

Study of the most brightest explosions of the universe by supercomputer simulations

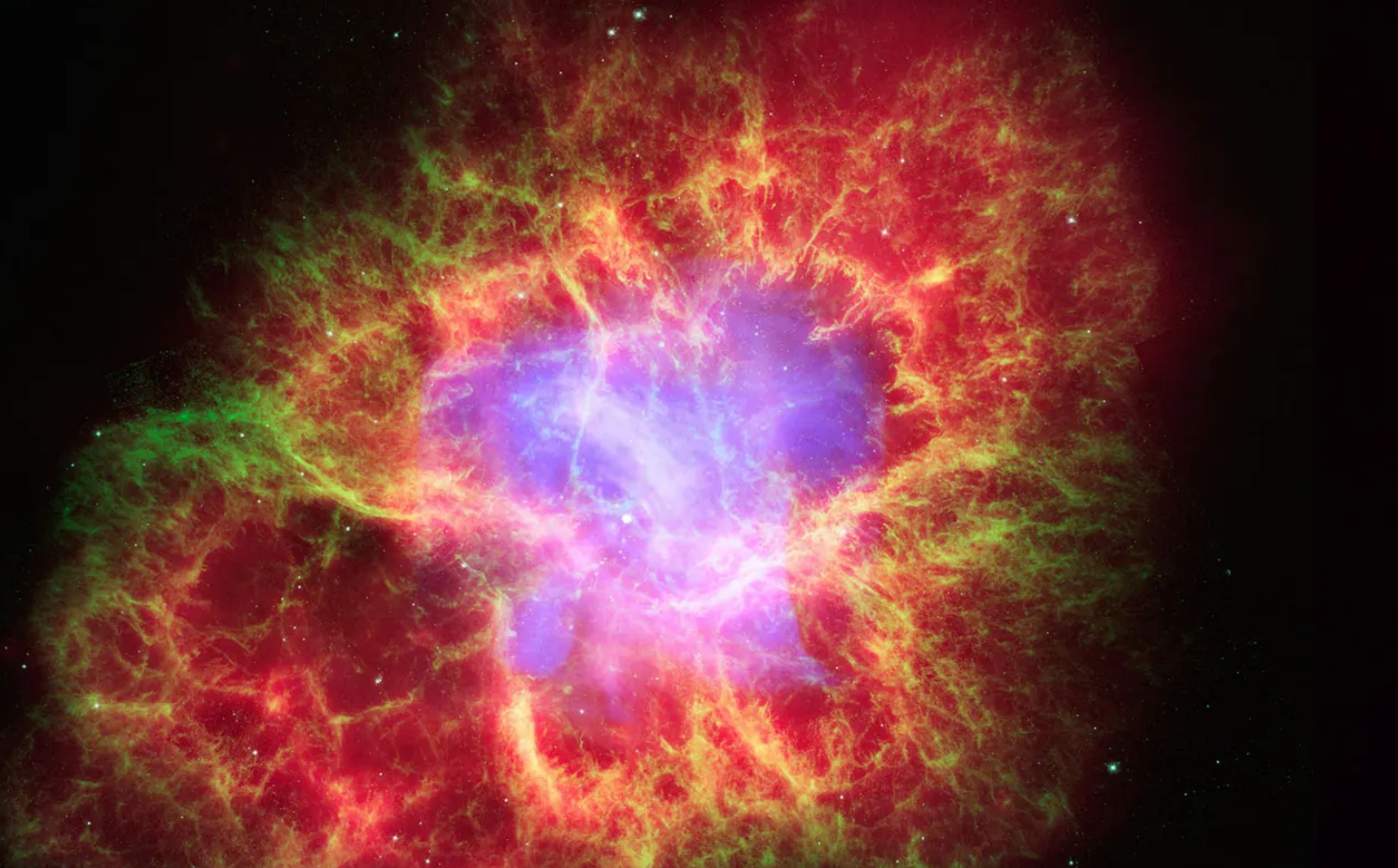


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Warsaw Science Festival 2025

Where does this gas expansion come from?



The answer is provided by stars

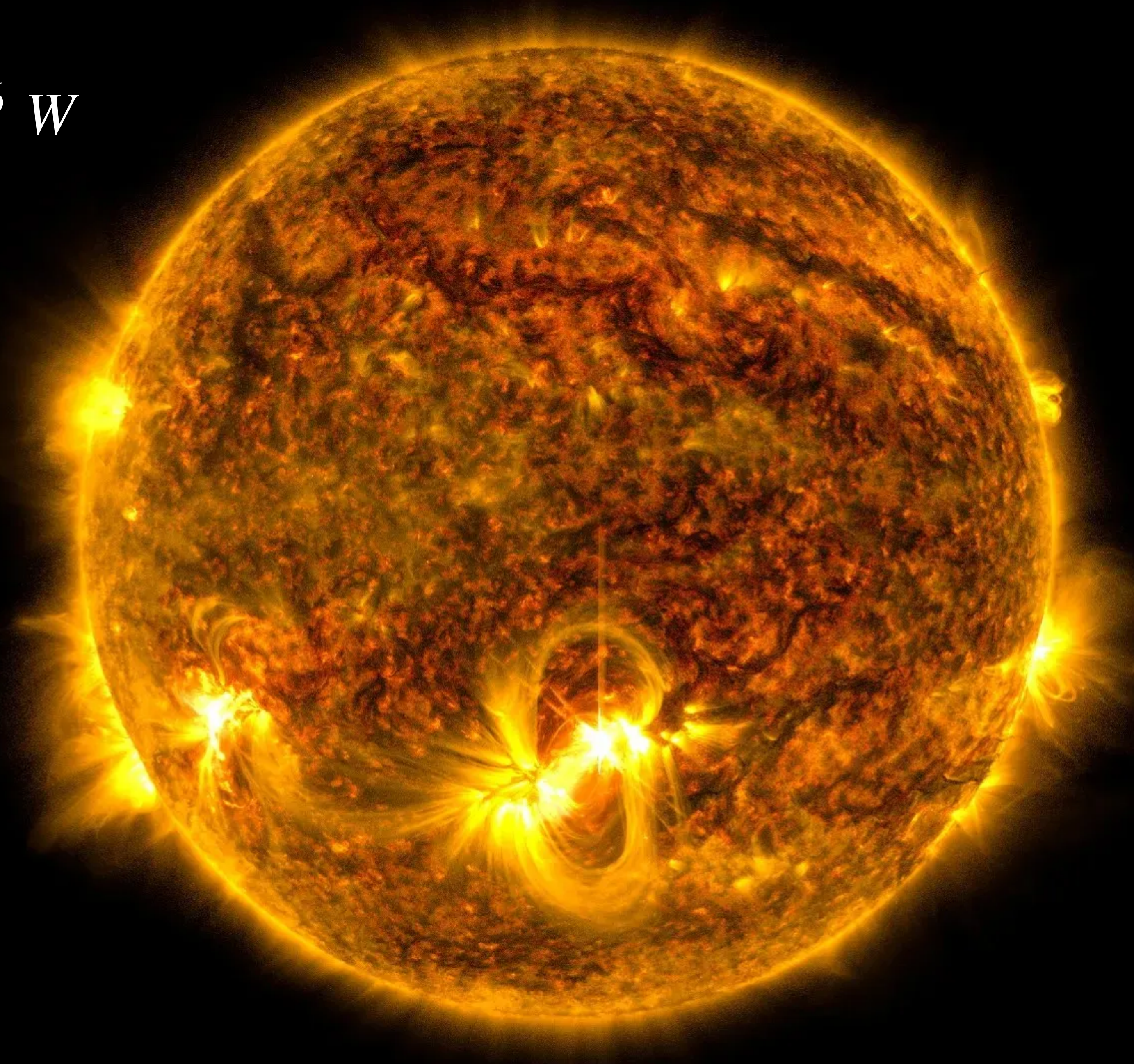
$$L_{\odot} \sim 3.8 \times 10^{26} \text{ W}$$

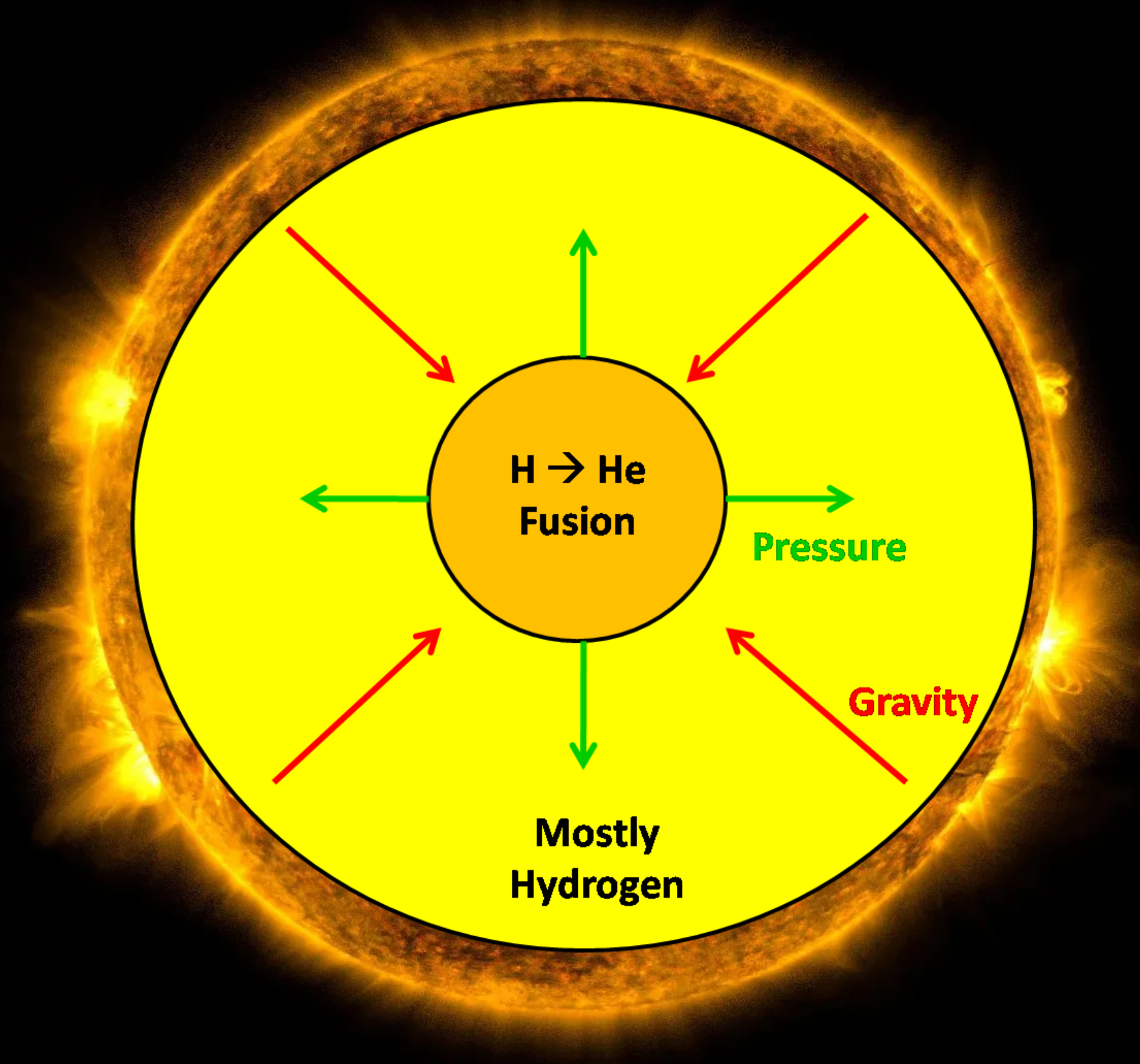


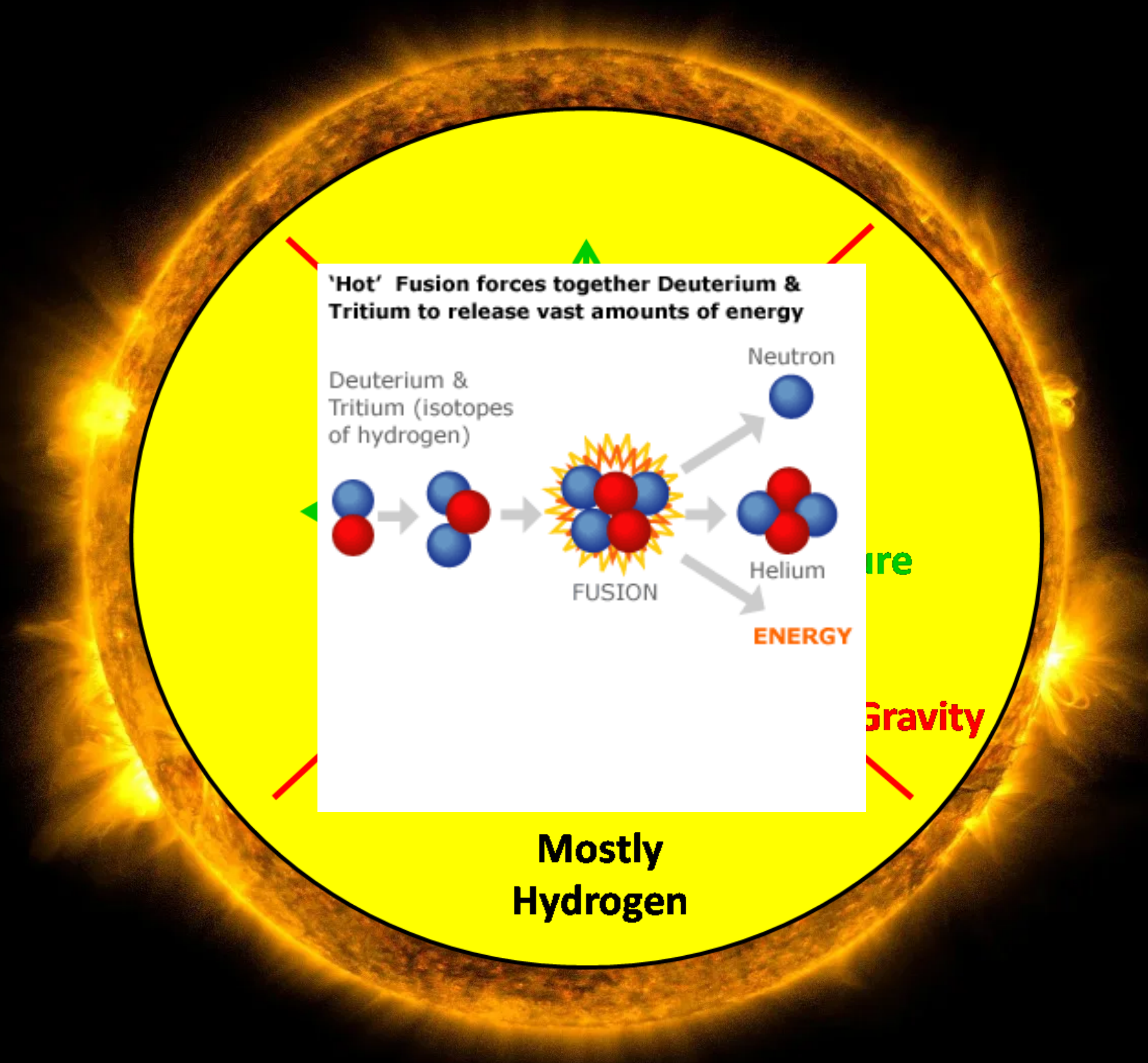
$$10^{24}$$

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

$$10$$

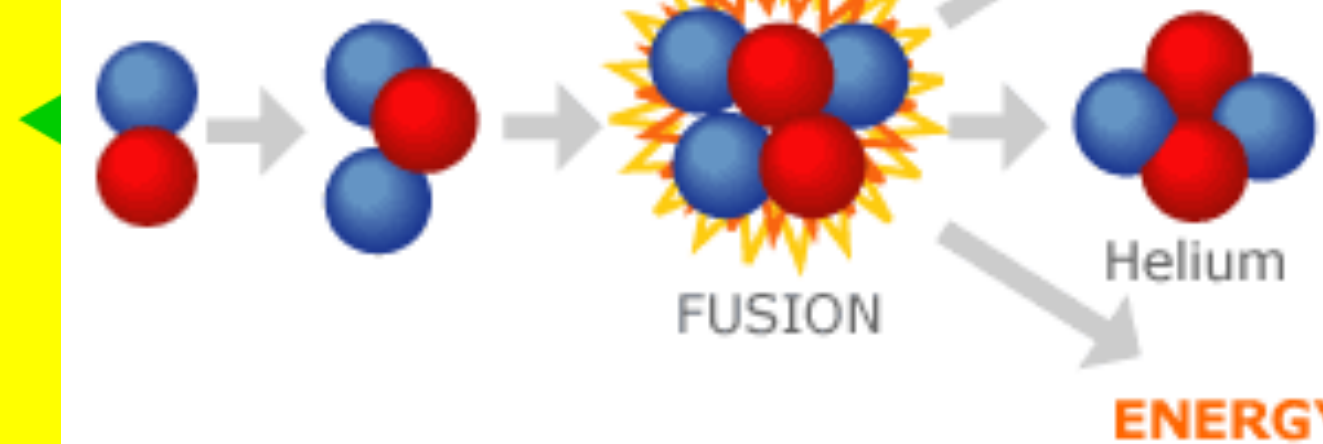






'Hot' Fusion forces together Deuterium & Tritium to release vast amounts of energy

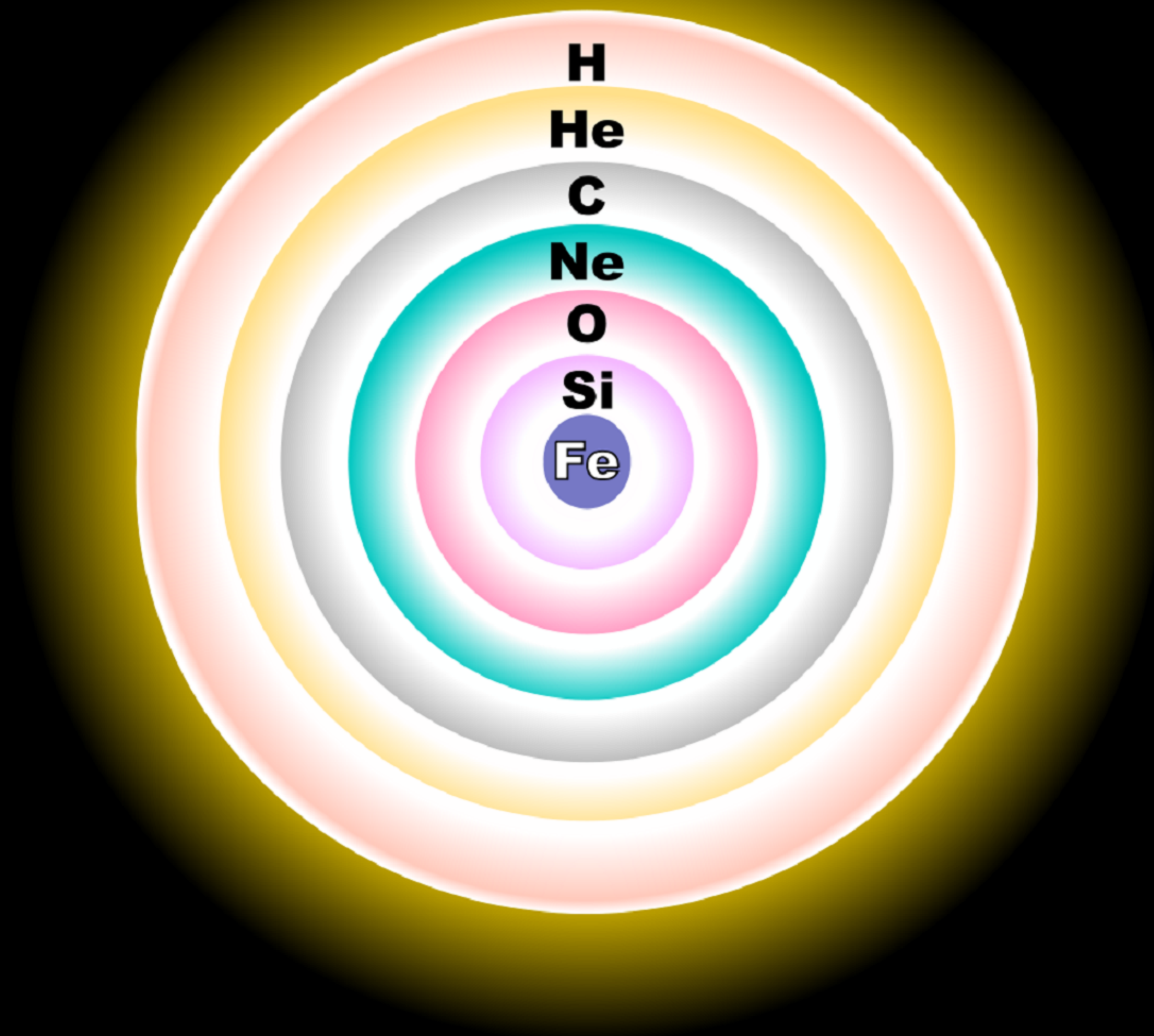
Deuterium & Tritium (isotopes of hydrogen)

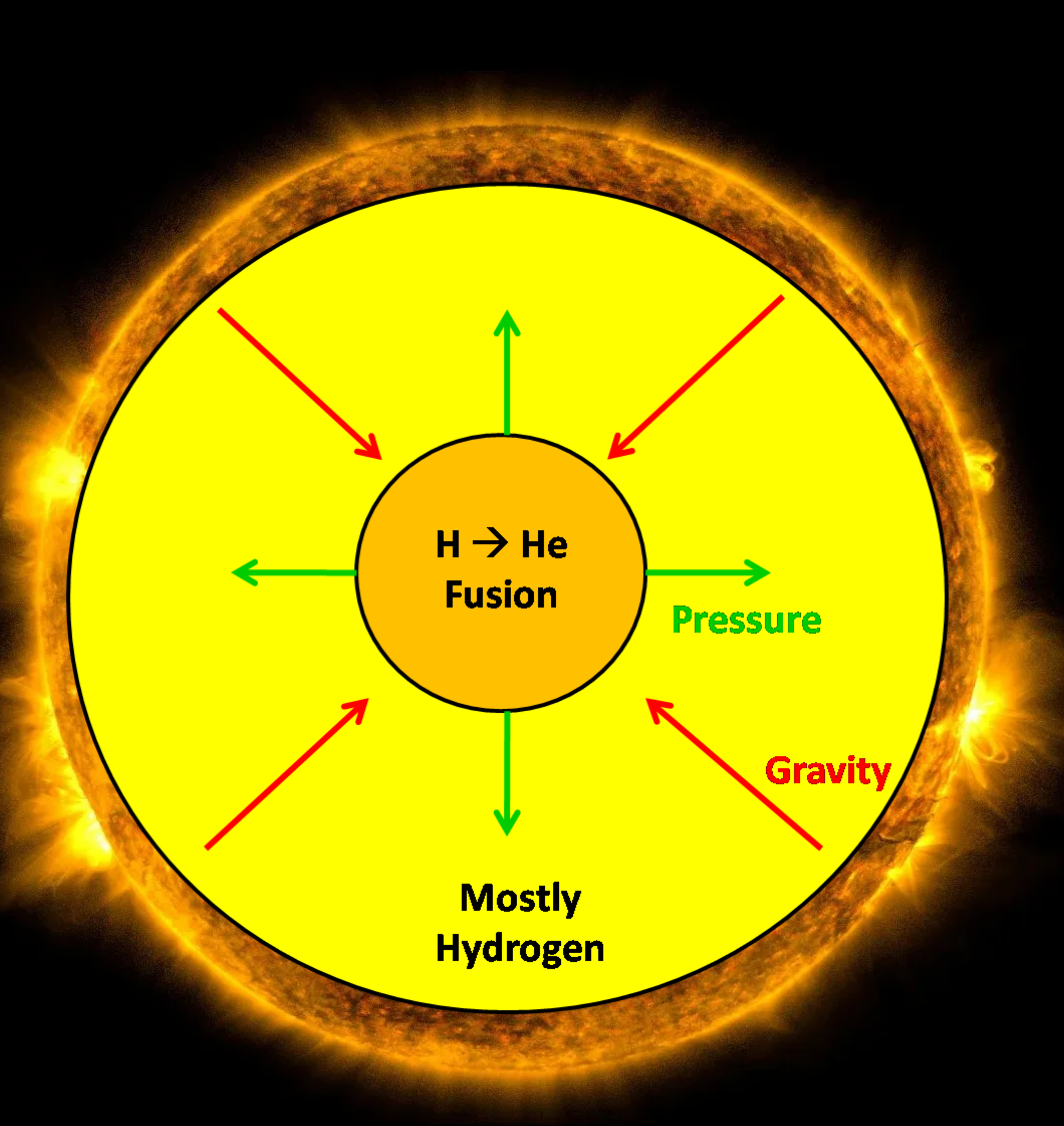


**Mostly
Hydrogen**

Pressure

Gravity





FUNDAMENTAL STELLAR STRUCTURE EQUATIONS (FSSE) IN TIME-INDEPENDENT (STATIC) FORM

$$\frac{dP}{dr} = -G \frac{M_r \rho}{r^2}$$

HYDROSTATIC EQUILIBRIUM

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

MASS CONSERVATION

$$\frac{dL_r}{dr} = 4\pi r^2 \rho \epsilon$$

ENERGY EQUATION

$$\left. \frac{dT}{dr} \right|_{rad} = -\frac{3}{4} \frac{\bar{\kappa} \rho}{ac T^3} \frac{L_r}{4\pi r^2}$$

RADIATIVE TRANSPORT

$$\left. \frac{dT}{dr} \right|_{ad} = -\left(1 - \frac{1}{\gamma}\right) \frac{\mu m_H}{k} \frac{GM_r}{r^2}$$

ADIABATIC
CONVECTION

FUNDAMENTAL STELLAR STRUCTURE EQUATIONS (FSSE)
IN TIME-INDEPENDENT (STATIC) FORM



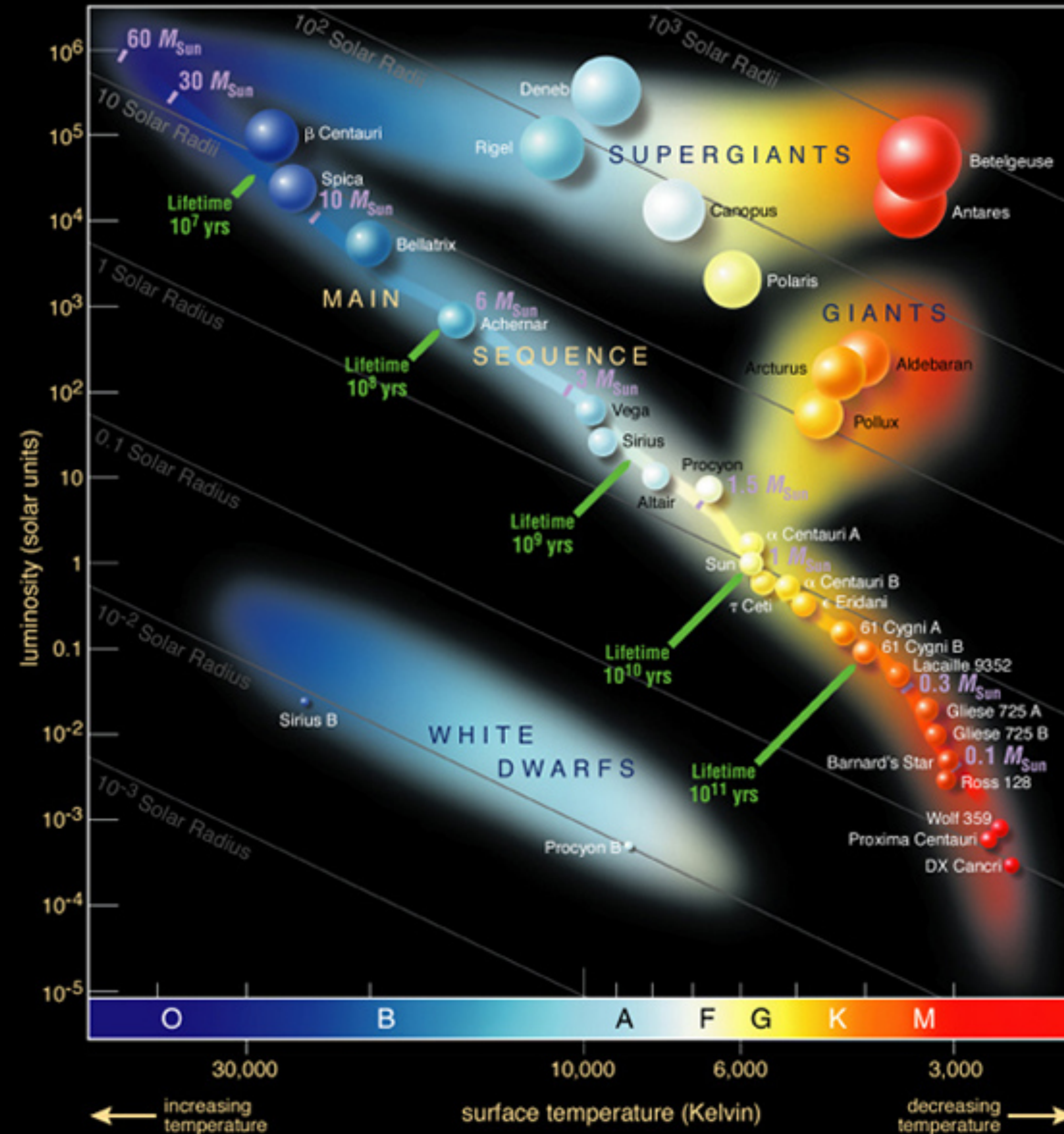
Key idea:
The mass of the star

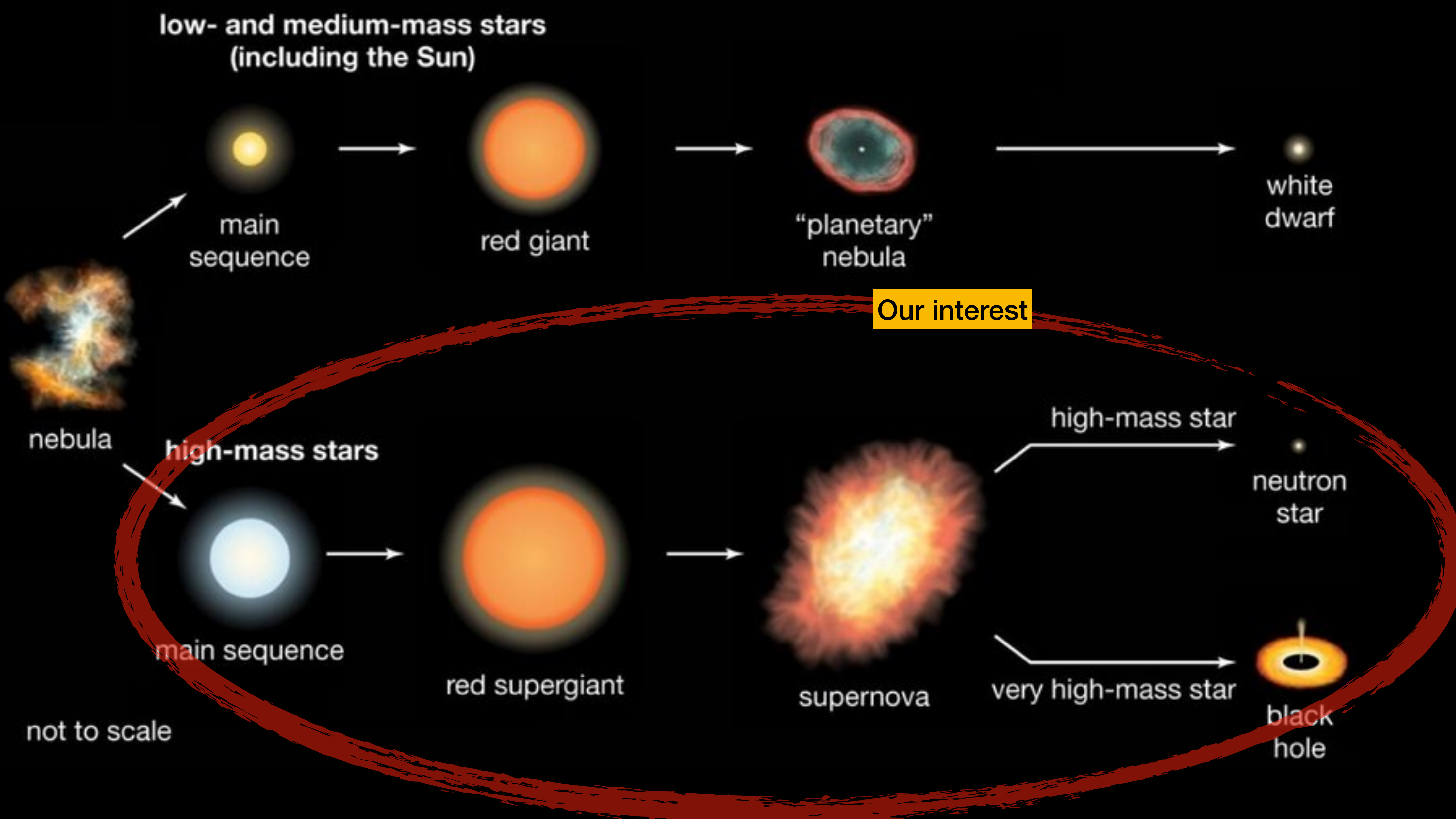
Gravity

**Mostly
Hydrogen**

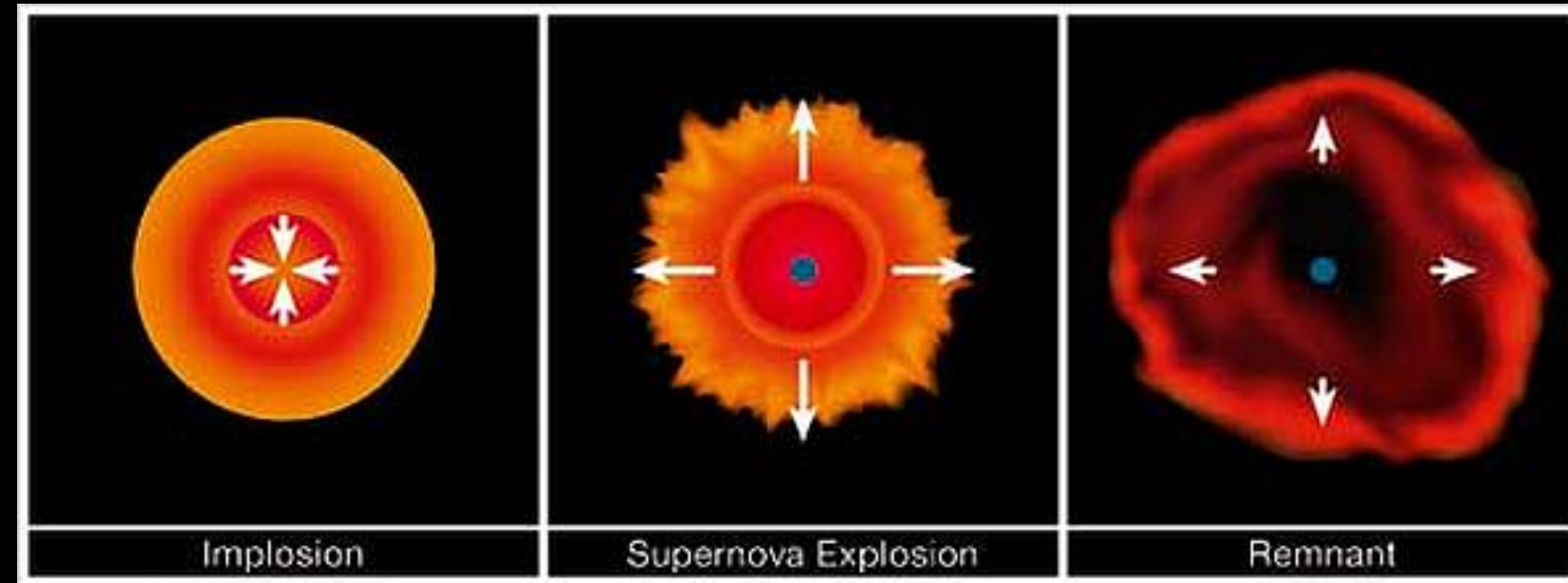
$$\left. \frac{dT}{dr} \right|_{\text{ad}} = - \left(1 - \frac{1}{\gamma} \right) \frac{\mu m_H}{k} \frac{GM_r}{r^2} \quad \text{ADIABATIC CONVECTION}$$

The initial mass of the star determines its evolution



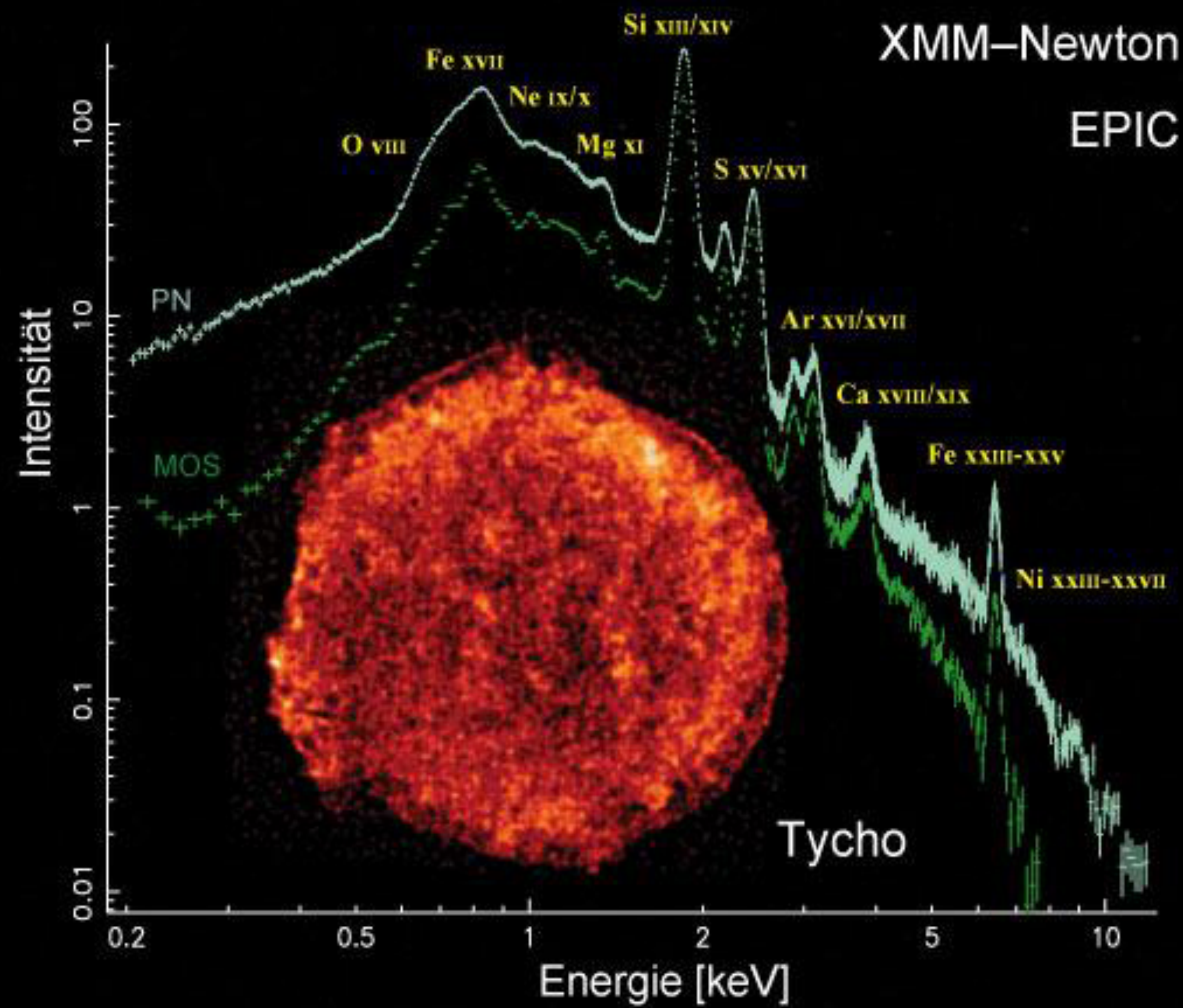


The incredible star's dead!



$$L_{\text{SN}} \sim 10^{43} \text{ erg s}^{-1} \sim 10^{10} L_{\odot}$$





Ancient records of Supernovae



Kashmir, India

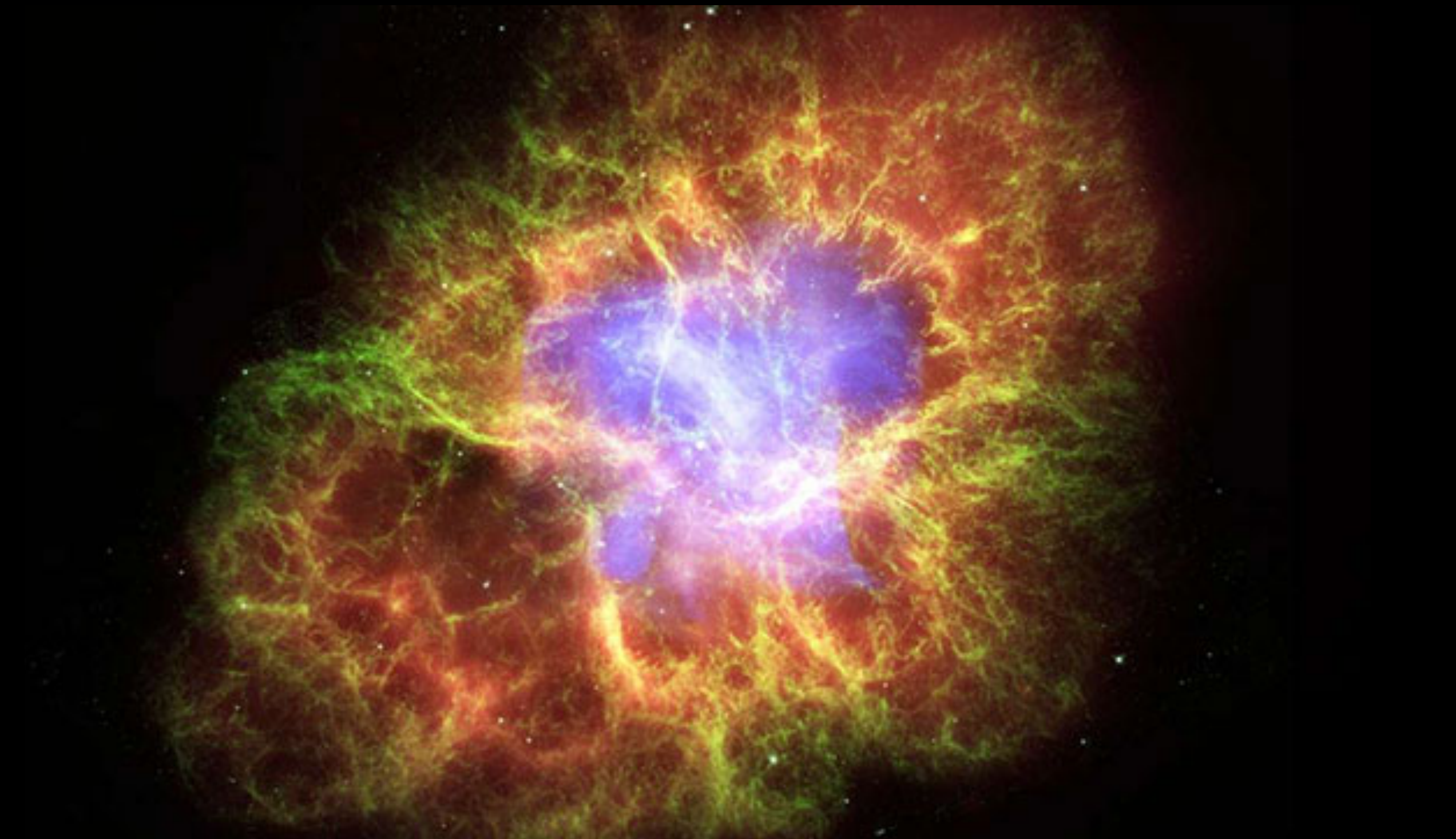
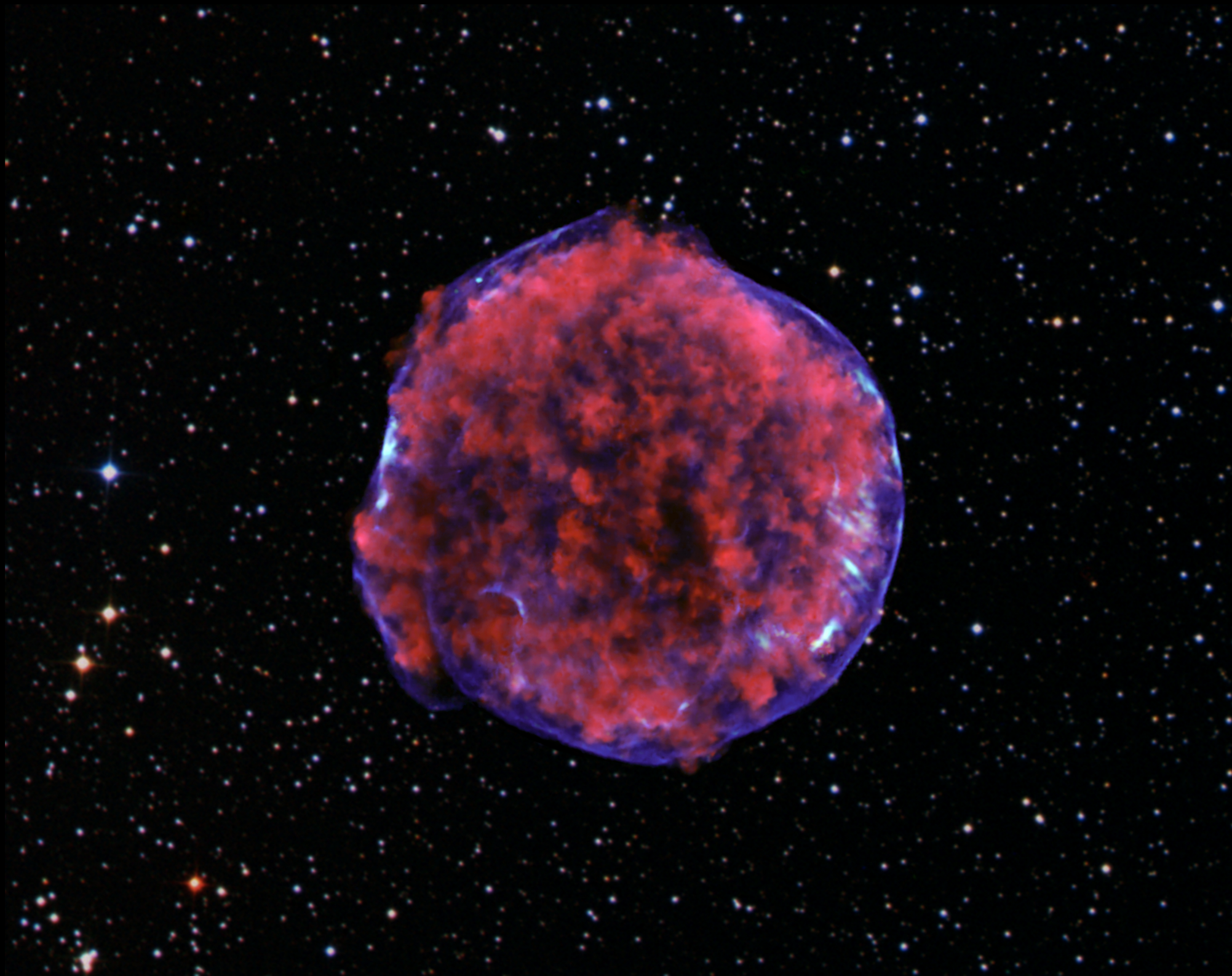


New Mexico



Henri III, Tivoli, Italy

The remnants





Collapsing stars

- Accretion disk
- Launching of relativistic jets



Neutron Star

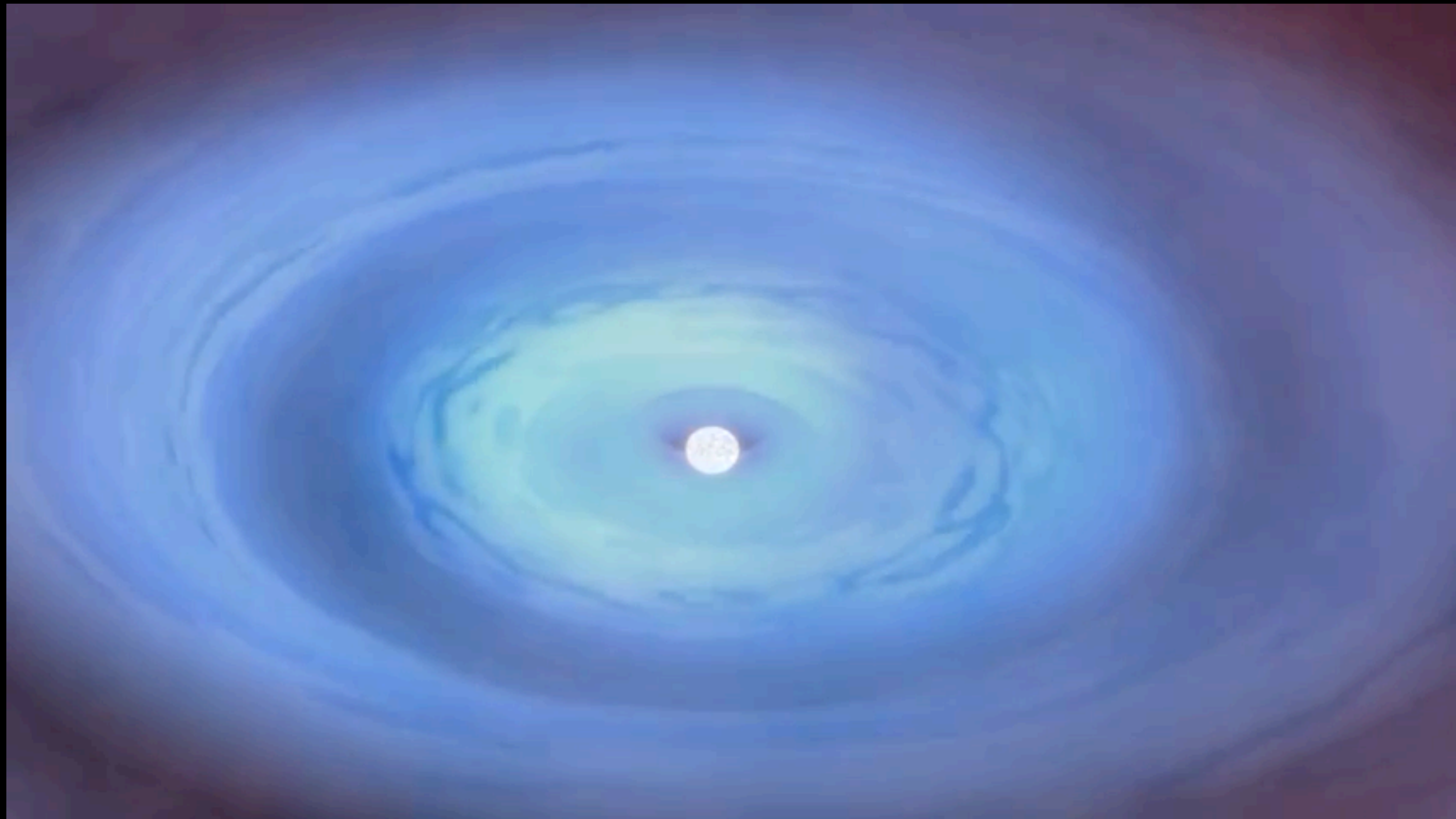
10^9 



$r \sim 10 \text{ Km}$

$\rho \sim 10^{14} \text{ gr cm}^{-3}$

$M_{\text{NS}} < 2.17 M_{\odot}$



The power of the accretion

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



300 grams

The power of the accretion



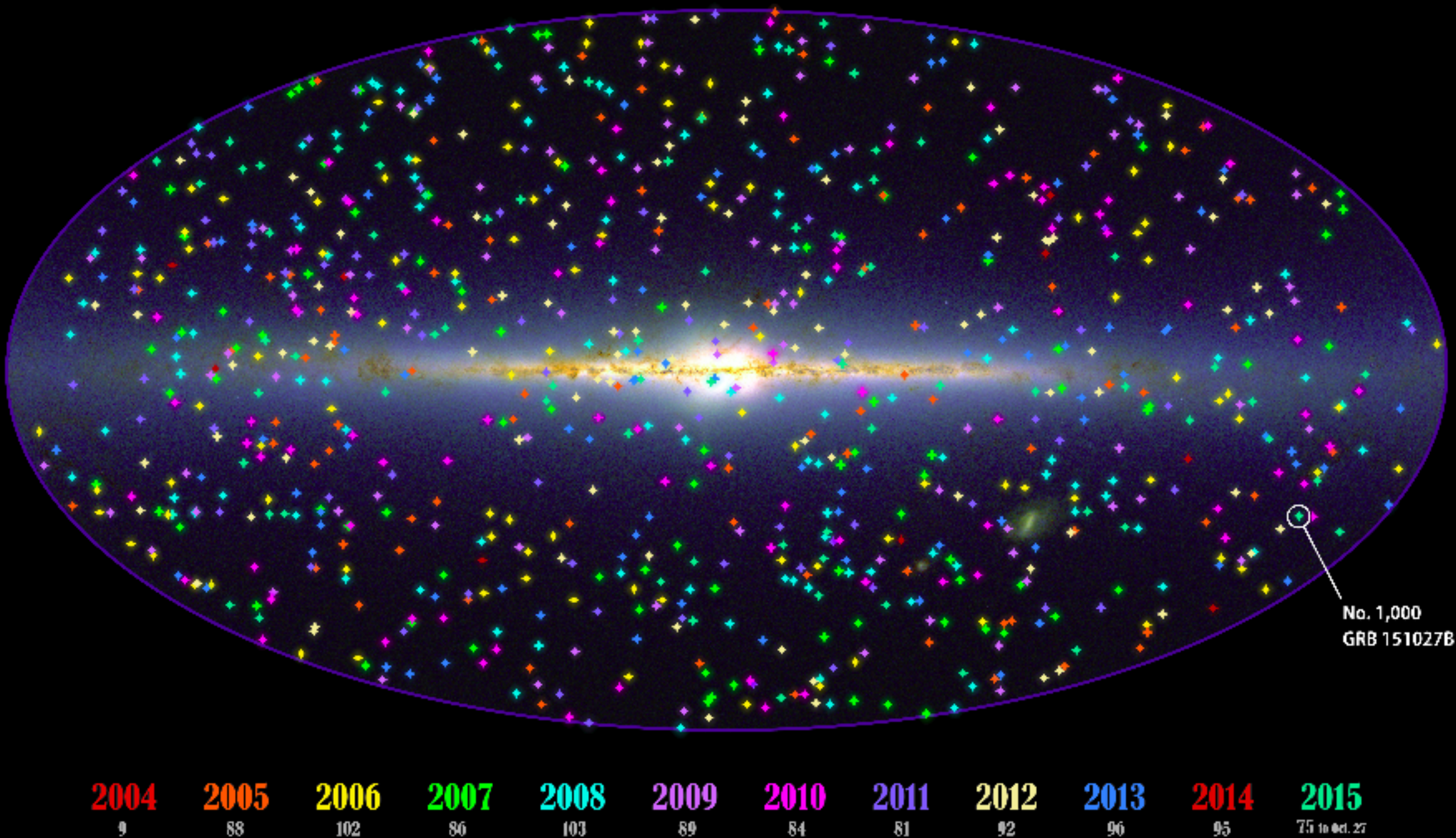
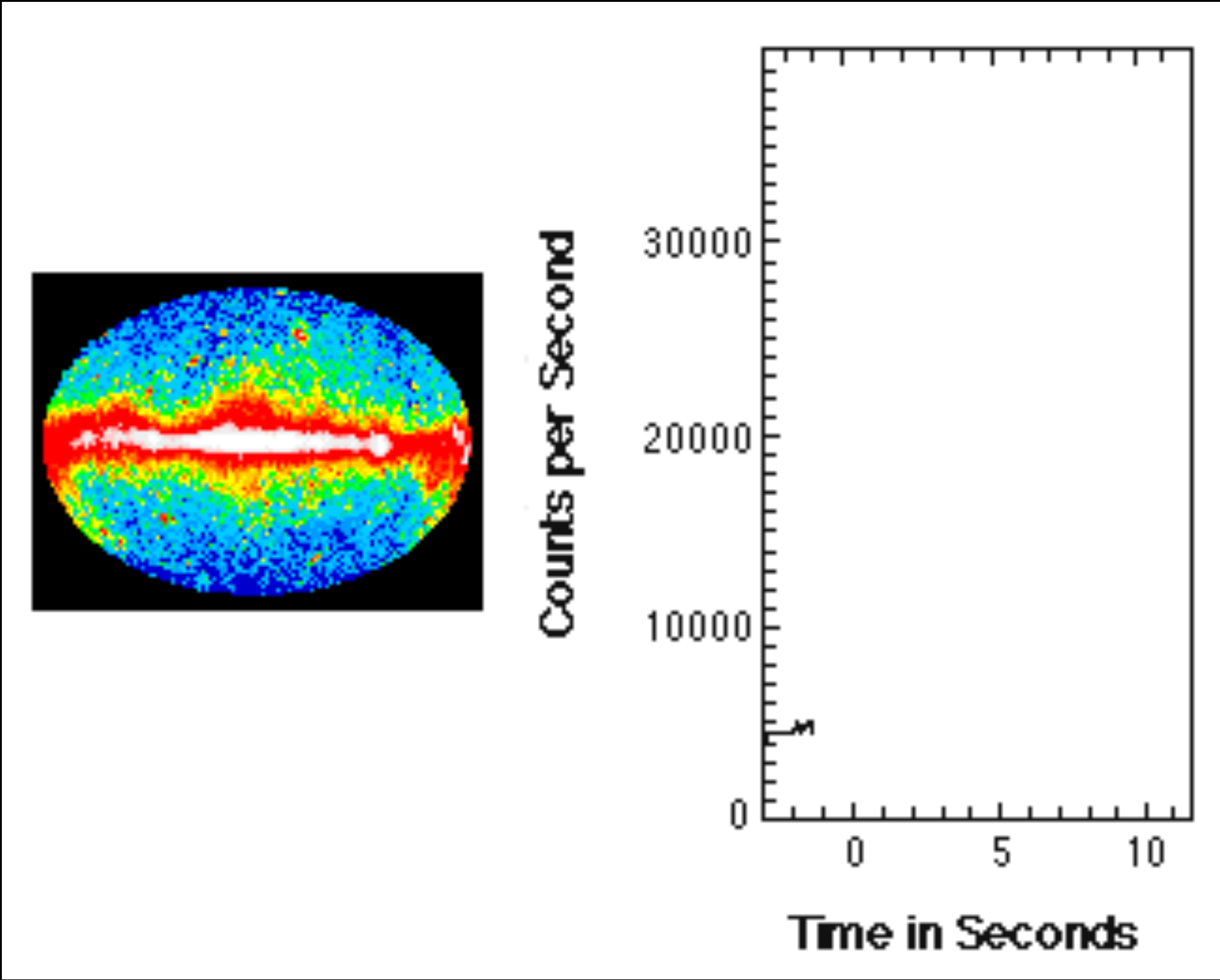
$$\dot{E} \sim \eta \dot{M} c^2$$

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

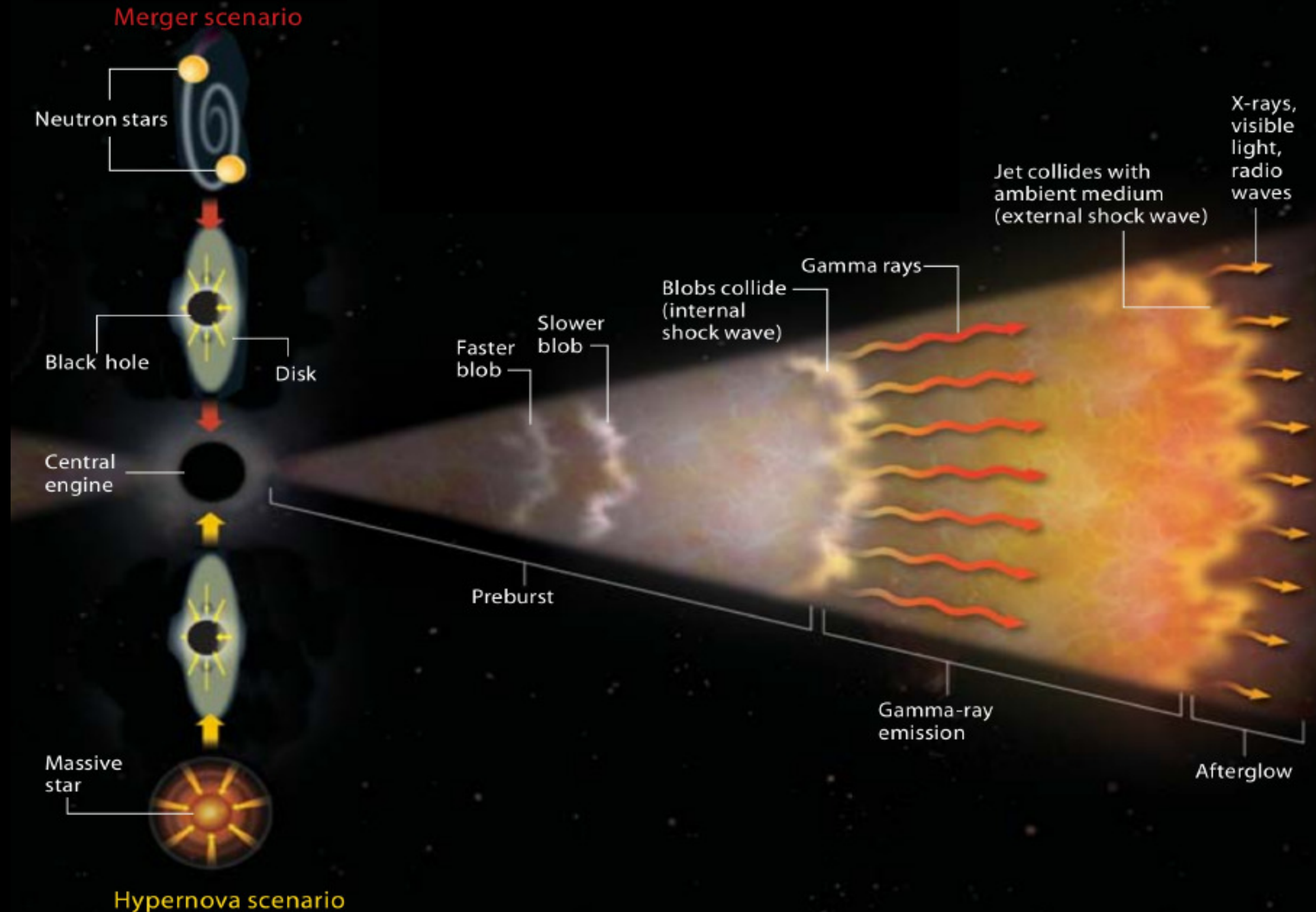
$$E_{\text{atomic bomb}} \sim 10^{13} J$$

If I launched a pierogi I could obtain
100-1000 times the energy of AB

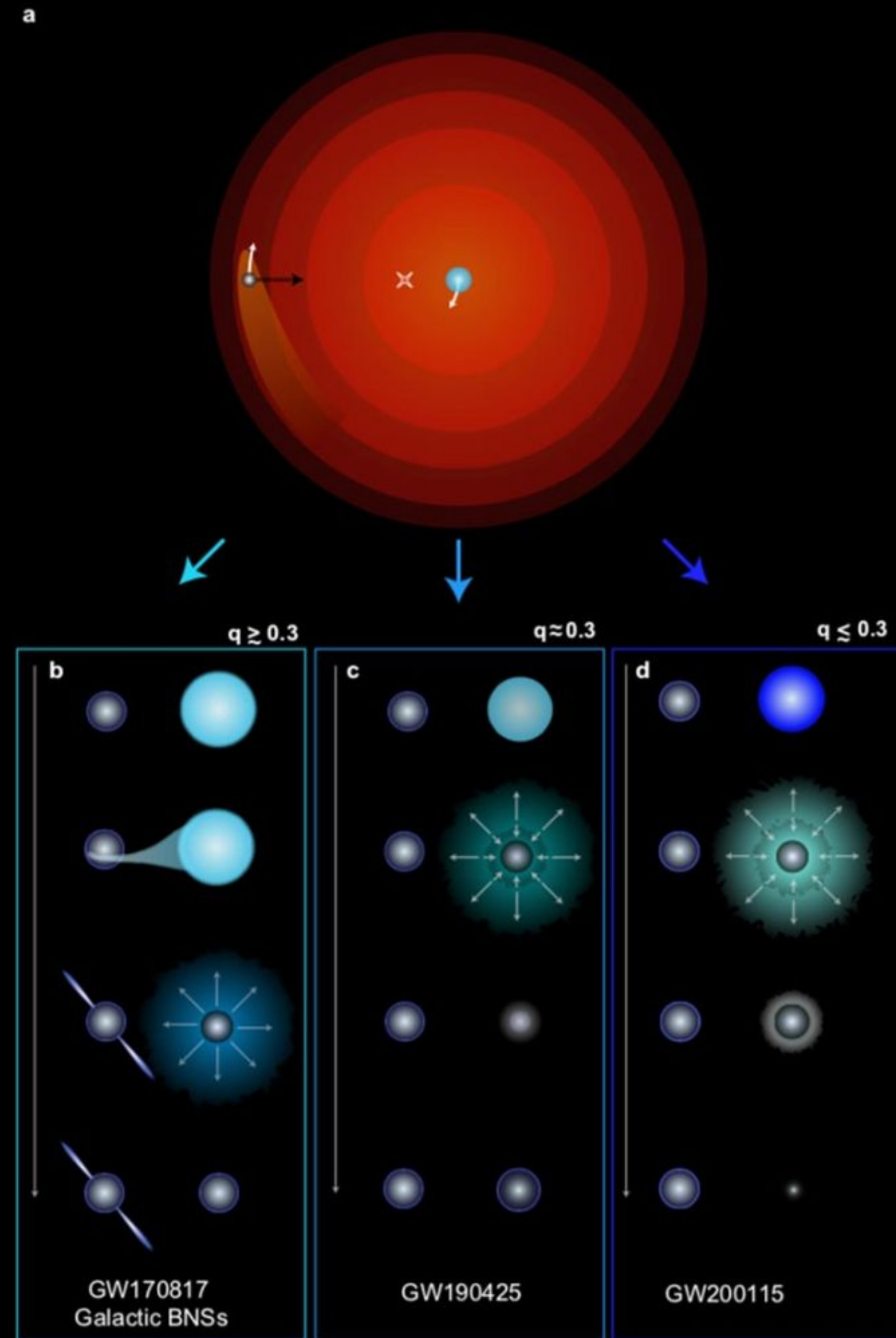
Gamma-Ray Bursts, The most powerful explosions in the universe!



The origin and evolution of Gamma-Ray Bursts



The case of the mergers



Credit: Alejandro Vigna-Gomez

FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries

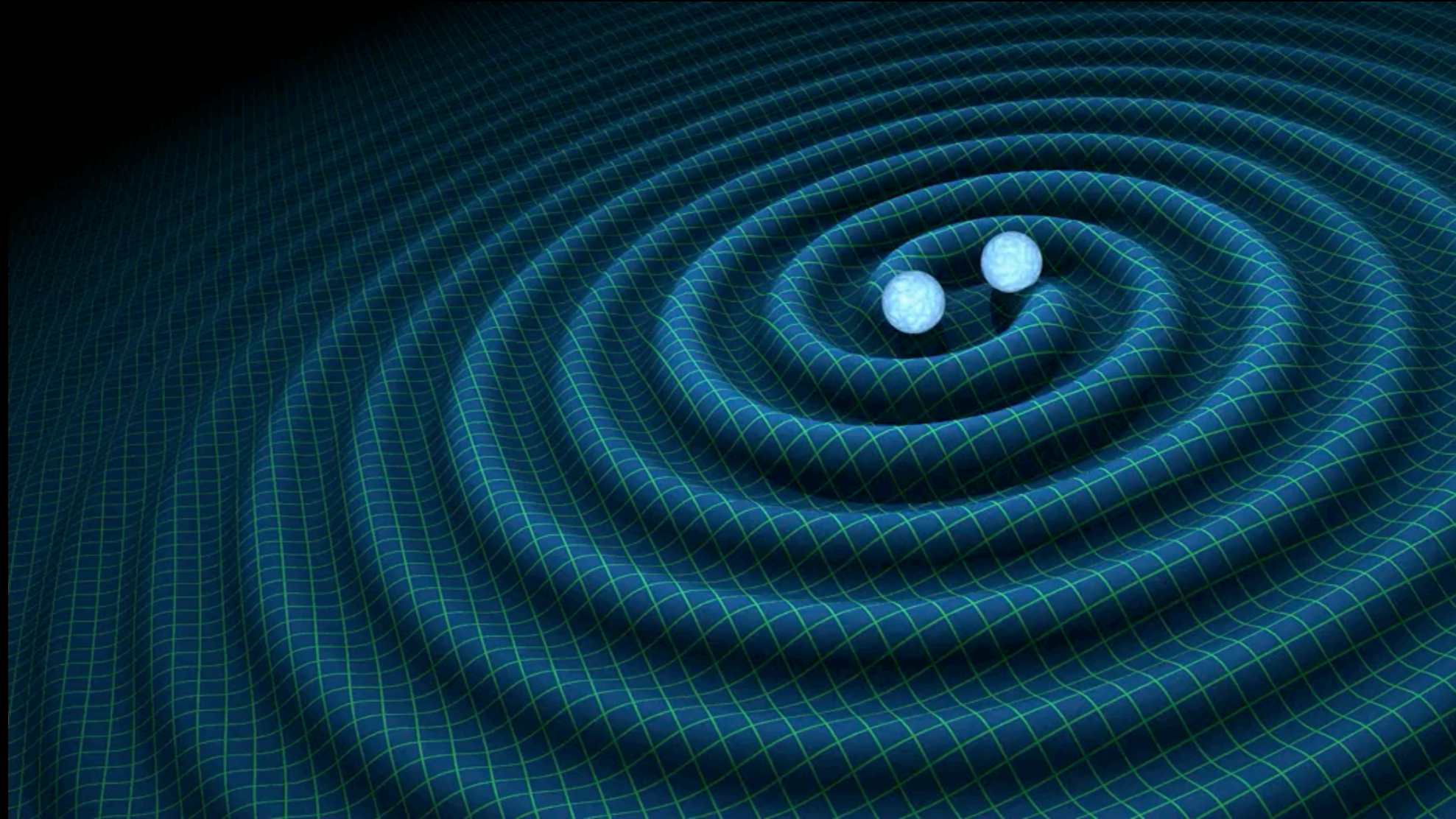
Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum

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.

Gravitational waves

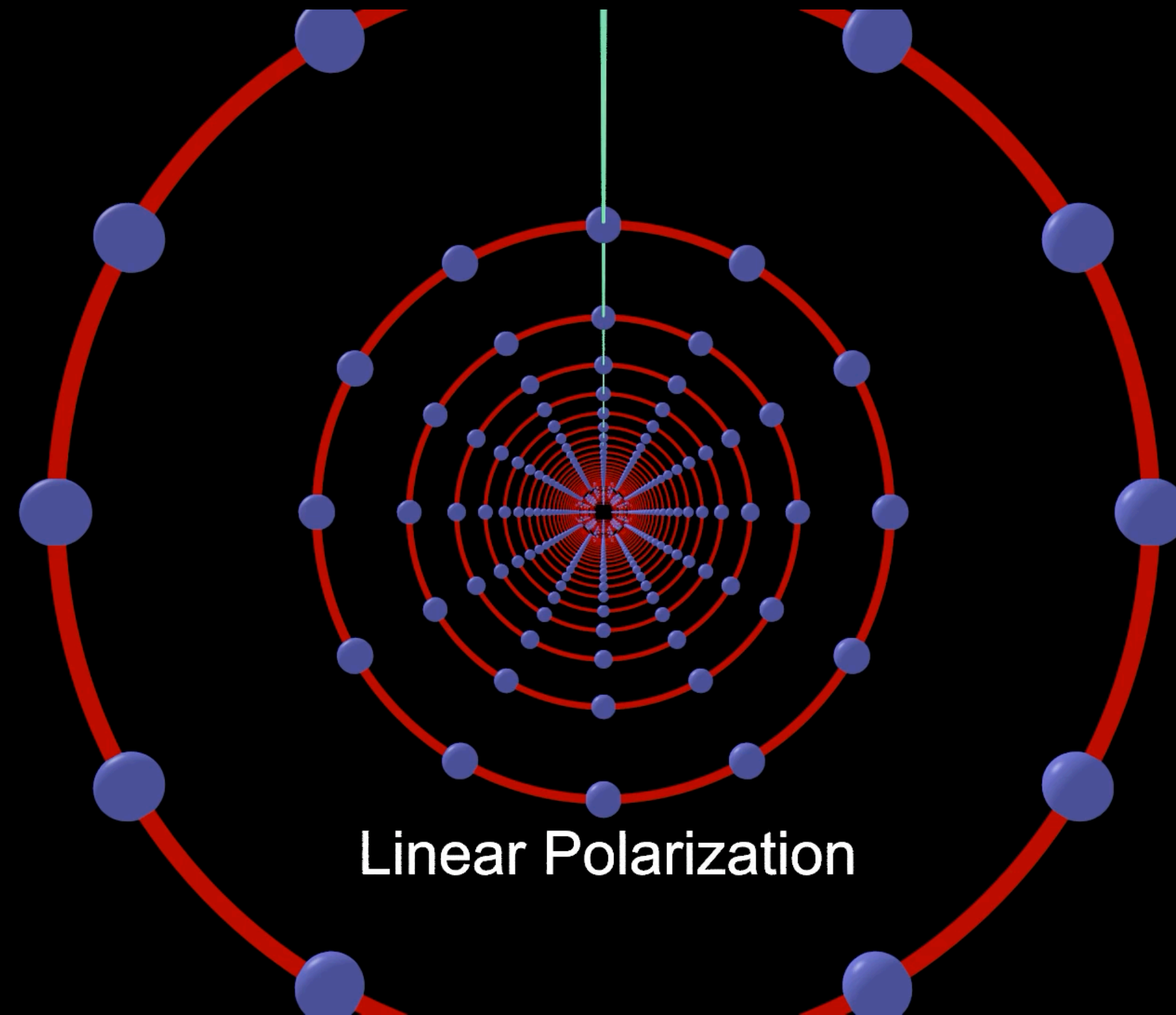


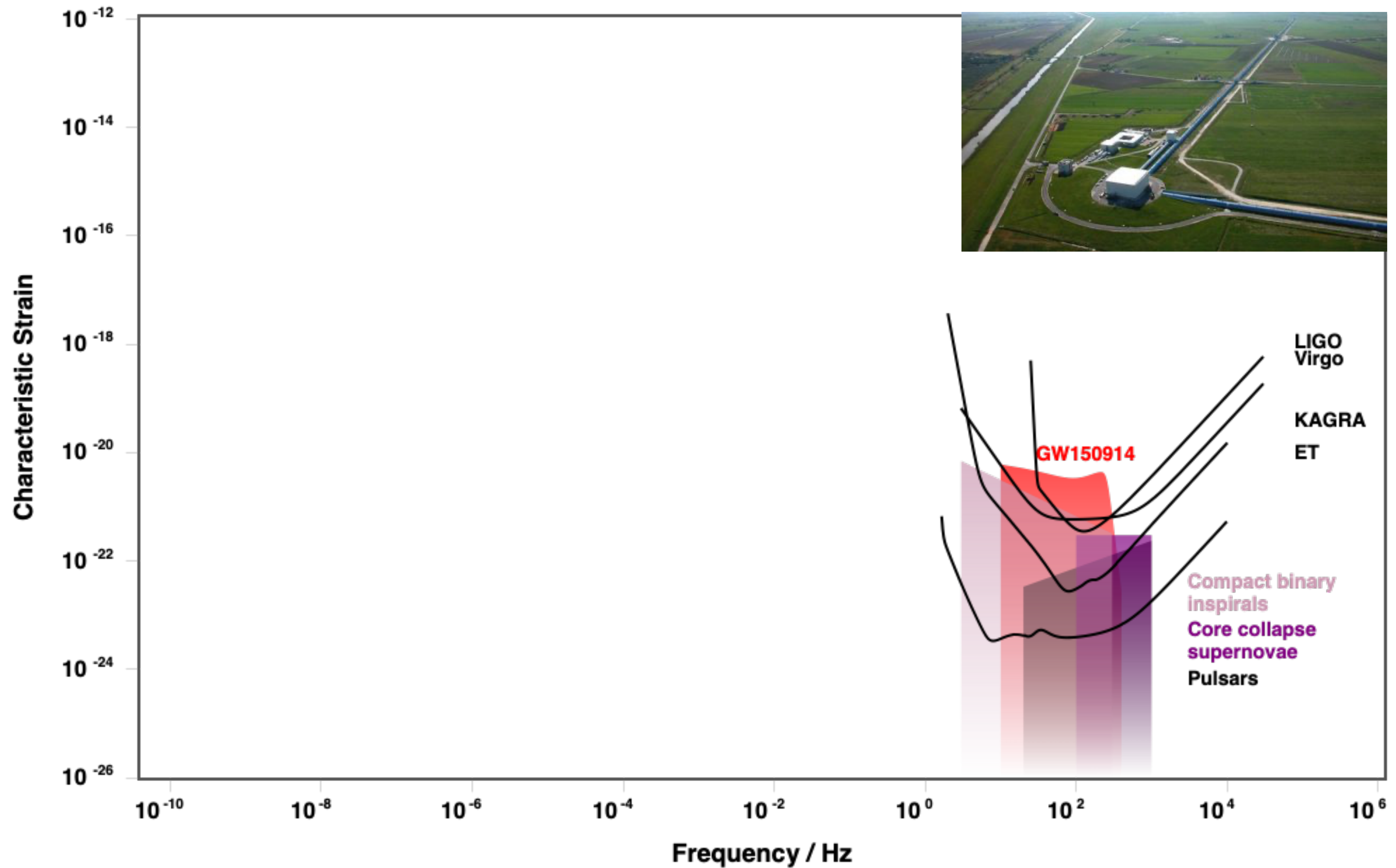
$$\square \bar{h}^{\mu\nu} = -16\pi T^{\mu\nu}$$



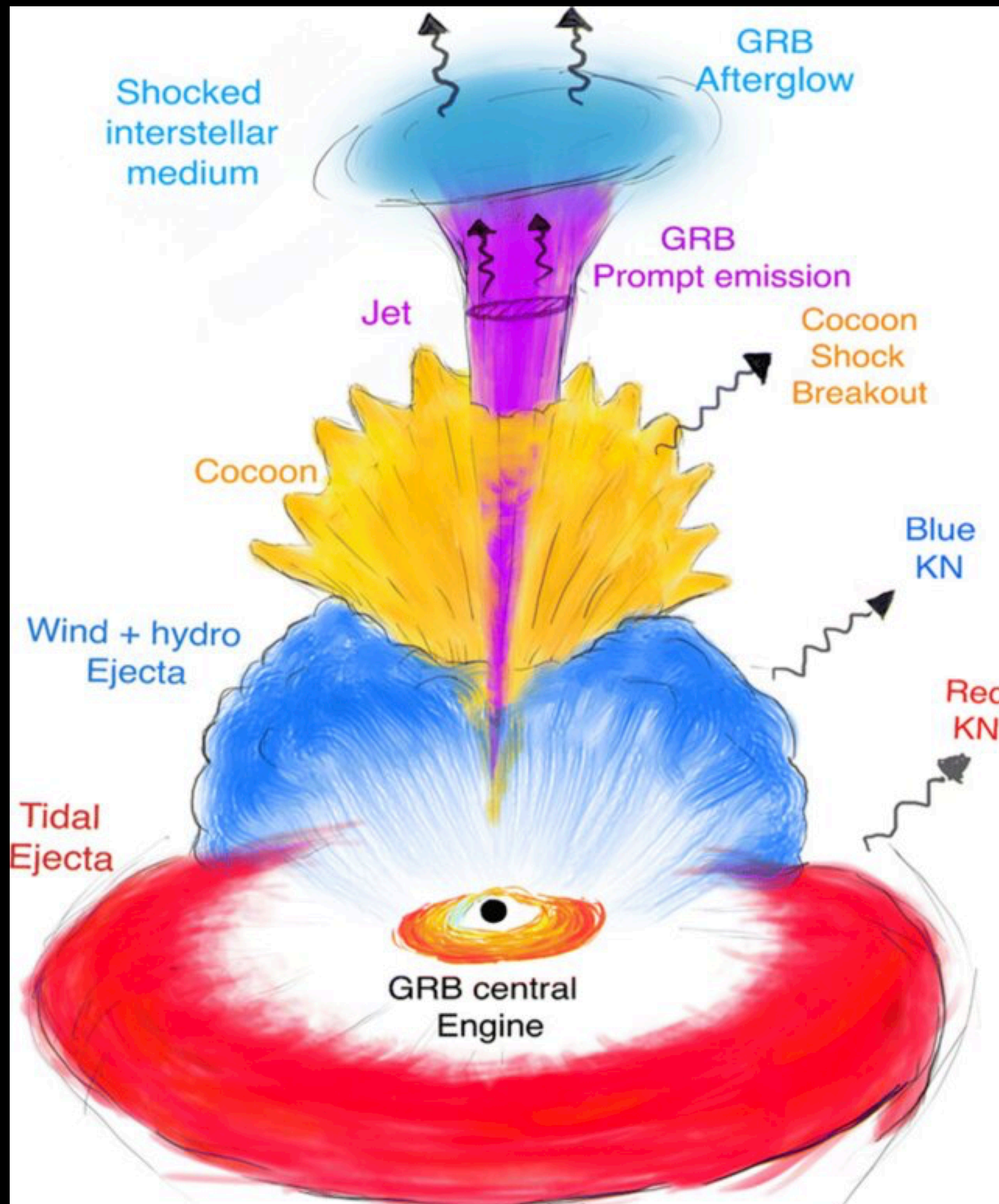
$$h \sim \frac{G}{c^4} \frac{E_{\text{GW}}}{d} \sim 10^{-21}$$

Gravitational waves

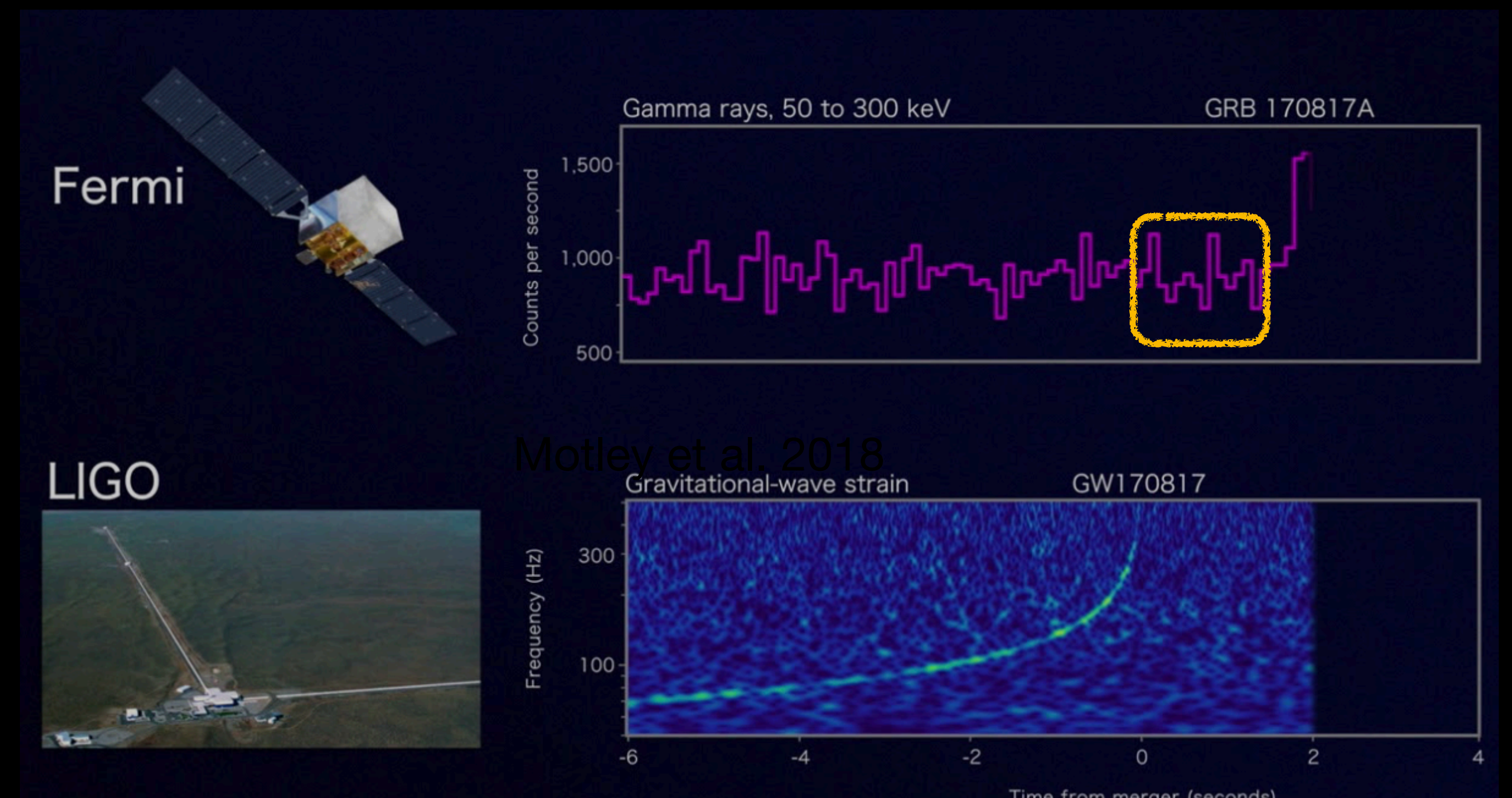




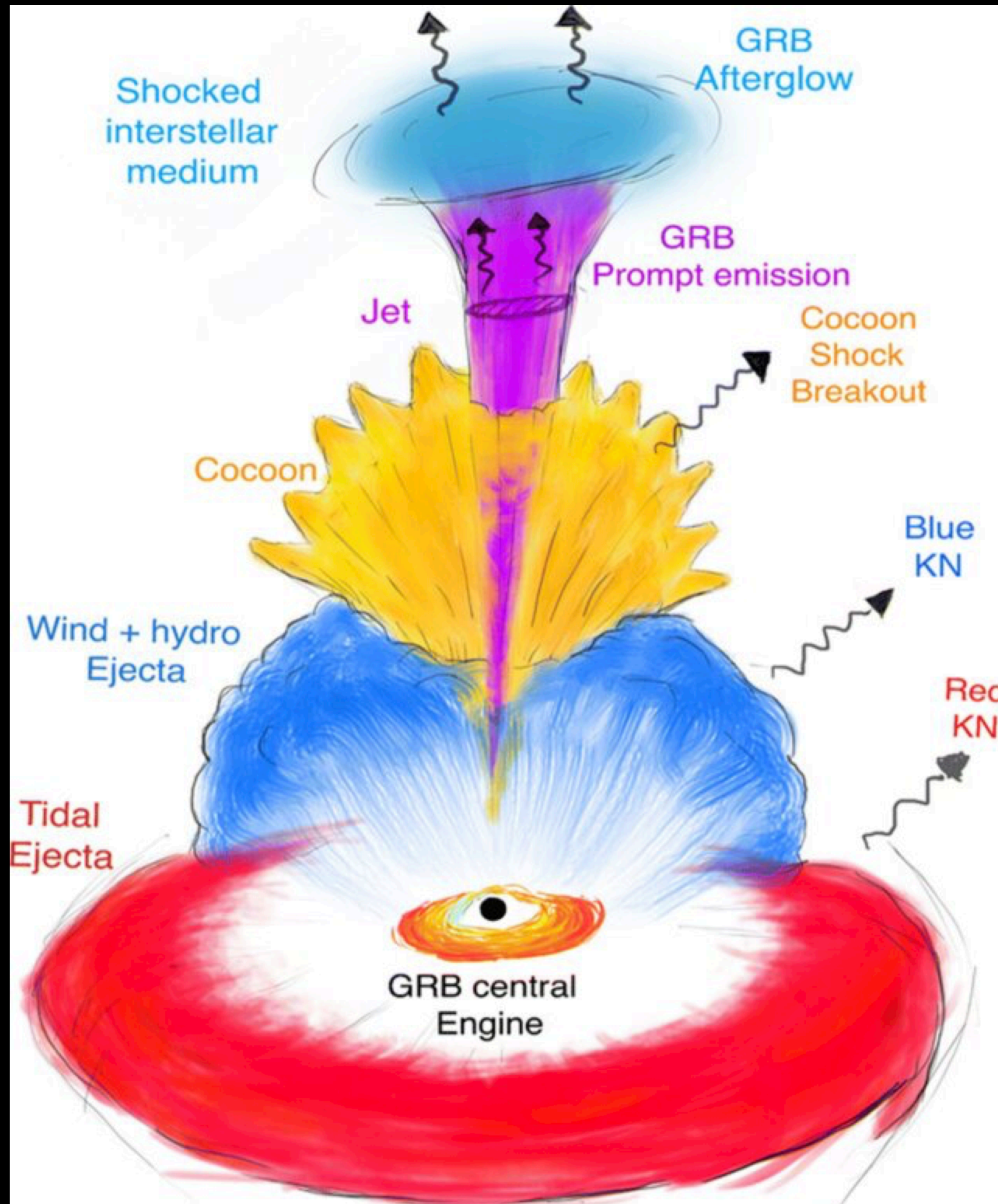
Observations from August 2017



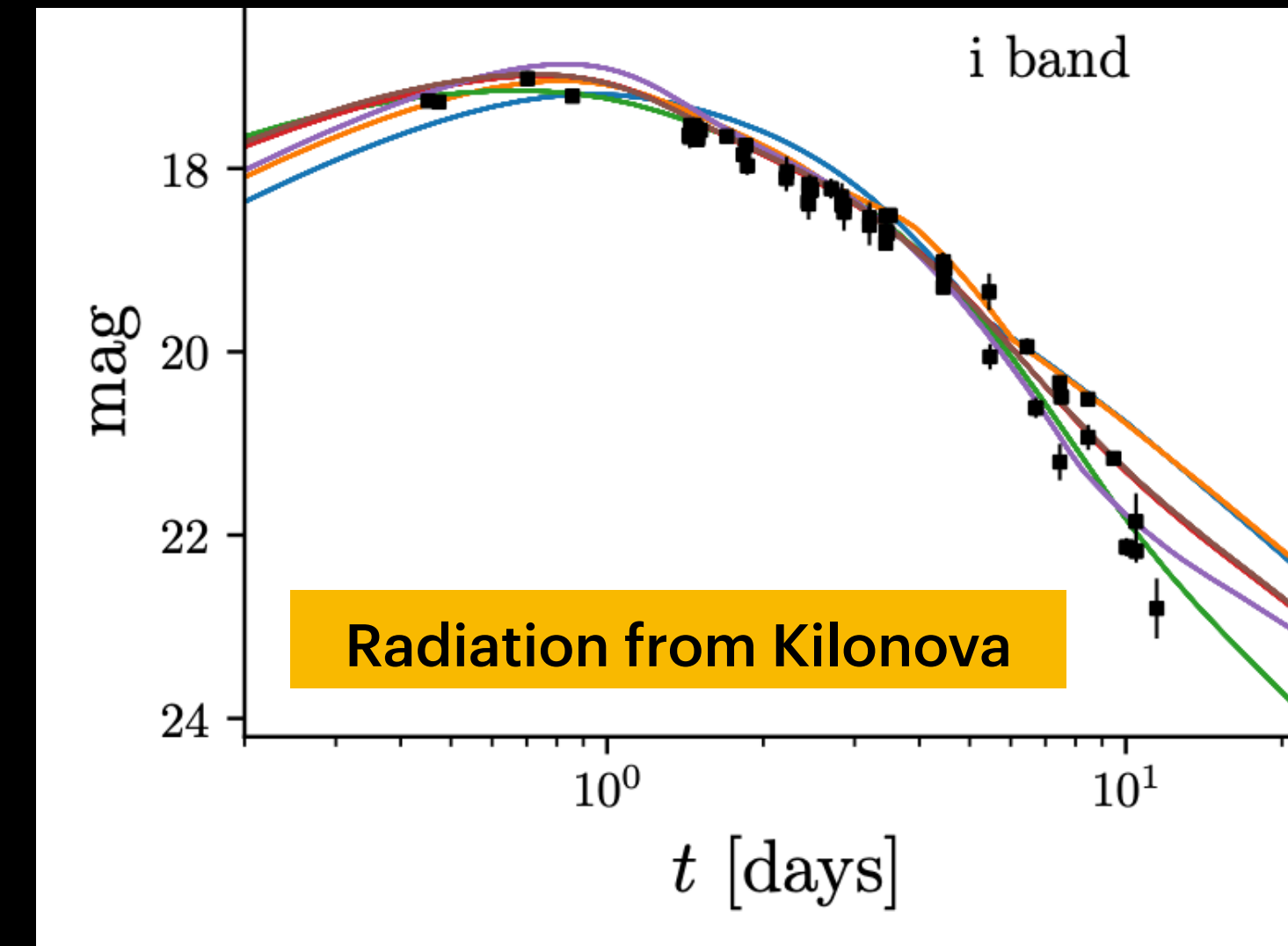
Credit: Stefano Ascenzi



Observations from August 2017



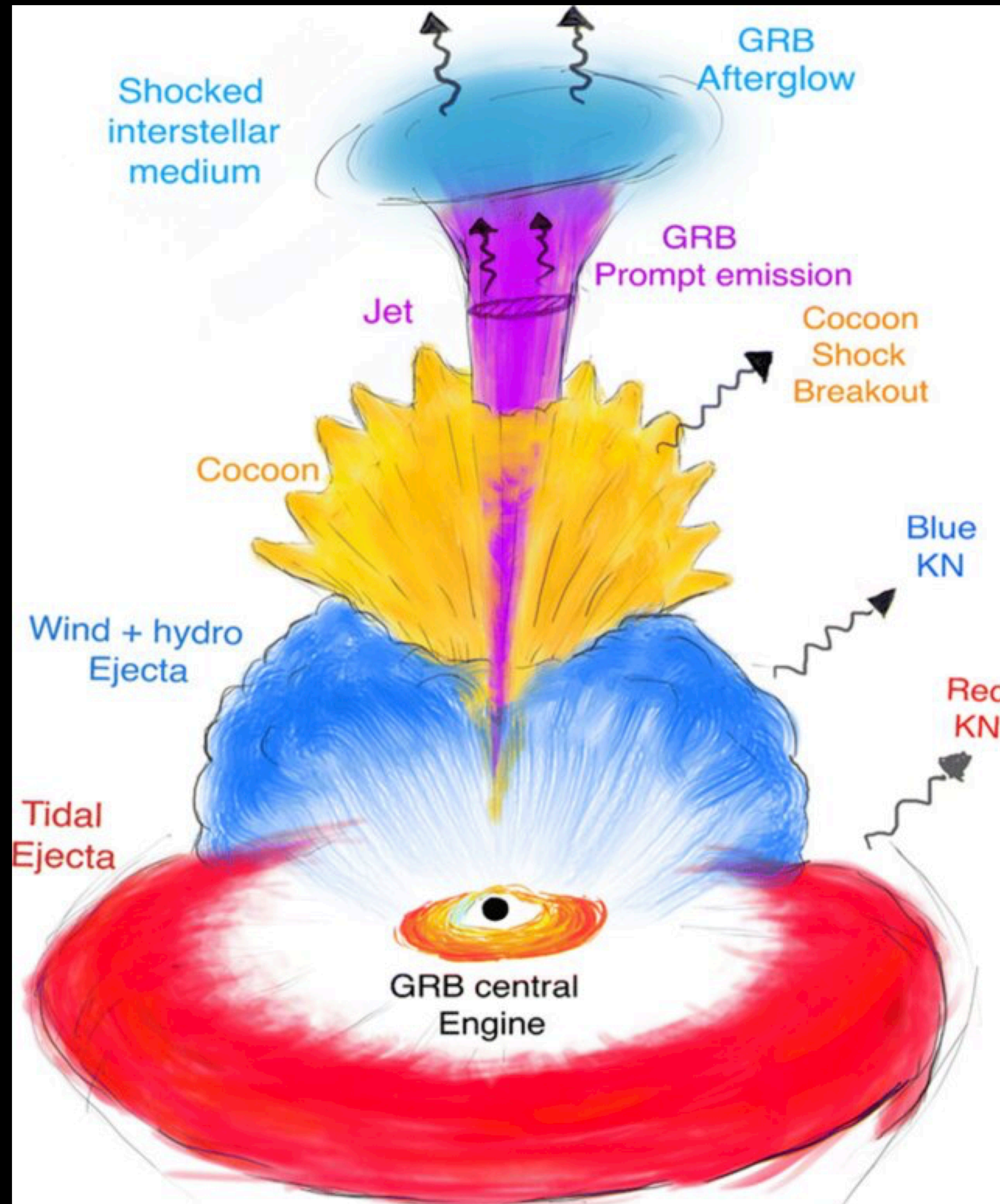
Credit: Stefano Ascenzi



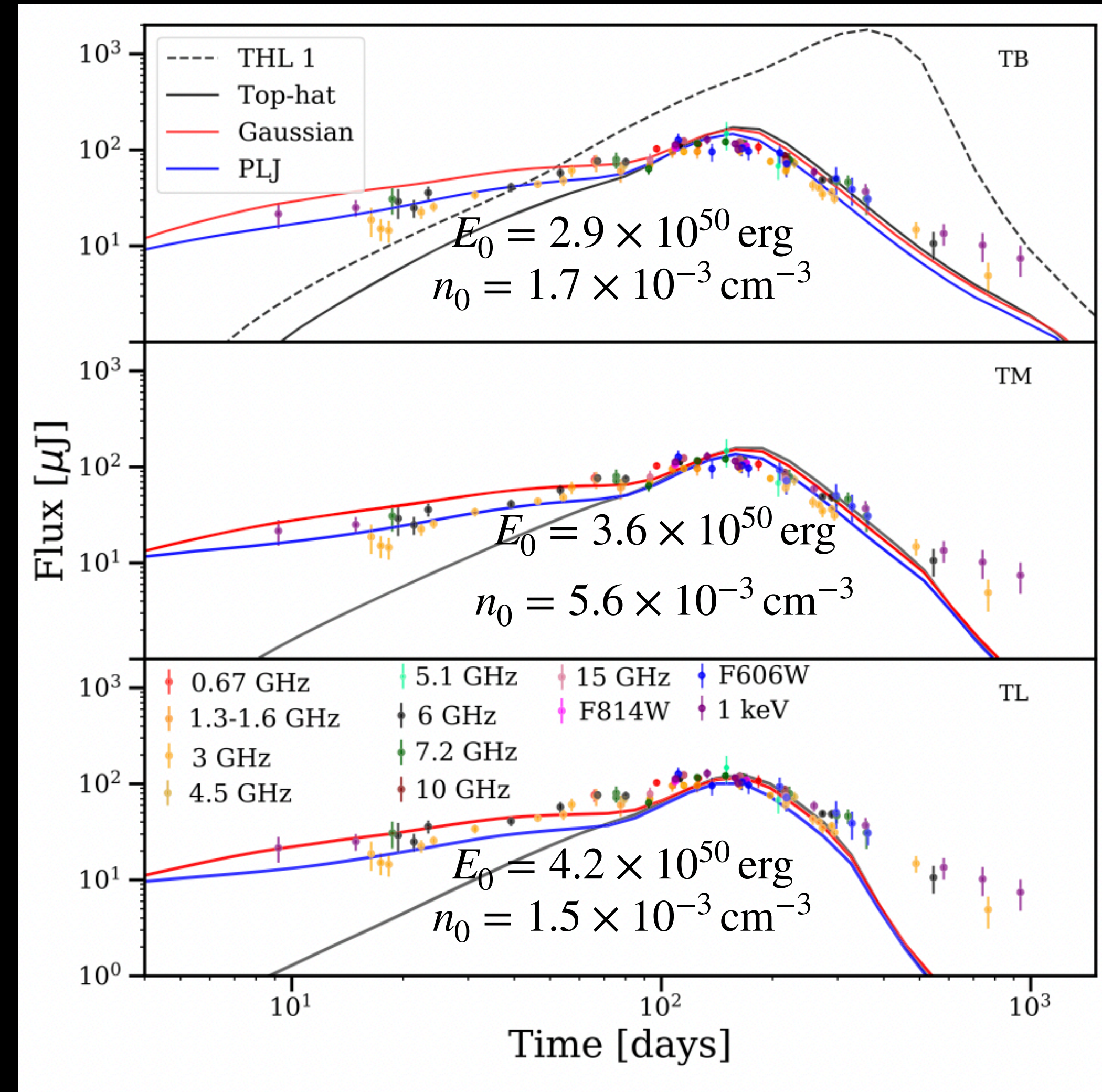
Breschi et al. 2021

Observations from August 2017

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



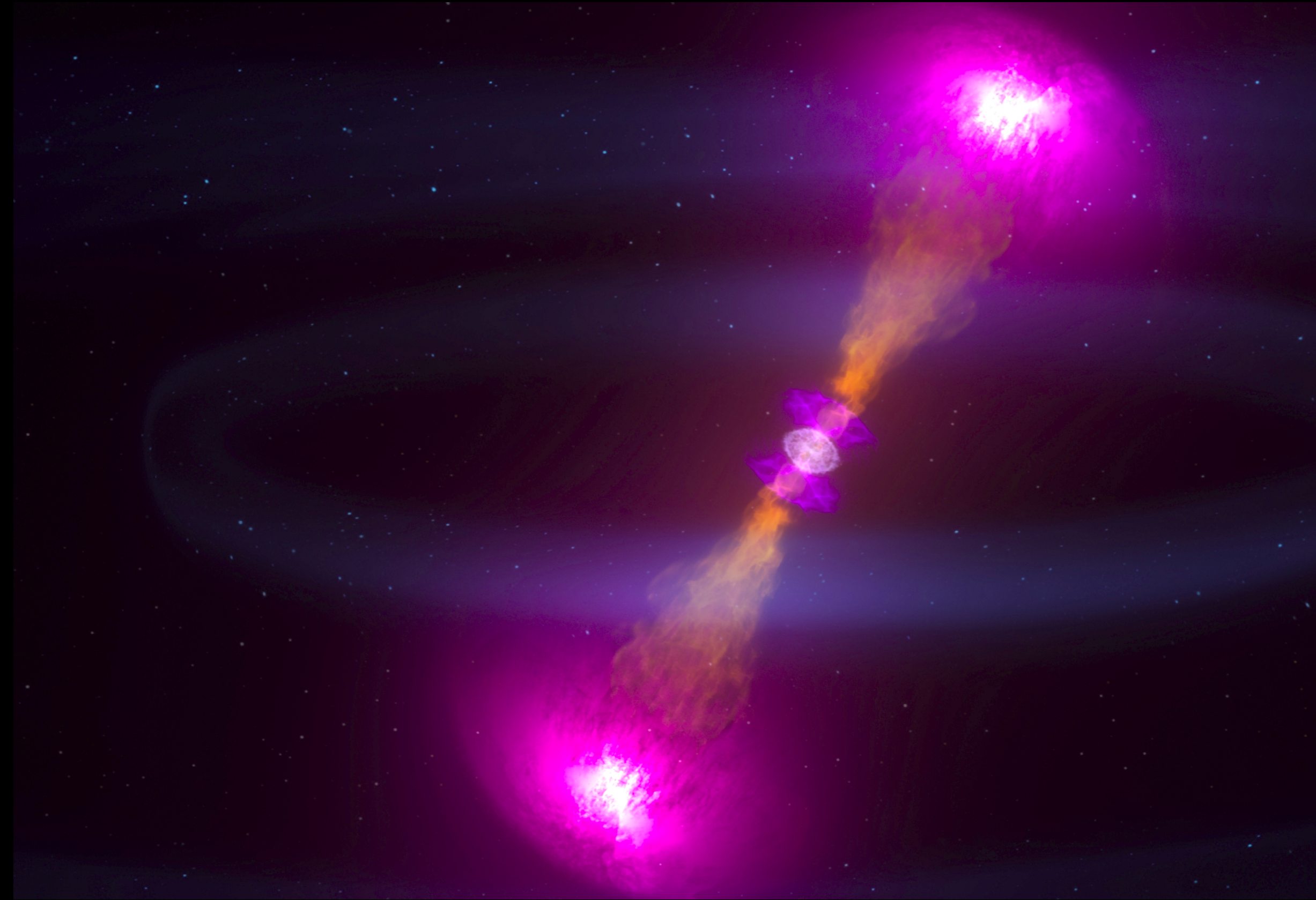
Credit: Stefano Ascenzi



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

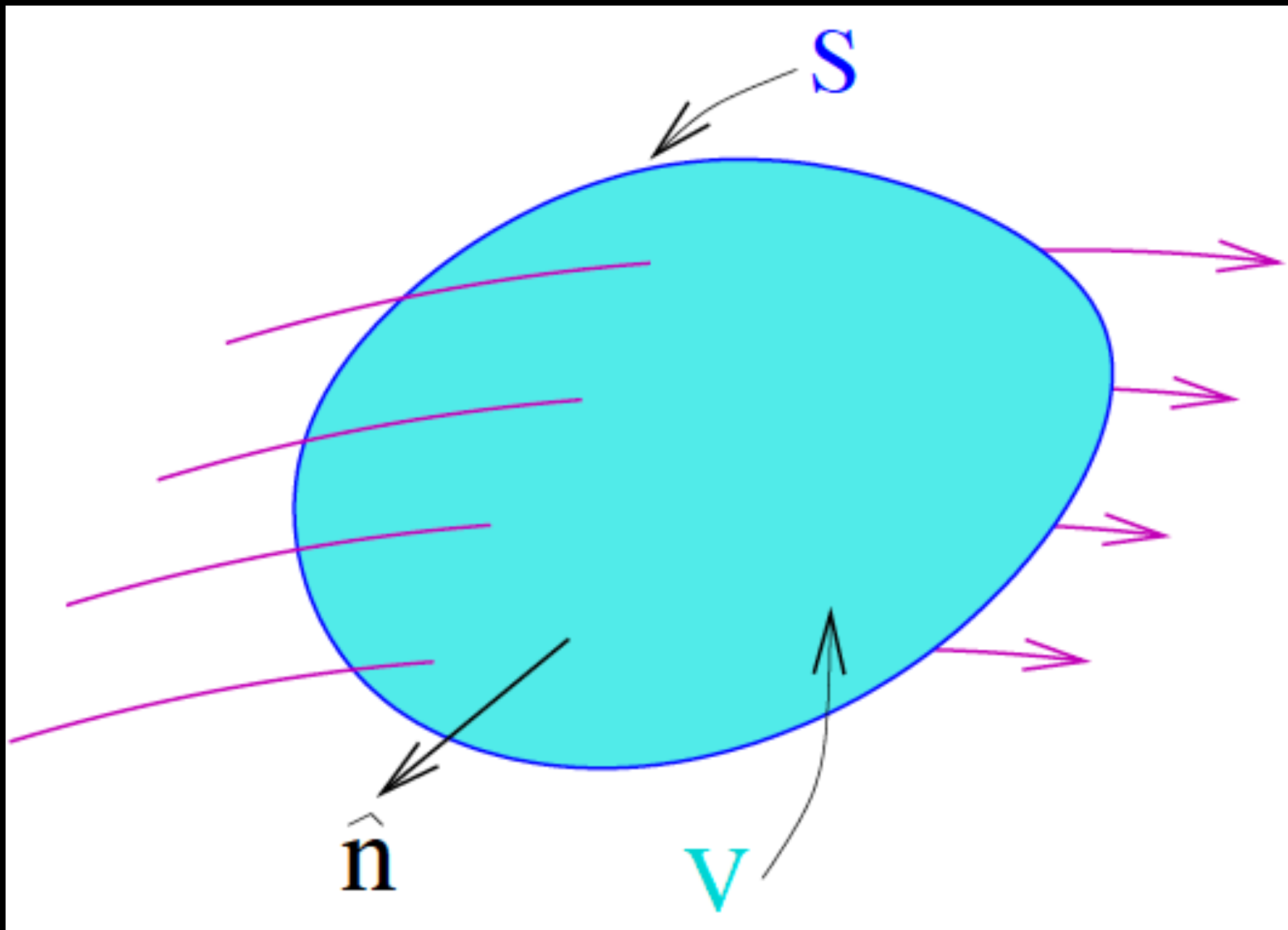
Ok, lets modeling

Bomb explosions are similar to astronomical explosions



Modeling Cosmic Explosions

Gas parcel



Density ρ

Pressure p

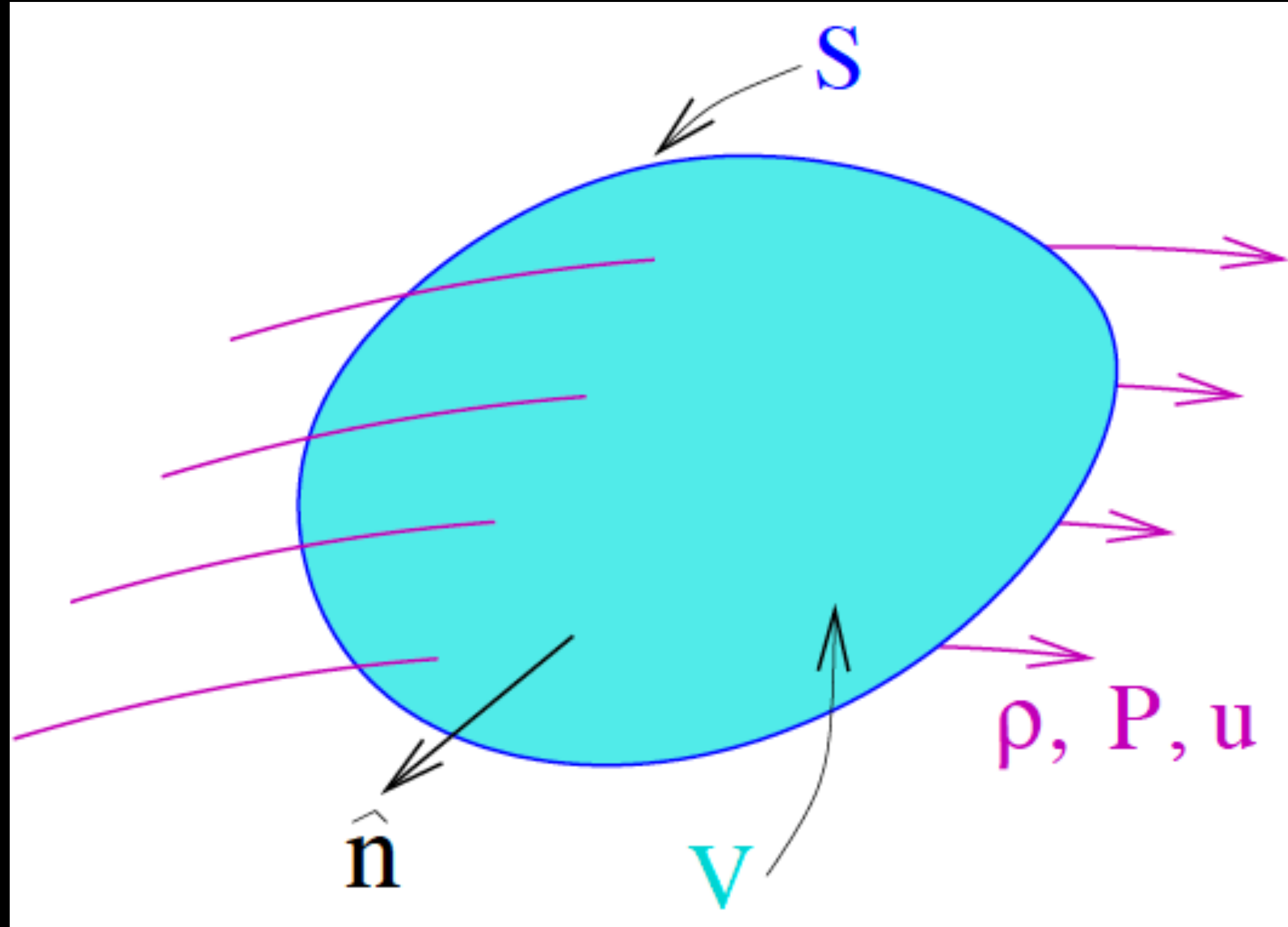
Velocity v

Lorentz Factor $\Gamma \equiv \left(1 - (v/c)^2\right)^{-1/2}$

Enthalpy $h = 1 + \frac{\gamma}{\gamma - 1} \frac{p}{\rho c^2}$

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

Special relativistic gas dynamics



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

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

We rewrite the equations to express a general rule

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

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

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

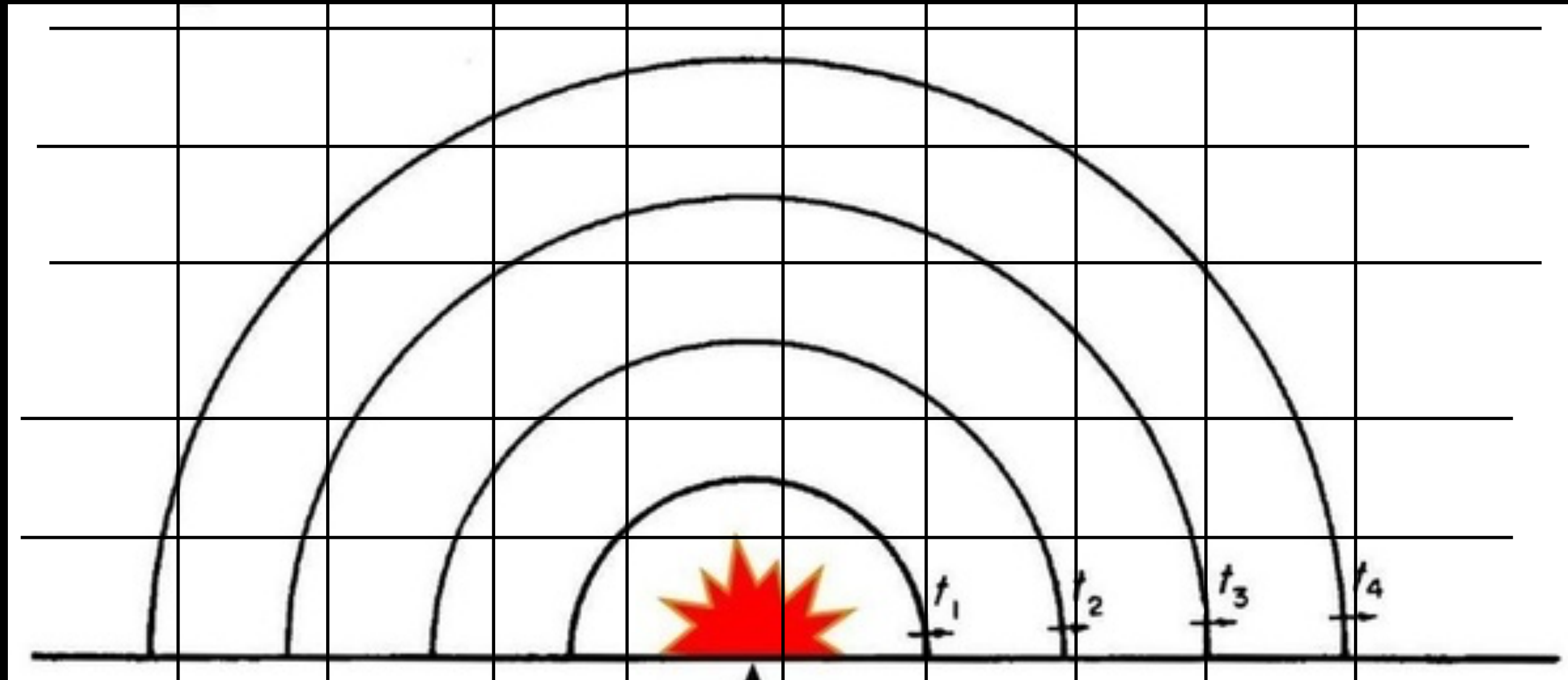
$$D = \Gamma \rho$$

$$m_j = D h \Gamma v_j$$

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

The solution of such global expression

Numerical simulations are our virtual laboratory to reproduce extreme conditions



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

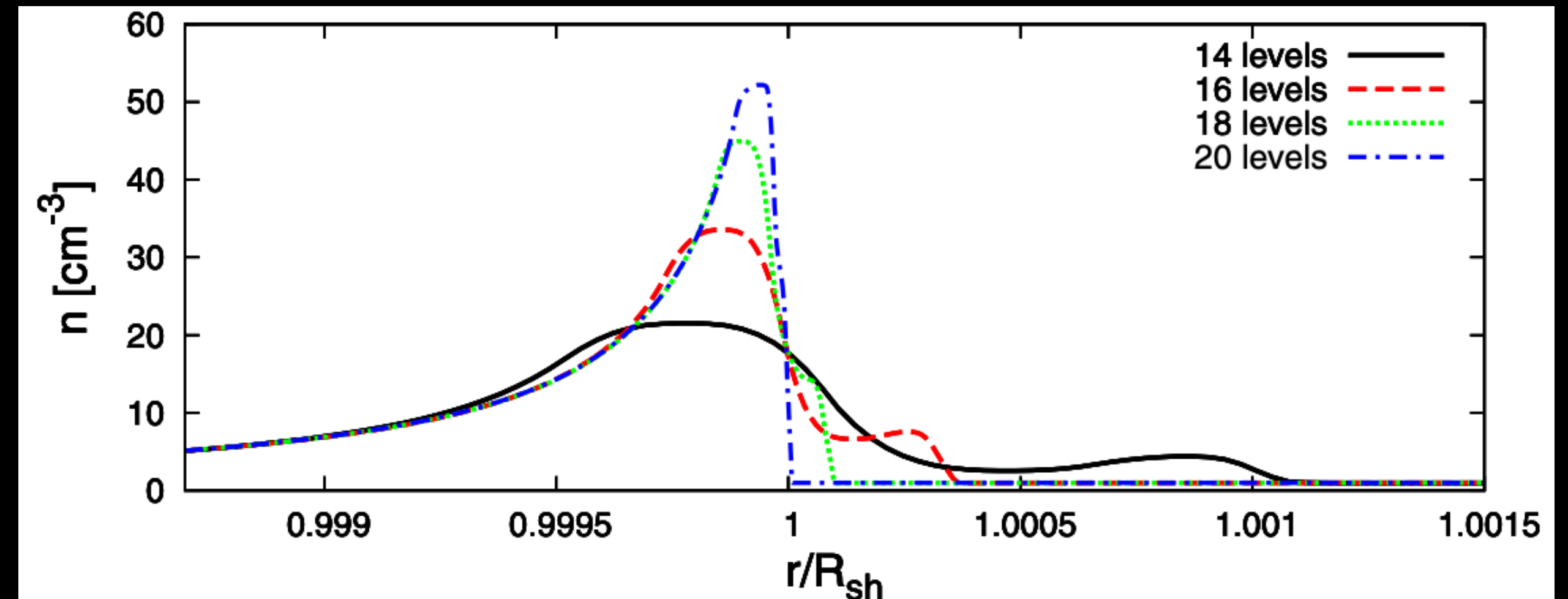
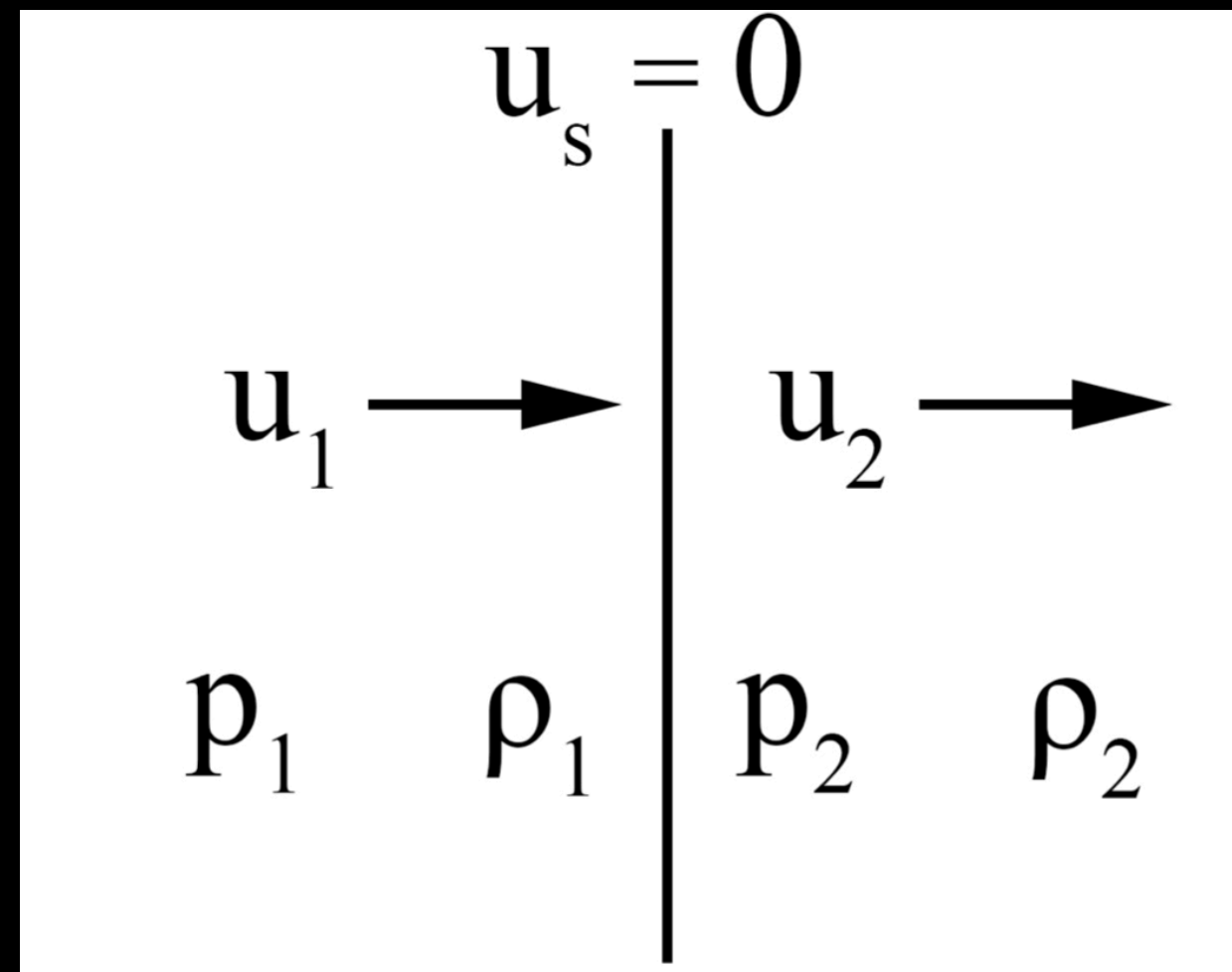
$$U_i^n = \frac{1}{\Delta x_i} \int_{x_{i-1/2}}^{x_{i+1/2}} u_i(t^n, x) dx$$

- Supersonic fluids
- Strong shocks

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

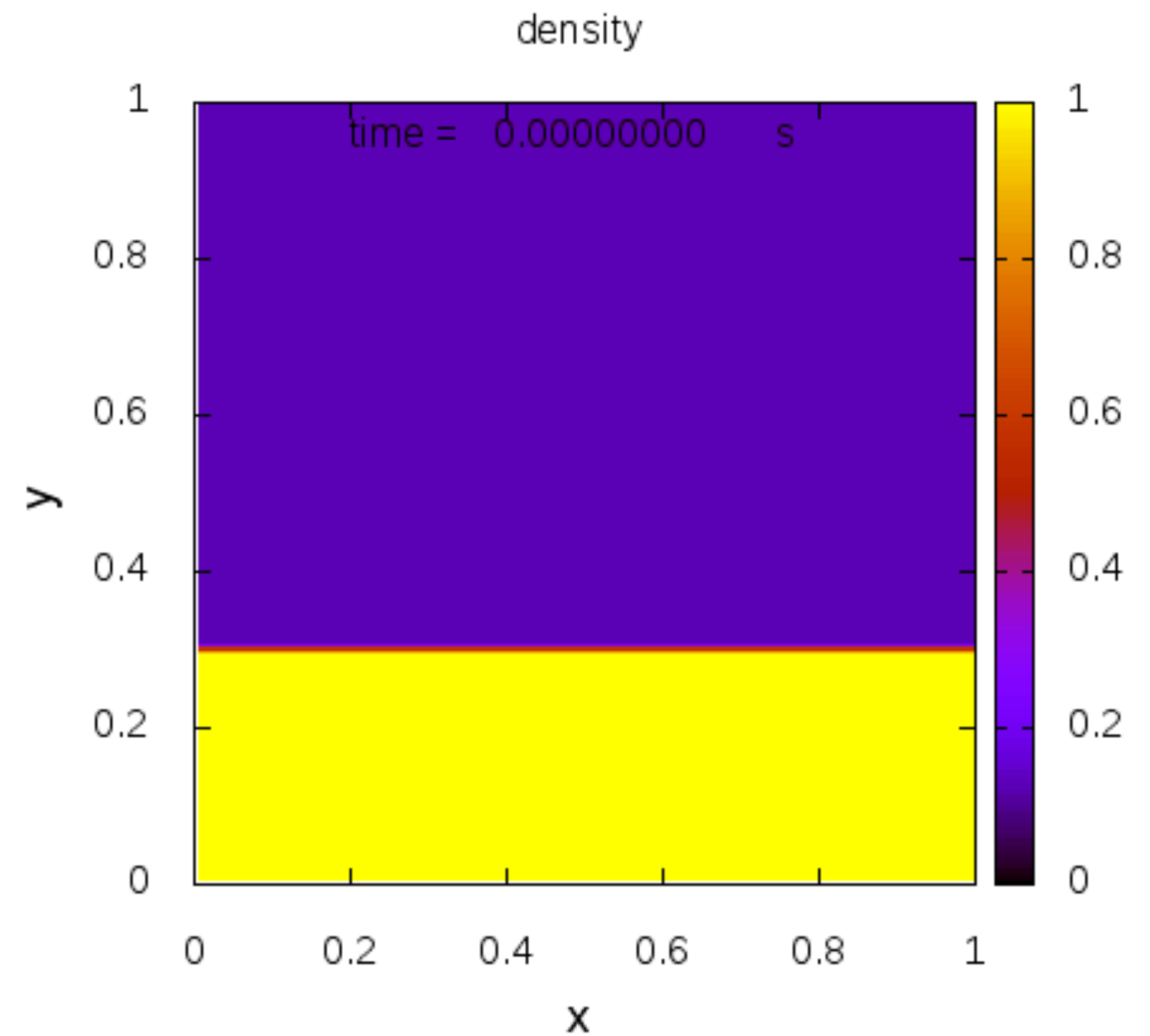
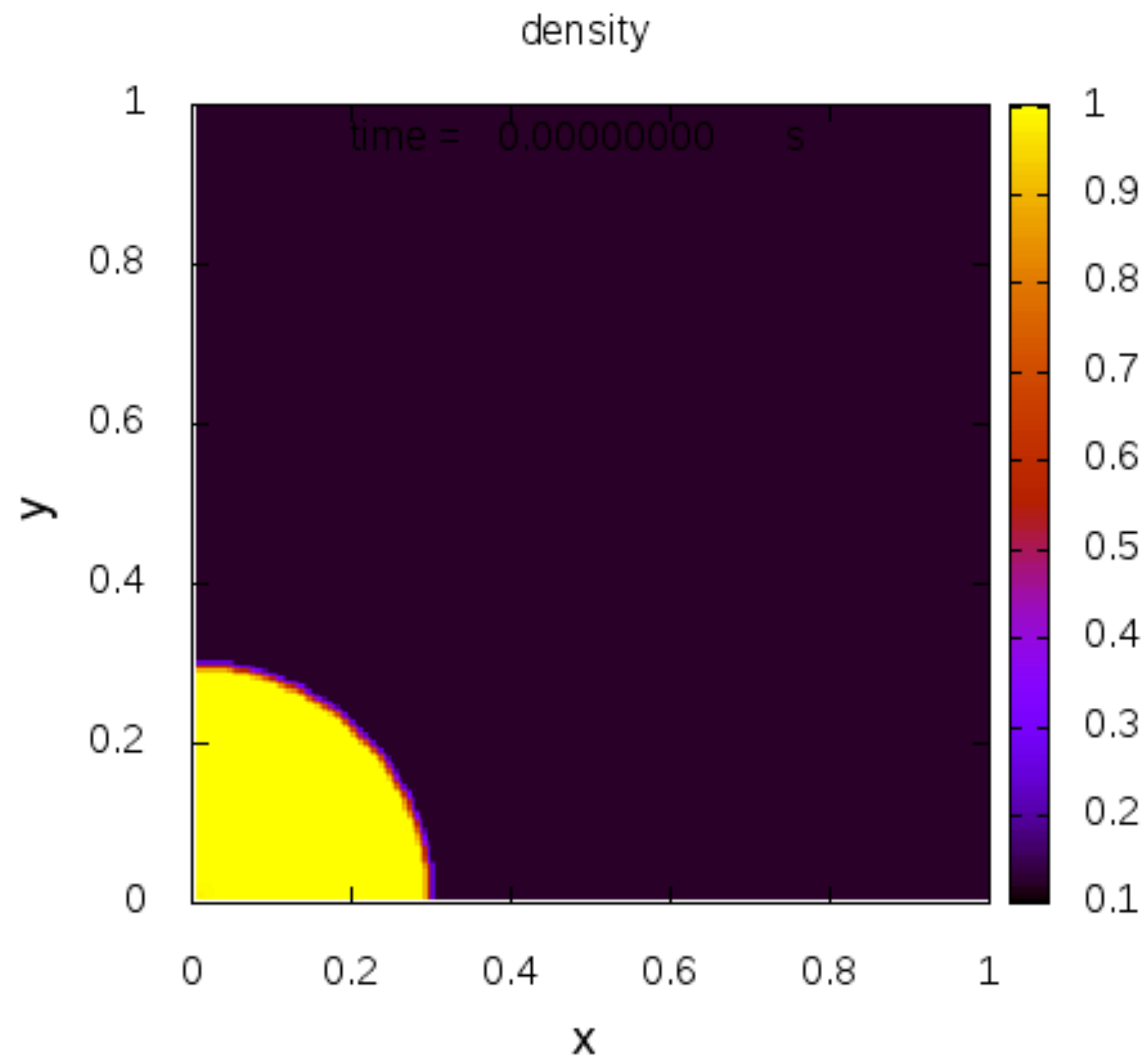
Shock capture scheme

Numerical simulations are our virtual laboratory to reproduce extreme conditions

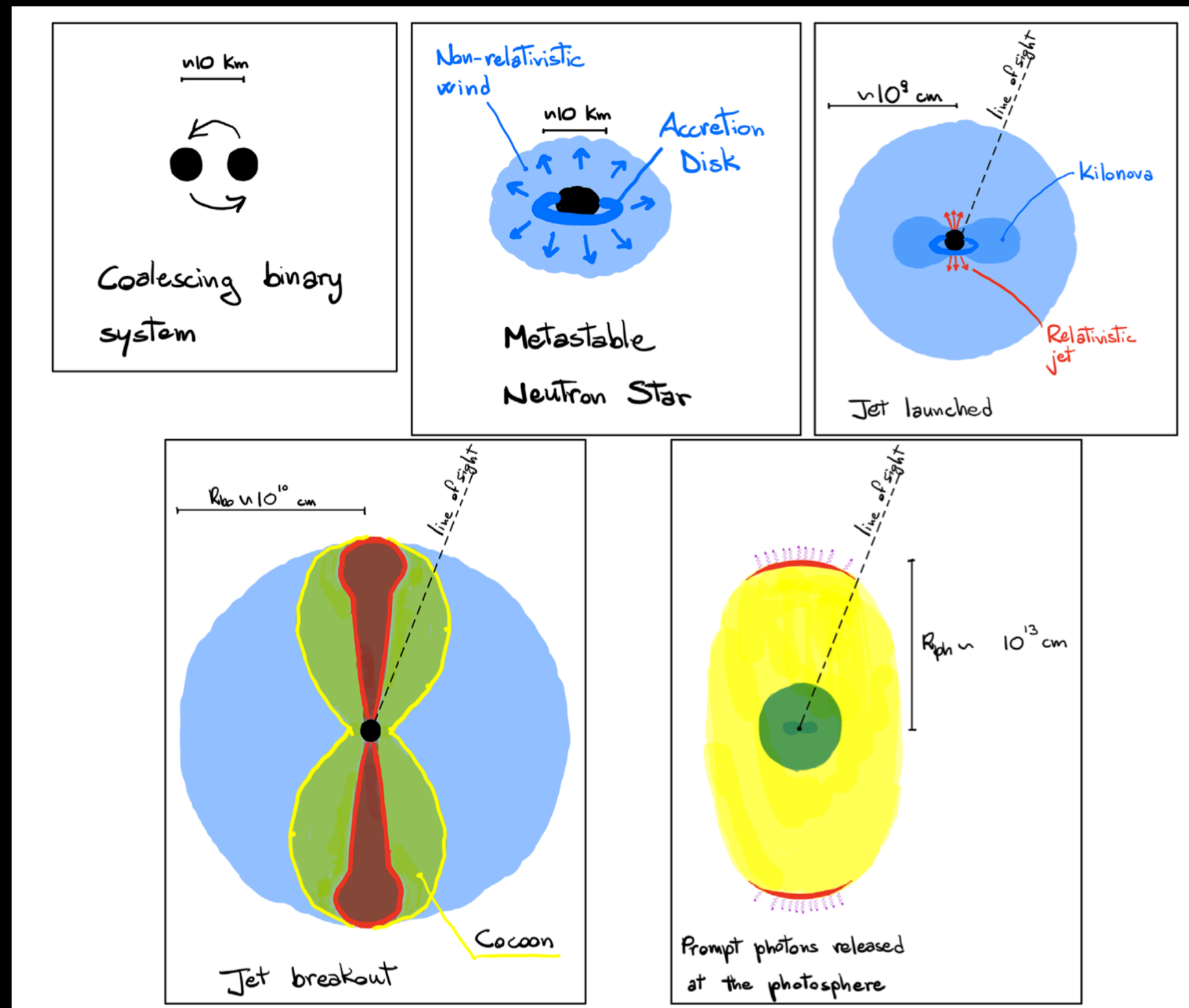


- Eulerian Special Relativistic Hydrodynamics
- Harten-Lax-van Leer-Contact; methods
- Fortran 90
- MPI

2D example



Computational costs associated to space/time resolution



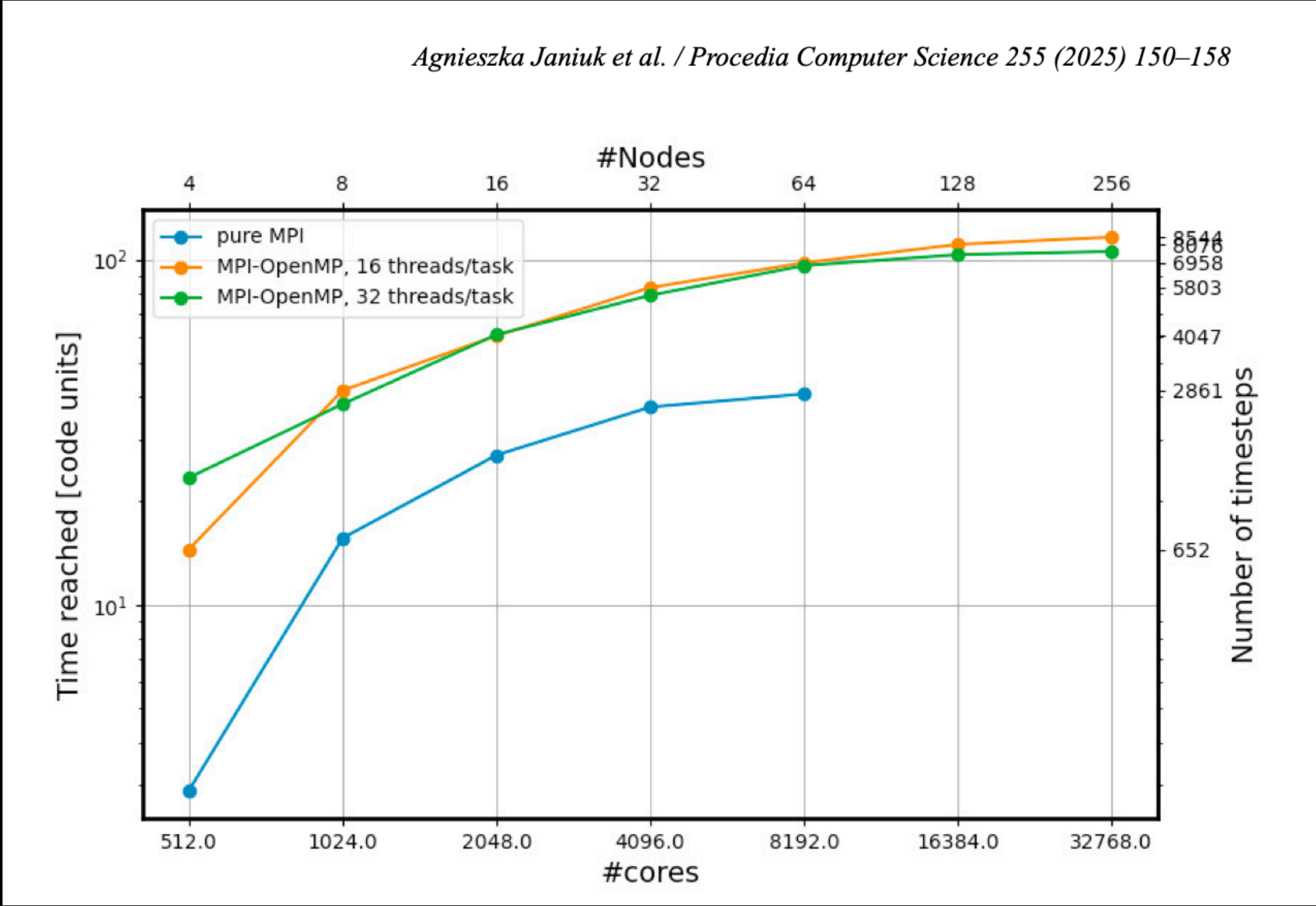
Lazzati, Cioffi & Perna 2020

- Simulation last slide, 5 minutes
- 3D simulation, Urrutia et al. 2023, 1 million h $\sim$ 100 years
- Fiducial model Urrutia et al. 2025, 120 000 h, 1~year
- Note: Models including different physical components and 3 spacial directions 10 - 100 million (e.g., Shibata et al. 2025, Mezzacapa 2022)

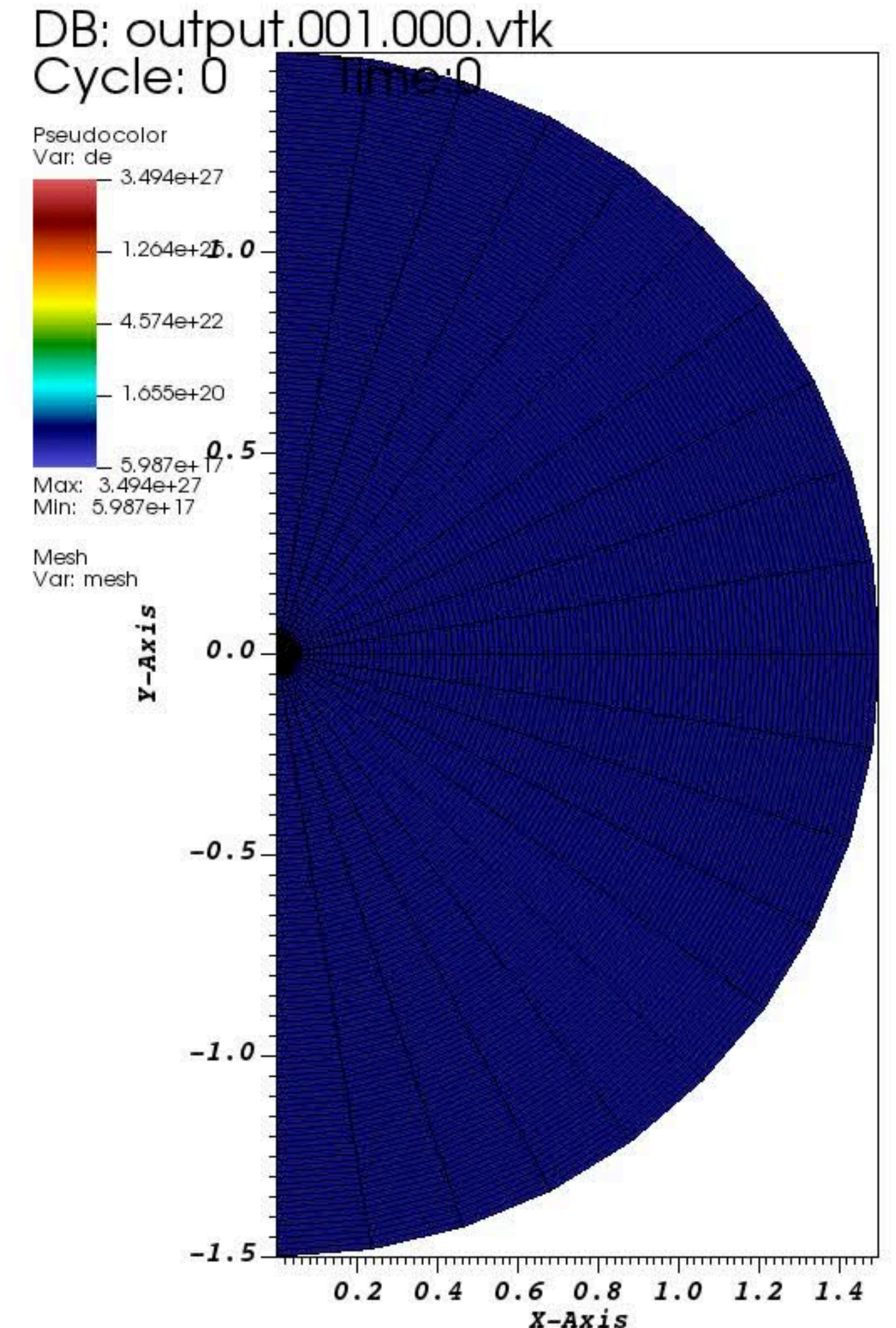
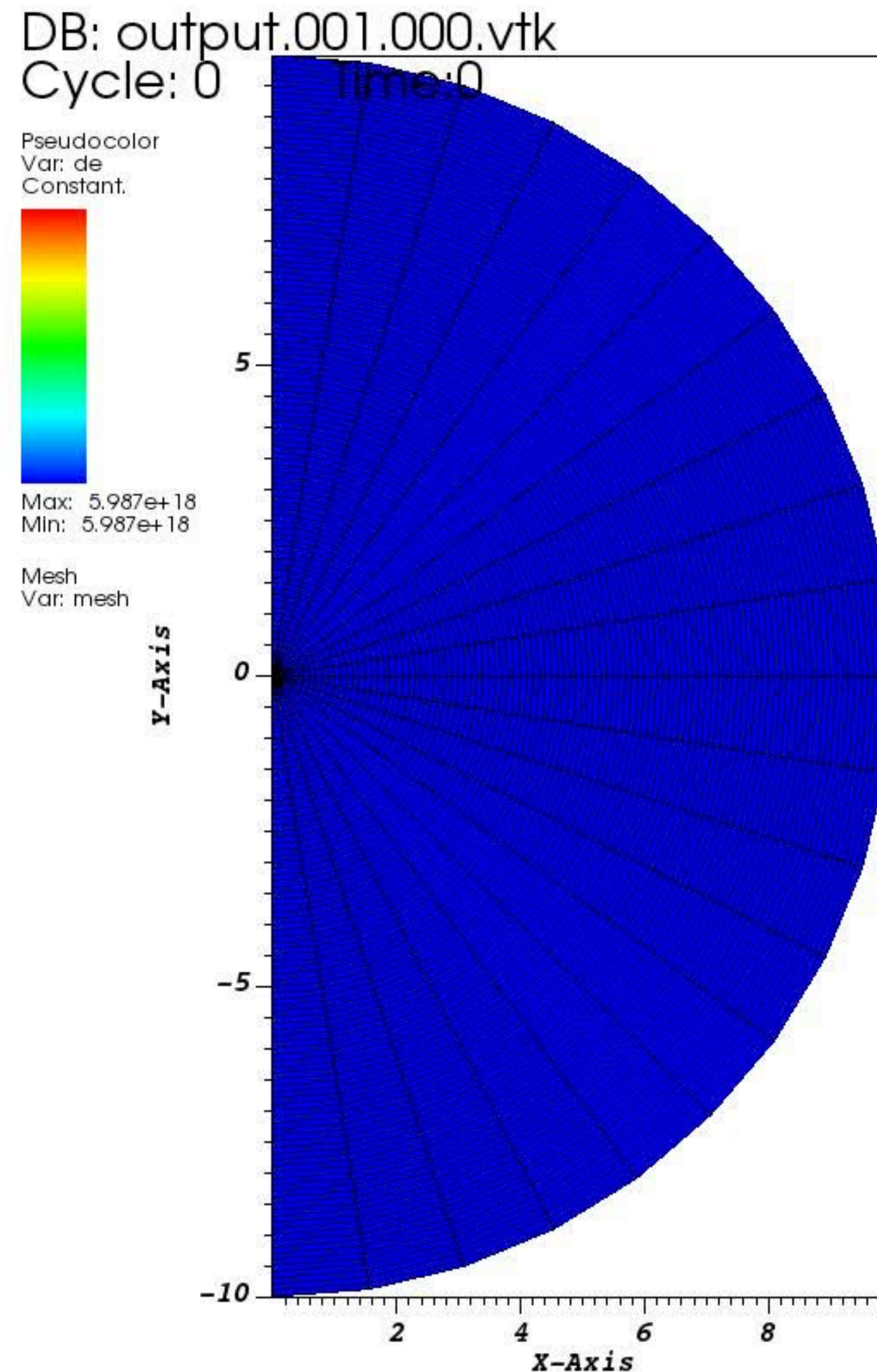
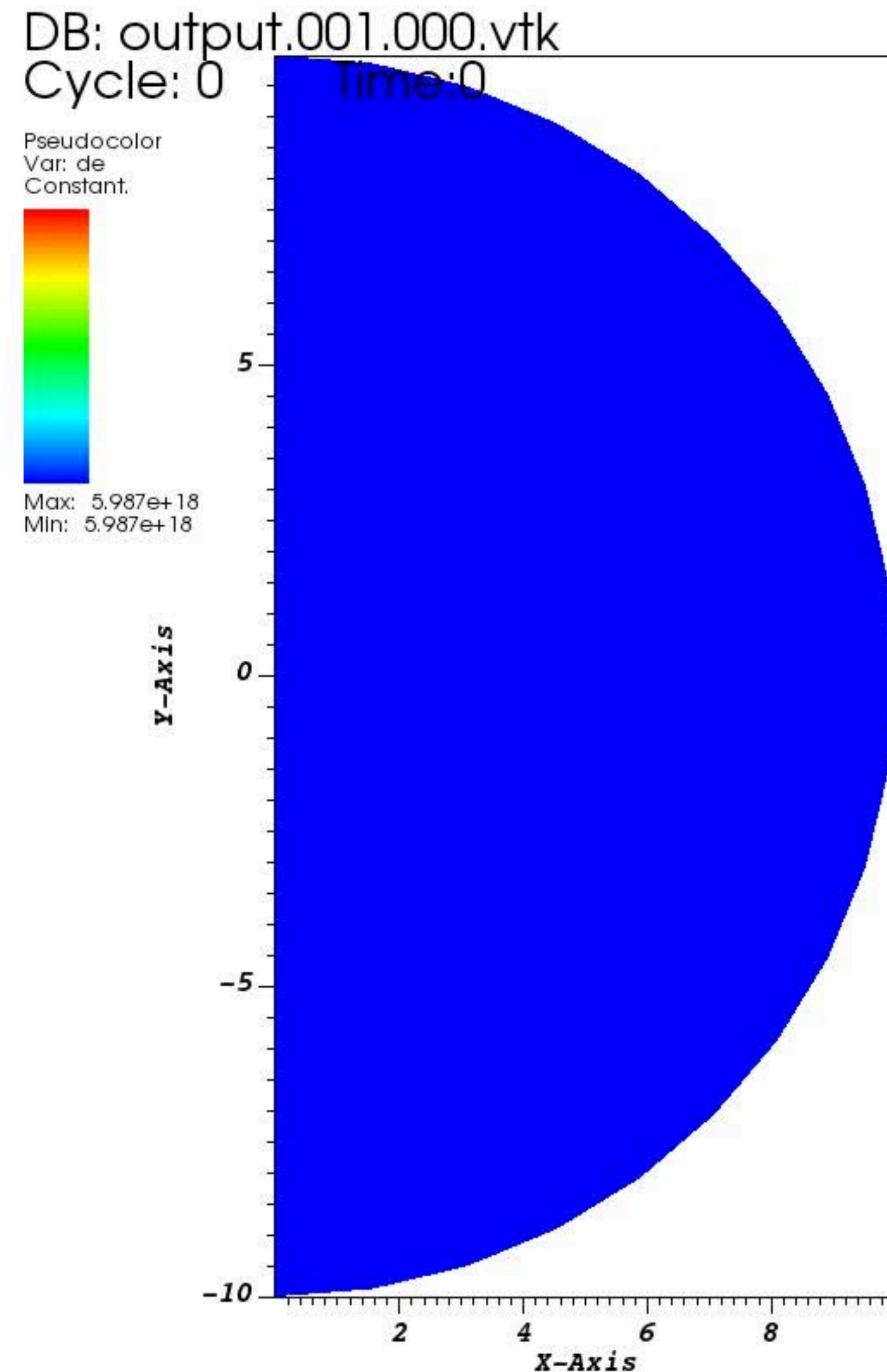
Resources



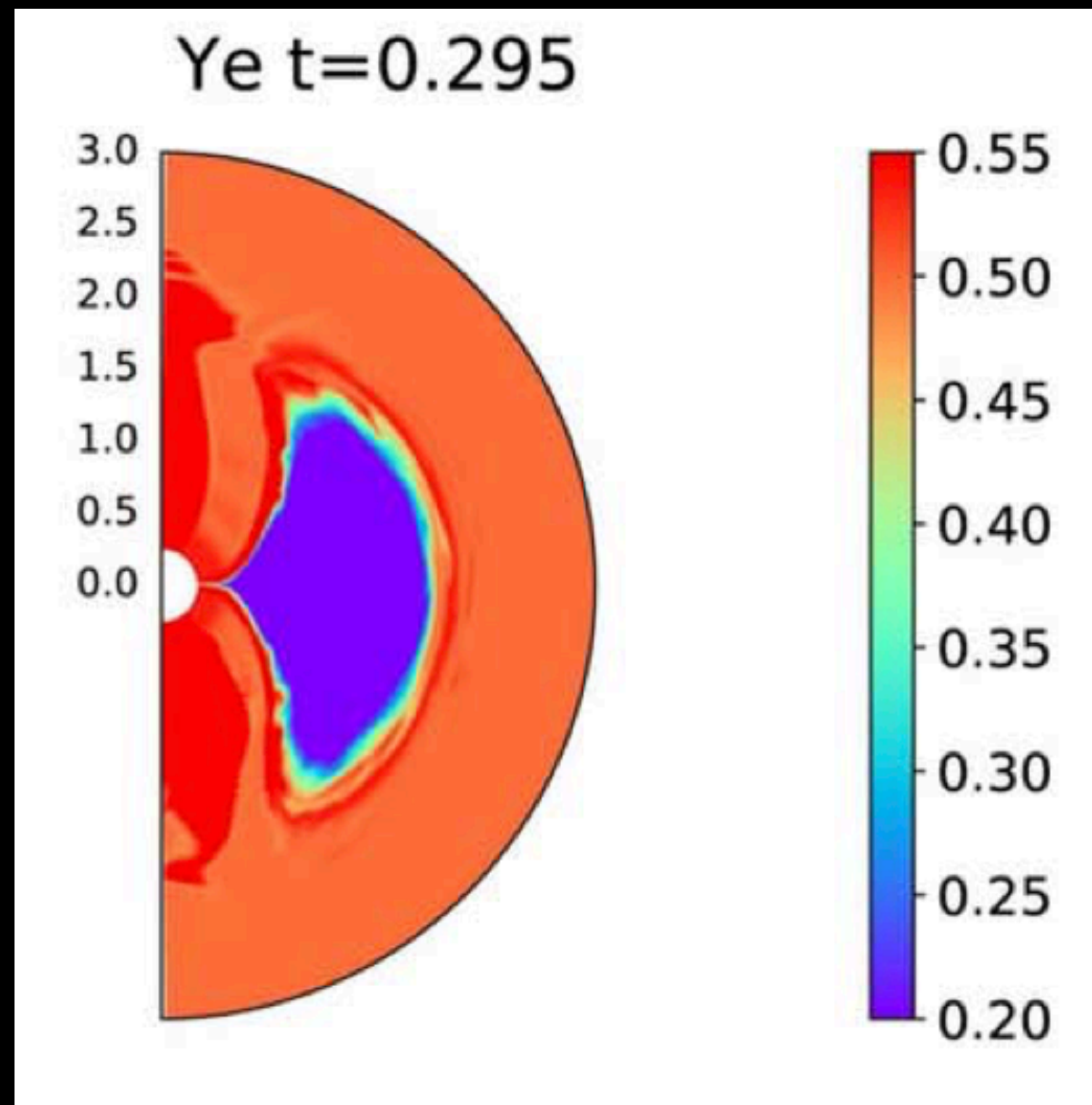
Computational resources



Spatial mesh can be dynamically adapted



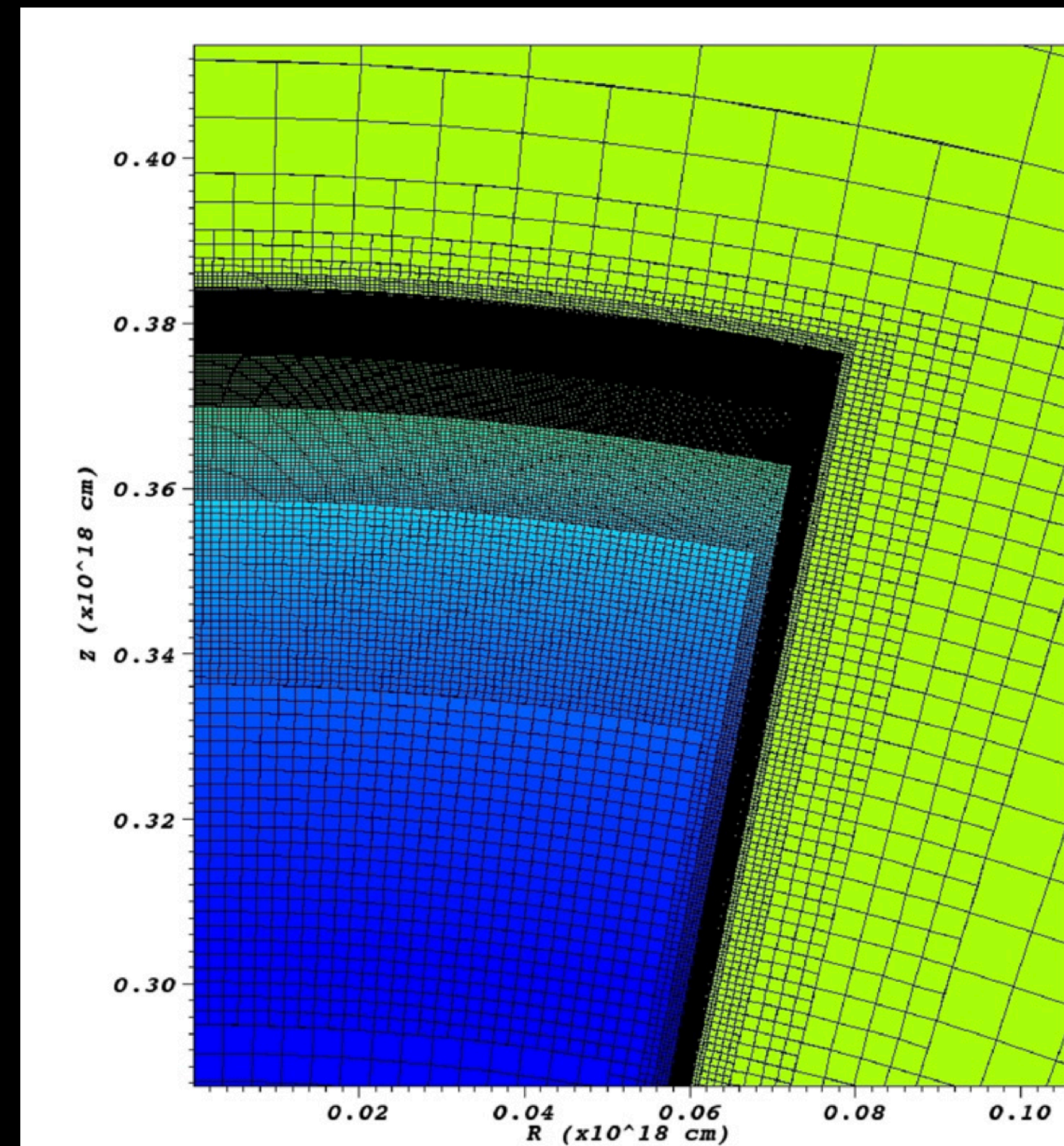
Codes: We separate by parts the entire problem



HARM_COOL (EOS):

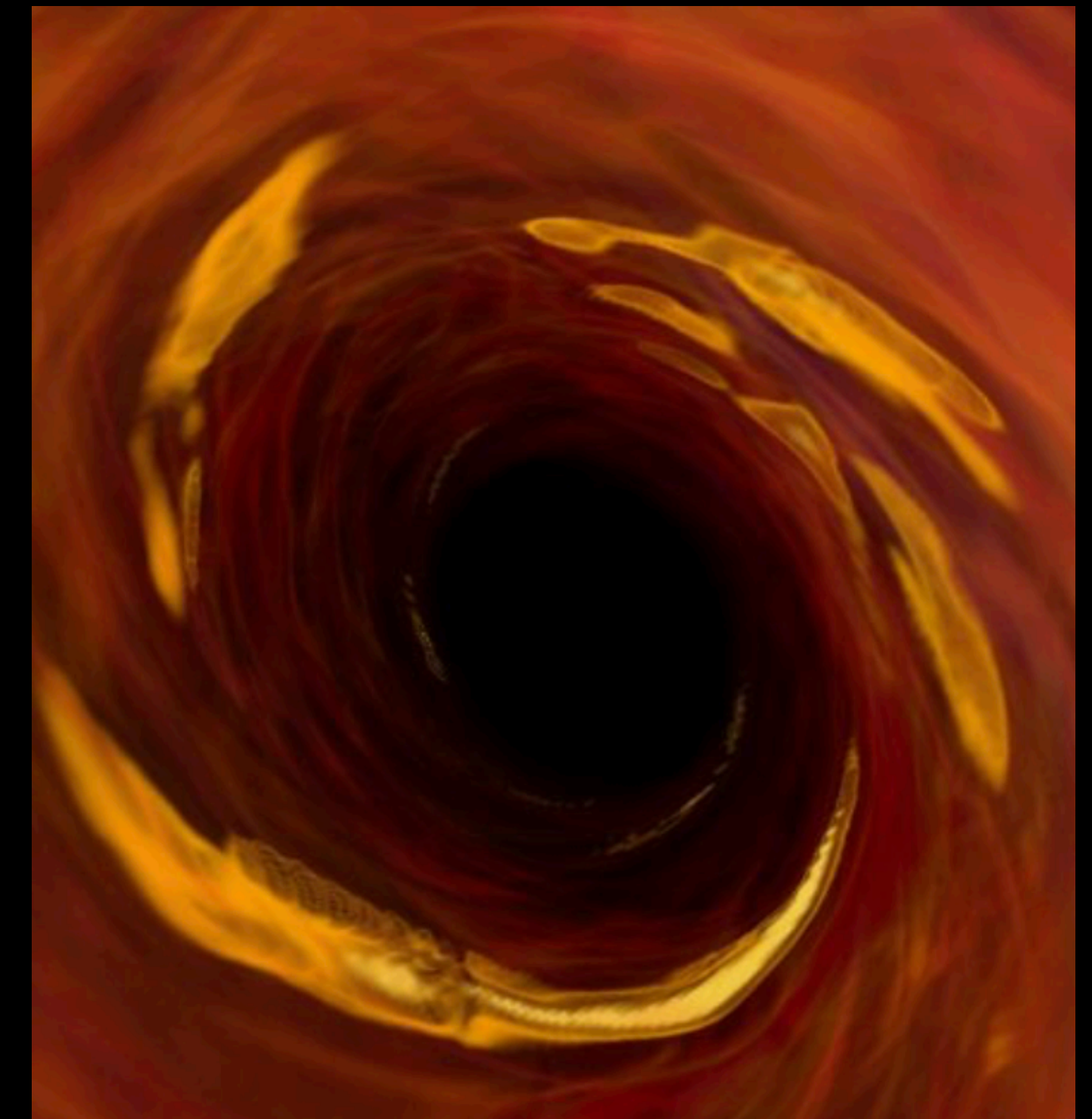
A.Janiuk

-> https://github.com/agnieszkajaniuk/HARM_COOL



MEZCAL (AMR):

De Colle, Granot, Ramirez-Ruiz, Lopez-Camara (2012)

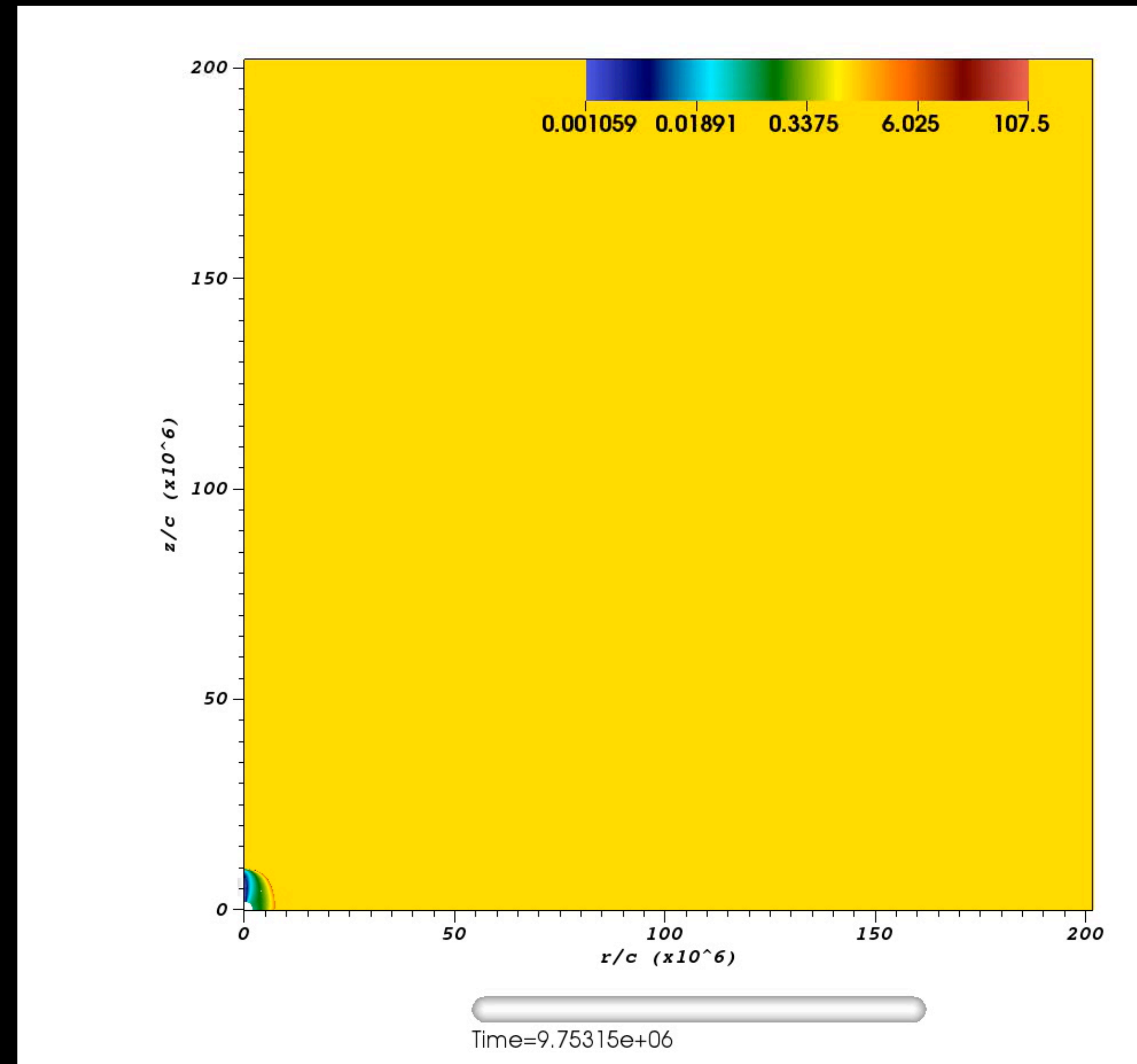


BHAC (AMR):

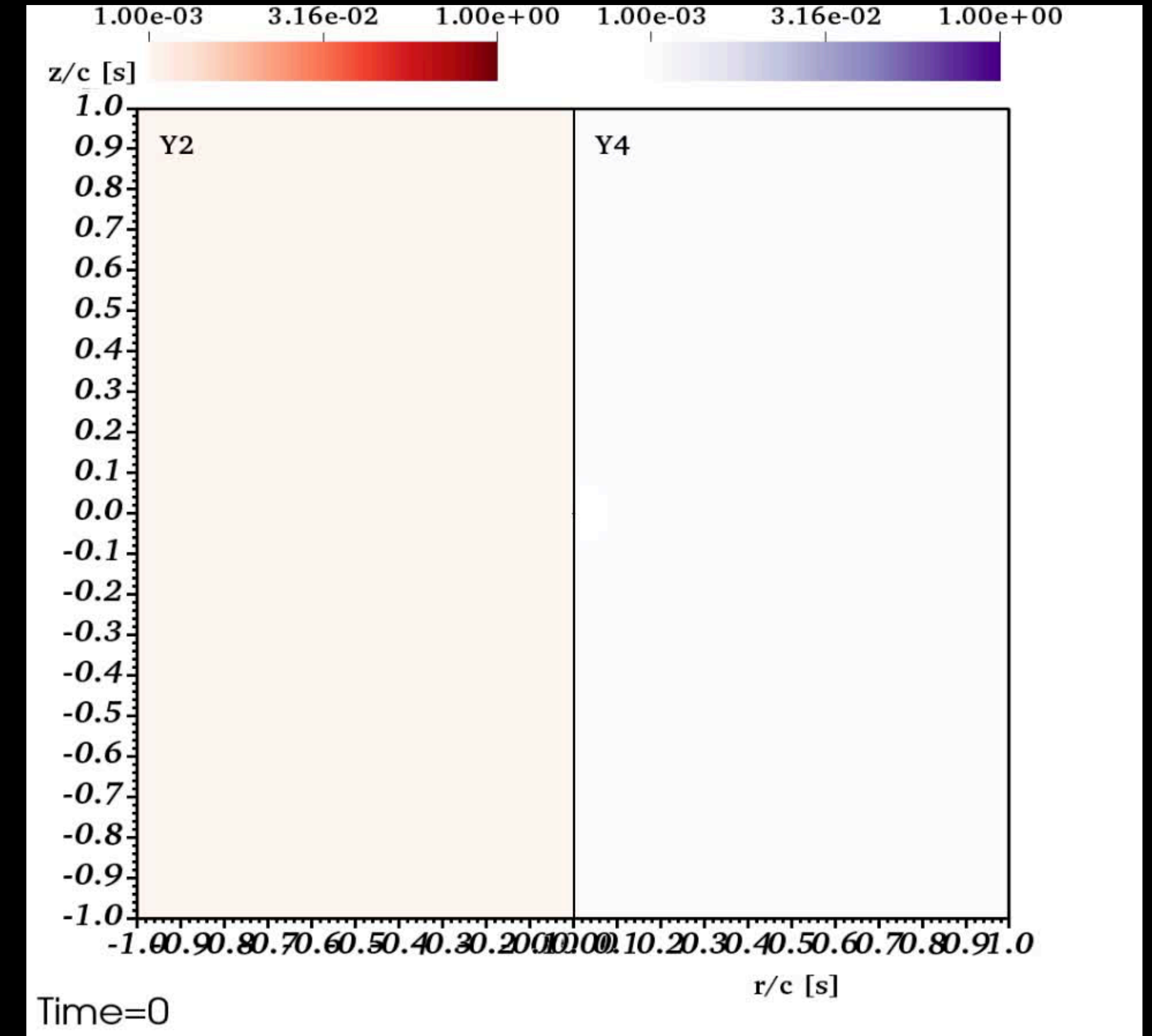
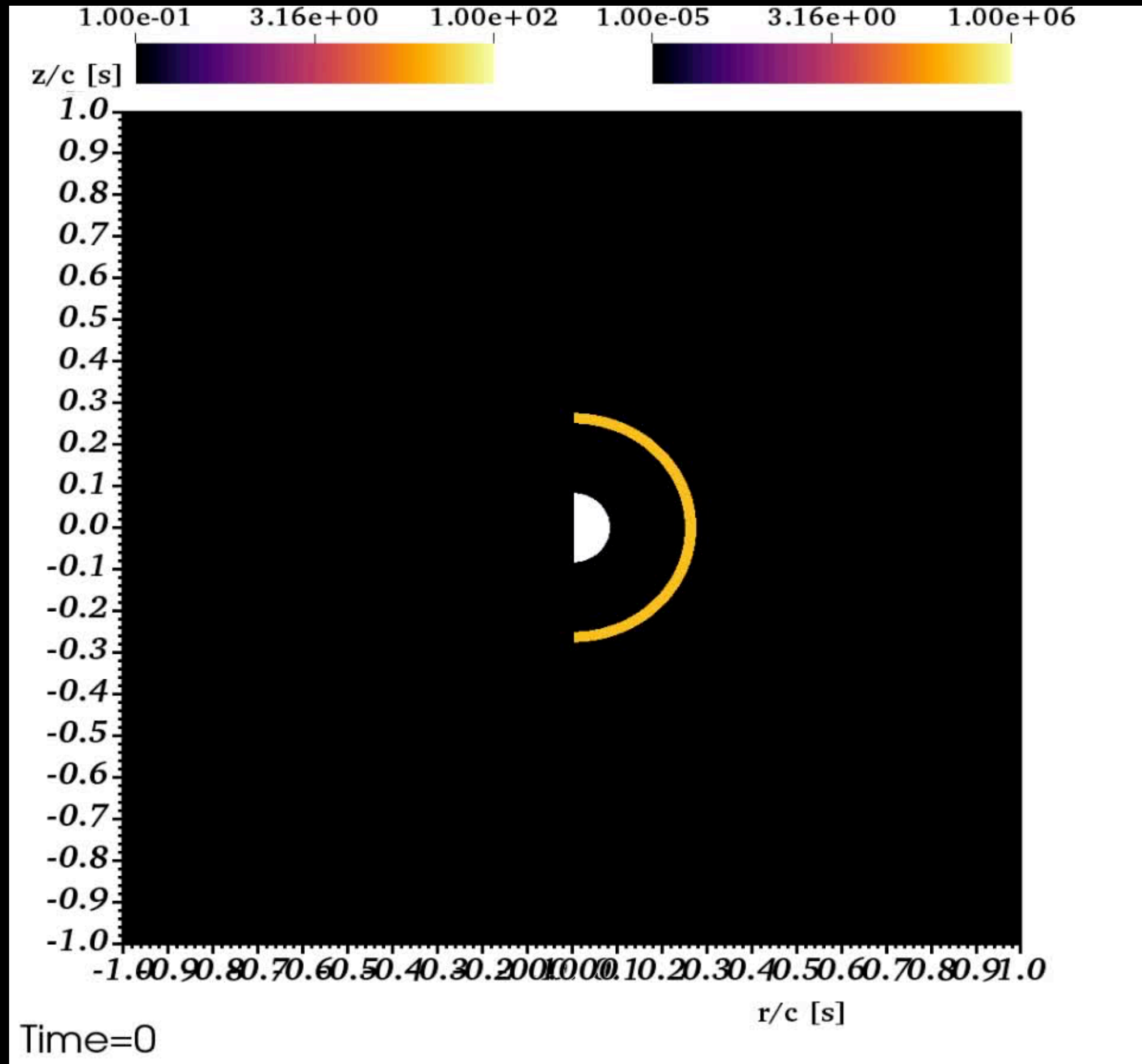
Port, Olivares, Mizuno et al

-> <https://bhac.science/>

Simulation of a blast wave explosion

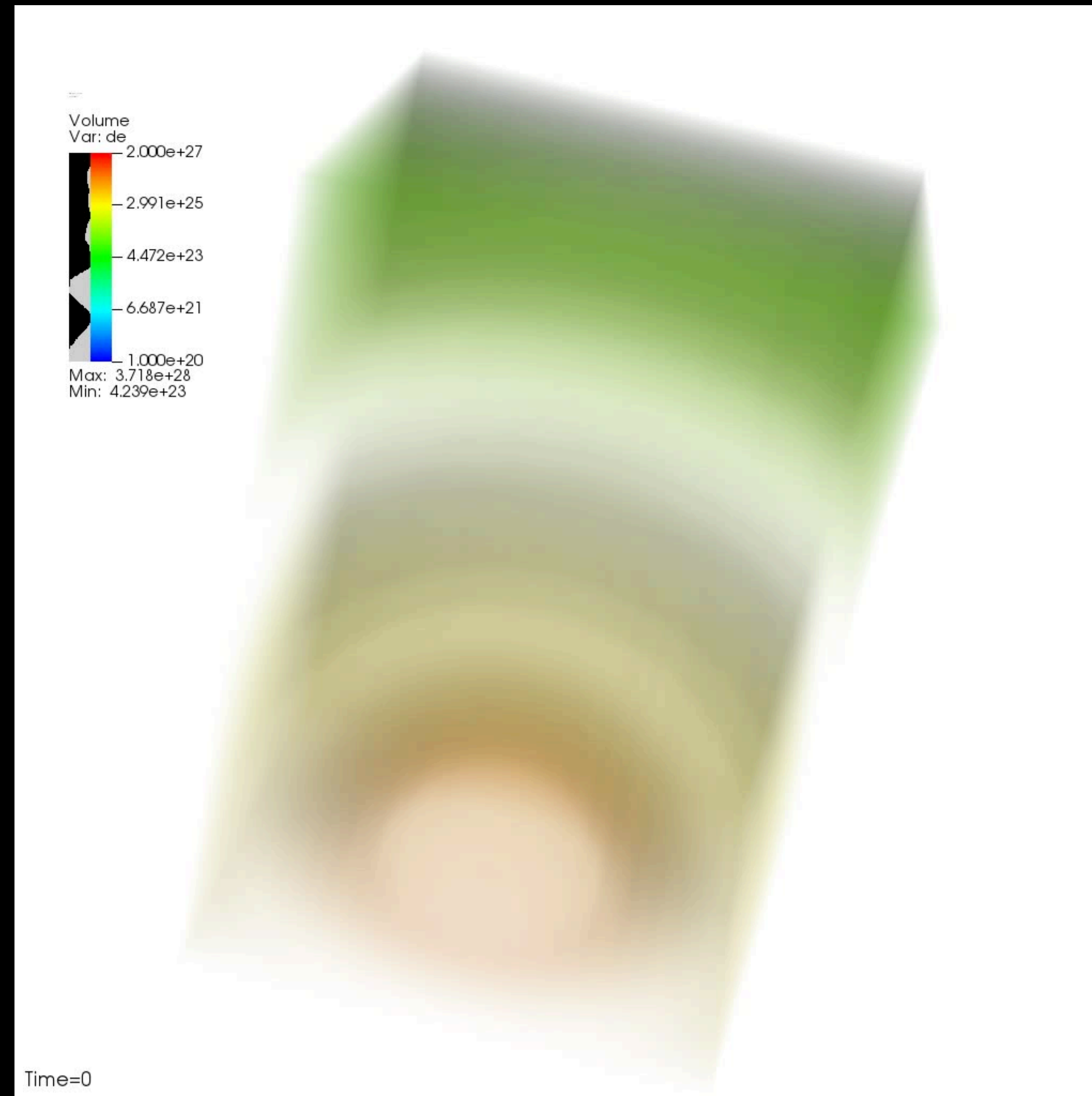


Simulation post neutron star merger explosion

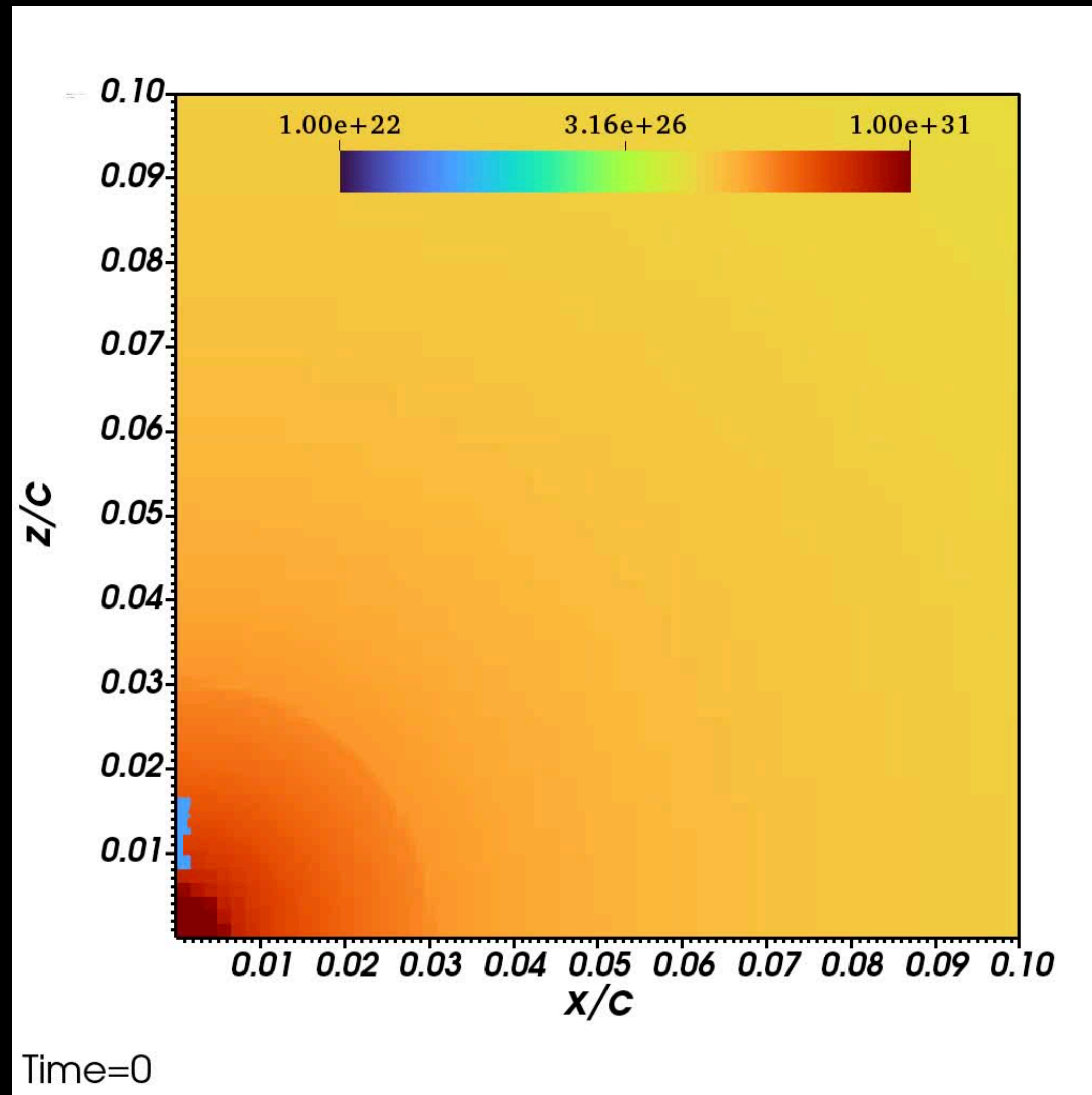


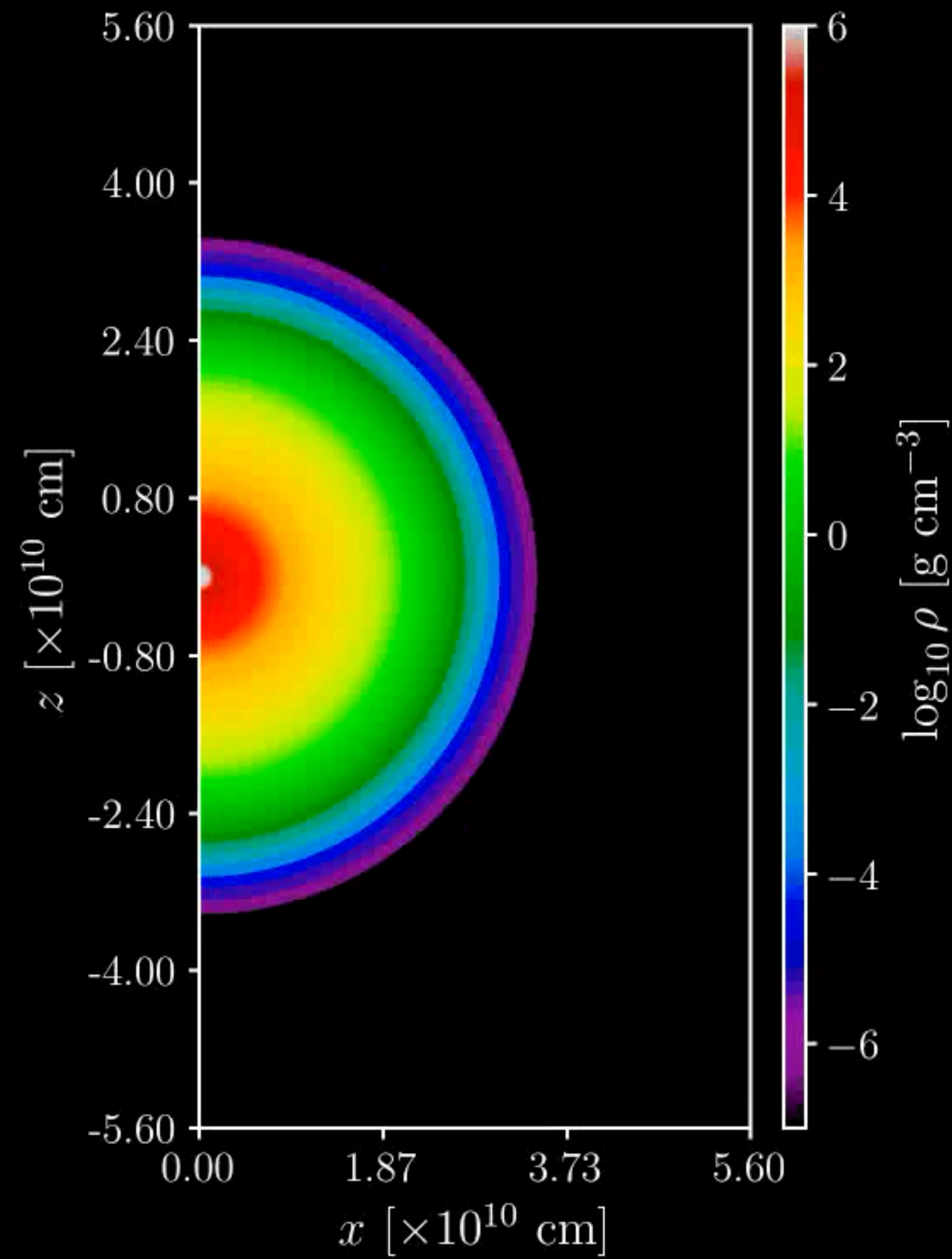
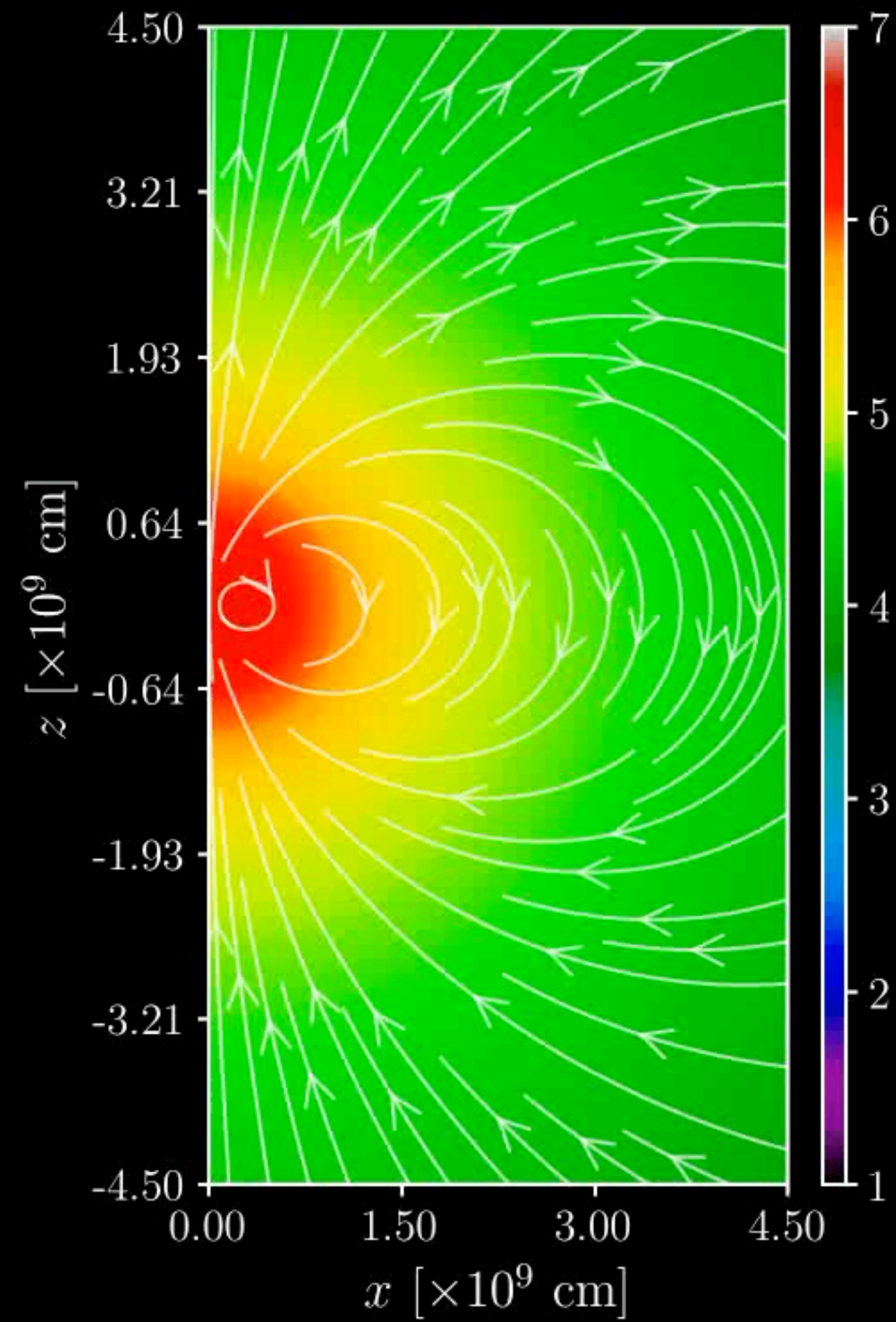
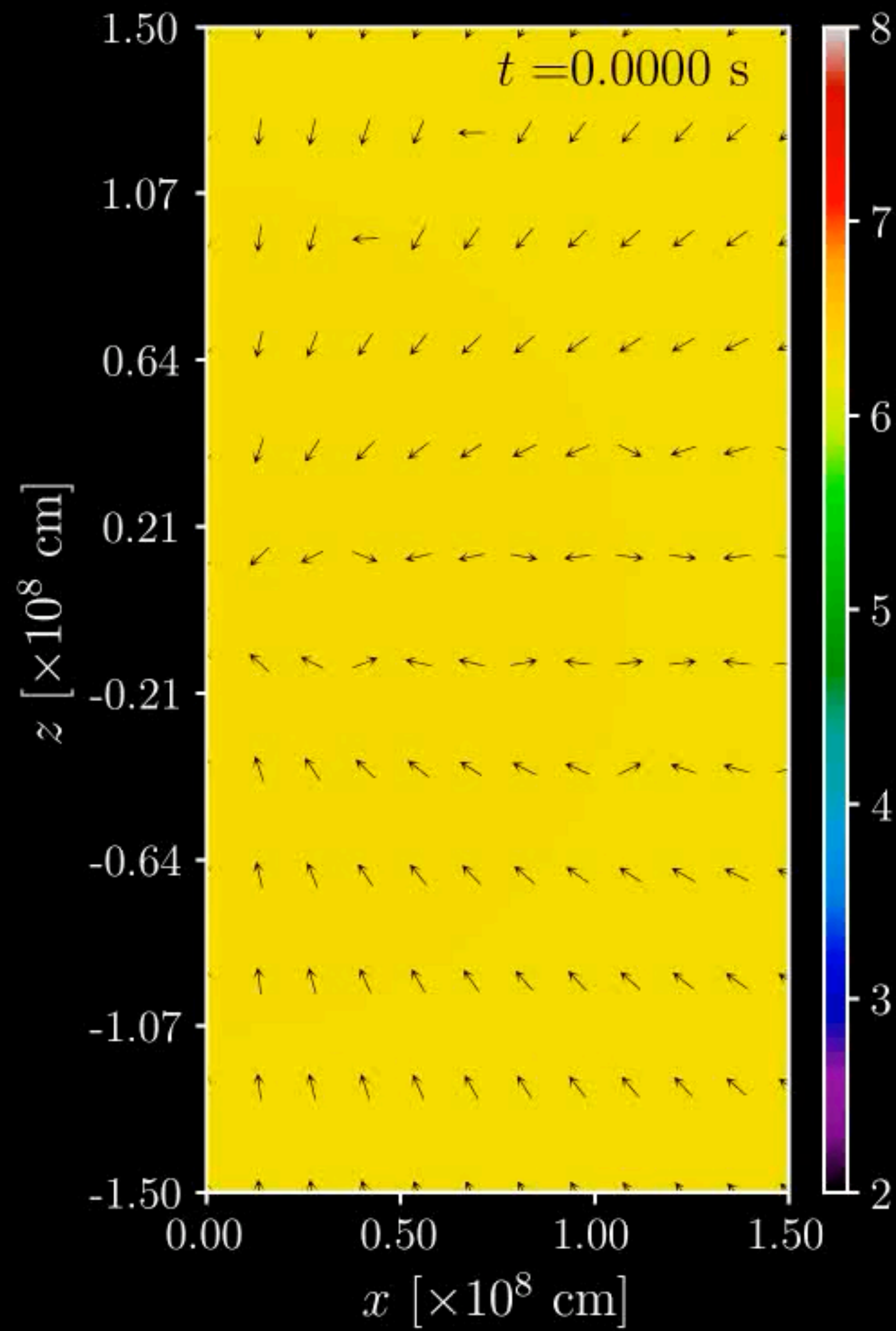
Jet + Supernova crossing a massive star

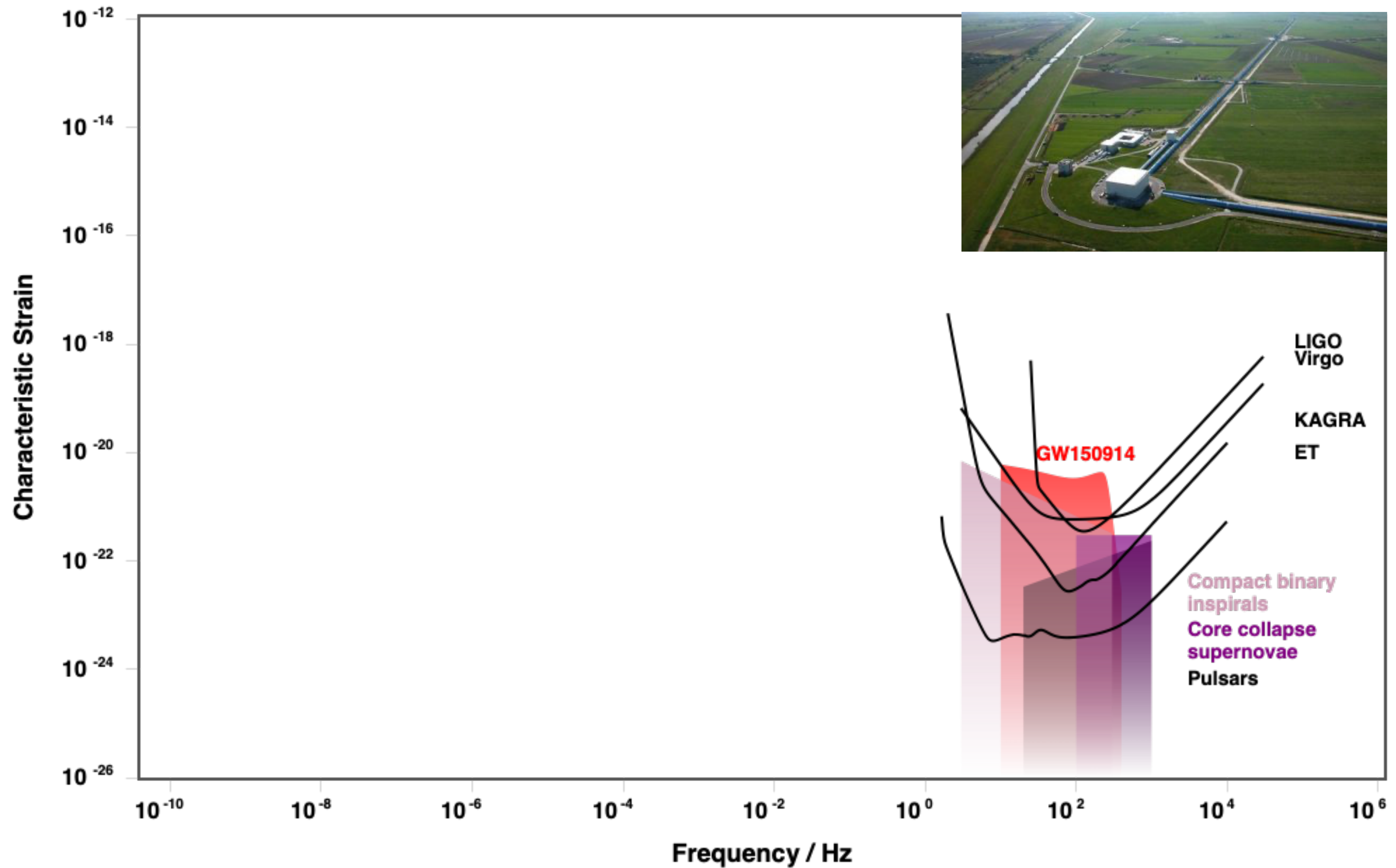
Gaussian jet + Supernova

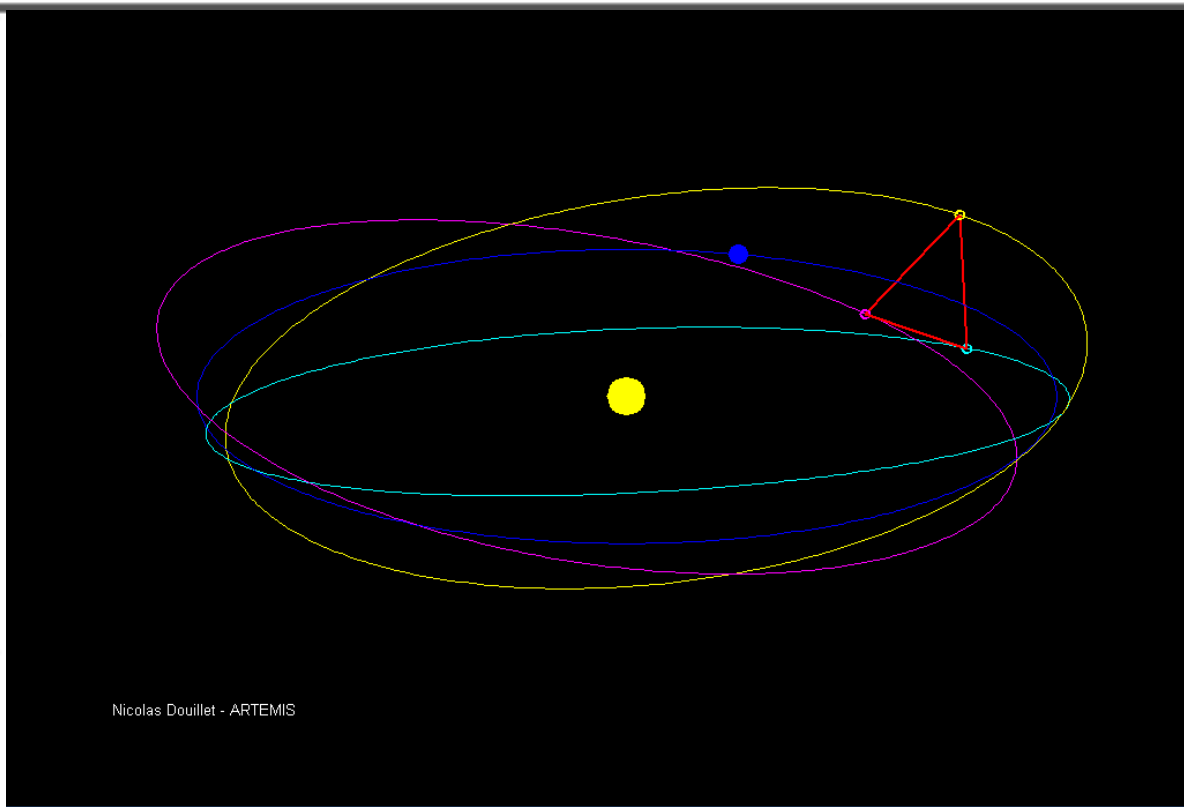
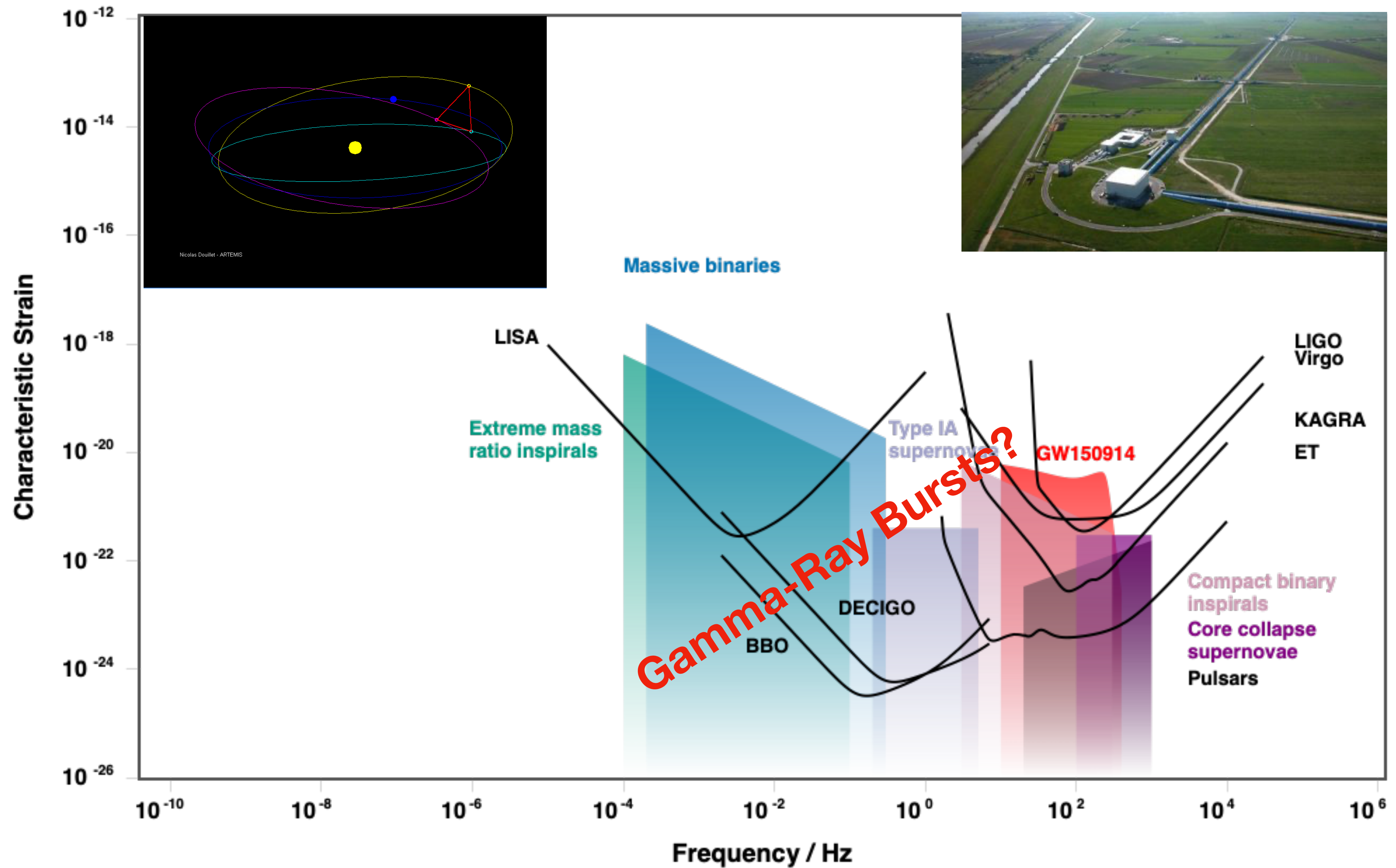


Simulation of a relativistic jet crossing a massive star

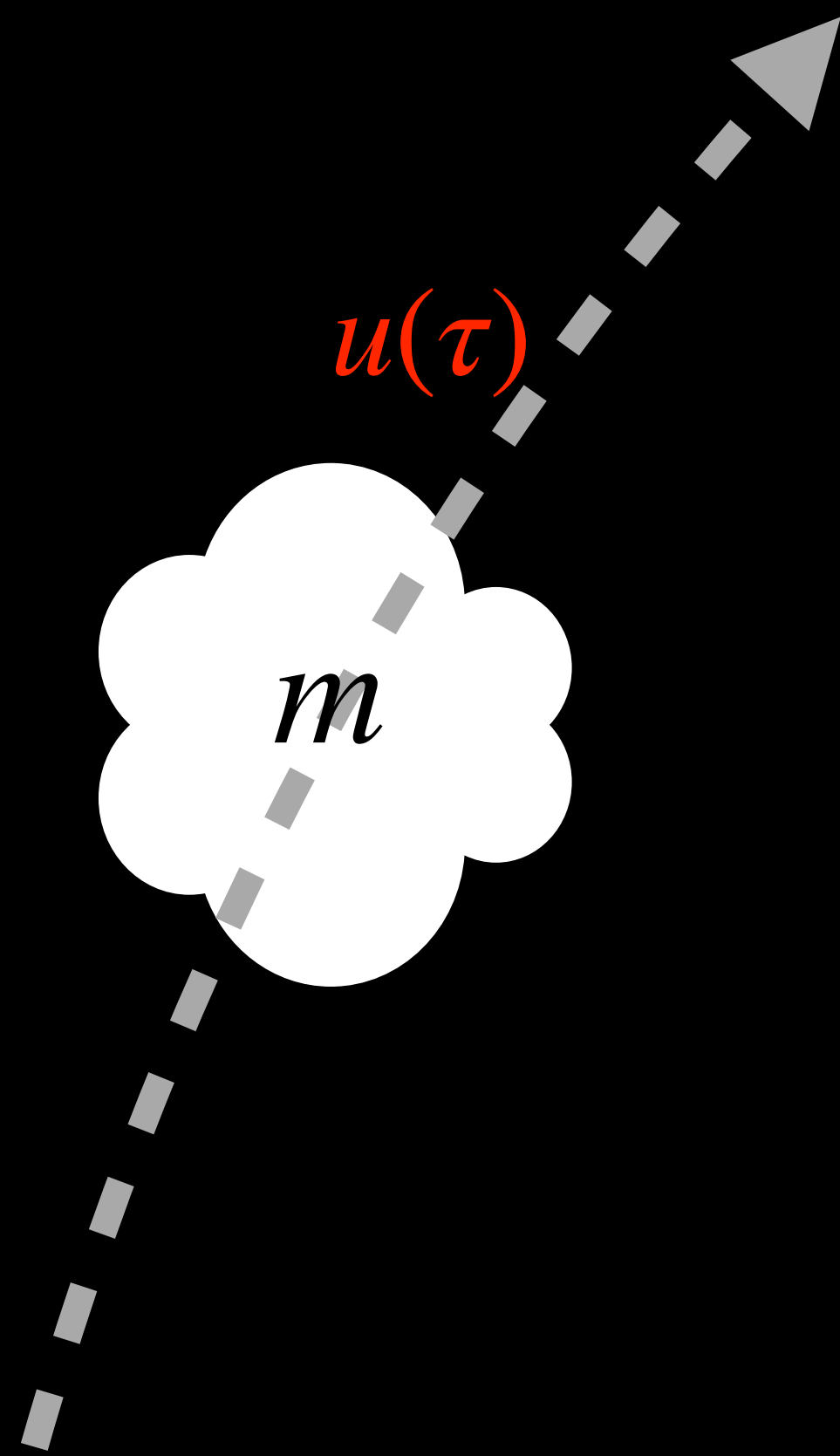








GW from ultra-relativistic sources

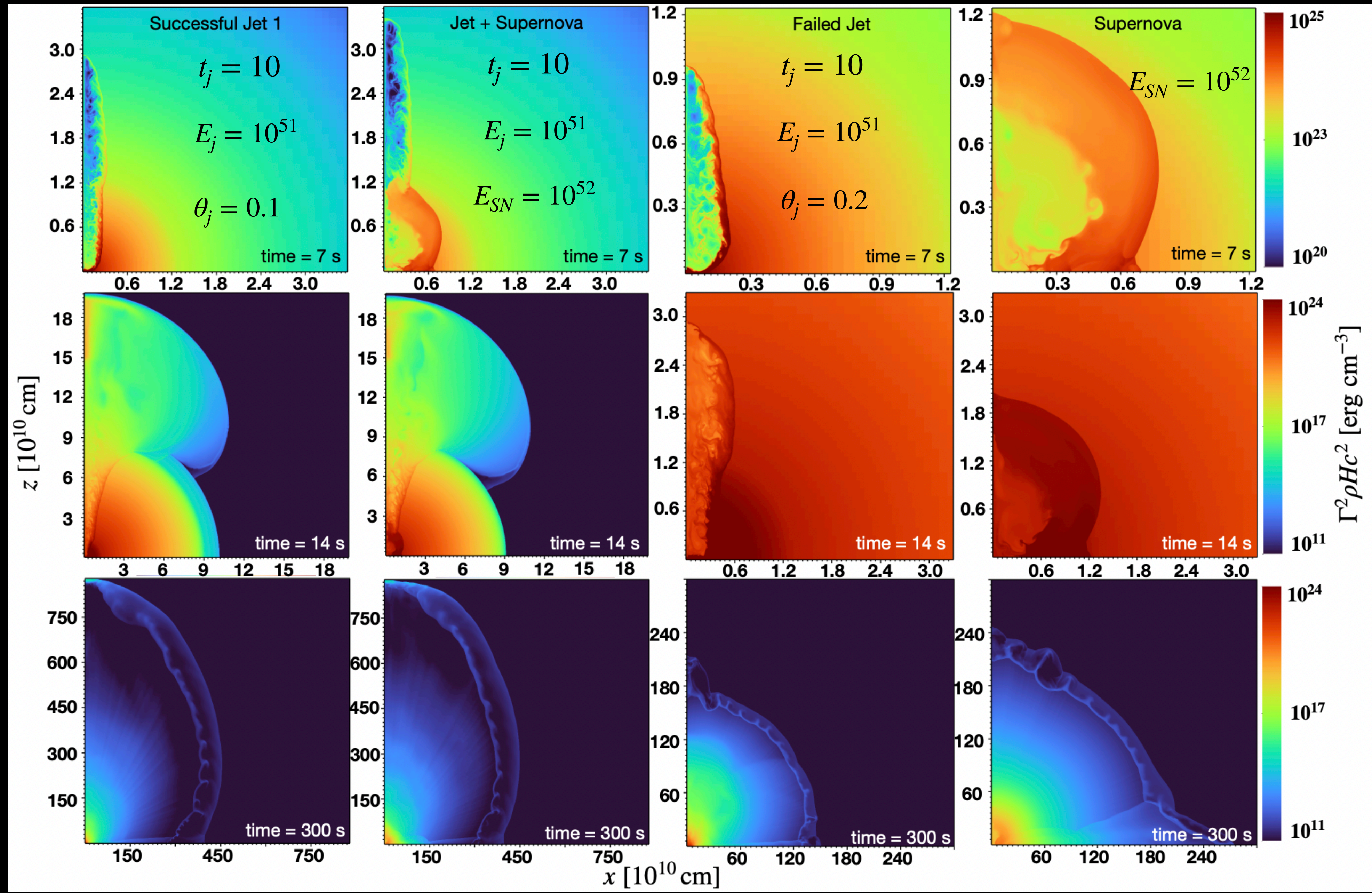


$$T^{\mu\nu} = \int m u^{\mu}(\tau) u^{\nu}(\tau) \delta^{(4)}[x - x(\tau)] d\tau$$

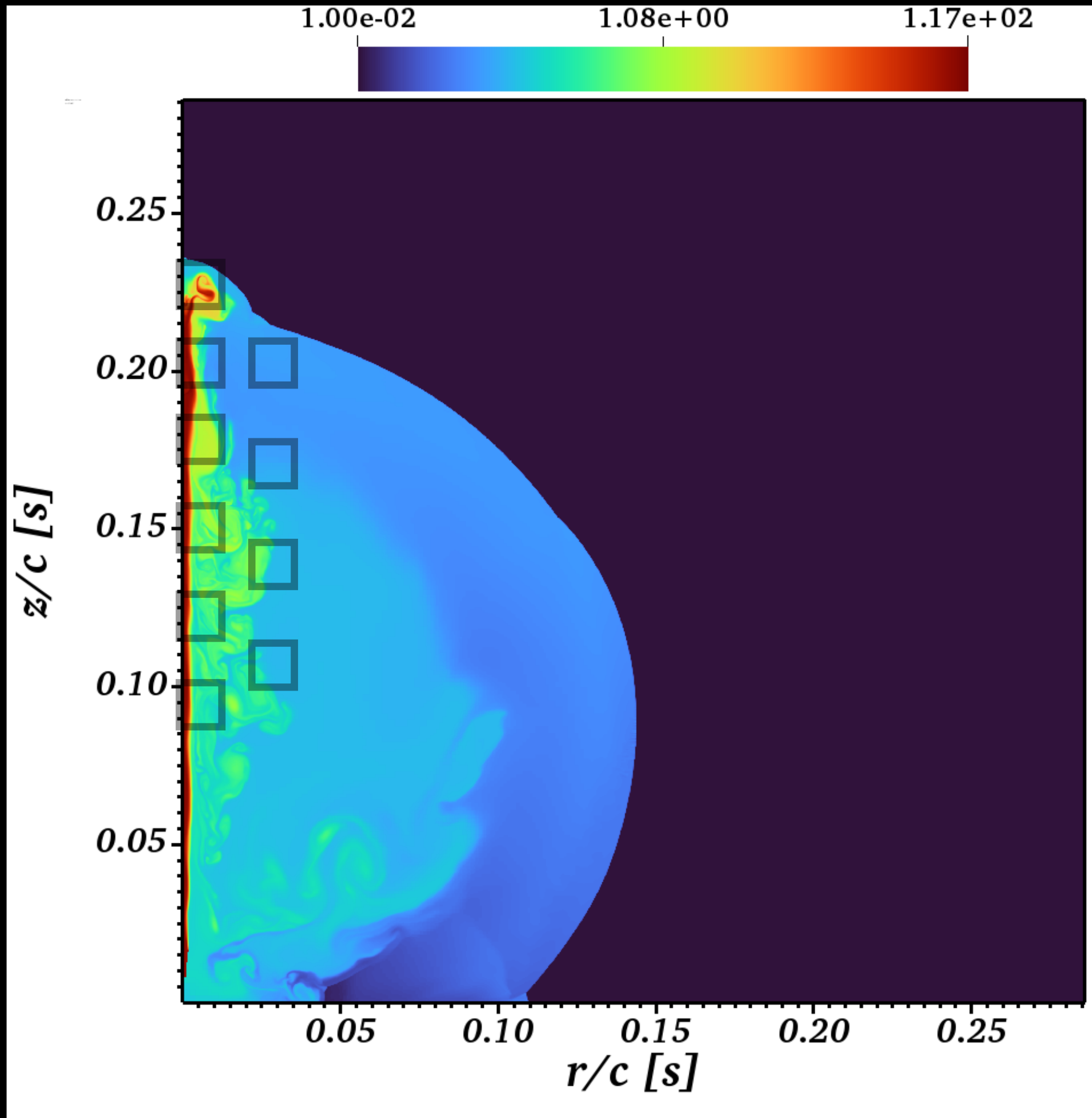
$$\square \bar{h}^{\mu\nu} = -16\pi T^{\mu\nu}$$

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

Jet dynamics



GW from ultra-relativistic sources

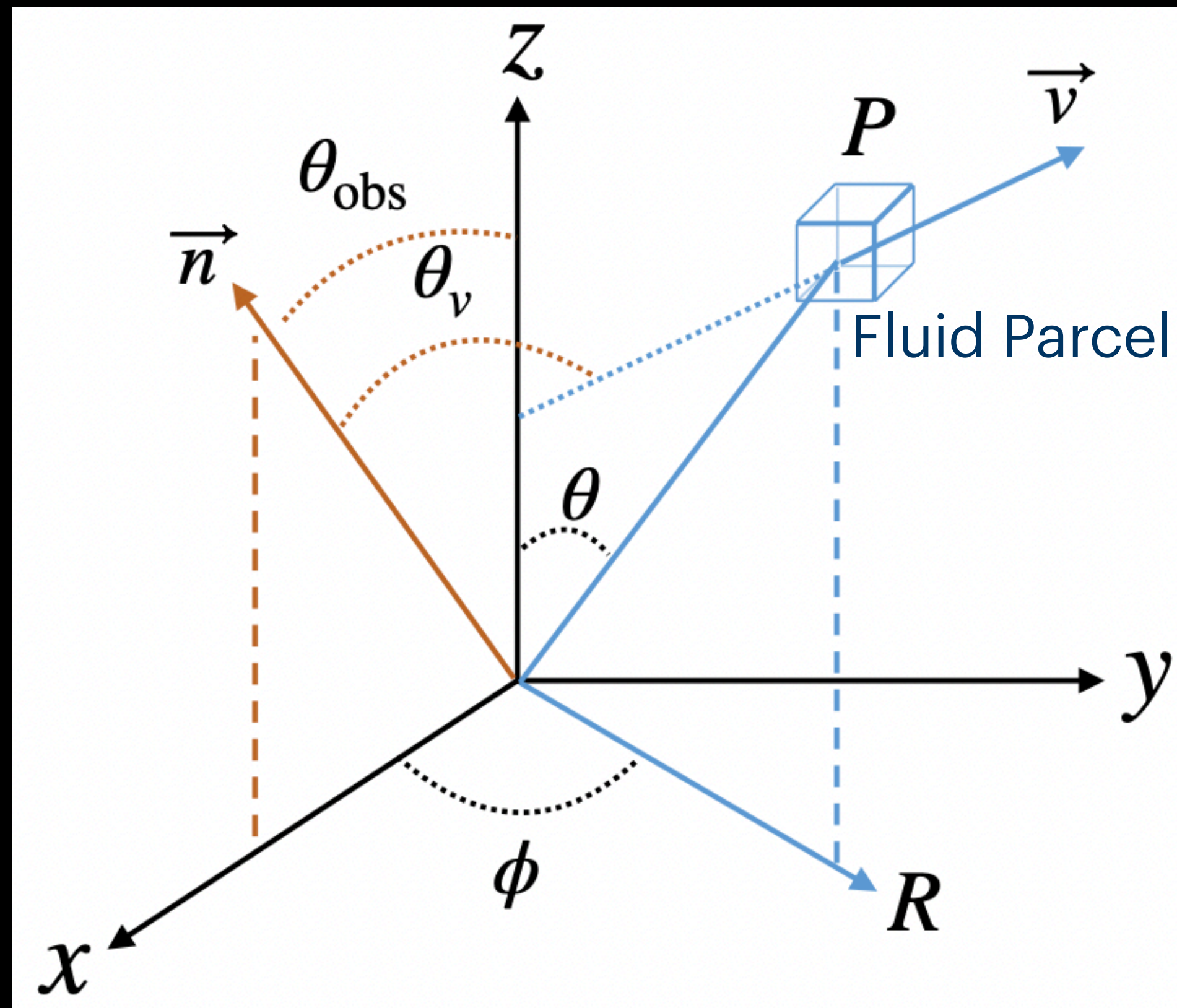


$$T^{\mu\nu} = \int m \, u^{\mu}(\tau) u^{\nu}(\tau) \delta^{(4)}[x - x(\tau)] d\tau$$

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

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

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)

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

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

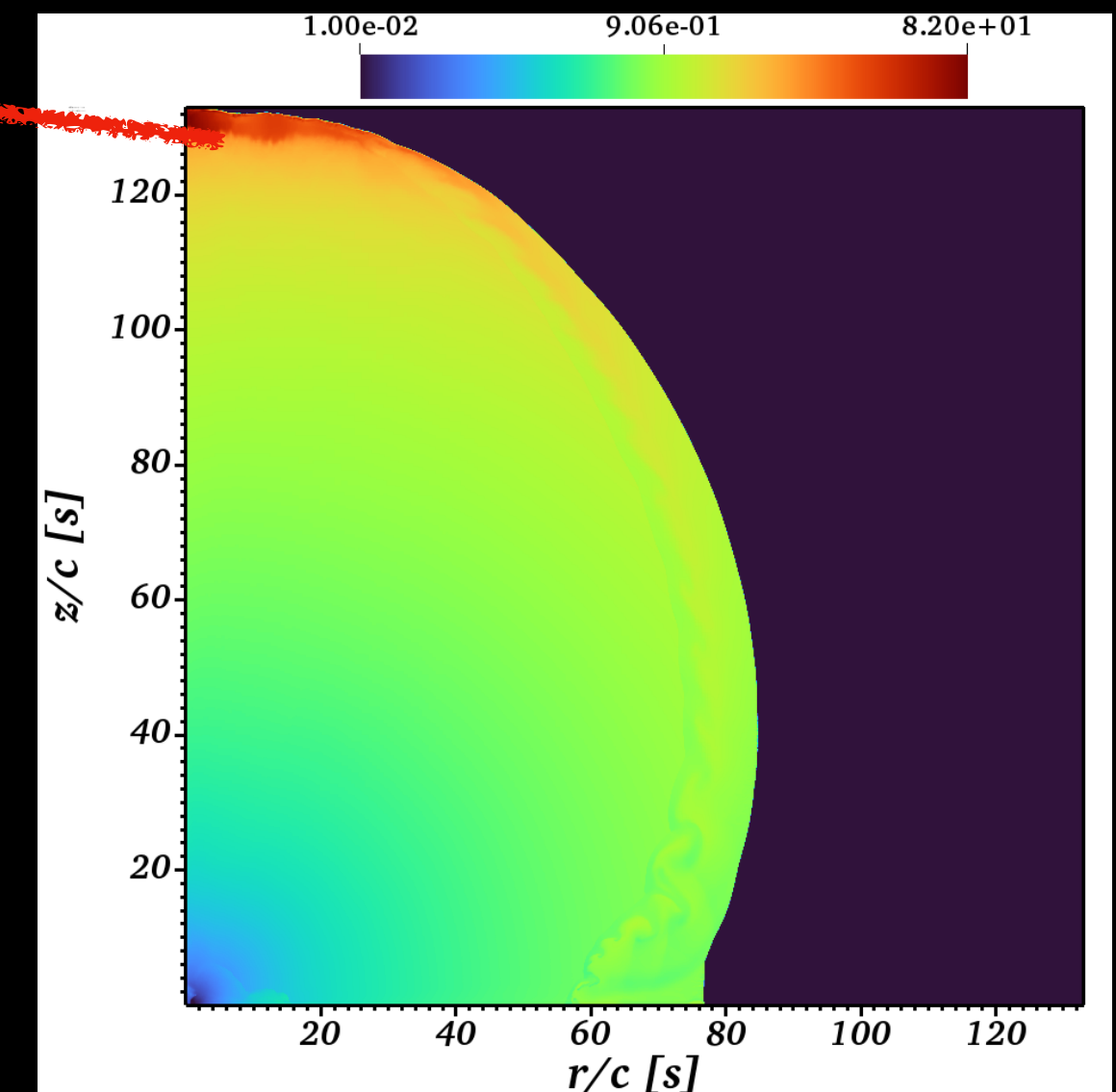
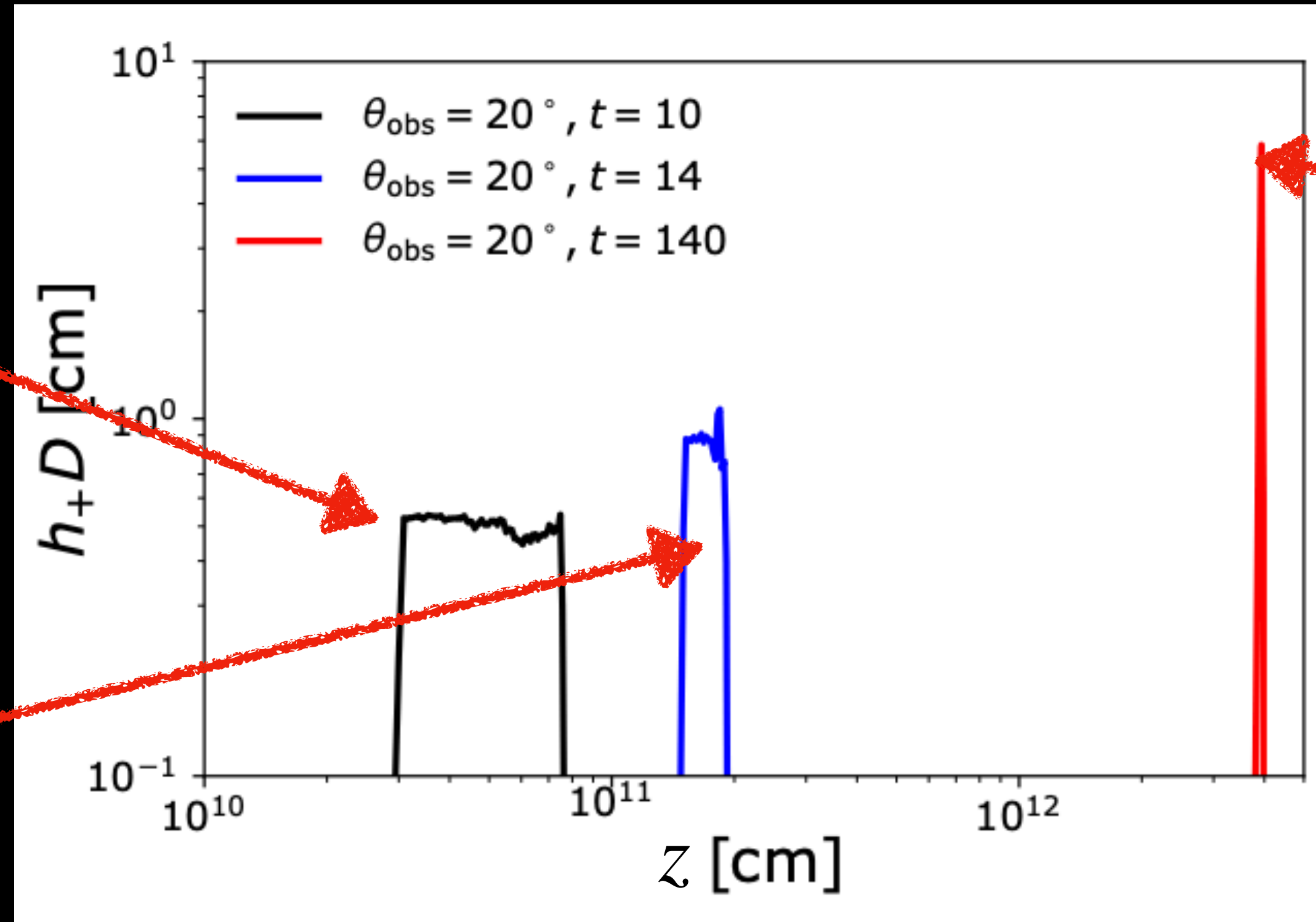
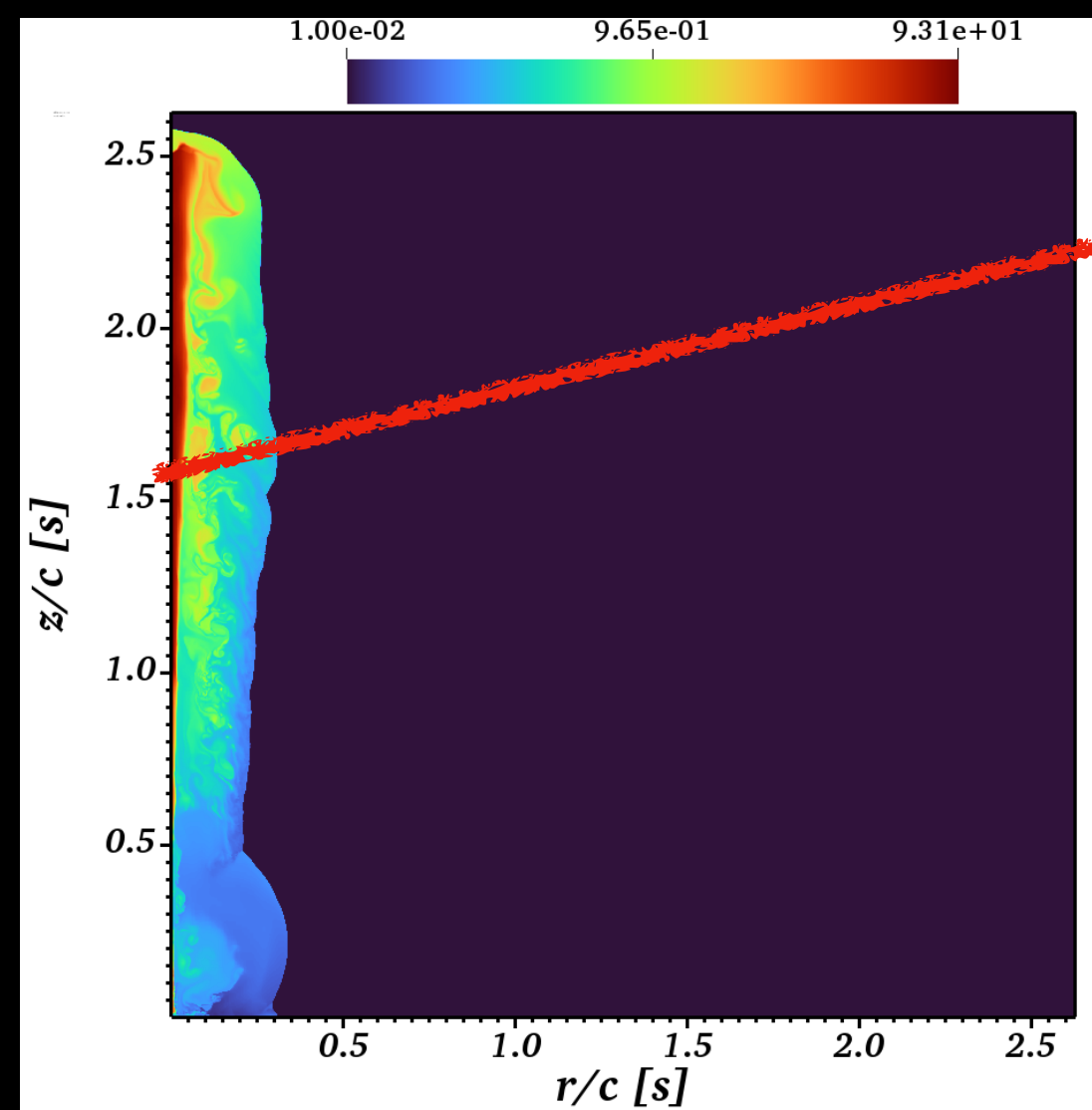
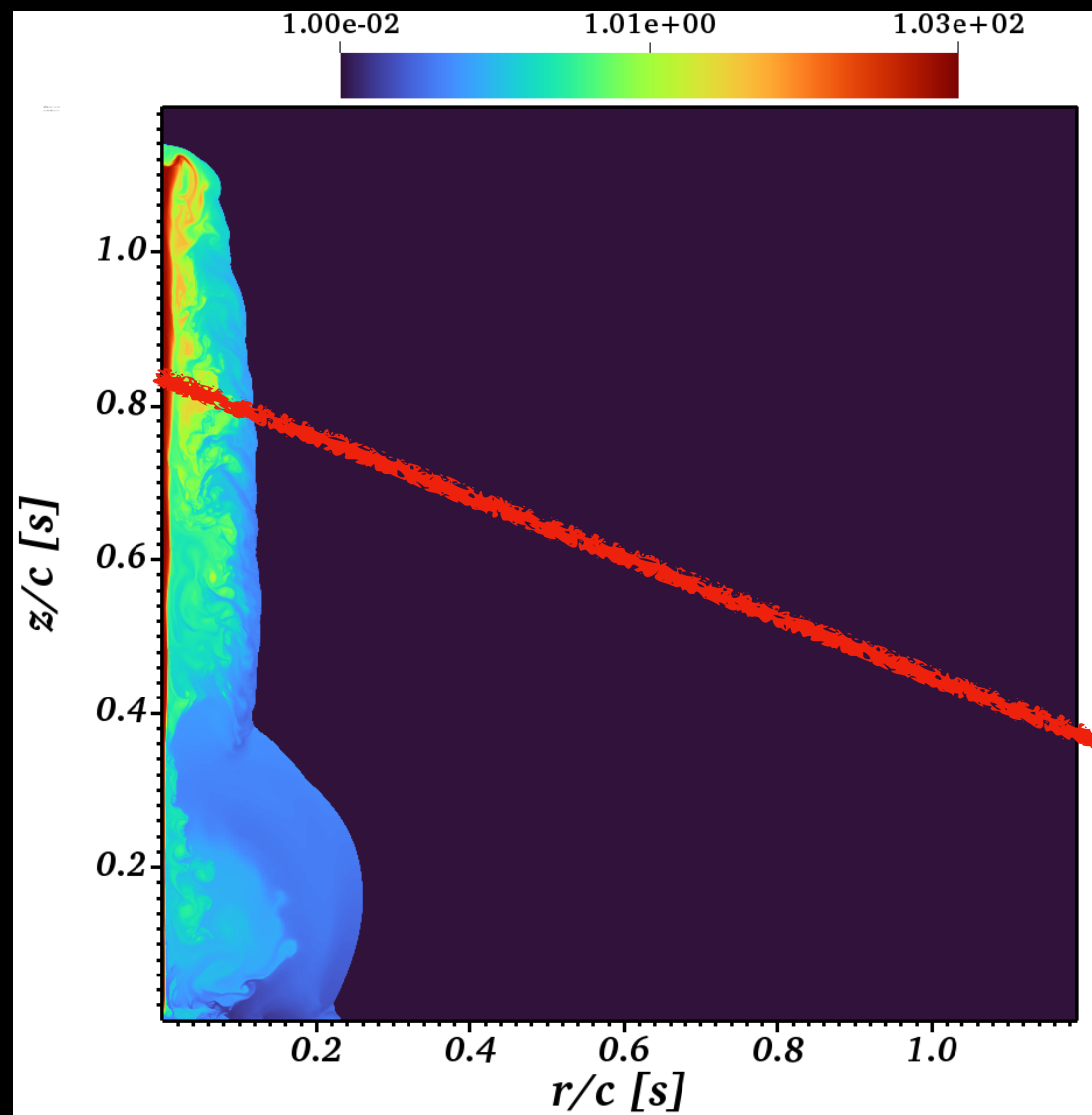
$$\sin \theta \cos \phi = \sin \Theta \cos \Phi \cos \theta_{\text{obs}} + \cos \Theta \sin \theta_{\text{obs}},$$

which lead to

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

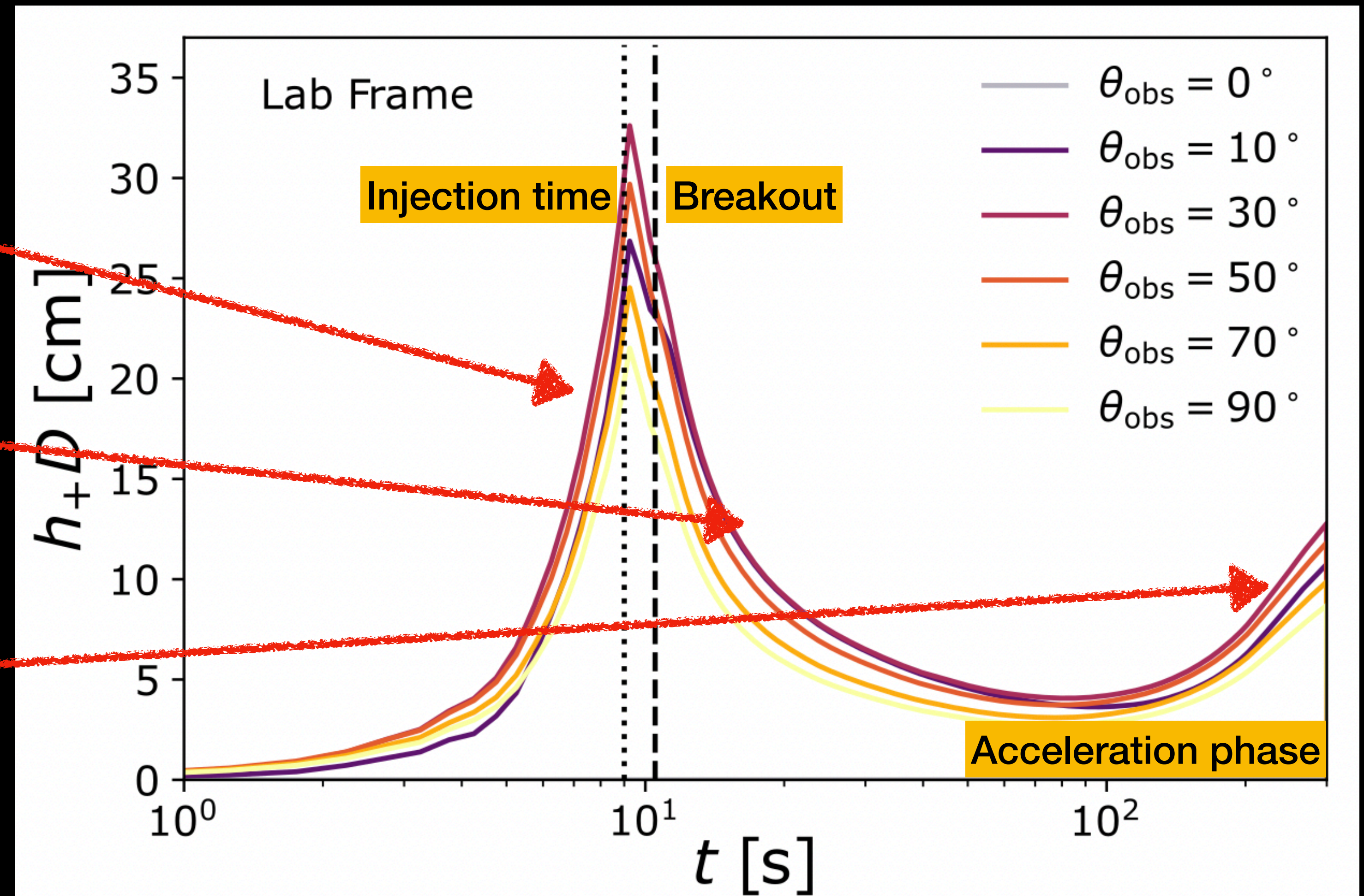
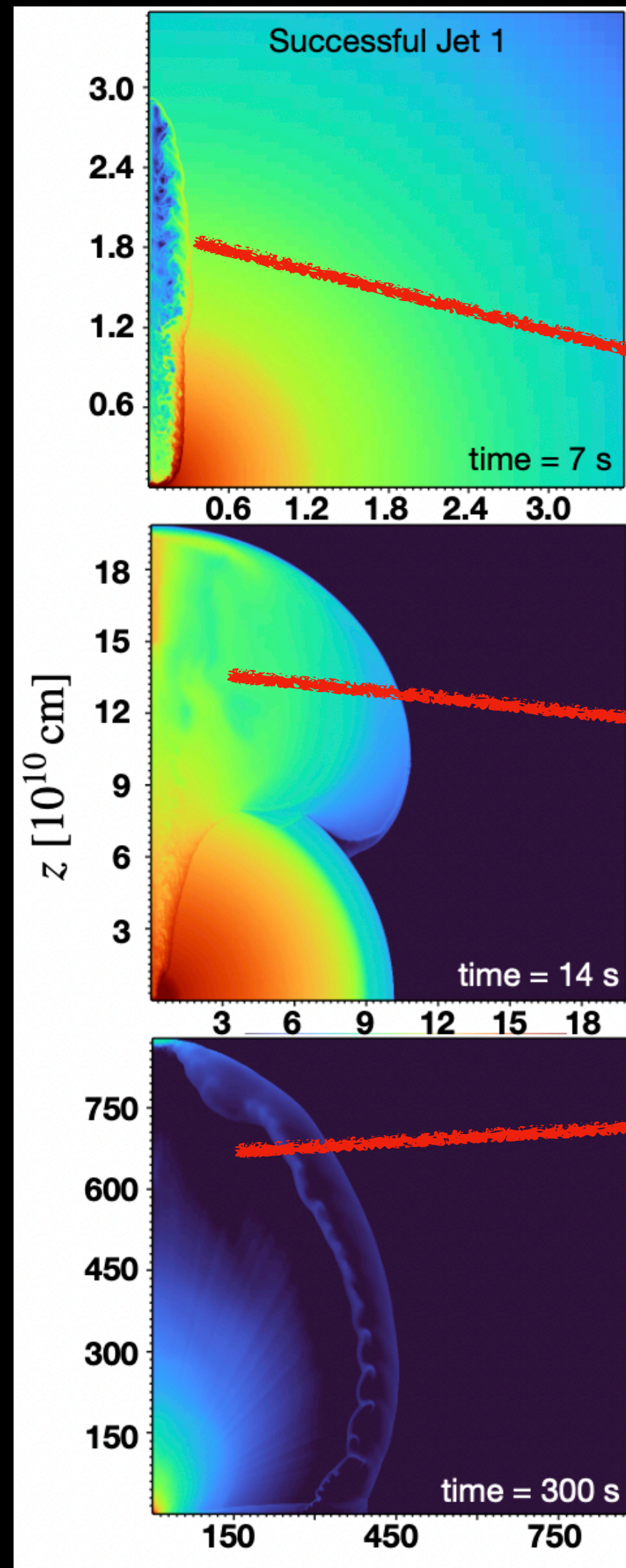
$$\cos(2\Phi) = \frac{(\sin \theta \cos \phi \cos \theta_{\text{obs}} - \cos \theta \sin \theta_{\text{obs}})^2 - \sin^2 \theta \sin^2 \phi}{\sin^2 \Theta}$$

Where is the GW emission produced?

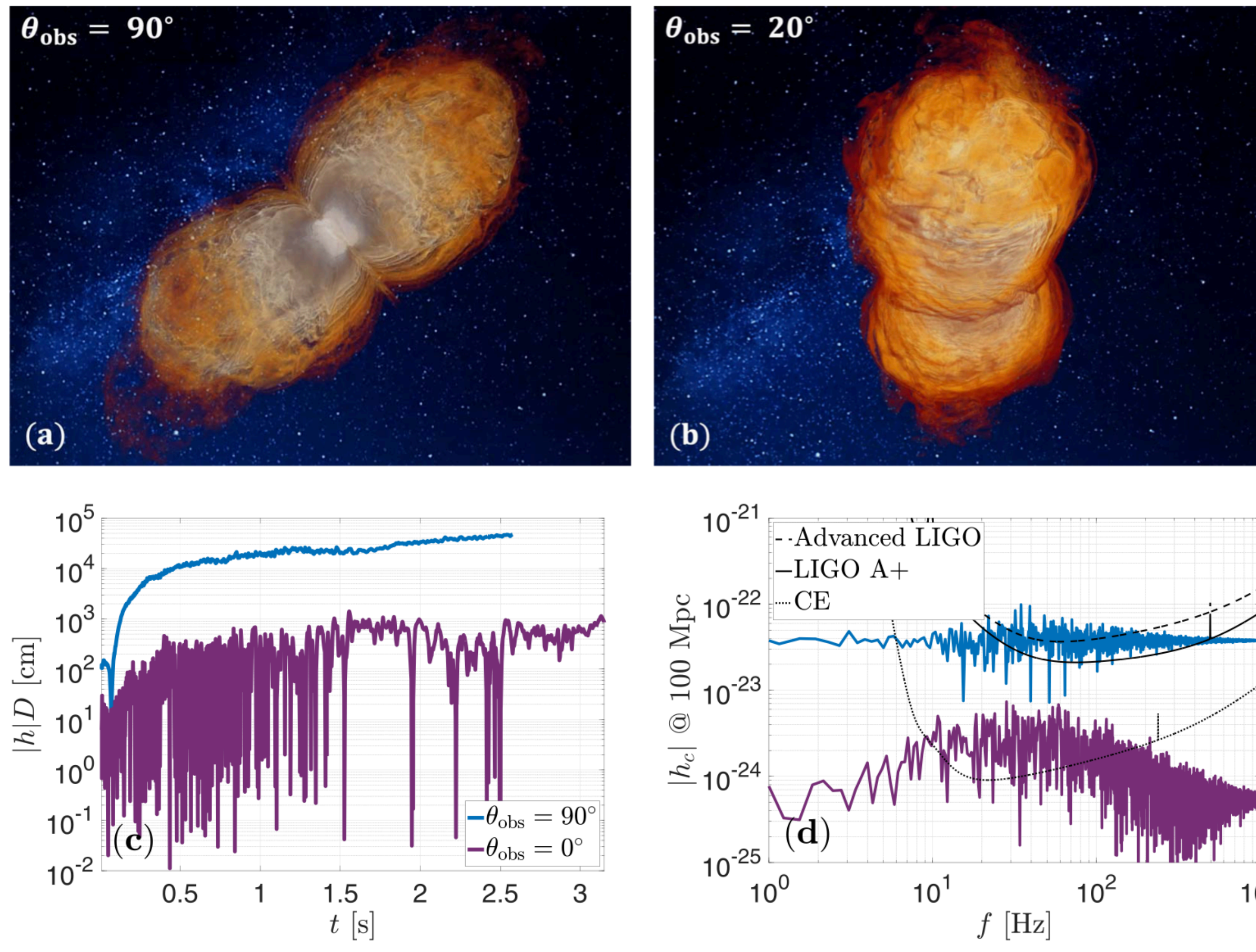


Successful jet - GW signal

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



High frequency?



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

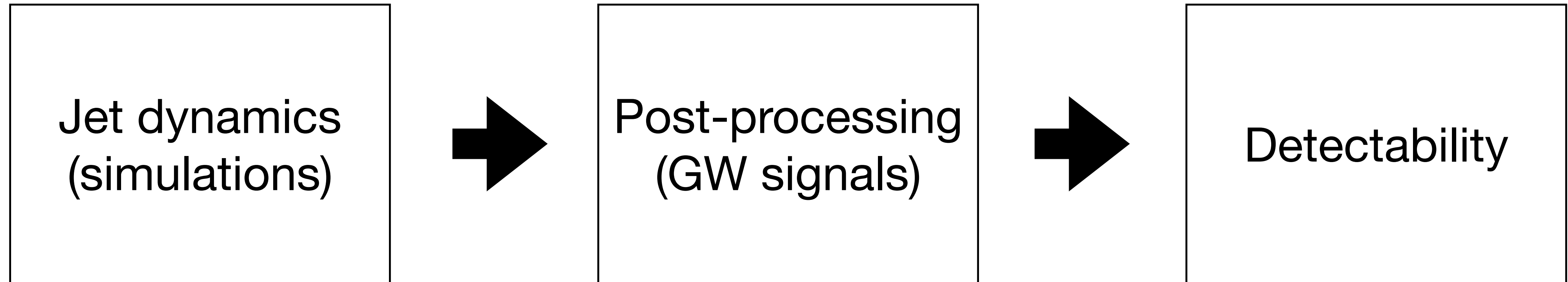
$$E_{\text{cocoon}} = 10^{52} - 10^{53} \text{ erg}$$

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

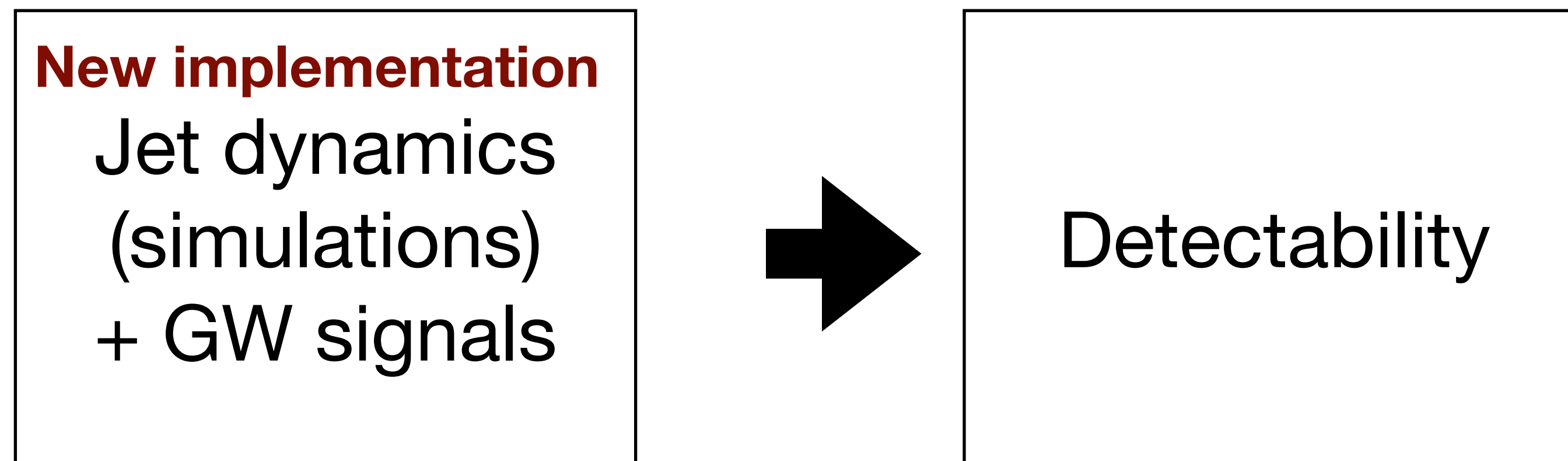
Storage ~ Petabytes

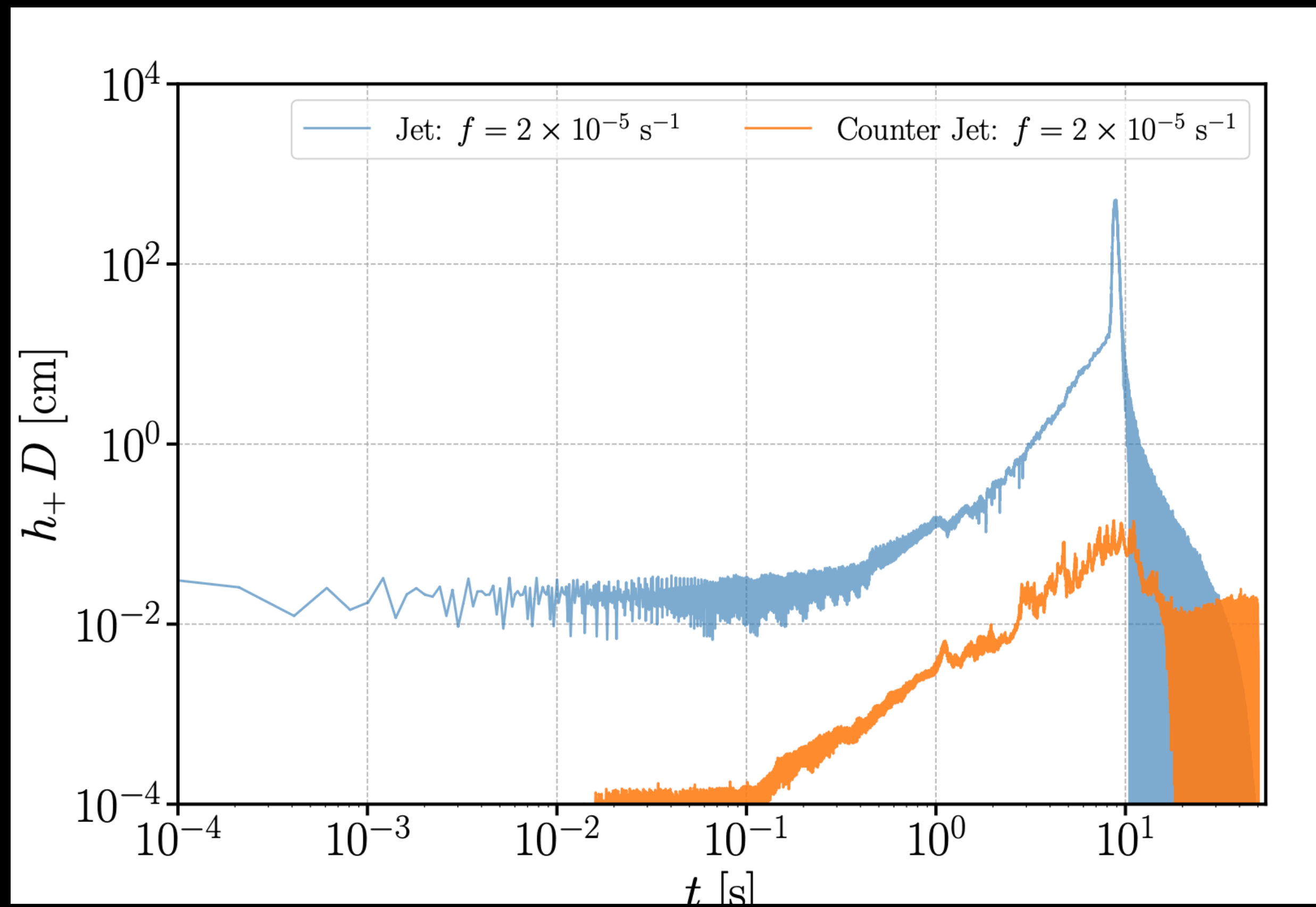
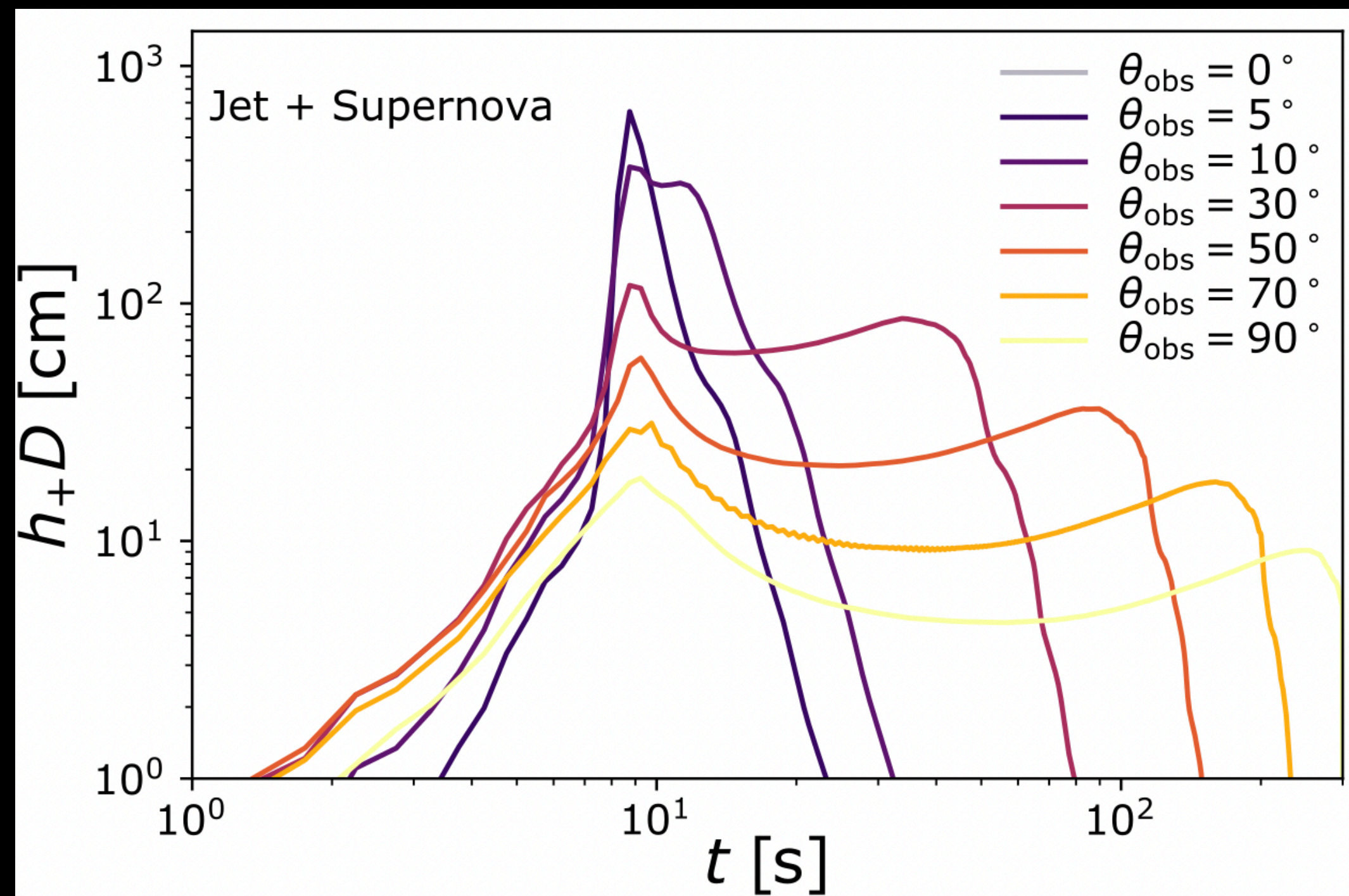
Gottlieb et al. 2023

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

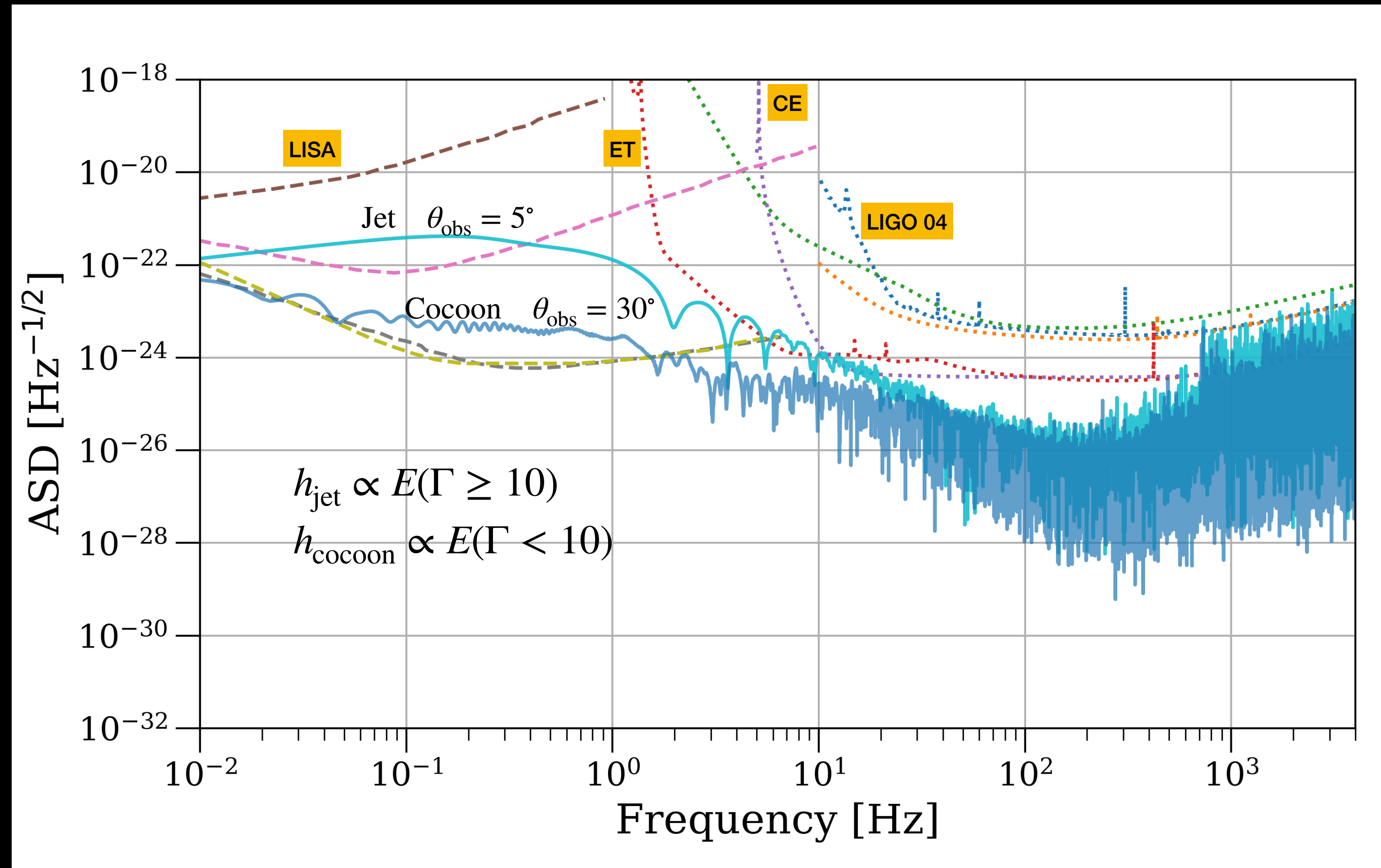
$$ASD = 2f^{1/2} |\tilde{h}(f)|$$

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

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

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

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



Urrutia (in Prep)

Conclusions

- Numerical simulations are our virtual laboratories to solve extreme phenomena.
- The computational time increases, due to the spacial scales and physical process involved.
- We can extract information about electromagnetic and gravitational radiation.
- Several techniques are applied on this research field.

<https://ra.cft.edu.pl/>

Dziękuję bardzo - ¡Gracias! - Thank you!

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