Gravitational wave signals from Long Gamma Ray Bursts jets

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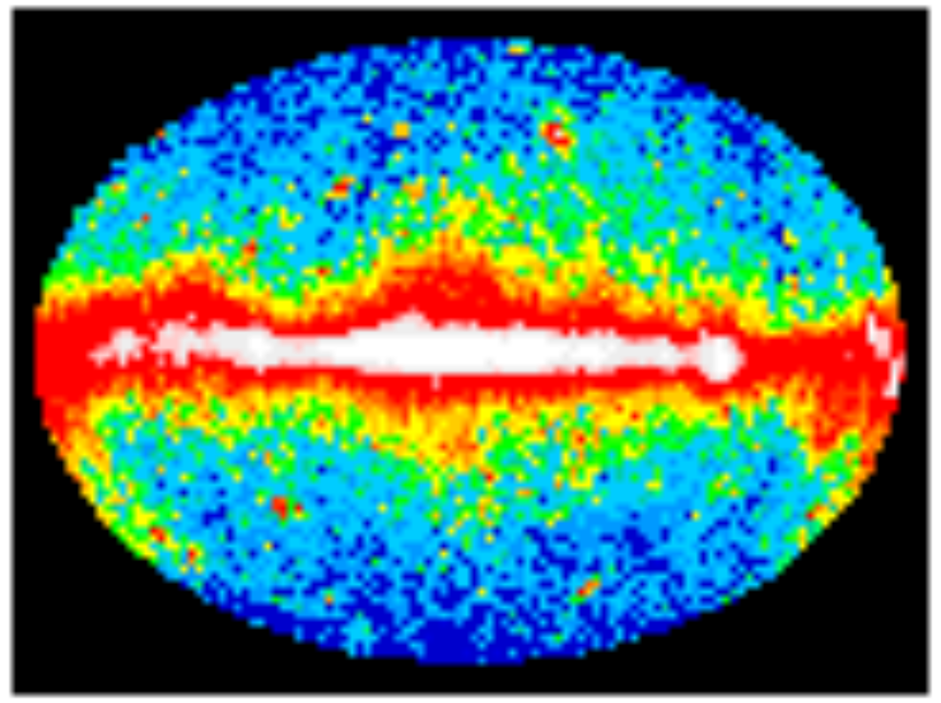
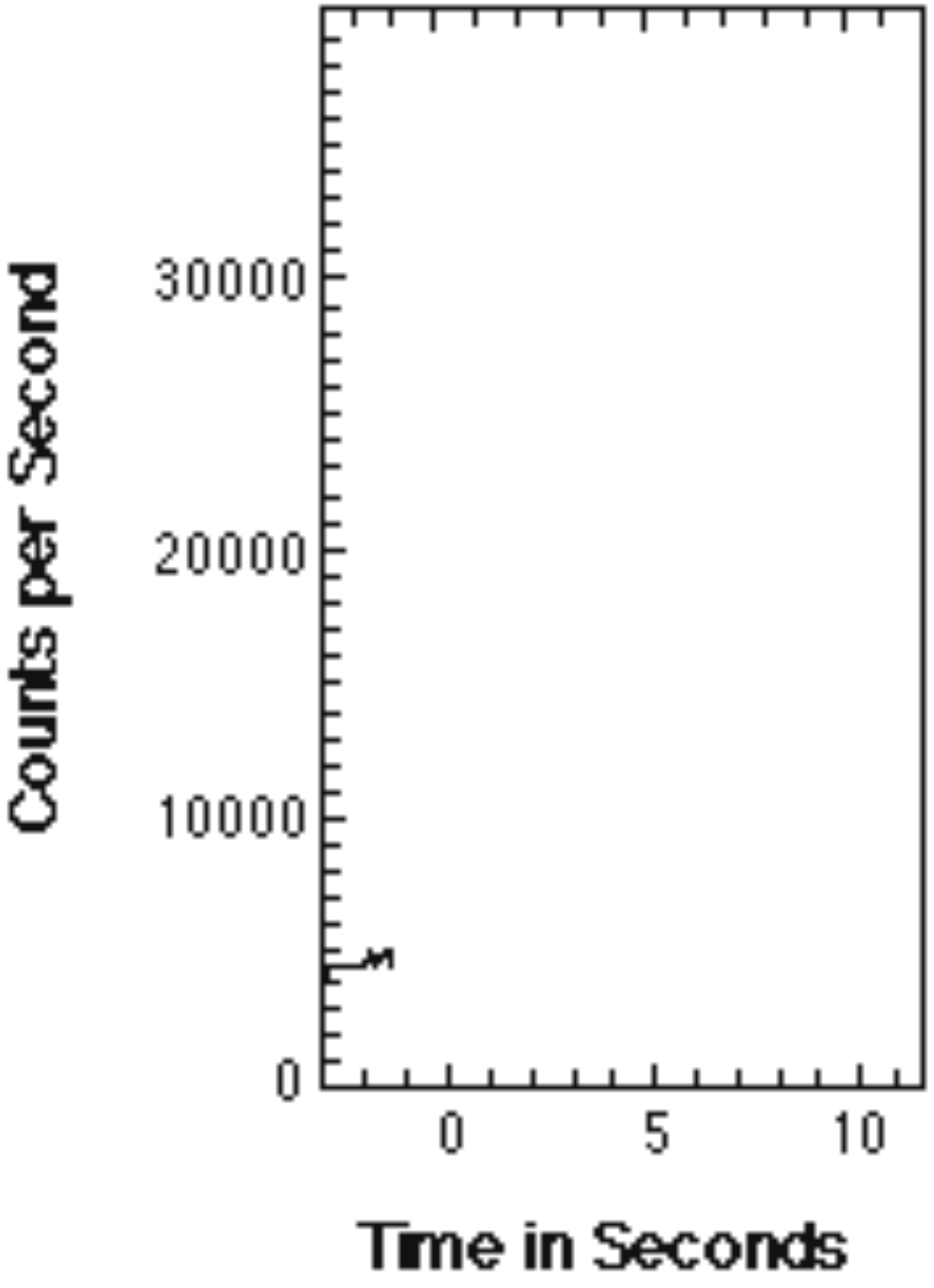
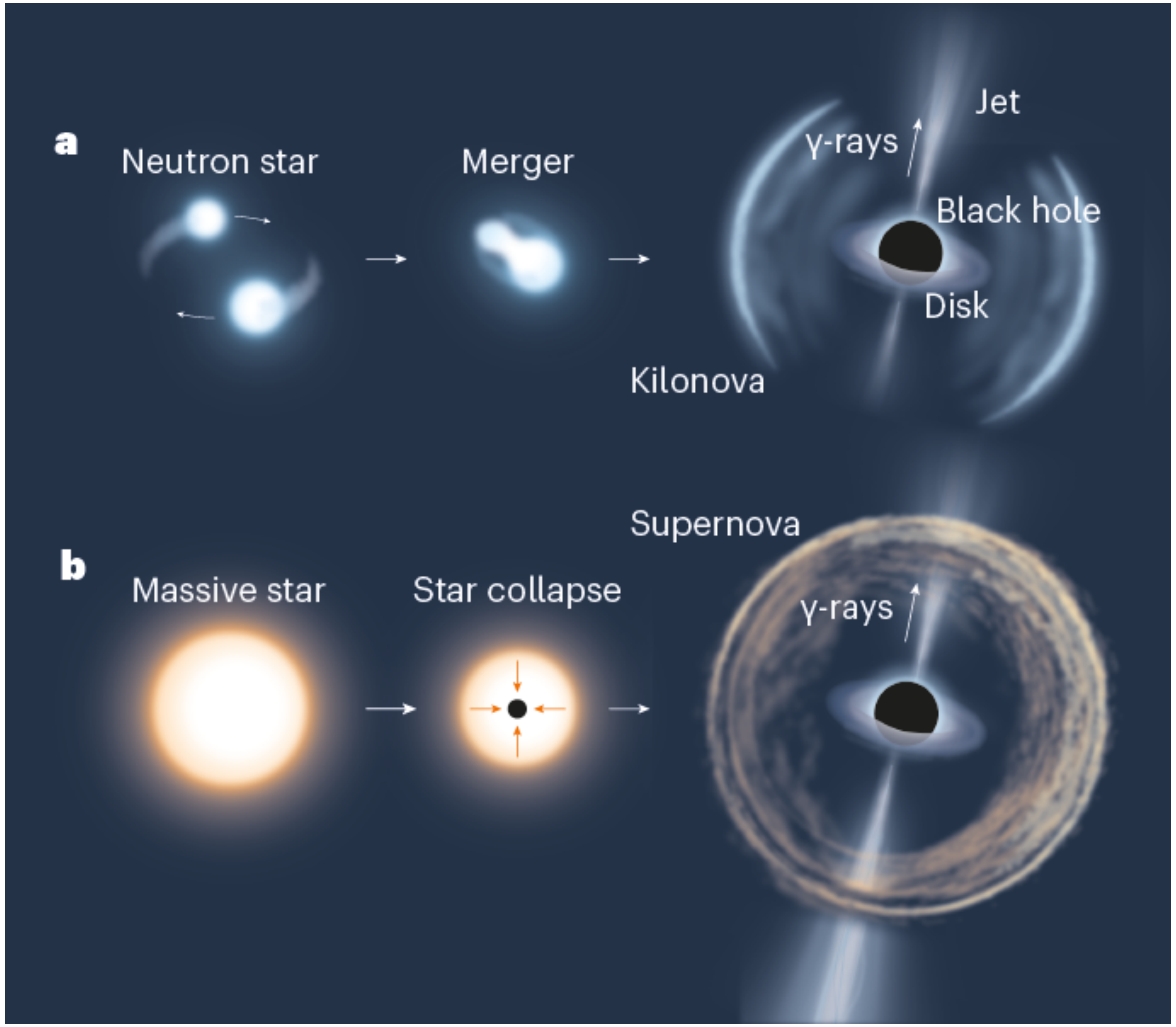
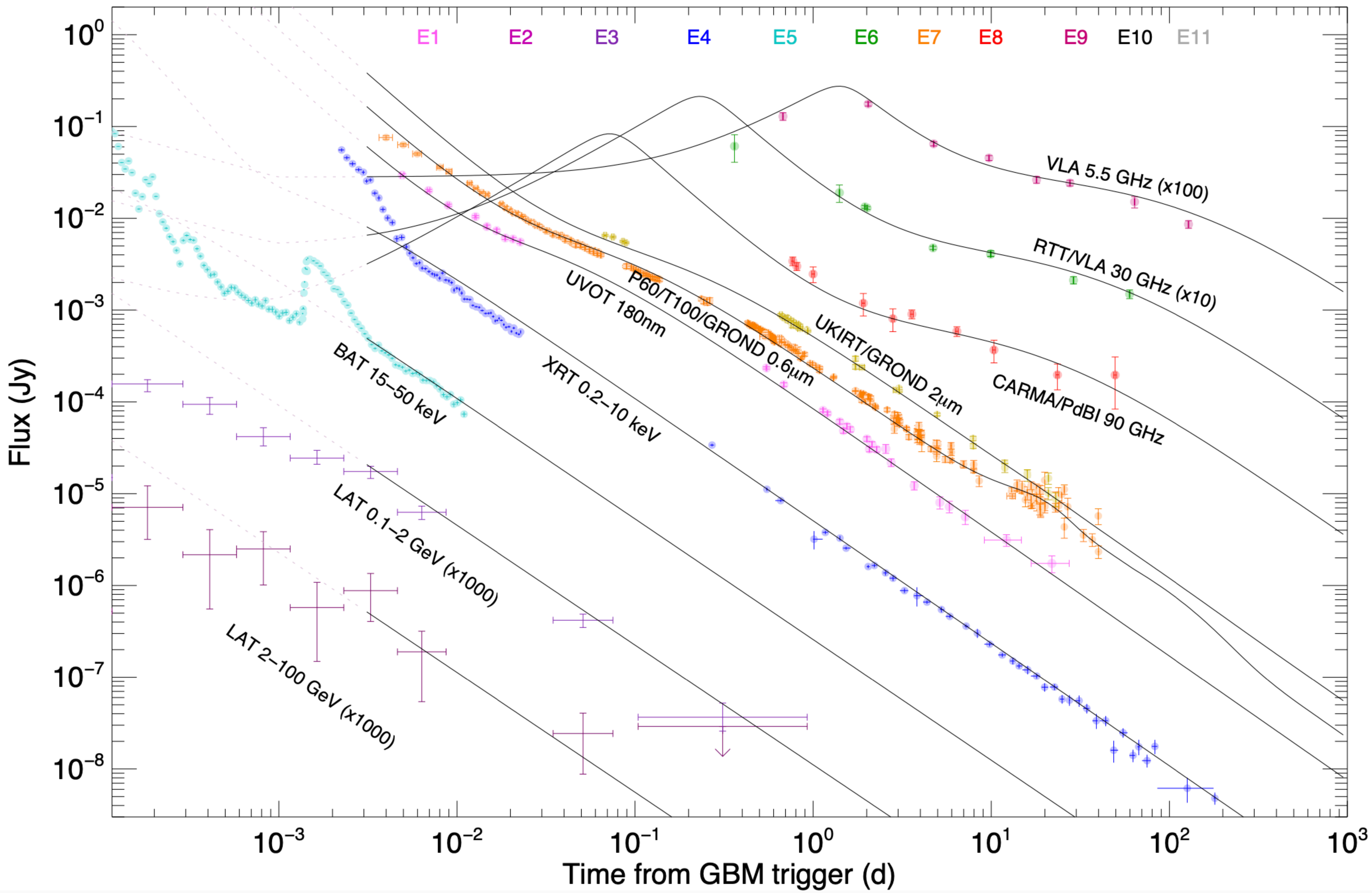
Prompt emission and Progenitors



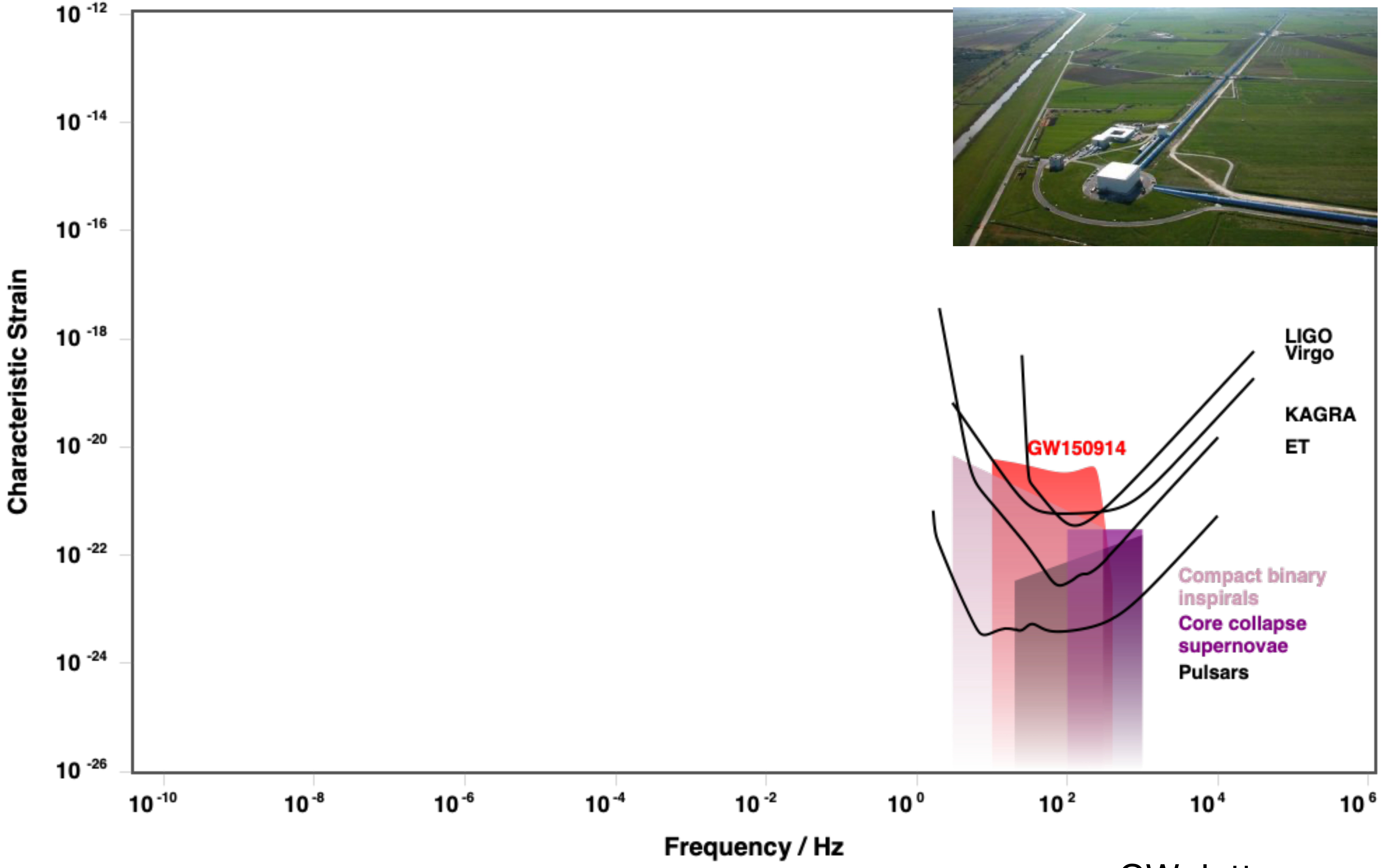




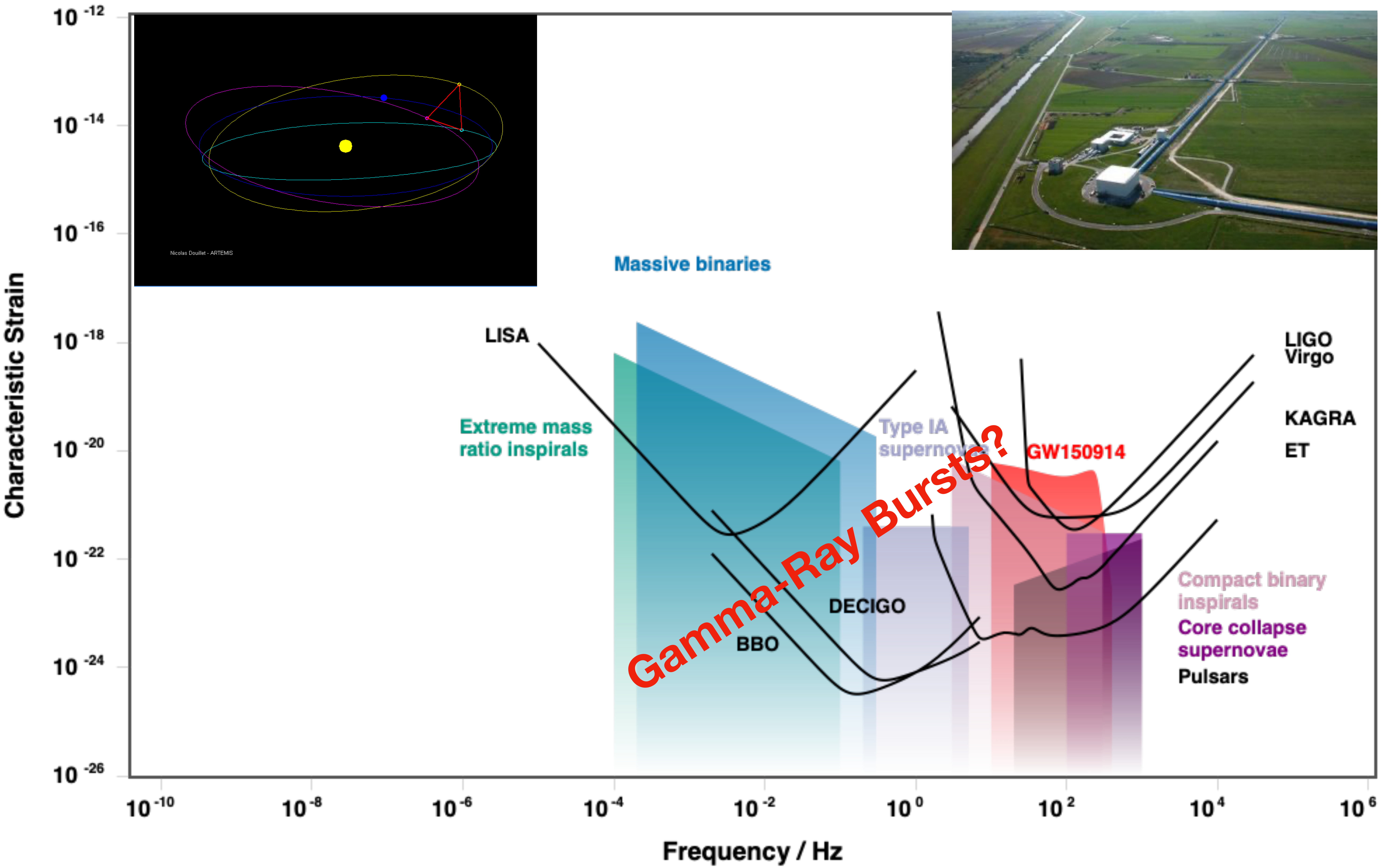
Gamma-Ray Bursts (afterglow emission)



GRB 130427, Perley et al. 2013



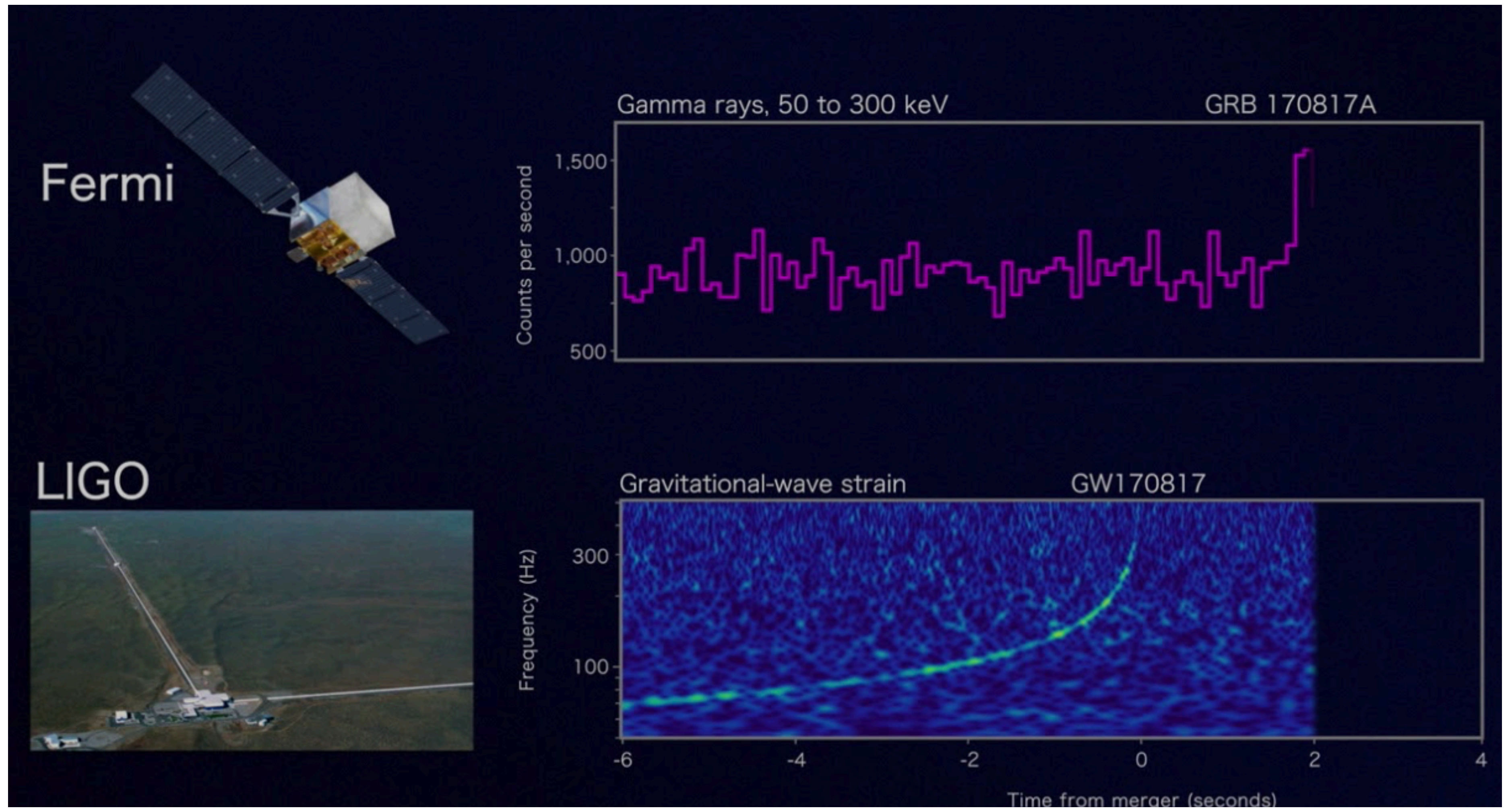
GWplotter.com

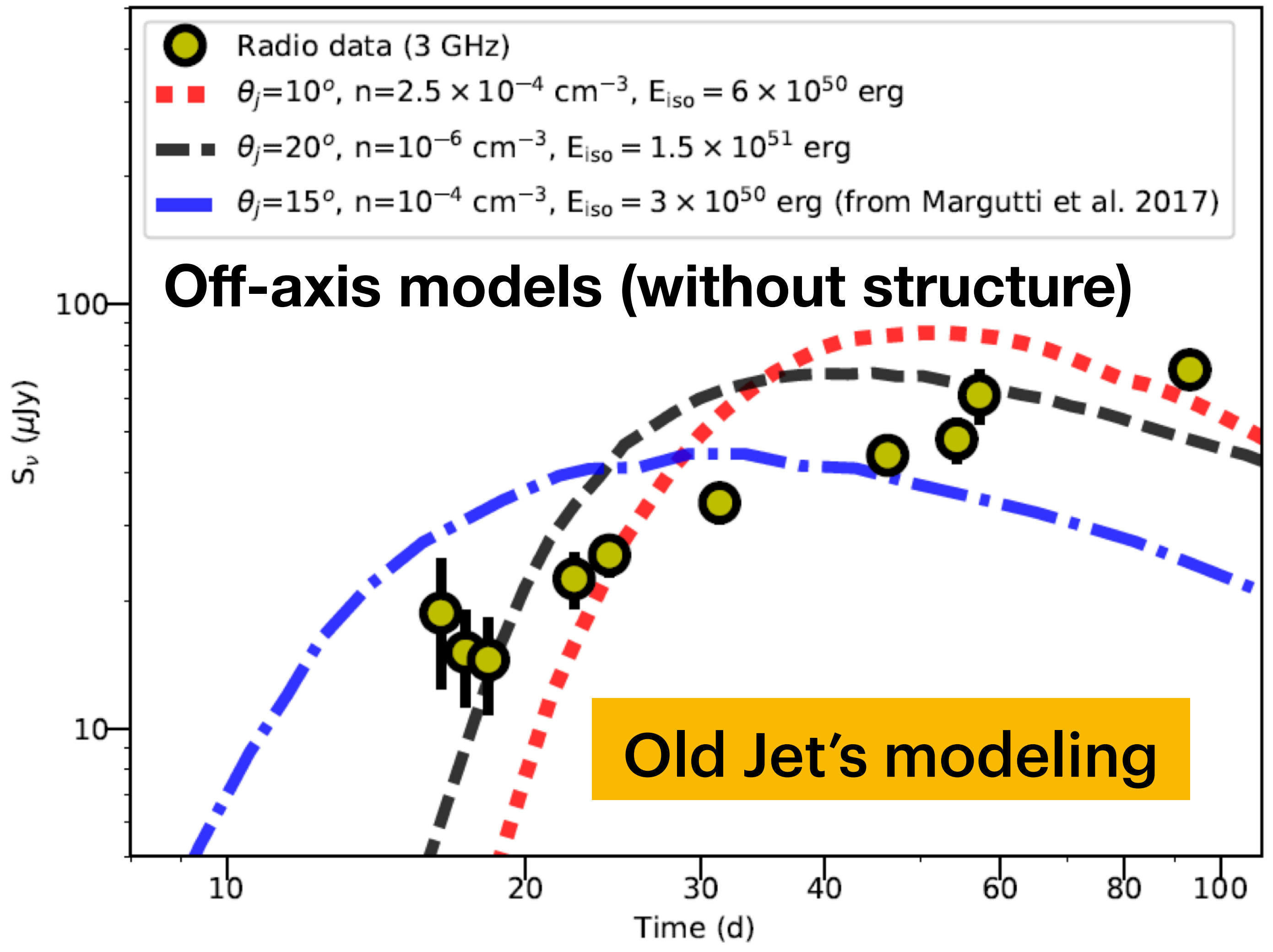


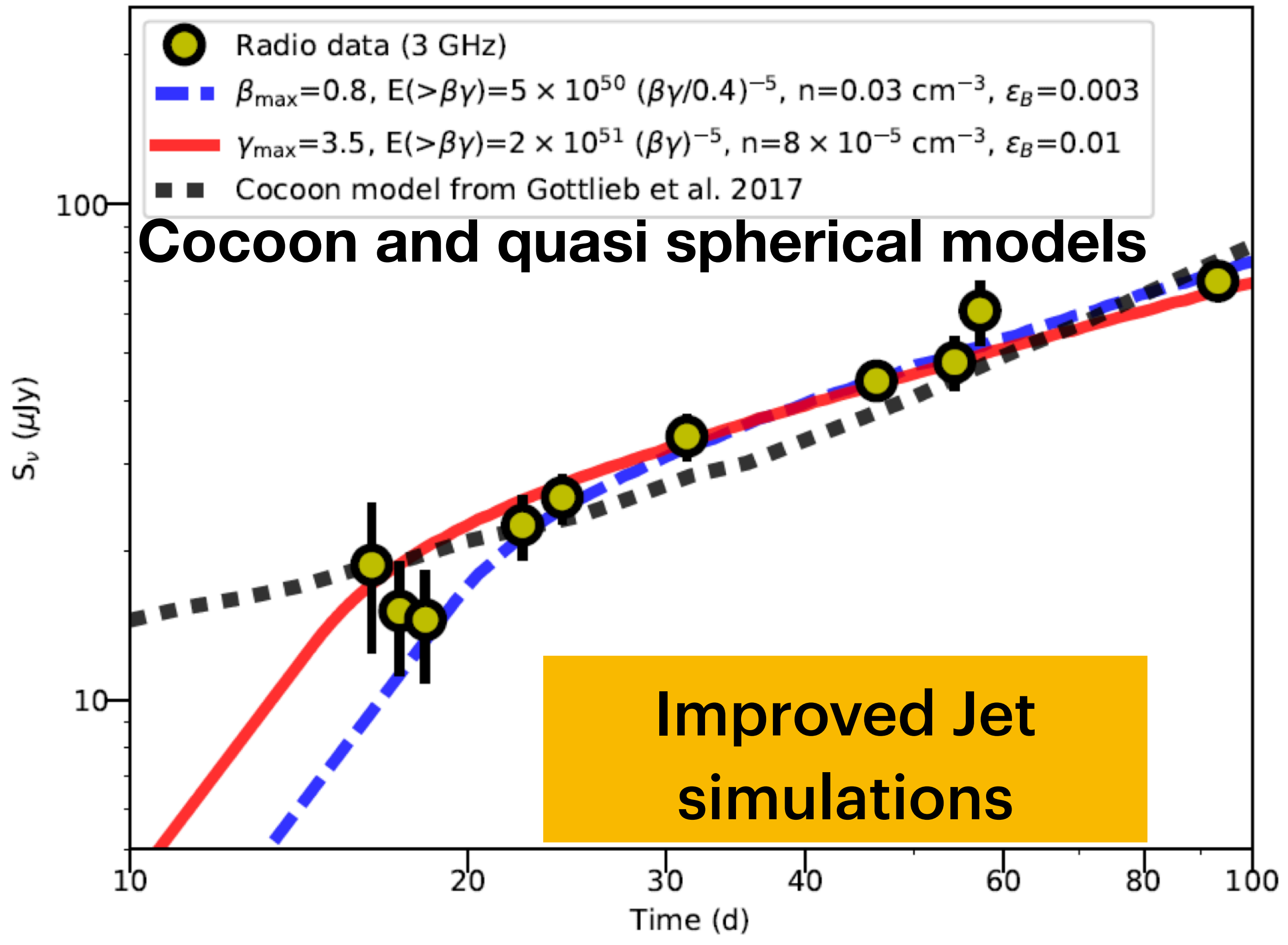
GWplotter.com

Multi-messenger Astrophysics

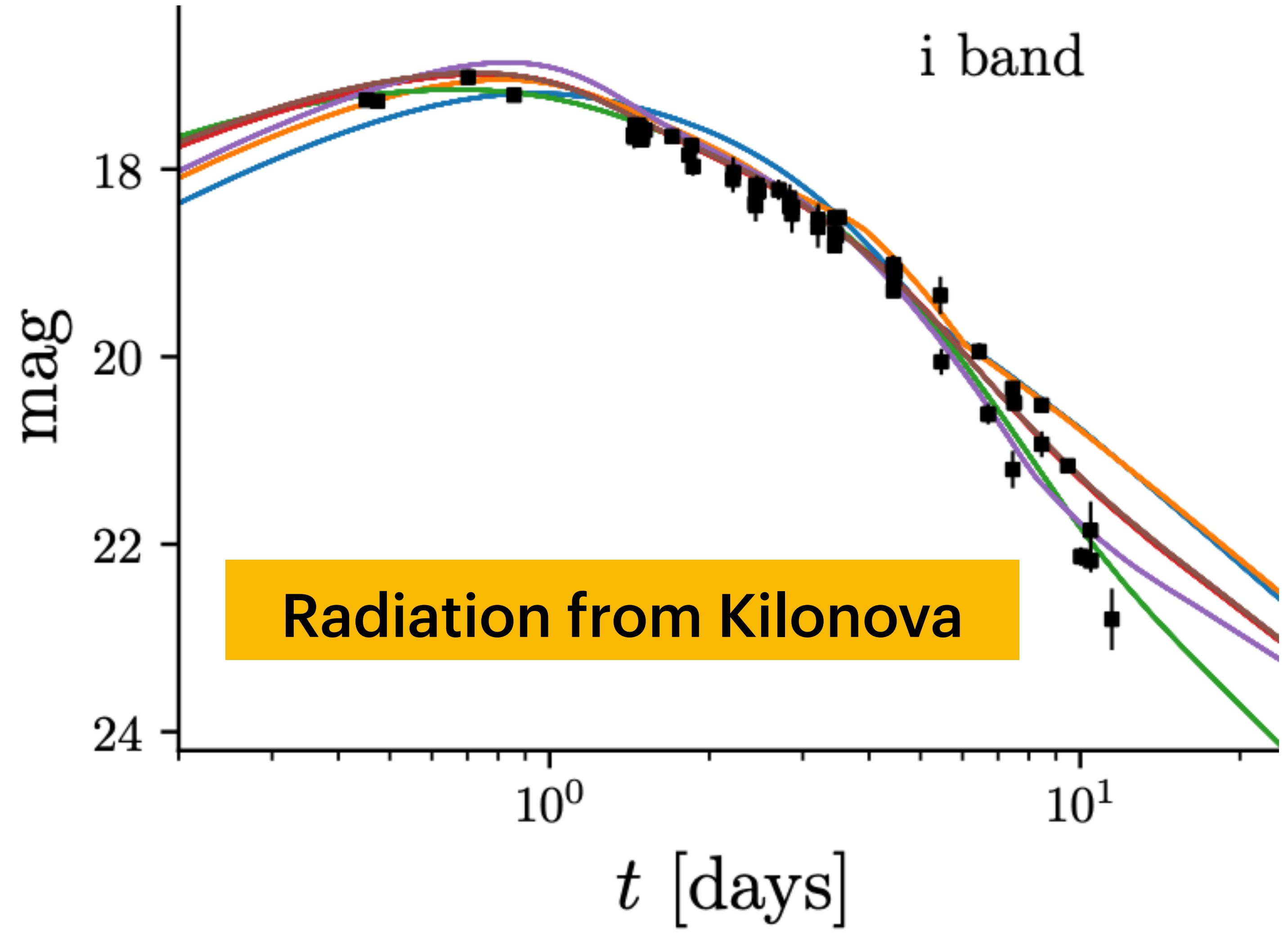
Non-photonic signals + Electromagnetic counterparts







Mooley et al. 2018



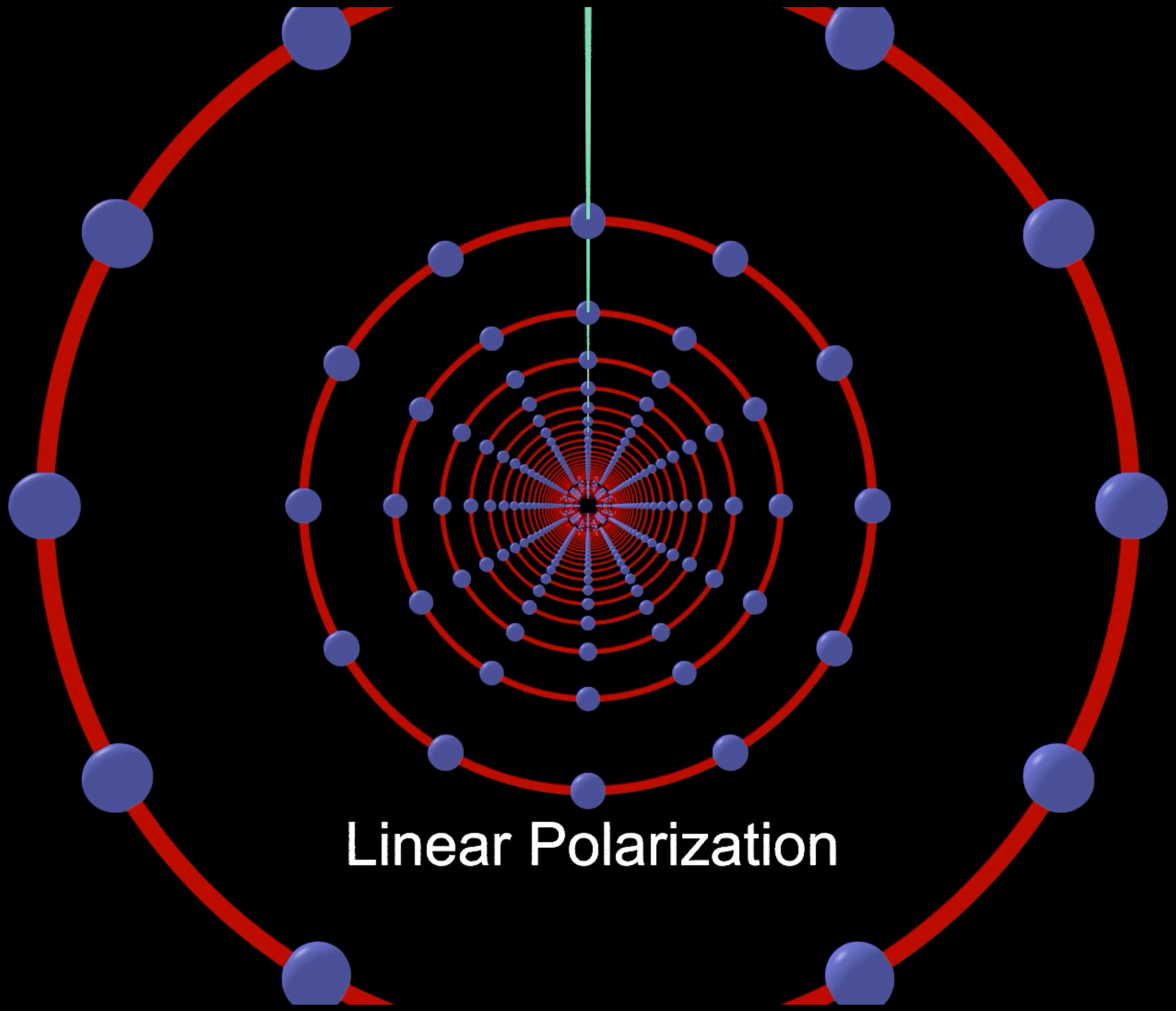
Breschi et al. 2021

Figure Credits: Dado et al. 2022

Gravitational waves

$h_+ \rightarrow$ linear

$h_\times \rightarrow$ circular



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

Chanel: Animations for physics and astronomy

GW signal from a radiating point mass

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

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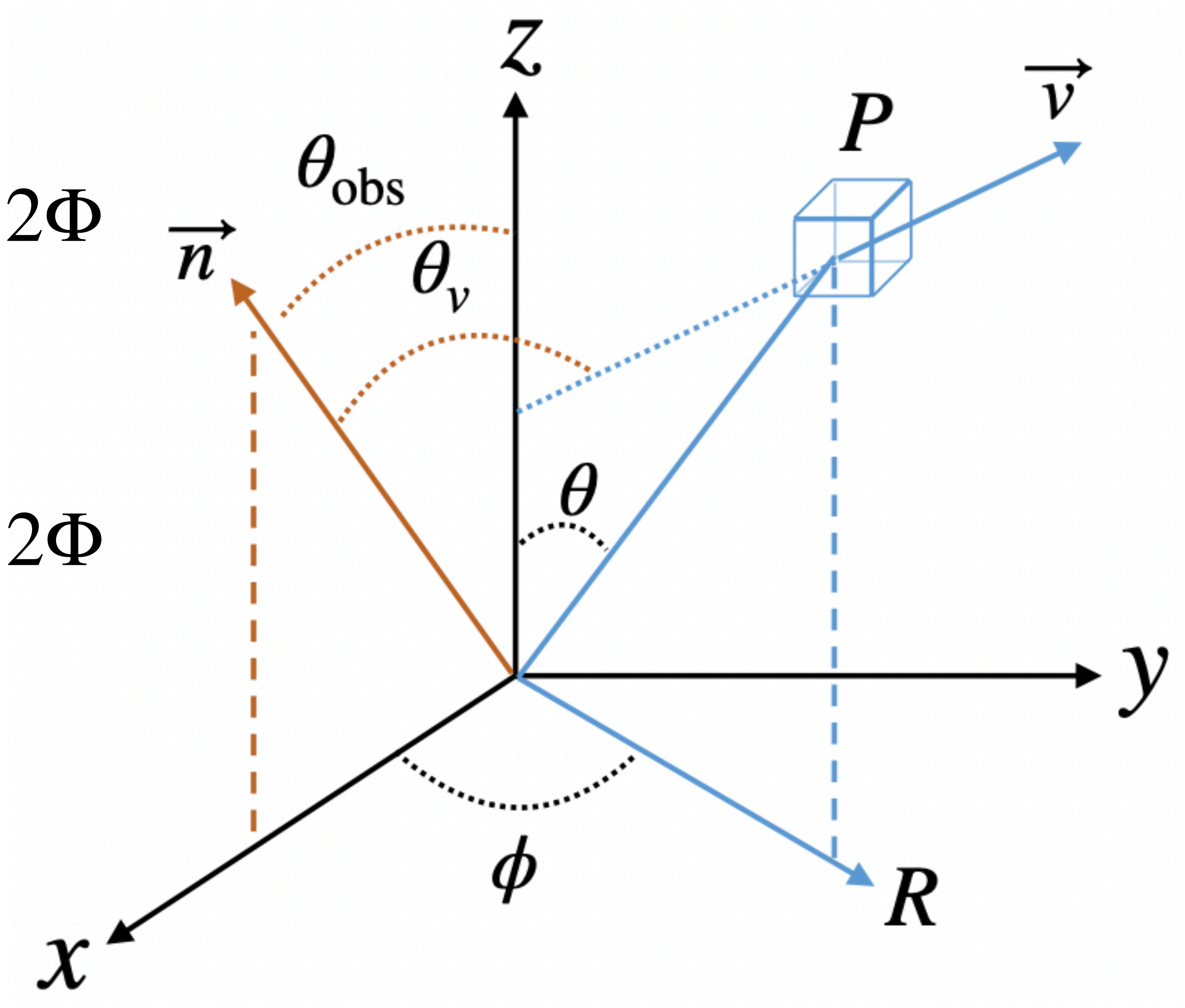

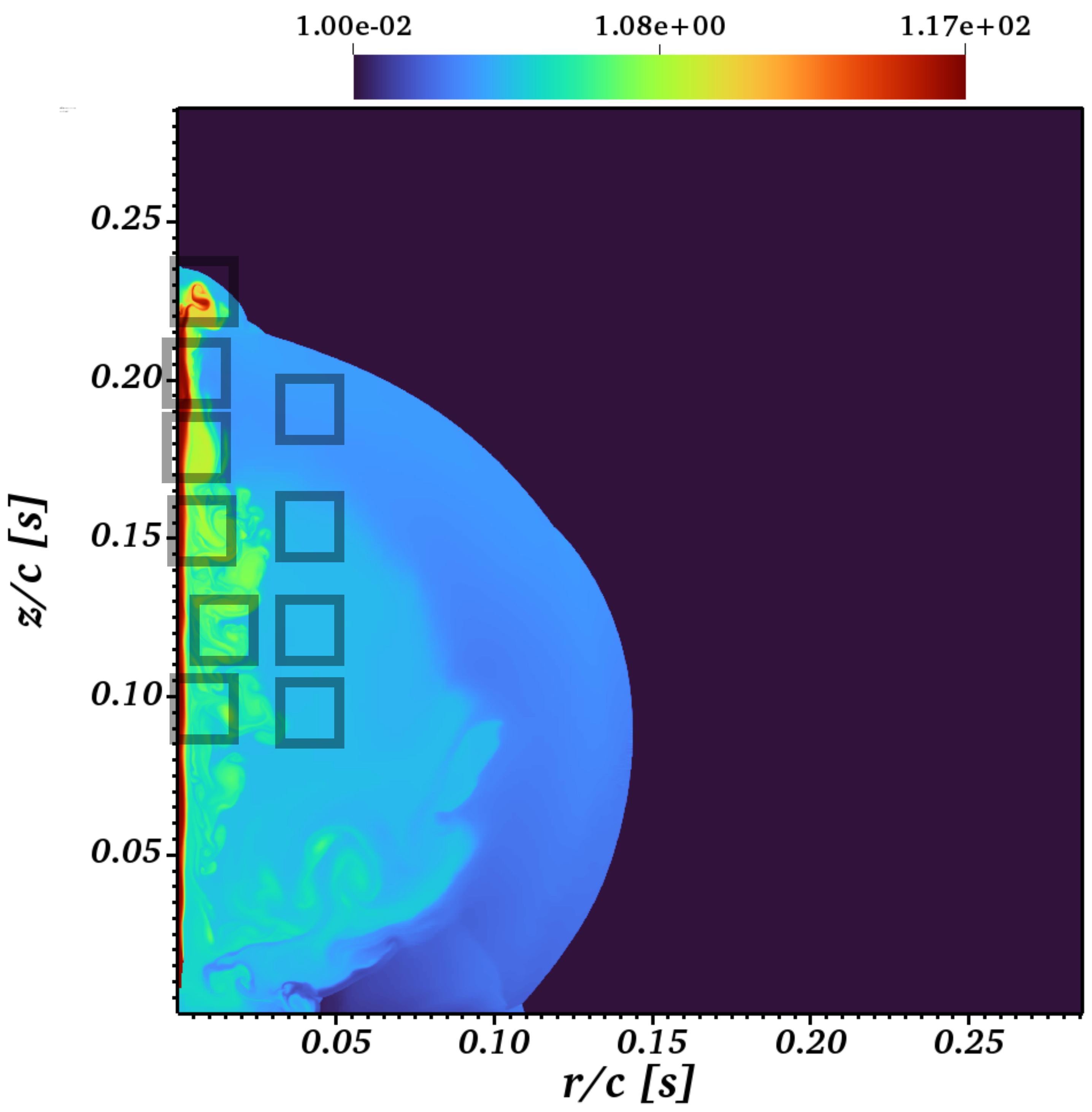

Braginskii & Thorne 1987,

Segalis & Ori 2001,

Birnholtz & Piran (2018),

Leiderschneider & Piran 2021

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

GW signal from a radiating point mass

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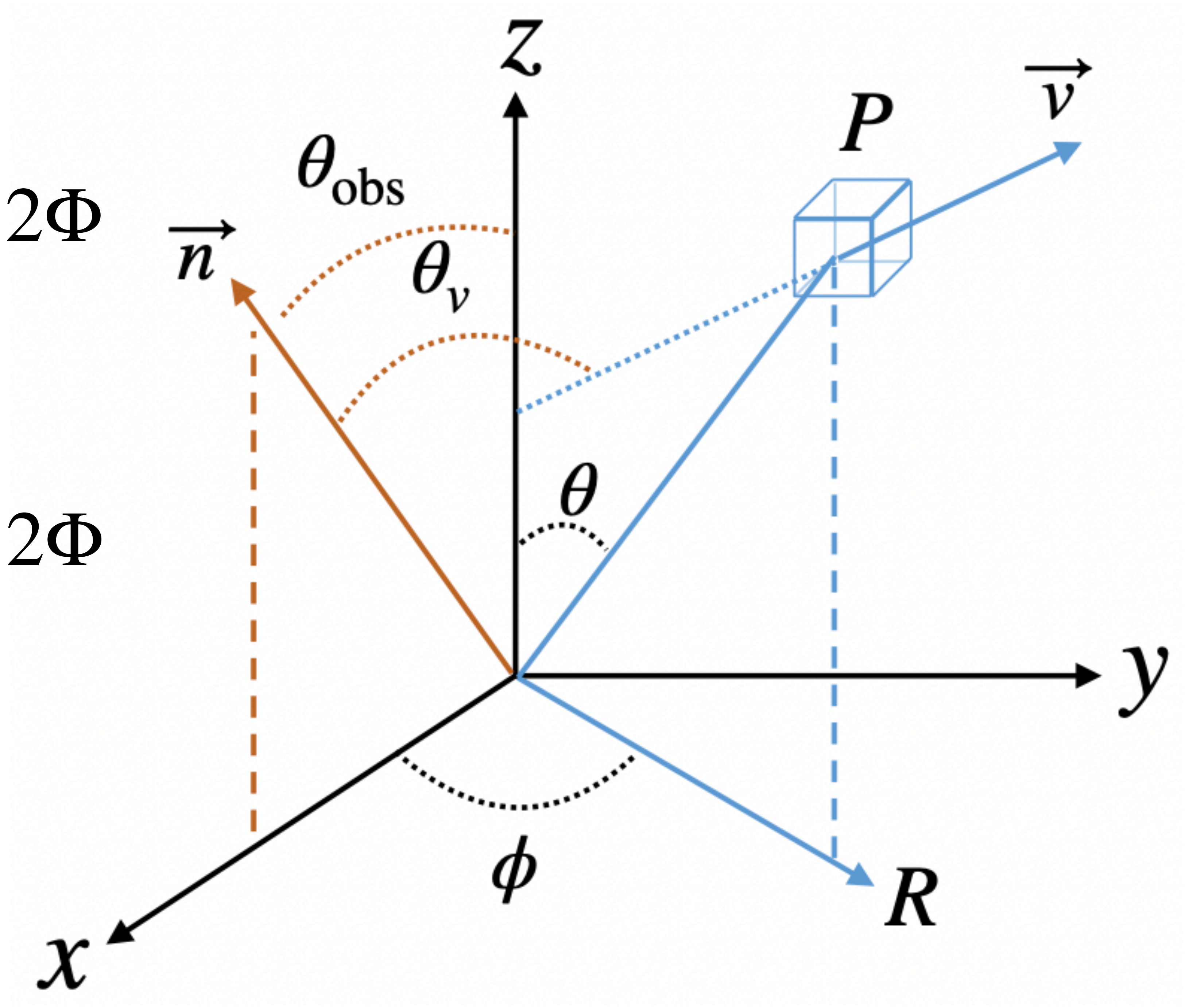

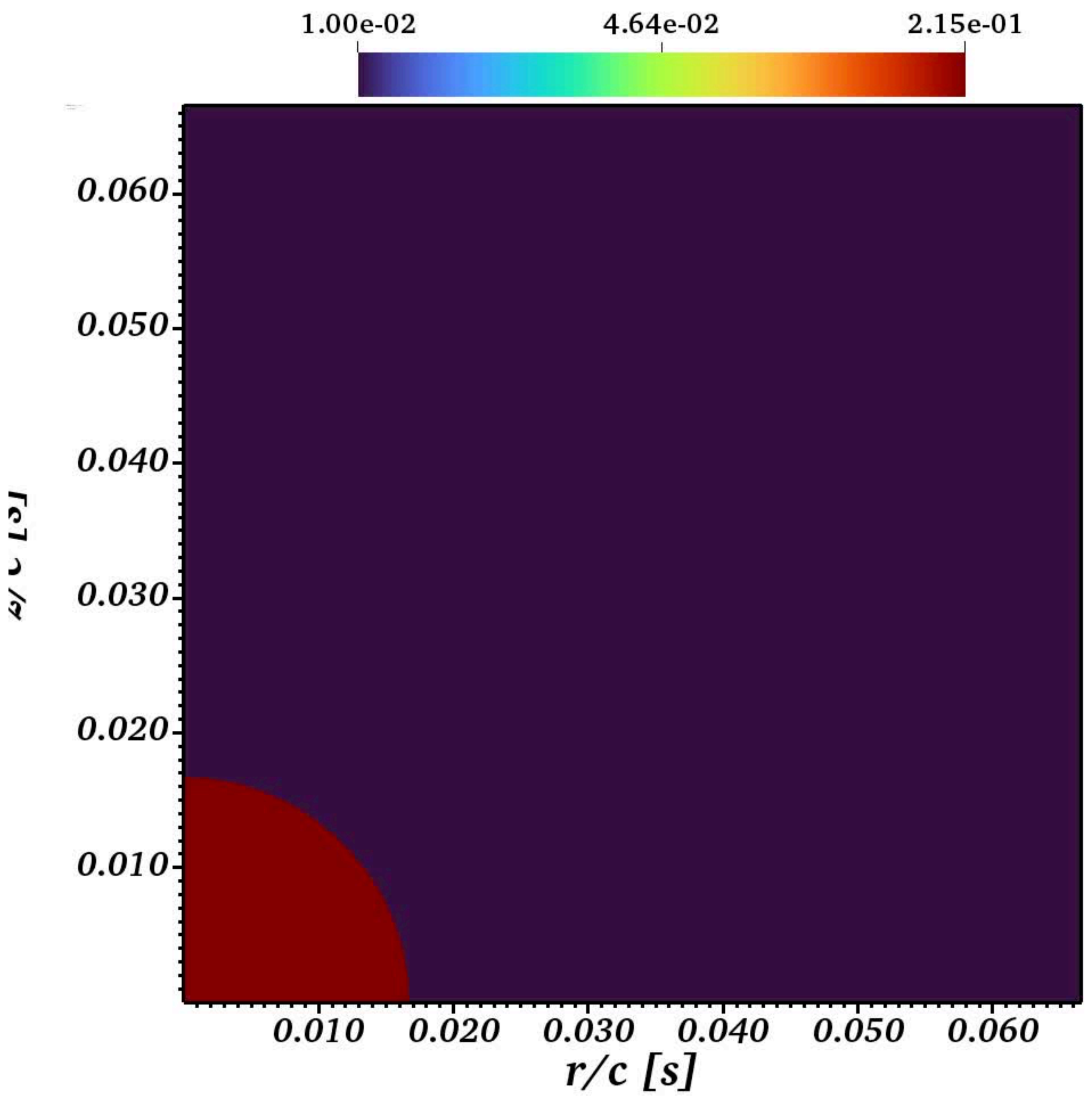

Time=0

Braginskii & Thorne 1987,

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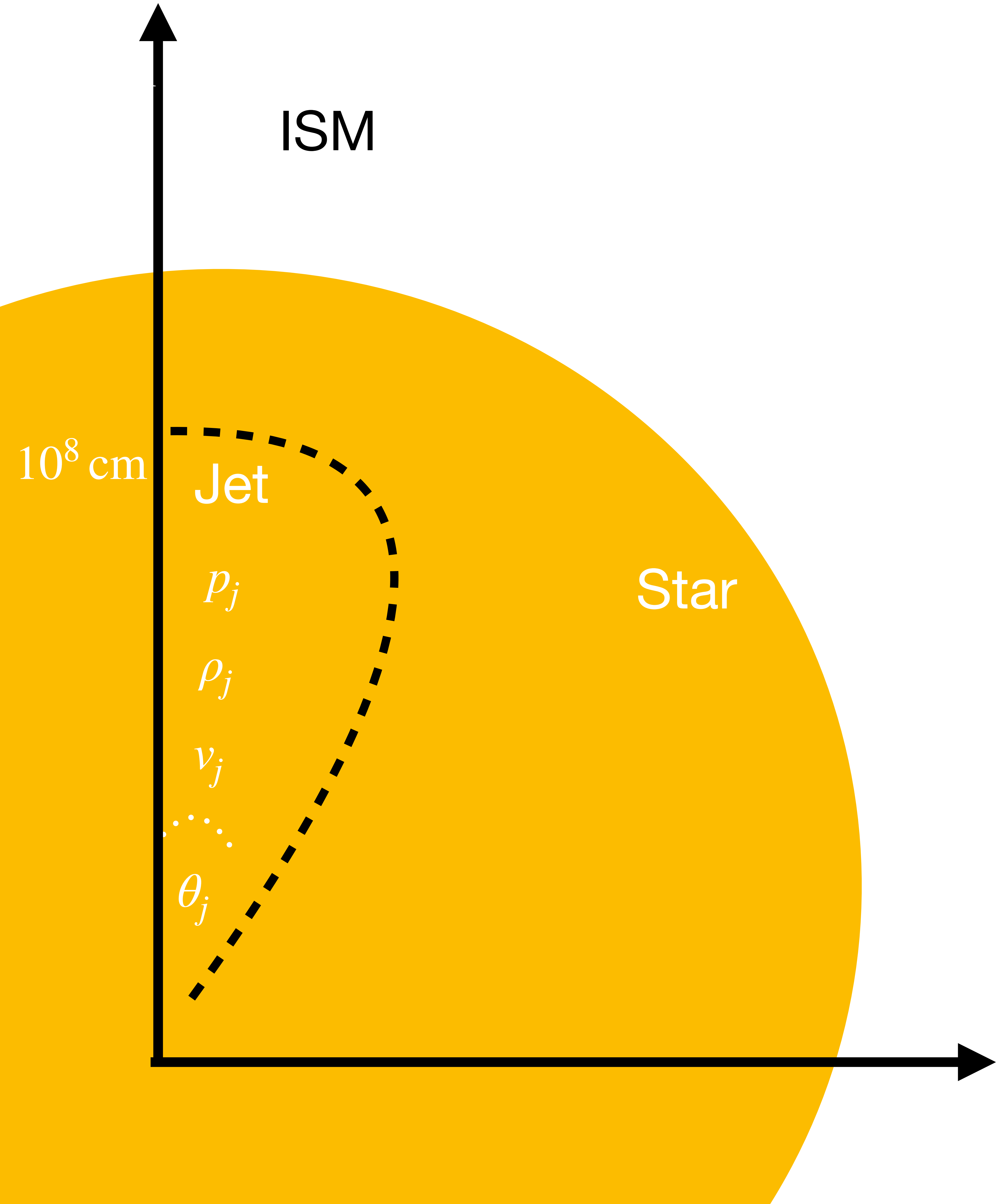
Leiderschneider & Piran 2021

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

Initial conditions

(Mezcal Code: De Colle et al. 2012)



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

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

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

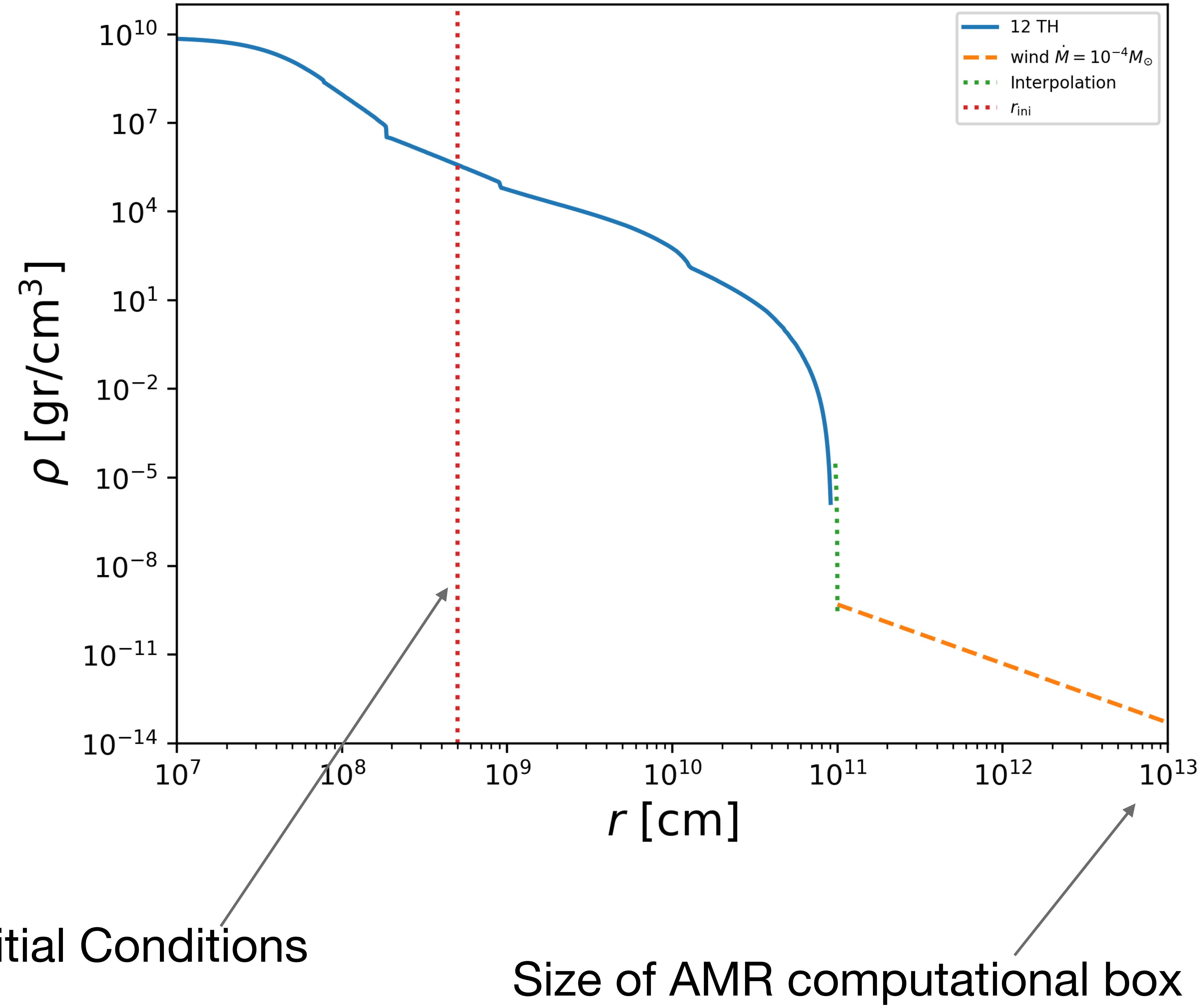
$$D = \Gamma \rho$$

$$m_j = D h \Gamma v_j$$

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

Initial conditions

(Mezcal Code: De Colle et al. 2012)



- Stellar striped envelope WR (Woosley & Heger 2006)

- AMR computational cylindrical box 2D: 40 x 40 cells
  - Minimal size: 4e-6 cm

- Jets dominated by pressure
  - Initial Lorentz factor = 10
  - Asymptotic Lorentz factor = 100

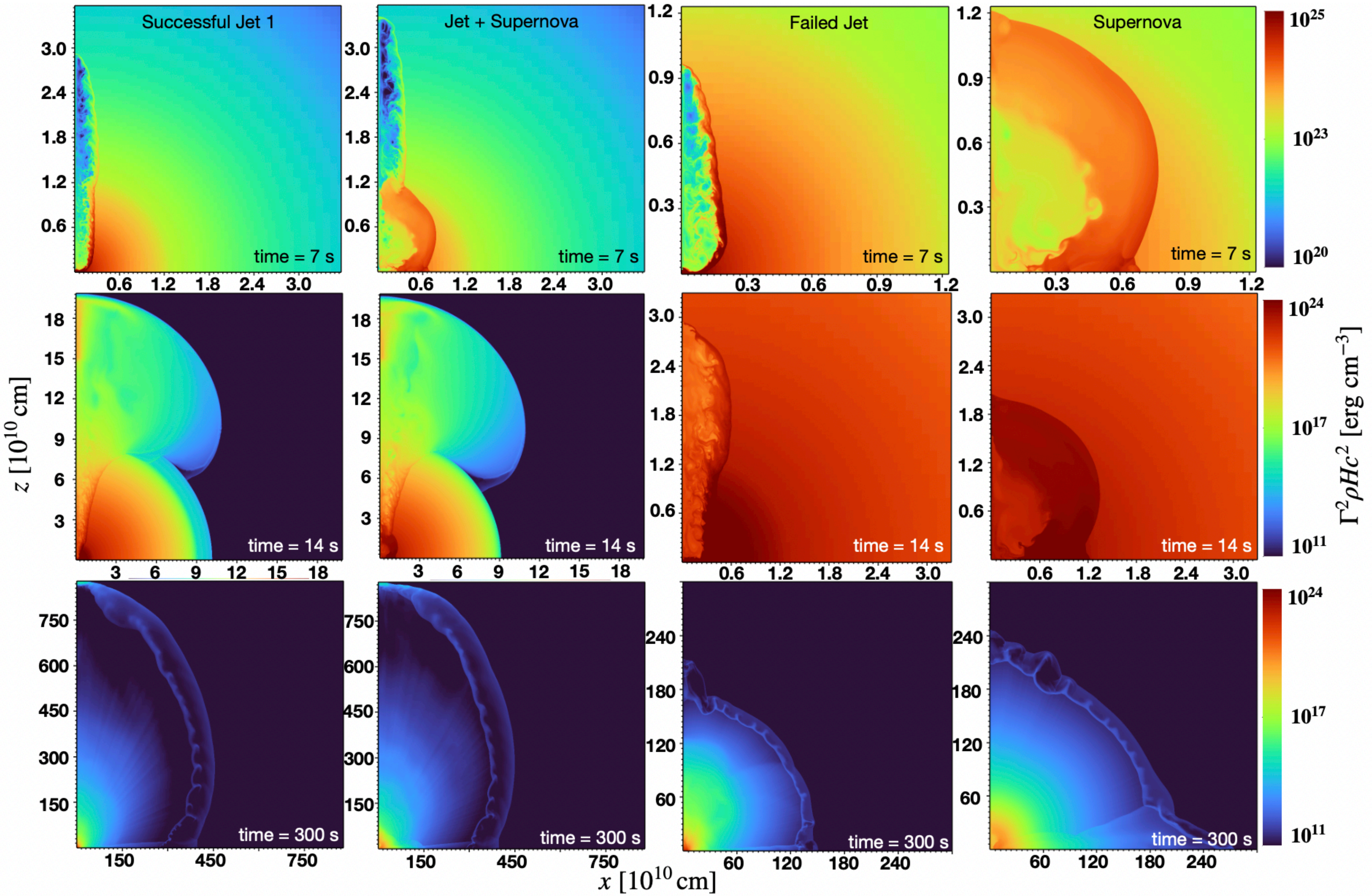
$$\rho_j = \frac{L_j}{\Gamma_\infty \Gamma_j v_j c^2 \Delta S}$$

$$P_j = \frac{\rho_j c^2}{4}\left(\frac{\Gamma_\infty}{\Gamma_j} - 1\right)$$

(Urrutia, De Colle & López-Cámara 2022)

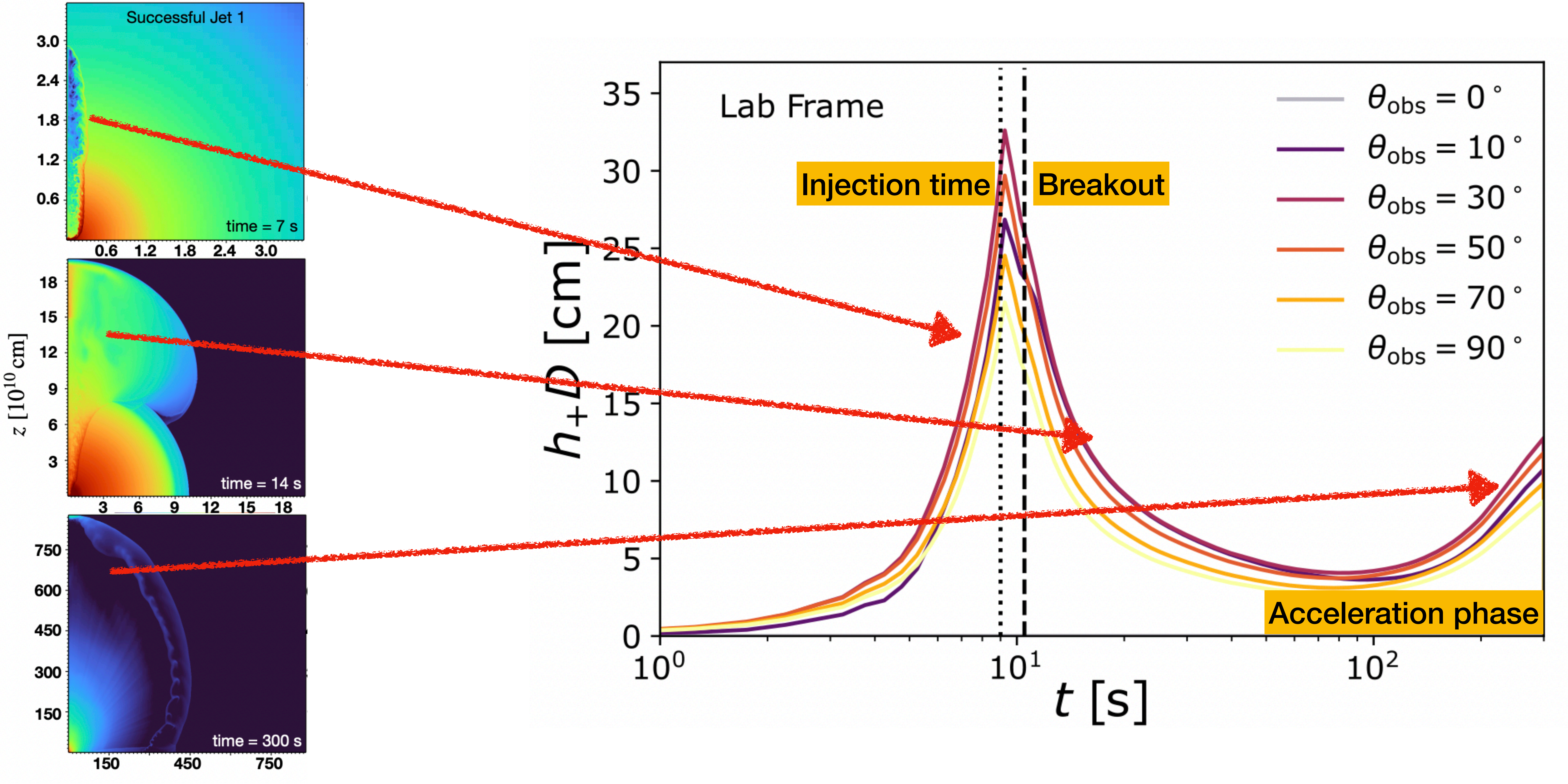
Scenario	$t_{\rm inj}$ (s)	Energy (erg)
Successful jet	10	10^{51}
Successful jet	2.5	10^{52}
Failed jet	10	10^{51}
Supernova	1	10^{52}
Jet + Supernova	10	10^{51}

Jet dynamics

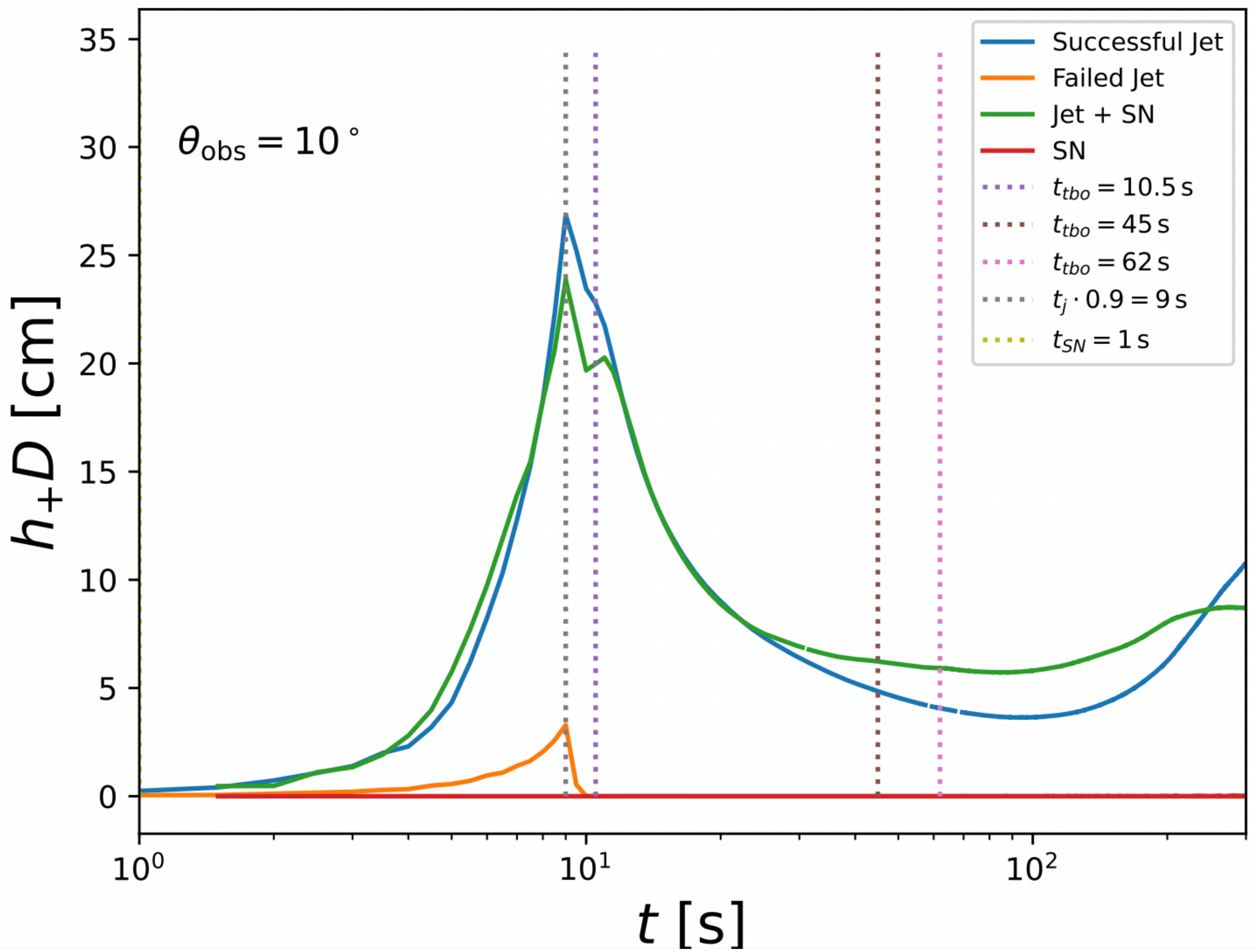


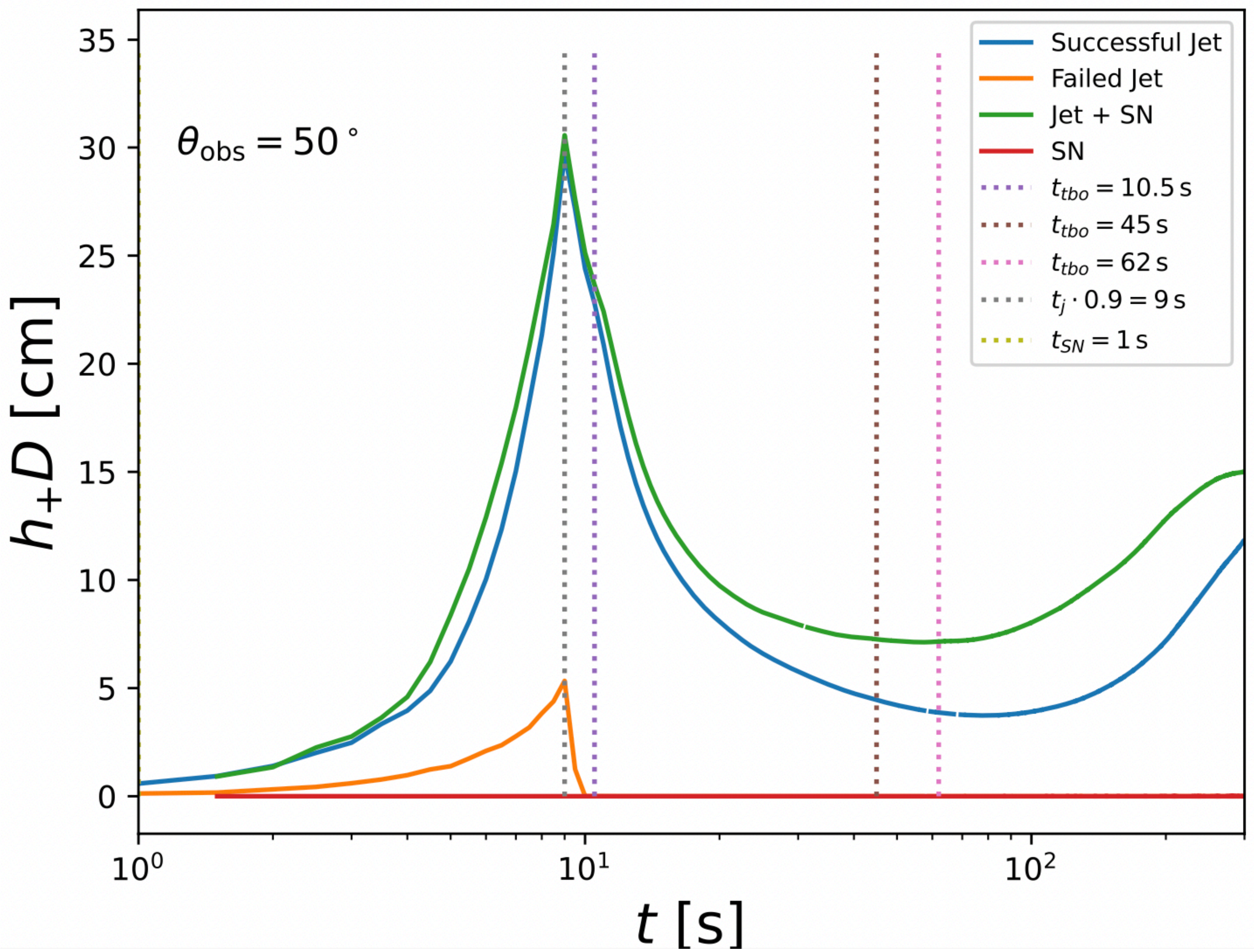
Succesful jet - GW signal

$t = t_{\rm obs}$



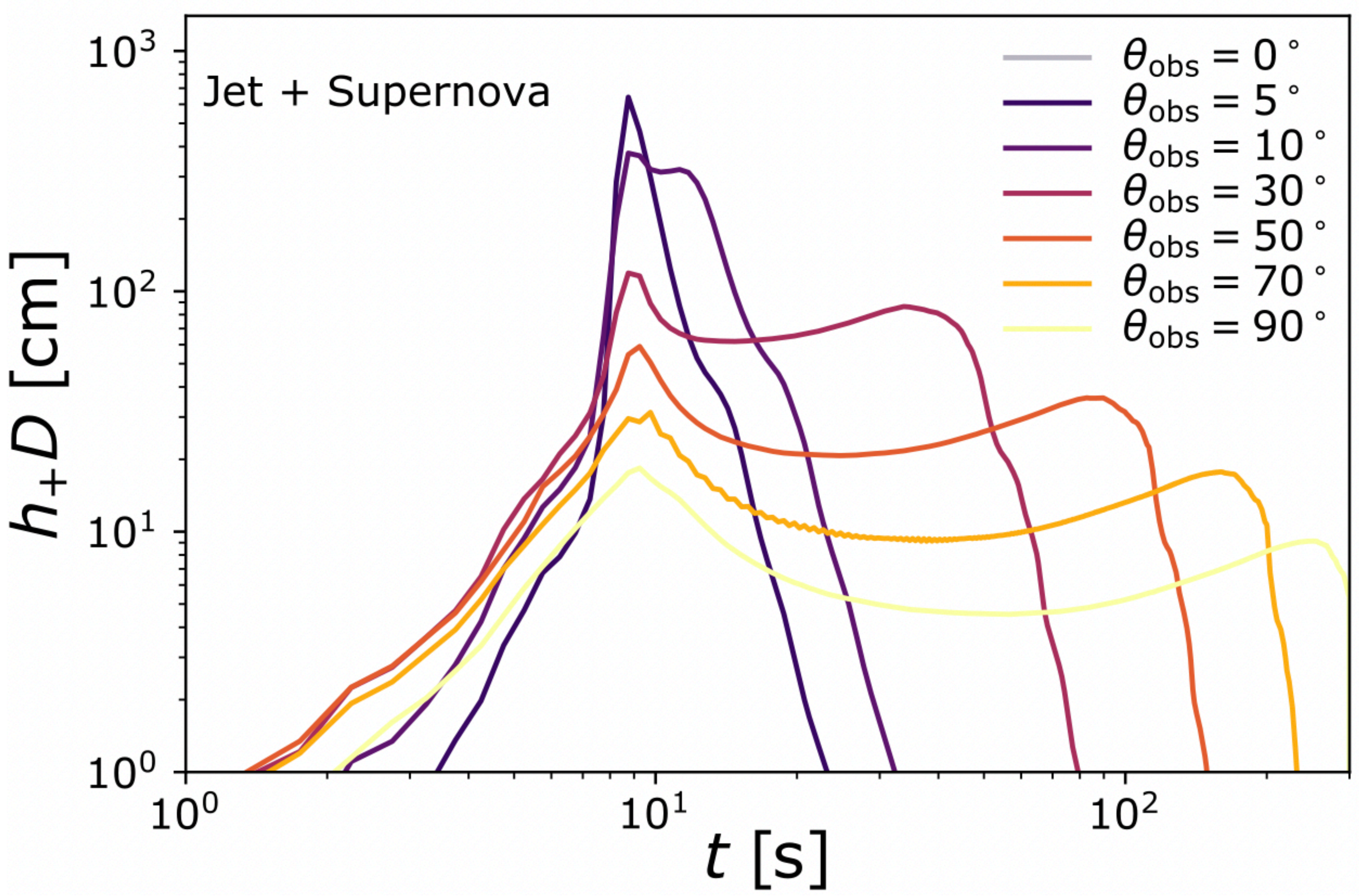
All models $t = t_{obs}$

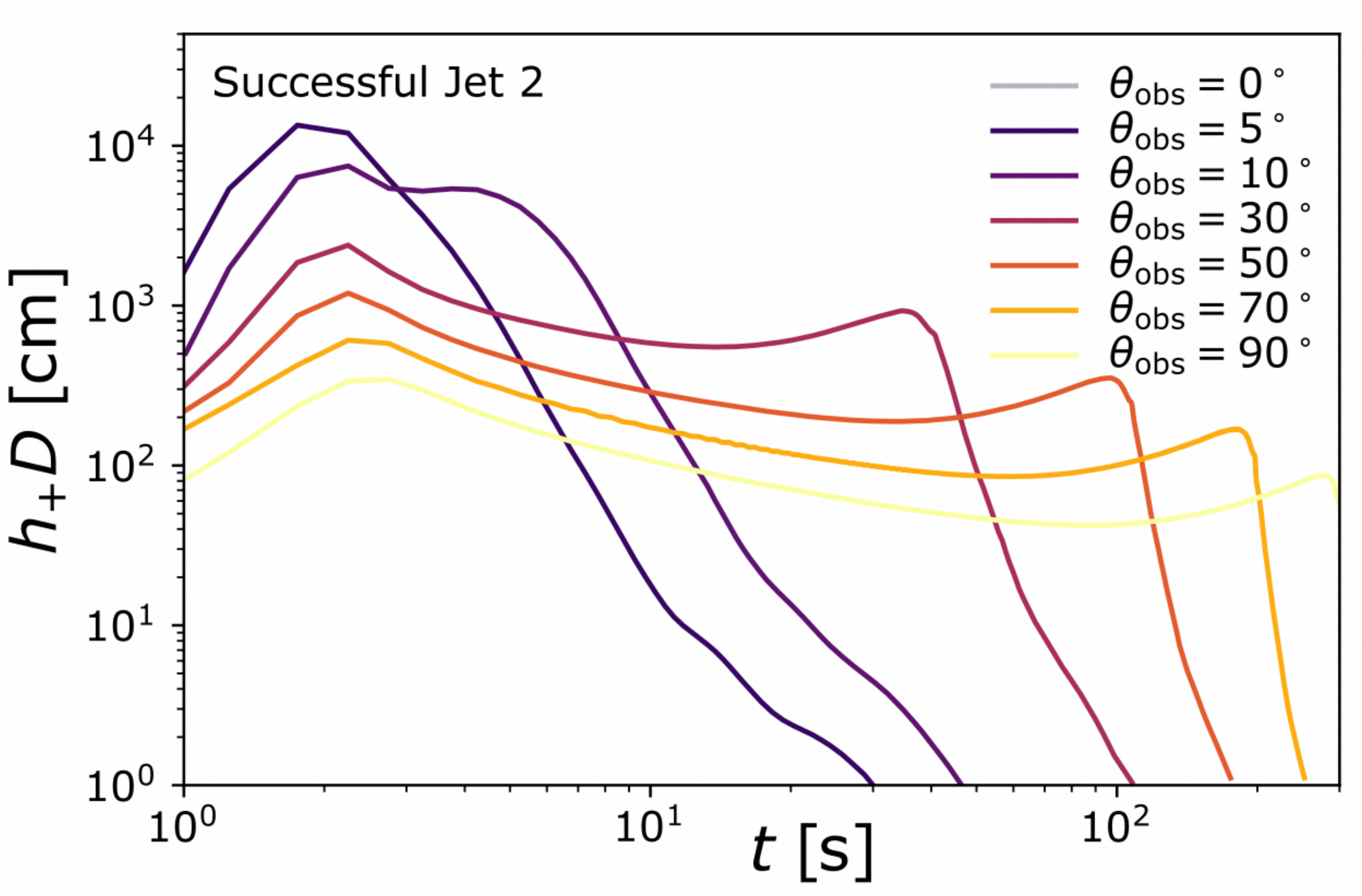




GW signal

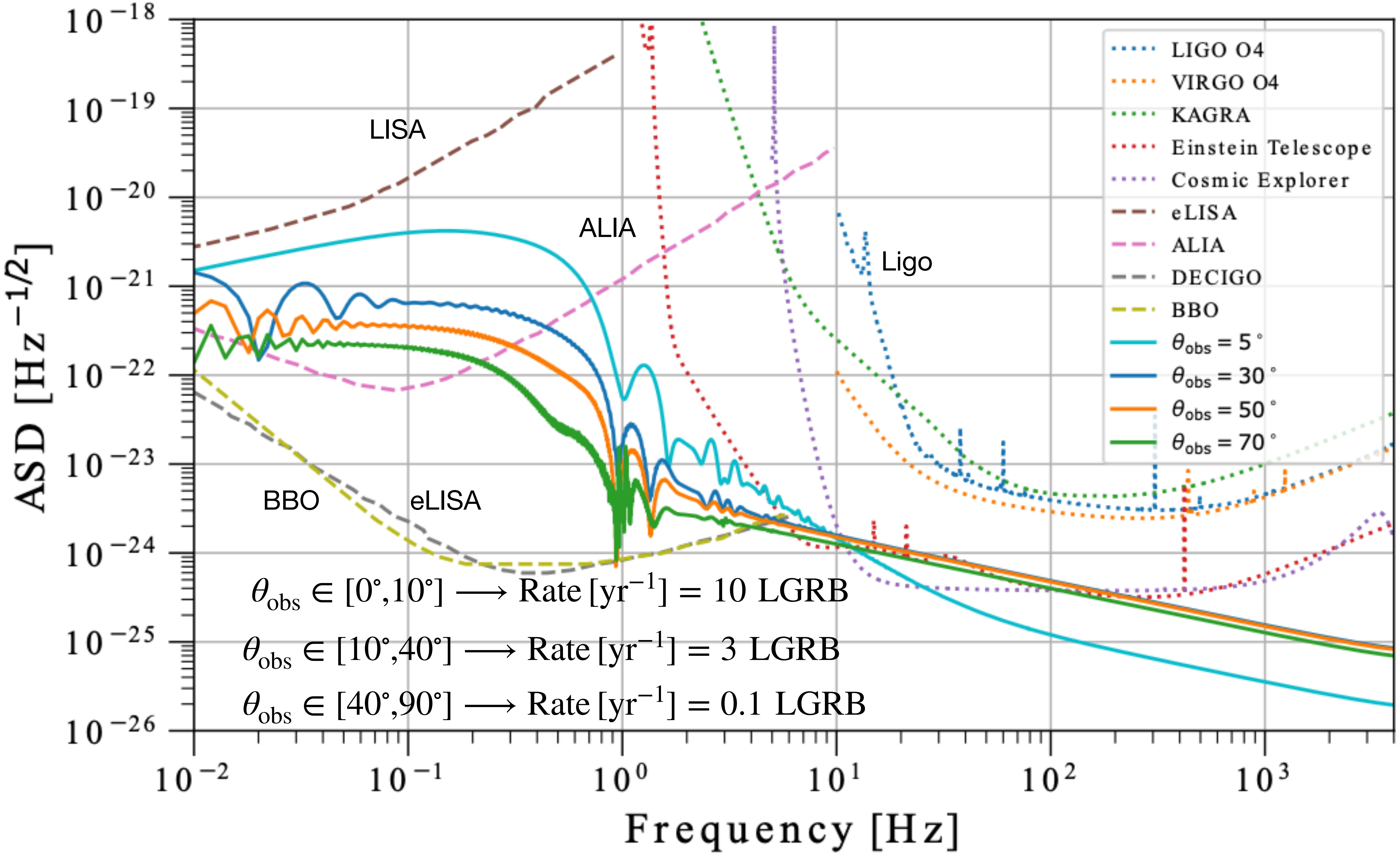
$$t_{\rm obs} = t - \cos\phi \sin\theta_{\rm obs} R/c - \cos\theta_{\rm obs} z/c$$





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

Detectability



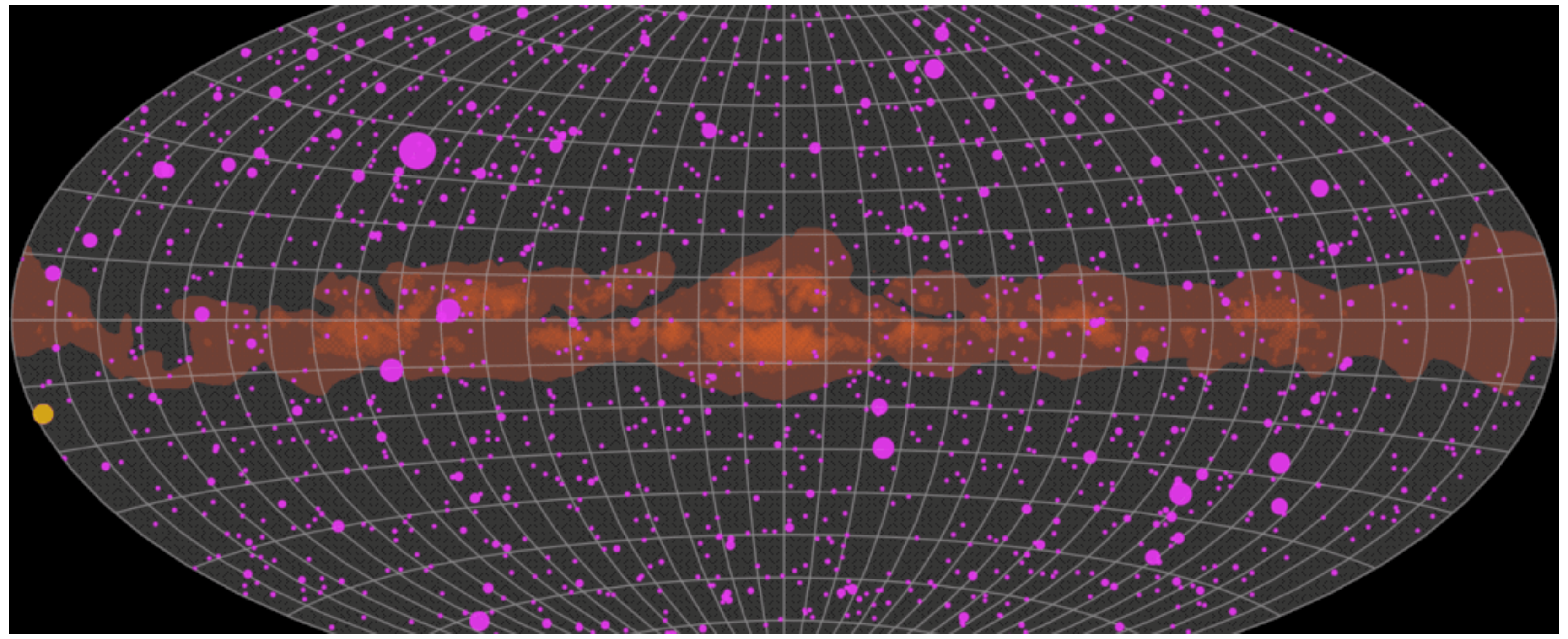
Sensitivity curves from Moore et al. 2014

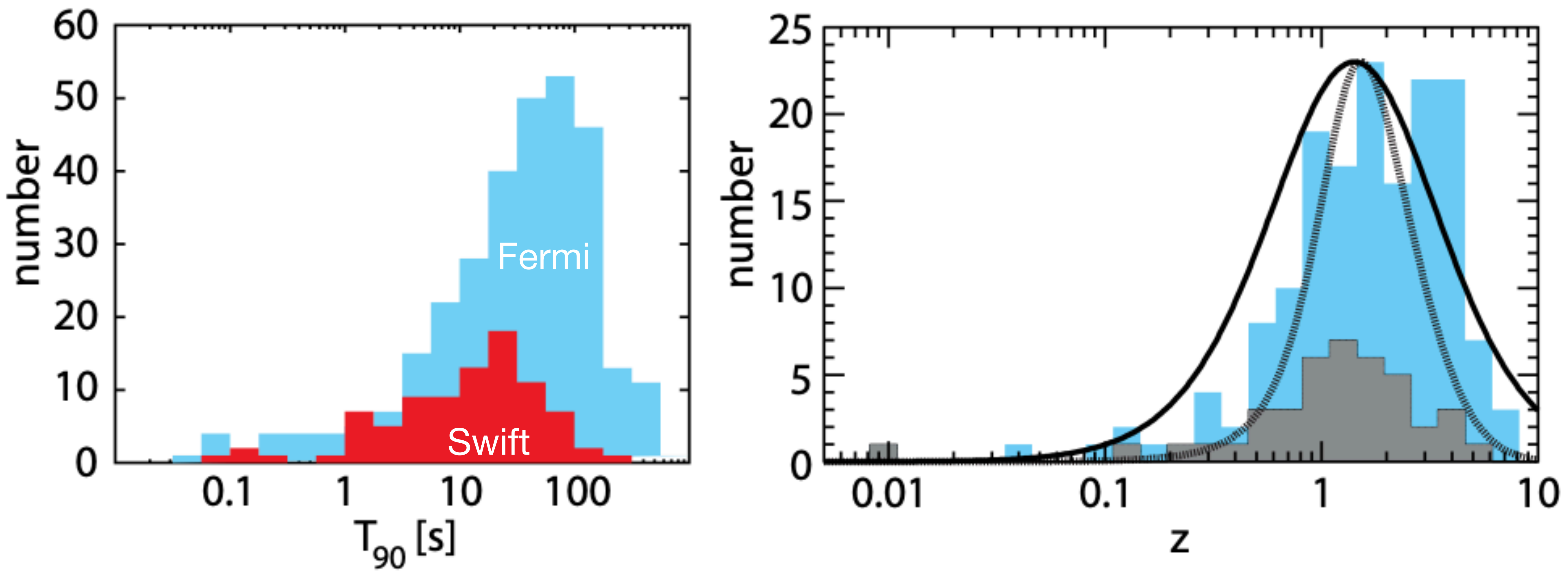
$$h \propto \frac{E}{Dc^4}$$

$$E = 10^{52}\,\mathrm{erg}$$

$$D = 1\,\mathrm{Mpc}$$

Detectability



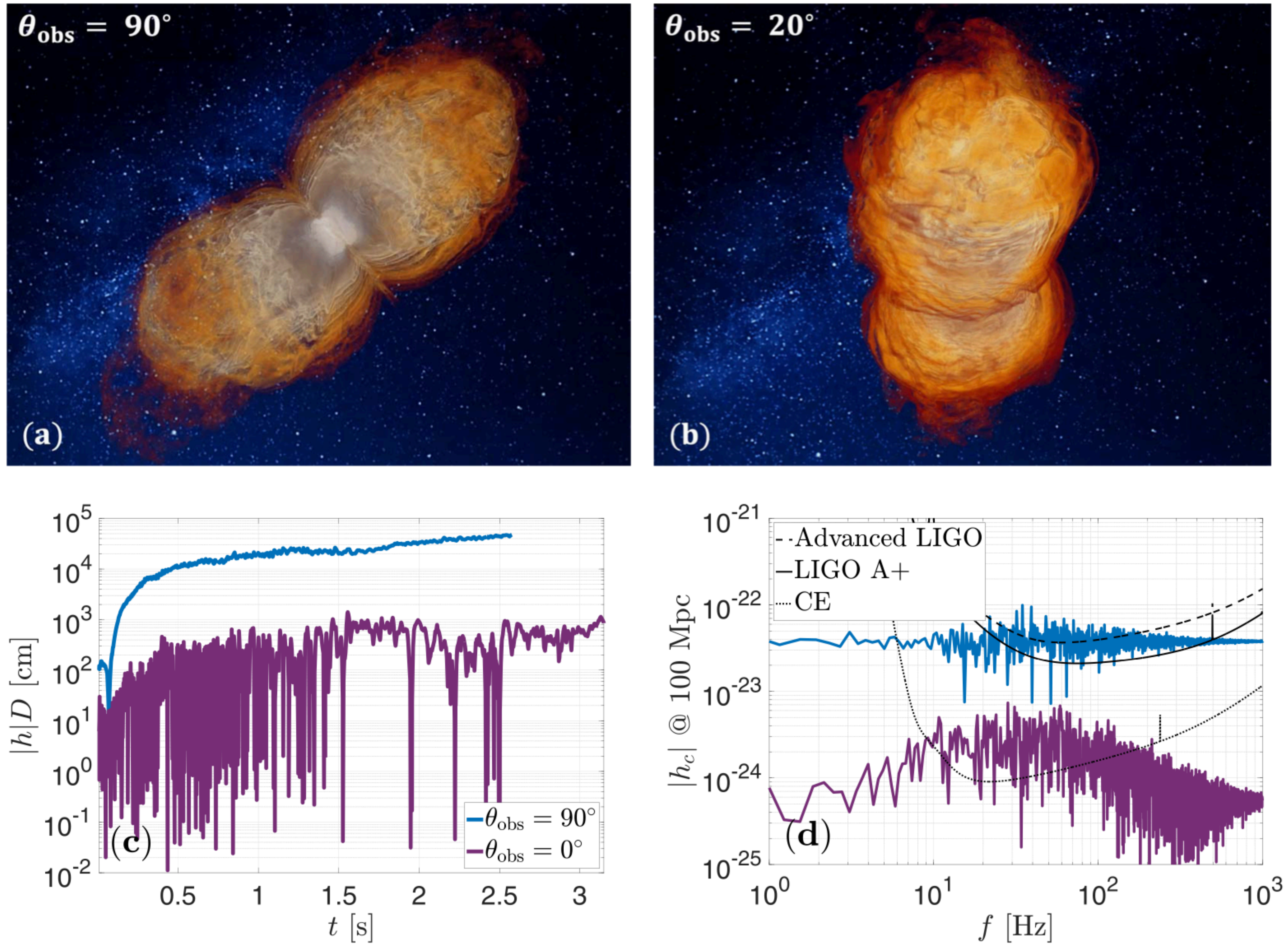


Gehrels, Ramirez-Ruiz & Fox (2009)

Detector	Distance [Mpc]		Rate [yr^{-1}]		
	$5°$	$70°$	$0° - 10°$	$10° - 40°$	$40° - 90°$
LIGO O4	1.5×10^{-2}	5.1×10^{-2}	1.5×10^{-12}	1.9×10^{-10}	4.2×10^{-10}
VIRGO O4	2.2×10^{-2}	2.2×10^{-2}	7.3×10^{-13}	1.8×10^{-11}	3.6×10^{-11}
KAGRA	7.3×10^{-3}	2.3×10^{-2}	1.6×10^{-14}	2.1×10^{-12}	5.0×10^{-12}
Einstein Telescope	3.5×10^{-1}	5.0×10^{-1}	3.9×10^{-10}	2.3×10^{-8}	5.3×10^{-8}
Cosmic Explorer	3.0×10^{-1}	5.3×10^{-1}	3.4×10^{-10}	2.8×10^{-8}	6.4×10^{-8}
eLISA	8.5×10^{-2}	1.5×10^{-2}	5.5×10^{-11}	3.7×10^{-10}	4.0×10^{-11}
ALIA	6.4	3.7×10^{-1}	1.3×10^{-5}	1.2×10^{-5}	4.5×10^{-7}
DECIGO	6.0×10^{2}	1.8×10^{1}	7.5	2.2	1.0×10^{-1}
BBO	6.0×10^{2}	2.1×10^{1}	7.9	2.5	1.2×10^{-1}

Urrutia, De Colle, Moreno & Zanollin (2022)

High resolution 3D simulation



Gottlieb et al. 2023

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

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

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

Storage ~ Petabytes

Currently methodology

Jet dynamics (simulations) → Post-processing (GW signals) → Detectability

Sotorage ~ TB
Computational time: 3 days

New methodology

New implementation
Jet dynamics (simulations) + GW signals → Detectability

Sotorage ~ GB
Computational time: 1 week

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

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

Ram memory ~ GB
Storage ~ GB

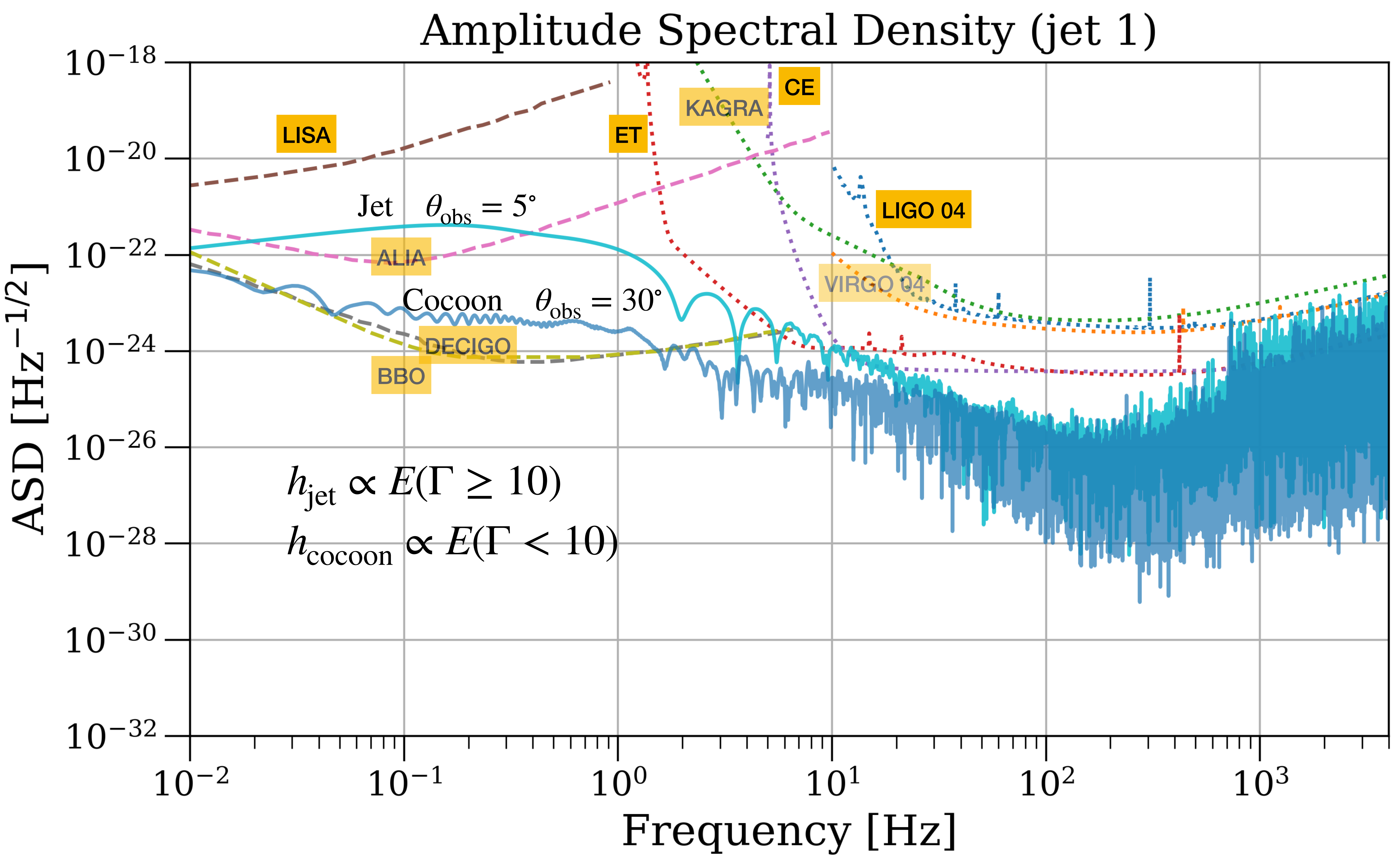
$$ASD = 2 f^{1/2} |\tilde{h}(f)|$$

$$E_j = 10^{51}\,\mathrm{erg}$$

$$t_j = 10\,\mathrm{s}$$

$$R_\star = 10^{11}\,\mathrm{cm}$$

$$D_{\mathrm{obs}} = 1\,\mathrm{Mpc}$$



Urrutia (in Prep)

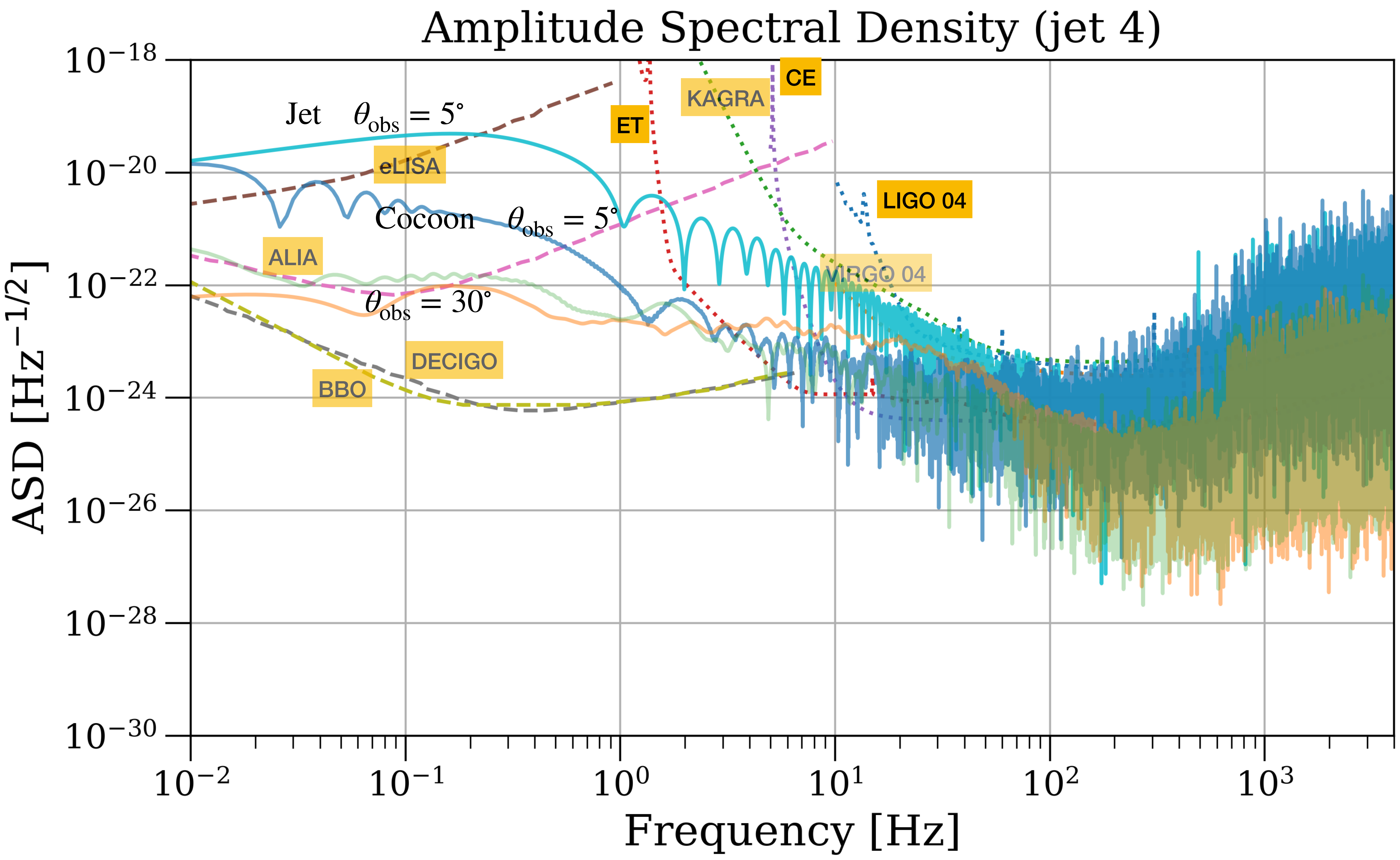
Estimation of GW signals during the jet propagation (not post-processing)

$E_j = 10^{52}\,\mathrm{erg}$

$t_j = 2.5\,\mathrm{s}$

$R_\star = 10^{11}\,\mathrm{cm}$

$D_{\rm obs} = 1\,\mathrm{Mpc}$



Urrutia (in Prep)

Conclusions

- A new generation of observatories will observe GW signals from GRB jets.
- The rate of detection by DECIGO and BBO may be $10\,\mathrm{GRBs}\,\mathrm{yr}^{-1}\,\mathrm{Gpc}^{-3}$
- Jet parameters: injection time, L(t), velocity, size of GRB progenitor, acceleration region, jet observing angle are strongly connected to the shape of the GW signal.
- GW signal will provide unique information about the early jet dynamics, the progenitor and the physics of central engine.