3D PIC Simulations for Relativistic Jets with a Toroidal Magnetic Field and results from 2D GRPIC simulations

Kenichi Nishikawa (*AAMU/Physics*)

Collaborators:

K. Hirotani (*Inst. of Astron and Astrophys, Academia Sinica, Taiwan*)
R. Krsnoplsky (*Inst. of Astron and Astrophys, Academia Sinica, Taiwan*)
H. Shang (*Inst. of Astron and Astrophys, Academia Sinica, Taiwan*)
A. Meli (*NC A&T State University, USA*)
I. Duţan (*Institute of Space Science, Rumania*)
C. Köhn (*Technical University of Denmark*)
N. MacDonald (*University of Mississippi, USA*)
O. Kobzar (*Krakow University of Technology, Krakow*)
Y. Mizuno (*Shanghai Jiao Tong University*)
J. L. Gómez (*IAA, CSIC, Spain*)

Acknowledged

J. Niemiec (*Institute of Nuclear Physics PAN, Poland*)
M. Pohl (*U- Potsdam/DESY, Germany*)
K.-W. Wong (*SUNY Brackport*)
H. Sol (*Paris Observatory, France*)
A. Pe'er (*Bar Ilan University, Israel*)
J. T. Frederiksen (*AI Developer, Denmark*)
Å. Nordlund (*Niels Bohr Institute, Denmark*)

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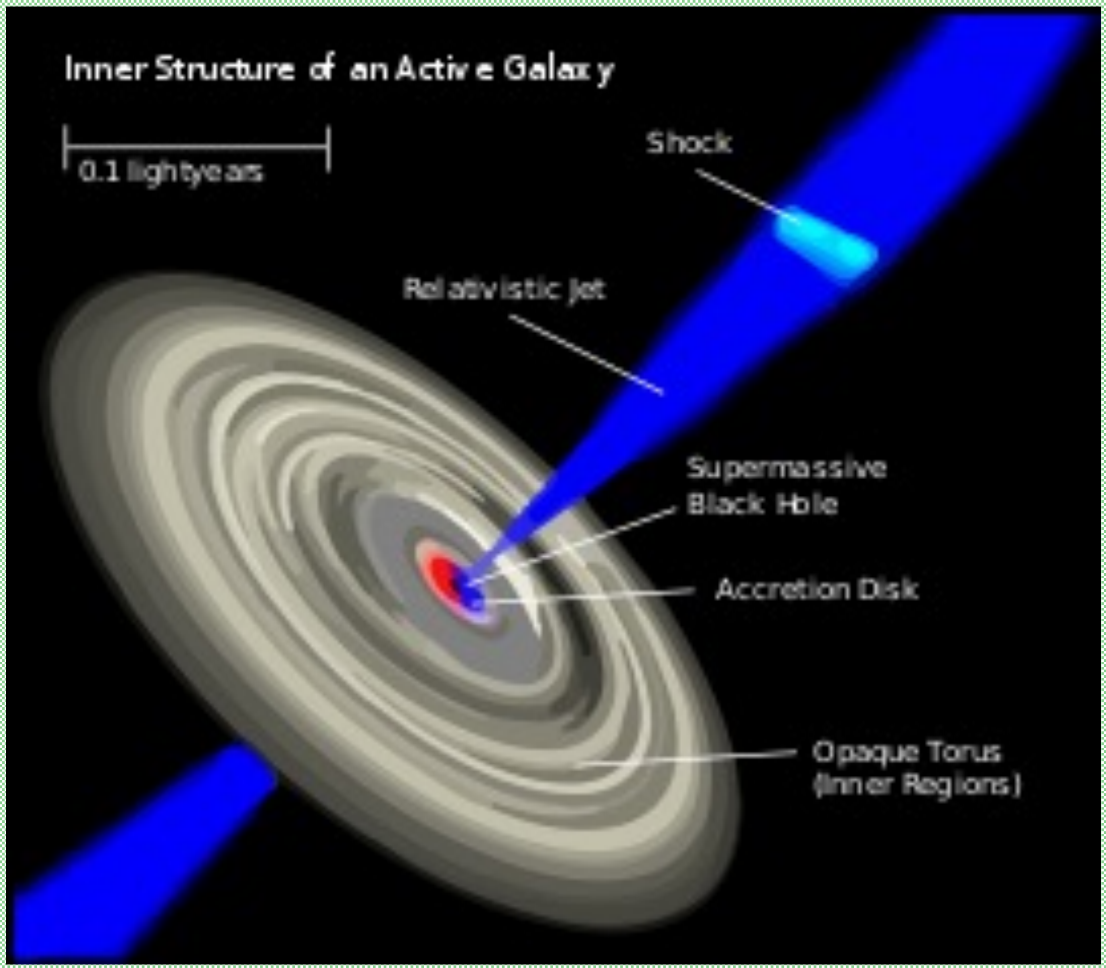
Outline

1. Global (cylindrical) jet simulations with MI and KKHI with large simulation system (Nishikawa et al. ApJ, 820, 94, 2016a) (**r_{jt} = 100Δ**)
2. Recent Simulations of Particle Acceleration and Reconnection in Relativistic Jets (Nishikawa et al. MNRAS, 493, 2652, 2020; Meli et al. MNRAS, 2023; Nishikawa et al. LRCA 2021, TRISTAN-MPI is available upon requests))
3. Synthetic spectra from cylindrical jets (Duţan et al. MNRAS, revising, 2024)
4. 2D GRPIC simulations with B-L coordinates with spherical coordinates (Hirotani et al. 2021, 2023, 2024)
5. Reconnection near the event horizon (Hirotani et al. 2023)
6. Jet collimation (Hirotani et al. 2024)
7. Summary and Future plans

Astrophysical systems

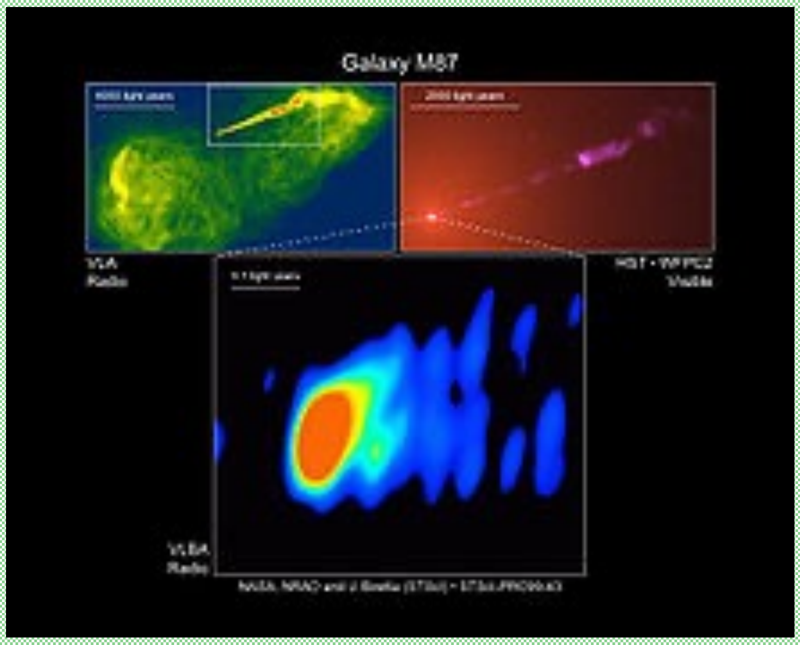
Fiuza's and Mignone's talks

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

Crab Nebula

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

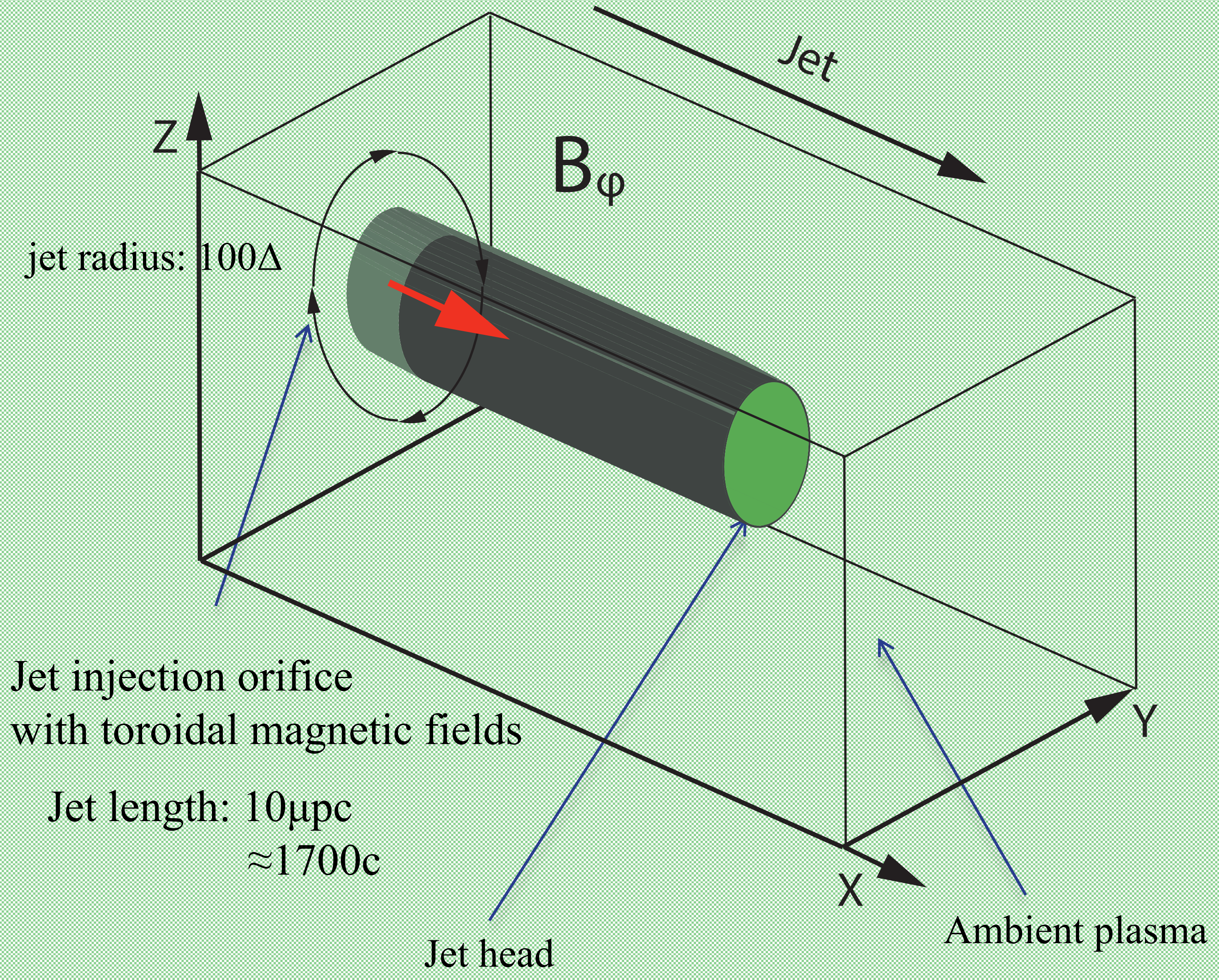
3D global jet simulation

NASA Pleiades
TACC Frontera

Simulation grid size: (L_x, L_y, L_z) = $(1285\Delta, 789\Delta, 789\Delta)$, with Δ the size of the grid cell Jet radius: $r_{\rm jt}$ = 100Δ, Top-hap jet density profile

Two types of plasma: pair plasma and electron-ion plasma (with mass ratio $m_{\rm i}/m_{\rm e}$ = 4)

Jet Lorentz factor, Γ = 15 (AGN), and amplitude of initial toroidal magnetic field, B_0 = 0.5, as in Meli+ (2023) We also consider here: Γ = 100 (GRBs) and B_0 = 0.1



Key Scientific questions (Meli et al. MNRAS, 2023)

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

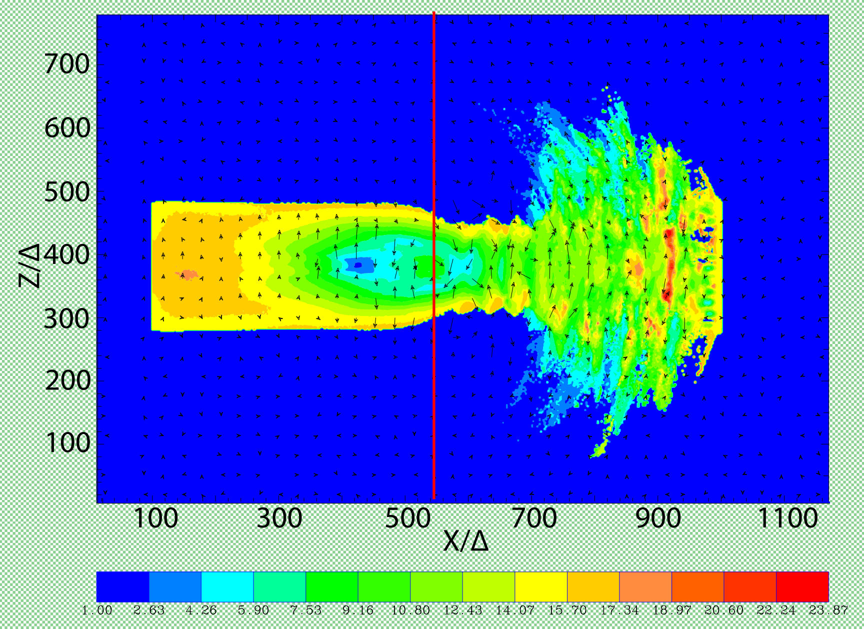
Why we need to perform PIC simulations of relativistic jets

- **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 (toroidal) magnetic fields are crucial in understanding these instabilities**
- **PIC *global* jets simulations are new and an innovative approach and provide the complex evolution of relativistic jets with kinetic processes including radiation, which cannot be done by the RMHD approach**
- **Nonthermal acceleration due to reconnection may generate flares**

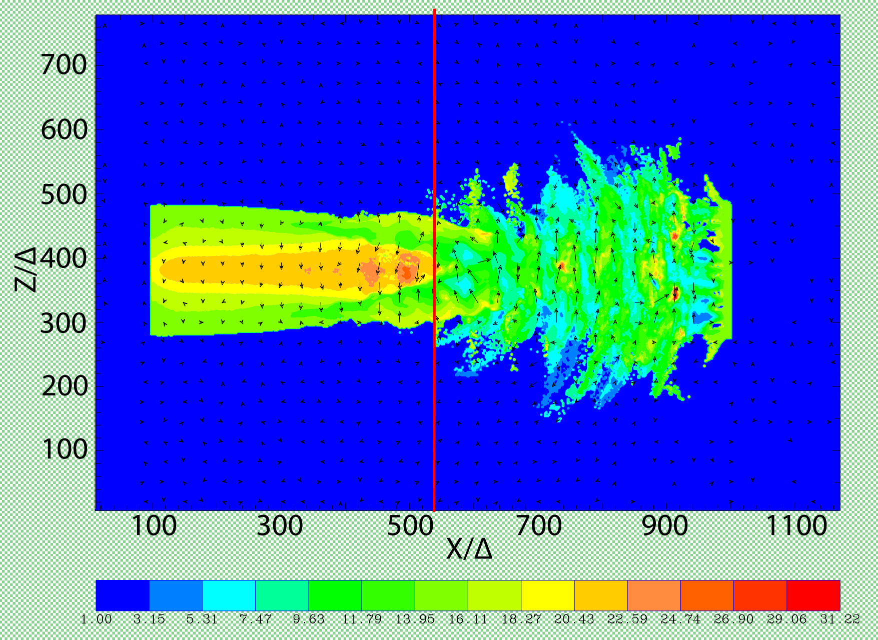
Jet Lorentz factor and velocity density distributions

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

e^{-} - e^{+} jet



e^{-} - i^{+} jet



$x/\Delta > 550$

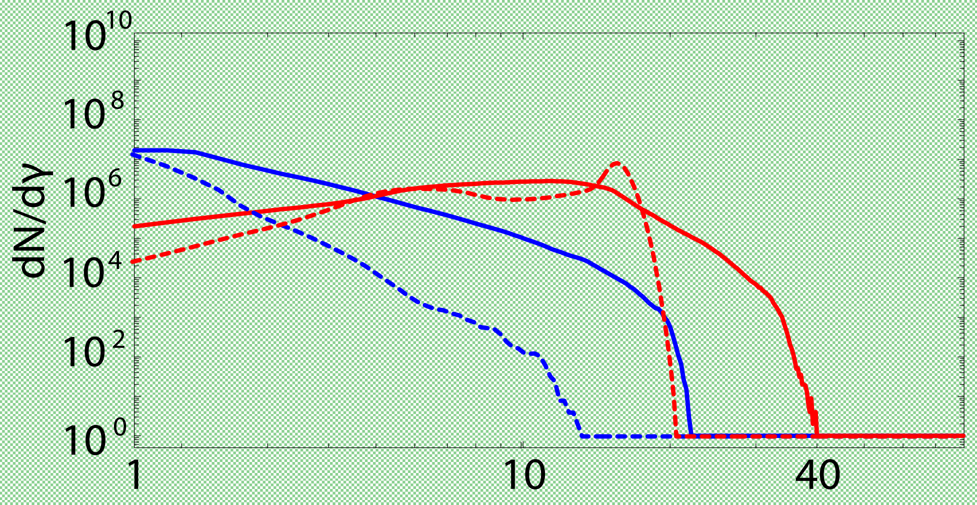
jet electrons

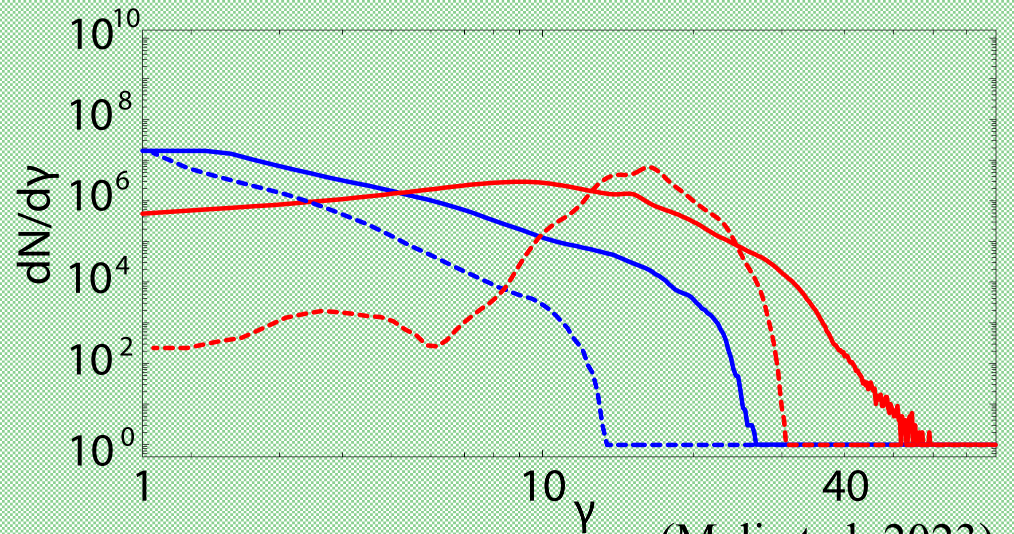
ambient electrons

$x/\Delta < 550$

jet electrons

ambient electrons





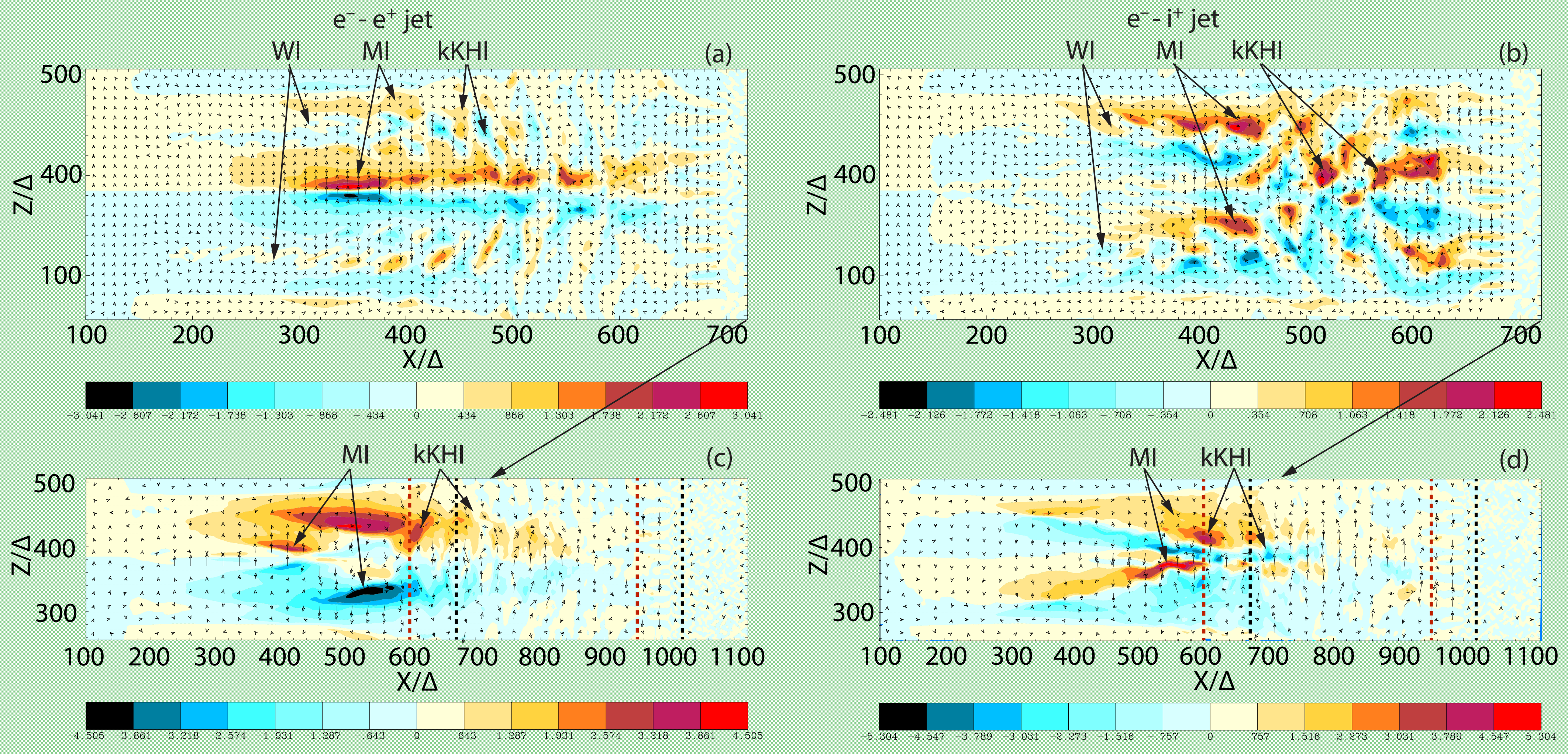
(Meli et al. 2023)

Colormap of the magnetic-field amplitude B_y

e⁻ - i⁺ jet

$t = 600\ \omega_{pe}^{-1}$

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



(Meli et al. 2023)

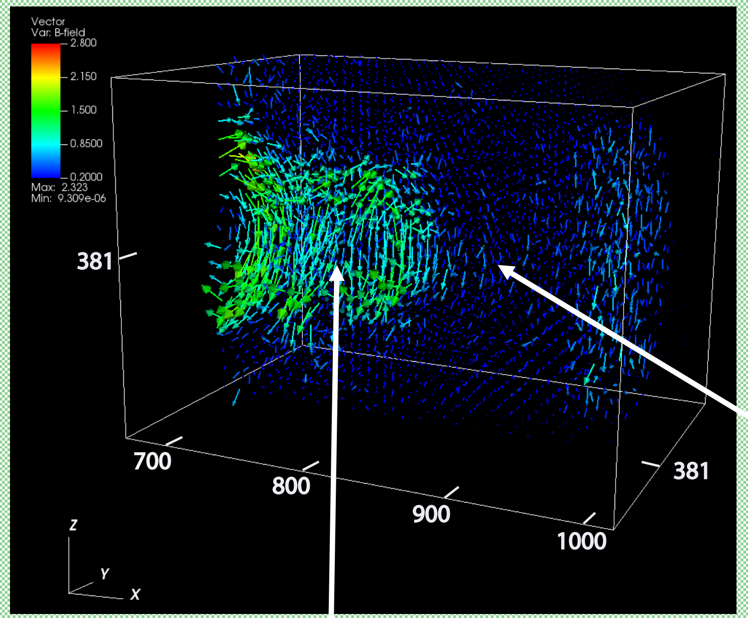
By with arrows of Bx,z for electron-ion jet

Time 1000 to 9000

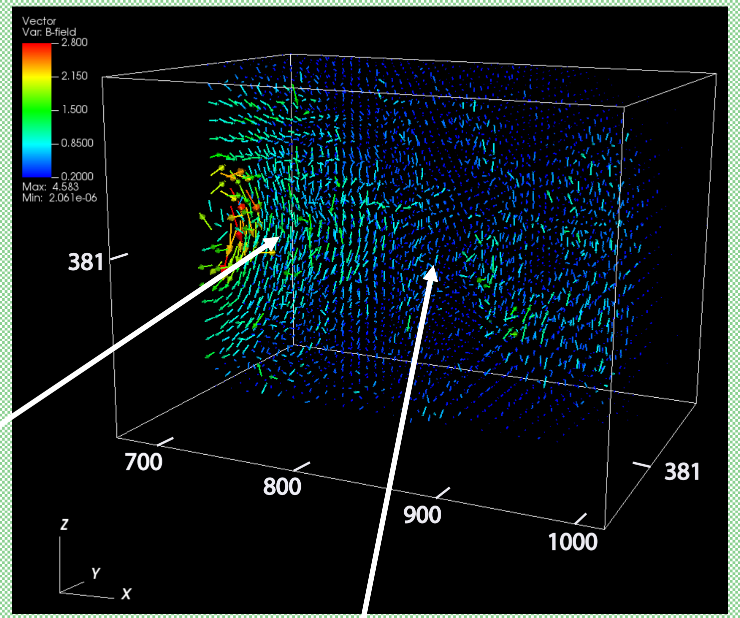
Magnetic field vectors: Nonlinear to Chaotic transition (Blandford et al. 2017) t = 900 ω_{pe}^{-1}

(Meli + 2023)

$e^- - e^+$ jet



$e^- - i^+$ jet



Nonlinear

Hokusai: Great wave (British Museum)

Chaotic

Van Gogh: Starry Night (MoMA)

Synthetic spectra from Particle-in-cell Simulations of Relativistic Jets (Synchrotron radiation)

Head-on

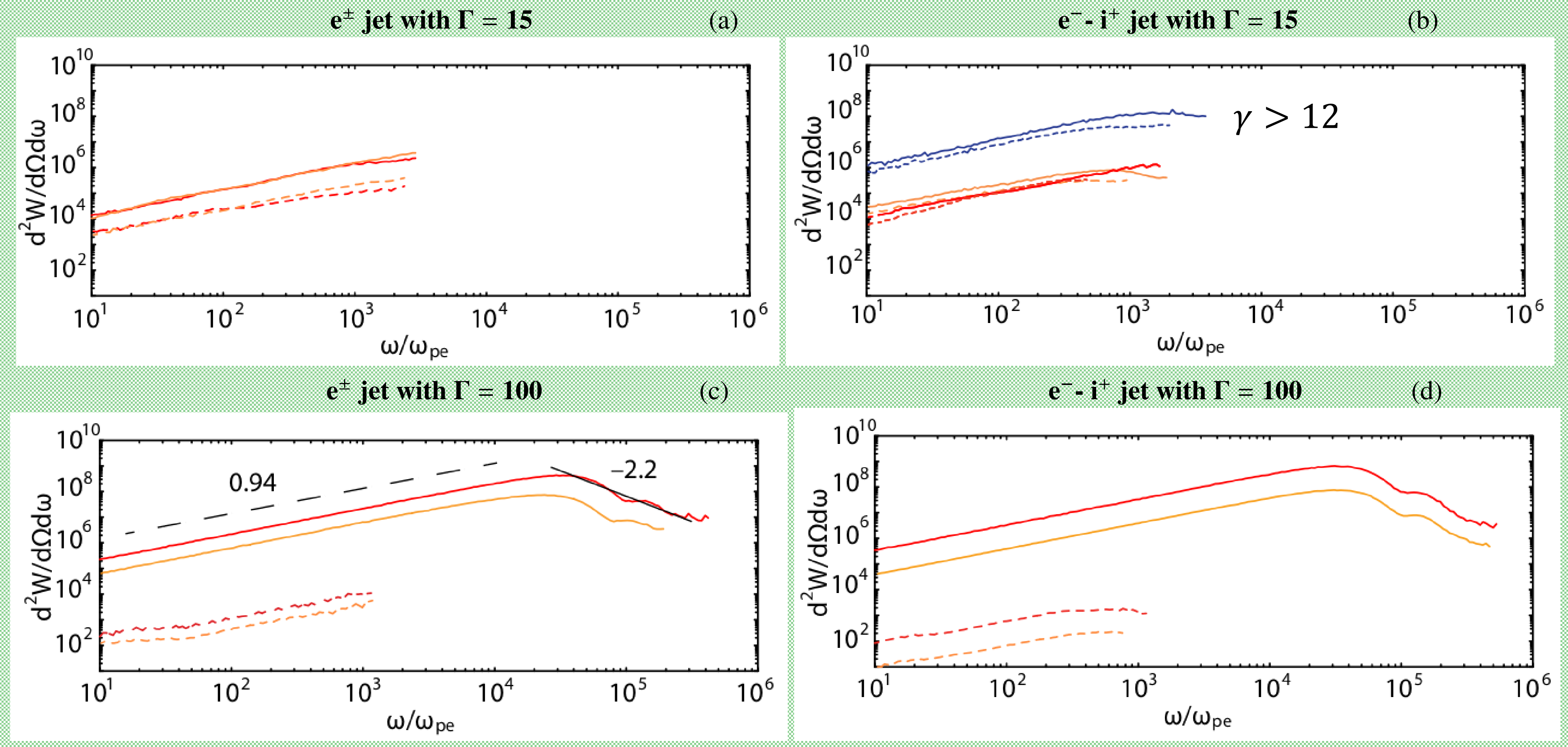
$B_0 = 0.5$

$B_0 = 0.1$

5° off

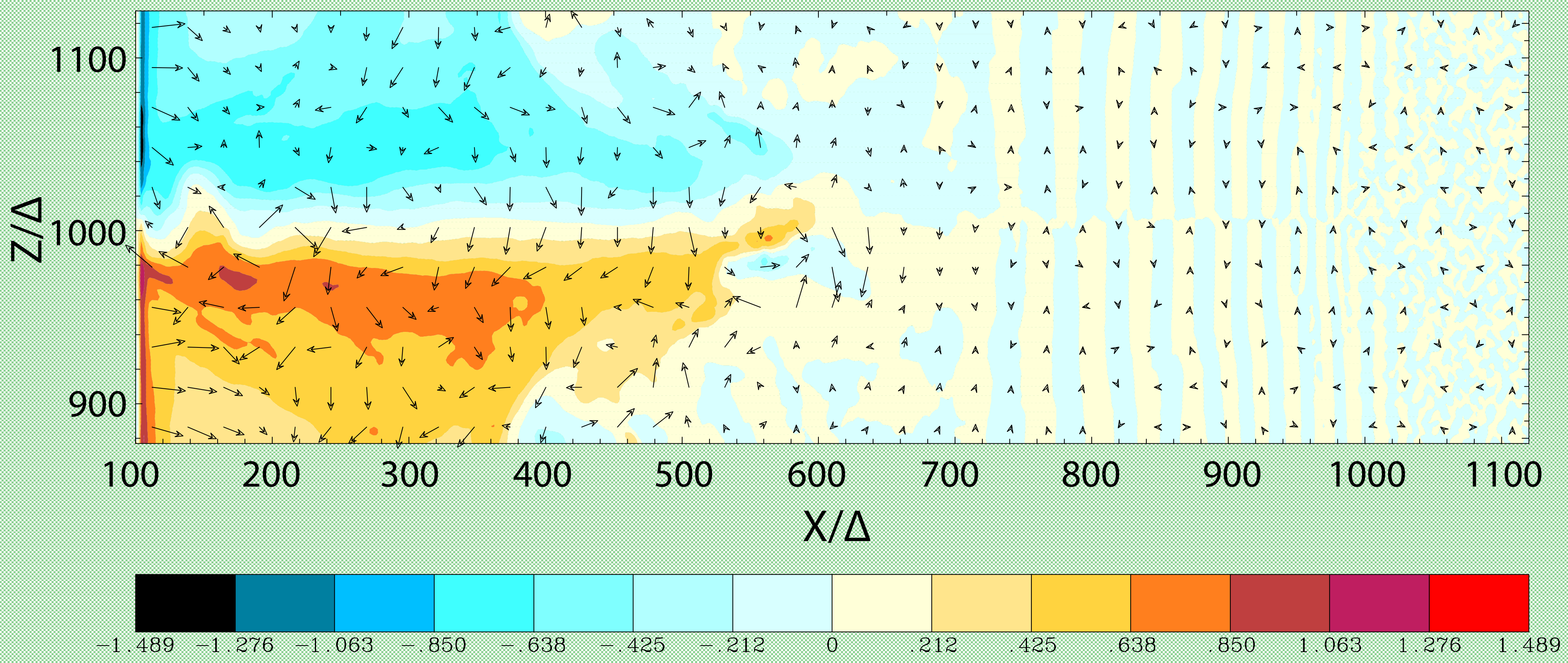
$B_0 = 0.5$

$B_0 = 0.1$



(Dutan et al. revising, 2024)

B_y in $x - z$ plane of Gaussian jet density (Preliminary)

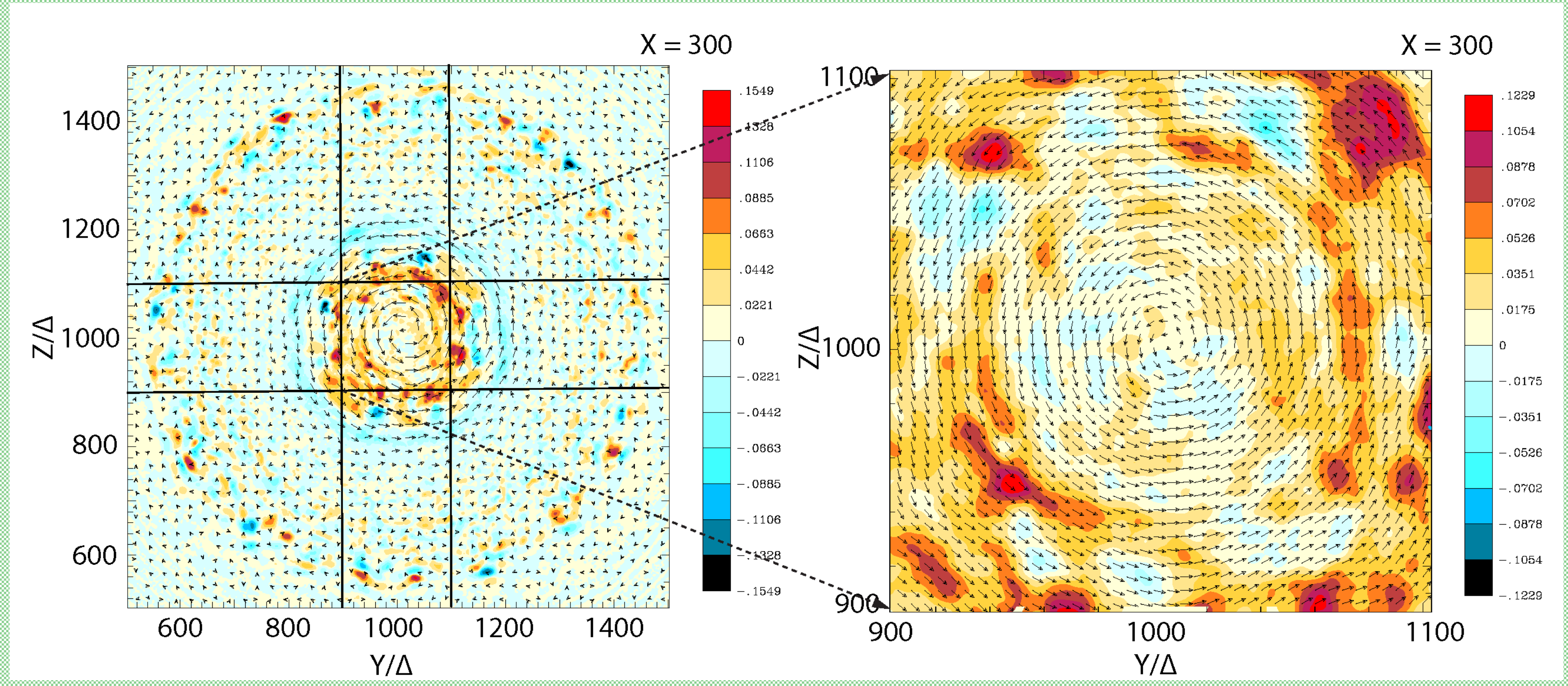


color maps of the B_y electric field with arrows depicting the magnetic field components in the $x - z$ plane for $e^{\pm}$ plasma jets with $\Gamma = 15$ and $B_0 = 0.2$, at $t = 1000\ \omega_p^{-1}$

WI, kKHI and MI are suppressed due to Gaussian jet density profile.

maximum and minimum are: ±0.1489

Further work: preliminaries with Gaussian jet density



Nishikawa+ (2024, in prep.)

color maps of the E_x electric field with arrows depicting the magnetic field components in the $y - z$ plane for $e^{\pm}$ plasma jets with $\Gamma = 15$ and $B_0 = 0.2$, at $X = 300\Delta$ at $t = 1000\,\omega_p^{-1}$

MI seems to grow

maximum and minimum are: ±0.1549 (left) and ± 0.1229 (right)

GRPIC simulations

1D: Levinson + Cerutti 2018, Chen + Yuan 2020, Kisaka + 2020
2D: Purfrey + 2019, Crinquand + 2020, 2021, Hirotani + 2021, 2023, 2024,
El Mellah + 2022, Torres + 2023, Galishnikova + 2023
3D: Crinquand + 2022,

- Plasma kinetics in the magnetosphere: reconnection physics, plasma injection, spark gaps, flares, pair-creation, etc.

Artificial disk (set up as boundary condition)

Requires rescaling (an issue for radiative PICs)

2DGRPIC simulations (Hirotani +2023)

Assume a BH spin $a = 0.9M$, M=10$M_\odot$, $\dot{m} = 2.5\times10^{-4}$

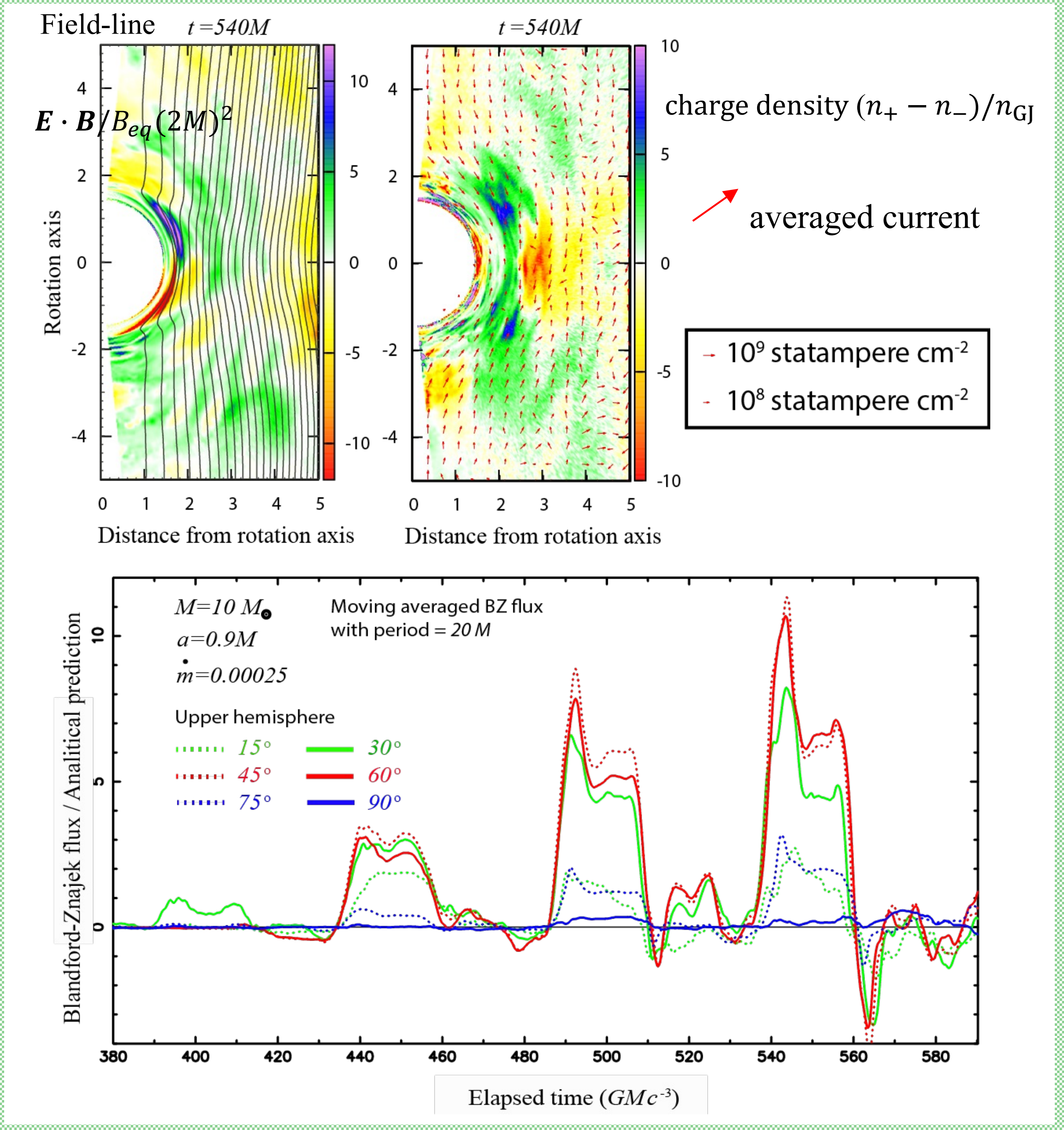
(a) Angle-dependent BZ process:

BH's rotational energy is electromagnetically extracted, being concentrated along the magnetic (***B***) field lines threading the event horizon in the middle latitudes.

(b) Magnetic reconnection in the BH vicinity:

B islands are created by reconnection near the equator, expelling ***B*** flux tubes to halt the BZ process. However, when ***B*** islands disappear, ***B*** flux tubes efficiently thread the horizon to cause a flare. → BH's rotational energy is extracted intermittently.

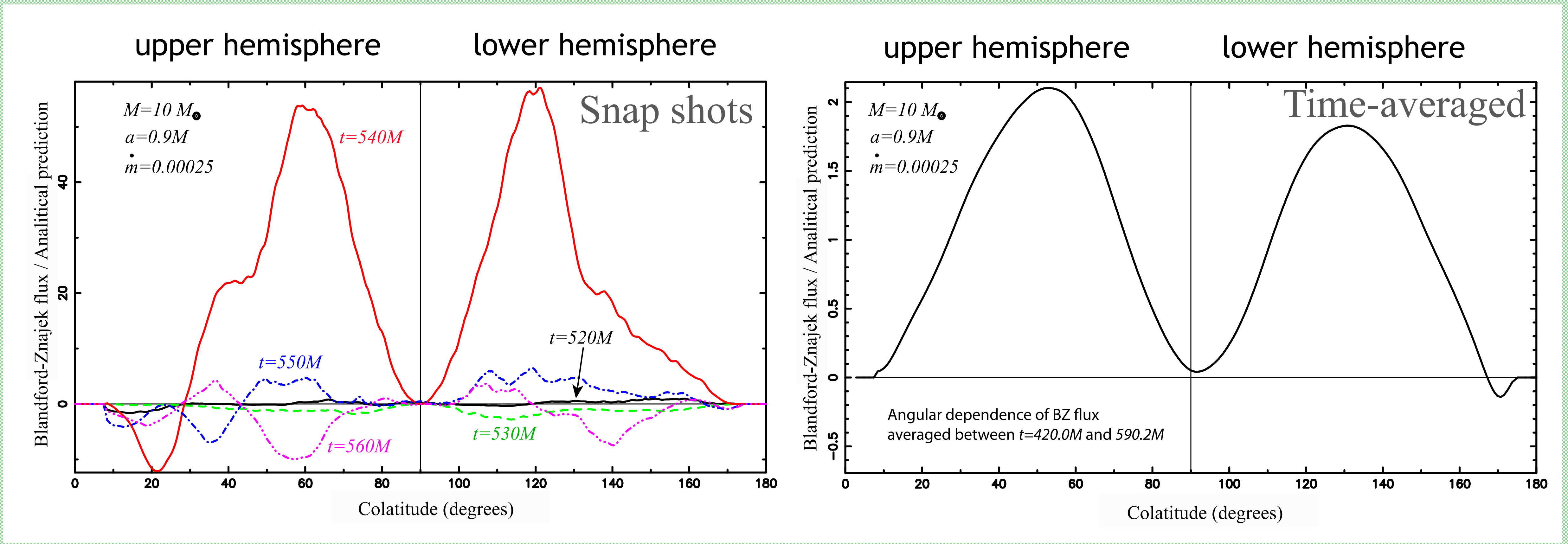
Flaring activity of BH magnetosphere by reconnection



At $t \sim 540\ GM/c^3$, ***B*** **field lines** efficiently threads the ergosphere (*top left*), where the BH's rotational energy is stored. It results in a strong meridional current (*top right*) near the horizon, extracting the BH's rotational energy by ***J*x*B*** force intermittently (*bottom*).

Fig.) *Top left:* $\boldsymbol{E}\cdot\boldsymbol{B}/B_{eq}^{2}$ (color) and ***B*** field lines (black curves).
To right: charge density $(n_+ - n_-)/n_{GJ}$ (color) and electric currents (cgs, red arrows).
Bottom: Time evolution of the BZ flux along six discrete colatitudes.

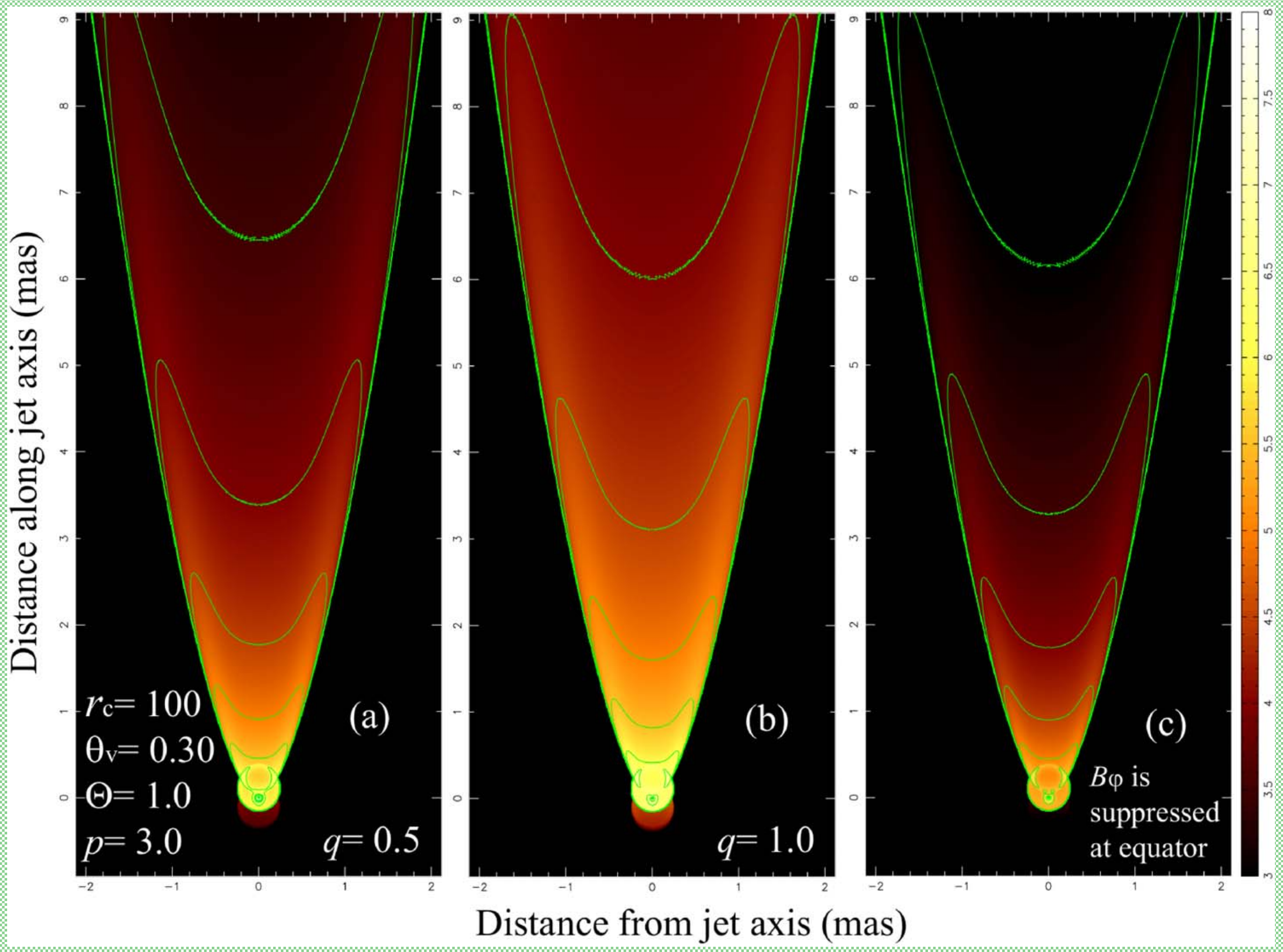
Angular dependence of the BZ flux



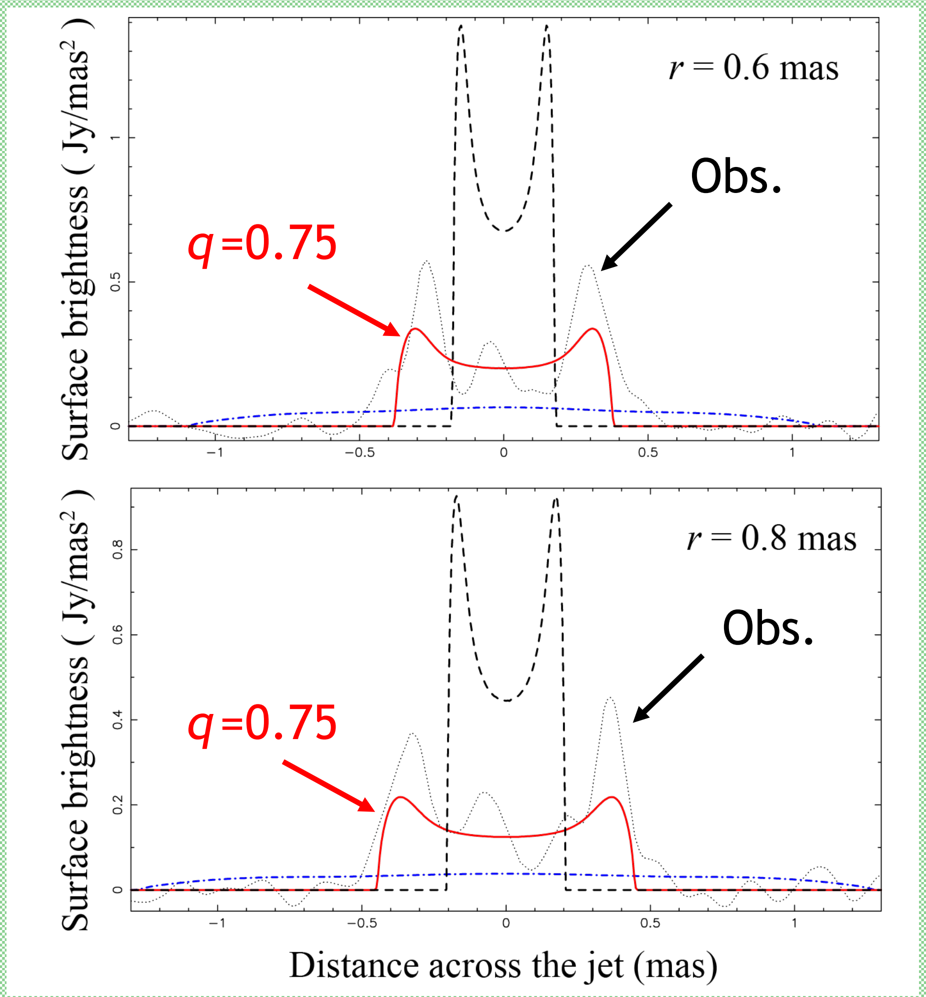
Angular dependence of the BZ flux measured at radius $r = 2.335\ M$. ***Left:*** BZ fluxes at five discrete elapsed times. ***Right:*** BZ flux averaged over time between $t = 480$ and $590\ M$. The left (or right) half of each panel corresponds to the upper (or lower) hemisphere.

*Limb-brightness depend on **B** configuration*

Hirotani + (2024, ApJ 965, 50)



Surface brightness distribution of synchrotron emission from the M87 jet at 86 GHz.
θ_v=*0.30* rad, $\Theta = kT_e/m_ec^2 = 1.0$, $p=3.0$, $r_c = 100R_S$.



Intensity slice at *r=0.6* and *0.8* mas. Moderate collimation (*q=0.75*) is consistent with VLBI obs. (Asada & Nakamura 2012, ApJL 745, L28).

Reconnection near the event horizon

Magnetic islands are created by reconnection near the equator and migrate toward the event horizon, expelling magnetic flux tubes from the BH vicinity during a large fraction of time.

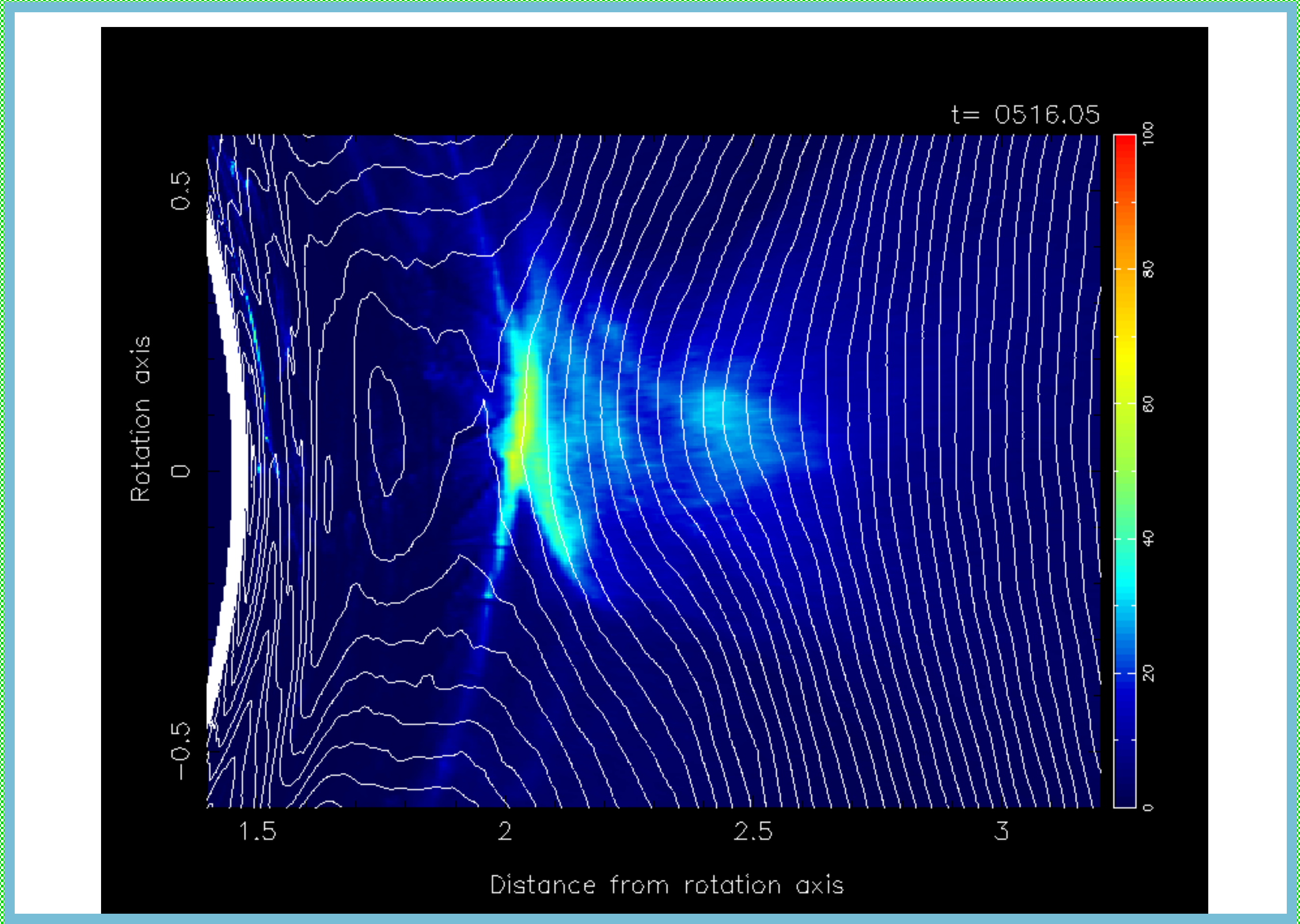


Figure 8. Magnetic field lines (white curves) and the pair density (color, in Goldreich-Julian unit) on the poloidal plane near the horizon, $1.4M < x = r\sin\theta < 3.2M$ and $|r\cos\theta| < 0.6M$, at elapsed time $t = 516.05M$. The ordinate $y = r\cos\theta = 0$ corresponds to the equatorial plane. Magnetic reconnection takes place at the X-type point that appears at $(x, y) = (1.95M, 0.14M)$ at this timing. The horizon resides at $r = 1.435M$ in the left-most part. An animation of this simulation is available in the online journal. The animation covers the simulation from $t = 515.60M$ to $516.99M$.

movie is available:
knishika27@gmail.com

(Hirotani et al. 2023)

Summary (relativistic jets)

- We simulated electron-positron and electron-ion (proton) relativistic jets with toroidal magnetic fields (see Meli et al. 2023)
- For pair jet MI is excited and combined with kKHI: **a non-oscillatory $\mathbf{E}_\mathbf{x}$** modulates jet particles
- The electron-ion jet suffers kinetic instabilities dominantly mushroom instability
- MI and kKHI produce a non-oscillatory electric field (E_x) for both jets
- These electric fields accelerate and decelerate electrons and positrons (ions)
- Electrons are further accelerated due to turbulent magnetic fields generated by dissipations of toroidal magnetic fields (**reconnection**)
- Further investigations is important in order to confirm and/or find other acceleration mechanisms with varying simulation parameters such as, jet radius, magnetization factor, jet structure, etc.
- Rigorous analysis of reconnection with magnetic field topology (Cai et al. 2007)

Summary (GRPIC simulations)

- We examined the temporary evolution of axisymmetric magnetospheres around rapidly rotating stellar-mass black holes (BHs). (see Hirotani et al. 2021, 2023)
- The key parameters: $a = 0.9M$, M=10$M_{\odot}$, $\dot{m} = 2.5\times10^{-4}$
- Created pairs fail to screen the electric field along the magnetic field, provided that the mass accretion rate is much small compared to the Eddington limit
- Magnetic islands are created by reconnection near the equator and migrate toward the event horizon, expelling magnetic flux tubes from the BH vicinity
- The extracted energy flux concentrates along the magnetic field lines threading the horizon in the middle latitudes
- Rigorous analysis of reconnection with magnetic field topology (Cai et al. 2007)

Future plans

- **Further simulations with a systematic parameter survey will be performed in order to understand jet evolution with toroidal magnetic fields with Gaussian (not top-hat) jet density profiles**
- **Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability using larger systems for GRBs, SNRs, AGNs, etc.**
- **Magnetic field topology analysis for understanding reconnection evolution and associated flares with transient particle acceleration**
- **Synthetic imaging of polarity with new larger simulations and compared with IXPE experiments**
- **Develop a 3D GRPIC code with Kerr-Schild coordinates**