Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

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G. J. Fishman (*NASA/MSFC*)

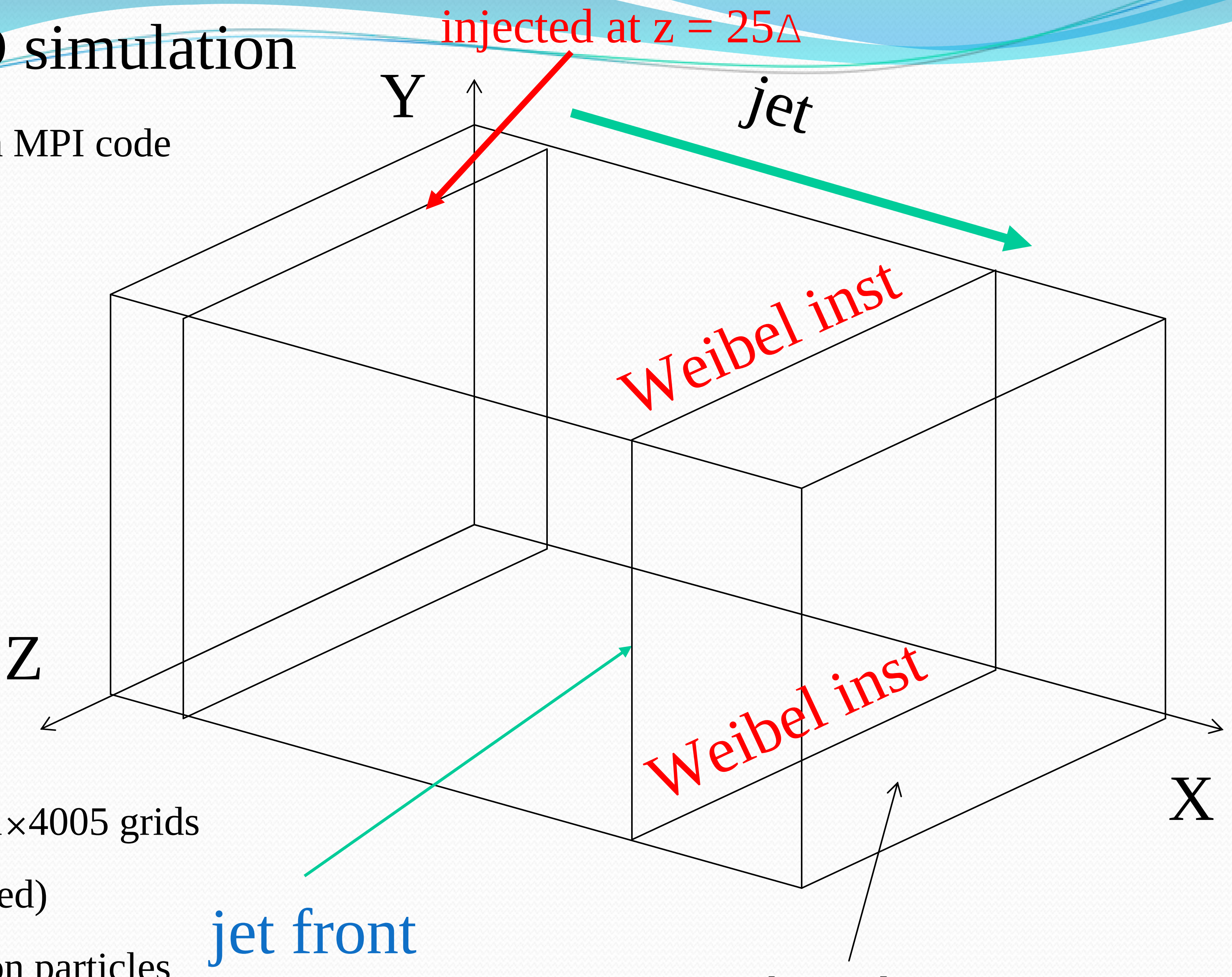
Particle Acceleration in Astrophysical Plasmas, July 27 - October 2, 2009,
Kavli Institute for Theoretical Physics, **Santa Barbara, CA**

Outline of talk

- **Recent 3-D particle simulations of relativistic jets**
  *** $e^{\pm}$pair jet into $e^{\pm}$pair, γ= 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**

3-D simulation

with MPI code



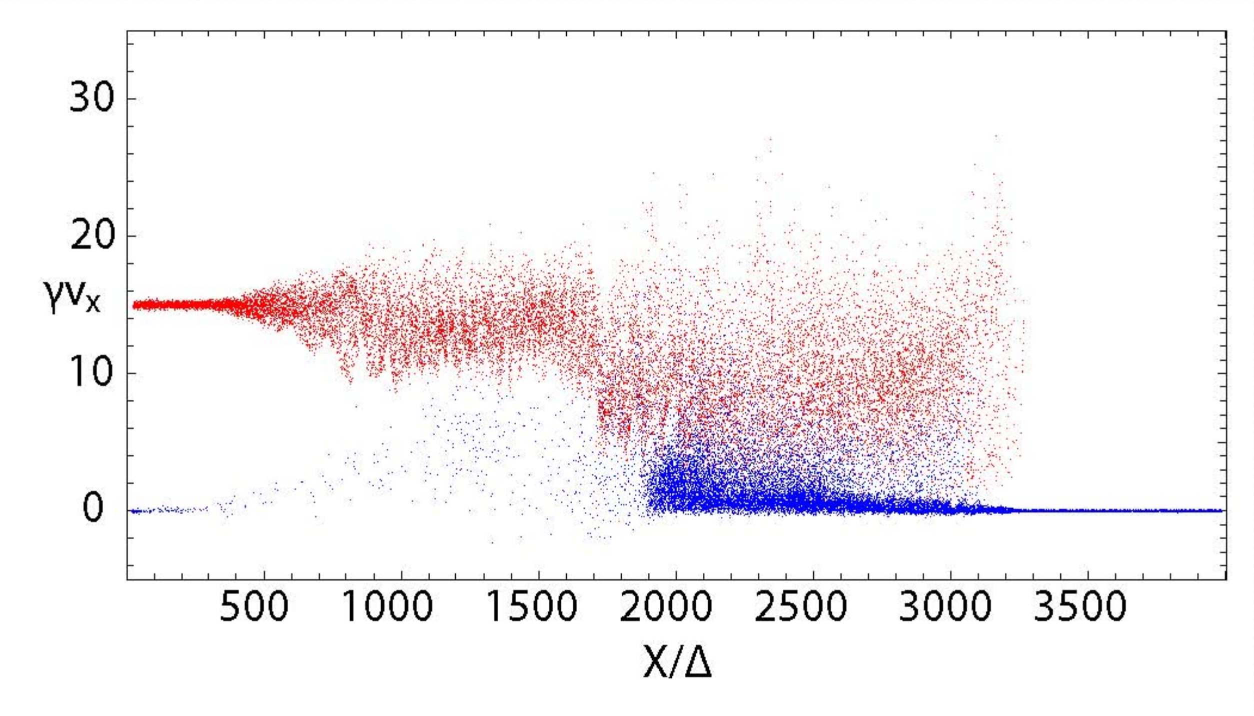
131×131×4005 grids

(not scaled)

1.2 billion particles

Phase space of electrons

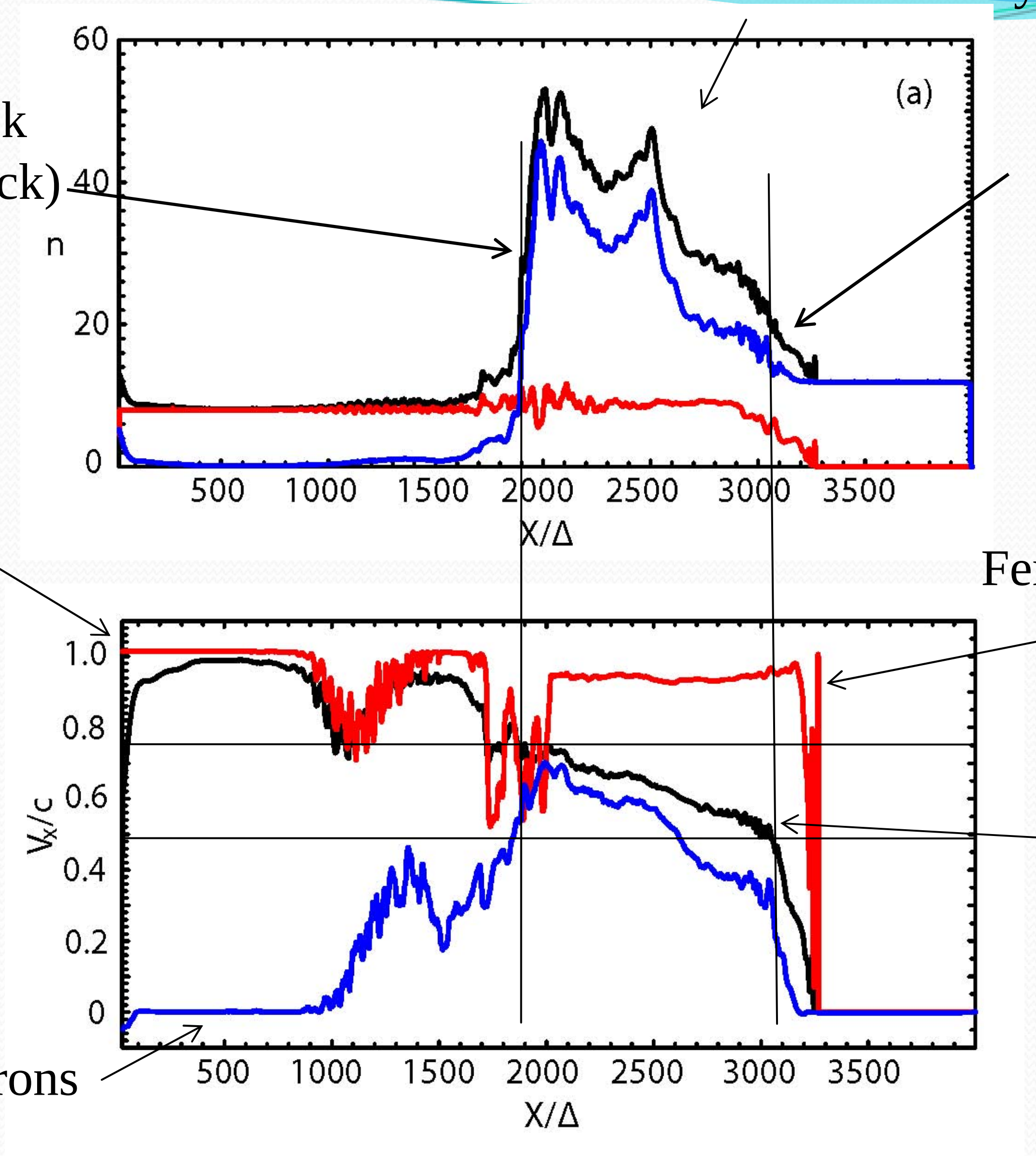
red: jet electrons, blue: ambient electrons



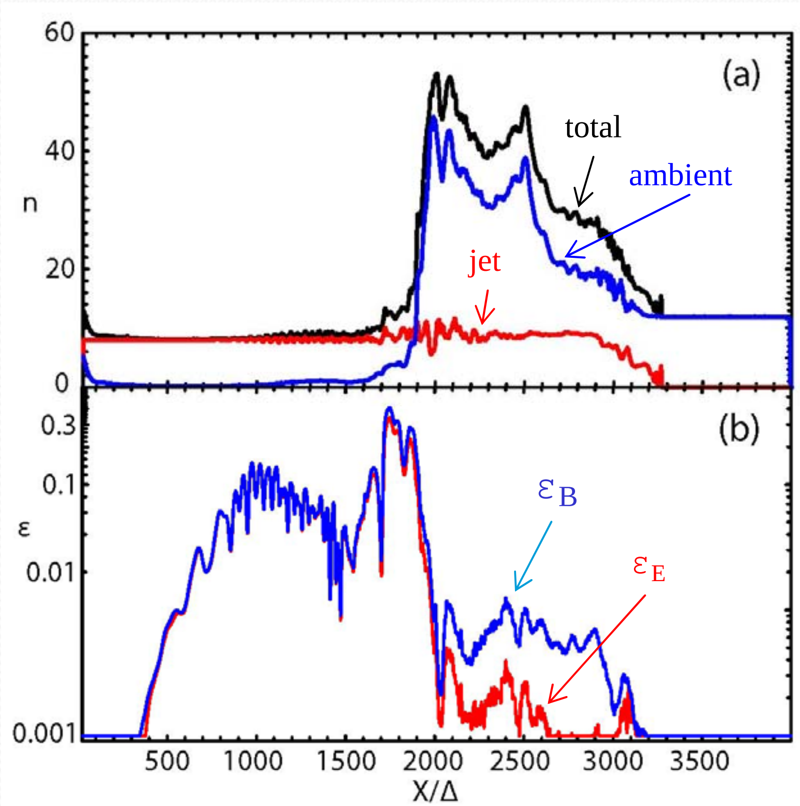
Phase space of electrons in the $x/\Delta - \gamma v_x$ at $t = 3250\omega_{pe}^{-1}$.
Red dots show jet electrons which are injected from the left with $\gamma v_x = 15$

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

Shock velocity and bulk velocity

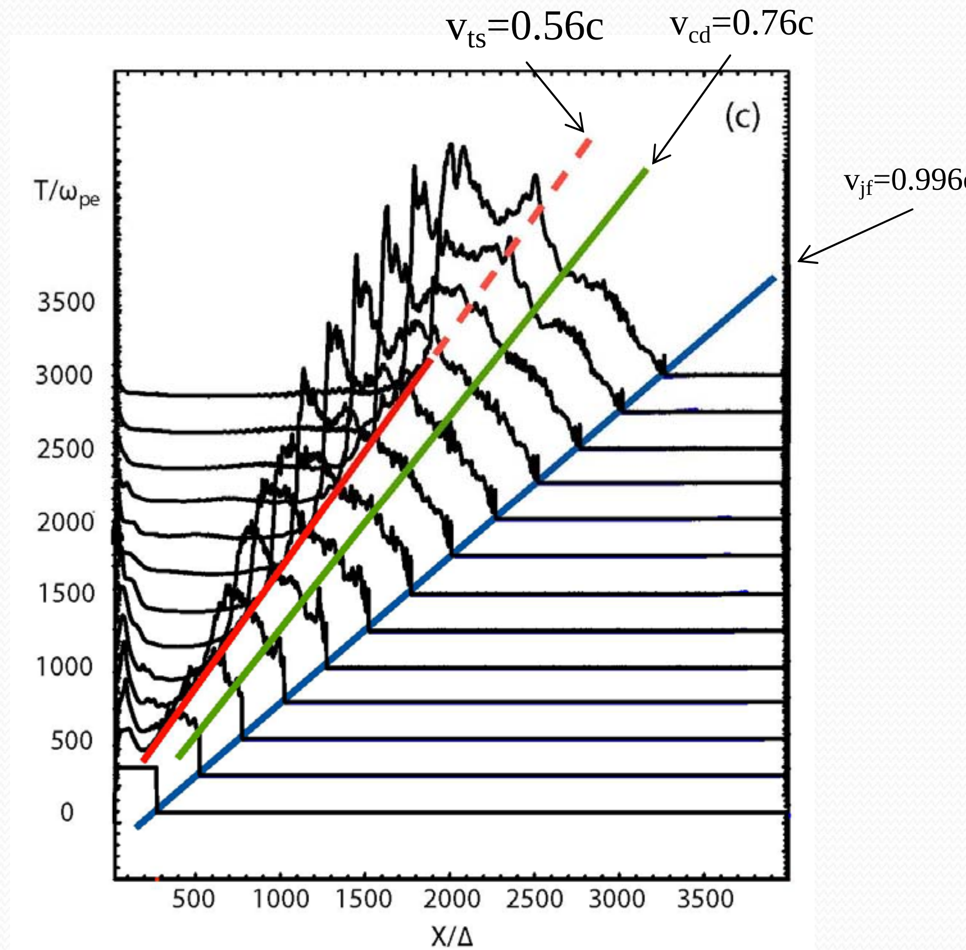


Shock formation, forward shock, reverse shock



(a) electron density and (b) electromagnetic field energy (ε_B, ε_E) divided by the total kinetic energy at t = $3250\omega_{pe}^{-1}$

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



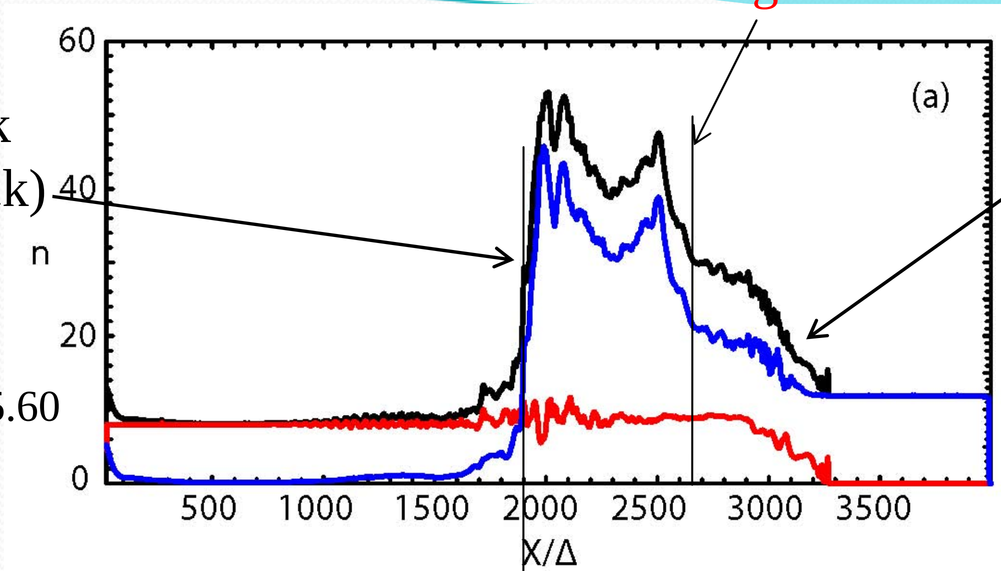
Time evolution of the total electron density. The velocity of jet front is nearly c, the predicted contact discontinuity speed is 0.76c, and the velocity of trailing shock is 0.56c.

Shock velocity and structure based on 1-D HD analysis

moving contact discontinuity

trailing shock
(reverse shock)

leading shock
(forward shock)



(Nishikawa et al. 2009)

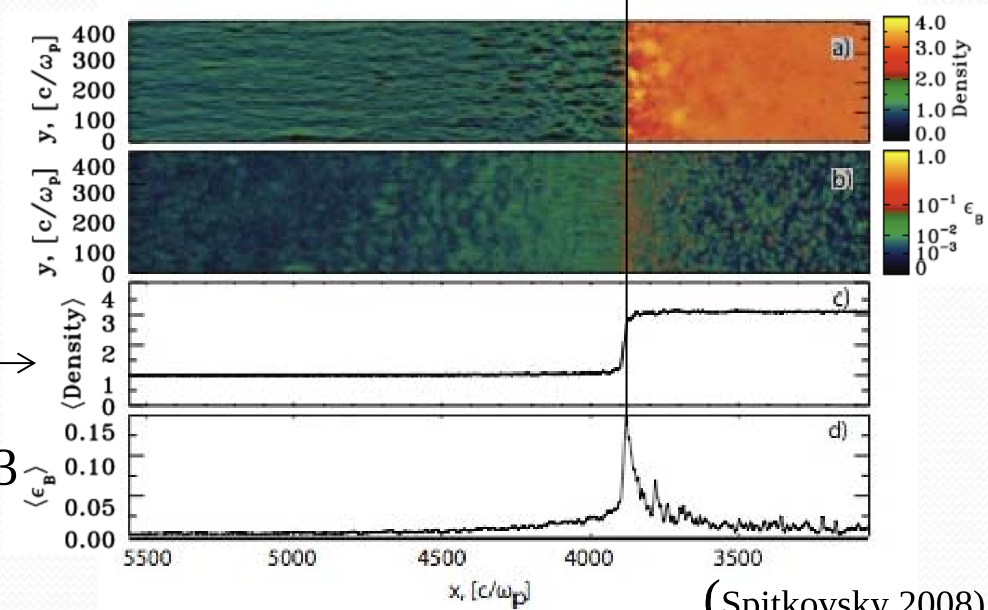
in CD frame

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

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

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

fixed CD



Density →

$n_2/\gamma_0 n_1 = 3.13$

$\beta_c = 0.47$

$\gamma_0 = 15$

0

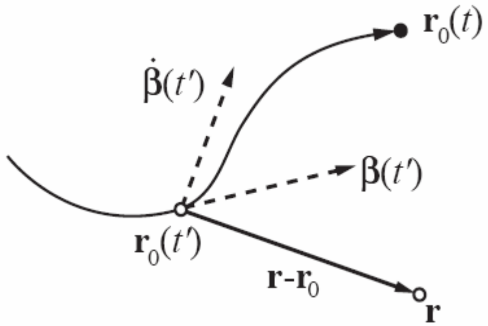
(Spitkovsky 2008)

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



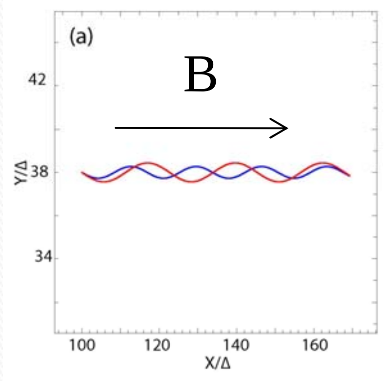
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

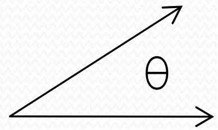
Hededal, Thesis 2005 (astro-ph/0506559)
Nishikawa et al. 2008 (astro-ph/0802.2558)
Sironi & Spitkovsky, 2009 (astro-ph/0908.3193)
Martins et al. 2009, Proc. of SPIE Vol. 7359

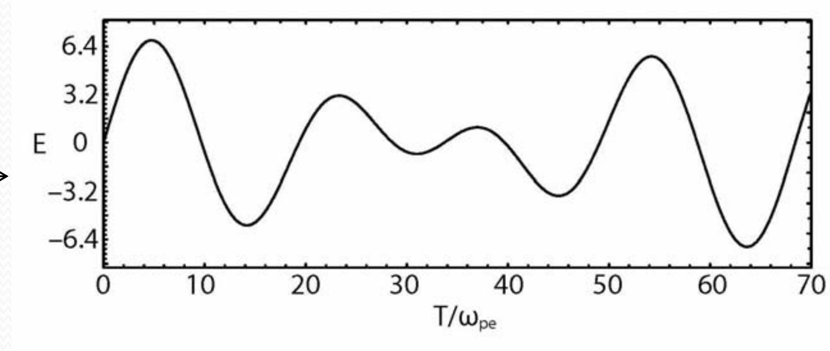
Synchrotron radiation from propagating electrons in a uniform magnetic field

electron trajectories

radiation electric field observed at long distance





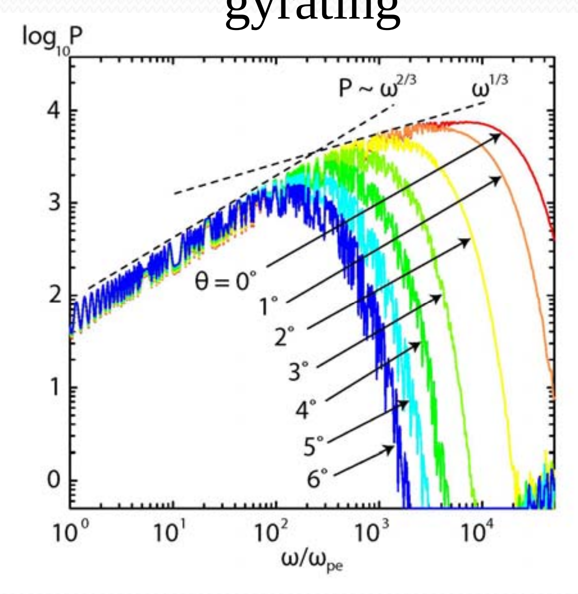


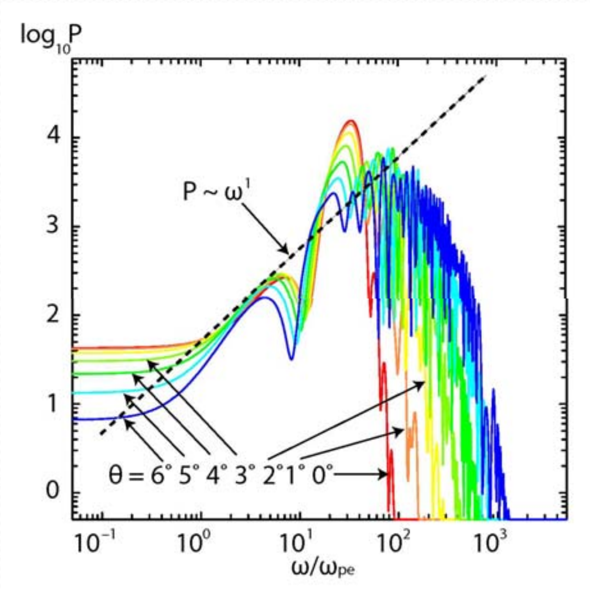
observer

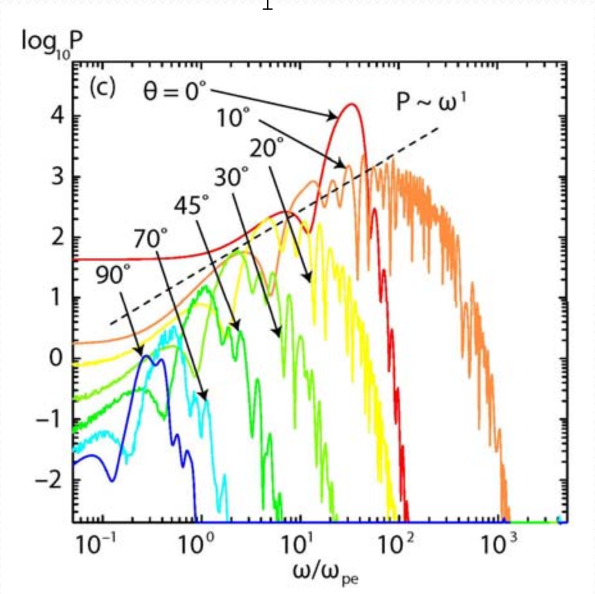
spectra with different viewing angles

$\theta_\Gamma = 4.25°$

gyrating







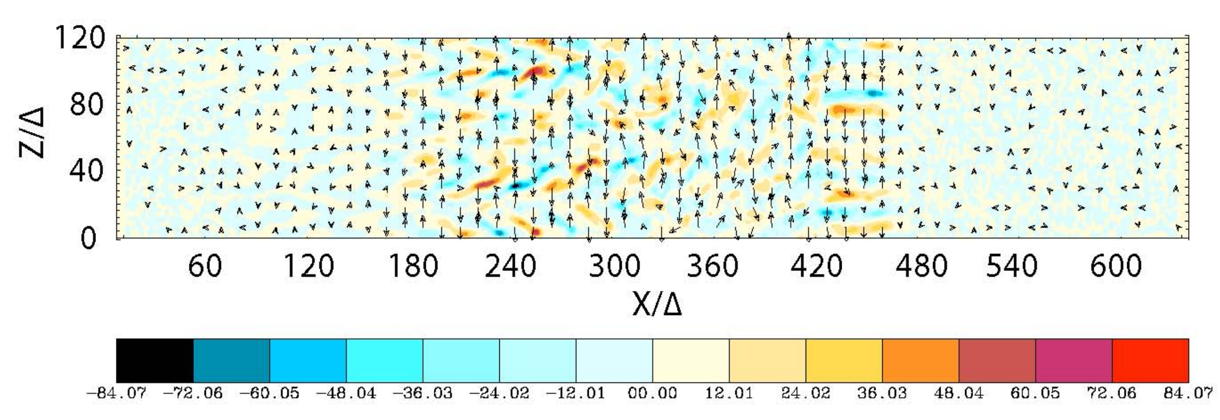
Nishikawa et al. astro-ph/0809.5067

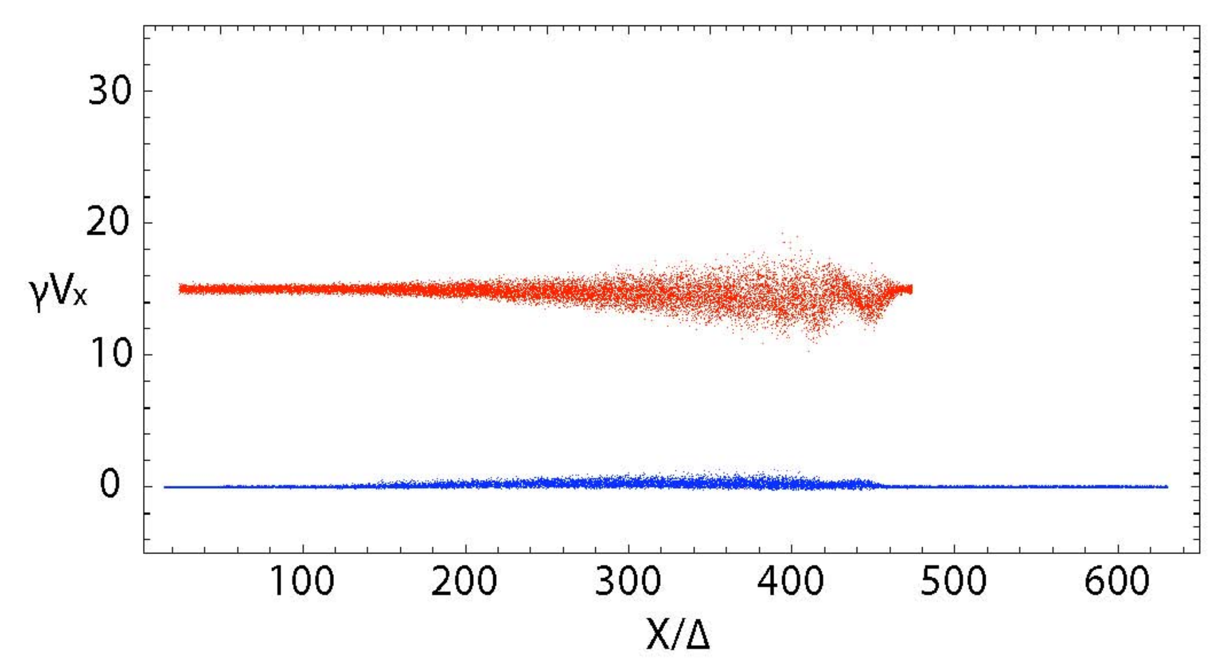
Jitter radiation from electrons by tracing trajectories self-consistently

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

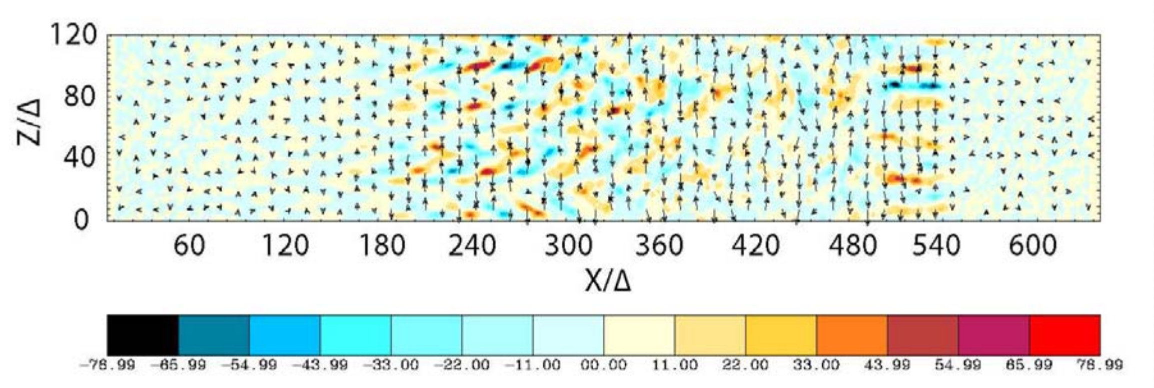
dt = 0.005 ω_{pe}^{-1}

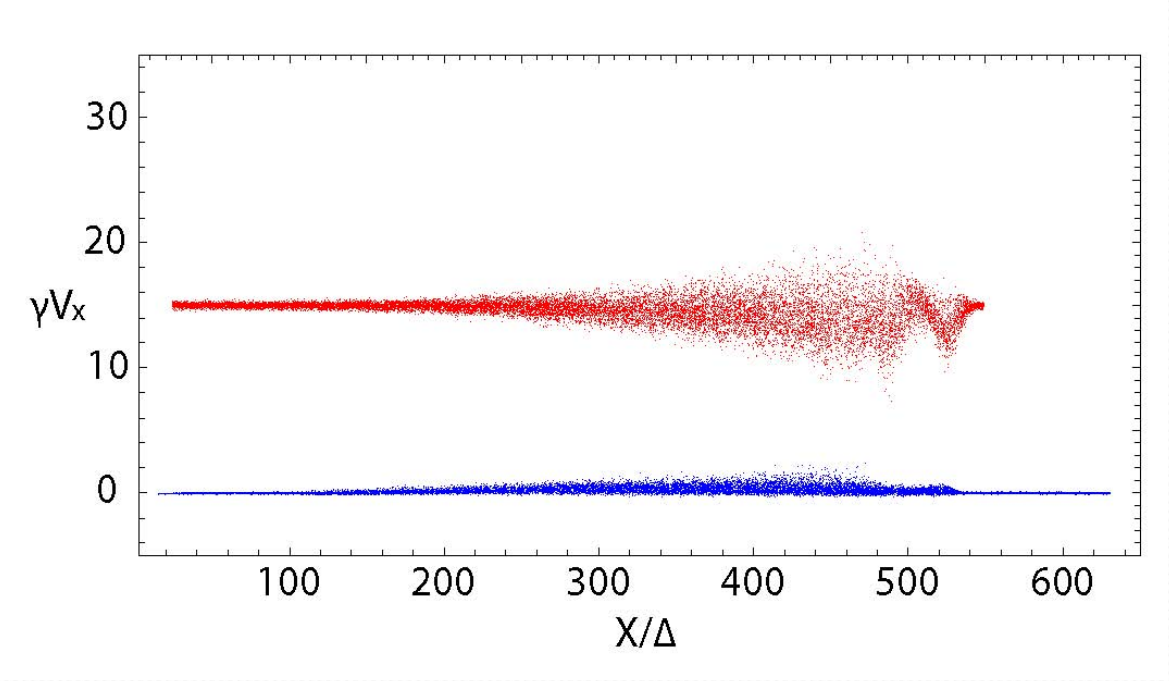
ω_n = 100

θ_n = 2

Δxjet = 75Δ

Δt_{jitt} = 75 ω_{pe}^{-1}

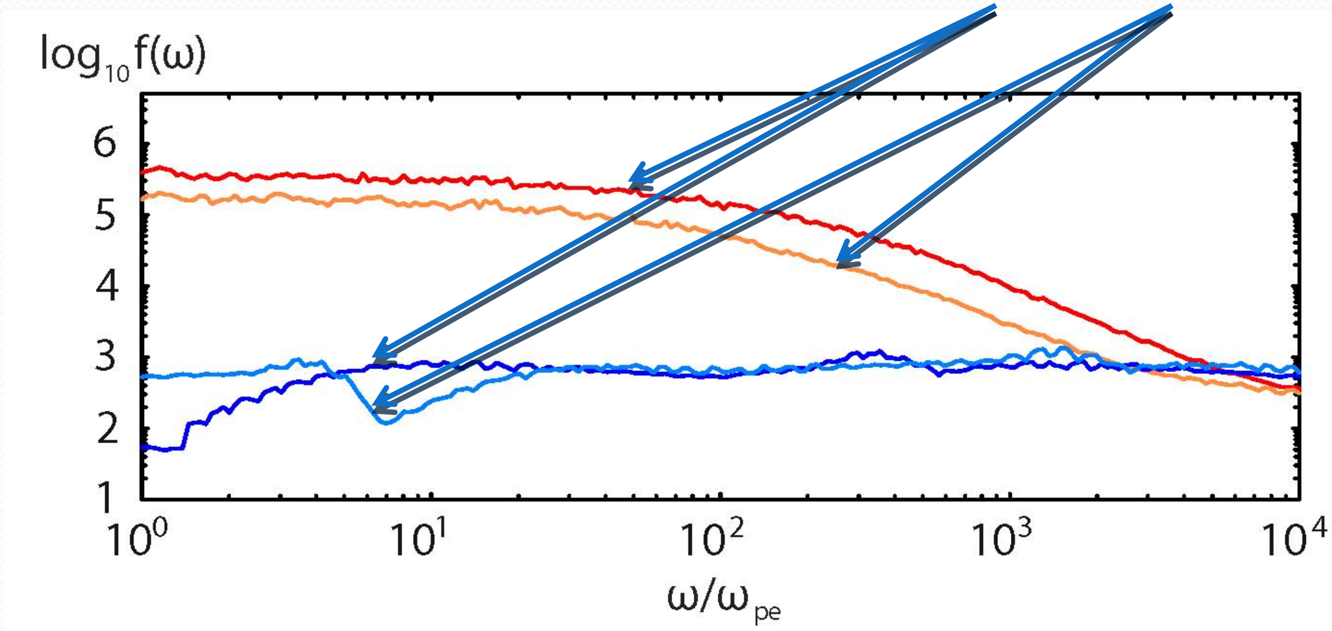




Calculated spectra for jet electrons and ambient electrons

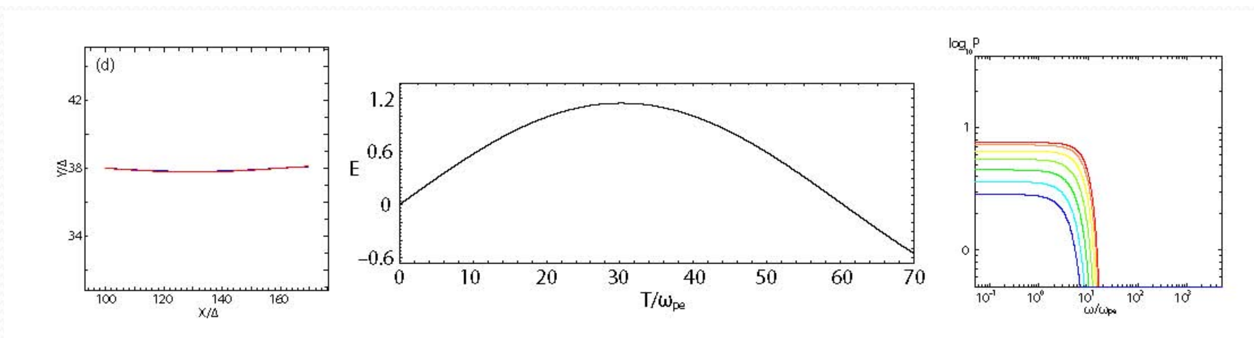
$\gamma = 15$

$\theta = 0°$ and $5°$



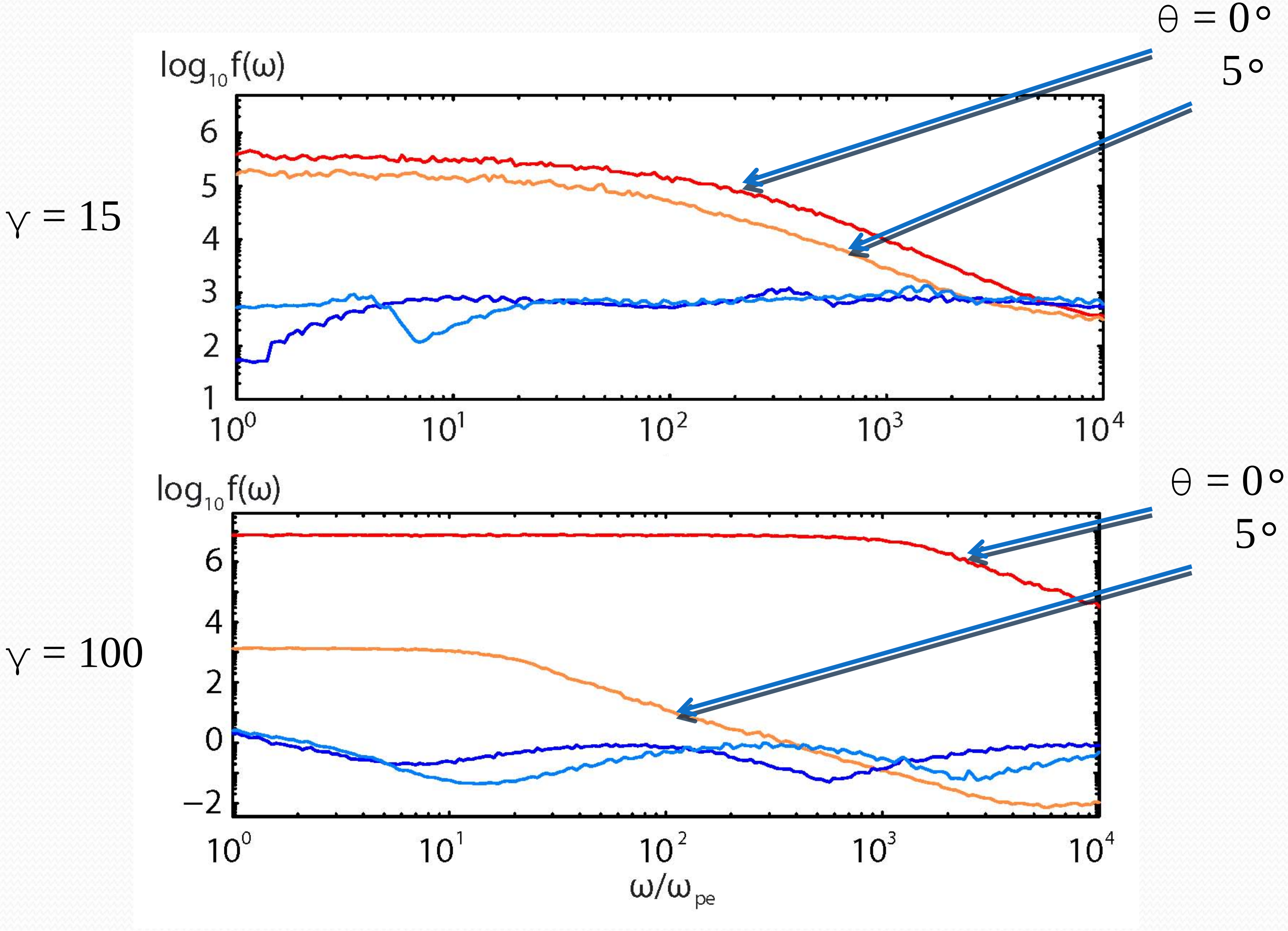
Case D

$\gamma = 7.11$



Nishikawa et al. 2009 (arXiv:0906.5018)

Dependence on Lorentz factors of jets



Future plans of our simulations of relativistic jets

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

- Simulations with magnetic fields including turbulent magnetic fields

- Non-relativistic jet simulations for understanding SNRs

- Further examination and improvement with numerical Cherenkov radiation and other issues

- Construct an overview on PIC, Monte Carlo simulations, Diffusive Shock Acceleration and other methods