Numerical simulations of Short and Long Gamma Ray bursts

Gerardo Urrutia

A. Janiuk, F. Nouri, B. James and H. Olivares

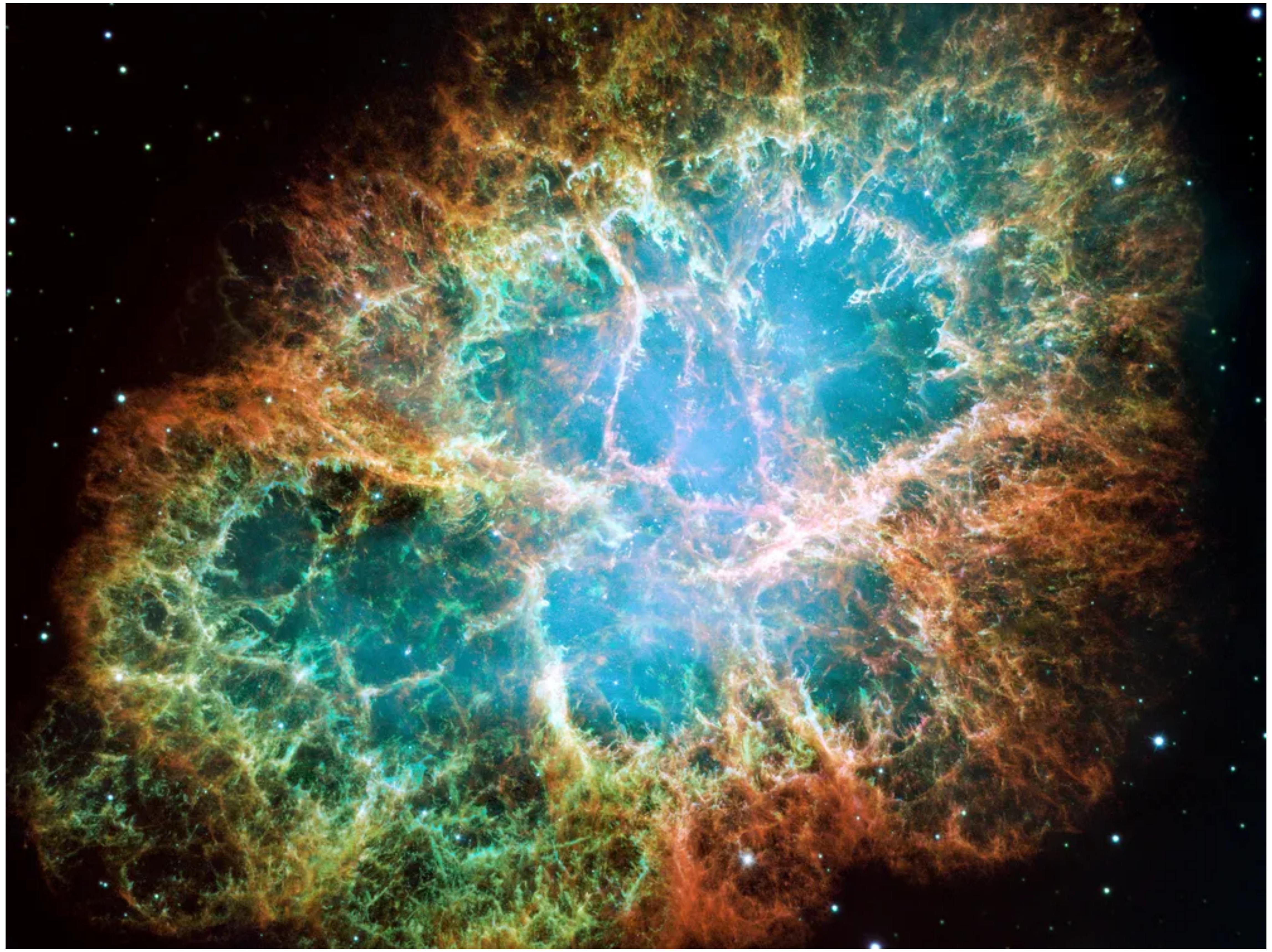
Centre for Theoretical Physics PAS, Warsaw, Poland

gurrutia@cft.edu.pl

KU KDM conference, Zakopane, March 2024

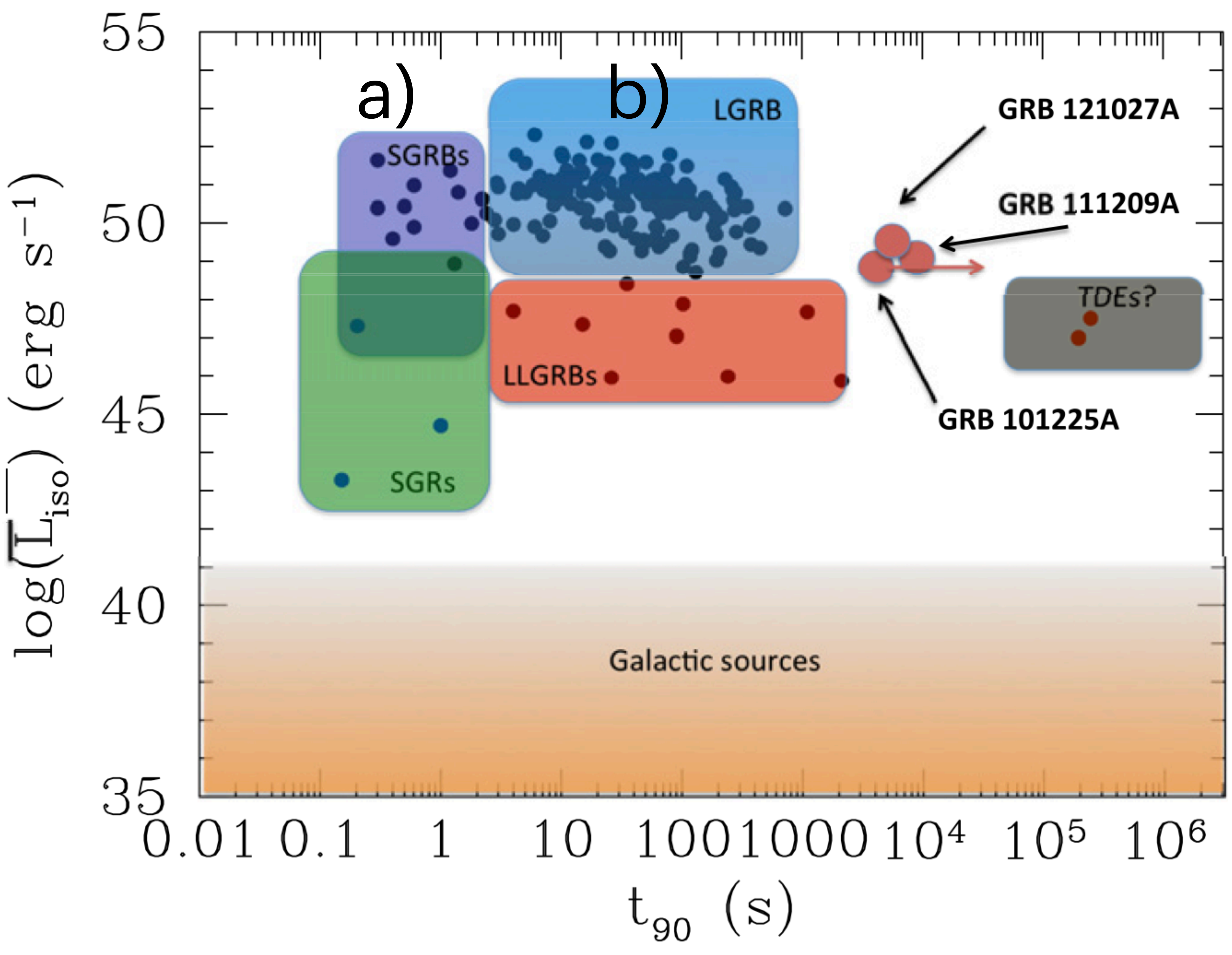
Cosmic Explosions

HH221 by JWST Telescope

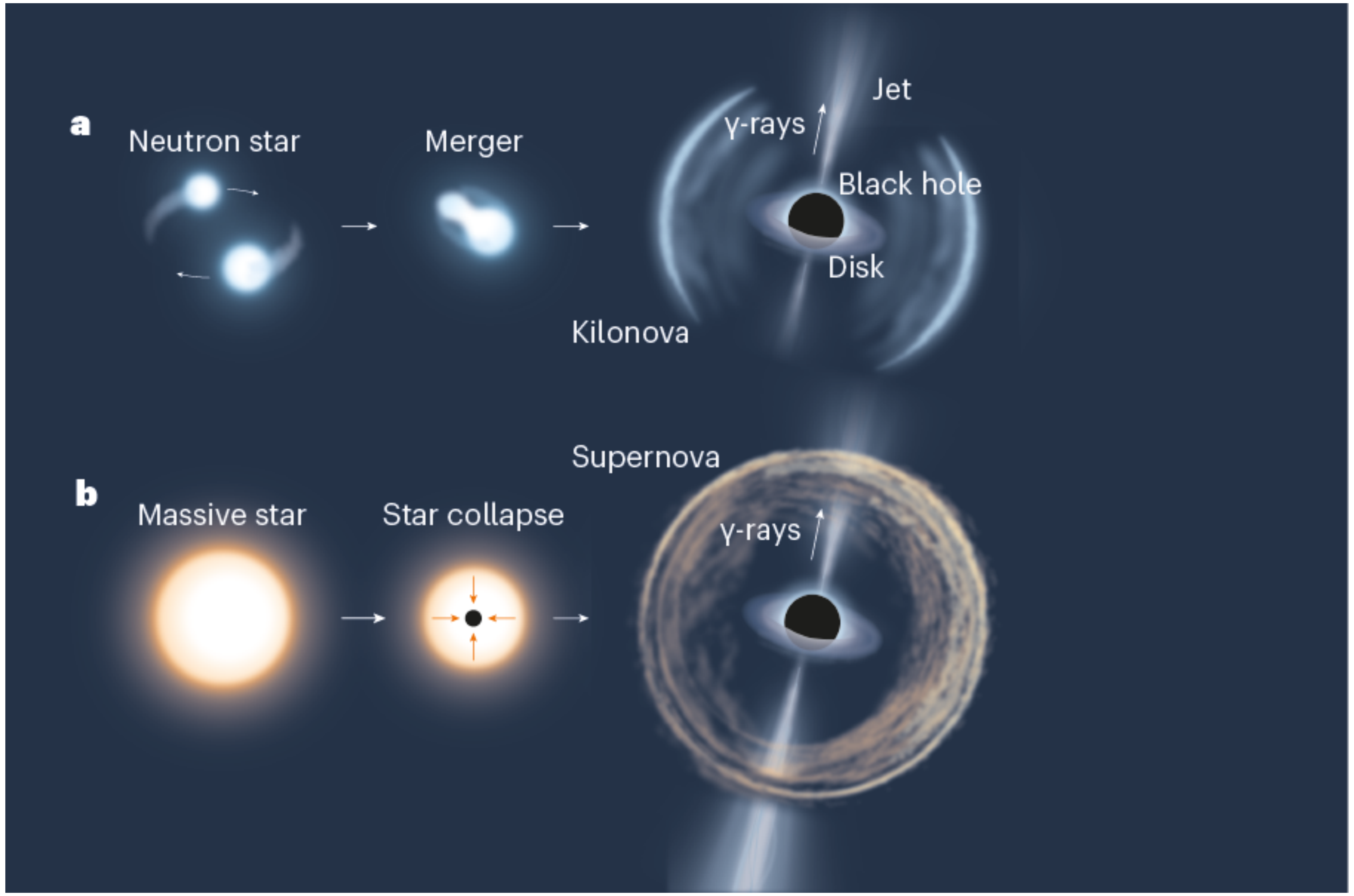


Crab Nebula by Hubble Telescope

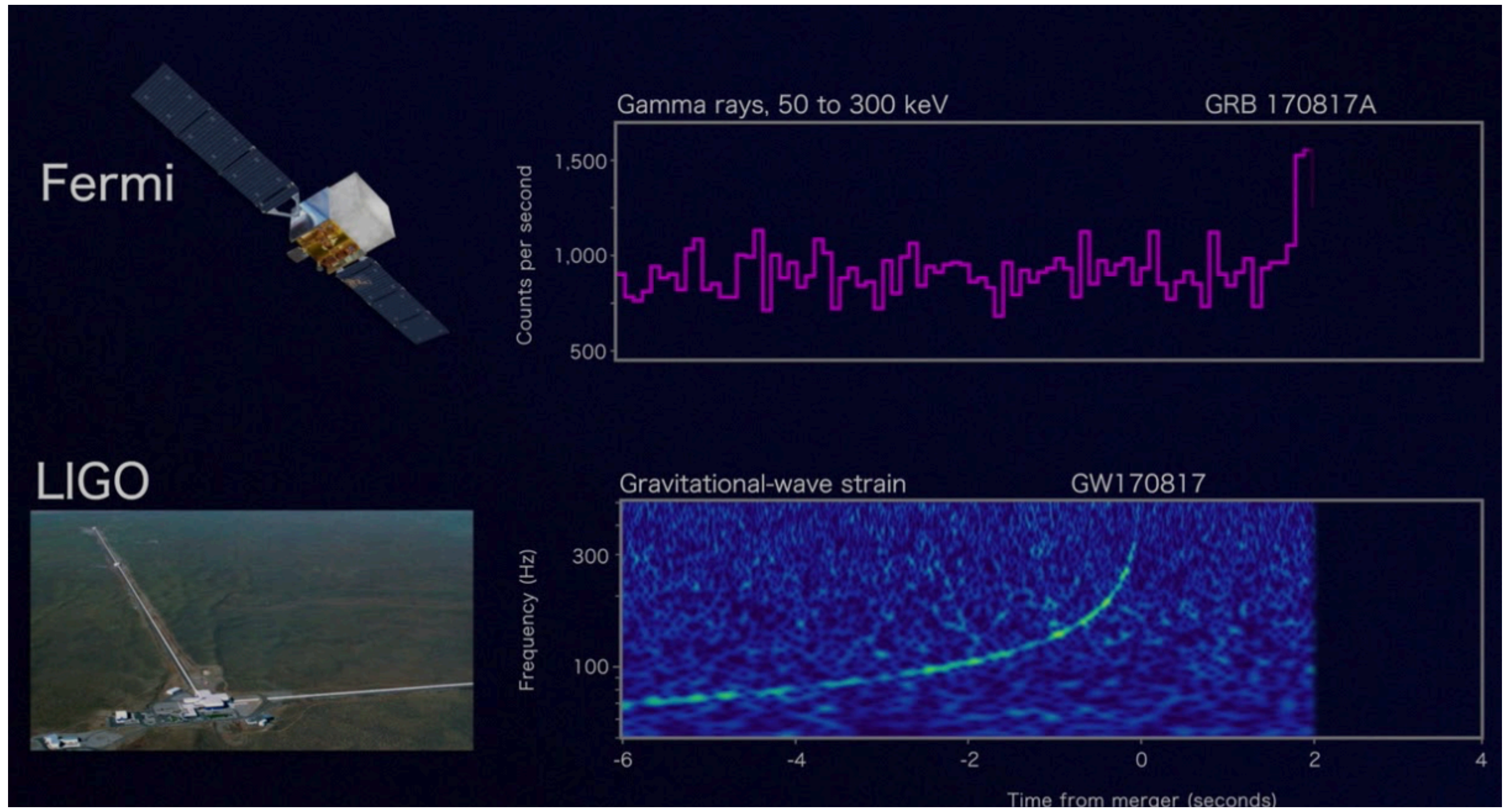
Short and Long Gamma-Ray Bursts

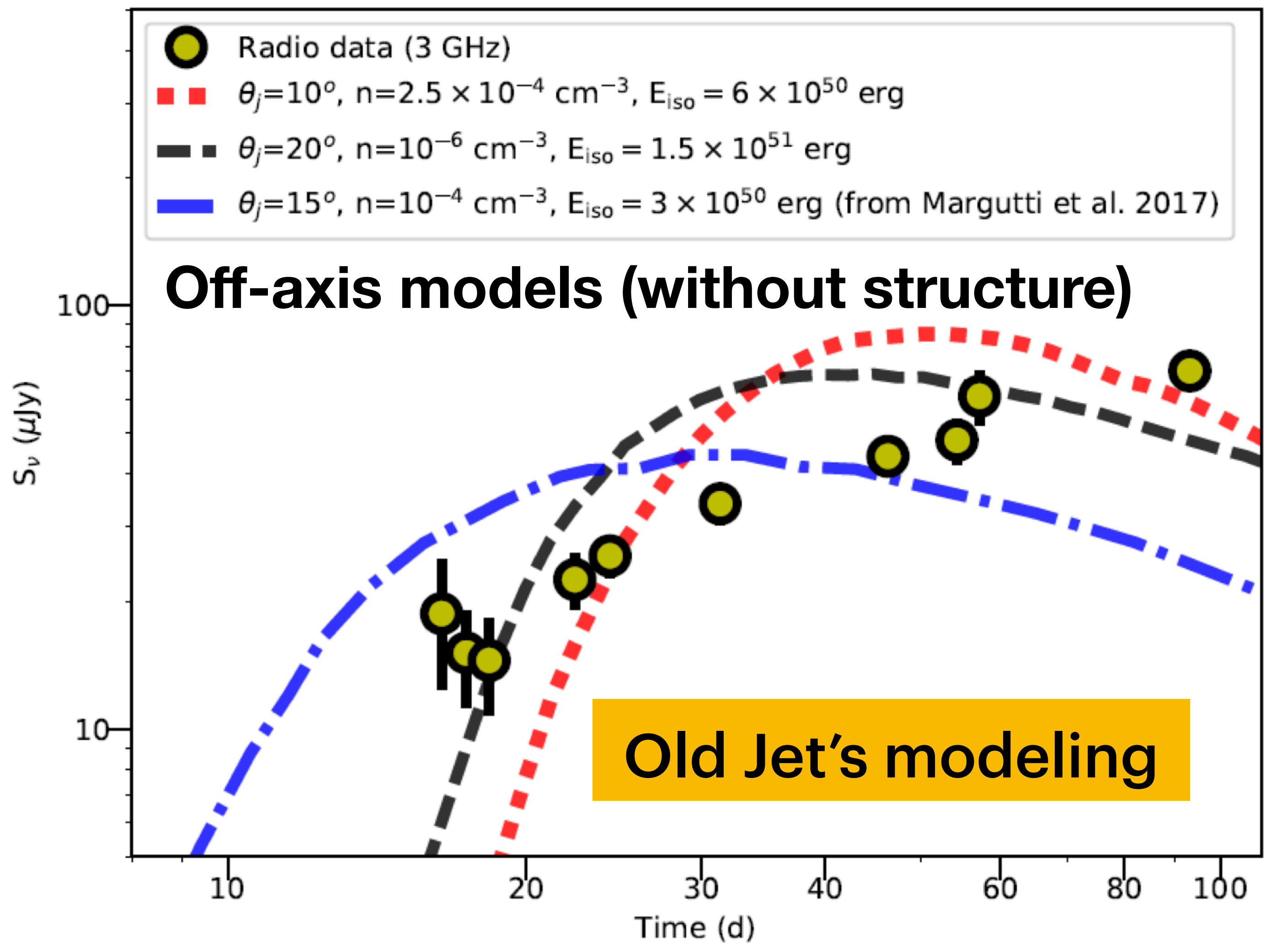


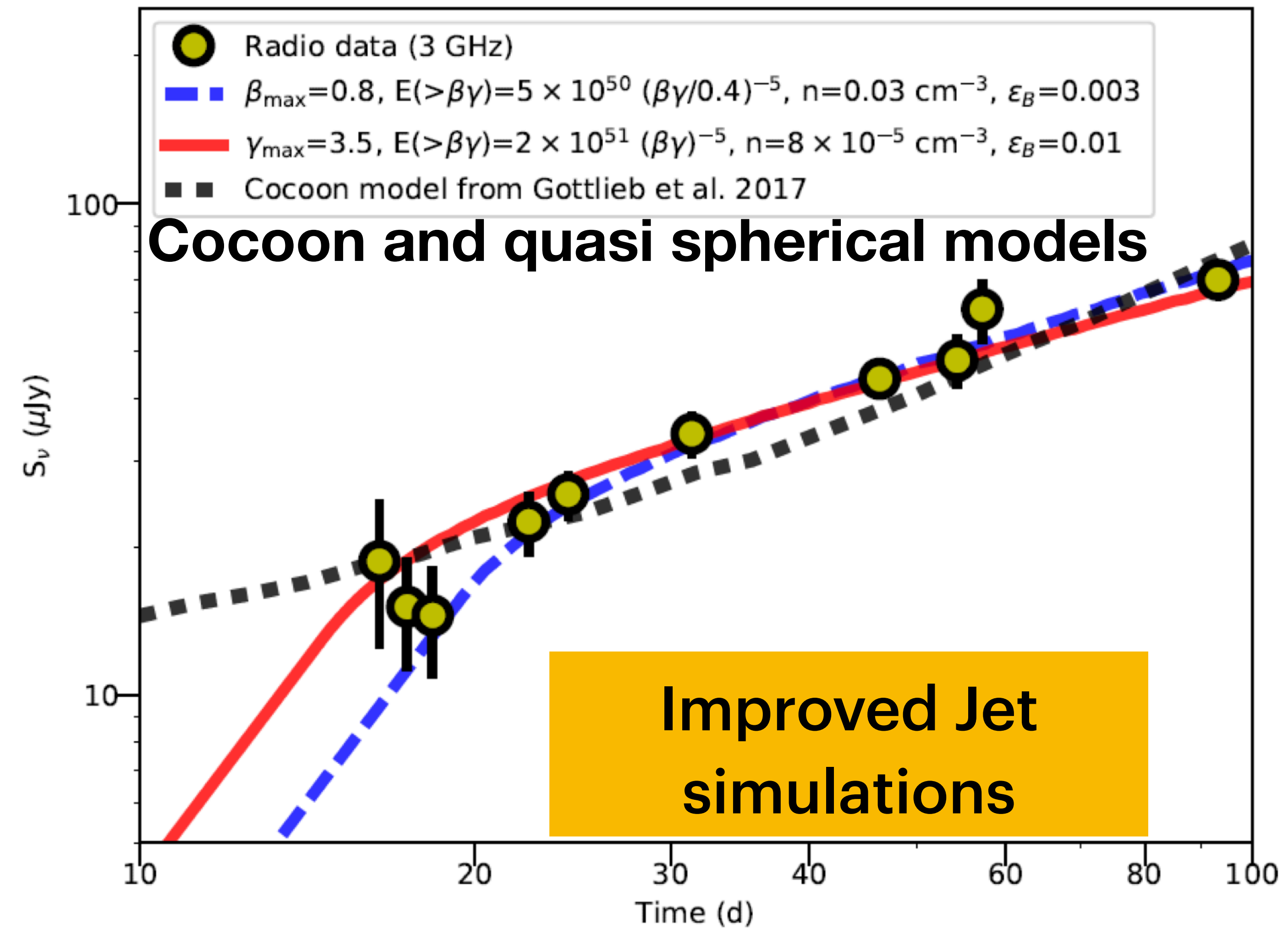
Levan et al. 2014



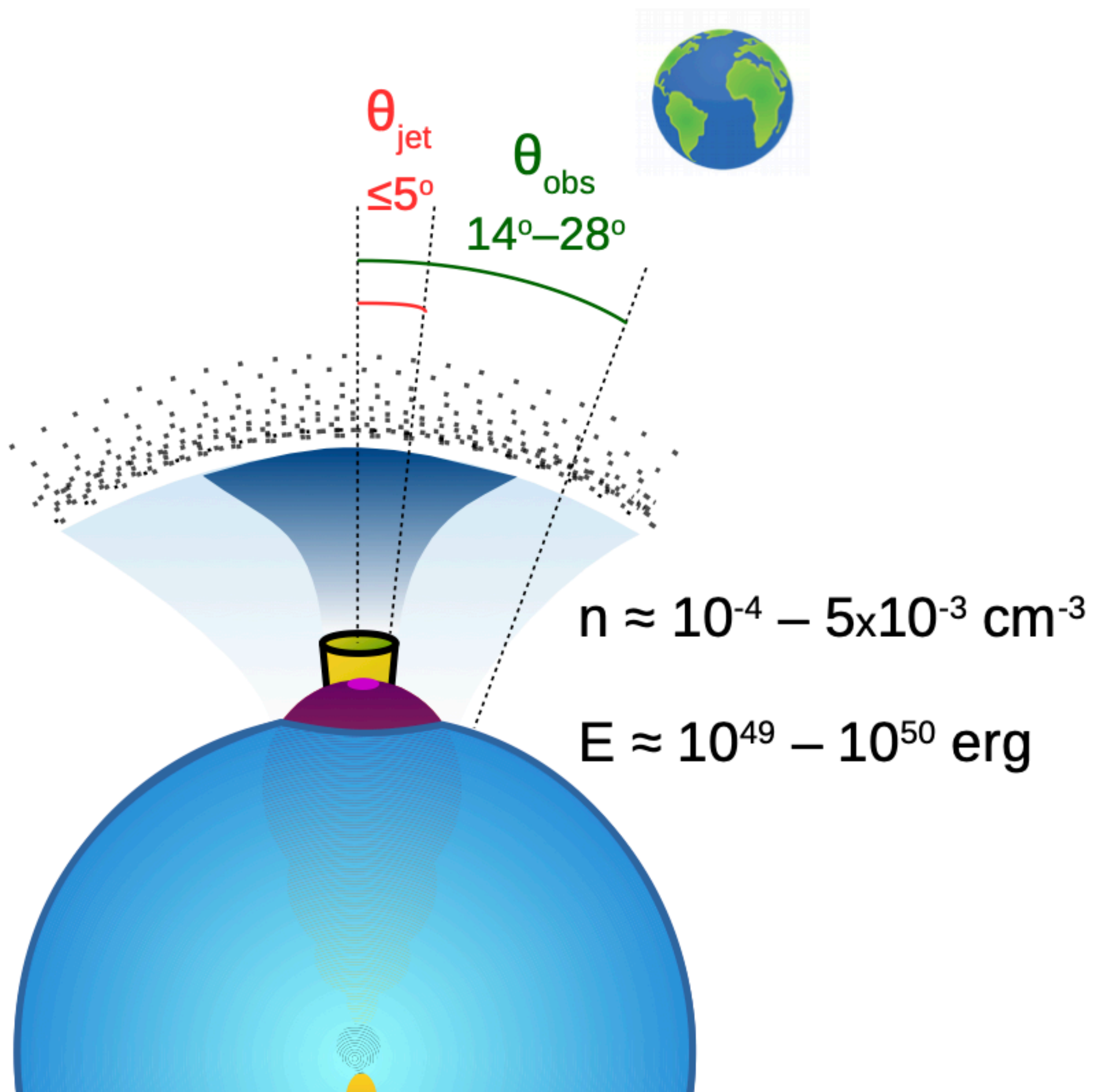
Lessons from August 2017

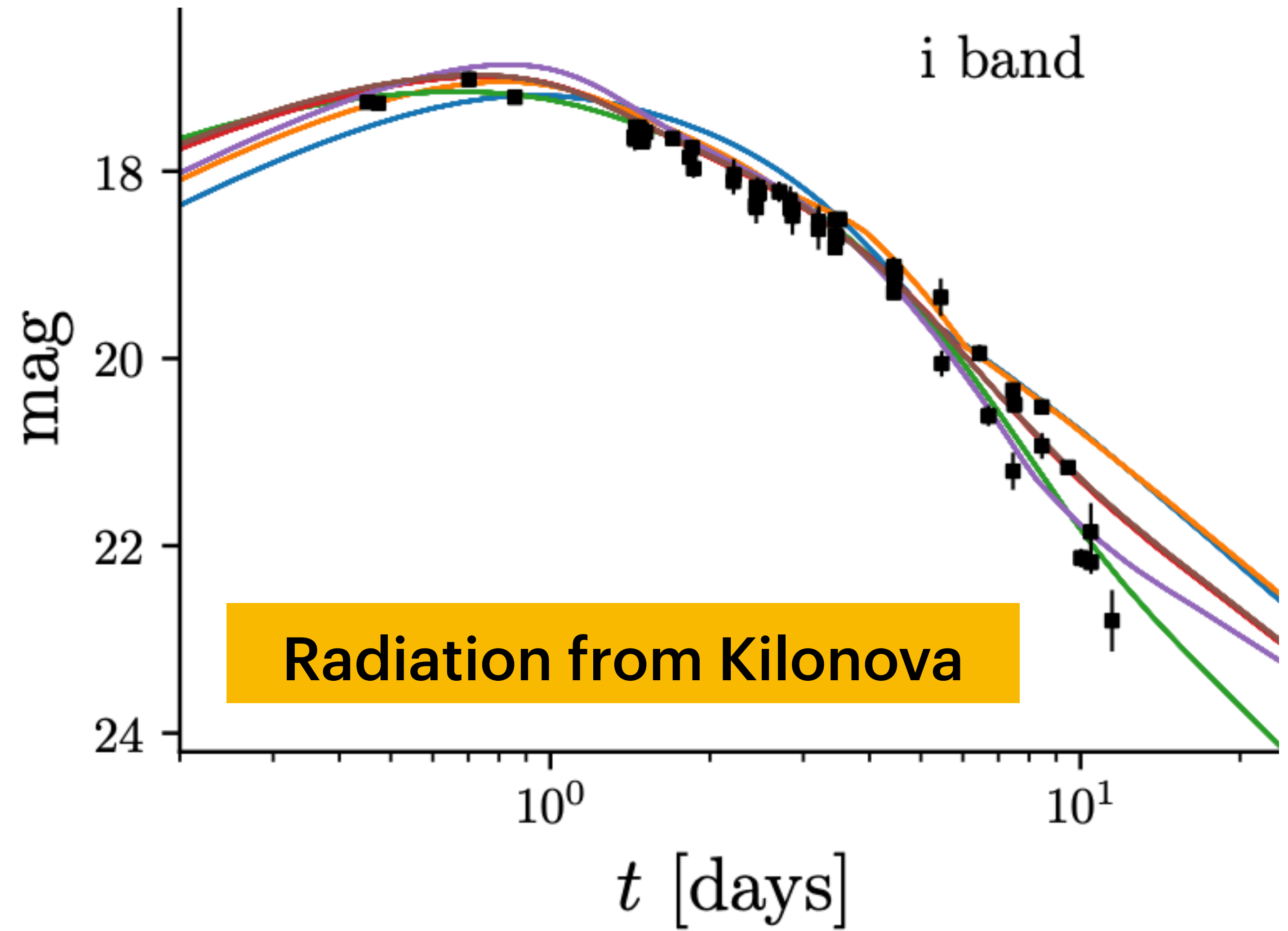






Motley et al. 2018





Breschi et al. 2021

Methods

Numerical simulations are our virtual laboratory to reproduce extreme conditions

$$\frac{\partial}{\partial t}[\Gamma\rho] + \nabla \cdot [\Gamma\rho\vec{v}] = 0$$

$$\frac{\partial}{\partial t}[\Gamma^2\rho h\vec{v}] + \nabla \cdot [\Gamma^2\rho h\vec{v}\vec{v} + p\,I] = 0$$

$$\frac{\partial}{\partial t}[e] + \nabla \cdot [e\vec{v} + p\vec{v}] = 0$$

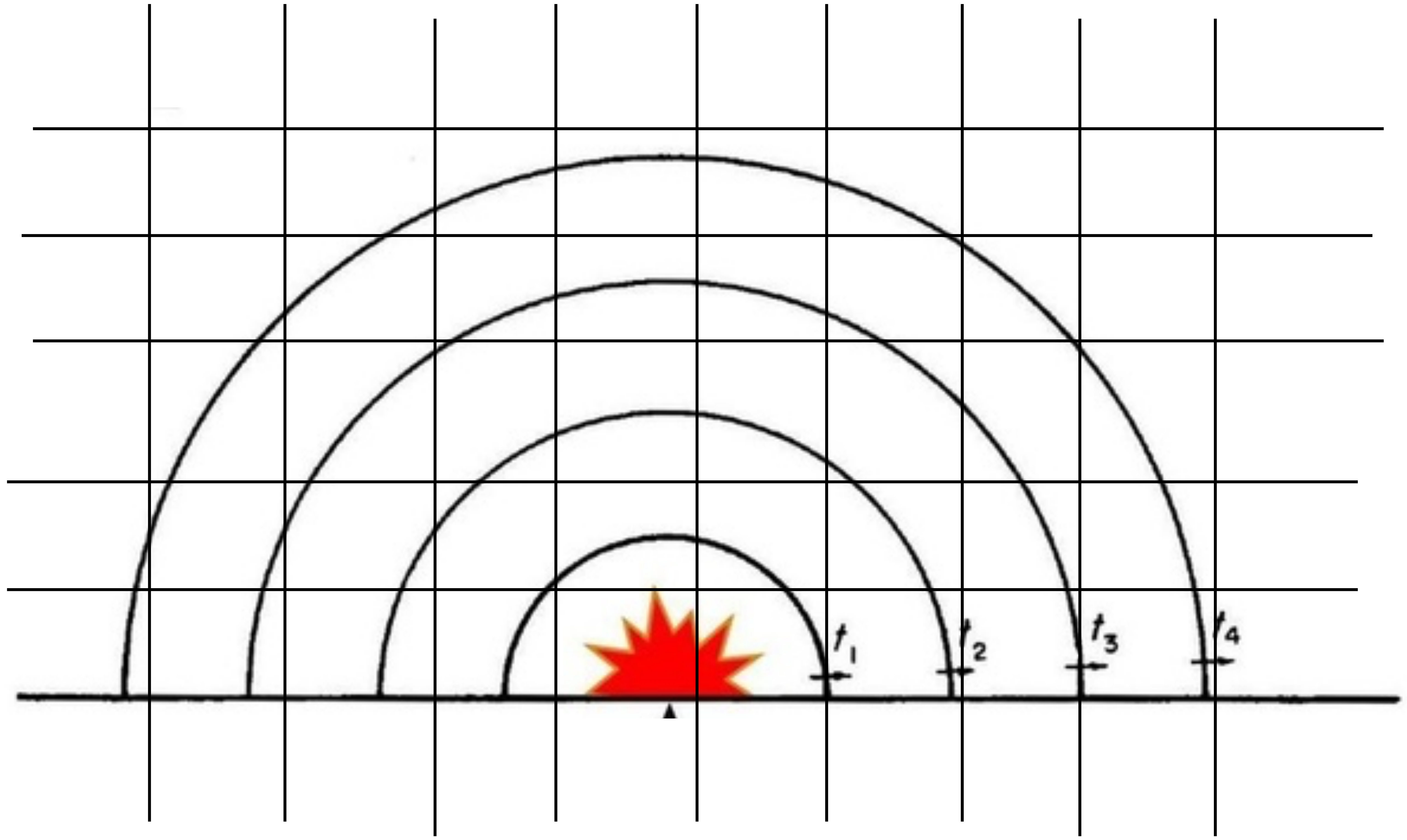
$$e \equiv \Gamma^2\rho hc^2 - p - \Gamma\rho c^2$$

$$\Gamma \equiv \left(1 - \beta^2\right)^{-1/2}$$

- Fluid dynamics simulations

Methods

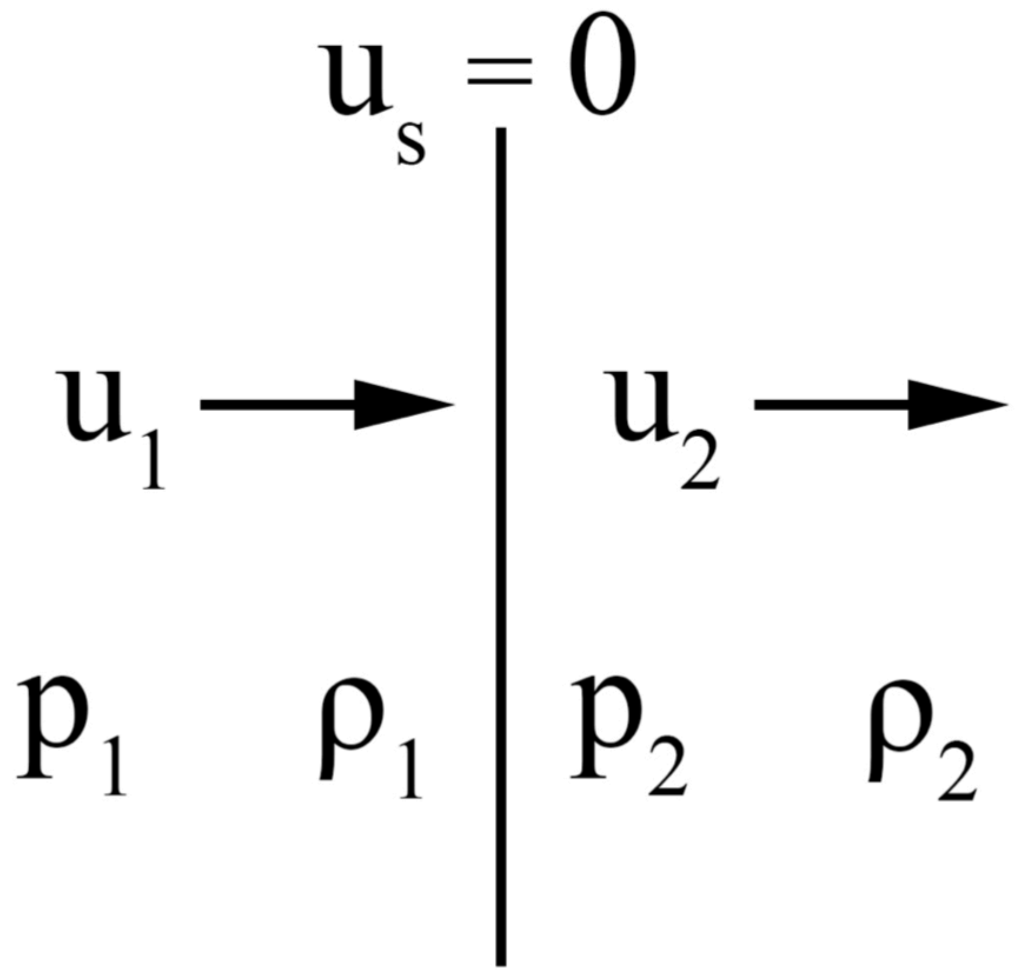
Numerical simulations are our virtual laboratory to reproduce extreme conditions



- Fluid dynamics simulations
  - Supersonic fluids
  - Strong shocks

Methods

Numerical simulations are our virtual laboratory to reproduce extreme conditions



- Fluid dynamics simulations
  - Supersonic fluids
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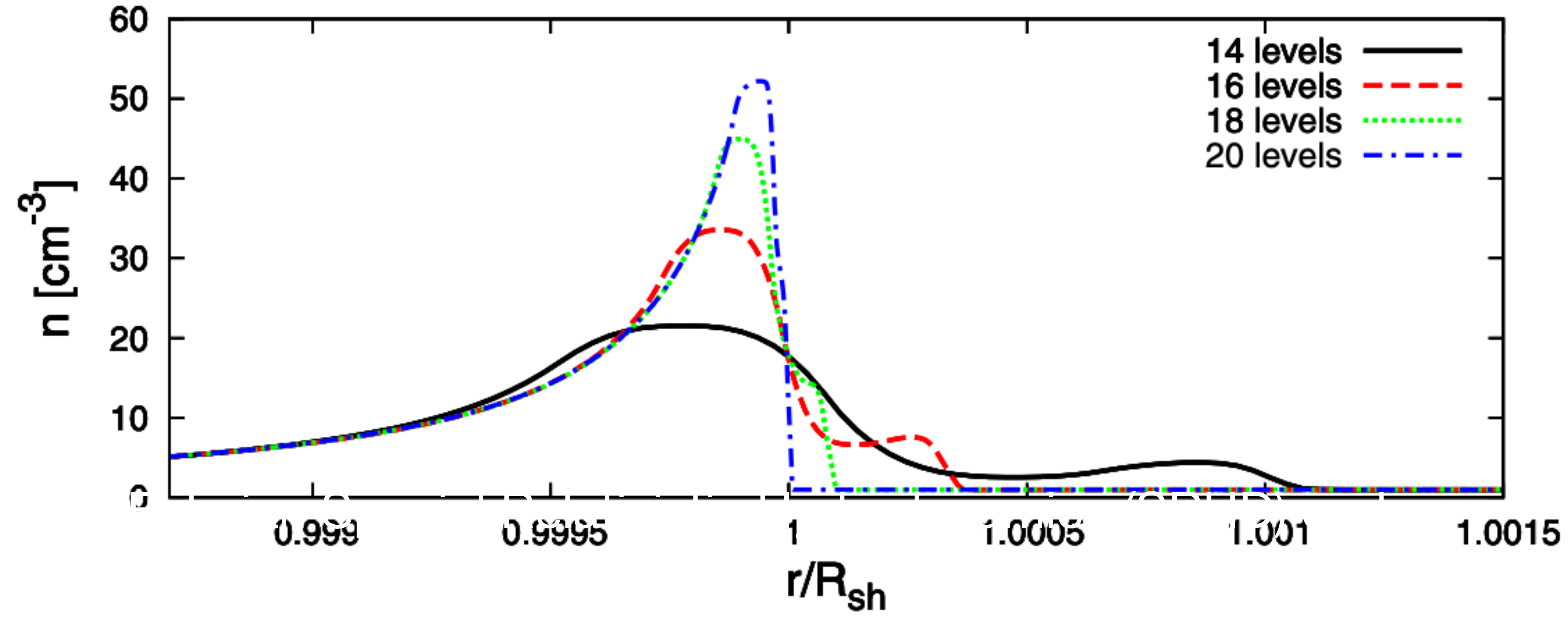
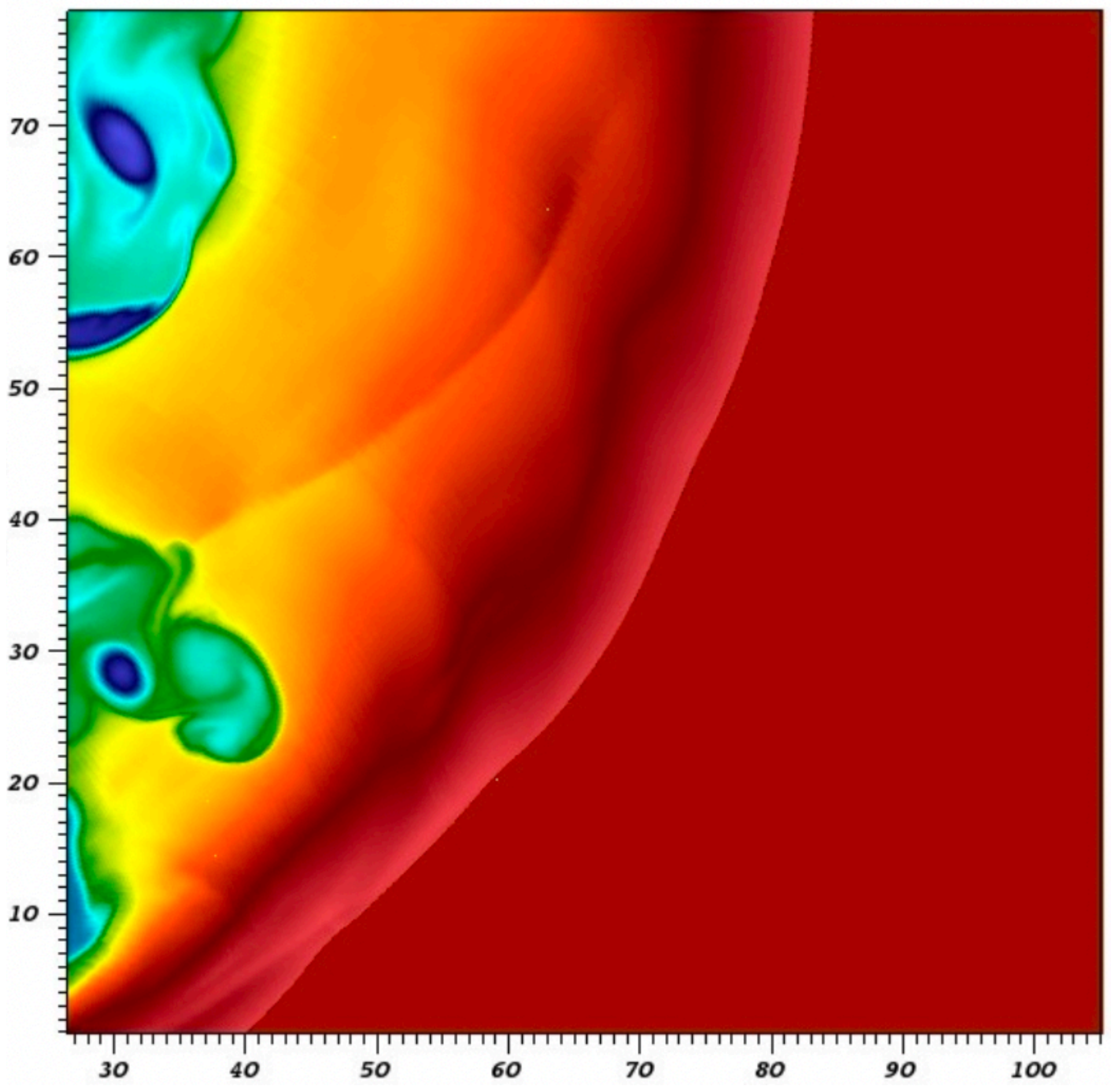


Mezcal Code (De Colle et al. 2012)

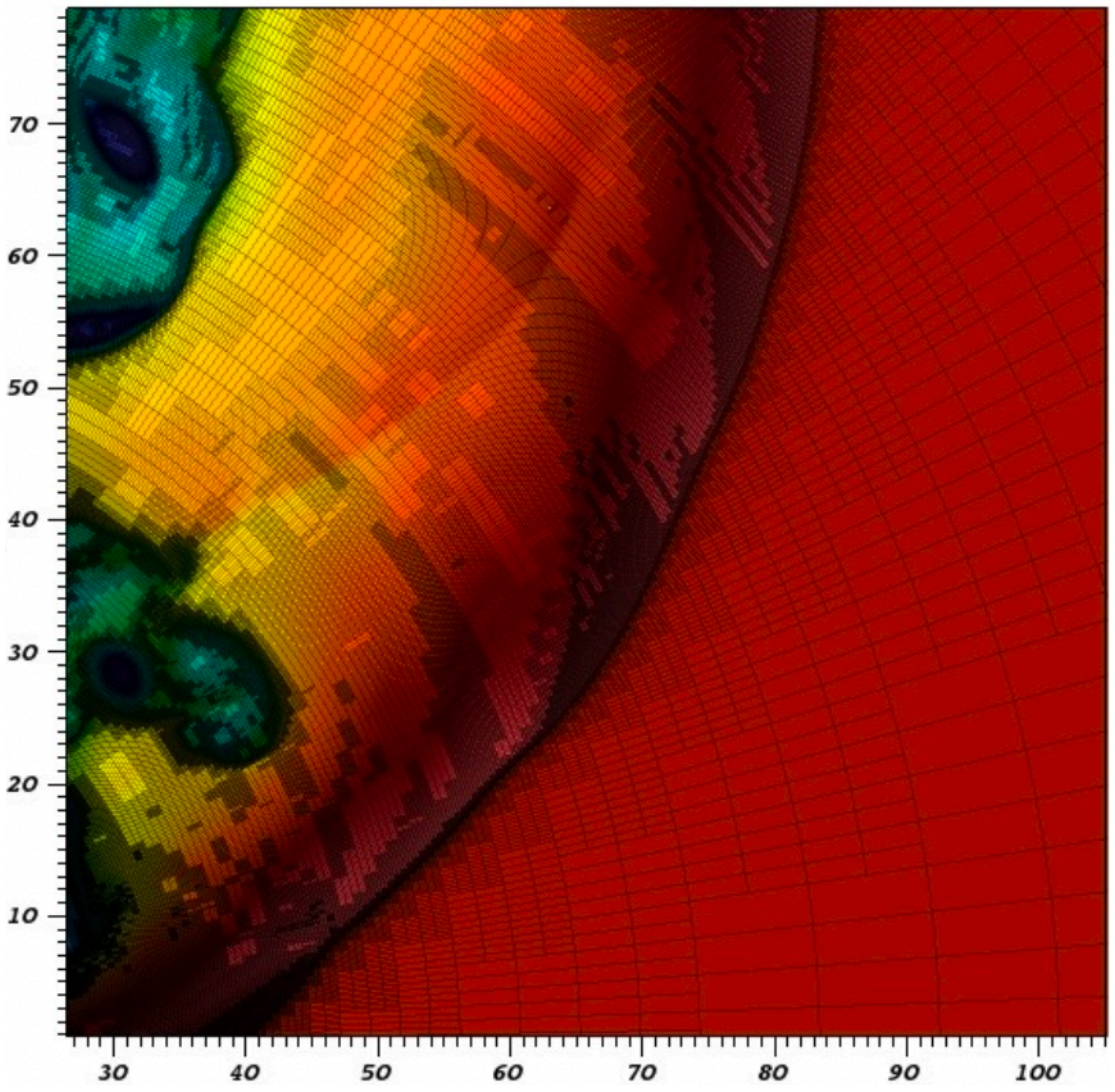
- Eulerian Special Relativistic Hydrodynamics
- Harten-Lax-van Leer-Contact; methods
- Fortran 90
- MPI

Methods

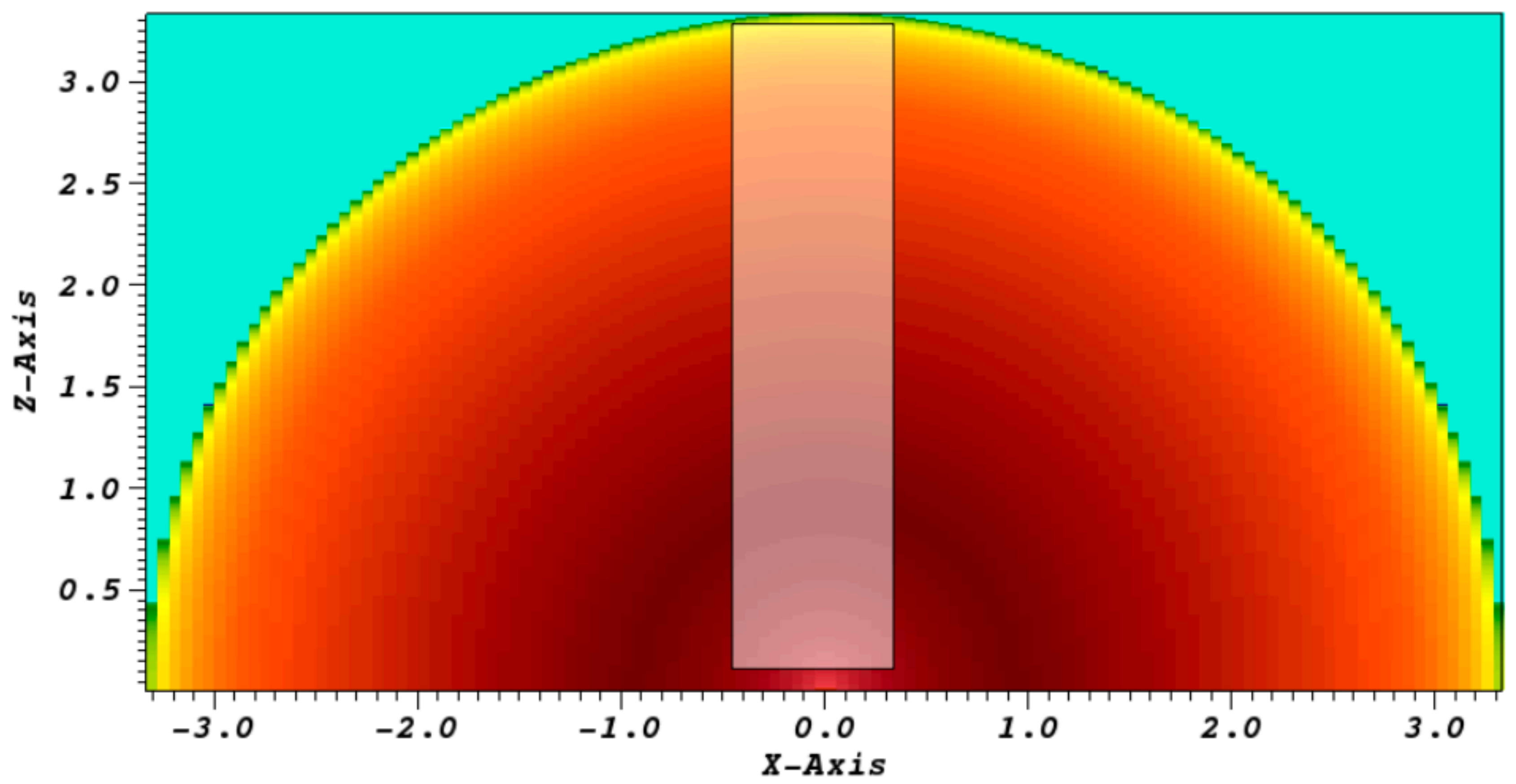
- E.g., Mezcal Code (De Colle et al 2012)
- Adaptative Mesh Refinement (AMR)
- Multiple core runs (MPI)

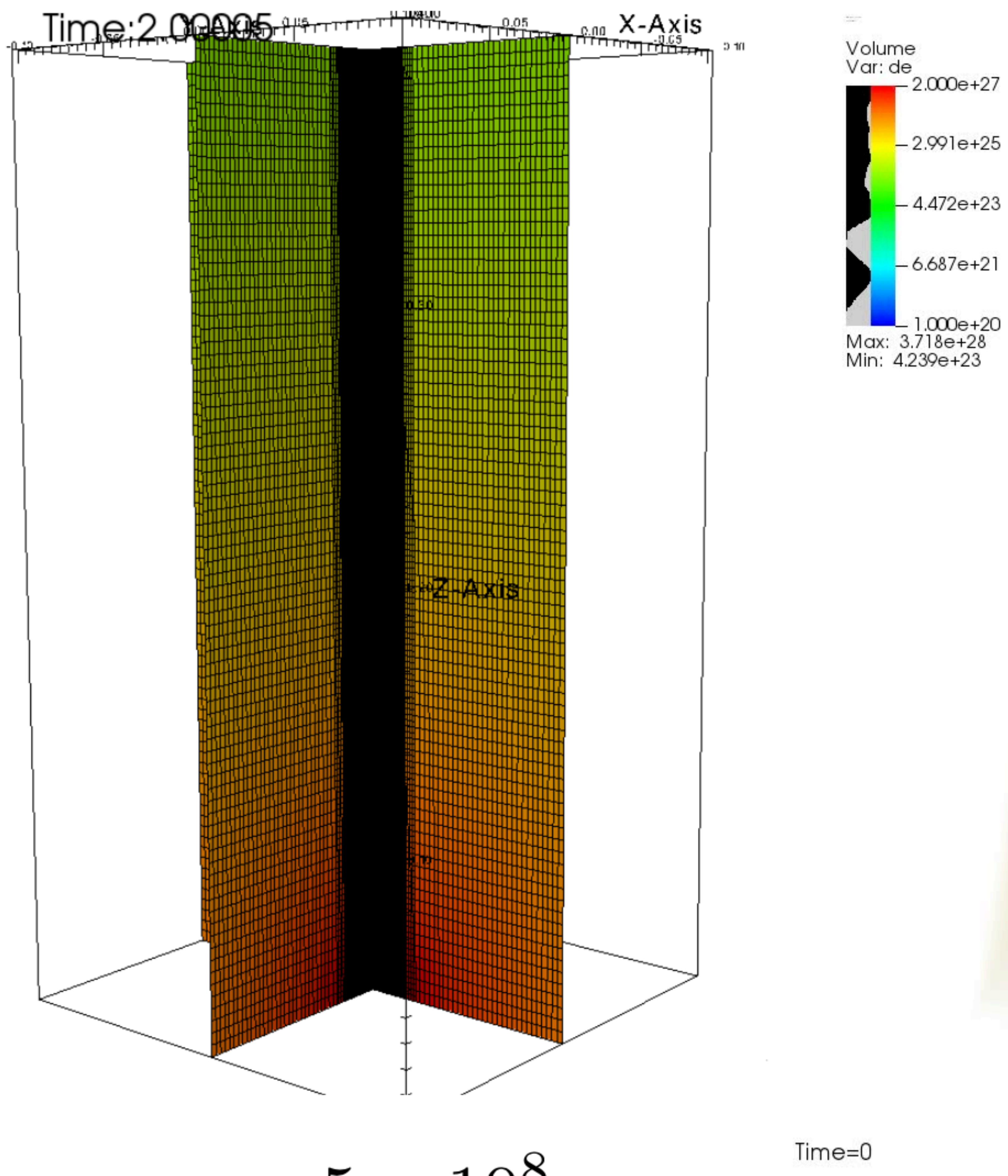


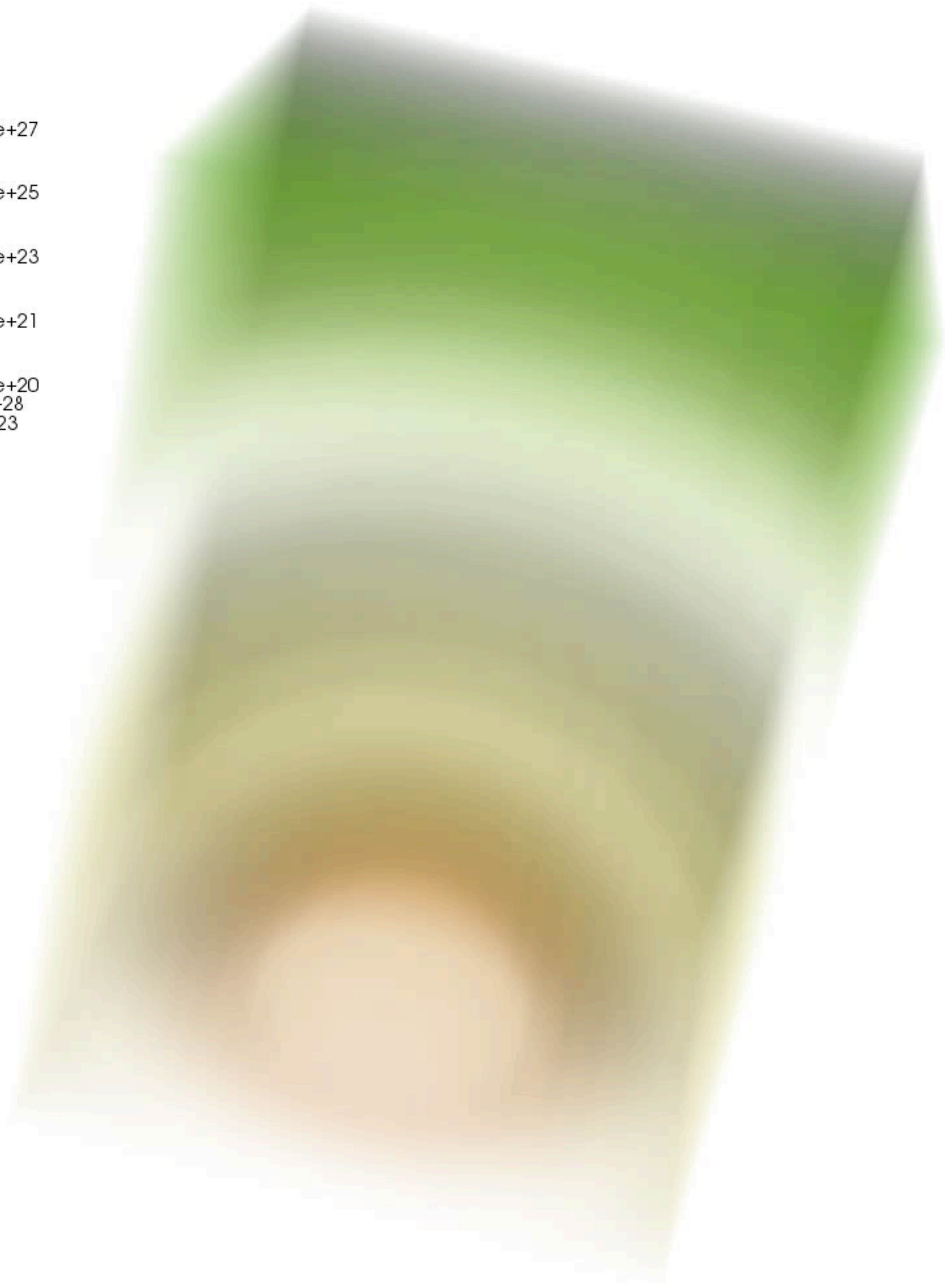
AMR



Refine your area of interest







Cells: $72 \times 72 \times 144$

Axis: $x \in [-1.5, 1.5] \times 10^{10}$ cm

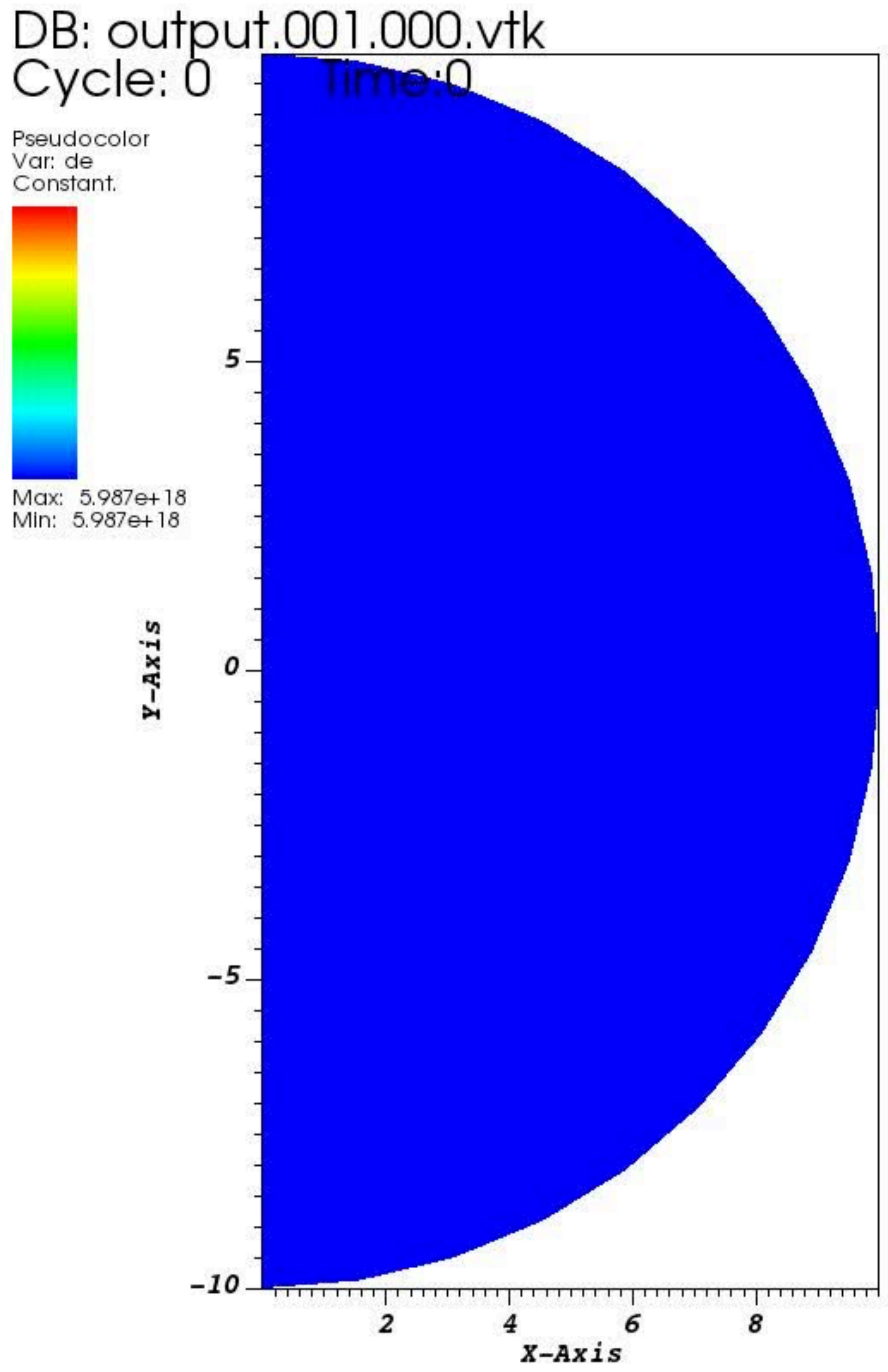
$y \in [-1.5, 1.5] \times 10^{10}$ cm

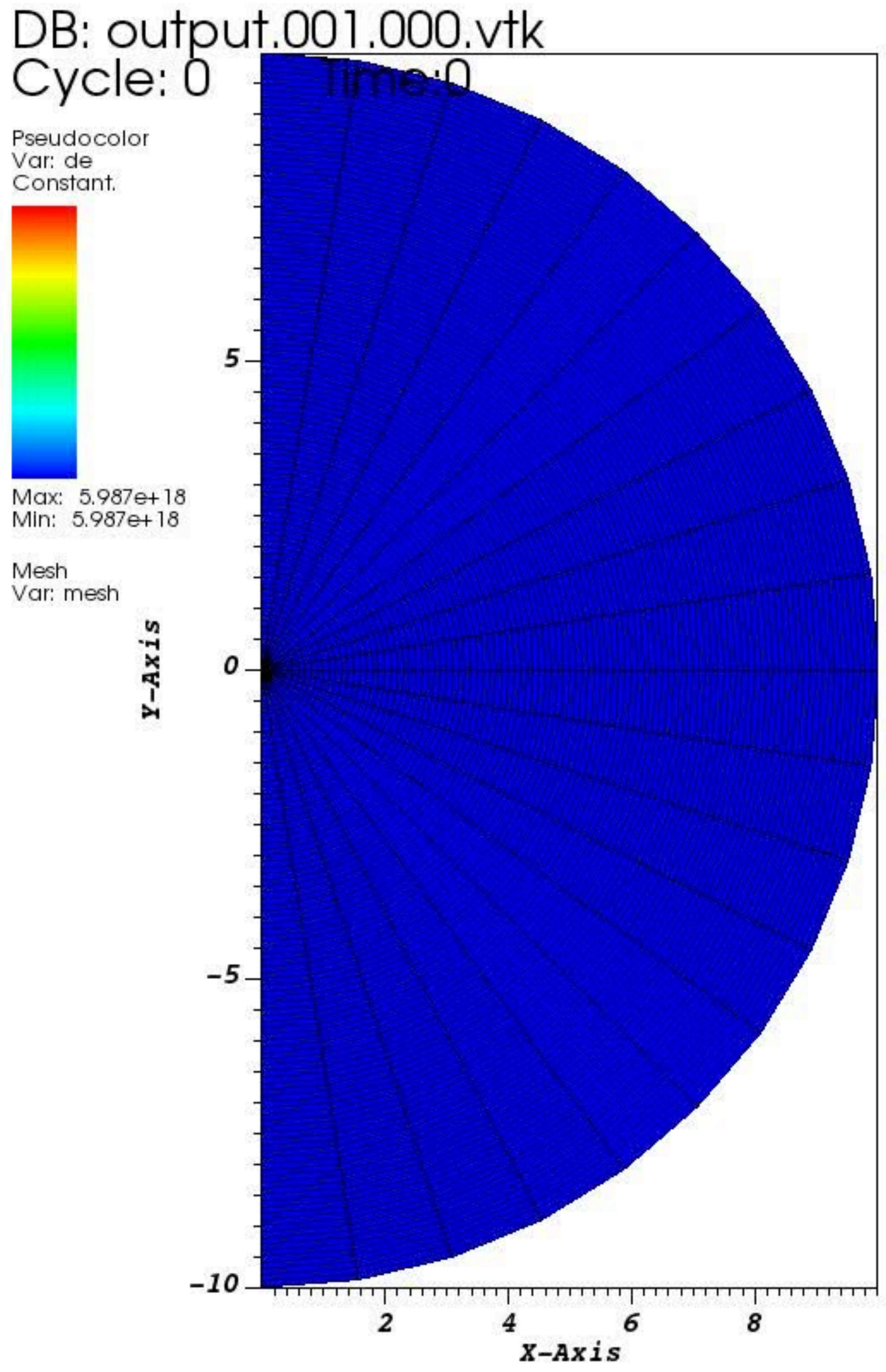
$z \in [0, 4.5] \times 10^{10}$ cm

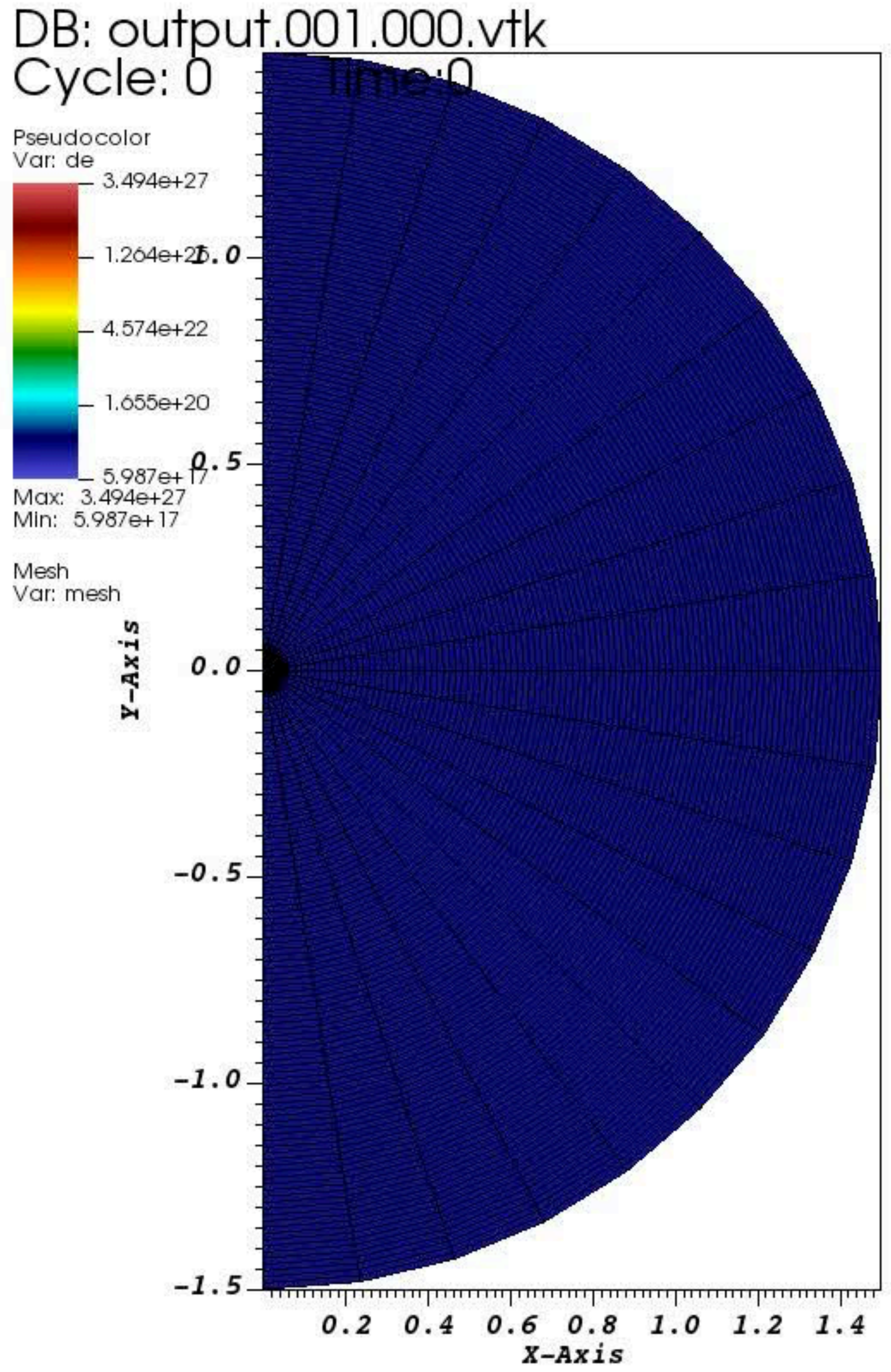
6 levels of refinement for the jet channel: $r_{\rm chanel} = 5 \times 10^{8}$cm

$\Delta_{min\,x,y,z} \sim 9 \times 10^{6}$ cm

Urrutia et al. 2022


DB: output.001.000.vtk
Cycle: 0 Time:0
Pseudocolor
Var: de
Constant.
Max: 5.987e+18
Min: 5.987e+18
Y-Axis
X-Axis


DB: output.001.000.vtk
Cycle: 0 Time:0
Pseudocolor
Var: de
Constant.
Max: 5.987e+18
Min: 5.987e+18
Mesh
Var: mesh
Y-Axis
X-Axis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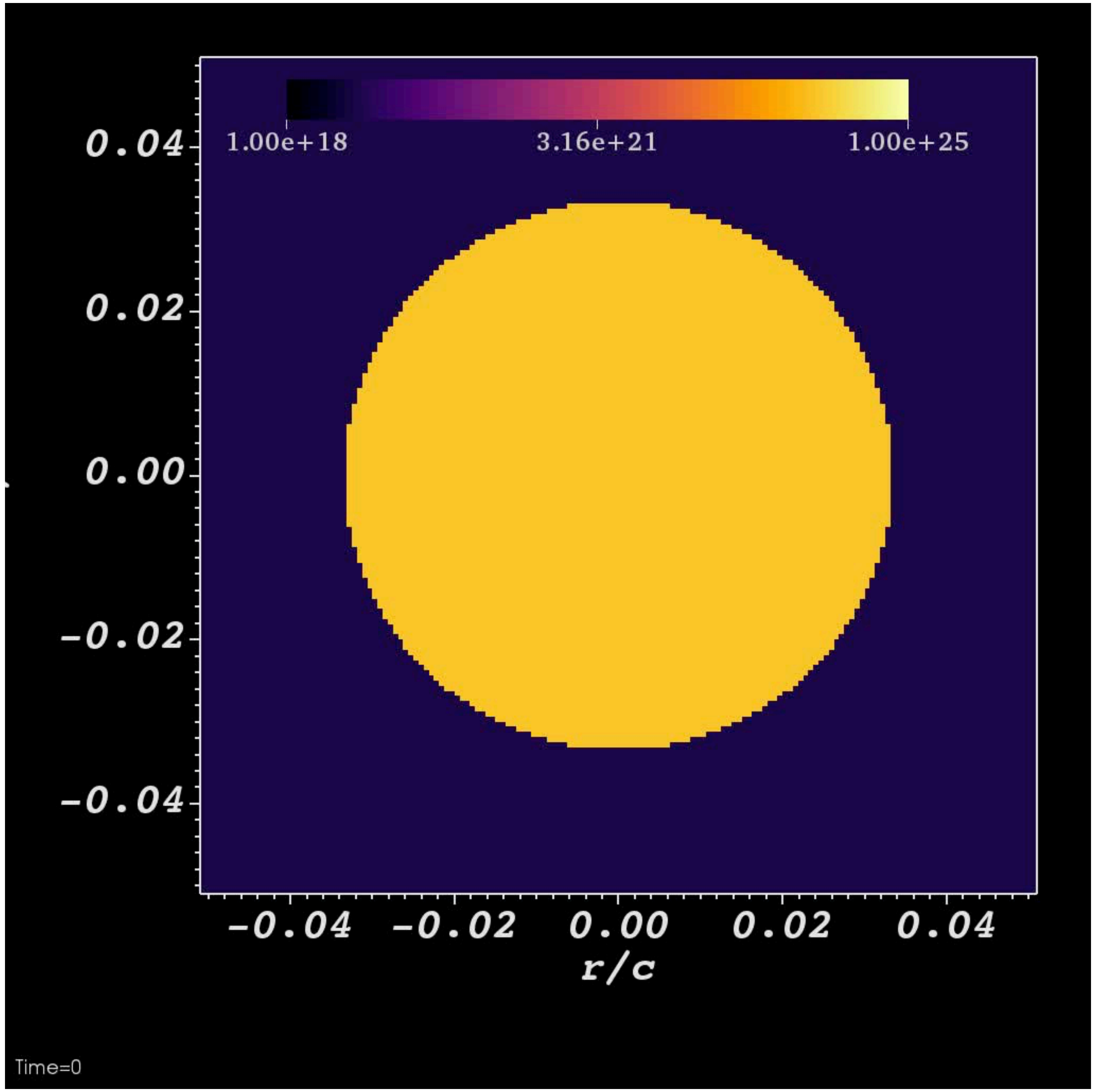
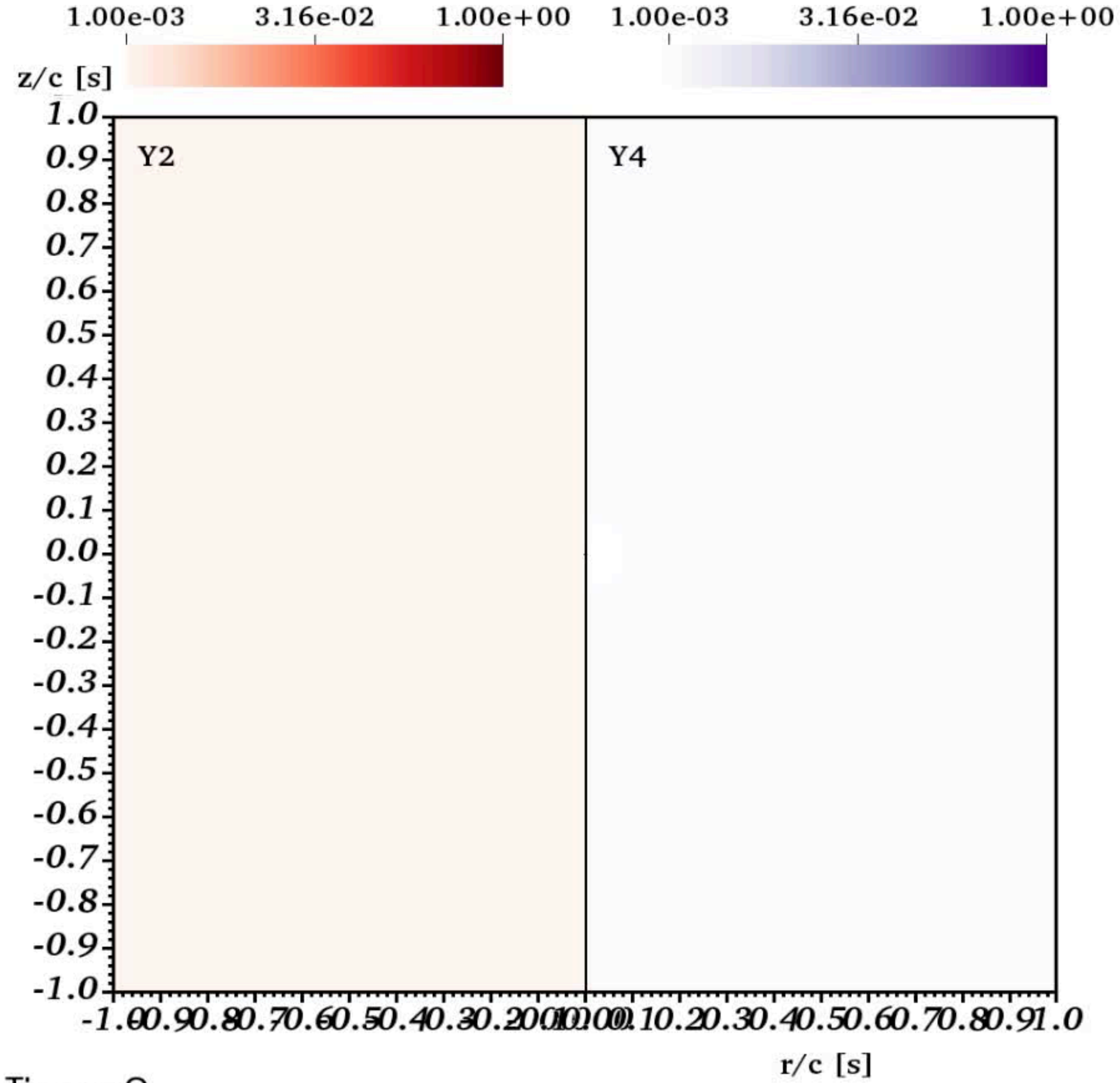
Cycle: 0 Time:0
Pseudocolor
Var: de
3.494e+27
1.264e+25
4.574e+22
1.655e+20
5.987e+17
Max: 3.494e+27
Min: 5.987e+17
Mesh
Var: mesh
Y-Axis
X-Axis

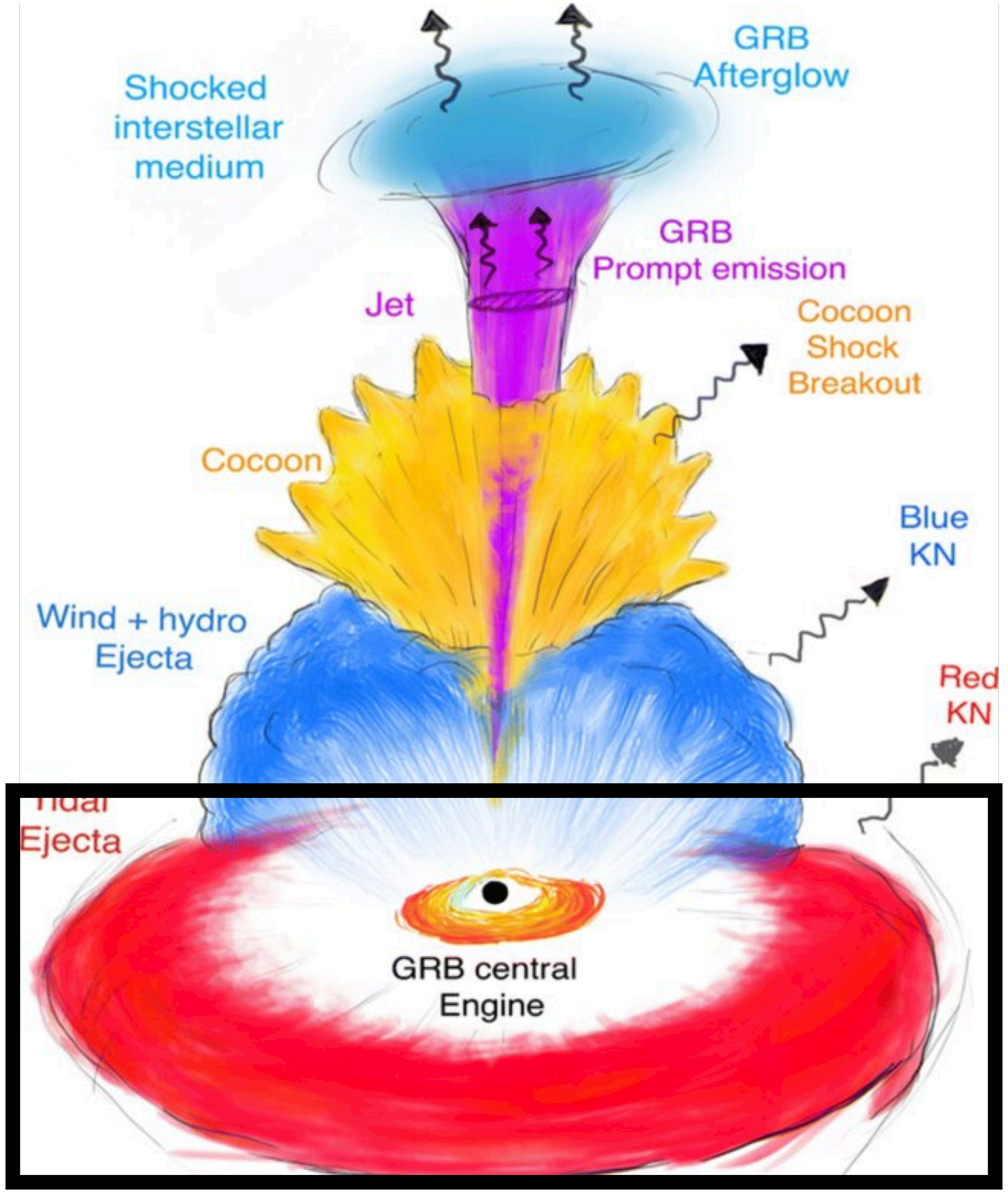


e.g., Urrutia et al. 2021



Time=0

Post-merger evolution of the jet is a multi-scale problem

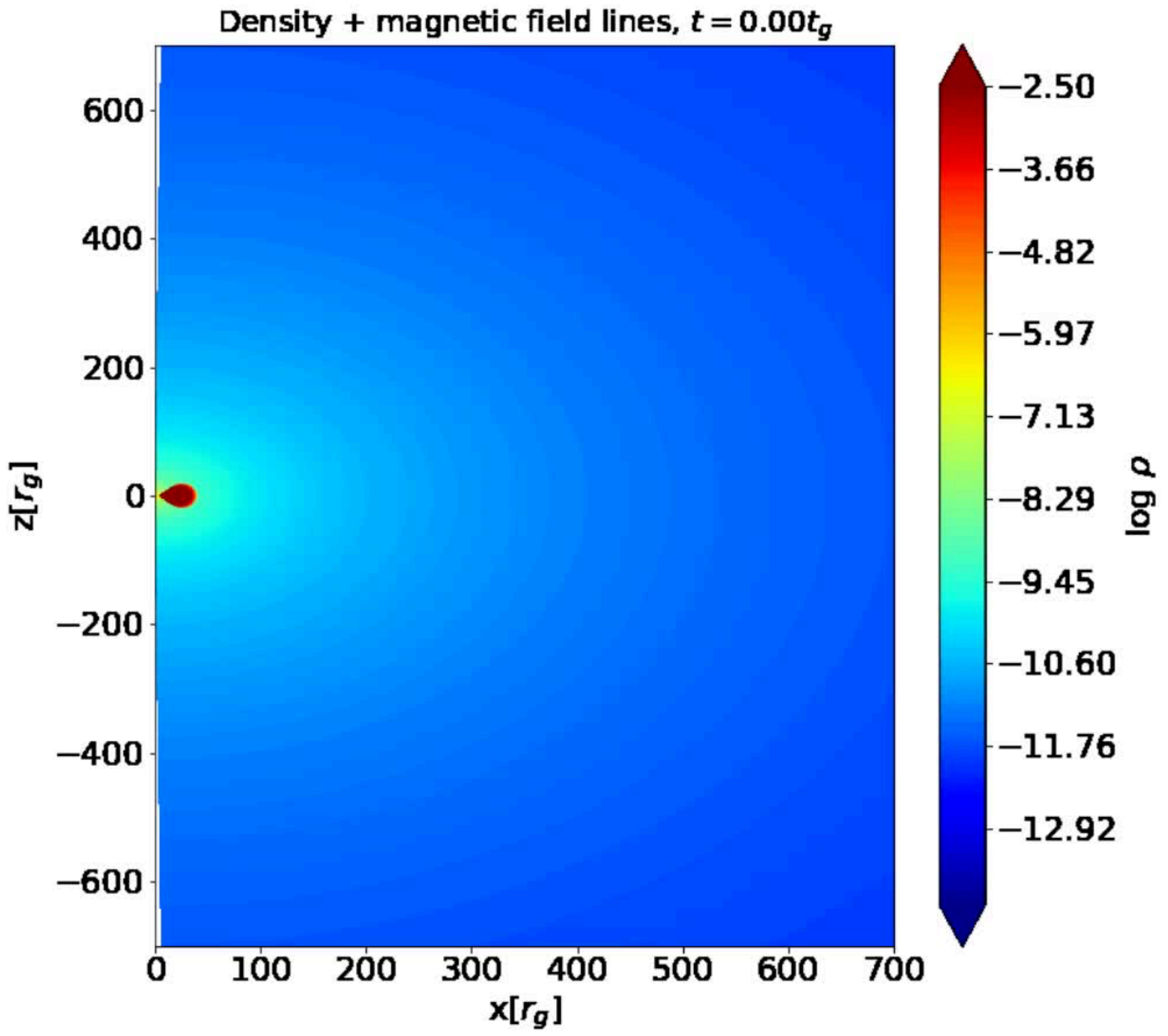


Cartoon of GRB evolution (Stefano Ascenzi)

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

GRMHD simulations

Post-merger evolution of the jet is a multi-scale problem



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

GRMHD simulations

e.g., Nouri et al. 2023

Our Connection between small and large scales

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

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:

$$p + e^- \to n + \nu_e$$
$$n + e^+ \to p + \bar{\nu}_e$$
$$e^+ + e^- \to \nu_i \bar{\nu}_i$$

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.**

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

Special Relativistic HD simulation

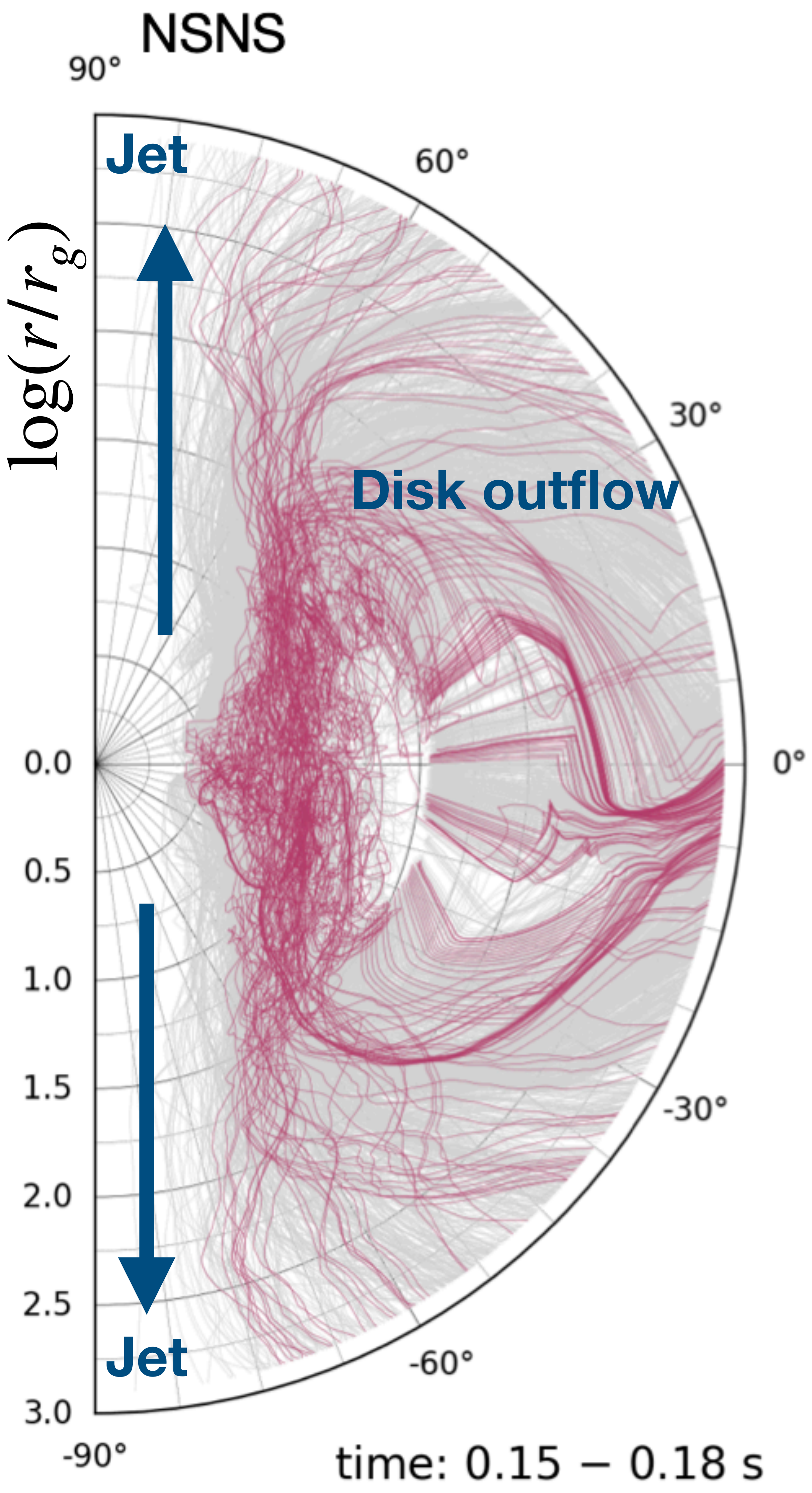
$$(\rho u_\mu)_{;\nu} = 0$$

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

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

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

Outflow characteristics



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

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

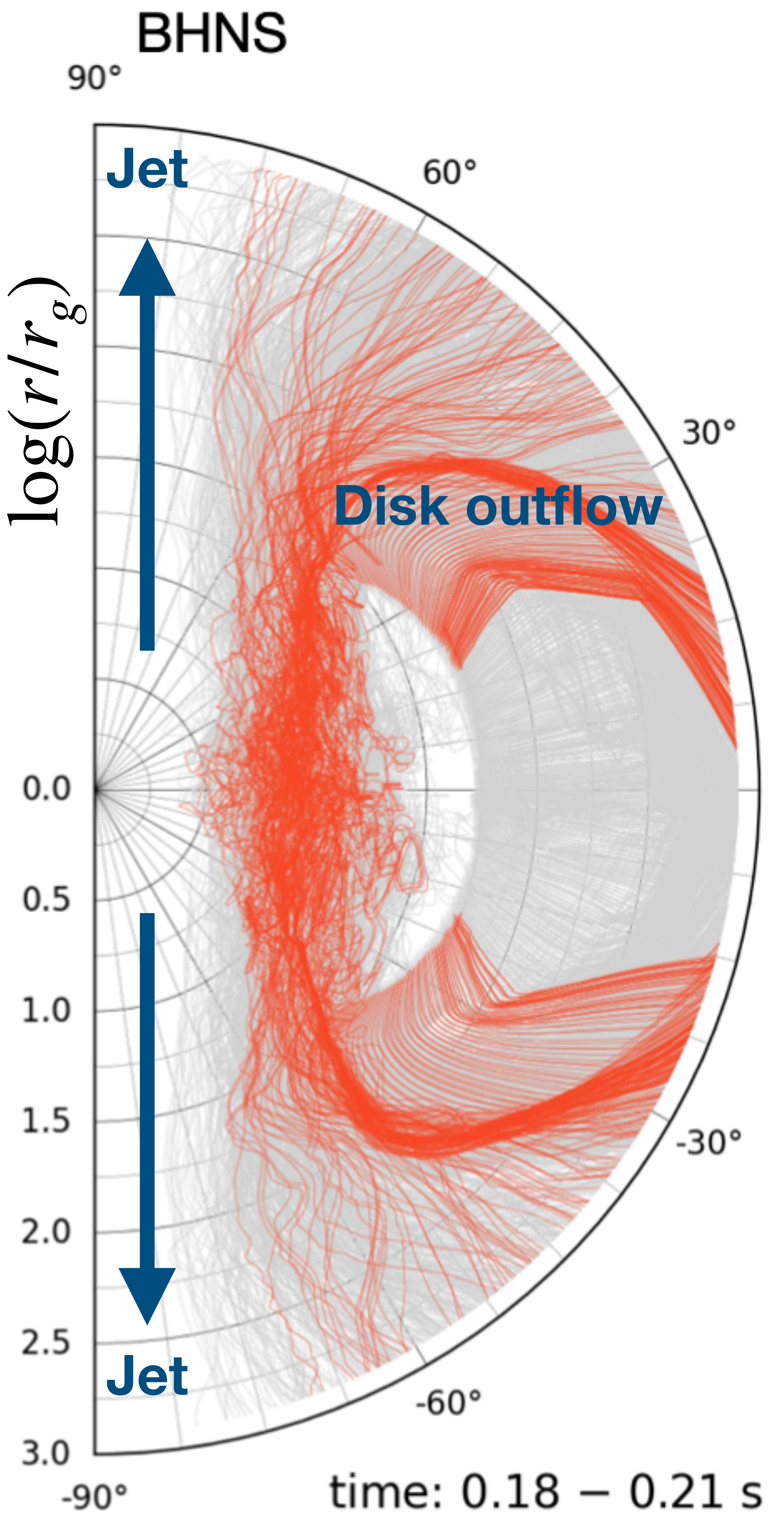
$\dot{M}_{\rm out} = 3.27 \times 10^{-2}\, M_\odot\ {\rm s}^{-1}$

$\Gamma_j = 7.2$

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

$\theta_j = 15^\circ$

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



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

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

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

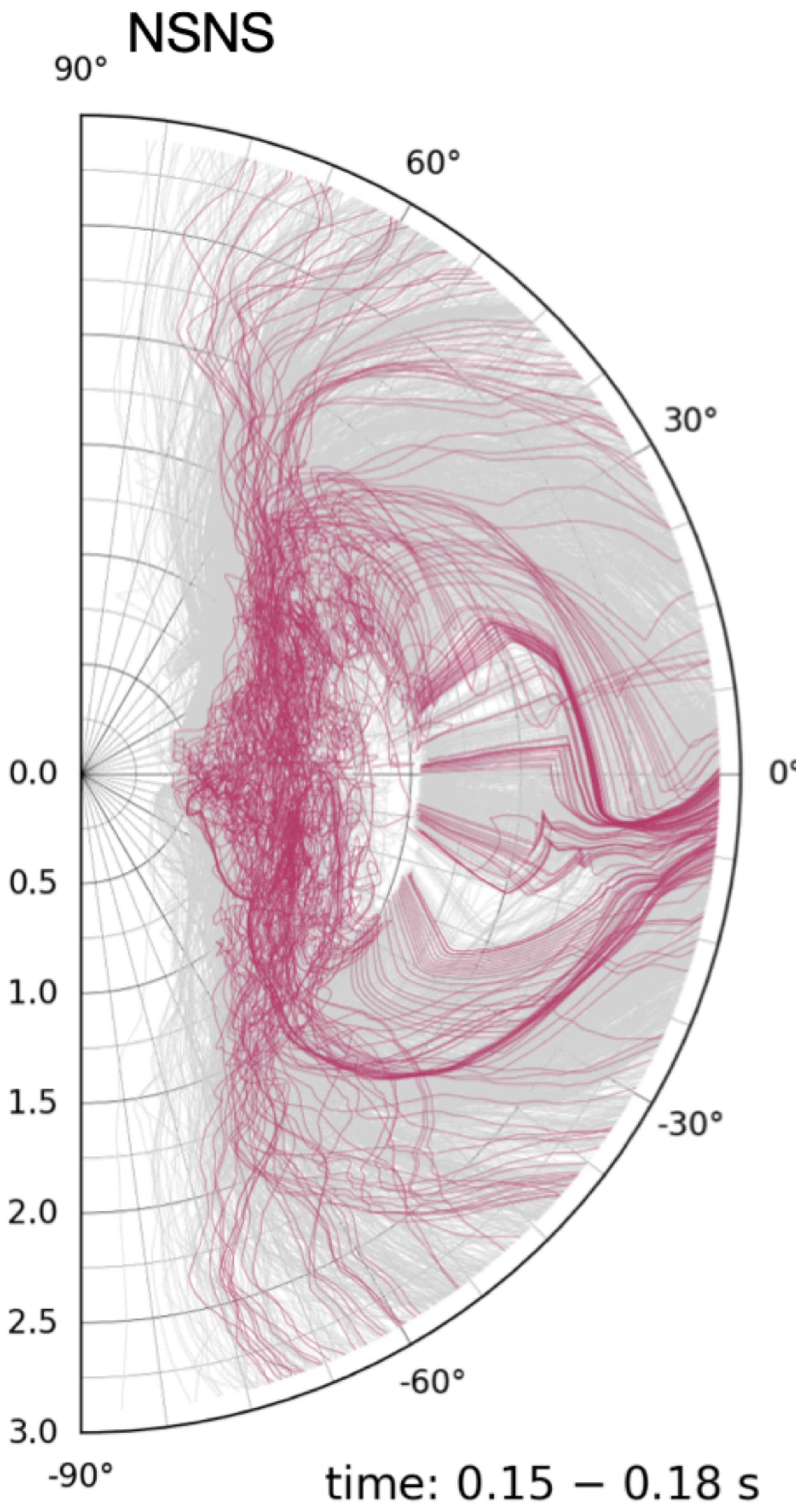
$\Gamma_j = 12$

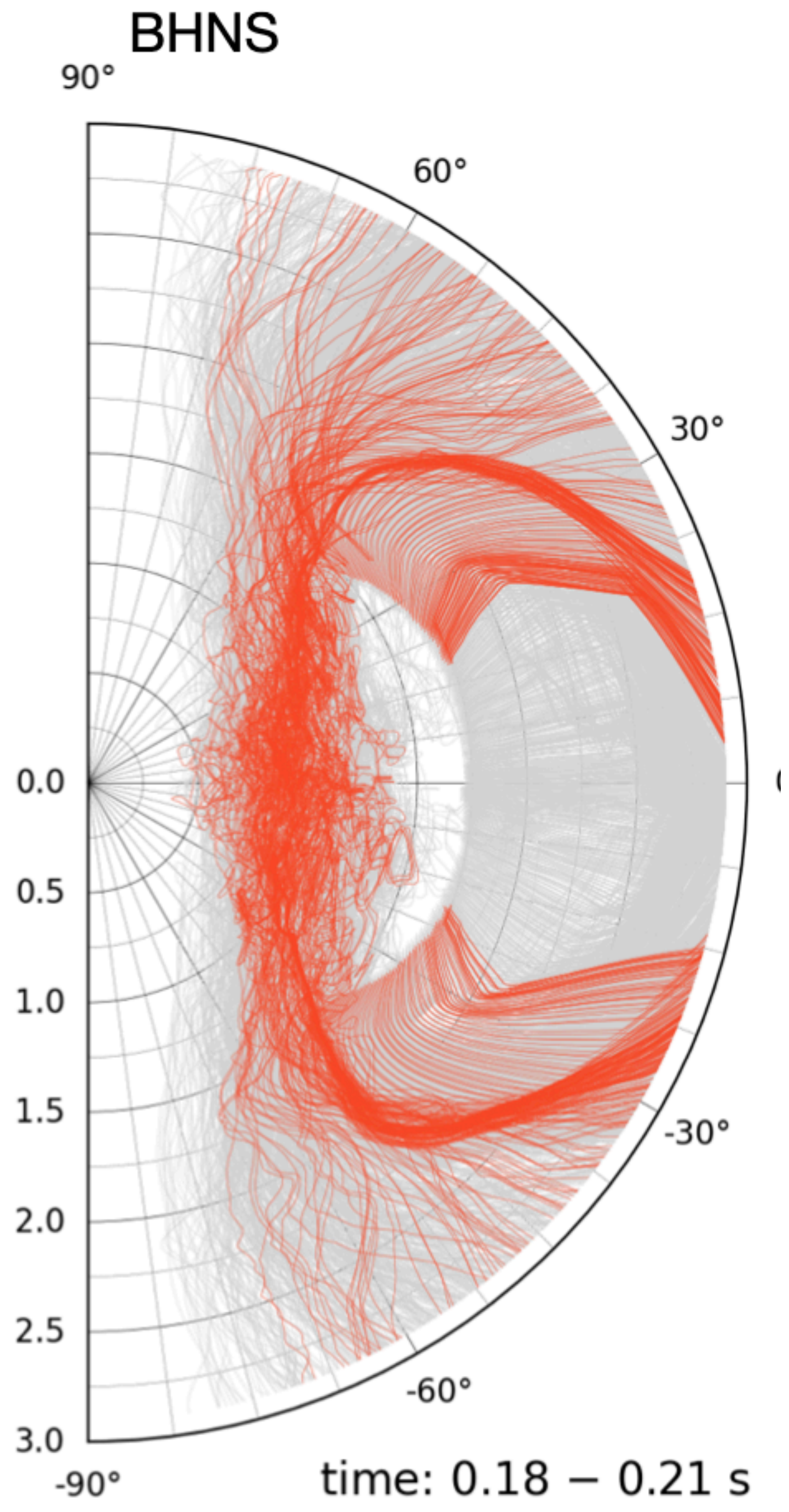
$t_{\rm j} \propto M_{\rm disk}/\dot{M} \sim 1.07\,{\rm s}$

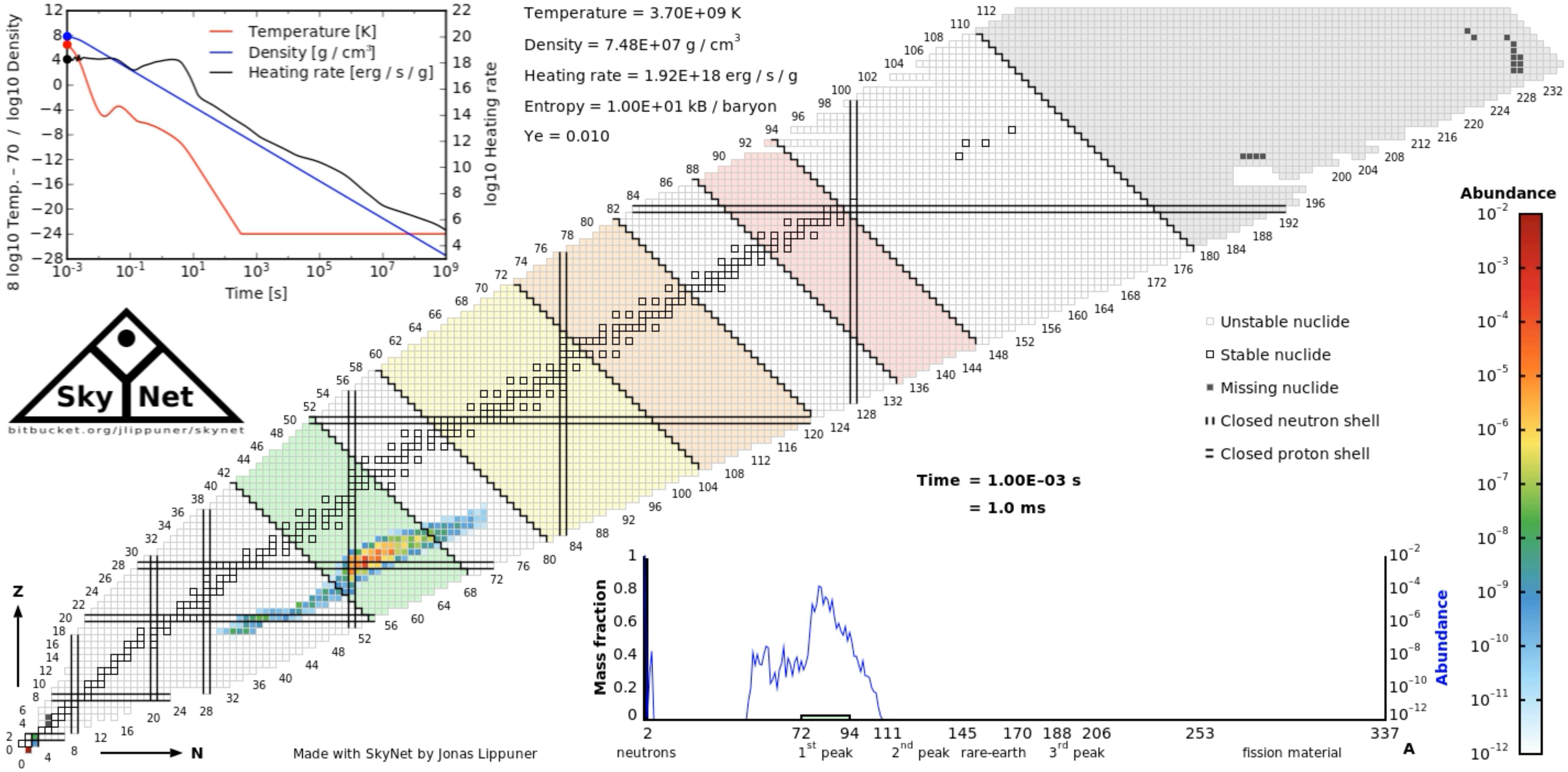
$\theta_j = 15^\circ$

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

Outflow tracers proceed to follow r-process and get the gas pressure

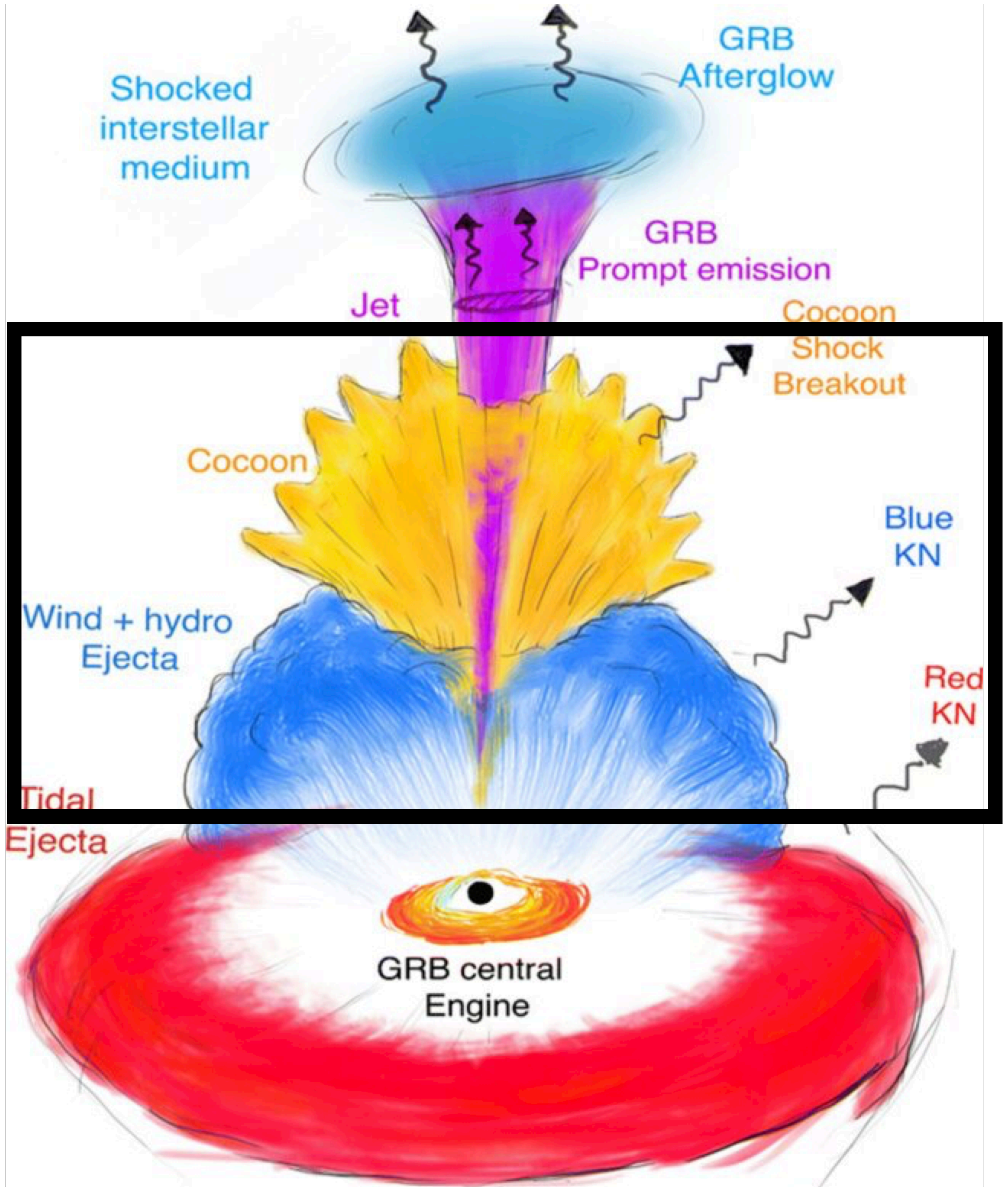






(Lippuner & Roberts 2017)

Post-merger evolution of the jet is a multi-scale problem

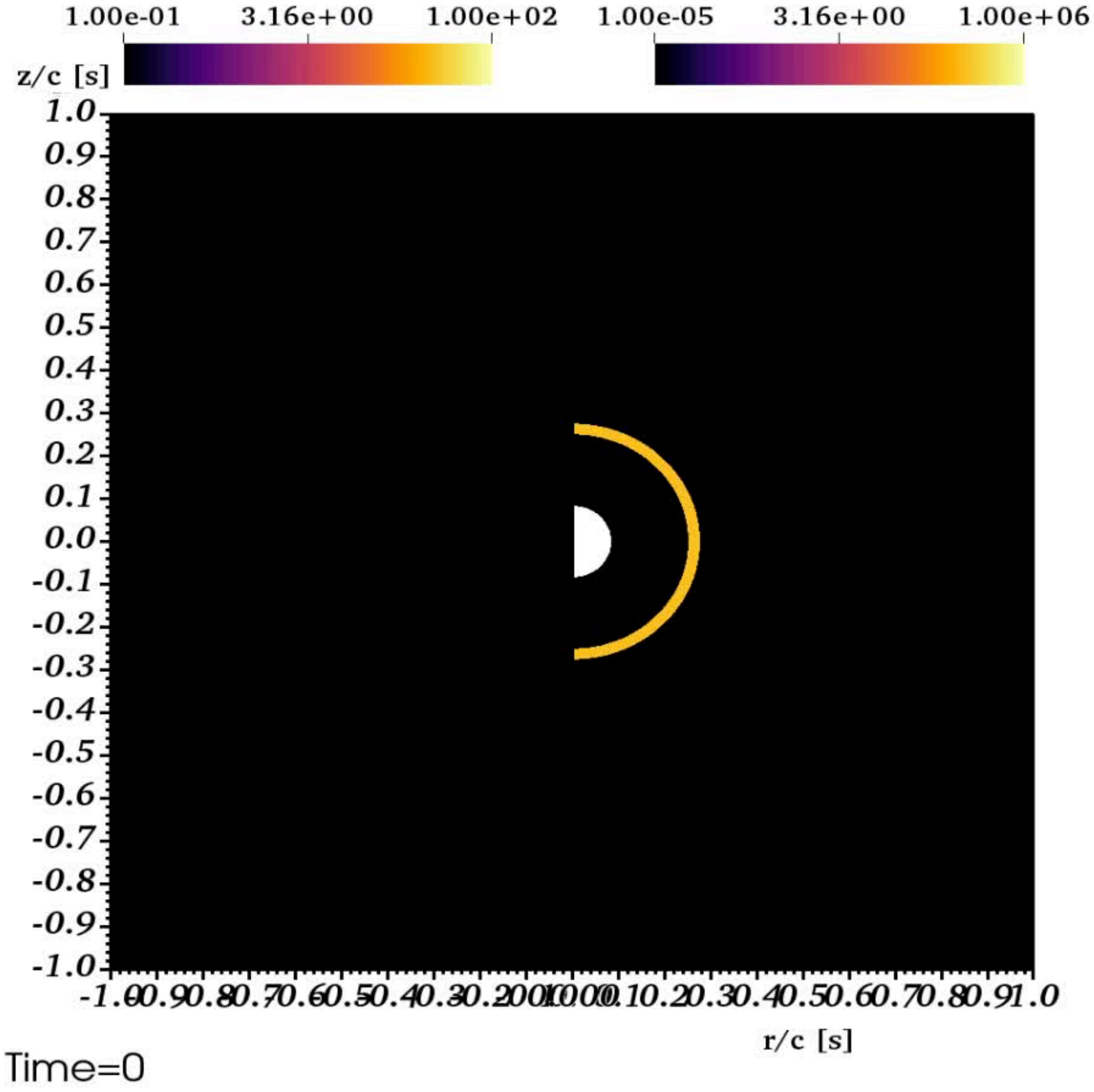


Intermediate Scales $10^8 \lesssim r \lesssim 10^{11}\,\mathrm{cm}$

RMHD or RHD simulations

Cartoon of GRB evolution (Stefano Ascenzi)

Post-merger evolution of the jet is a multi-scale problem

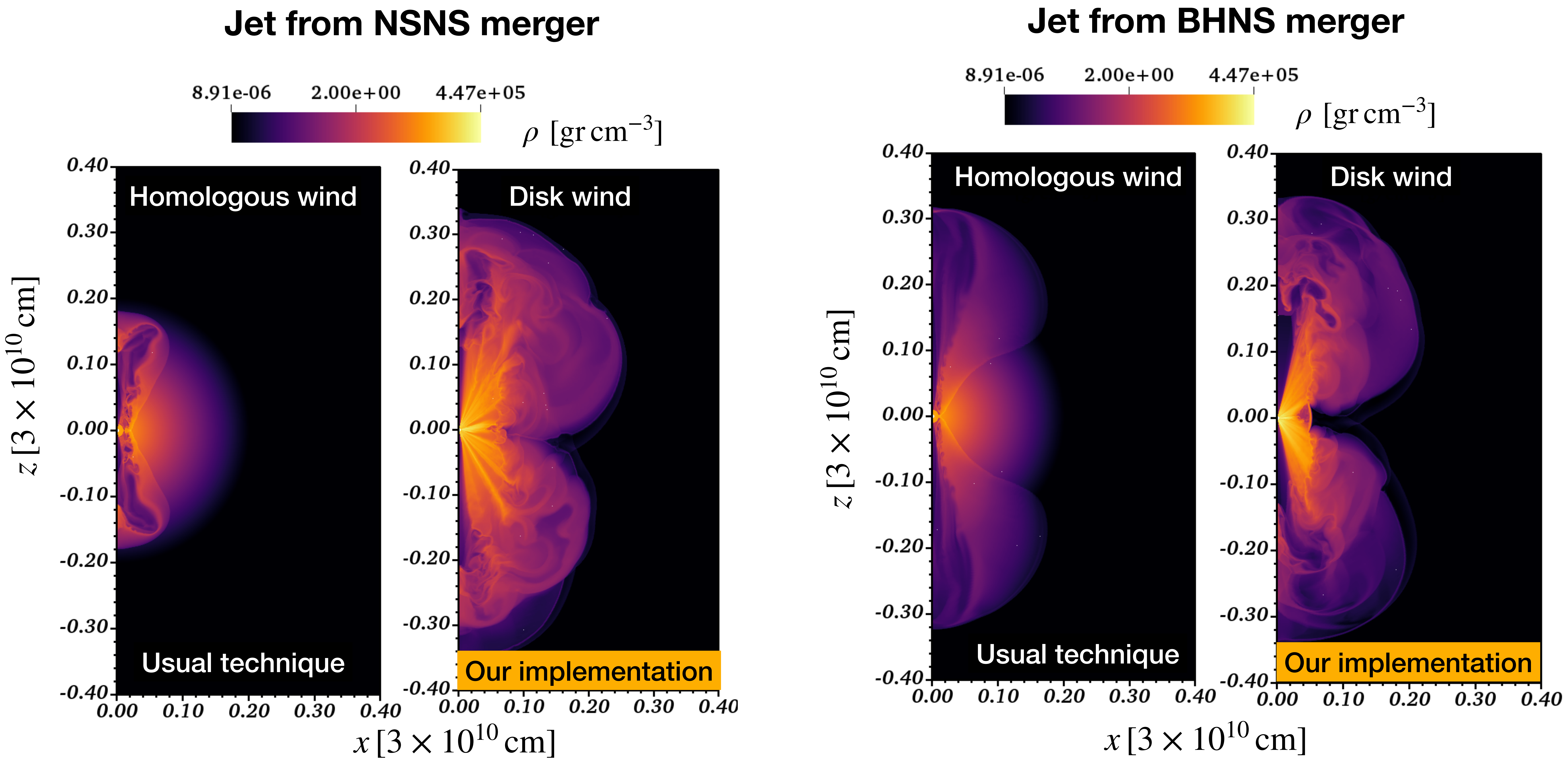


diate $10^8 \lesssim r \lesssim 10^{11}\,\mathrm{cm}$

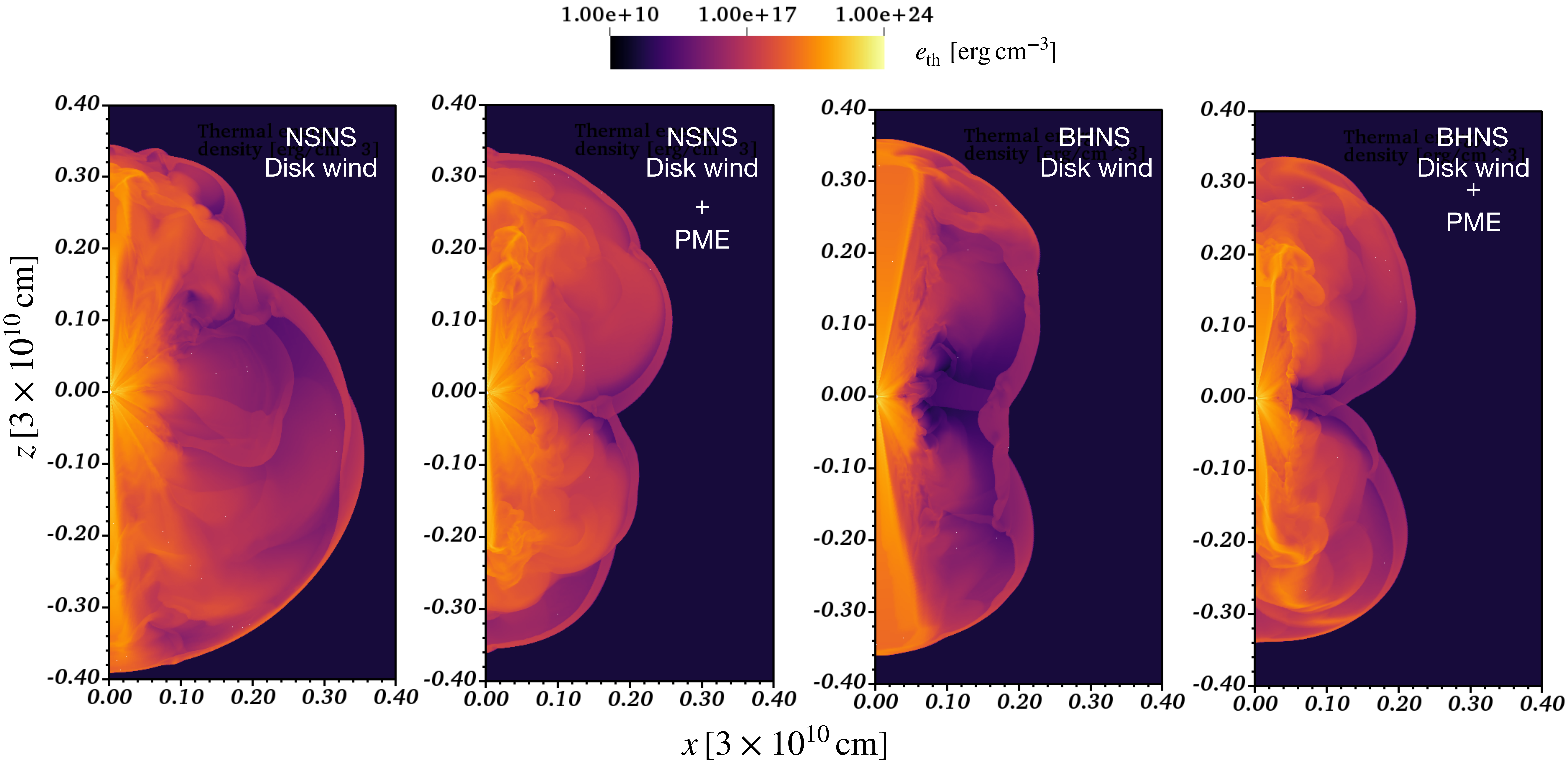
HD simulations

Urrutia, Janiuk, et al. 2024

Results of jet interaction

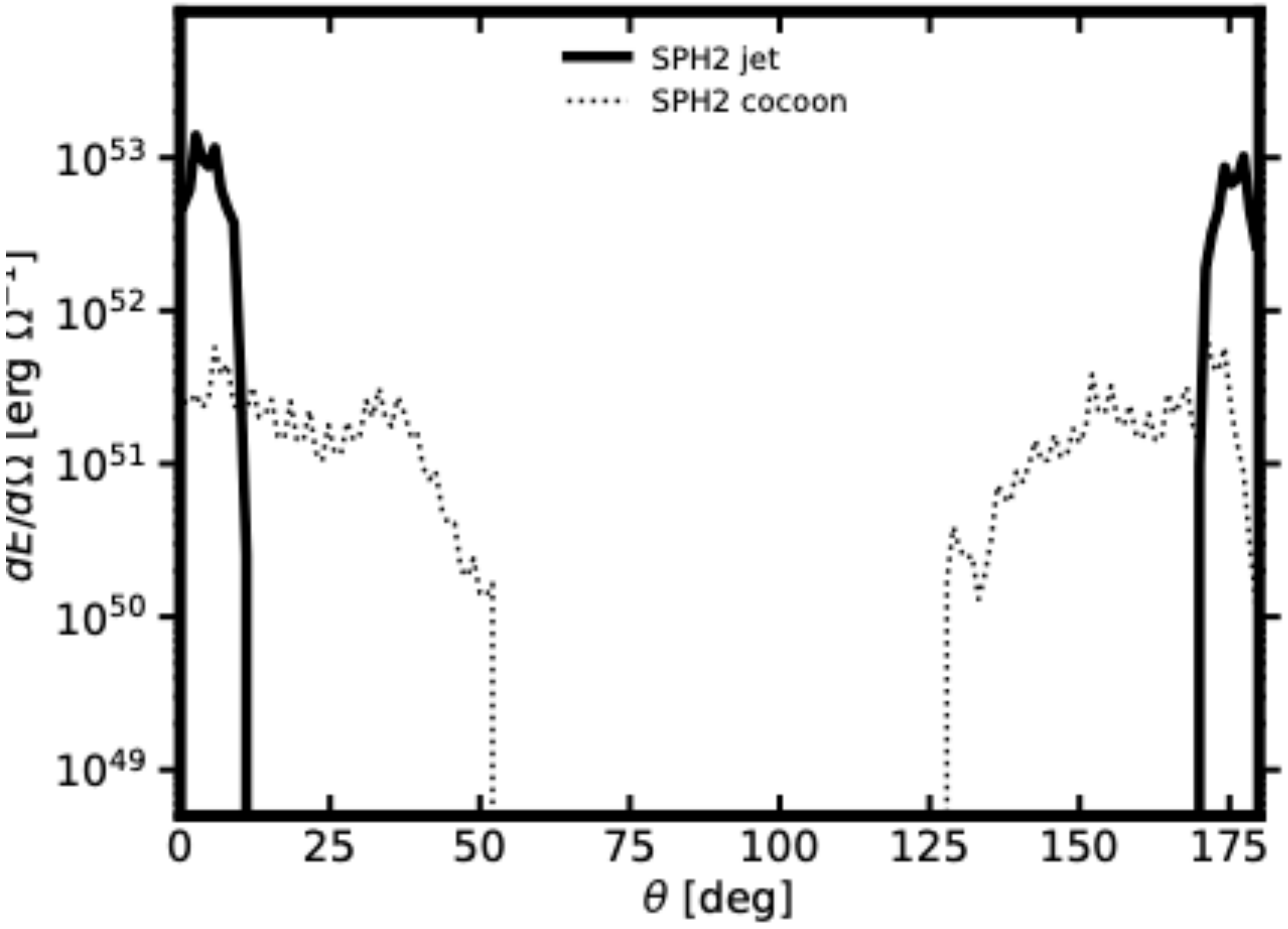


Results of jet interaction



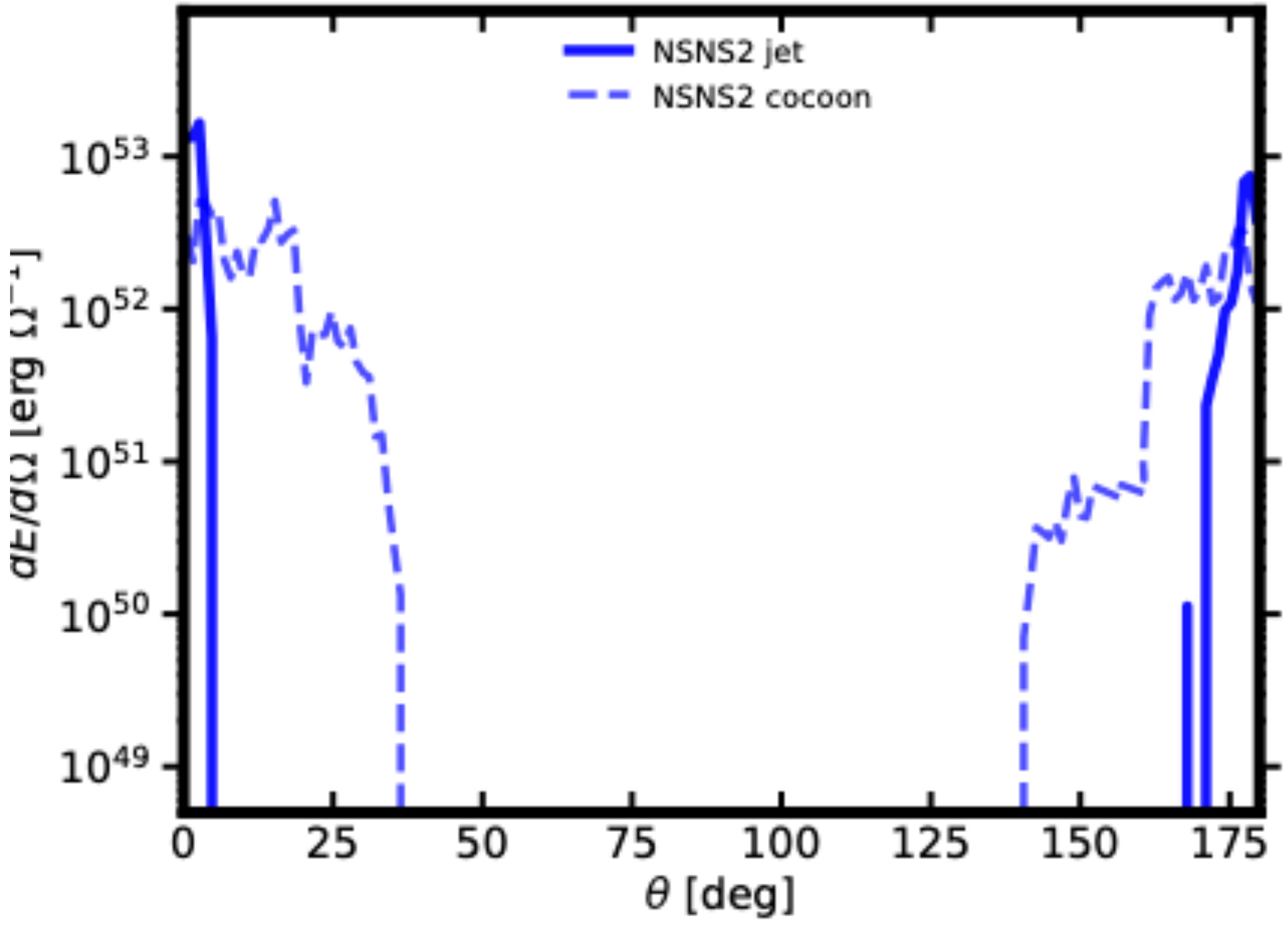
Disk wind changes the jet collimation and cocoon lateral expansion

Homologous wind

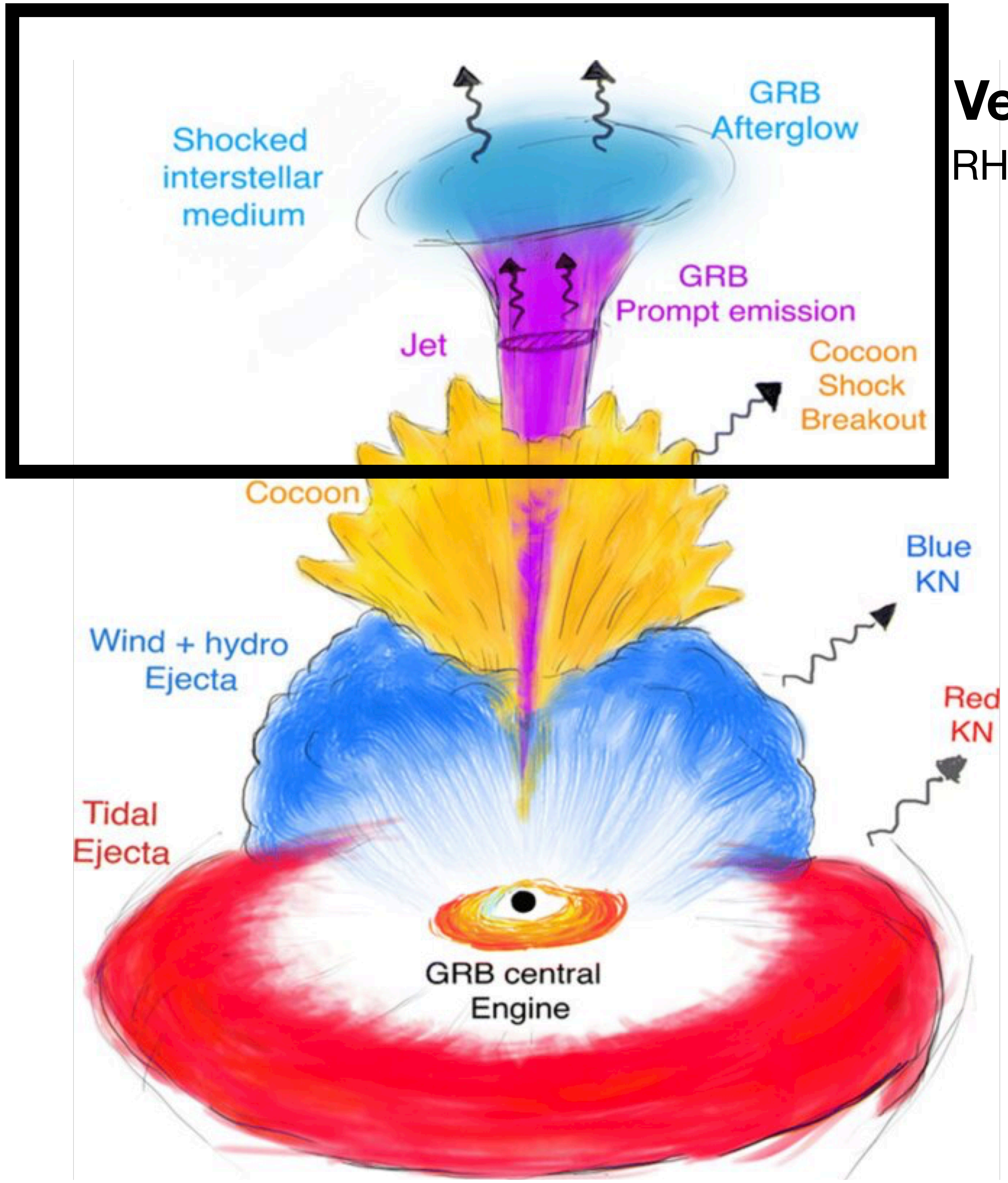


$$e = \Gamma^2 \rho h c^2 - p - \Gamma \rho c^2$$

Disk wind



Post-merger evolution of the jet is a multi-scale problem

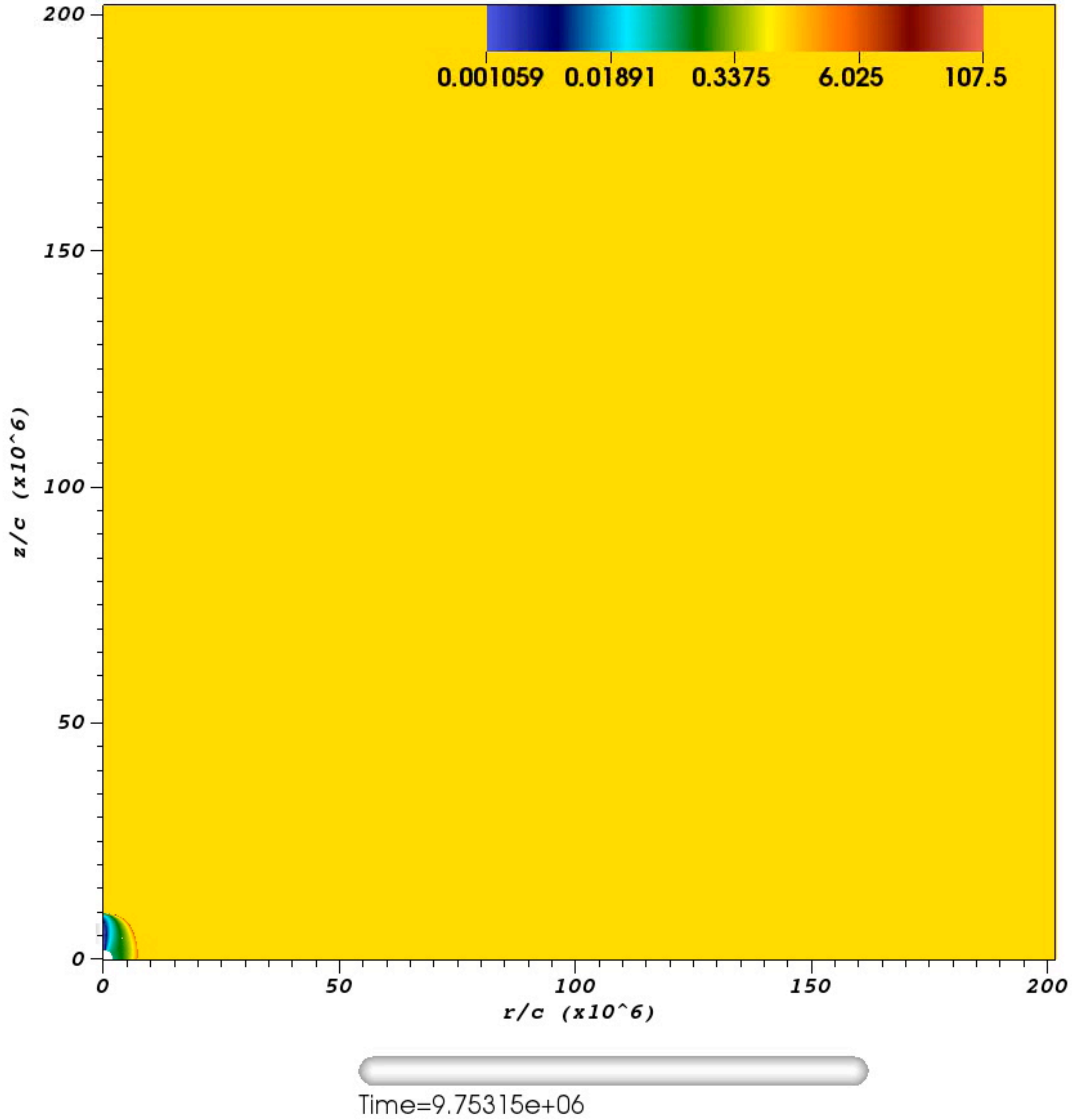


Cartoon of GRB evolution (Stefano Ascenzi)

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

RHD simulations or Analytical extrapolations

Pos ulti-scale problem

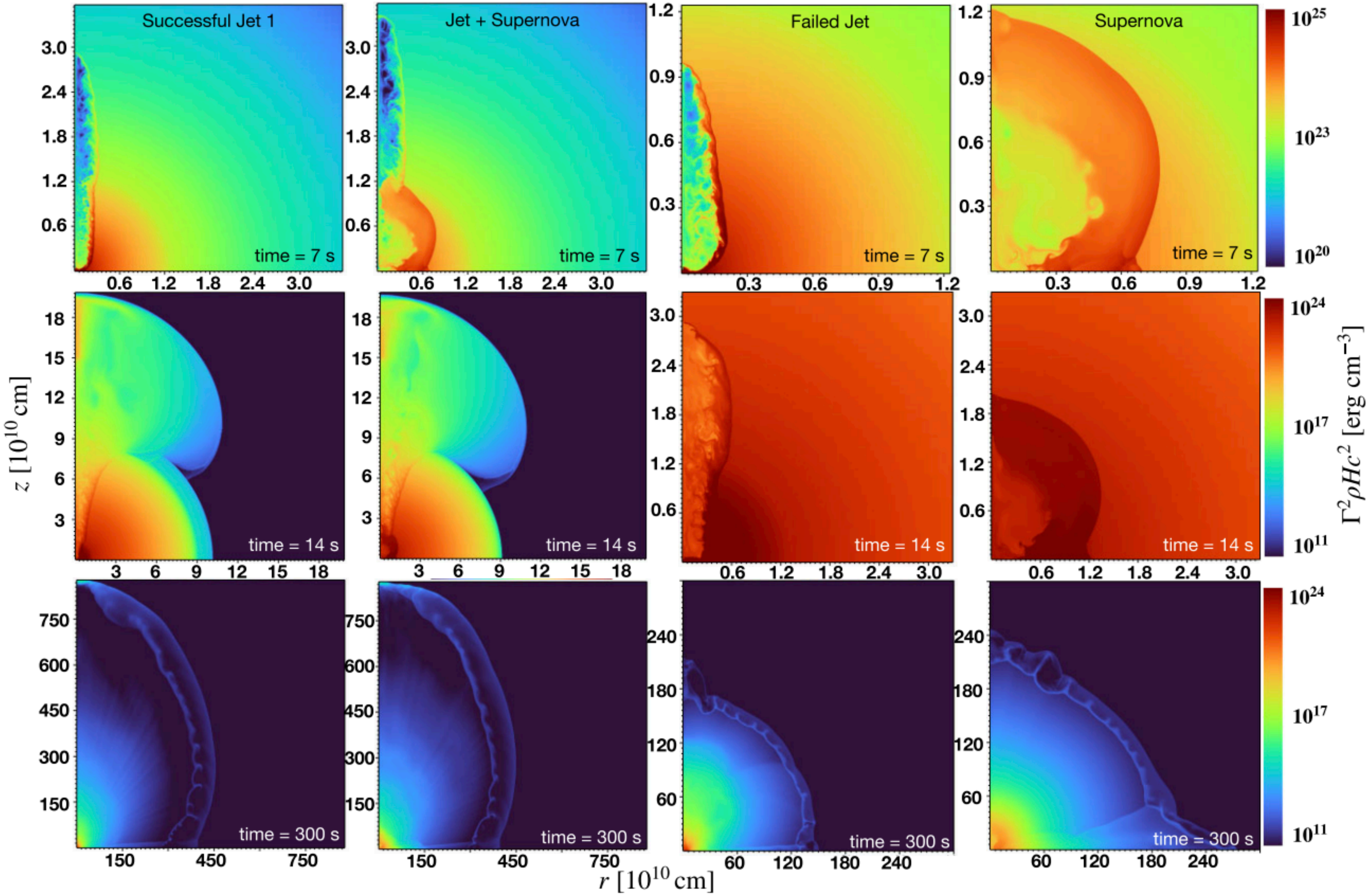


Very Large Scales $r \gtrsim 10^{16}\,\mathrm{cm}$

RHD simulations or Analytical extrapolations

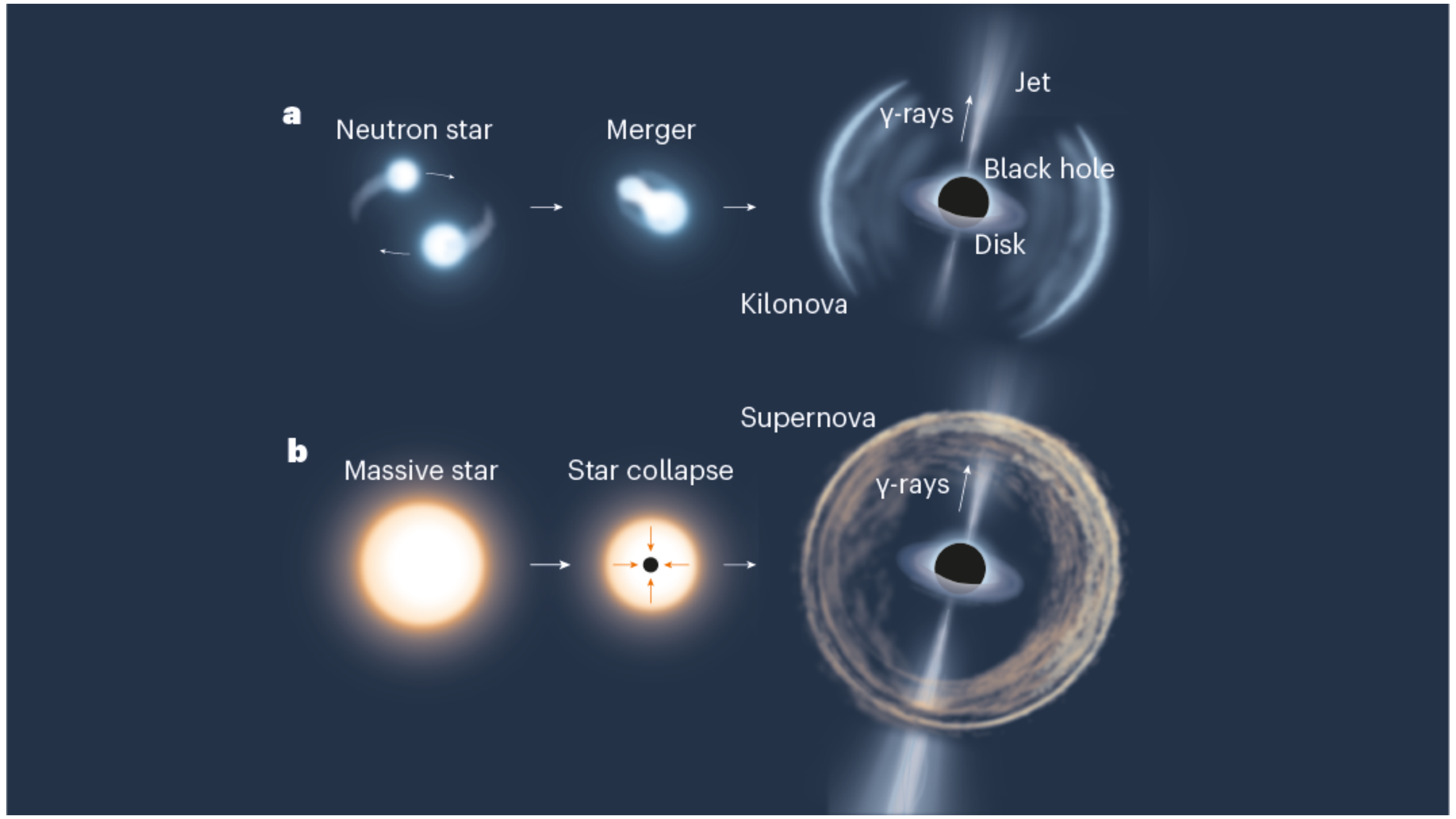
Urrutia in prep

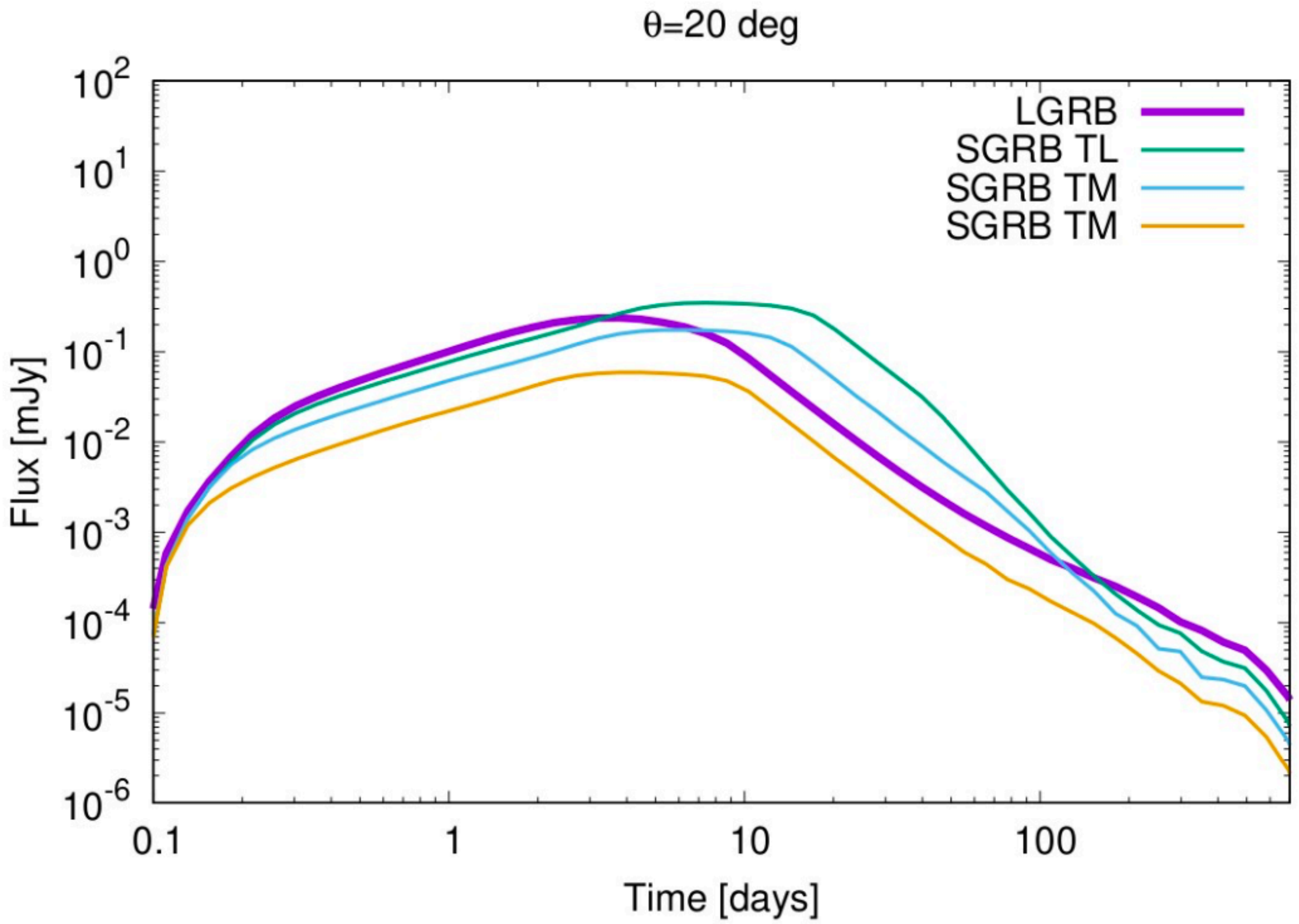
Long GRBs



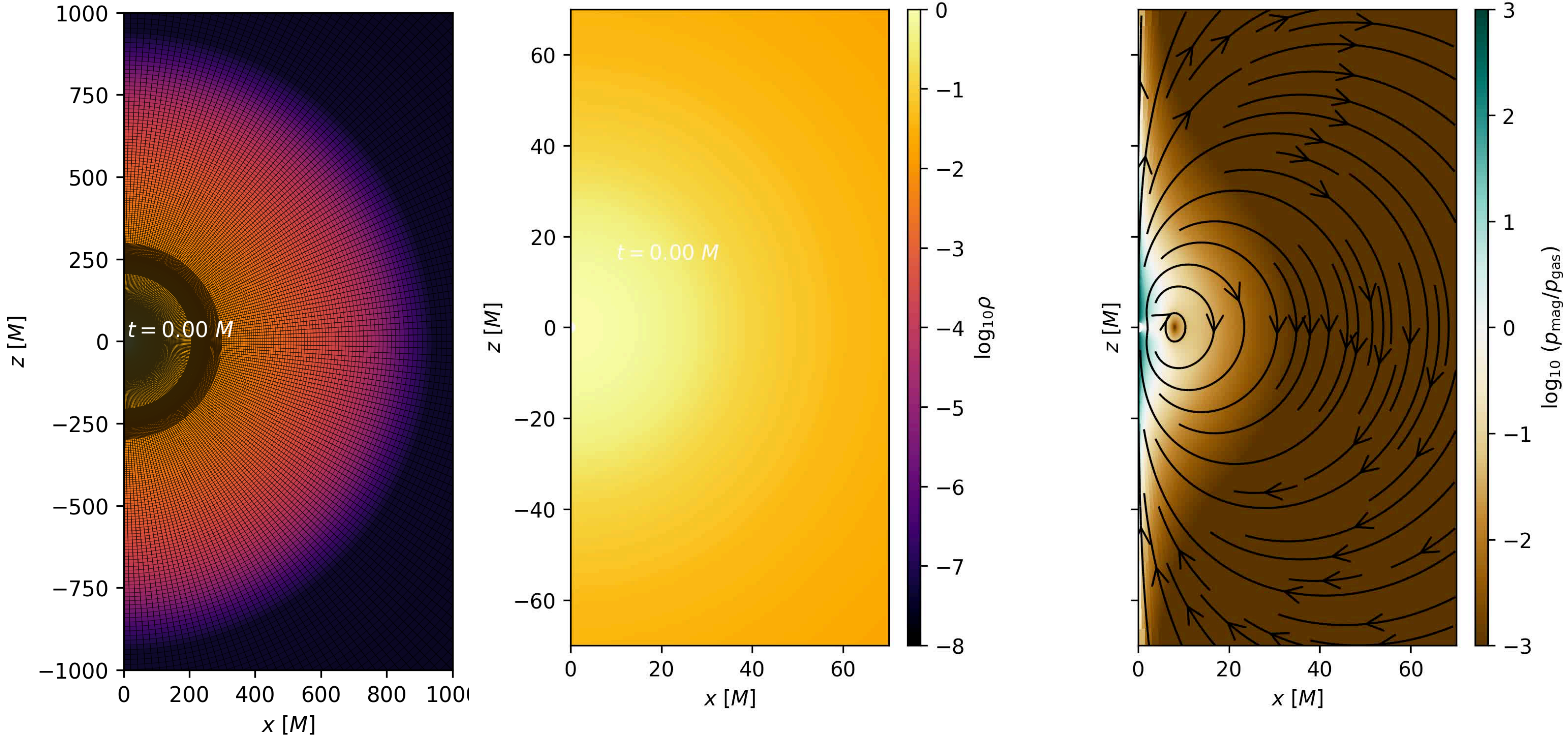
Successful Jet 1
Jet + Supernova
Failed Jet
Supernova
time = 7 s
time = 14 s
time = 300 s
$z\ [10^{10}\,\mathrm{cm}]$
$r\ [10^{10}\,\mathrm{cm}]$
$\Gamma^2 \rho H c^2\ [\mathrm{erg\ cm^{-3}}]$
10^{25}
10^{23}
10^{20}
10^{24}
10^{17}
10^{11}

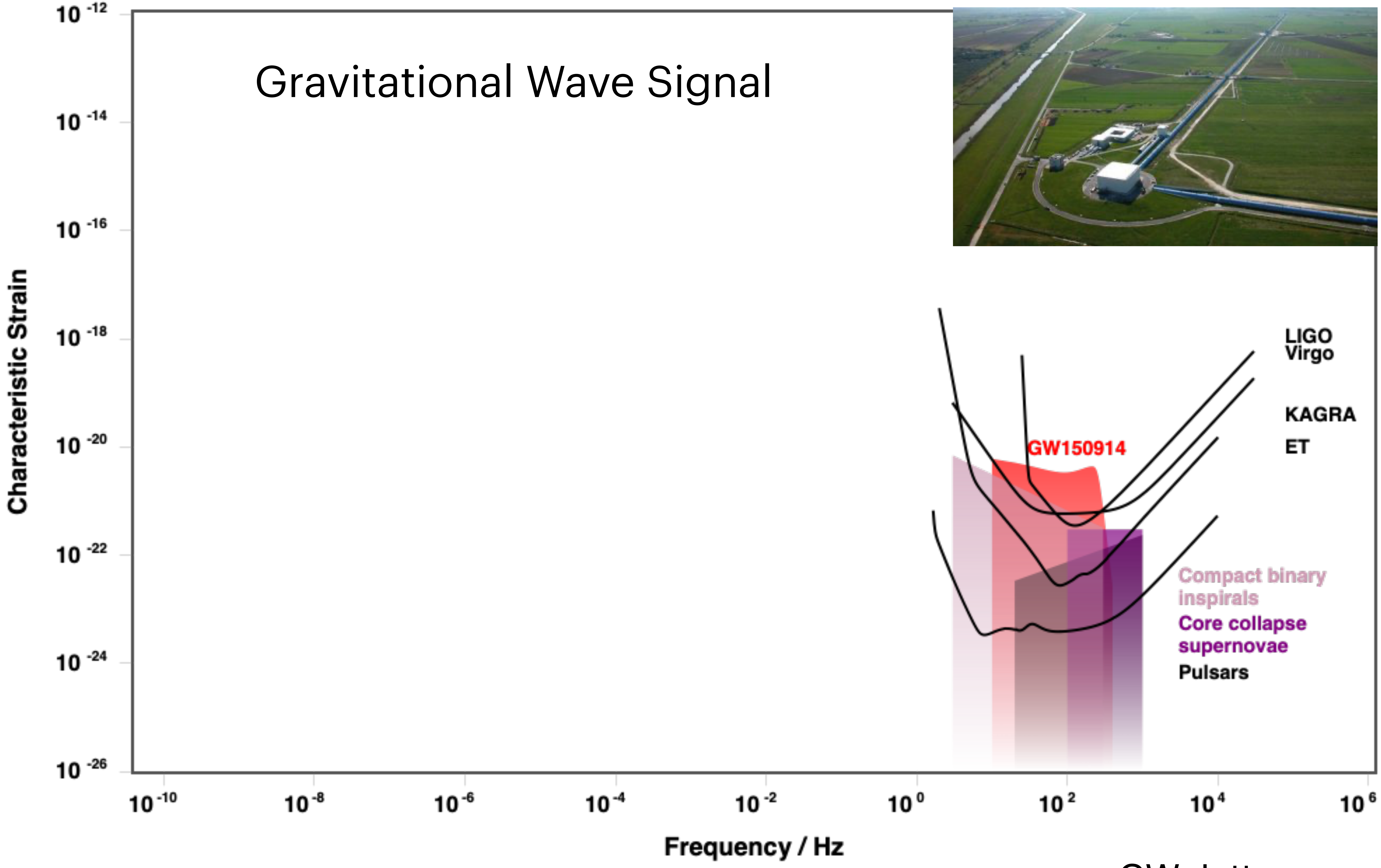
What element modifies the radiation at large scales?



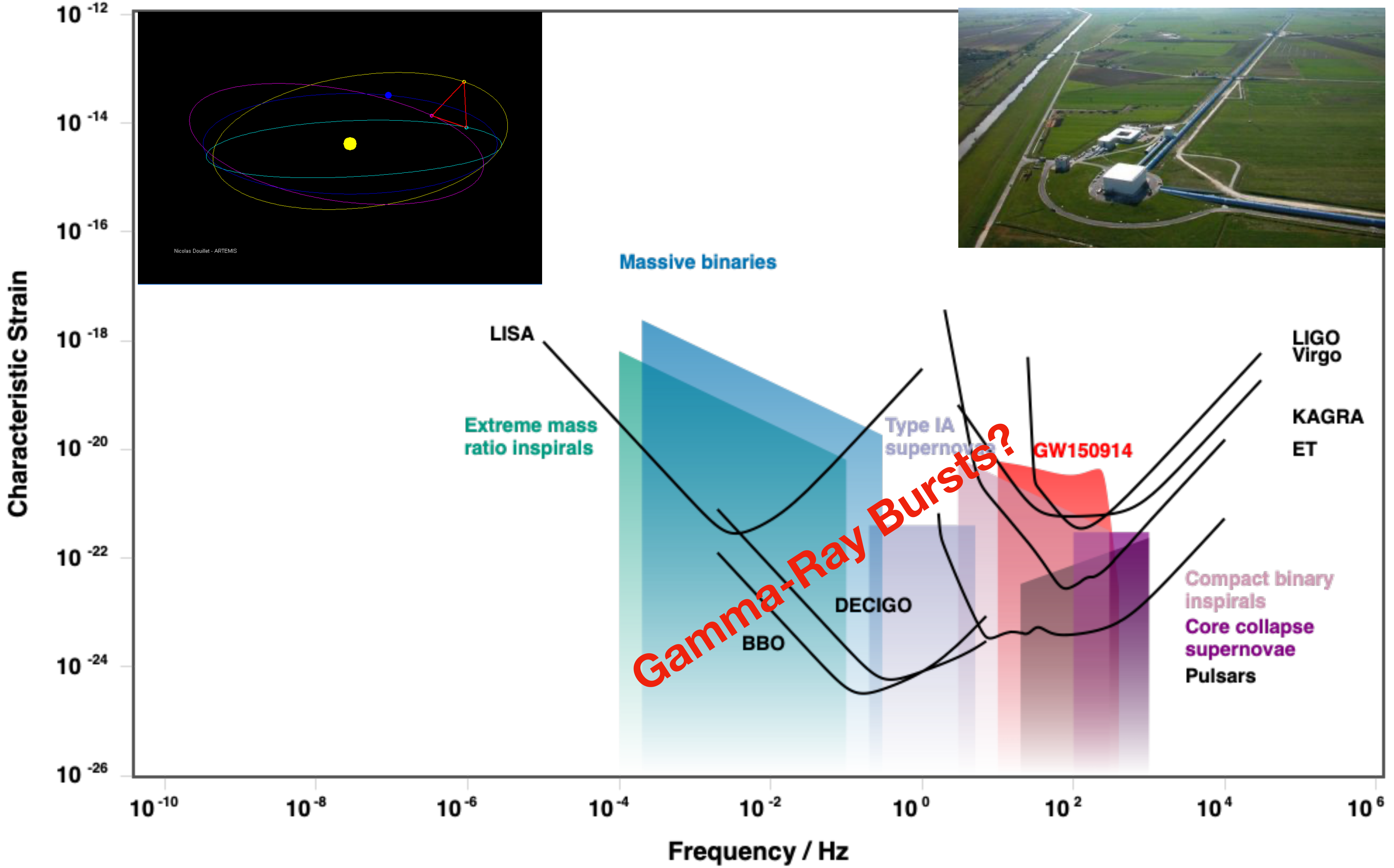


Exploring the central engine for Long GRBs





GWplotter.com



GWplotter.com

GW signal from jet simulations (Urrutia et al. 2023)

$$h_+ \equiv h_{xx}^{TT} = -h_{yy}^{TT} = \frac{2G}{c^4}\frac{E}{D}\frac{\beta^2 \sin^2\theta_v}{1-\beta\cos\theta_v}\cos 2\Phi$$

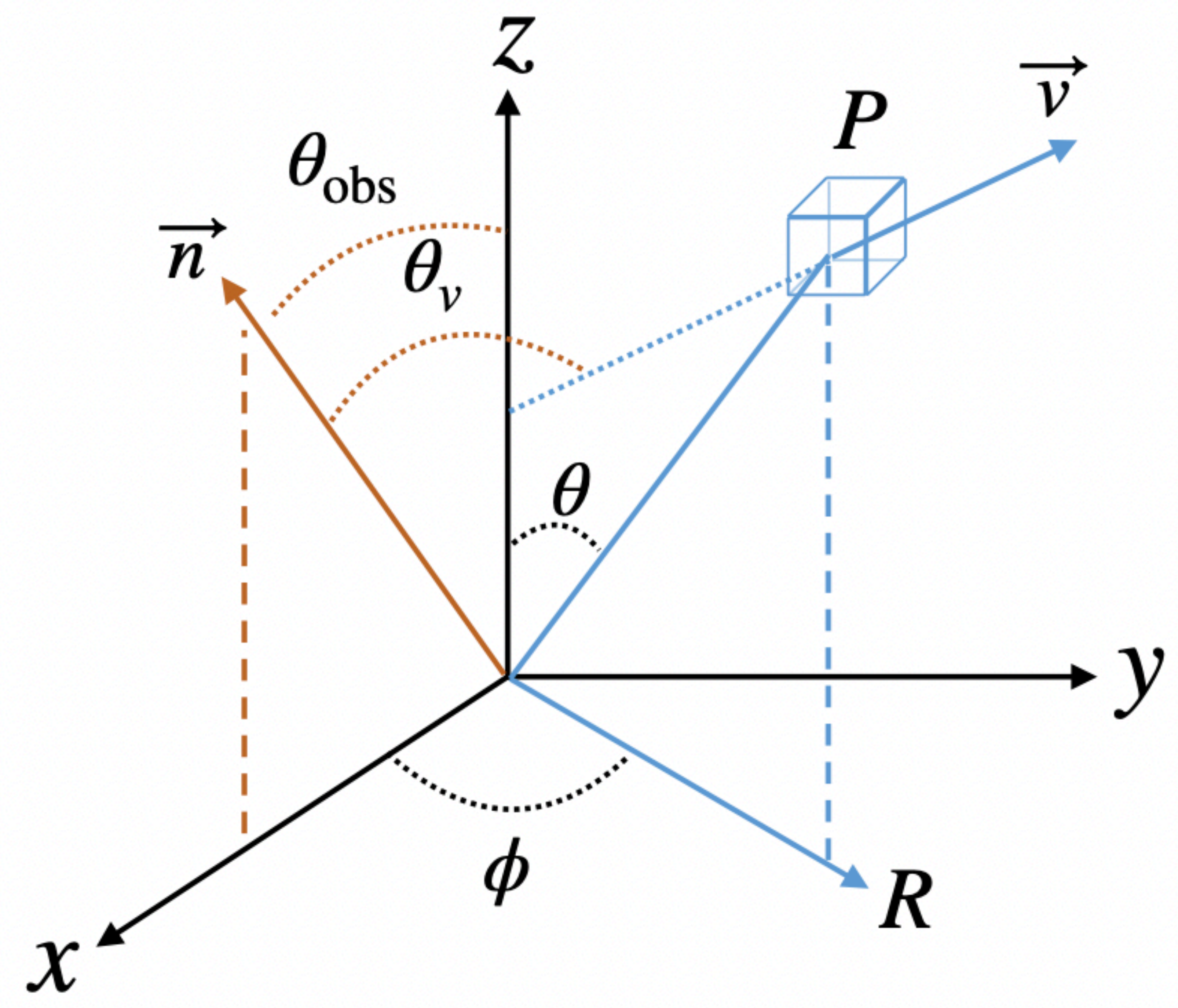
$$h_\times \equiv h_{xy}^{TT} = h_{yx}^{TT} = \frac{2G}{c^4}\frac{E}{D}\frac{\beta^2 \sin^2\theta_v}{1-\beta\cos\theta_v}\sin 2\Phi$$

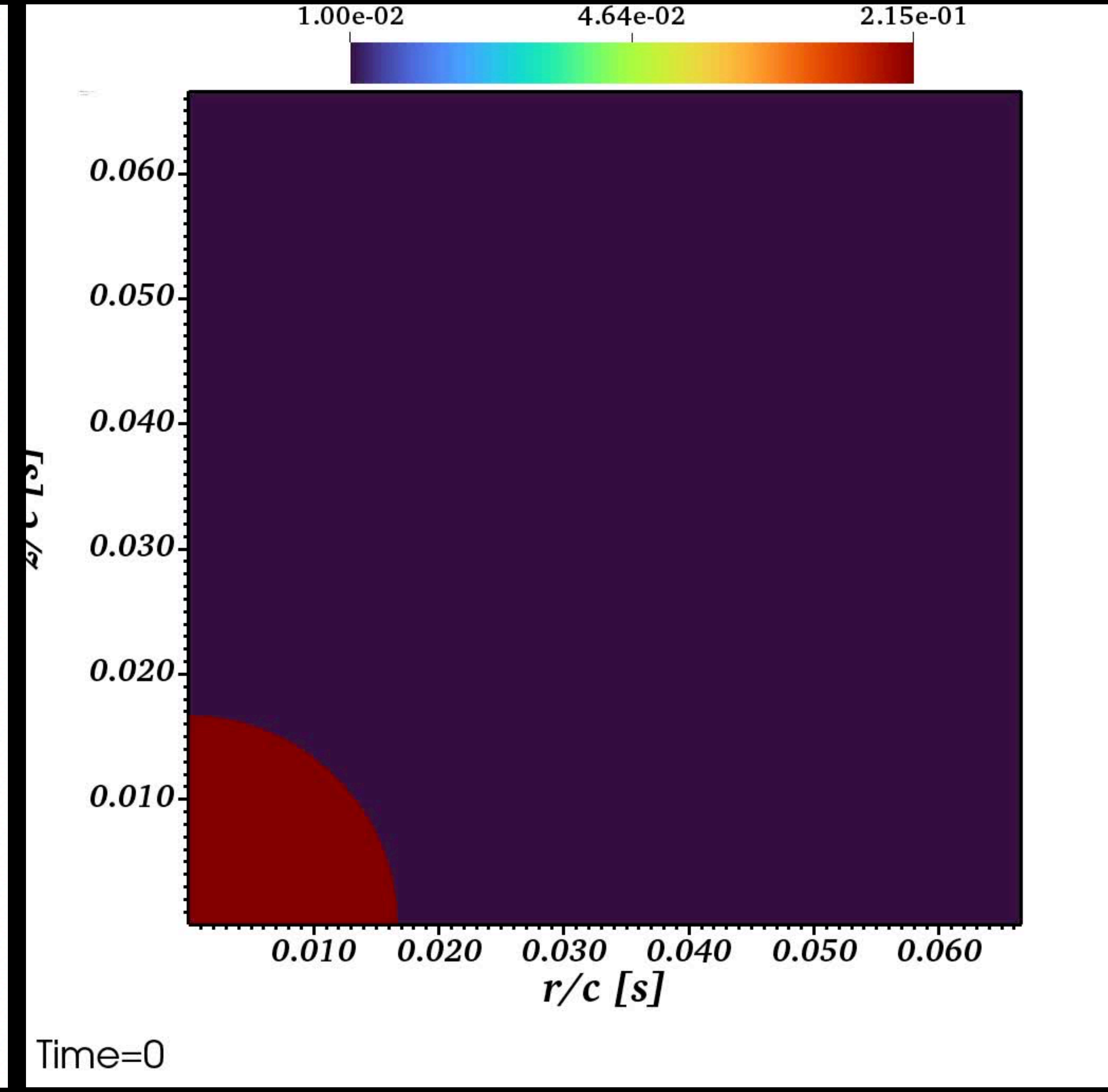
Braginskii & Thorne 1987,

Segalis & Ori 2001,

Birnholtz & Piran (2018),

Leiderschneider & Piran 2021

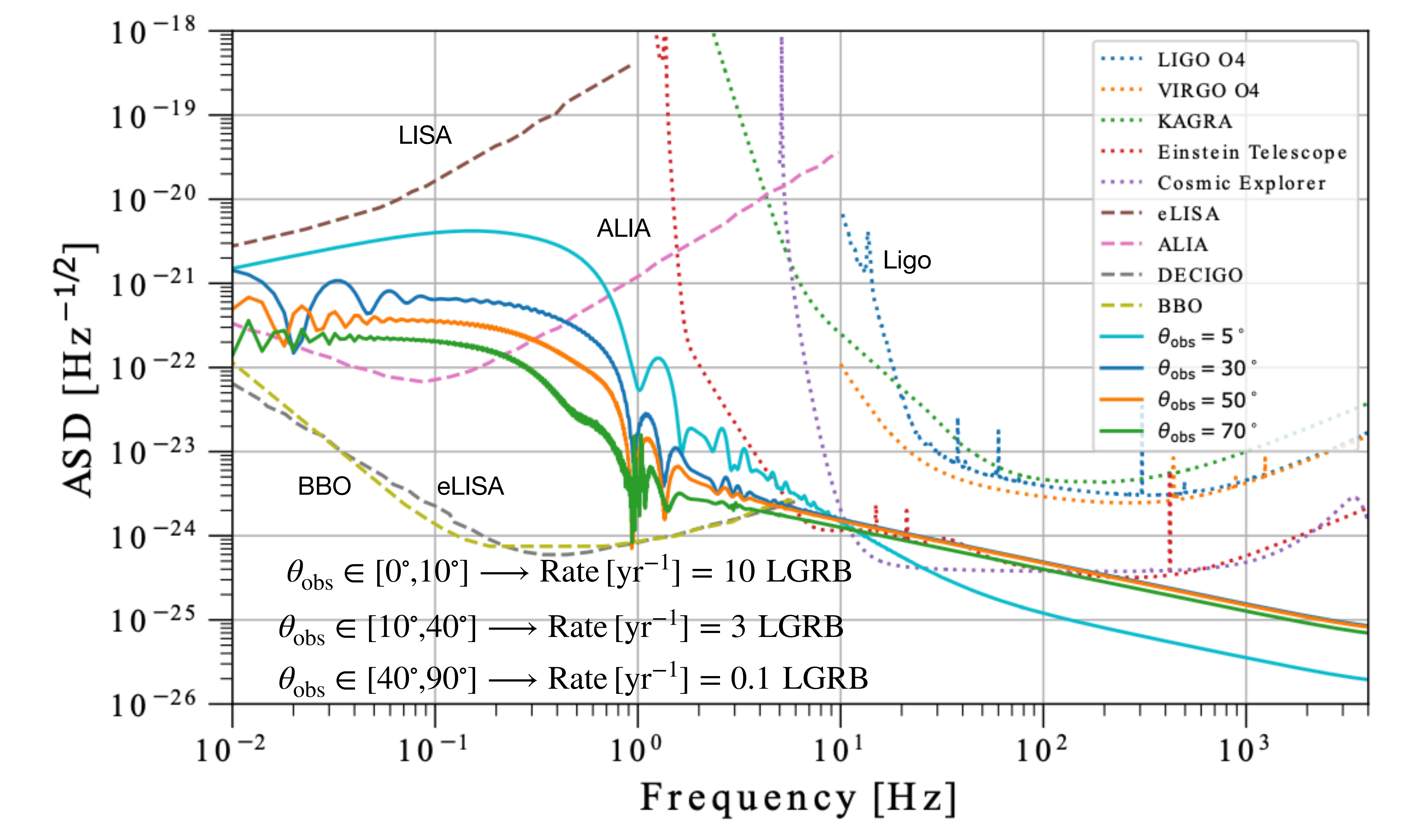




$$\cos\theta_v = \hat{n}\cdot\hat{\beta} = \left(\beta_R \sin\theta_{obs}\cos\phi + \beta_z\cos\theta_{obs}\right)/\beta$$

Detectability

$$h \propto \frac{E}{Dc^4}$$

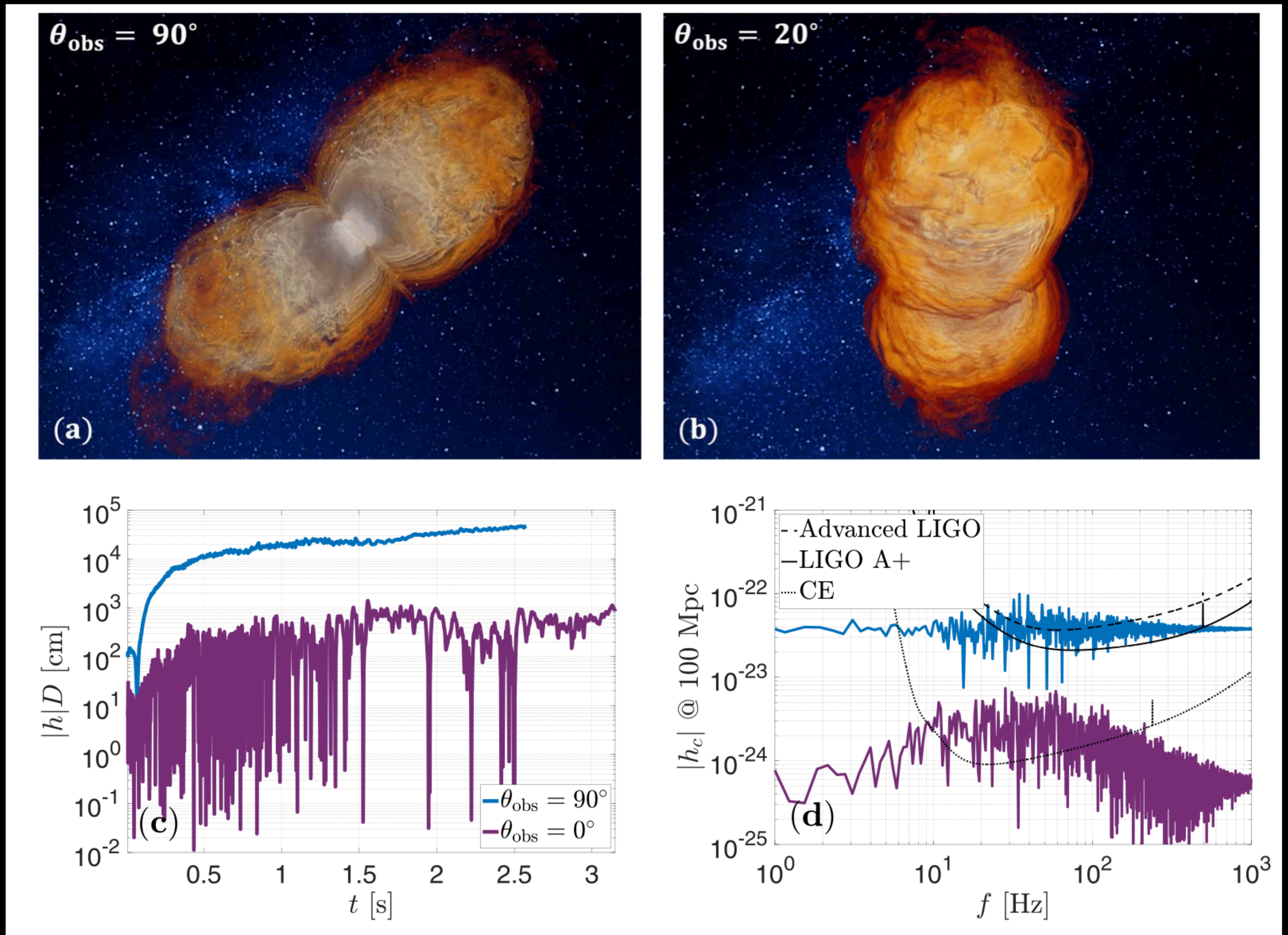


Sensitivity curves from Moore et al. 2014

Our jet model from Urrutia et al. 2022

$E = 10^{52}\,\mathrm{erg}$ $\quad D = 1\,\mathrm{Mpc}$

High resolution 3D simulation



Gottlieb et al. 2023

$$h \approx 10^{-22} \frac{40\,\mathrm{Mpc}}{D} \frac{E}{10^{53}\,\mathrm{erg}}$$

$$E_{\mathrm{cocoon}} = 10^{52} - 10^{53}\,\mathrm{erg}$$

$$\Delta t \propto 10^{-4}\,\mathrm{s}$$ (Temporal resolution)

Storage ~ Petabytes

Our Currently methodology

Jet dynamics
(simulations)

Post-processing
(GW signals)

Detectability

Sotorage ~ TB
Computational time ~ 8000 h
Post-processing ~ 100 h

New methodology

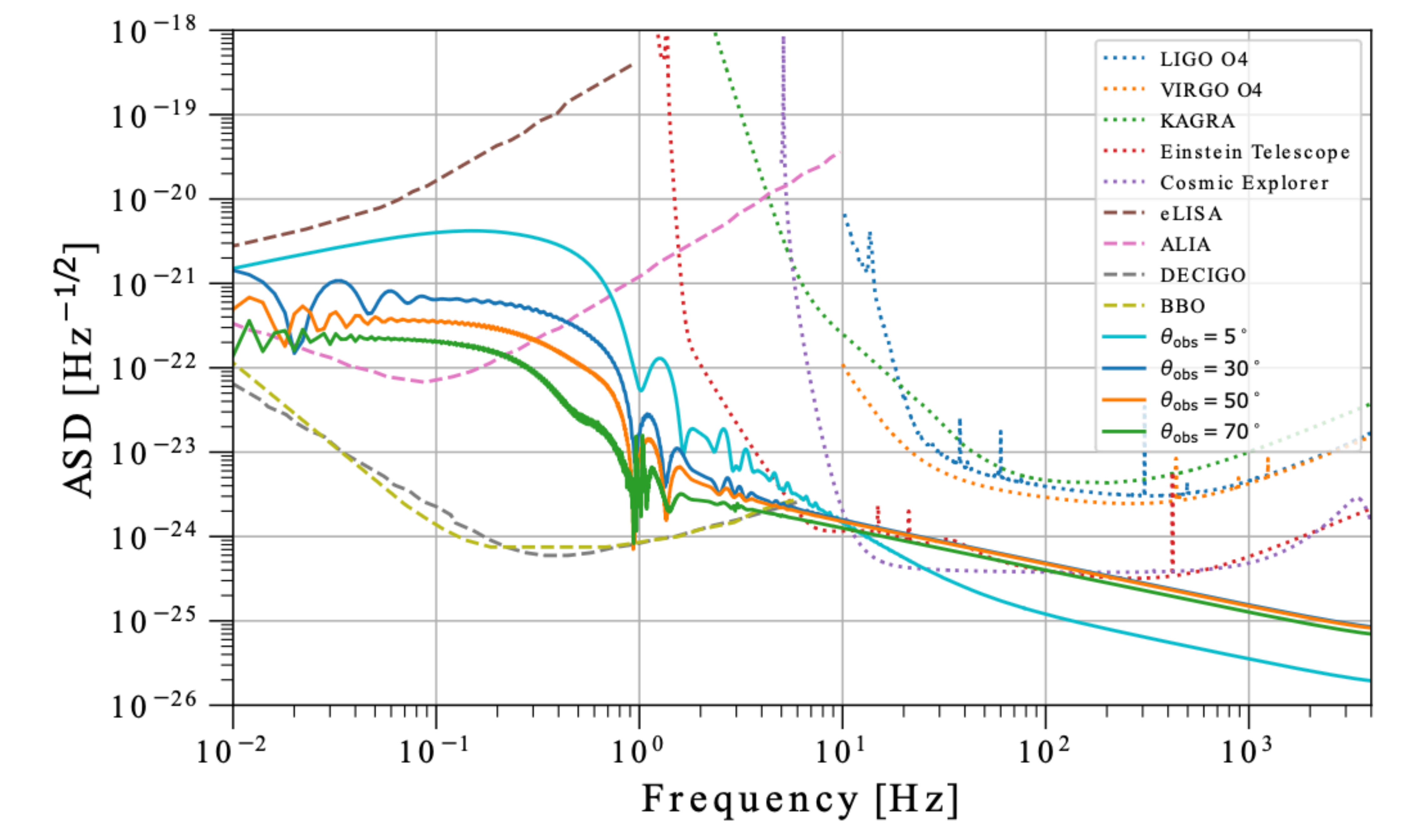
New implementation
Jet dynamics
(simulations)
+ GW signals

Detectability

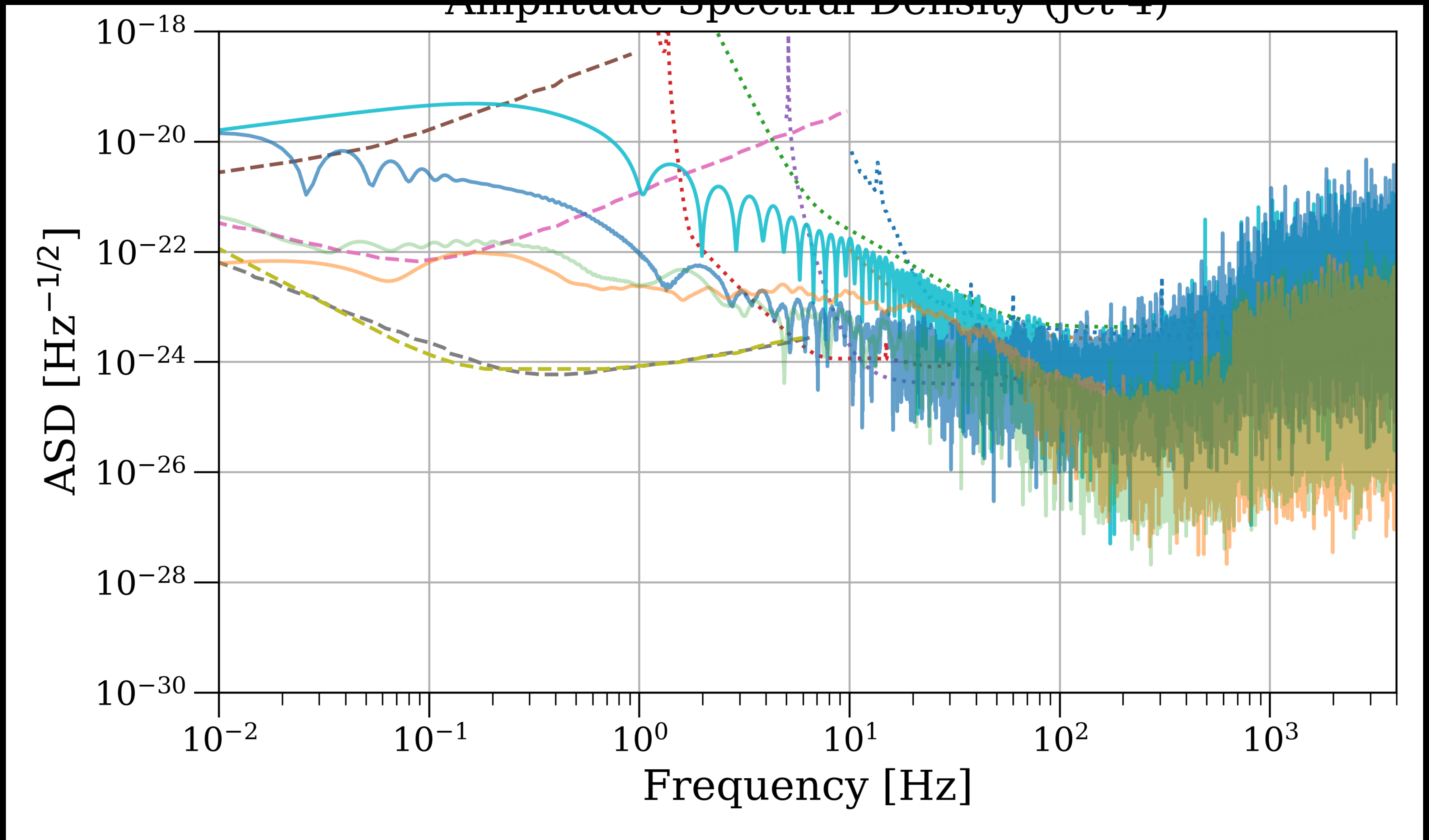
Sotorage ~ GB
Computational time: 120 000 h

Tests with the new numerical setup

Old numerical setup



New numerical setup

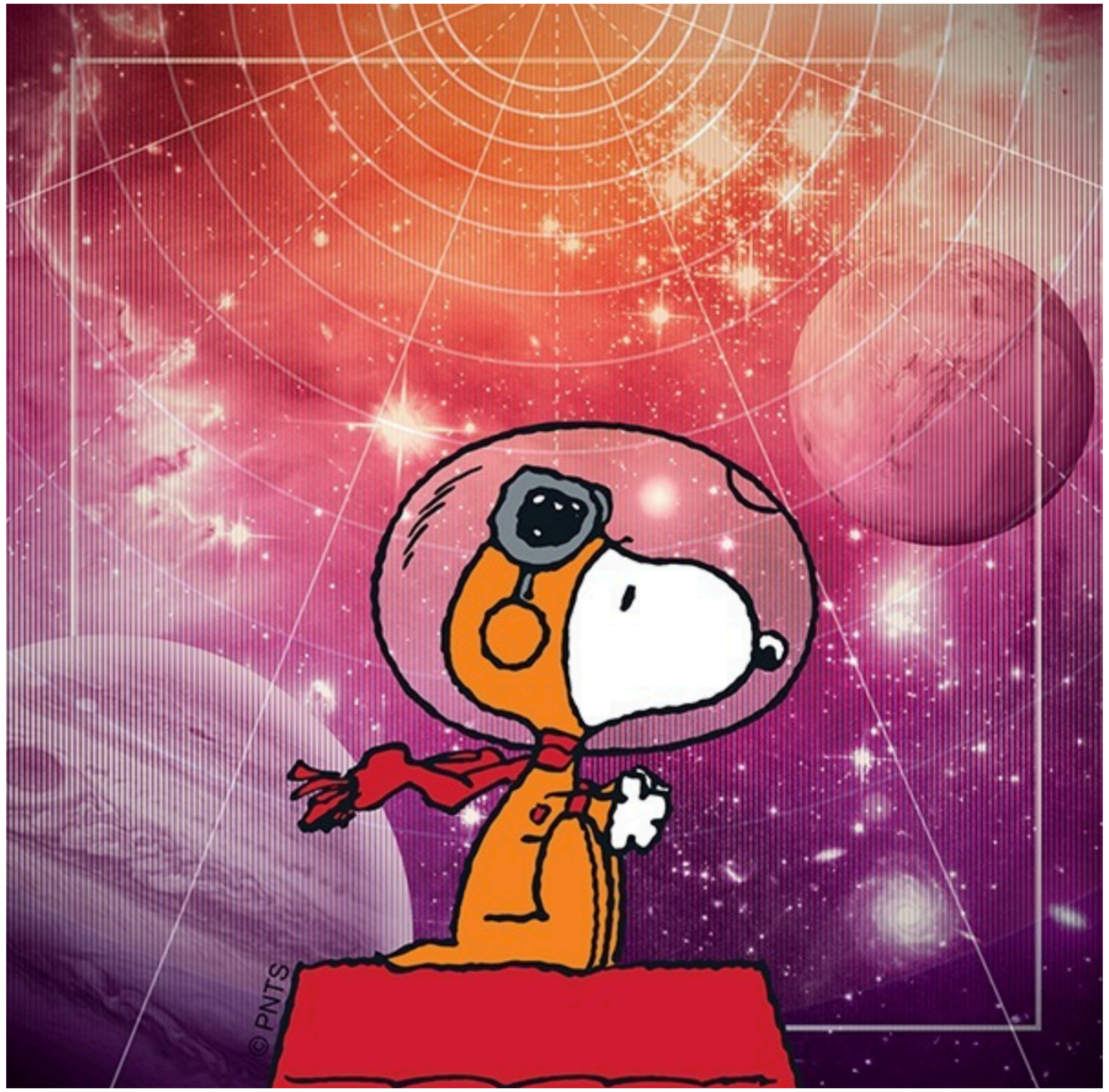


Conclusions

- Astrophysical models need to be improved due to the information obtained by a new generation of telescopes and GW detectors.
- Self-consistency with the central engine modifies substantially the propagation at a large scale, modifies predictions and probably reduces the degree of degeneracy.
- Predictions for multi-messenger astronomy.
- High-cost simulations are modified strategically to reduce computational time or storage and open the possibility to run more models.

Simulations	# Models	# Tests	# Simulations	Time per each simulation (hr)	# cpus	Time for tests (hr)	Time of simulations (hr)	Total hours
3D simulations of Long GRBs	10	5	10	360	120	1,920	432,000	433,920
Gravitational waves by GRBs	10	10	10	360	120	3,720	432,000	435,720
Post Processing Radiation			20	36	1		720	720
Post Processing 3D			20	122	1		2,440	2,440
Total						**5,640**	**867,160**	**872,800**

Dziękuję - Thank you! - ¡Gracias!

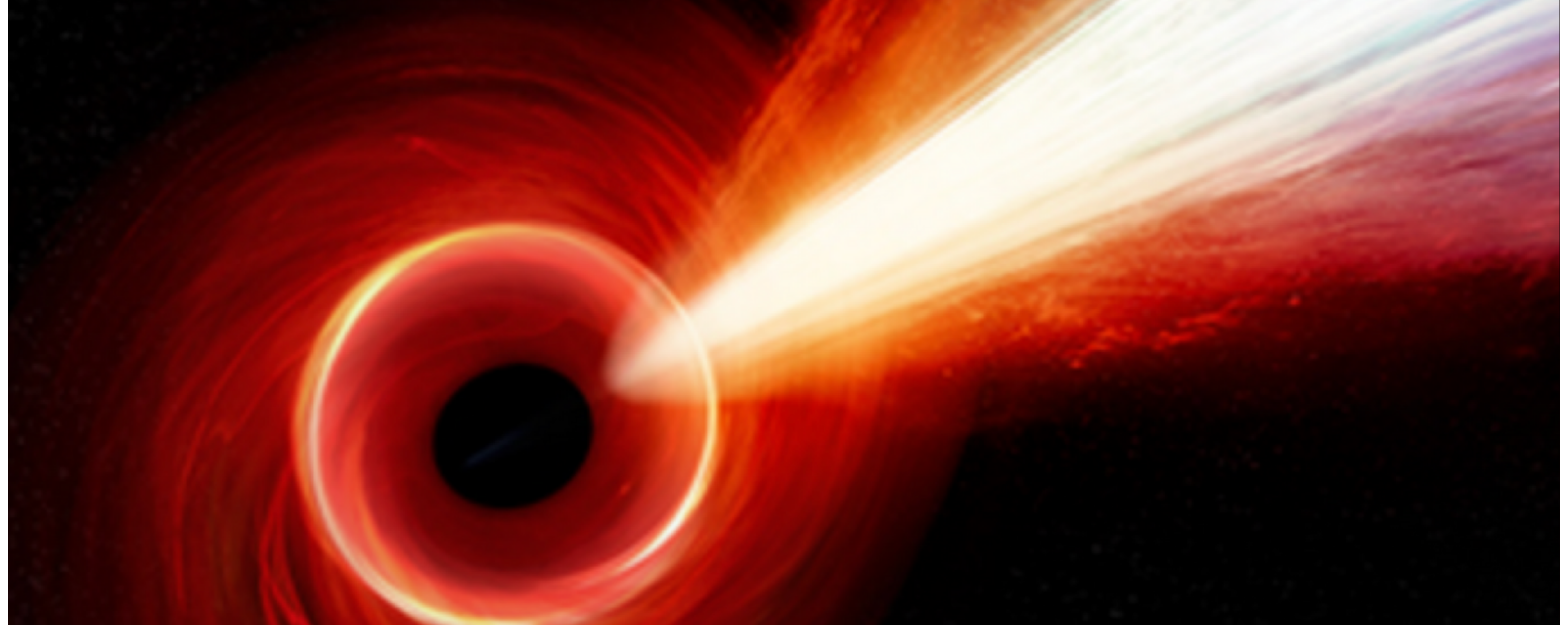


Gerardo Urrutia
gurrutia@cft.edu.pl

National Science Centre
Poland

Galactic and Extragalactic X-ray Transients

Theory and observational perspectives



Key topics:
1. Quasi periodic eruptions in accreting black holes
2.Tidal disruption events
3. Changing activity of supermassive black holes
4. Fast variability of Galactic X-ray sources
5. Accretion instabilities and gravitational waves from black hole and neutron star binaries
6. Testing General Relativity with supermassive black holes

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https://cl-agn.cft.edu.pl

Abstract submision deadline: May 1 st

SOC

Bozena Czerny (CFT PAN) - Co-Chair
Agnieszka Janiuk. (CFT PAN) - Co-Chair
Szymon Kozłowski (University of Warsaw)
Vladimir Karas (Astronomical Institute, Prague)
Mikołaj Korzyński (CFT PAN)
Alex Markowitz (CAMK PAN, Warsaw)
Benny Trakhtenbrot (Tel Aviv University)
Michal Zajacek (Masaryk University, Brno)

LOC

Gerardo Urrutia (CFT PAN)
Ashwani Pandey (CFT PAN)
Raj Prince (CFT PAN)

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Afterglow Recipe

- Energy distribution
- Evolution of blast wave
- Standar model synchrotron

$$\Gamma_{\rm sh}^2 = \frac{(17-4k)E}{8\pi\rho(r)c^5t^3} \ .$$

$$B = (32\pi m_p \varepsilon_B n)^{1/2}\Gamma c \ . \tag{1.47}$$

The blast wave amplifies the magnetic field of the external media environment, and the magnetic field lines acquire a random orientation. As a consequence, the electron population is randomly oriented with the Lorentz factor $\Gamma \gg 1$. The power spectrum [$\mathrm{Hz}^{-1}\mathrm{s}^{-1}$] in the observer frame is given by $P(\Gamma_e) = \frac{4}{3}\sigma_T c\Gamma^2\Gamma_e^2 B^2/8\pi$, and the frequency $\nu(\Gamma_e) = \Gamma\Gamma_e q_e B/2\pi m_e c$, being Γ the Lorentz factor of the fluid. The spectral characteristic peak is given by,

$$P_{\rm max} \approx \frac{P(\Gamma_e)}{\nu(\Gamma_e)} = \frac{m_e c^2 \sigma_T}{3q_e}\Gamma B \ , \tag{1.48}$$

1998; Granot & Sari, 2002). The total number of swept-up electrons in the post shock fluid is $N_e = 4\pi R^3 n/3$. The maximum flux is given by the frequency $\nu_m = \nu(\Gamma_m)$. The observed peak flux at distance D from the source is $F_{\nu,\rm max} = N_e P_{\nu,\rm max}/4\pi D^2$. In the fast cooling regime, the spectrum is,

$$F_\nu = \begin{cases} (\nu/\nu_c)^{1/3} F_{\nu,\rm max} & \text{if} \quad \nu_c > \nu \ , \\ (\nu/\nu_c)^{-1/2} F_{\nu,\rm max} & \text{if} \quad \nu_m > \nu > \nu_c \ , \\ (\nu_m/\nu_c)^{-1/2}(\nu/\nu_m)^{-p/2} F_{\nu,\rm max} & \text{if} \quad \nu > \nu_m \ . \end{cases} \tag{1.50}$$