Reconnection and Associated Flares in Global Relativistic Jets Containing Helical Magnetic Fields with RPIC Simulations

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J. T. Frederiksen (*AI Developer*)
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Half a Century of Blazars and Beyond,
June 11 - 15, 2018, Torino, Italy

Outline of talk

1. **Introduction of relativistic jets and Weibel instability** (Nisikawa et al 2009)
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, 2016a) **($r_{jt} = 100\Delta$)**
4. **Global jet simulations with helical B fields (reconnection)** (Nishikawa et al. Galaxies, 4, 38, 2016b) **($r_{jt} = 20\Delta$)**
5. **New results with larger jet radius with short system ($r_{jt} = 40\Delta, 80\Delta, 120\Delta$)** (Nishikawa et al. Galaxies, 5, 58, 2017)
6. **Two different Helical Magnetic Field structure ($a = r_{jt} = a/4$ and $a/2$)**
7. **Synthetic Spectra and Polarity Images**
8. **Summary**
9. **Future plans**

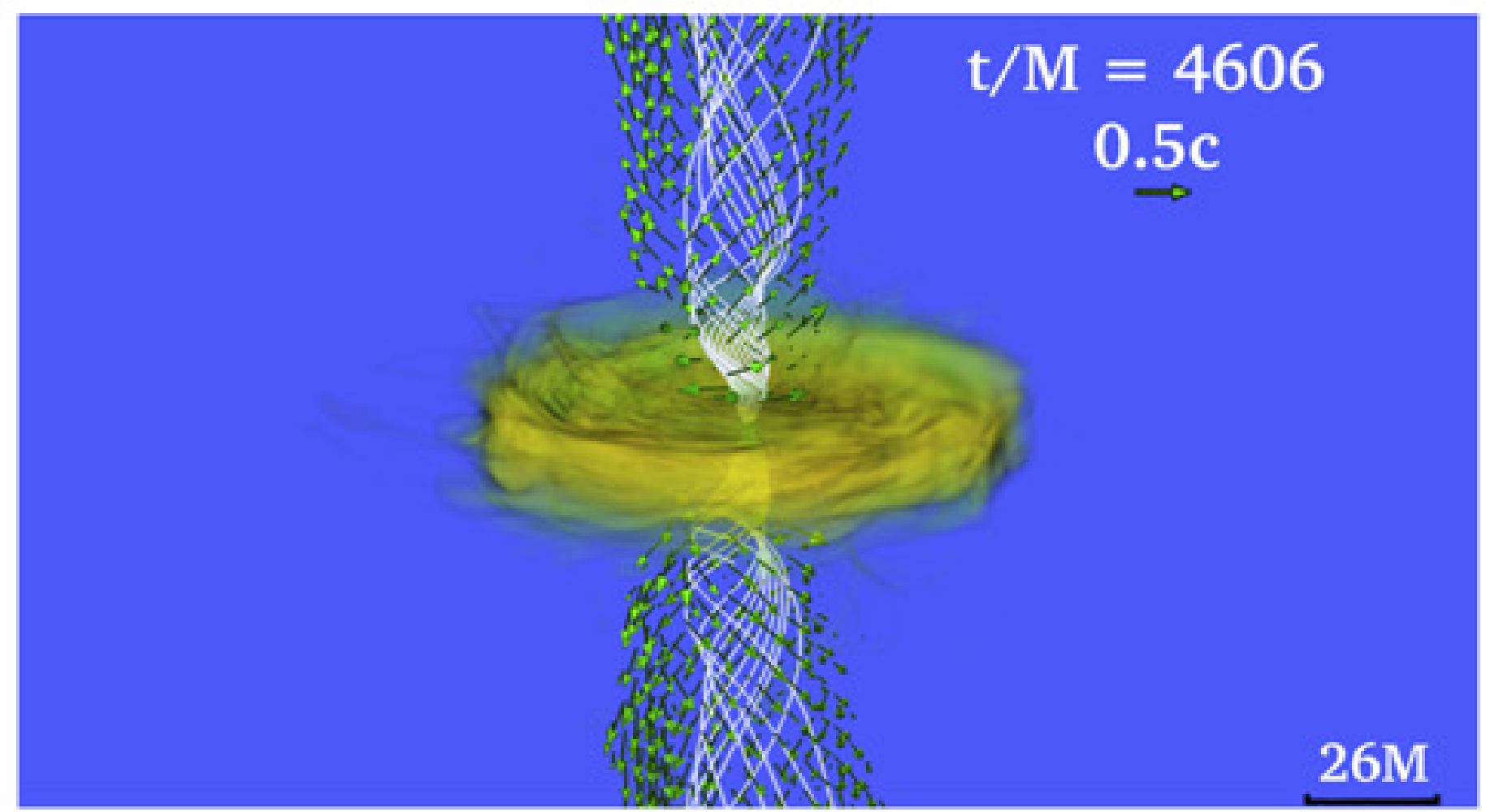
Key Scientific questions

- How do global jets evolve with different species?
- How do helical magnetic fields affect kinetic instabilities, shocks and reconnection?
- Jets in Jets really happen due to reconnection?

Why we need to perform RPIC simulations of relativistic jets

- Kinetic instabilities (e.g., kKHI, (MI), and the Weibel instability) are key in understanding jet evolution
- Helical magnetic fields are crucial in understanding these instabilities
- RPIC global jets simulations are new and innovative and provide complex evolution of relativistic jets with kinetic processes including radiation which cannot be done by RMHD simulations

Multi-frequency emission from relativistic jets generated by mergers with realistic jet structures



Ruiz et al. 2016

3D global jet simulation

NASA Pleiades

system size: 2000Δ×1000Δ×1000Δ

jet radius: 100Δ

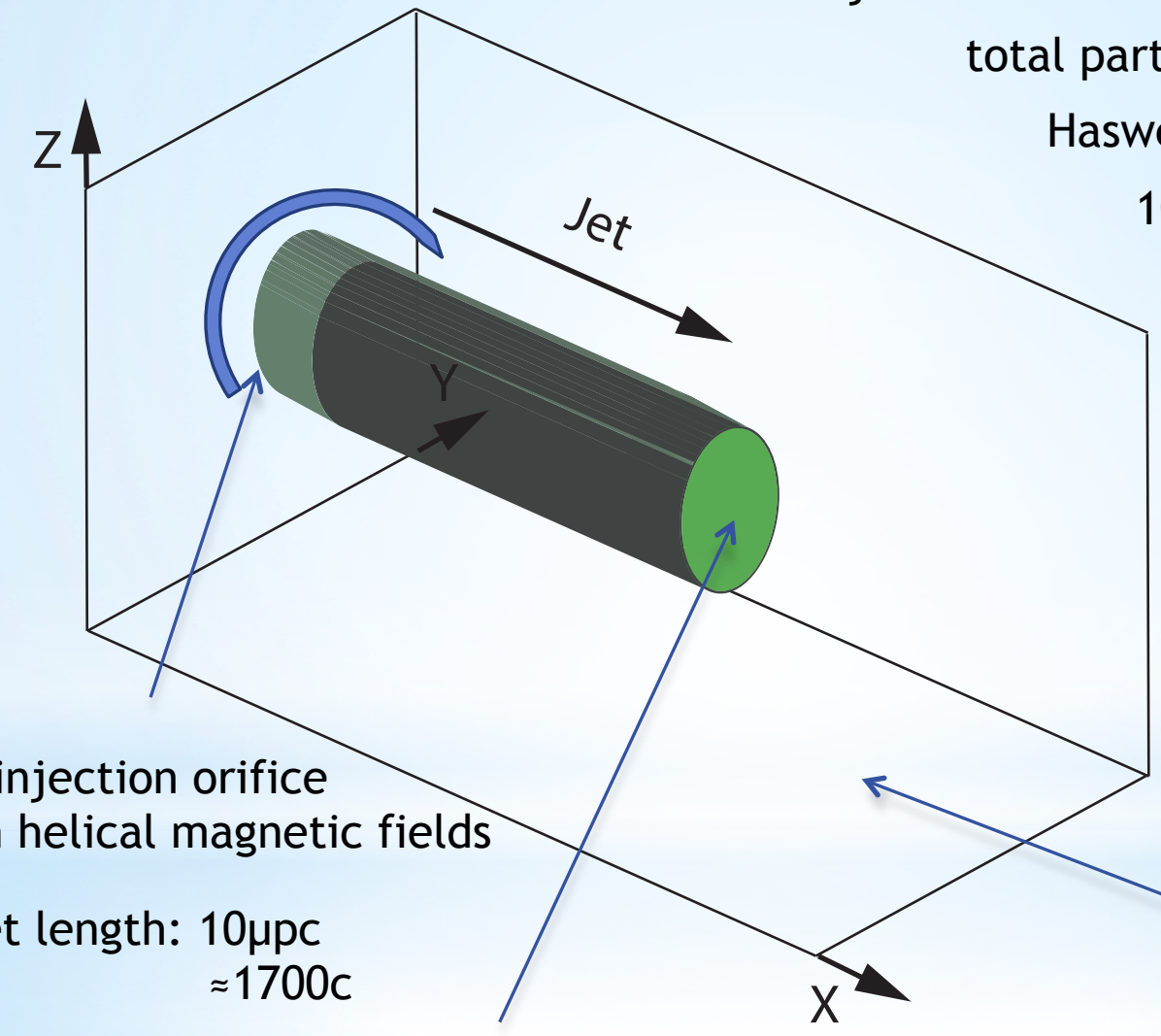
total particles: 48.8 billions

Haswell 7.1GB/processor

10,000 processors

5.76TB memory

7:55 hours



Jet injection orifice
with helical magnetic fields

Jet length: 10μpc
≈1700c

Jet head

Ambient plasma

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

Pleiades ($2000\times1000\times1000\Delta^3$)

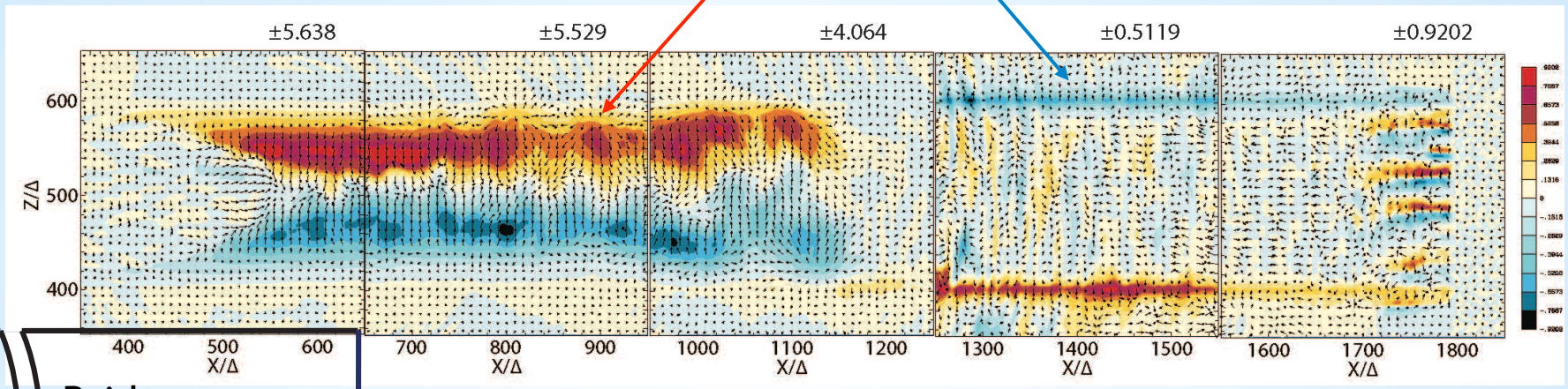
no helical magnetic fields

polarity switched

e− - p+

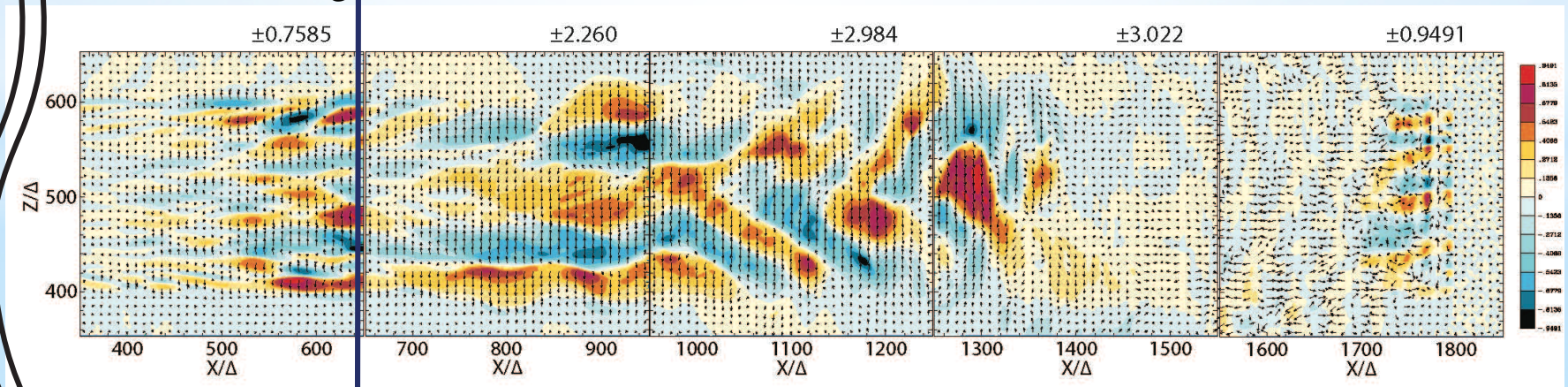
clockwise

counterclockwise



Bridges

$e^{\mp}$



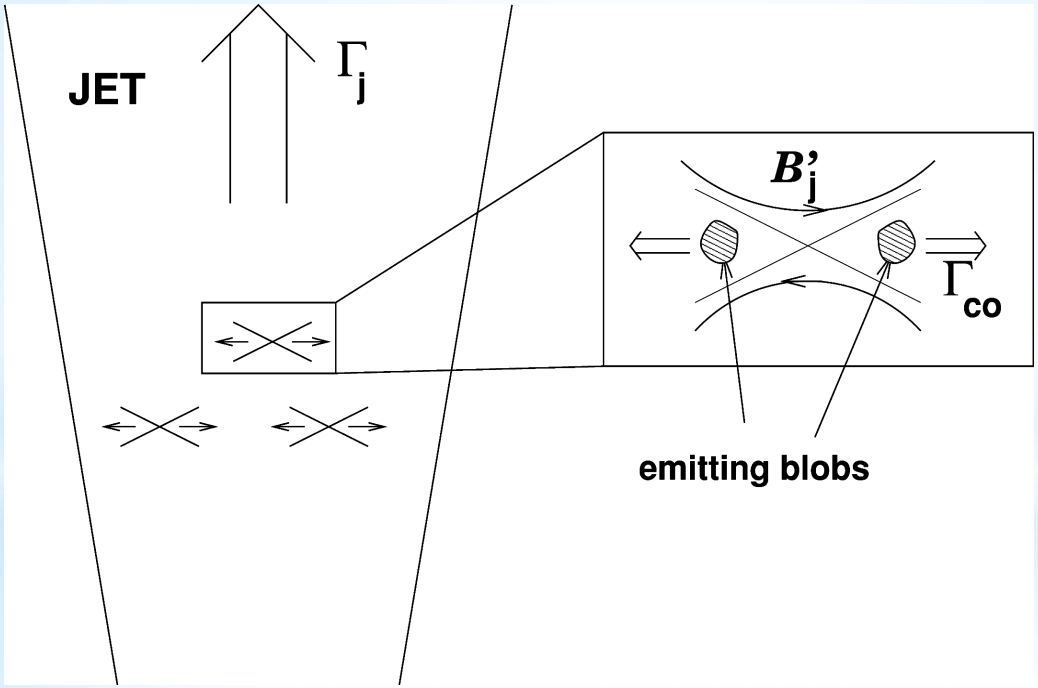
($640\times505\times505\Delta^3$)

present short simulations

(Nishikawa et al. 2016a)

Reconnection in astrophysical system

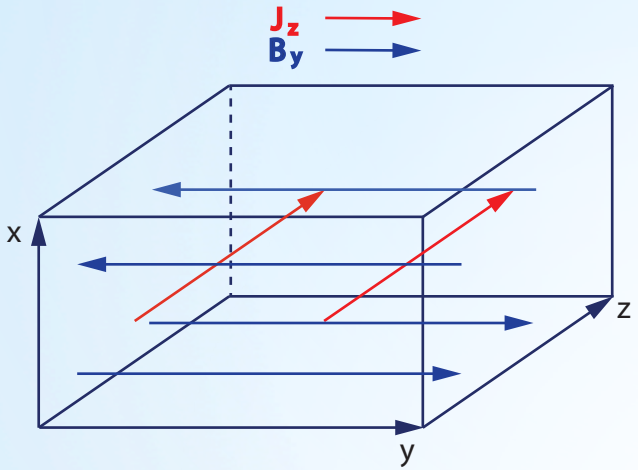
Jet in jets are discussed by Giannios et al. 2009; Komissarov et al. 2009; Zhang & Yan 2011; Nalewajko et al. 2011; Cerutti et al. 2012, Granot et al. 2012; Komissarov 2012; McKinney & Uzdensky 2012; Sironi et al. 2015; Duran, Leng, & Gianios 2016



(Giannios et al. 2009)

Reconnection with Harris model

Initial conditions: anti-parallel magnetic field generated by sheet current
(extensive simulation studies with “Harris model”)



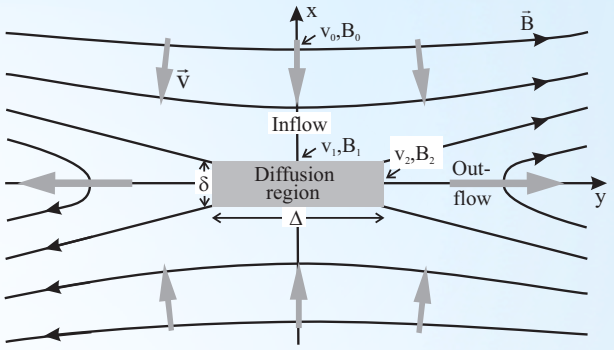
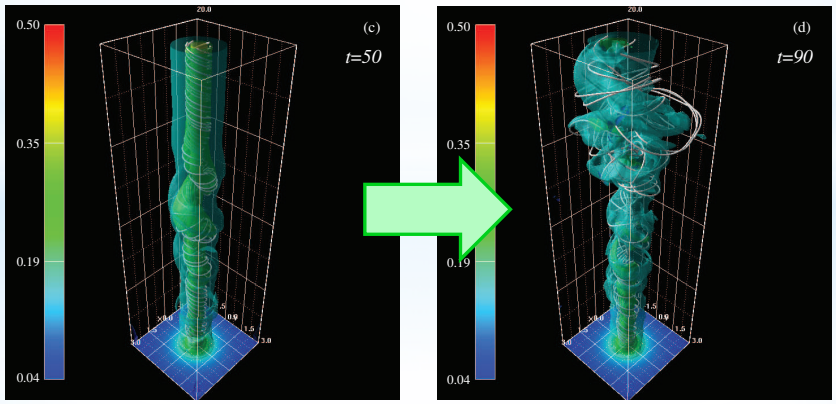


Figure 1. Qualitative pattern of two-dimensional reconnection.

In global jets (helical magnetic fields: Harris model cannot be applied)



(Mizuno et al. 2014)

Current-driven instability may trigger reconnection?

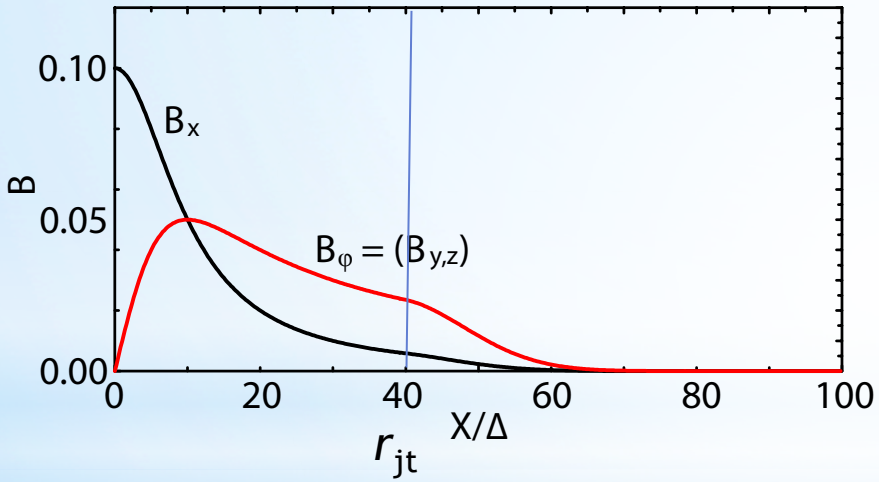
Global simulations with helical magnetic field

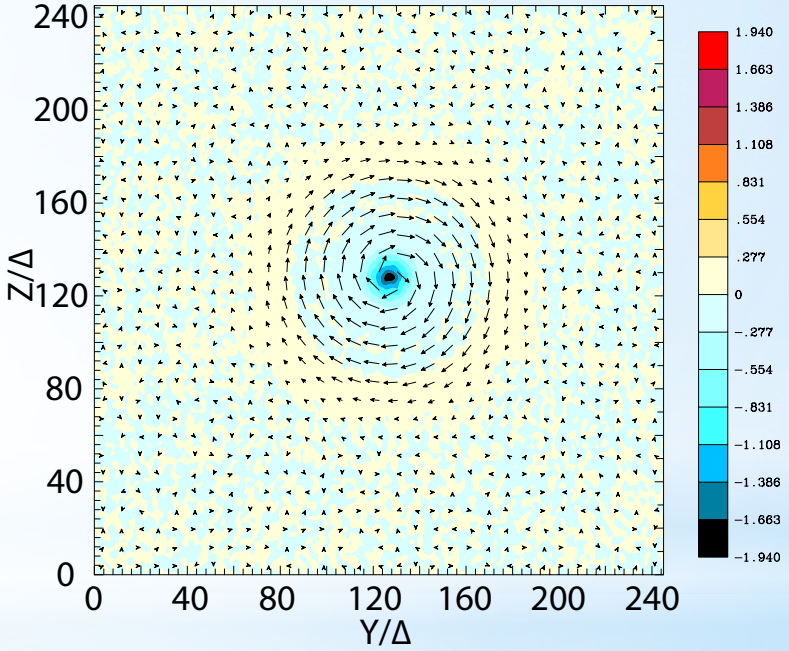
Helical magnetic field

e± jet with γ=15 $t = 500\omega_{pe}^{-1}$

J_x with helical magnetic field

B_0 = 0.1 r_{jt}=40Δ





r_{jt}=80Δ, and 120Δ

X = 101Δ

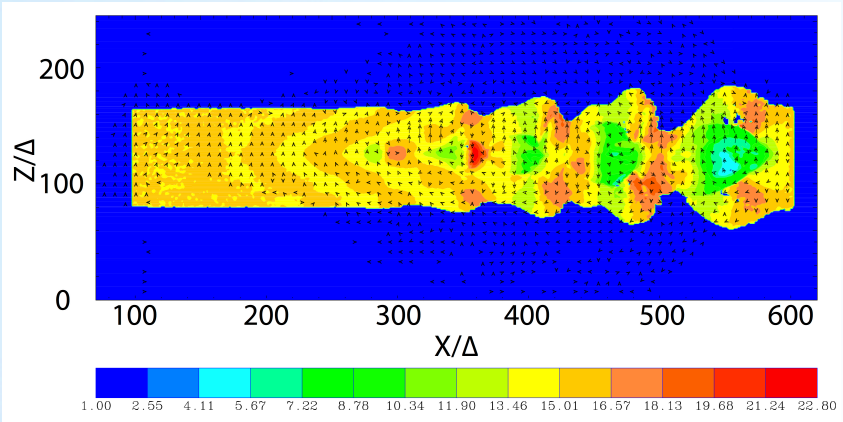
Average Lorentz factor of jet electrons

γ=15 B_0 = 0.1

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

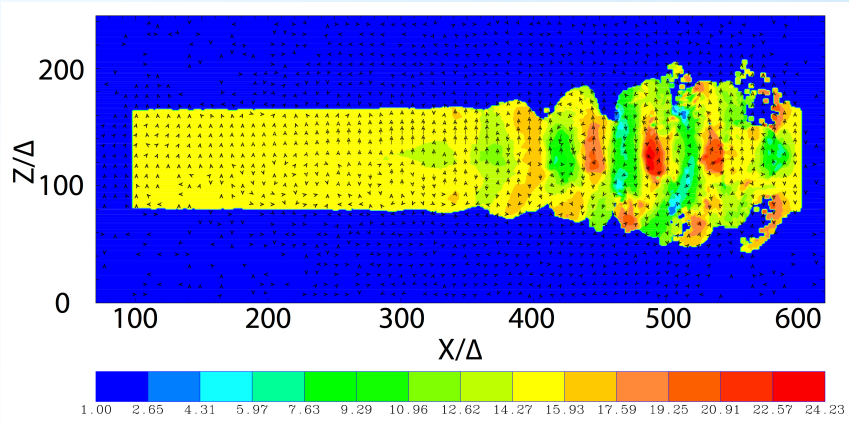
e− - p+ jet

r_{jt}=40Δ



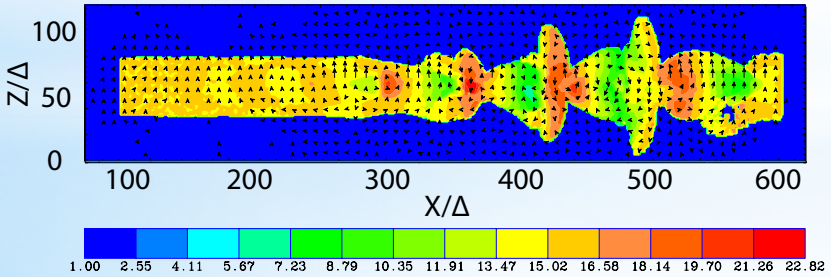
1.00 22.80

e± jet

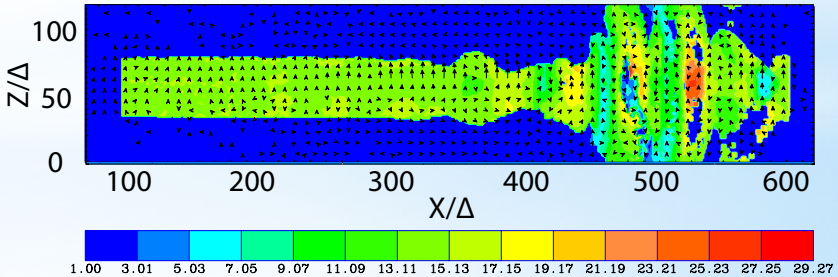


1.00 24.23

r_{jt}=20Δ



1.00 22.82

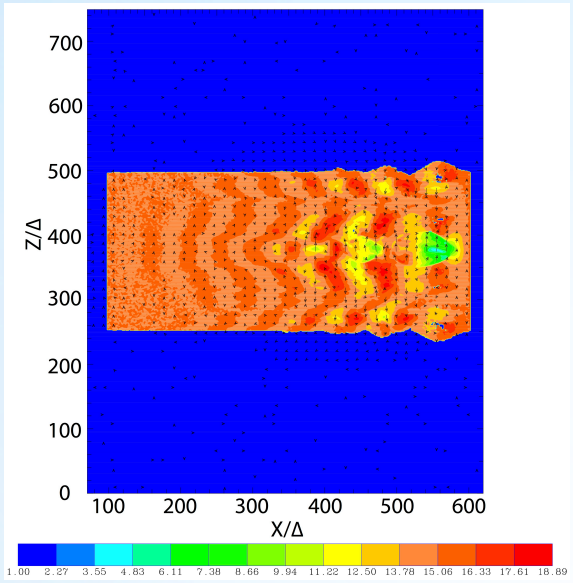


1.00 29.27

Average Lorentz factor of jet electrons

γ=15 $B_0 = 0.1$ $t = 500\omega_{pe}^{-1}$

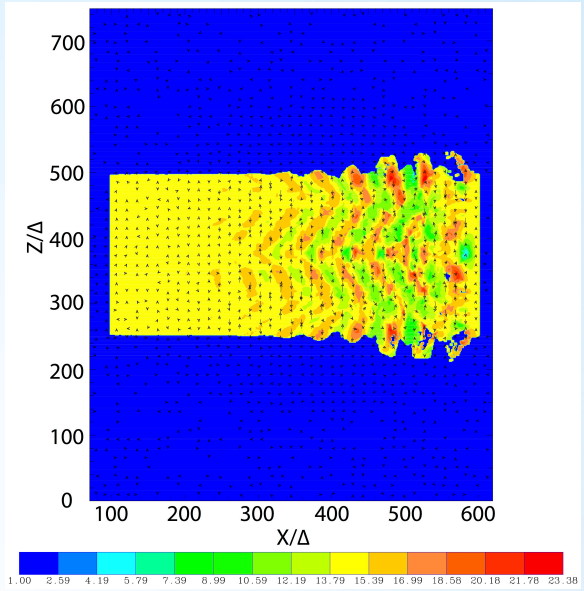
e− - p+ jet



r_{jt}=120Δ

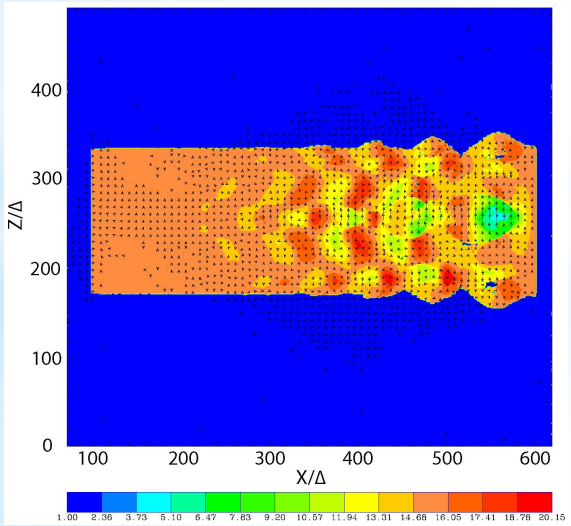
1.00 18.89

e± jet

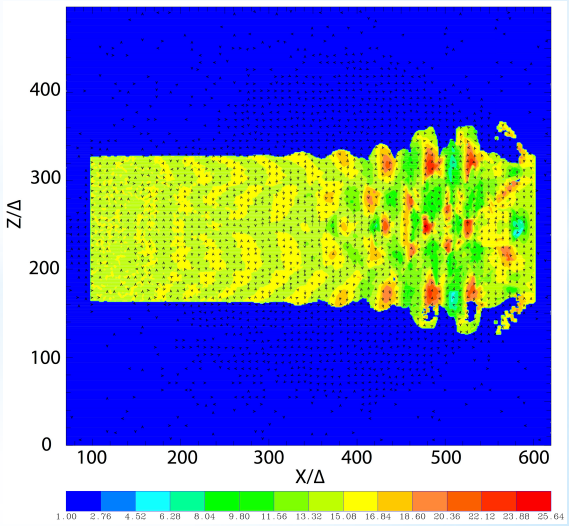


1.00 23.38

r_{jt}=80Δ



1.00 20.15



1.00 25.64

Particle Acceleration in Helically Magnetized RPIC Jets

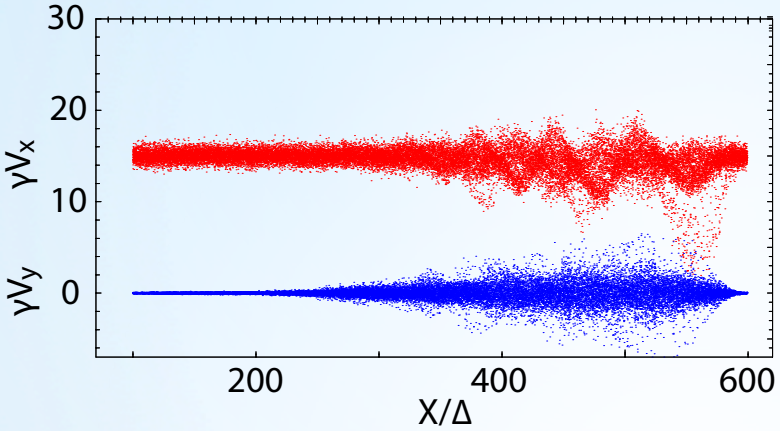
red: γv_x
blue: γv_y

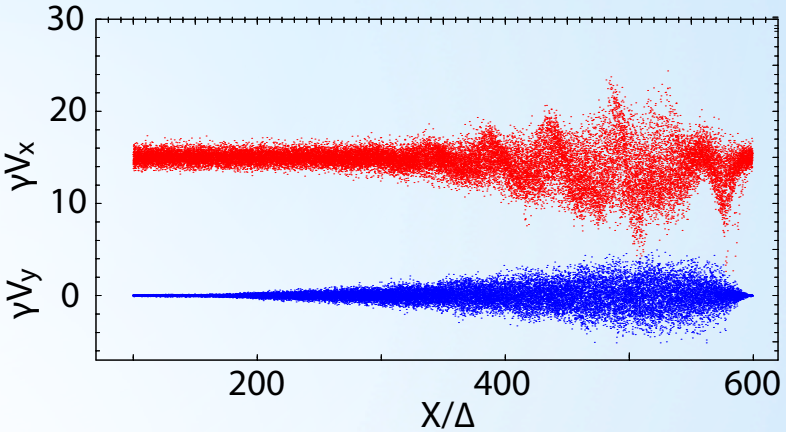
$B_0 = 0.1$ $\gamma=15$ $t = 500\omega_{pe}^{-1}$

e− - p+ jet

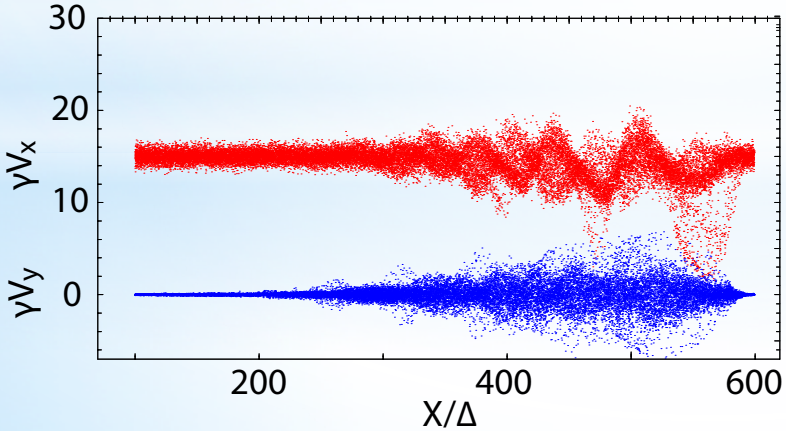
e± jet

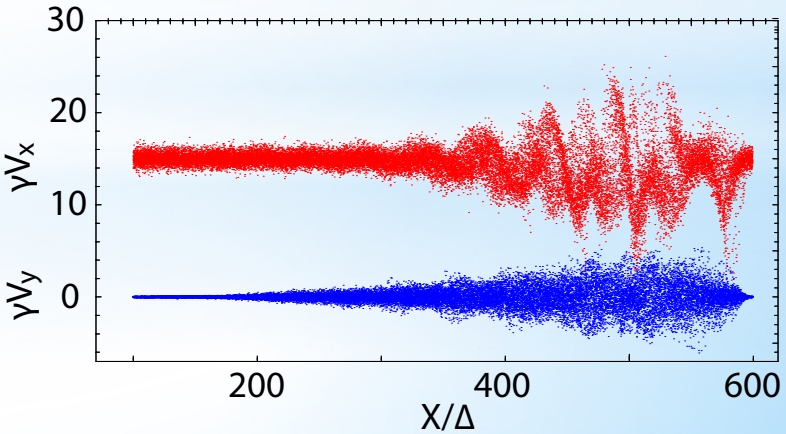
r_{jt} =120Δ





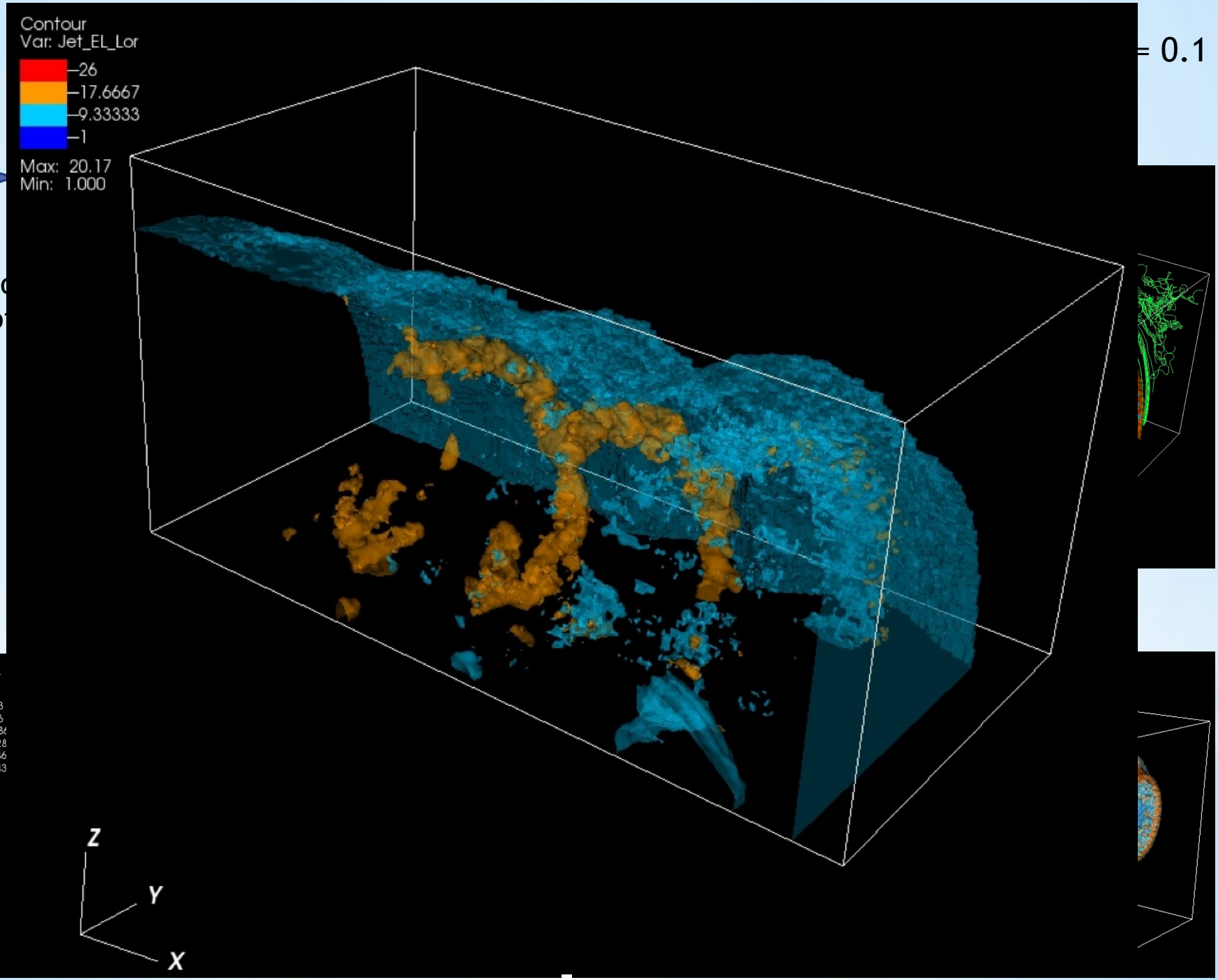
r_{jt} =80Δ





= 0.1

Mushr
instab



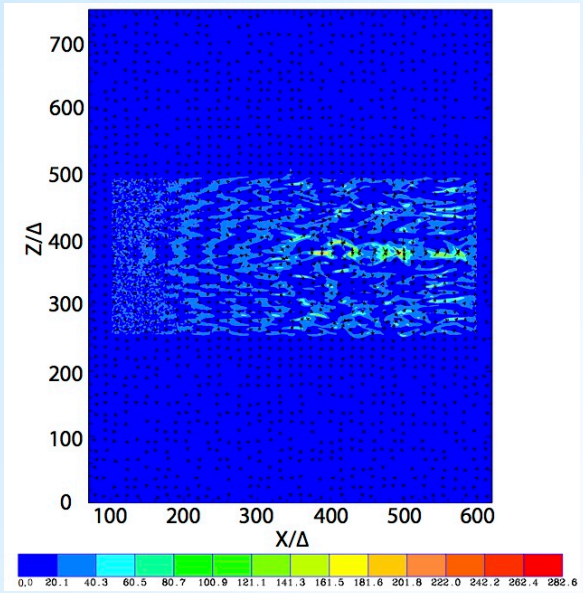
Electron densities and B_y

r_{jt} =120Δ γ=15 B_0 = 0.1 $t = 500\omega_{pe}^{-1}$

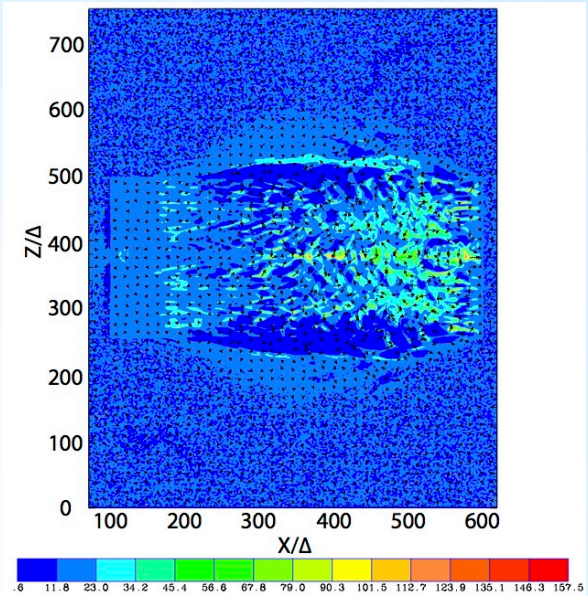
e− - p+ jet

electron density

e± jet

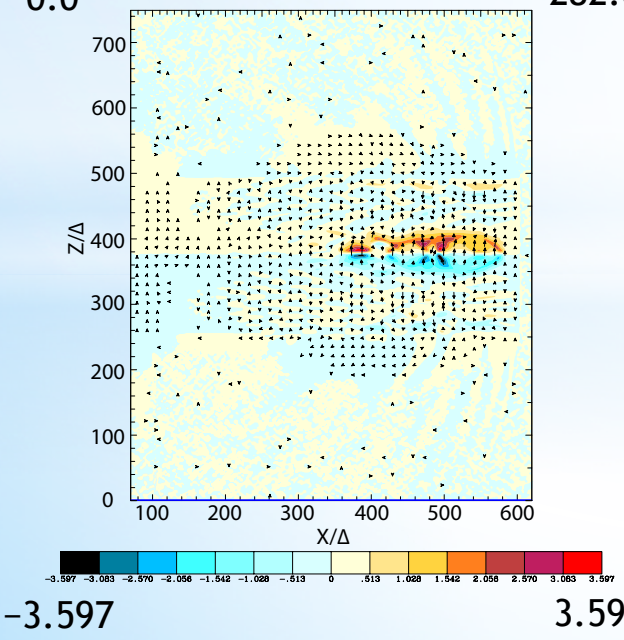


0.0 282.6

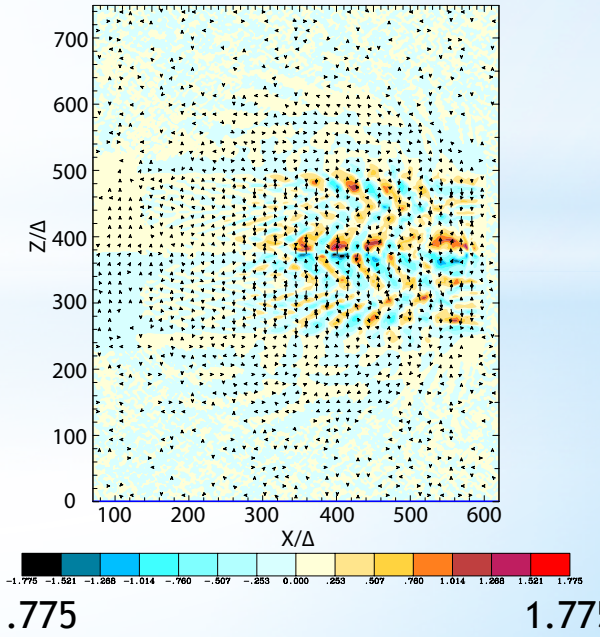


0.6 157.5

B_y



−3.597 3.597



−1.775 1.775

Current density J_x in jets and MF streaming lines

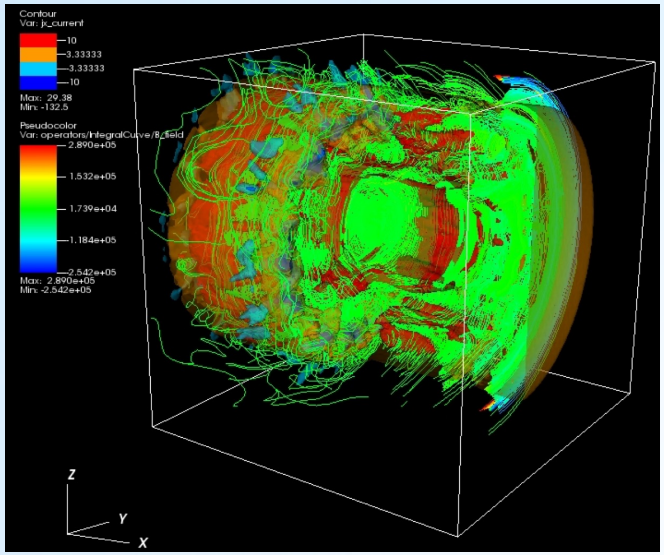
γ=15 B_0 = 0.1

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

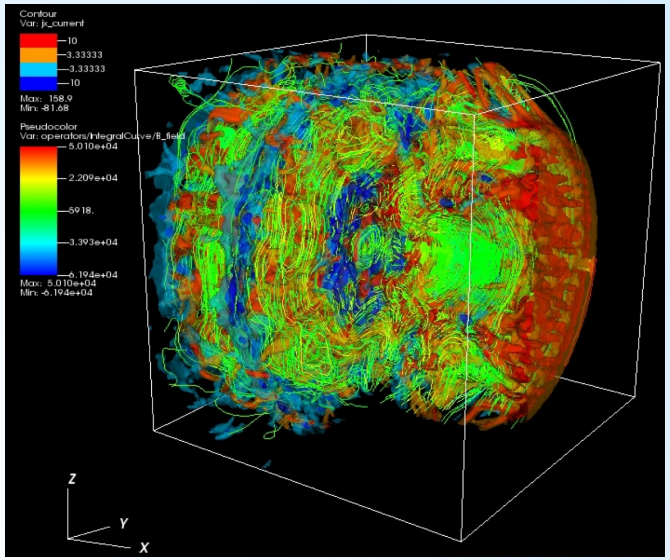
e− - p+ jet

r_{jt} =80Δ

e± jet

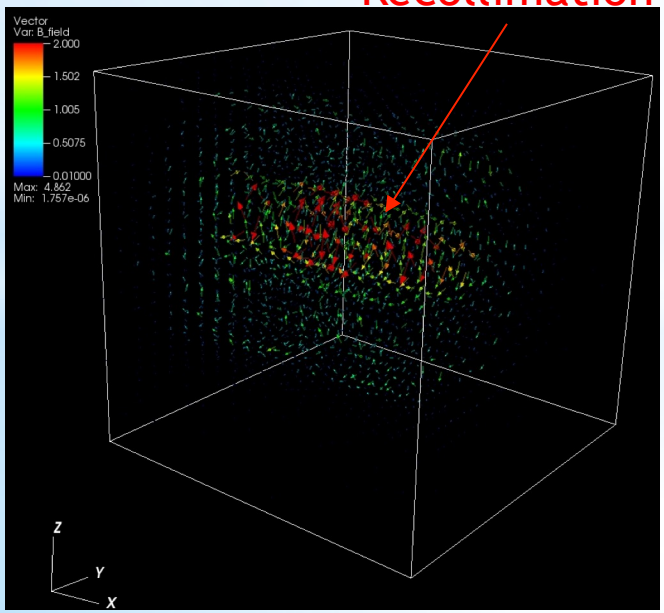


J_x



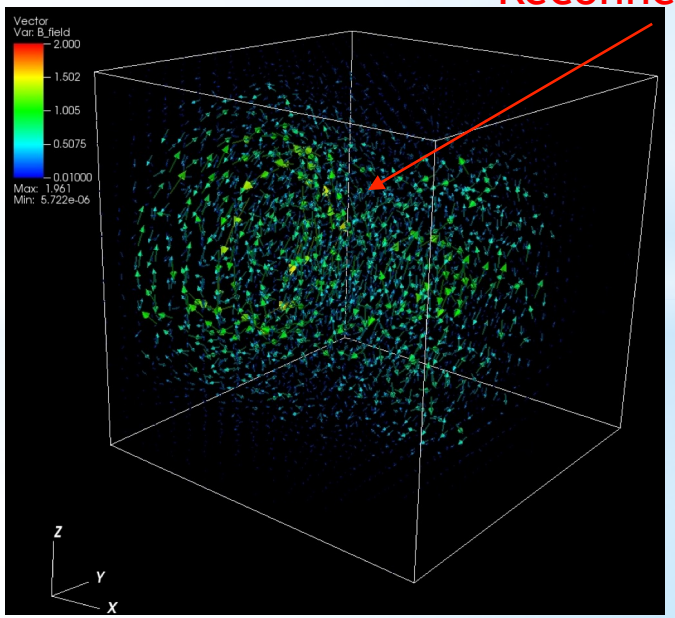
Recollimation

Reconnection?



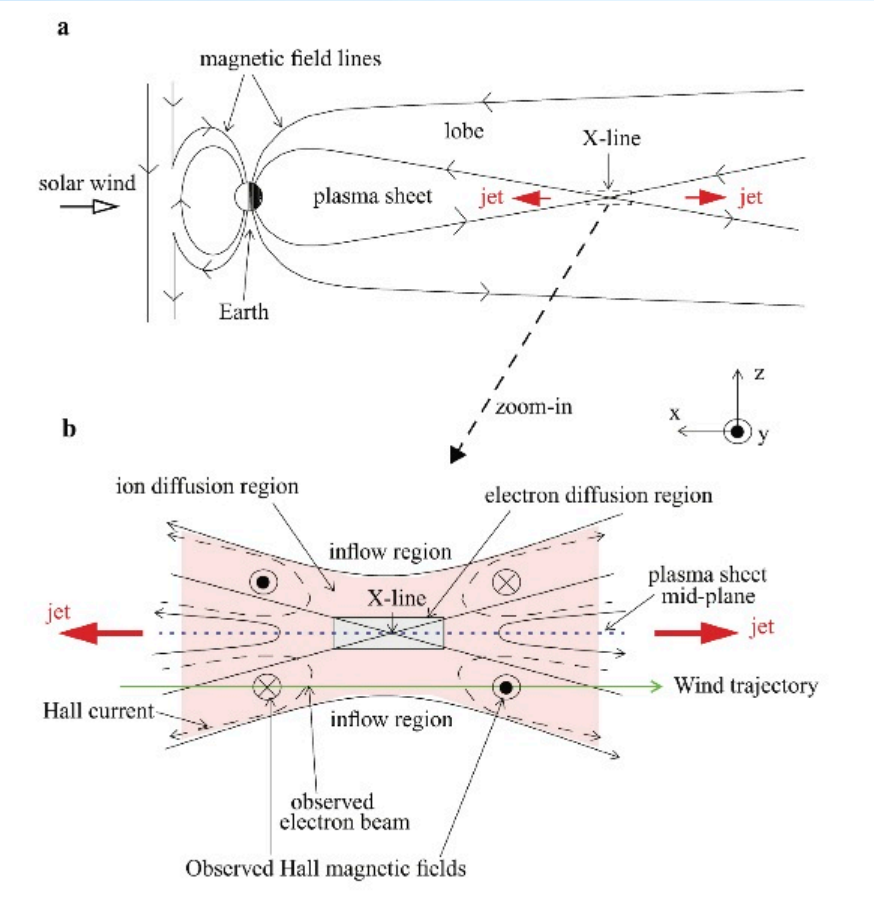
B

vecters

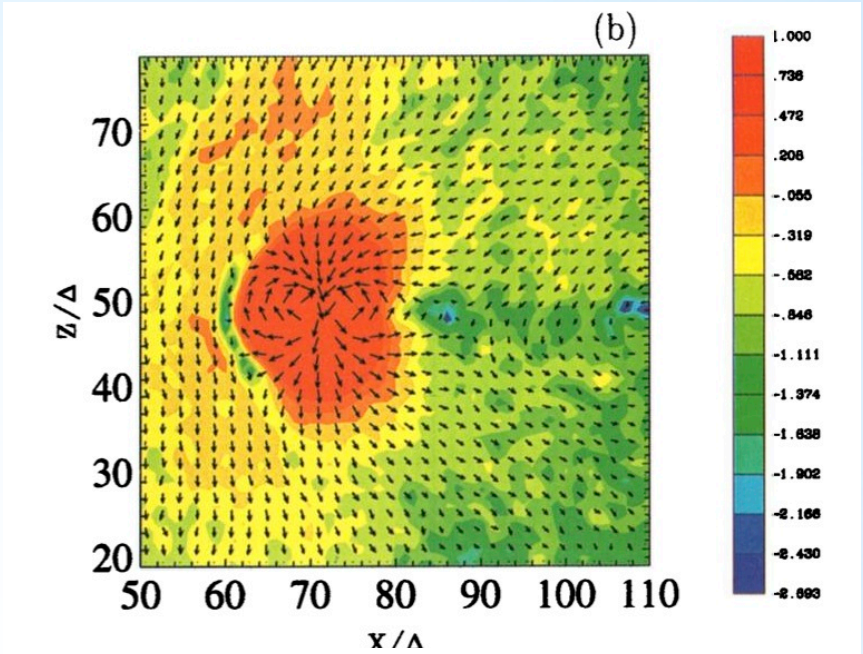


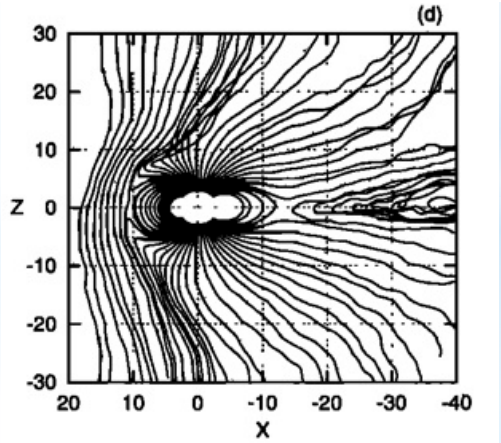
* Reconnection with southward IMF

schematic reconnection



from *Report of the Workshop on Opportunities in Plasma Astrophysics*

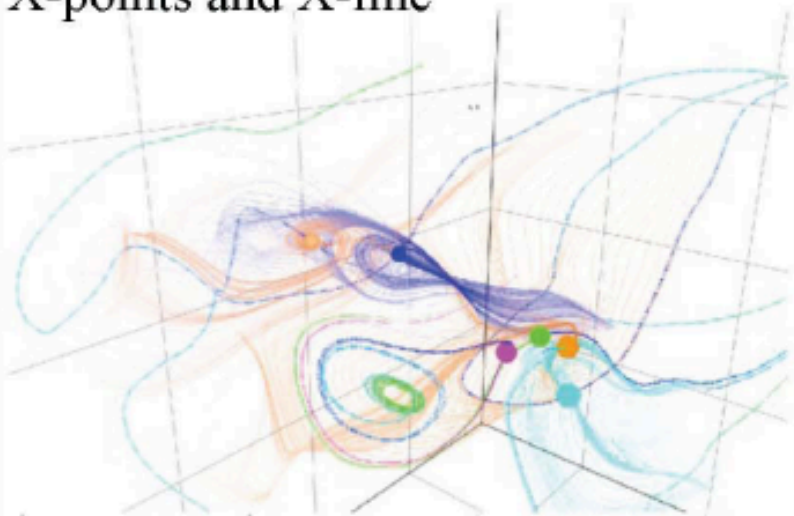


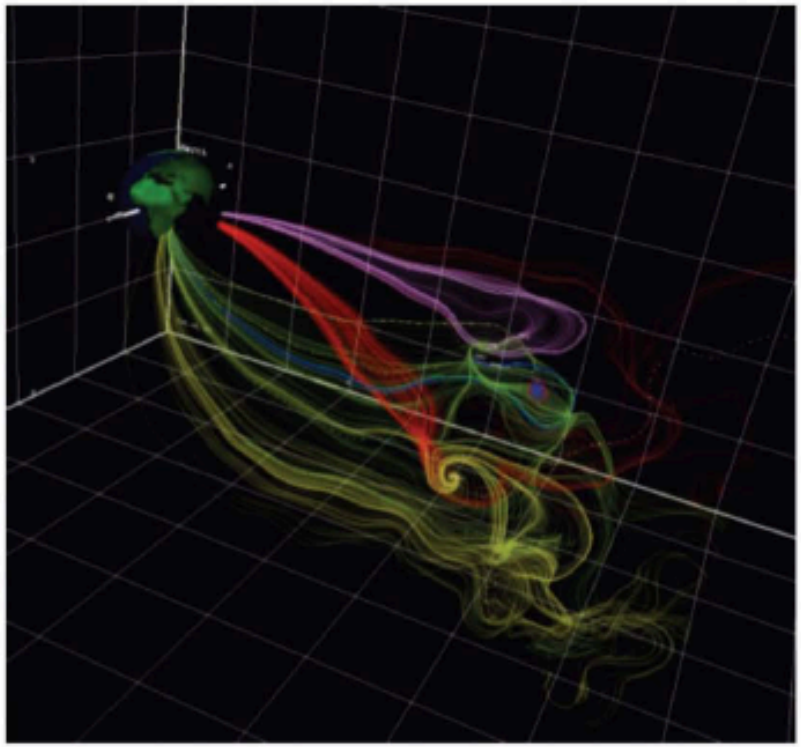


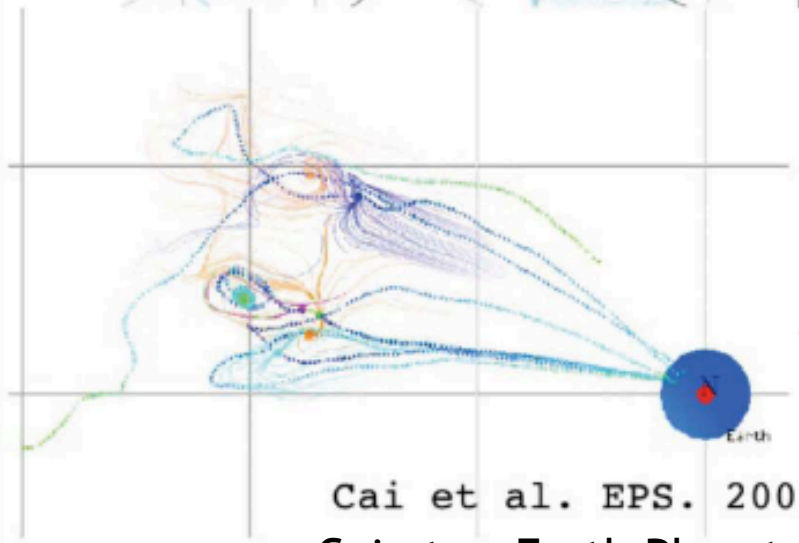
(Nishikawa, JGR, 1997)

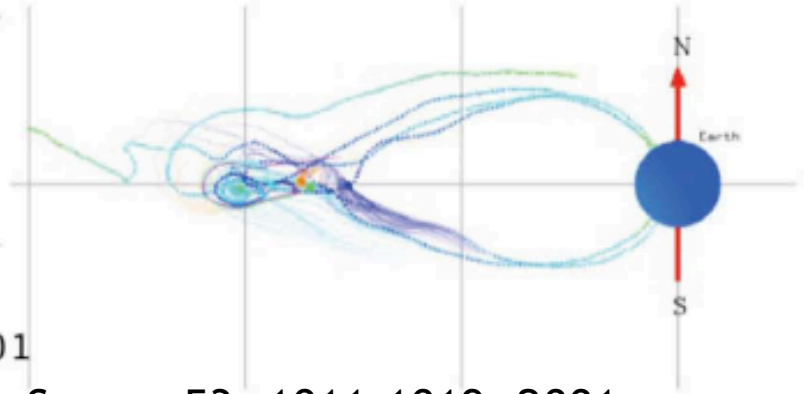
Three-dimensional topology of magnetic fields in the magnetotail

X-points and X-line





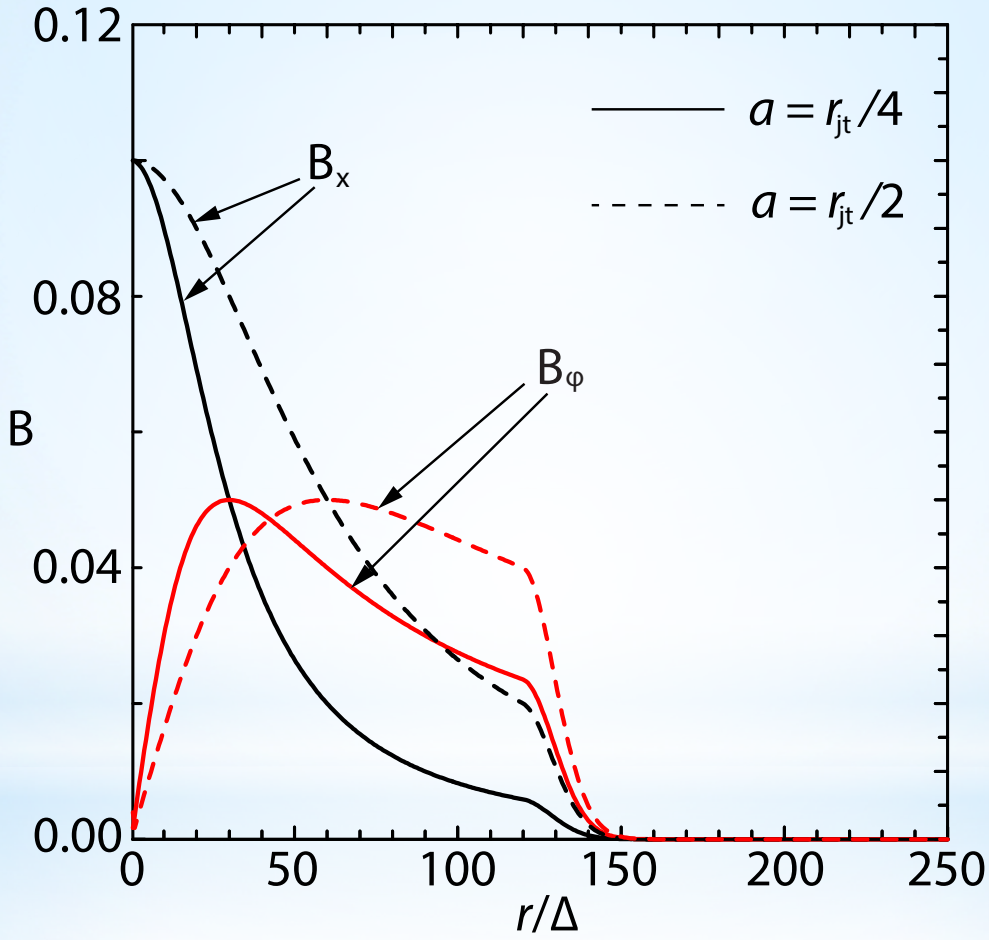




Cai et al. EPS. 2001

Cai et a. Earth Planets Space, 53, 1011–1019, 2001

Growth of instabilities dependence on helical magnetic field structure a



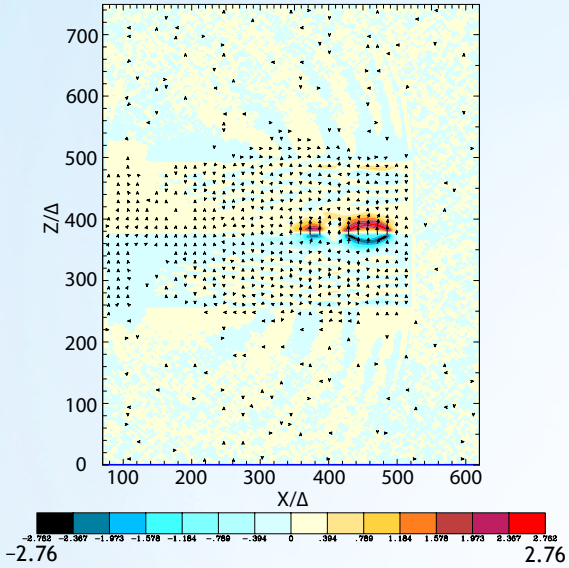
Poloidal component (B_y) $a = r_{jt}/4$ and $r_{jt}/2$

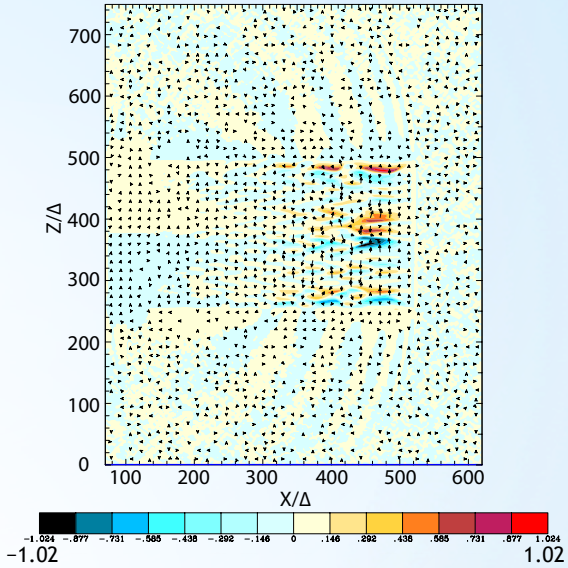
$a = r_{jt}/4$

$a = r_{jt}/2$

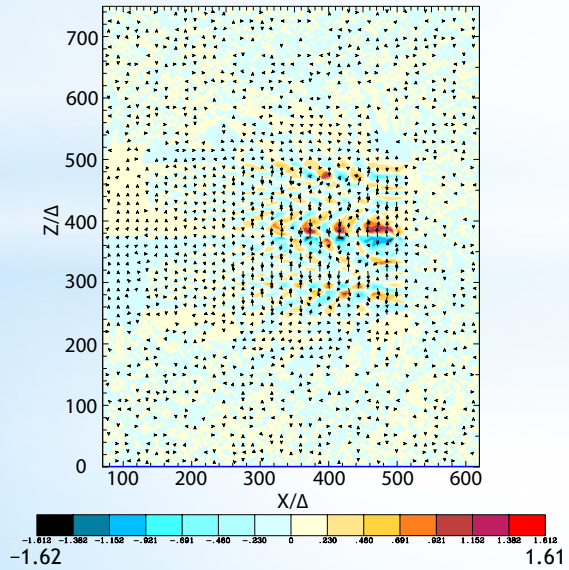
B_{h0}=0.1c

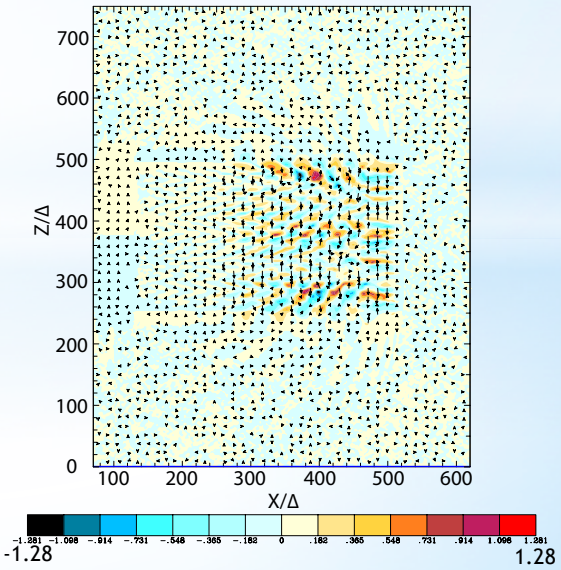
e^- - p^+





$e^{\pm}$



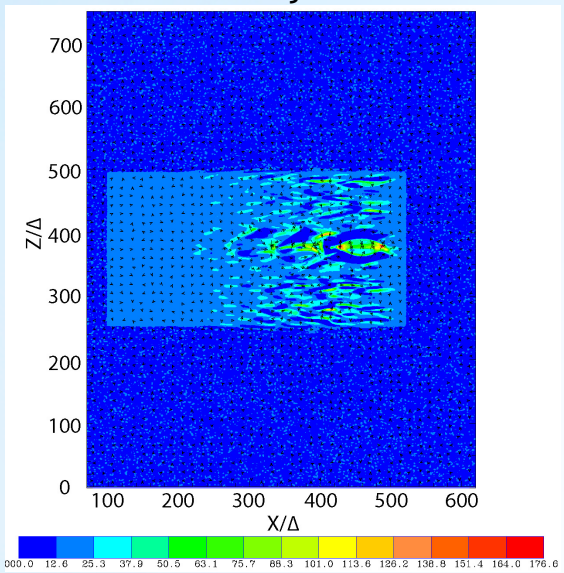


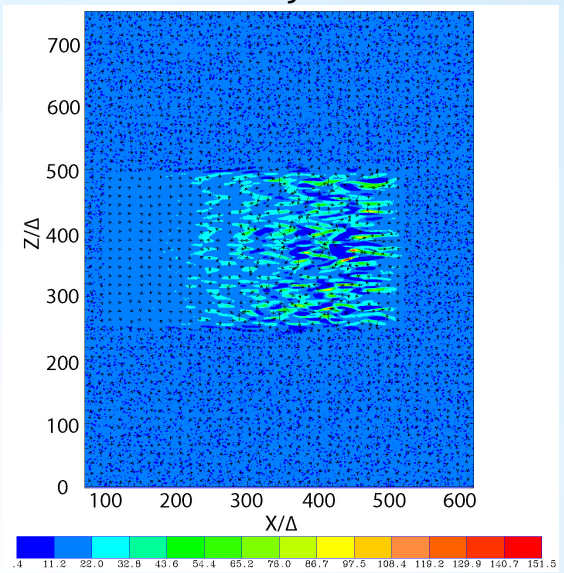
Electron Density in x - z plane $a = r_{jt}/4$ and $r_{jt}/2$

$a = r_{jt}/4$

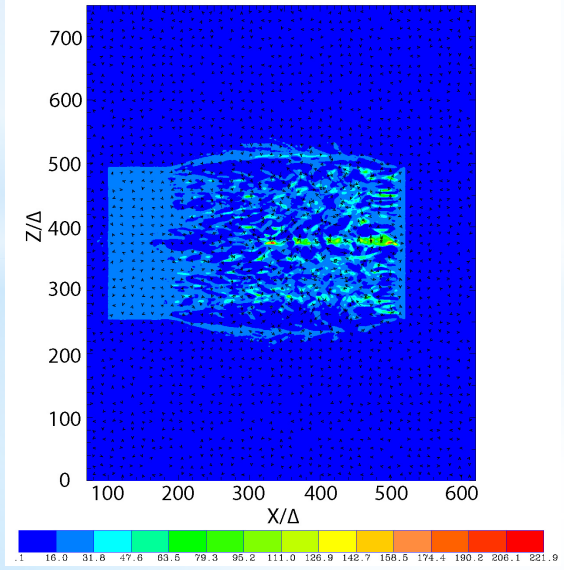
$a = r_{jt}/2$

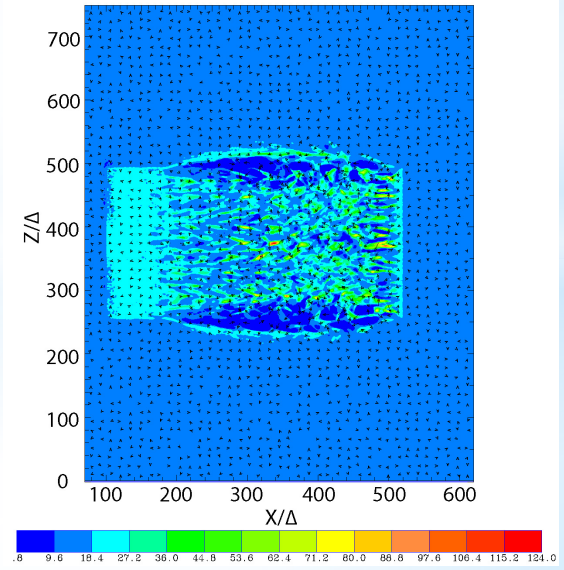
$e^- - p^+$



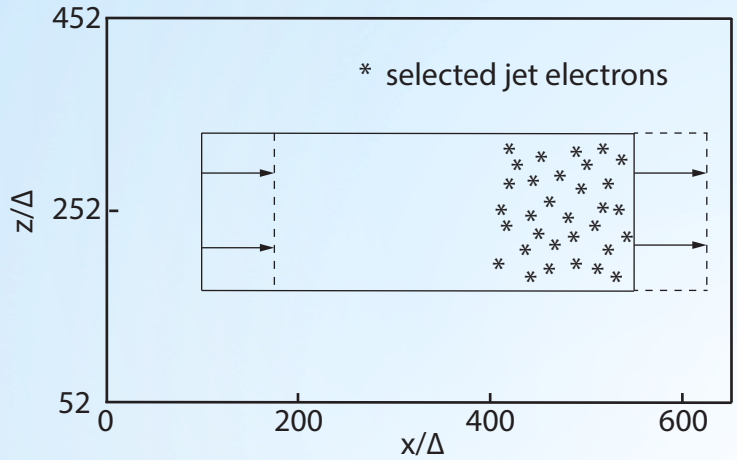


$e^{\pm}$





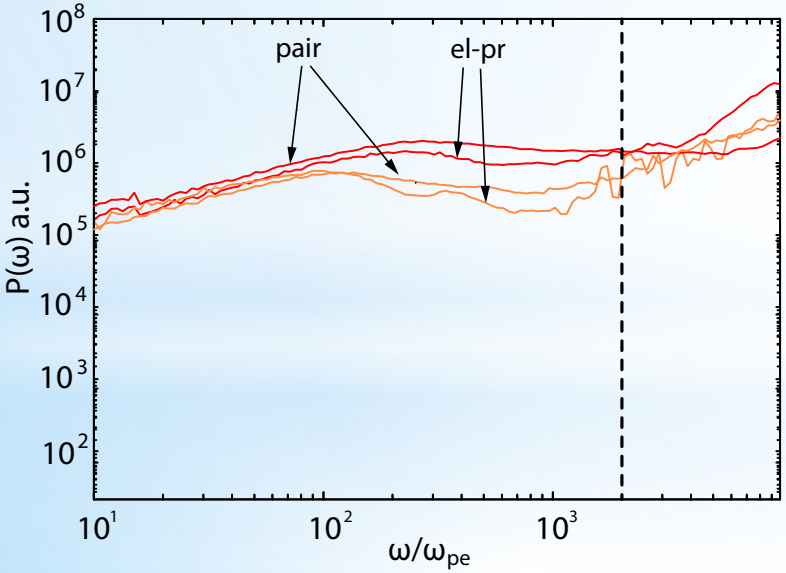
Synthetic Spectra

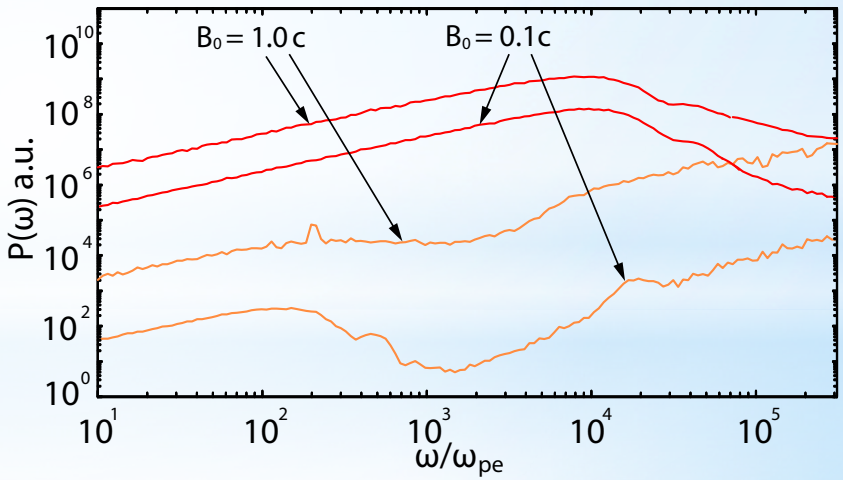


r_{jt} =80Δ

head-on radiation

5° off-axis angle





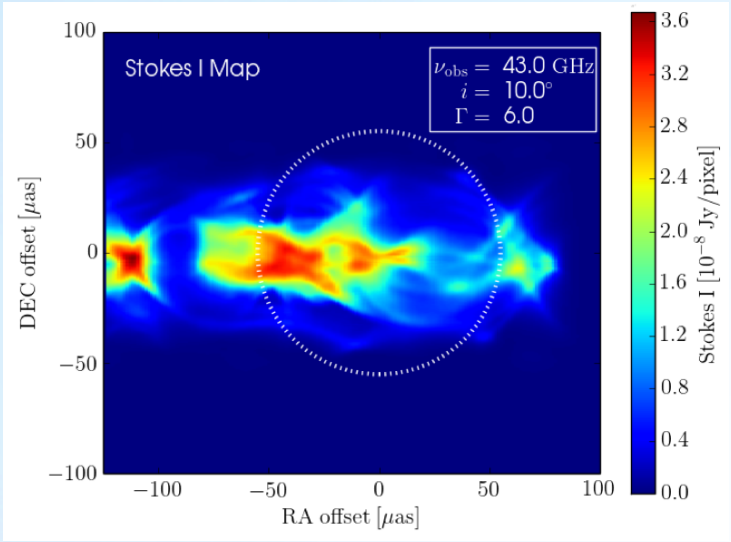
B_0 = 0.1c, γ_{jet} = 15

γ_{jet} = 100, pair jet

Image maps of polarity

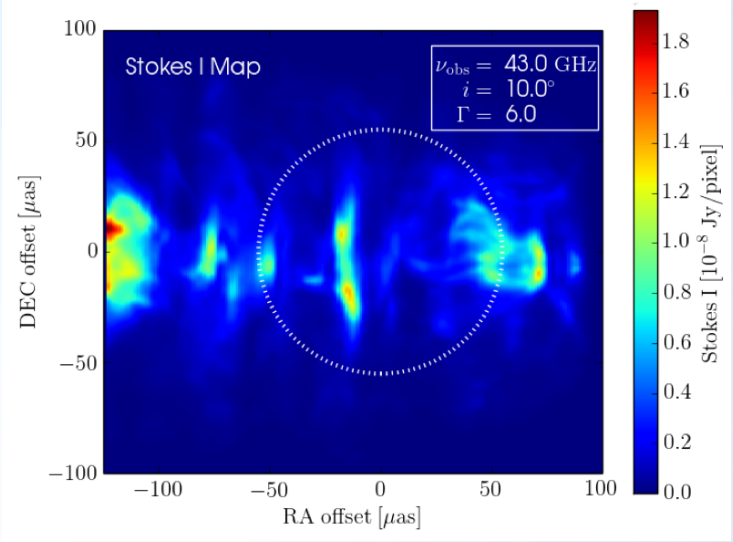
$r_{jet} = 40\Delta$ at time $t = 500\ \omega_{pe}^{-1}$ $\gamma_{jet} = 15$

e− - p+ jet

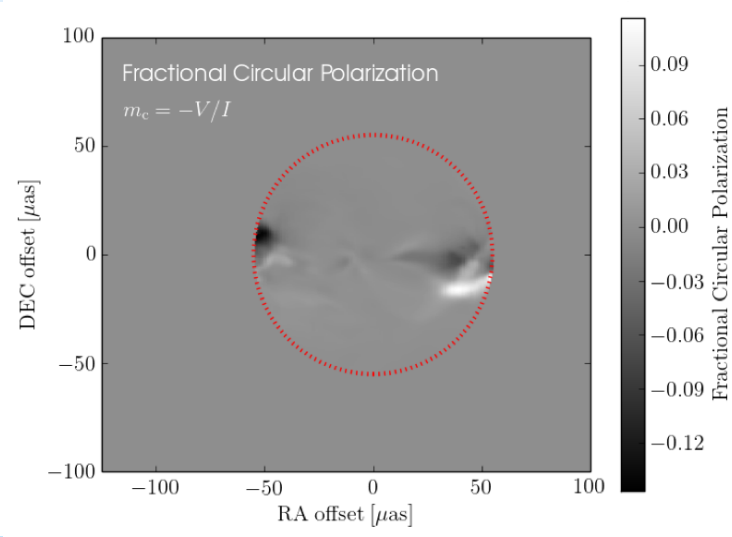


I-map

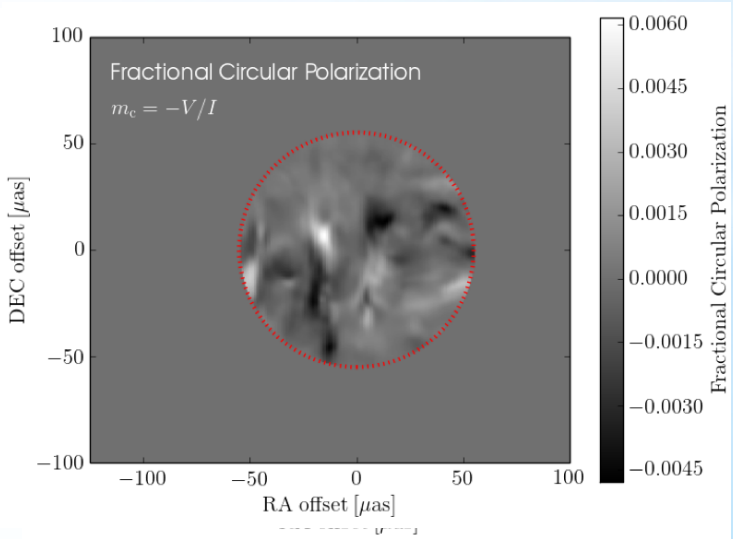
e± jet



$$m_c = \sqrt{Q^2 + U^2}/I$$



LPI



See talk (Friday) by MacDonald

Summary for global jet simulations with helical magnetic fields

- The evolution of jets depends on the size of jet radius
- For the small jet radius (r_{jt} =20Δ) (Nisihkawa et al 2016b)
  The electron-proton jet shows recollimation shocks due to the kinetic instabilities (MI)
  The electron-positron jet shows the growth of kink-like instability which generate the turbulent current filaments expanding outside the jet
- For the larger jet radius (r_{jt} =80Δ and 120Δ)
  The more complicated structures are generated by the mixed instabilities (Weibel, kKHI, MI and kink-like instability).
- Further simulations with a even larger system (larger jet radius) need to be investigated with varying the strength and structure of helical magnetic fields

We have simulated global jets with zero opening angle (cylindrical) we will perform global jets with more realistic jet structures as shown below

Possible scenarios with different jet structures

helical magnetic fields in relativistic jets play important roles

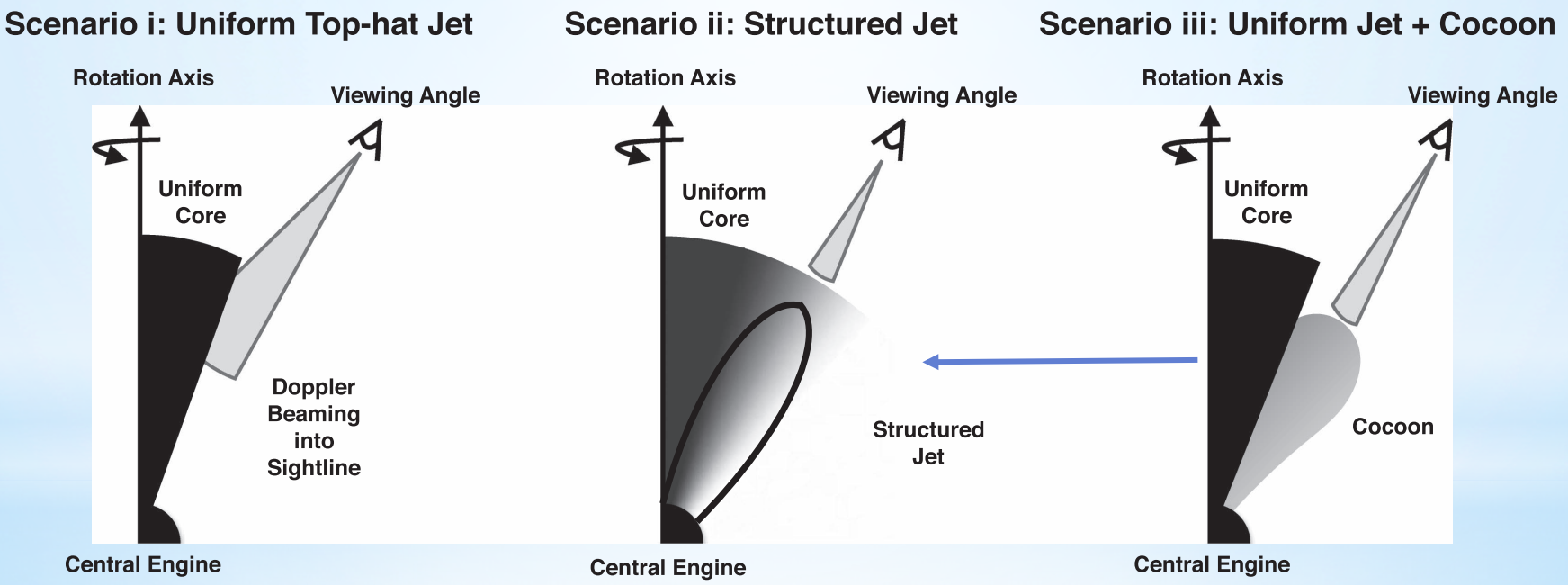


Figure 5. Three potential jet viewing geometries and jet profiles that could explain the observed properties of GRB 170817A, as described by scenarios (i)–(iii) in Section 6.2.

(Abbott et al. 2017)

Future plans

- Further simulations with a systematic parameter survey will be performed in order to understand jet evolution with helical magnetic fields
- 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 and associated flares
- Particle acceleration and radiation and flares in shocks and reconnection with helical magnetic field
- Synthetic imaging with polarity