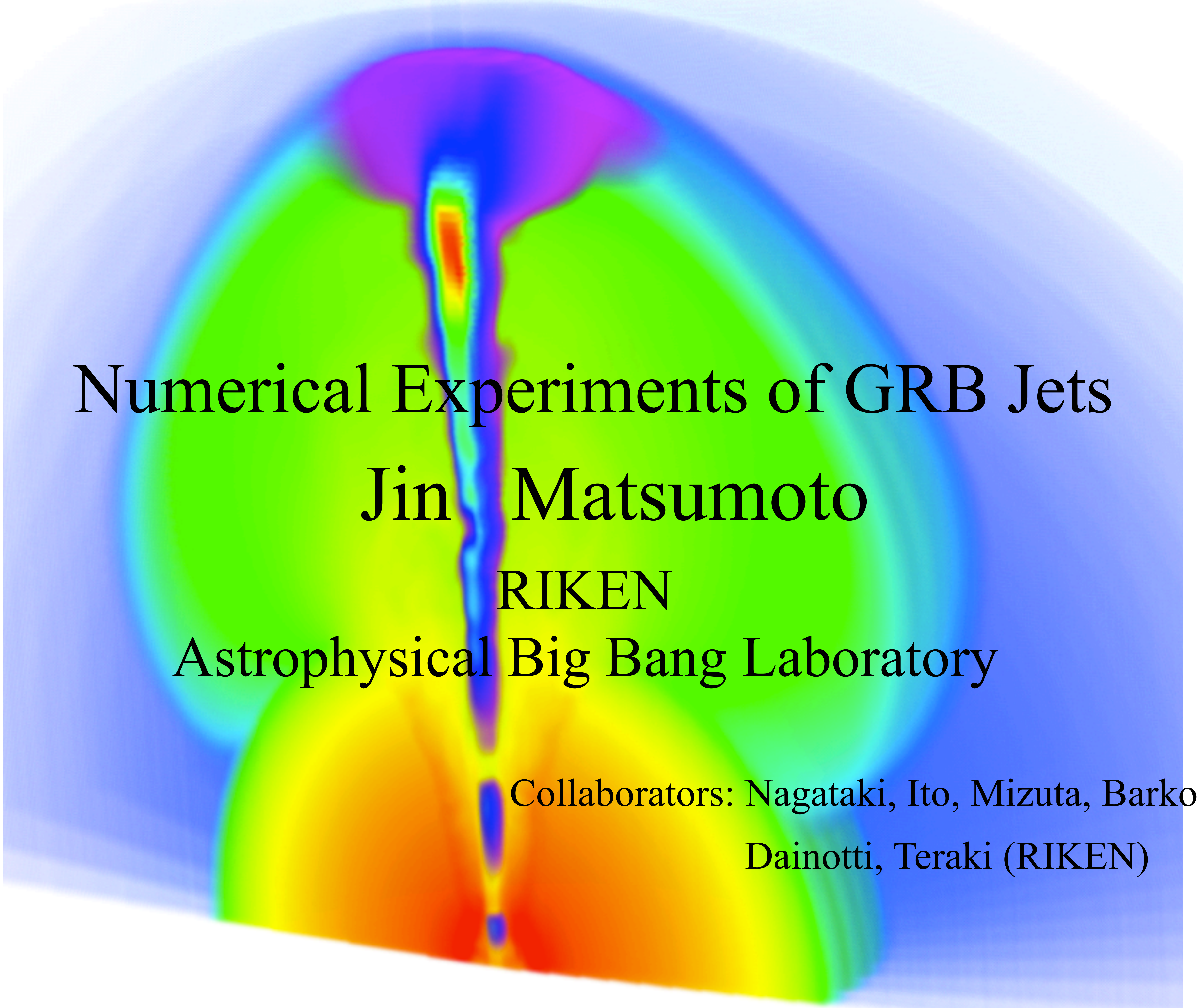

Numerical Experiments of GRB Jets

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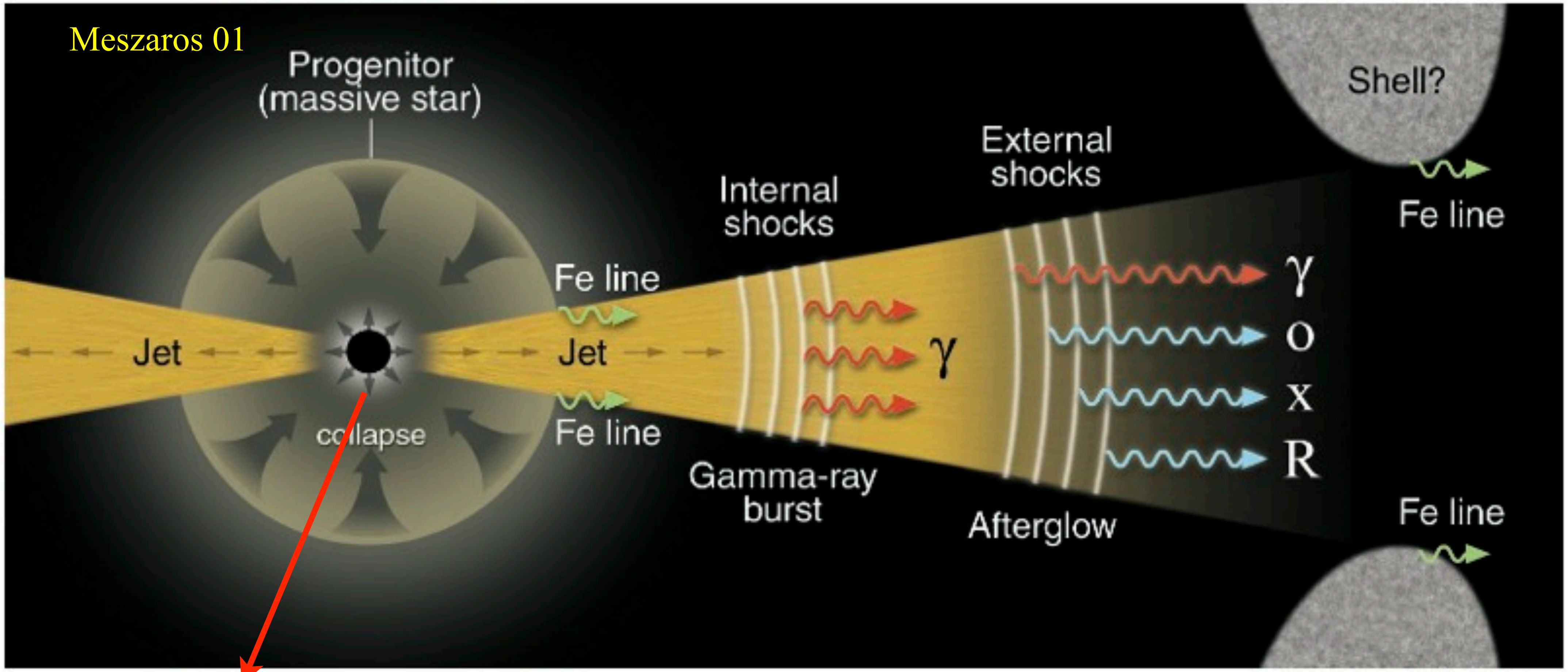
RIKEN

Astrophysical Big Bang Laboratory

Collaborators: Nagataki, Ito, Mizuta, Barkov,
Dainotti, Teraki (RIKEN)

Schematic Picture of the GRB Jet



Central engine

- MHD process

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

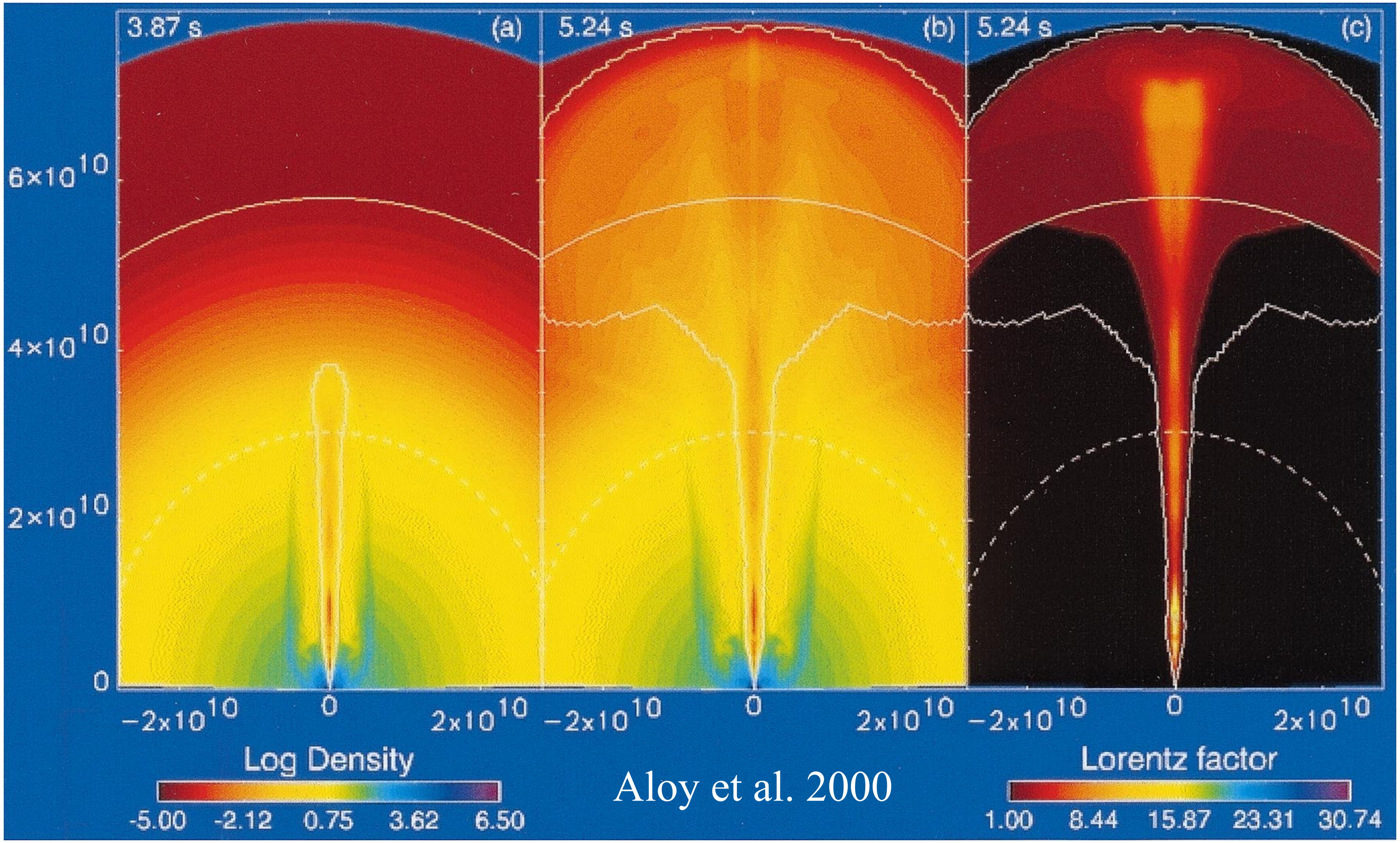
- thermal process

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

- relativistic jet is launched from the central engine
- associated the death of the massive star

The dynamics and stability of the relativistic jet is important in order to understand the GRB emissions.

First Simulation of GRB Jet Propagation



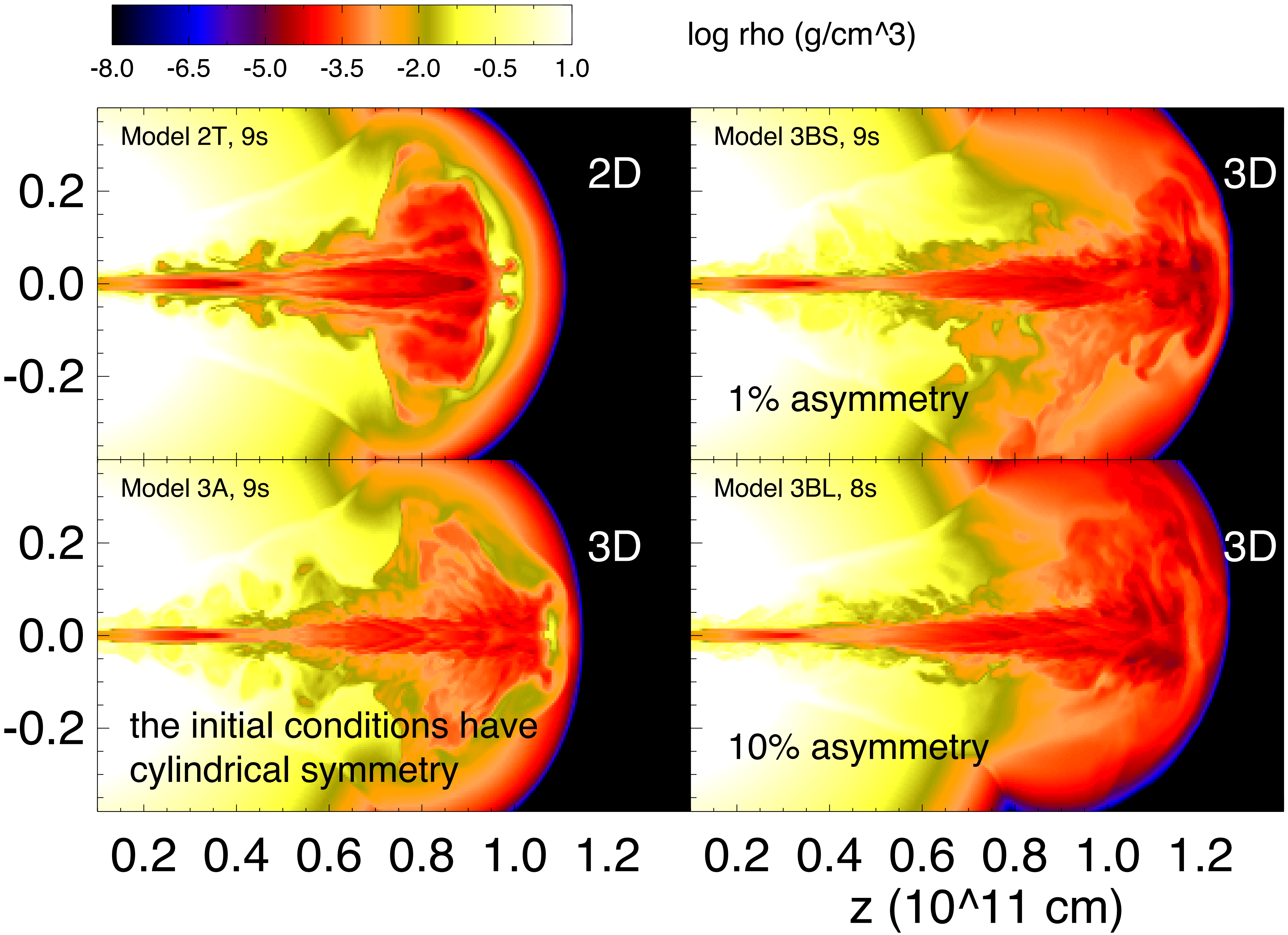
Aloy et al. 2000

- inside star: collimation by cocoon
- outside star: drastic acceleration

⟵ adiabatic expansion: energy conversion from $E_{\rm th}$ to $E_{\rm kine}$

⟵ Bernoulli equation: $\gamma h = \text{const.}$ $h = 1 + 4P/\rho$

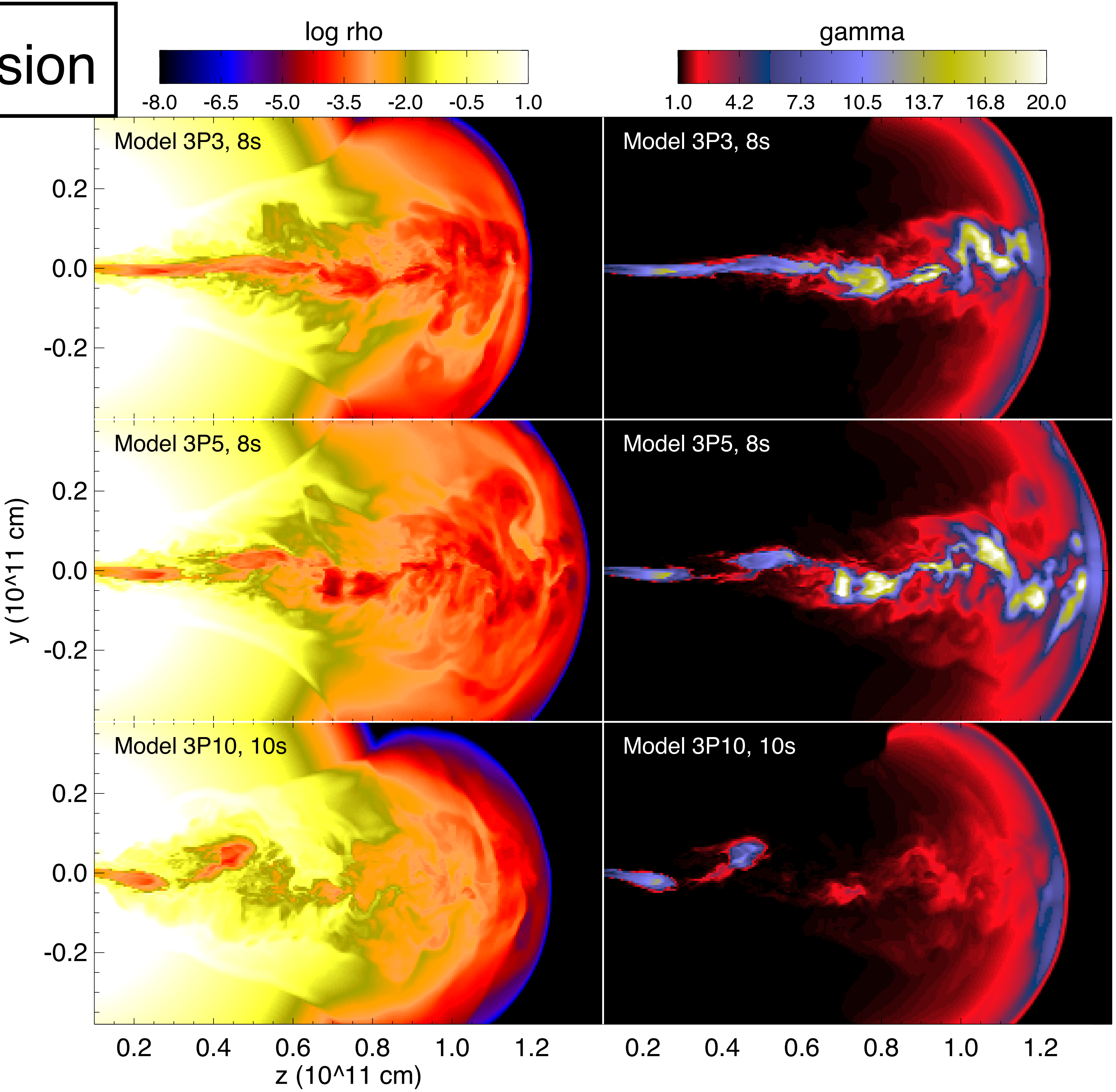
3D calculation: Zhang+ 2004



The dynamics of the jet does not drastically change in between 2D and 3D

3D calculation: Zhang+ 2004

with precession



inclination angle

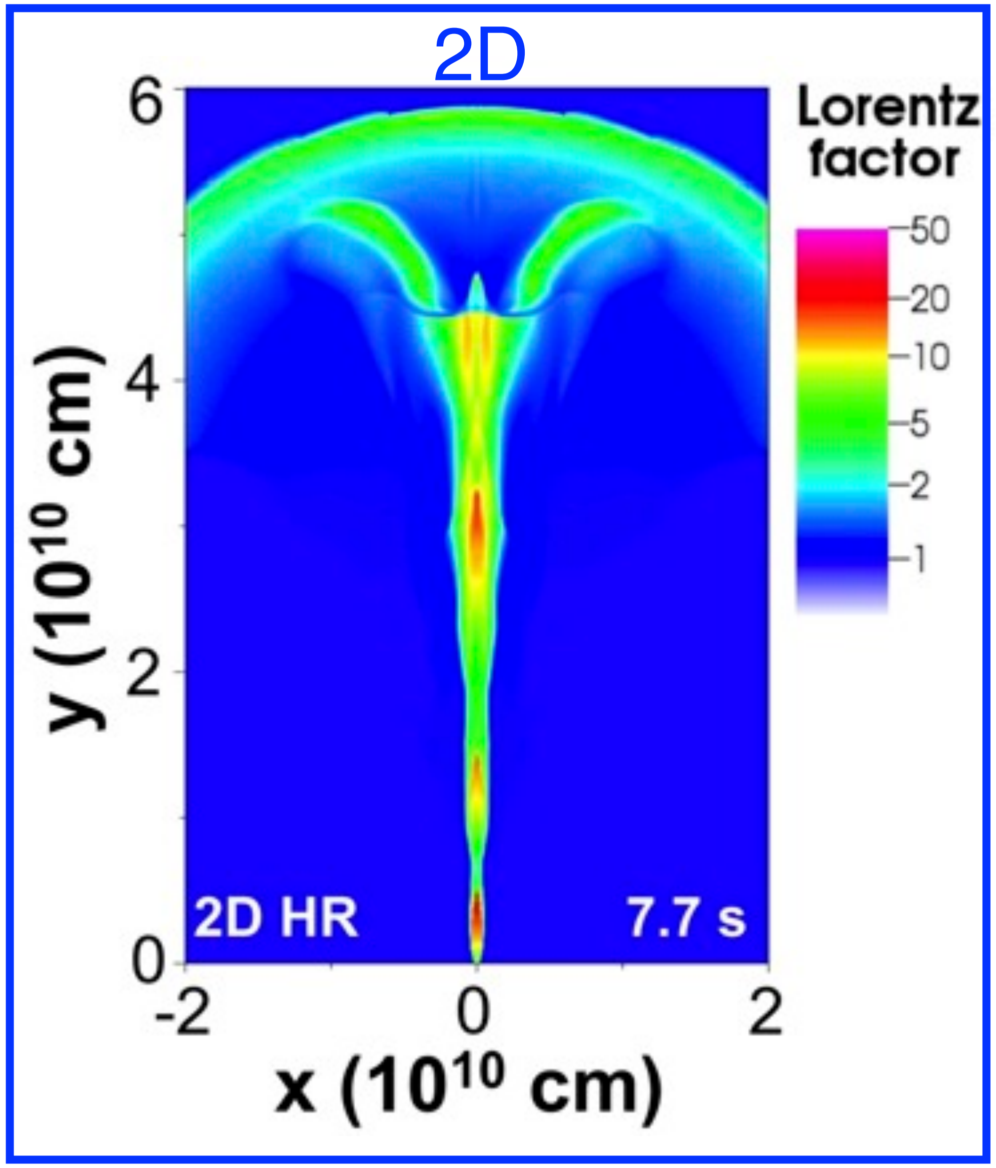
3°

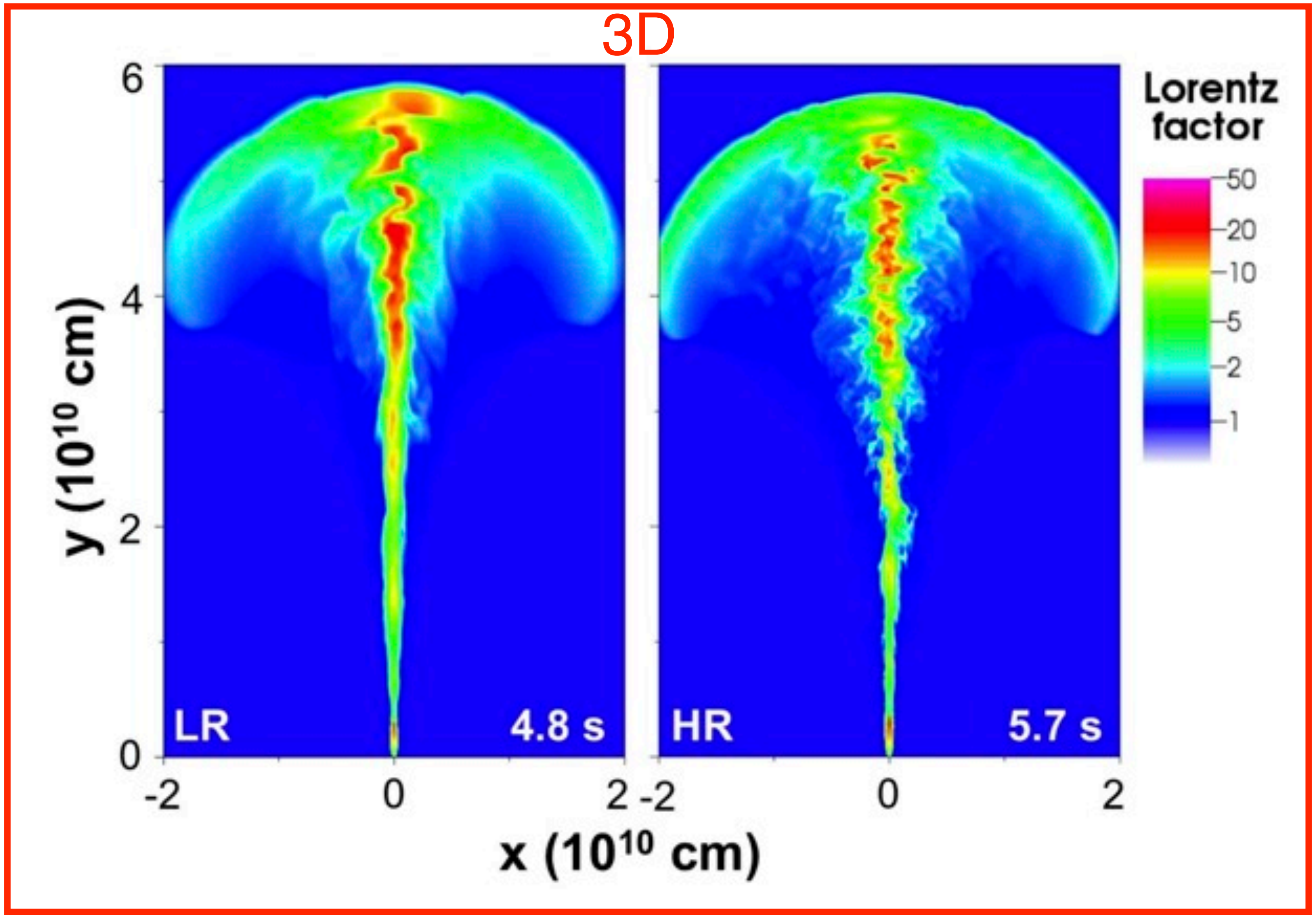
5°

10°

The jet is decelerated due to the material mixing between the jet and surrounding medium.

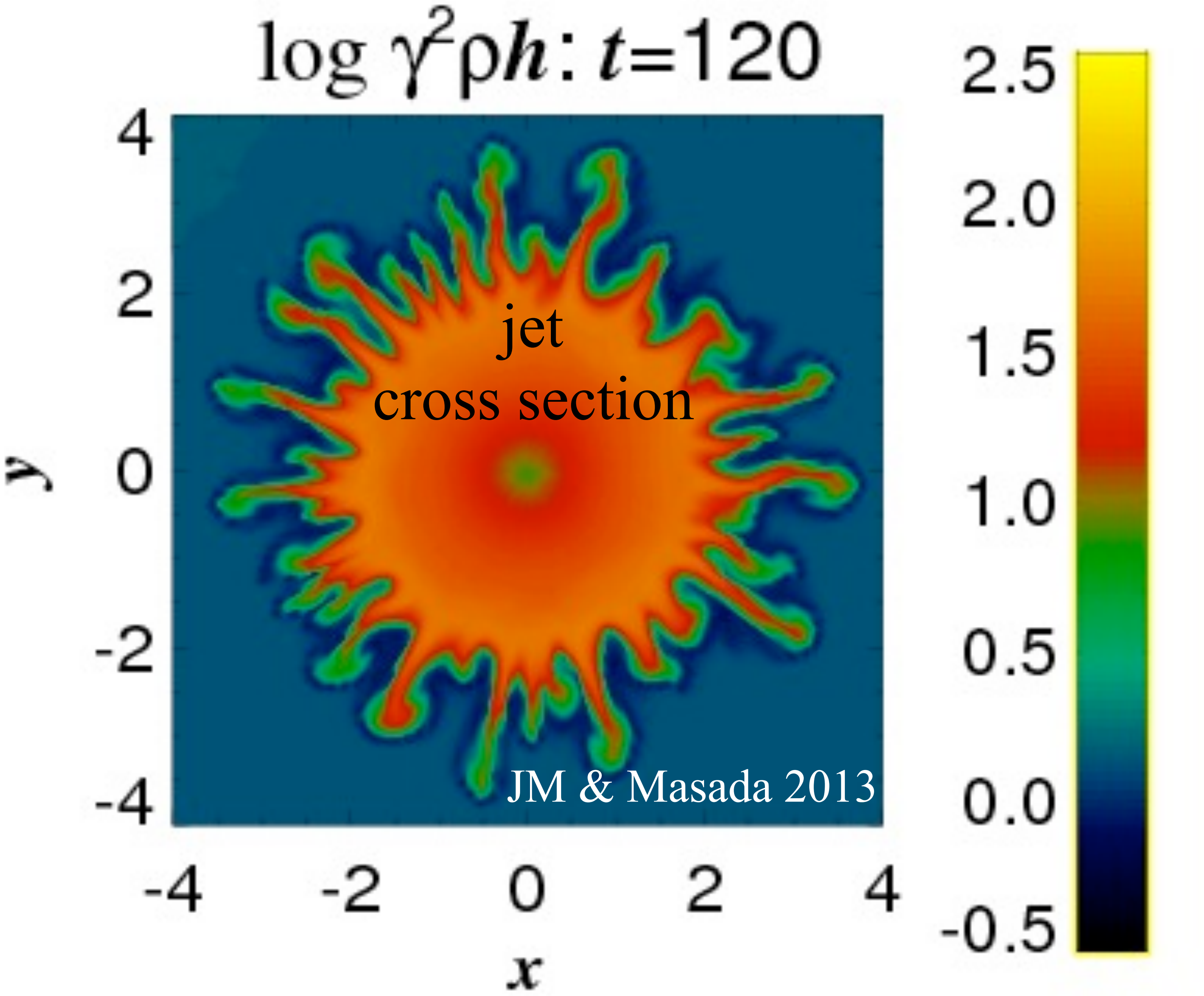
3D calculation: Lopez-Camara+ 2013





- The relativistic jet can propagate and break out the progenitor star while remaining relativistic without the dependence of the resolution.
- The amount of turbulence and variability observed in the simulations is greater at higher resolutions.
- Jet properties are only marginally affected by the dimensionality.

Oscillation Induced RTI and RMI



JM & Masada 2013

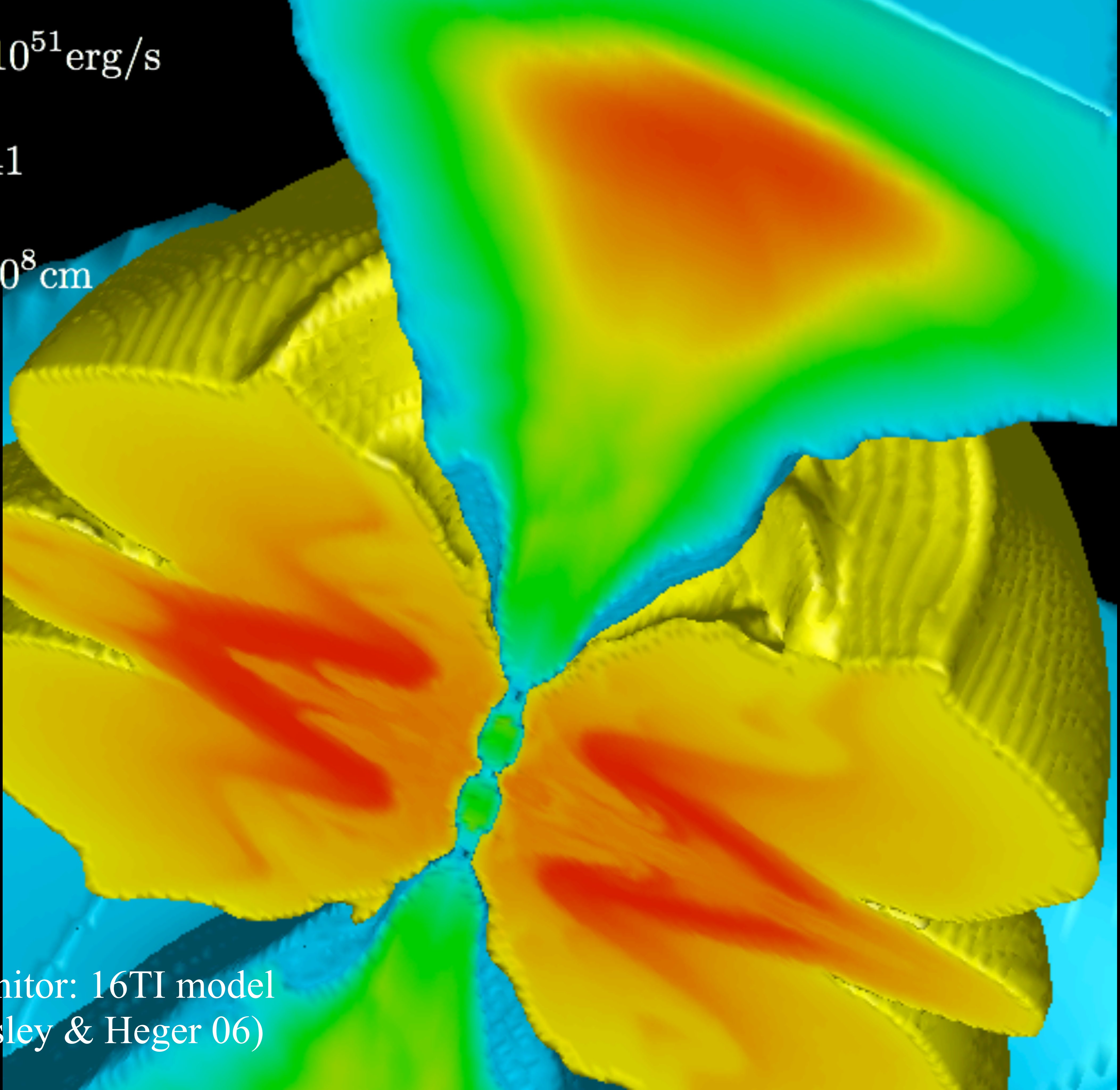
- radial oscillation motion of the jet
- growth of the Rayleigh-Taylor and Richtmyer-Meshkov instabilities

These instabilities grow in GRB jet?

3D simulation:
propagation of the relativistic jet

focusing on the impact of the oscillation-induced
Rayleigh-Taylor and Richtmyer-Meshkov instabilities
(JM & Masada 2013) on the 3D jet propagation.

$L_{\rm jet} = 10^{51} {\rm erg/s}$
$\gamma_{\rm jet} = 5$
$h_{\rm jet} = 41$
$\theta_{\rm jet} = 0$
$r_{\rm jet} = 10^8 {\rm cm}$



progenitor: 16TI model
(Woosley & Heger 06)

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

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

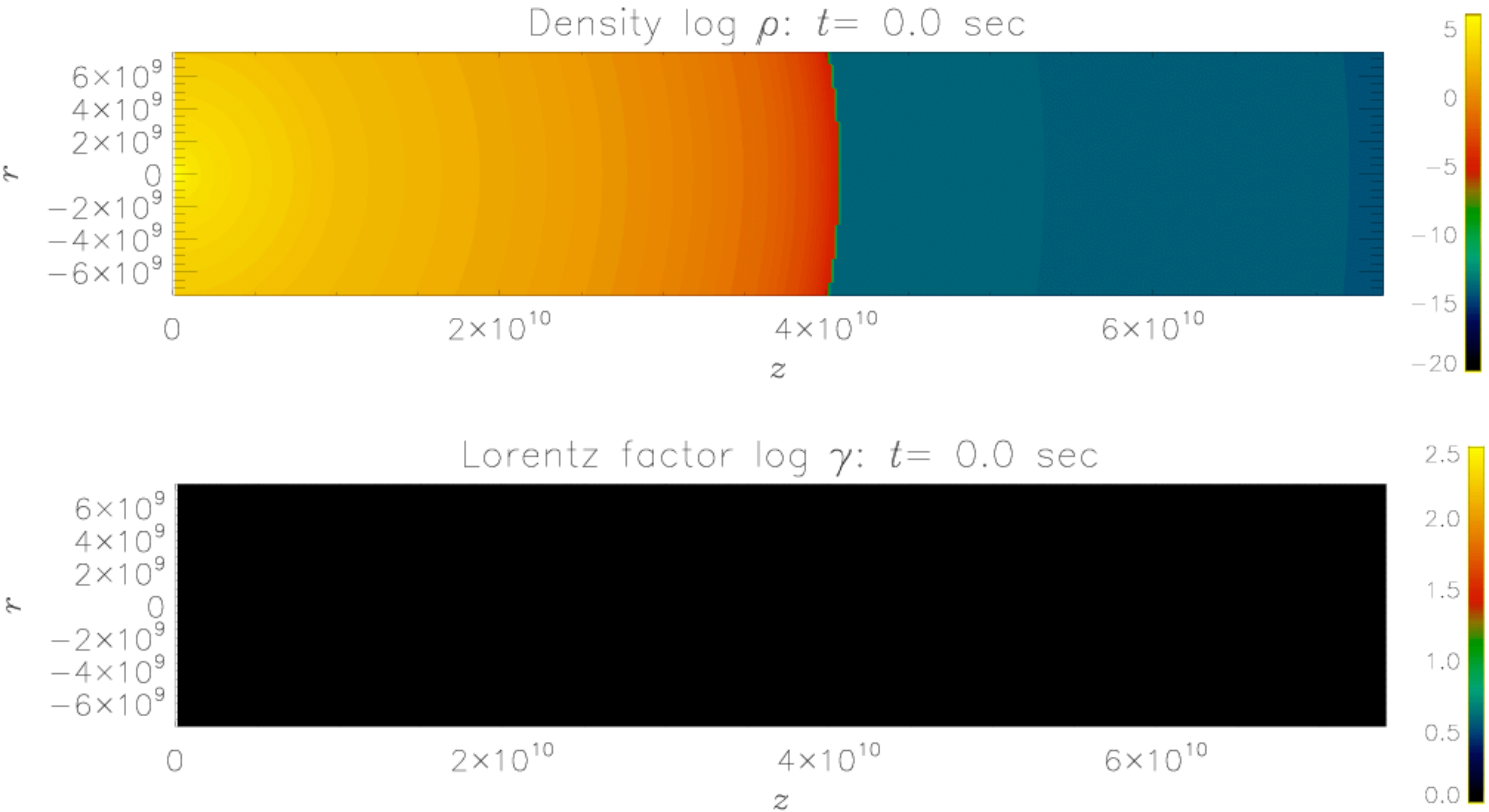
ratio of specific heats

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

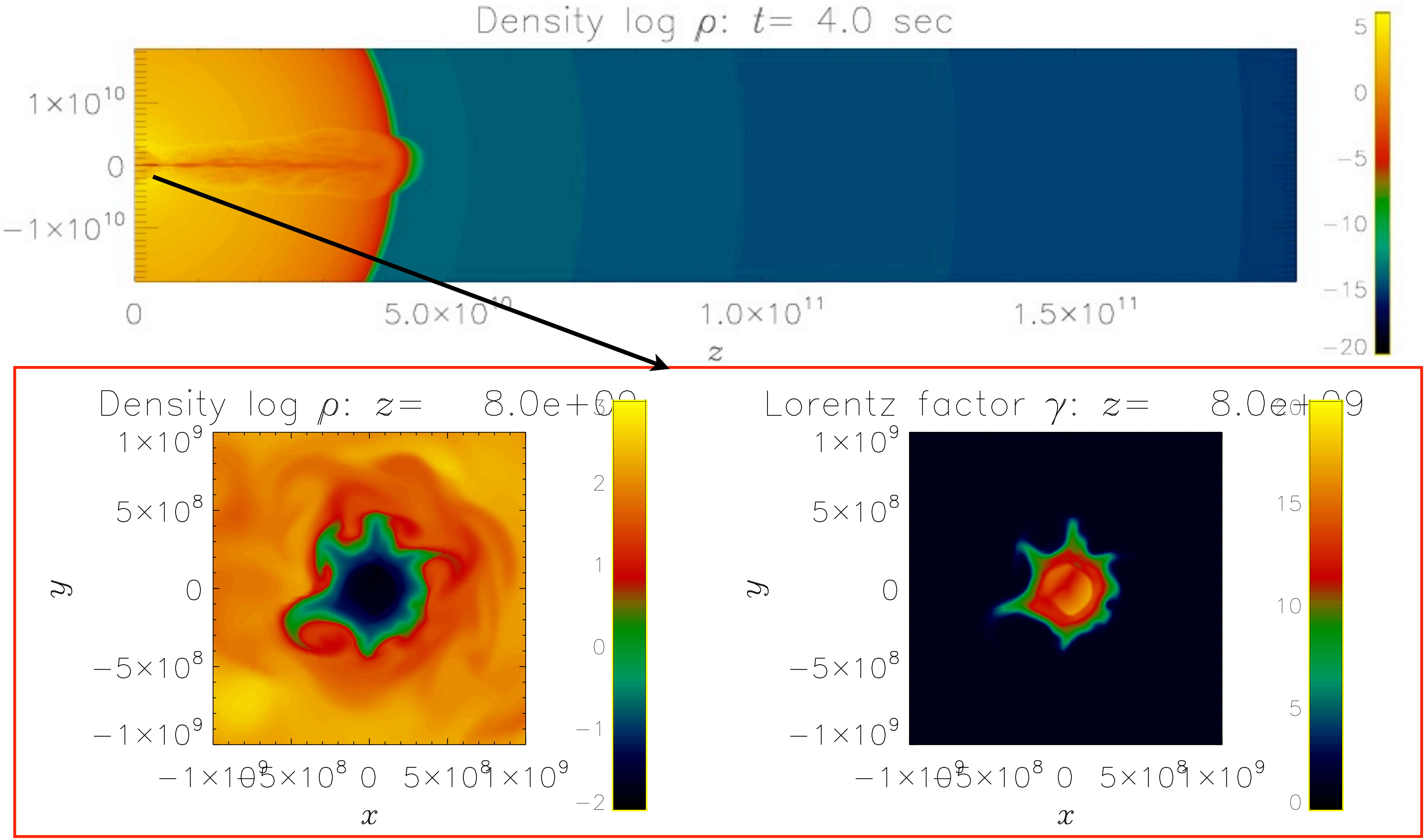
Lorentz factor

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

3D HD GRB Jet Propagation

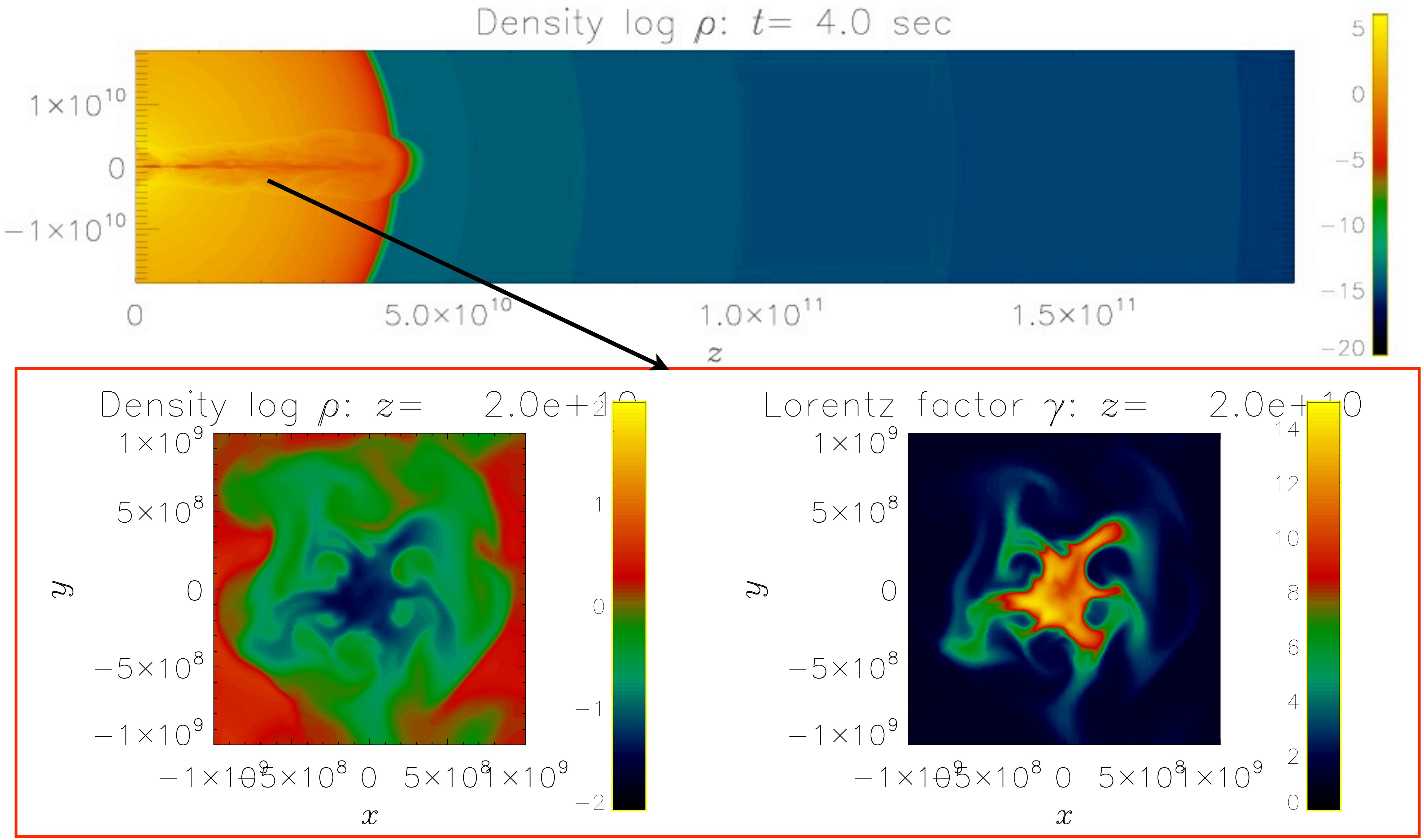


Finger-like structures inside star



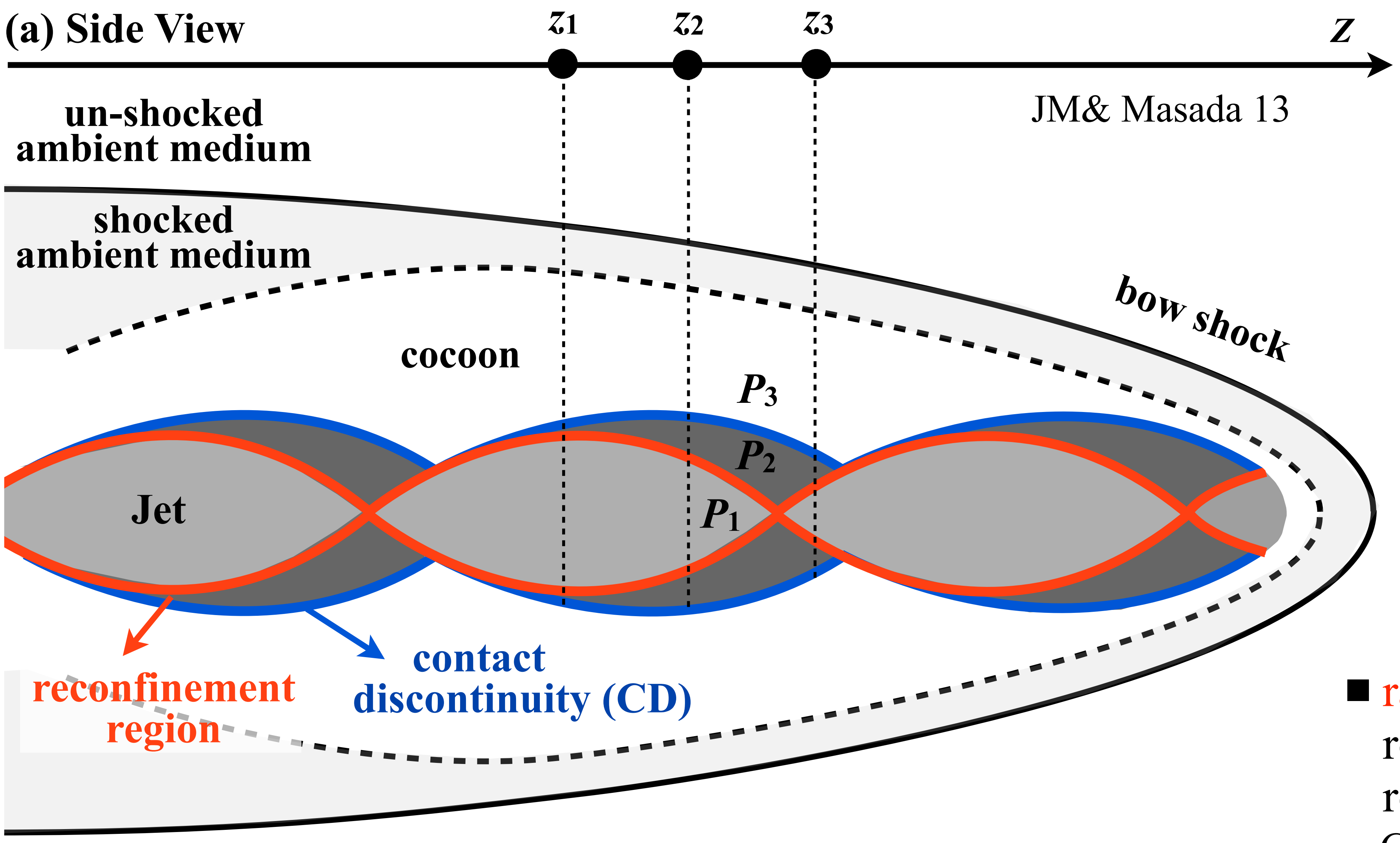
- Finger like structures are excited at the interface between the jet and cocoon.

Finger-like structures inside star



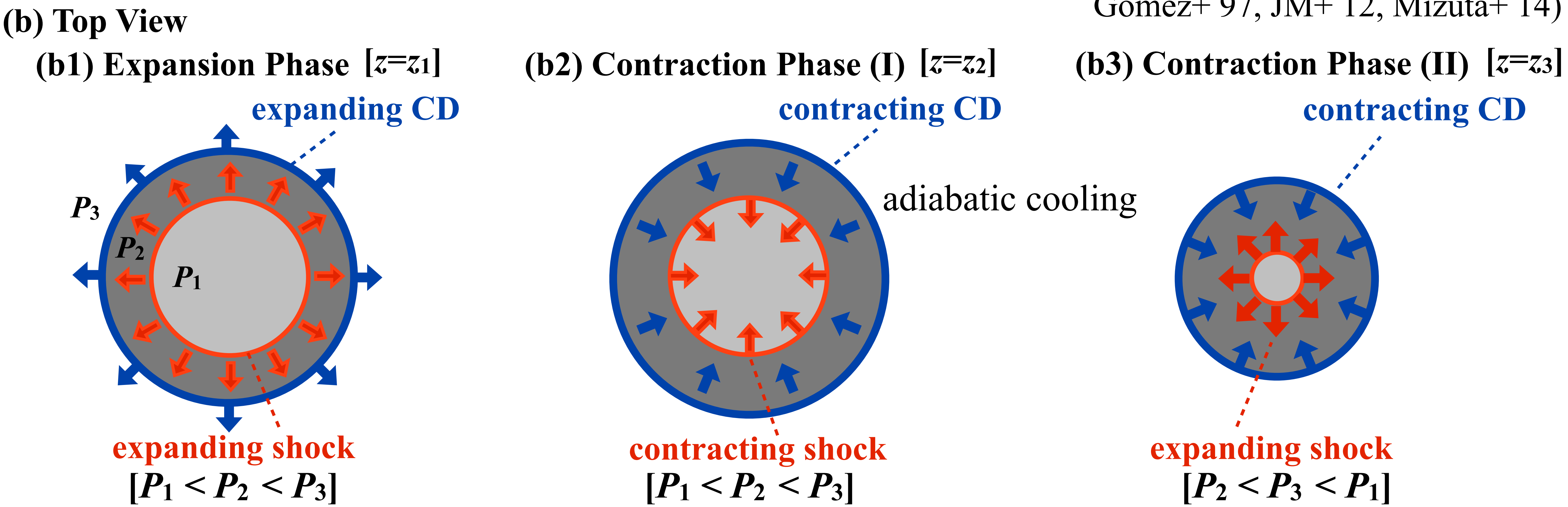
- Finger like structures are excited at the interface between the jet and cocoon.

3D simulations:
evolution of the cross section of the relativistic jet

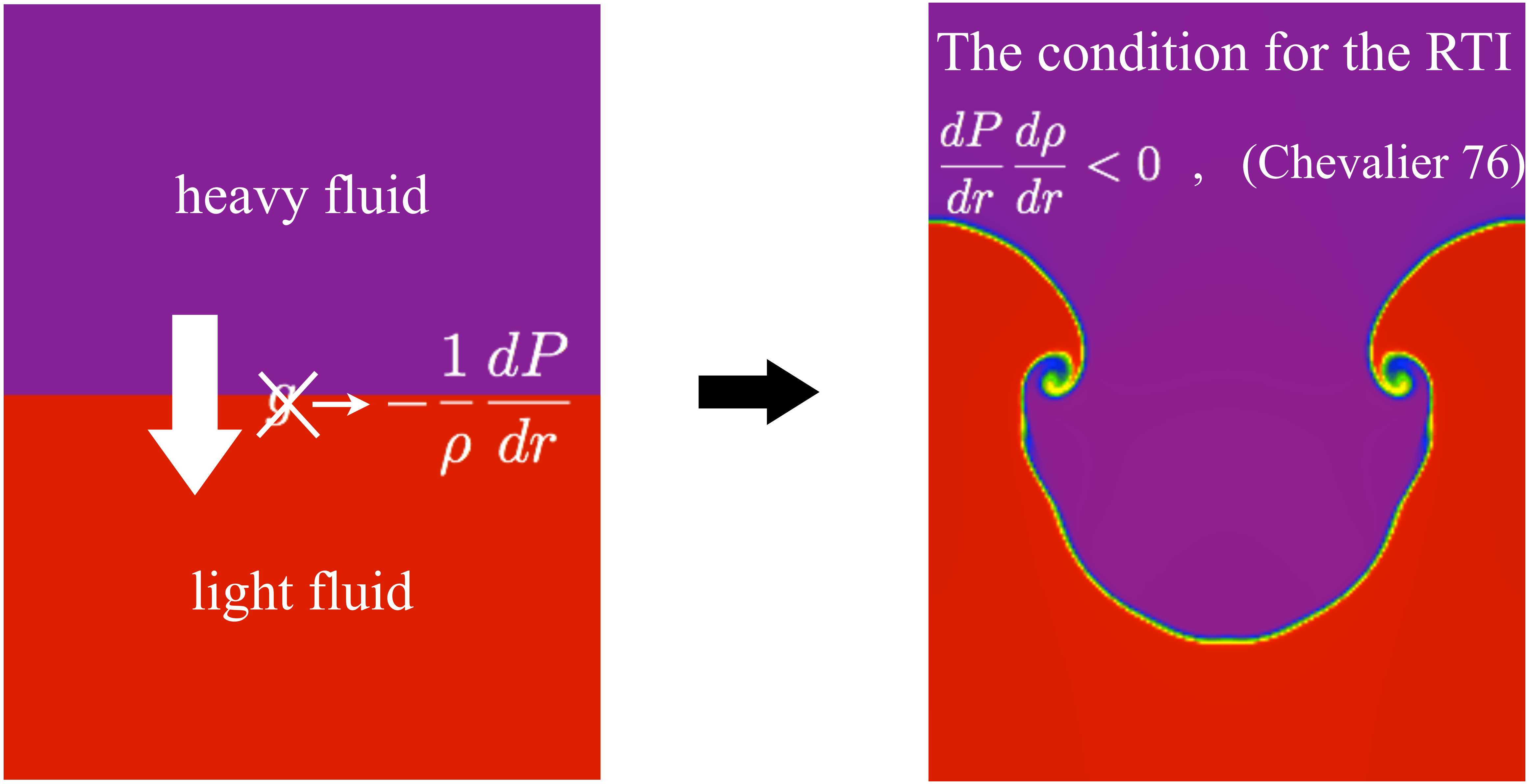


JM& Masada 13

- 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, Mizuta+ 14)



Growth of RTI in SN Explosion



heavy fluid

$$\cancel{g} \rightarrow -\frac{1}{\rho}\frac{dP}{dr}$$

light fluid

The condition for the RTI

$$\frac{dP}{dr}\frac{d\rho}{dr} < 0 \quad , \qquad \text{(Chevalier 76)}$$

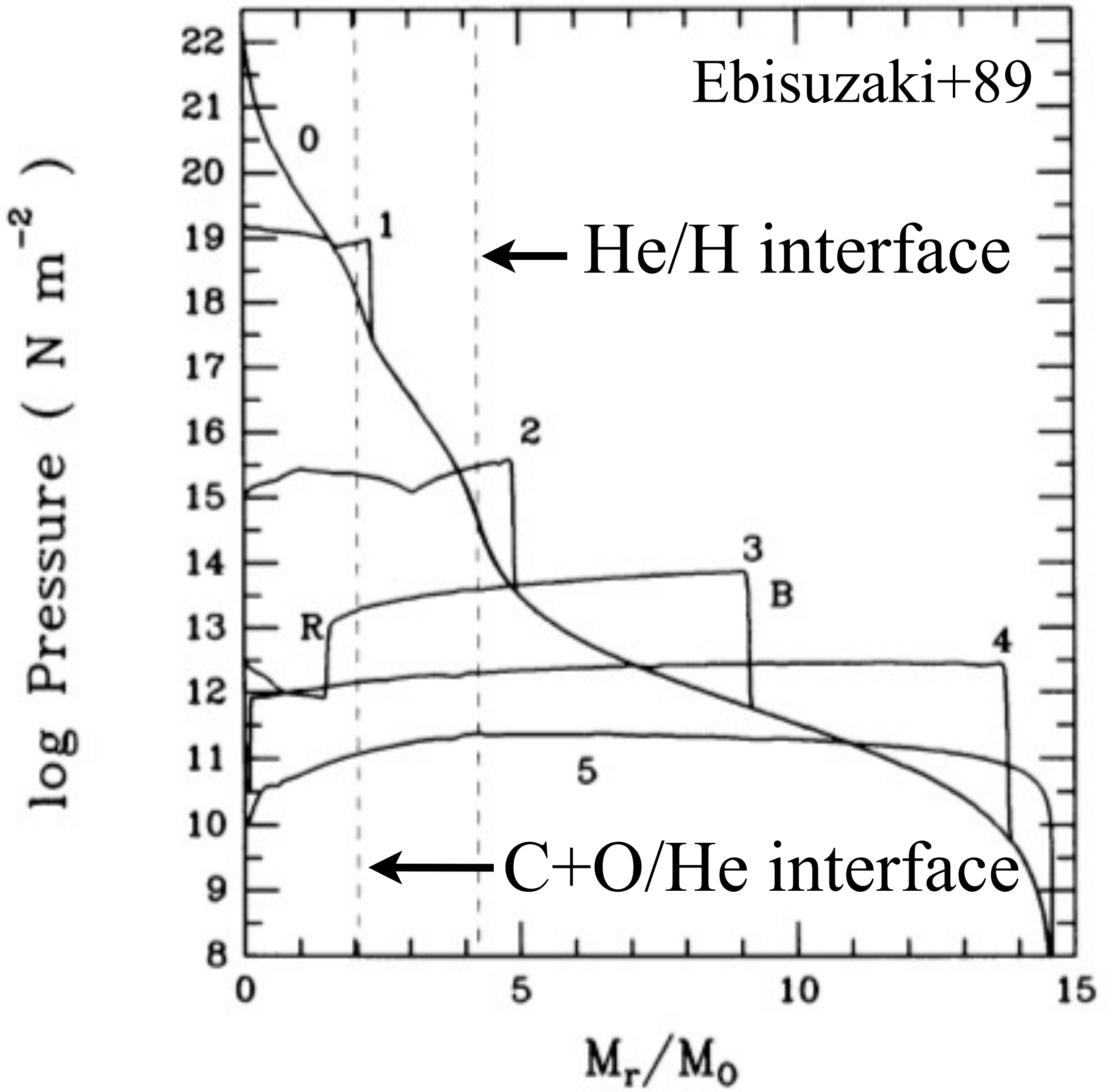
It is well known that a contact discontinuity, formed where a heavy fluid is supported above a light fluid against gravity, is unstable to perturbations to the boundary between the two fluids.

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

Growth of RTI in SN Explosion

The condition for the RTI for a compressible fluid in the absence of the gravity is given by

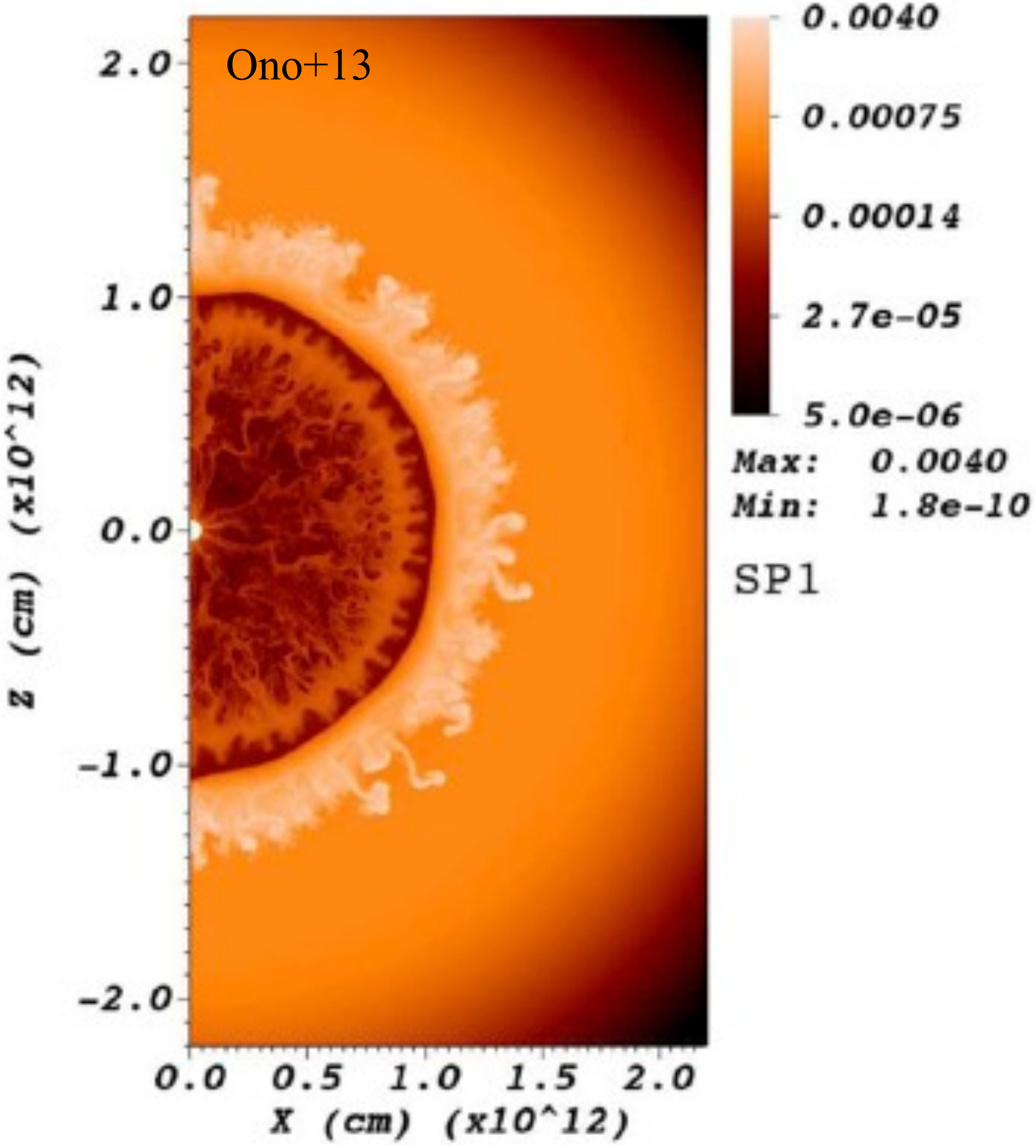
$$\frac{dP}{dr}\frac{d\rho}{dr} < 0 \quad , \quad \text{(Chevalier 76)}$$



Ebisuzaki+89

← He/H interface

← C+O/He interface



Ono+13

The mechanism of the growth of RTI

The effective inertia is important.

relativistically hot plasma:

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

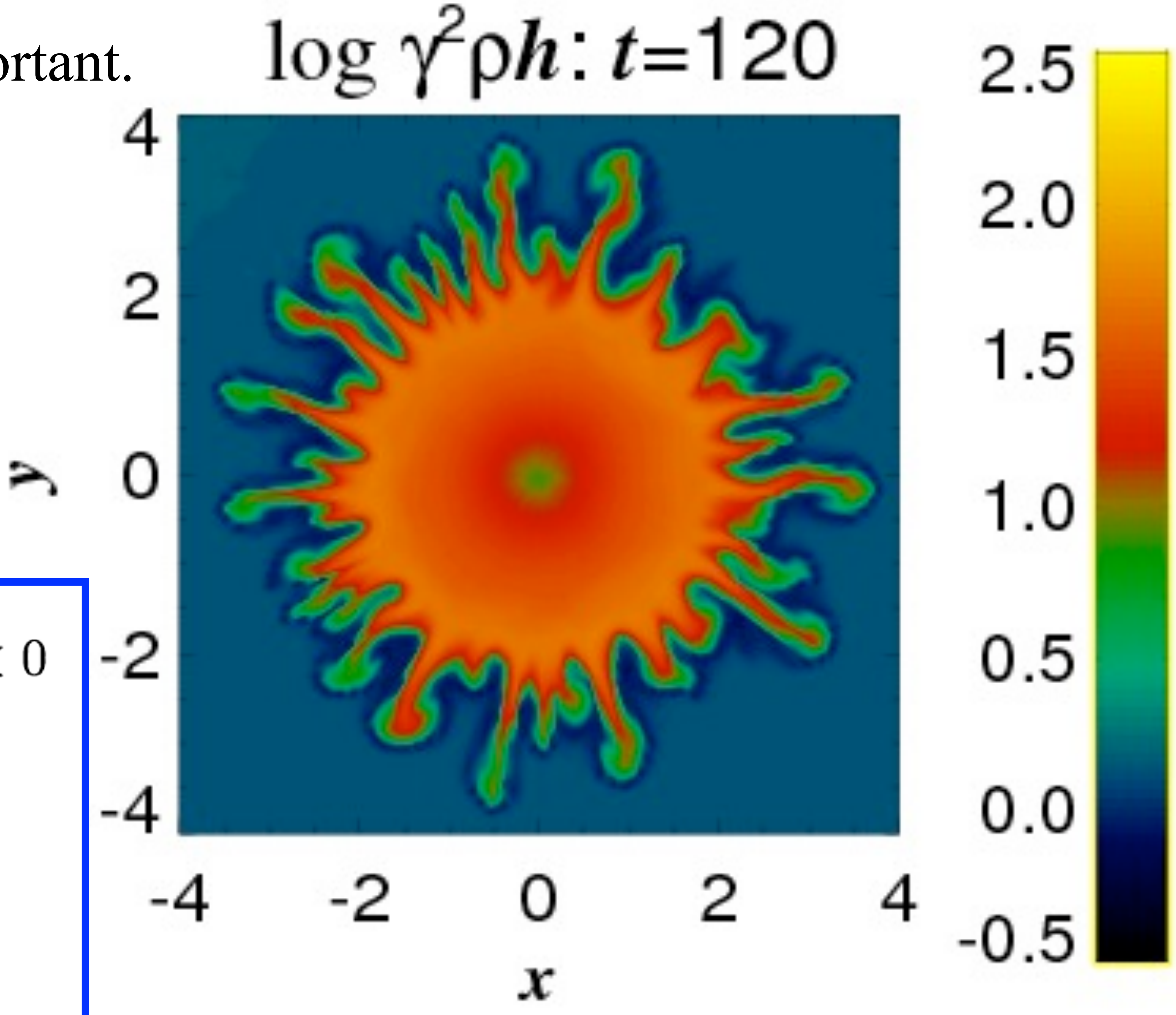
effective inertia:

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

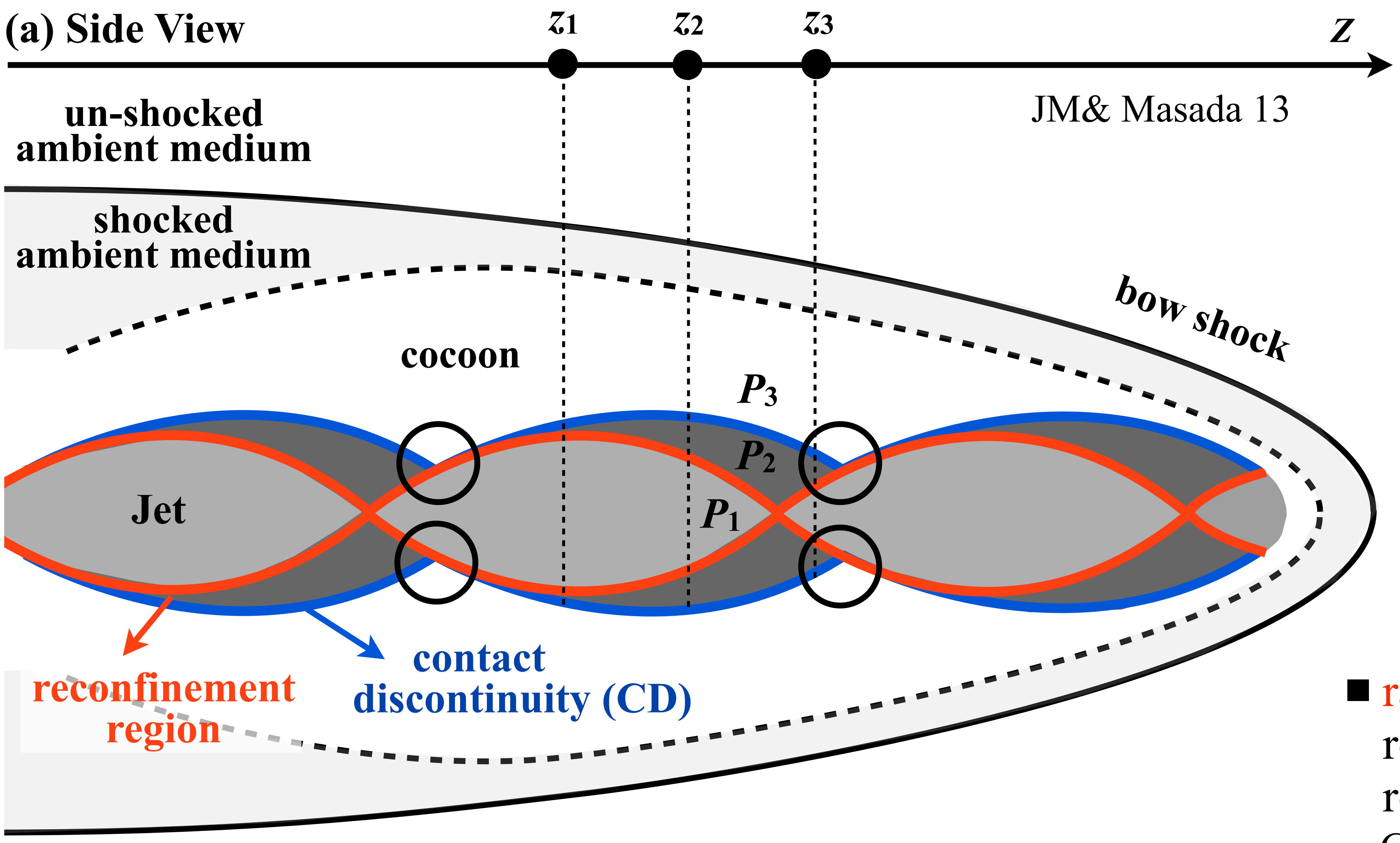
$$\frac{d\rho}{dr} > 0, \quad \frac{dP}{dr} > 0, \quad \frac{d(\gamma^2 \rho h)}{dr} < 0$$

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

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



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.



(a) Side View

JM& Masada 13

- 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)
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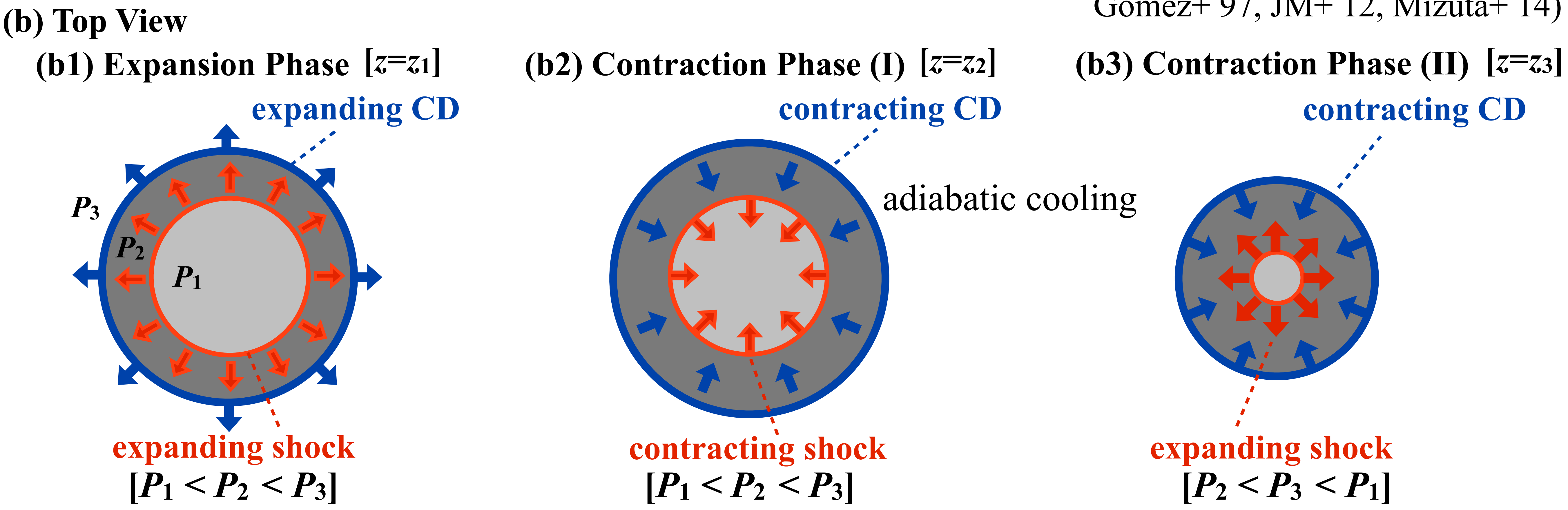


(b) Top View

(b1) Expansion Phase [z=z_1]

(b2) Contraction Phase (I) [z=z_2]

(b3) Contraction Phase (II) [z=z_3]

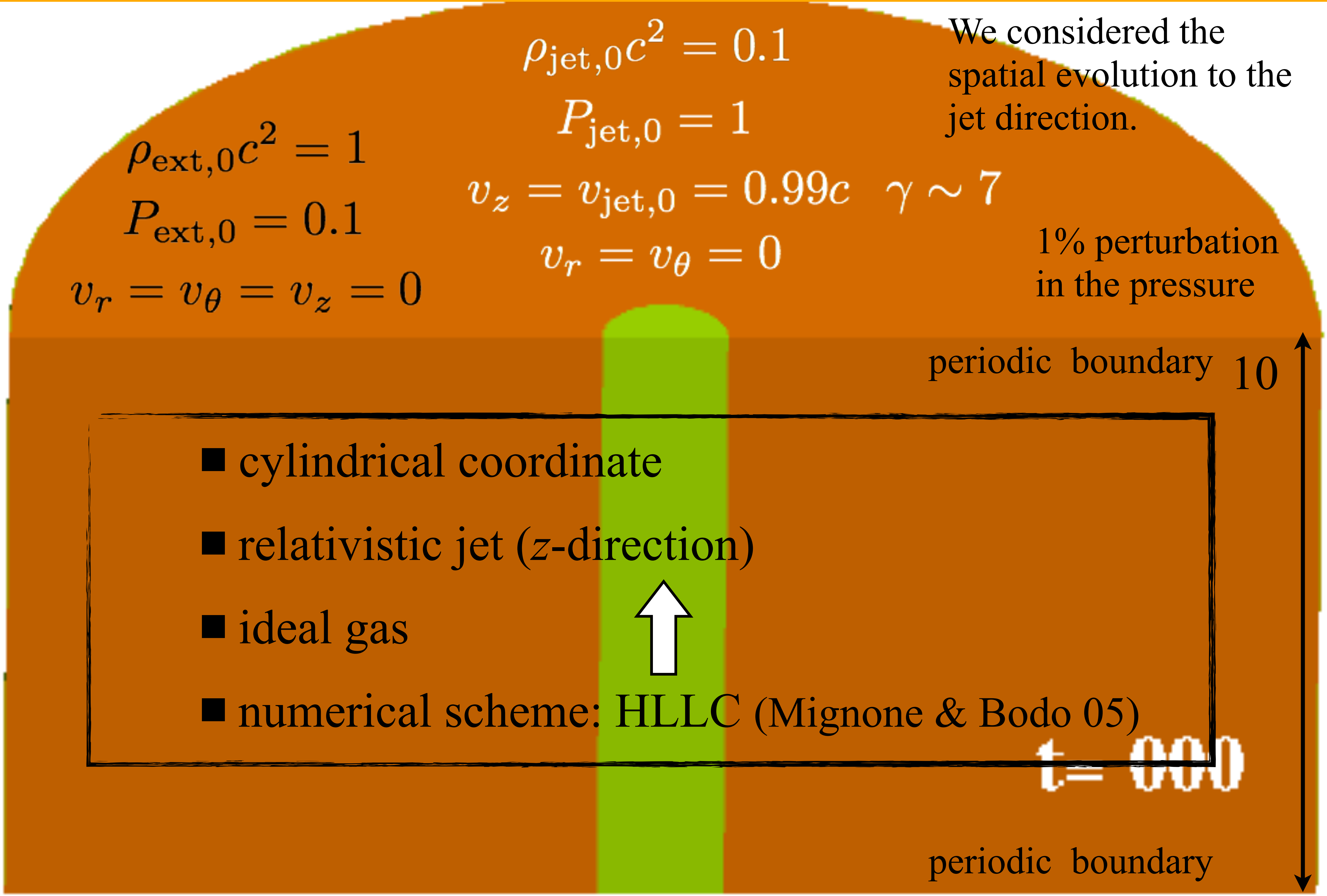
Richtmyer-Meshkov Instability

contact discontinuity

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

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

Numerical Setting: 3D Toy Model



$\rho_{\mathrm{ext},0}c^2 = 1$

$P_{\mathrm{ext},0} = 0.1$

$v_r = v_\theta = v_z = 0$

$\rho_{\mathrm{jet},0}c^2 = 0.1$

$P_{\mathrm{jet},0} = 1$

$v_z = v_{\mathrm{jet},0} = 0.99c \quad \gamma \sim 7$

$v_r = v_\theta = 0$

We considered the spatial evolution to the jet direction.

1% perturbation in the pressure

periodic boundary

10

- cylindrical coordinate
- relativistic jet (*z*-direction)
- ideal gas
- numerical scheme: HLLC (Mignone & Bodo 05)

periodic boundary

Result: Density

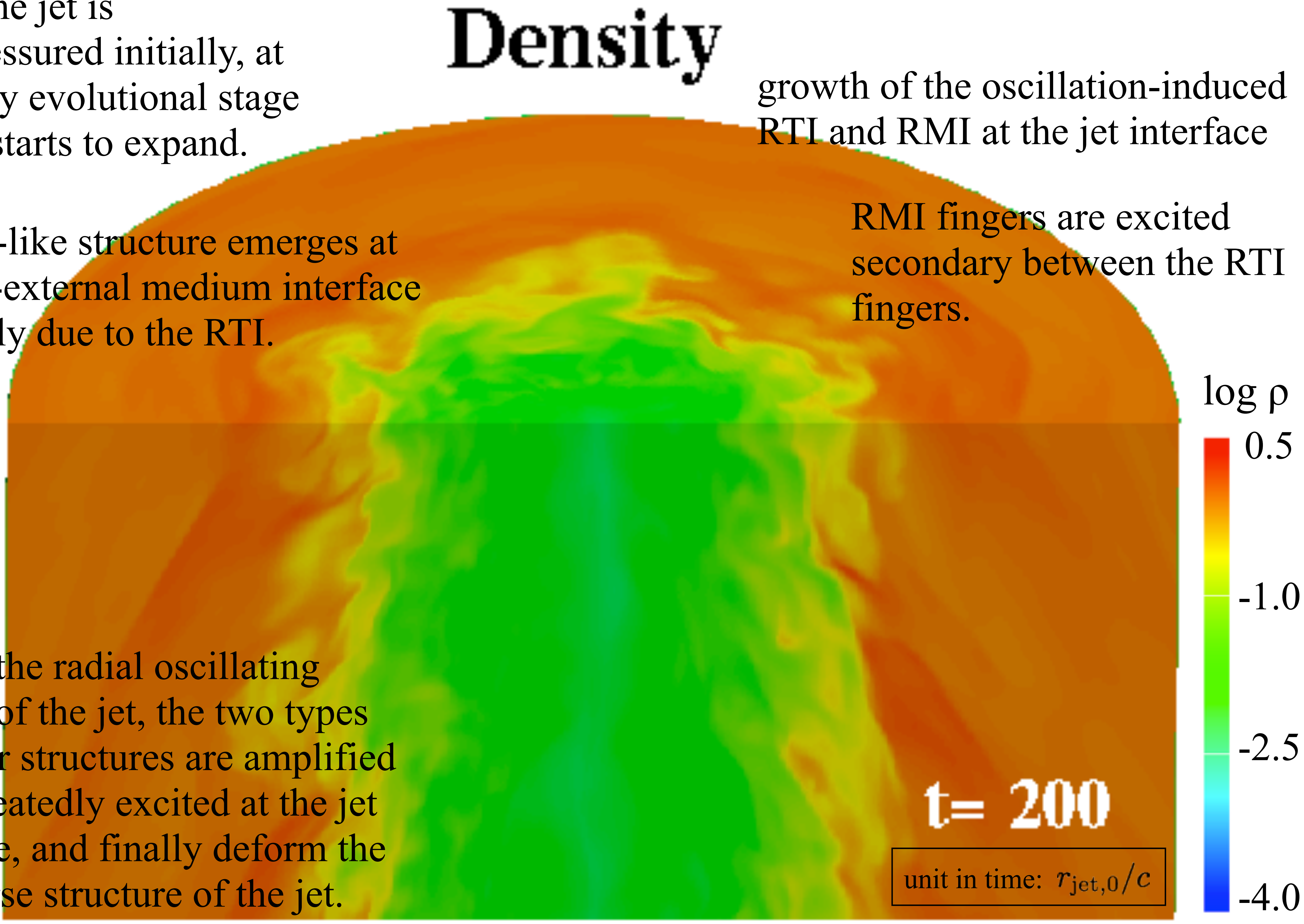
Since the jet is overpressured initially, at the early evolutional stage the jet starts to expand.

growth of the oscillation-induced RTI and RMI at the jet interface

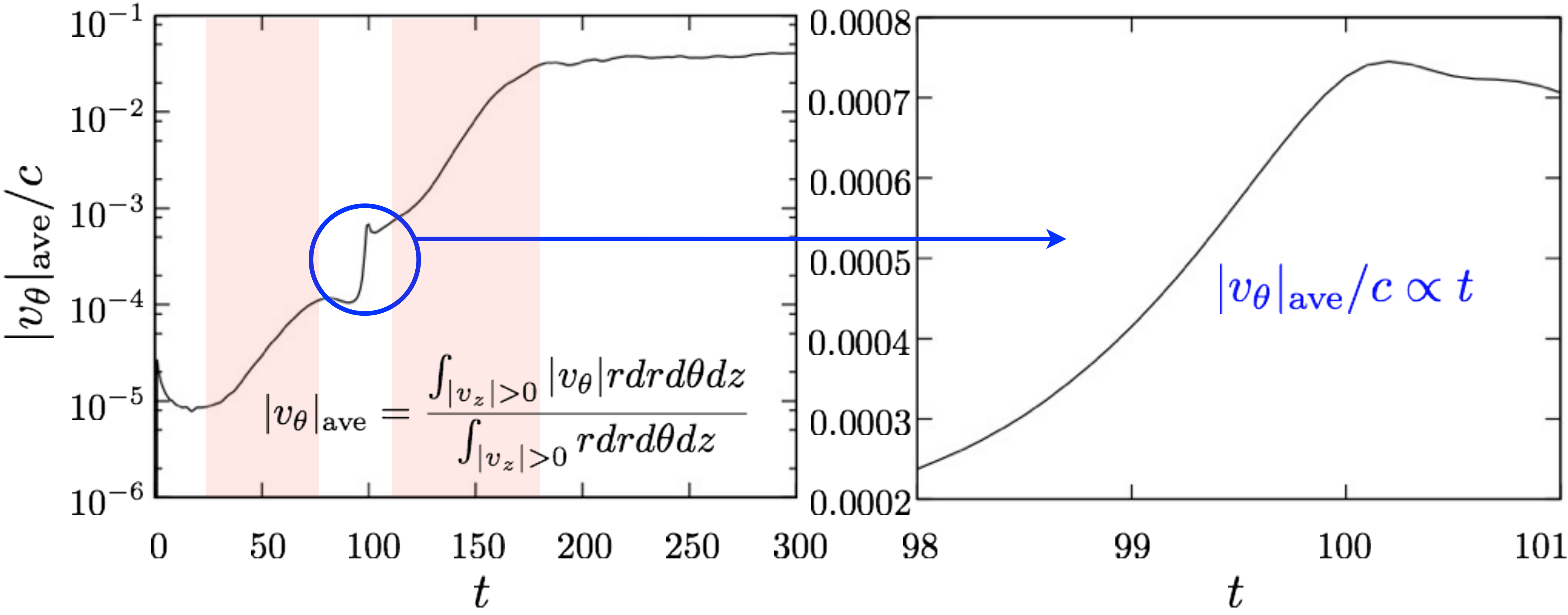
Finger-like structure emerges at the jet-external medium interface primally due to the RTI.

RMI fingers are excited secondary between the RTI fingers.

During the radial oscillating motion of the jet, the two types of finger structures are amplified and repeatedly excited at the jet interface, and finally deform the transverse structure of the jet.



Synergetic Growth of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities



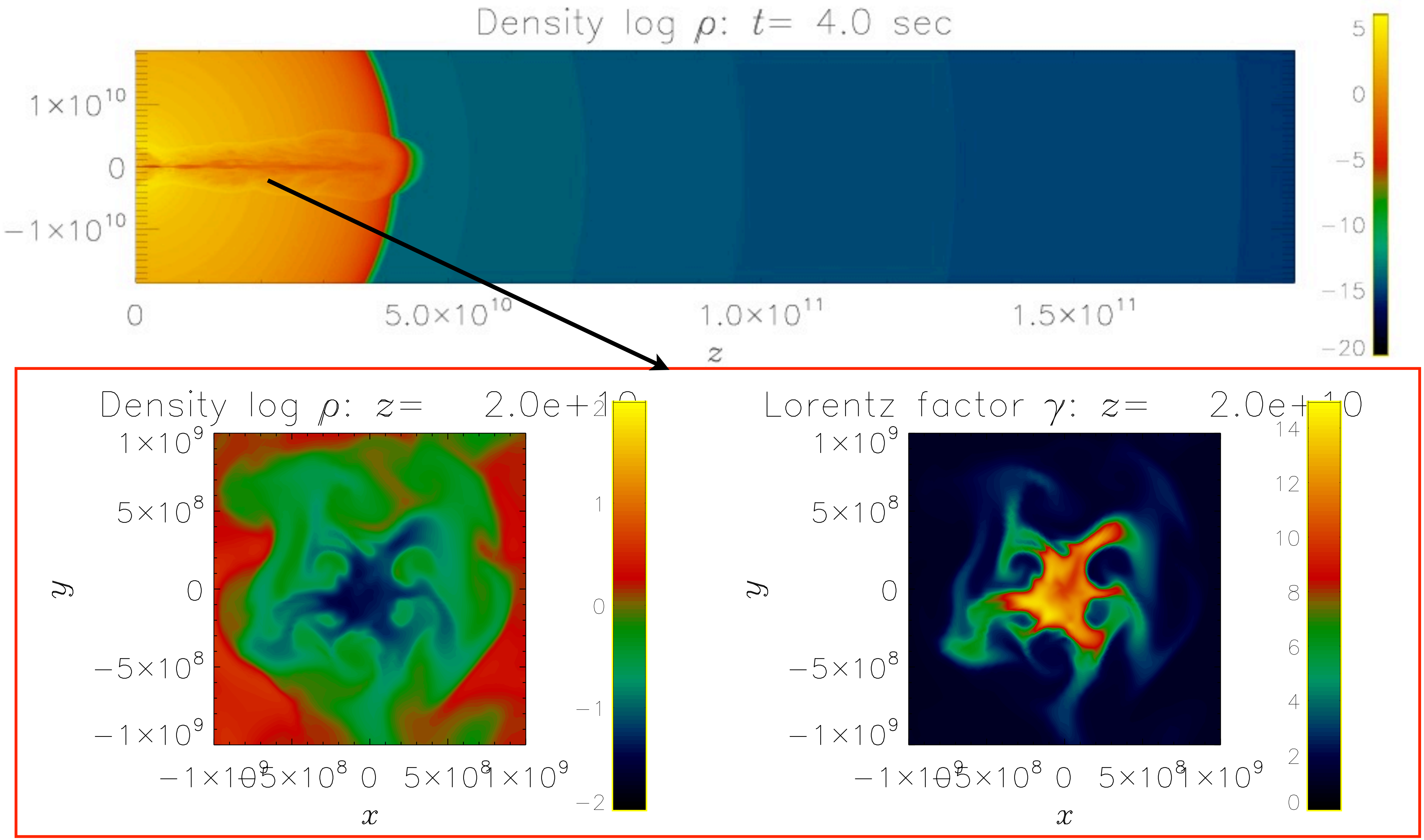
development of the Rayleigh-Taylor instability at the jet interface

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

excitation of the Richtmyer-Meshkov instability at the jet interface

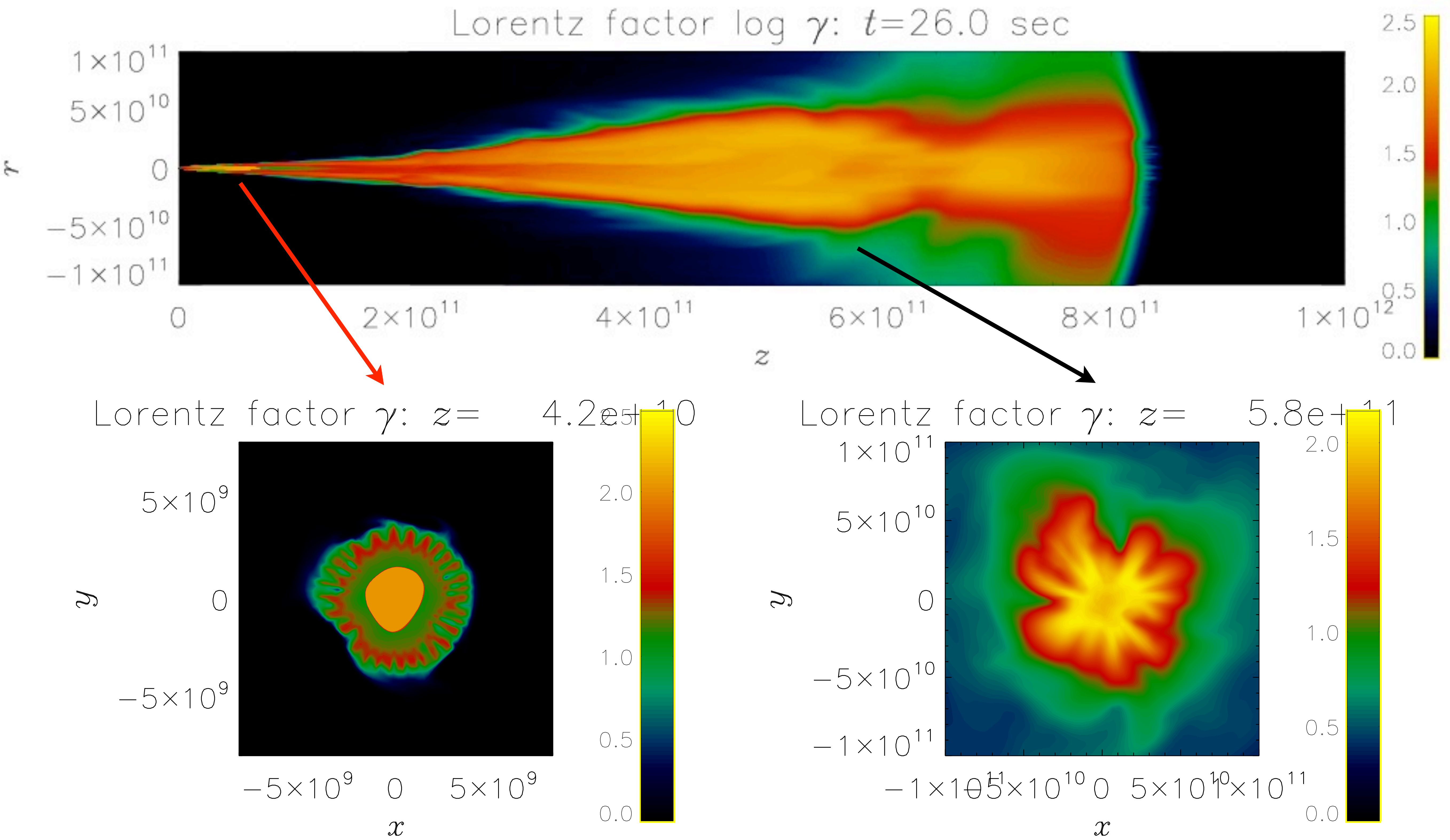
$|v_\theta|_{\rm ave}$ grows linearly with time.

Finger-like structures inside star



- Finger like structures are excited at the interface between the jet and cocoon.

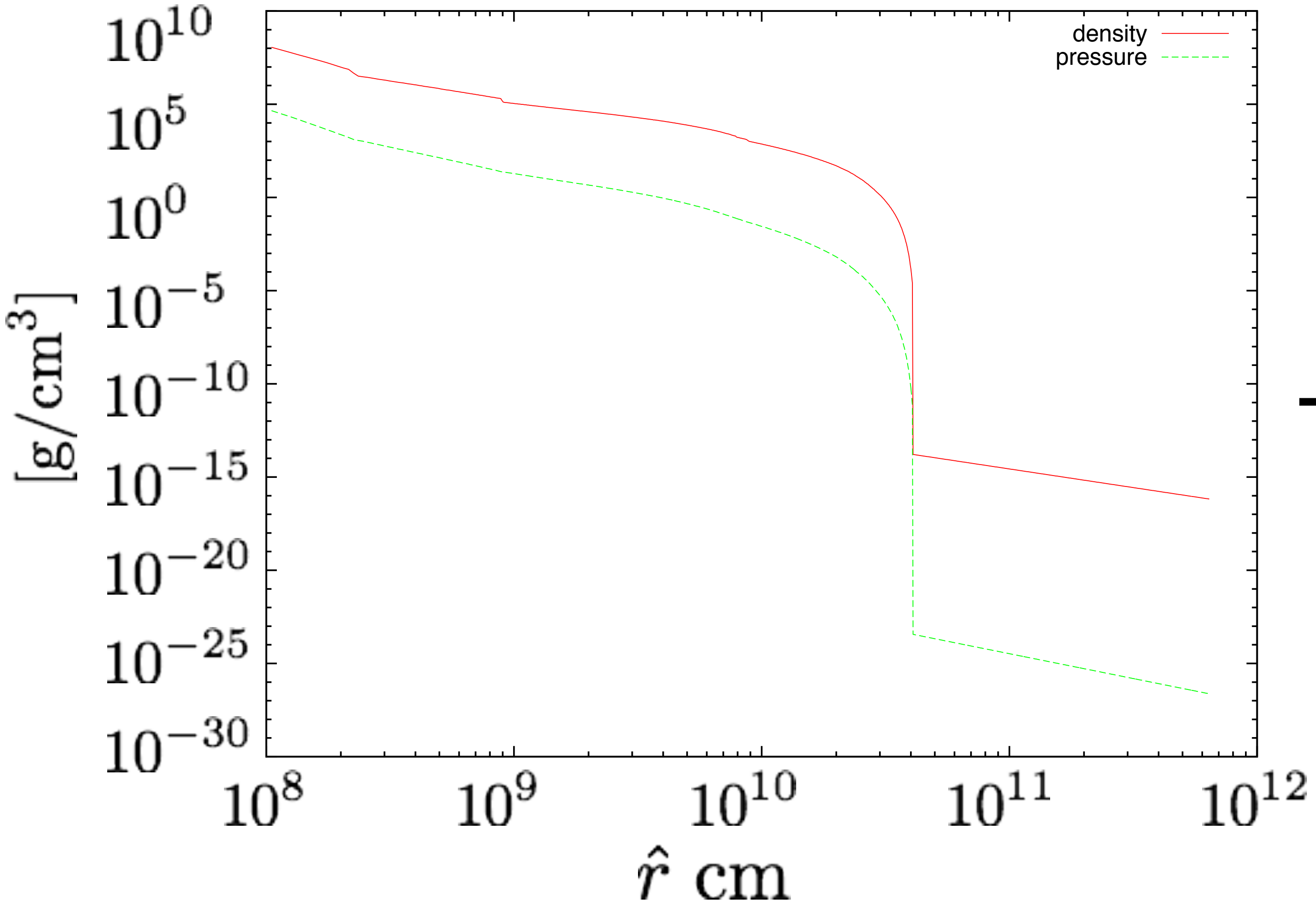
Growth of RTI and RMI outside star



Growth of the RTI and RMI is also observed after the jet breaks out the progenitor star.

2D simulation:
propagation of the relativistic MHD jet

Toy Model for MHD Jet: Pure Toroidal



progenitor:

16TI model (Woosley & Heger 06)

+ stellar wind

$$z_{\rm jet,in} = 10^9 {\rm cm} \qquad r_{\rm jet} = 4 \times 10^8 {\rm cm}$$

$$\theta_{\rm jet} = 0$$

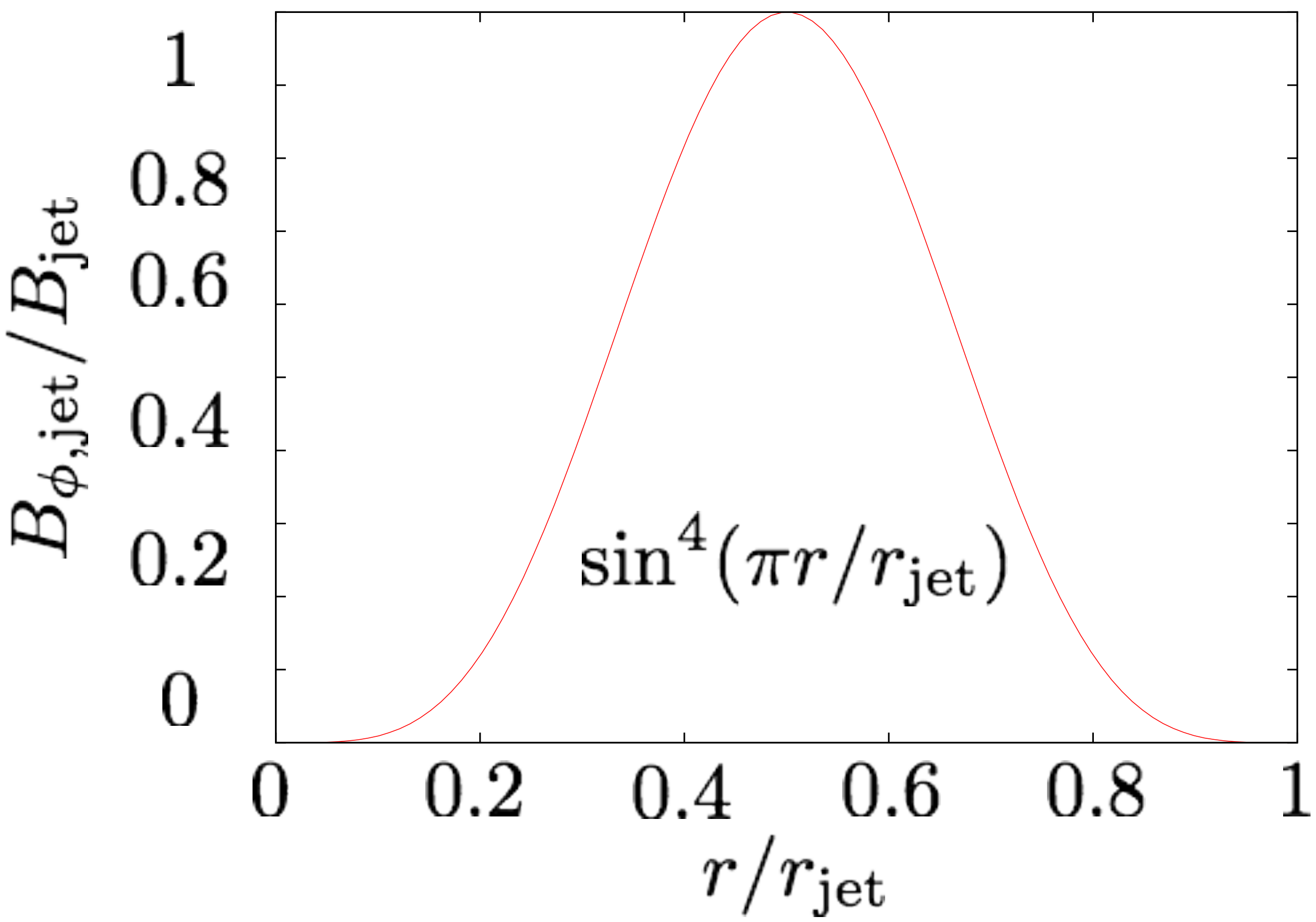
$$L_{\rm jet} = 10^{51}\ {\rm erg/s} \qquad \gamma_{\rm jet} = 5$$

$$h_{\rm jet} = 60 \qquad B = B_{\phi,{\rm jet}}$$

$$\sigma_{\rm jet} = \frac{B_{\rm jet}^2}{4\pi\gamma_{\rm jet}^2\rho_{\rm jet}c^2}$$

$$= 0,\ 0.1,\ 1,\ 5,\ 10,\ 30,\ 60$$

Asahina et al. 2014



Basic Equations

mass conservation

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

momentum conservation

$$\frac{\partial\mathbf{R}}{\partial t} + \nabla\cdot\left[\gamma^2\rho h\frac{\mathbf{vv}}{c^2} + \left(P + \frac{B^2+E^2}{8\pi}\right)\mathbf{I} - \frac{\mathbf{BB}+\mathbf{EE}}{4\pi}\right] = 0$$

energy conservation

$$\frac{\partial\epsilon}{\partial t} + \nabla\cdot\mathbf{R}c^2 = 0$$

induction equation

$$\frac{\partial\mathbf{B}}{\partial t} - \nabla\times(\mathbf{v}\times\mathbf{B}) = 0$$

$$\mathbf{E} = -\frac{\mathbf{v}\times\mathbf{B}}{c}$$

momentum density vector

$$\mathbf{R} \equiv \gamma^2\rho h\frac{\mathbf{v}}{c^2} + \frac{\mathbf{B}\times\mathbf{E}}{4\pi c}$$

energy density

$$\epsilon \equiv \gamma^2\rho h - P + \frac{B^2+E^2}{8\pi}$$

specific enthalpy

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

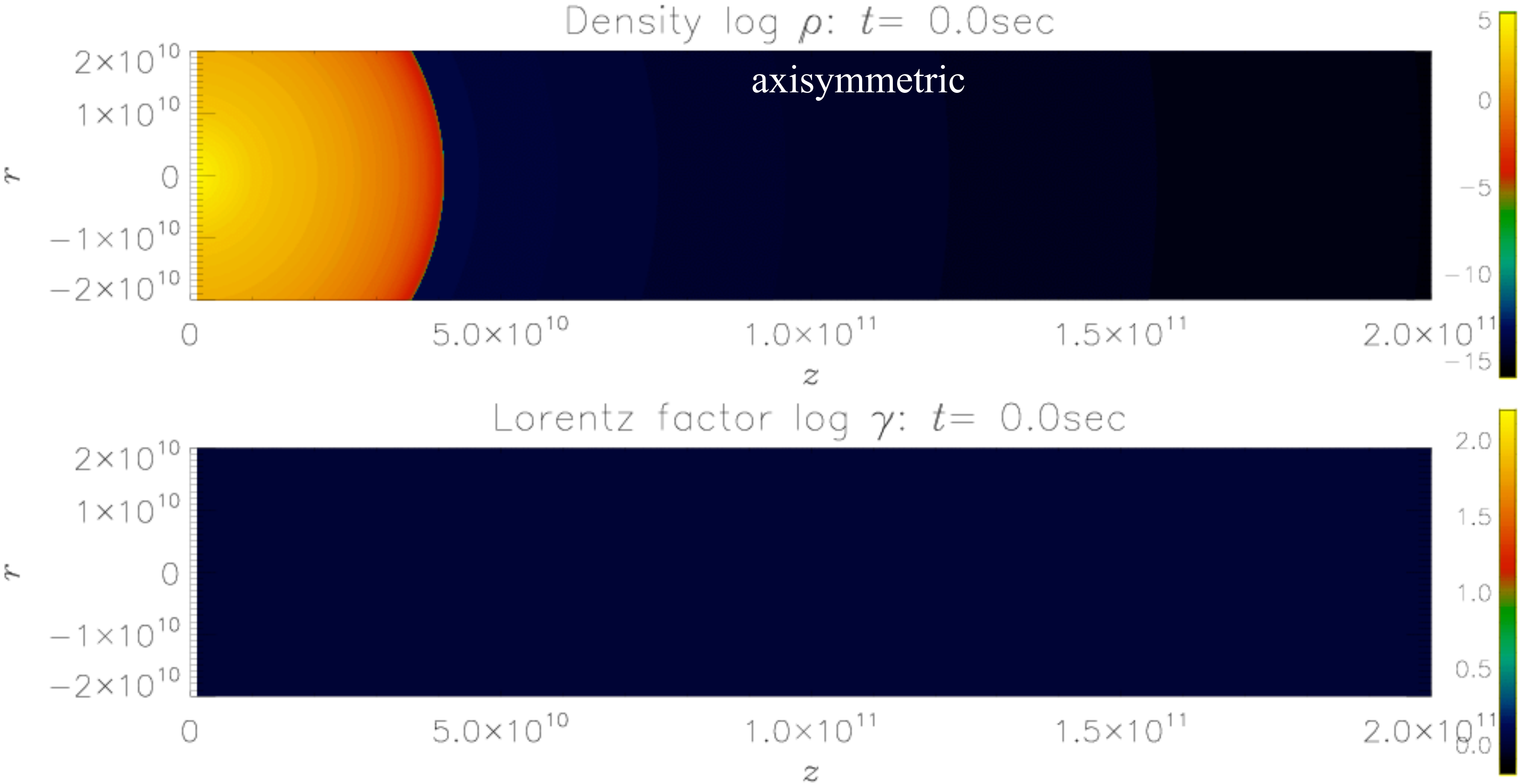
ratio of specific heats

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

Lorentz factor

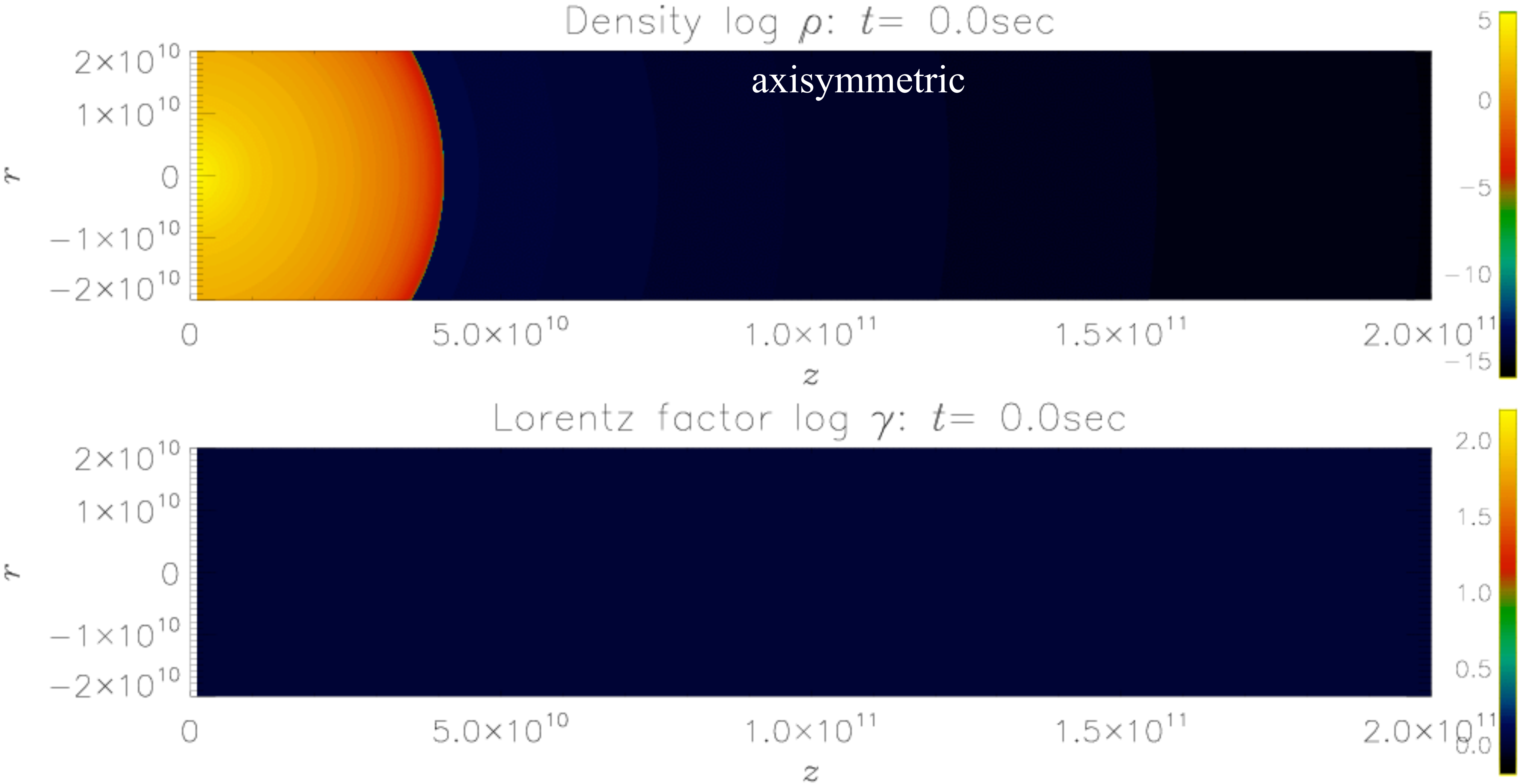
$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

hydro case: σ=0



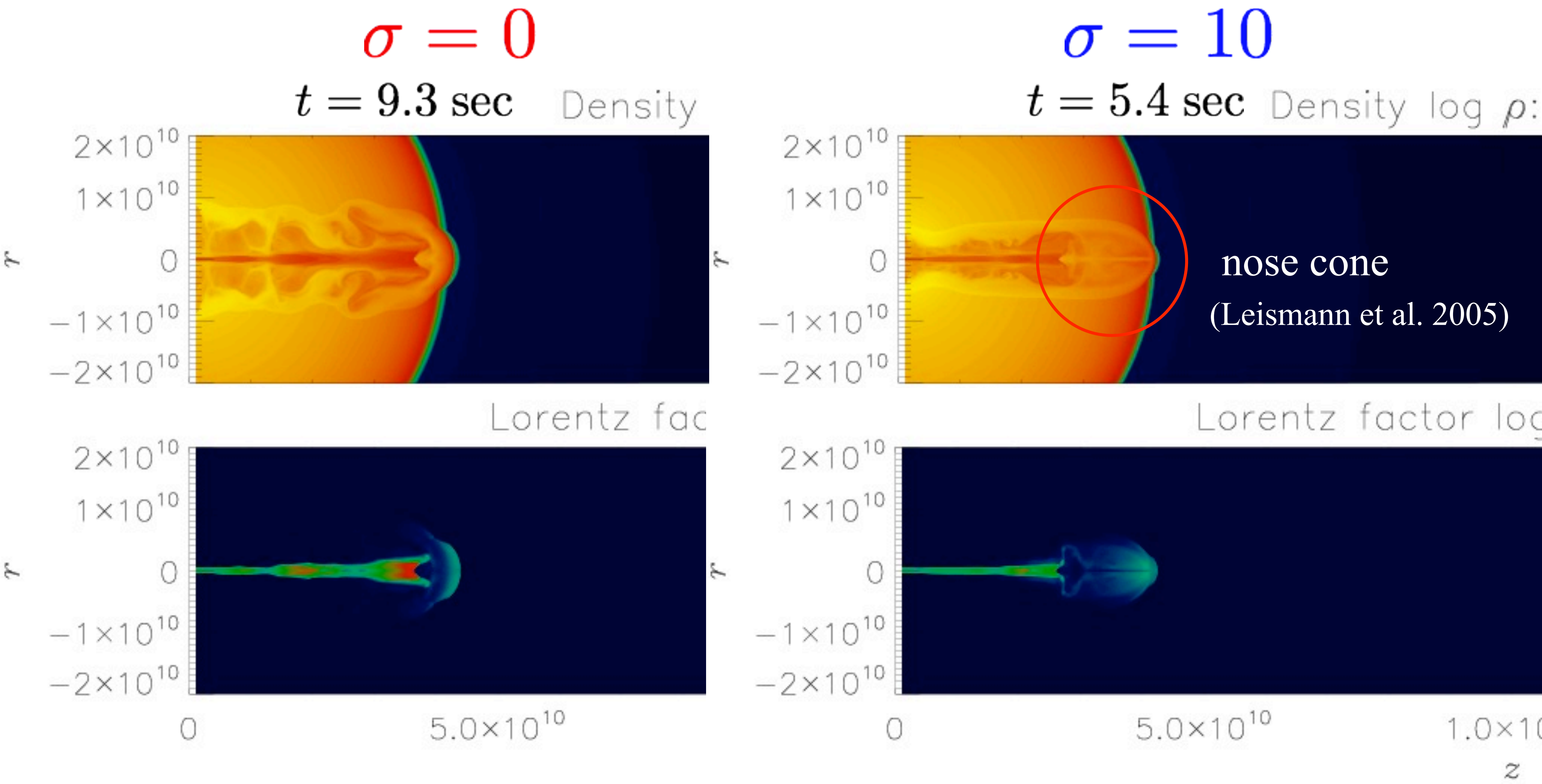
- consistent with previous studies
  - Jet successfully drills through the progenitor star
  - drastically accelerated after jet breaks out of the stellar surface

Model: σ=10



- Jet reaches the progenitor surface the progenitor surface faster.
- Maximum Lorentz factor is almost same as pure hydro case.

HD vs MHD jet



$\sigma = 0$

$t = 9.3$ sec

$\sigma = 10$

$t = 5.4$ sec

nose cone

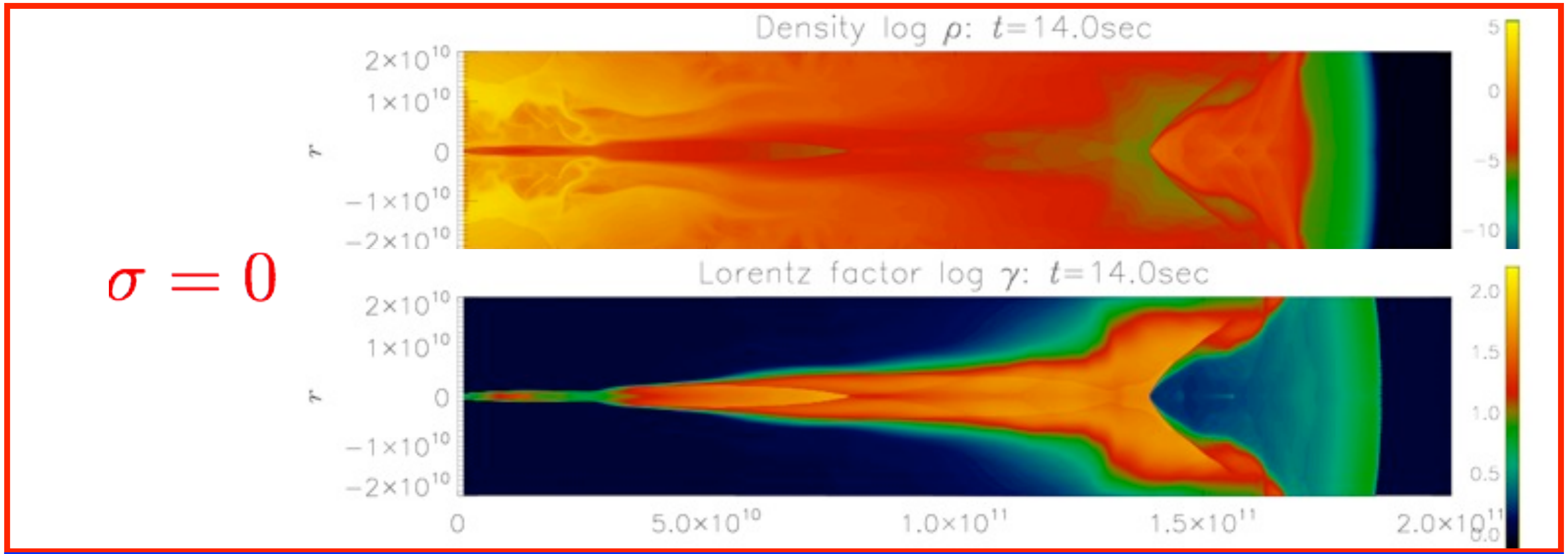
(Leismann et al. 2005)

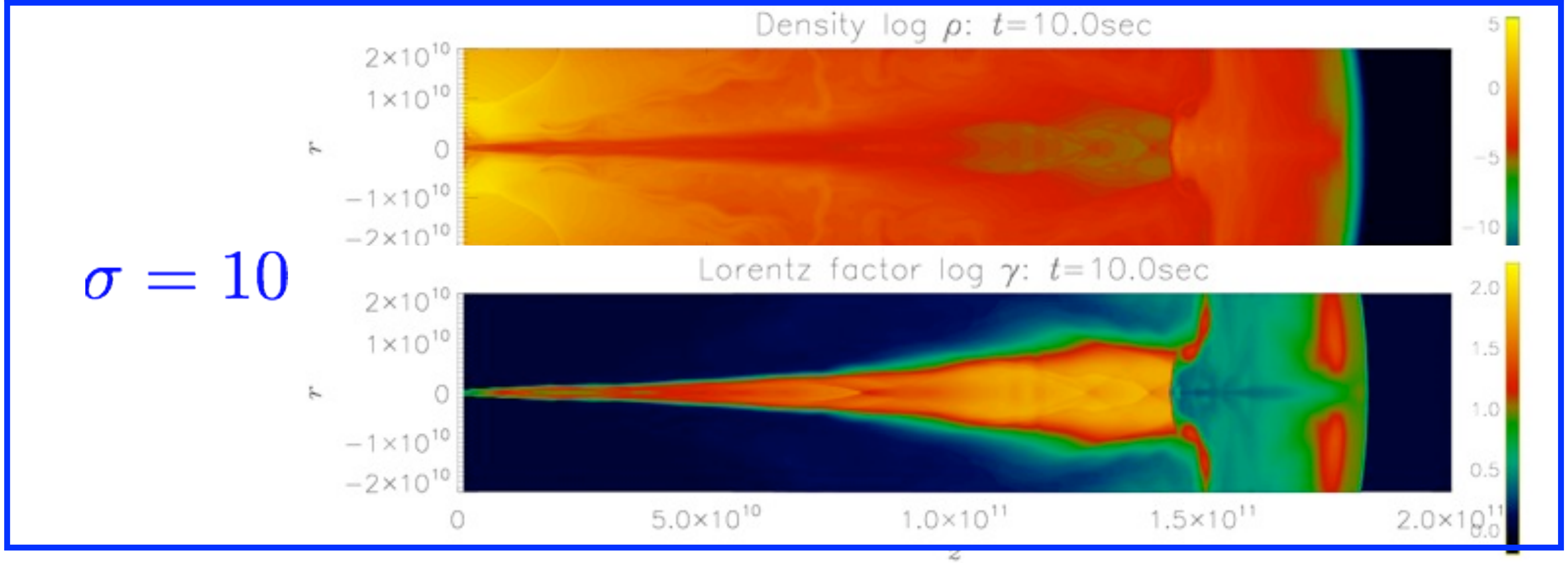
- formation of nose cone

→ confinement of hot gas ← hoop stress

→ low Lorentz factor

HD vs MHD jet


$\sigma = 0$


$\sigma = 10$

- Pure toroidal magnetic field is not responsible for the further acceleration of the jet compared to the pure hydro jet.

Summary

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

3D HD GRB jet

- ■ 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

2D MHD GRB jet

- ■ A nose cone is formed between forward and reverse shocks.
- ■ Lorentz factor of the nose cone is smaller than the jet core.
- ■ Pure toroidal magnetic field is not responsible for the further acceleration of the jet compared to pure hydro jet.

Next Study:

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