Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

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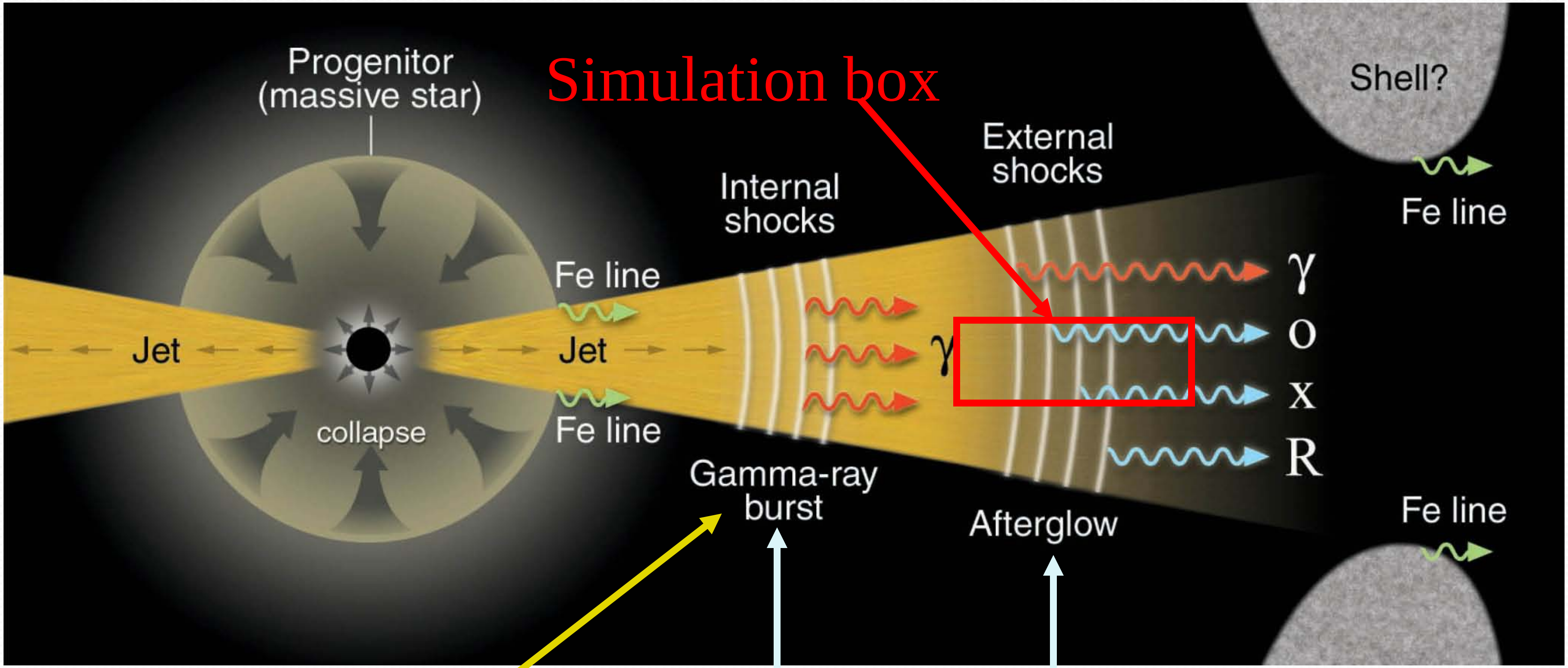
5th Astrophysics Workshop on Shock Waves, Turbulence, and Particle Acceleration
Asia Pacific Center for Theoretical Physics (APCTP), Pohang, KOREA
November 18-21, 2009

Outline of talk

- Recent 3-D particle simulations of relativistic jets
  - * e±pair jet into e±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)



Simulation box

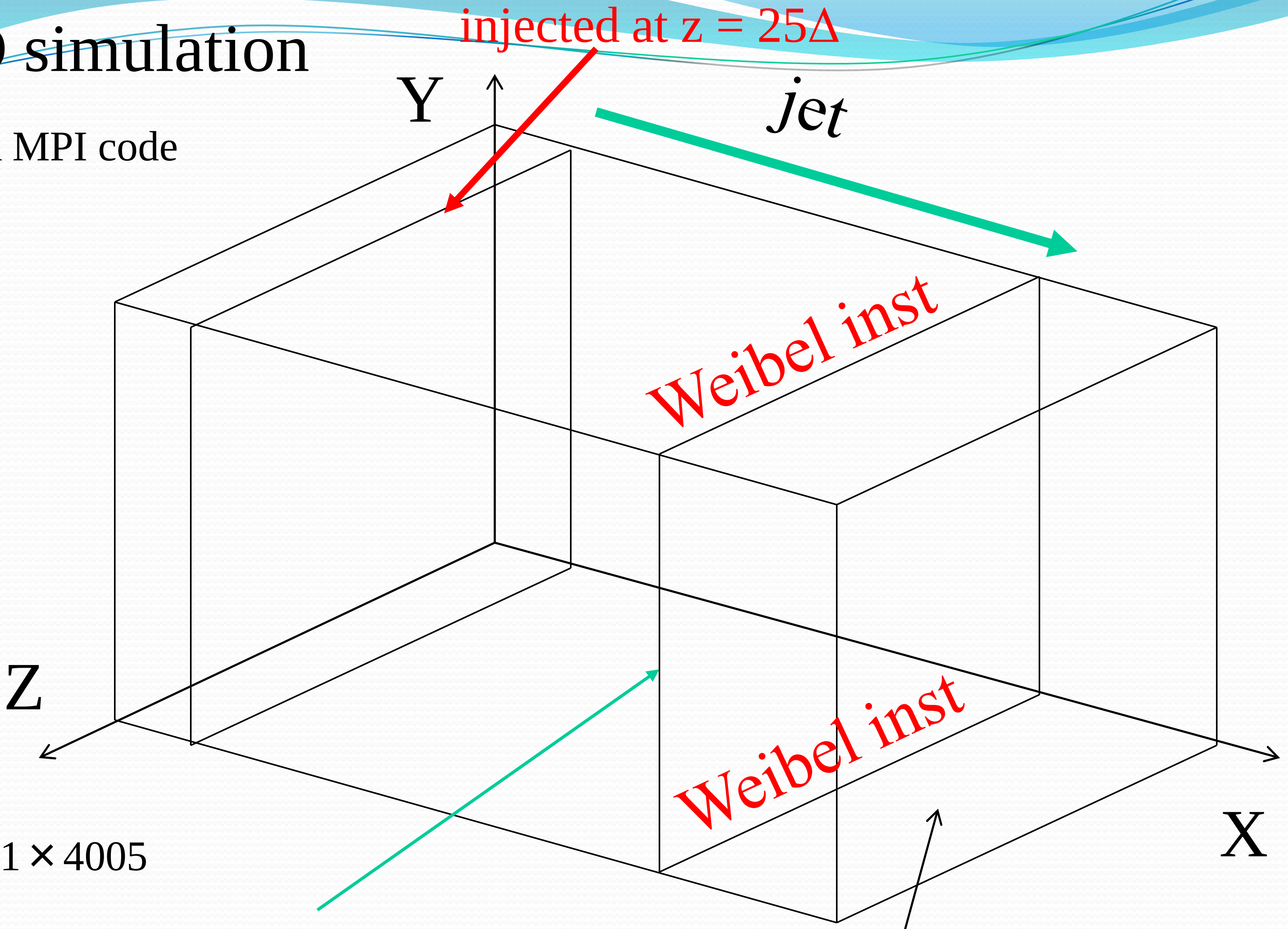
Prompt emission

Polarization ?

Accelerated particles emit waves at shocks

3-D simulation

with MPI code



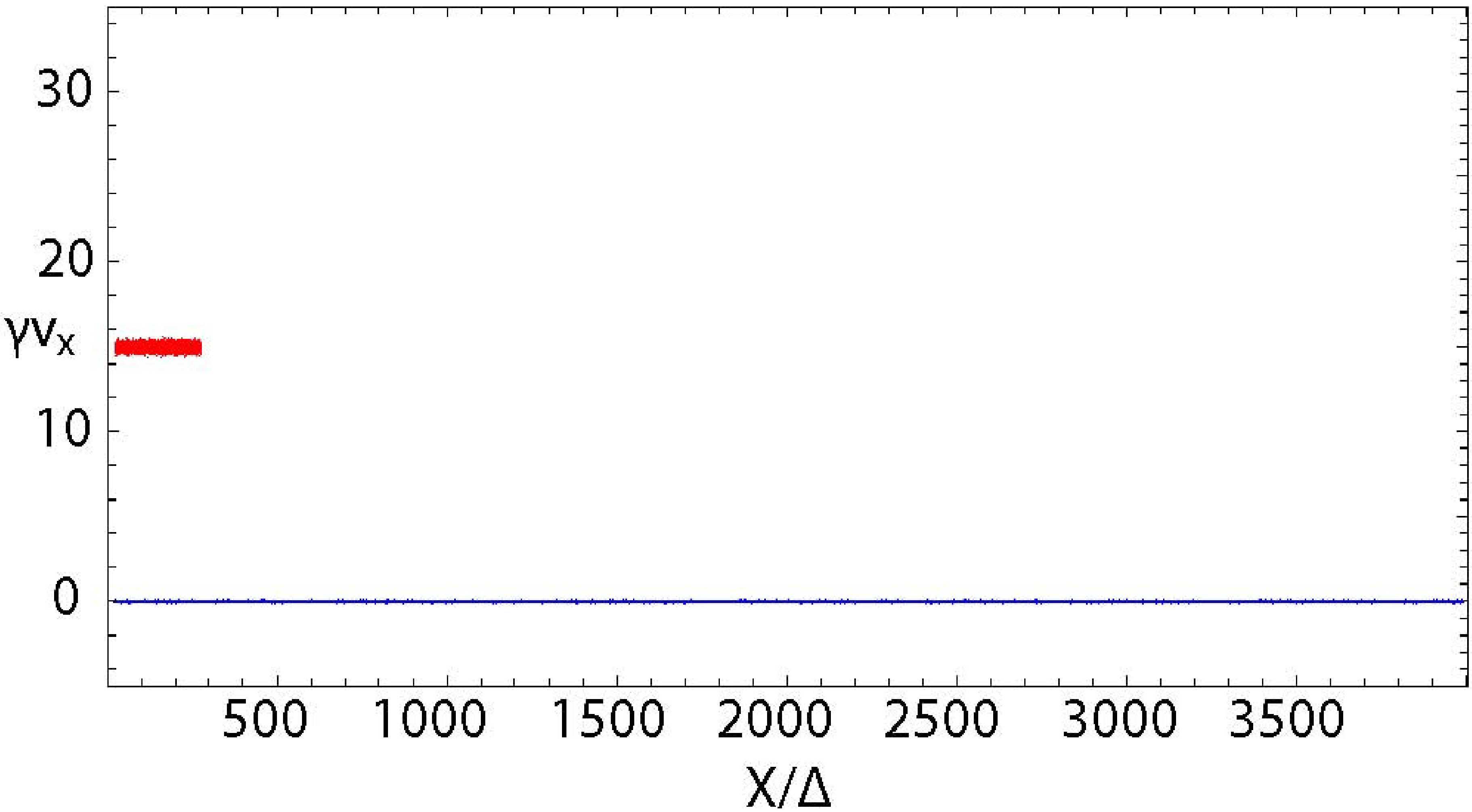
131 × 131 × 4005 grids

(not scaled)

1.2 billion particles

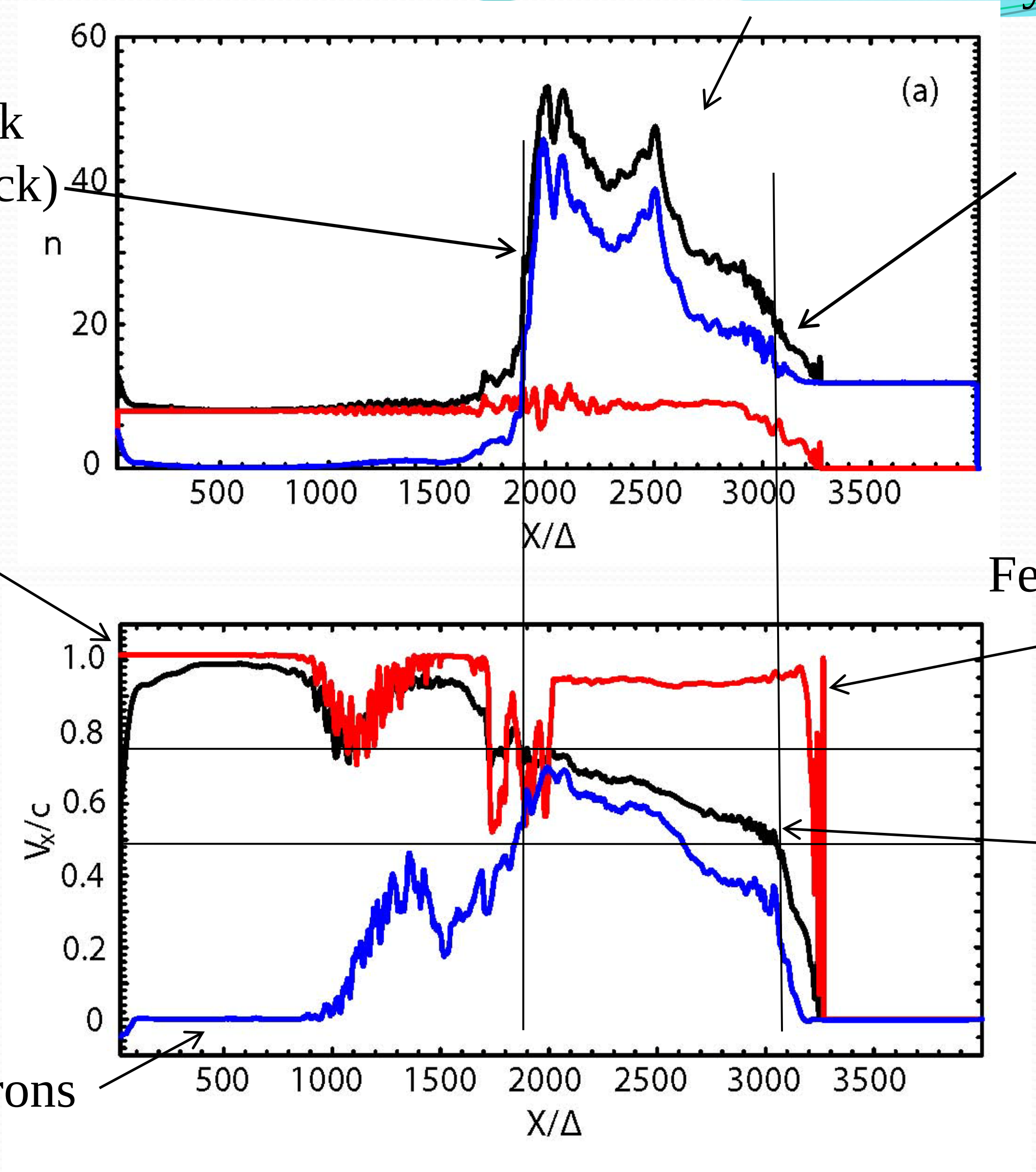
jet front

ambient plasma



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

Shock velocity and bulk velocity



contact discontinuity

trailing shock
(reverse shock)

leading shock
(forward shock)

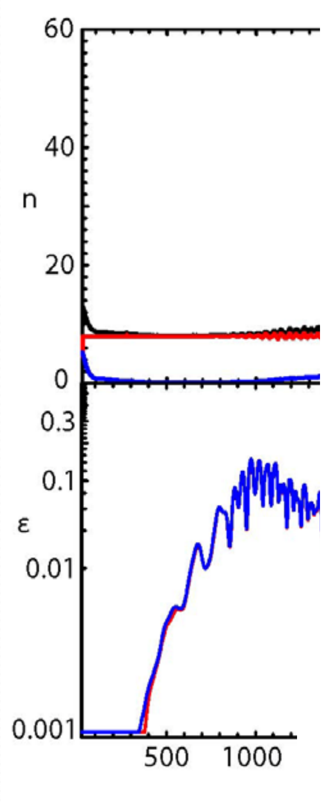
jet electrons

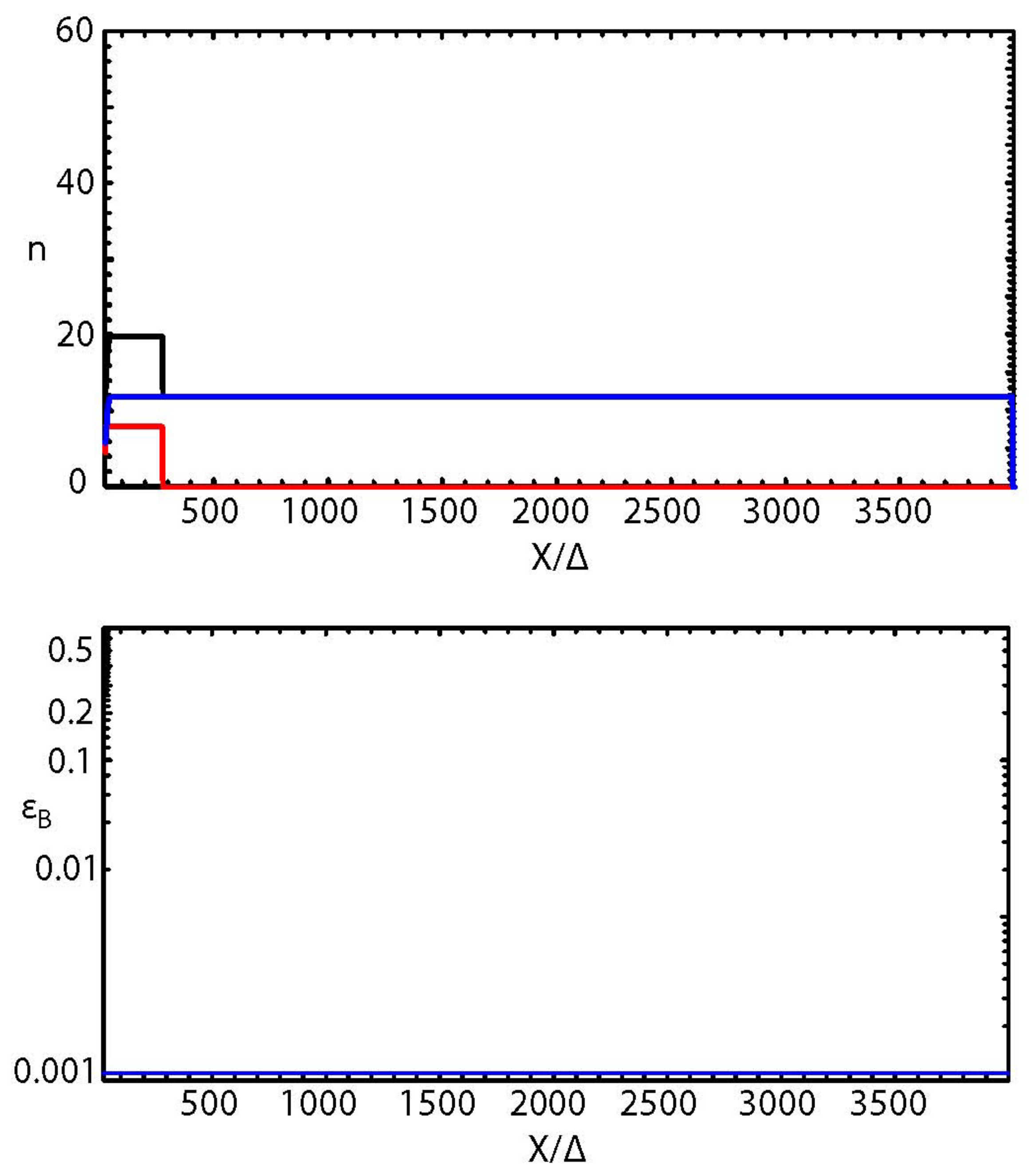
Fermi acceleration ?

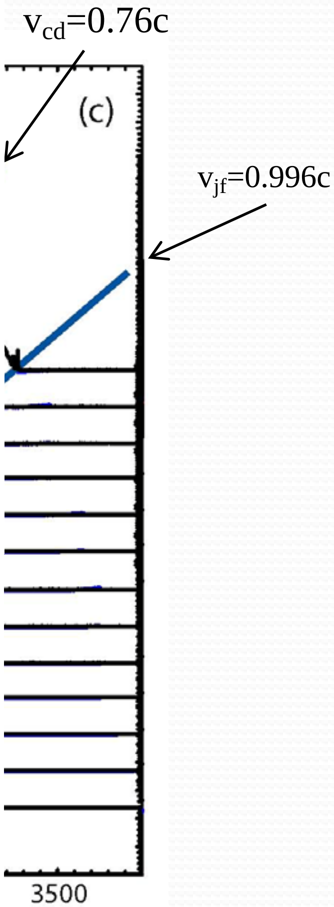
total electrons

ambient electrons

Shock ock







(a) electron densi

field energy (ε_B, ε

kinetic energy at t

density.

the predicted

, and the

(Nishikawa et al

Shock velocity and structure based on 1-D HD analysis

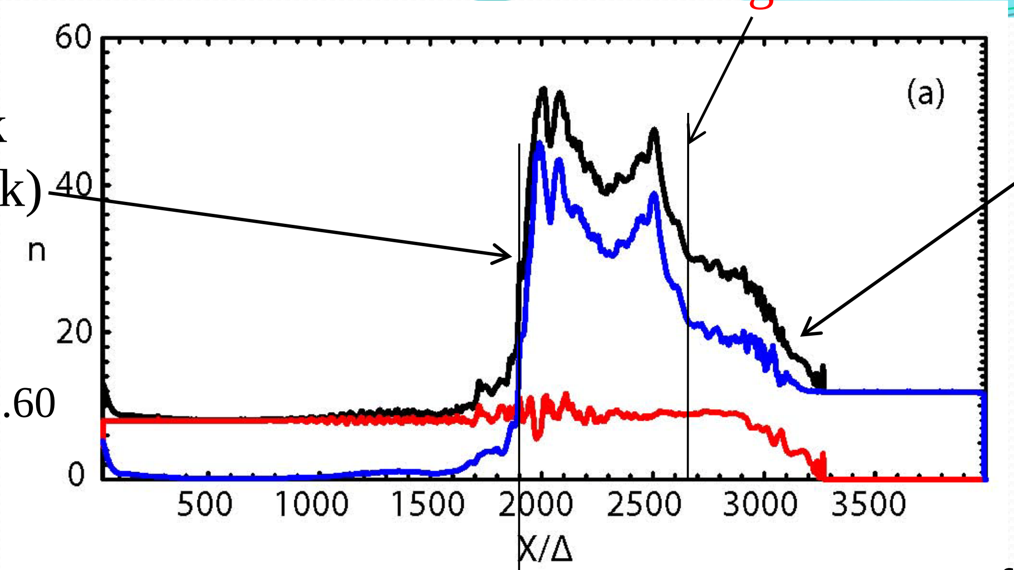
moving contact discontinuity (CD)

trailing shock
(reverse shock)

in CD frame

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

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

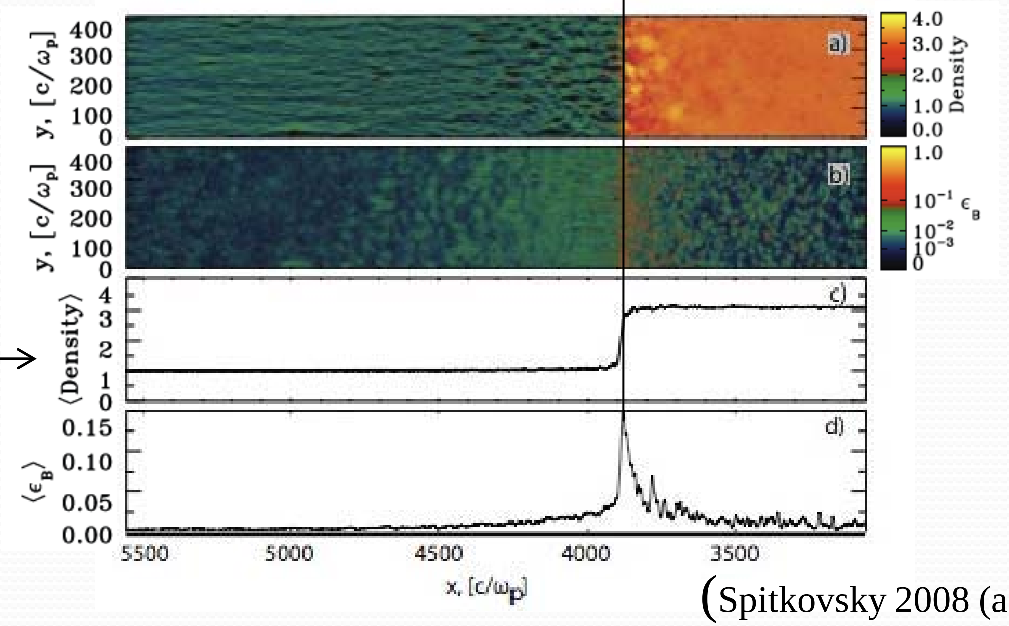


leading shock
(forward shock)

(Nishikawa et al. 2009)

$$^{4}\!/_{3} < \Gamma = {}^{3}\!/_{2} < {}^{5}\!/_{3}$$

fixed CD



Density

$n_2/\gamma_0 n_1 = 3.13$

$\beta_c = 0.47$

$\gamma_0 = 15$

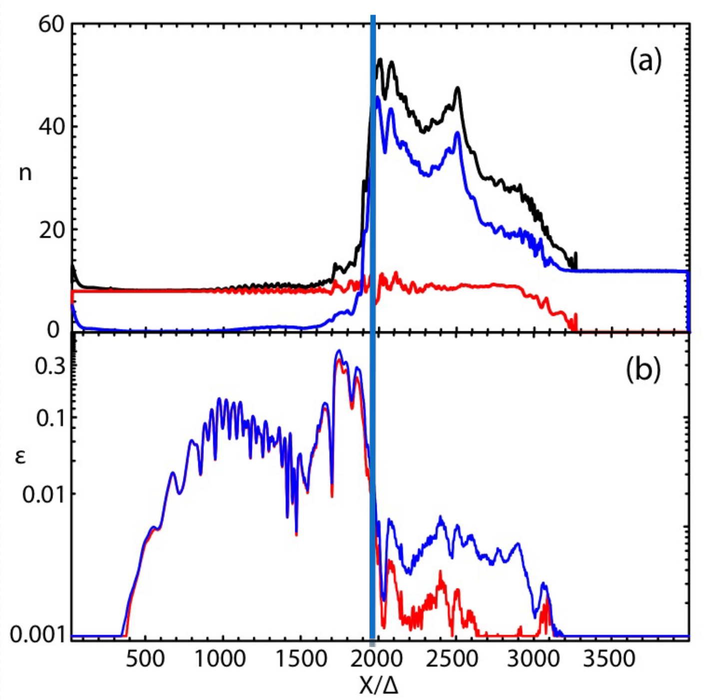
0

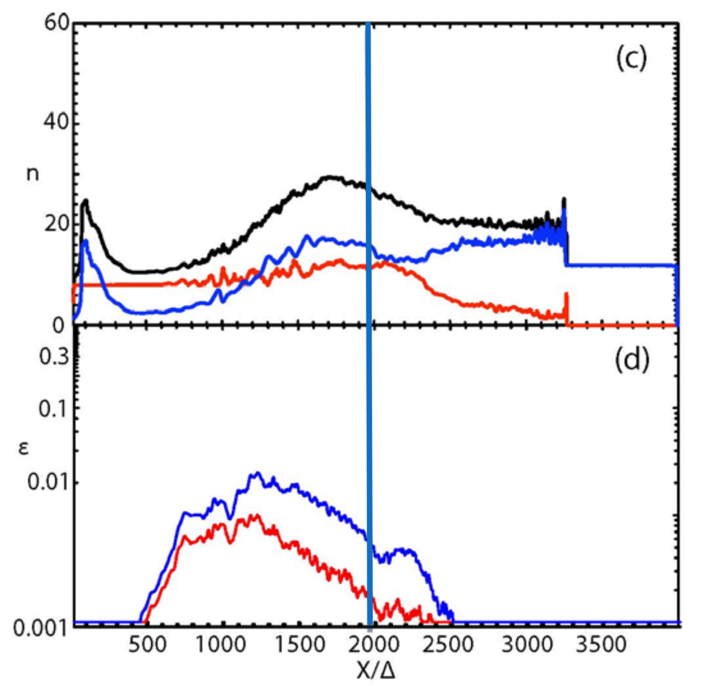
(Spitkovsky 2008 (adapted))

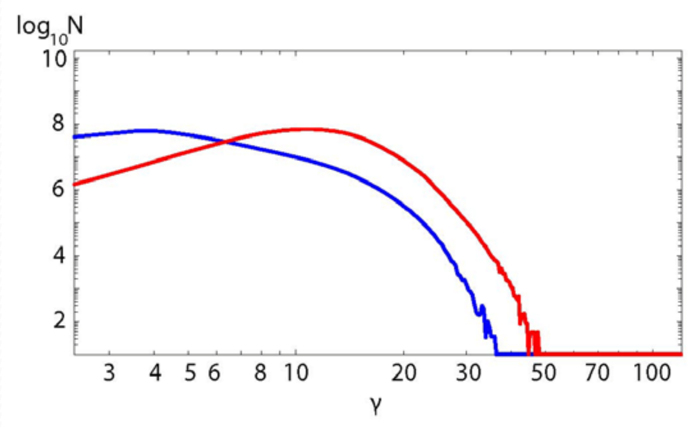
Comparison with different mass ratio (electron-positron and electron-ion)

electron-positron

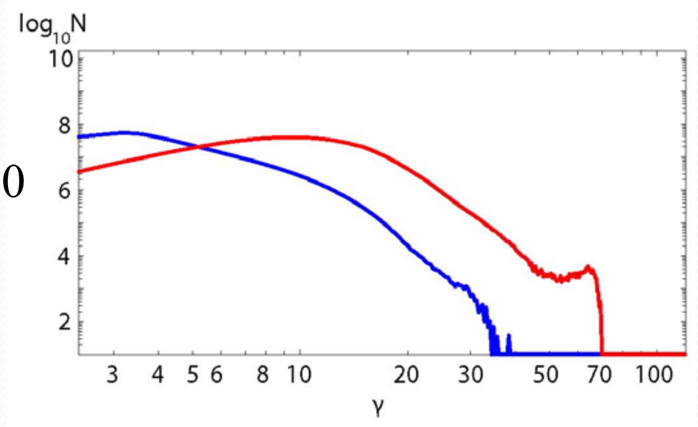
electron-ion ($m_i/m_e = 20$)





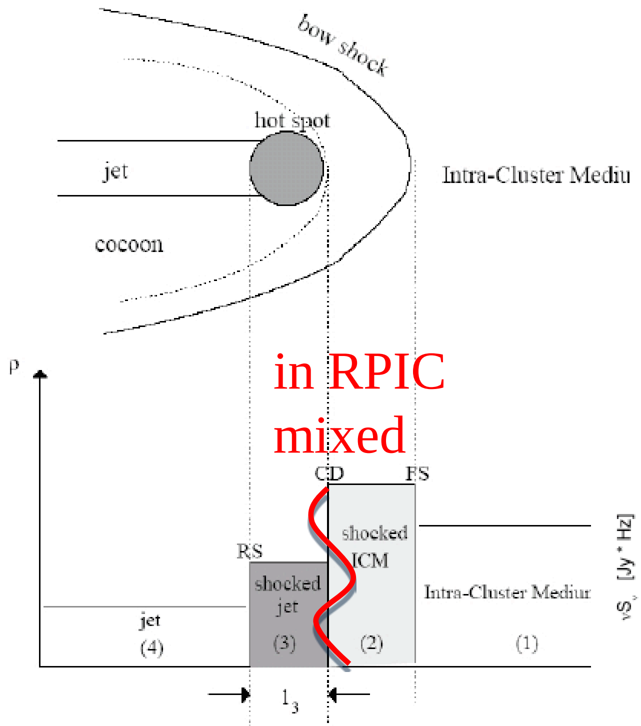


X/Δ>2000



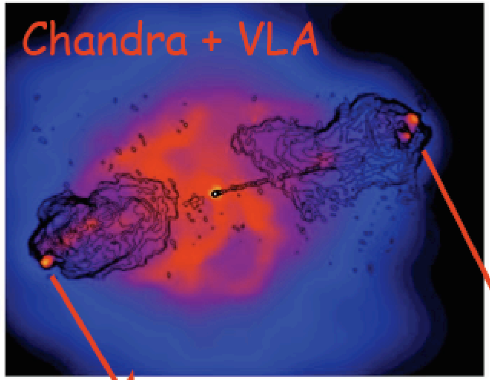
Terminal Hotspots

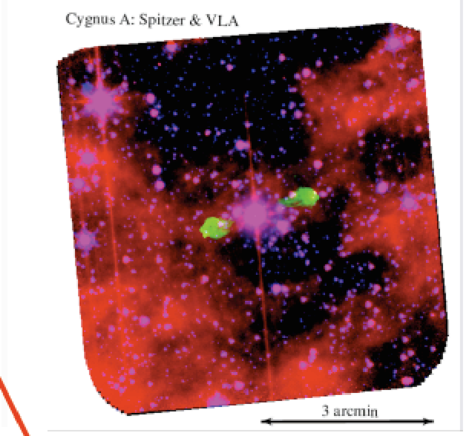
Kino & Takahara 04

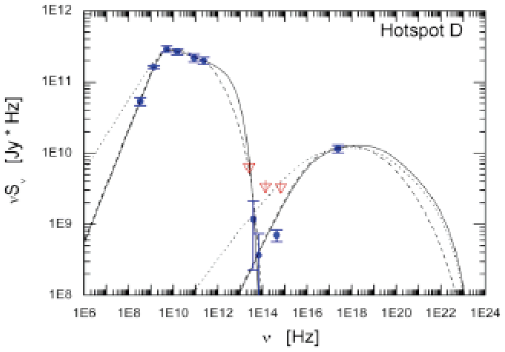


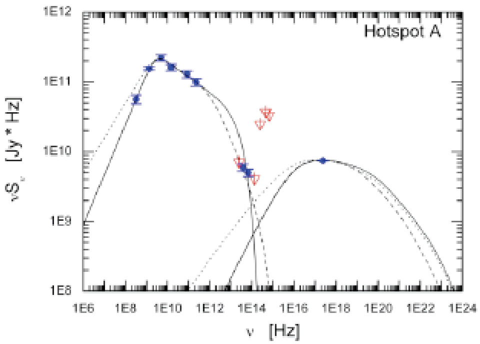
in RPIC mixed

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**).

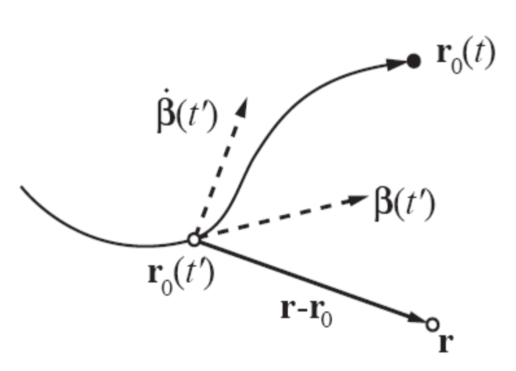
from the talk by L. Stawarz

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



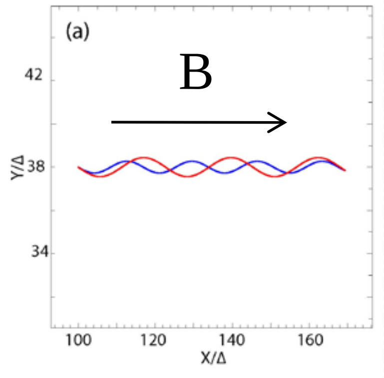
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

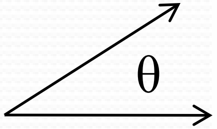
Hededal, Thesis 2005 (astro-ph/0506559)
Nishikawa et al. 2008 (astro-ph/0802.2558)
Sironi & Spitkovsky, 2009 (astro-ph/0908.3193)
Martins et al. 2009, Proc. of SPIE Vol. 7359
(see also two posters by J. Martins and S. Martins)

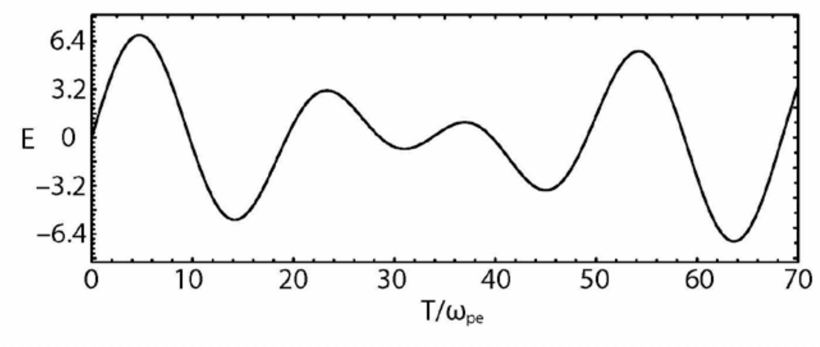
Synchrotron radiation from propagating electrons in a uniform magnetic field

electron trajectories

radiation electric field observed at long distance





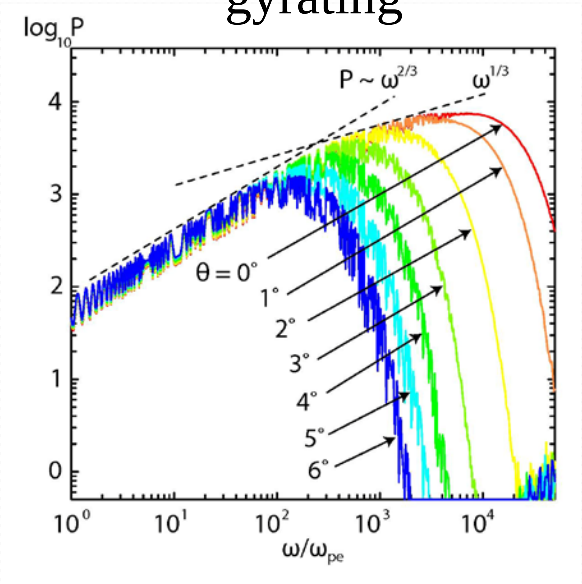


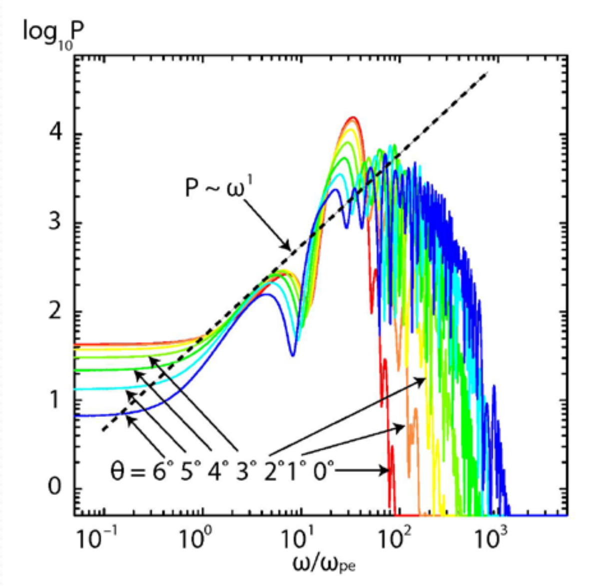
observer

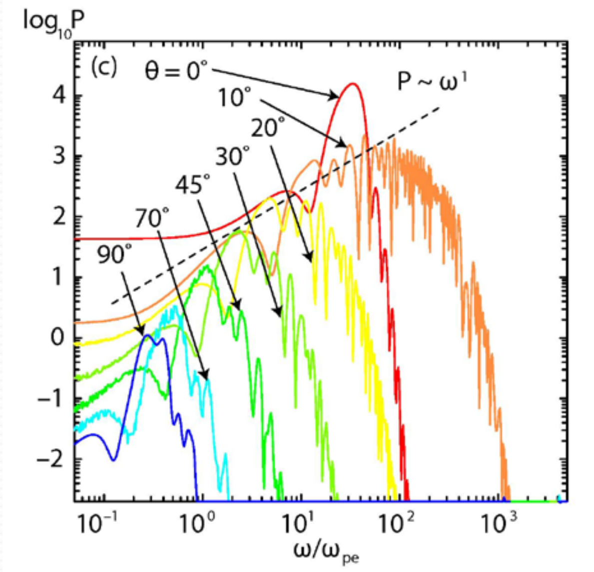
spectra with different viewing angles

gyrating

$\theta_\gamma = 4.25^\circ$





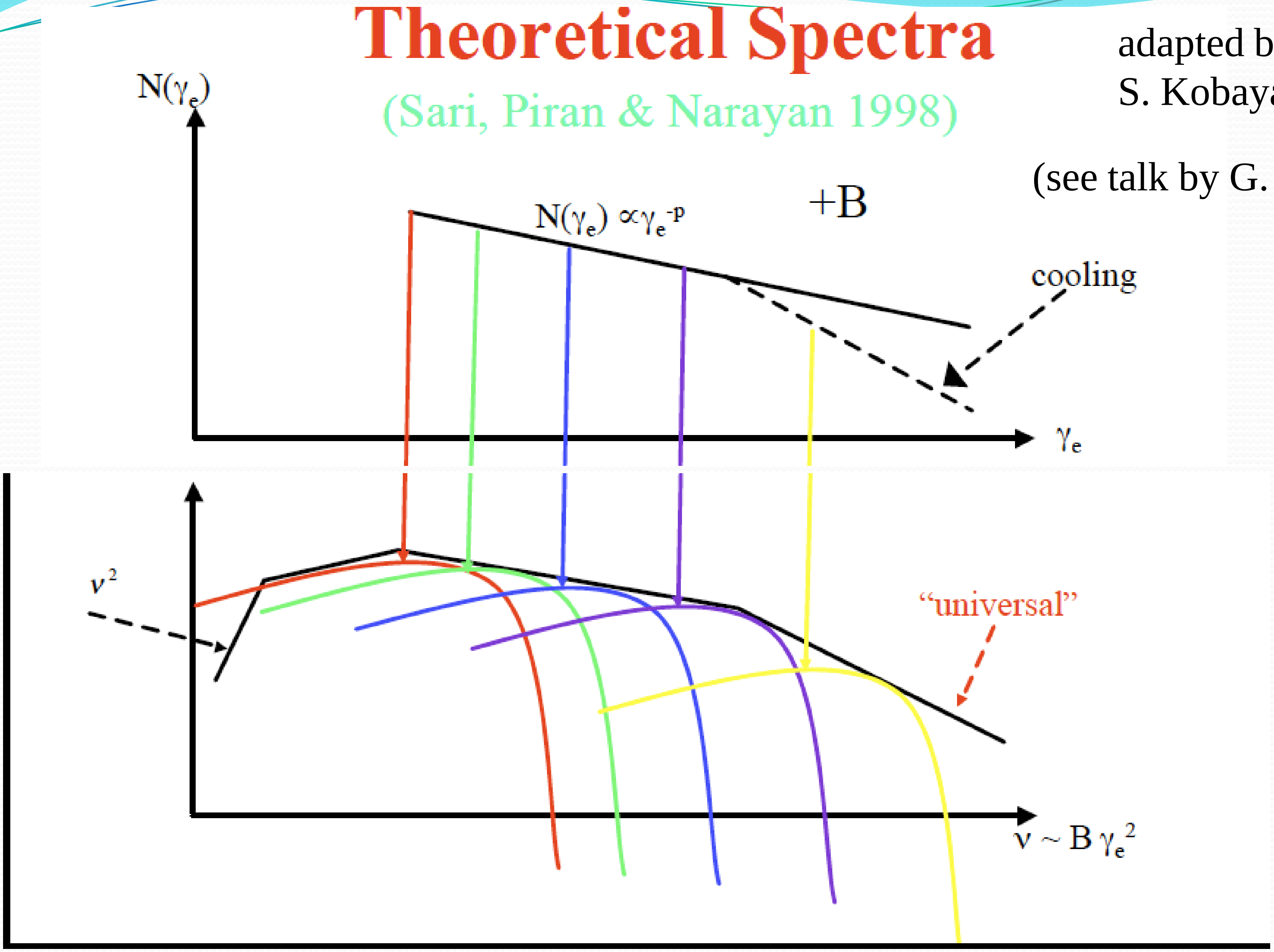


Nishikawa et al. astro-ph/0809.5067

Synchrotron Emission: radiation from accelerated

adapted by
S. Kobayashi

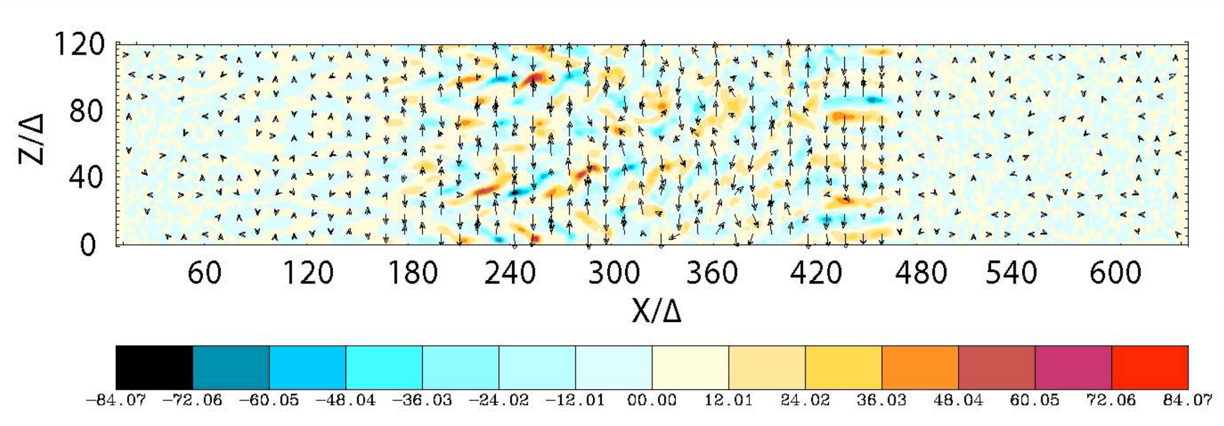
(see talk by G. Vila)



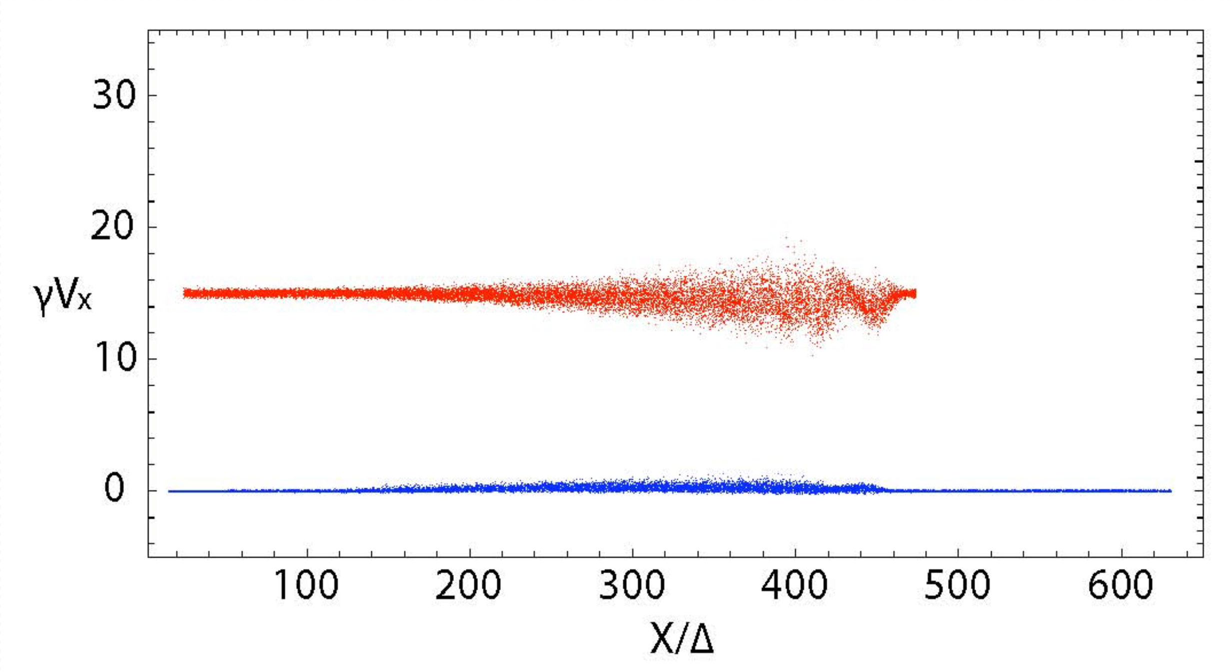
Jitter radiation from electrons by tracing trajectories self-consistently

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

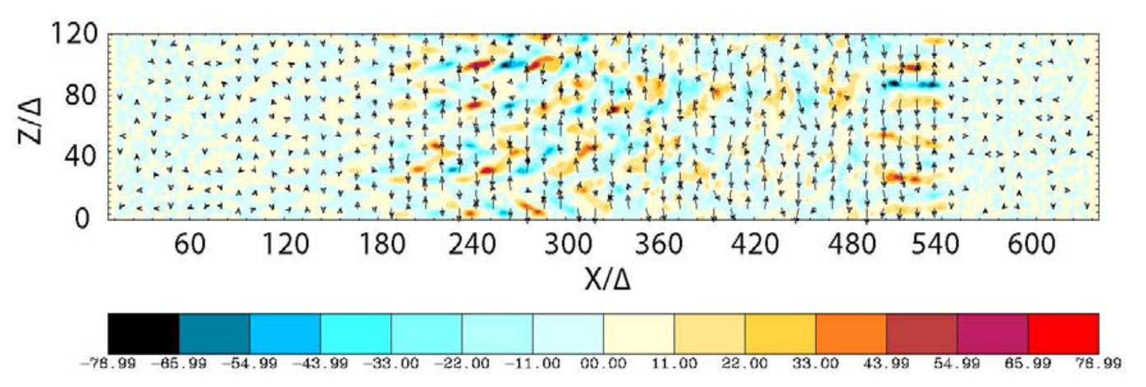
dt = 0.005 ω_{pe}^{-1}

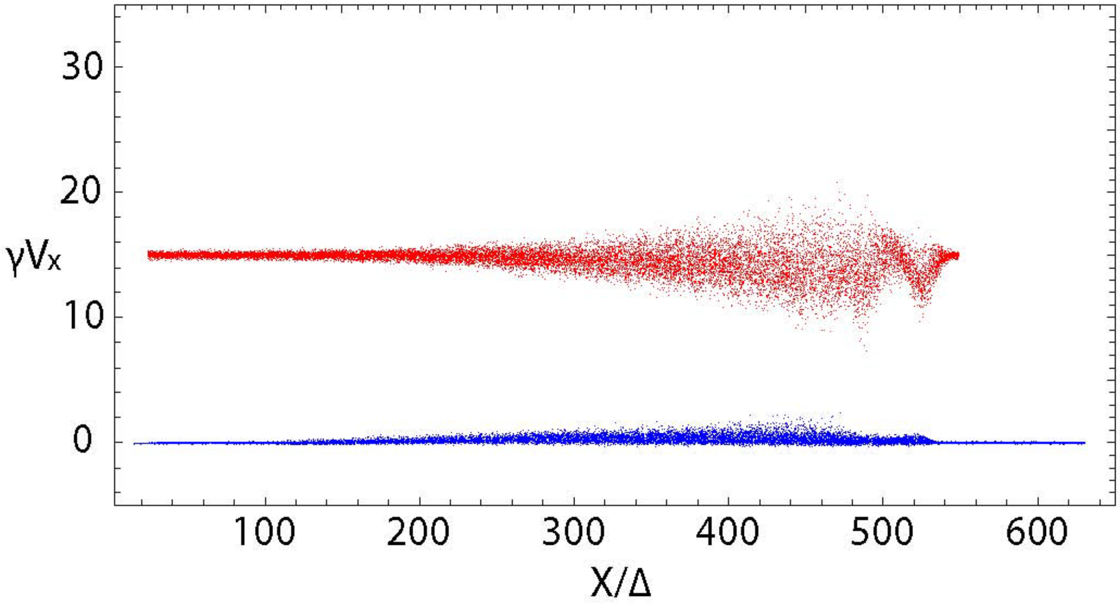
$\omega_n = 100$

$\theta_n = 2$

$\Delta xjet = 75\Delta$

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

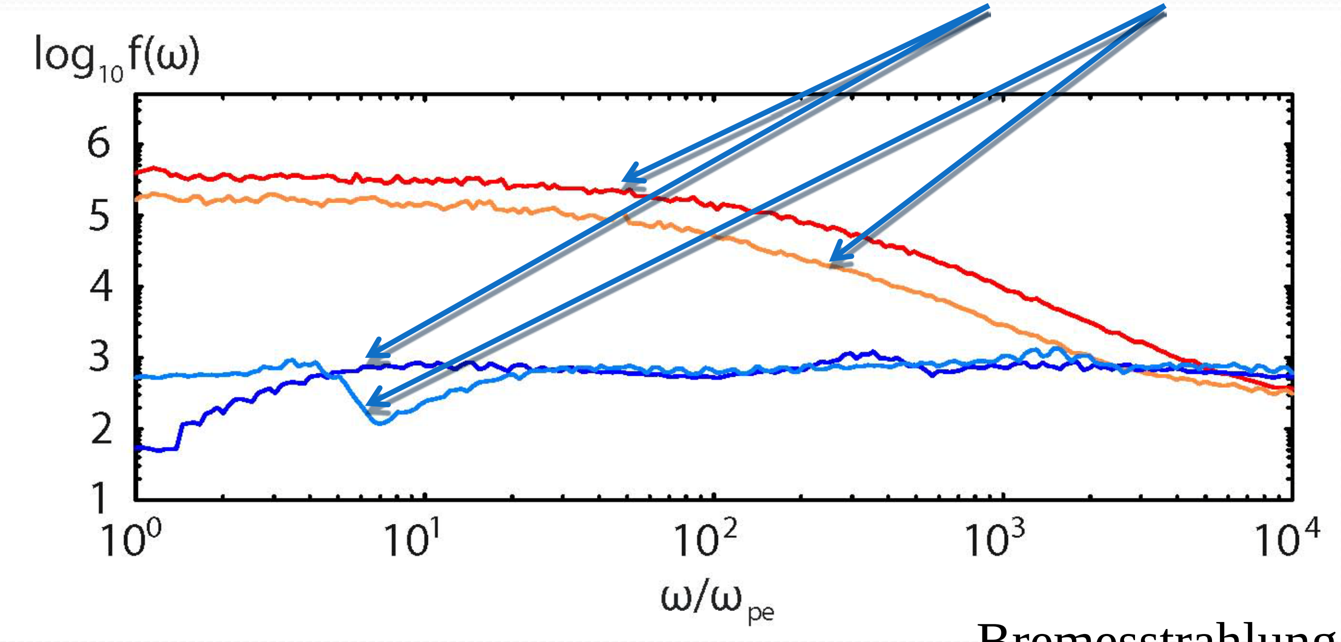




Calculated spectra for jet electrons and ambient electrons

$\gamma = 15$

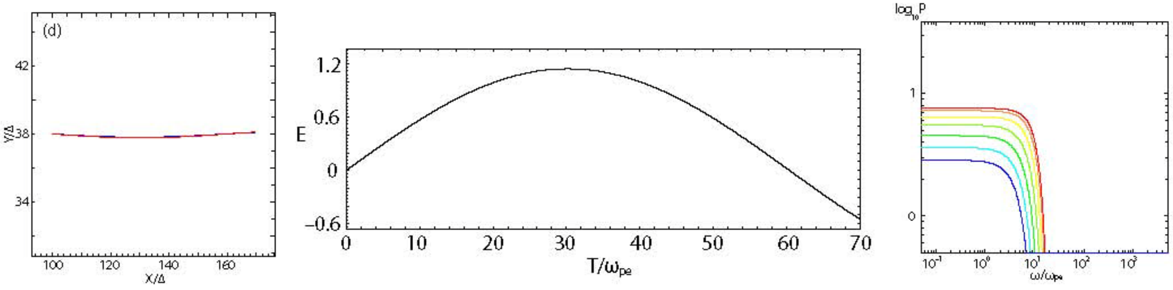
$\theta = 0°$ and $5°$ $\theta_\gamma = 3.81$



Bremesstrahlung

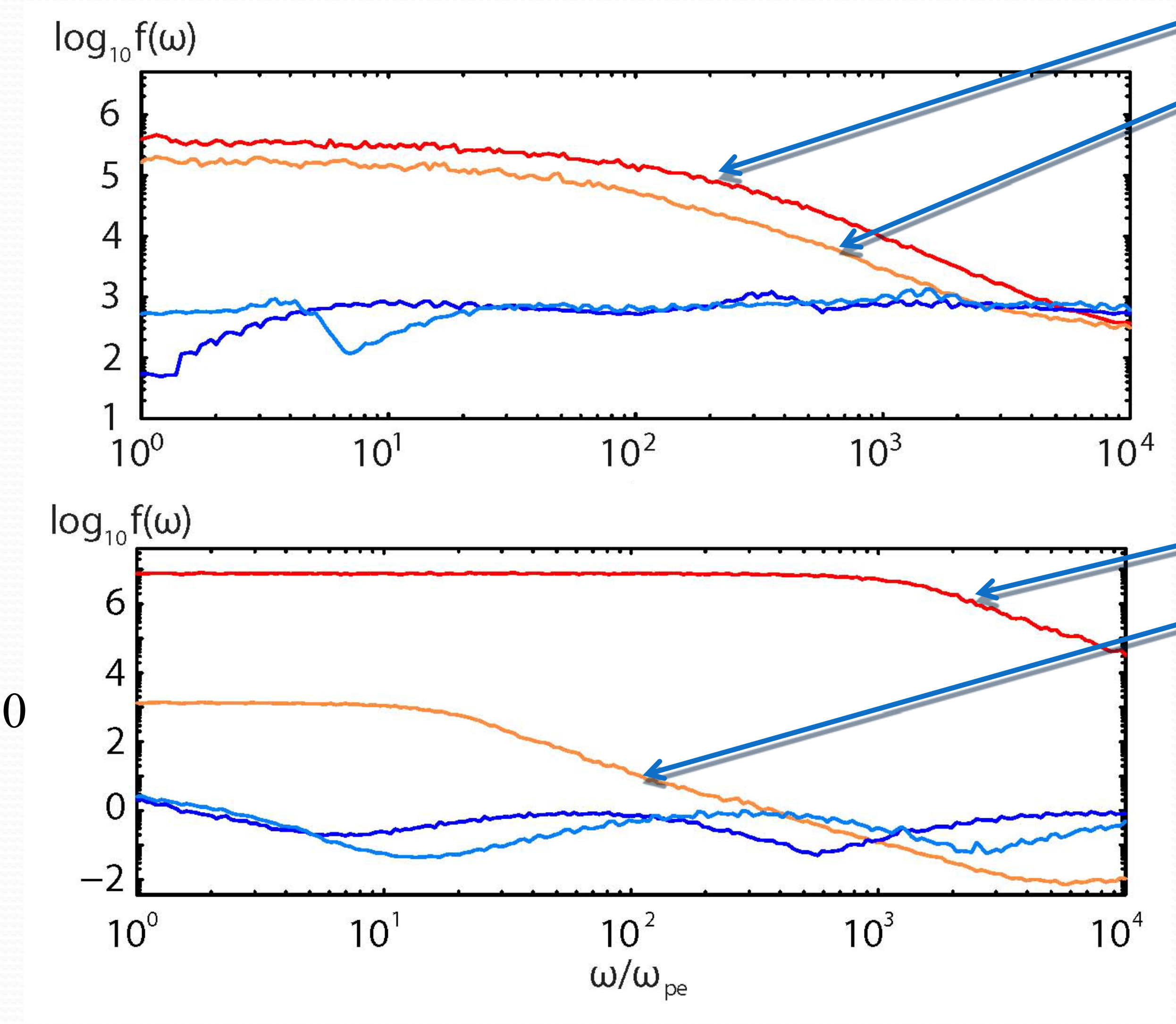
Case D

$\gamma = 7.11$



Nishikawa et al. 2009 (arXiv:0906.5018)

Dependence on Lorentz factors of jets



$\gamma = 15$

$\theta = 0°$

5°

$\theta_\gamma = 3.81$

$\gamma = 100$

$\theta = 0°$

5°

$\theta_\gamma = 0.57$

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 radiation beside synchrotron radiation**

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

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

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.