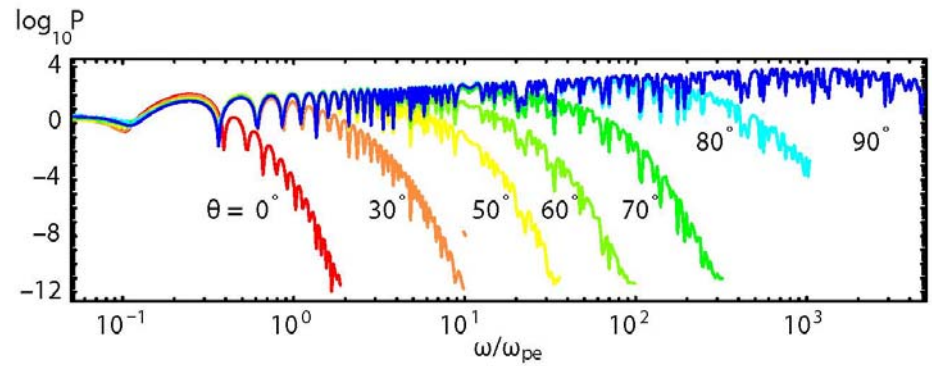
Self-consistent calculation of radiation

- Electrons are accelerated by the electromagnetic field generated by the Weibel instability (without the assumption used in test-particle simulations for Fermi acceleration)
- Radiation is calculated by the particle trajectory in the self-consistent magnetic field
- This calculation include Jitter radiation (Medvedev 2000, 2006) which is different from standard synchrotron emission
- Some synchrotron radiation from electron is reported (Nishikawa et al. 2008 (astro-ph/0801.4390;0802.2558;0809.5067)

Cyclotron radiation

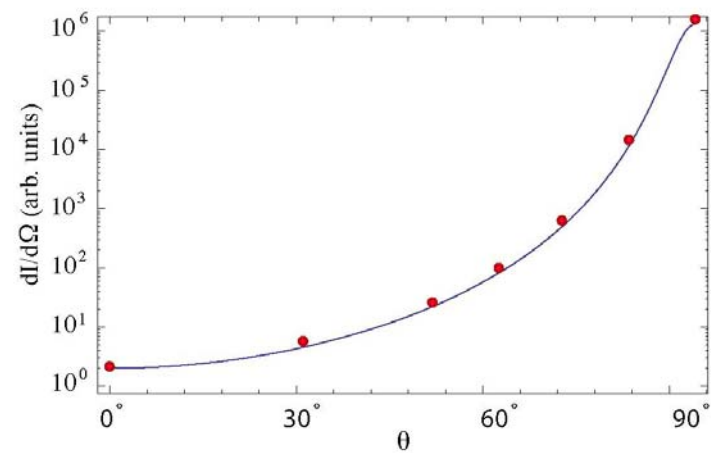
$\gamma = 15$





Angle dependence of radiation

$$\frac{\overline{dI}}{d\Omega} = \frac{e^4 H^2 v^2 (1-\frac{v^2}{c^2})}{8\pi^2 m^2 c^5}\left\{\frac{2+\frac{v^2}{c^2}\sin^2\theta}{(1-\frac{v^2}{c^2}\sin^2\theta)^{5/2}} - \frac{(1-\frac{v^2}{c^2})(4+\frac{v^2}{c^2}\sin^2\theta)\sin^2\theta}{4(1-\frac{v^2}{c^2}\sin^2\theta)^{7/2}}\right\} \quad (74.4)$$



Radiation ratio at $\theta = 0$ and $\pi/2$

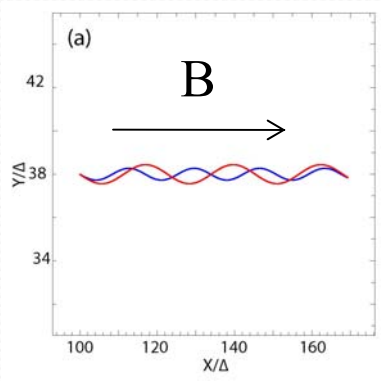
$$\frac{\left(\frac{dI}{d\Omega}\right)_{\pi/2}}{\left(\frac{dI}{d\Omega}\right)_0} = \frac{4+3\frac{v^2}{c^2}}{8\left(1-\frac{v^2}{c^2}\right)^{5/2}} : \gamma^5$$

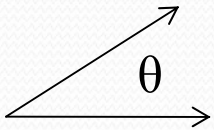
from Landau & Lifshitz, ***The Classical Theory of Fields***, 1980

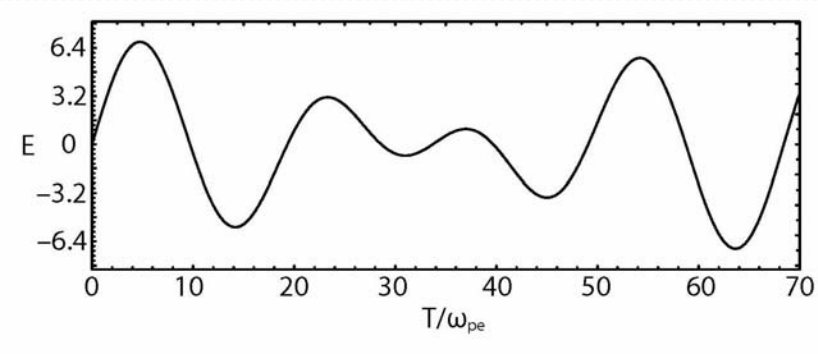
Synchrotron radiation from propagating electrons in a uniform magnetic field

electron trajectories

radiation electric field observed at long distance





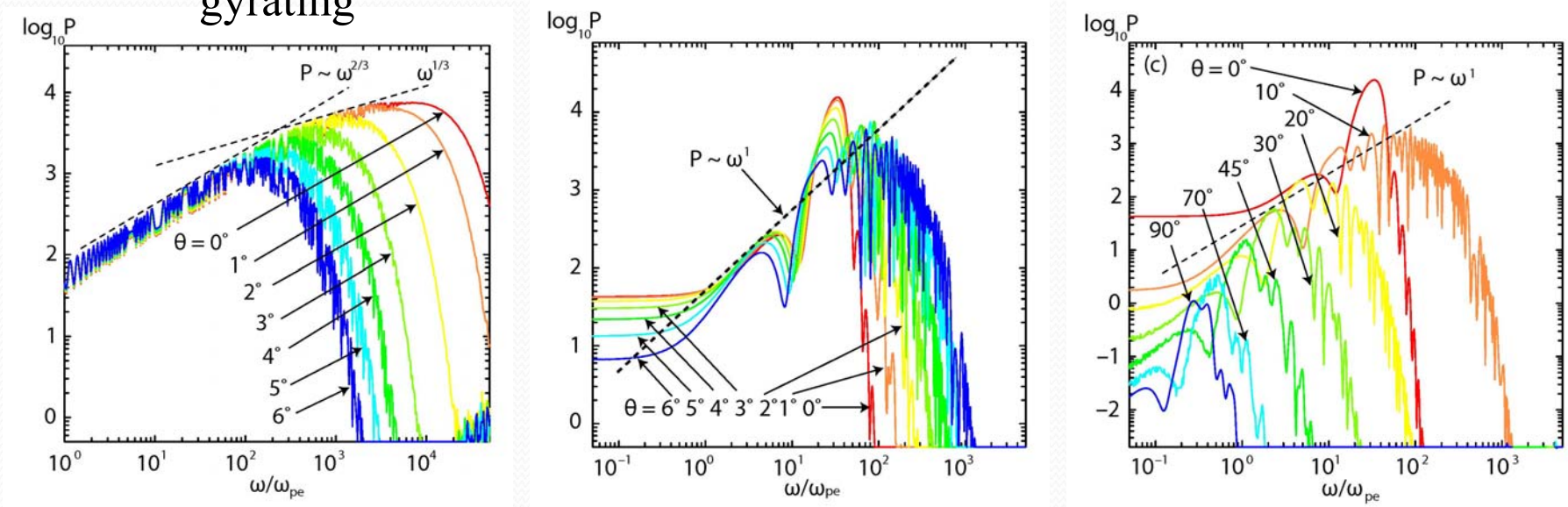


observer

spectra with different viewing angles

gyrating

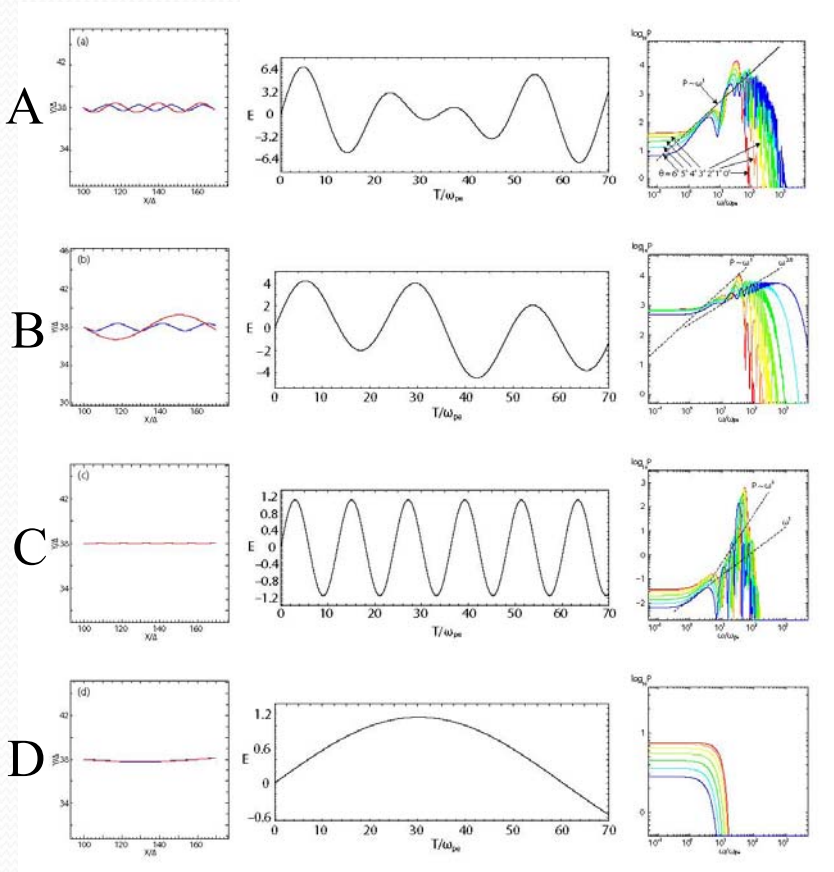
$\theta_r = 4.25°$

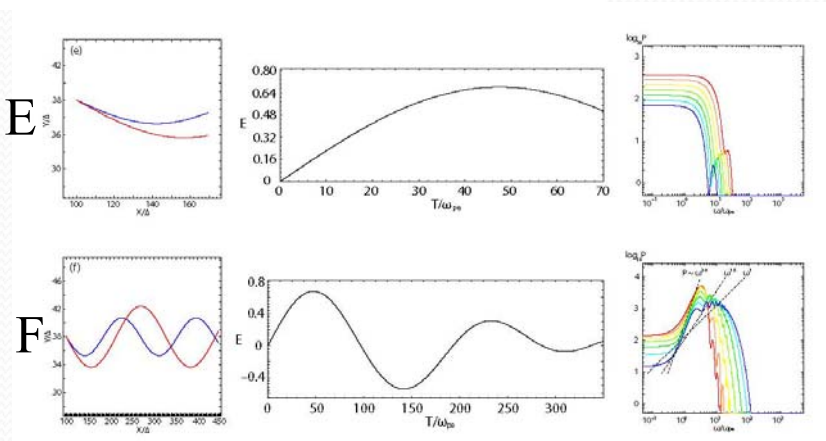


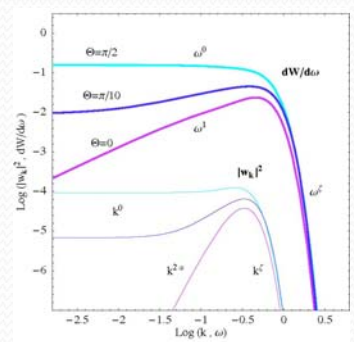
Nishikawa et al. astro-ph/0809.5067

TABLE 1. Seven cases of radiation

	B_x	$V_{j1,2}$	$V_{\perp,1}$	$V_{\perp,2}$	γ_{max}	θ_T	Remarks
P	3.70 (B_z)	0.0c	0.998c	0.9997c	40.08	1.43	gyrating
A	3.70	0.99c	0.1c	0.12c	13.48	4.25	jet
B	3.70	0.9924c	0.1c	0.12c	36.70	1.56	jet
C	3.70	0.99c	0.01c	0.012c	7.114	8.05	jet
D	0.370	0.99c	0.01c	0.012c	7.114	8.05	jet
E	0.370	0.99c	0.1c	0.12c	13.48	4.25	$\Delta t = 0.005$
F	0.370	0.99c	0.1c	0.12c	13.48	4.25	$\Delta t = 0.025$







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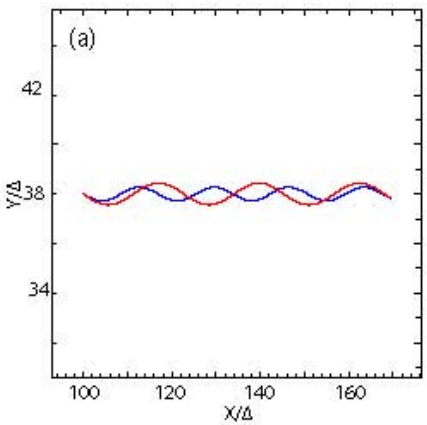
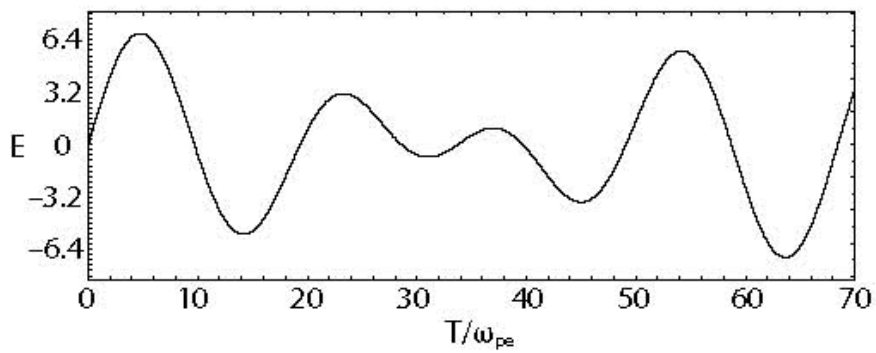
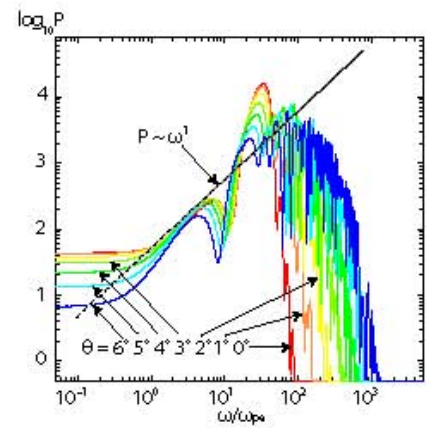
Case A







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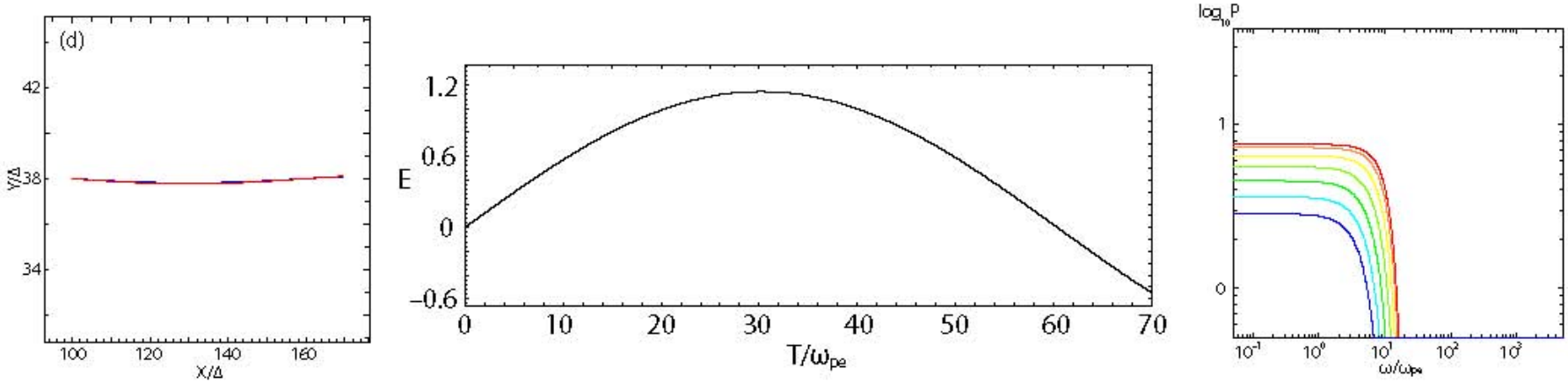
Case D

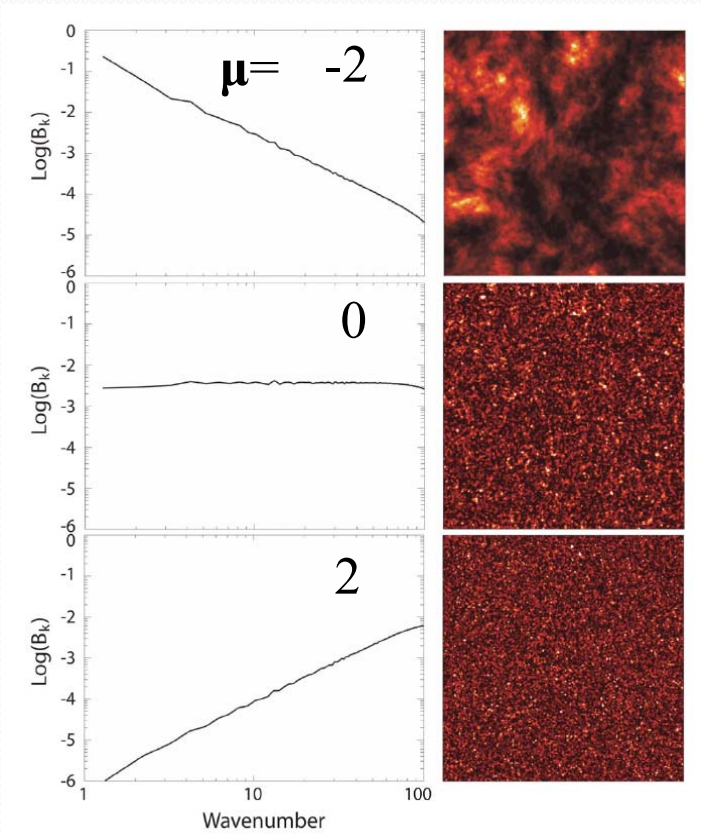


(Nishikawa et al. astro-ph/0809.5067)

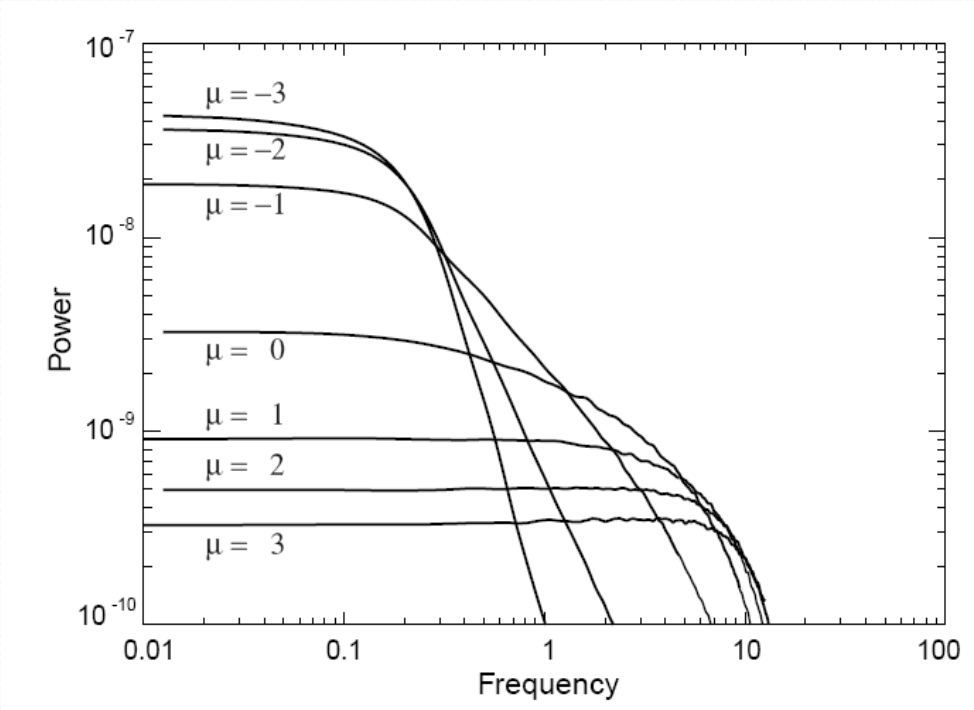
3D jitter radiation (diffusive synchrotron radiation) with a ensemble of mono-energetic electrons (γ = 3) in turbulent magnetic fields (Medvedev 2000; 2006, Fleishman 2006)

$$P_B(k) \propto k^{\mu}$$

2d slice of magnetic field

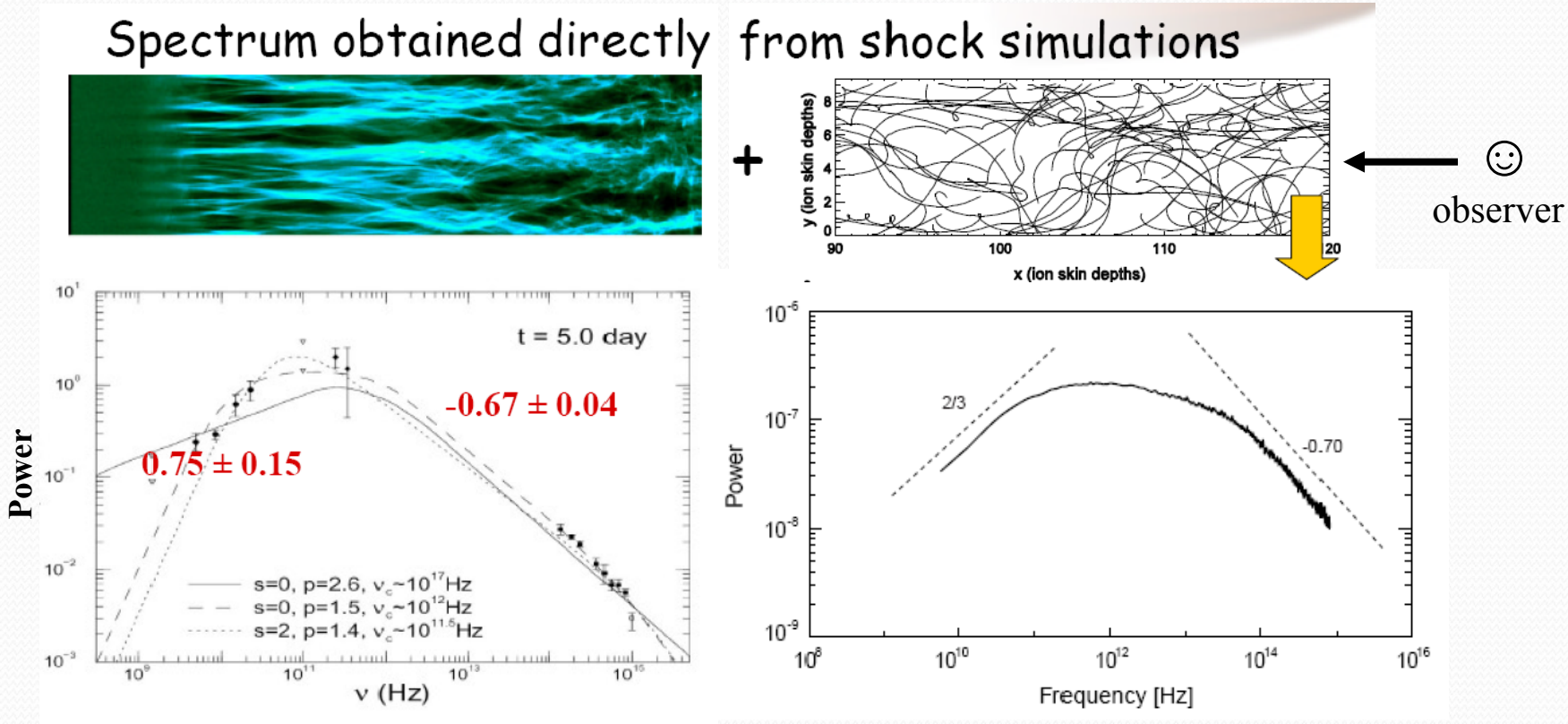


3D jitter radiation with γ = 3 electrons



Hededal & Nordlund (astro-ph/0511662)

Radiation from collisionless shock



GRB 000301c (Panaitescu 2001)

Shock simulations

Hededal Thesis: http://www.astro.ku.dk/~hededal

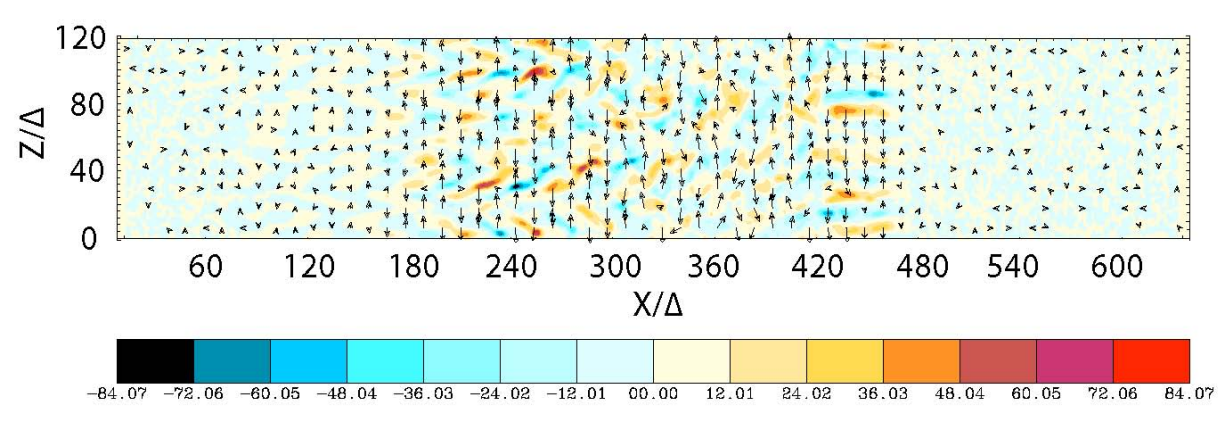
Hededal & Nordlund 2005, submitted to ApJL (astro-ph/0511662)

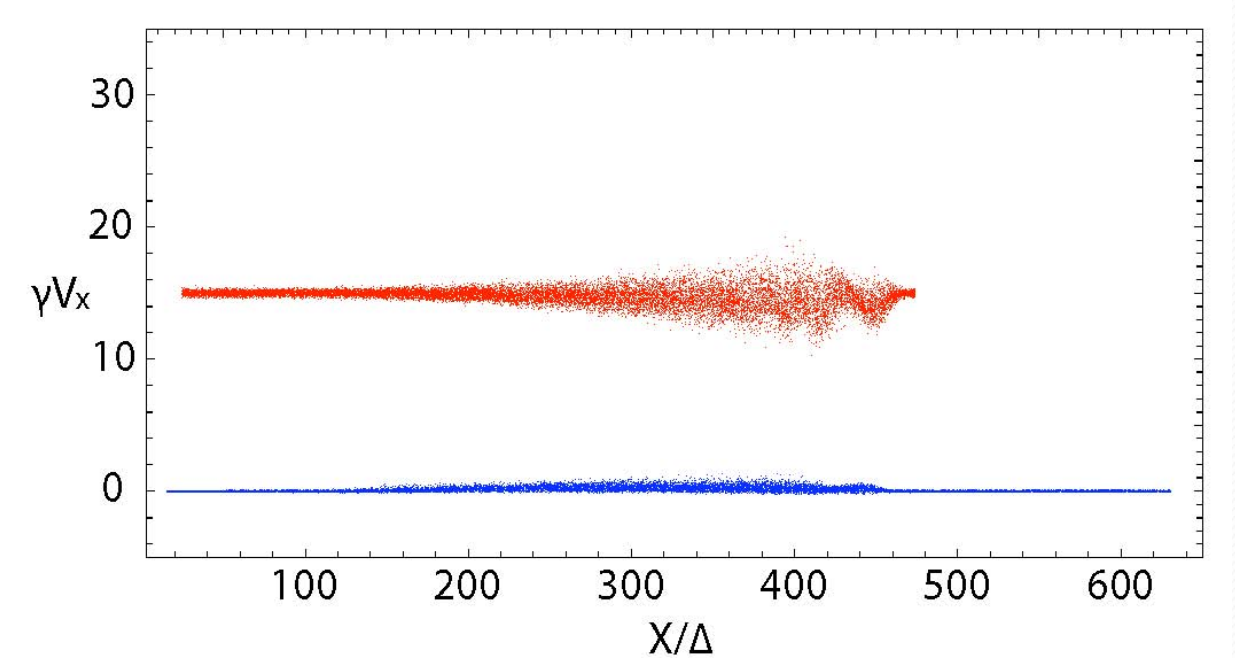
Jitter radiation from electrons by tracing trajectories self-consistently

using a small simulation system

initial setup for jitter radiation

select electrons
(12,150)
in jet and ambient





final condition for jitter radiation

15,000 steps

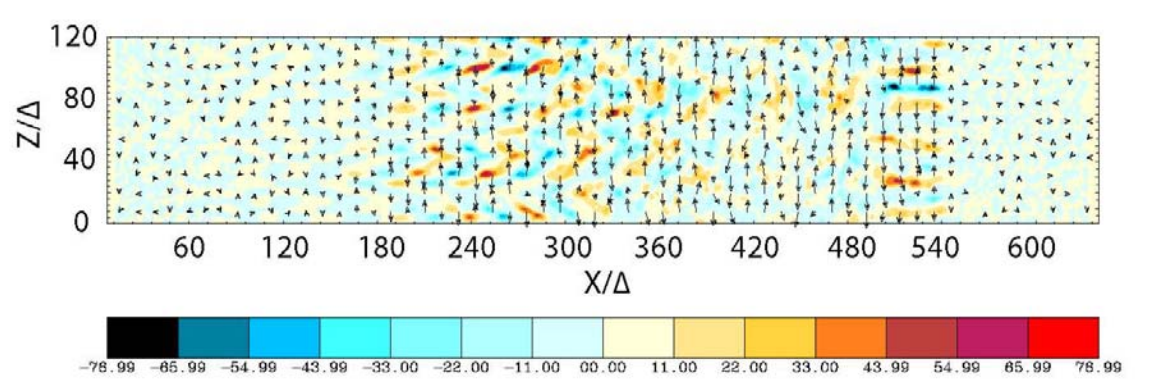
$dt = 0.005\ \omega_{pe}^{-1}$

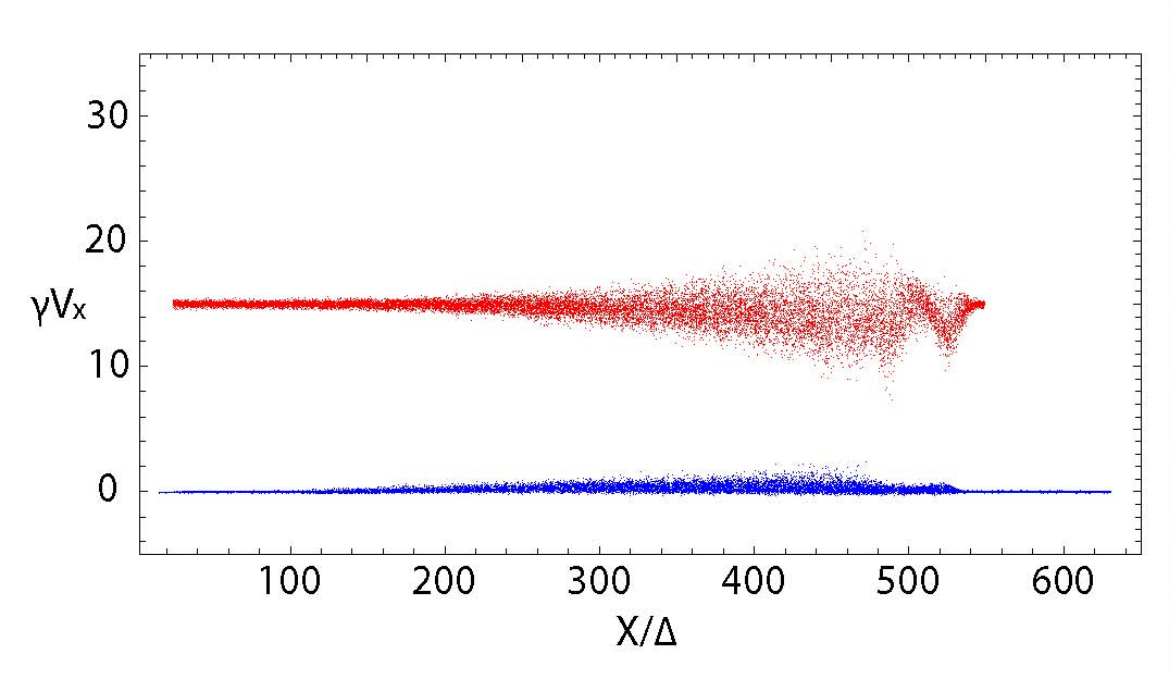
$\omega_n = 100$

$\theta_n = 2$

$\Delta x_{jet} = 75\Delta$

$\Delta t_{jitt} = 75\ \omega_{pe}^{-1}$

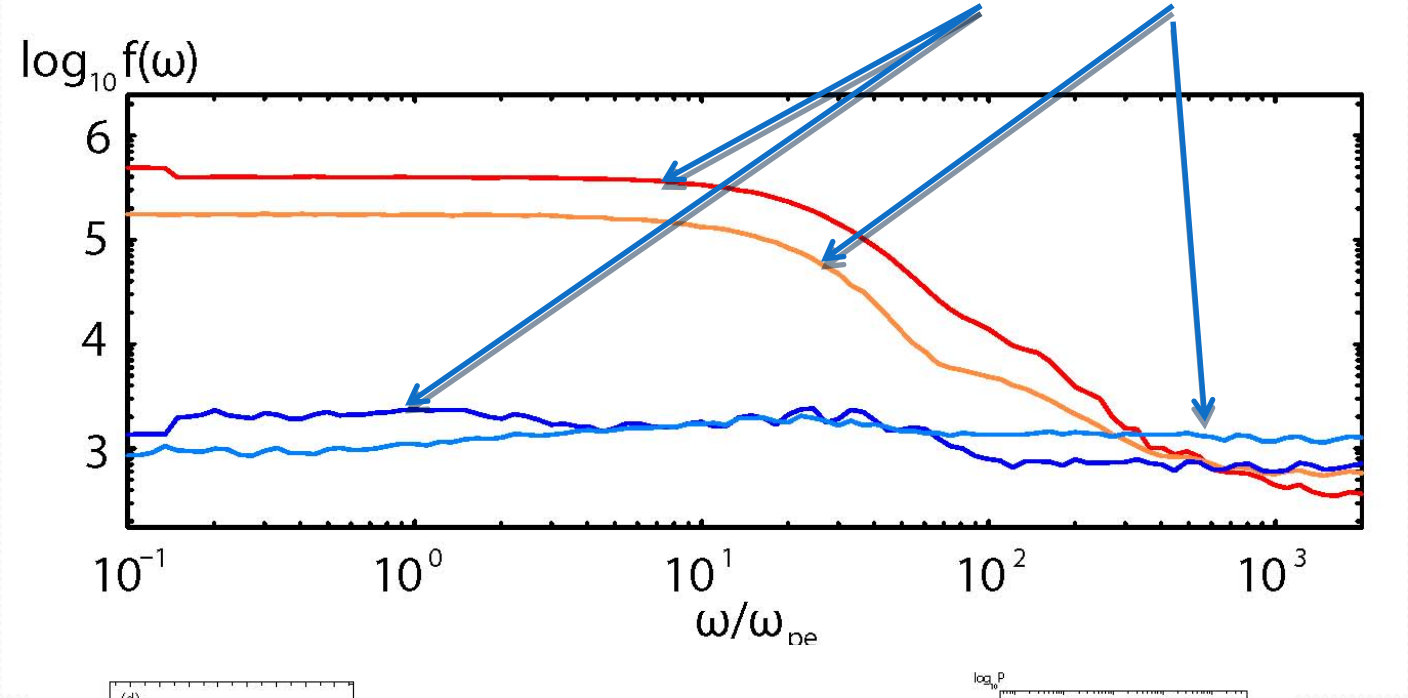




Calculated spectra for jet electrons and ambient electrons

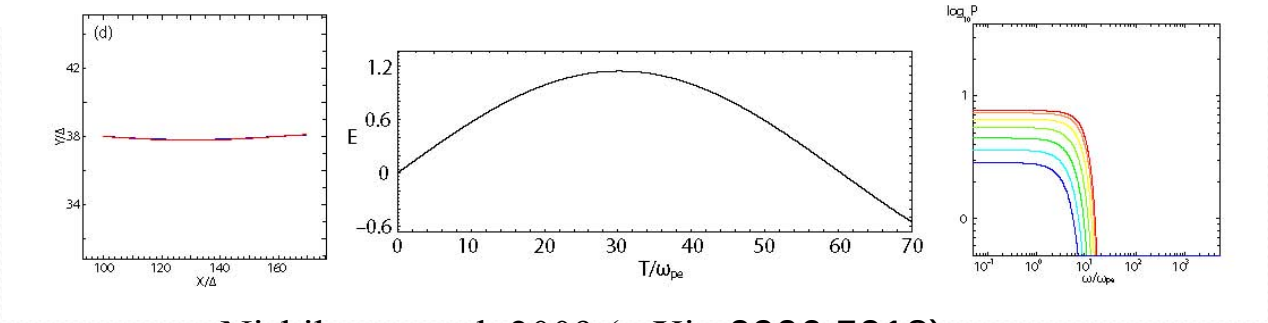
$\gamma = 15$

$\theta = 0°$ and $5°$



Case D

$\gamma = 7.11$



Nishikawa et al. 2009 (arXiv:0906.5018)

Summary

- Simulation results show electromagnetic stream instability driven by streaming $e^{\pm}$ pairs are responsible for the excitation of near-equipartition, turbulent magnetic fields.
- Ambient ions assist in generation of stronger magnetic fields.
- Weibel instability plays a major role in particle acceleration due the quasi-steady radial electric field around the current filaments and local reconnections during merging filaments in relativistic jets.
- The magnetic fields created by Weibel instability generate highly inhomogeneous magnetic fields, which is responsible for jitter radiation (Medvedev, 2000, 2006; Fleishman 2006).

Future plans for particle acceleration in relativistic jets

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics with larger systems**
- **Simulations with magnetic field may accelerate particles further?**
- **In order to investigate shock dynamics further diagnostics will be developed**
- **Investigate synchrotron (jitter) emission, and/or polarity from the accelerated electrons in inhomogeneous magnetic fields and compare with observations (Blazars and gamma-ray burst emissions) (Medvedev, 2000, 2006; Fleishman 2006)**

Gamma-Ray Large Area Space Telescope (FERMI)

(launched on June 11, 2008) http://www-glast.stanford.edu/

Compton Gamma-Ray Observatory (CGRO)

Burst And Transient Source Experiment (BATSE) (1991-2000)

PI: Jerry Fishman

Fermi (GLAST)

All sky monitor

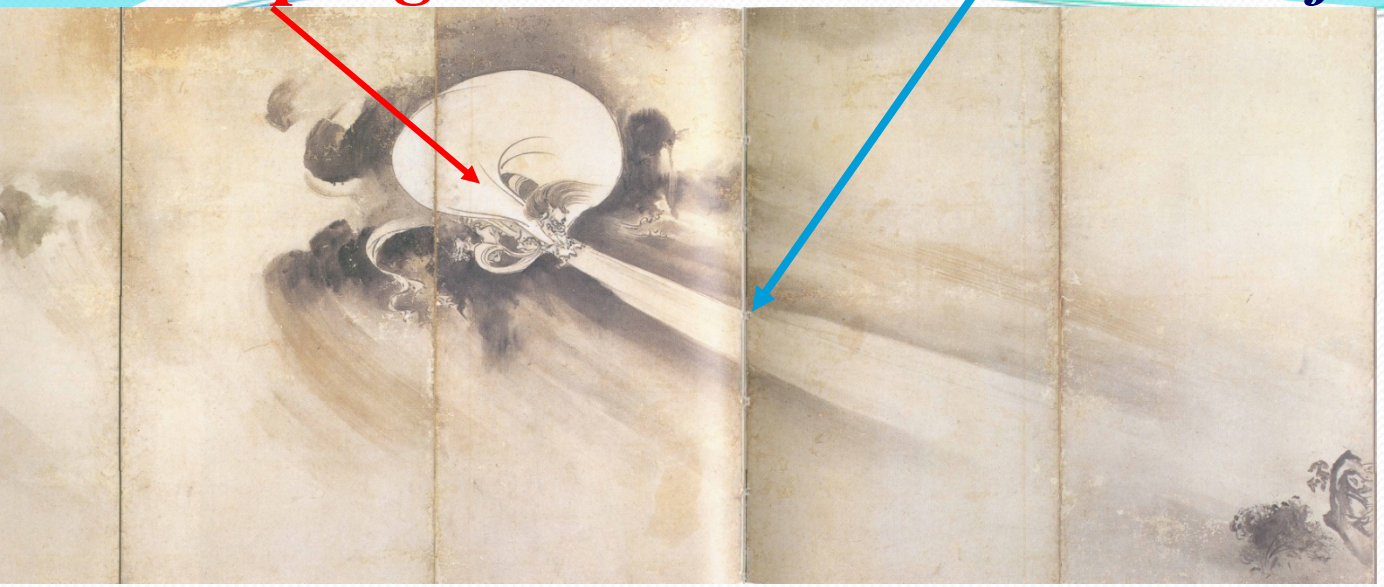
- **Large Area Telescope (LAT) PI: Peter Michaelson: gamma-ray energies between 20 MeV to about 300 GeV**
- **Fermi Gamma-ray Burst Monitor (GBM) PI: Bill Paciaas (UAH) (Chip Meegan (Retired;USRA)): X-rays and gamma rays with energies between 8 keV and 25 MeV**

  (http://gammaray.nsstc.nasa.gov/gbm/)

  The combination of the GBM and the LAT provides a powerful tool for studying radiation from relativistic jets and gamma-ray bursts, particularly for time-resolved spectral studies over very large energy band.

GRB progenitor

relativistic jet



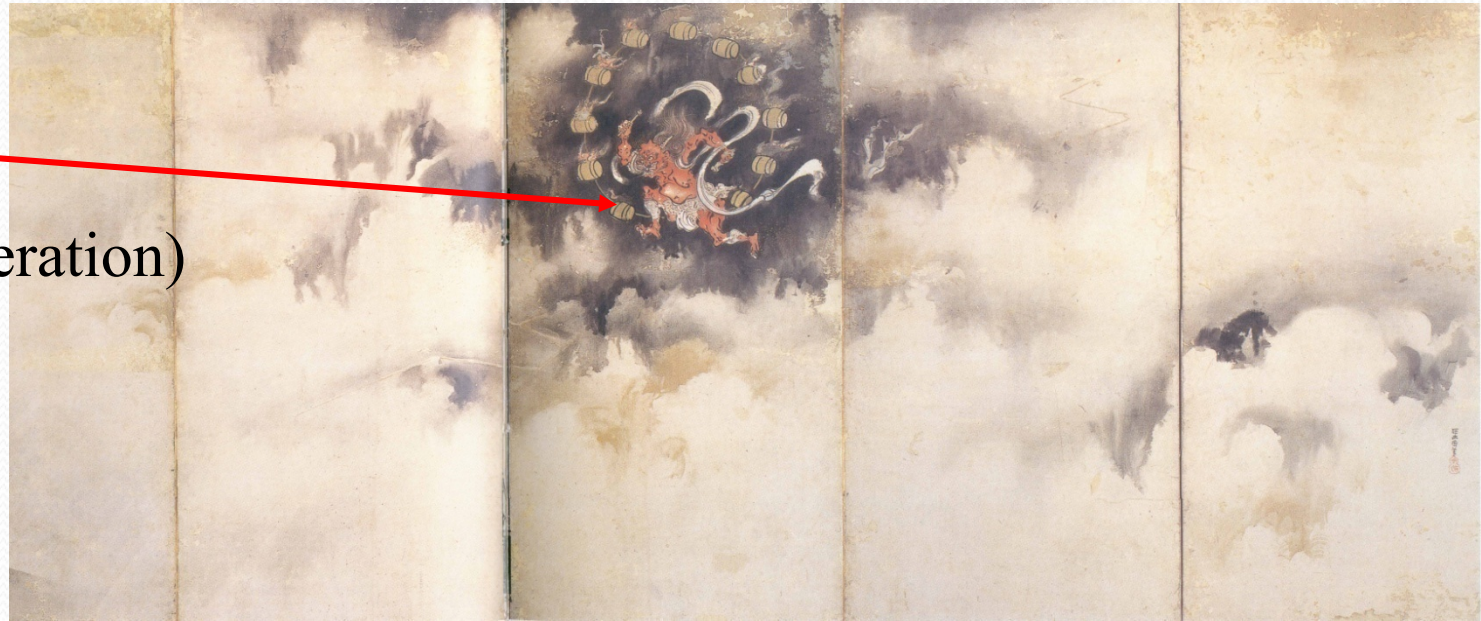
Fushin

(god of wind)

(Tanyu Kano 1657)

emission

(shocks, acceleration)



Raishin

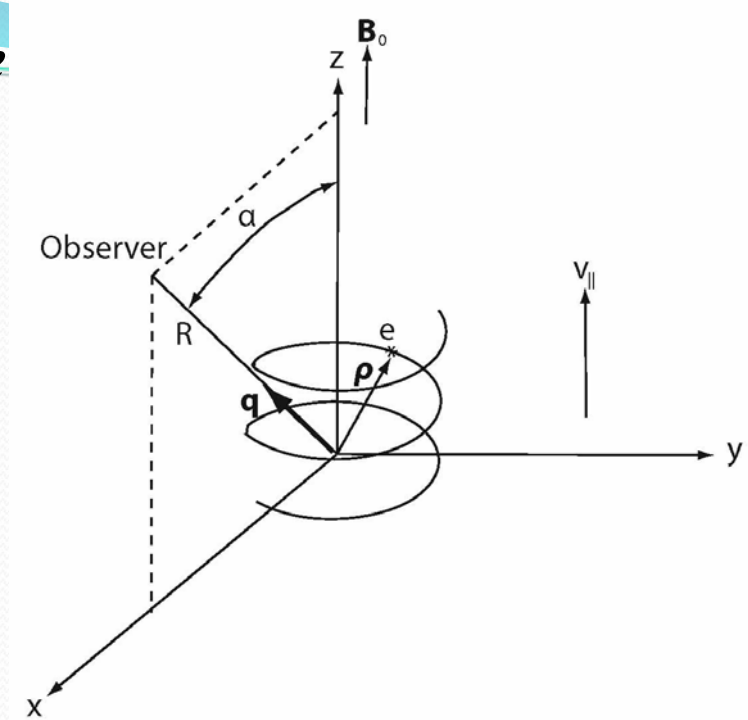
(god of lightning)

Good text books for radiation

- ***Classical Electrodynamics***, by Jackson, J. D., Interscience, 1999
- ***Radiative Processes in Astrophysics***, by Rybicki, G. B., & Lightman, A. P., John Wiley & Sons, New York, 1979
- ***Radiation Processes in Plasmas***, by Bekefi, G., Wiley & Sons, New York, 1966
- ***The Classical Theory of Fields***, by Landau, L. D., Pergamon Press, 1975

Synchrotron emission from a particle pitch angle α

G. B. Rybicki & A. P. Lightman,
Radiative rocesses in Astrophysics



$$\frac{dW_\perp}{d\omega} = \frac{2q^2\omega^2a^2\sin\alpha}{3\pi c^3\gamma^4}\int_{-\infty}^{\infty}\theta_\gamma^4 K_{2/3}^2(\eta)\,d\theta$$

$$\frac{dW_\mathrm{P}}{d\omega} = \frac{2q^2\omega^2a^2\sin\alpha}{3\pi c^3\gamma^4}\int_{-\infty}^{\infty}\theta_\gamma^2\theta^2 K_{1/3}^2(\eta)\,d\theta$$

$$\theta_\gamma^2 \equiv 1+\gamma^2\theta^2 \qquad \eta \equiv \frac{\omega a\theta_\gamma^3}{3c\gamma^3} \approx \eta(\theta=0) = \frac{\omega}{2\omega_c}$$

$$\omega_c \equiv \frac{3}{2}\gamma^3\omega_B\sin\alpha \qquad \omega_B = \frac{qB}{\gamma mc}$$

for $\alpha = 0°$ radiation becomes zero??

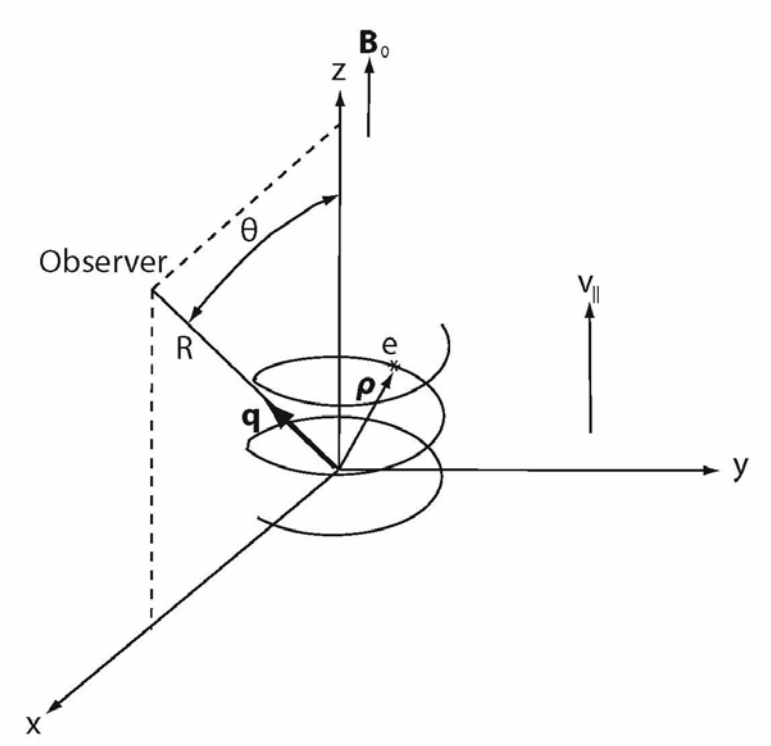
Cyclotron emission of an electron in helical motion

resultant electric field

$$\beta^2 = \beta_{\mathrm{P}}^2 + \beta_\perp^2 = \left(\frac{v_{\mathrm{P}}}{c}\right)^2 + \left(\frac{v_\perp}{c}\right)^2 \qquad \gamma = (1-\beta^2)^{-1/2}$$

$$x = \frac{\omega}{\omega_0}\beta_\perp \sin\theta \qquad \omega_0 = -\frac{eB_0}{m_0\gamma}$$

$$y = m\omega_0 - \omega(1-\beta_{\mathrm{P}}\cos\theta)$$



$$\eta_m(\omega,v,\theta) = \frac{e^2\omega^2}{8\pi^2\varepsilon_0 c}\left[\sum_1^\infty\left(\frac{\cos\theta-\beta_{\mathrm{P}}}{\sin\theta}\right)^2 J_m^2(x) + \beta_\perp^2 J_m'^2(x)\right]\delta(y)$$

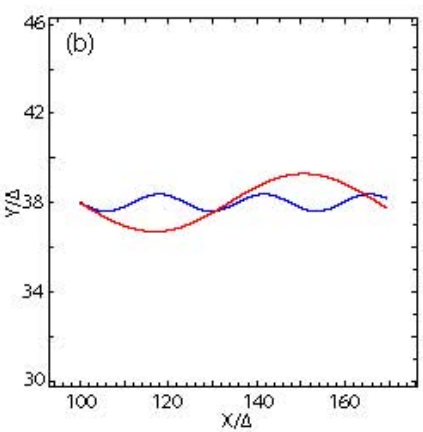
$$J_m' \equiv dJ_m(x)/dx \quad \neq 0 \text{ even } \theta = 0$$

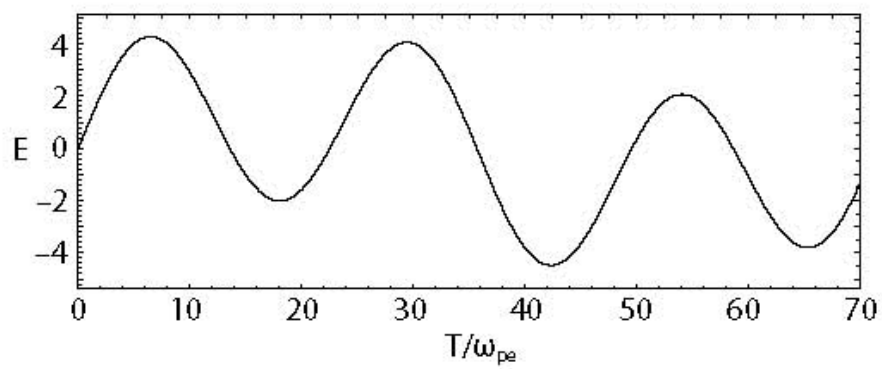
G. Bekefi, *Radiation Processes in Plasma*, 1966, John Wiley & Sons, Inc

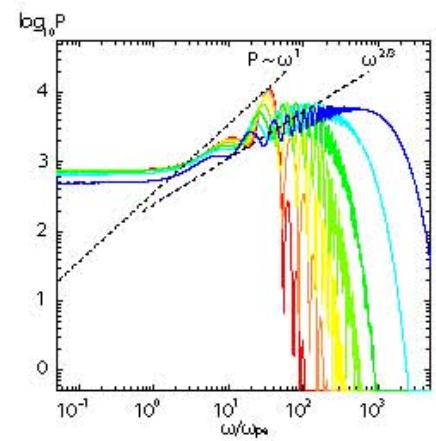
TABLE 1. Seven cases of radiation

	B_x	$V_{j1,2}$	$V_{\perp,1}$	$V_{\perp,2}$	γ_{max}	θ_T	**Remarks**
P	3.70 (B_z)	0.0c	0.998c	0.9997c	40.08	1.43	gyrating
A	3.70	0.99c	0.1c	0.12c	13.48	4.25	jet
B	3.70	0.9924c	0.1c	0.12c	36.70	1.56	jet
C	3.70	0.99c	0.01c	0.012c	7.114	8.05	jet
D	0.370	0.99c	0.01c	0.012c	7.114	8.05	jet
E	0.370	0.99c	0.1c	0.12c	13.48	4.25	$\Delta t = 0.005$
F	0.370	0.99c	0.1c	0.12c	13.48	4.25	$\Delta t = 0.025$

Case B







(Nishikawa et al. astro-ph/0809.5067)

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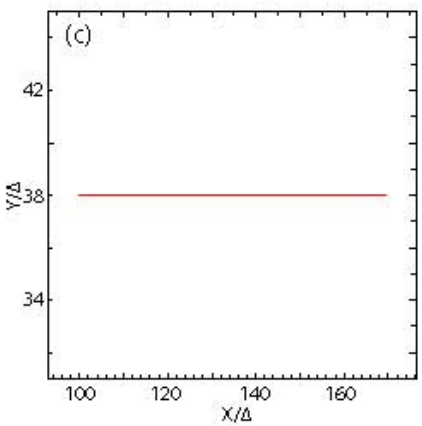
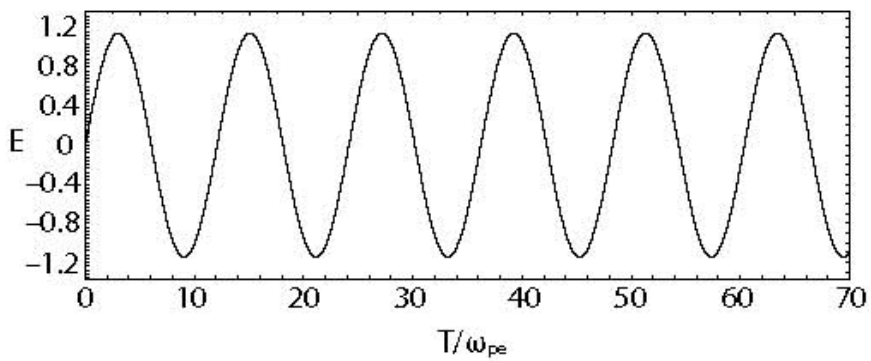
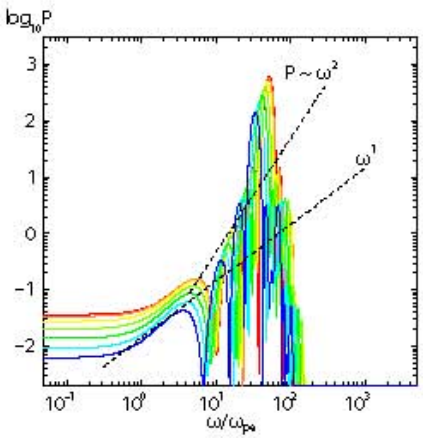
Case C







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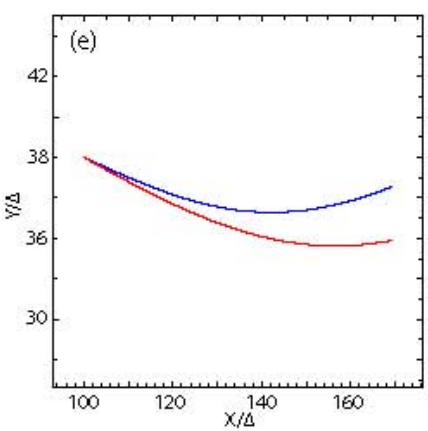
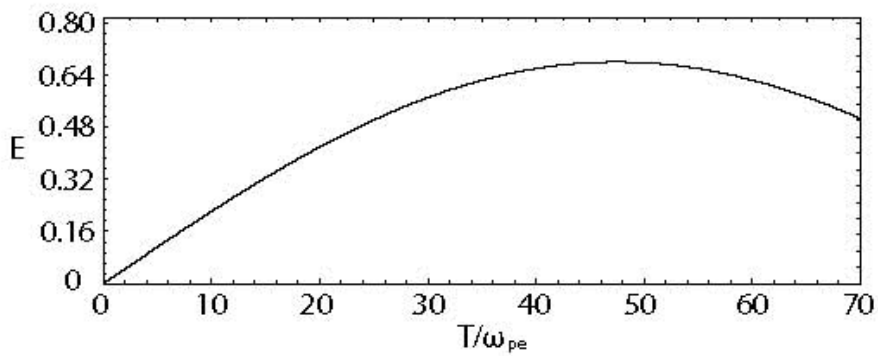
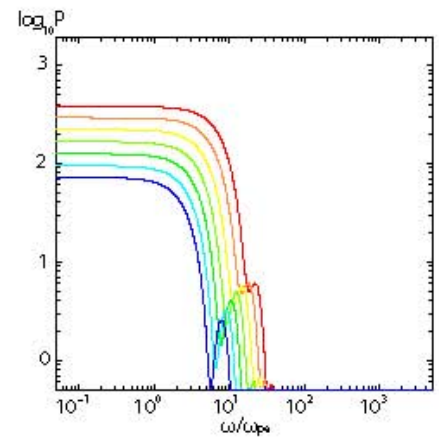
Case E







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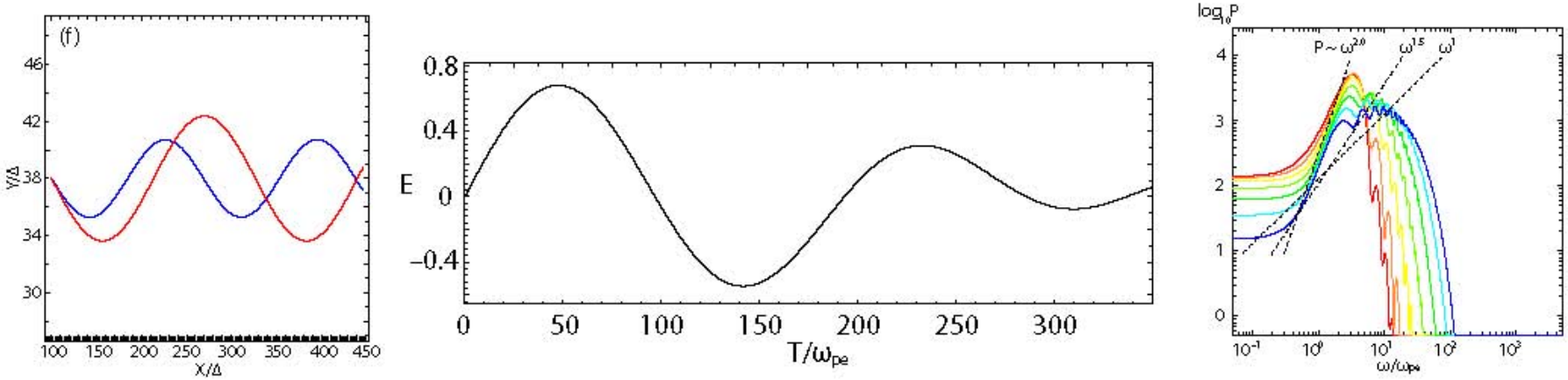
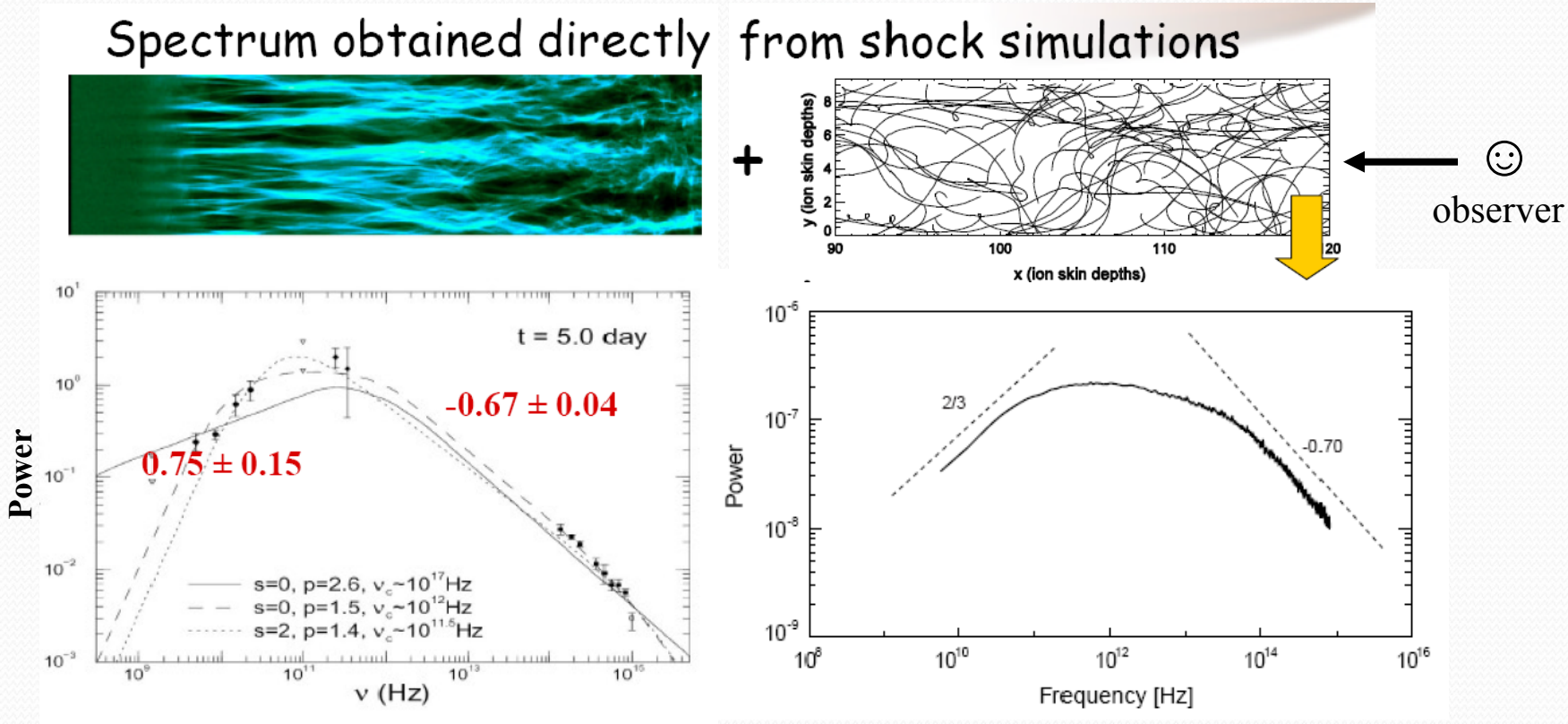
Case F



(Nishikawa et al. astro-ph/0809.5067)

Radiation from collisionless shock



GRB 000301c (Panaitescu 2001)

Shock simulations

Hededal Thesis: http://www.astro.ku.dk/~hededal

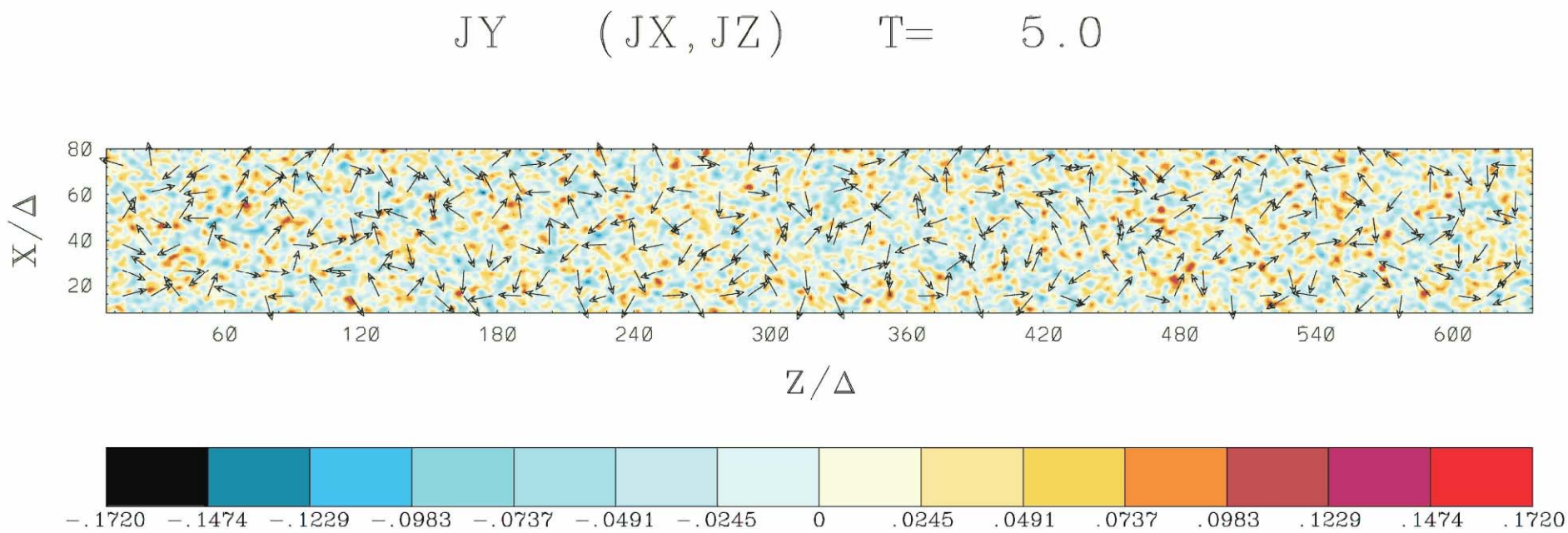
Hededal & Nordlund 2005, submitted to ApJL (astro-ph/0511662)

Perpendicular current J_z (arrows: $J_{z,x}$)

$n_{ISM} = 1/cm^3$
$\omega_{pe}^{-1} \approx 0.1$ msec
$c/\omega_{pe} = 5.3$ km
$L \approx 300$ km

electron-positron $\gamma = 15$ (B) at $Y = 43\Delta$

$$\omega_{pe} t = 59.8 \approx 6 \text{msec}$$



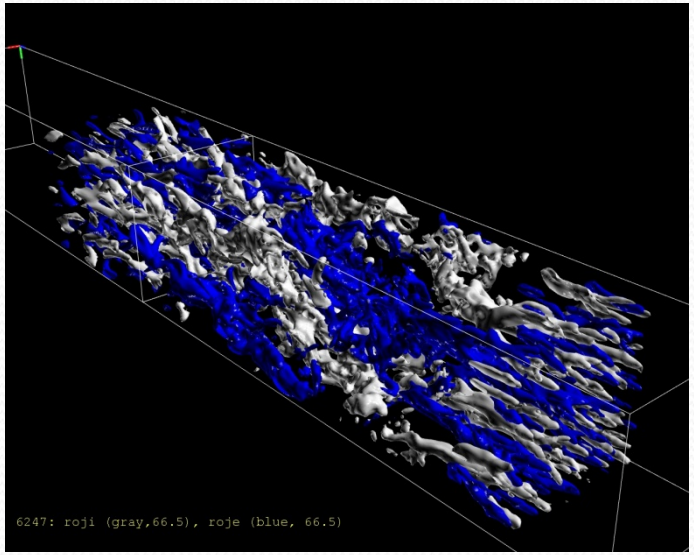
Weibel instability

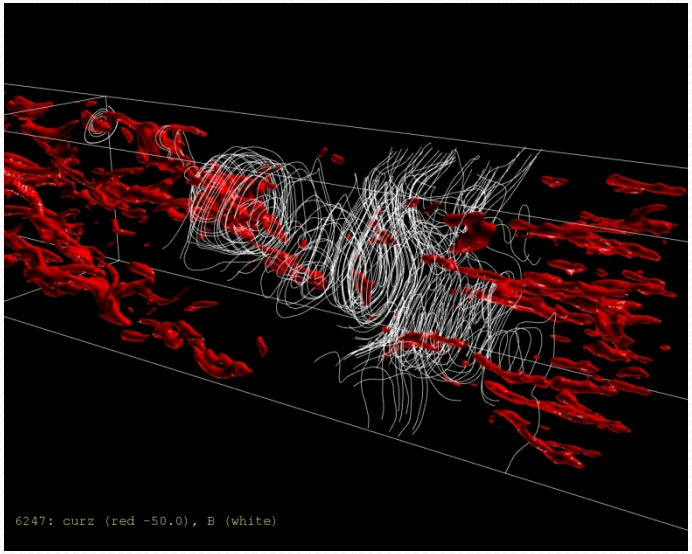
jet front

(Nishikawa et al. 2005)

3-D isosurfaces of density of jet particles and J_z for narrow jet ($\gamma v_{\parallel}$=12.57)

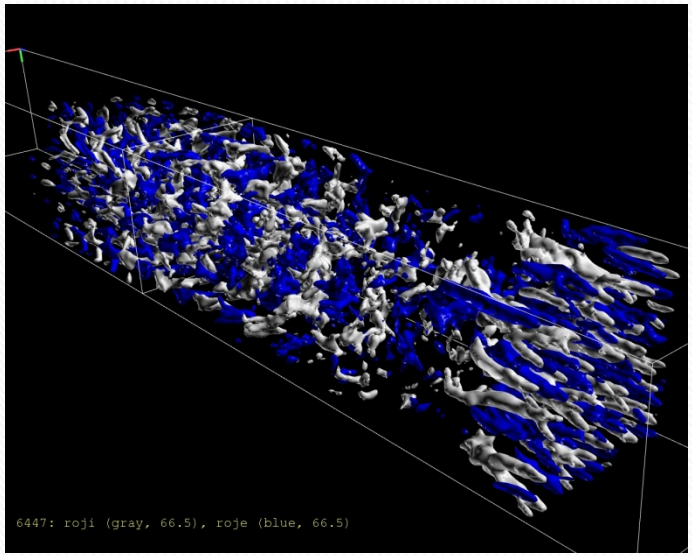
electron-ion ambient

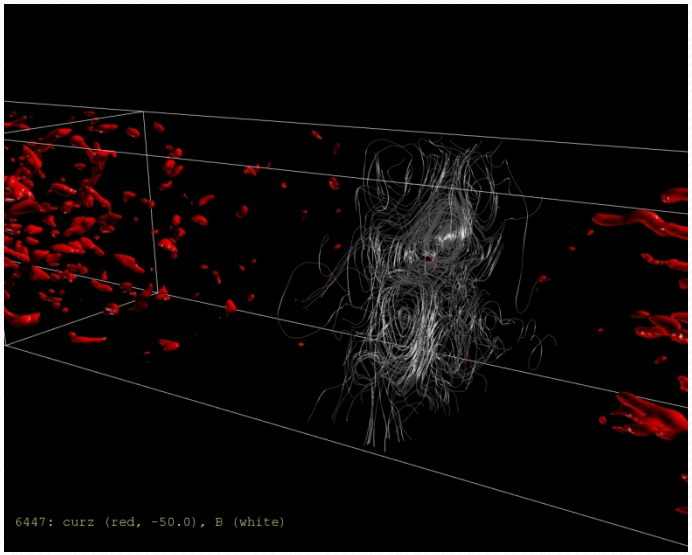




$t = 59.8\omega_e^{-1}$ **jet electrons (blue), positrons (gray)** **$-J_z$ (red), magnetic field lines (white)**

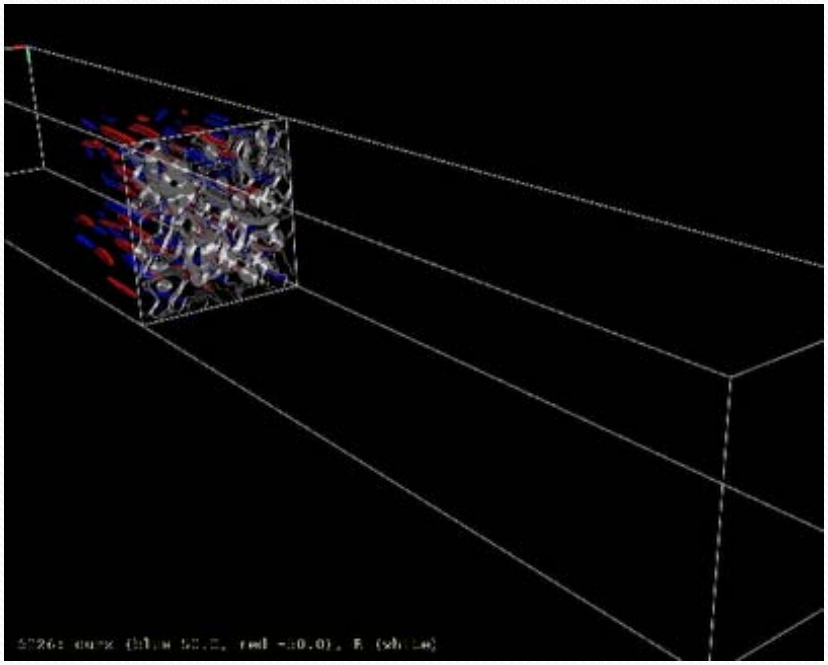
electron-positron ambient



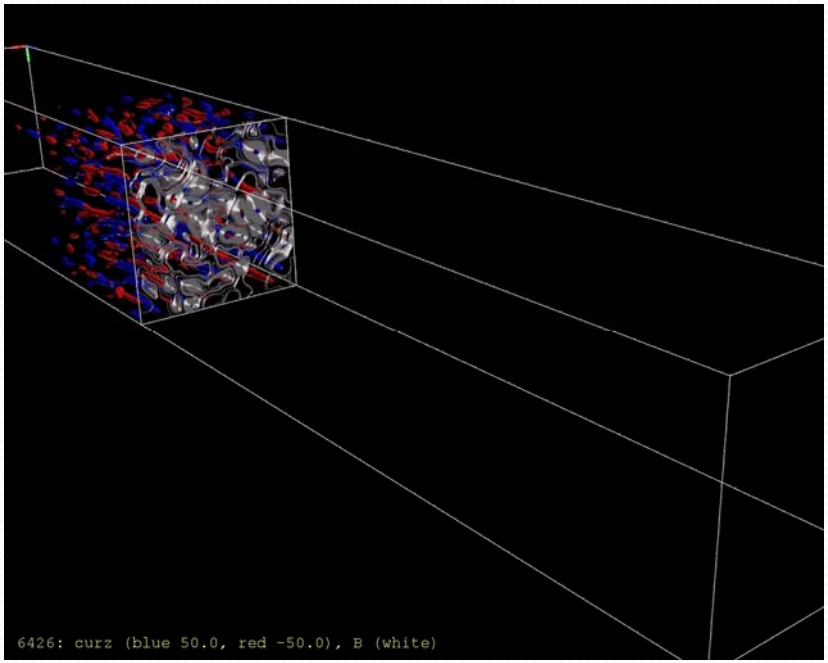


Isosurfaces of z-component of current density for narrow jet ($\gamma v_{\parallel}$= 12.57)

electron-ion ambient plasma



electron-positron ambient plasma



(+J_z: blue, -J_z:red) **local magnetic field lines (white curves)**