Radiation from acceleration Particles in relativistic jets with shocks and shear-flow

Ken Nishikawa *UAH/Physics*

Collaborators:

Y. Mizuno (*Goethe-Universität Frankfurt am Mein*)
P. Hardee (*Univ. of Alabama, Tuscaloosa*)
J. Niemiec (*Institute of Nuclear Physics PAN*)
A. Meli (*Unv. of Gent*)
B. Zhang (*Univ. Nevada, Las Vegas*)
I. Duțan (*Institute of Space Science, Romania*)
Å. Nordlund (*Niels Bohr Institute*)
J. Frederiksen (*Niels Bohr Institute*)
H. Sol (*Meudon Observatory*)
M. Pohl (*U-Potsdam/DESY*)
M. Medvedev (*Univ. of Kansas*)
J. Gómez (*IAA, CSIC*)

Relativistic Jets: Creation, Dynamics, and Internal Physics,
April 22, 2015

Outline of talk

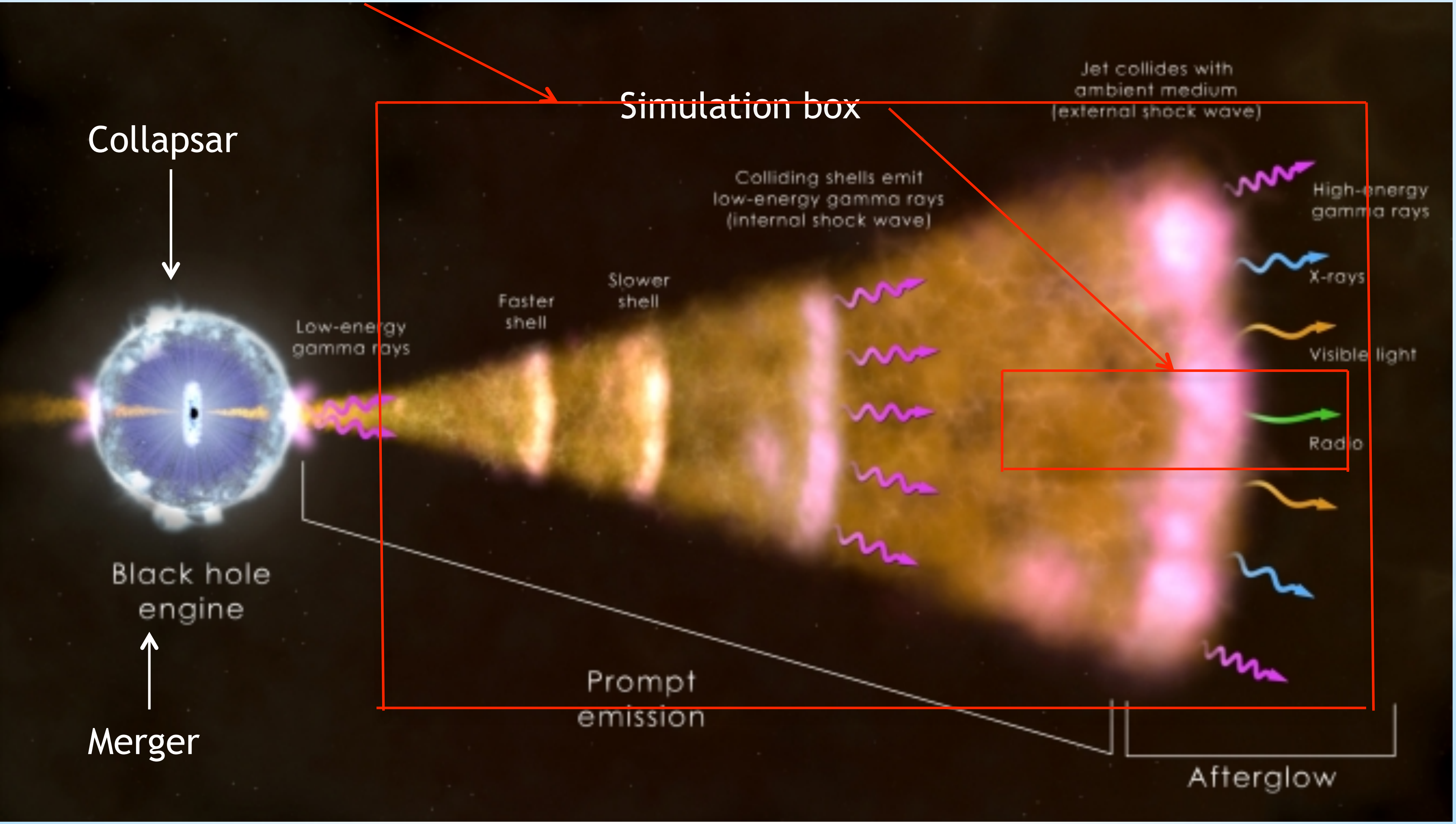
1. **Introduction and Weibel instability**
2. **Recent 3-D particle simulations of relativistic jets**
   *** $e^{\pm}$pair jet into $e^{\pm}$pair, γ= 15 and**
   electron-ion (m_i/m_e = 20) into electron-ion γ= 15
   shock structures (Choi et al. 2014, PhPl)
3. **Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability** (Nishikawa et al. 2014, ApJ)
4. **Global jet simulations with shock and KKHI**
5. **Synthetic spectra in shocks generated by the Weibel instability**
6. **Summary**
7. **Future plans**

Key Scientific questions

- How do shocks in relativistic jets evolve?
- How do magnetic fields affect shocks and reconnection?
- How are particles accelerated?
- What are the dominant radiation processes?
- How do 3-D relativistic PIC simulations reveal the dynamics of shock fronts and transition regions (CD and RS)?
- How do shocks in relativistic jets evolve in various ambient plasma- and magnetic field configurations?
- How do magnetic fields generated by the Weibel instability contribute to the emerging radiation?
- How do velocity shears generate magnetic fields and accelerate particles?
- How the Weibel instability and kKHI affect the evolution of shock with global jets?

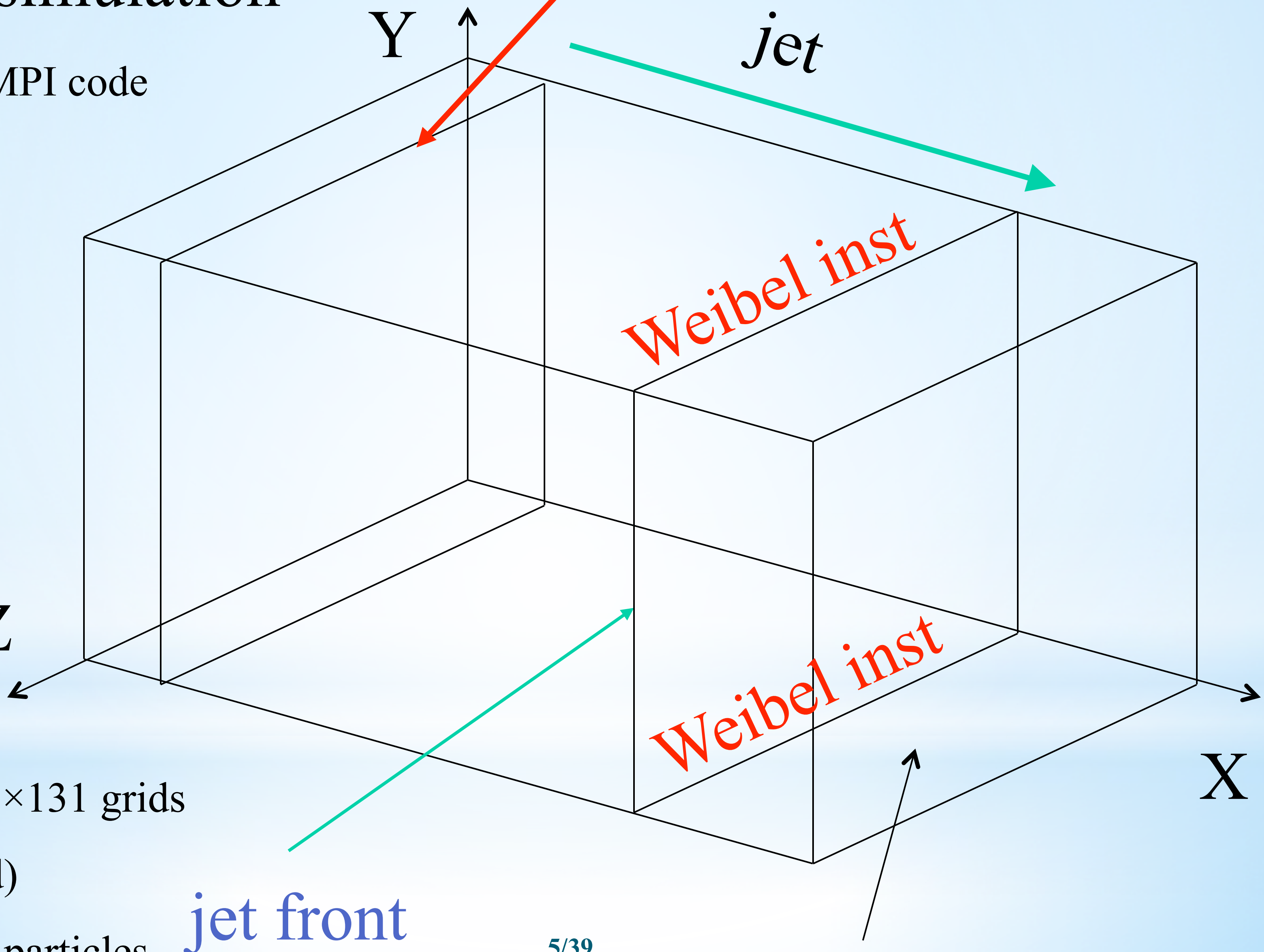
Gamma-ray bursts

Global jet simulation



3-D simulation

with MPI code



4005 ×131×131 grids

(not scaled)

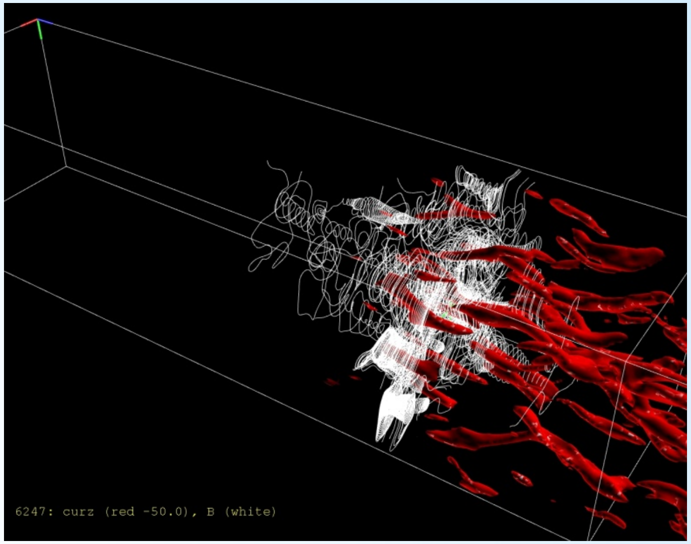
1.2 billion particles

3-D isosurfaces of z-component of current J_z for narrow jet ($\gamma v_{||}$=12.57)

electron-ion ambient $t = 59.8\omega_e^{-1}$

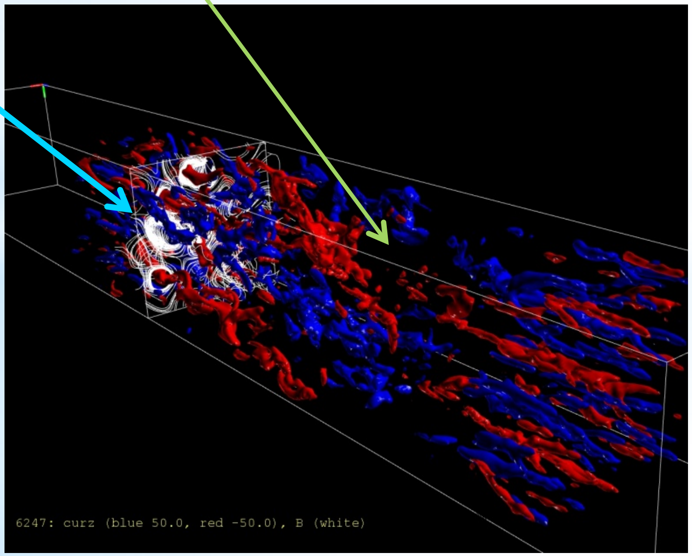
$-J_z$ (red), $+J_z$ (blue),

magnetic field lines (white)

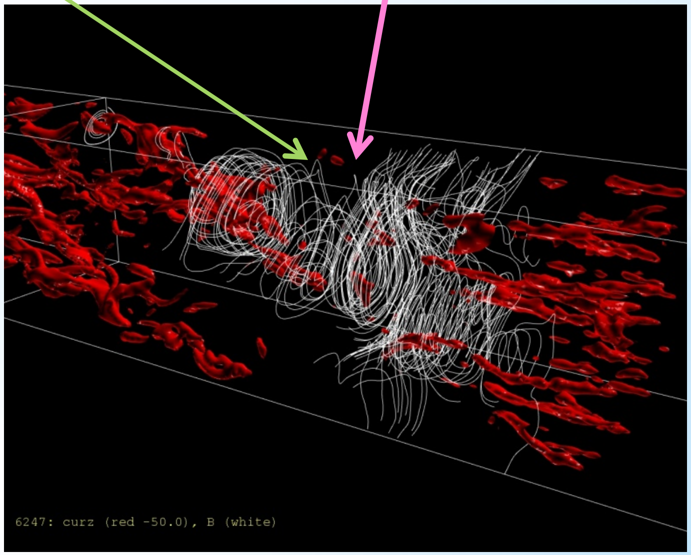


***Particle acceleration** due to the **local reconnections** during **merging current filaments** at the nonlinear stage*

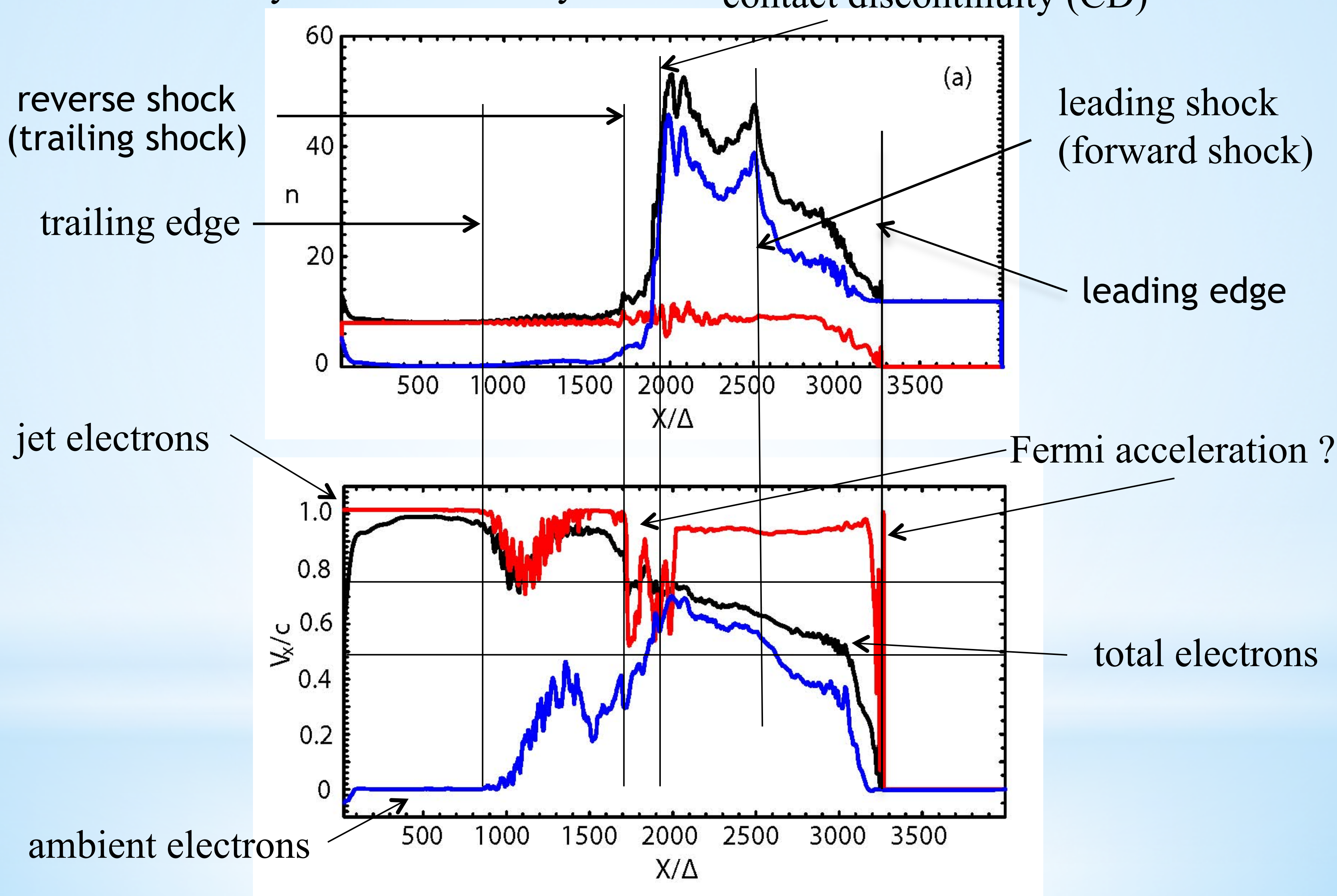
thin filaments



merged filaments



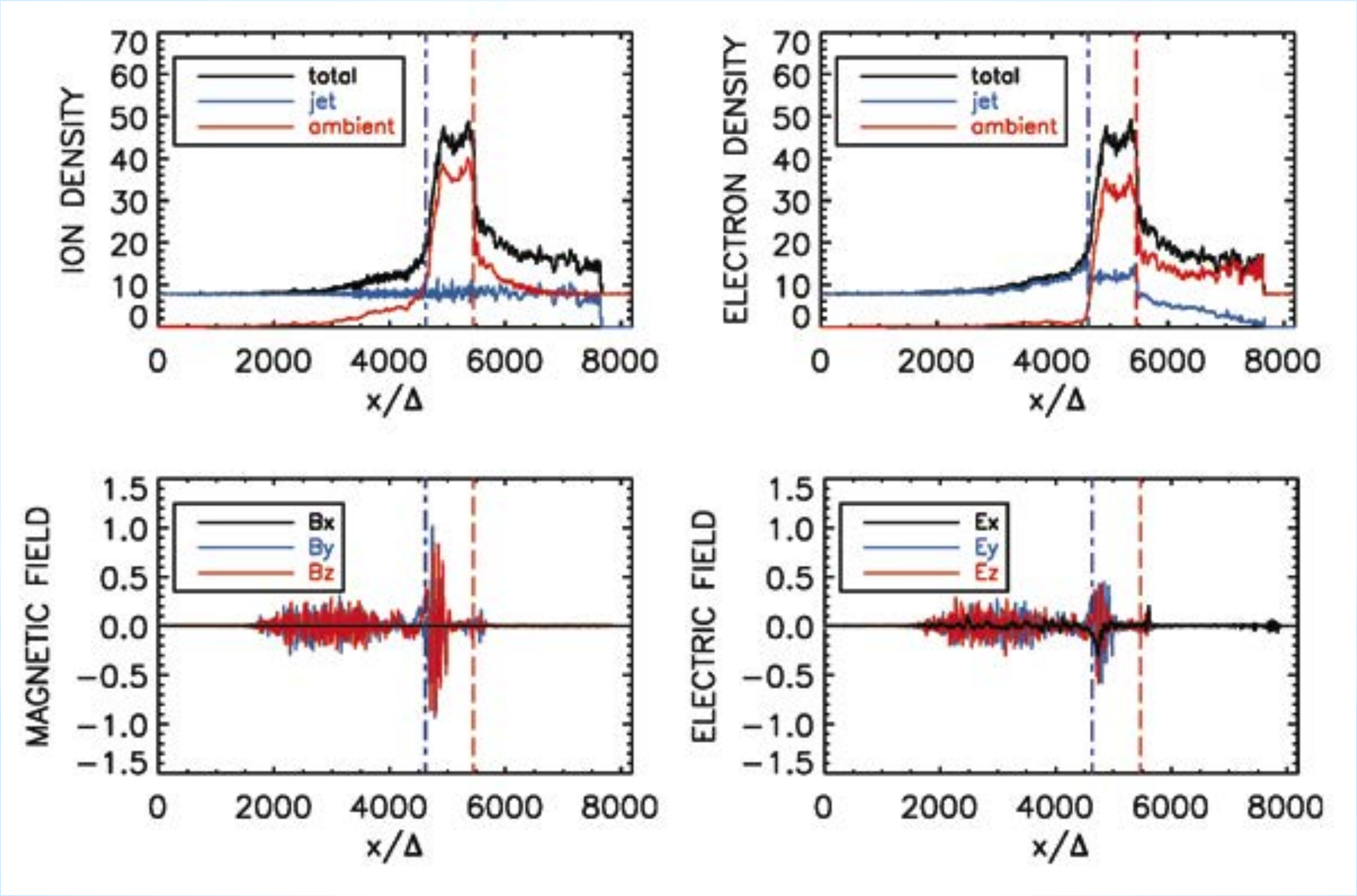
Shock velocity and bulk velocity



(Nishikawa et al. 2009)

Recent electron-ion simulation (Electrostatic shock and double layer)

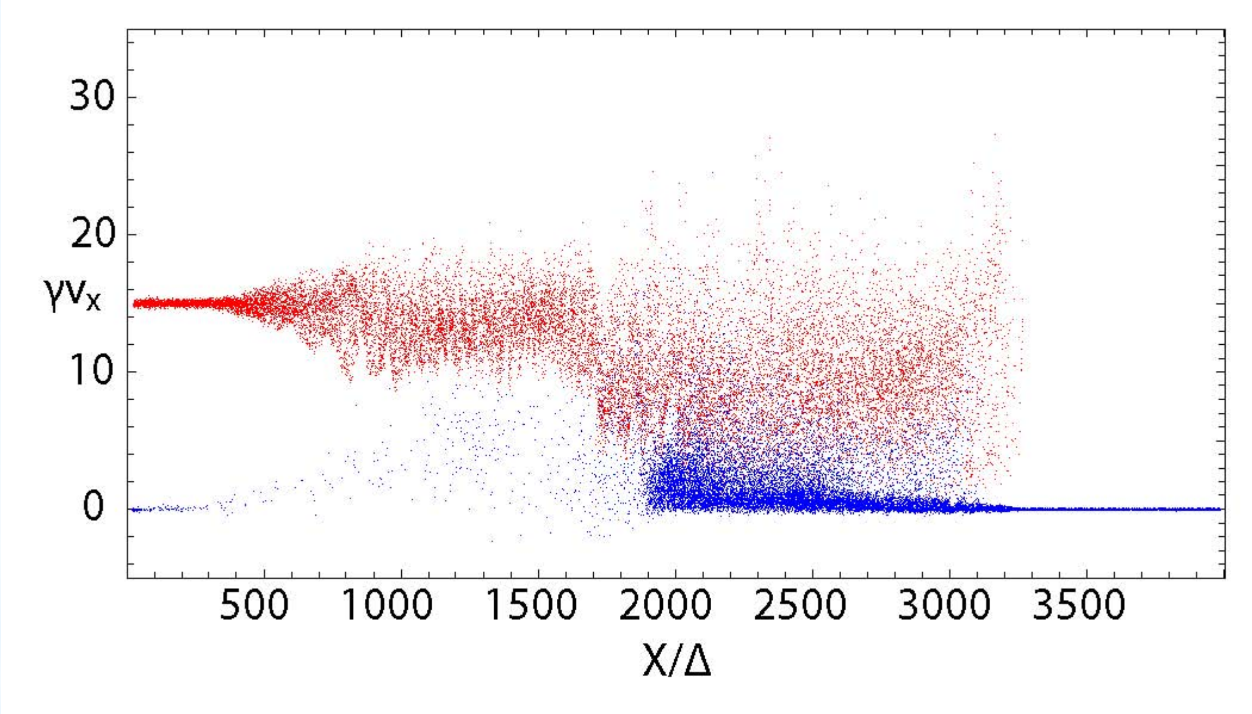
$m_i/m_e = 20$



(Choi et al. PhPl, 2014)

Phase space of electrons

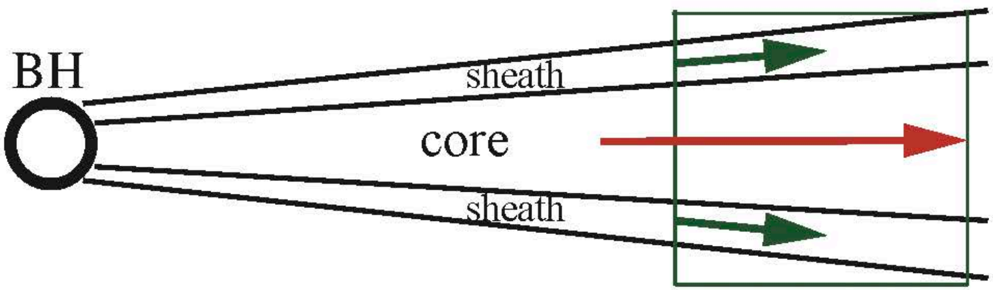
red: jet electrons, blue: ambient electrons



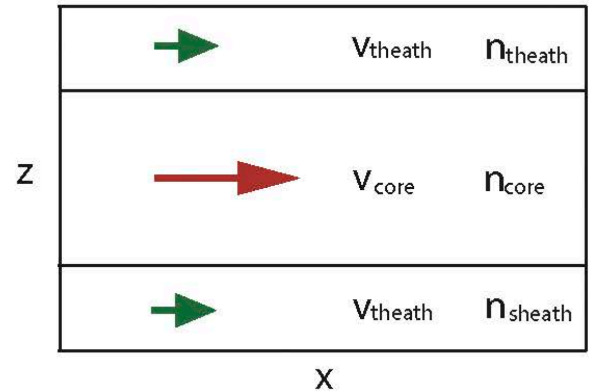
Phase space of electrons in the $x/\Delta - \gamma v_x$ at $t = 3250\omega_{pe}^{-1}$.
Red dots show jet electrons which are injected from the left with $\gamma v_x = 15$

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

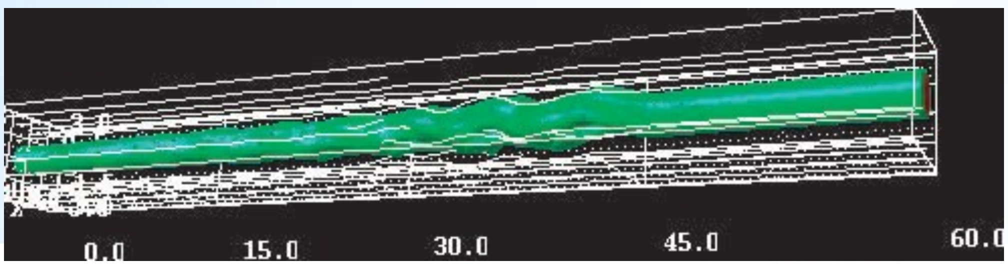
Simulations of KHI with core and sheath jets



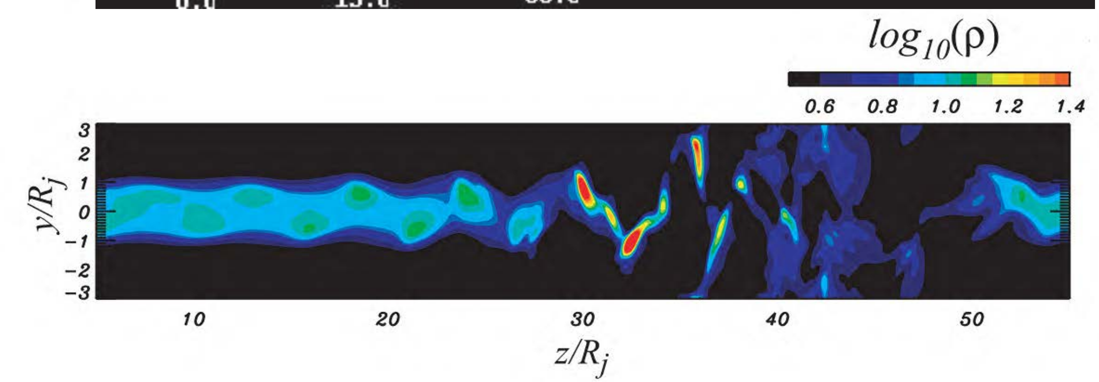
slab model

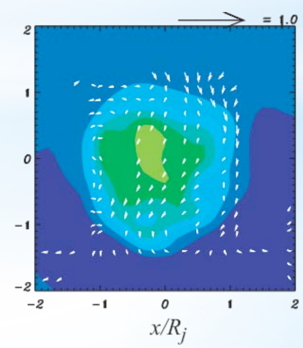


RMHD, no wind ω=0.93, time=60.0



case of $V_{theath} = 0$





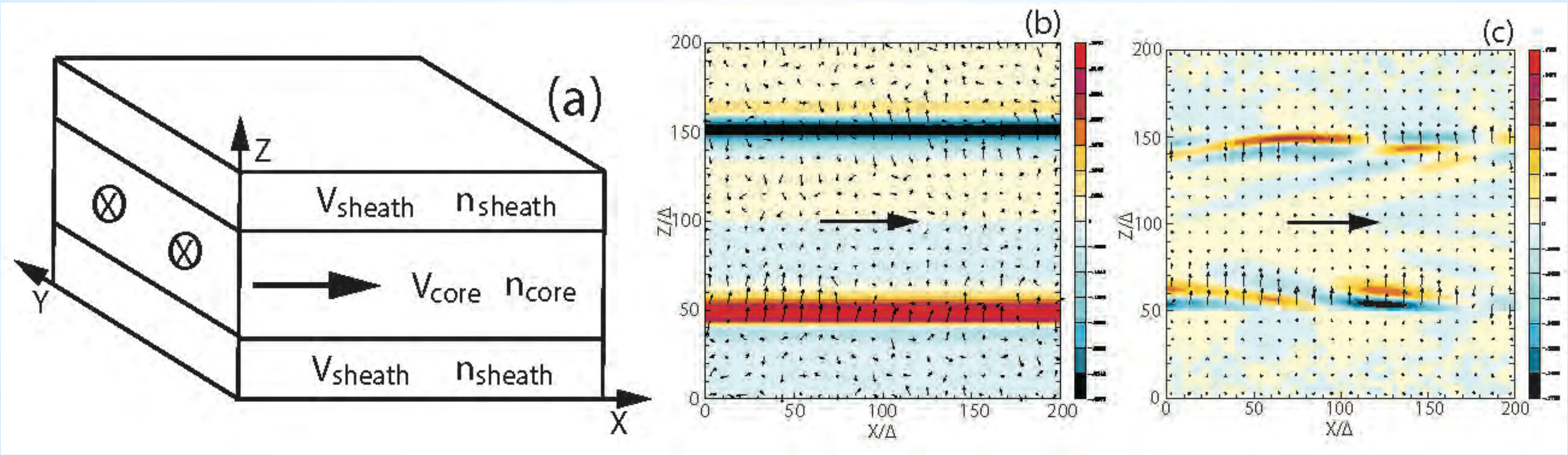
Mizuno, Hardee & Nishikawa, ApJ, 662, 835, 2007

KKHI with Core-sheath plasma scheme

$\gamma_{jt} = 15$ $t = 300\omega_{pe}^{-1}$

B_y

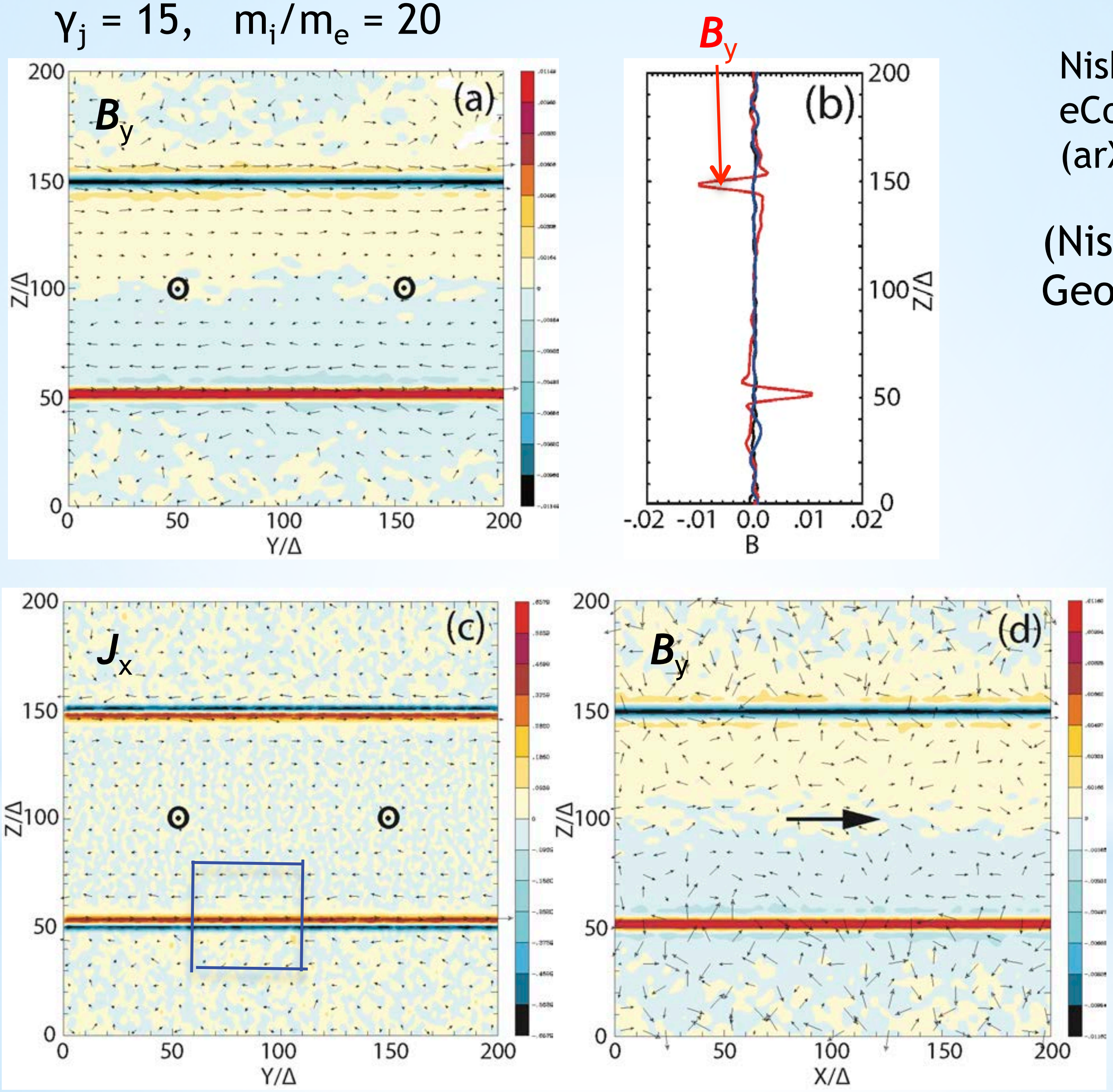
$V_{sheath} = 0$ $n_{core} = n_{sheath}$ e - p $e^{\pm}$



(Nishikawa et al. 2014, ApJ)

New KKHI simulations with core and sheath jets in slab geometry

$\gamma_j = 15, \quad m_i/m_e = 20$



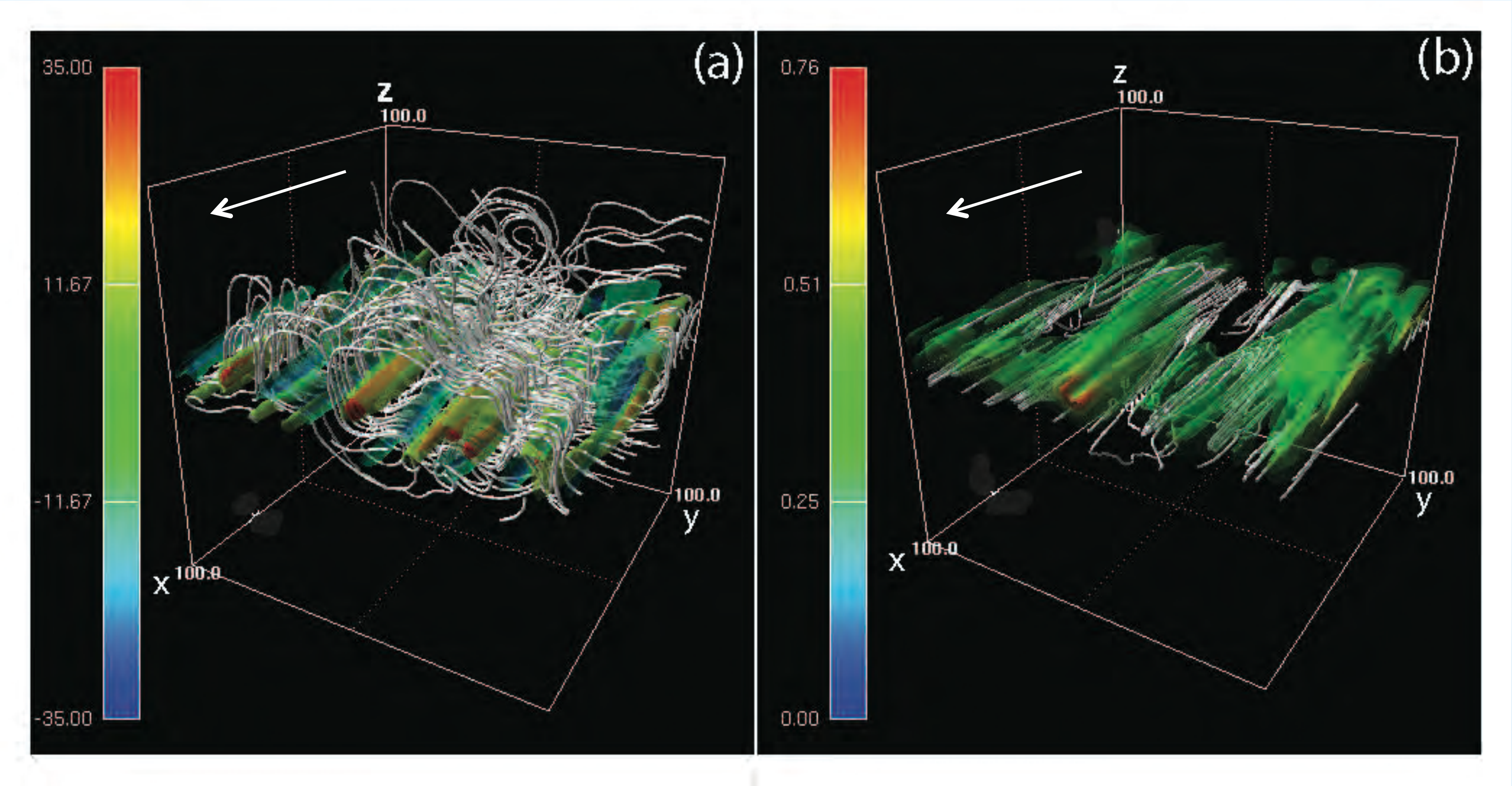
Nishikawa et al. 2013
eConf C121028
(arXiv:1303.2569)

(Nishikawa et al. Ann. Geo, 2013)

3D structure of current filaments and magnetic field

$e_{\pm}$ $\gamma_{jt} = 5$ $t = 250\omega_{pe}^{-1}$

J_x with magnetic field lines B^2 with current streaming lines

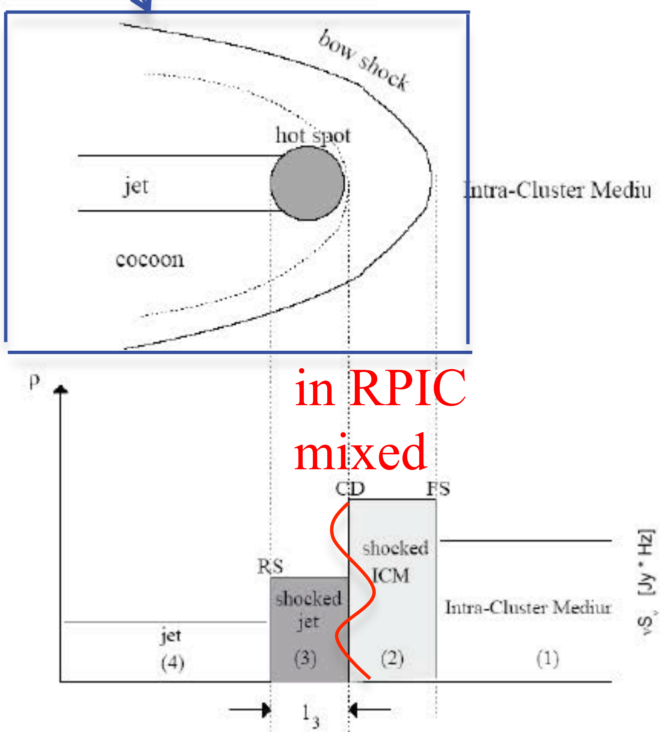


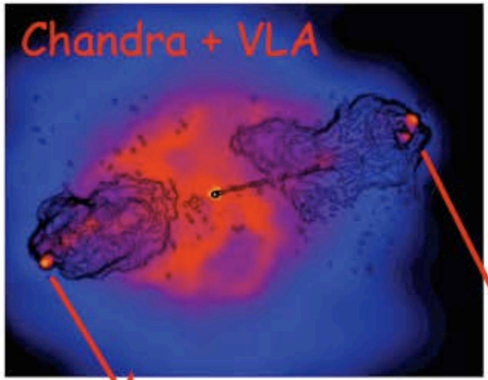
(Nishikawa et al. 2014, ApJ)

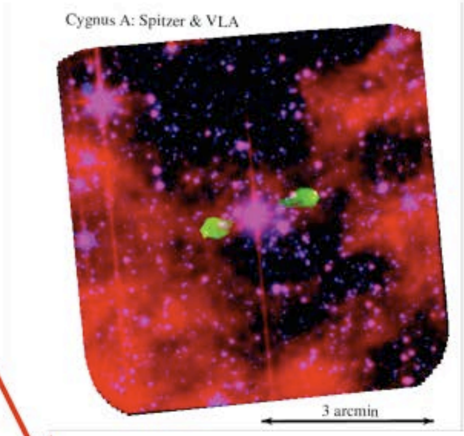
Terminal Hotspots

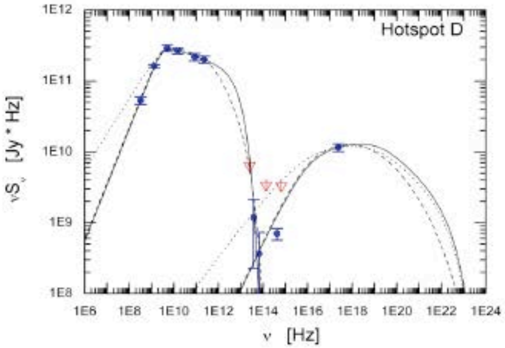
Global jet

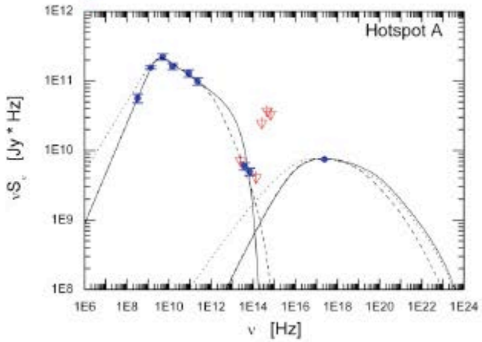
Kino & Takahara 04











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.

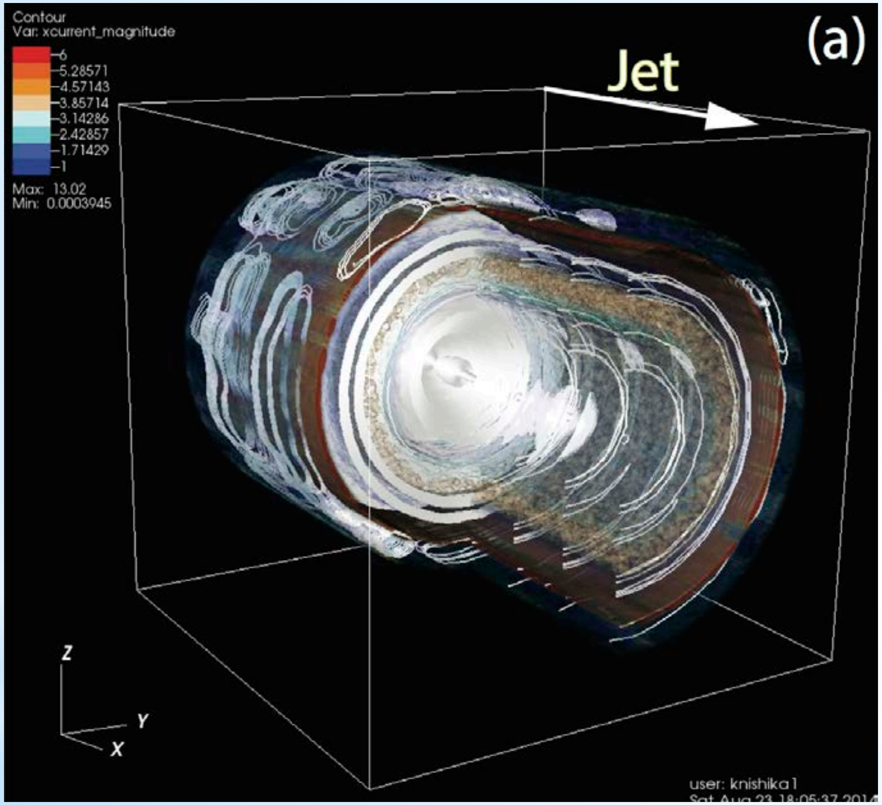
Hotspots of exceptionally bright radio galaxy Cygnus A (d_L = 250 Mpc) can be resolved at different frequencies (VLA, Spitzer, Chandra), enabling us to understand how (mildly) relativistic shocks work (LS+ 07).

courtesy of L. Stawarz

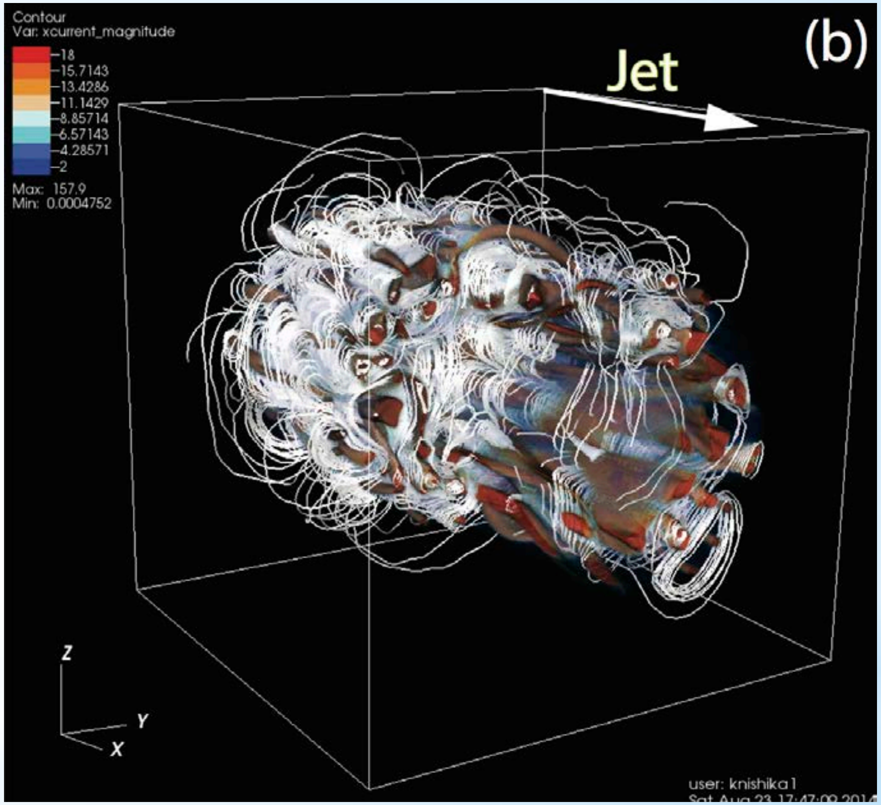
Cylindrical kKHI simulations

$\gamma_{jt} = 5$ $t = 300\omega_{pe}^{-1}$ $n_{jet} = n_{sheath}$

e - p

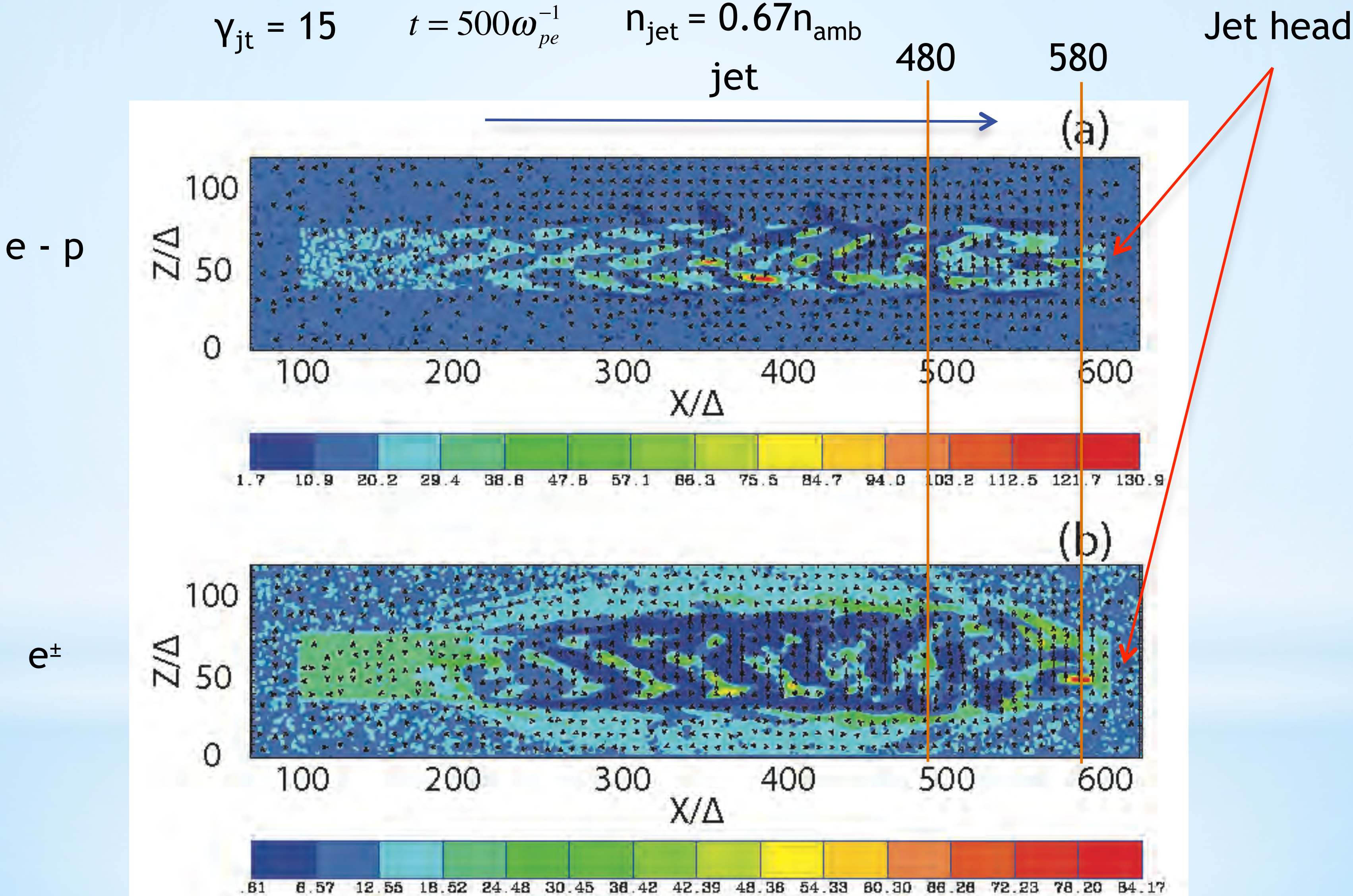


e±



Snap shot of electron density of global jet simulations

$\gamma_{jt} = 15$ $t = 500\omega_{pe}^{-1}$ $n_{jet} = 0.67 n_{amb}$



(Nishikawa et al. 2014)

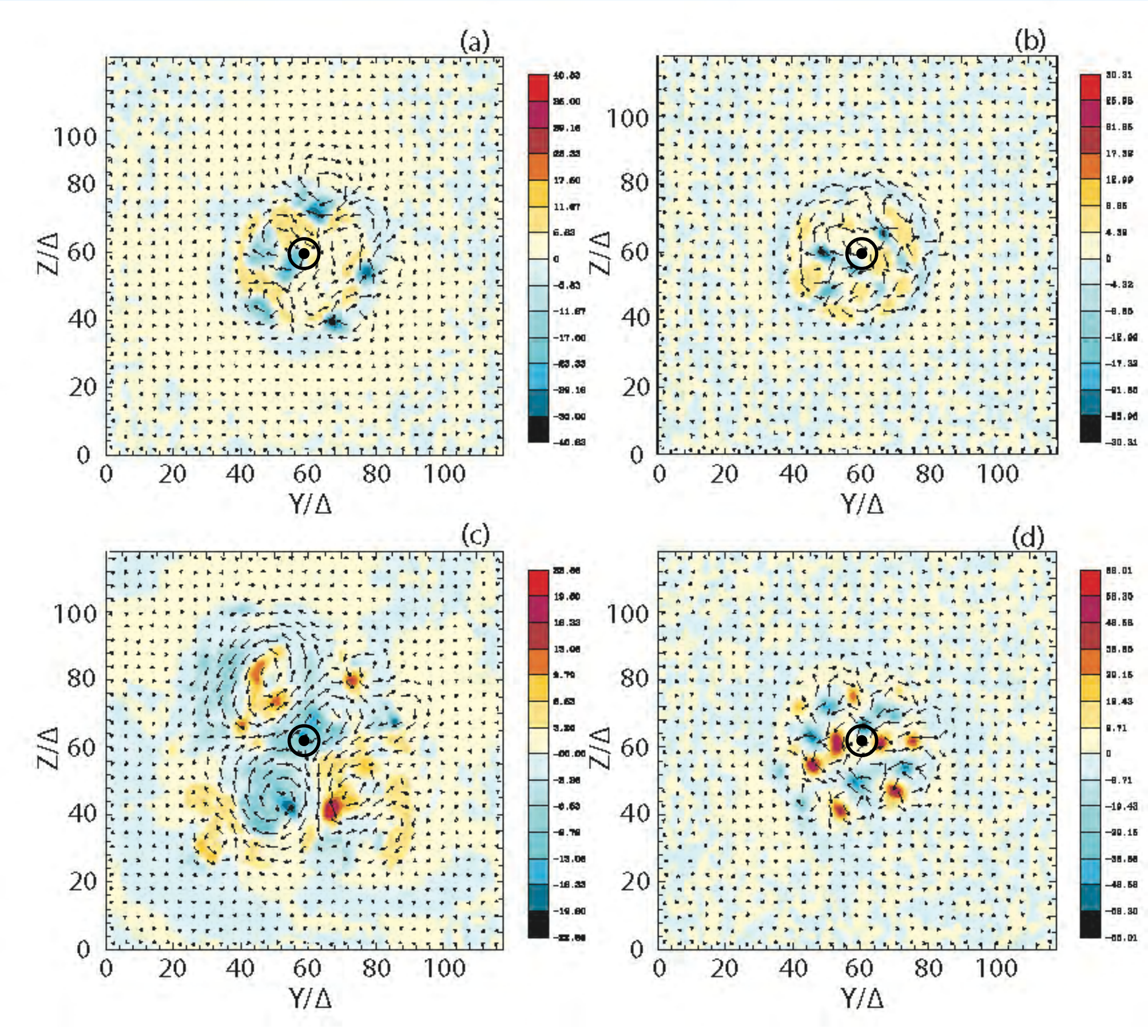
Snap shots of current structures with transverse magnetic fields

γ_{jt} = 15 $t = 500\omega_{pe}^{-1}$

X/Δ = 480 X/Δ = 580

e - p

e±



⊙ Jet center

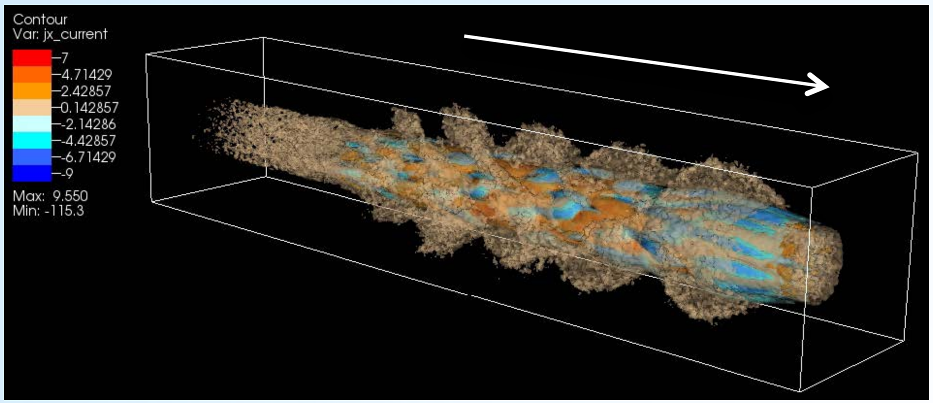
(Nishikawa et al. 2014)

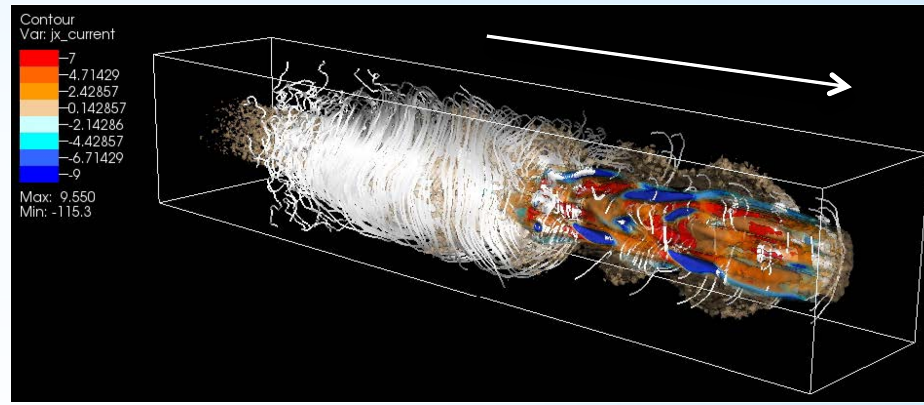
3D snapshots of current (J_x) isosurfaces with magnetic field lines

Evolution of shock and instability is different for electron-proton and electron-positron $\gamma_{jt} = 15$ $t = 500\omega_{pe}^{-1}$

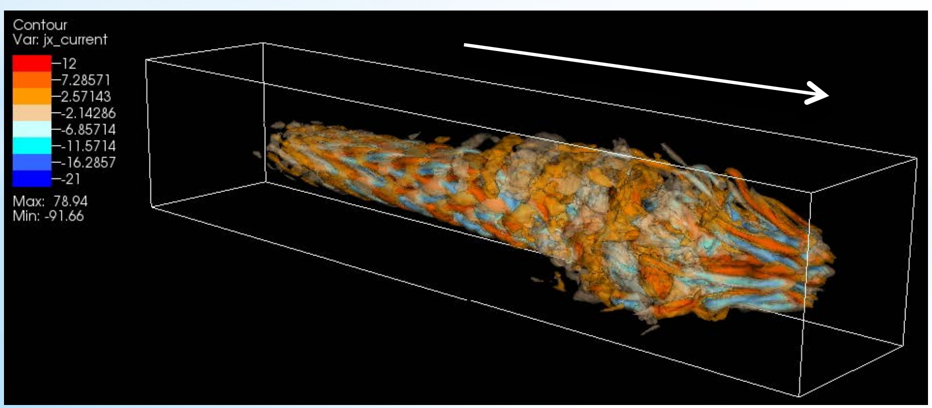
white lines: magnetic filed lines

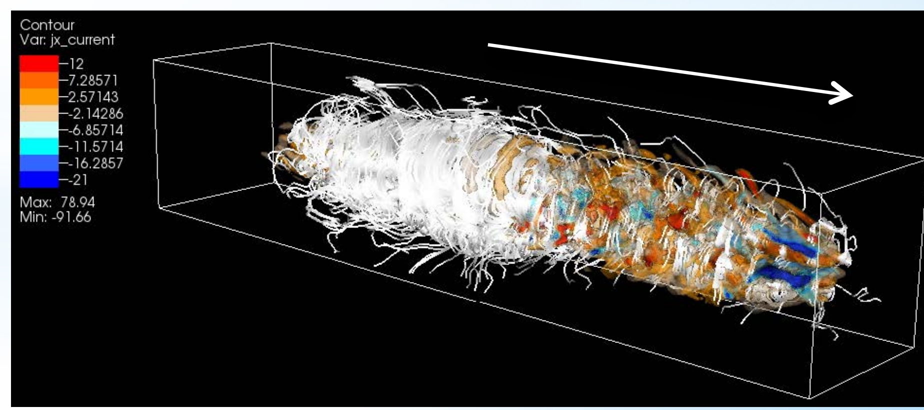
e - p





$e^{\pm}$



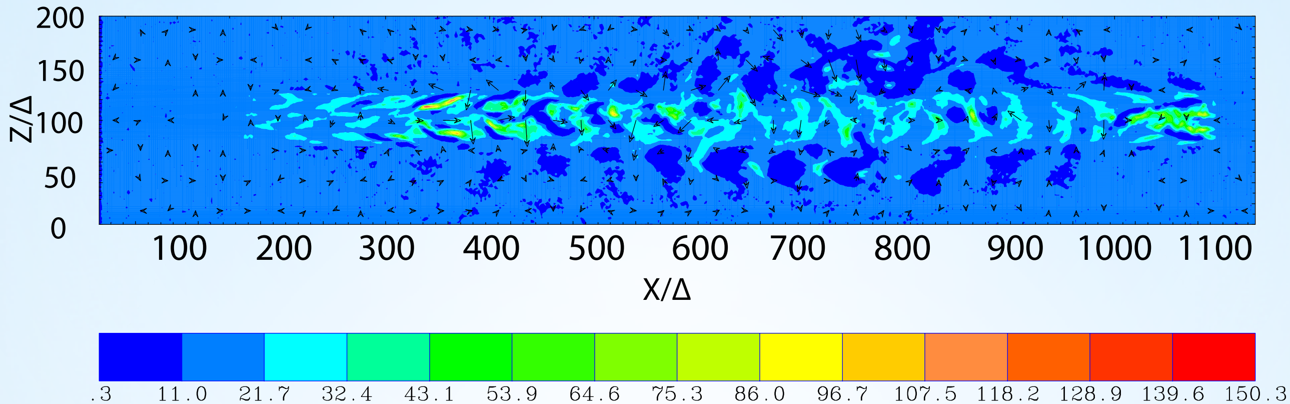


(Nishikawa et al. 2014)

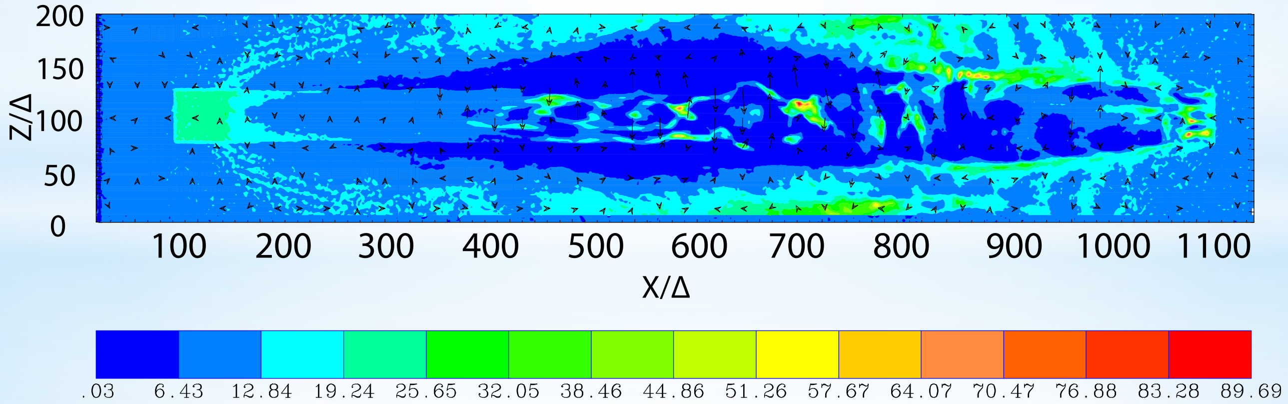
Snap shot of electron density of global jet simulations

$\gamma_{jt} = 15$ $\quad t = 1{,}000\omega_{pe}^{-1}$ $\quad n_{jet} = 0.67n_{amb}$

e-p



e±



(Nishikawa et al. 2015)

Snap shots of current structures with transverse magnetic fields

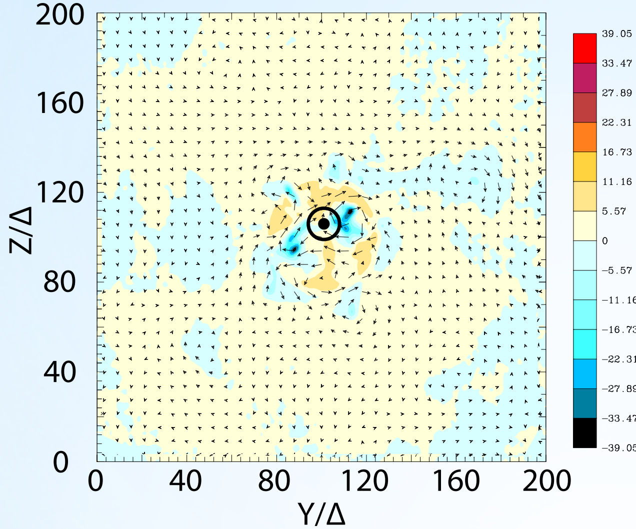
$\gamma_{jt} = 15$

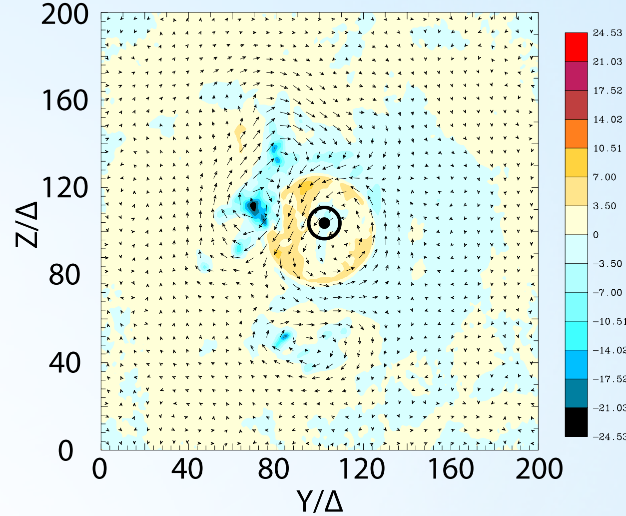
$t = 1{,}000\,\omega_{pe}^{-1}$

X/Δ = 500

X/Δ = 700

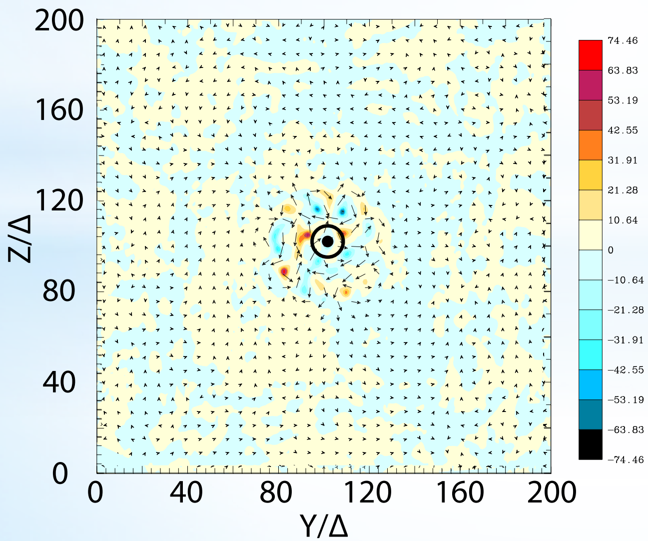
e-p

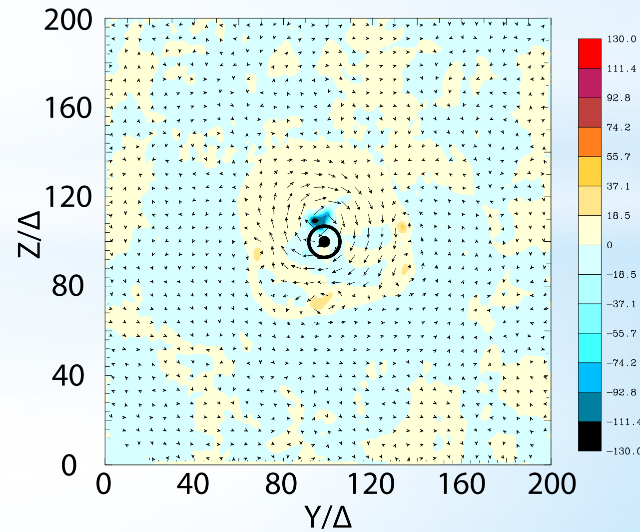




⊙ Jet center

e±



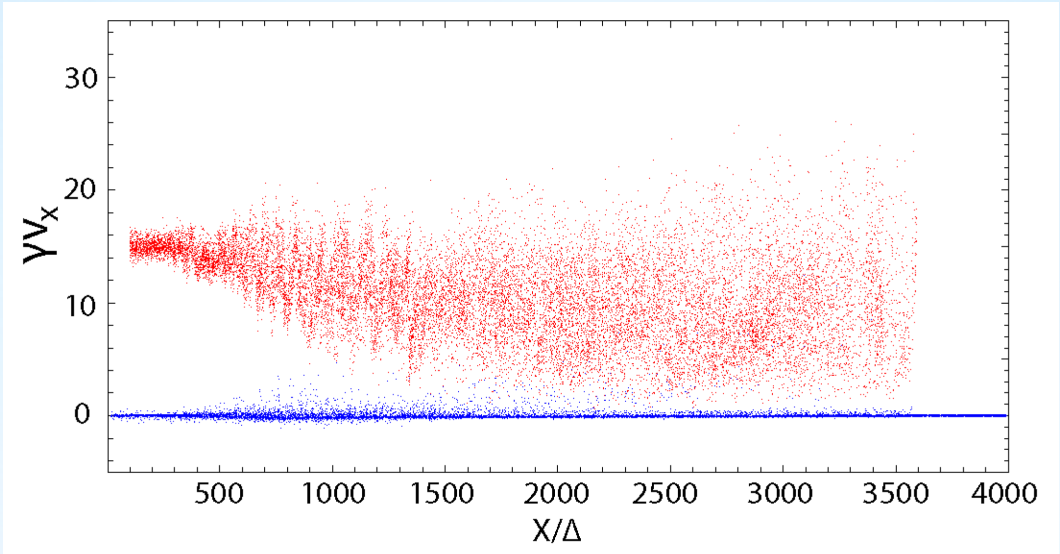


Phase space plot x - γv_x

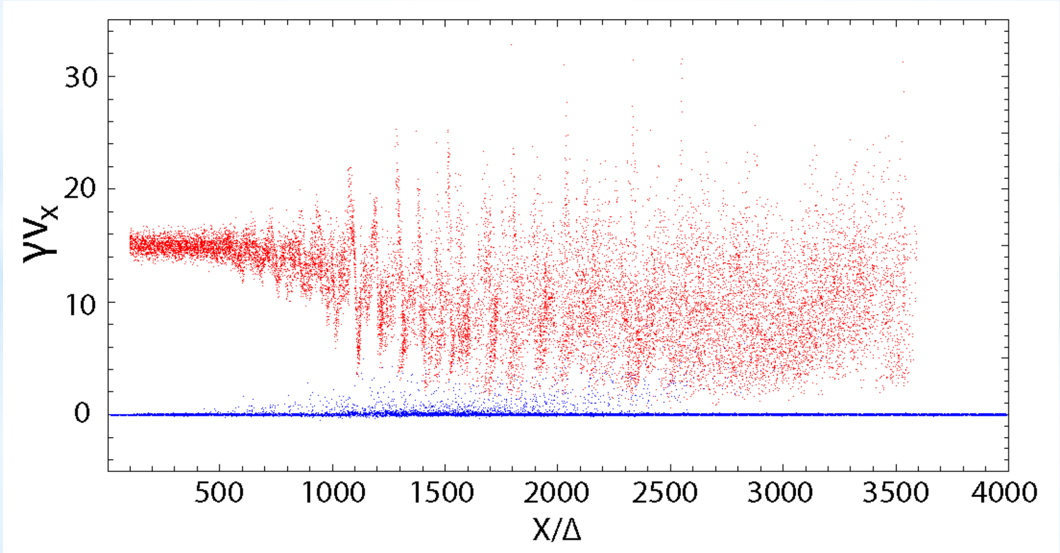
γ_{jt} = 15 $t = 3{,}500\omega_{pe}^{-1}$

red: jet electrons blue: ambient electrons

e-p



e±

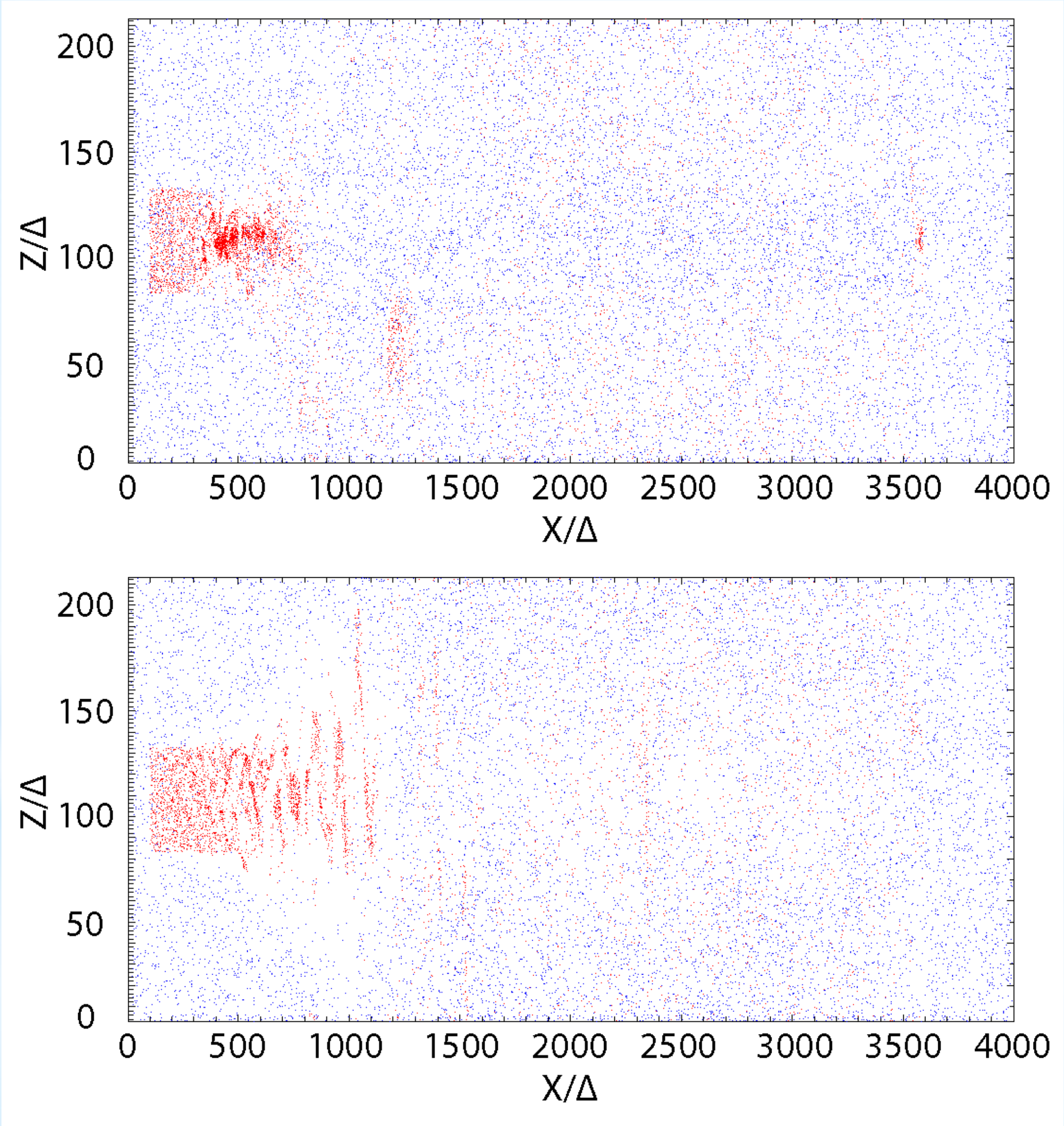


Phase space plot in x - z plane (105<y/Δ<101)

red: jet electrons   blue: ambient electrons $\gamma_{jt} = 15$ $t = 3{,}500\omega_{pe}^{-1}$

e-p

e±

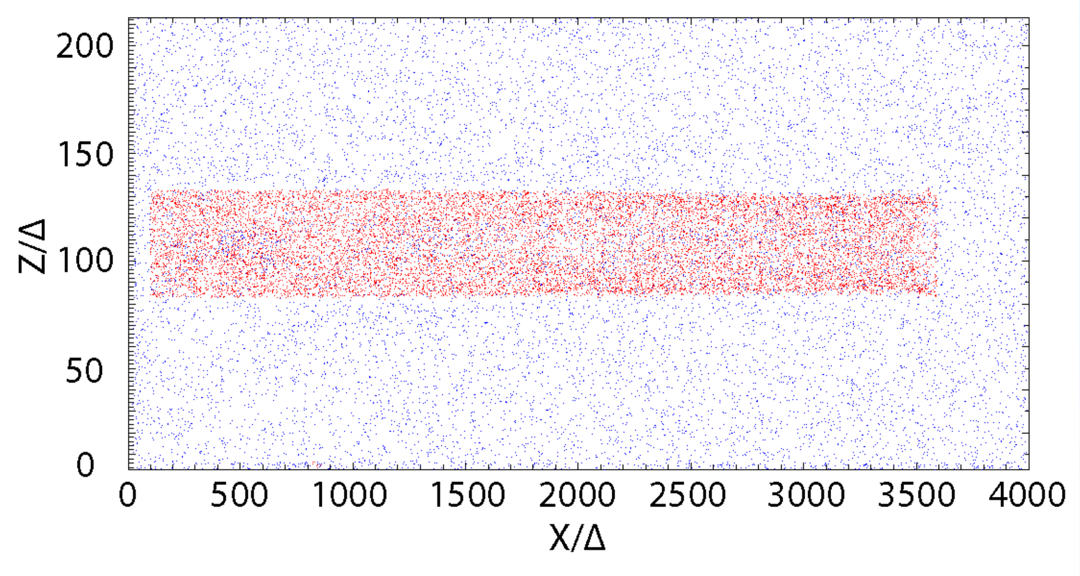


Phase space plot in x -z plane for e-p jet (105<y/Δ<101)

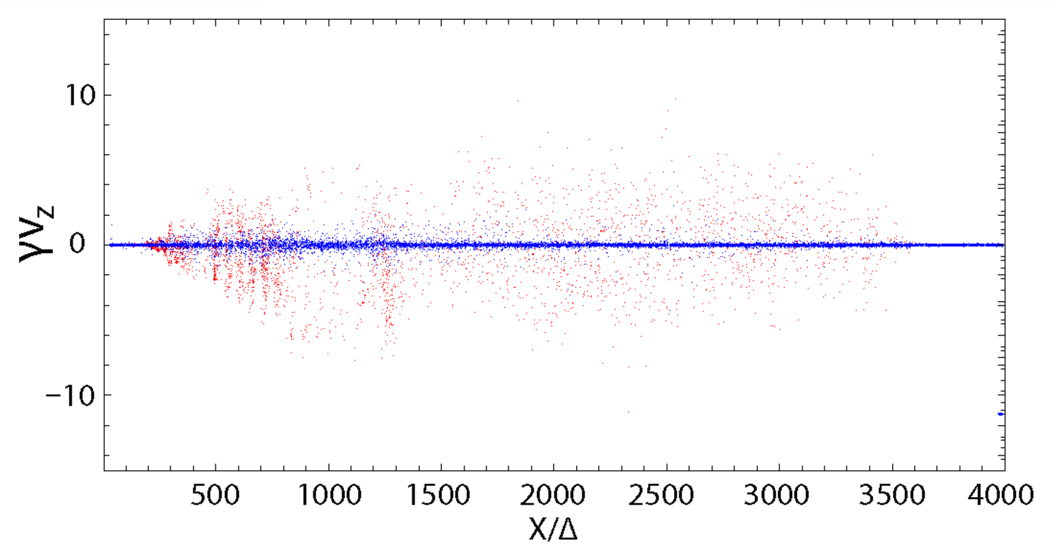
red: jet ions blue: ambient ions

$\gamma_{jt} = 15$

$t = 3{,}500\omega_{pe}^{-1}$



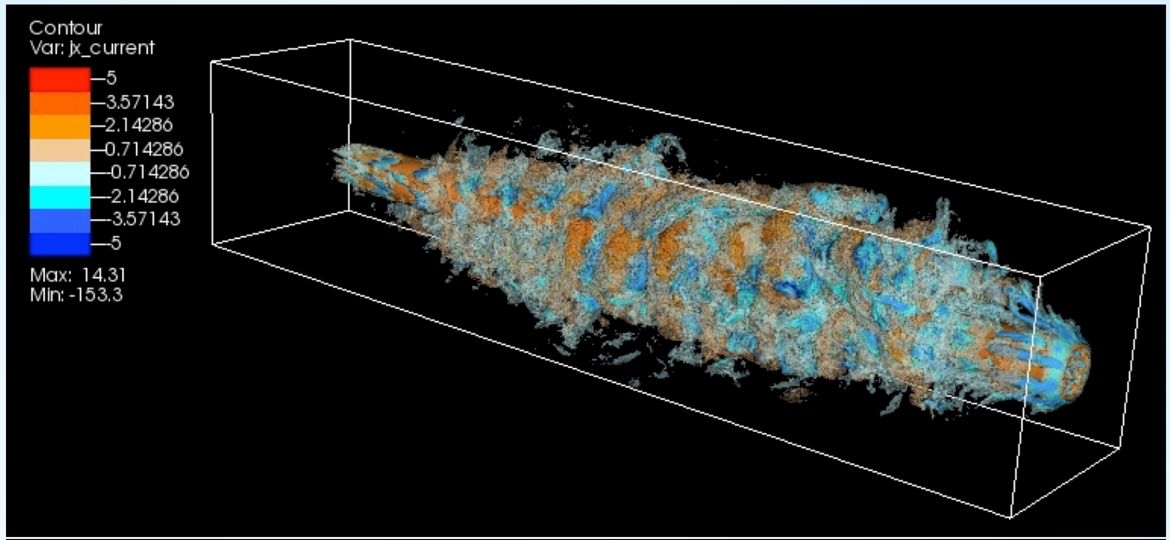
red: jet electrons blue: ambient electrons



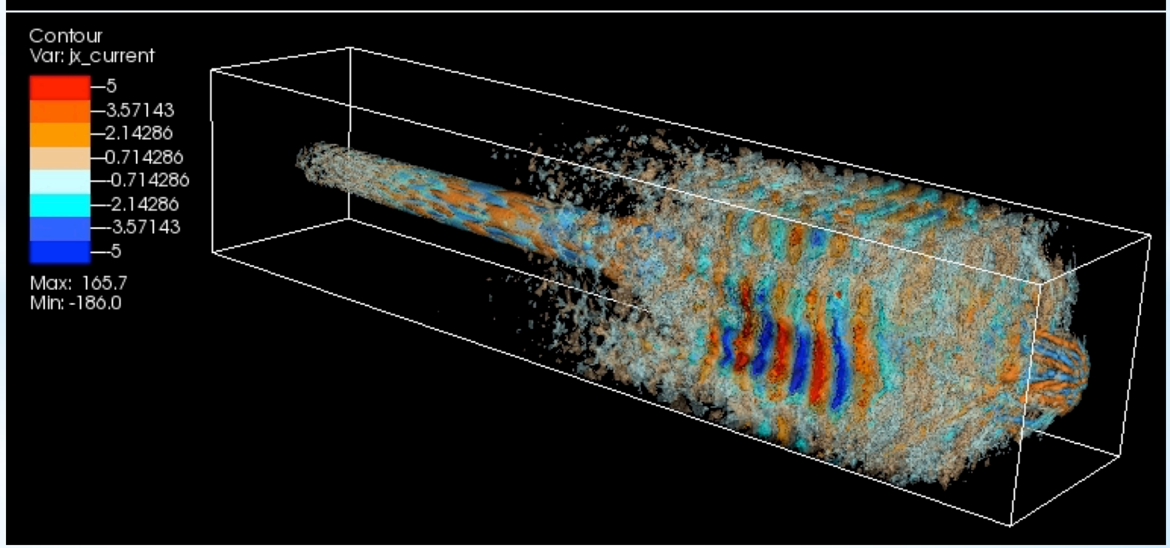
3D snapshots of current (J_x) isosurfaces without magnetic field lines

Evolution of shock and instability is different for electron-proton and electron-positron $\gamma_{jt} = 15$ $t = 1000\omega_{pe}^{-1}$

e-p



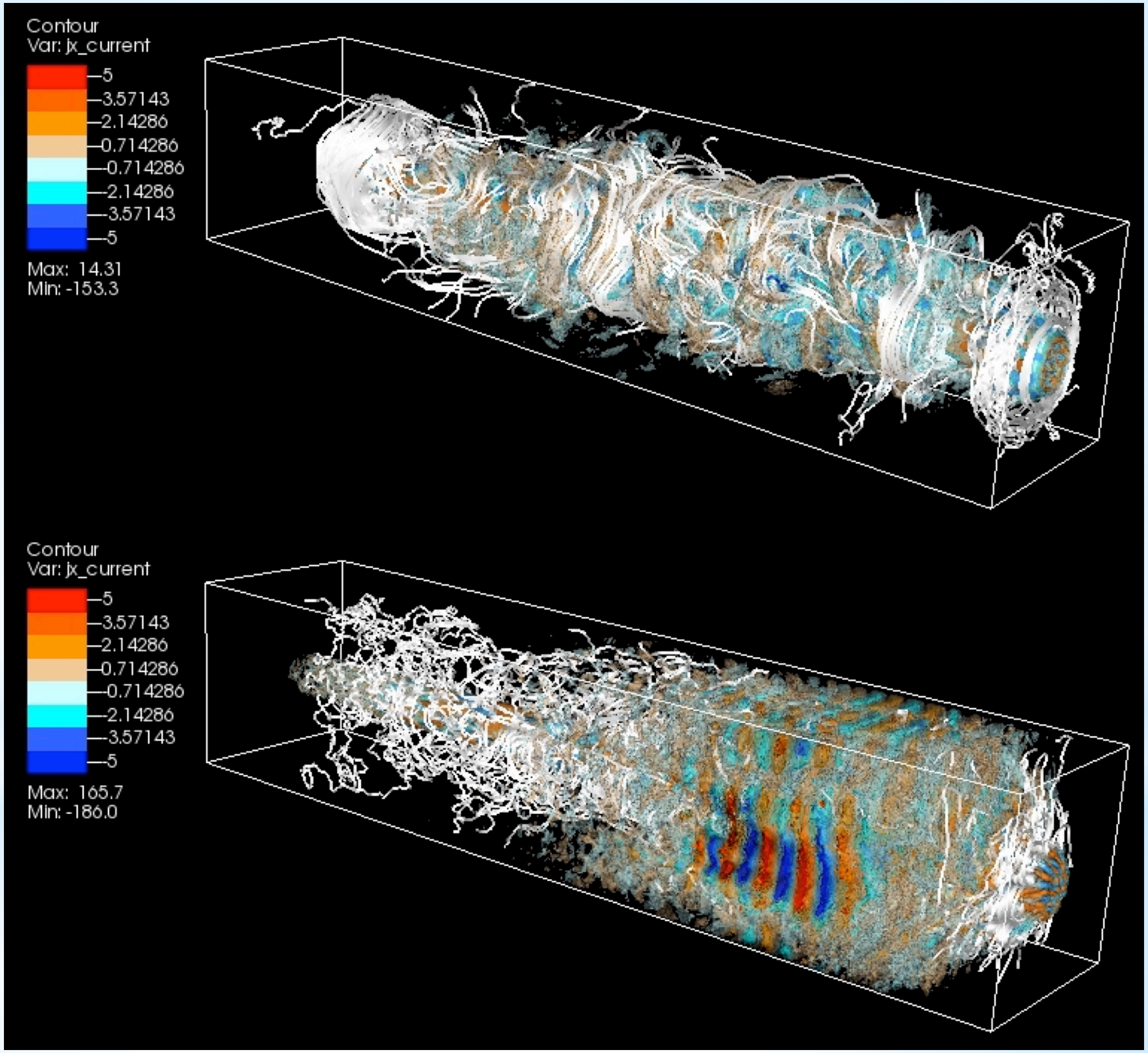
$e^{\pm}$



3D snapshots of current (J_x) isosurfaces with magnetic field lines

$\gamma_{jt} = 15 \quad t = 1000\omega_{pe}^{-1}$

e-p



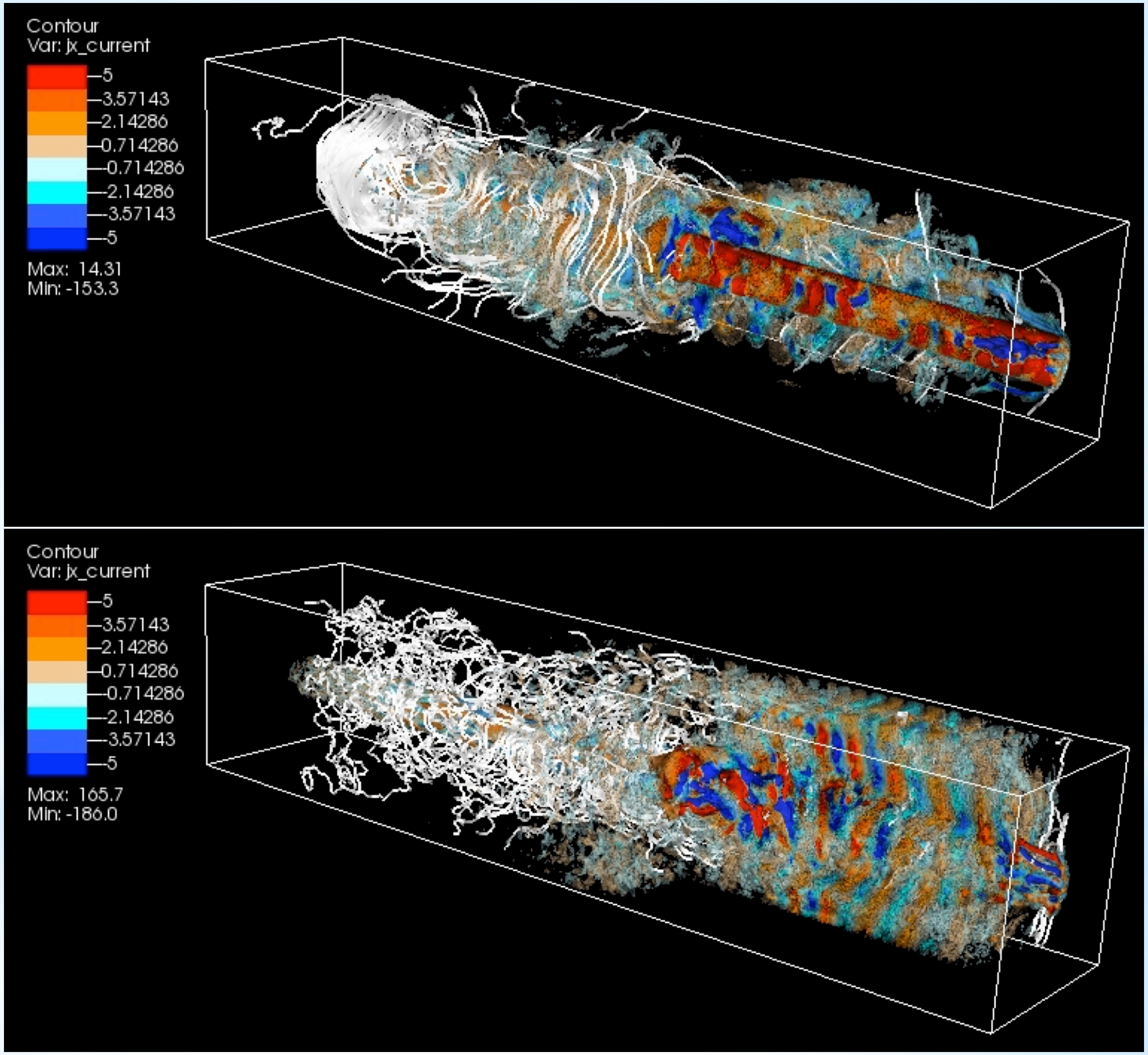
$e^{\pm}$

3D snapshots of current (J_x) isosurfaces with magnetic field lines clipped at the center of jet

$\gamma_{jt} = 15$ $t = 1000\omega_{pe}^{-1}$

e-p

e±

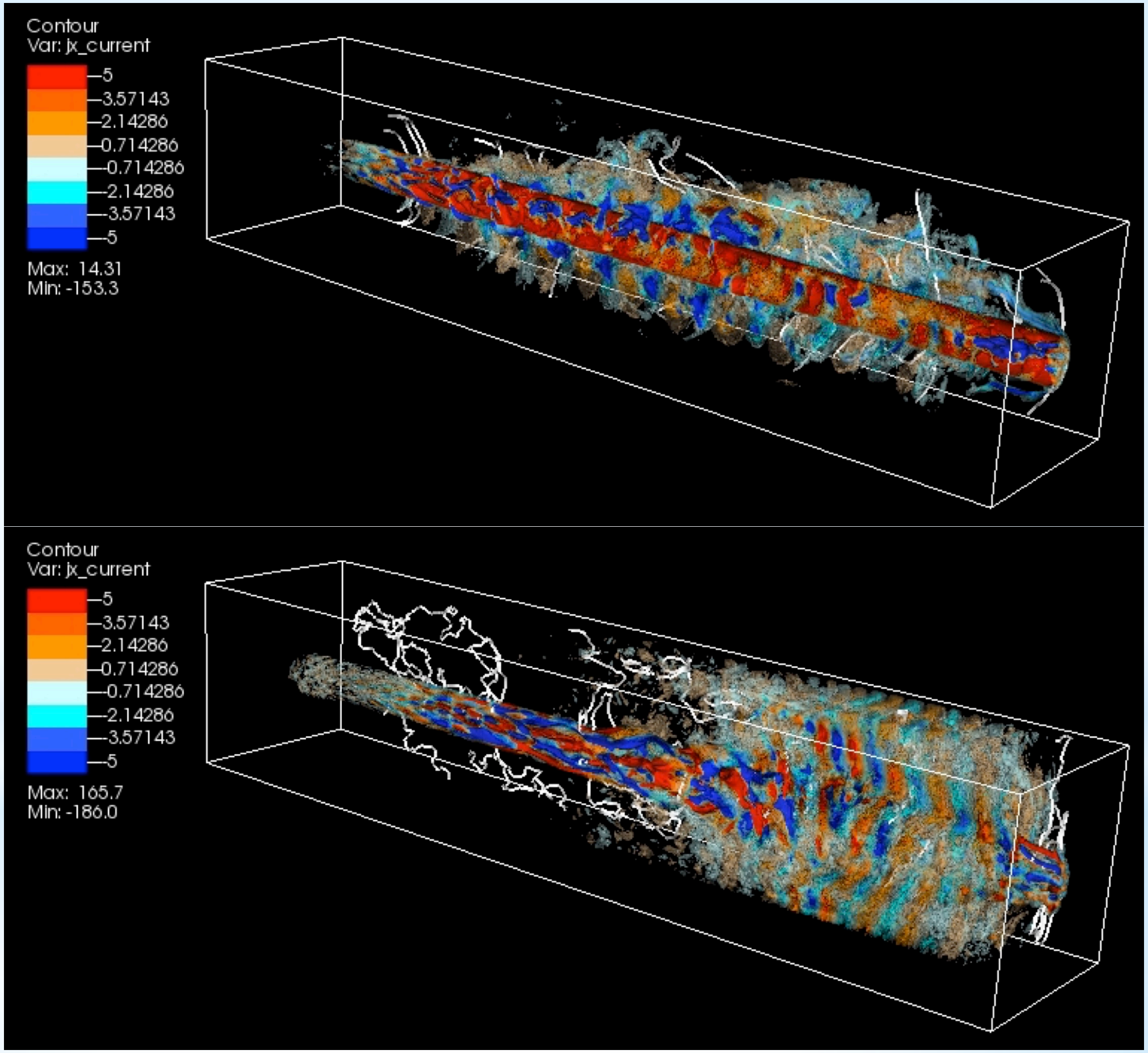


3D snapshots of current (J_x) isosurfaces with magnetic field lines clipped at the center of jet (2D plane)

$\gamma_{jt} = 15$ $t = 1000\omega_{pe}^{-1}$

e-p

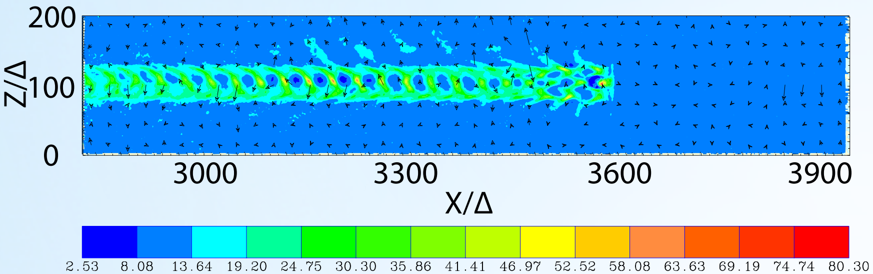
e±

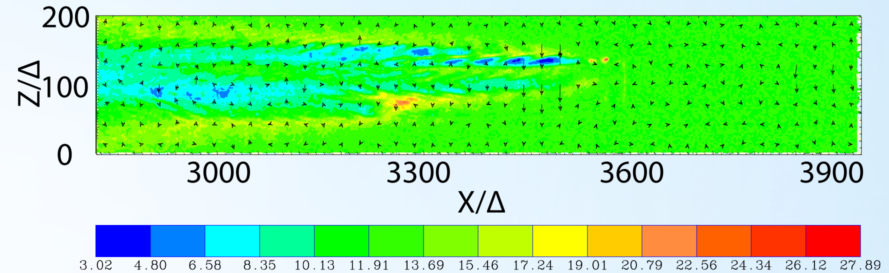


Jet structure at the head of jets

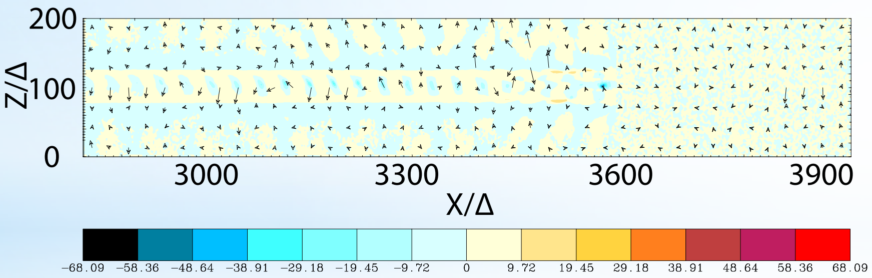
$\gamma_{jt} = 15 \quad t = 3500\omega_{pe}^{-1}$

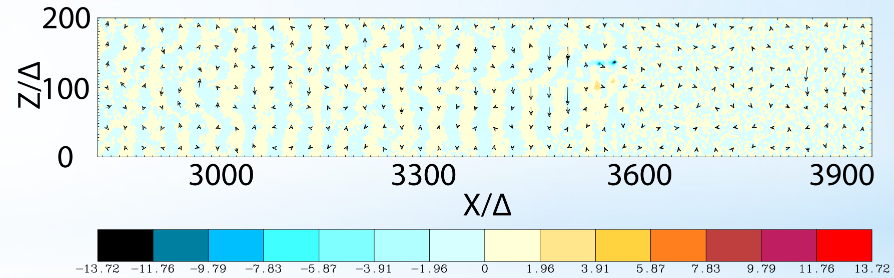
e-p | electron density | e±





current density





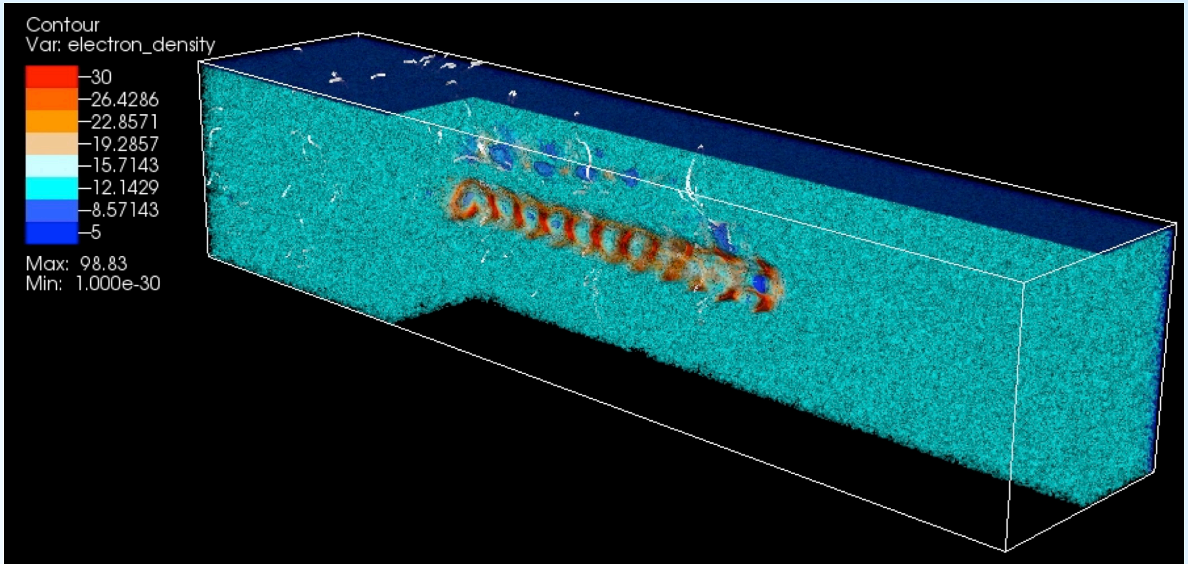
Jet structure at the head of jets in 3D

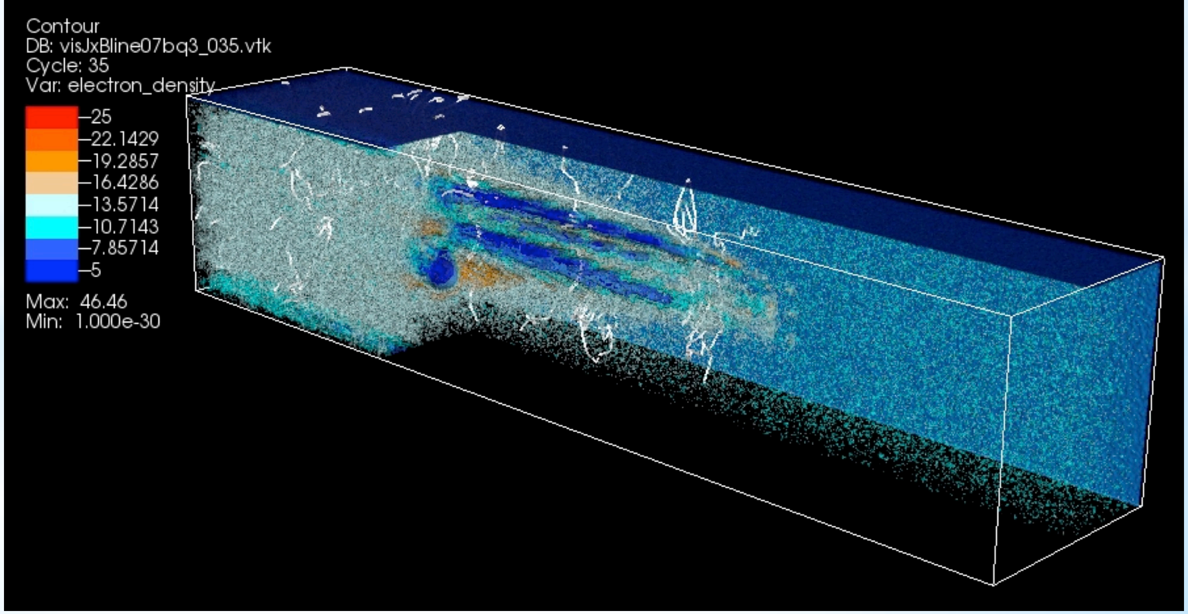
$\gamma_{jt} = 15 \quad t = 3500\omega_{pe}^{-1}$

e-p

electron density

e±





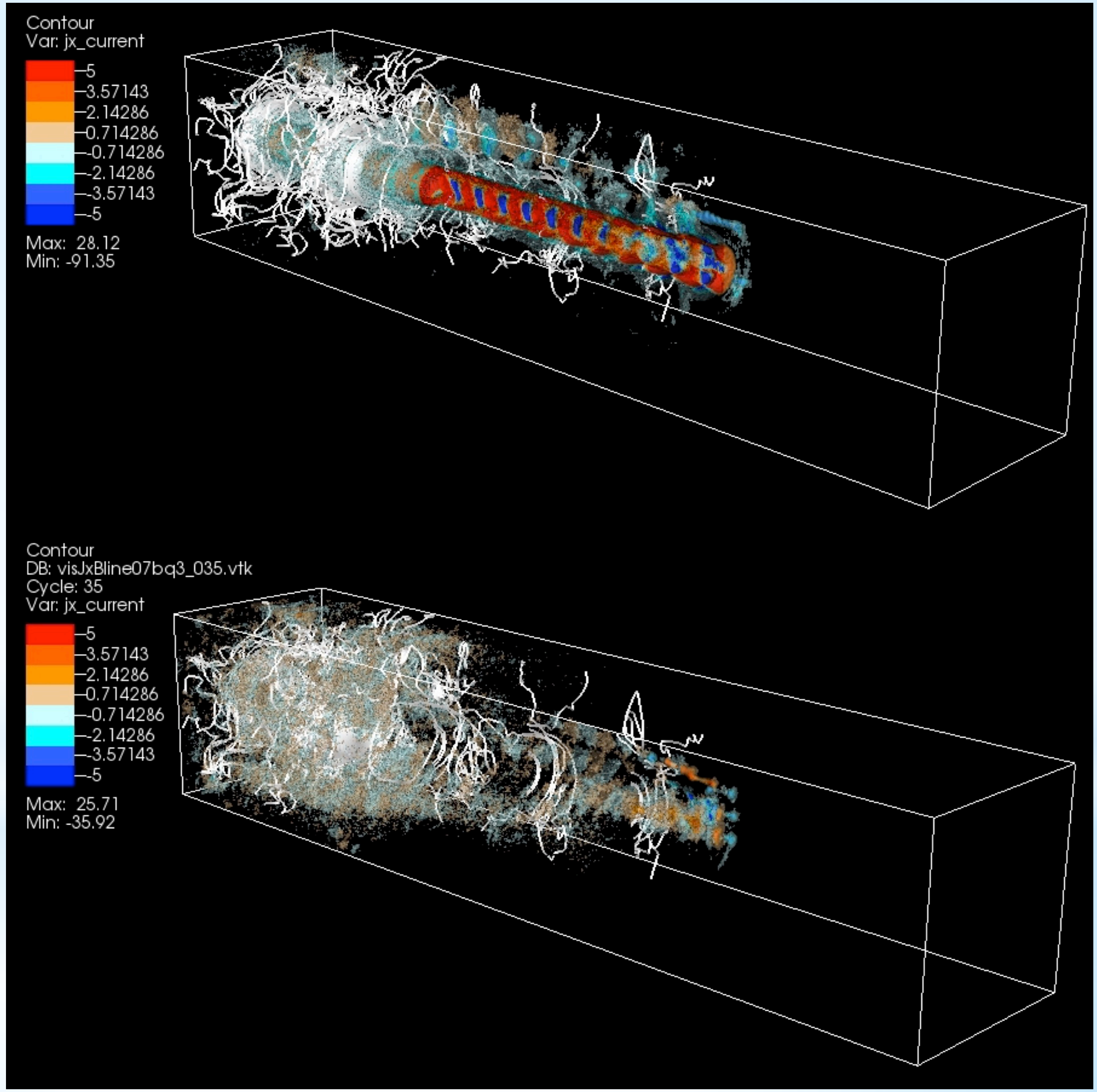
Jet structure at the head of jets in 3D

$\gamma_{jt} = 15$ $t = 3500\omega_{pe}^{-1}$

e-p

current density

$e^{\pm}$



Summary of Kinetic Kelvin-Helmholtz Instability

1. Static electric field grows due to the charge separation by the negative and positive current filaments
2. Current filaments at the velocity shear generate magnetic field transverse to the jet along the velocity shear
3. Jet with high Lorentz factor with core-sheath case generate higher magnetic field even after saturated in the case counter-streaming case with moderately relativistic jet
4. Non-relativistic jet generate KKHI quickly and magnetic field grows faster than the jet with higher Lorentz factor
5. For the jet-sheath case with Lorentz factor 15 the evolution of KKHI does not change with the mass ratio between 20 and 1836
6. Strong magnetic field will affect electron trajectories and create synchrotron-like (jitter) radiation which will be investigated
7. Global jets with combined of Weibel instability and kKHI need to be investigated further and with helical magnetic field

(for detail please see (Nishikawa et al. 2014, ApJ)

Self-consistent calculation of radiation

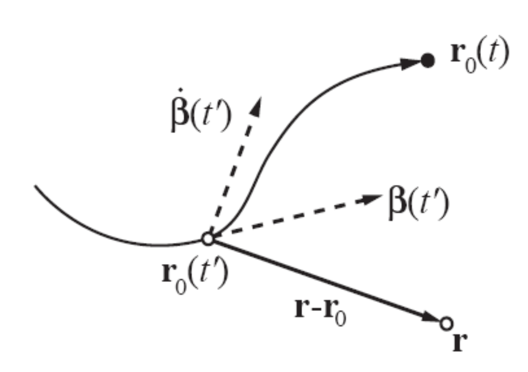
- Electrons are accelerated by the electromagnetic field generated by the Weibel instability and KKHI (without the assumption used in test-particle simulations for Fermi acceleration)
- Radiation is calculated using the particle trajectory in the self-consistent turbulent magnetic field
- This calculation 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

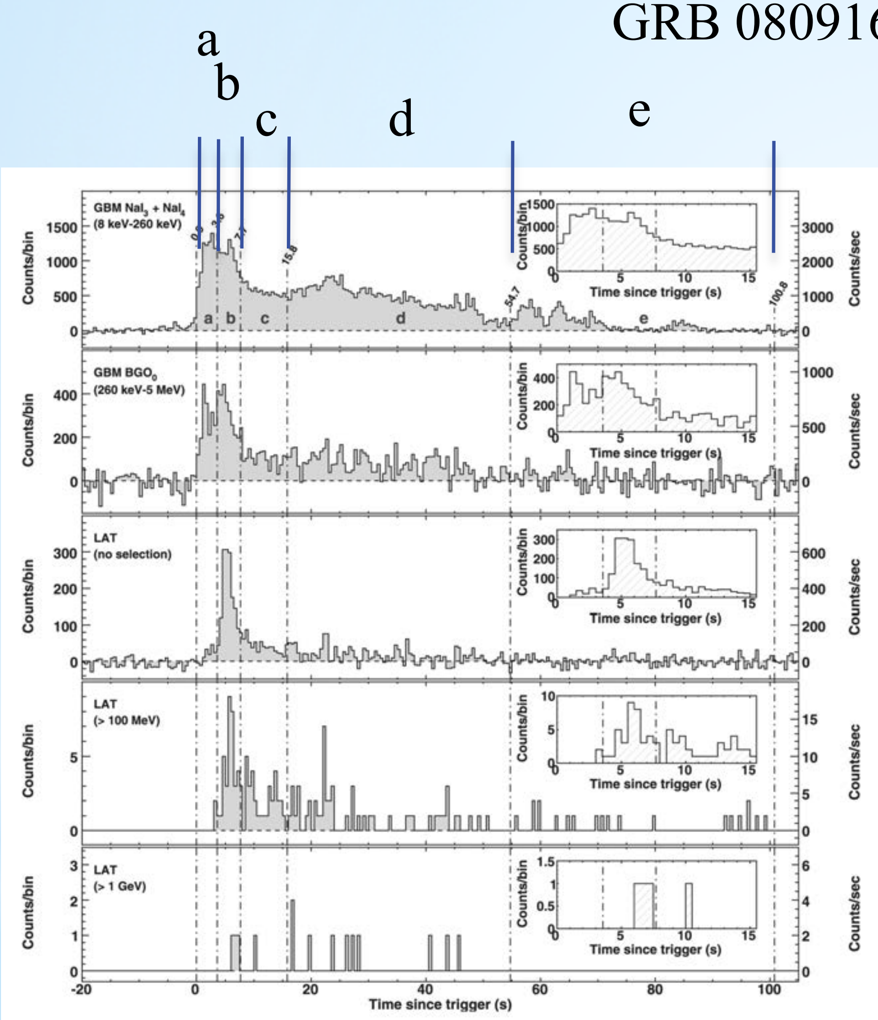


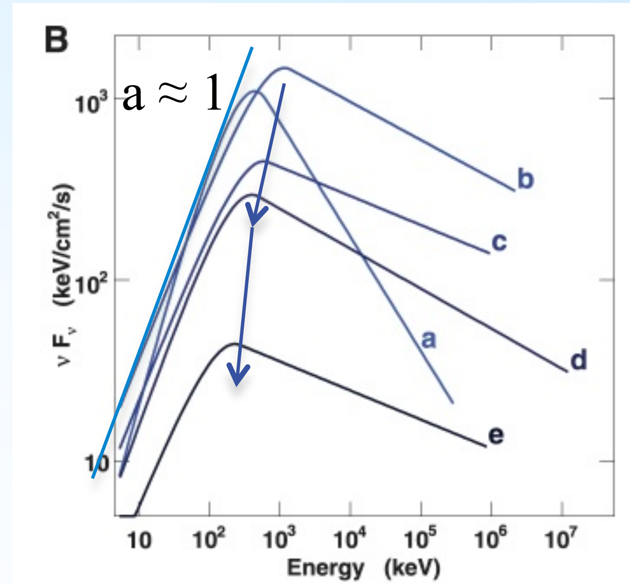
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

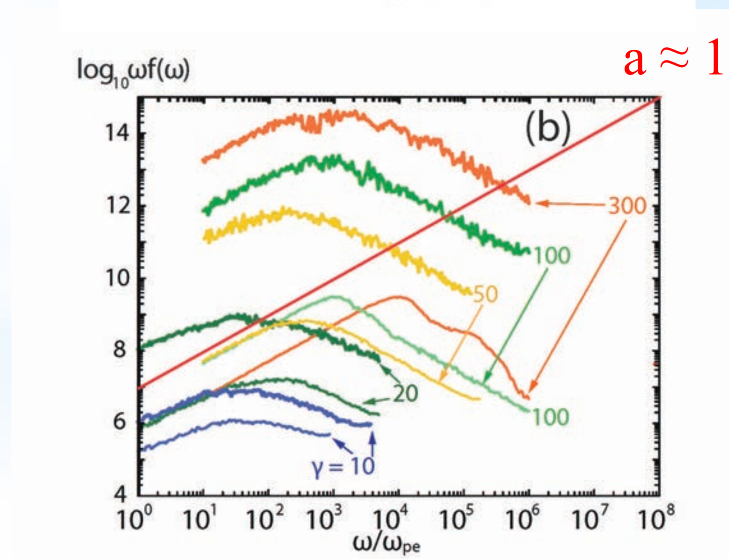
Hededal, Thesis 2005 (astro-ph/0506559)
Nishikawa et al. 2008 (astro-ph/0802.2558), 2011
Sironi & Spitkovsky, 2009, ApJ
Martins et al. 2009, Proc. of SPIE Vol. 7359
Frederiksen et al. 2010, ApJL

Observations and numerical spectrum

GRB 080916C







Abdo et al. 2009, Science

(Nishikawa et al. 2012)

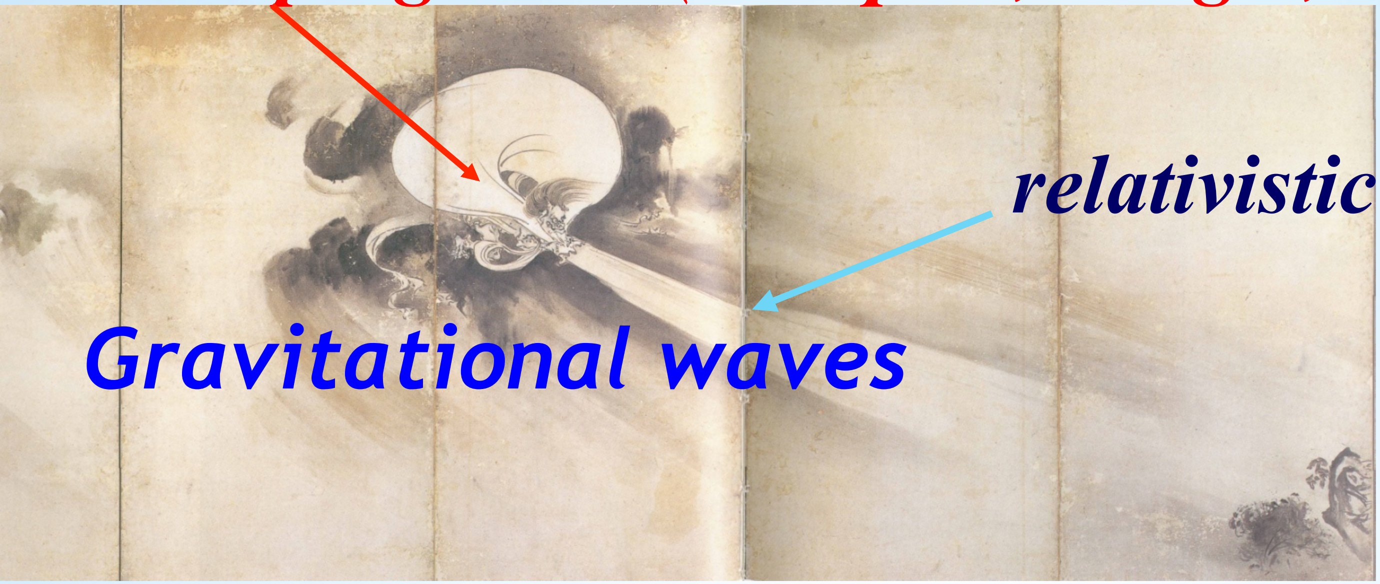
Summary

- 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, Nishikawa et al. 2011)
- Our new numerical approach of calculating radiation from electrons based on self-consistent simulations provides more realistic spectra including jitter radiation
- Need further calculation of synthetic spectra with spectral evolution
- Reconnection is very important to release magnetic field energy to kinetic energy
- Recollimation shock may create gamma-ray flash by moving perturbation

Future plans

- Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics including KKHI and reconnection
- 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 using global jet simulation of shock, KKHI and reconnection with helical magnetic field in jet (GRBs, SNRs, AGNs, etc)
- Polarization of global jets needs to be investigated including helical magnetic field

GRB progenitor (collapsar, merger, magnetar)



Fushin

(god of wind)

EM emission

(shocks, acceleration)

Raishin

(god of lightning)