Gravitational wave signals from Long Gamma Ray Bursts jets

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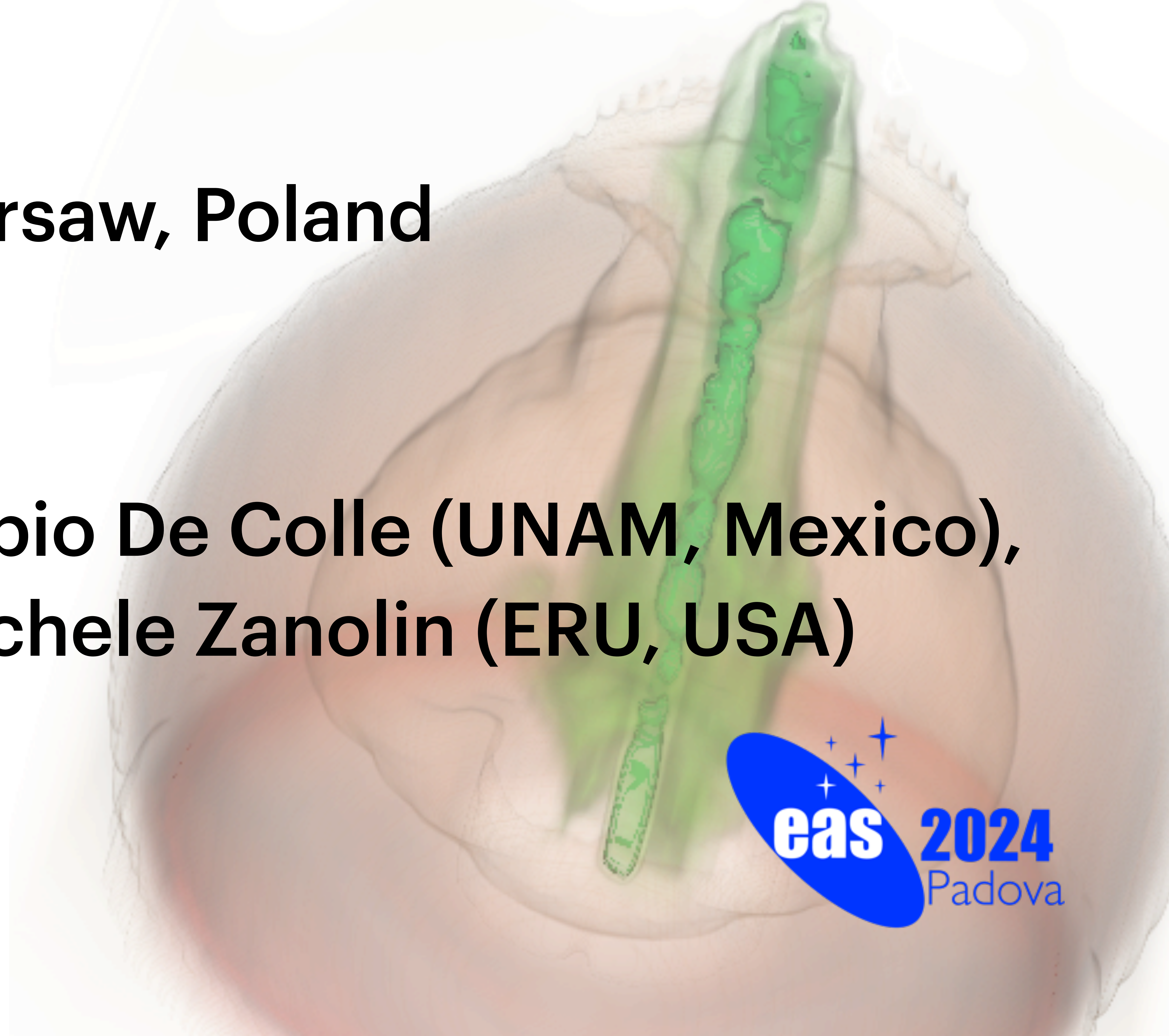

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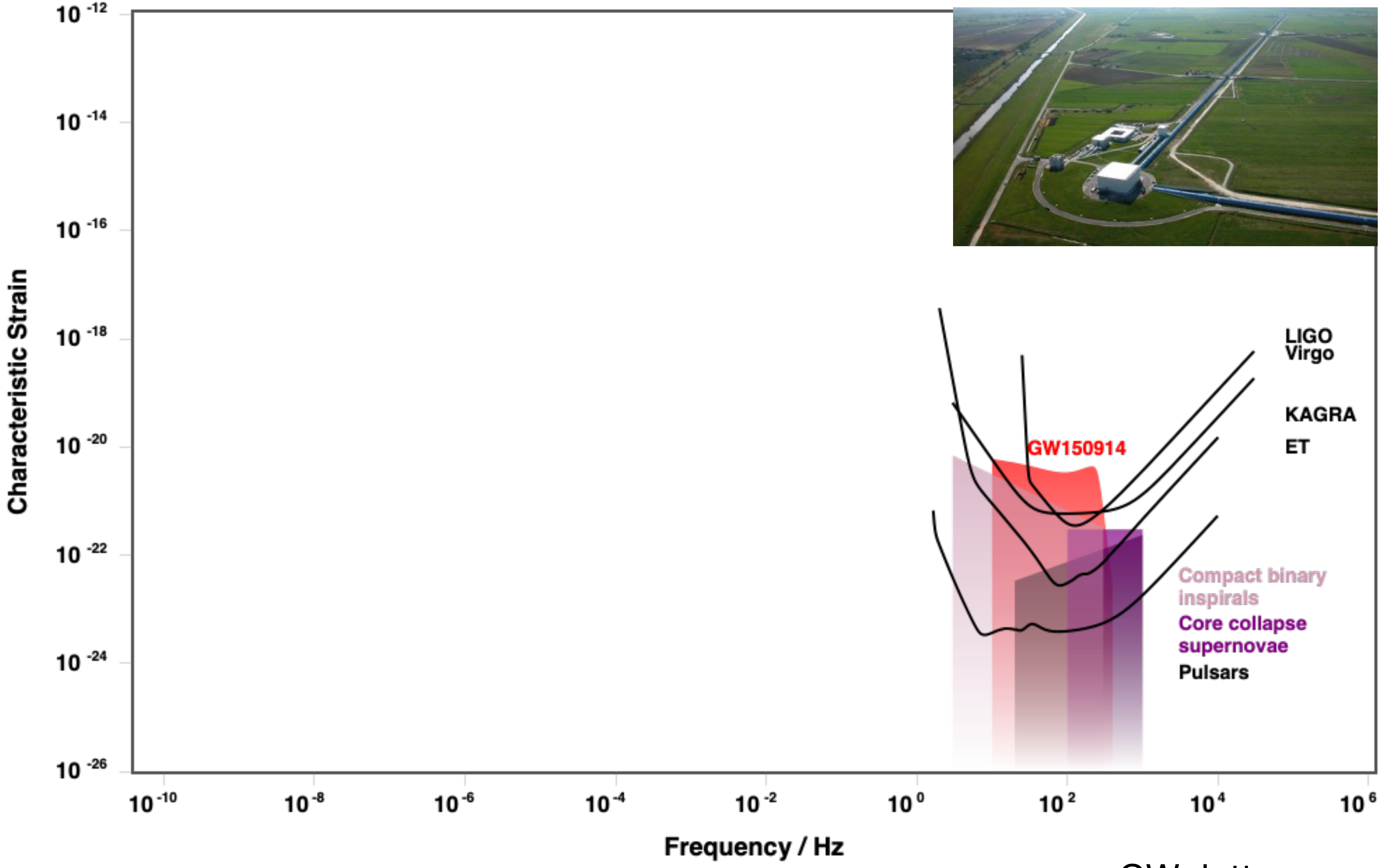
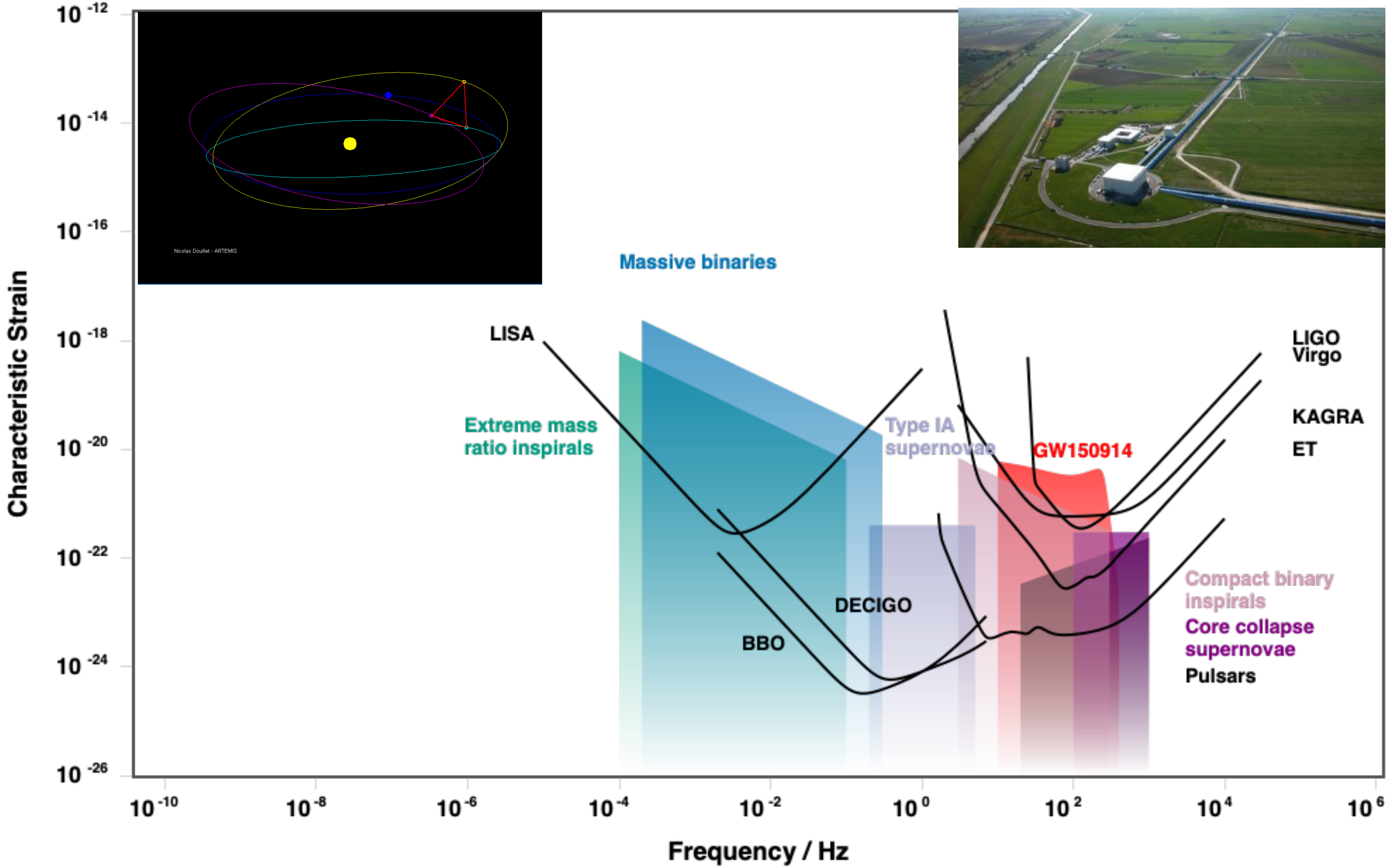


GWplotter.com



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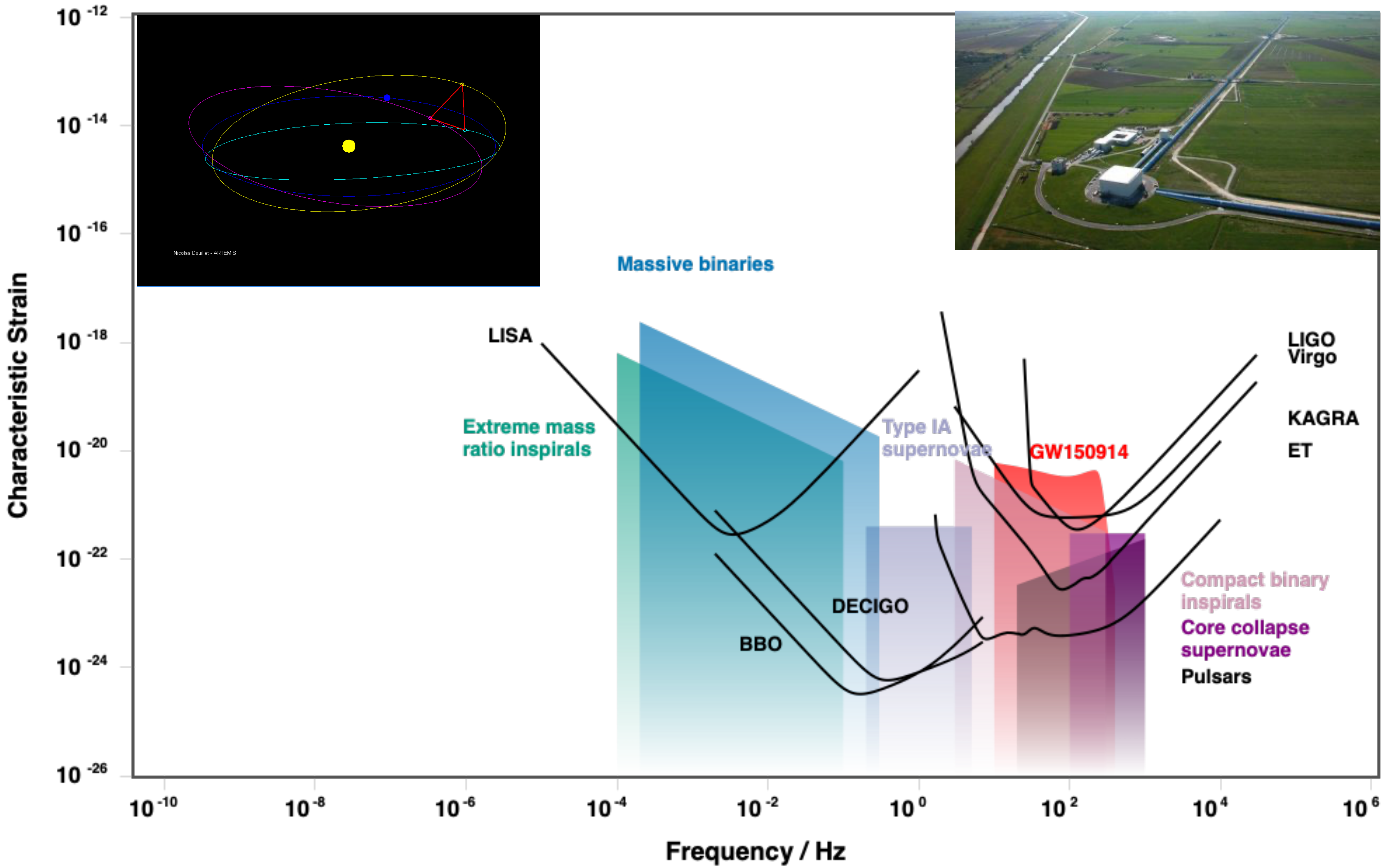

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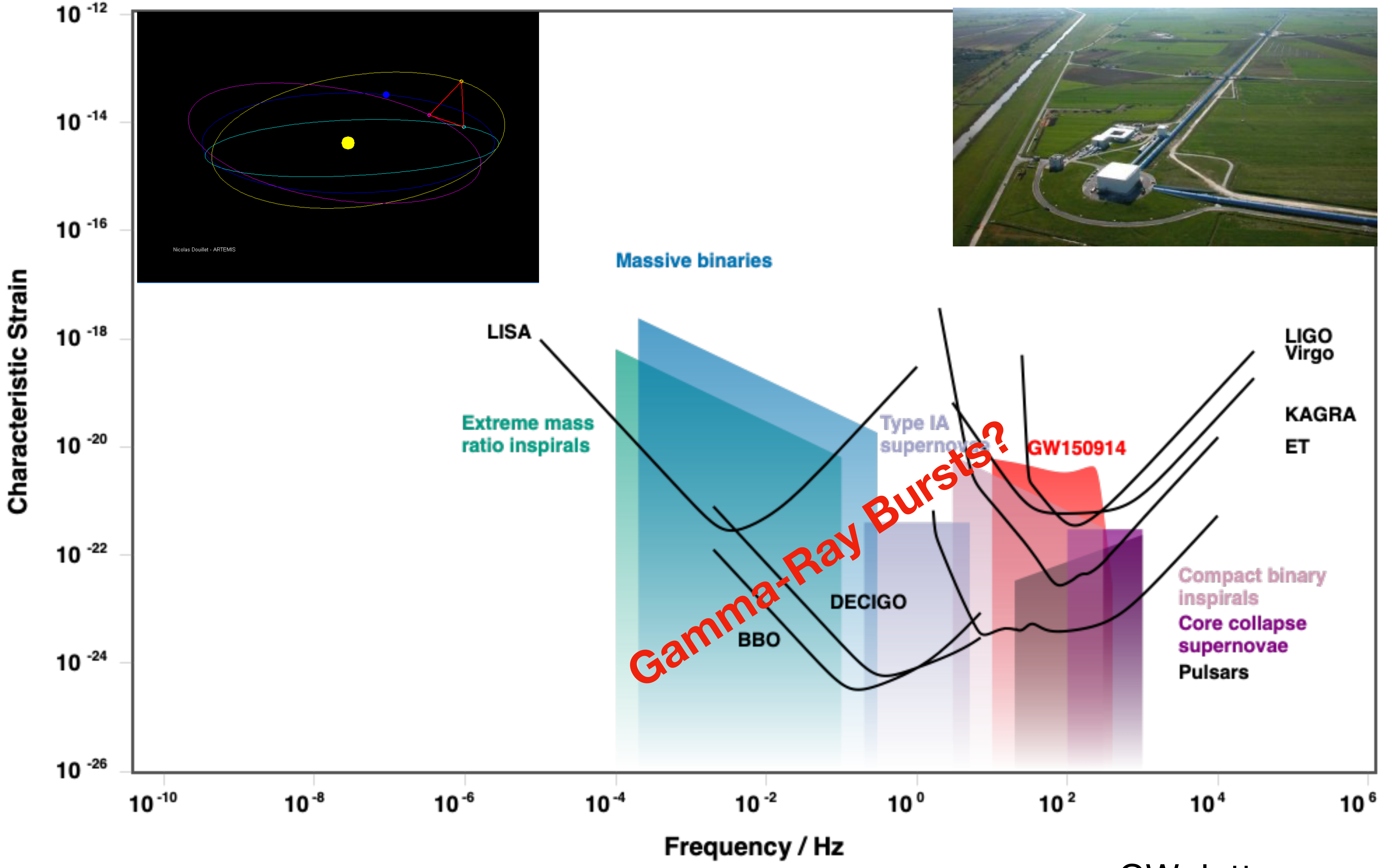
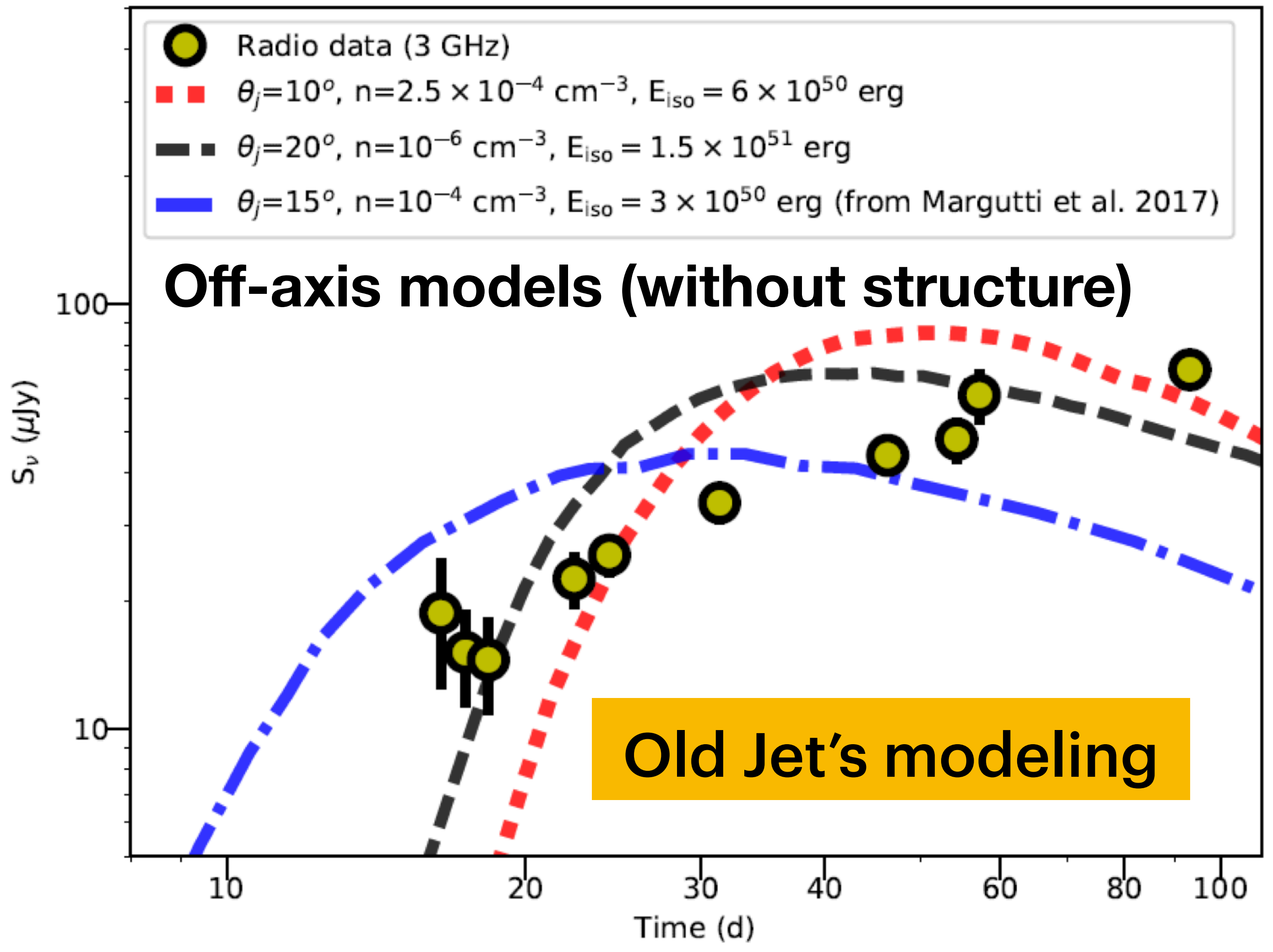
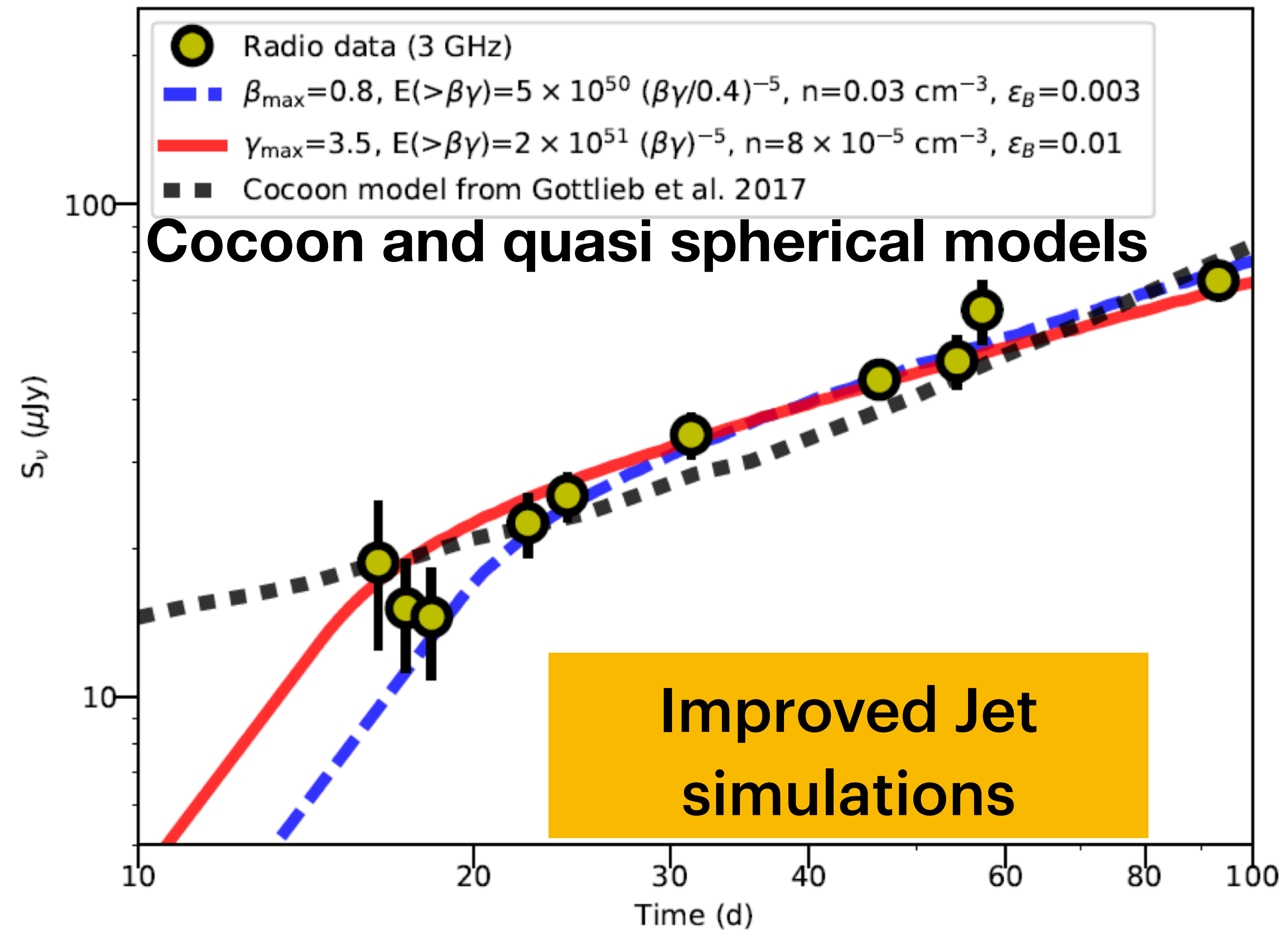


GWplotter.com

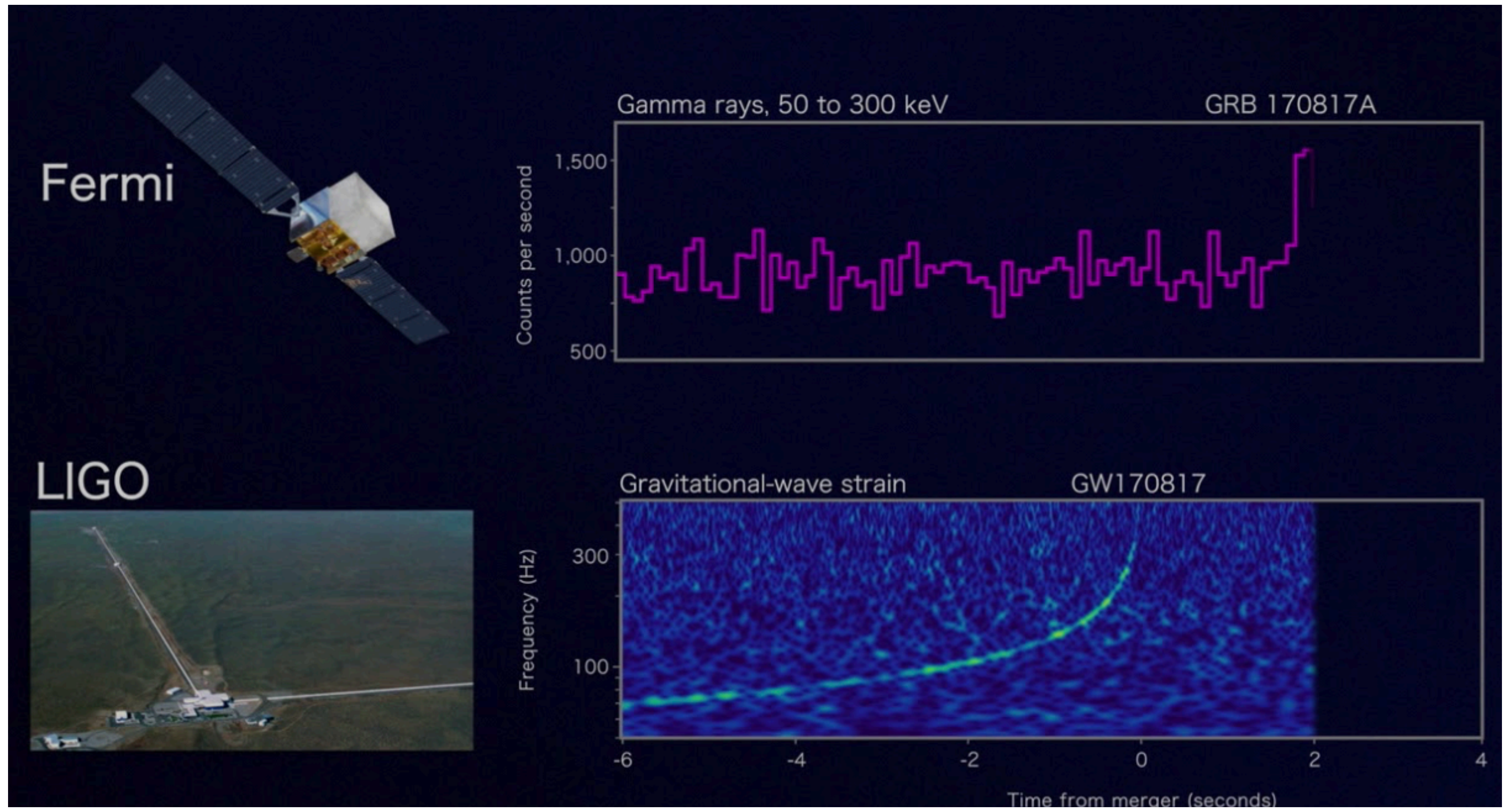
Multi-messenger Astrophysics: GRBs

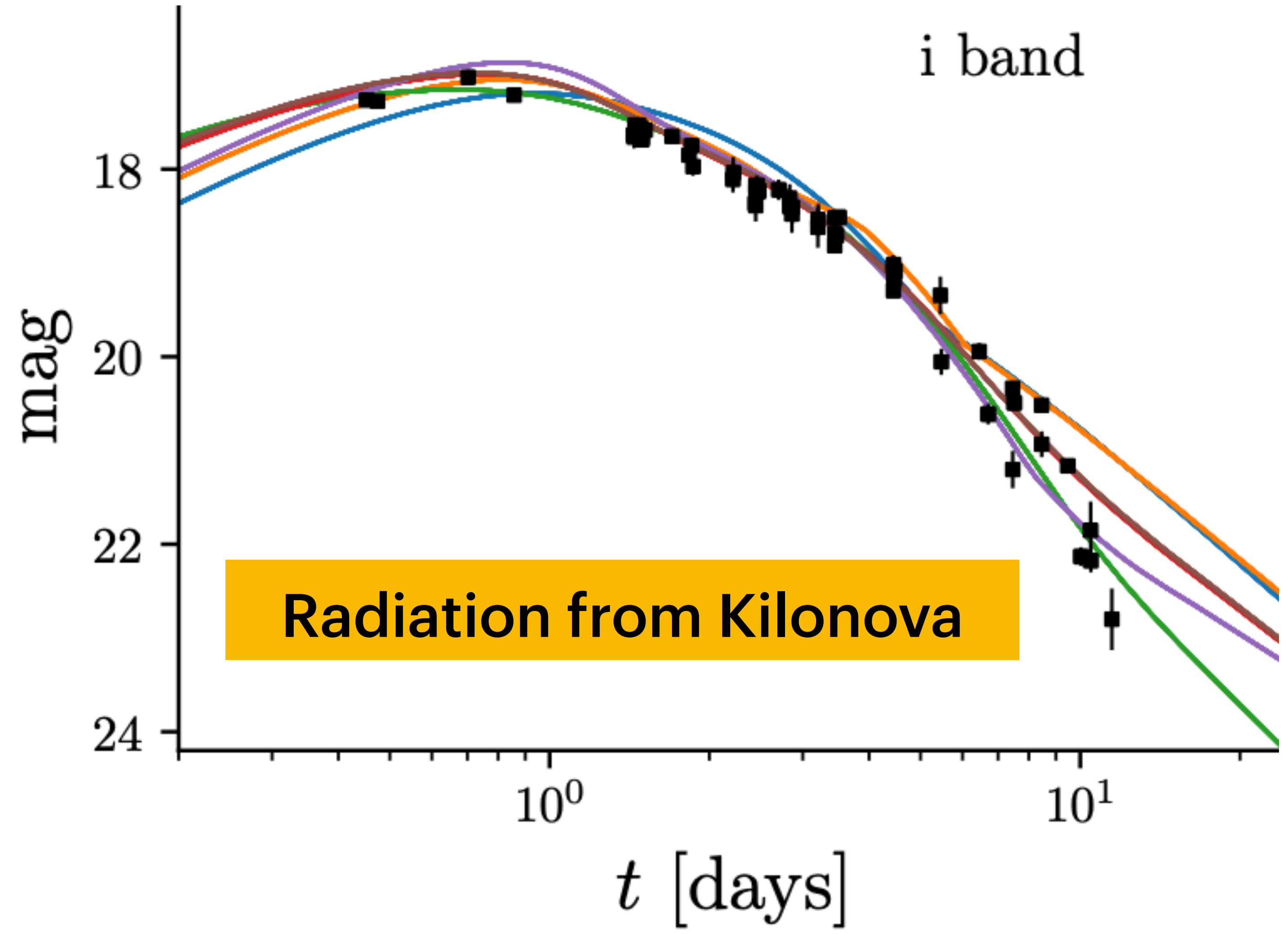
Non-photonic signals + Electromagnetic counterparts





Mooley et al. 2018





Breschi et al. 2021

Figure Credits: Dado et al. 2022

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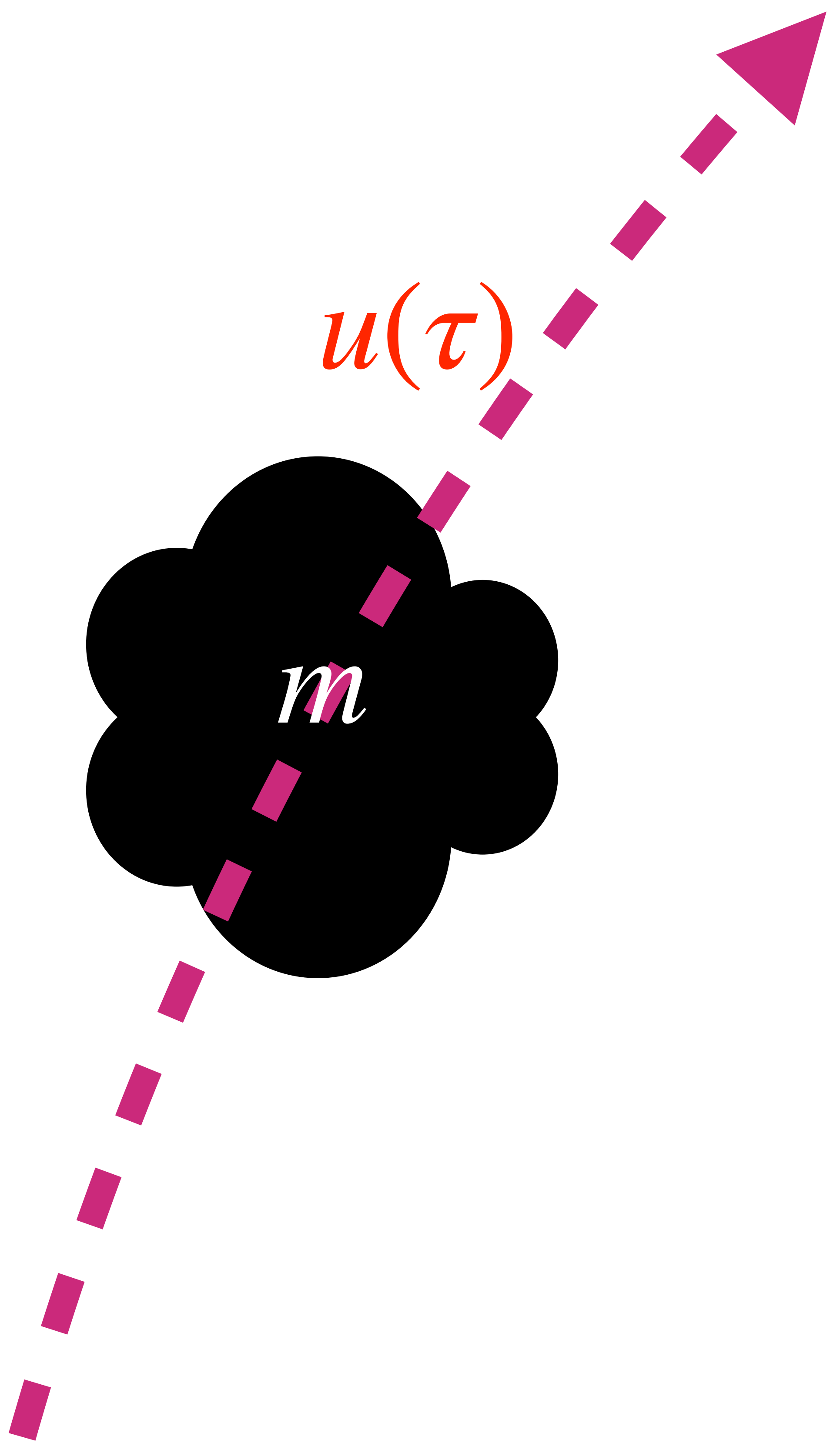
GW memory from ultra-relativistic sources



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

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

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

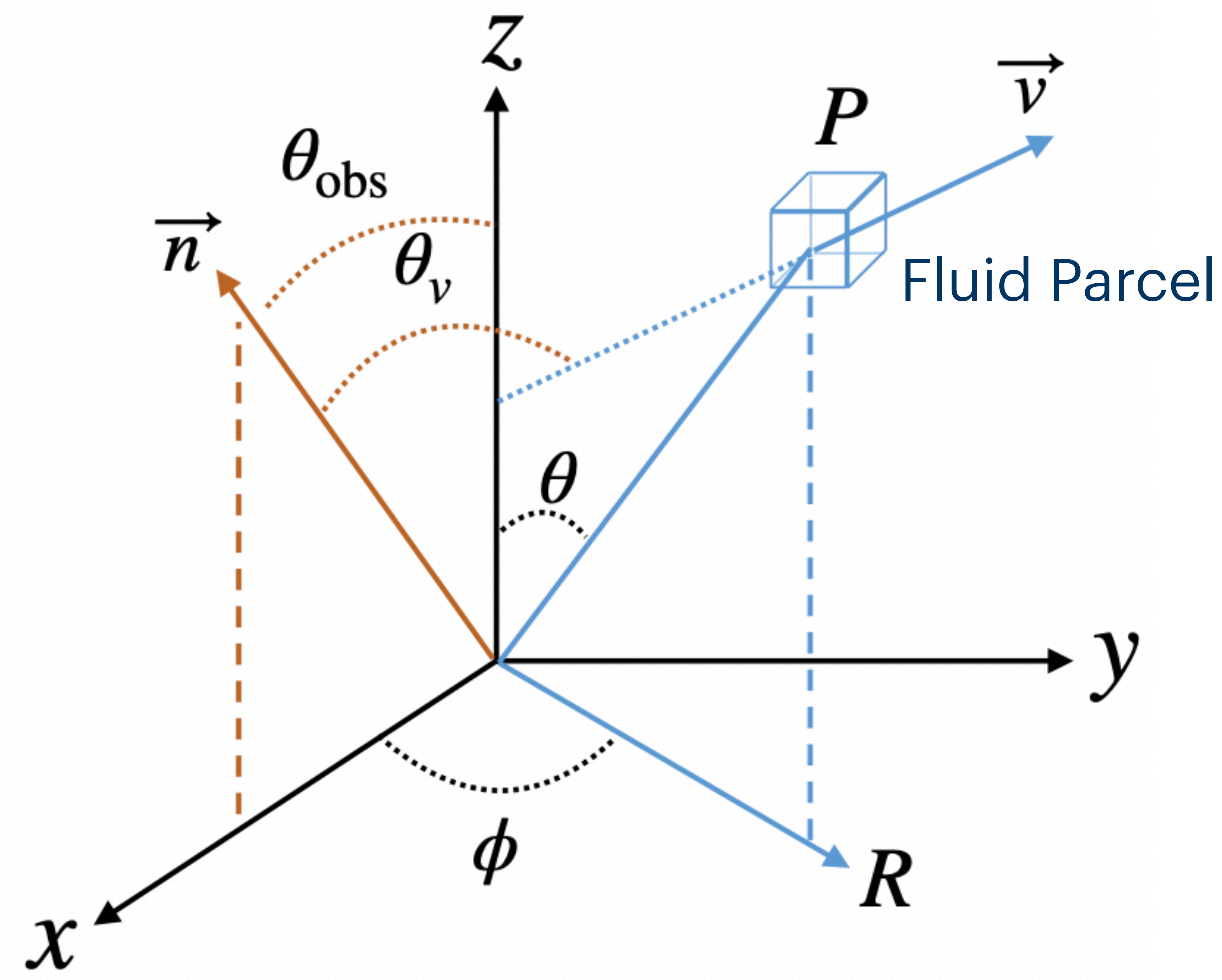
Braginskii & Thorne 1987, Segalis & Ori 2001, Sago 2004, Akiba et al. 2013, Birnholtz & Piran (2018), Leiderschneider & Piran 2021

GW memory from ultra-relativistic sources

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

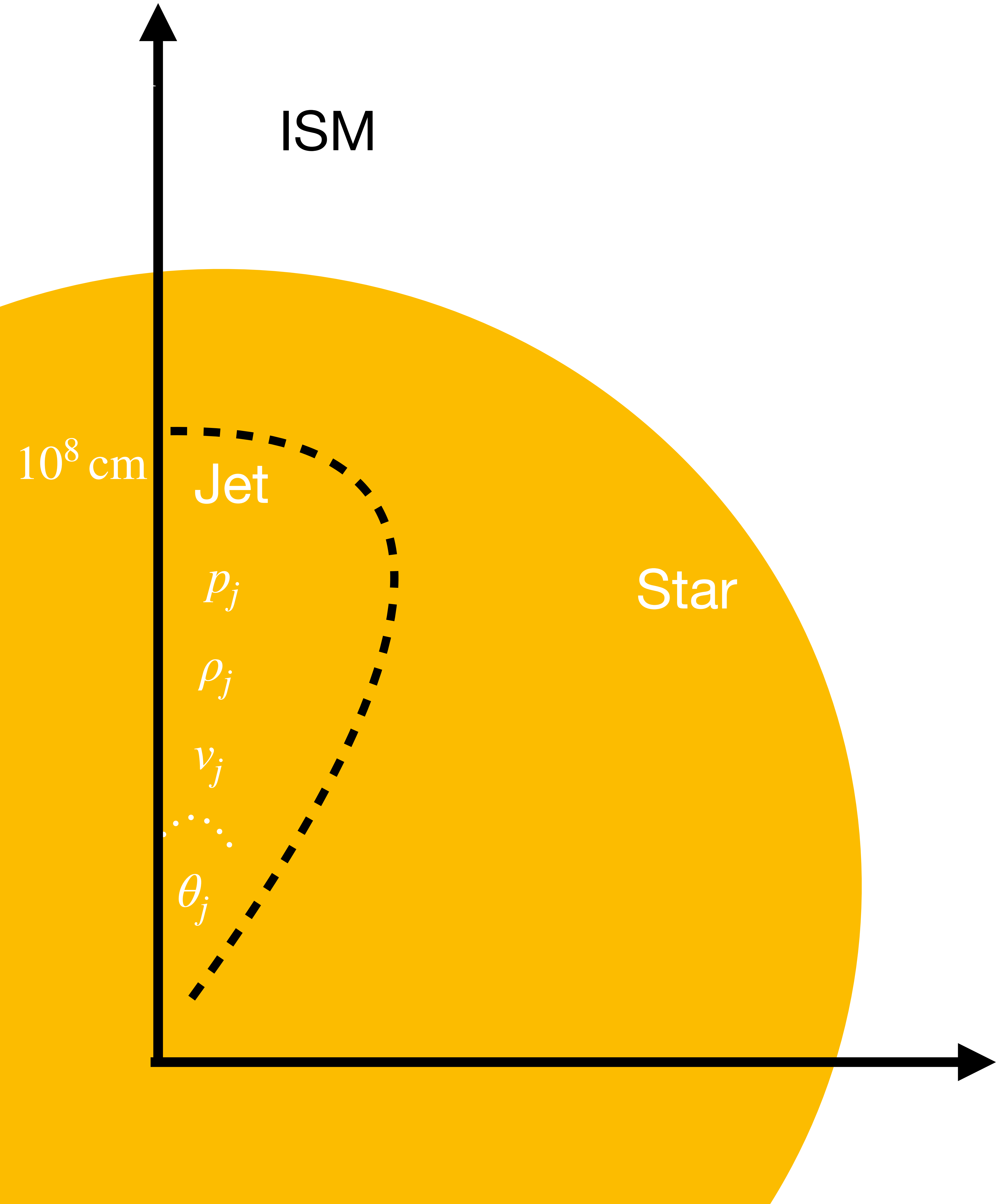
$$h_\times \equiv h_{xy}^{TT} = h_{yx}^{TT} = \frac{2G}{c^4}\frac{E}{D}\frac{\beta^2 \sin^2\theta_v}{1-\beta^2\cos\theta_v}\sin 2\Phi$$

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

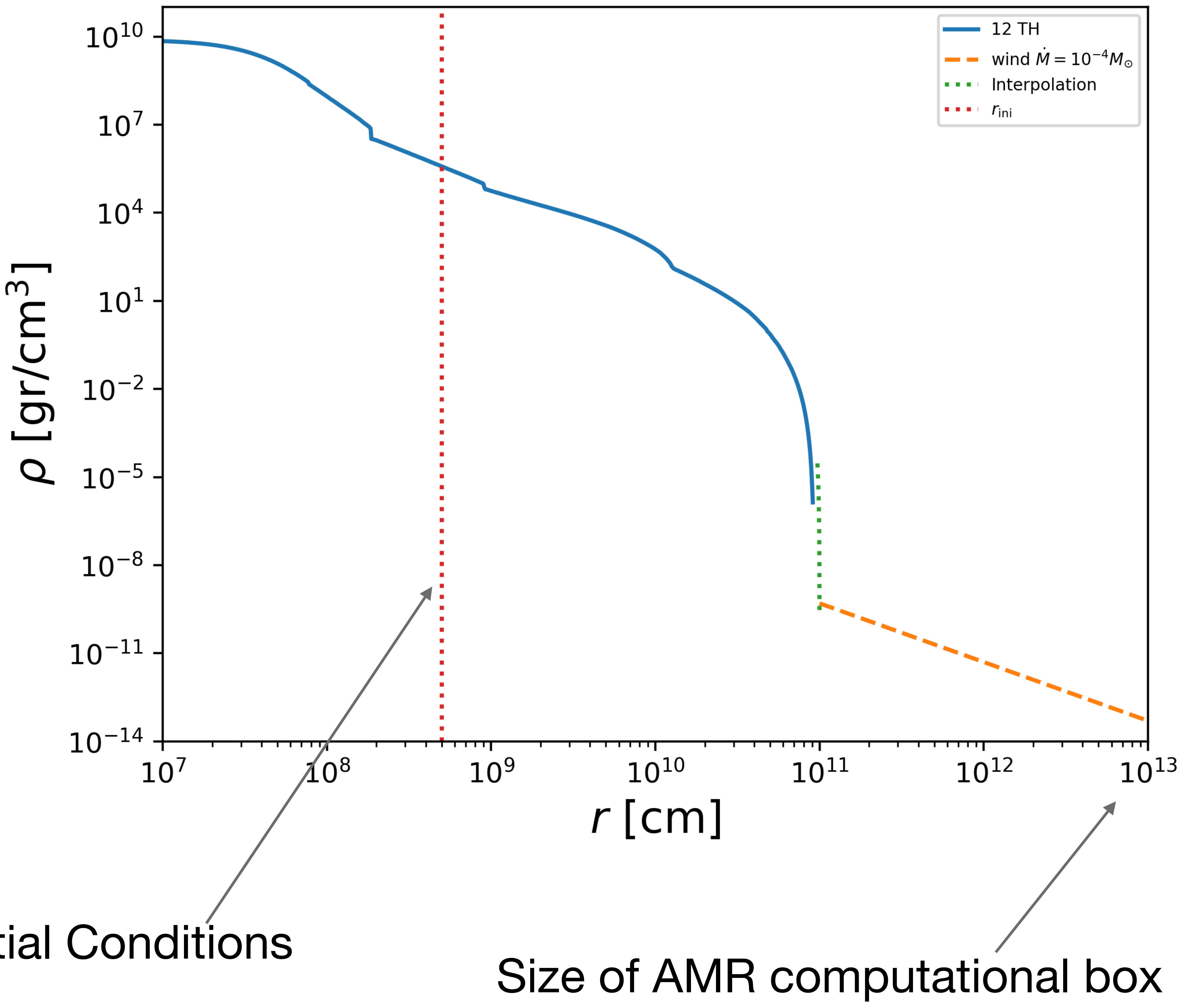


Initial conditions

(AMR Mezcal Code: De Colle et al. 2012)

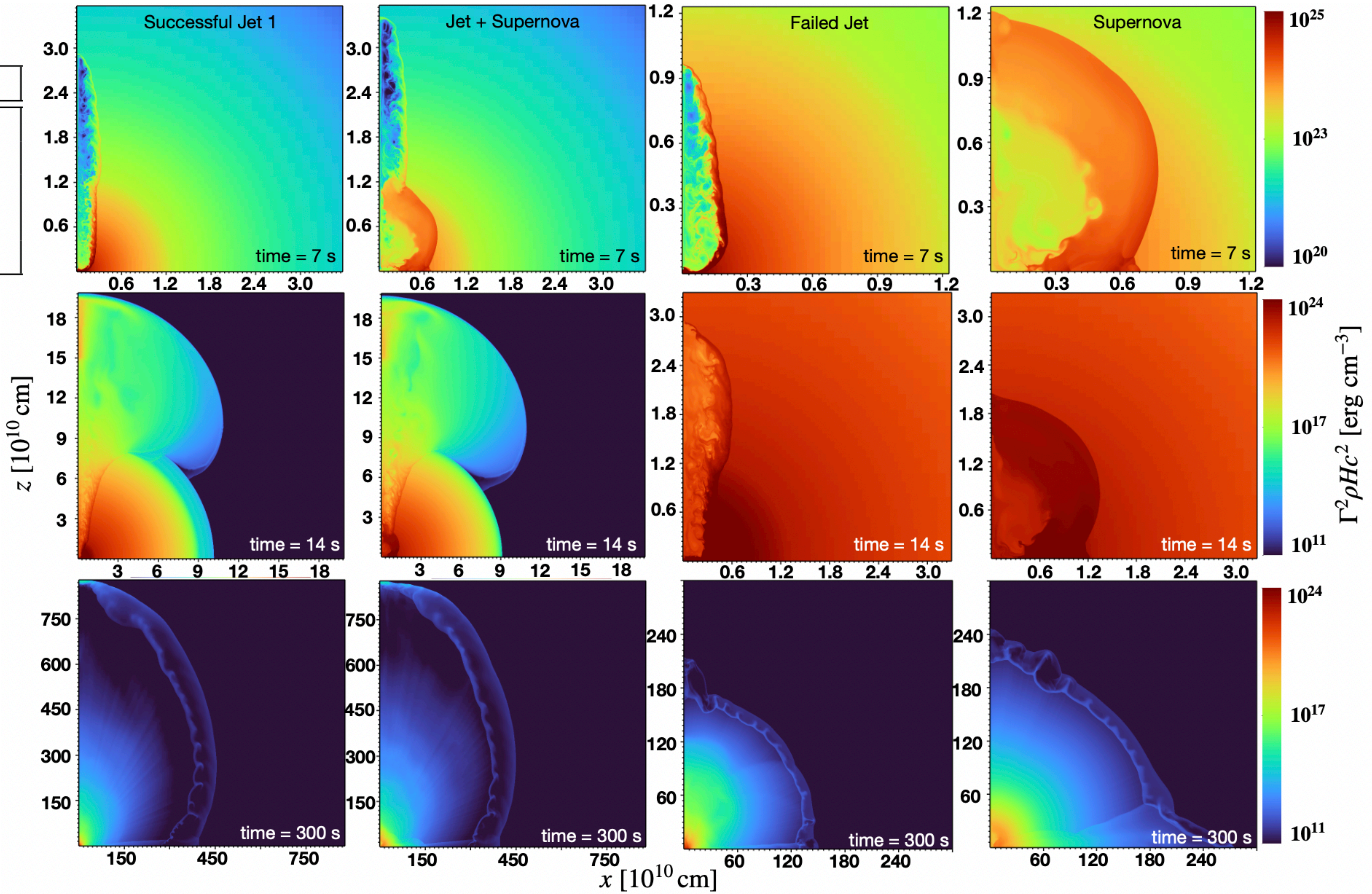


- Stellar striped envelope WR (Woosley & Heger 2006)

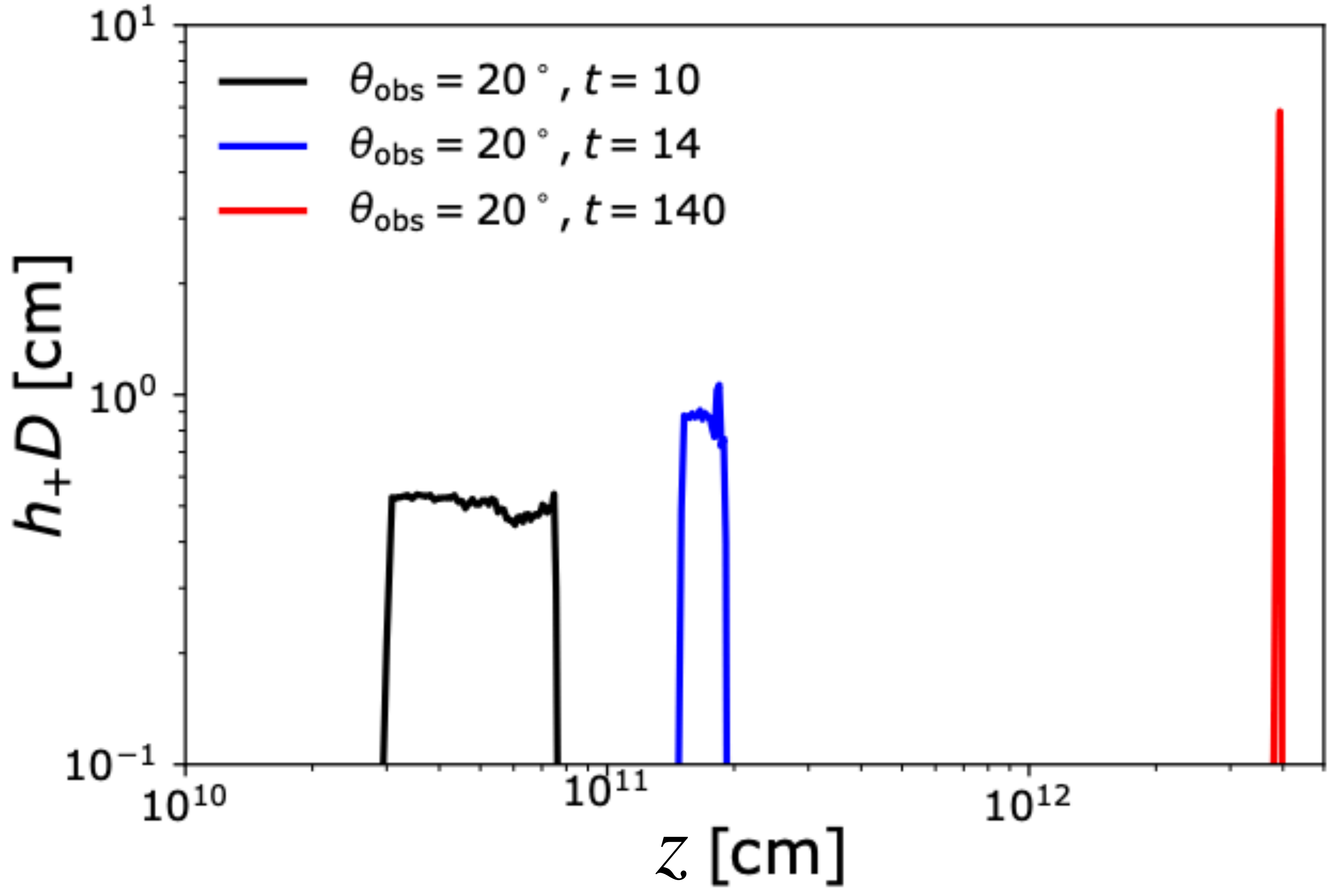


Jet dynamics

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}



Where is the GW emission produced?



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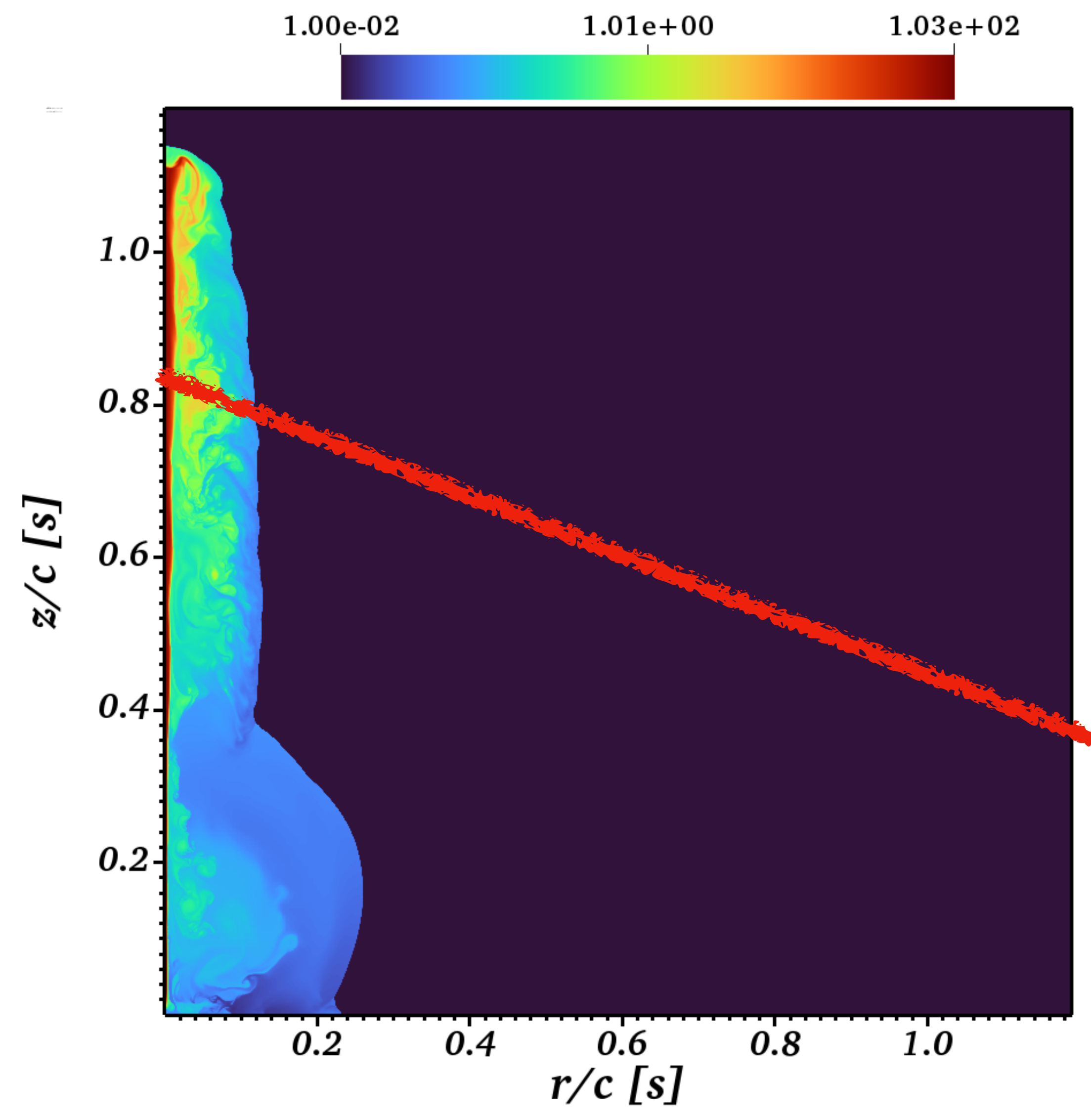
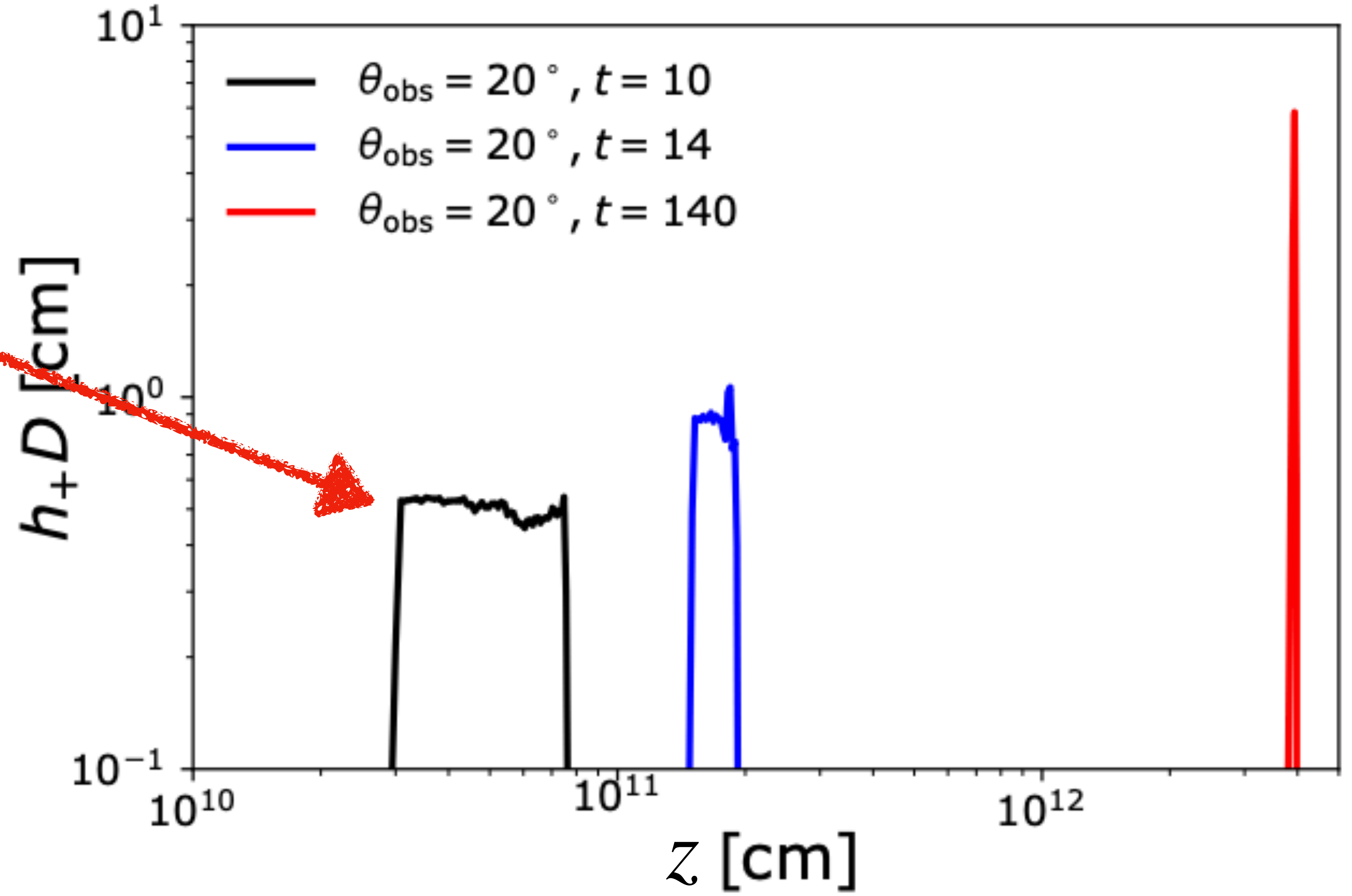
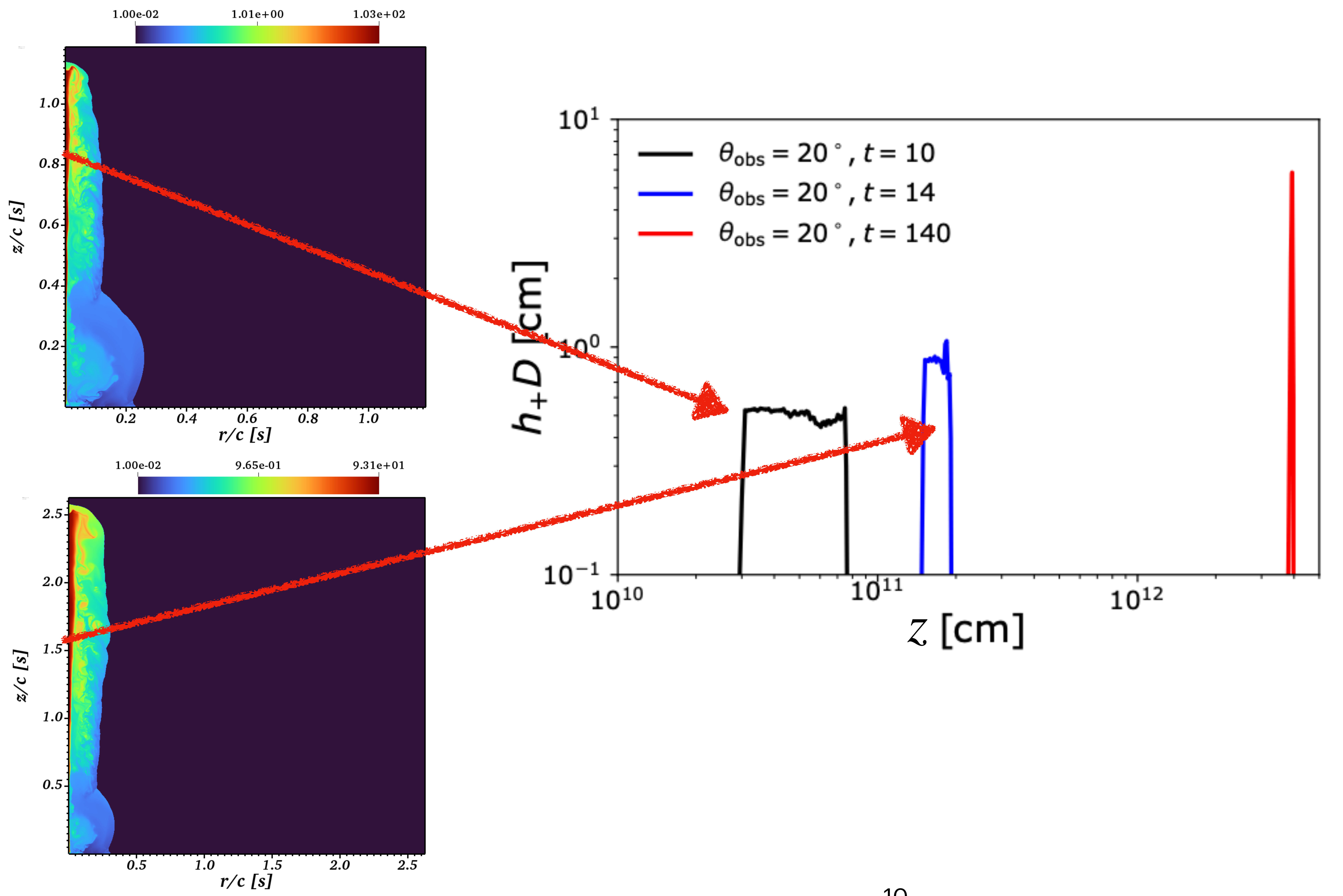
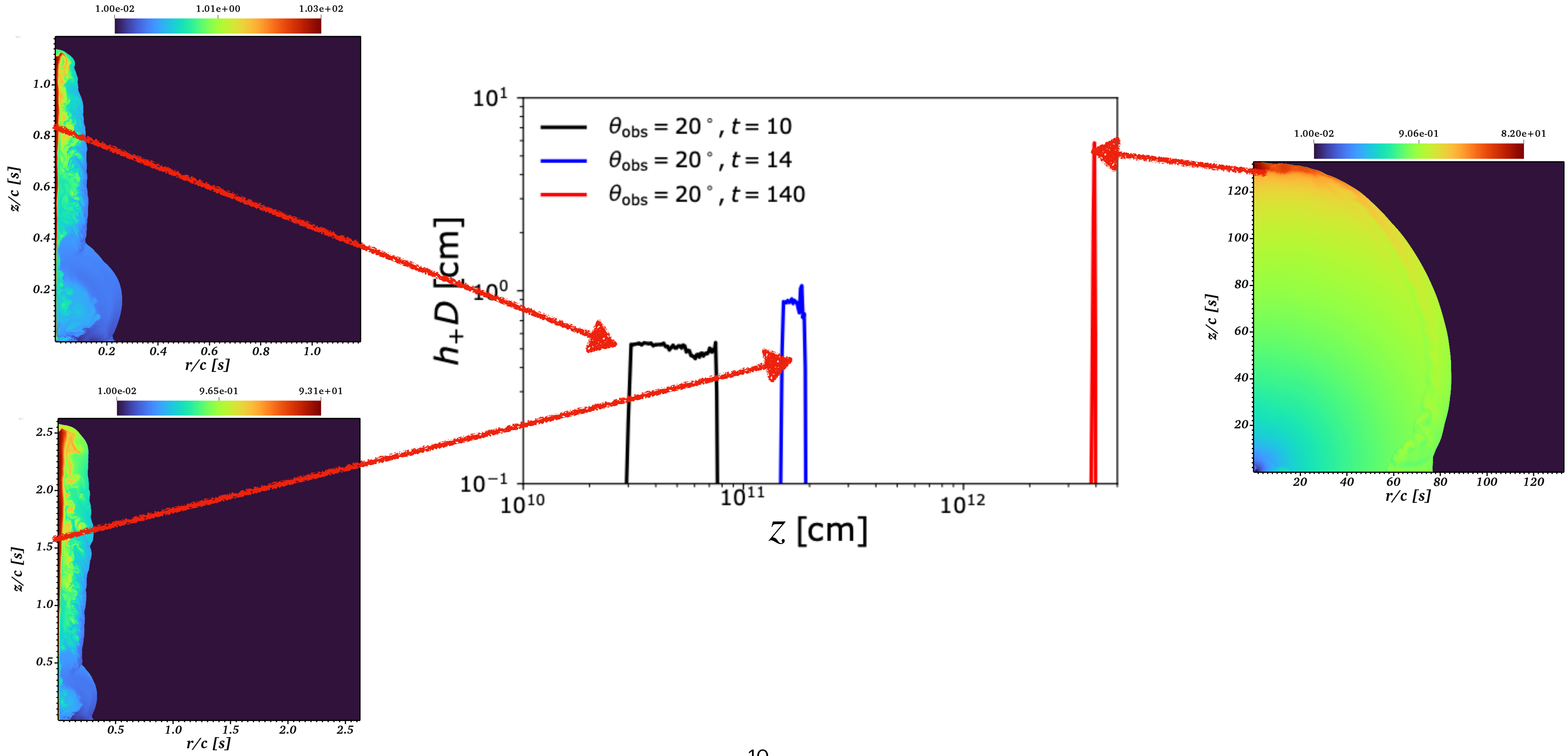




Where is the GW emission produced?

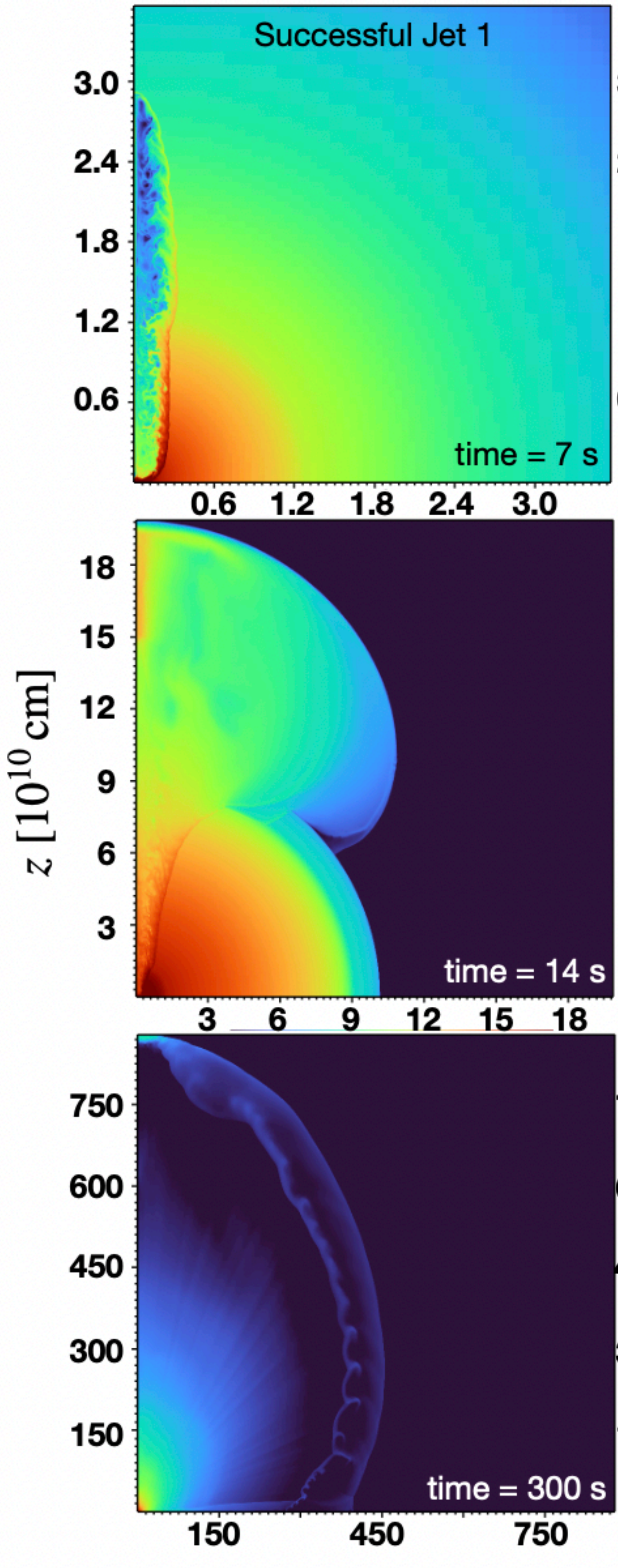


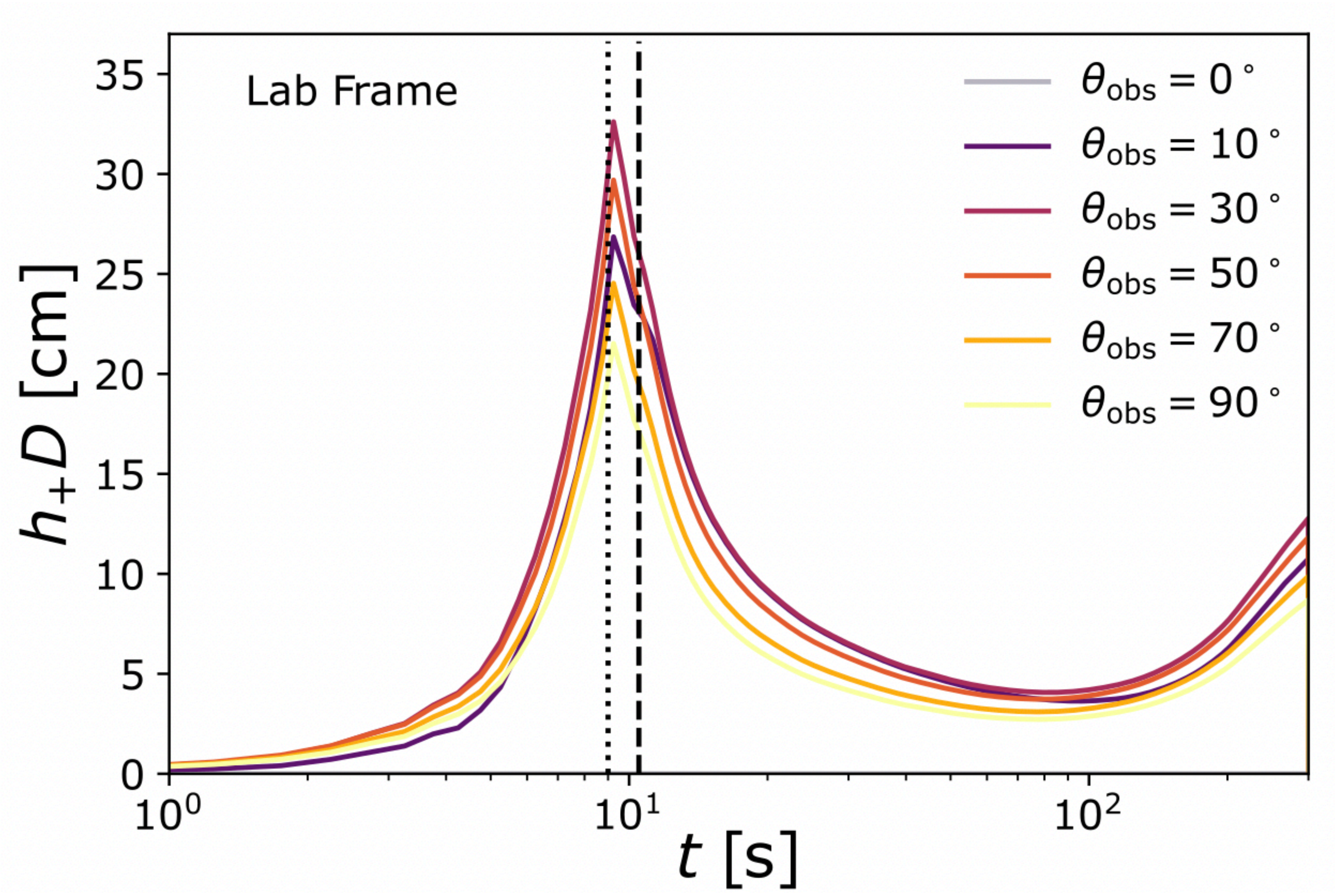
Where is the GW emission produced?



Succesful jet - GW signal

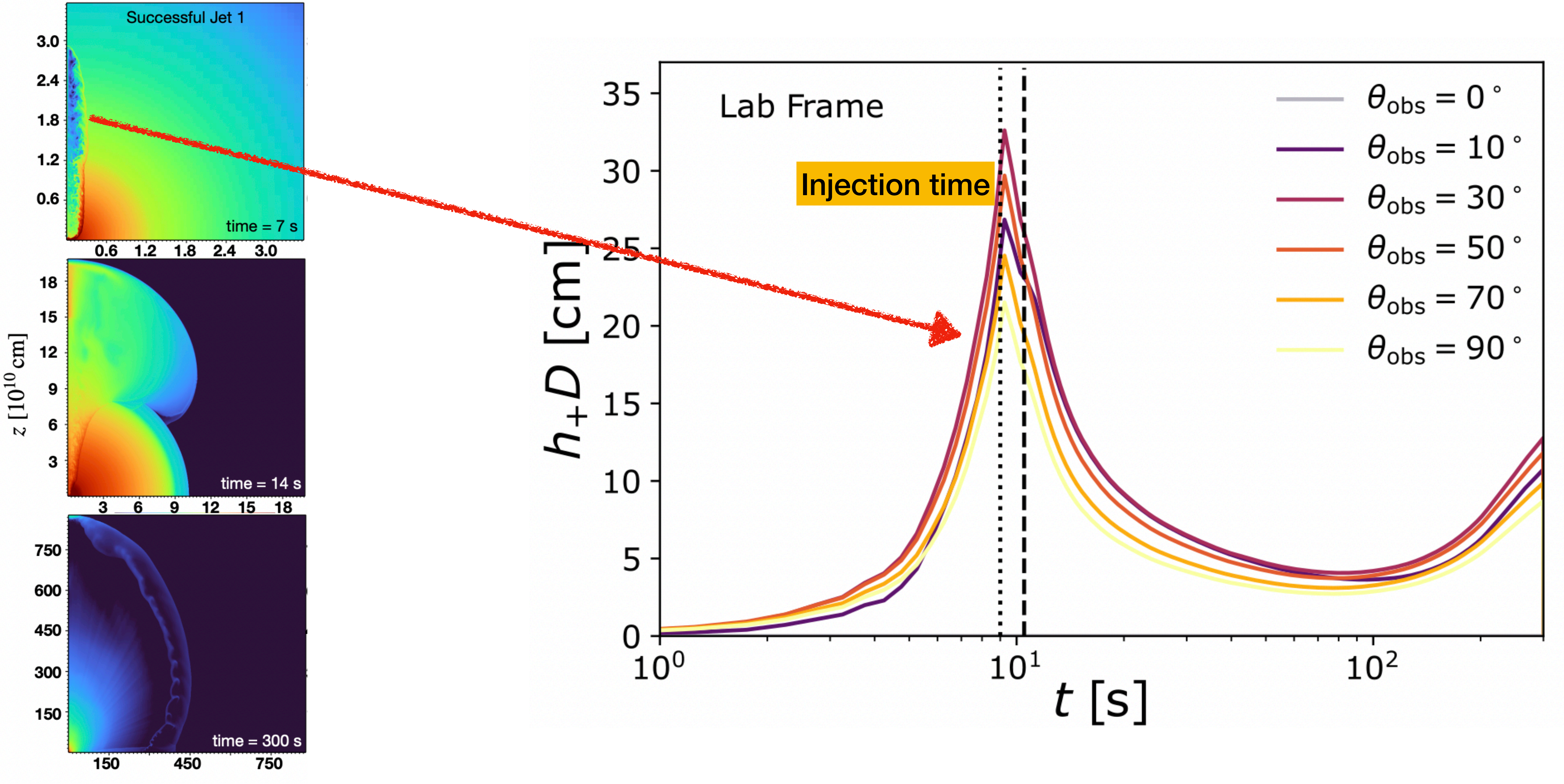
$t = t_{\mathrm{obs}}$





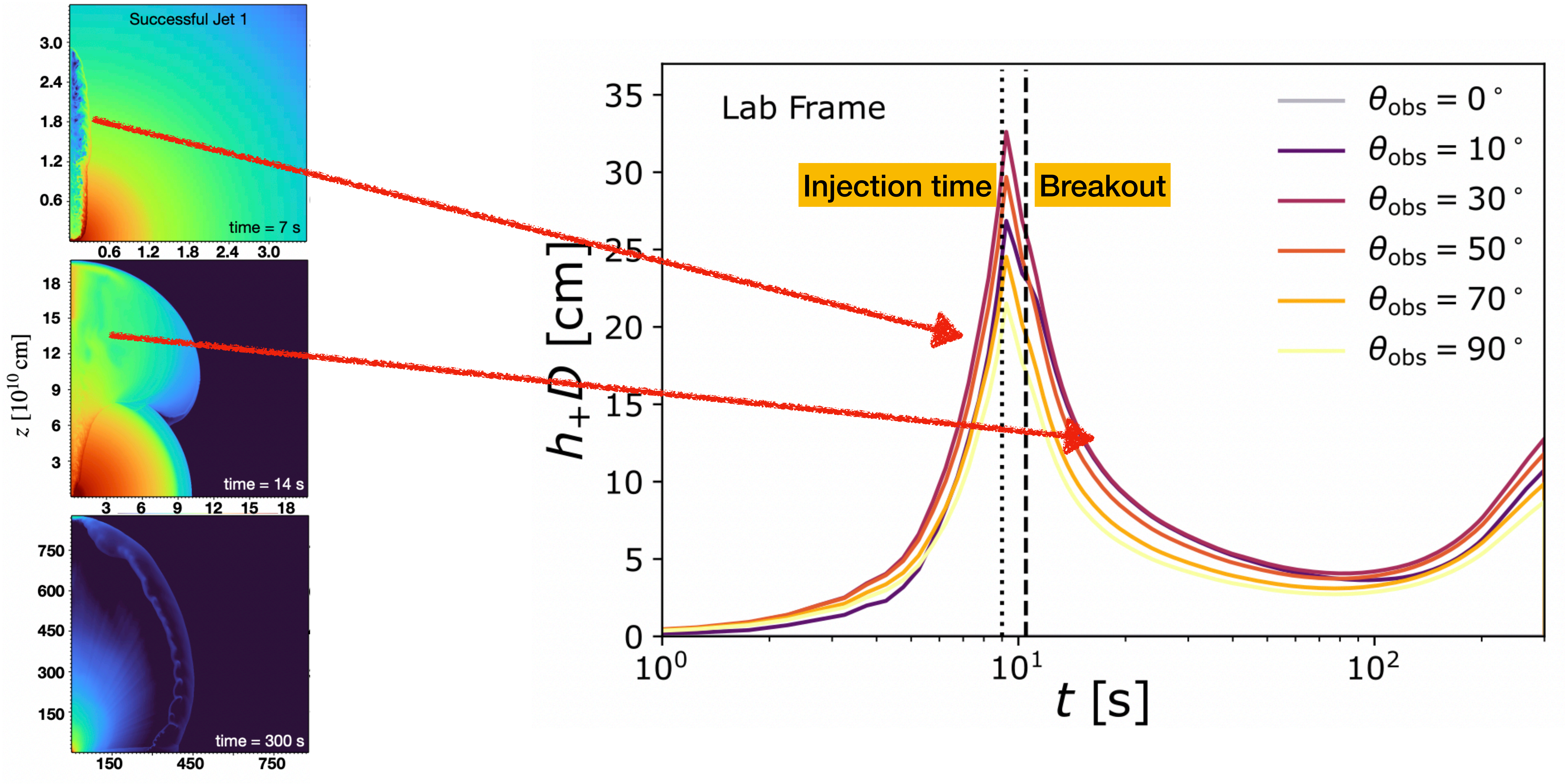
Succesful jet - GW signal

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



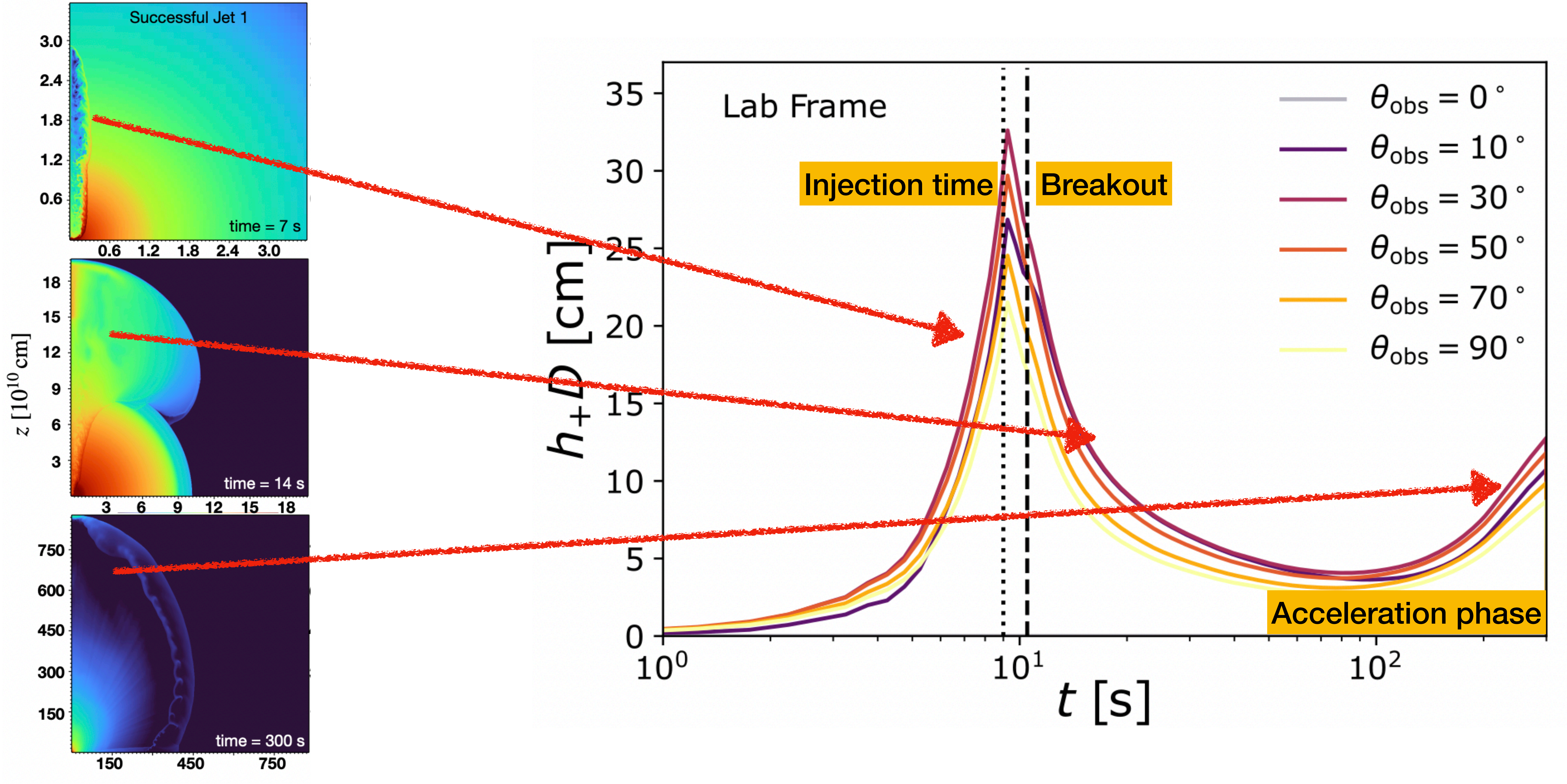
Succesful jet - GW signal

$$t = t_{obs}$$



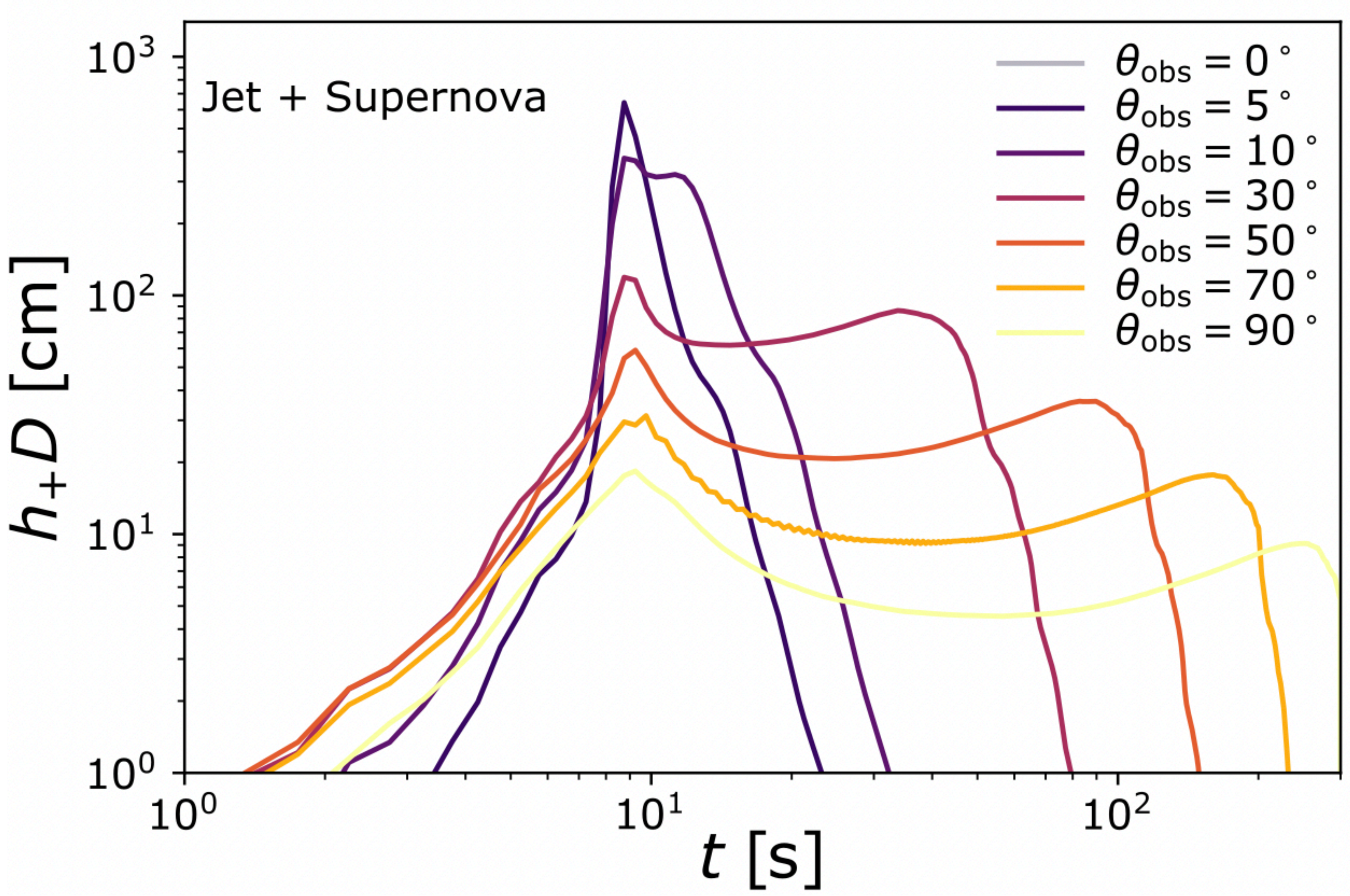
Succesful jet - GW signal

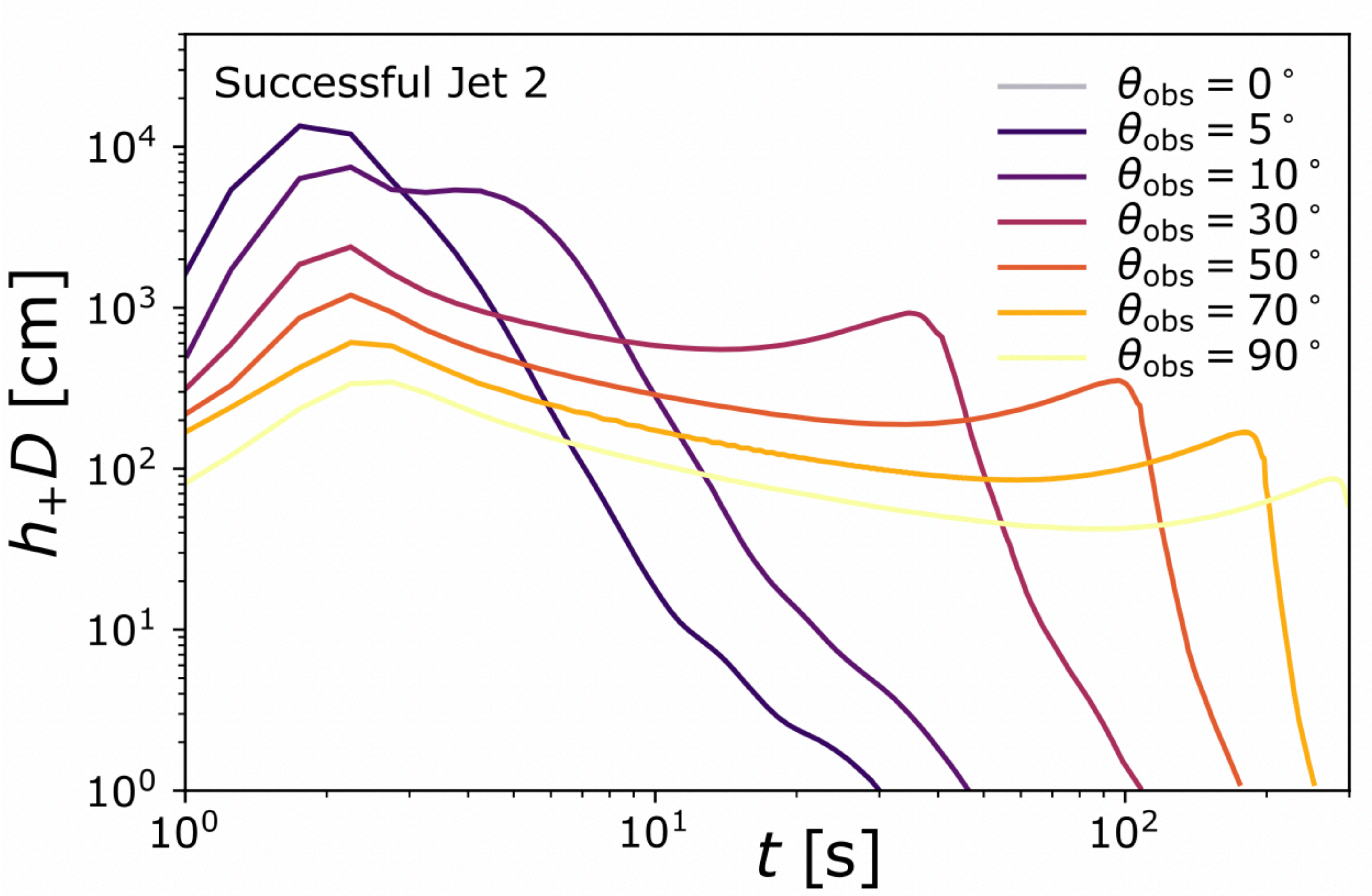
$$t = t_{\rm obs}$$



GW signal

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





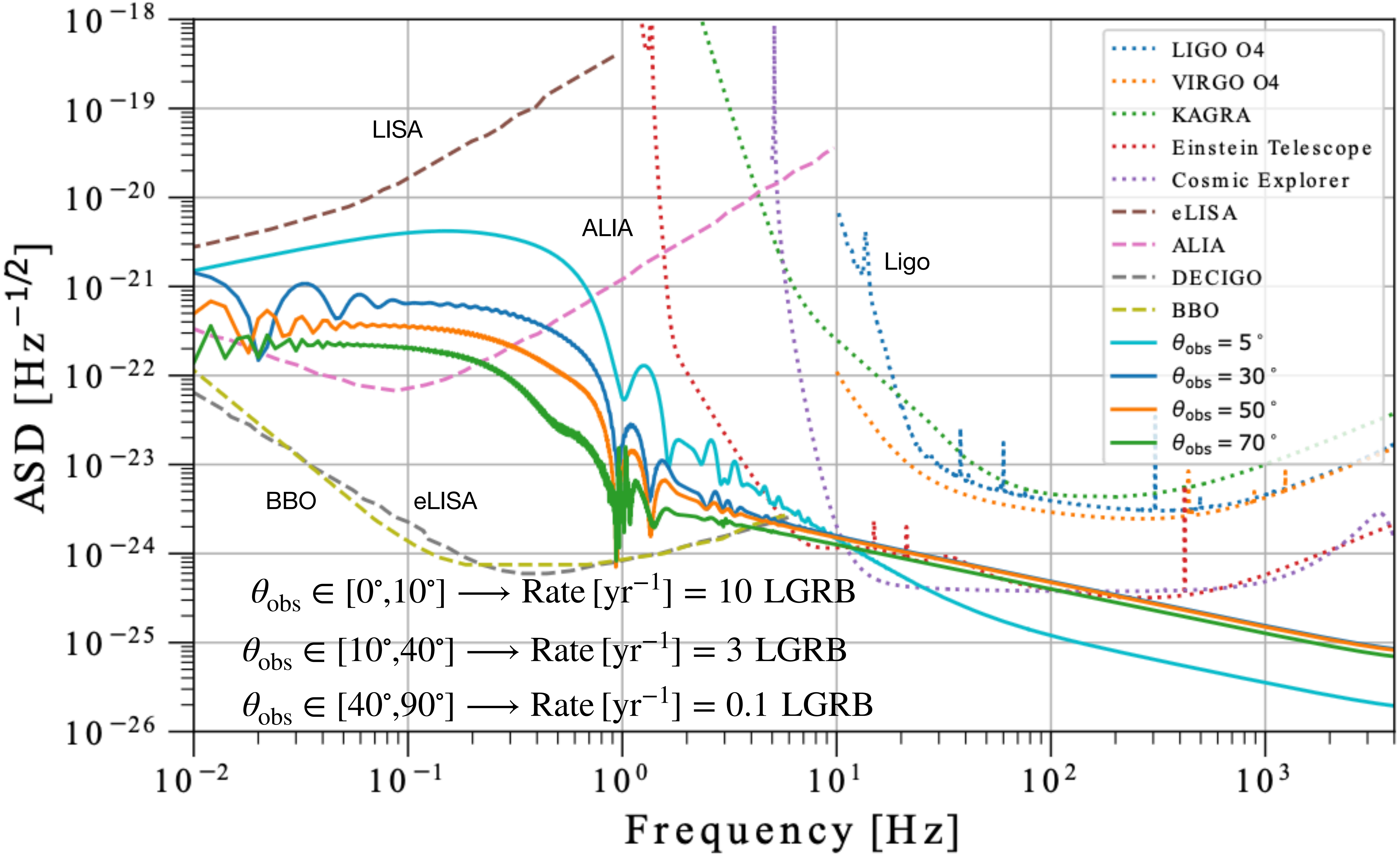
Detectability

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

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

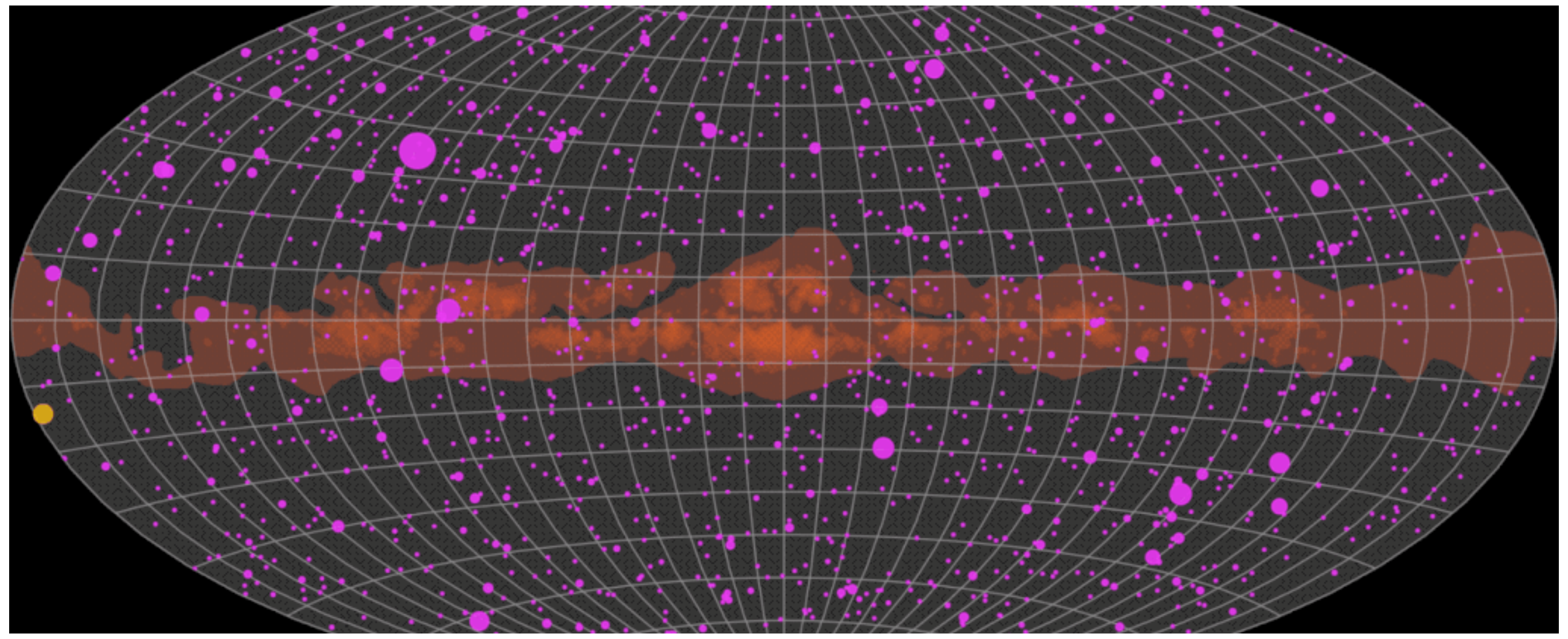
$$D = 1\,\mathrm{Mpc}$$

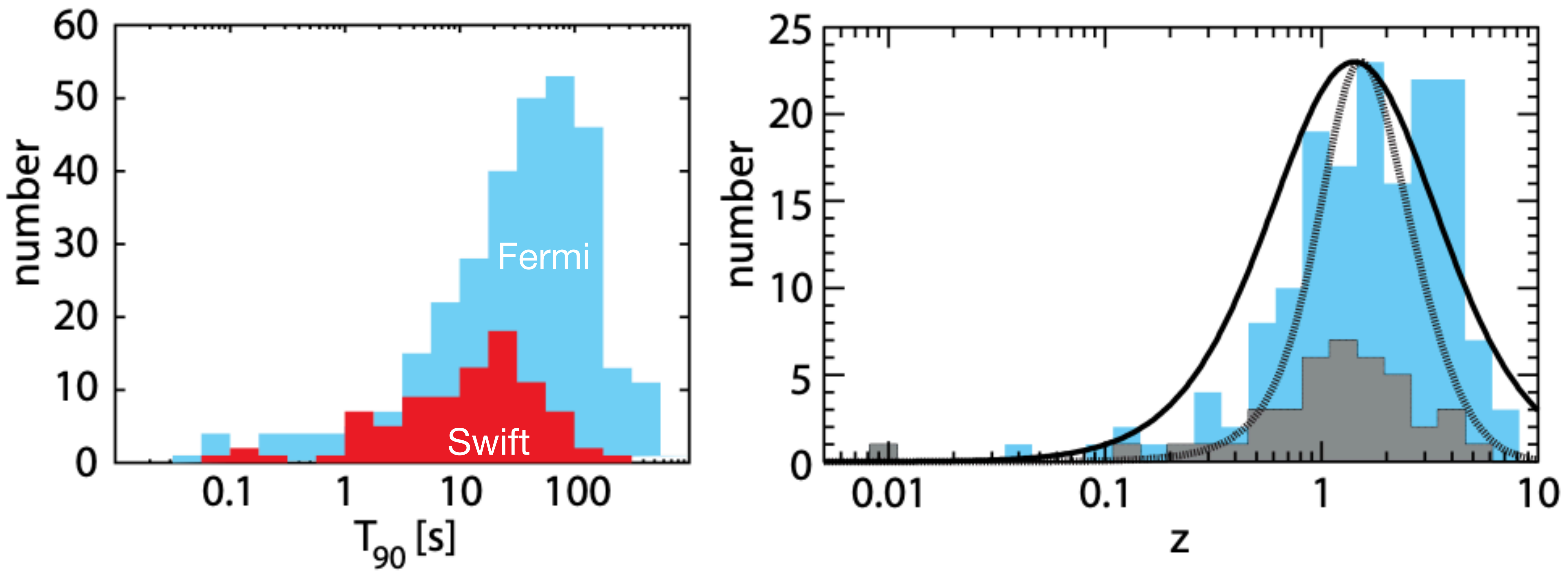
$$ASD = 2f^{1/2}\,|\tilde{h}(f)|$$



Sensitivity curves from Moore et al. 2014

Detectability



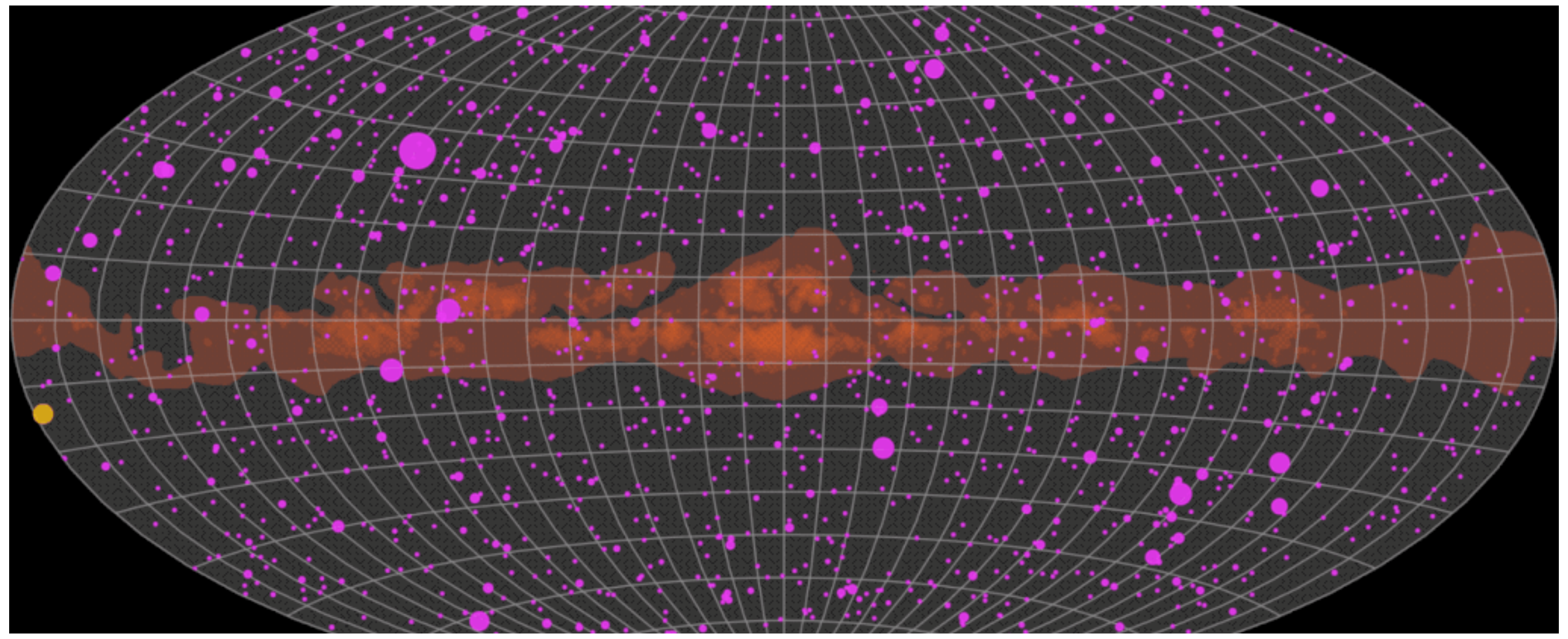


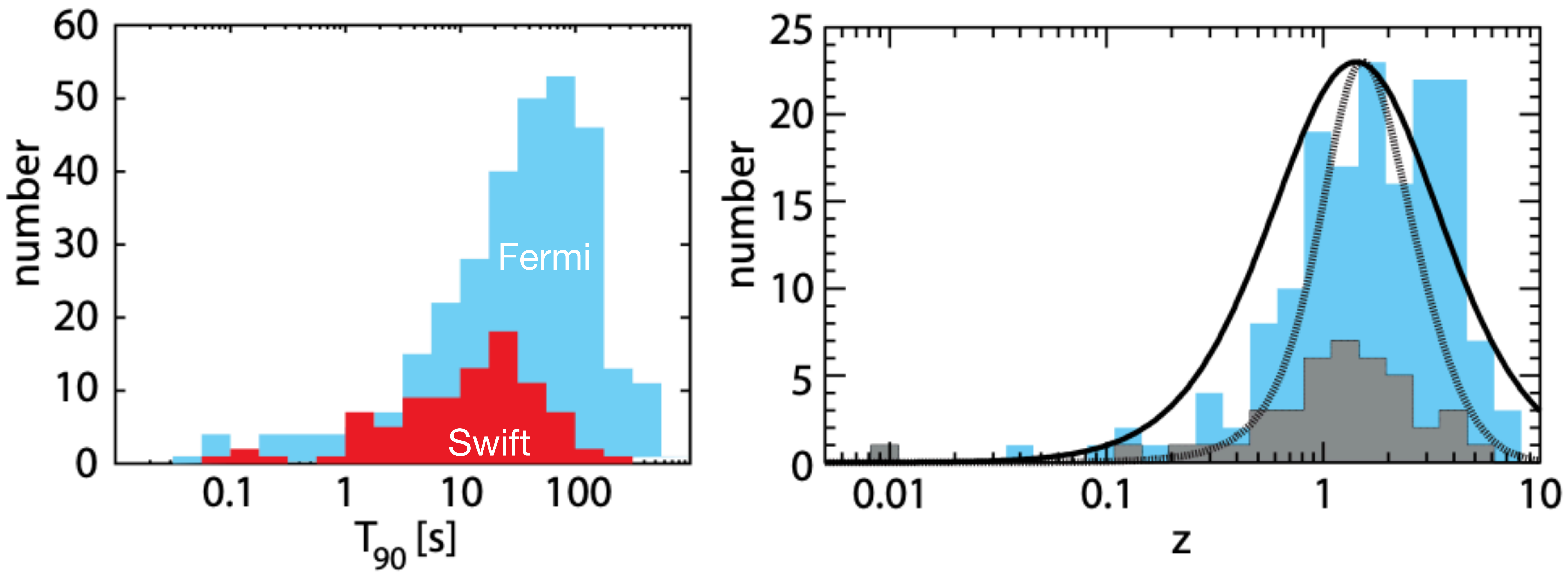
Gehrels, Ramirez-Ruiz & Fox (2009)

Detector	Distance [Mpc]		Rate [yr^{-1}]		
	5°	70°	$0^\circ - 10^\circ$	$10^\circ - 40^\circ$	$40^\circ - 90^\circ$
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}
LISA	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)

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}
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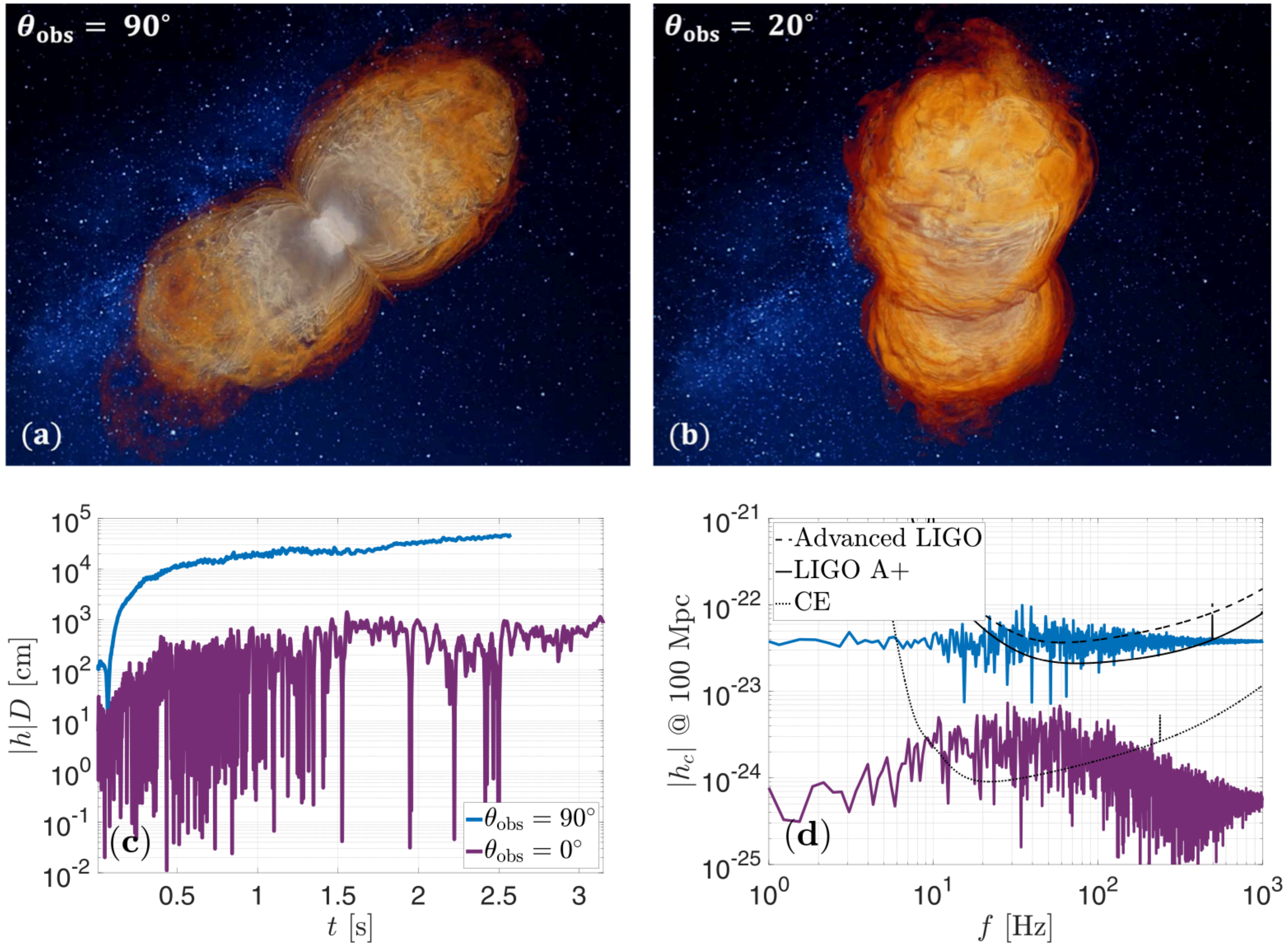
Urrutia, De Colle, Moreno & Zanollin (2022)

High frequency?



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

Our Currently methodology

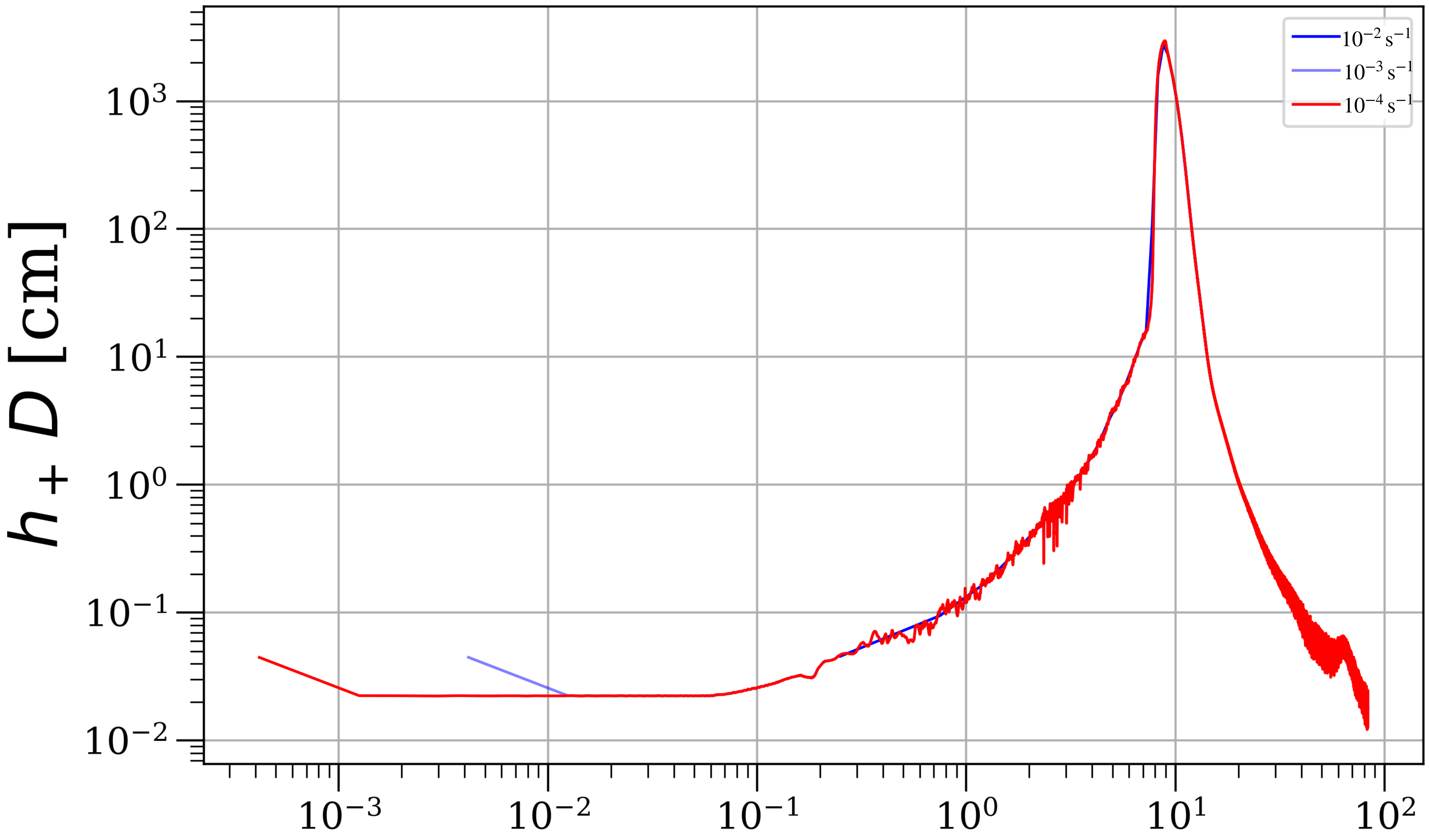
Jet dynamics (simulations) → Post-processing (GW signals) → Detectability

Sotorage ~ TB
Computational time: 3 days

New methodology

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

Sotorage ~ GB
Computational time: 1 week


$h_+ D$ [cm]
$10^{-2}\,s^{-1}$
$10^{-3}\,s^{-1}$
$10^{-4}\,s^{-1}$
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

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

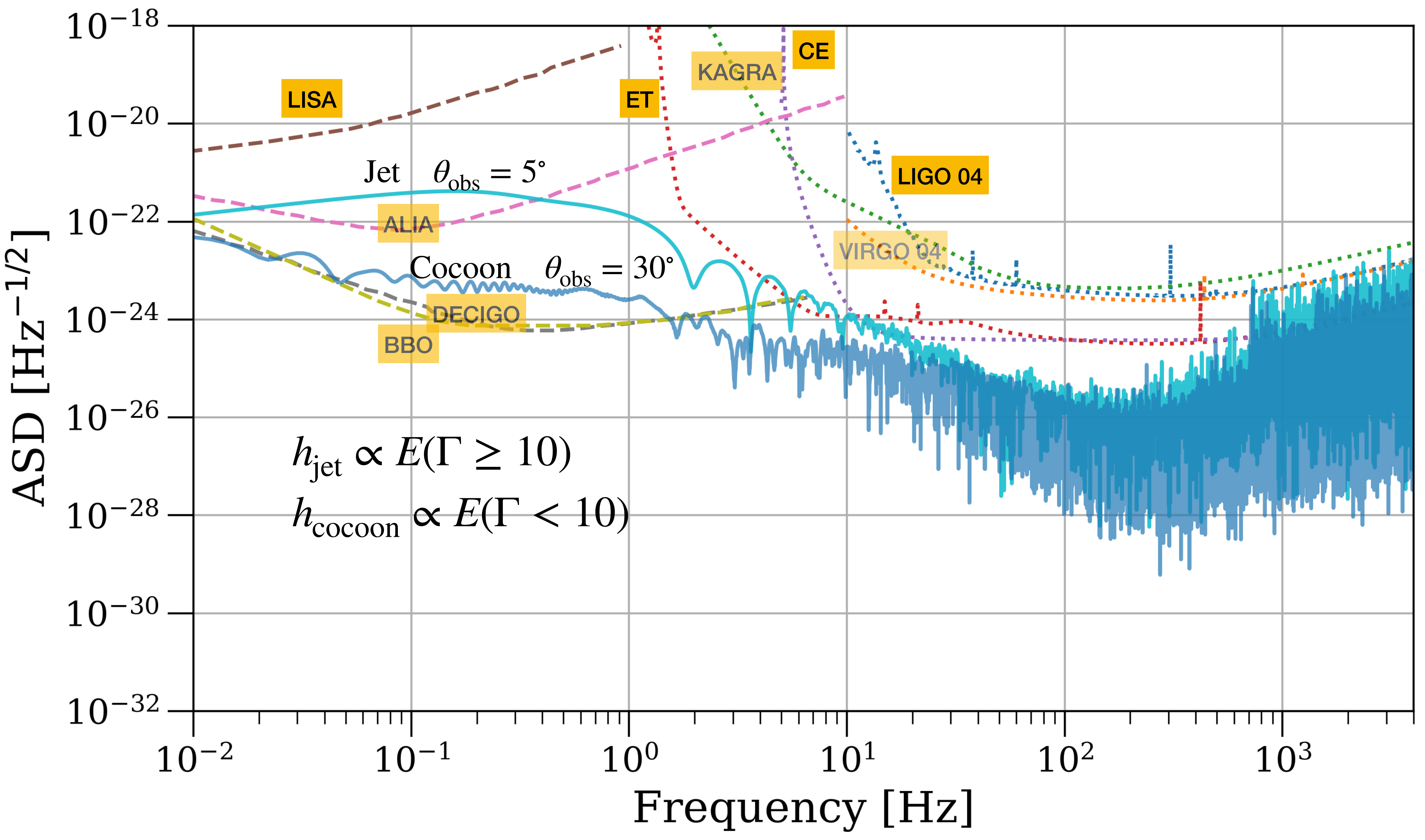
$ASD = 2 f^{1/2} |\tilde{h}(f)|$

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

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

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

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



Urrutia (in Prep)

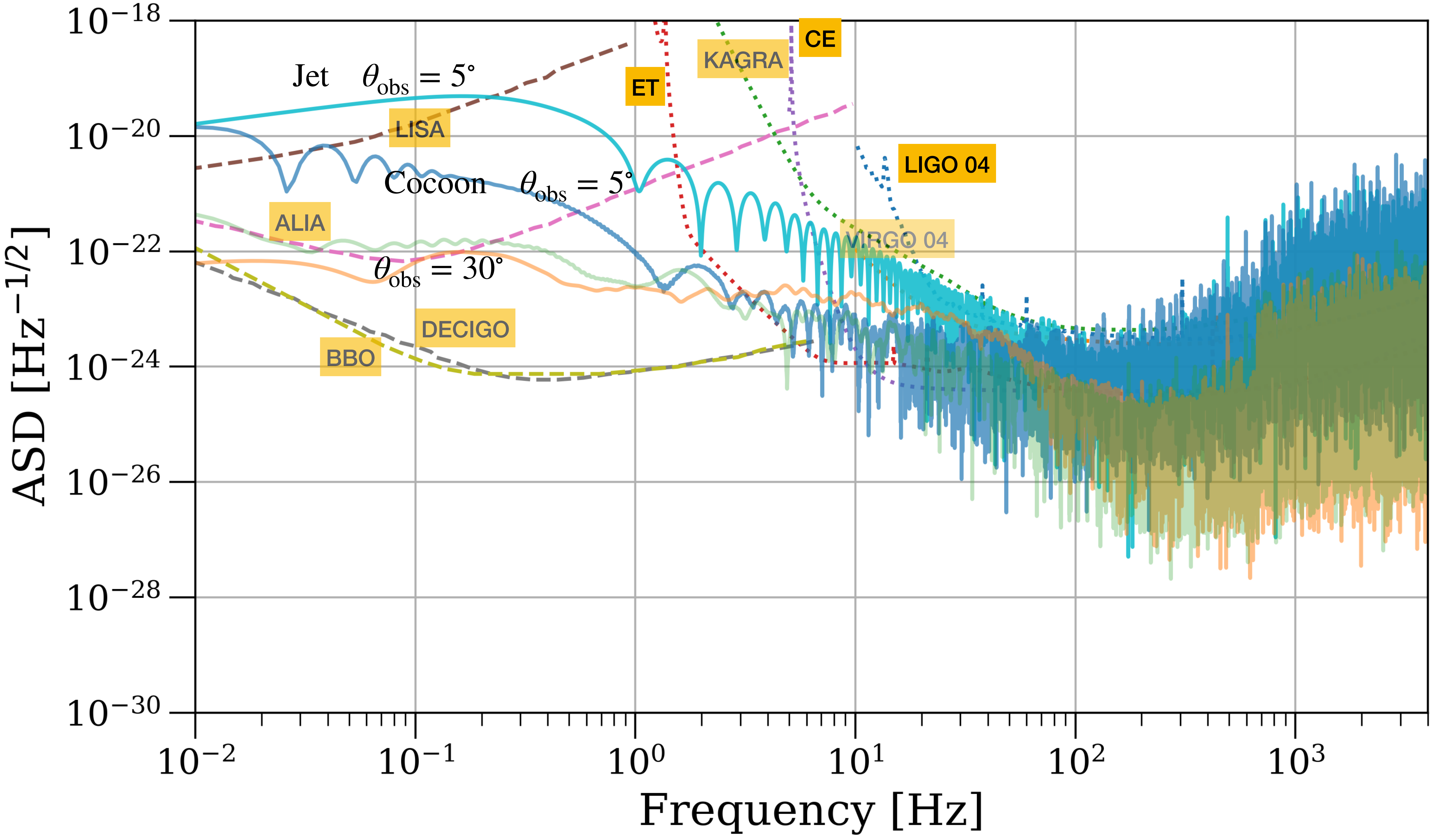
Estimation of GW signals during the jet propagation (not post-processing)

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

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

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

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

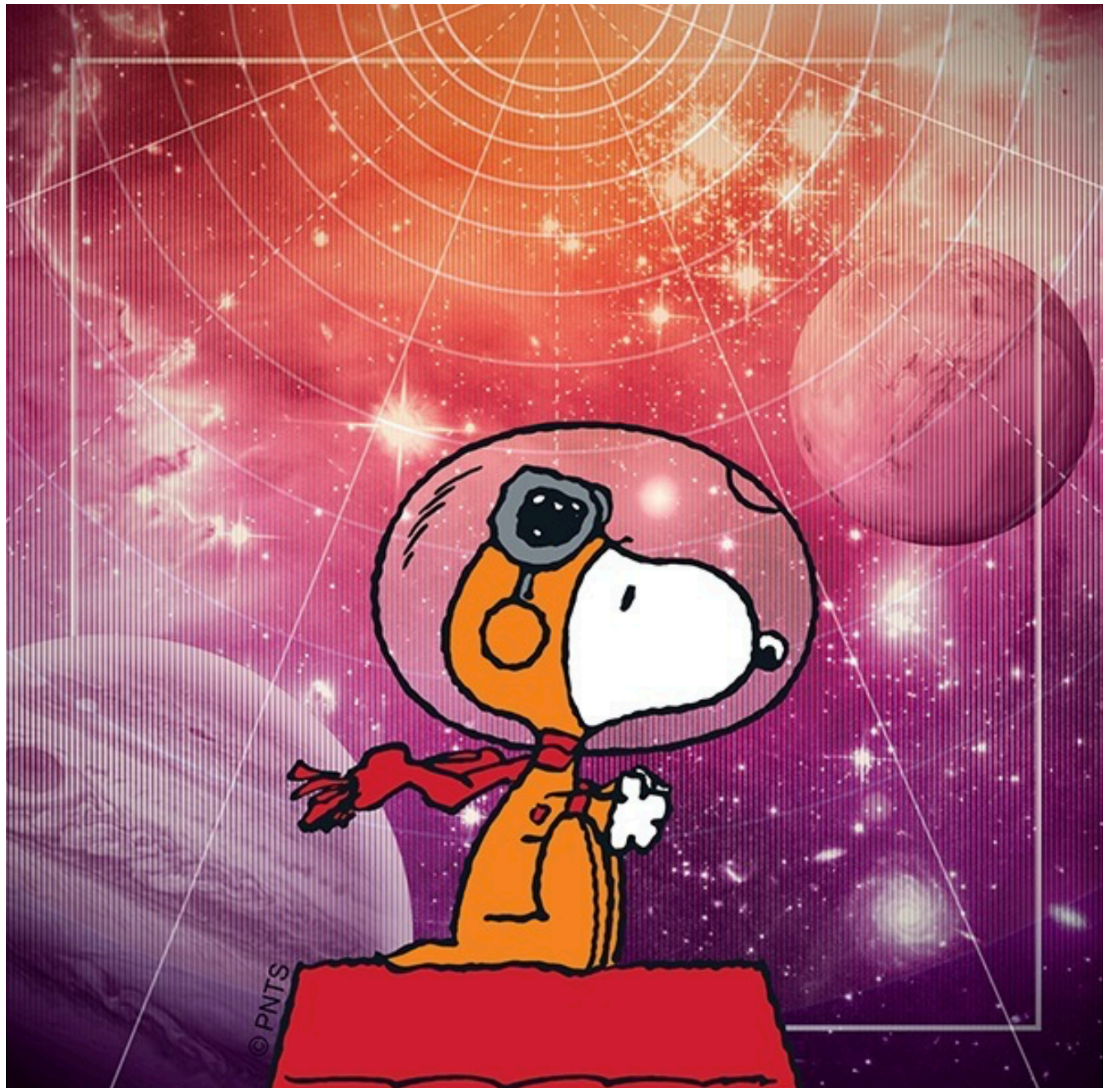


Urrutia (in Prep)

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.

Thank you! - Grazie! - ¡Gracias!



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