3D PIC Simulations for Relativistic Jets with a Toroidal Magnetic Field

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Presented on January 12, 2022

28th Krakow Epiphany on Recent Advances in Astroparticle Physics, 10 – 14, 2022

Outline

1. **Introduction of reconnection and relativistic jets and Weibel instability** (Nisikawa et al 2009)
2. **Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability (kKHI) and Mushroom instability (MI)** (Nishikawa et al. ApJ, 793, 60, 2014)
3. **Global jet simulations with MI and KKHI with large simulation system** without magnetic field (Nishikawa et al. ApJ, 820, 94, 2016a) **(r_{jt} = 100Δ)**
4. **Global jet simulations with helical magnetic fields (reconnection)** (Nishikawa et al. Galaxies, 4, 38, 2016b) **(r_{jt} = 20Δ)**
5. **New results with larger jet radius with short system** **(r_{jt} = 40Δ, 80Δ, 120Δ)** (Nishikawa et al. Galaxies, 5, 58, 2017)
6. **Recent Simulations of Particle Acceleration and Reconnection in Relativistic Jets** (Nishikawa et al. MNRAS, 493, 2652, 2020; Meli et al. MNRAS, 2021)
7. **Summary and Future plans**

Key Scientific questions

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

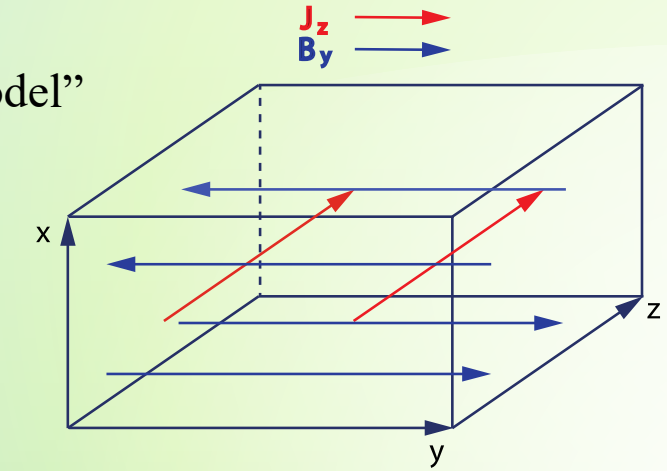
Why we need to perform PIC simulations of relativistic jets

- **Kinetic instabilities (e.g., kKHI, MI, and the Weibel instability) are a key issue in understanding jet evolution besides the kink instability in RMHD simulations**
- **Helical magnetic fields are crucial in understanding these instabilities**
- **PIC 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**
- **Nonthermal acceleration due to reconnection may generate flares**

Reconnection with Harris model

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

“Harris model”



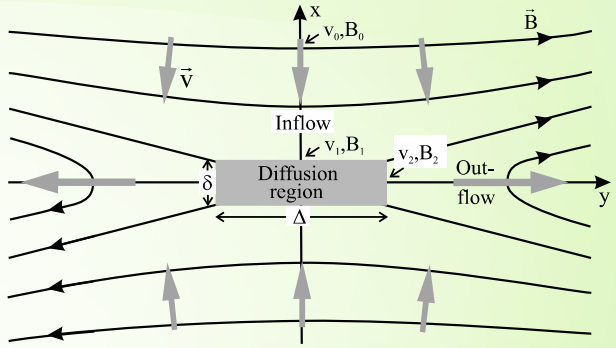
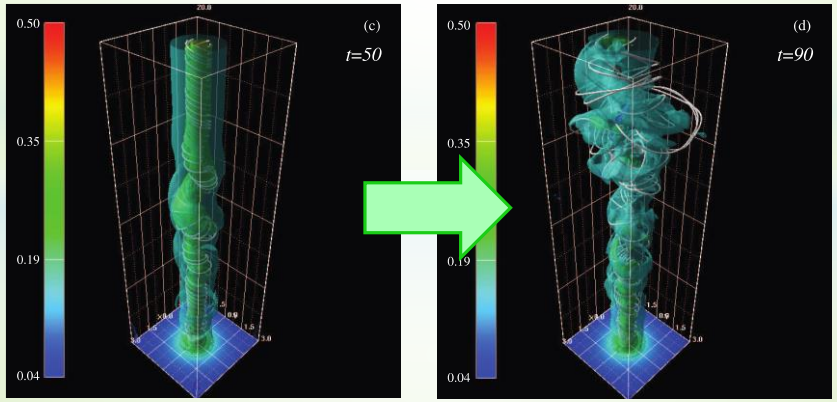


Figure 1. Qualitative pattern of two-dimensional reconnection.

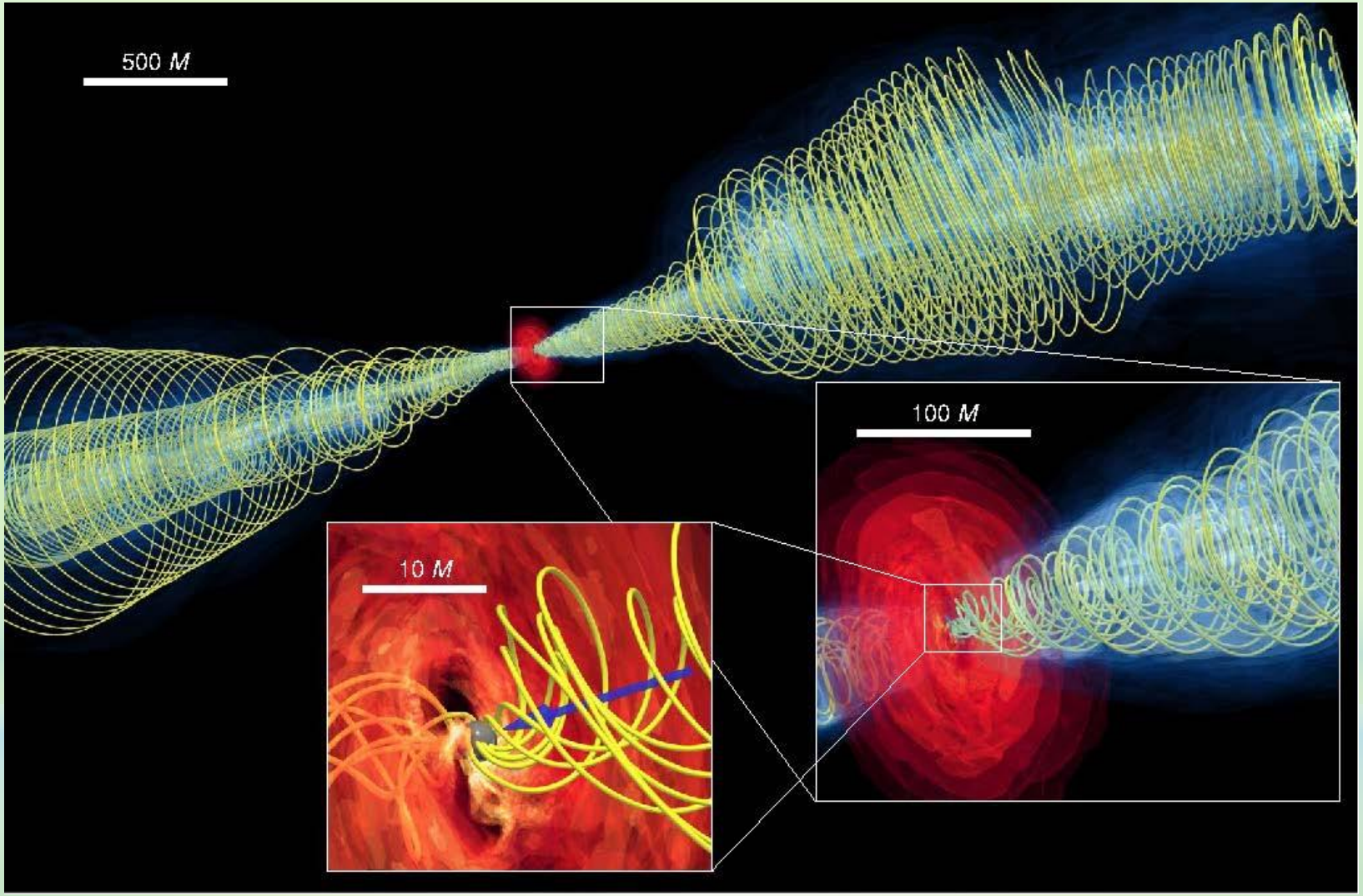
In global jets (helical magnetic fields: Harris model with slab geometry cannot be applied)



(Mizuno et al. 2014)

Current-driven instability may trigger reconnection?

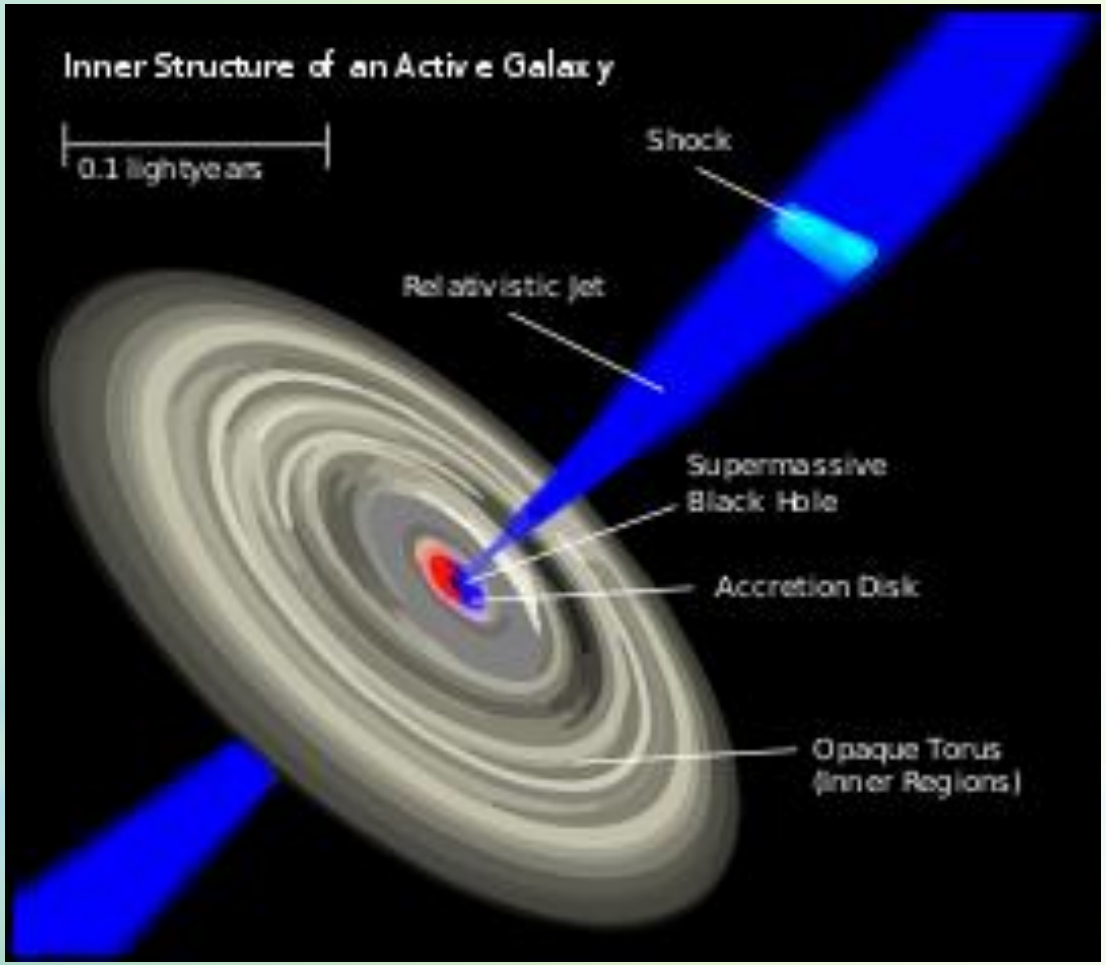
Launching site of M87



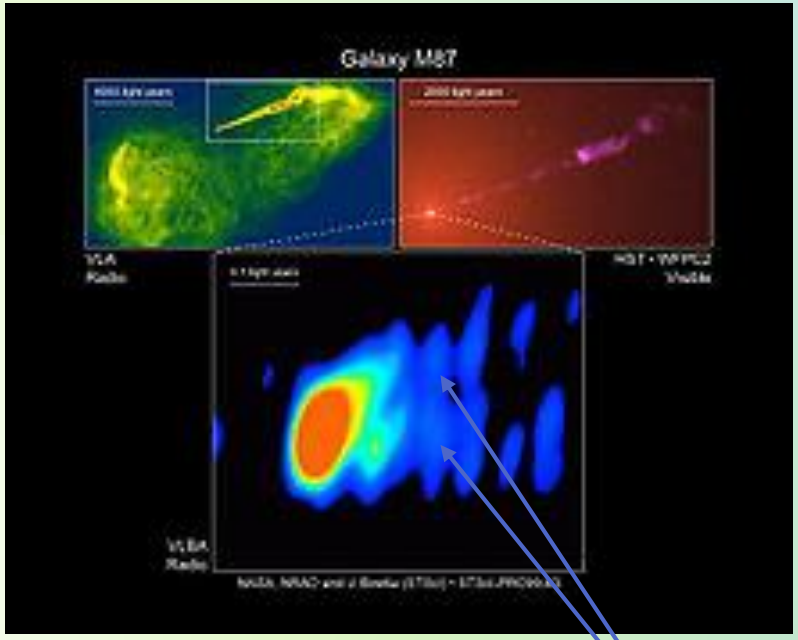
Cruz-Osorio et al. Nature Astronomy 2021

Astrophysical systems

Relativistic jets from black holes



https://commons.wikimedia.org/wiki/File:Galaxies-AGN-Inner-Structure.svg



M87
(credit to
NASA)

https://commons.wikimedia.org/wiki/File:Close-Up_Look_at_a_Jet_Near_a_Black_Hole.jpg

Hirotani +
ApJ, 2021

Crab Nebula

https://commons.wikimedia.org/wiki/File:Chandra-crab.jpg

Profile of magnetic fields and jet density in jet frame

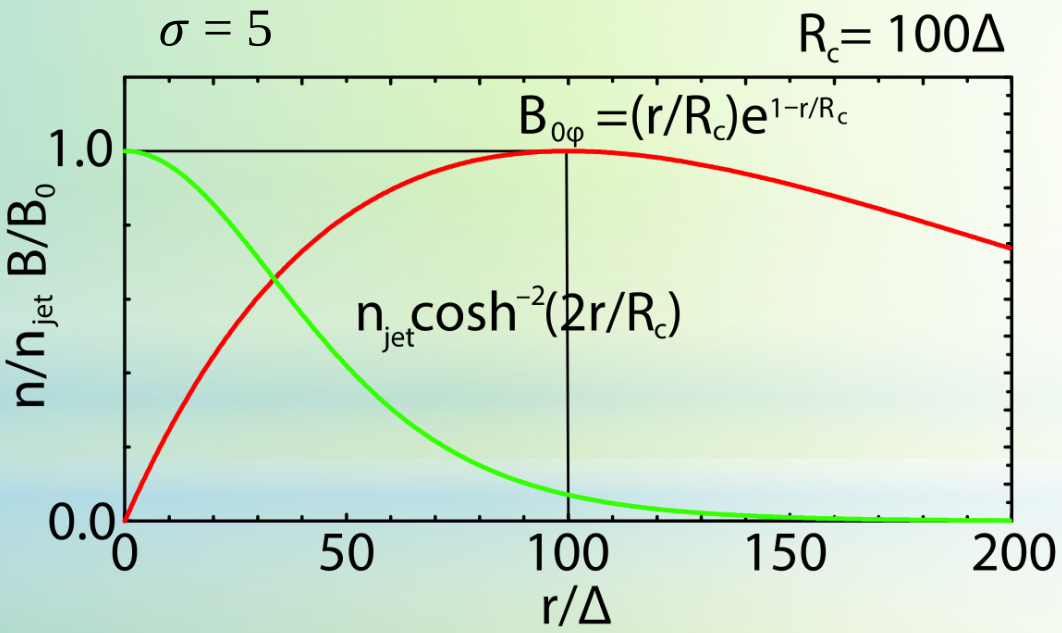
Current-driven Kink Instability

in Theta pinch experiments (jet?)

no bulk flow (imbedded with the ambient)

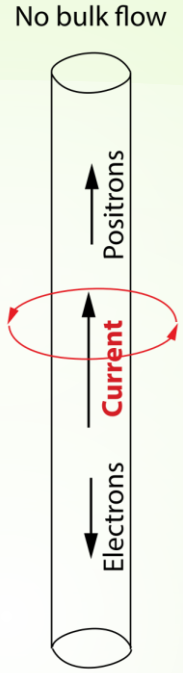
toroidal magnetic fields by

oppositely flowing electrons and positrons



Alves et al. prl, 121, 245101, 2018 (scaled)

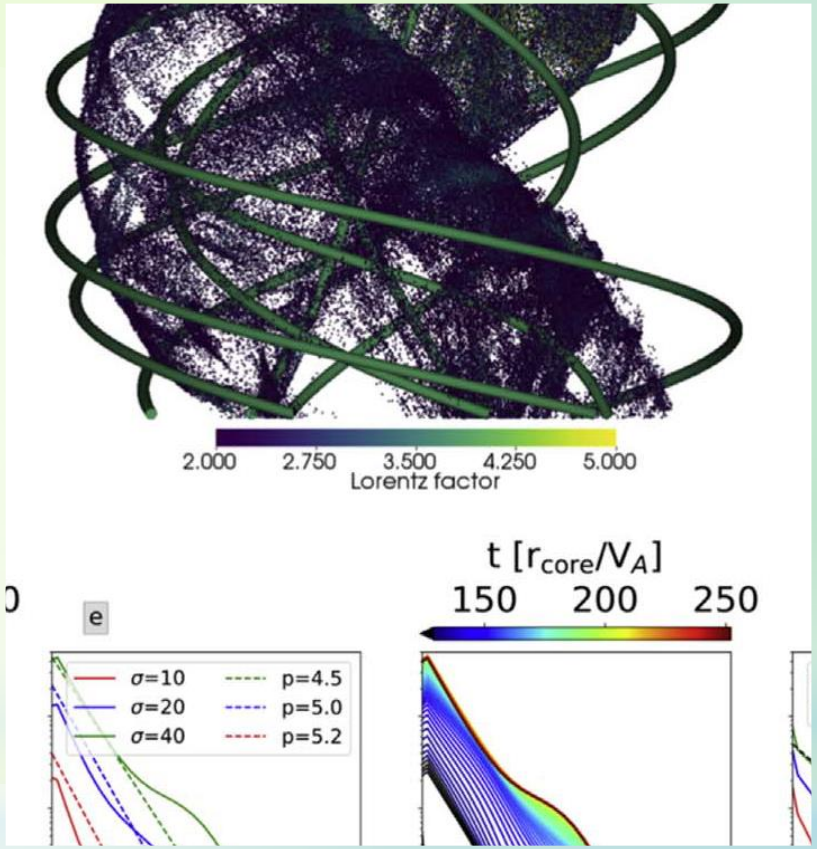
Pinch experiment



toroidal magnetic field

periodic boundary condition (no propagation)

Helical magnetic field



Davelaar et al. ApJL, 896, L31, 2020

3D global jet simulation

NASA Pleiades

system size: 2000Δ×1000Δ×1000Δ

jet radius: 100Δ

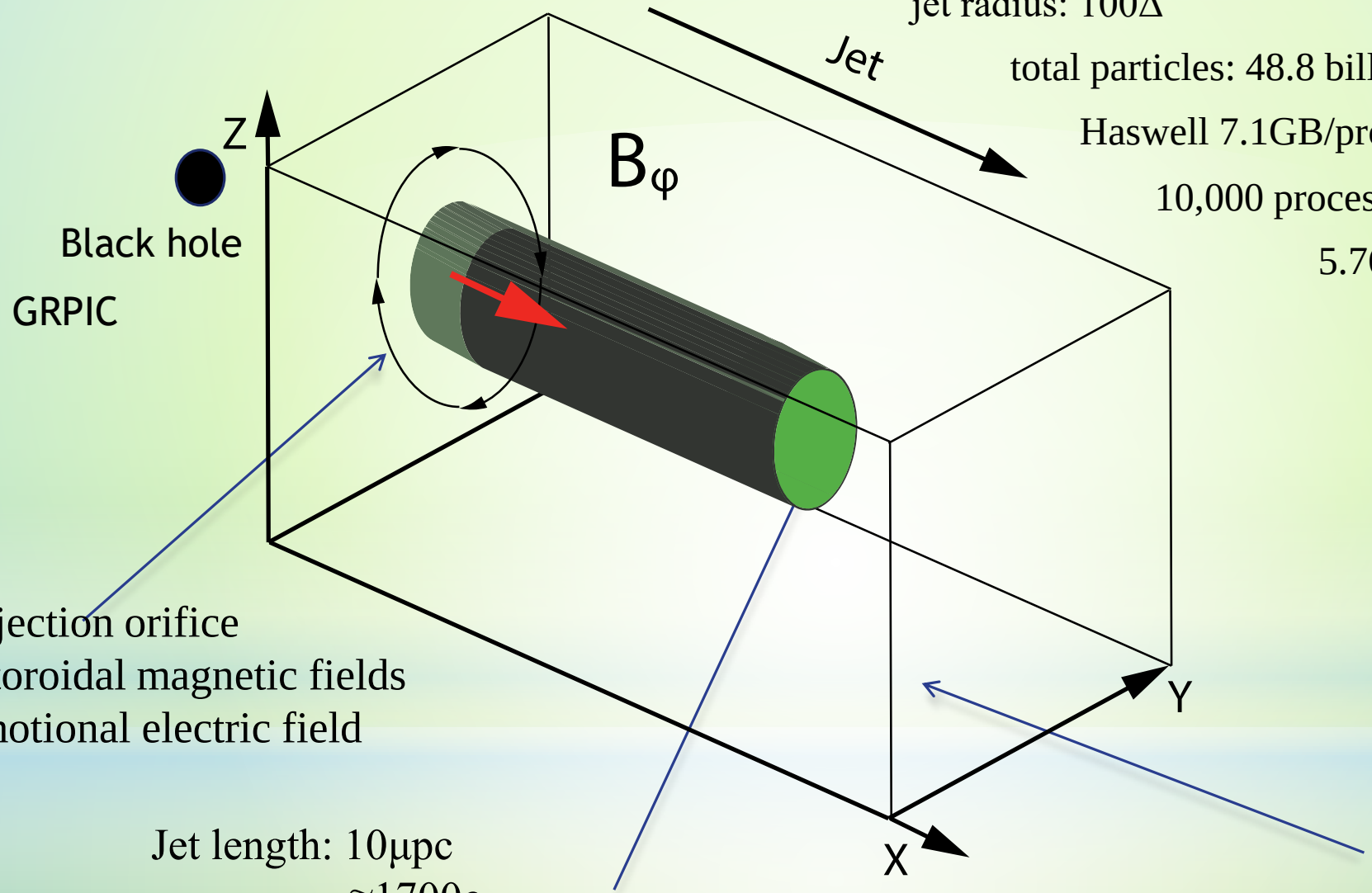
total particles: 48.8 billions

Haswell 7.1GB/processor

10,000 processors

5.76TB memory

run times: 7:55 hours



Jet injection orifice
with toroidal magnetic fields
and motional electric field

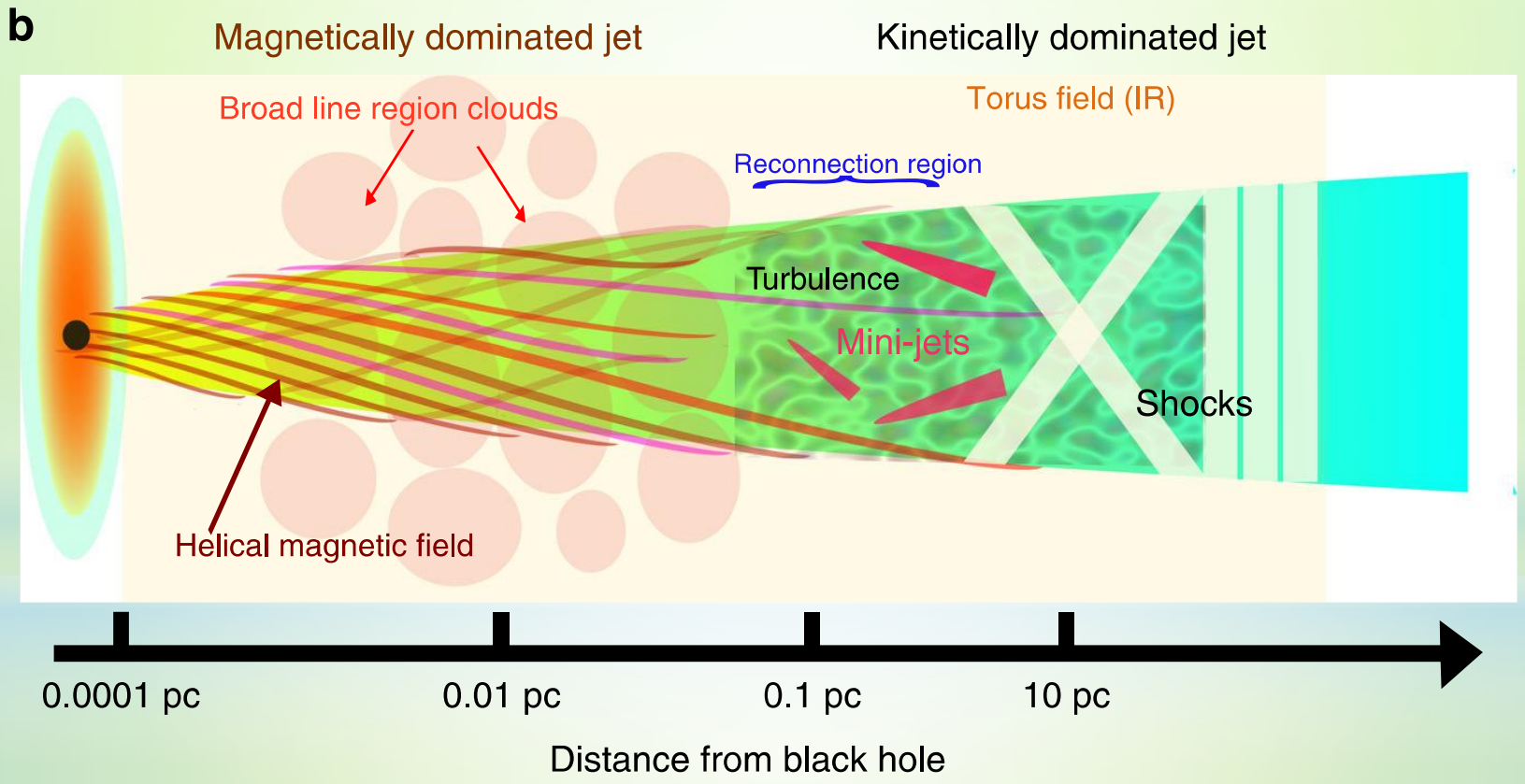
Jet length: 10μpc
≈1700c

Jet head

Ambient plasma

Minute-scale flare as a diagnostic tool for the jet geometry

Jet-in-jet magnetic reconnection



Manuel Meyer's talk (Monday afternoon): Shukla & Mannheim Nature Communications 2020

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

color map
B_y

$E_{x,z}$

no helical magnetic fields

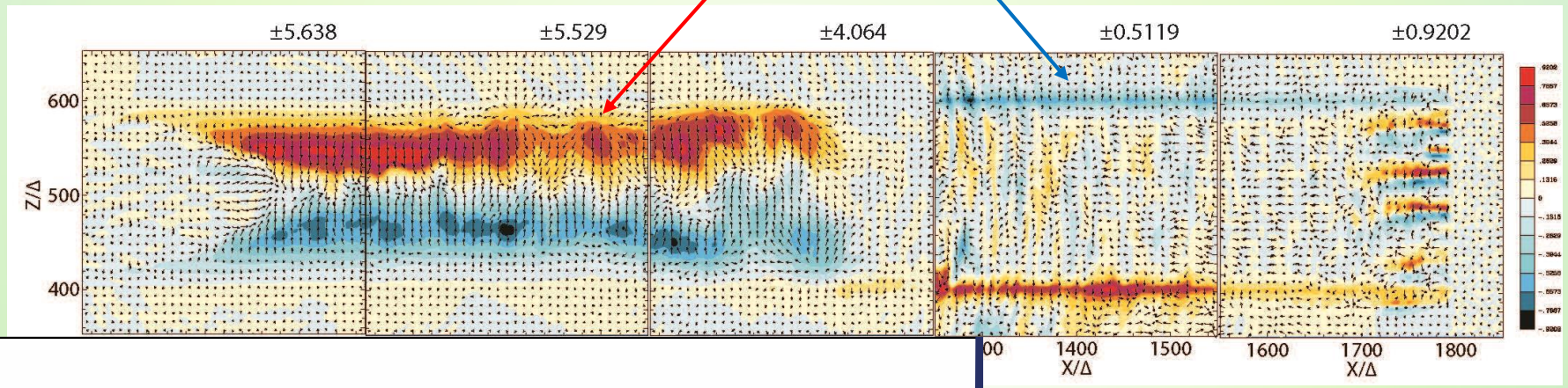
$e^- - p^+$

clockwise

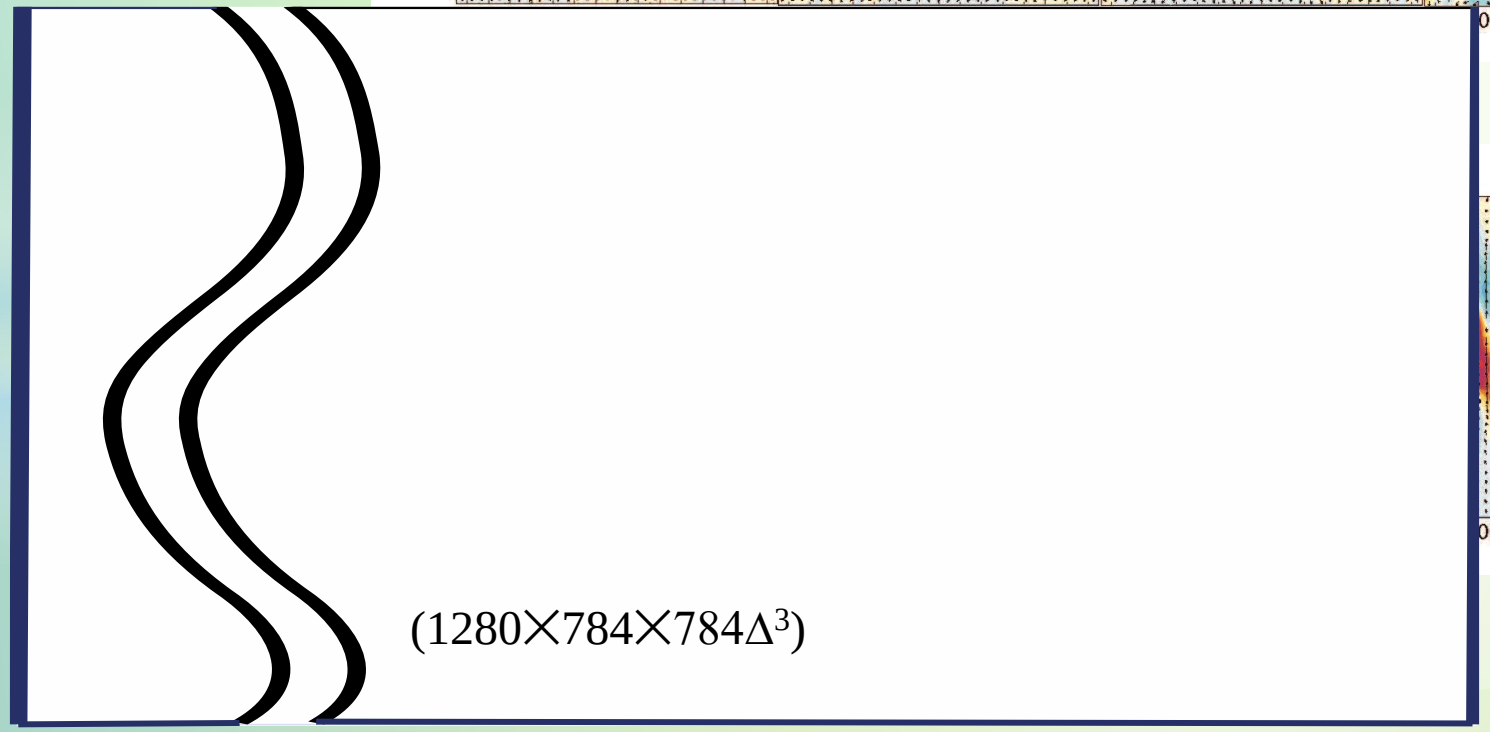
polarity switched

counterclockwise

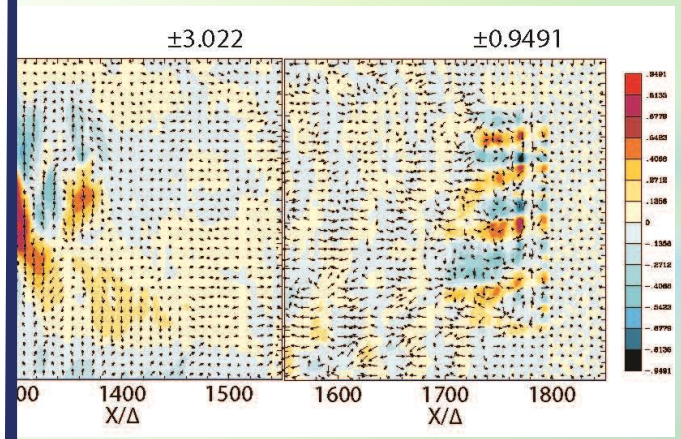
Pleiades ($2000\times1000\times1000\Delta^3$)



$m_e/m_{proton}=1836$



($1280\times784\times784\Delta^3$)



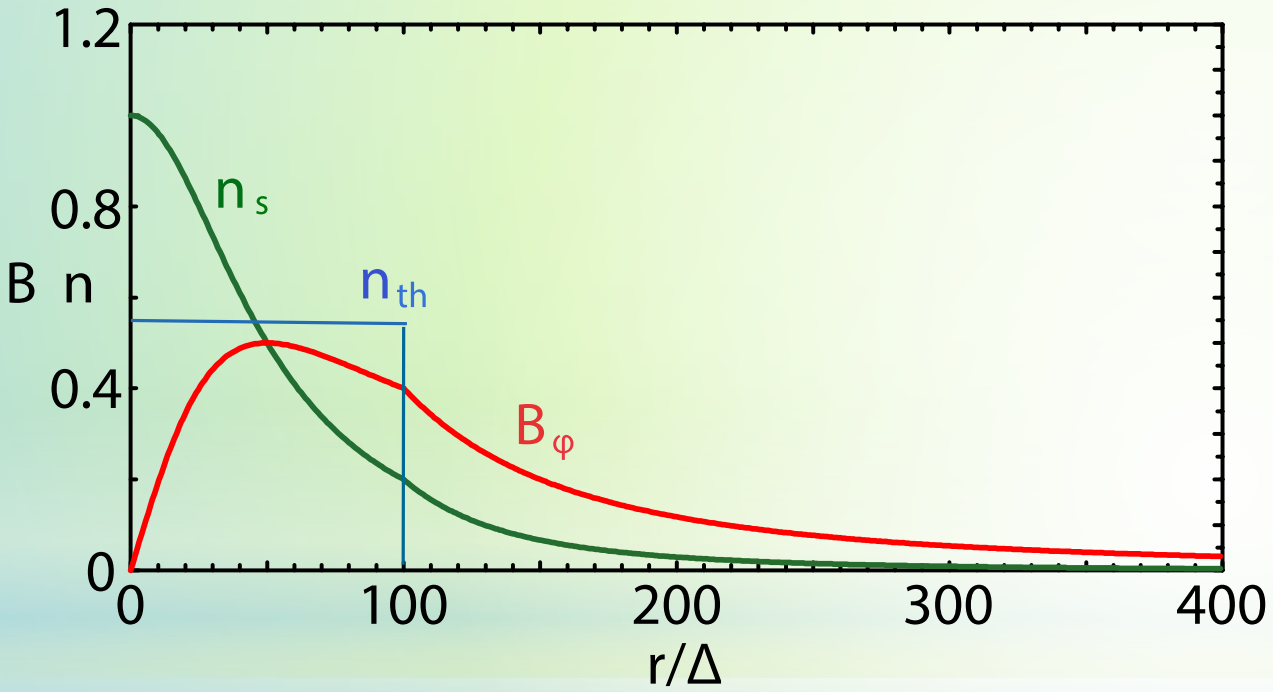
$m_e/m_{positron}=1$

(Nishikawa et al. 2016a)

Recent simulations with Pleiades (preliminary results)

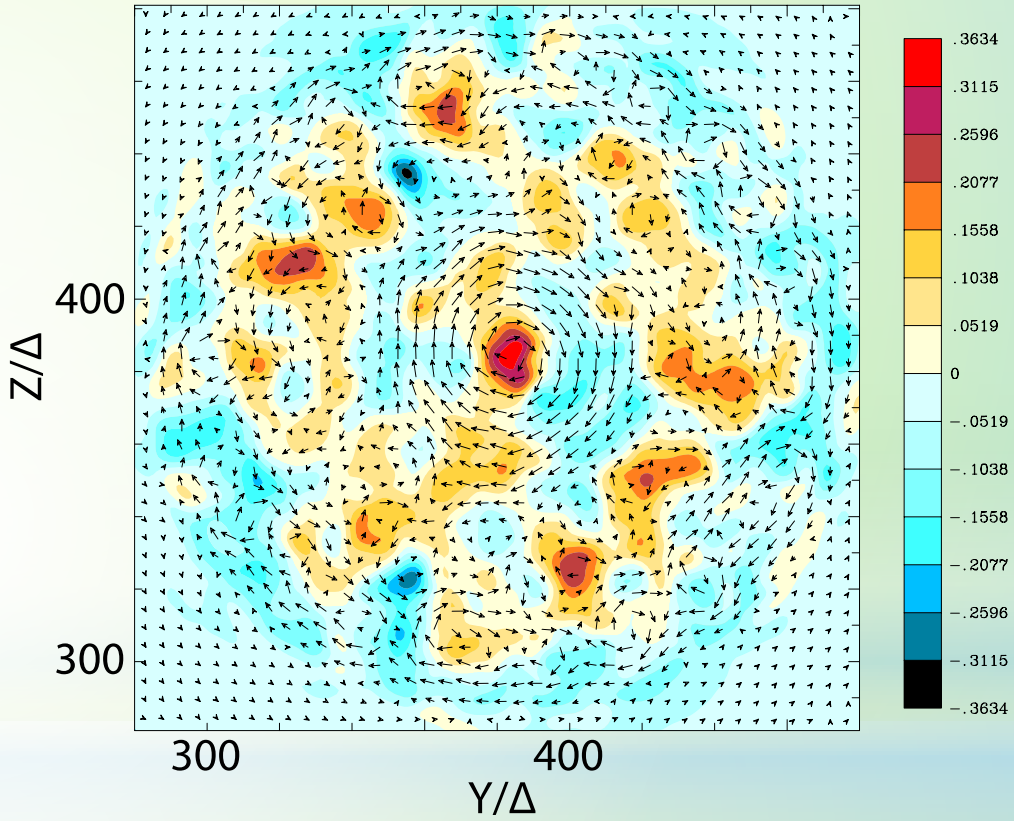
Helical magnetic field structure

$B_0 = 0.1$



(Meli et al. 2021)

Contour of E_x arrows: $B_{y,z}$



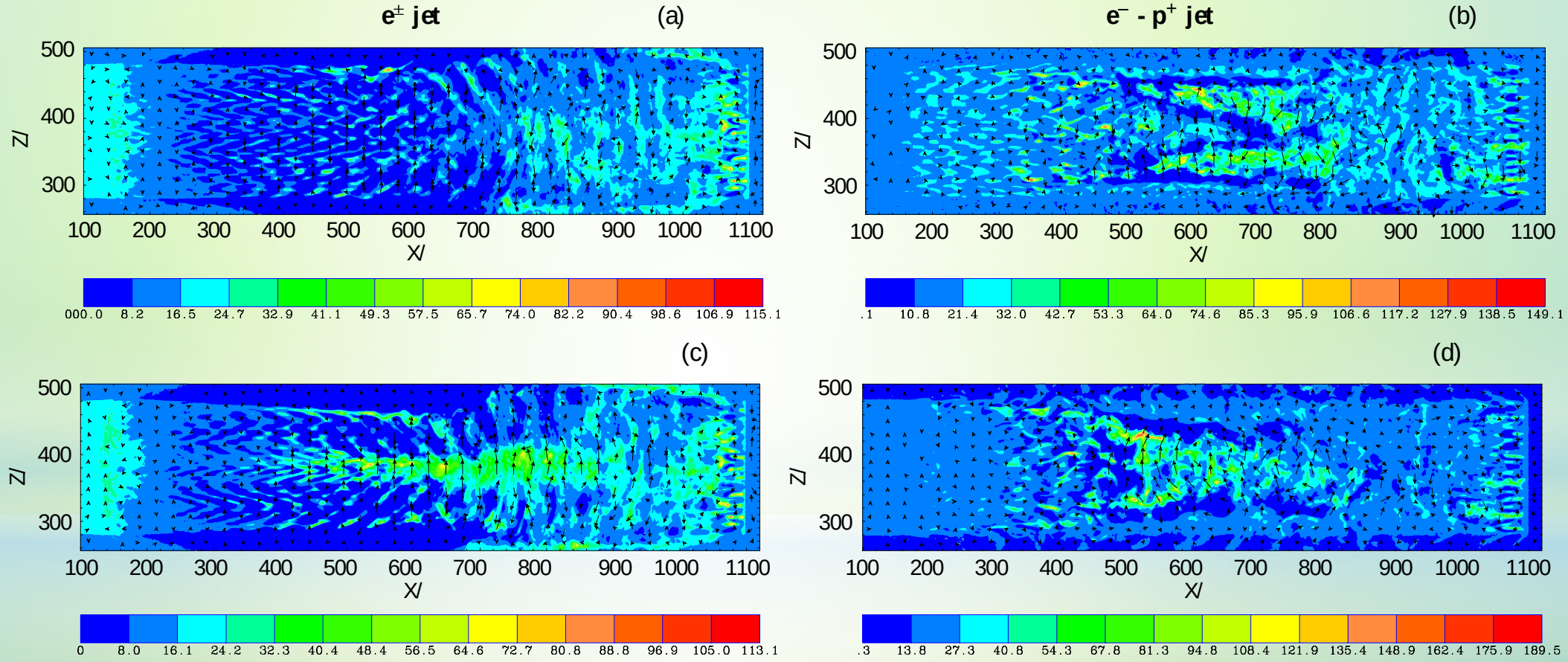
e^- - p^+ jet, t = 500 W_{pe}^{-1}, x = 520Δ

Jet electron density

$t = 1000\, W_{pe}^{-1}$

no MF

toroidal MF

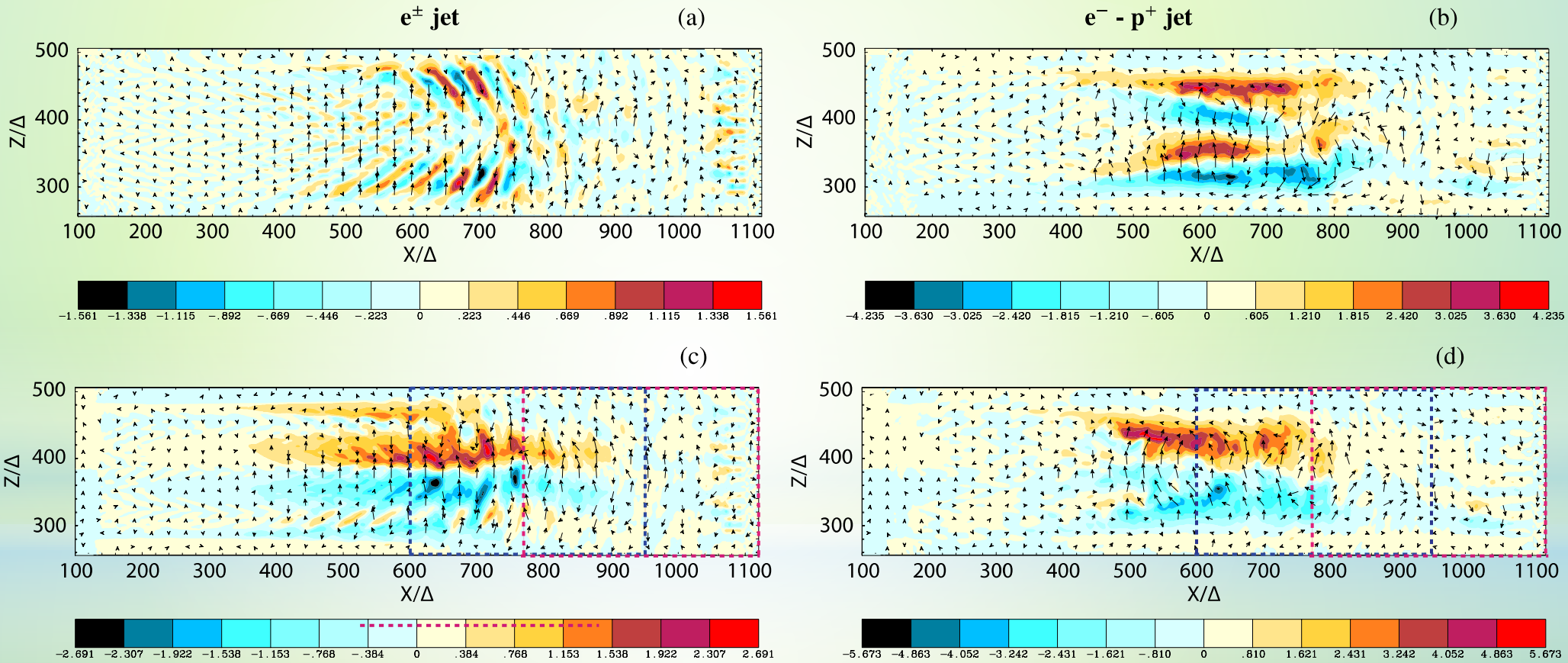


(Meli et al. 2021)

B_y component of generated instabilities $t = 1000\, W_{pe}^{-1}$

no MF

toroidal MF



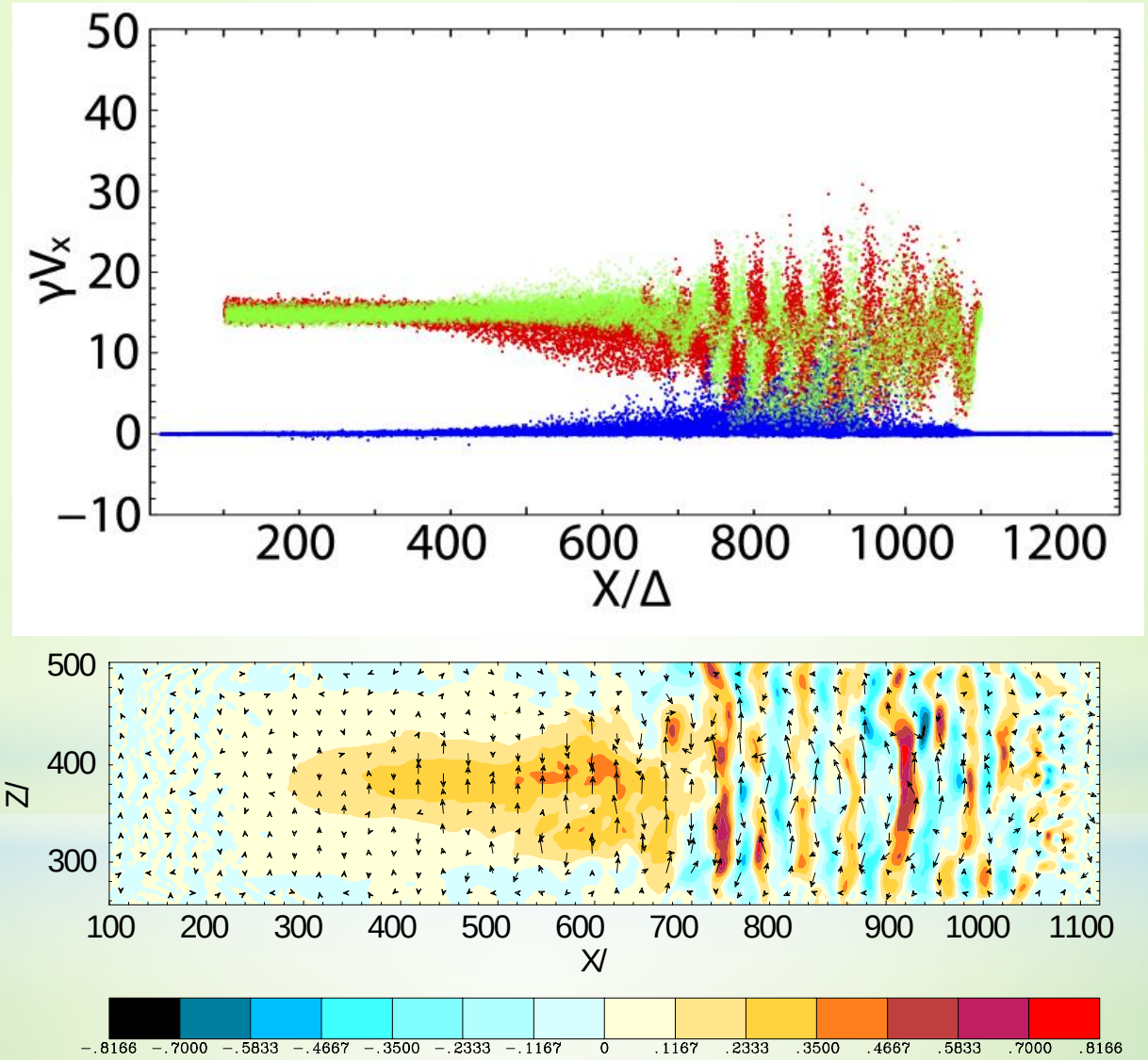
(Meli et al. 2021)

Jet electrons and positrons are out of phase

$t = 1000\ W_{pe}^{-1}$

Red: jet electrons

Green: jet positrons

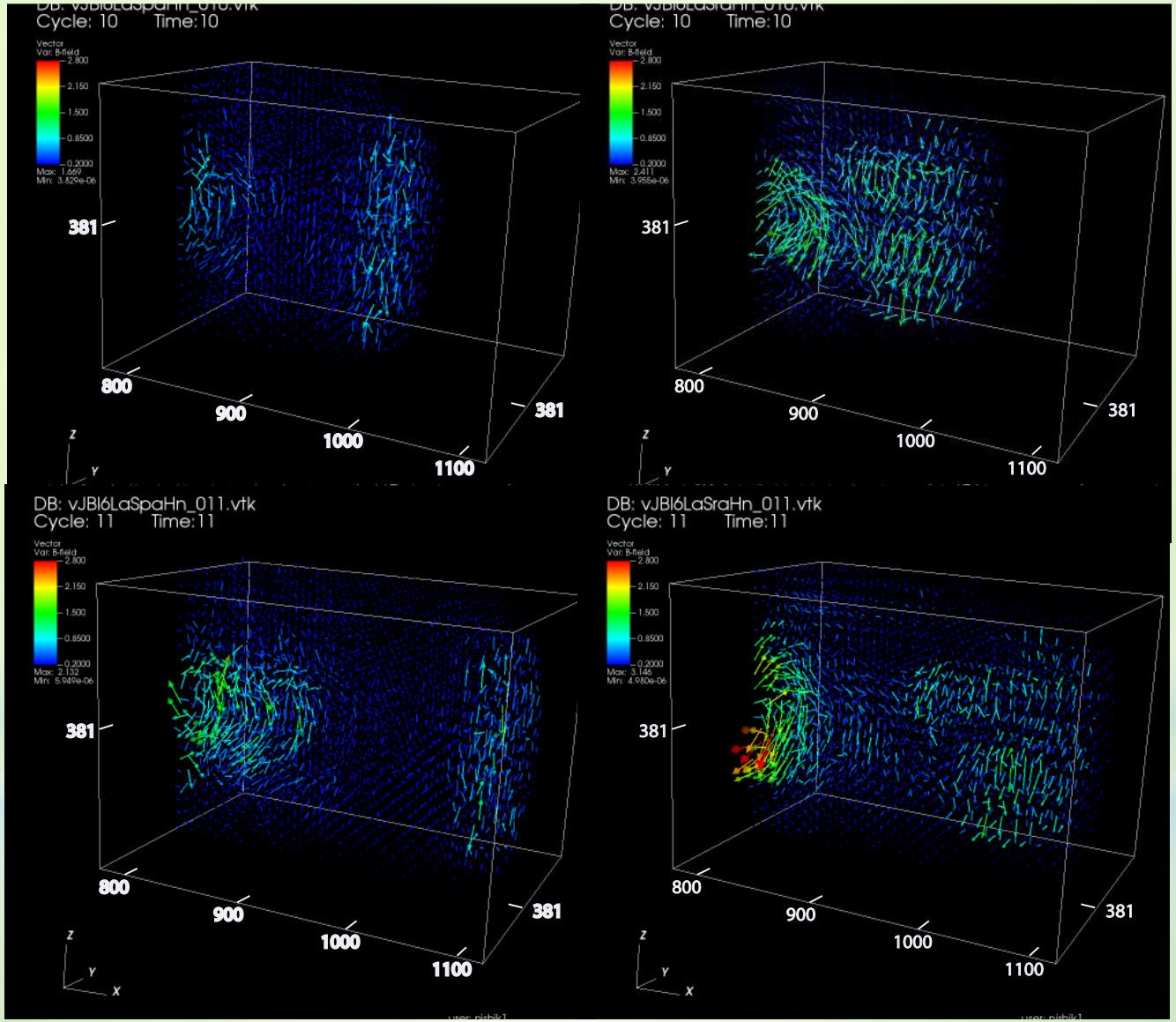


(Meli et al. 2021)

The magnetic field vectors within the cuboid

$t = 900\ \omega_{pe}^{-1}$

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



(Meli et al. 2021)

Summary

- A better jet injection scheme need to be implemented for HMF and MEF
- Electron-proton jet suffers kinetic instabilities dominantly mushroom instability
- MI and kKHI produce quasi-steady electric field (E_x) for both jets
- These electric fields accelerate and decelerate electrons and positrons
- Electrons are further accelerated due to turbulent magnetic fields generated by dissipation of the helical magnetic field (reconnection)
- Further investigations are required in order to confirm and/or find other acceleration mechanisms with varying parameters of simulations such as jet radius, magnetization factor, jet structure, etc.
- Need to perform simulations with very large systems (3000×2000×2000 grids)

Image maps of polarity

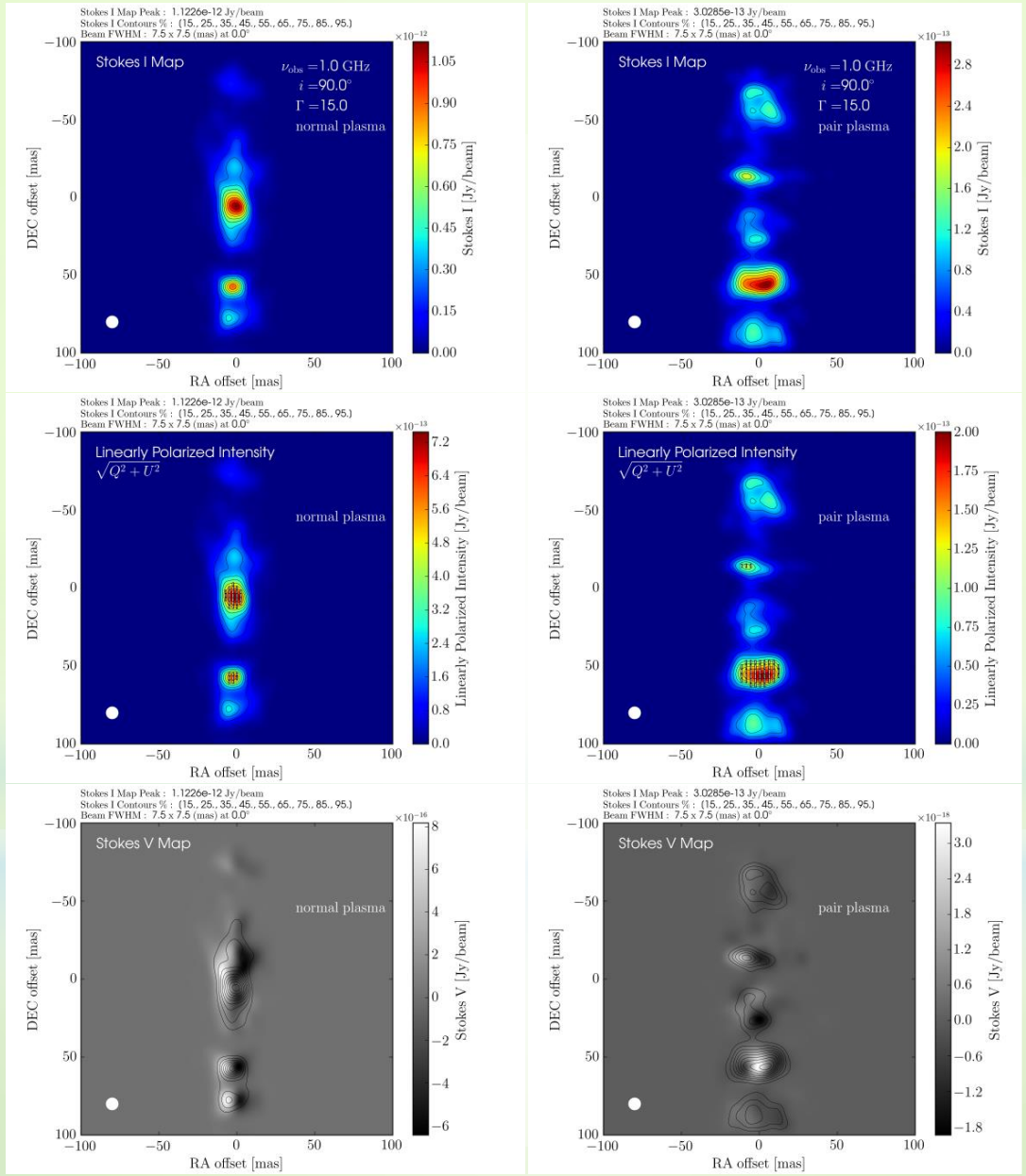
$r_{jet} = 40\Delta$ at time $t = 500\ w_{pe}^{-1}$ $\gamma_{jet} = 15$

$e^- - p^+$ jet | $e^{\pm}$ jet

I-image

LPI

v-image



MacDonald & Nishikawa
A&A 653, A10 (2021)

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**