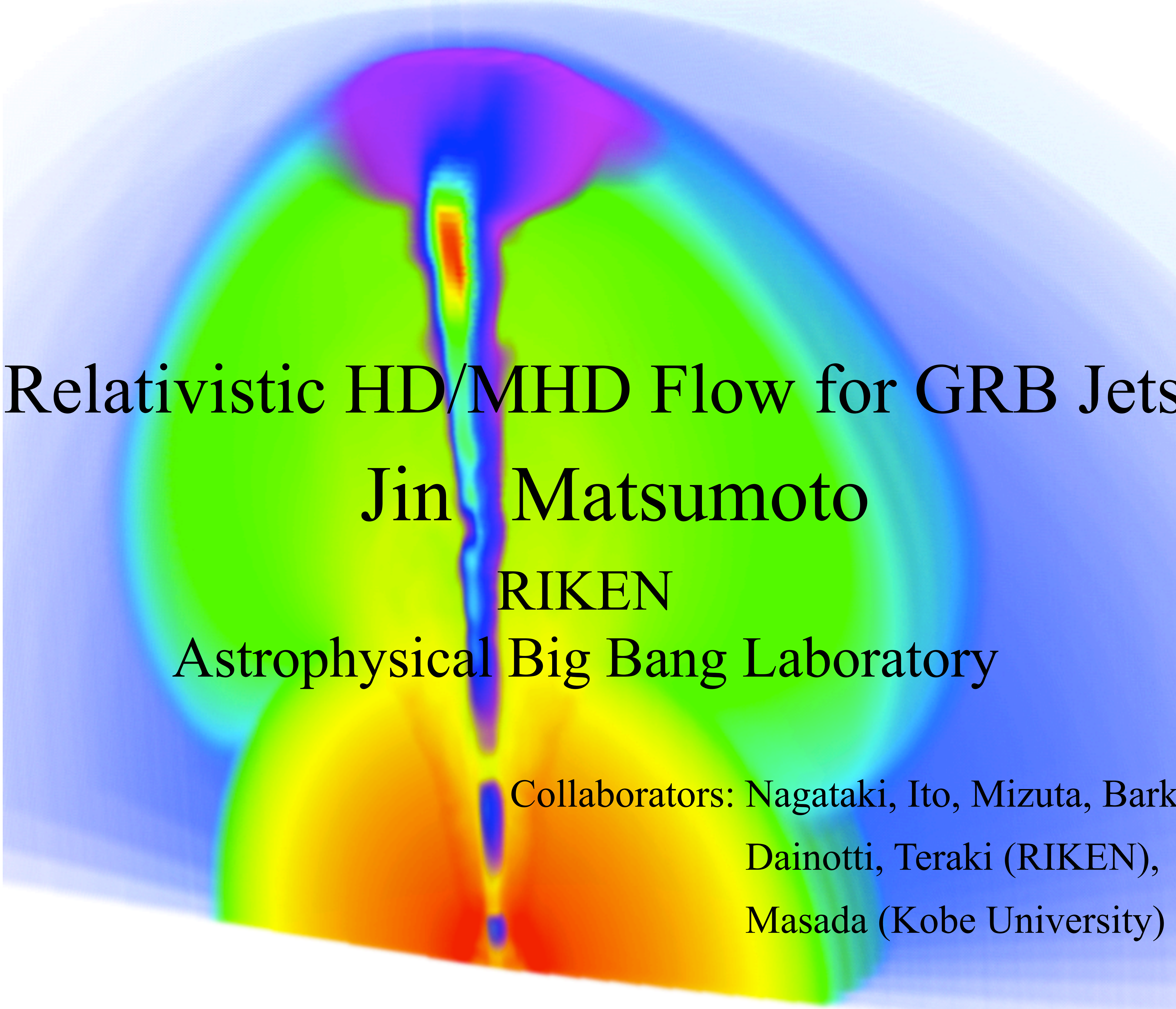

Relativistic HD/MHD Flow for GRB Jets

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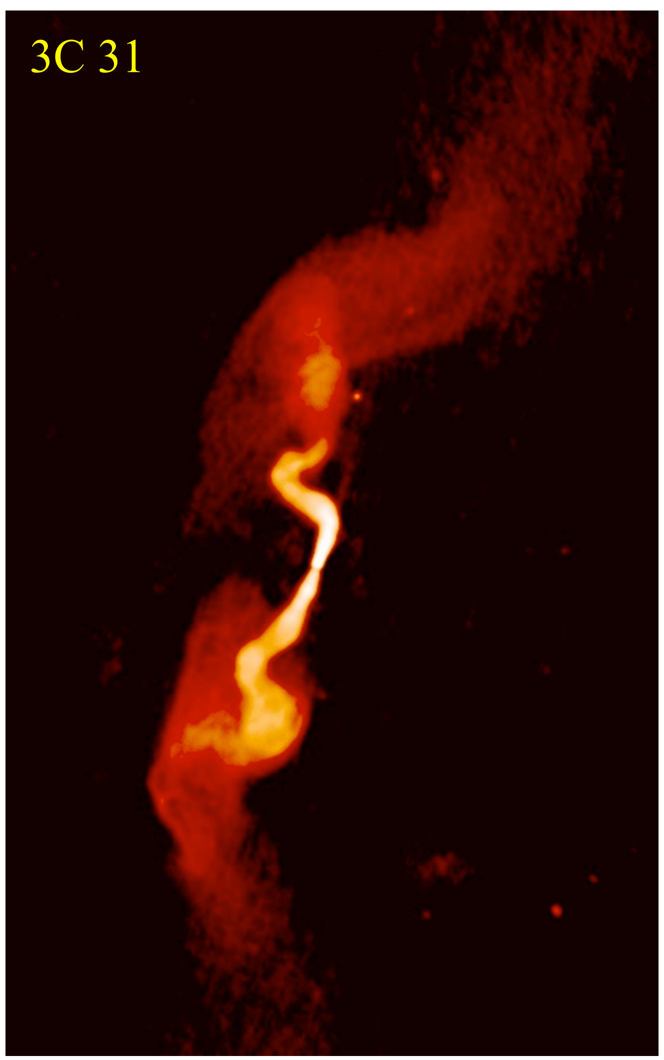
What a relativistic jet?

collimated bipolar outflow from gravitationally bounded object

- active galactic nuclei (AGN) jet: $\gamma \sim 10$
- microquasar jet: $v \sim 0.9c$
- Gamma-ray burst: $\gamma > 100$

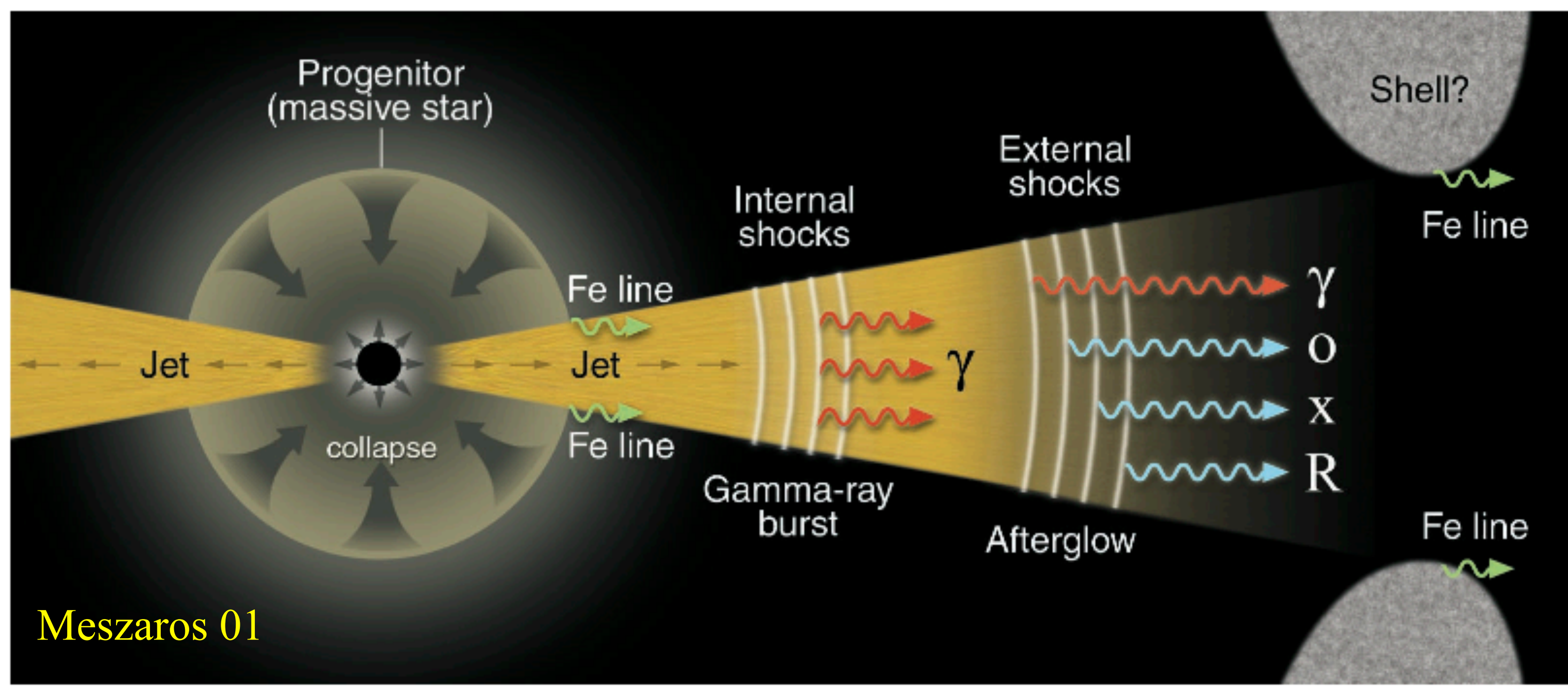
Lorentz factor

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

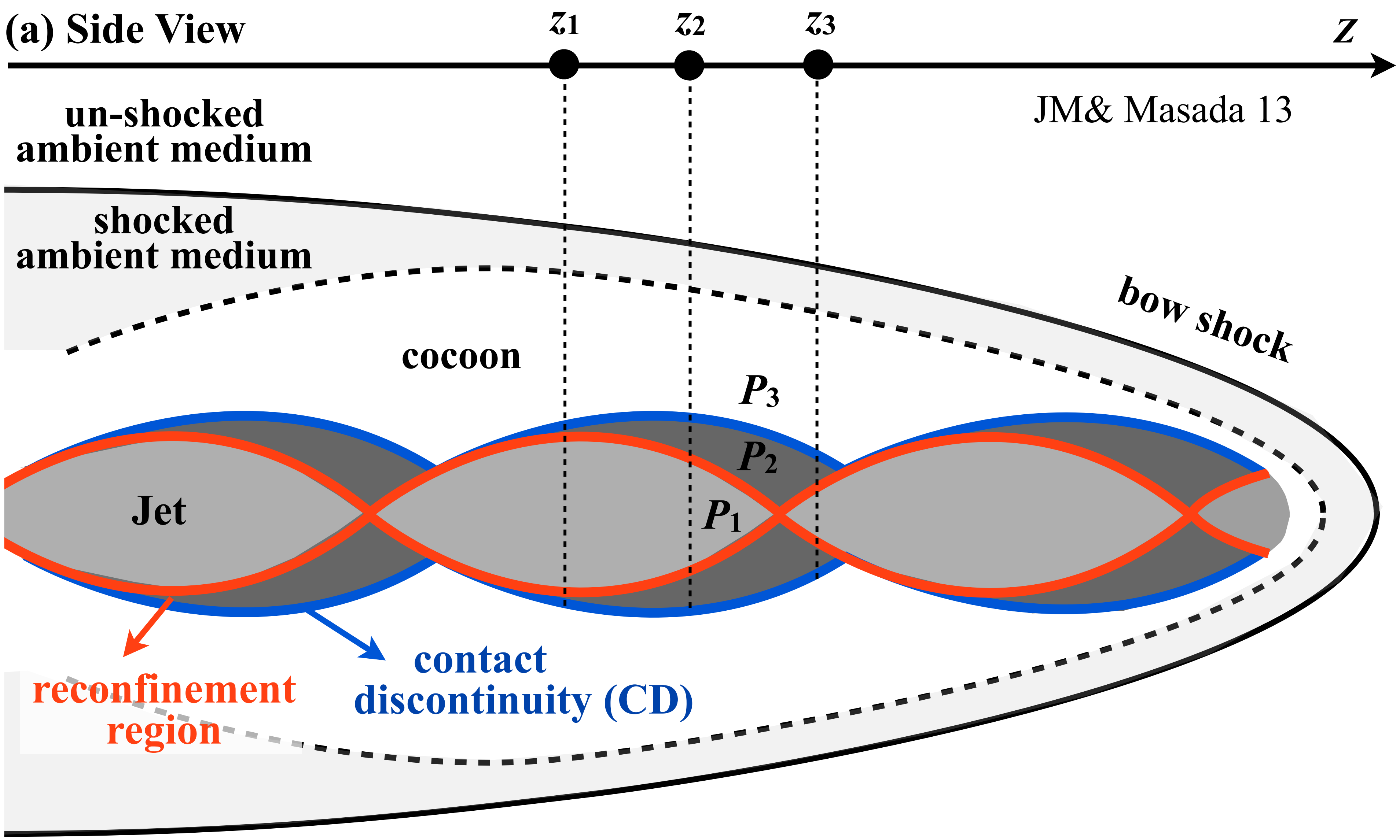


AGN jet

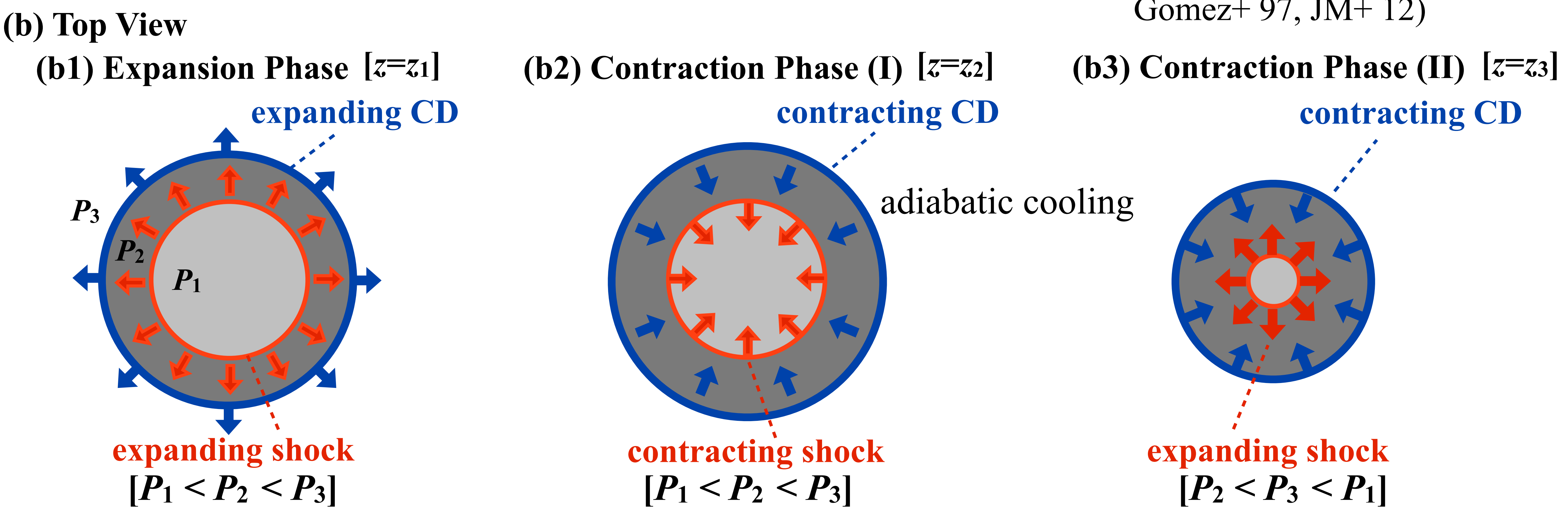
schematic picture of the GRB jet



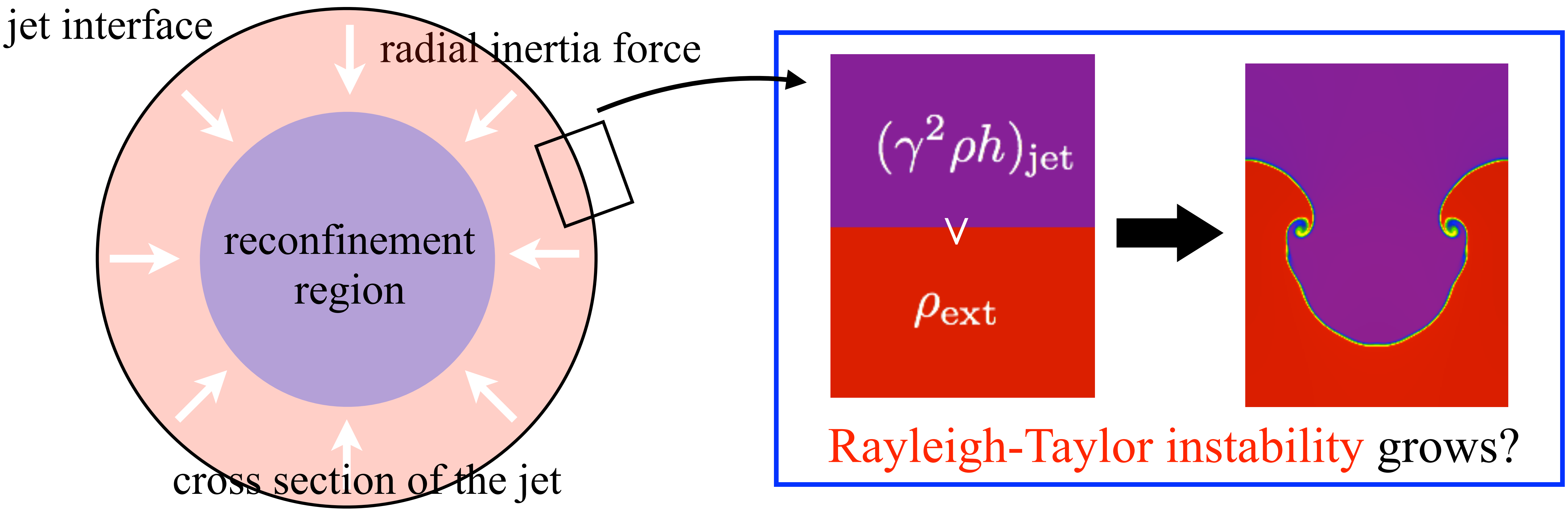
A relativistic jet is considered to be launched form the central engine and propagates the progenitor star.



- many numerical works in order to investigate the propagation dynamics of the relativistic jet (e.g., Marti+ 97, Aloy+ 00, Zhang+ 03,04, Mizuta+ 06, Perucho+ 08, Morsony+07, Lazzati+ 09, Lopez-Camara+ 13)
- reconfinement shock in the collimated jet (Norman et al. 1982; Sanders 1983)
- radial oscillating motion and repeated excitation of the reconfinement region (e.g., Gomez+ 97, JM+ 12)



Motivation of Our Study



To investigate the propagation dynamics and stability of the relativistic jet

- using relativistic hydrodynamic simulations

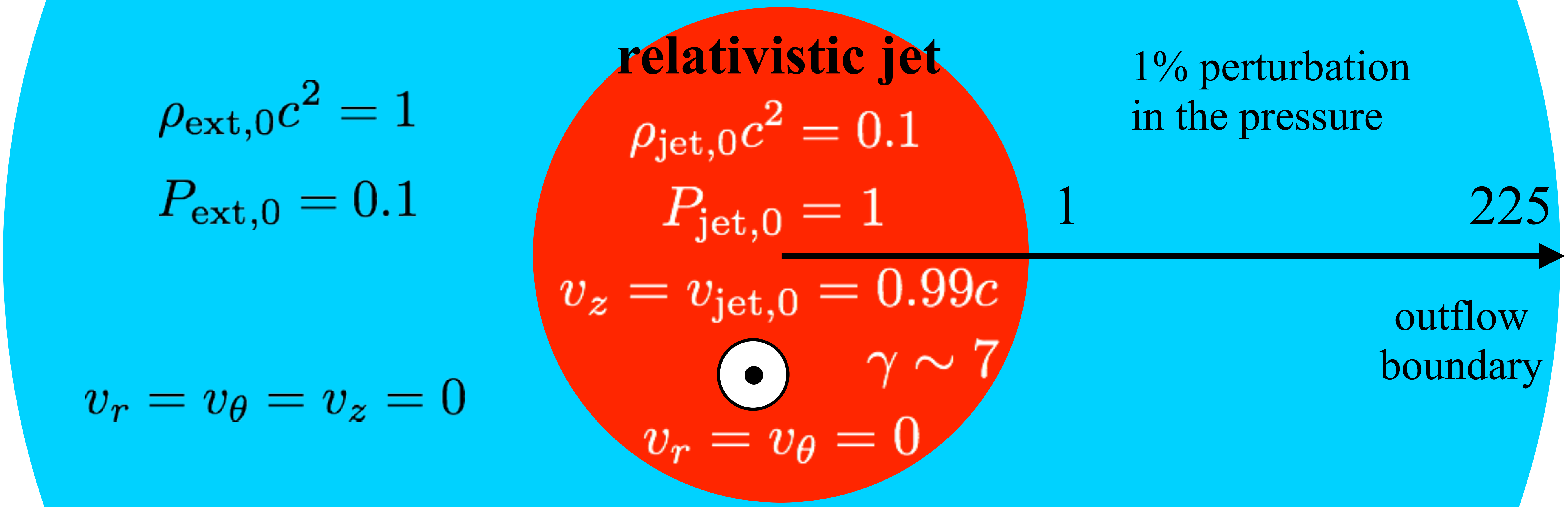
focus on the transverse structure of the jet

- ■ 2D simulations: evolution of the cross section of the relativistic jet
- ■ 3D simulation: propagation of the relativistic jet

2D simulations:
evolution of the cross section of the relativistic jet

JM & Masada, ApJL, **772**, L1 (2013)

Numerical Setting: 2D Toy Model



- cylindrical coordinate: (r - θ plane)
- relativistically hot jet (z-direction)
- ideal gas
- numerical scheme: HLLC (Mignone & Bodo 05)
- $\Delta r = 20/640$ $(0 < r < 20)$, $\Delta \log r = \mathrm{const.}$ $(20 < r < 225)$
- $\Delta\theta = 2\pi/200$

Basic Equations

mass conservation

$$\frac{\partial}{\partial t}(\gamma\rho) + \frac{1}{r}\frac{\partial}{\partial r}(r\gamma\rho v_r) + \frac{1}{r}\frac{\partial}{\partial \theta}(\gamma\rho v_\theta) = 0 \qquad \cancel{\frac{\partial}{\partial z}}$$

momentum conservation

$: r$

$$\frac{\partial}{\partial t}(\gamma^2\rho h v_r) + \frac{1}{r}\frac{\partial}{\partial r}(r(\gamma^2\rho h v_r^2 + P)) + \frac{1}{r}\frac{\partial}{\partial \theta}(\gamma^2\rho h v_r v_\theta) = \frac{P}{r}$$

$: \theta$

$$\frac{\partial}{\partial t}(\gamma^2\rho h v_\theta) + \frac{1}{r}\frac{\partial}{\partial r}(r(\gamma^2\rho h v_\theta v_r)) + \frac{1}{r}\frac{\partial}{\partial \theta}(\gamma^2\rho h v_\theta^2 + P) = -\frac{\gamma^2\rho h v_r v_\theta}{r}$$

$: z$

$$\frac{\partial}{\partial t}(\gamma^2\rho h v_z) + \frac{1}{r}\frac{\partial}{\partial r}(r(\gamma^2\rho h v_z v_r)) + \frac{1}{r}\frac{\partial}{\partial \theta}(\gamma^2\rho h v_z v_\theta) = 0$$

energy conservation

$$\frac{\partial}{\partial t}(\gamma^2\rho h - P) + \frac{1}{r}\frac{\partial}{\partial r}(r(\gamma^2\rho h v_r)) + \frac{1}{r}\frac{\partial}{\partial \theta}(\gamma^2\rho h v_\theta) = 0$$

specific enthalpy

$$\frac{h}{c^2} = 1 + \frac{\Gamma}{\Gamma - 1}\frac{P}{\rho c^2}$$

ratio of specific heats

$$\Gamma = \frac{4}{3}$$

Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - (v_r^2 + v_\theta^2 + v_z^2)}}$$

Time Evolution of Jet Cross Section

The effective inertia is important.

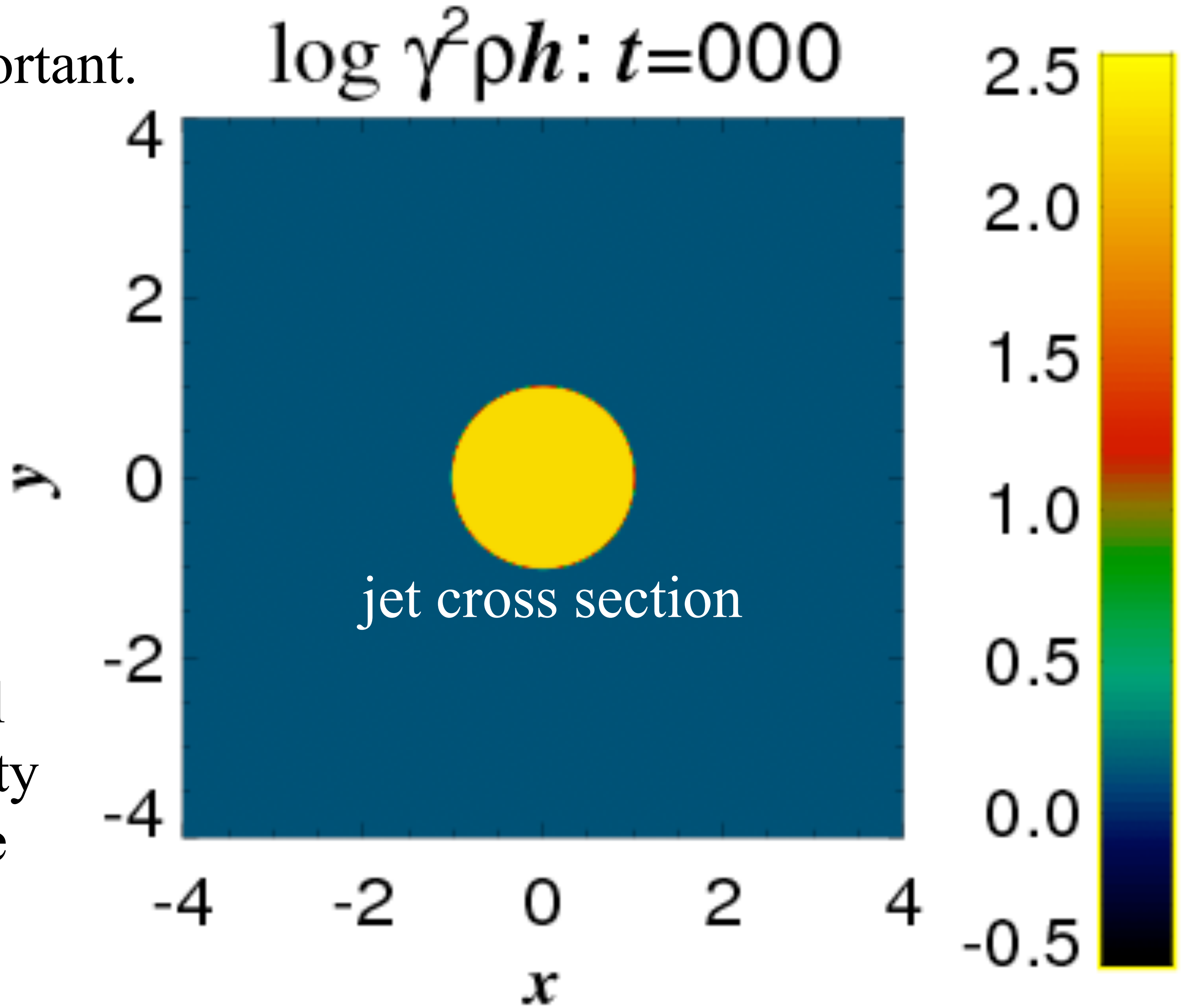
relativistically hot plasma:

$$\rho_{\rm jet} c^2 \leq P_{\rm jet}$$

effective inertia:

$$\gamma^2 \rho h = \gamma^2 (\rho c^2 + 4P)$$

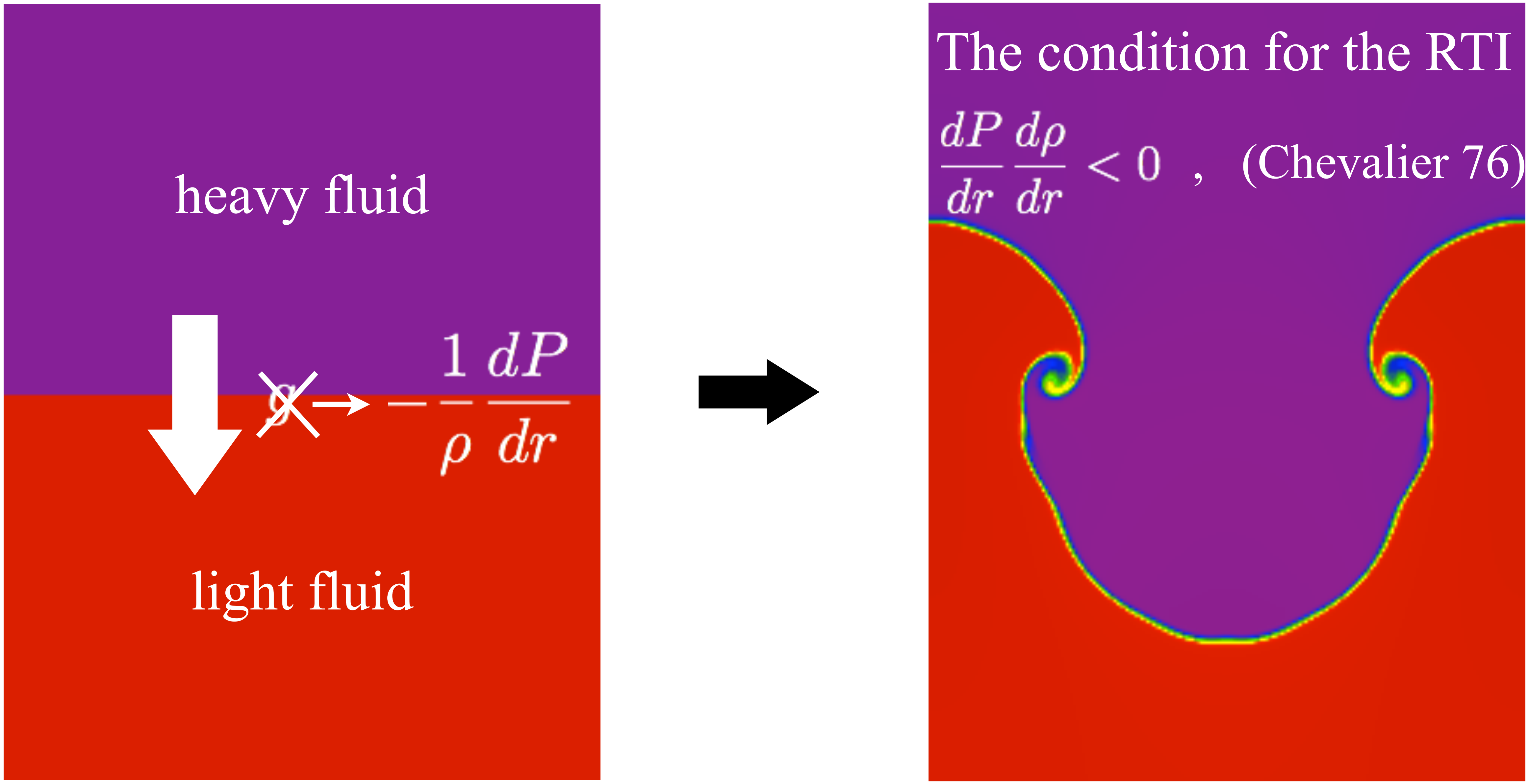
The effective inertia of the jet is lager than the external medium although the density of the jet is smaller than the external medium in our setting.



The amplitude of the corrugated jet interface grows as time passes.

A finger-like structure is a typical outcome of the Rayleigh-Taylor instability.

Growth of RTI in SN Explosion



It is well known that a contact discontinuity, formed where a heavy fluid is supported above a light fluid against gravity, is unstable to perturbations to the boundary between the two fluids.

Although the gravity is negligible in SN explosions, the acceleration of the gas works as a gravity.

The mechanism of the growth of RTI

The effective inertia is important.

relativistically hot plasma:

$$\rho_{\rm jet} c^2 \leq P_{\rm jet}$$

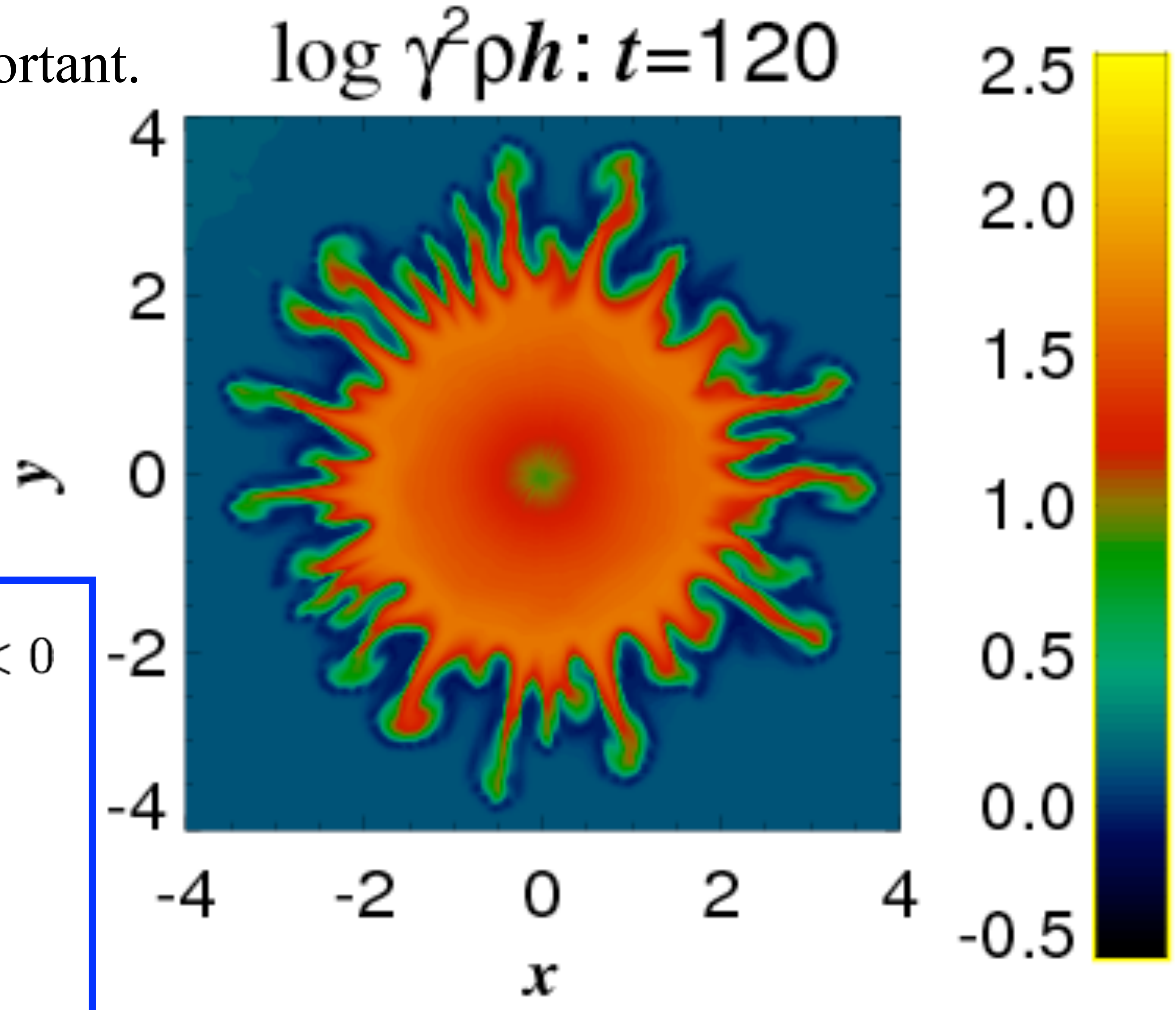
effective inertia:

$$\gamma^2 \rho h = \gamma^2 (\rho c^2 + 4P)$$

$$\frac{d\rho}{dr} > 0, \quad \frac{dP}{dr} > 0, \quad \frac{d(\gamma^2 \rho h)}{dr} < 0$$

$$\frac{dP}{dr}\frac{d\rho}{dr} > 0$$

$$\frac{dP}{dr}\frac{d(\gamma^2 \rho h)}{dr} < 0$$



In addition to the growth of the Rayleigh-Taylor instability, the growth of the Richtmyer-Meshkov instability is also contributed to the finger like structures.

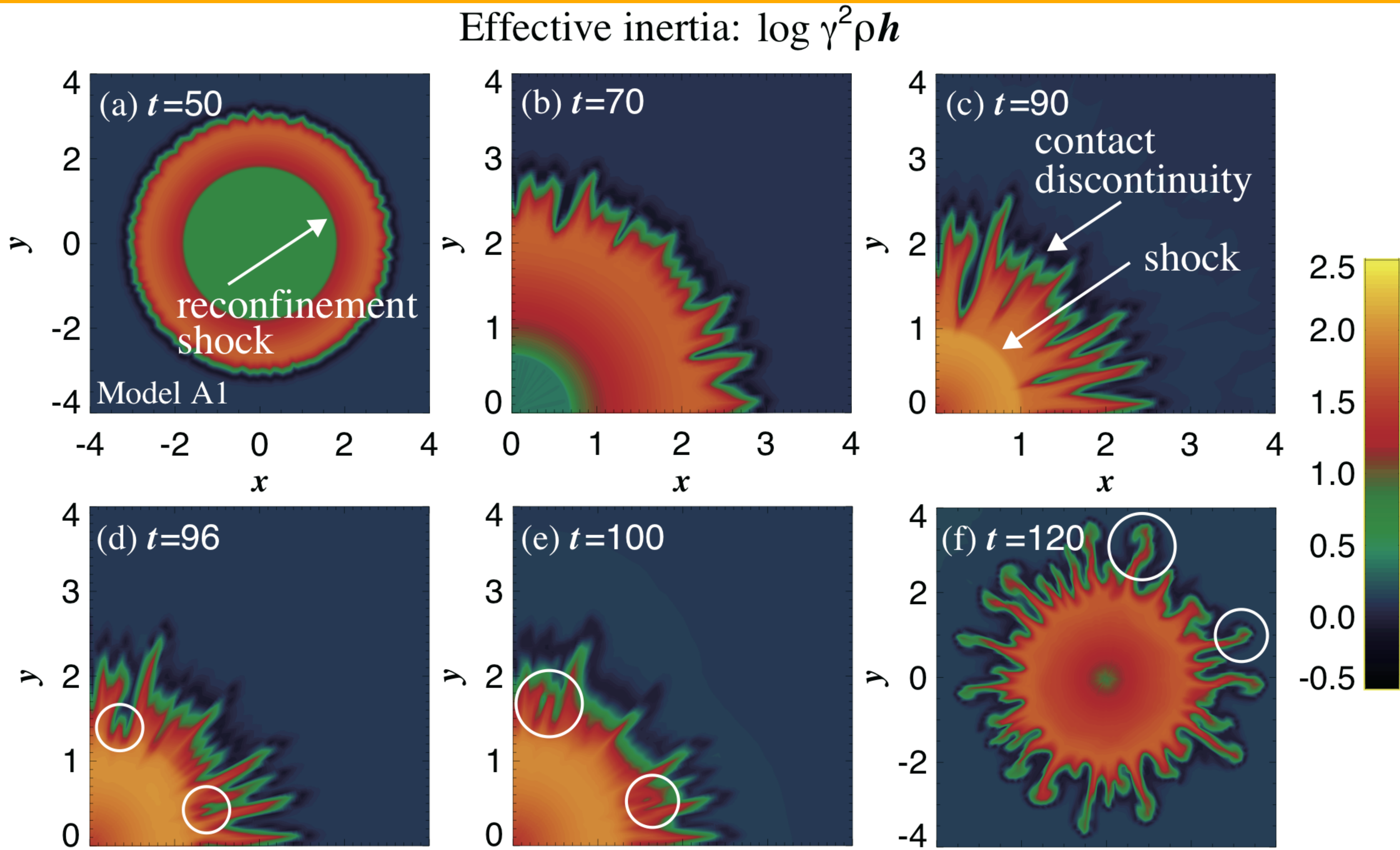
Richtmyer-Meshkov Instability

contact discontinuity

- The Richtmyer-Meshkov instability is induced by impulsive acceleration due to shock passage.
- The perturbation amplitude grows linearly in time (Richtmyer 1960)

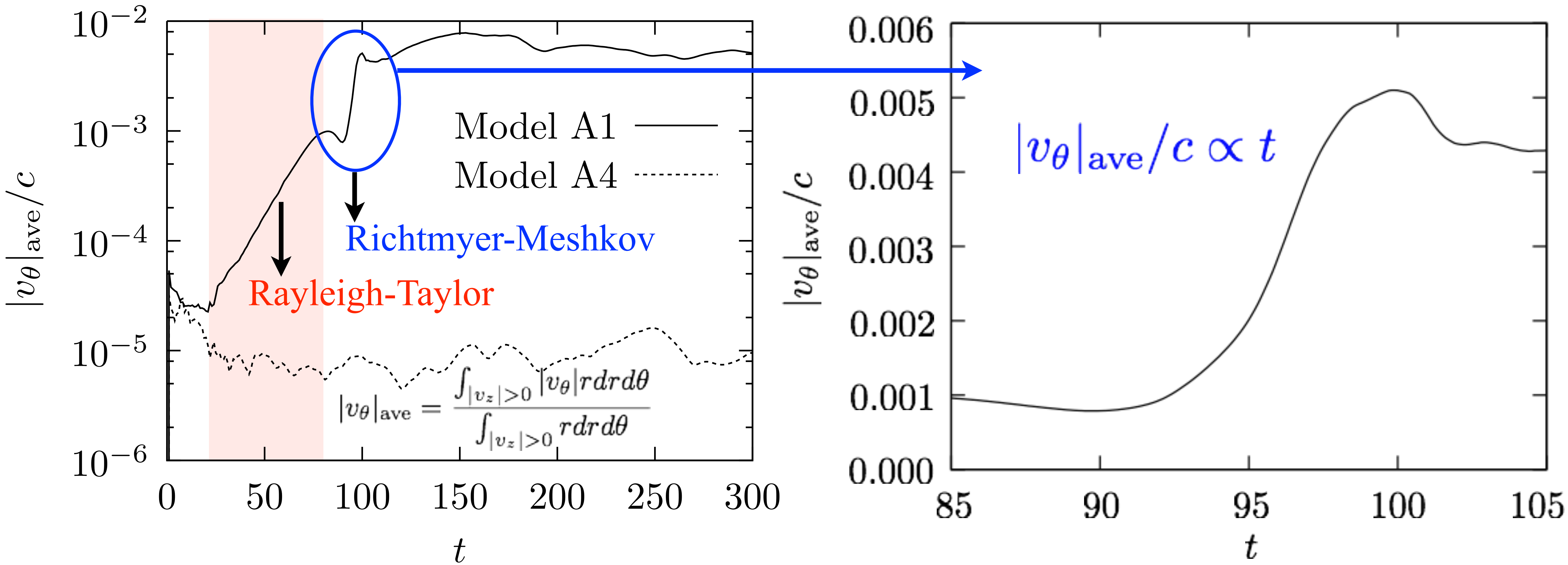
$$\frac{\partial \delta}{\partial t} = k\delta_0^* A^* v^* \quad , \qquad A^* = \frac{\rho_1^* - \rho_2^*}{\rho_1^* + \rho_2^*}$$

Time Evolution of Jet Cross Section



Richtmyer-Meshkov instability is secondary excited between the RTI fingers. Almost all finger-like structures in panel (f) have their origin in the RMI.

Synergetic Growth of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities



development of the Rayleigh-Taylor instability at the jet interface

$|v_\theta|_{\rm ave}$ increases exponentially.

excitation of the Richtmyer-Meshkov instability at the jet interface

$|v_\theta|_{\rm ave}$ grows linearly with time.

The transverse structure of the jet is dramatically deformed by a synergetic growth of the Rayleigh-Taylor and Richtmyer-Meshkov instabilities once the jet-external medium interface is corrugated in the case with the pressure-mismatched jet.

3D simulation:
propagation of the relativistic jet

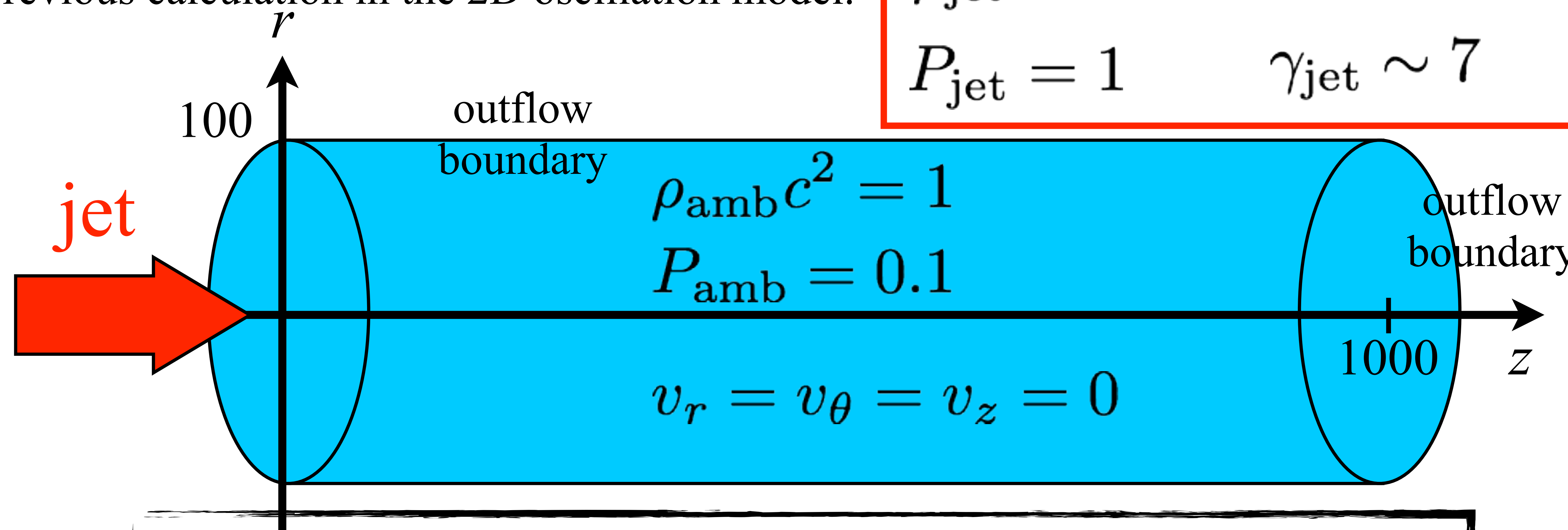
focusing on the impact of the oscillation-induced Rayleigh-Taylor and Richtmyer-Meshkov instabilities on the 3D jet propagation.

Numerical Setting: 3D Toy Model

Hydrodynamic variables are the same as the previous calculation in the 2D oscillation model.

$$\rho_{\mathrm{jet}} c^2 = 0.1 \quad v_z = 0.99c$$

$$P_{\mathrm{jet}} = 1 \qquad \gamma_{\mathrm{jet}} \sim 7$$



- cylindrical coordinate
- relativistic jet (z-direction)
- ideal gas
- numerical scheme: HLLC (Mignone & Bodo 05)
- uniform grid: $\Delta r = 0.0666$, $\Delta\theta = 2\pi/160$, $\Delta z = 1$

Basic Equations

mass conservation

$$\frac{\partial}{\partial t}(\gamma\rho) + \nabla\cdot(\gamma\rho\mathbf{v}) = 0$$

momentum conservation

$$\frac{\partial}{\partial t}(\gamma^2\rho h\mathbf{v}) + \nabla\cdot(\gamma^2\rho h\mathbf{v}\mathbf{v} + Pc^2\mathbf{I}) = 0$$

energy conservation

$$\frac{\partial}{\partial t}(\gamma^2\rho h - P) + \nabla\cdot(\gamma^2\rho h\mathbf{v}) = 0$$

specific enthalpy

$$\frac{h}{c^2} = 1 + \frac{\Gamma}{\Gamma - 1}\frac{P}{\rho c^2}$$

ratio of specific heats

$$\Gamma = \frac{4}{3}$$

Lorentz factor

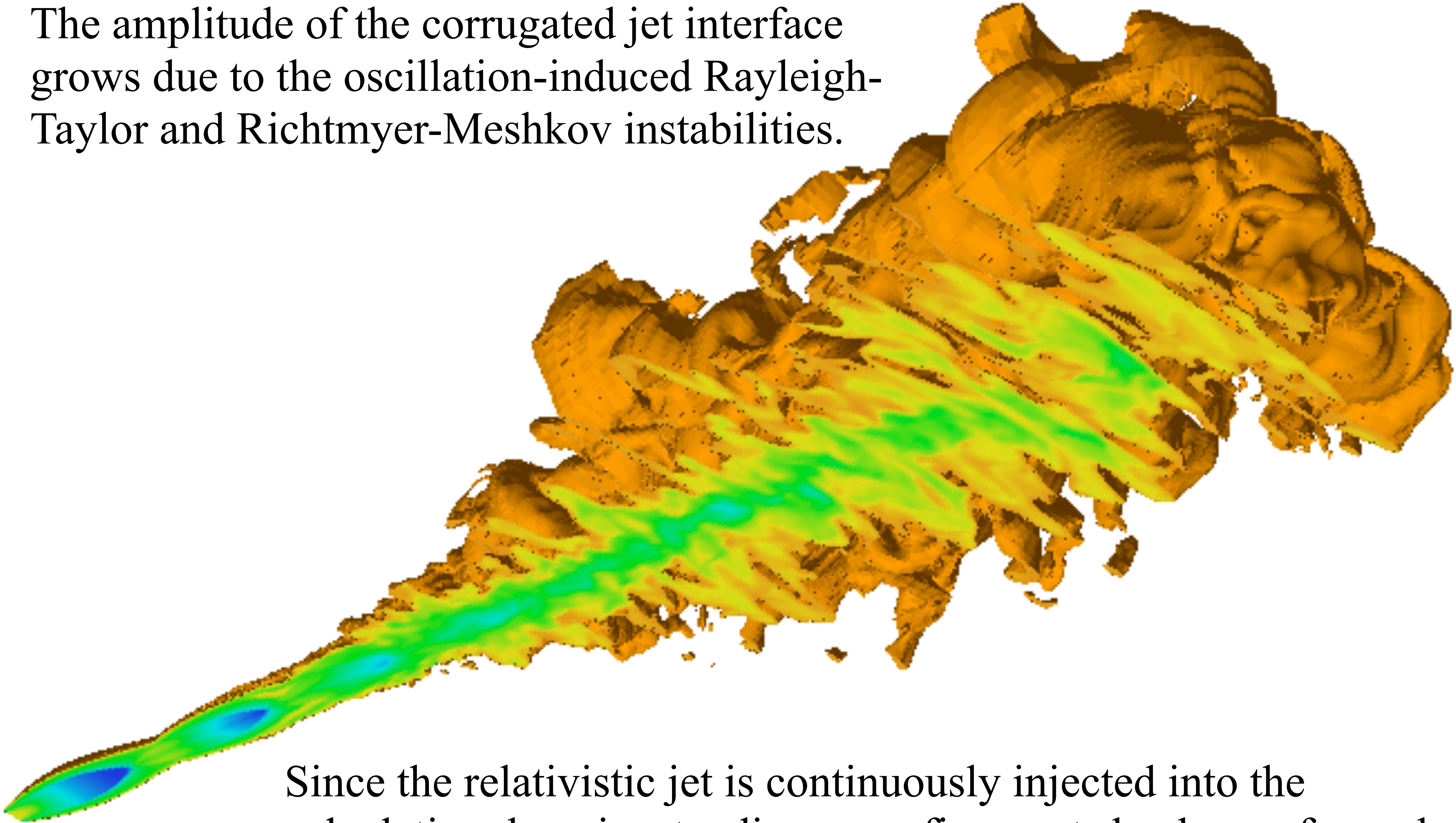
$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

In 3D case, we calculated the numerical flux to all directions.

Result: Density

Only the jet component is shown.

The amplitude of the corrugated jet interface grows due to the oscillation-induced Rayleigh-Taylor and Richtmyer-Meshkov instabilities.

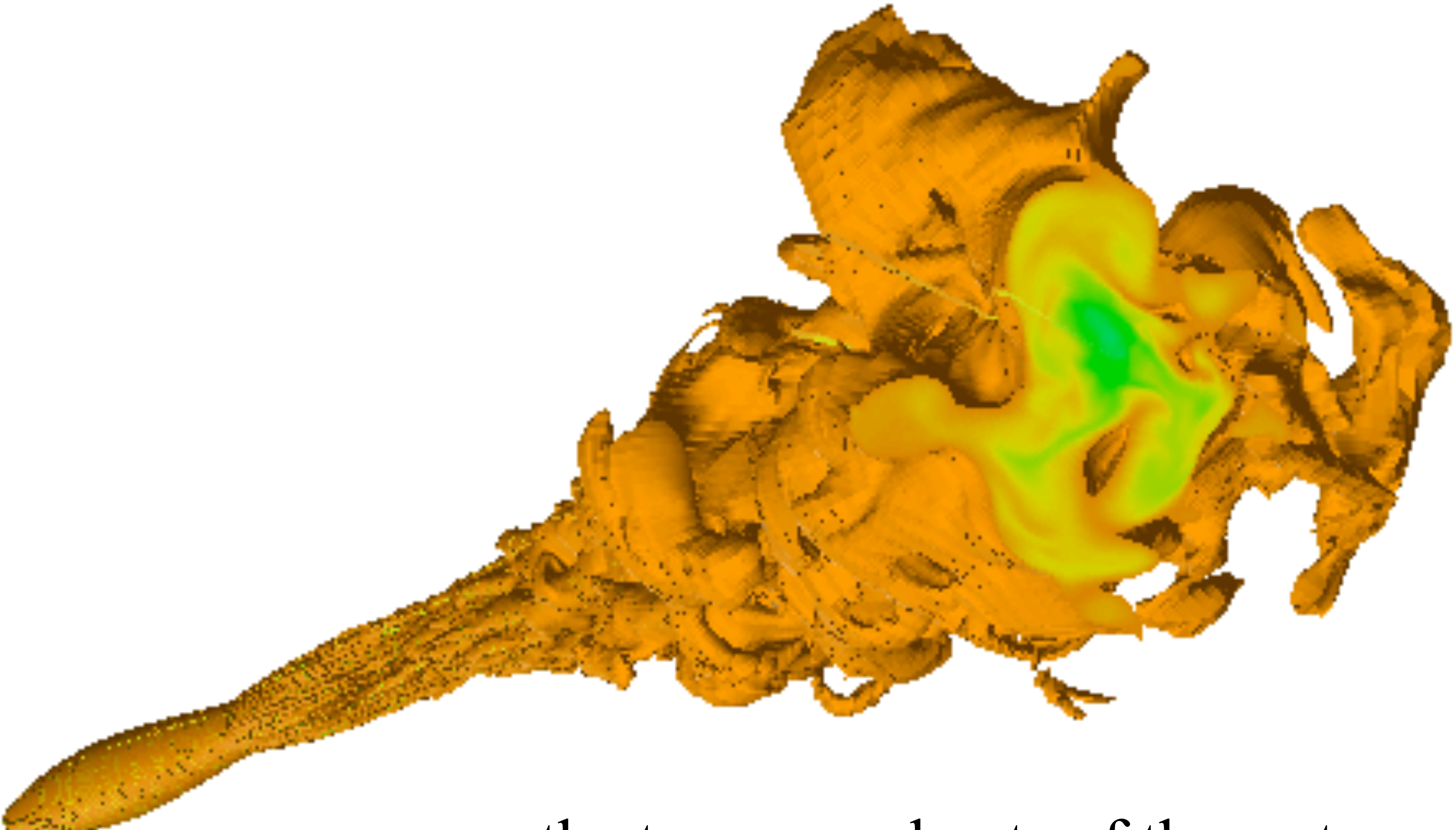


Since the relativistic jet is continuously injected into the calculation domain, standing reconfinement shocks are formed.

Result: Density

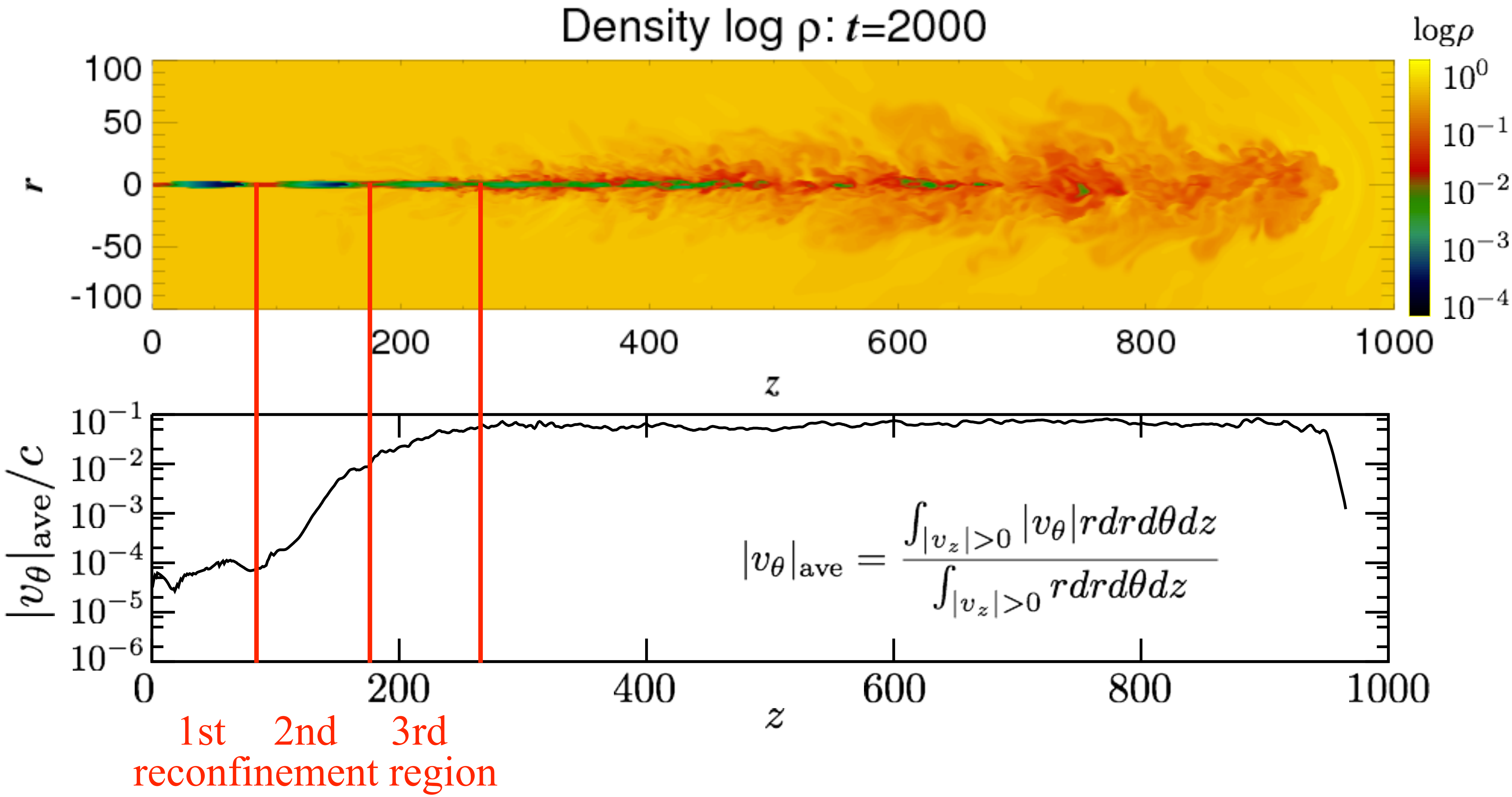
Only the jet component is shown.

We confirmed that the Rayleigh-Taylor and Richtmyer-Meshkov instabilities grows at the interface of the jet. The material mixing due to the Rayleigh-Taylor and Richtmyer-Meshkov instabilities between the jet and surrounding medium leads to the deformation of the jet.



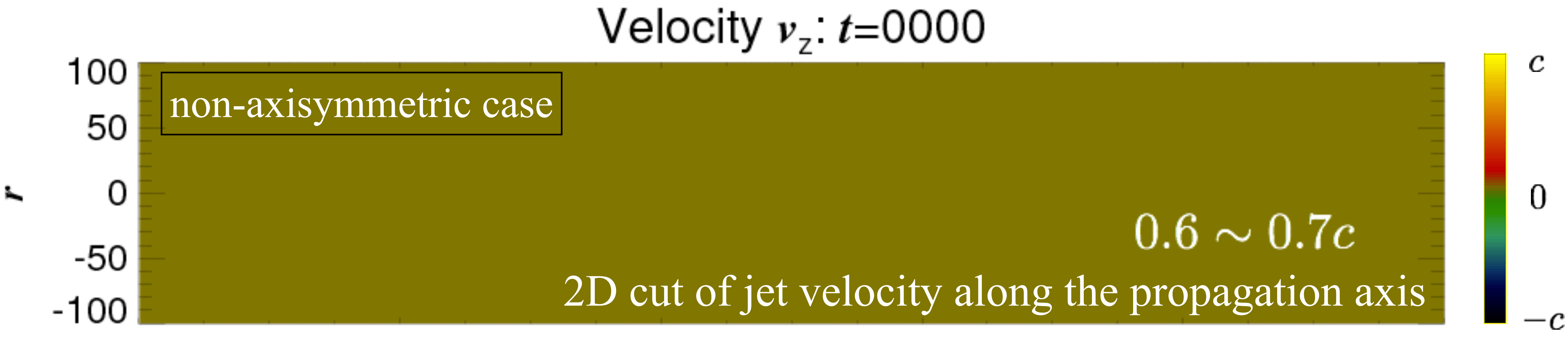
the transversal cuts of the rest-mass density

Spatial Growth Rate of Azimuthal Velocity

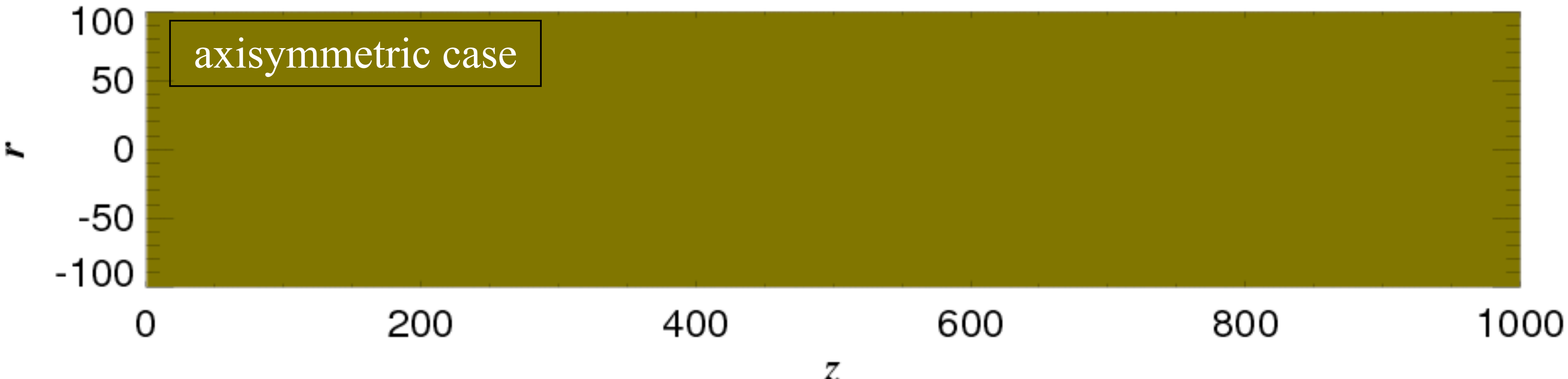


■ Growth of the volume-averaged azimuthal velocity is saturated around the 3rd reconfinemet region.

non-Axisymmetric vs Axisymmetric

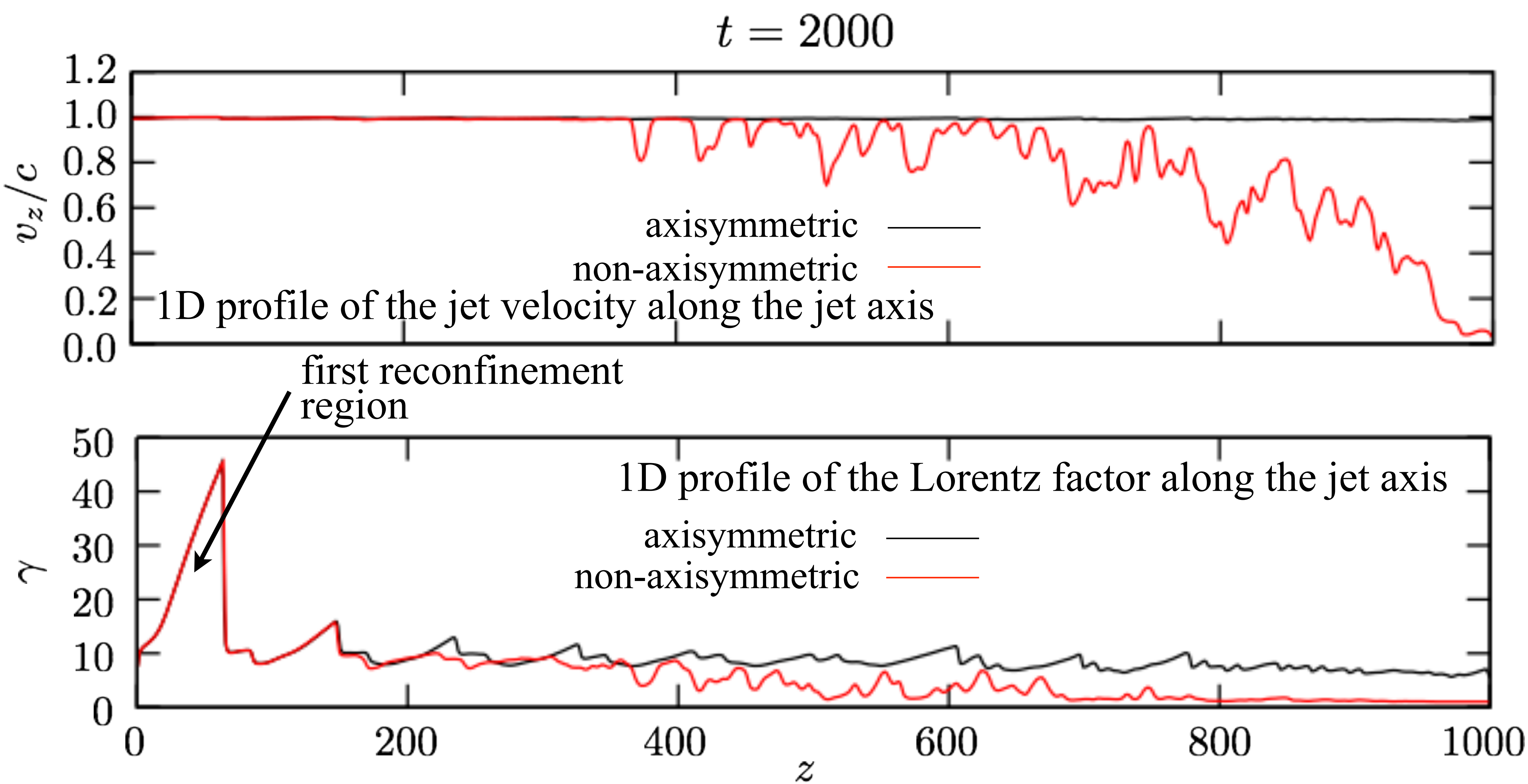


The numerical settings of the axisymmetric case are same as the 3D case except the azimuthal direction.



- deceleration of the jet due to the mixing between the jet and surrounding medium in the non-axisymmetric case.
- Three-dimensionality is essential for the non-linear dynamics and stability of the relativistic jet.

Deceleration of the jet due to mixing



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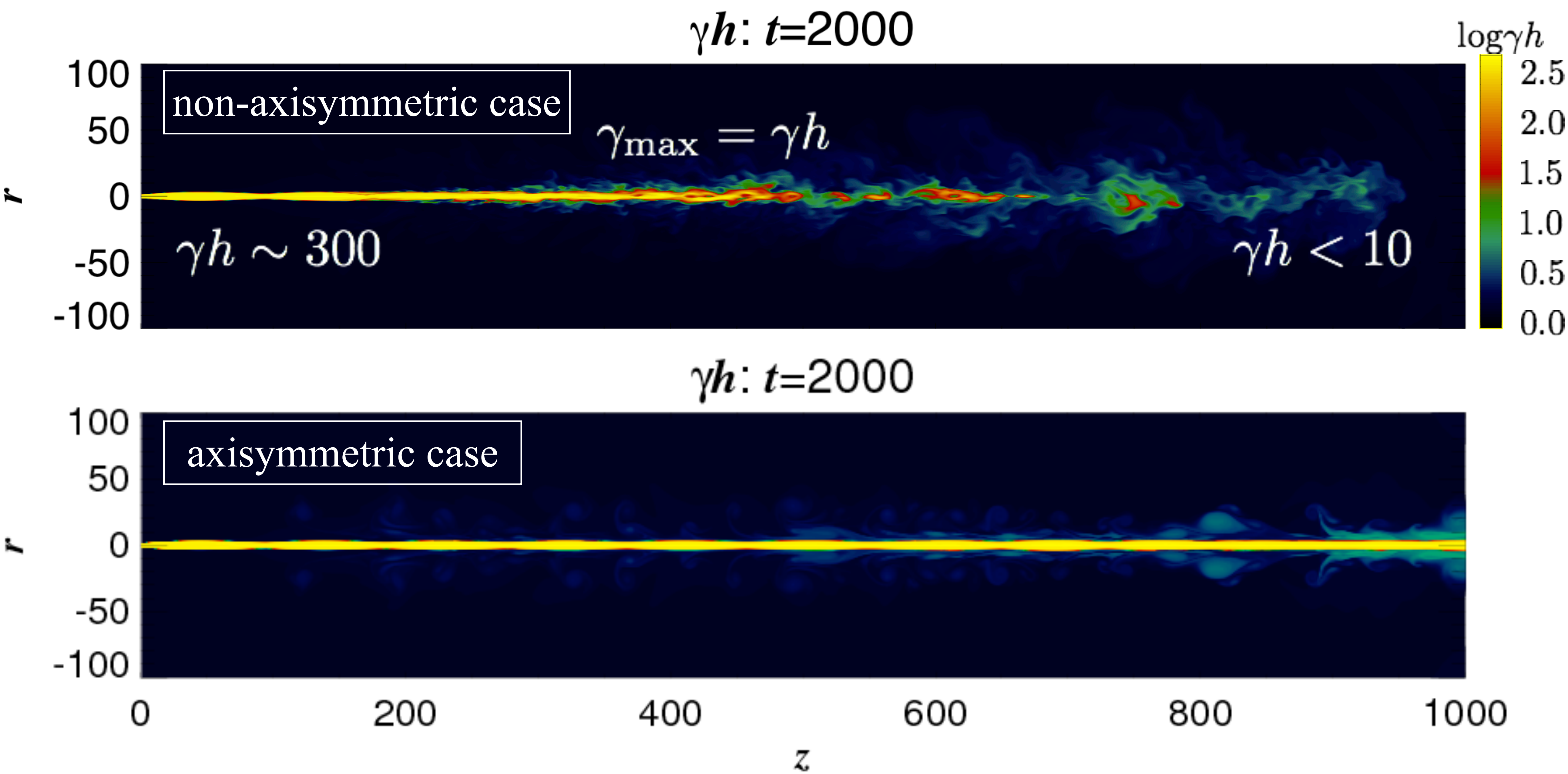
Deceleration of the jet due to mixing

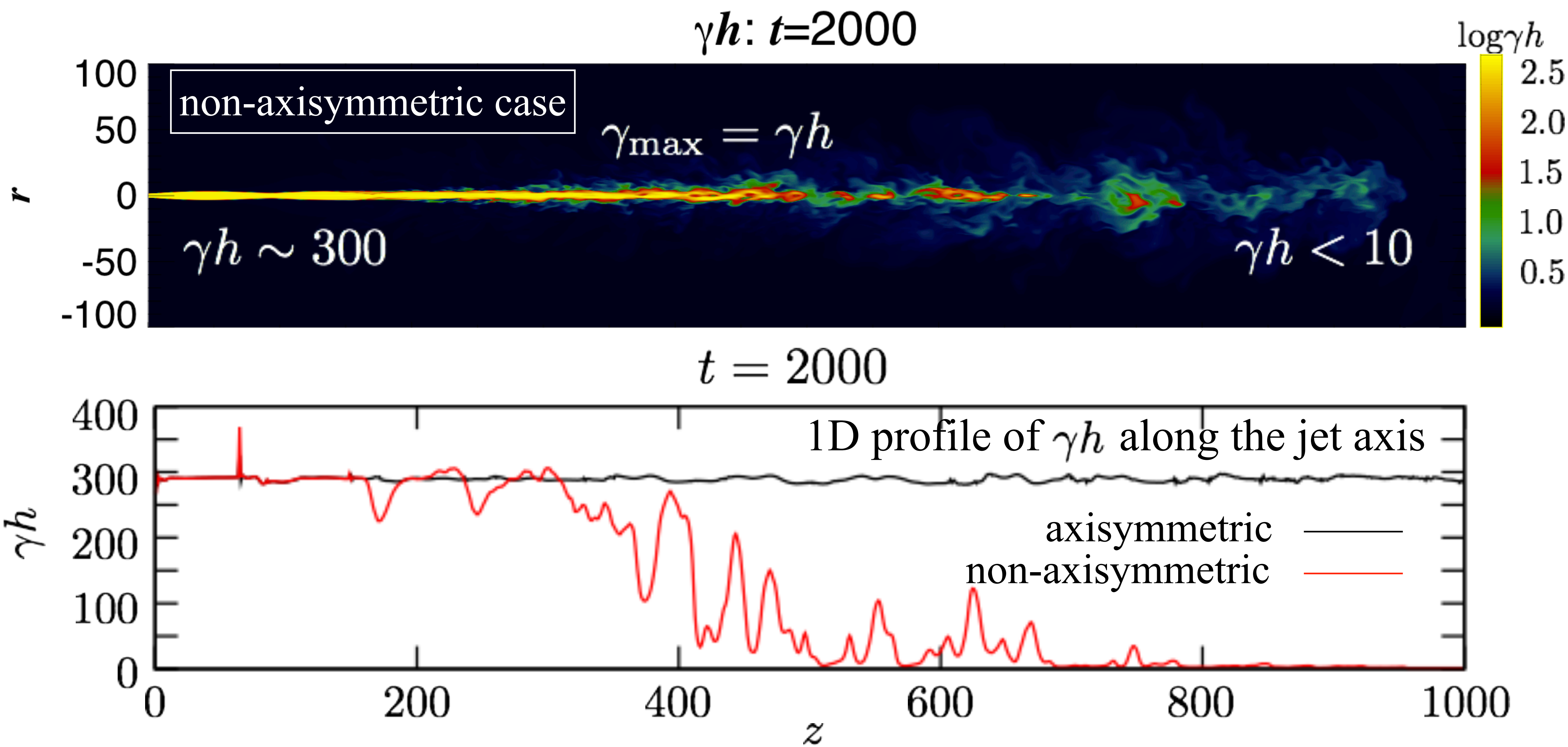


■ relativistic Bernoulli equation: $\gamma h \sim \text{const.}$

γh gives the maximum Lorentz factor of the jet after adiabatic expansion.

However, γh drops to ~ 10 due to the mixing in this case.

Deceleration of the jet due to mixing



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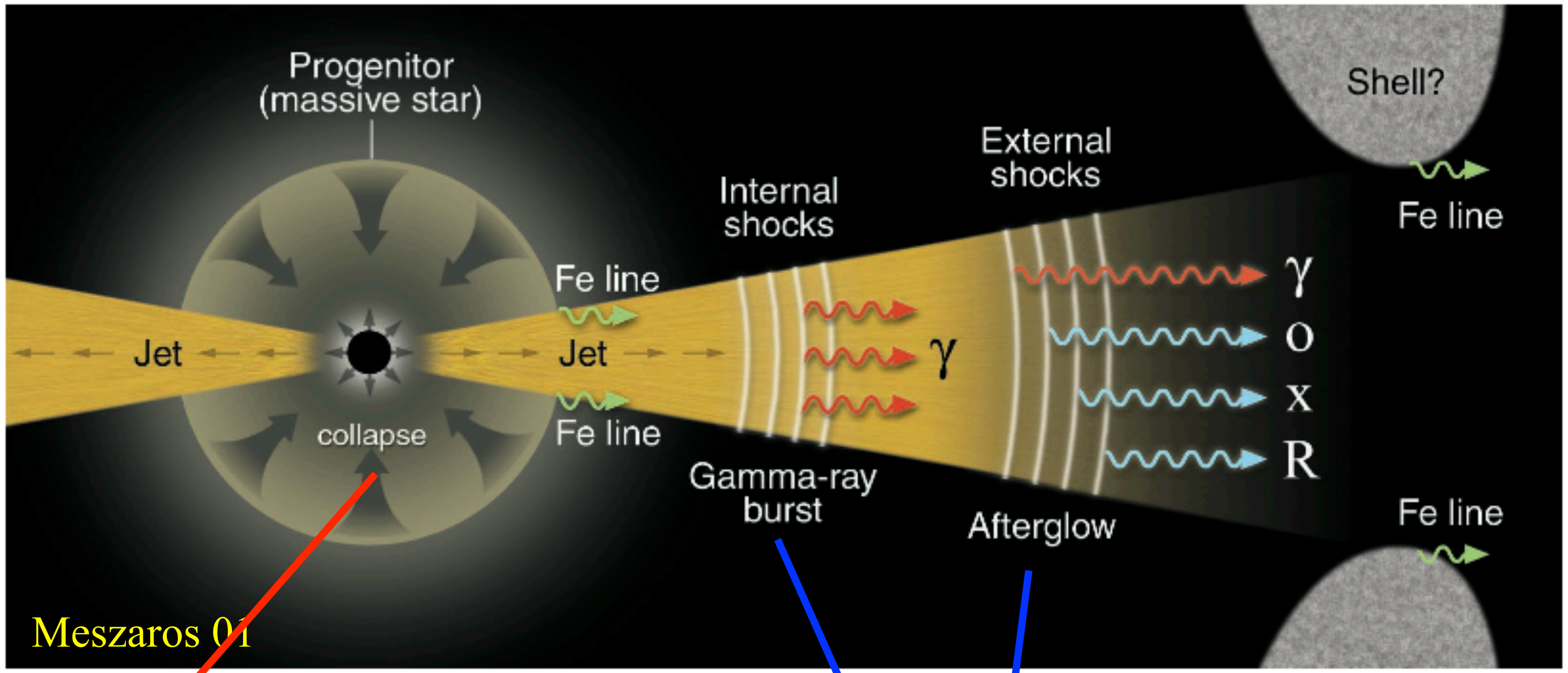
γh gives the maximum Lorentz factor of the jet after adiabatic expansion.

However, γh drops to ~ 10 due to the mixing in this case.

Magnetically Driven Jet?

schematic picture of the GRB jet



Central engine

- MHD process

  Extraction of the rotational energy of the BH or accretion disk through B-field

- thermal process

  $\nu\bar{\nu}$ -annihilation $\rightarrow e^{+}e^{-}$-annihilation
  $\rightarrow$ fireball

Observation

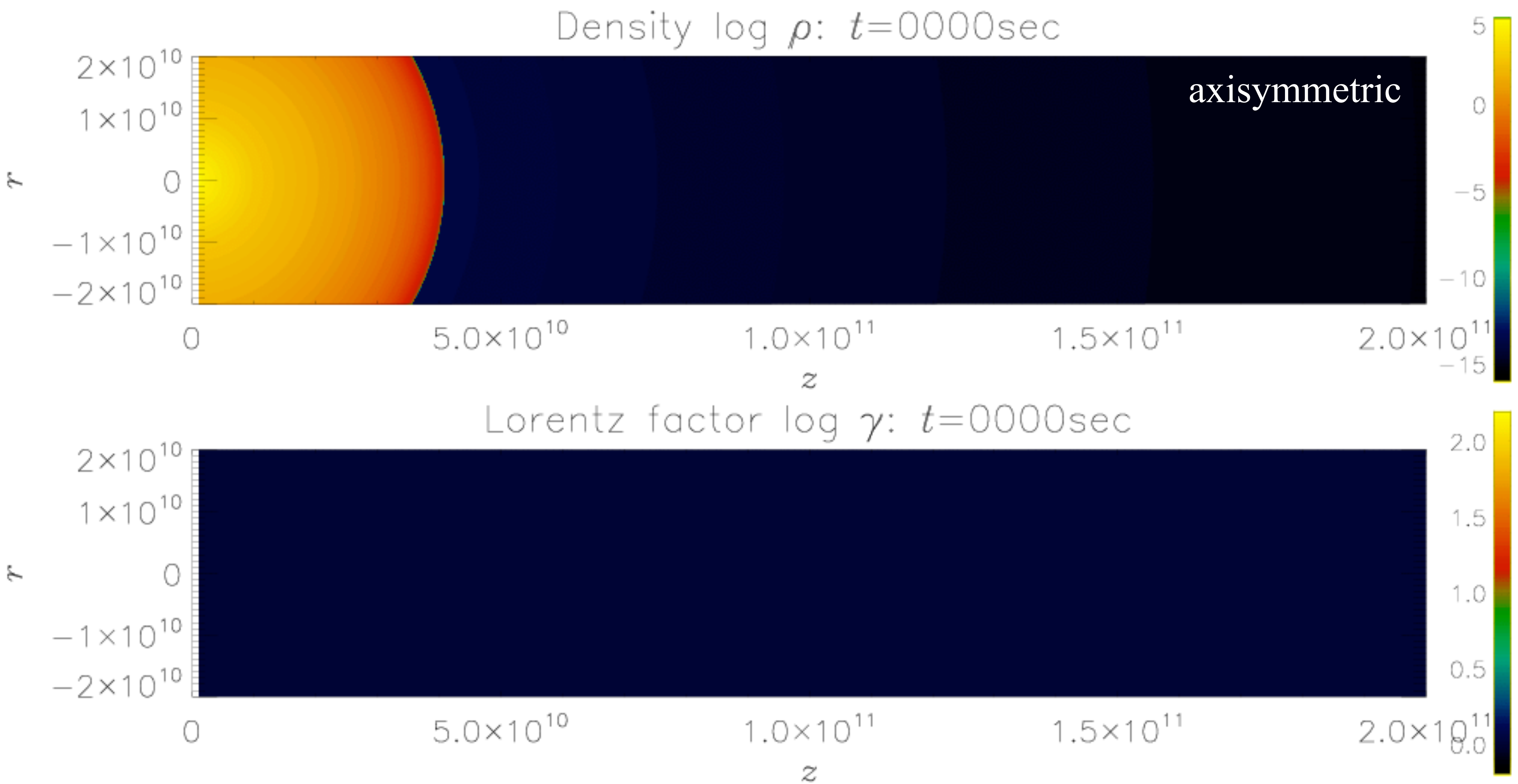
- polarization in prompt phase

  (Yonetoku et al. 2011, 2012)

- polarization in afterglow phase

  (Mundell et al. 2014, Wiersema et al. 2014)

Propagation of MHD jet for GRB



progenitor: 16TI model (Woosley & Heger 06)

jet:

$$L_{\rm jet} = 10^{51}\ {\rm erg/s} \qquad \beta_{\rm jet} = P_{\rm gas}/P_{\rm mag} = 1$$

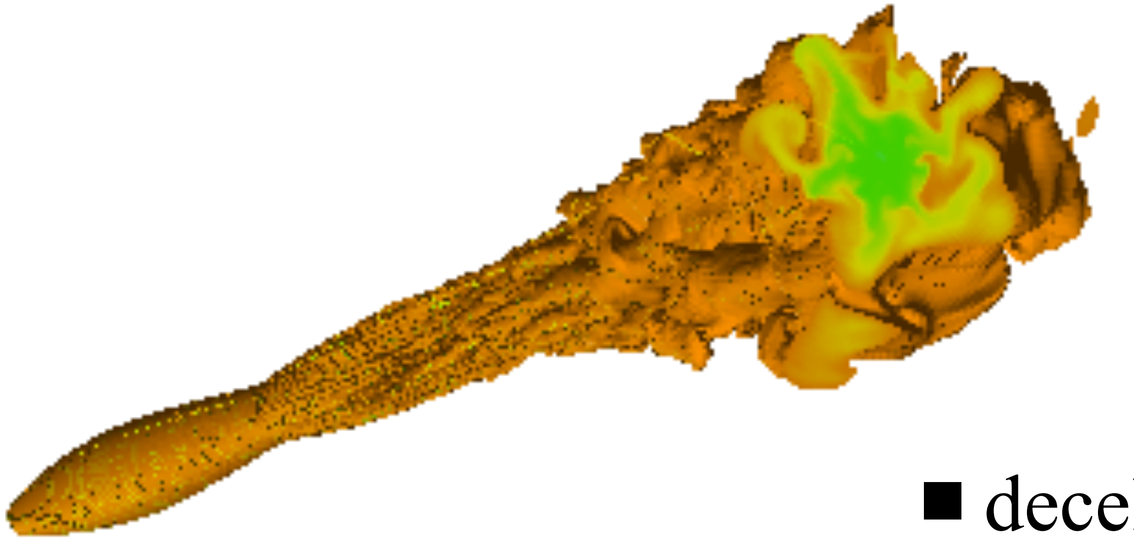
$$\gamma_{\rm jet} = 5 \qquad h_{\rm jet}/\sigma_{\rm jet} \sim 2$$

$$B_{\rm jet} = B_\phi$$

Summary

Basic physics of the propagation of the relativistic jet is investigated though 3D HD/2D MHD numerical simulations.

■ A pressure mismatch between the jet and surrounding medium leads to the radial oscillating motion of the jet.



■ The jet-external medium interface is unstable due to the oscillation-induced

⇐ { Rayleigh-Taylor instability
Richtmyer-Meshkov instability

■ deceleration of the jet due to the mixing between the jet and surrounding medium

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Next Study:

■ more realistic situation for relativistic MHD jets in the context of GRBs