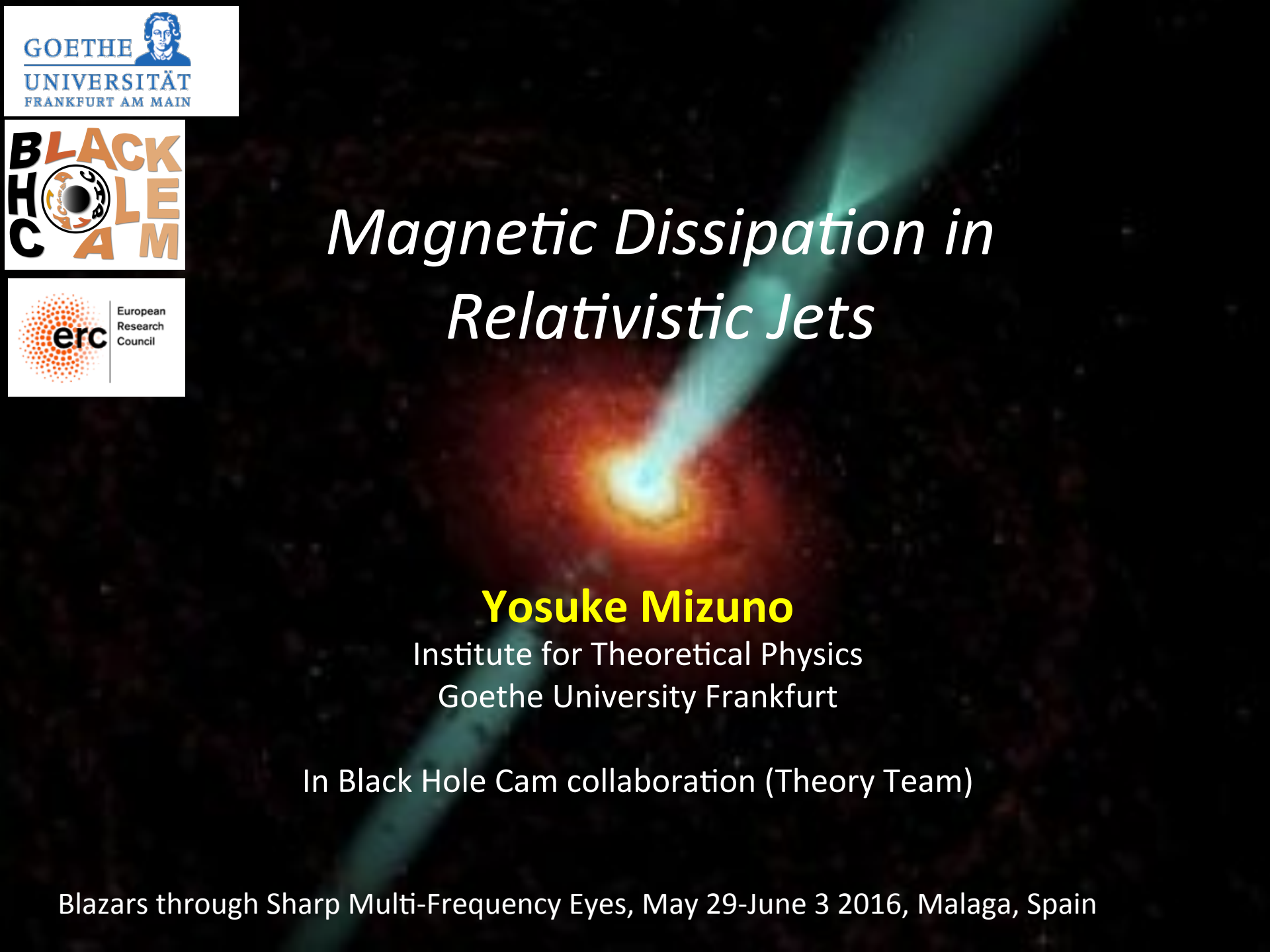


Magnetic Dissipation in Relativistic Jets

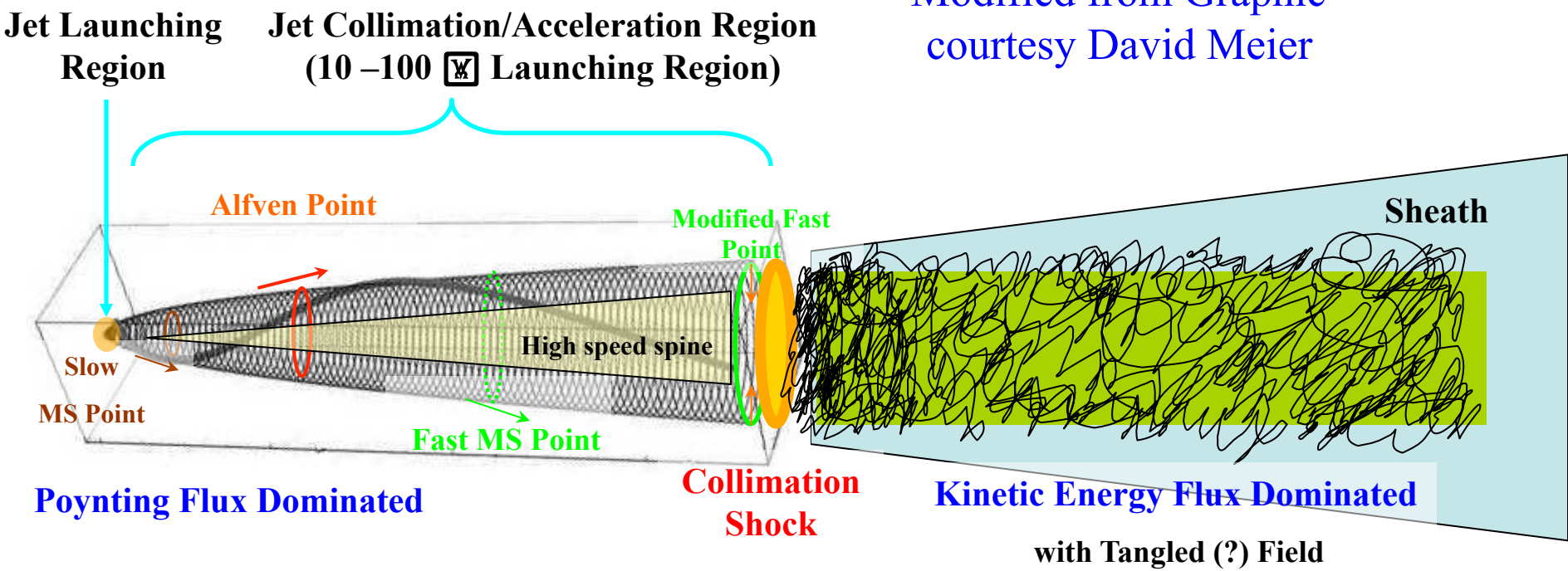
Yosuke Mizuno
Institute for Theoretical Physics
Goethe University Frankfurt

In Black Hole Cam collaboration (Theory Team)

Blazars through Sharp Multi-Frequency Eyes, May 29-June 3 2016, Malaga, Spain

Regions of AGN Jet Propagation

Modified from Graphic courtesy David Meier



- Jet launching by MHD process => Poynting flux dominated jet with twisted magnetic field
- Need rapid magnetic energy dissipation to make a kinetic energy dominated jet

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 & Turbulence

- Several instabilities (CD kink & KH) are potentially growth

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

CD Kink Instability in Rotating Relativistic Jets: Spatial Properties

Chandra et al. (16)

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

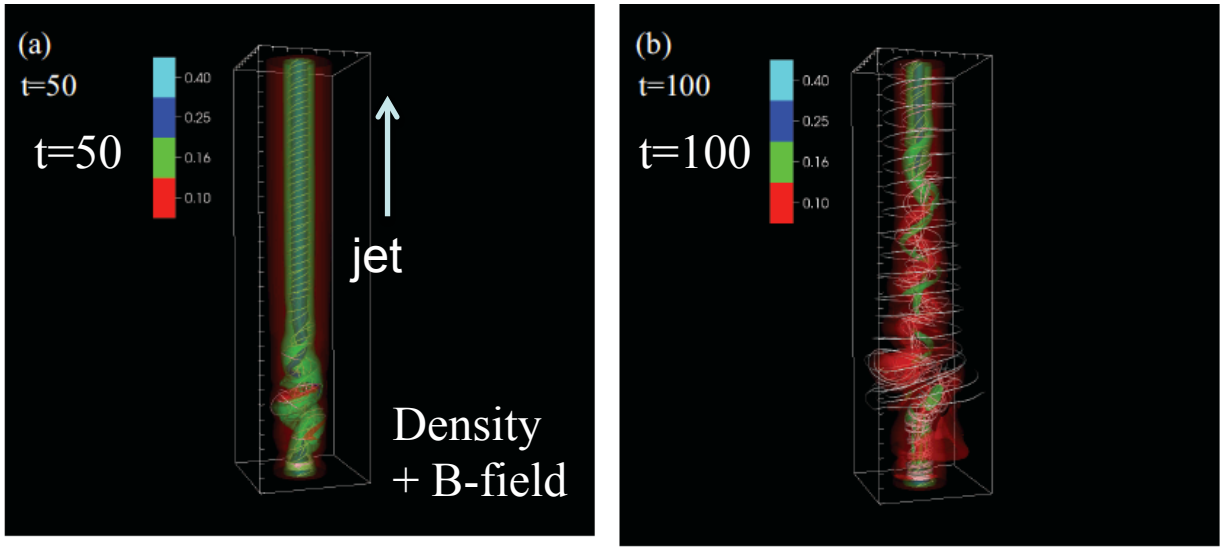
Initial Condition

- Cylindrical rotating jet established across the computational domain with a helical force-free magnetic field (mostly *sub-Alfvenic speed*)
- Change radial profile: decreasing density (*heavy jet*) or increasing density (*light jet*)
- Put the precession perturbation from jet inlet to break the symmetry to excite instability

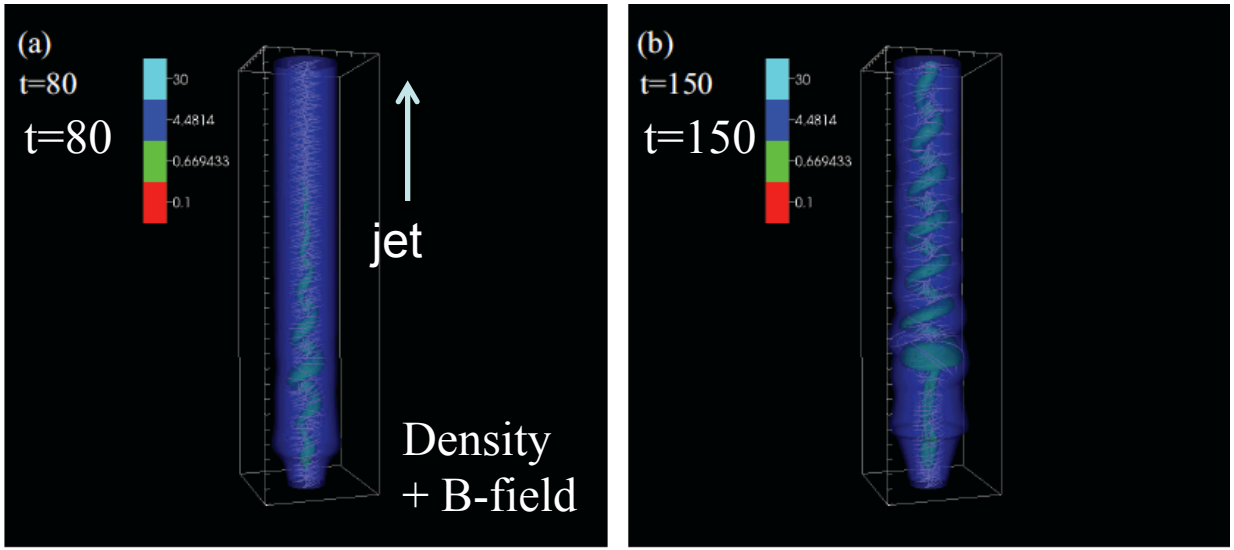
3D Helical Structure

- Precession perturbation from jet inlet produces the growth of CD kink instability with helical density distortion.
- Helical kink structure is *advected* with the axial flow with continuous growth of kink amplitude in non-linear phase.
- Radially decreasing density case (*heavy jet*): helical jet structure is *disrupted* though multiple (axial) mode interaction.
- Radially increasing density case (*light jet*): Growth of kink structure is *saturated* & maintain helically *distorted* structure

Decreasing density (W_0=1)



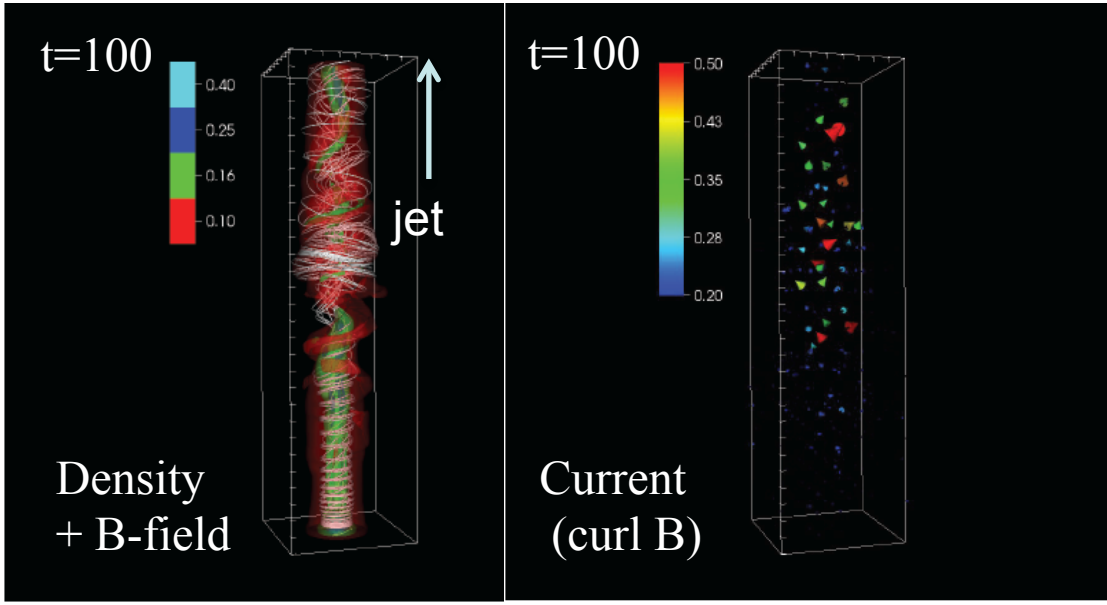
Increasing density (W_0=1)



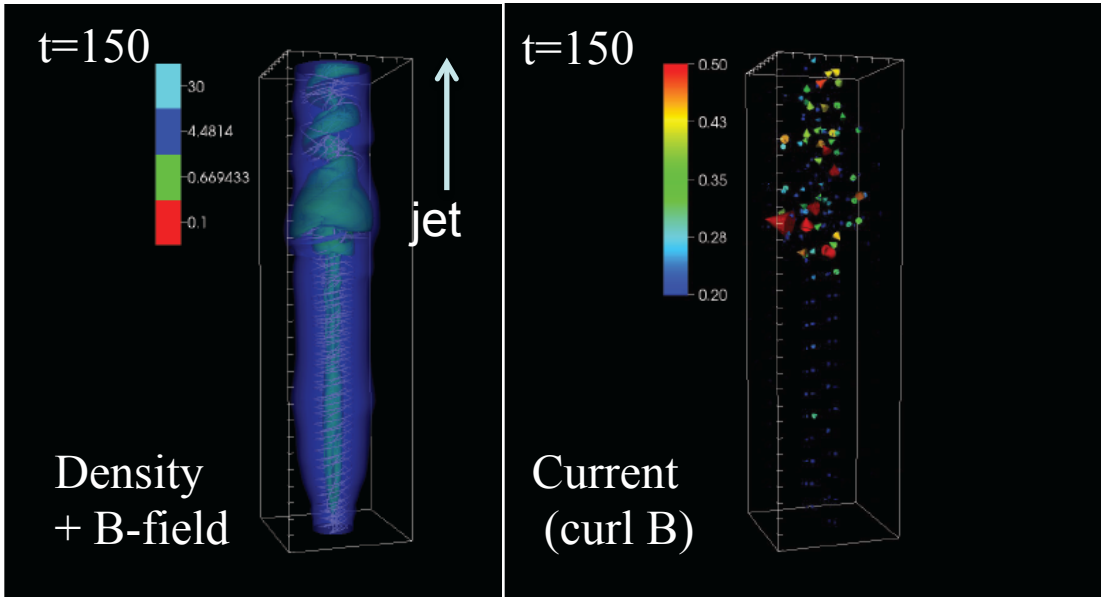
Possible magnetic reconnection in jet

- Calculate local current density (curl B)
- Both cases show localized large values of current at helically distorted region in the jet
- In these sites, magnetic reconnection may be occurred.
- Magnetic reconnection driven by kink instability leads for dissipation of magnetic energy and jet acceleration locally

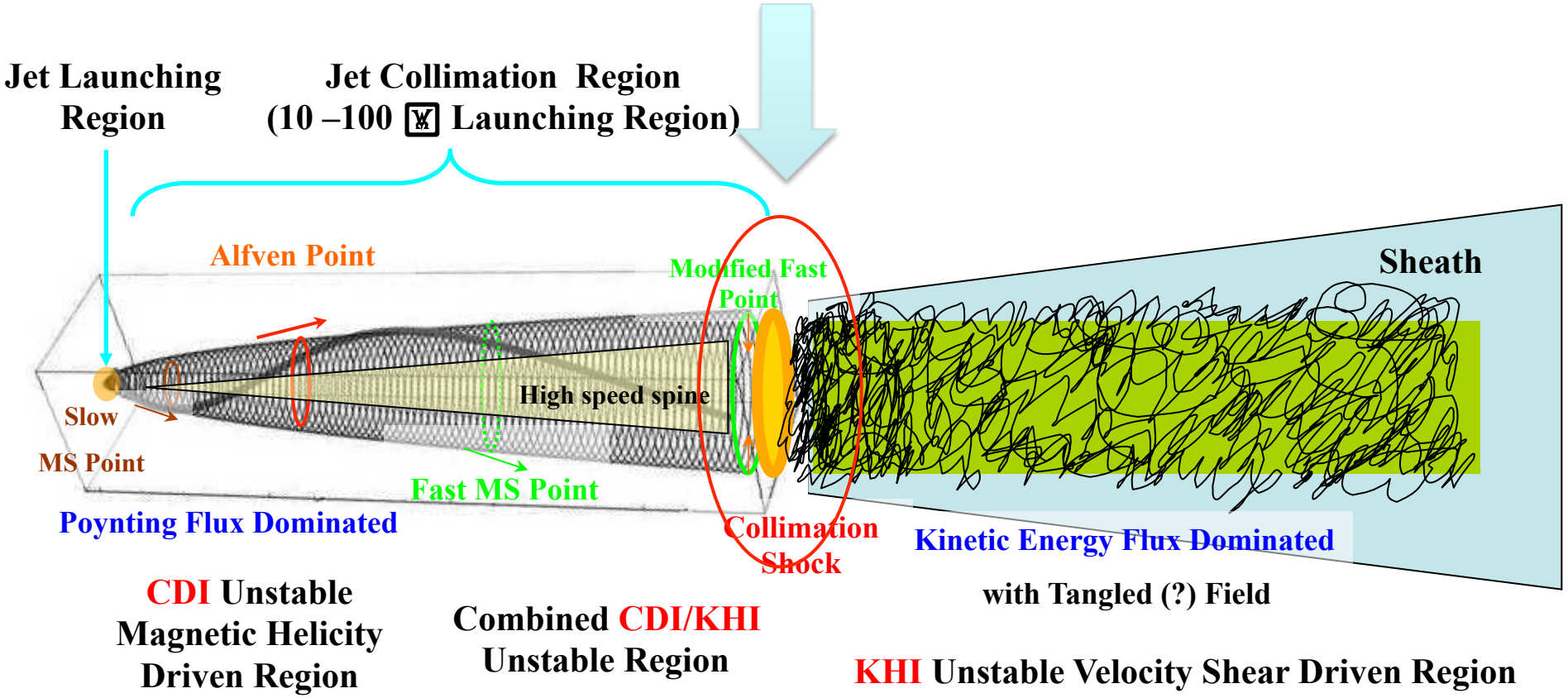
Decreasing density (W_0=2)



Increasing density (W_0=2)



Recollimation Shock (Transition region)



Recollimation shock (cont.)

- The dynamics of jet is strongly affected by the difference in pressures between the jet and ambient medium
- If ambient pressure decrease when a jet propagates

pressure mismatch (jet ⇔ ambient)

a radial oscillating motion of the jet (expansion and recollimation) by propagations of shocks/rarefaction waves inside the jet

multiple recollimation shocks inside the jet

- If a significant rarefaction wave is produced and propagates into the jet interior

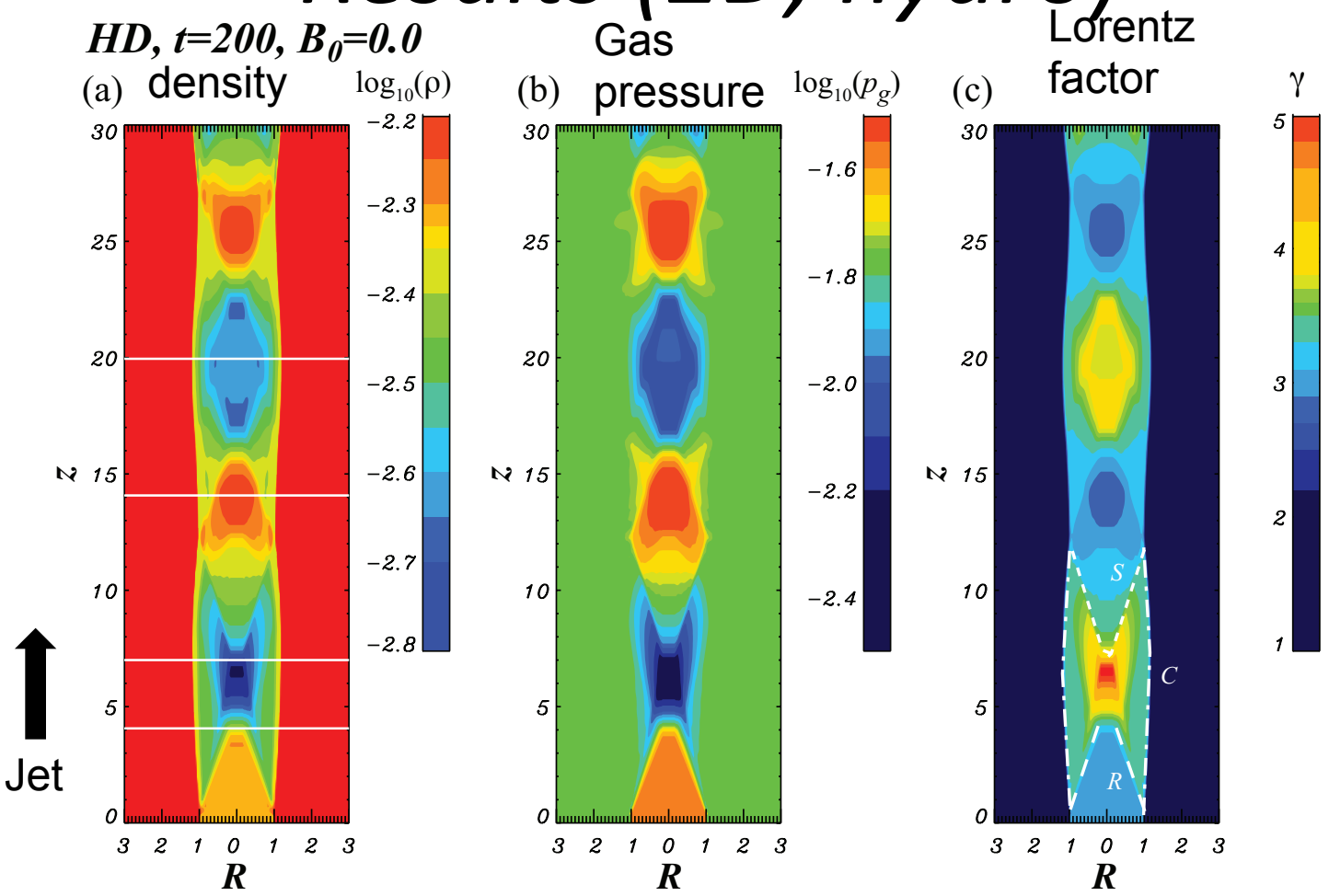
Plasma thermal + EM energies are converted into jet kinetic energy

Increasing jet Lorentz factor locally (Aloy-Rezzolla booster)

- In this work, study how magnetic field affect the recollimation-shock structure through 2DSRMHD simulations

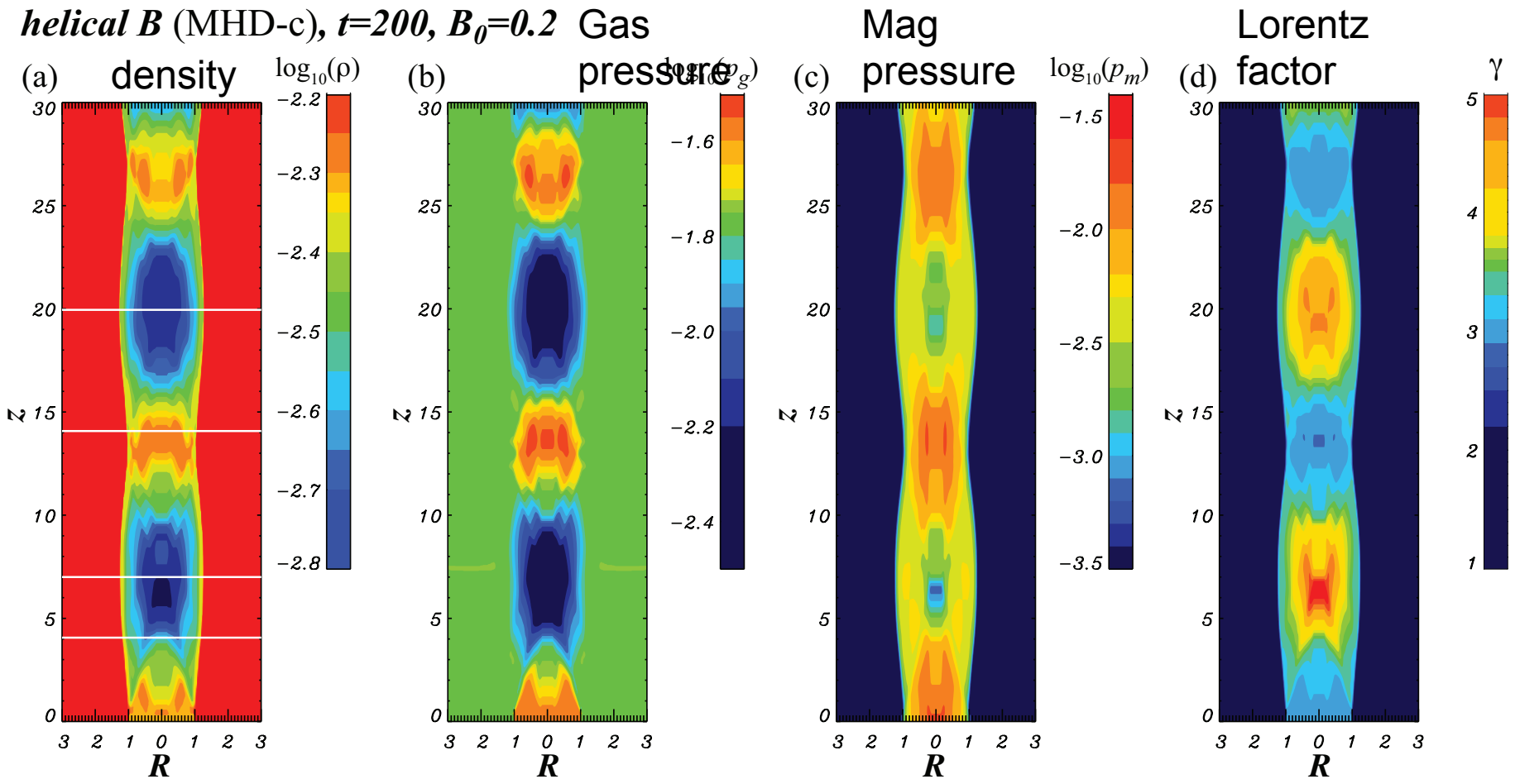
Results (2D, hydro)

Mizuno et al. (15)



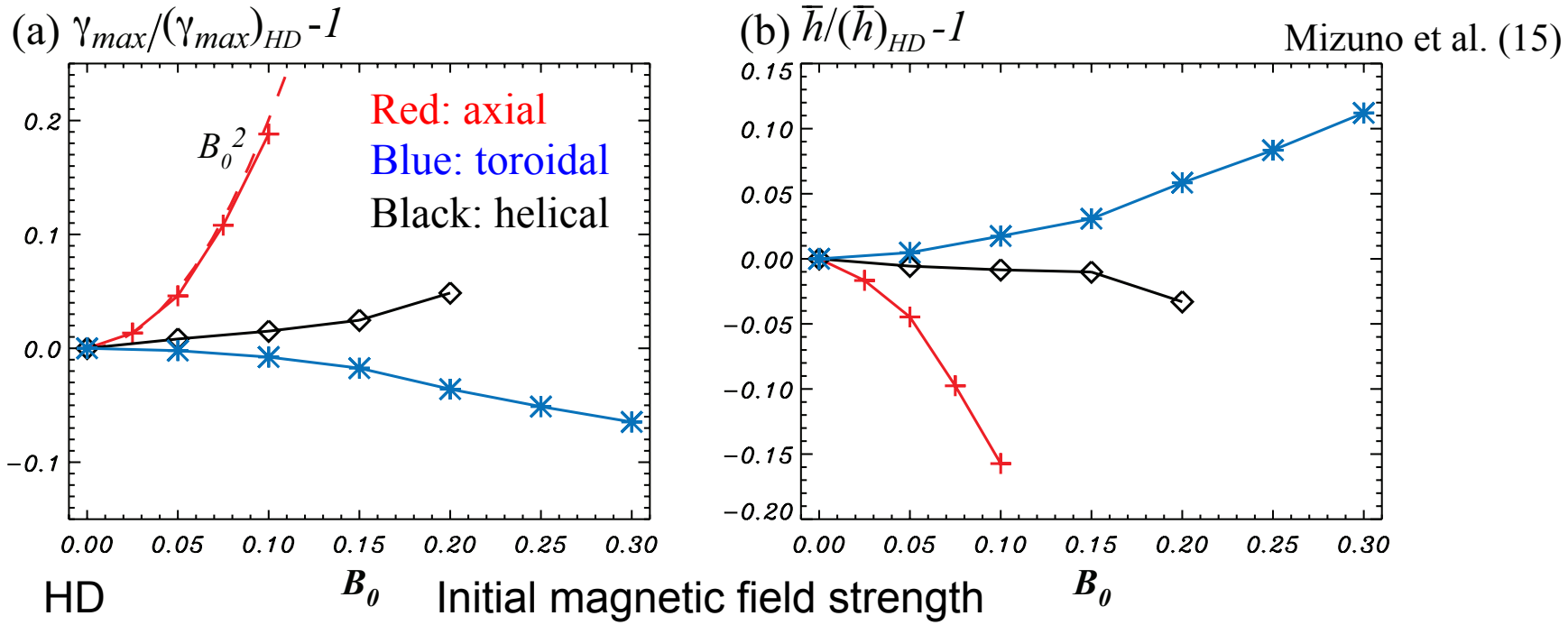
- Consider 2D non-equilibrium over-pressured jet in cylindrical geometry (g_j~3)
- Due to overpressure in the jet, multiple stationary recollimation and rarefaction structures are produced along the jet
- Jet is partially boosted by rarefaction acceleration (g_j~3 => g_j~5)
- Jet accelerated region is low density & low gas pressure

Simulation Results (helical field)



- General behavior is similar but more complex (see small sub-structure in jet)
- Structure Looks mixed with the effect of toroidal and axial fields
- Jet is (a little) more boosted than hydro case ($g_j \sim 3 \Rightarrow g_j \sim 5$)

Dependence on B-field strength



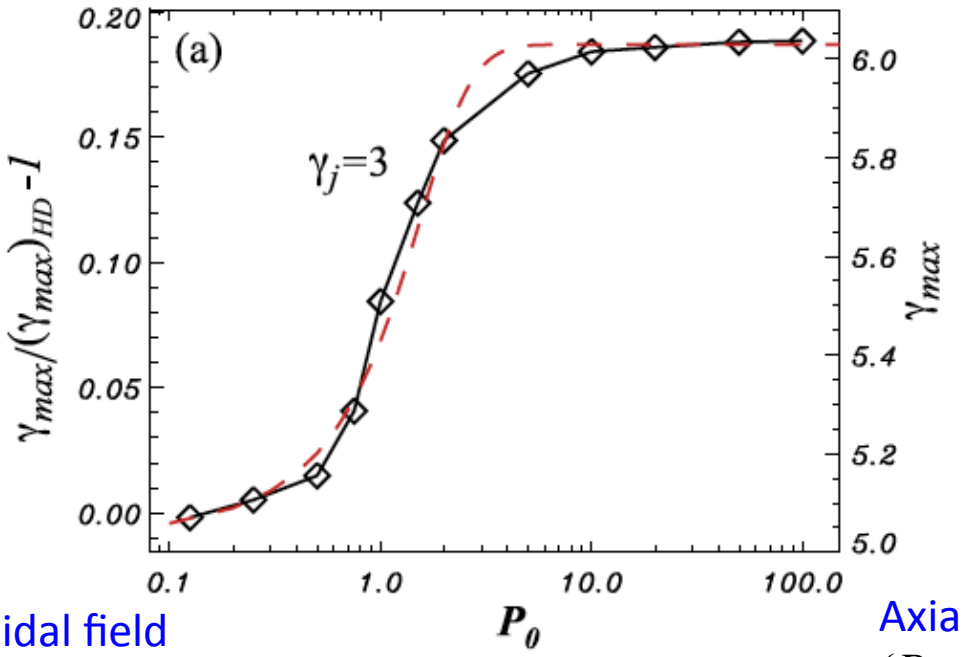
- $g_{max}/(g_{max})_{HD}$-*1*: relative difference of maximum Lorentz factor with respect to the purely hydro case (B_0=0)

- Acceleration: result of conversion E_{th} => E_{kin} of jet
- Axial case: *larger* Lorentz boost (quadratic dependence of B-field strength)
- Toroidal case: *smaller* Lorentz boost due to magnetic tension
- Helical case: between two extreme (axial and toroidal) but depends on magnetic pitch (=> *next slide*)

Dependence on magnetic pitch

Mizuno et al. (15)

Relative difference of the maximum Lorentz factor



Maximum Lorentz factor

Fixed field strength: B_0=0.1

Toroidal field ($P_0 << 1$)

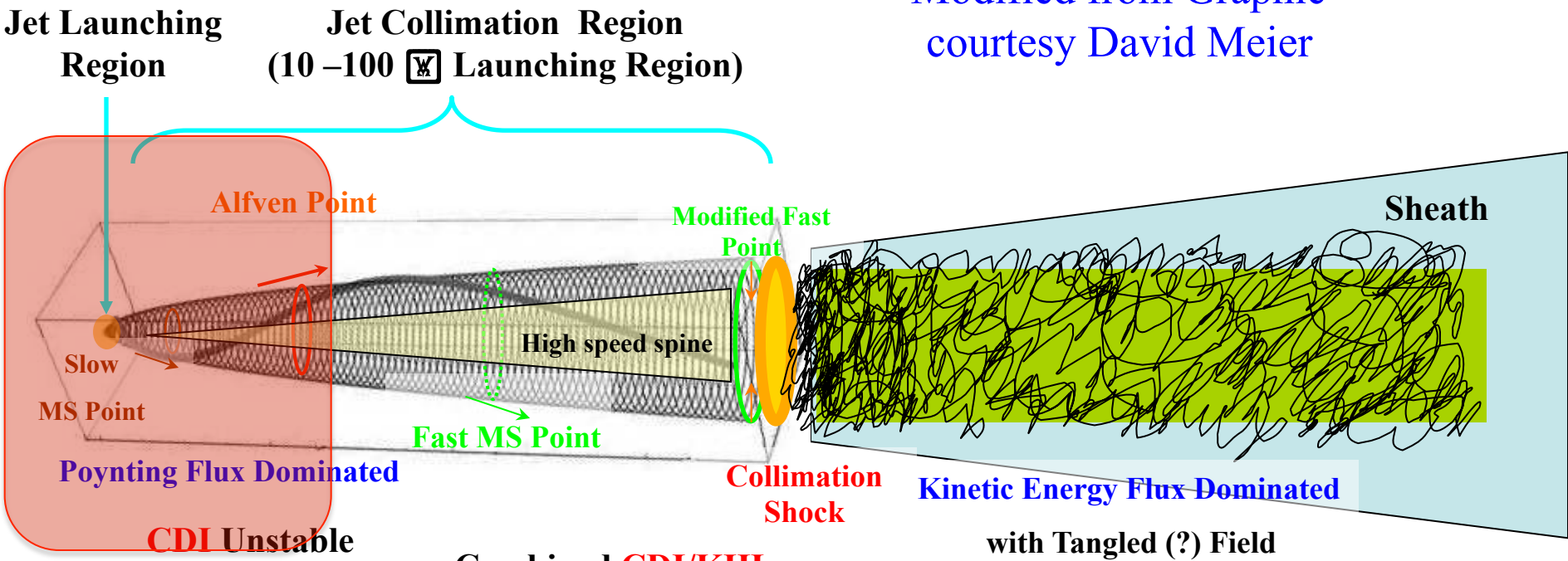
Initial Magnetic pitch = $RB_z/B_f = a/R_j$

Axial field ($P_0 >> 1$)

- Relative difference of the maximum Lorentz factor smoothly joins two extreme cases: toroidal ($P_0 << 1$) and axial ($P_0 >> 1$)
- 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)

Jet Formation/Acceleration Region

Modified from Graphic courtesy David Meier



Jet Formation/Acceleration Region

- Jet formation & acceleration region is possibly seen in mm-VLBI
- What need to reach realistic radiation image of jet formation region?
- 1. Plasma behavior surrounding BH
  - Consider time evolution of accreting matter onto BH and formation of relativistic jets
- 2. Radiation process
  - Consider GR effects (geodesic, redshift), thermal/non-thermal radiation process, optical thickness etc.
- 3. BH spacetime

- Tools: General Relativistic MHD (GRMHD) code + General Relativistic Radiation Transfer (GRRT) code

Development of New GRMHD code

- Developing new 3D AMR-GRMHD code BHAC (Black Hole Accretion Code) in BHCam project
  - Based on SRMHD version of MPIAMRVAC (Keppens et al. 2011)
  - Solving 3+1 form of GRMHD equations (Valencia formulation, axisymmetric static metric)
  - Finite-volume scheme
  - Block-Adapted Mesh Refinement in Cartesian and curvilinear coordinates
  - Fully parallelized by MPI
- GR Hydro is well-tested and working nicely (Meliani et al. 2016, *in prep.*)
- GRMHD (ideal) is in testing phase of magnetized torus
- Simulation results are directly compared with other GRMHD code RAISHIN & HARM2D to verify the code

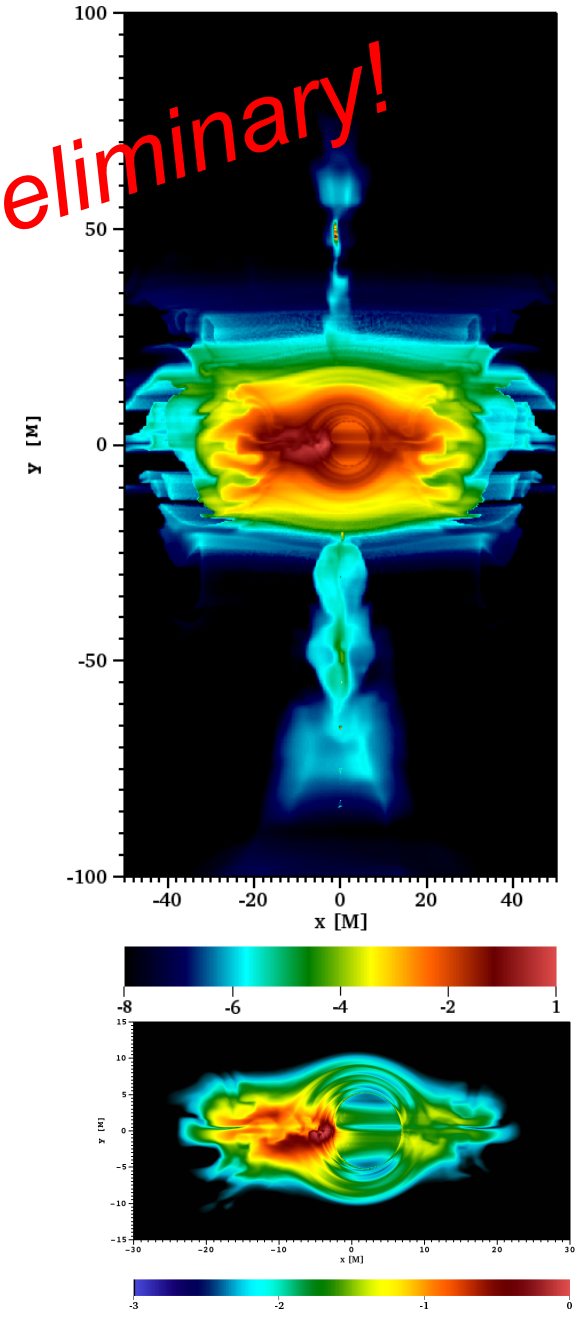
GRMHD simulations of magnetized torus

Porth et al. (16) in prep.

Preliminary!

Calculated Radiation image by GRRT code
(Thermal synchrotron total intensity)

Preliminary!



- Initial: Accretion torus + weak single magnetic field loop
- Inside torus becomes turbulent by MRI
- Poynting flux dominated jet is developed near the axis

Summary

- Helical kink structure is advected with jet flow. Advection speed is similar to axial jet flow speed. In observation, we see advection of helically twisted structure.
- The strongly deformed magnetic field via CD kink instability may become a trigger of magnetic reconnection in the jet (= rapid energy dissipation)
- The recollimation shock structure can be modified by the presence of magnetic field, especially helical field yields more complex substructure.
- Newly developed AMR-GRMHD code has reproduced previous accretion torus simulations by other GRMHD codes. We will investigate the AMR ability for complex structure in jet formation site.