Rayleigh-Taylor and Richtmyer-Meshkov Instabilities in Relativistic Hydrodynamic Jets

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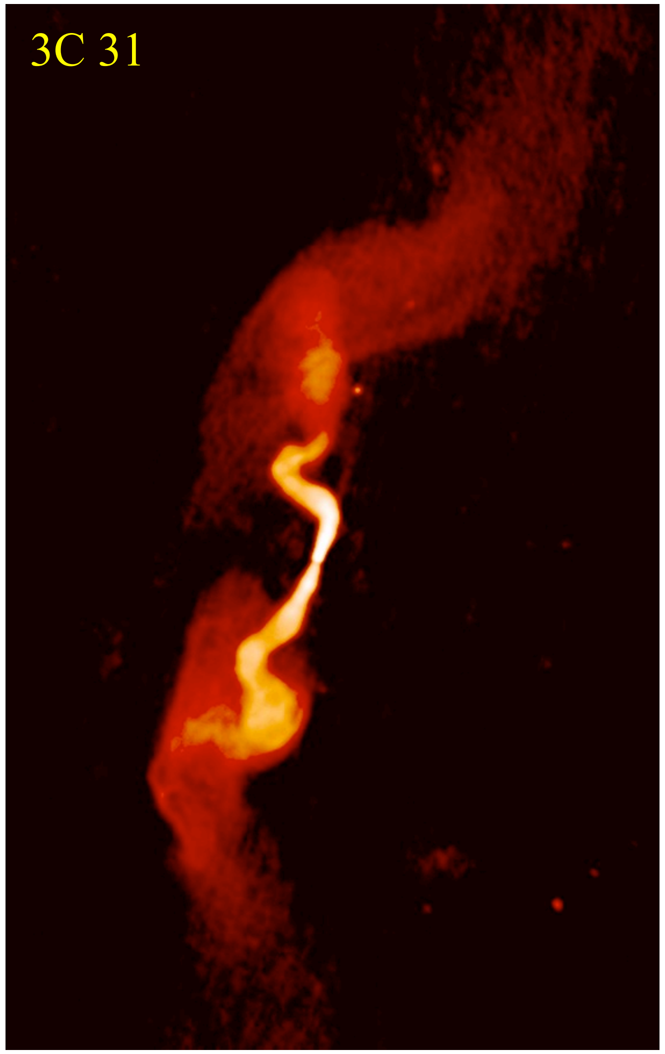
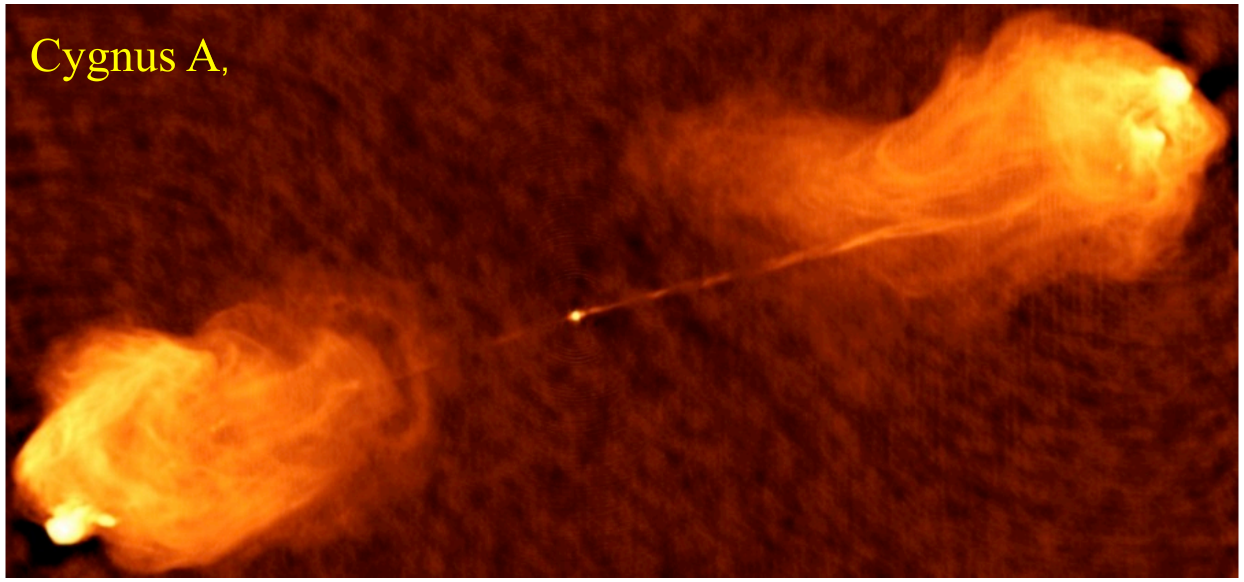
Morphological Dichotomy of the Jet

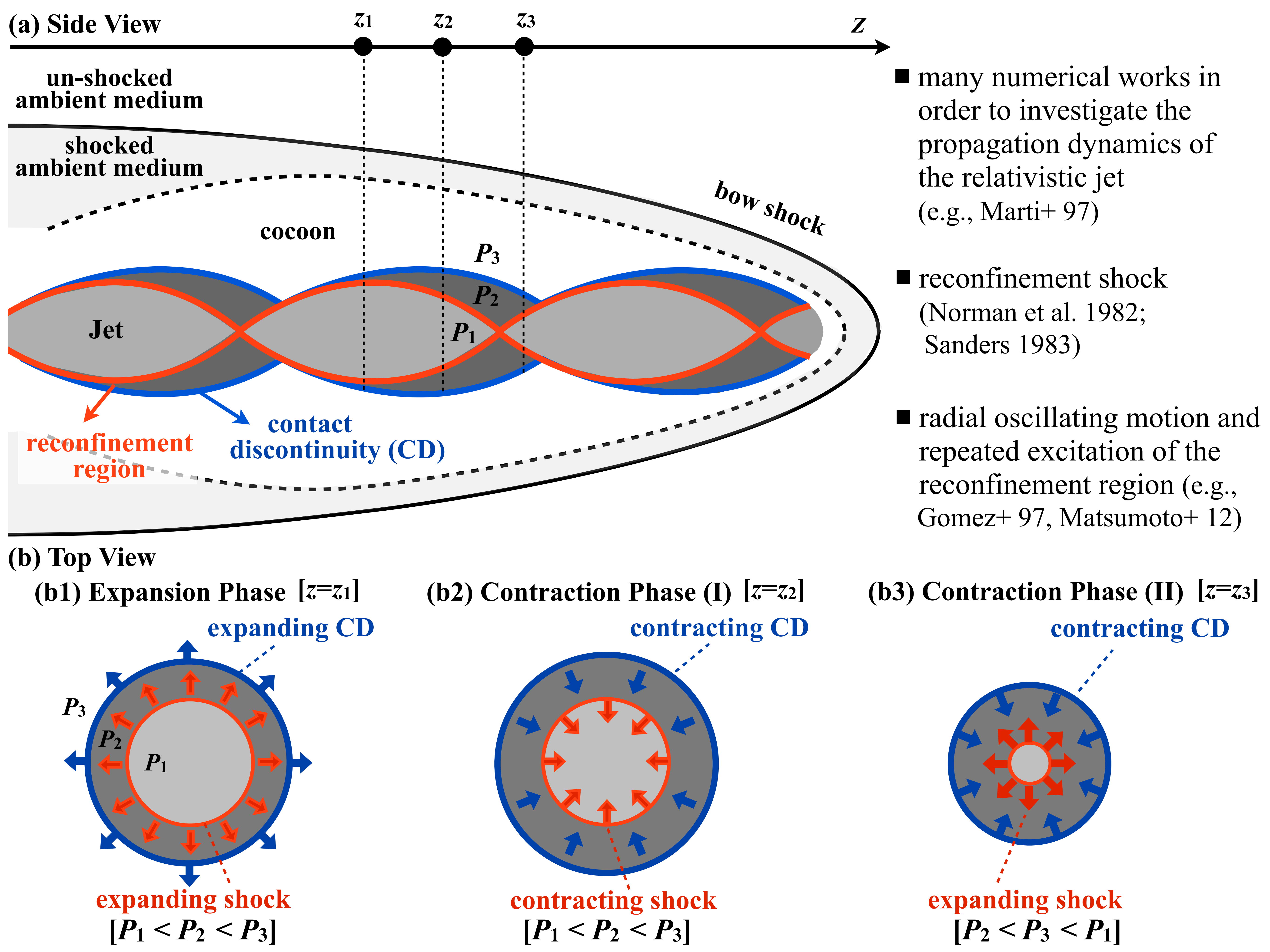


FR I

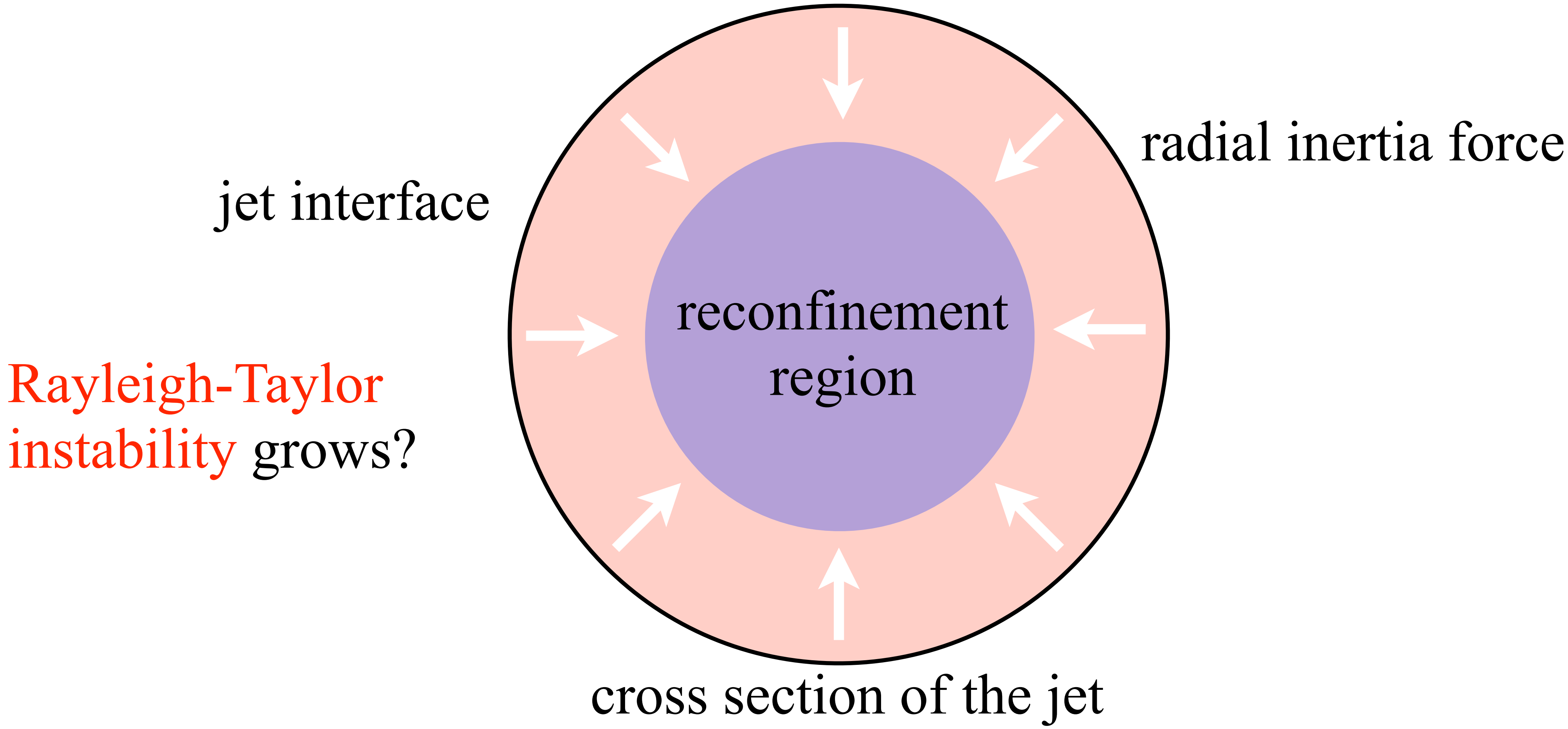


FR II

- Morphology is one of the most fundamental property of the relativistic jet.
- A morphological dichotomy between FR I and FR II
  - A complex combination of several intrinsic and external factors
- Instabilities play an important role in the morphology and stability of the jet through the interaction between the jet and external medium.


(a) Side View
z1
z2
z3
Z
un-shocked
ambient medium
shocked
ambient medium
bow shock
cocoon
P3
P2
P1
Jet
reconfinement
region
contact
discontinuity (CD)
■ many numerical works in order to investigate the propagation dynamics of the relativistic jet (e.g., Marti+ 97)
■ reconfinement shock (Norman et al. 1982; Sanders 1983)
■ radial oscillating motion and repeated excitation of the reconfinement region (e.g., Gomez+ 97, Matsumoto+ 12)
(b) Top View
(b1) Expansion Phase [z=z1]
expanding CD
P3
P2
P1
expanding shock
[P1 < P2 < P3]
(b2) Contraction Phase (I) [z=z2]
contracting CD
contracting shock
[P1 < P2 < P3]
(b3) Contraction Phase (II) [z=z3]
contracting CD
expanding shock
[P2 < P3 < P1]

Motivation of Our Study

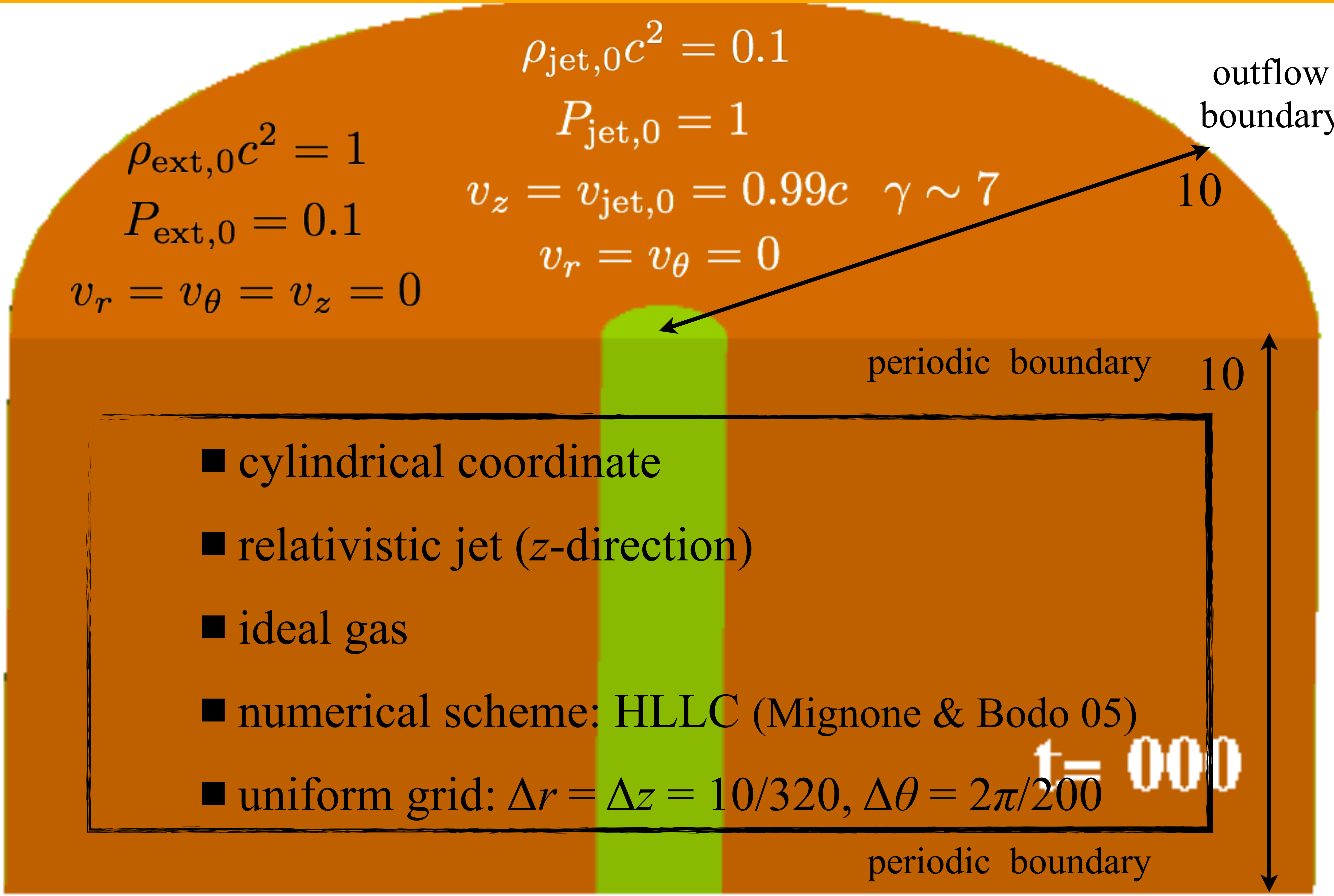


To investigate the propagation dynamics and stability of the relativistic jet

- using 3D relativistic hydrodynamic simulations

focus on the transverse structure of the jet

Numerical Setting: 3D Toy Model 1



- cylindrical coordinate
- relativistic jet (*z*-direction)
- ideal gas
- numerical scheme: HLLC (Mignone & Bodo 05)
- uniform grid: $\Delta r = \Delta z = 10/320$, $\Delta\theta = 2\pi/200$

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

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

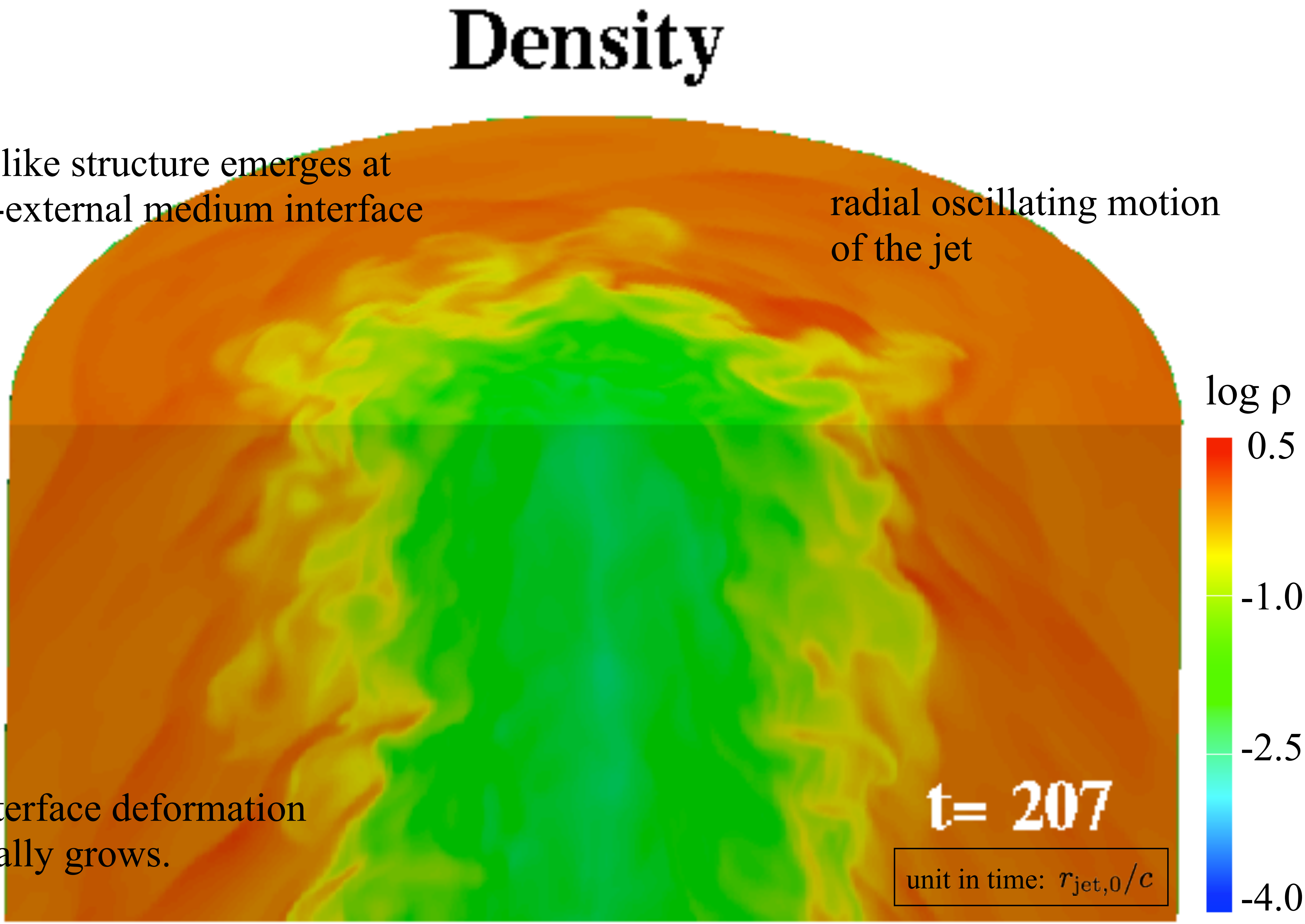
ratio of specific heats

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

Lorentz factor

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

Result: Density

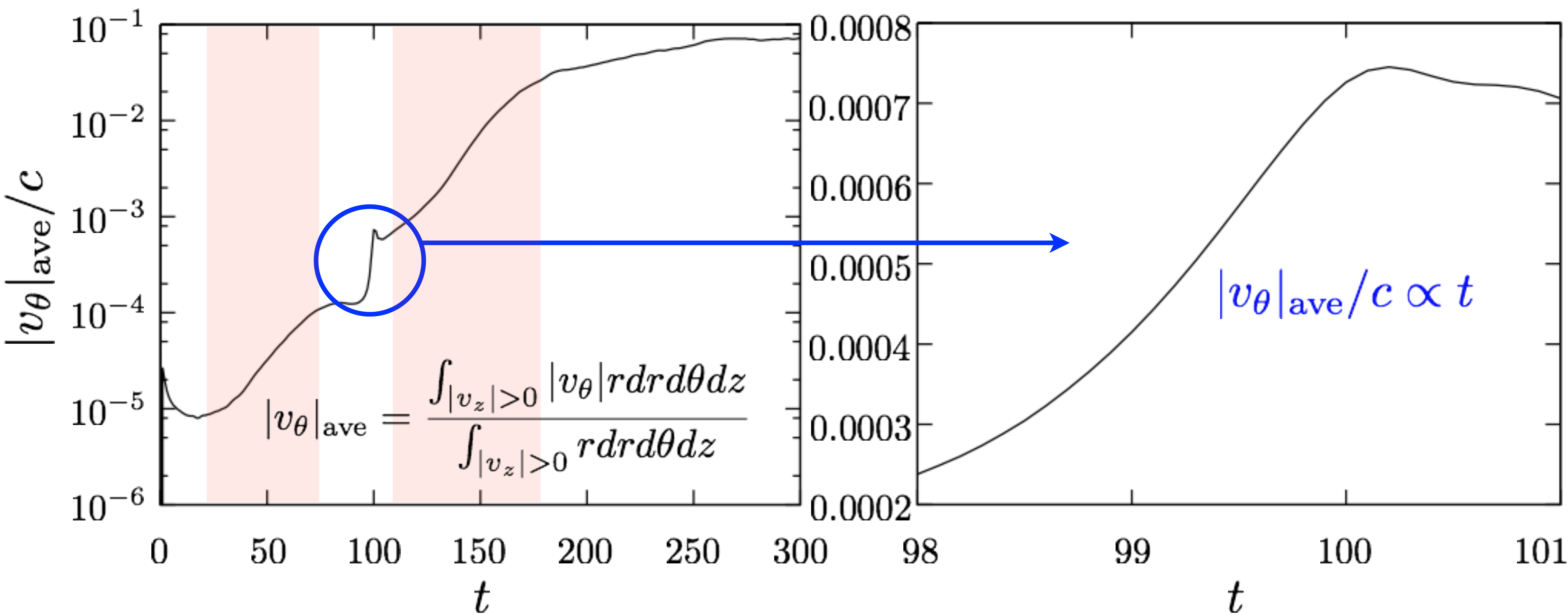


finger-like structure emerges at the jet-external medium interface

radial oscillating motion of the jet

the interface deformation gradually grows.

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

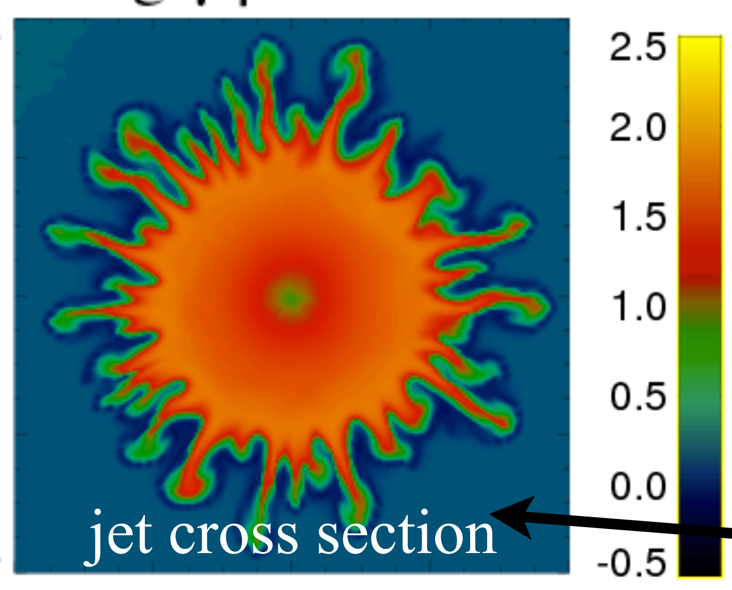
$|v_\theta|_{\rm ave}$ grows linearly with time.

The transverse structure of the jet is dramatically deformed by a synergetic growth of the RTI and RMI once the jet-external medium interface is corrugated in the case with the pressure-mismatched jet.

Stability Condition of the Jet

complementary **2D** simulations of transverse structure of the jet
excluding the destabilization effects by the **Kelvin-Helmholtz** mode

log $\gamma^2 \rho h$: t=120



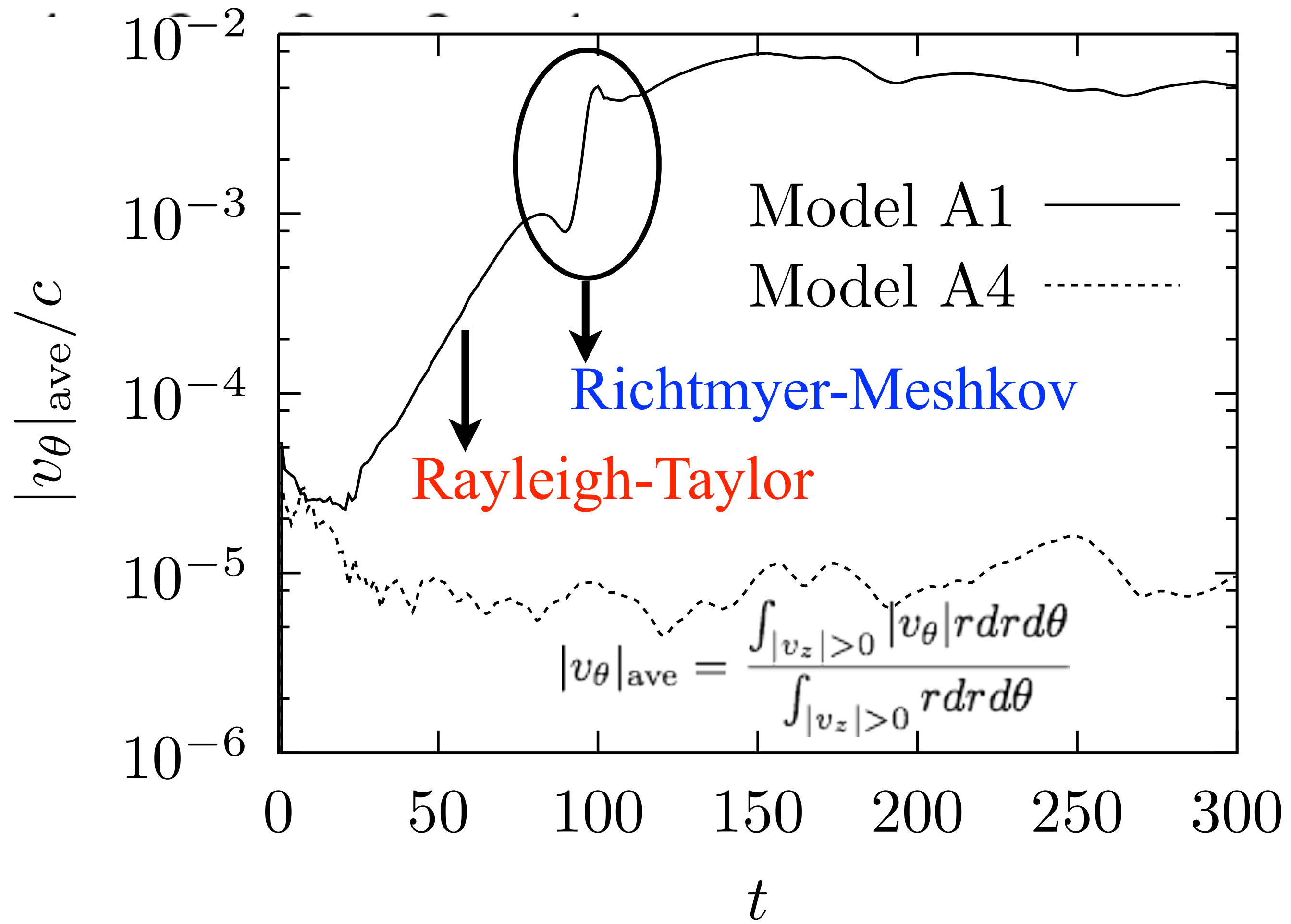
the stability criterion of the jet

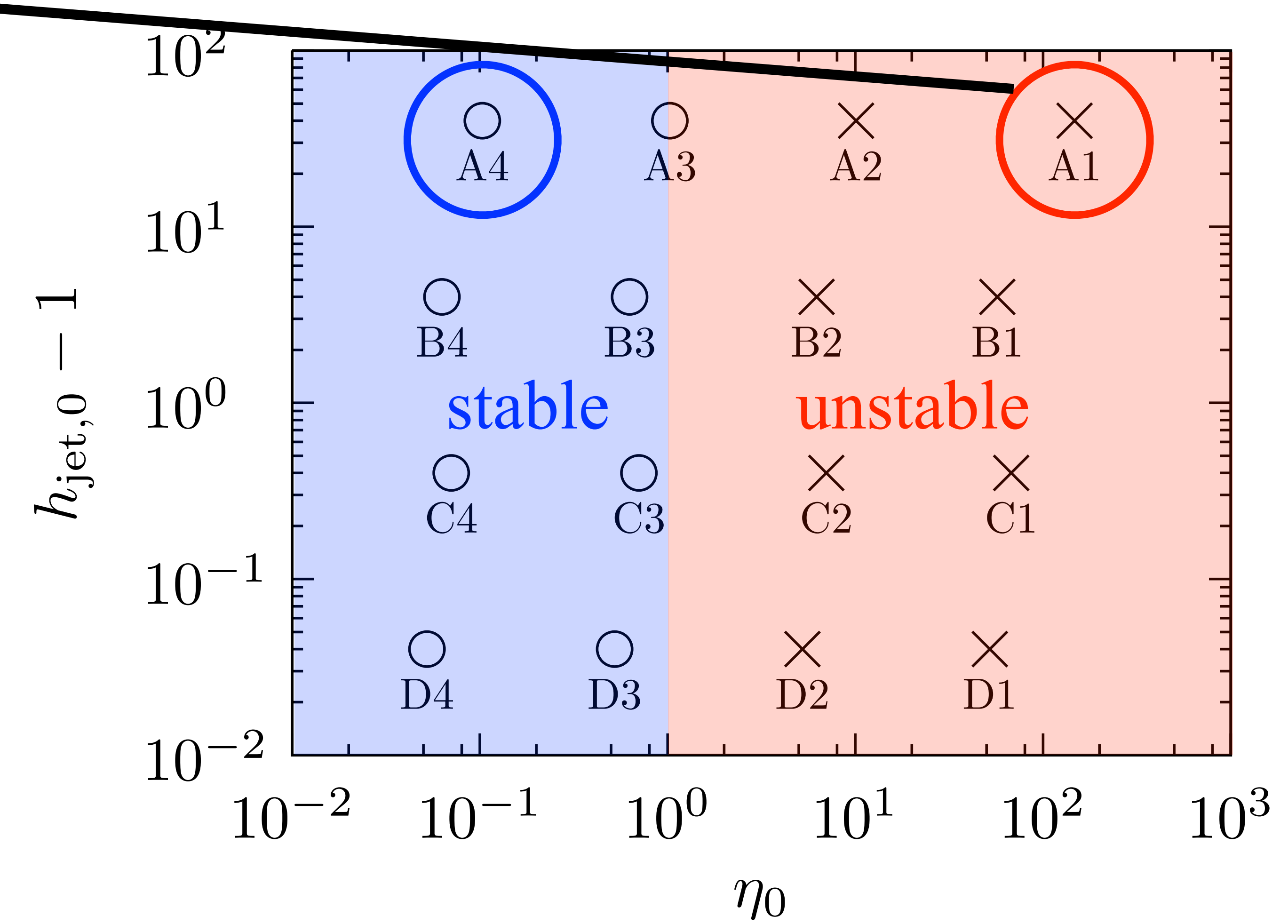
$$\eta_0 = \frac{{\gamma_{\mathrm{jet},0}}^2 \rho_{\mathrm{jet},0} h_{\mathrm{jet},0}}{\rho_{\mathrm{ext},0} h_{\mathrm{ext},0}} > 1$$

fixed

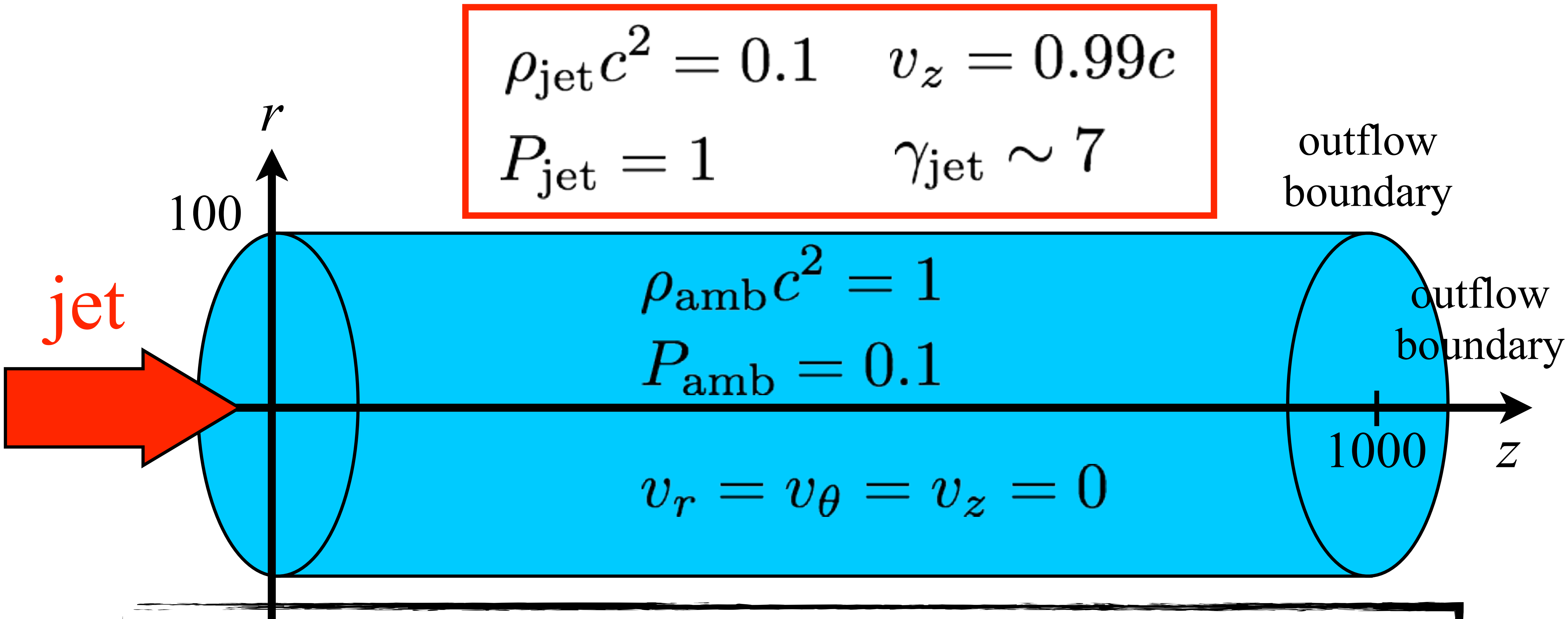
$$\begin{cases} P_{\mathrm{jet},0}/P_{\mathrm{ext},0} = 10 \\ \gamma_{\mathrm{jet}} = 7 \end{cases}$$

$$h_{\mathrm{jet},0} = 1 + \frac{\Gamma}{\Gamma - 1} \frac{P_{\mathrm{jet},0}}{\rho_{\mathrm{jet},0} c^2}$$



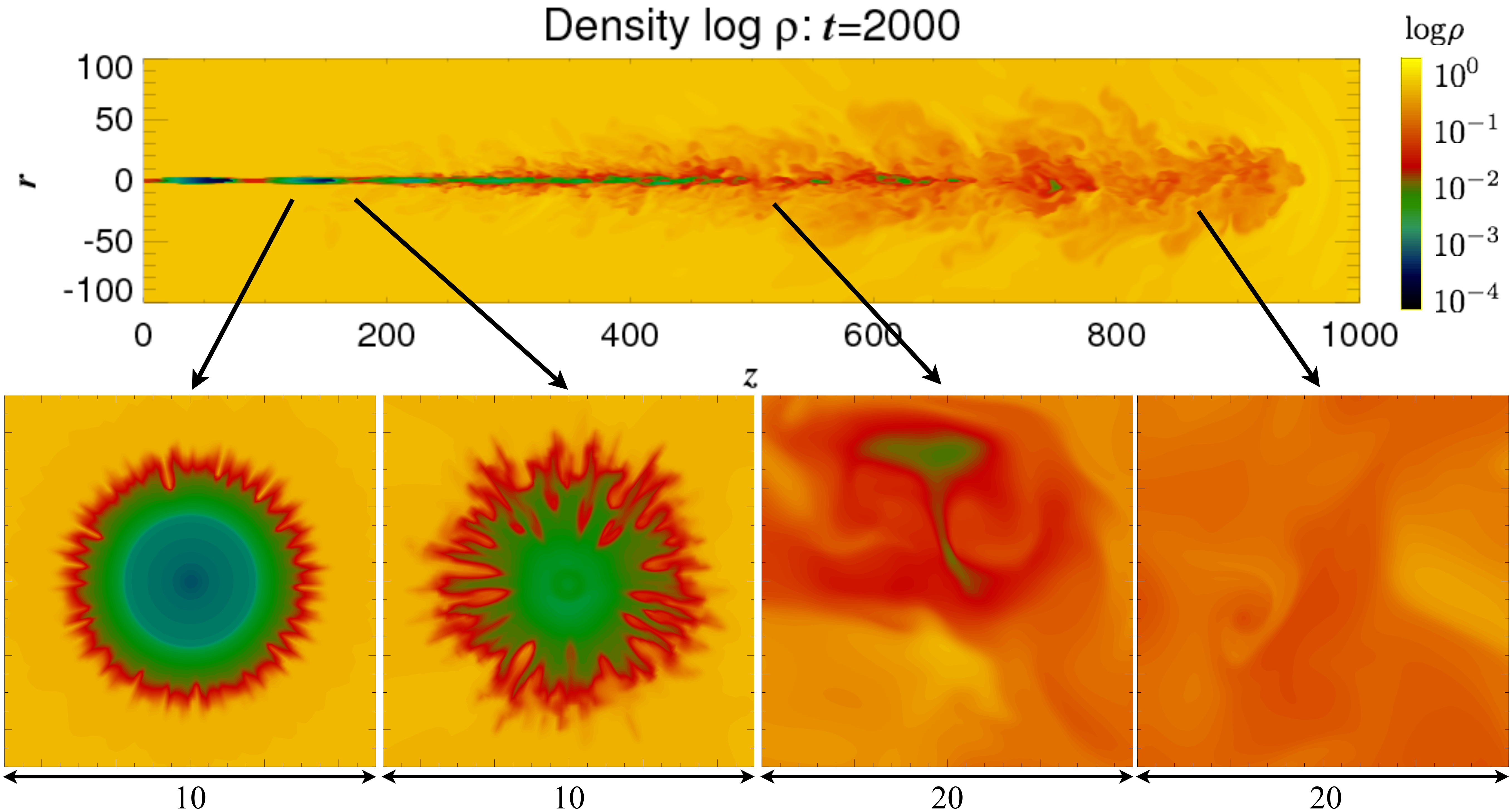


Numerical Setting: 3D Toy Model 2



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

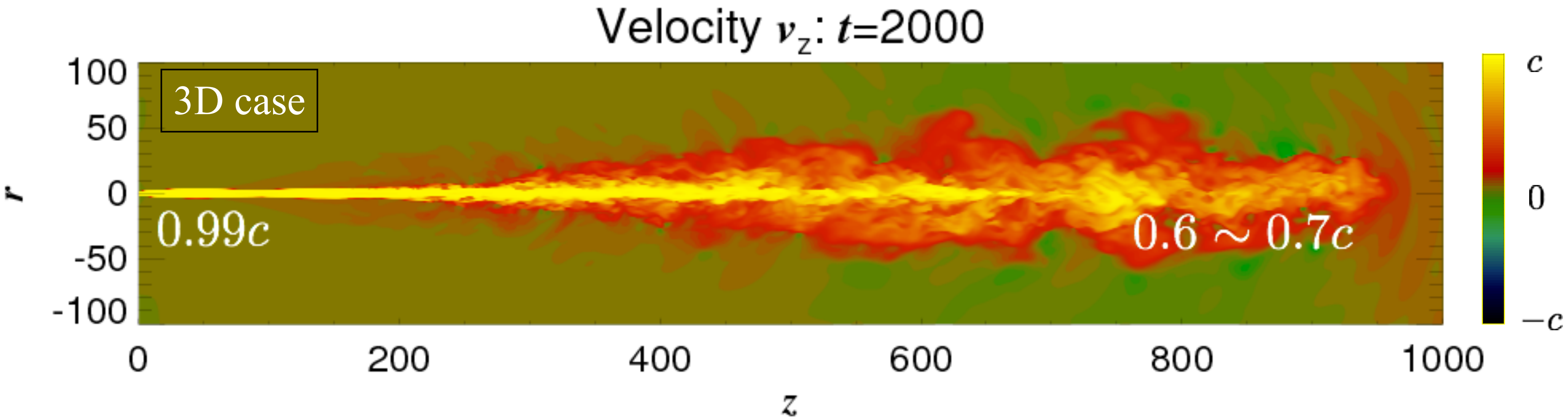
Result: Density

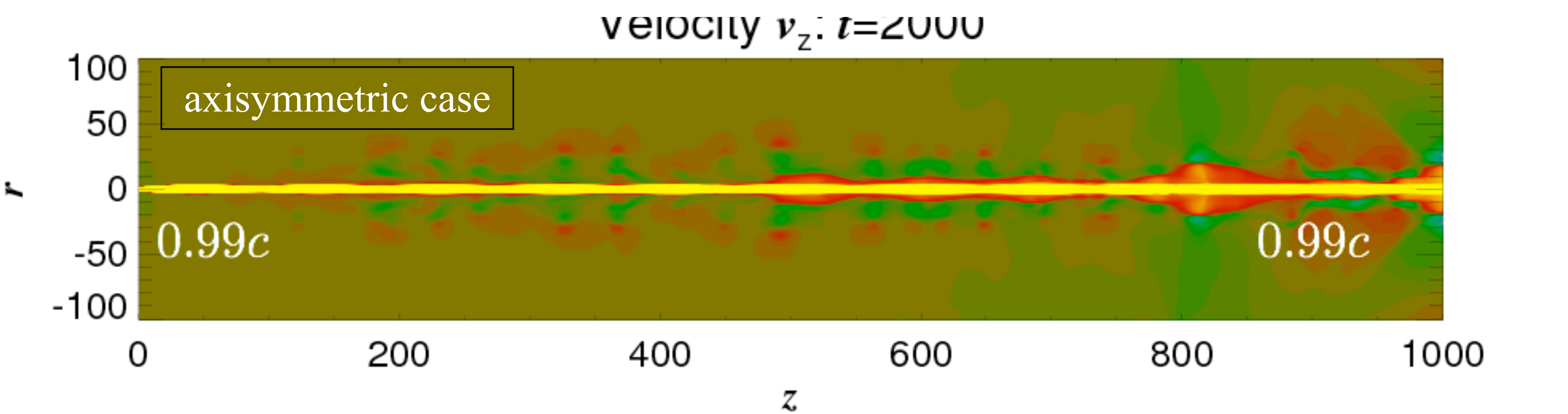


Rayleigh-Taylor instability develops at the interface of the jet.

The mixing produced by Rayleigh-Taylor and Richtmyer-Meshkov instabilities between the jet and surrounding medium leads to the jet disruption.

Deceleration of the jet due to mixing

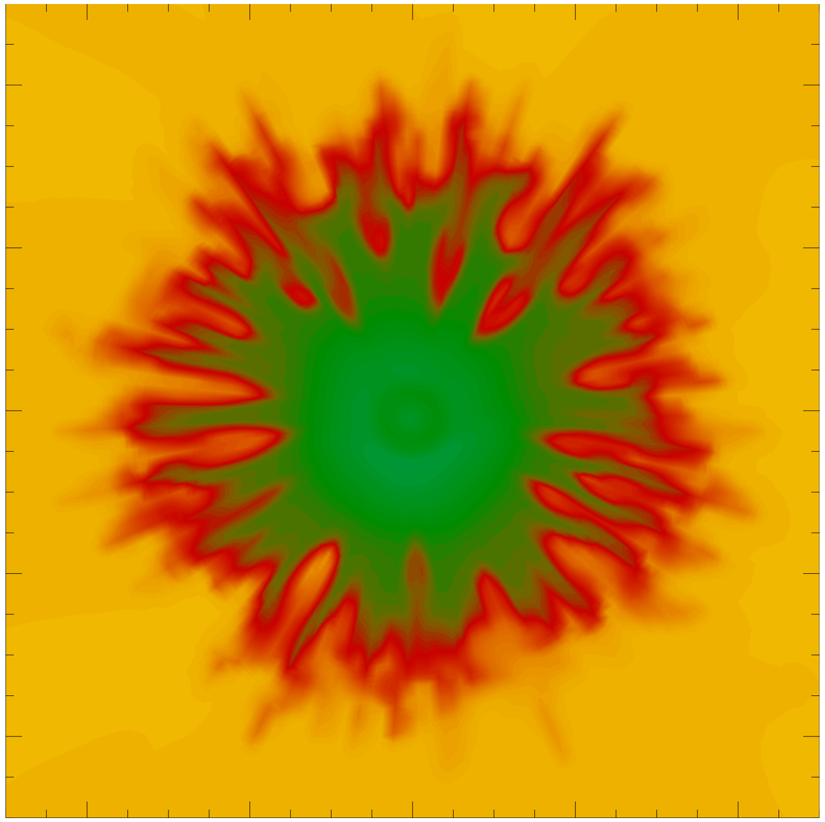




- deceleration of the jet due to the mixing between the jet and surrounding medium

Summary

Propagation dynamics and stability of the relativistically hot is studied through 3D relativistic hydrodynamic simulations.



- The jet-ambient medium interface is unstable when the effective inertia of the jet is larger than the surrounding medium.

  ⇐ { Rayleigh-Taylor instability / Richtmyer-Meshkov instability }

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

Next Study:

- more realistic situation for relativistic jets such as AGN jets and GRBs
- effect of the magnetic field on RT and RM instabilities