25 January 2023

# Rapid parameter estimation of compact binary sources using a meshfree approach

Pathak et al., arxiv:2210.02706 (2022)

## AAPCOS-2023
## SINP, Kolkata

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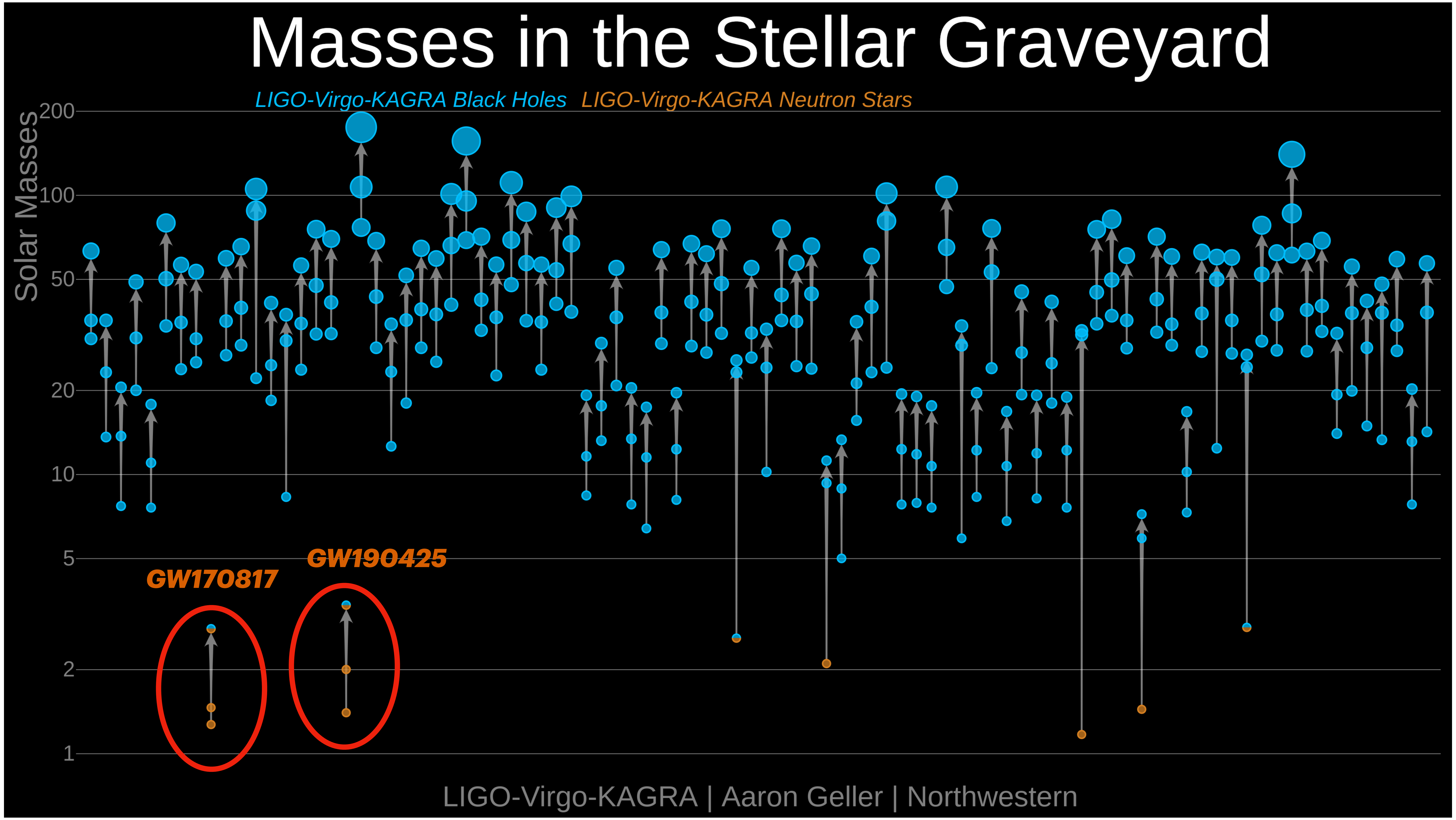
Amit Reza, Nikhef, Amsterdam

# Einstein's zoo

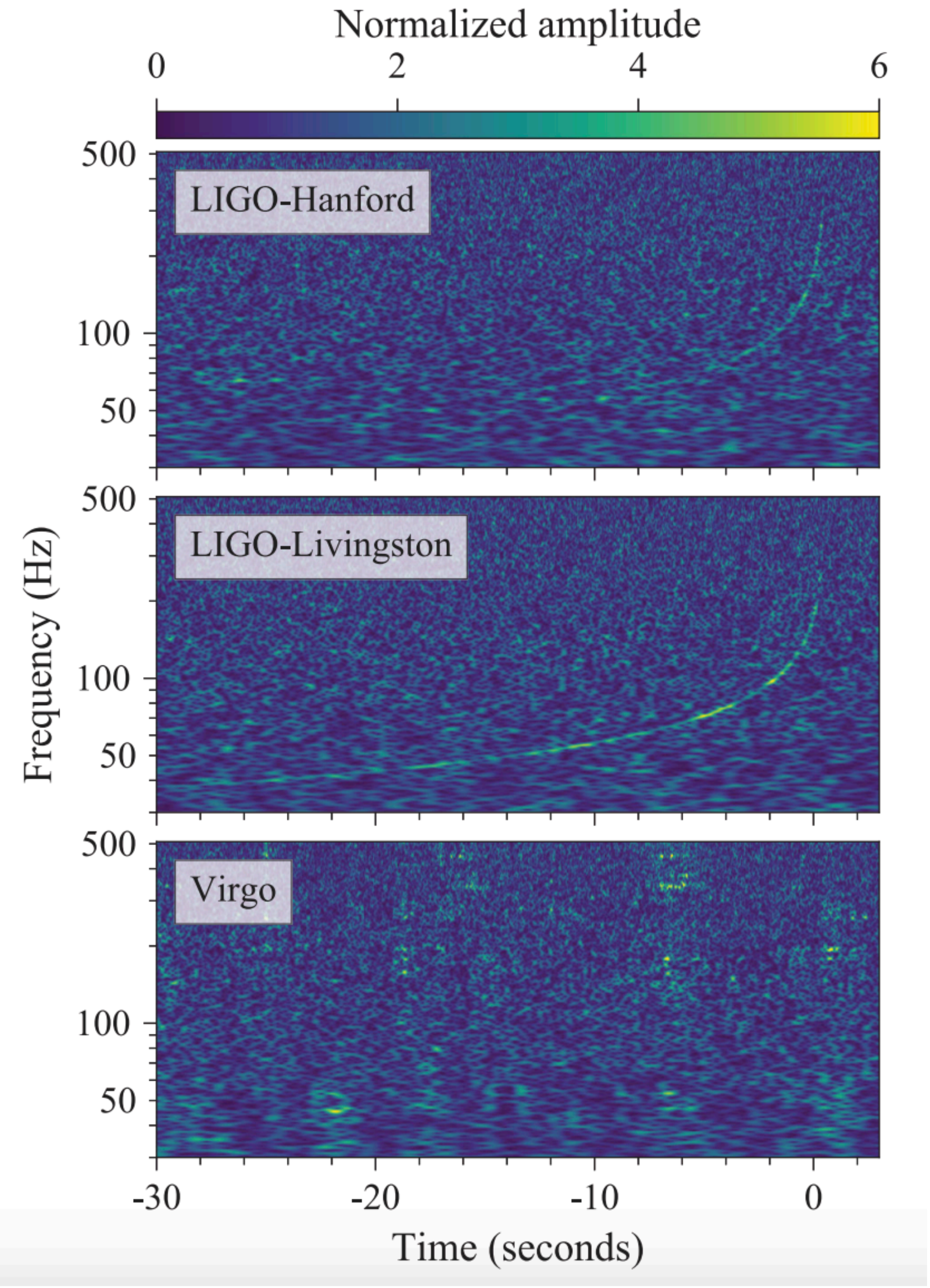
## Gravitational wave events




Credits: LIGO-Virgo-KAGRA Collaborations/Frank Elavsky, Aaron Geller/ Northwestern

# GW170817

## a γ-ray burst (GRB 170817A)




B.P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
PRL 119, 161101 (2017)

### A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration

*Nature* **551**, 85–88 (2017) | Cite this article

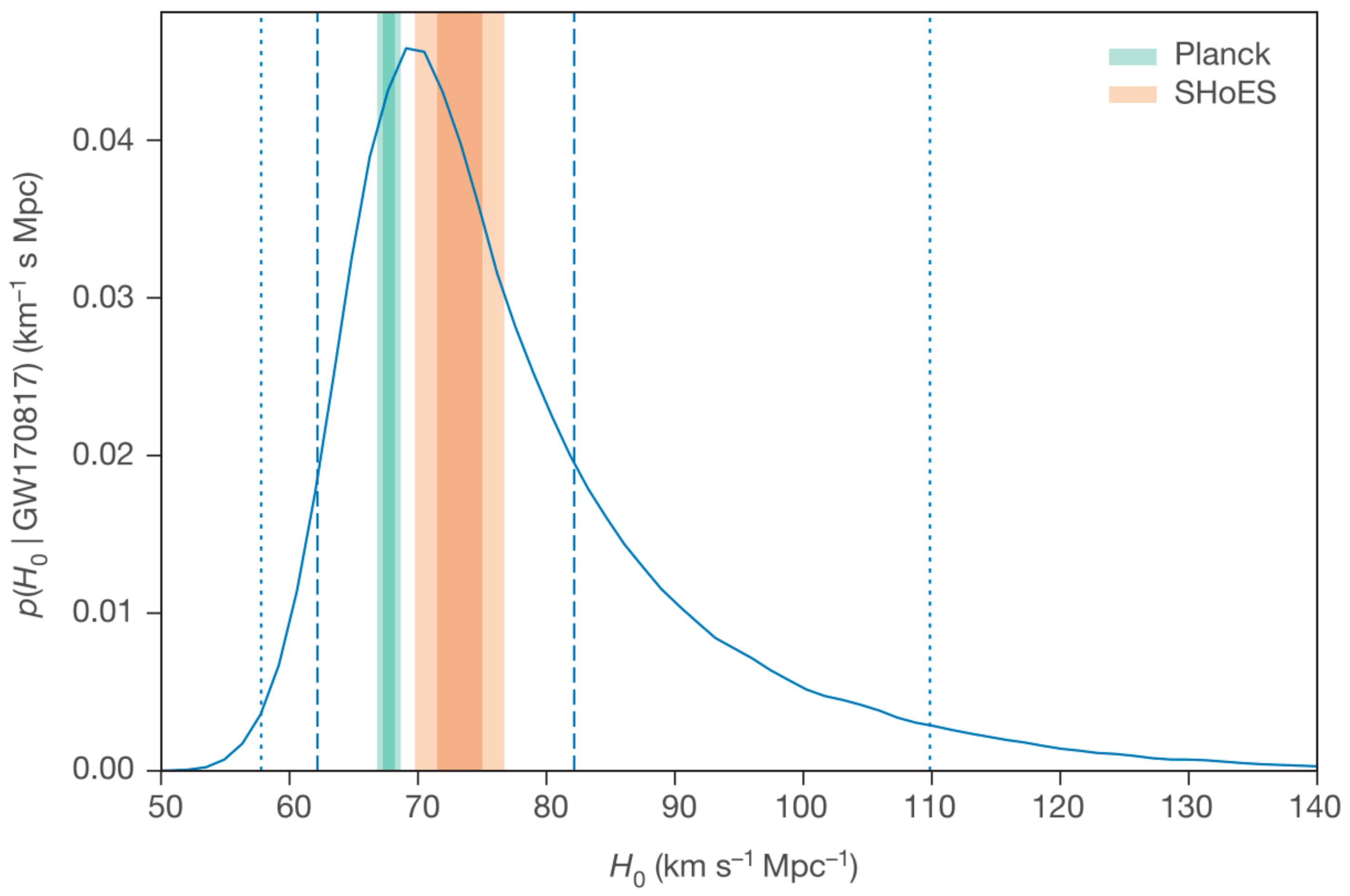
**44k** Accesses | **584** Citations | **369** Altmetric | Metrics

### The X-ray counterpart to the gravitational-wave event GW170817

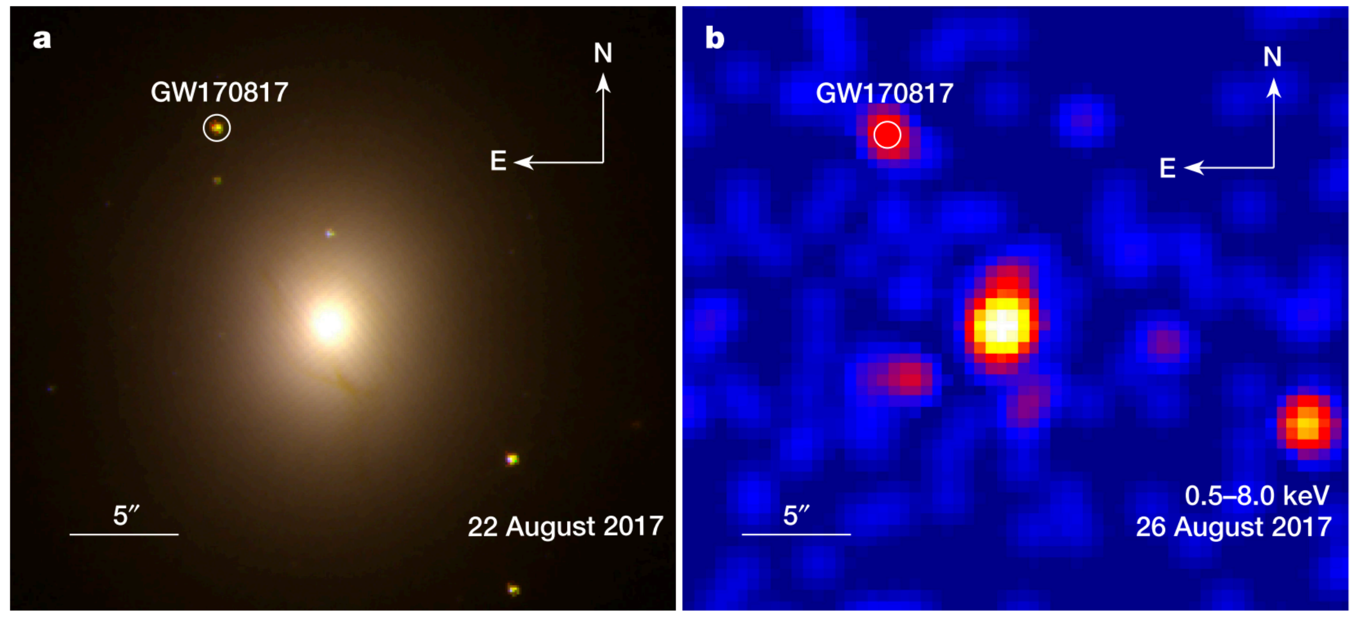
E. Troja, L. Piro, H. van Eerten, R. T. Wollaeger, M. Im, O. D. Fox, N. R. Butler, S. B. Cenko, T. Sakamoto, C. L. Fryer, R. Ricci, A. Lien, R. E. Ryan Jr, O. Korobkin, S.-K. Lee, J. M. Burgess, W. H. Lee, A. M. Watson, C. Choi, S. Covino, P. D'Avanzo, C. J. Fontes, J. Becerra González, H. G. Khandrika, ... Y. Yoon + Show authors

*Nature* **551**, 71–74 (2017) | Cite this article

**16k** Accesses | **460** Citations | **143** Altmetric | Metrics




*Nature* **551**, pages 85–88 (2017)




*Nature* **551**, pages 71–74 (2017)

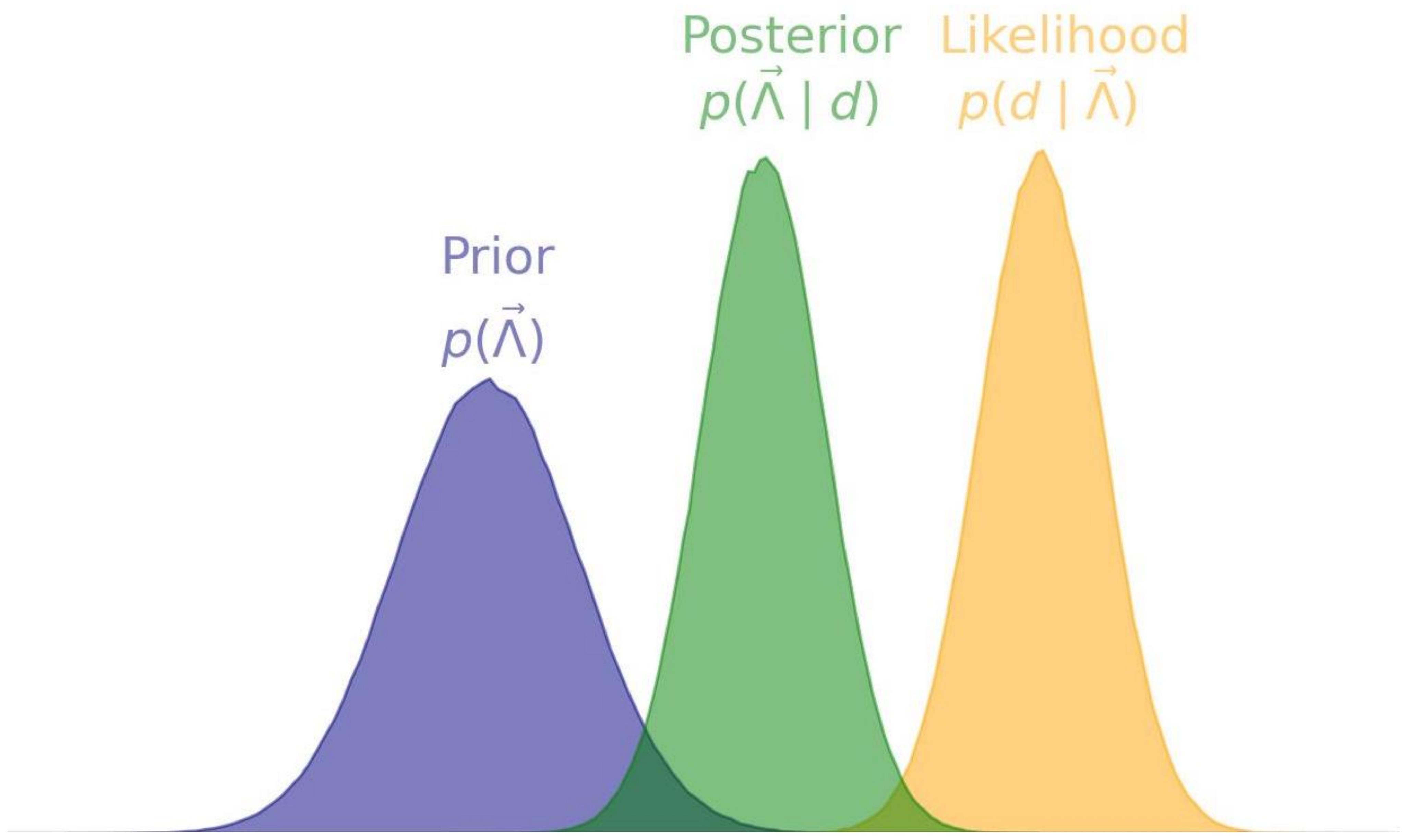
# Bayesian inference

## Parameter estimation

- Estimation of source's parameters ( $m_1, m_2, \vec{s}_1, \vec{s}_2, d_L, \alpha, \delta$.... Etc.)
- Bayes theorem

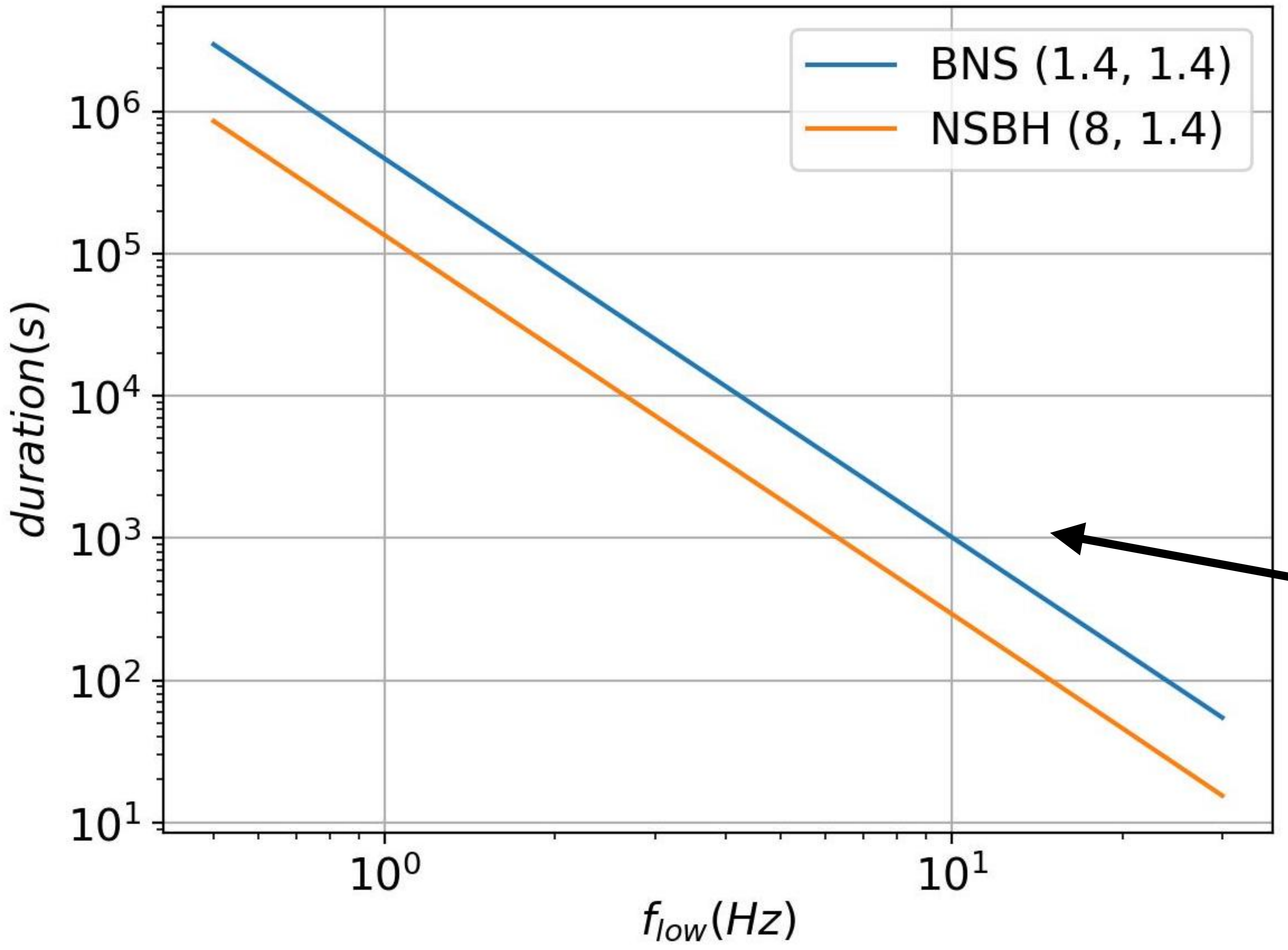
$$p(\overrightarrow{\Lambda} \mid \boldsymbol{d}) = \frac{p(\boldsymbol{d} \mid \overrightarrow{\Lambda})\, p(\overrightarrow{\Lambda})}{p(\boldsymbol{d})}$$

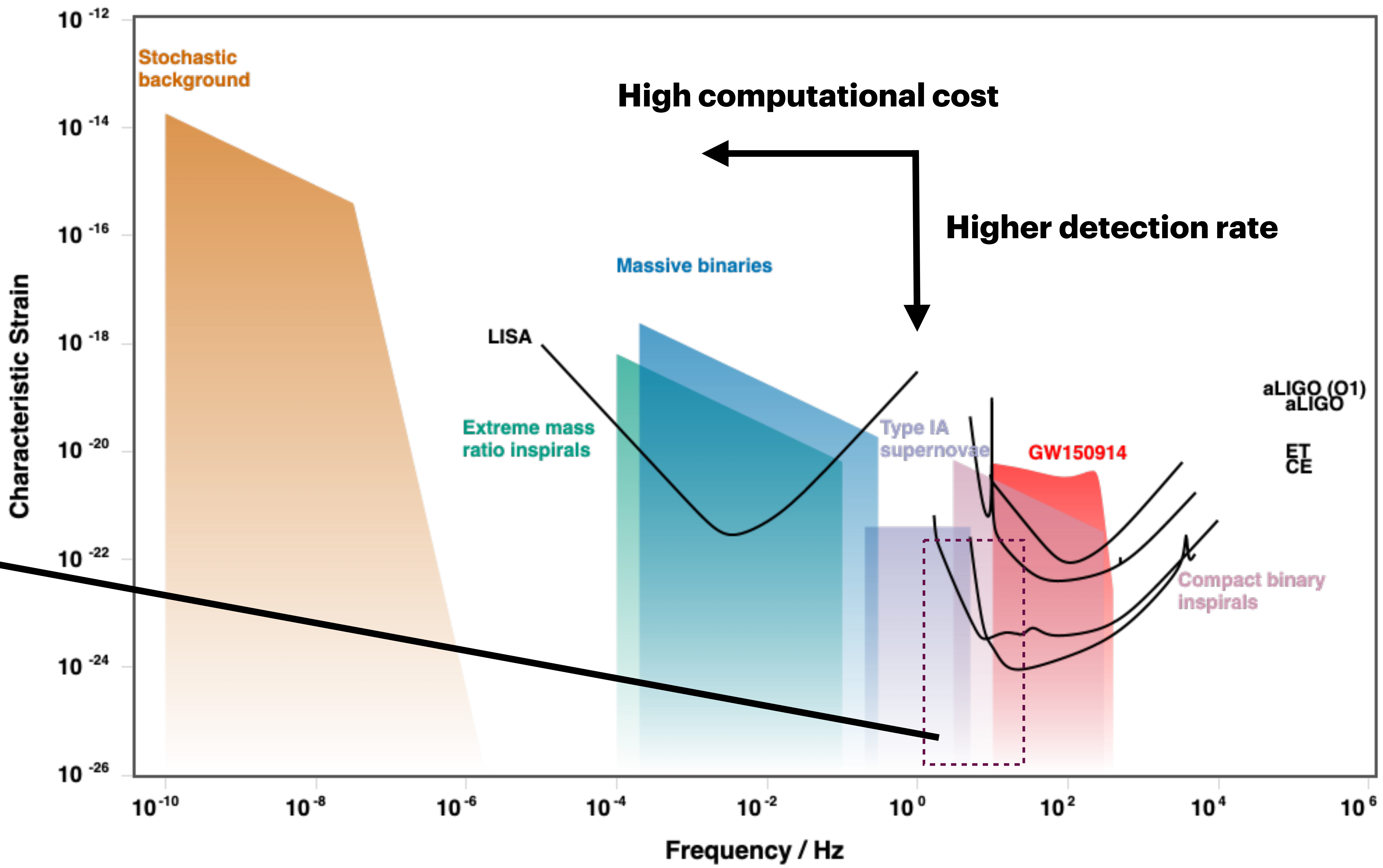
- Likelihood evaluation is "**expensive**"
- Days, weeks to months for posterior estimation



# Bottlenecks of PE

## For BNS/NSBH events



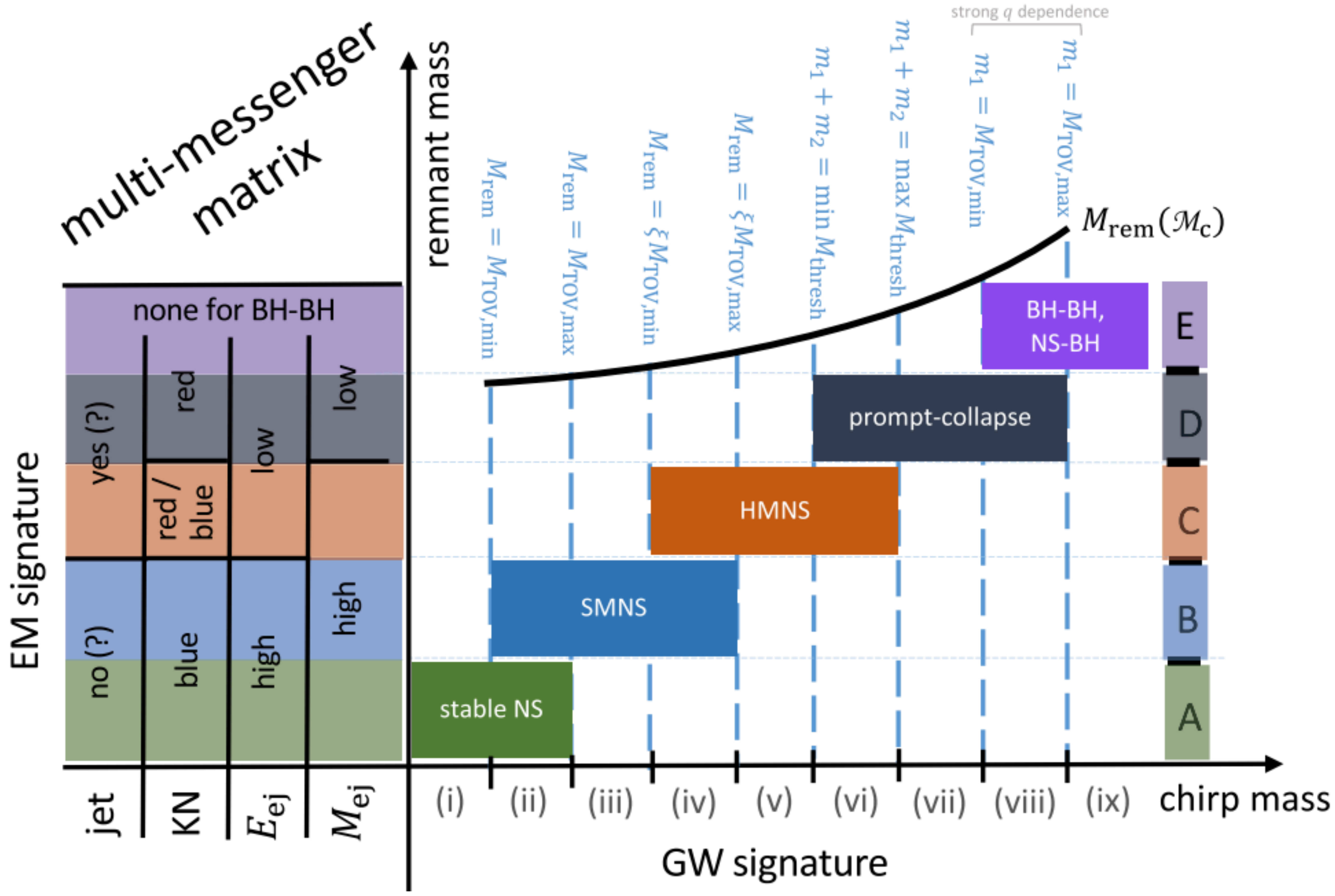






C J Moore et al 2015 Class. Quantum Grav. 32 015014

# Why Rapid PE?

## For BNS/NSBH events




Ben Margalit, Brian D. Metzger, *ApJL* **880** L15 (2019)

**Fast PE** required for **prioritization** of EM follow ups

BNS systems with different masses have different signatures

# Fast likelihood evaluation

## A meshfree approach

- Given $d = h(\overrightarrow{\Lambda}, t_c) + n$, $h$ is some assumed signal model, $n$ (Gaussian noise)

$$\textbf{Likelihood} \quad \mathscr{L} \propto \exp\left[-\frac{1}{2}\left(d - h(\overrightarrow{\Lambda}, t_c)\right)^T S^{-1}\left(d - h(\overrightarrow{\Lambda}, t_c)\right)\right]$$

- Our approach: Bypass **waveform generation** and directly interpolate likelihood

- Decompose likelihood into a **SVD basis** and interpolate the **SVD coefficients** over intrinsic parameter space using **Radial basis functions** (RBFs)

# Method

- Two stages are involved in our approach:

  (i) Start up stage

  (ii) Online stage

- Start up stage: Generation of interpolants triggered by a detection pipeline

- Online stage: Evaluation of likelihood at a given query point (Sampling)

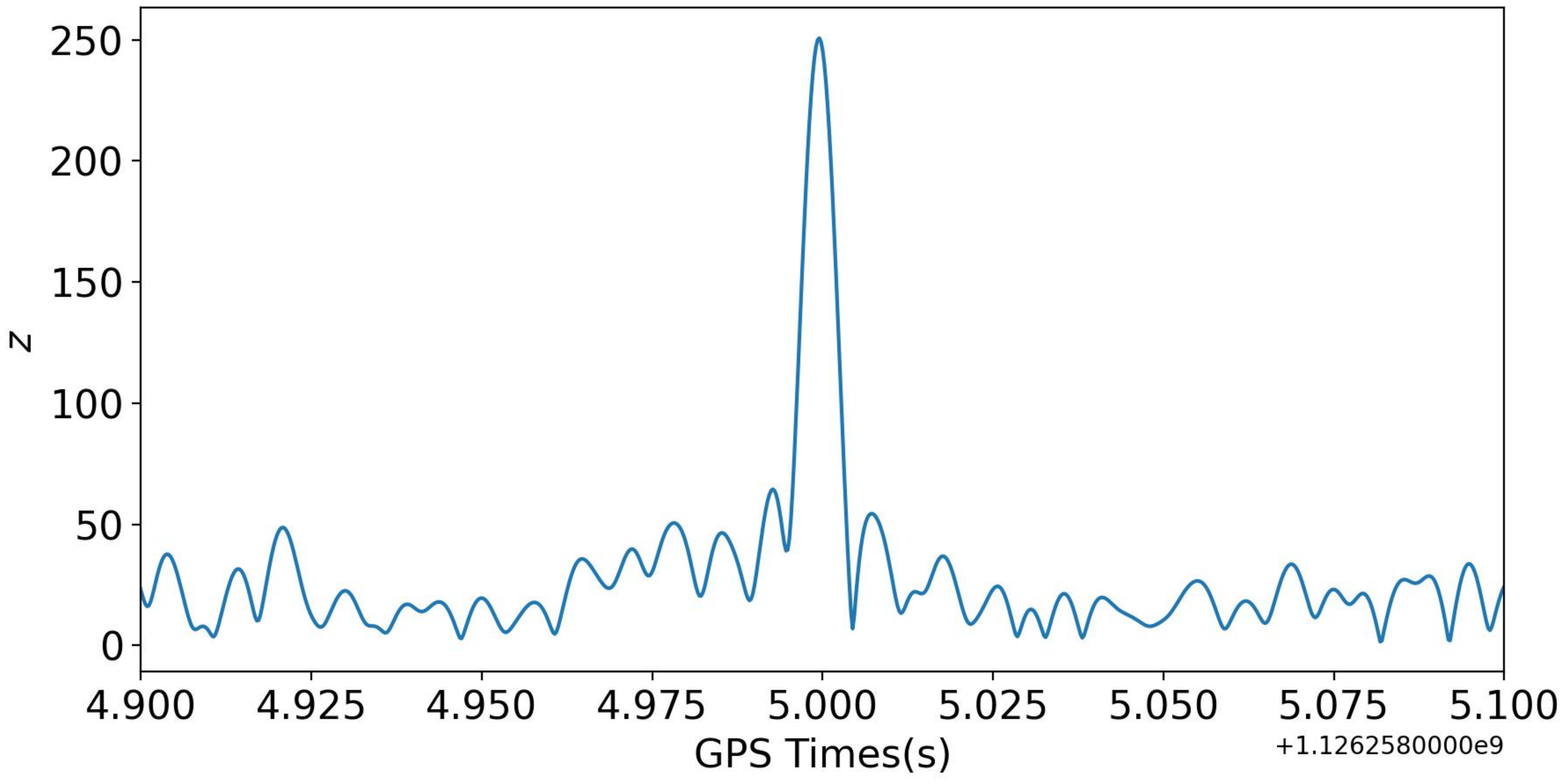
# Method

## Start up stage

### Generation of RBF Interpolants

SVD decomposition: $\langle d \mid h(\vec{\lambda}_\alpha, t_c)\rangle = \sum_\mu C_\mu^\alpha \vec{u}_\mu$

$$\sigma(\vec{\lambda}_\alpha)^2 = \langle h(\vec{\lambda}_\alpha) \mid h(\vec{\lambda}_\alpha)\rangle$$



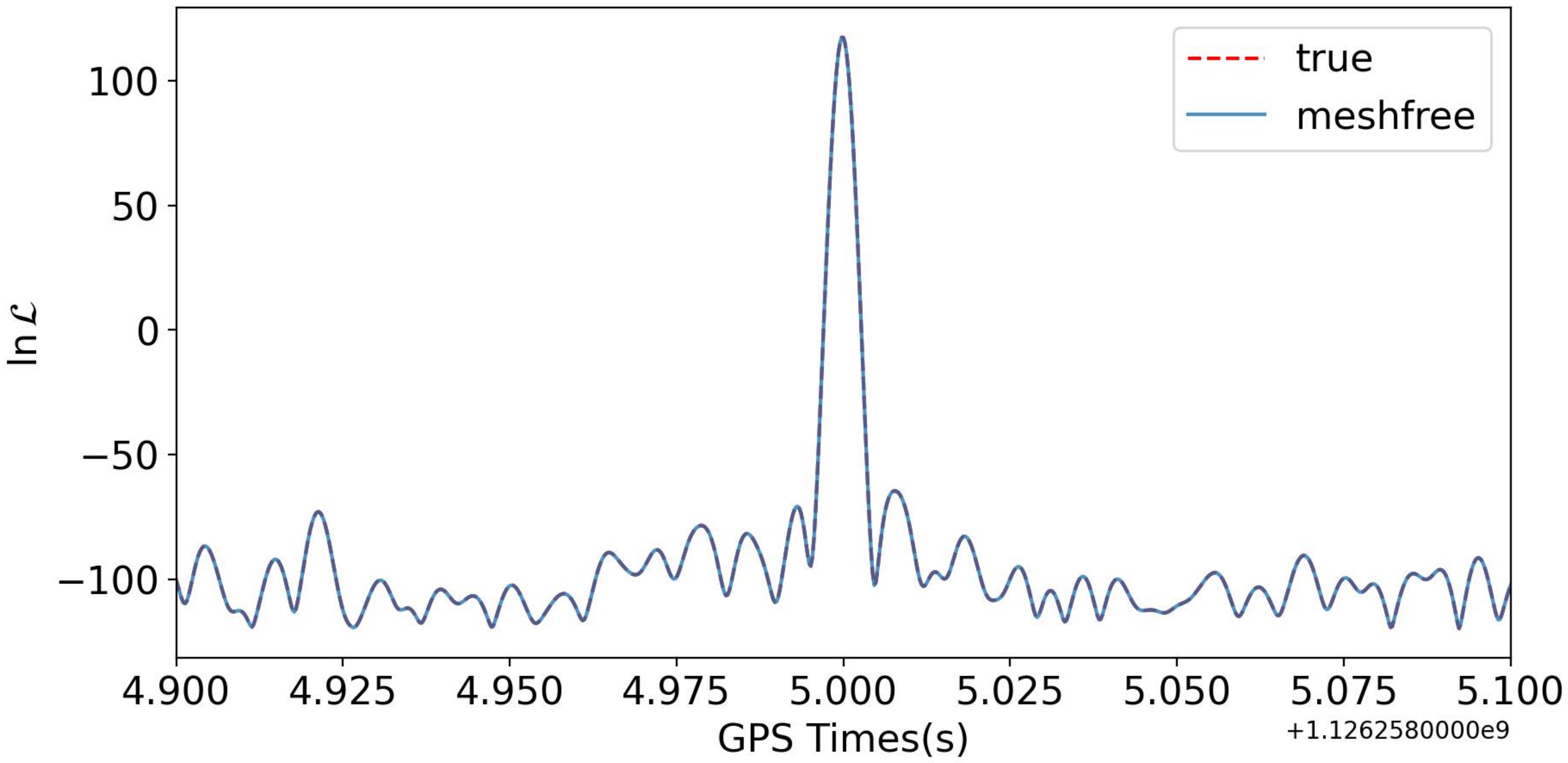

Generate interpolants for $C_\mu^q$ and $\sigma_q^2$

$$C_\mu^q = \sum_{\alpha=1}^{n} r_\alpha \phi(||\vec{\lambda}_q - \vec{\lambda}_\alpha||_2) + \sum_{j=1}^{M} b_j f_j(\vec{\lambda}_q)$$

# Method

## Online stage

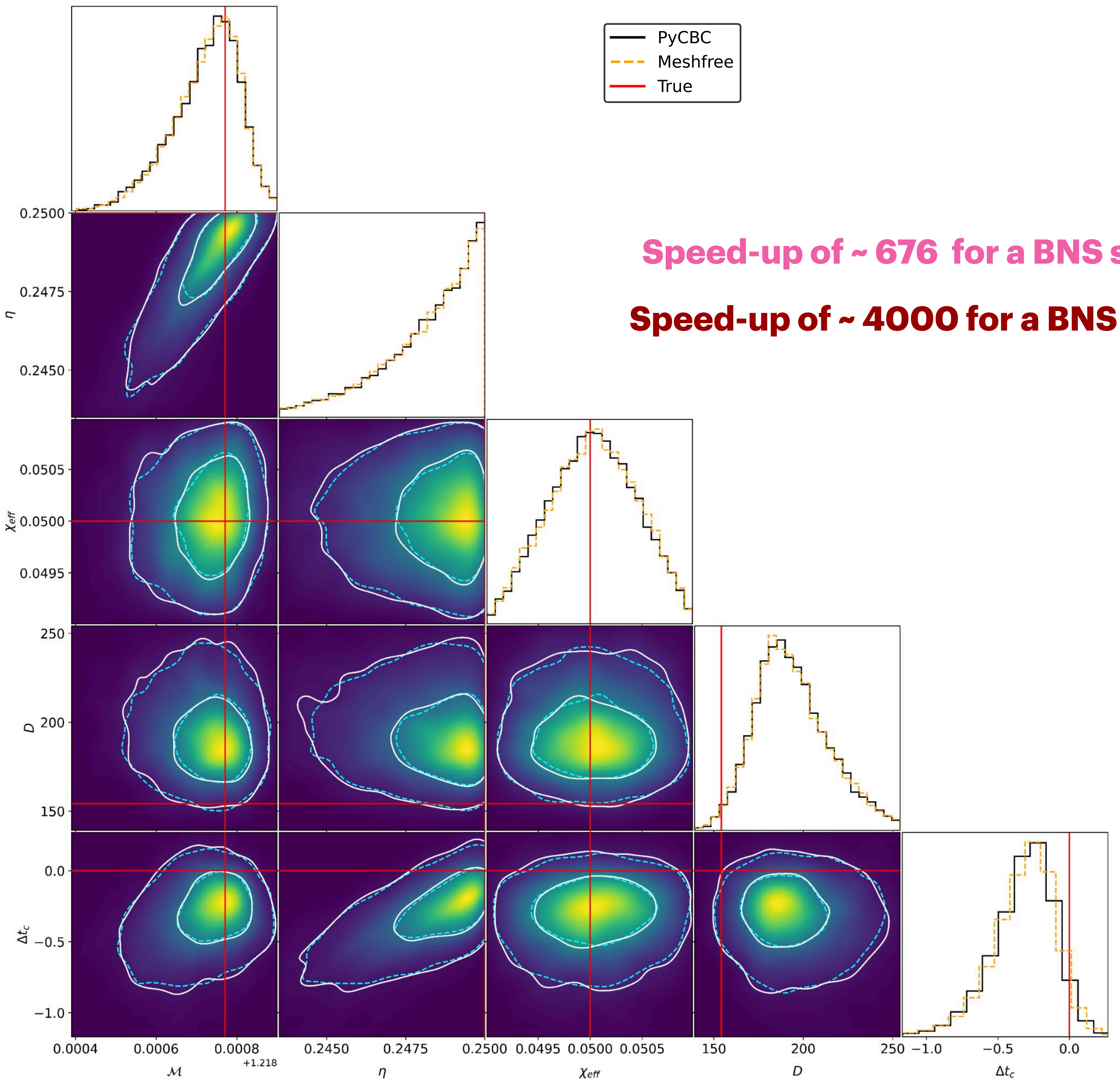
- Evaluate $C_\mu^q$ and $\sigma_q^2$ at a query point $\vec{\lambda}_q$
- Combine with $\vec{u}_\mu$ and extrinsic factors to calculate the likelihood at $\overrightarrow{\Lambda}_q$



# Results

## Simulated events (Single detector)

Pathak et al., arxiv:2210.02706 (2022) (Under review)

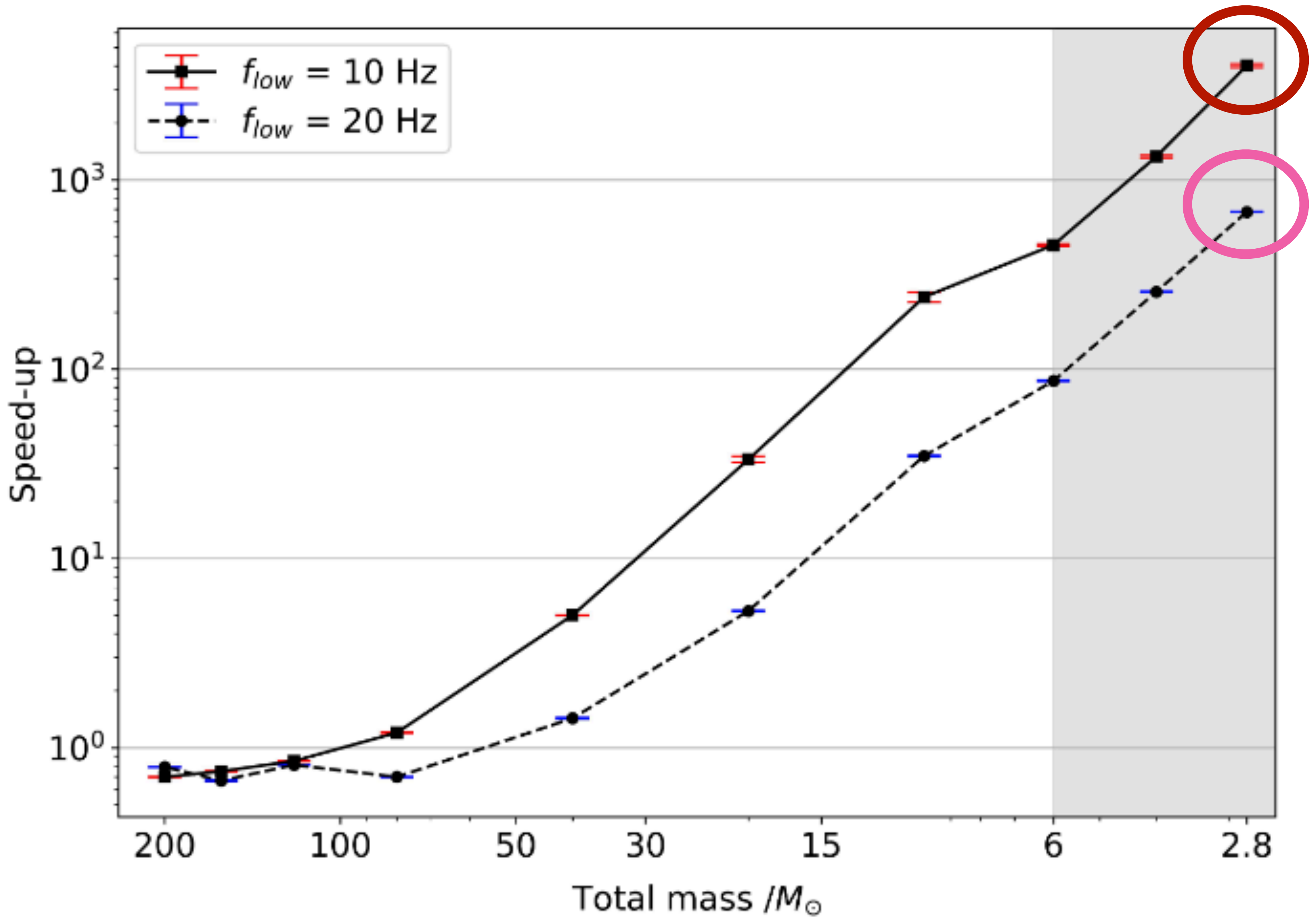



**Speed-up of ~ 676 for a BNS system at O4 like sensitivity**

**Speed-up of ~ 4000 for a BNS system at O5 like sensitivity**

| | $\mathcal{M}/M_\odot$ | $\eta$ | $\chi_{\rm eff}$ | SNR |
|---|---|---|---|---|
| Injection | 1.2187 | 0.25 | 0.05 | 10.0 |
| Standard | $1.2187^{1.2188}_{1.2185}$ | $0.2487^{0.2498}_{0.2456}$ | $0.050^{0.051}_{0.049}$ | 9.67 |
| Meshfree | $1.2187^{1.2188}_{1.2185}$ | $0.2487^{0.2498}_{0.2456}$ | $0.050^{0.051}_{0.049}$ | 9.67 |

TABLE I. Reconstruction of a canonical BNS event.



# Coherent network PE*

- What's different in coherent PE?

  Assumption: uncorrelated noise across detectors

  Likelihood: coherent sum of the individual likelihoods

$$\ln \mathscr{L}(\overrightarrow{\Lambda}, t_c) = \sum_{i=1}^{N_d} \langle d \mid h(\overrightarrow{\Lambda}, t_c) \rangle^{(i)} - \frac{1}{2} \sum_{i=1}^{N_d} \left[ \langle h(\overrightarrow{\Lambda}) \mid h(\overrightarrow{\Lambda}) \rangle^{(i)} - \langle d \mid d \rangle^{(i)} \right]$$

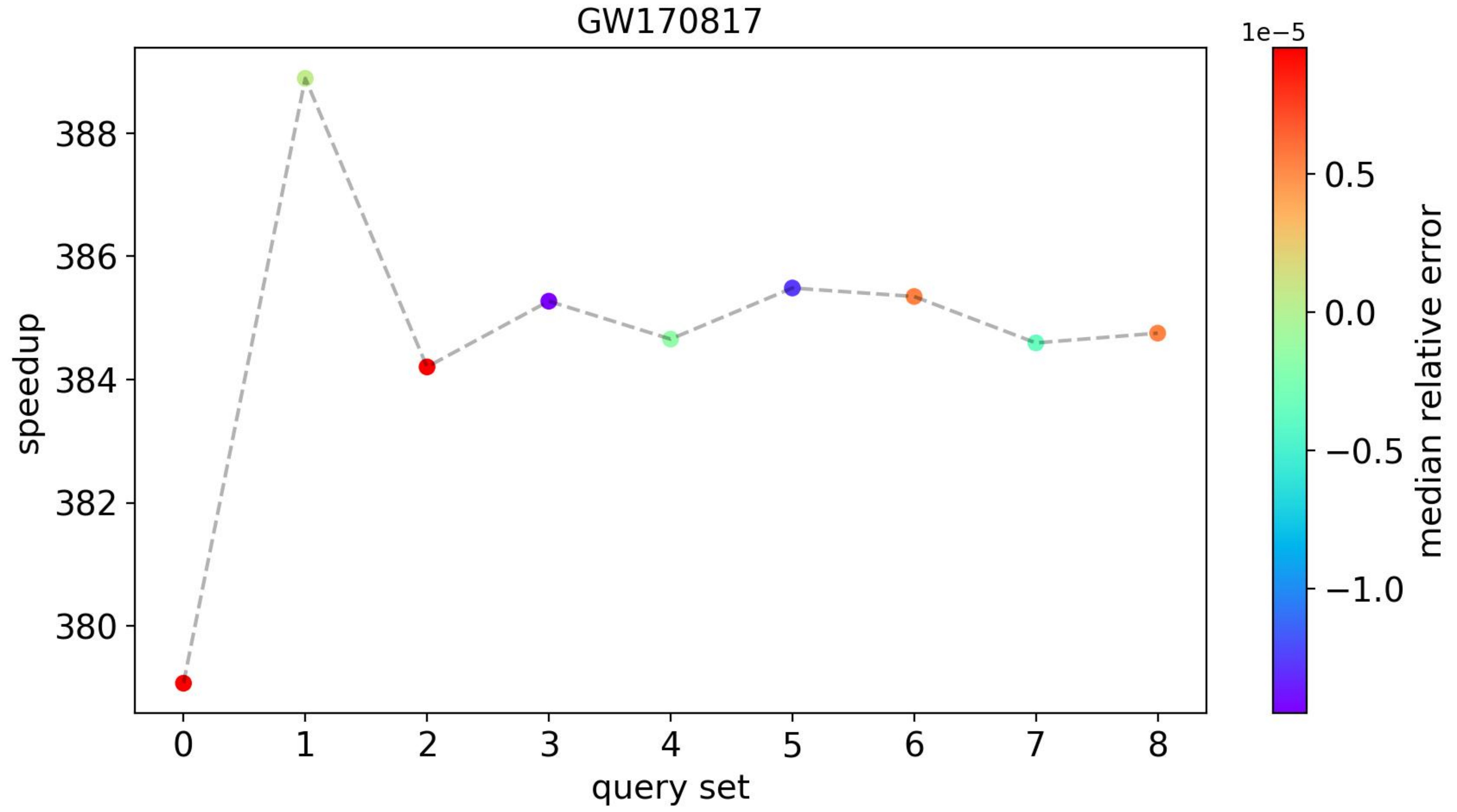
- Important for source localization in sky

*Ongoing work In Collaboration with Sanket Munishwar, Amit Reza and Anand S. Sengupta

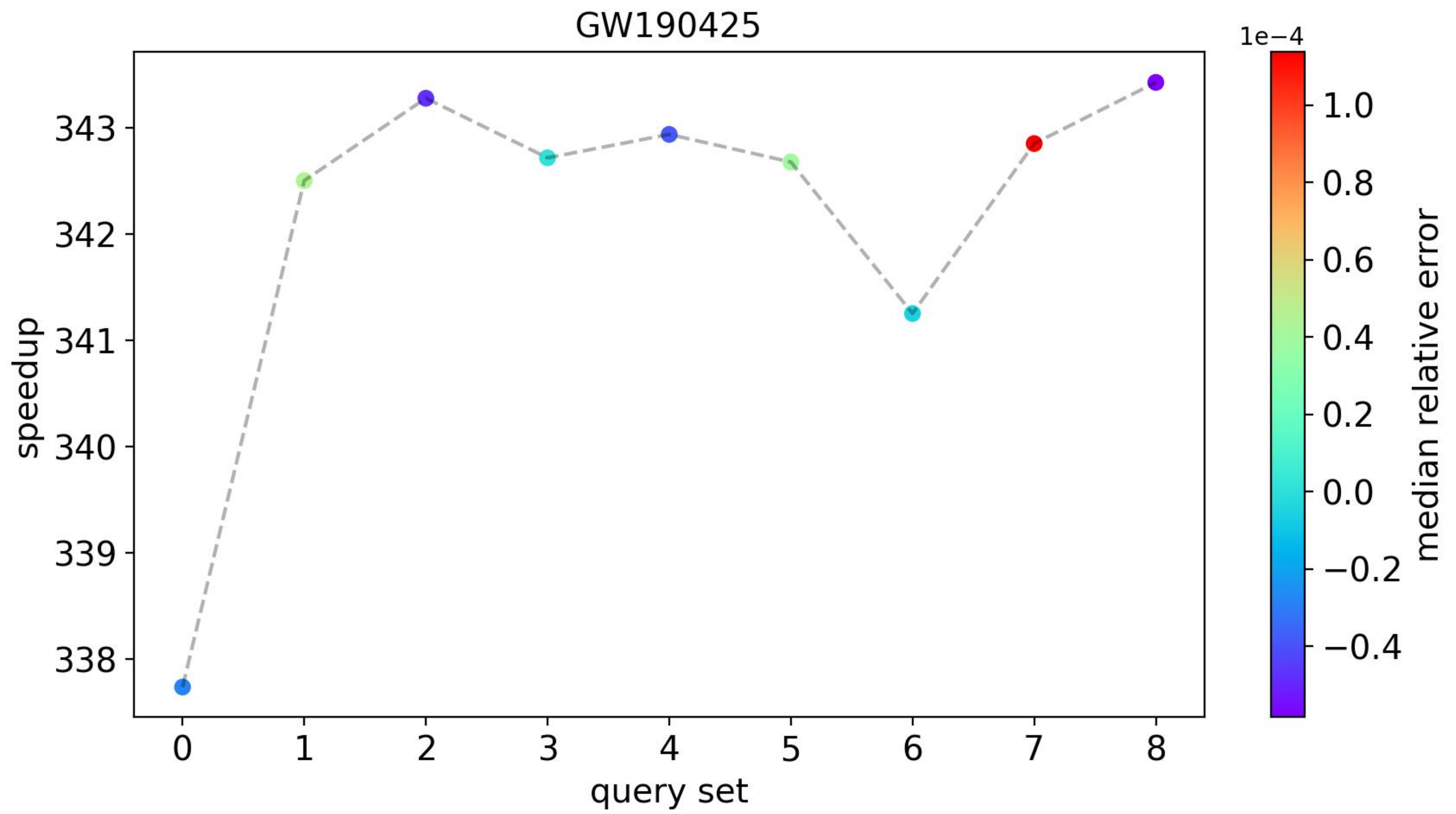
# Early results

## GW170817 and GW190425

$M \sim 2.74\,M_\odot$




$M \sim 3.4\,M_\odot$



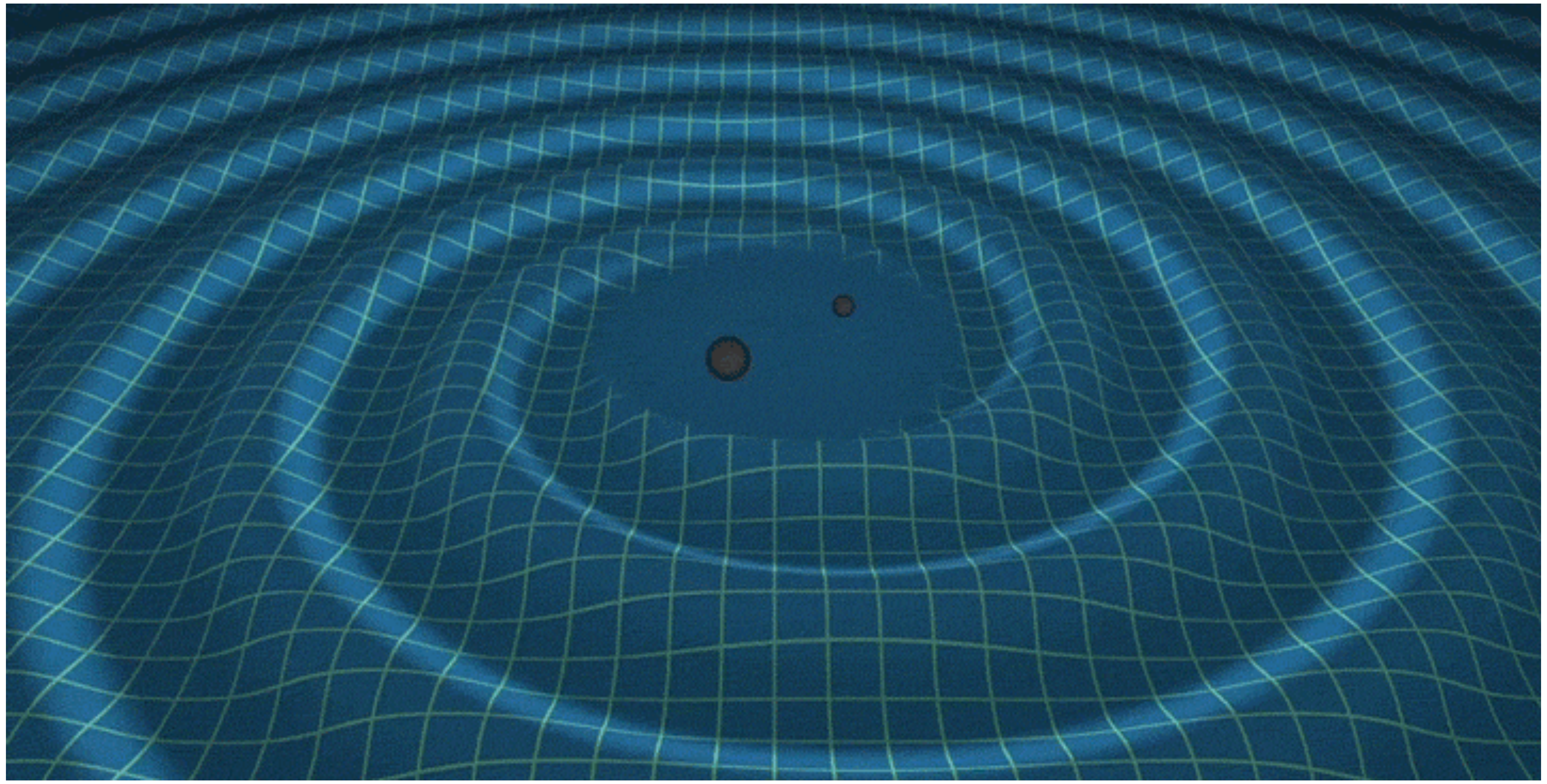

Speedups of $340 - 390$ observed at nominal relative error $\sim O(10^{-4} - 10^{-5})$

# Conclusion

- A Fast PE method crucial for future observing runs (especially BNS/NSBH)
- Our technique has the potential to interface with low-latency PE framework of LIGO
- Soon to be a part of PyCBC (ongoing)
- Future development to include precessing systems (and possibly eccentric?)

# Thank you

LET THERE BE MORE WAVES



~ LIGO/T. Pyle