Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

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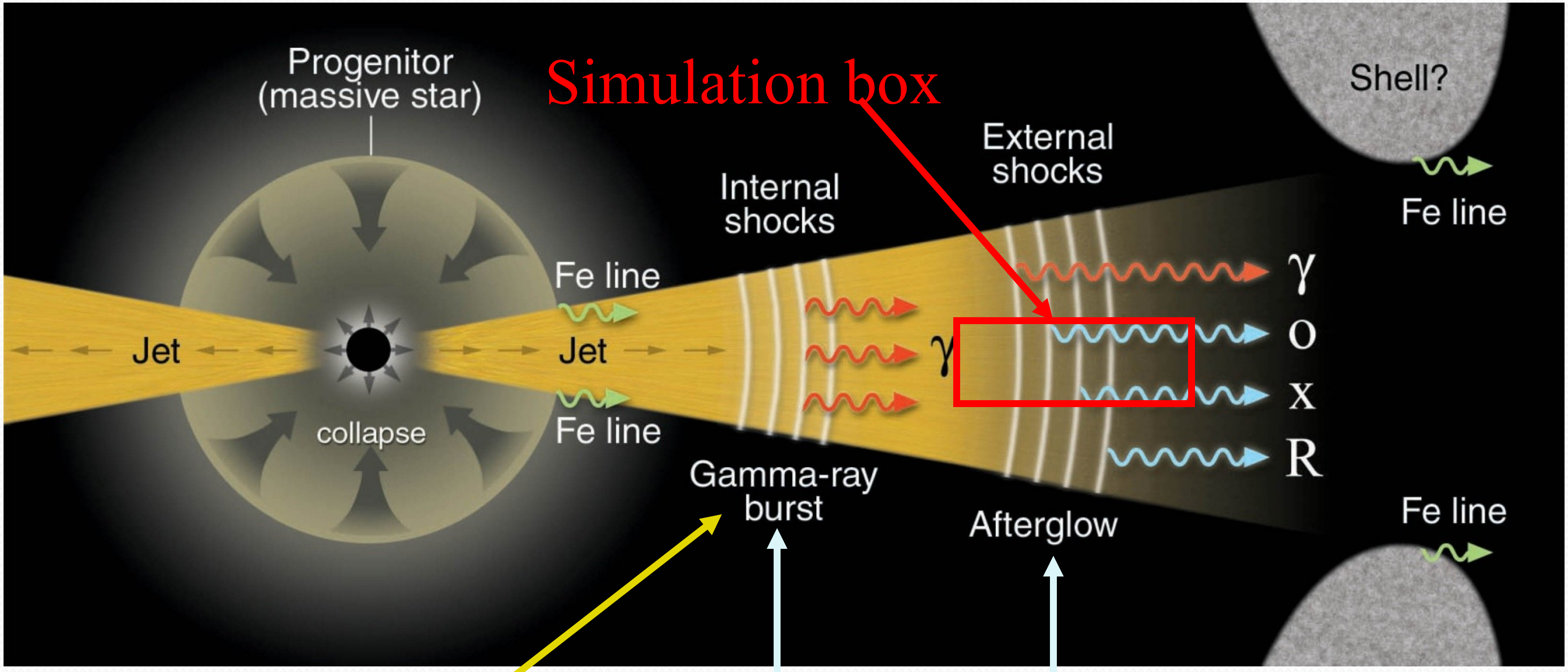
Acceleration & Emission Processes at High Energies and their Application to AGN
Observatoire de Paris, January 25 -26, 2010

Outline of talk

- Recent 3-D particle simulations of relativistic jets
  * $e^{\pm}$pair jet into $e^{\pm}$pair, $\gamma = 15$ and
  electron-ion ($m_i/m_e = 20$) into electron-ion $\gamma = 15$
  shock structures
- Radiation from two electrons
- New initial results of radiation from jet electrons which are traced in the simulations self-consistently
- Future plans of our simulations of relativistic jets

Schematic GRB from a massive stellar progenitor

(Meszaros, Science 2001)



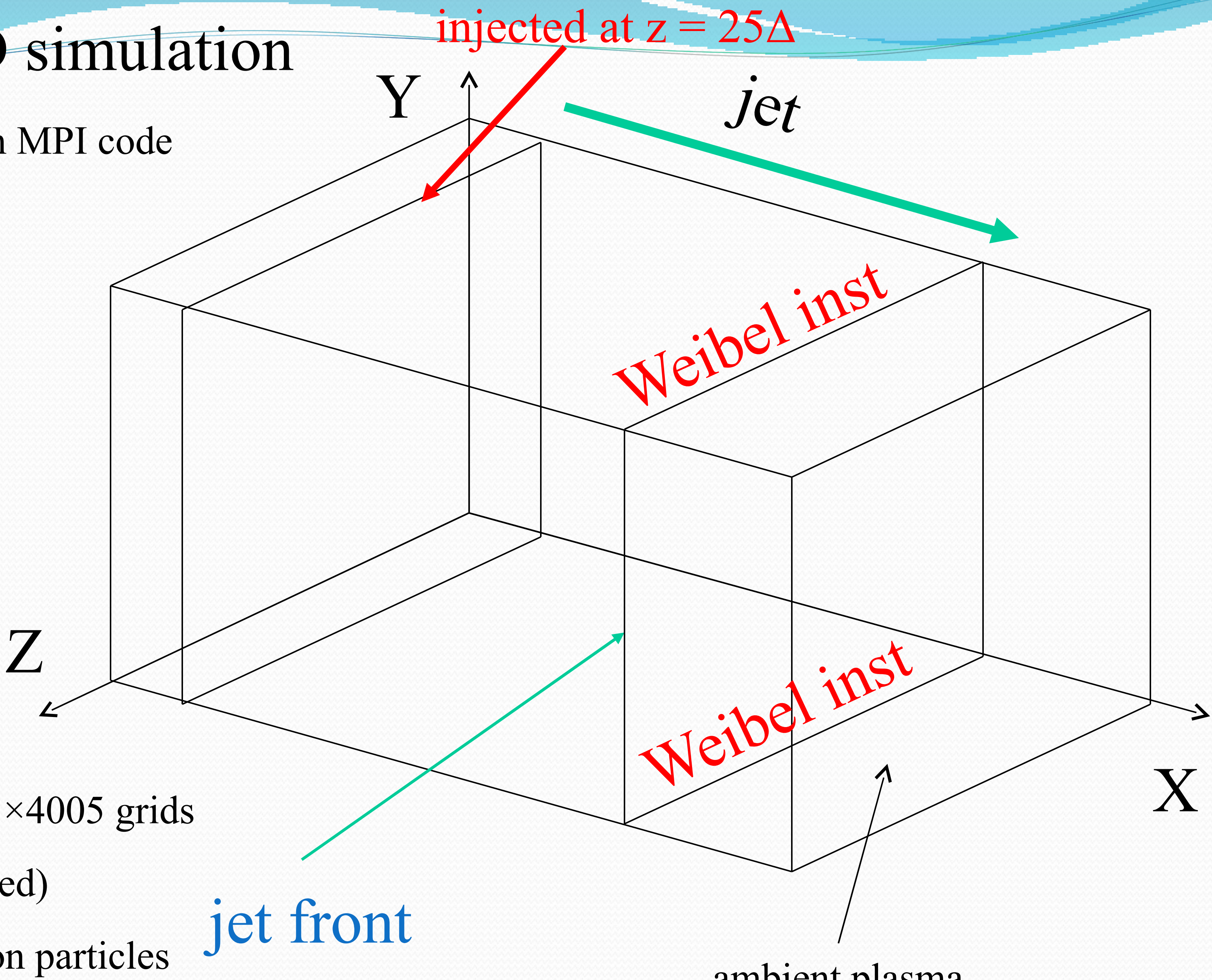
Prompt emission

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

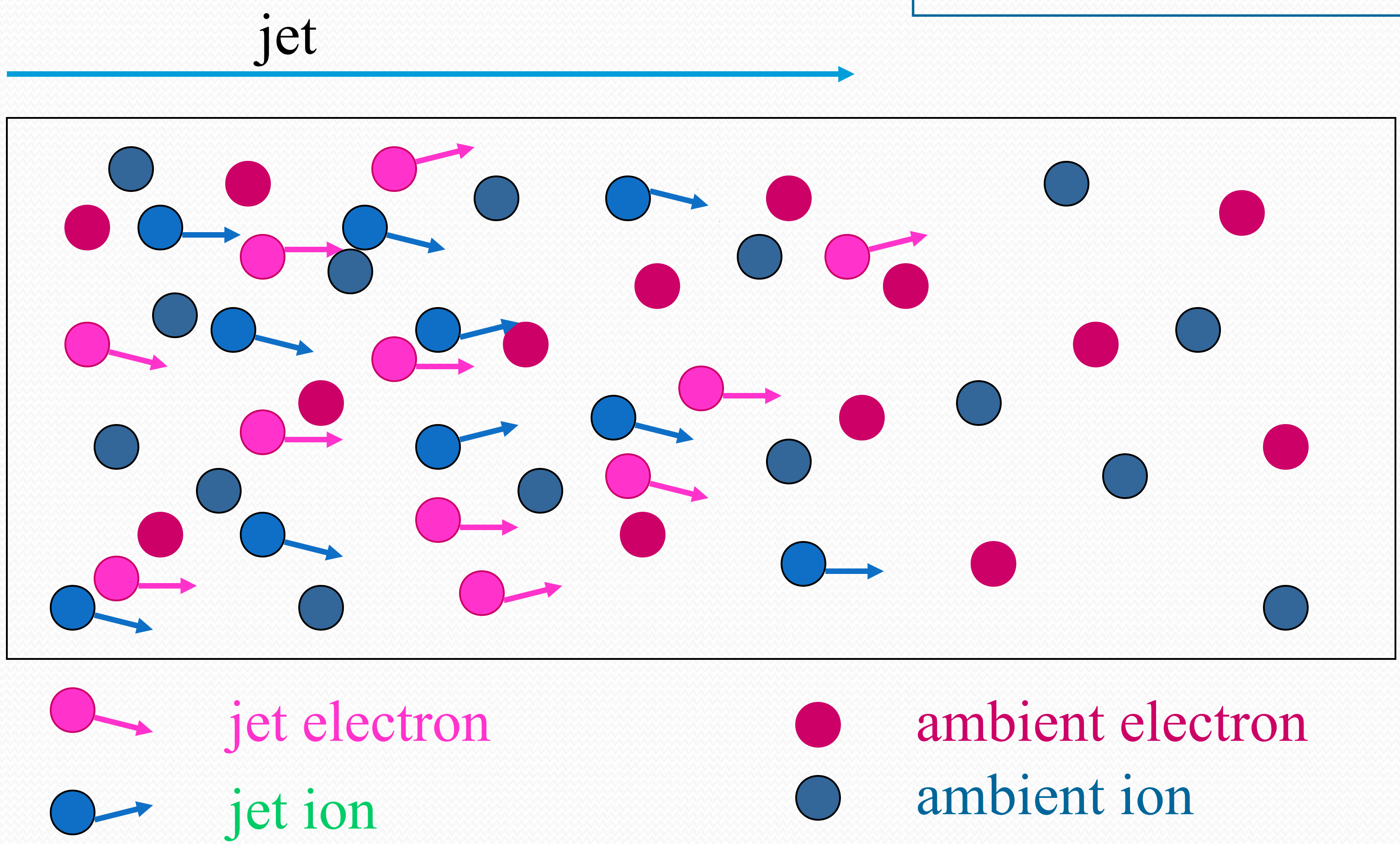
(Buneman 1993)

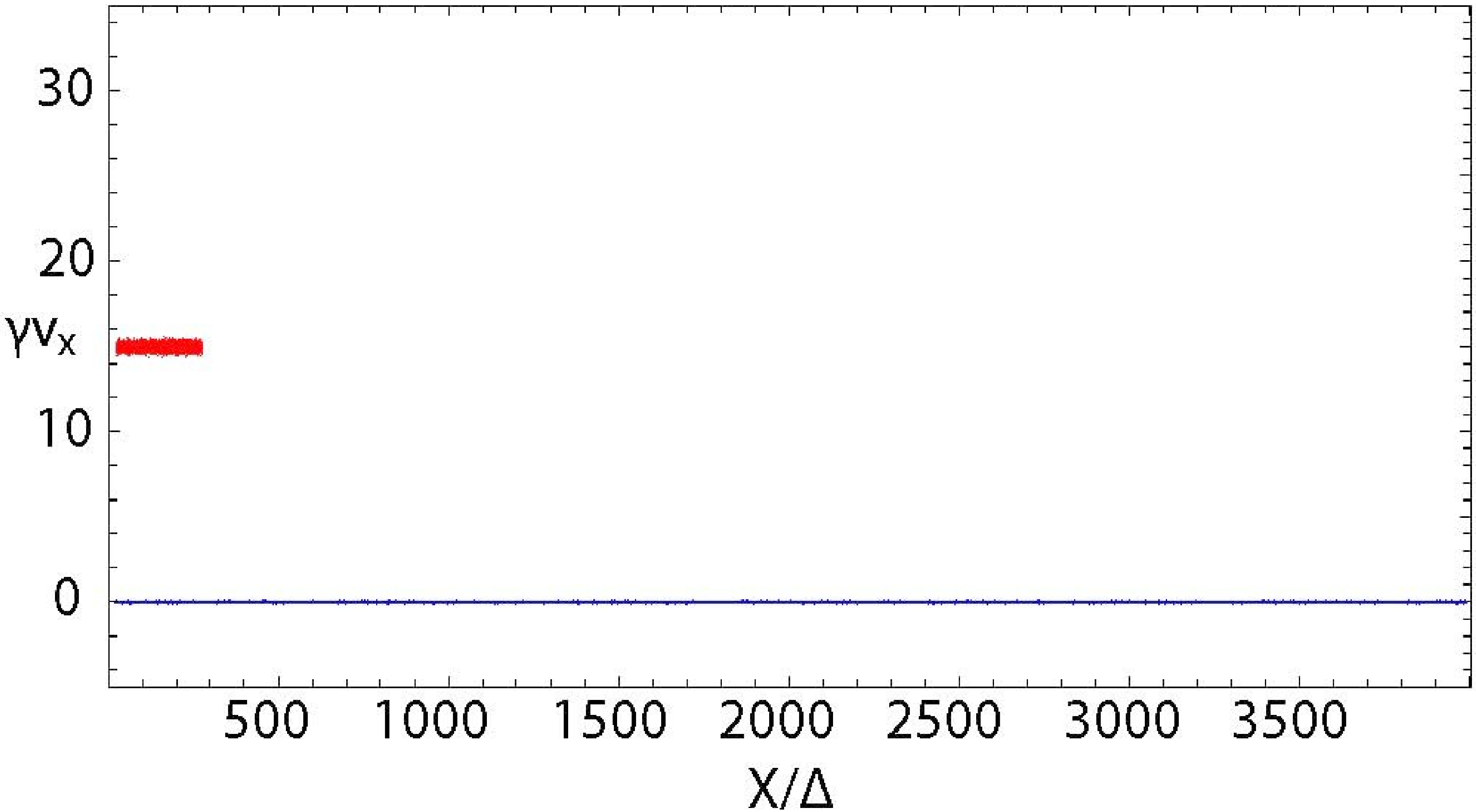
$$\partial B / \partial t = -\nabla \times E$$

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

$$d m_0 \gamma v / dt = q(E + v \times B)$$

$$\partial \rho / \partial t + \nabla \cdot J = 0$$





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

Weibel instability

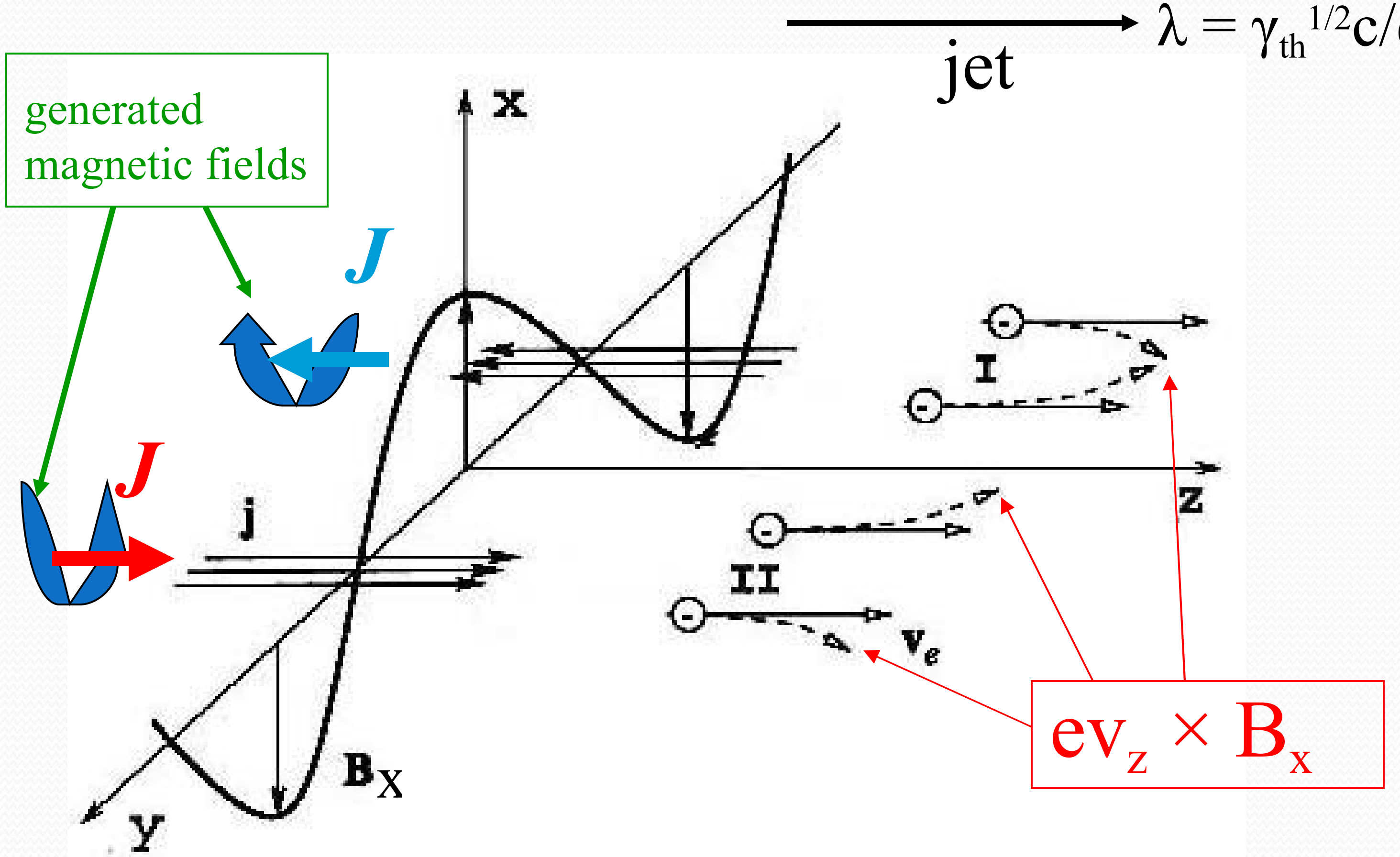
current filamentation

Time:

$\tau = \gamma_{sh}^{1/2}/\omega_{pe} \approx 21.5$

Length:

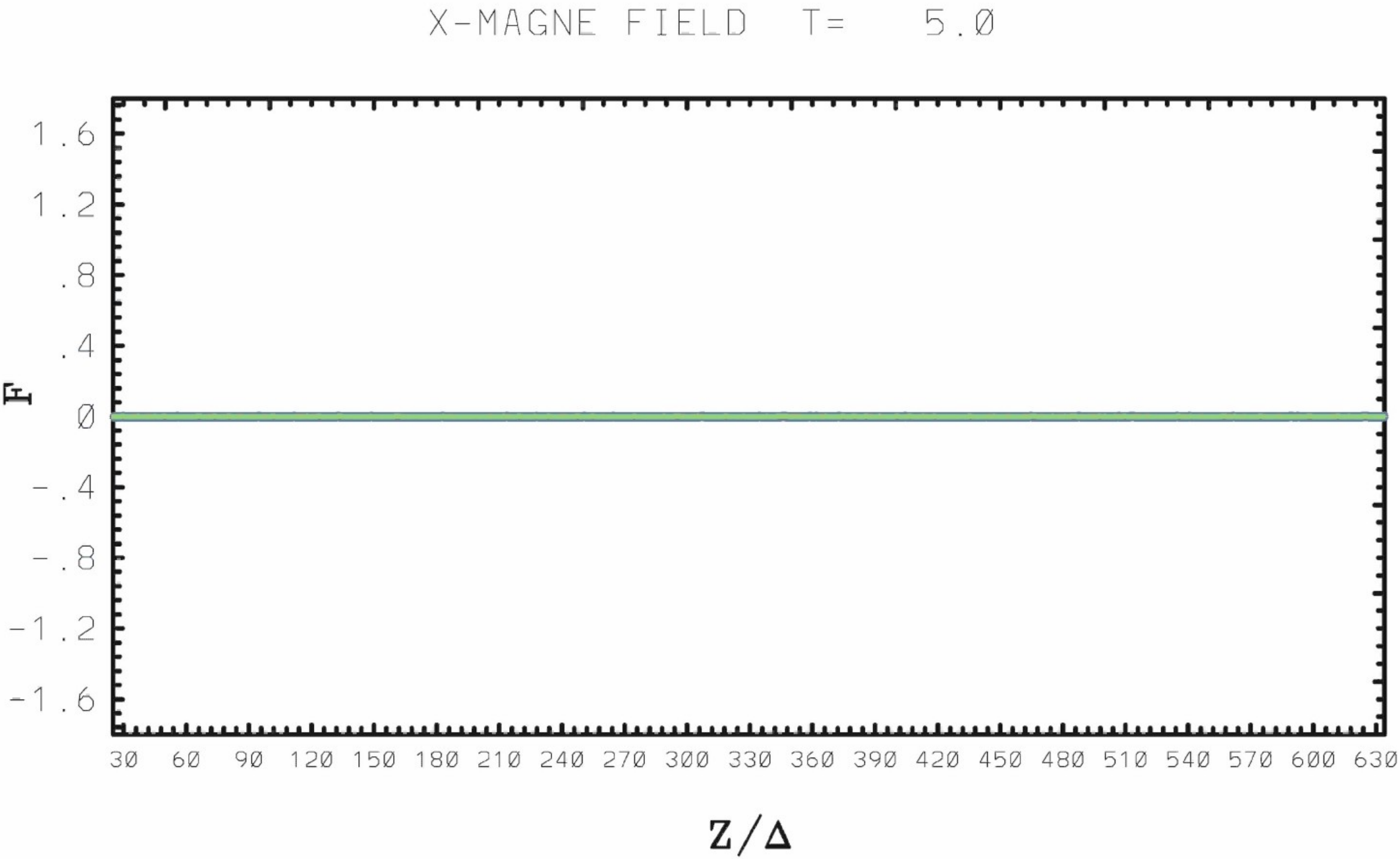
$\lambda = \gamma_{th}^{1/2}c/\omega_{pe} \approx 9.6\Delta$



(electrons)

(Medvedev & Loeb, 1999, ApJ)

Evolution of B_x due to the Weibel

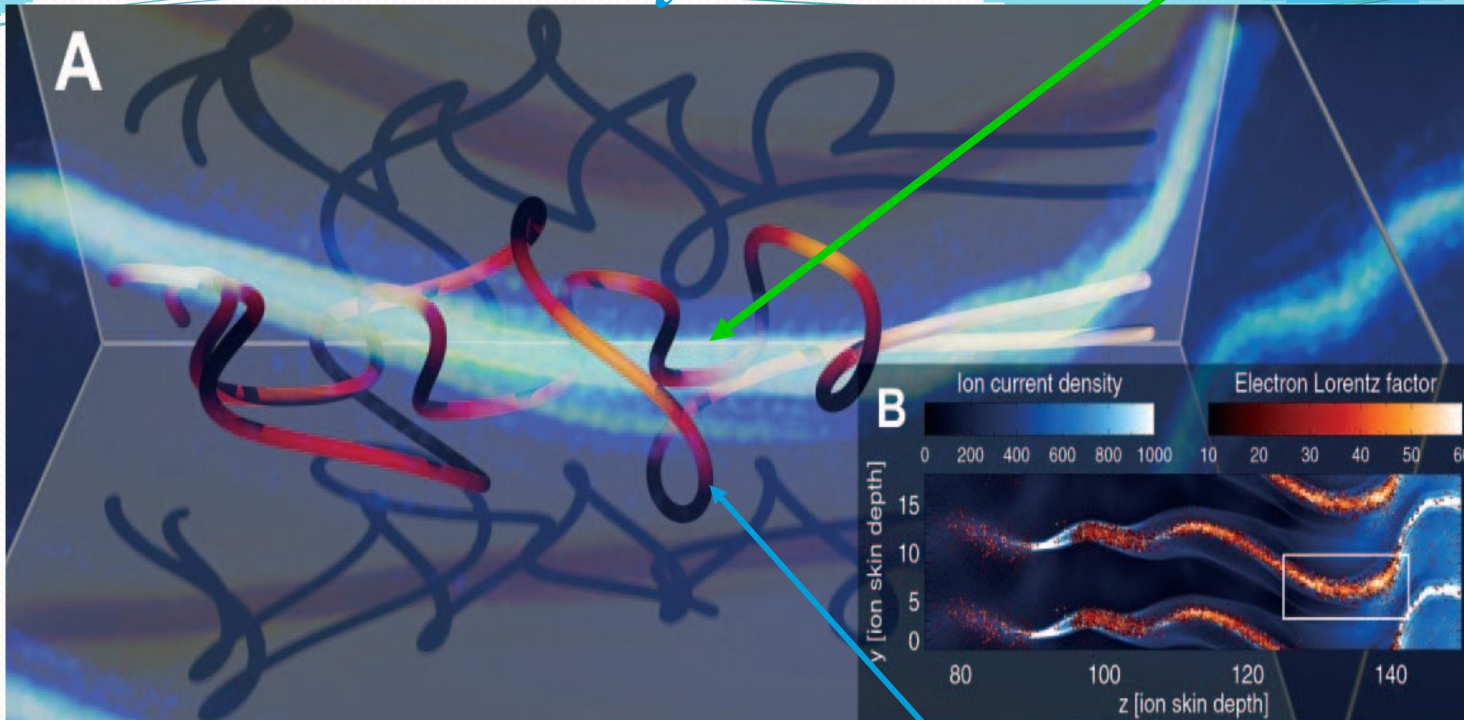


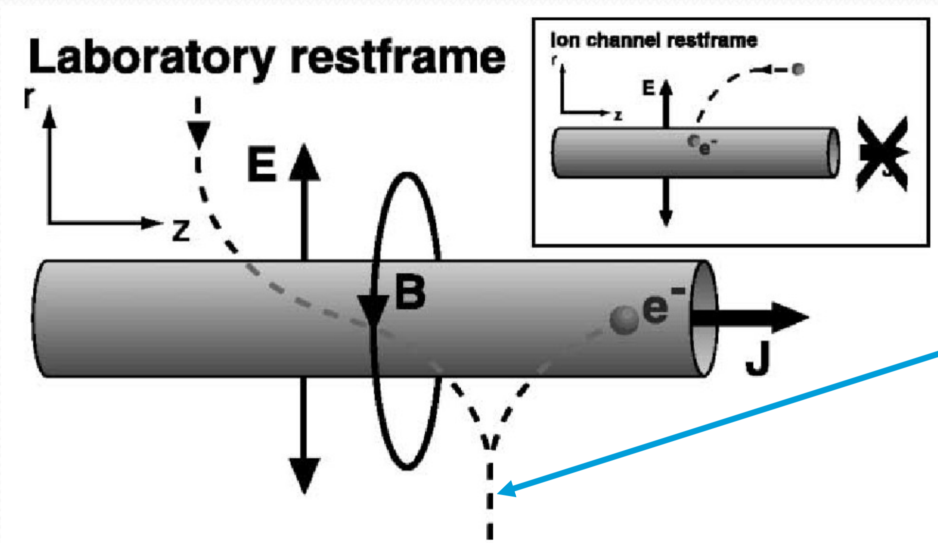
Weibel instability

(Nishikawa et al. 2005)

Ion Weibel instability

ion current

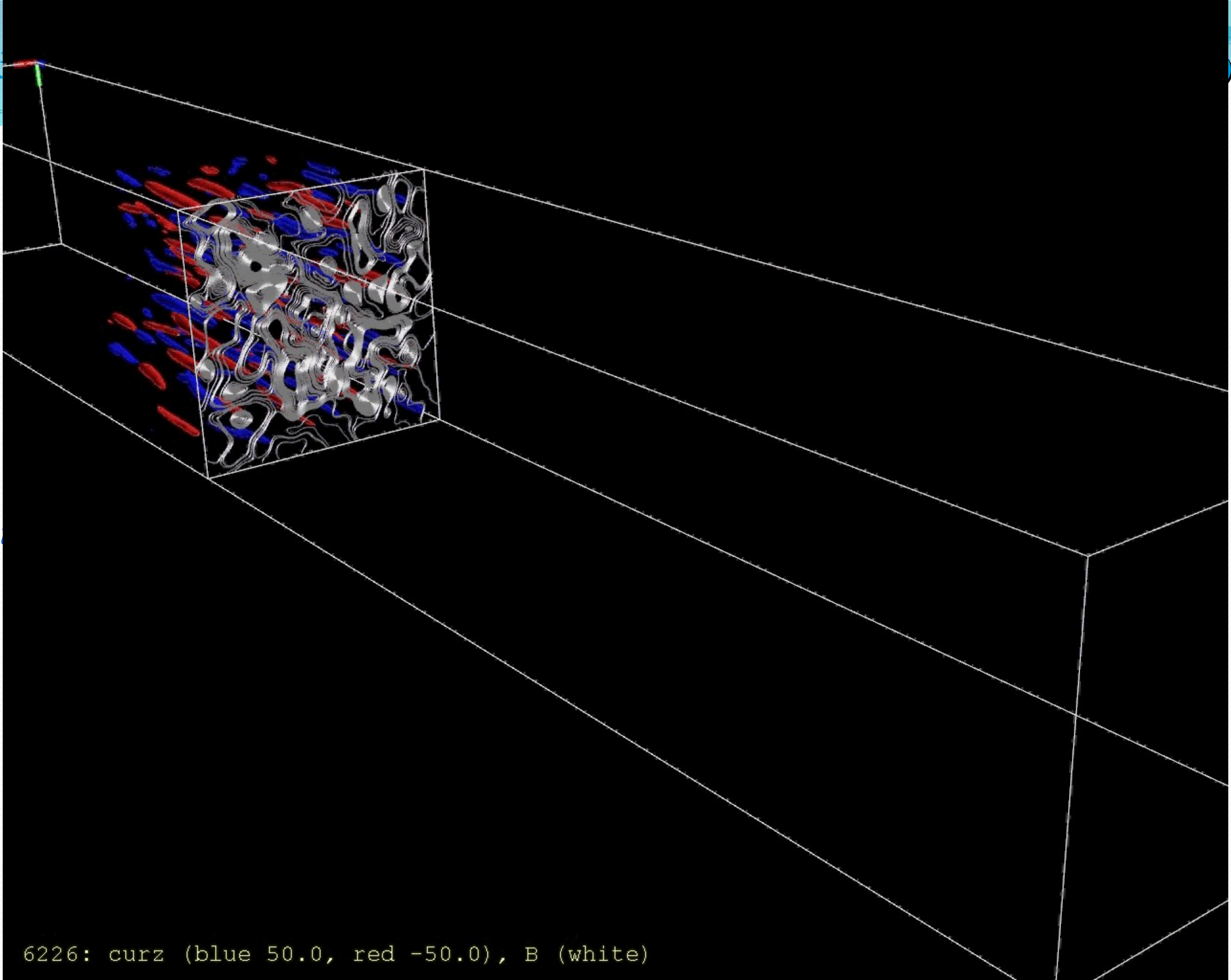




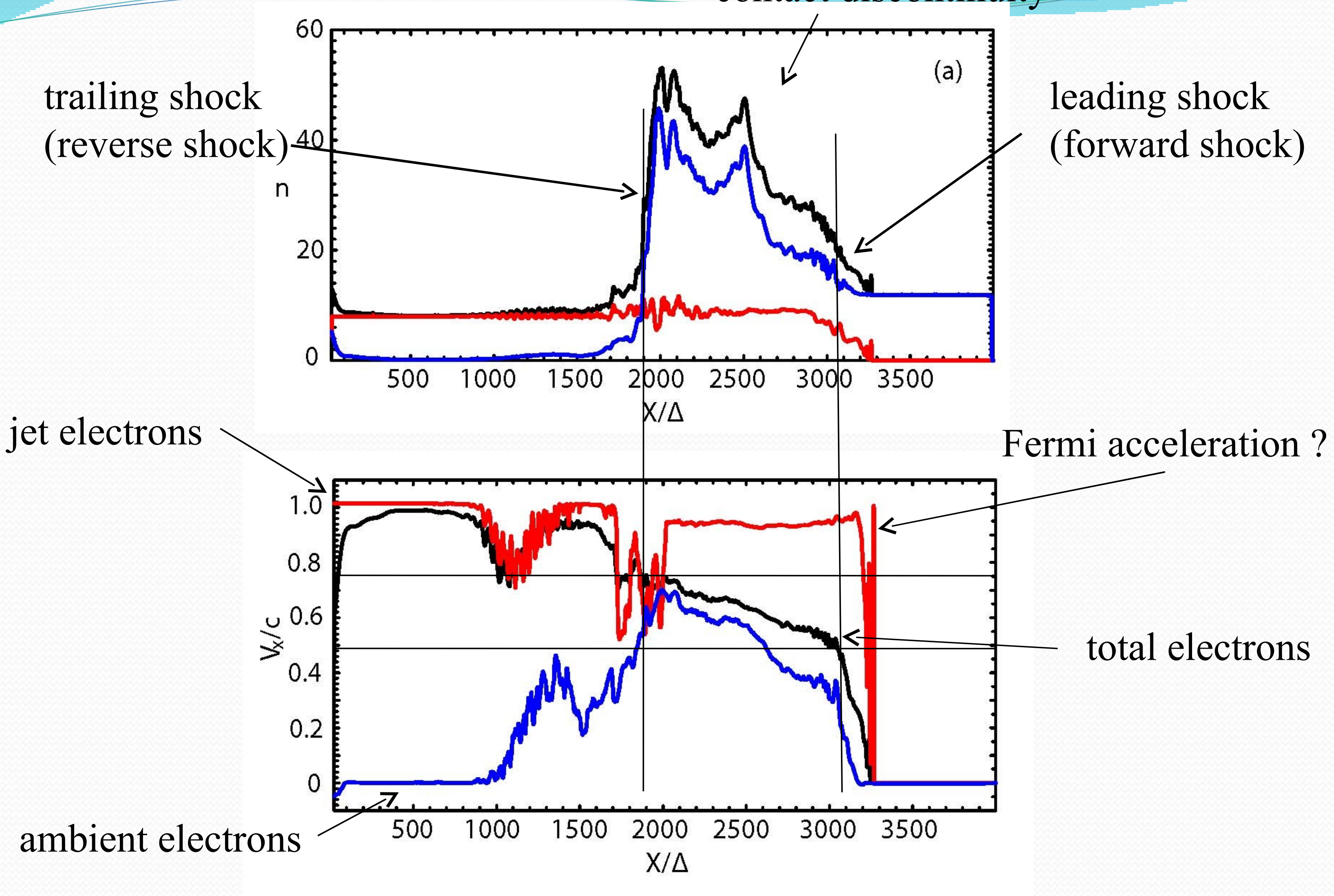
E × B acceleration

electron trajectory

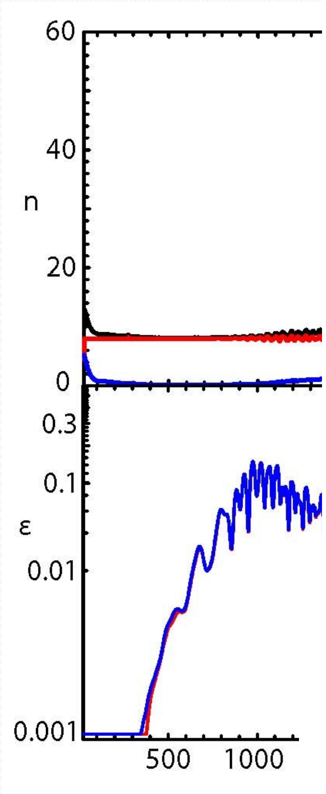
(Hededal et al 2004)

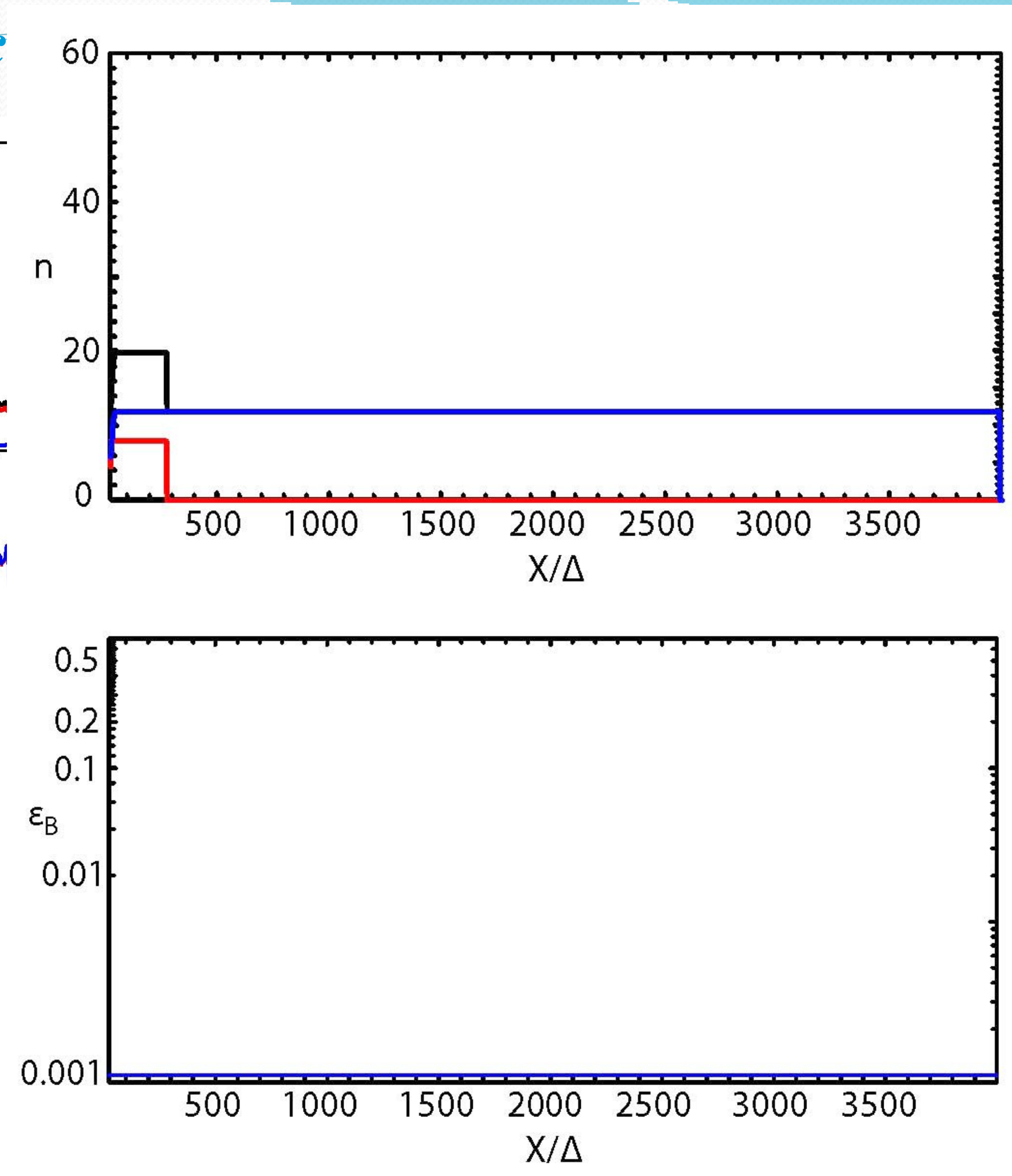

6226: curz (blue 50.0, red -50.0), B (white)

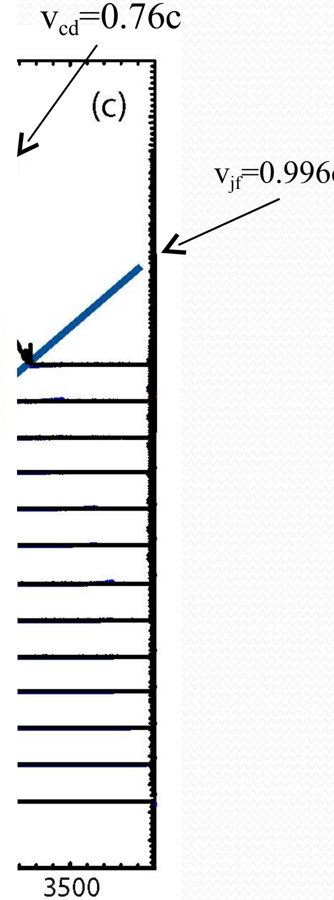
Shock velocity and bulk velocity



Shoc … hock







(a) electron density … field energy (ε_B, ε_E) … kinetic energy at t = …

… density. … the predicted … , and the

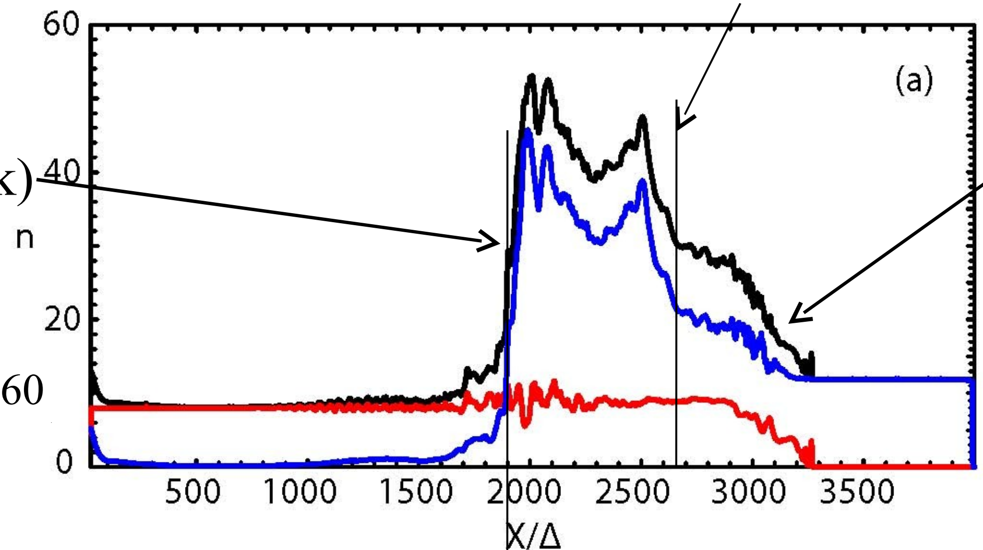
(Nishikawa et al …

Shock velocity and structure based on 1-D HD analysis

moving contact discontinuity (CD)

trailing shock
(reverse shock)

leading shock
(forward shock)



in CD frame

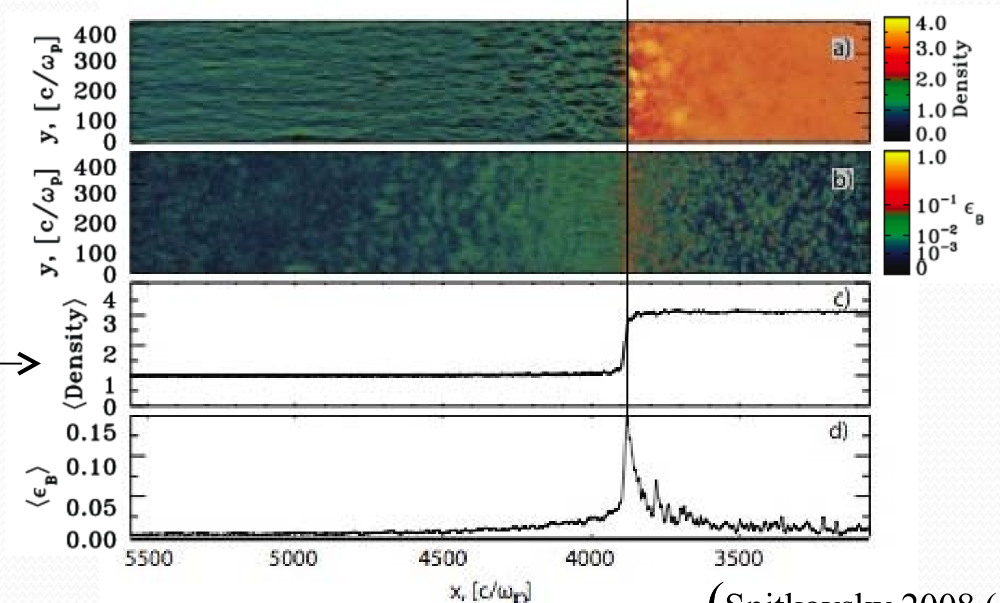
$n_{sj}/\gamma'_{cd} n_j = 3.36$

$\beta_s = 0.417 \quad \gamma'_{cd} = 5.60$

(Nishikawa et al. 2009)

$4/3 < \Gamma = 3/2 < 5/3$

fixed CD



Density

$n_2/\gamma_0 n_1 = 3.13$

$\beta_c = 0.47$

$\gamma_0 = 15$

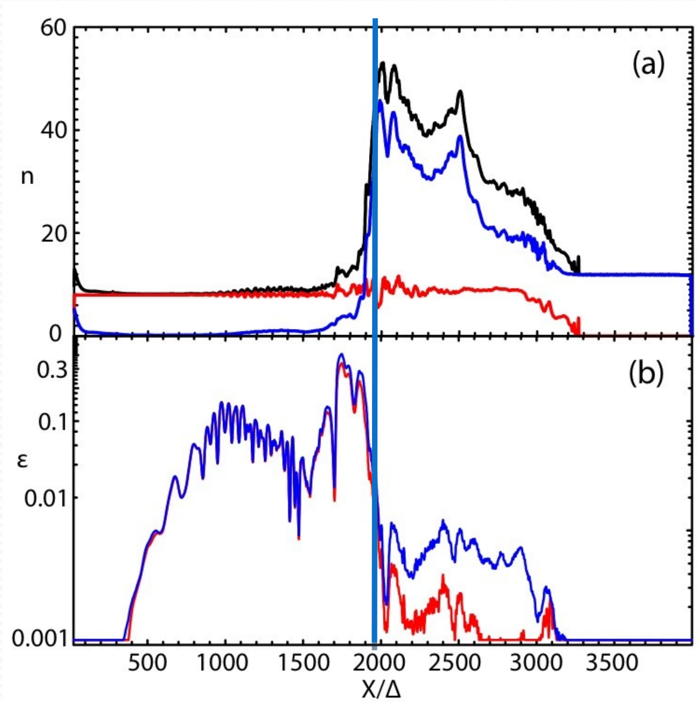
0

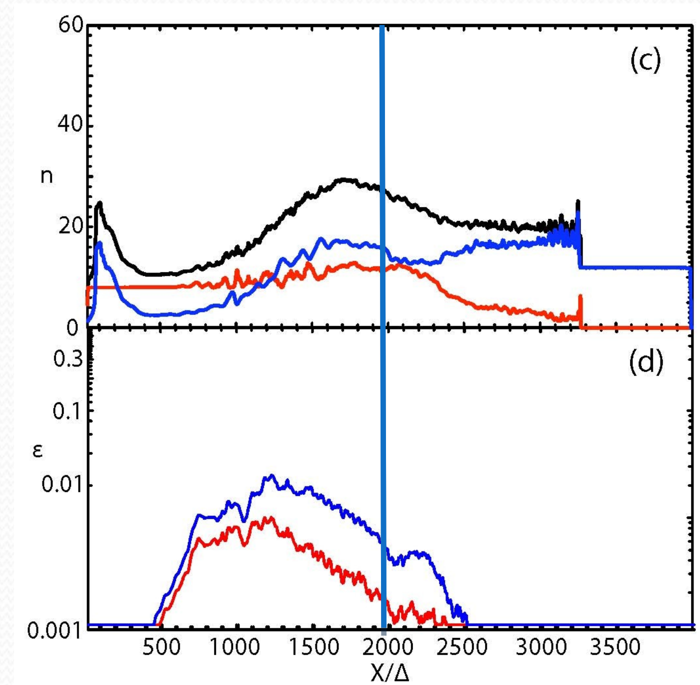
(Spitkovsky 2008 (adapted))

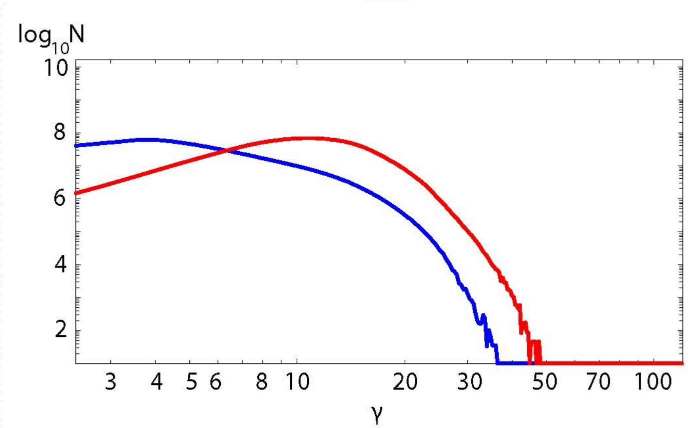
Comparison with different mass ratio (electron-positron and electron-ion)

electron-positron

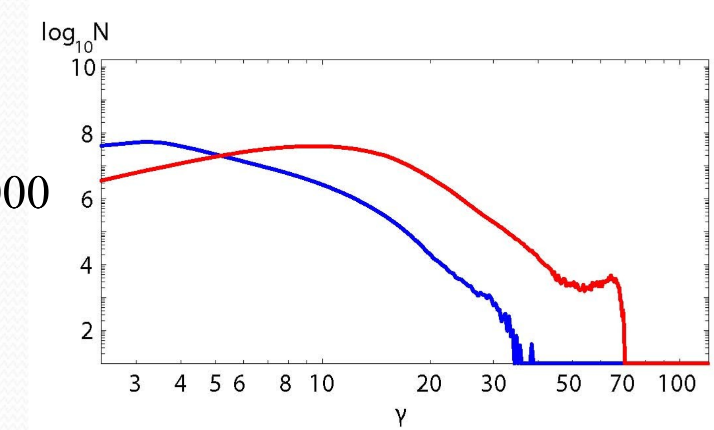
electron-ion ($m_i/m_e = 20$)





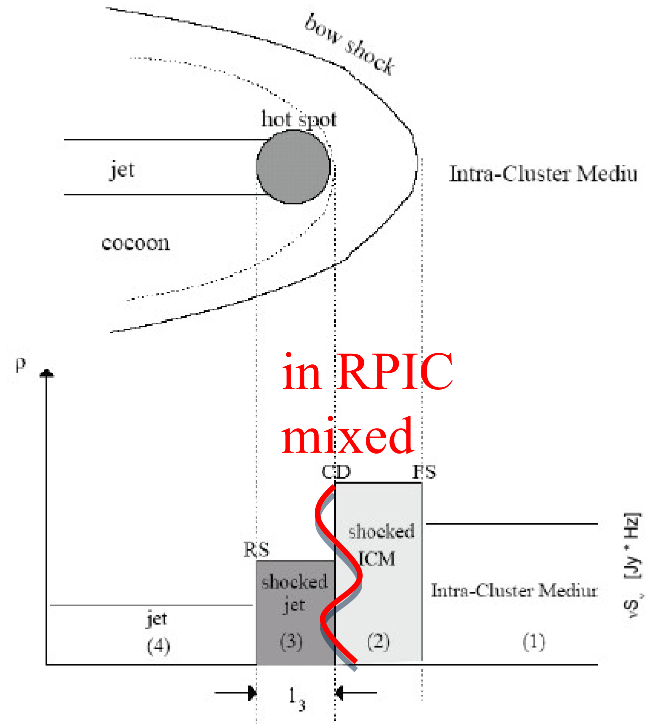


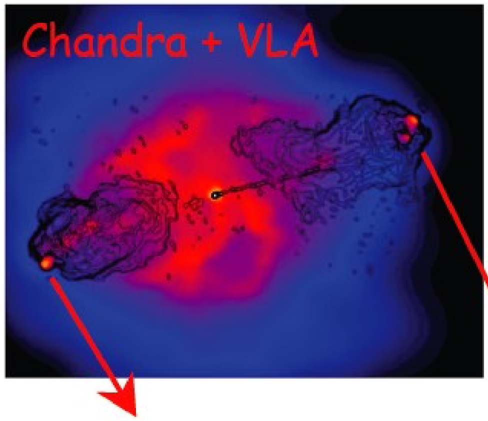
X/Δ>2000

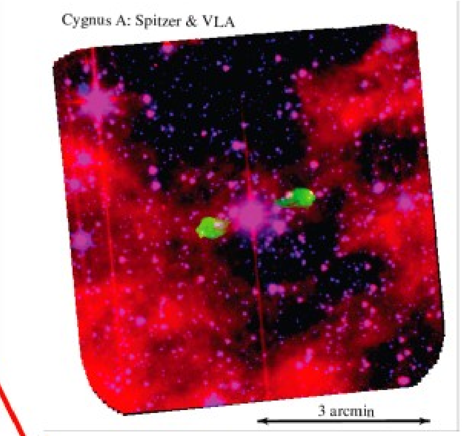


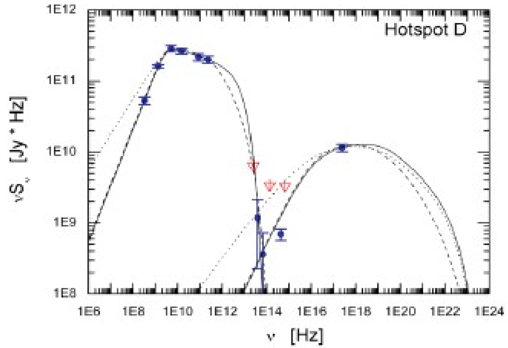
Terminal Hotspots

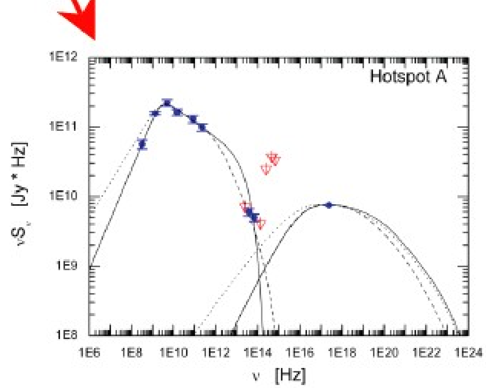
Kino & Takahara 04











Hotspots in powerful radio sources are understood as the terminal regions of relativistic jets, where bulk kinetic power transported by the outflows from the active centers is converted at a strong shock (formed due to the interaction of the jet with the ambient gaseous medium) to the internal energy of the jet plasma.

Hotspots of exceptionally bright radio galaxy Cygnus A (d_L = 250 Mpc) can be resolved at different frequencies (VLA, Spitzer, Chandra), enabling us to understand how (mildly) relativistic shocks work (LS+ 07).

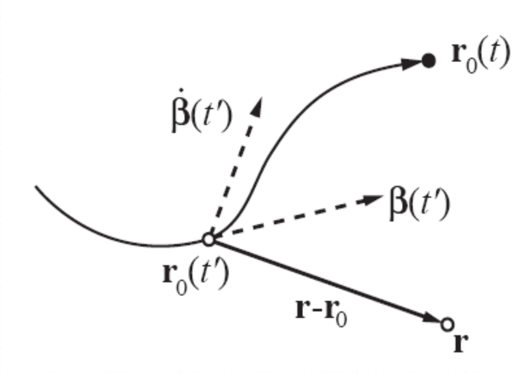
from the talk by L. Stawarz

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, β the velocity and $\dot{\beta}$ the acceleration



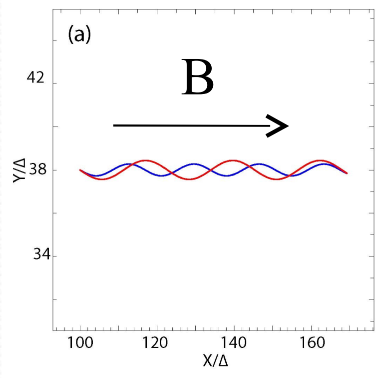
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

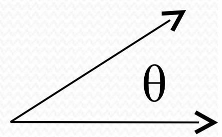
Hededal, Thesis 2005 (astro-ph/0506559)
Nishikawa et al. 2008 (astro-ph/0802.2558)
Sironi & Spitkovsky, 2009, ApJ
Martins et al. 2009, Proc. of SPIE Vol. 7359

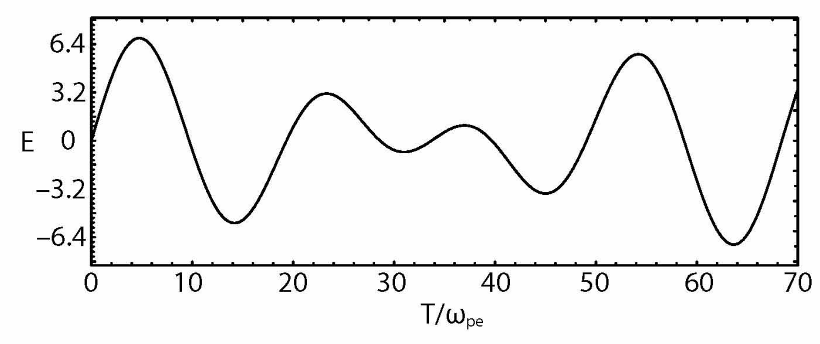
Synchrotron radiation from propagating electrons in a uniform magnetic field

electron trajectories

radiation electric field observed at long distance



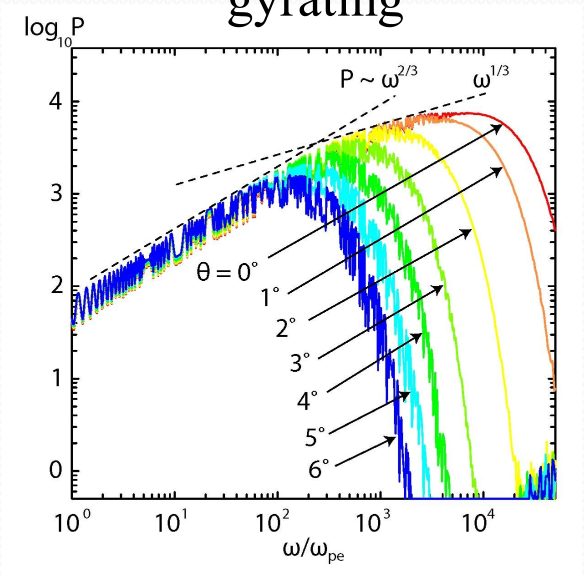


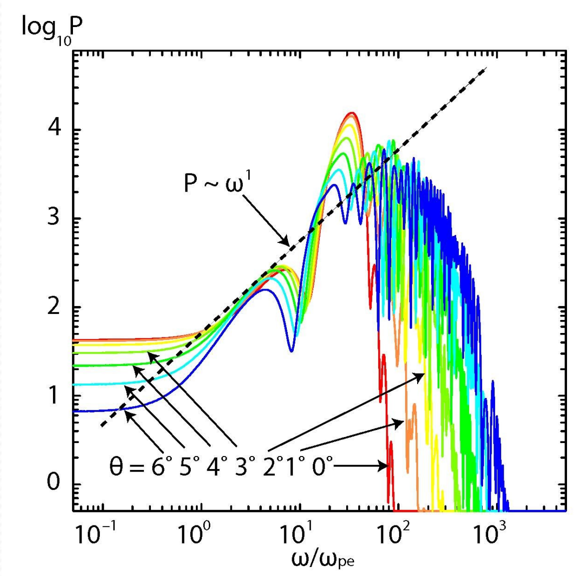


observer

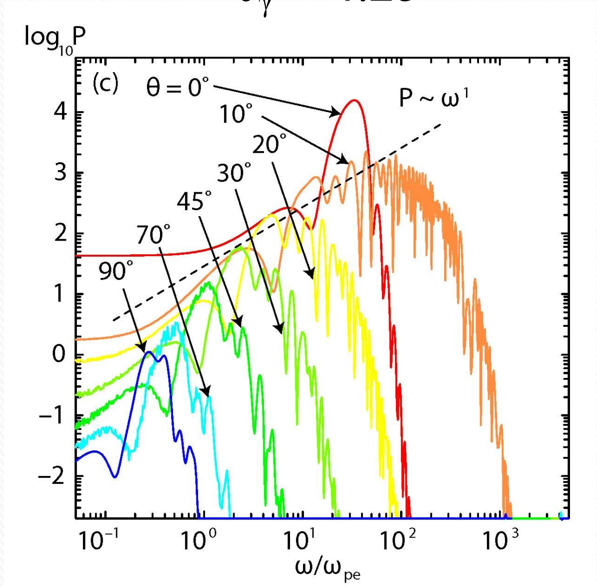
spectra with different viewing angles

gyrating



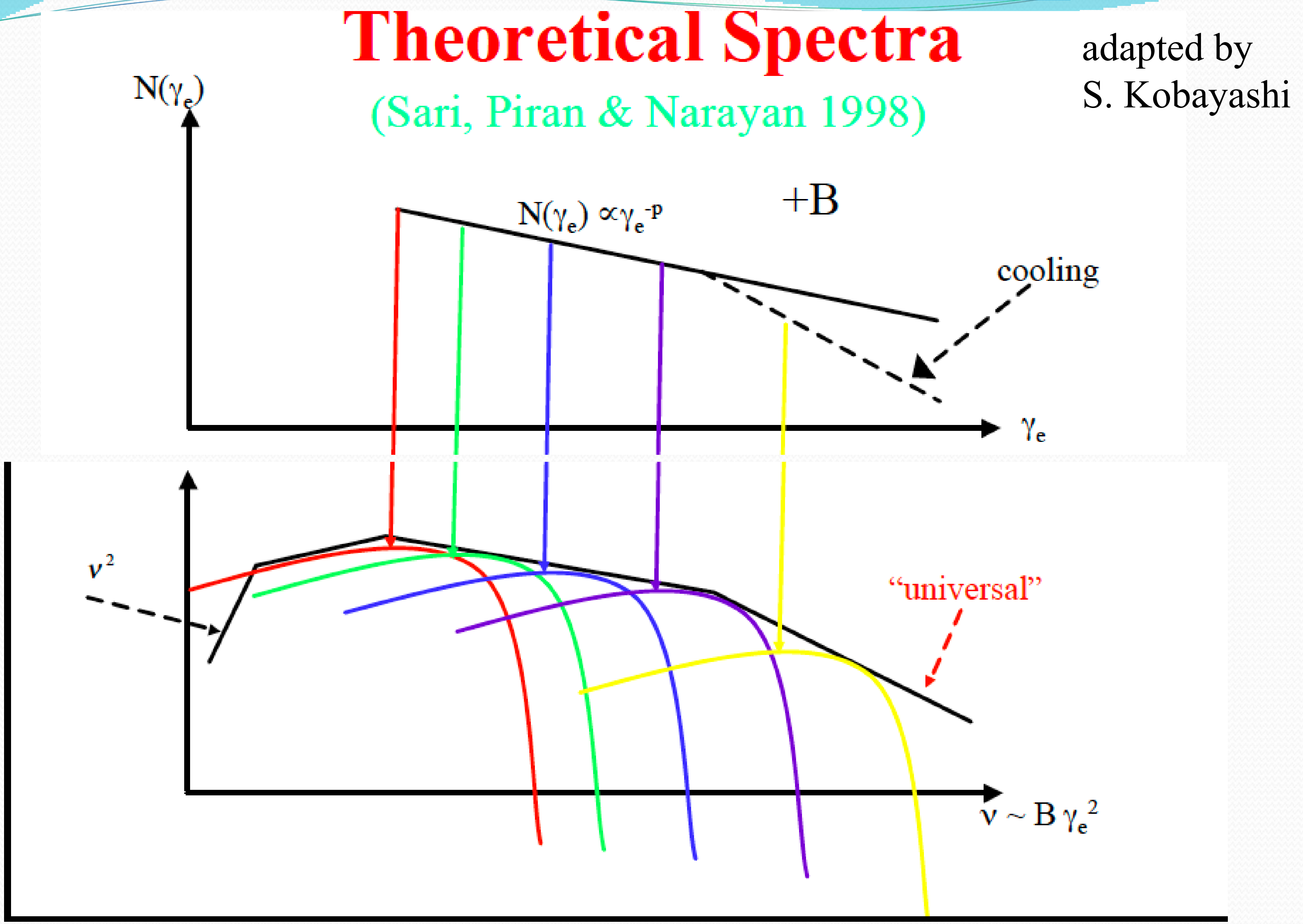


$\theta_\gamma = 4.25°$



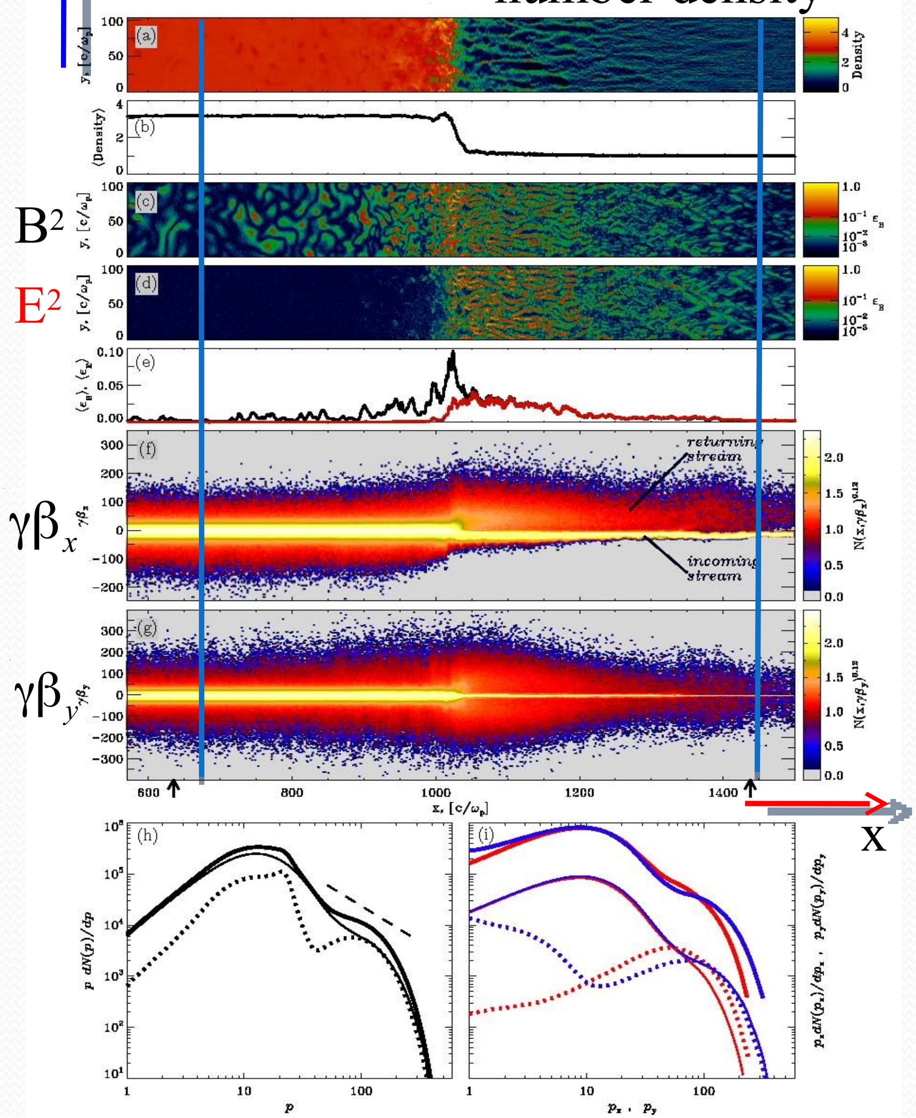
Nishikawa et al. astro-ph/0809.5067

Synchrotron Emission: radiation from accelerated



Radiation from test (accelerated) particles in static turbulent magnetic fields generated by the Weibel instability in 2D PIC simulation

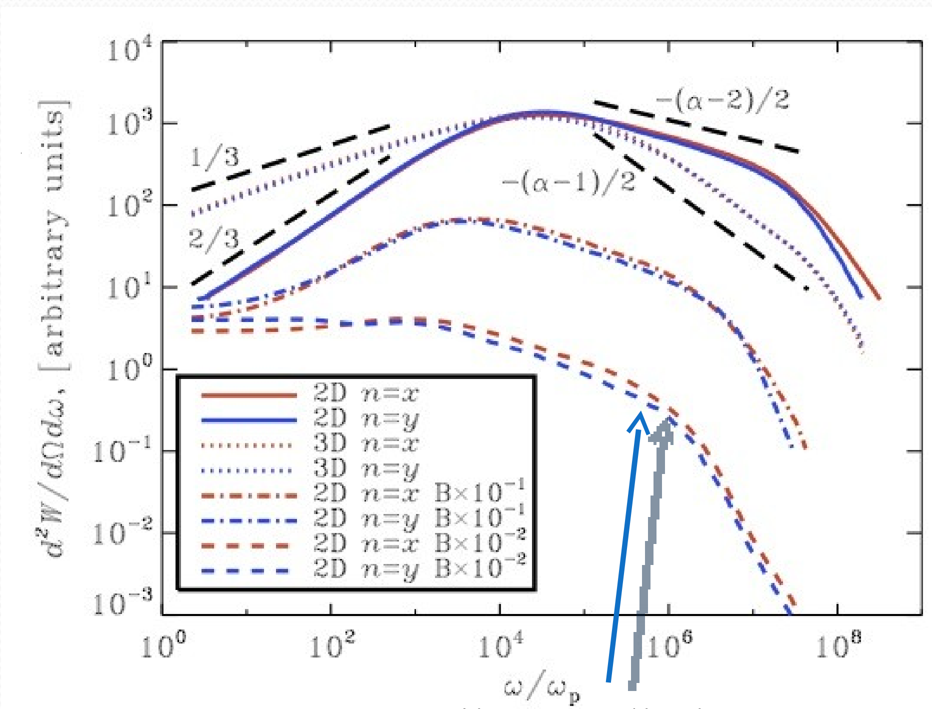
$t = 2250\omega_{pe}^{-1}$ number density



$t_s = 3000\Delta t = 135\omega_p^{-1}$ $\Delta t = 0.045\omega_p^{-1}$

N_s : 10,000

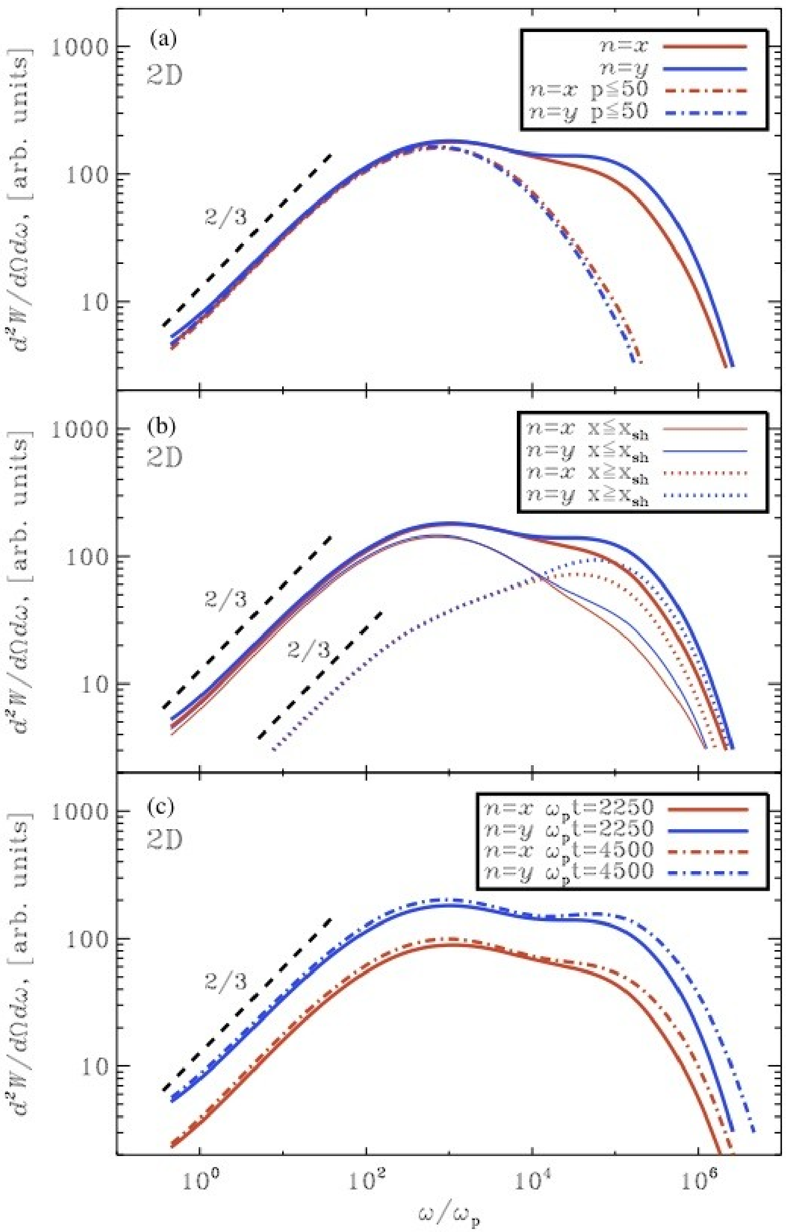
test particle simulation in a
fixed snapshot of electromagnetic filed



jitter radiation

(Sironi & Spitkovsky 2009)

Radiation from electrons in self-consistent electromagnetic field from a 2D PIC simulation



Due to the radiation is calculated in downstream frame the radiation is isotropic. An additional Lorentz transformation is required, if the down-stream medium is moving with respect to the observer (no beaming effect is taken account and they are different from the observed radiation).

They conclude that jitter regime is obtained only if with artificially reduced the strength of the electromagnetic filed?
$(K \equiv qB\lambda / mc^2)$

This conclusion is due to that radiation is calculated in downstream frame?

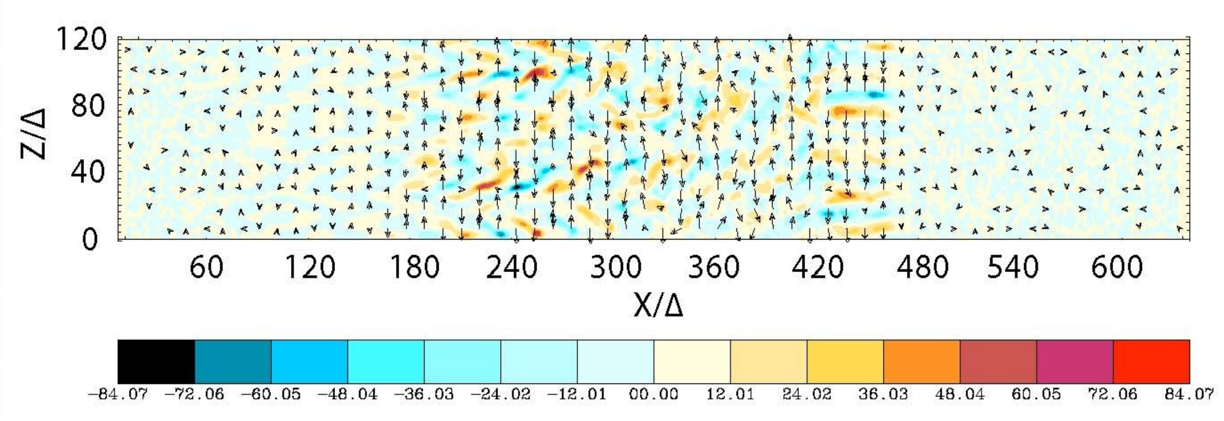
(Sironi & Spitkovsky 2009)

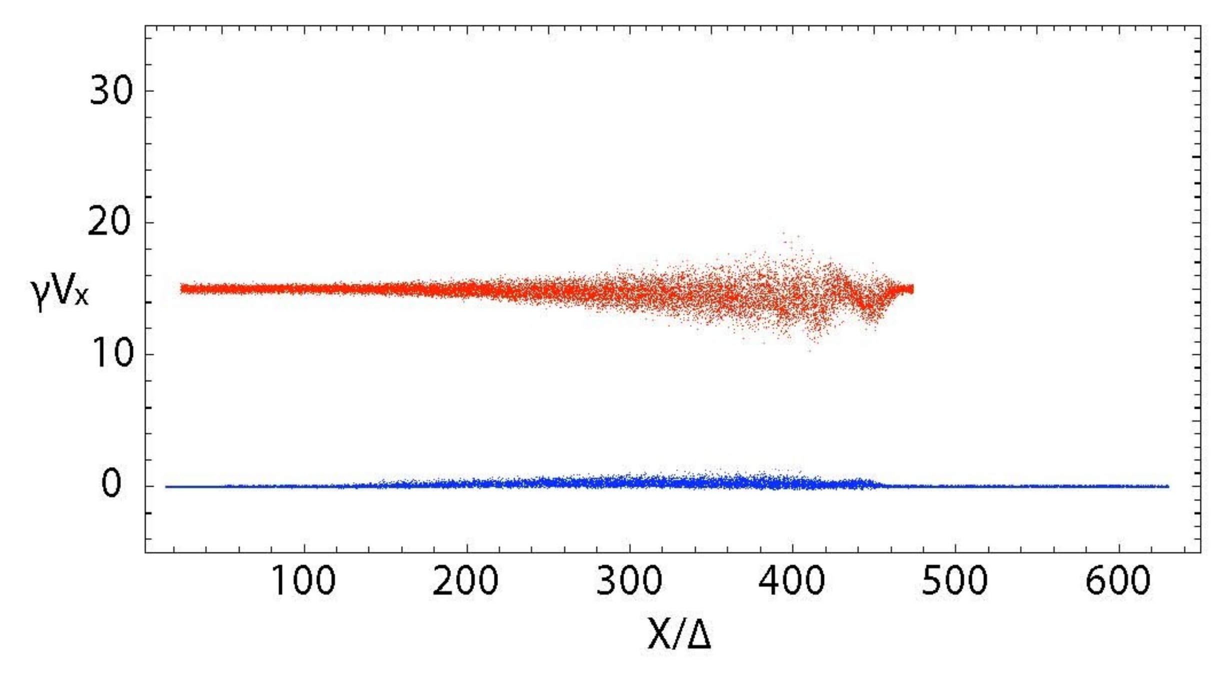
Radiation from electrons by tracing trajectories self-consistently

using a small simulation system

initial setup for jitter radiation

select electrons randomly (12,150) in jet and ambient





final condition for radiation

15,000 steps

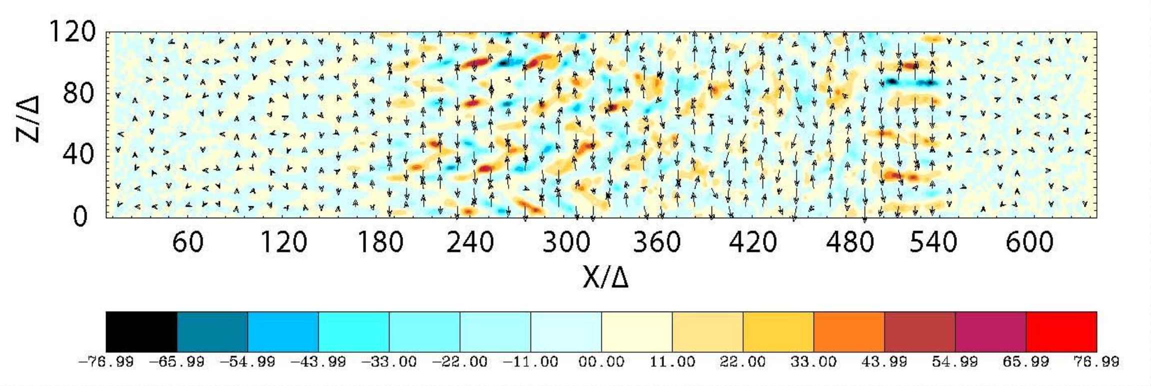
$dt = 0.005\ \omega_{pe}^{-1}$

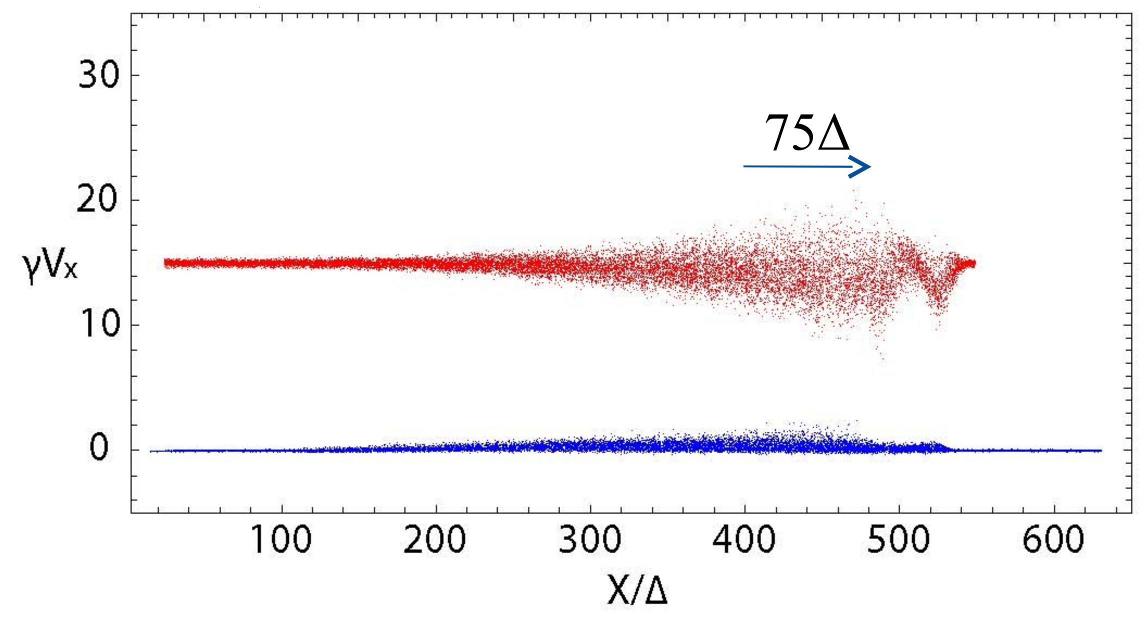
$n_\omega = 100$

$n_\theta = 2$

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

$t_r = 75\ \omega_{pe}^{-1}$

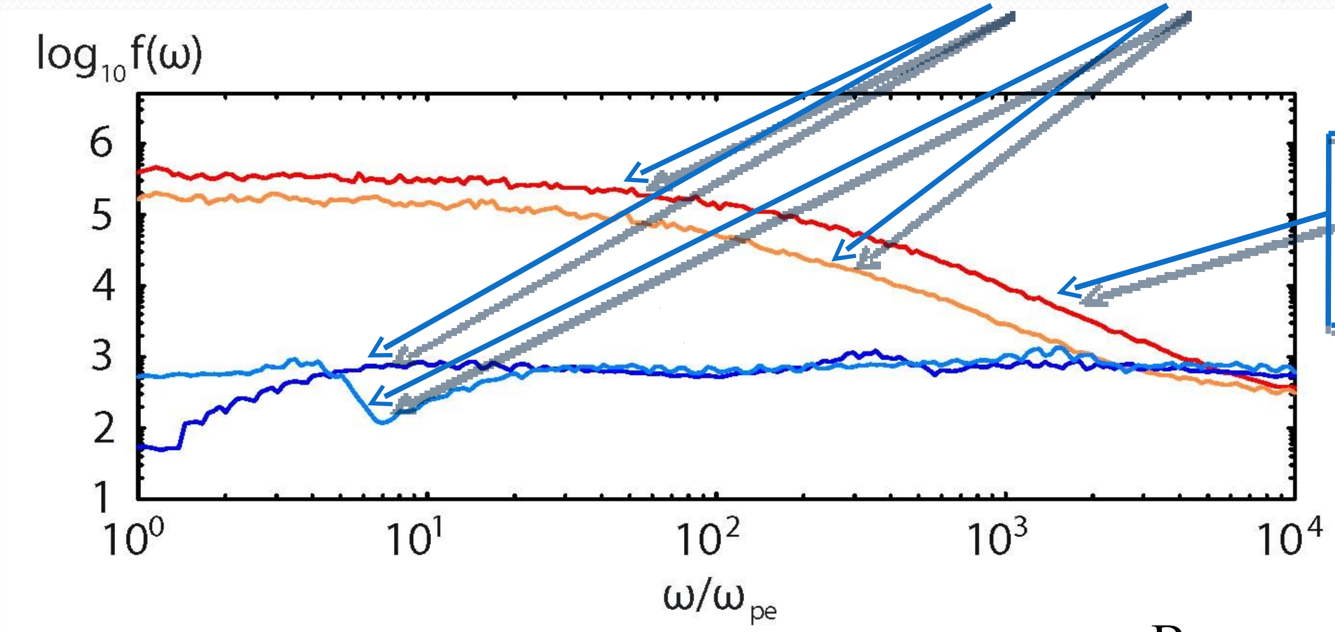




Calculated spectra for jet electrons and ambient electrons

$\gamma = 15$

$\theta = 0°$ and $5°$ $\theta_\gamma = 3.81°$

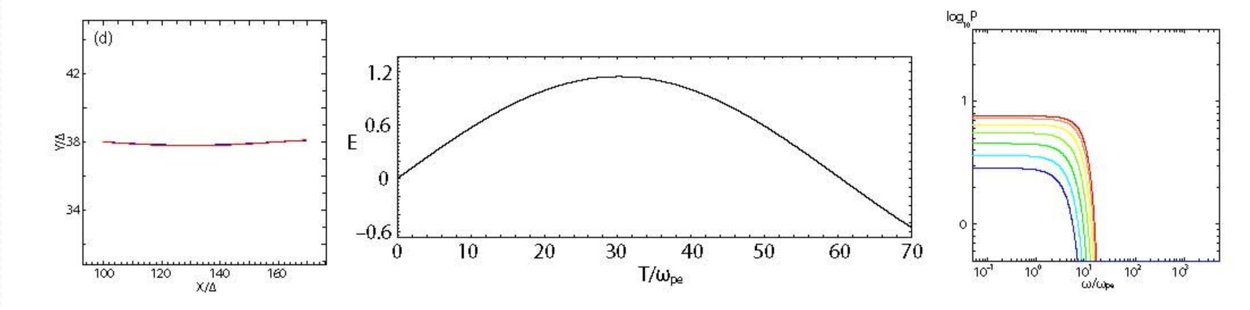


high frequency due to turbulent magnetic field

Bremesstrahlung

Case D

$\gamma = 7.11$



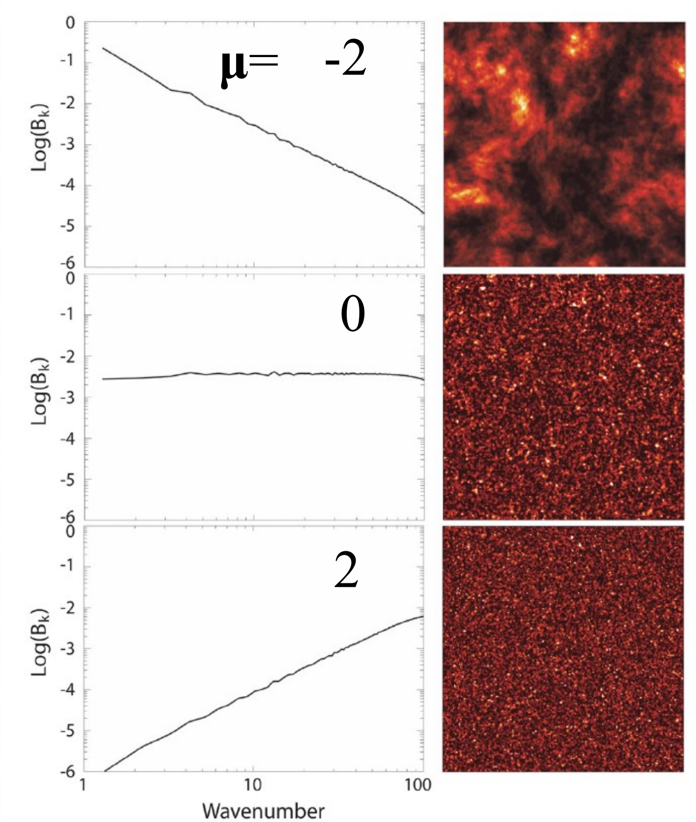
Nishikawa et al. 2009 (arXiv:0906.5018)

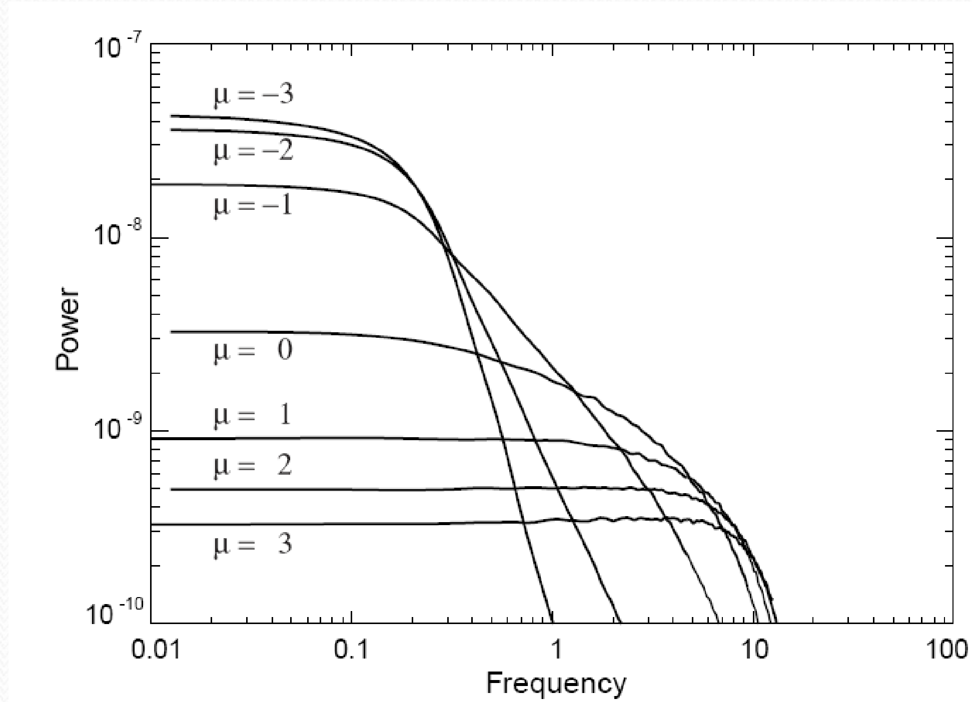
3D jitter radiation (diffusive synchrotron radiation) with a ensemble of mono-energetic electrons (γ = 3) in turbulent magnetic fields (Medvedev 2000; 2006, Fleishman 2006)

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

2d slice of magnetic field

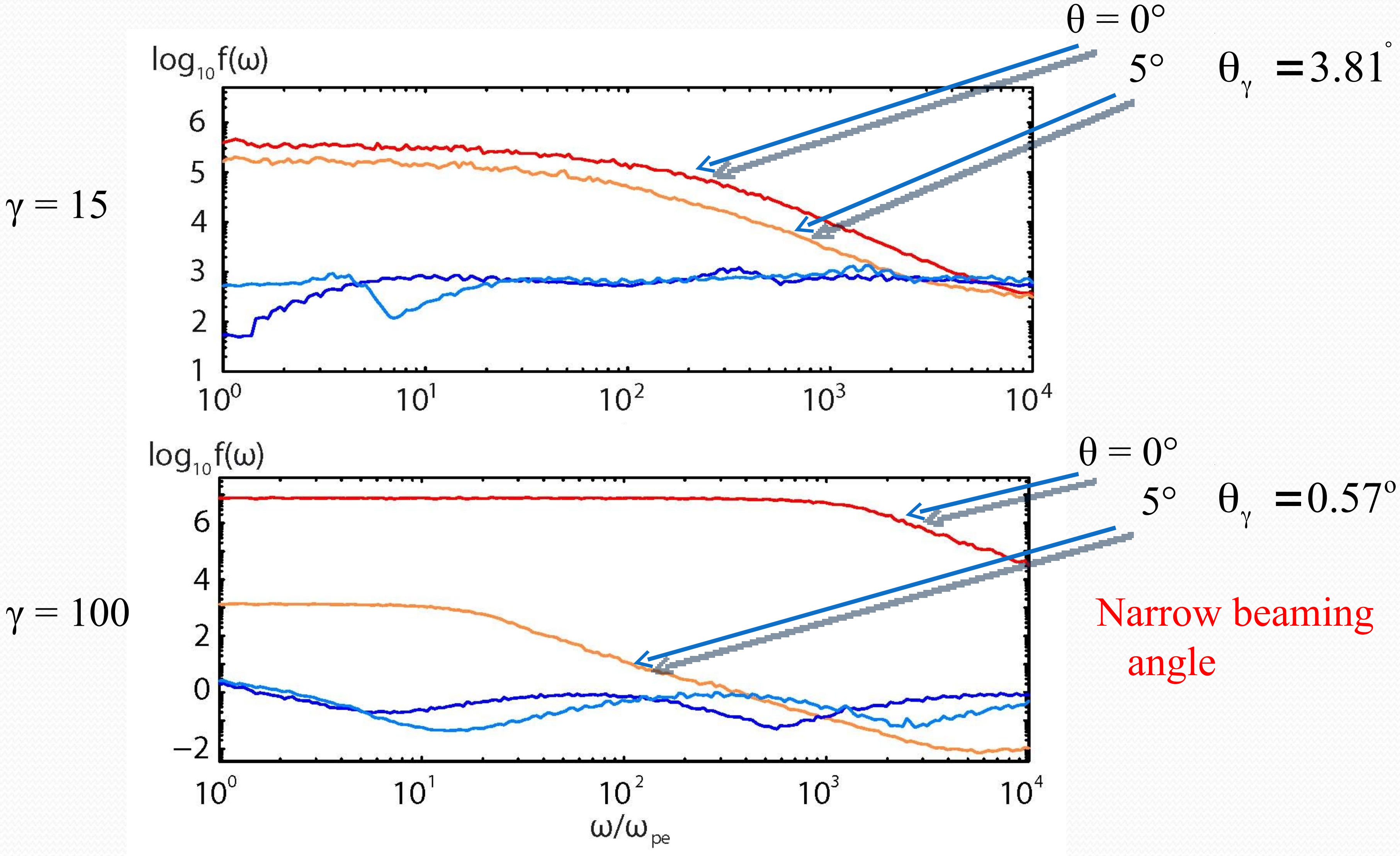
3D jitter radiation with γ = 3 electrons





Hededal & Nordlund (astro-ph/0511662)

Dependence on Lorentz factors of jets

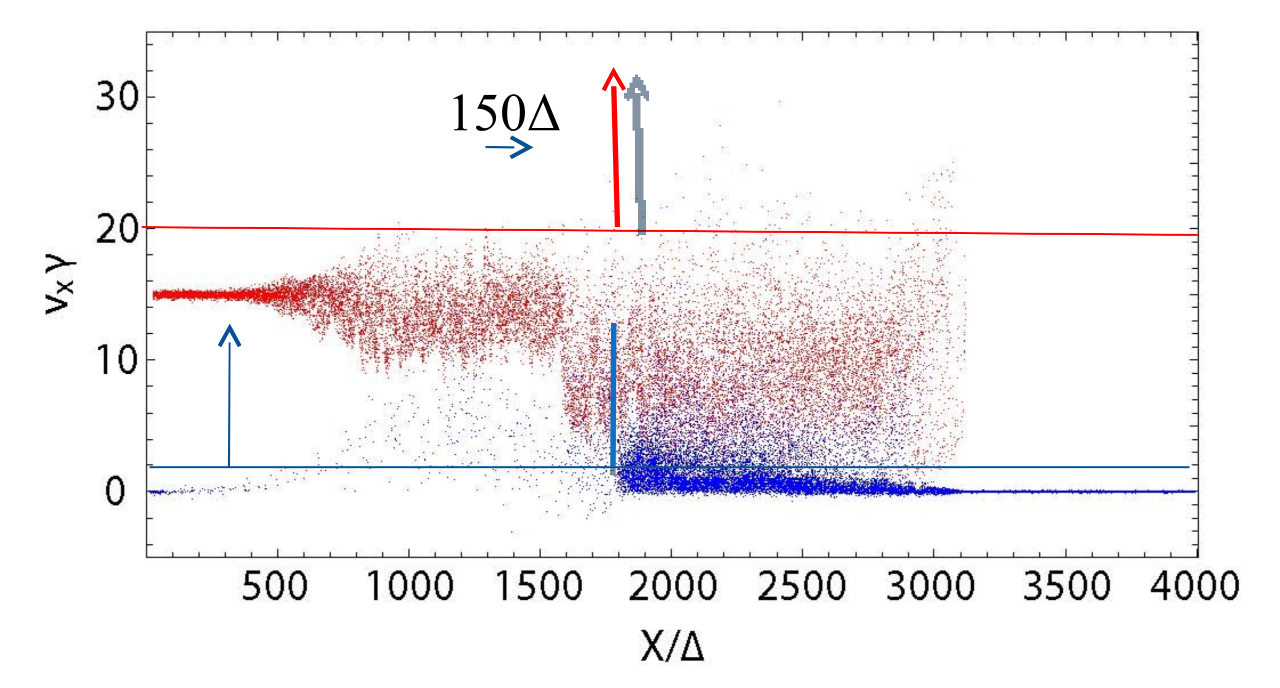


Initial particle selection at t = 3100 ω_{pe}^{-1}

jet electrons: $v_x\gamma > 20$

$1800 > X/\Delta > 300$

ambient electrons: $v_x\gamma > 2$



Radiation from electrons in dynamical electromagnetic field

$n \approx 10{,}000$, initially $300 < x/\Delta < 1800$

3,000 steps

jet: $v_x\gamma > 20$

ambient: $v_x\gamma > 2$

$dt = 0.05\ \omega_{pe}^{-1}$

(integrated $\Delta t = 0.1$ dt)

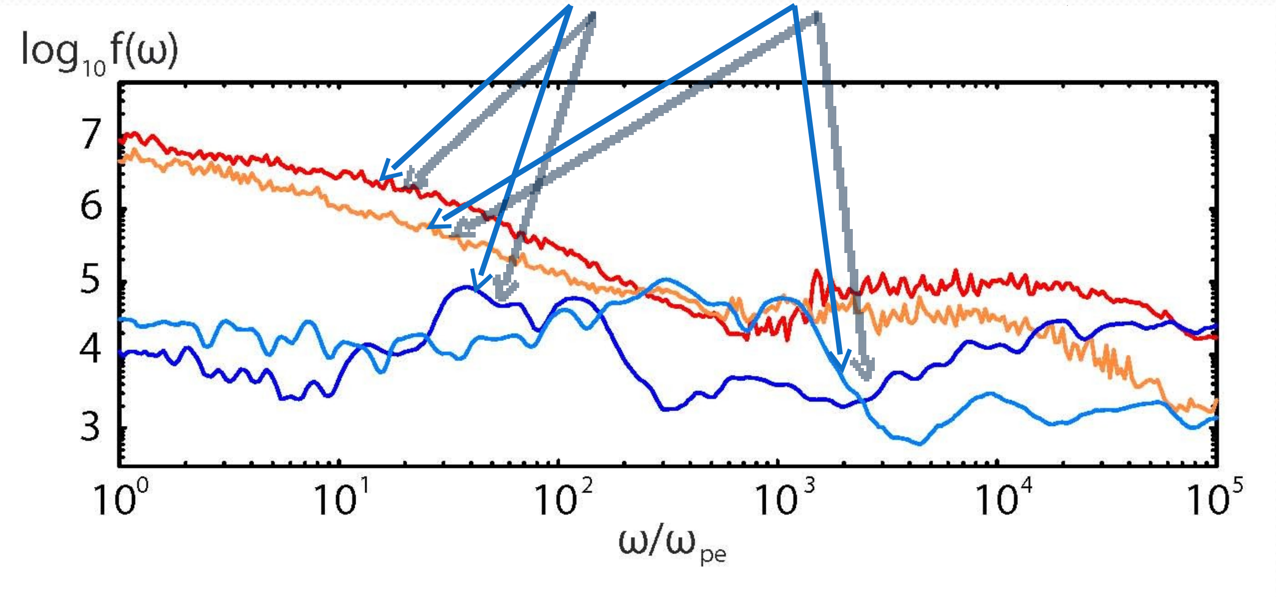
$\theta = 0°$ and $5°$ $\theta_\gamma = 3.81°$ ($\gamma = 15$)

$n_\omega = 200$

$n_\theta = 2$

$\Delta x_{jet} = 150\Delta$

$t_r = 150\,\omega_{pe}^{-1}$
$= (3250 - 3100)\,\omega_{pe}^{-1}$



Summary

- Simulation results show electromagnetic stream instability driven by streaming $e^{\pm}$ pairs are responsible for the excitation of near-equipartition, turbulent magnetic fields and

  a structure with leading and trailing shocks.
- Shock is similar to the shock in simulations with the constant contact discontinuity.
- The spectrum from jet electrons in a weak magnetic field in a small system shows a Bremsstrahlung like spectrum with higher frequency enhancement with turbulent magnetic field.
- 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 of our simulations of relativistic jets

- **Calculate radiation with larger systems for different parameters in order to compare with observational data**

- **Include inverse Compton beside synchrotron radiation to obtain high frequency radiation**

- **Simulations with magnetic fields including turbulent magnetic fields with pair plasma and electron-ion plasma**

- **Reconnection simulations for additional acceleration mechanism including magnetic reconnection**

- **Non-relativistic jet simulations for understanding SNRs**

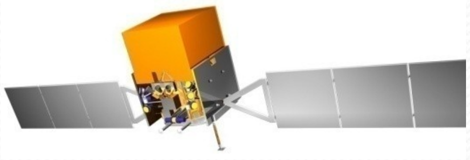
(FERMI)
(launched on June 11, 2008) http://www-glast.stanford.edu/

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.