Effect of Interacting Rarefaction Waves on Relativistically hot Jets

Jin MATSUMOTO

National Astronomical Observatory of Japan

Collaborators: Youhei Masada (Kobe University)

Kazunari Shibata (Kyoto University)

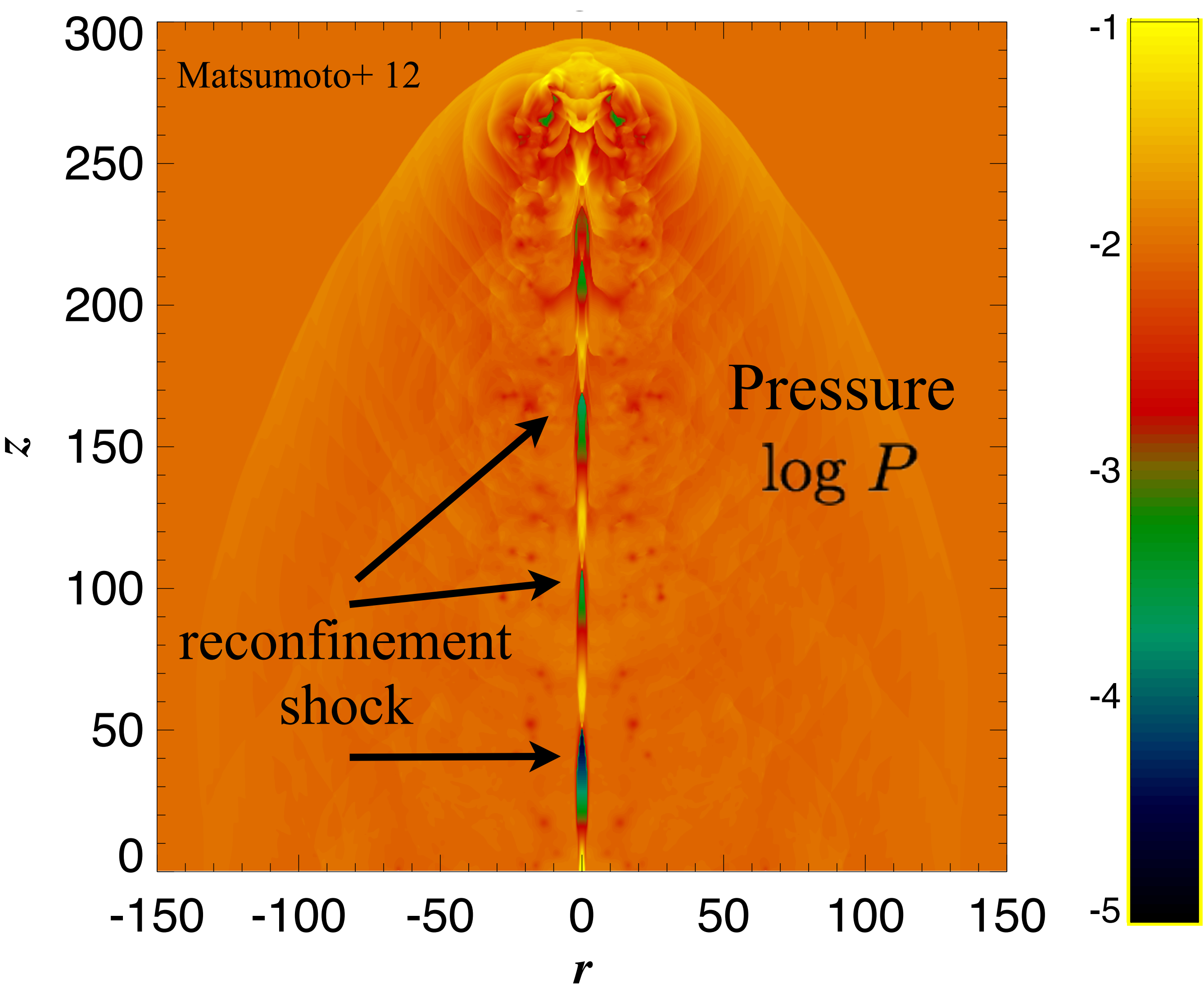
What a relativistic jet?

collimated bipolar outflow from gravitationally bounded object

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

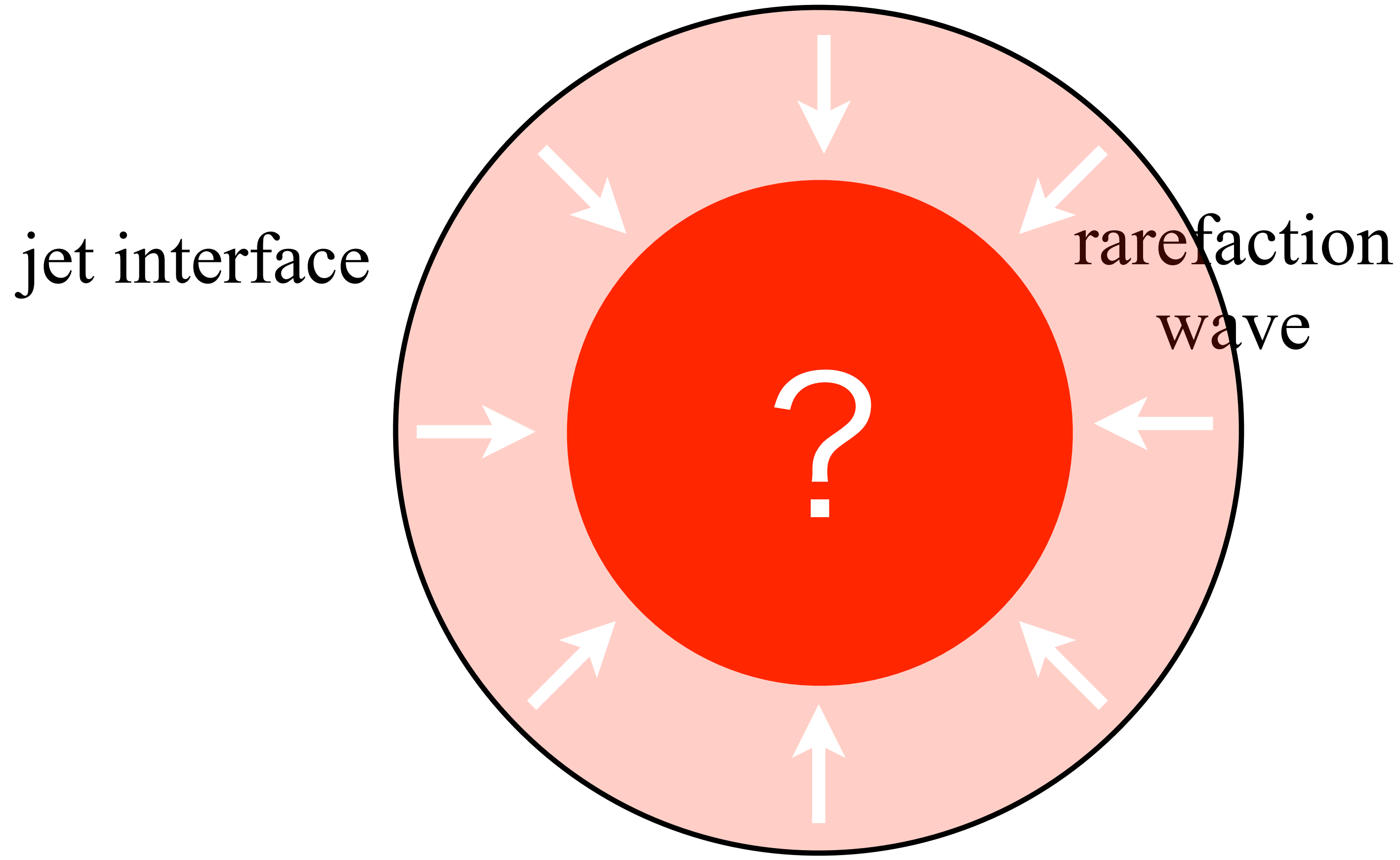
Lorentz factor

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



- many numerical works in order to investigate the propagation dynamics of the relativistic jet (e.g., Marti+ 97, Aloy+ 99, Mizuta+ 04)
- reconfinement shock (Norman et al. 1982; Sanders 1983)
- repeated excitation and convergence of the rarefaction waves (e.g., Daly & Marscher 88, Matsumoto+ 12)

Motivation of Our Study



cross section of the jet

To investigate the propagation dynamics and stability of the relativistic jet

- using 3D relativistic hydrodynamic simulations

focus on the transverse structure of the jet

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

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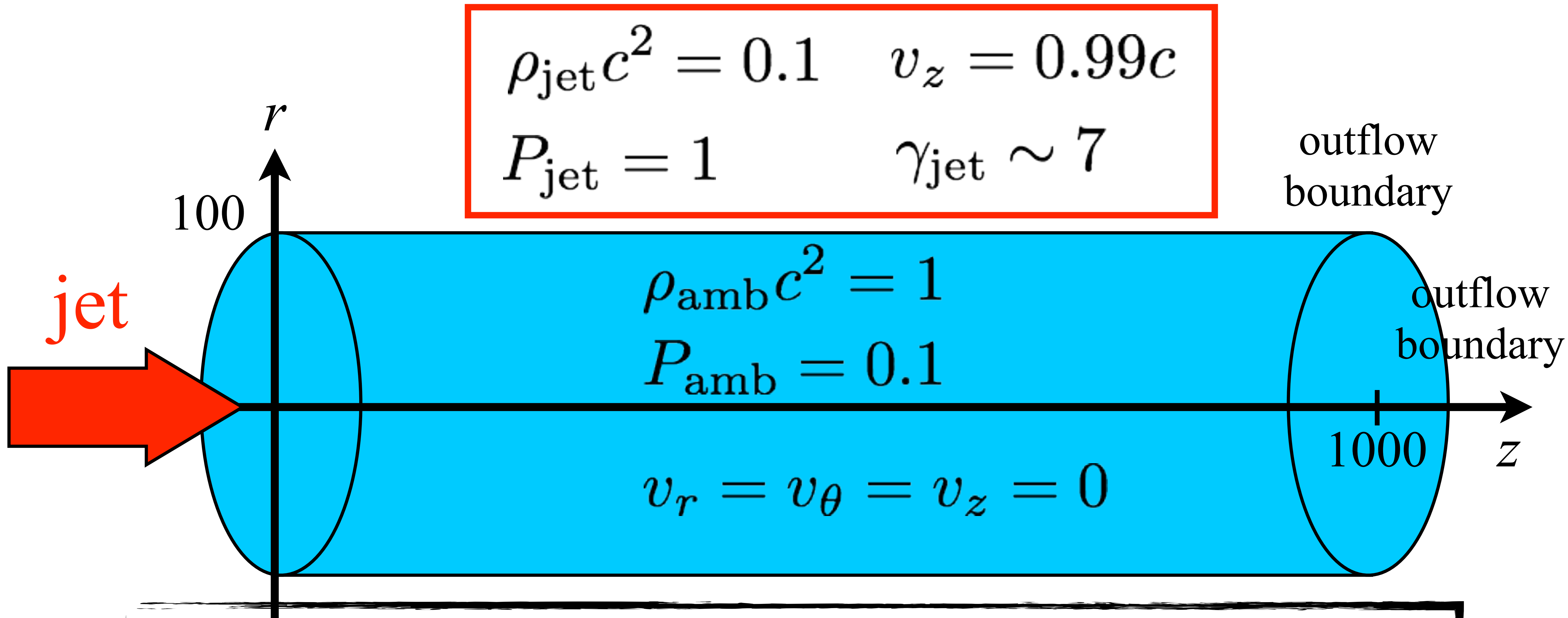
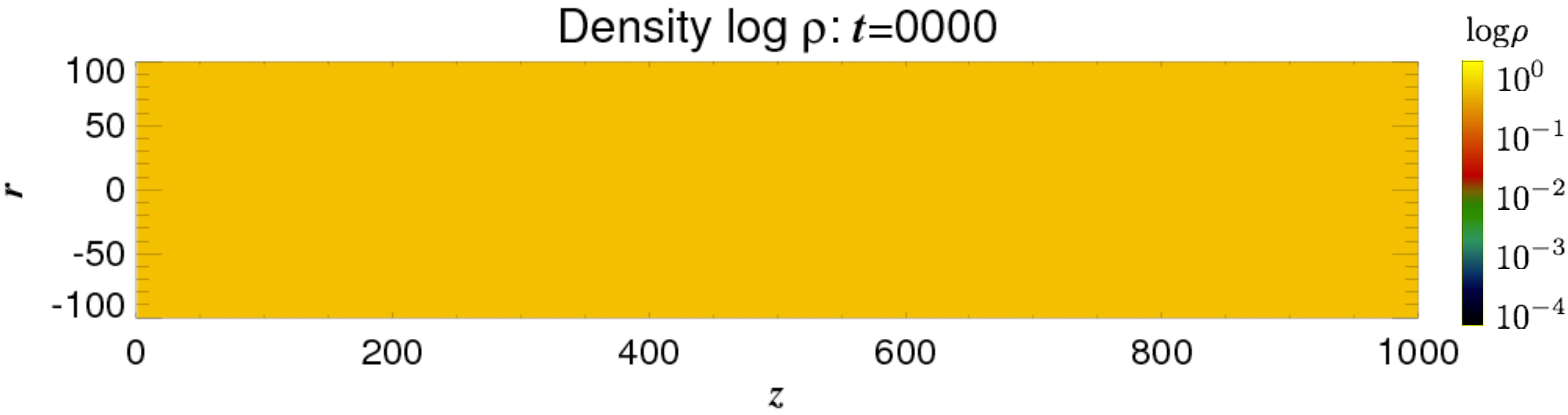
Numerical Setting: 3D Toy Model

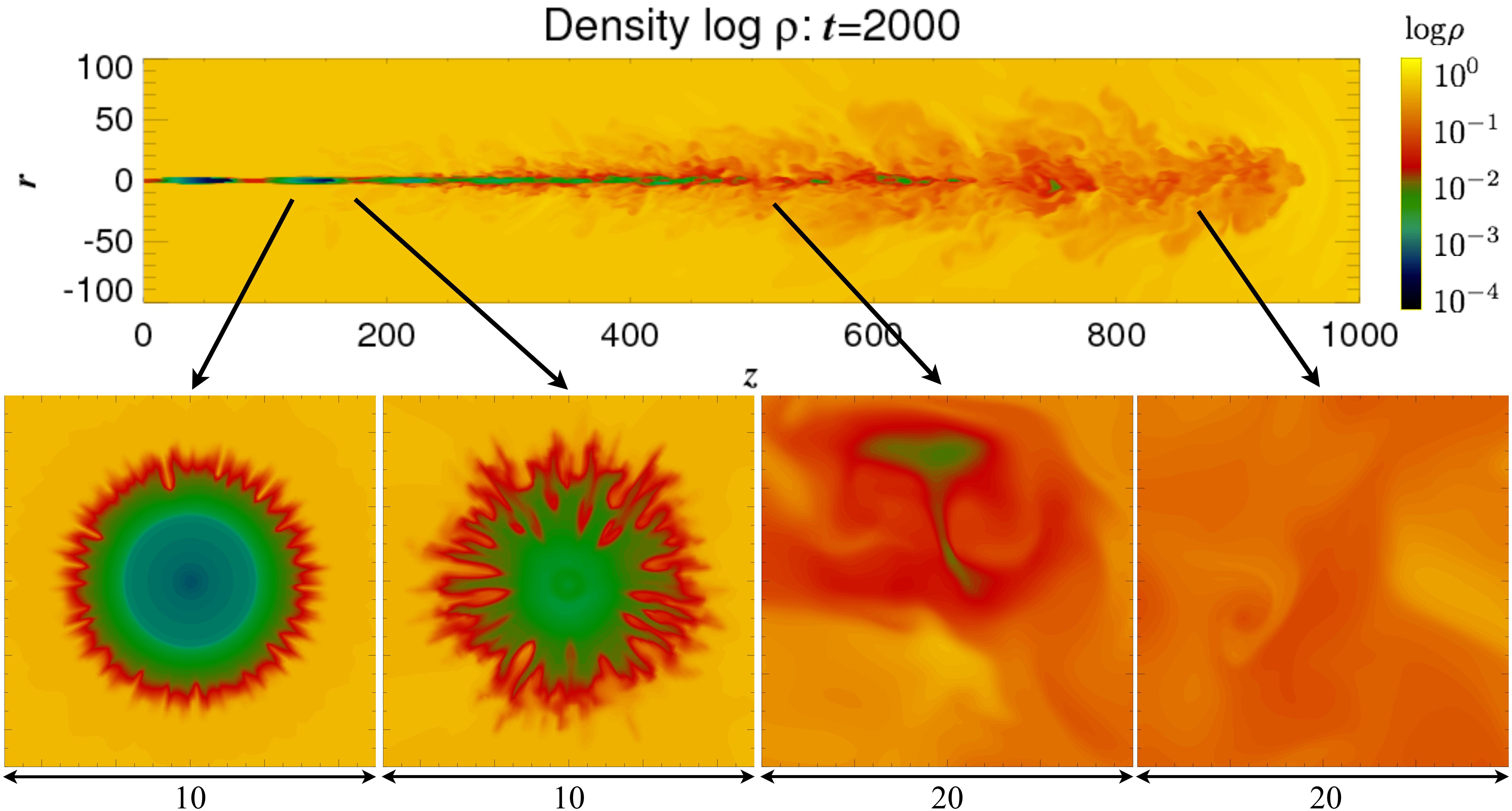


- cylindrical coordinate
- relativistically hot jet (*z*-direction)
- ideal gas
- numerical scheme: HLLC (Mignone & Bodo 05)
- uniform grid: $\Delta r = 0.0666$, $\Delta\theta = 2\pi/160$, $\Delta z = 1$

Result: Density



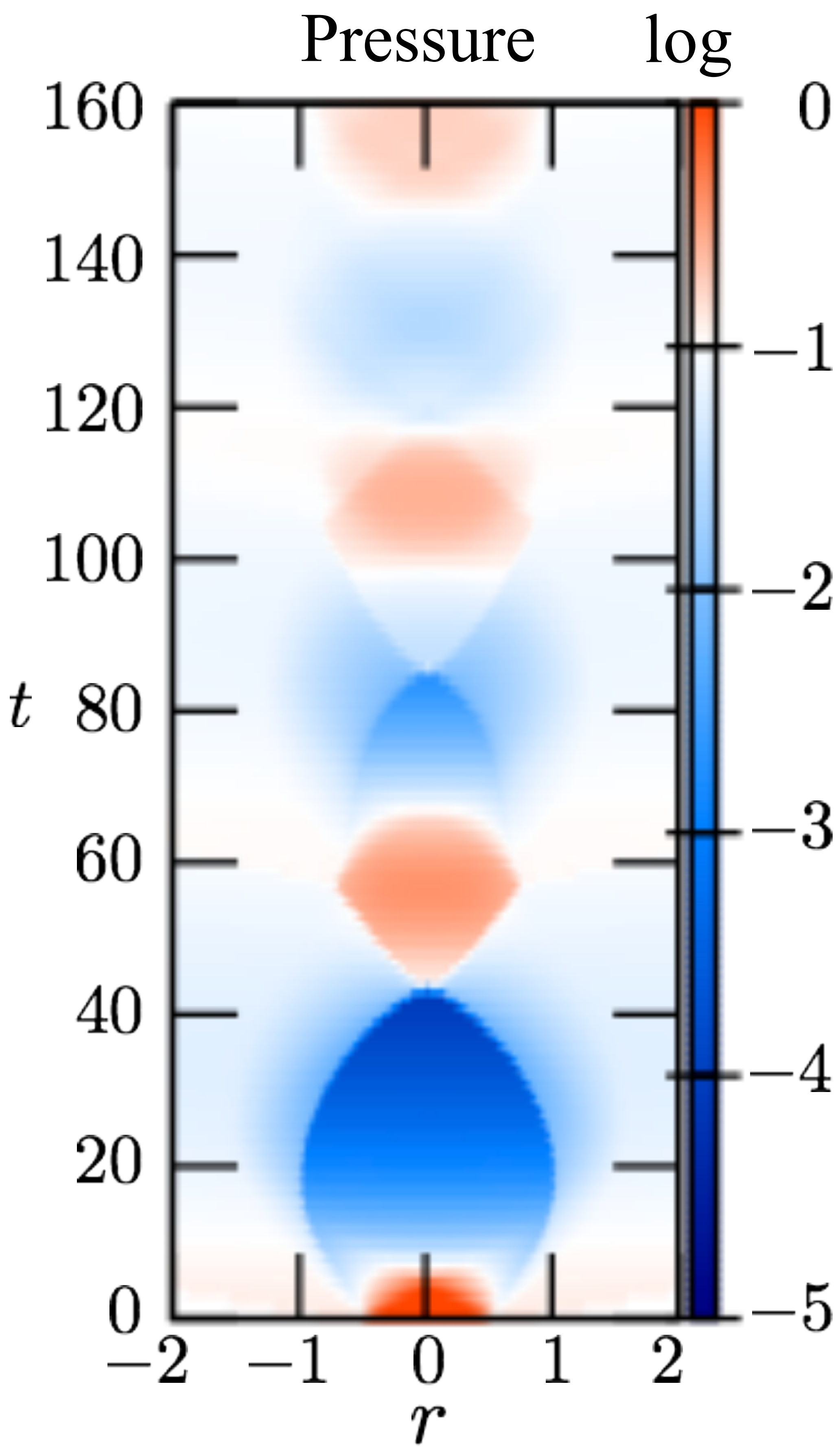
Result: Density

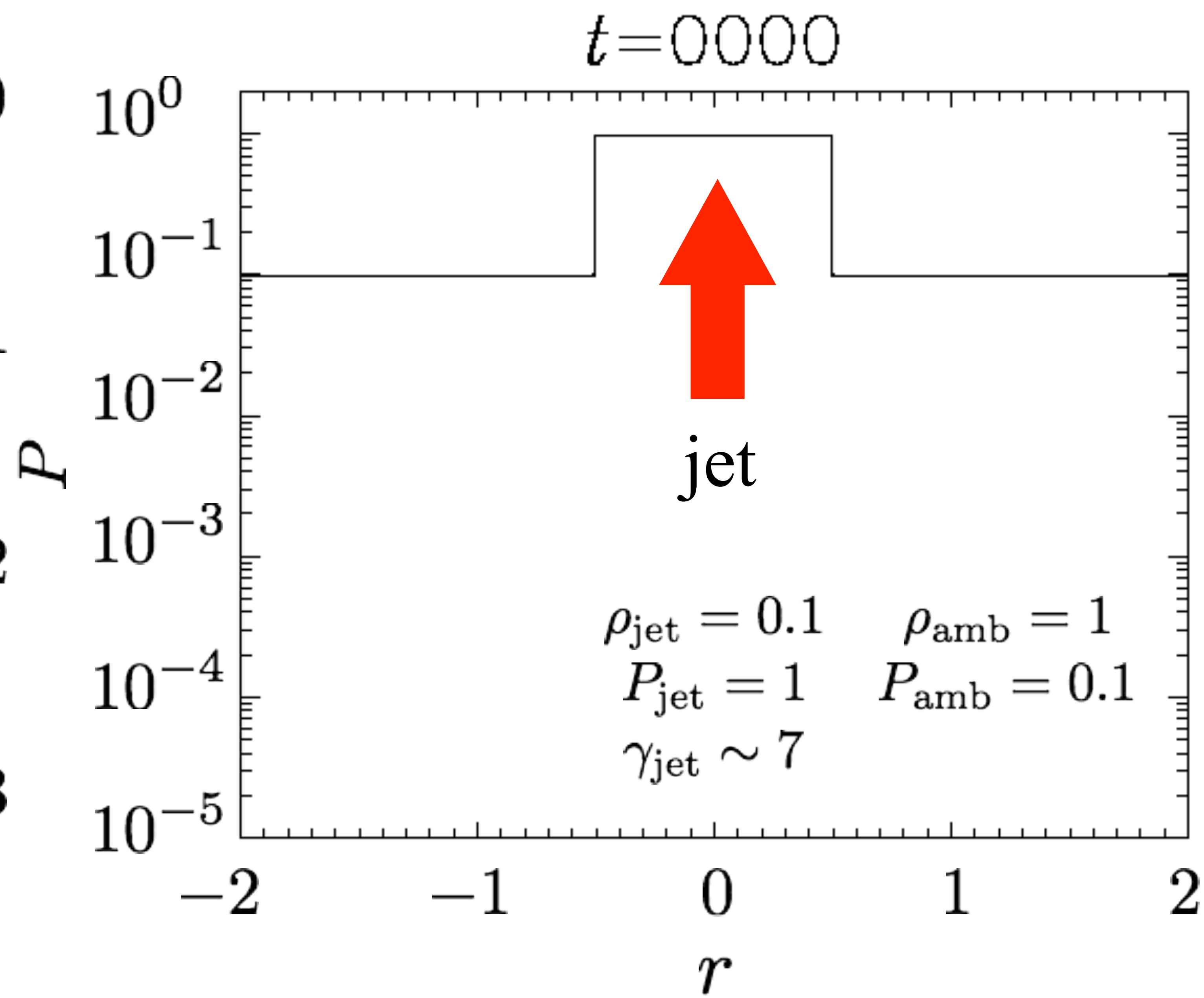


Rayleigh-Taylor instability develops at the interface of the jet.

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

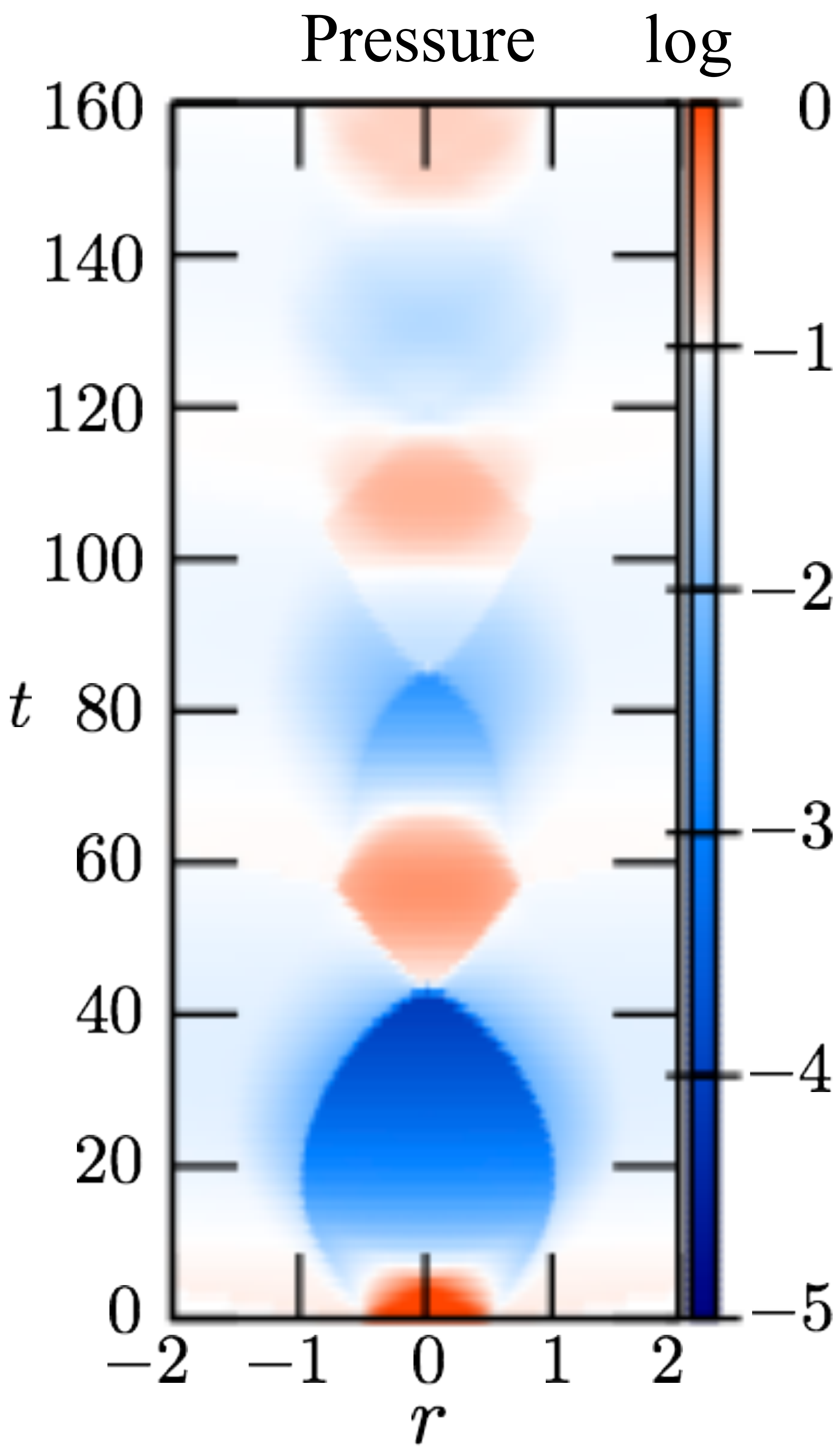
1D Calculation (r-direction): Pressure

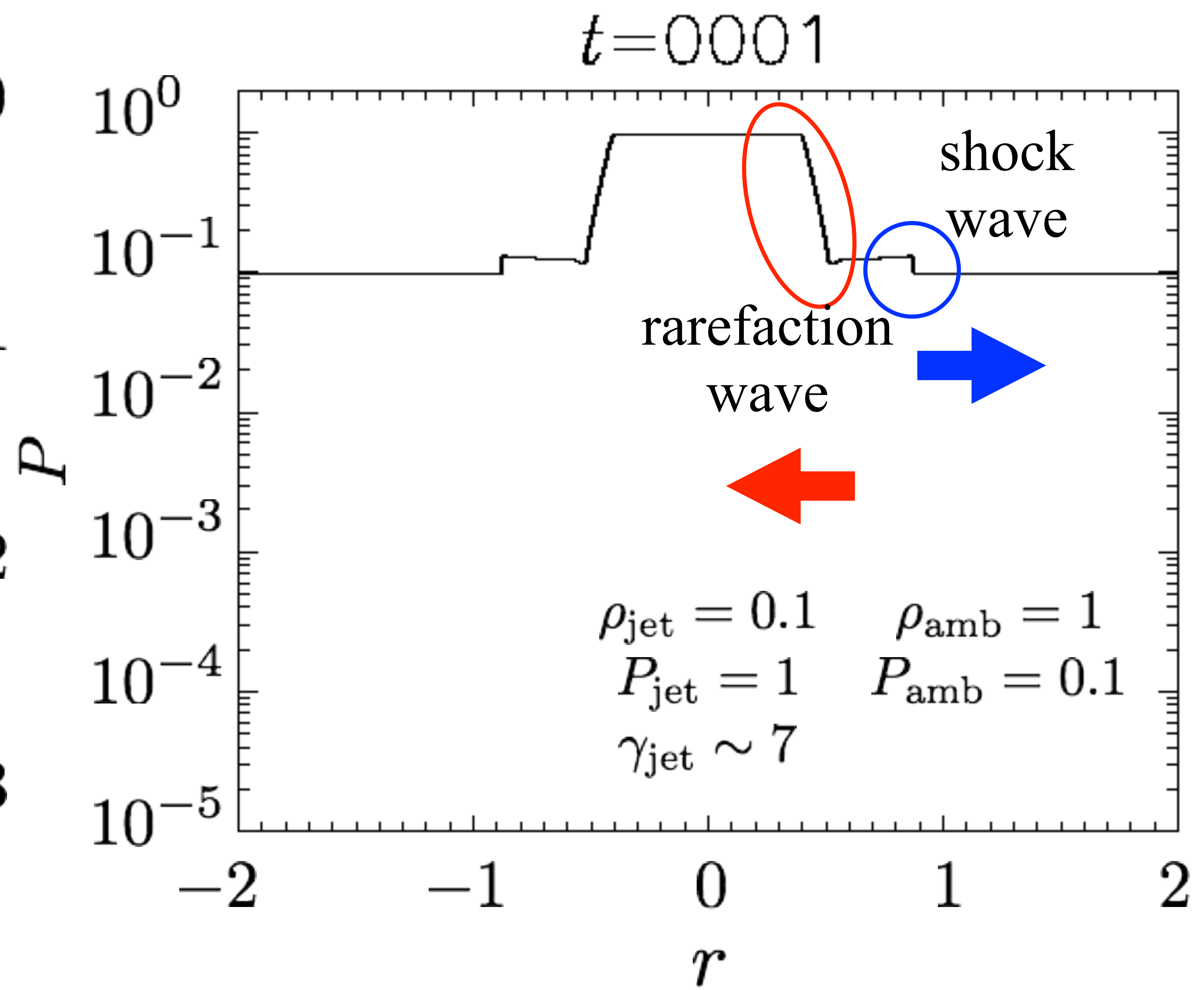




- Since the jet is initially over-pressured, an outward propagating shock wave and an inward propagating rarefaction wave are excited at the jet-ambient medium interface.

1D Calculation (r-direction): Pressure





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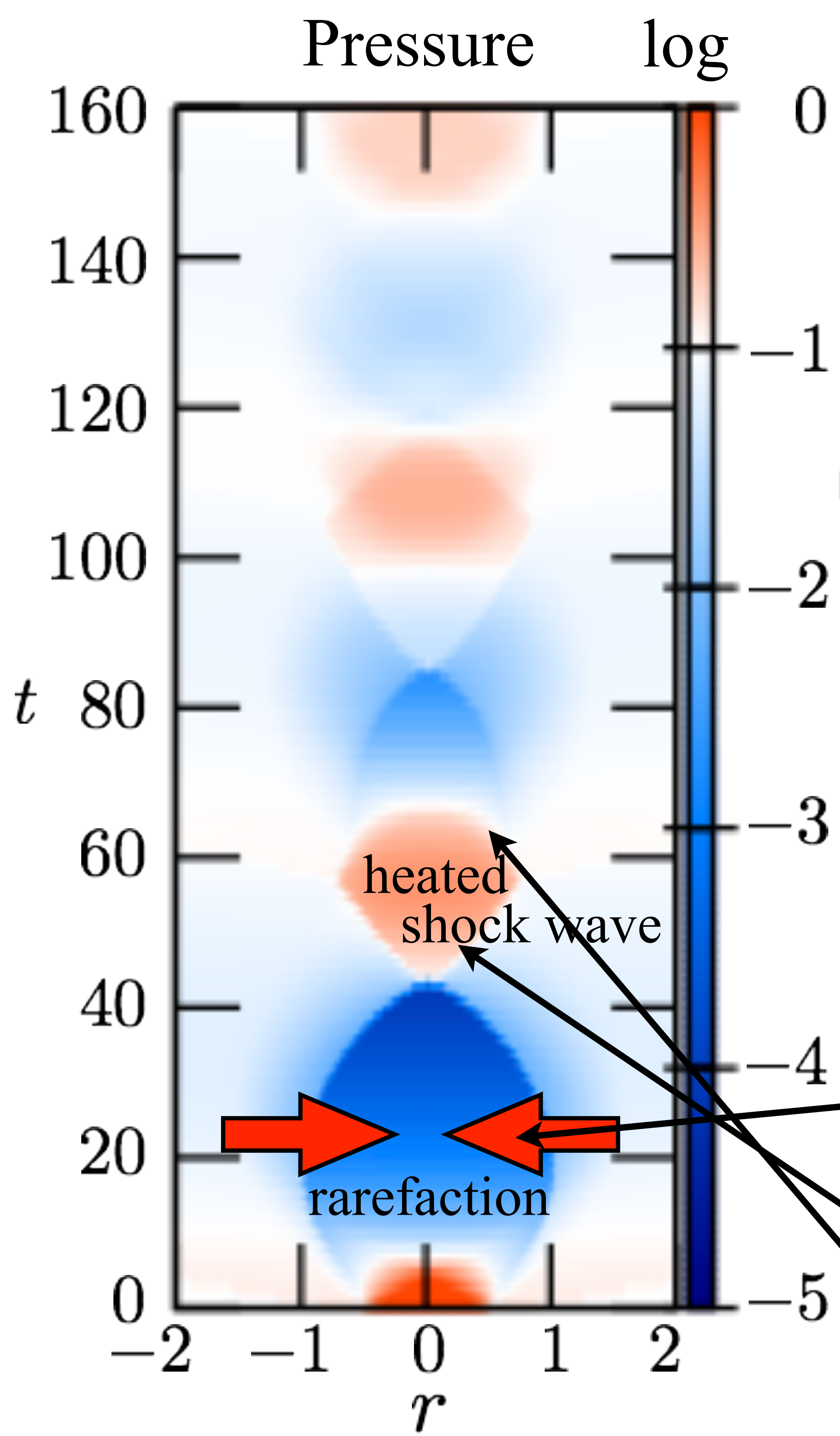
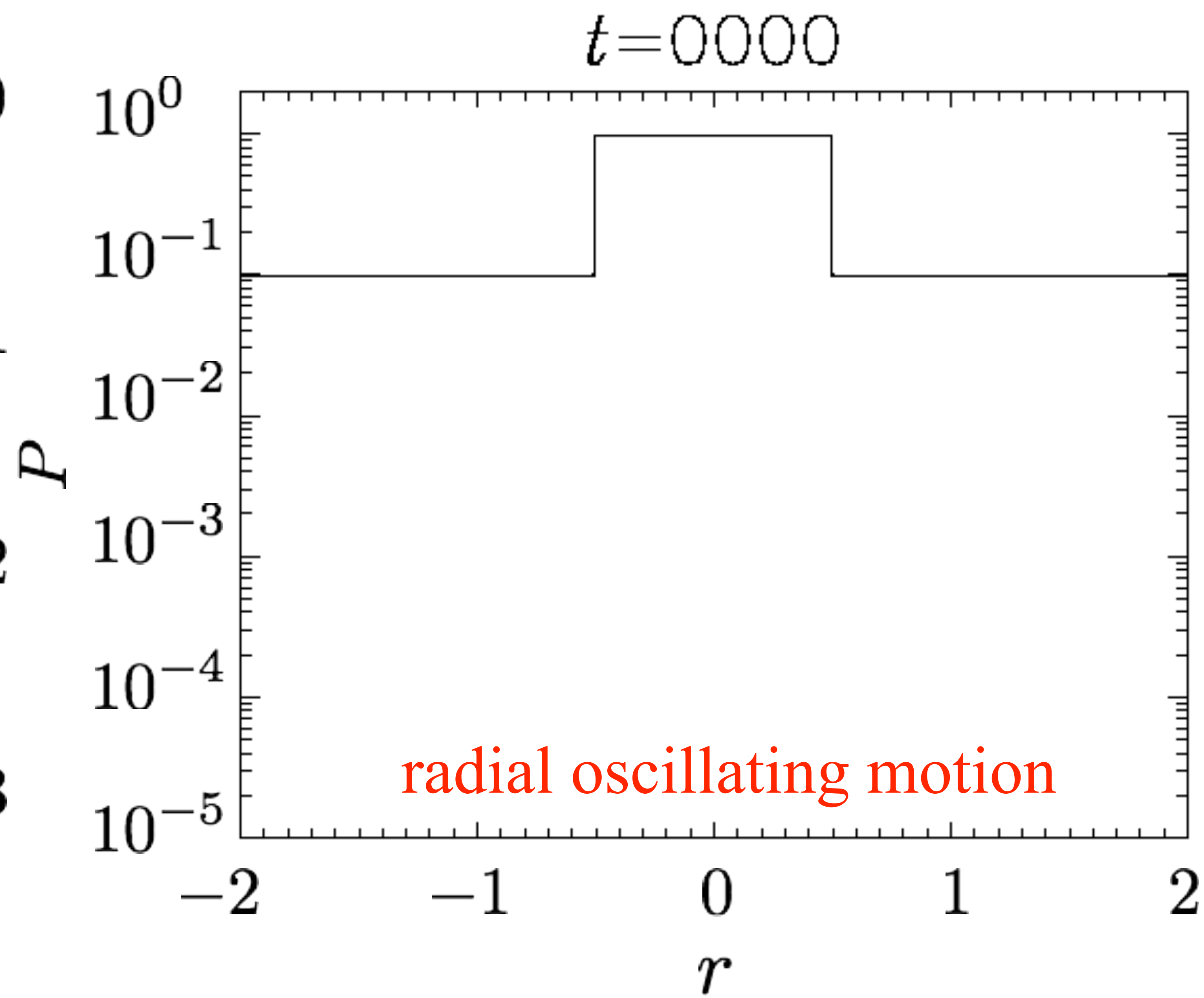
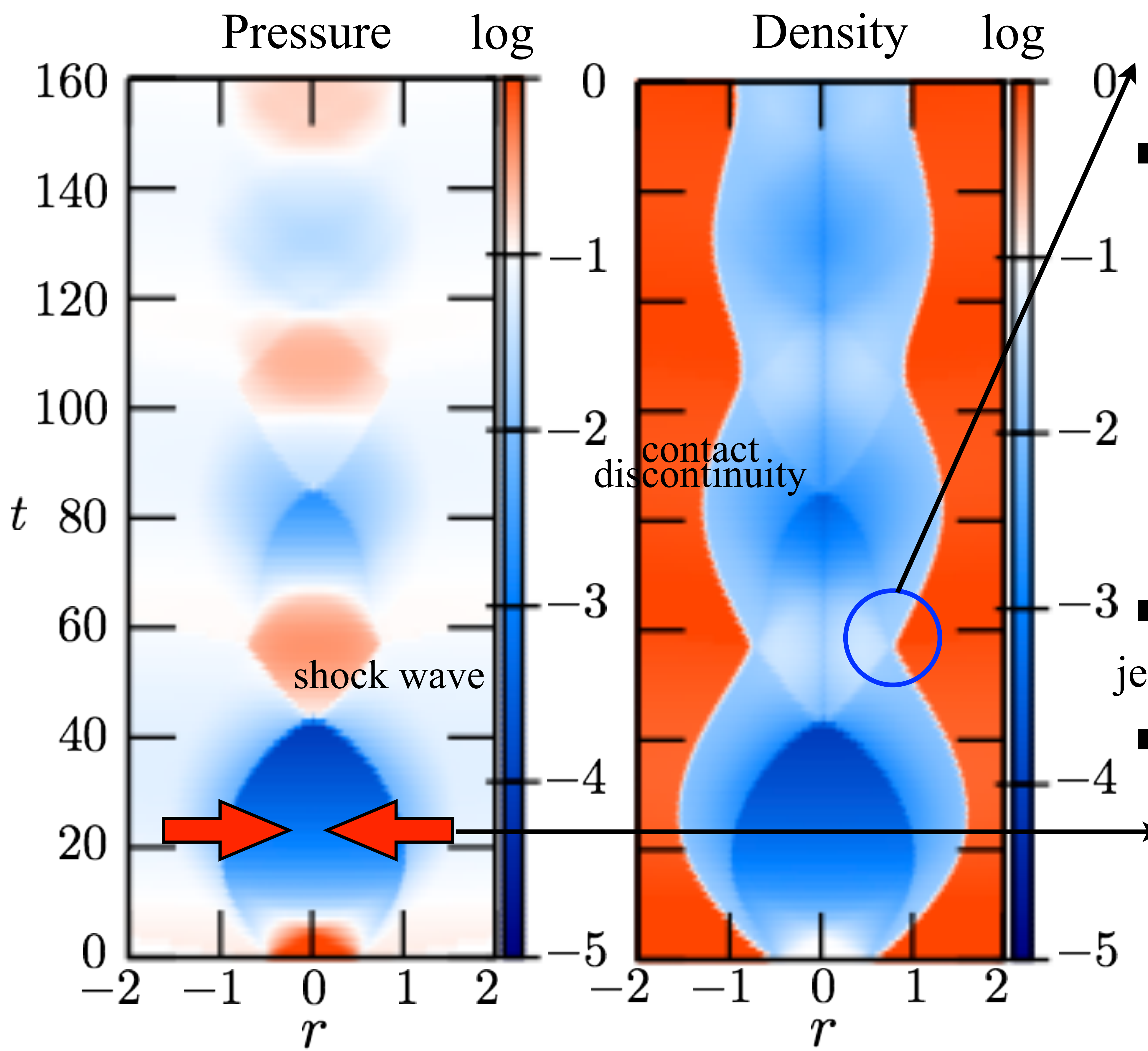




- inward pressure gradient force
  - ⇨ converging flow inside the jet
- outward propagating shock wave
- inward propagating rarefaction wave

Expected Instabilities in 3D Case



Richtmyer-Meshkov instability

- interaction of a shock wave with the contact discontinuity

➡ distortion of the jet interface

Rayleigh-Taylor instability

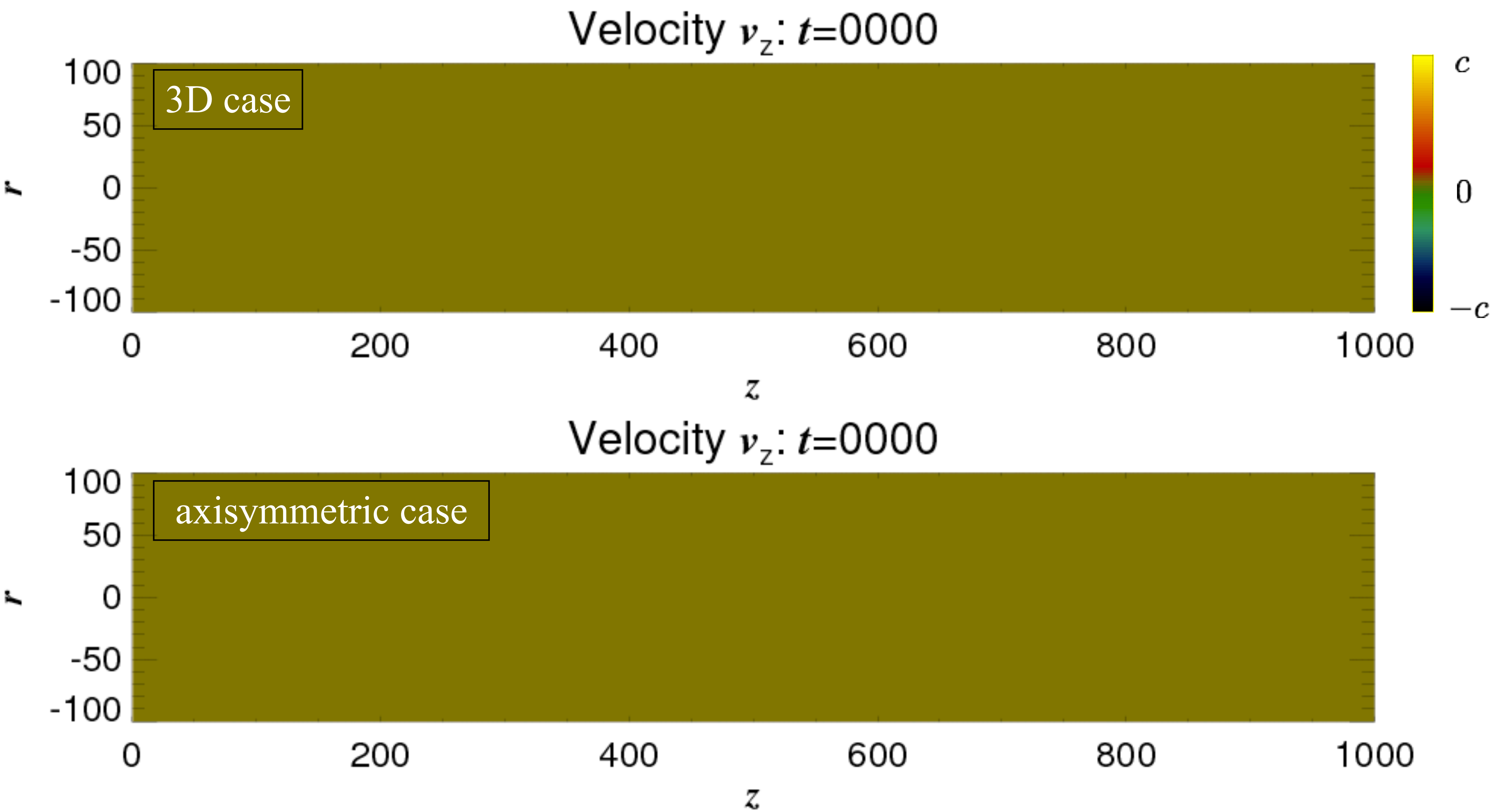
- effective inertia: $\gamma^2 \rho h$

jet > surrounding medium

- Radial expansion velocity of the jet is decelerated by the pressure gradient force.

➡ interface of the jet is unstable.

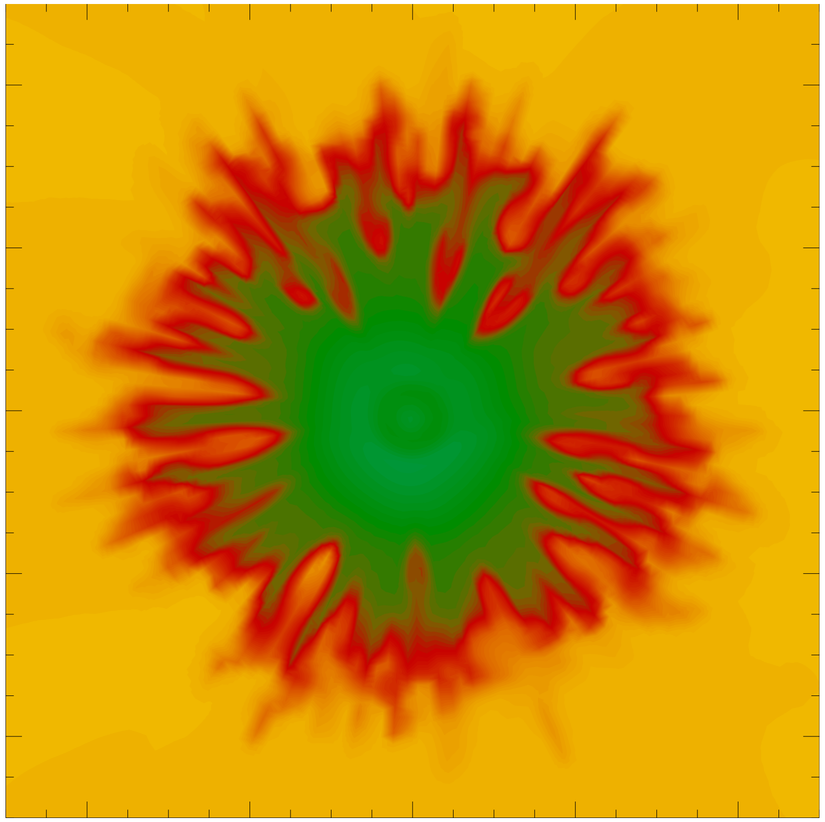
Deceleration of the jet due to mixing



- The coherent fast backflows in axisymmetric case are not present in 3D case. (Aloy+ 99)
- 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

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Next Study:

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