Radiation from accelerated particles in relativistic jets with shocks, shear-flow and reconnections

Ken Nishikawa
UAH/CSPAR

Collaborators:

B. Zhang (*Univ. Nevada, Las Vegas*)
E. J. Choi (*KAIST*)
K. W. Min (*KAIST*)
J. Niemiec (*Institute of Nuclear Physics PAN*)
M. Medvedev (*Univ. of Kansas*)
P. Hardee (*Univ. of Alabama, Tuscaloosa*)
Y. Mizuno (*National Tsing Hua University, Taiwan*)
Å. Nordlund (*Neils Bohr Institute*)
J. Frederiksen (*Neils Bohr Institute*)
H. Sol (*Meudon Observatory*)
M. Pohl (*U-Potsdam/DESY*)
D. H. Hartmann (*Clemson Univ.*)

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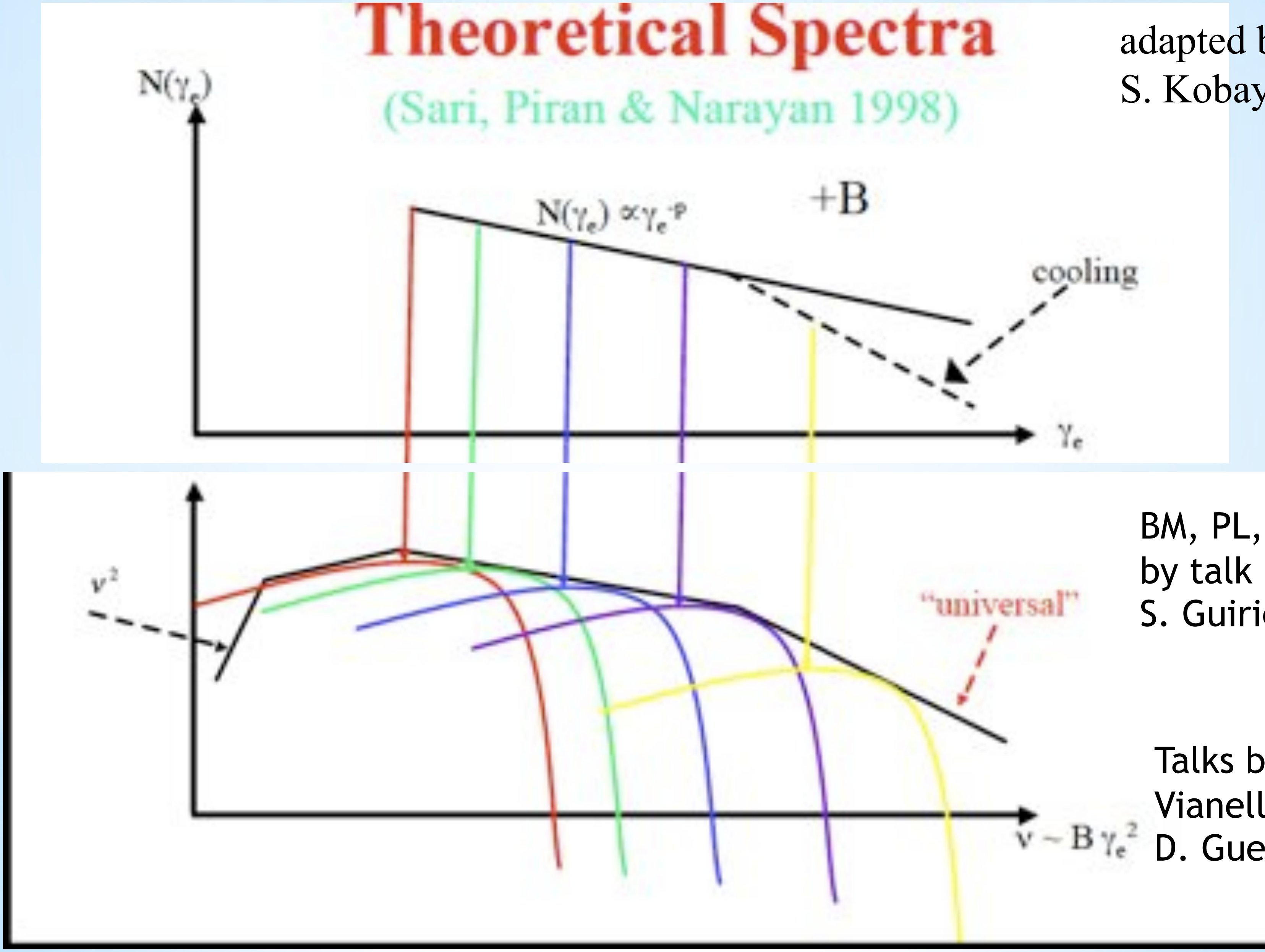
Outline

1. Standard radiation mode
2. Self-consistent radiation method using PIC simulations
3. Synthetic spectra in shocks generated by the Weibel instability
4. Importance of reconnection in relativistic jet
5. Strong magnetic field amplification with magnetic fields
6. Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability
7. Summary
8. Future plans

Present theory of Synchrotron radiation

- Fermi acceleration (Monte Carlo simulations are not self-consistent; particles are crossing the shock surface many times and remain accelerated, the strengths of turbulent magnetic fields are assumed), Some simulations exhibit Fermi acceleration (Spitkovsky 2008)
- The strength of magnetic fields is estimated based on equipartition - magnetic field energy is comparable to the thermal energy): $\varepsilon_B \sim u(T)$
- The distribution of accelerated electrons is approximated 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

BM, PL, BB
by talk by
S. Guiriec

Talks by G.
Vianello and
D. Guetta

Self-consistent calculation of radiation

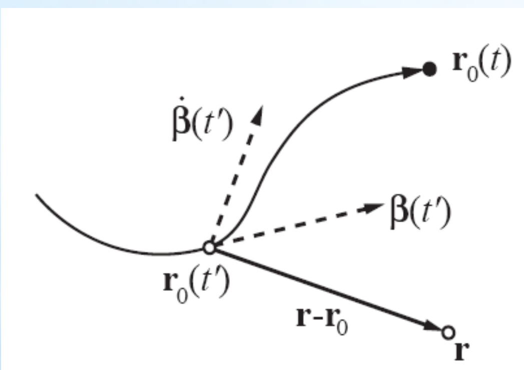
- Electrons are accelerated by the electromagnetic field generated by the Weibel instability and KKHI (without the assumption used in test-particle simulations for Fermi acceleration)
- Radiation is calculated using the particle trajectory in the self-consistent turbulent magnetic field
- This calculation includes Jitter radiation (Medvedev 2000, 2006) which is different from standard synchrotron emission
- Radiation from electrons in our simulation is reported in Nishikawa et al. Adv. Sci. Rev, 47, 1434, 2011.

Radiation from particles in collisionless shock

To obtain a spectrum, "just" integrate:

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

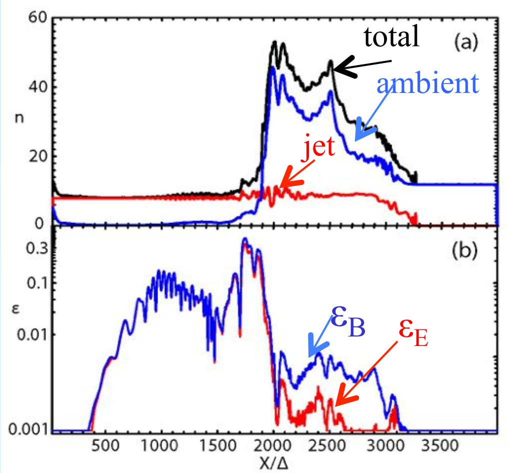
where $\mathbf{r}_0$ is the position, β the velocity and $\dot{\beta}$ the acceleration



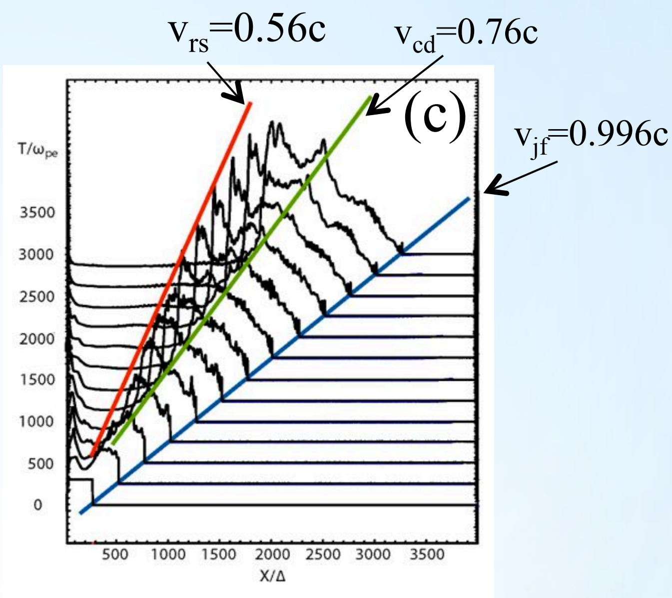
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

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
Frederiksen et al. 2010, ApJL

Shock formation, forward shock, reverse shock



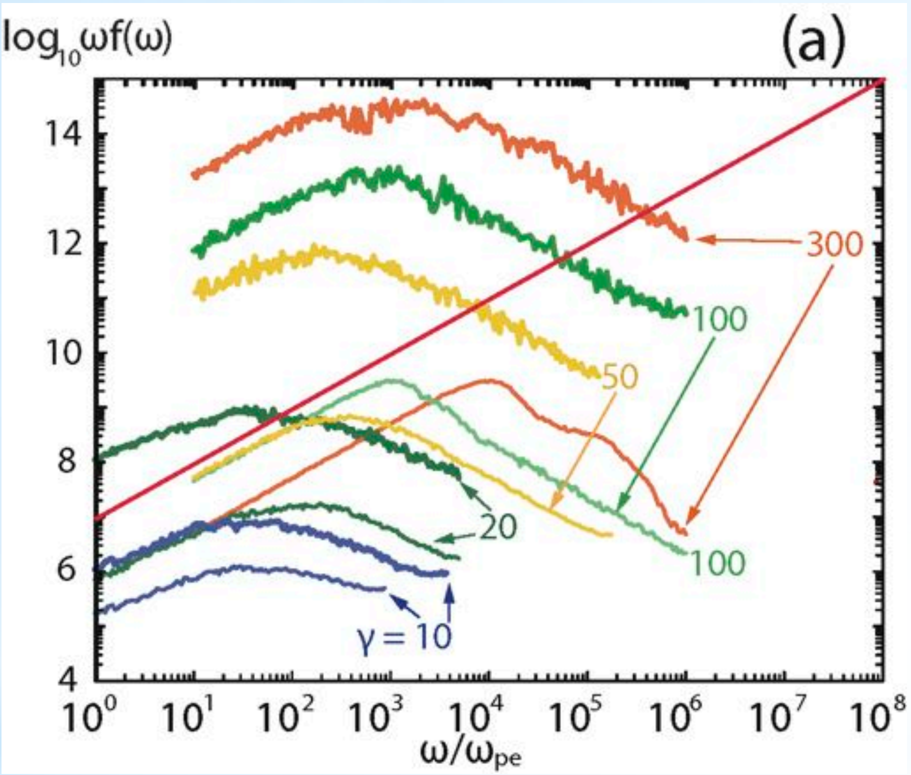
(a) electron density and (b) electromagnetic field energy (ε_B, ε_E) divided by the total kinetic energy at $t = 3250\omega_{pe}^{-1}$



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

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

Synthetic spectra with different Lorentz factors with cold and warm thermal temperatures



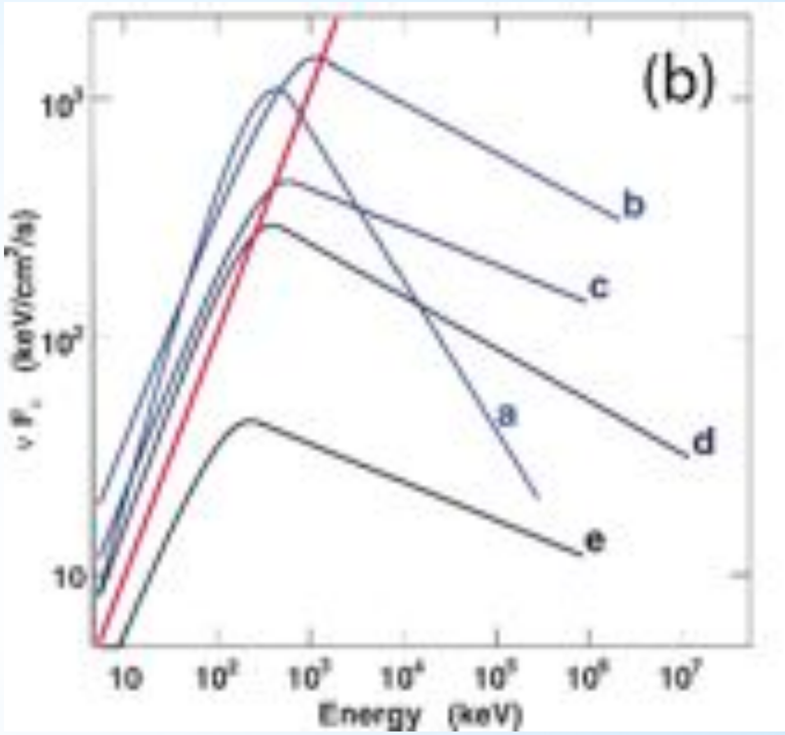


Figure a shows the spectra for the cases of γ = 10, 20, 50, 100, and 300 with cold (thin lines) and warm (thick lines) electron jets. Fig. b shows modeled Fermi spectra in vF units at early (a) to late (e) times (Abdo et al. 2009). The red lines indicate slope in vF ~ 1

Radiation in a larger system

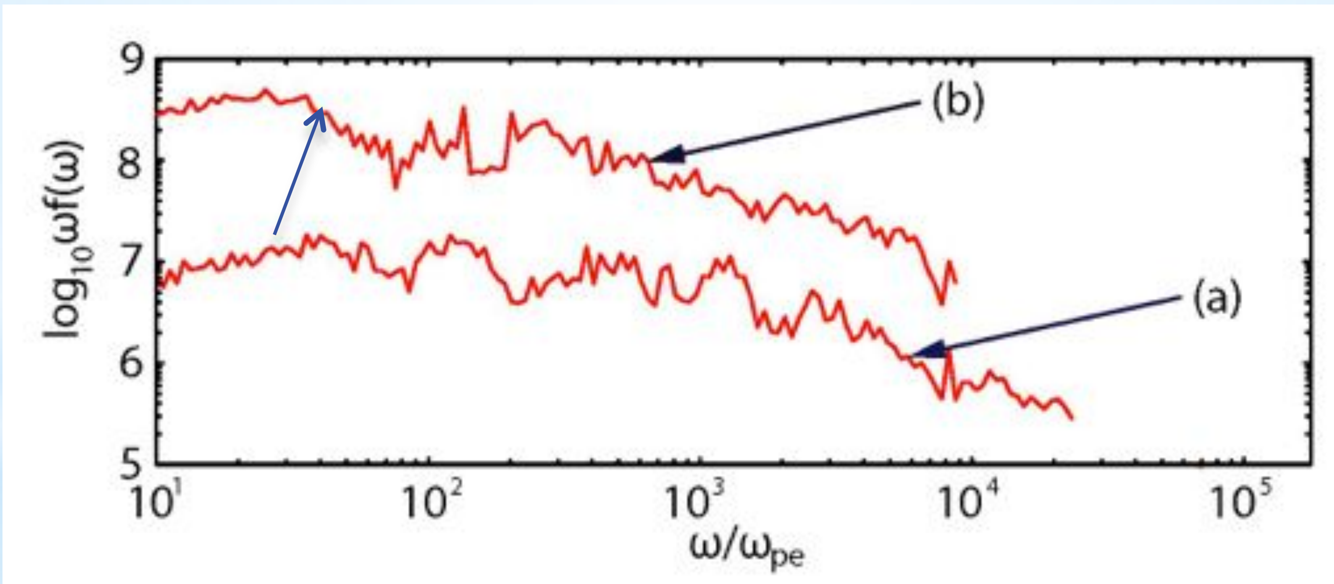
System size: 8000 × 240 × 240

Electron-positron: $\gamma = 15$

Sampled particles 115,200

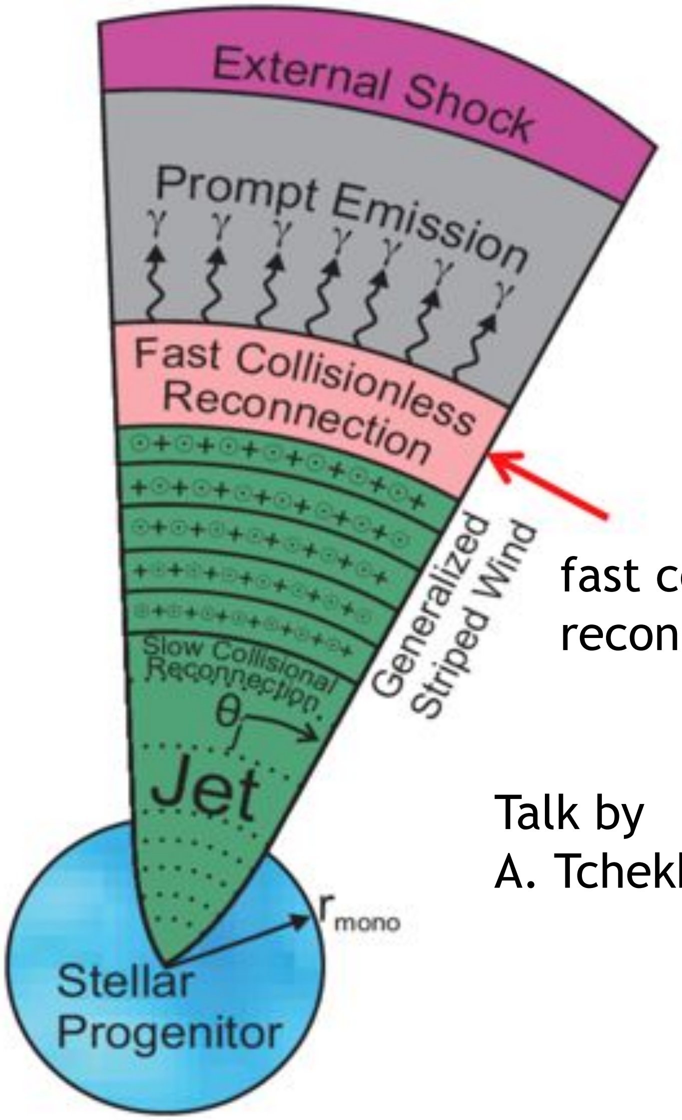
(a) $150\,\omega_{pe}^{-1} \leq t \leq 225\,\omega_{pe}^{-1}$

(b) $200\,\omega_{pe}^{-1} \leq t \leq 275\,\omega_{pe}^{-1}$



Nishikawa et al. in progress

Reconnection in jet

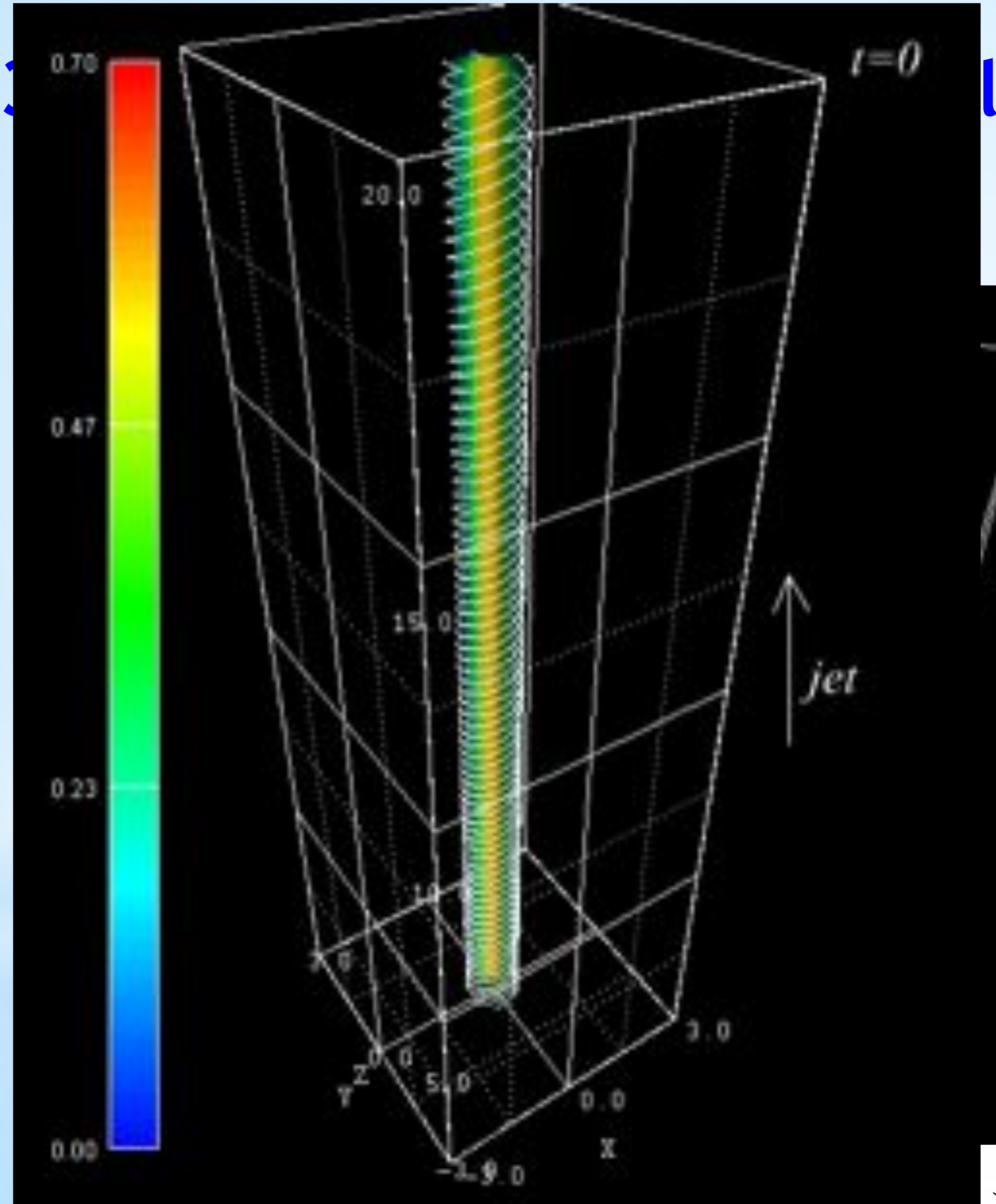


fast collisionless reconnection

Talk by
A. Tchekhovskov

Reconnection switch concept: Collapsar model or some other system produces a jet (with opening half-angle θ_j) corresponding to a generalized stripped wind containing many field reversals that develop into dissipative current sheets (McKinney and Uzdensky, 2012, MNRAS, 419, 573). This reconnection needs to be investigated by resistive RMHD, which is in progress within our research effort.

lical magnetic field

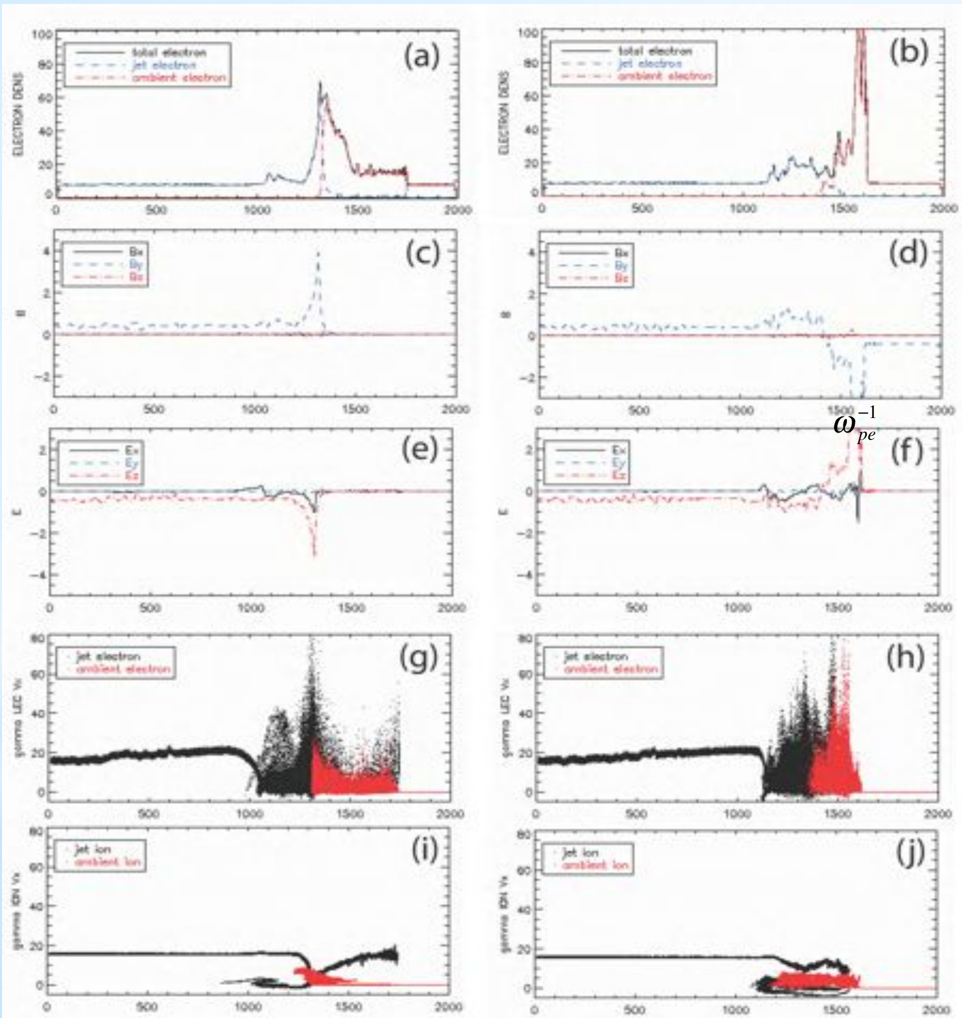


(Mizuno et al. ApJ, 734:19 (18pp), 2011)

Relativistic jet with helical magnetic field, which leads to the kink instability and subsequent reconnection, can be simulated using resistive relativistic MHD (this simulation was performed with ideal RMHD code).

Simulations with magnetic field in jets

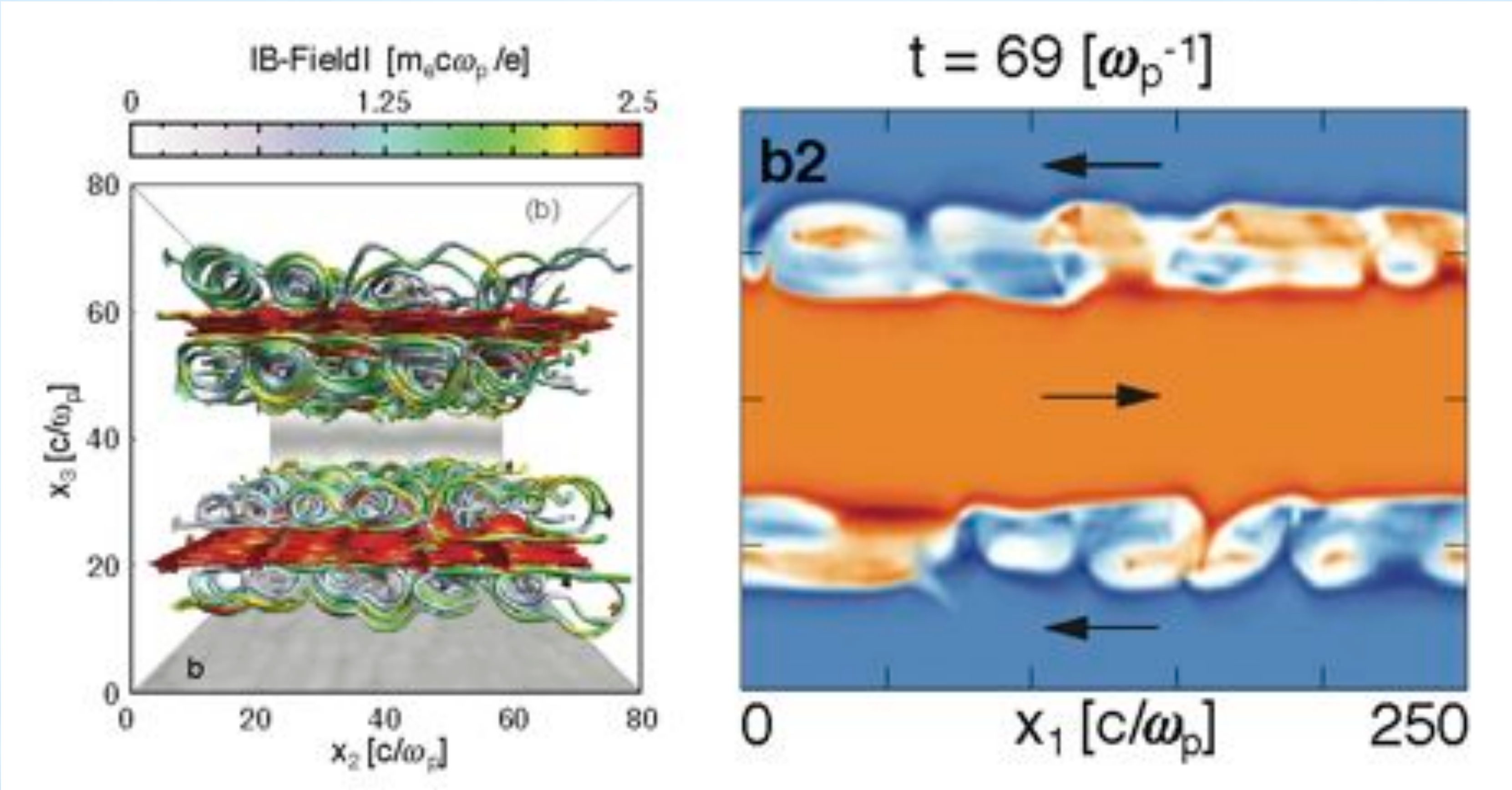
no magnetic field anti-parallel magnetic field



Snapshots for unmagnetized ambient plasma (left column) and anti-parallel magnetic field in the ambient plasma (right column) at t = 1450 ω_{pe}^{-1} (Choi, Min, and Nishikawa, 2012). The averaged values of electron density (a) and (b), magnetic field (c) and (d), electric field (e) and (f), phase space of electrons (g) and (h), and phase space of ions (i) and (j). Reconnection occurs for the case of anti- parallel magnetic fields and is indicated by the positive E_y component in (f).

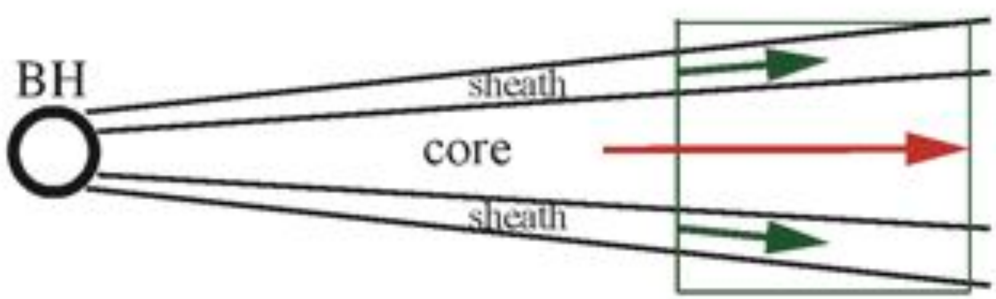
Choi, Min, KN, 2012 (in progress)

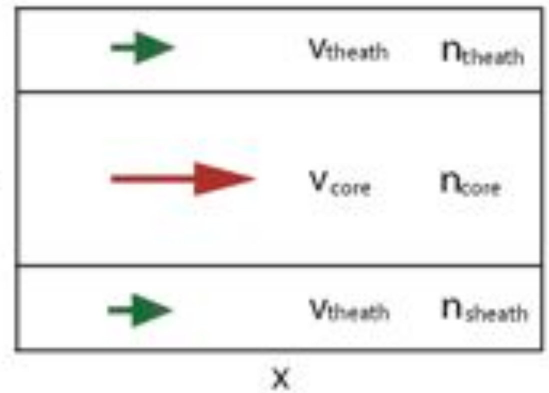
Simulations of Kinetic Kelvin-Helmholtz instability with counter-streaming flows



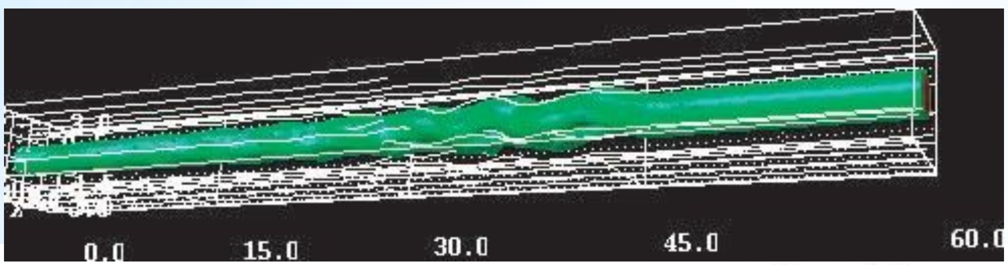
The left panel shows magnetic field lines generated in the relativistic shear scenario of Alves et al. (2012). The right panel shows the electron density in orange (blue) of the plasma that flows in the positive (negative) x_1 direction. In this panel darker regions in the color map indicate high electron density, whereas lighter regions indicate low electron density.

Simulations of KHI with core and sheath jets

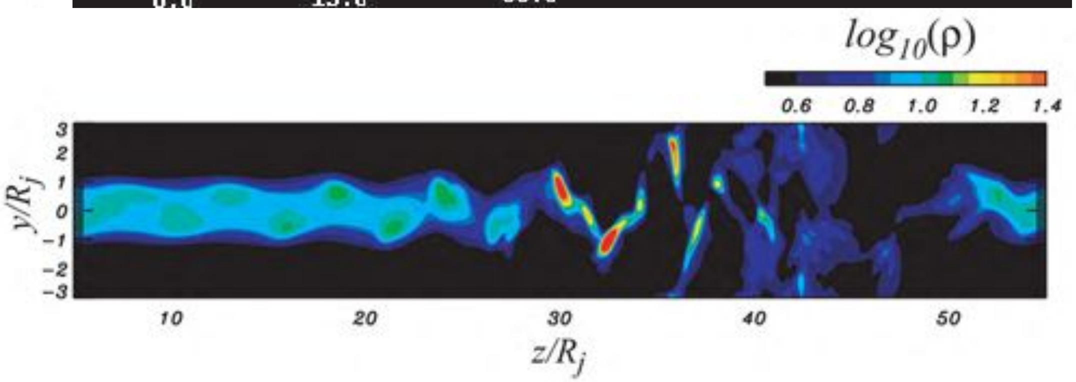


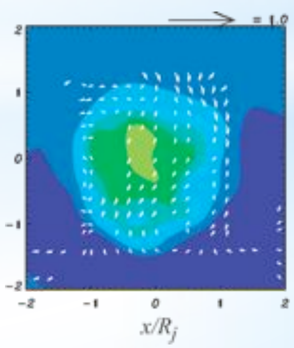


RMHD, no wind ω=0.93, time=60.0



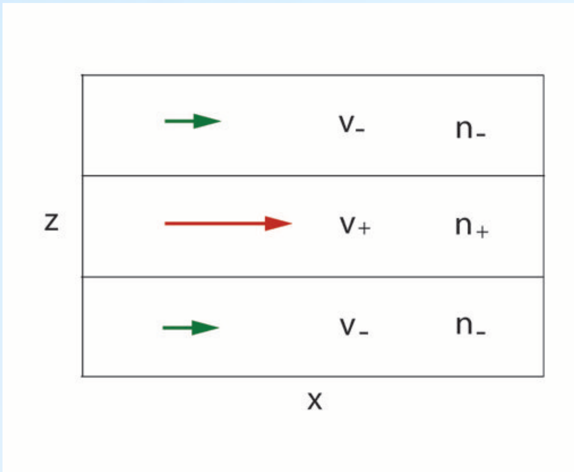
case of V_{theath} = 0





Mizuno, Hardee & Nishikawa, ApJ, 662, 835, 2007

Study of the relativistic velocity shear interface KKHI instability

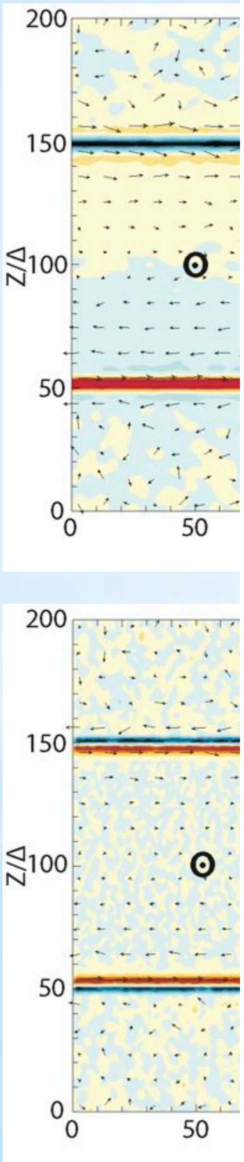


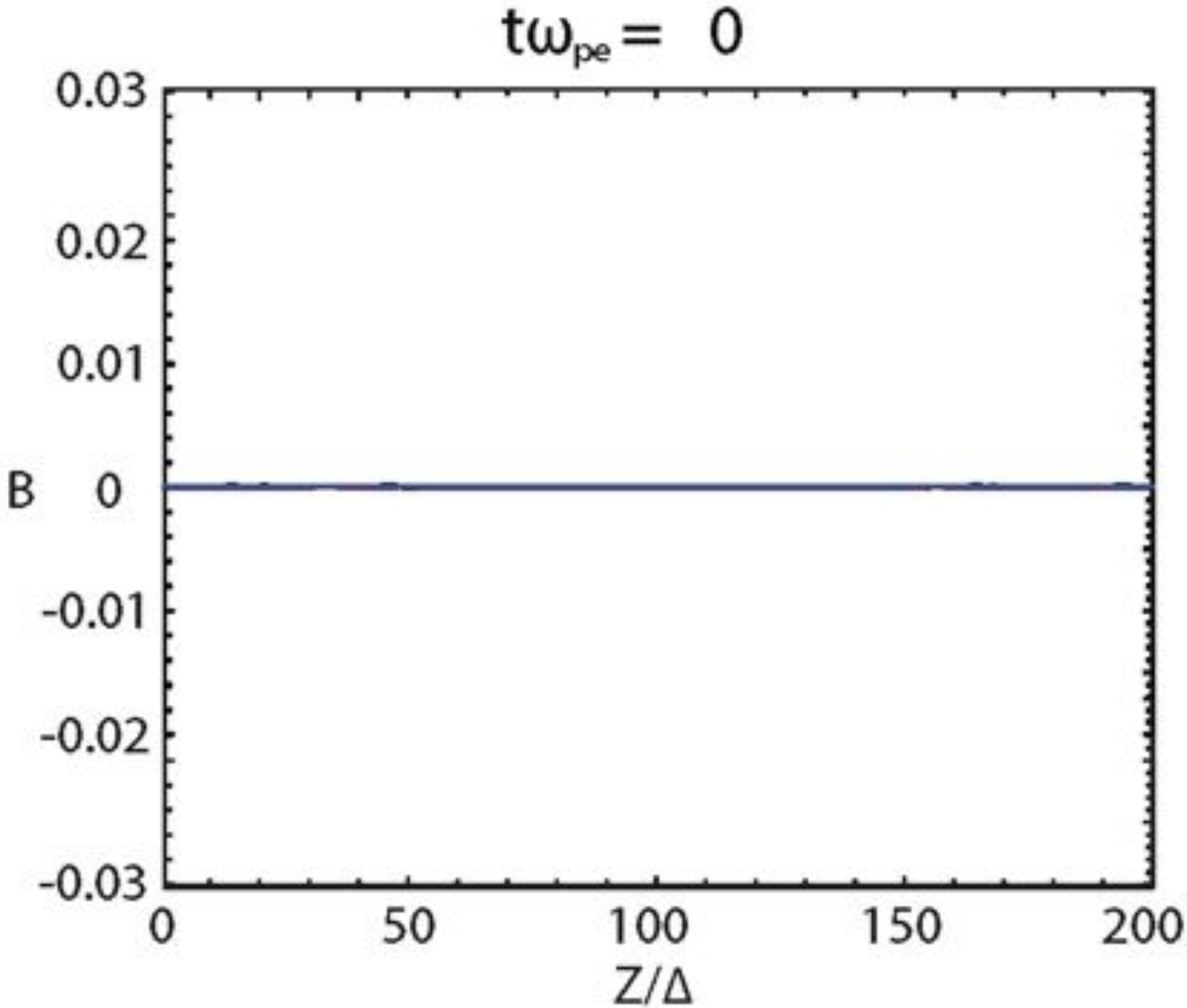
$$(k^2c^2 + \gamma_-^2\omega_{p-}^2 - \omega^2)^{1/2}(kV_- - \omega)^2[(kV_+ - \omega)^2 - \omega_{p+}^2]$$
$$+(k^2c^2 + \gamma_+^2\omega_{p+}^2 - \omega^2)^{1/2}(kV_+ - \omega)^2[(kV_- - \omega)^2 - \omega_{p-}^2] = 0$$

Low-frequency limit (V_-=0)

$$\omega \sim \frac{(\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}{(1+\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}kV_{jt} \pm i\frac{(\gamma_{jt}\omega_{p,am}/\omega_{p,jt})^{1/2}}{(1+\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}kV_{jt}.$$

New KKH


200
150
Z/Δ
100
50
0
0
50
200
150
Z/Δ
100
50
0
0
50


$t\omega_{pe} = 0$
0.03
0.02
0.01
B
0
-0.01
-0.02
-0.03
0
50
100
150
200
Z/Δ

Summary of Results

- The Weibel instability creates filamented currents and density structure along the propagation axis of the jet.
- The growth rate of the Weibel instability depends on the Lorentz factor, composition, and strength and direction of ambient B fields.
- The presence of ions in the ambient plasma enhances the strength of the generated magnetic fields due to the excitation of the ion Weibel instability.
- This enhanced magnetic field with electron-ion ambient plasma may be the cause of large upstream magnetic fields in GRB shocks.
- In order to understand the complex shock dynamics of relativistic jets, further simulations with additional physical mechanisms such as radiation loss and inverse Compton scattering are necessary.
- Spectra from two electrons were calculated for different conditions.
- The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006; Frederiksen et al. 2010, Medvedev et al 2011).
- Our new numerical approach of calculating radiation from electrons based on a self-consistent simulations provides more realistic spectra including jitter radiation.

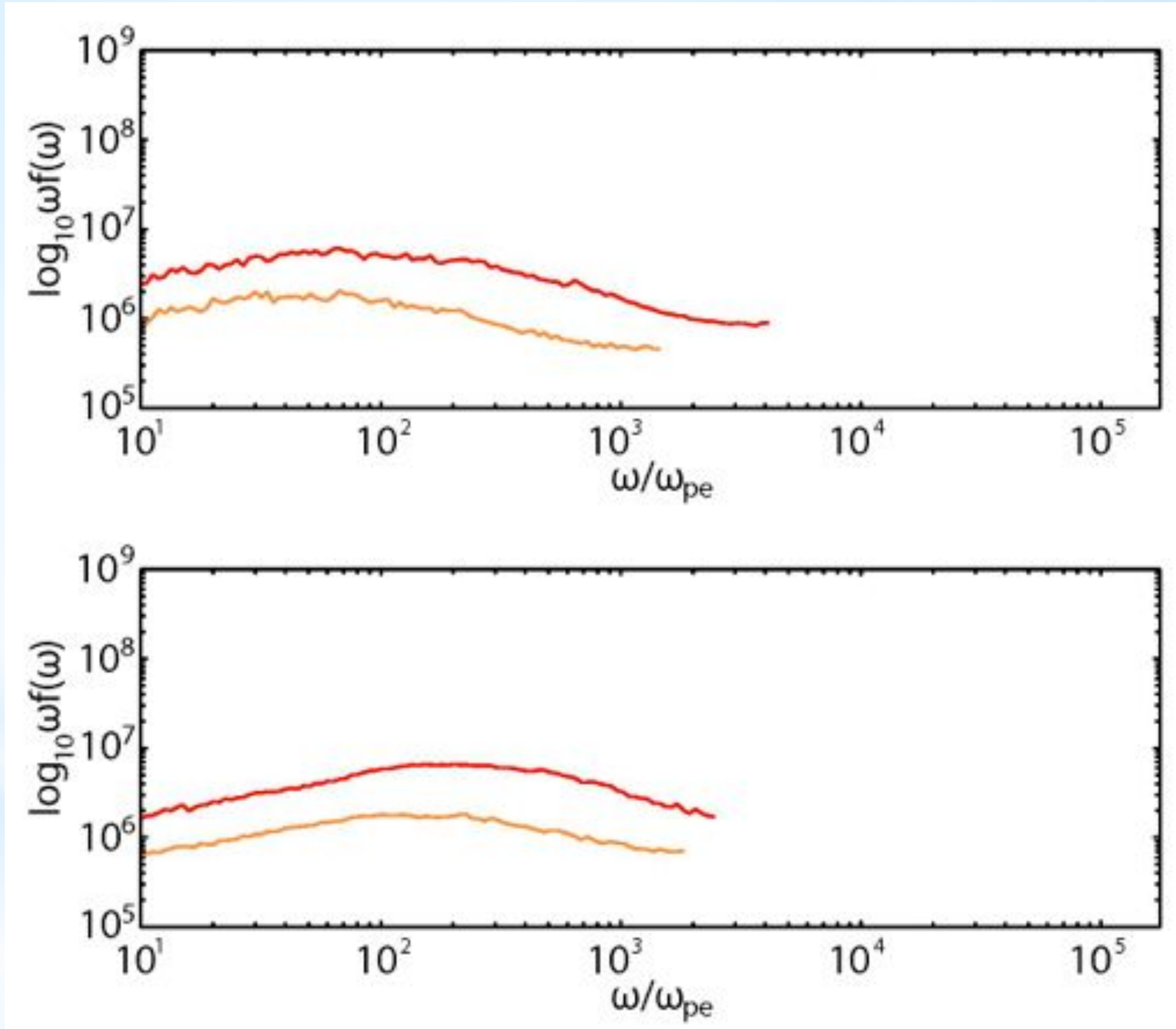
Future plans

- Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics including reconnection and KKHI.
- Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability using larger systems.
- Investigate radiation processes from the accelerated electrons in turbulent magnetic fields and compare with observations (GRBs, SNRs, AGNs, etc).

Radiation in a small system

without iteration

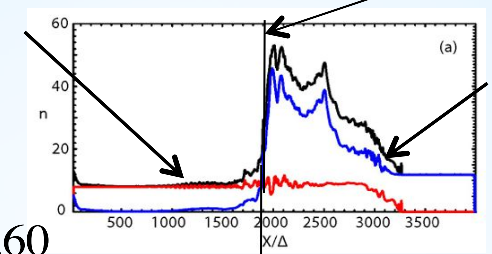
with iteration



Shock velocity and structure based on 1-D HD analysis

moving contact discontinuity (CD)

reverse shock



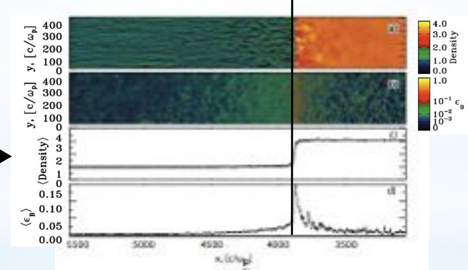
forward shock

(Nishikawa et al. 2009)

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

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

$\frac{4}{3} < \Gamma = \frac{3}{2} < \frac{5}{3}$



fixed CD

Density

$n_2/\gamma_0 n_1 = 3.13$

$\beta_c = 0.47$

$\gamma_0 = 15$

0

(Spitkovsky, ApJ, 682:L5, 2008 (adapted))