Hybrid Modeling of Particle Acceleration in Astrophysical Jets

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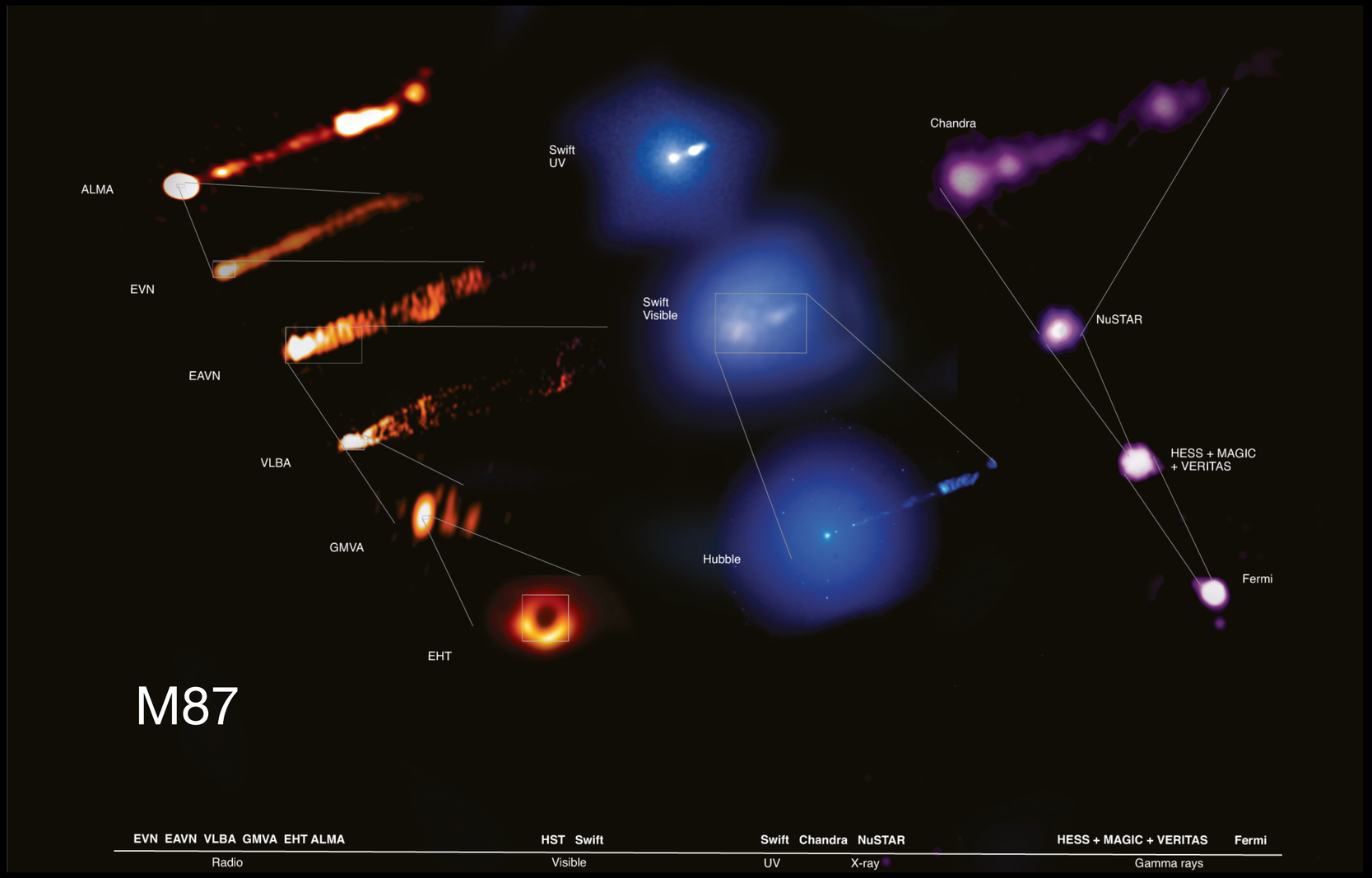
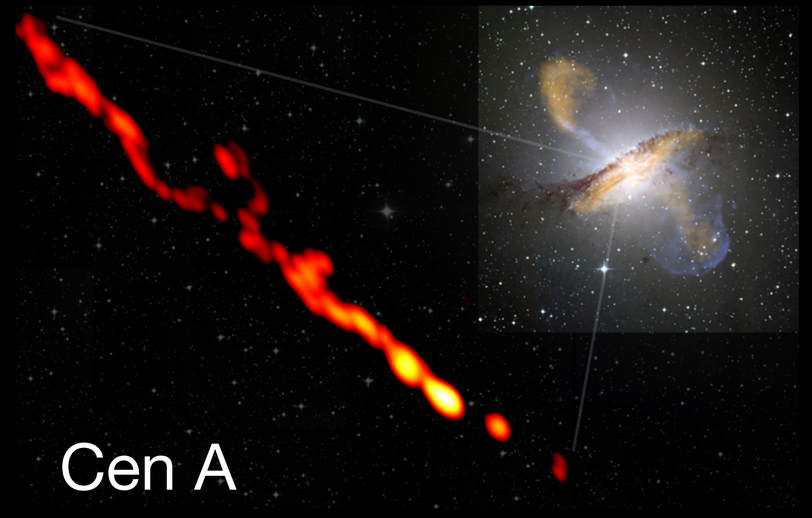
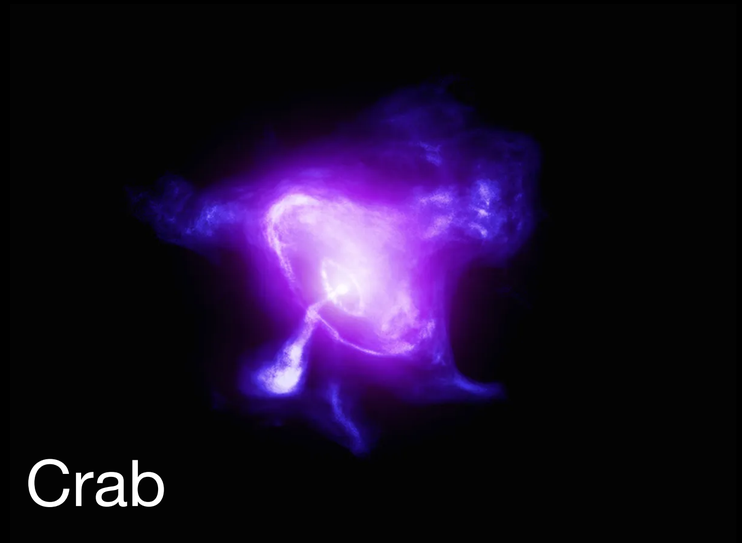
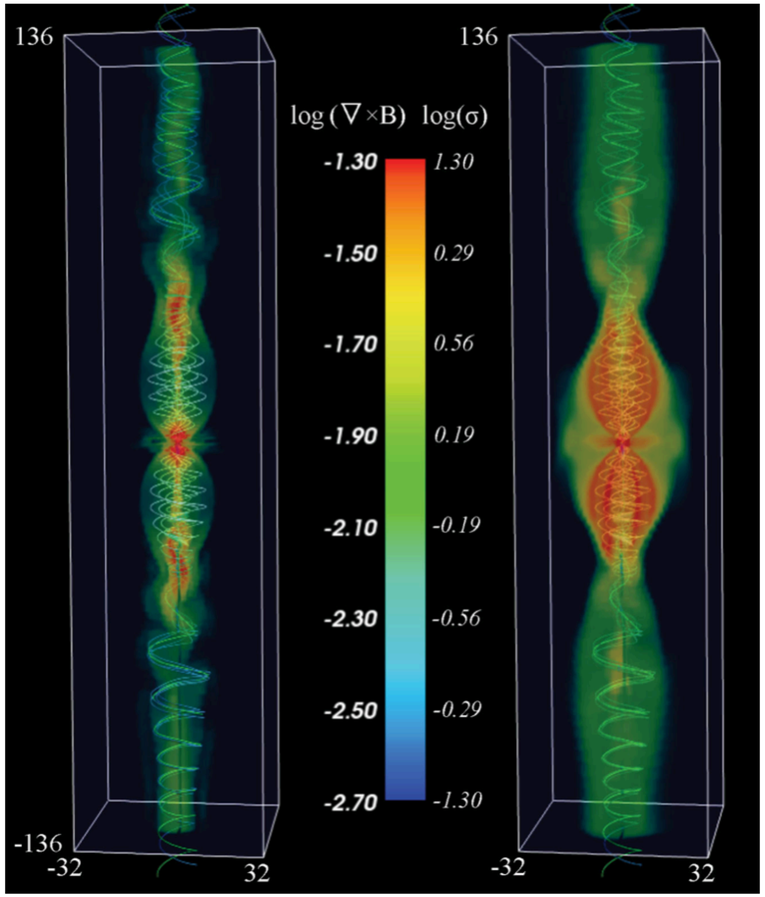
Astrophysical Jets

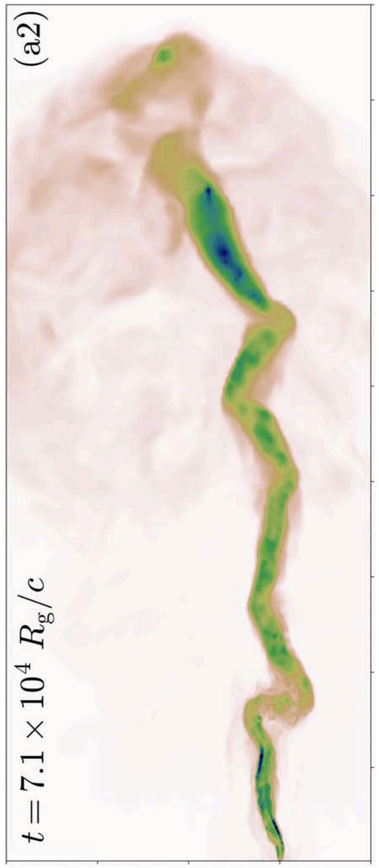


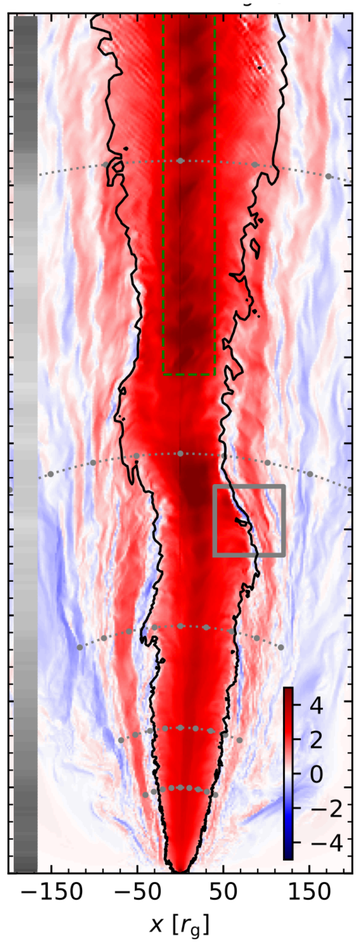




Modeling Astrophysical Jets : Global (GR)MHD







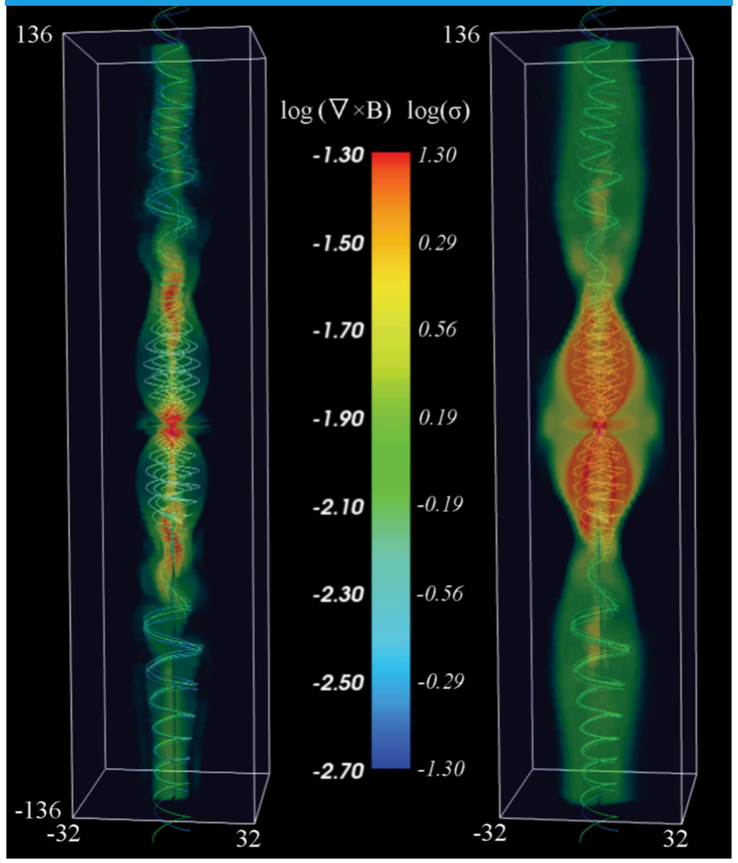
A. Lalakos et al 2024 ApJ 964 79

K. Nalewajko et al 2026 ApJ 1003 174

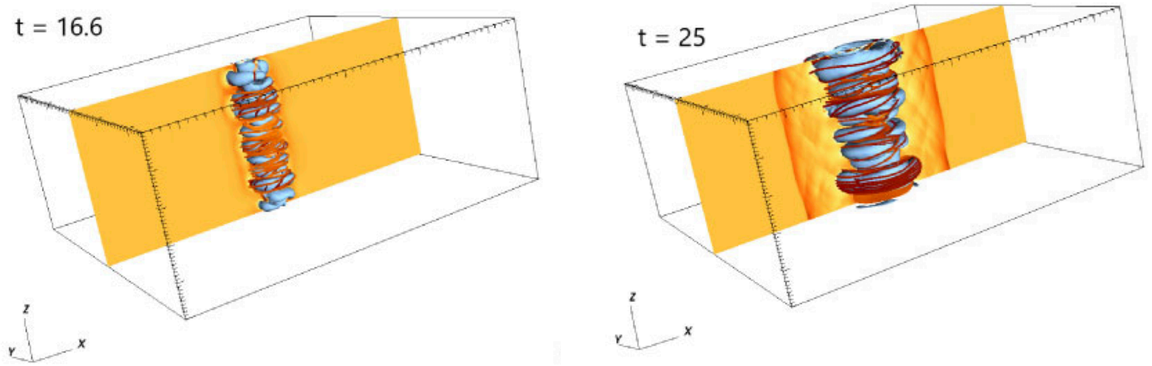
O. Bromberg et al MNRAS Vol 456, Issue 2, 21 Feb 2016, Pages 1739–1760

Modeling Astrophysical Jets : Local MHD

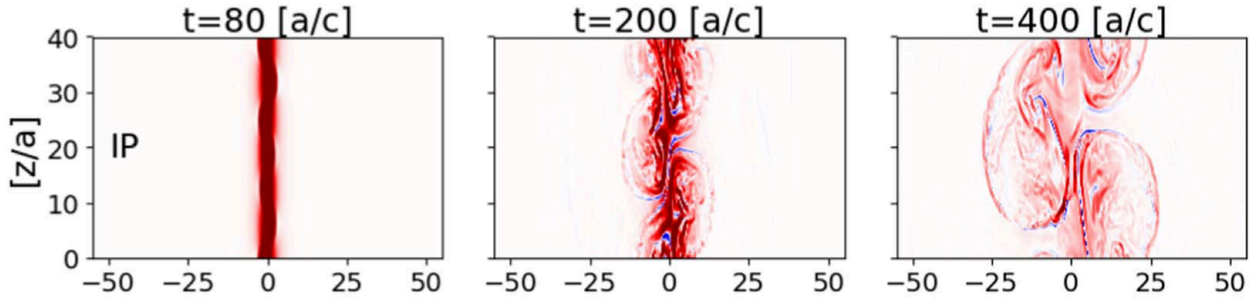
Global MHD



Local MHD : Pressure-Supported Jet



Local MHD : Force-Free Jet

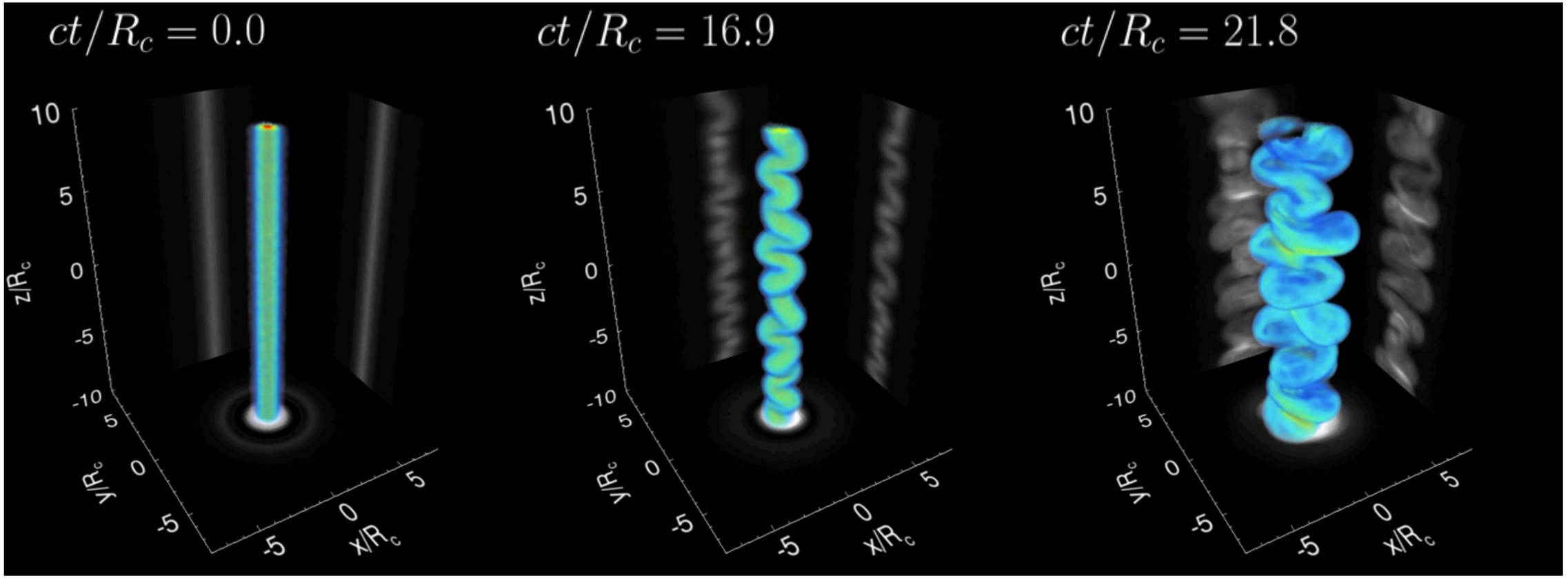


O. Bromberg et al 2019 ApJ 884 39

M. Musso et al MNRAS, Vol 532, Issue 4, Aug 2024, Pages 4810–4825

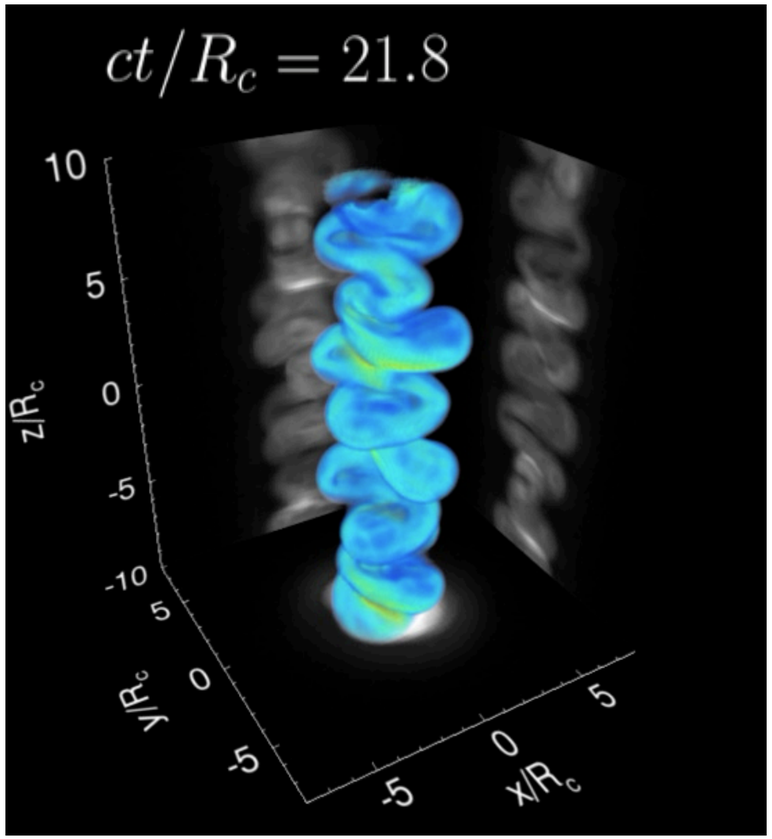
O. Bromberg et al MNRAS Vol 456, Issue 2, 21 Feb 2016, Pages 1739–1760

Fully Kinetic Modeling shows Efficient Non-Thermal Particle Acceleration

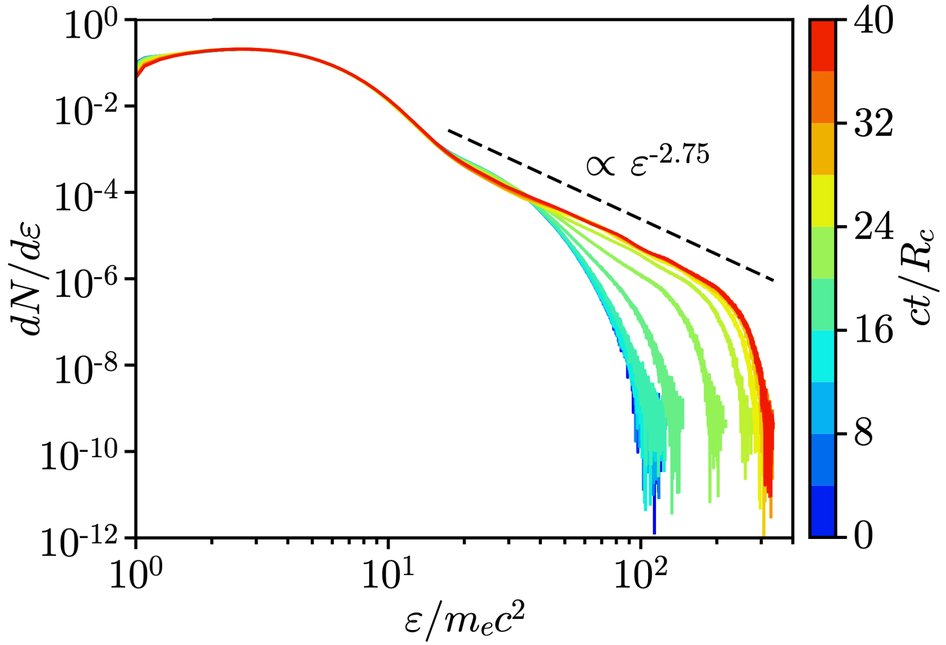


E. P. Alves et al 2018 Phys. Rev. Lett. 121, 245101

Fully Kinetic Modeling shows Efficient Non-Thermal Particle Acceleration



Non-thermal tails form over timescales $\sim 10\ c/R_{\rm jet}$



$\epsilon_{\rm max} \approx 2 \times \epsilon_{\rm confinement}$

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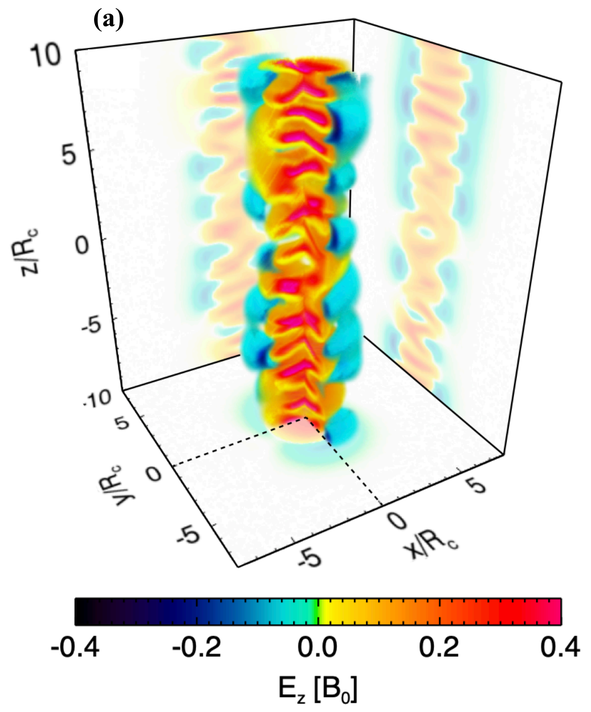
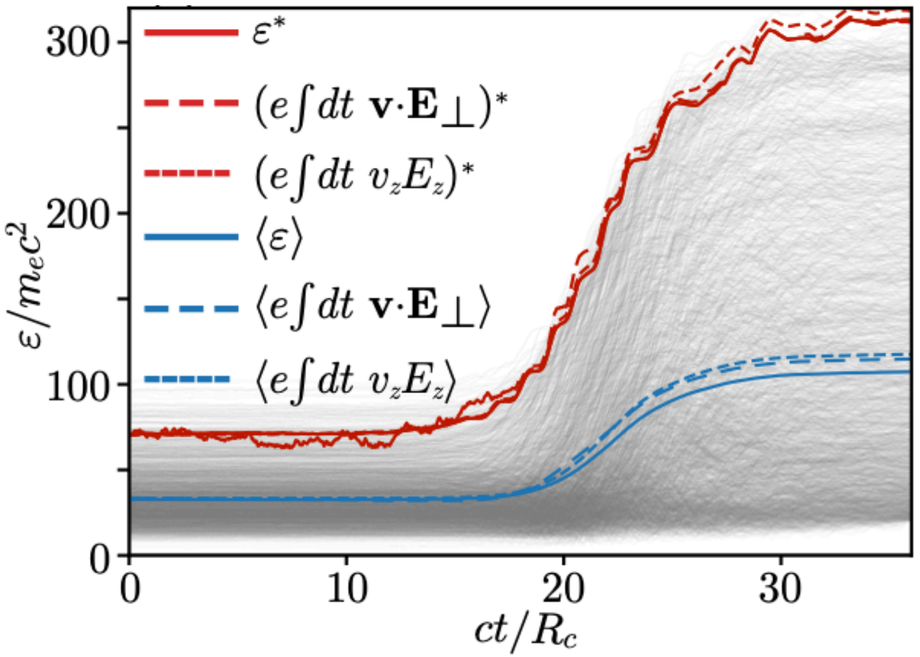
J. Ortuño-Macías et al 2022 ApJ 931 137

Structures Responsible for Particle Acceleration

Large-Scale Axial Electric Field



Most energization is caused by $E_\perp$.



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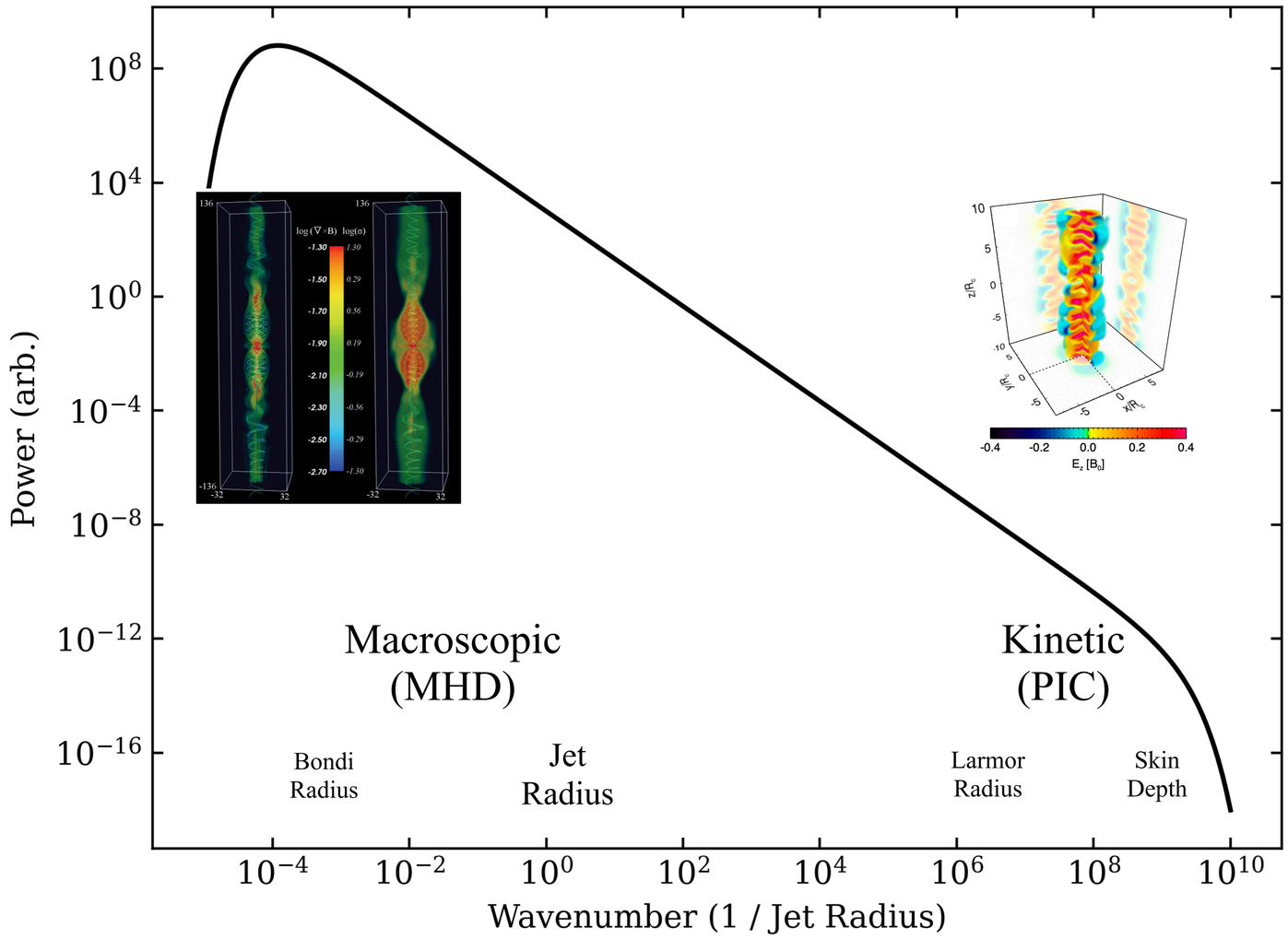
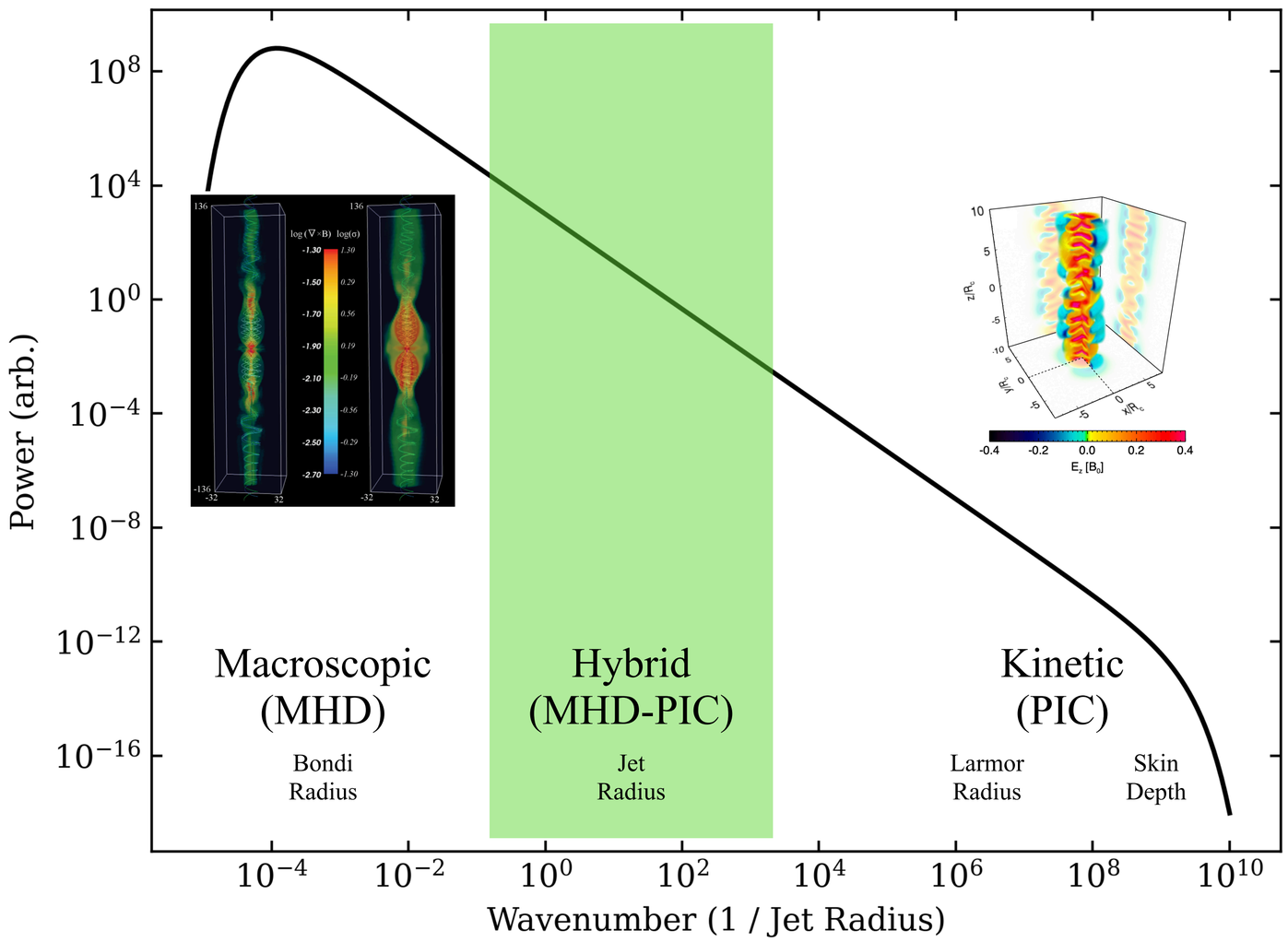
The Challenge of Scale Separation



Apply MHD-PIC Methods to Bridge Scale Separation



MHD + Test Particles

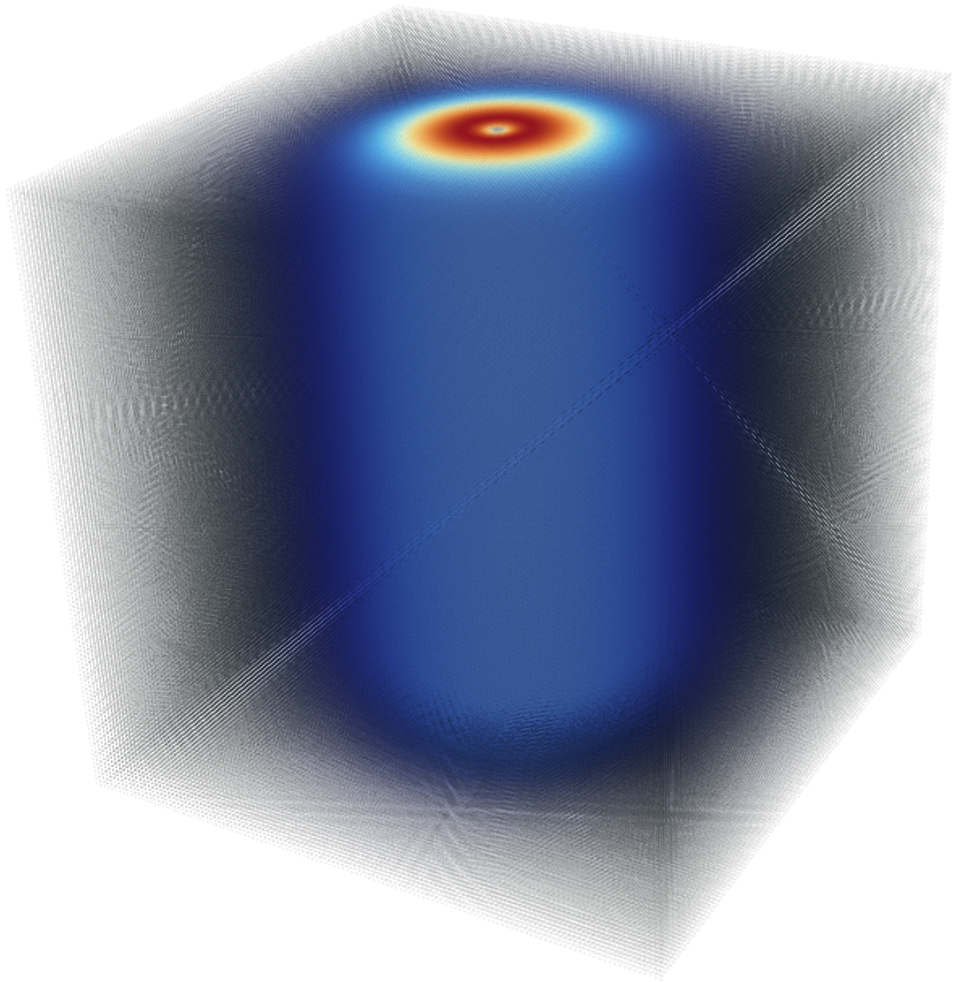
- Use relativistic MHD to capture non-linear development of the kink instability.
- Simulate test particles experiencing dynamically evolving MHD fields.

The PLUTO Code for Astrophysical GasDynamics

plutocode.ph.unito.it

A. Mignone et al 2018 ApJ 859 13

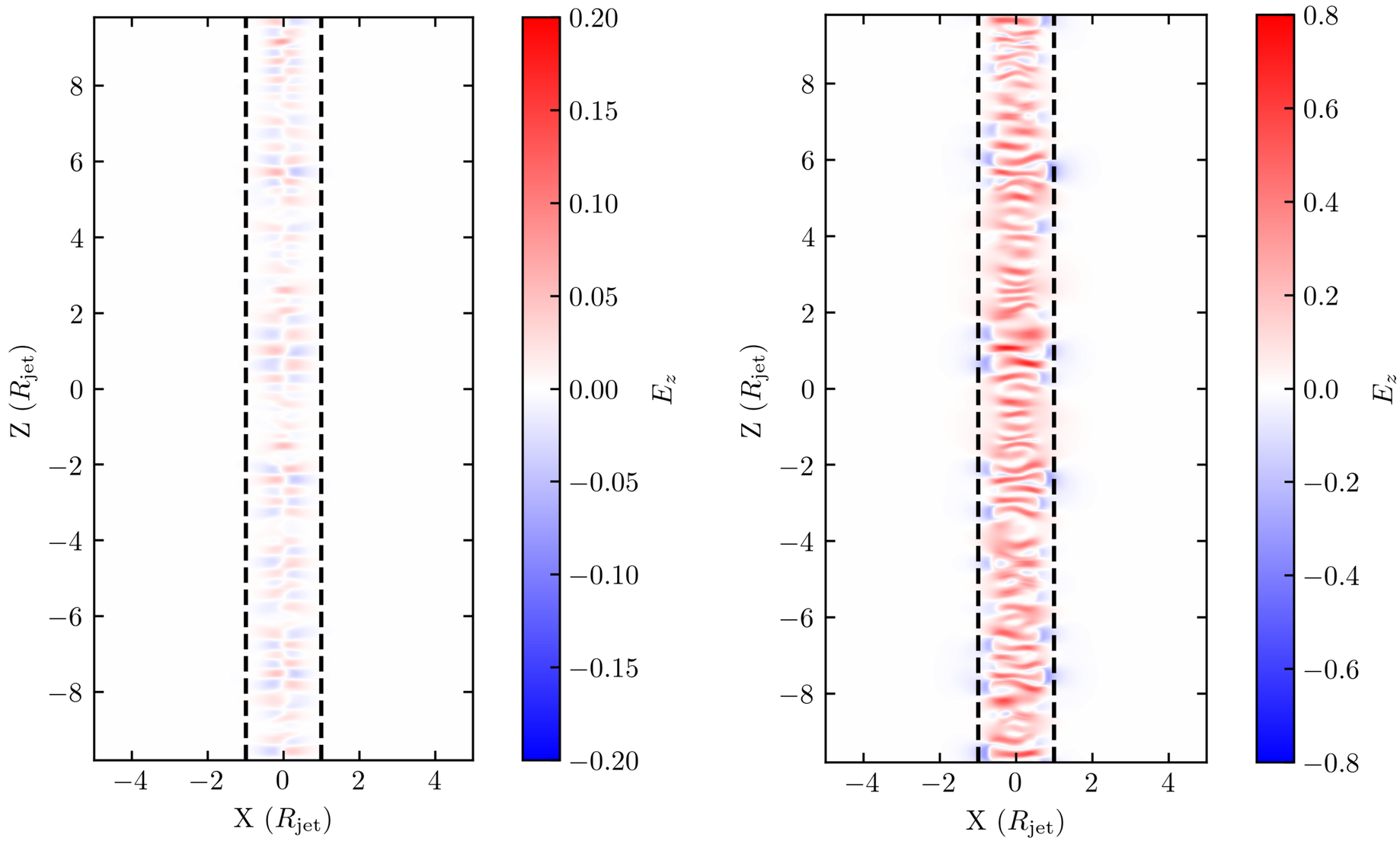
Set-Up of Local Hybrid Simulation



MHD + Test Particles

- Is Field Structure and Dissipation Consistent between MHD and PIC?
- Can particle acceleration and the mechanisms responsible be captured?

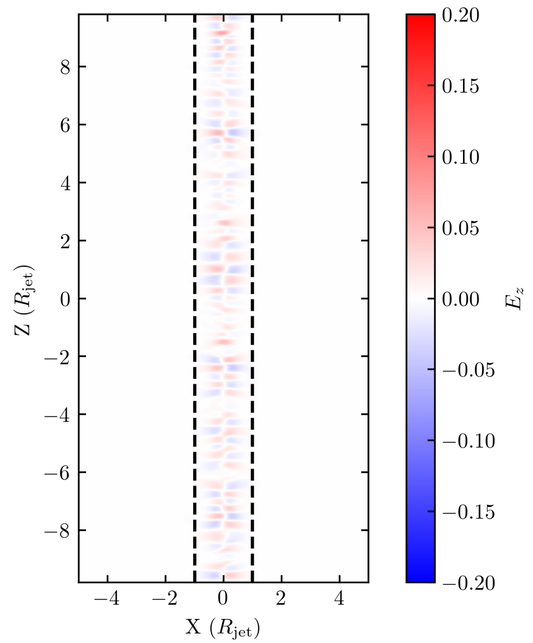
Internal kink instability develops in the jet core



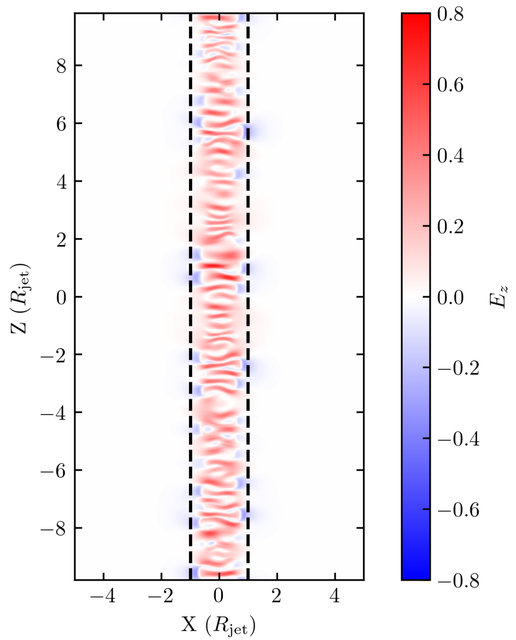
Large scale axial electric field consistent with PIC

MHD

Linear

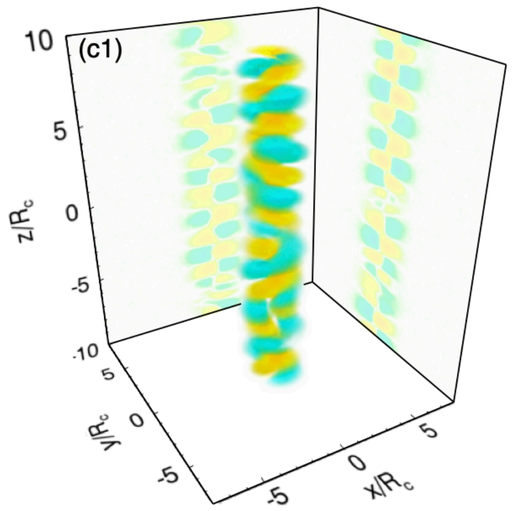


Non-Linear

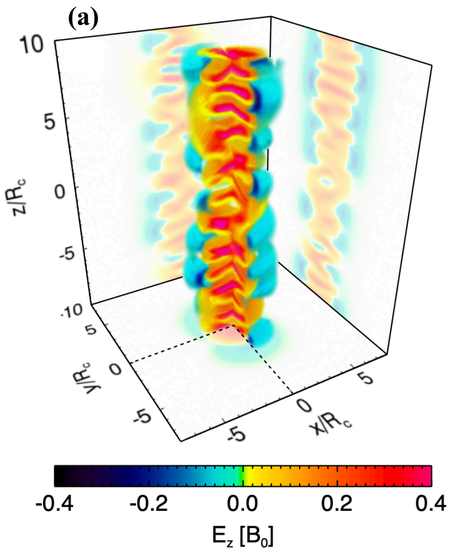


PIC

Linear



Non-Linear



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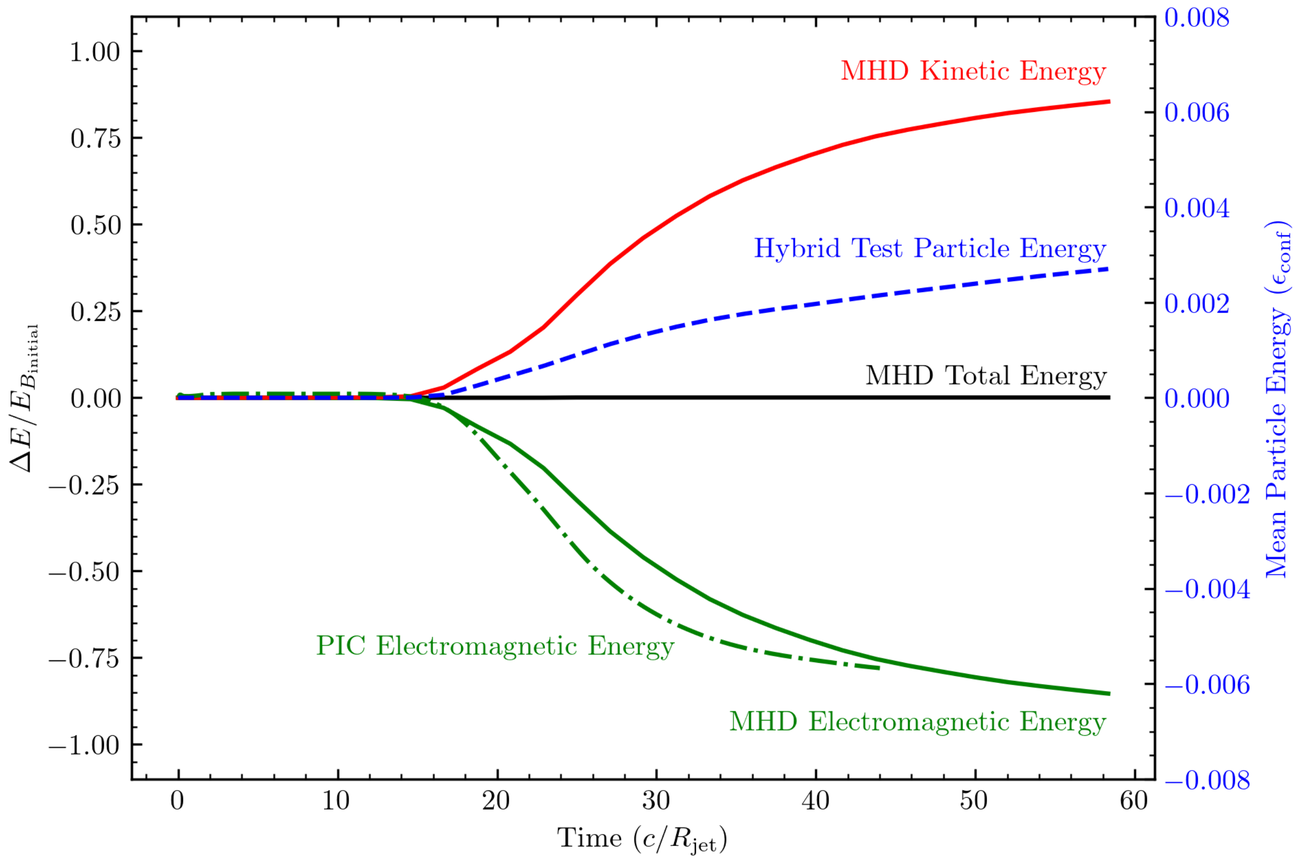
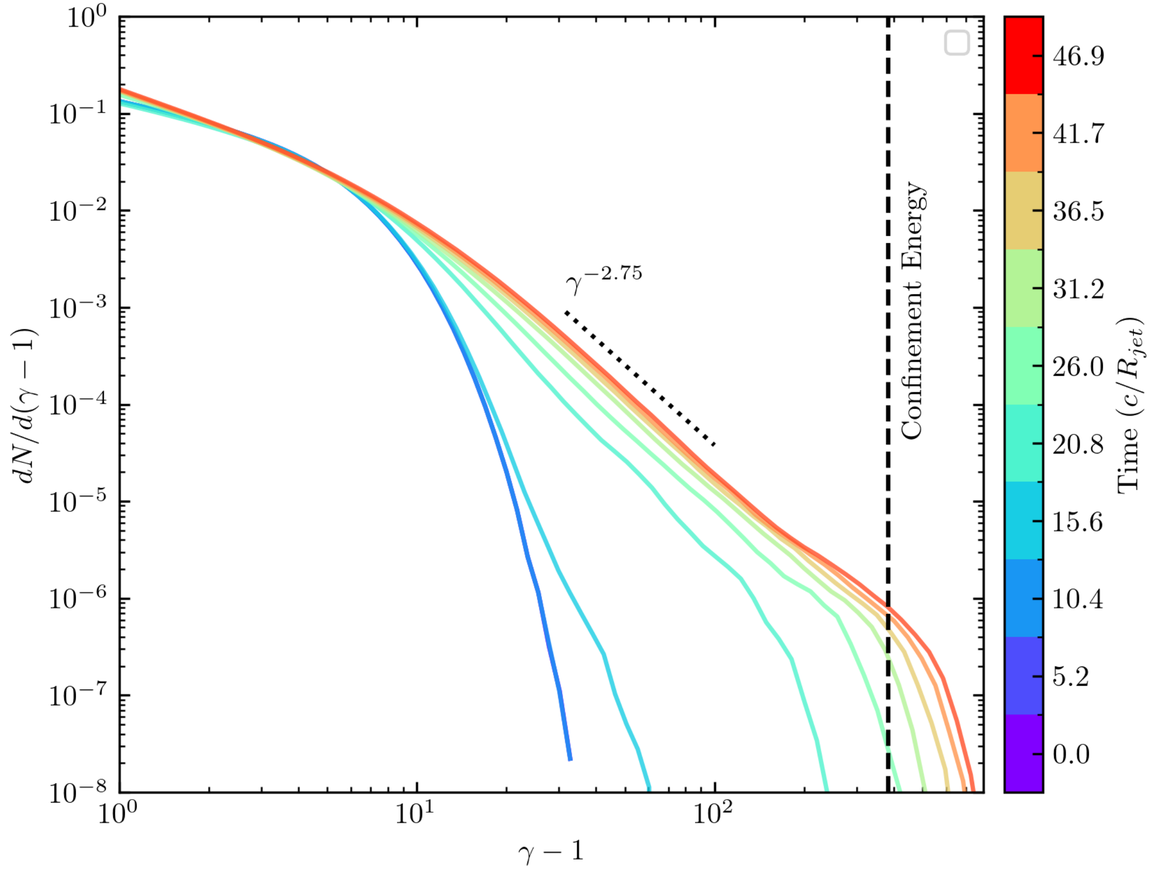
Global energetics is consistent between MHD and PIC

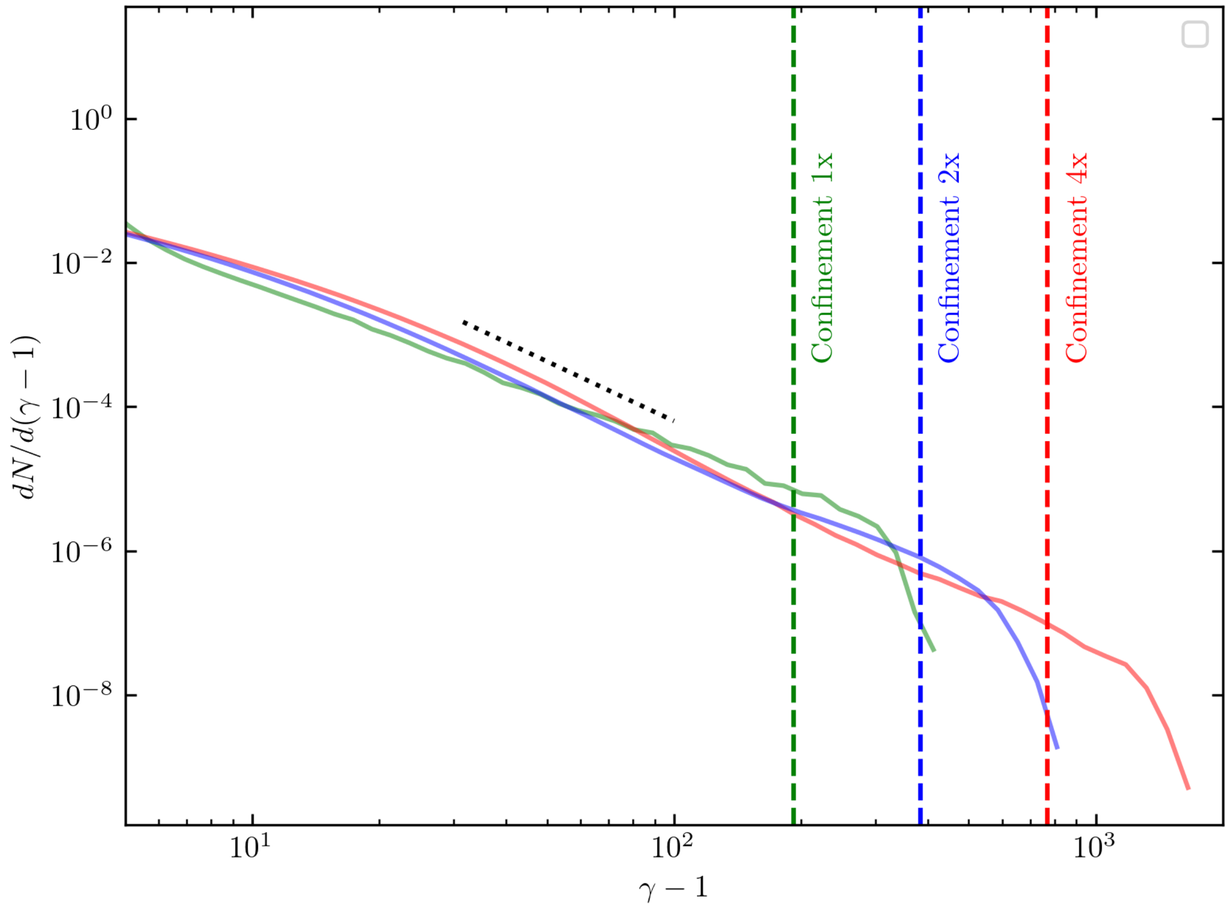


Test particles develop similar spectra as PIC over similar timescales



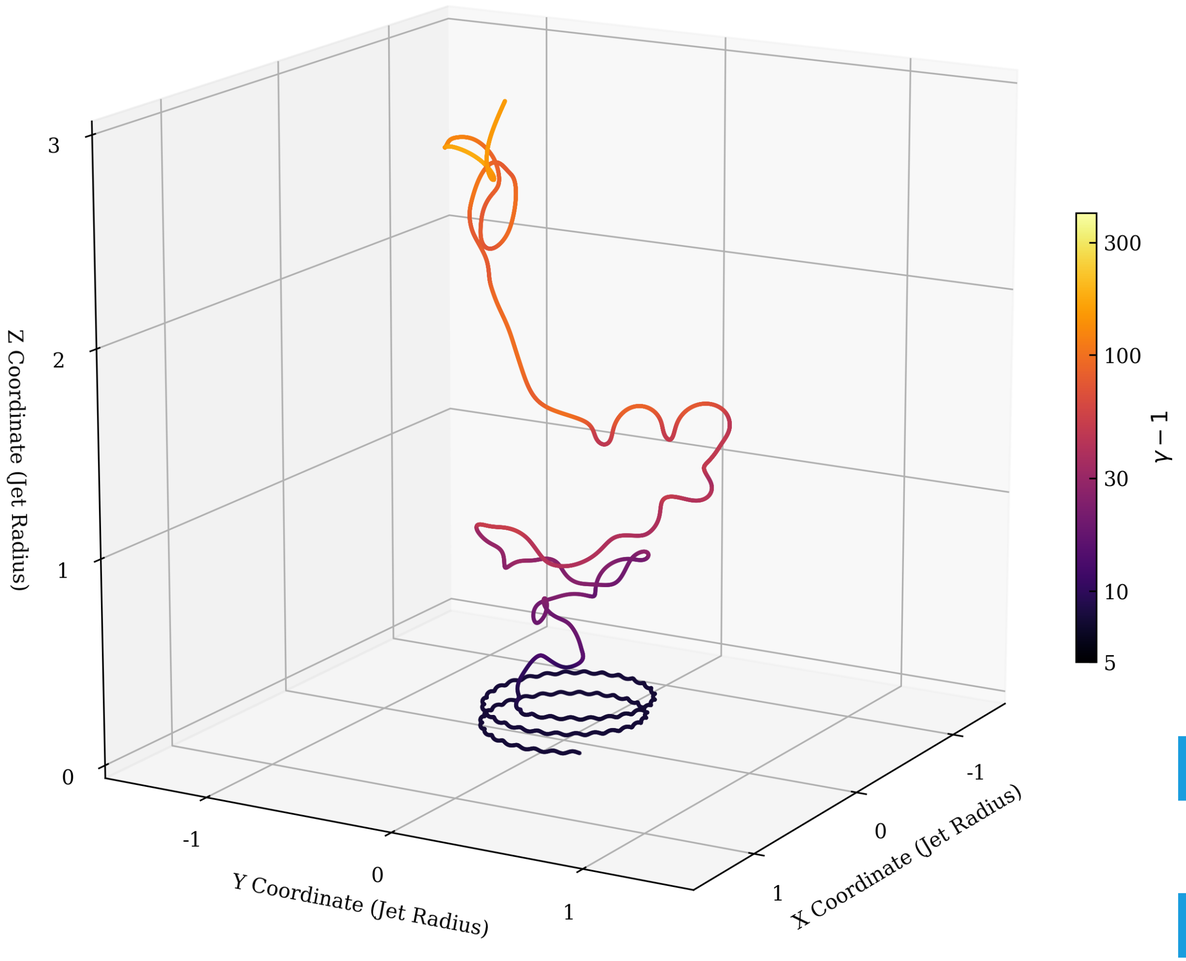
Most particle acceleration occurs during non-linear stage of kink instability.

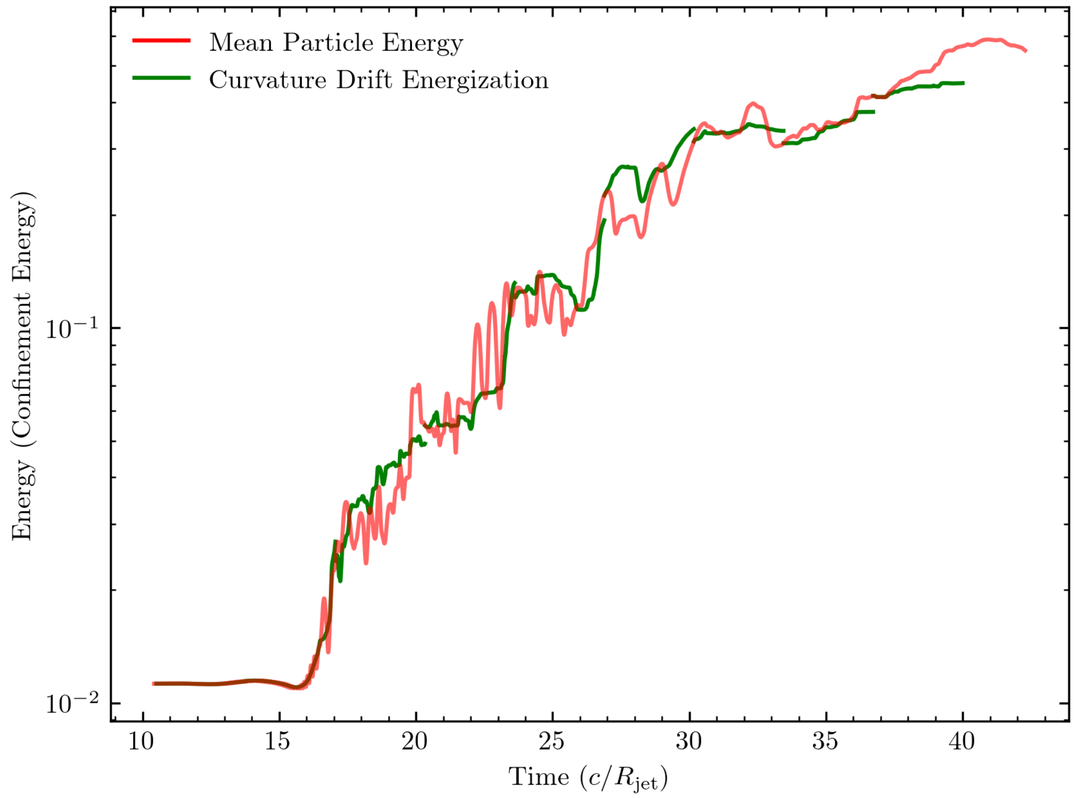
Consistent acceleration to beyond confinement energy



>100x computational gain as compared to PIC.

How do particles accelerate?

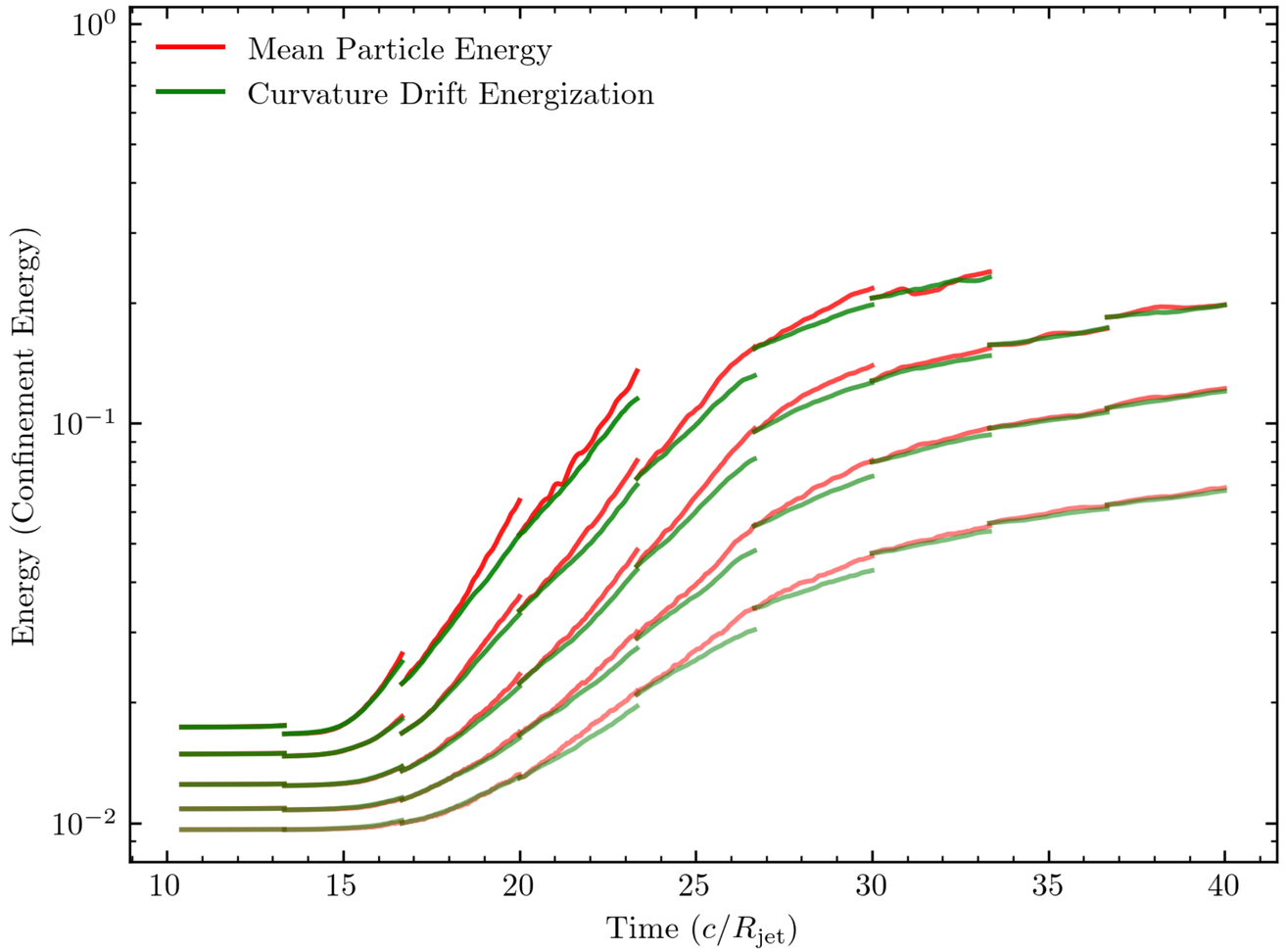




- **Particles cross magnetic field lines due to curvature drift.**
- **Axial electric field concurrently accelerates particles.**

Curvature drift is central to particle acceleration

Ensemble average of ~7000 particles in the non-thermal tail



Curvature drift accounts for particle energization upto ~20% of confinement energy.

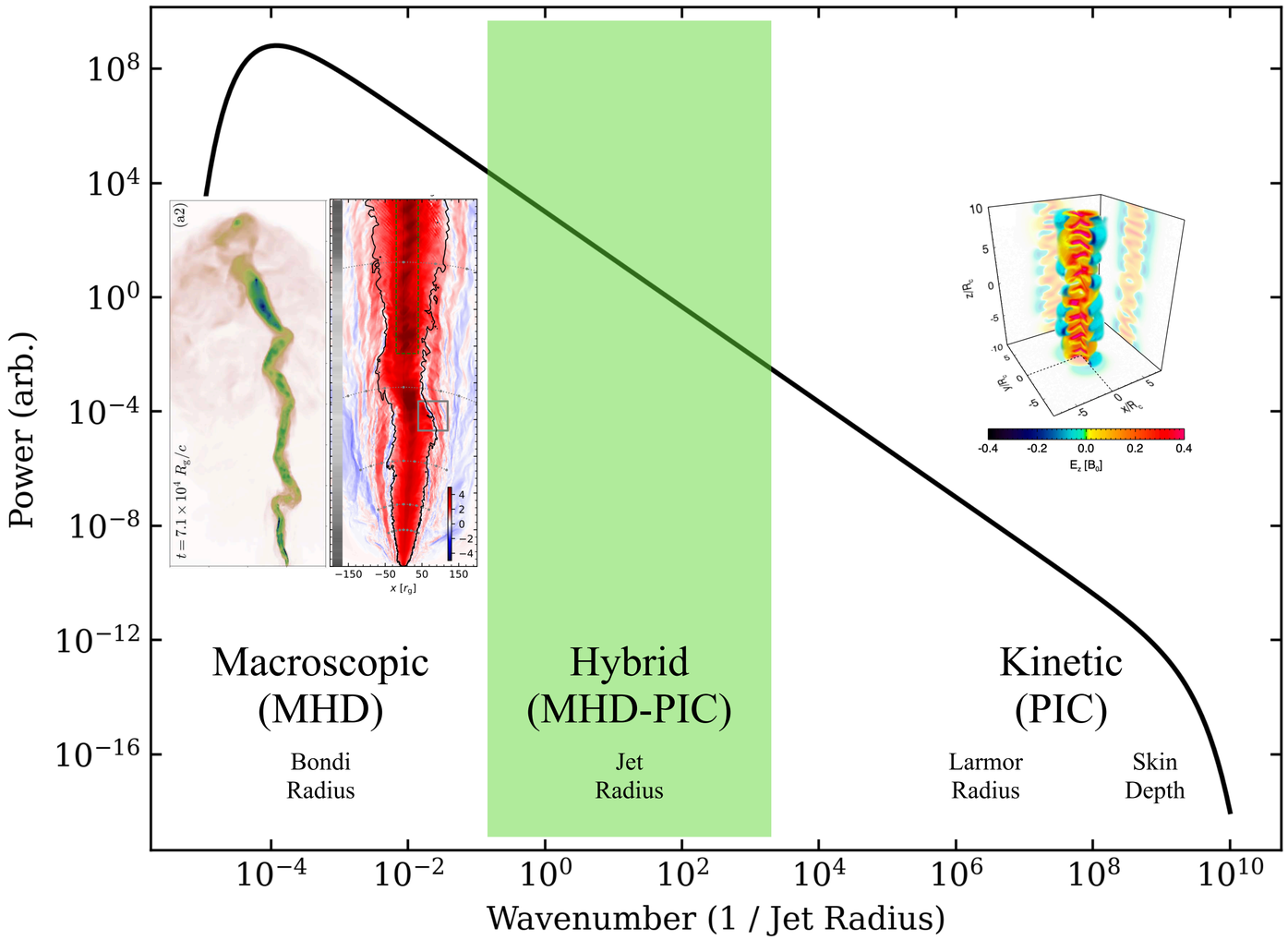
Summary

Kink instability drives efficient particle acceleration in astrophysical jets.

Central role of MHD structures enable hybrid MHD-PIC modeling.

Hybrid models are useful to capture all essential physics and are key to tackle the challenge of scale-separation in jets.

Outlook



Future Steps

- Particle injection and acceleration in force-free jets.
- Effects of particle feedback on MHD fields.
- Connect the local comoving frame studies with global simulations of jets.

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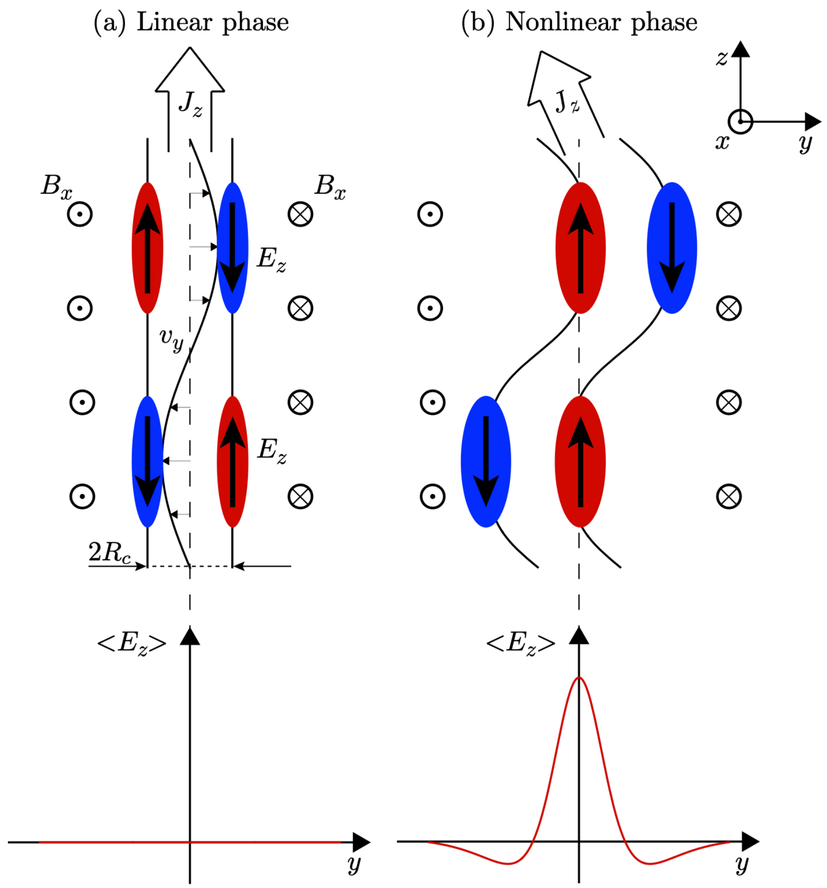
A. Lalakos et al 2024 ApJ 964 79

Axial Alignment of Electric Field



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