New black hole mergers from a GW search with higher harmonics

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with

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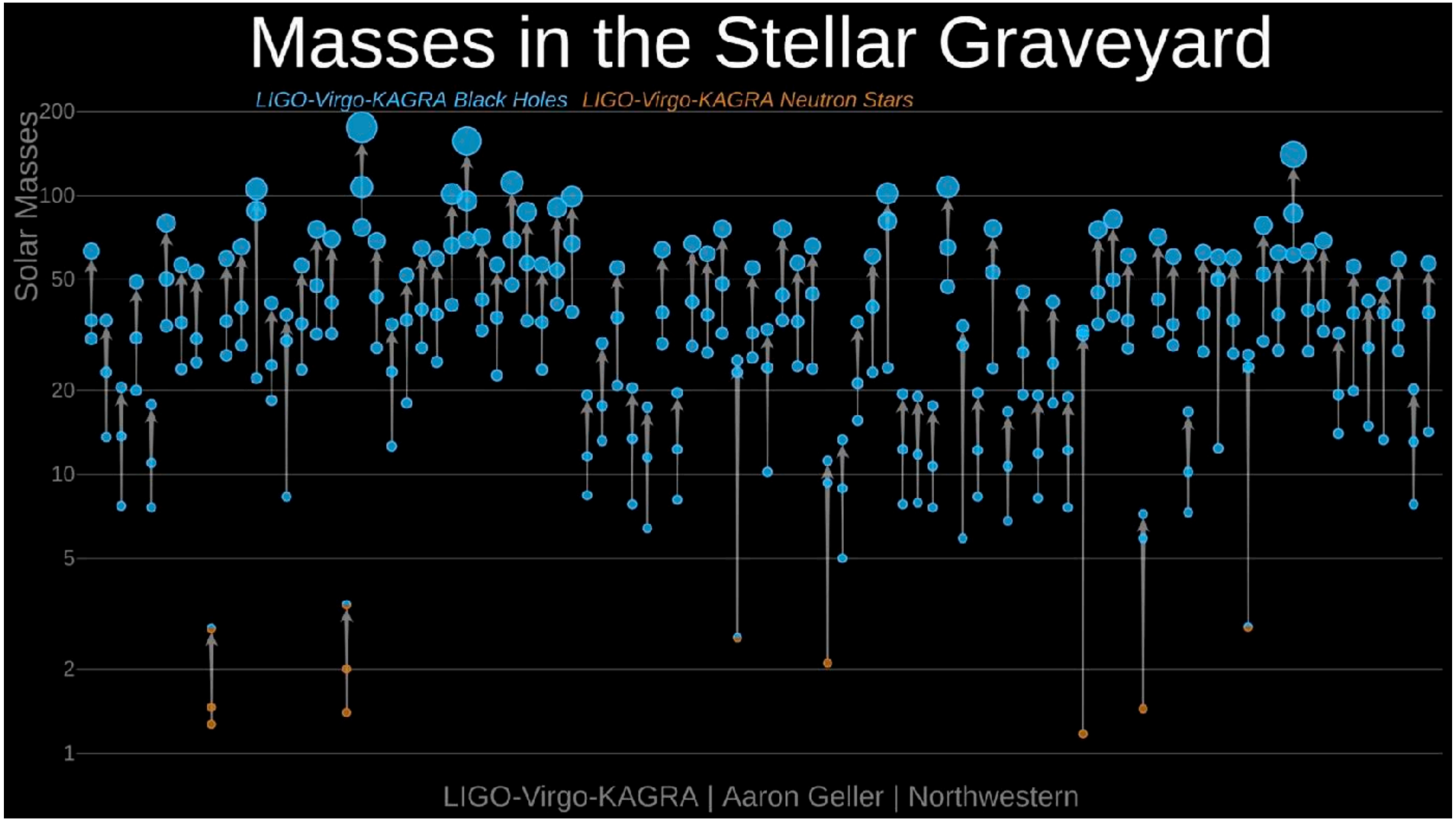
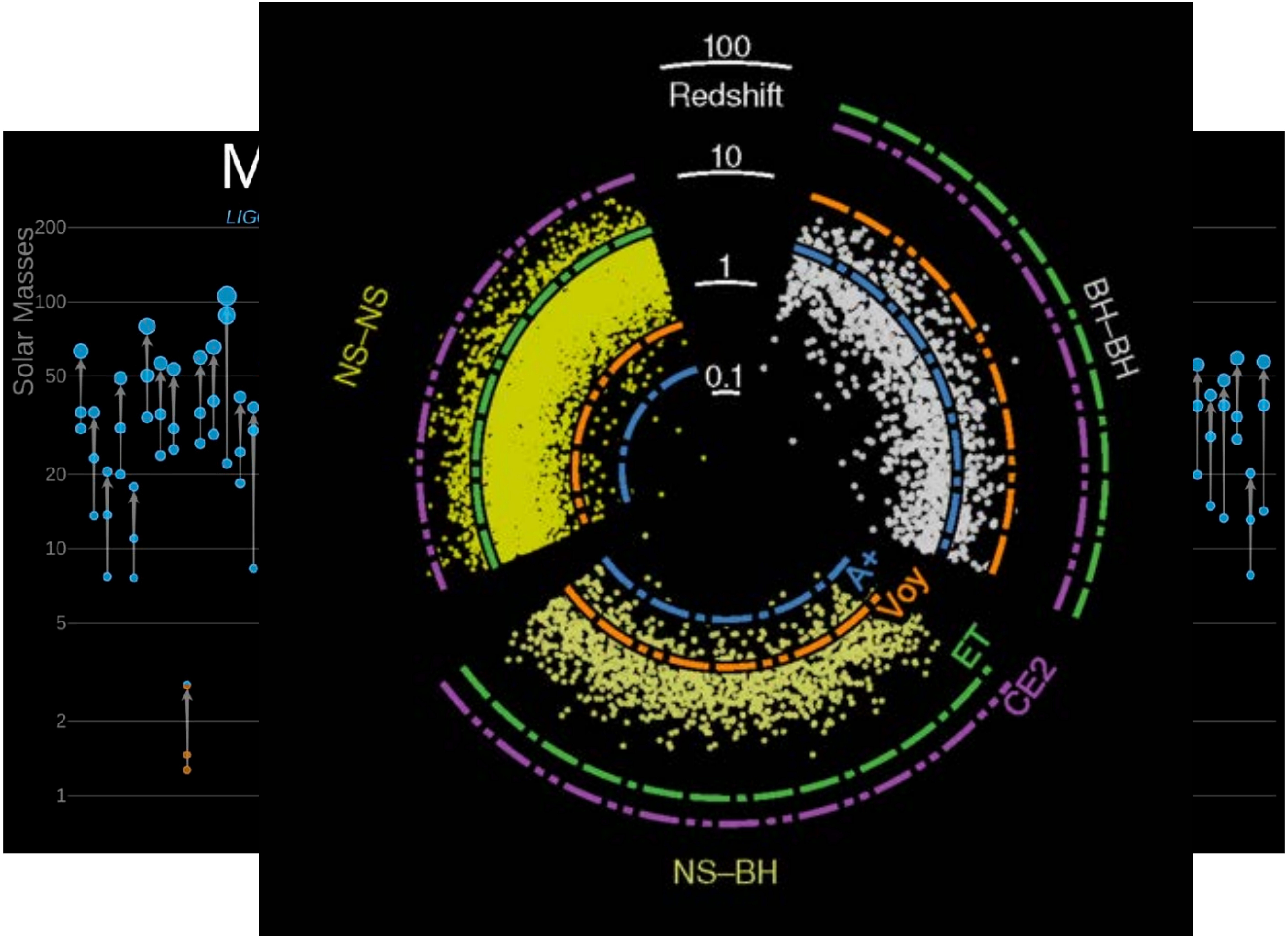
The era of GW astrophysics has begun!





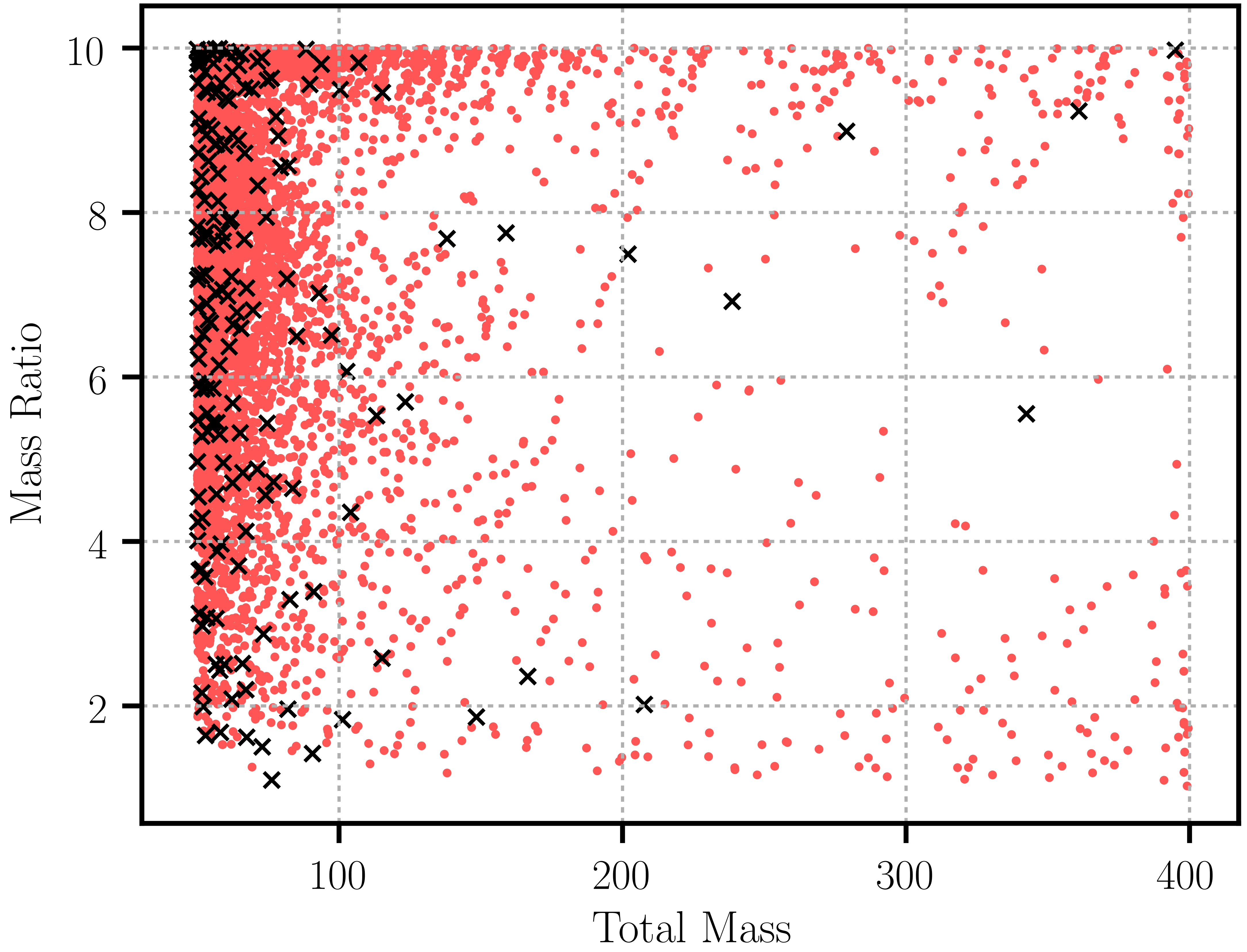
ET (Einstein telescope)

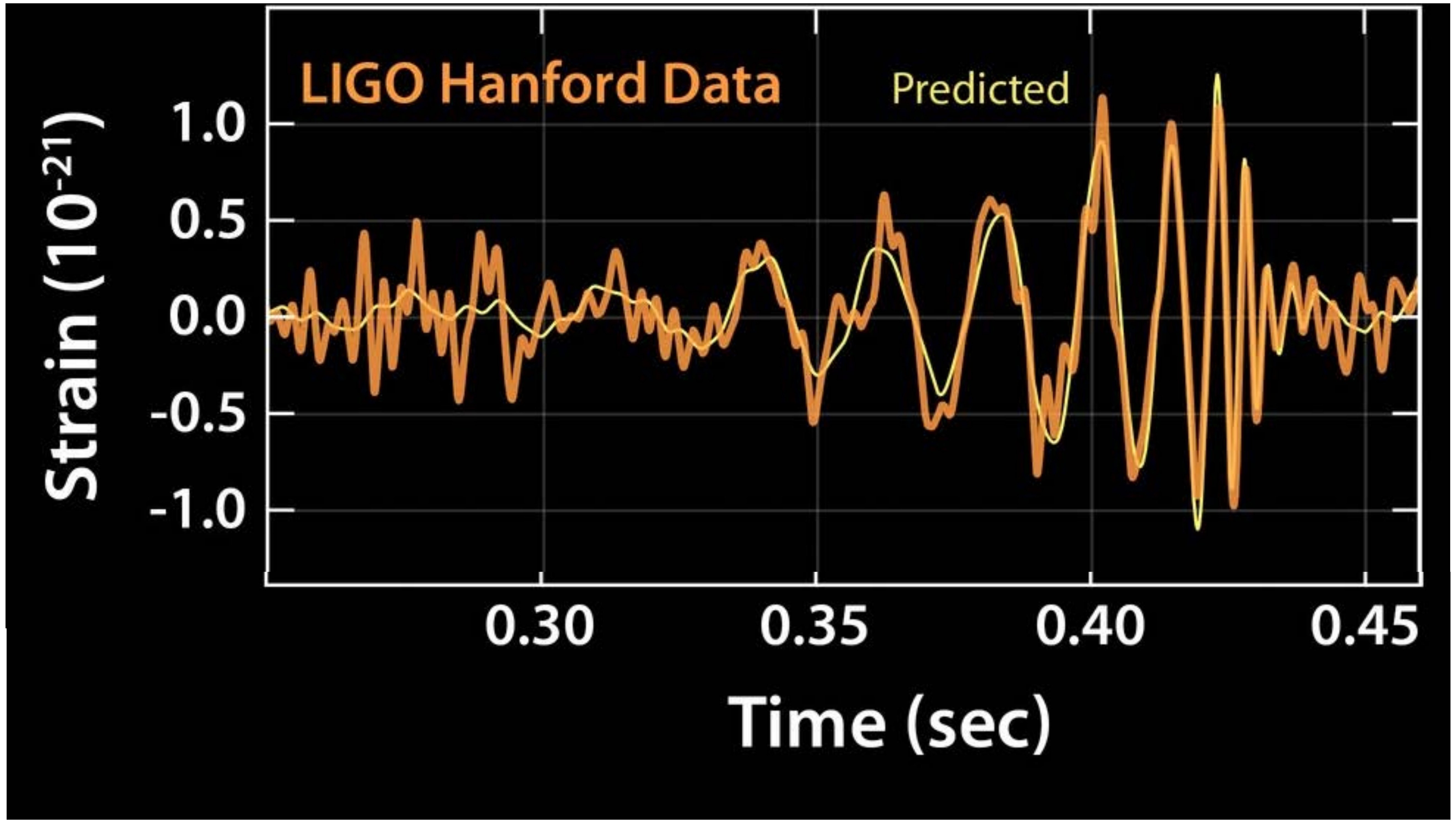
CE (Cosmic explorer)

Overview of a (templated) GW search pipeline

Convolve LIGO-Virgo data with templates in bank

$\sim 10^5$ triggers



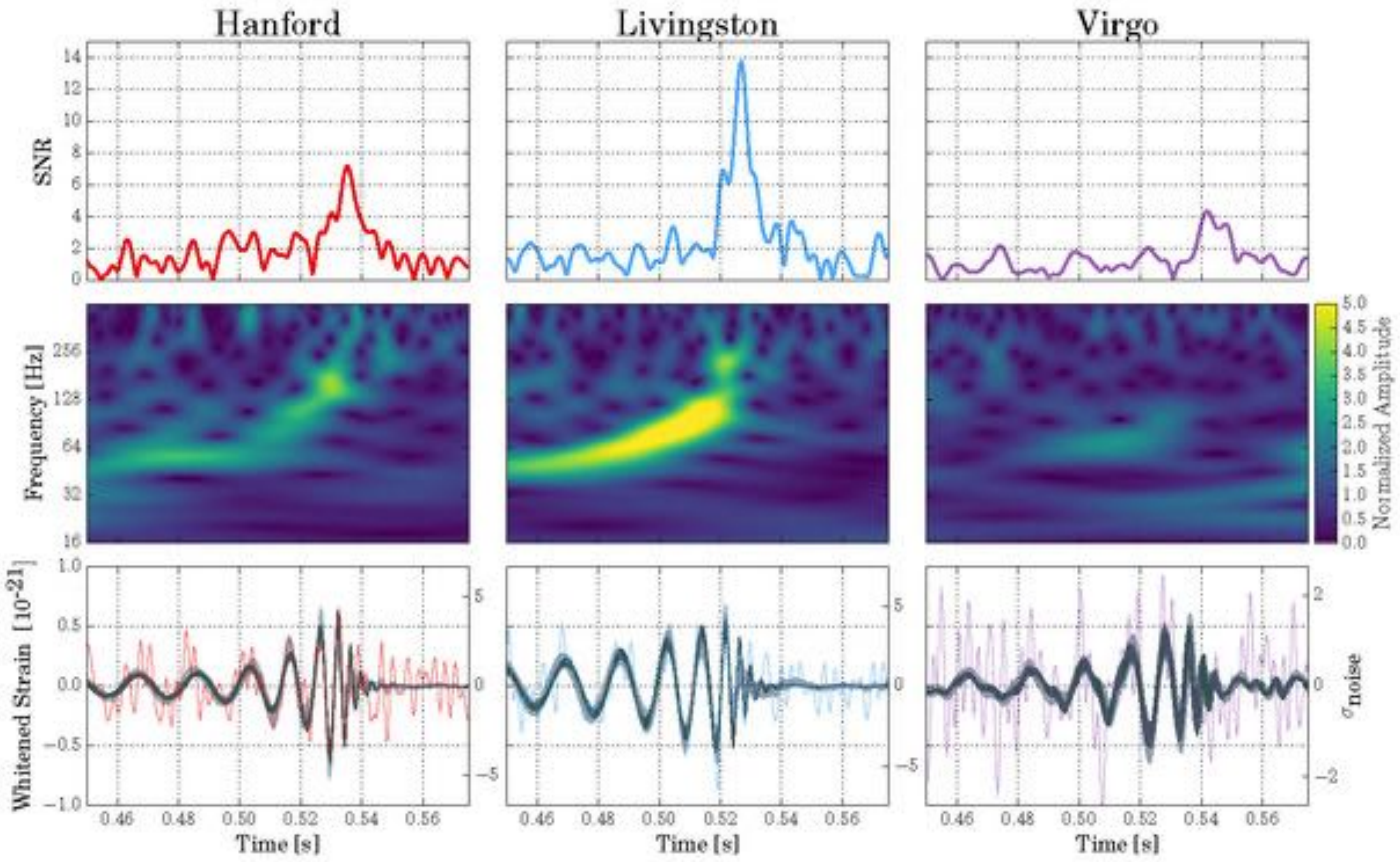


Overview of a GW search pipeline

Convolve LVK data with templates

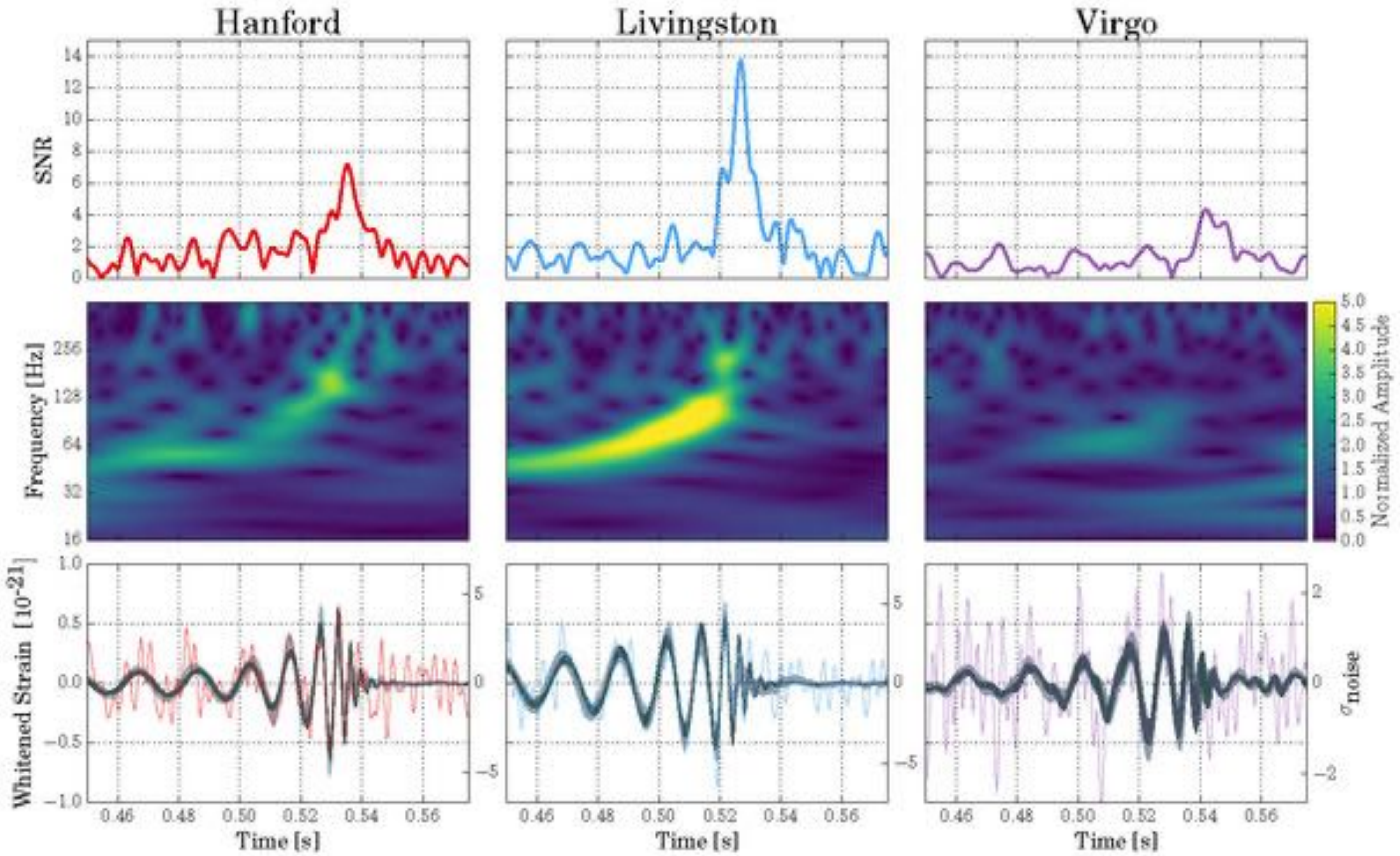
$\sim 10^5$ triggers →

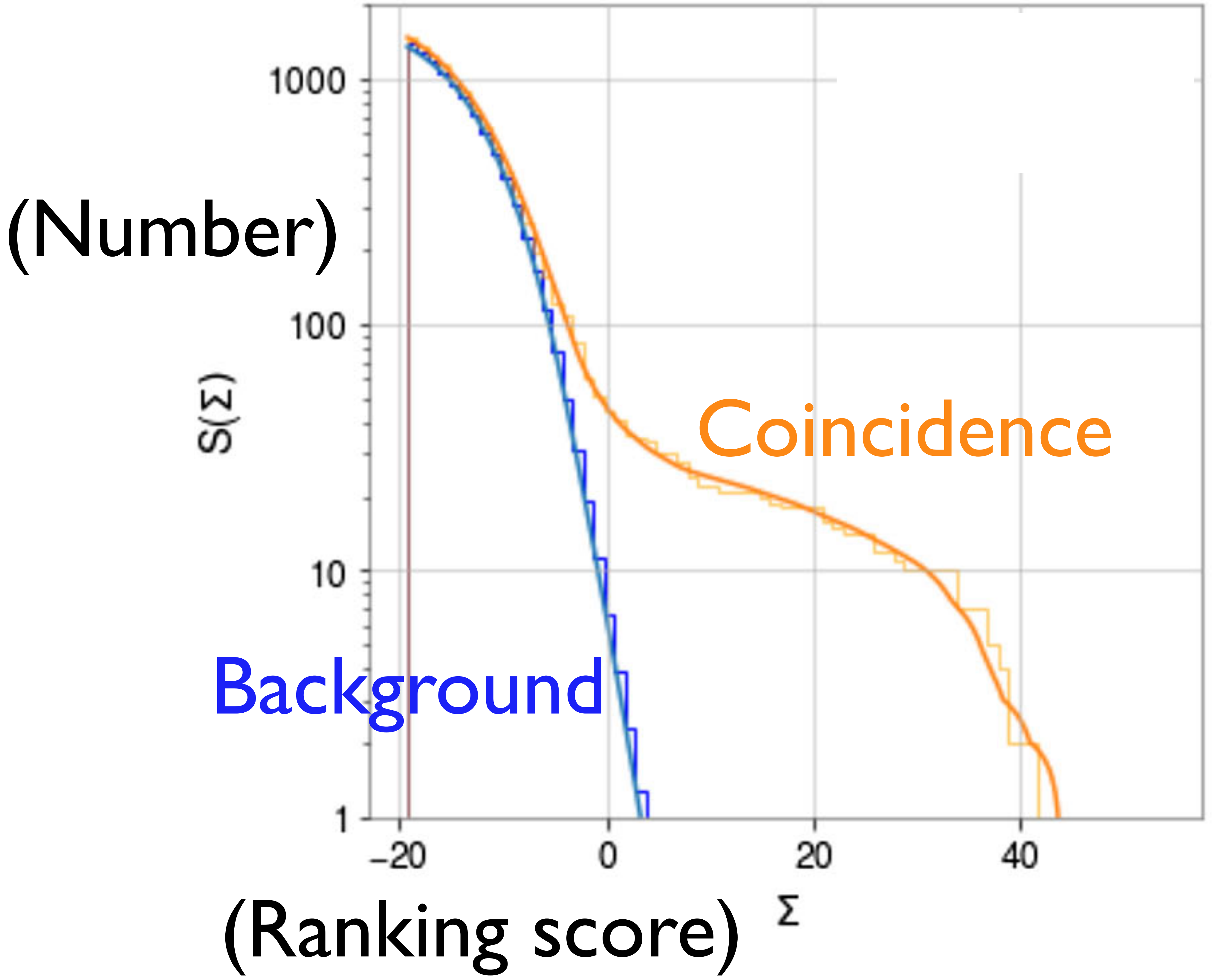
Rank triggers based on coherence of detectors



Overview of a GW search pipeline

Convolve LVK data with templates $\xrightarrow{\sim 10^5 \text{ triggers}}$ Rank triggers based on coherence of detectors $\xrightarrow{\sim 100 \text{ triggers}}$





Overview of a GW search pipeline

Convolve LVK data with templates

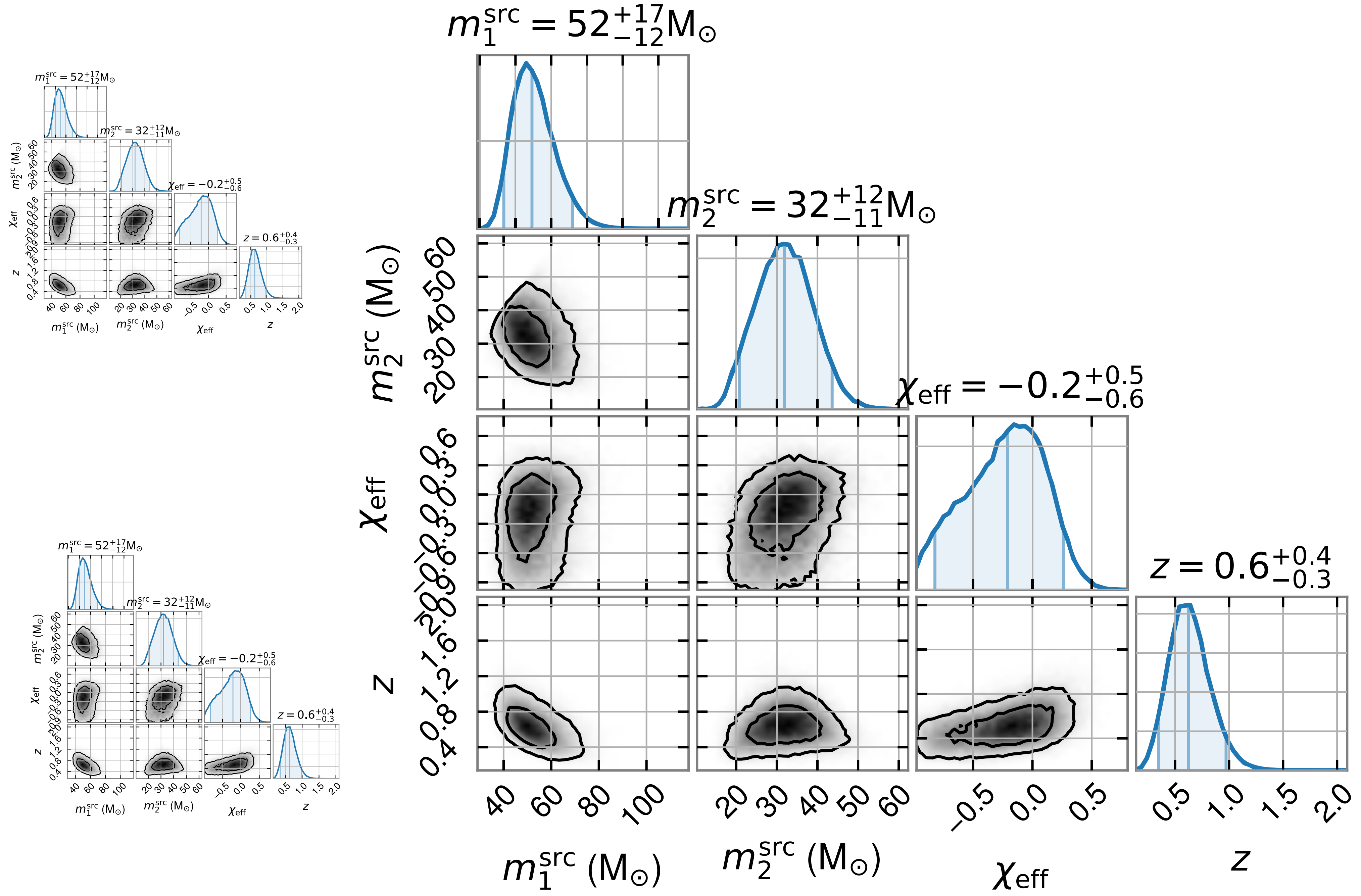
$\sim 10^5$ triggers →

Rank triggers based on coherence of detectors

~ 100 triggers →

Perform PE (param. estimation)

↓



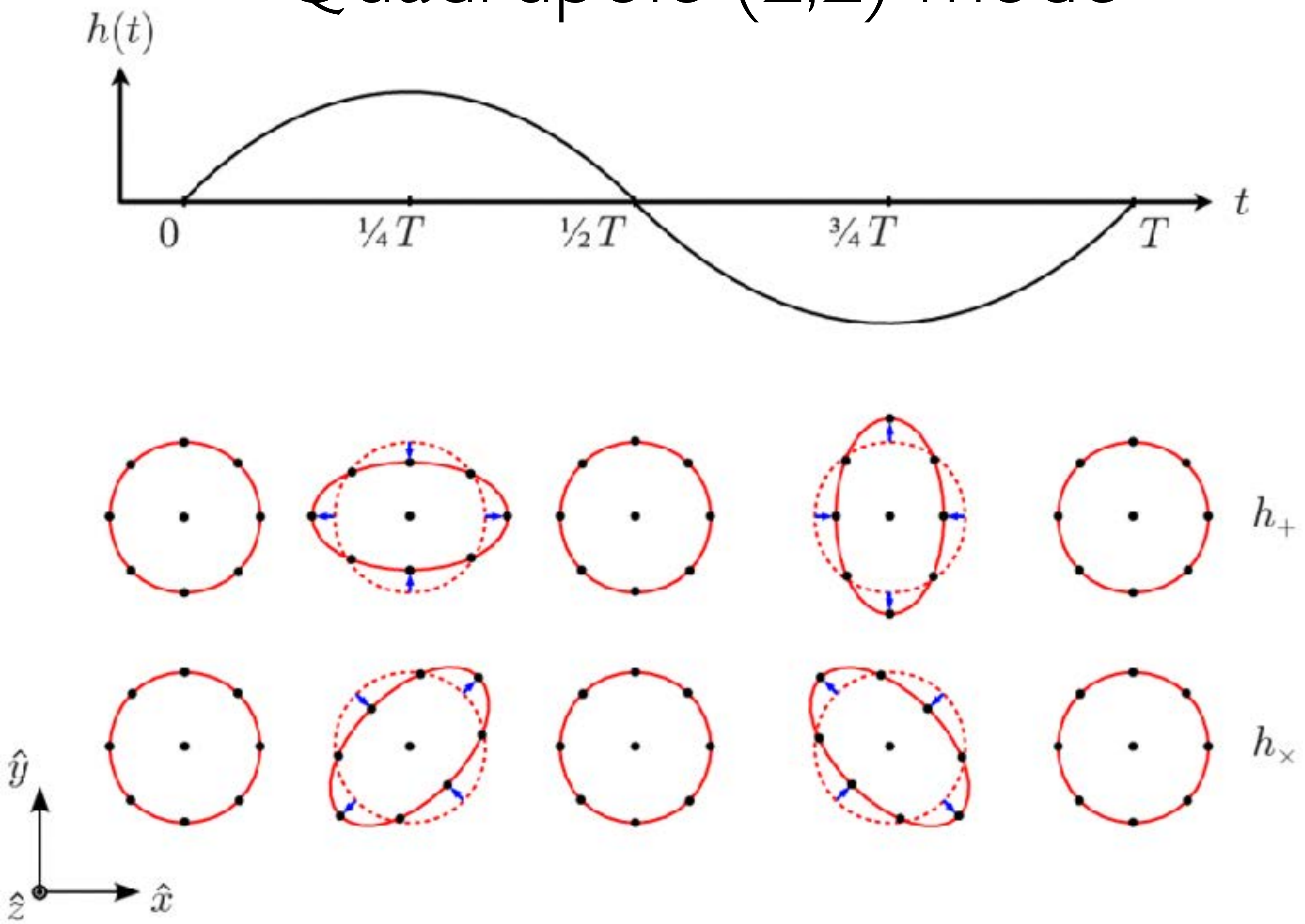
Overview of a GW search pipeline

Convolve LVK data with templates → $\sim 10^5$ triggers → Rank triggers based on coherence of detectors → ~ 100 triggers → Perform PE (param. estimation)

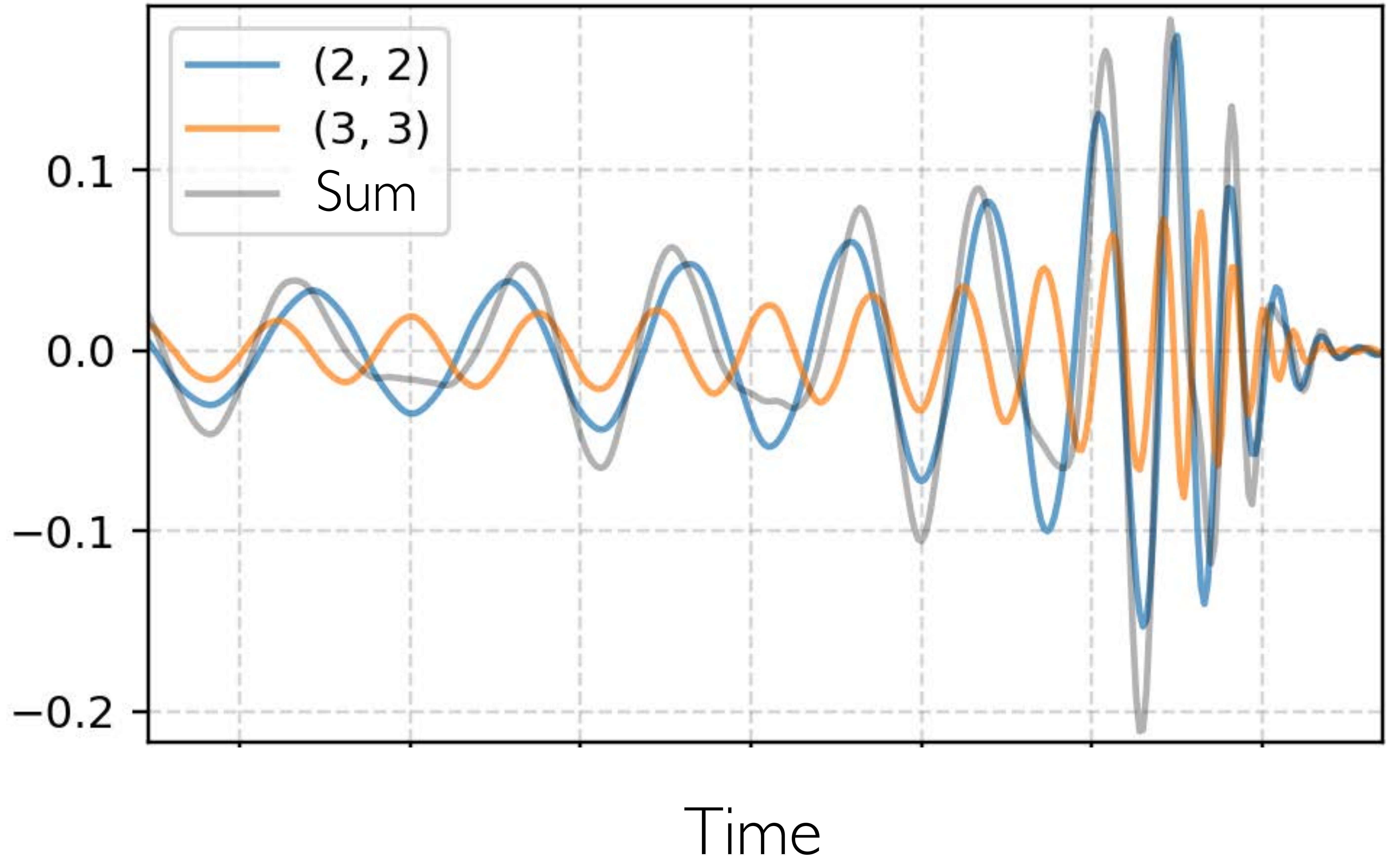
Generally only 22 mode and aligned-spins assumed in GW template banks

Generally only (2,2) mode and aligned-spins assumed in GW template banks

Quadrupole (2,2) mode



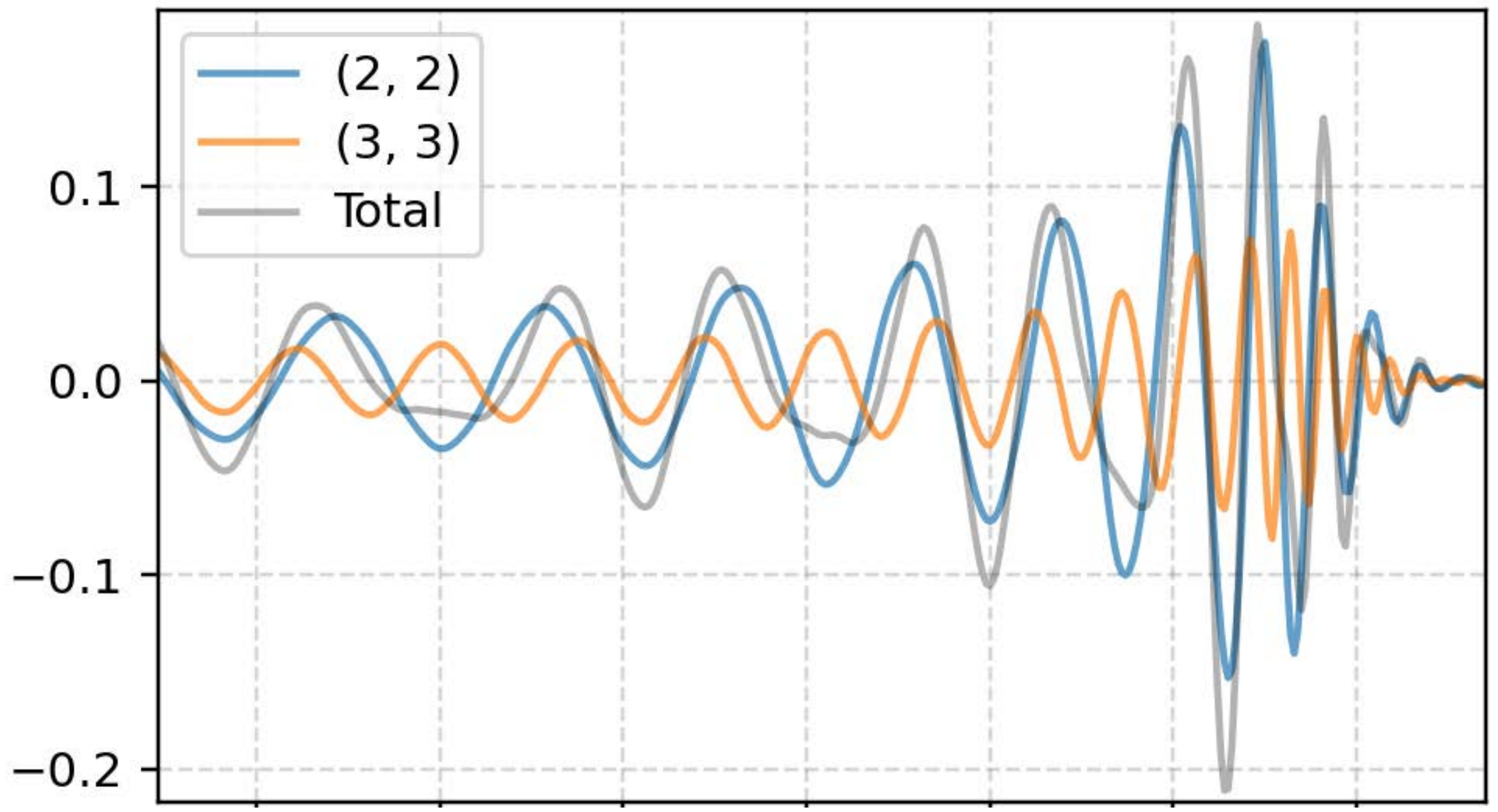
$$\frac{|h_{33}|}{|h_{22}|} \propto \left[\frac{m_1 - m_2}{m_1 + m_2}\right] \text{velocity}^{1/3} \sin(i)$$



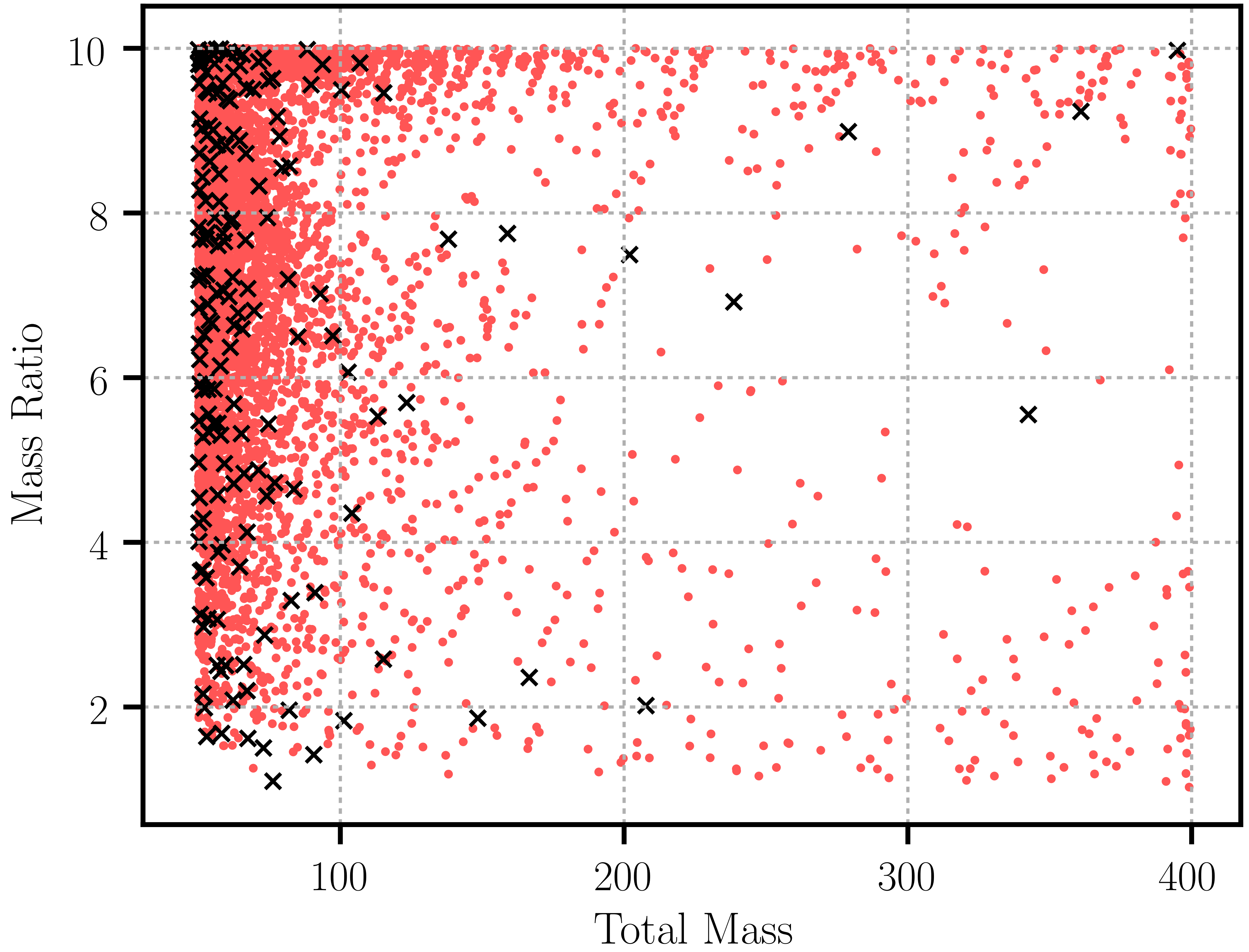
Why is searching with HM difficult?

1. Template bank size increases by a factor of ~100 w.r.t 22-only

(as we now need to sample over amplitude and phase of HMs: i, ϕ_{ref})



Templates × 22 only • 22 + HM



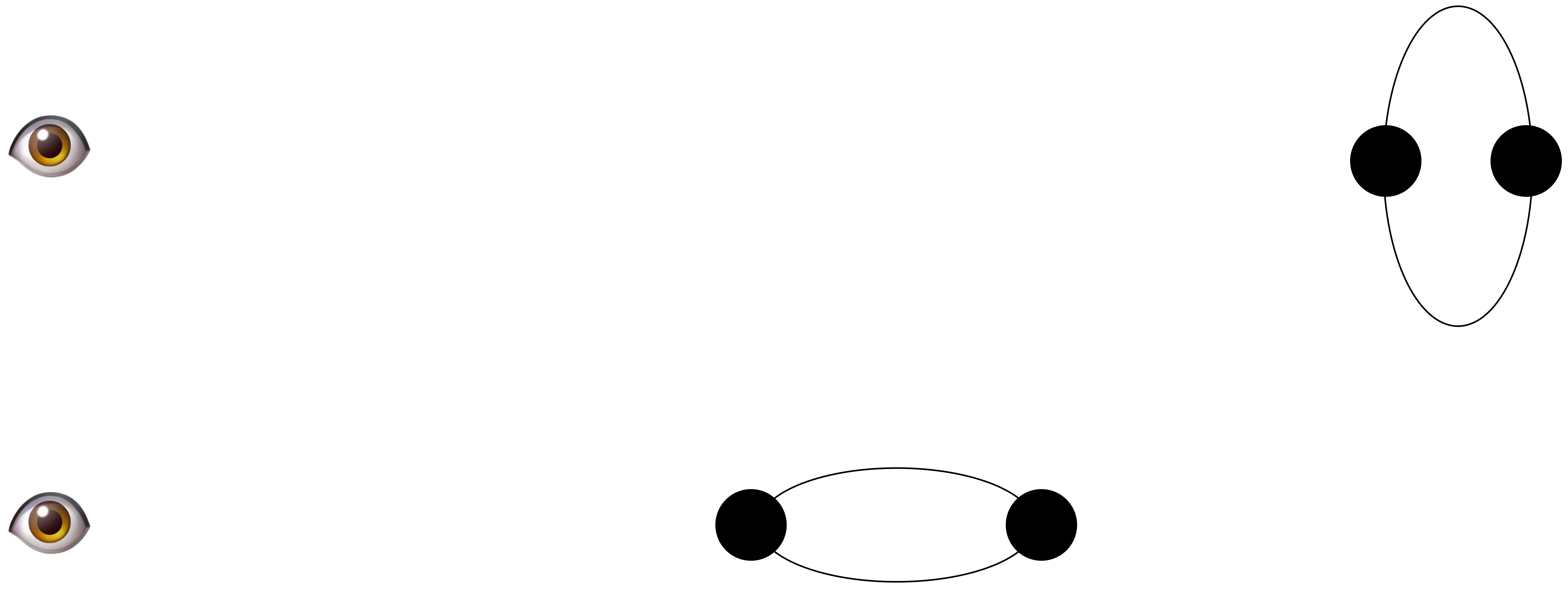
Harry et al. 18, Chandra et al. 22, Capano et al. 14

Significance of higher modes (HM)

- Breaking important parameter degeneracies

  - Distance vs inclination
    (useful for precise determination of H_0)

$$\frac{|h_{33}|}{|h_{22}|} \propto \left[\frac{m_1 - m_2}{m_1 + m_2}\right] \text{velocity}^{1/3} \sin(i_{\text{incl}})$$



Significance of higher modes (HM)

- Breaking important parameter degeneracies
- Testing GR in the strong field regime
- Probing properties of remnant (recoil kick, ringdown spectrum)

$$\frac{|h_{33}|}{|h_{22}|} \propto \left[\frac{m_1 - m_2}{m_1 + m_2}\right] \text{velocity}^{1/3} \sin(i_{\text{incl}})$$

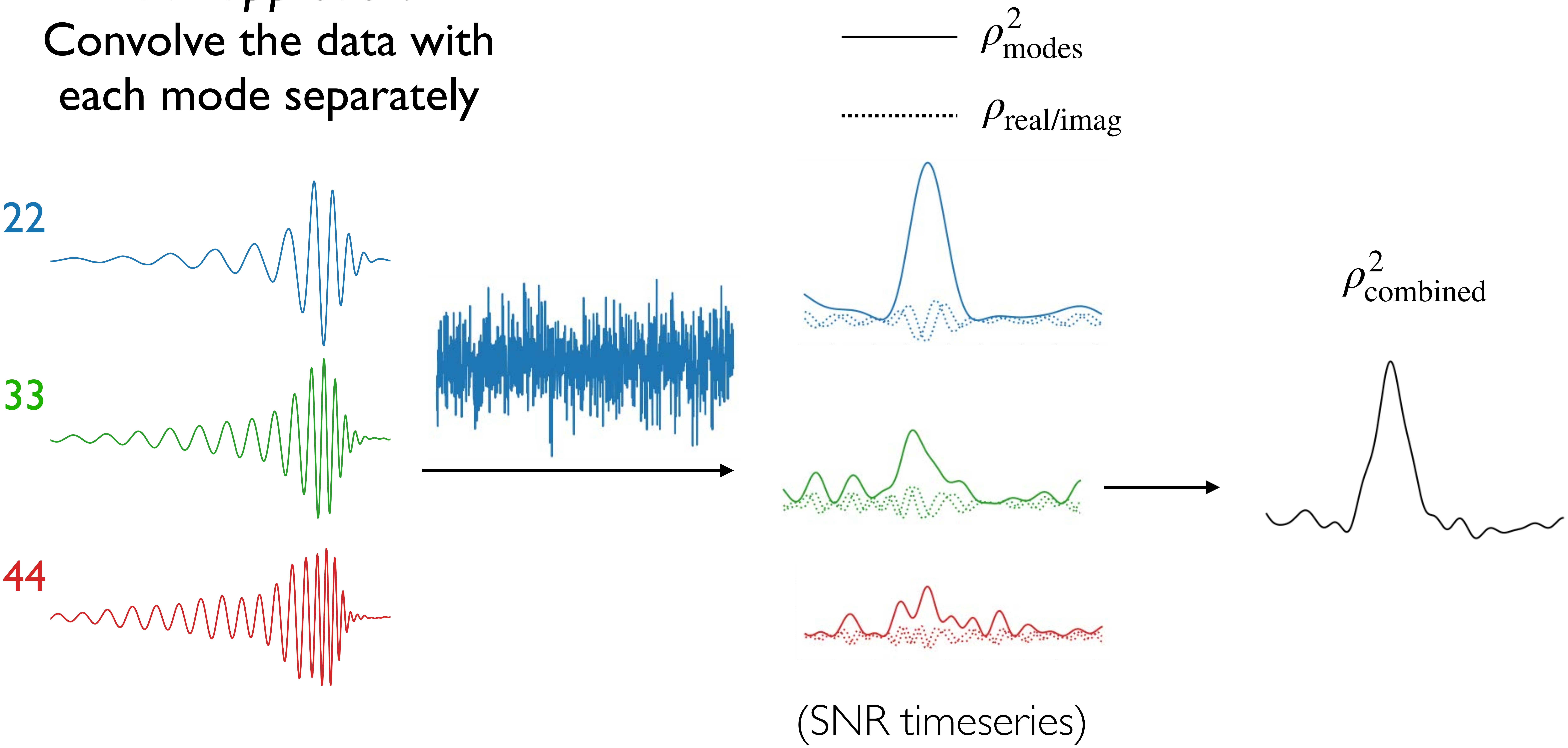
$$\text{velocity} \propto M_{\text{tot}}\, f$$

Bustillo et al 18, Kastha et al 18,
Varma et al 20, Kapadia et al 20,
Singh et al 21,

Prev. approaches for HM search

Our approach:

Convolve the data with each mode separately

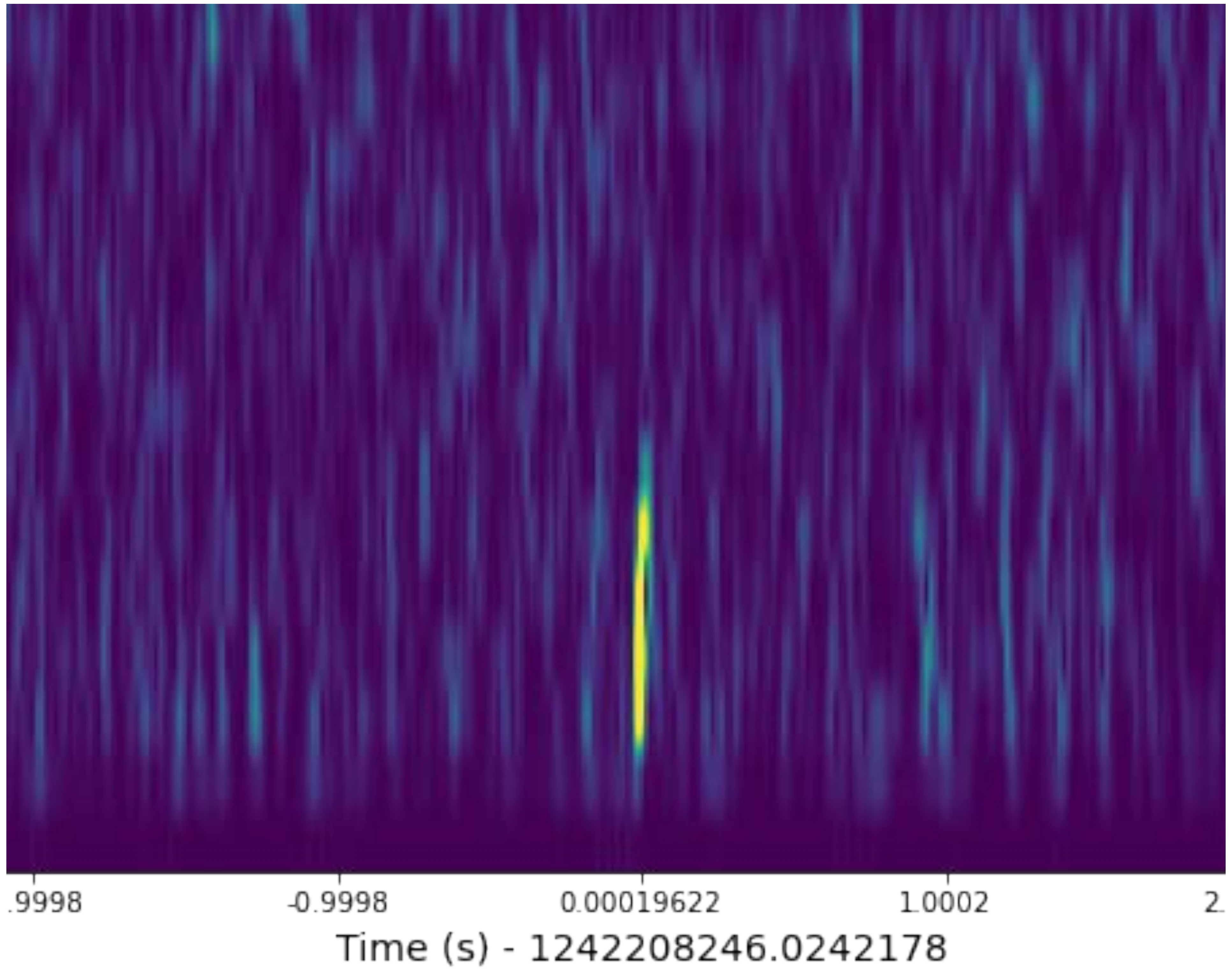


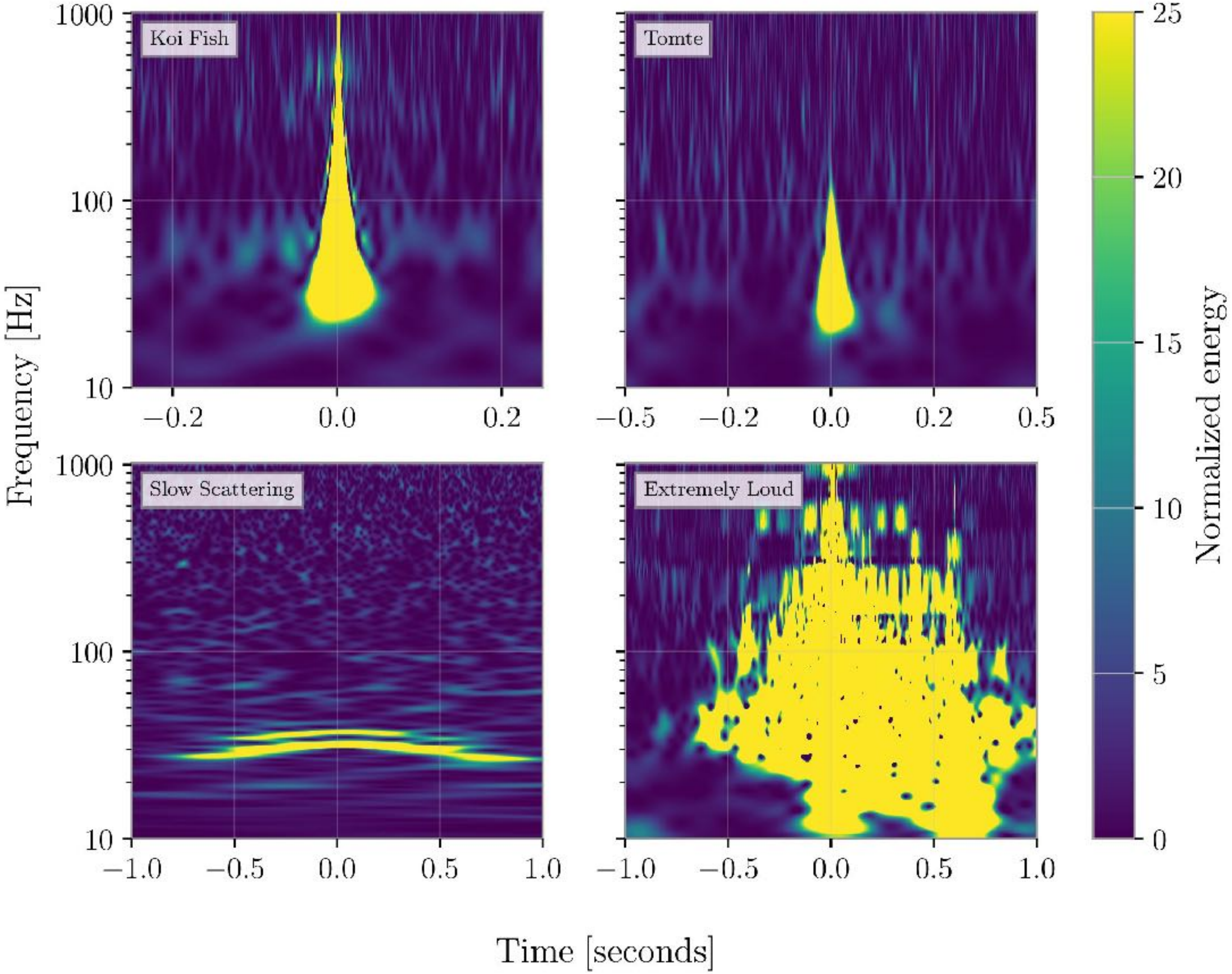
We also improve sensitivity of all modes the high-mass regime

High mass wfs can be effectively mimicked by noise transients

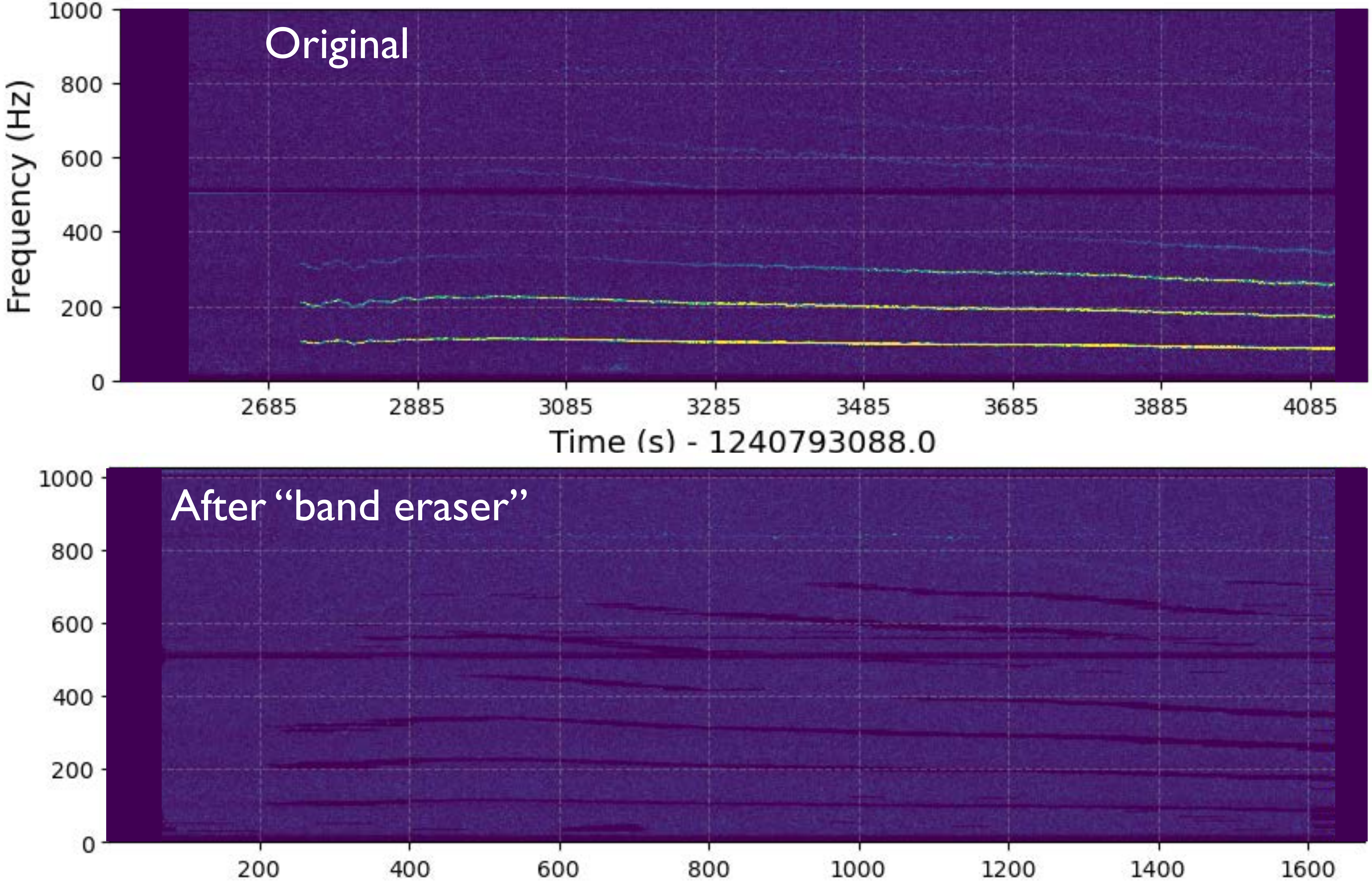
Injected BBH merger

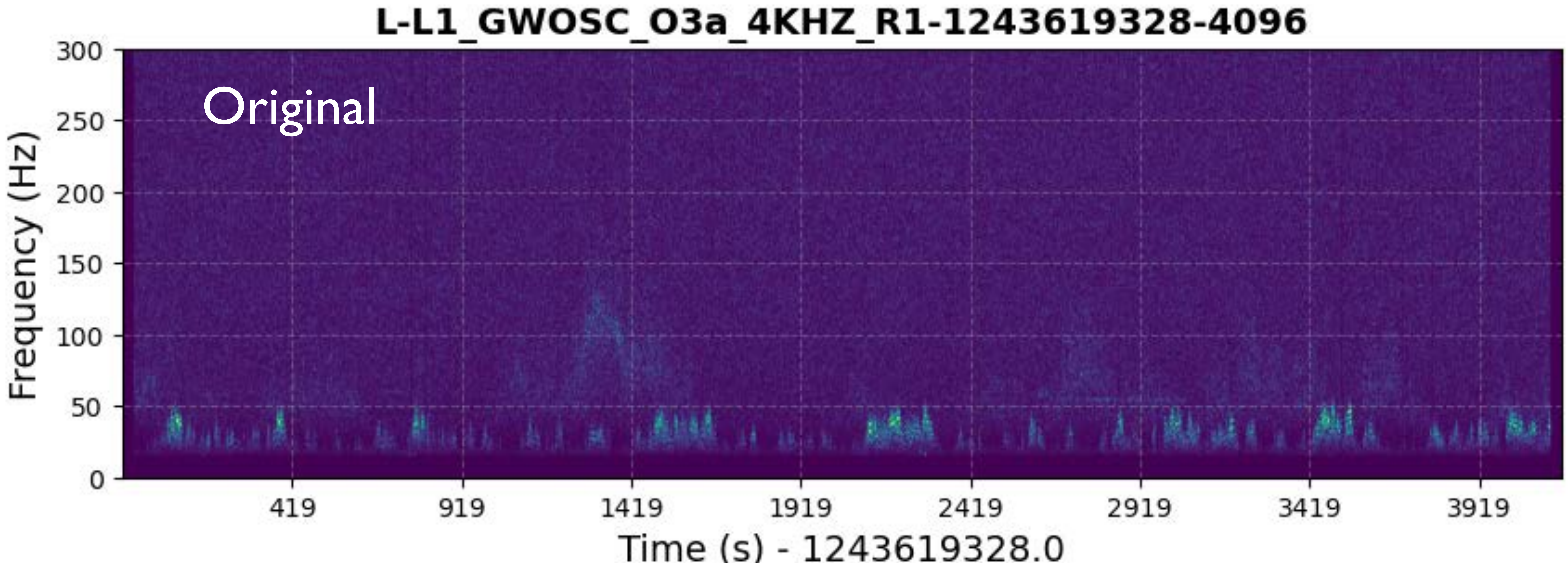
$m_1, m_2 = 280,70$

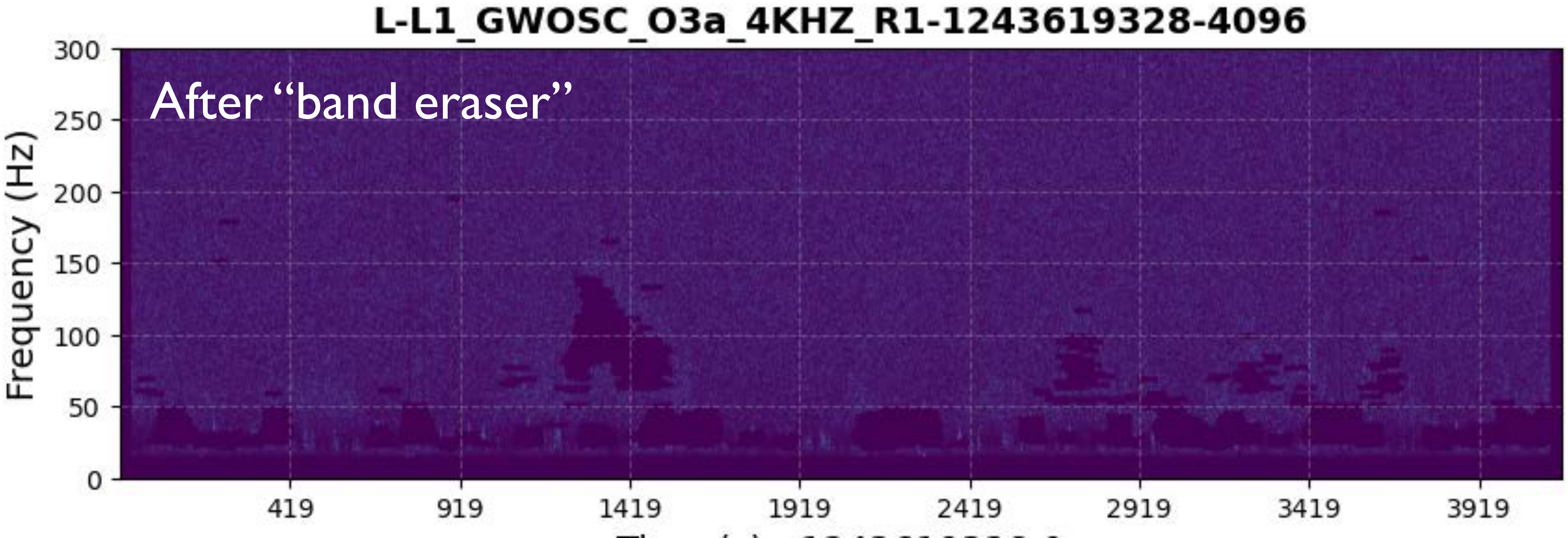




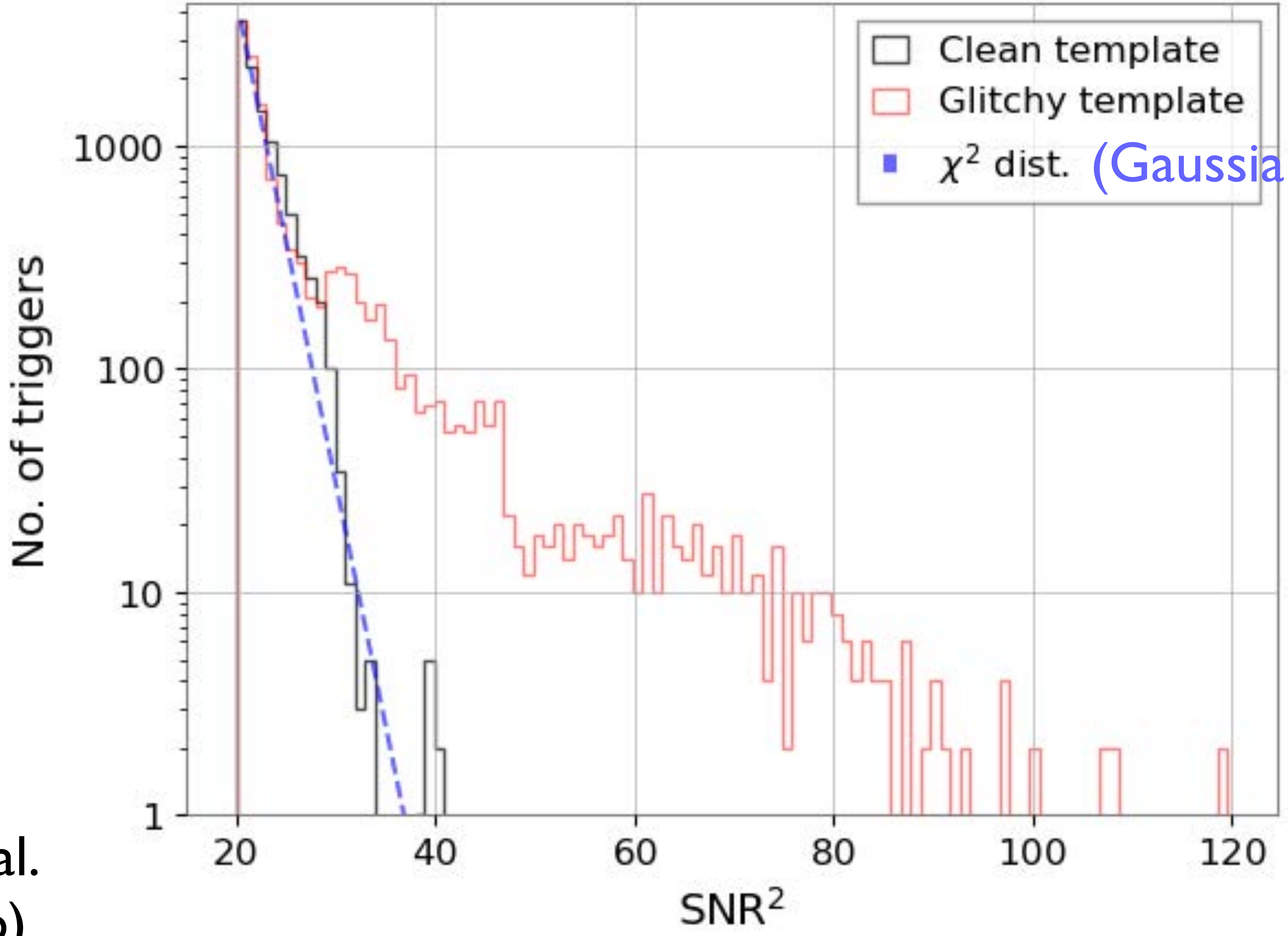
We remove noise transients in GW data ("Glitches")




L-L1_GWOSC_O3a_4KHZ_R1-1243619328-4096
Original
Frequency (Hz)
300
250
200
150
100
50
0
419
919
1419
1919
2419
2919
3419
3919
Time (s) - 1243619328.0


L-L1_GWOSC_O3a_4KHZ_R1-1243619328-4096
After “band eraser”
Frequency (Hz)
300
250
200
150
100
50
0
419
919
1419
1919
2419
2919
3419
3919

New improvements : We isolate templates which are glitchy and penalize them



(Gaussian noise)

$$P(\rho^2) \propto e^{-\rho^2/2}$$

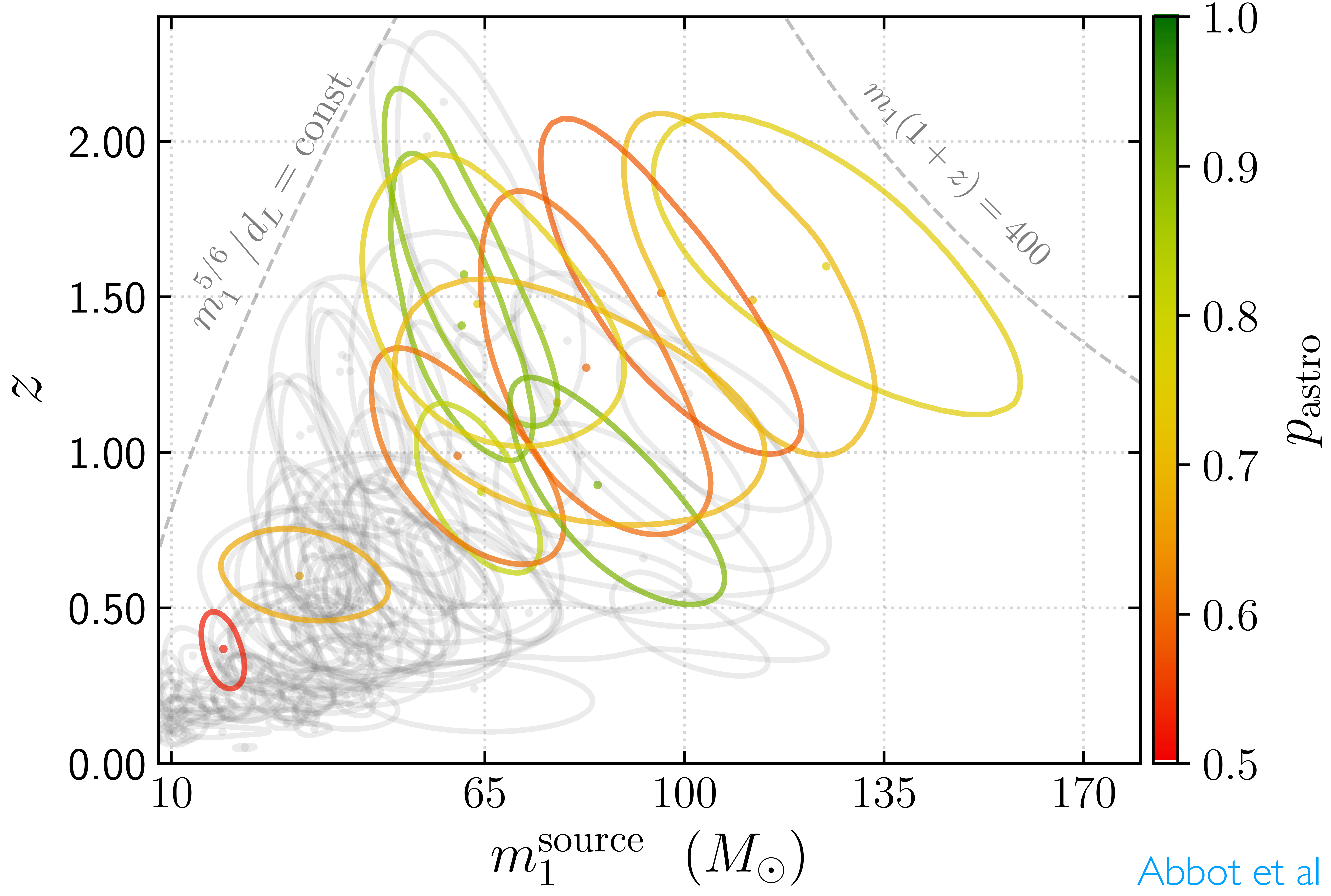
DW et al. (in prep)

New events from our search with higher modes

(PRELIMINARY)

Colored: New detections

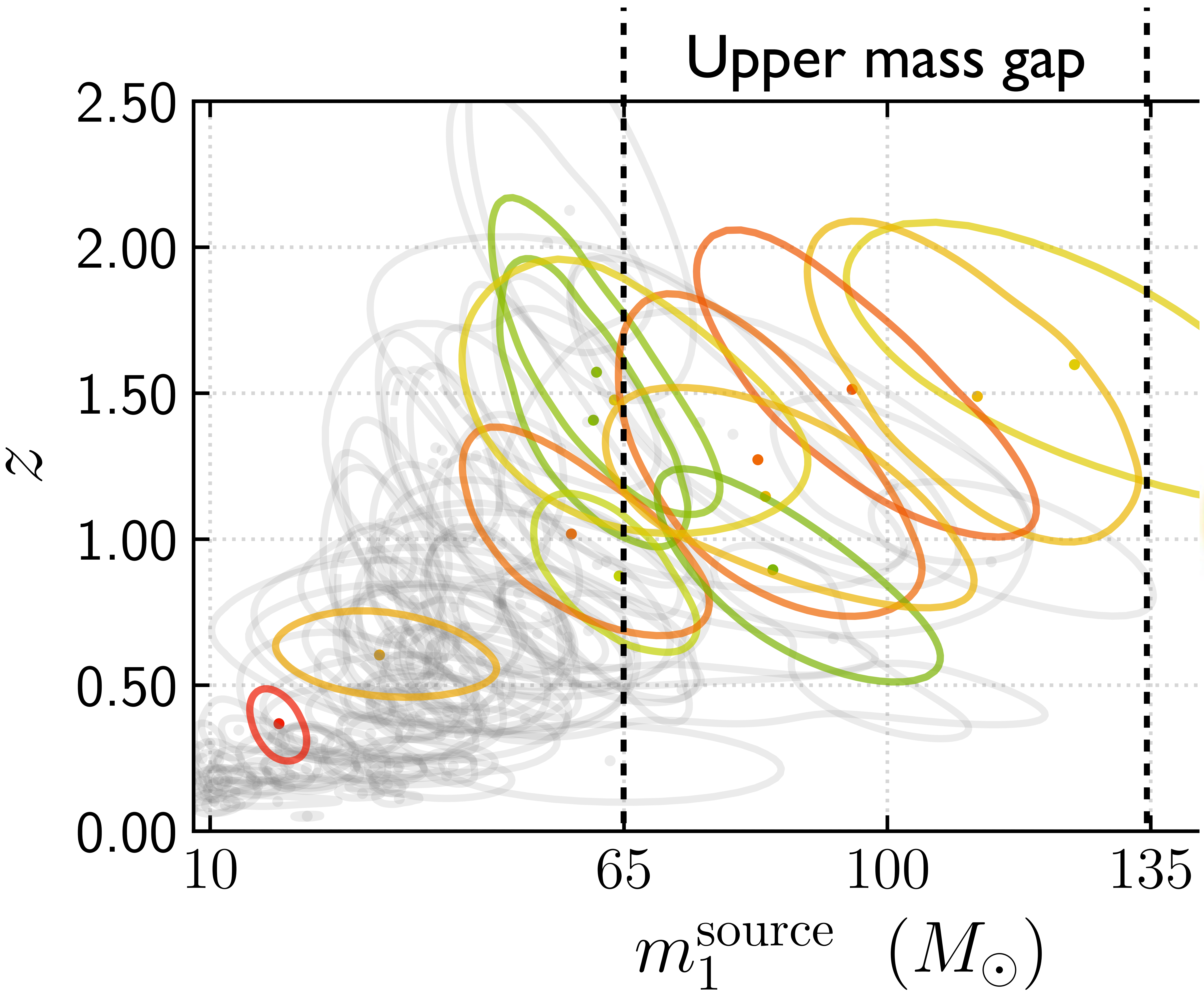
Gray: LVC catalog + Other pipelines (OGC + IAS-22)



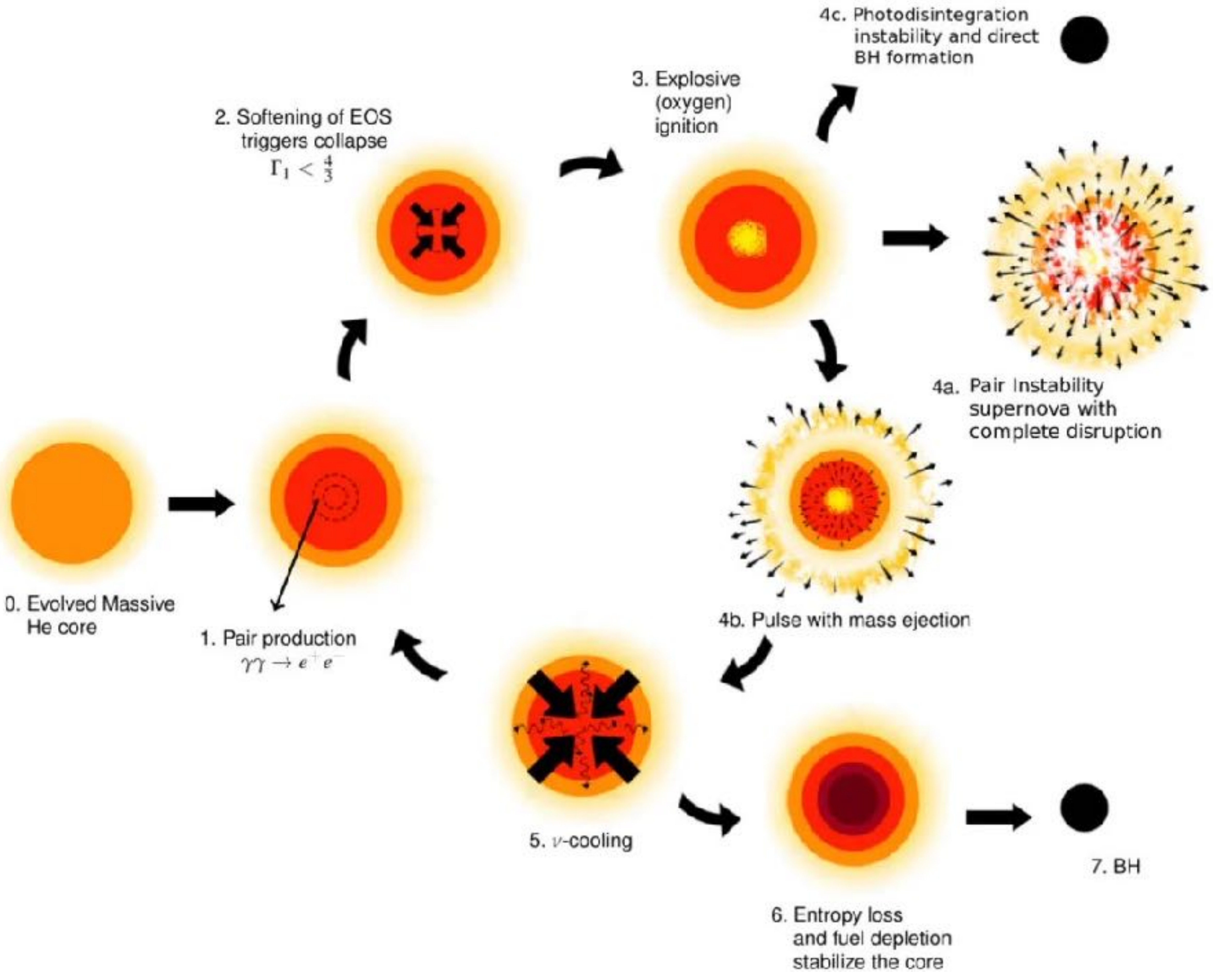
Probability of being of astrophysical origin

DW et al. (in prep)

Abbot et al 22, Nitz et al 22, Olsen et al 22

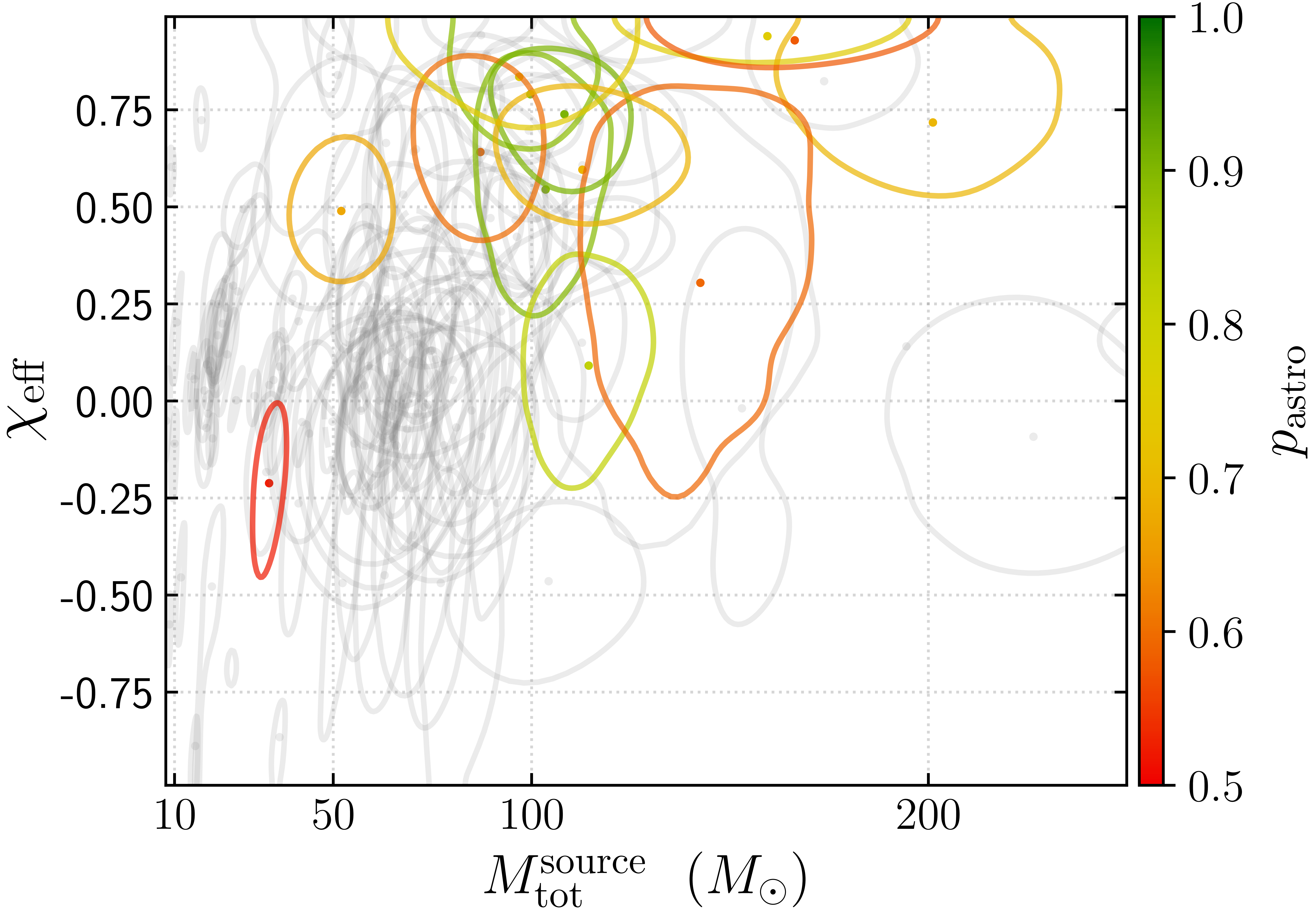


Upper mass gap
2.50
2.00
1.50
1.00
0.50
0.00
z
10
65
100
135
$m_1^{\mathrm{source}}\ (M_\odot)$



0. Evolved Massive He core
1. Pair production $\gamma\gamma \to e^+e^-$
2. Softening of EOS triggers collapse $\Gamma_1 < \frac{4}{3}$
3. Explosive (oxygen) ignition
4c. Photodisintegration instability and direct BH formation
4a. Pair Instability supernova with complete disruption
4b. Pulse with mass ejection
5. ν-cooling
6. Entropy loss and fuel depletion stabilize the core
7. BH

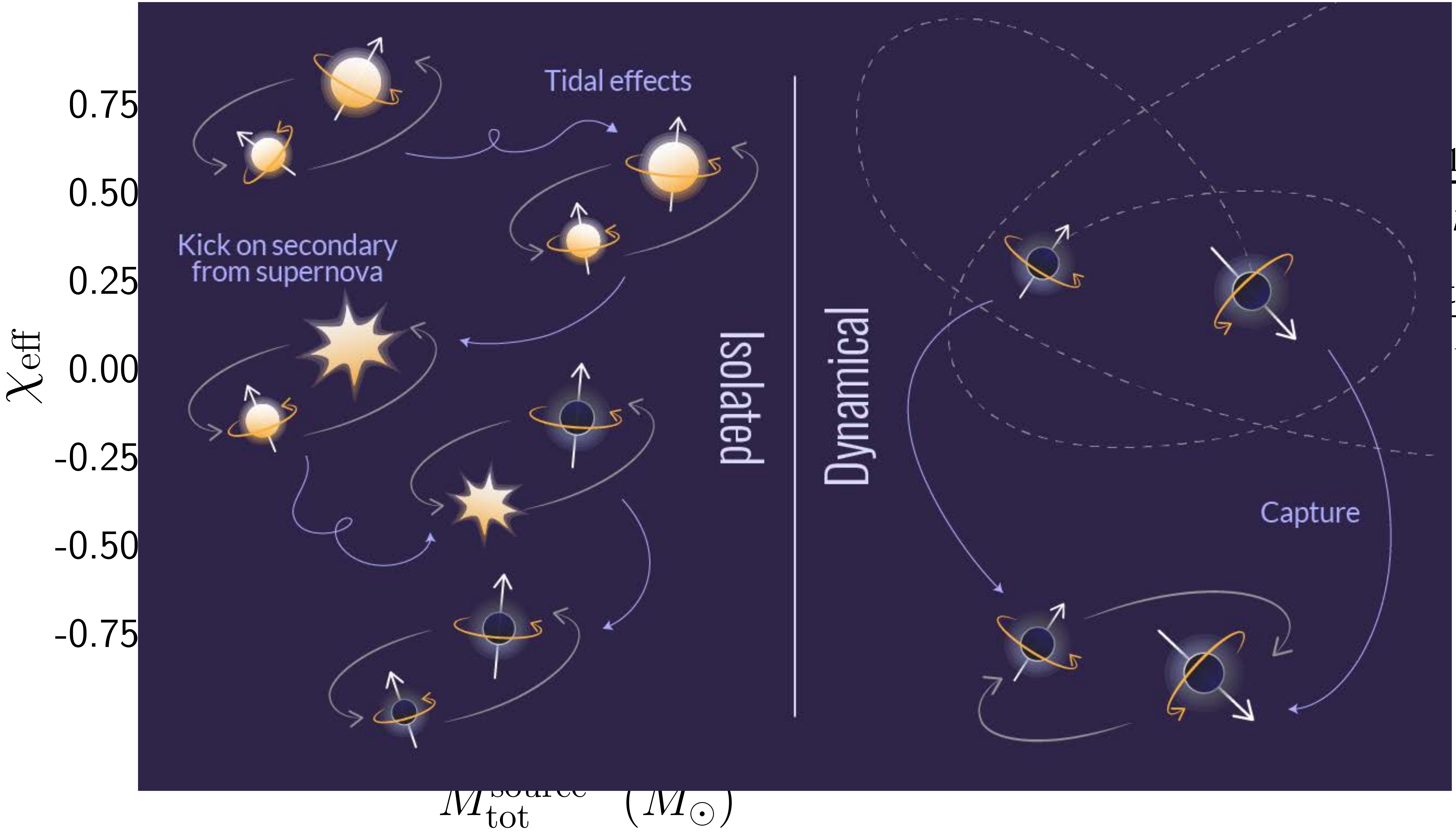
Colored: New detections



$$\chi_{\mathrm{eff}} = \frac{m_1\chi_1 + m_2\chi_2}{m_1 + m_2}$$

(Component of BH spins aligned with $\vec{L}_{\mathrm{orb}}$)

Colored: New detections



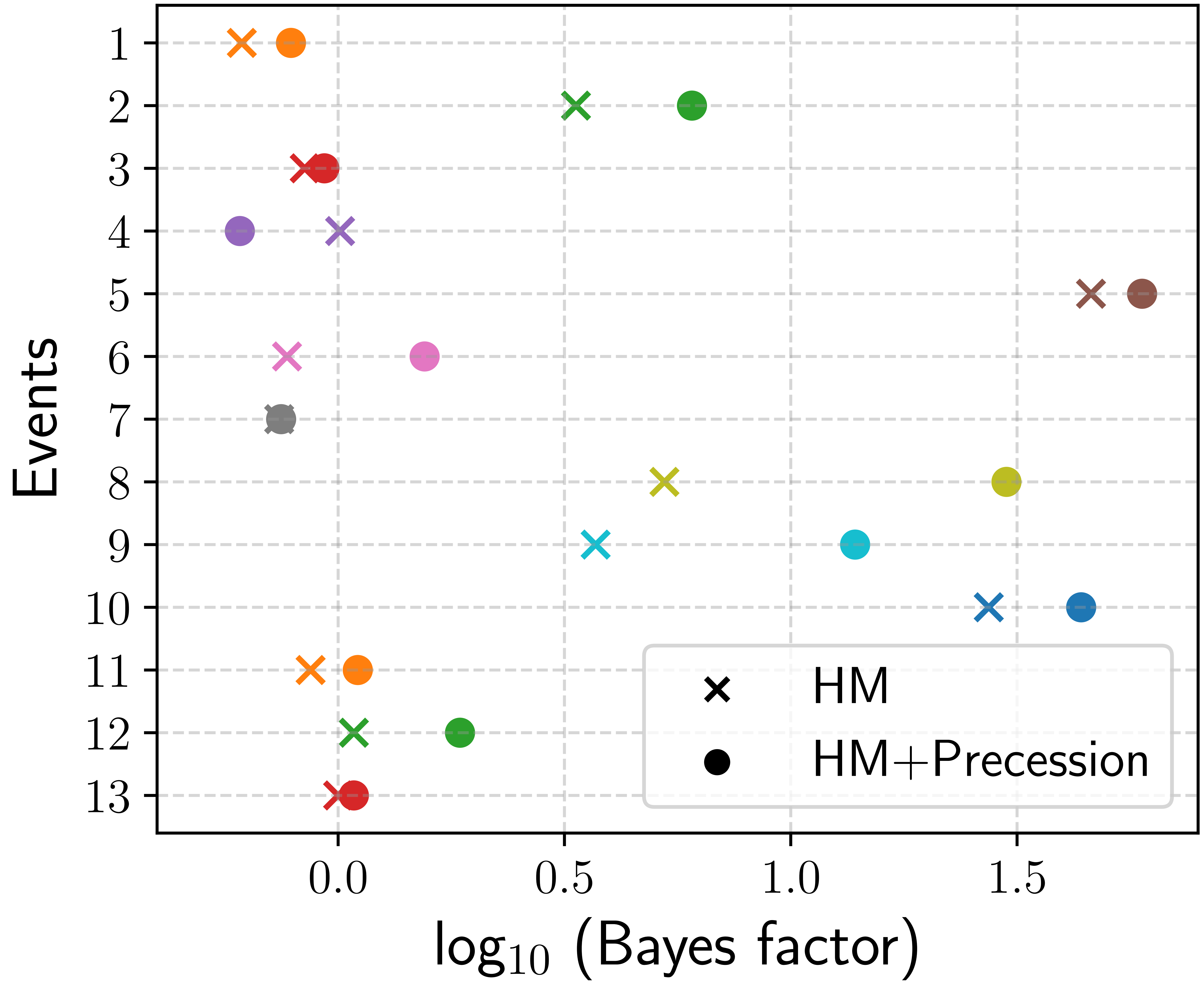
$\chi_1 + m_2\chi_2$

$m_1 + m_2$

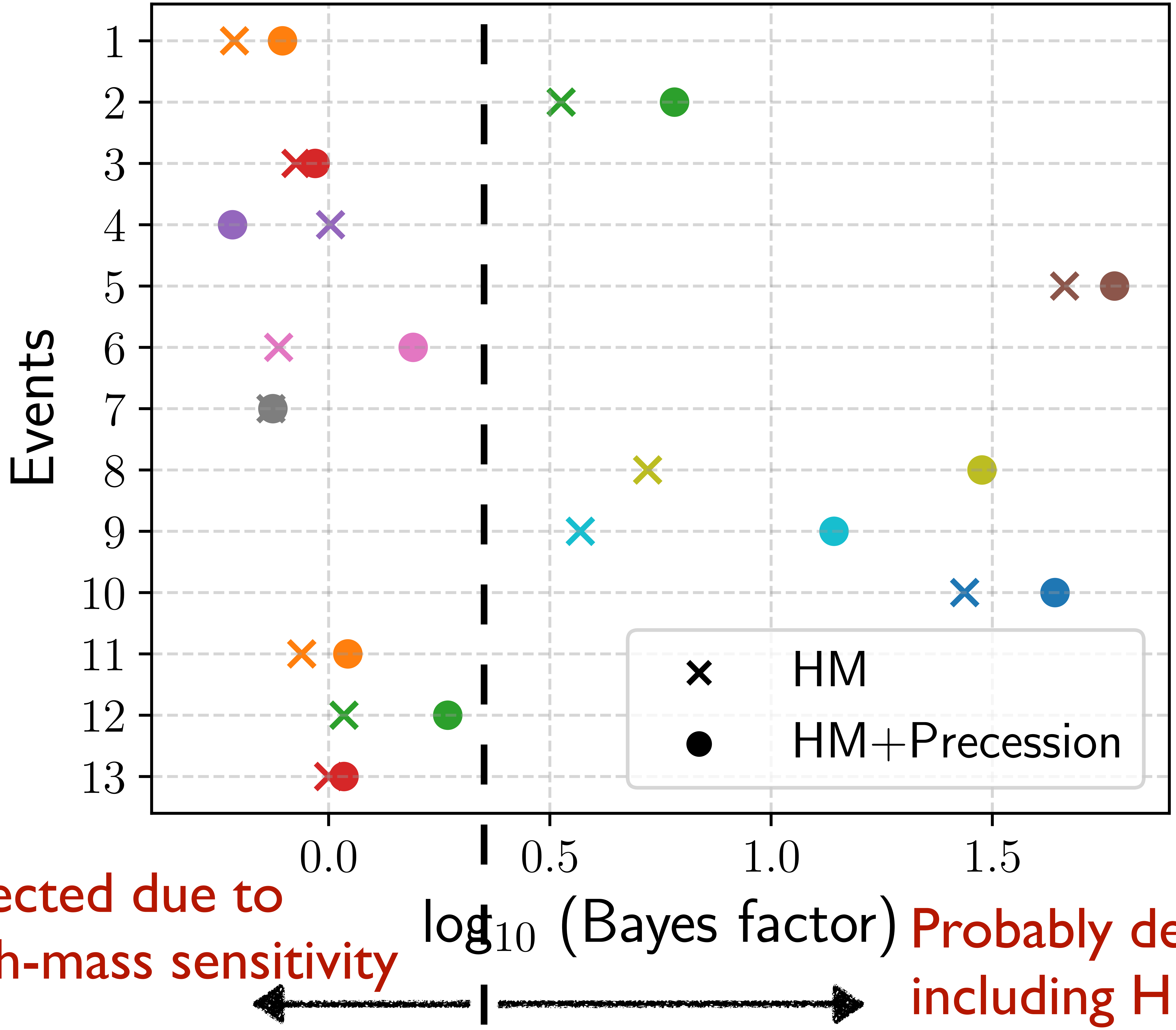
of BH spins

$\vec{L}_{\mathrm{orb}}$)

Bayesian evidence for HM or spin-precession in new events



Evidence for HM or precession in new events



Probably detected due to increased high-mass sensitivity

Probably detected due to including HMs in search

Part II

Searching for love

with
H. S. Chia
T. Edwards
A. Zimmerman
& IAS group

arXiv: 2306.00050

Part II

Searching for love

(i.e. objects with large tidal deformability)

with
H. S. Chia
T. Edwards
A. Zimmerman
& IAS group

arXiv: 2306.00050

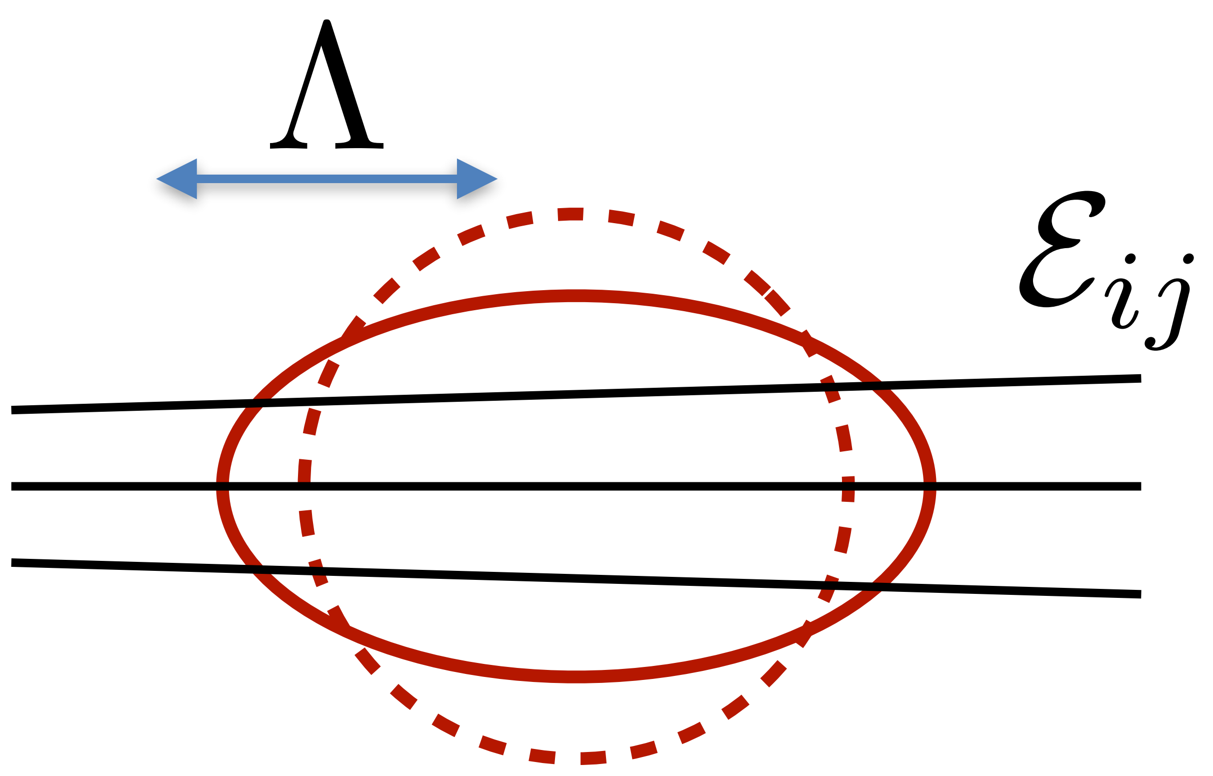
Introduction

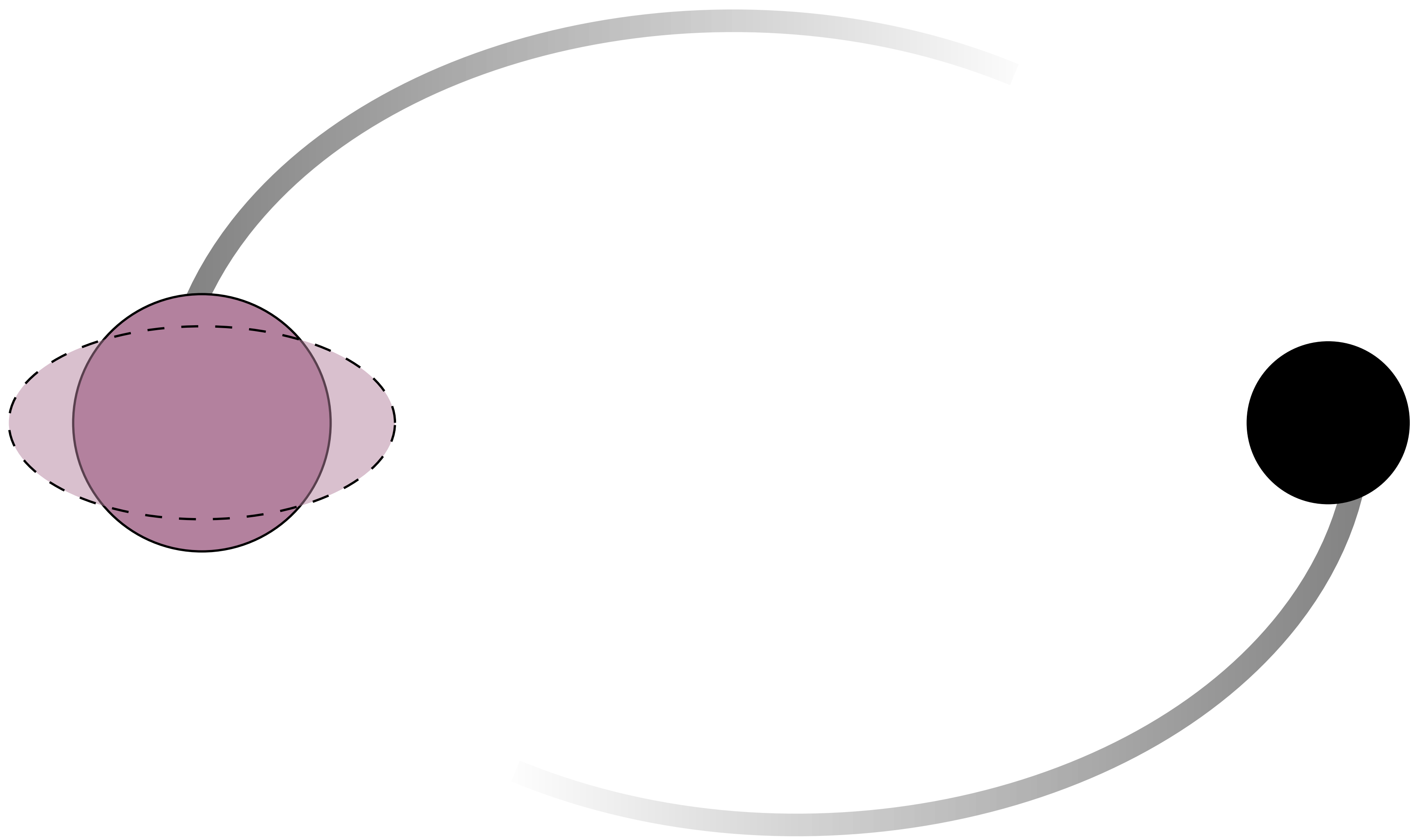
- Tidal deformability scales sensitively with compactness

$$\delta Q_{ij} = -\Lambda\, m^5\, \mathcal{E}_{ij}$$

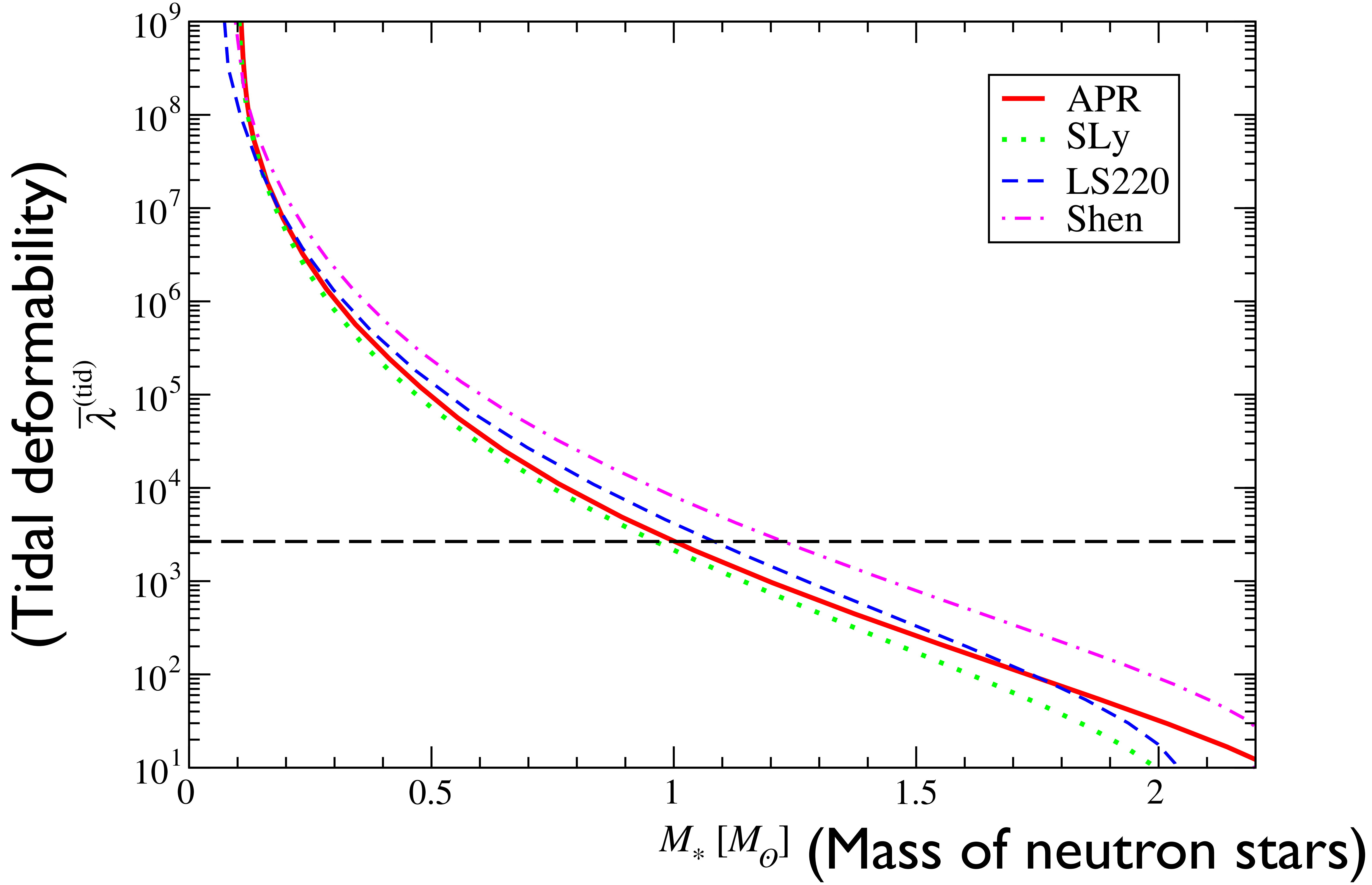
$$\Lambda = \frac{2}{3} k \left(\frac{r}{m}\right)^5$$

k :Love number (Love 1912)



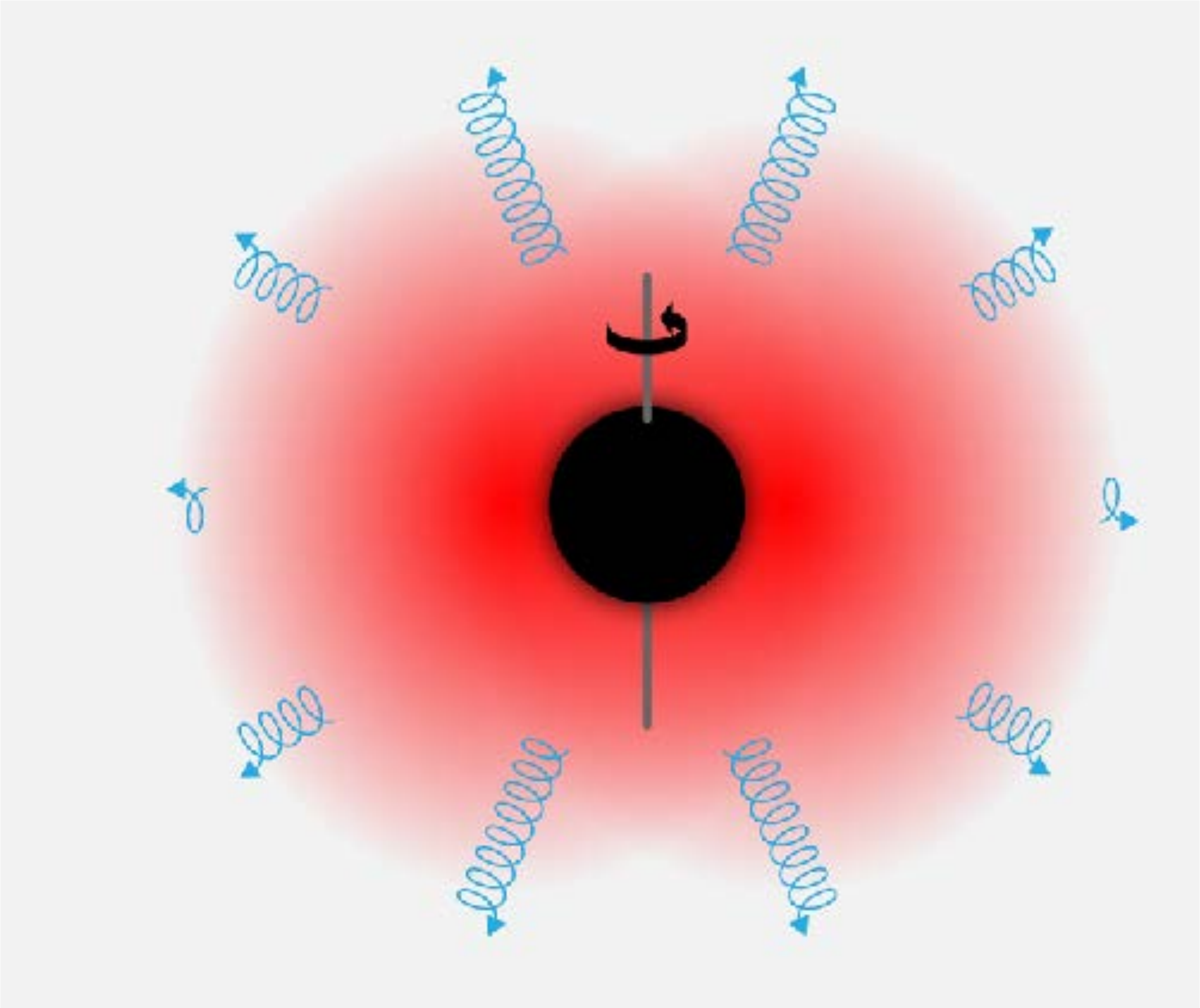


- Tidal deformability scales sensitively with compactness



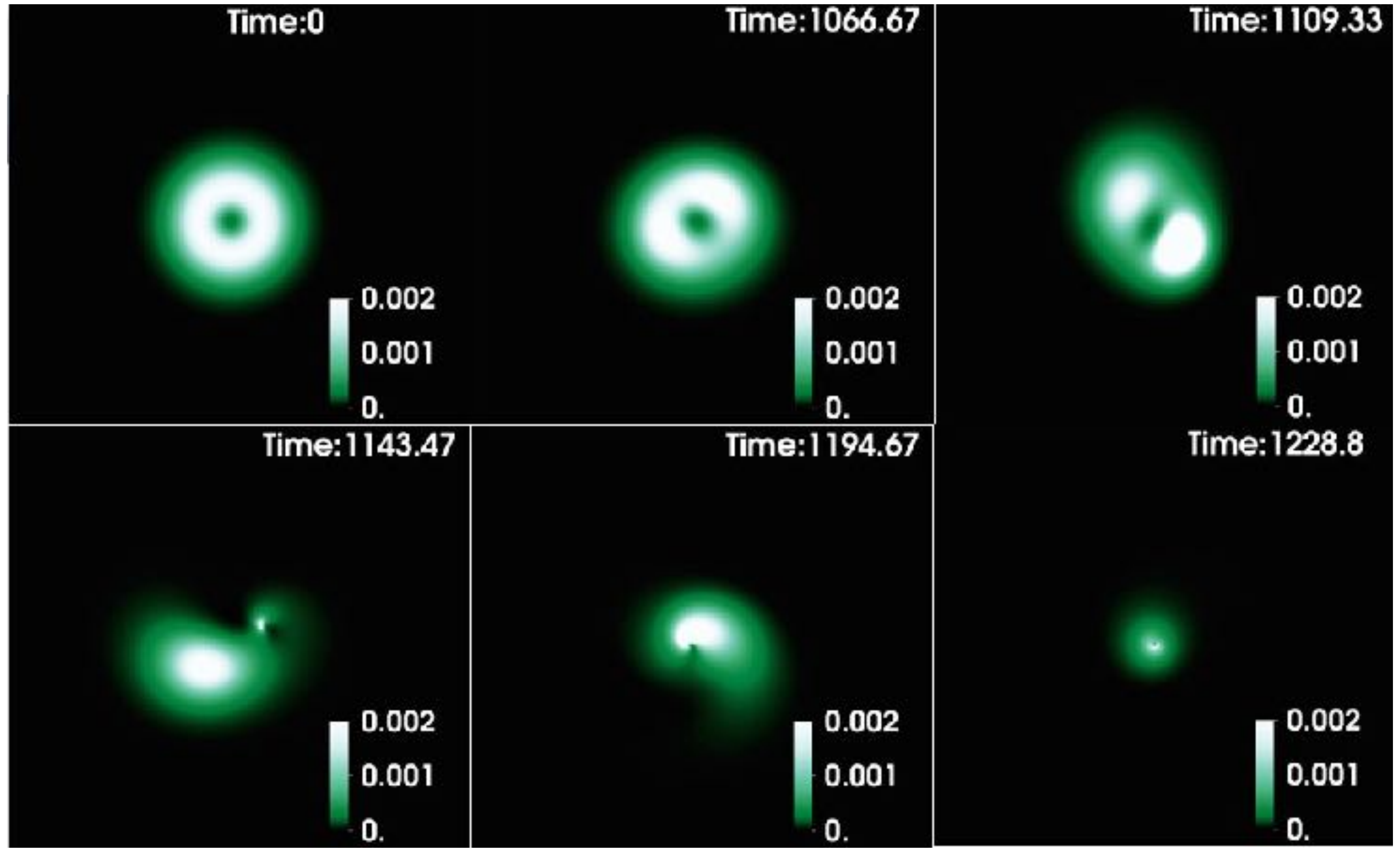
$$\Lambda = \frac{2}{3} k \left(\frac{r}{m} \right)^5$$

Could there be exotic massive objects with large Λ?



BHs with scalar clouds

Arvanitaki et al 11, Baryakhtar et al 15



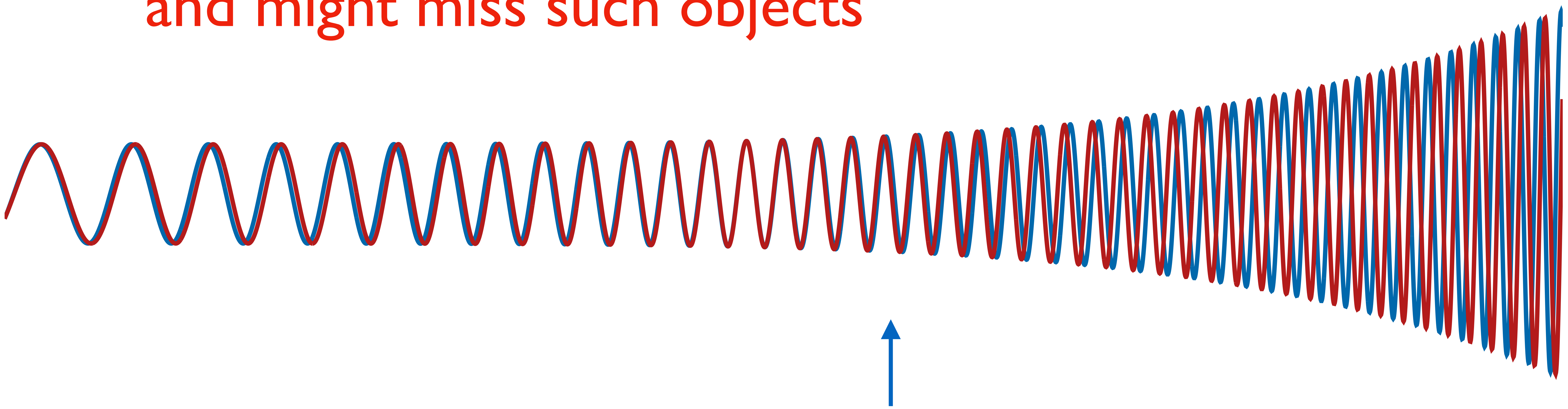
Boson stars
(compact, stationary configurations of scalar field bound by gravity)

Sanchis-Gual et al. 22, Leibling et al

General GW search pipeline

Convolve LVK data with templates $\sim 10^5$ triggers → Rank triggers based on coherence of detectors ~ 100 triggers → Perform PE (param. estimation)

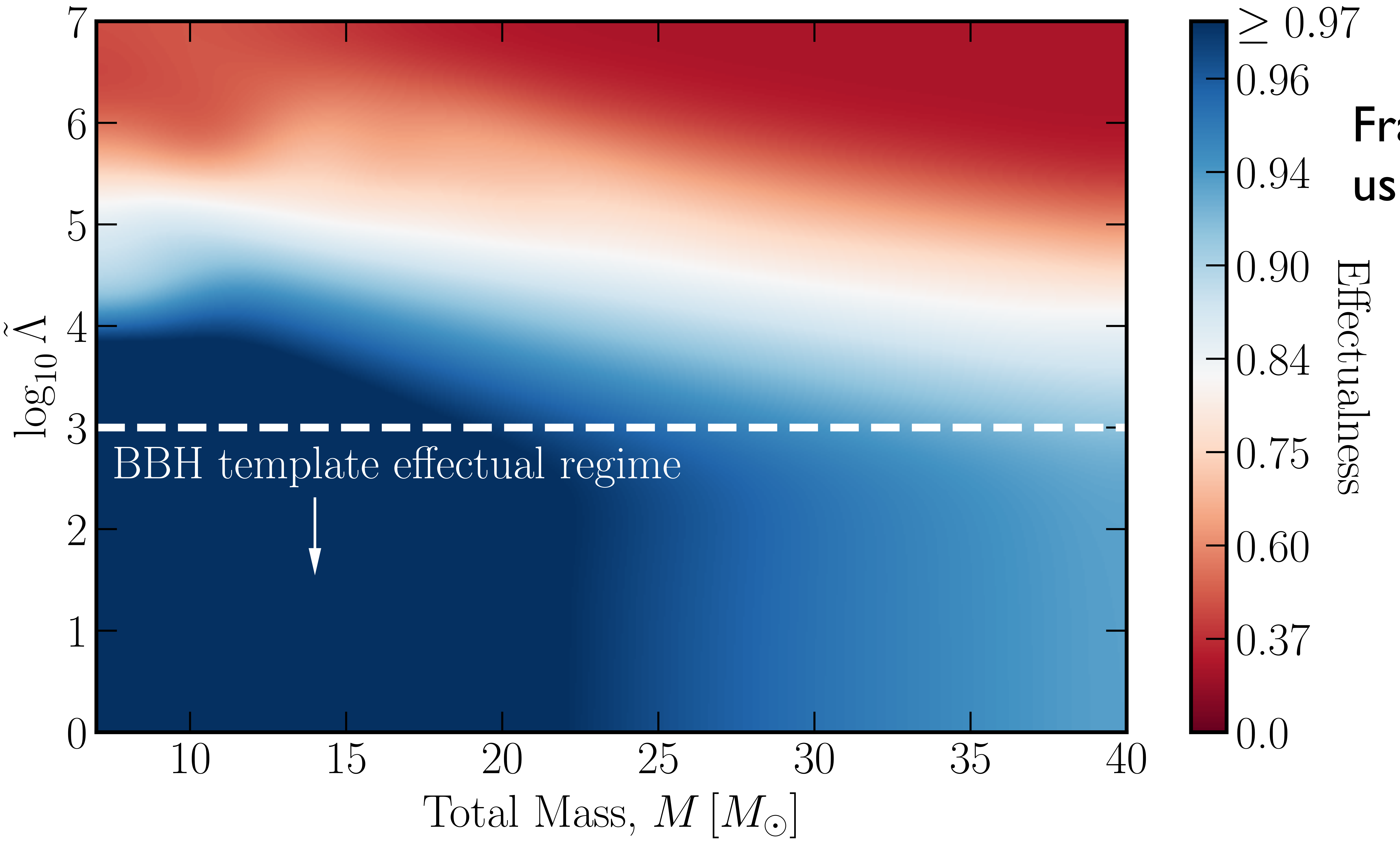
All matched filtering pipelines assume use black hole templates and might miss such objects



Phase shift in inspiral waveform (5PN order onwards)

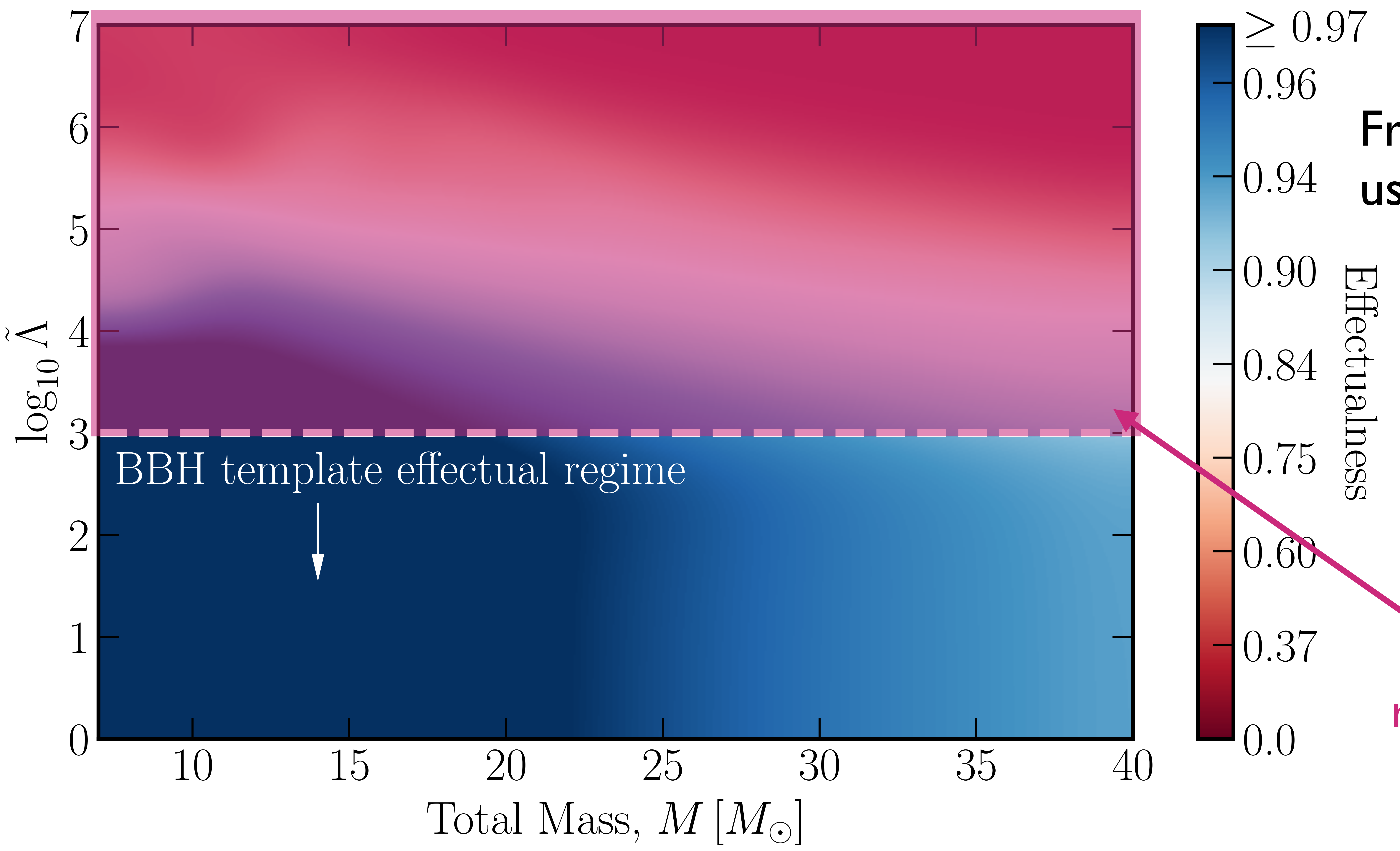
(when $\Lambda \neq 0$)

Current BBH template banks can miss such objects



Frac. SNR recovered using BBH templates

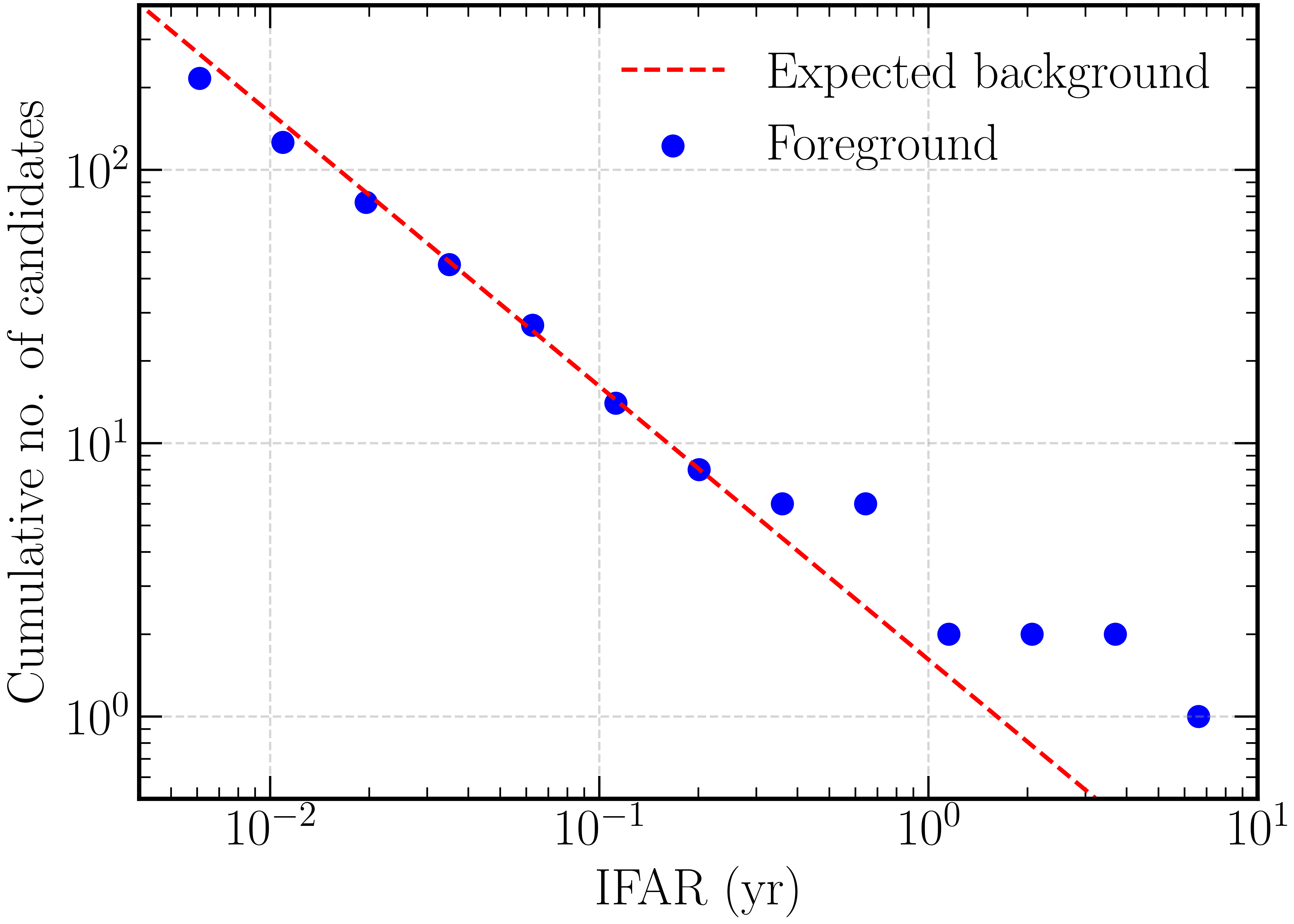
Current BBH template banks can miss such objects



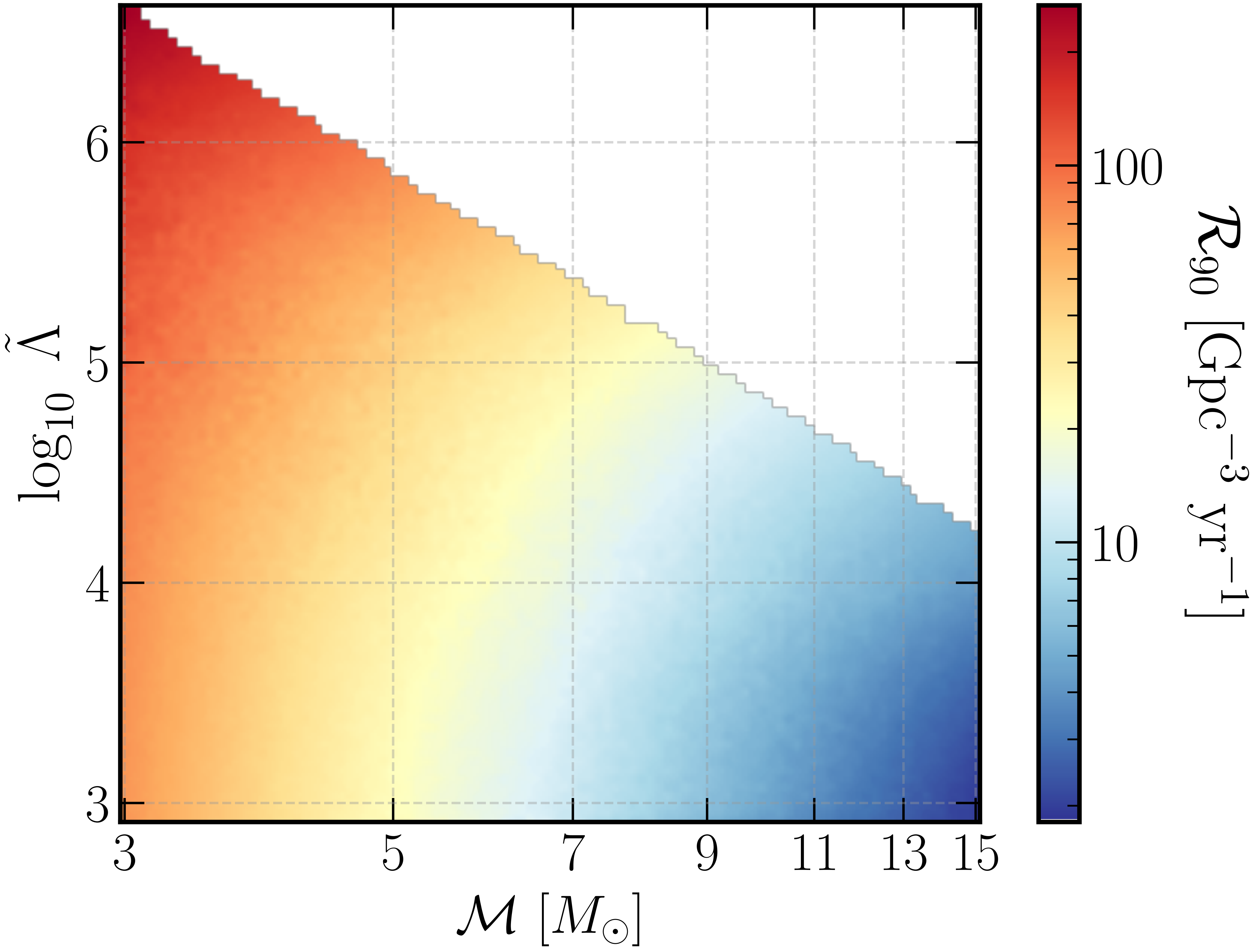
Frac. SNR recovered using BBH templates

We target this regime in our search

Searching over LVC O1-O3 data: null results



Constraints on merger rate



Summary

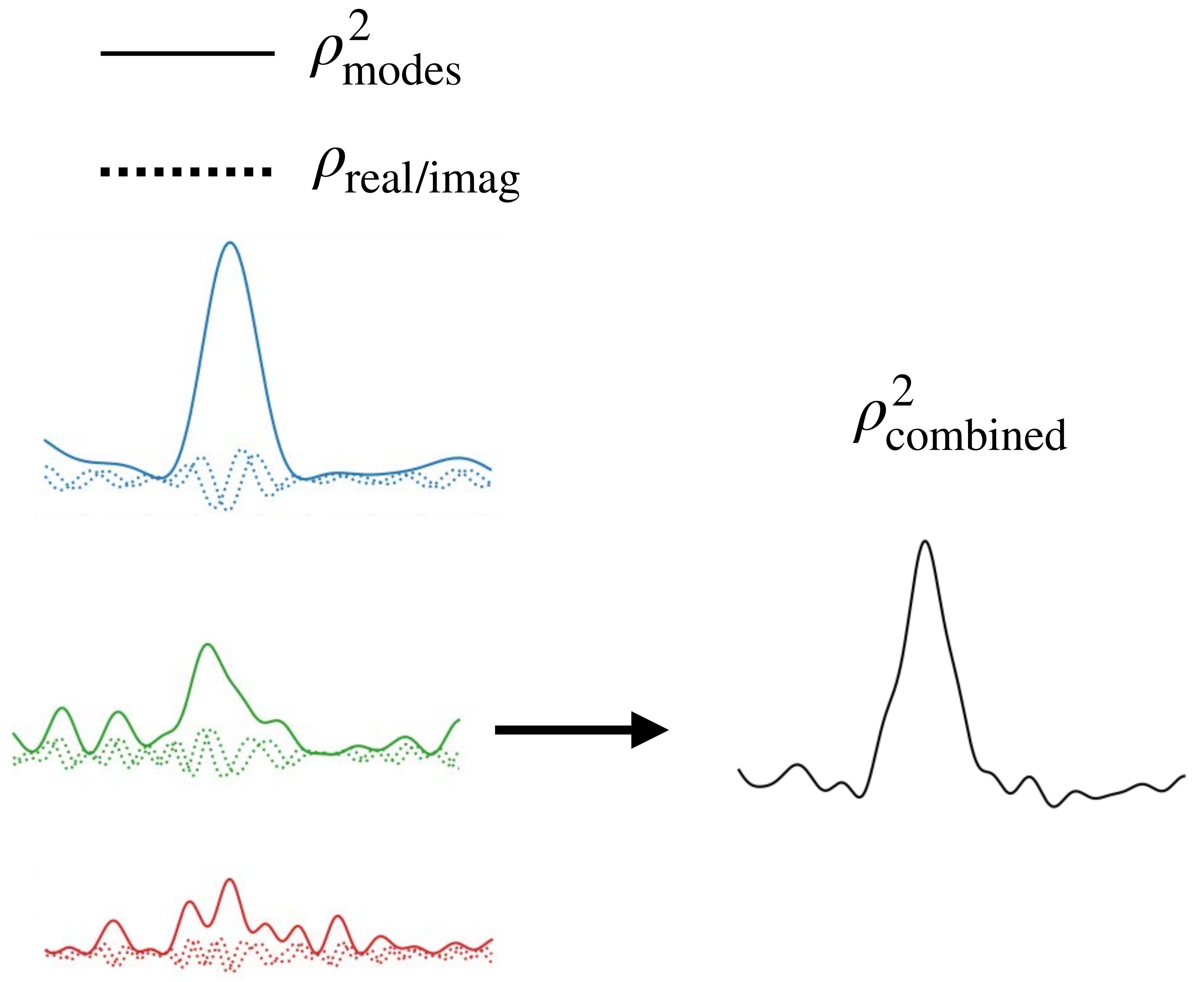
- We showed a efficient method of searching with GW higher harmonics

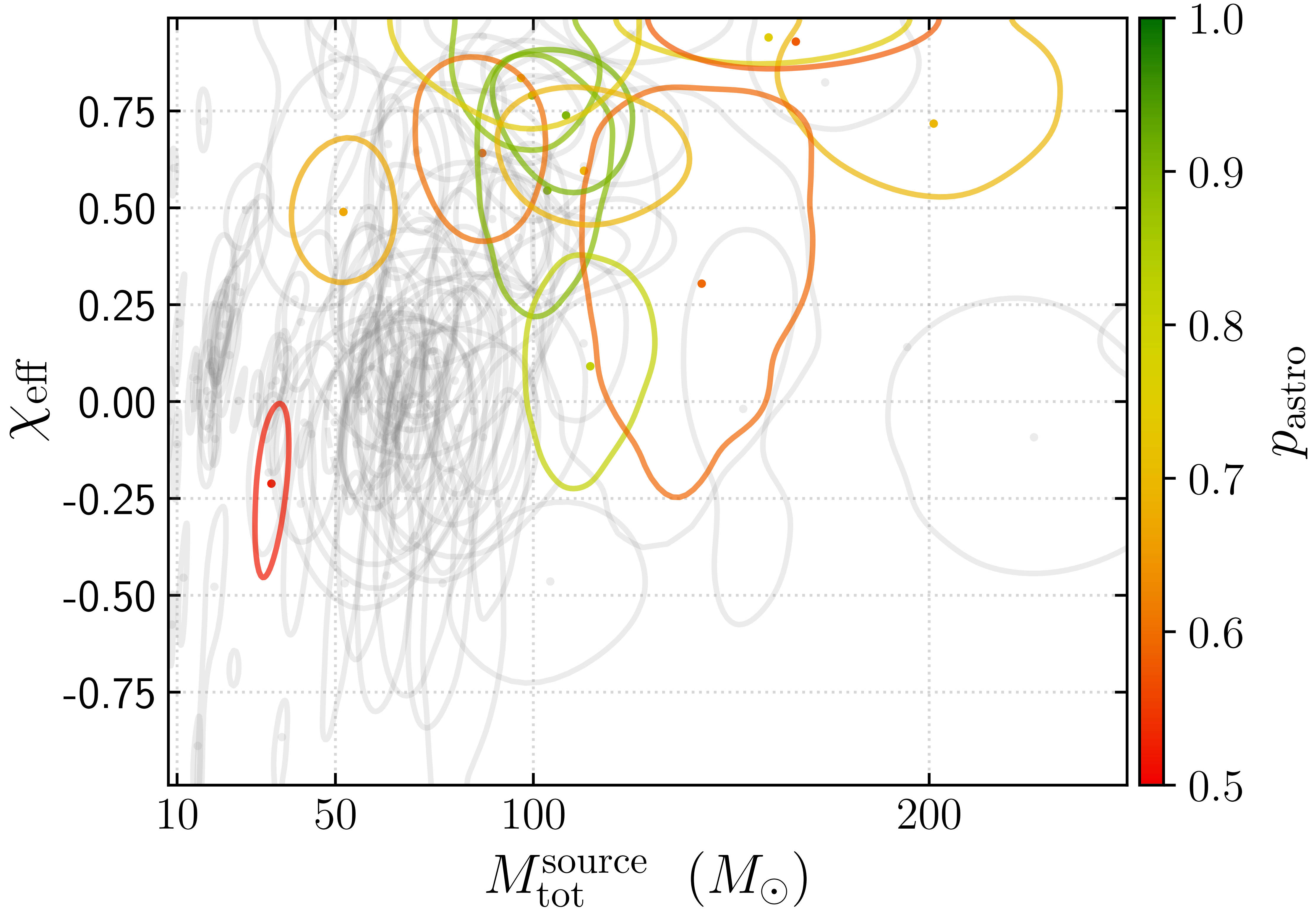
(only 3 × more expensive w.r.t (2,2) search)

- Searched in O3 data and found new mergers

- We also performed a search for high-Λ exotic objects with null results

jayw@ias.edu





Backup slides

TABLE I. New events in our search $p_{\rm astro} > 0.5$. The PE section shows results from parameter estimation runs with the IMRPhenomXPHM model. The errorbars correspond to 90% uncertainties and $\ln \mathcal{L}_{\rm max}$ denotes the maximum log likelihood. Note that the PE results here incorporate precession and use Virgo data when available, unlike our search. $\rho^2_{\rm H,L}$ denote the SNR of the search triggers in the Hanford and Livingston detectors. We also perform PE separately with 22-only aligned-spin waveforms and report the change in evidence when aligned-spin HM and precession are iteratively included.

Sr. No.	Event	Bank	PE					Δ ln(evidence)		$\rho^2_{\rm H}$	$\rho^2_{\rm L}$	IFAR (yr)		$p_{\rm astro}$
			$m_1^{\rm src}(\rm M_\odot)$	$m_2^{\rm src}(\rm M_\odot)$	$\chi_{\rm eff}$	z	$\ln \mathcal{L}_{\rm max}$	HM	HM+P			per bank	overall	
1	GW190524_134109	10,0	61^{+21}_{-14}	43^{+18}_{-15}	$0.5^{+0.4}_{-0.6}$	$1.4^{+0.7}_{-0.6}$	34.2	-0.49	-0.24	23.3	44.4	5.9	0.74	0.89
2	GW191113_103541	9,0	80^{+30}_{-30}	23^{+22}_{-7}	$0.7^{+0.2}_{-0.2}$	$0.9^{+0.7}_{-0.4}$	38.6	1.21	1.8	36.4	39.1	5.8	0.71	0.91
3	GW190806_033721	8,1	61^{+23}_{-16}	38^{+17}_{-13}	$0.79^{+0.18}_{-0.44}$	$1.6^{+0.7}_{-0.7}$	27.7	-0.17	-0.07	35.8	33.8	6.4	0.68	0.89
4	GW190615_030234	10,0	64^{+18}_{-12}	50^{+15}_{-12}	$0.1^{+0.3}_{-0.5}$	$0.9^{+0.3}_{-0.4}$	44.7	0.01	-0.5	24.1	50.5	3.1	0.35	0.82
5	GW190604_103812	12,0	130^{+40}_{-40}	35^{+17}_{-10}	$0.94^{+0.05}_{-0.15}$	$1.6^{+0.7}_{-0.7}$	27.2	3.83	4.09	29.6	38.1	2.1	0.21	0.75
6	GW200210_100022	9,0	64^{+23}_{-20}	40^{+20}_{-20}	$0.83^{+0.16}_{-0.83}$	$1.5^{+0.9}_{-0.6}$	32.2	-0.26	0.44	29.2	35.9	1.8	0.19	0.74
7	GW190605_025957	13,0	110^{+40}_{-20}	90^{+30}_{-30}	$0.7^{+0.3}_{-0.6}$	$1.5^{+0.7}_{-0.7}$	40.3	-0.3	-0.29	43.0	46.5	2.0	0.15	0.69
8	GW200304_172806	8,1	80^{+30}_{-30}	35^{+28}_{-17}	$0.61^{+0.18}_{-0.84}$	$1.2^{+0.7}_{-0.5}$	31.0	2.0	3.74	40.8	28.1	1.5	0.14	0.69
9	GW190530_030659	4,2	33^{+17}_{-12}	19^{+7}_{-7}	$0.5^{+0.2}_{-0.3}$	$0.60^{+0.22}_{-0.19}$	34.7	1.31	2.63	34.5	36.0	2.3	0.12	0.67
10	GW190708_211916	8,1	60^{+20}_{-20}	28^{+15}_{-11}	$0.6^{+0.3}_{-0.3}$	$1.0^{+0.6}_{-0.4}$	32.6	3.04	4.09	42.1	32.8	0.89	0.086	0.60
11	GW190530_133833	12,0	80^{+40}_{-20}	60^{+26}_{-20}	$0.3^{+0.5}_{-0.9}$	$1.3^{+0.8}_{-0.6}$	26.6	-0.14	0.1	38.2	31.7	0.80	0.084	0.59
12	GW190907_111633	12,0	100^{+30}_{-30}	70^{+30}_{-20}	$0.93^{+0.06}_{-0.19}$	$1.5^{+0.8}_{-0.6}$	31.0	-0.07	0.54	27.1	42.3	0.75	0.077	0.58
13	GW200301_211019	1,2	19^{+7}_{-3}	14^{+4}_{-3}	$-0.2^{+0.4}_{-0.3}$	$0.37^{+0.18}_{-0.15}$	33.4	-0.0	0.08	36.5	38.3	2.2	0.069	0.52