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Particle Acceleration by Magnetic Reconnection Driven by Current-Driven Kink Instability Turbulence in Relativistic Jets

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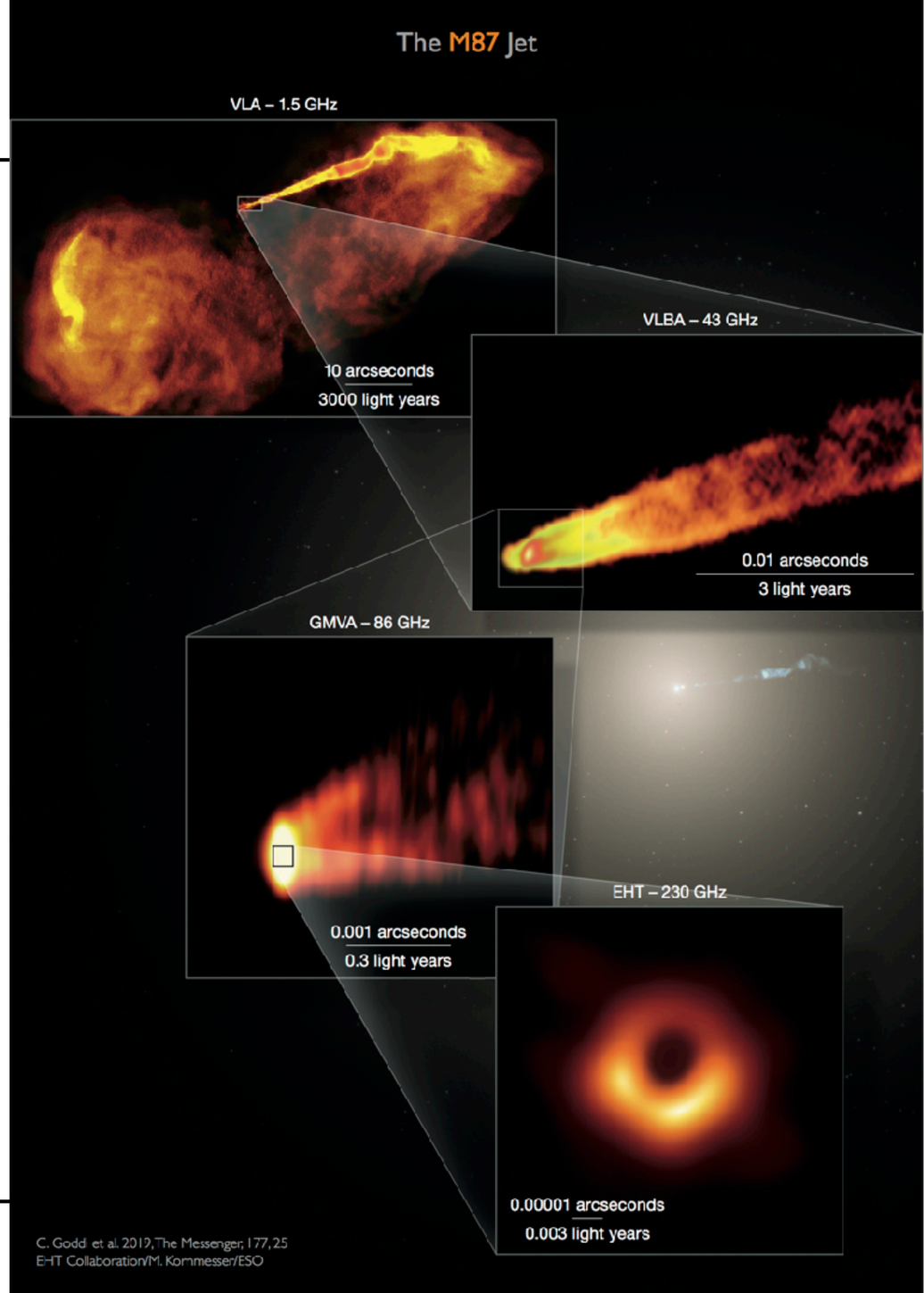
Relativistic Jets

- Outflow of highly collimated plasma
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocity ～c
  - Generic systems: Compact object (Neutron Star, Black Hole） + accretion flows
  - Jets are common in the universe

- Key Issues of Relativistic Jets
  - Acceleration & Collimation
  - Propagation & Stability
  - Origin of high energy particle (particle acceleration)



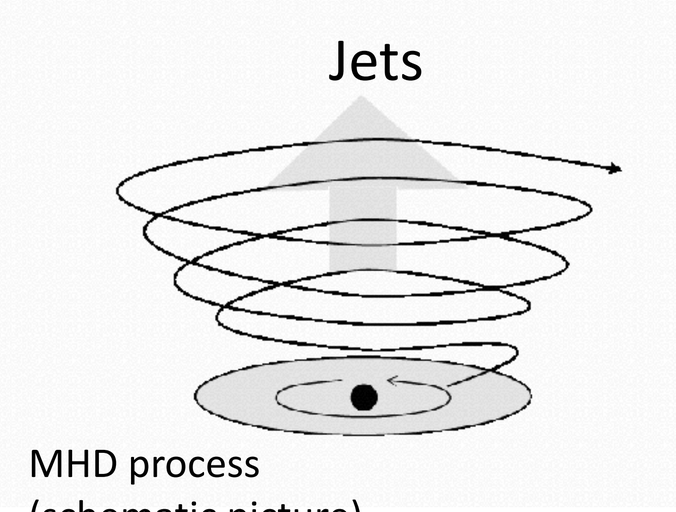
Theory of Jet Formation & Acceleration

- Relativistic jet is formed and accelerated by macroscopic plasma (MHD) process with helically twisted magnetic field

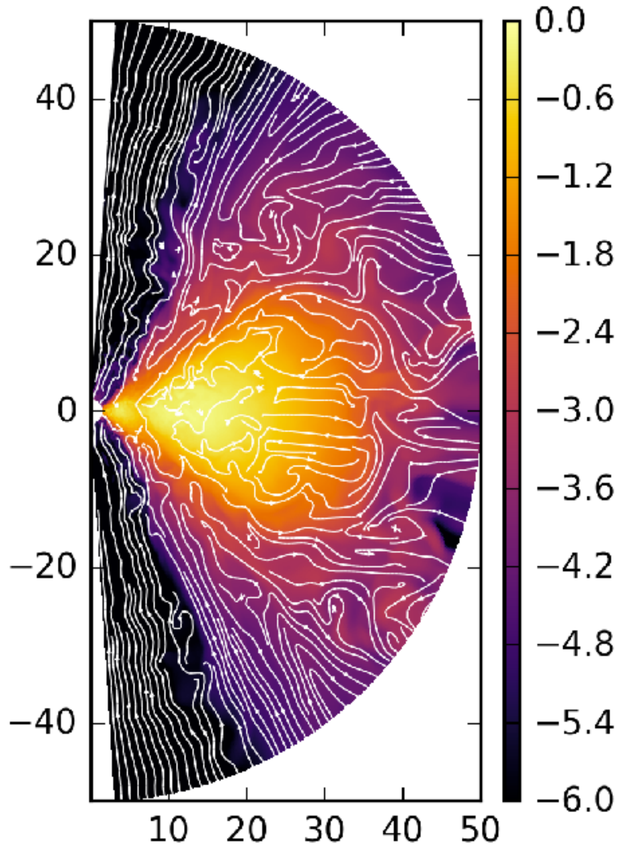
- Collimated jet is formed near the central BH and accelerates $\gamma \gg 1$ with mildly-relativistic sheath wind

- But, it has problems
  - Most of energy remains in Poynting energy (magnetic energy) even at large scale
  - Acceleration need take longer time (slow acceleration efficiency)

⇒ Need Rapid energy conversion (dissipation)

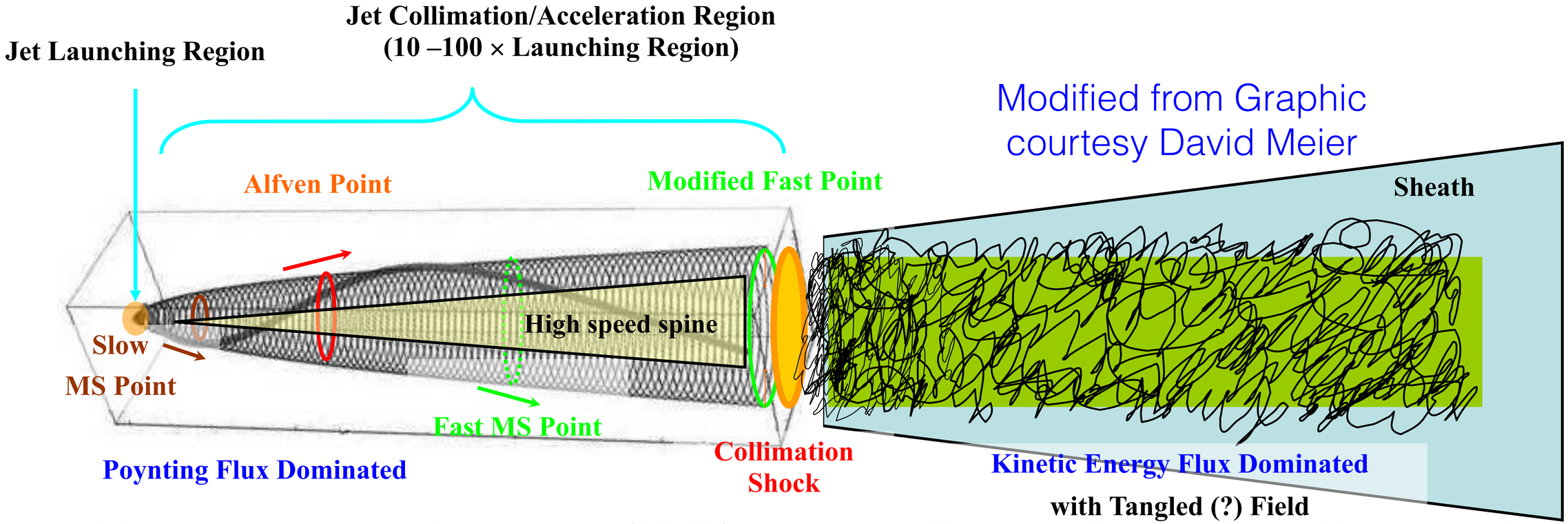


MHD process
(schematic picture)



GRMHD simulations
(Porth, YM et al. 17)

Regions of AGN Jet Propagation



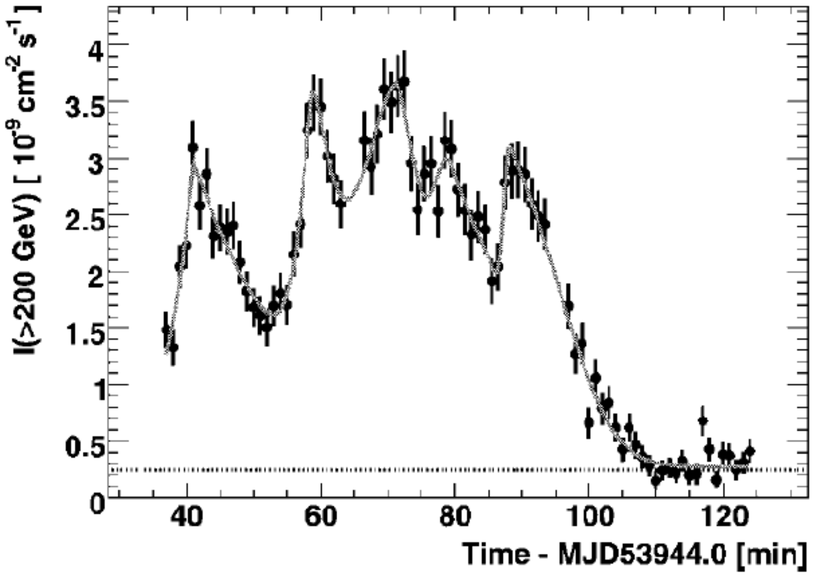
Modified from Graphic courtesy David Meier

- Jet launching by magnetohydrodynamic (MHD) process ⇒ Poynting flux dominated jet with twisted magnetic field
- Need rapid magnetic energy dissipation to make a kinetic energy dominated jet at large scale (observationally supported)
- Energy dissipation may related particle acceleration and high-energy emission with short-time variability

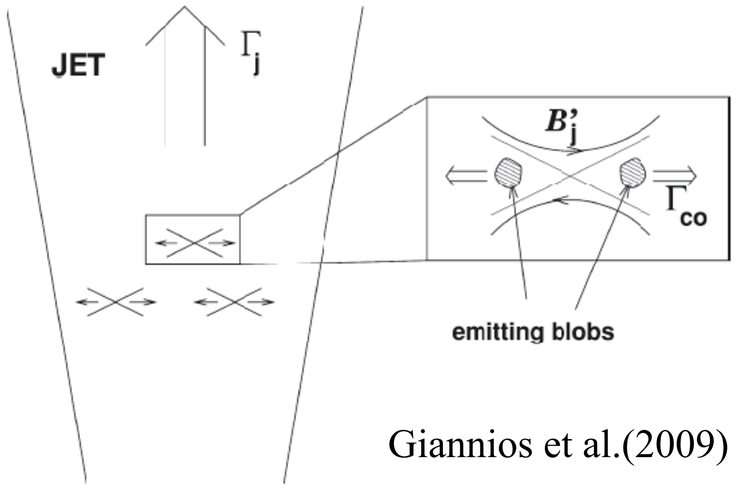
Ultra-Fast TeV Flare in Blazars

- Ultra-Fast TeV flares are observed in some Blazars.
- Variation timescale: t_v~3min << R_s/c ~ $3M_9$ hour
- For the TeV emission to escape pair creation γ_{em}>50 is required (Begelman+ 08)
- But bulk jet speed is not so high (γ~ 5-10)
- Emitter: compact & extremely fast

PKS2155-304 (Aharonian et al. 2007)
See also Mrk501, PKS1222+21



- Proposed Model: Magnetic Reconnection inside jet (Giannios+ 09)
- Questions: *How to make magnetic reconnection in jet?*

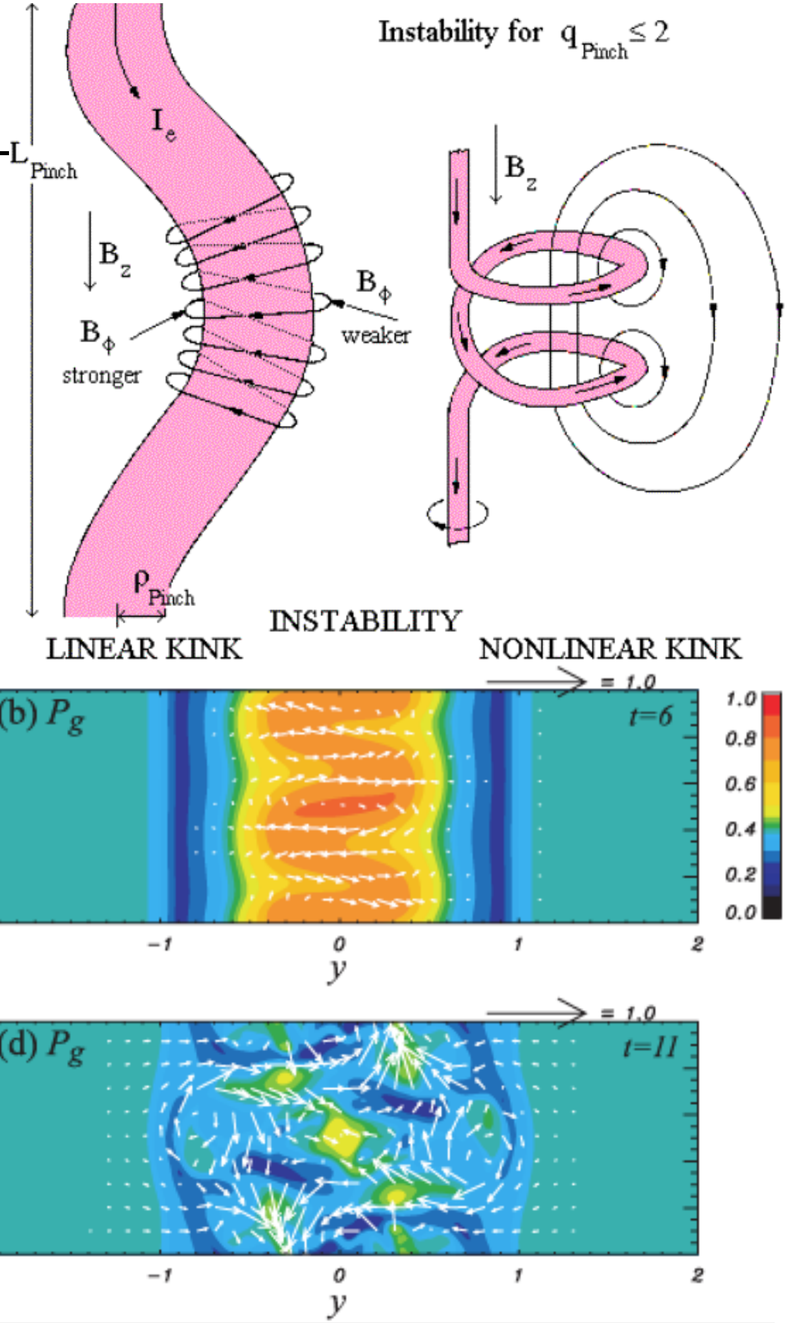


Giannios et al.(2009)

CD Kink Instability

- Well-known instability in laboratory plasma (TOKAMAK), astrophysical plasma (Sun, jet, pulsar etc).
- In configurations with strong toroidal magnetic fields, current-driven (CD) kink mode (m=1) is unstable.
- This instability excites large-scale helical motions that can be strongly distort or even disrupt the system
- Distorted magnetic field structure may trigger of magnetic reconnection.

Schematic picture of CD kink instability

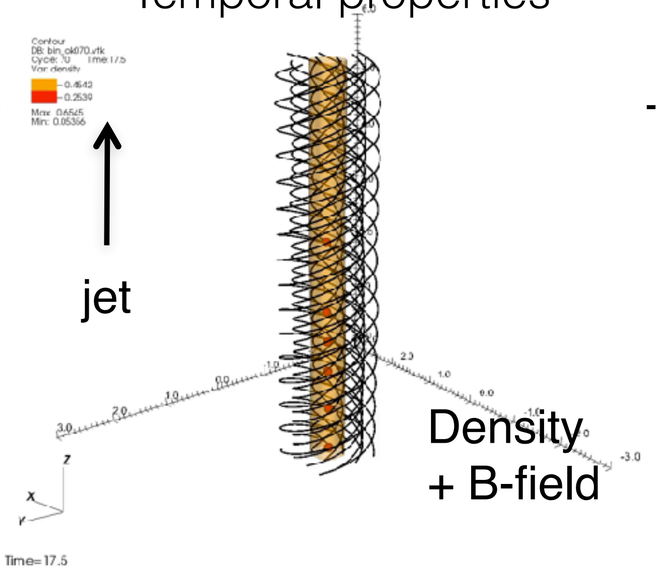


3D RMHD simulation of CD kink instability in PWNe (Mizuno+ 11)

CD Kink Instability in Jets

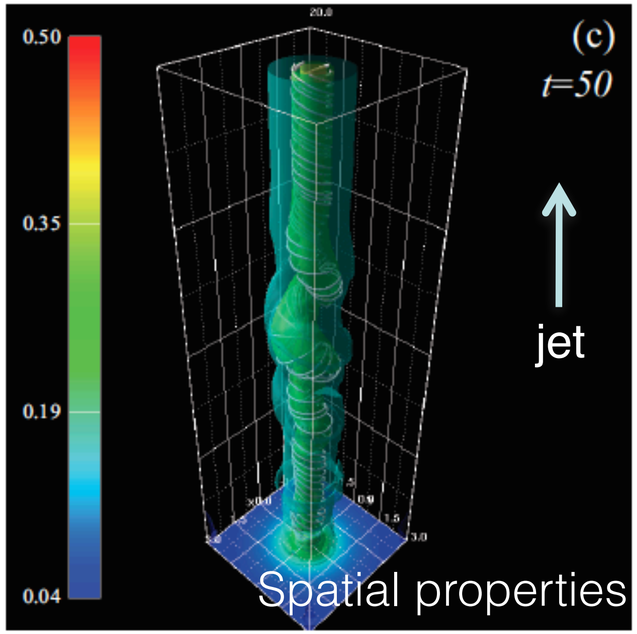
- Helical structure is developed by CD kink instability.
- Magnetic energy in the jets converts thermal & kinetic energies by development of instability (via turbulence)
- Jet structure is strongly deformed but may be not disrupted entirely (depends on magnetic pitch, density, & flow profiles).

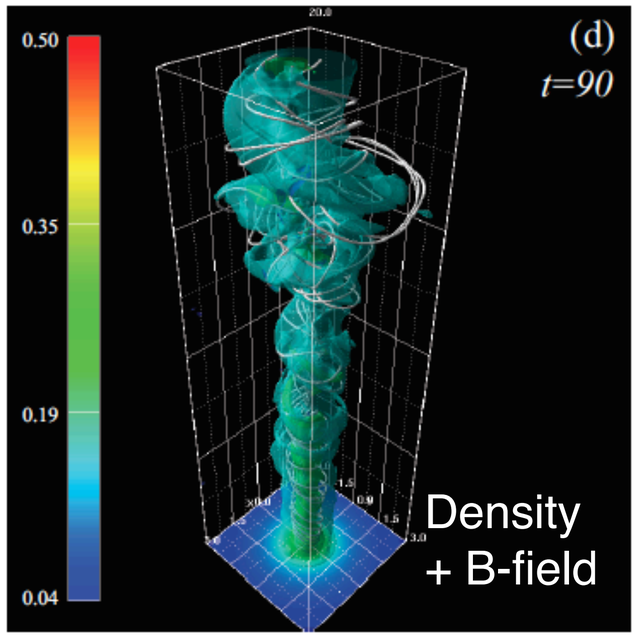
Temporal properties



- Instability is trigger of magnetic dissipation through magnetic reconnection & turbulence

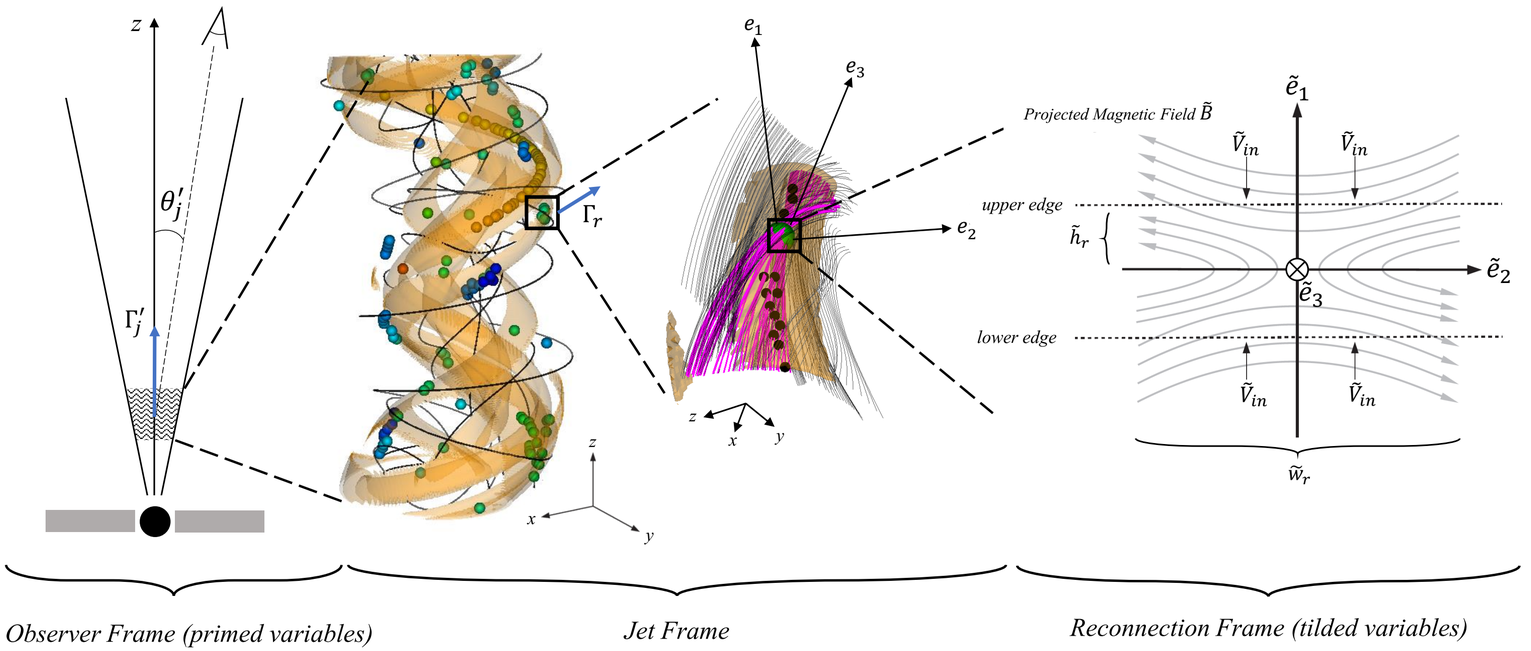
⇒ rapid magnetic dissipation





Mizuno+ (09, 11b, 12, 14b), Singh, YM+ (15), Kadowaki, YM+ (20)

Searching of Magnetic Reconnection Site

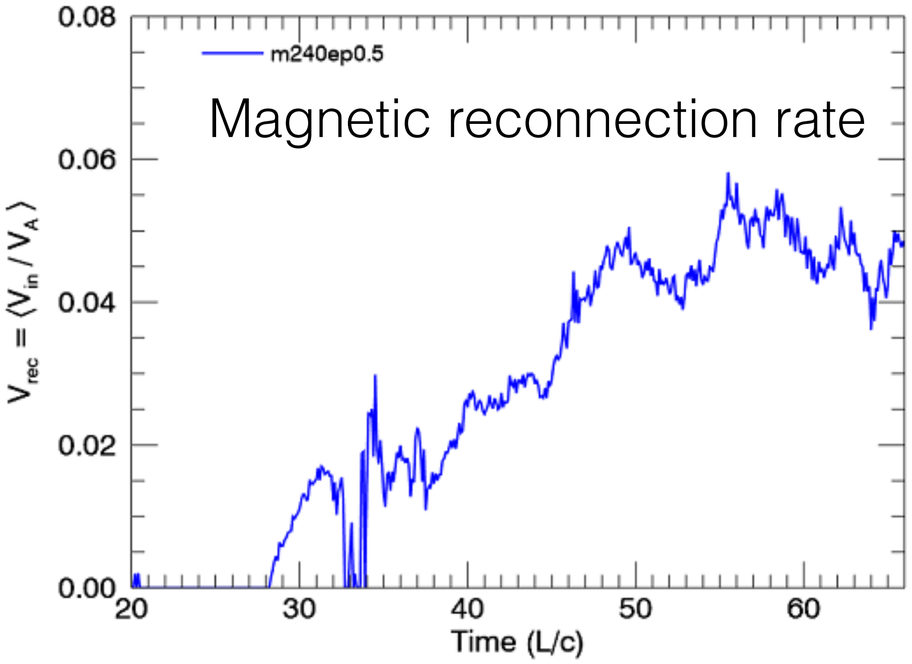


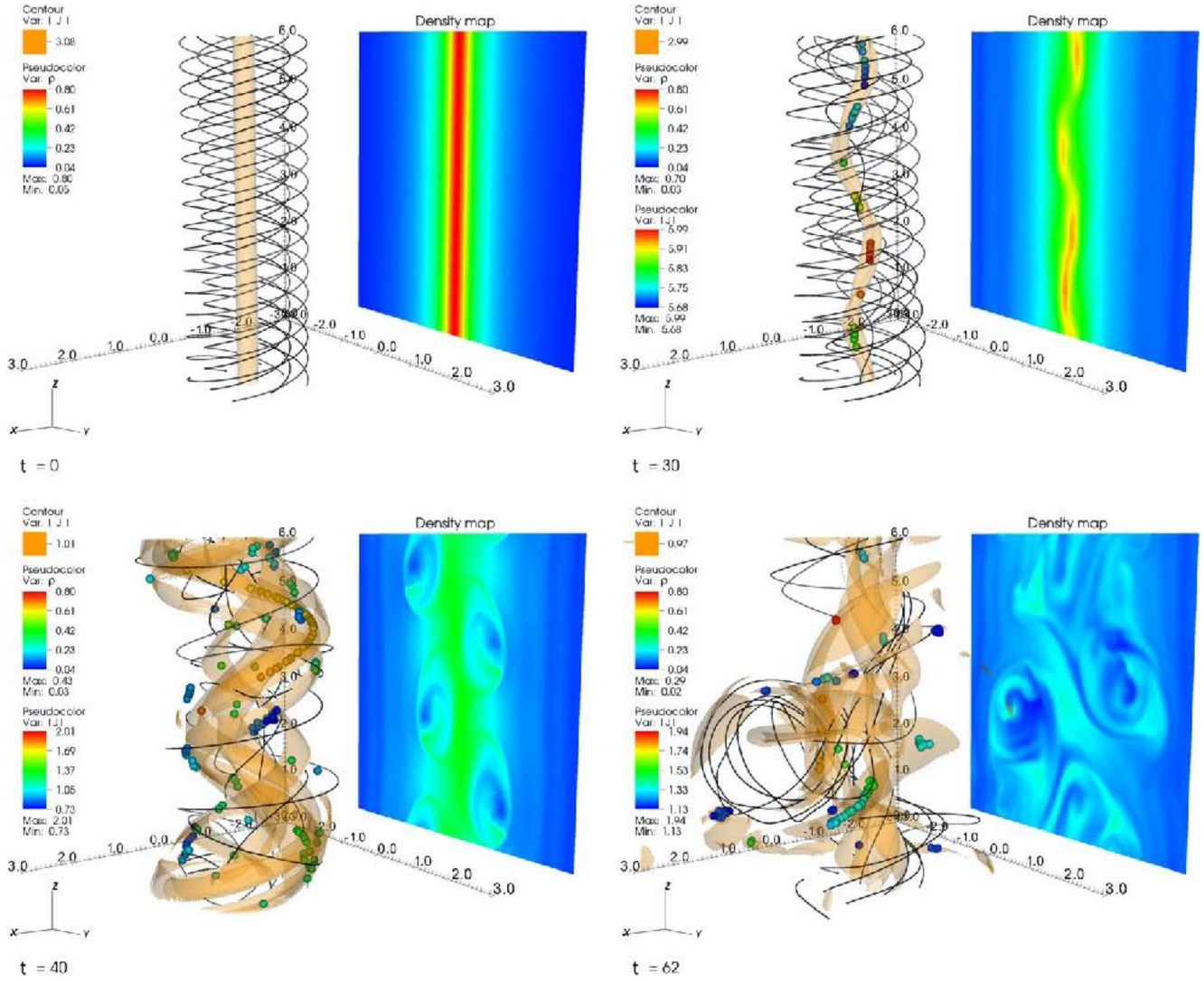
- Using data from 3D RMHD simulations of CD kink instability based on Mizuno+ (12)
  - using periodic boundary along jet direction and follows growth of a few wavelength of CD kink instability
- Using magnetic reconnection search algorithm to find the local reconnection site
- Evaluate magnetic reconnection rate

Kadowaki, YM+ (2021)

Magnetic Reconnection in Jets

- Looking for magnetic reconnection site (opposite field topology) in helically twisted jets by CD kink instability
- Calculate reconnection rate, $\langle v_{rec} \rangle \sim 0.05$
- In agreement with relativistic turbulent reconnection simulation (Takamoto+ 15)

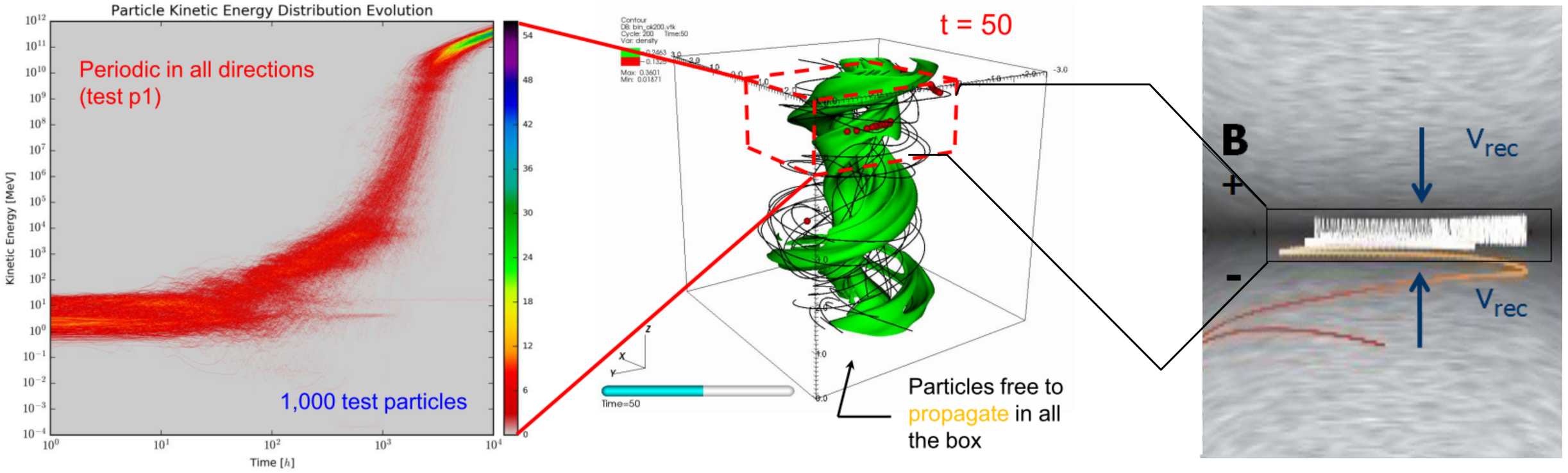




Kadowaki, YM+ (2021)

Particle Acceleration in Jets

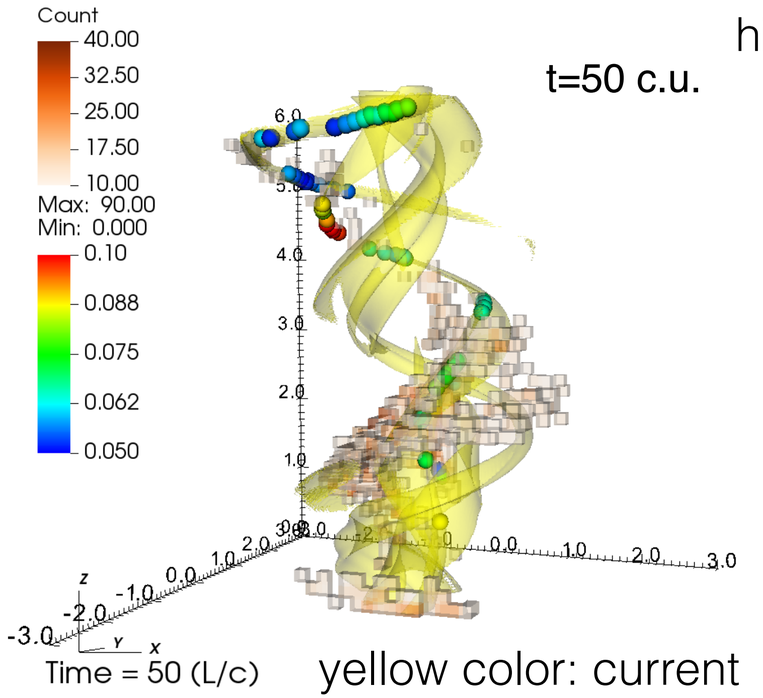
- Local magnetic reconnection in jets will heat the plasma and accelerates particles to relativistic velocities by1st-order Fermi acceleration process.
- Performed test-particle simulations of Fermi acceleration in turbulent fields developed by CD kink instability in relativistic jets



Medina-Torrejon, YM+ (2020)

Particle Acceleration

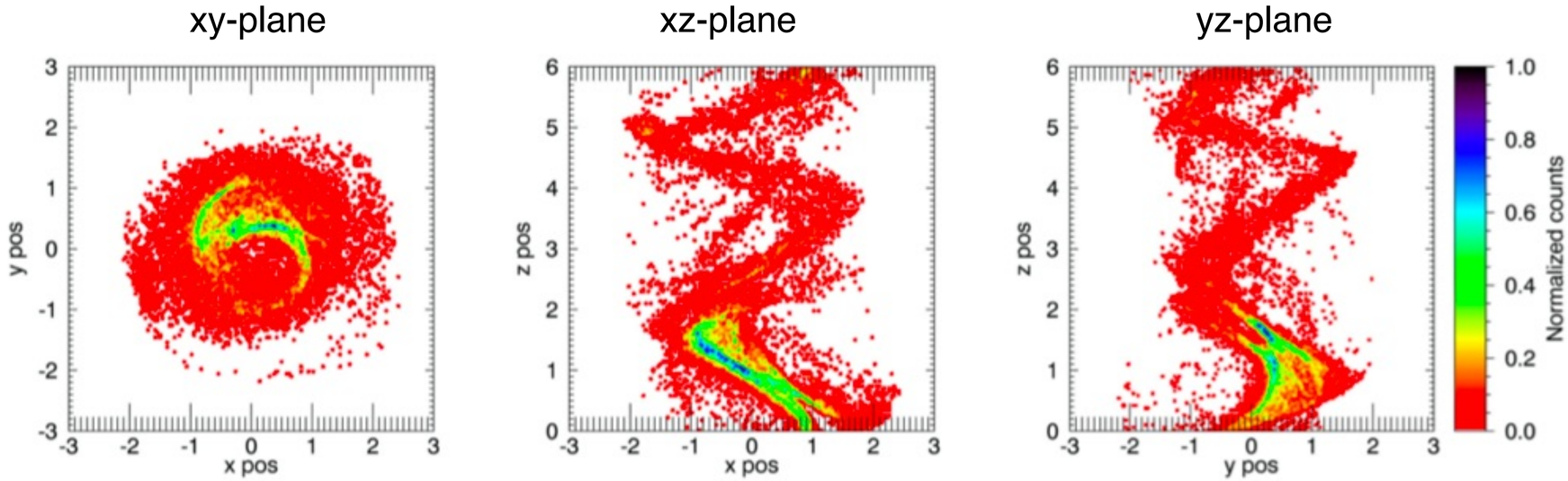
- Injected 10,000 particles (initially Maxwellian with 10^{10} K and mean $E_{kin} \sim 1\mathrm{MeV}$ ($\sim 10^{-3}$ $m_p c^2$)) for background $B \sim 0.1\mathrm{G}$
- Particles are mainly accelerated along wiggling jet spine which has large distortion by CD kink instability and development of turbulence.
- Particle accelerated larger than 100 MeV ($\sim 0.1 m_p c^2$)



t=50 c.u.

yellow color: current

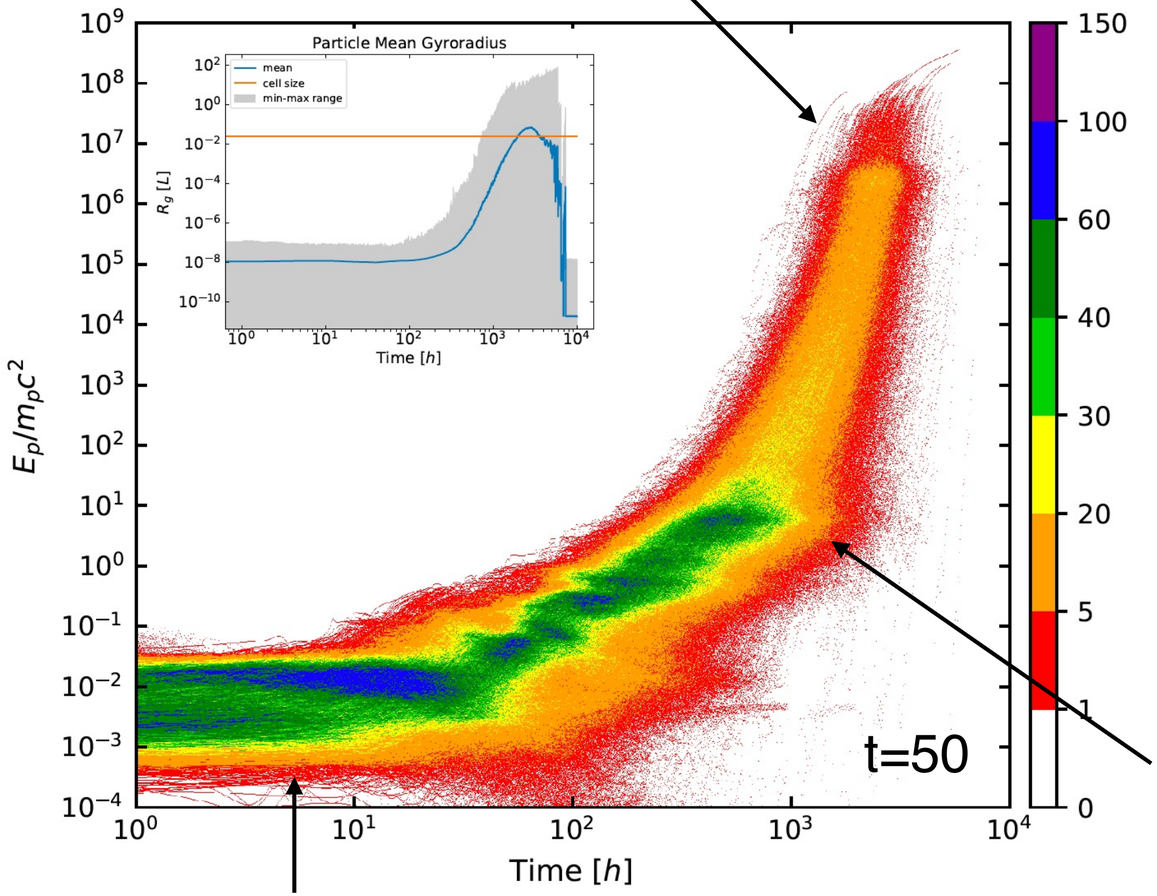
histogram of particles larger than 100 MeV



Particle Acceleration

max energy growth (saturation)
~ Larmor radius (E/qB)= jet diameter

number of particles

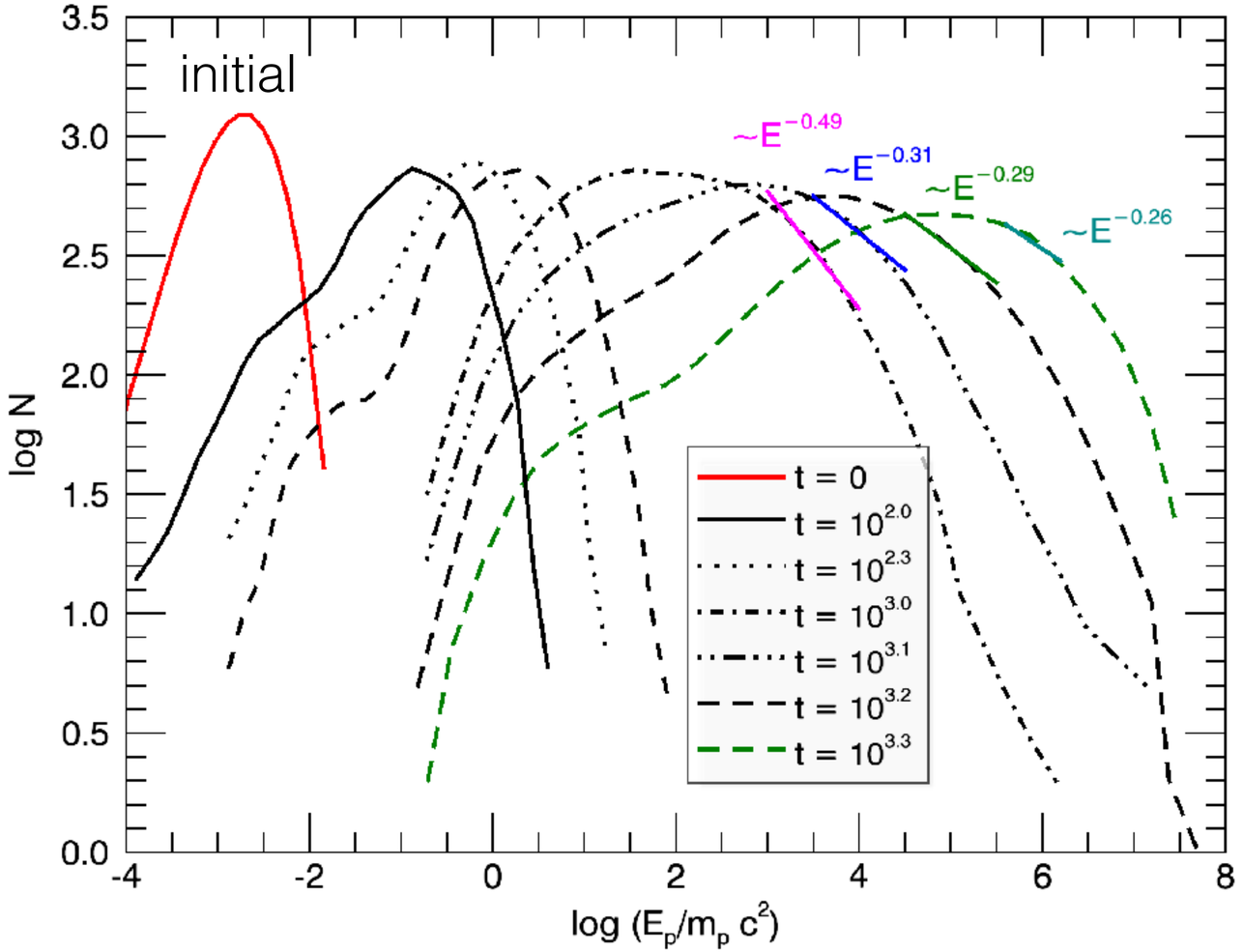


exponential growth due to stochastic Fermi-like acceleration in current sheet

initial slow drift

Particle Spectrum

- Particles have Maxwellian distribution initially (red)
- As particles accelerate, populate higher energy tail, spectrum becomes flatter.
- In late acceleration time, distribution has very flat power-law profile. Due to no escape from acceleration zone (particles are re-enter) & radiative loss (nature should have p>1)



Summary

- Evaluate how magnetic reconnection structure evolve in 3D RMHD simulations of CD kink instability in magnetically dominated relativistic jets by using search algorithm to identify magnetic reconnection site
- Average reconnection rate is ~ 0.05 which is comparable to the prediction from the theory of turbulent-induced magnetic reconnection
- Investigate particle acceleration injected in 3D RMHD simulations of kink instability turbulence in magnetically dominated relativistic jets
- Injected low energy protons are accelerated exponentially by stochastic Fermi-like acceleration mechanism, up to ~ 10^{10} MeV for background B ~ 0.1G which create a power-law distribution
- Clear association of acceleration particles with fast magnetic reconnection
- This mechanism would explain very high energy particles (protons) and associated neutrino emission observed some blazars