Particle-In-Cell Simulations of Astrophysical Relativistic Jets

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Blazars through Sharp Multi-Wavelength Eyes
Málaga, Spain, May 30 – June 3, 2016

Outline of talk

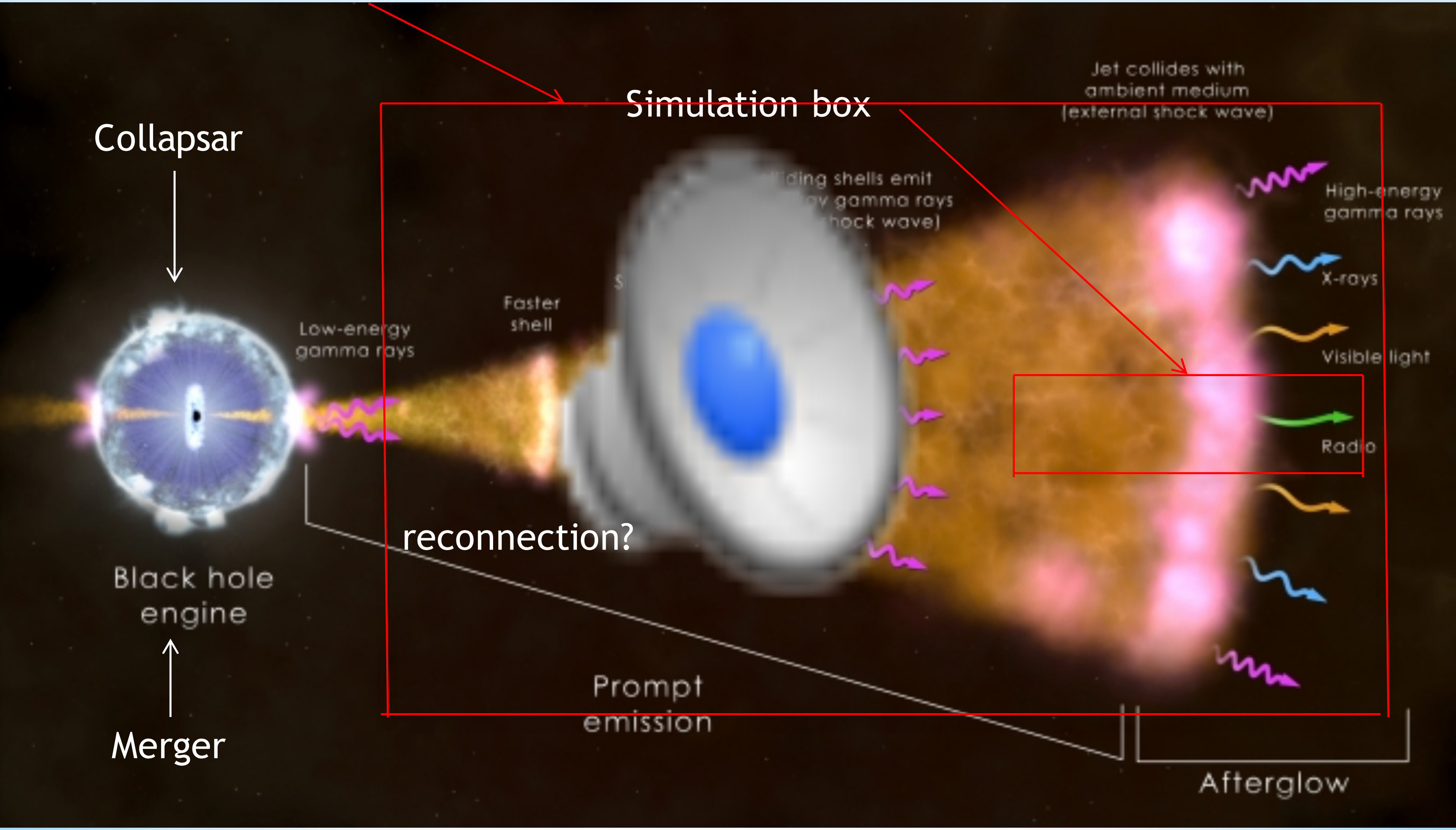
1. **Introduction of relativistic jets and Weibel instability**
2. **Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability** (Nishikawa et al. ApJ, 793, 60, 2014)
3. **Global jet simulations with shock and KKHI with large simulation system** (Nishikawa et al. ApJ, 820, 94, 2016)
4. **Global jet simulations with helical magnetic field (reconnection)**
5. **Summary**
6. **Future plans**

Key Scientific questions

- How do velocity shears generate magnetic fields and accelerate particles?
- How do global jets evolve with different species?
- How the Weibel instability and kKHI affect the evolution of shock with global jets?
- How are particles accelerated?
- How do helical magnetic fields affect shocks and reconnection?
- What are the dominant radiation processes?
- How do shocks in relativistic jets evolve in various ambient plasma- and magnetic field configurations?
- How is magnetic field energy in jets released?
- Jets in Jets really happen due to reconnection?

Gamma-ray bursts

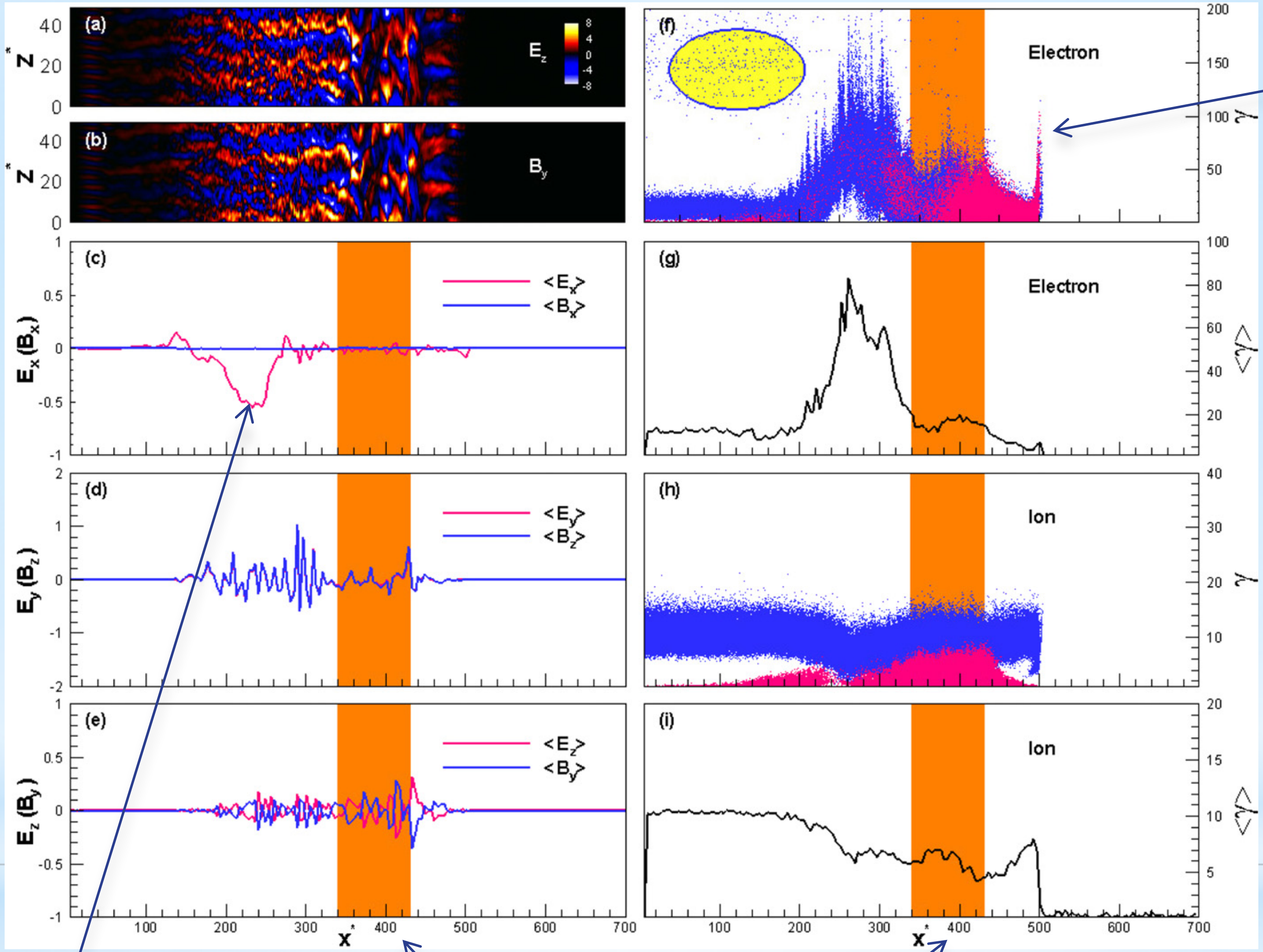
Global jet simulation



Structure of shock and particle acceleration at t = 500.*

E_z

B_y



quasi-steady E_x accelerates electrons like a Fermi acceleration

strong E_x contribute particle acceleration

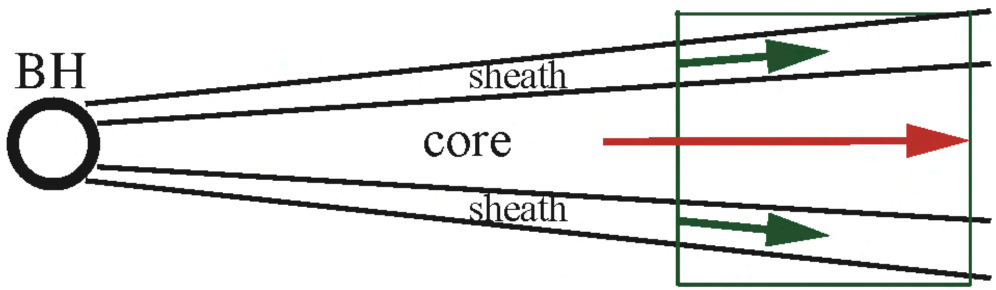
shocked region

blue: jet particles

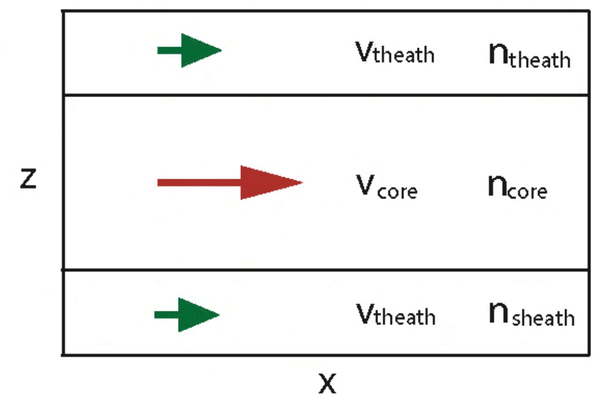
red: ambient particles

(Ardaneh et al. 2015)

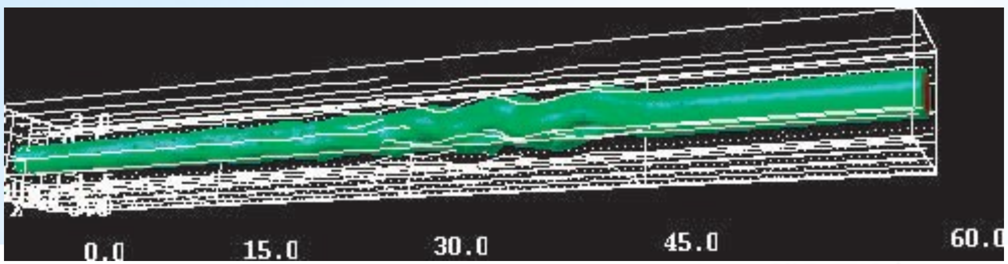
Simulations of KHI with core and sheath jets



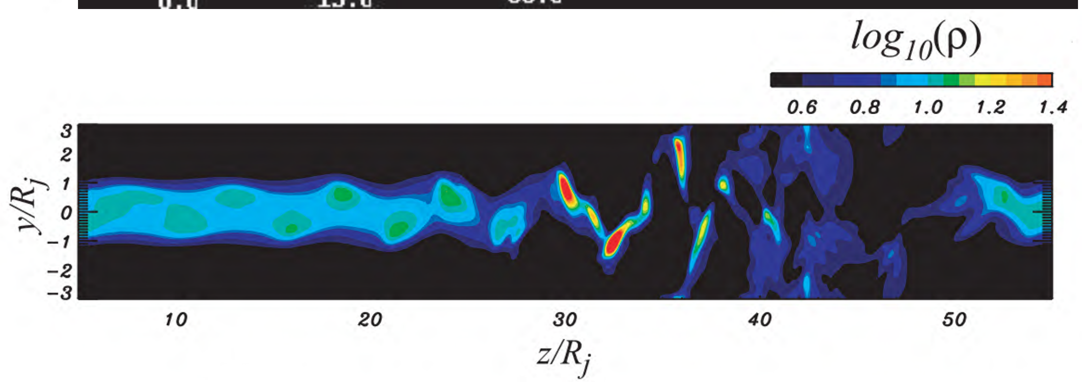
slab model

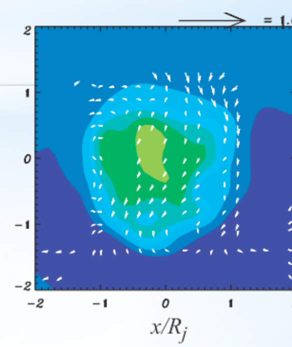


RMHD, no wind ω=0.93, time=60.0



case of V_{theath} = 0





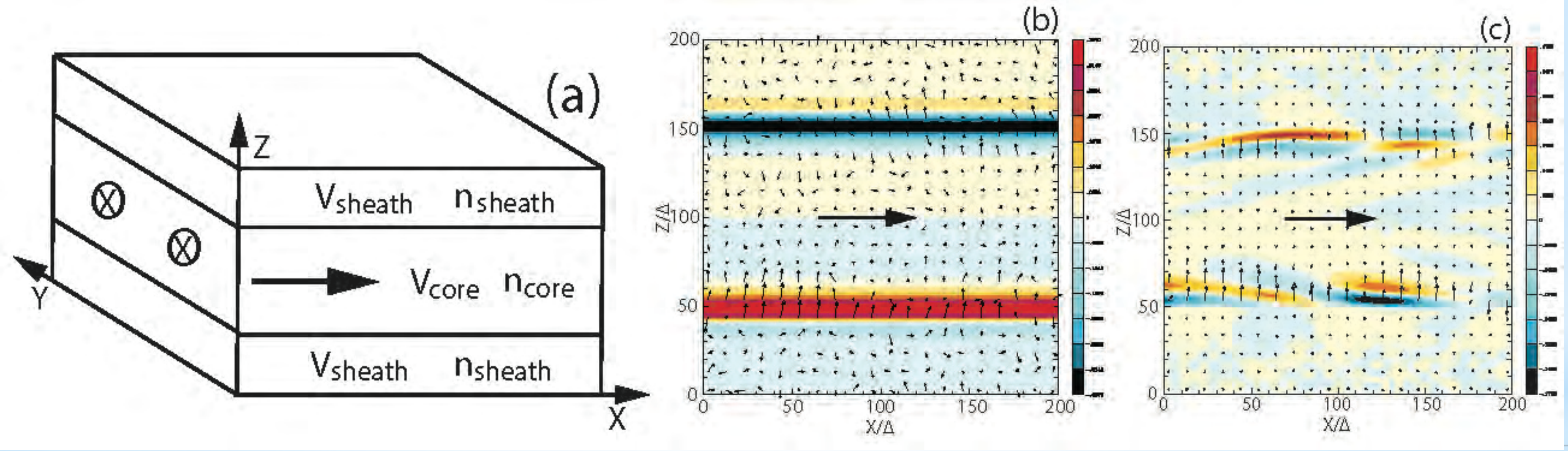
Mizuno, Hardee & Nishikawa, ApJ, 662, 835, 2007

KKHI with Core-sheath plasma scheme

γ_{jt} = 15 $t = 300\omega_{pe}^{-1}$

B_y

e – p (proton) $e^{\pm}$



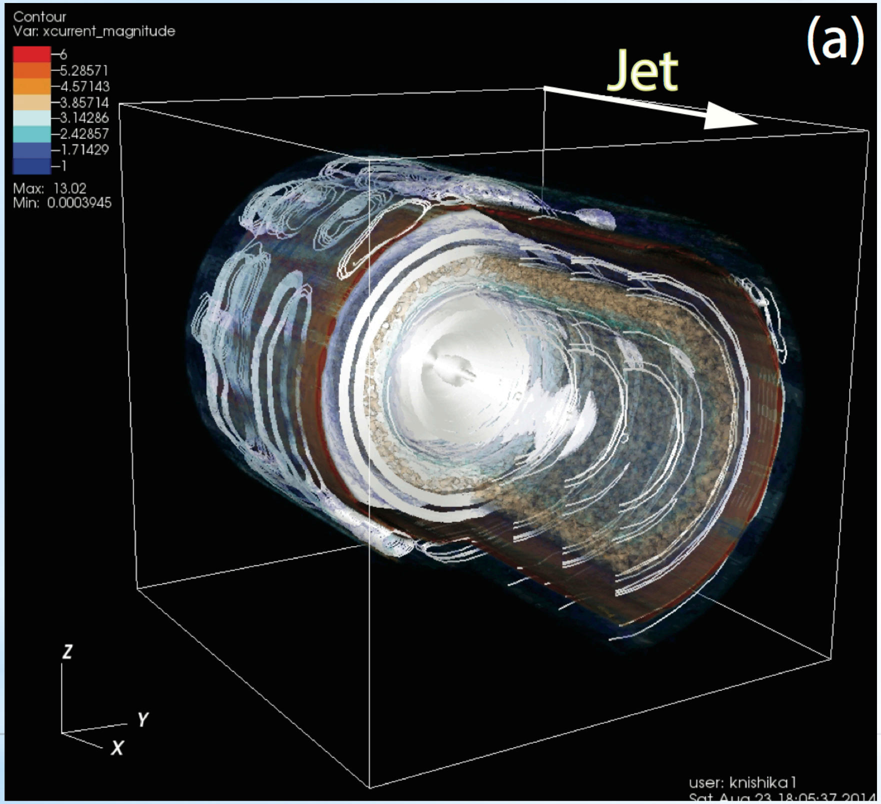
(Nishikawa et al. 2014, ApJ)

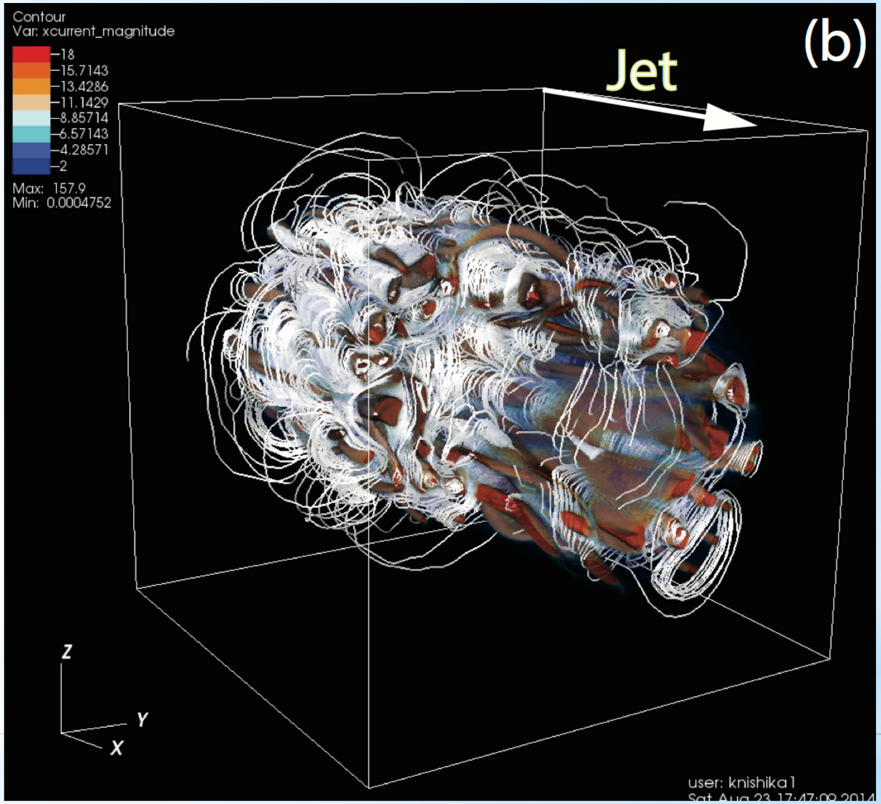
Cylindrical kKHI simulations

$\gamma_{jt} = 5 \qquad t = 300\omega_{pe}^{-1}$

e - p

e±





3D global jet simulation

NASA Pleiades

system size: 2000Δ×1000Δ×1000Δ

jet radius: 100Δ

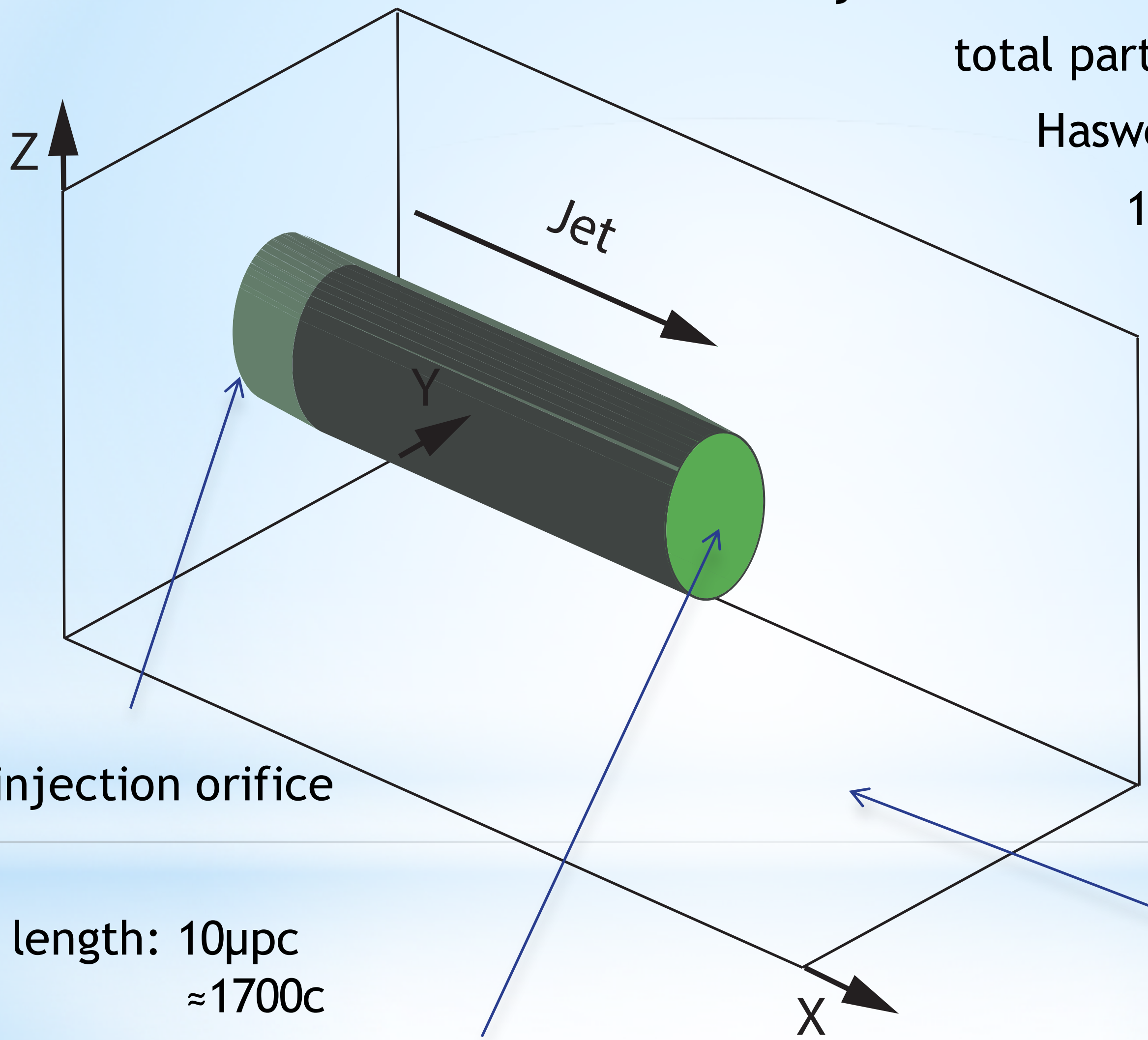
total particles: 48.8 billions

Haswell 7.1GB/processor

10,000 processors

5.76TB memory

7:55 hours



Jet injection orifice

Jet length: 10μpc
≈1700c

Jet head

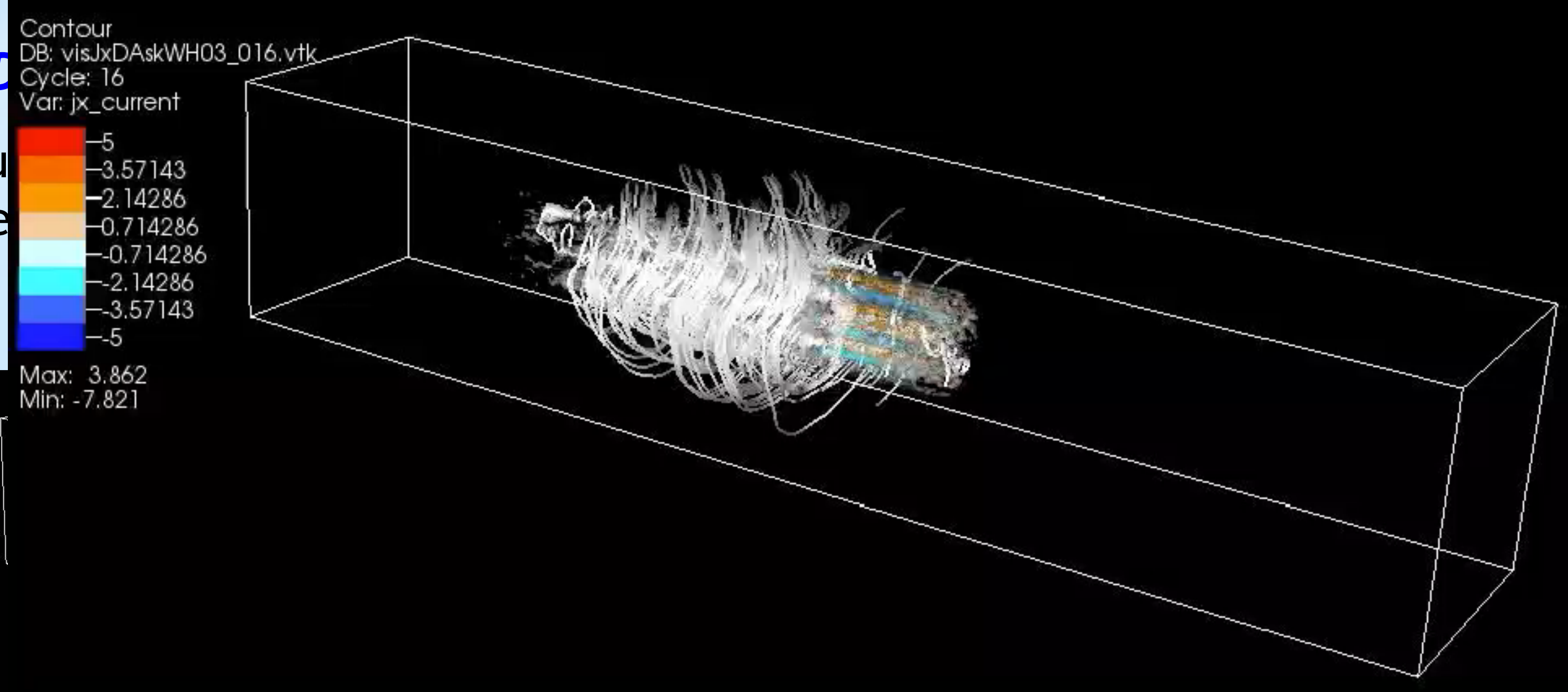
Ambient plasma

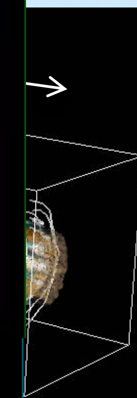
3D

Evolu ... $00\omega_{pe}^{-1}$

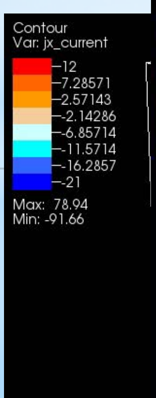
and e

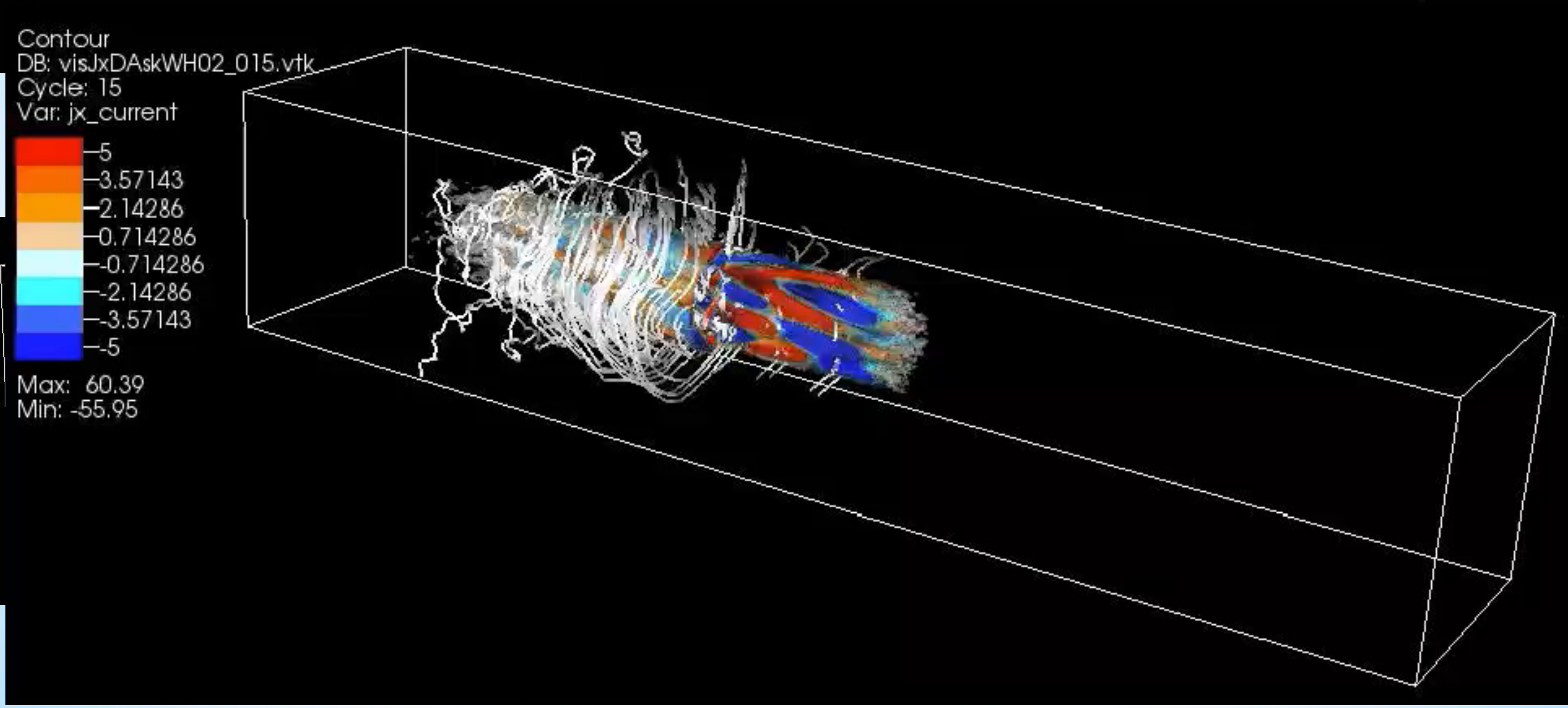
e - ... s

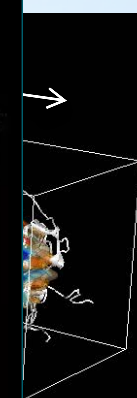




e±





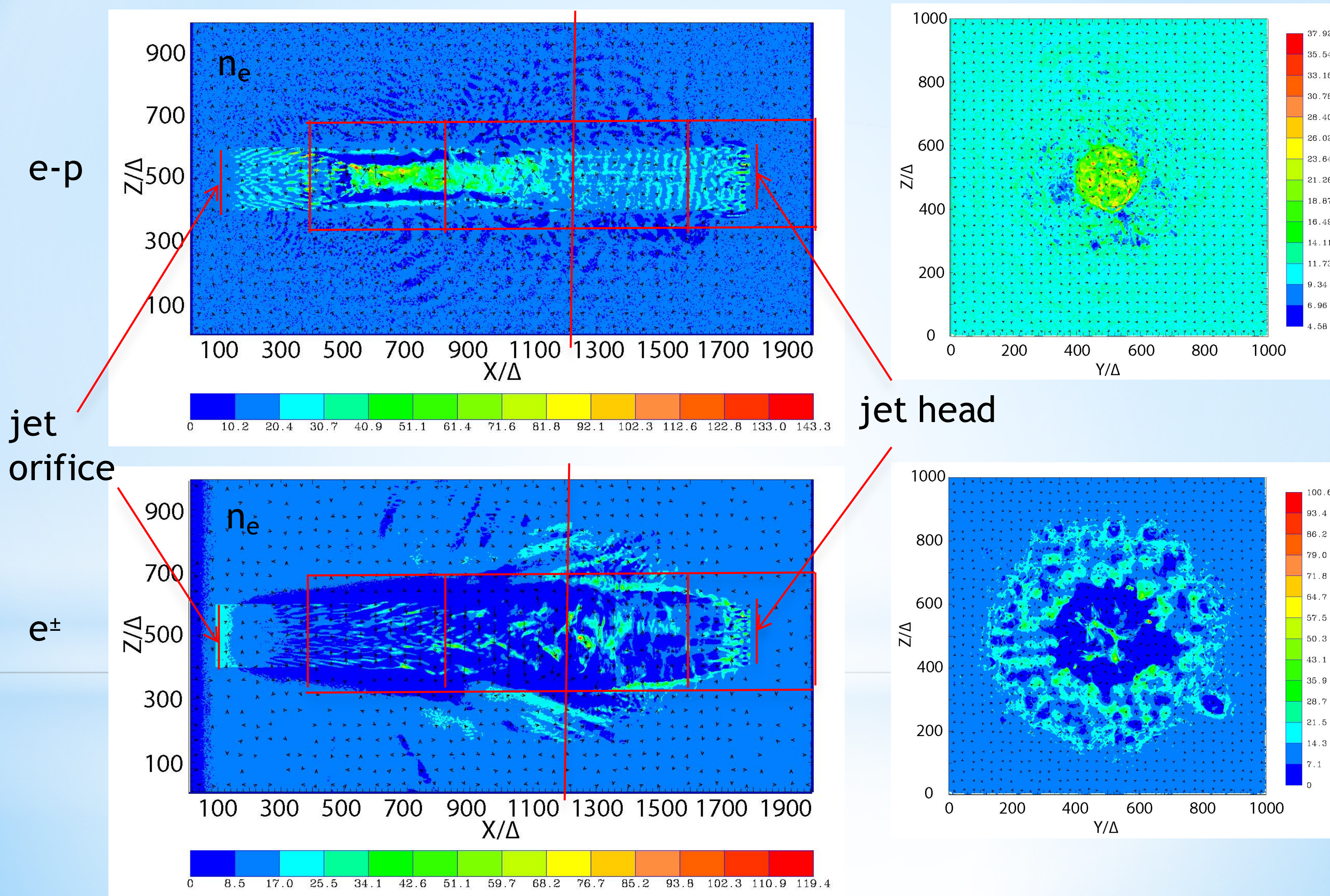


Why we need to perform huge RPIC simulations of relativistic jets

- Kinetic processes are important for particle acceleration and global evolution
- Kinetic instability such as kinetic Kelvin-Helmholtz instability (kKHI), Mushroom instability (MI), and the Weibel instability are ubiquitous and responsive to global evolution of jets
- AGN jets are considered for generation of high energy cosmic ray, but it requires global kinetic simulations to take into account of particle acceleration due to reconnection, which has been proposed one of possible mechanism
- Relativistic jets are generated from black hole with twisted strong magnetic field, which contributes for accelerate particles to very high energy via reconnection, therefore RPIC simulations of relativistic jets with helical magnetic fields can give an answer to this issue
- Investigate the cross-scale coupling for two of the most ubiquitous plasma processes that are essential to the dynamics of the relativistic jets: magnetic reconnection and plasma turbulence
- Huge supercomputer such as Blue Waters will make it possible for us to do a study by being able to push our simulations to the largest size possible on any supercomputer today in order to implement macroscopic processes as in fluid models
- The ability to simulation the microphysical processes responsible for reconnection, turbulence and for high energy particle acceleration is increasingly important as new cosmic-ray and neutrino observation such as Cherenkov Telescope Array (CTA), IceCube and present missions advance their observations
- This RPIC global jet simulations are new and innovative and will provide complex evolution of relativistic jets with kinetic processes which cannot be done by RMHD simulations

Snap shots of electron density of global jet simulations with arrows ($B_{x,y,z}$)

$\gamma_{jt} = 15$ $t = 1{,}700\omega_{pe}^{-1}$ $n_{jet} = 0.67n_{amb}$ at the center of the jet X/Δ=1200

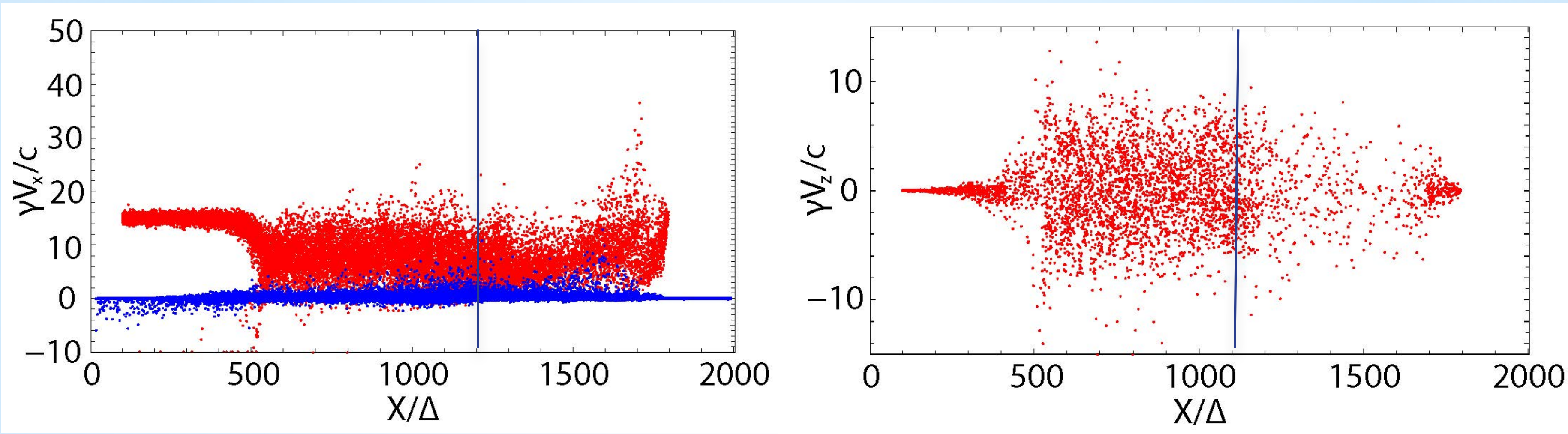


(Nishikawa et al. in progress, 2015)

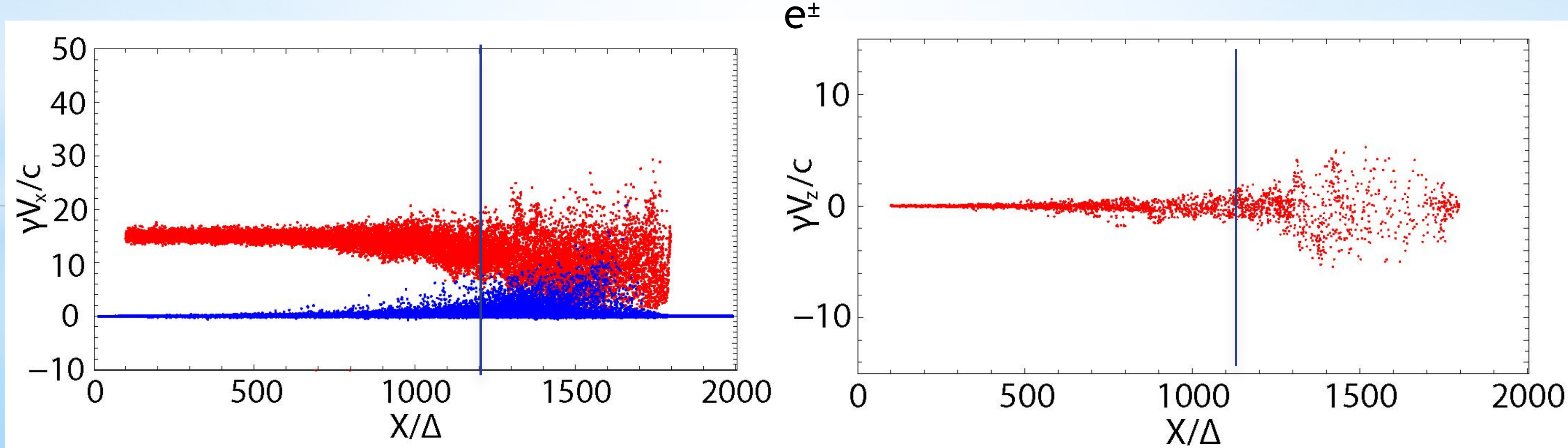
Phase-space distributions of electrons (X - Vx, and X - Vz)

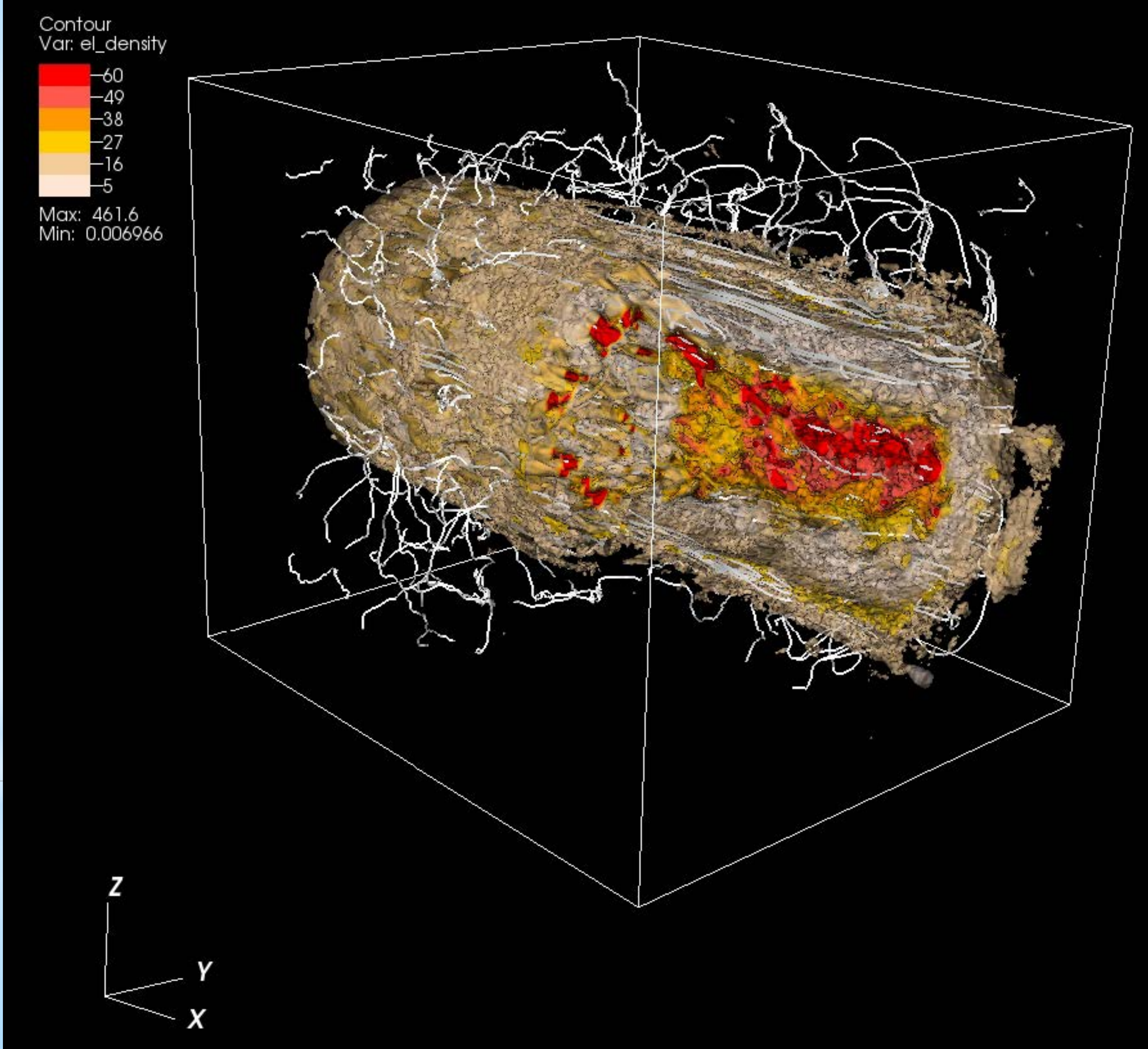
red: jet electrons, blue: ambient electrons

e-p



e±



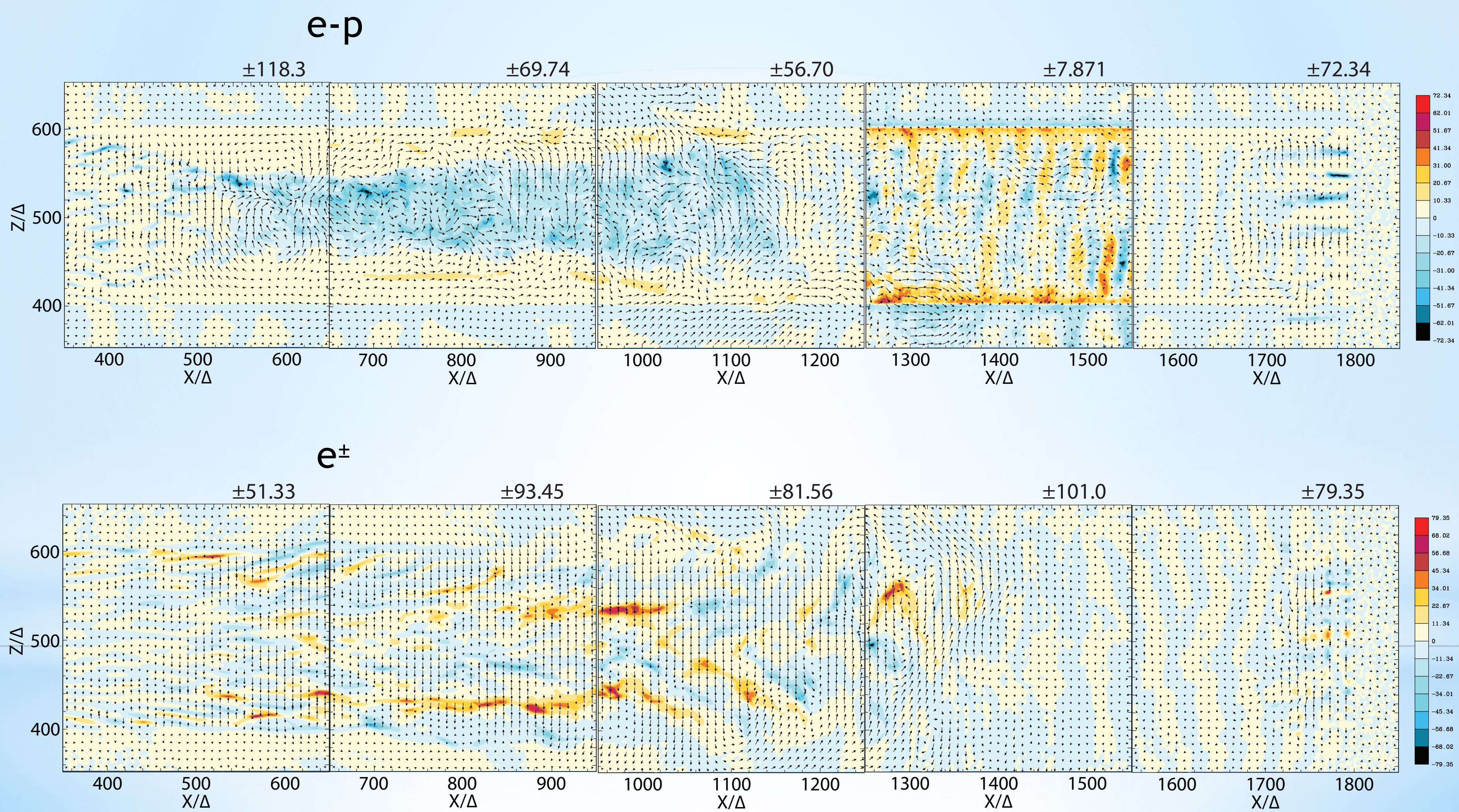


current
filaments
disappear

et
ollimates
ue to kKHI

current
filaments
remain at
jet head

Current density in x-z plane at the center of jet ($B_{x,z}$)



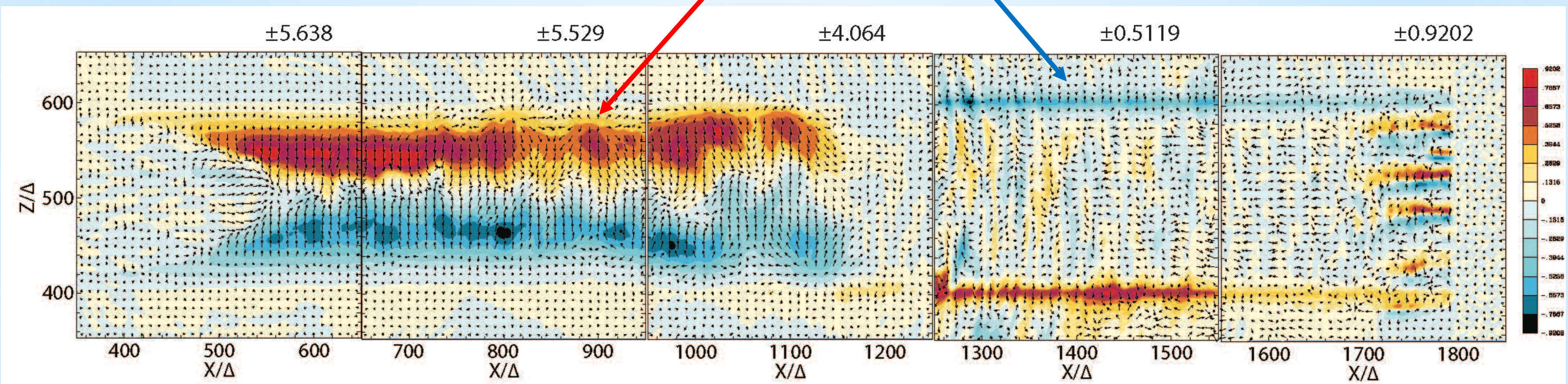
The y component of magnetic field (B_y) in x-z plane at the center of jet ($E_{x,z}$)

polarity

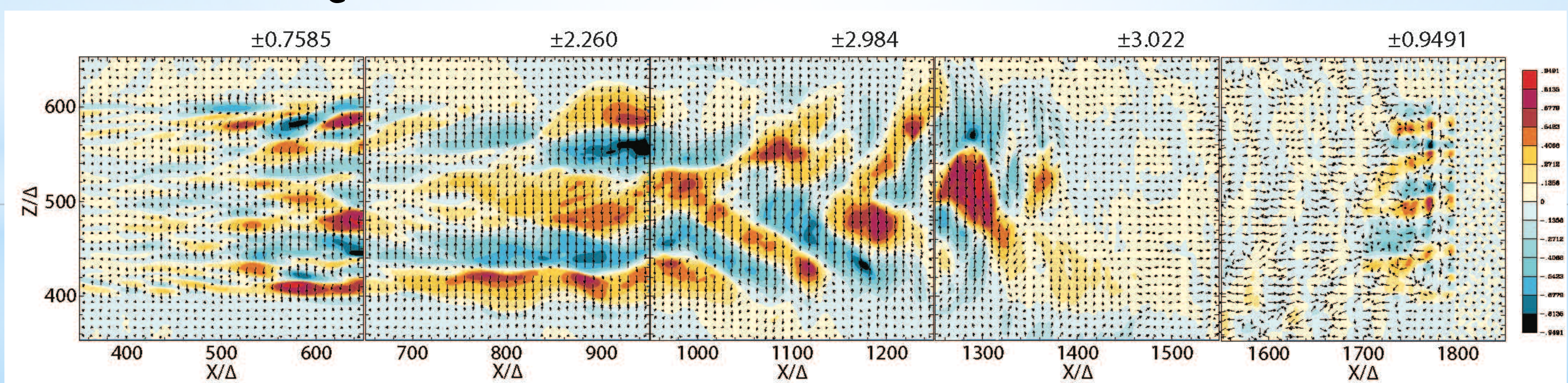
clockwise

counterclockwise

e-p



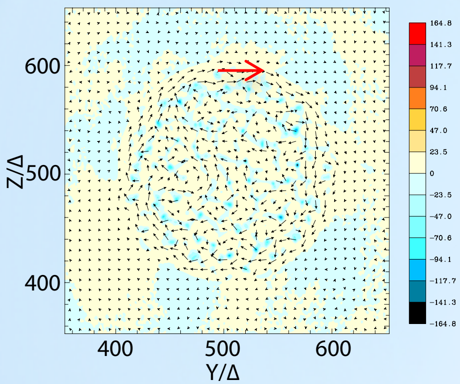
$e^{\pm}$



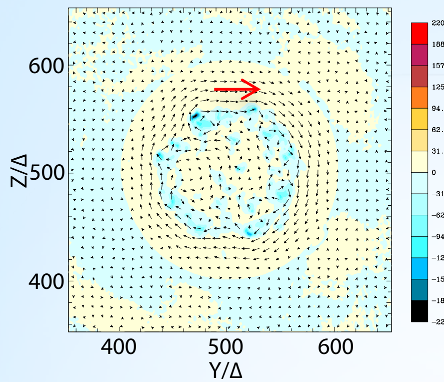
J_x with $B_{y,z}$ e-p

→ polarity: clockwise

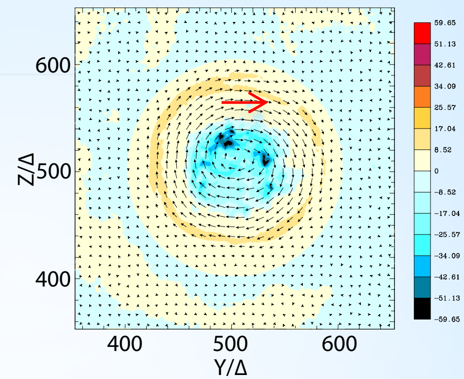
x/Δ = 400



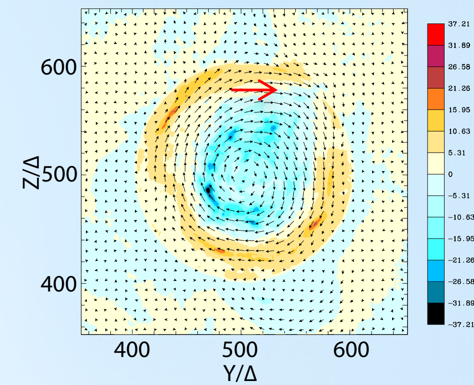
500



700

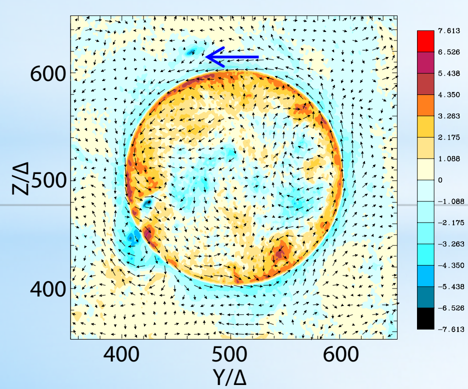


1000

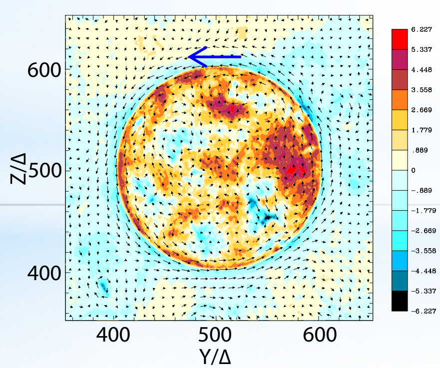


← polarity: counterclockwise

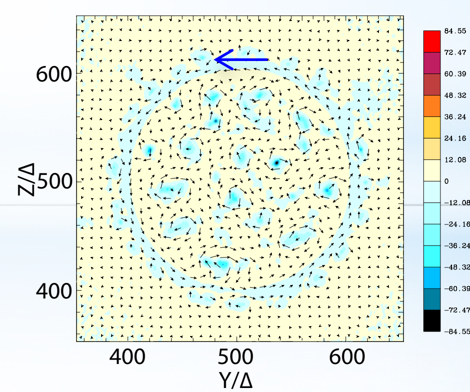
x/Δ = 1300



1600



1750



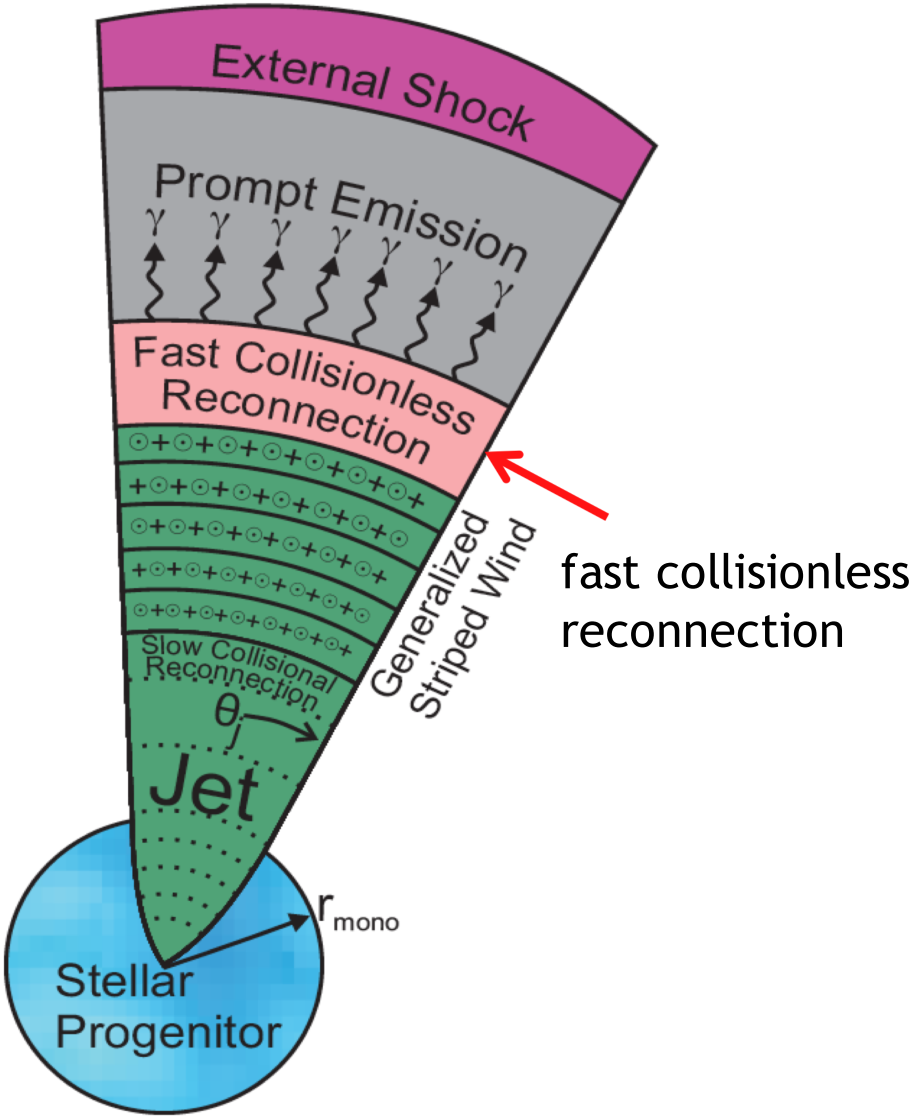
Summary and Discussions

The key simulation results for both case are following:

for the e^- - p^+ case
* Jet electrons are collimated due to the strong toroidal magnetic fields generated by the MI.
* Electrons are perpendicularly accelerated with jet collimation.
* The magnetic polarity switches from the clockwise to anti-clockwise in the middle of jet.

for the $e^\pm$ case
* Jet electrons and positrons are mixed with ambient plasma, which creates a bow shock.
* The magnetic fields around current laments generated by the combination of kKHI, MI and Weibel instability merges, then generate density bumps which initiate a shock.

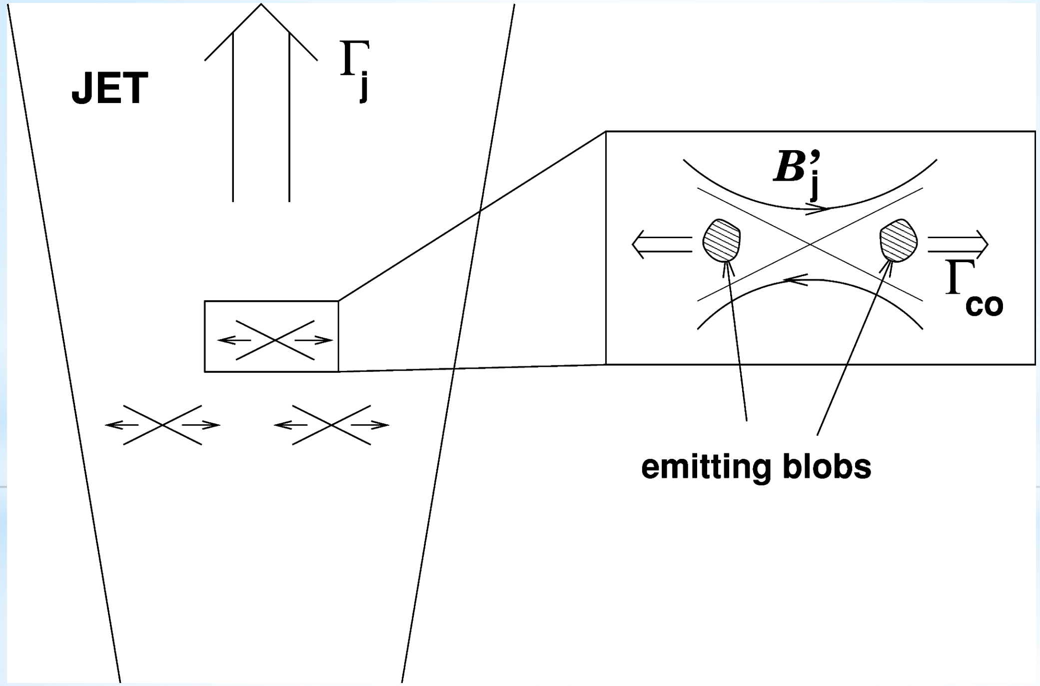
Reconnection in jet



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.

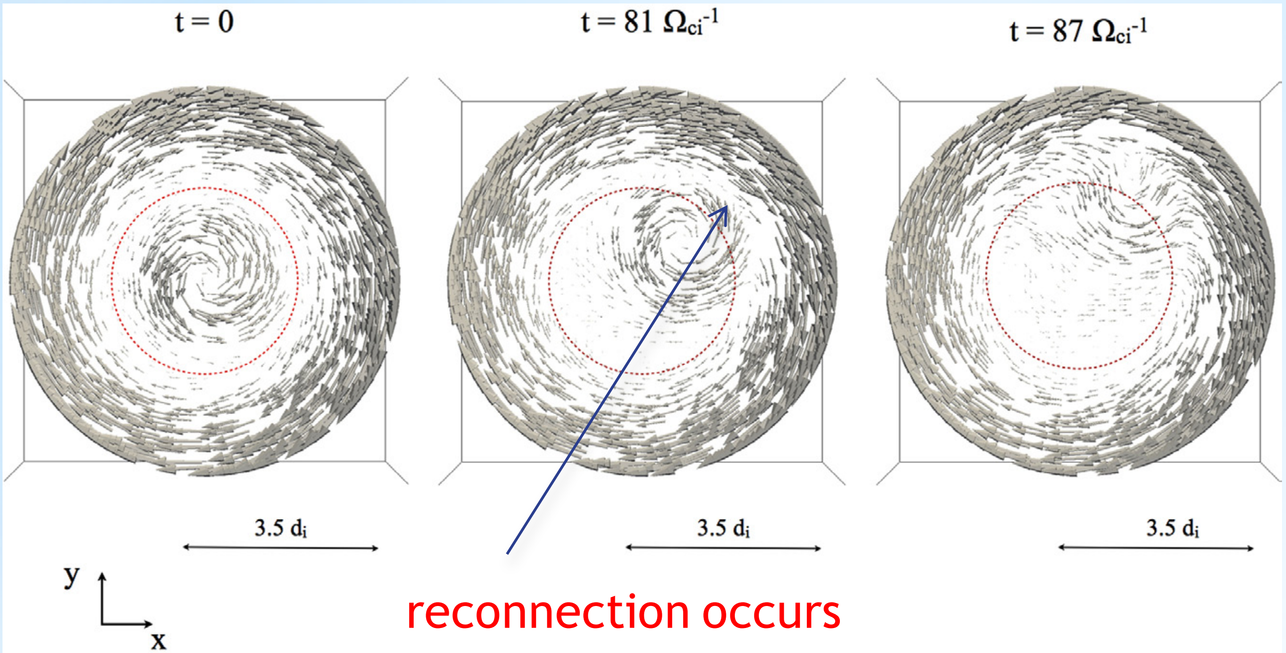
Reconnection in astrophysical system

Jet in jets are discussed by Giannios et al. 2009; Komissarov et al. 2009; Zhang & Yan 2011; Nalewajko et al. 2011; Cerutti et al. 2012, Granot et al. 2012; Komissarov 2012; McKinney & Uzdensky 2012; Sironi et al. 2015

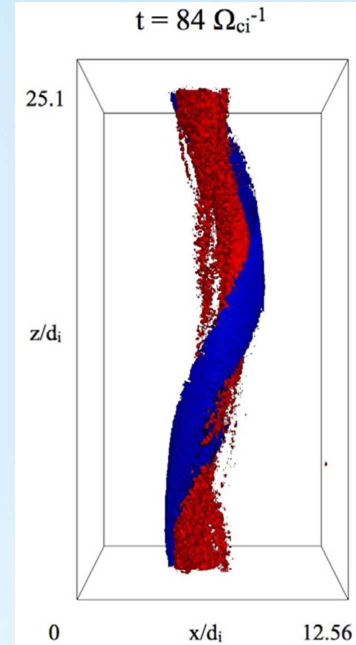


(Giannios et al. 2009)

Signatures of secondary collisionless magnetic reconnection driven by kink instability of a flux rope



Quiver plot of B* at time t = 0, t = 81Ω_{ci}^{-1} and t = 87 Ω_{ci}^{-1} in the plane z = $L_z/2$, r < 3.5 d_i. Initially, the quiver plot shows two disconnected B∗ regions (B∗ pointing at different directions). At time t = 81Ω_{ci}^{-1}, the B∗ internal region moves outward as effect of the kink instability. At time t = 87 Ω_{ci}^{-1}, the two initially disconnected B∗ regions reconnect. The resonant surface is shown with dashed red line.

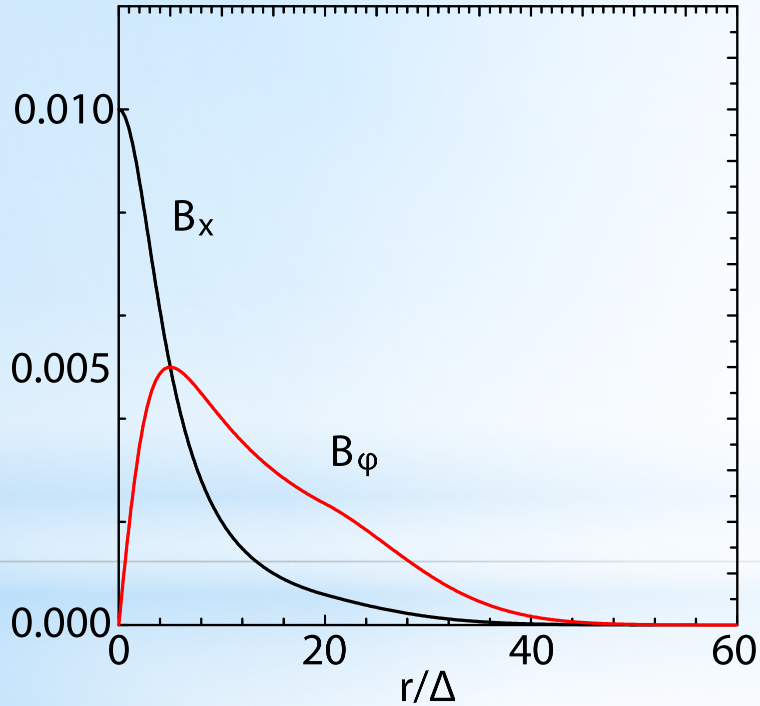


Isocontour of the axial component of the electron current J_{ez} = 0.005en_0c (red color) and J_{ez} = −0.005en_0c (blue color) at time t = 84 Ω_{ci}^{-1}

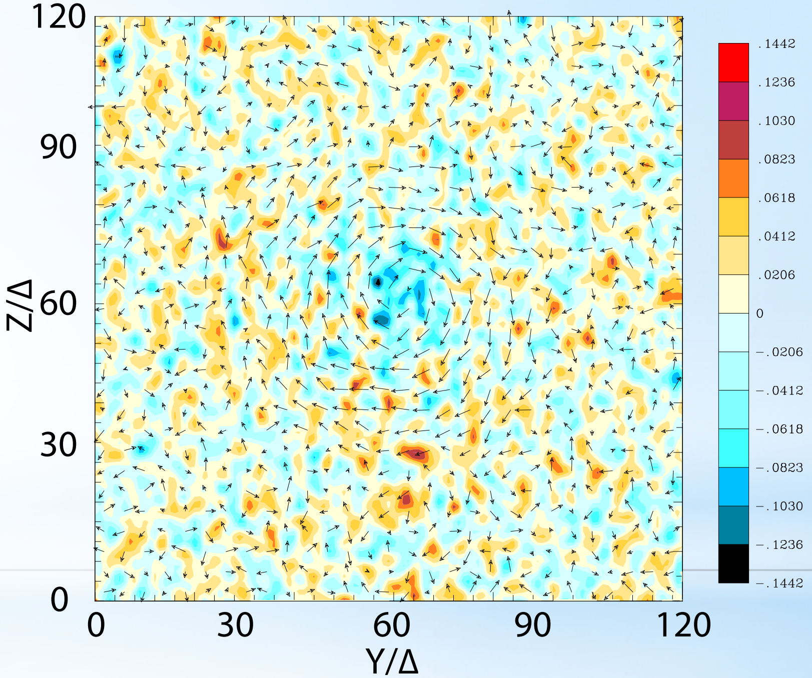
(Markidis et al. 2014)

Global simulations with helical magnetic field

Helical magnetic field



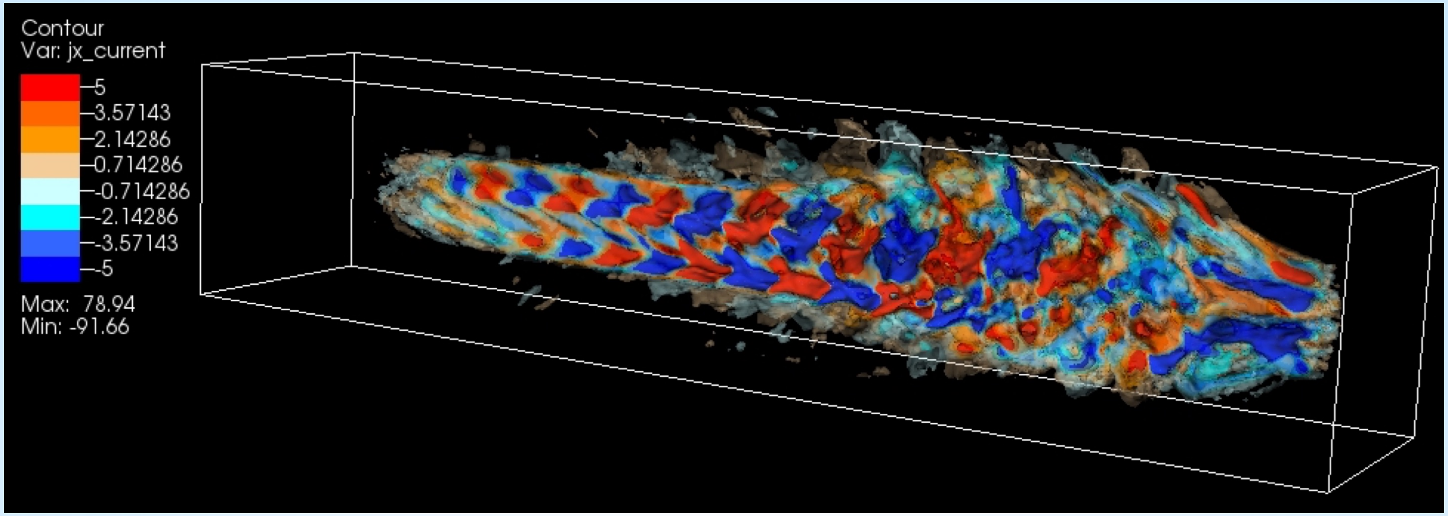
J_x with helical magnetic field



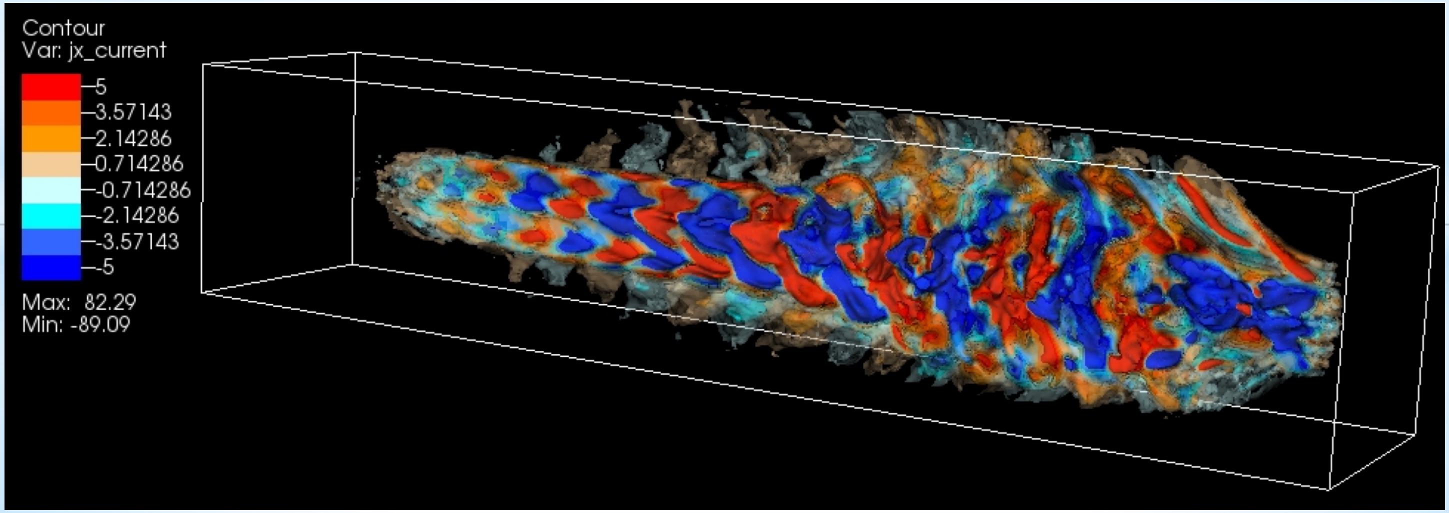
X = 101Δ

$e^{\pm}$ jet with $\gamma = 15$ $\qquad t = 500\omega_{pe}^{-1}$

$B_0 = 0$

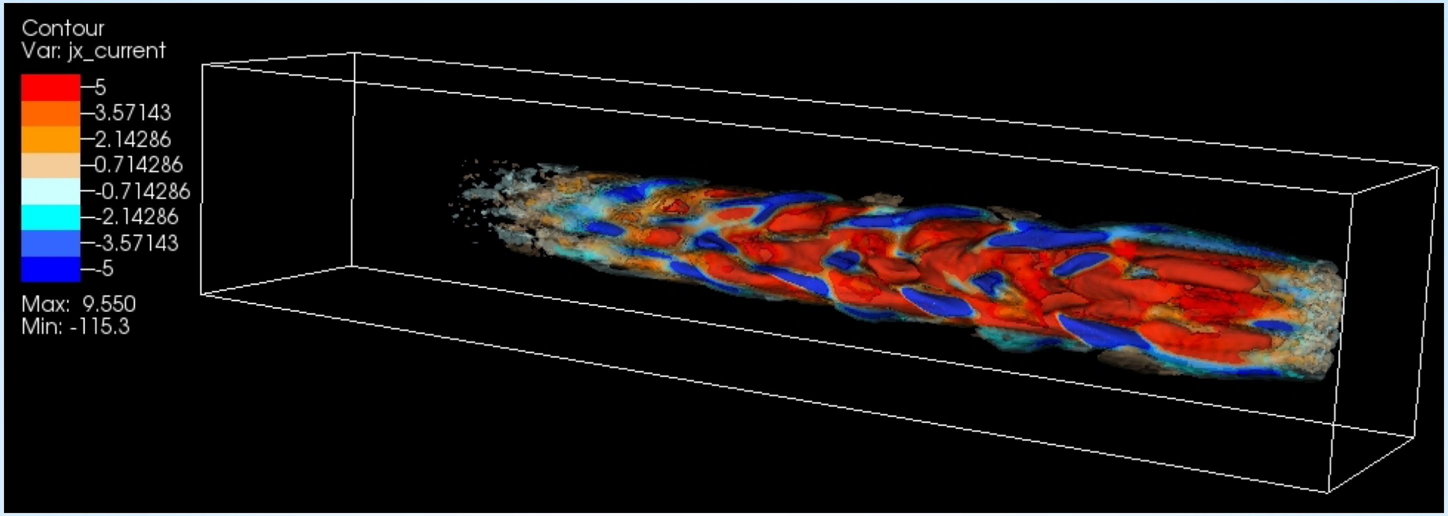


$B_0 = 0.01c$ without motional electric field

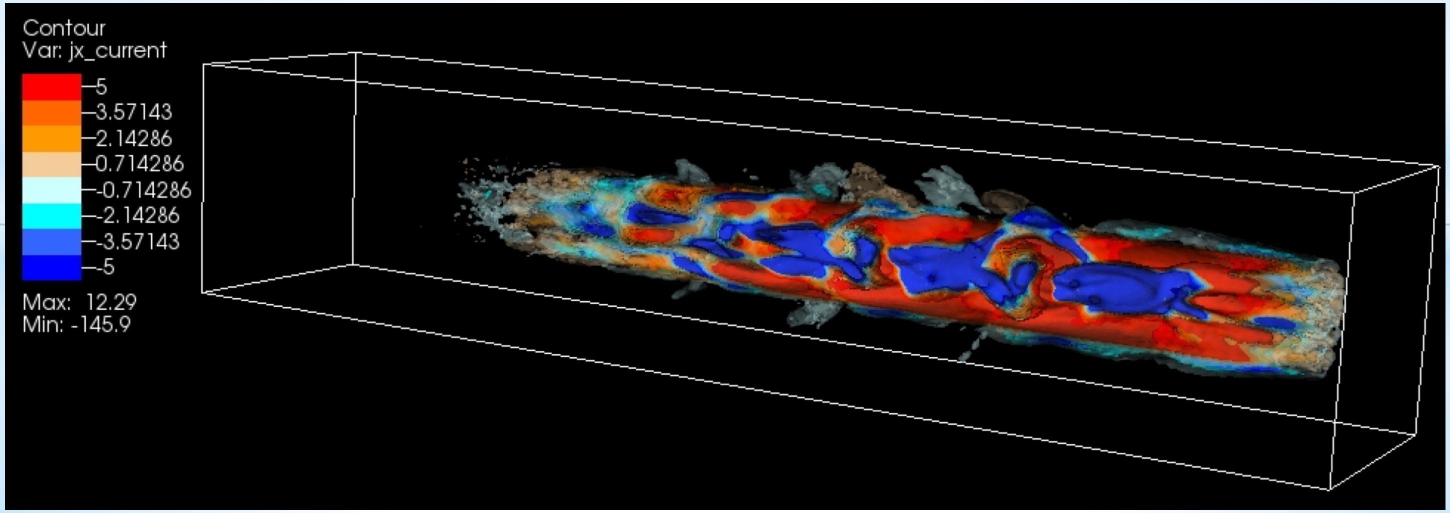


e^{-} - p^{+} jet with $\gamma = 15$

$B_0 = 0$

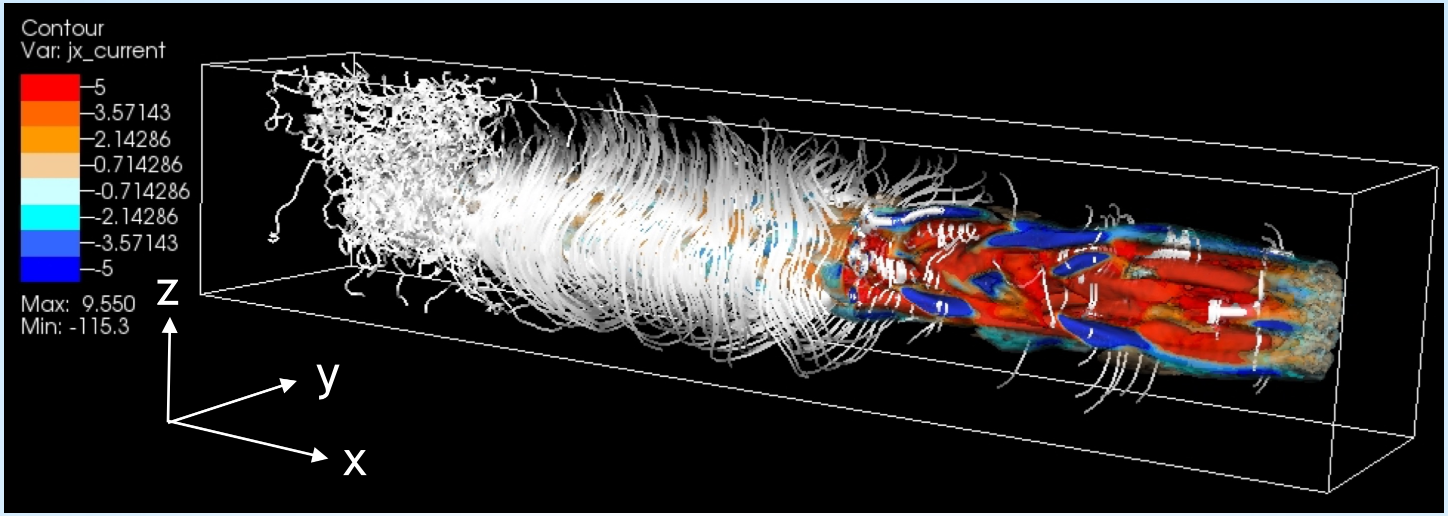


$B_0 = 0.01c$ without motional electric field

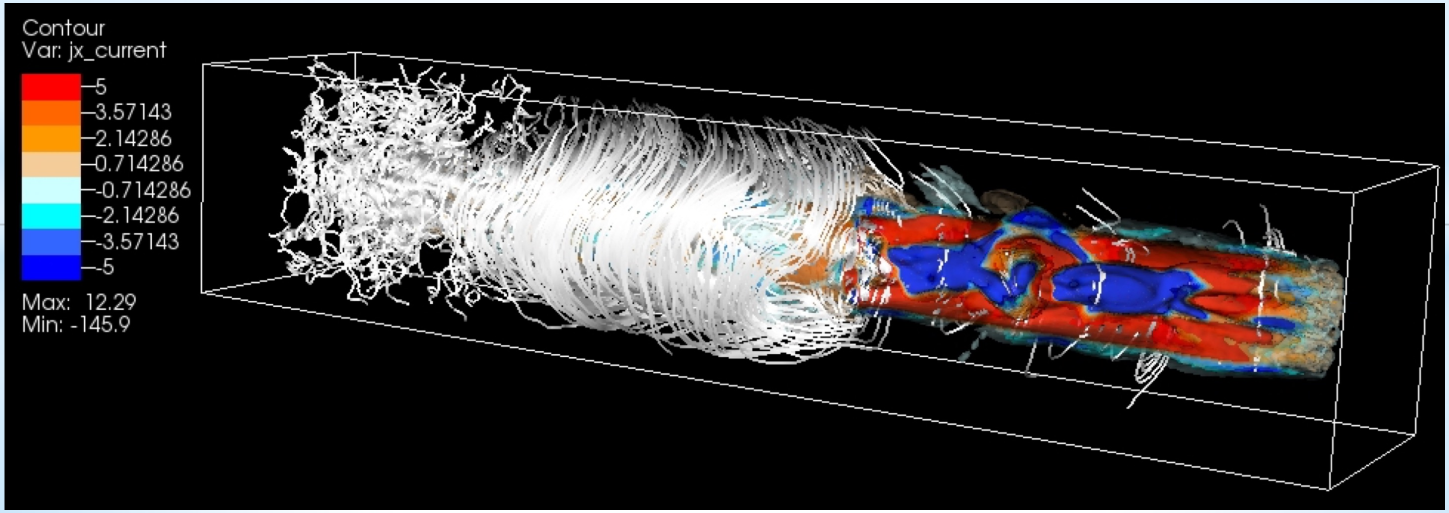


e^{-} - p^{+} jet with $\gamma = 15$ $\quad (120\Delta < x < 620\Delta,\ 16\Delta < y, z < 116\Delta)$

$B_0 = 0$ Clipped at x = $316\Delta, y = 56\Delta)$

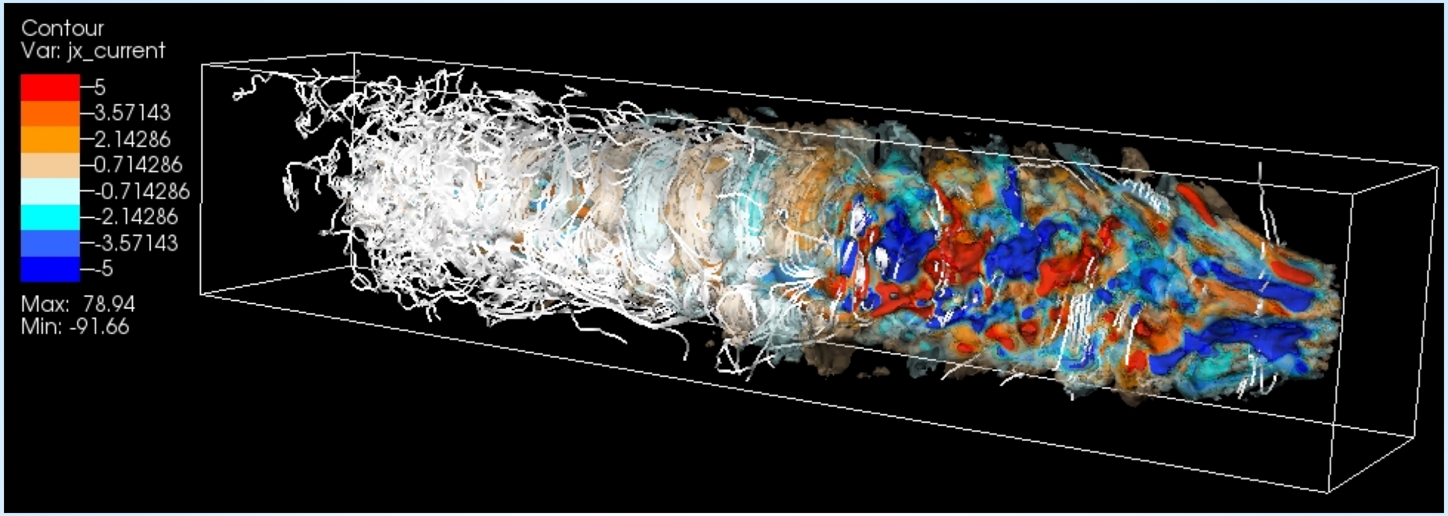


B_0 = 0.01c without motional electric field

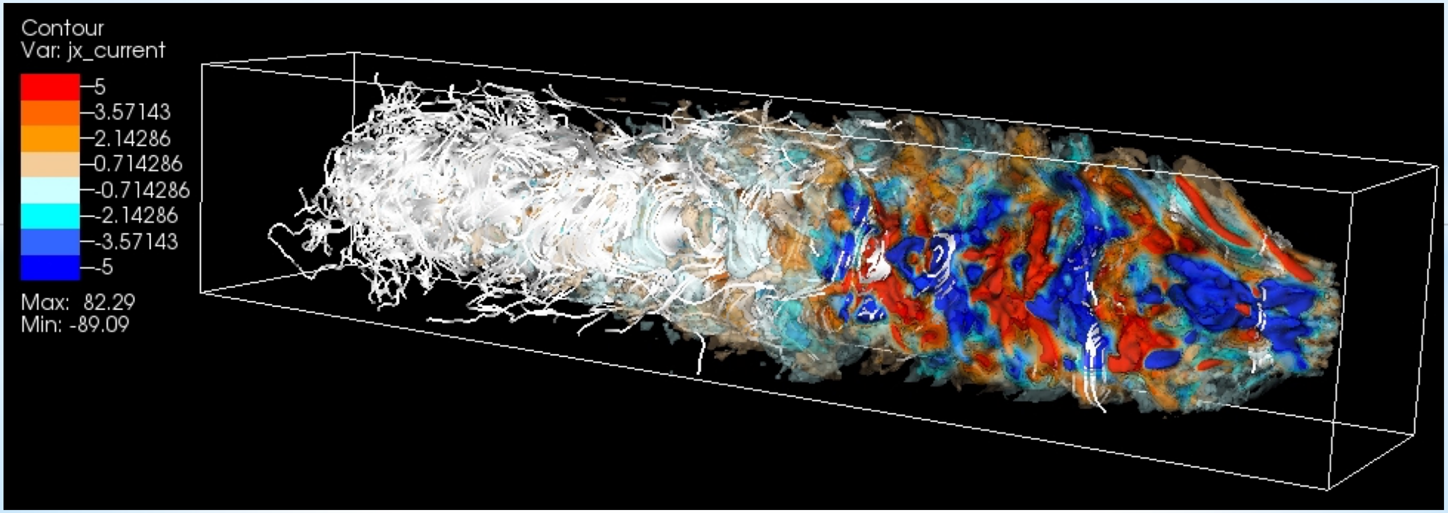


$e^{\pm}$ jet with $\gamma = 15$

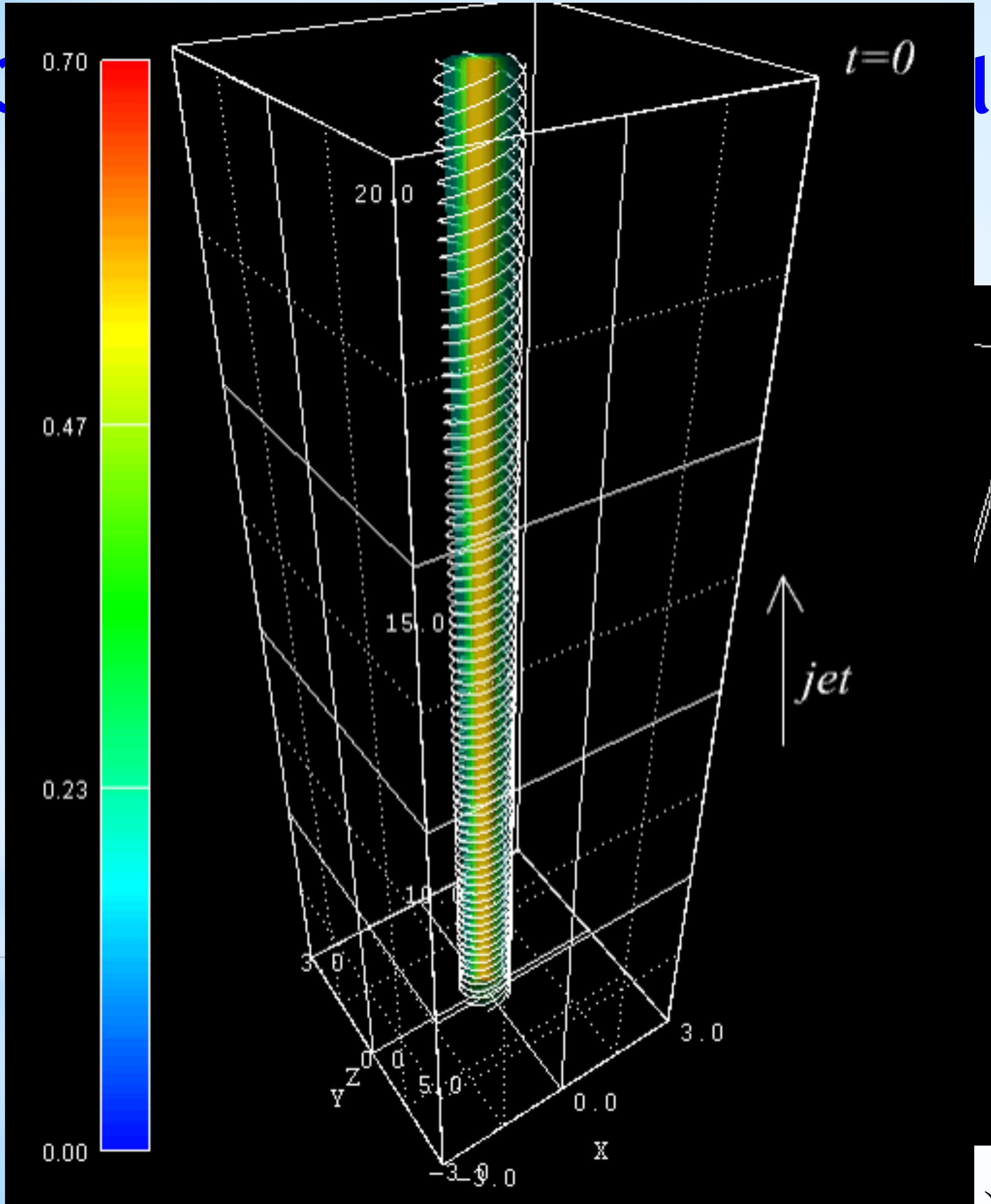
$B_0 = 0$



$B_0 = 0.01c$ without motional electric field



lical magnetic field



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).

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

Summary for global jet simulations

- The size of jet radius is critical for the evolution of jets
- The simulations with jet radius $r_{jet} = 200\Delta$ show the clear differences electron-proton and electron-positron jets
- The electron-proton jet shows jet collimation due to the toroidal magnetic field generated by kKHI
- The electron-proton jet shows the well-defined jet boundary by the edge current by protons
- The electron-positron jet shows the growth of kKHI and the Weibel instability which generate the strong current filaments expanding outside the jet
- The electron-proton jet shows strong toroidal magnetic field in the whole jet which may contribute circularly-polarized radiation
- Further simulations with a even larger system (larger jet radius) need to be investigated

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 simulation of shock, KKHI and reconnection with helical magnetic field in jet (GRBs, SNRs, AGNs, etc)
- Magnetic field topology analysis for understanding reconnection evolution
- Particle acceleration and radiation in recollimation shocks