

Numerical simulations of GRB jets from the BH horizon to post-breakout in collapsing stars

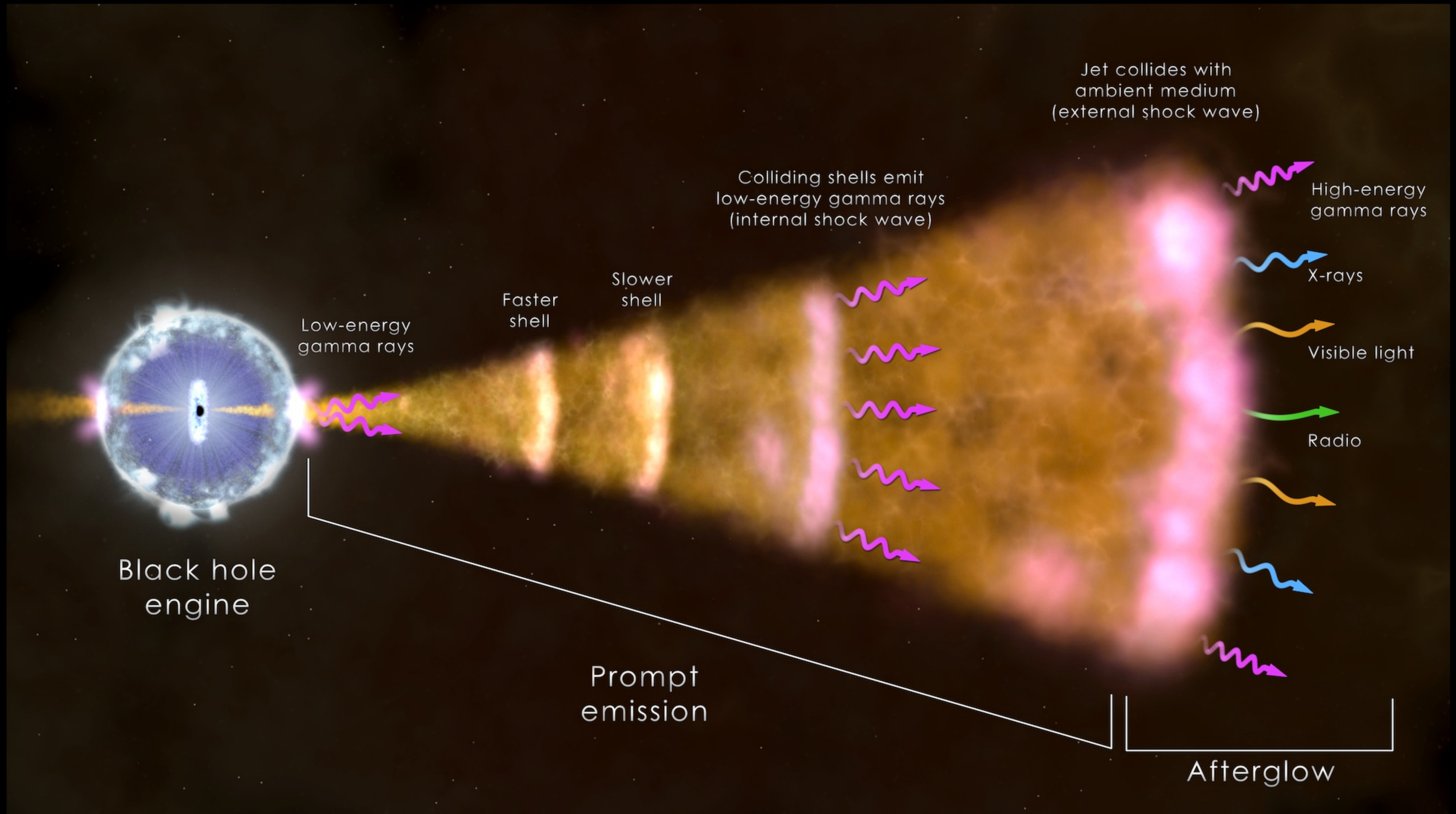
ArXiv:2507.10231

Gerardo Urrutia

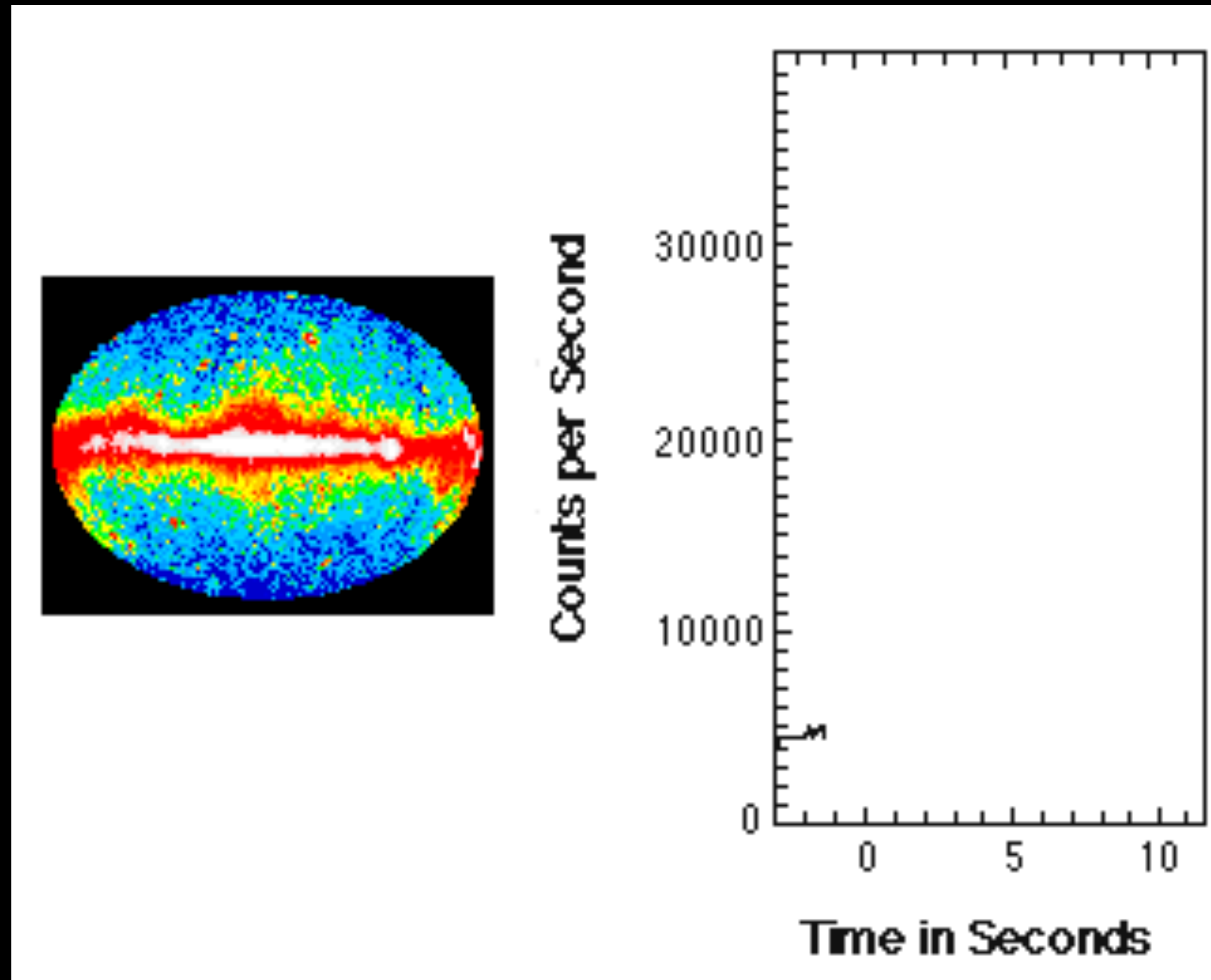
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Agnieszka Janiuk (CFT, Poland), Héctor Olivares (UA, Portugal)

Seminar of Warsaw Astronomical Observatory, October 21st 2025

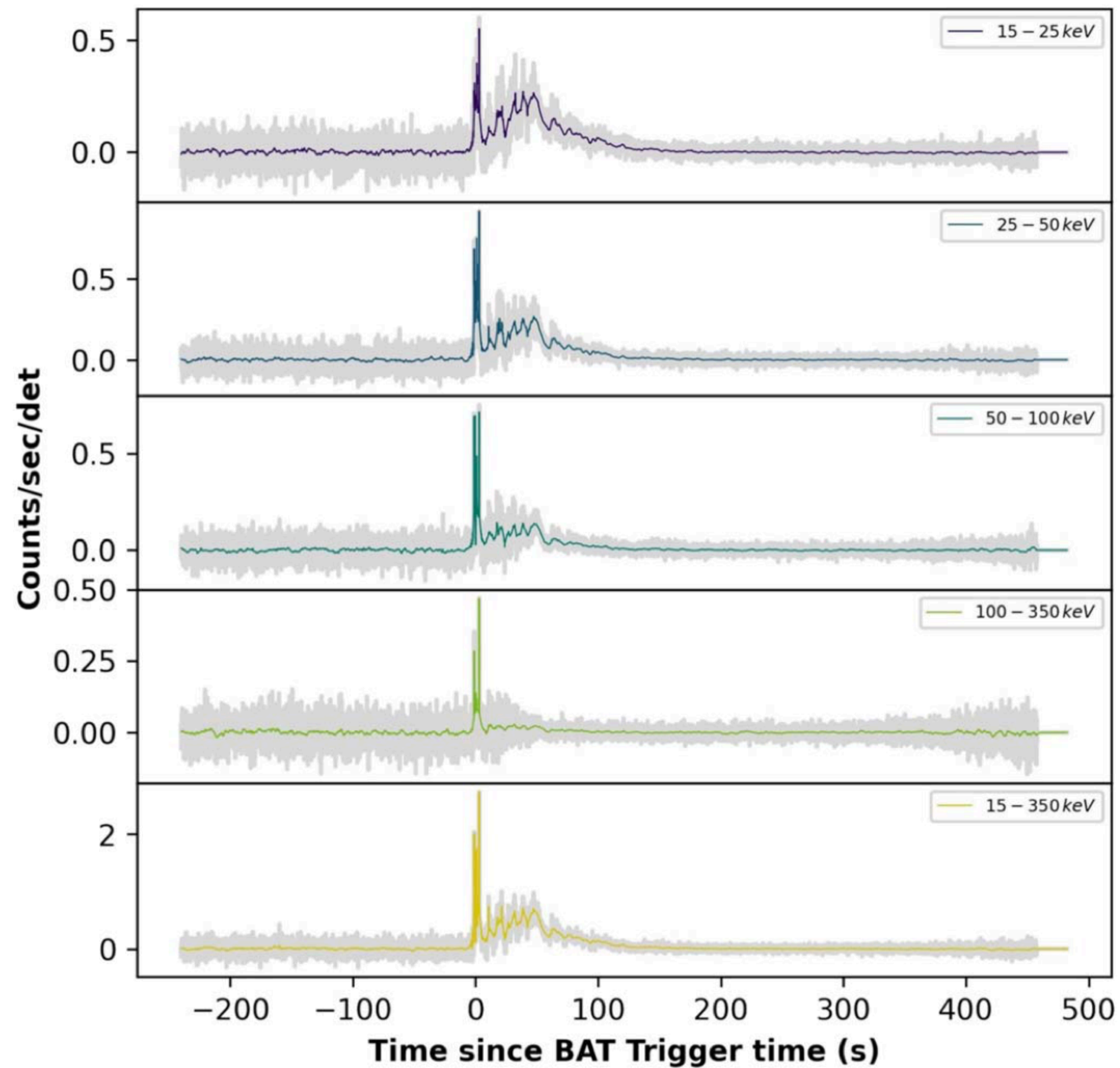


Gamma Ray Bursts (prompt emission)



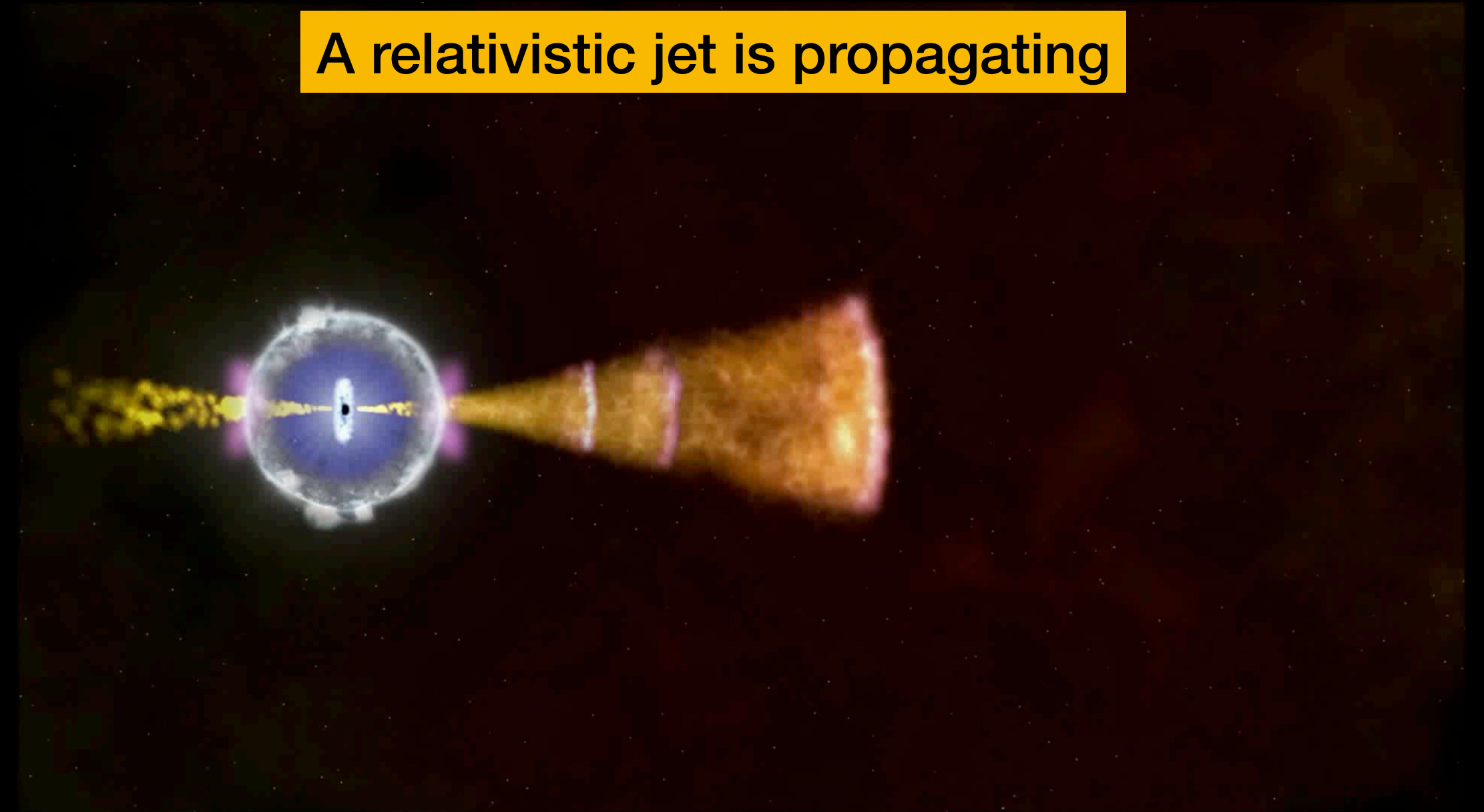
Variability due to shock front collision

Observational data

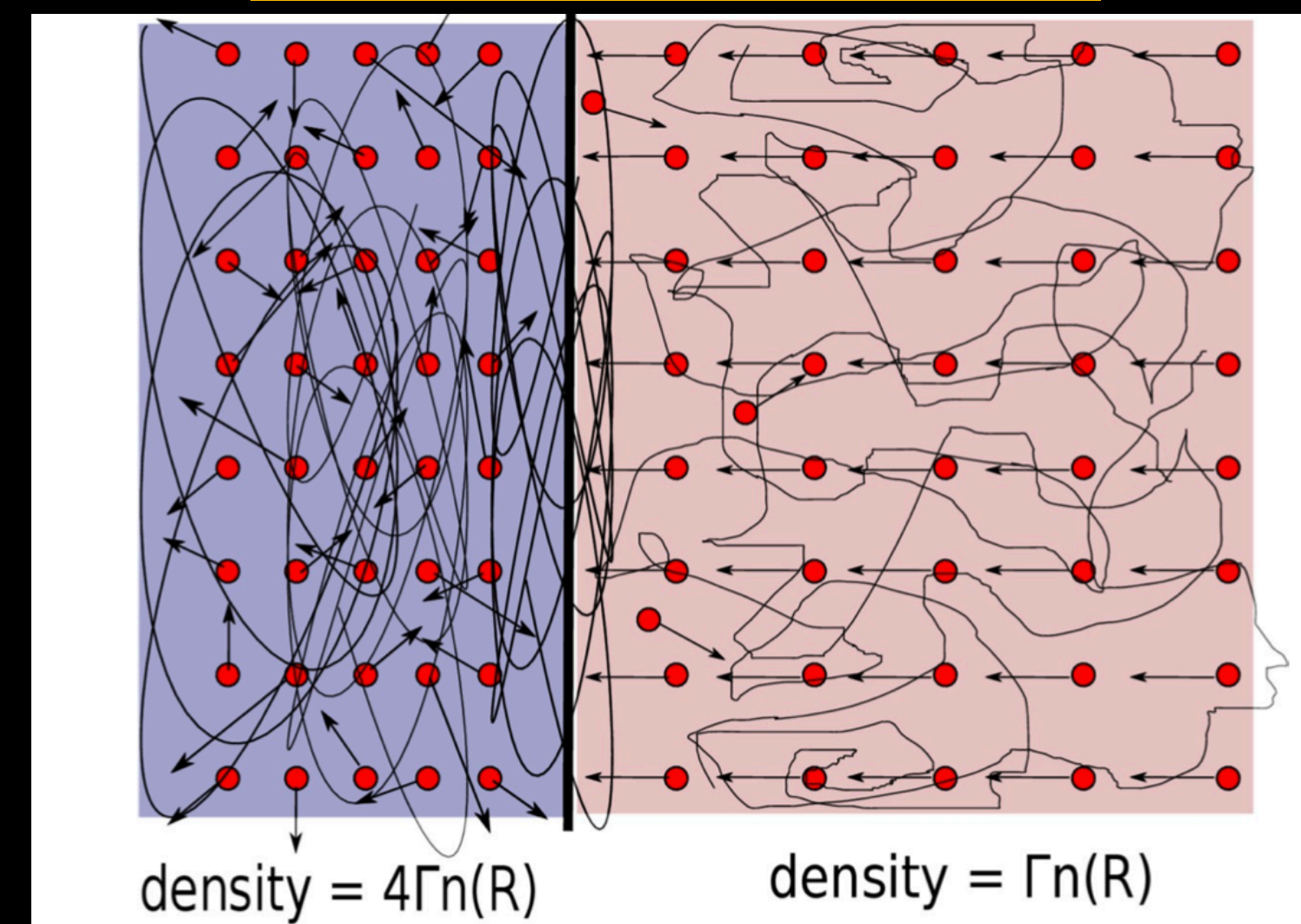


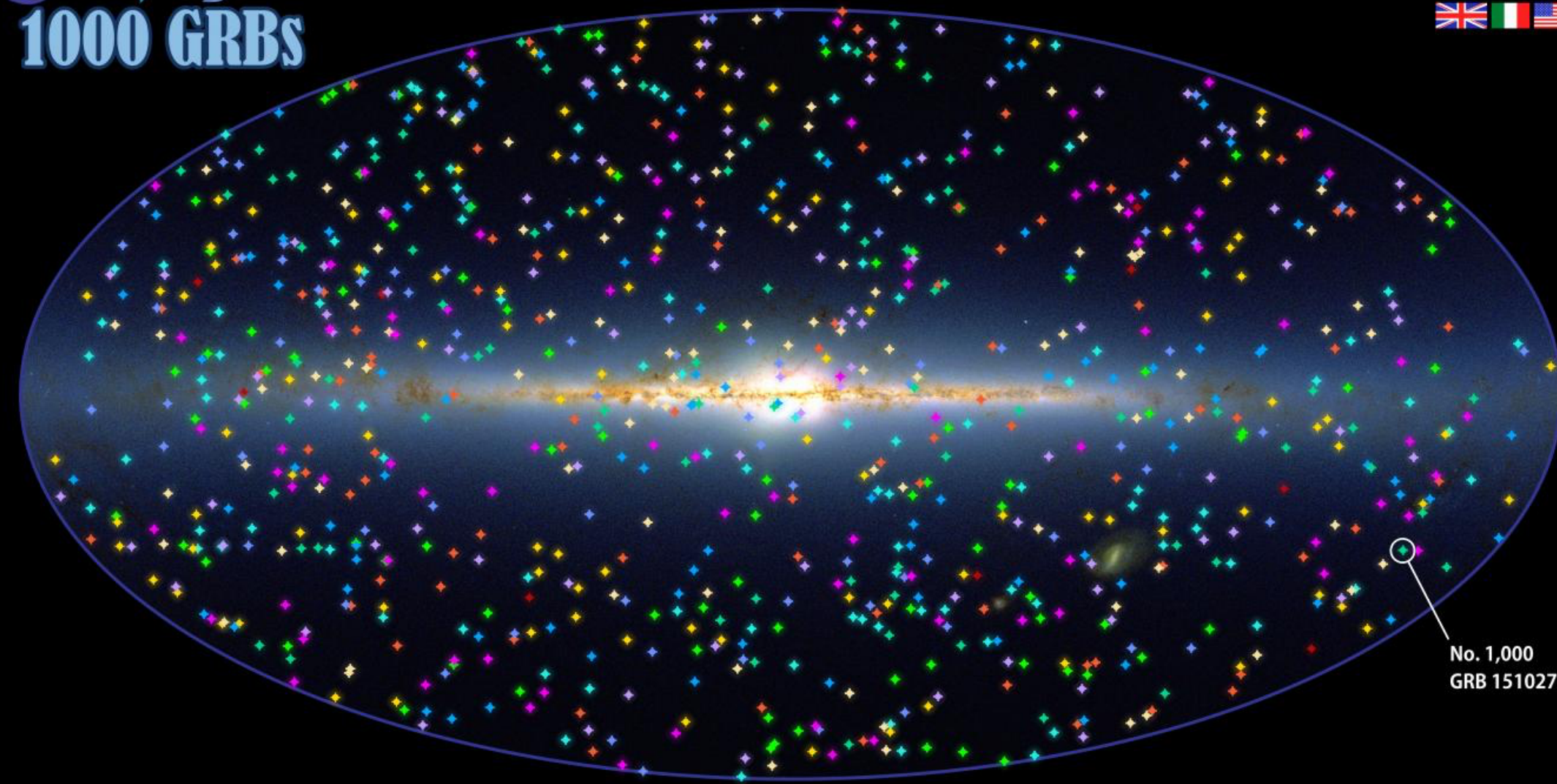
GRB060614, from Gracia-Cifuentes, Becerra & De Colle (2023)

A relativistic jet is propagating

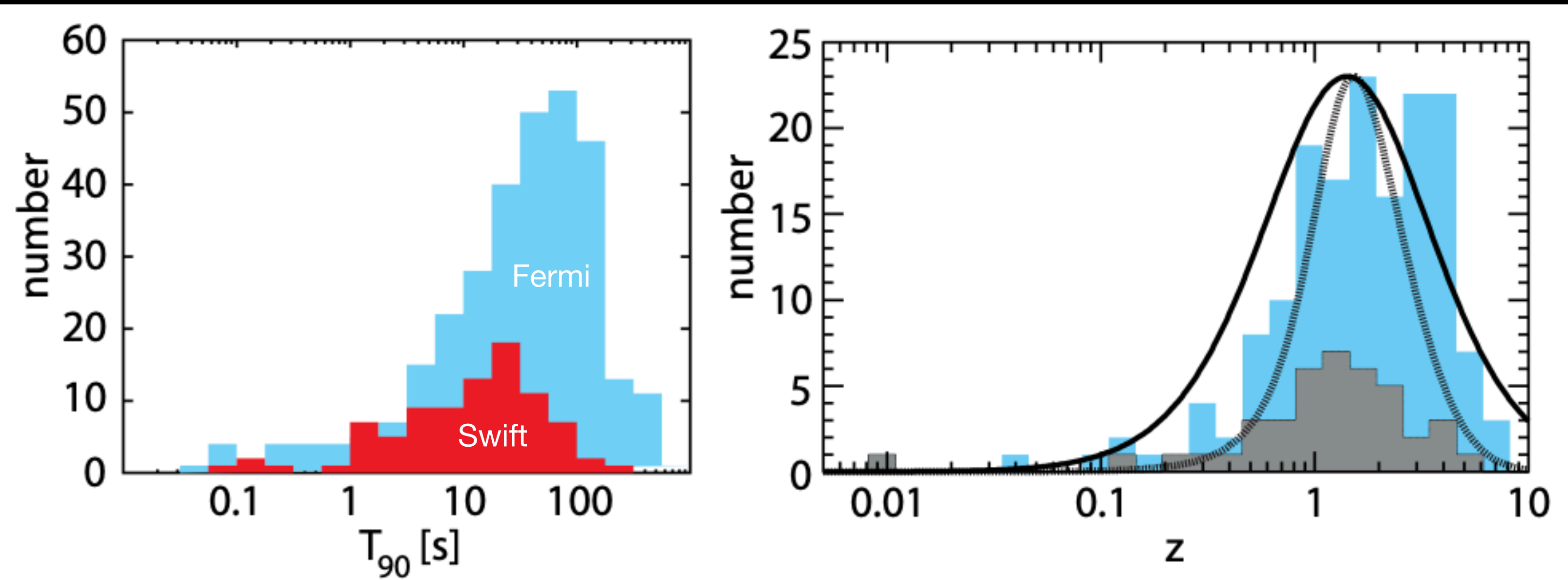


The shock region zoom

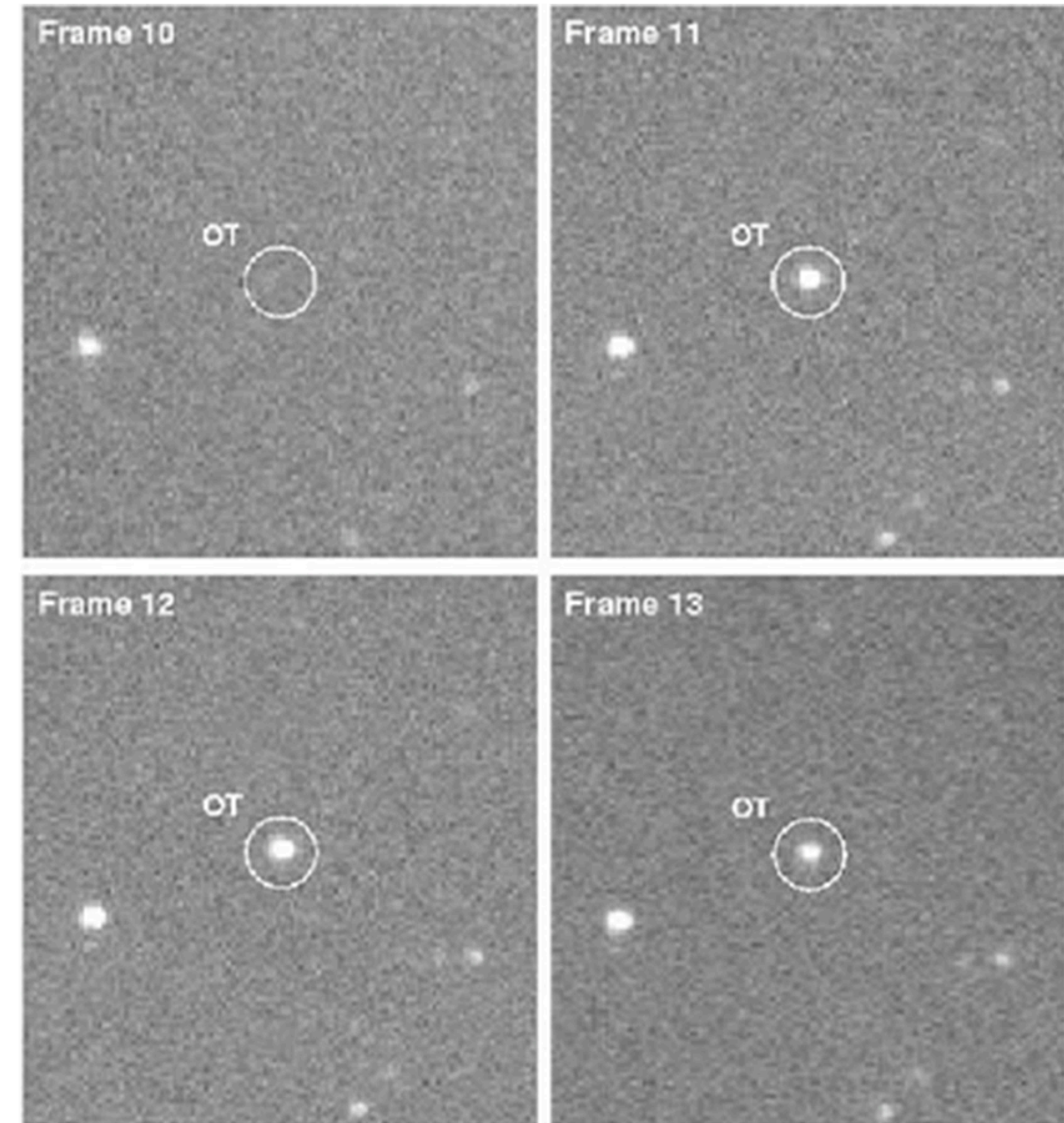
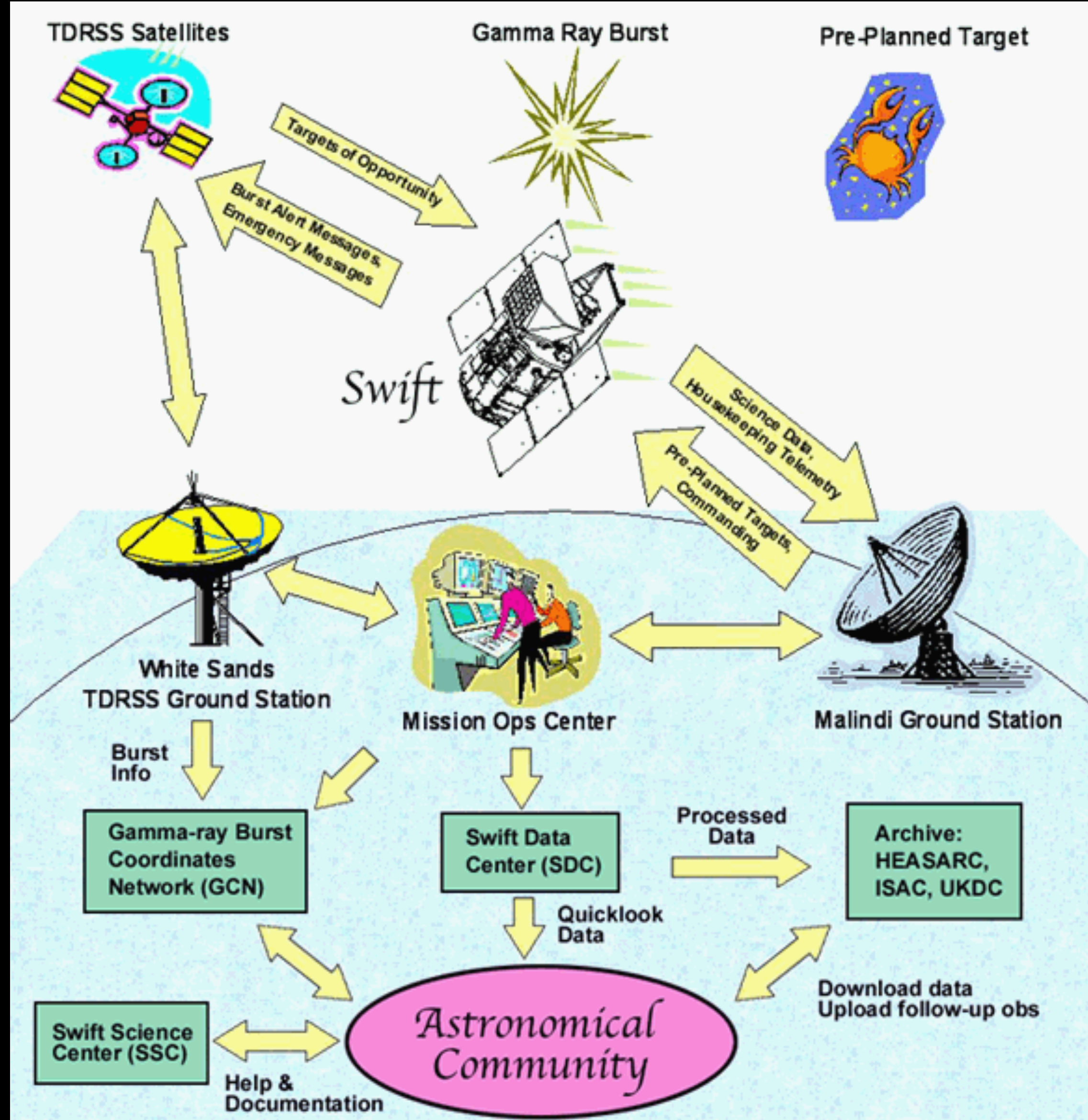




2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
9	88	102	86	103	89	84	81	92	96	95	75 to Oct. 27

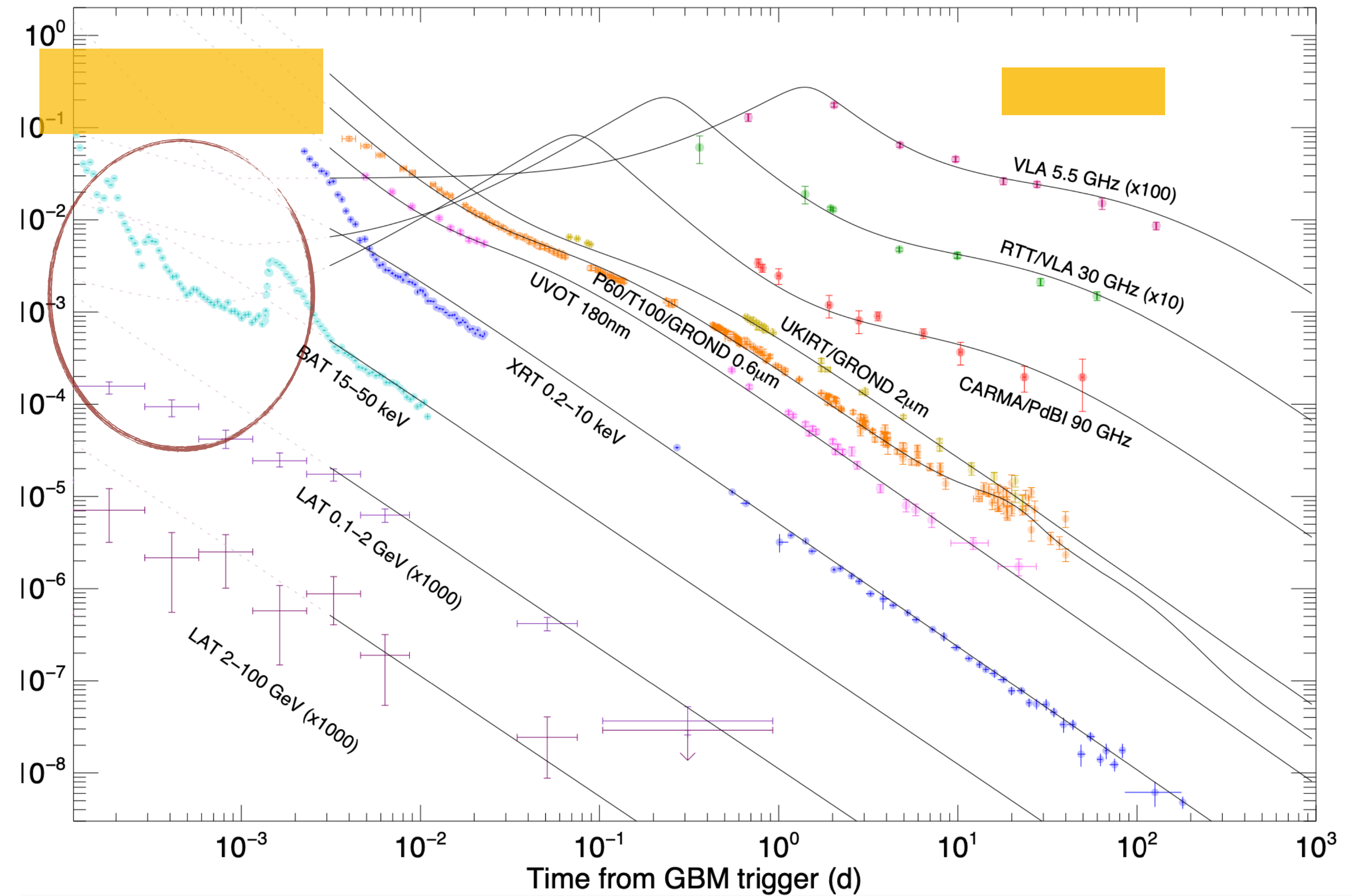
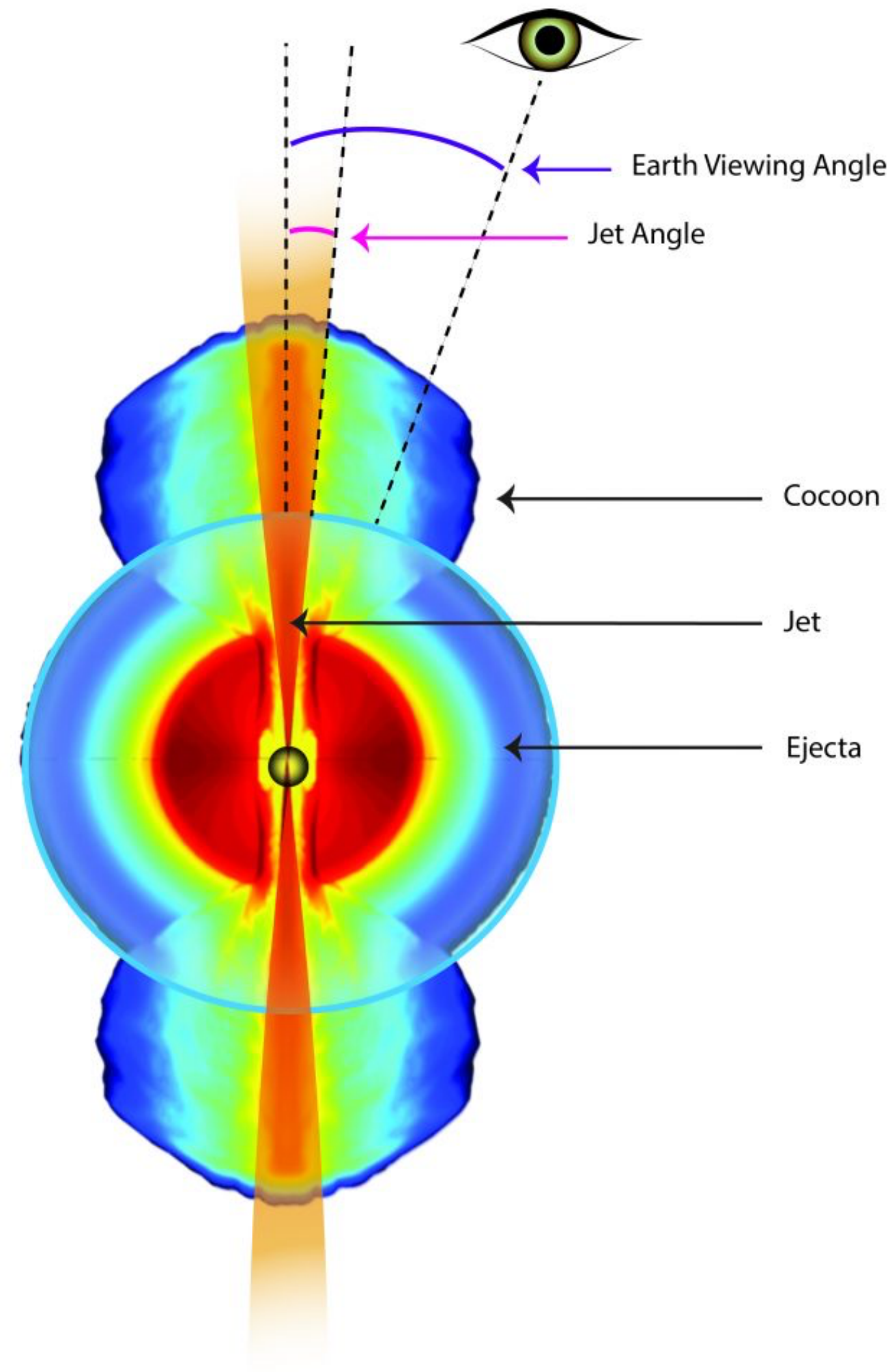


Afterglow emission



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

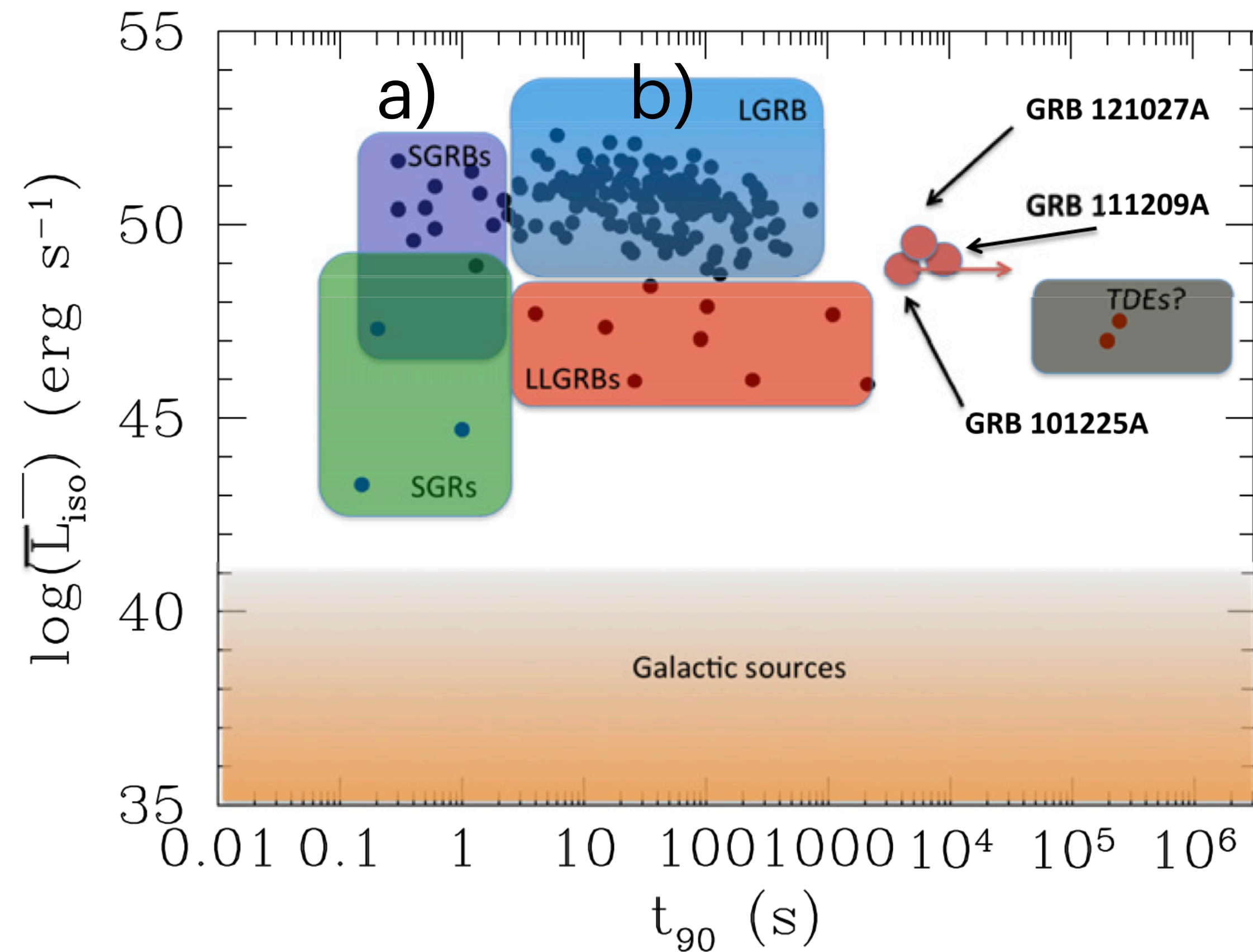
The complete GRB emission (on-axis)



Credit: Sophia Dagnello

GRB 130427, Perley et al. 2013

The Progenitors of Gamma Ray Bursts

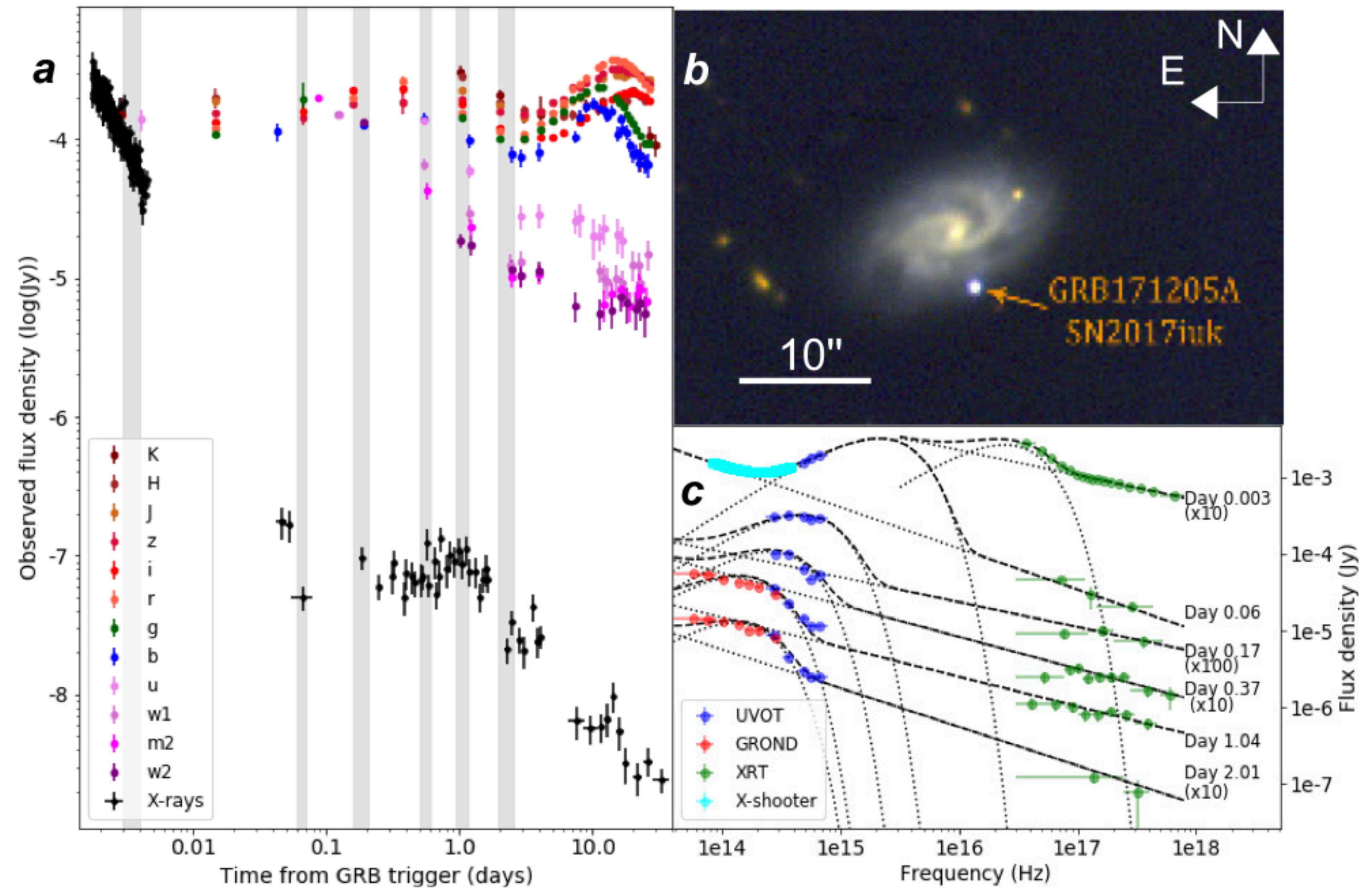
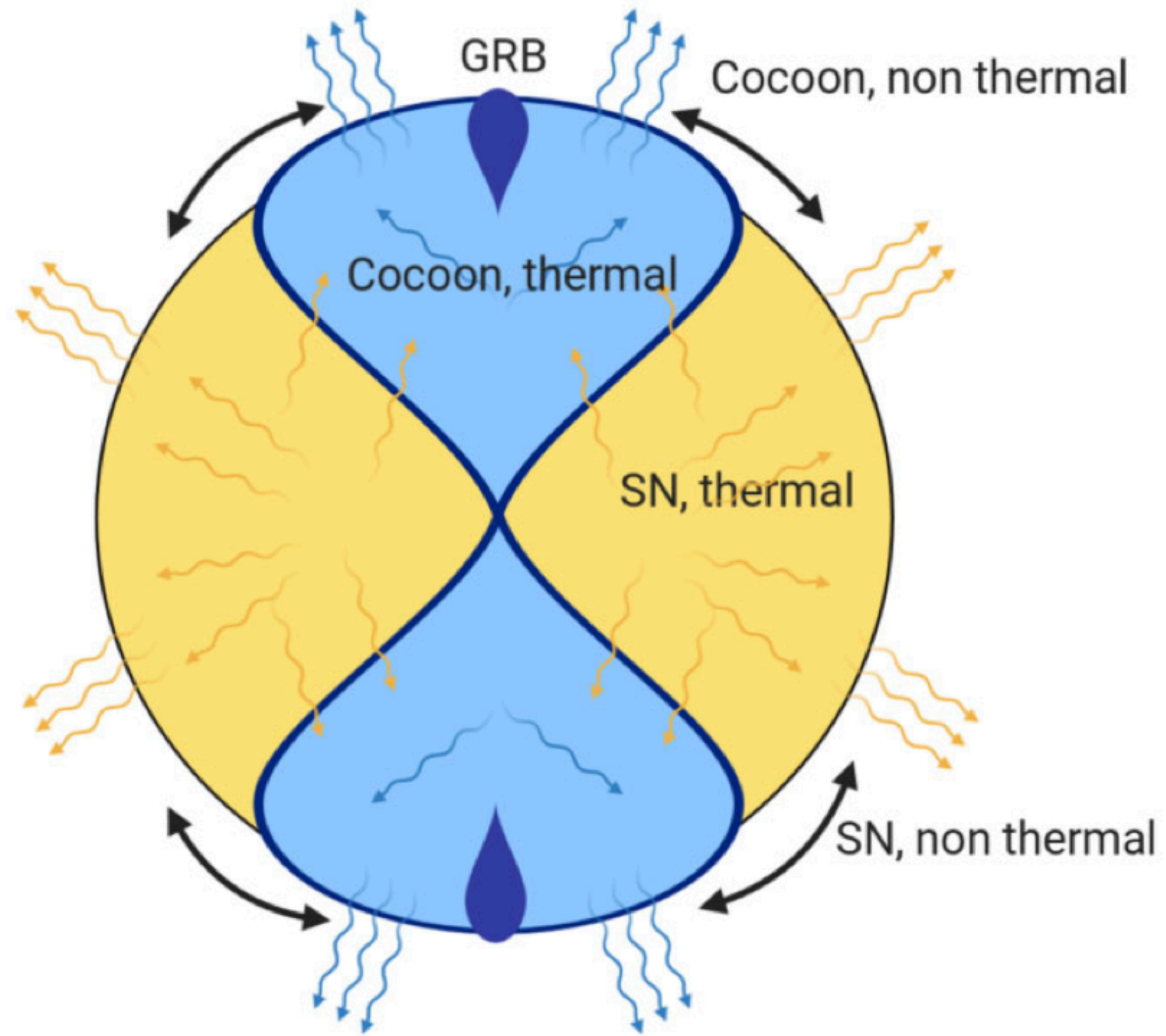


Levan et al. 2014



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

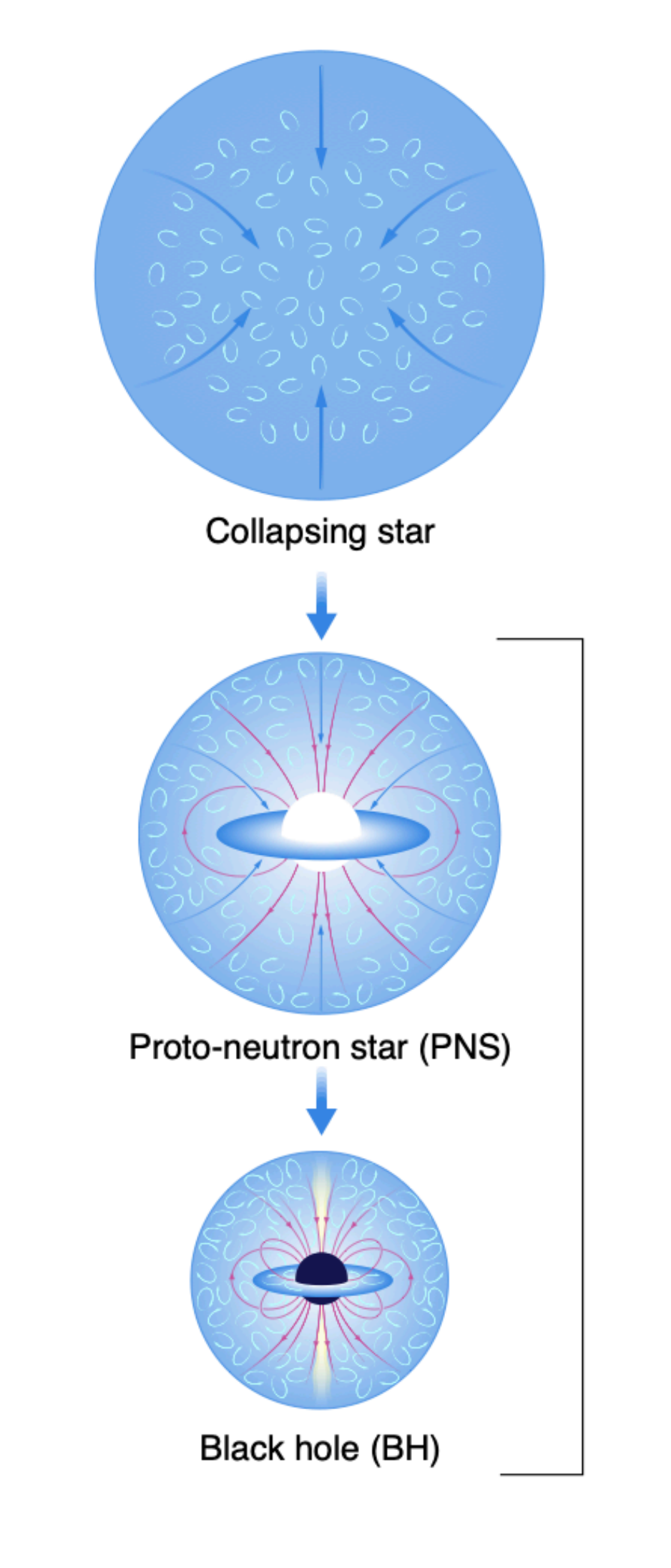
Jet, Cocoon and supernova from collapsars



De Colle et al 2022

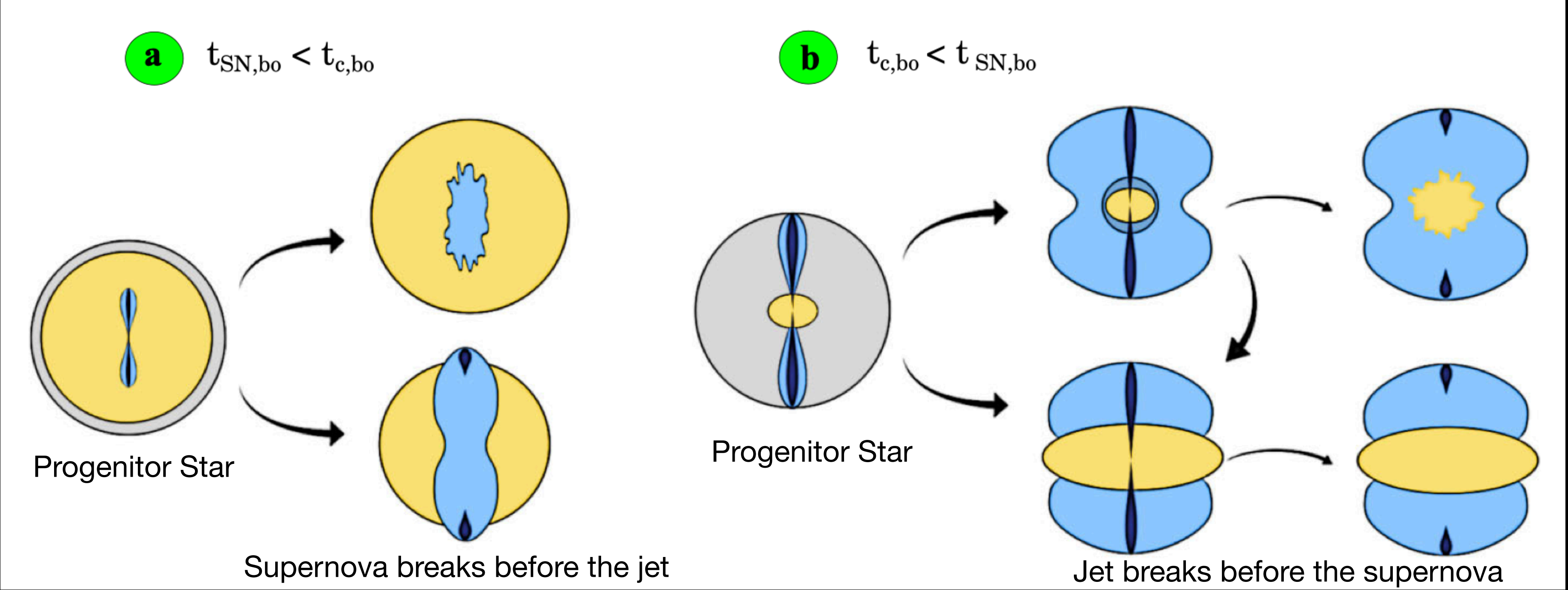
Izzo et al 2019

Central engine formation



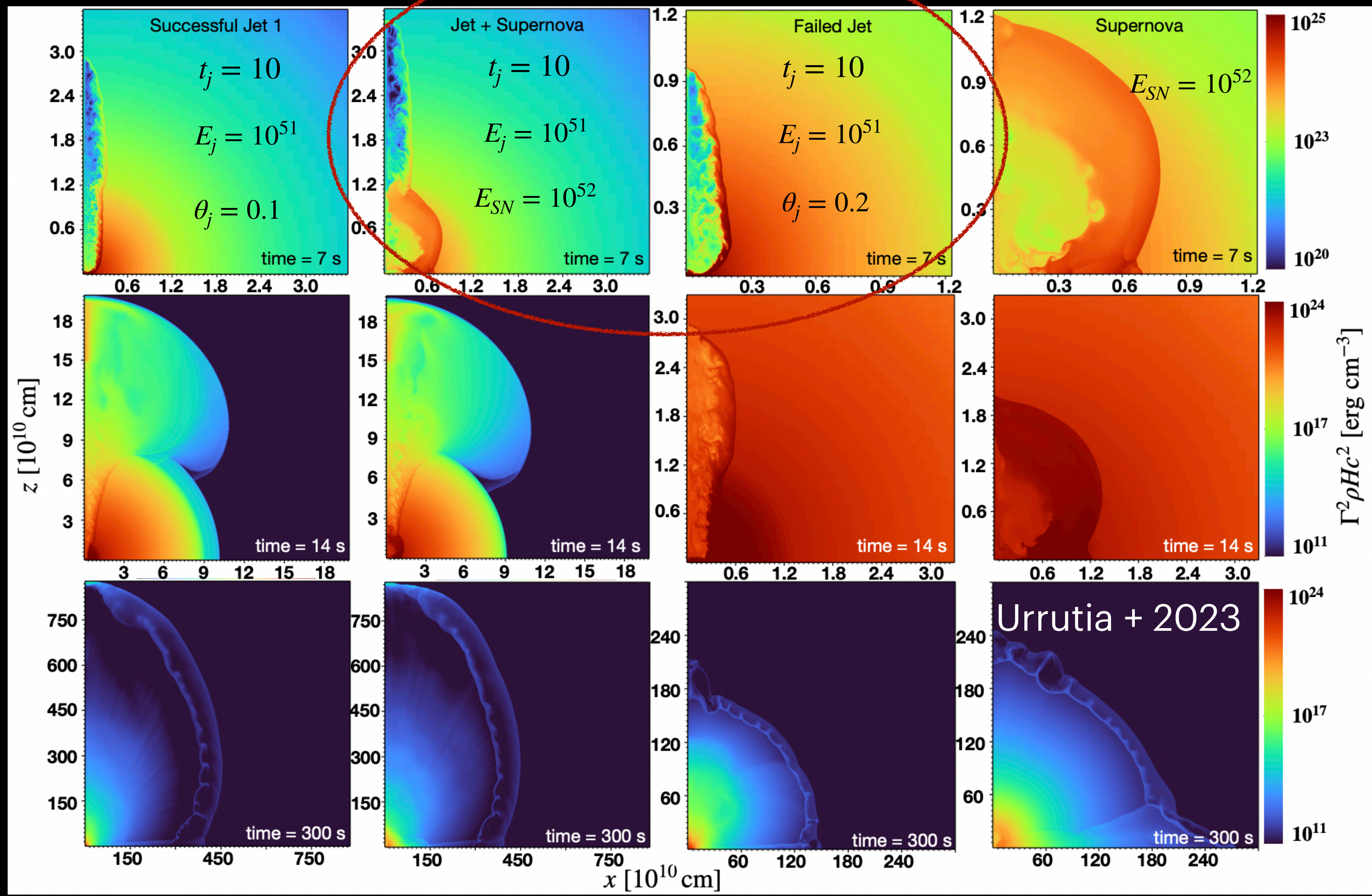
Gottlieb 2024

Breakout from the star



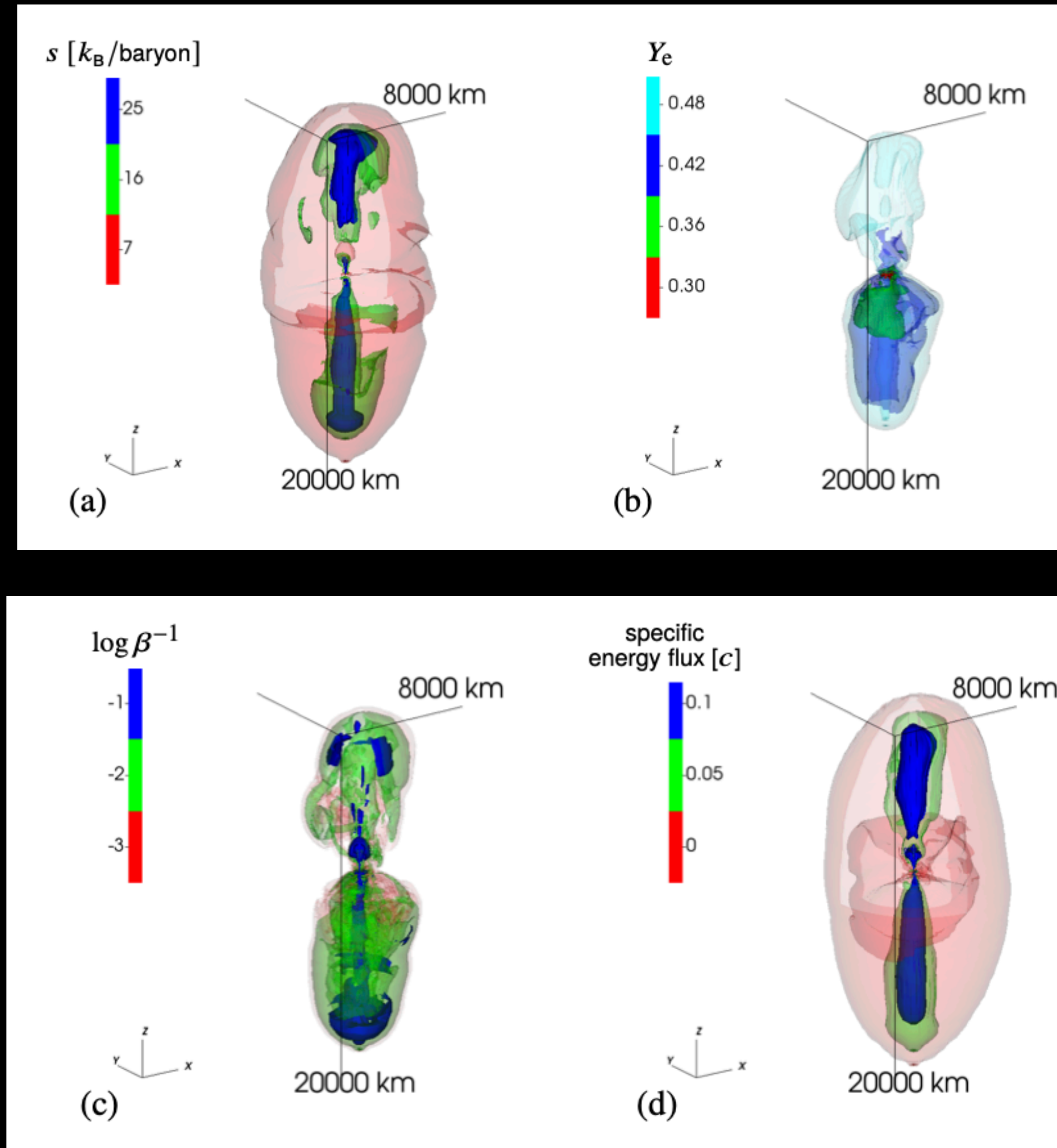
De Colle 2022

Explosions from massive stars

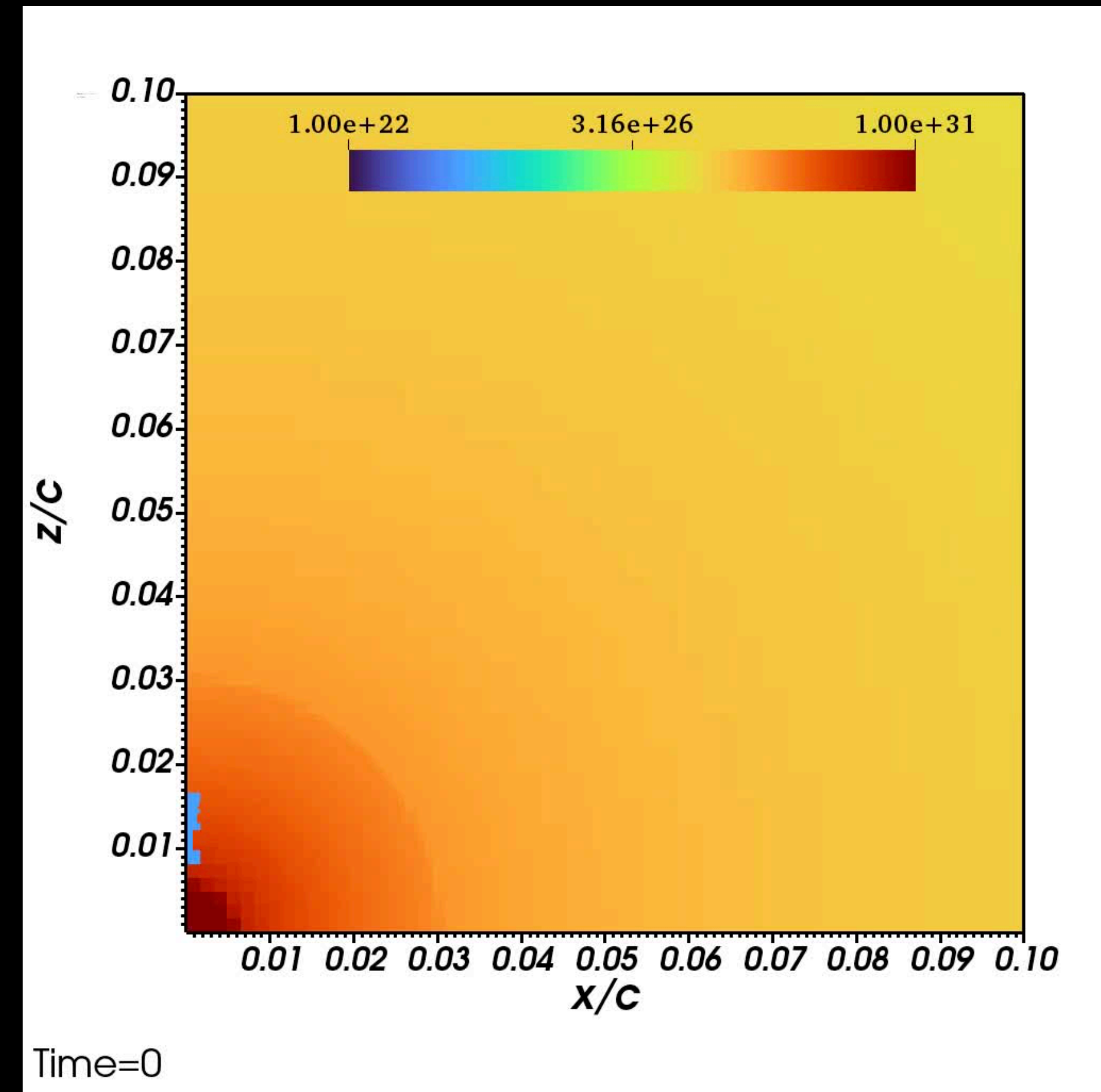


Collapsars are studied at two different scales

Small scales, e.g, Obergaulinger & Aloy 2020



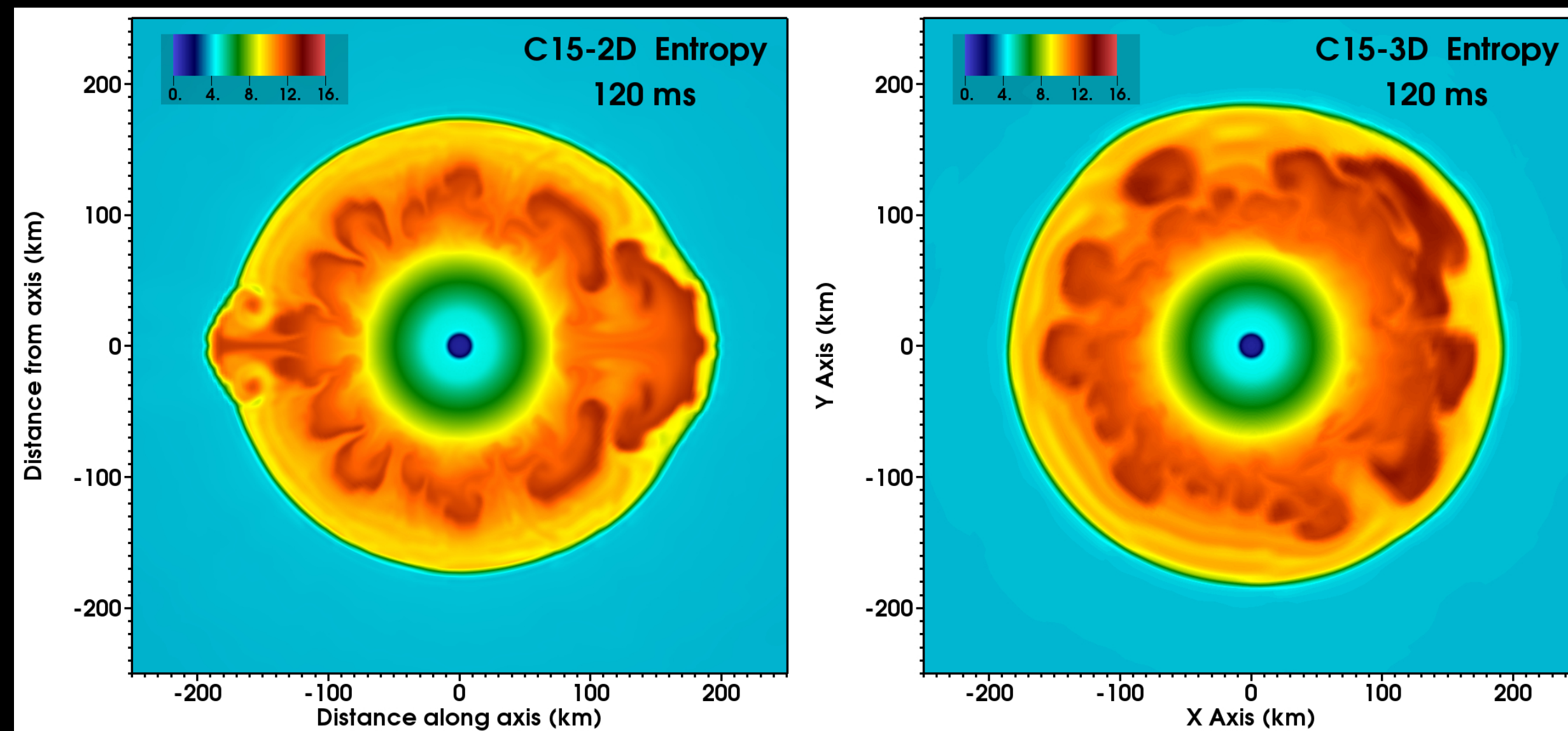
e.g., beyond the star surface Urrutia + 2023



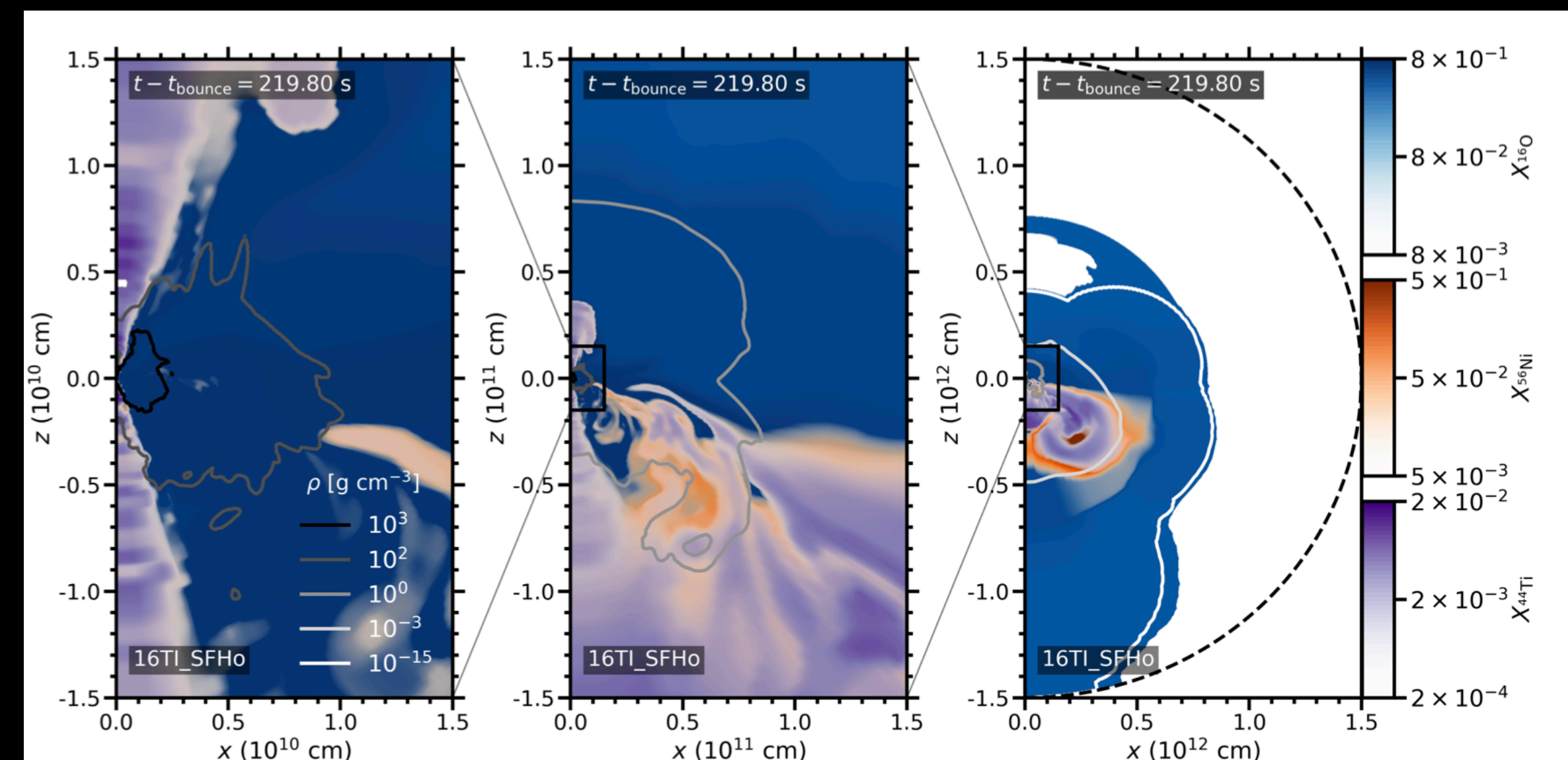
Also see, McFadyen & Woosley 1999 , Shibata + 2025

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

Neutrino transport is not included in our study

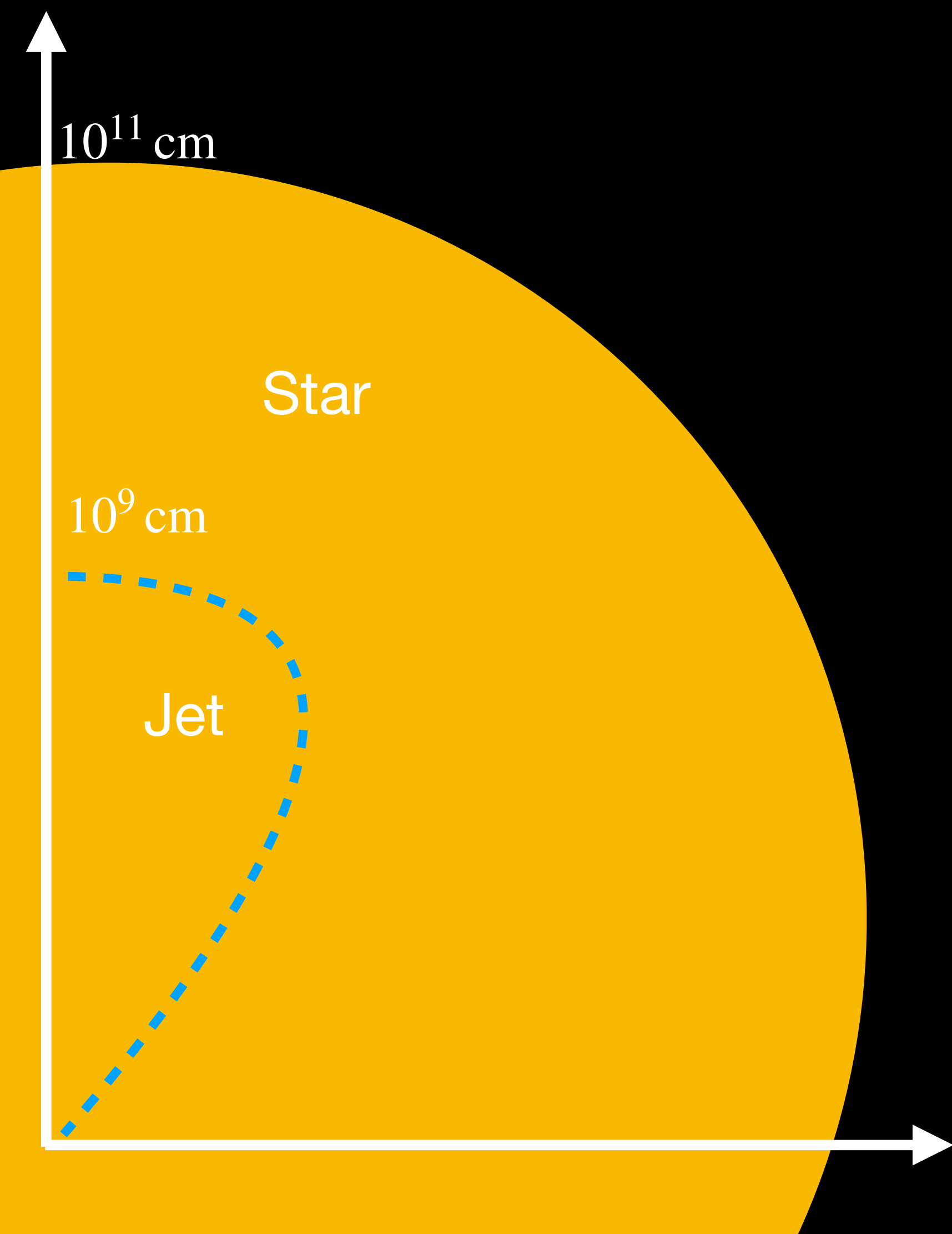


Yakunin, Mezzakapa, et al. 2017



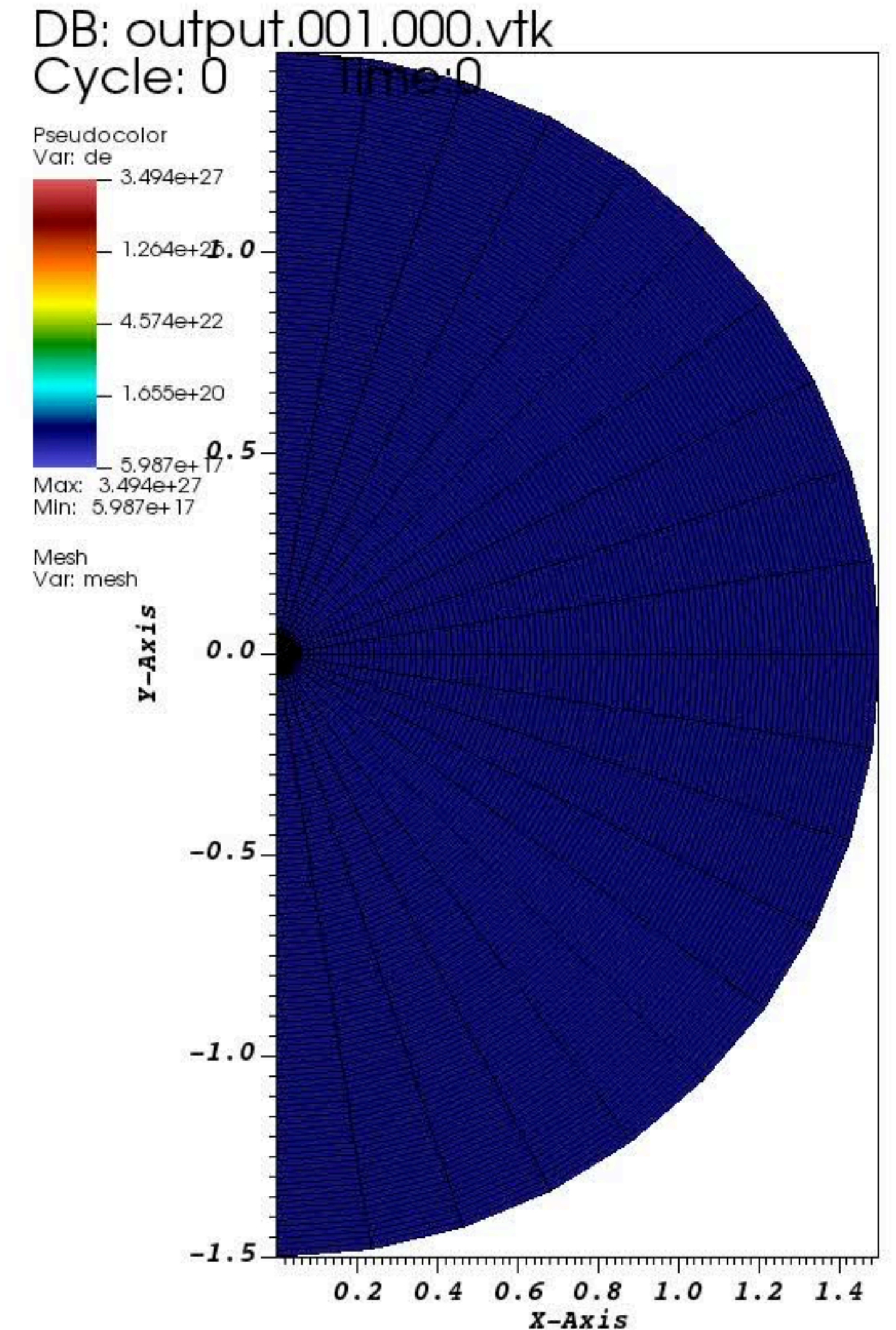
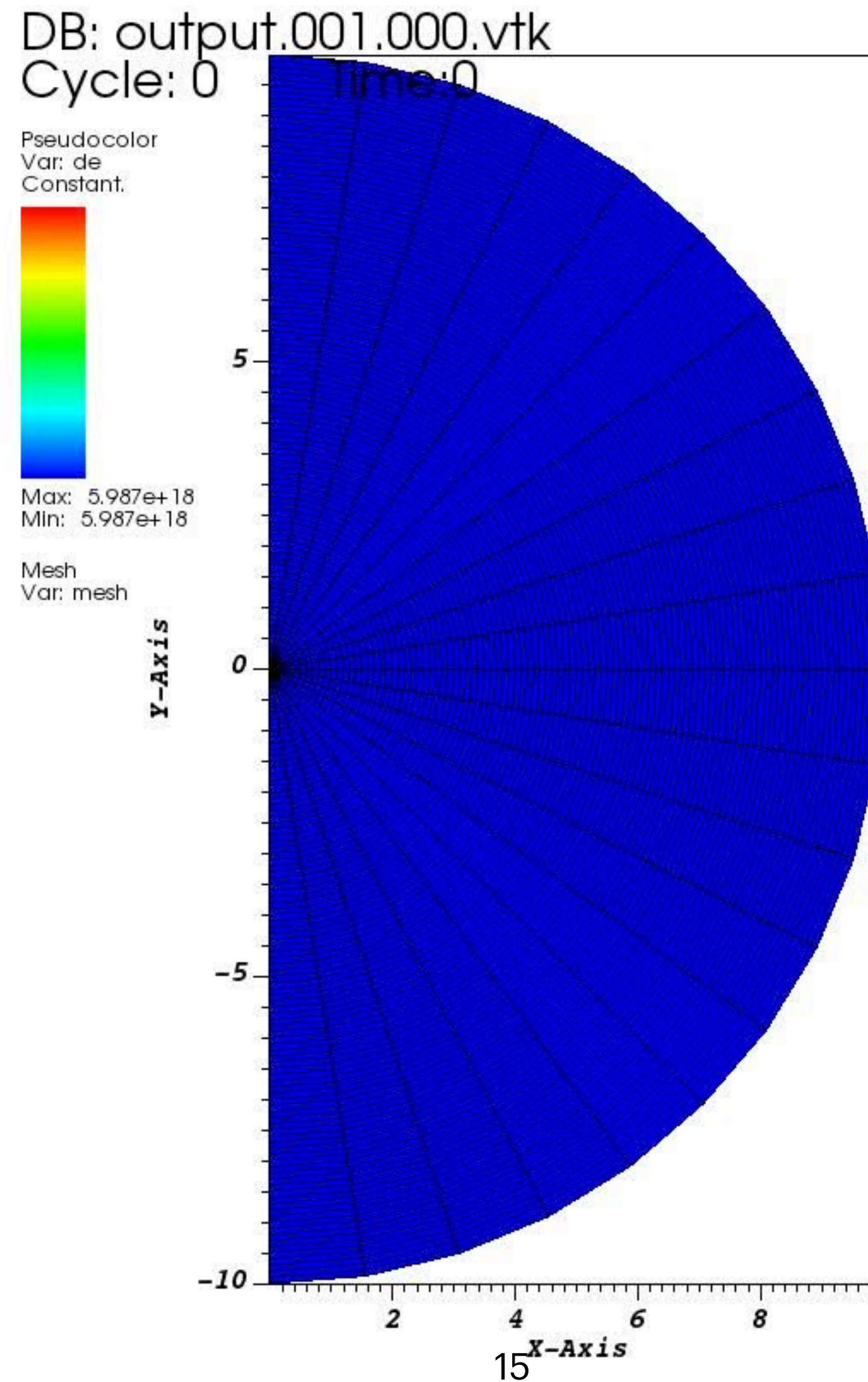
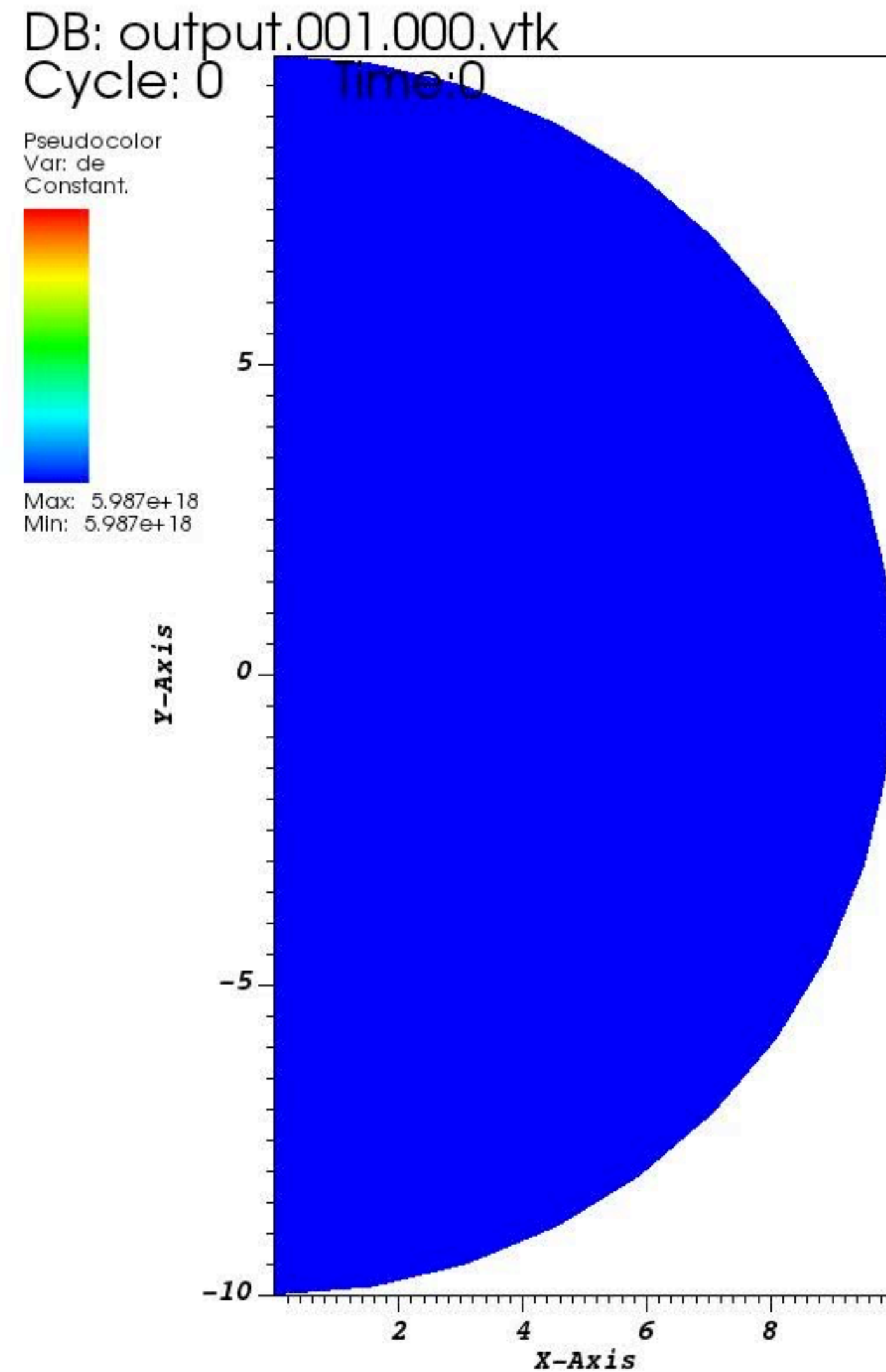
Coleman & Fernandez 2024

Connection of central engine activity with large scale dynamics?



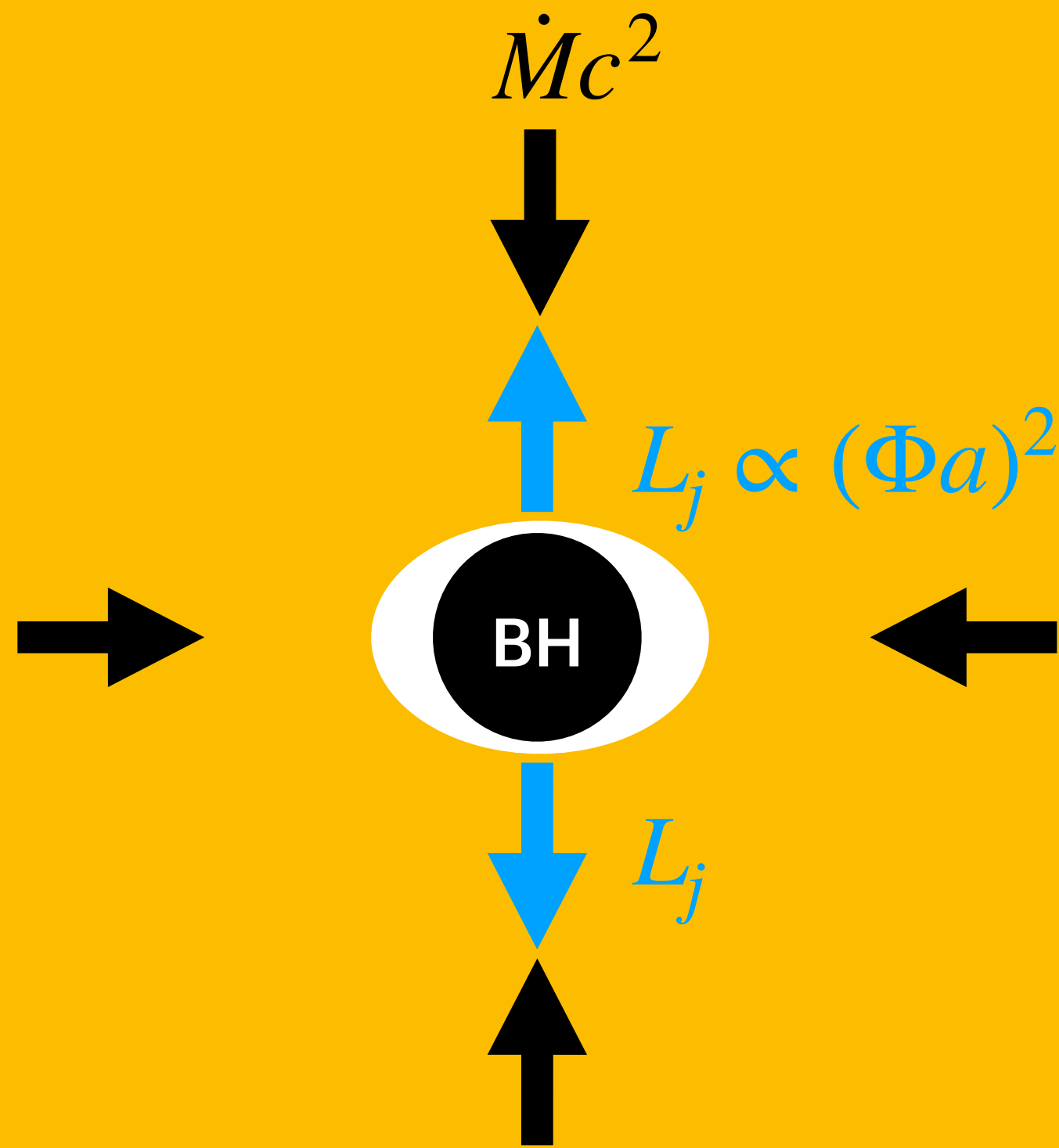
- Magnetically driven explosions e.g. Burrows 2007; Moesta 2014
- Luminosity vs time
- Distribution of velocities
- Variability
- Mean life time of the progenitor
- Jet opening angle
- Final structure of the jet

Spatial mesh can be dynamically adapted



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

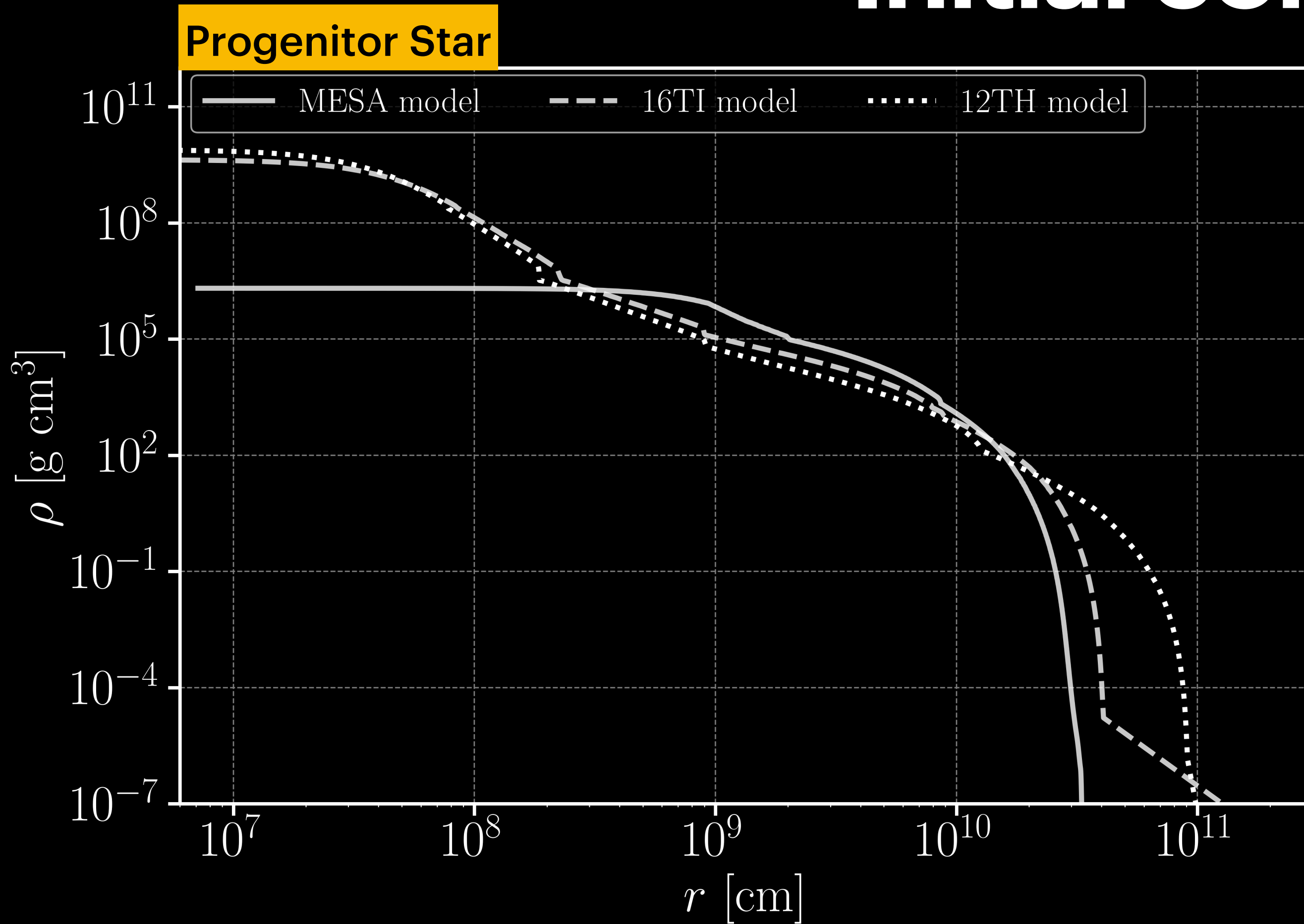
Accretion rate $\dot{M} \sim 0.1 M_{\odot} \text{ s}^{-1}$

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

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

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

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

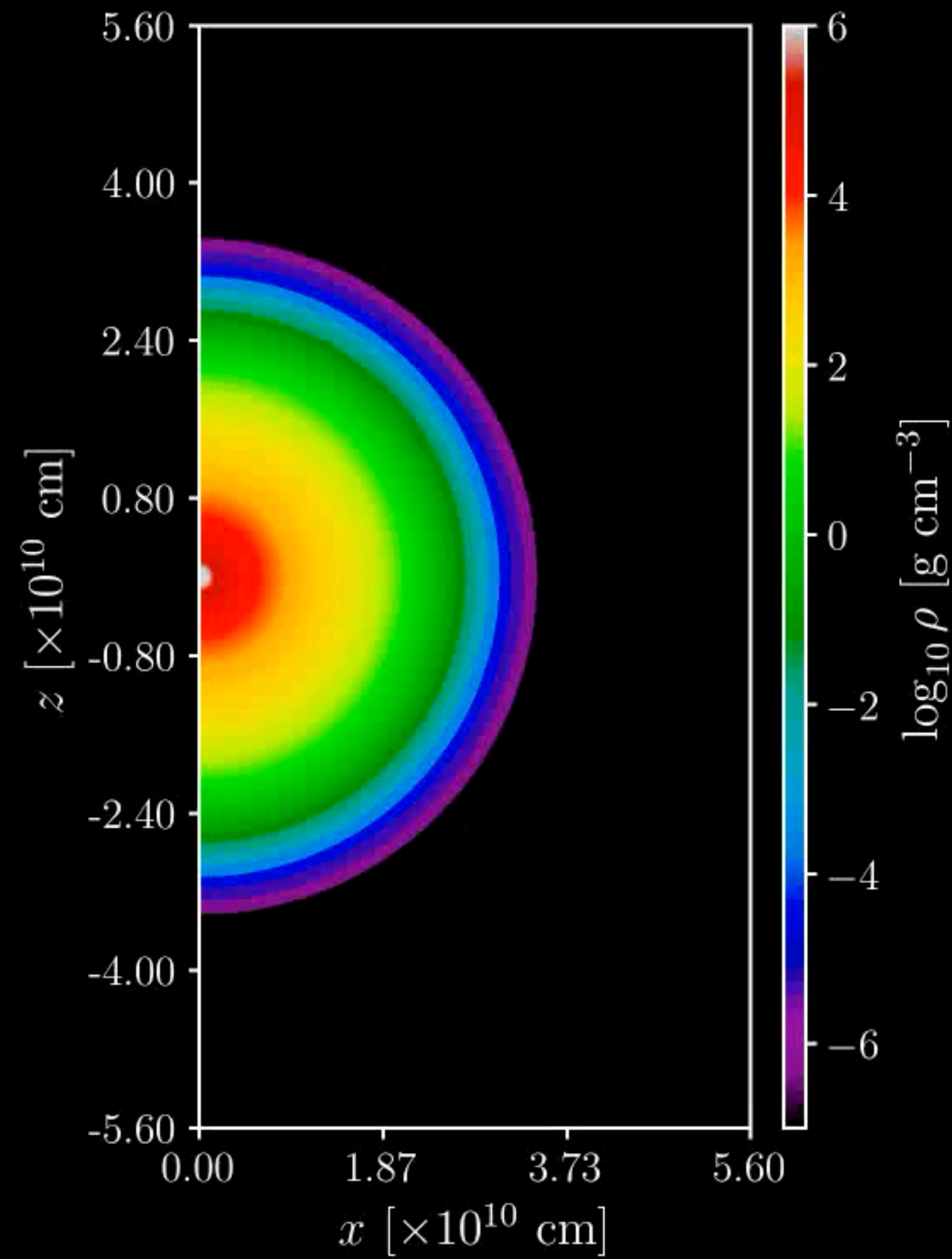
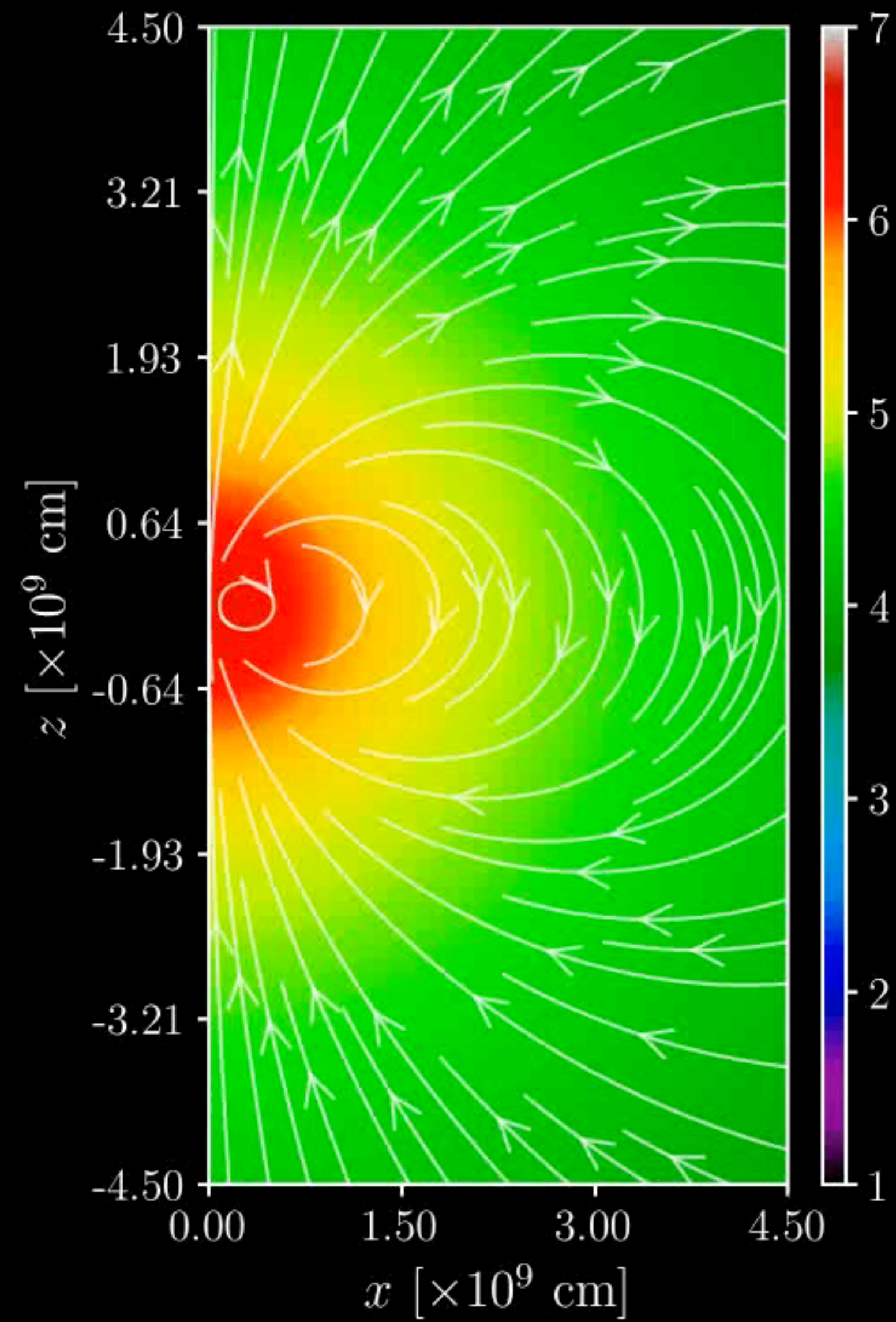
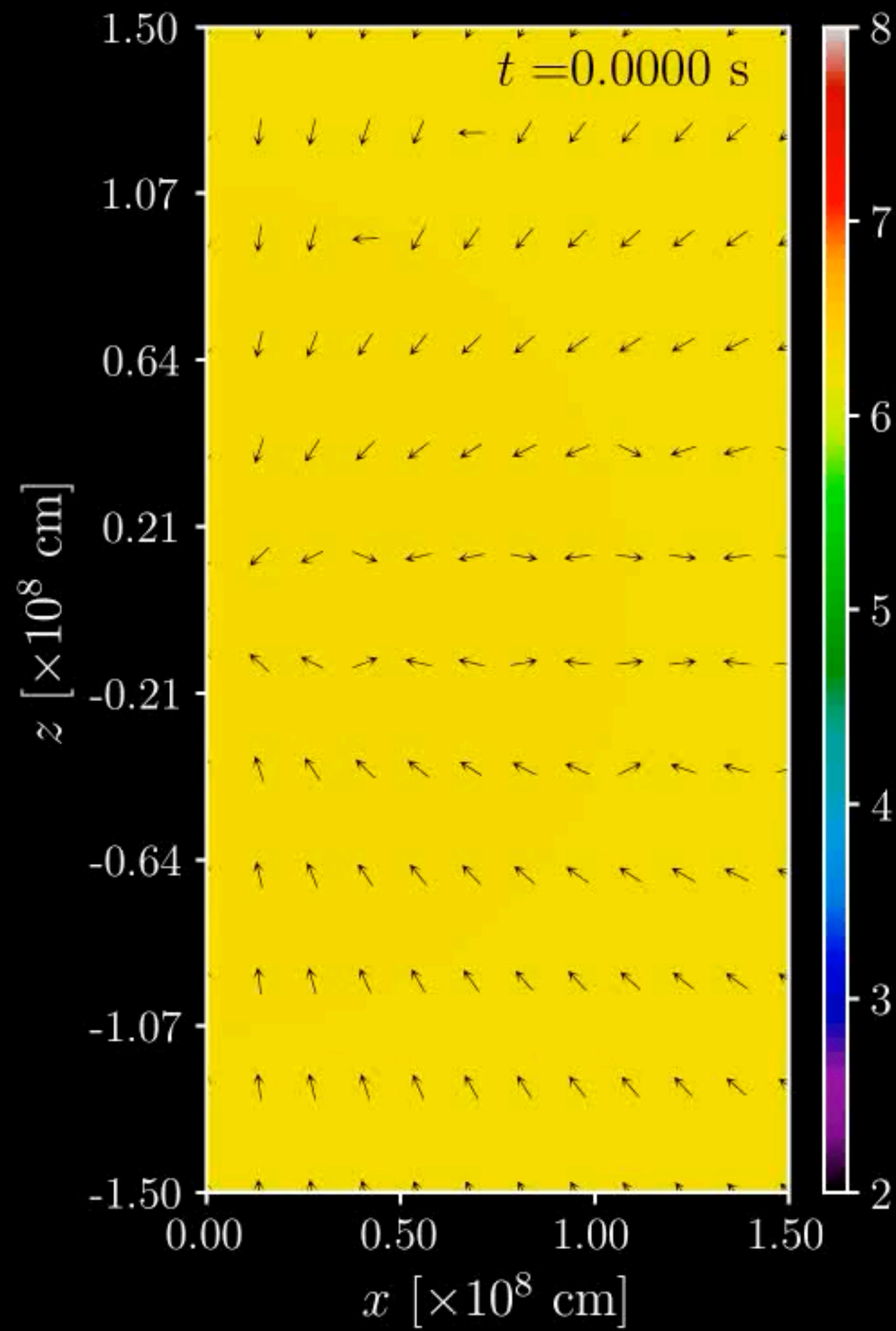
Magnetic Field Strength

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

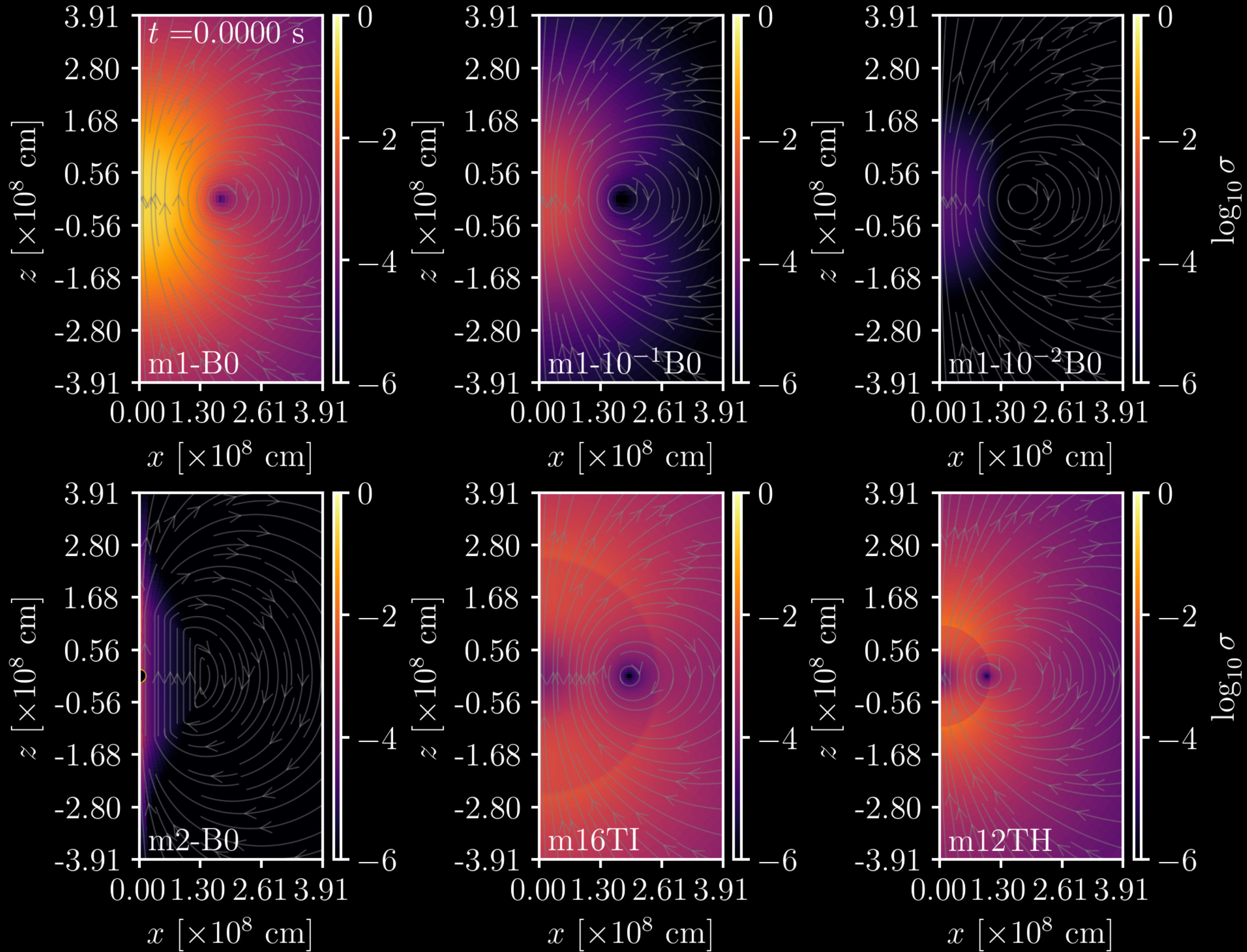
Magnetic Field Potential

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

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

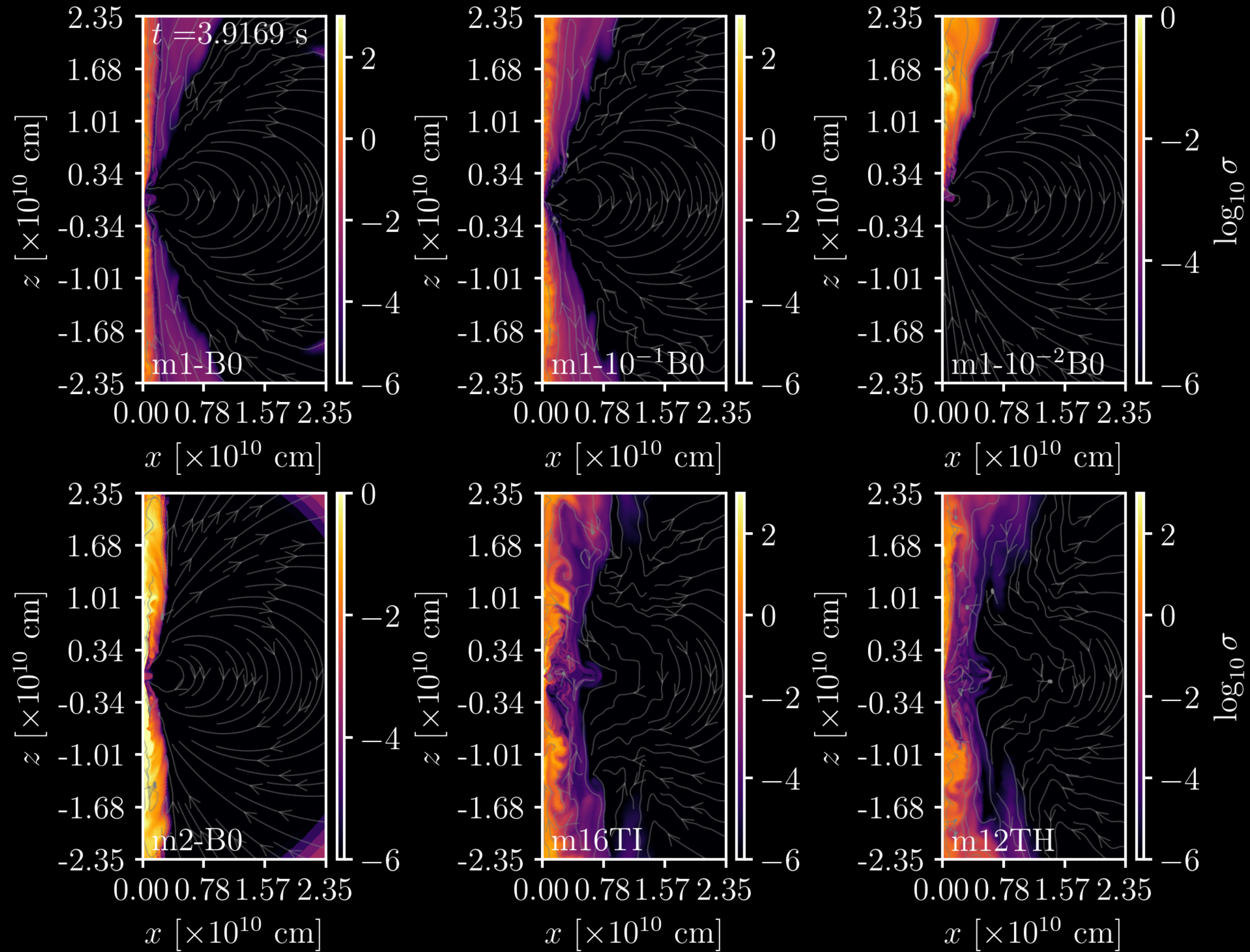


Magnetization



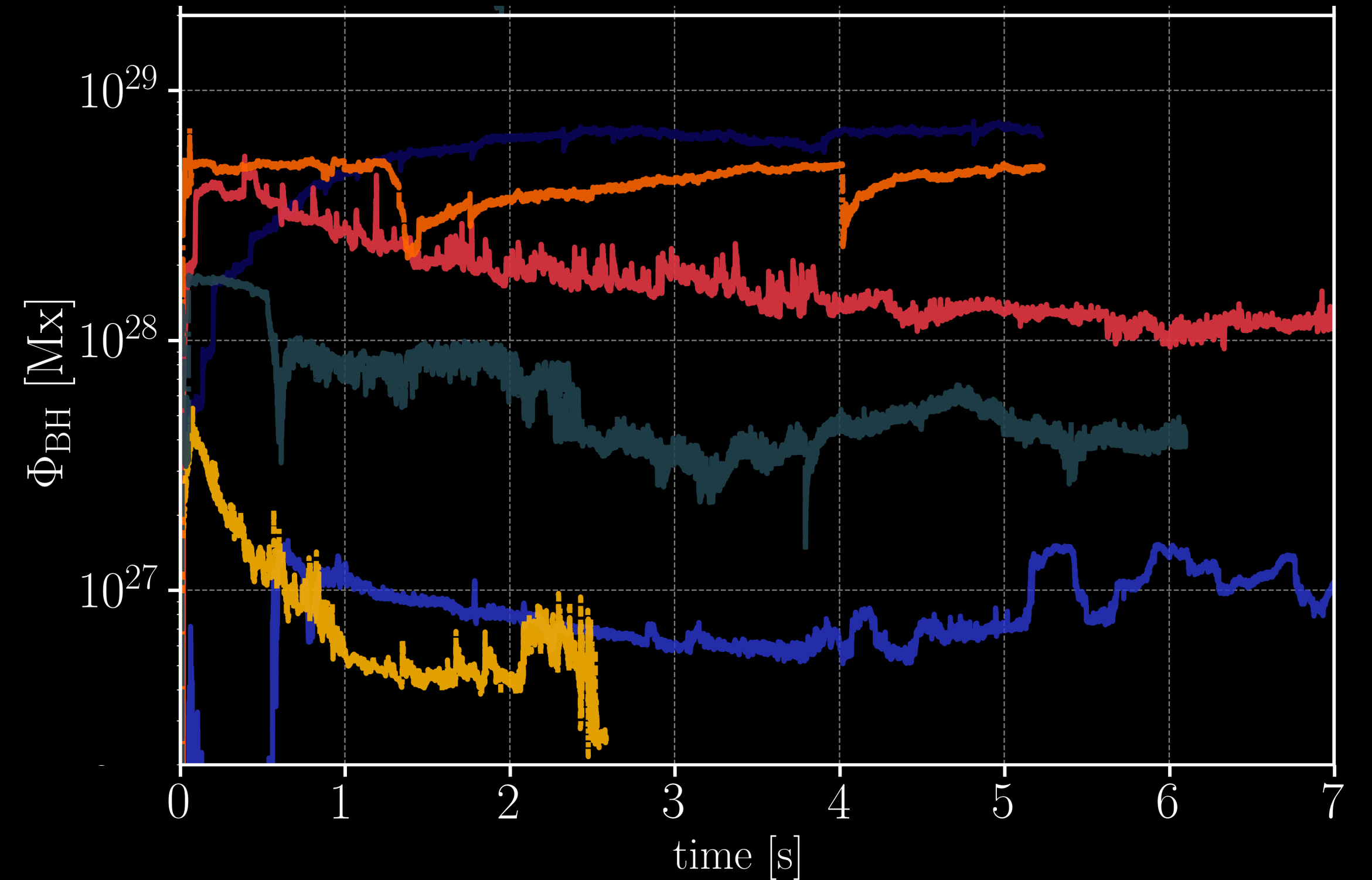
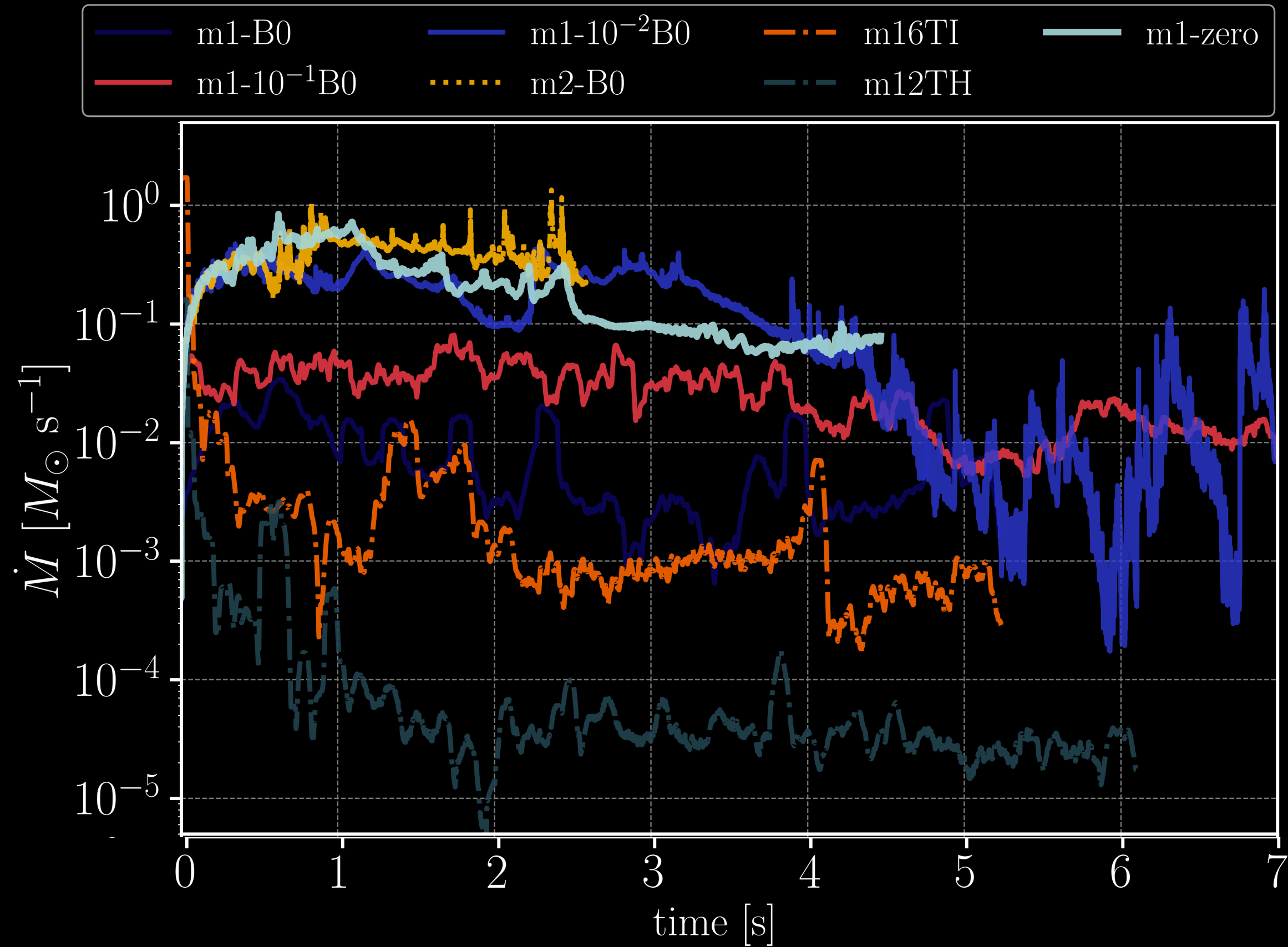
$$\sigma = B^2/8\pi\rho c^2$$

Magnetization



$$\sigma = B^2/8\pi\rho c^2$$

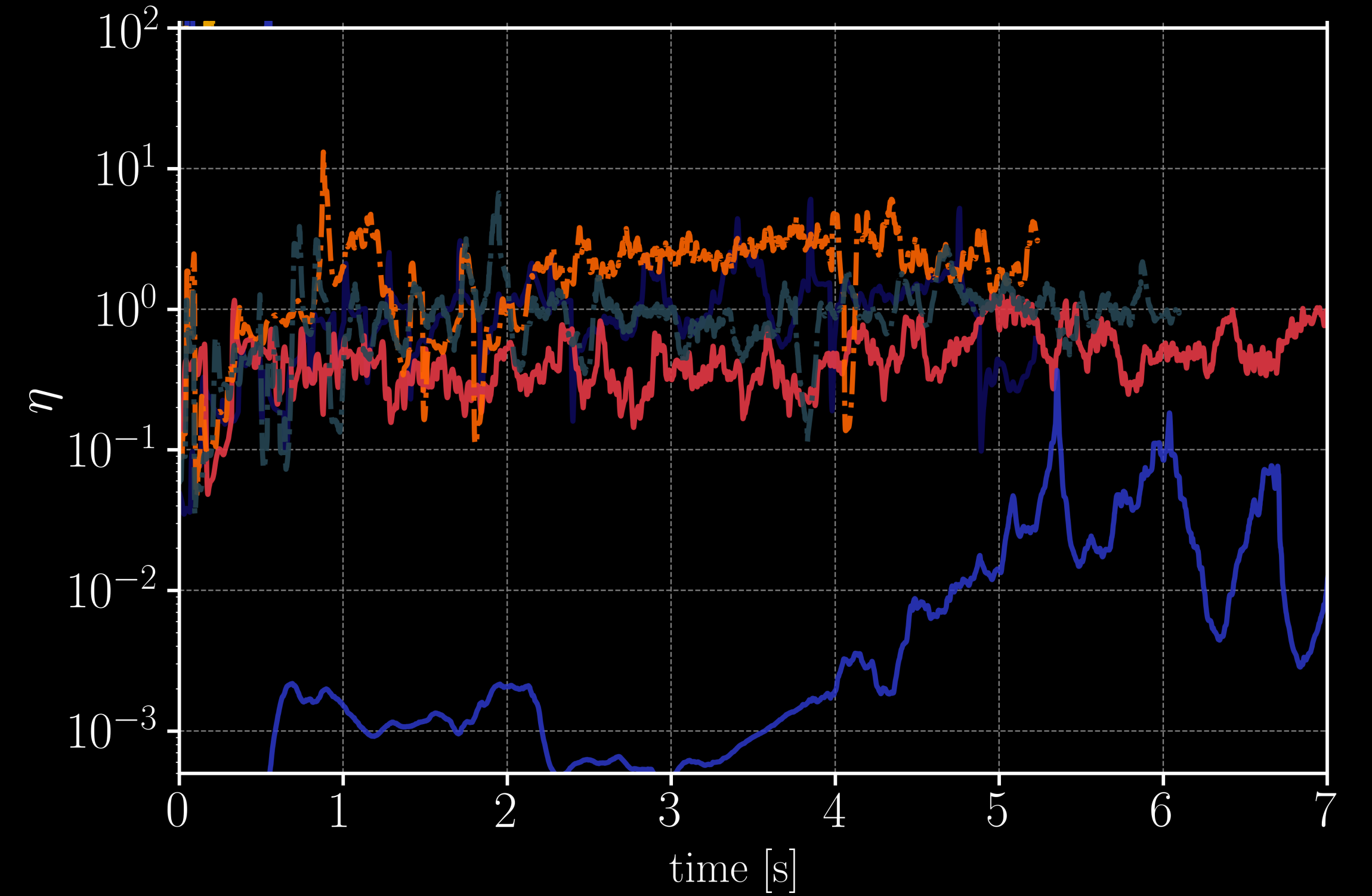
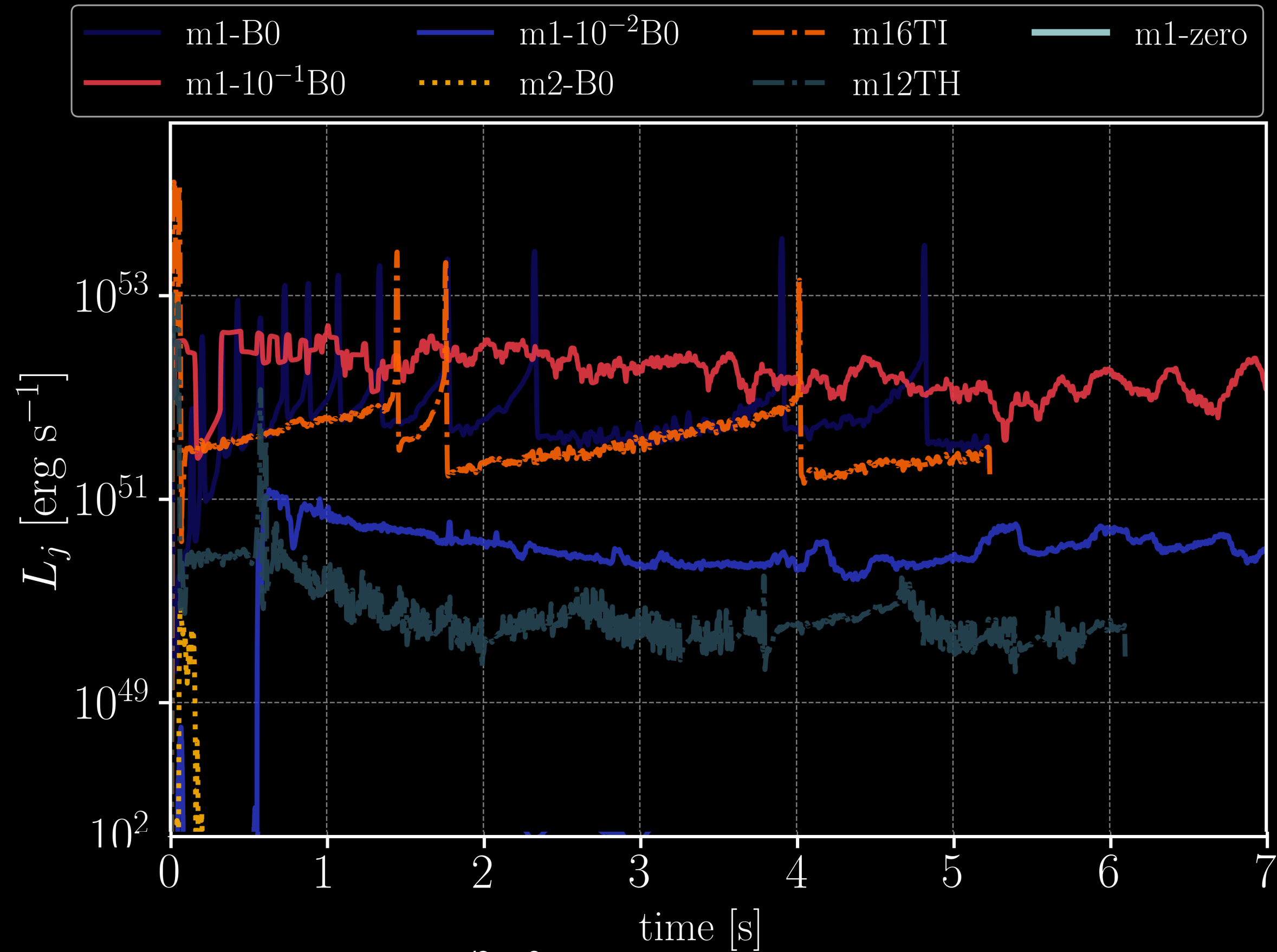
Central engine activity



$$\dot{M} = - \iint \rho c^2 u^r \sqrt{-g} d\theta d\phi$$

$$\Phi_{\text{BH}} = \frac{1}{2} \iint |B^r| \sqrt{-g} d\theta d\phi$$

Jet luminosity and efficiency



$$L_{\text{EM}} = -\frac{1}{4\pi} \int_0^{\pi/2} \int_0^{2\pi} (b^2 u^r u_t - b^r b_t) \sqrt{-g} d\phi d\theta$$

$$L_{\text{TH}} = -\int_0^{\pi/2} \int_0^{2\pi} (u_g + p_g) u^r u_r \sqrt{-g} d\phi d\theta$$

$$L_{\text{KE}} = -\int_0^{\pi/2} \int_0^{2\pi} \rho c^2 u^r u_r \sqrt{-g} d\phi d\theta$$

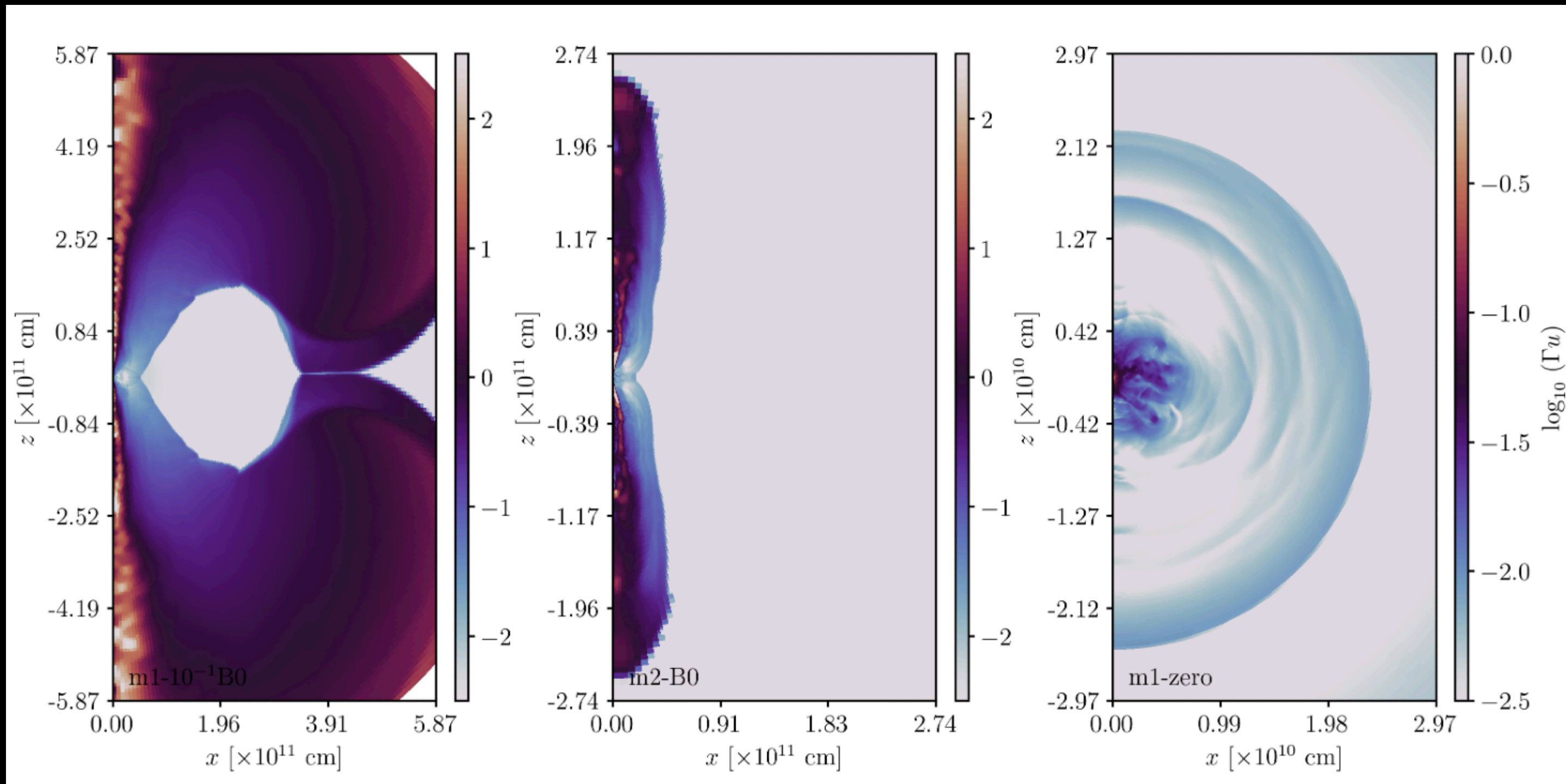
$$\eta = \frac{L_j}{\dot{M} c^2}$$

Jet propagation

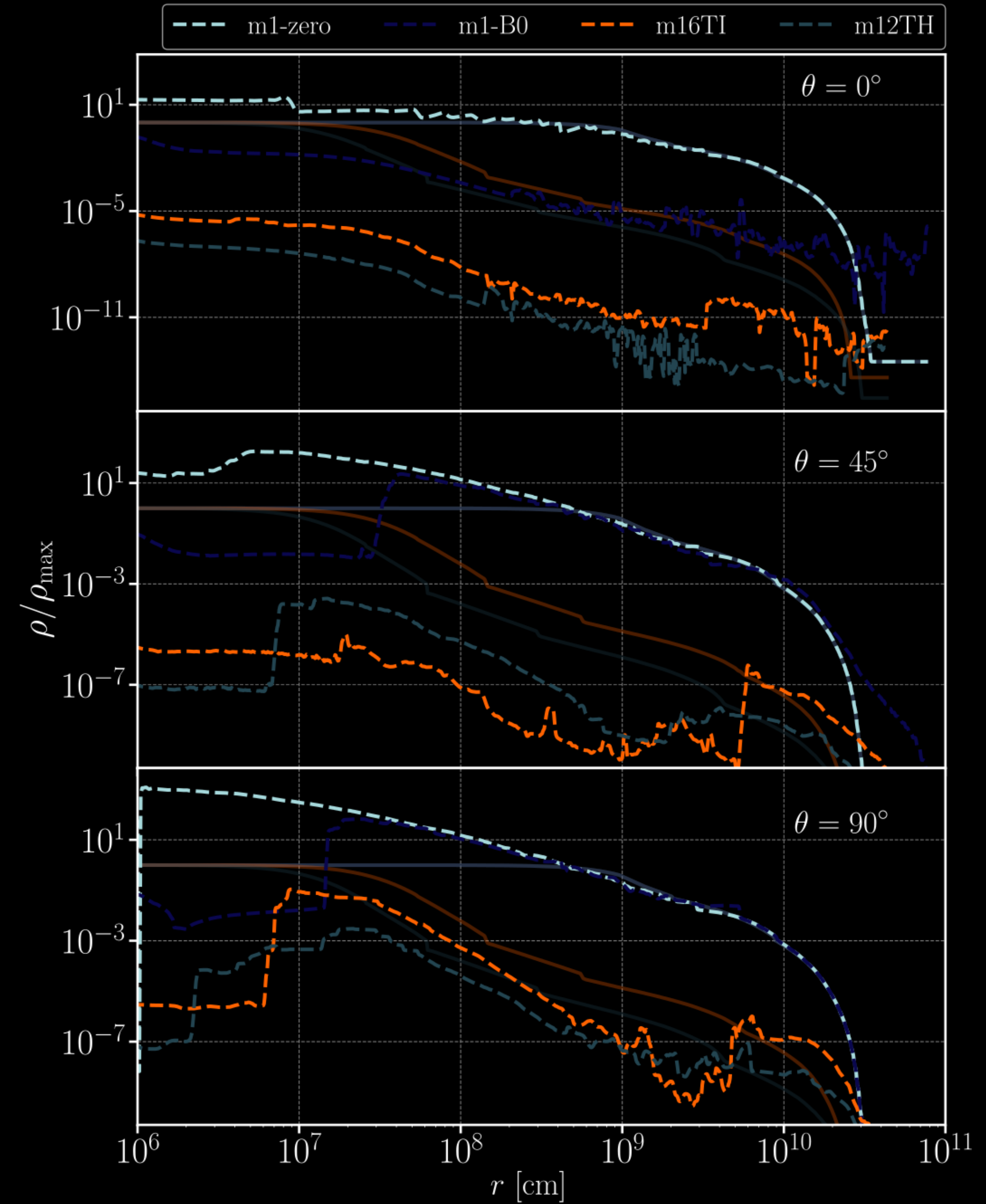
High magnetized

Weakly magnetized

Non magnetized



Progenitor's evolution

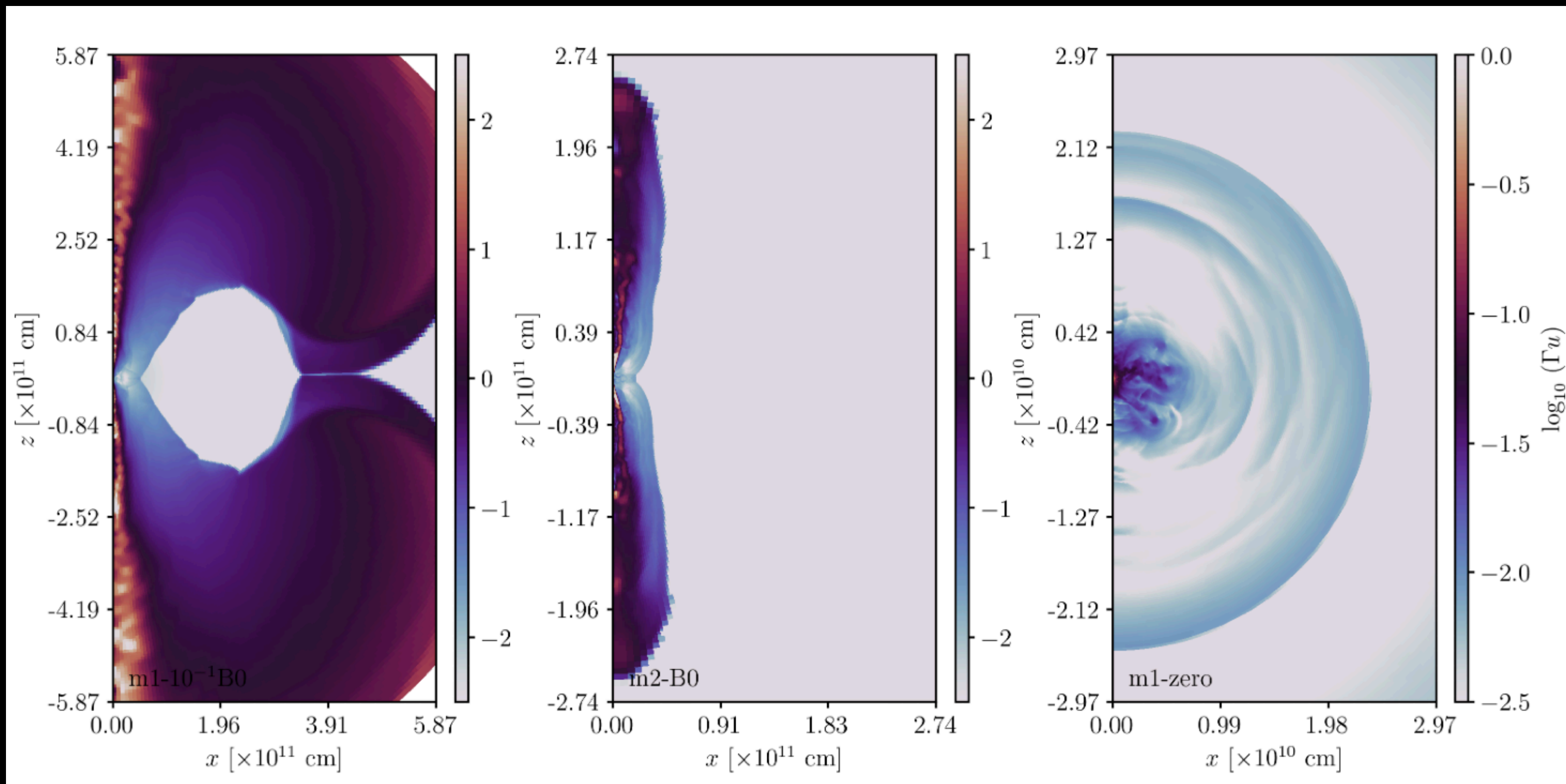


Jet propagation

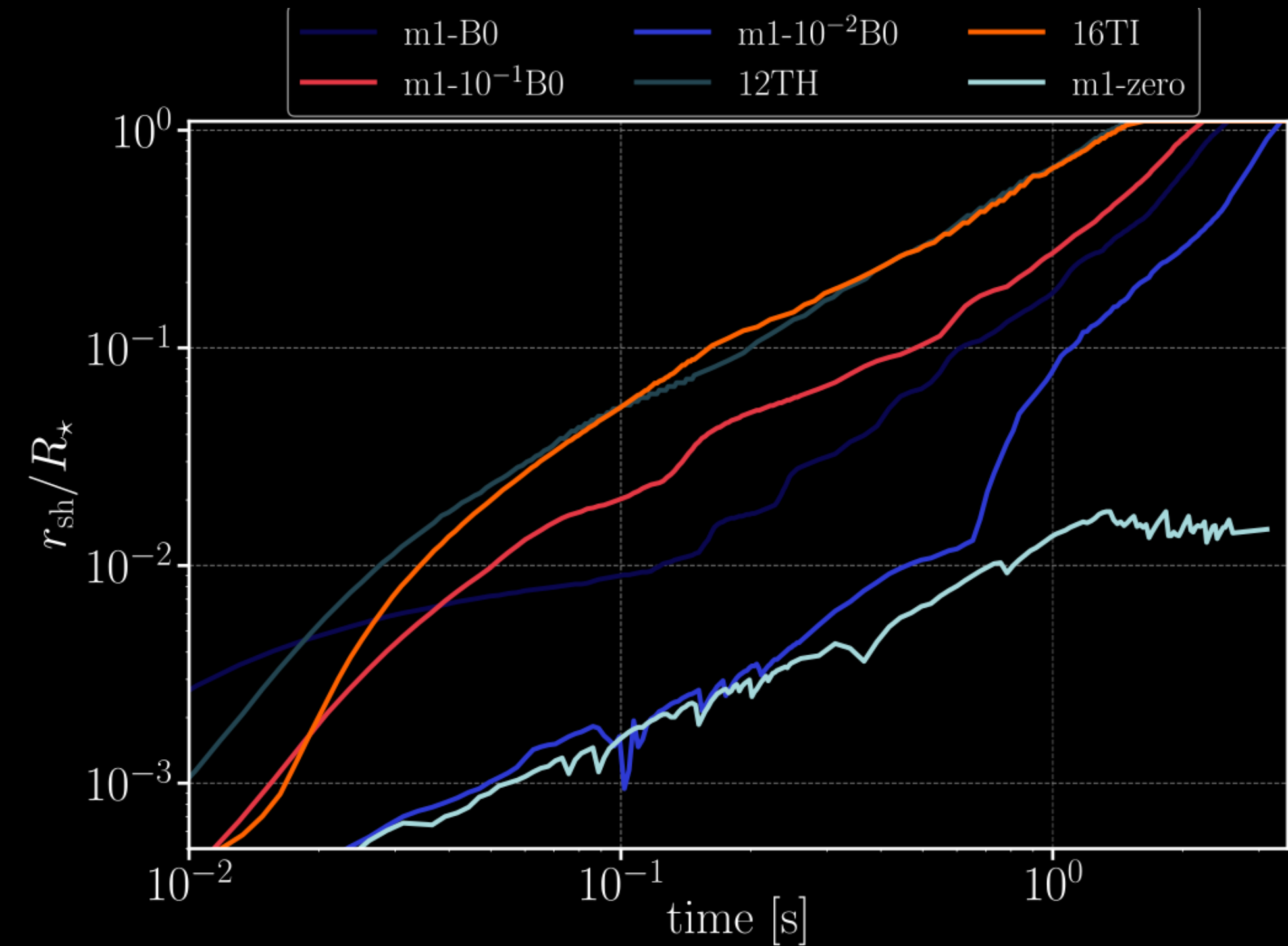
High magnetized

Weakly magnetized

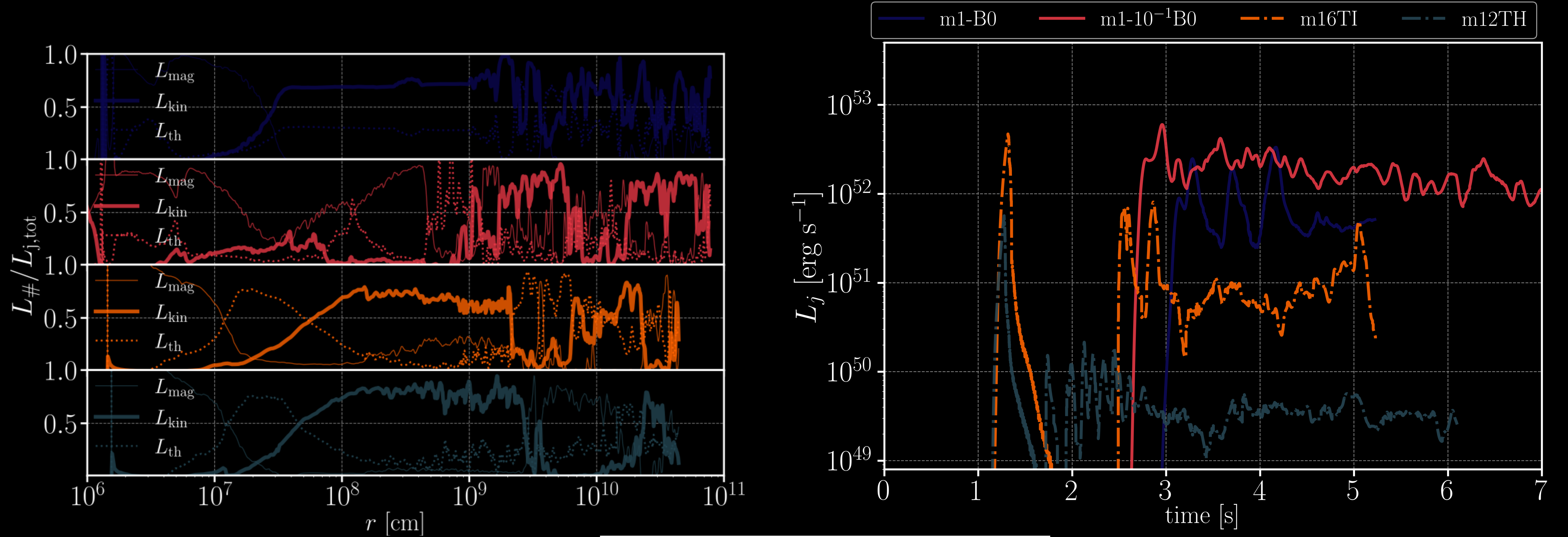
Non magnetized



Shock front

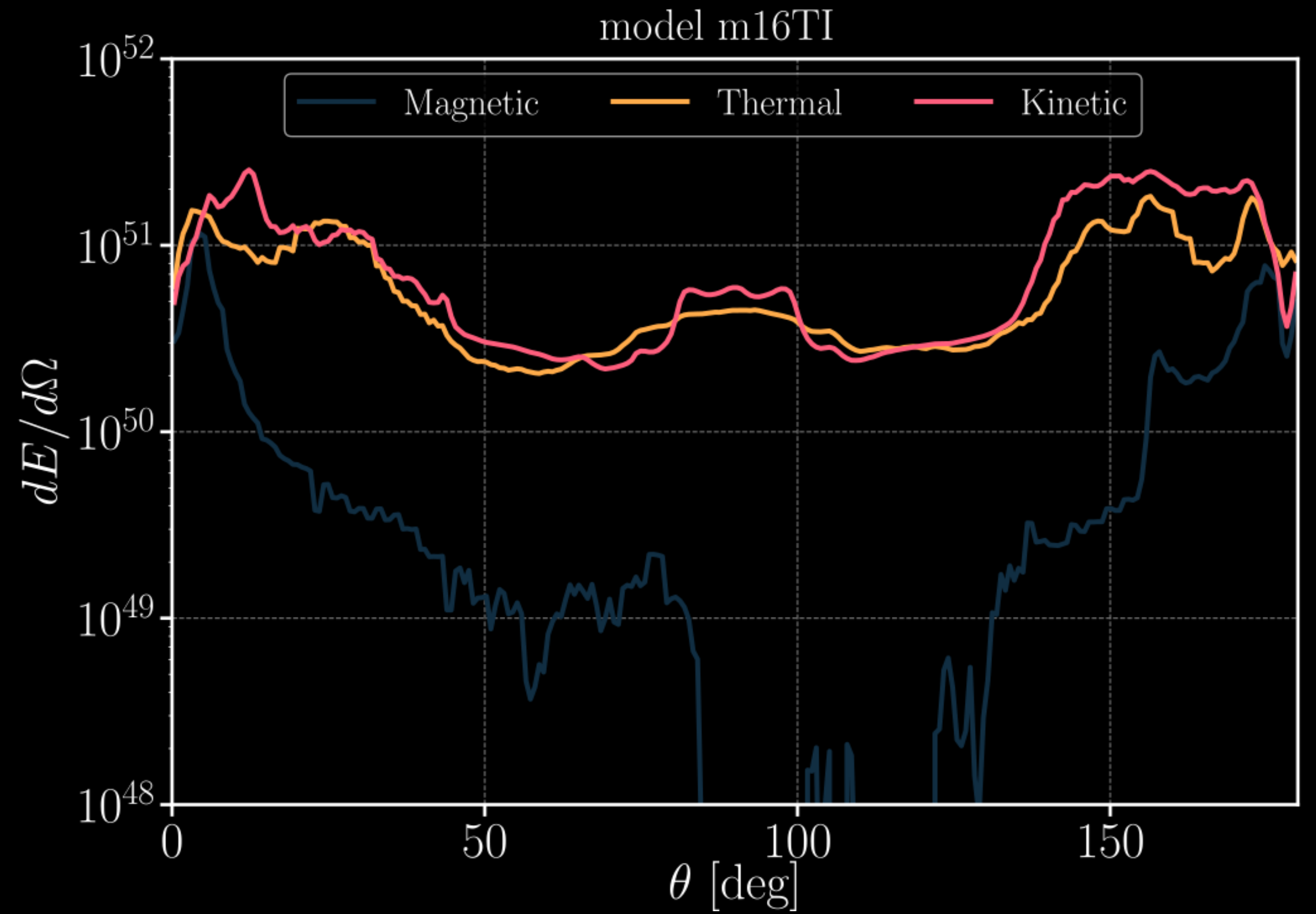
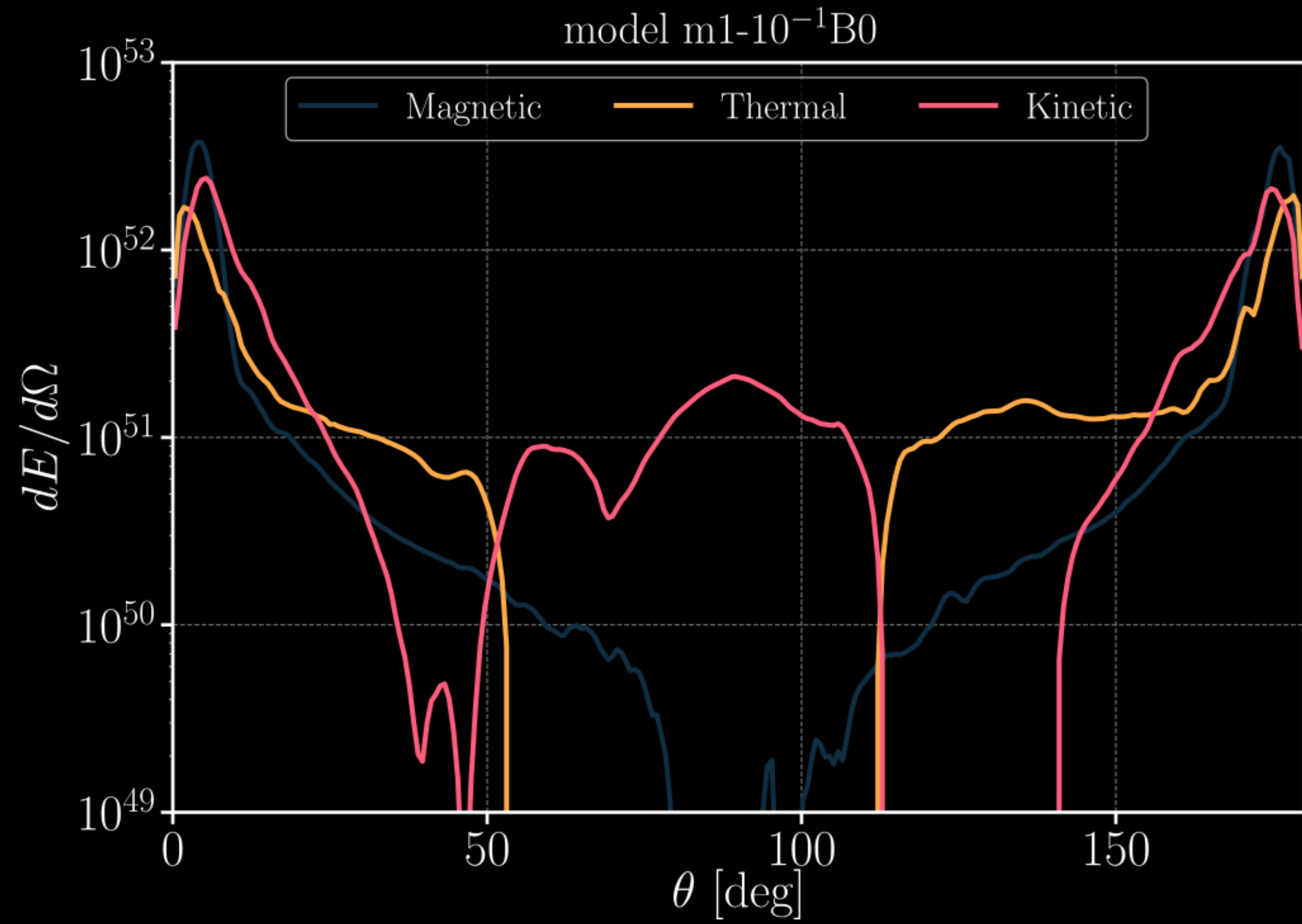


Successful jets

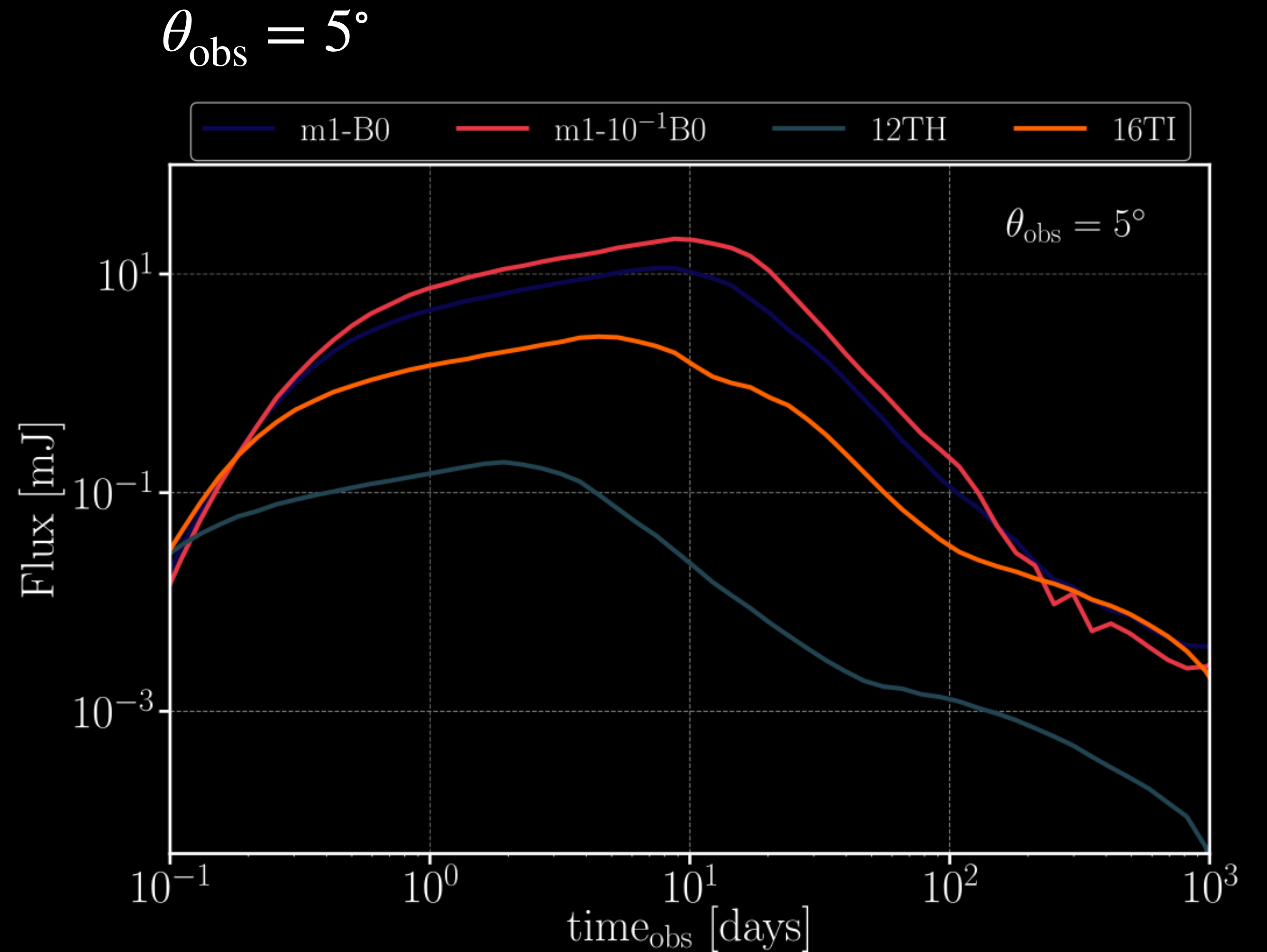
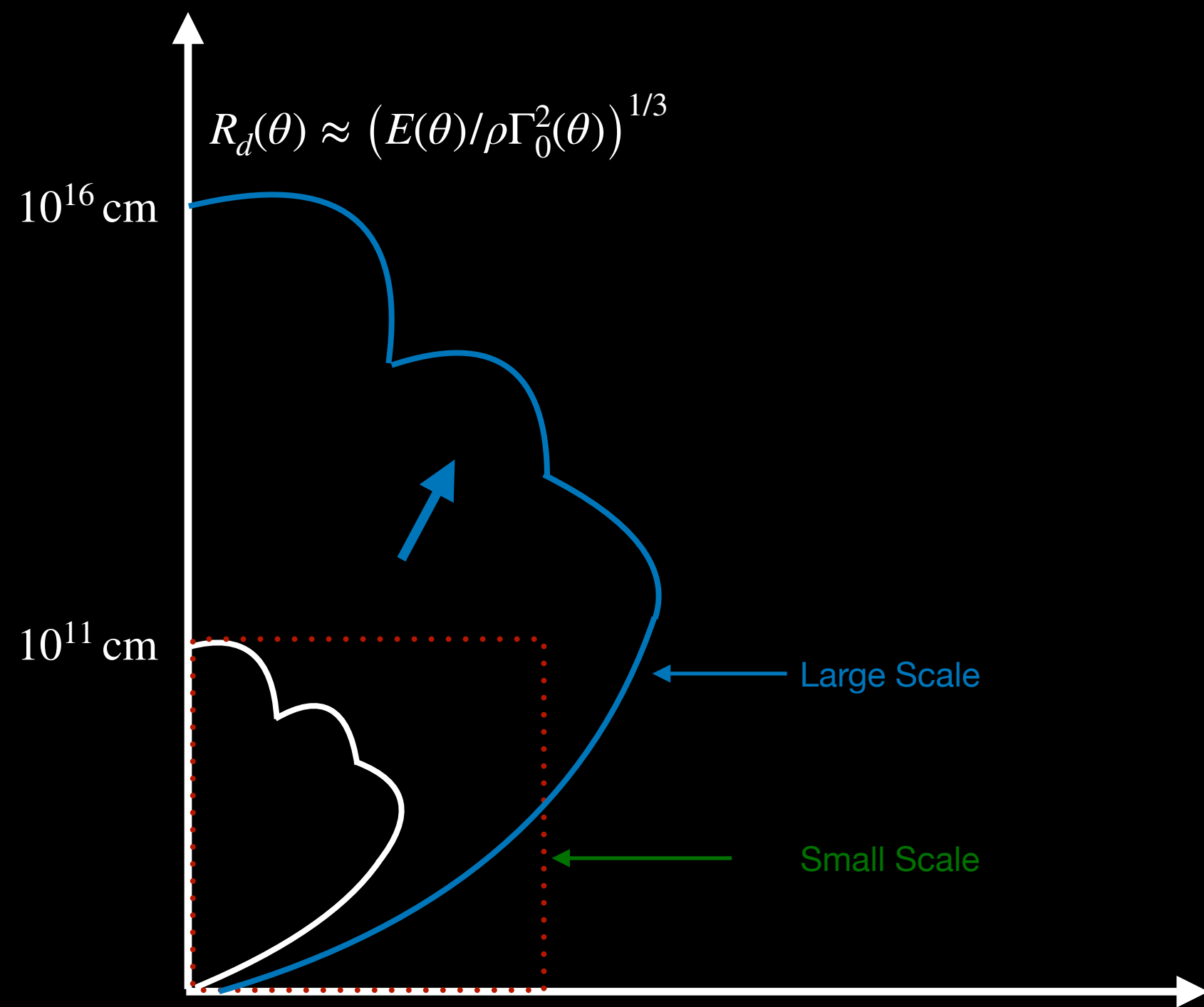


Model	$\theta_{j,50}$ [°] $\sigma > 1$	$\theta_{j,R_{\star}}$ [°] $\sigma > 1$	$\Gamma u > 2$
m1-B0	8.6	4.5	8.4
m1- 10^{-1} B0	6.4	6.6	8.7
m1- 10^{-2} B0	6.7	2.6	5.2
16TI	4.9	8.4	10.6
12TH	5.8	4.6	7.5

Jet structure

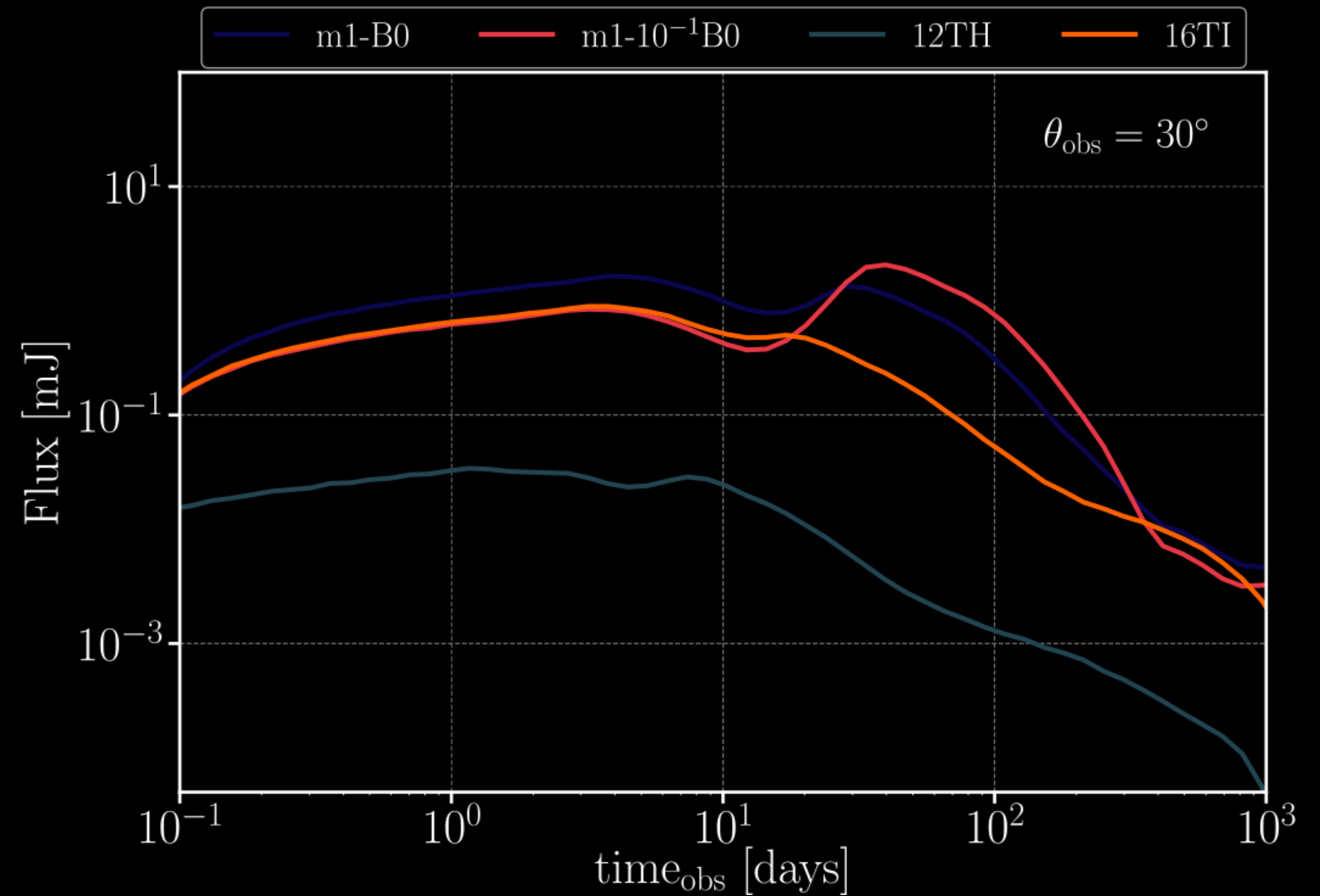
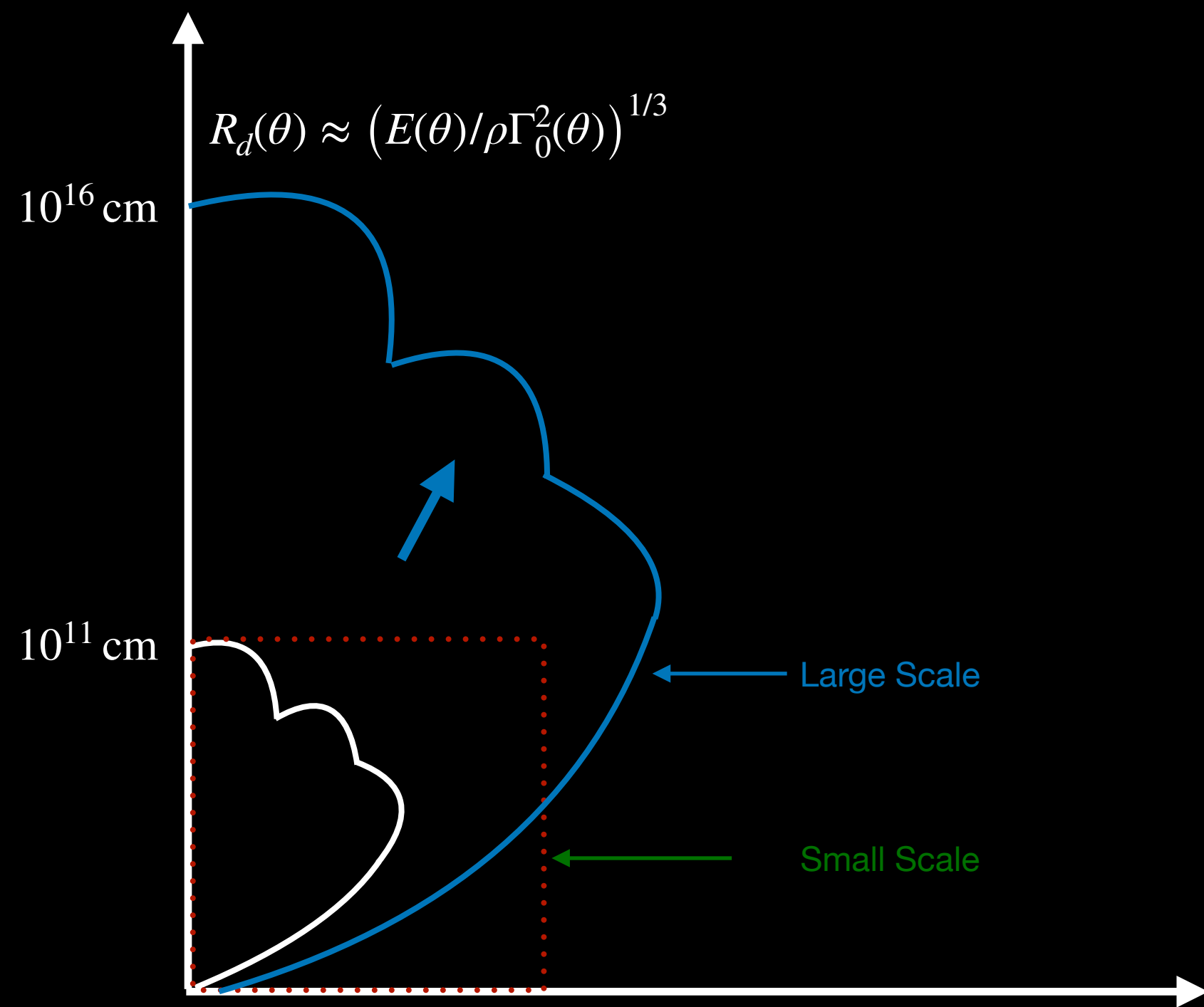


Afterglow estimation from jet structure at 3 GHz



Afterglow estimation from jet structure at 3 GHz

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



Summary

- Jets are launched only when a dipolar field with peak strength $B_0 > 10^{12}$ G. It produces a magnetic flux $> 10^{25}$ Mx.
- We obtained jet luminosities: 10^{50} - 10^{53} .
- Strongly magnetized models develop a narrow, highly magnetized core surrounded by moderately magnetized wings.
- Hybrid field geometries yield a quasi-cylindrical outflow described as a failed jet.
- The progenitor star impacts the final structure, morphology and emission of the jet.

Limitations:

- Only GR-MHD evolution in 2D, for example, hybrid 3d simulations Gottlieb 2020;2022;2024
- Not radiative transfer, or neutrino leakage. **See Agnieszka Janiuk and Joseph Saji's** project about improvements on these methods.
- Evolution of BH spin, **see Piotr Plonka's** project improvements on this approximation.

Dziękuję bardzo - ¡Gracias! - Thank you!

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