Following the GRB jet interaction from small to large scales

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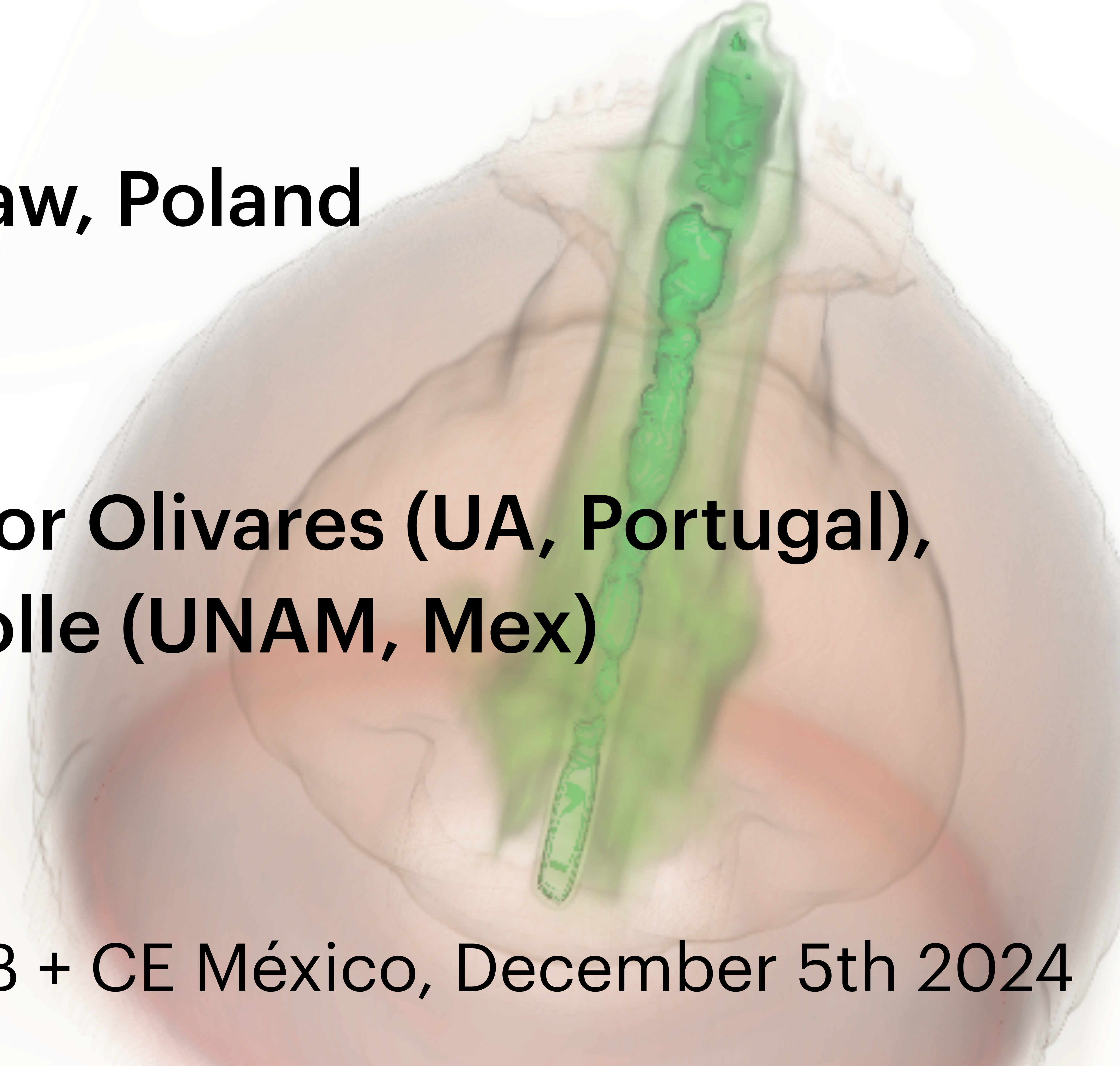

dxdx
dxdxdx
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PL GRID

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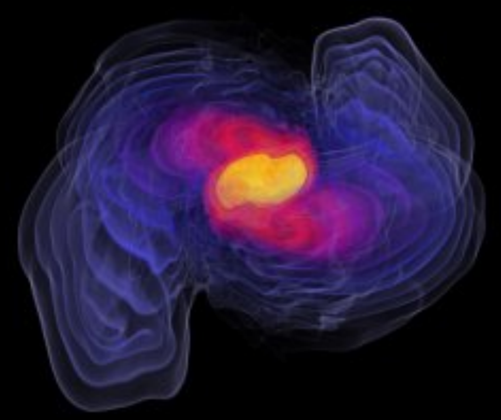
GRB + CE México, December 5th 2024

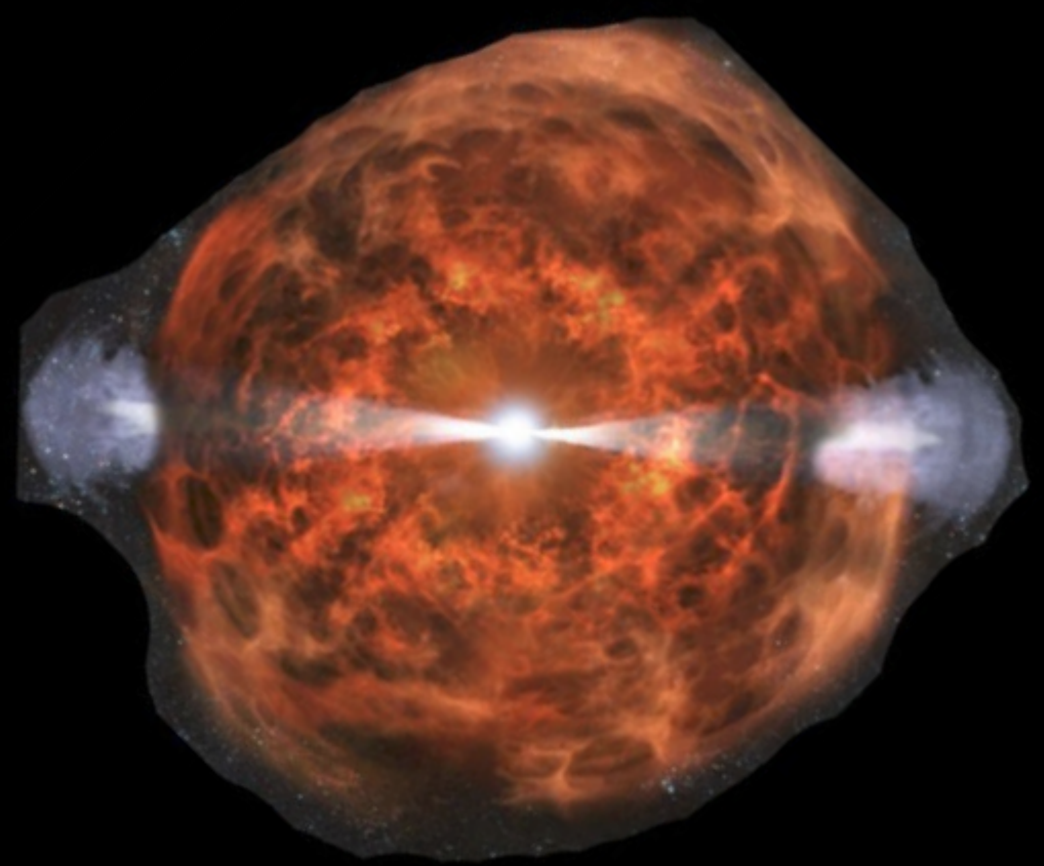
GRB jet evolution is a multi-scale problem

NS-NS merger
Or
BH-NS merger



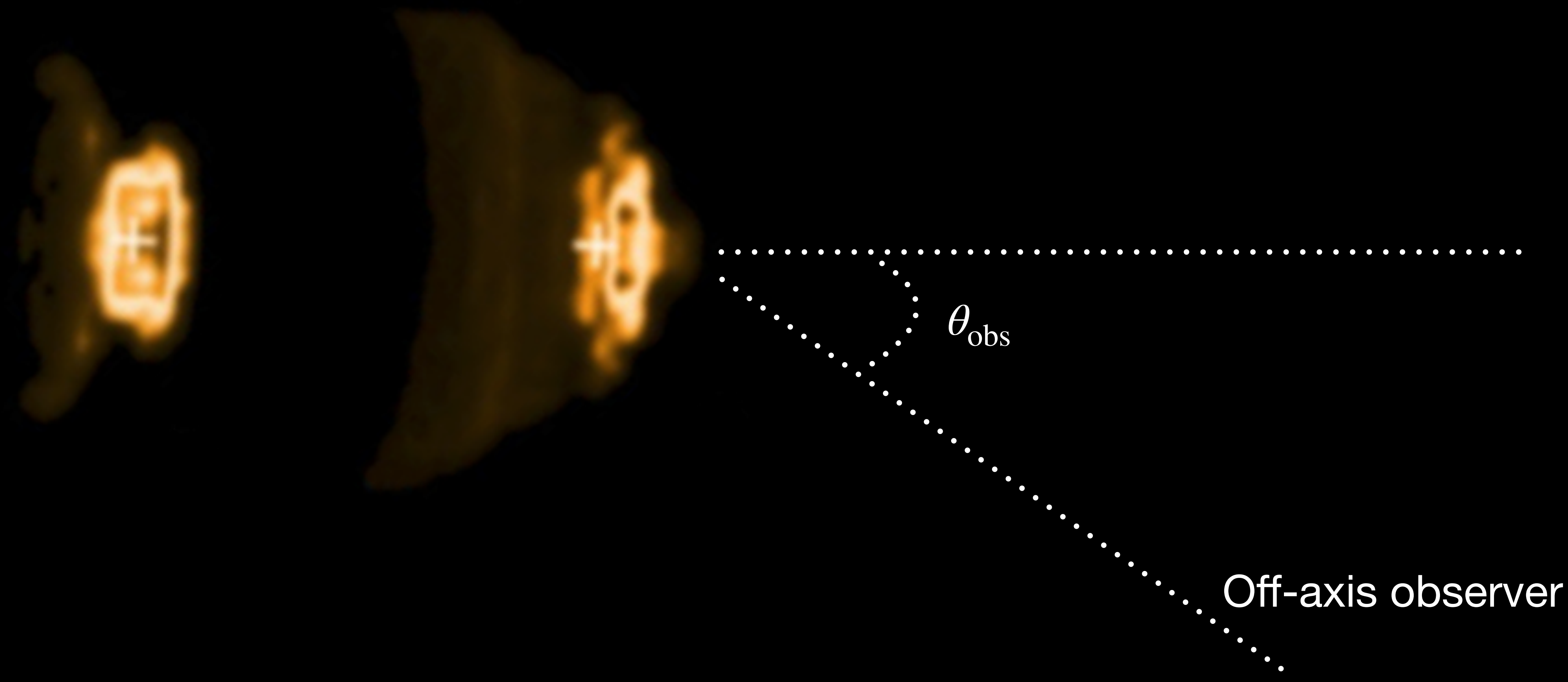
Central Engine

Jet Propagation within
Post-merger outflows



$r \lesssim 10^{10}\,\mathrm{cm}$

Shell propagation in External ISM

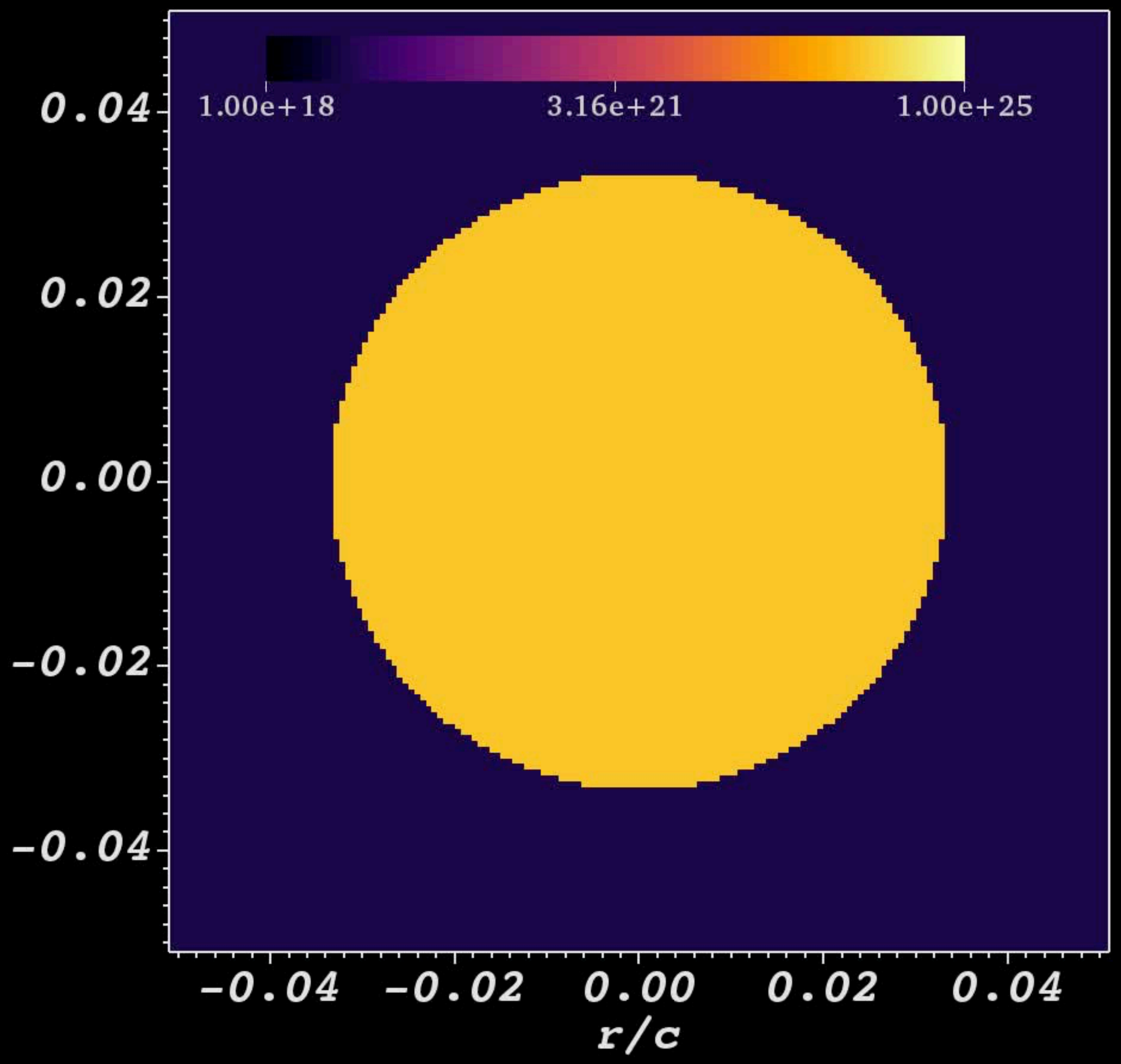


$r \sim 10^{16}\,\mathrm{cm}$

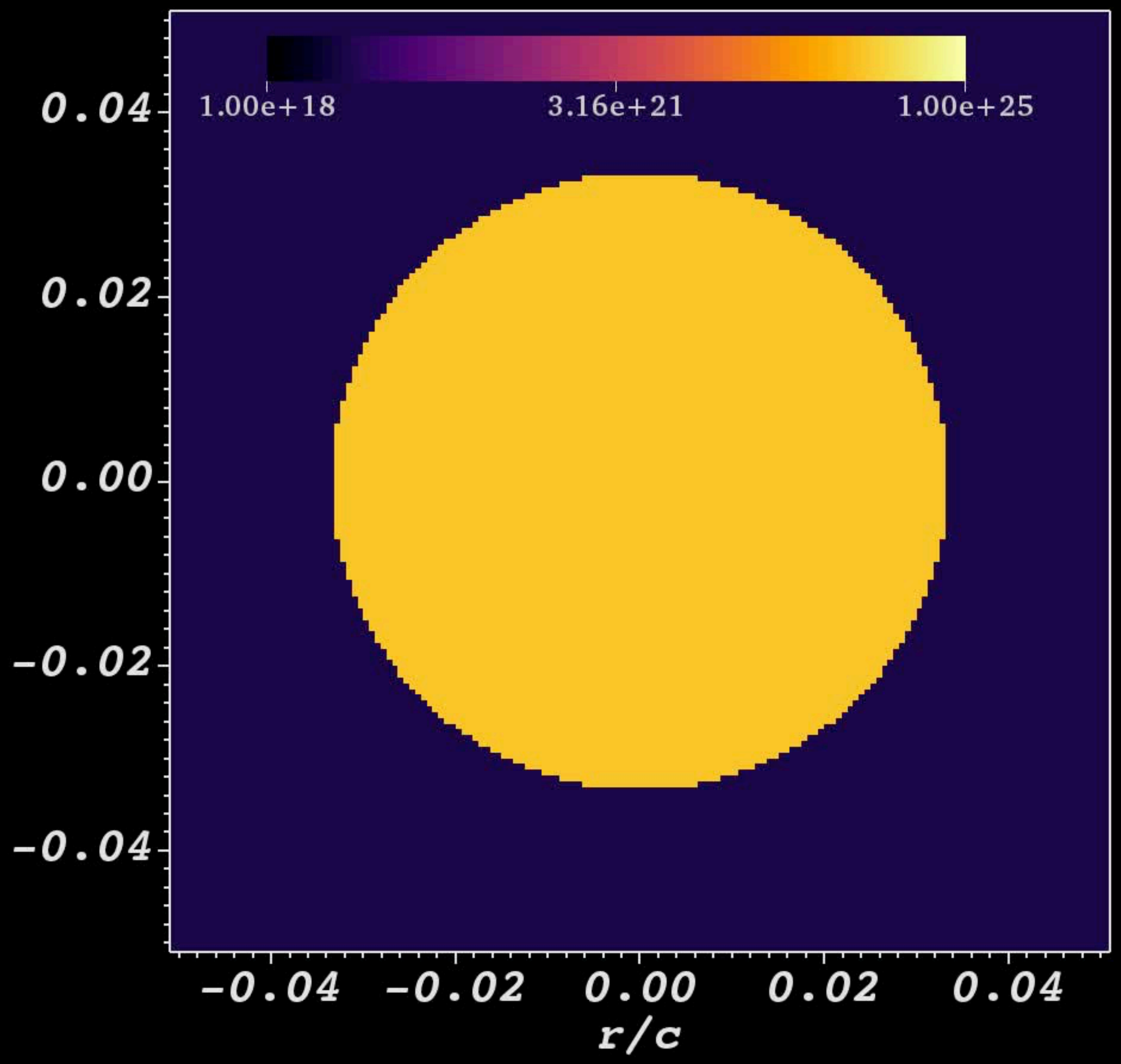
Afterglow Emission

Is the initial jet structure deleted by the interaction with environment?

Top-hat jet



PLJ structured jet

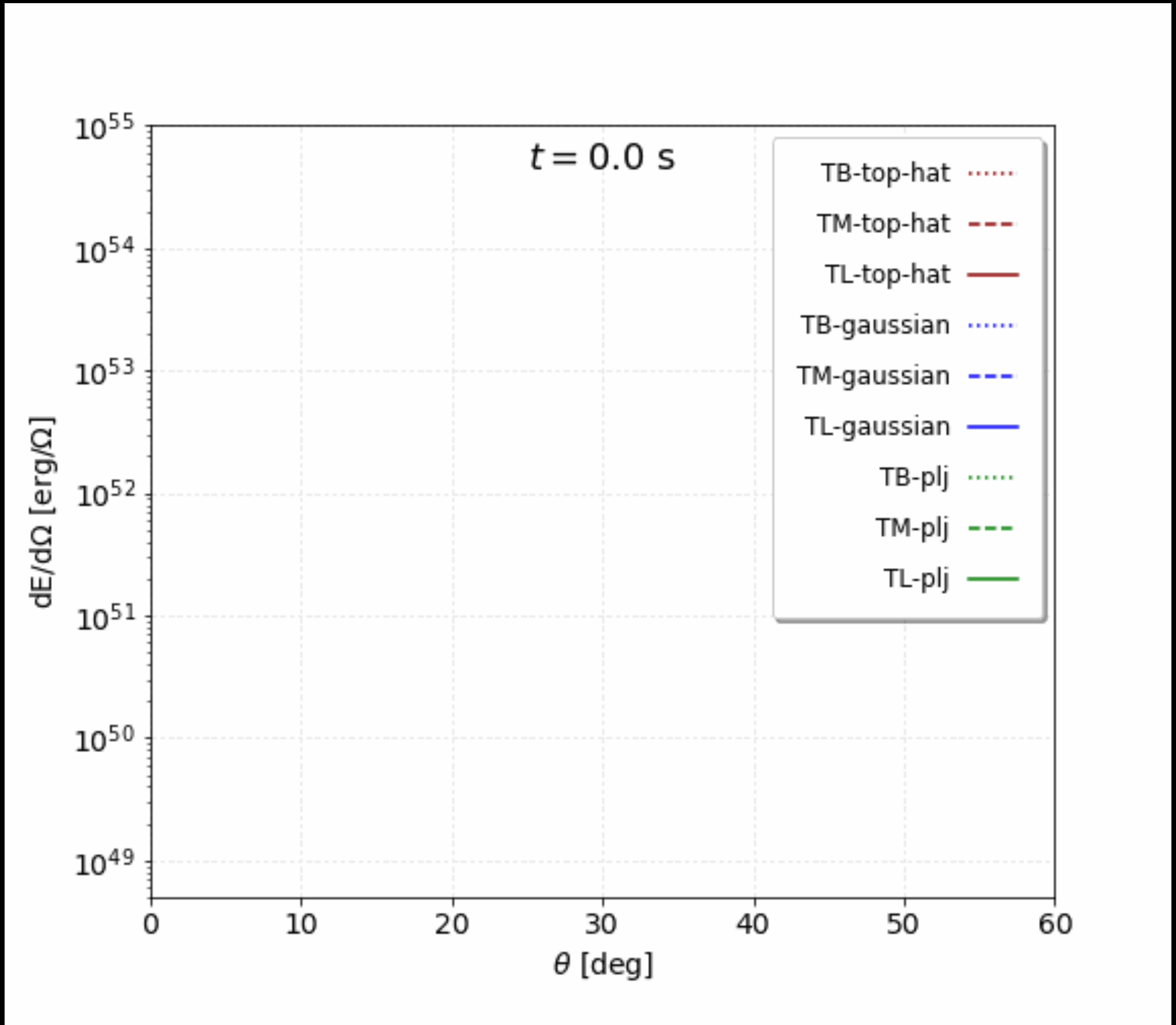


Urrutia, De Colle, Murguia-Berthier, Ramirez-Ruiz 2021

Time=0

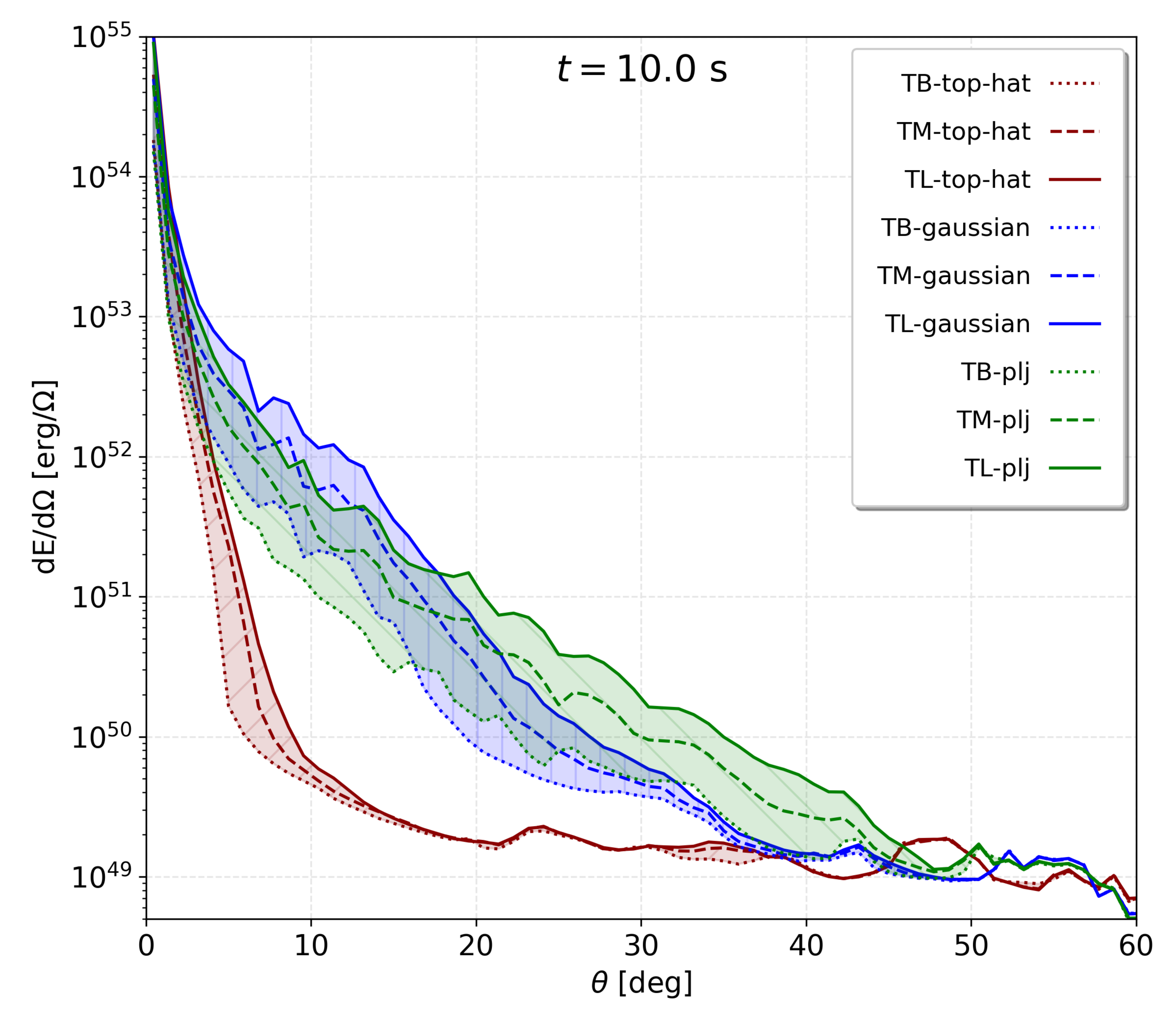
Time=0

Evolution of the jet structure



Urrutia, De Colle, Murguia-Berthier, Ramirez-Ruiz 2021

The jet structure is partially preserved after the breakout



Urrutia, De Colle, Murguia-Berthier, Ramirez-Ruiz 2021

Short GRBs simulations

Methods: remapping disk wind data and jet properties from GRMHD simulations to AMR SRHD simulations

Our Connection between small and large scales

Small scales $r < 3 \times 10^8\,\mathrm{cm}$

Large scales $10^8\,\mathrm{cm} < \mathrm{r} < 10^{11}\,\mathrm{cm}$

General Relativistic MHD simulation

$$(\rho u_\mu)_{;\nu} = 0$$

$$T^{\mu}_{\nu;\mu} = 0$$

$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{m}} + T^{\mu\nu}_{\mathrm{em}}$$

-HARM CODE (Gammie 2003)
-HLL solver
-Kerr-schild metric

Neutrino treatment (Janiuk et al. 2013)
The neutrino optical depth

$$\tau_{\mathrm{a},\nu_{\mathrm{i}}} = \frac{H}{4\frac{7}{8}\sigma T^4} q_{\mathrm{a},\nu_{\mathrm{i}}},$$

Species:

$$p + e^- \rightarrow n + \nu_e$$

$$n + e^+ \rightarrow p + \bar{\nu}_e$$

$$e^+ + e^- \rightarrow \nu_i \bar{\nu}_i$$

Importing data

Methods:

- **The disc wind outflow was performed by Nouri et al. 2023 by GRMHD simulation.**
- **We constrain the jet parameters from GRMHD simulation.**
- **We import outflow data as an initial condition for a large-scale simulation.**

Special Relativistic HD simulation

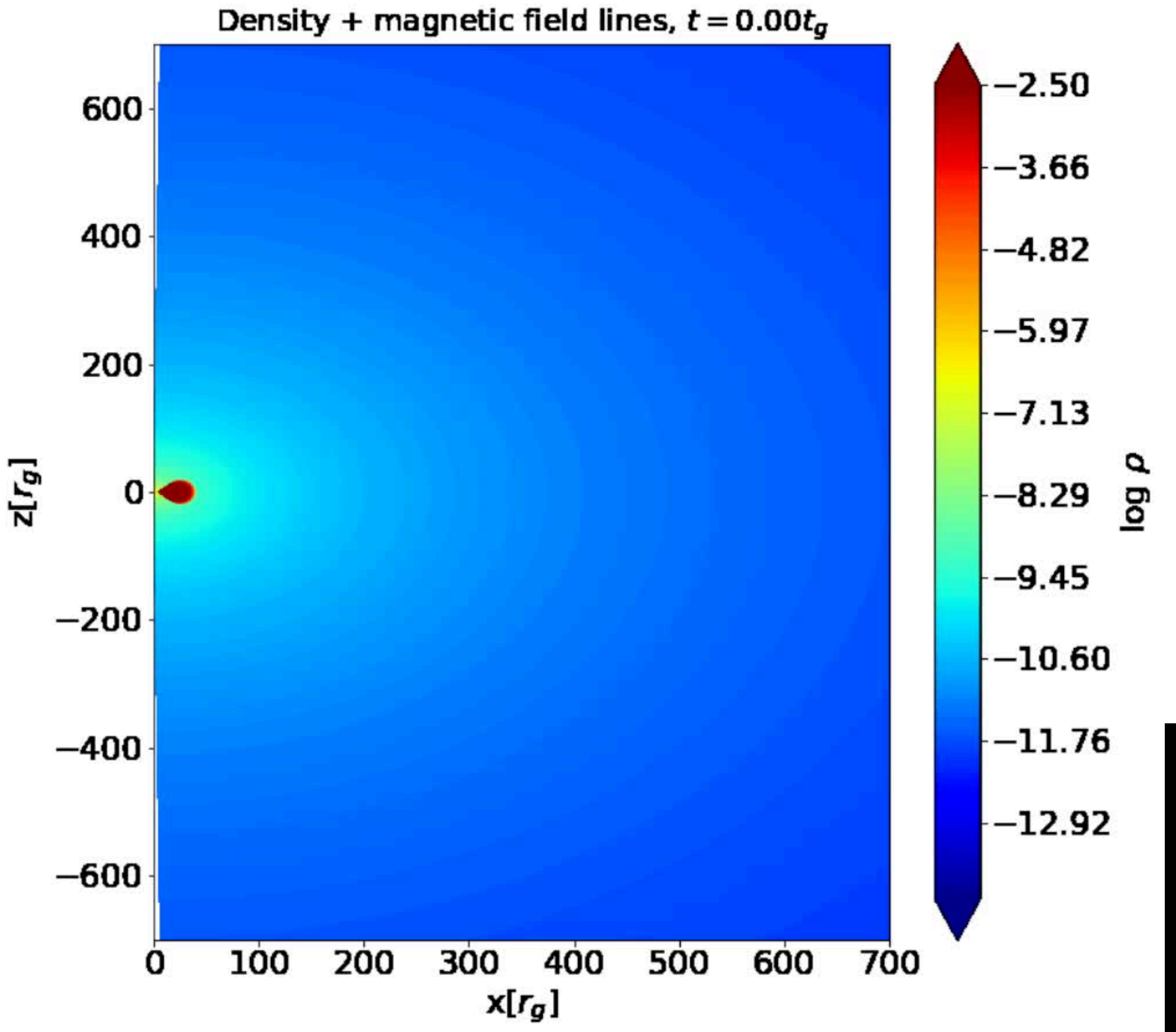
$$(\rho u_\mu)_{;\nu} = 0$$

$$T^{\mu}_{\nu;\mu} = 0$$

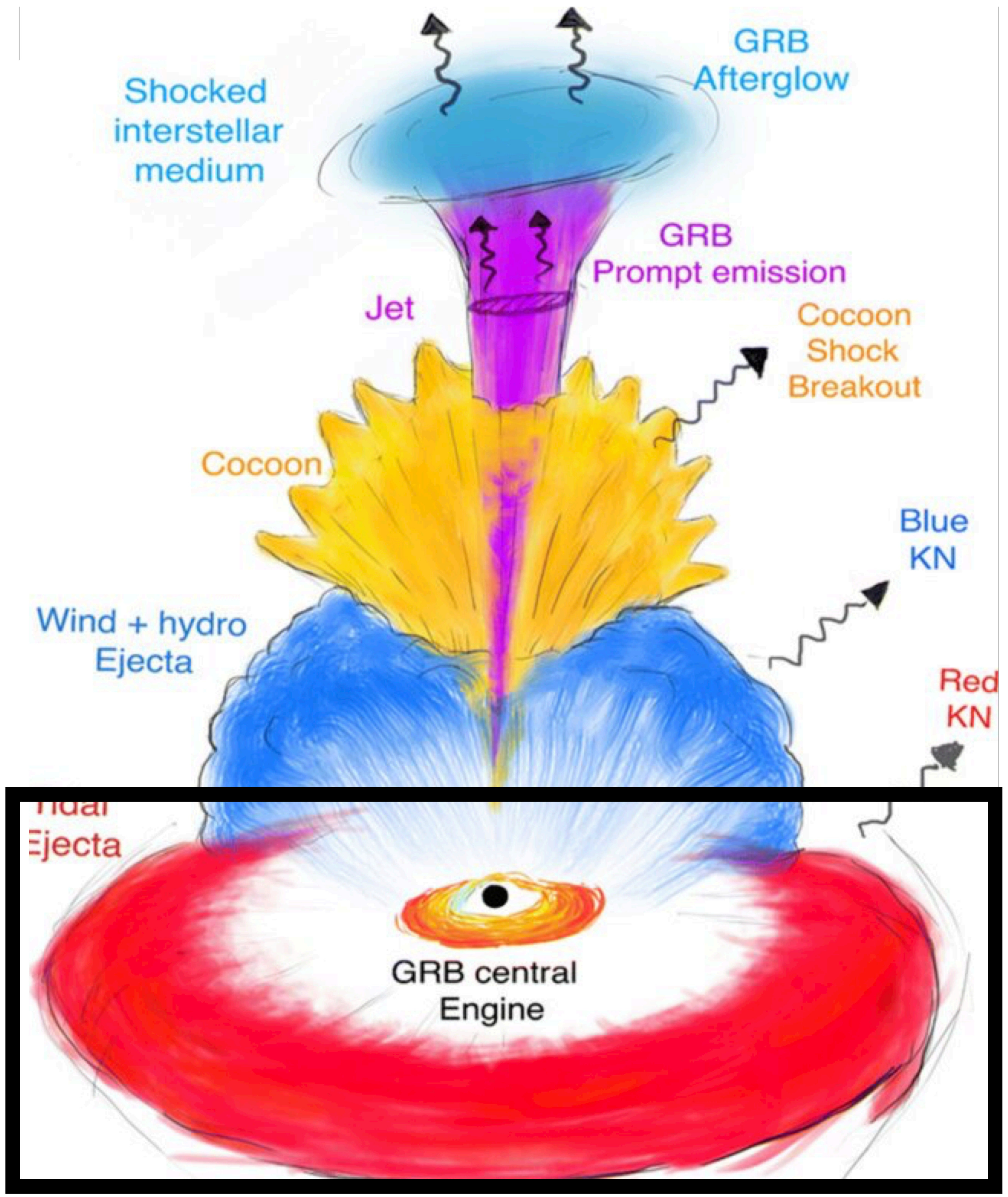
$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{m}}$$

- Mezcal Code (De Colle 2012)
- Adaptive Mesh Refinement
- HLLC solver
- GR effects not considered

Post-merger evolution of the jet



Nouri, Janiuk (2023)

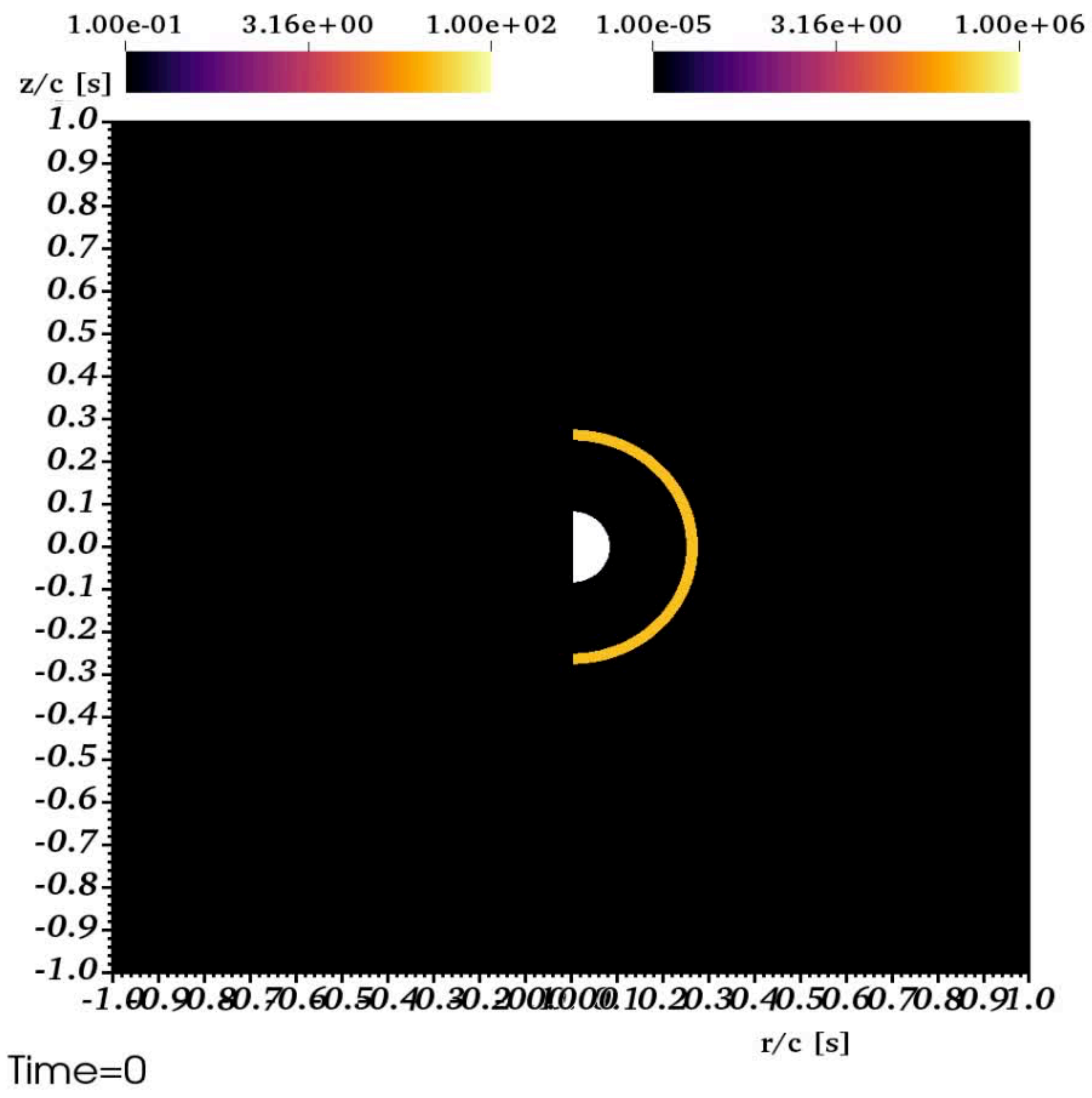


Cartoon of GRB evolution (Stefano Ascenzi)

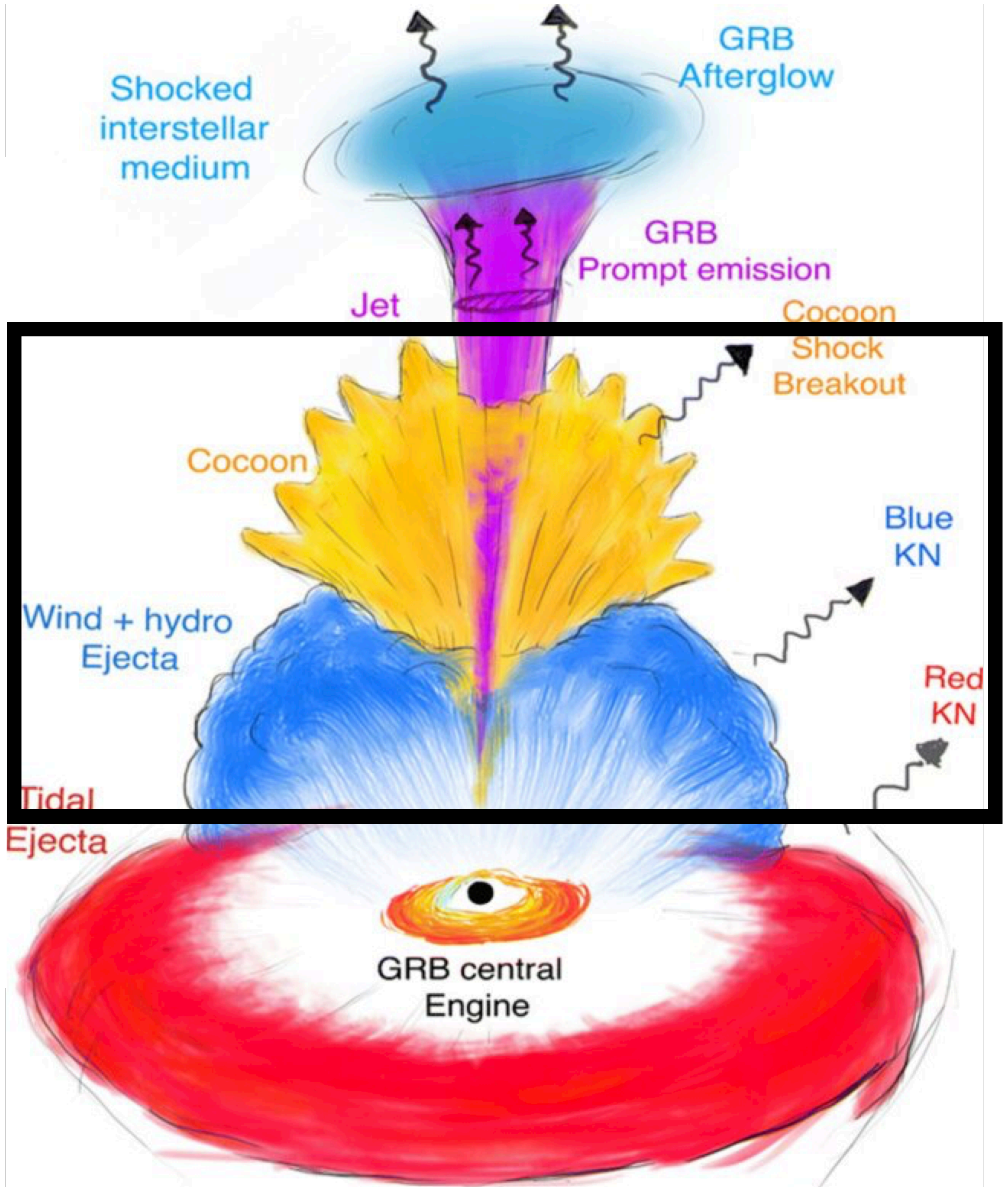
Small Scales $r \lesssim 10^8\,\mathrm{cm}$

GRMHD simulations

Post-merger evolution of the jet



Urrutia, Janiuk, et al. 2024



Cartoon of GRB evolution (Stefano Ascenzi)

Intermediate Scales $10^8 \lesssim r \lesssim 10^{11}\,\mathrm{cm}$

RMHD or RHD simulations

Disk wind outflows

Post NSNS merger configuration

$M_{\rm BH} = 2.65 M_\odot$

$M_{\rm disc} = 0.10276\, M_\odot$

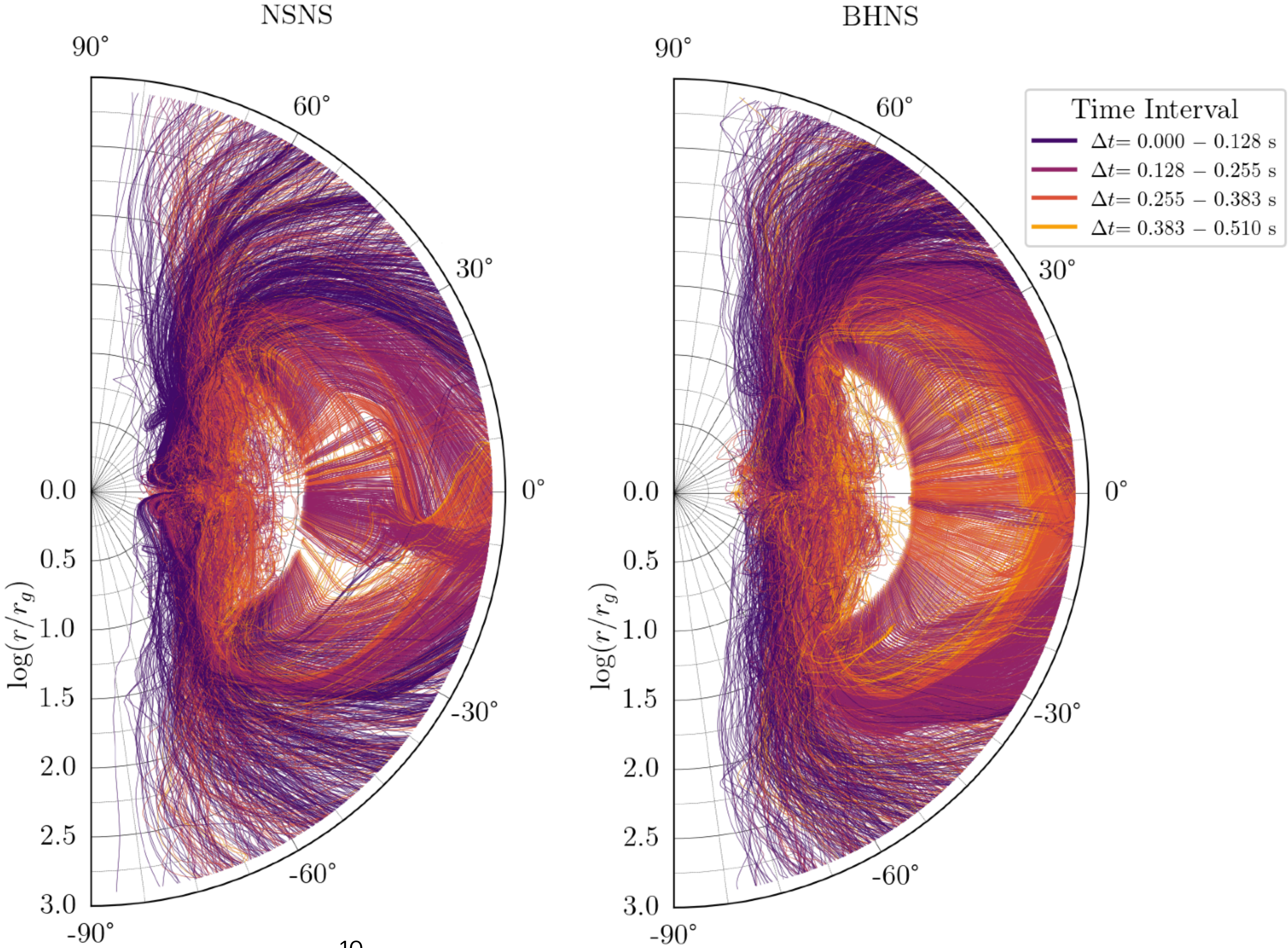
$\dot{M}_{\rm out} = 3.27 \times 10^{-2}\, M_\odot\ {\rm s}^{-1}$

Post BHNS merger configuration

$M_{\rm BH} = 5.0 M_\odot$

$M_{\rm disc} = 0.3120\, M_\odot$

$\dot{M}_{\rm out} = 1.49 \times 10^{-1}\, M_\odot\ {\rm s}^{-1}$



Jet Characteristics

$\Gamma_j = 7.2$

$t_{\rm j} \propto M_{\rm disk}/\langle \dot{M} \rangle \sim 1.57\,{\rm s}$

$\theta_j = 15^{\circ}$

$L_j \approx 1.7 \times 10^{50}\,{\rm erg/s}$

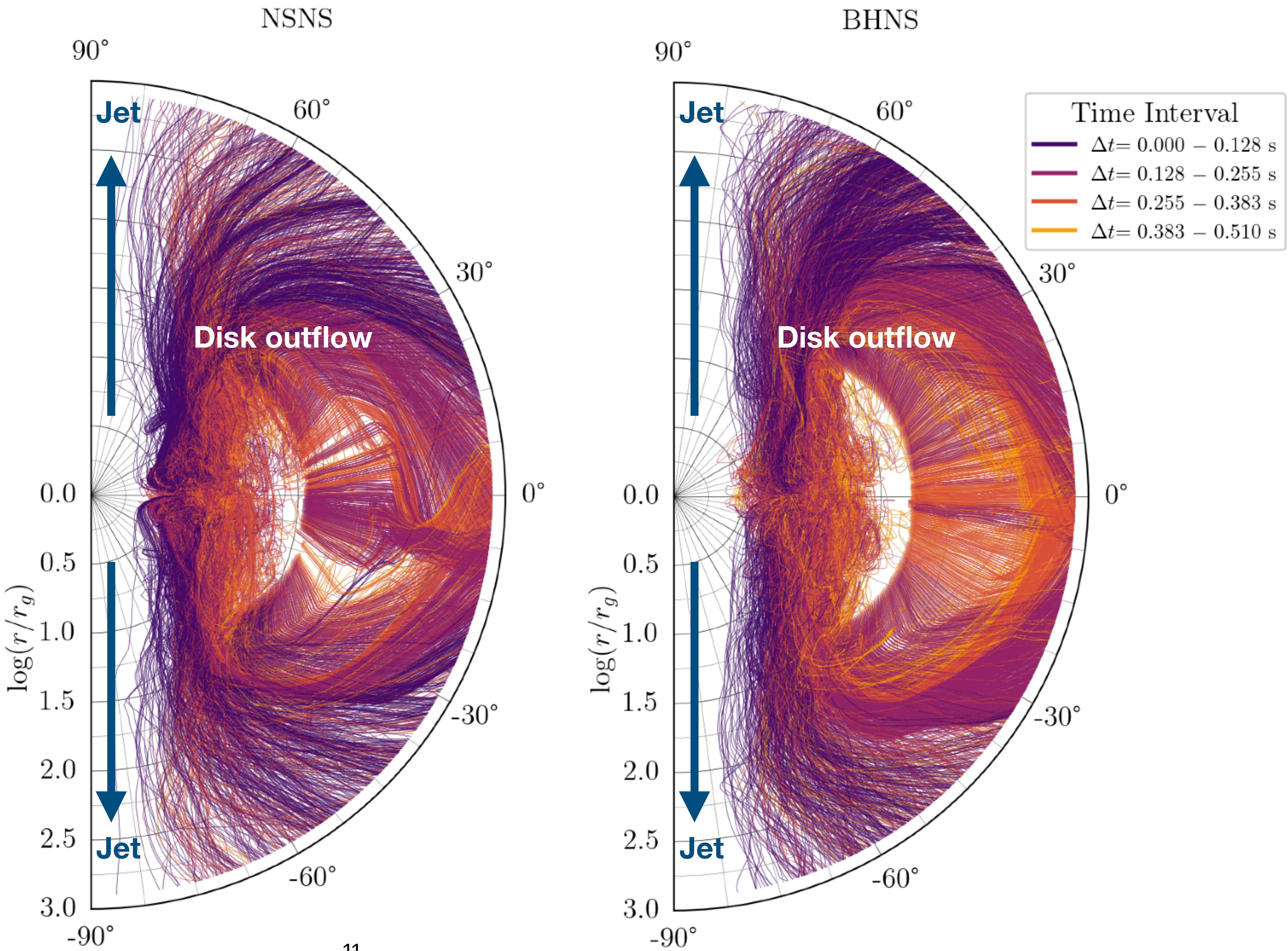
Jet Characteristics

$\Gamma_j = 12$

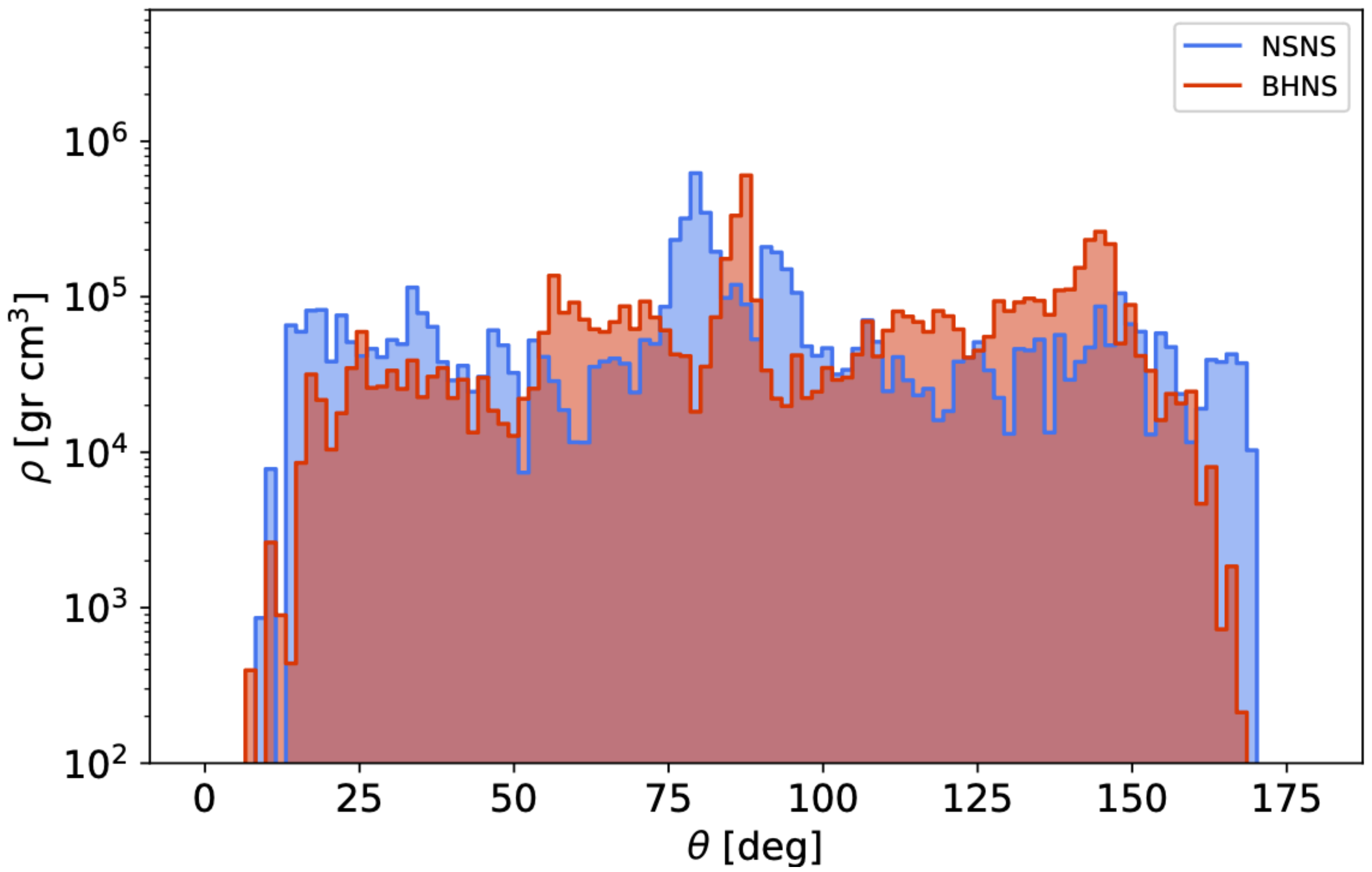
$t_{\rm j} \propto M_{\rm disk}/\langle \dot{M} \rangle \sim 1.07\,{\rm s}$

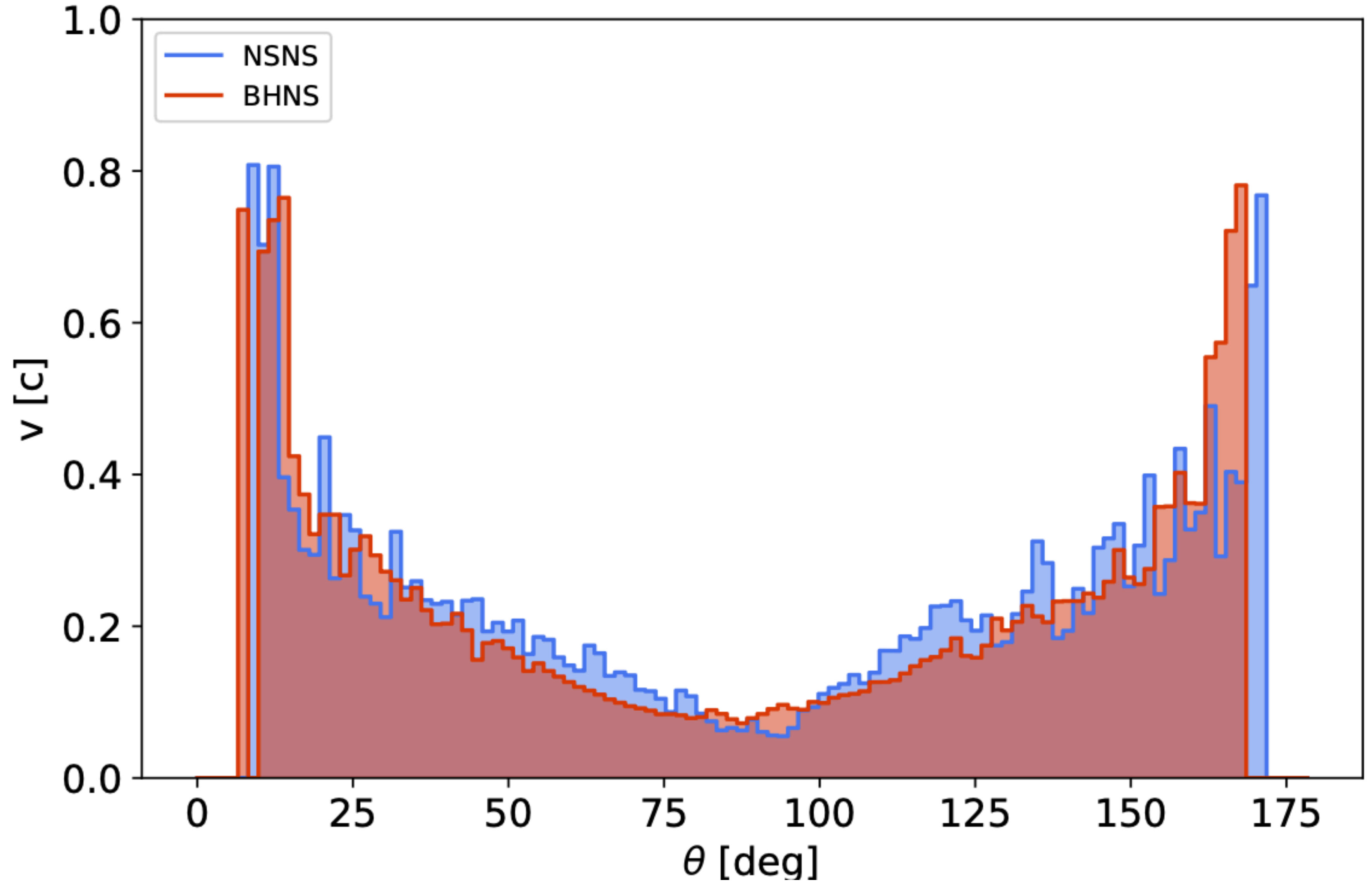
$\theta_j = 15^{\circ}$

$L_j \approx 2.2 \times 10^{50}\,{\rm erg/s}$

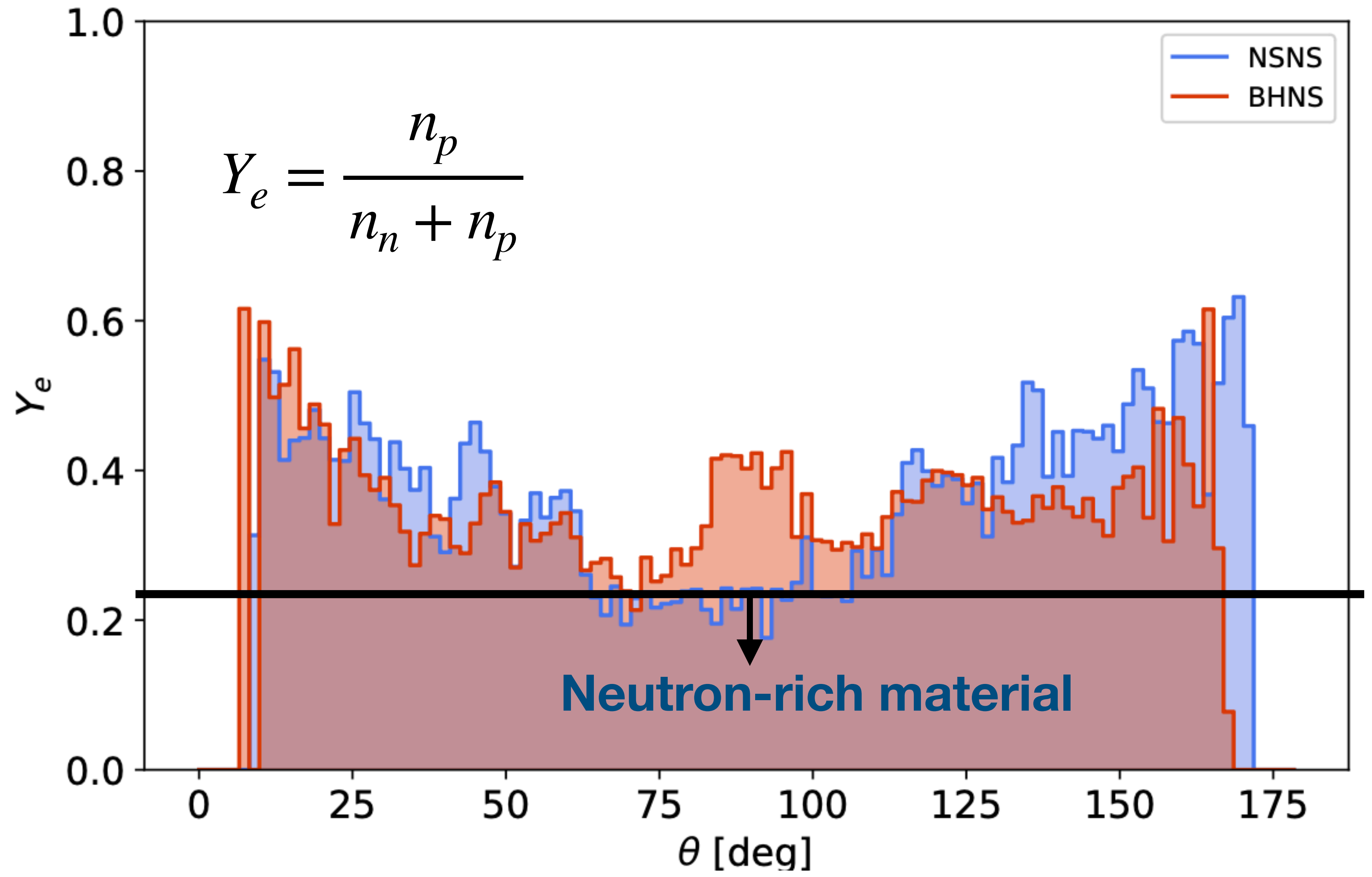


Wind distributions at $r_{\rm inj} \sim 2 \times 10^8$ [cm]





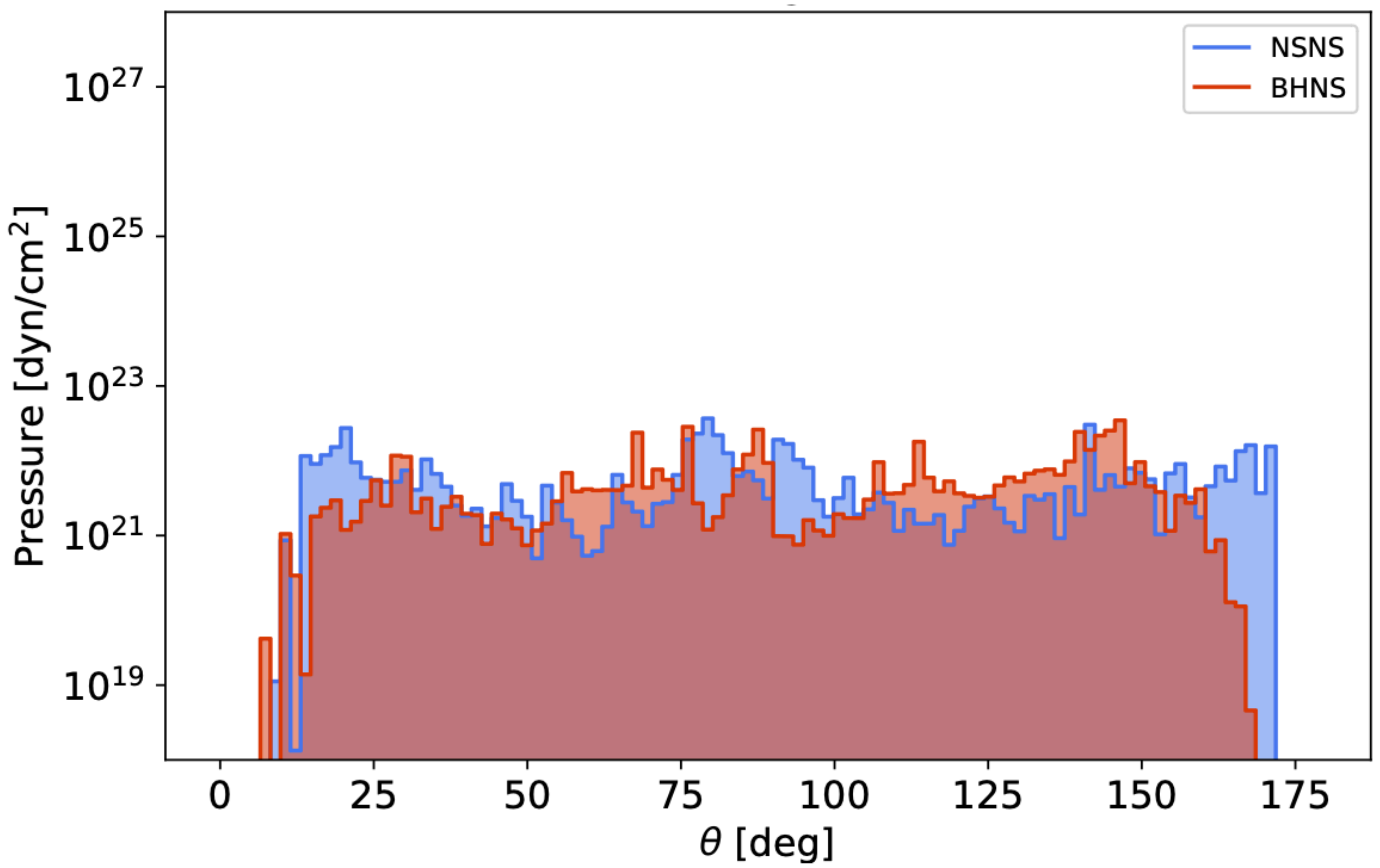
Processing



SkyNet nuclear reaction network (Lippuner & Roberts 2017)

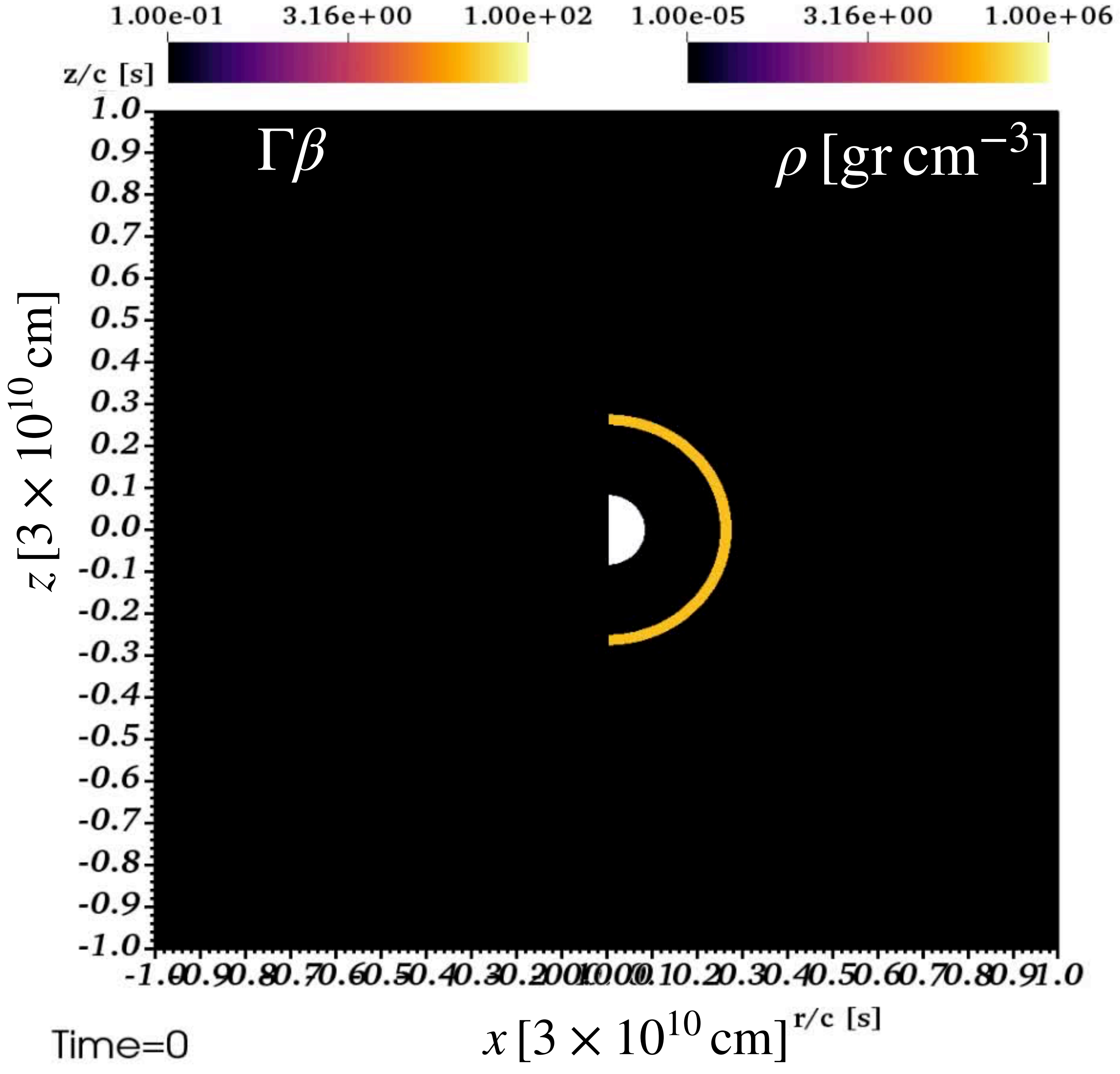
Inversion of Helmholtz equation (Timmes & Arnet 1999)

Note: Abundances of these models are discussed in Nouri et al., 2023

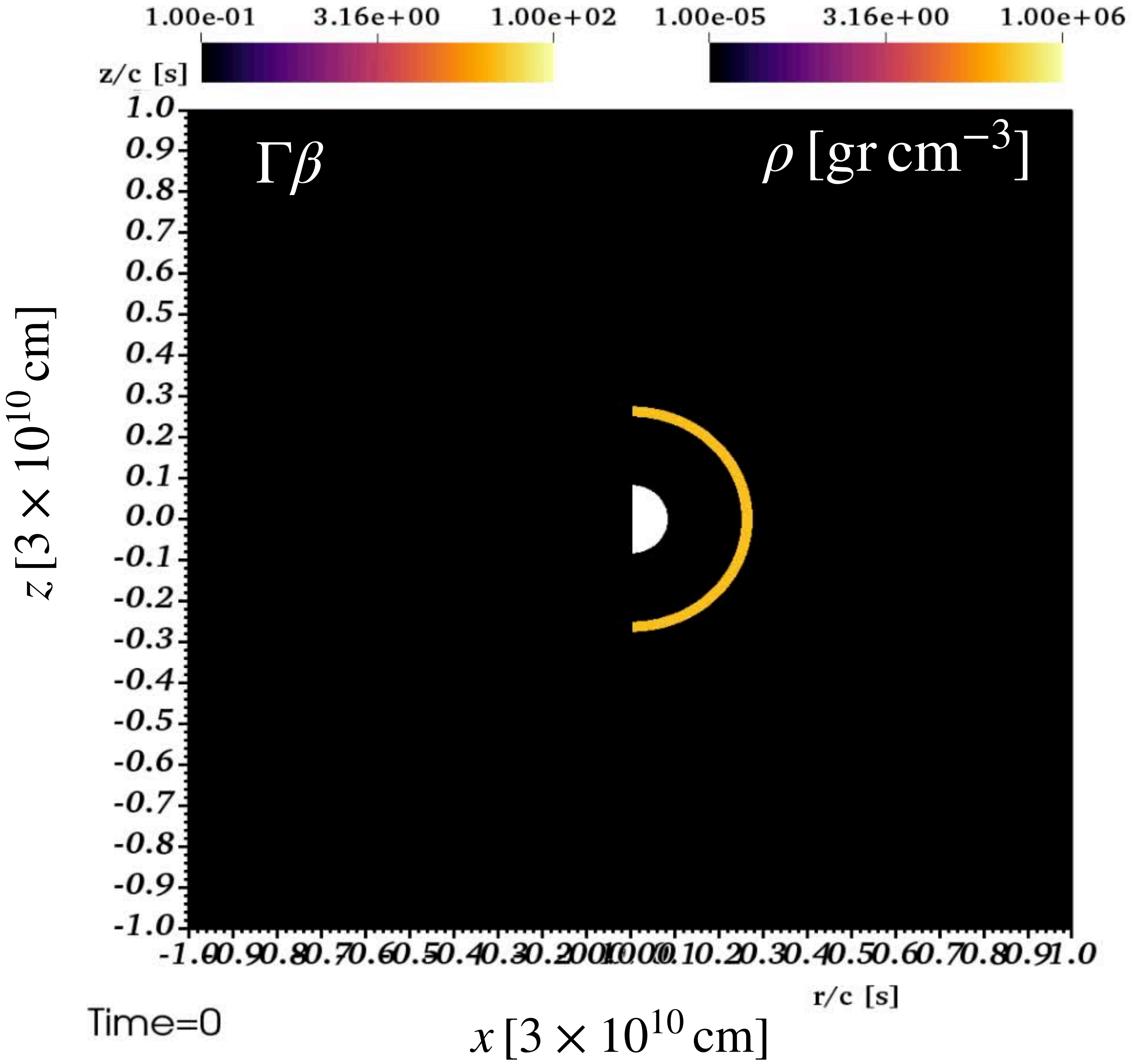


Results of jet interaction

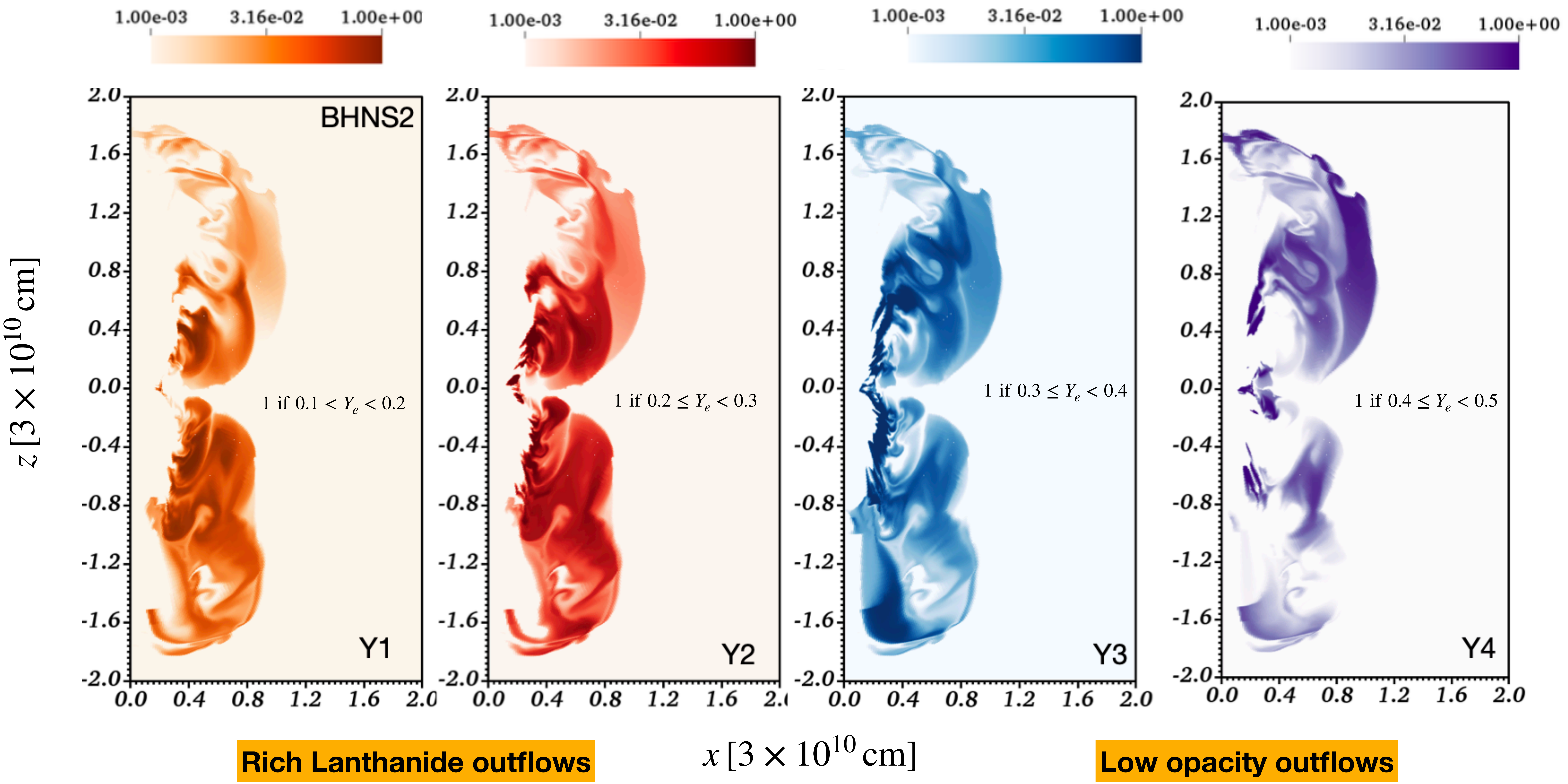
Jet from NSNS merger



Jet from BHNS merger



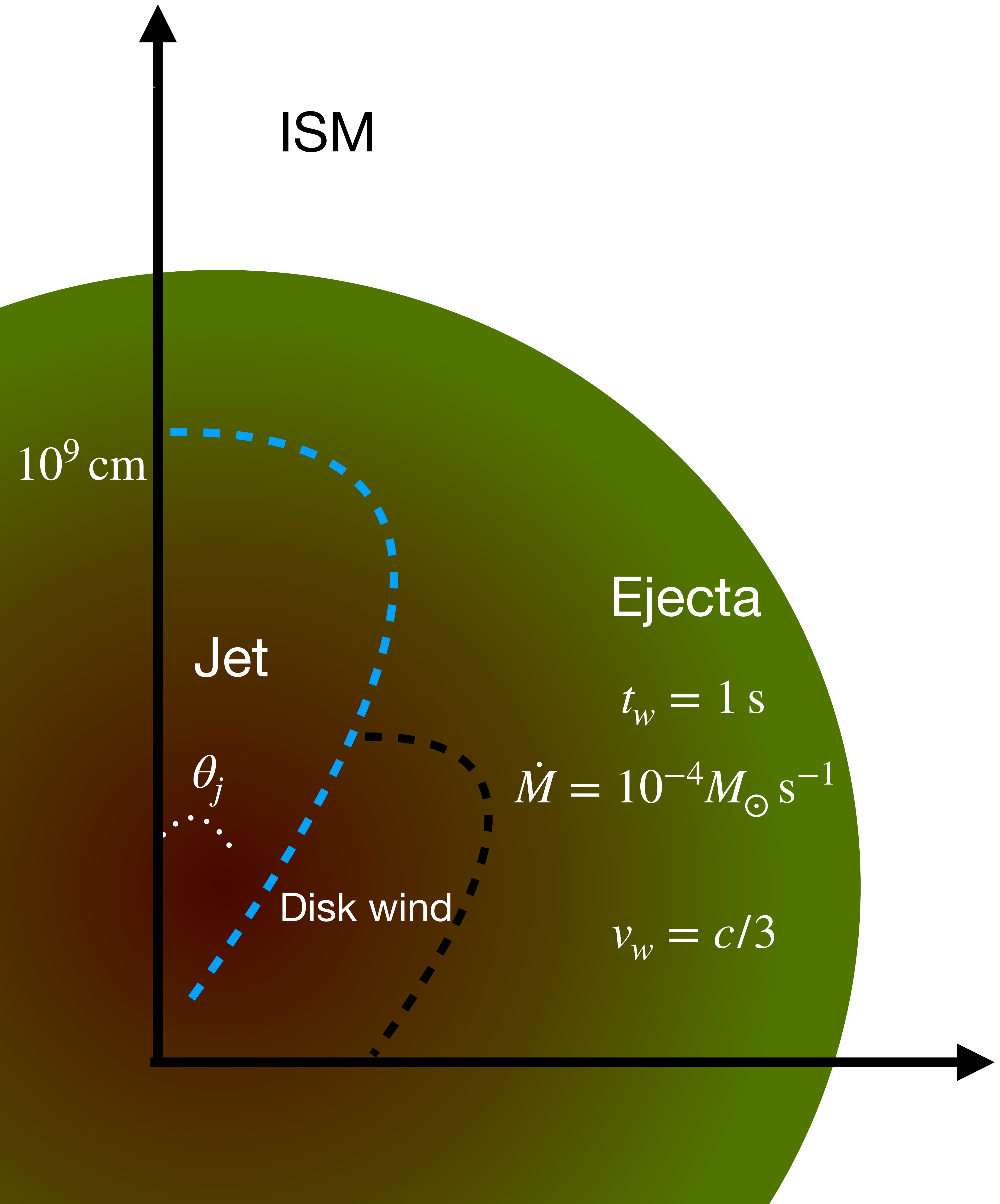
Future distribution of the kilonova

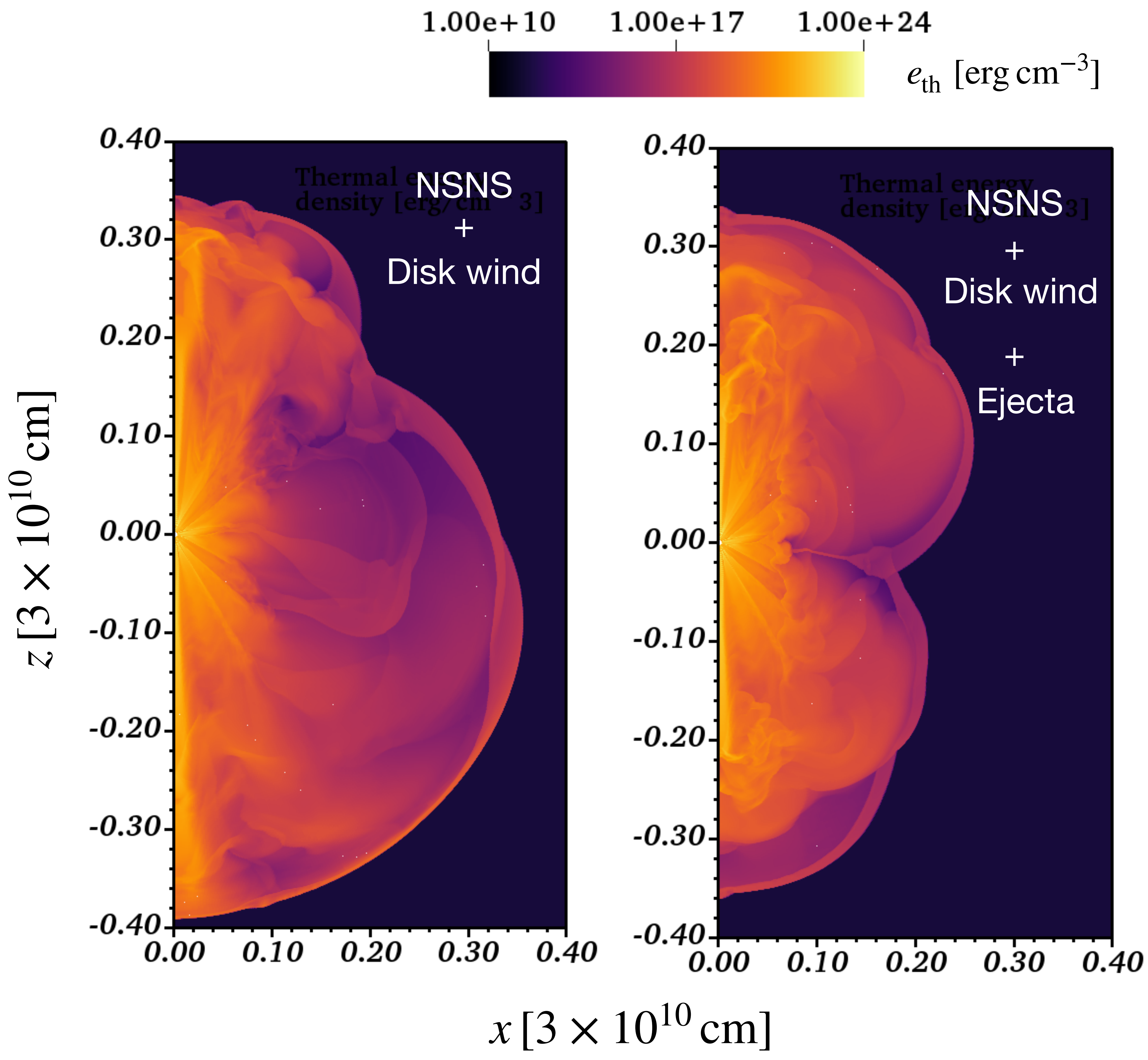


Rich Lanthanide outflows

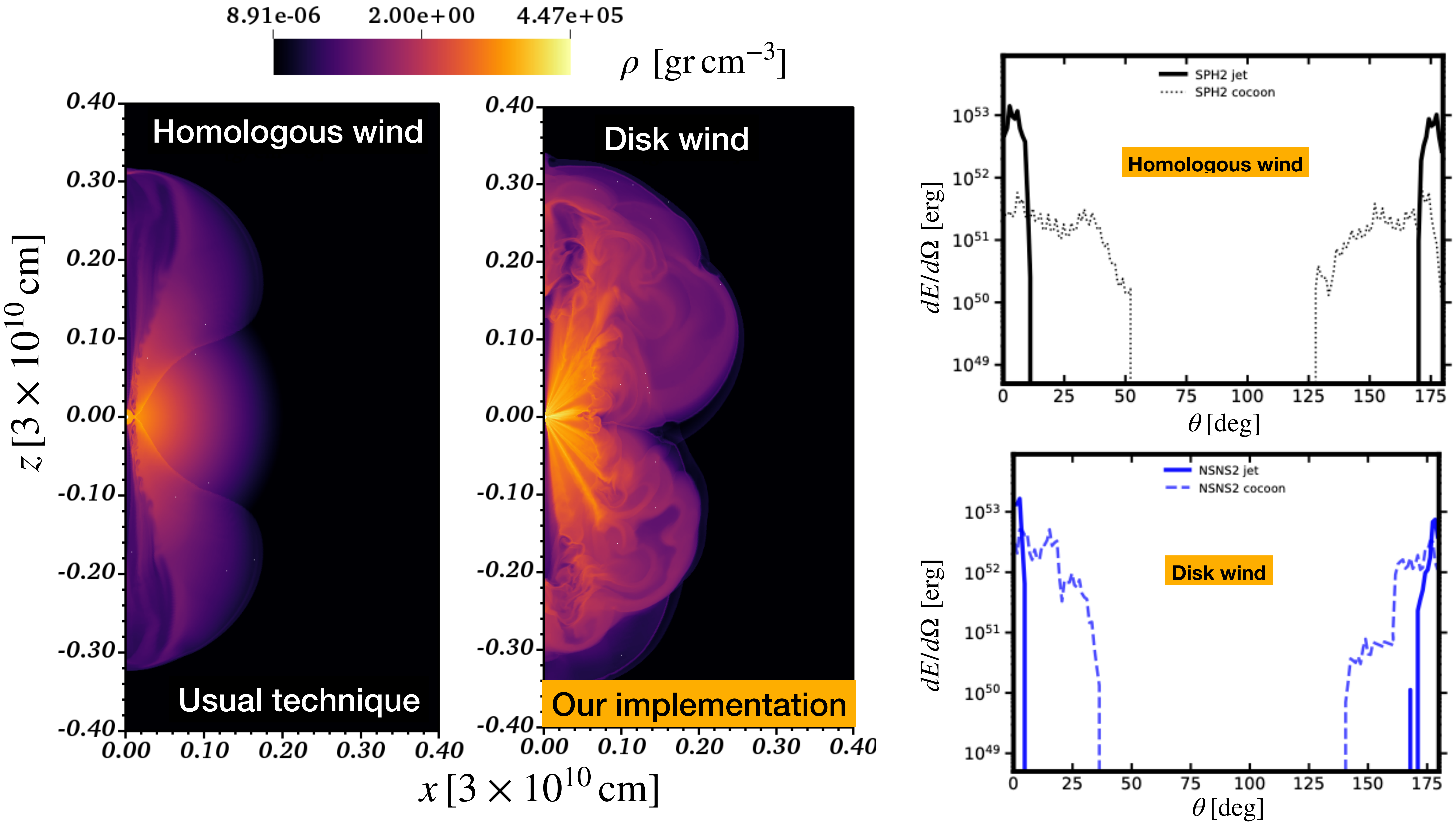
Low opacity outflows

Results of jet interaction

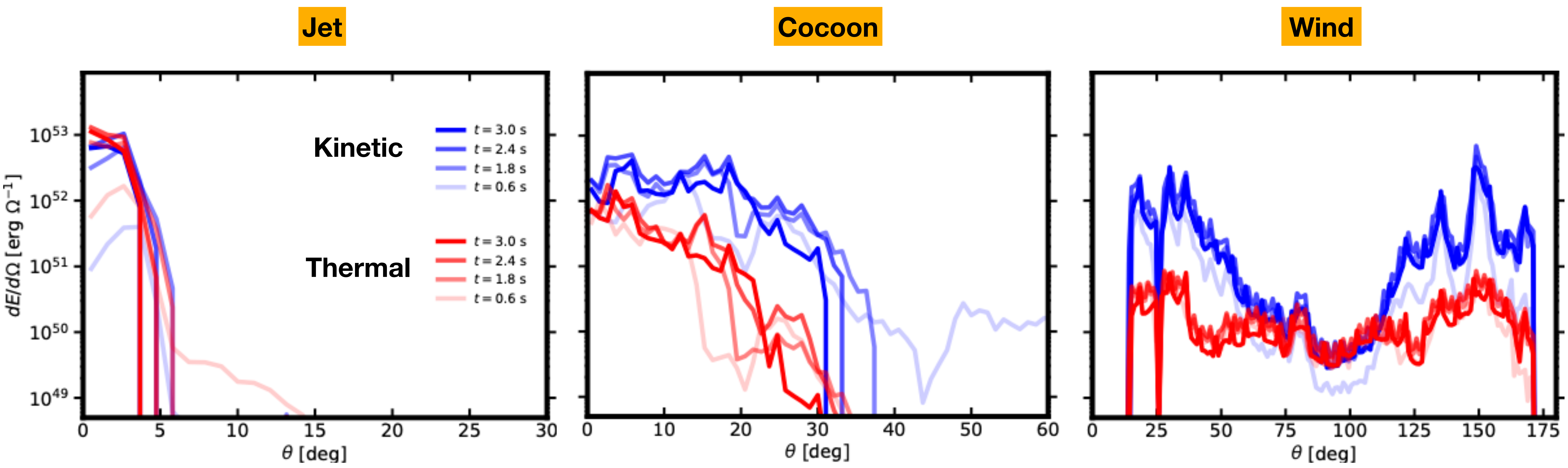




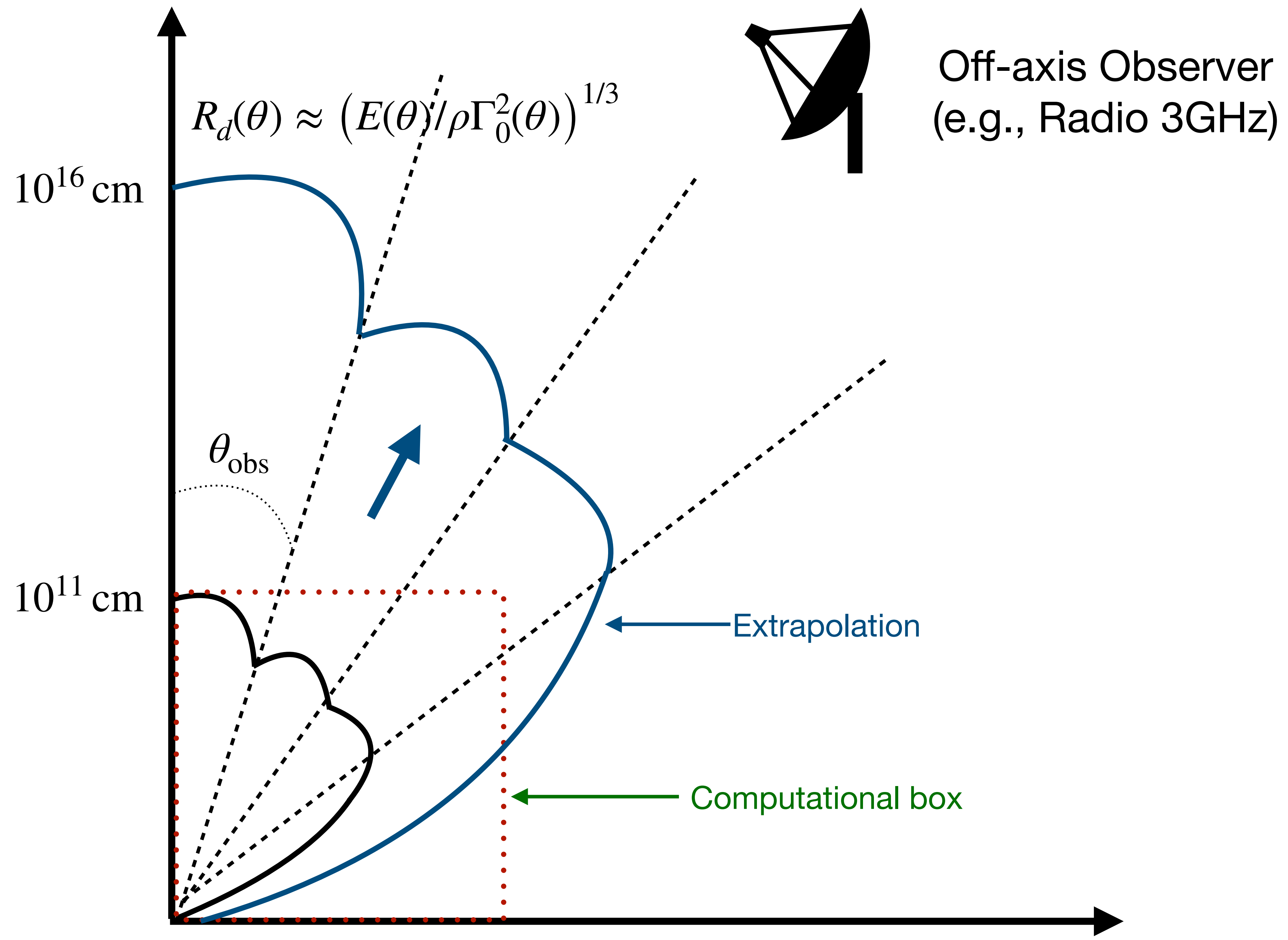
Jet from NSNS merger

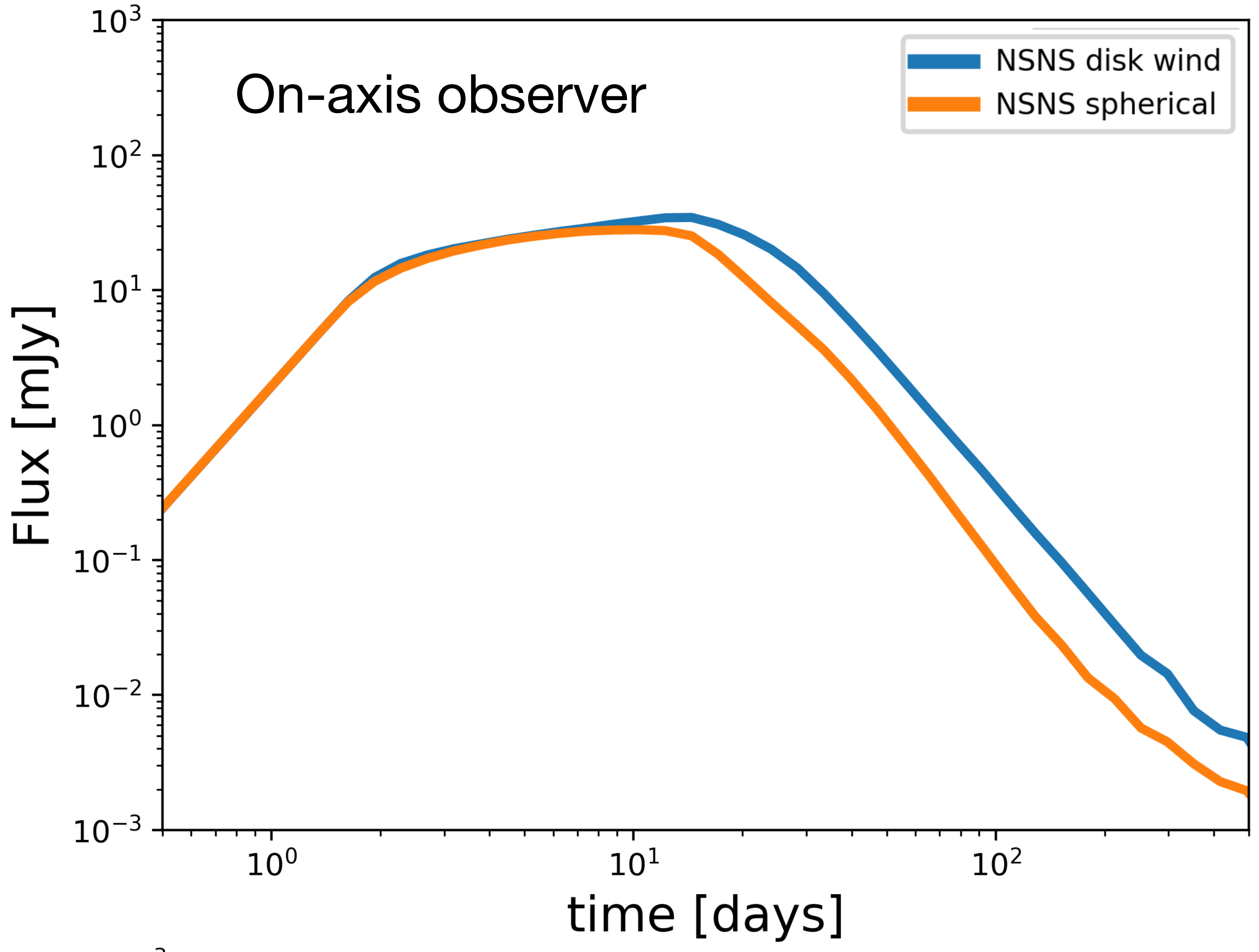


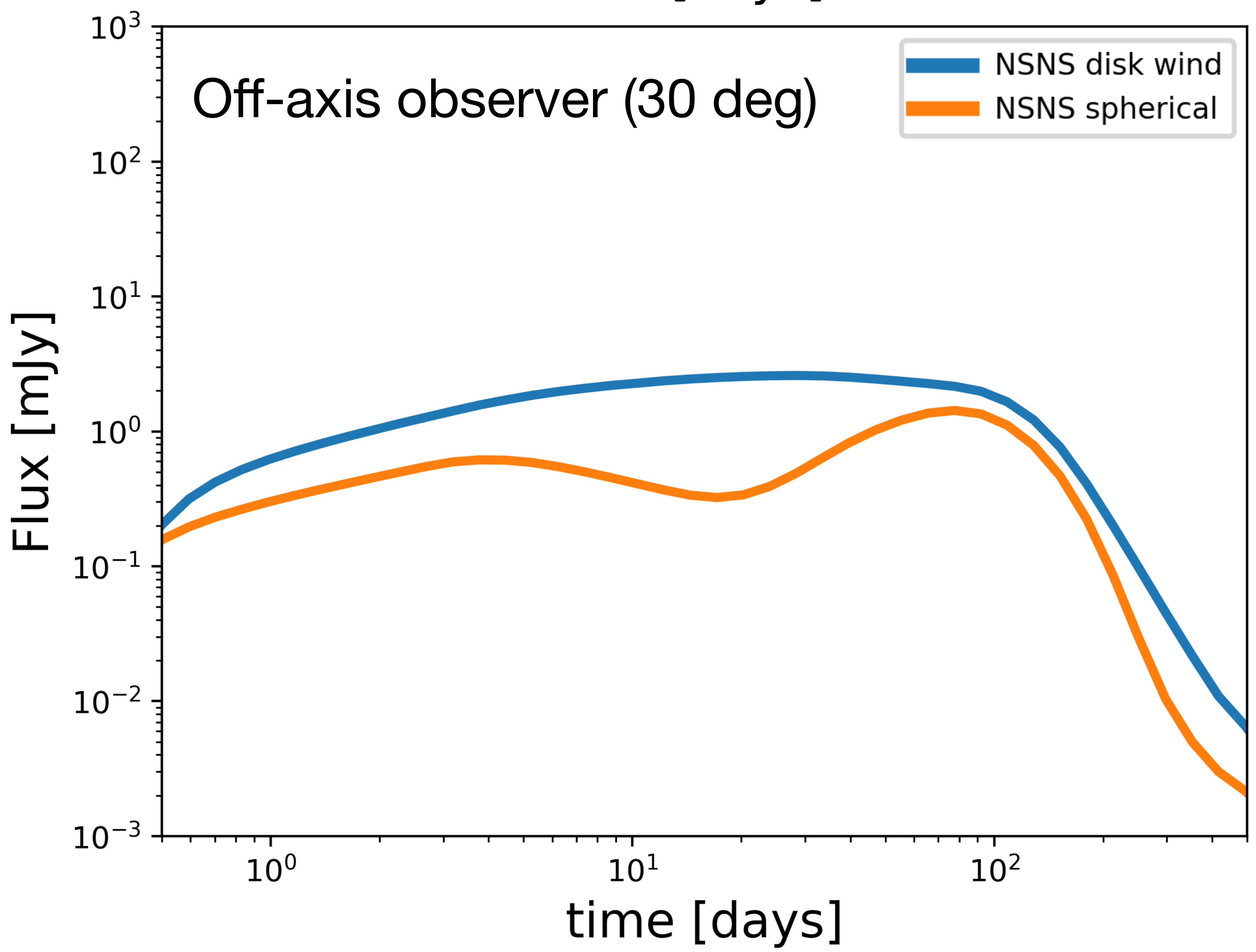
Energy evolution (jet from NSNS)



$$E = \int \left(\Gamma(\Gamma - 1)\rho c^2 + p(4\Gamma^2 - 1) \right) dV$$



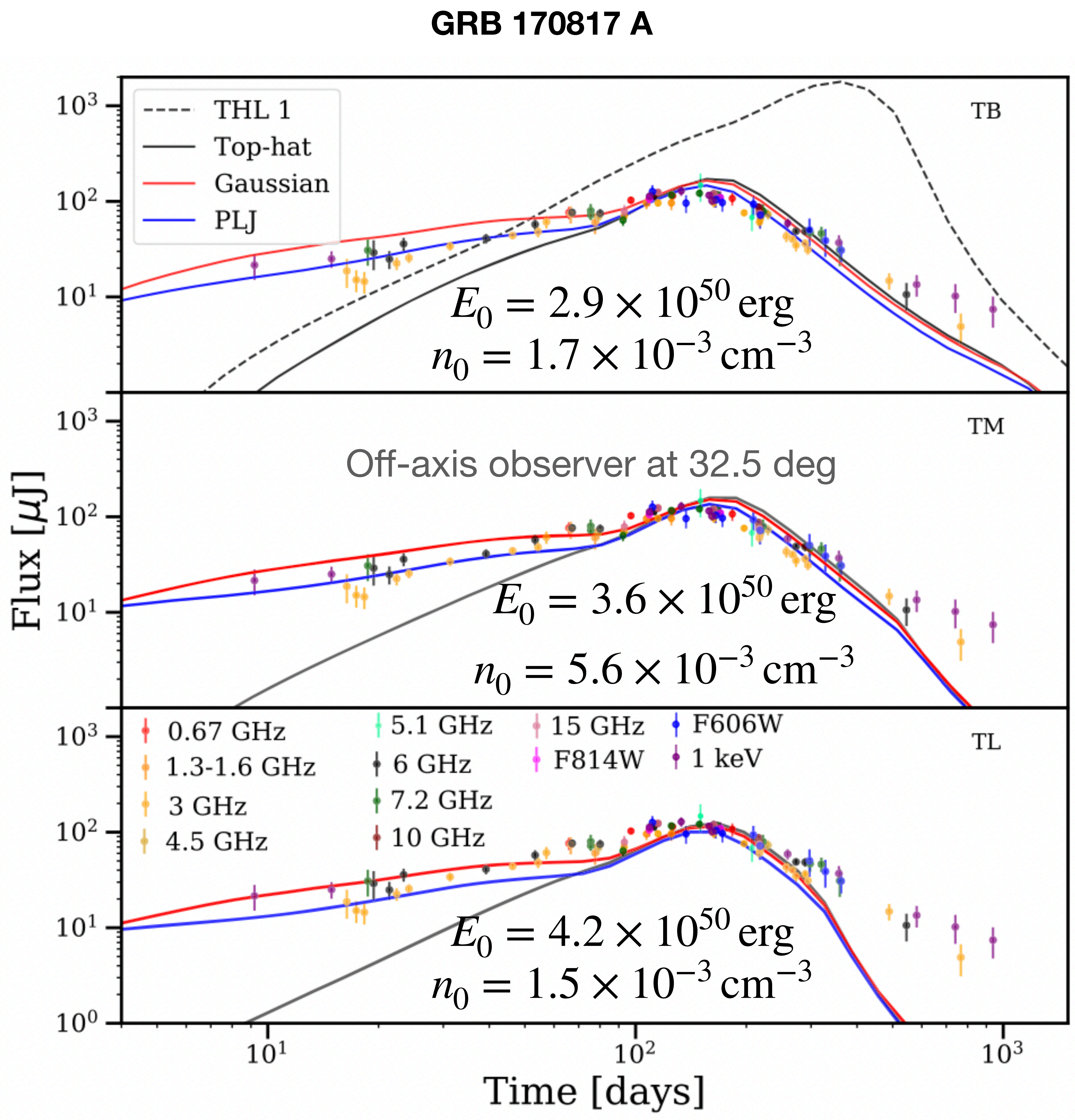




We follow the standard afterglow estimation
(Sari, Piran & Narayan 1990; Granot & Sari 2002)

- Blandford & Mckee 1976 model
- Synchrotron emission. Magnetic field amplified in the shock front.

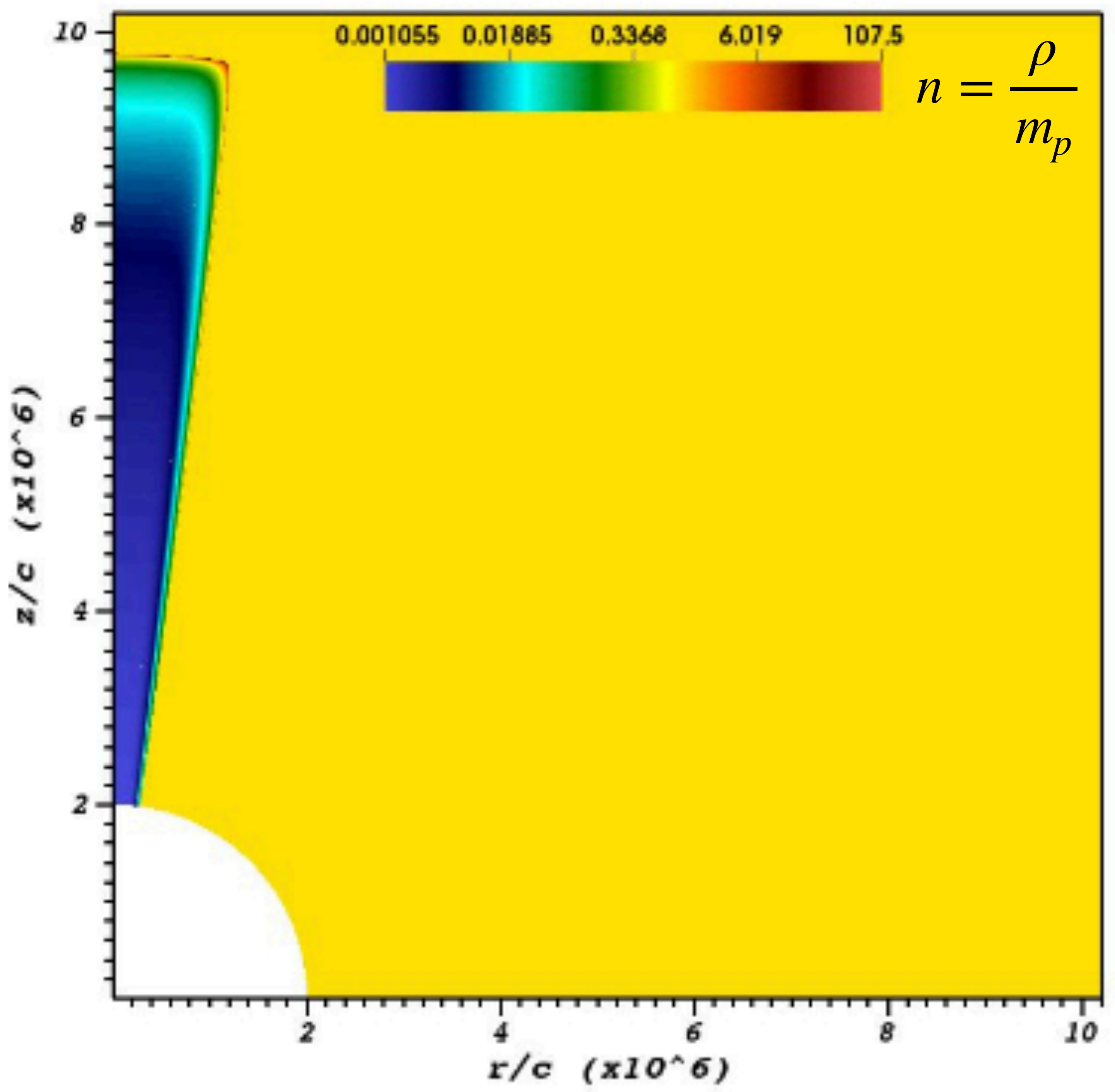
Example

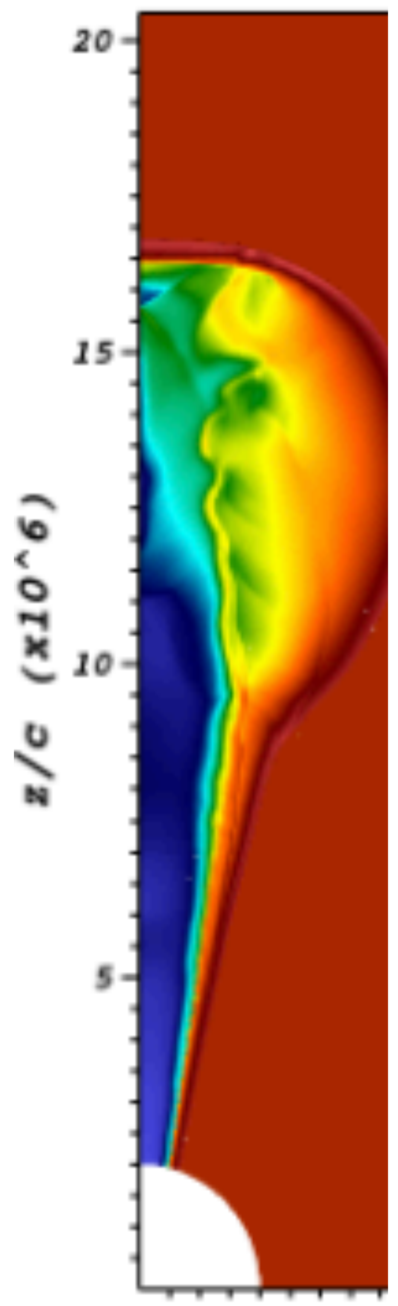


Urrutia, De Colle, Murguia-Berthier & Ramirez-Ruiz (2021)

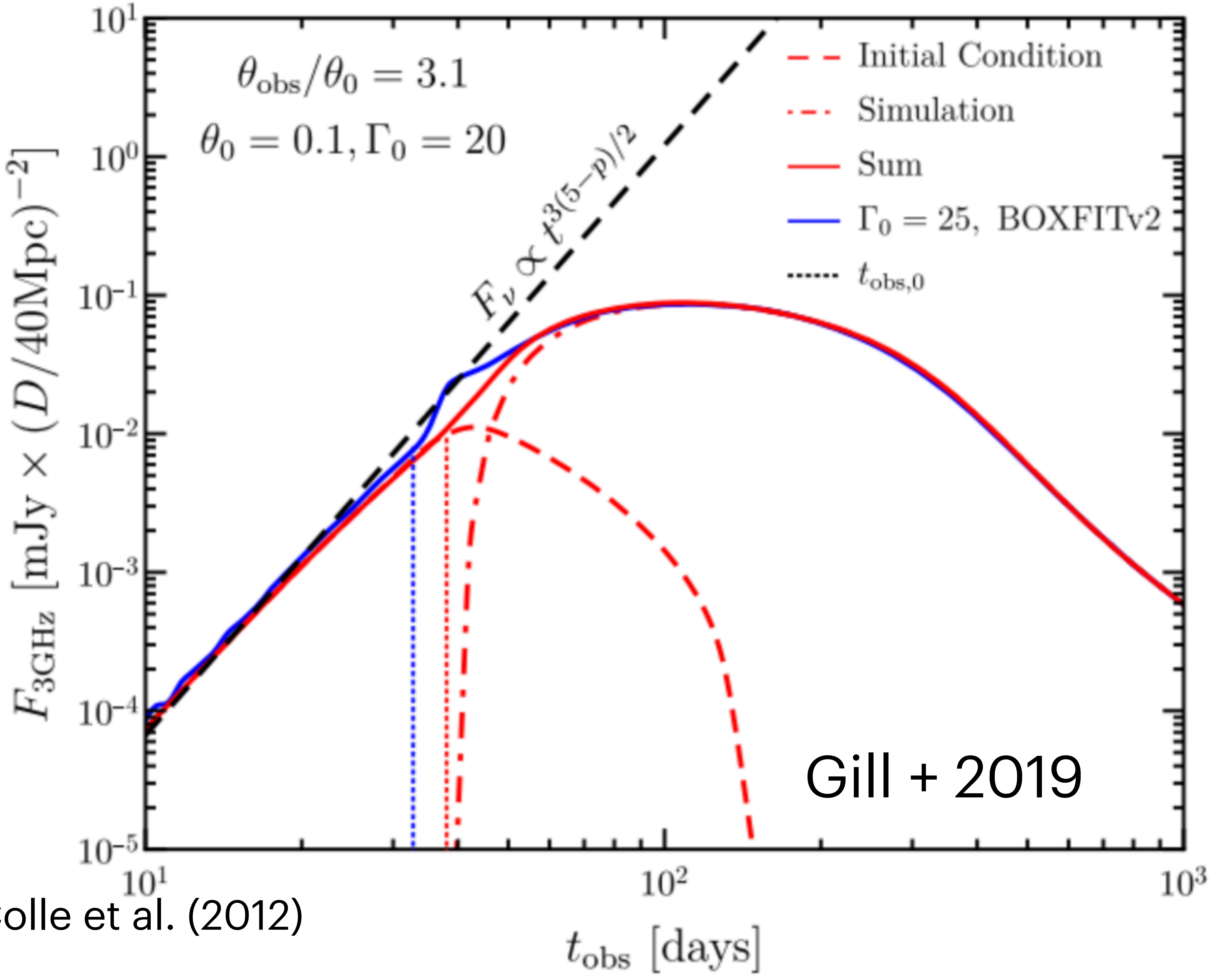
GRB jet without structure

$r \gtrsim 10^{16}\,\mathrm{cm}$



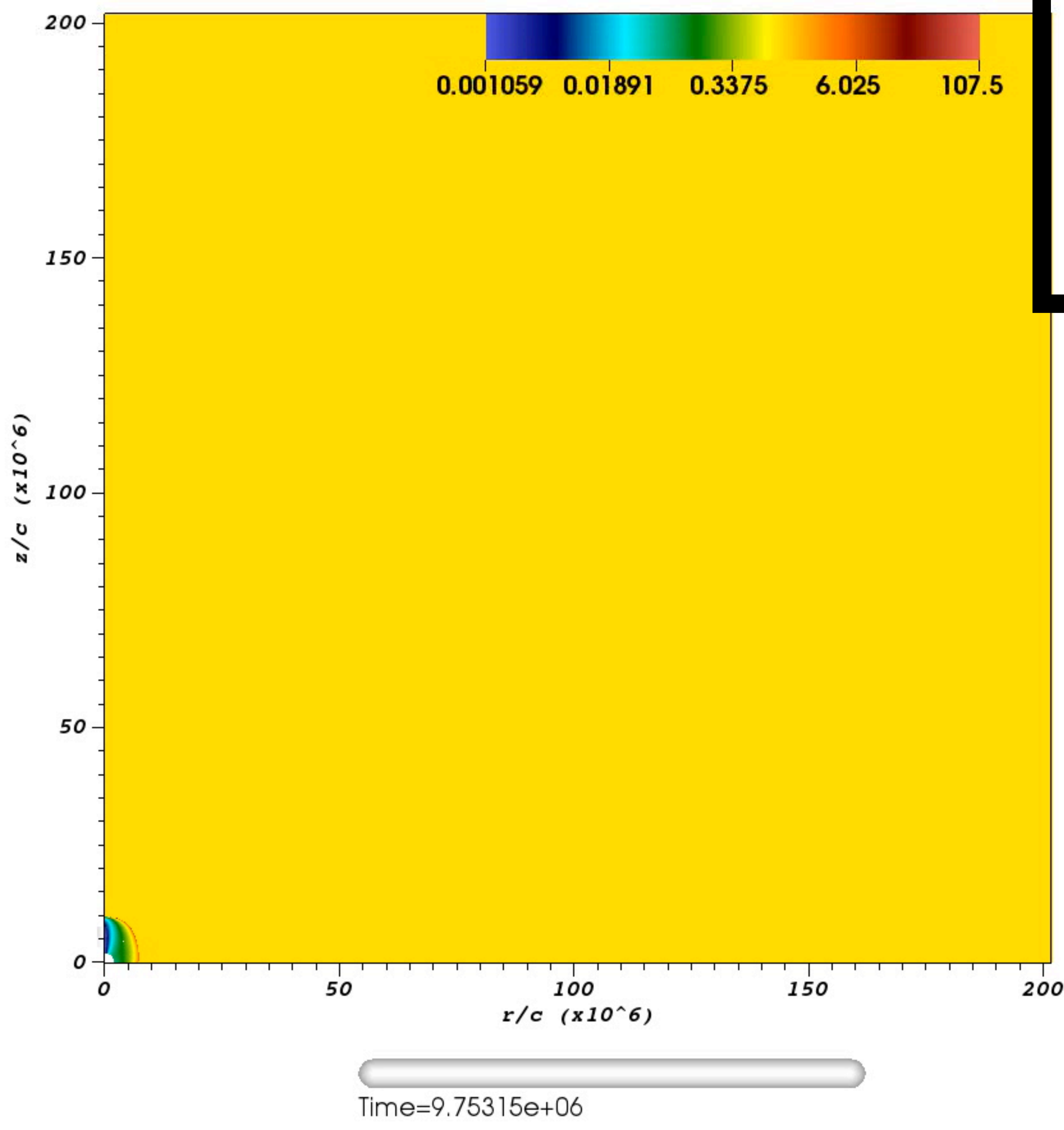


Numerical simulation of top-hat jet perform

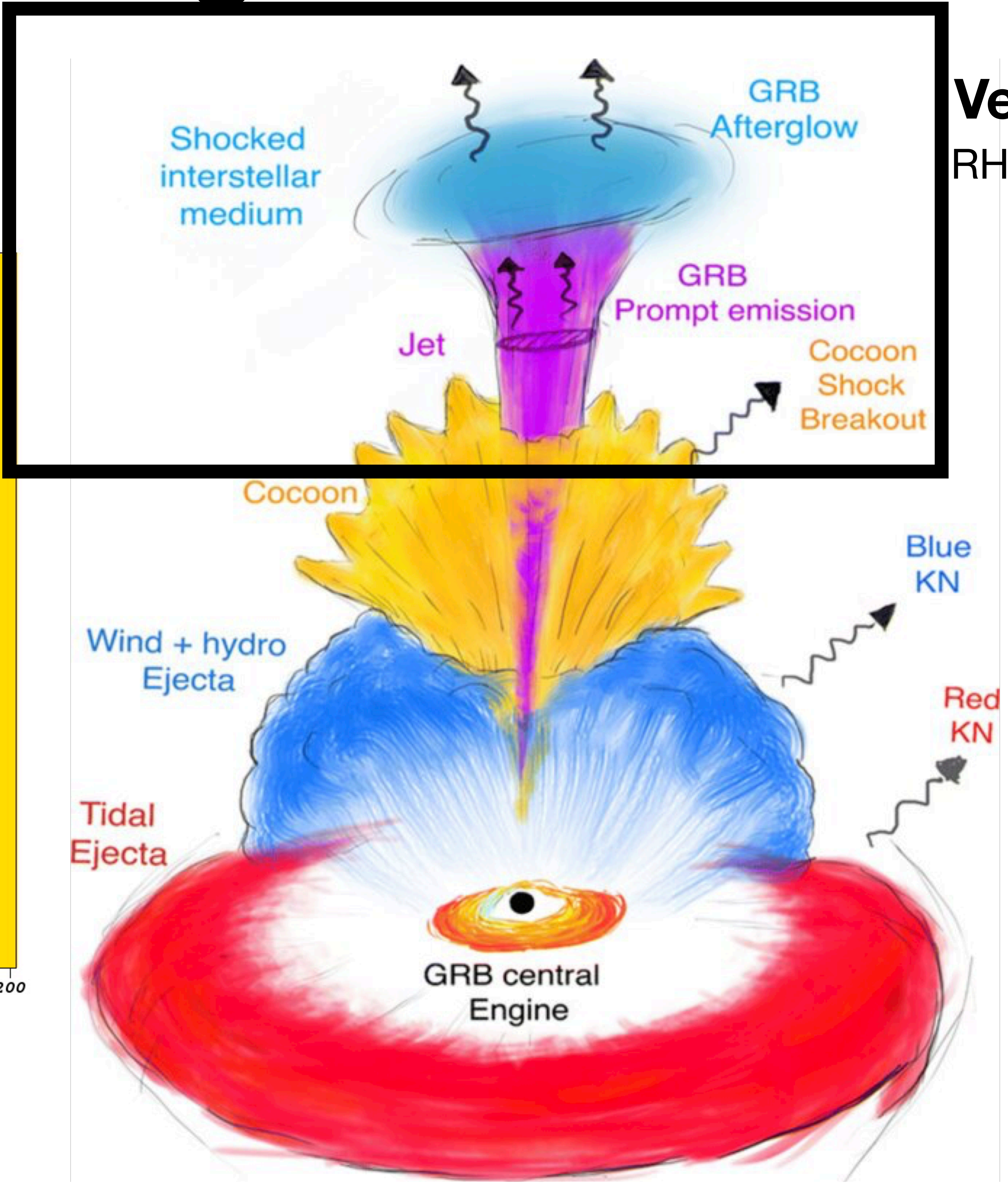


AMR simulations: MacFadyen et al. 2006, De Colle et al. (2012)

Post-merger evolution of the jet



Urrutia (in prep),
Covarruvias, De Colle & Urrutia (2023),
Gill, Granot, De Colle & Urrutia (2019)



Cartoon of GRB evolution (Stefano Ascenzi)

Very Large Scales $r \gtrsim 10^{16}\,\mathrm{cm}$

RHD simulations or Analytical extrapolations

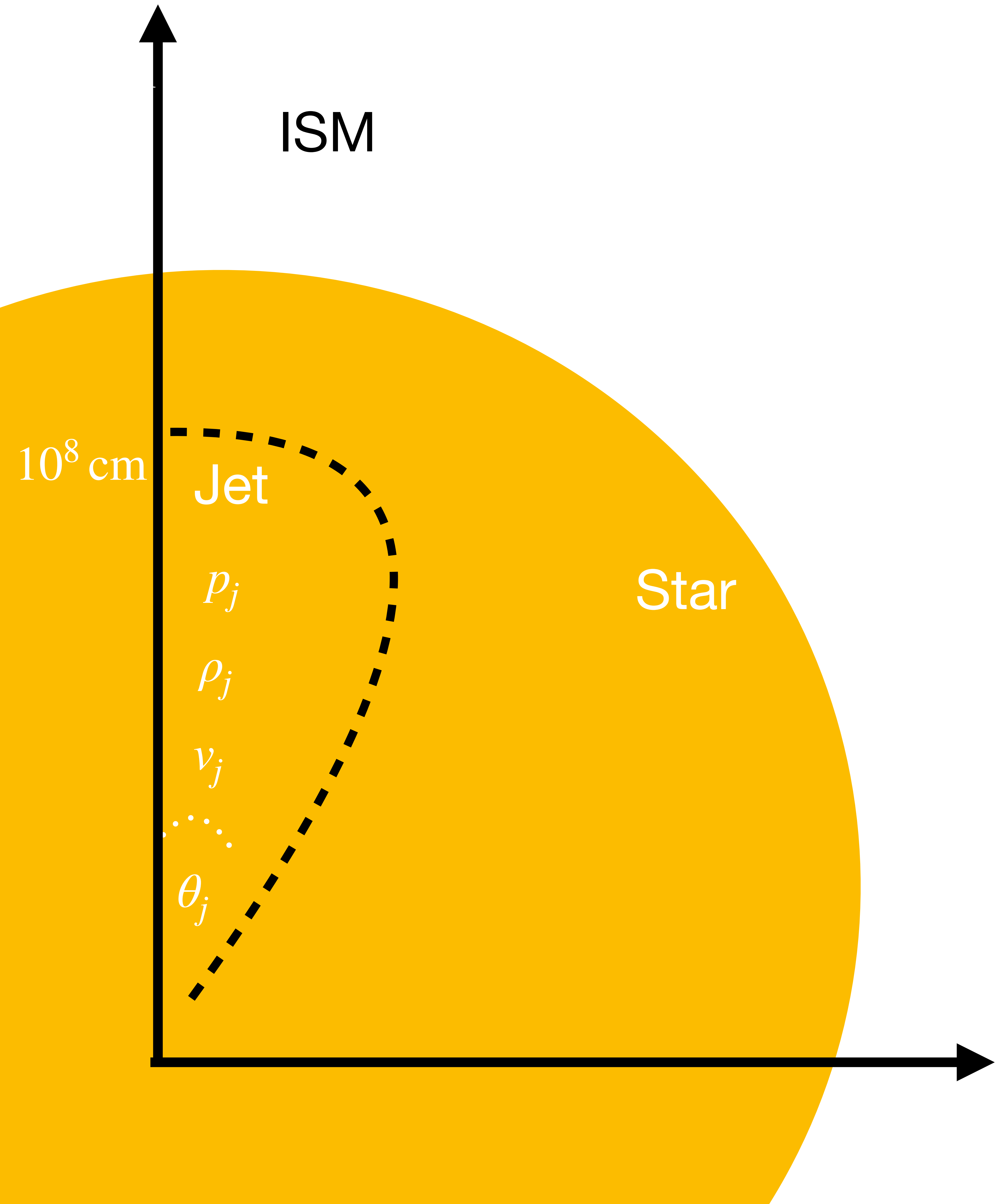
Long GRBs simulations

Objetive: Follow the jet propagation from the BH horizon to the exterior of the star

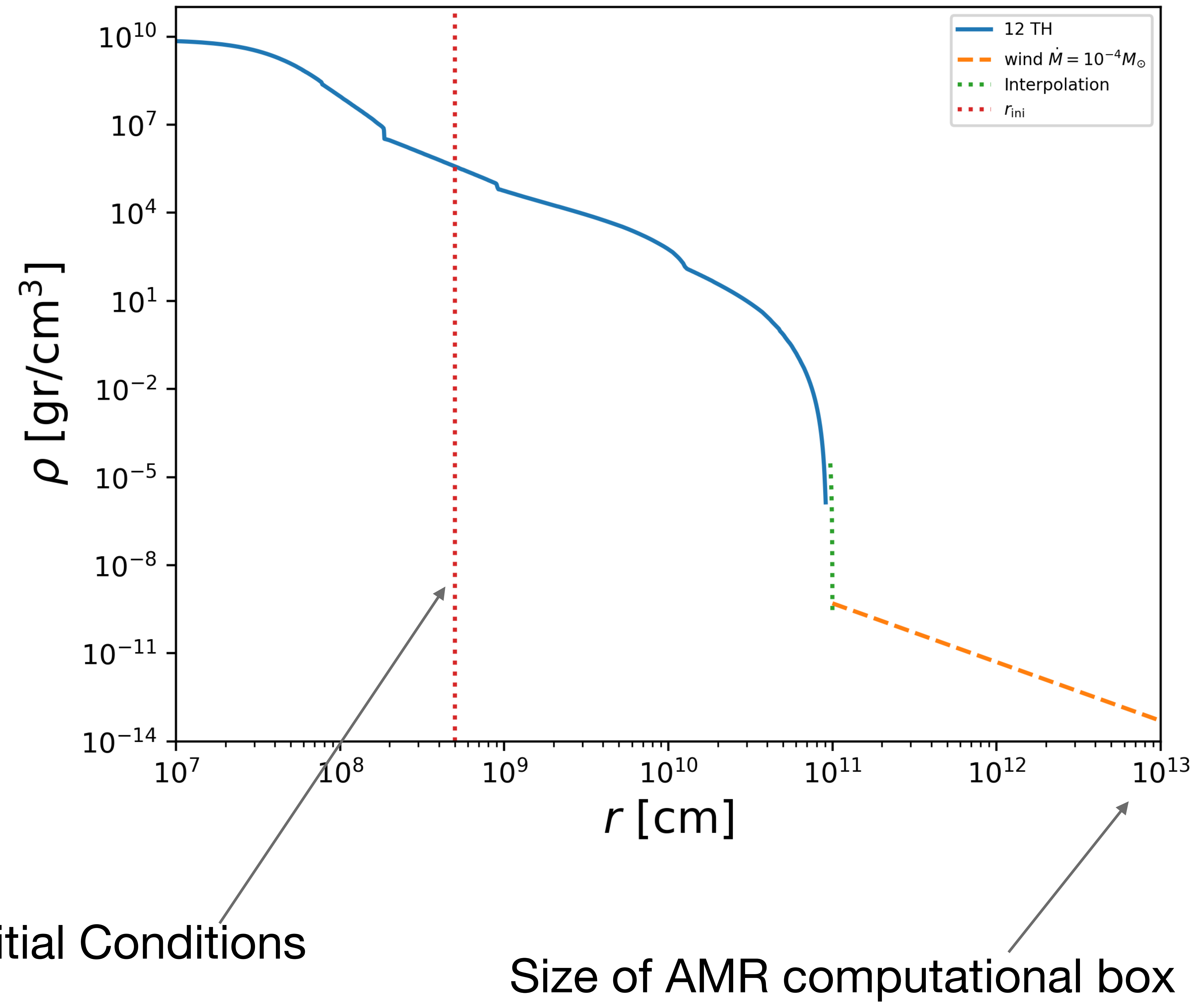
Methods: remap a pre evolved massive star to AMR GRMHD simulations

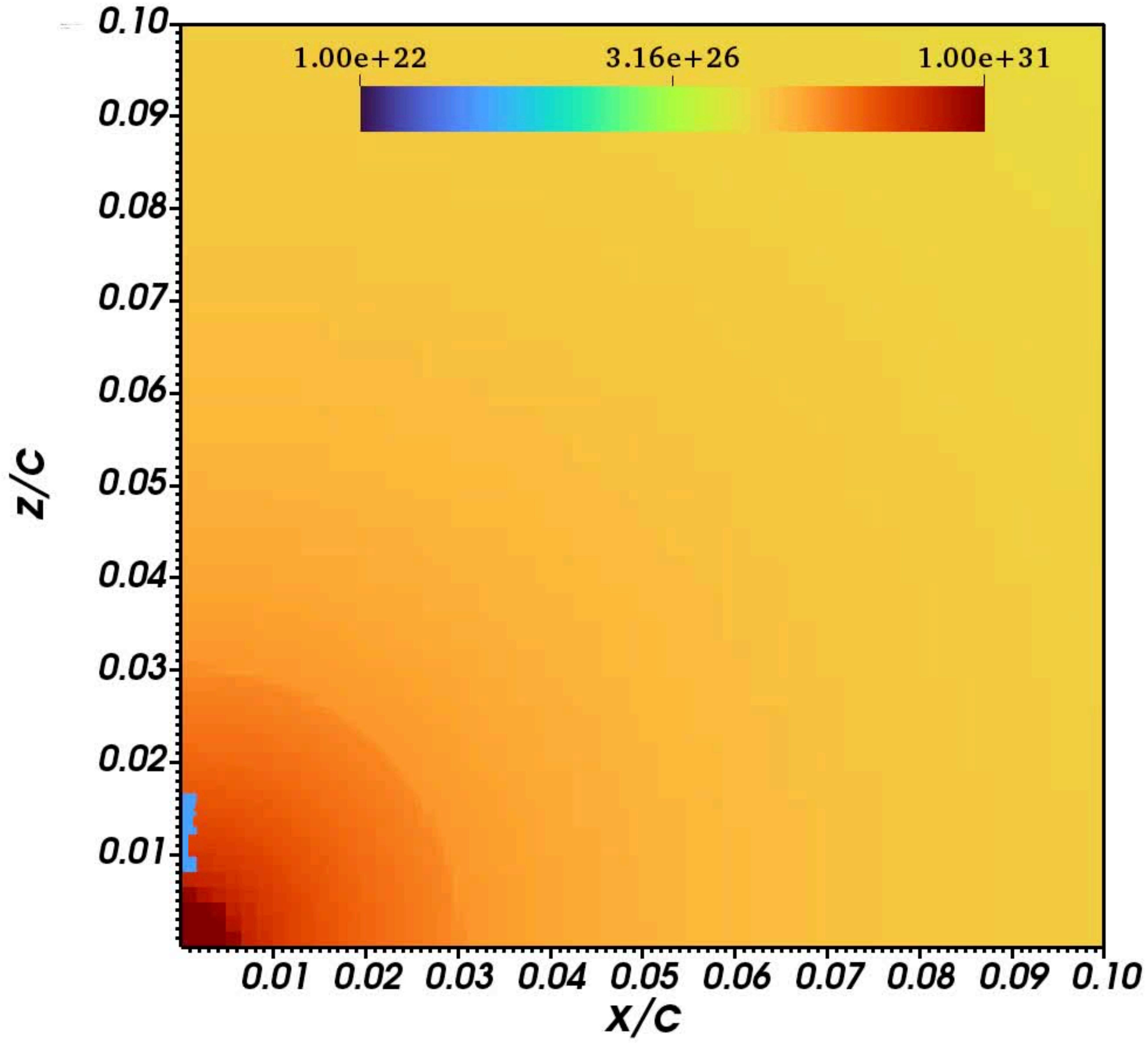
Intermediate scales (classic methodology)

The jet is imposed as a strong shock condition



- Stellar striped envelope WR (Woosley & Heger 2006)

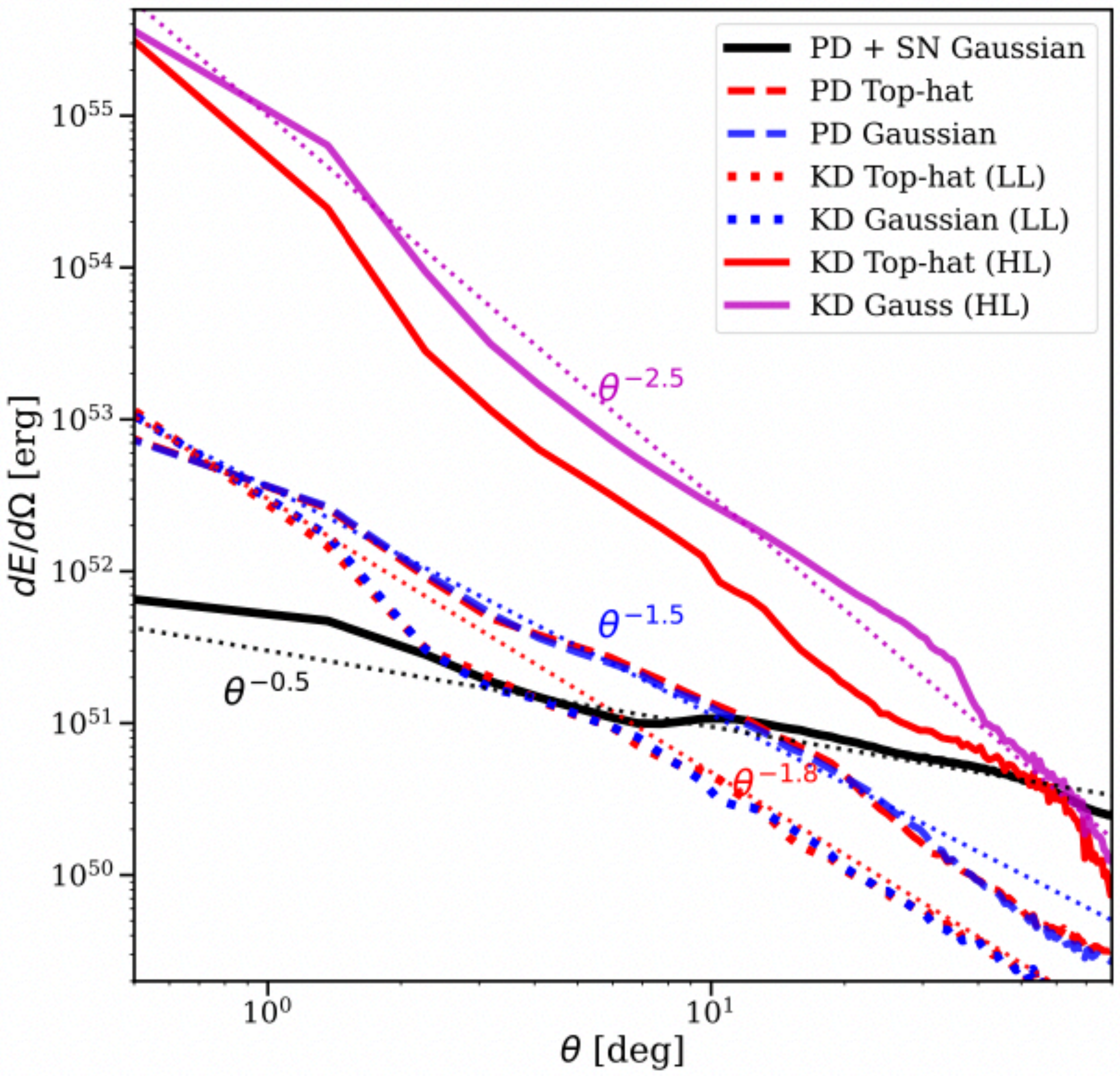




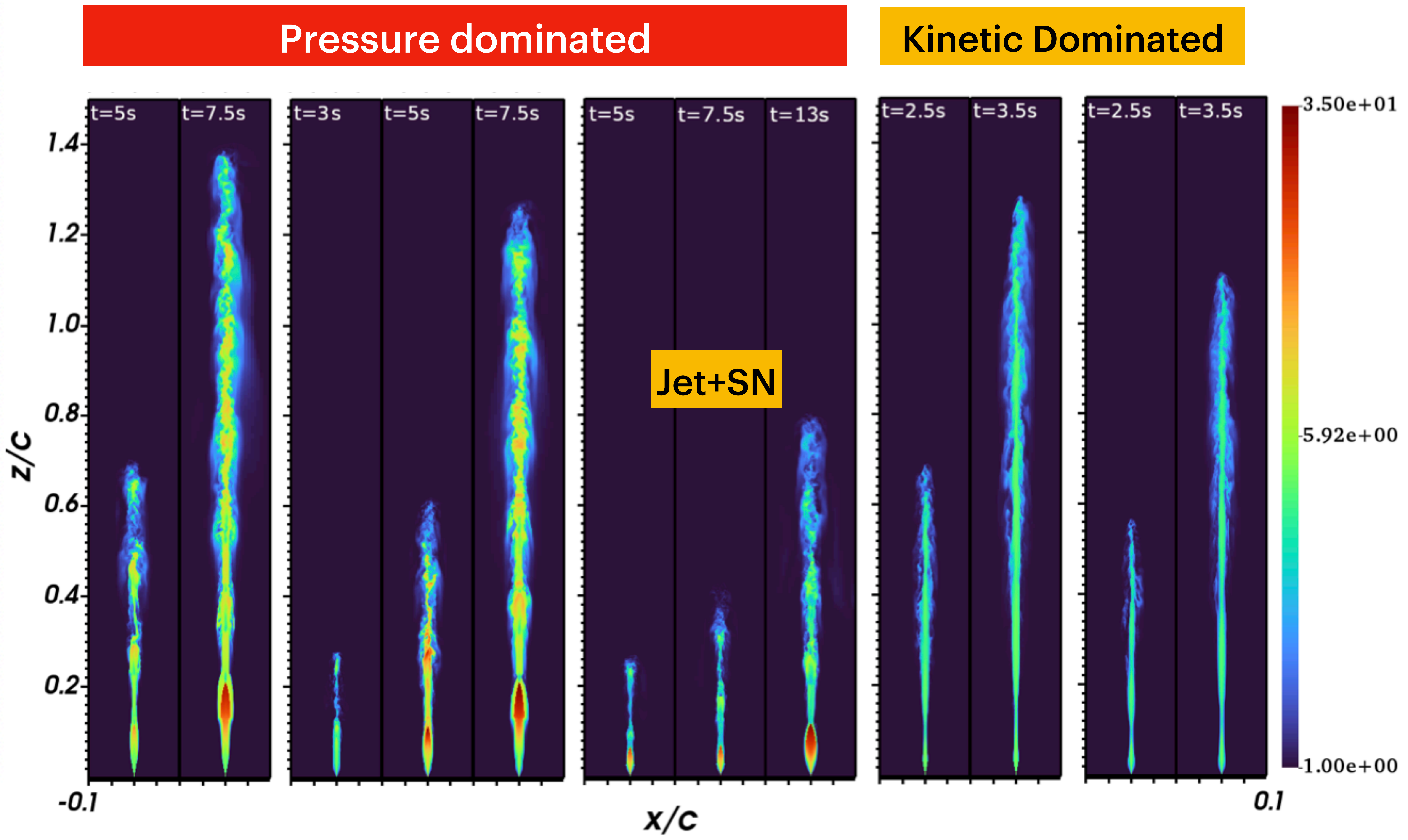
Time=0

Urrutia, De Colle, Lopez-Camara 2022

Jets initially structured



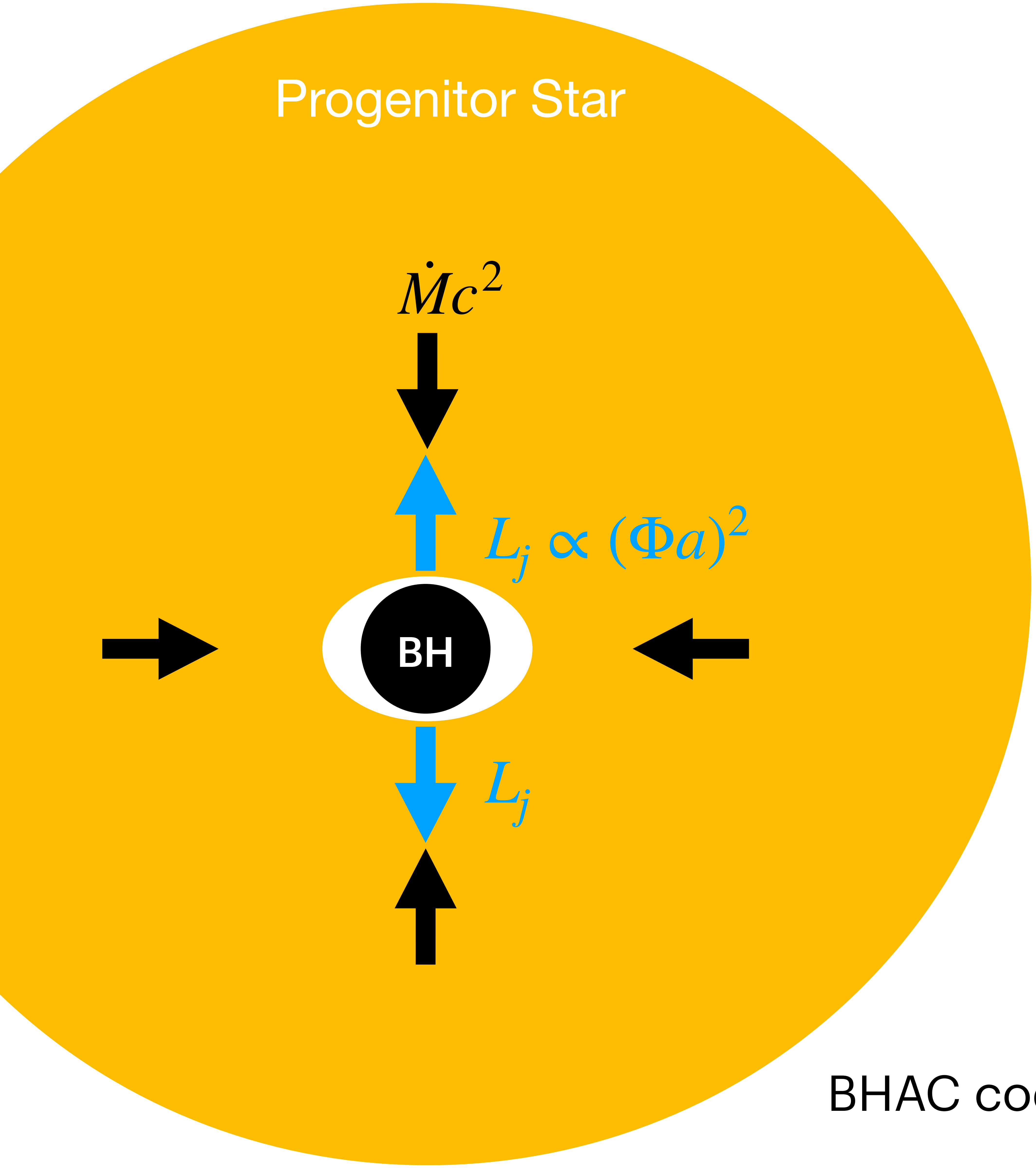
Time=0

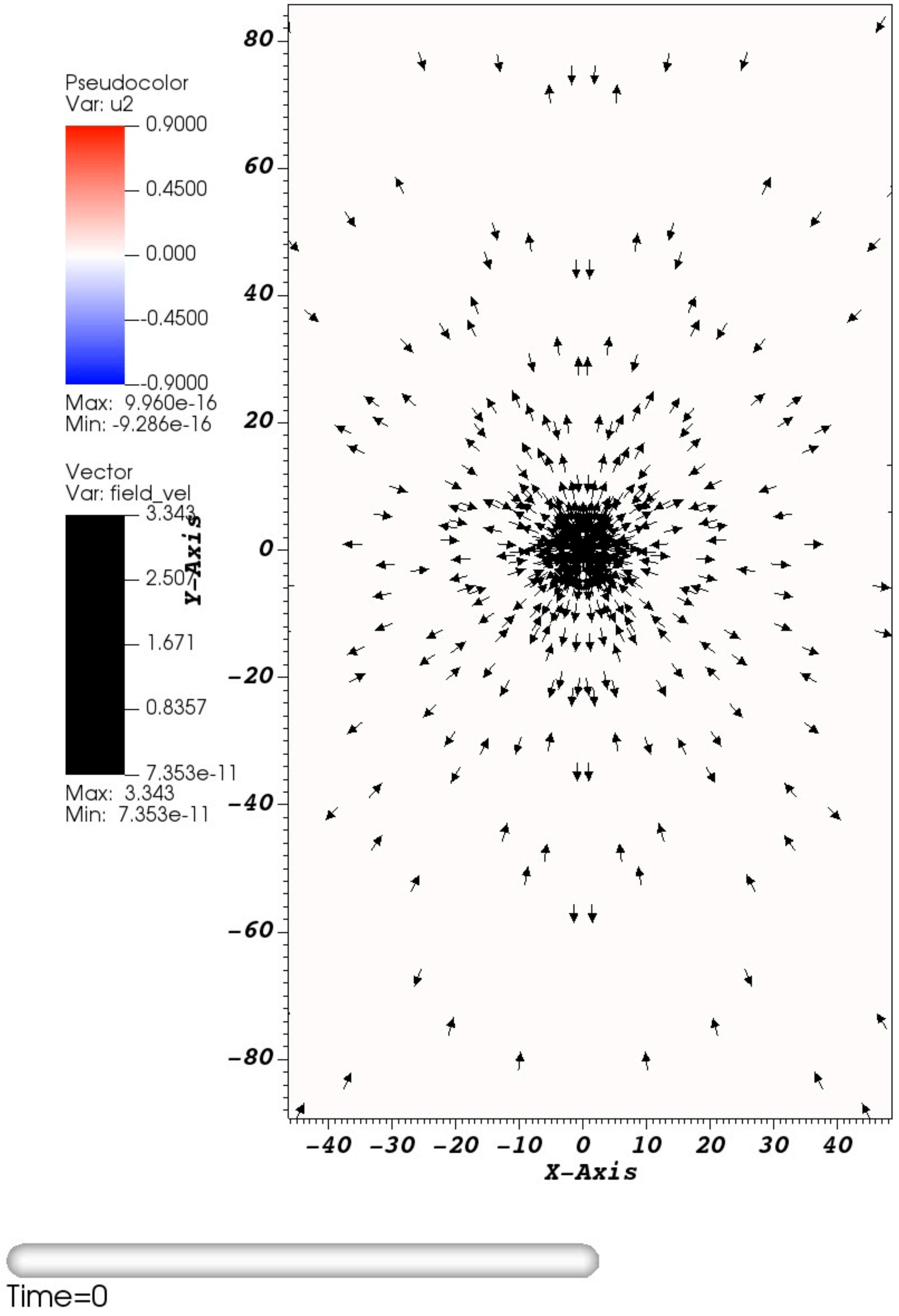


Urrutia, De Colle & Lopez-Camara 2023

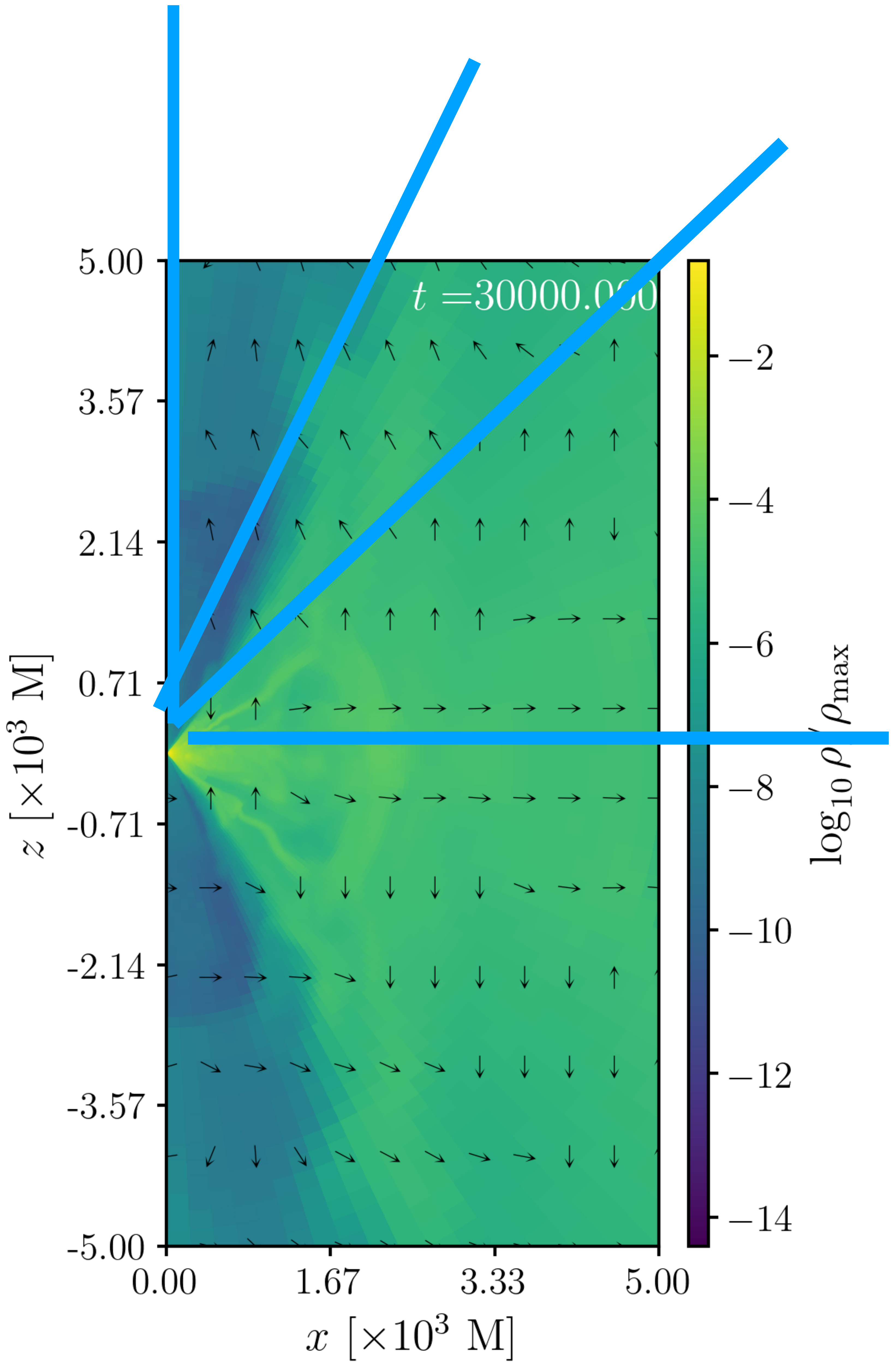
Simulations from small scales :)

Urrutia, Janiuk & Olivares in prep

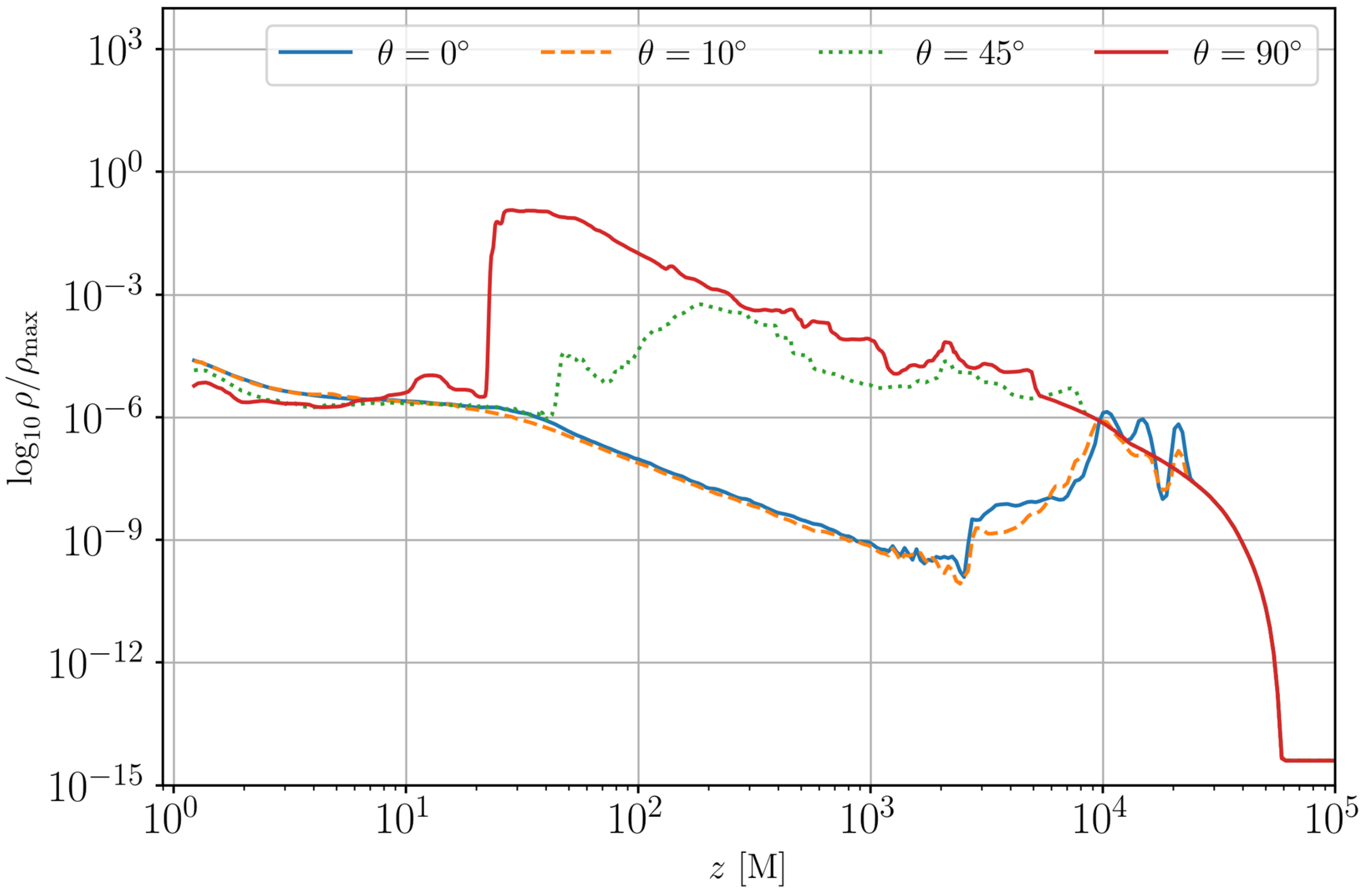




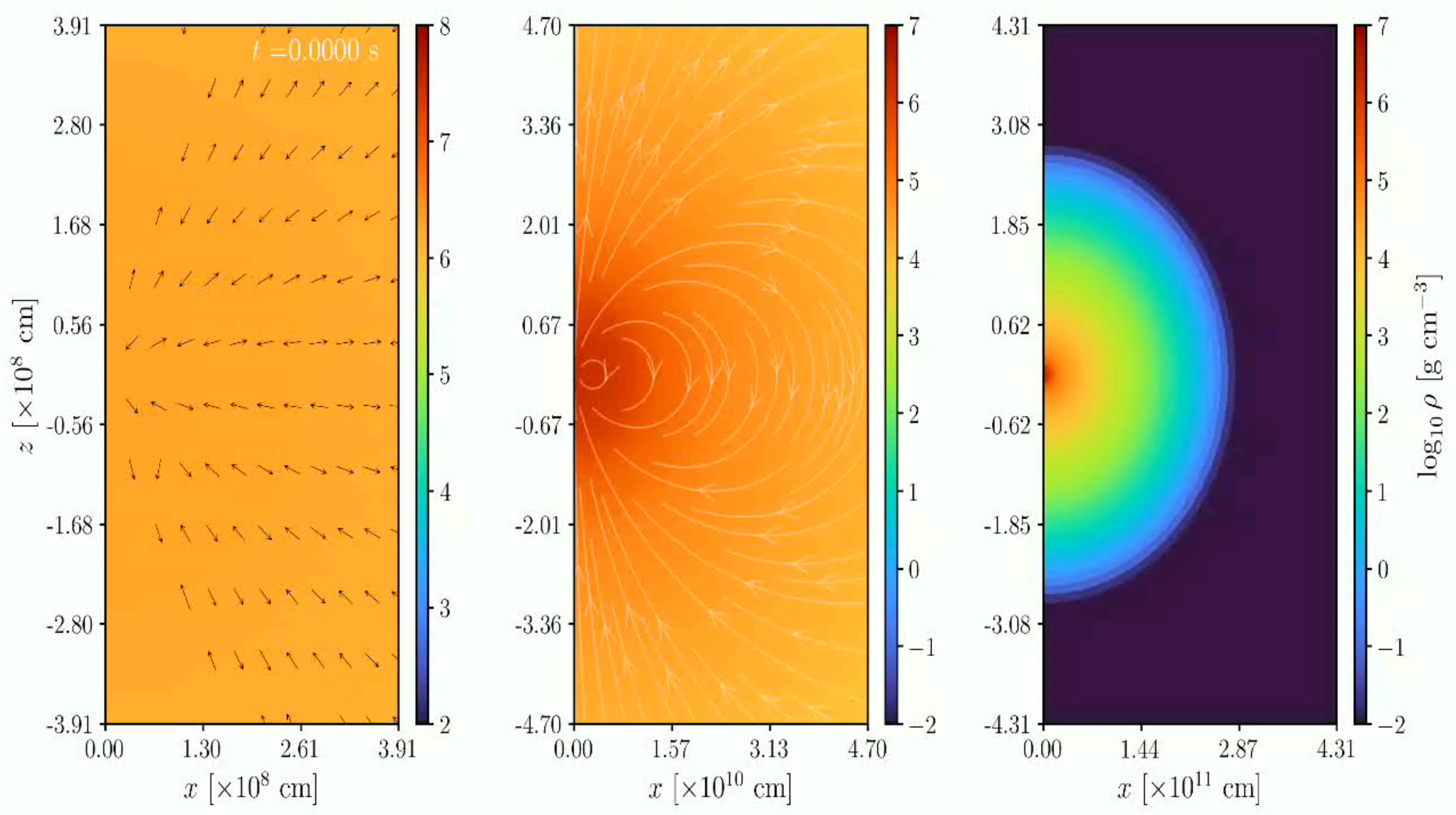
BHAC code AMR (Port, Olivares et al. 2017; Olivares, Port, et al. 2019)



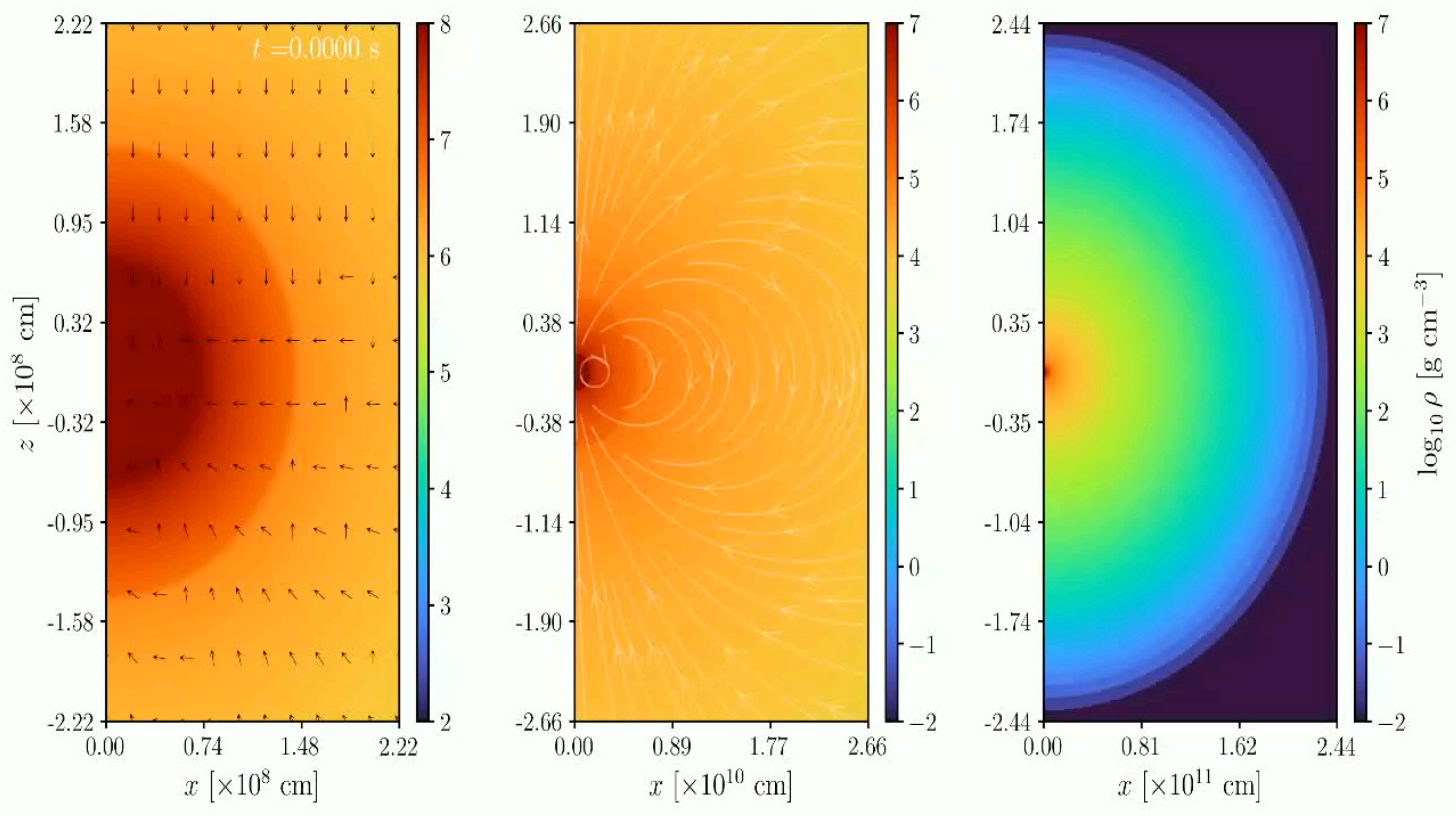
t =30000.000
5.00
3.57
2.14
0.71
-0.71
-2.14
-3.57
-5.00
0.00
1.67
3.33
5.00
z [$\times 10^3$ M]
x [$\times 10^3$ M]
-2
-4
-6
-8
-10
-12
-14
$\log_{10}\rho/\rho_{\max}$



$\theta = 0°$
$\theta = 10°$
$\theta = 45°$
$\theta = 90°$
10^3
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^0
10^1
10^2
10^3
10^4
10^5
$\log_{10}\rho/\rho_{\max}$
z [M]

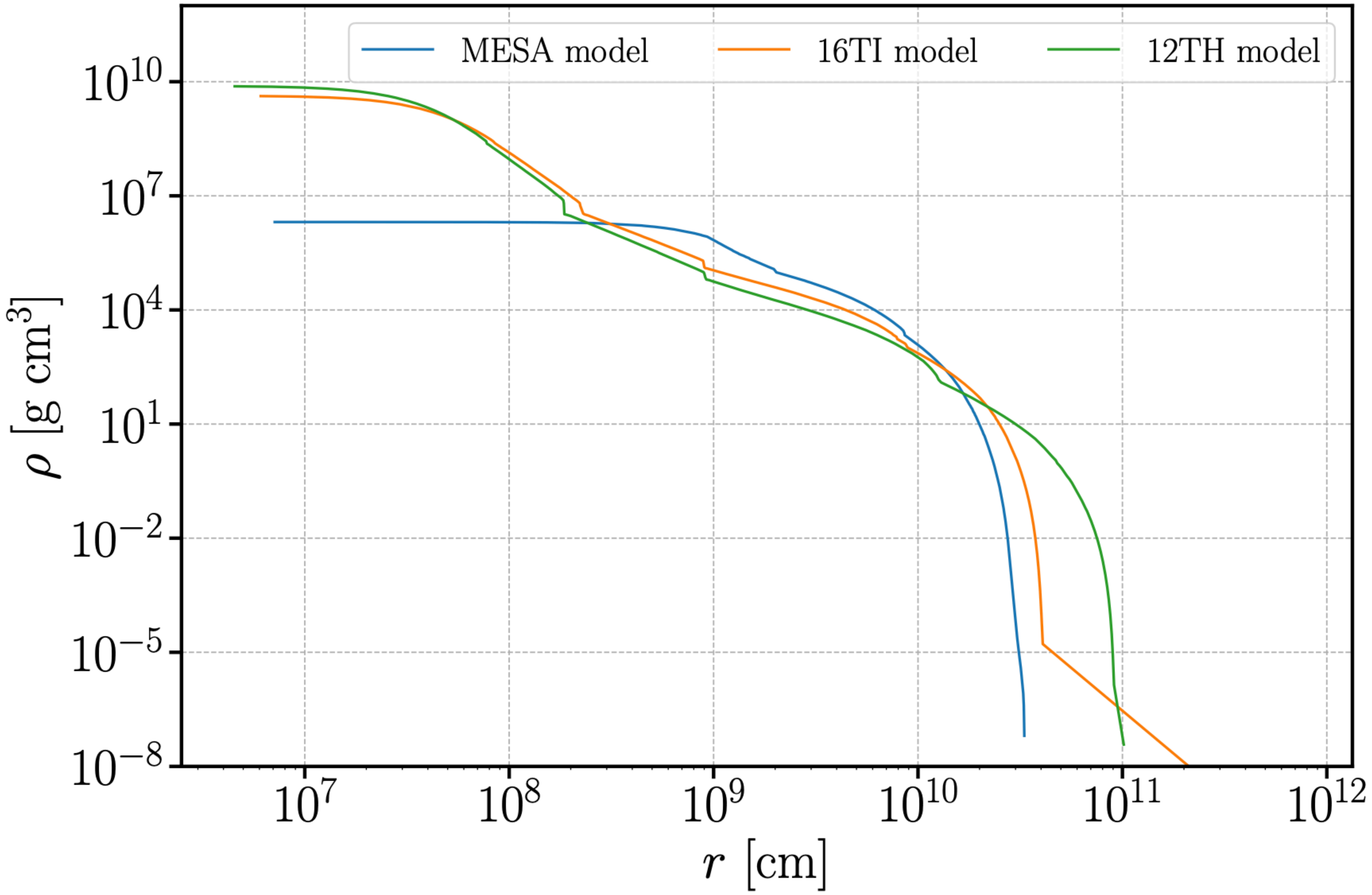


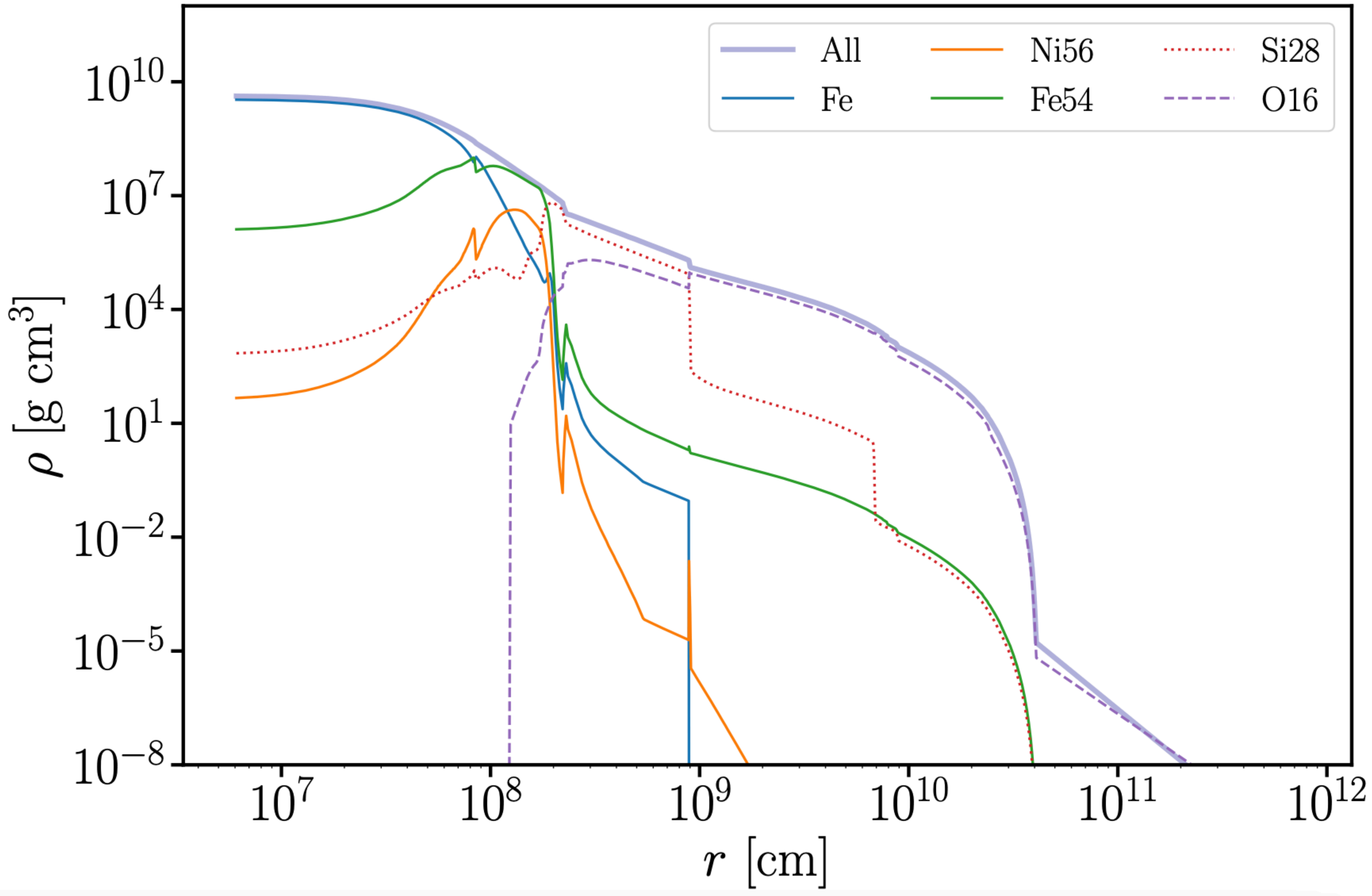
t =0.0000 s
3.91
2.80
1.68
0.56
-0.56
-1.68
-2.80
-3.91
z [$\times 10^8$ cm]
0.00
1.30
2.61
3.91
x [$\times 10^8$ cm]
8
7
6
5
4
3
2
4.70
3.36
2.01
0.67
-0.67
-2.01
-3.36
-4.70
0.00
1.57
3.13
4.70
x [$\times 10^{10}$ cm]
7
6
5
4
3
2
1
0
−1
−2
4.31
3.08
1.85
0.62
-0.62
-1.85
-3.08
-4.31
0.00
1.44
2.87
4.31
x [$\times 10^{11}$ cm]
7
6
5
4
3
2
1
0
−1
−2
$\log_{10} \rho$ [g cm^{-3}]

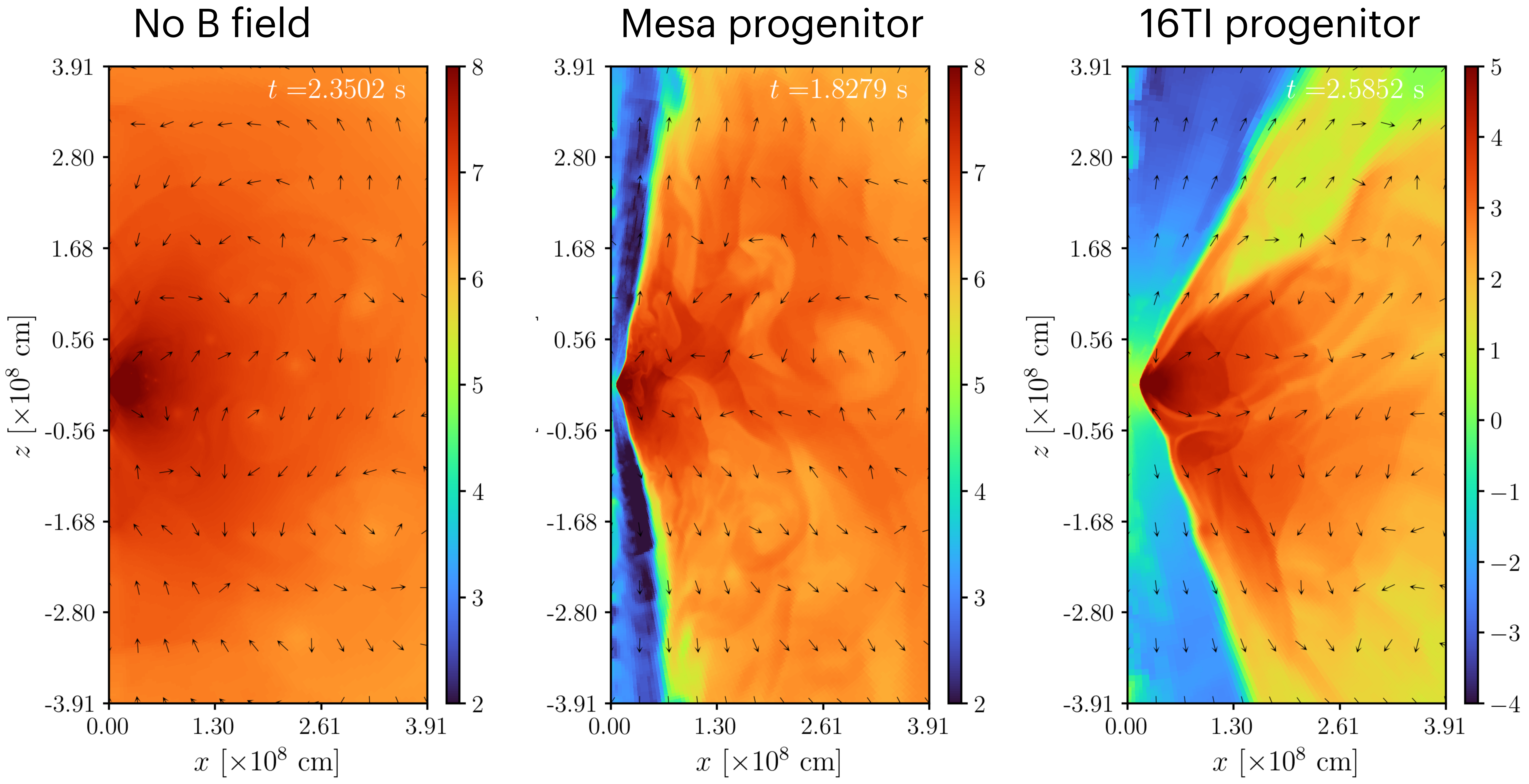


t =0.0000 s
2.22
1.58
0.95
0.32
-0.32
-0.95
-1.58
-2.22
z [×10^8 cm]
0.00
0.74
1.48
2.22
x [×10^8 cm]
8
7
6
5
4
3
2
2.66
1.90
1.14
0.38
-0.38
-1.14
-1.90
-2.66
0.00
0.89
1.77
2.66
x [×10^10 cm]
7
6
5
4
3
2
1
0
−1
−2
2.44
1.74
1.04
0.35
-0.35
-1.04
-1.74
-2.44
0.00
0.81
1.62
2.44
x [×10^11 cm]
7
6
5
4
3
2
1
0
−1
−2
log10 ρ [g cm^−3]

Three different progenitors

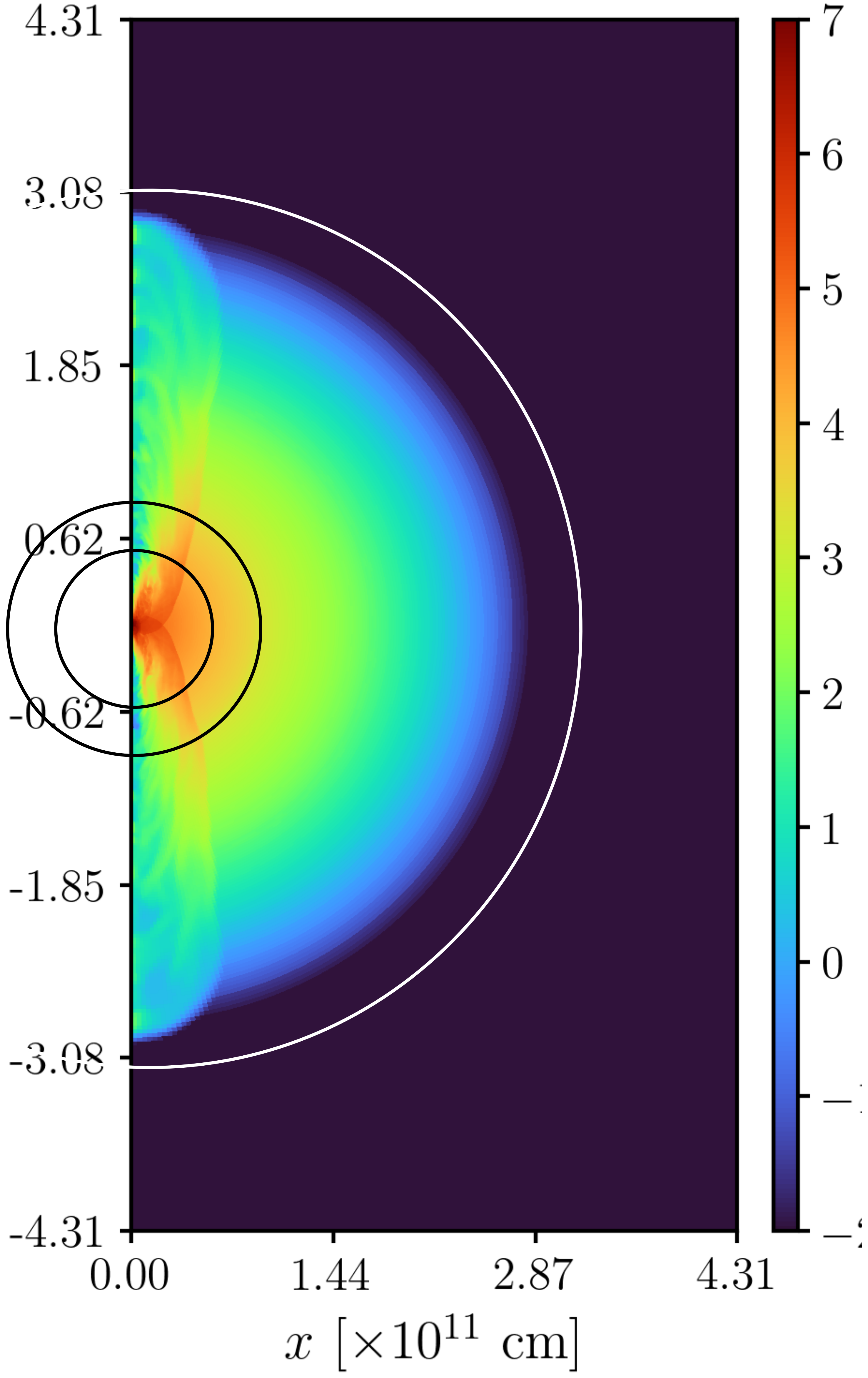


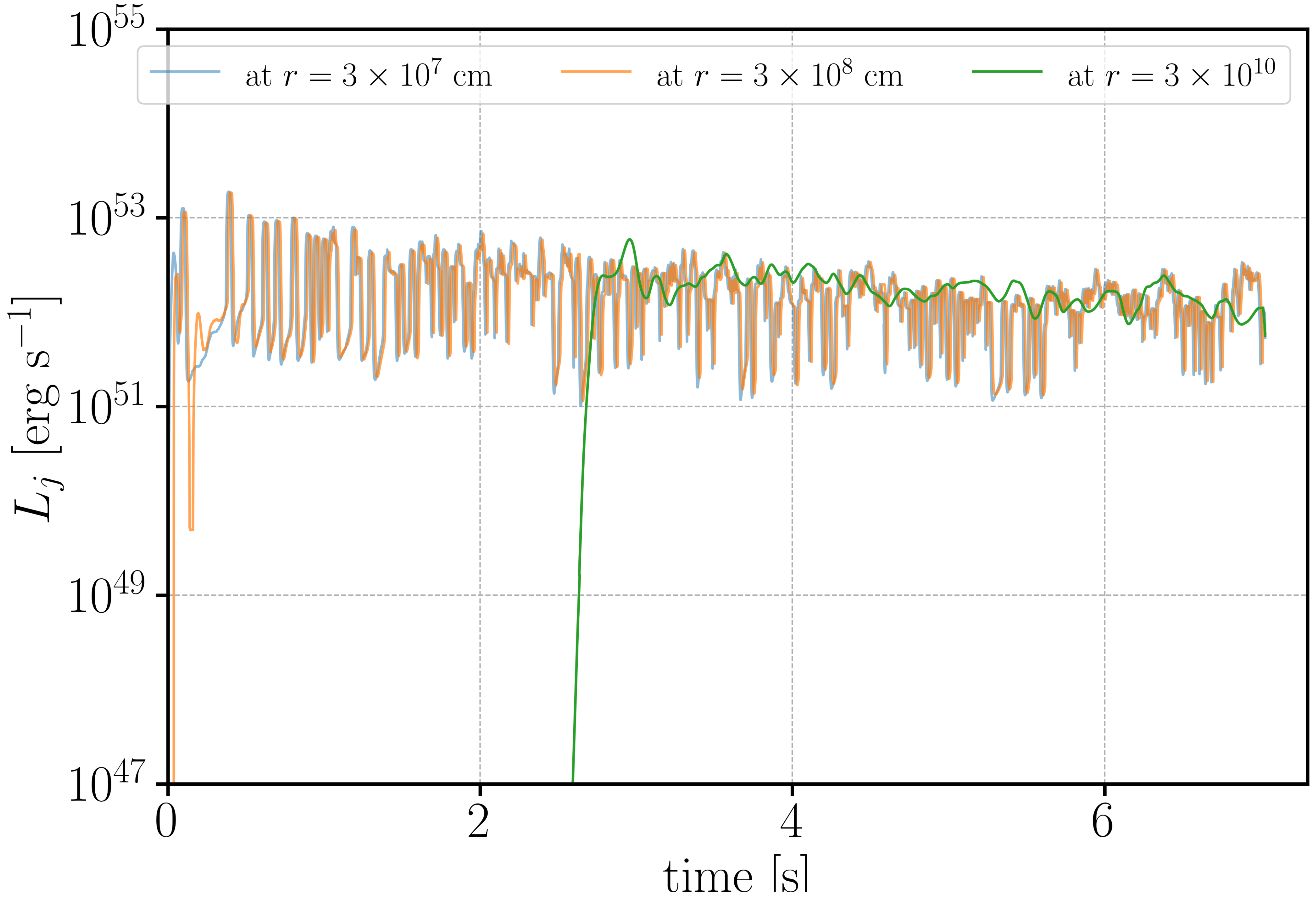




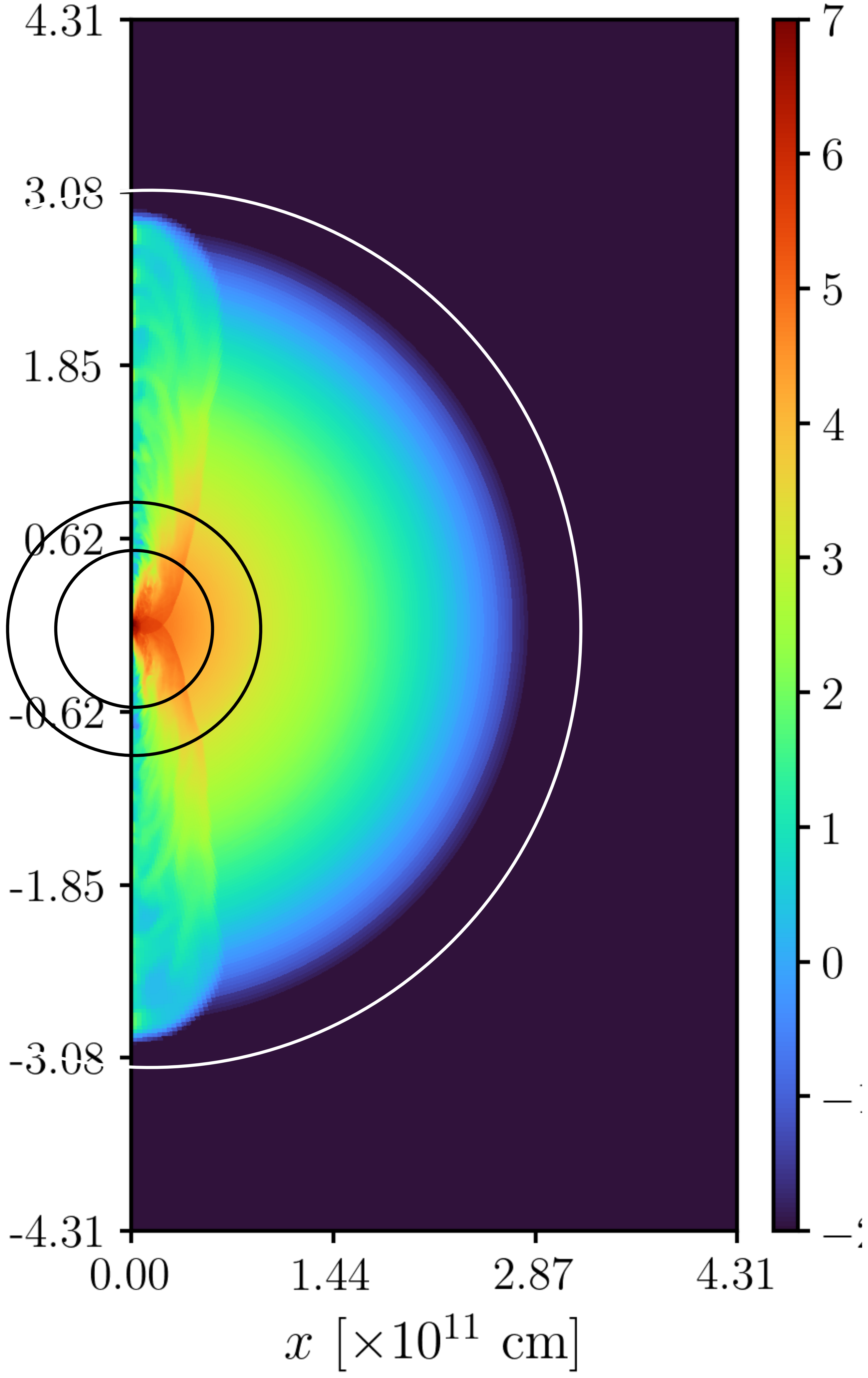
No B field
Mesa progenitor
16TI progenitor
t =2.3502 s
t =1.8279 s
t =2.5852 s
z [$\times 10^8$ cm]
x [$\times 10^8$ cm]
3.91
2.80
1.68
0.56
-0.56
-1.68
-2.80
-3.91
0.00
1.30
2.61
3.91

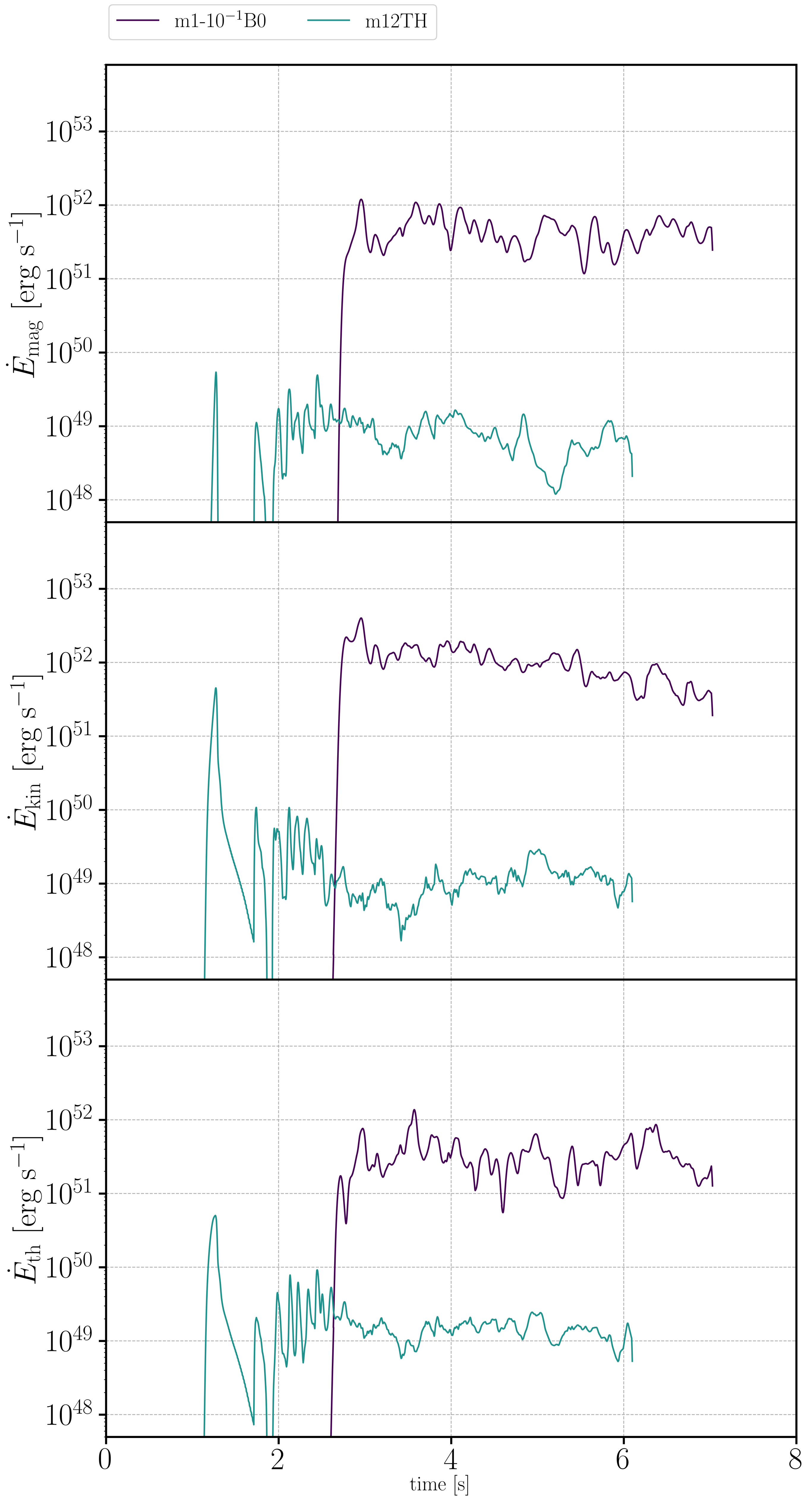
Jet variability at different regions





Energy components after breakout

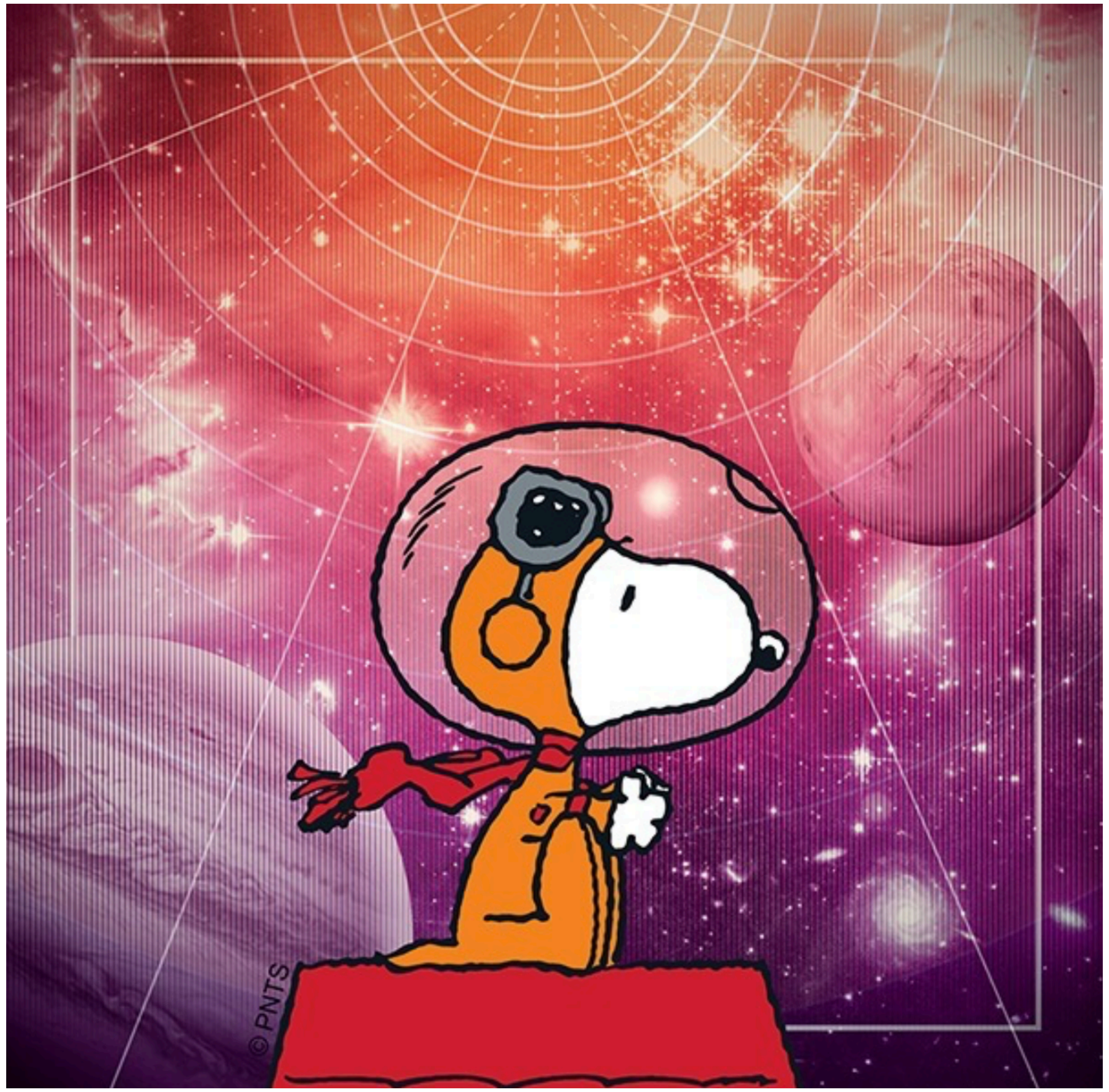




Conclusions

- **Short GRB simulations:**
  - We include self-consistent disk winds to large scale simulations
  - After the jet interaction, the energy structure, cocoon expansion presents substantial changes with respect to usual homologous models
  - The collimation of the jet is modified by the pressure balance (self-consistent with r-process)
- **Long GRB simulations:**
  - The structure of the progenitor affects, magnetization and properties of the central engine such as disc formation
  - Luminosities and accretion rates were affected and the evolution of each energy component
- **Both:**
  - The interaction of the jet with the progenitor environment determines whether the structure is conserved from small to large scales. Therefore, simulations are necessary at least at the scales of progenitor environments

Dziękuję - Thank you! - ¡Gracias!



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