



# Gravitational Waves from **Dark Matter Capture-Induced Low-Mass Black Holes**

**Sulagna Bhattacharya**

**Tata Institute of Fundamental Research, Mumbai**

Dark Matter & Neutrinos  
21 May 2025, IHP Paris

# Outline

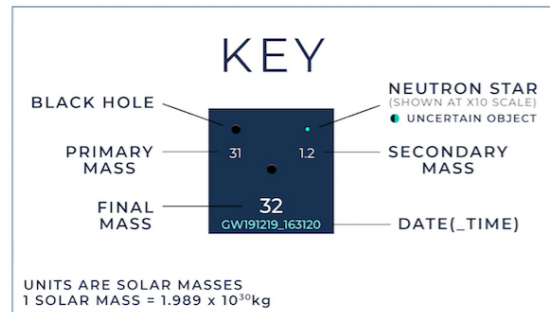
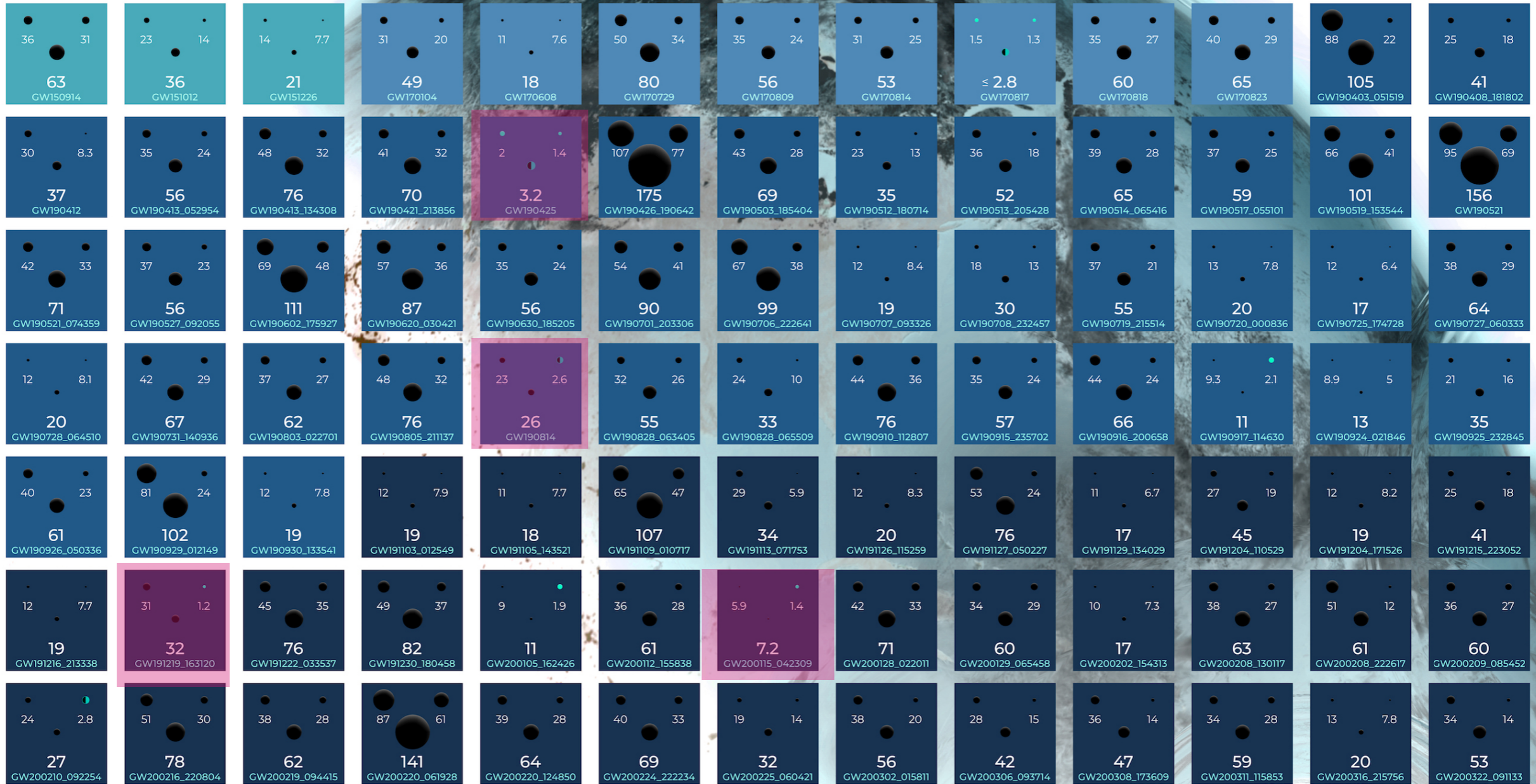
- Potential Low-Mass Black Holes (LMBH) detections by LVK
- Waveforms of Binary Neutron Stars (BNS) & LMBH mergers
- Match & Fitting Factor
- Bayes Factor of LMBH model over BNS model
- Dark Matter (DM) capture induced LMBHs from Neutron Stars

**GW detectors can be a complementary probe of particle DM**

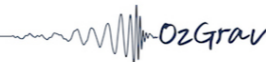
**OBSERVING RUN 01**  
2015 - 2016

**02**  
2016 - 2017

**03a+b**  
2019 - 2020



GRAVITATIONAL WAVE  
**MERGER**  
DETECTIONS  
SINCE 2015



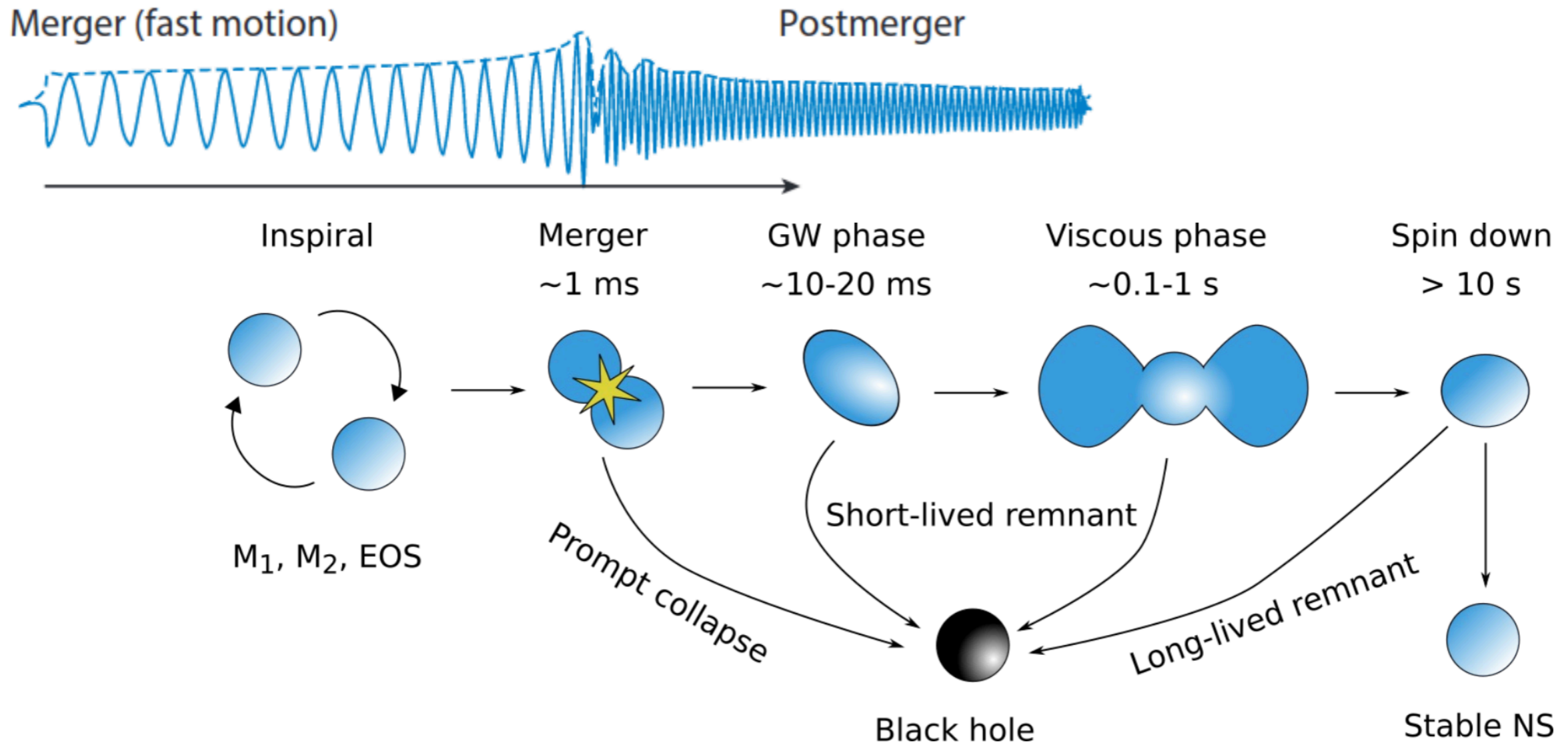
# BNS mergers vs LMBH Mergers

	BNS $m_1 \in [1, 2.5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	NSBH $m_1 \in [2.5, 50]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	BBH $m_1 \in [2.5, 100]M_\odot$ $m_2 \in [2.5, 100]M_\odot$	NS-Gap $m_1 \in [2.5, 5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	BBH-gap $m_1 \in [2.5, 100]M_\odot$ $m_2 \in [2.5, 5]M_\odot$	Full $m_1 \in [1, 100]M_\odot$ $m_2 \in [1, 100]M_\odot$
PDB (pair)	$170^{+270}_{-120}$	$27^{+31}_{-17}$	$25^{+10}_{-7.0}$	$19^{+28}_{-13}$	$9.3^{+15.7}_{-7.2}$	$240^{+270}_{-140}$
PDB (ind)	$44^{+96}_{-34}$	$73^{+67}_{-37}$	$22^{+8.0}_{-6.0}$	$12^{+18}_{-9.0}$	$9.7^{+11.3}_{-7.0}$	$150^{+170}_{-71}$
MS	$660^{+1040}_{-530}$	$49^{+91}_{-38}$	$37^{+24}_{-13}$	$3.7^{+35.3}_{-3.4}$	$0.12^{+24.88}_{-0.12}$	$770^{+1030}_{-530}$
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$	$1.7^{+30.0}_{-1.7}$	$5.2^{+12.0}_{-4.1}$	$180.0^{+270.0}_{-110.0}$
MERGED	10 – 1700	7.8 – 140	16 – 61	0.02 – 39	$9.4 \times 10^{-5} - 25$	72 – 1800

LVK—arXiv:2111.03634

- $1.35 M_\odot - 1.35 M_\odot$  LMBH waveform
- $1.35 M_\odot - 1.35 M_\odot$  BNS waveform from CoRe Database (arXiv:2210.16366)
- Analysing the maximum match (Fitting Factor, FF) between these two waveforms in the frequency range of 500-4000 Hz.
- Turns out FF to be poor in the high-frequency regime (postmerger part)

Bhattacharya, Dasgupta, Kapadia (In Preparation)

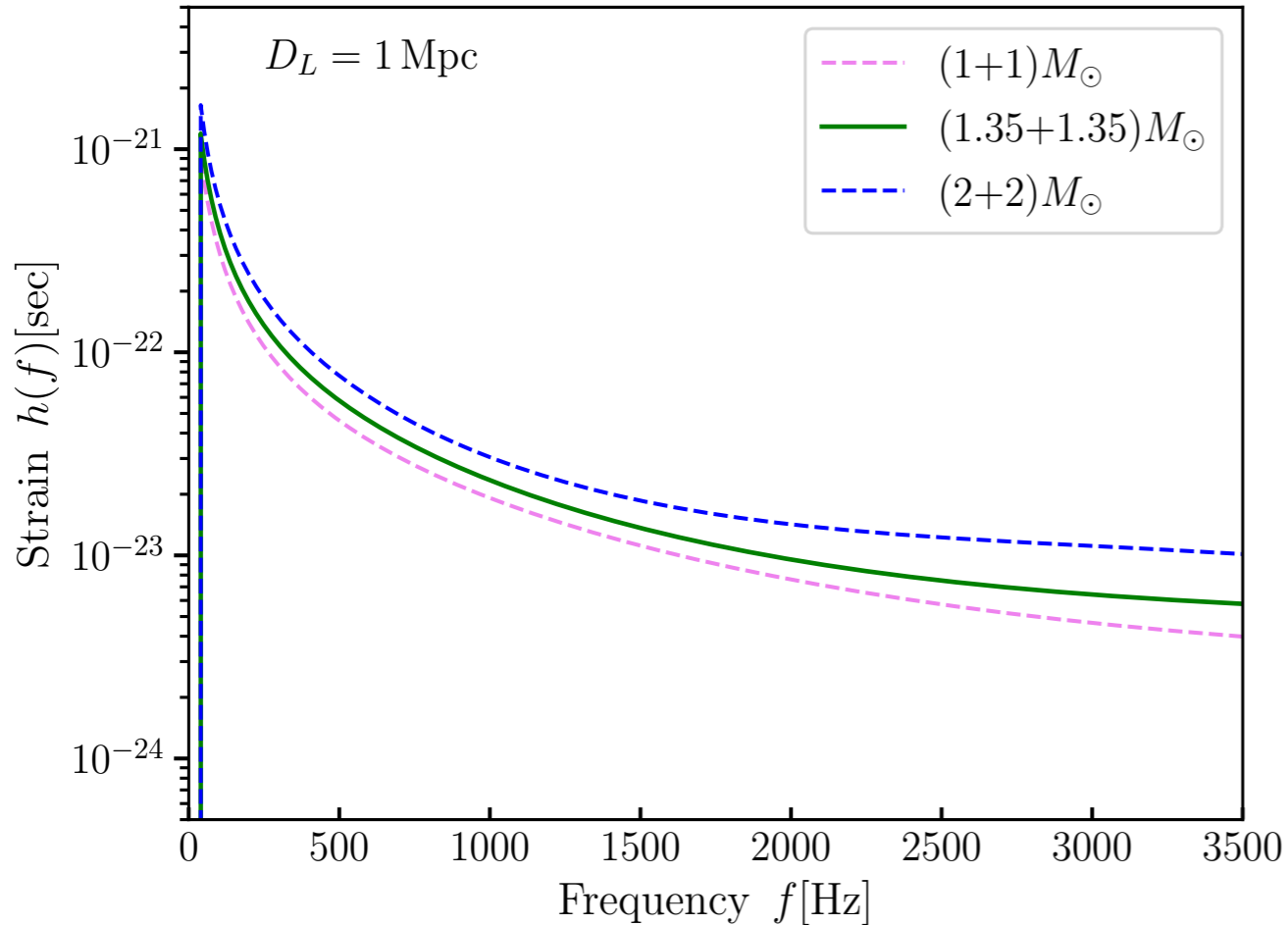


From Radice+, Ann. Rev. Nucl. Part. Sci. 70:95 (2020)

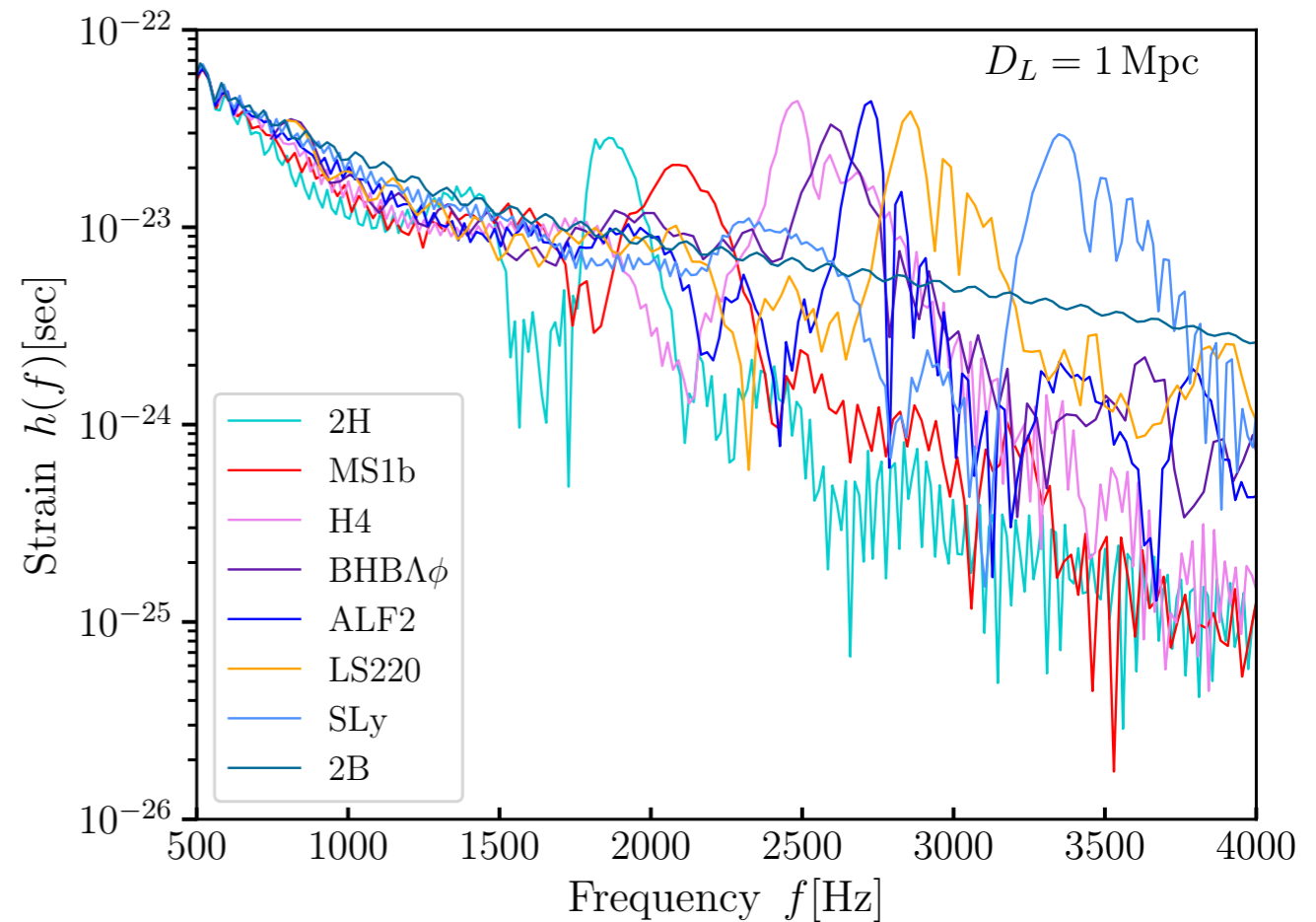
From David Radice's talk on May 13 (NDM)

# Waveform Templates

## LMBH



## BNS



Noise-Weighted Inner Product,  $\langle h_1(f) | h_2(f) \rangle = 2 \int_{f_{\min}}^{f_{\max}} \frac{(h_1^*(f)h_2(f) + h_1(f)h_2^*(f))}{S_n(f)} df$

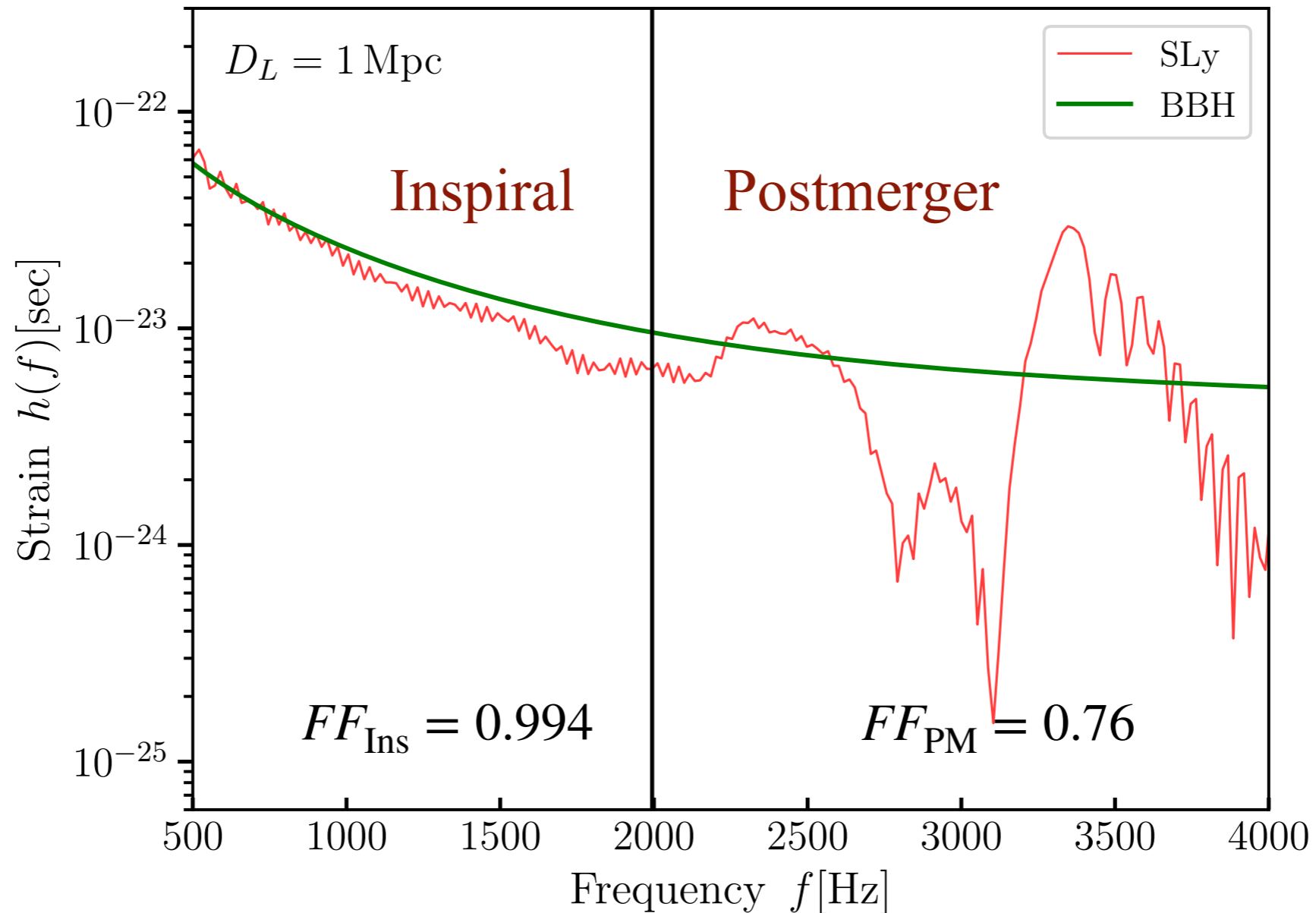
$S_n(f)$  = the power spectral density of the detector.

Match ( $\mathcal{M}$ ) =  $\langle \hat{h}_{\text{LMBH}}(f) | \hat{h}_{\text{BNS}}(f) \rangle$  lies between 0 and 1

Bhattacharya, Dasgupta, Kapadia (In Preparation)

# Fitting Factor

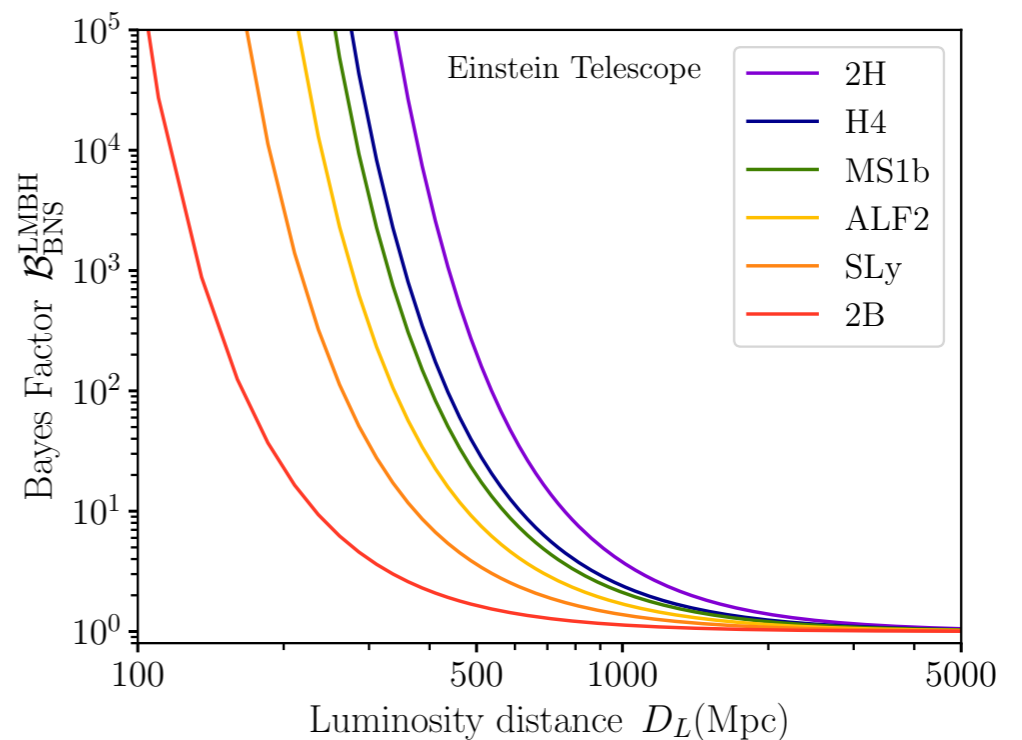
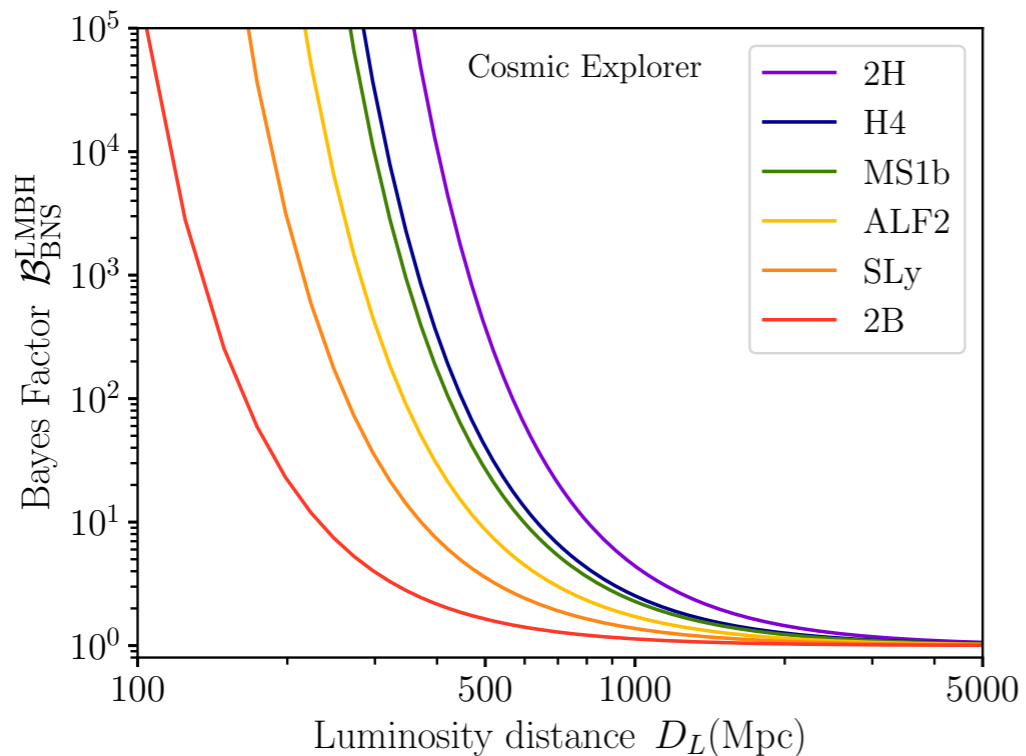
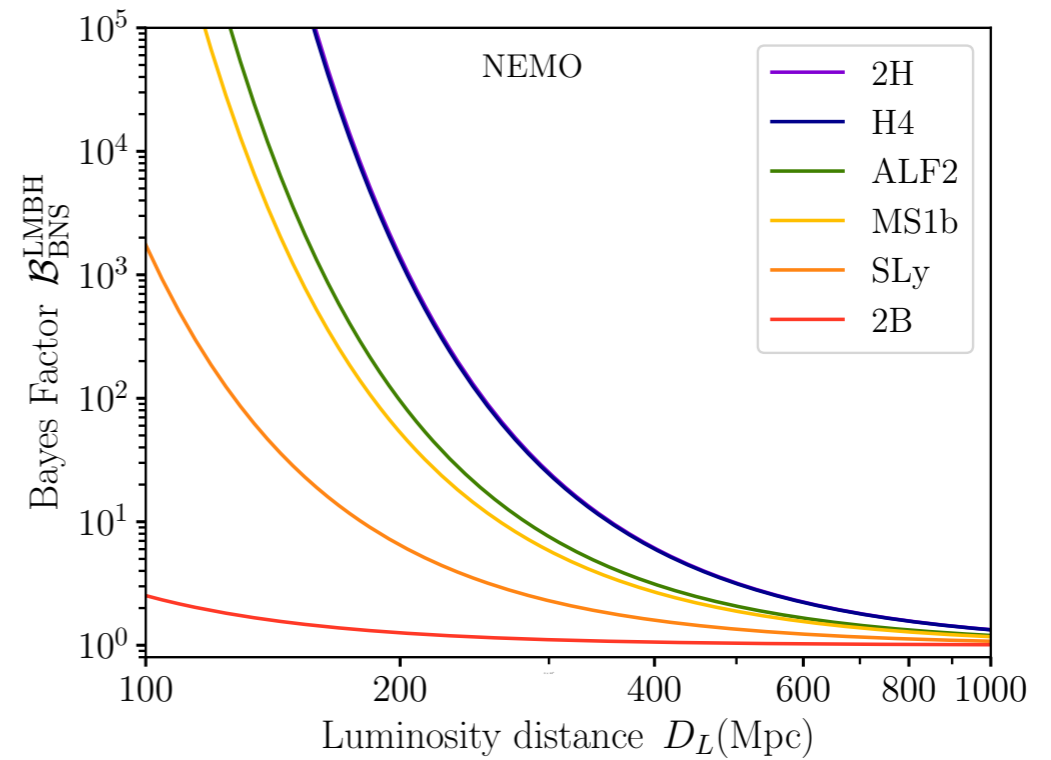
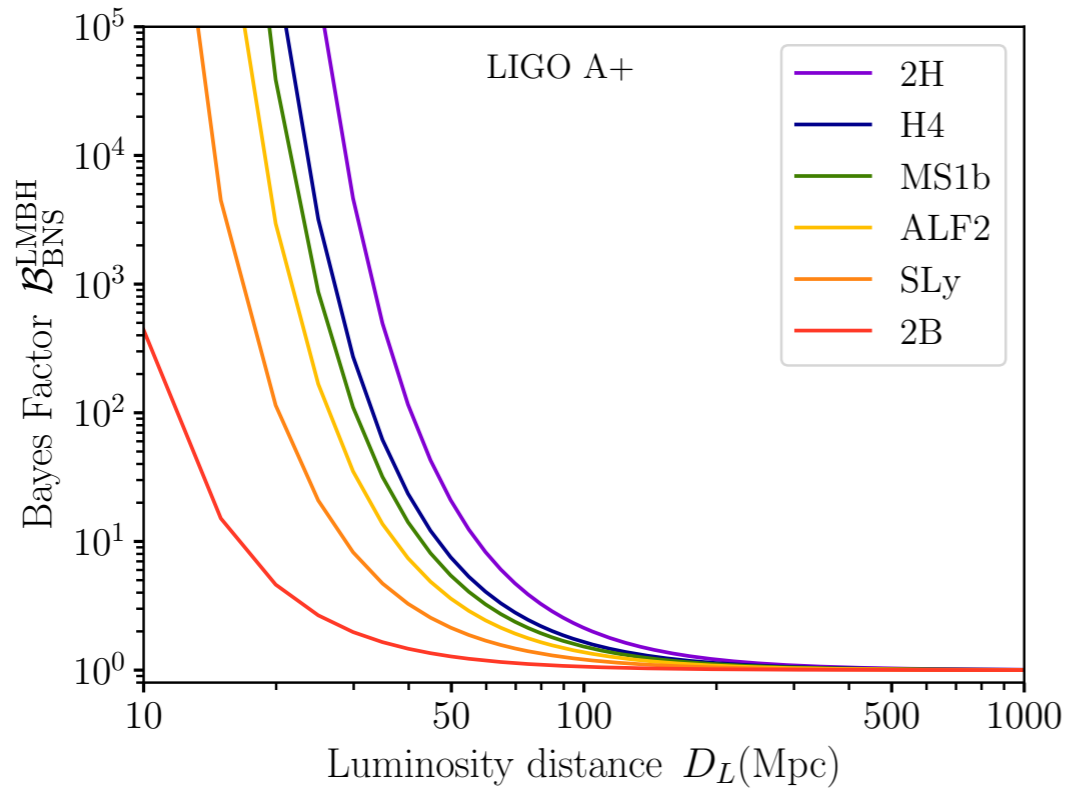
$$FF_2^1 = \max_{\text{templates}} \mathcal{M} = \max_{\text{templates}} 2 \int_{f_{\min}}^{f_{\max}} \frac{(h_1^*(f)h_2(f) + h_1(f)h_2^*(f))}{S_n(f) \times \sqrt{\langle h_1(f) | h_1(f) \rangle} \times \sqrt{\langle h_2(f) | h_2(f) \rangle}} df$$



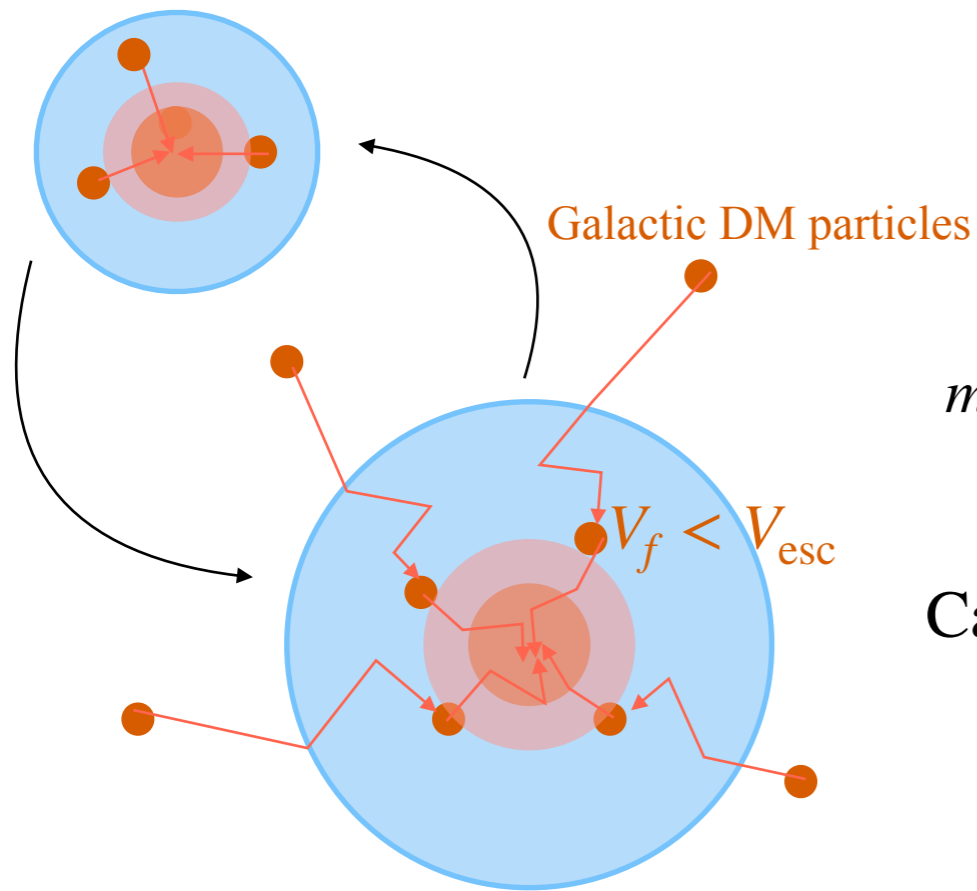
Bhattacharya, Dasgupta, Kapadia (In Preparation)

# Bayes Factor

$$\mathcal{B}_2^1 = \frac{p(s | \mathcal{H}_1)}{p(s | \mathcal{H}_2)} = e^{(1 - FF_2^{12}) \frac{\rho_{1 \text{opt}}^2}{2}}$$



# DM Capture



$$m_\chi = 10^5 \text{ GeV}, \sigma_{\chi n} = 10^{-45} \text{ cm}^2, T = 2.1 \times 10^6 \text{ K}, M_{\text{NS}} = 1.35 M_\odot$$

$$\text{Captured DM mass over 1 Gyr} \approx 4.9 \times 10^{42} \text{ GeV} \approx 10^{-15} M_\odot$$

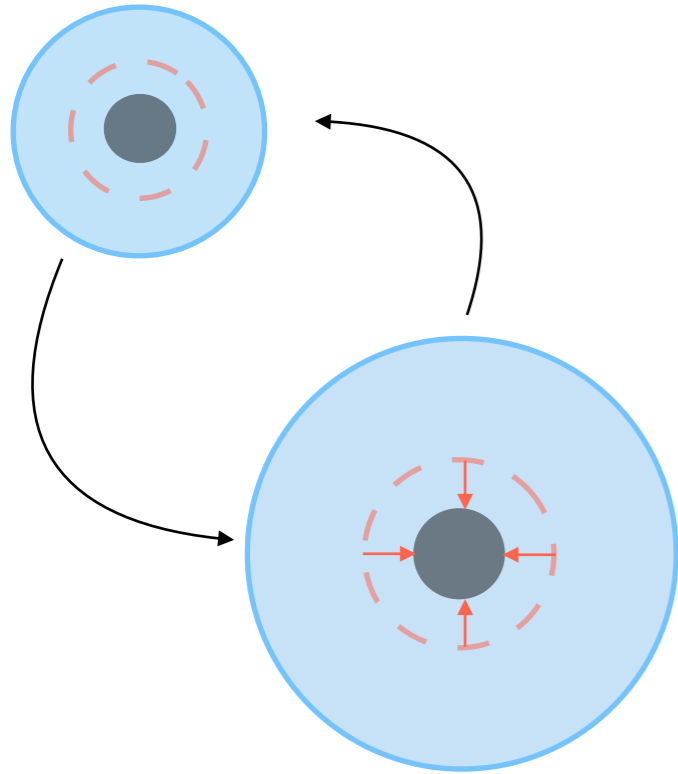
Single scatter capture rate for Neutron Stars

$$\mathbf{C} = \underbrace{\pi R_{\text{NS}}^2 \frac{\rho_\chi}{m_\chi} \int \frac{f(u) du}{u} (u^2 + v_{\text{esc}}^2)}_{\text{Incoming rate}} \times \frac{\sigma_{\chi n}}{\sigma_{\text{sat}}} \times \left( 1 - \frac{1 - e^{-A^2}}{A^2} \right)$$

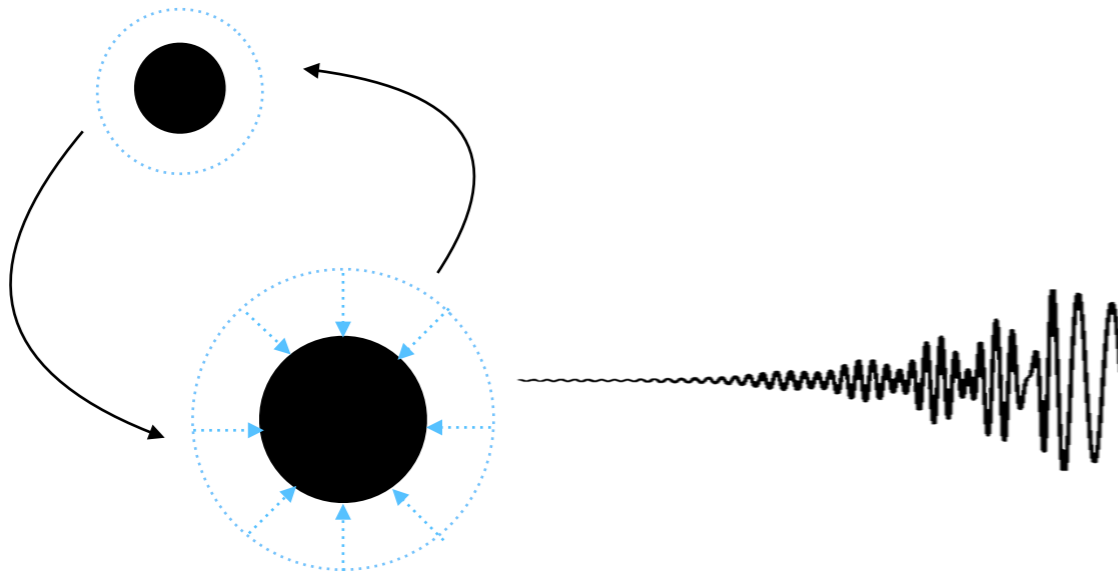
Incoming rate

Talk by Anupam Ray, Arpan Kar this week

# Transmutation



**2.** The dark core collapses and forms a tiny black hole



**3.** Seed black hole eats up the host star and forms Transmuted black hole

**DM thermalisation**

$$r_{\text{th}} \propto \sqrt{\frac{T_{\text{NS}}}{m_\chi}} \sim 5 \text{ cm}$$

**Growth of the micro BH & it eats the host star**

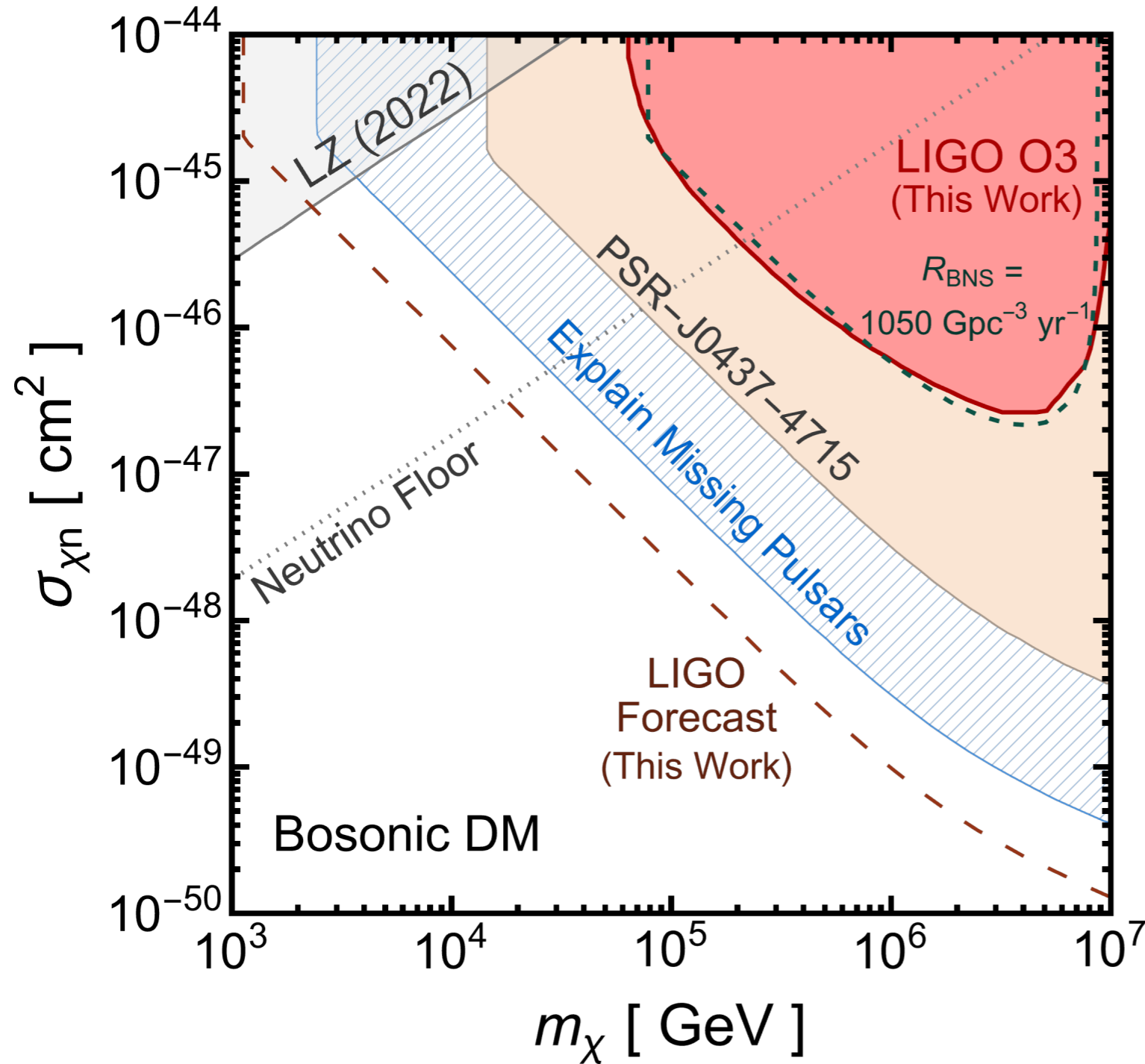
Mass of the micro BH  $\sim 10^{-16} M_\odot$

$$\tau_{\text{swallow}} = 3 \times 10^4 \text{ years}$$

$$\tau_{\text{collapse}} = 4.8 \times 10^8 \text{ years}$$

$$\tau_{\text{transmutation}} = (\tau_{\text{collapse}} + \tau_{\text{swallow}}) < (t_0 = 13.8 \times 10^9 \text{ yrs})$$

# Results



SB, Dasgupta, Laha, Ray, PRL(2023)

## Priors for Bayesian Analysis

$$m_\chi \in [10^4 - 10^8 \text{ GeV}]$$

$$\sigma_{\chi n} \in [10^{-50} - 10^{-44} \text{ cm}^2]$$

$$R_{\text{BNS}} \in [10 - 1700 \text{ Gpc}^{-3} \text{ yr}^{-1}]$$

## Hybrid Analysis

No priors on DM parameters.

Forecast with  $50 \times \langle VT \rangle$

# Concluding Remarks

- Ambiguous events observed in LVK, where classifying the origin is difficult
- Postmerger part of the binary can shed light on the origin
- We need high sensitivity in the post-merger part and closer events
- One of the BSM ways to produce these LMBHs can be DM capture-induced transmutation.
- GW observations can shed light on the nature of dark matter

# THANKS

**Questions & Comments**  
[sulagna@theory.tifr.res.in](mailto:sulagna@theory.tifr.res.in)