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Role of Magnetic Field for Instabilities in Relativistic Jets

ERC Synergy project
Black Hole Cam

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- CD kink instability in relativistic jets (strongly magnetized regime)
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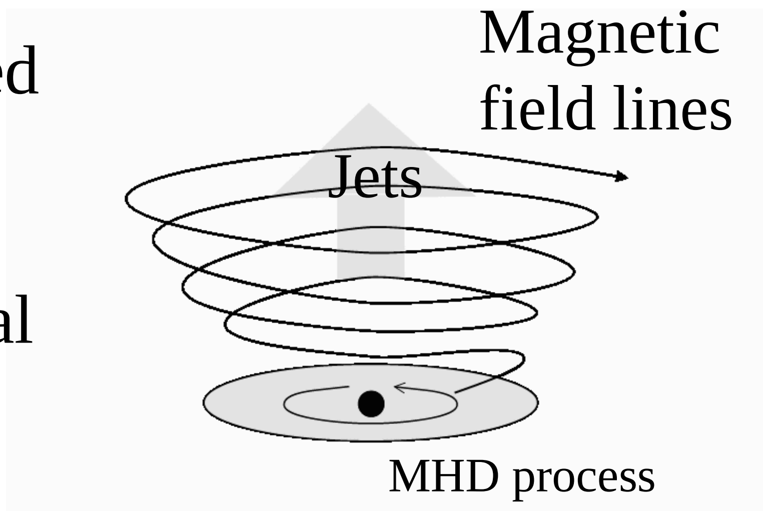
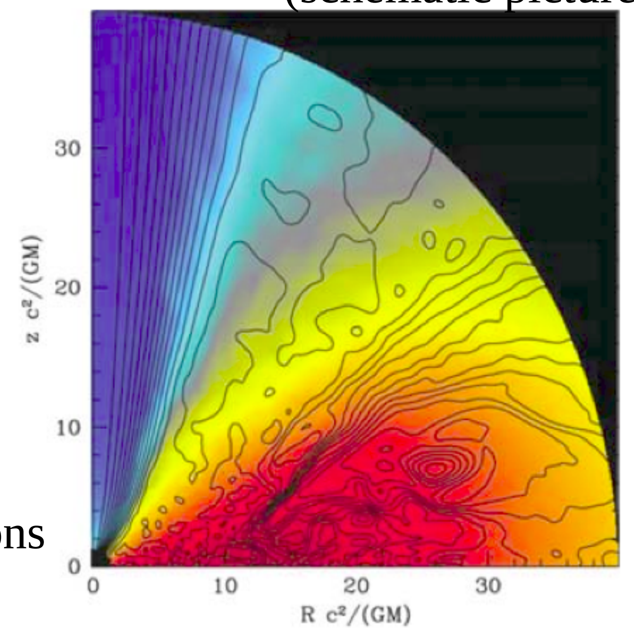
Simulation and Theory of Jet Formation & Acceleration

- 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 $\gamma >> 1$
- *But*, it has problems
  - Most of energy remains in Poynting energy (magnetic energy)
  - Acceleration need take longer time (slow acceleration efficiency)

=> Rapid energy conversion (dissipation) should be considered



MHD process (schematic picture)



GRMHD simulations (McKinney 06)

Dissipation in the Relativistic Jet

Shocks

- Time-dependent energy injection (internal shock)
- Change of external medium spatial structure (recollimation shock)

Magnetic Reconnections

- Magnetic field reversal or deformation of ordered magnetic field

MHD Instabilities

- Several instabilities are potentially growth

=> Turbulence in the jets and/or magnetic reconnection?

Turbulences

- Leads from MHD instabilities in jets

Key Questions of Jet Stability

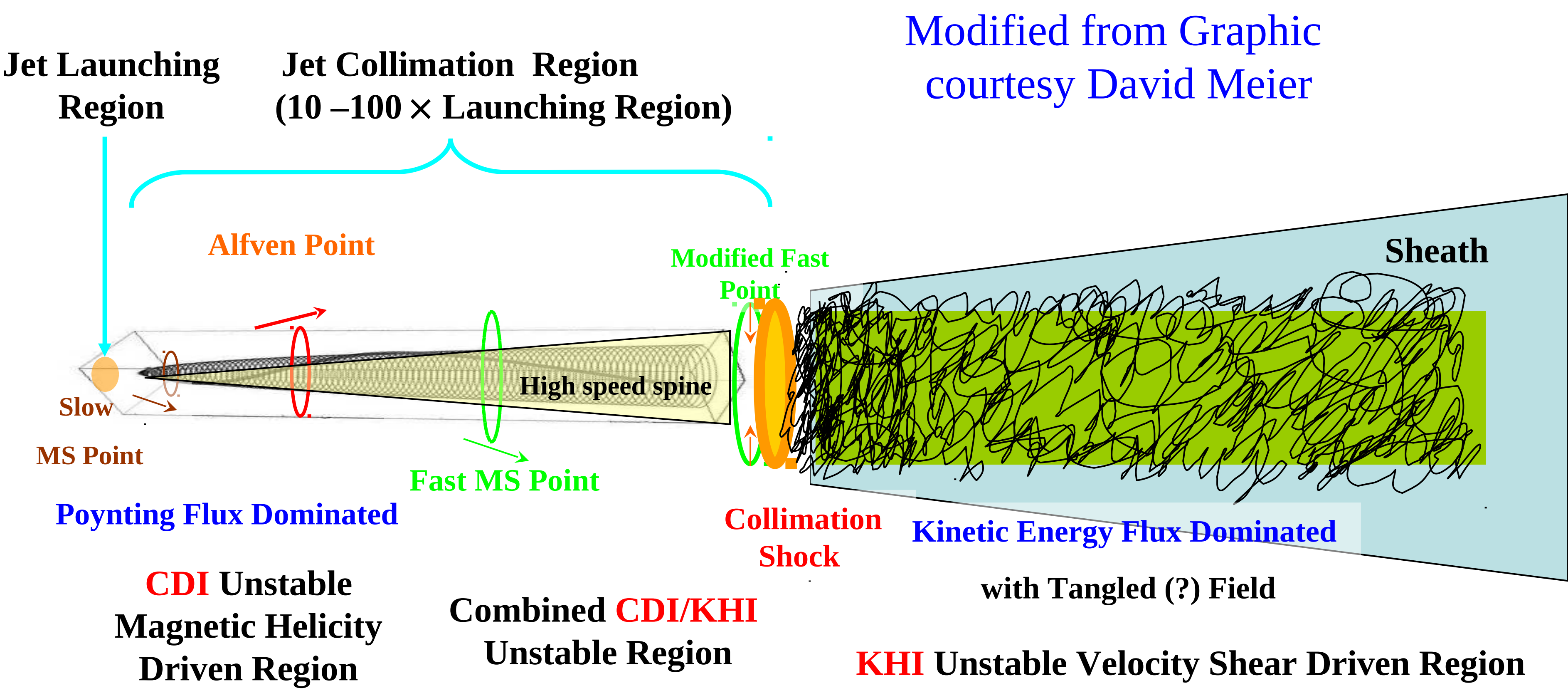
- When jets propagate outward, there are possibility to grow of two major instabilities
  - Kelvin-Helmholtz (KH) instability
    - Important at the shearing boundary flowing jet and external medium
    - In kinetic-flux dominated jet (>10^3 r_s)
  - Current-Driven (CD) instability
    - Important in existence of twisted magnetic field
    - Twisted magnetic field is expected jet formation simulation & MHD theory
    - Kink mode (*m=1*) is most dangerous in such system
    - In Poynting-flux dominated jet (<10^3 r_s)

Questions:

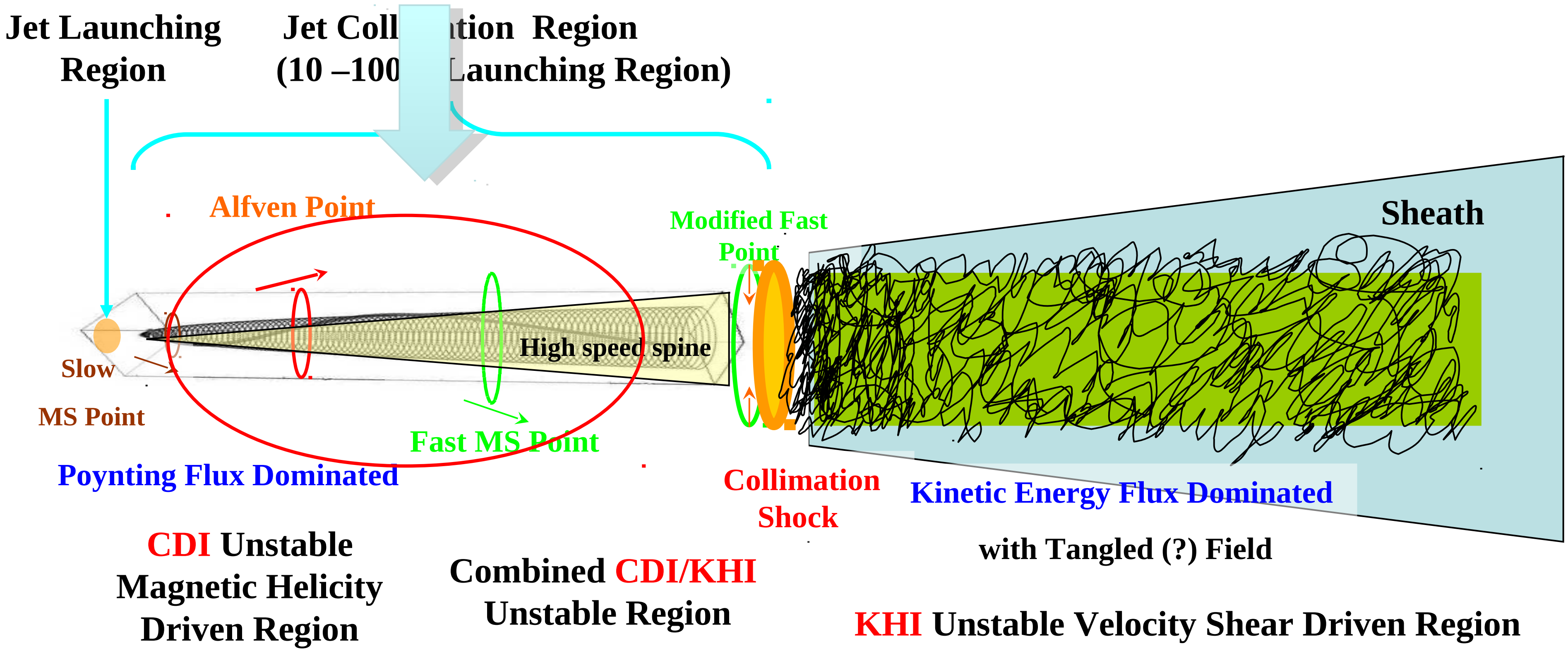
- How do jets remain sufficiently stable?
- What are the Effects & Structure of instabilities in particular jet configuration?

We try to answer the questions through 3D RMHD simulations

Regions of AGN Jet Propagation

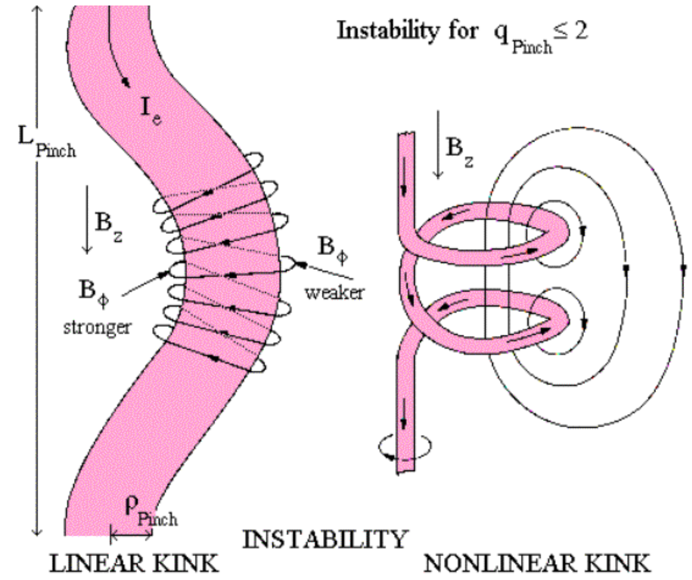


Current-Driven Kink Instability (strongly magnetized regime)

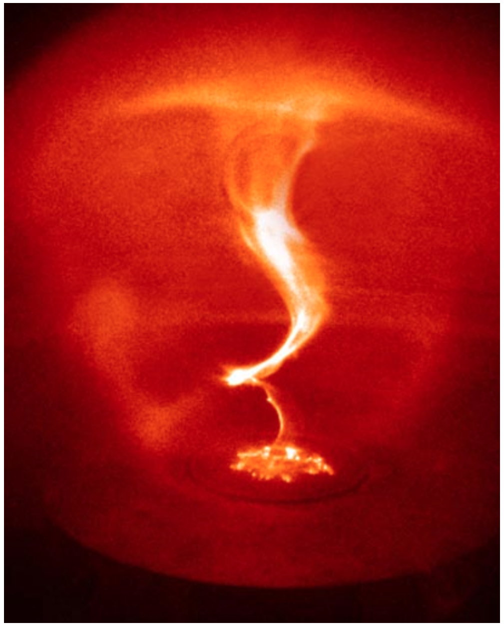


CD Kink Instability

- 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



Kink instability in experimental plasma lab (Moser & Bellan 2012)

Previous Work for CD Kink Instability

- For relativistic force-free configuration
  - Linear mode analysis provides conditions for the instability but say little about the impact instability has on the system (Istomin & Pariev (1994, 1996), Begelman(1998), Lyubarskii(1999), Tomimatsu et al.(2001), Narayan et al. (2009))
  - Instability of potentially disruptive kink mode must be followed into the non-linear regime

- We investigate detail of non-linear behavior of relativistic CD kink instability in relativistic jets
  - Static plasma column (rigidly moving jet), (Mizuno et al. 09)
  - Rotating relativistic jets

CD Kink Instability in Rotating Relativistic Jets

- **Here**: we investigate the influence of jet rotation and bulk motion on the stability and nonlinear behavior of CD kink instability.

- We consider differentially rotating relativistic jets motivated from analytical work of Poynting-flux dominated jets (Lyubarsky 2009).

- The jet structure relaxes to a locally equilibrium configuration if the jet is narrow enough (the Alfven crossing time is less than the proper propagation time). So cylindrical equilibrium configuration is acceptable.

Initial Condition

Mizuno et al. (2012)

- Consider: Differential rotation relativistic jet with force-free helical magnetic field
- Solving RMHD equations in 3D Cartesian coordinates
- Magnetic pitch ($P=RB_z/B_\phi$): constant (in no-rotation case)
  - a=1/4: characteristic radius of helical B-field (maximum of toroidal field)
- Angular velocity (Ω_0=0,1,2,4,6)
- Density profile: decrease ($\rho=\rho_0 B^2$)
- Boundary: periodic in axial (z) direction
- Small velocity perturbation with *m=1* and *n=0.5 ~ 4* modes

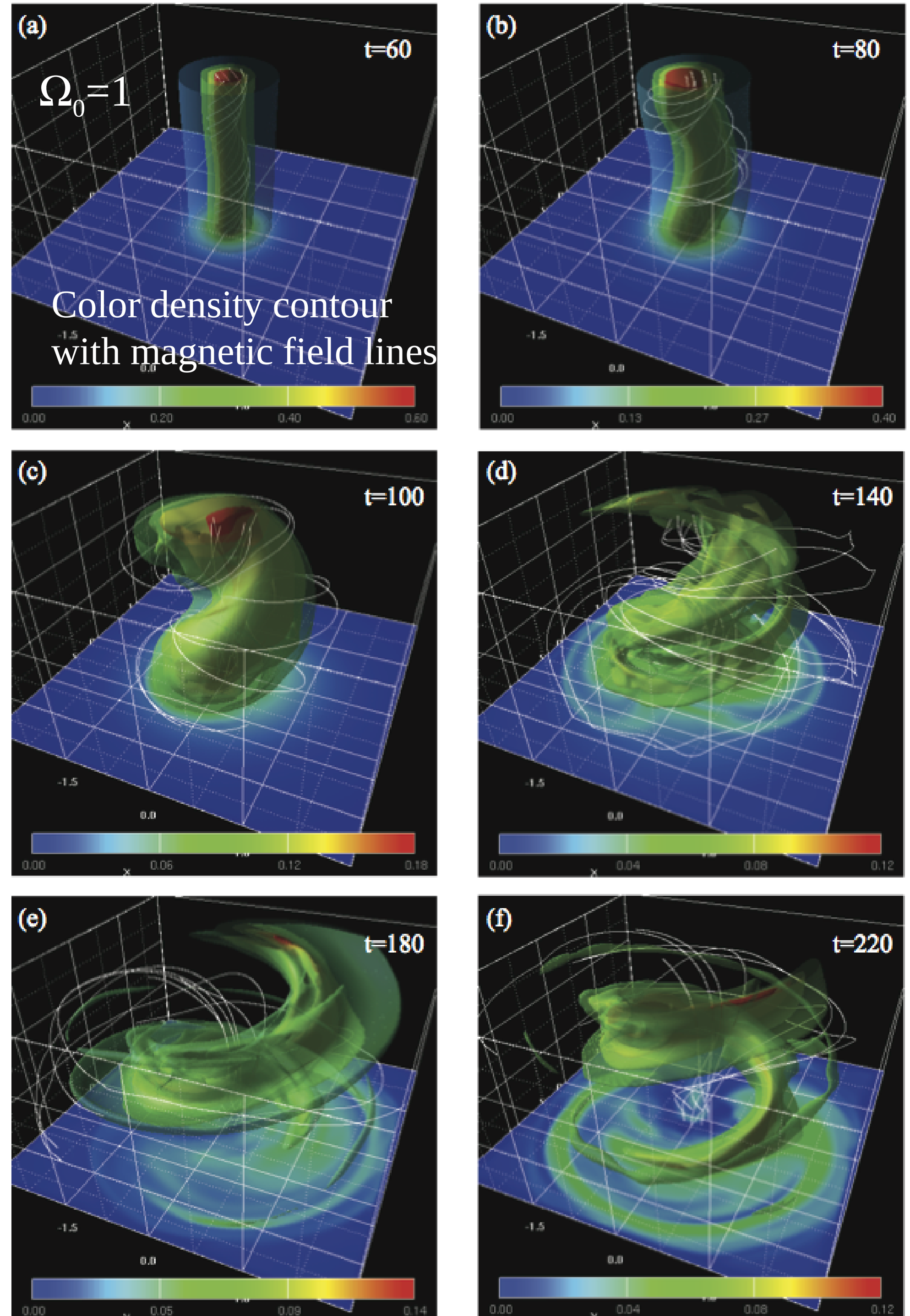
$$v_R/c = \frac{\delta v}{N} \exp\left(-\frac{R}{R_p}\right) \sum_{n=1}^{N} \cos(m\theta) \sin\left(\frac{\pi n z}{L_z}\right)$$

Time Evolution of 3D Structure

• Displacement of the initial force-free helical field leads to a helically twisted magnetic filament around the density isosurface with n=1 mode by CD kink instability

• From transition to non-linear stage, helical twisted structure is propagates in flow direction with continuous increase of kink amplitude.

• The propagation speed of kink ~0.1c (similar to initial maximum axial drift velocity)

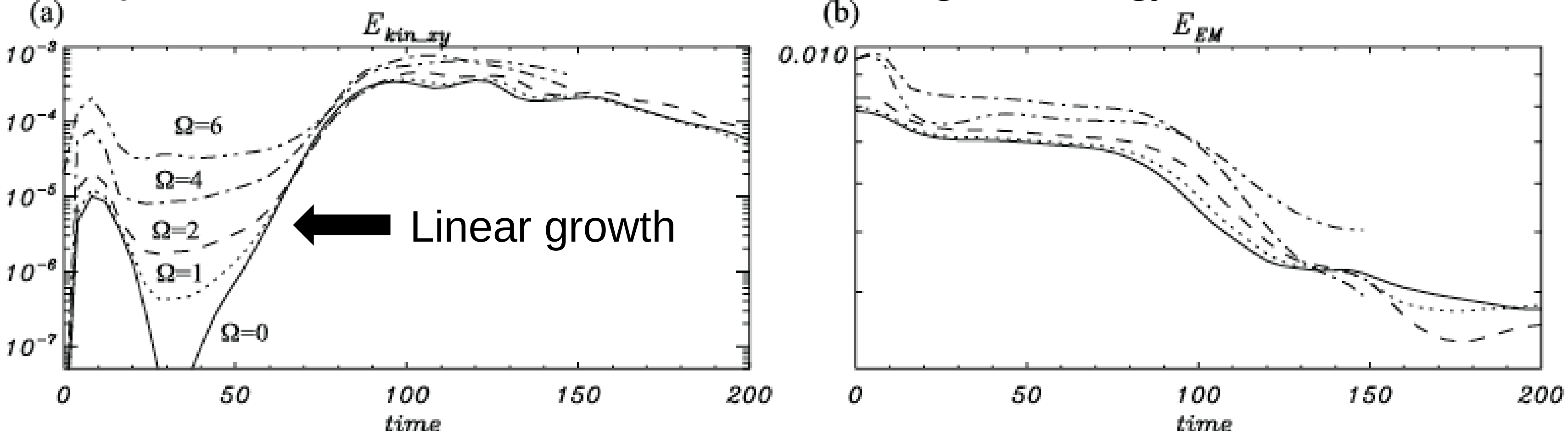


Dependence on Jet Rotation Velocity: growth rate

solid: Ω_0=0
dotted: Ω_0=1
dashed: Ω_0=2
dash-dotted: Ω_0=4
dash-two-dotted: Ω_0=6

Volume-averaged Kinetic energy of jet radial motion

Volume-averaged magnetic energy



Alfven crossing time

- First bump at t < 20 in E_{kin} is initial relaxation of system
- Initial exponential linear growth phase from t ~ 40 to t ~120 (dozen of Alfven crossing time) in all cases
- Agree with general estimate of growth rate, $\Gamma_{max} \sim 0.1 v_A/R_0$

- Growth rate of kink instability does not depend on jet rotation velocity

Dependence on Jet Rotation Velocity: 3D Structure

Larger Ω_0 => faster jet rotation

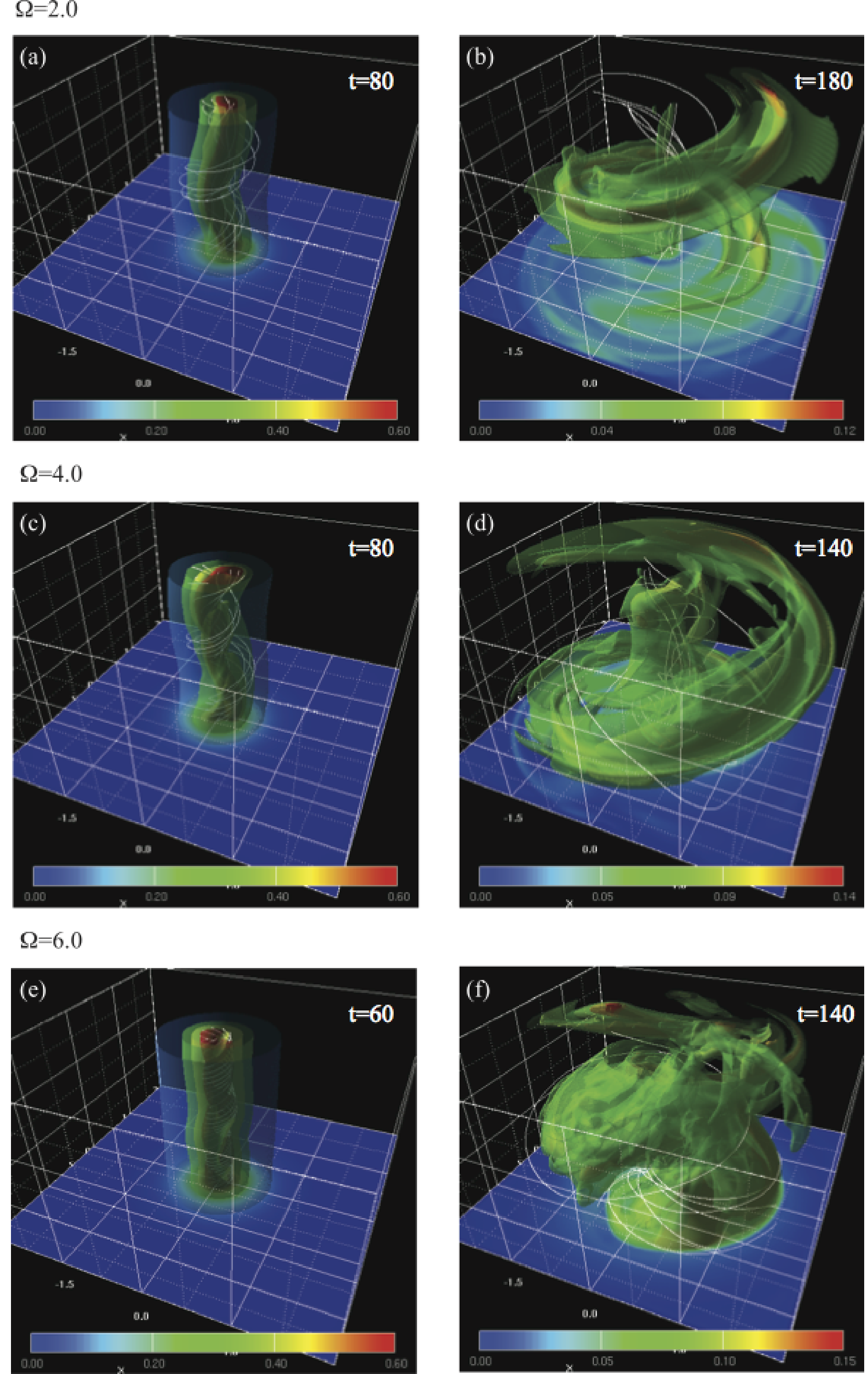
∀ Ω_0=2 case: very similar to Ω_0=1 case, excited n=1 axial mode

• Ω_0=4 & 6 cases: n=1 & n=2 axial modes start to grow near the axis region

• Because pitch decrease with increasing Ω_0

• Propagation speed of kink is increase with increase of angular velocity

• Fast rotating jet case, the multiple mode interaction is happened => turbulent jet structure is developed

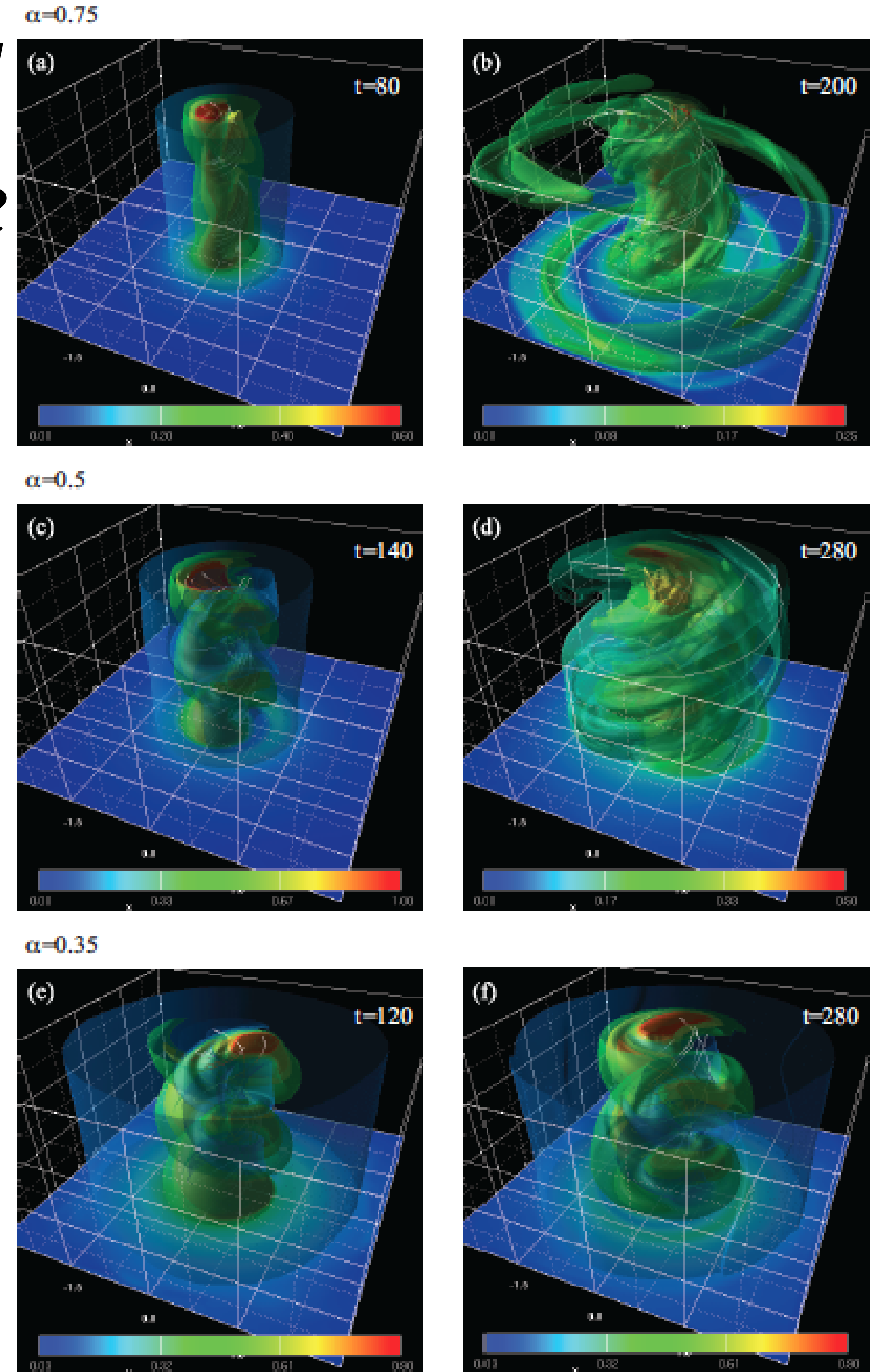


Dependence on B-field structure: 3D structure

$\alpha < 1$ => B_p dominated at larger radius

• α=0.75 case: Nonlinear evolution is similar to α=1 case.
∀ α=0.5 case: growth of *n=2* axial mode near the jet axis. Helical structure is slowly evolving radially.
∀ α=0.35 case: growth of *n=2* axial mode near the axis. In nonlinear phase, helical structure does not evolve radially and maintain the structure = nonlinear evolution is saturated

• The growth of instability saturates when the magnetic pitch increases with radius = jet is stabilized.



CD Kink Instability in Sub-Alfvenic Jets: Spatial Properties

Mizuno et al. (2014)

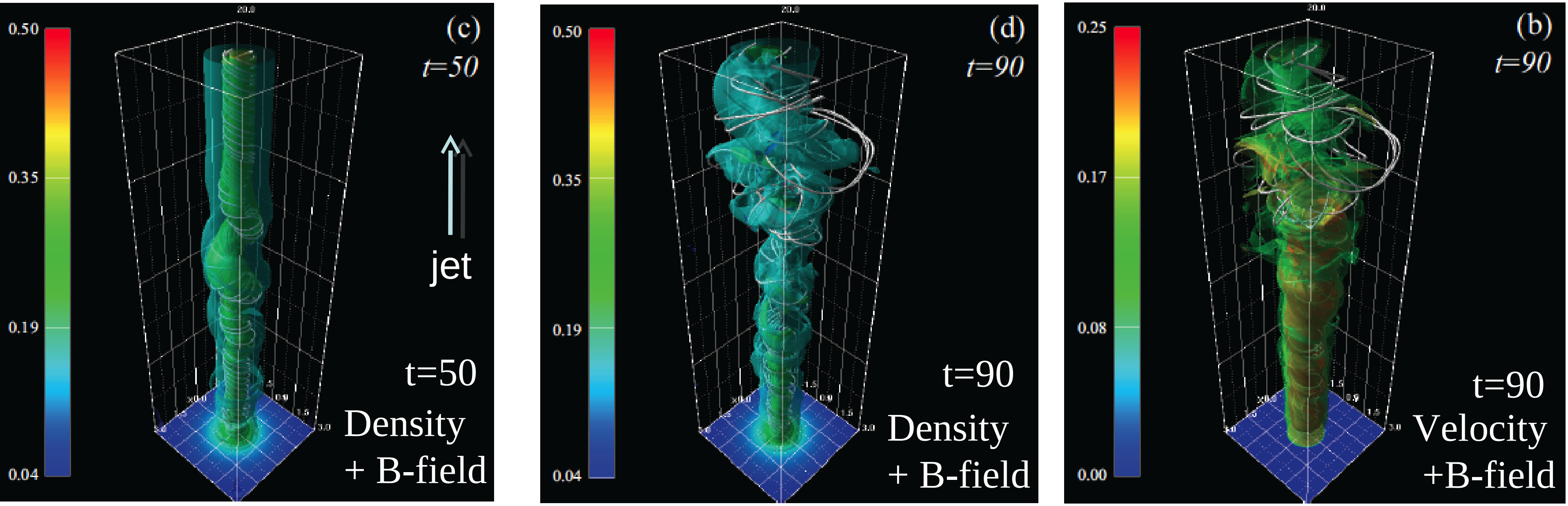
- In previous study, we follow temporal properties (a few axial wavelengths) of CD kink instability in relativistic jets using periodic box.
- Here, we investigate spatial properties of CD kink instability in relativistic jets using non-periodic box.

Initial Condition

- Cylindrical (top-hat) non-rotating jet established across the computational domain with a helical force-free magnetic field (mostly sub-Alfvenic speed)
- V_j=0.2c, R_j=1.0
- Radial profile: Decreasing density with constant magnetic pitch (a=1/4R_j, characteristic radius of helical B-field)
- Jet spine precessed to break the symmetry (λ~3L) to excite instability

3D Helical Structure

Decreasing density
$R_j > a$

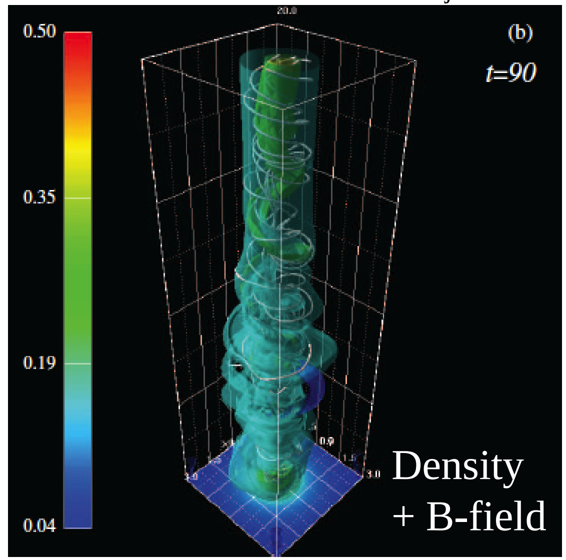


- Precession perturbation from jet inlet produces the growth of CD kink instability with helical density distortion.
- Helical kink structure is advected with the flow with continuous growth of kink amplitude in non-linear phase.
- Helical density & magnetic field structure appear disrupted far from the jet inlet though multiple (axial) mode interaction.

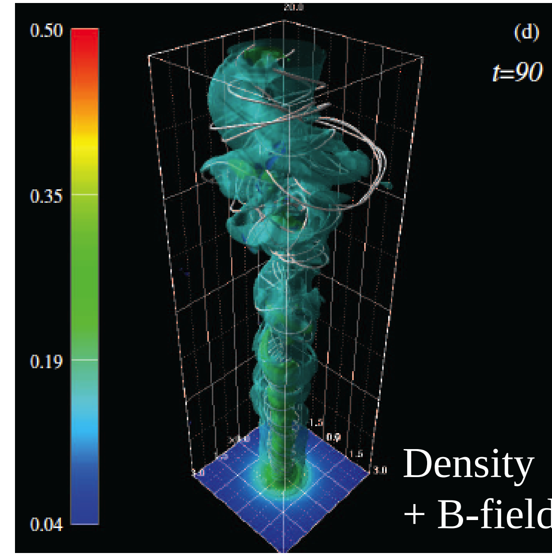
Dependence on density profile & jet shear

Radially decreasing density

$R_j < a$

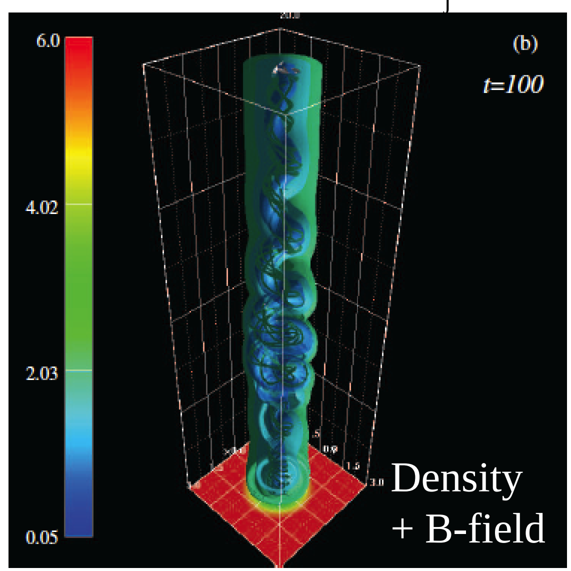


$R_j > a$

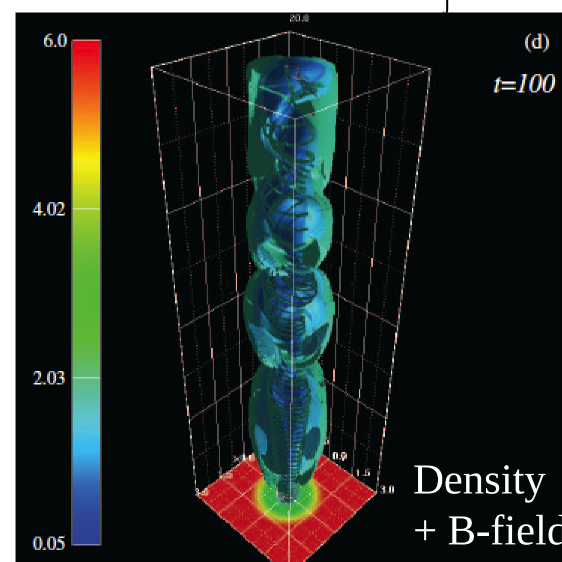


Radially increasing density

$R_j=1/2a$



$R_j=4a$



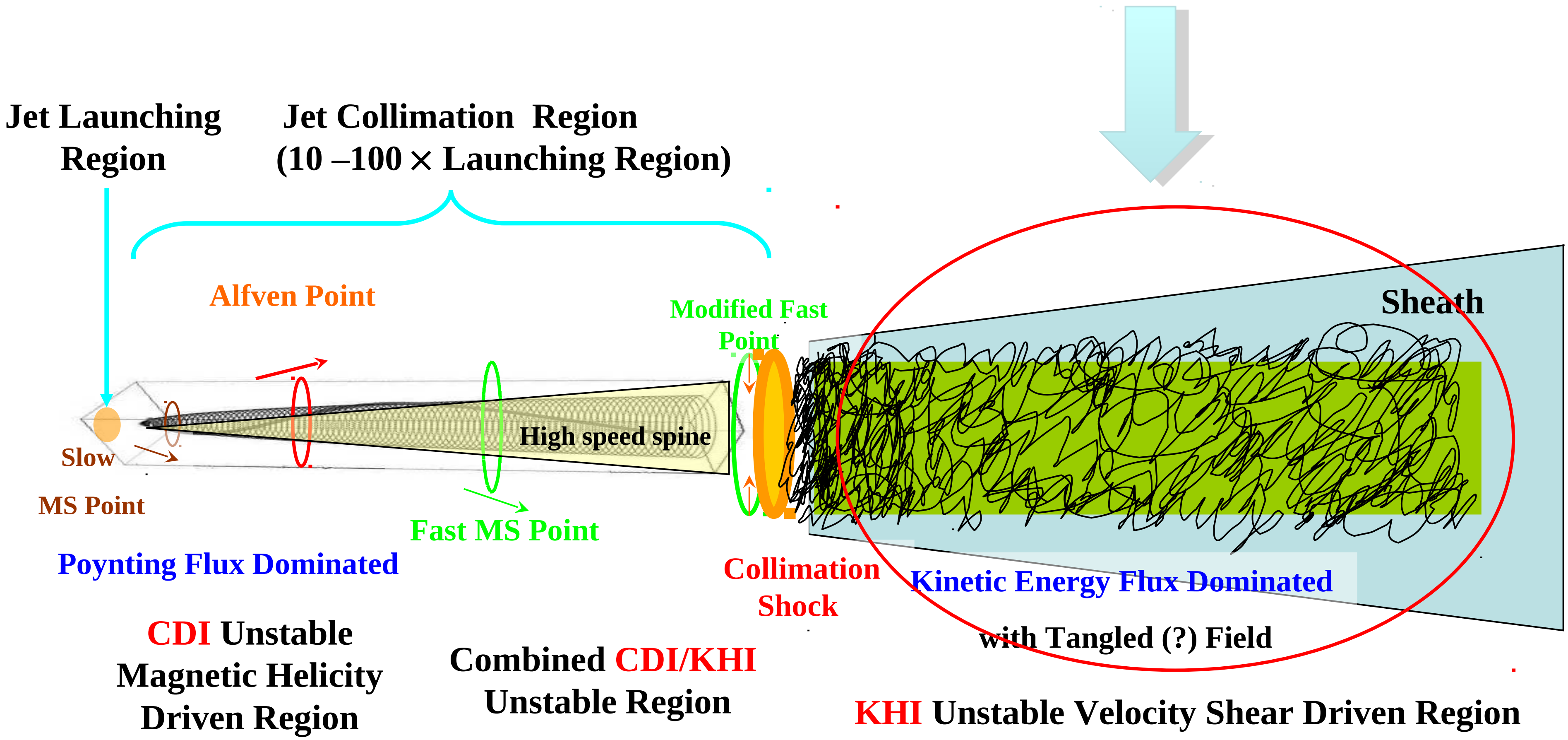
$R_j < a$: developed helical kink does not propagate with jet (perturbation is propagate through jet).

$R_j > a$: developed helical kink propagates with jet (jet is maintained much larger distances)

Decreasing density: helical kink continuously grows => disruption of helical twist

Increasing density: growth of helical kink is saturated => relatively stable configuration

Kelvin-Helmholtz Instability (weakly magnetized regime)



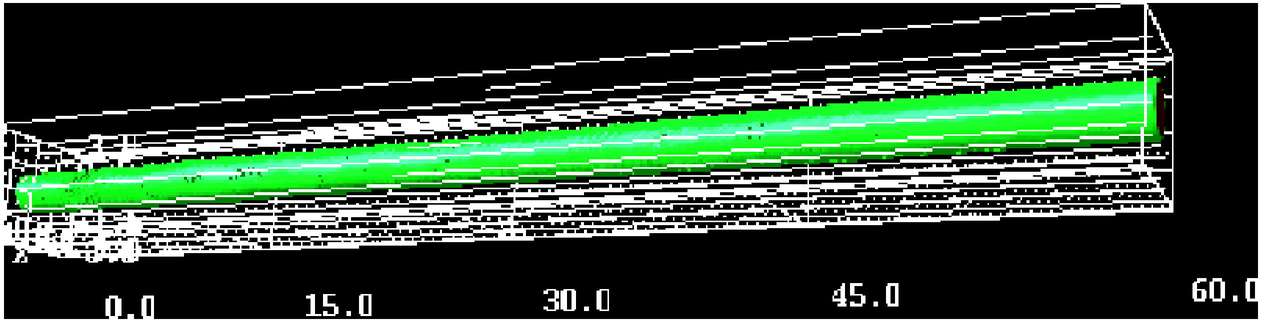
Stabilities of magnetized spine-sheath jets against KH modes

- In previous works, KH instability is stable in sub-Alfvenic jet regime (magnetic field is strong).
- But observed jet is kinetic energy is dominated (magnetic energy is week) and jet is super-Alfvenic.
- Is relativistic jet unstable for KH mode everywhere?

- New idea: spine-sheath configuration (two-flow components)

Initial Condition

Mizuno et al. (2007)



- Cylindrical super-Alfvenic jet established across the computational domain with a parallel magnetic field (stable against CD instabilities)

- Solving 3D RMHD equations in Cartesian coordinates

Jet (spine): $u_{jet} = 0.916\, c$ ($\gamma_j = 2.5$), $\rho_{jet} = 2\, \rho_{ext}$ (dense, cold super-Alfvenic jet)

- External medium (sheath): $u_{ext} = 0$ *(static), 0.5c (sheath wind)*

- RHD: *weakly-magnetized (sound velocity > Alfven velocity)*
- RMHD: *mildly-magnetized (sound velocity < Alfven velocity)*

- Jet spine precessed to break the symmetry

Global Structure

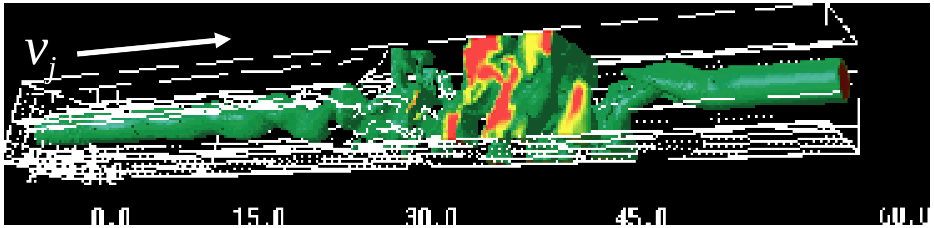
3D isovolume density at t=60

No wind (single jet) case

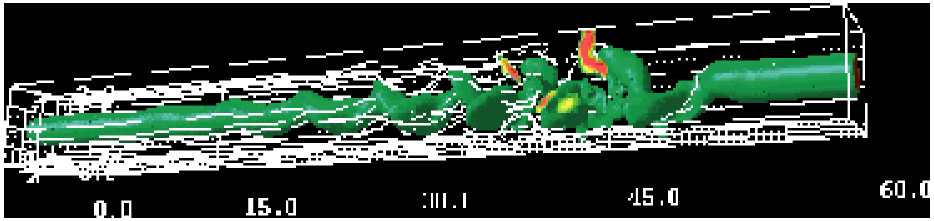
External wind (spine-sheath) case

Weakly-magnetized

RHD, no wind, ω=0.93, time=60.0

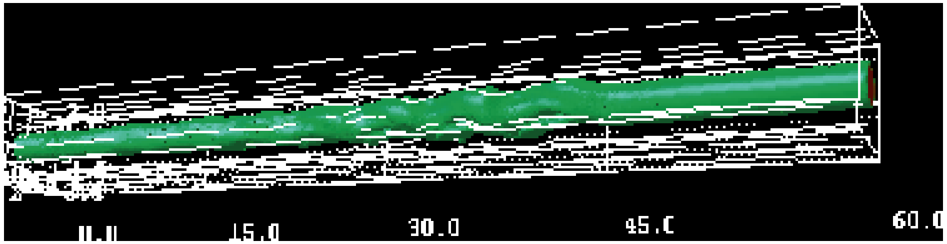


RHD, wind, ω=0.93, time=60.0

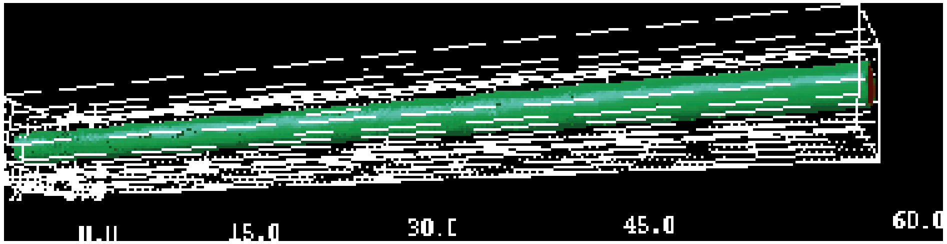


Mildly-magnetized

RMHD, no wind, ω=0.93, time=60.0



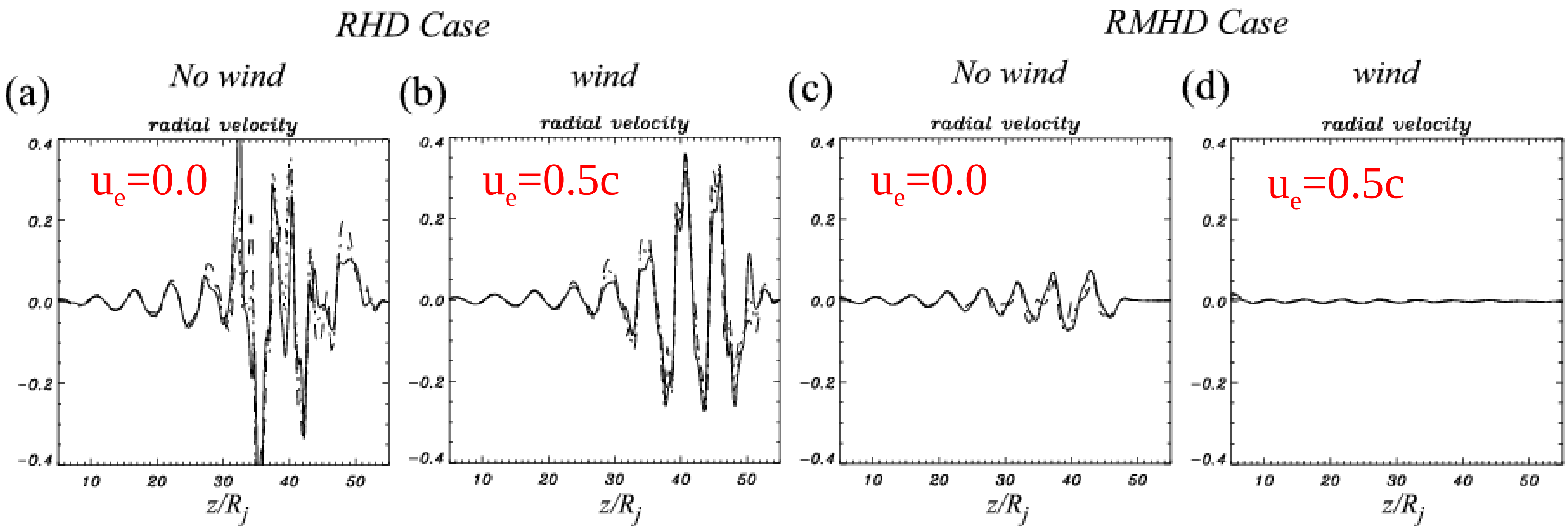
RMHD, wind, ω=0.93, time=60.0



- The precession perturbation from jet inlet leads to grow of KH instability and it disrupts jet structure in non-linear phase.
- Growth/damp of KH instability and jet structure is different in each cases.

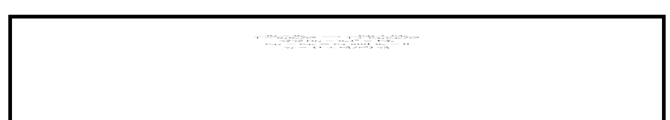
Effect of magnetic field and sheath wind

1D radial velocity profile along jet

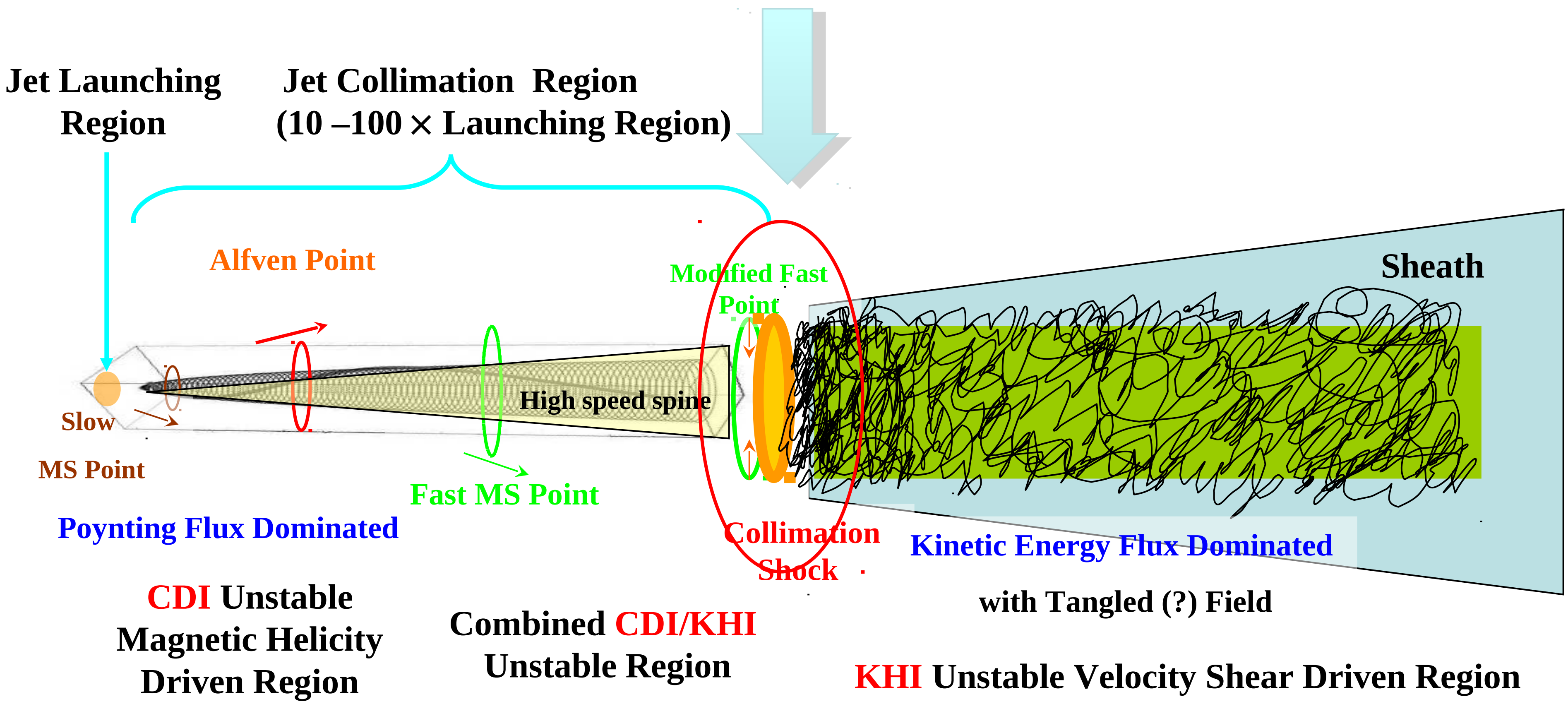


- The sheath flow reduces the growth rate of KH modes
- The magnetized sheath reduces growth rate relative to the weakly magnetized case
- The magnetized sheath flow damped growth of KH modes = *stabilize*.

Criterion for damped KH modes:
(linear stability analysis)



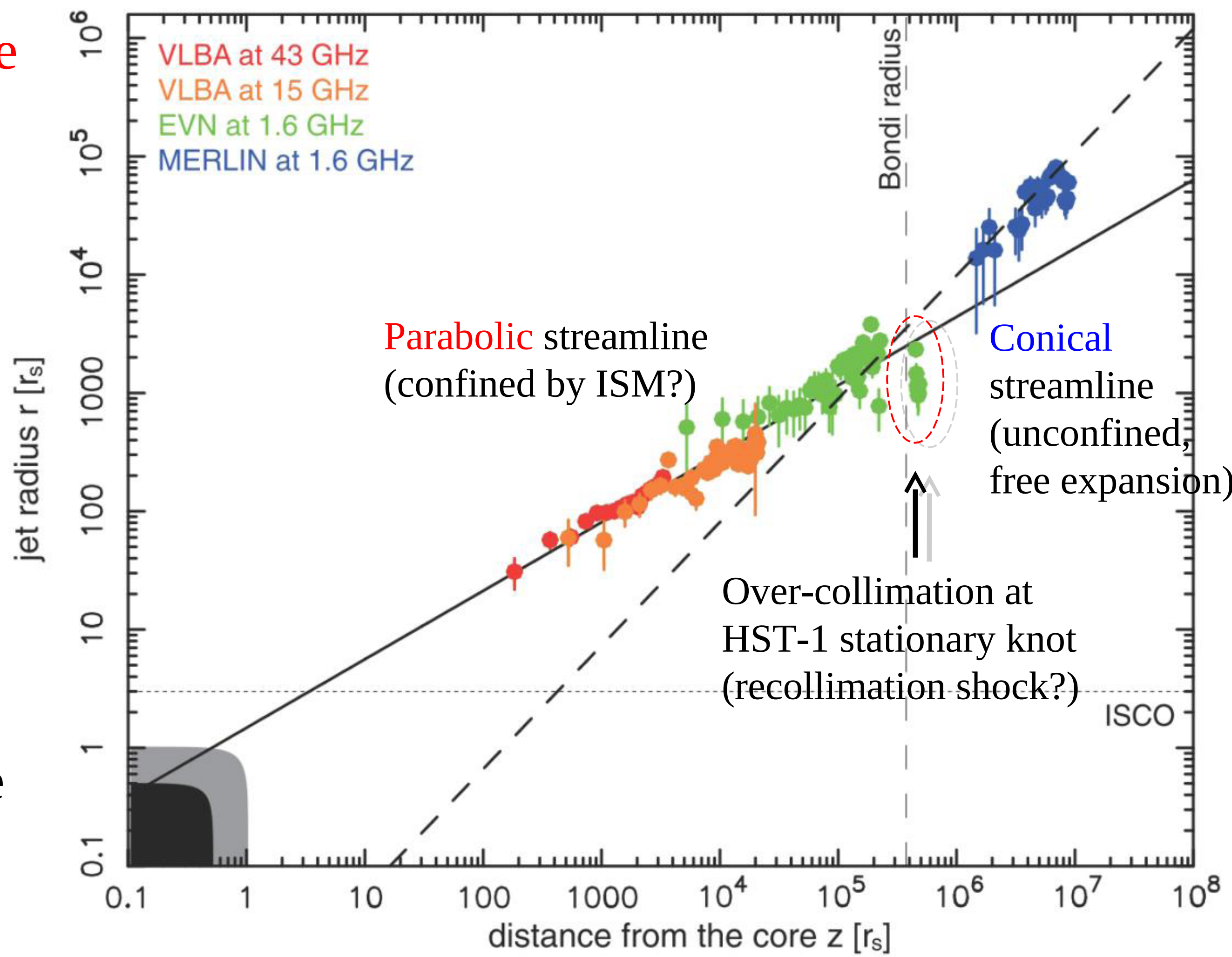
Recollimation Shock
(Transition region)



Observed Jet structure

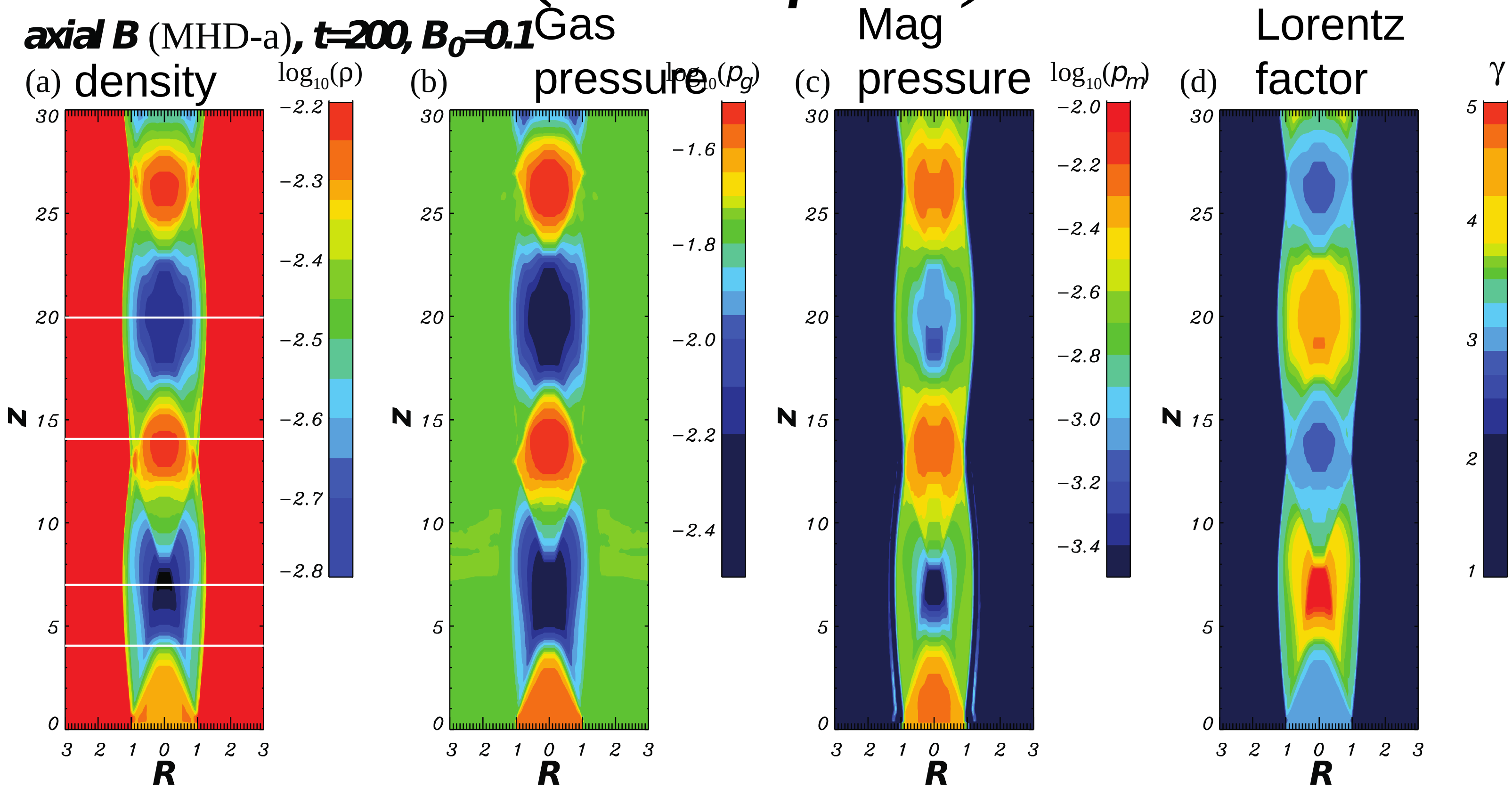
Global structure of M87 jet (Asada & Nakamura 2012, Hada et al. 2013)

- The parabolic structure ($z \propto r^{1.7}$) maintains over 10^5 r_s, external confinement is worked.
- The transition of streamlines presumably occurs beyond the gravitational influence of the SMBH (= Bondi radius)
- Stationary feature HST-1 is a consequence of the jet recollimation due to the pressure imbalance at the transition
- In far region, jet stream line is conical ($z \propto r$)



Recollimation Shock Simulation (axial field)

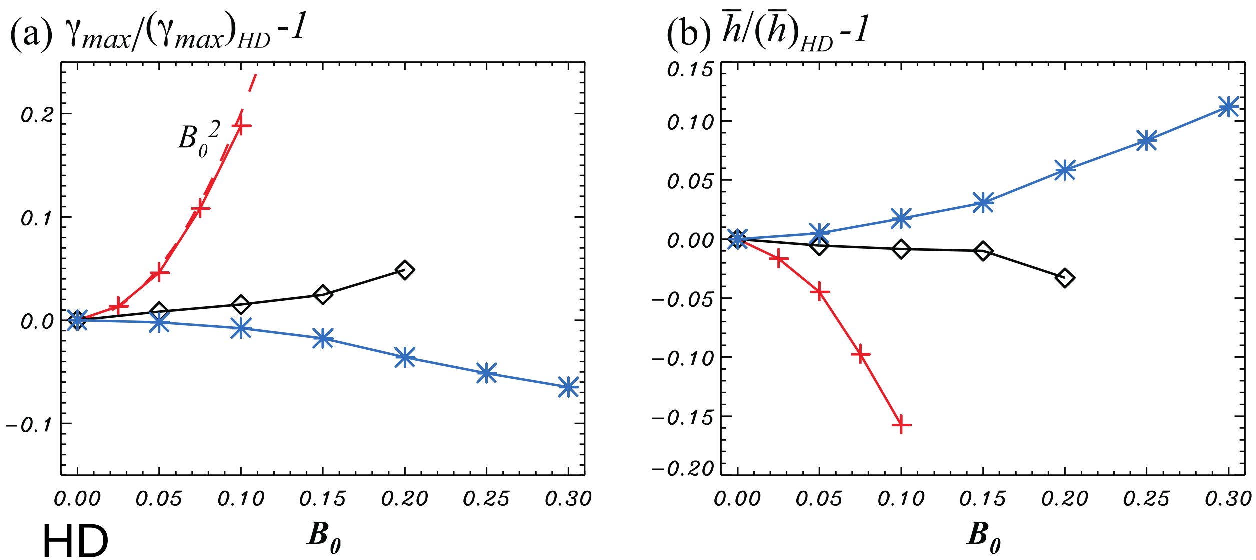
Mizuno et al. (2015)



- 2D non-equilibrium over-pressured jet in cylindrical geometry (γ_j~3)
- Multiple stationary recollimation and rarefaction structures are produced along the jet by the nonlinear interaction of shocks and waves
- jet is partially boosted by rarefaction acceleration

Dependence on B-field strength

Red: axial
Blue: toroidal
Black: helical

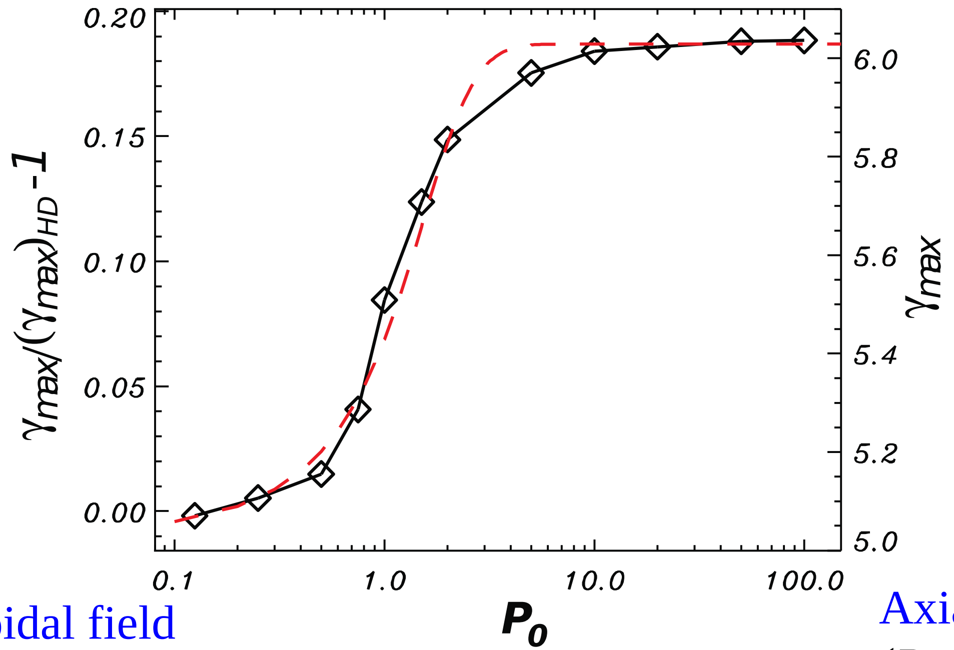


- $\gamma_{max}/(\gamma_{max})_{HD}$-*1*: relative increase of Lorentz factor with respect to the purely HD case

- Acceleration is the result of conversion of plasma thermal energy into jet kinetic energy (quantity γh is conserved across a rarefaction wave)
- Axial case: *larger* Lorentz boost. Relative boost has a simple quadratic dependence
- Toroidal case: *smaller* Lorentz boost due to magnetic tension
- Helical case: depends on magnetic pitch (=> next slide)

Dependence on magnetic pitch

Relative difference of the maximum Lorentz factor



Maximum Lorentz factor

Fixed field strength: B_0=0.1

Toroidal field (P_0 << 1)

Magnetic pitch = $RB_z/B_\phi = a/R_j$

Axial field (P_0 >> 1)

- Relative difference of the maximum Lorentz factor smoothly joins two extreme cases of toroidal and axial fields
- Transition between two regimes takes place at $P_0 > 1$, that is, when a: characteristic radius of helical field (maximum of toroidal field) $> R_j$
- Saturate to the axial field case when $a \sim 10\ R_j$
- Simple fitting with a hyperbolic tangent function (red-dashed lines)

Summary

- The CD kink instability is partially stabilized by a radially increasing density structure (= non-destructive kink structure in observed jet).
- Advection of helical kink structure depends on location of velocity shear inside/outside of the characteristic radius of helical field (most likely advects with jet motion)
- The strongly deformed magnetic field via multiple mode interaction of CD kink instability may trigger of magnetic reconnection in the jet (rapid energy dissipation)
- The KH instability is stabilized by the presence of magnetized sheath wind even when the jet is super-Alfvenic flow.
- The recollimation shock structure can be modified by the presence of magnetic field, especially helical field yields more complex substructure.