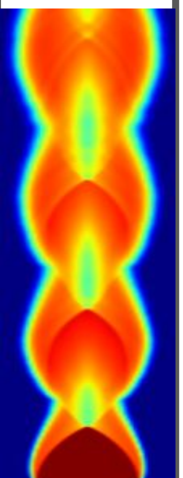


Exploring the structure of AGN Jet Recollimation Shocks

Insights from 2D and 3D RMHD Simulations

Stella S. Boula

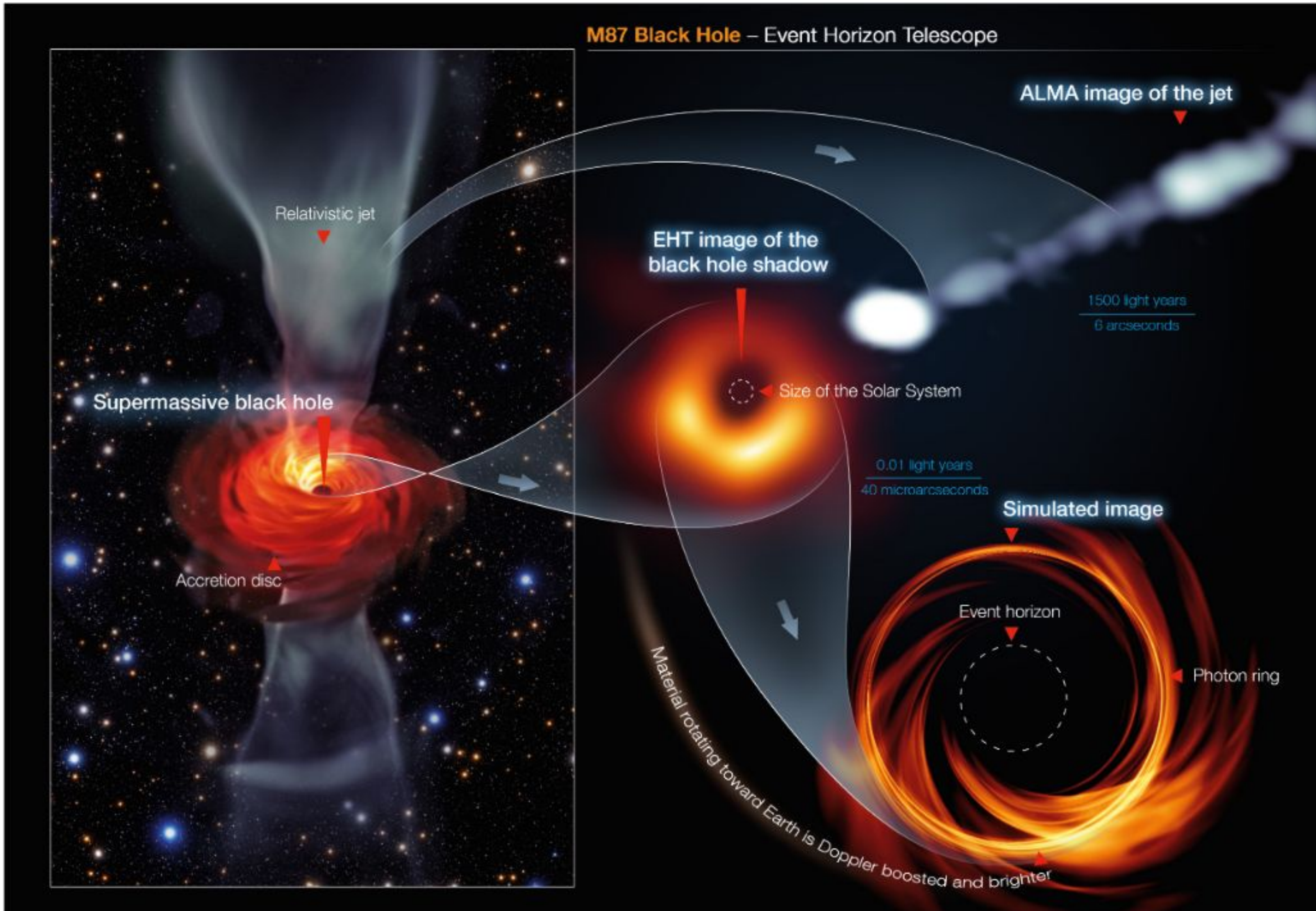
INAF - Osservatorio Astronomico di Brera

ISSS 15 - IPELS 16

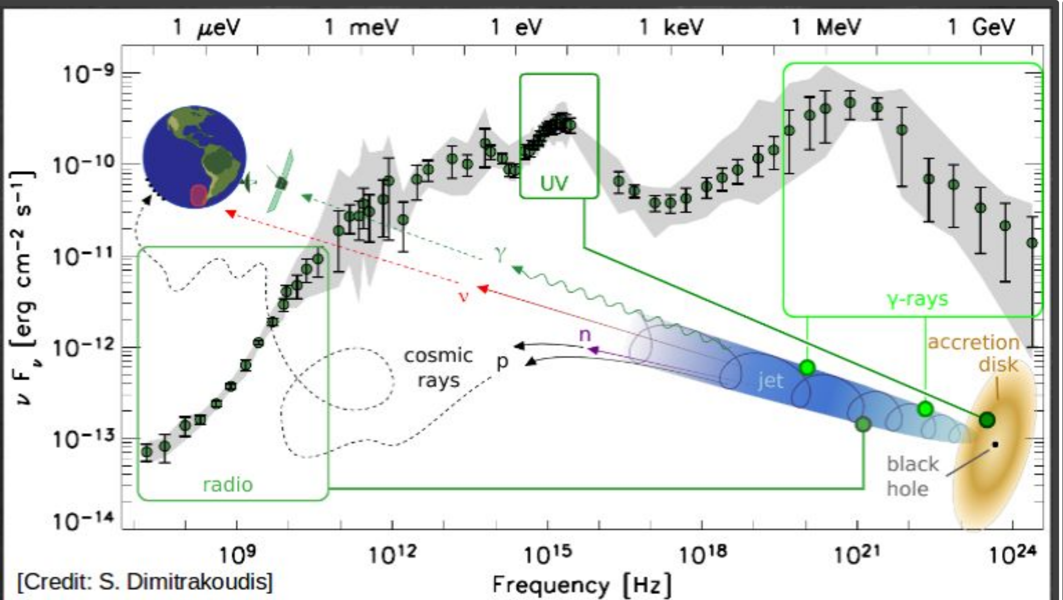
06/08/2024

Collaborators:
Fabrizio Tavecchio (INAF - OAB),
Gianluigi Bodo (INAF - OAT)

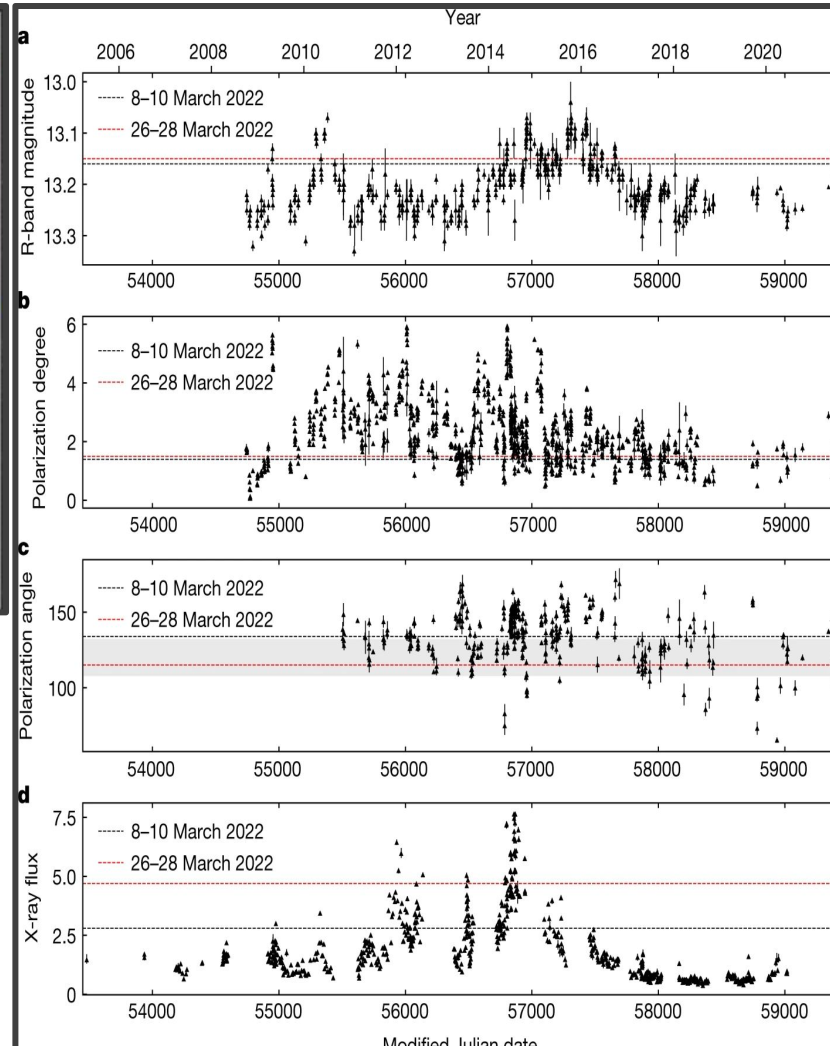
Jets



Credit: EHT Collaboration



Rani et al., 2019



Liodakis et al., 2022

Motivation

Electron Acceleration:

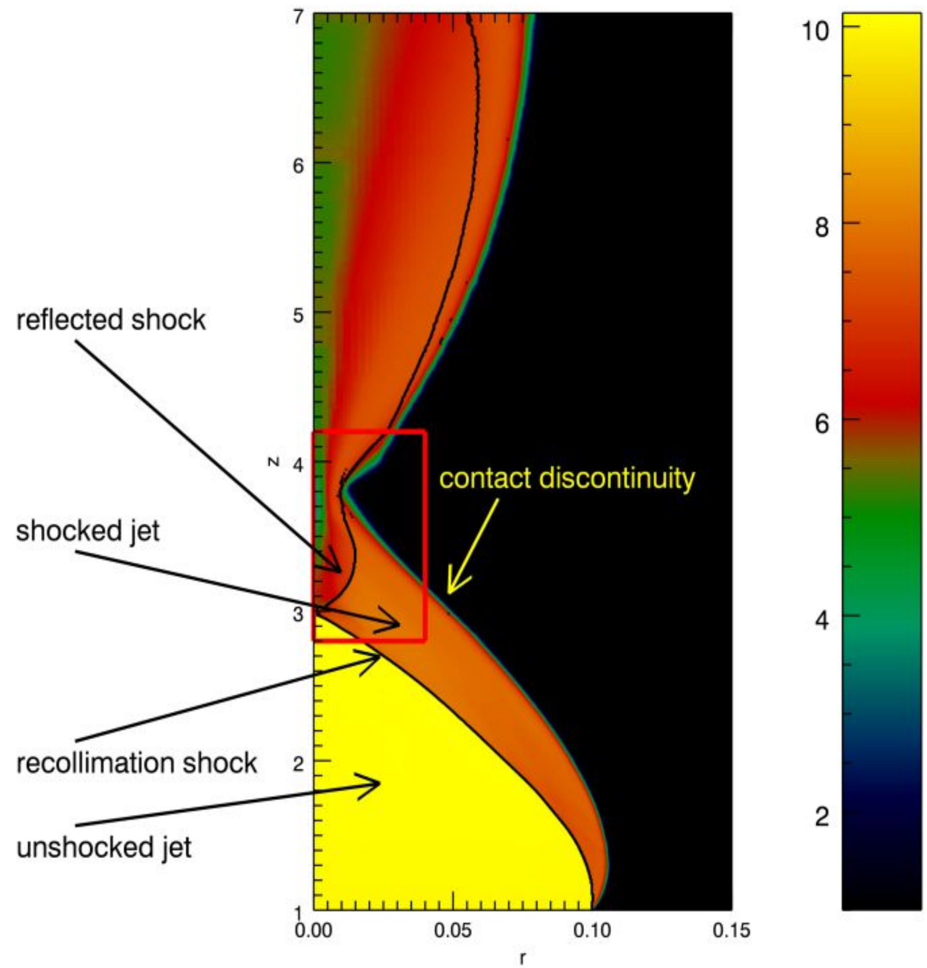
- Electrons can be accelerated in a series of oblique shocks induced by the recollimation of relativistic jets

3D Simulations Findings:

- New 3D simulations of recollimated, weakly magnetized jets (post-first recollimation shock) show:
  - Rapidly growing instability in the flow
  - Development of high turbulence
  - Flow deceleration
  - Inhibition of multiple shock structure formation as seen in 2D simulations

Research Question:

- Can electrons be accelerated at the recollimation shock and further energized through stochastic acceleration in the turbulent downstream?



Bodo & Tavecchio 2018

e.g. Komissarov & Falle 1997, Mizuno et al. 2015, Gourgouliatos & Komissarov 2018, Bodo & Tavecchio 2018, Costa et al. 2024 +++

PLUTO

Explicit, Compressible Code (FV):

- Shock capturing
- High Mach number flows
- Works in 1D, 2D, 3D

Modular Structure:

- Physics modules
- Time stepping
- Interpolations
- Riemann solvers

Supported Physics:

- HD (Hydrodynamics)
- MHD (Magnetohydrodynamics)
- RHD (Relativistic Hydrodynamics)
- RMHD (Relativistic Magnetohydrodynamics)

Geometry Support:

- Cartesian
- Cylindrical
- Spherical

Additional Features:

- Radiative losses

Mignone et al. 2007, 2005, 2019

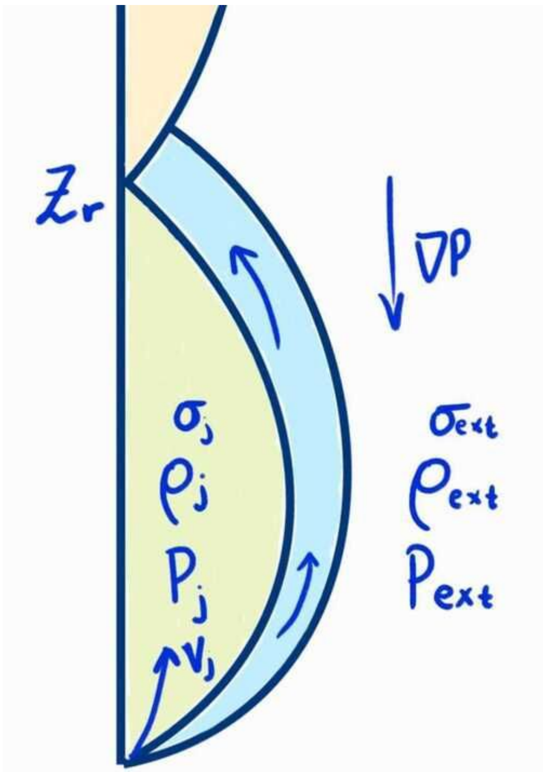
The RMHD Module

$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ \boldsymbol{m} \\ E_t \\ \boldsymbol{B} \end{pmatrix} + \nabla\cdot\begin{pmatrix} D\boldsymbol{v} \\ w_t\gamma^2\boldsymbol{v}\boldsymbol{v} - \boldsymbol{b}\boldsymbol{b} + \mathsf{I}p_t \\ \boldsymbol{m} \\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} \end{pmatrix}^T = \boldsymbol{0}$$

$$\begin{aligned} D &= \gamma\rho \\ \boldsymbol{m} &= w_t\gamma^2\boldsymbol{v} - b^0\boldsymbol{b} \\ E_t &= w_t\gamma^2 - b^0 b^0 - p_t \end{aligned} \quad , \quad \left\{\begin{aligned} b^0 &= \gamma\boldsymbol{v}\cdot\boldsymbol{B} \\ \boldsymbol{b} &= \boldsymbol{B}/\gamma + \gamma(\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{v} \\ w_t &= \rho h + \boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2 \\ p_t &= p + \frac{\boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2}{2} \end{aligned}\right.$$

$$h = \tfrac{5}{2}\mathcal{T} + \sqrt{\tfrac{9}{4}\mathcal{T}^2 + 1}, \qquad \mathcal{T} = p/(\rho c^2)$$

Physical parameters



Initial opening angle, θ_j

Lorentz factor, Γ

Density, ρ (jet + ambient)

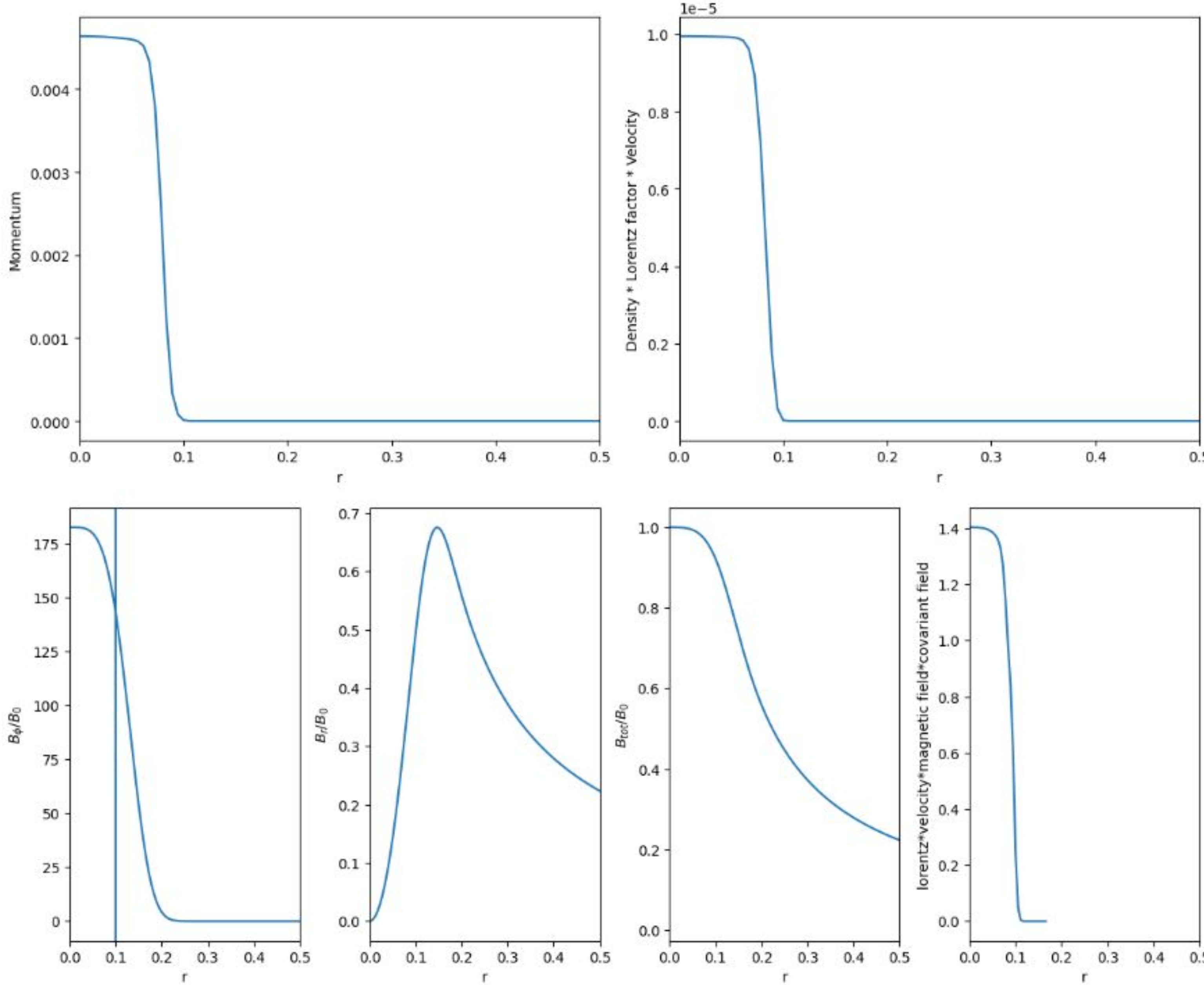
Pressure, P (jet + ambient)

Magnetization, σ (jet + ambient)

↓

Magnetic field structure

Osservatorio Astronomico di Brera



2D simulations

The setup of each 2D simulation is:

Cylindrical coordinates (r,z) in a domain [0,6]x[1,30], where the lengths are in units of z_0, that represents the distance from the jet launching site.

The grid is uniform with 1000x1500 points in [0,2]x[1,20] and geometrically stretched with 400x700 grid points in the outer region.

Jet injection: non-equilibrium (the simulations follows the equilibrating of the jet)

Boundaries:

x axis: axisymmetric, outflow

z axis:user define outflow

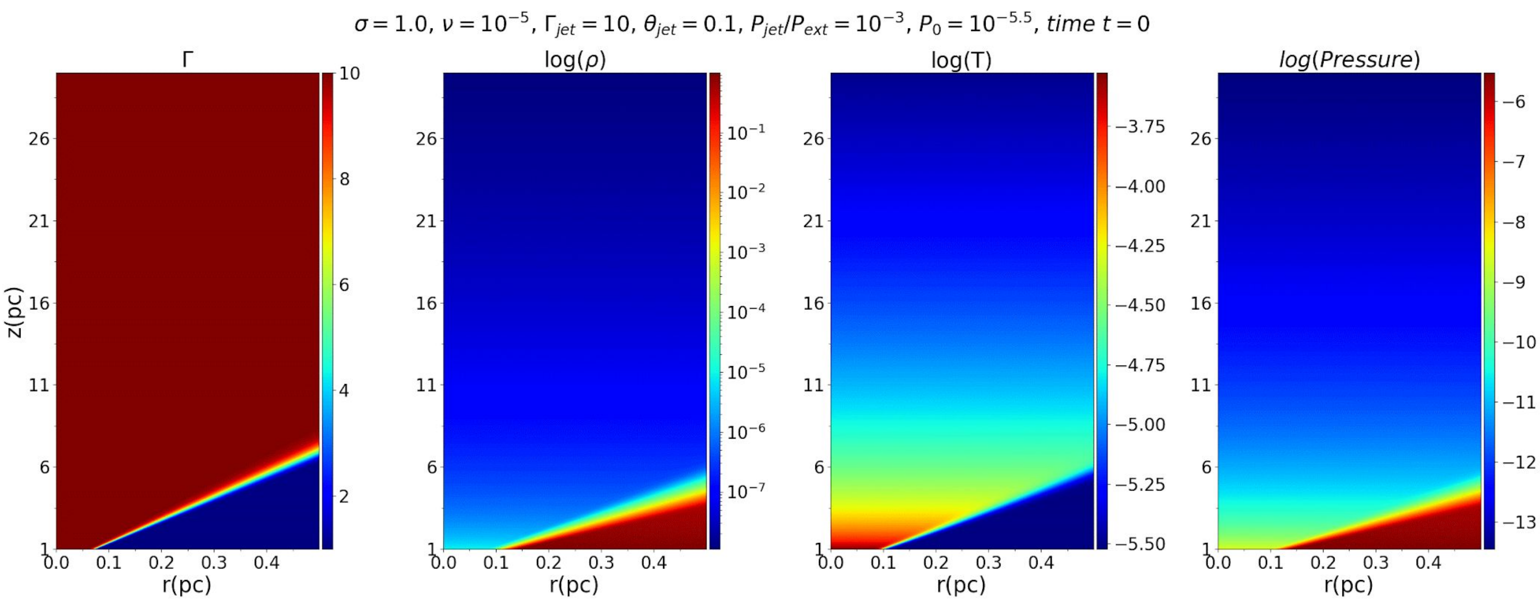
Parameters

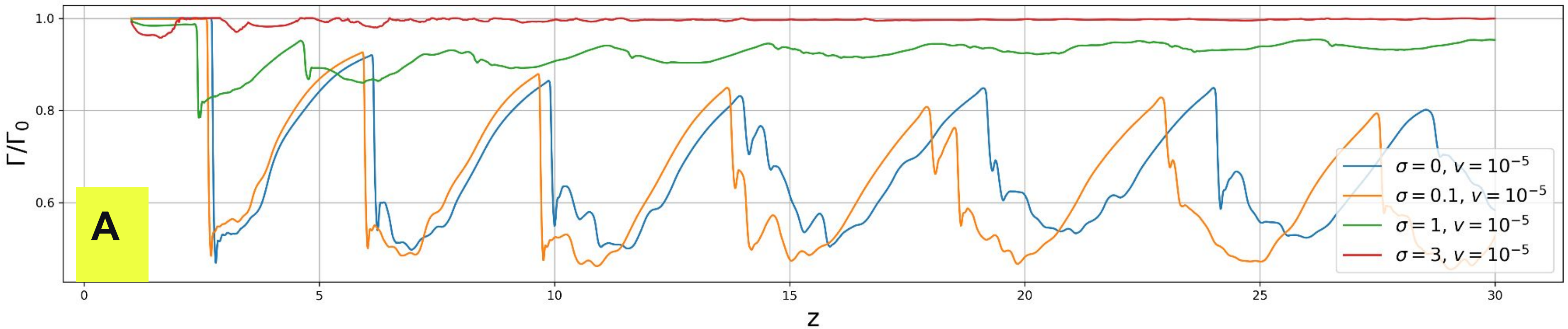
$$\sigma_r = (B_p^2 + B_\phi^2/\Gamma^2)/h \qquad \beta = P/(B_p^2 + B_\phi^2/\Gamma^2).$$

$$\nu = \frac{\rho_{j,0}}{\rho_{ext,0}} \qquad P_{ratio} = \frac{p_{j,0}}{p_{ext,0}}$$

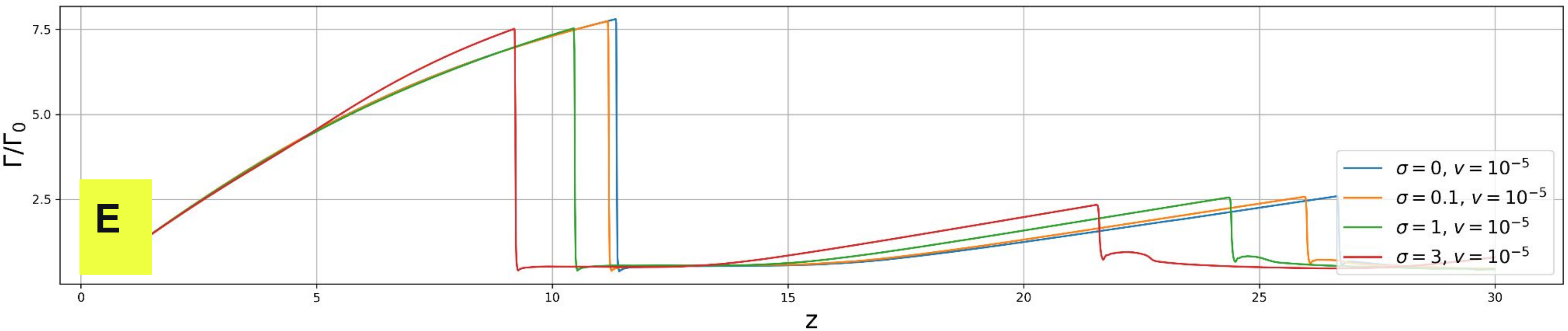
Cases	v	kT/mc2
A	light	<<1
B	heavy	<<1
C	light	~1
D	heavy	~1
E	light	>>1
F	heavy	>>1

Light: $v=10^{-5}$
Heavy: $v=10^{-4}$


$\sigma = 1.0$, $\nu = 10^{-5}$, $\Gamma_{jet} = 10$, $\theta_{jet} = 0.1$, $P_{jet}/P_{ext} = 10^{-3}$, $P_0 = 10^{-5.5}$, time $t = 0$
Γ
log(ρ)
log(T)
log(Pressure)
z(pc)
r(pc)
r(pc)
r(pc)
r(pc)

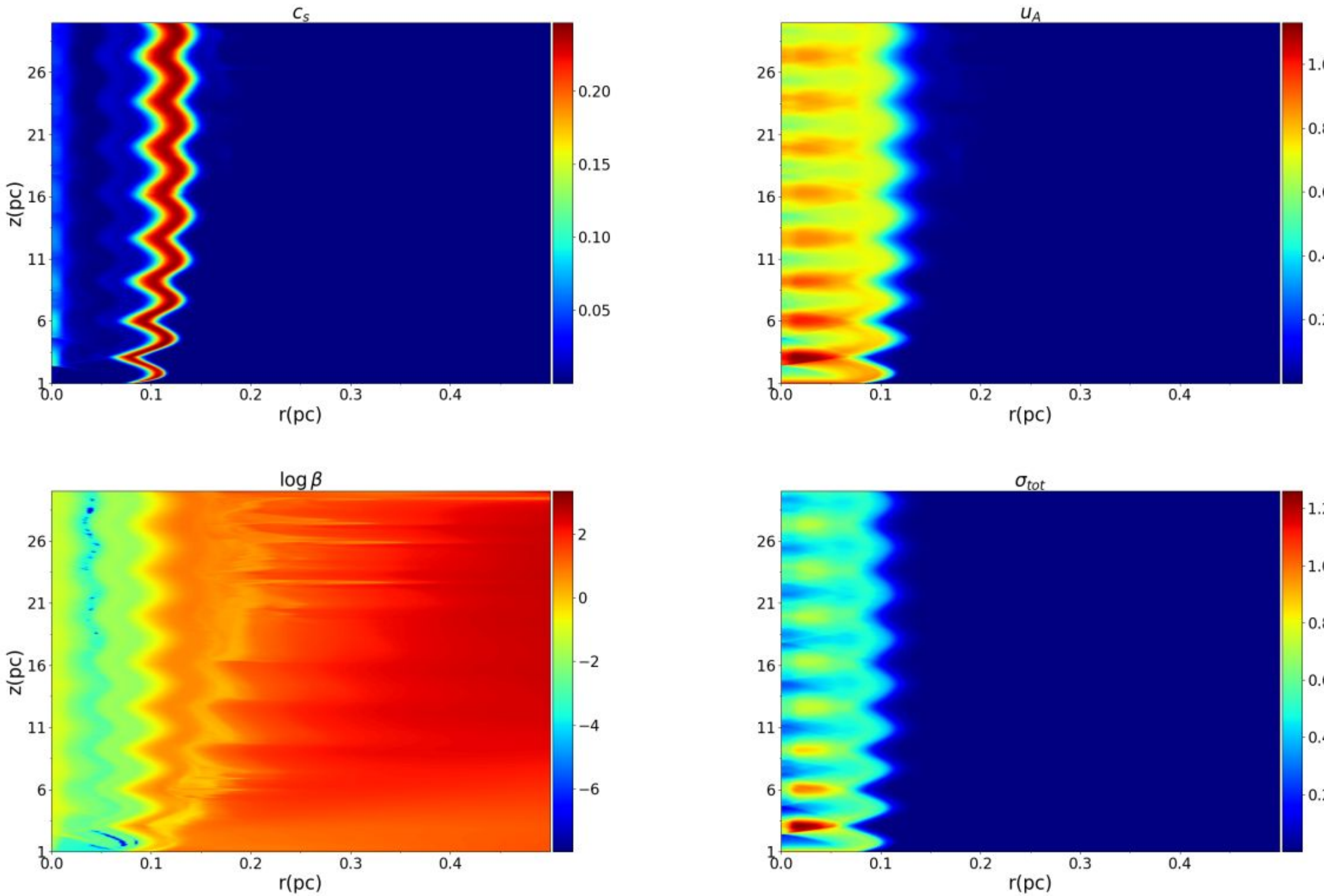


A
Γ/Γ0
z
σ = 0, ν = 10−5
σ = 0.1, ν = 10−5
σ = 1, ν = 10−5
σ = 3, ν = 10−5



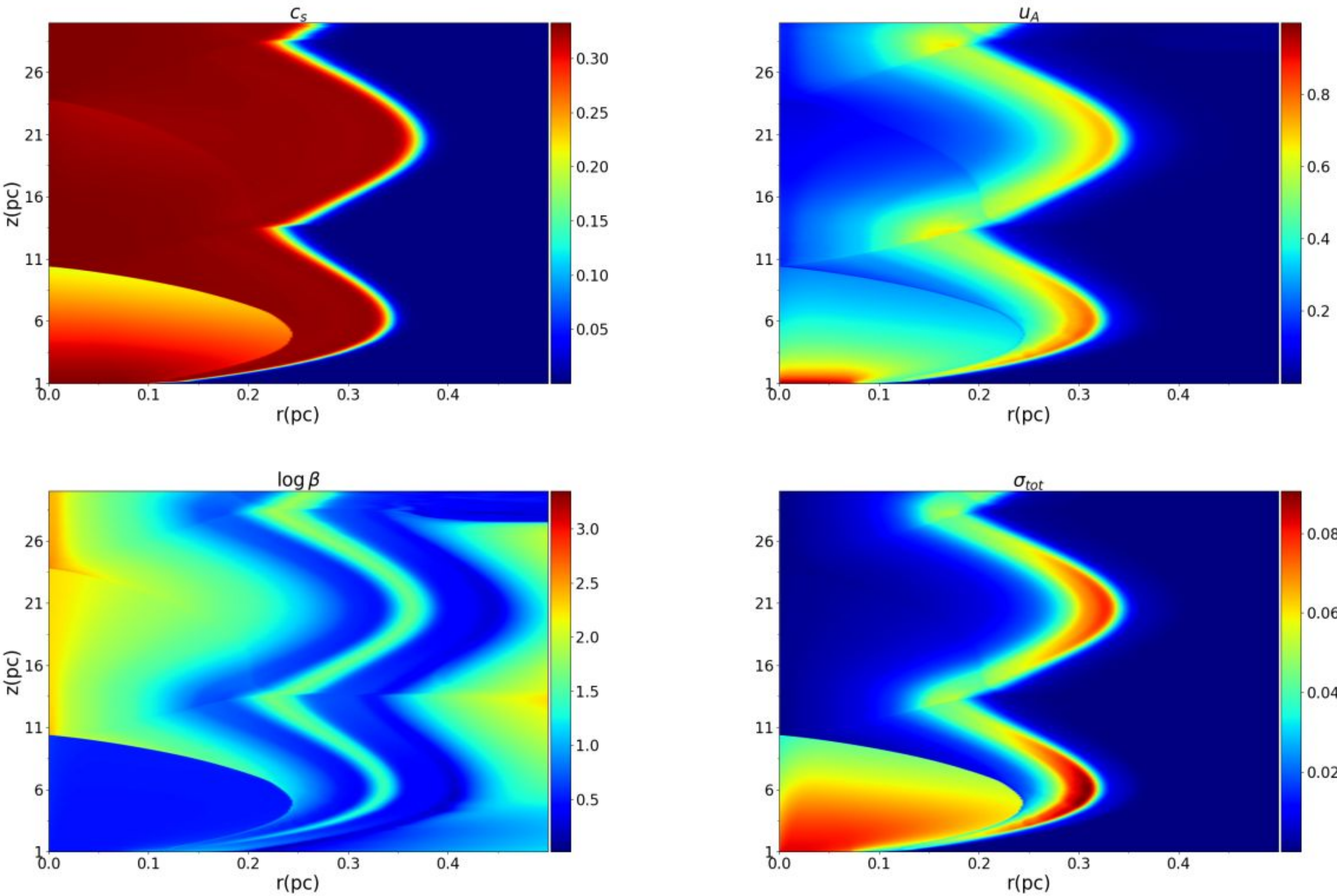
E
Γ/Γ0
z
σ = 0, ν = 10−5
σ = 0.1, ν = 10−5
σ = 1, ν = 10−5
σ = 3, ν = 10−5

$\sigma = 1.0$, $\nu = 10^{-5}$, $\Gamma_{jet} = 10$, $\theta_{jet} = 0.1$, $P_{jet}/P_{ext} = 10^{-3}$, $P_0 = 10^{-5.5}$, *time* $t = 2000$

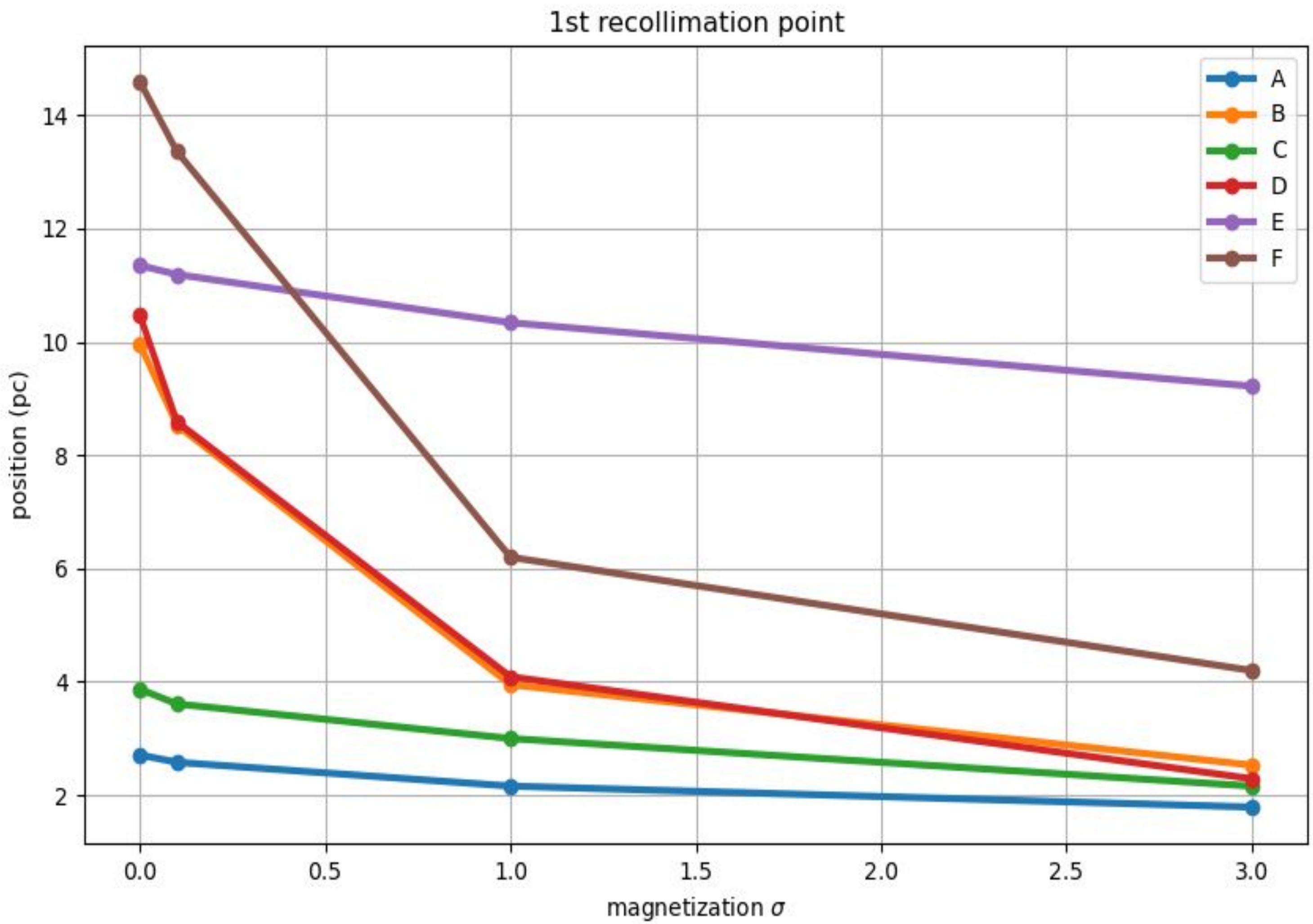


INAF
ISTITUTO NAZIONALE DI ASTROFISICA

$\sigma = 1.0,\ \nu = 10^{-5},\ \Gamma_{jet} = 10,\ \theta_{jet} = 0.1,\ P_{jet}/P_{ext} = 10^{--1},\ P_0 = 10^{-5.5},\ time\ t = 2000$



Osservatorio Astronomico di Brera



Osservatorio Astronomico di Brera

Basic conclusions

Impact of Magnetization on Recollimation Points:

- As magnetization increases, the position of the recollimation points decreases. This is due to the additional pressure from the poloidal magnetic components and the extra tension from the toroidal component.

Effect of Pressure Ratio on Jet Expansion:

- Higher pressure ratios (hotter cases) lead to freer jet expansion, resulting in recollimation occurring at larger distances. In these cases, the magnetic field is unable to destroy the jet's structure.

Behavior in Cold, High Magnetization Cases:

- In cold cases with high magnetization, recollimation shocks are almost absent. This is because the contribution of the poloidal component dominates, allowing the jet's core to resist external forces.

Jet Acceleration and Expansion:

- The jet accelerates less when it expands less. This reduced expansion limits the jet's overall acceleration.

Heavier Jet Cases:

- Recollimation occurs at larger distances in heavier jets, indicating a stronger resistance to external forces.

3D simulations

Perform the 2D simulations to start the 3D from a nearly equilibrium state.

2D (cylindrical) → 3D (cartesian)

Extra functions:

InputDataInterpolate

StaggeredRemap ($\nabla B = 0$)

Boundaries

x axis: outflow

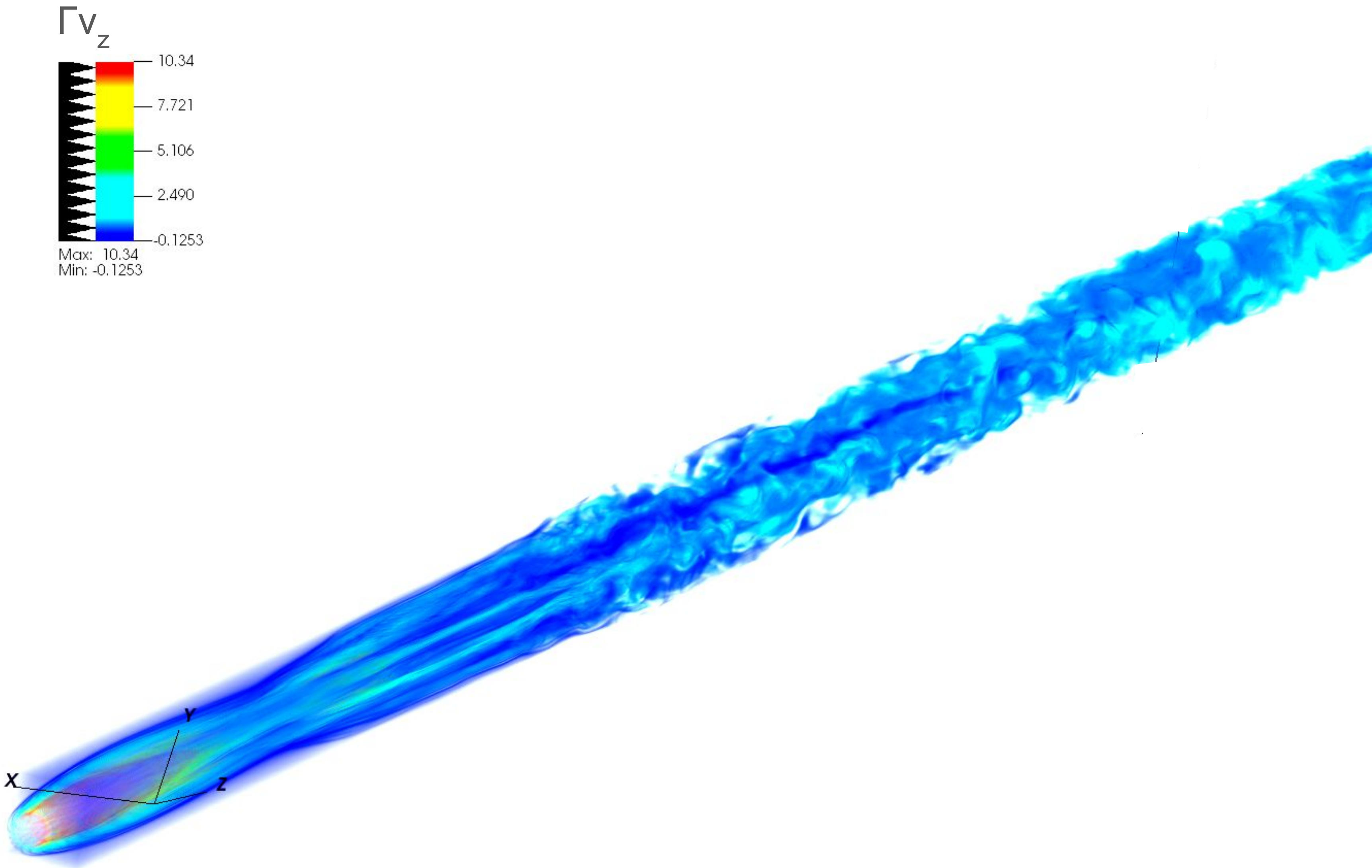
y axis: outflow

z axis: userdef, outflow

Resolution

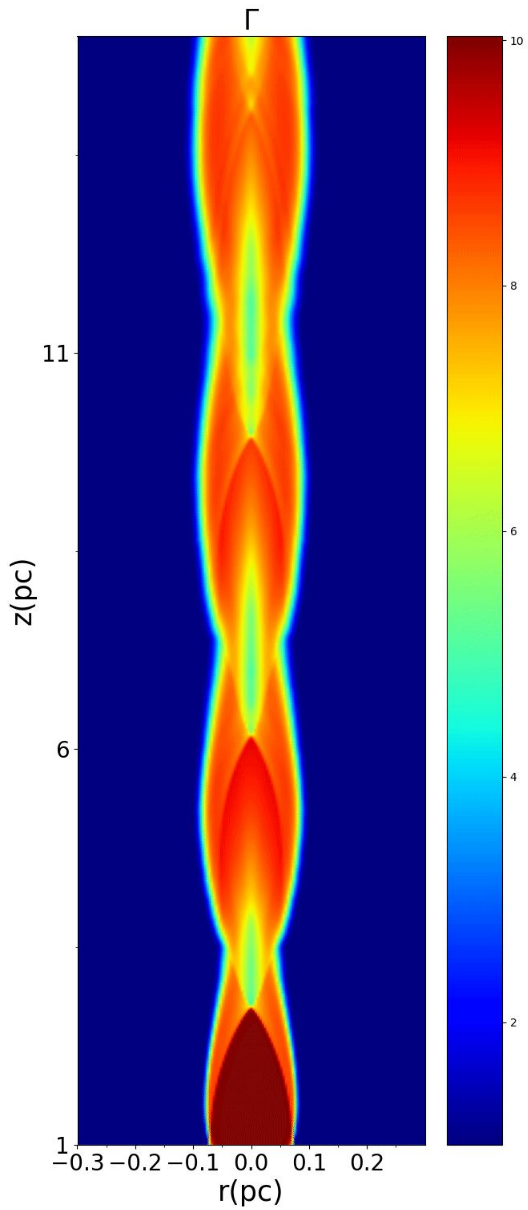
Important for the instabilities that will be triggered

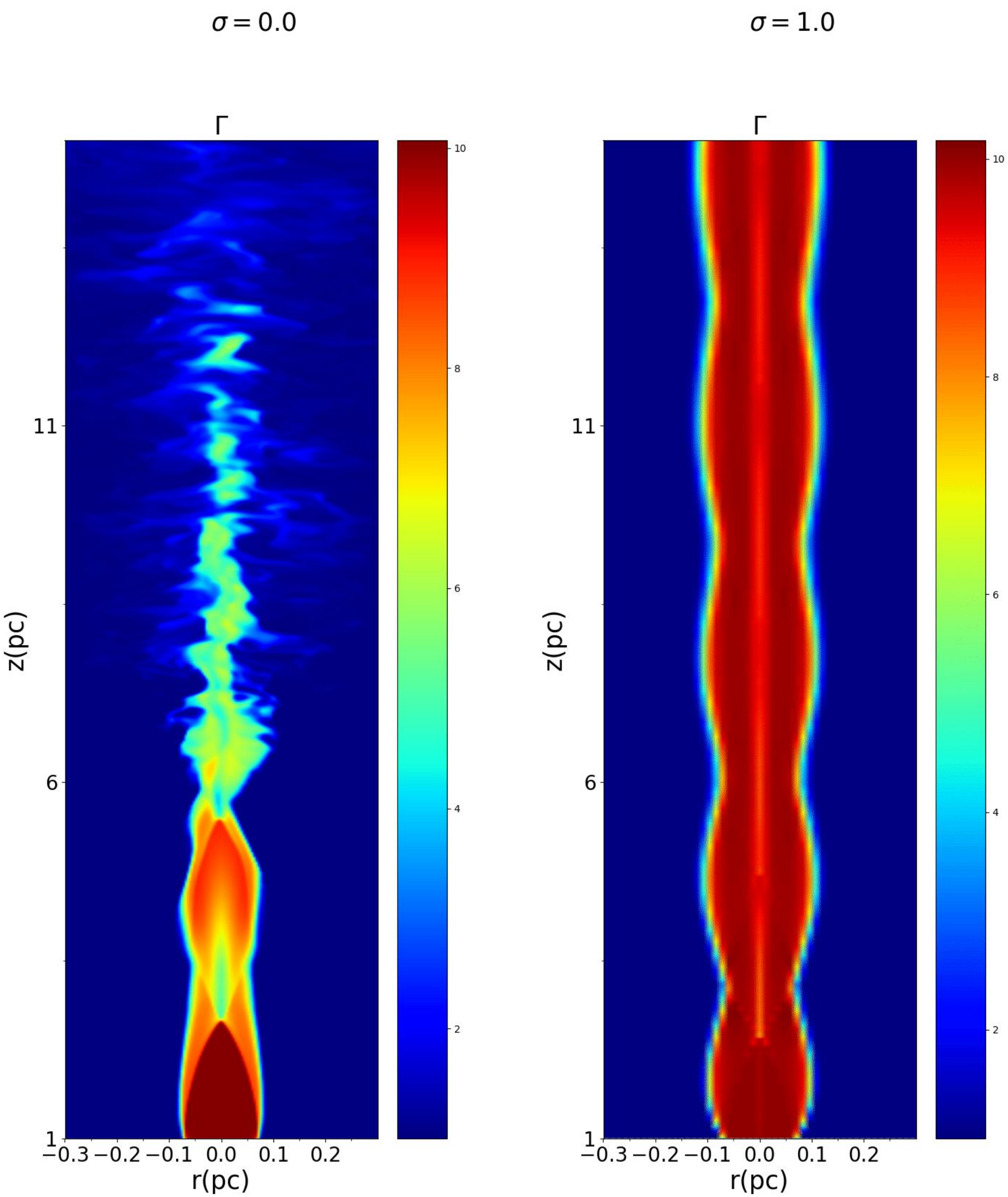
INAF
ISTITUTO NAZIONALE DI ASTROFISICA



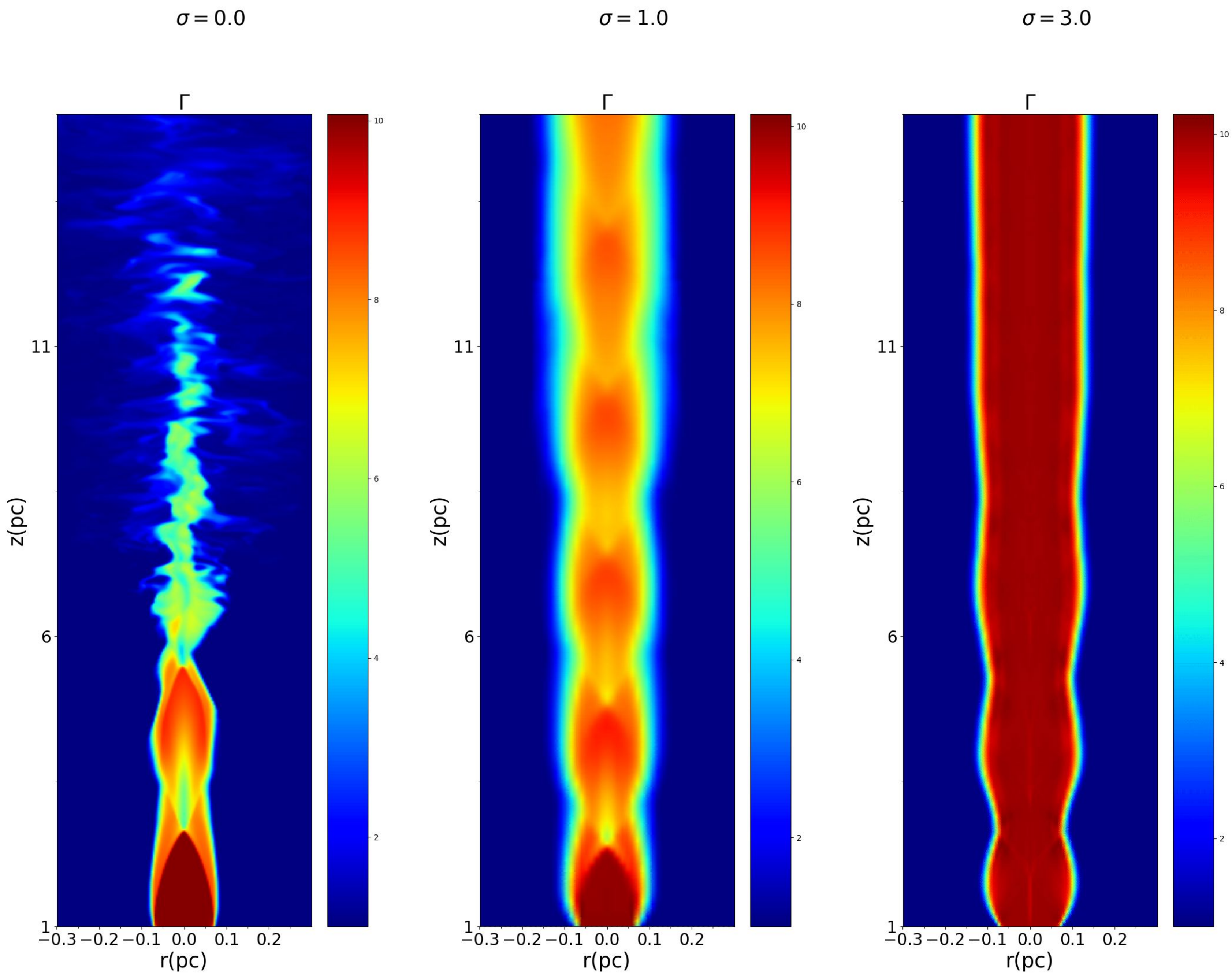
Osservatorio Astronomico di Brera

$\sigma = 0.0$

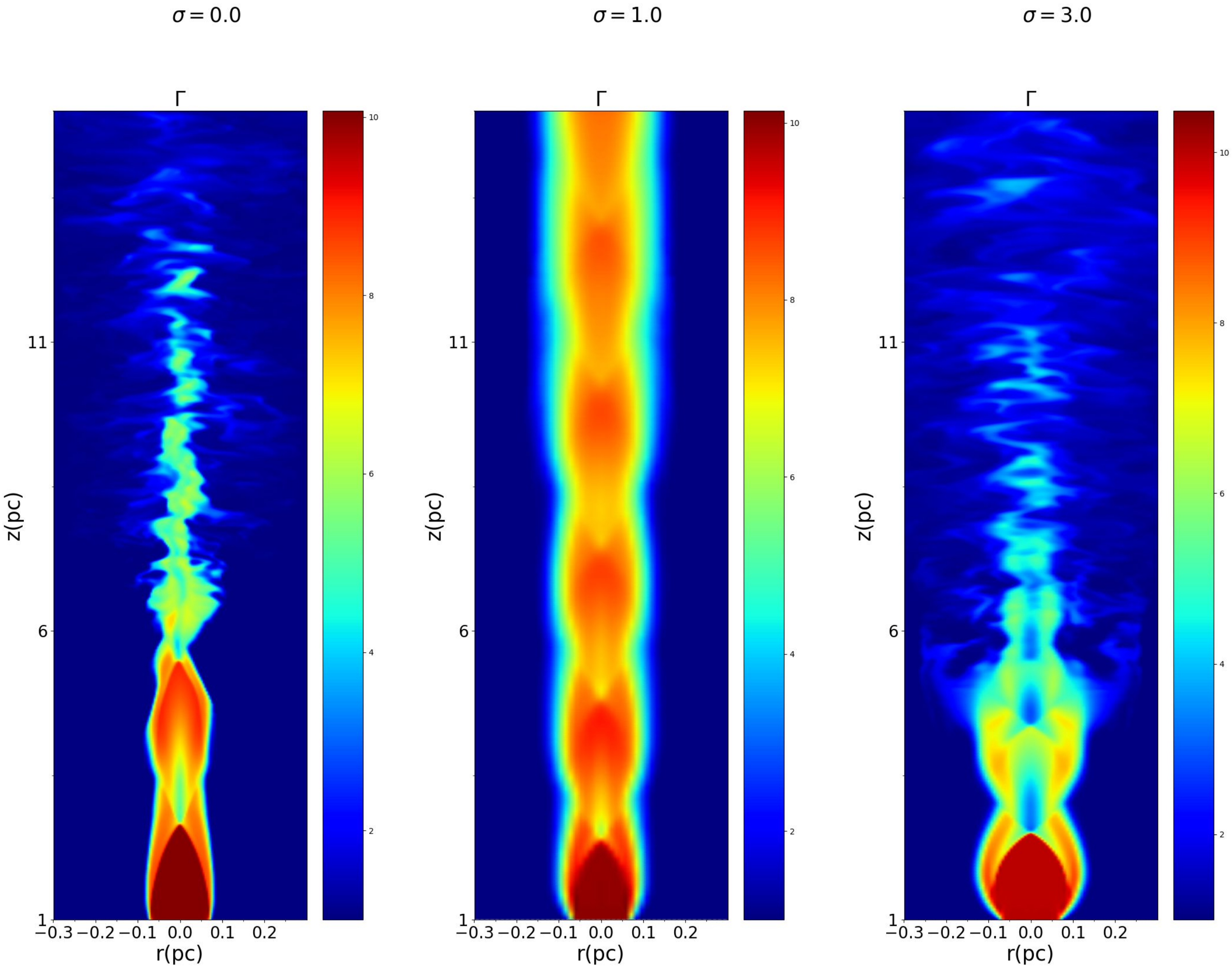




σ = 0.0
σ = 1.0
Γ
Γ
z(pc)
z(pc)
r(pc)
r(pc)
11
6
1
−0.3 −0.2 −0.1 0.0 0.1 0.2
10
8
6
4
2

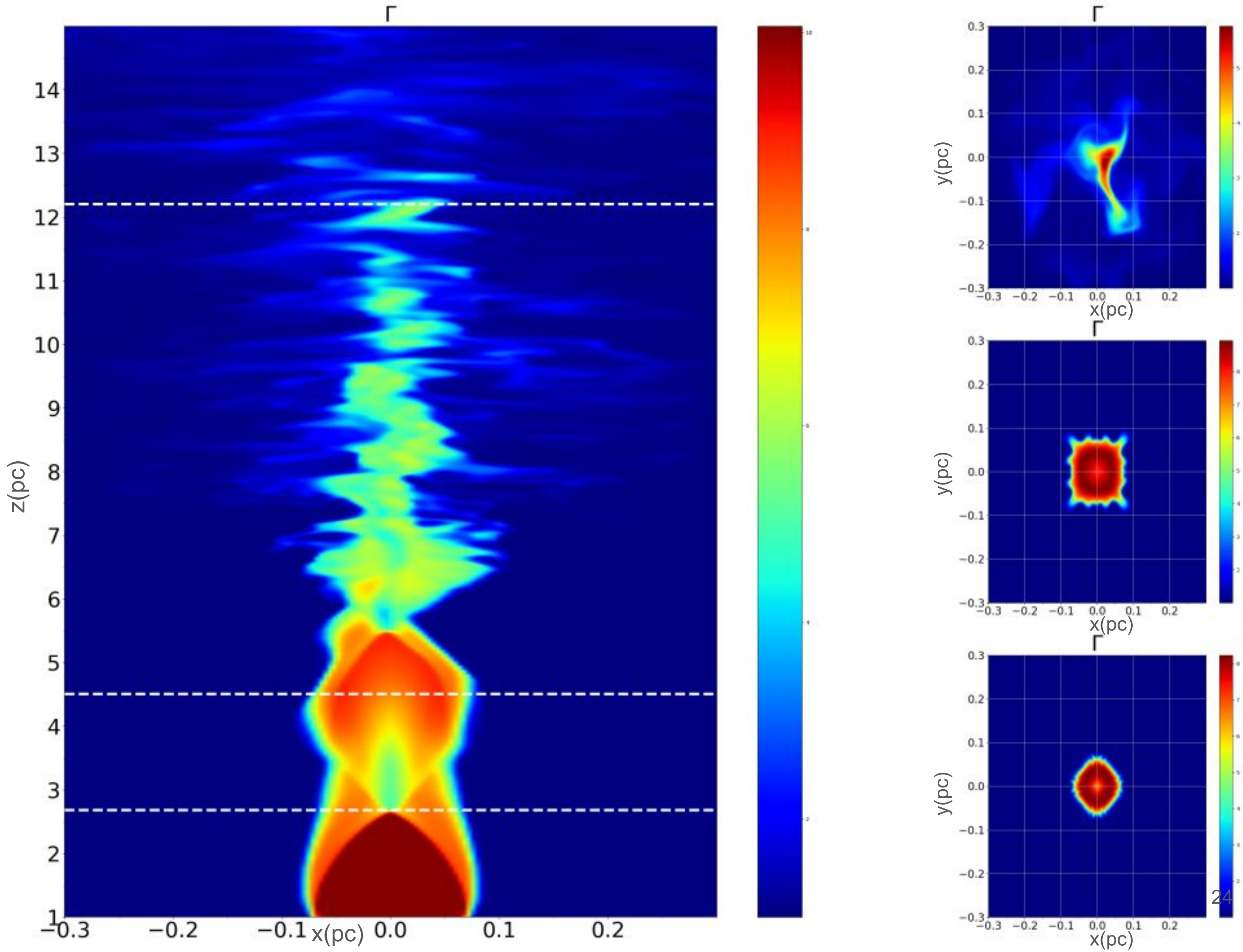


Osservatorio Astronomico di Brera

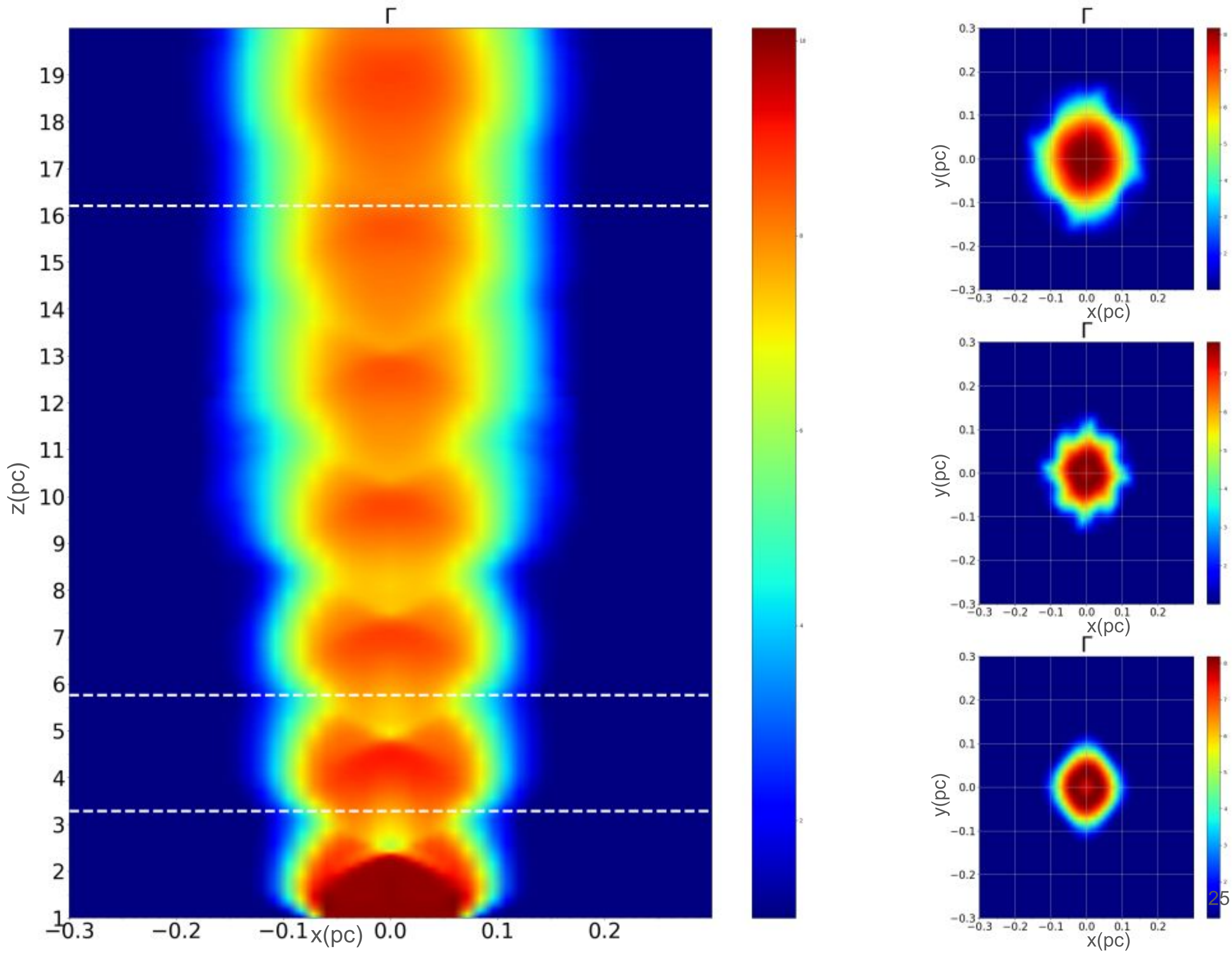


σ = 0.0
σ = 1.0
σ = 3.0
Γ
z(pc)
r(pc)

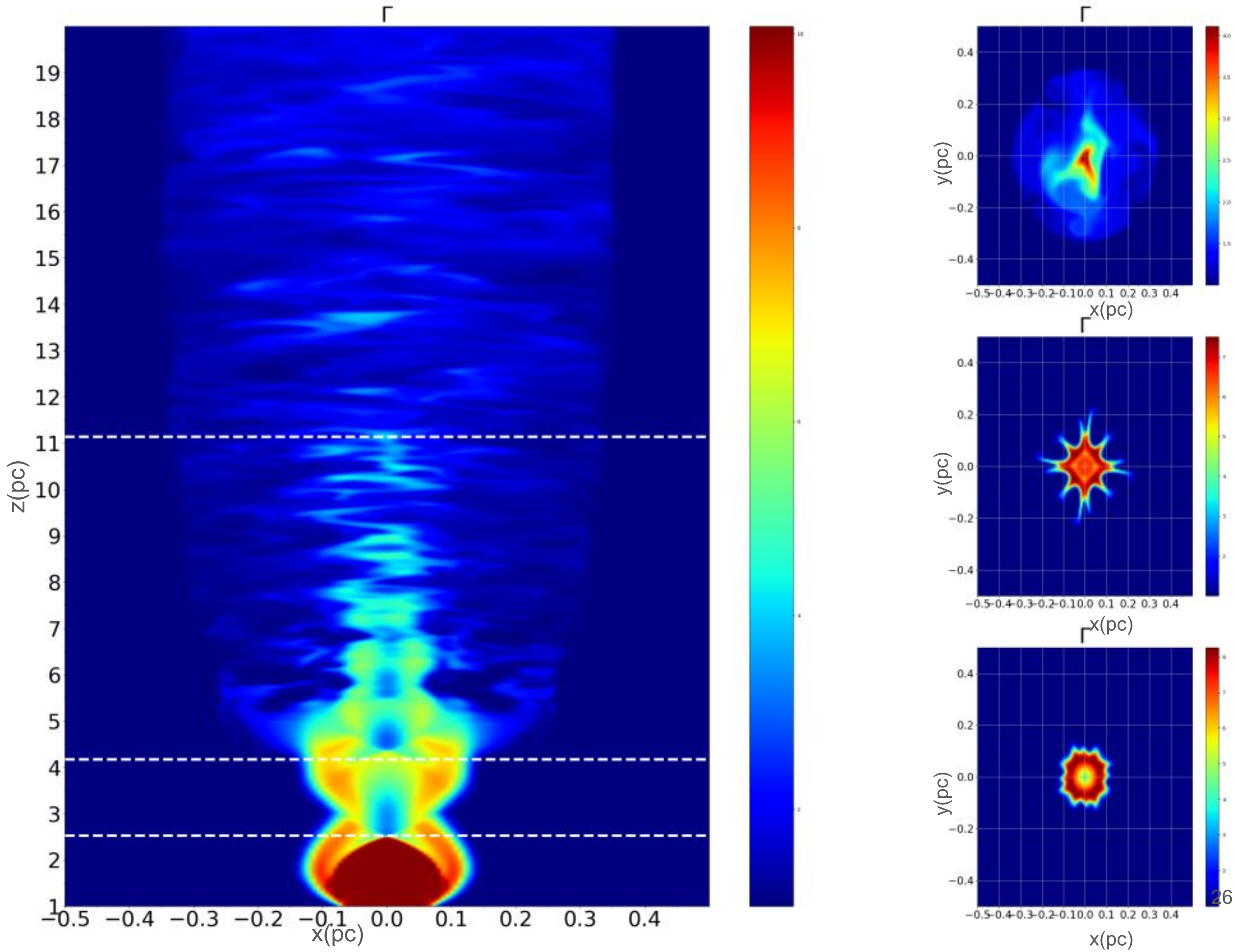
$\sigma = 0.0$, $\nu = 10^{-5}$, $\Gamma_{jet} = 10$, $\theta_{jet} = 0.1$, $P_{jet}/P_{ext} = 10^{-3}$, $P_0 = 10^{-5.5}$, *time* $t = 40$



$\sigma = 1.0$, $\nu = 10^{-5}$, $\Gamma_{jet} = 10$, $\theta_{jet} = 0.1$, $P_{jet}/P_{ext} = 10^{-3}$, $P_0 = 10^{-5.5}$, *time* $t = 60$



$\sigma = 3.0$, $\nu = 10^{-5}$, $\Gamma_{jet} = 10$, $\theta_{jet} = 0.1$, $P_{jet}/P_{ext} = 10^{-3}$, $P_0 = 10^{-5.5}$, $time\ t = 80$



Basic conclusions

Simulation Resolution and Instabilities:

- The resolution of the simulation is crucial for observing and understanding the instabilities that may be triggered.

HD Case:

- In the HD case, a rapidly growing instability develops at the first/second recollimation/reflection shock system. This results from the interplay between recollimation-induced instabilities and Richtmyer-Meshkov modes.

Low Magnetization Case (σ_r= 0.01):

- For magnetization σ_r= 0.01, the magnetic field suppresses recollimation instabilities, leading to a stable jet structure.

Moderate Magnetization Case (σ_r= 0.03):

- For magnetization σ_r= 0.03, recollimation shocks are weak even in 2D simulations. Instabilities such as Kelvin-Helmholtz and Kink modes can be triggered after the first recollimation shock, necessitating further exploration.

The instabilities promote strong mixing and entrainment, rapidly decelerating the jet and spreading its momentum to the slowly moving, highly turbulent gas.

.

Key findings:

Magnetization Impact: Increased magnetization decreases recollimation points due to poloidal pressure and toroidal tension.

Pressure Ratio: Higher pressure ratios allow freer jet expansion and larger recollimation distances, preserving jet structure.

Cold, High Magnetization Jets: Almost absent recollimation shocks due to poloidal dominance.

Jet Acceleration: Less expansion results in less acceleration.

Heavy Jets: Recollimation at larger distances.

3D Simulation Insights:

- HD cases show strong instabilities and rapid jet deceleration.
- Low magnetization ($\sigma_r = 0.01$) stabilizes jets by suppressing instabilities.
- Moderate magnetization ($\sigma_r = 0.03$) allows instabilities like Kelvin-Helmholtz and Kink modes post-rec. shock.

Osservatorio Astronomico di Brera

Thank you!

styliani.boula@inaf.it

Back up slides

Density and Pressure:

$$\rho_j(r,z,t=0)=\rho_j(0,z_0,0)\left(\frac{R}{R_0}\right)^{-2},$$

$$p_j(r,z,t=0)=p_j(0,z_0,0)\left(\frac{R}{R_0}\right)^{-2\gamma}$$

The smoothing profiles for the hydro-quantities:

$$q=q_{\rm ext}+(q_{\rm j}-q_{\rm ext})\,{\rm sech}\left(\left(\frac{r}{z\theta_{\rm q}}\right)^{\alpha_q}\right).$$

The profiles for the magnetic field in spherical coordinates:
The r component of the magnetic field has the form:

$$B_r=\frac{h(\theta)}{r},$$

the ϕ component:

$$B_{phi}=\frac{g(\theta)}{r^2},$$

where:

$$h(\theta)=\frac{B_0}{r}\sqrt{-\exp\left(-2\frac{(\cos(\theta)-1)^2}{a^2}\right)-0.5\frac{a}{\sin^2(\theta)}\left(a-a\exp\left(-2\frac{(\cos(\theta)-1)^2}{a^2}\right)+\sqrt{2\pi}\,{\rm erf}\left(\sqrt{2}\frac{\cos(\theta)-1}{a}\right)\right)},$$

and

$$g(\theta)=\frac{B_0}{r^2}\exp\left(-2\frac{(\cos(\theta)-1)^2}{a^2}\right).$$

PLUTO algorithms

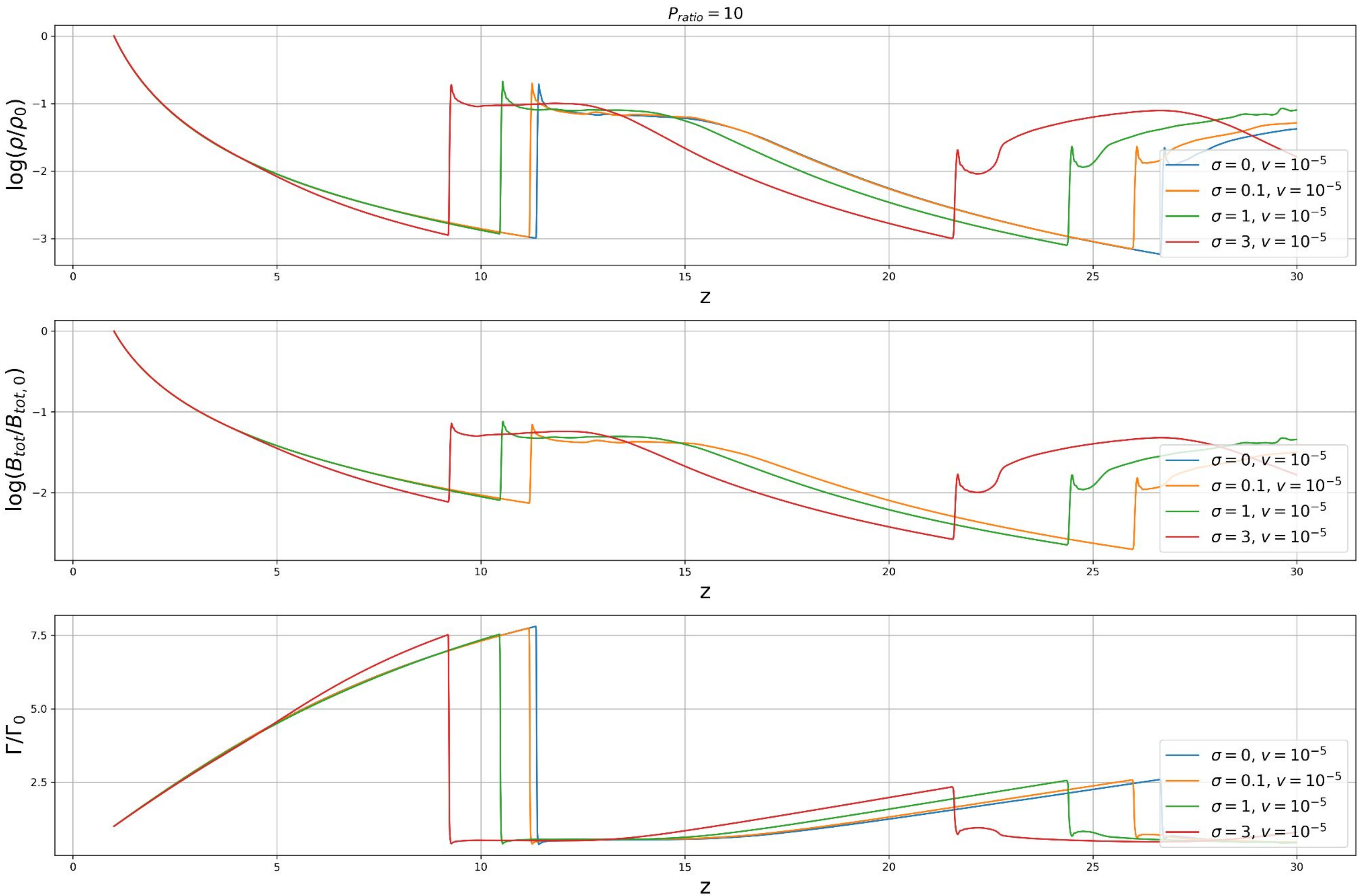
Assigning Initial Conditions from Input Files

- Assign initial conditions using user-supplied binary data:
  - **Grid Data Files**: One or more files containing grid data.
  - **Raw Binary Files**: Files containing the variables to be read.
- Input grid can differ in size, dimensions, and geometry from the actual grid used by PLUTO.
  - Requires implementation of coordinate transformation.
- Flexibility to use different input data files with varying sizes and geometries.
- Enables mapping of data values from different computational domains:
  - Example: Map a 2D spherical grid onto a 2D axisymmetric cylindrical domain.
  - Example: Generate a 3D Cartesian domain by rotating 2D axisymmetric data.

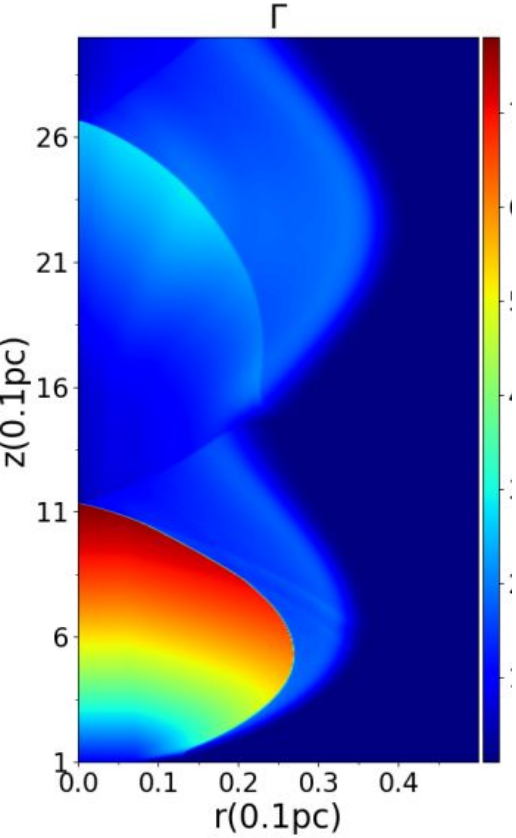
hlld:

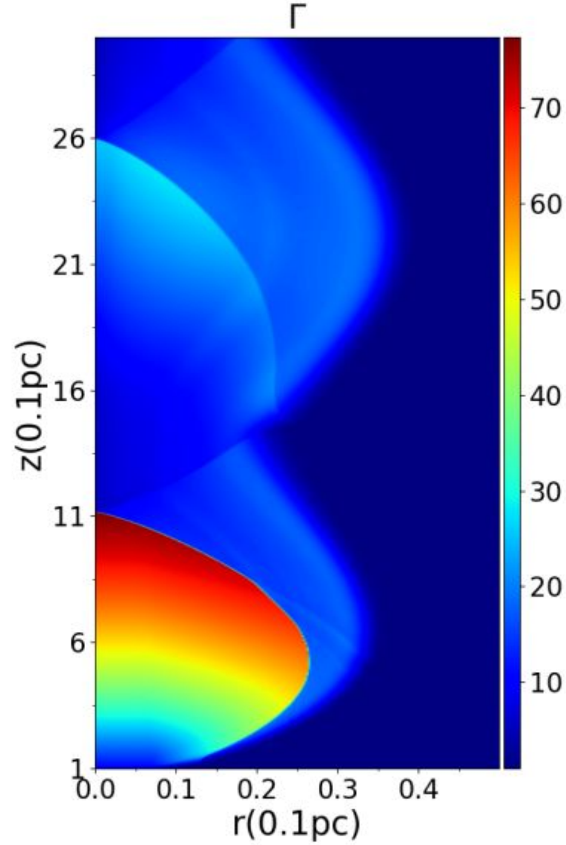
- **Approximate Riemann Solver:**
  - For the adiabatic case: Referenced as [MK05].
  - For the isothermal case: Referenced as [Mig07].
  - For relativistic MHD equations: Referenced as [MUB09].

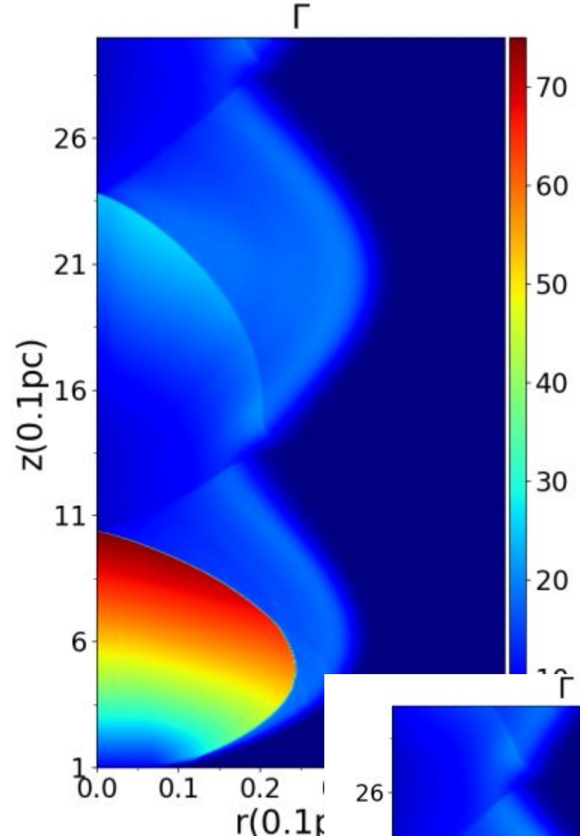
Cases E

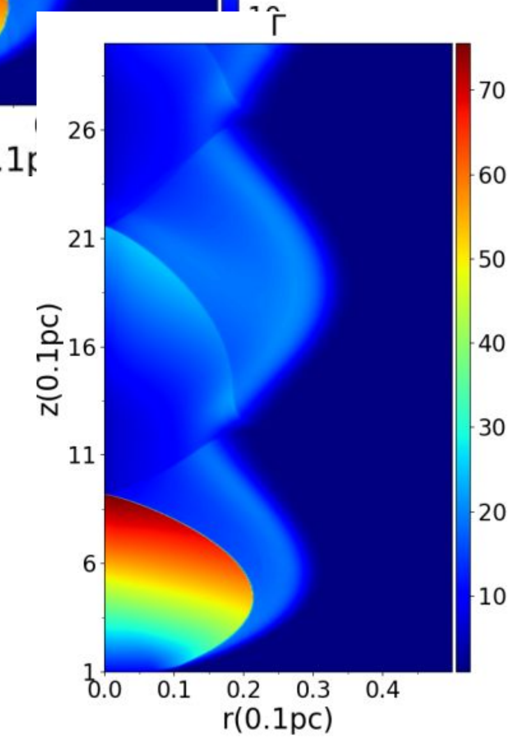


$P_{ratio} = 10$
$\log(\rho/\rho_0)$
$\log(B_{tot}/B_{tot,0})$
Γ/Γ_0
z
$\sigma = 0,\ \nu = 10^{-5}$
$\sigma = 0.1,\ \nu = 10^{-5}$
$\sigma = 1,\ \nu = 10^{-5}$
$\sigma = 3,\ \nu = 10^{-5}$

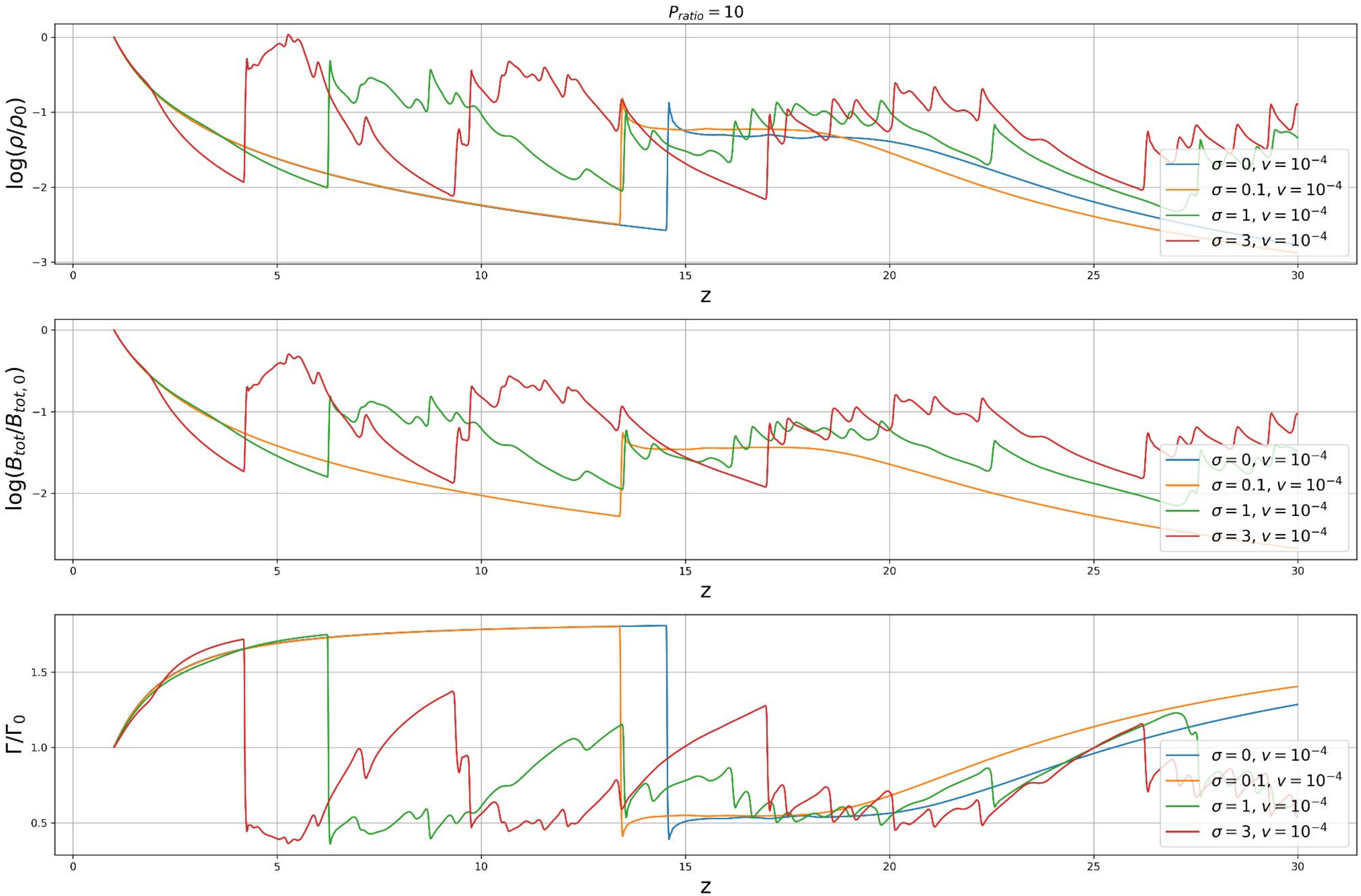

Γ
z(0.1pc)
r(0.1pc)
1 6 11 16 21 26
0.0 0.1 0.2 0.3 0.4

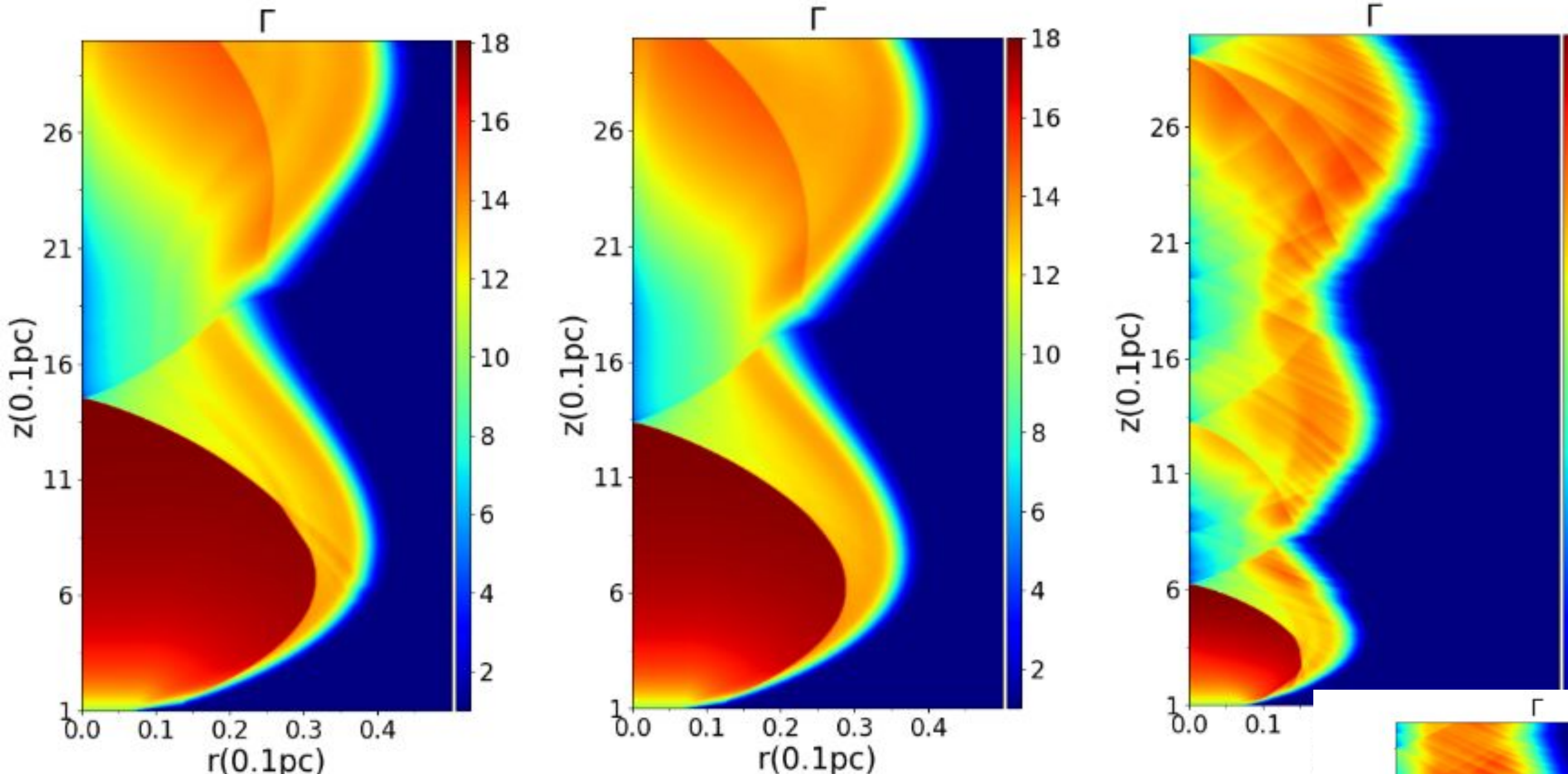

Γ
z(0.1pc)
r(0.1pc)
1 6 11 16 21 26
0.0 0.1 0.2 0.3 0.4
10 20 30 40 50 60 70

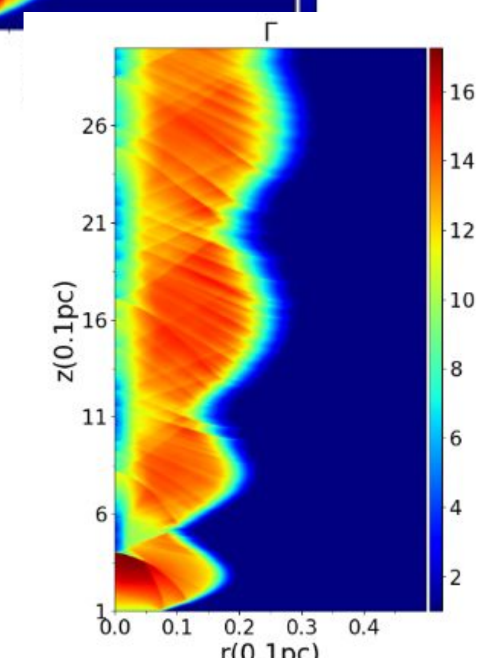

Γ
z(0.1pc)
1 6 11 16 21 26
0.0 0.1 0.2
20 30 40 50 60 70


Γ
z(0.1pc)
r(0.1pc)
1 6 11 16 21 26
0.0 0.1 0.2 0.3 0.4
10 20 30 40 50 60 70

Cases F


$P_{ratio} = 10$
$\log(\rho/\rho_0)$
$\log(B_{tot}/B_{tot,0})$
Γ/Γ_0
z
$\sigma = 0,\ \nu = 10^{-4}$
$\sigma = 0.1,\ \nu = 10^{-4}$
$\sigma = 1,\ \nu = 10^{-4}$
$\sigma = 3,\ \nu = 10^{-4}$


Γ
Γ
Γ
z(0.1pc)
z(0.1pc)
z(0.1pc)
r(0.1pc)
r(0.1pc)


Γ
z(0.1pc)
r(0.1pc)