

Numerical simulations of Long Gamma Ray Bursts Jets from small to large scales

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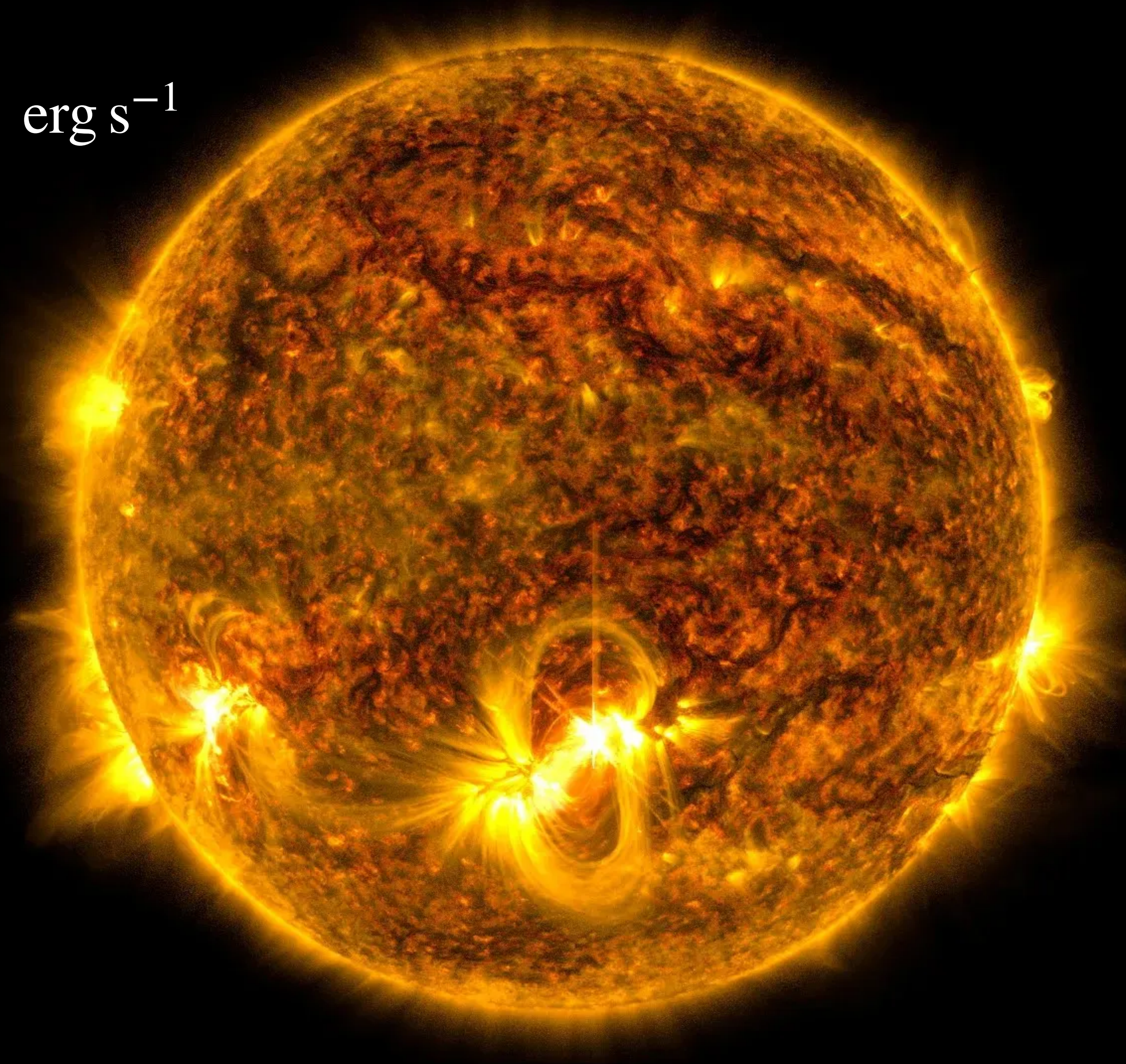
$$L_{\odot} \sim 3.8 \times 10^{33} \text{ erg s}^{-1}$$

10^{24}



$$R_{\star} \sim 10^{10} \text{ cm}$$

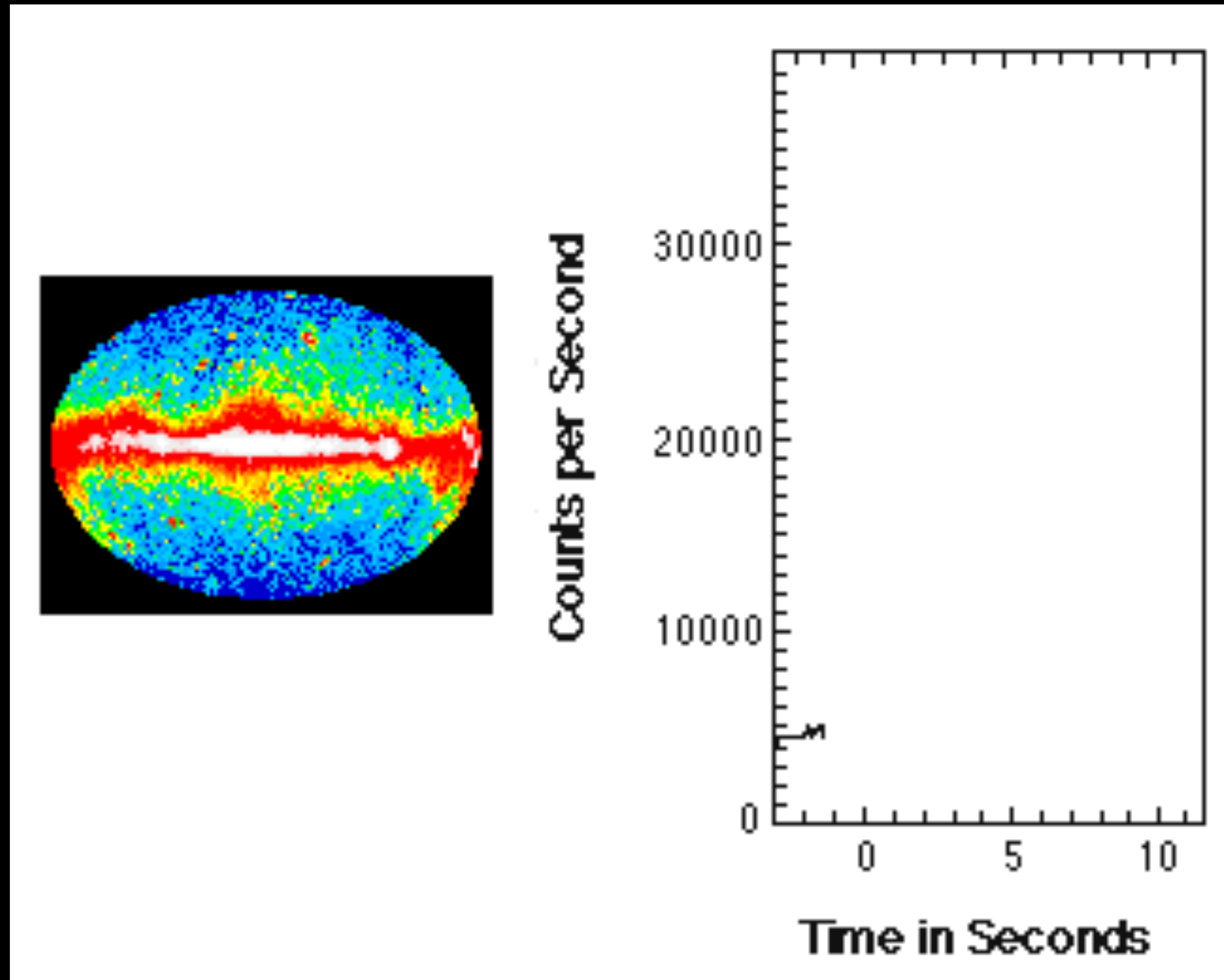
10



Gamma Ray Bursts (prompt emission)

$$L_{\text{GRB}} \sim 10^{50} - 10^{53} \text{ erg s}^{-1}$$

$$L_{\text{GRB}} \sim 10^{20} L_{\odot}$$



The power of the accretion



$$\dot{E} \sim \eta \dot{M} c^2$$

300 grams



The power of the accretion



$$\dot{E} \sim \eta \dot{M} c^2$$

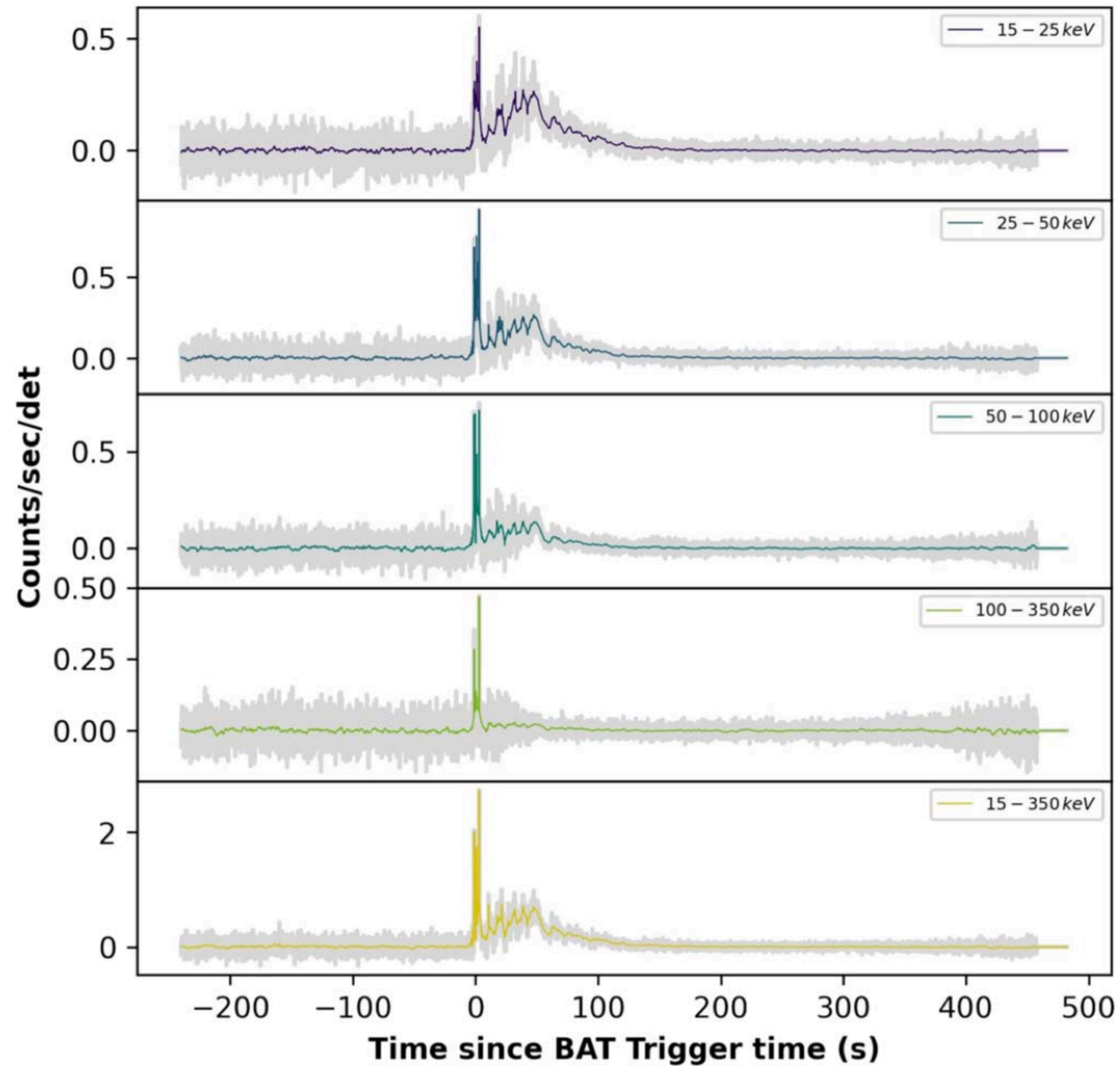
$$E_{\text{extracted}} \sim 10^{16} \text{ J}$$

$$E_{\text{atomic bomb}} \sim 10^{13} \text{ J}$$

100-1000 times the energy of AB

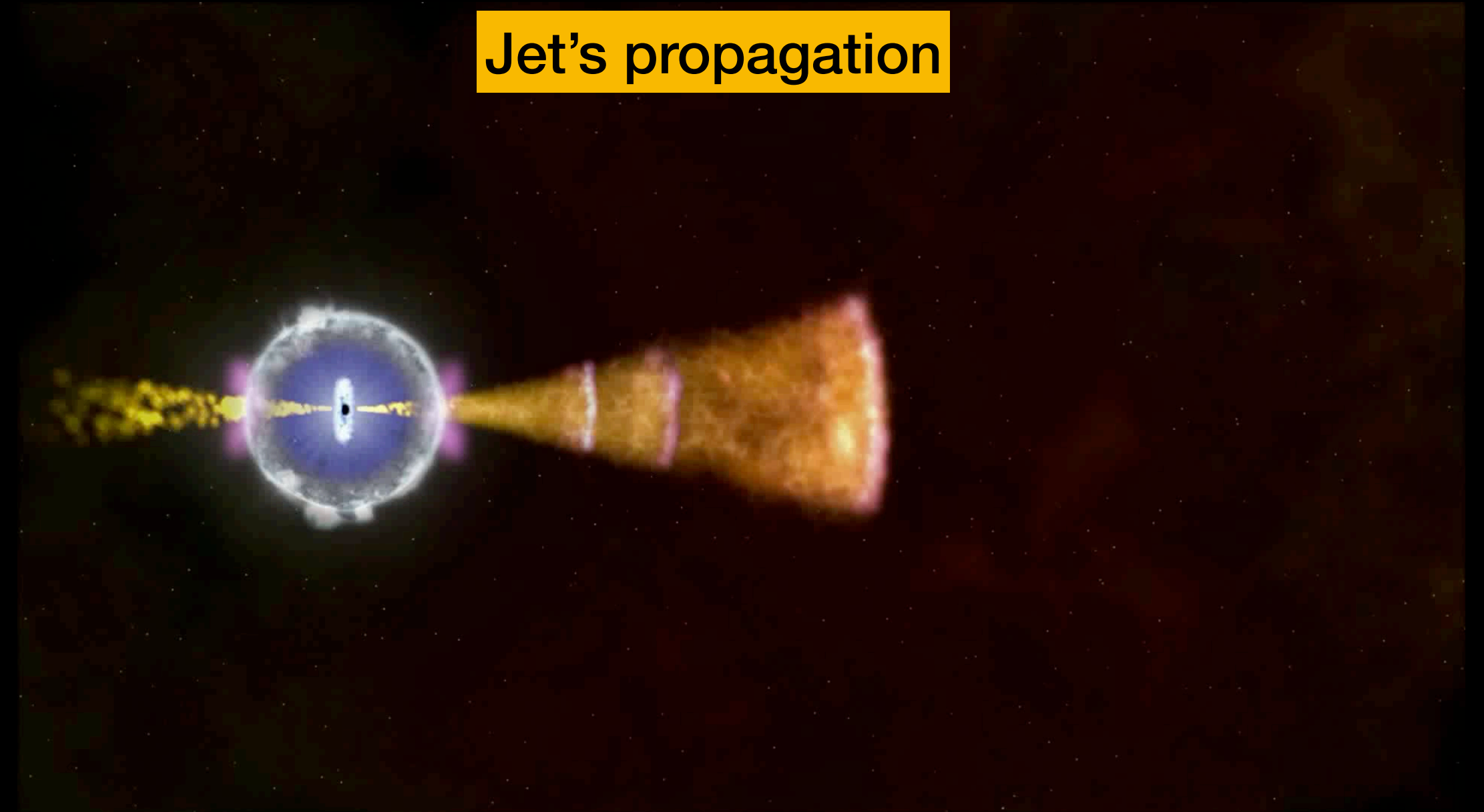
Variability due to shock front collision

Observational data

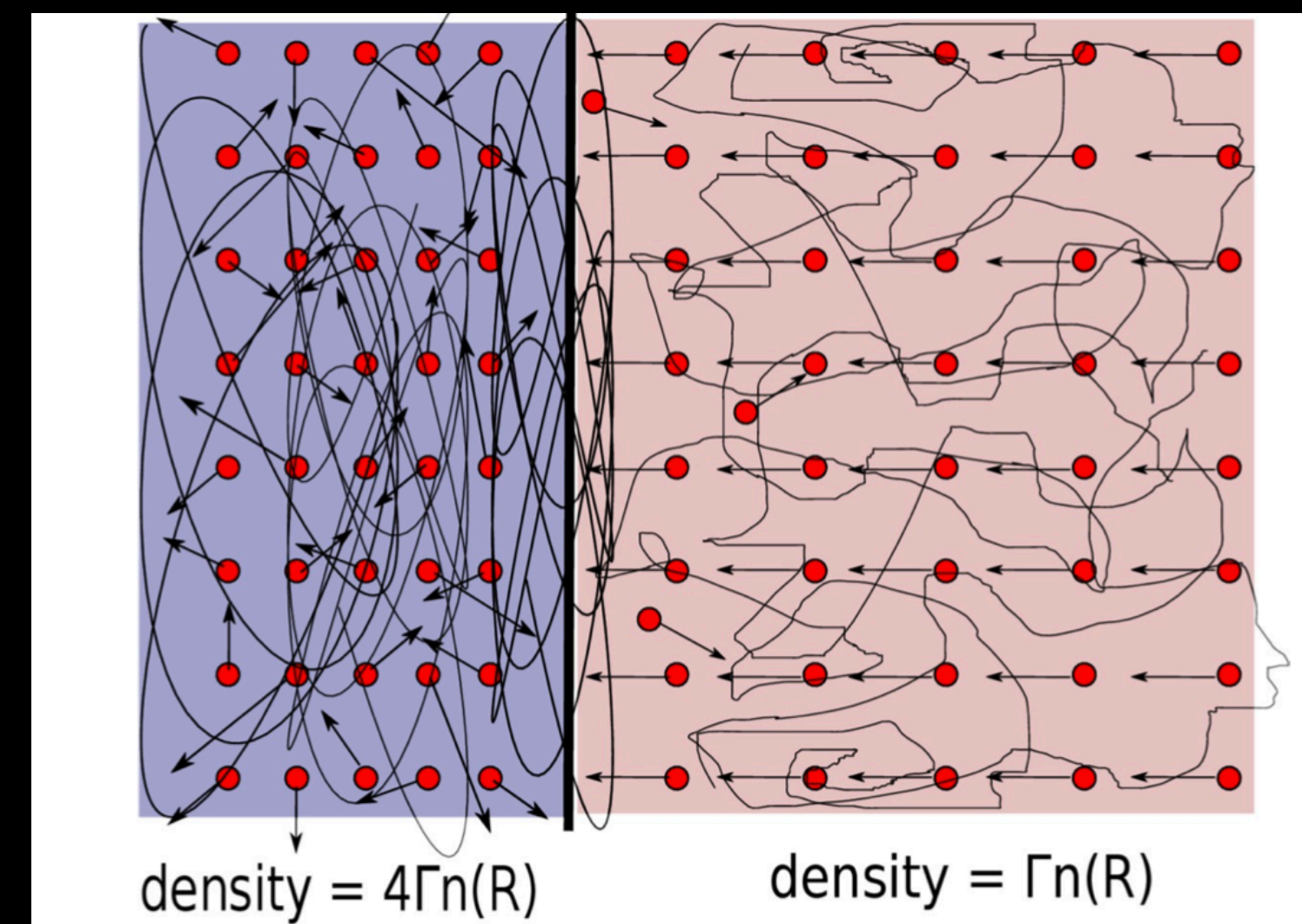


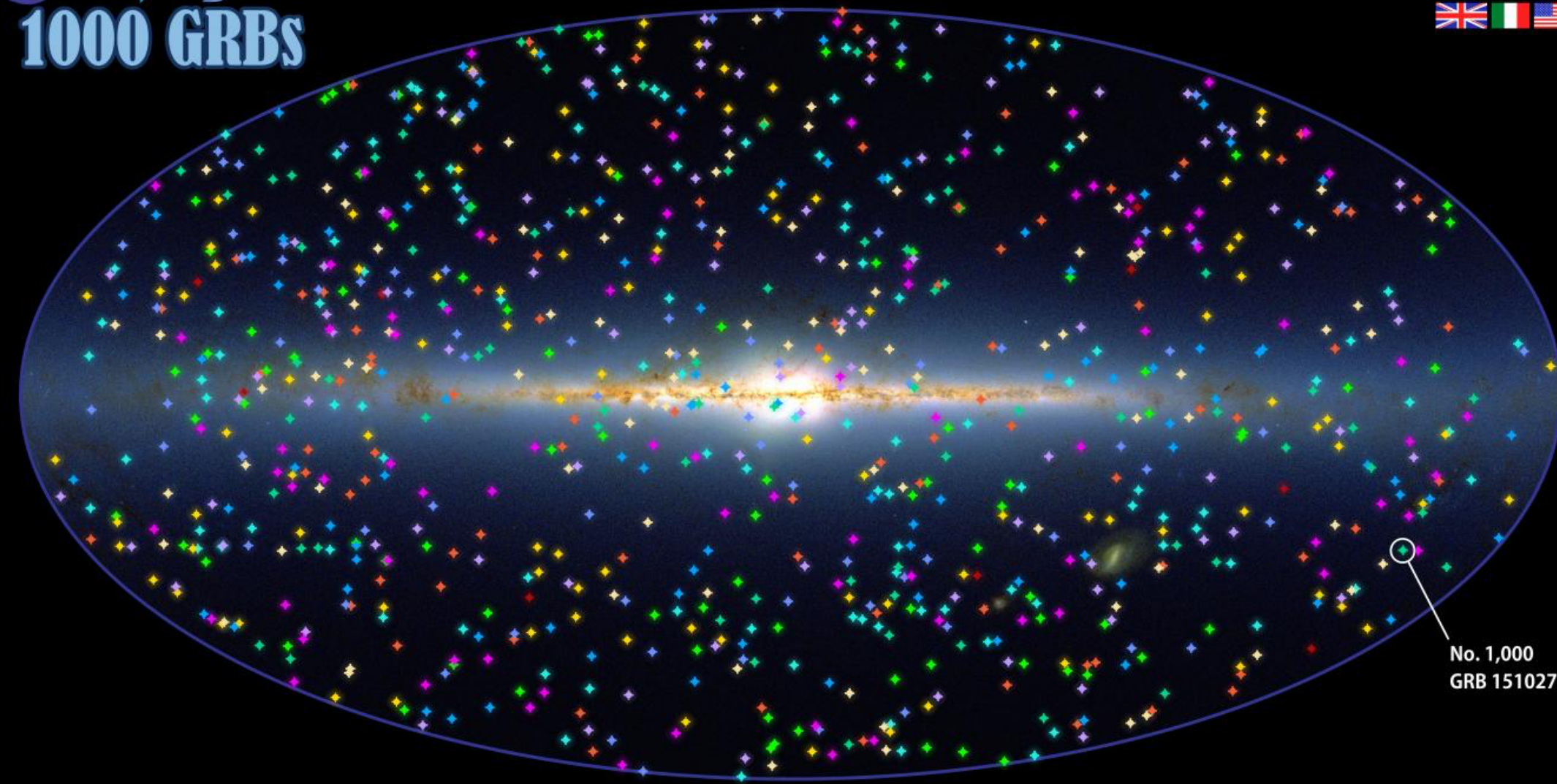
GRB060614, from Gracia-Cifuentes, Becerra & De Colle (2023)

Jet's propagation

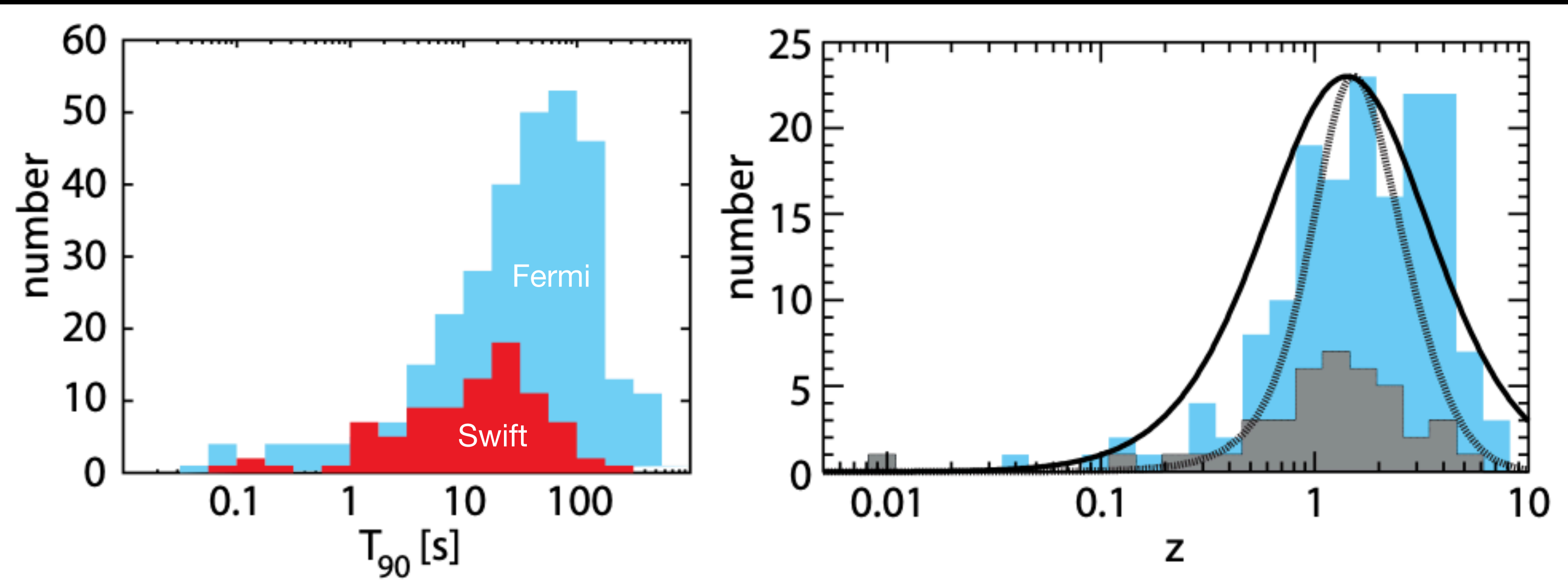


The shock region zoom

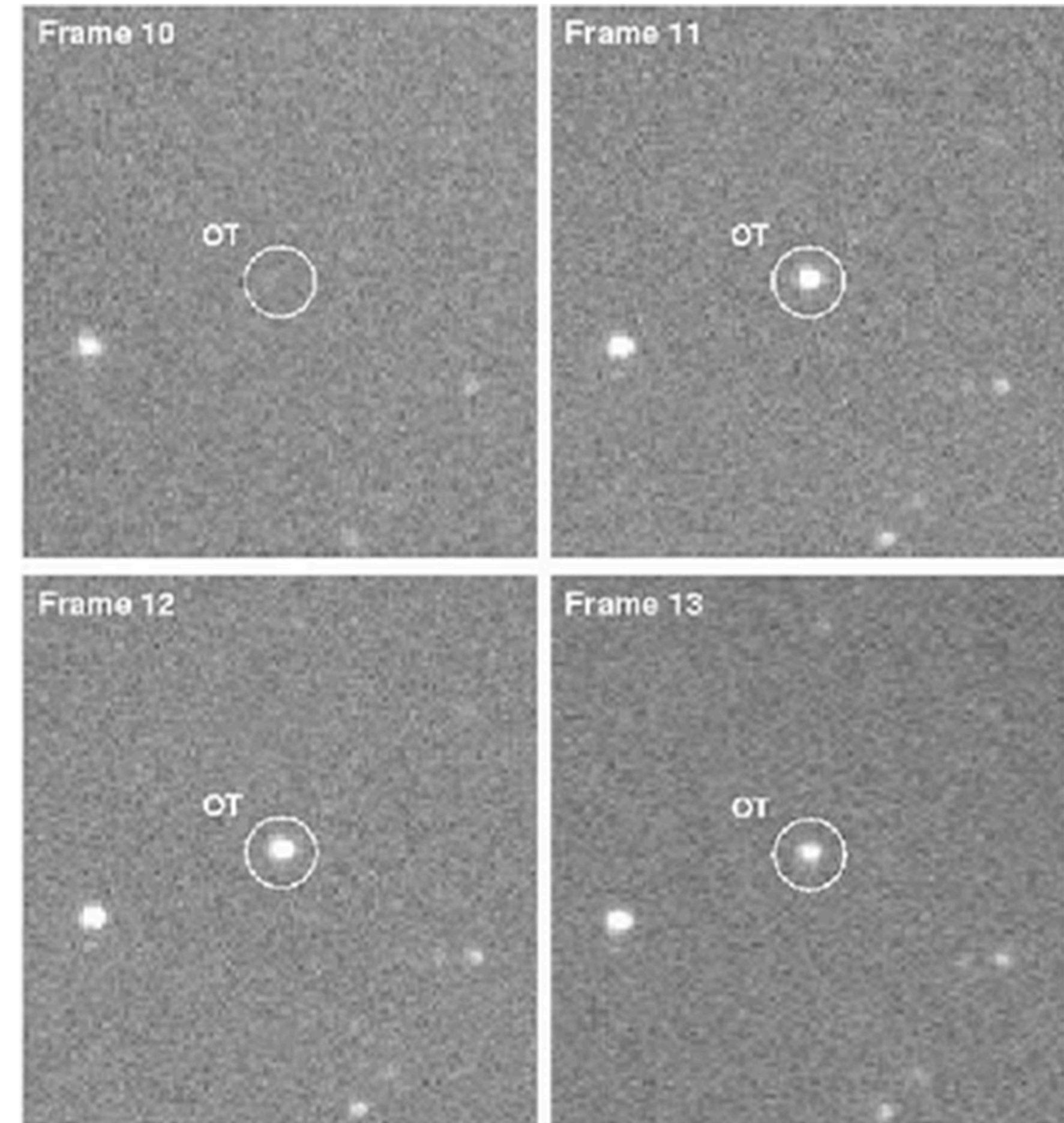
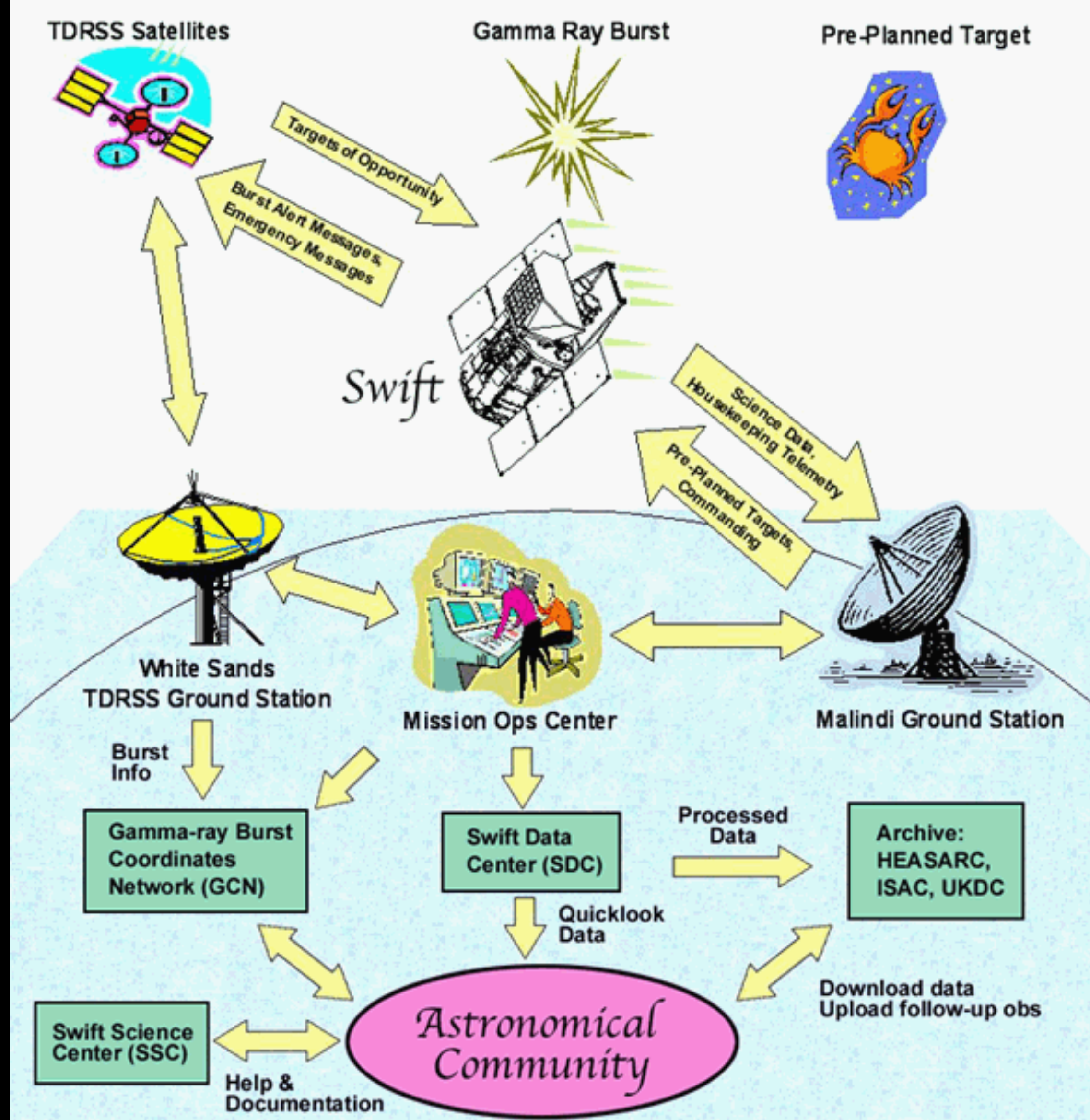




2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
9	88	102	86	103	89	84	81	92	96	95	75 to Oct. 27

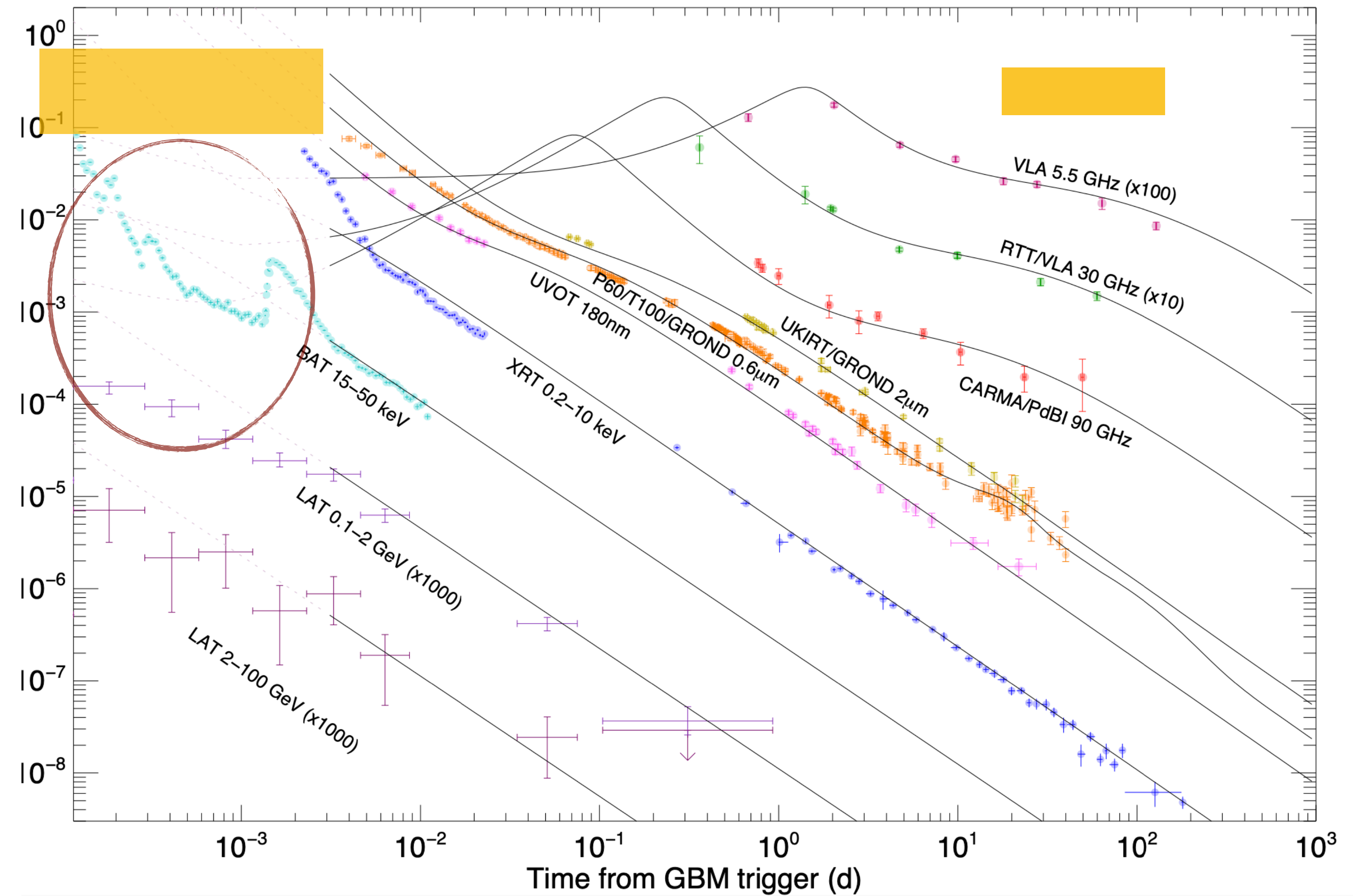
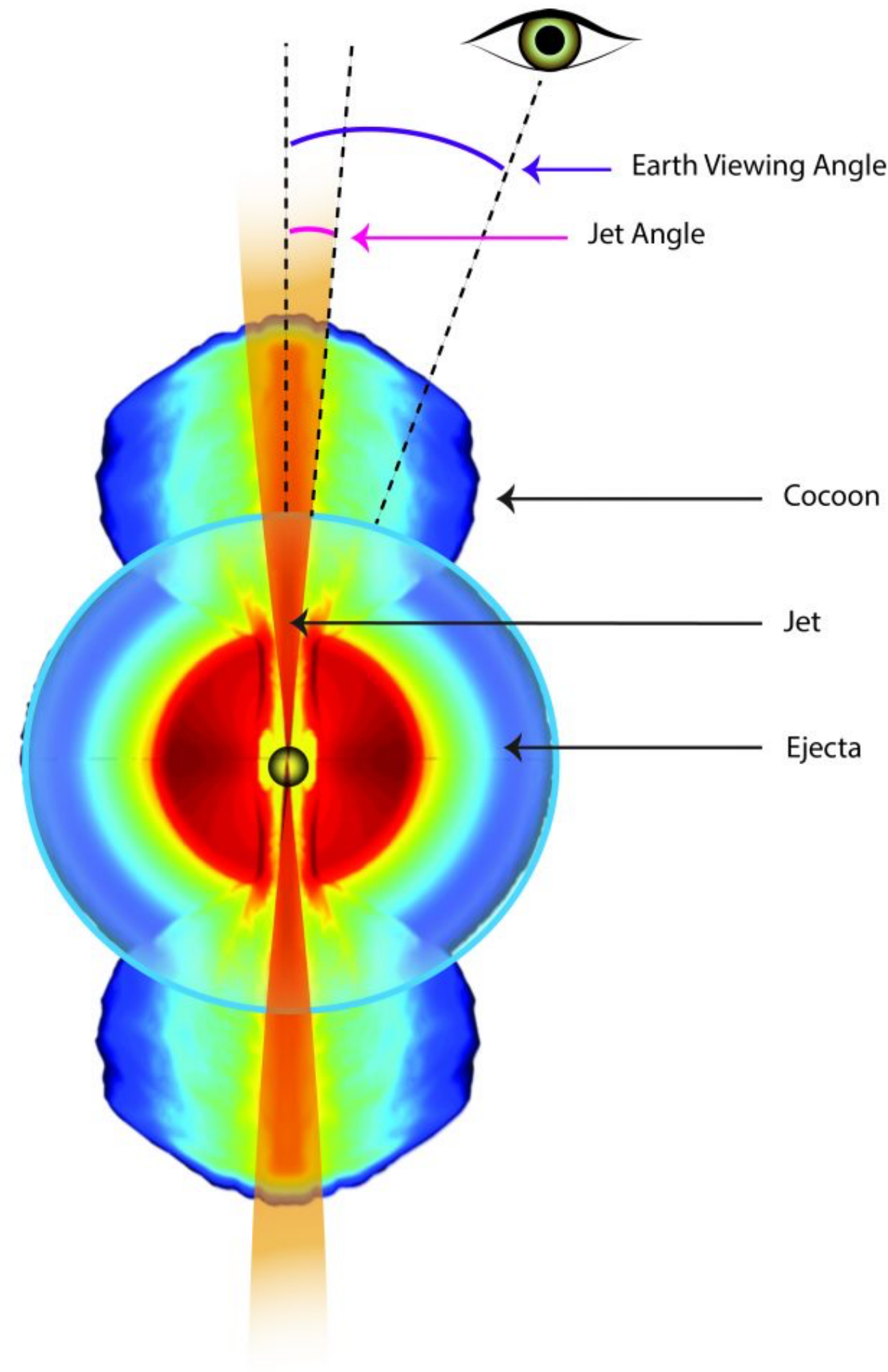


Afterglow emission



This gamma-ray burst was recorded on August 20, 2005, by the RAPTOR telescope system located at the Fenton Hill Observatory, near Los Alamos.

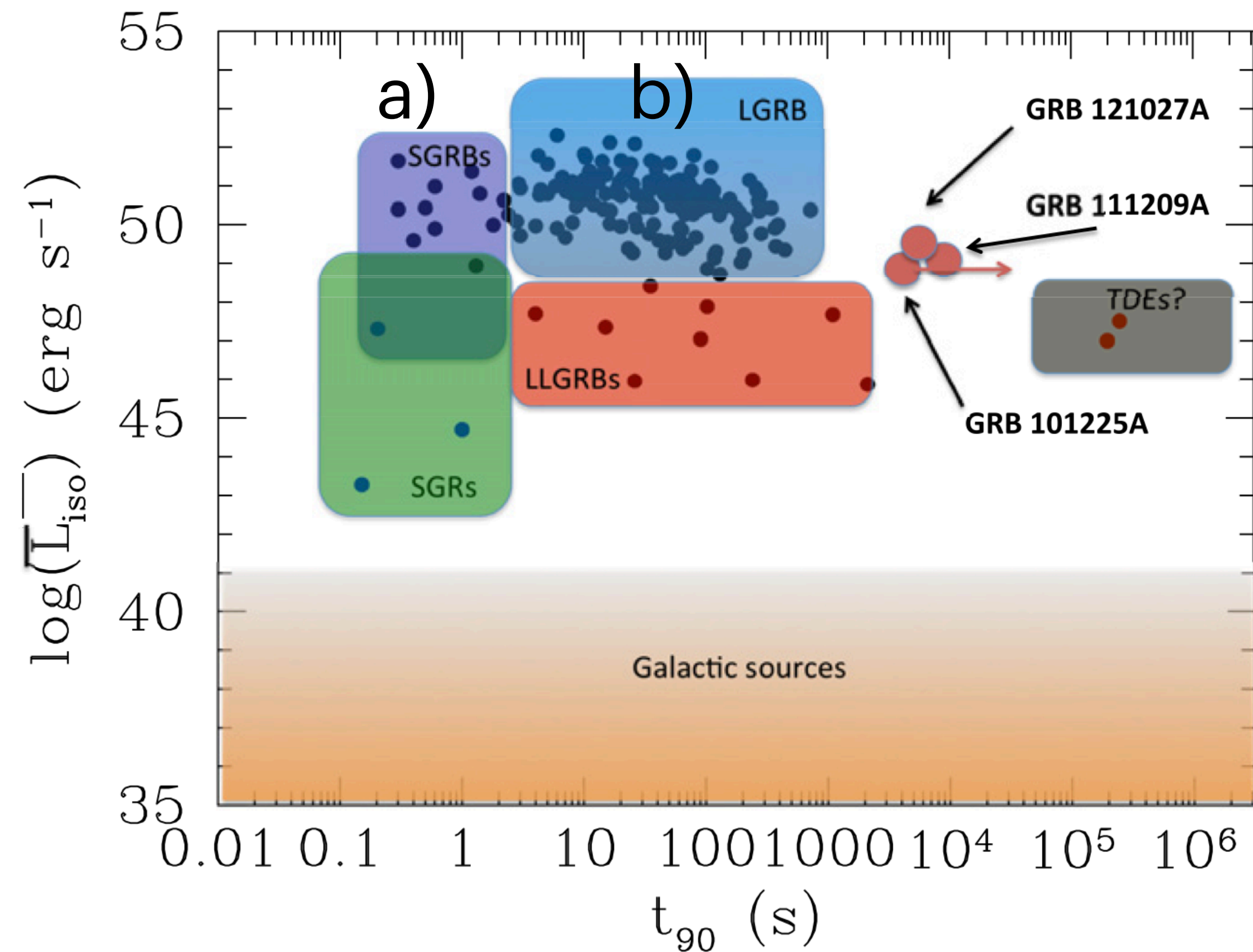
The complete GRB emission (on-axis)



Credit: Sophia Dagnello

GRB 130427, Perley et al. 2013

The Progenitors of Gamma Ray Bursts



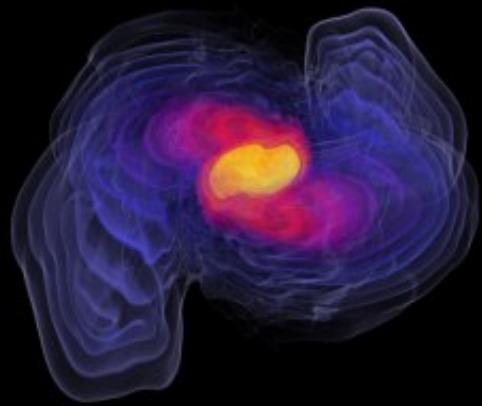
Levan et al. 2014



Eichler et al. (1989) and Paczynski (1991)

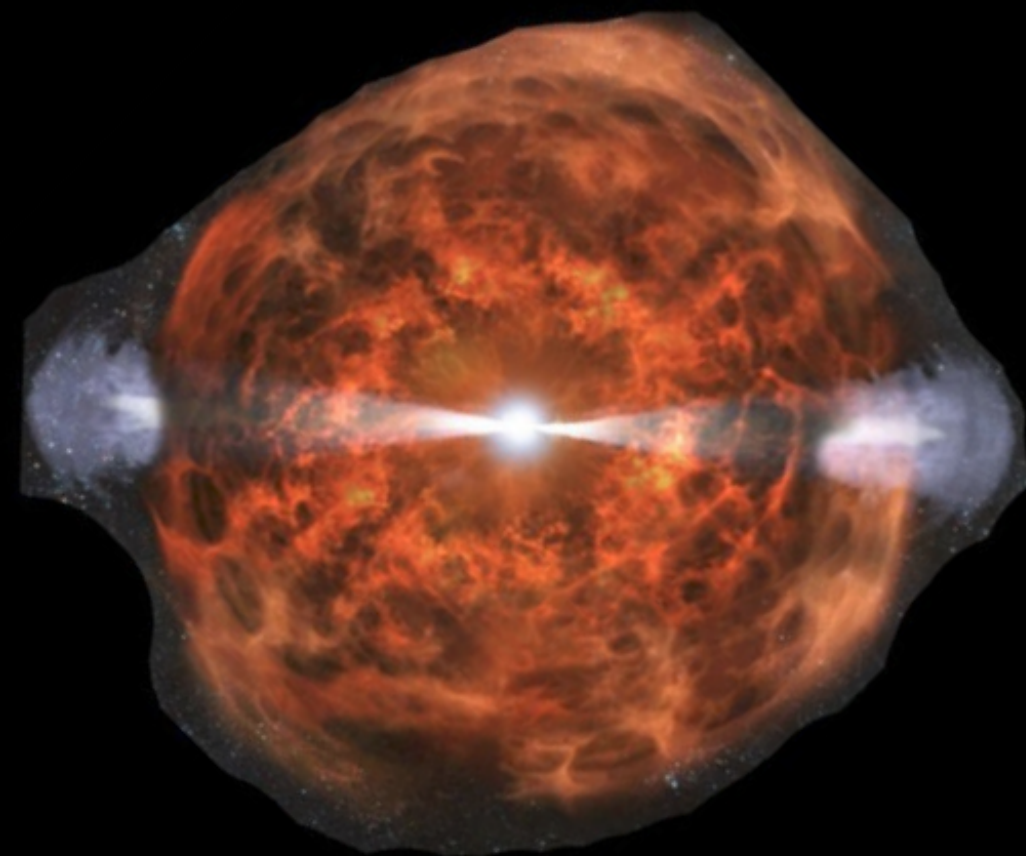
GRB jet evolution is a multi-scale problem

Accretion process



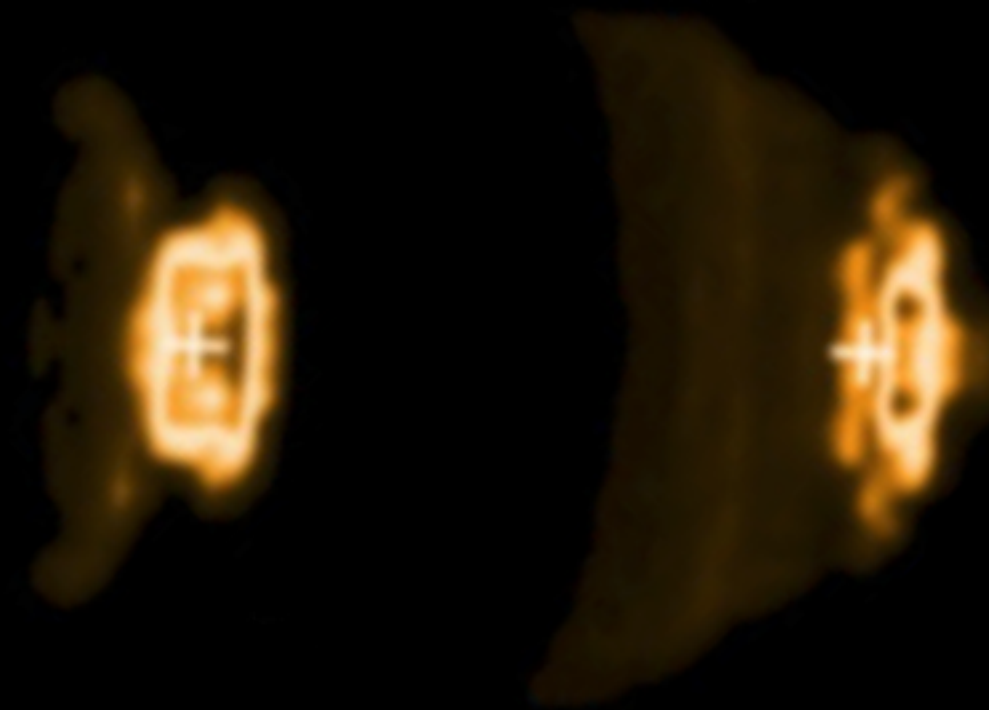
Central Engine

Jet Propagation within progenitor environment



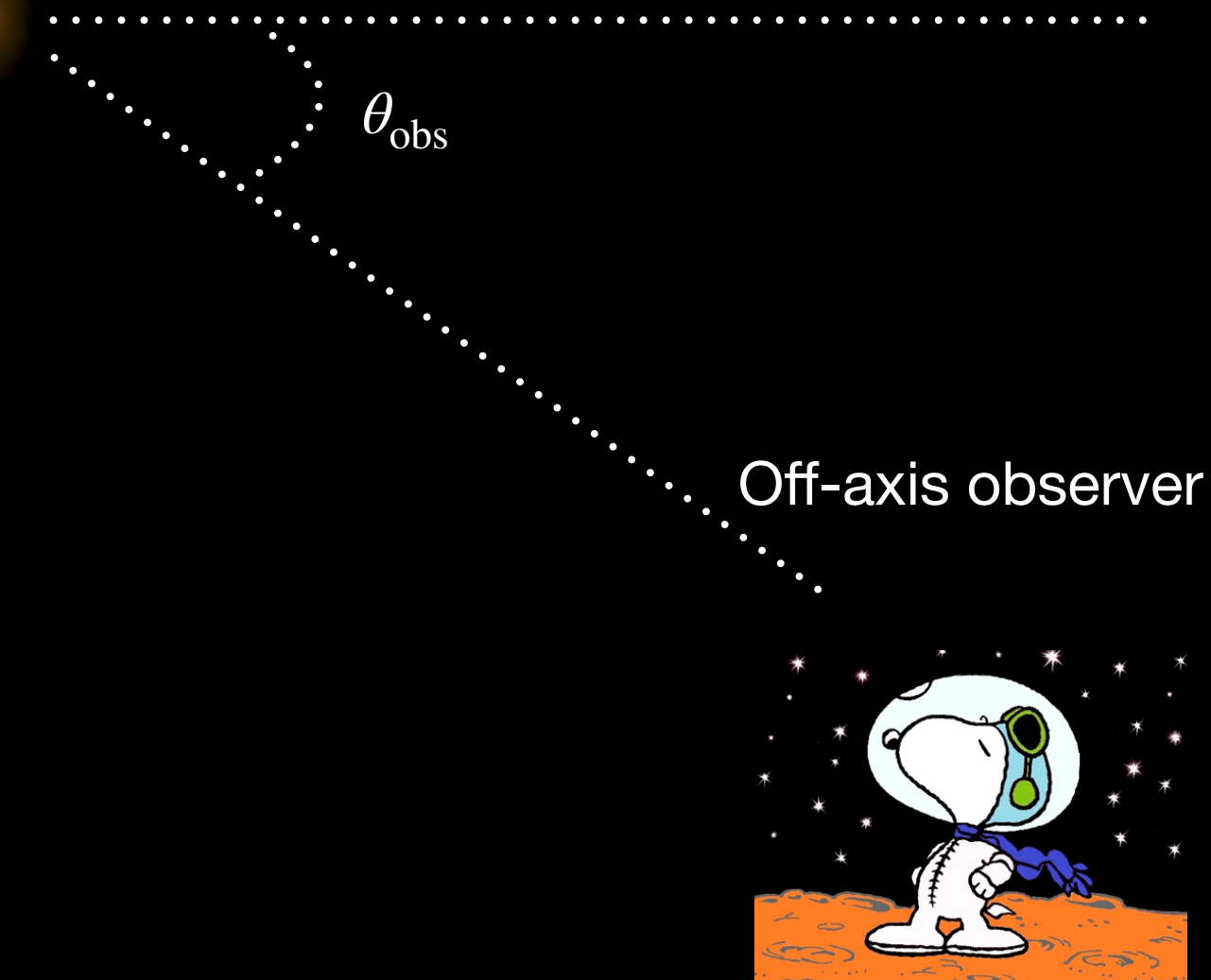
$$r \lesssim 10^{10} \text{ cm}$$

Shell propagation in External ISM



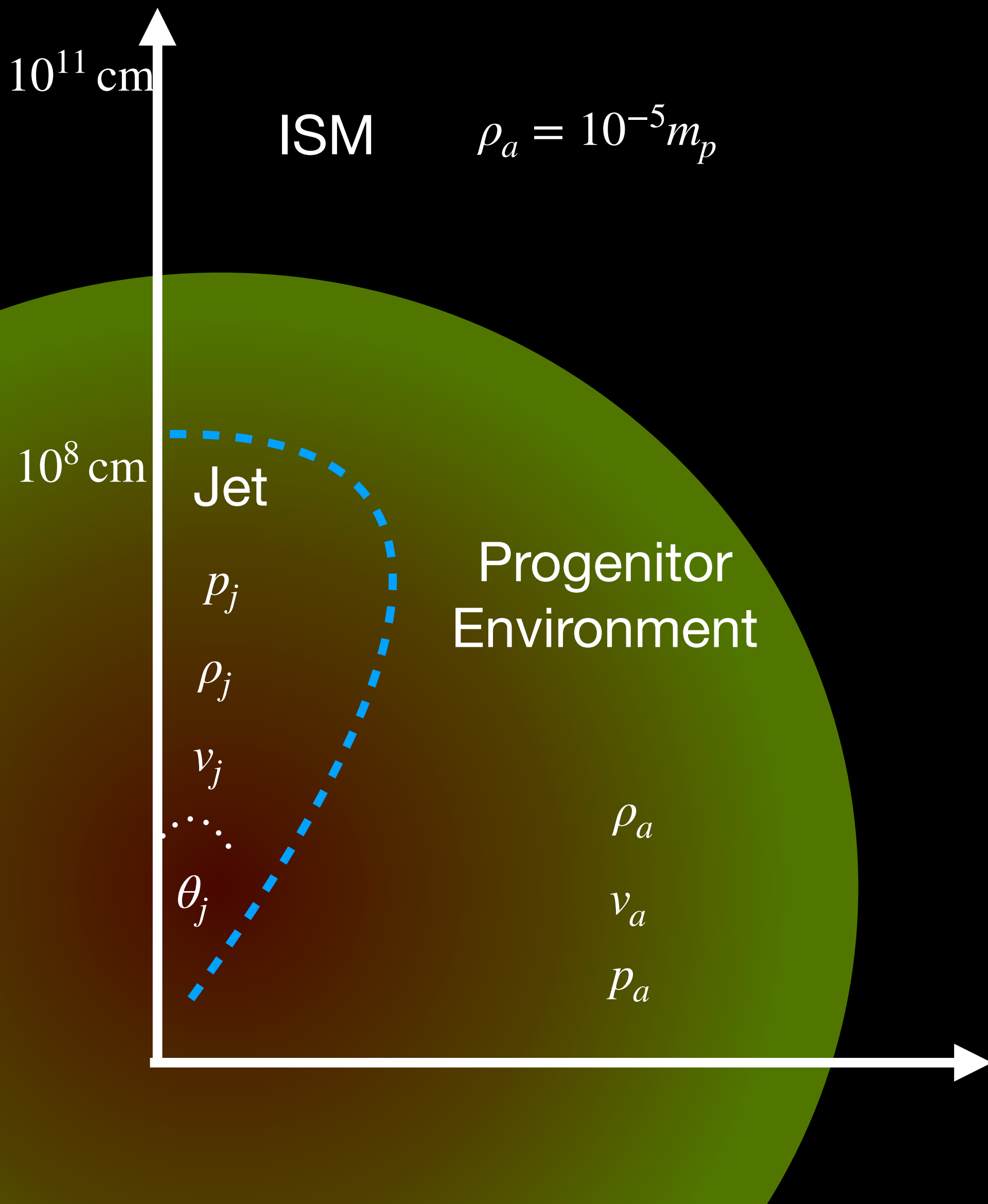
$$r \sim 10^{16} \text{ cm}$$

Afterglow Emission



- Connection between them
- Emission

Modeling Cosmic Explosions



Mass

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

Momentum

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

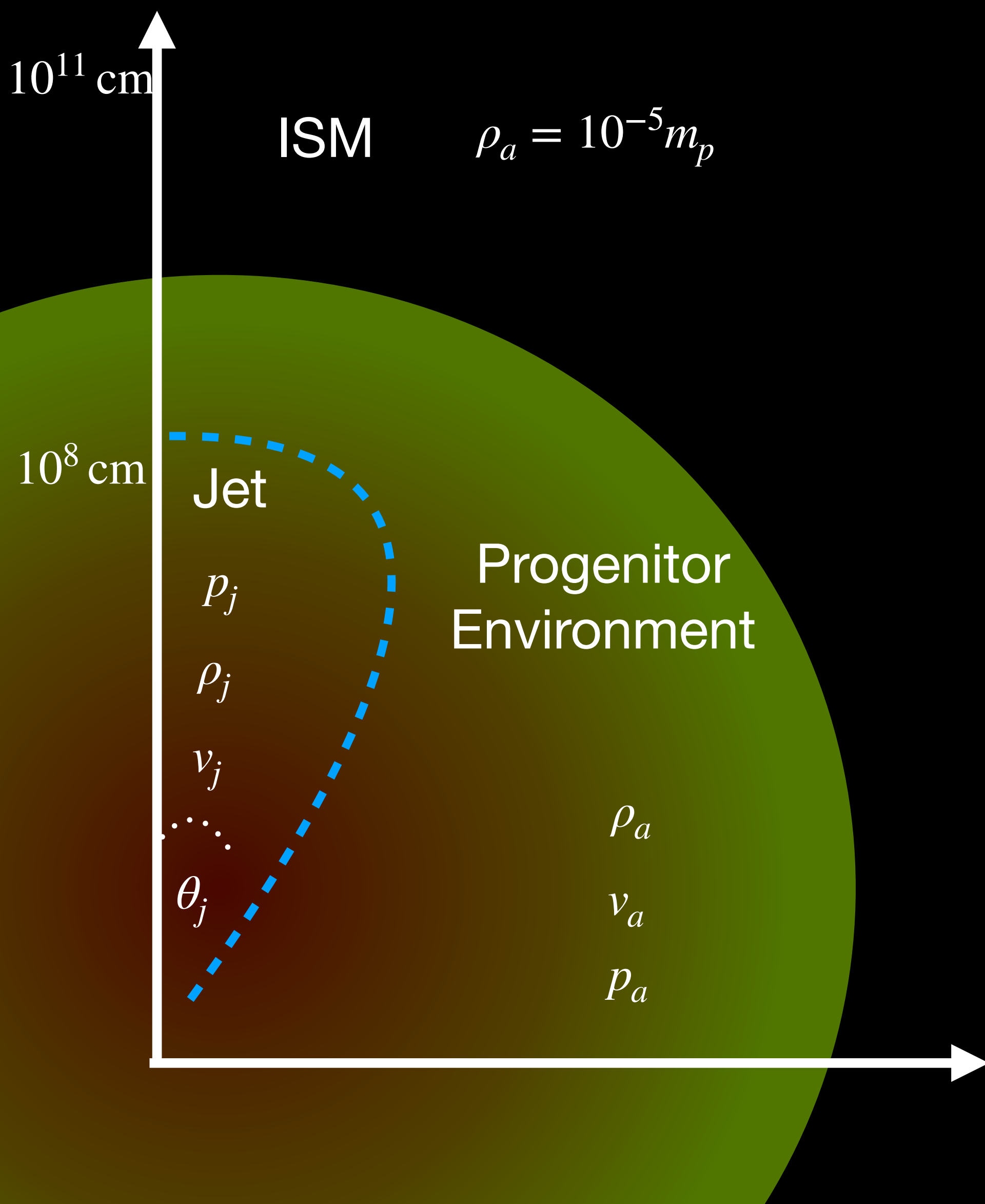
Energy

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

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

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

We rewrite the equations to express a general rule



$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}^i}{\partial x^i} = 0$$

$$\mathbf{U} = \left(D, m_j, \tau \right)$$

$$\mathbf{F}^i = \left(Dv^i, m_j v^i + p \delta_j^i, \tau v^i + p v^i \right)$$

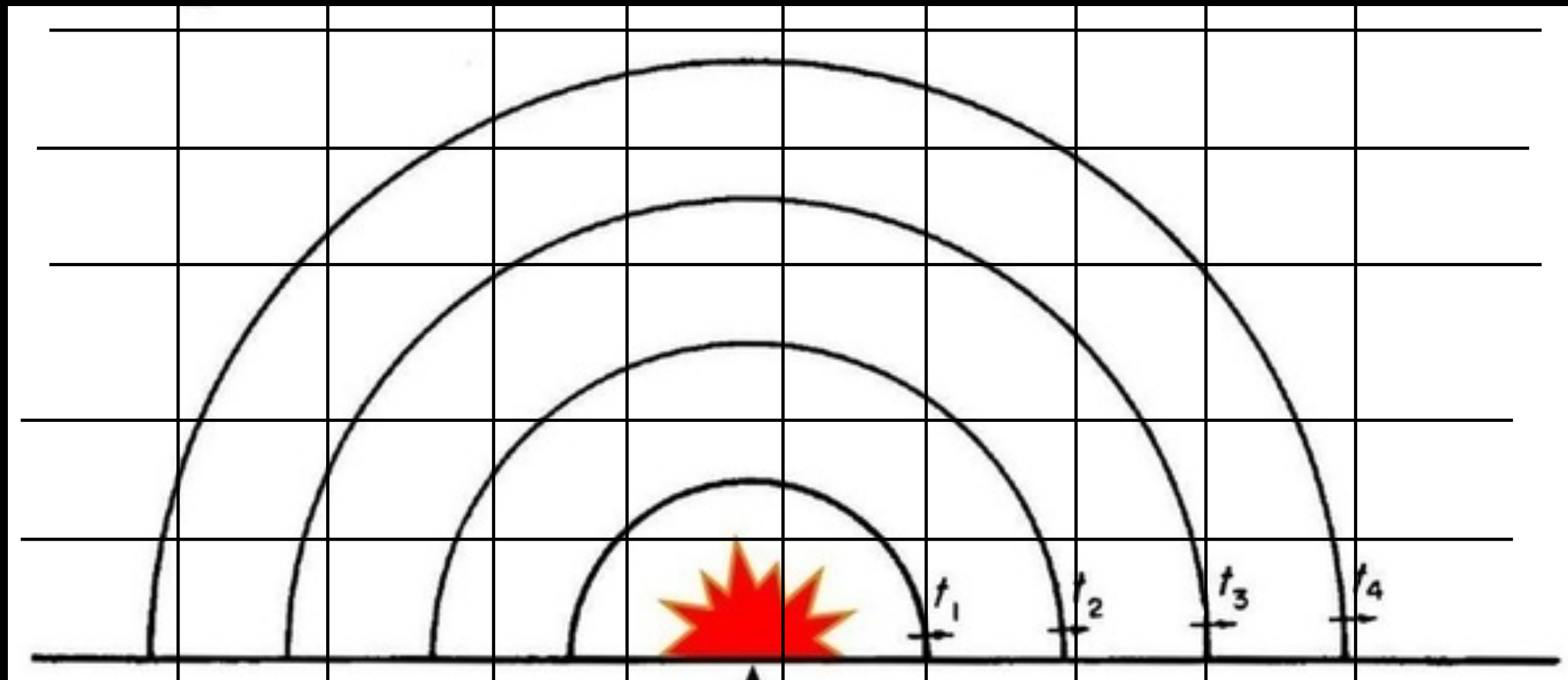
$$D = \Gamma \rho$$

$$m_j = D h \Gamma v_j$$

$$\tau = D h \Gamma c^2 - p - D c^2$$

The solution of such global expression

Numerical simulations are our virtual laboratory to reproduce extreme conditions



$$U_i^{n+1} = U_i^n - \frac{\Delta t}{\Delta x_i} \left(F_{i+1/2}^{n+1/2} - F_{i-1/2}^{n+1/2} \right)$$

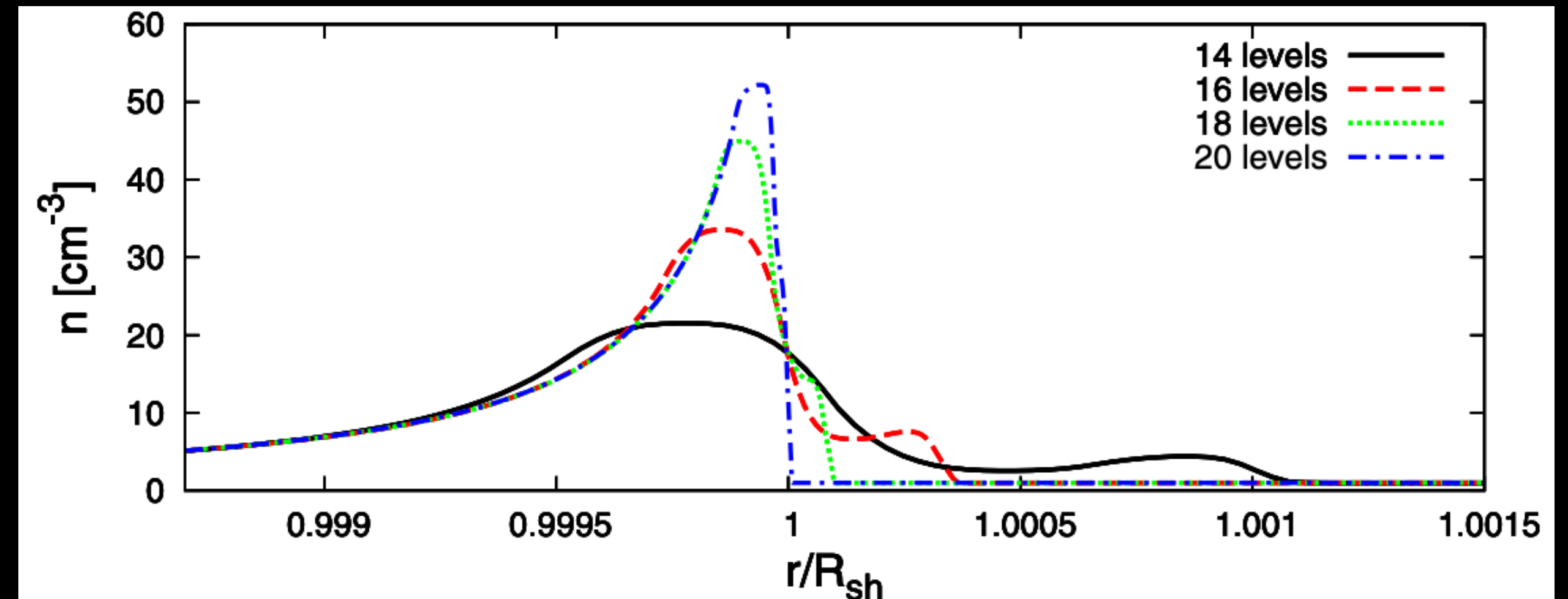
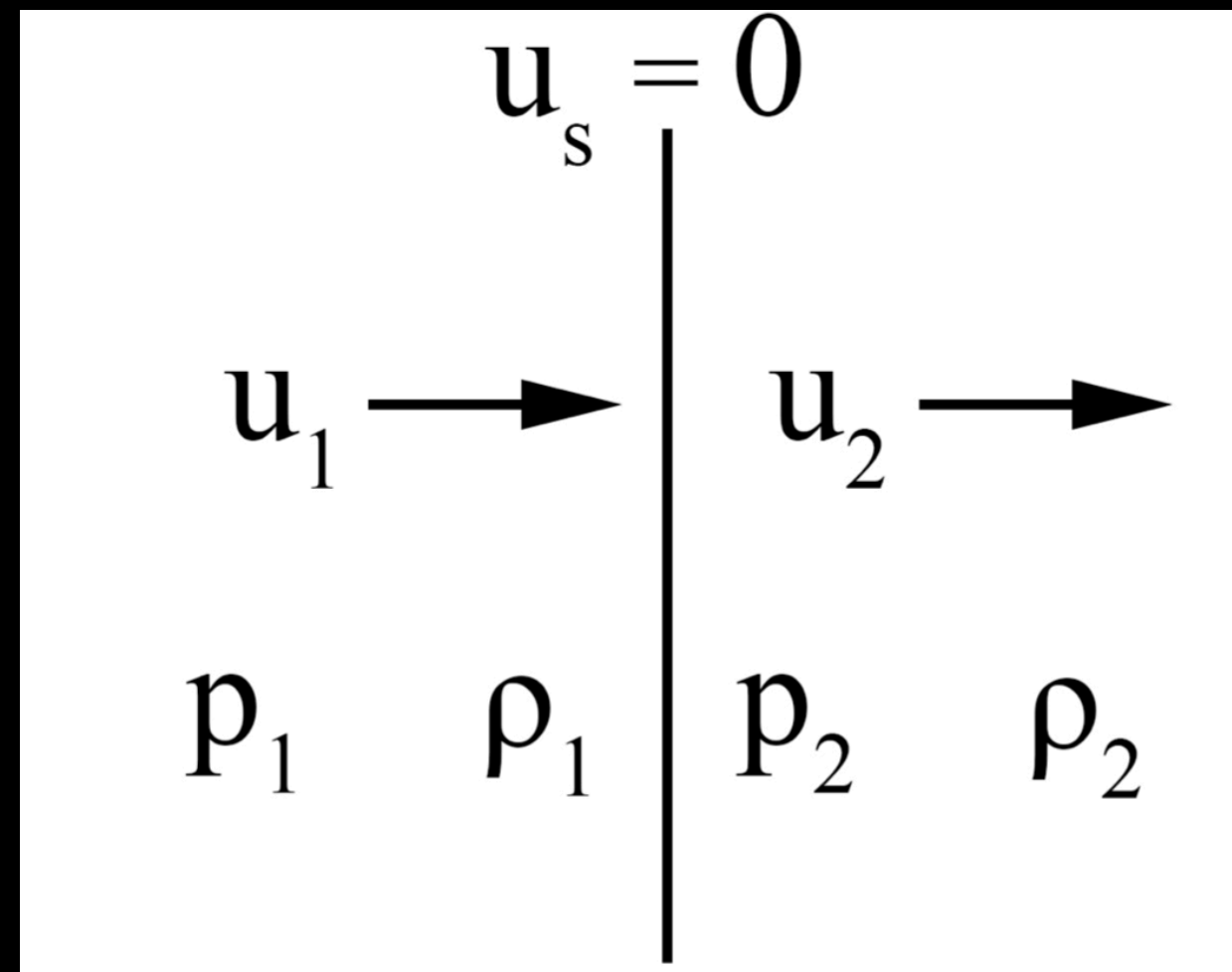
$$U_i^n = \frac{1}{\Delta x_i} \int_{x_{i-1/2}}^{x_{i+1/2}} u_i(t^n, x) dx$$

- Supersonic fluids
- Strong shocks

$$F_{i\pm 1/2}^{n+1/2} = \frac{1}{\Delta t} \int_{t_n}^{n+1} f(t, x_{i\pm 1/2}) dt$$

Shock capture scheme

Numerical simulations are our virtual laboratory to reproduce extreme conditions



De Colle et al. 2012

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

Jets from mergers

FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries

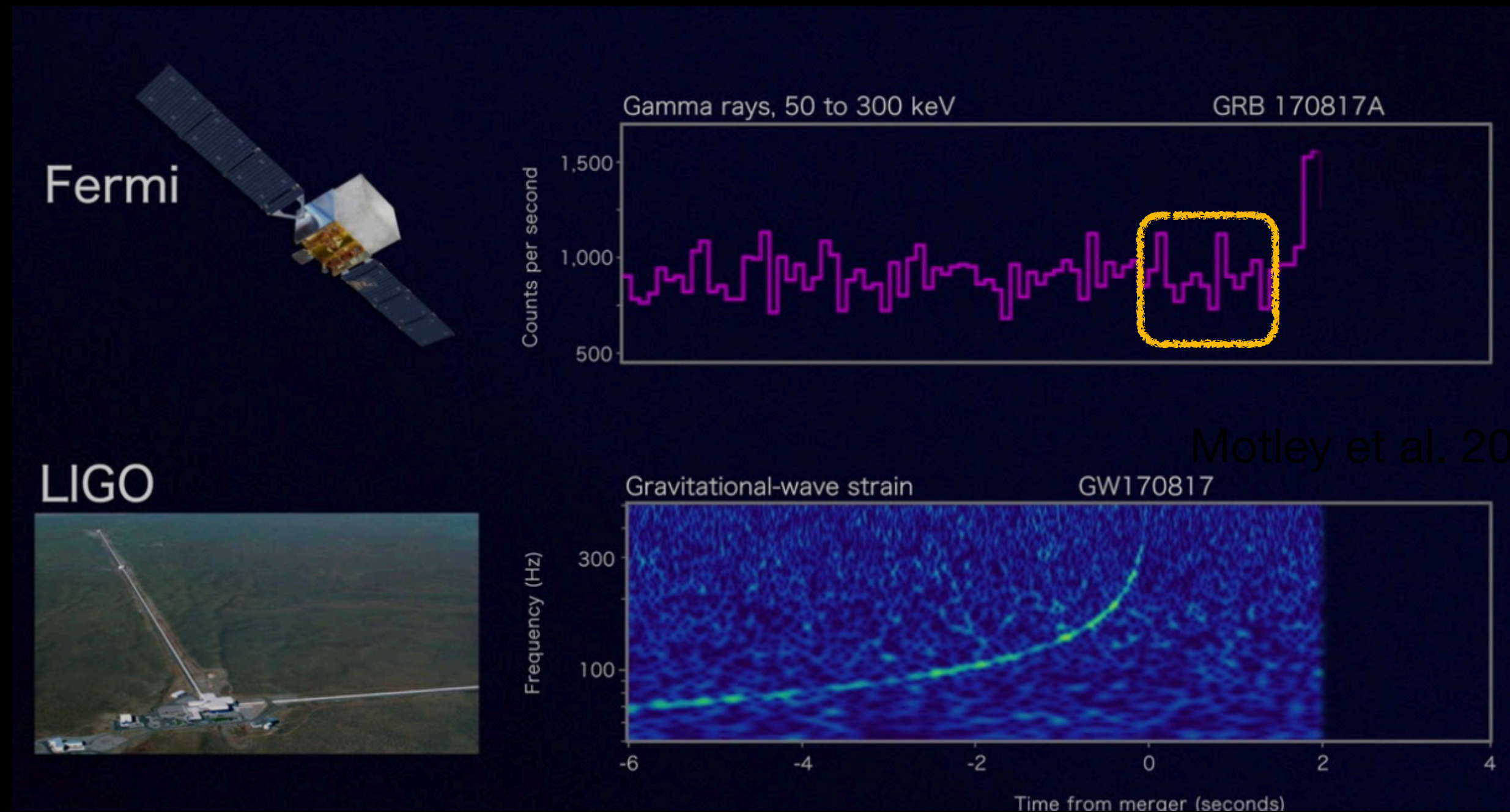
Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum

Gravitational wave lasted over 100 seconds

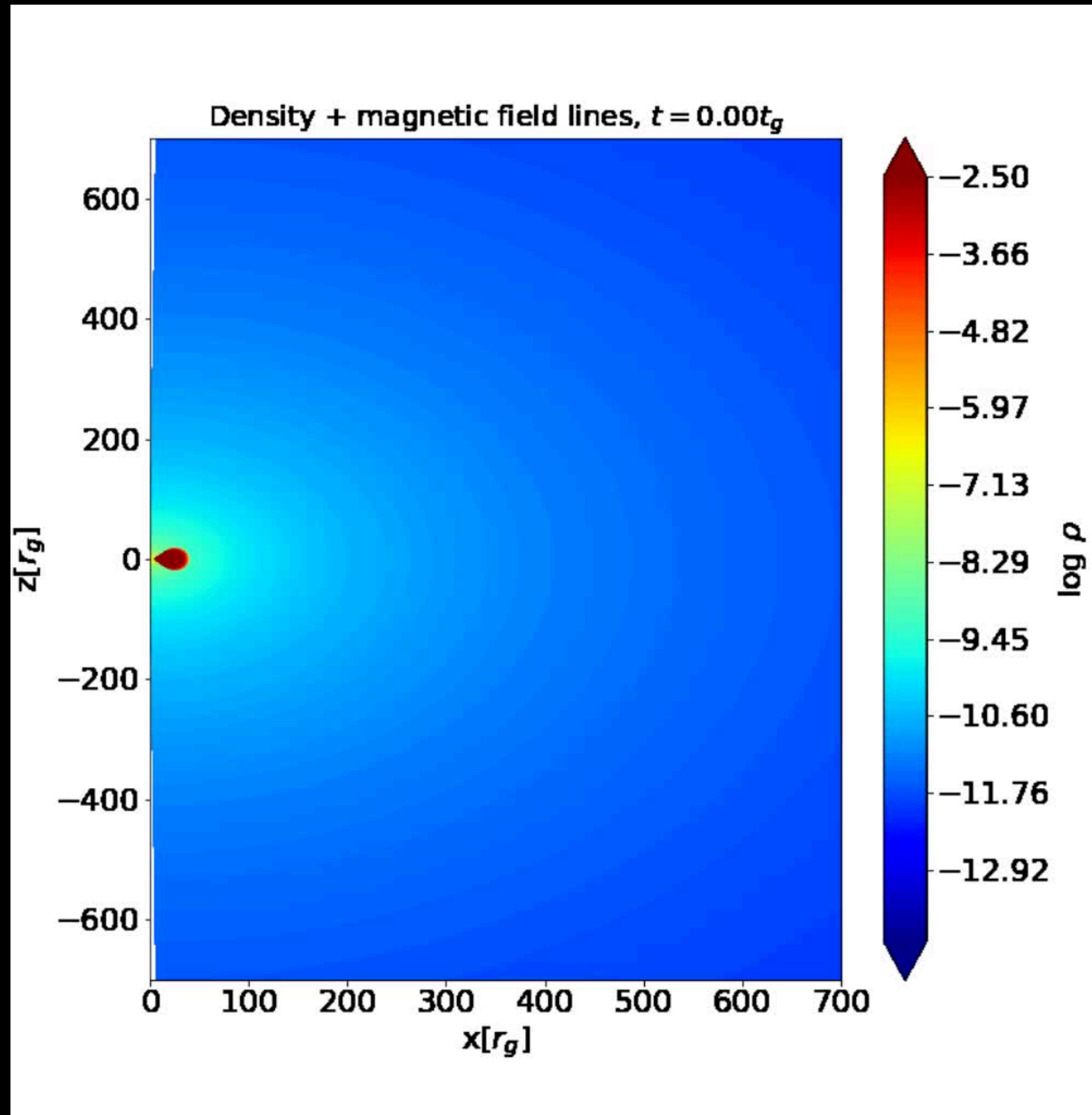
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.

Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.

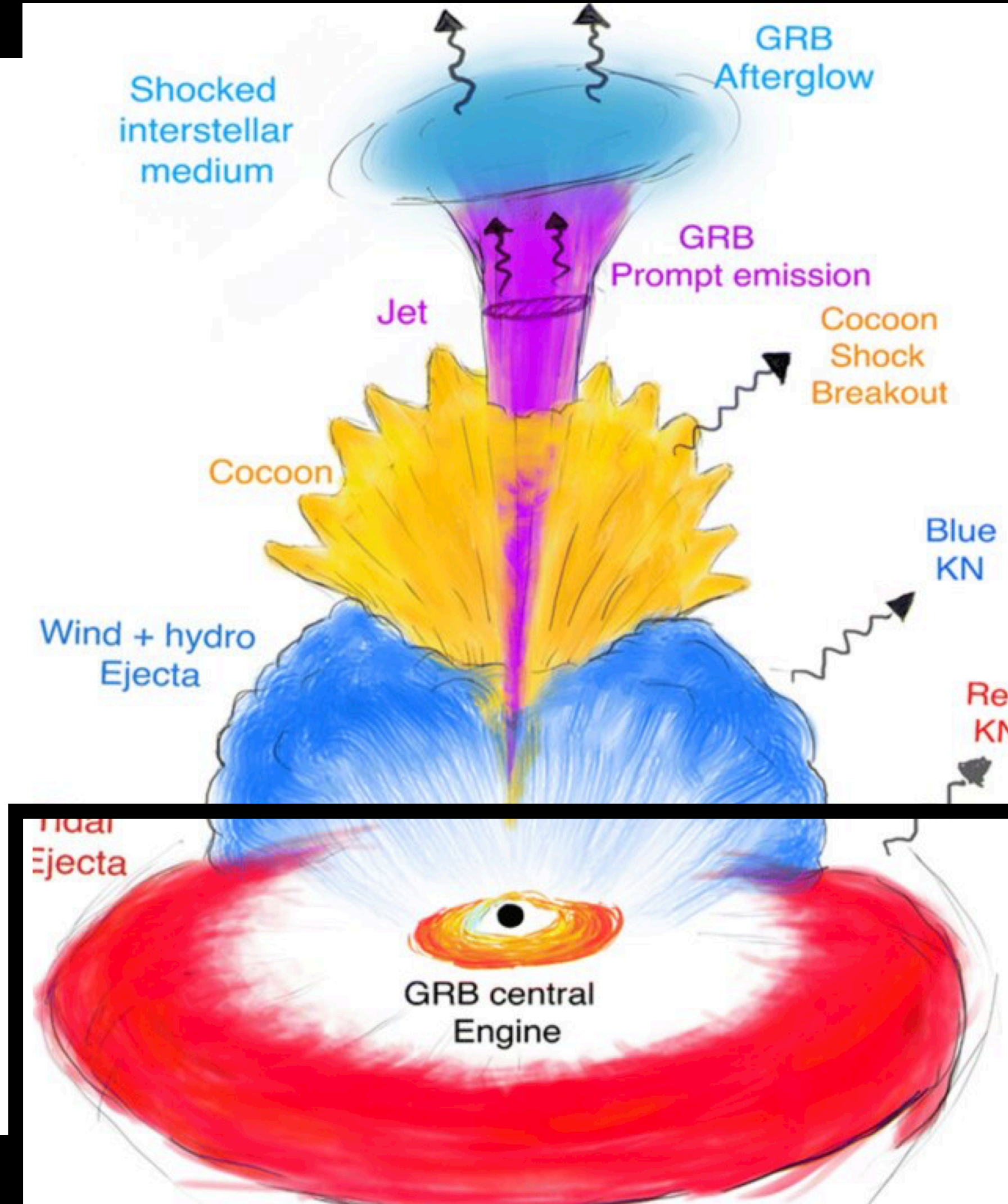
Observations from August 2017



Post-merger evolution of the jet



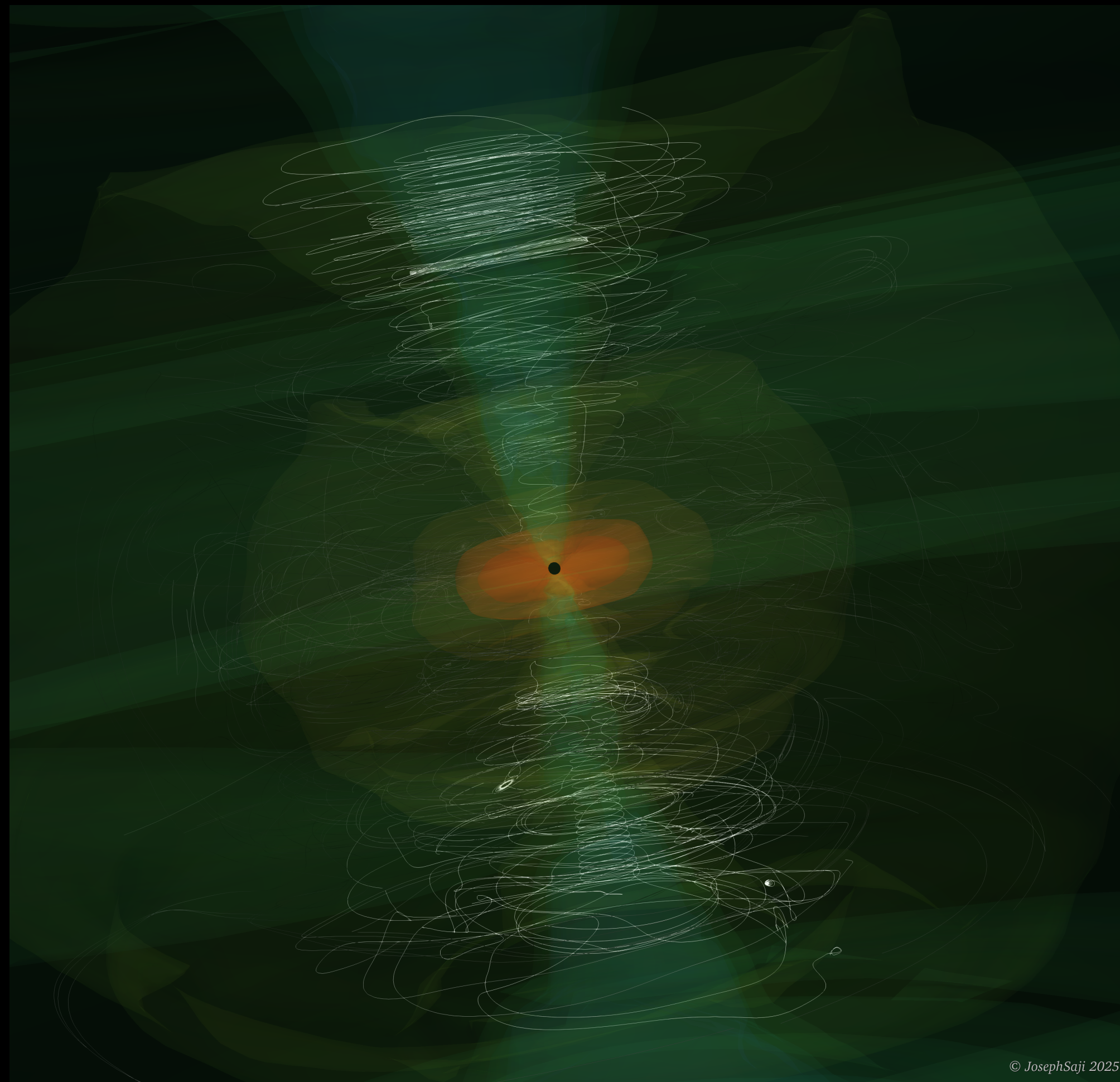
Nouri, Janiuk (2023)



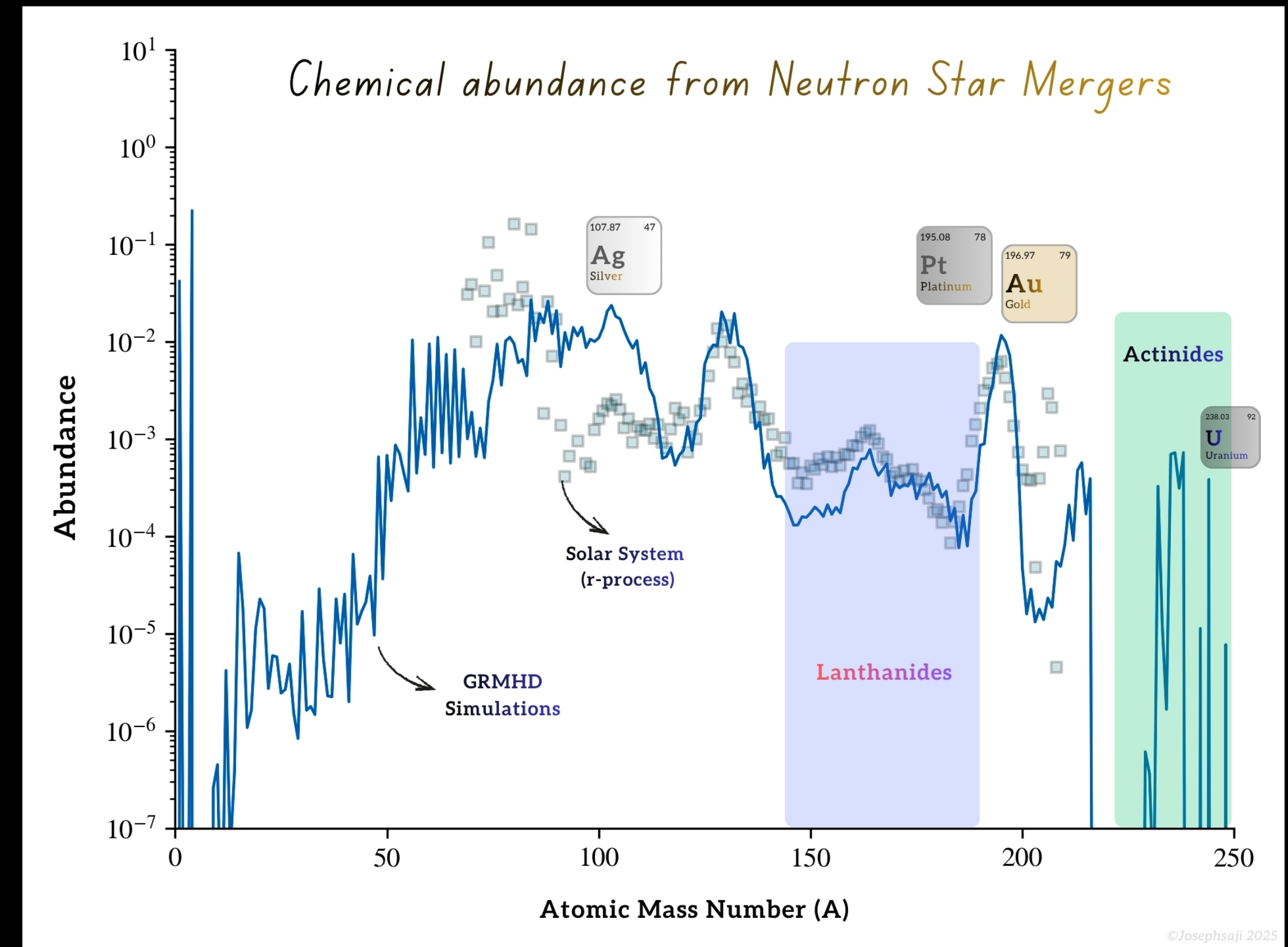
Cartoon of GRB evolution (Stefano Ascenzi)

Small Scales $r \lesssim 10^8$ cm
GRMHD simulations

Kilonova



Janiuk, Sahi & Urrutia 2025



Figures by Joseph Sahi

Our Connection between small and large scales

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

General Relativistic MHD simulation

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

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

$$T^{\mu\nu} = T^{\mu\nu}_m + T^{\mu\nu}_{\text{em}}$$

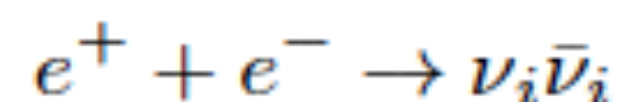
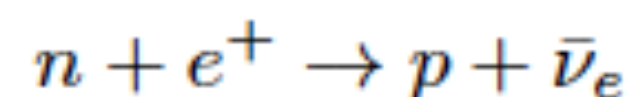
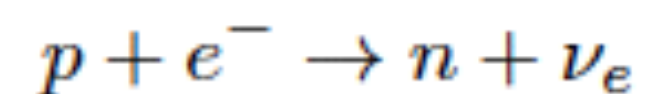
- HARM CODE (Gammie 2003)
- HLL solver
- Kerr-schild metric

Neutrino treatment (Janiuk et al. 2013)

The neutrino optical depth

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

Species:



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 $10^8 \text{ cm} < r < 10^{11} \text{ cm}$

Special Relativistic HD simulation

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

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

$$T^{\mu\nu} = T^{\mu\nu}_m$$

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

Disk wind outflows

Post NSNS merger configuration

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

$$M_{\text{disc}} = 0.10276 M_{\odot}$$

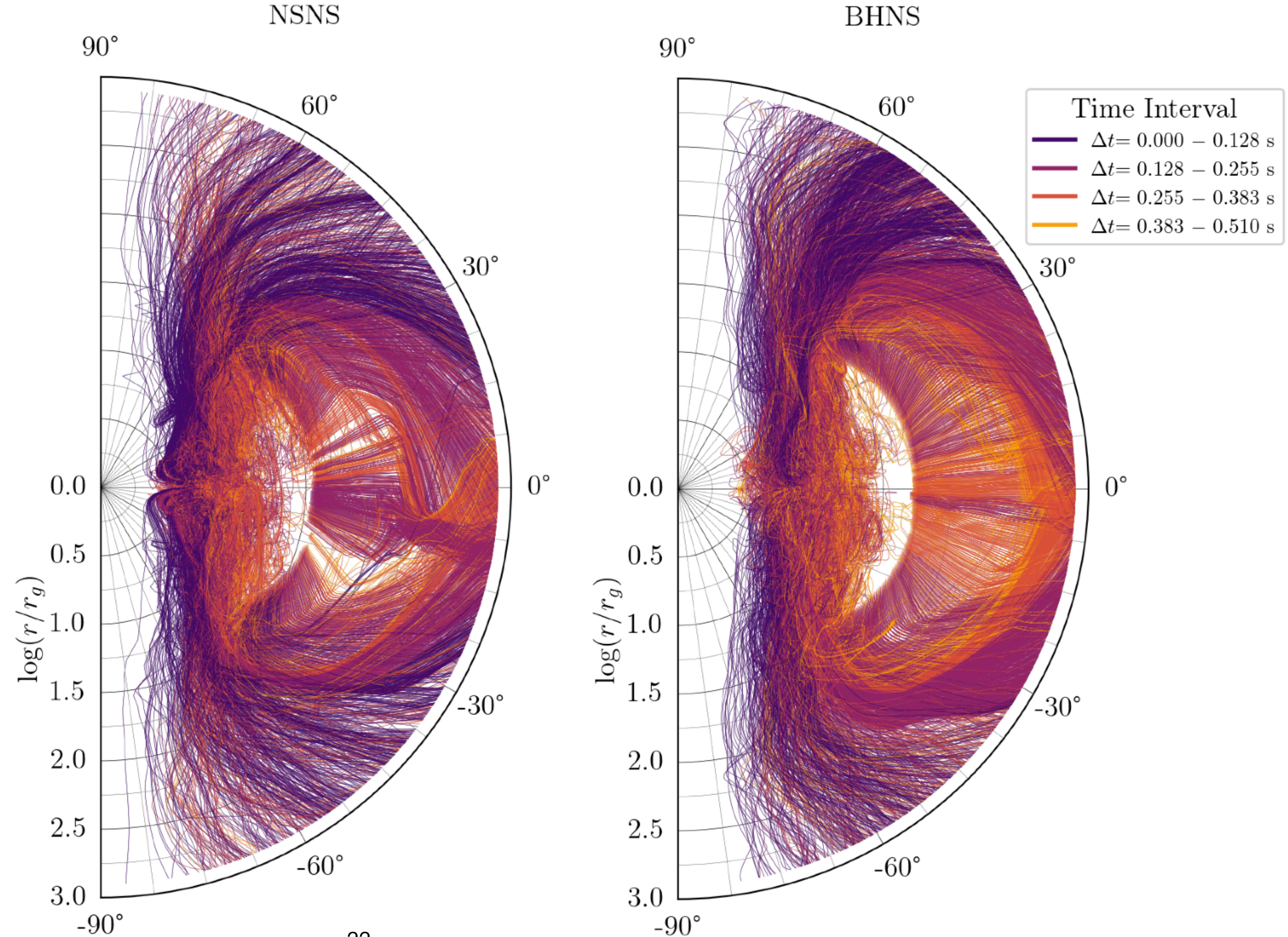
$$\dot{M}_{\text{out}} = 3.27 \times 10^{-2} M_{\odot} \text{ s}^{-1}$$

Post BHNS merger configuration

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

$$M_{\text{disc}} = 0.3120 M_{\odot}$$

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



Jet Characteristics

$$\Gamma_j = 7.2$$

$$t_j \propto M_{\text{disk}} / \langle \dot{M} \rangle \sim 1.57 \text{ s}$$

$$\theta_j = 15^\circ$$

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

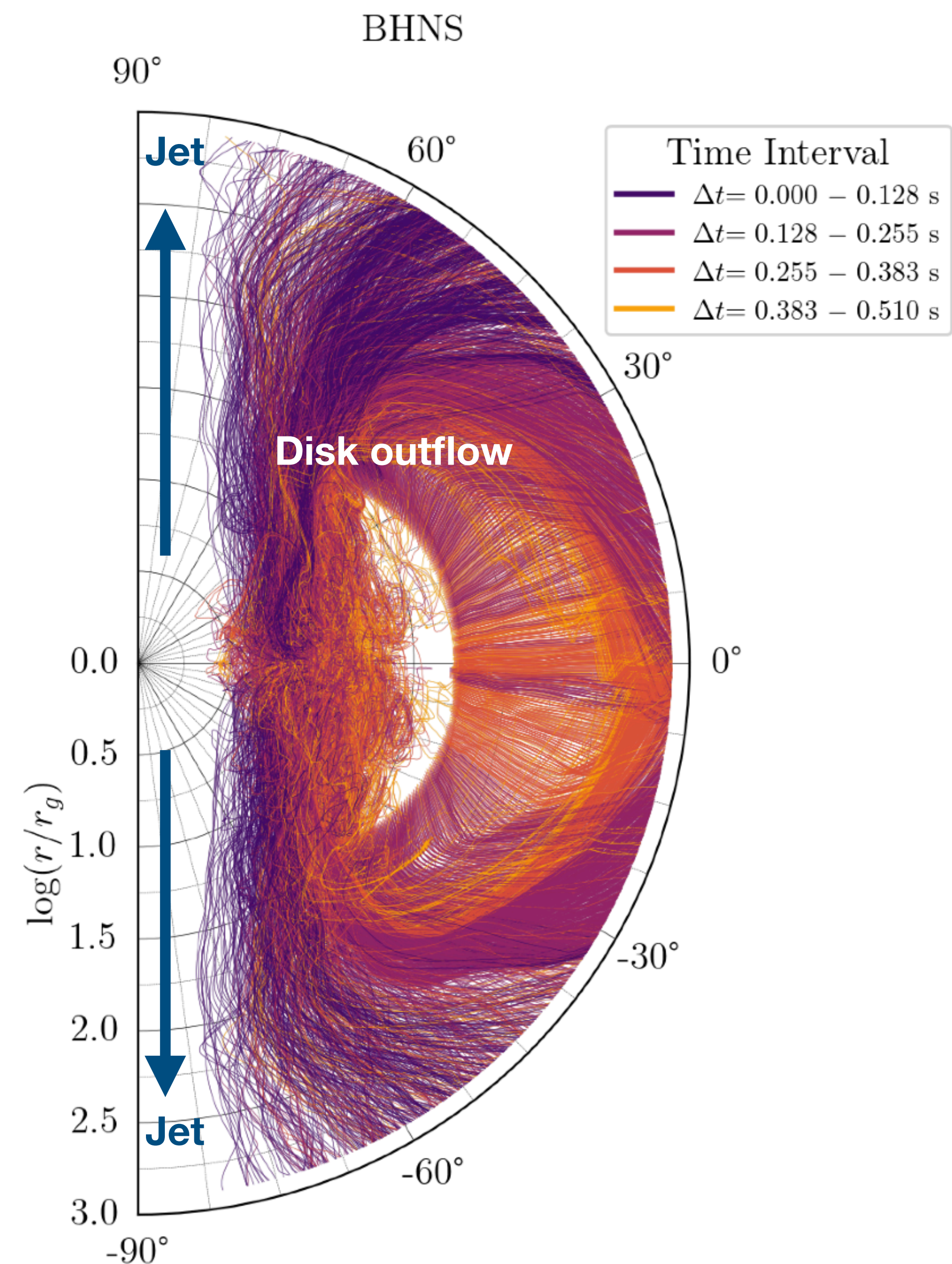
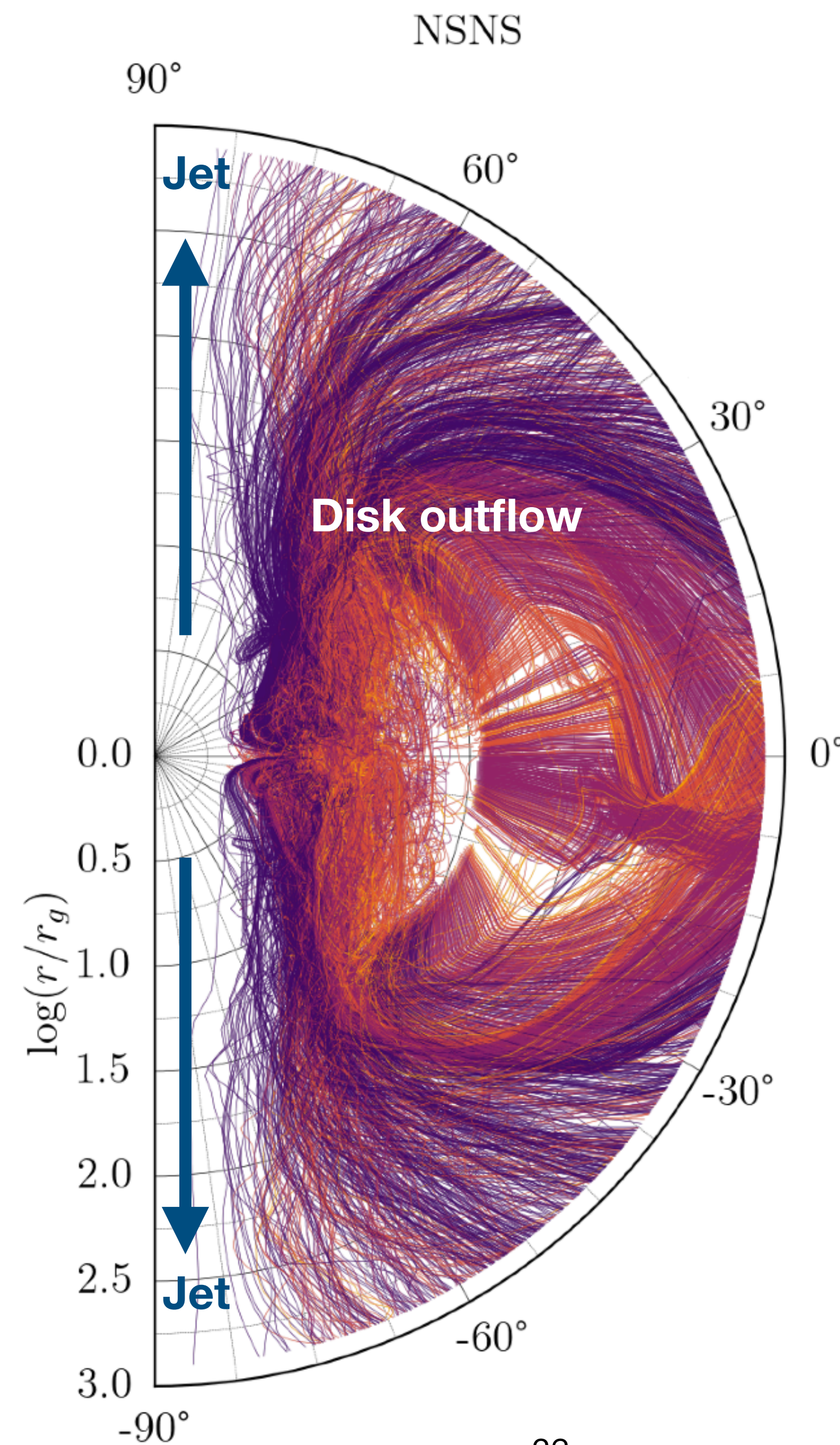
Jet Characteristics

$$\Gamma_j = 12$$

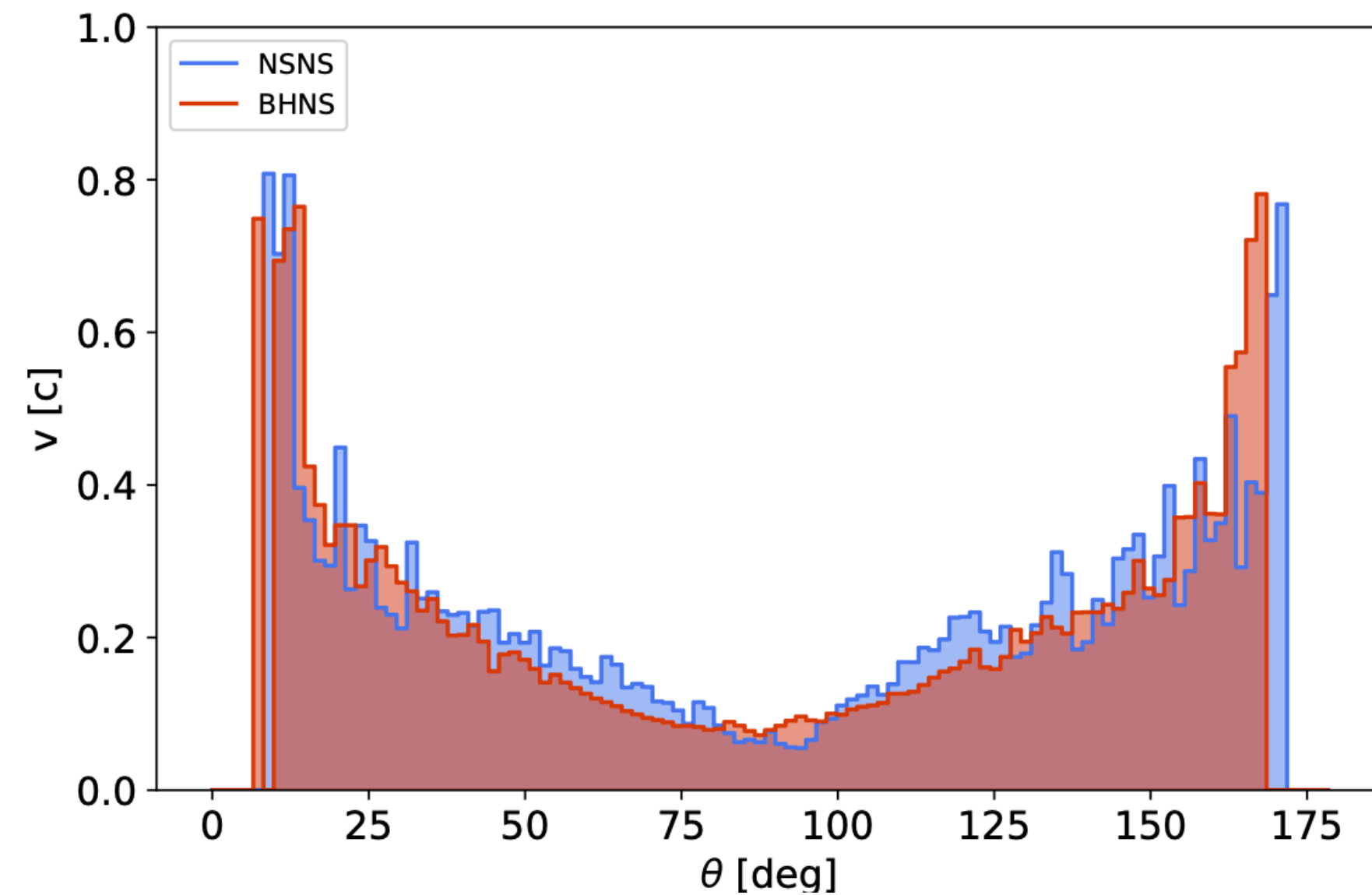
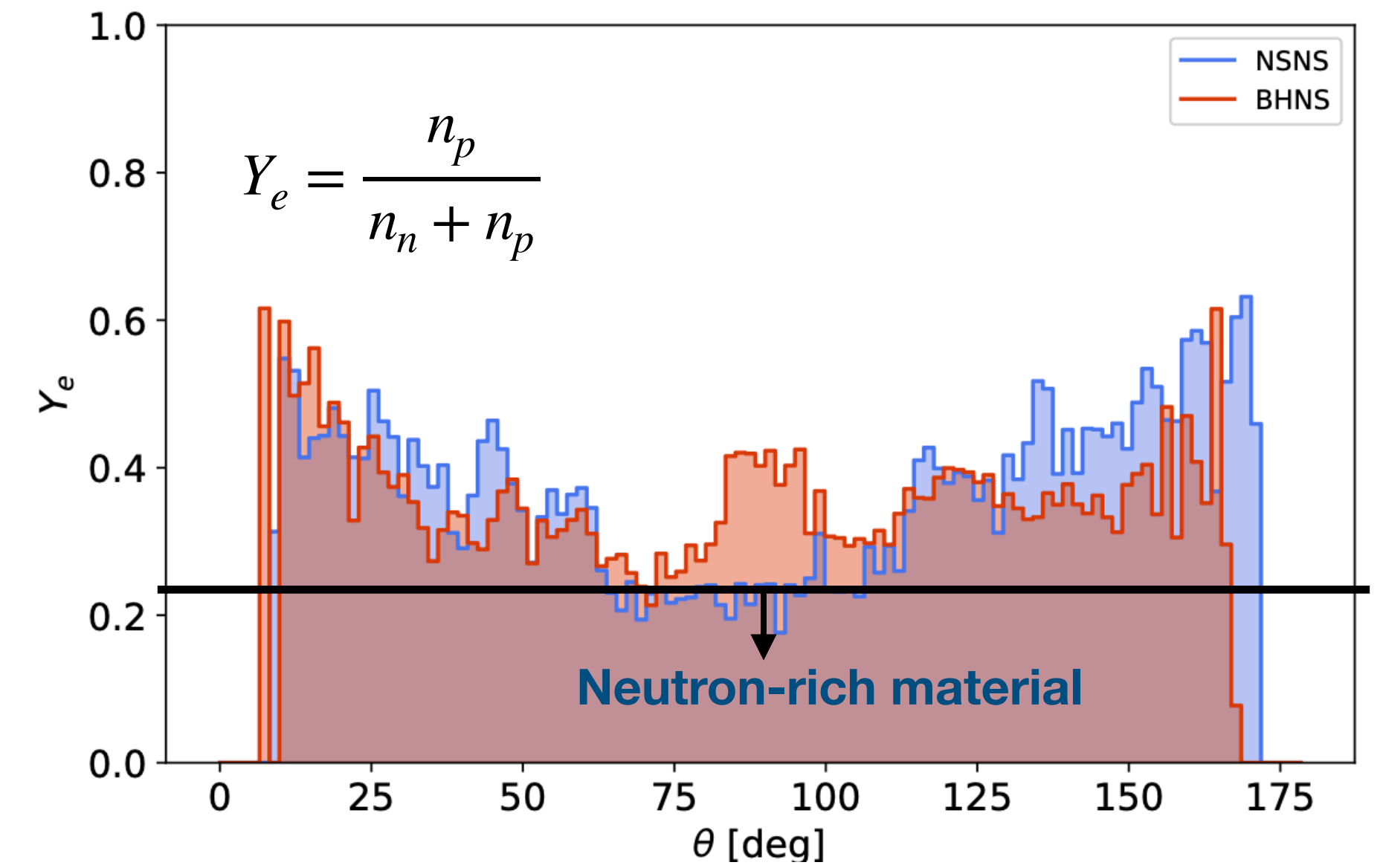
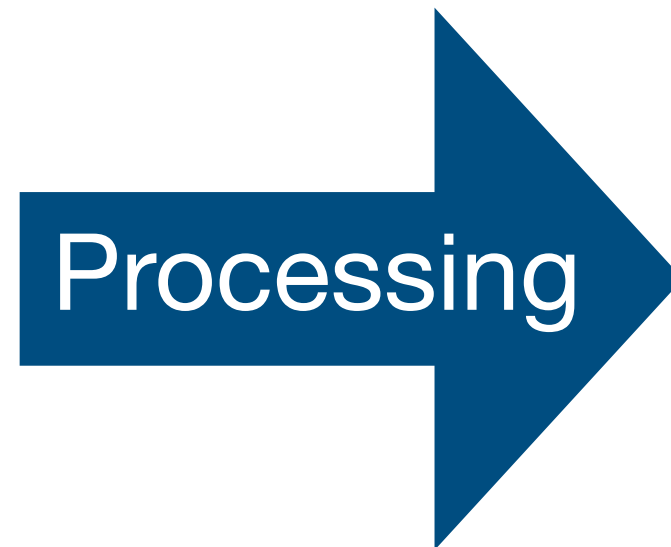
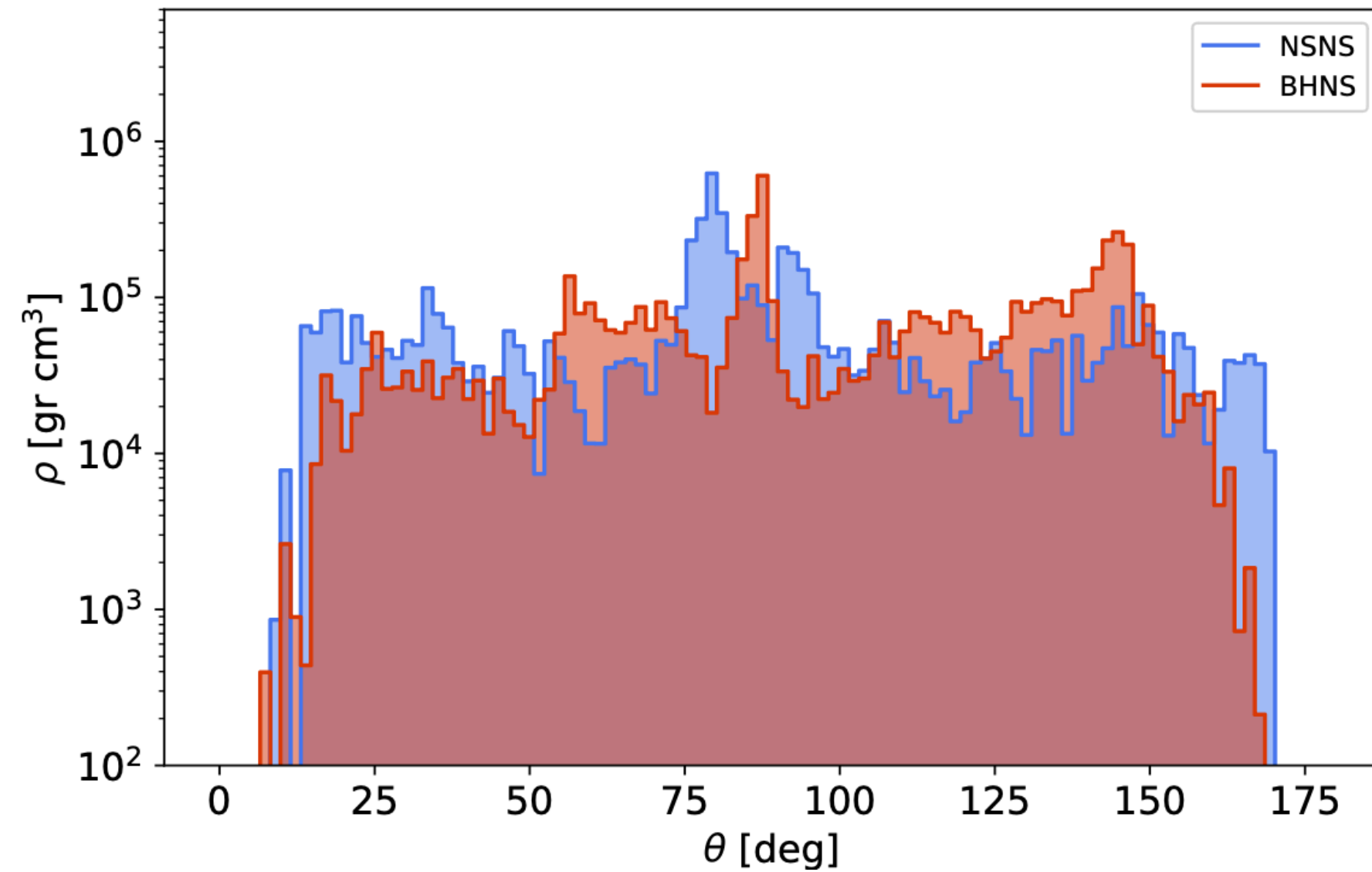
$$t_j \propto M_{\text{disk}} / \langle \dot{M} \rangle \sim 1.07 \text{ s}$$

$$\theta_j = 15^\circ$$

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



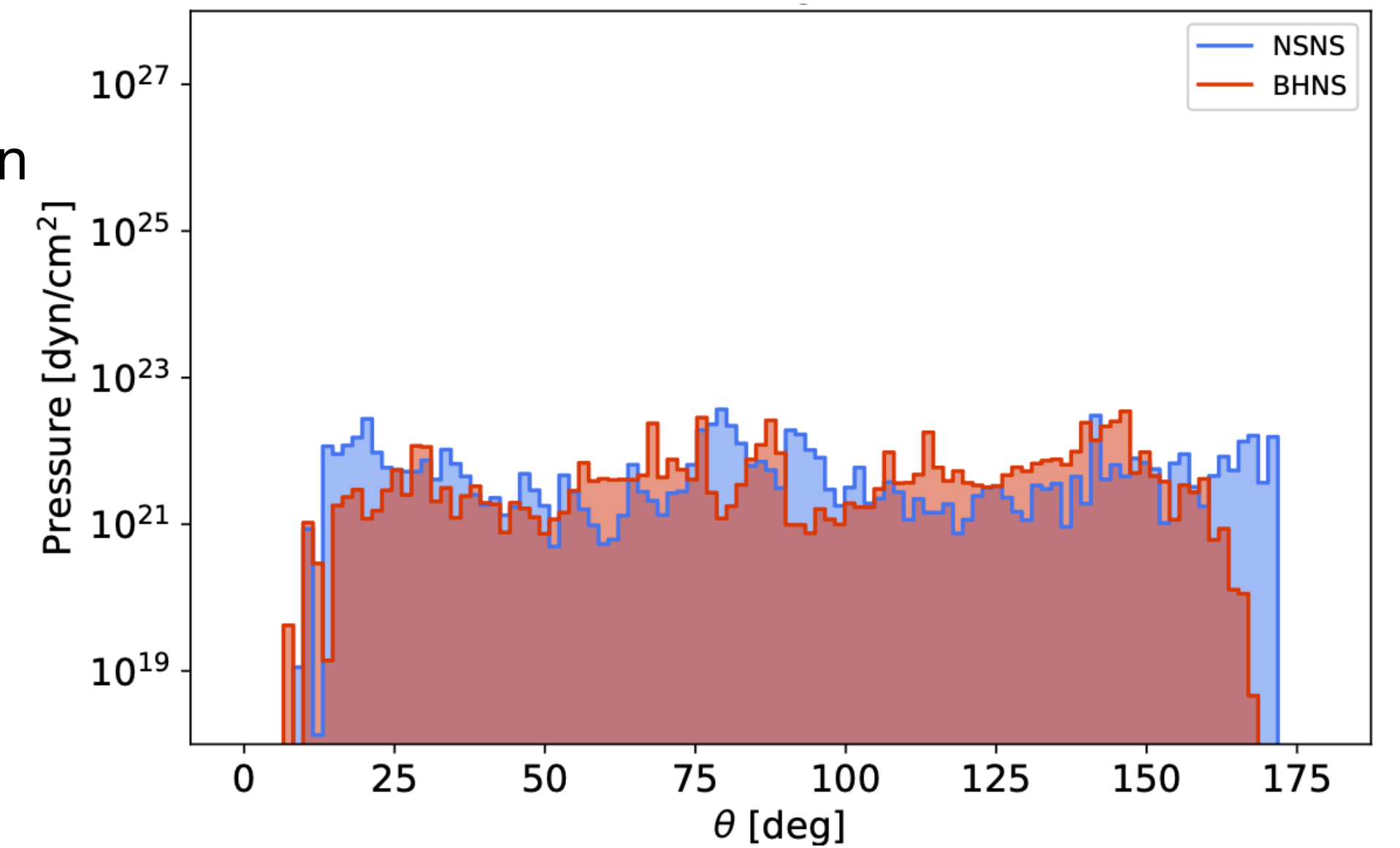
Wind distributions at $r_{\text{inj}} \sim 2 \times 10^8$ [cm]



SkyNet nuclear reaction network
(Lippuner & Roberts 2017)

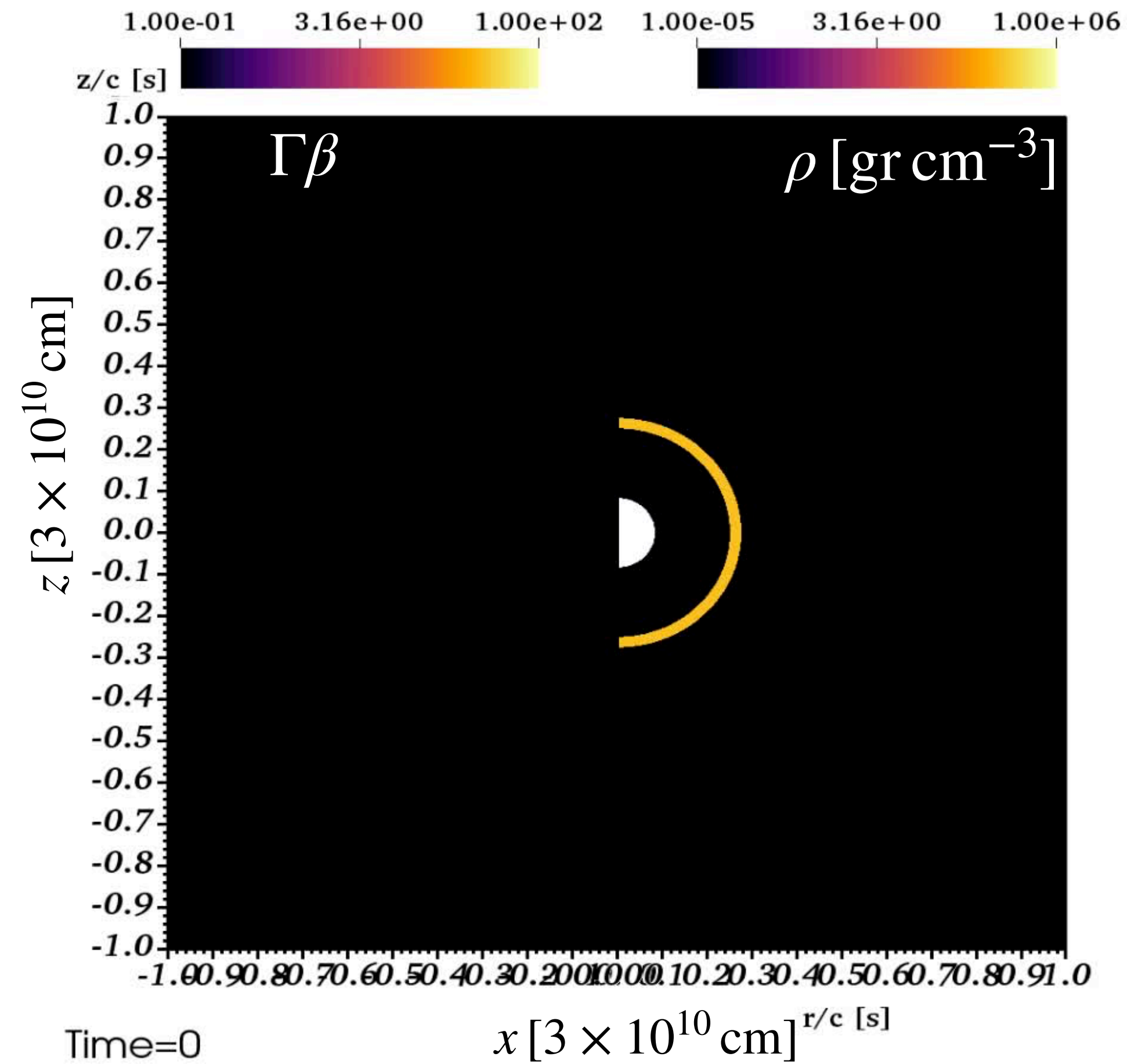
Inversion of Helmholtz equation
(Timmes & Arnet 1999)

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

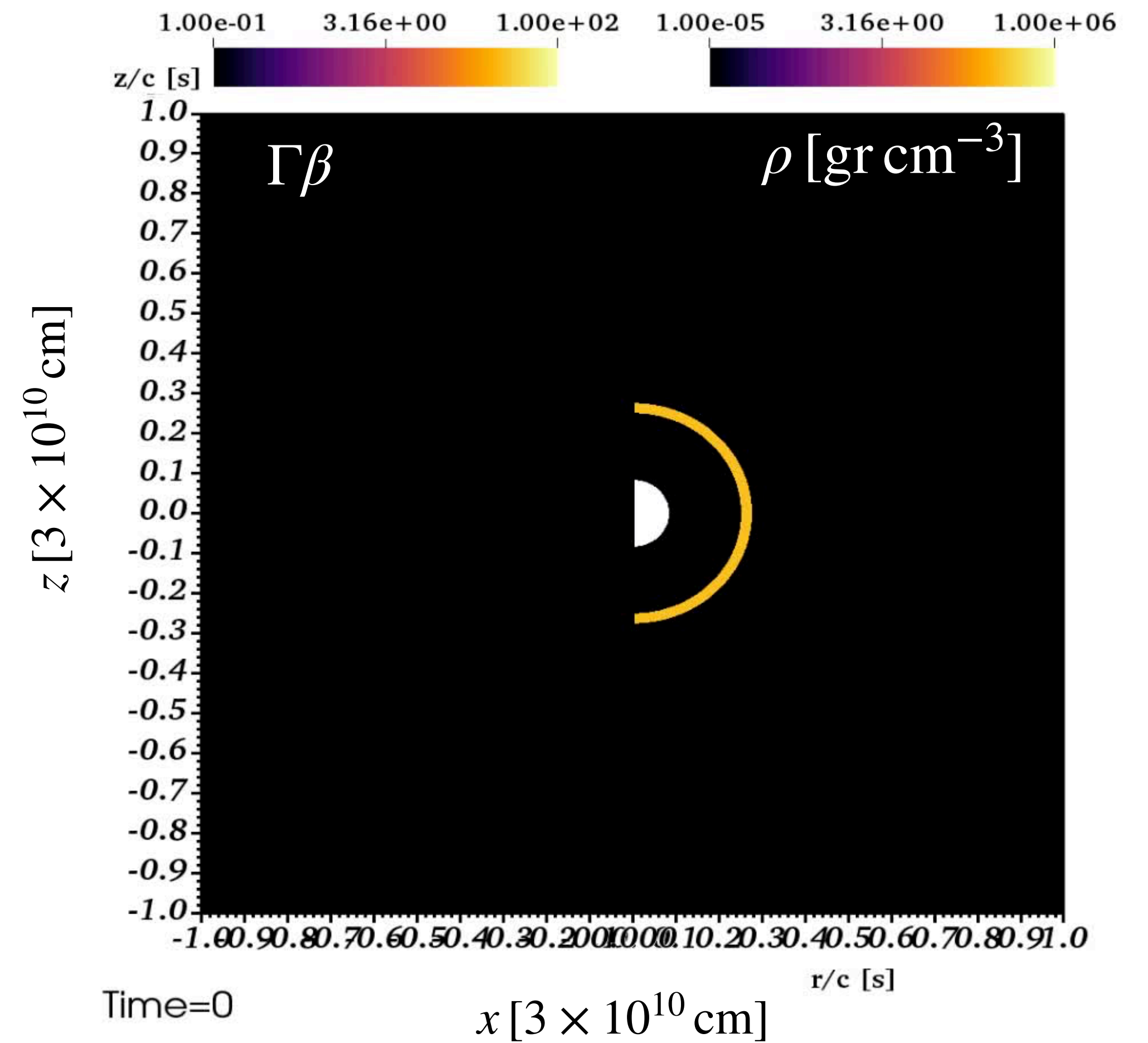


Results of jet interaction

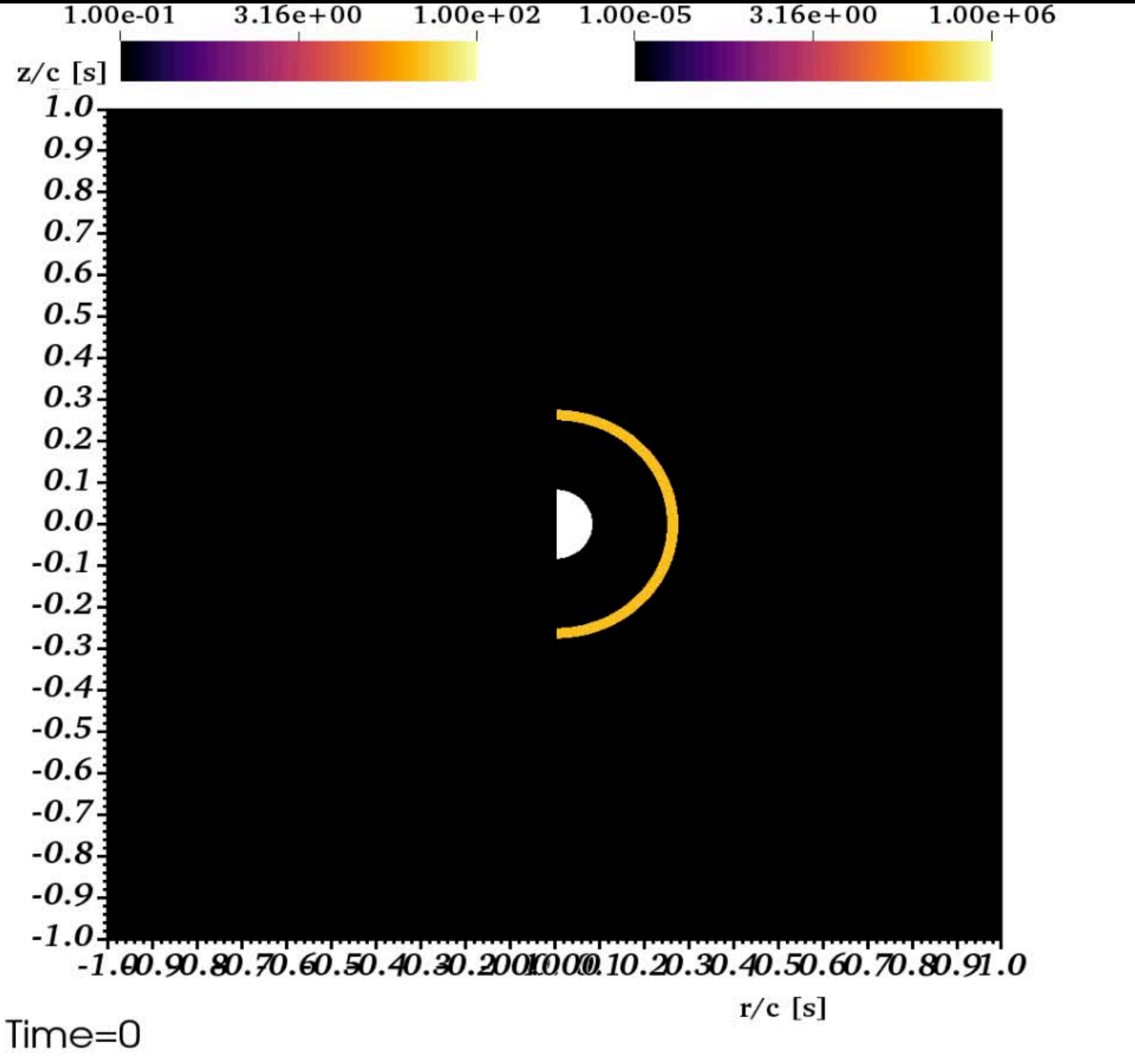
Jet from NSNS merger



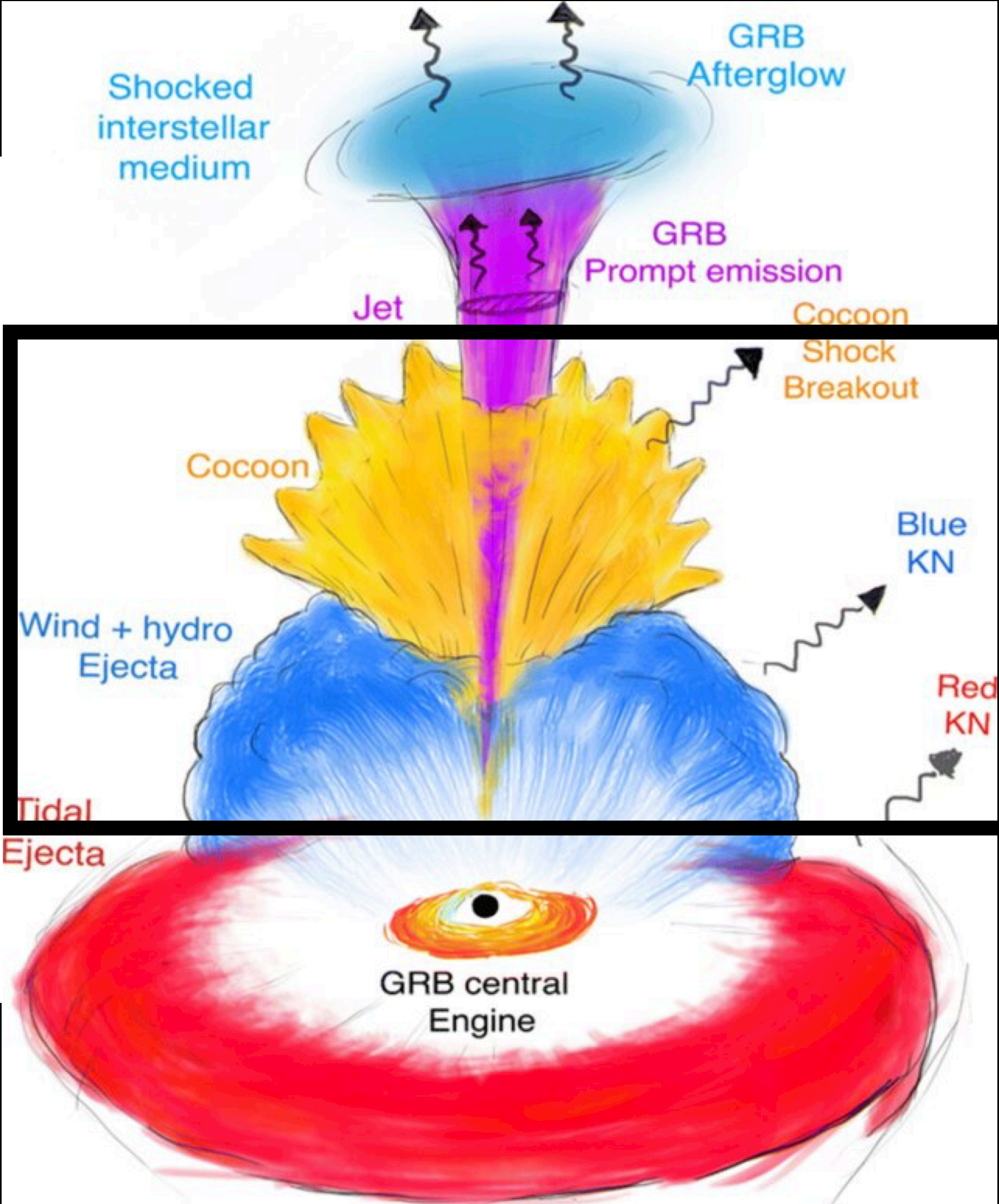
Jet from BHNS merger



Post-merger evolution of the jet



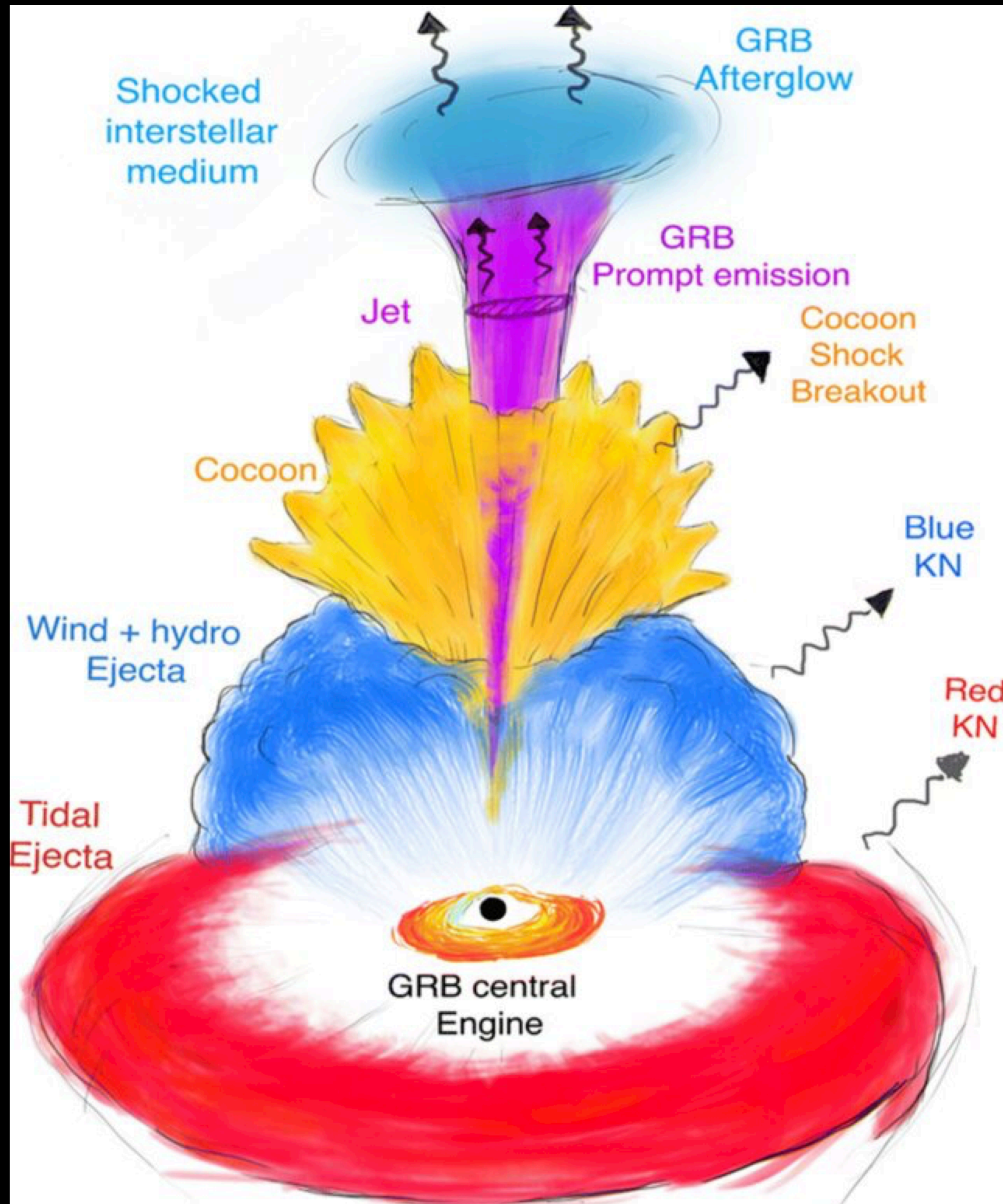
Urrutia, Janiuk and Nouri. 2024



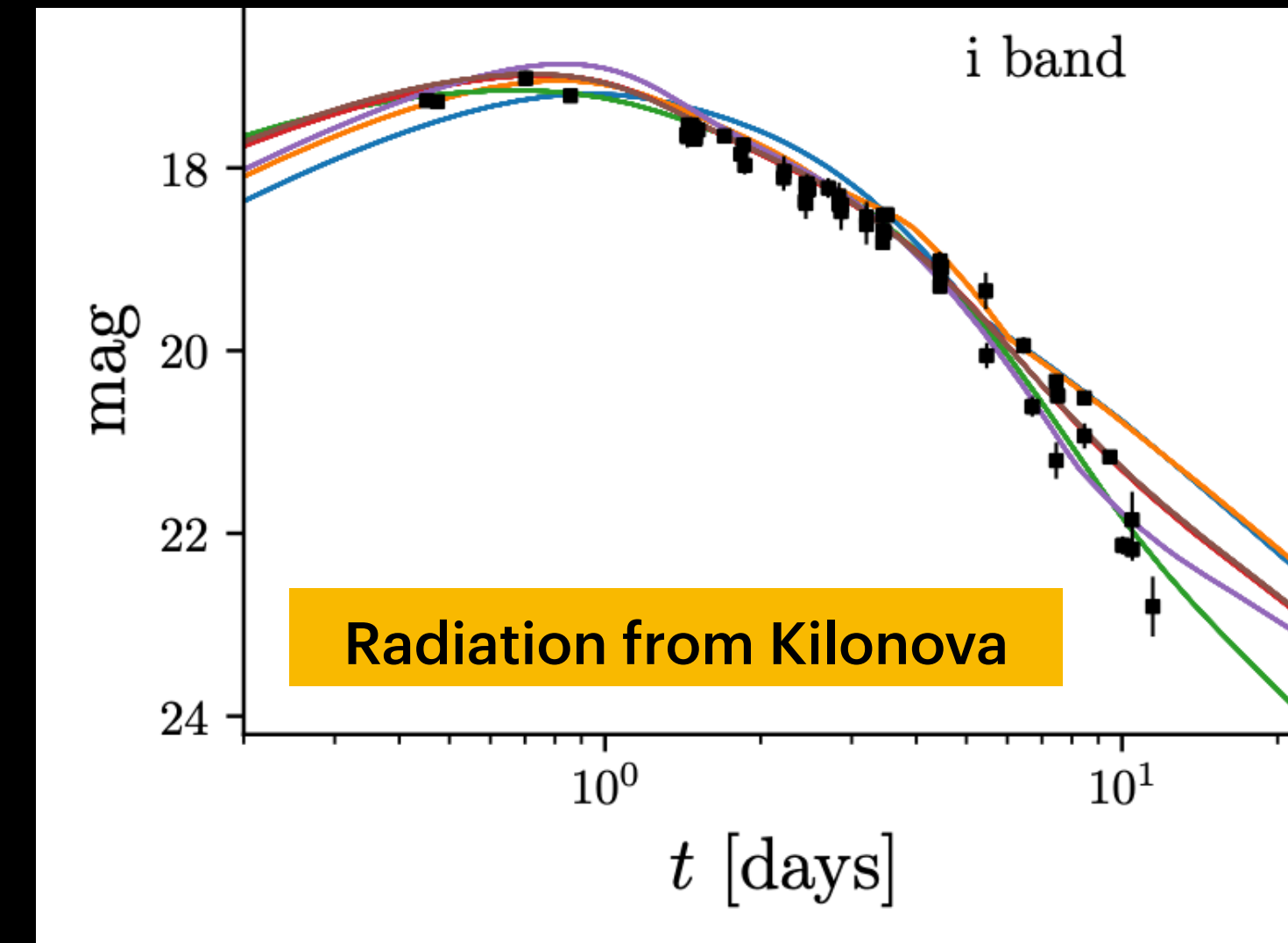
Cartoon of GRB evolution (Stefano Ascenzi)

Intermediate Scales $10^8 \lesssim r \lesssim 10^{11}$ cm
RMHD or RHD simulations

Observations from August 2017

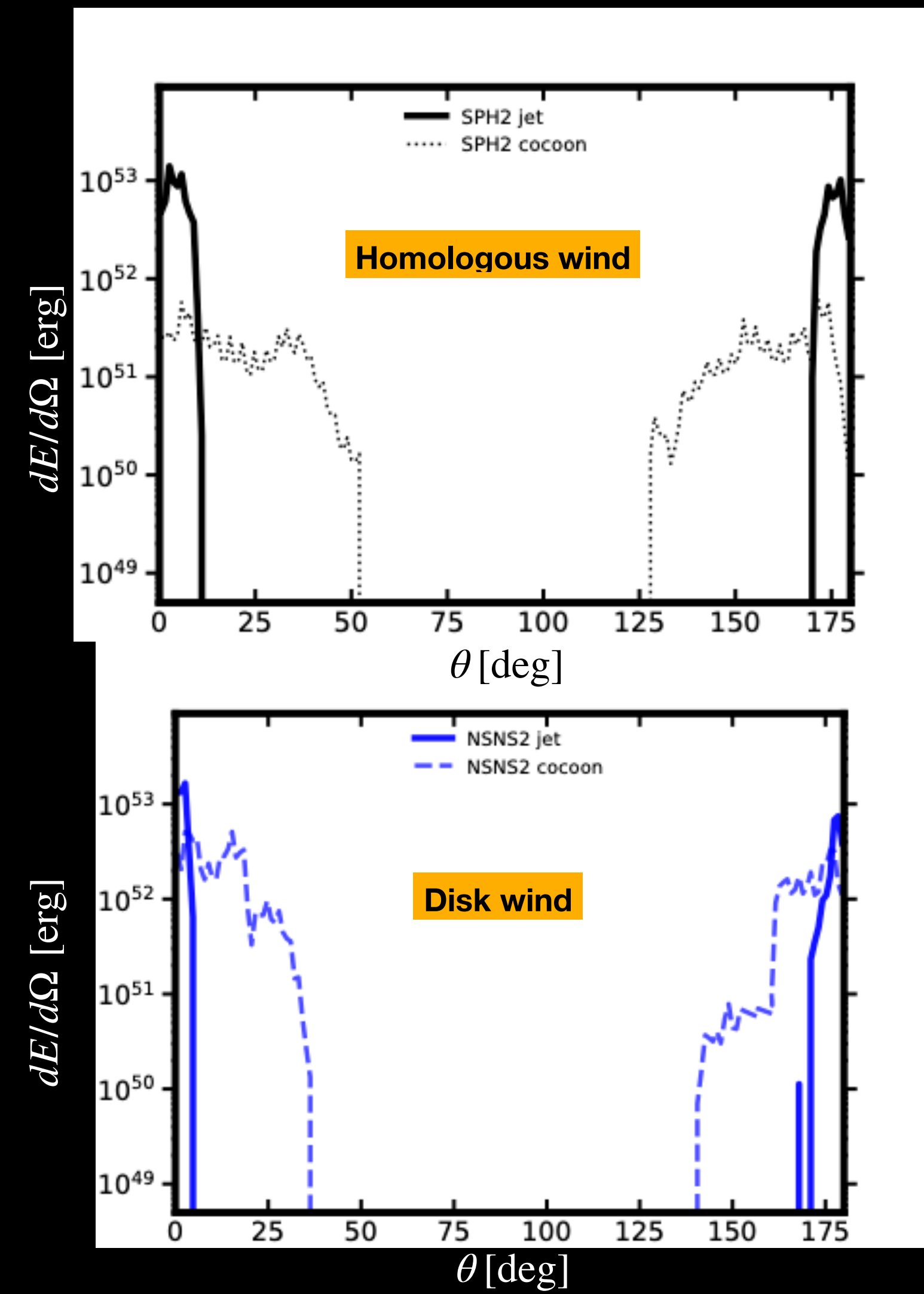
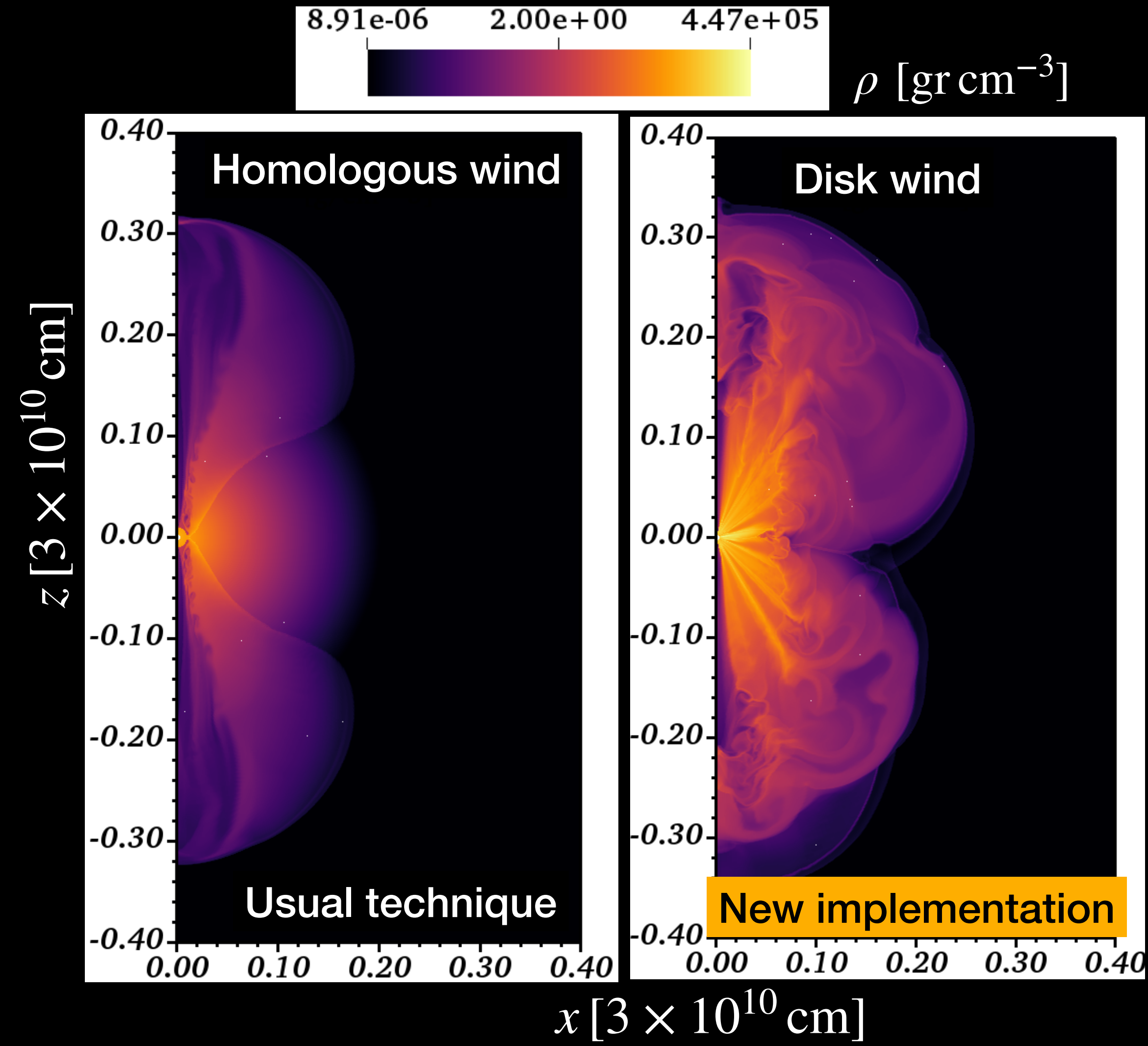


Credit: Stefano Ascenzi



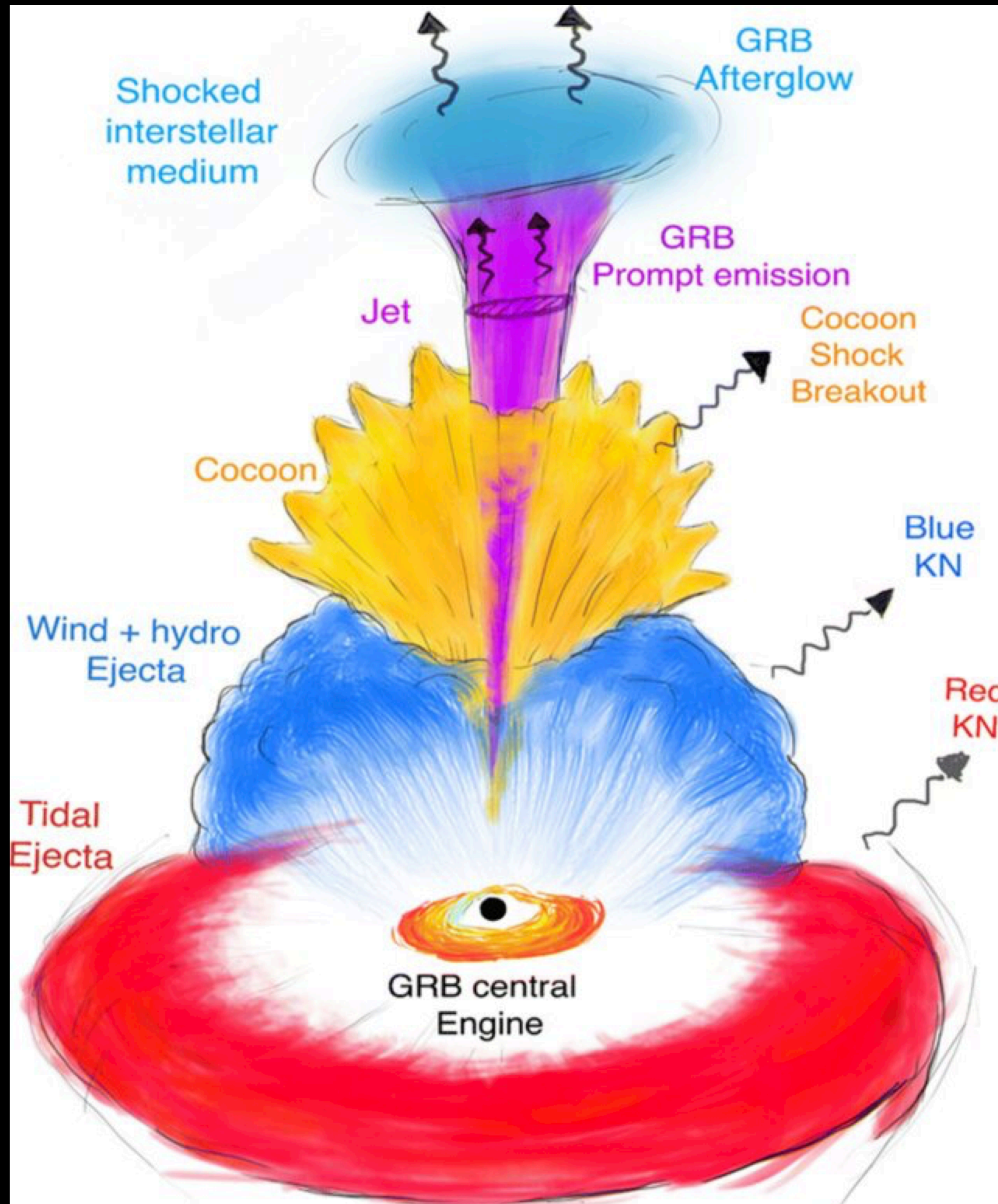
Breschi et al. 2021

Jet from NSNS merger

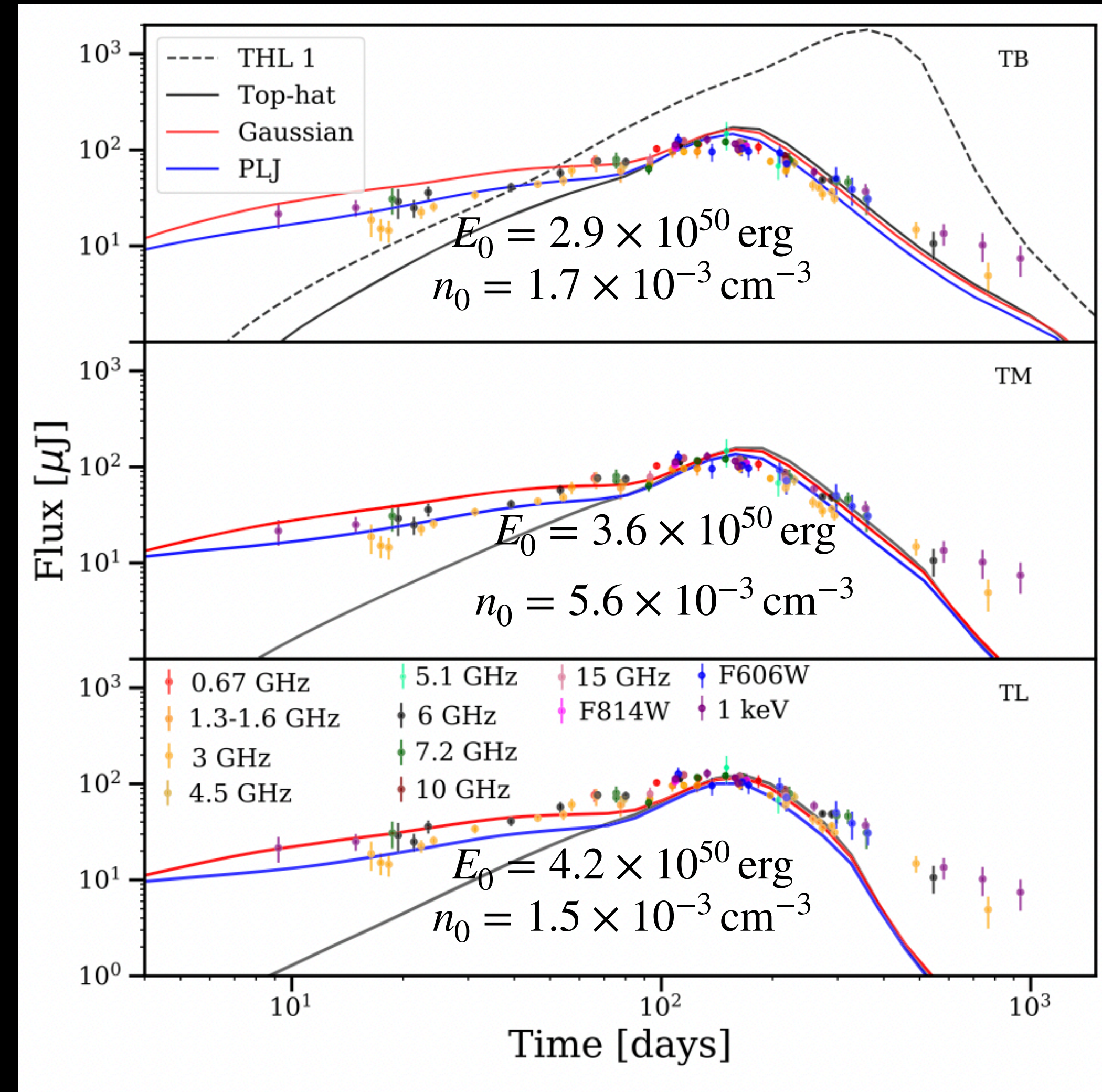


Observations from August 2017

GRB 170817 A $\theta_{\text{obs}} = 32.5^\circ$



Credit: Stefano Ascenzi

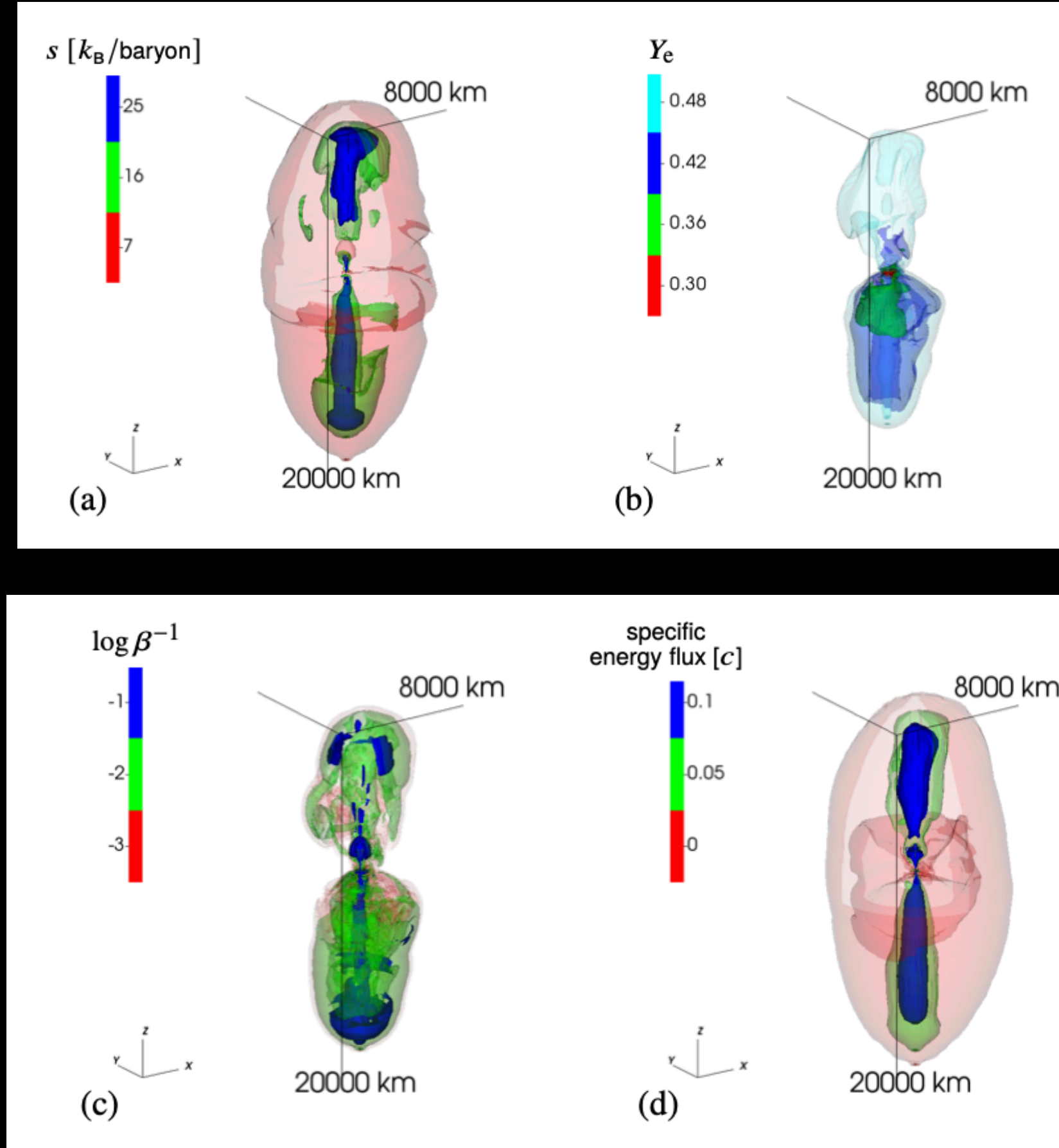


Urrutia, De Colle, Murguía-Berthier & Ramirez-Ruiz (2021)

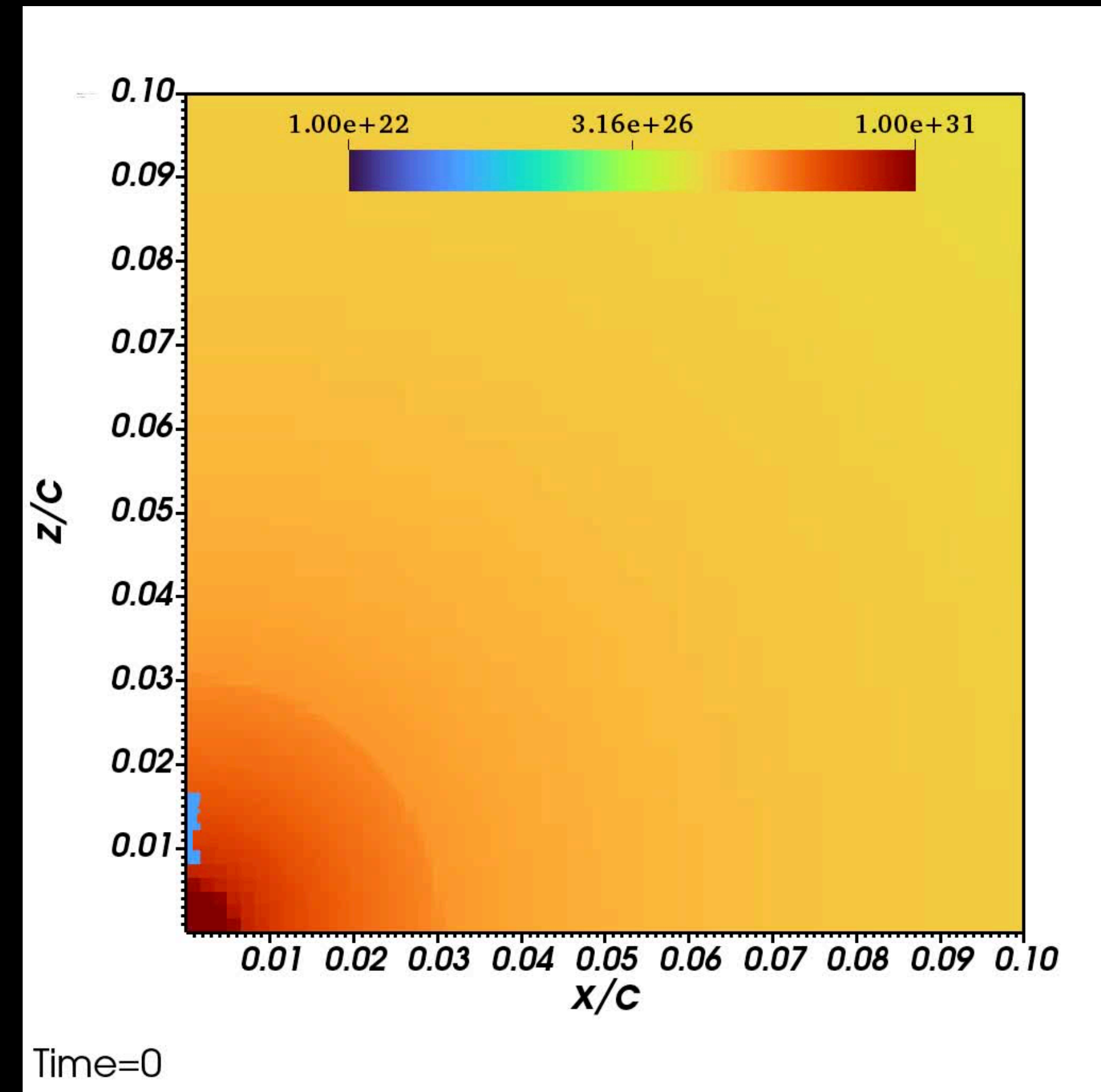
Jets from collapsing stars

Collapsars are studied at two different scales

Small scales, e.g, Obergaulinger & Aloy 2020



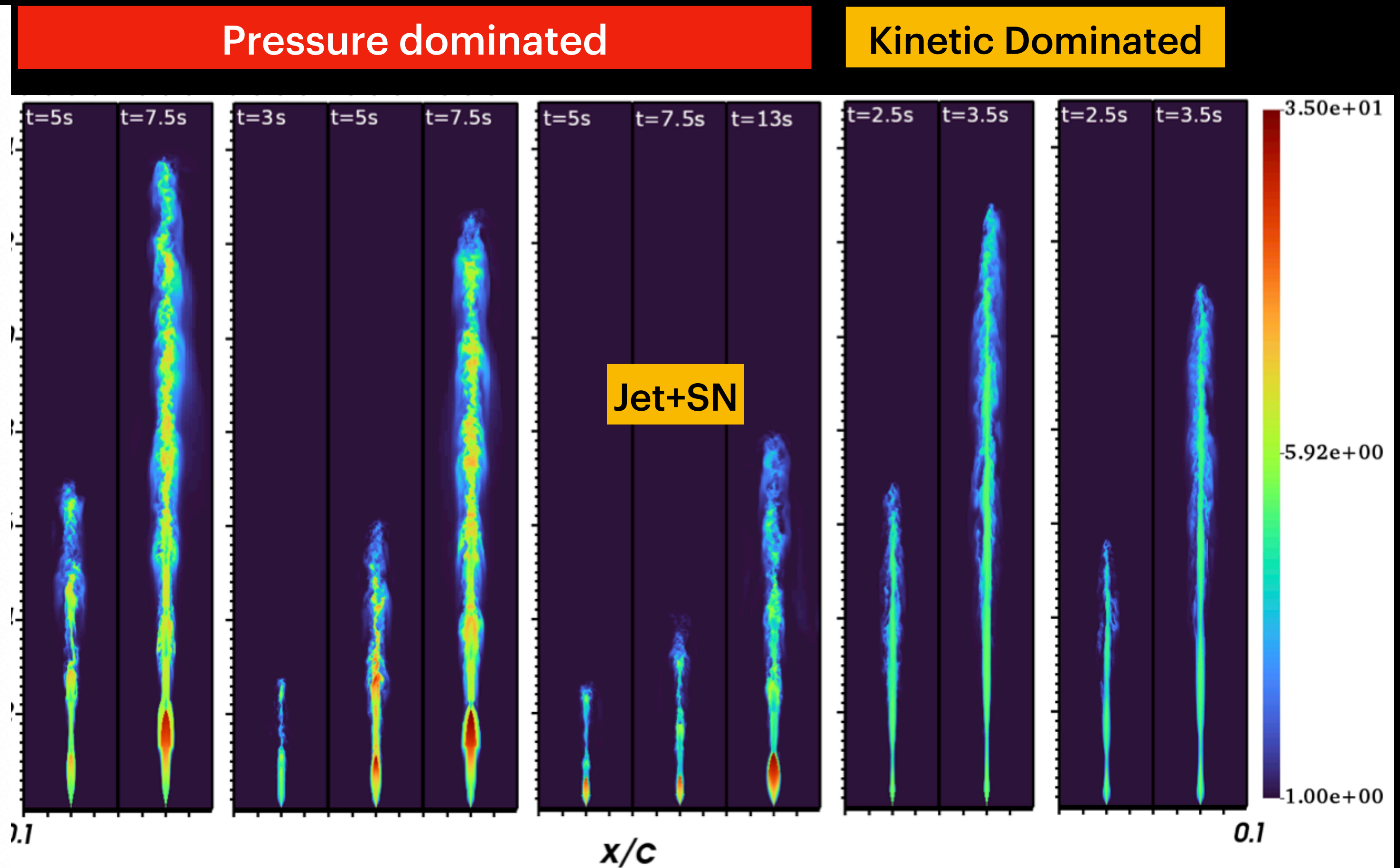
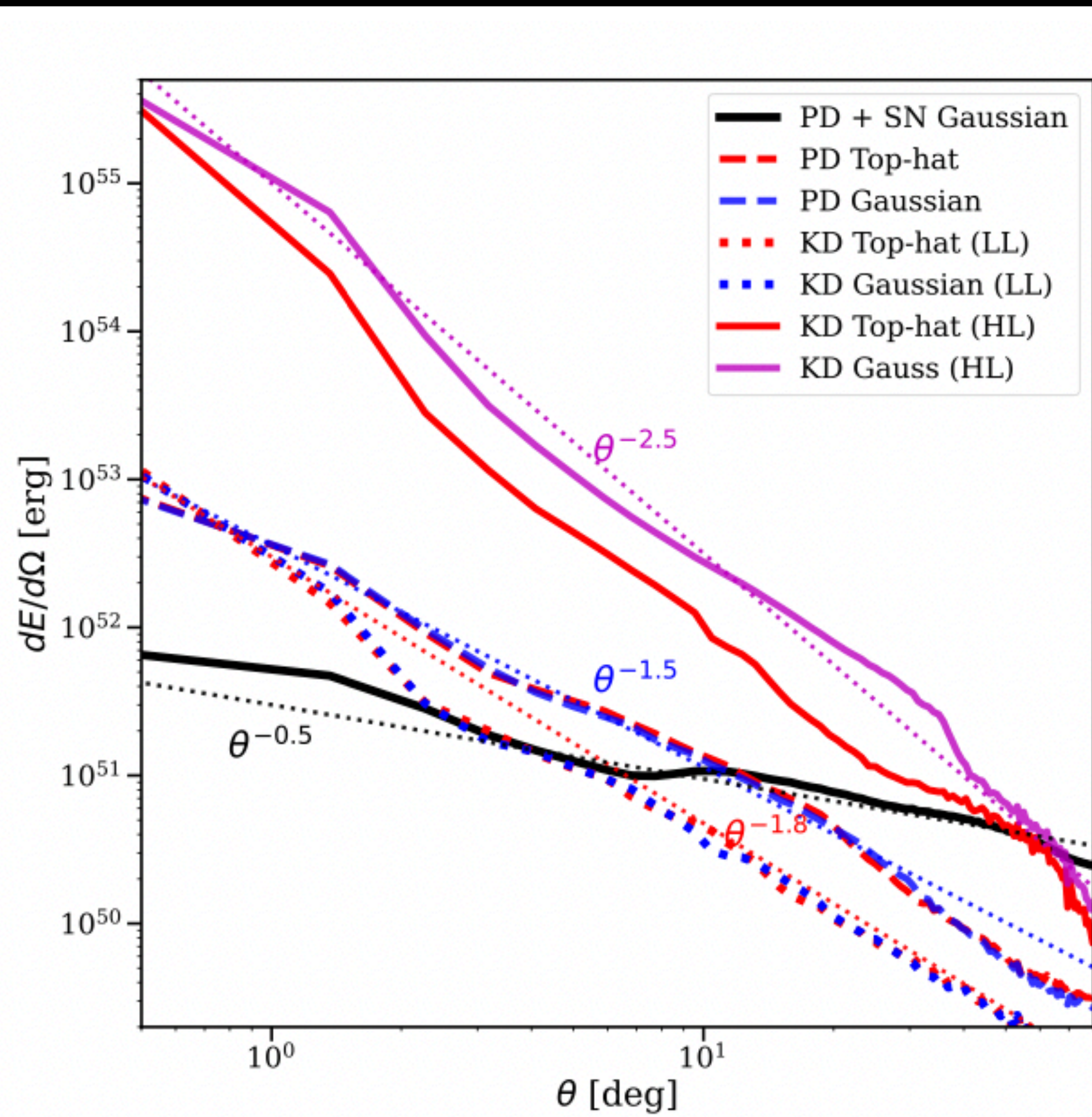
e.g., beyond the star surface Urrutia + 2023



Also see, McFadyen & Woosley 1999 , Shibata + 2025

Also see, Aloy + 2000, Harrison + 2019, Gottlieb + 2020, ...

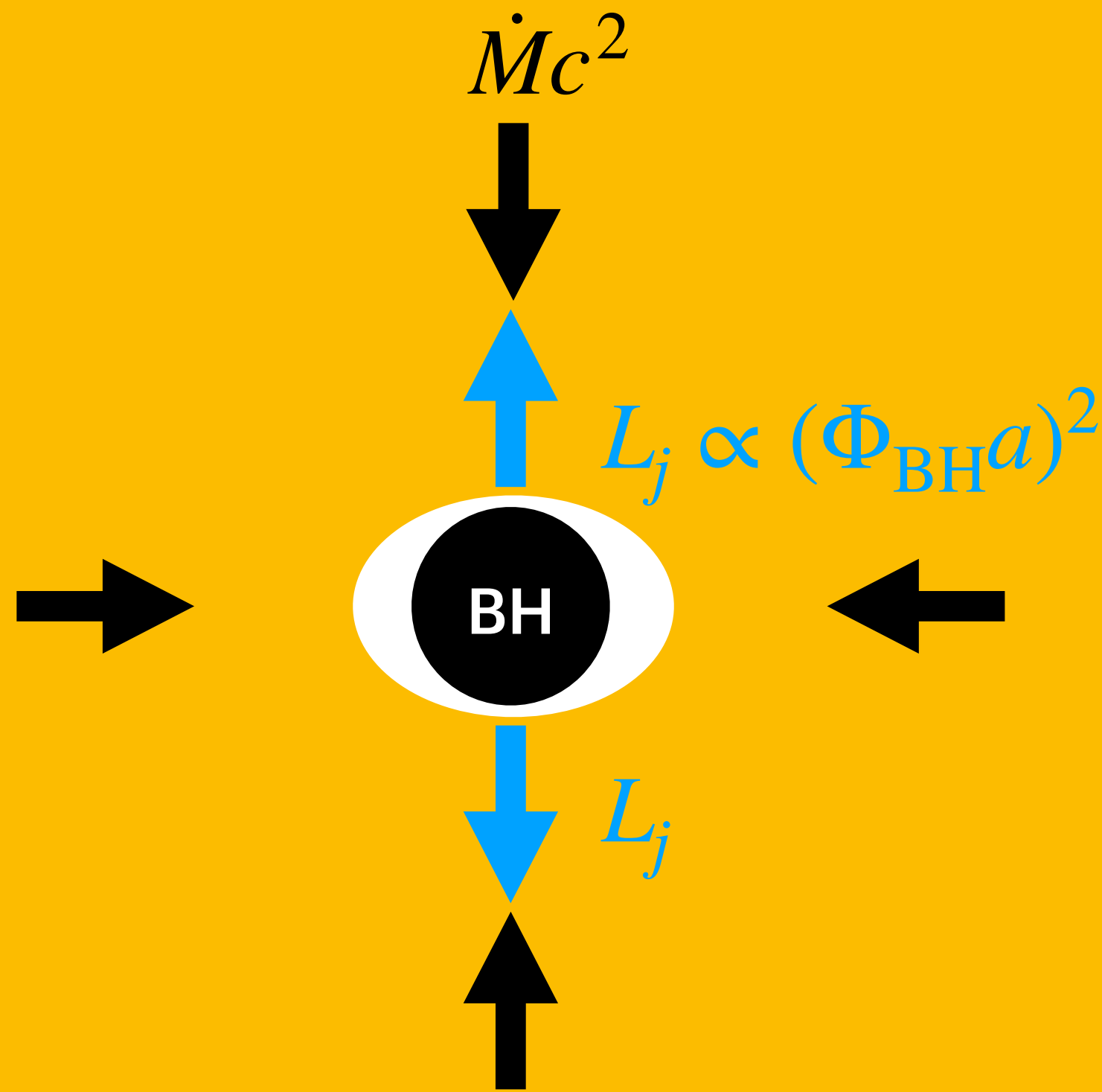
Jets beyond the iron core: jets initially structured



Urrutia, De Colle & Lopez-Camara 2023

Jet launching from the center

Progenitor Star



Fast spinning BH (e.g., MacFadyen & Woosley 1999)

Angular momentum distribution $l \propto l_0 \sin^2(\theta)$

Dynamical time $t_{\text{dyn}} \sim 10 \text{ s}$

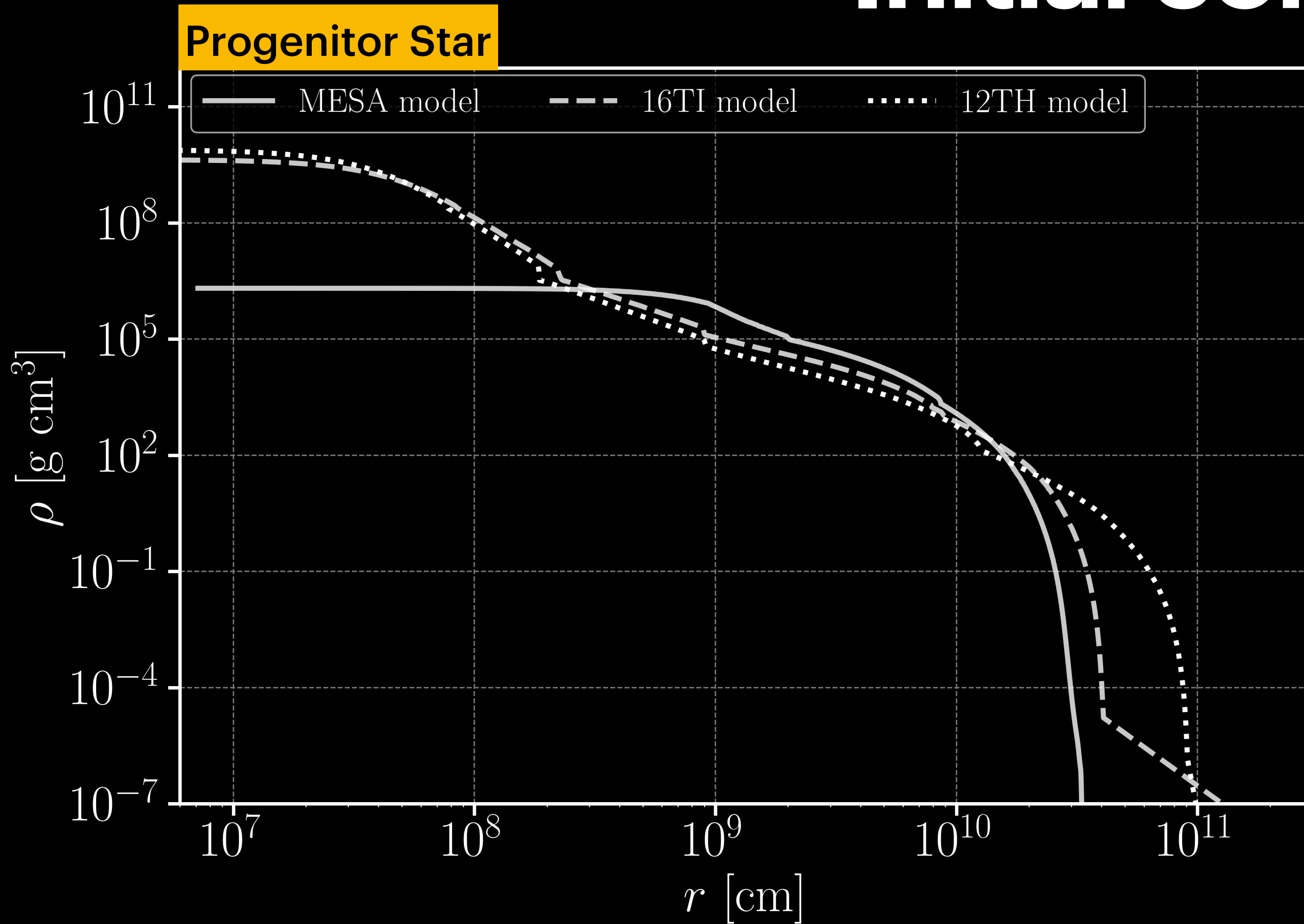
Accretion rate $\dot{M} \sim 0.1 M_{\odot} \text{ s}^{-1}$

Magnetic Field $B_0 \sim 10^{14} - 10^{15} \text{ G}$

Flux $\Phi \approx 10^{27} \text{ G m}^{-2}$

(e.g., Burrows 2007, Mösta 2014; 2015;
Obergaullinger & Aloy 2020; Gottlieb 2022)

Initial conditions



$$M_{\text{BH}} = 3M_{\odot}, 5M_{\odot}$$

Rotation

$$\epsilon_{\text{isco}} = -u_{t,\text{isco}} = \frac{1 - 2/r_{\text{isco}} + a/r_{\text{isco}}^{3/2}}{\sqrt{1 - 3/r_{\text{isco}} + 2a/r_{\text{isco}}^{3/2}}}$$

$$l_{\text{isco}} = u_{\phi,\text{isco}} = \frac{r_{\text{isco}}^{1/2} - 2a/r_{\text{isco}} + a^2/r_{\text{isco}}^{3/2}}{\sqrt{1 - 3/r_{\text{isco}} + 2a/r_{\text{isco}}^{3/2}}}$$

$$u^{\phi} = C \sin^2 \theta (-g^{t\phi} \epsilon_{\text{isco}} + g^{\phi\phi} l_{\text{isco}})$$

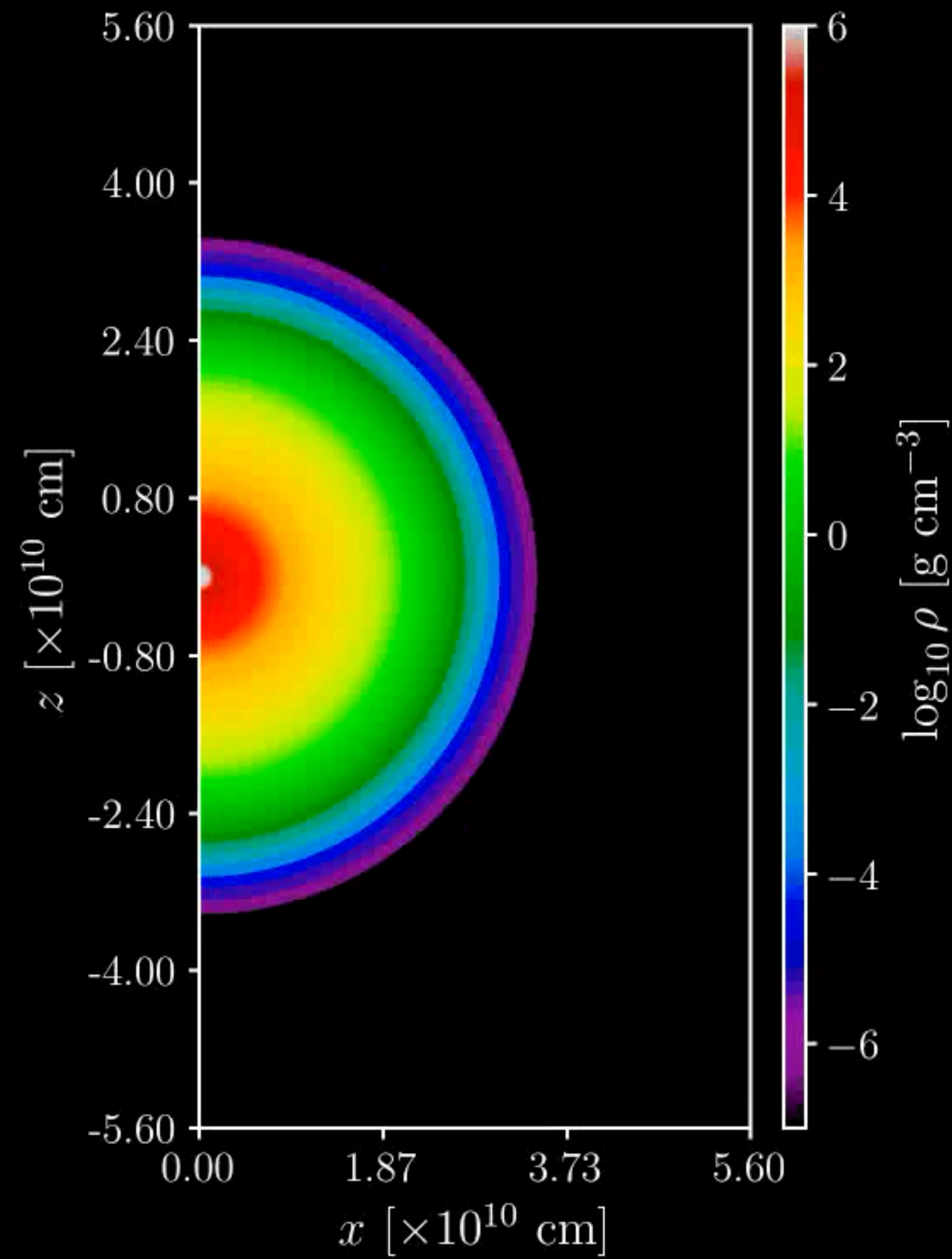
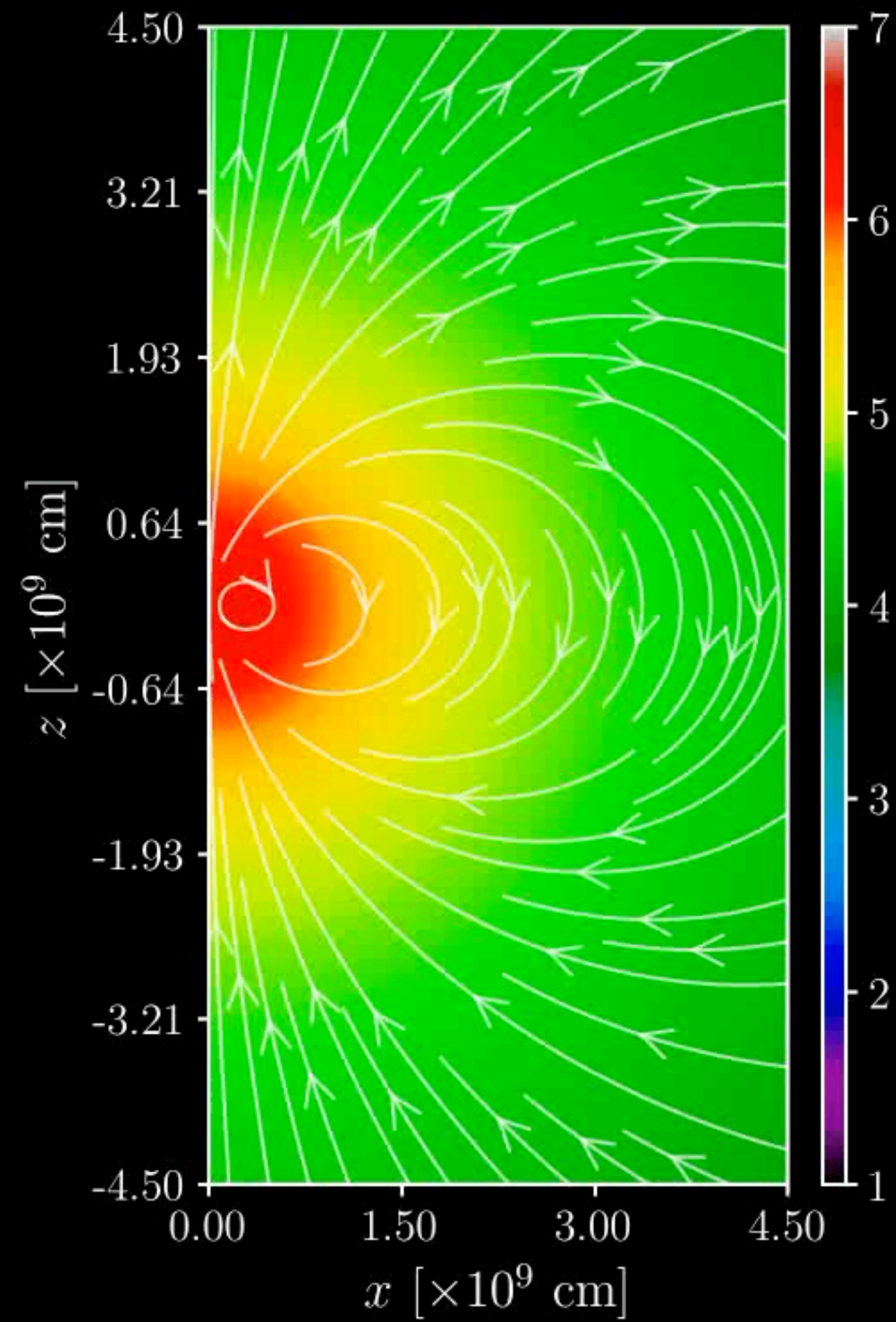
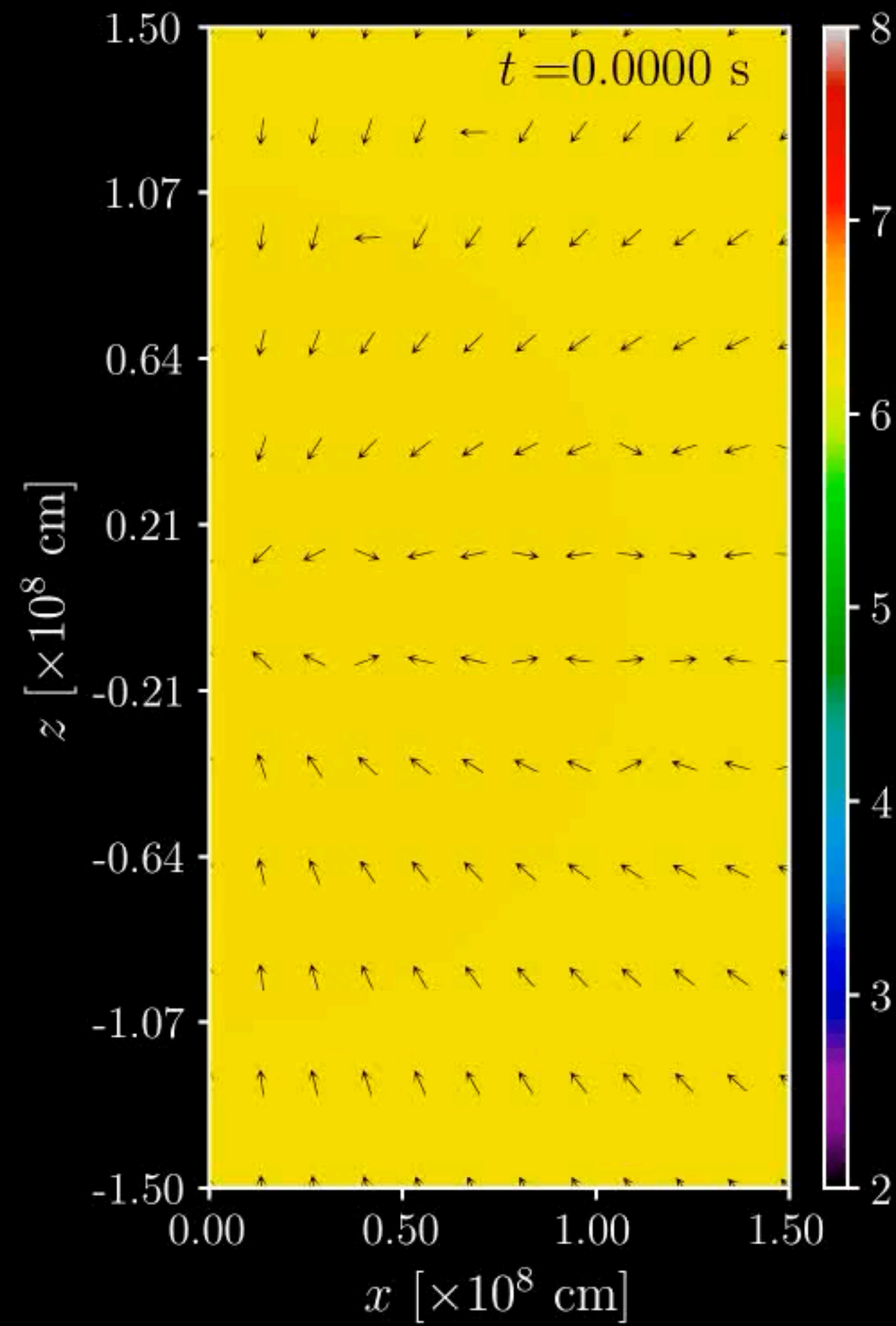
Magnetic Field Strength

$$B_0 = 10^{12} - 10^{14} \text{ G}$$

Magnetic Field Potential

$$A_{\phi} = \frac{B_0 r_c^3}{r^3 + r_0^3} \sin \theta$$

We are remapping the stellar profile in AMR- BHAC code (Porth + 2017; Olivares +2019)

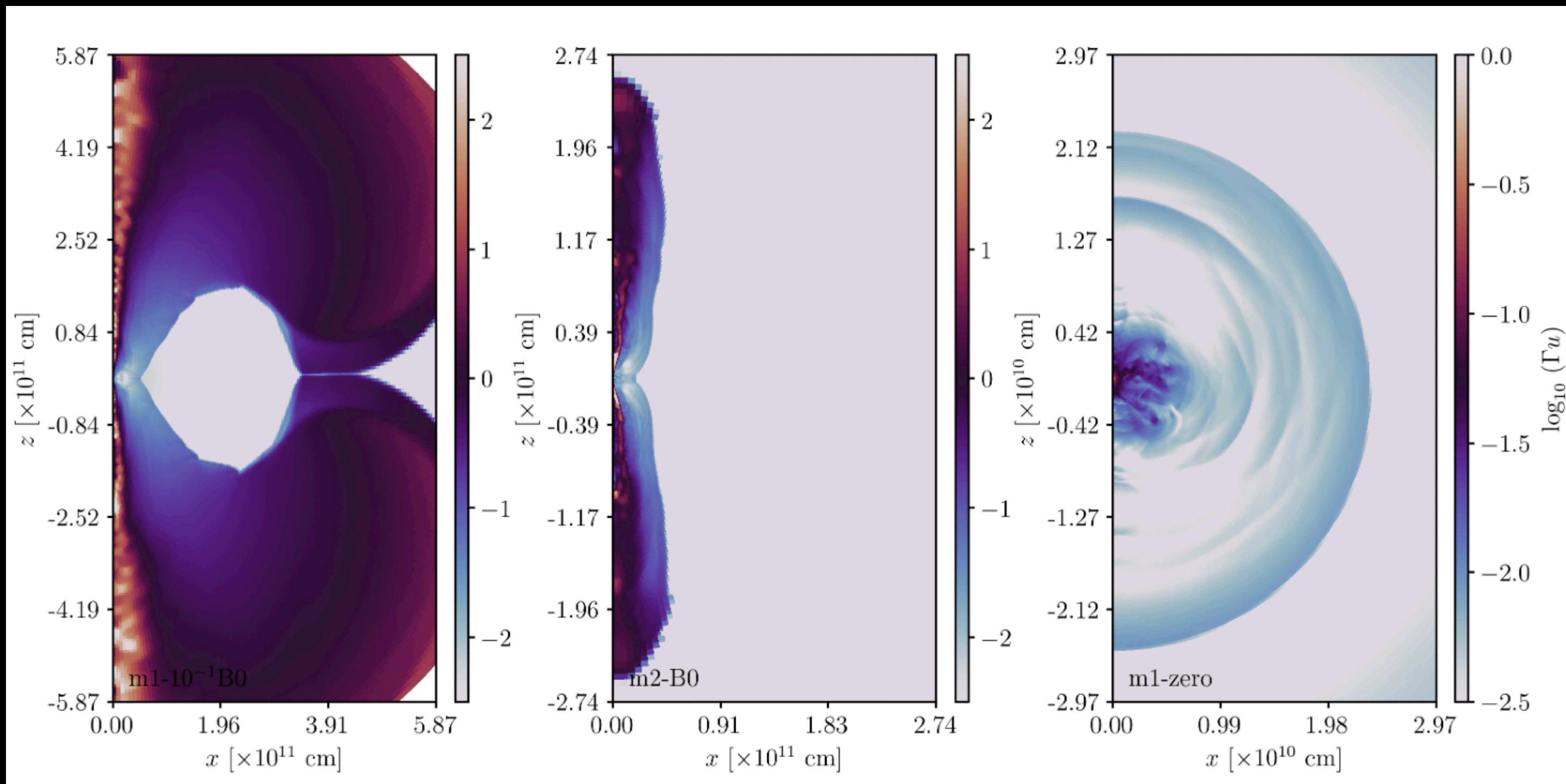


Jet propagation

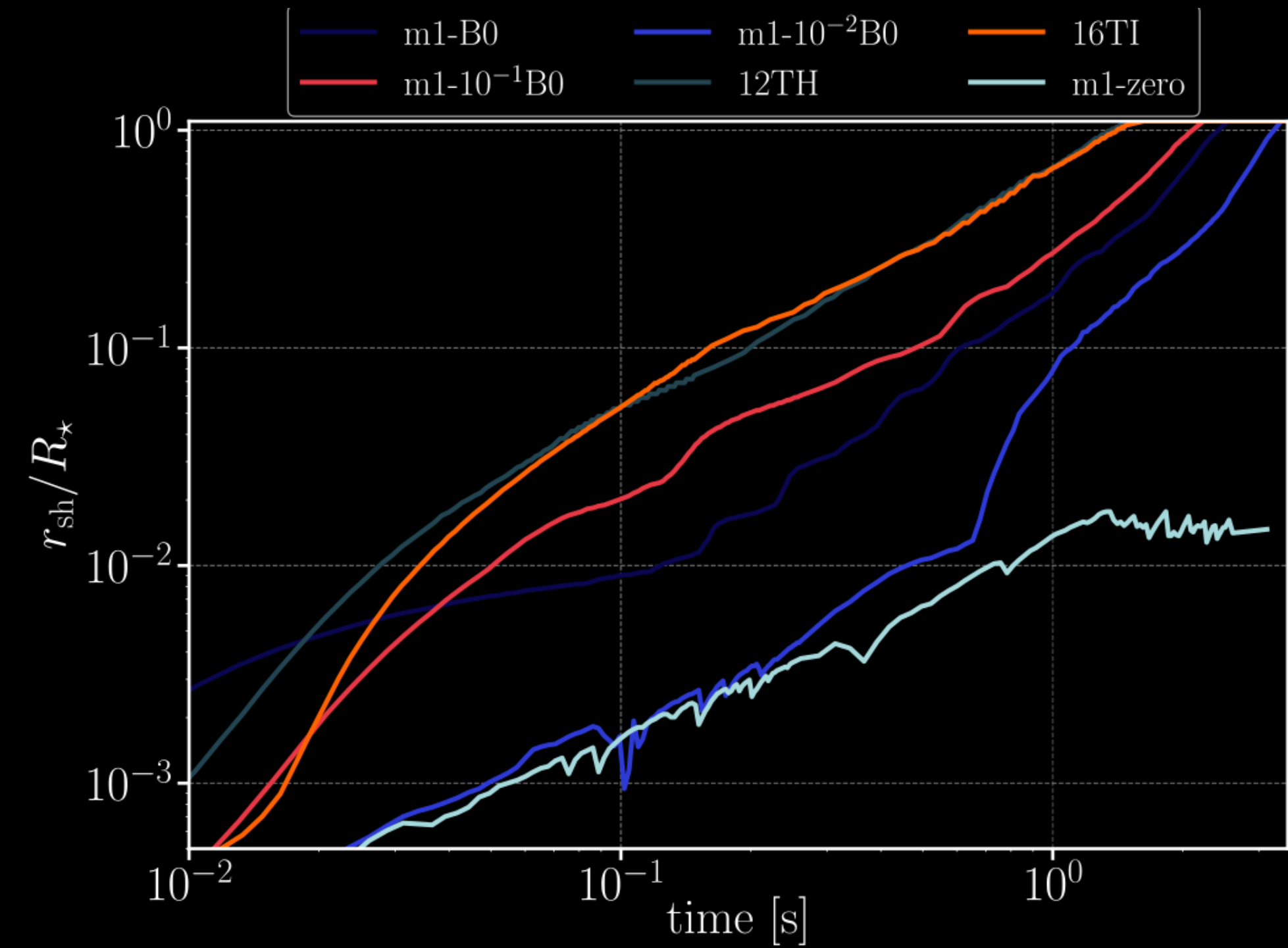
High magnetized

Weakly magnetized

Non magnetized

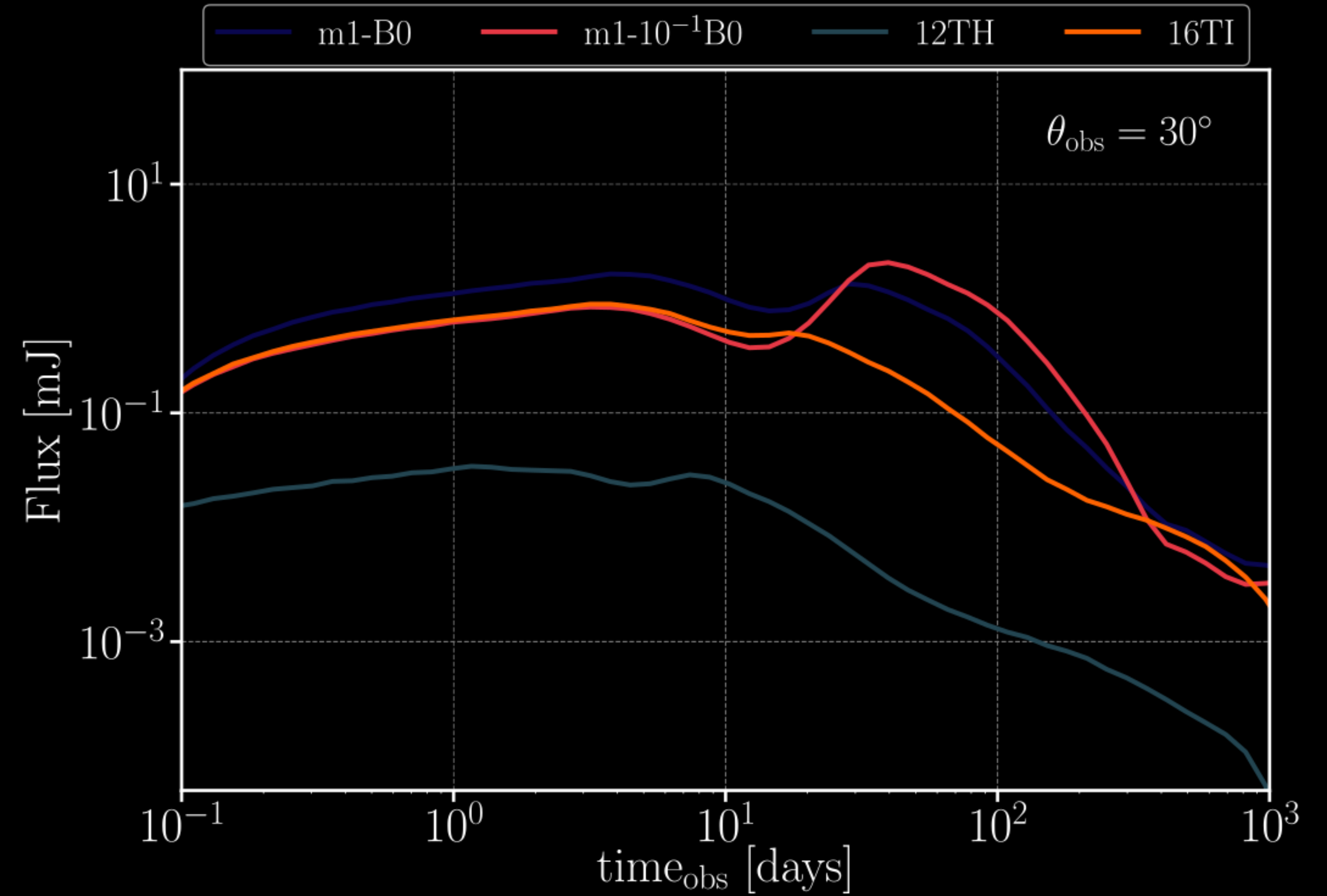
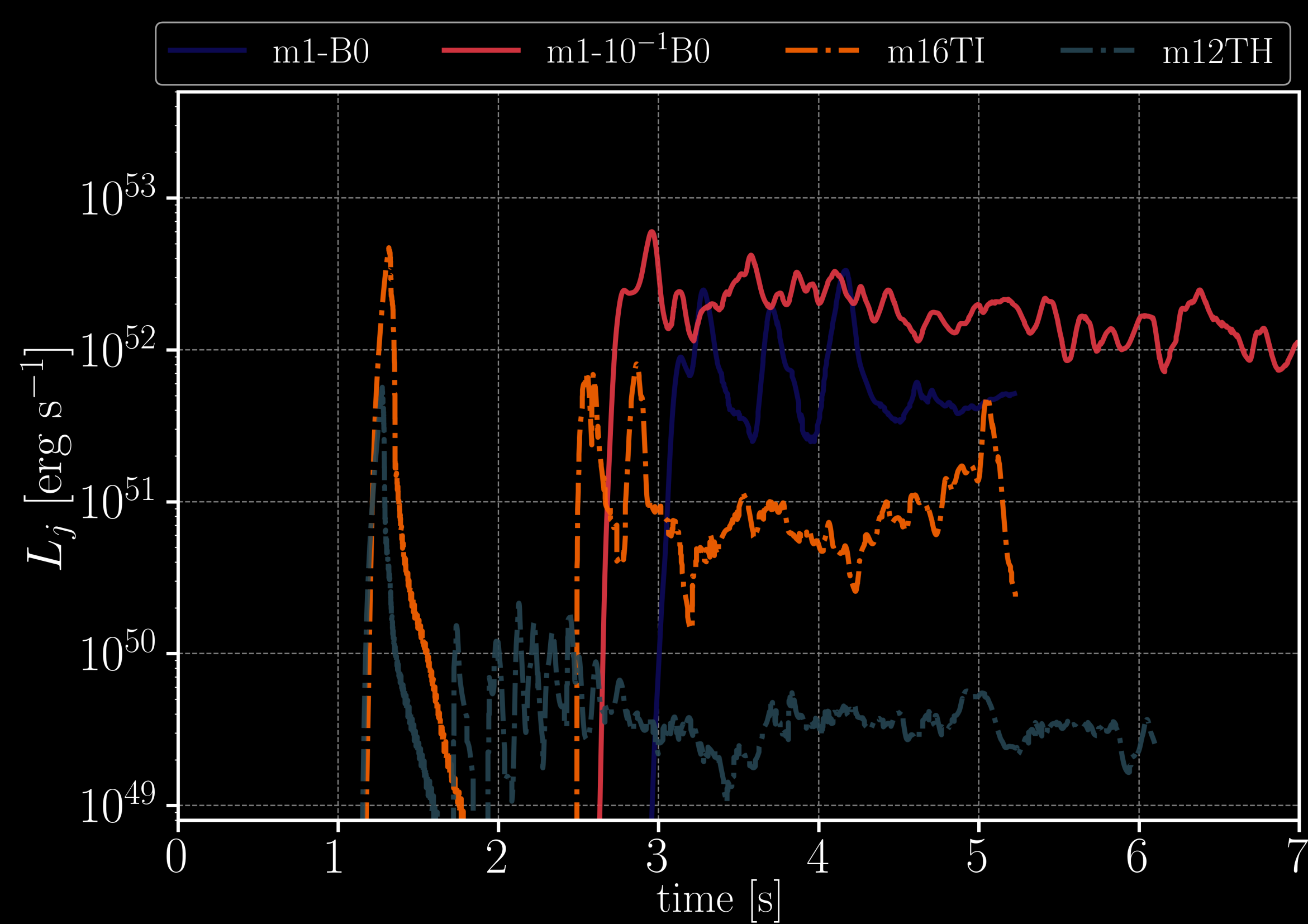


Shock front

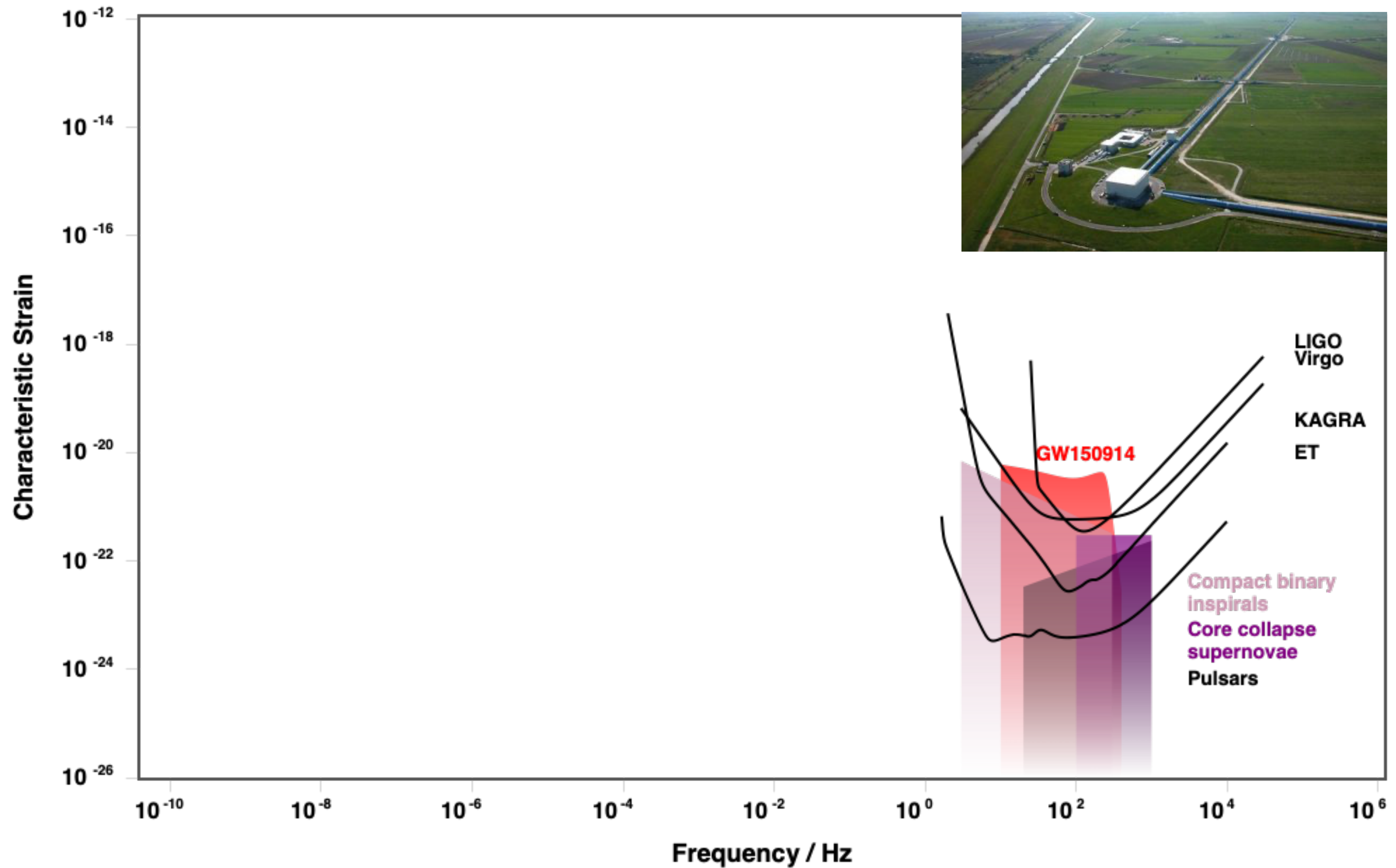


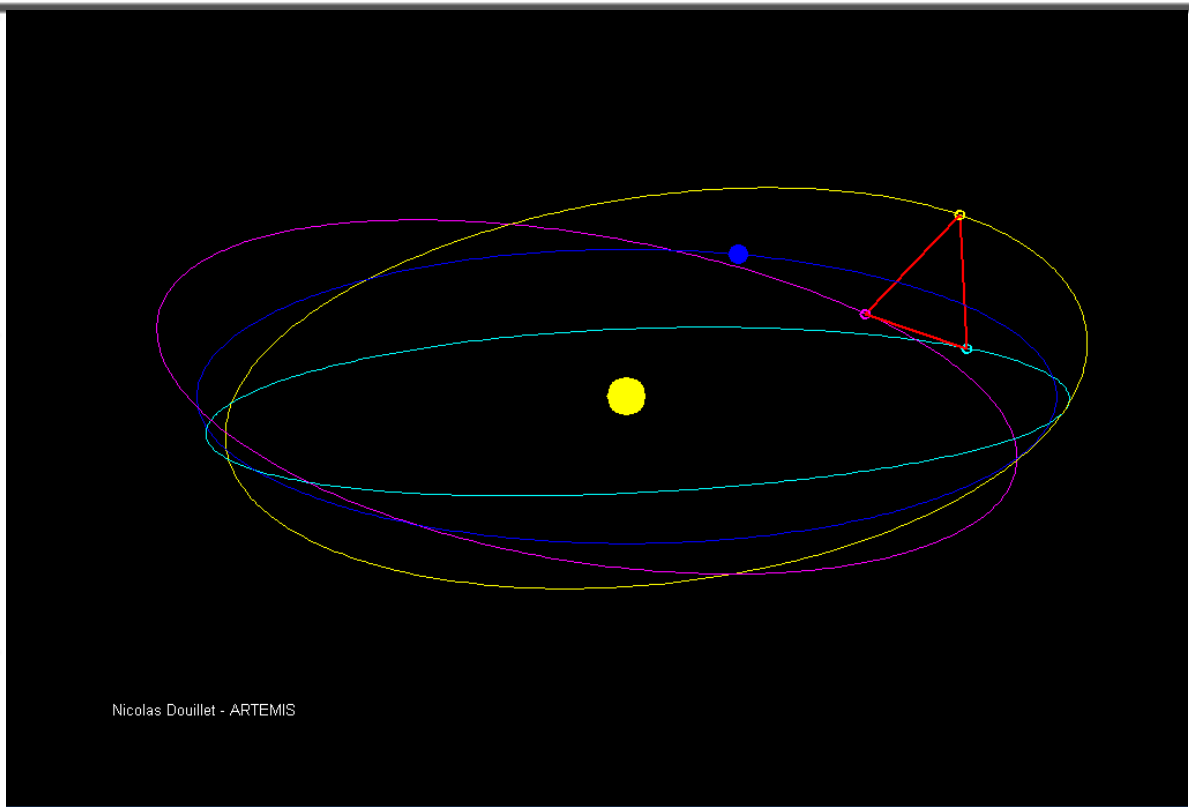
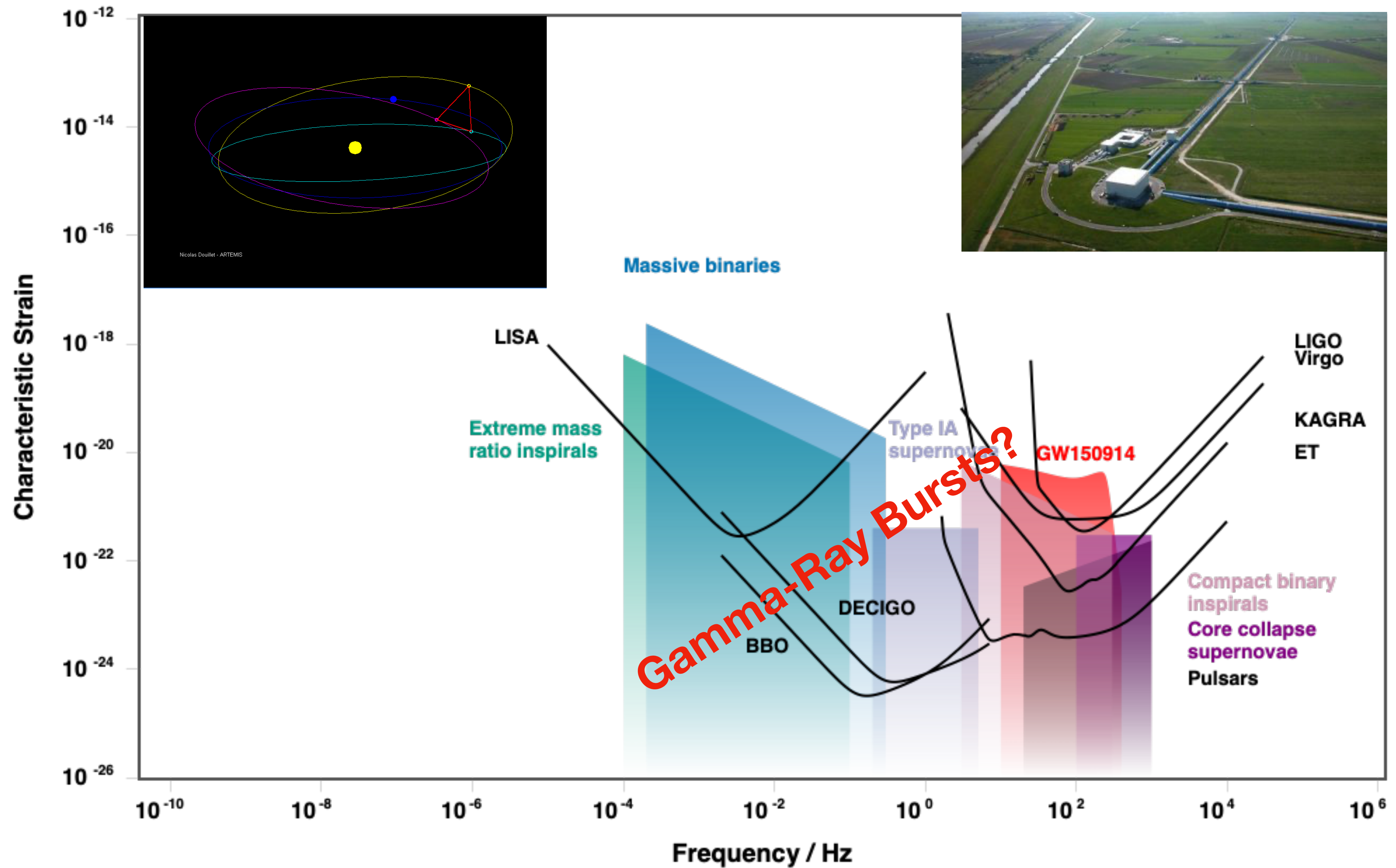
Observational insignes

$$\theta_{\text{obs}} = 30^\circ$$

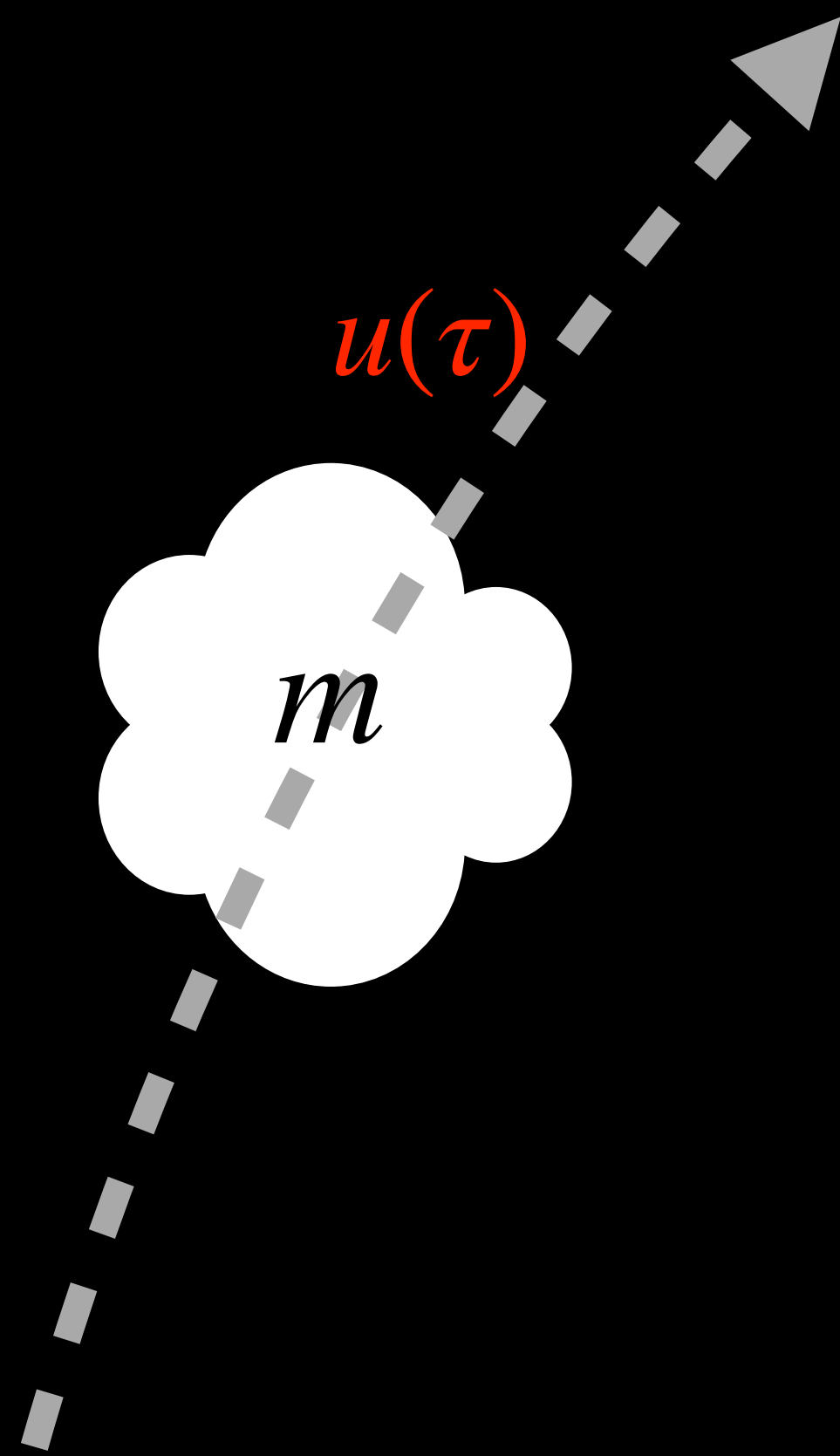


Gravitational Waves from Jets





GW from ultra-relativistic sources

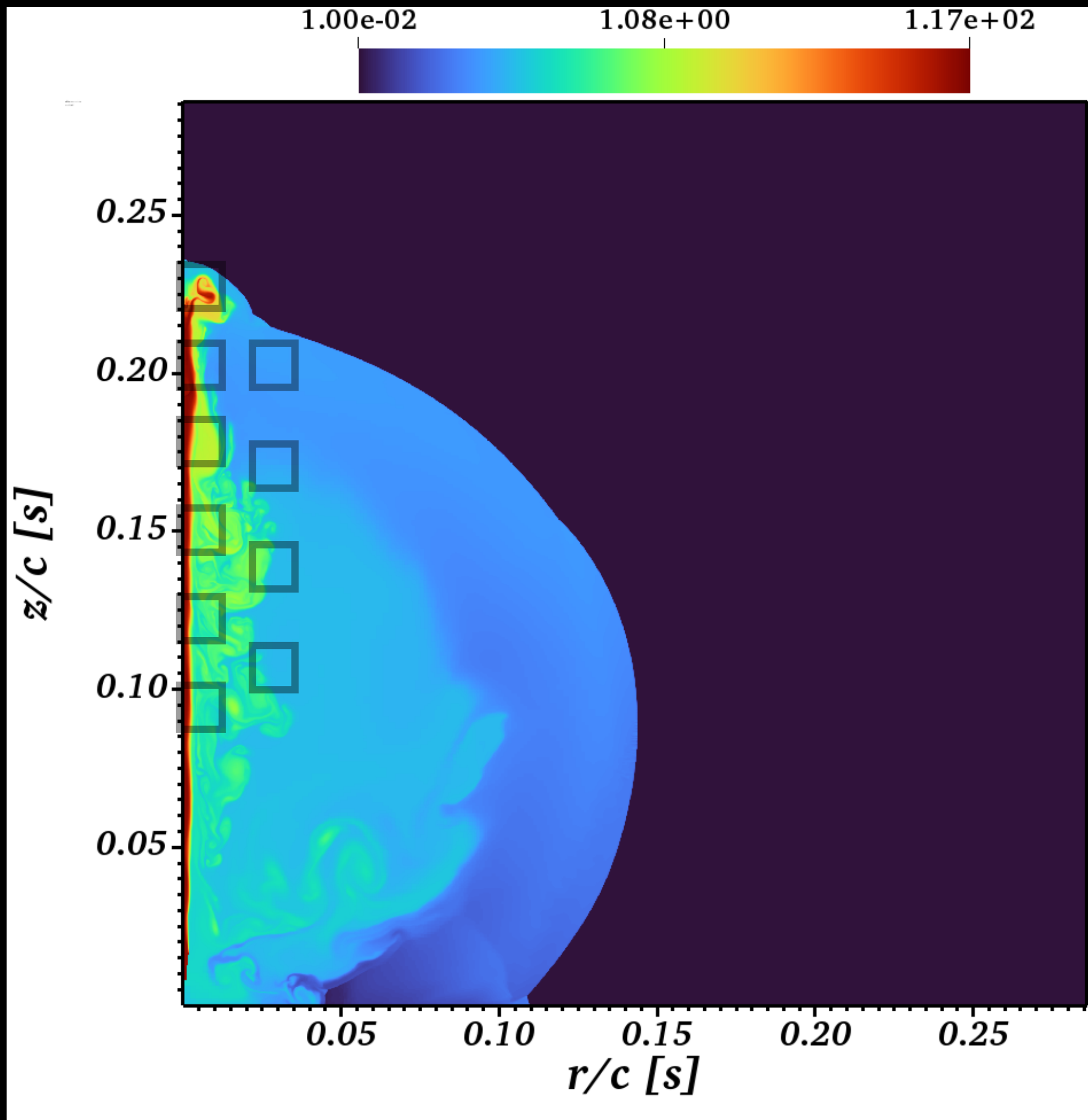


$$T^{\mu\nu} = \int m u^{\mu}(\tau) u^{\nu}(\tau) \delta^{(4)}[x - x(\tau)] d\tau$$

$$\square \bar{h}^{\mu\nu} = -16\pi T^{\mu\nu}$$

$$\bar{h}^{\mu\nu} = -4m \frac{u^{\mu}(\tau) u^{\nu}(\tau)}{-u_{\alpha} \cdot [x - x(\tau)]^{\alpha}}$$

GW from ultra-relativistic sources

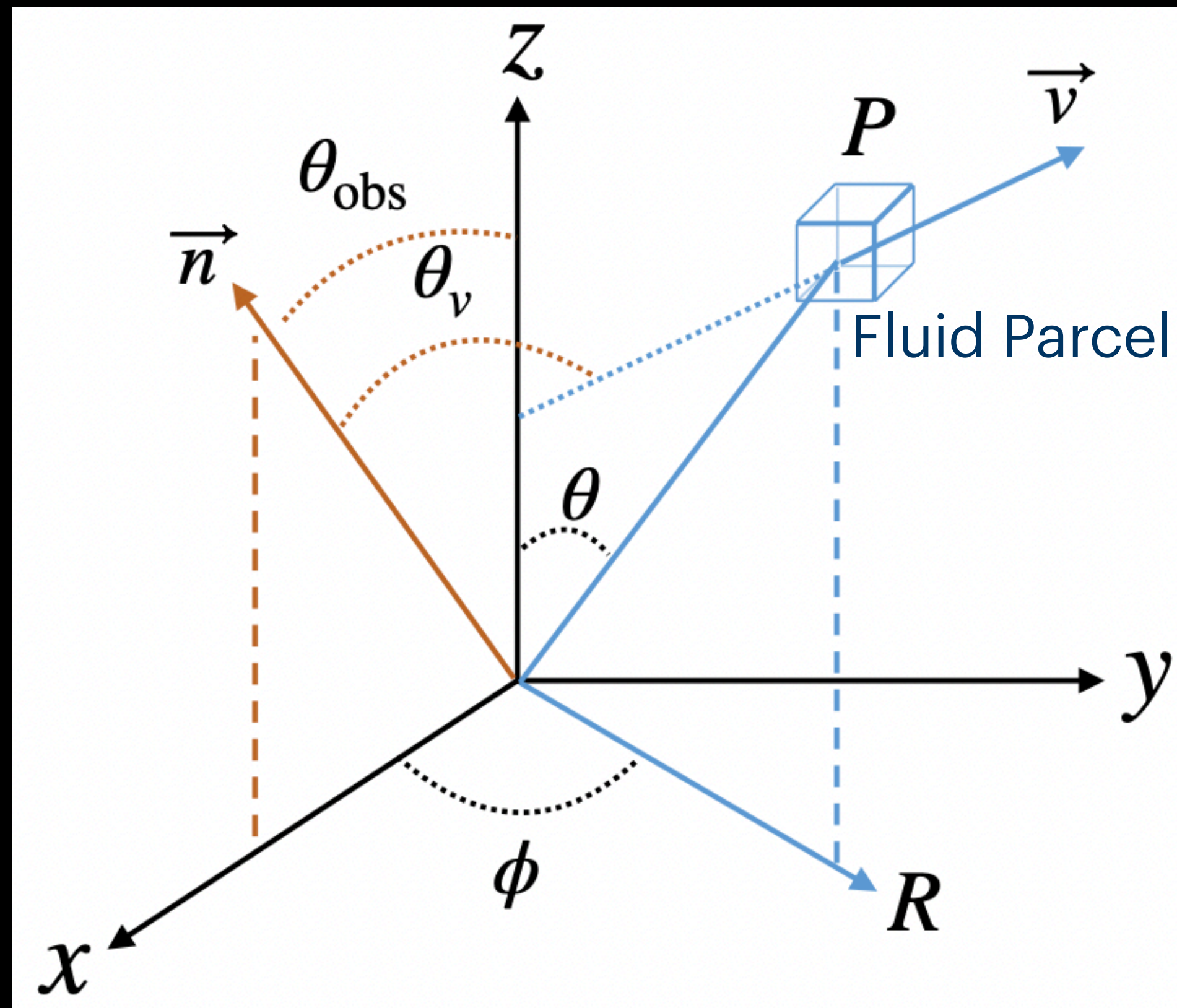


$$T^{\mu\nu} = \int m \, u^{\mu}(\tau) u^{\nu}(\tau) \, \delta^{(4)}[x - x(\tau)] d\tau$$

$$\square \bar{h}^{\mu\nu} = -16\pi T^{\mu\nu}$$

$$\bar{h}^{\mu\nu} = -4m \frac{u^{\mu}(\tau) u^{\nu}(\tau)}{-u_{\alpha} \cdot [x - x(\tau)]^{\alpha}}$$

GW memory from ultra-relativistic sources



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

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

(e.g., Urrutia et al. 2023)

$$\cos \Theta = \hat{n} \cdot \hat{r} = \sin \theta \cos \phi \sin \theta_{\text{obs}} + \cos \theta \cos \theta_{\text{obs}},$$

$$\sin \theta \sin \phi = \sin \Theta \sin \Phi,$$

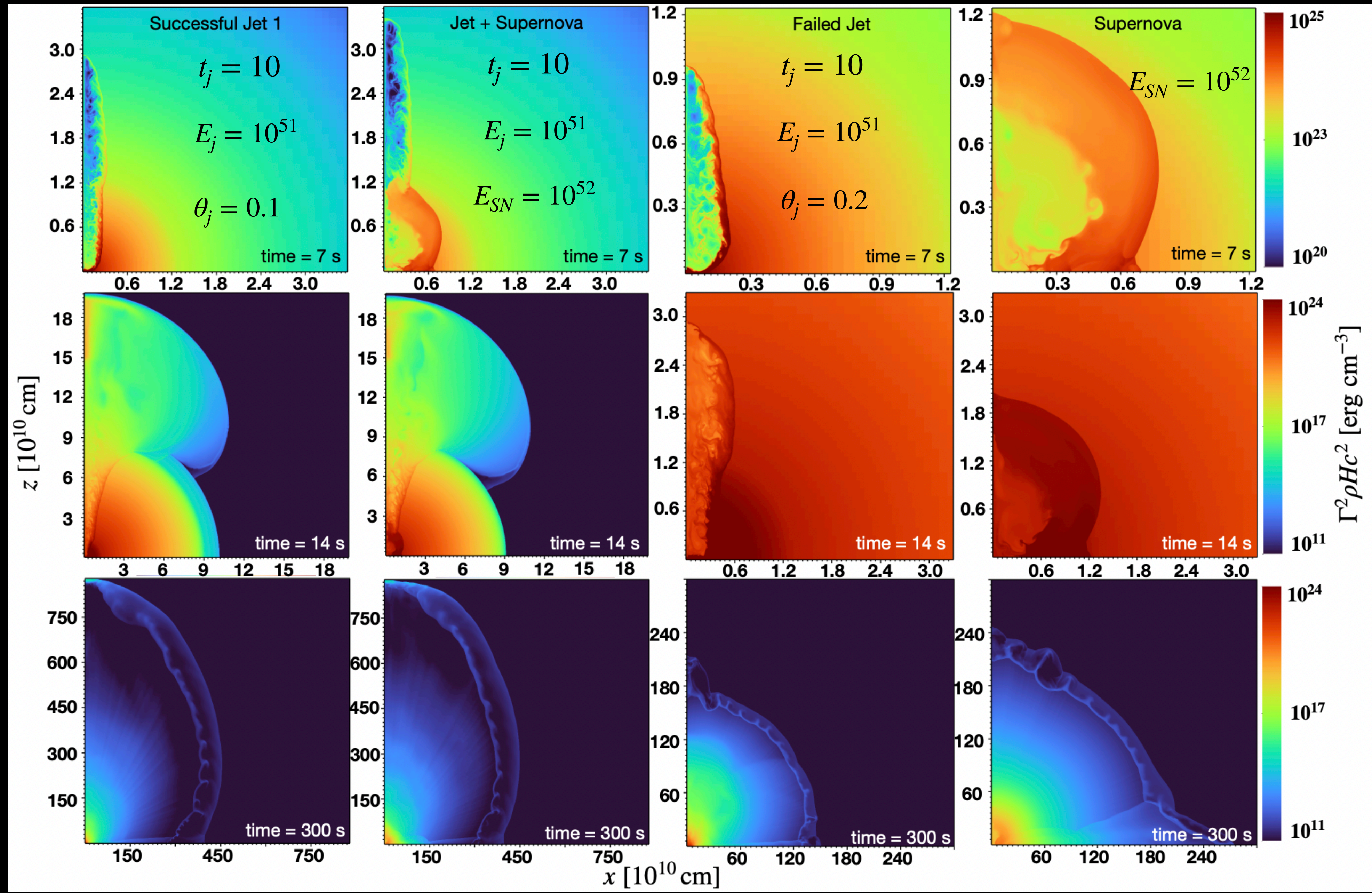
$$\sin \theta \cos \phi = \sin \Theta \cos \Phi \cos \theta_{\text{obs}} + \cos \Theta \sin \theta_{\text{obs}},$$

which lead to

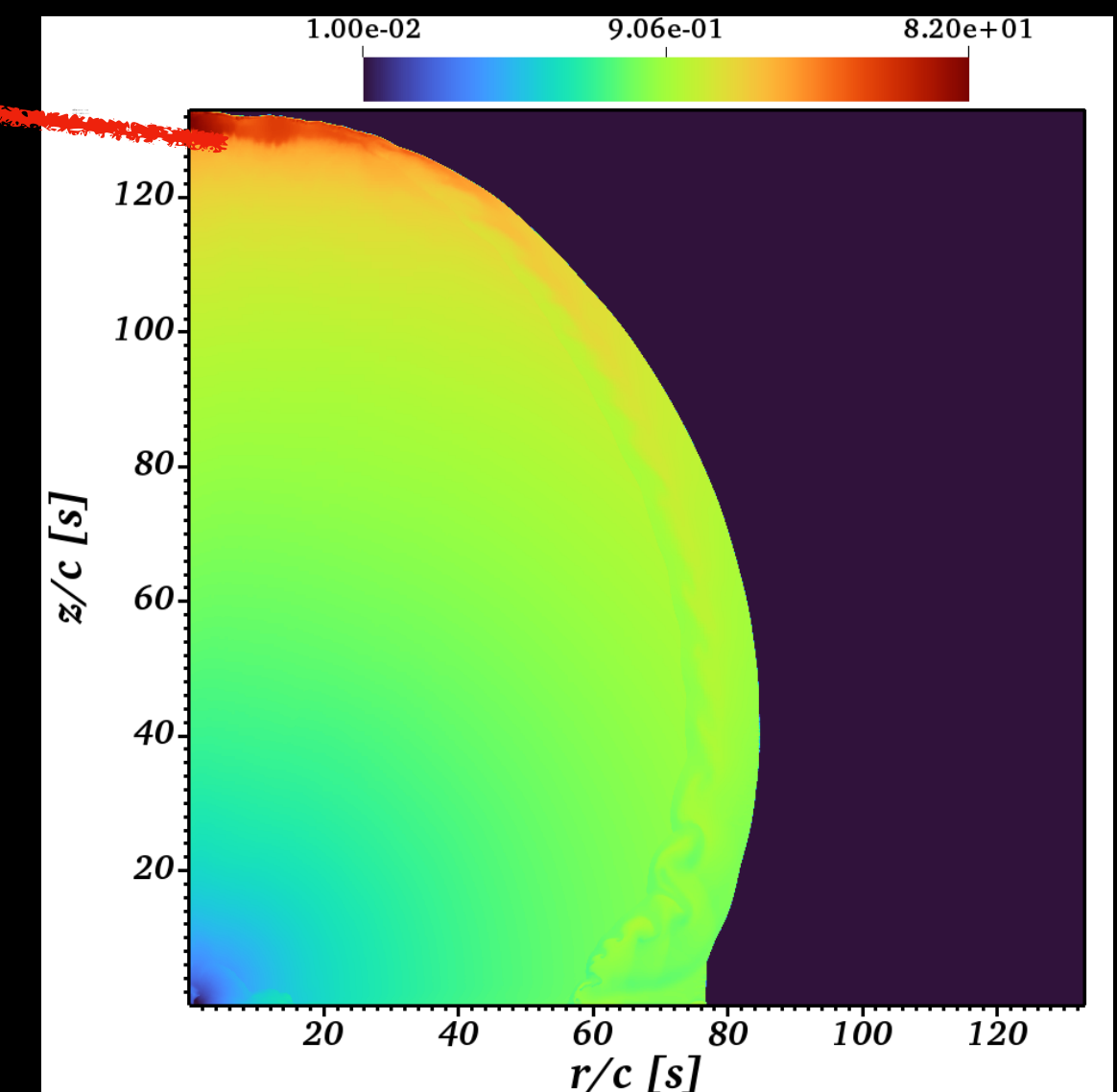
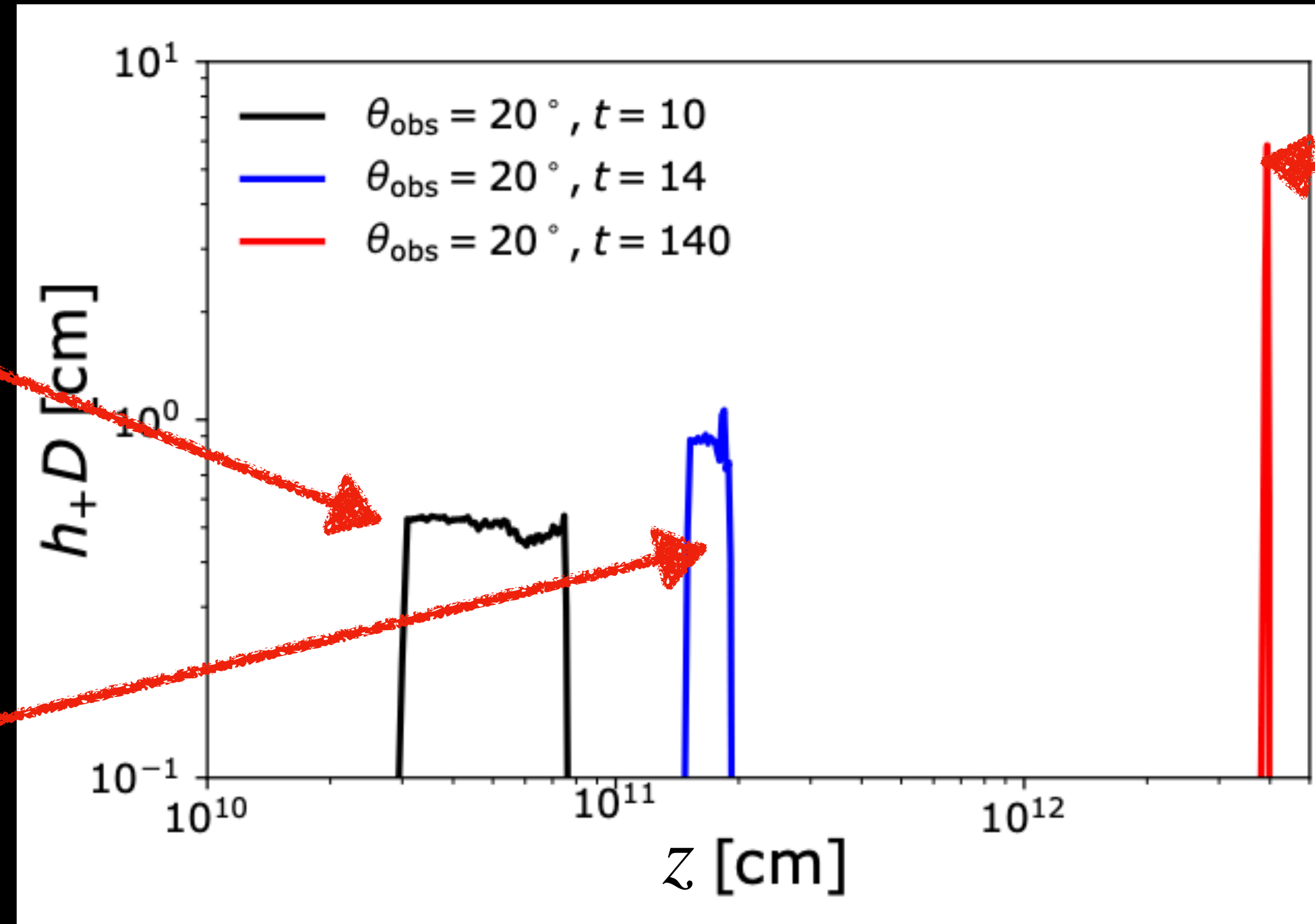
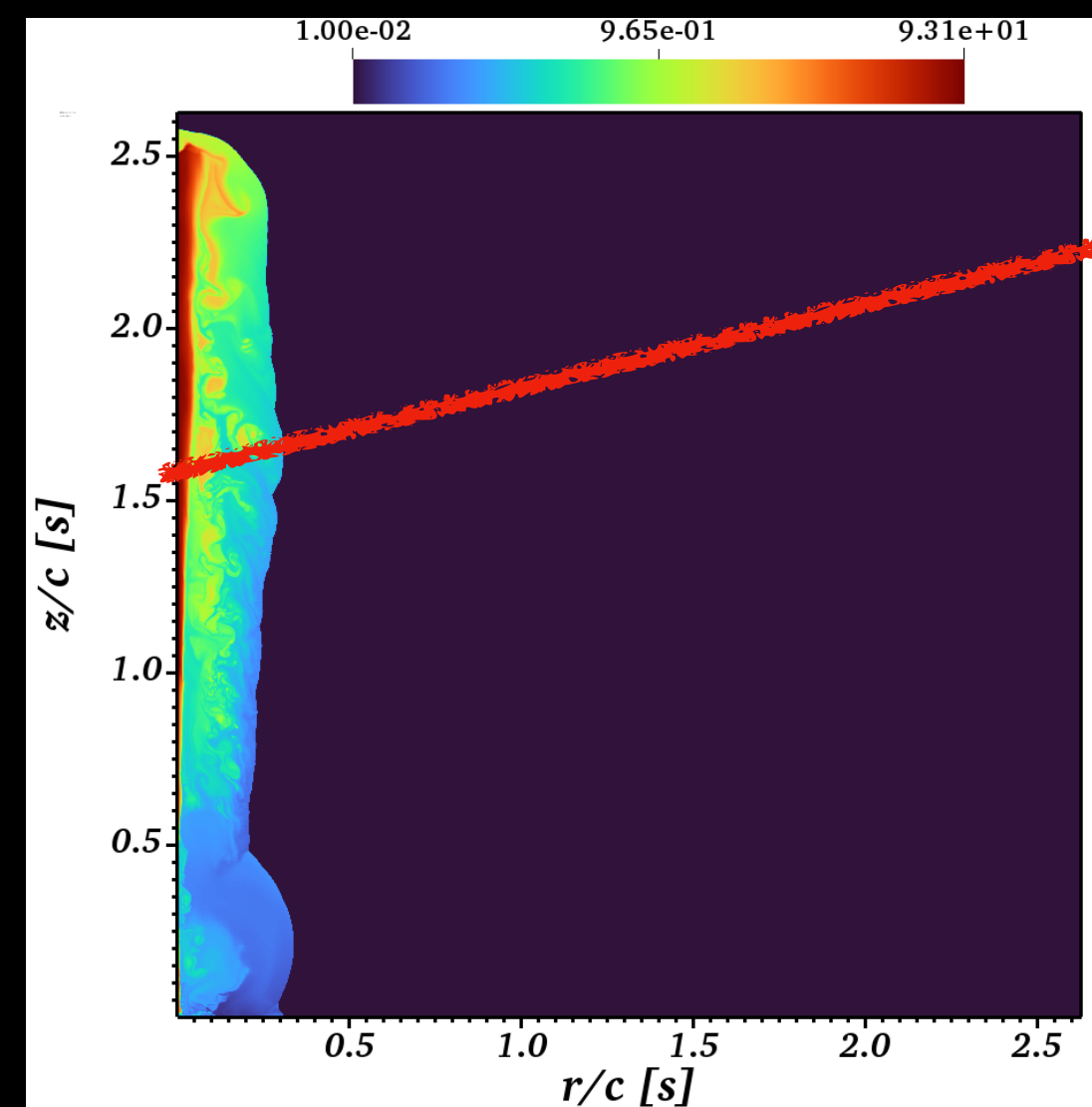
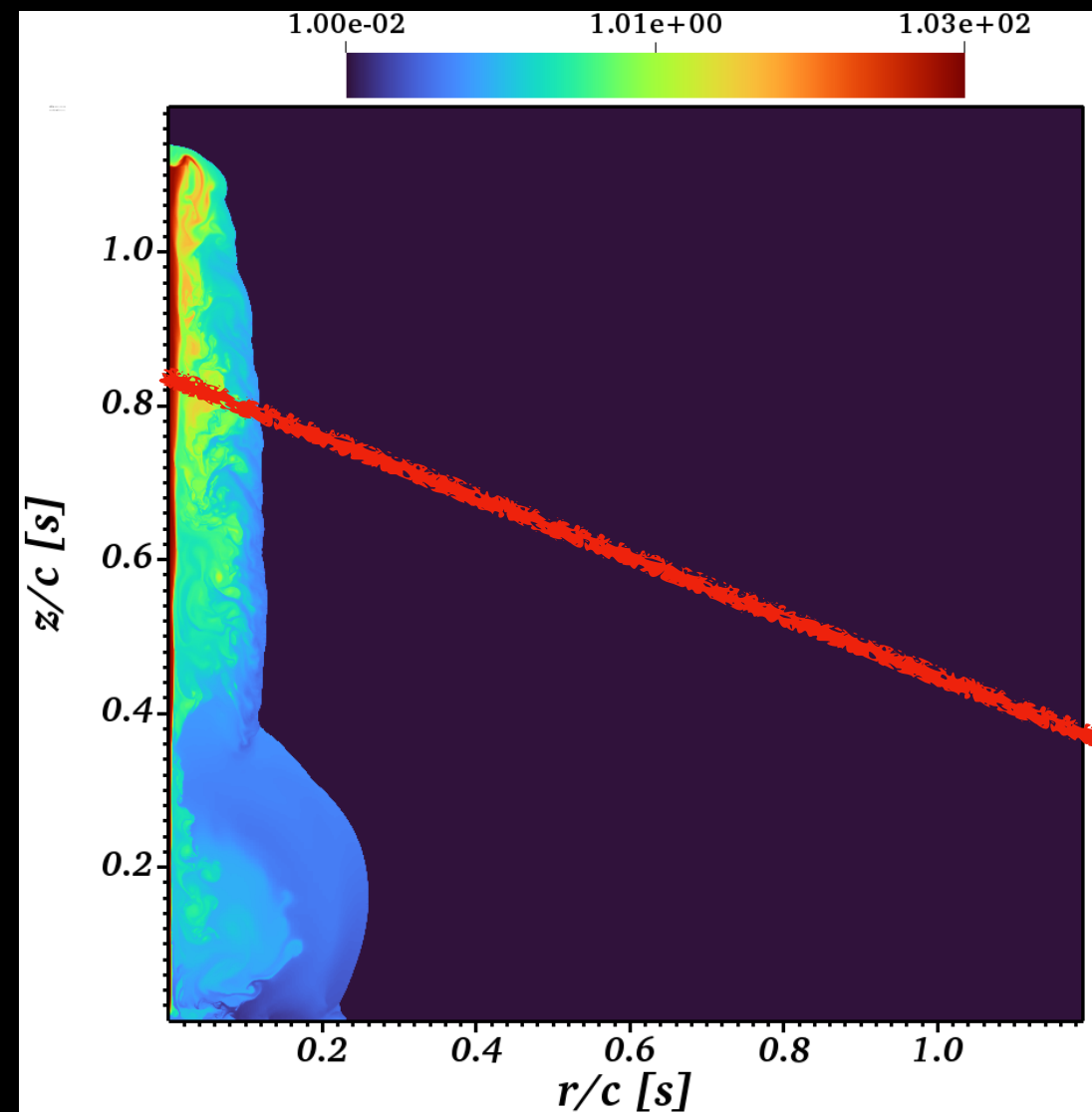
$$\sin(2\Phi) = 2 \sin \theta \sin \phi \left(\frac{\sin \theta \cos \phi \cos \theta_{\text{obs}} - \cos \theta \sin \theta_{\text{obs}}}{\sin^2 \Theta} \right),$$

$$\cos(2\Phi) = \frac{(\sin \theta \cos \phi \cos \theta_{\text{obs}} - \cos \theta \sin \theta_{\text{obs}})^2 - \sin^2 \theta \sin^2 \phi}{\sin^2 \Theta}$$

Jet dynamics

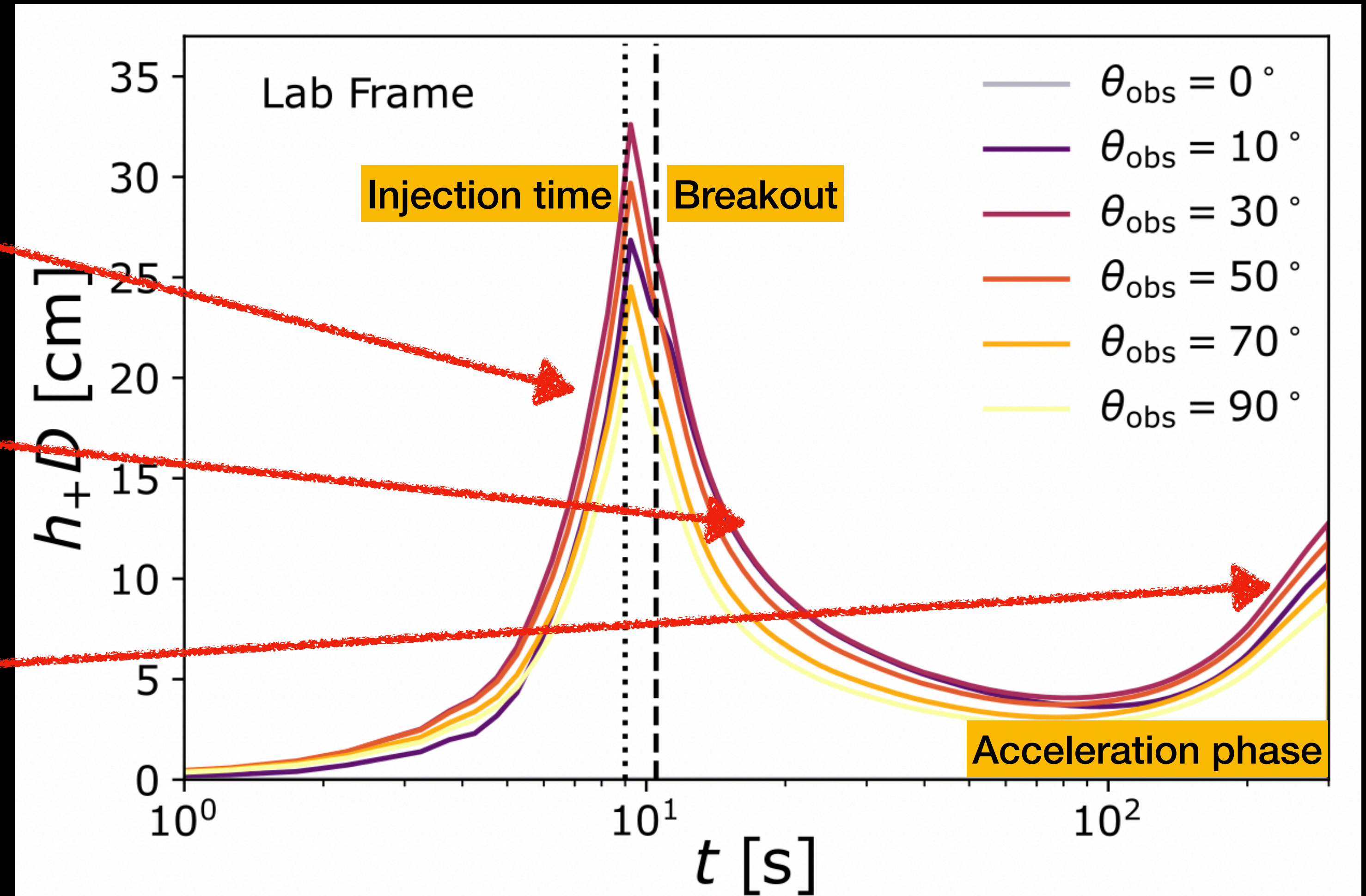
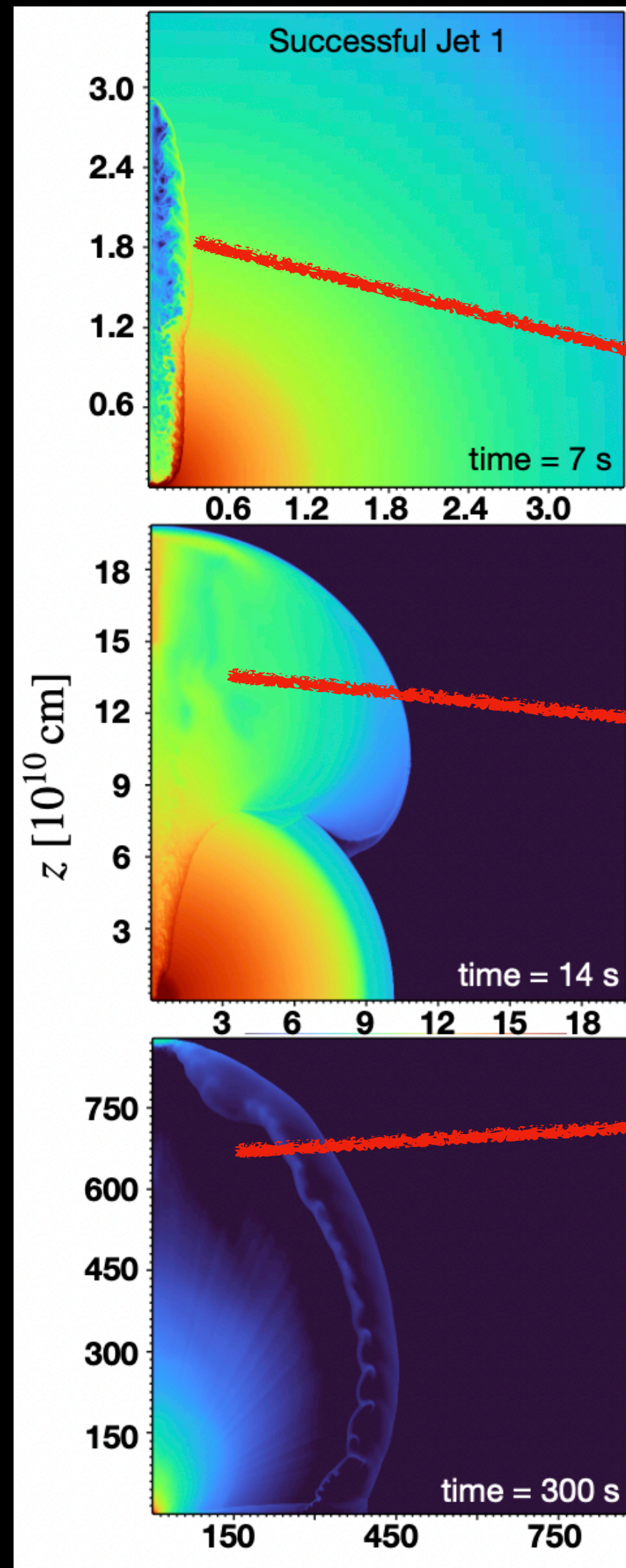


Where is the GW emission produced?



Successful jet - GW signal

$$t = t_{\text{obs}}$$



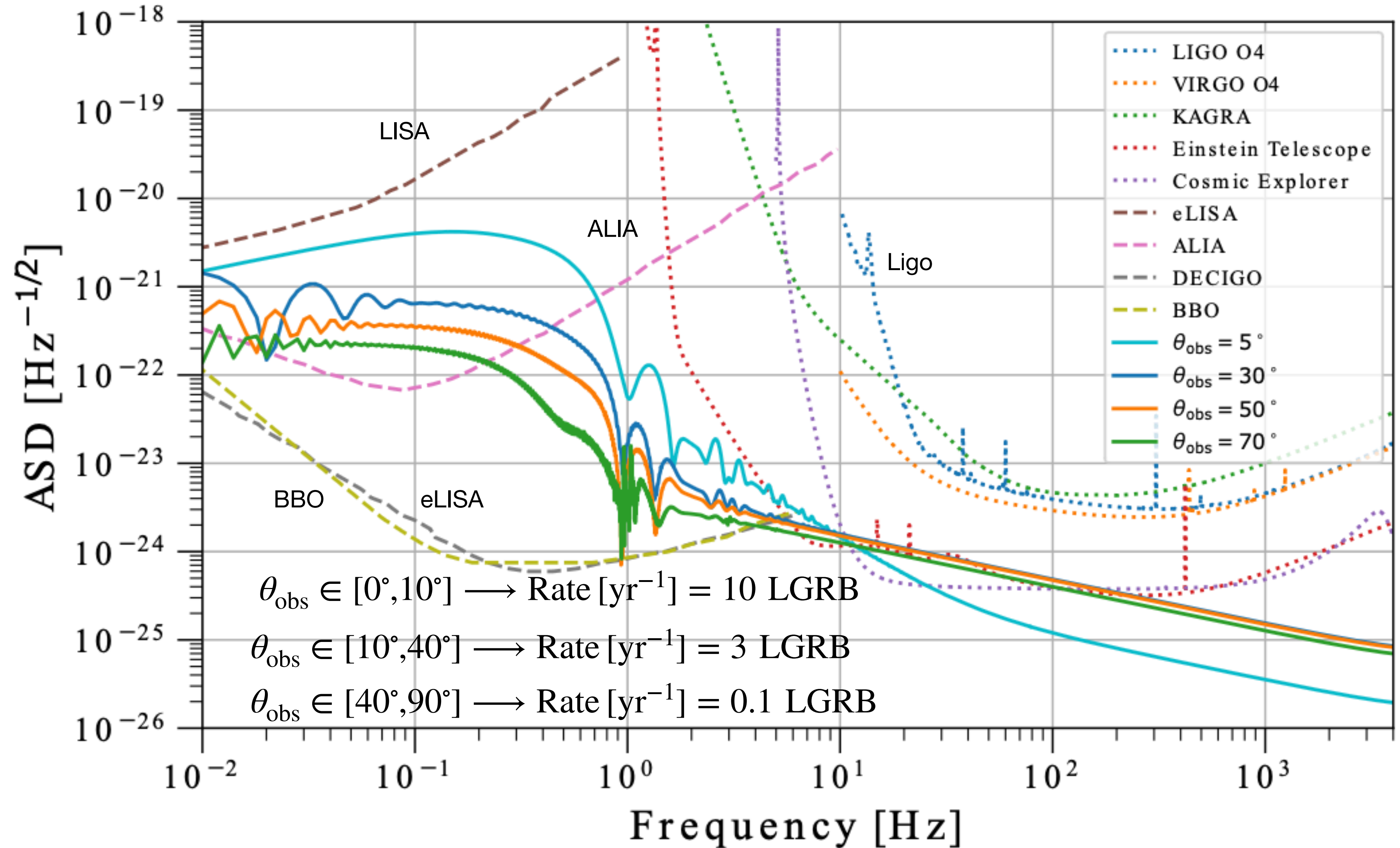
Detectability

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

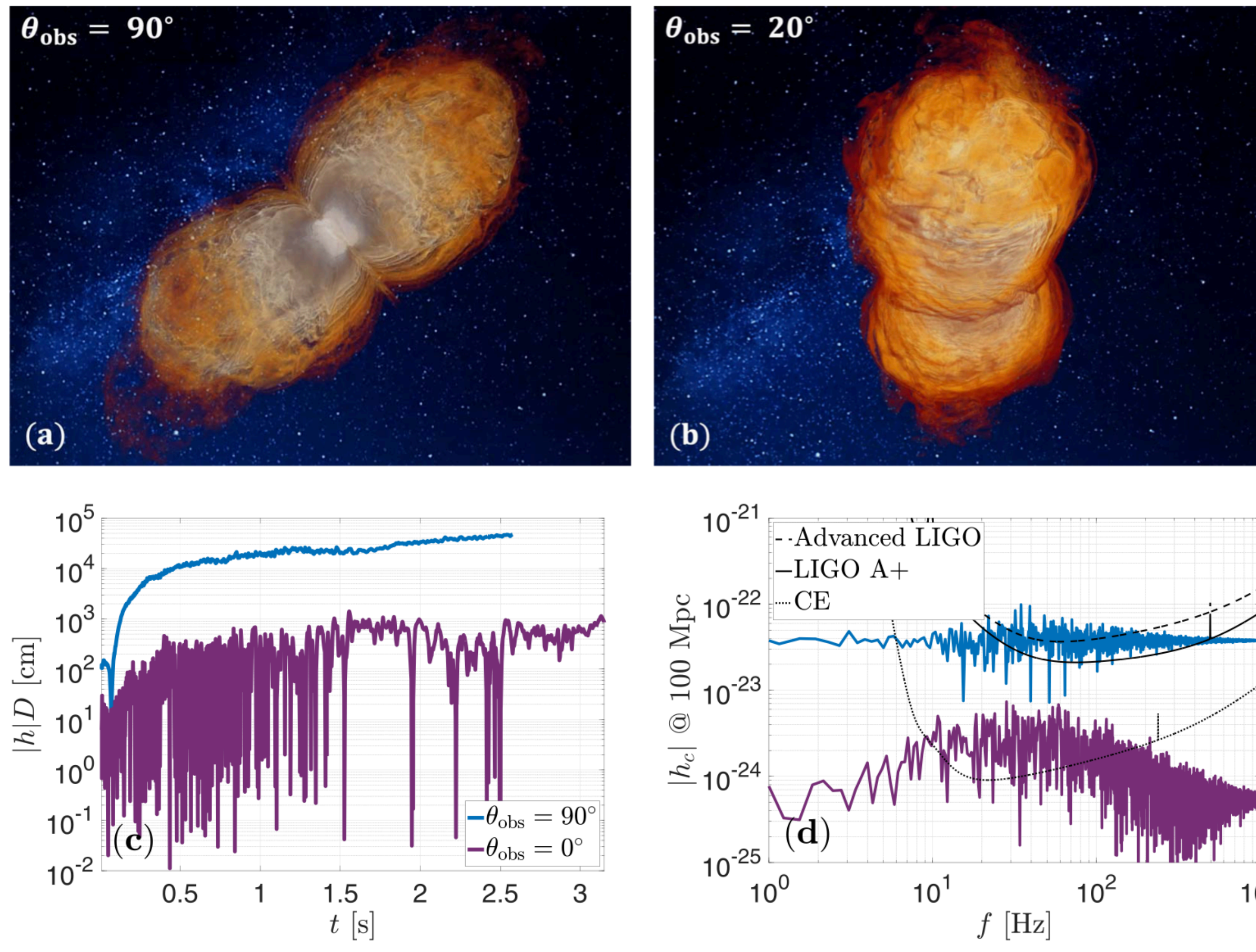
$$E = 10^{52} \text{ erg}$$

$$D = 1 \text{ Mpc}$$

$$ASD = 2f^{1/2} |\tilde{h}(f)|$$



High frequency?



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

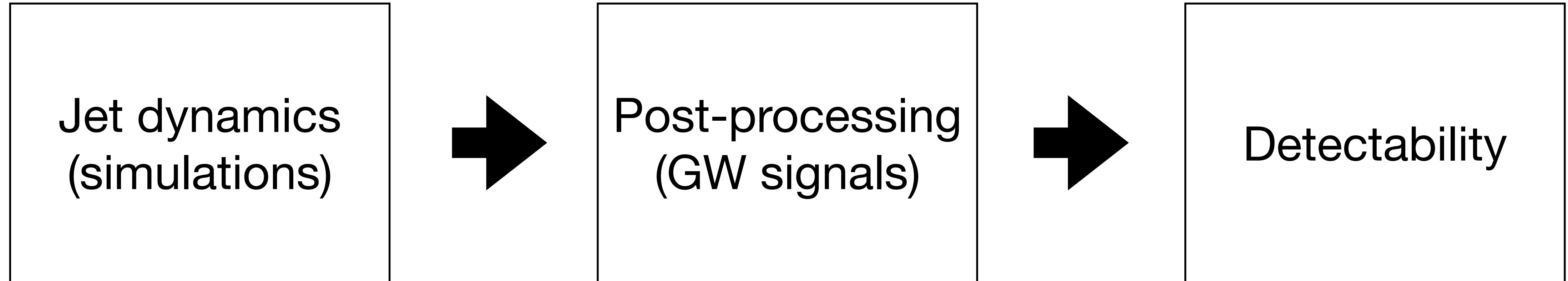
$$E_{\text{cocoon}} = 10^{52} - 10^{53} \text{ erg}$$

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

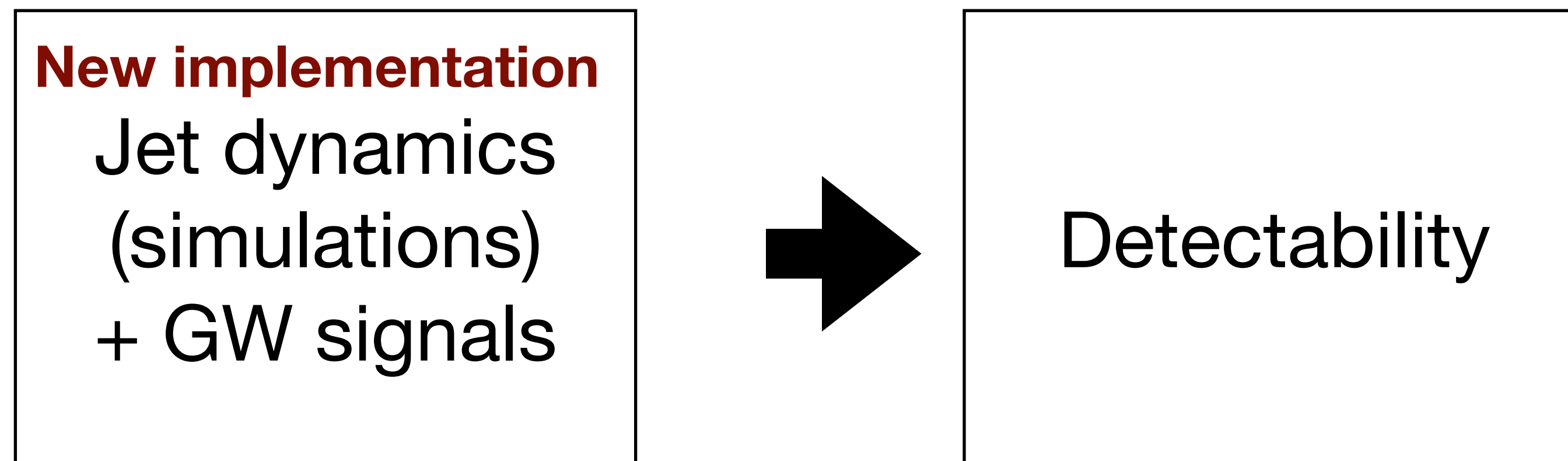
Storage ~ Petabytes

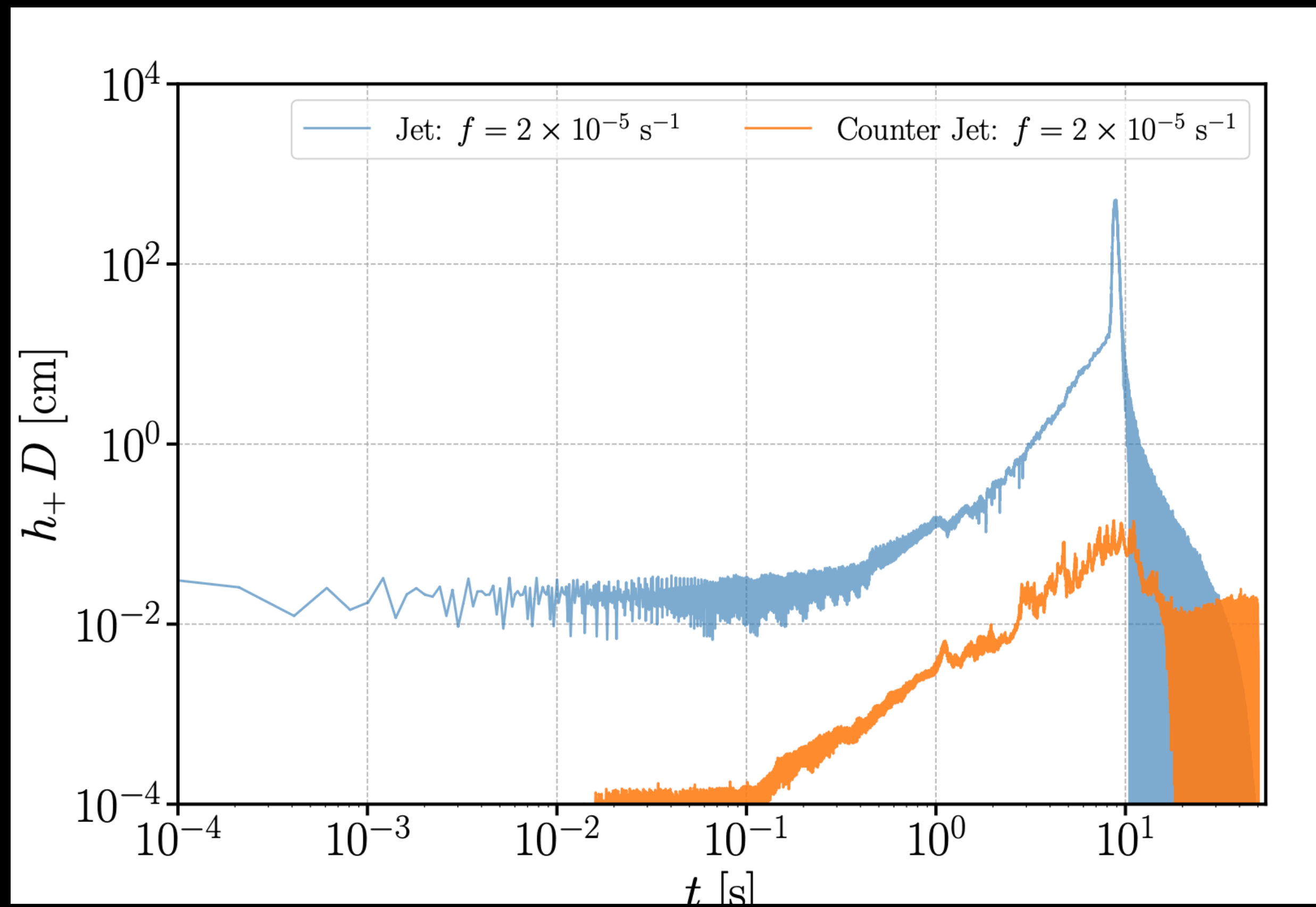
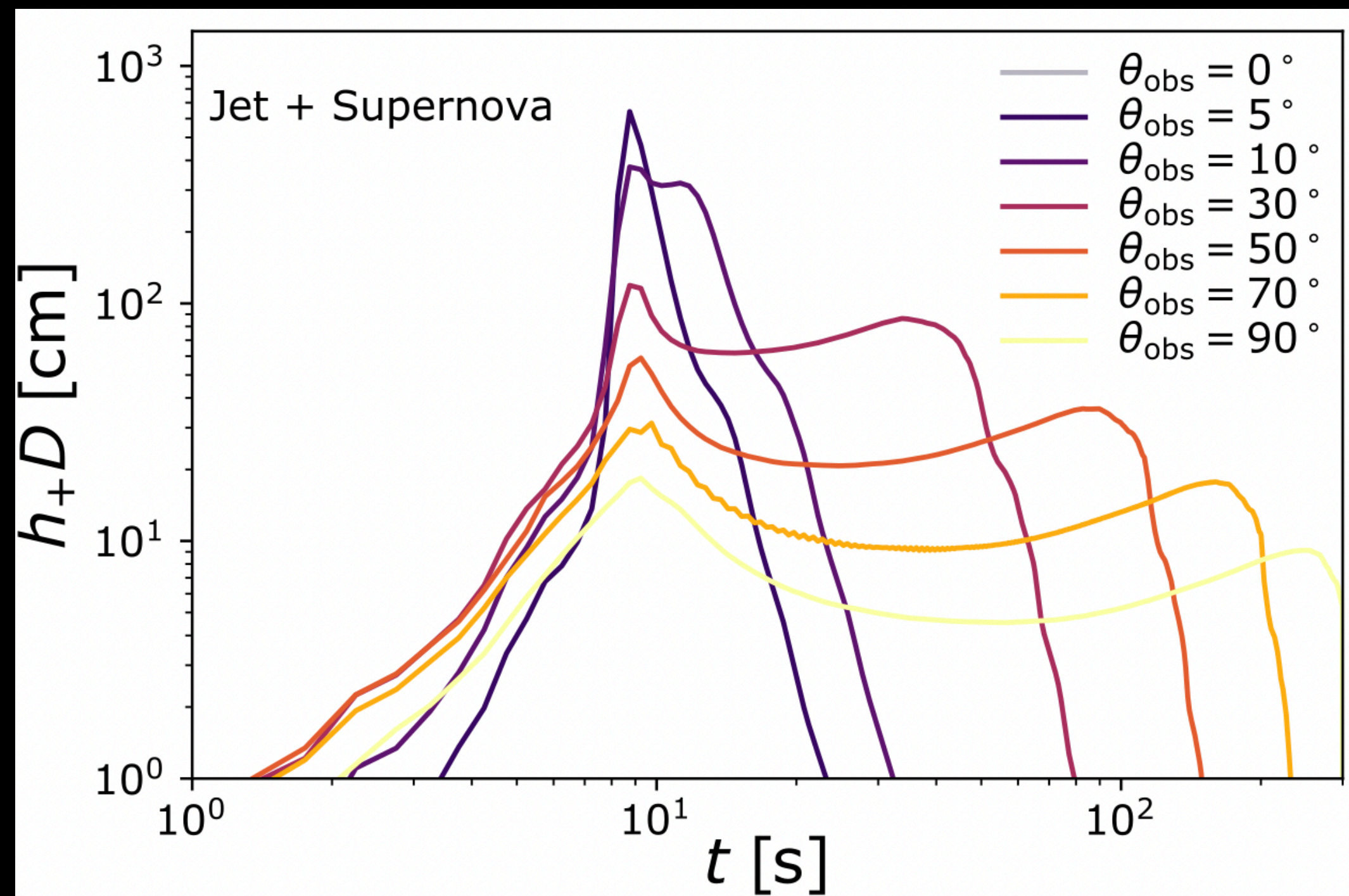
Gottlieb et al. 2023

Our Currently methodology



New methodology





Estimation of GW signals during the jet propagation (not post-processing)

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

Ram memory ~ GB

Storage ~ GB

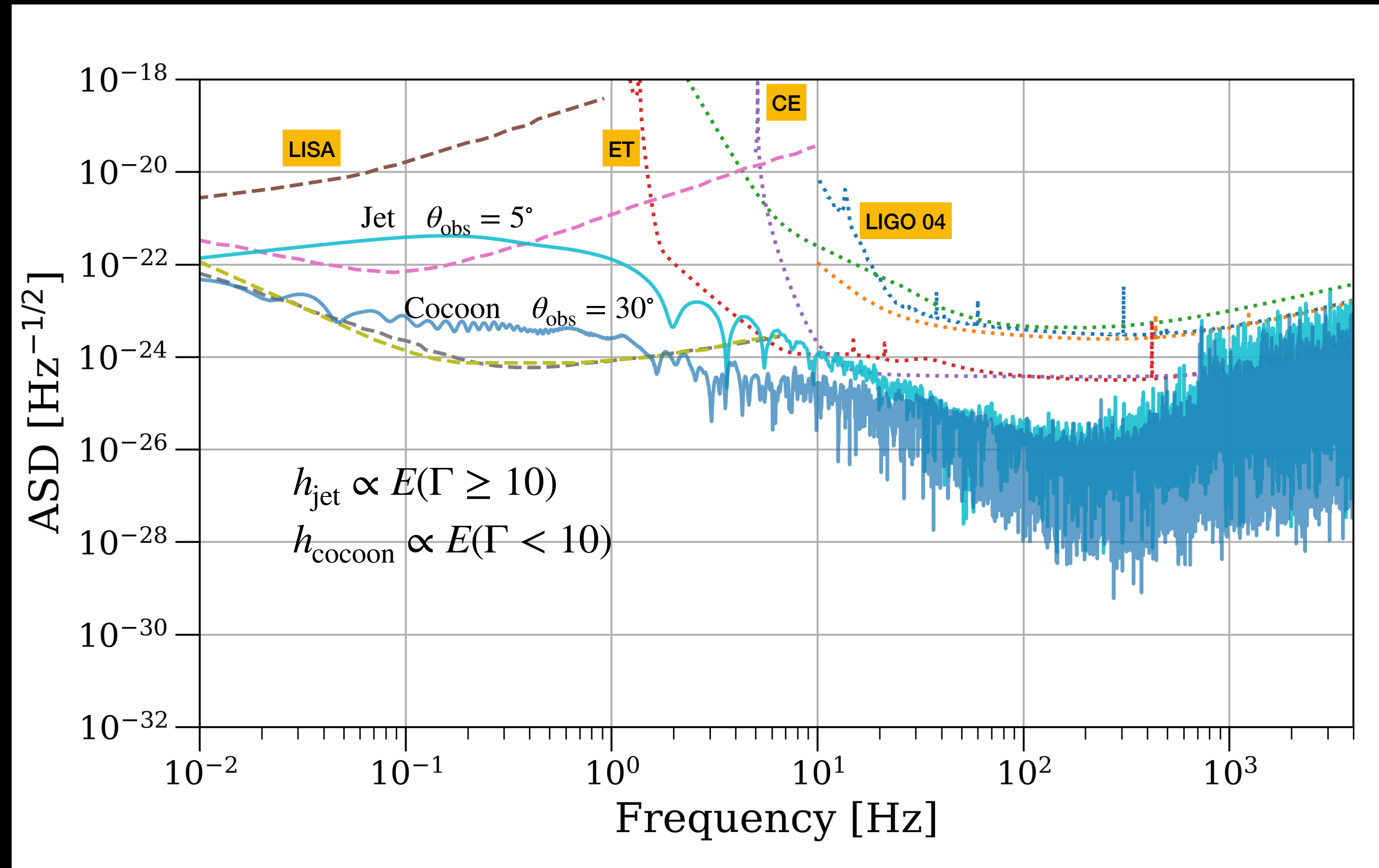
$$ASD = 2f^{1/2} |\tilde{h}(f)|$$

$$E_j = 10^{51} \text{ erg}$$

$$t_j = 10 \text{ s}$$

$$R_{\star} = 10^{11} \text{ cm}$$

$$D_{\text{obs}} = 1 \text{ Mpc}$$



Urrutia (in Prep)

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 by the magnetic field strength

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

¡Gracias! - Thank you!

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GROK

ICN UNAM

Servicio Social - Tesis Lic, dirigido por W. Bietenholz

Maestría-Doctorado, dirigido por F. De Colle

