

GRB jets with high-variability as sources of gravitational waves

Gerardo Urrutia

geurruti@ucsc.edu

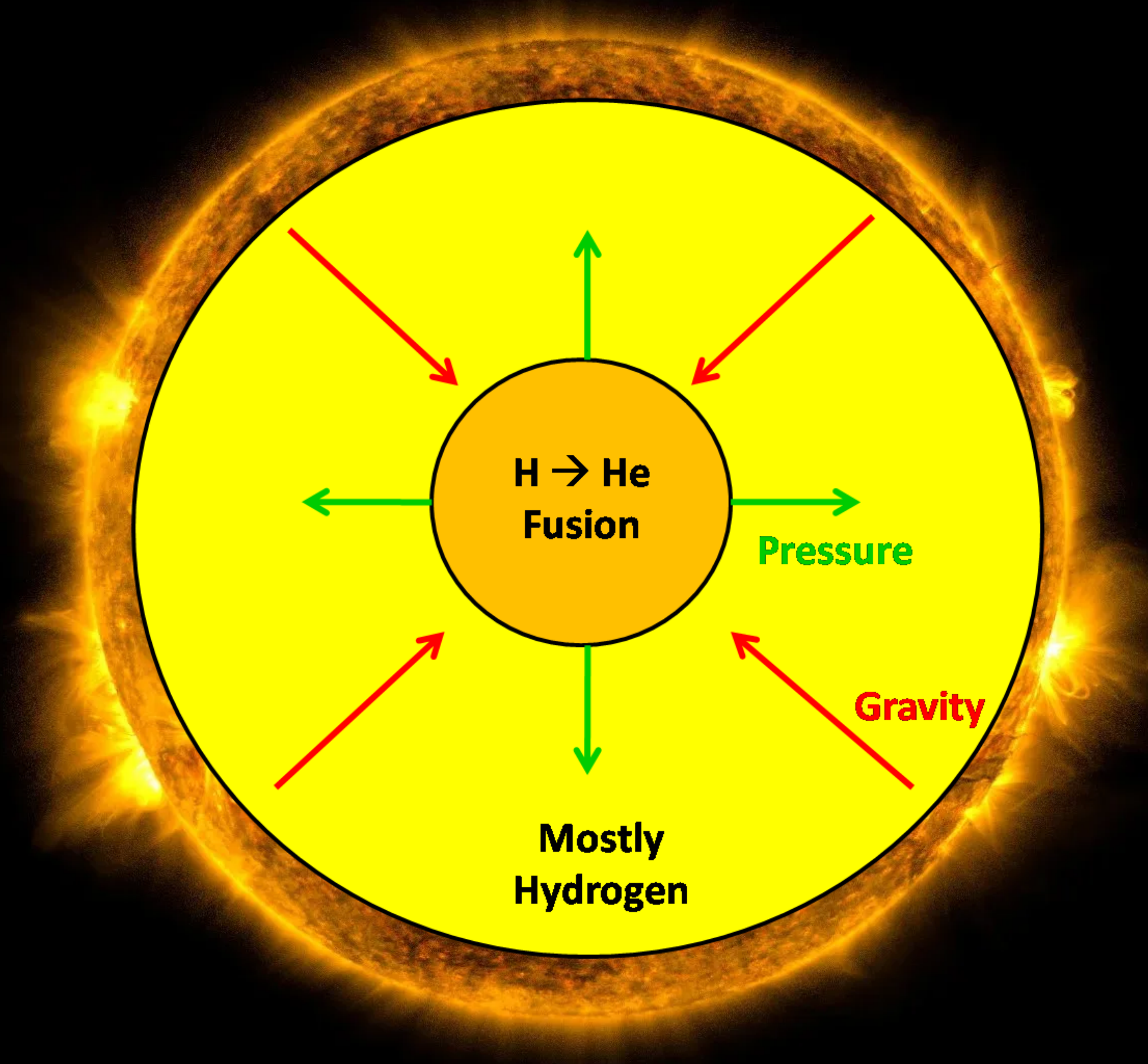
A. Janiuk (CFT, Poland), F. De Colle (UNAM, Mexico), E. Ramirez-Ruiz (UCSC, USA) and C. Moreno (UdG, Mexico)

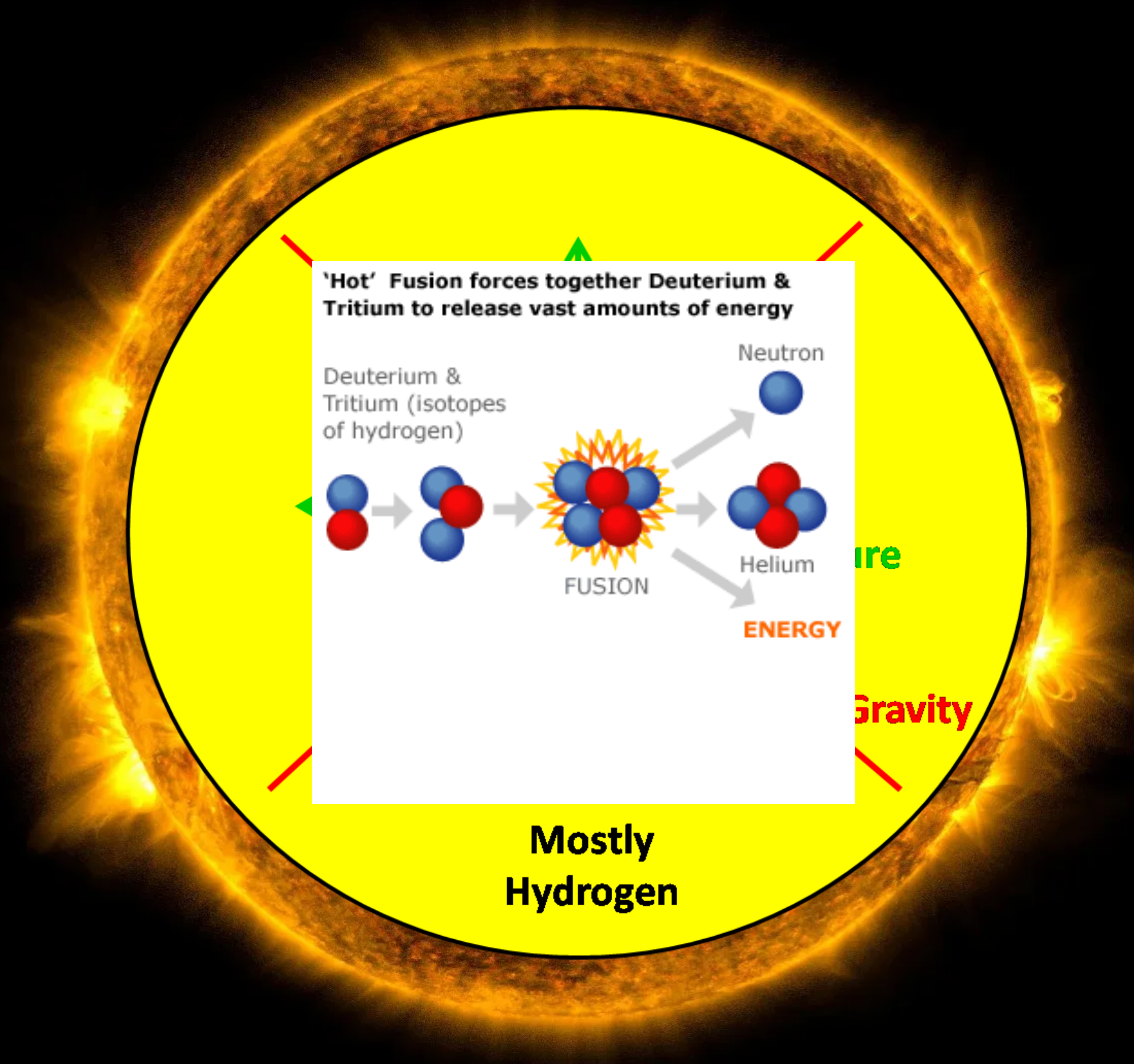
XII POTOR Conference, Poznan, Poland, August 2026



UNIVERSITY OF CALIFORNIA
SANTA CRUZ

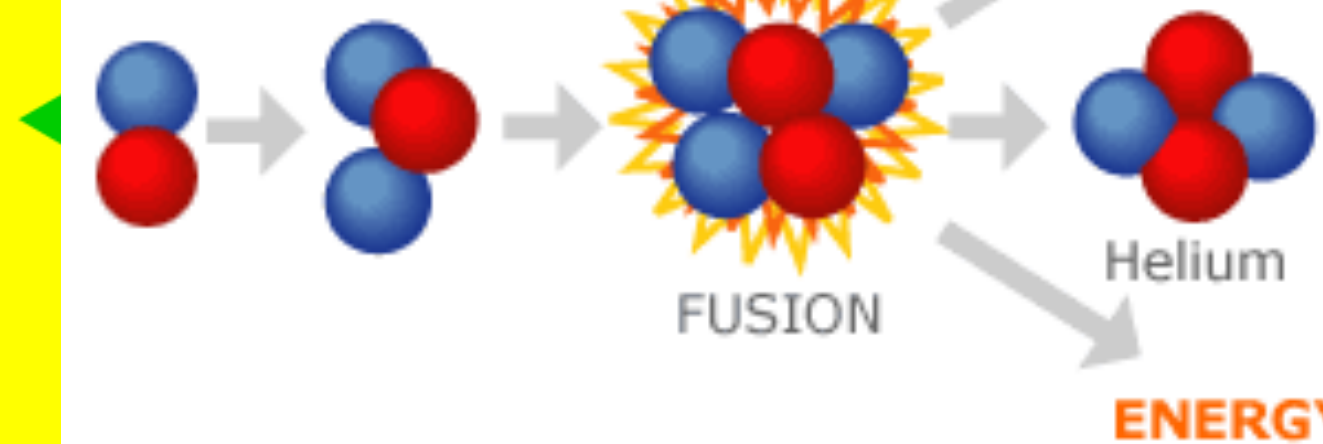
**Collapsars are multi-messenger
sources**





'Hot' Fusion forces together Deuterium & Tritium to release vast amounts of energy

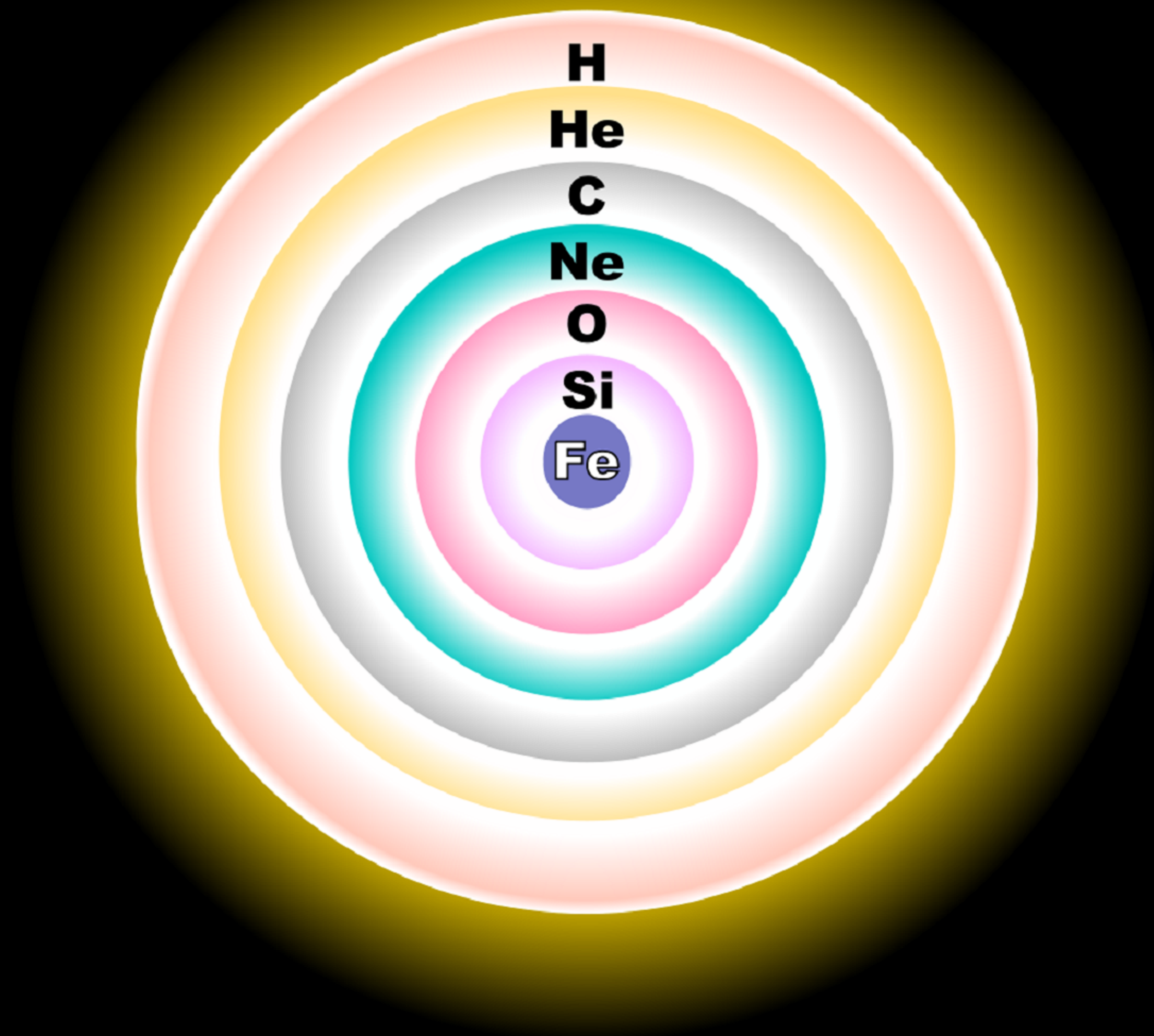
Deuterium & Tritium (isotopes of hydrogen)



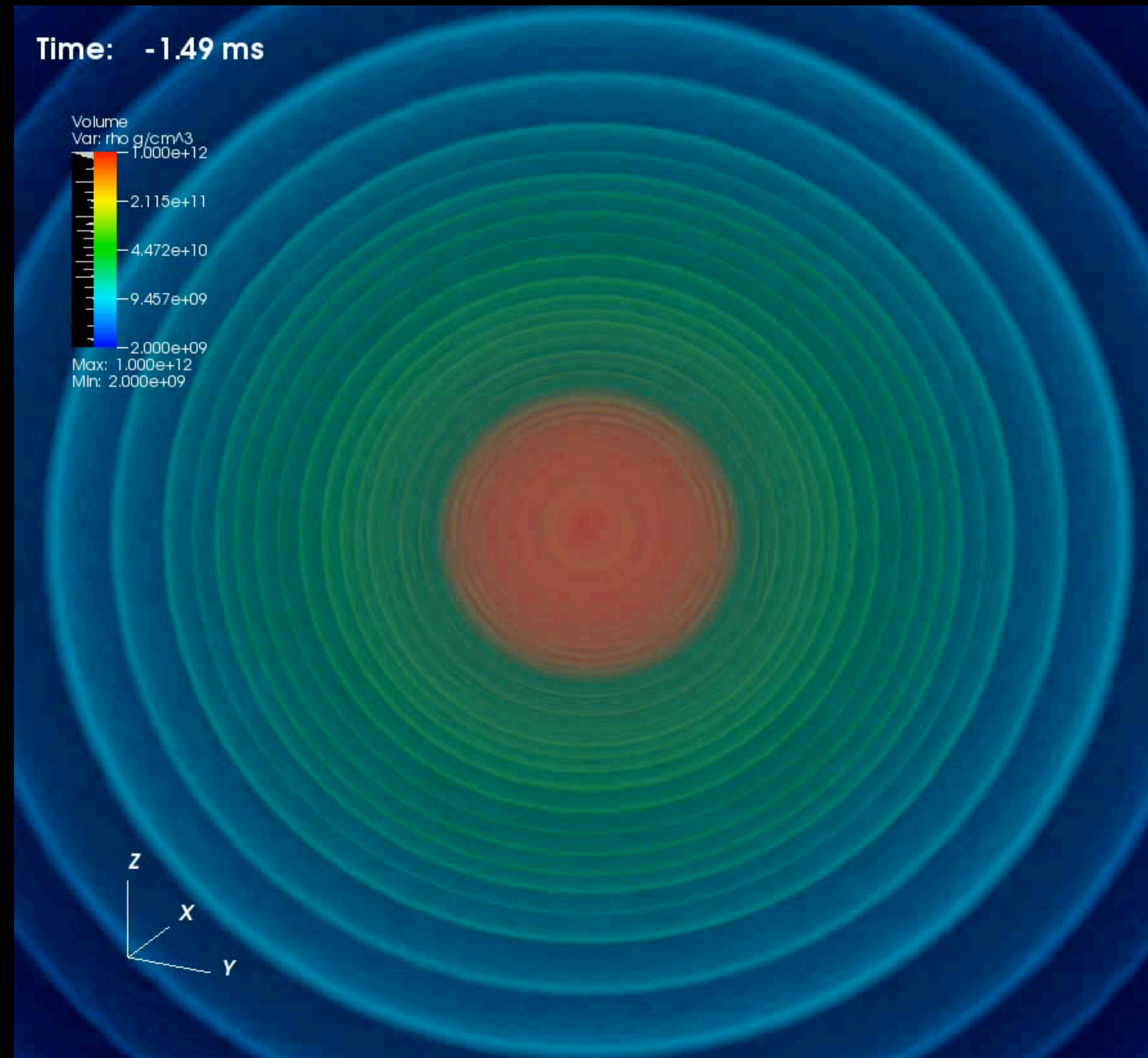
**Mostly
Hydrogen**

Pressure

Gravity

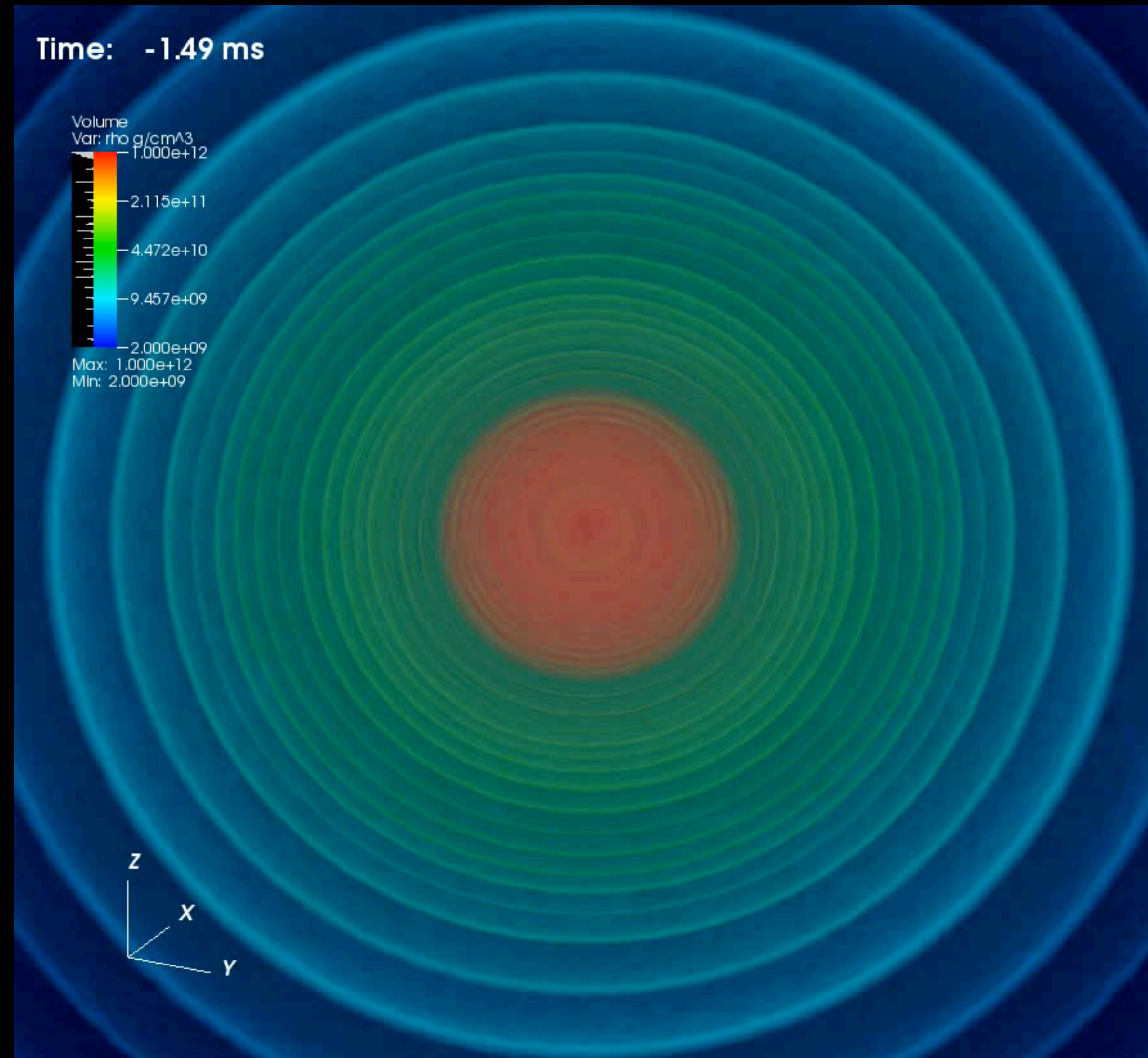


Collapsing star



Simulation & Visualization by Christian Reisswig (Caltech)

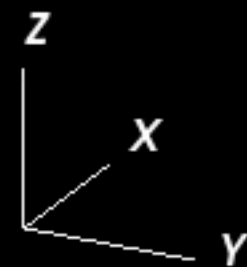
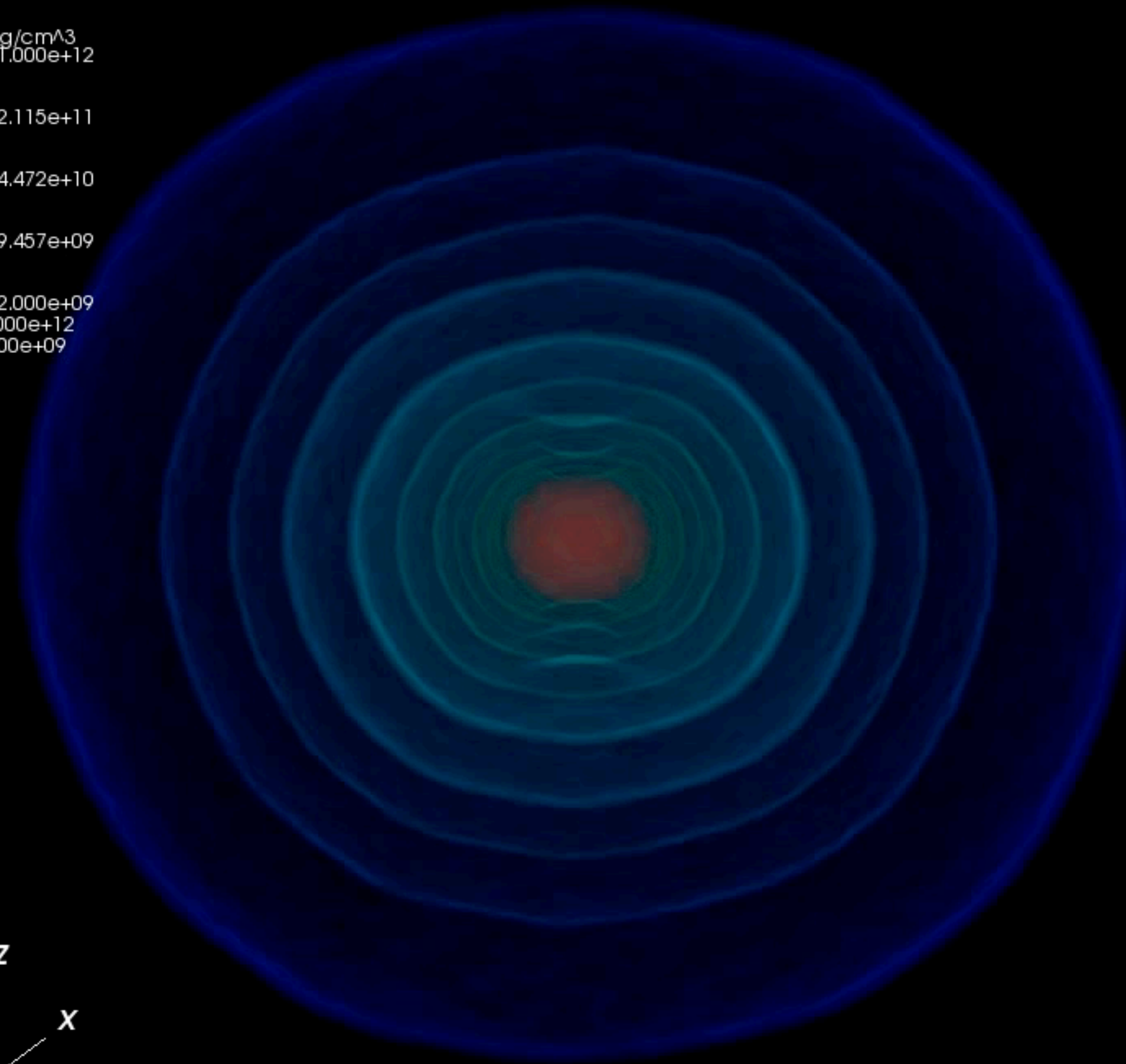
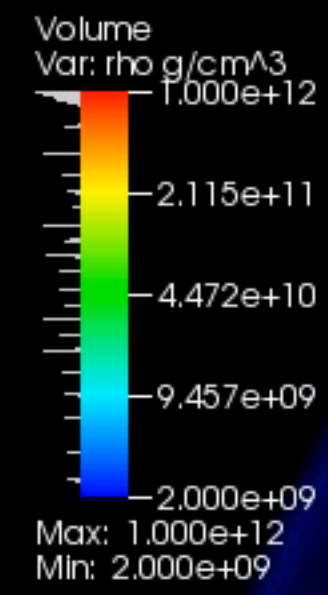
Collapsing star



Simulation & Visualization by Christian Reisswig (Caltech)

Collapsing star

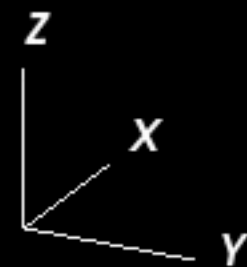
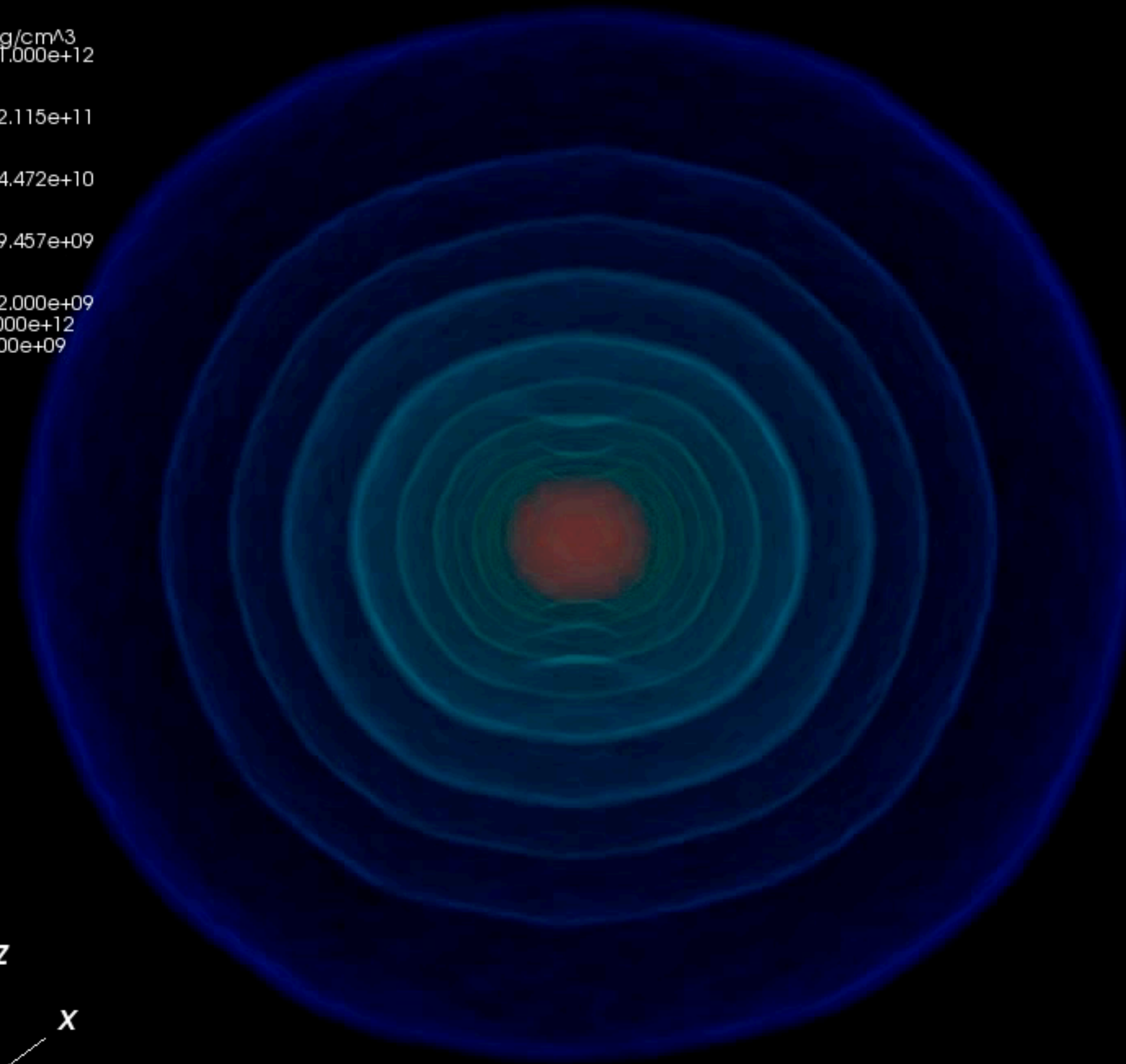
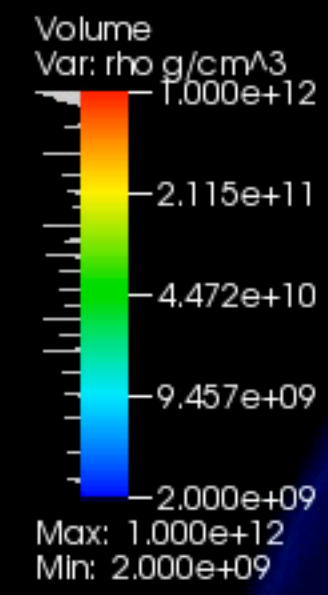
Time: 44.17 ms



Simulation & Visualization by Christian Reisswig (Caltech)

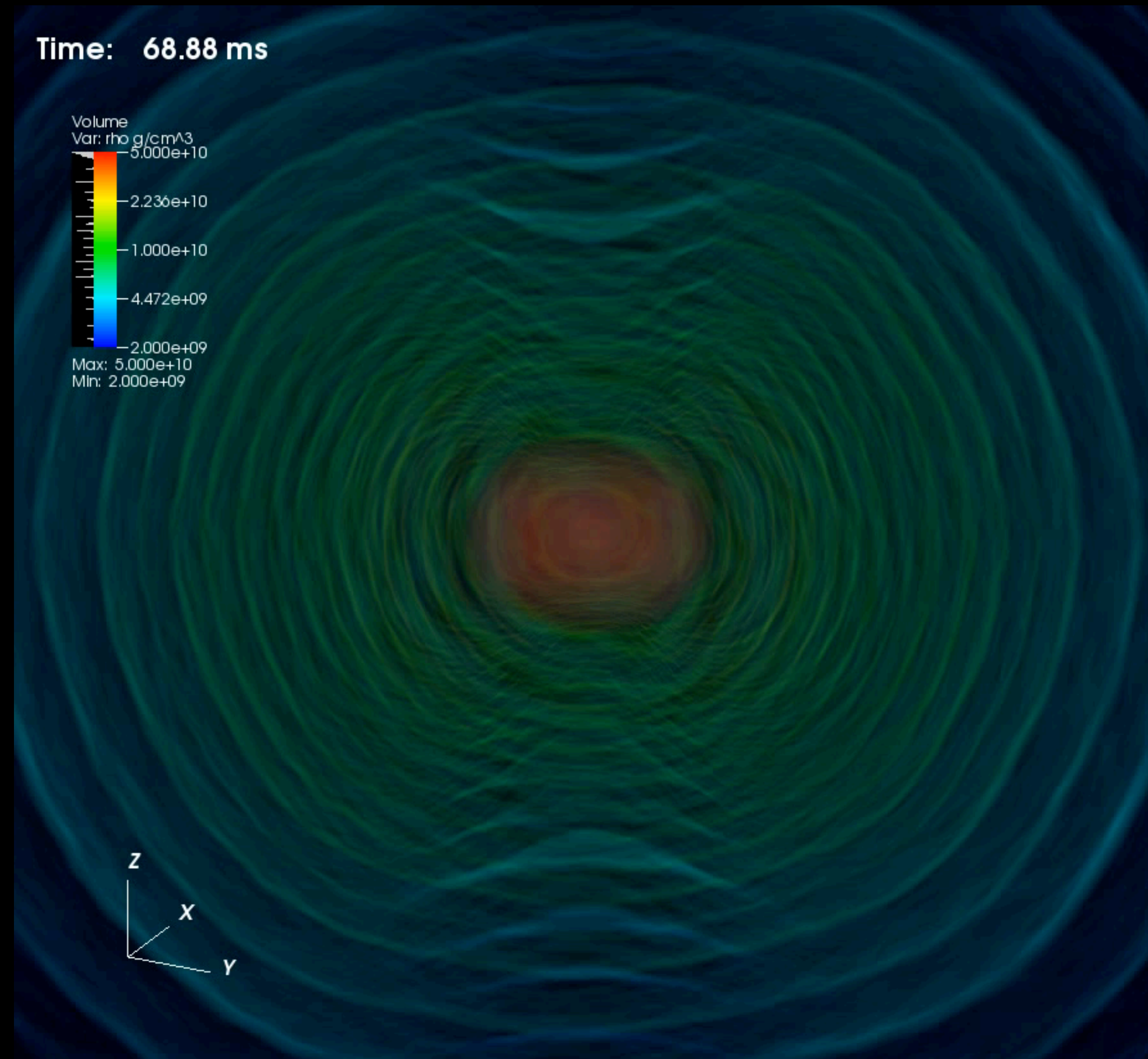
Collapsing star

Time: 44.17 ms



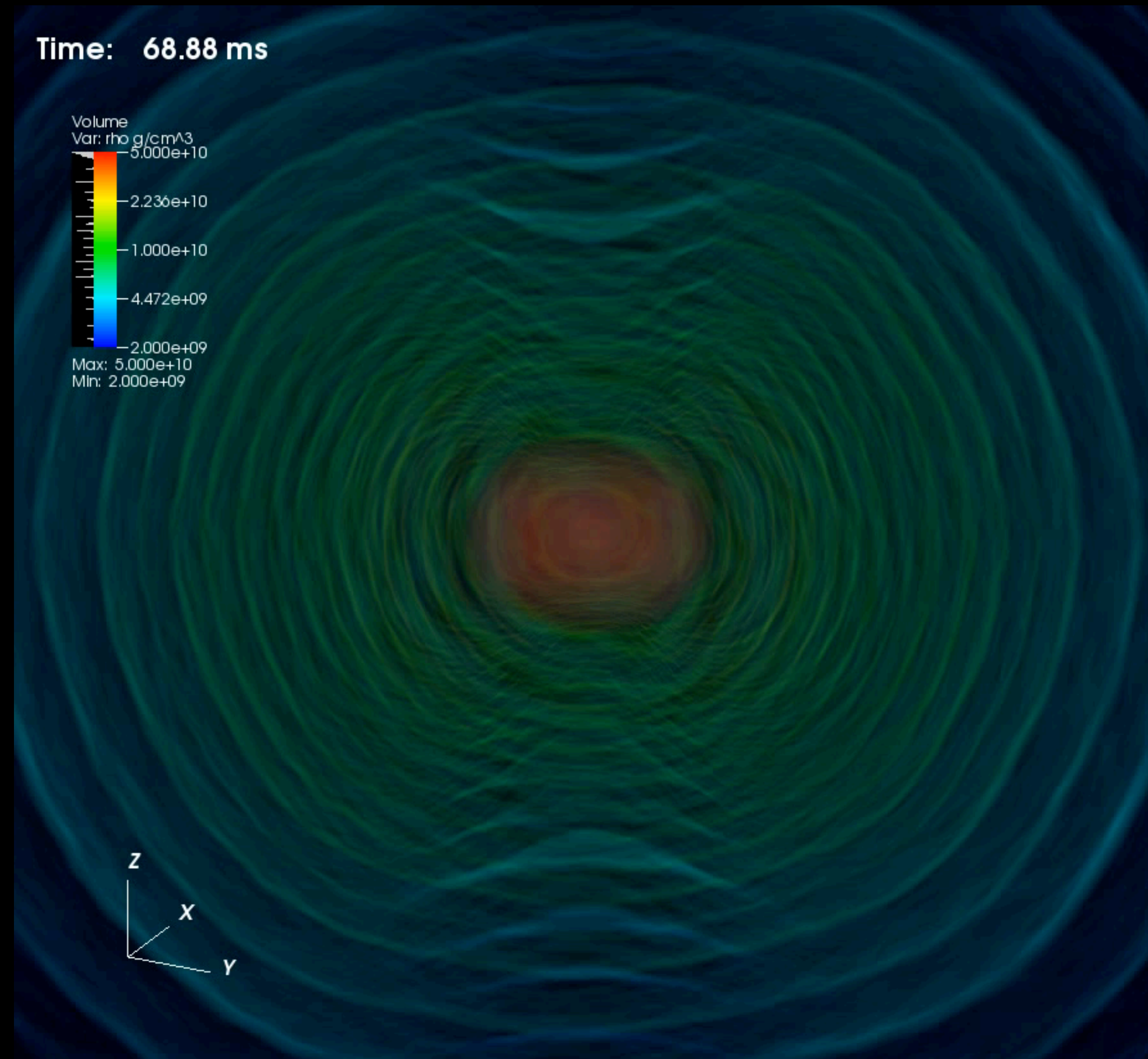
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Collapsing star



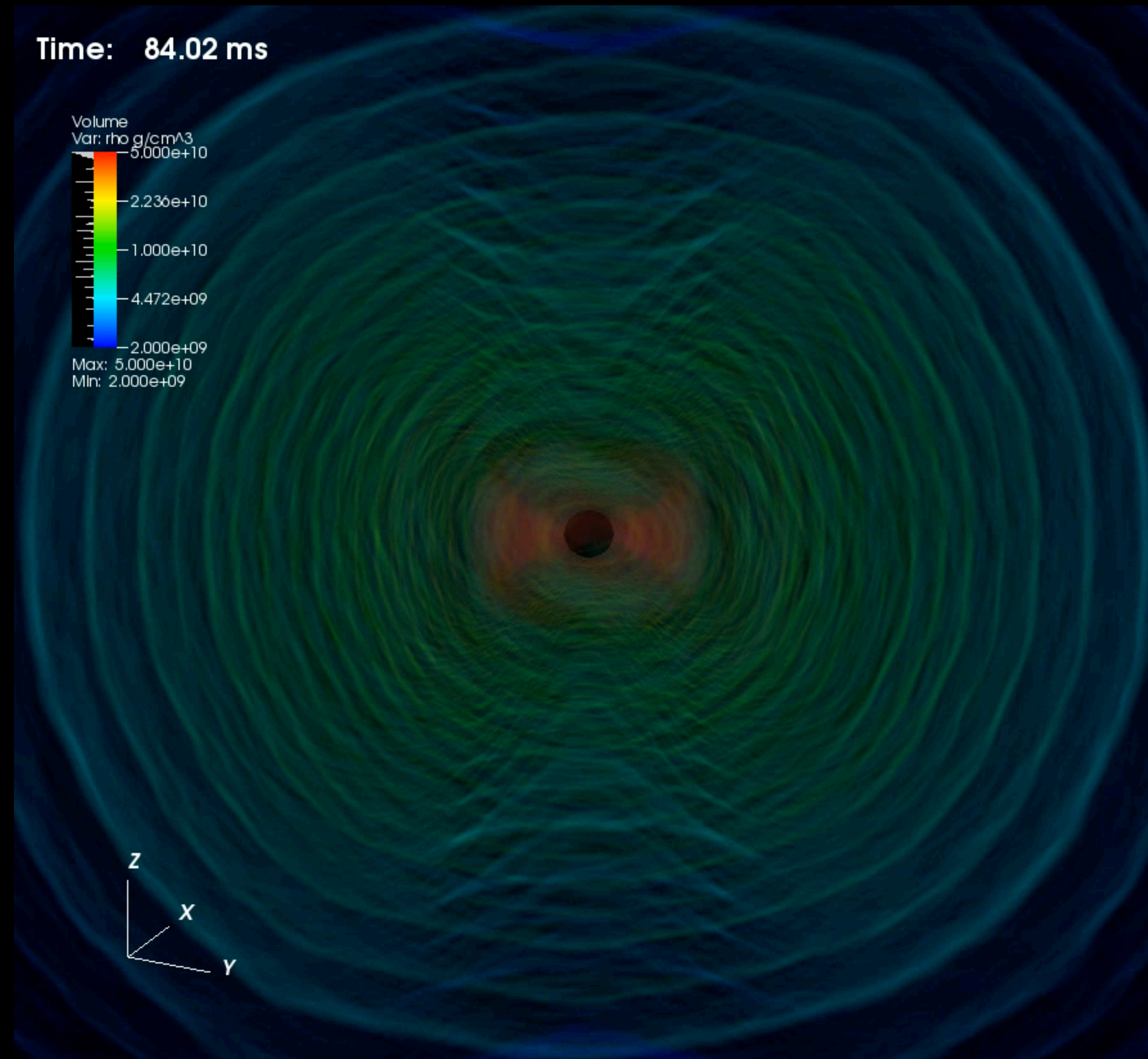
Simulation & Visualization by Christian Reisswig (Caltech)

Collapsing star



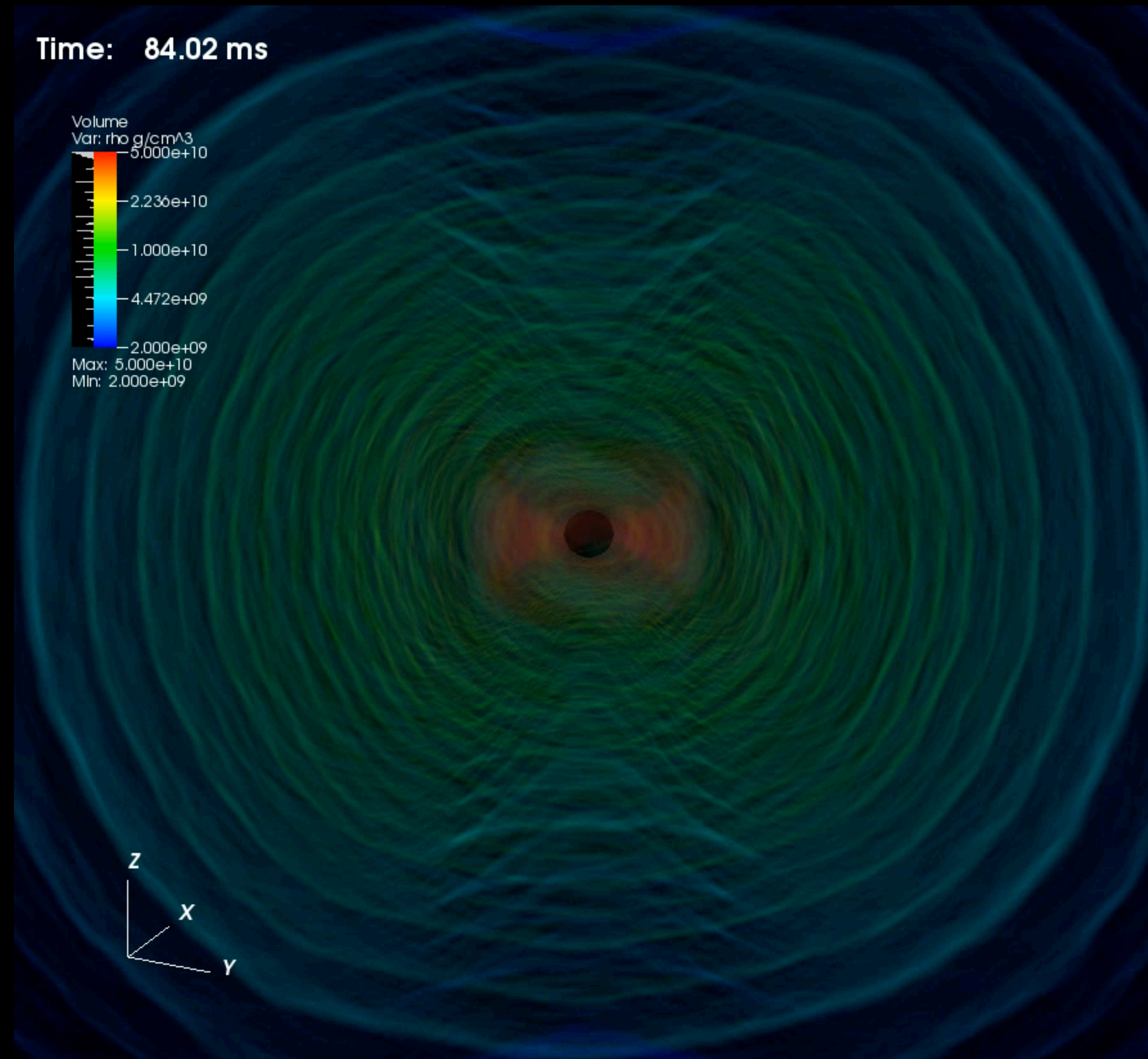
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Collapsing star



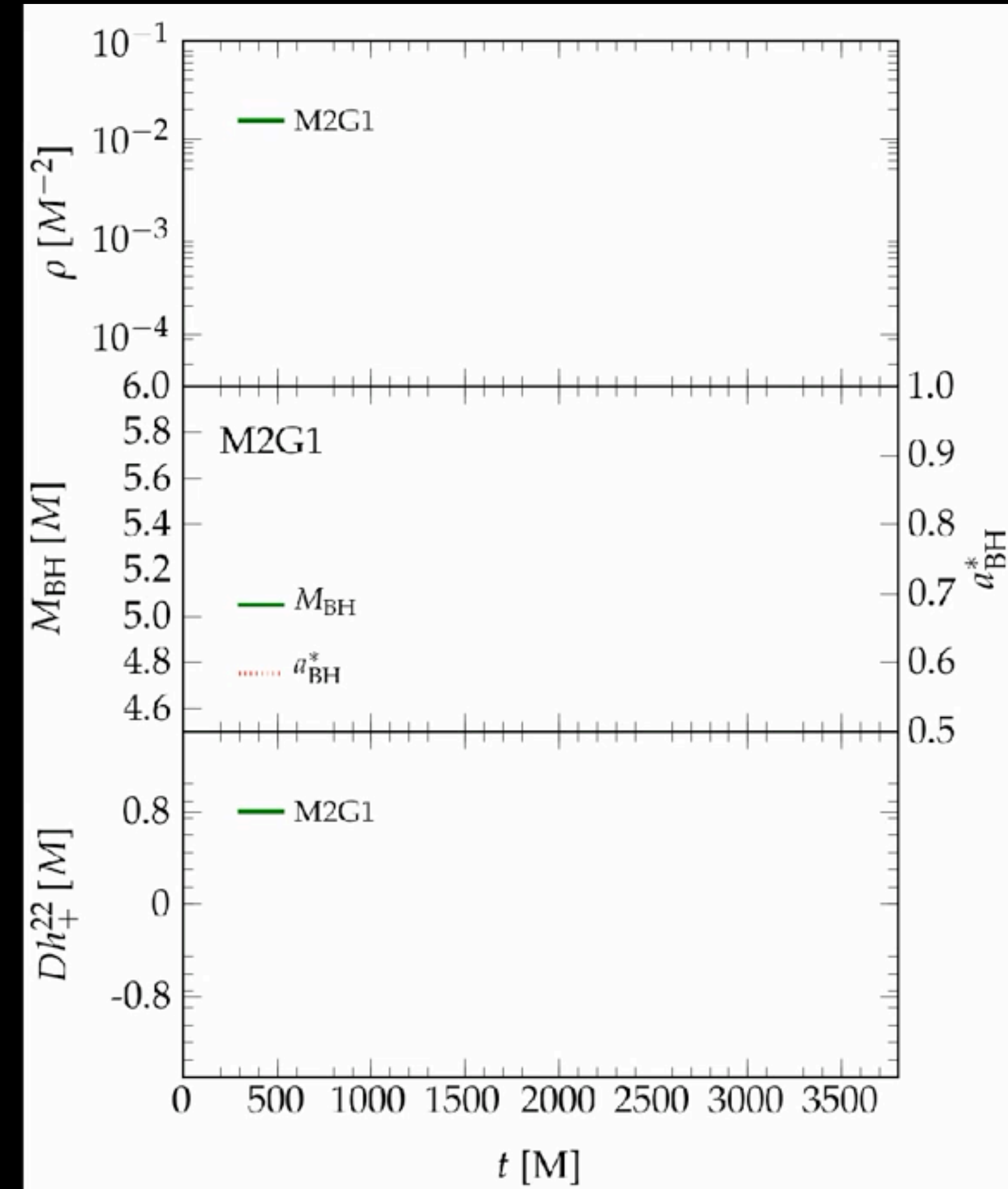
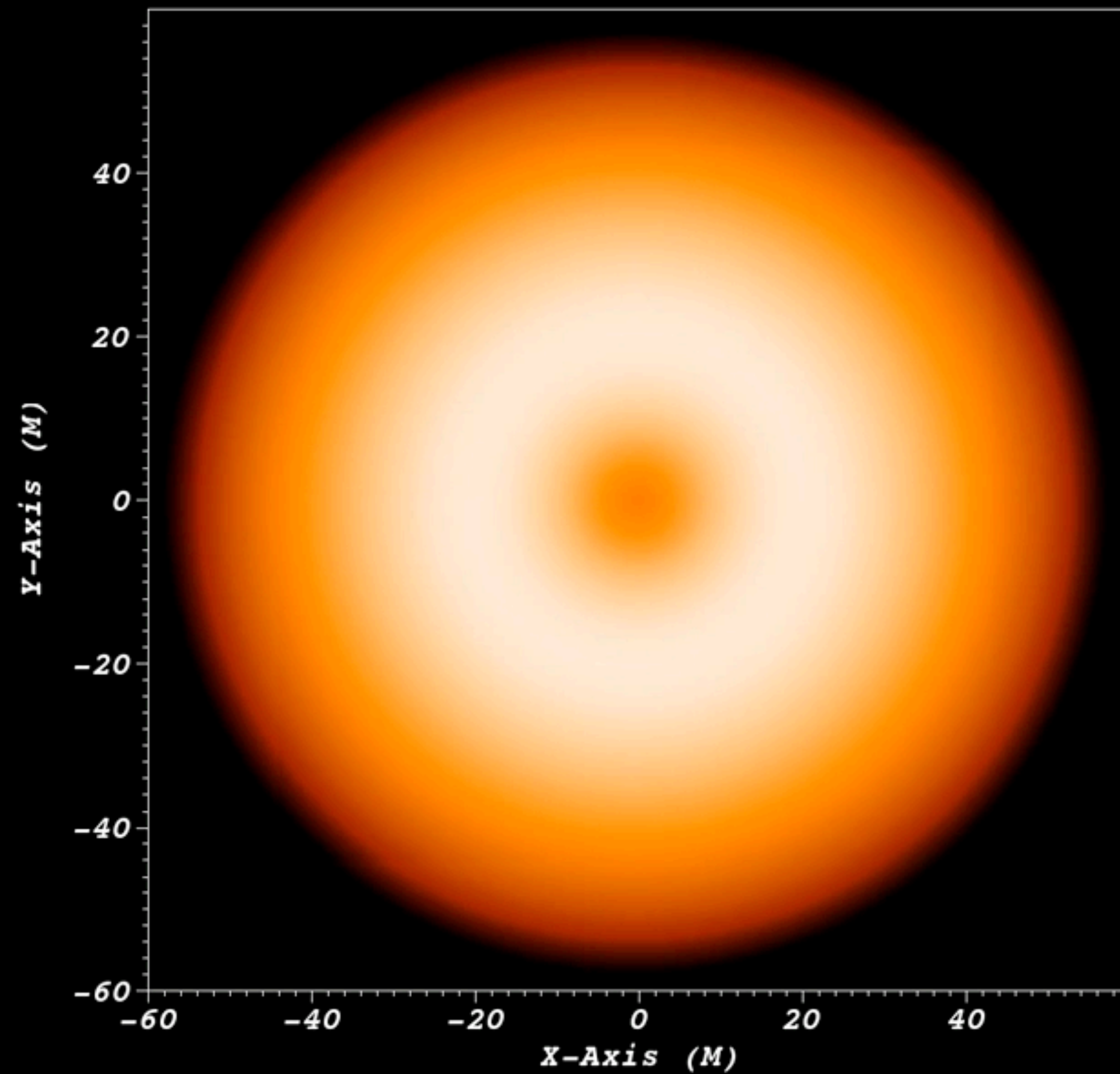
Simulation & Visualization by Christian Reisswig (Caltech)

Collapsing star



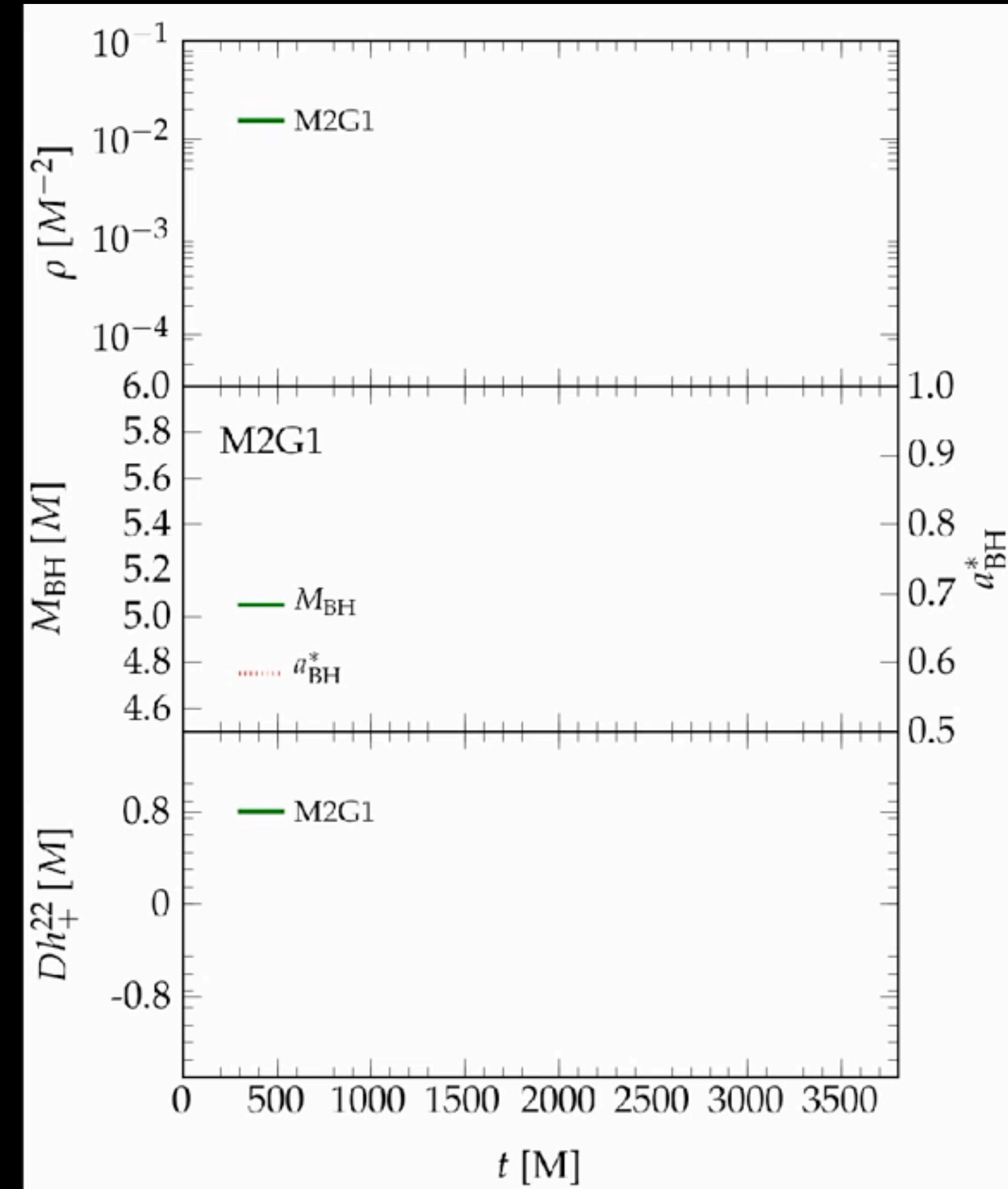
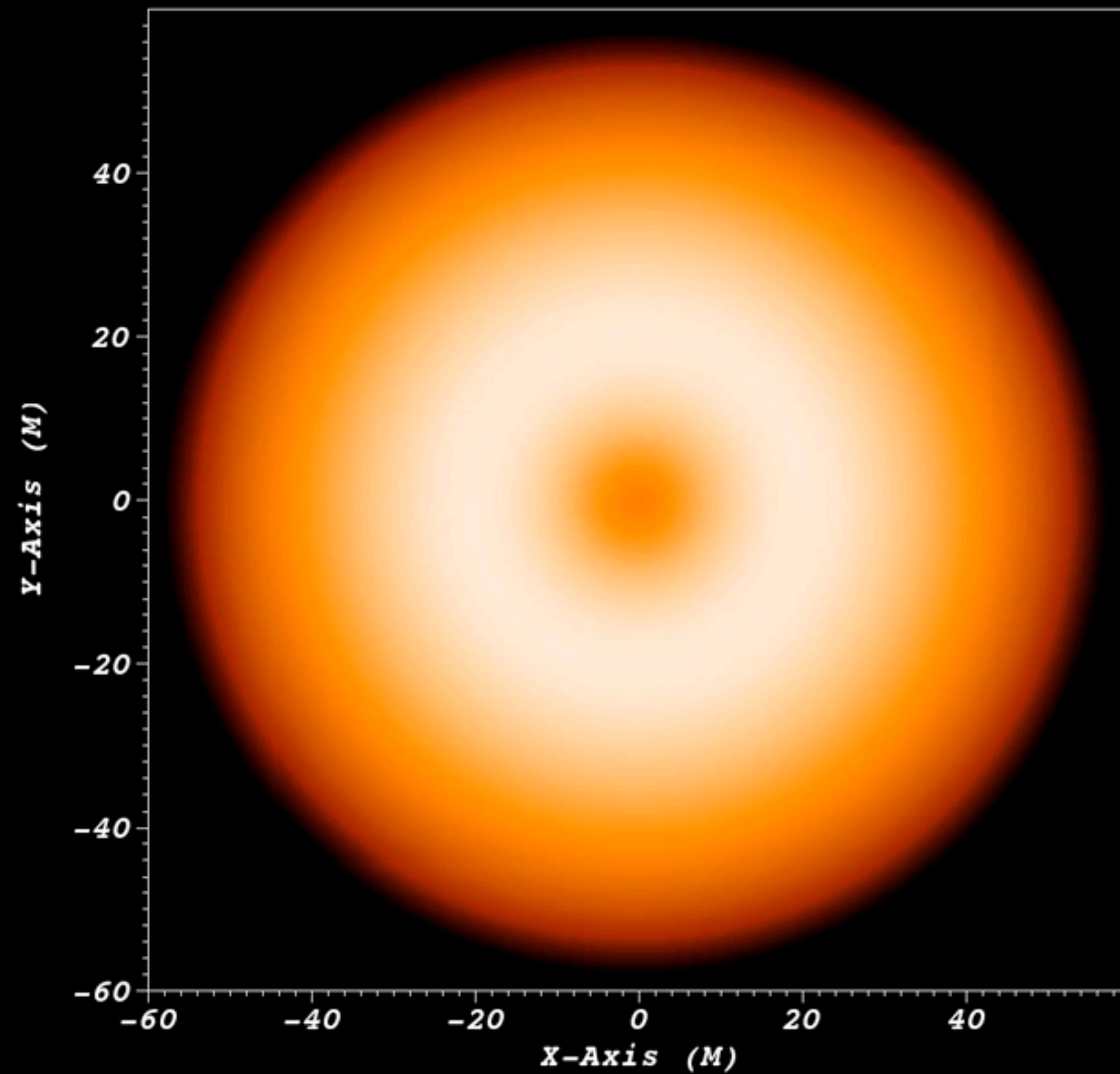
Simulation & Visualization by Christian Reisswig (Caltech)

Collapse of a rapidly differentially rotating supermassive star with an initial $m=1$ density perturbation



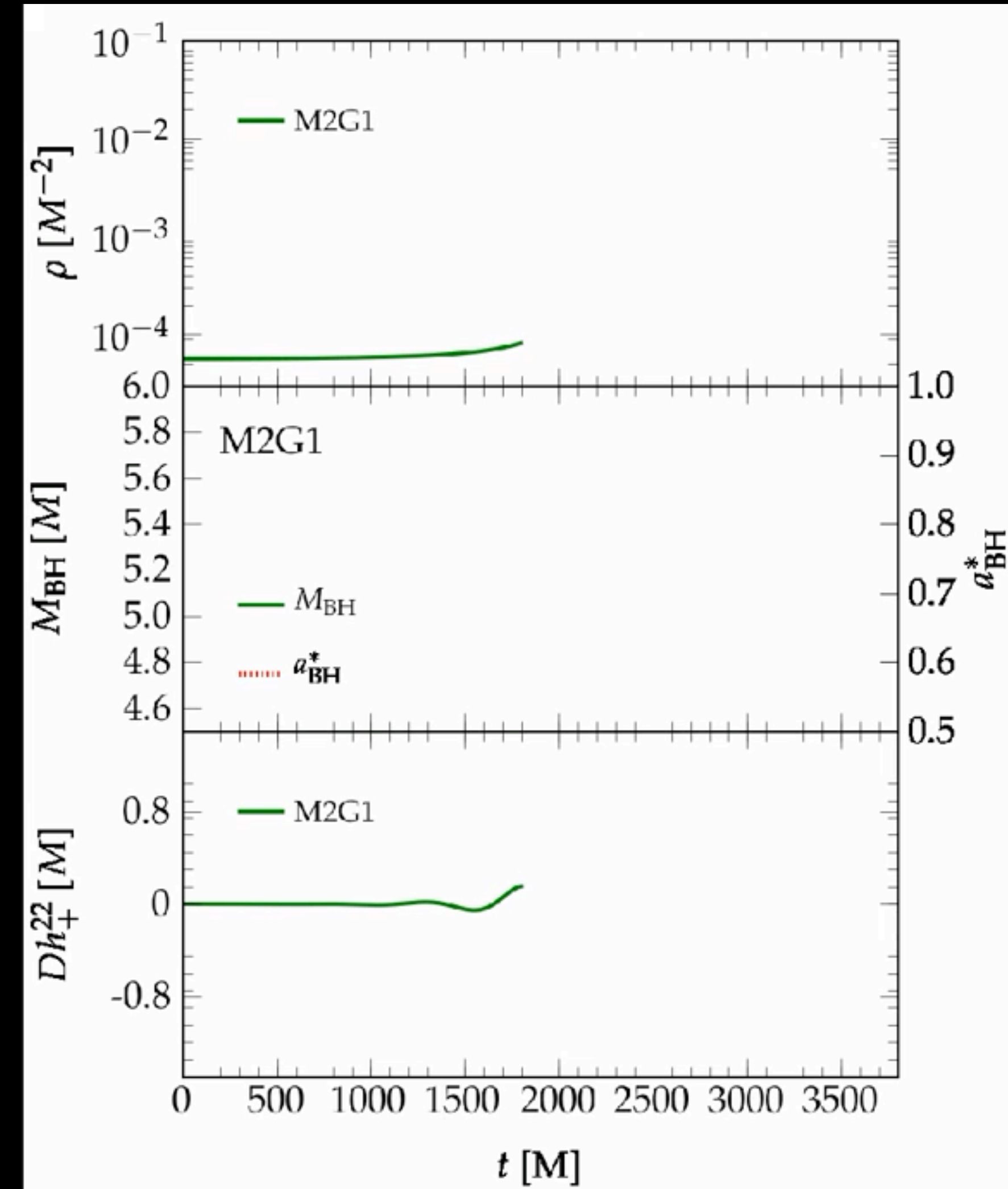
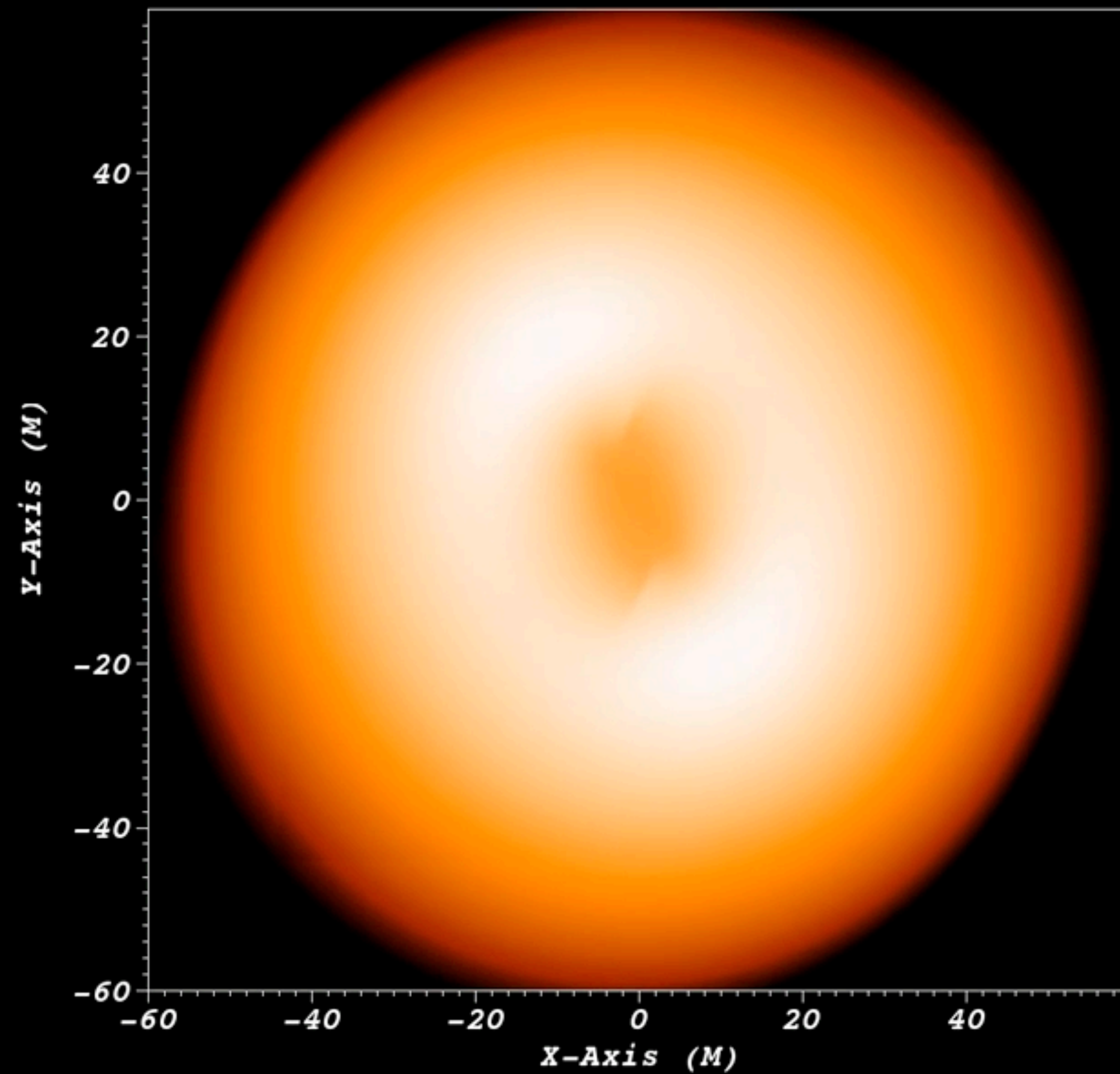
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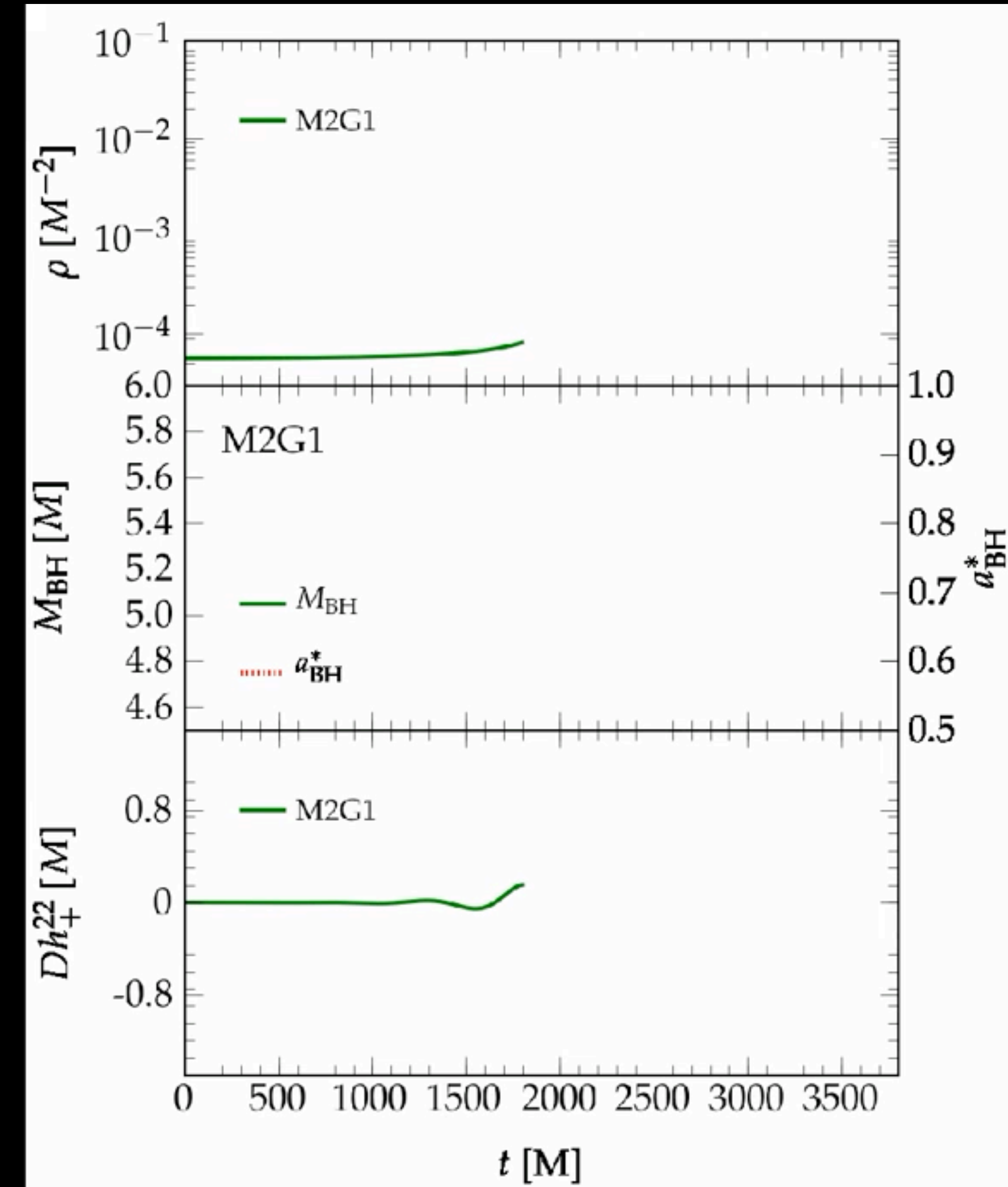
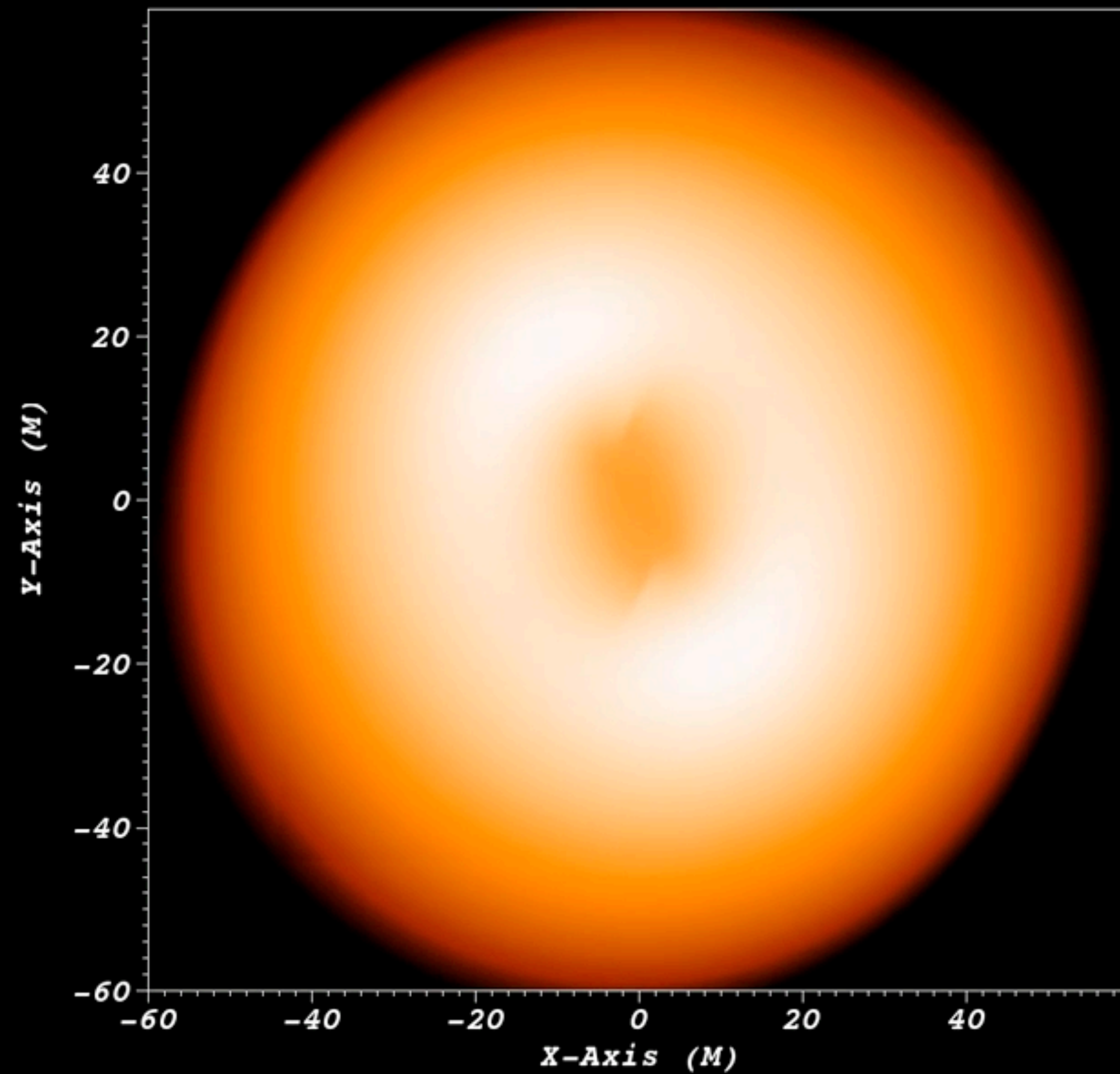
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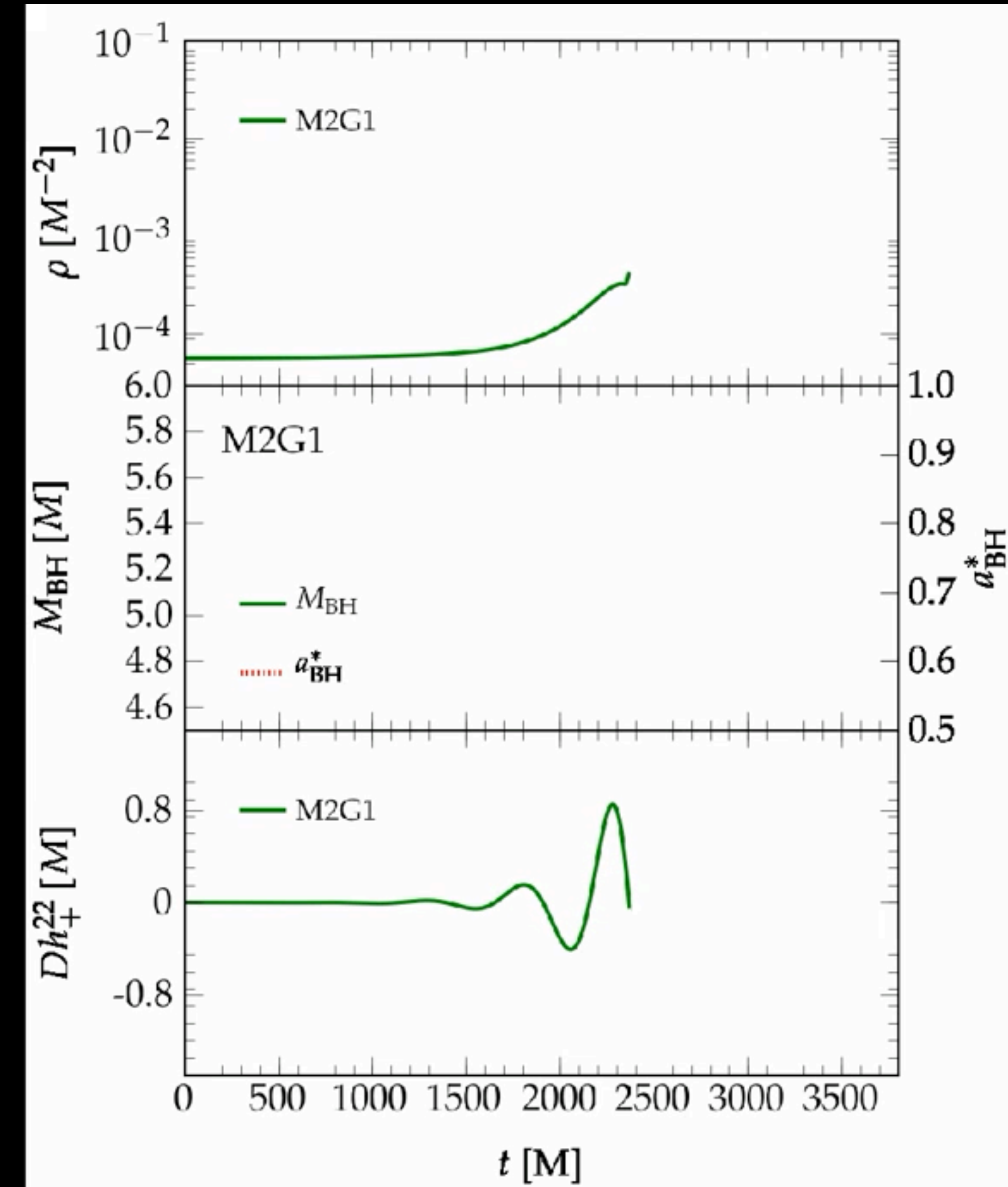
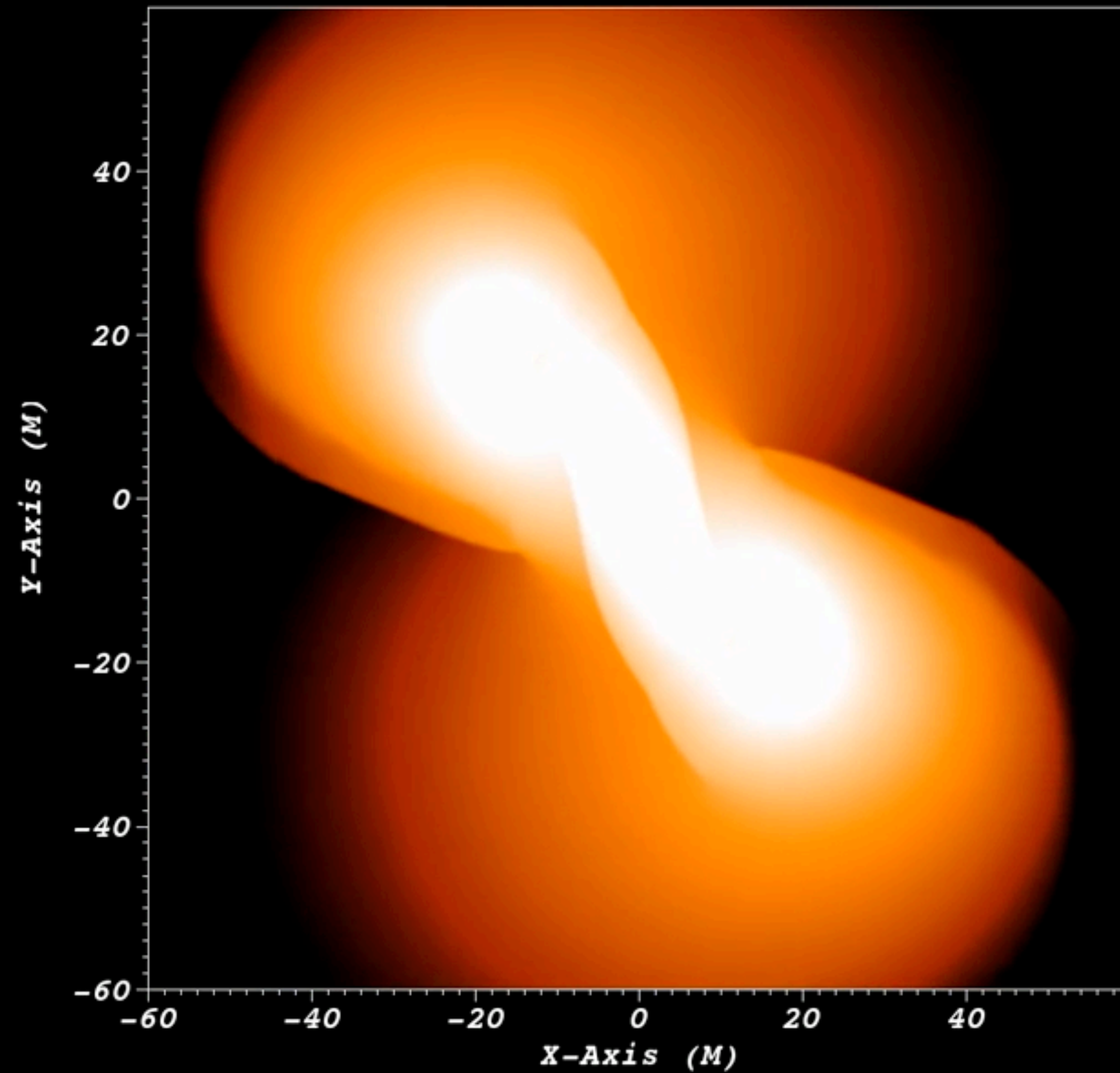
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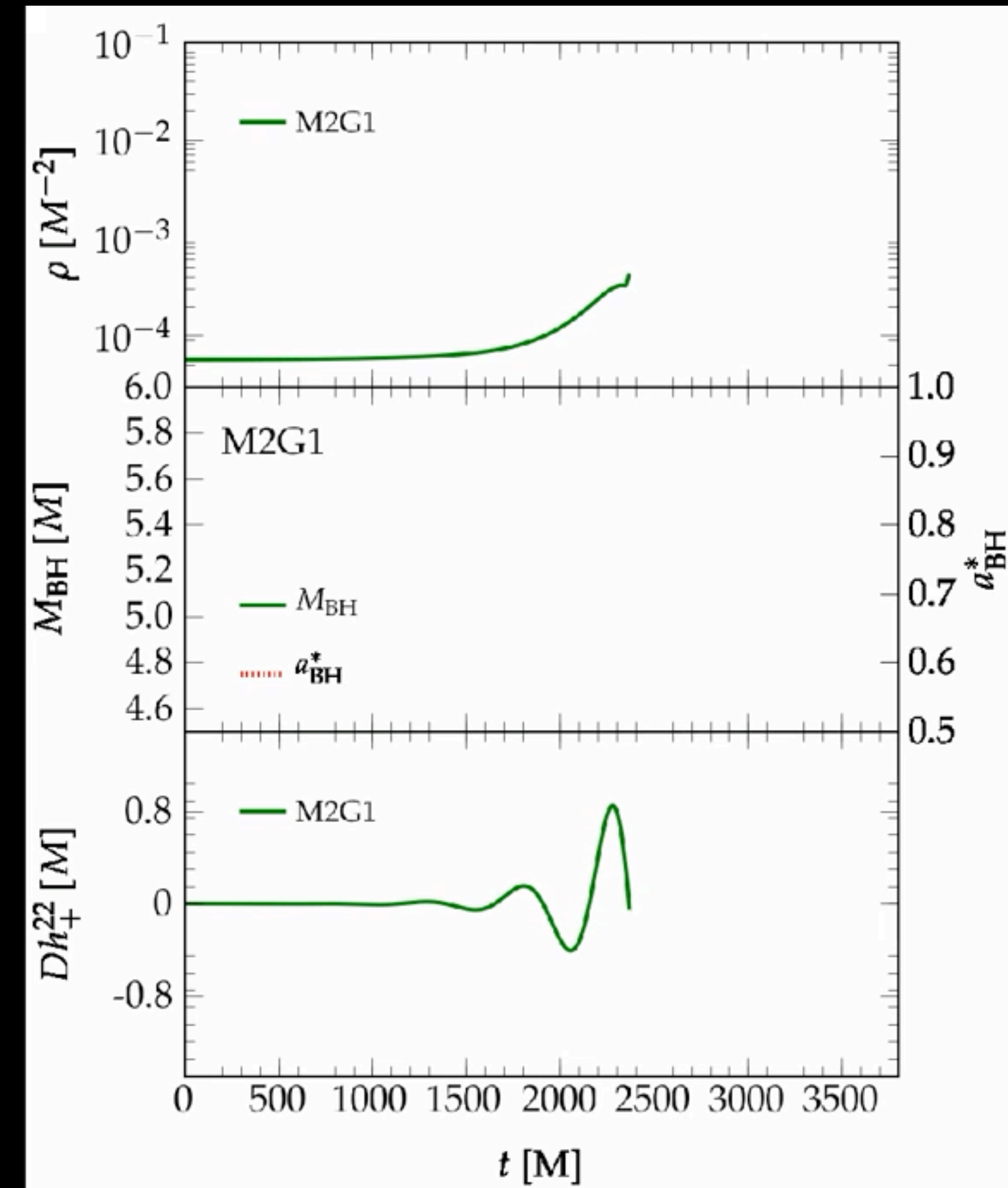
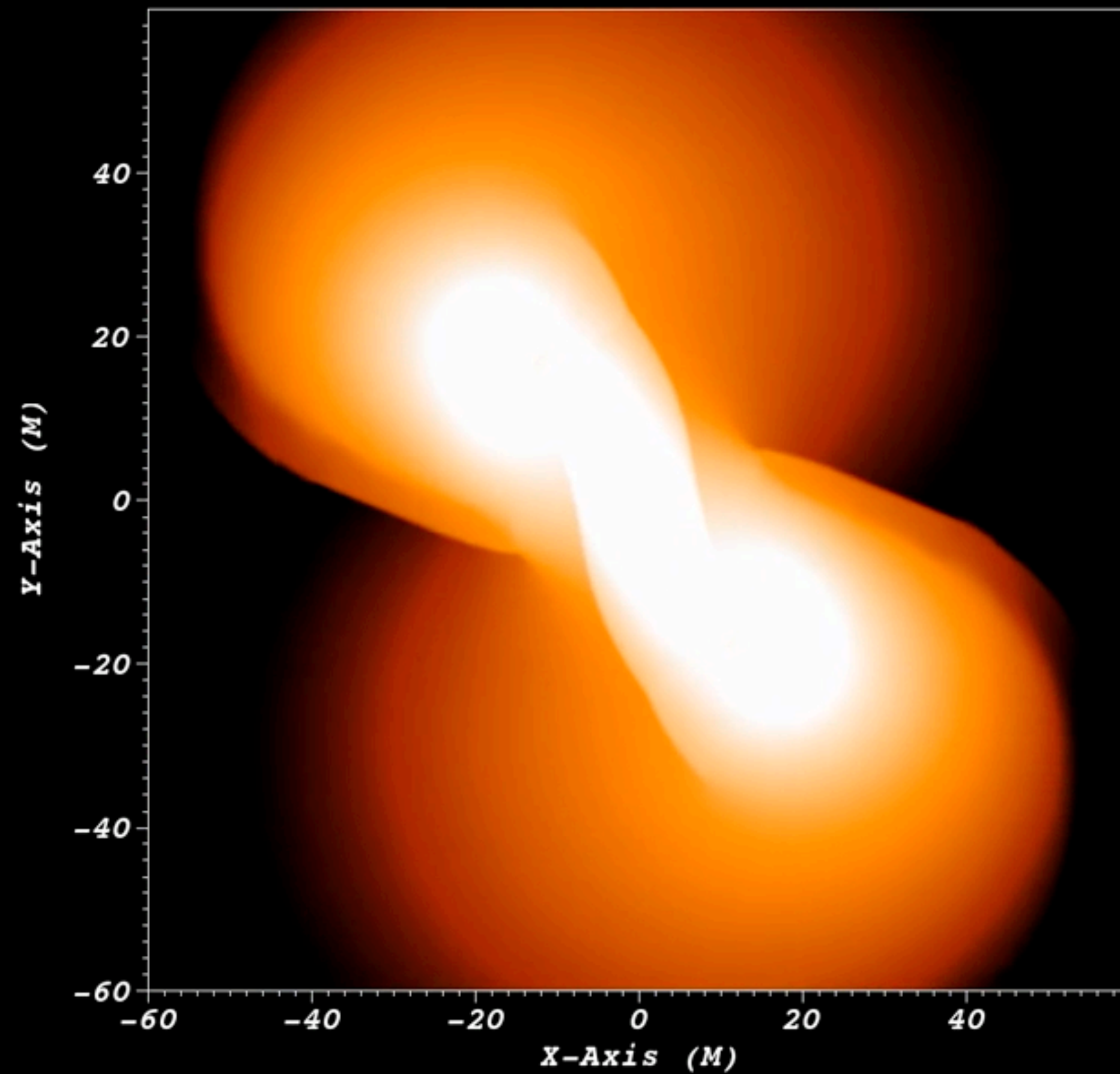
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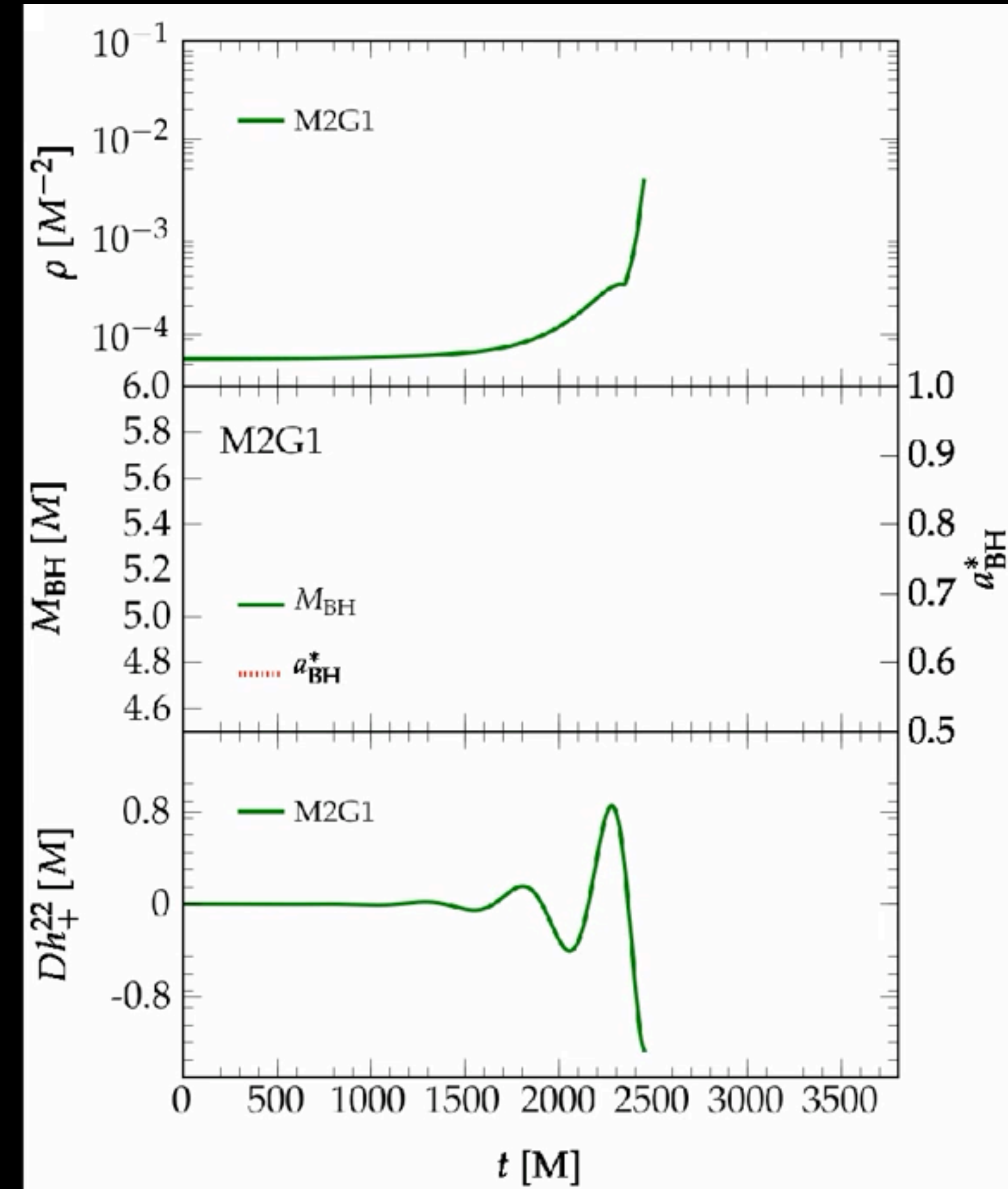
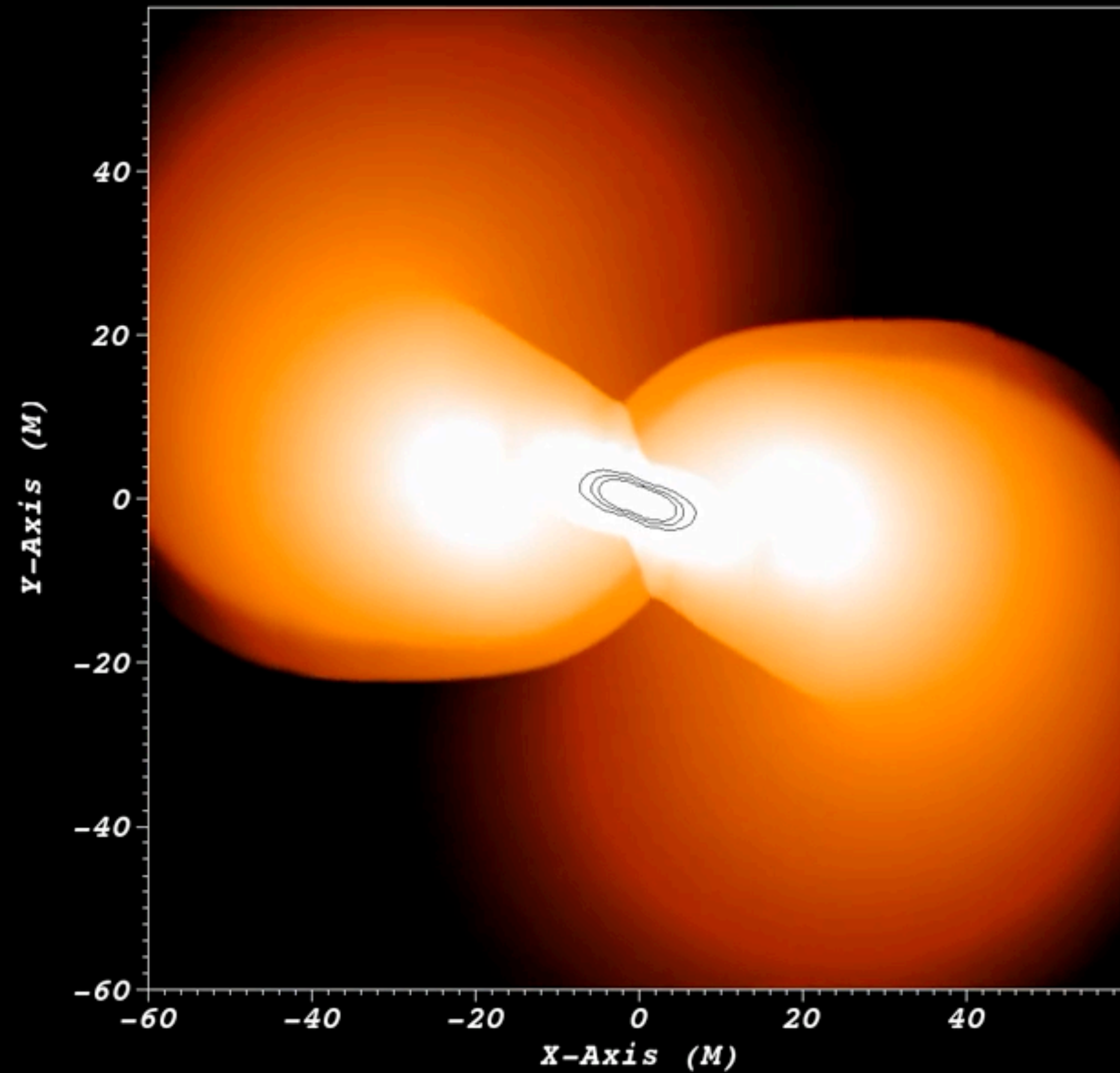
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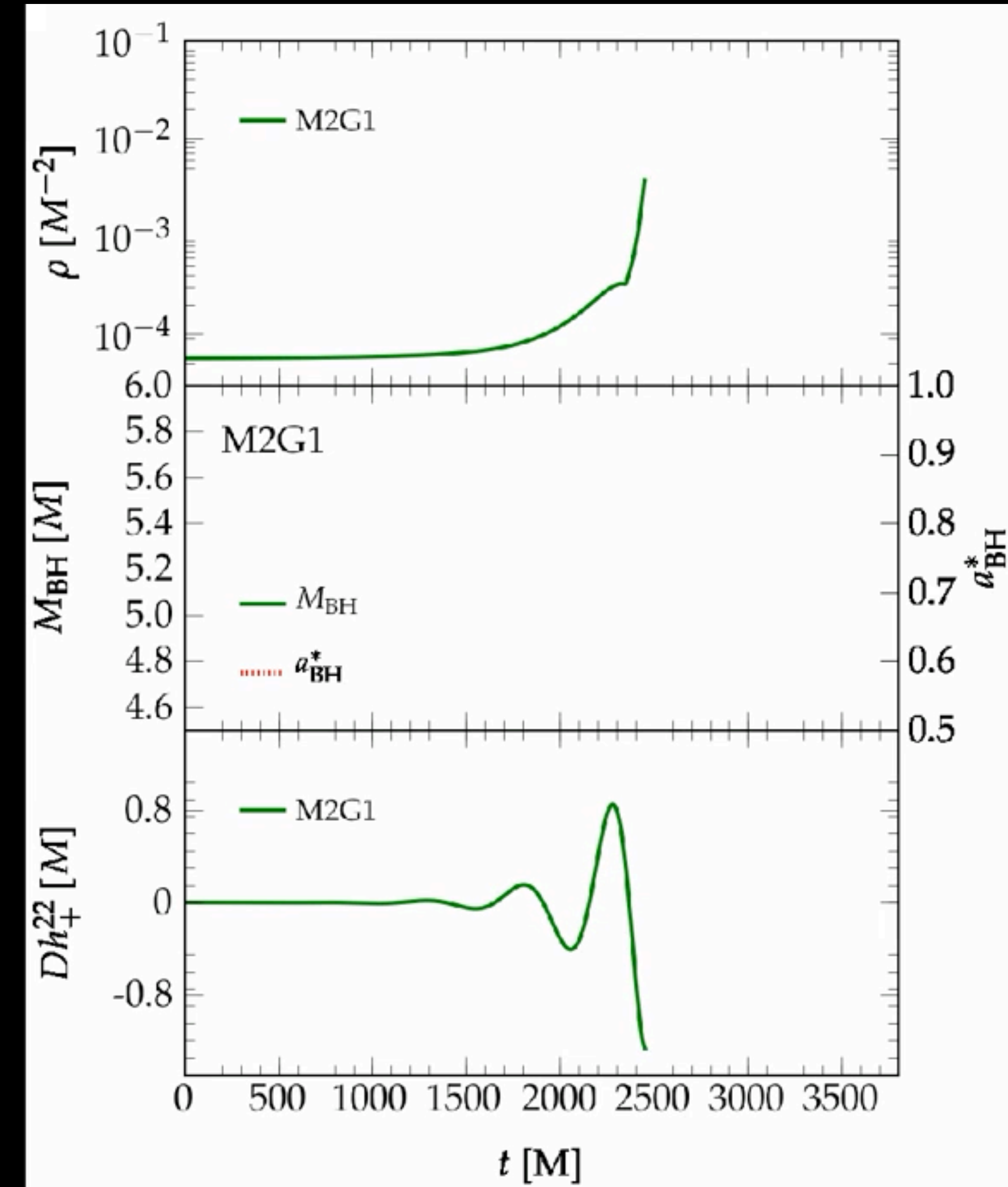
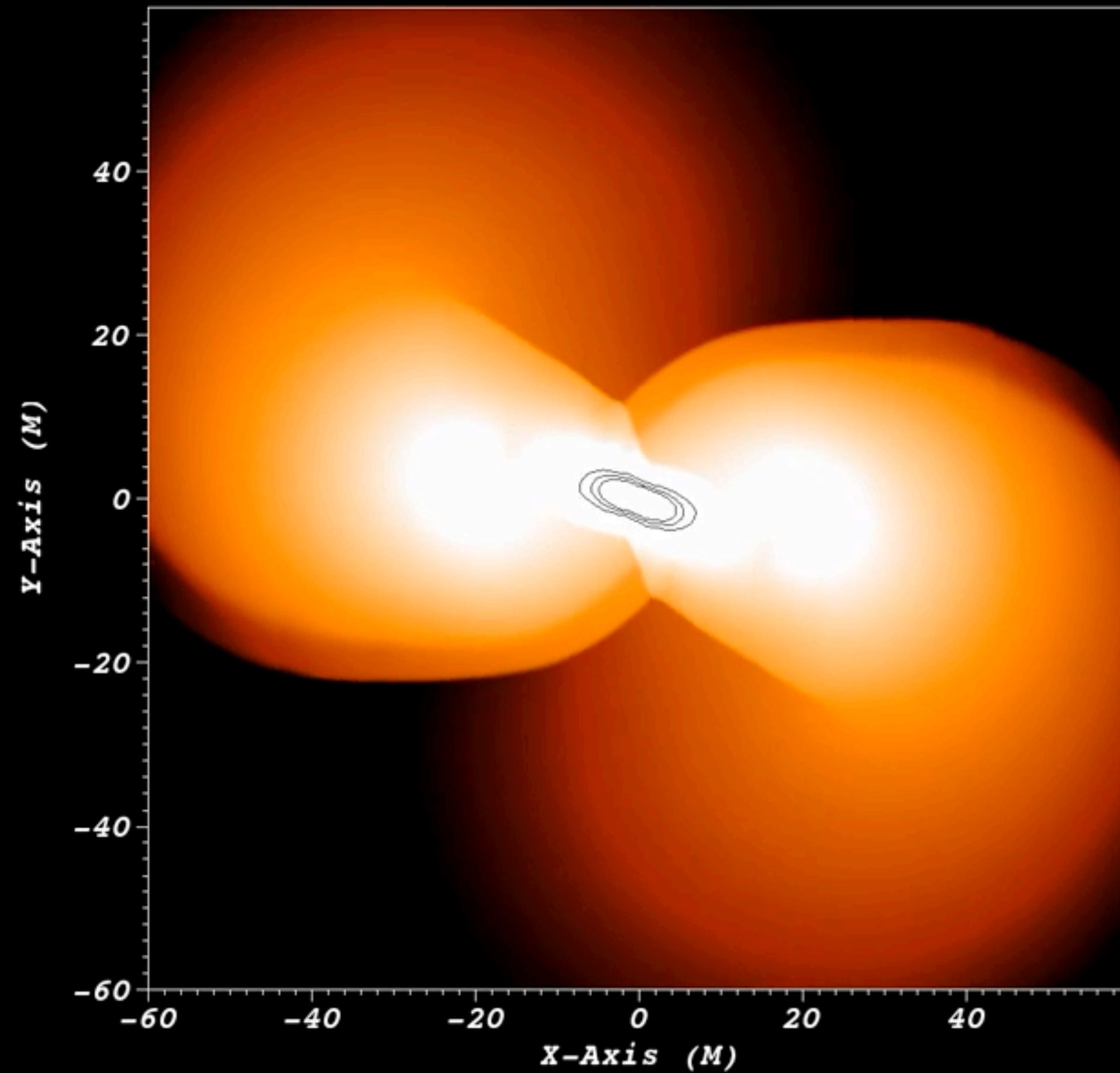
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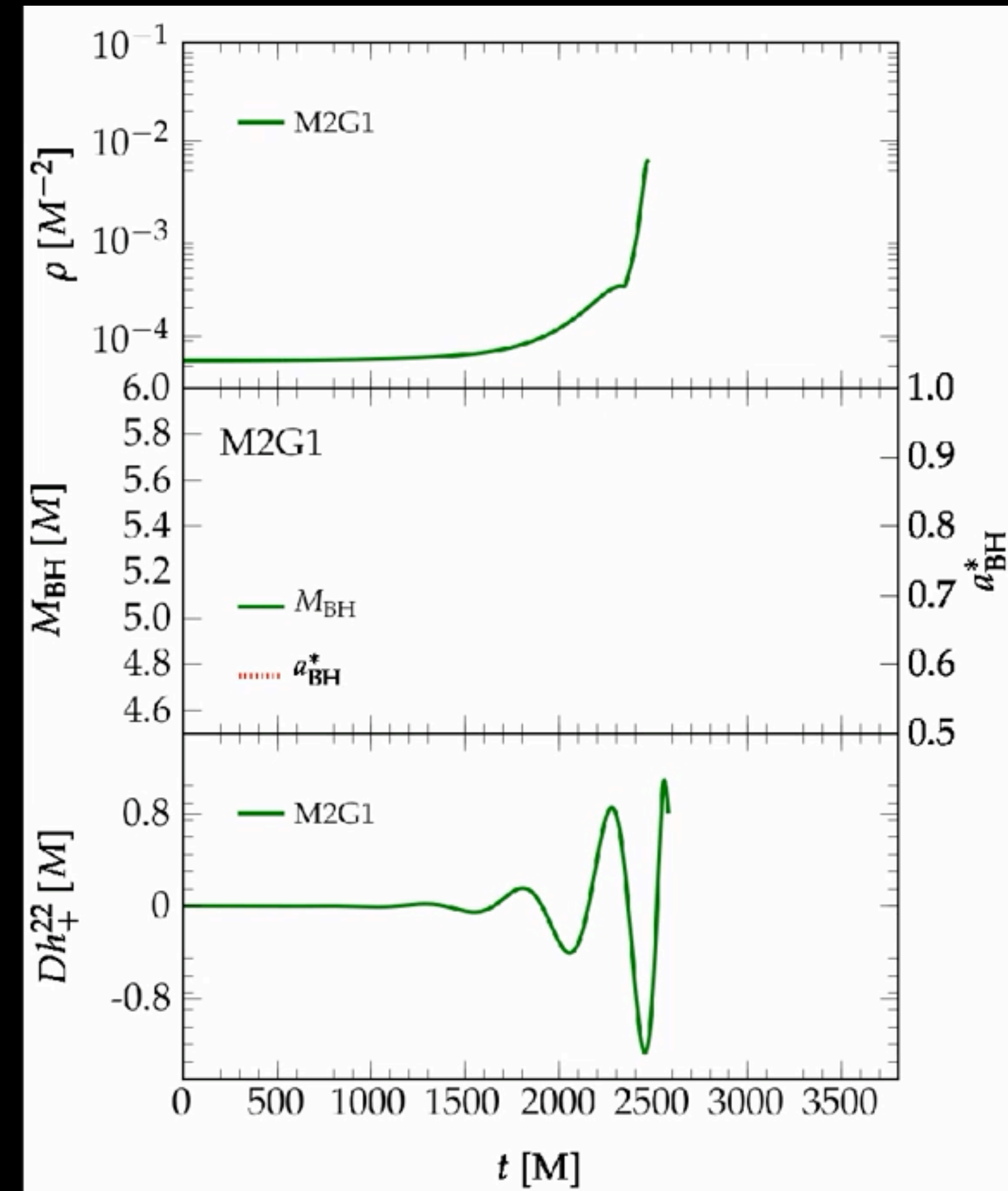
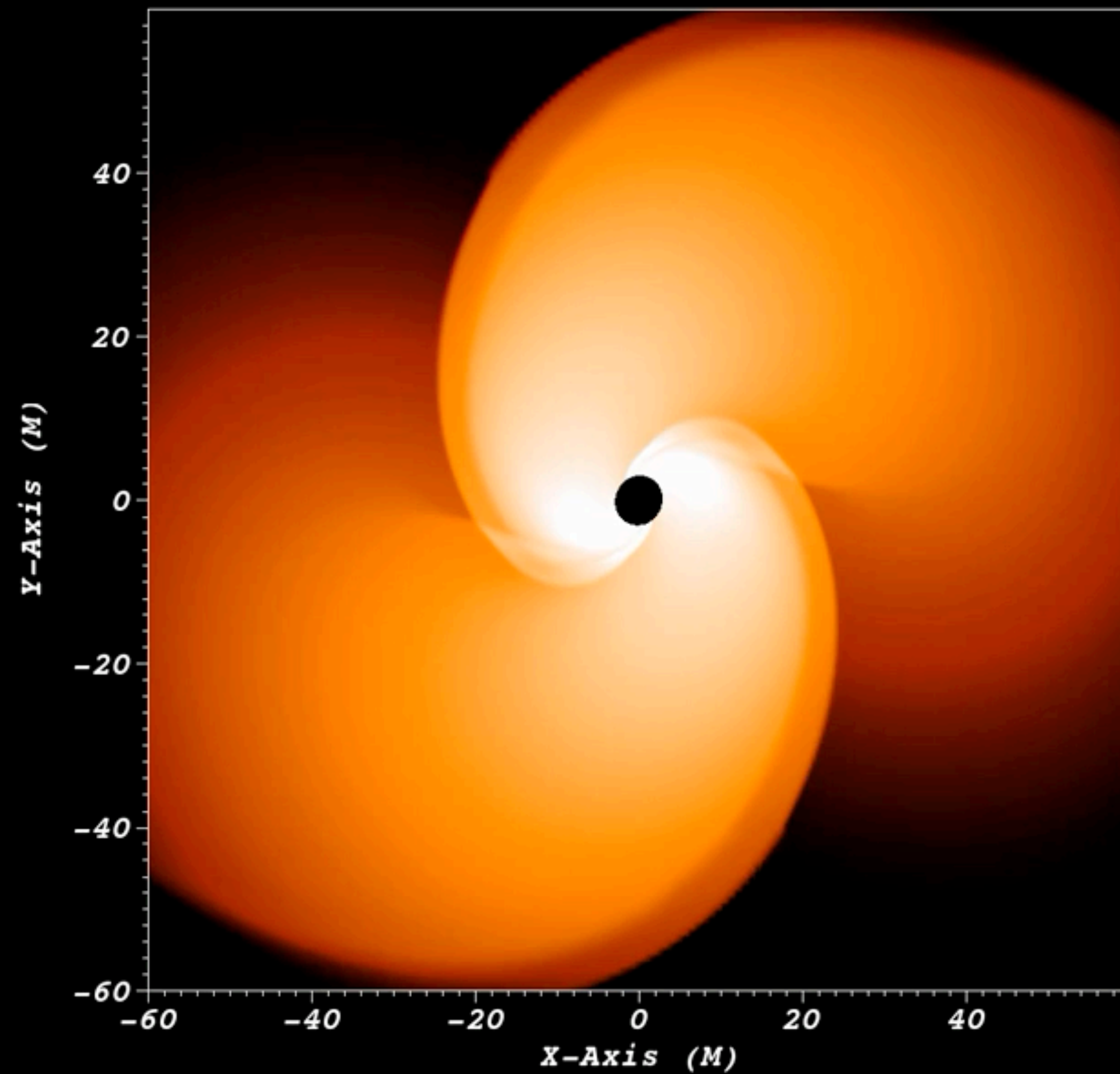
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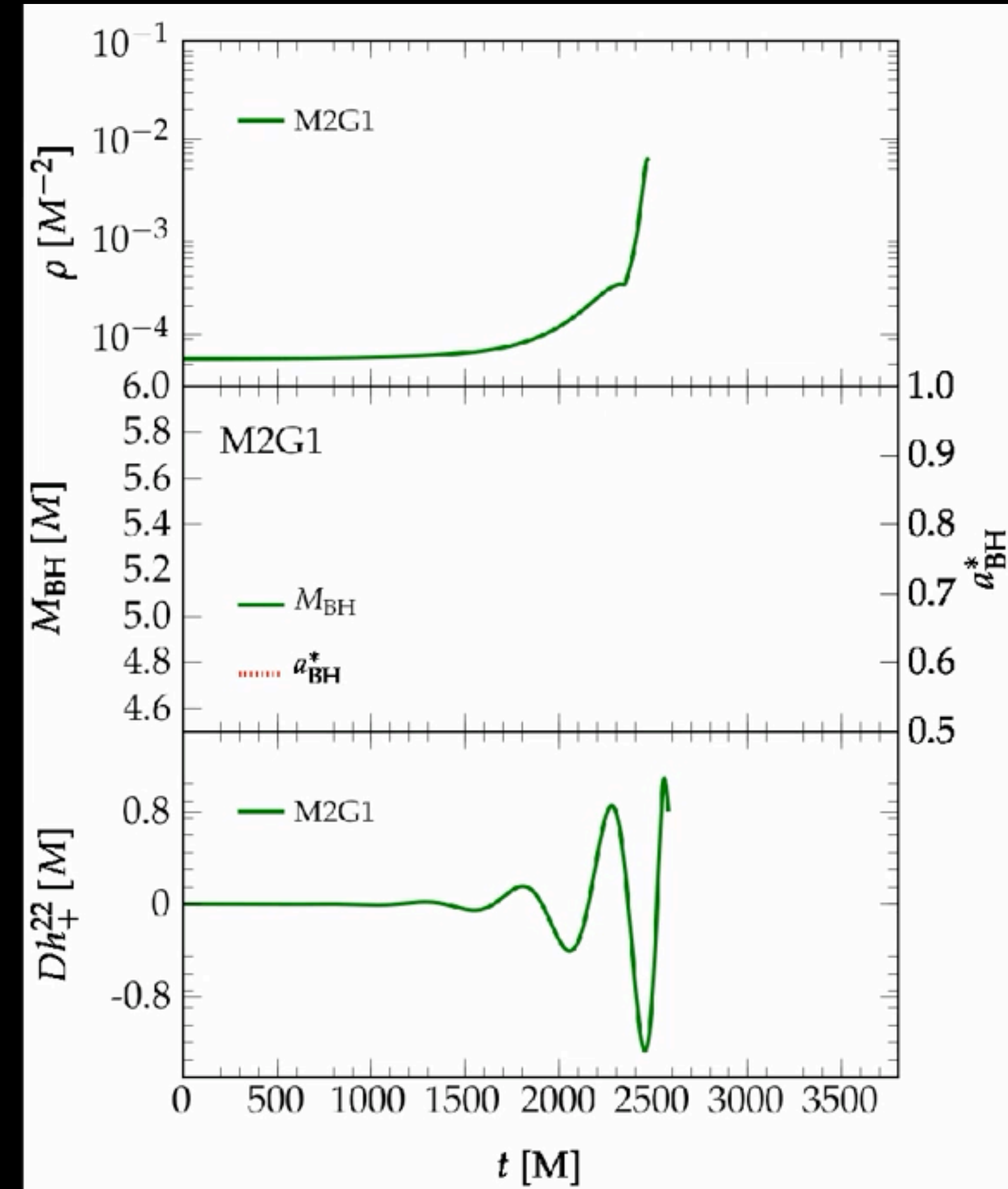
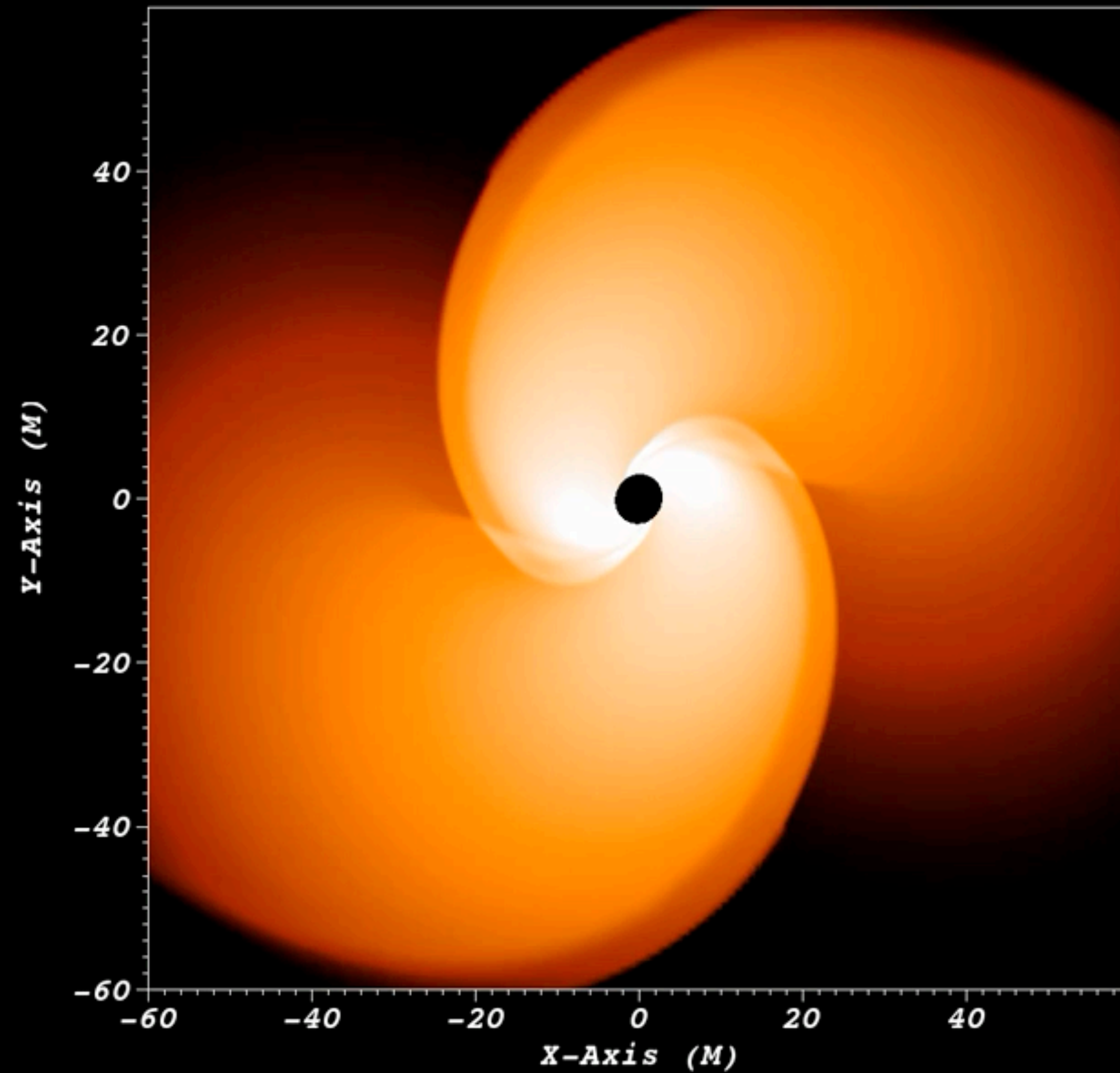
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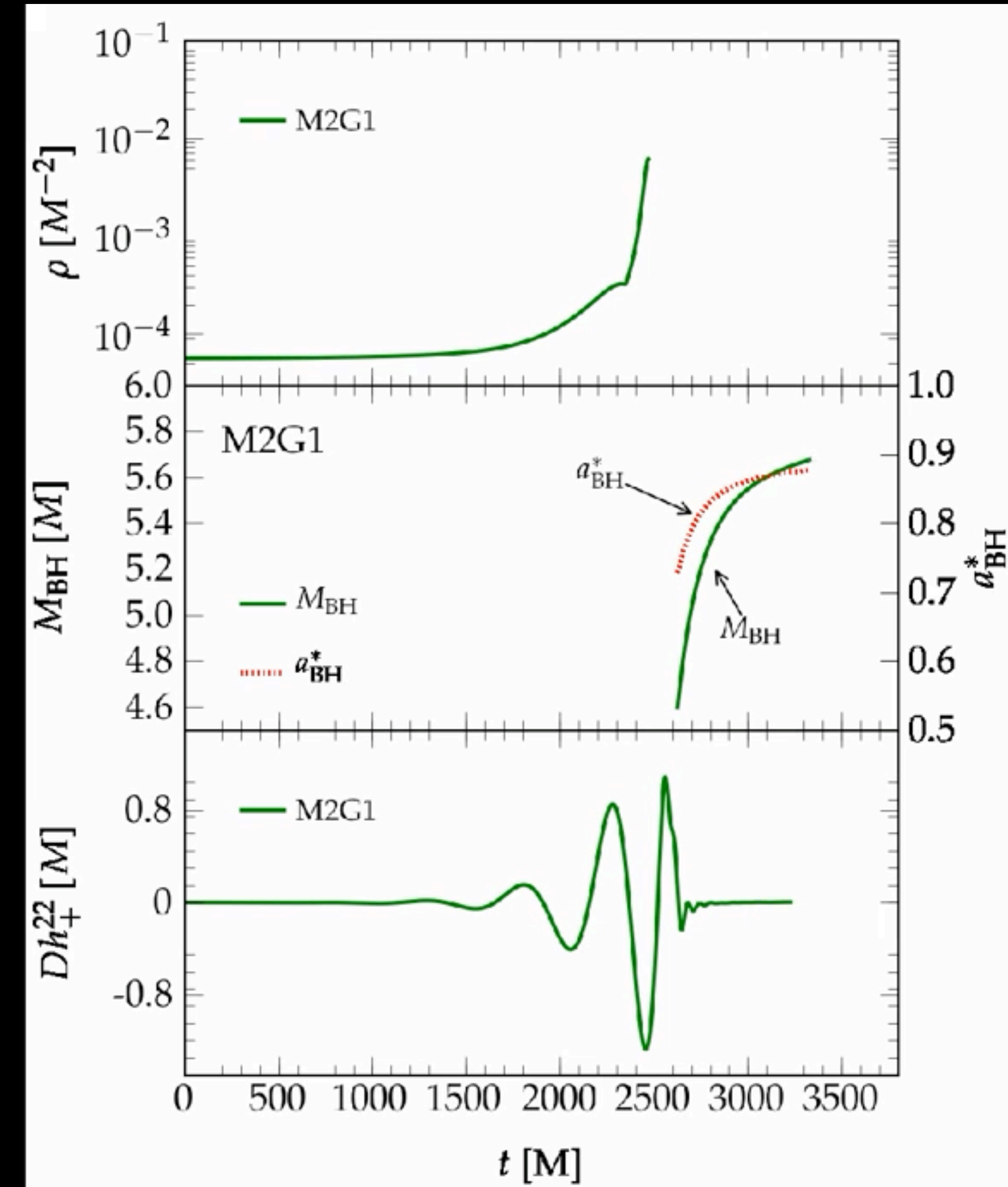
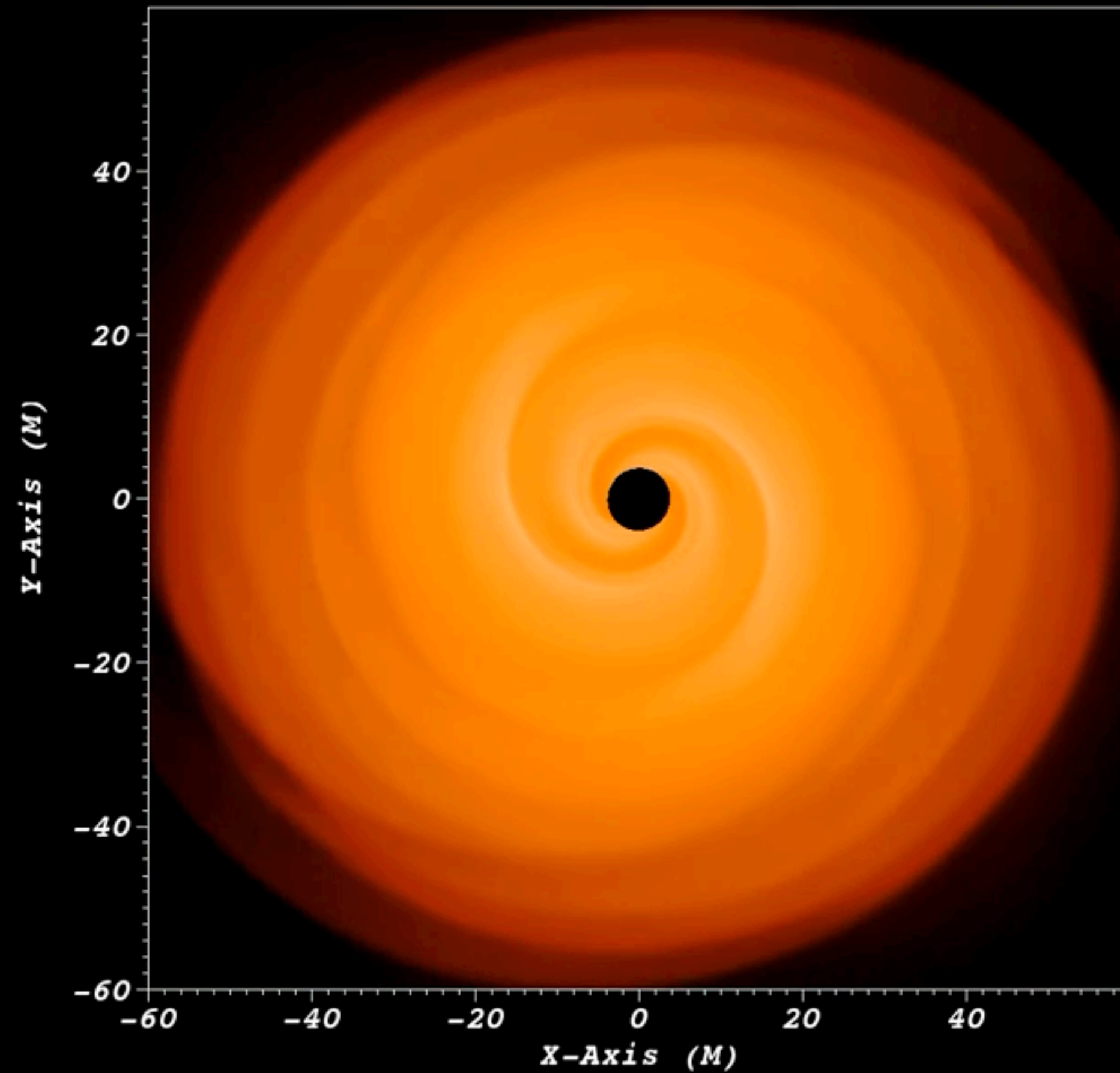
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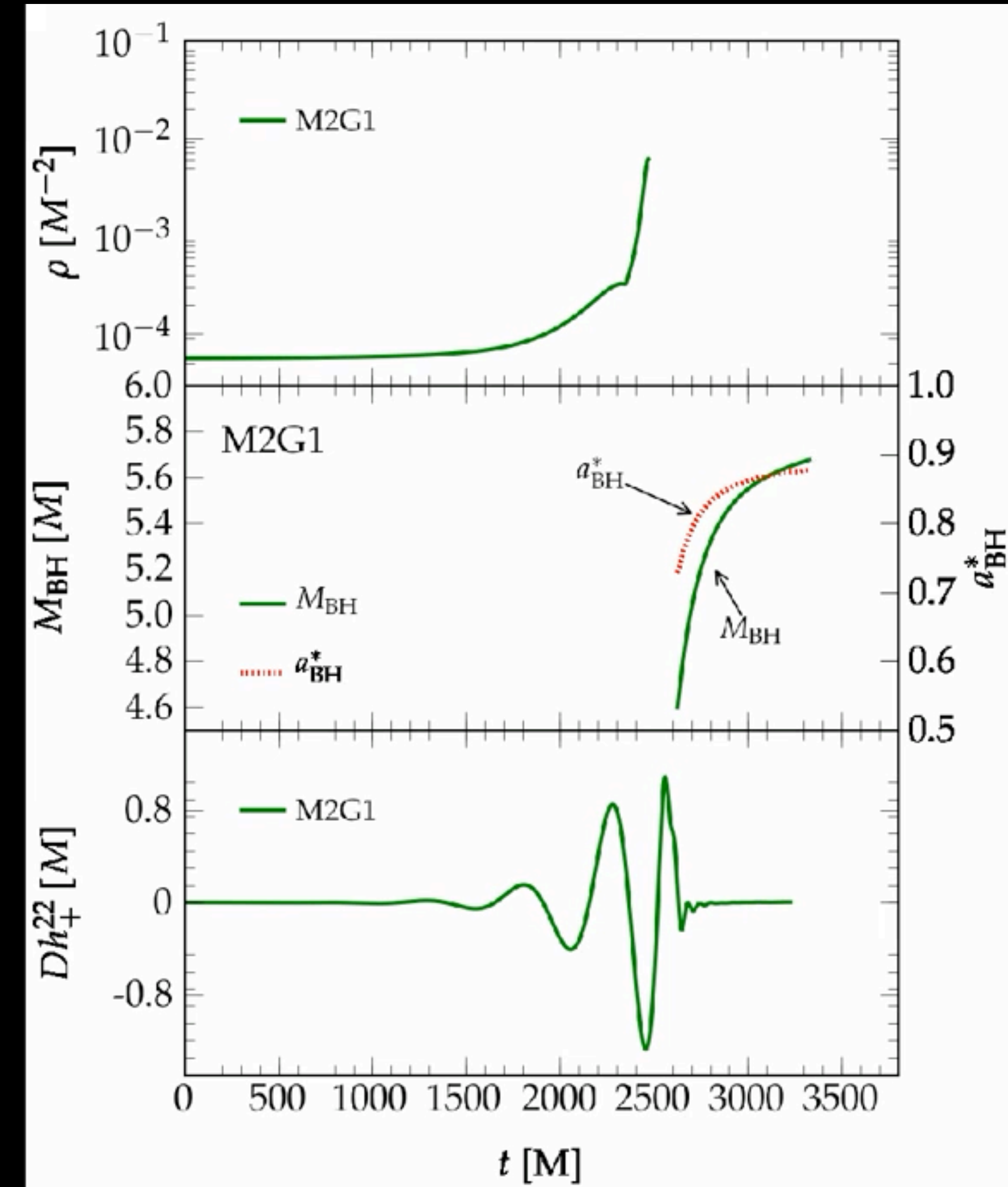
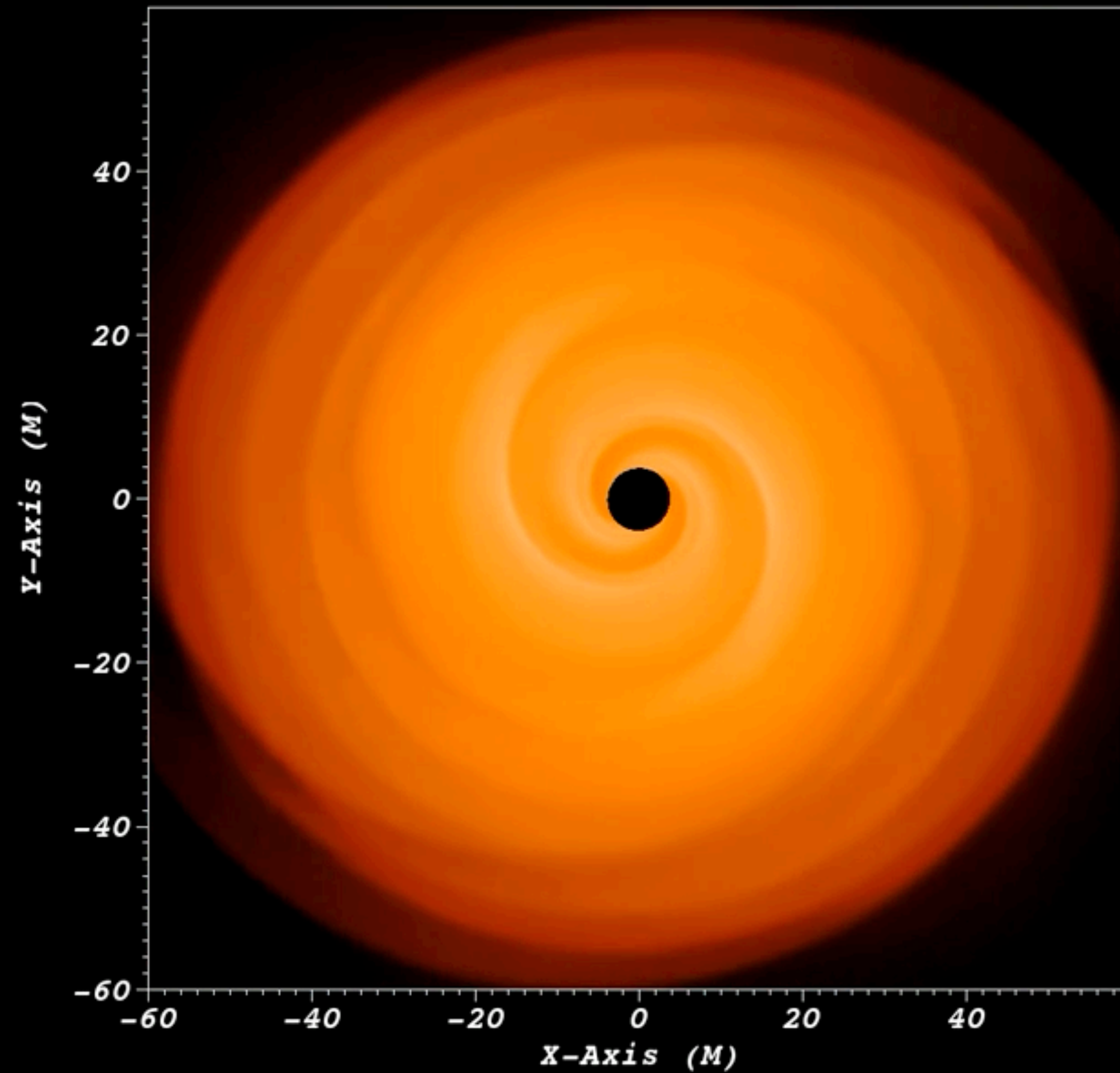
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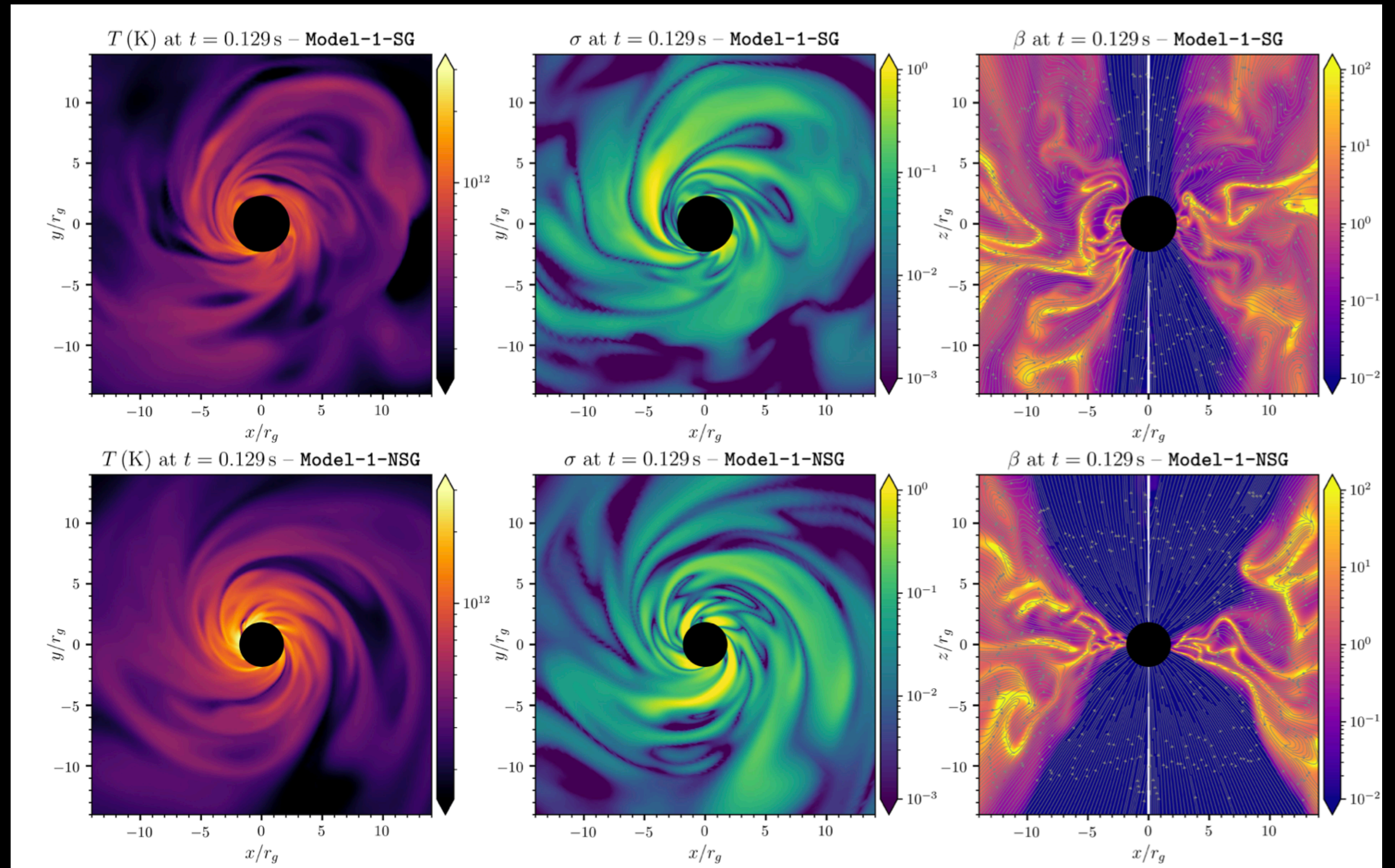


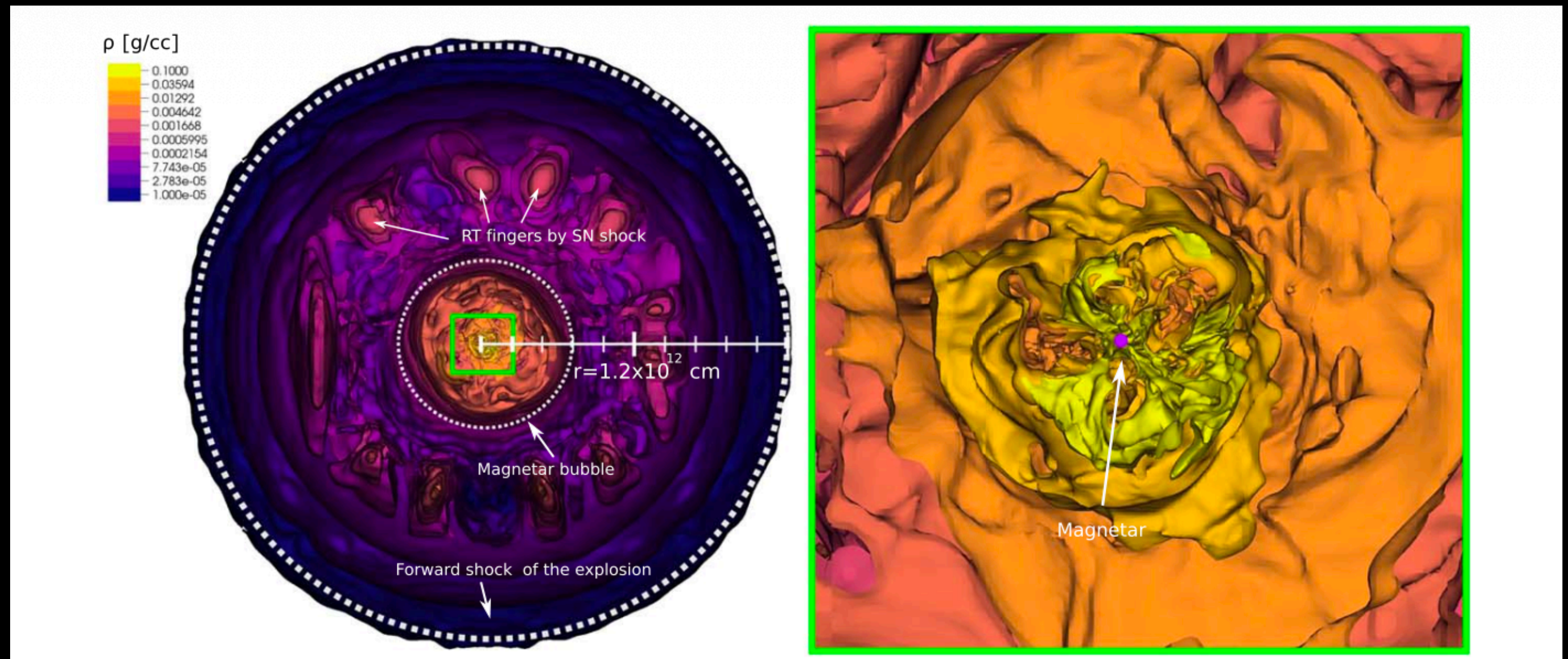
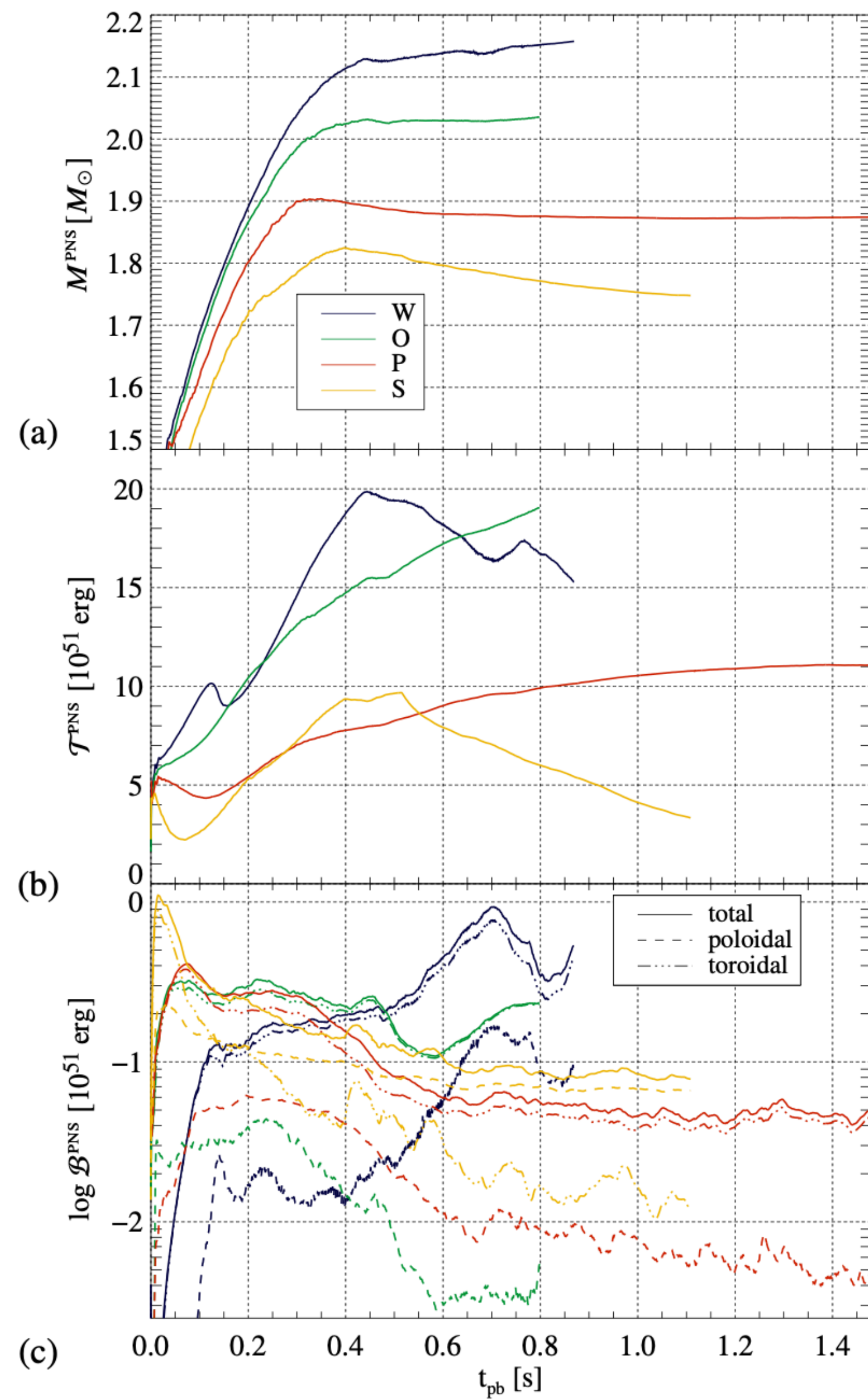
Simulation & Visualization by Christian Reisswig (Caltech)

Accretion + Magnetic field

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

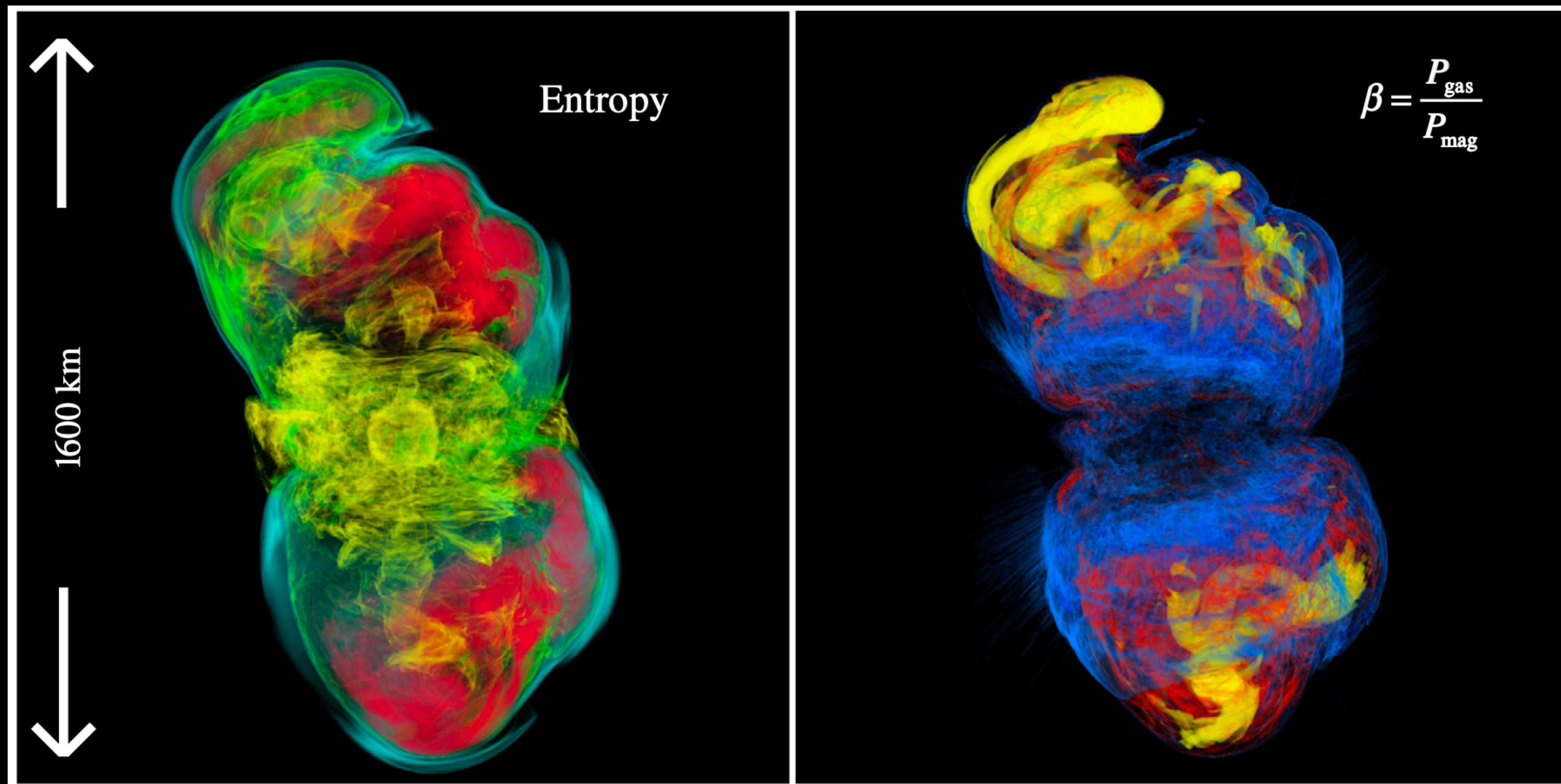
$$L_{\text{BZ}} \propto \Phi_{\text{BH}}^2 \Omega_{\text{H}}^2,$$



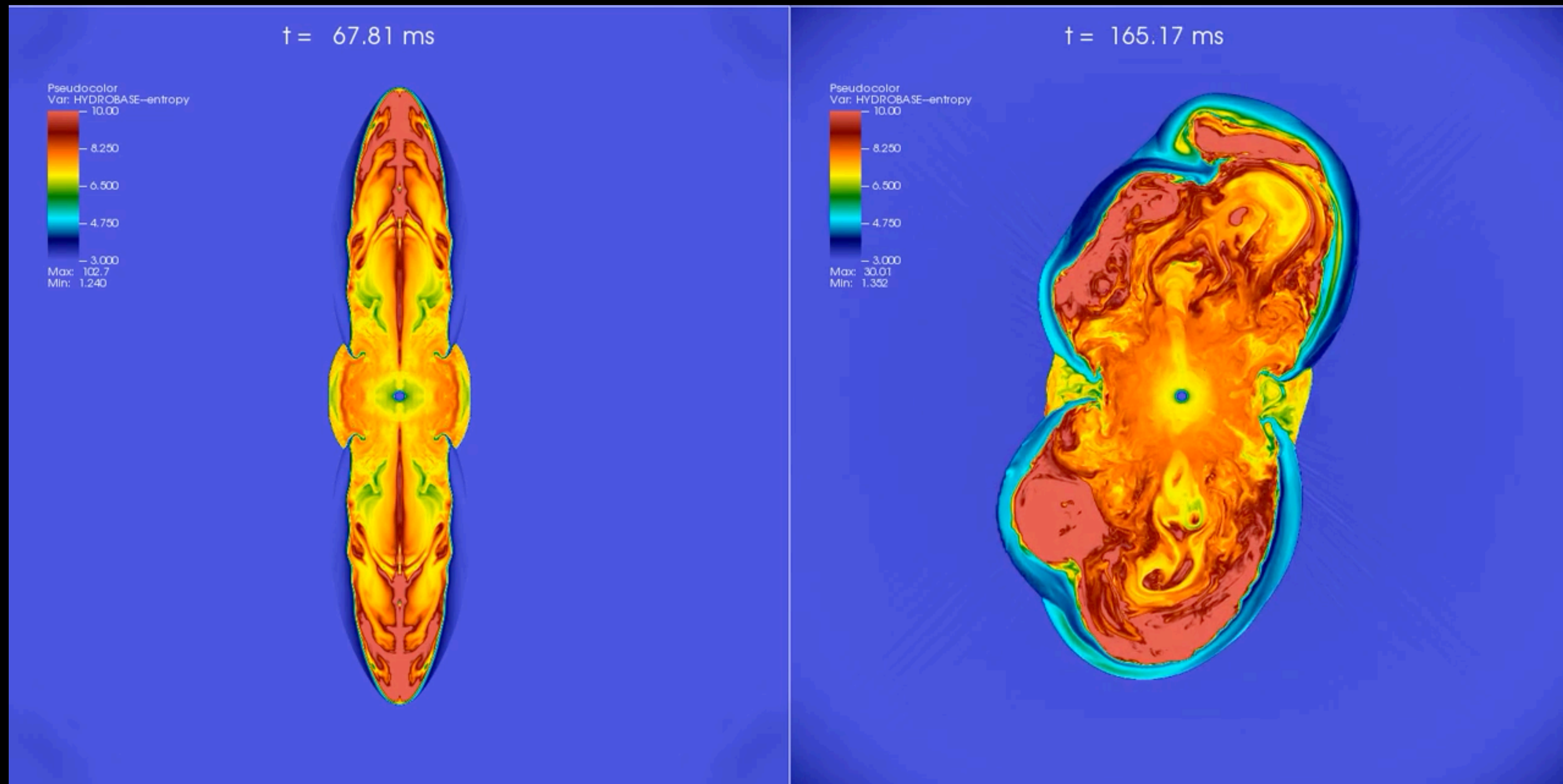


Chen, Woosley, Whalen 2020

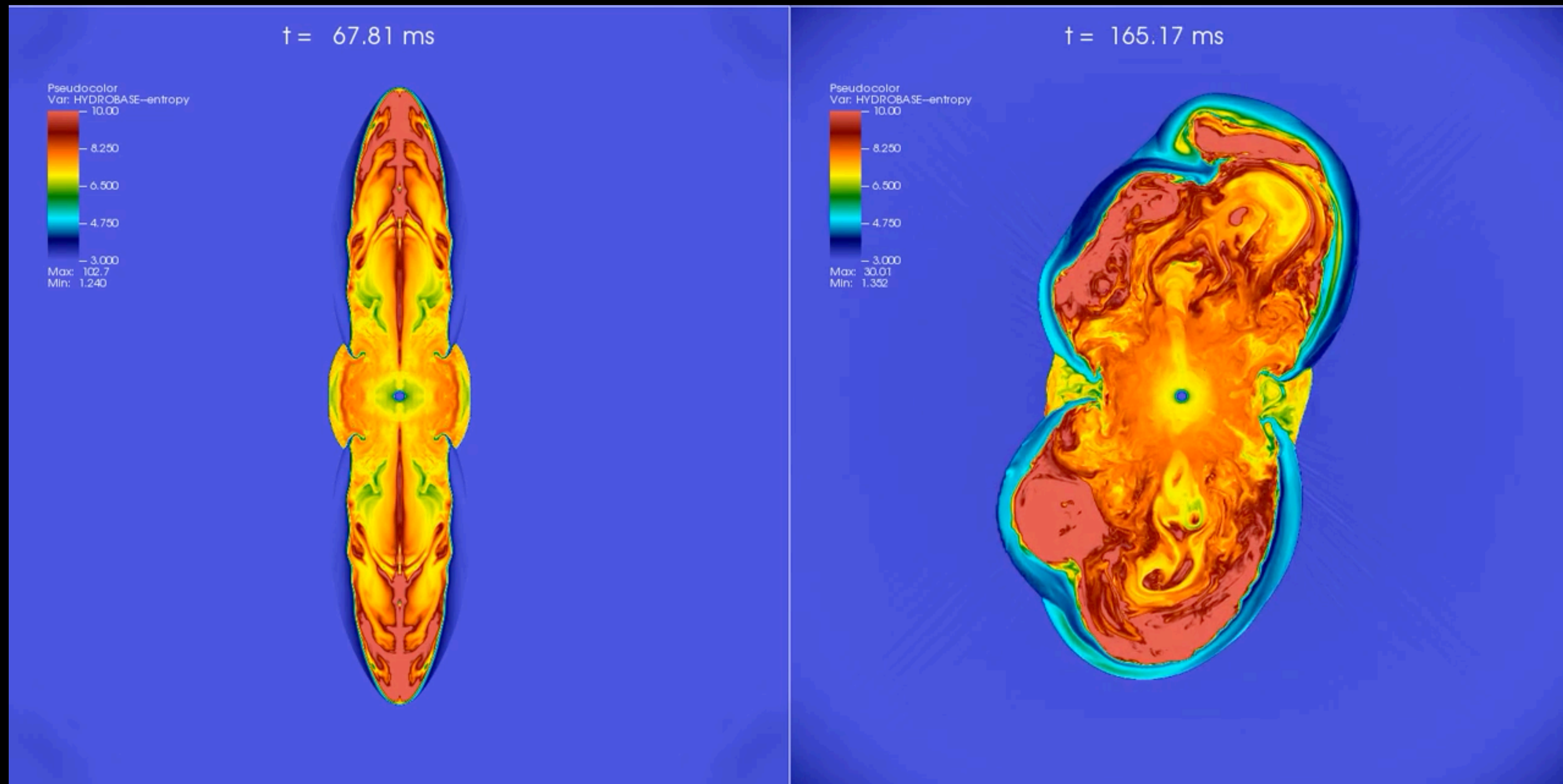
Aloy & Obergaulinger 2021-22



Magneto-rotational Core Collapse: Philip Moesta

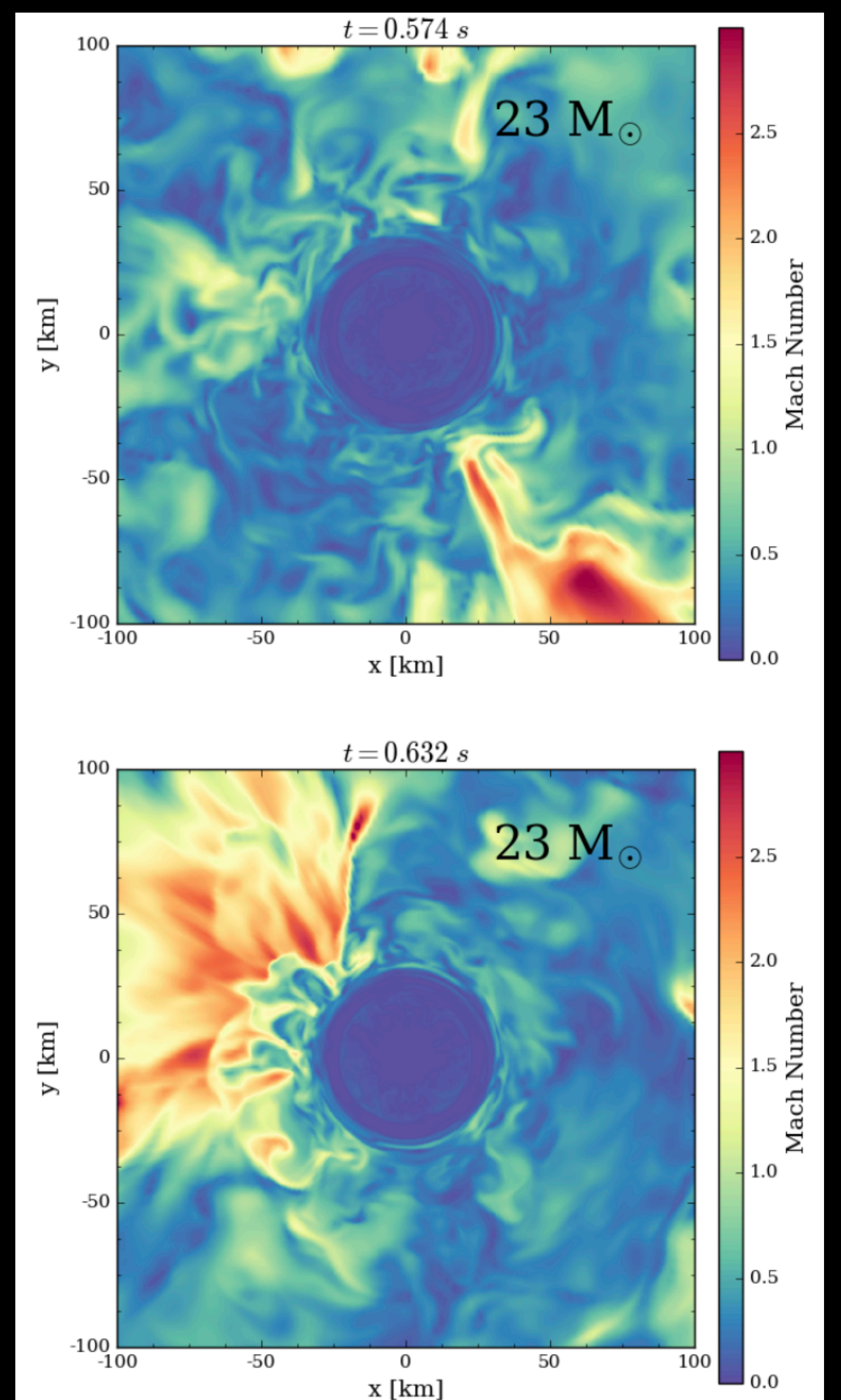
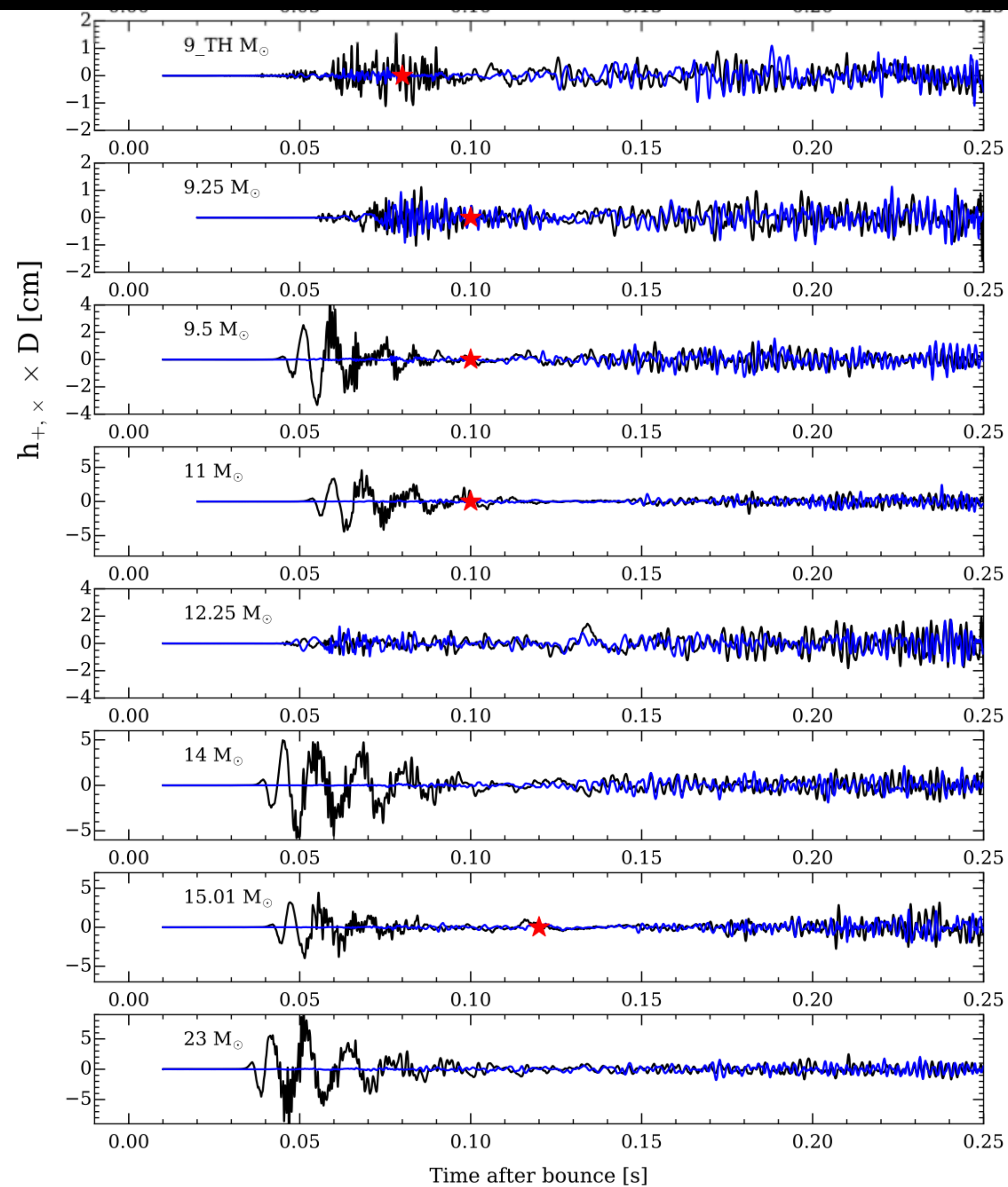


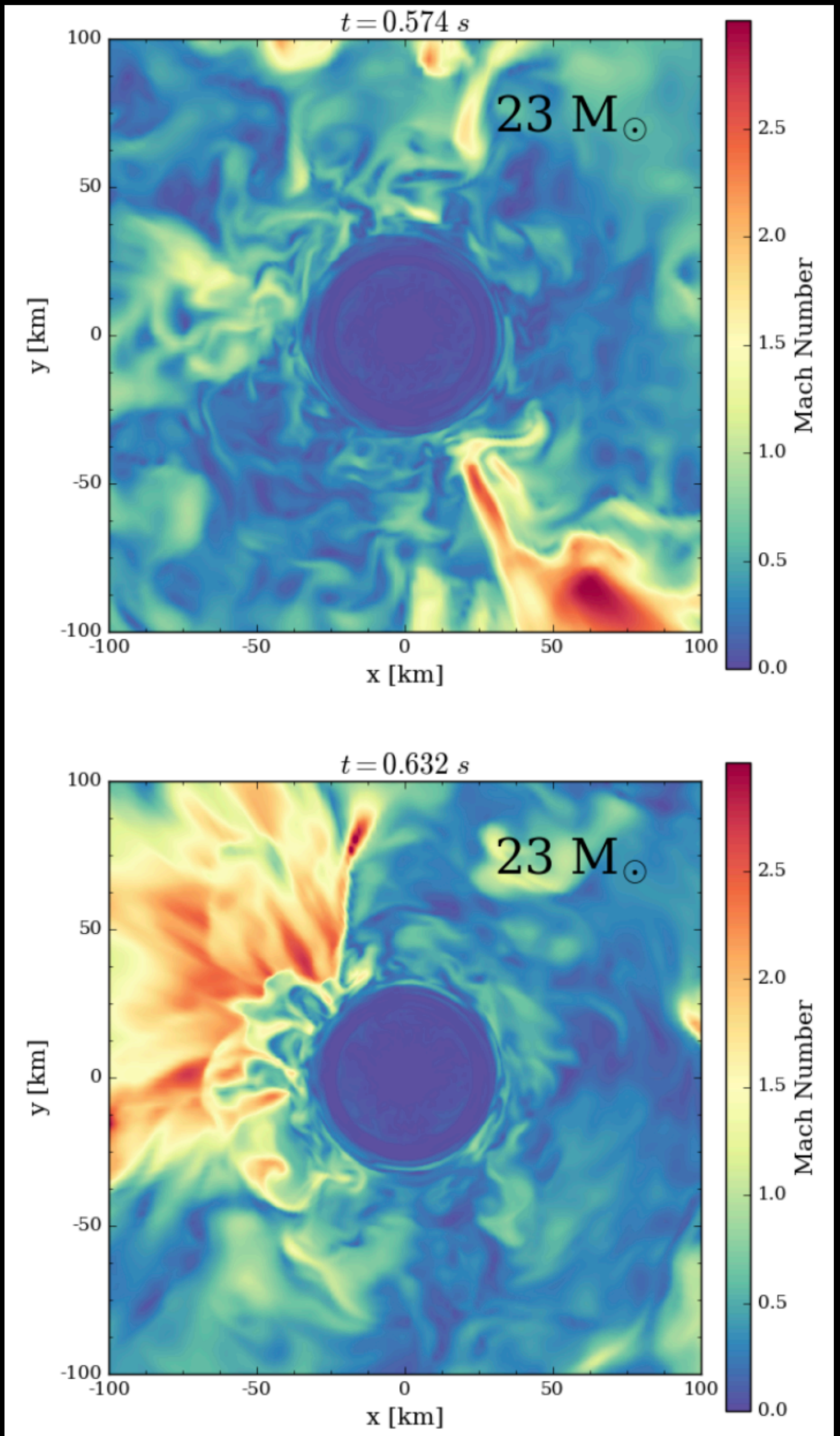
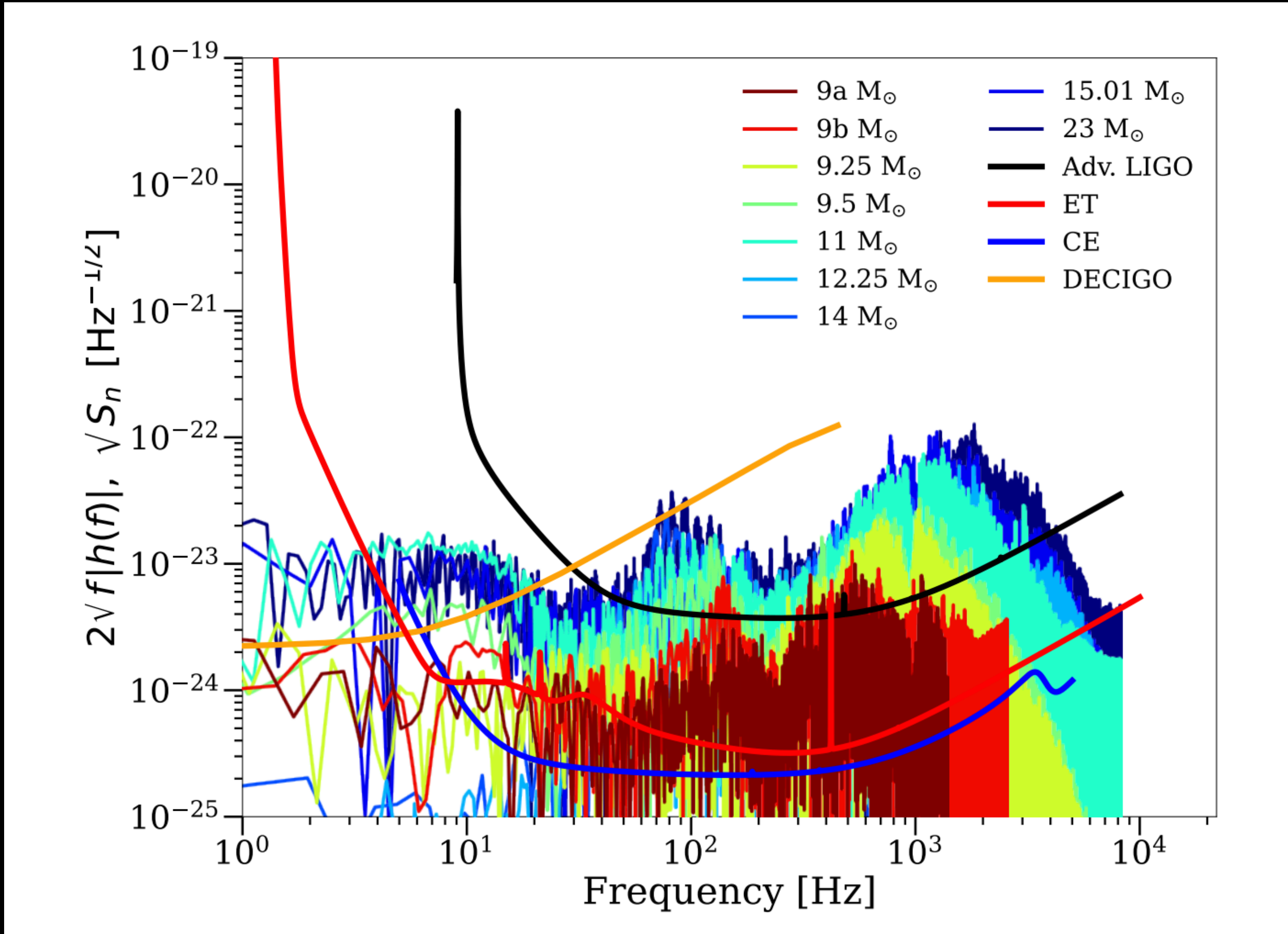
Mösta 2014



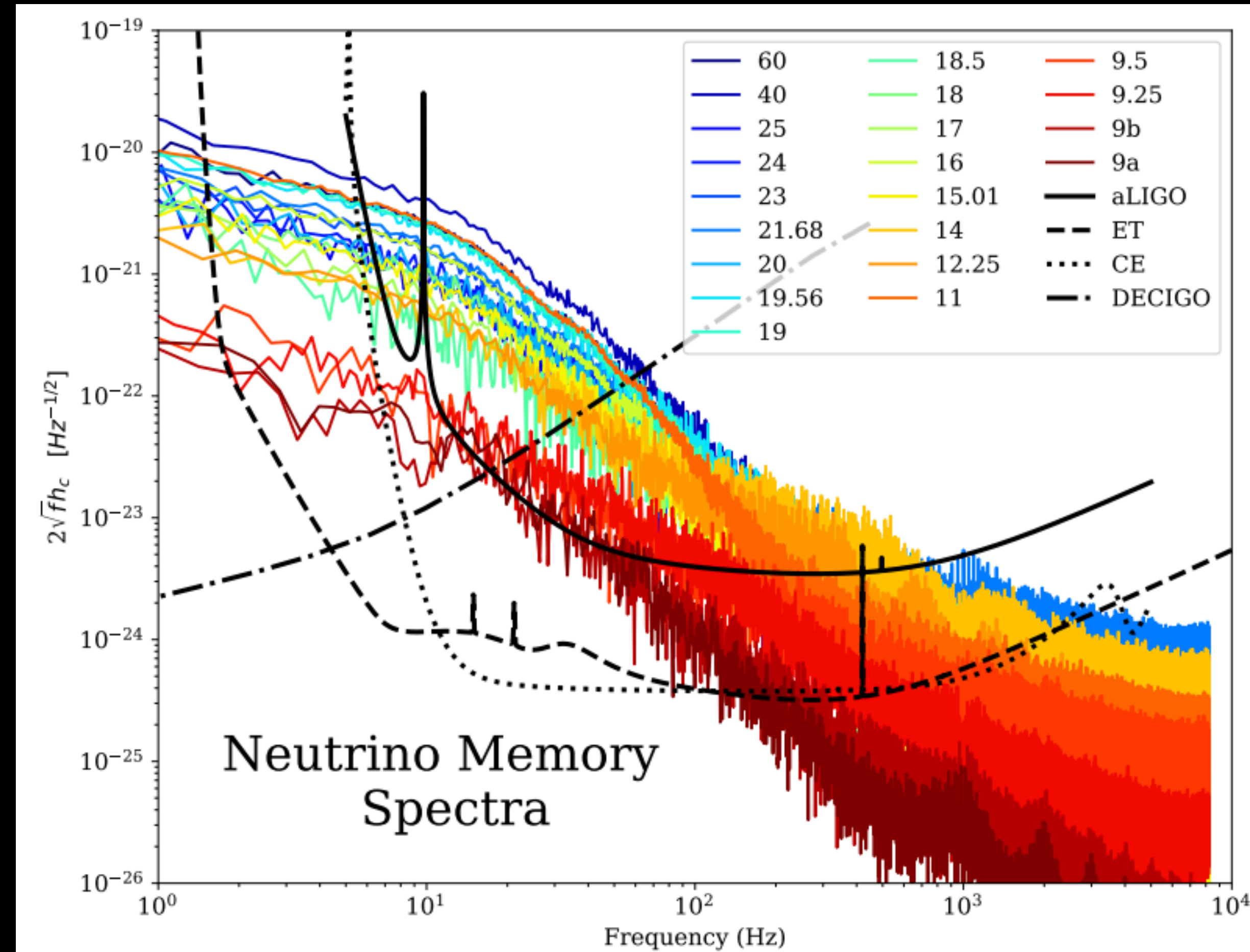
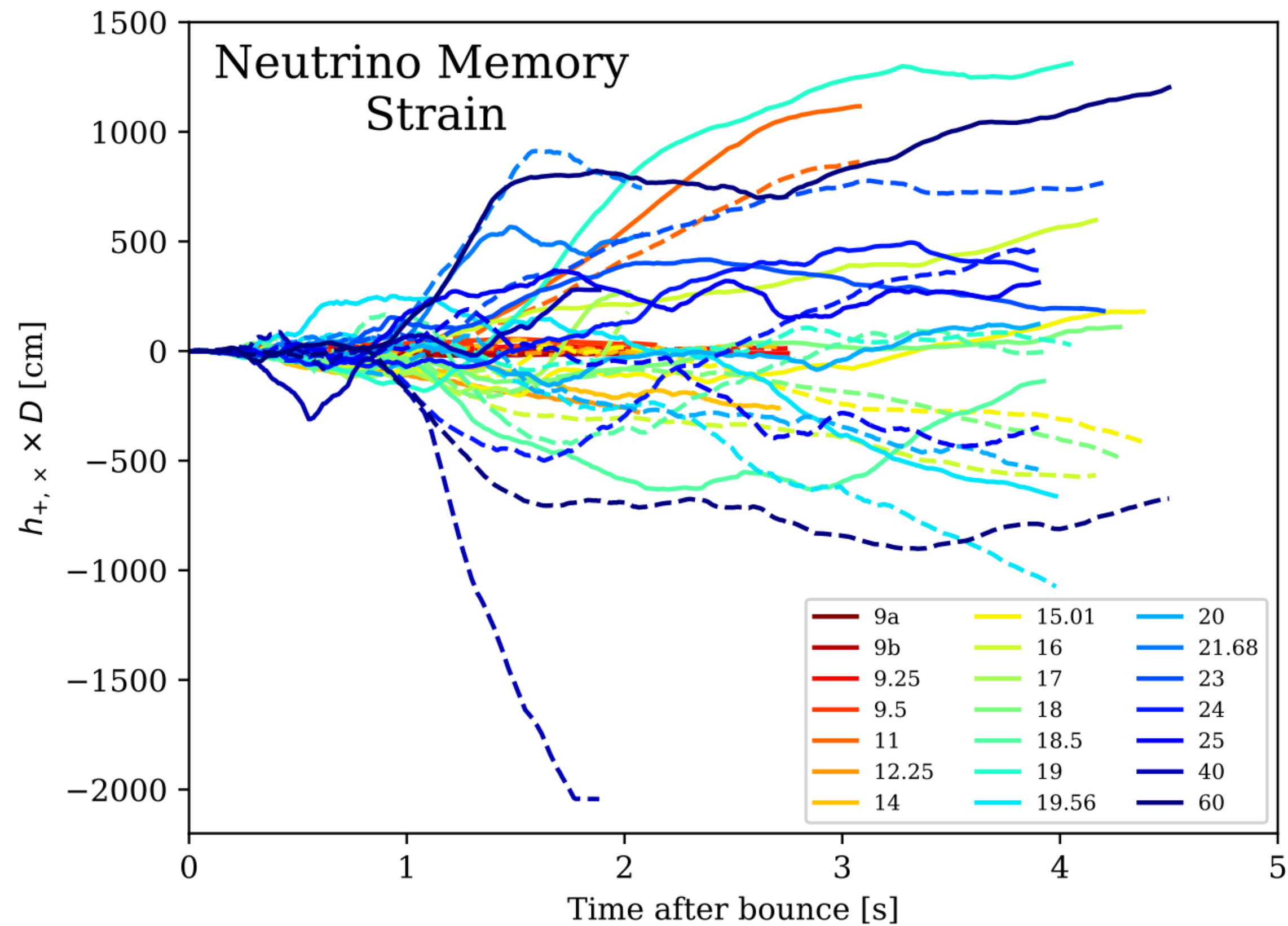
Mösta 2014

Gravitational waves in collapsars



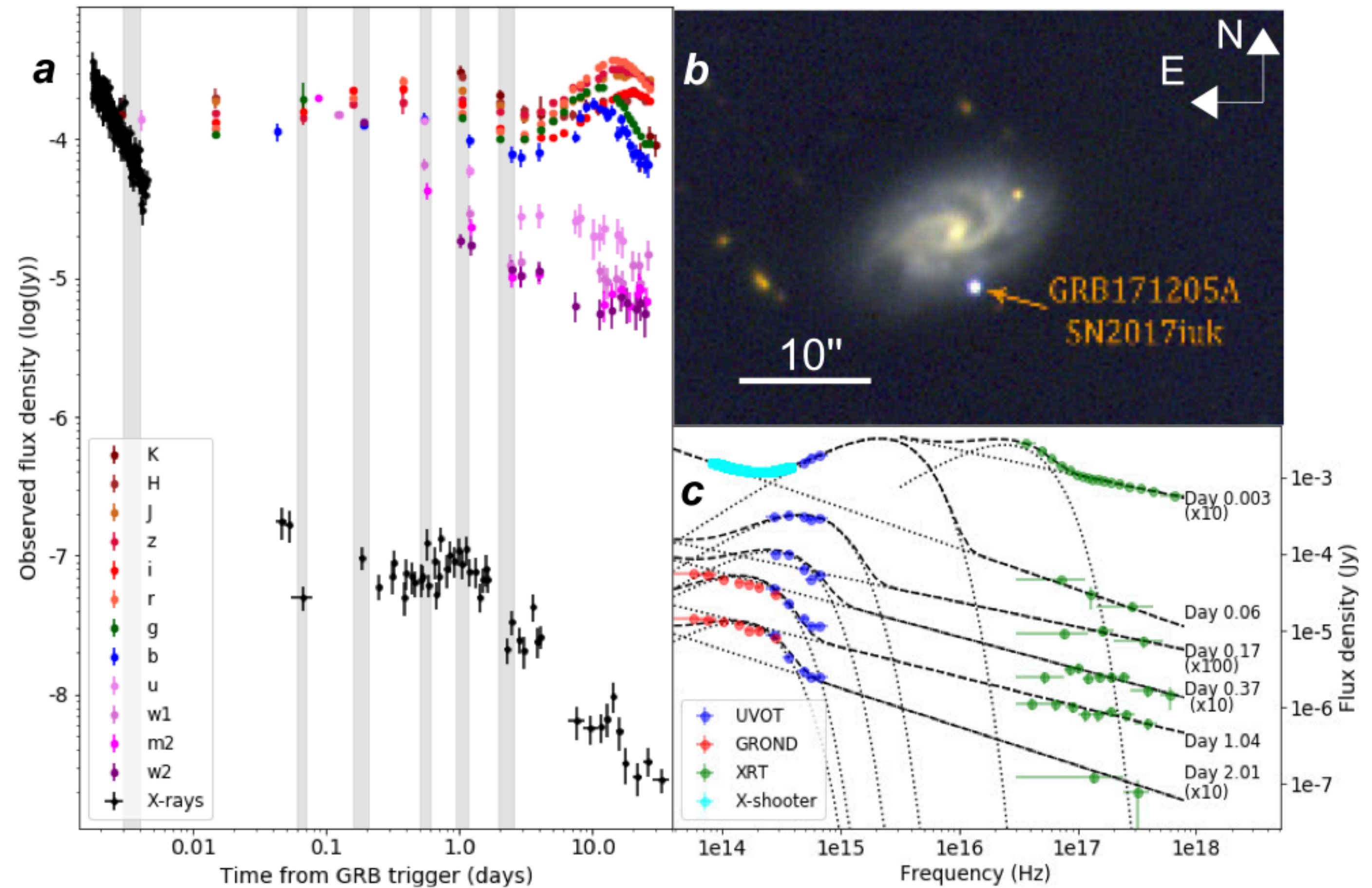
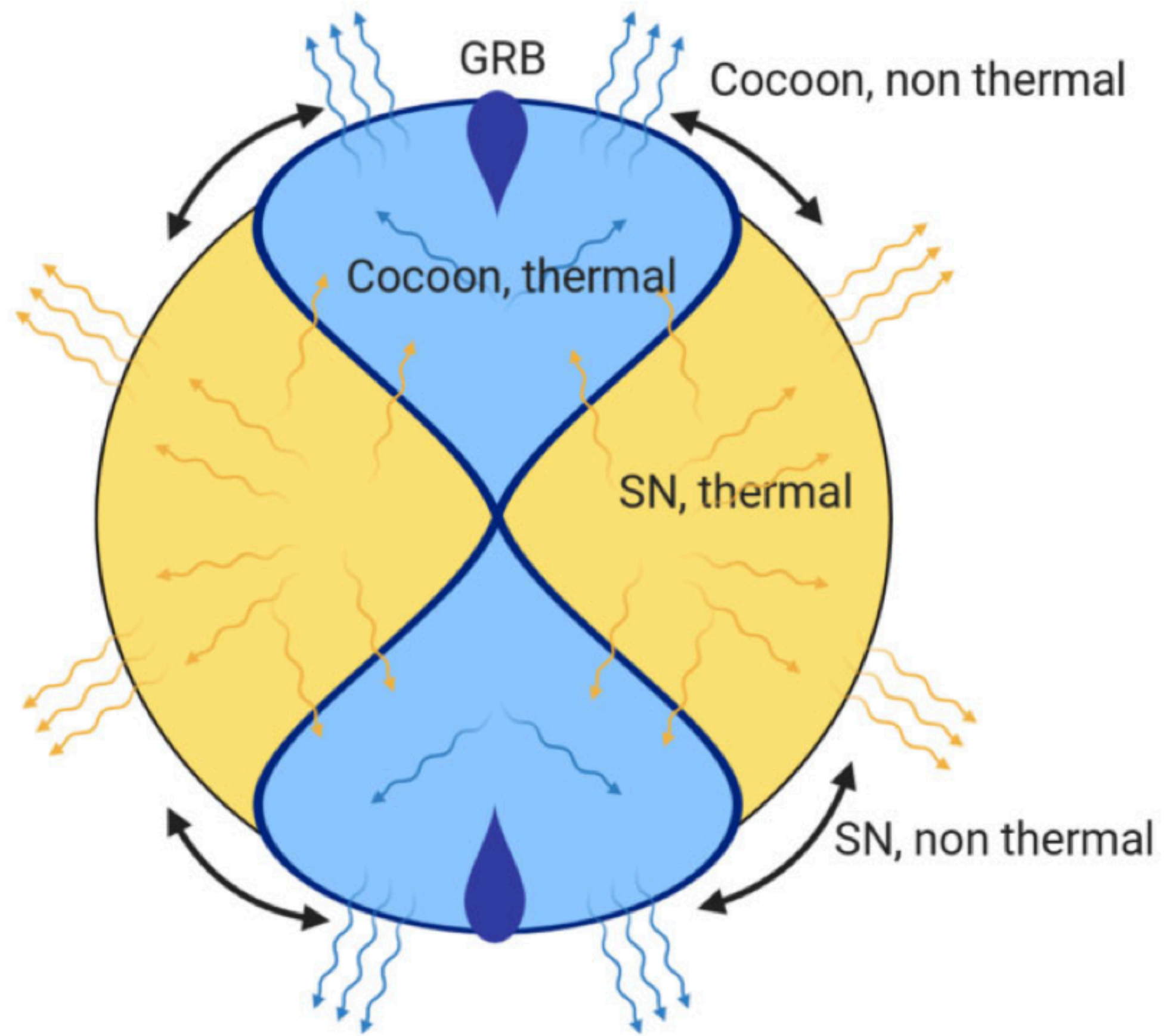


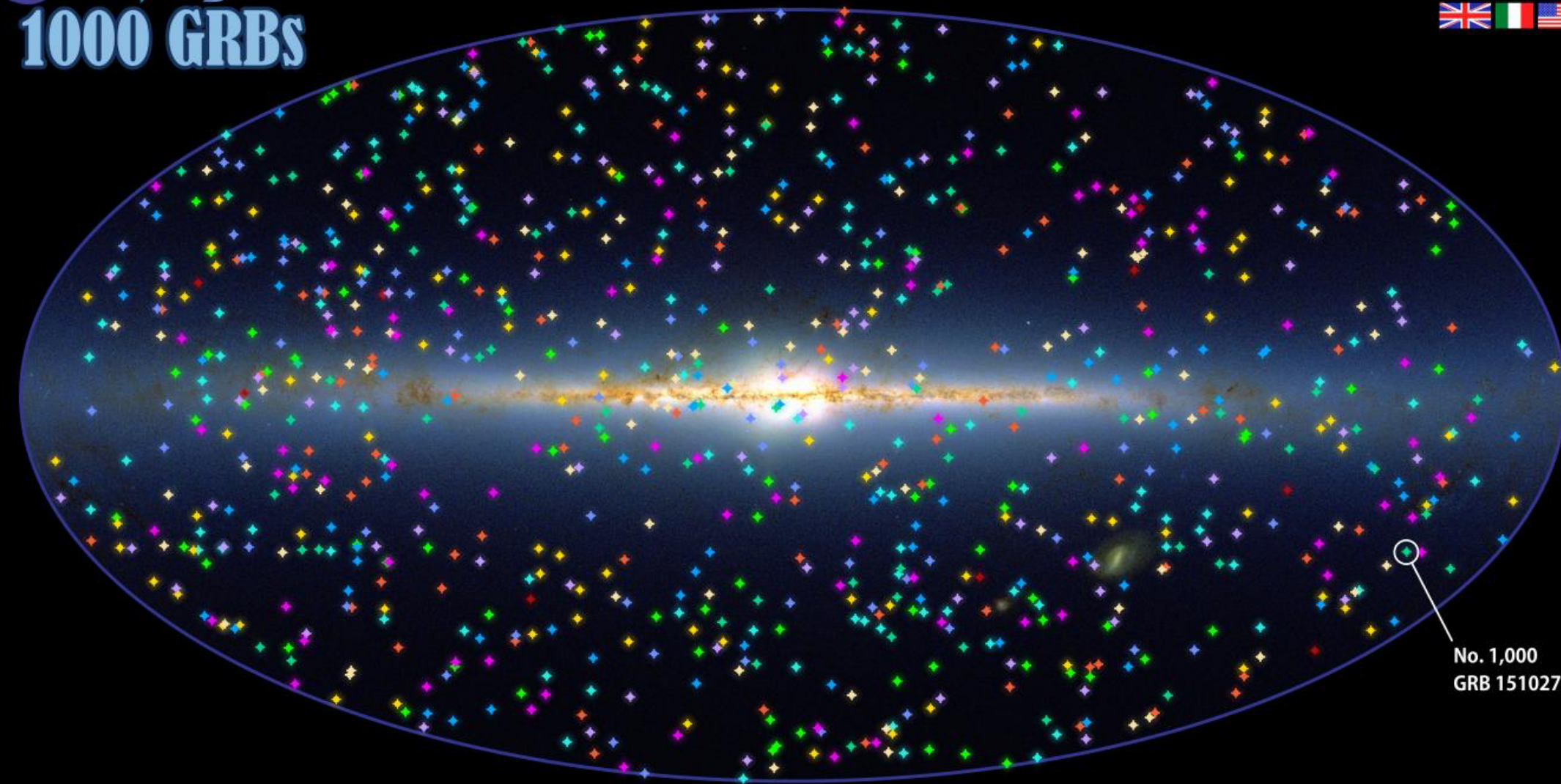
Equation of memory



Electromagnetic counterparts

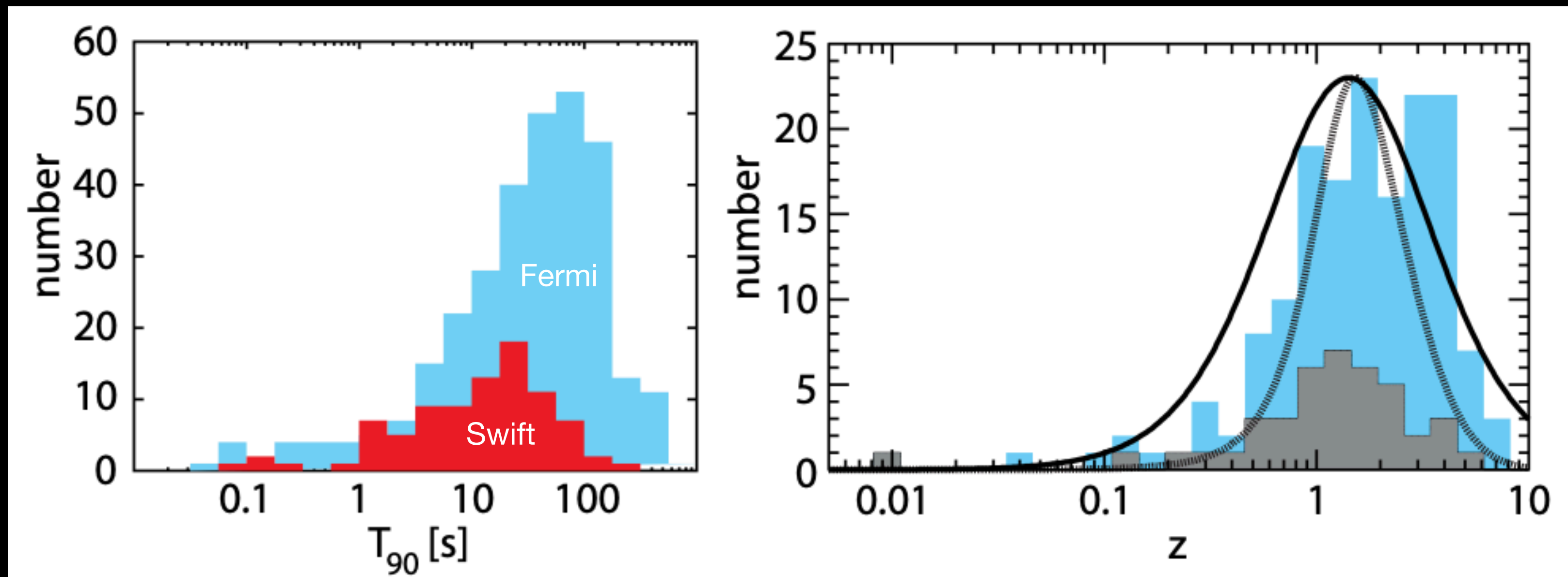
Jet, Cocoon and supernova from collapsars





Collapsars

Compact
mergers



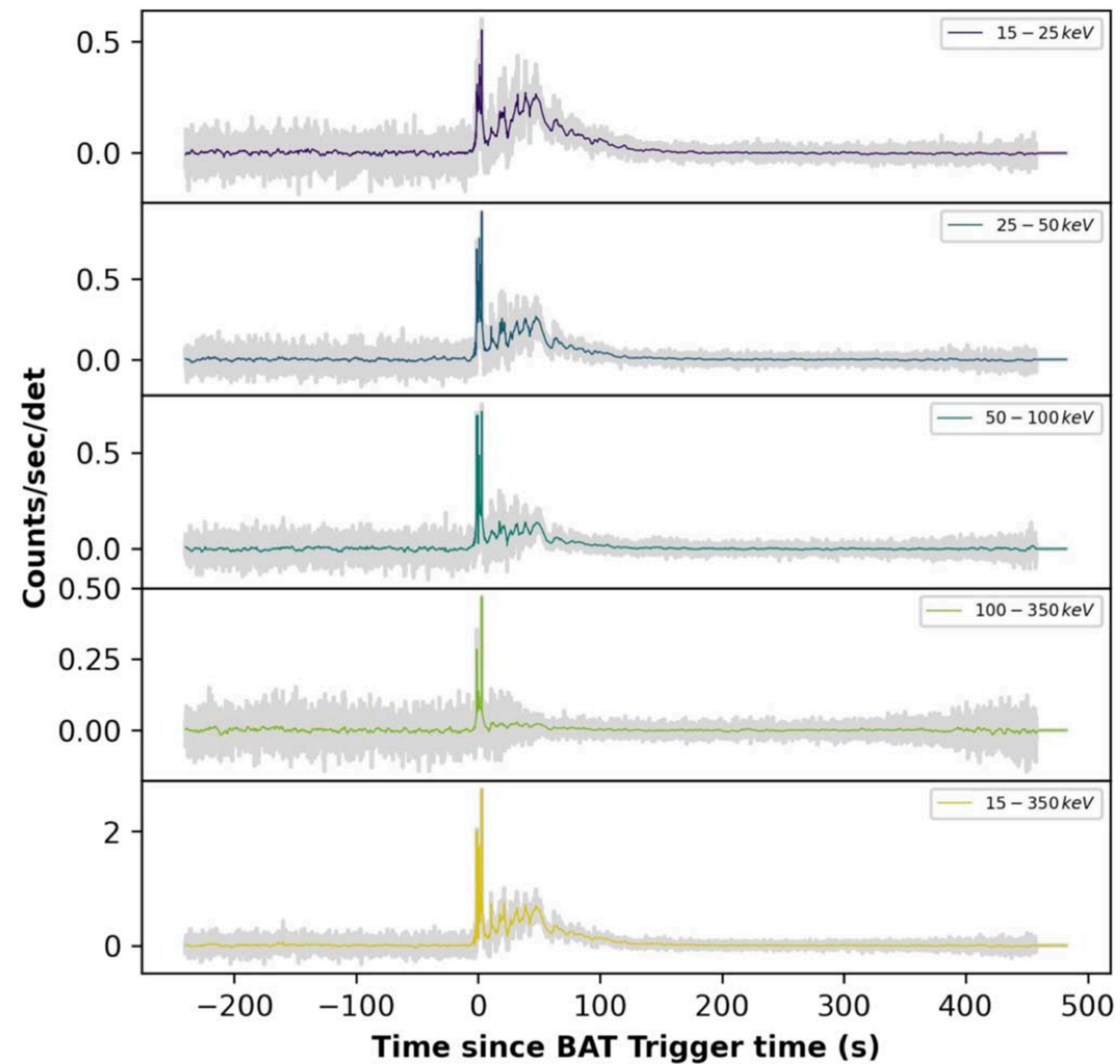
Gehrels, Ramirez-Ruiz & Fox (2009)

Jet Variability

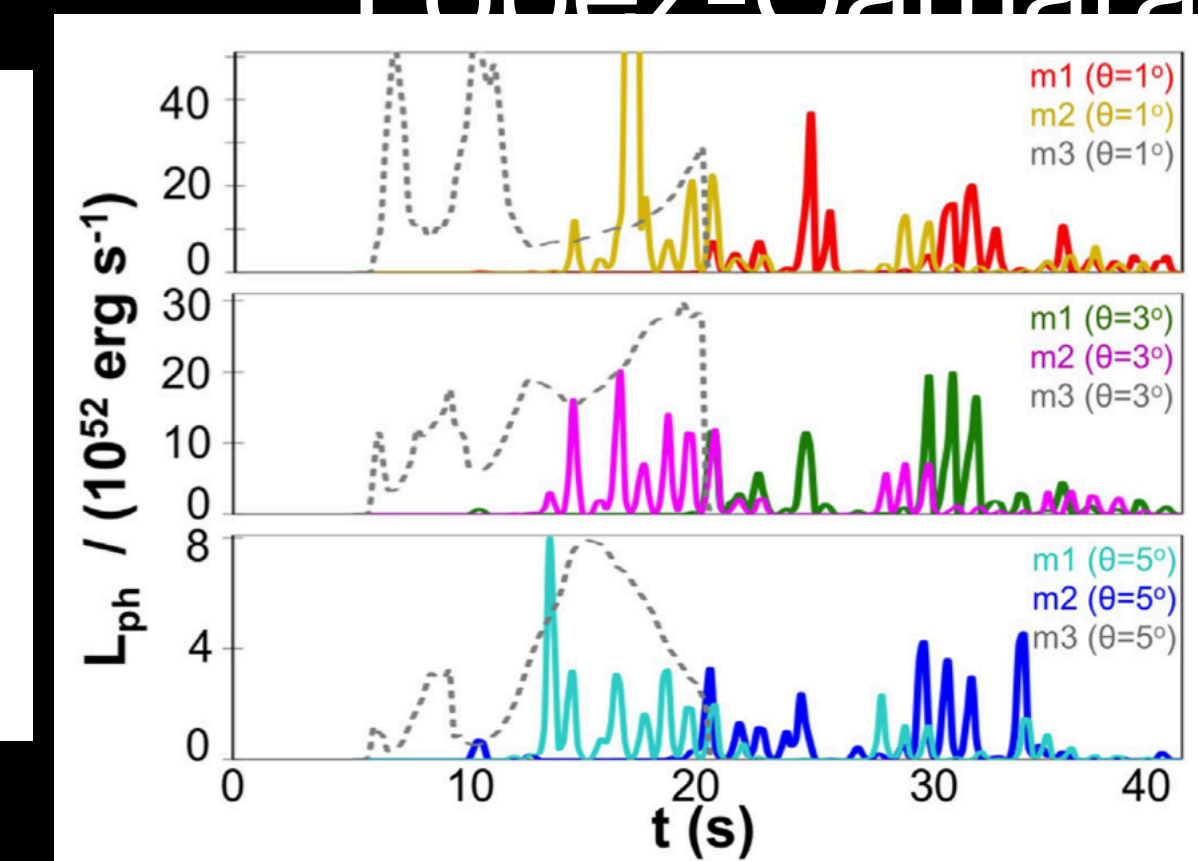
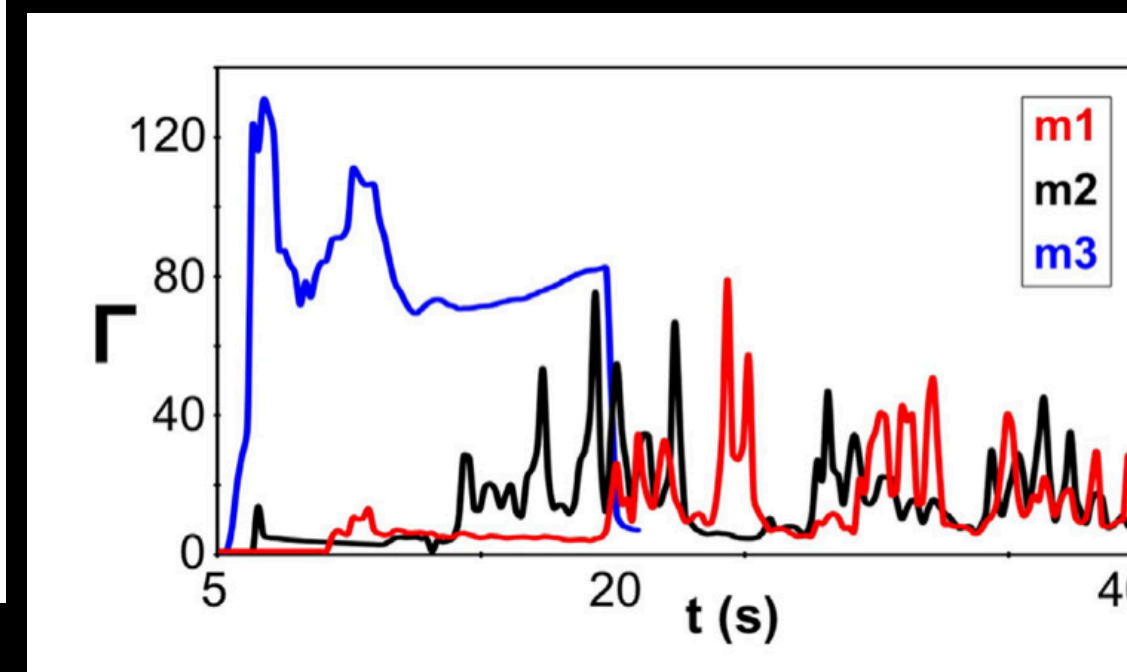
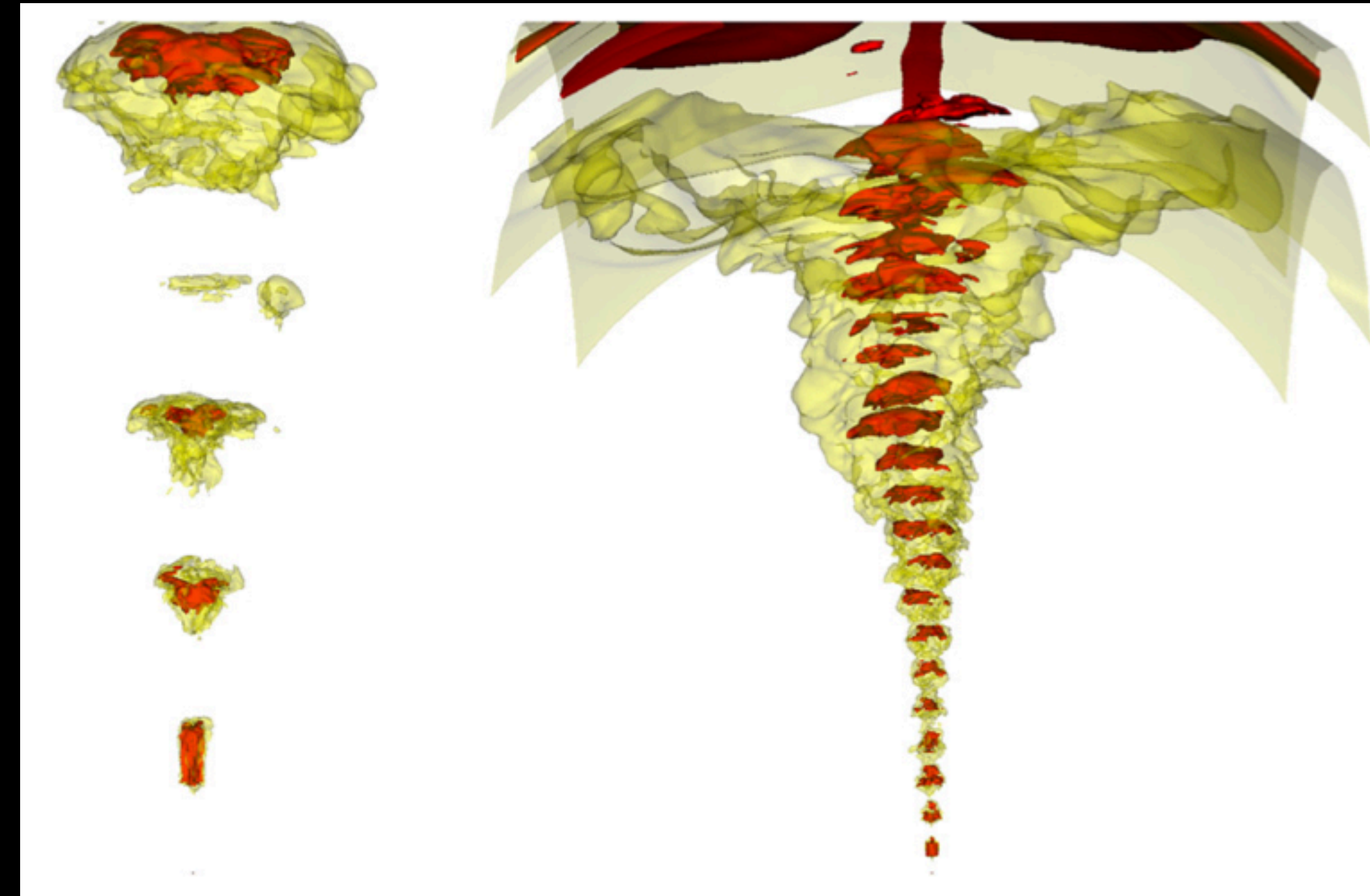
Simulations

Lazzati 2015

Observational data

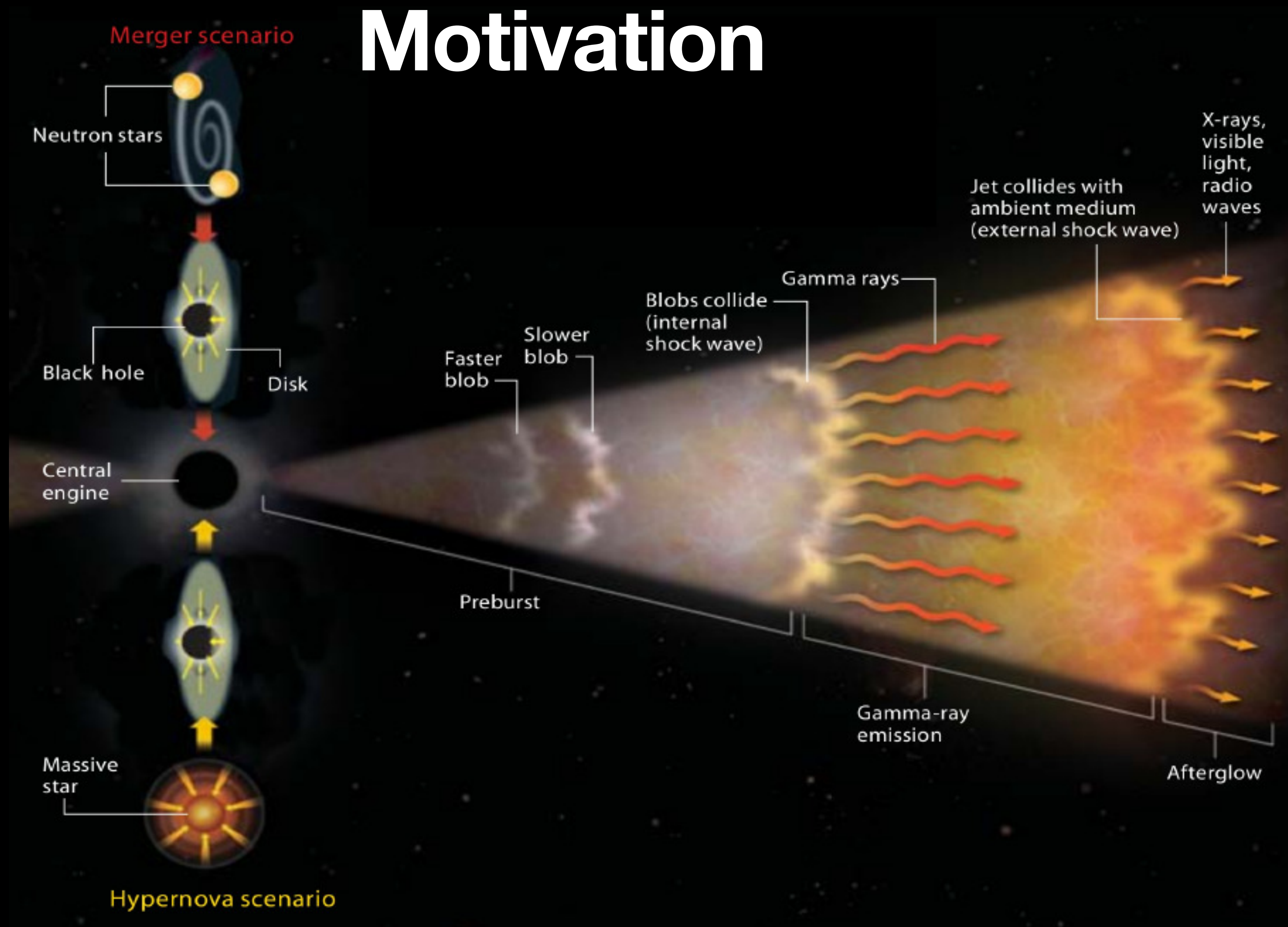


GRB060614, from Gracia-Cifuentes, Becerra & De Colle (2023)

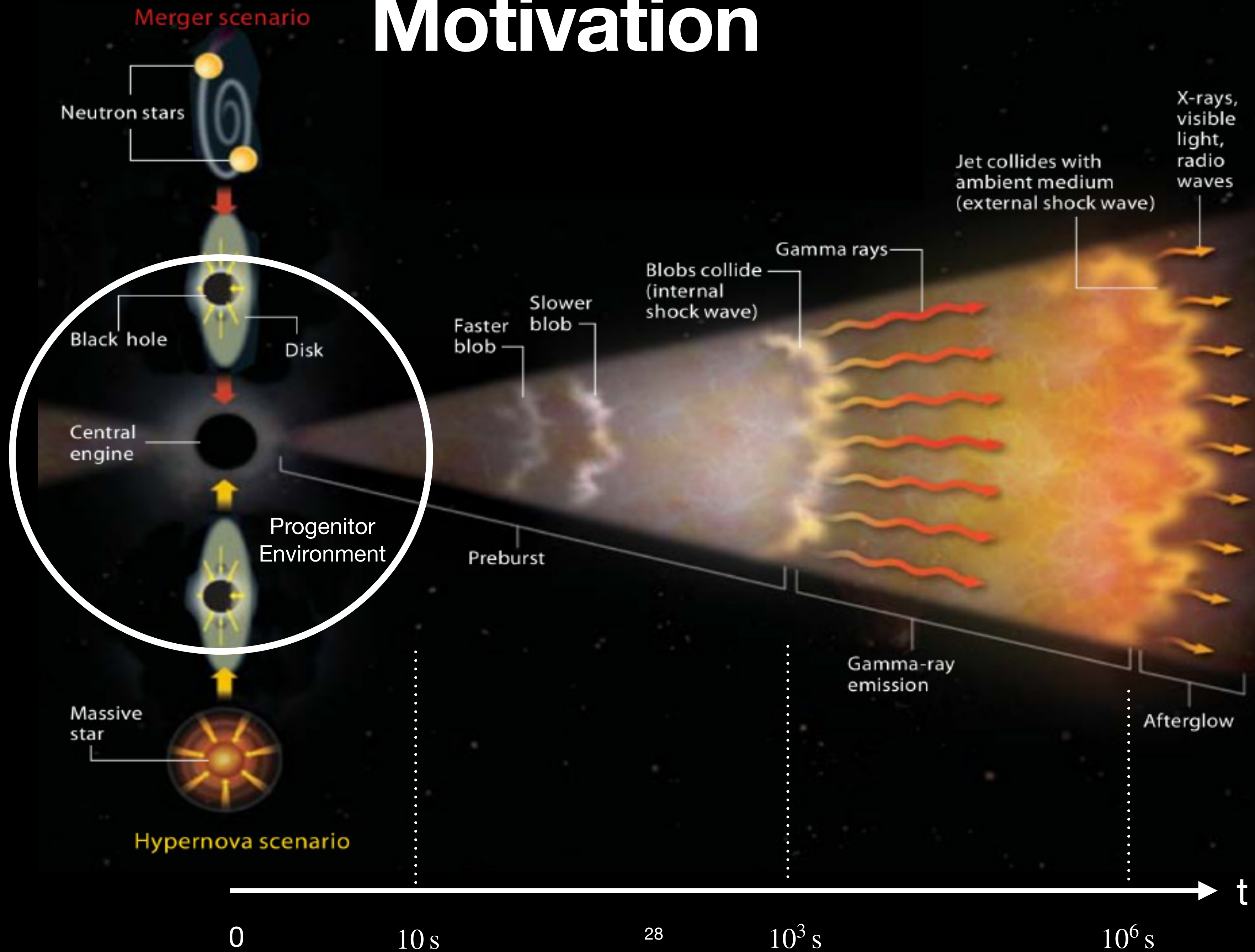


Motivation

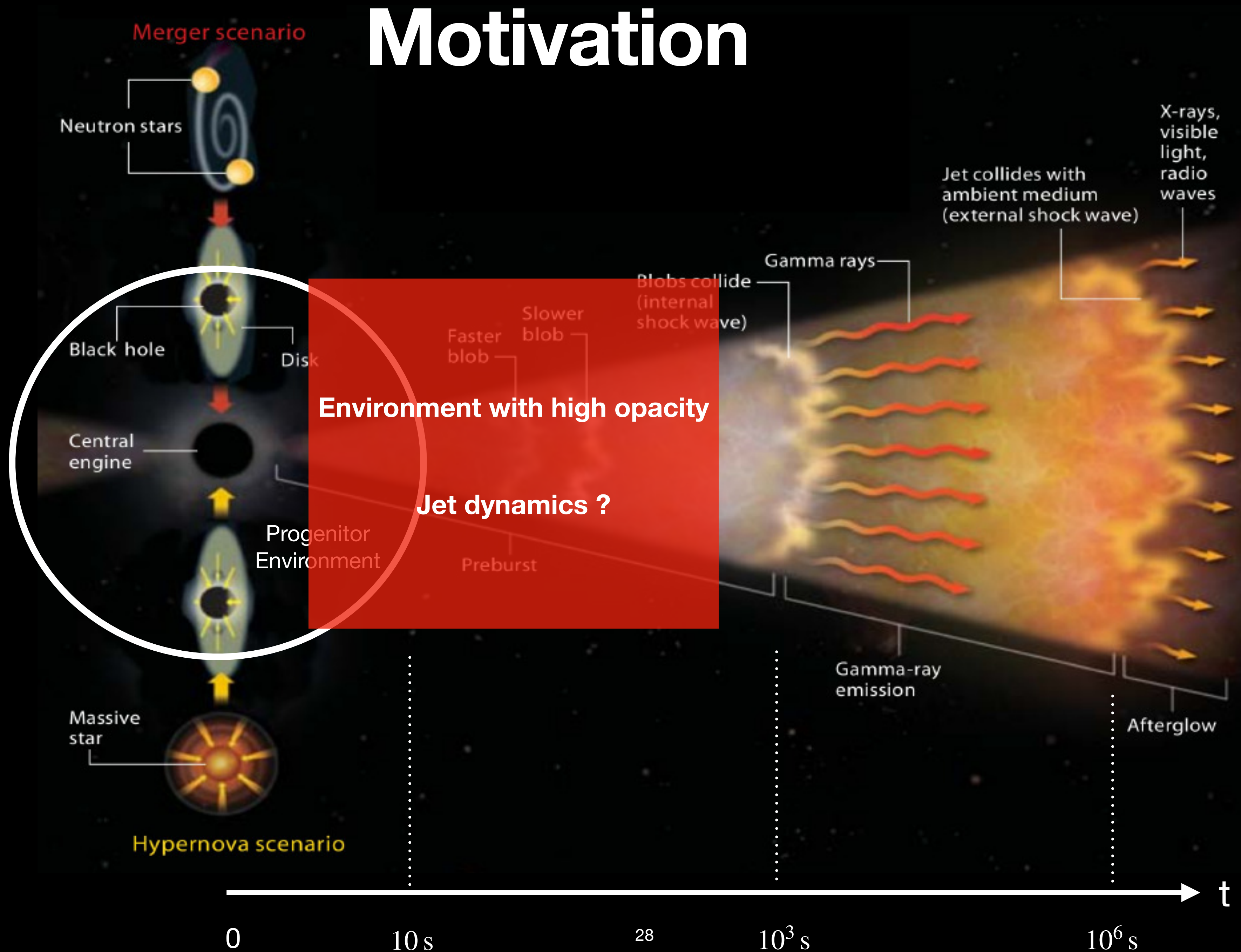
Motivation



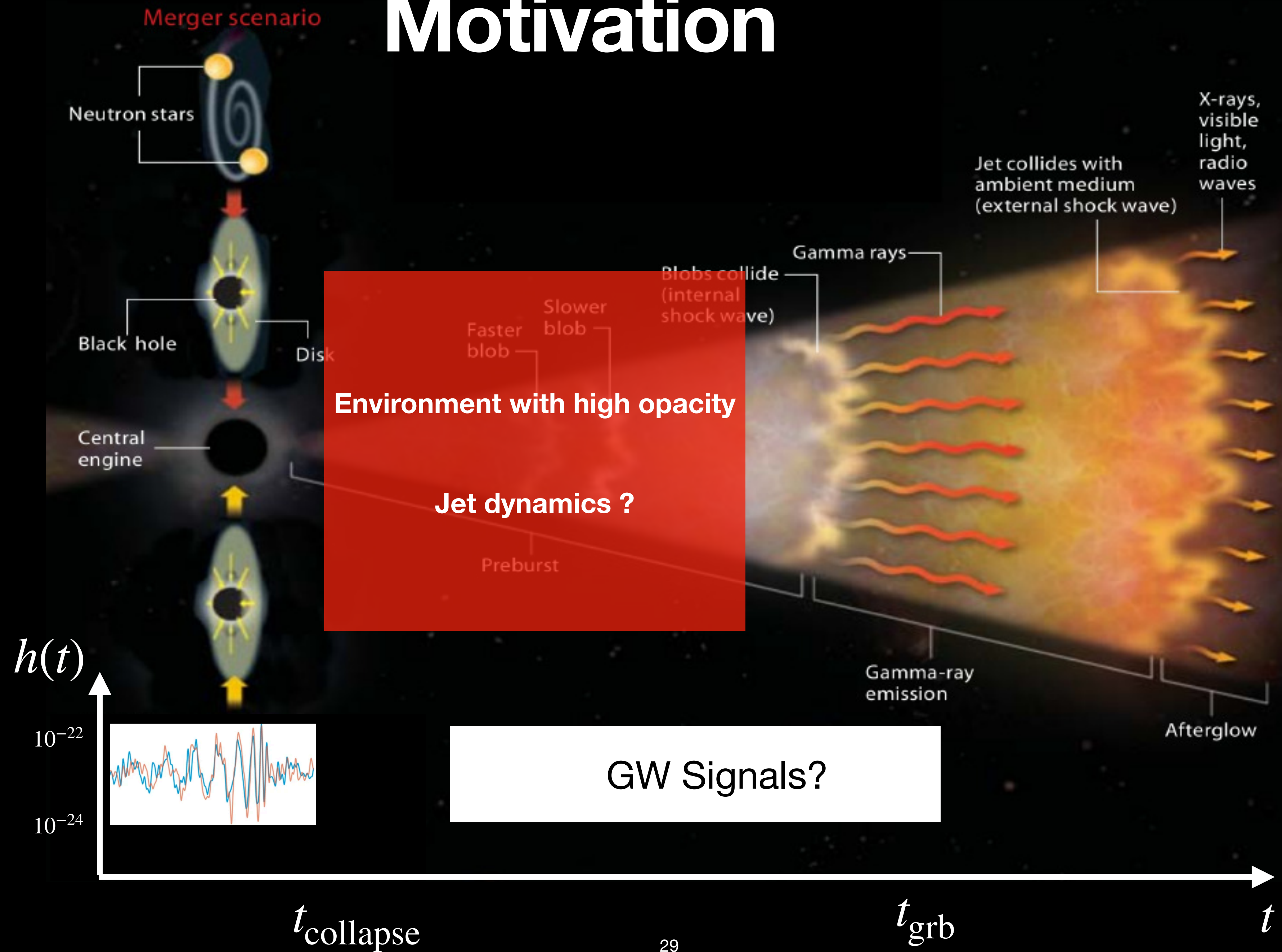
Motivation



Motivation



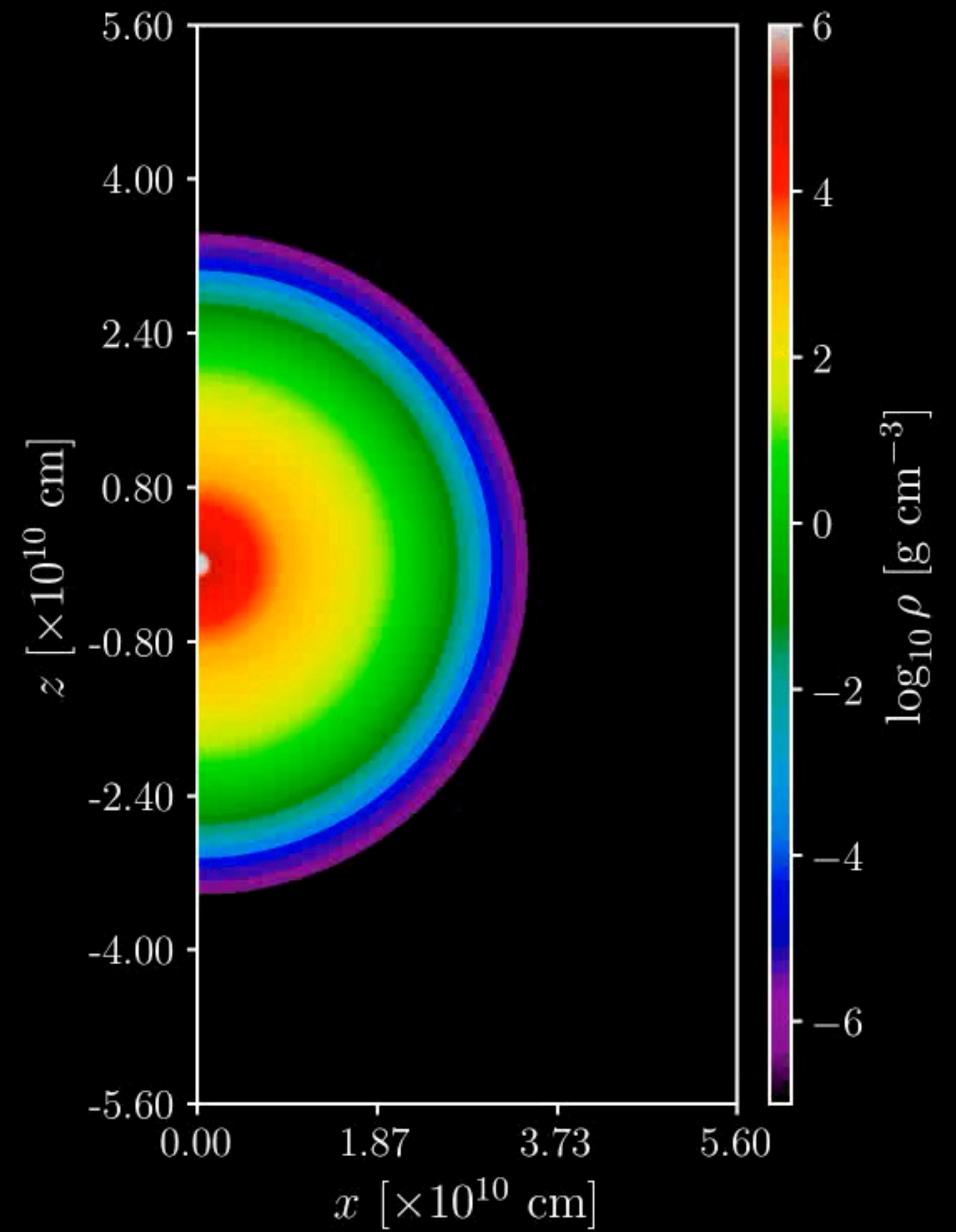
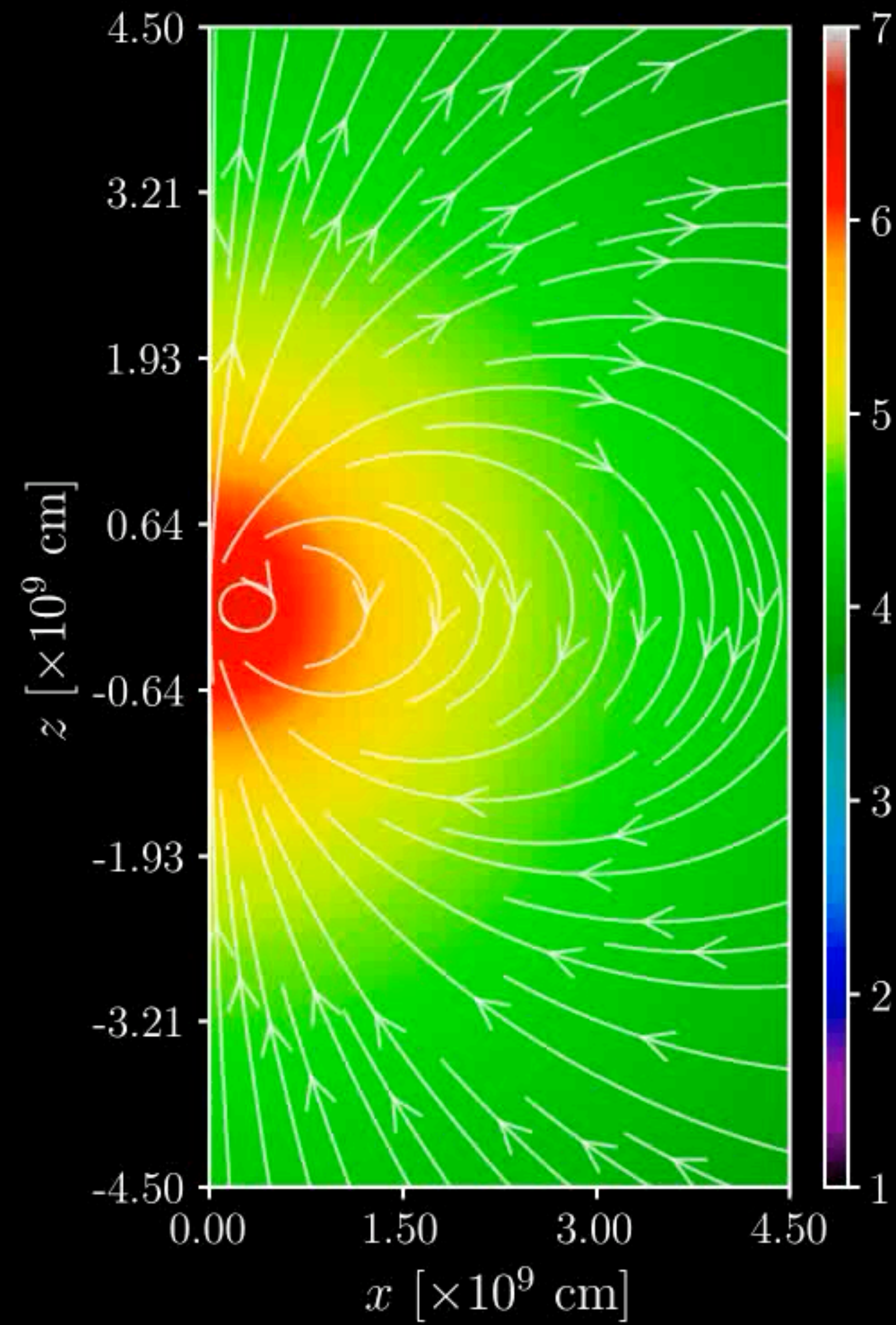
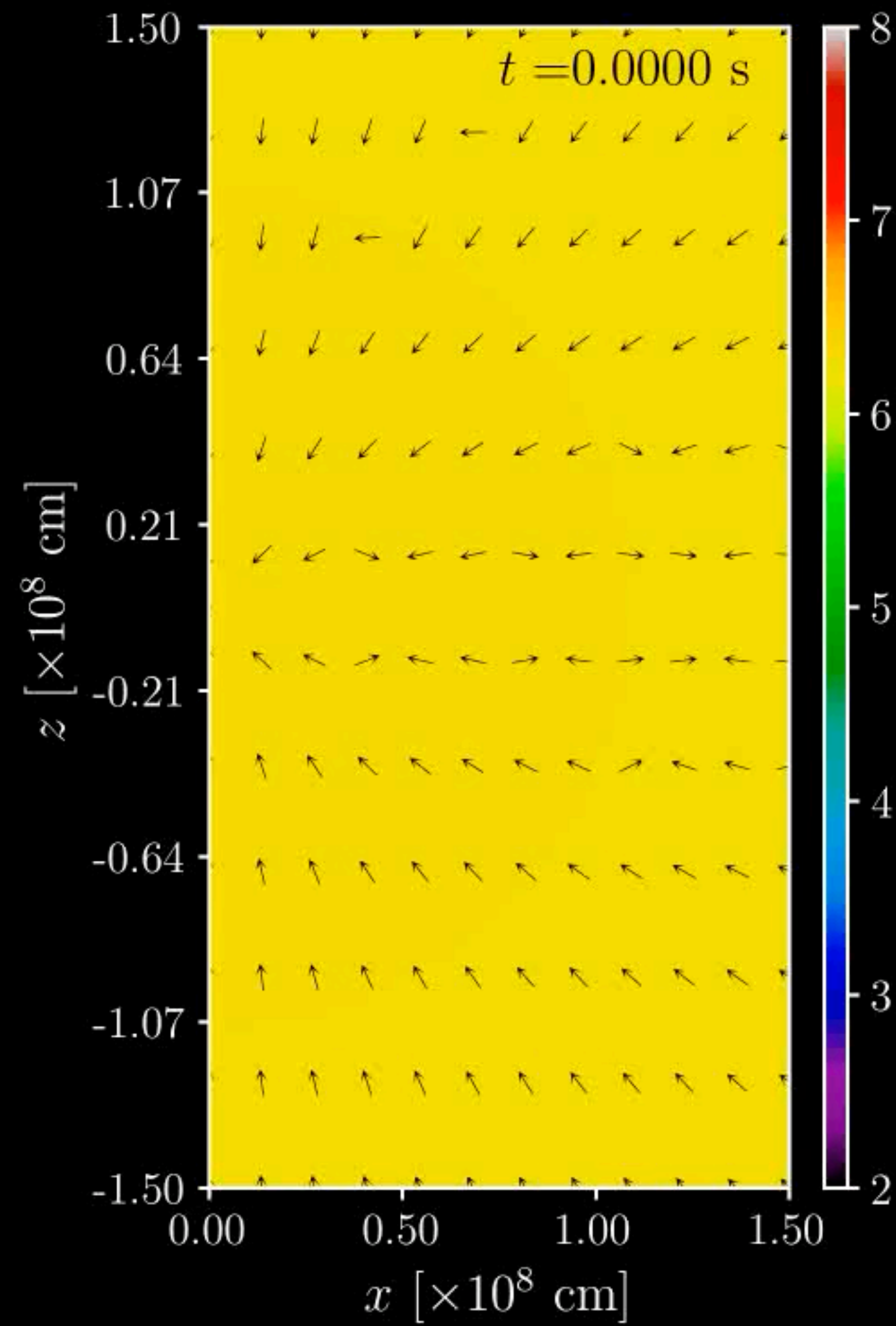
Motivation

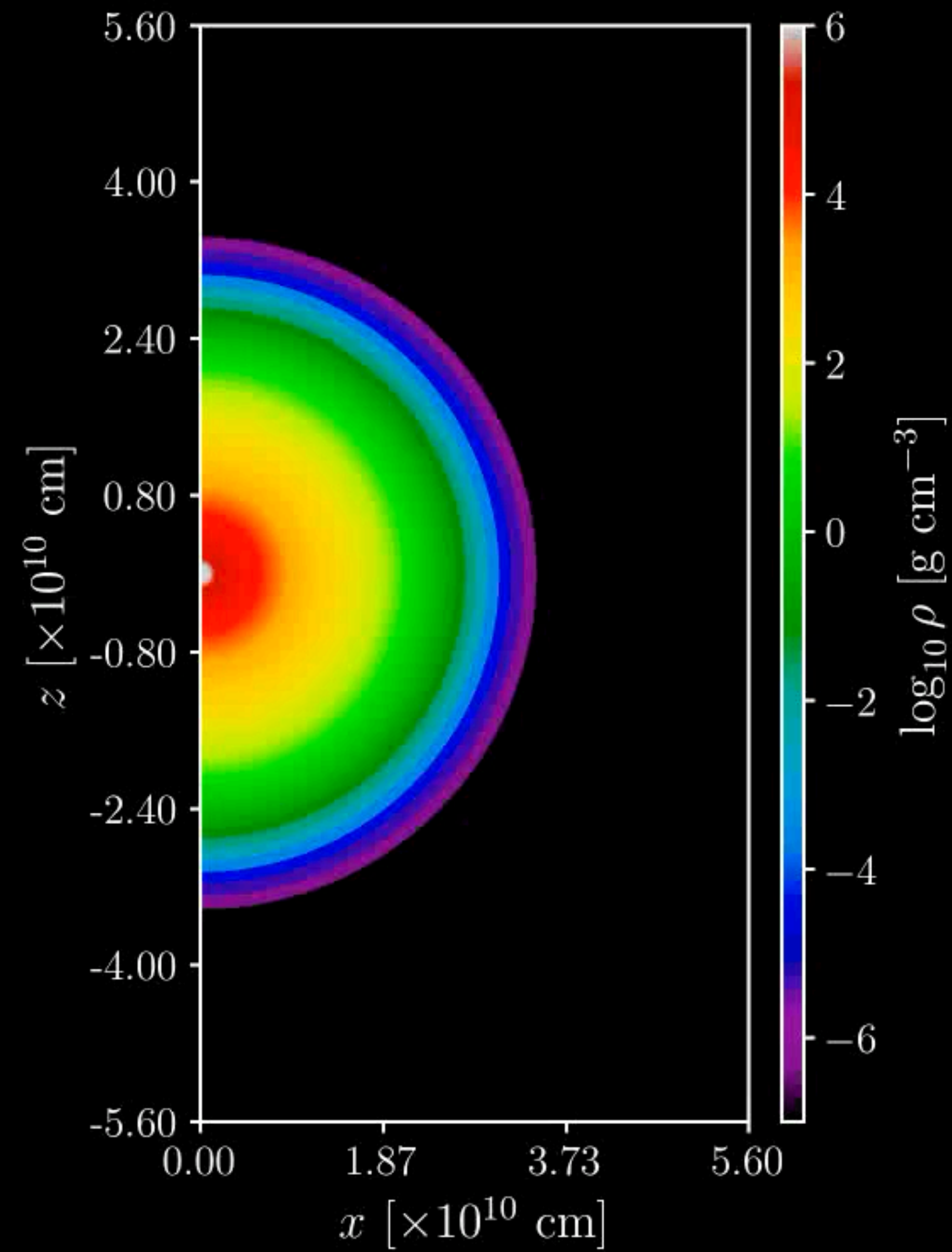
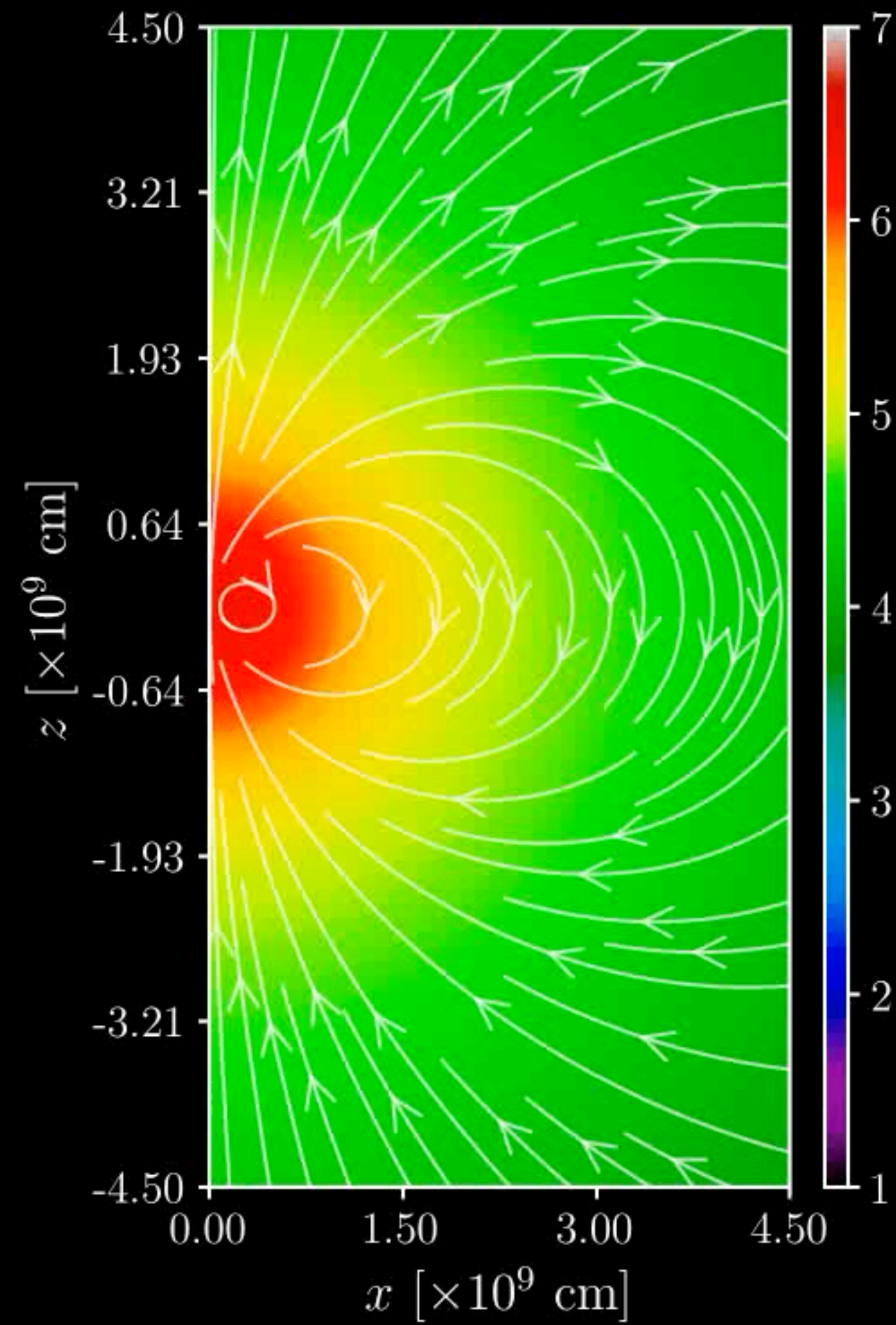
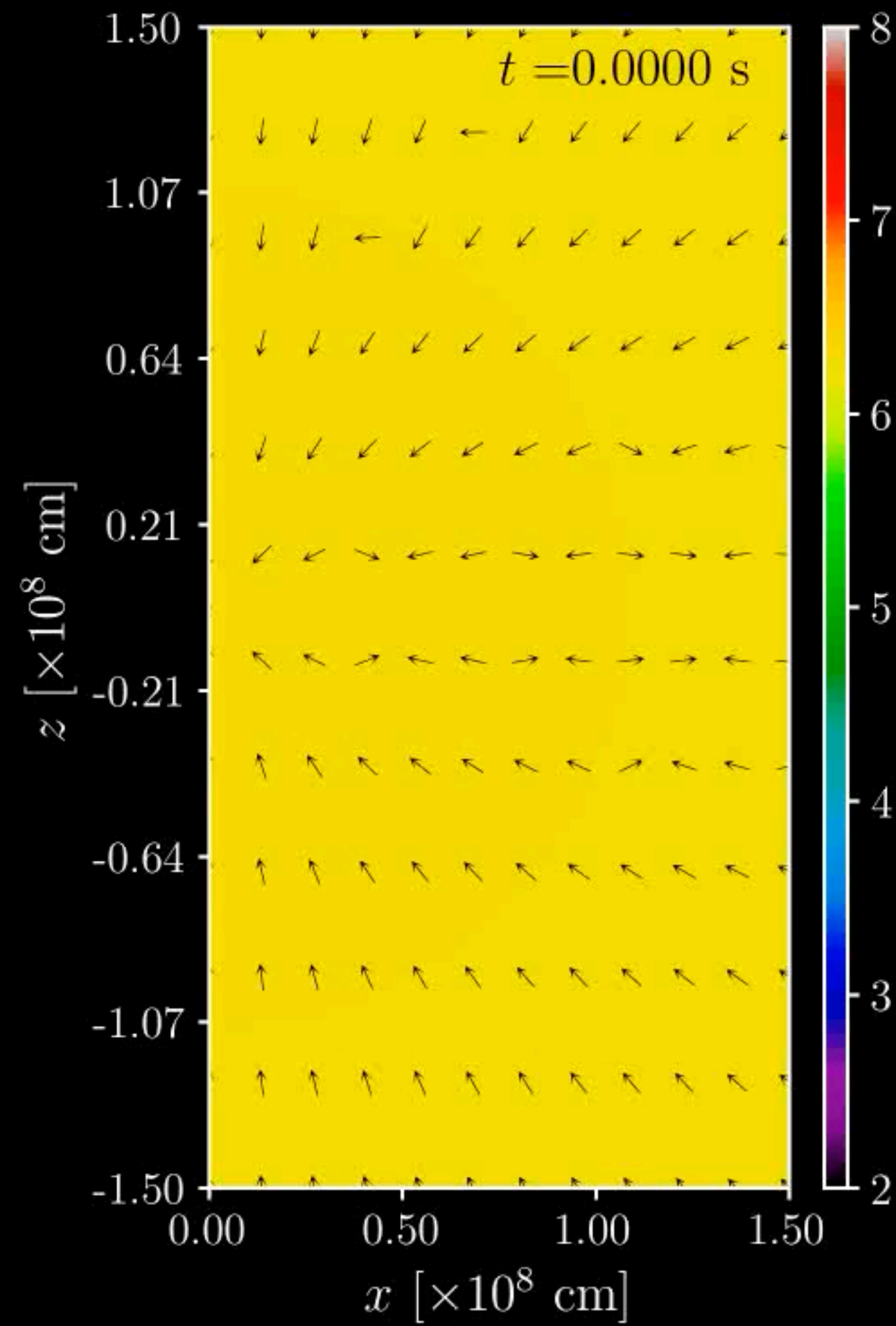


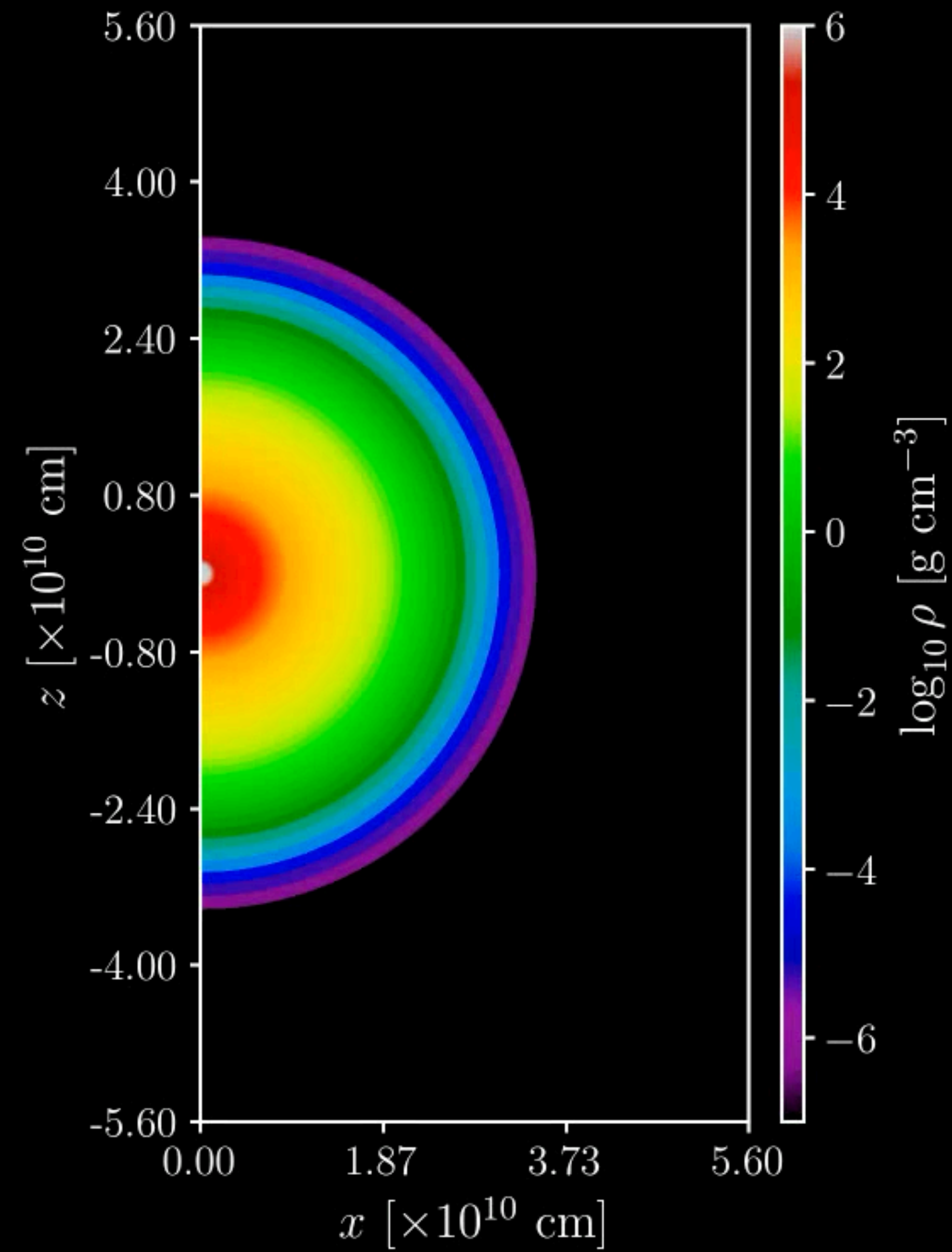
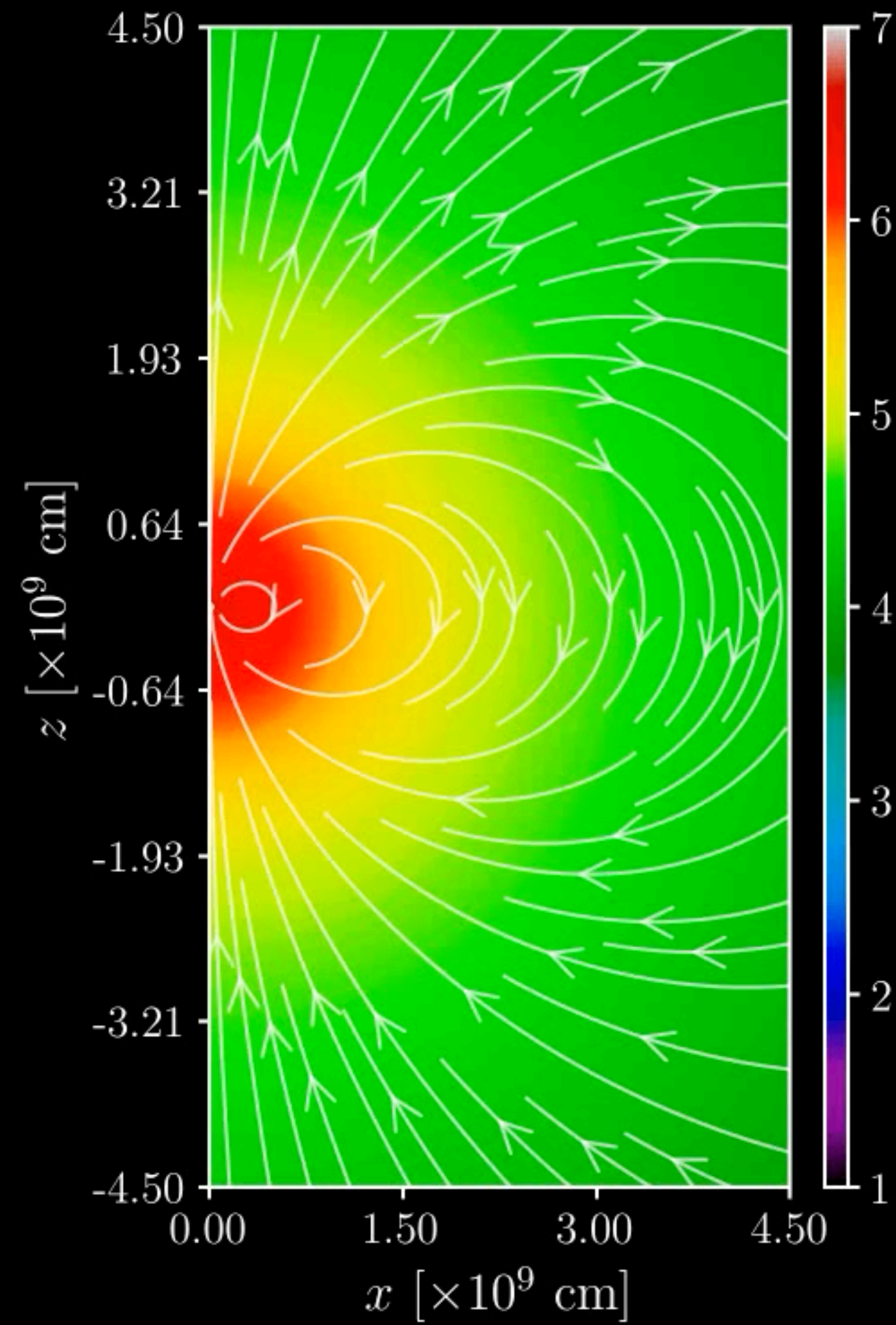
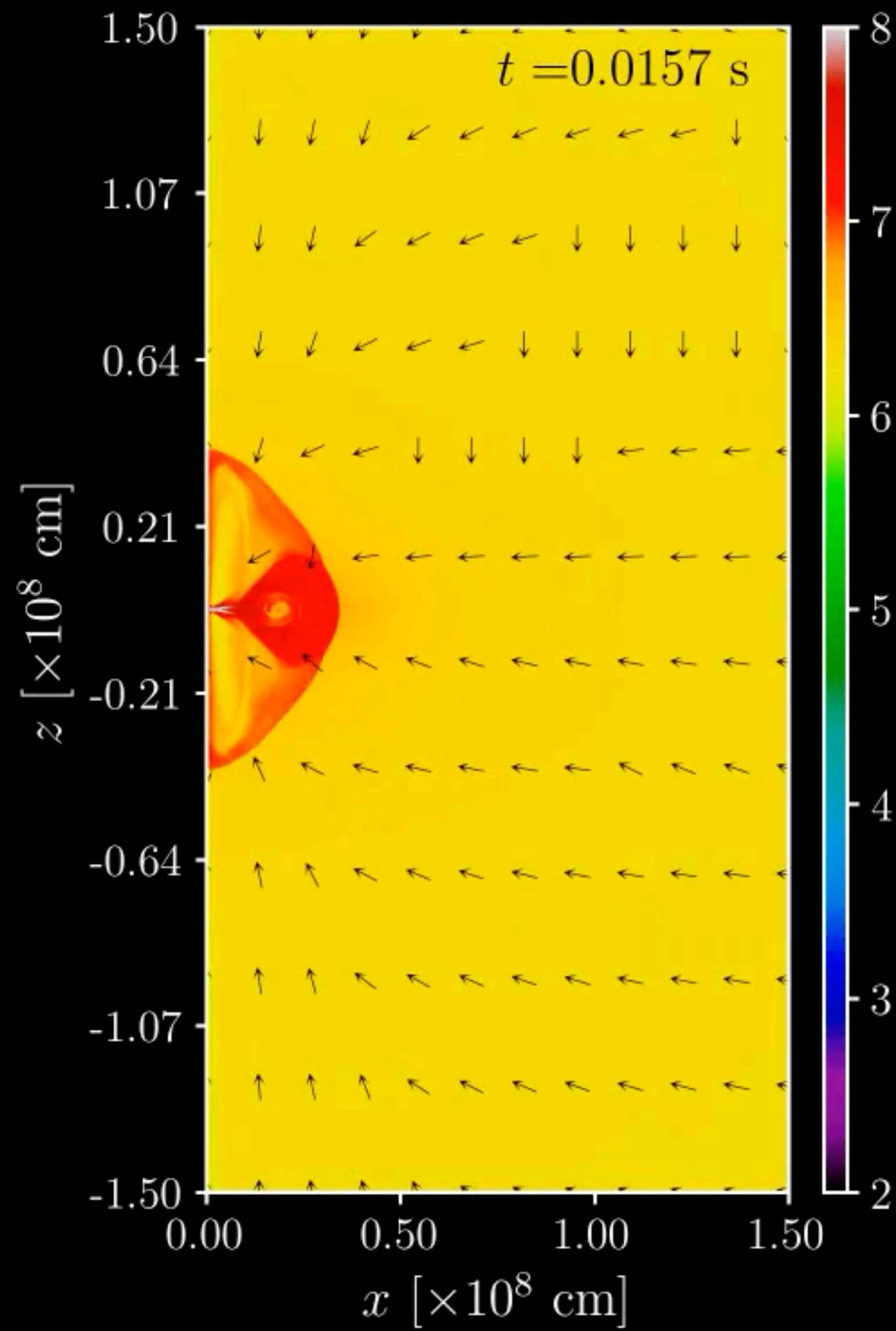
Merging GW signals and EM signals

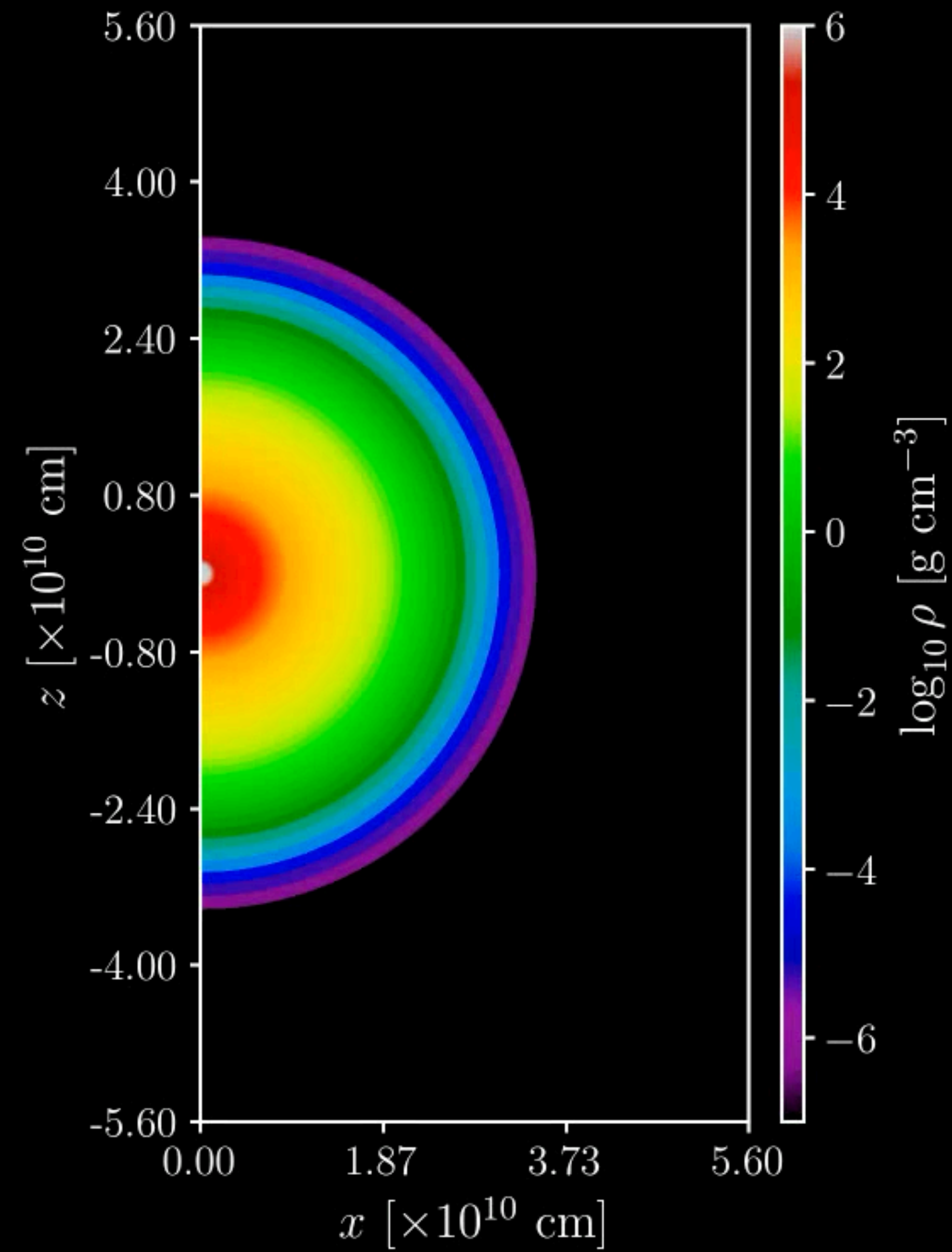
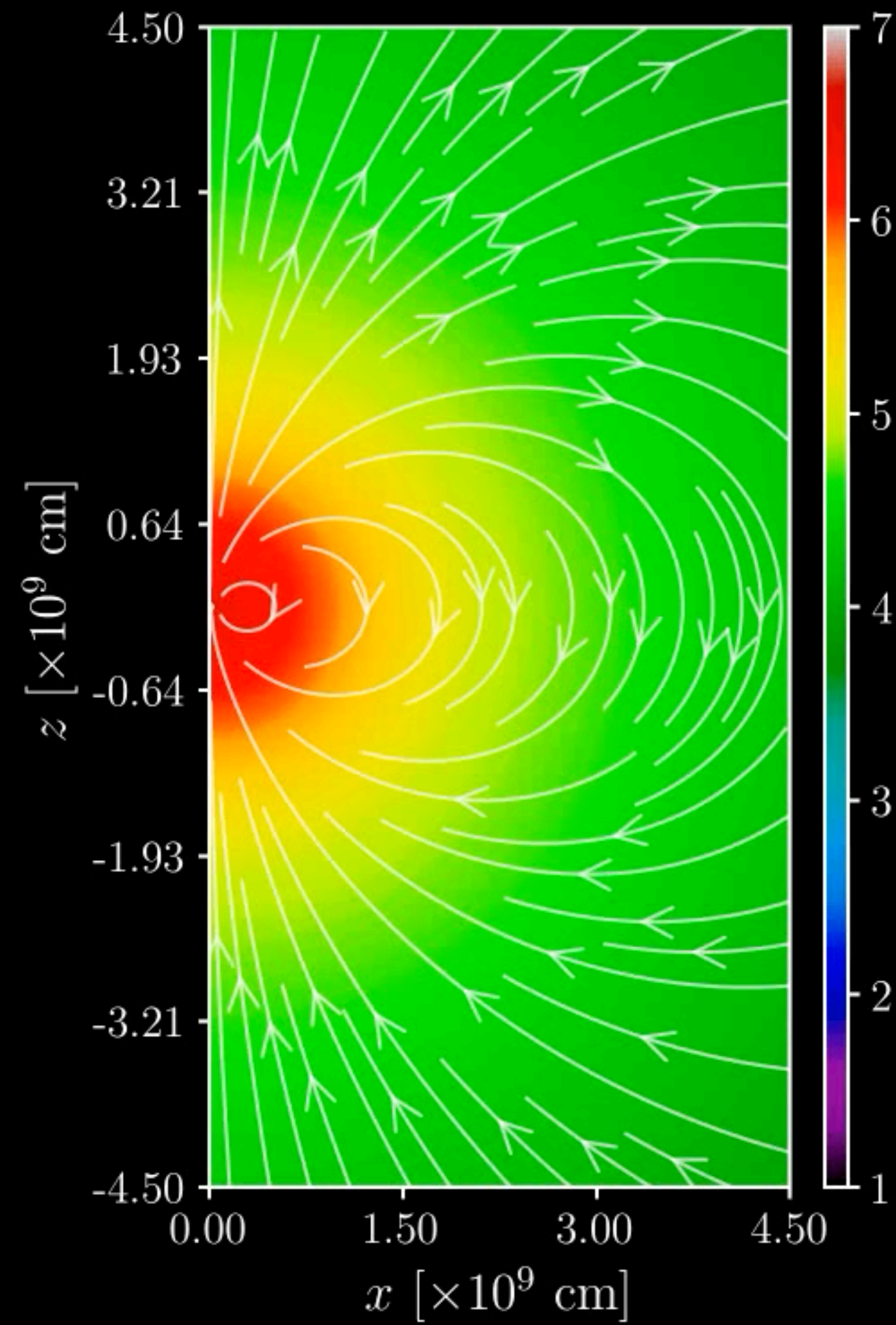
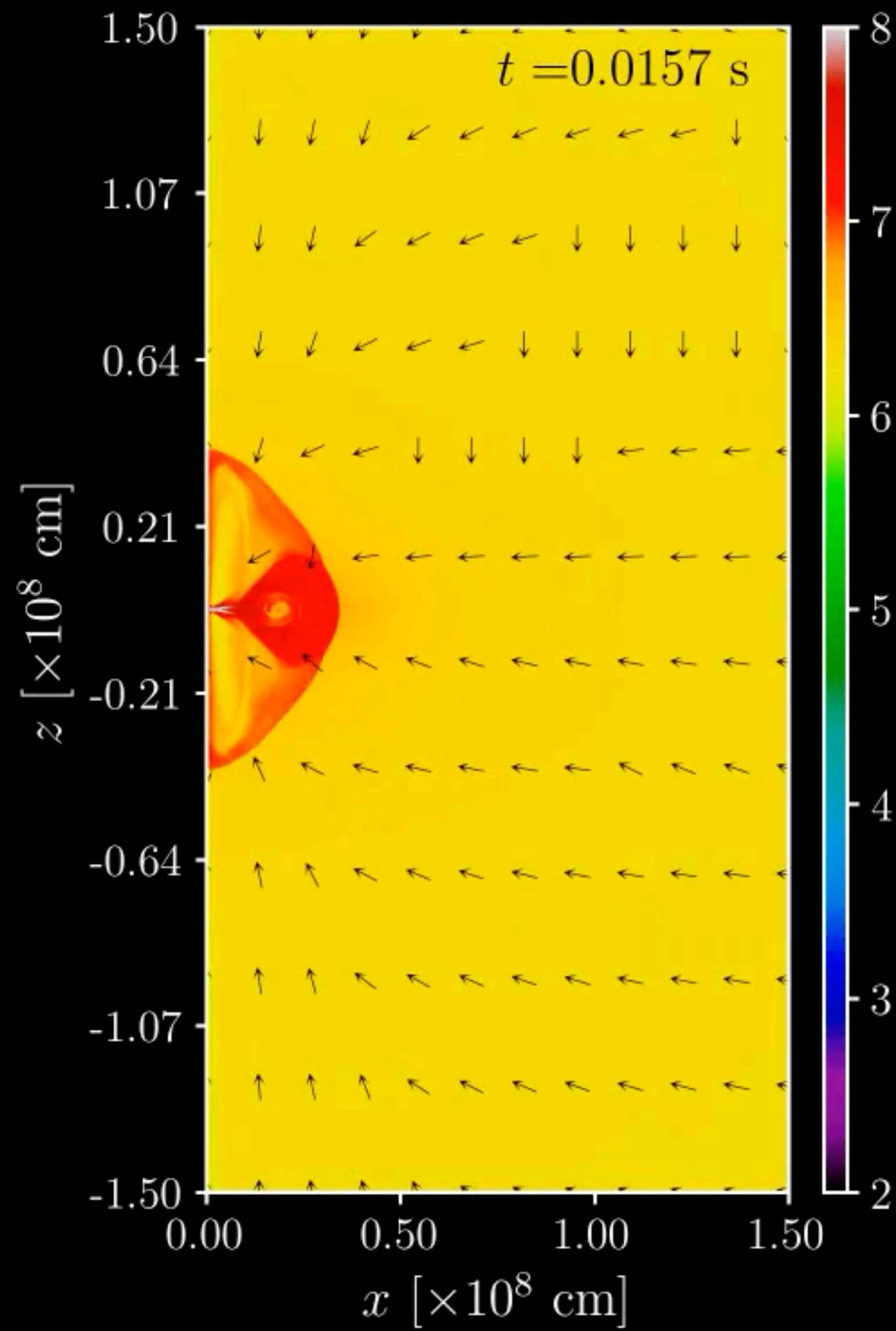
Main question

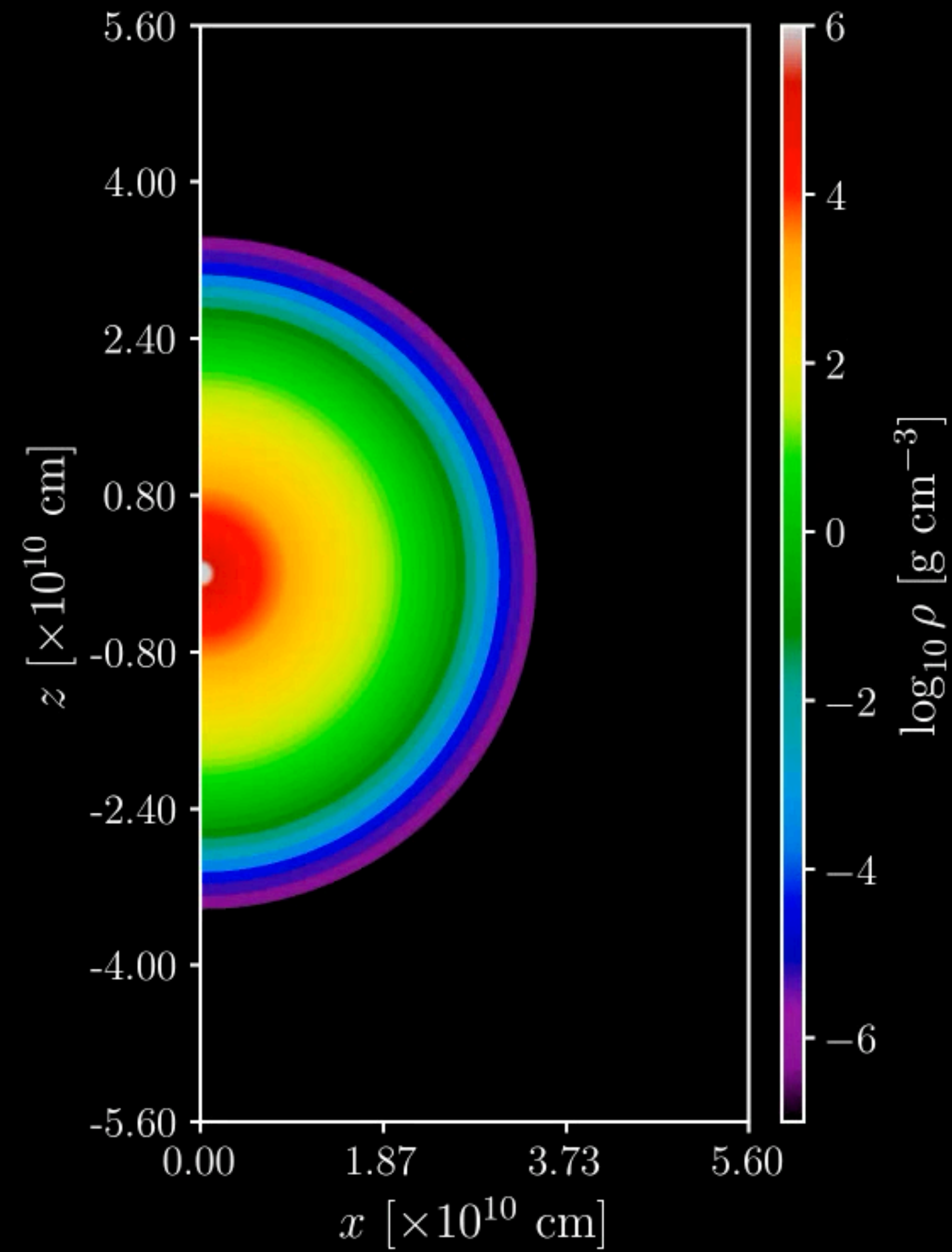
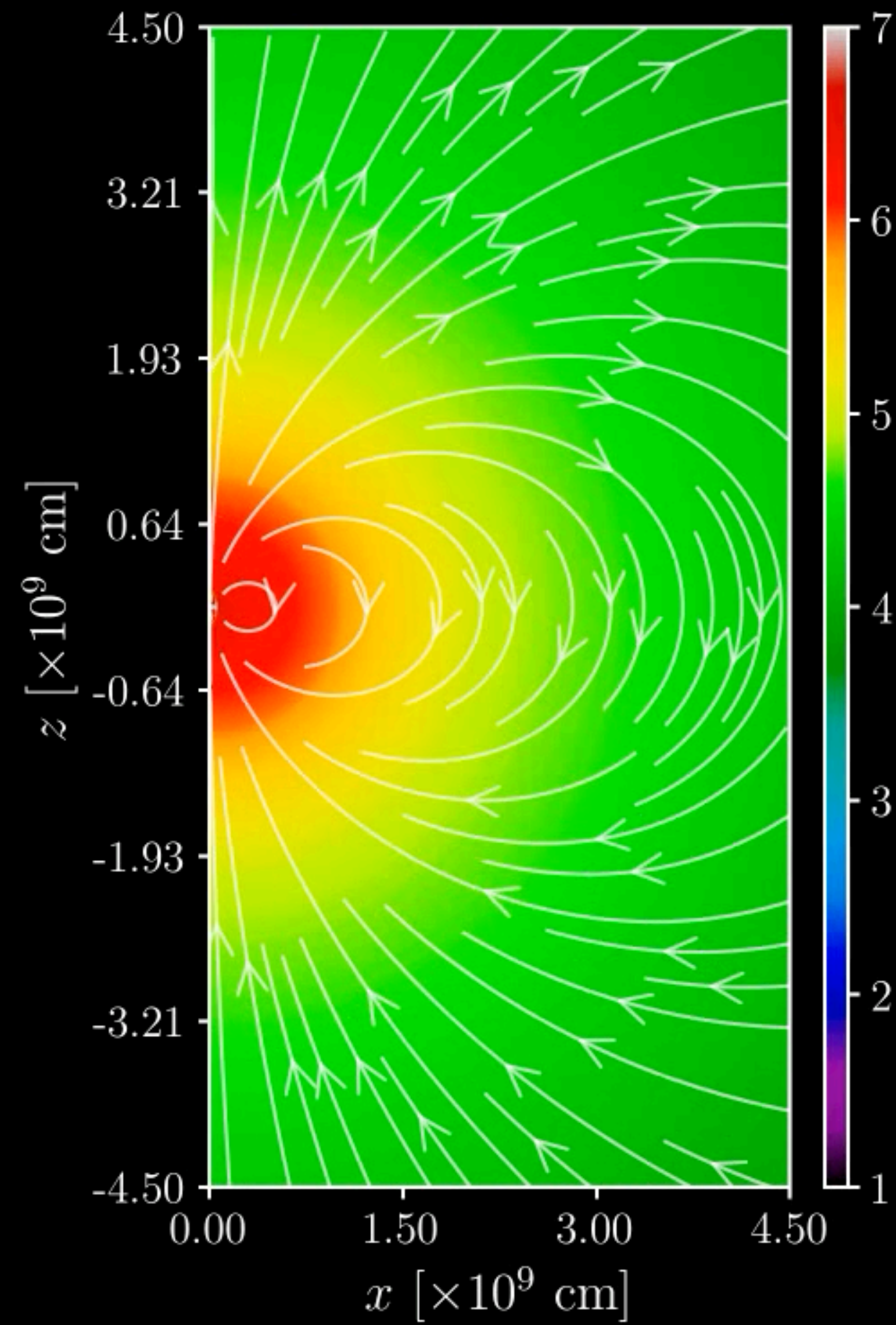
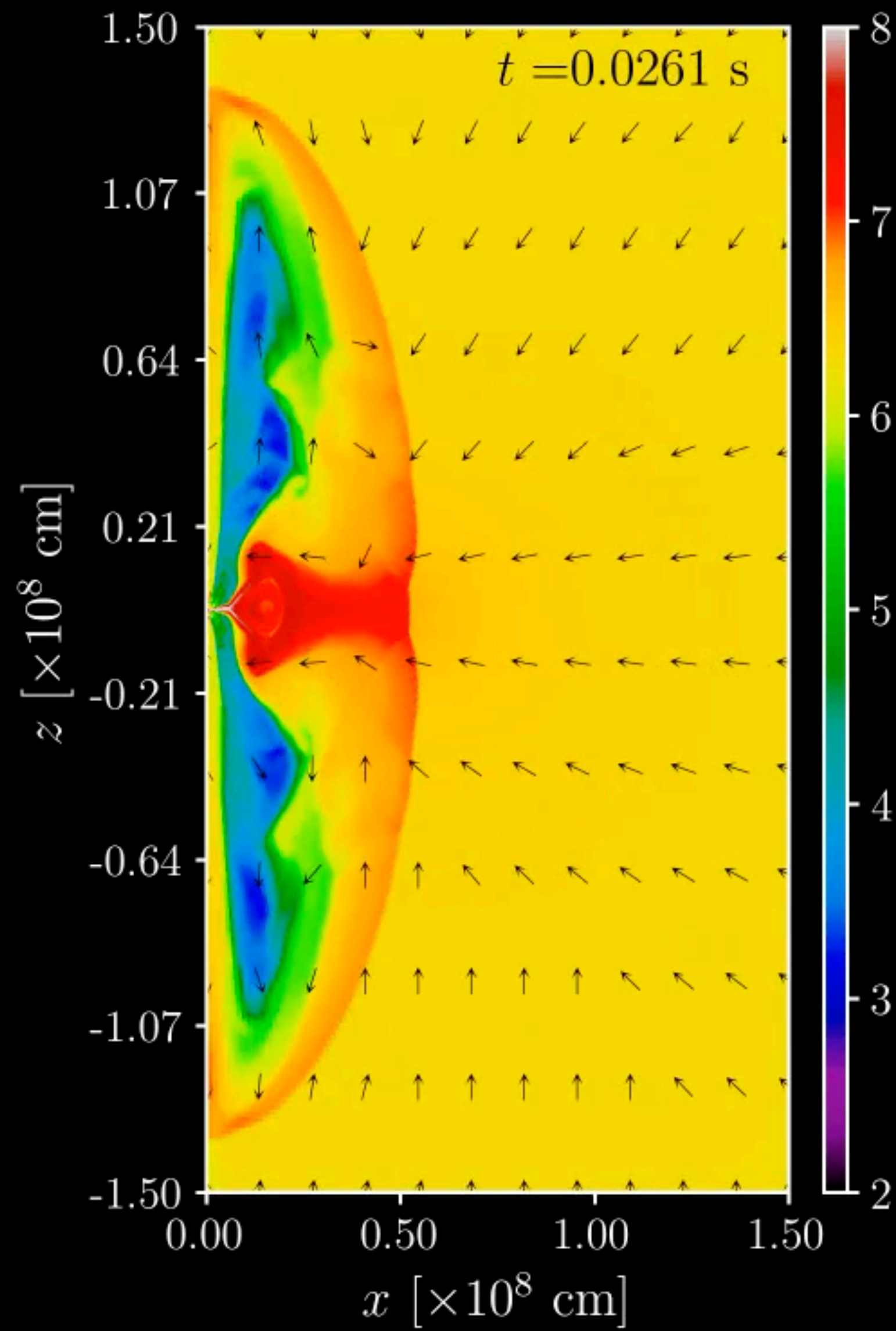
Can central-engine variability and energy injection in collapsar jets produce detectable GW signals?

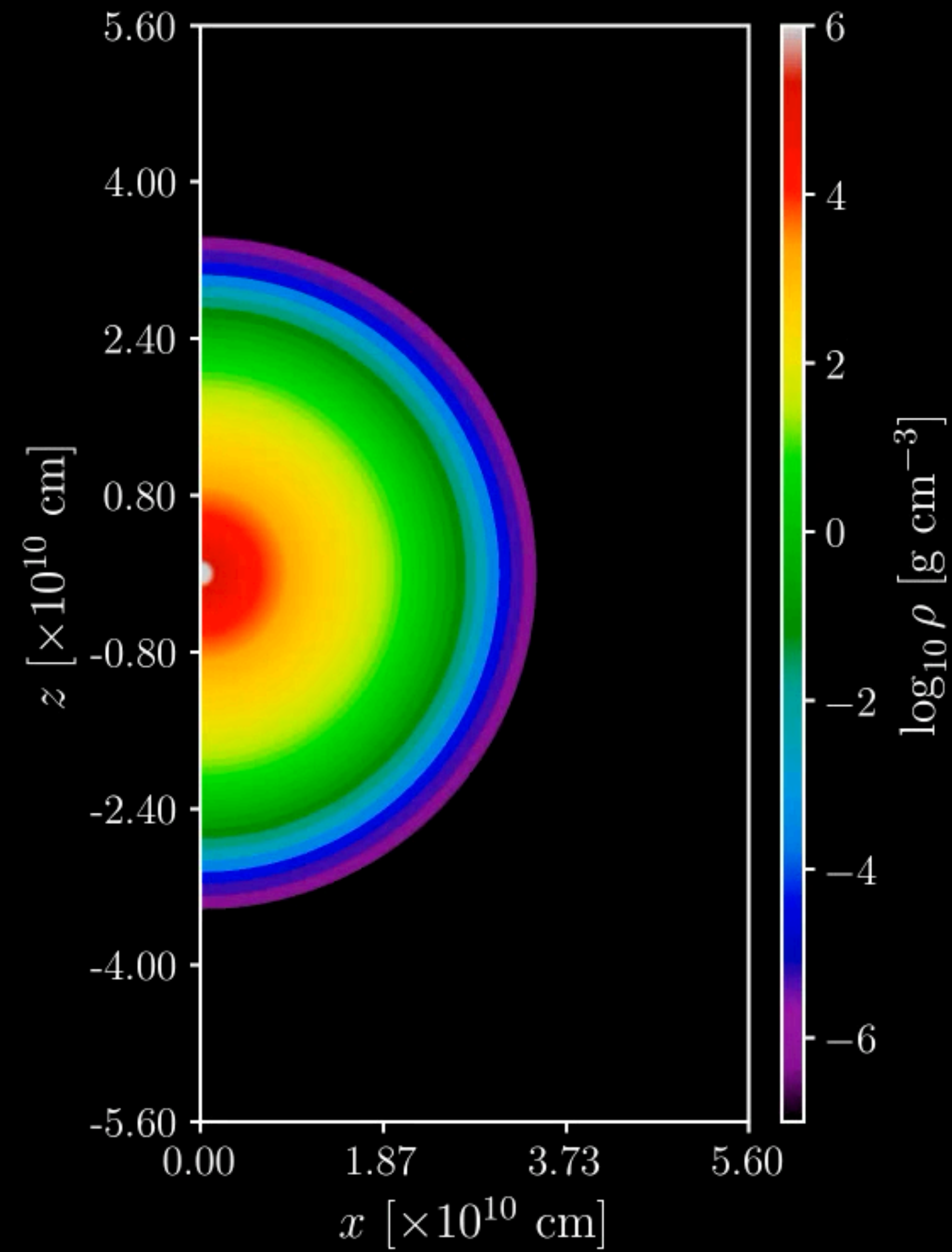
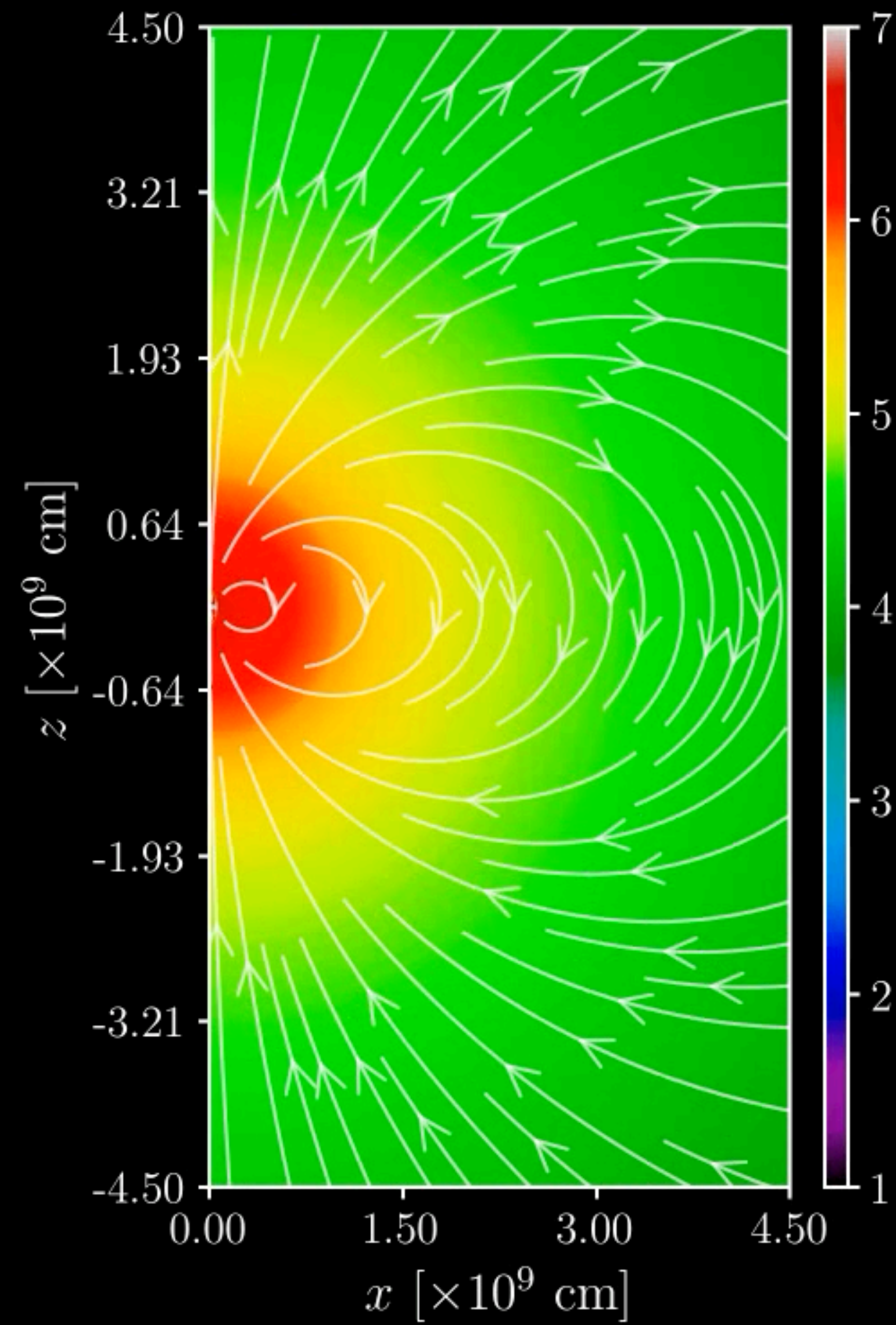
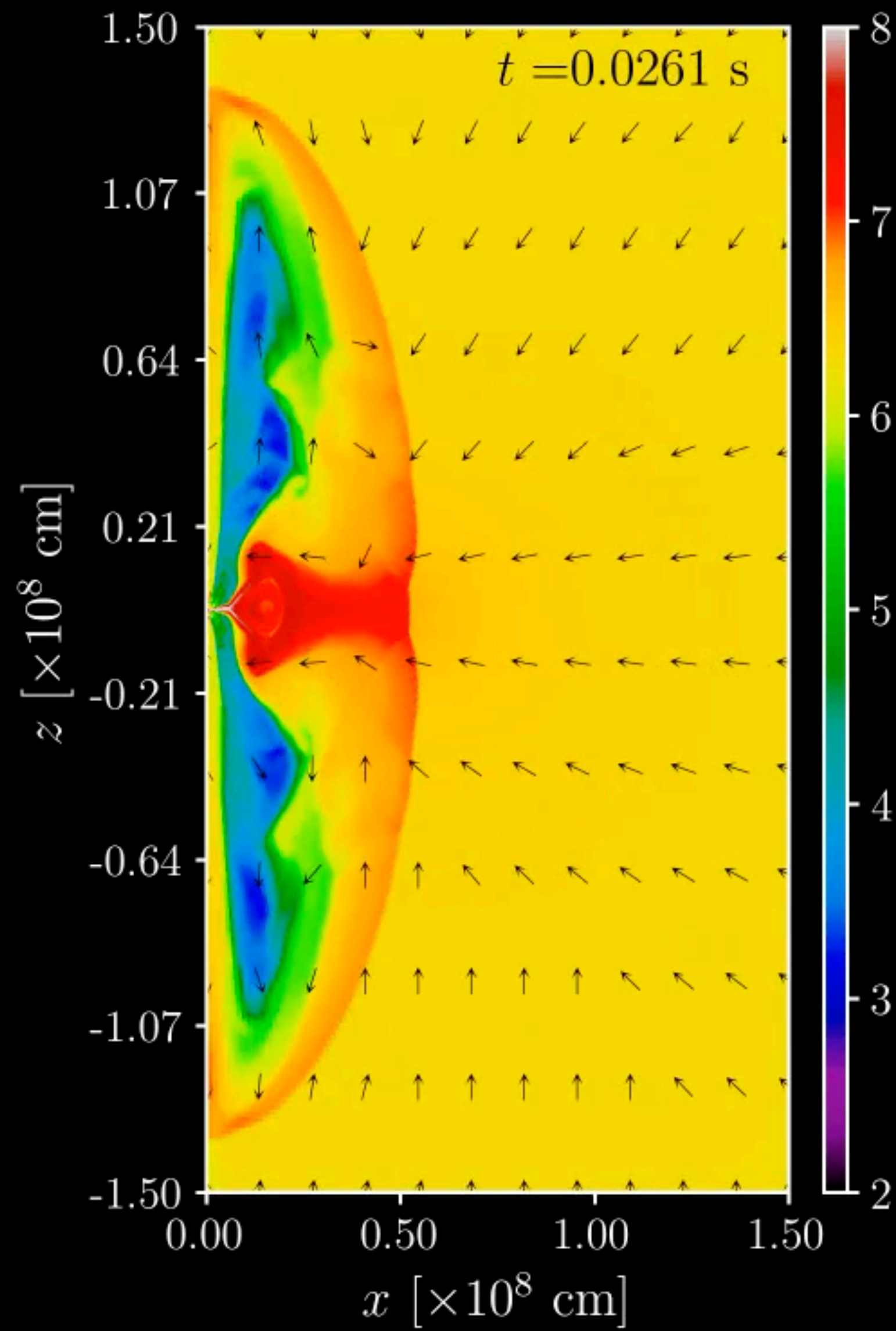


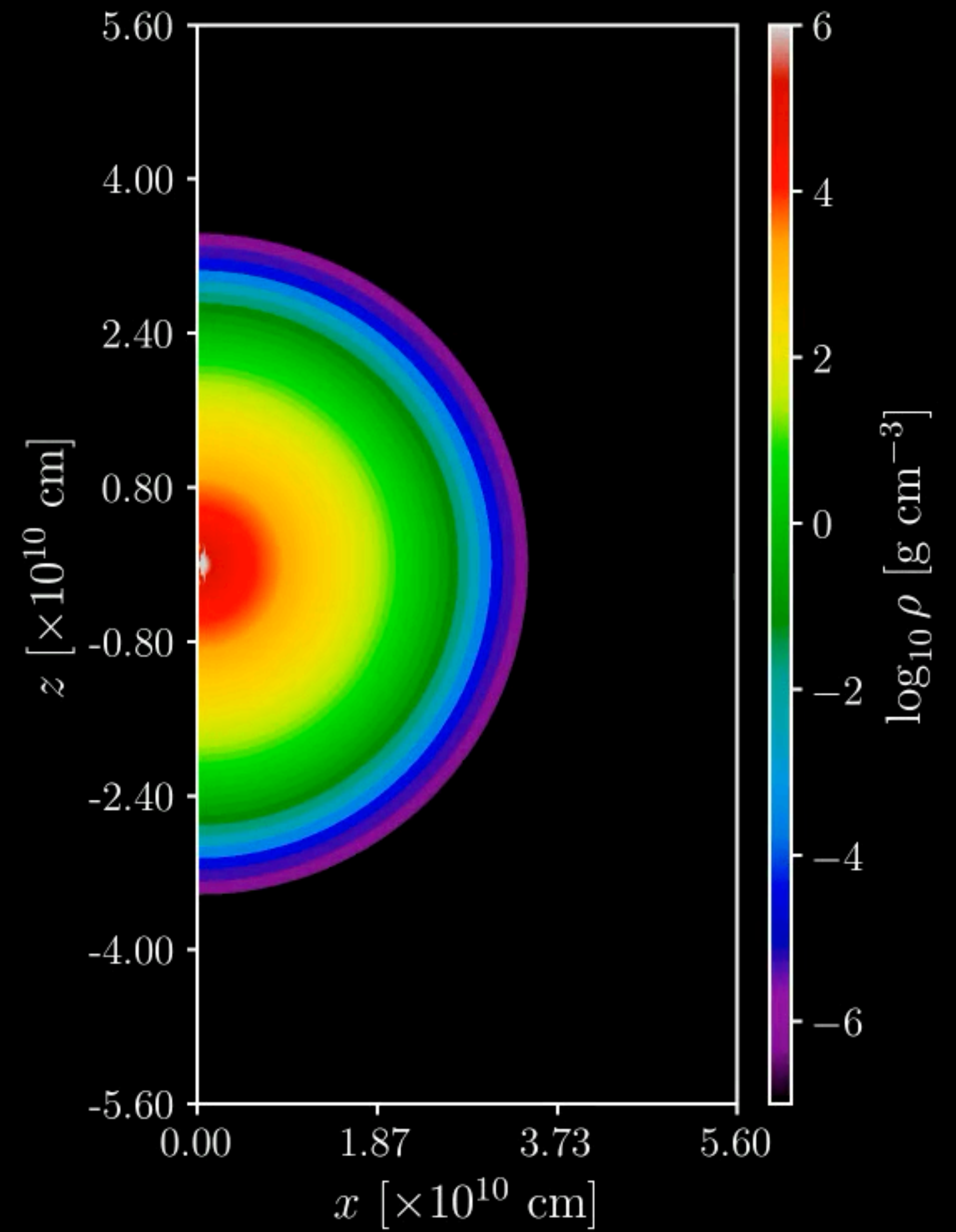
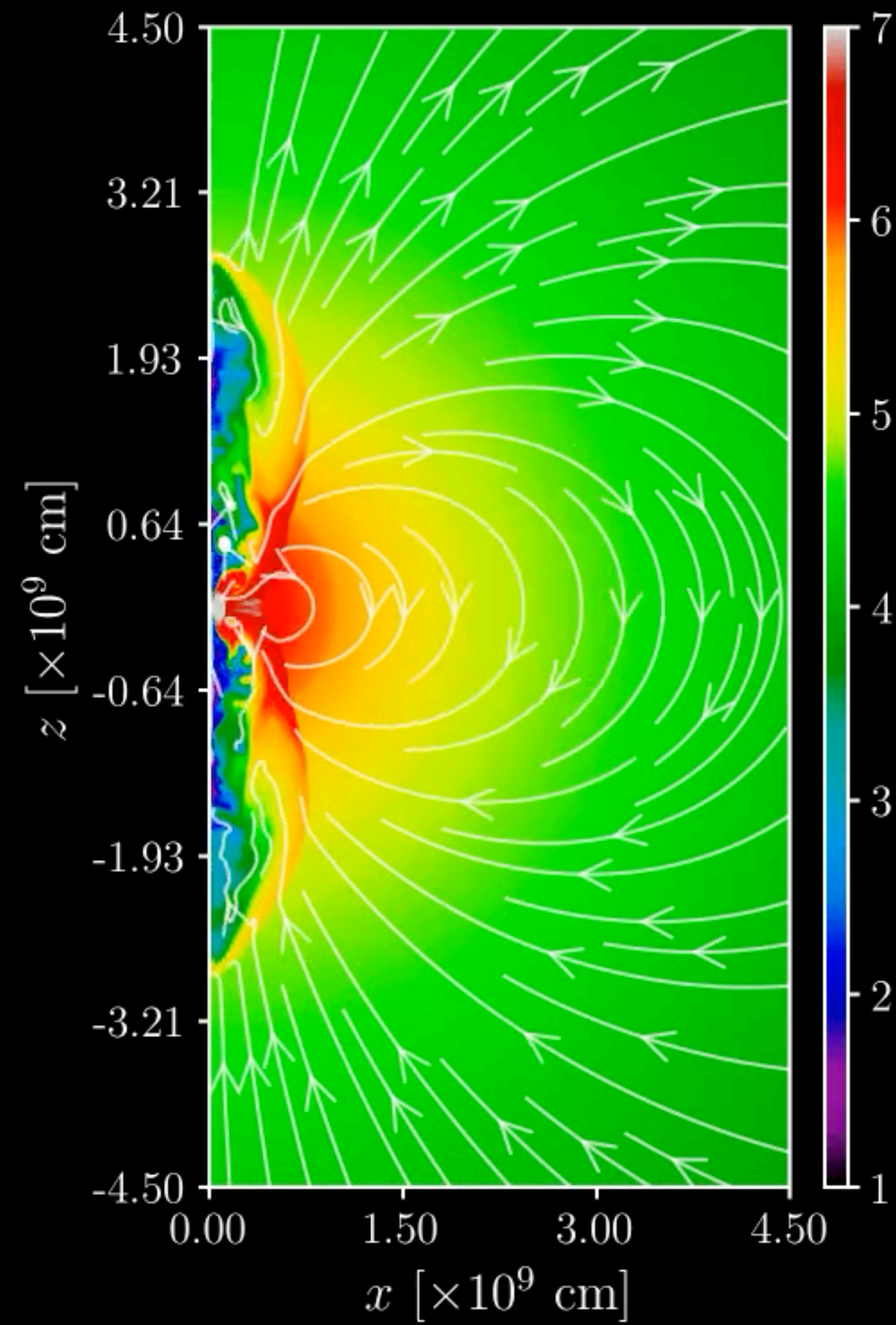
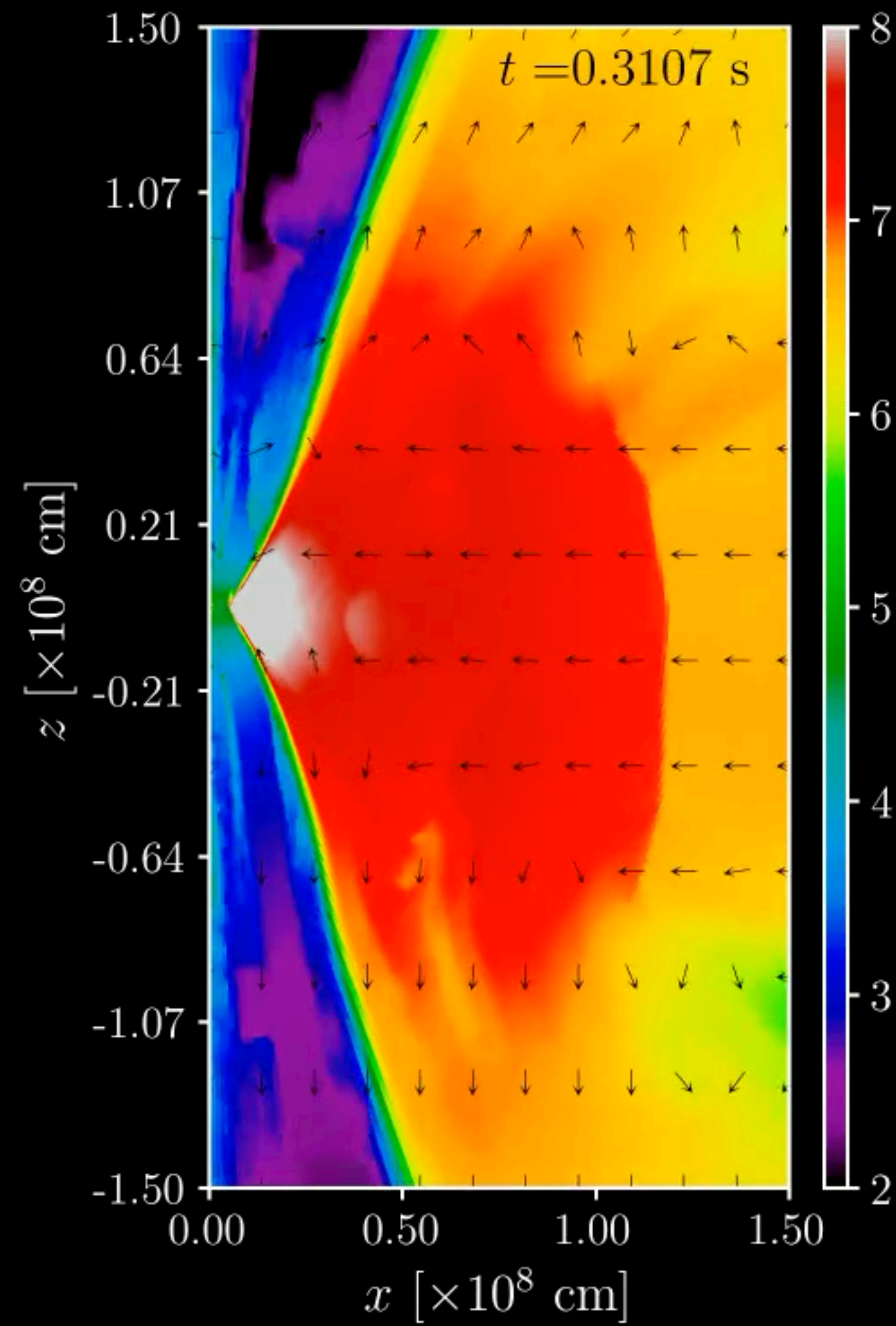


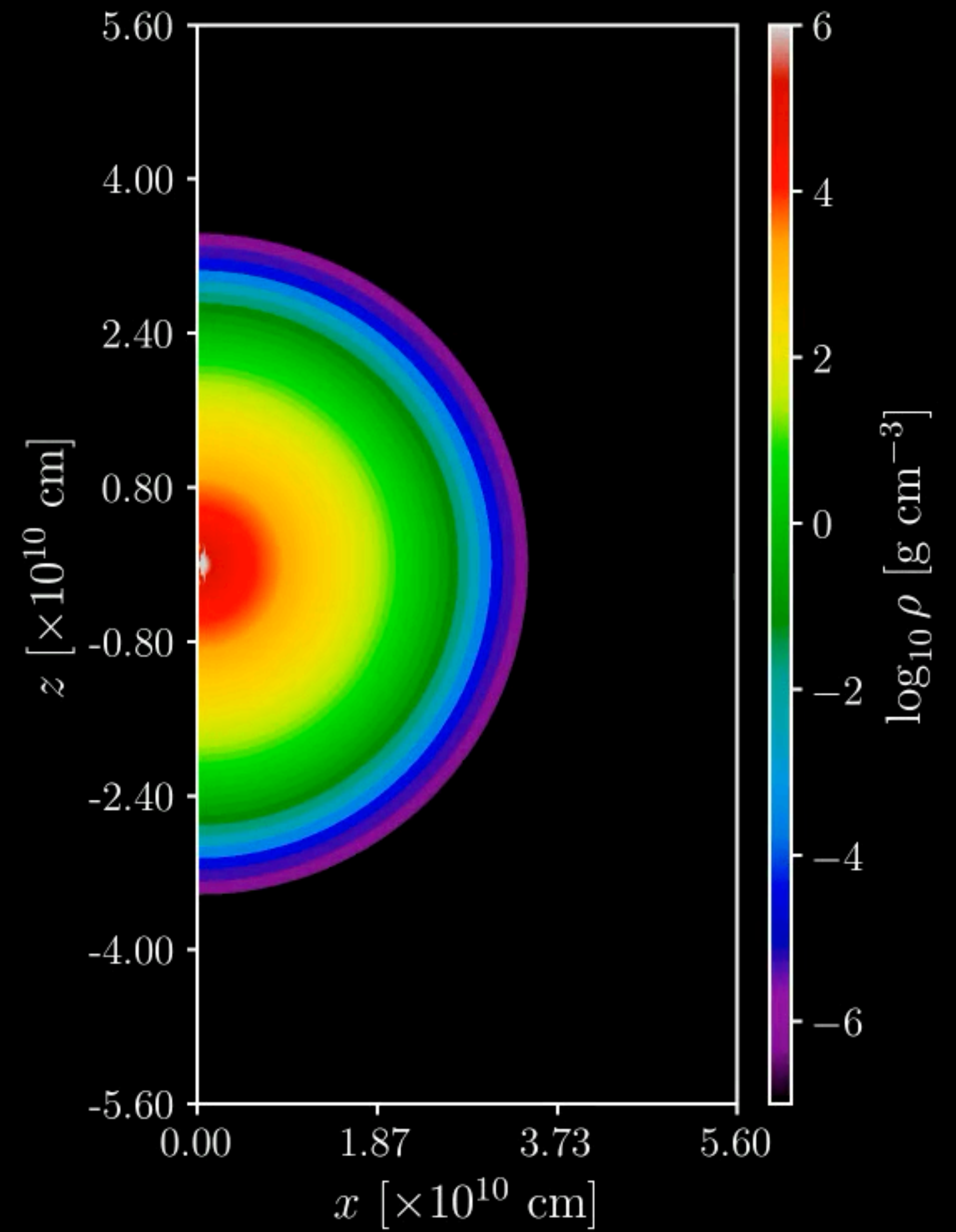
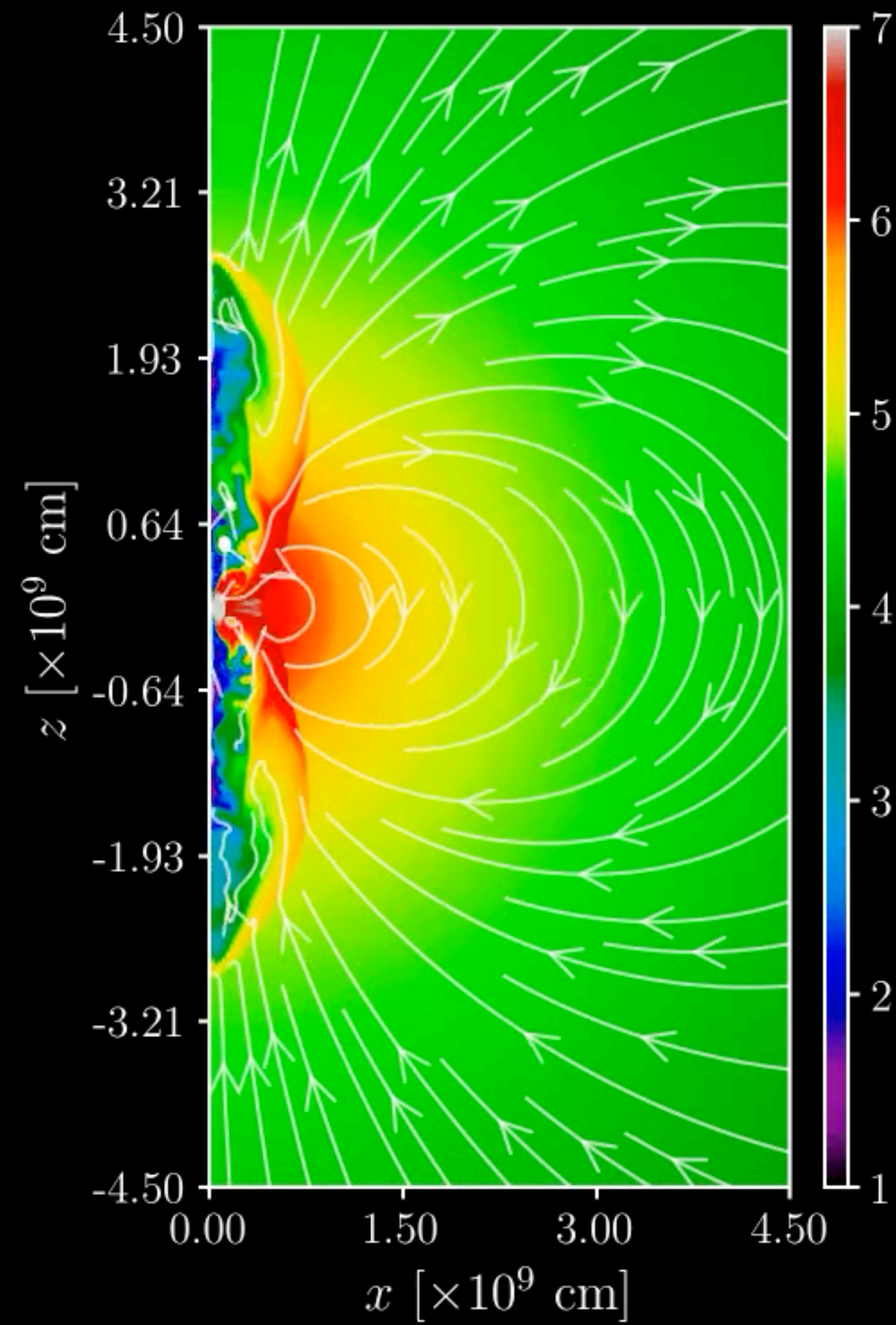
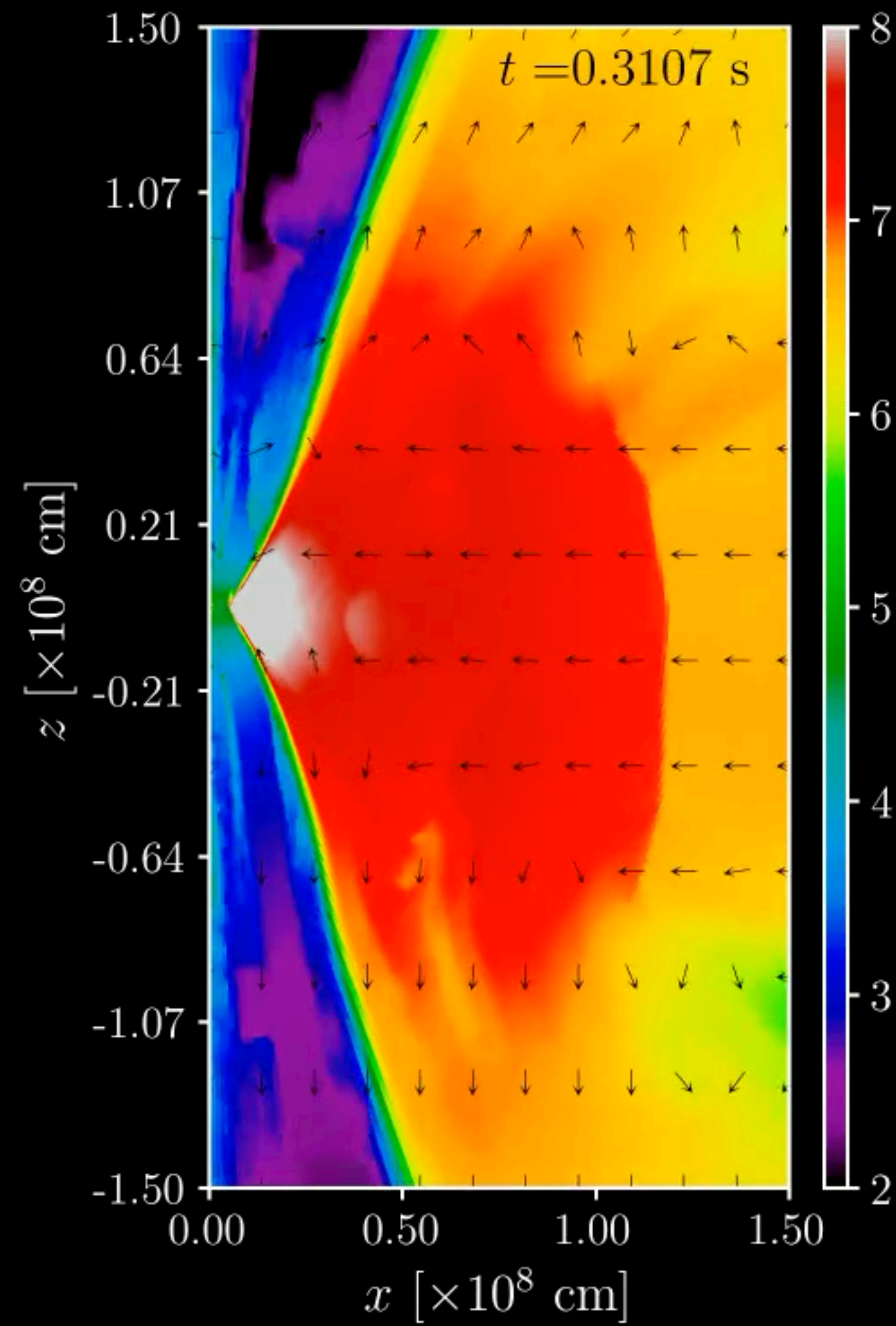


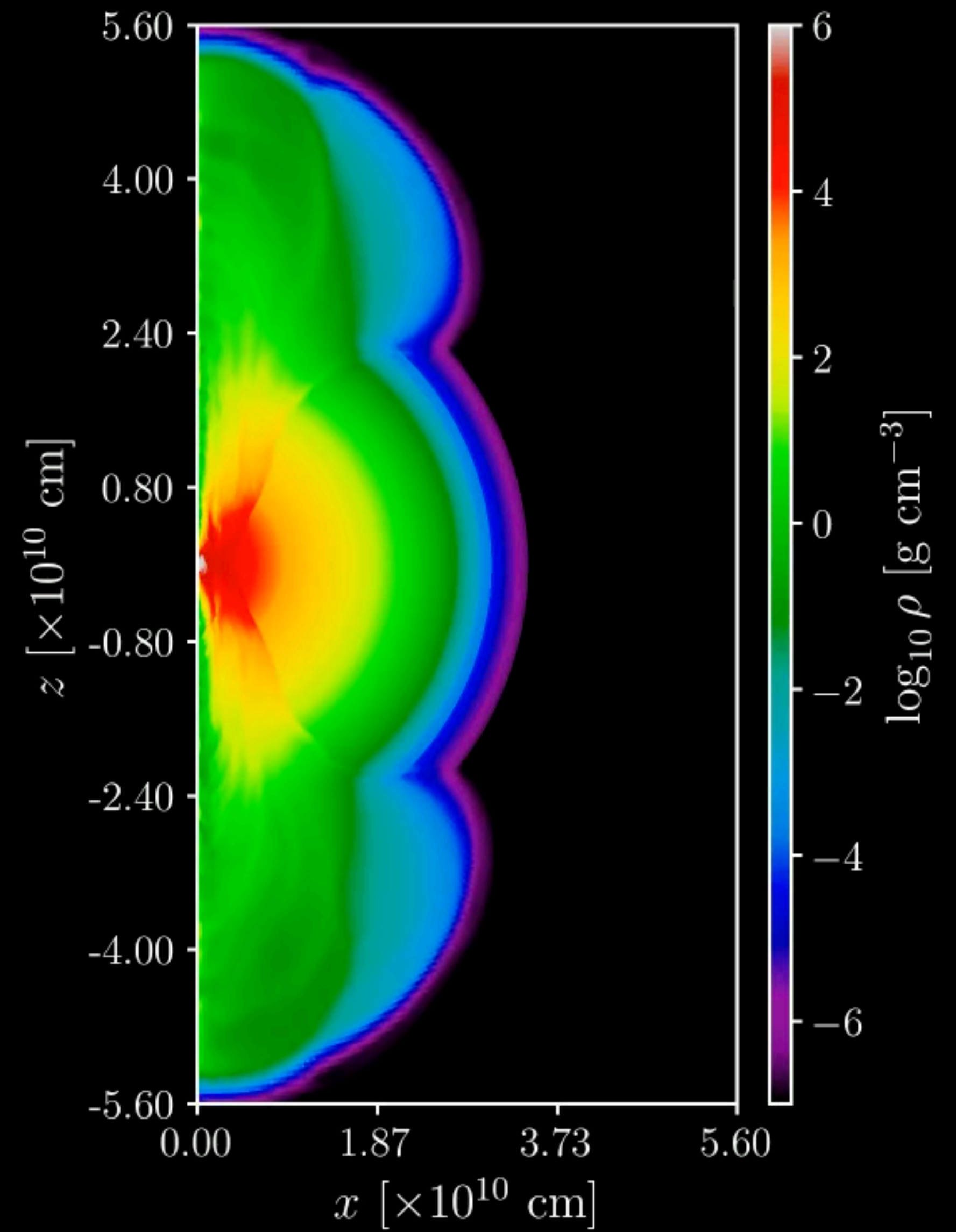
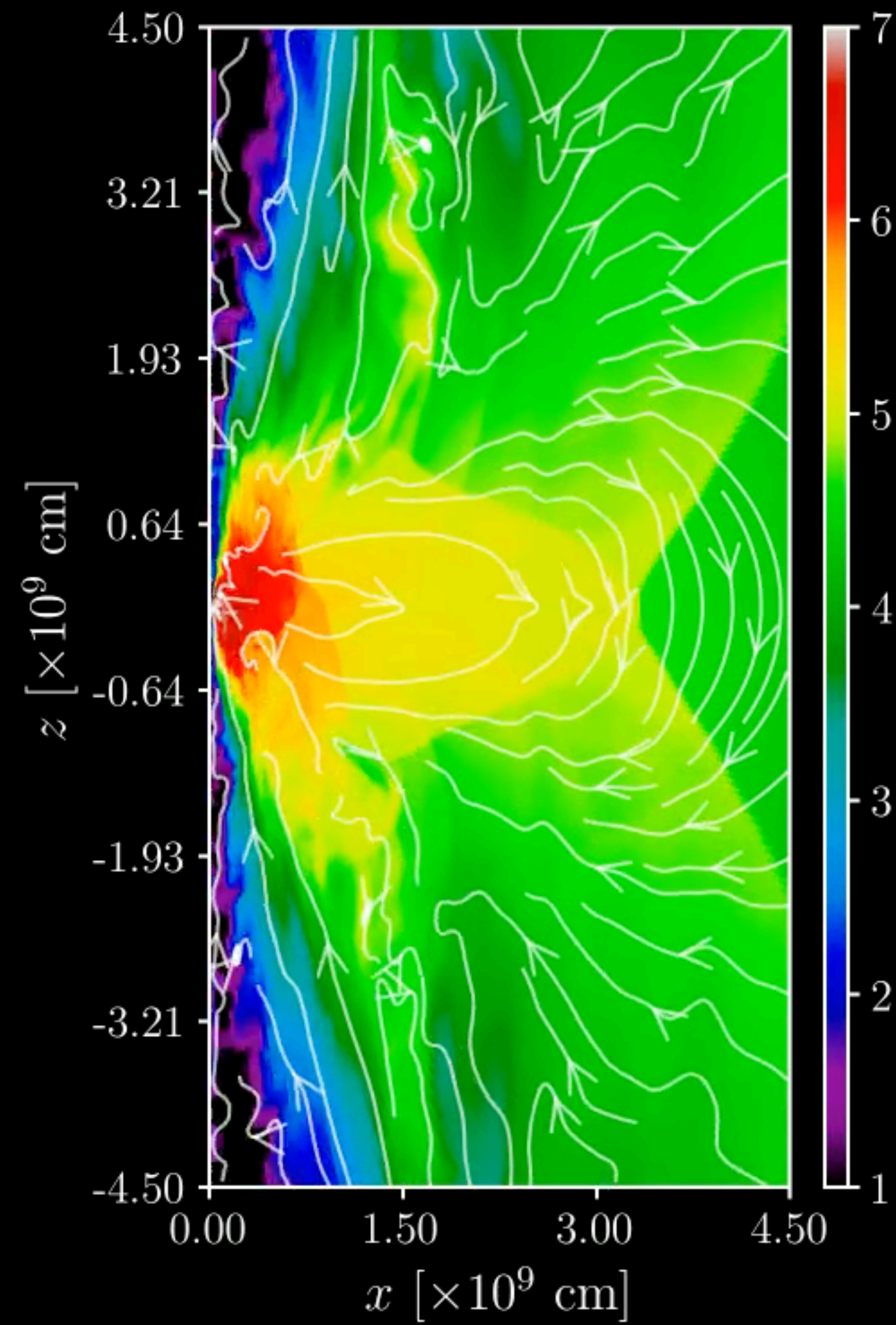
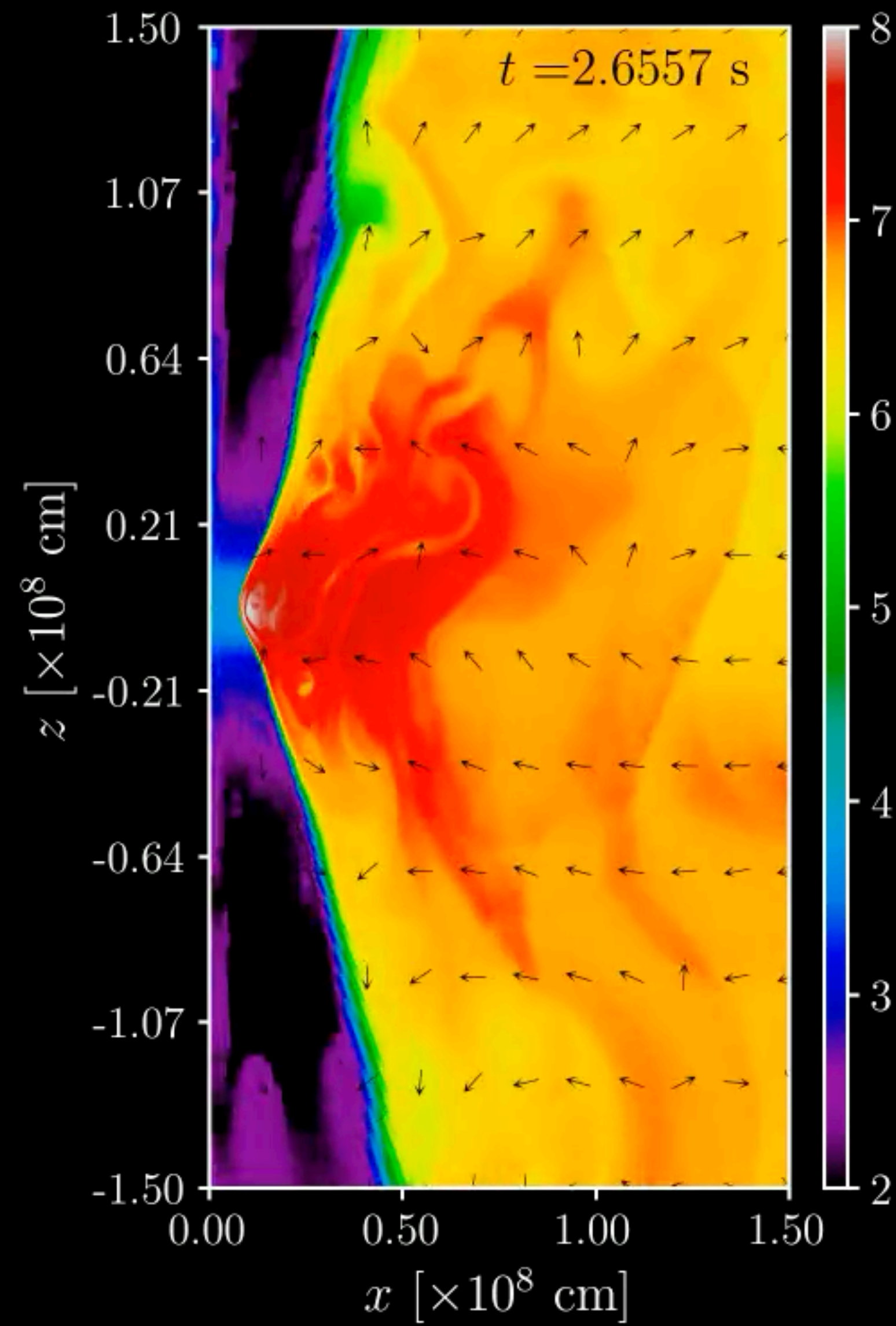


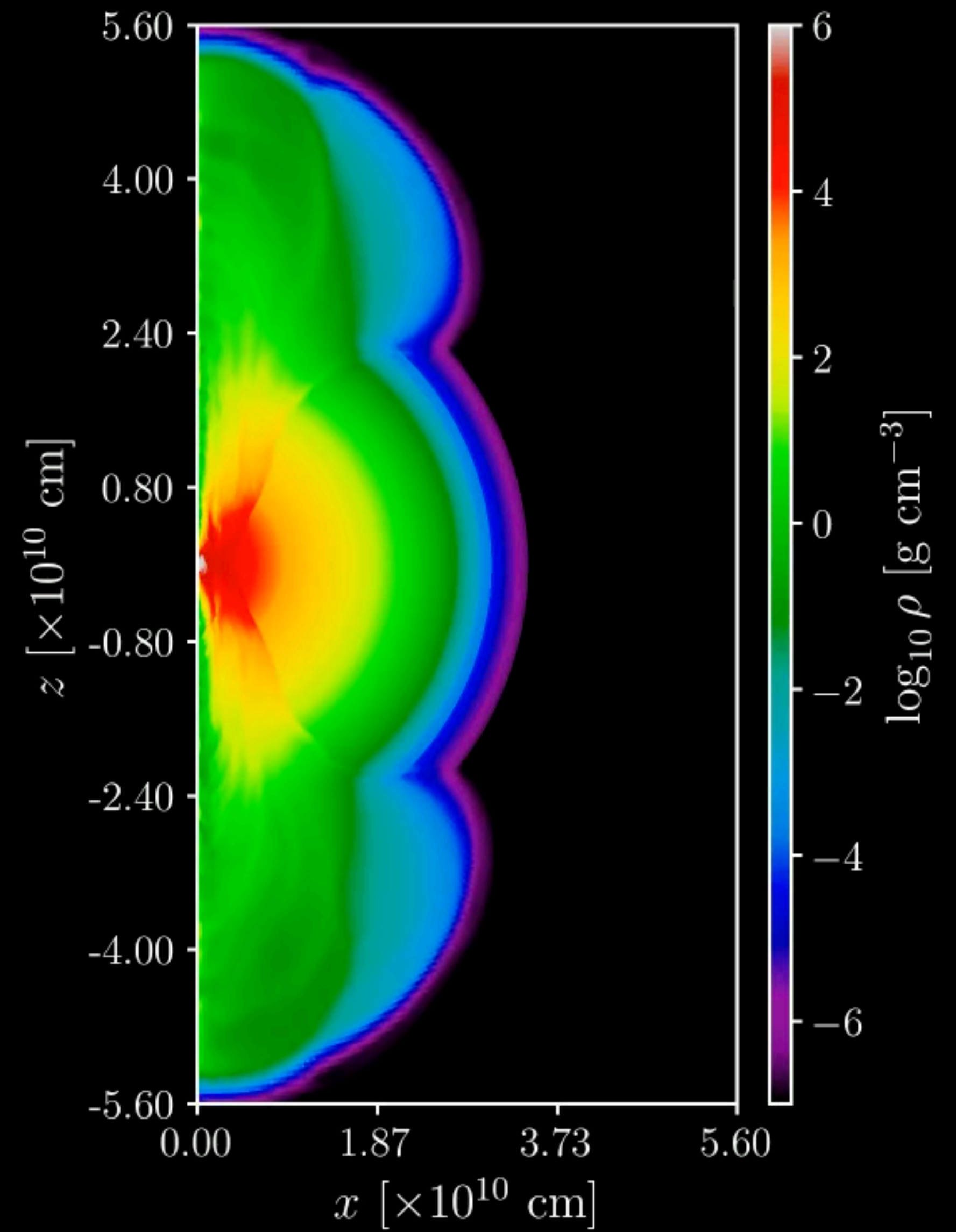
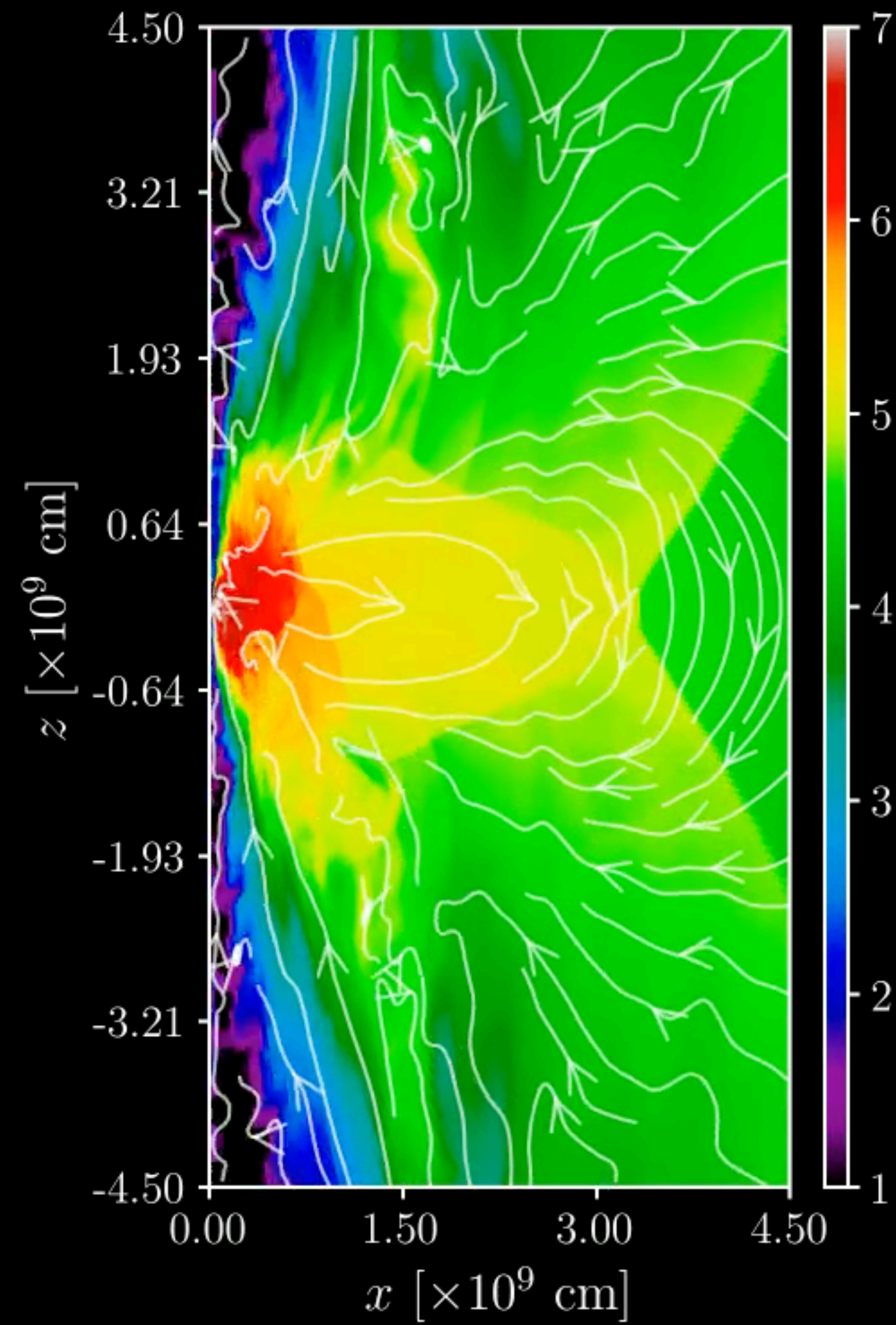
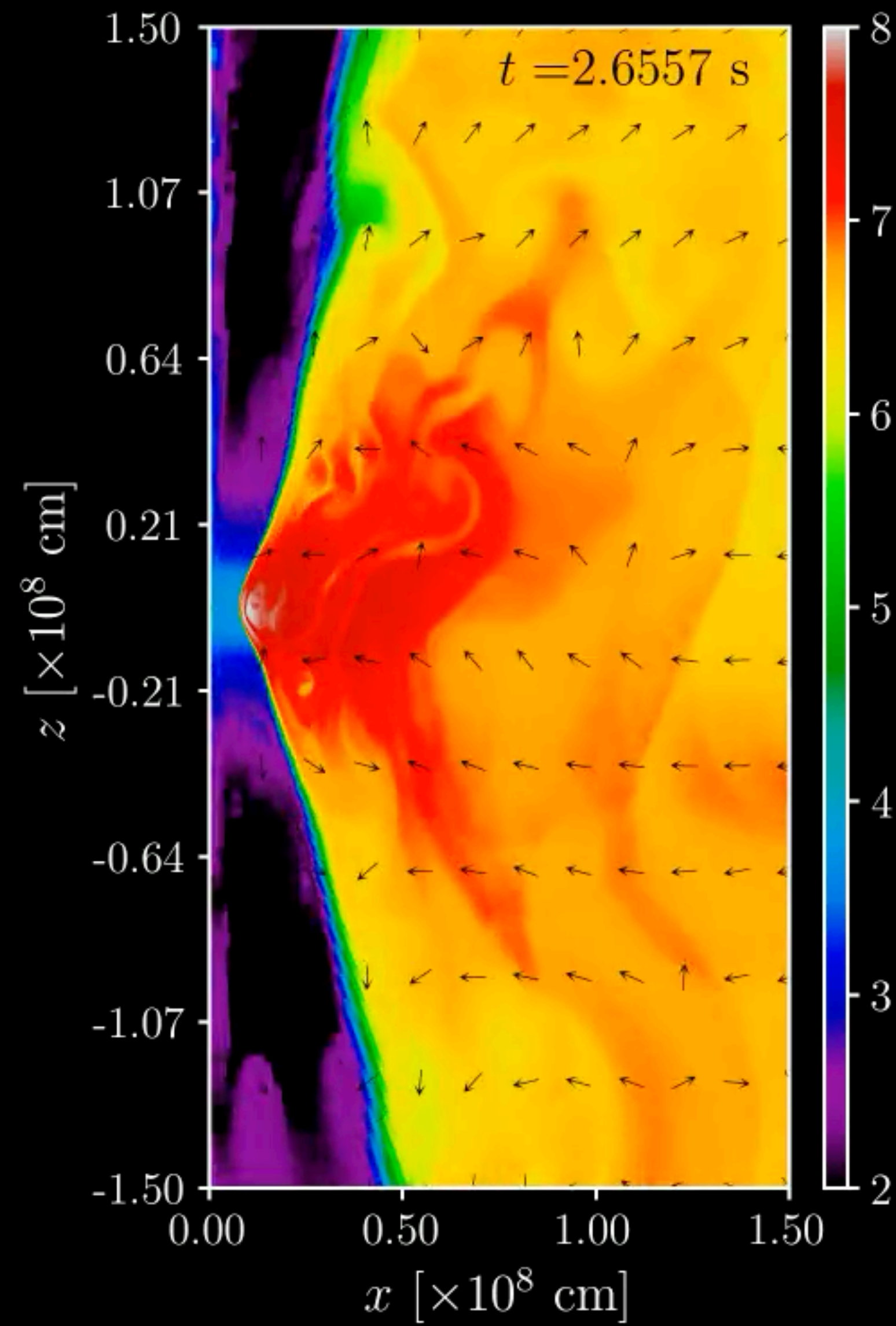


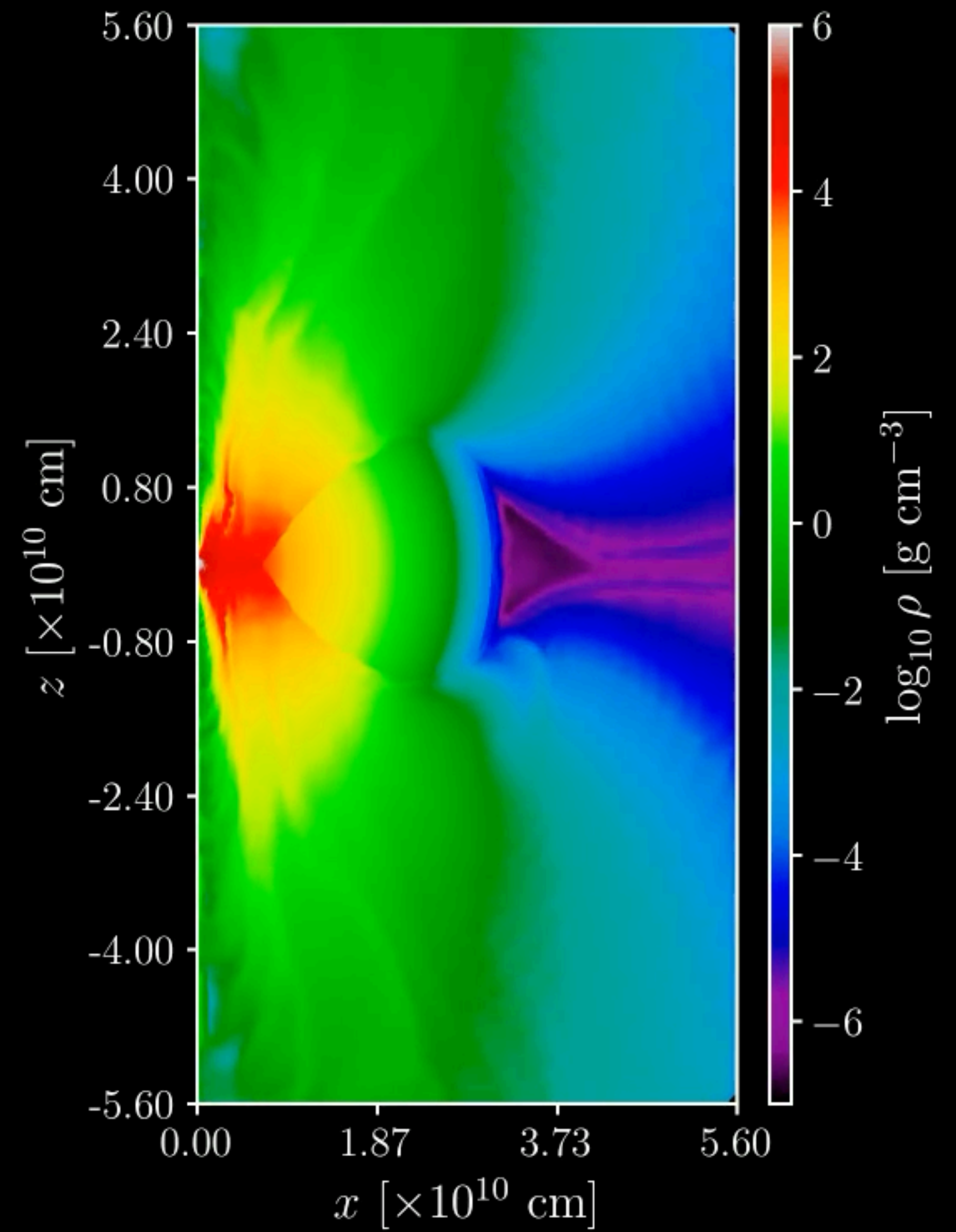
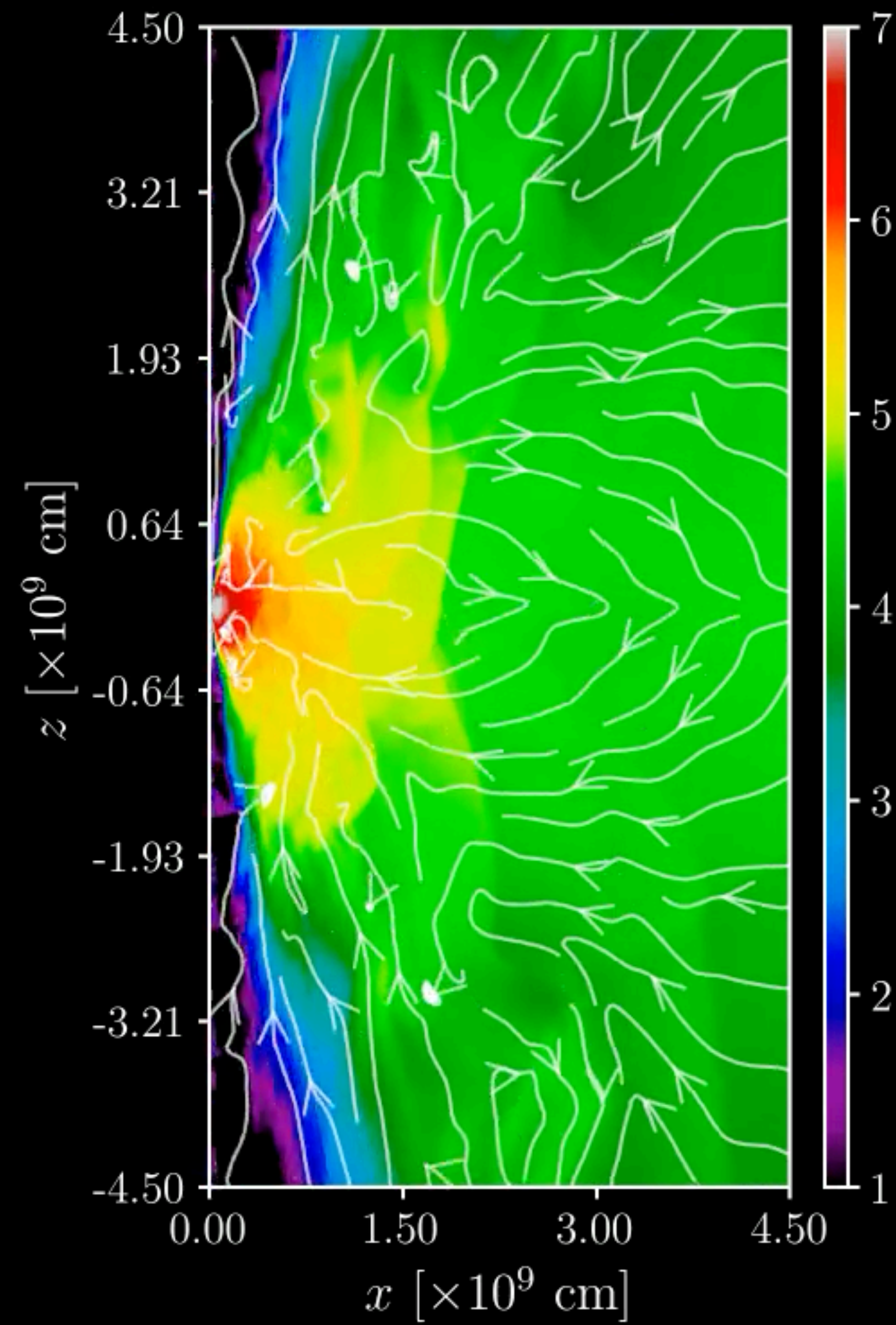
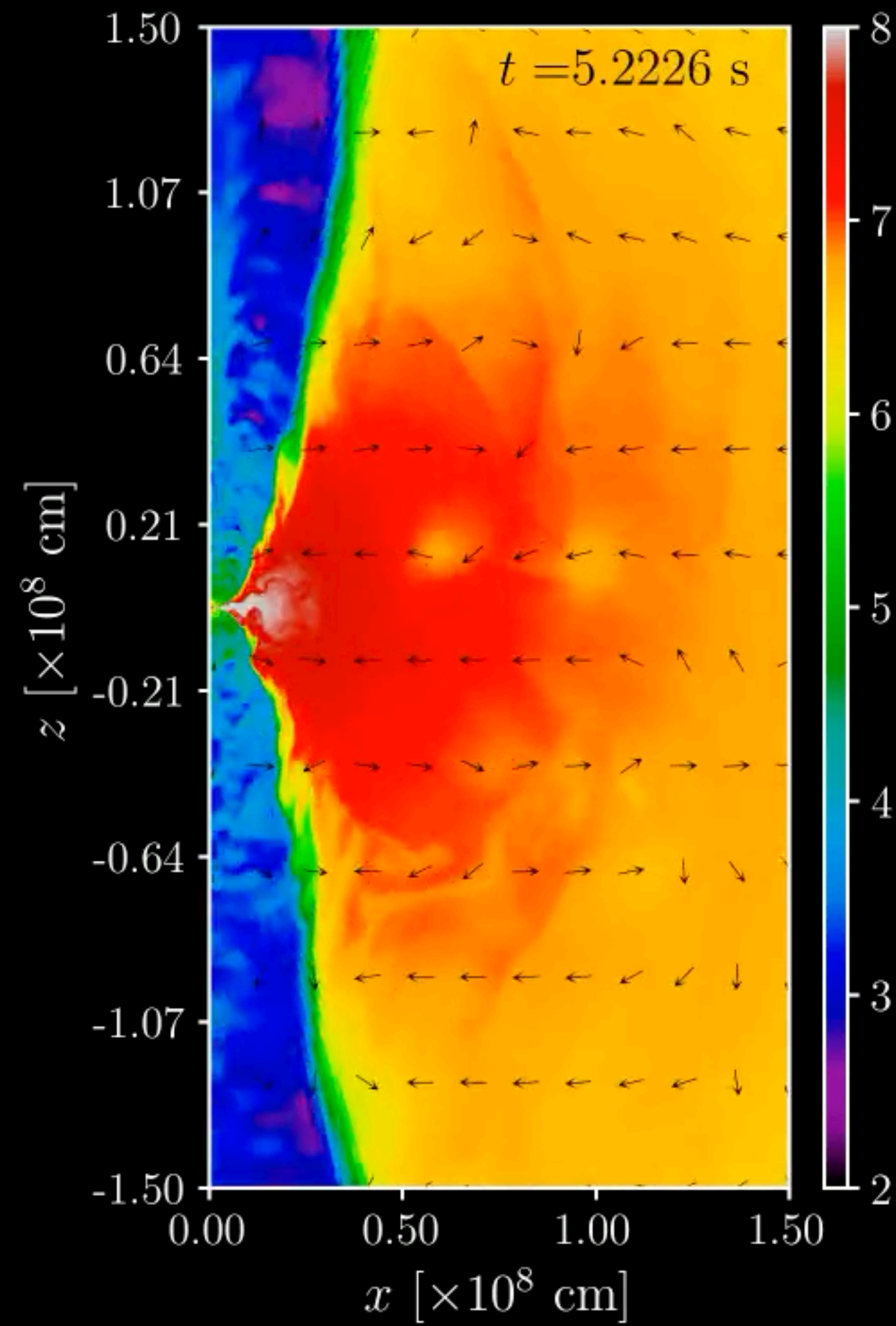


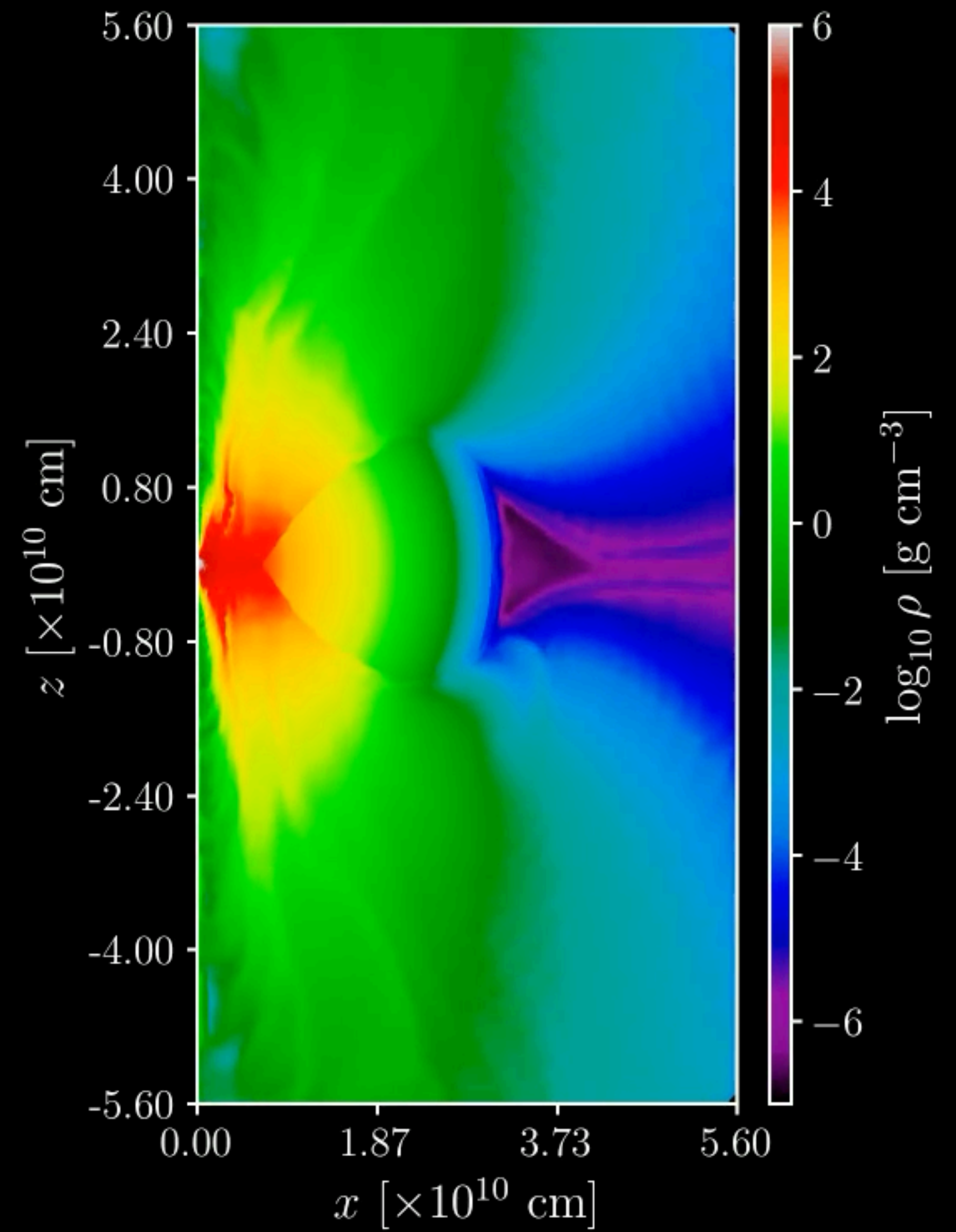
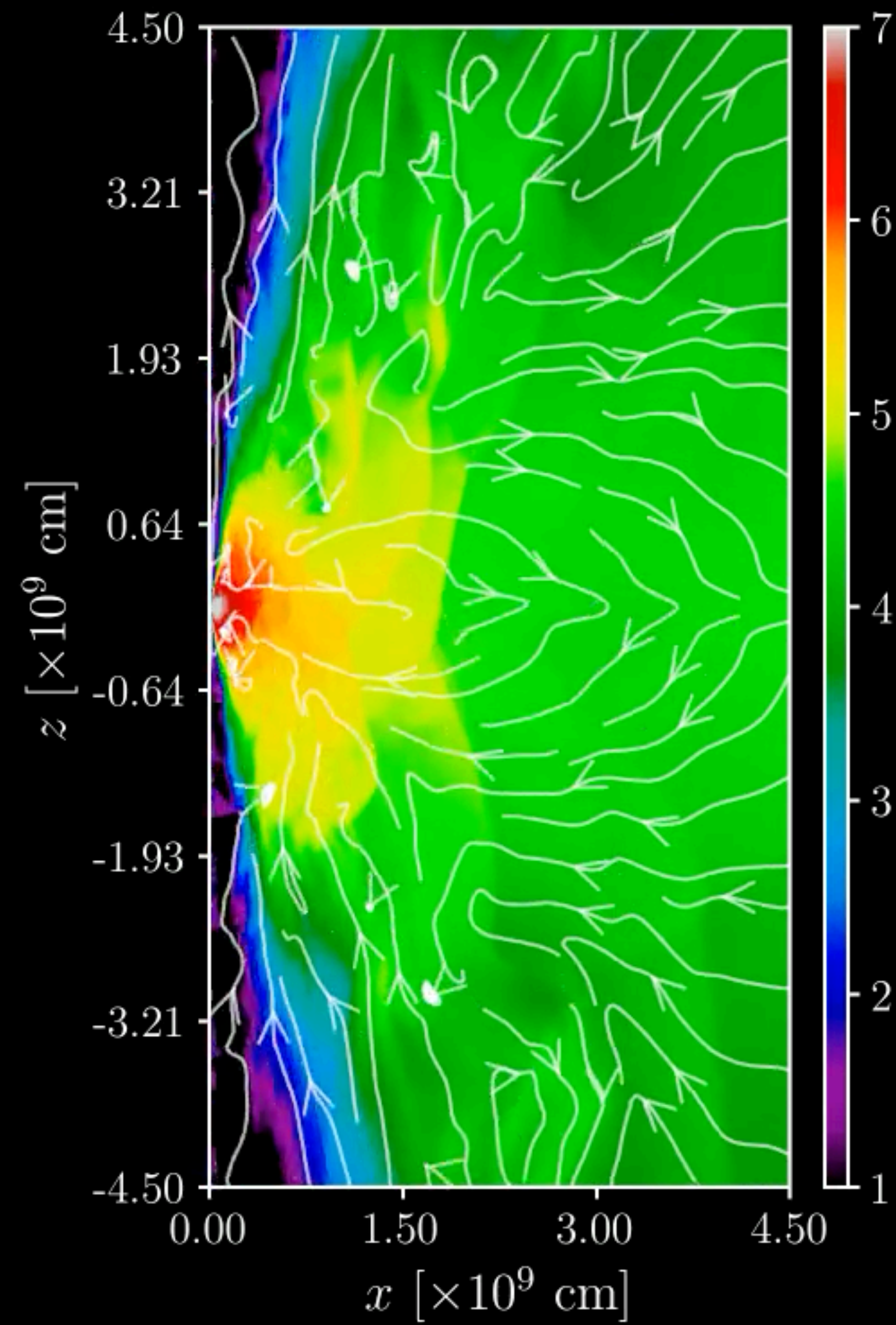
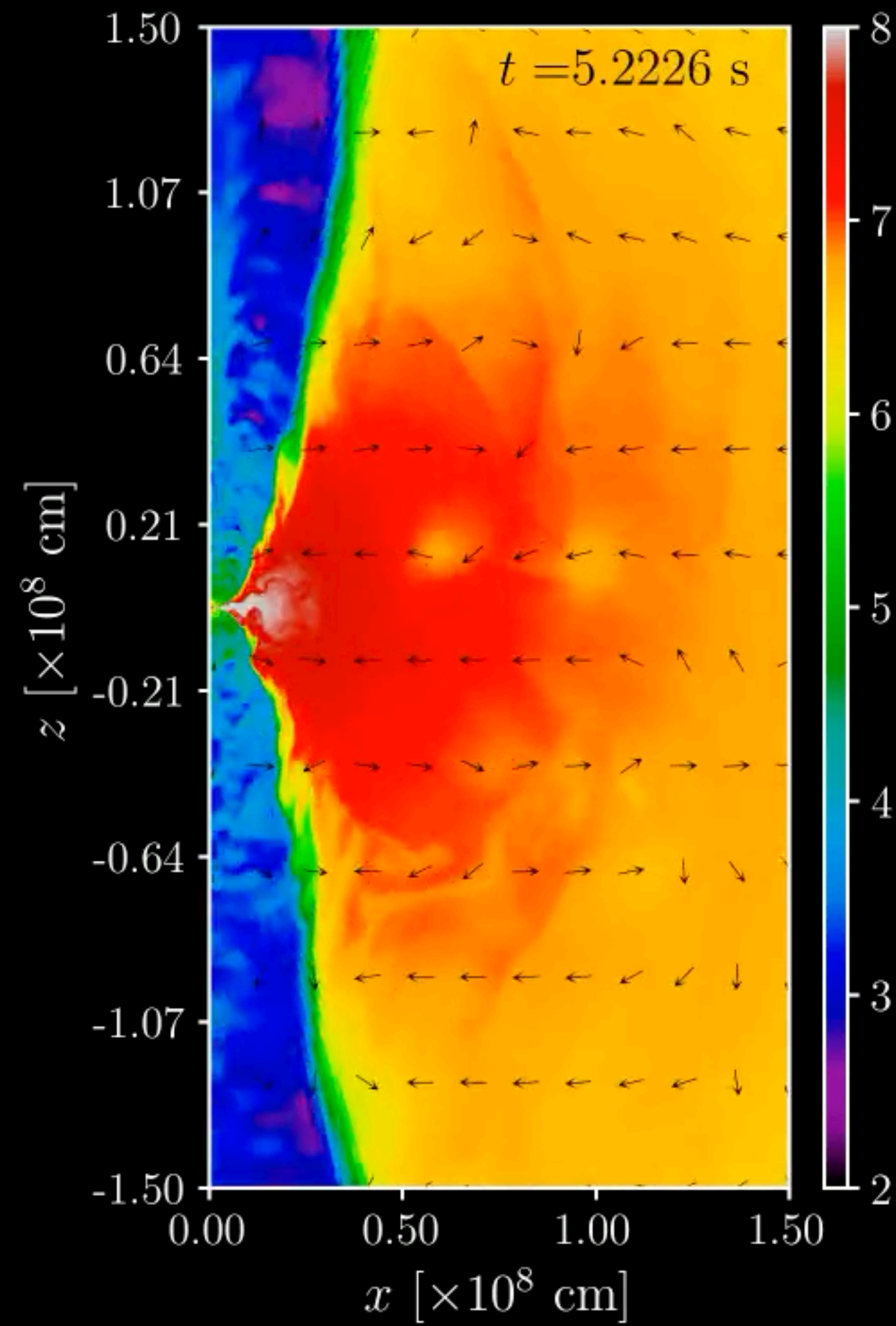






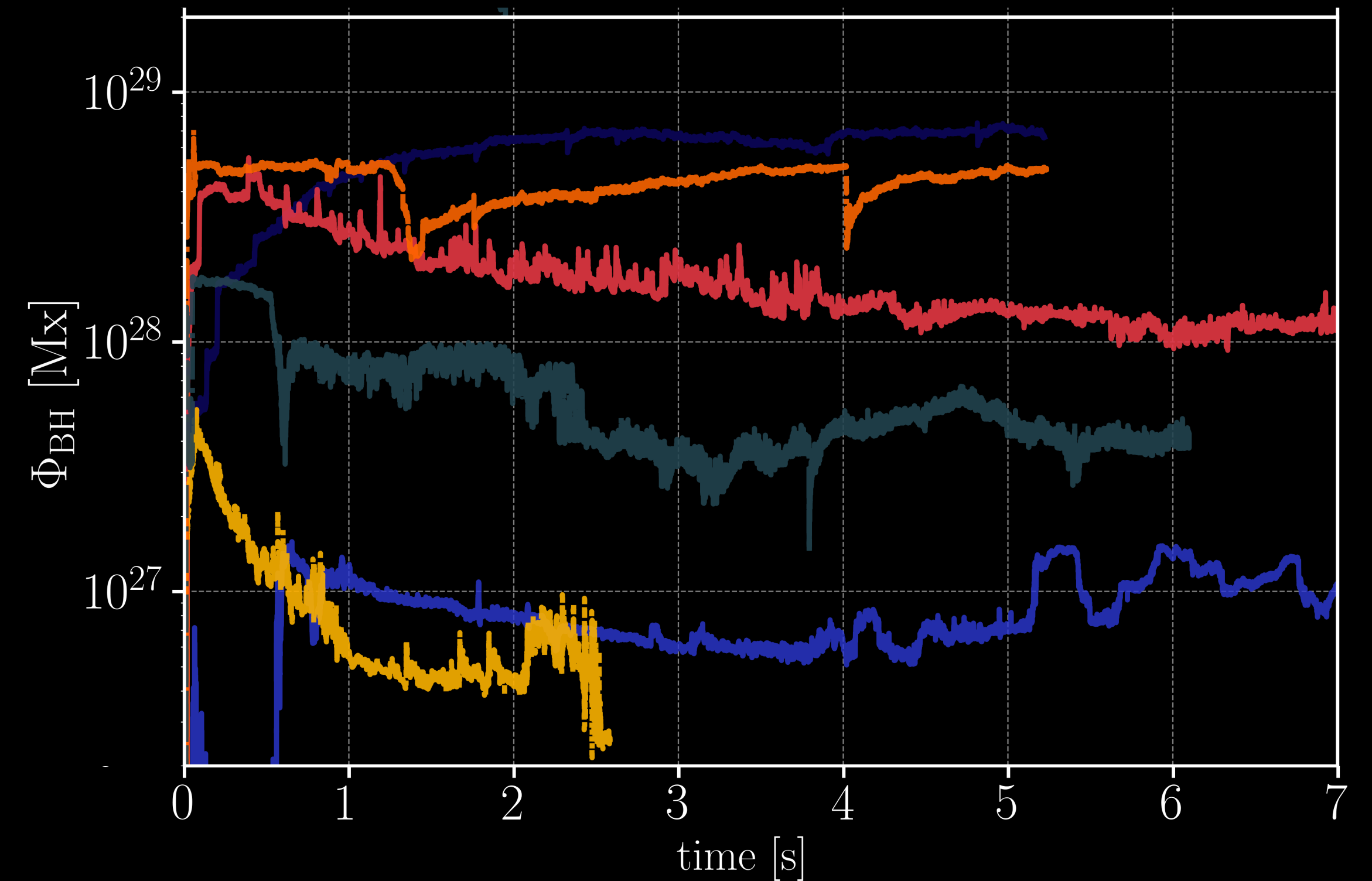






Central engine activity

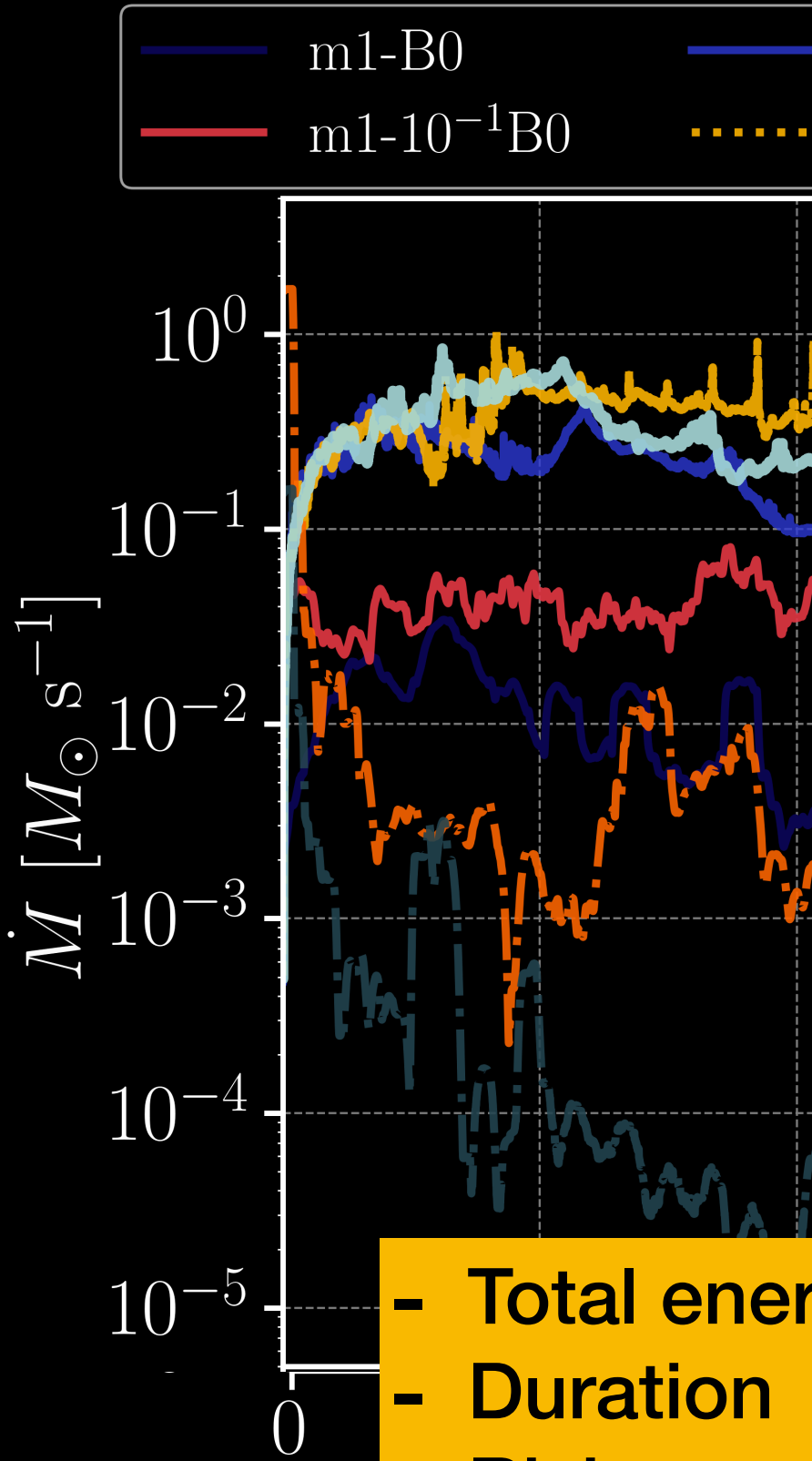
Urrutia, Janiuk & Olivares 2026



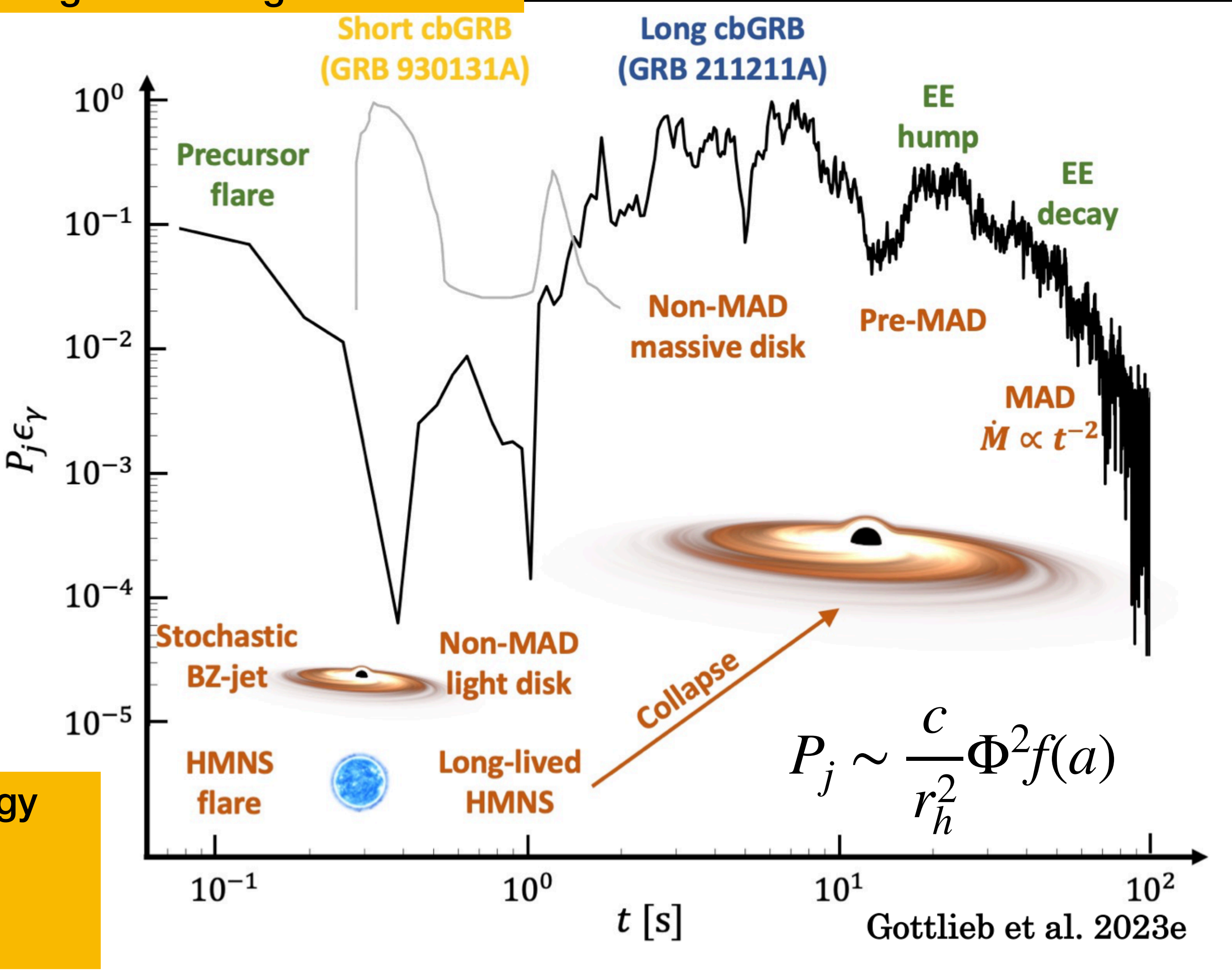
$$\dot{M} = - \iint \rho c^2 u^r \sqrt{-g} d\theta d\phi$$

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

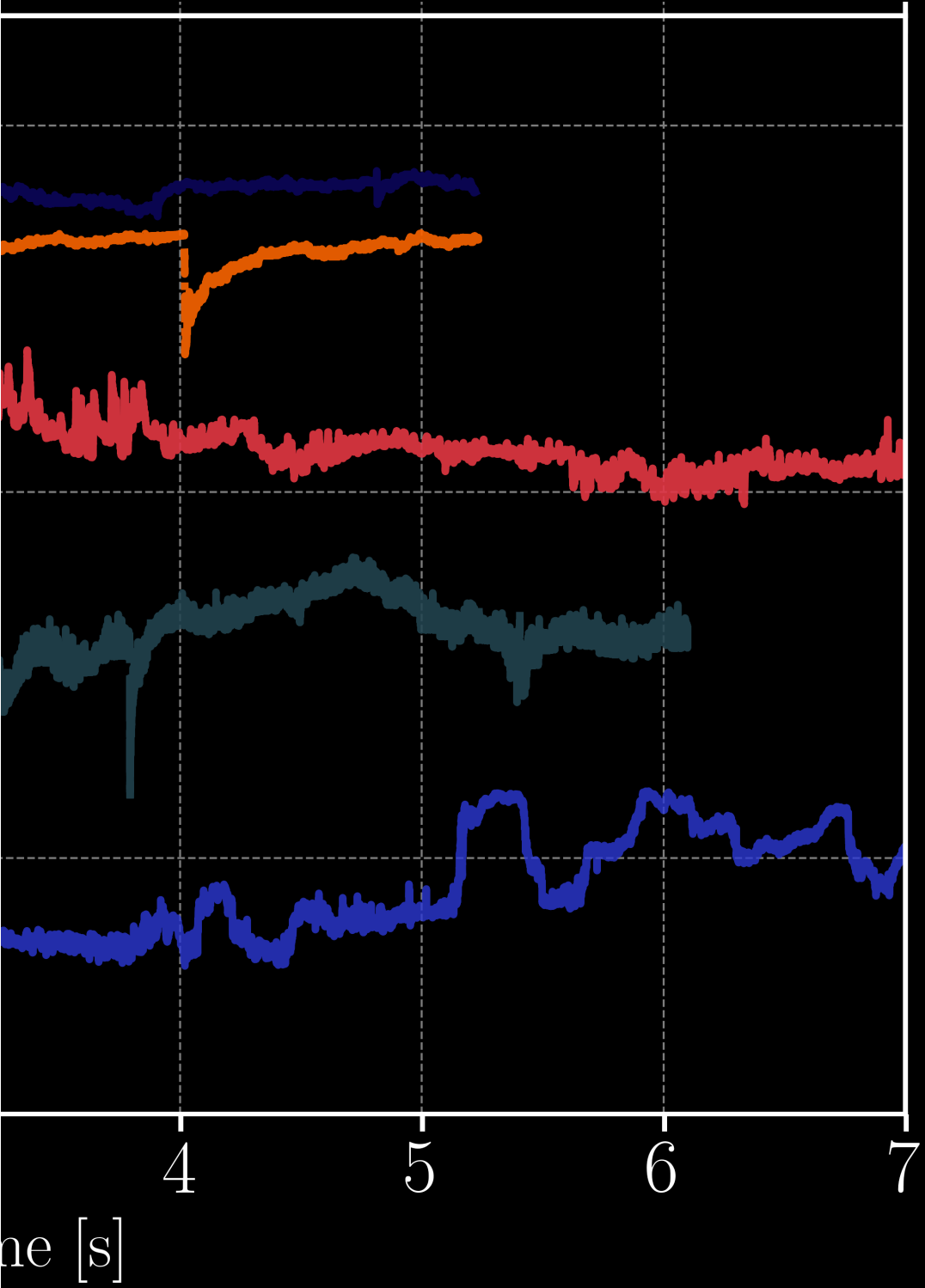
Conecting Central engine with Light curves



- Total energy
- Duration
- Rising
- Flares



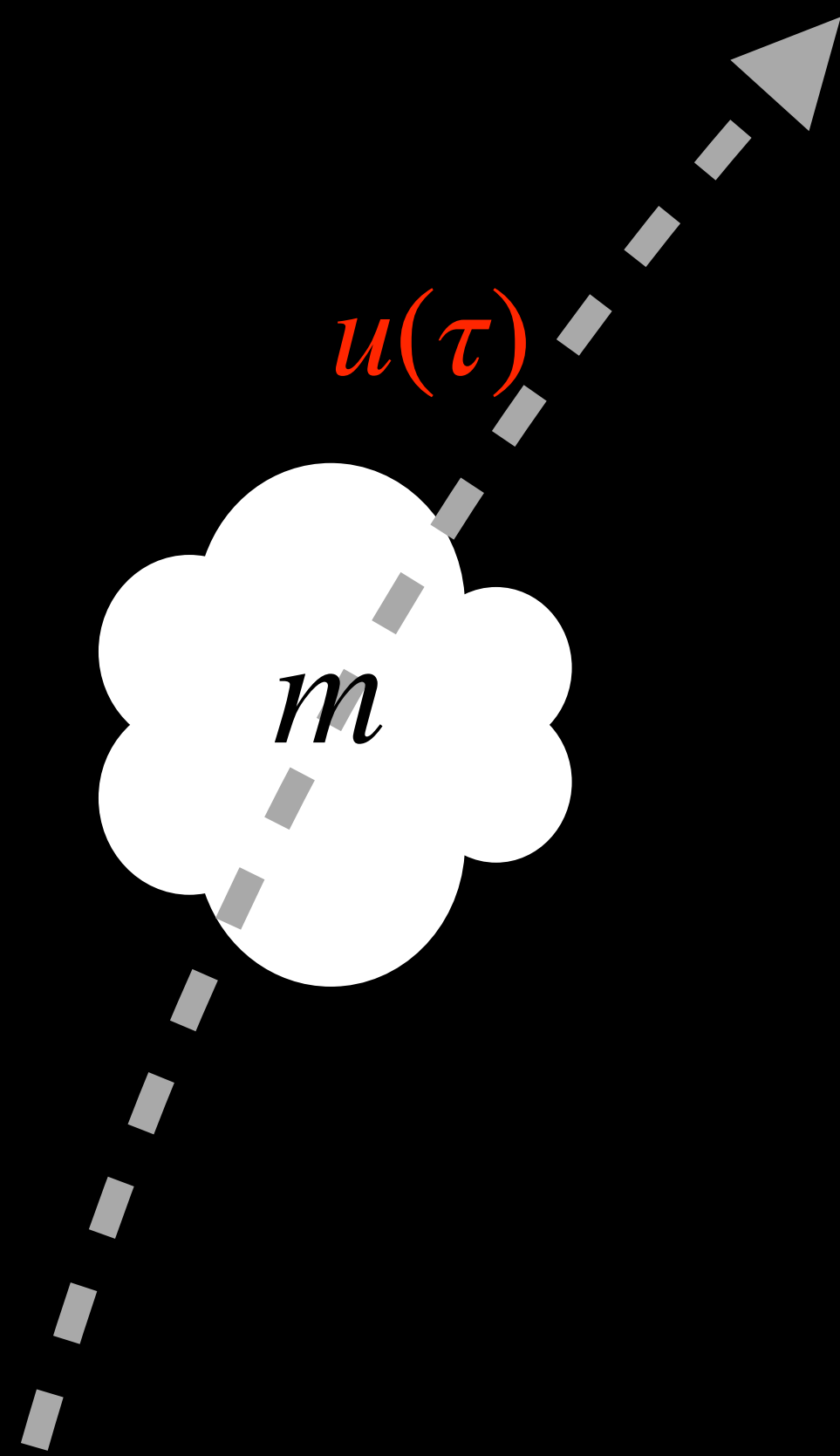
... & Olivares 2026



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

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

GW from ultra-relativistic sources

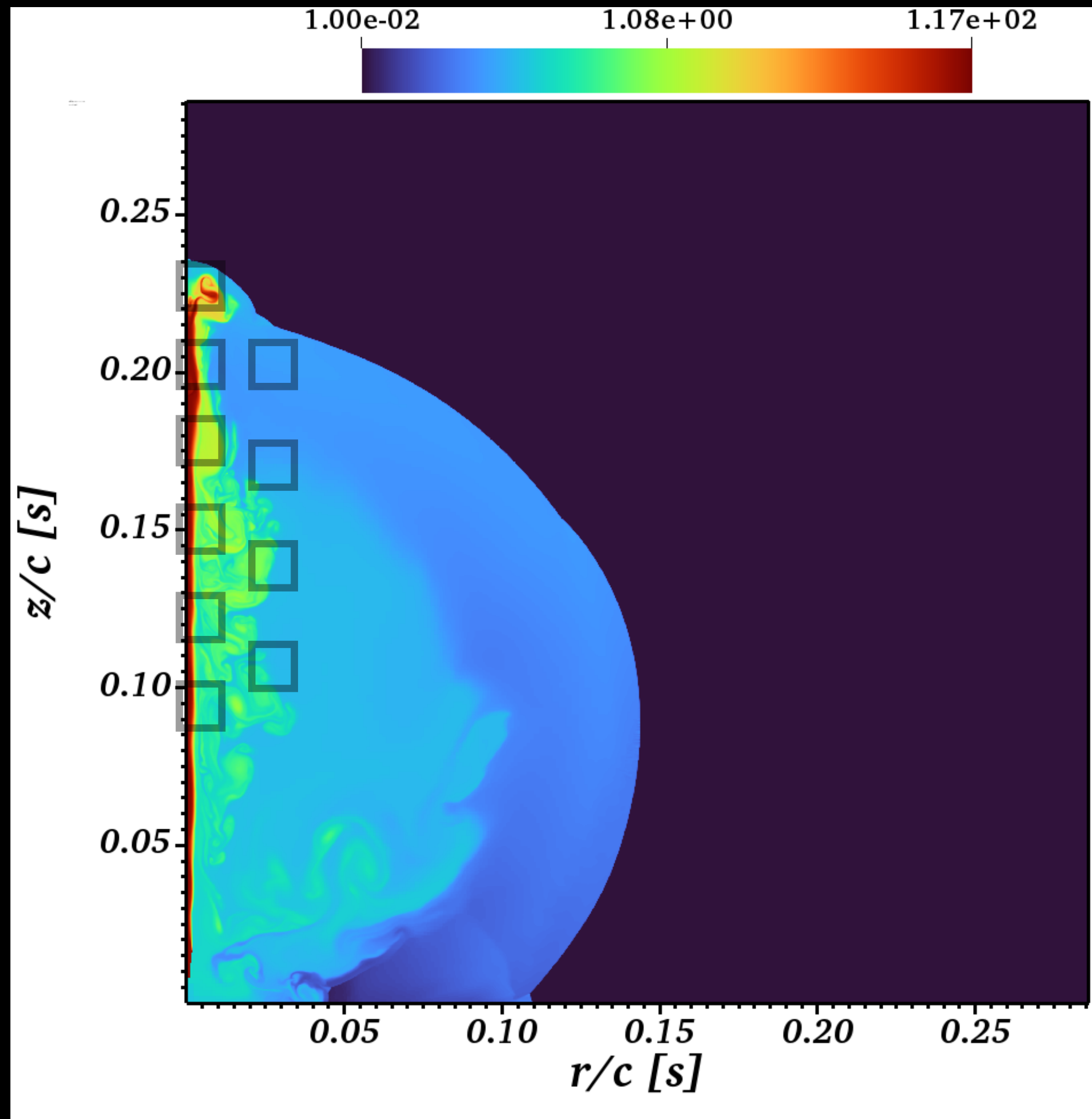


$$T^{\mu\nu} = \int m u^{\mu}(\tau) u^{\nu}(\tau) \delta^{(4)}[x - x(\tau)] d\tau$$

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

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

GW from ultra-relativistic sources

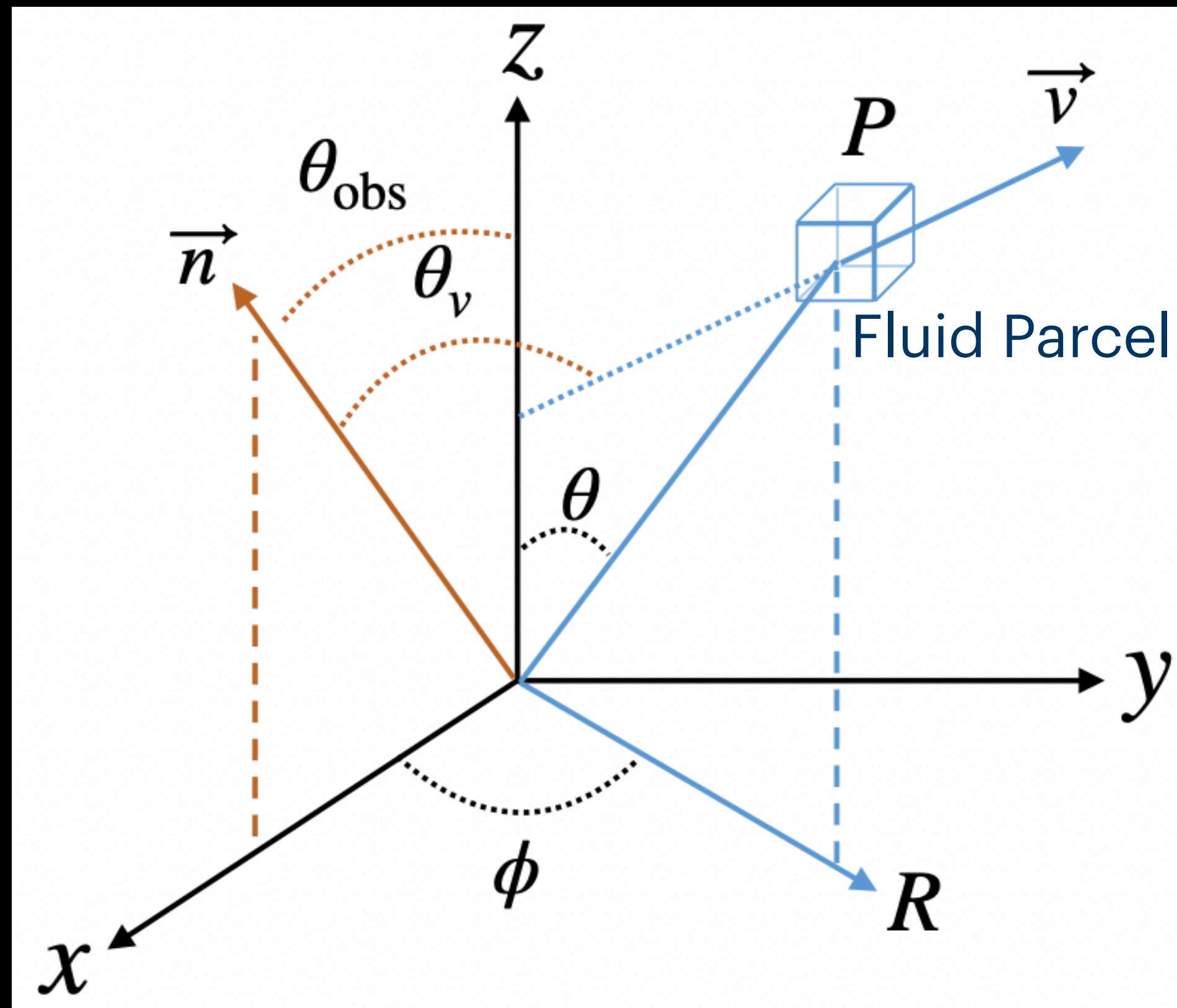


$$T^{\mu\nu} = \int m u^{\mu}(\tau) u^{\nu}(\tau) \delta^{(4)}[x - x(\tau)] d\tau$$

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

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

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

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

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

Previous estimations of GW signals from GRBs

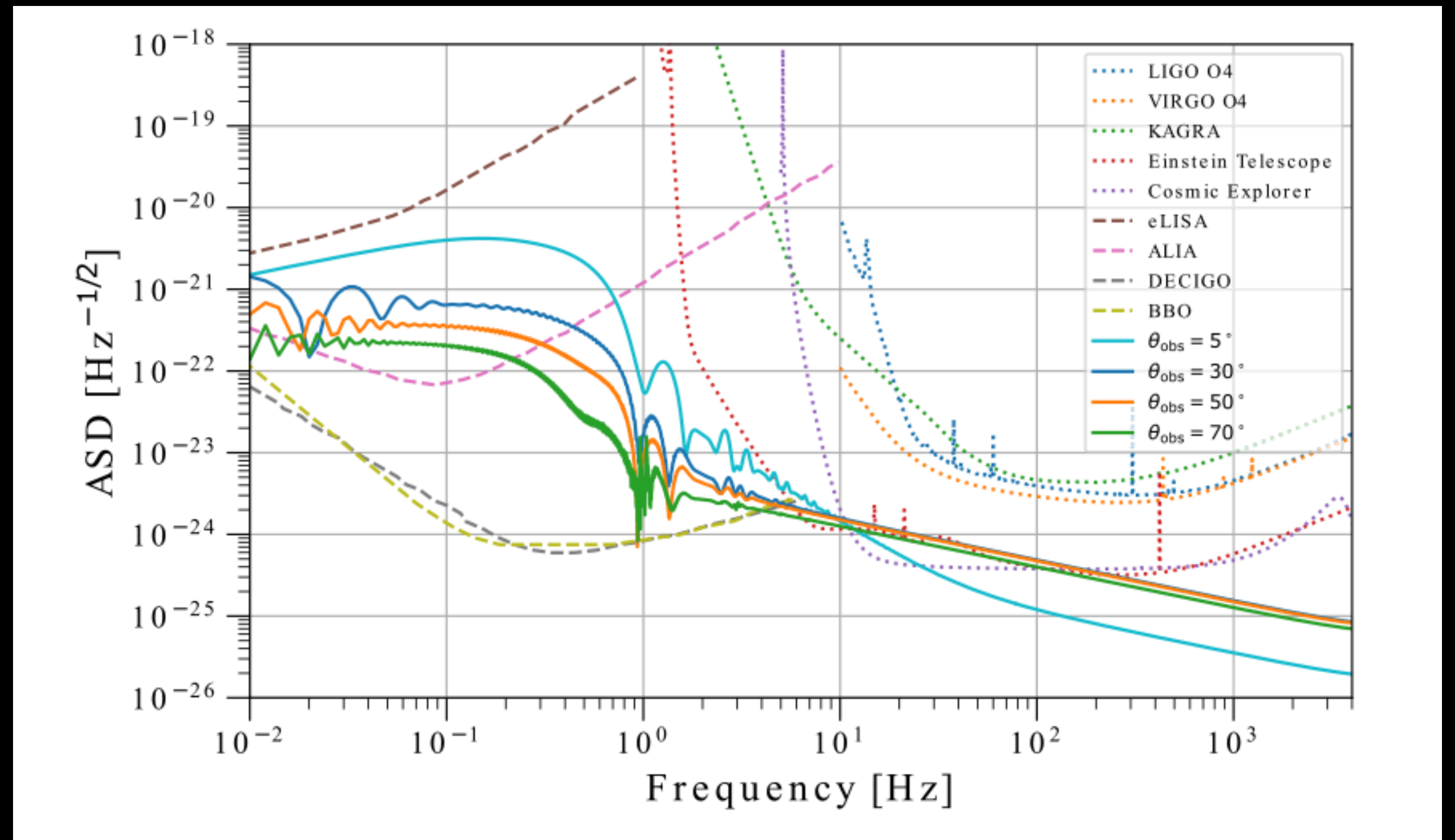
Urrutia, De Colle et al. 2023

It is expected the emission of GW memory, that depends of jet luminosity and geometric factors

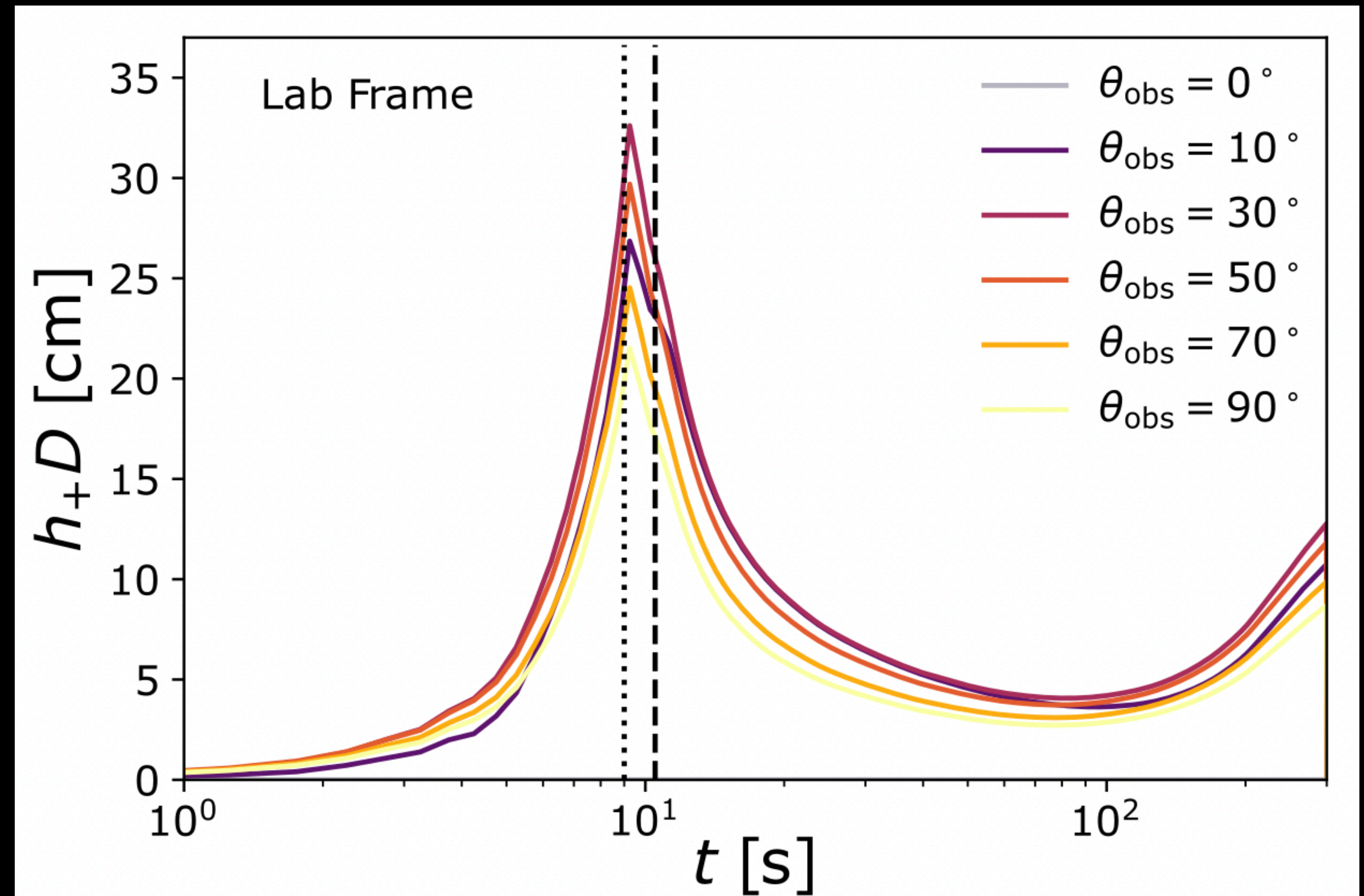
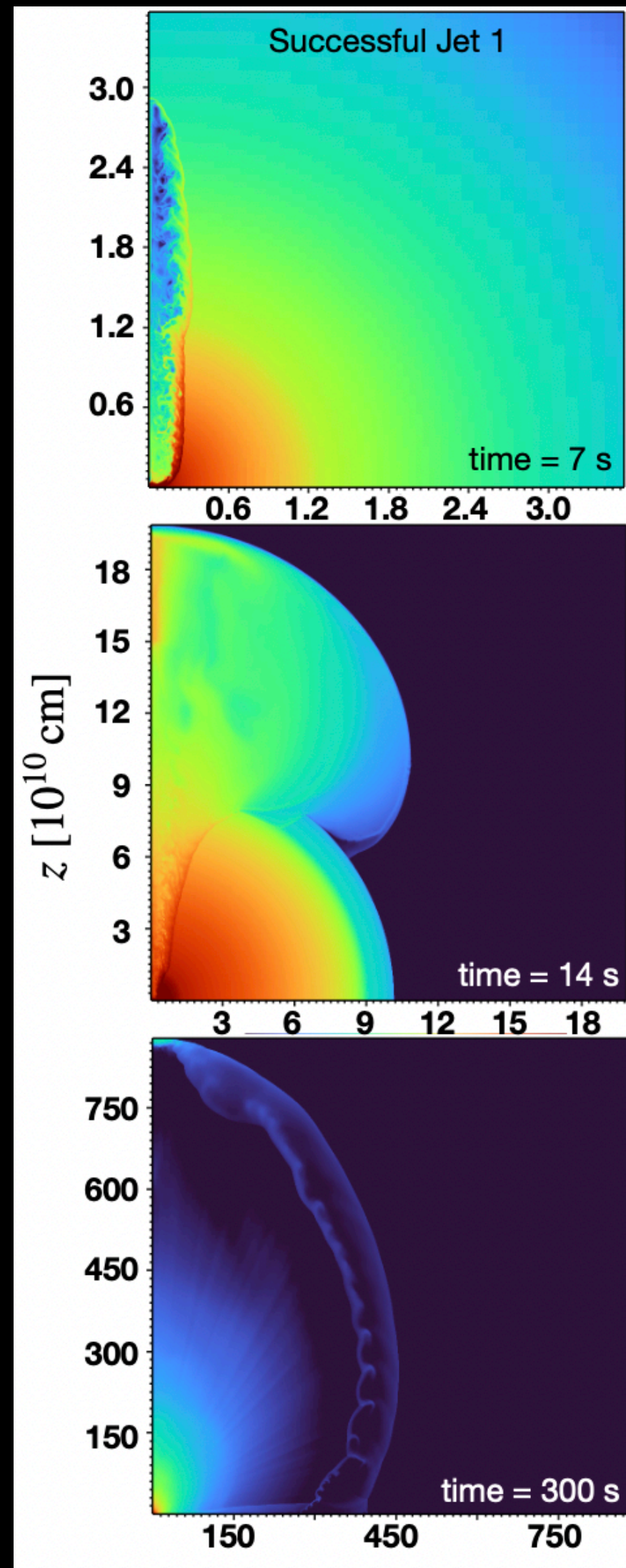
$$h \propto \frac{1}{D} \int dV L_j(t) \phi(\beta, \theta_{obs})$$

Peak of frequency is expected at lower frequency, since

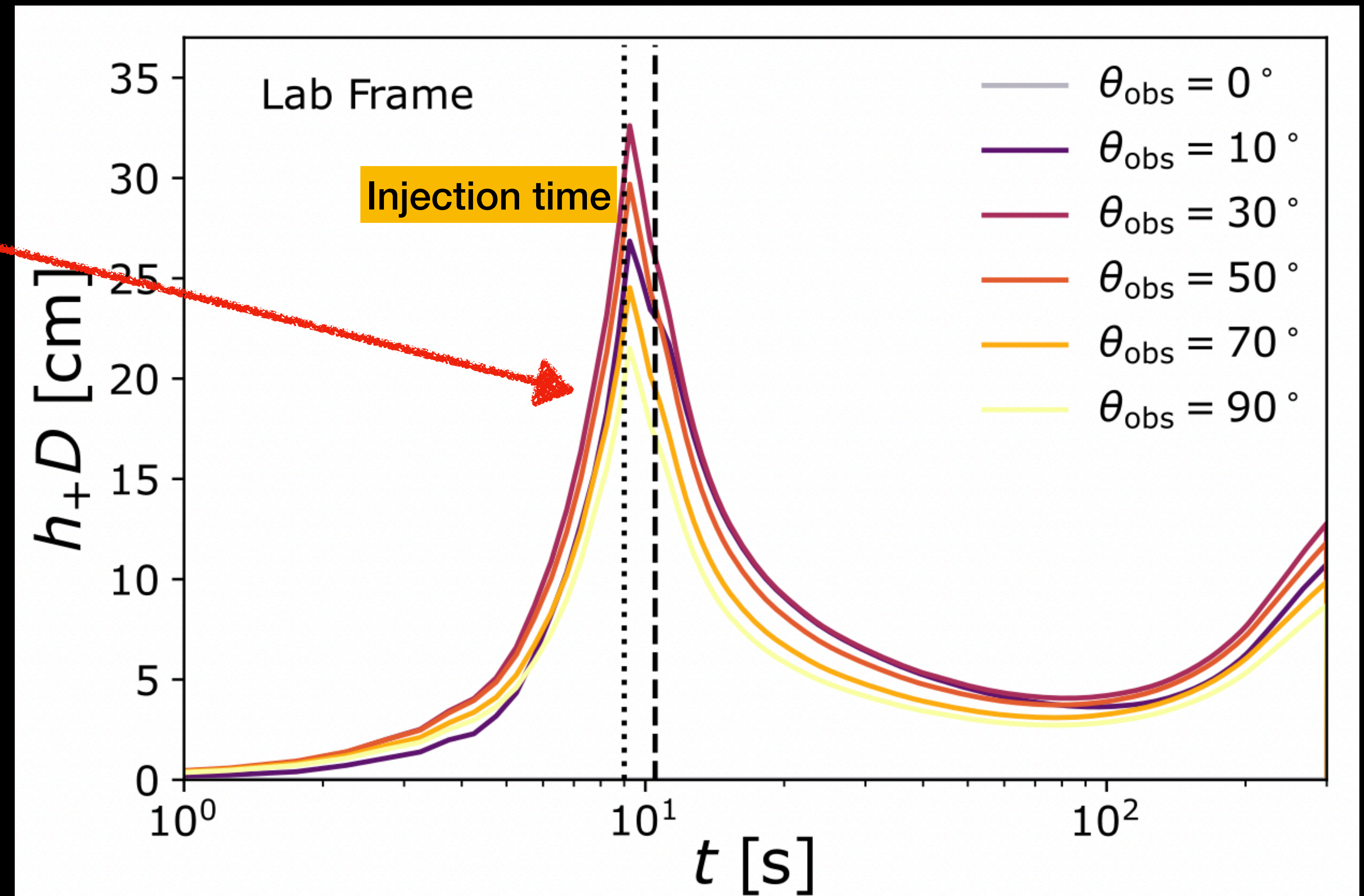
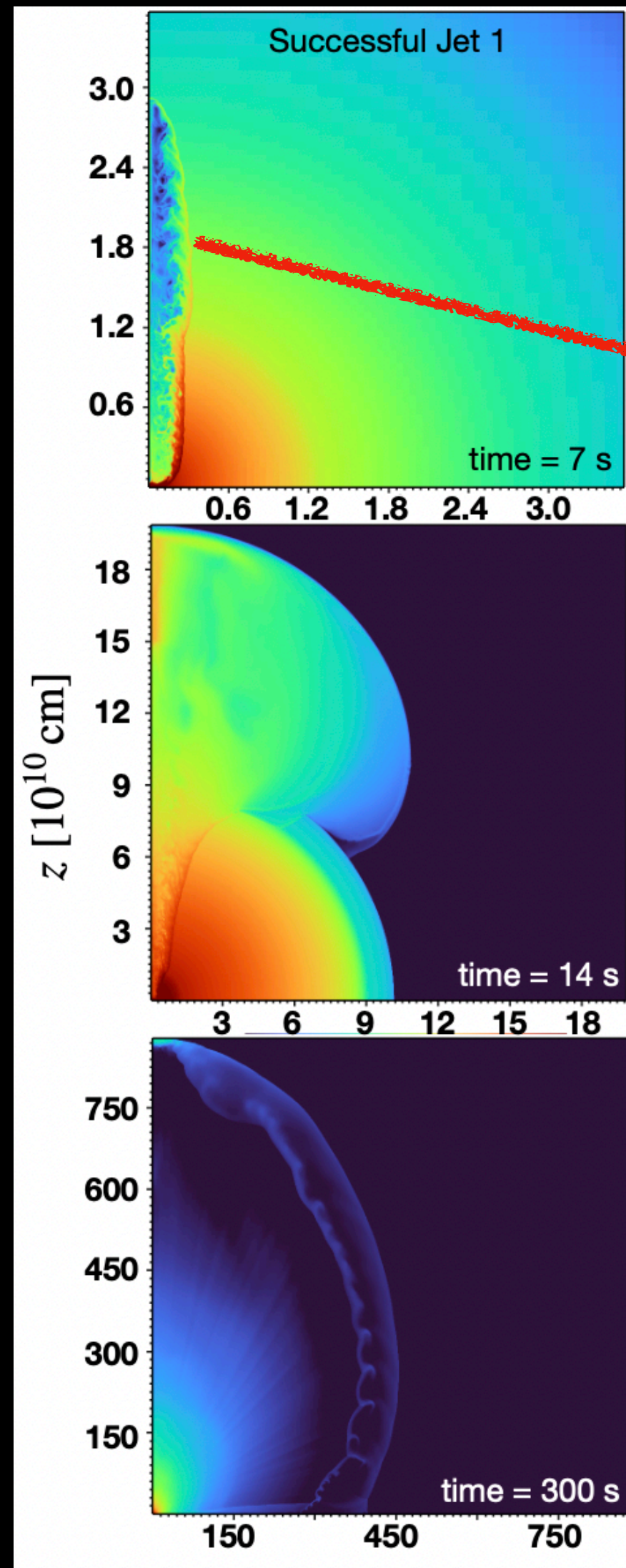
$$f_{GW} \sim \frac{1}{t_{GRB}} \lesssim 1 \text{ Hz}$$



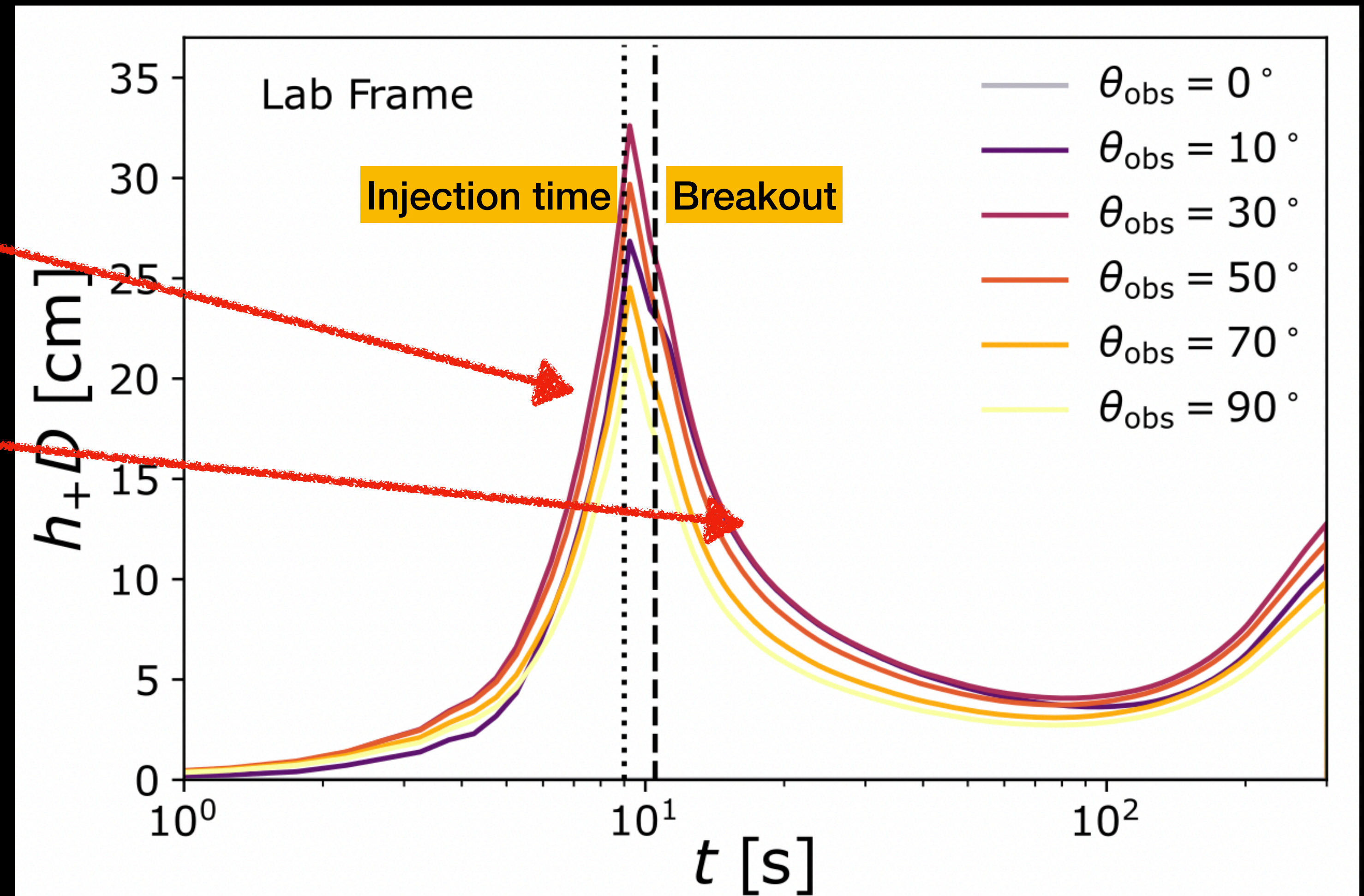
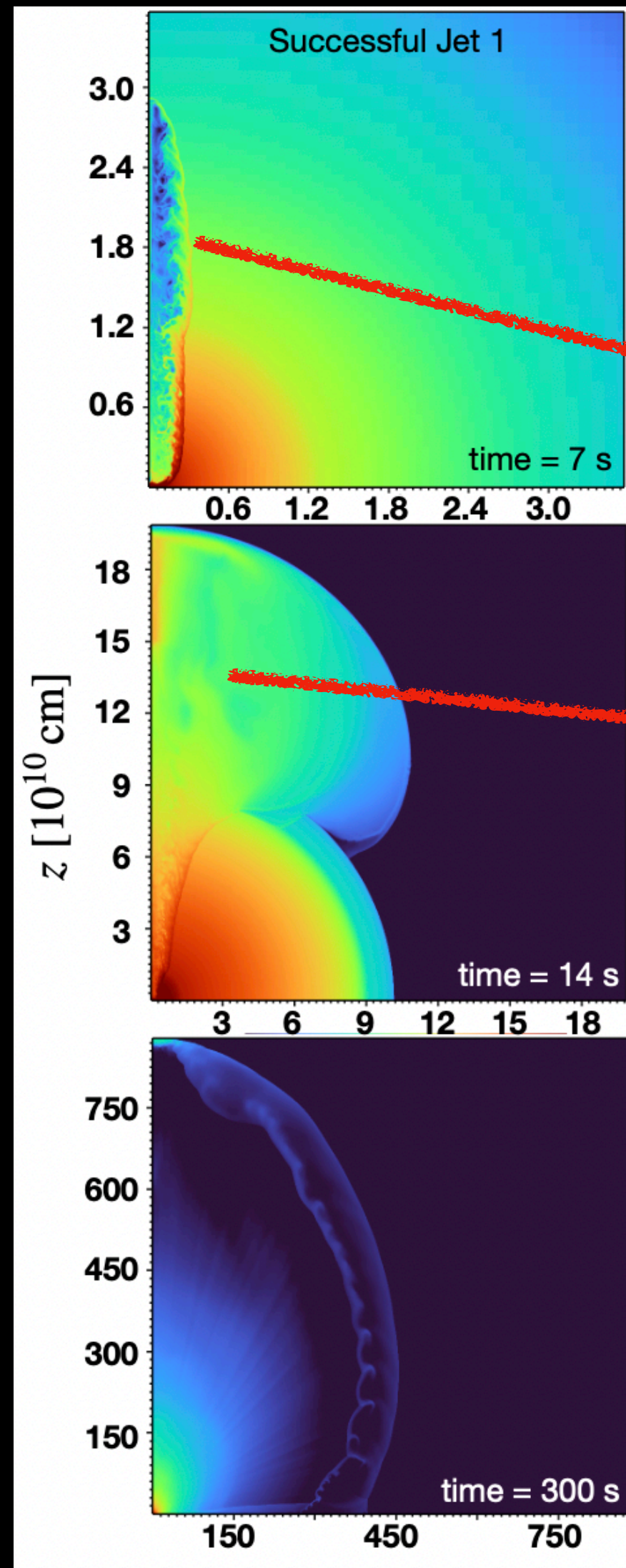
Connection with jet evolution



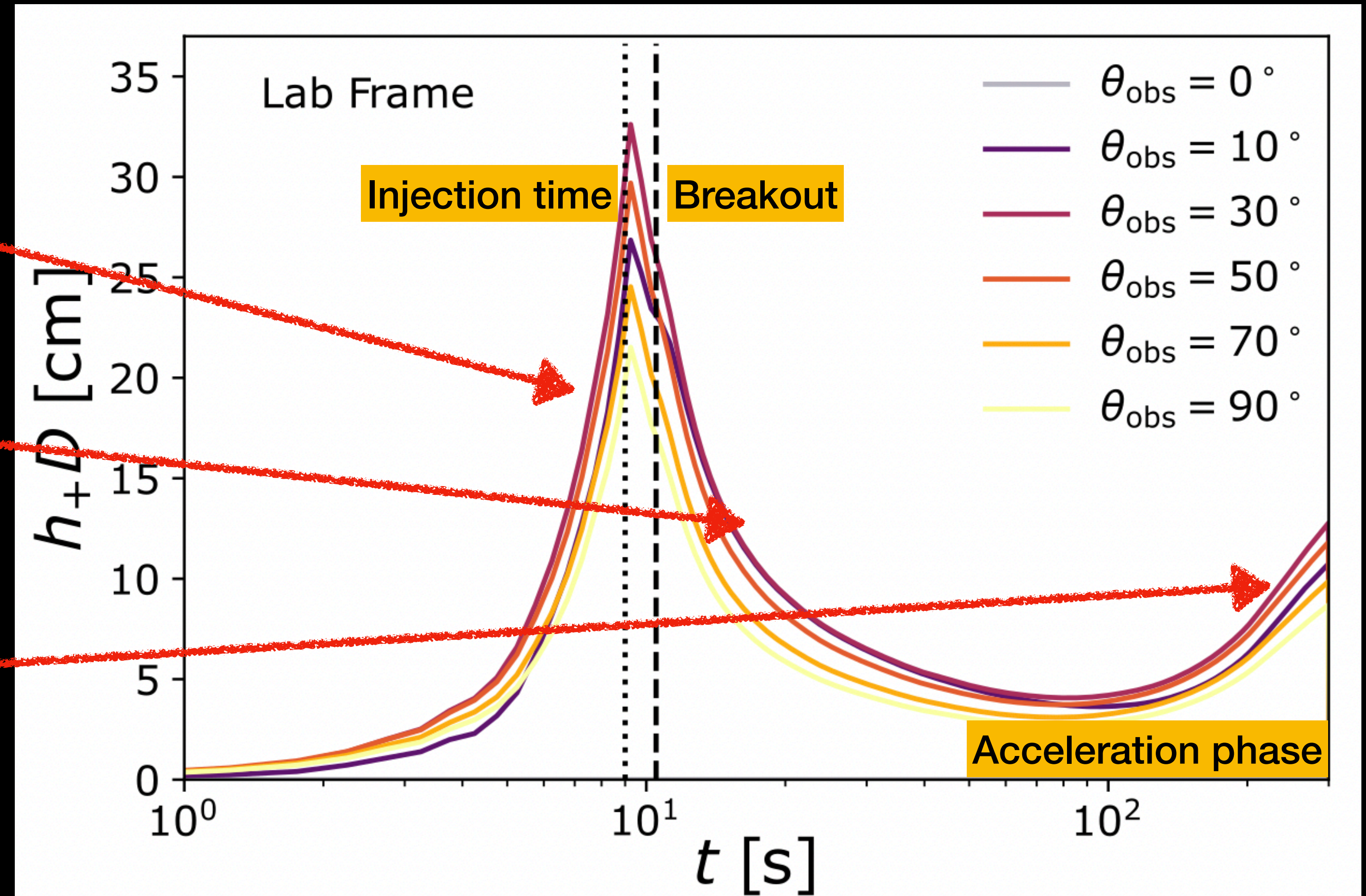
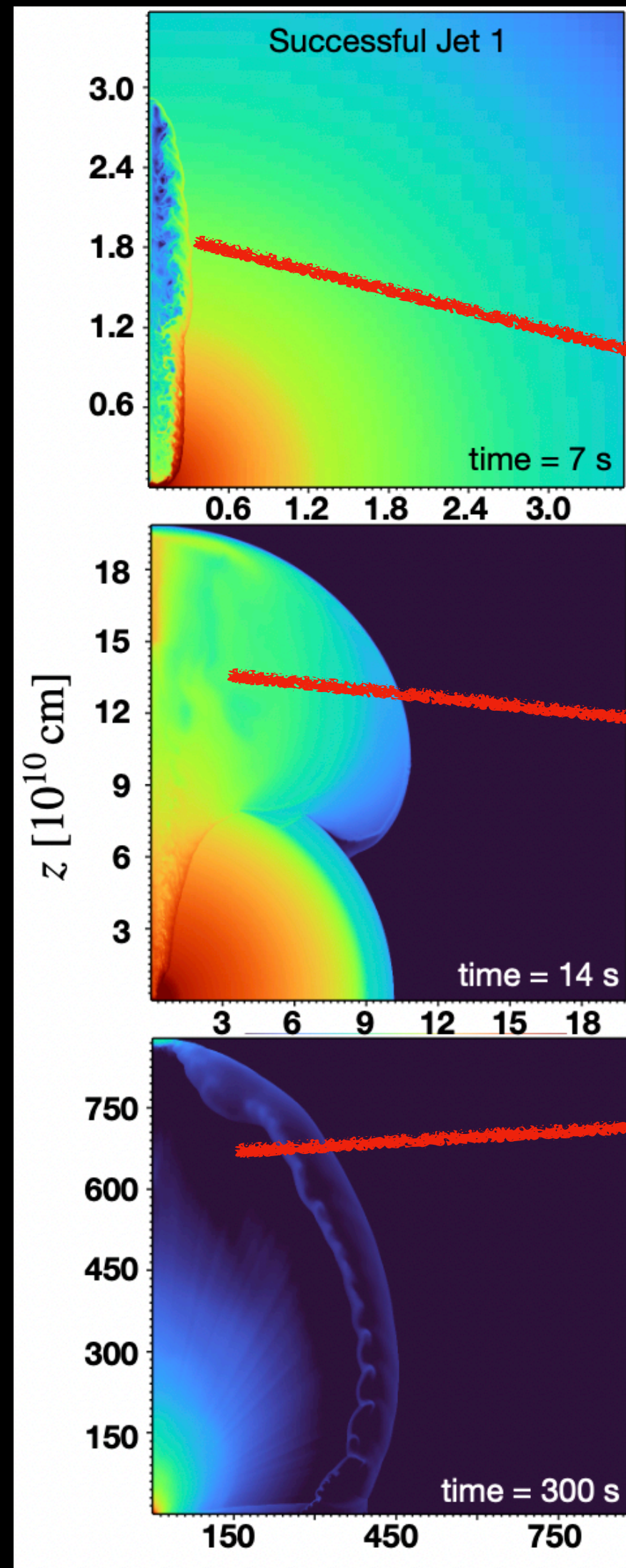
Connection with jet evolution



Connection with jet evolution



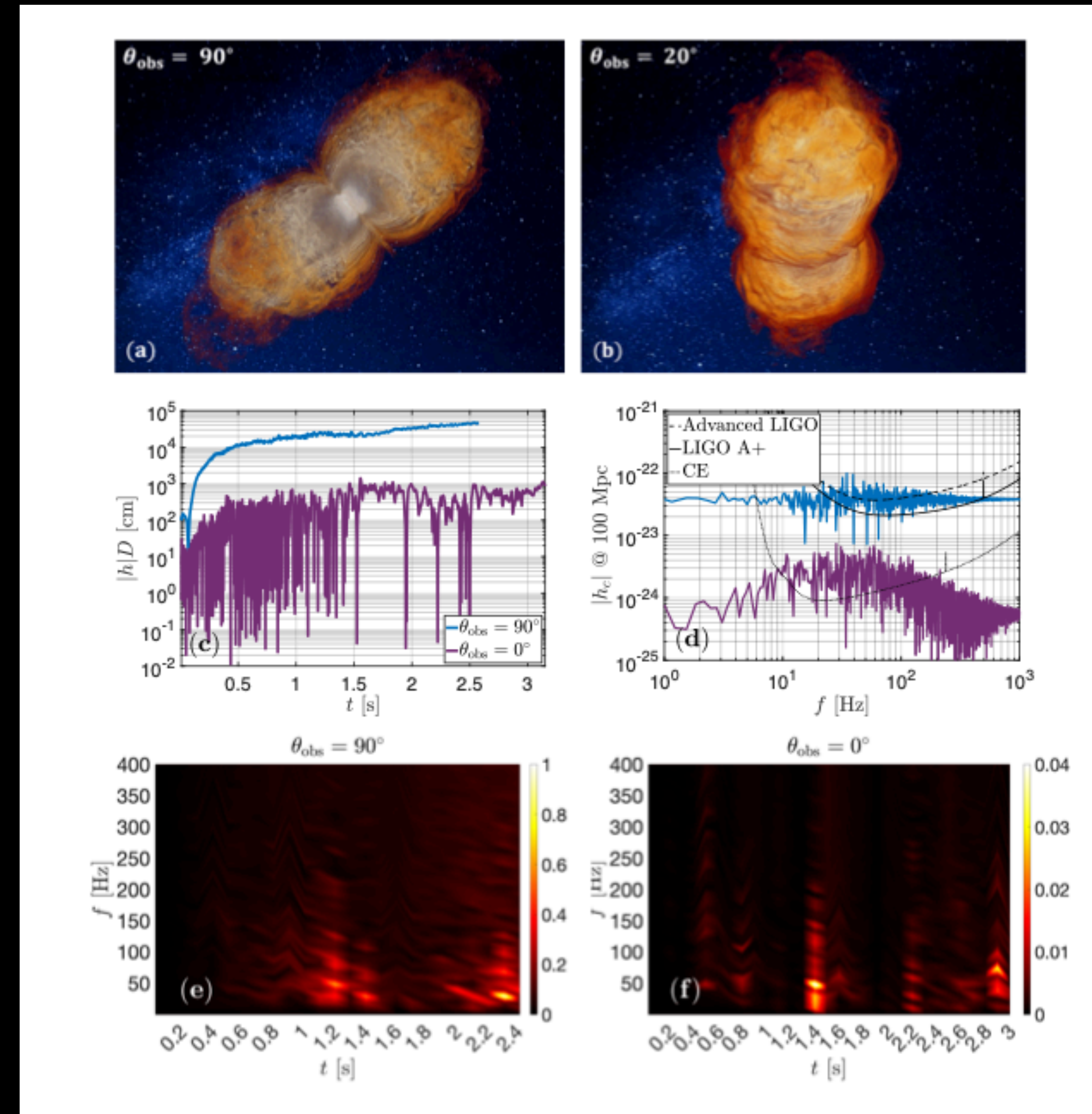
Connection with jet evolution



Previous estimations of GW signals from GRBs

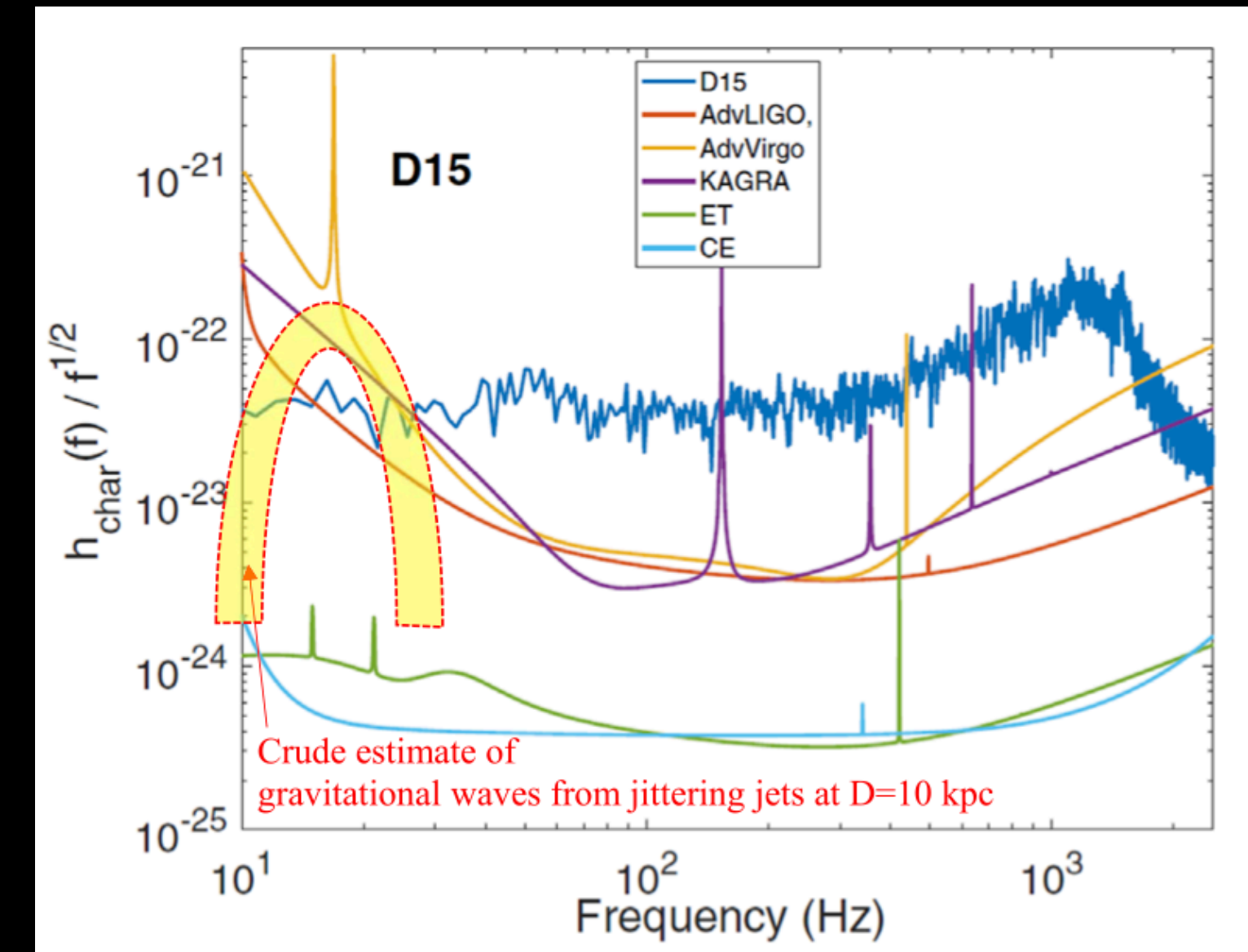
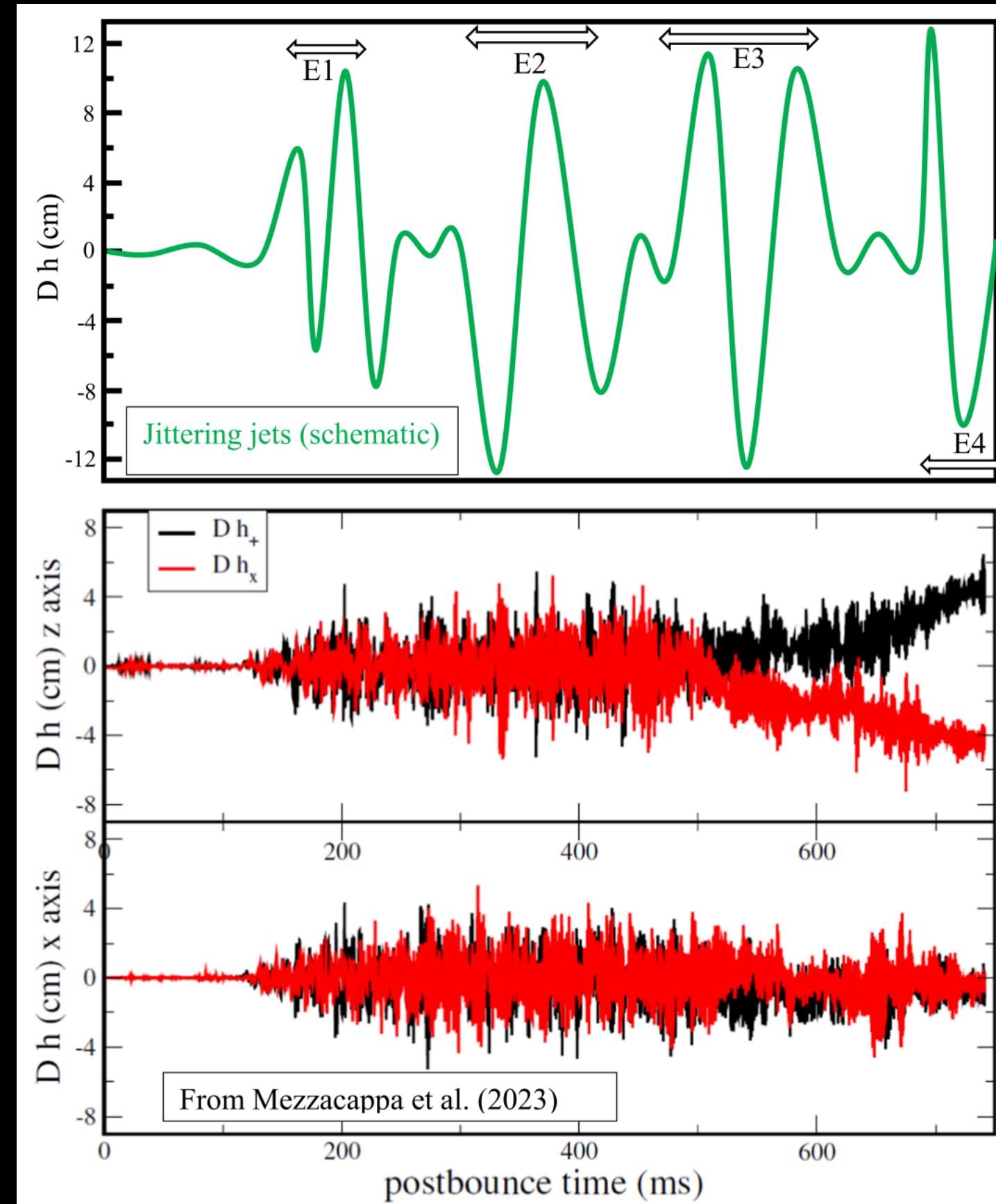
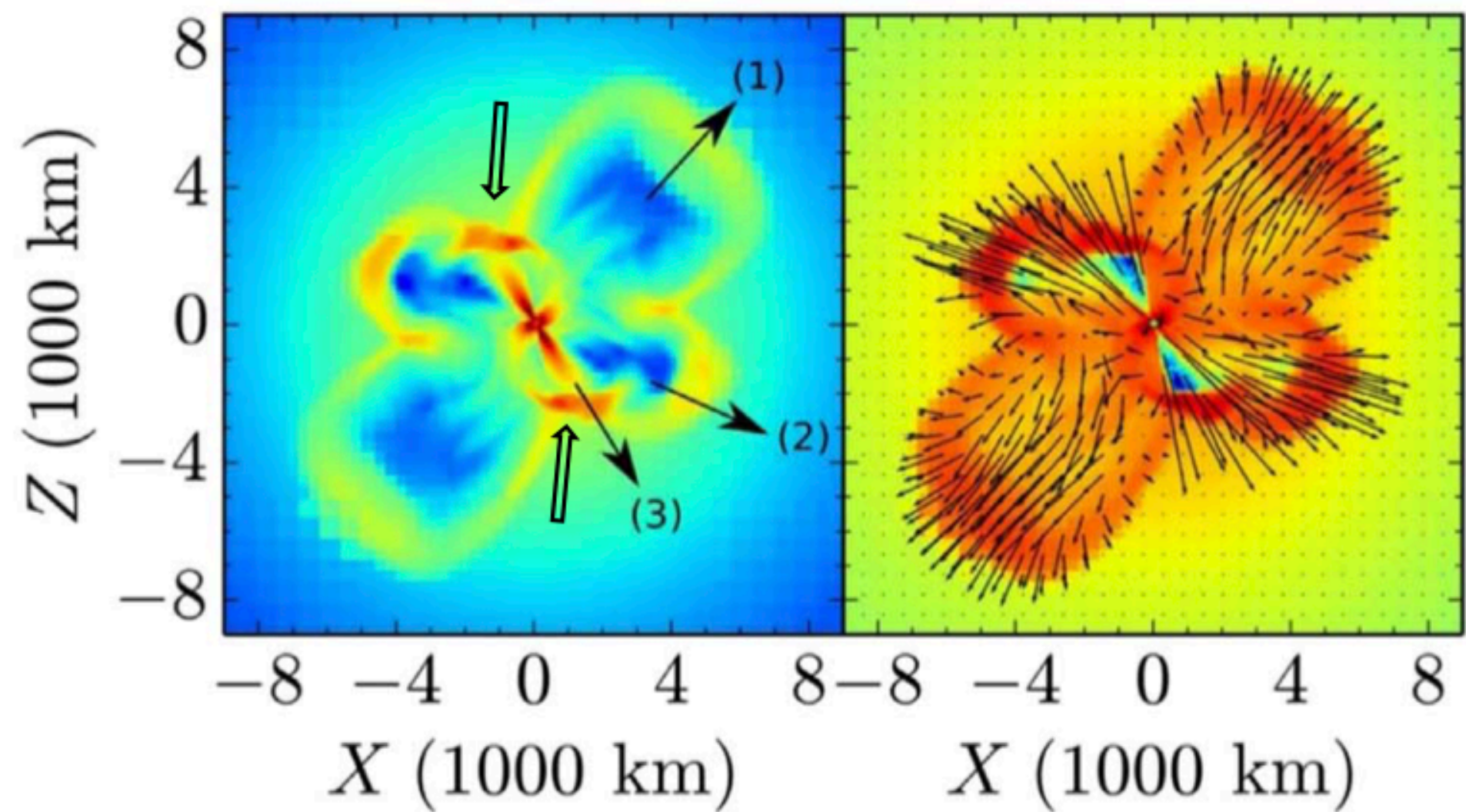
Gottlieb et al. 2023

- High frequency
- High luminosity
- Are those GW really given some physical interpretation ?



Previous estimations of GW signals from GRBs

Soker et al. 2023



$$\frac{h}{\sqrt{f}} \approx 10^{-22} \left(\frac{D}{10 \text{ kpc}} \right) \left(\frac{E_j}{10^{53} \text{ erg}} \right) \left(\frac{f_{Jj}}{15 \text{ Hz}} \right) \text{ Hz}^{-1/2}$$

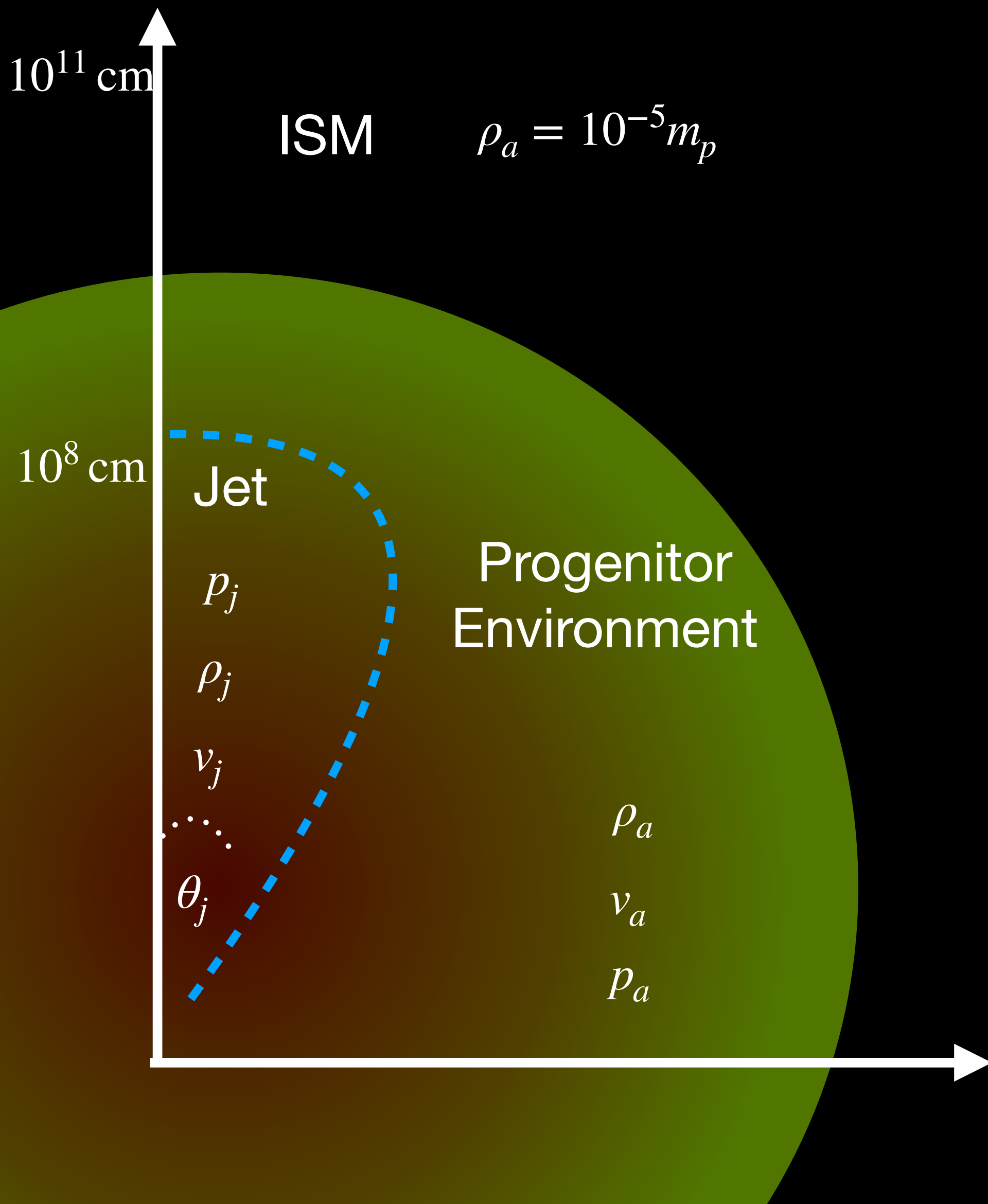
Intermediate summary

Elements to generate our hypothesis

- Can GW from jets generate high frequency GW?
- Which elements generate that: Turbulence, central engine activity ?
- Jittering jets or variability from the central engine?
- We would like to have an interpretation or direct observations of the physical properties of the jet

Methods

Modeling Cosmic Explosions



Mass

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

Momentum

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

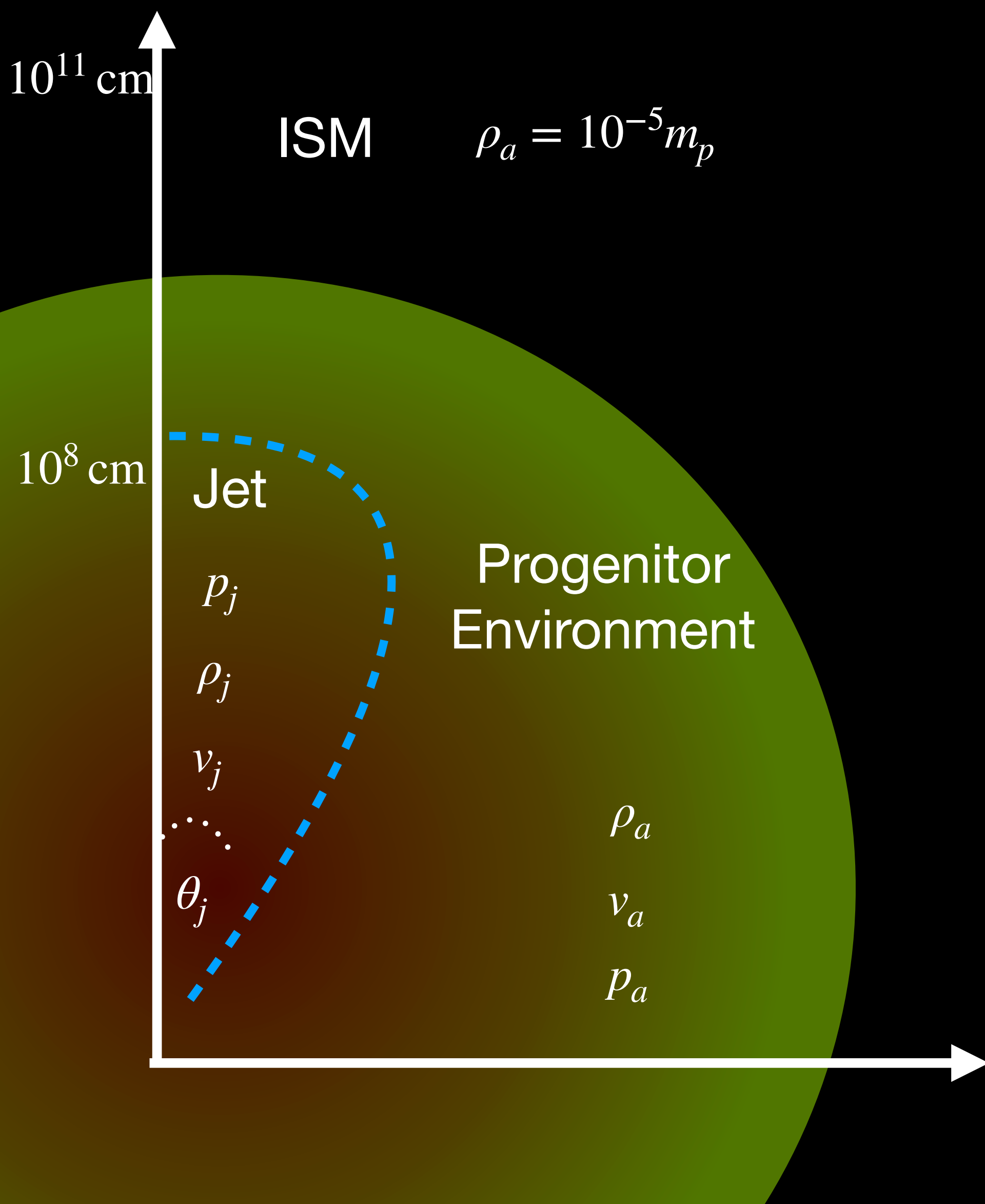
Energy

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

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

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

We rewrite the equations to express a general rule



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

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

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

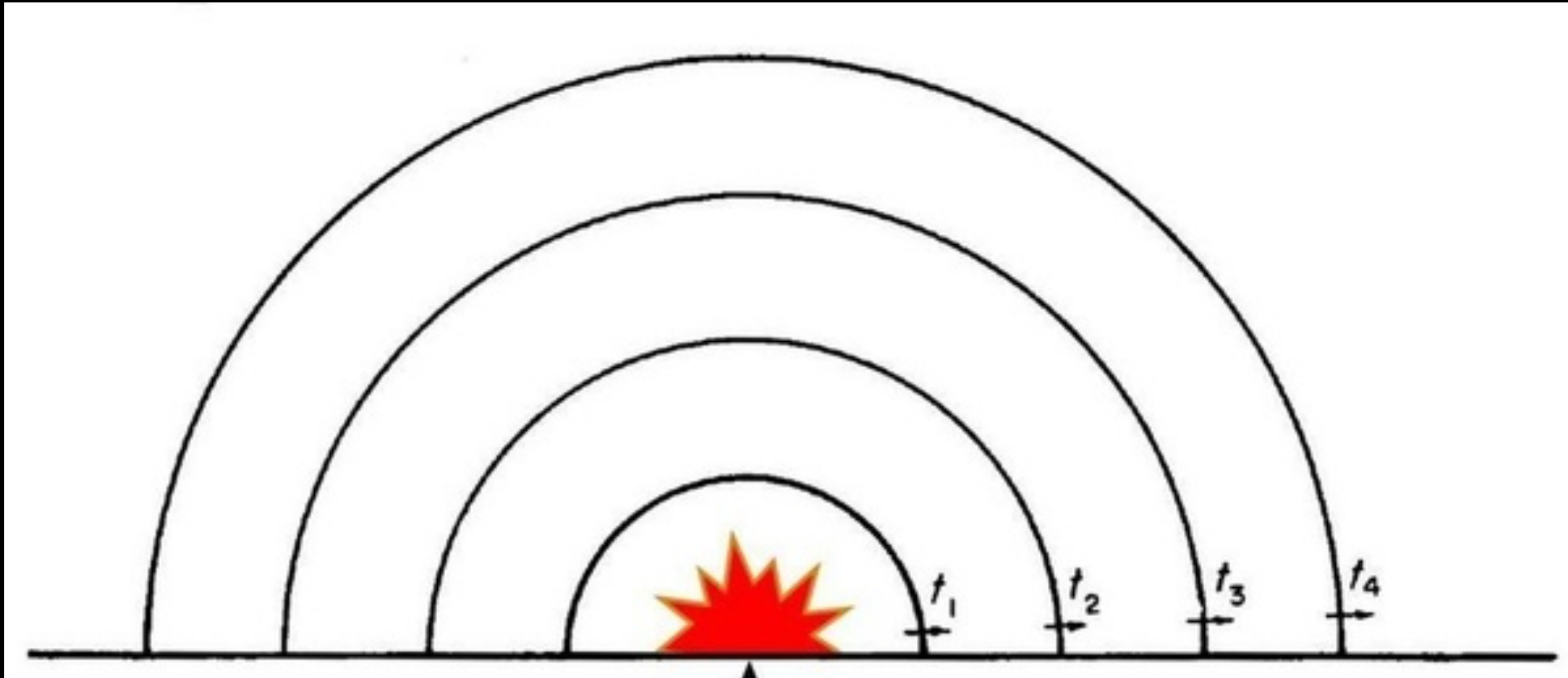
$$D = \Gamma \rho$$

$$m_j = D h \Gamma v_j$$

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

The solution of such global expression

Numerical simulations are our virtual laboratory to reproduce extreme conditions



- Supersonic fluids
- Strong shocks

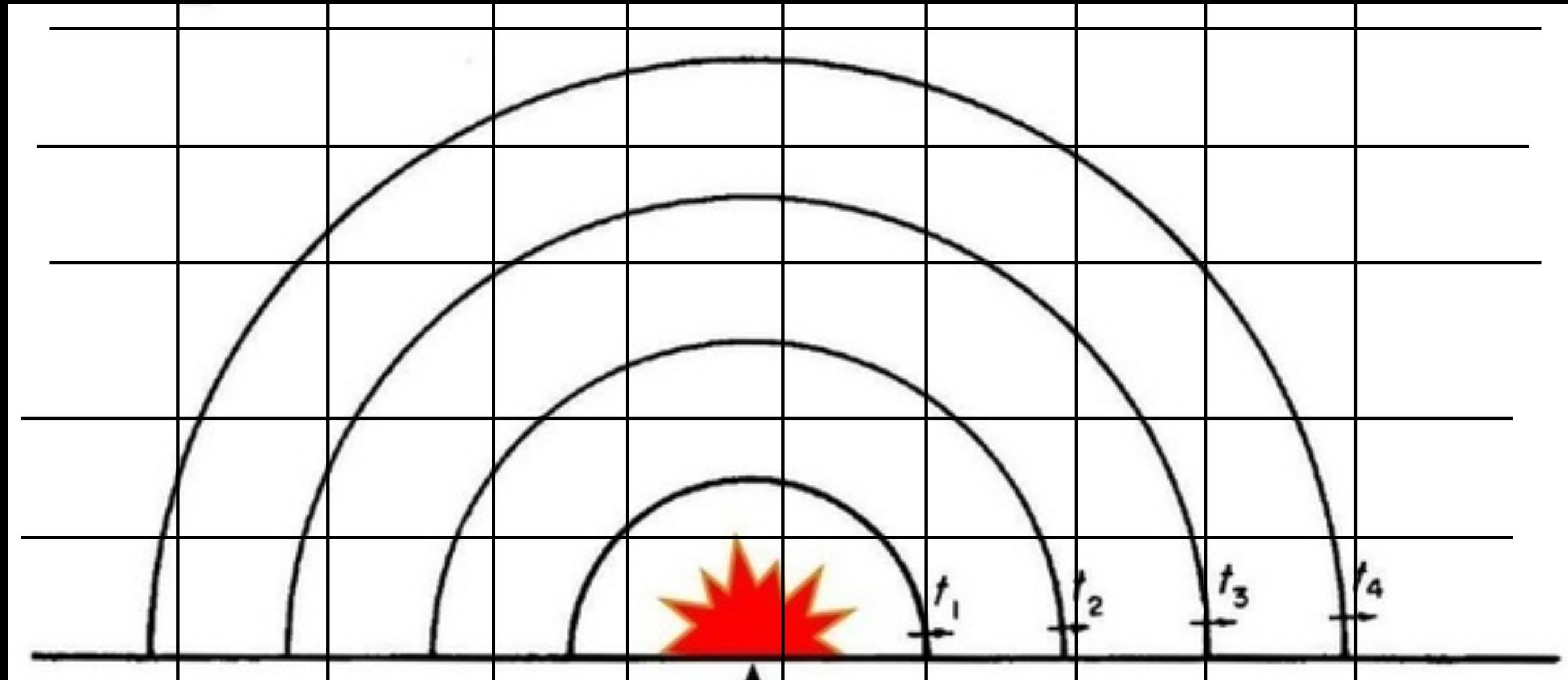
$$U_i^{n+1} = U_i^n - \frac{\Delta t}{\Delta x_i} \left(F_{i+1/2}^{n+1/2} - F_{i-1/2}^{n+1/2} \right)$$

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

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

The solution of such global expression

Numerical simulations are our virtual laboratory to reproduce extreme conditions



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

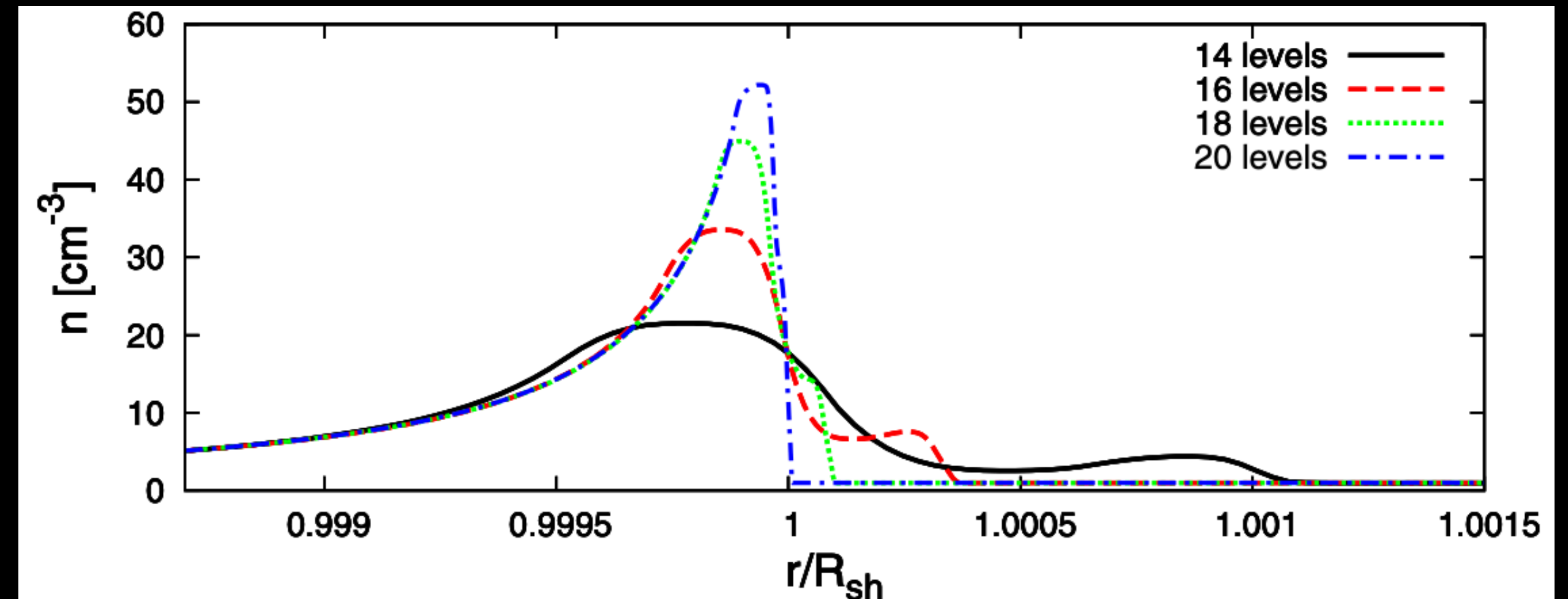
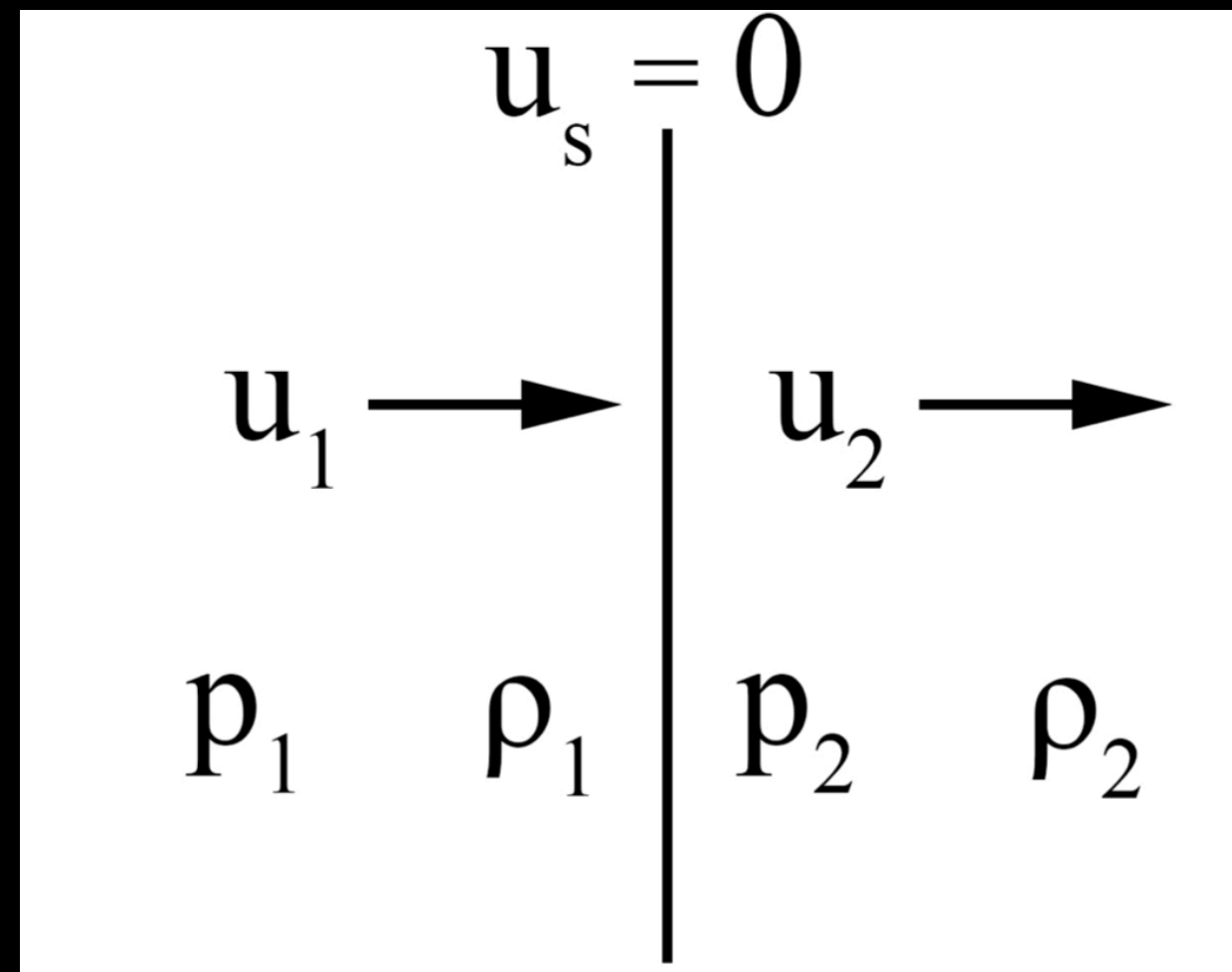
$$U_i^n = \frac{1}{\Delta x_i} \int_{x_{i-1/2}}^{x_{i+1/2}} u_i(t^n, x) dx$$

- Supersonic fluids
- Strong shocks

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

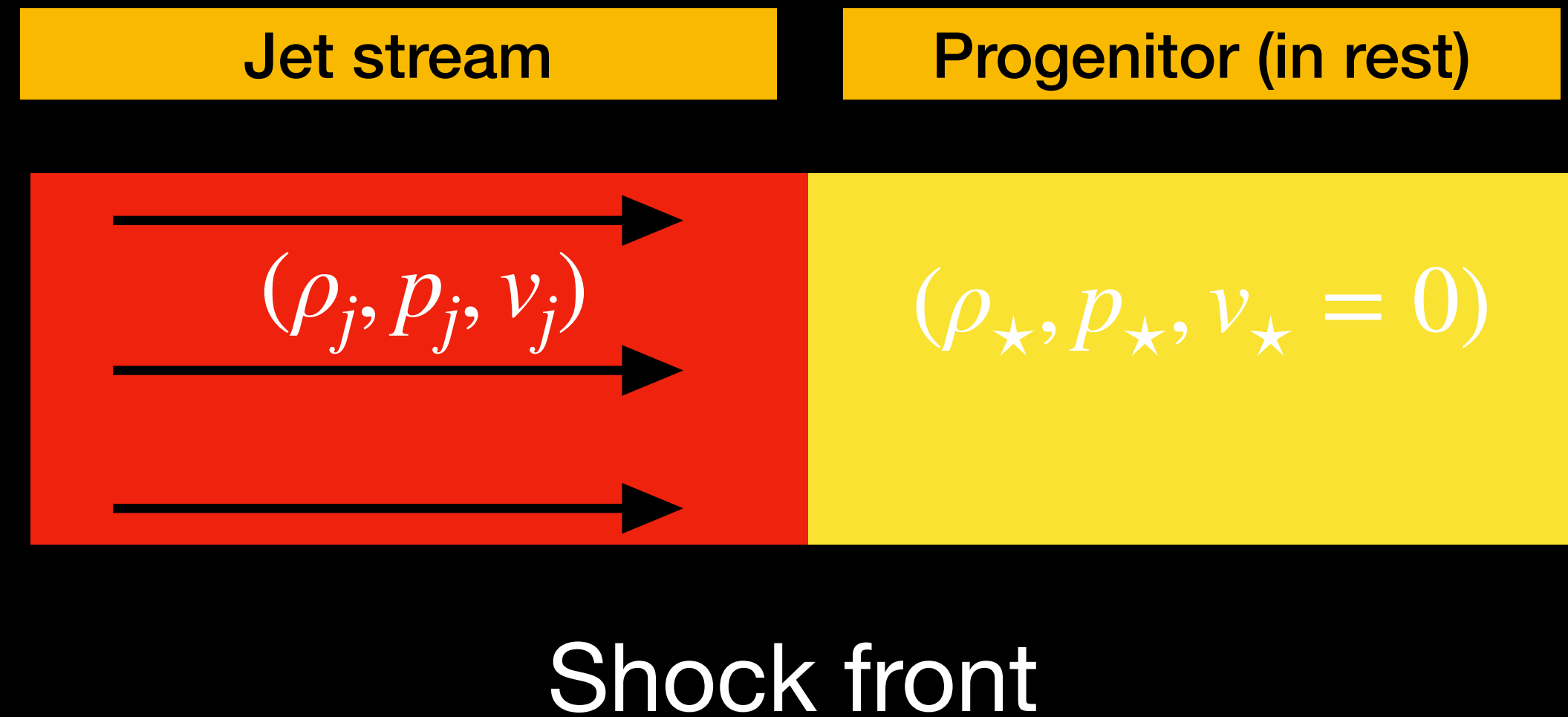
Shock capture scheme

Numerical simulations are our virtual laboratory to reproduce extreme conditions



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

The initial conditions of the jet

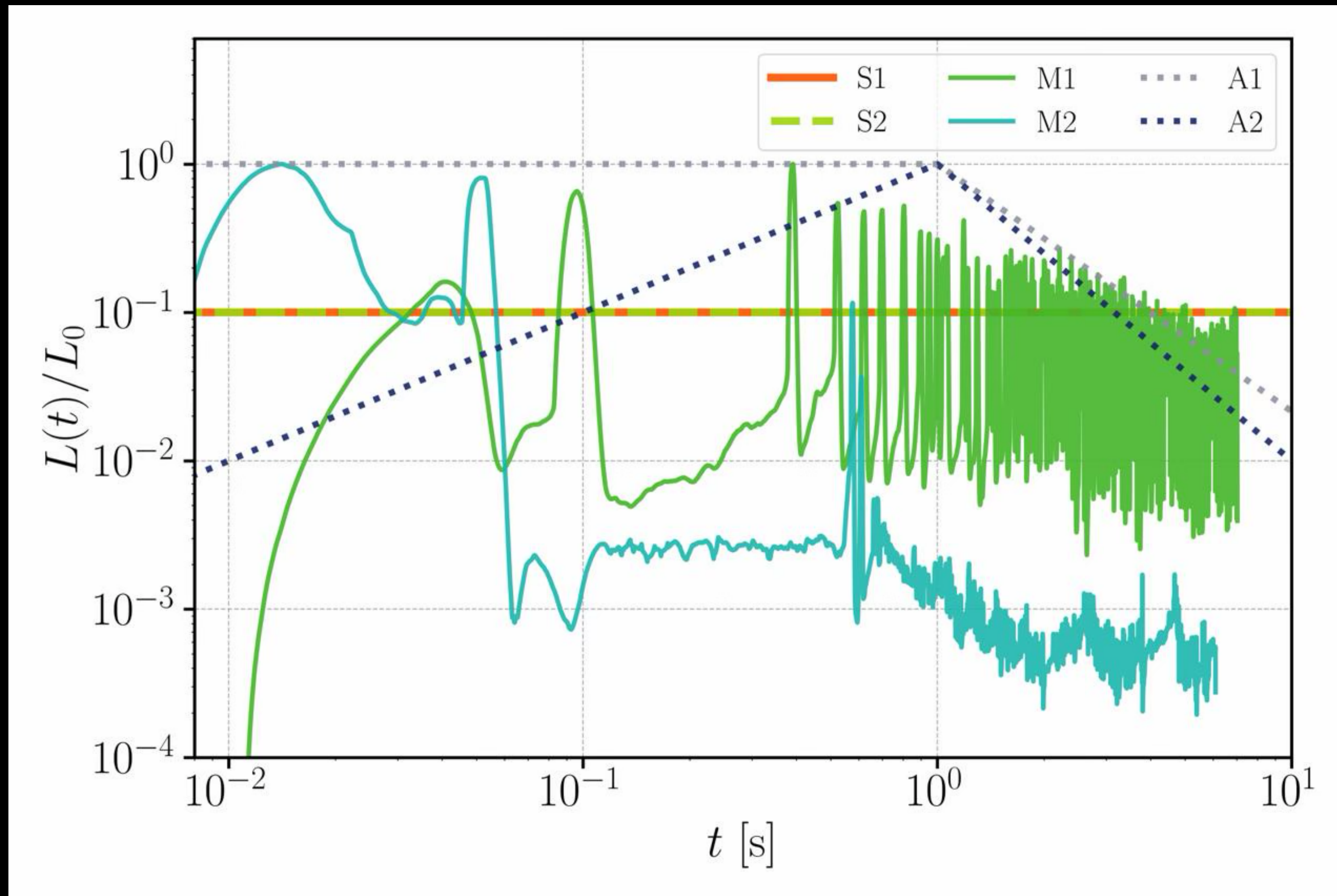


$$L_j \approx \frac{dE_j}{dt} = \dot{M}c^2 = c^2 \frac{d}{dt} \int \Gamma_j \rho_j v_j dS$$

$$\rho_j h_j \Gamma_j^2 \Gamma_h^2 (\beta_j - \beta_h)^2 c^2 + p_j = \rho_a \Gamma_h^2 \beta_h^2 c^2$$

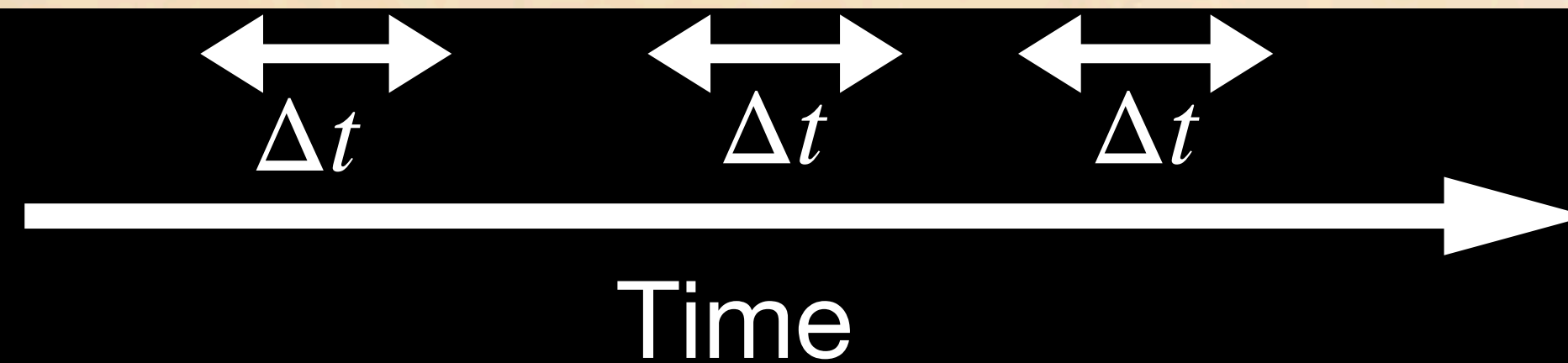
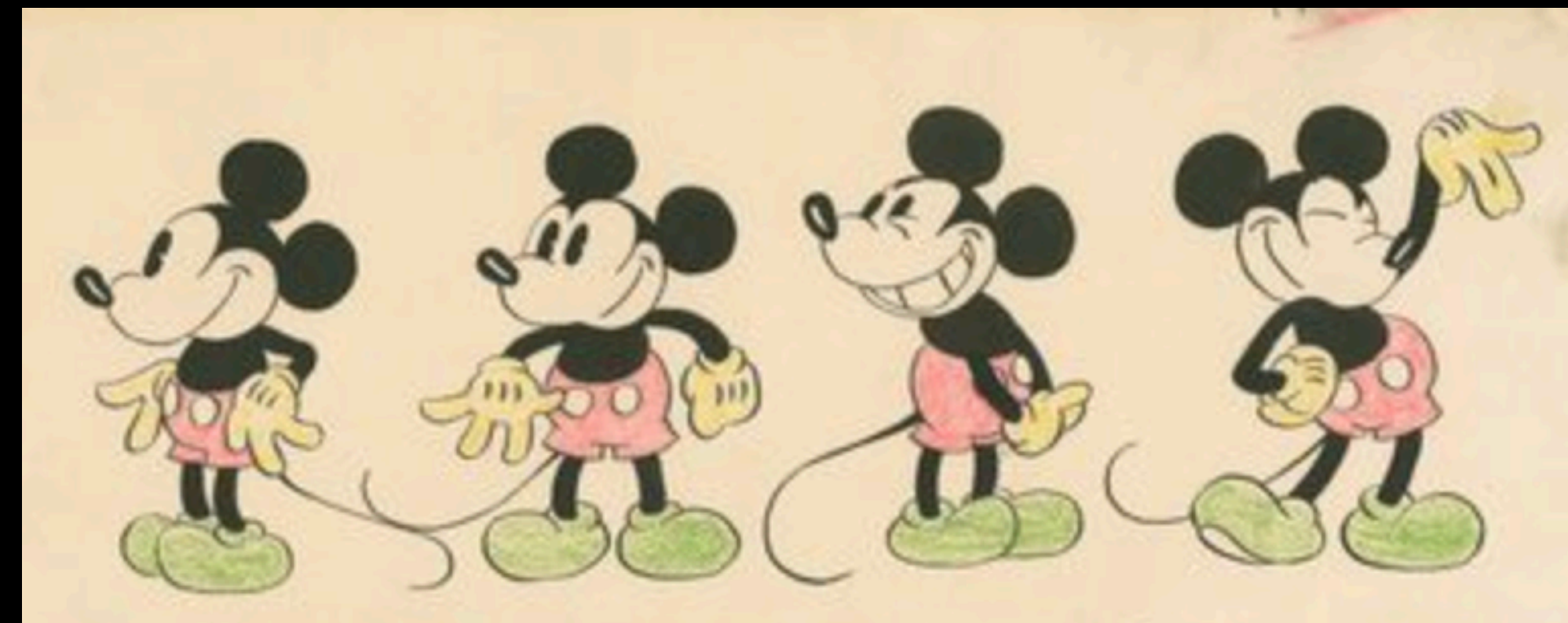
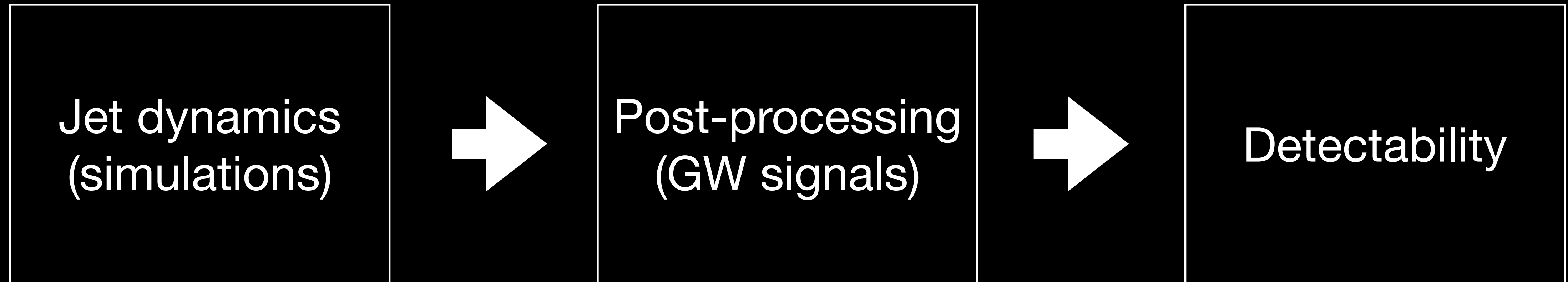
Jet models

Three numerical experiments

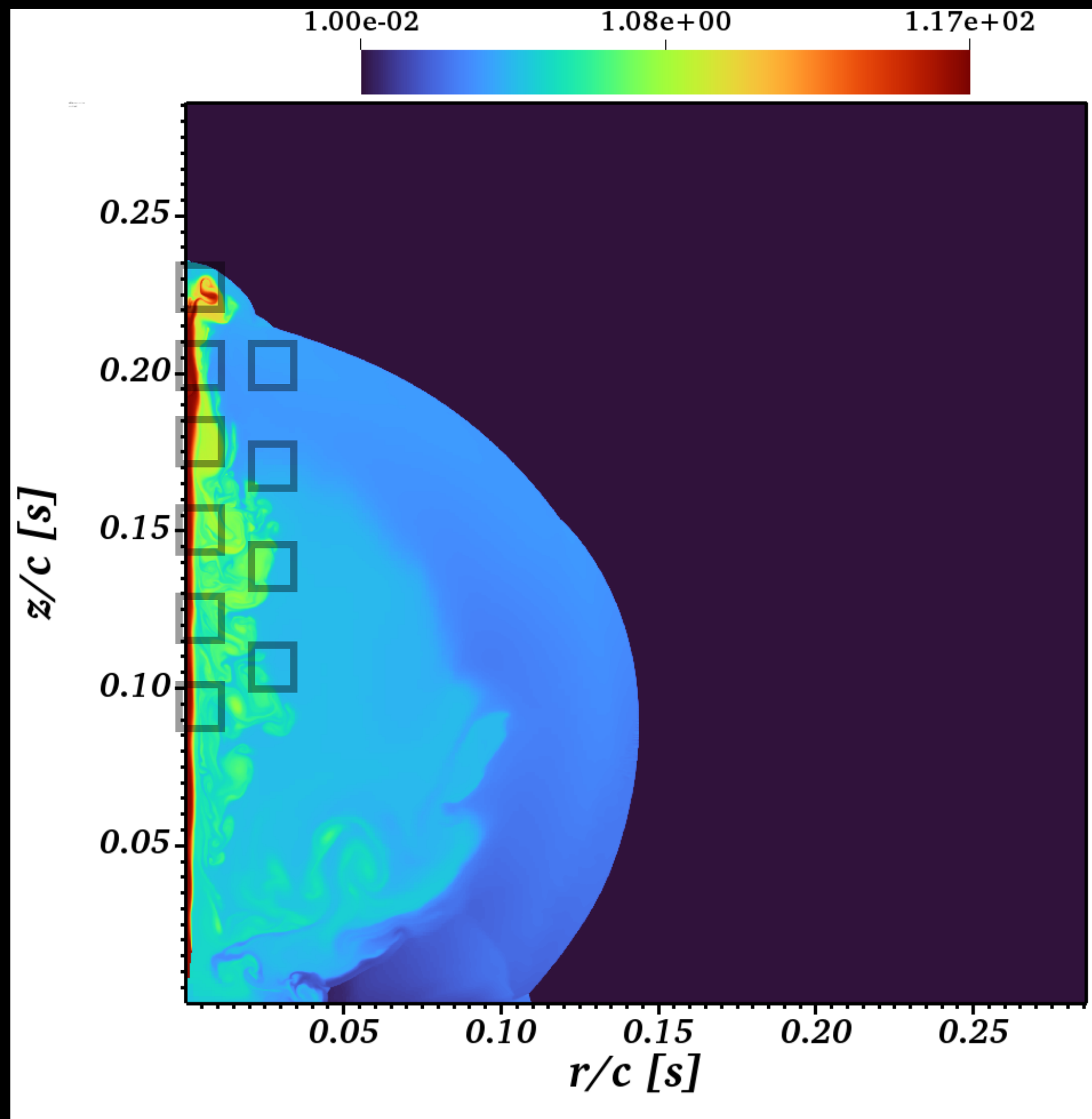


- Constant luminosity: to study the progenitor effects
- Smooth increasing: to study the rising effects
- Luminosity imported from GRMHD simulations

Our previous methodology



Our previous methodology



$$t_{\text{fin}} = 300 \text{ s}$$

$$N_{\text{out}} = 600$$

$\{t_i\}$ Equaled spaced time bins

$$h(t) \approx h(t_i)$$

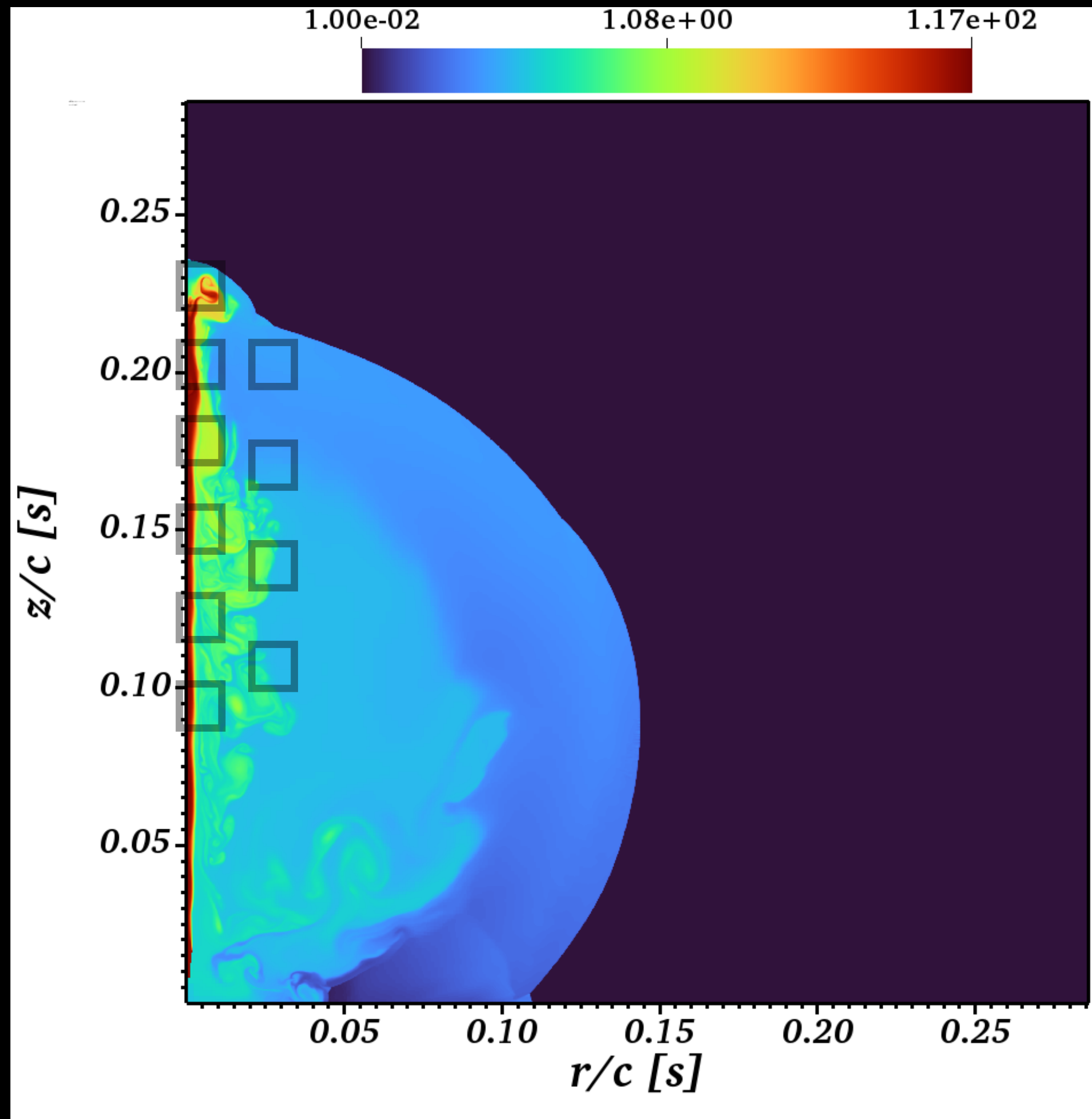
$$\Delta t = t_{\text{fin}}/N_{\text{out}}$$

$$\nu \approx 2 \text{ Hz}$$

However

$$\Delta r_{\text{min}} \approx 3.7 \times 10^6 \text{ cm}$$

New methodology: module coupled with simulation



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

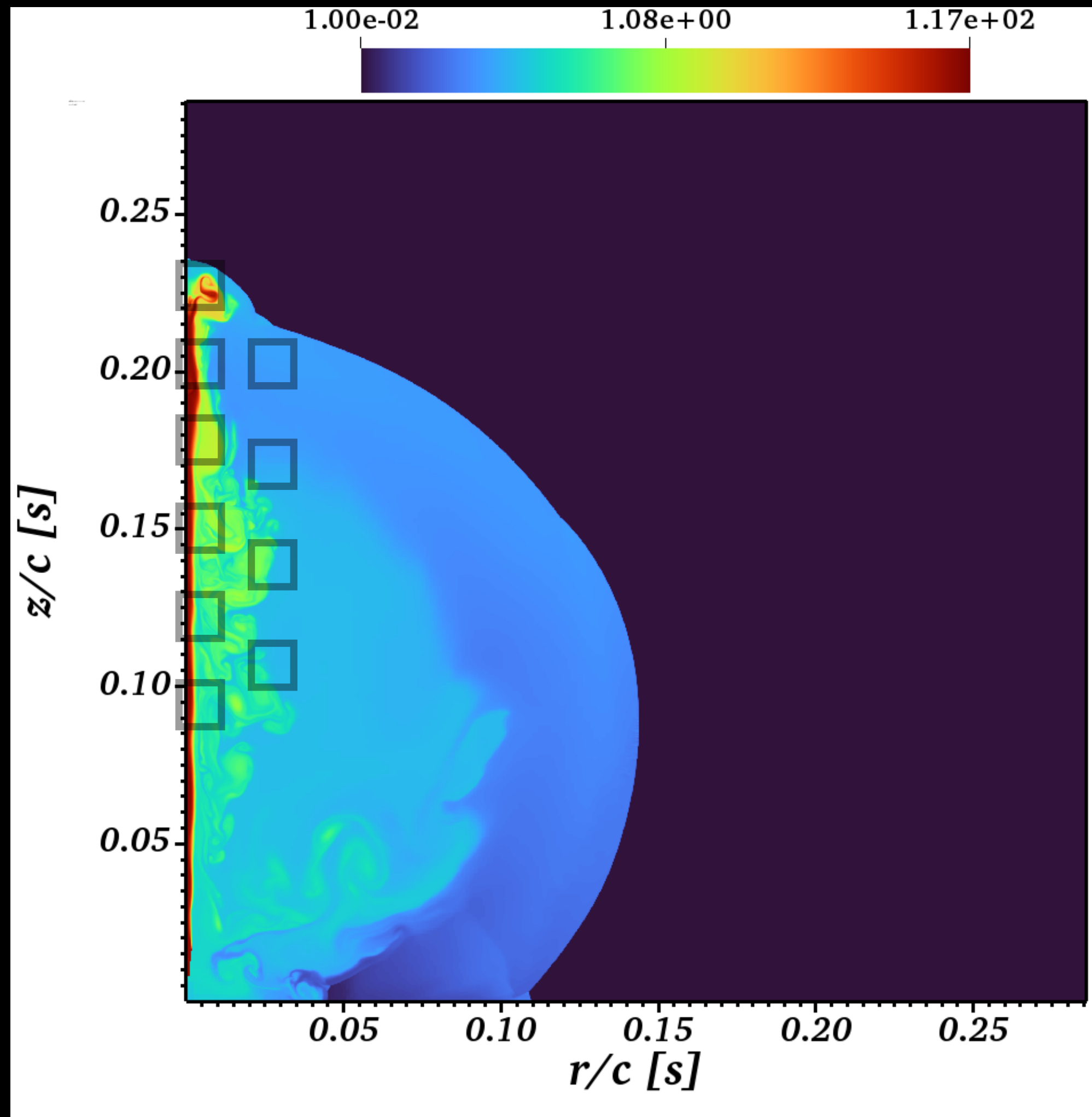
$$\Delta r_{\min} \approx 3.7 \times 10^6 \text{ cm}$$

$$\Delta t_{\text{sim}} \lesssim N_c \Delta r / c \sim 10^{-4} \text{ s}$$

$$\{t_i\}_{\text{lab}} \quad \{t_i\}_{\text{obs}}$$

$$t_{i,\text{obs}} = t_i - (R/c) \cos \phi \sin \theta_{\text{obs}} - (z/c) \cos \theta_{\text{obs}}$$

New methodology



We define arrays

$$\{h_{+}(t_i)\}_{\text{obs}} \quad \{h_{\times}(t_i)\}_{\text{obs}}$$

$$N_t = 5 \times 10^5$$

$$t_{\text{fin}} = 20$$

$$\Delta t_{\text{obs}} = 4 \times 10^{-5} \text{ s}$$

We capture signals at

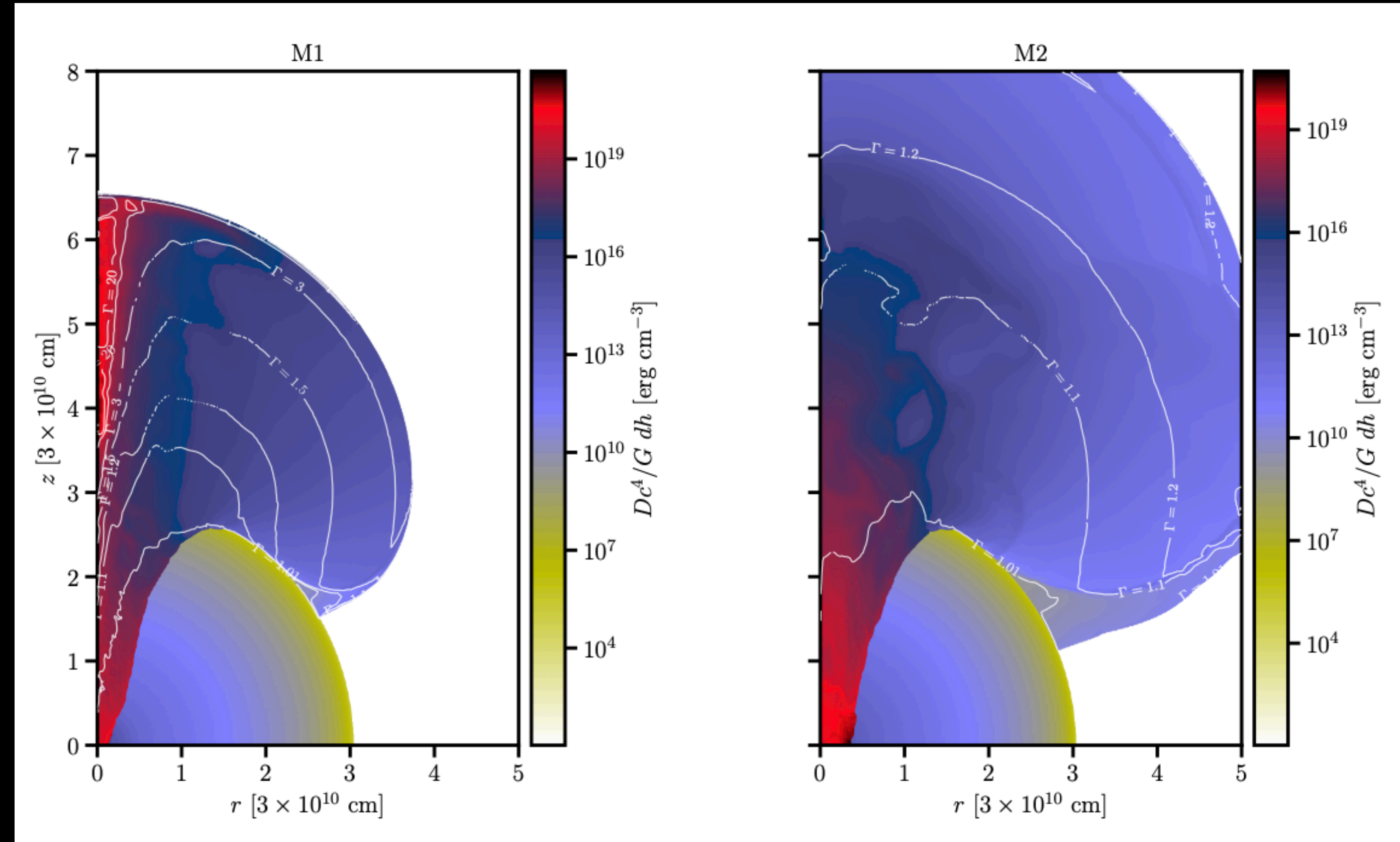
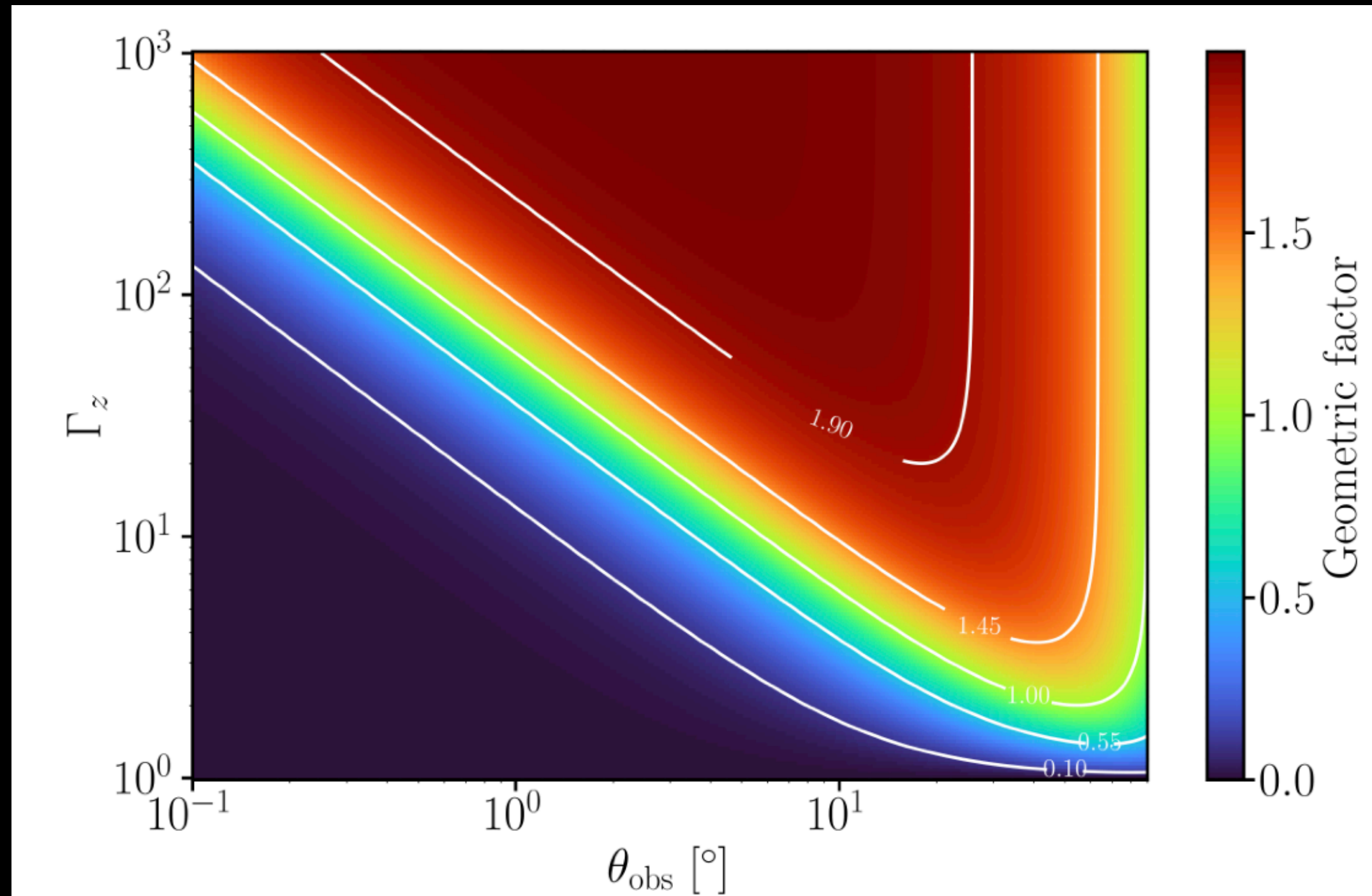
$$\nu_{\text{Nyquist}} \simeq 1.25 \times 10^4 \text{ Hz}$$

Results

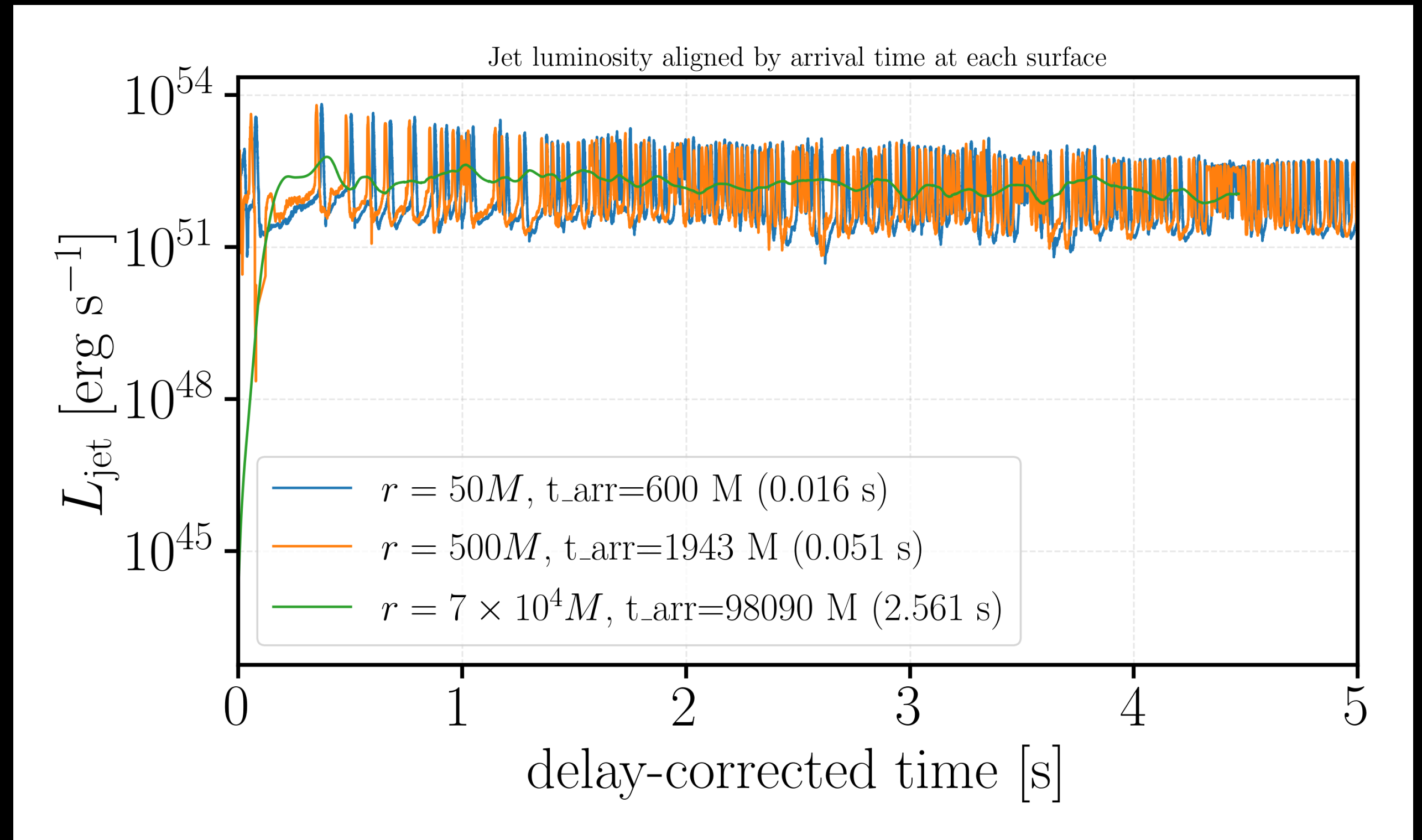
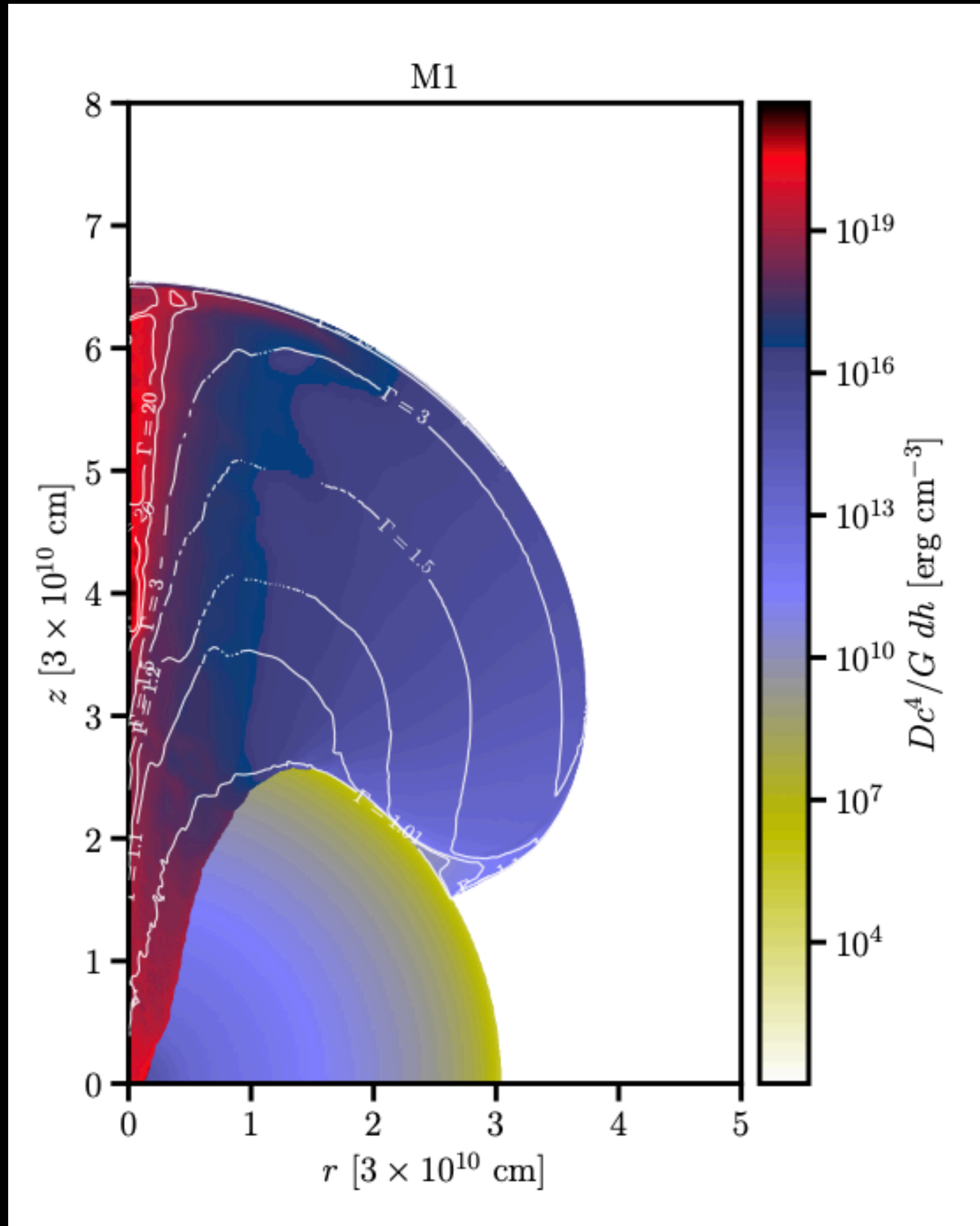
- Effects of observing angle
- Frequency regions of EM counterparts, jet activity, central engine and GW
- Effects of progenitor
- Effects from luminosity evolution
- Detectability

Regions of emission

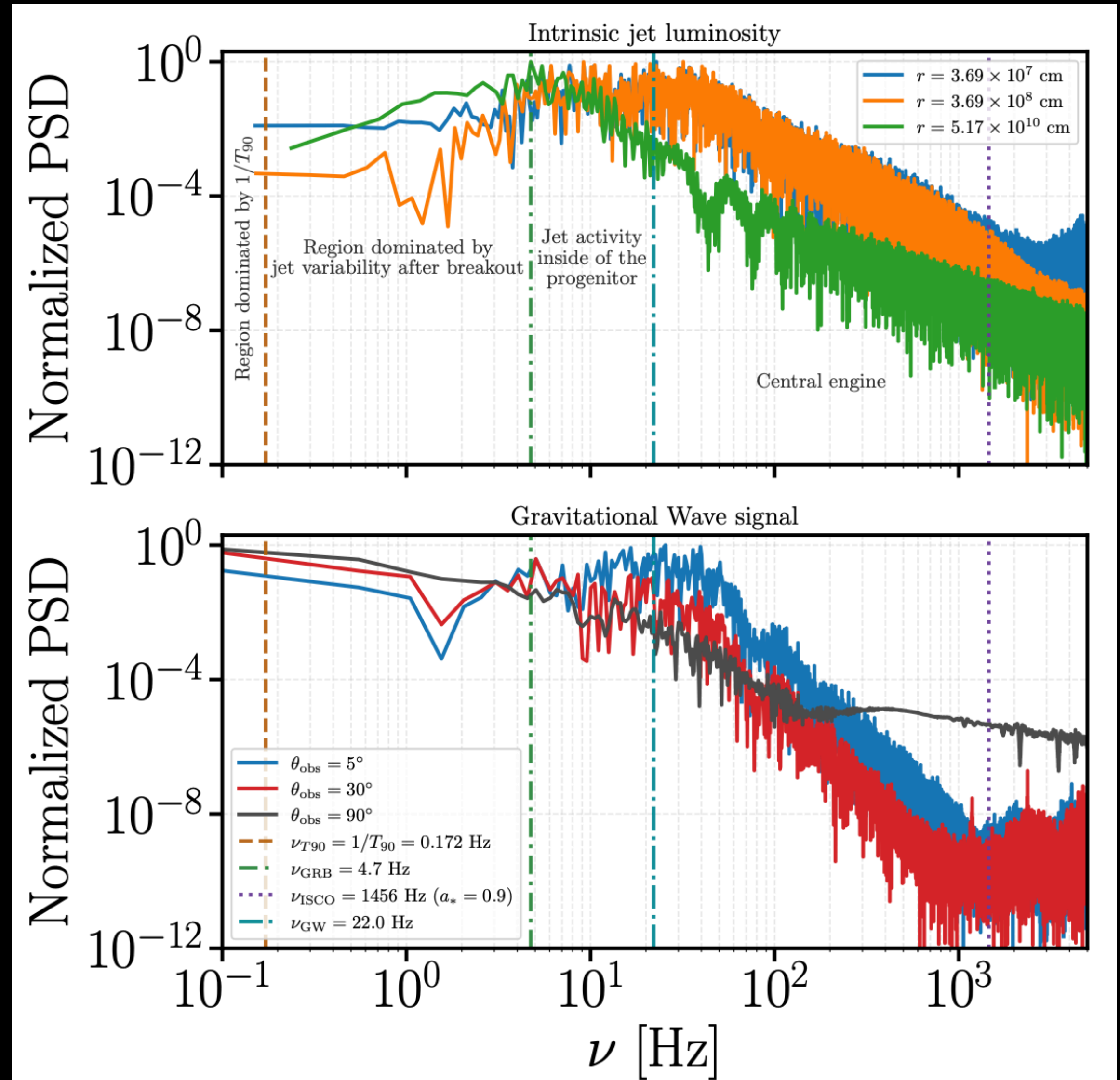
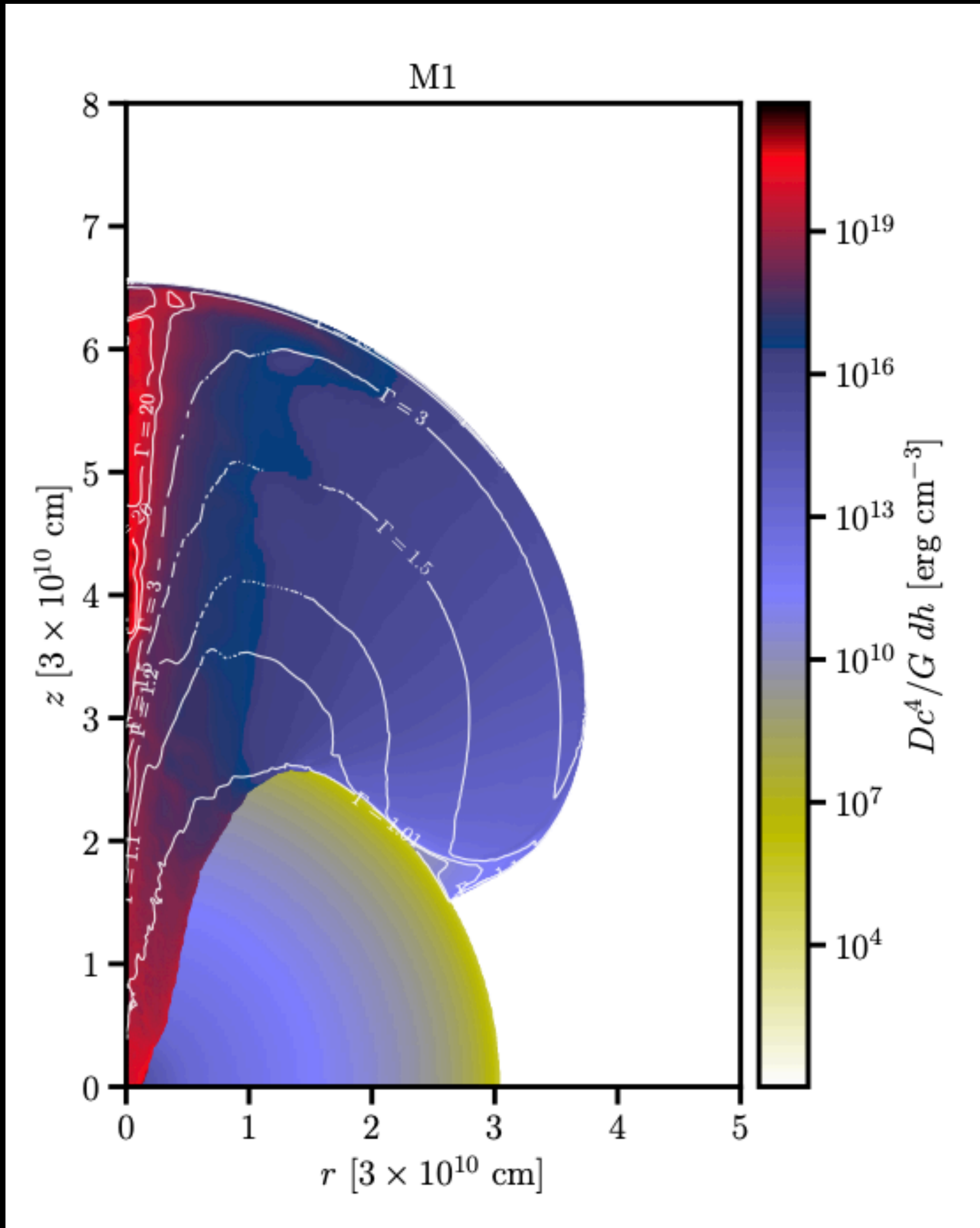
$$\mathcal{G}_+ \equiv \frac{\beta^2 \sin^2 \theta_v}{1 - \beta \cos \theta_v} \cos 2\Phi$$



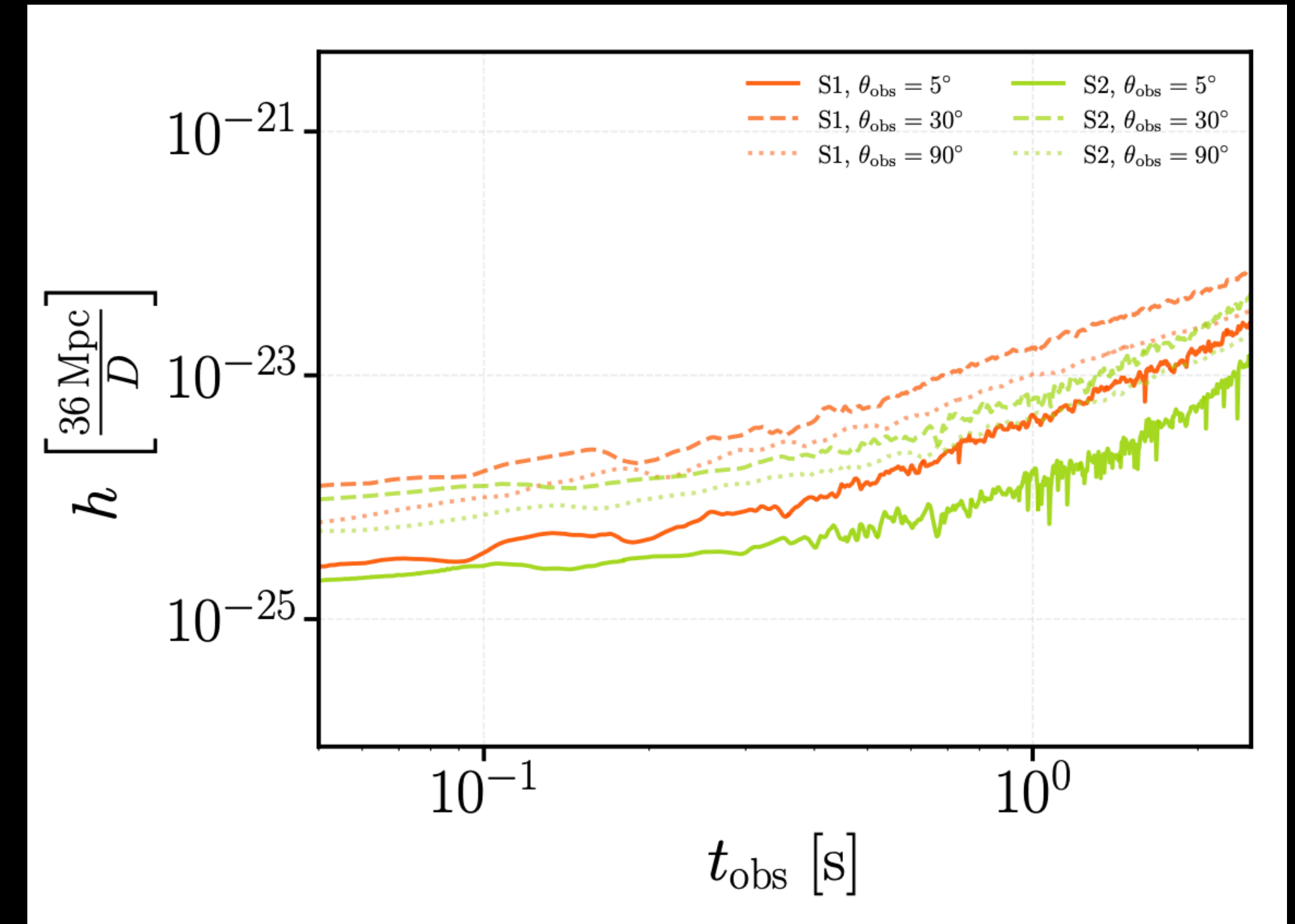
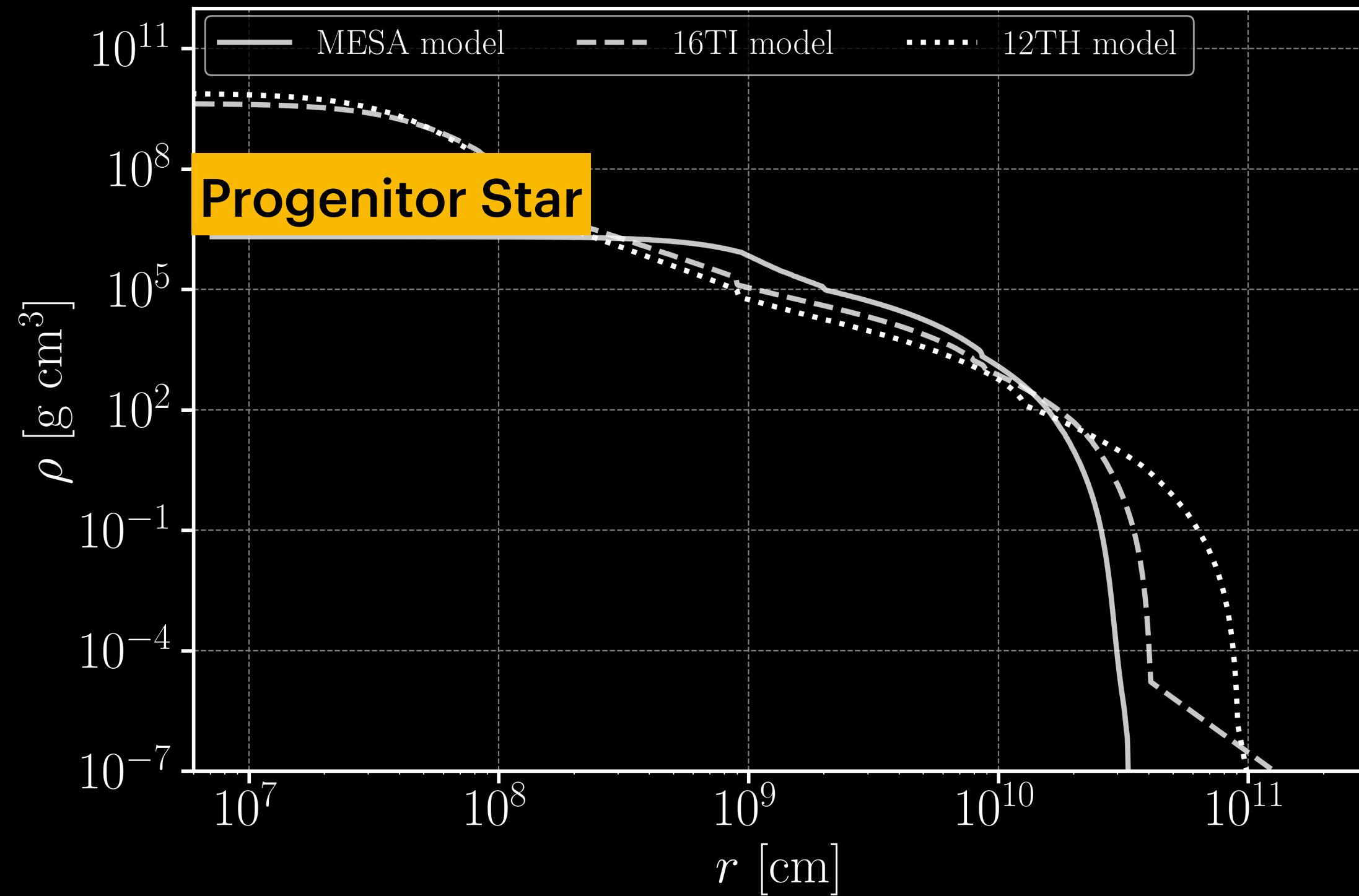
Measuring luminosity from different regions



Frequencies involved



The effects off progenitor star

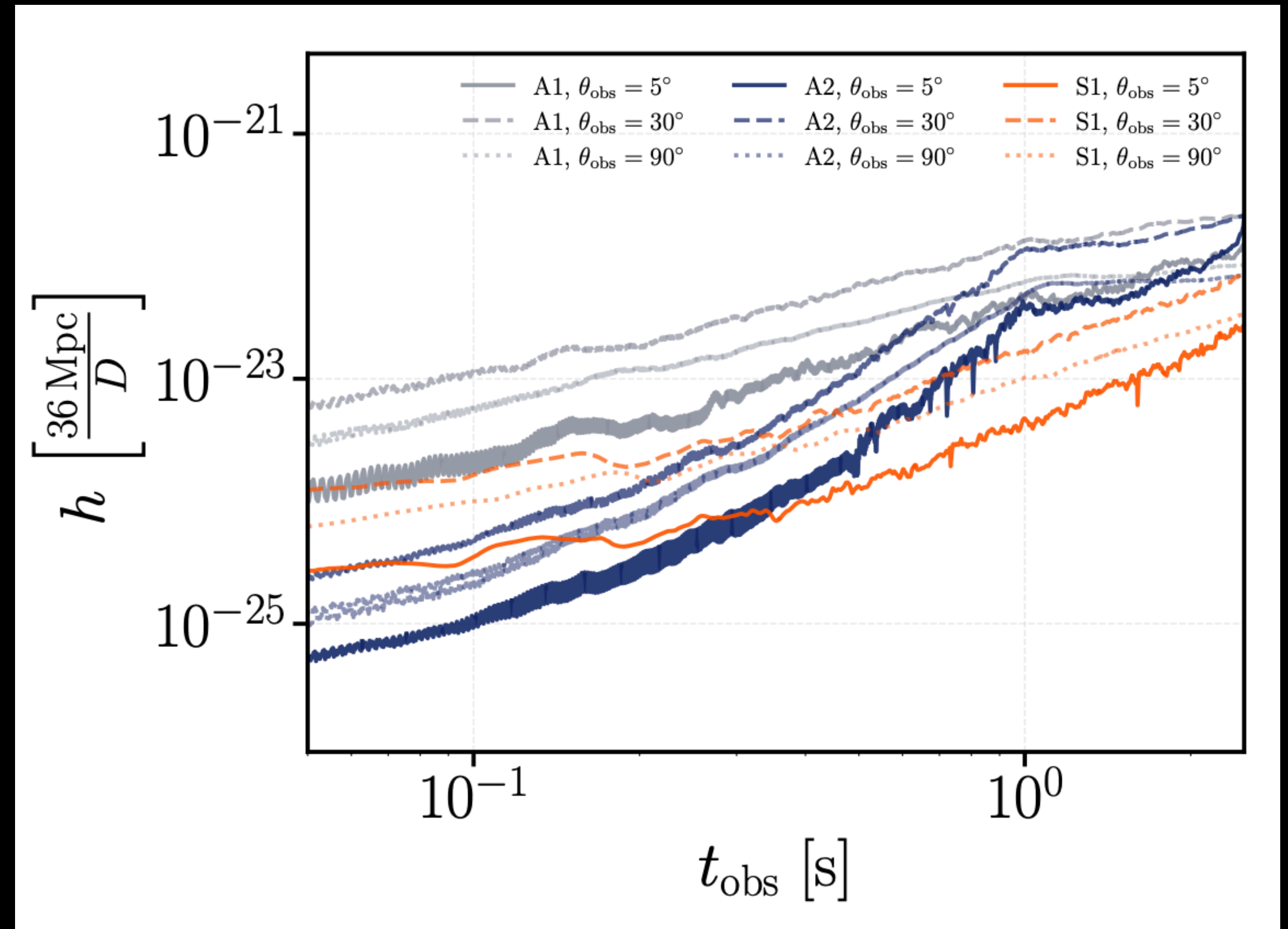


$$\rho_j h_j \Gamma_j^2 (\beta_j - \beta_h)^2 = \rho_\star \beta_h^2 \quad \rightarrow \quad \beta_h = \frac{\beta_j}{1 + (\rho_j h_j \Gamma_j^2 / \rho_\star)^{-1/2}}$$

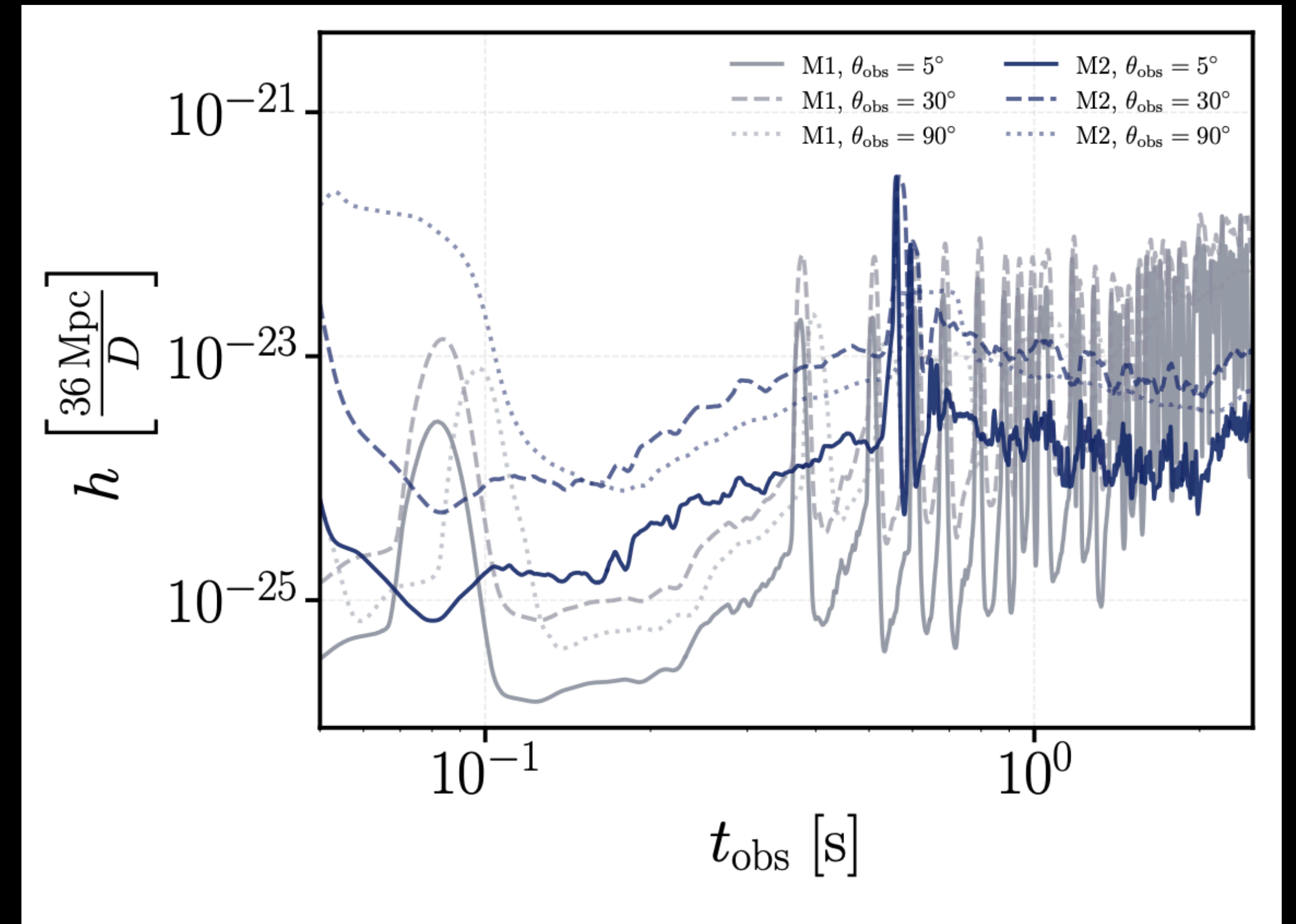
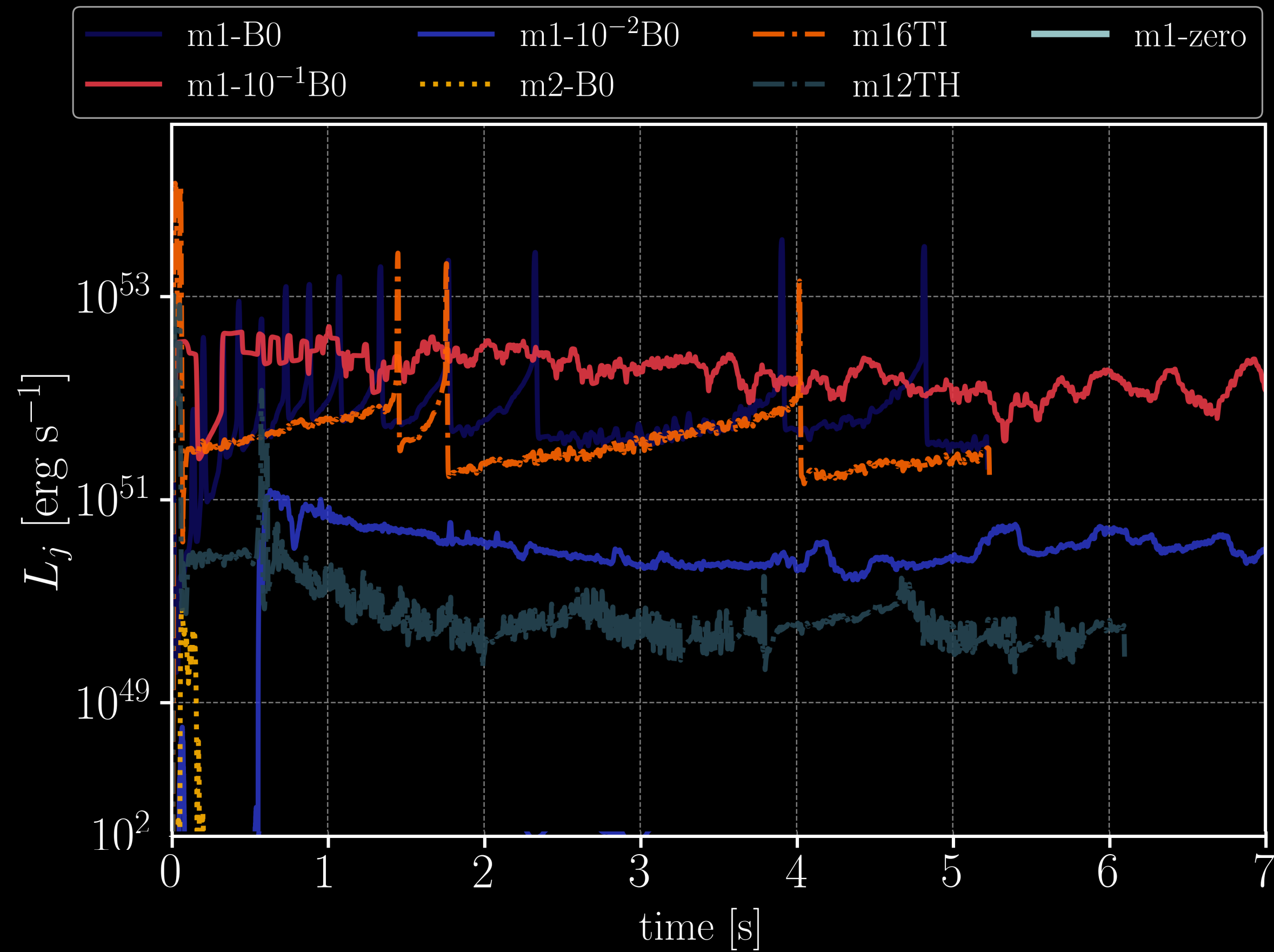
The effects of the energy injection

$$L(t) = L_0 \begin{cases} 1 & \text{if } t \leq t_0, \\ (t/t_0)^{-5/3} & \text{if } t_0 < t < t_j, \\ 0 & \text{if } t > t_j, \end{cases}$$

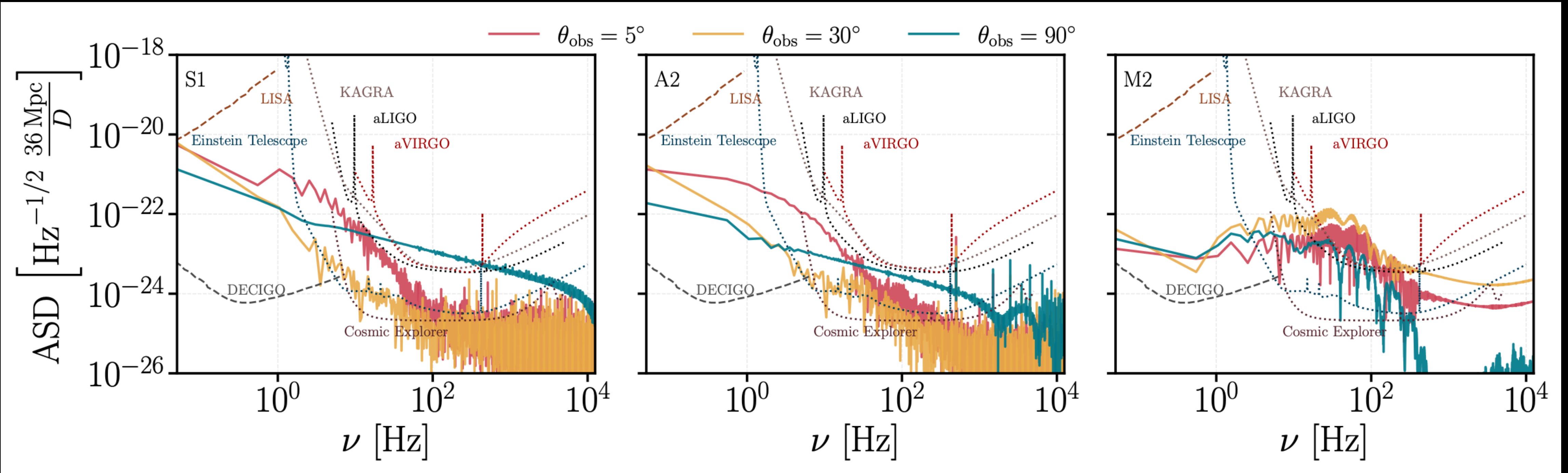
$$L(t) = L_0 \begin{cases} (t/t_0) & \text{if } t \leq t_0, \\ (t/t_0)^{-2} & \text{if } t_0 < t < t_j, \\ 0 & \text{if } t > t_j, \end{cases}$$



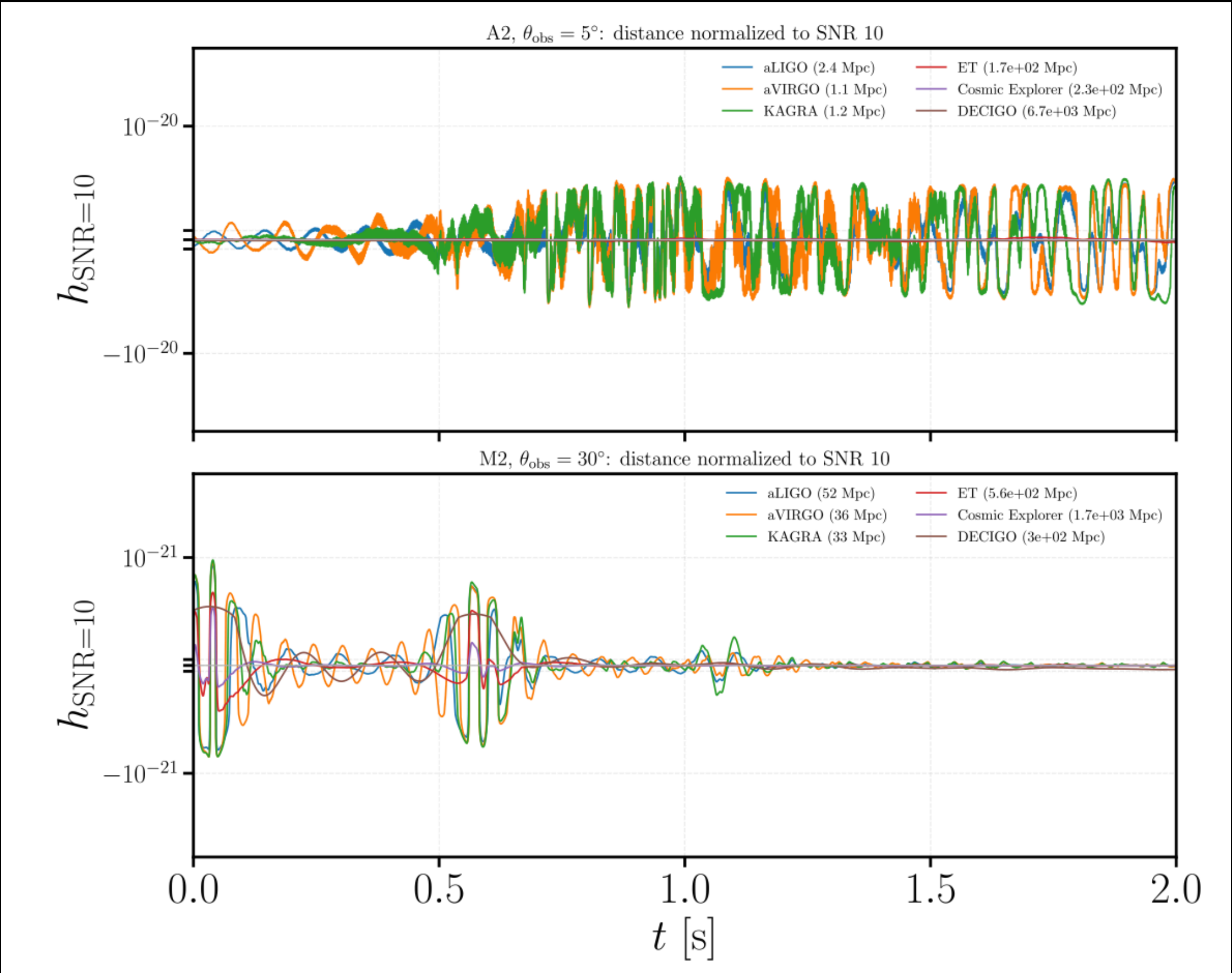
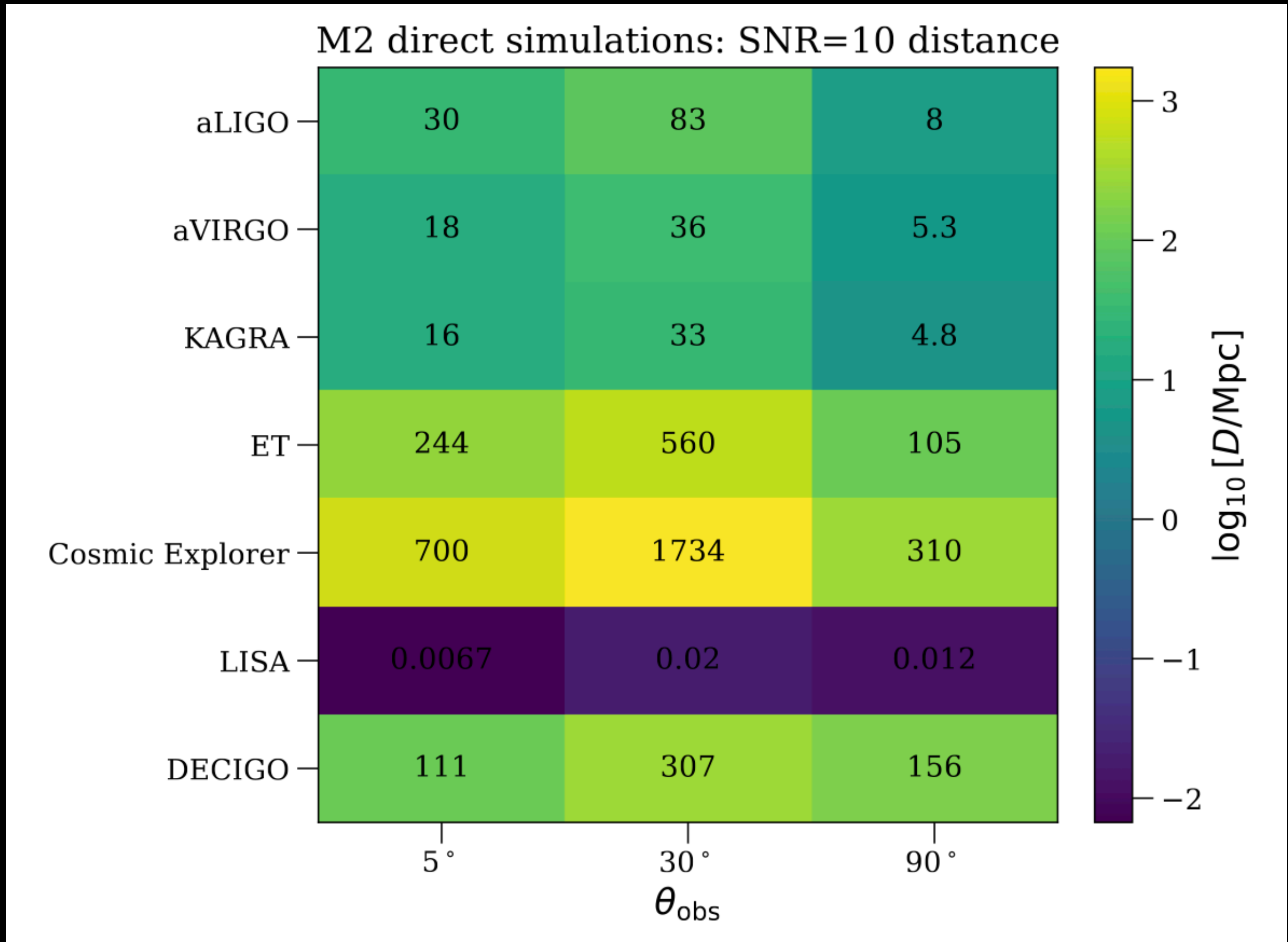
The luminosity is self-consistent with GRMHD simulations



From the strain evolution, we estimate the ASD



$$\frac{h_c}{\nu^{1/2}} \simeq 10^{-22} \left(\frac{E_{\text{jet}}}{10^{53} \text{ erg}} \right) \left(\frac{D}{36 \text{ Mpc}} \right)^{-1} \left(\frac{\nu}{10^2 \text{ Hz}} \right)^{-1/2}$$



Conclusions

- We developed a module that captures gravitational wave signals from SRHD simulations.
- GWs can reveal hidden jet activity, central-engine variability, viewing geometry, and choked/off-axis explosions even when EM counterparts are weak or absent.
- Jets that presents high peaks in luminosity at high frequencies could be candidates to observe with a new generation of ground based interferometers. ($\sim 100\text{Mpc}$)

¡Gracias! - Thank you!

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