TeVPA 2026, Takinoyu, August 31, 2026

Credit: Maggie Chiang

Search for Sub-Solar Mass Binary Black Holes by Gravitational Waves

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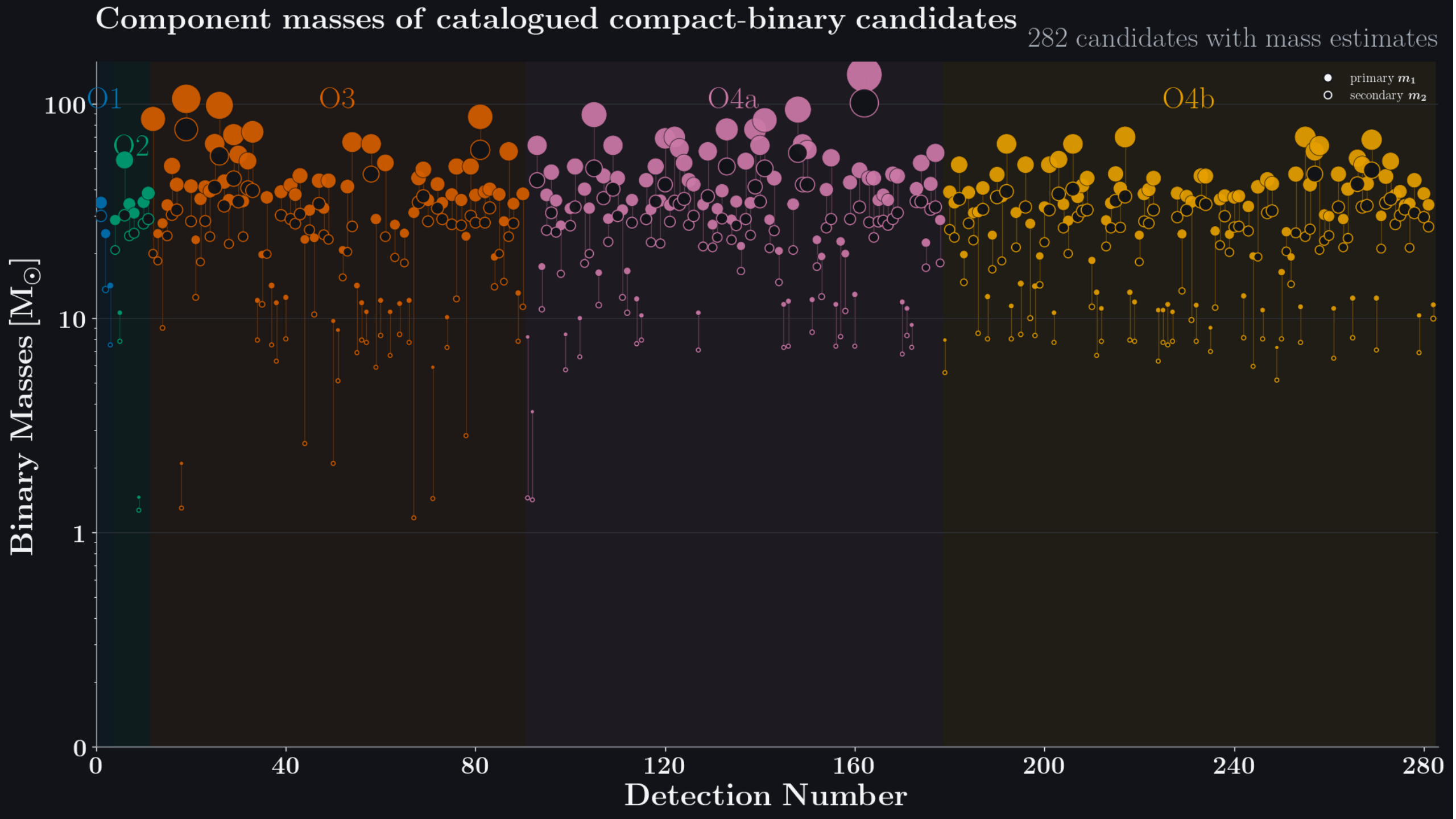
Component masses of catalogued compact-binary candidates
282 candidates with mass estimates
primary m_1
secondary m_2
O1
O2
O3
O4a
O4b
100
10
1
0
Binary Masses [M⊙]
0
40
80
120
160
200
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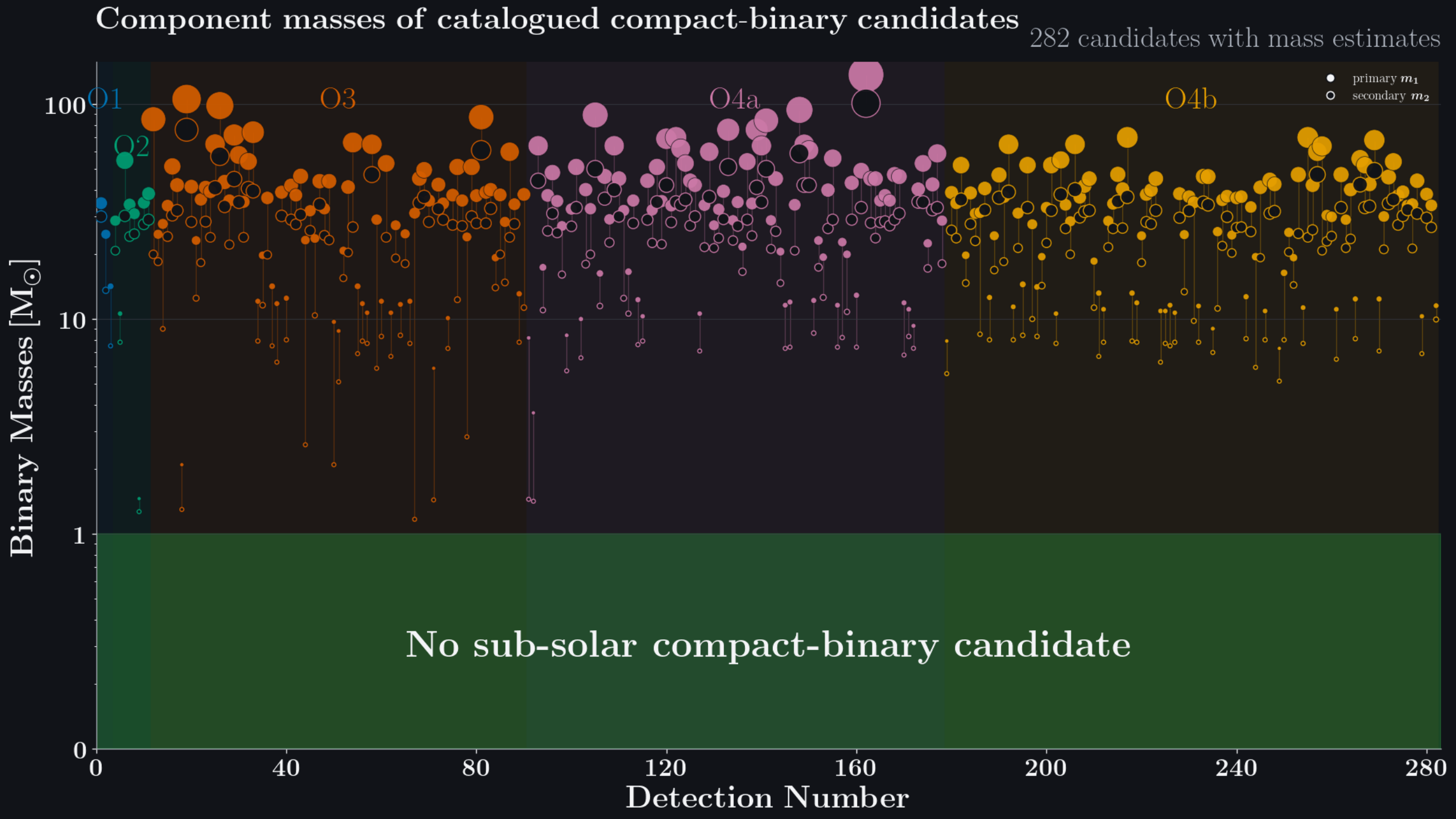
280
Detection Number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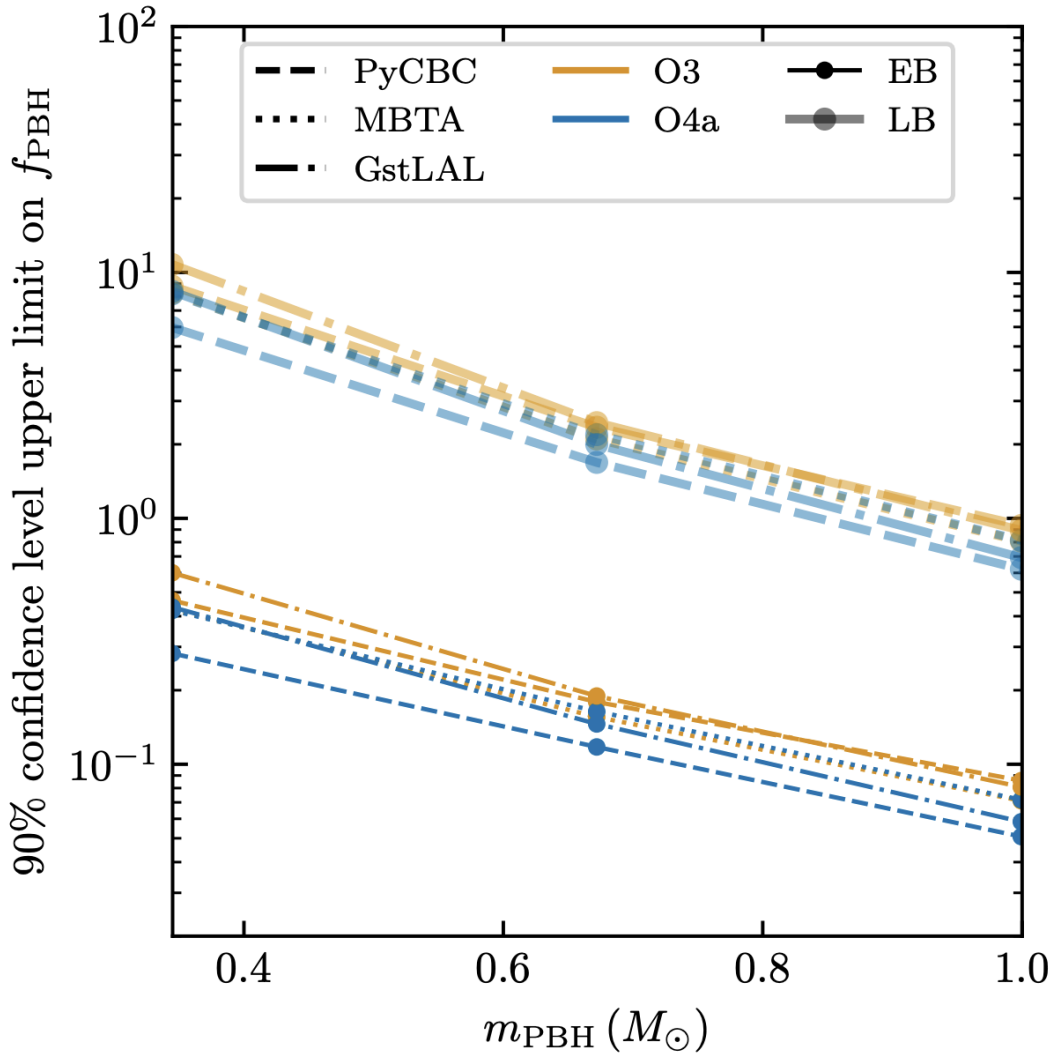
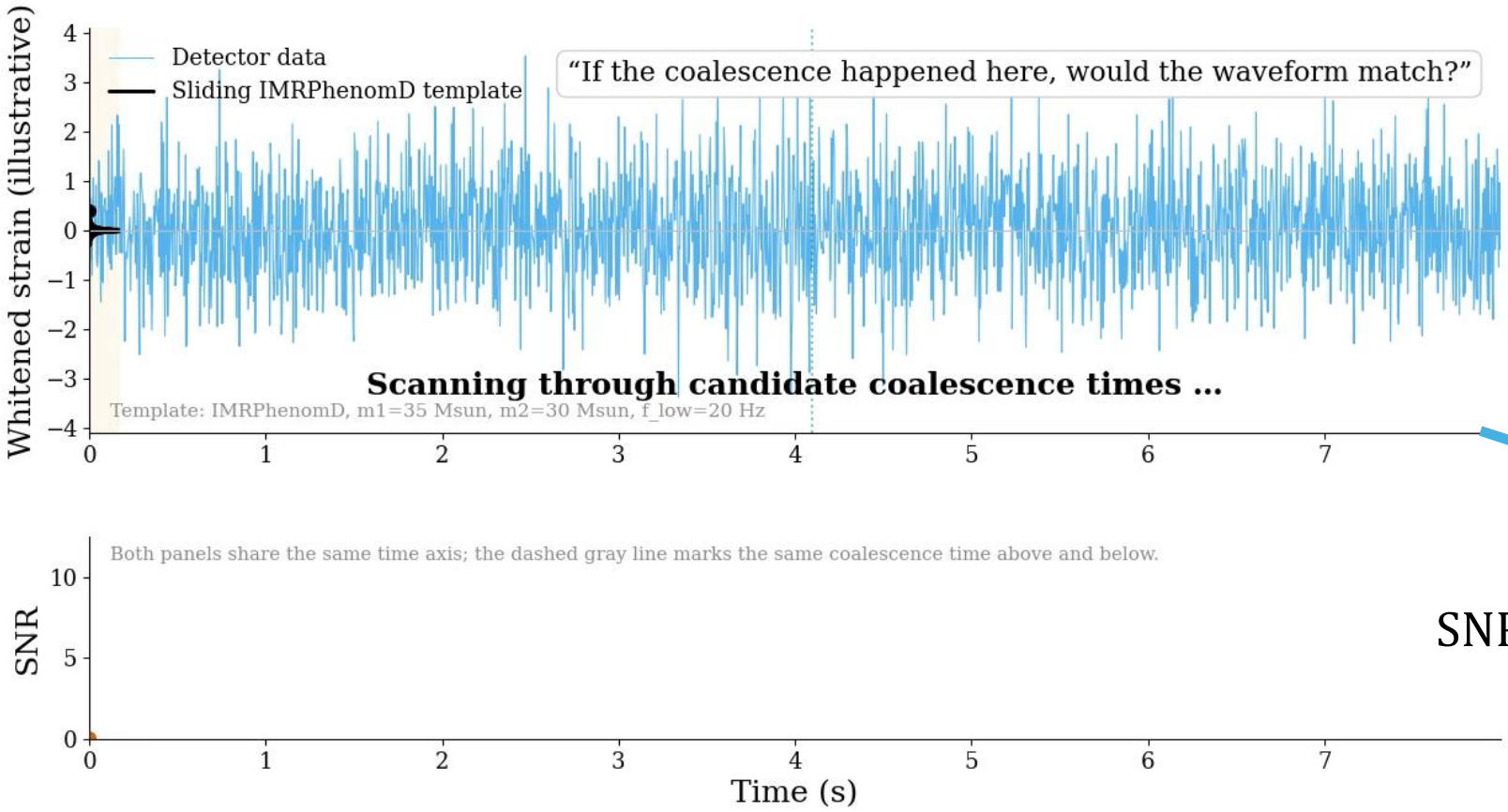
LVK sub-solar search for O4a

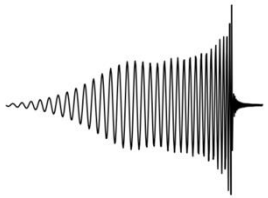


Credit: LVK collaboration (2026)

- LVK collaboration has reported sub-solar O4a result (arXiv:2605.05444).
  - ➢ No significant event
  - ➢ Space-time hypervolume VT
  - ➢ Constraint on the fraction of dark matter in Primordial Black Holes (PBH): f_{PBH}.

Matched filtering to find Gravitational Waves

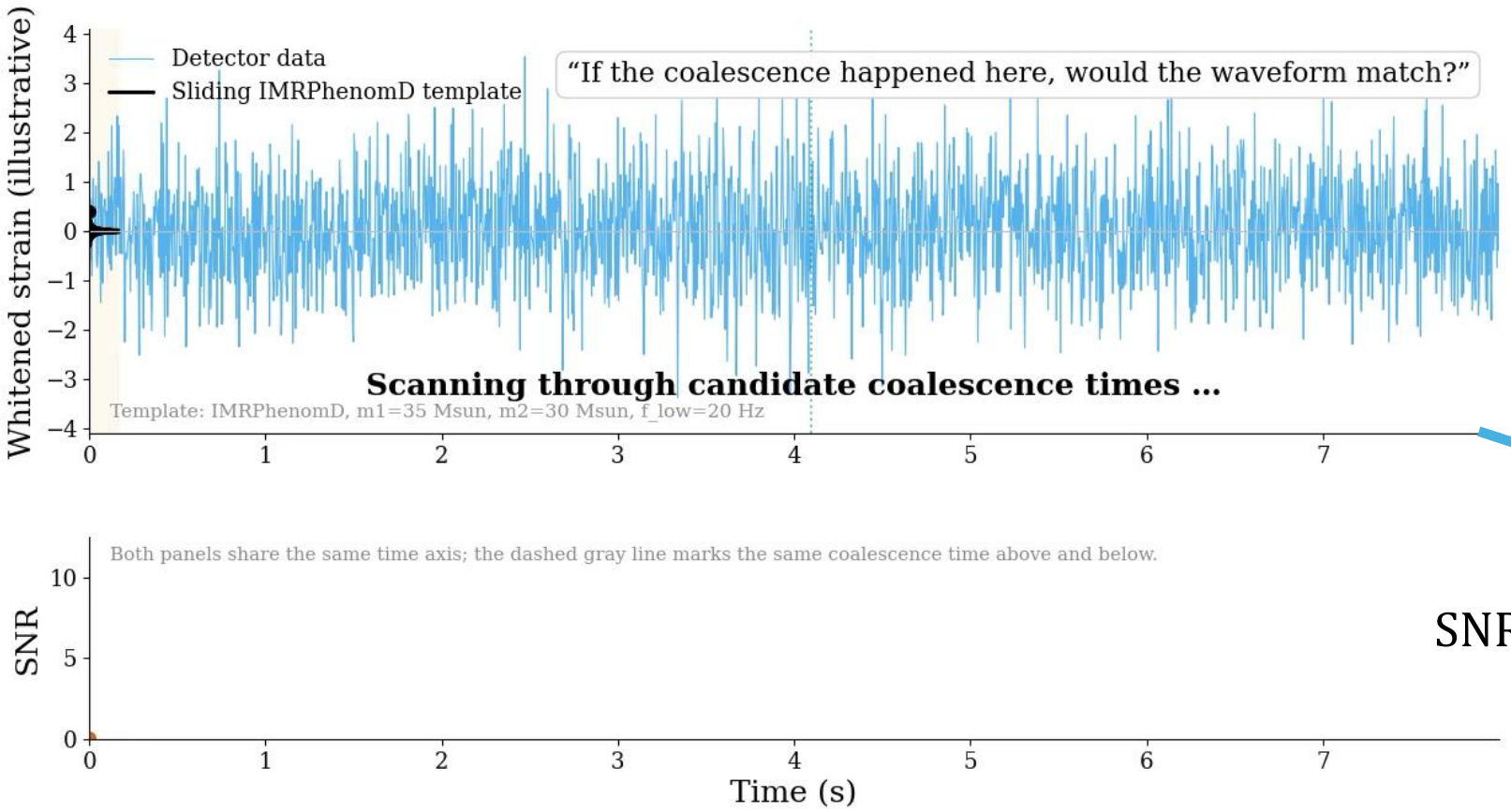




$$\mathrm{SNR}(t) = 4\left|\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{d}(f)\,\tilde{h}^{*}(f)}{S_n(f)}\, e^{2\pi i f t}\,\mathrm{d}f\right|$$

Noise Power Spectral Density (PSD)

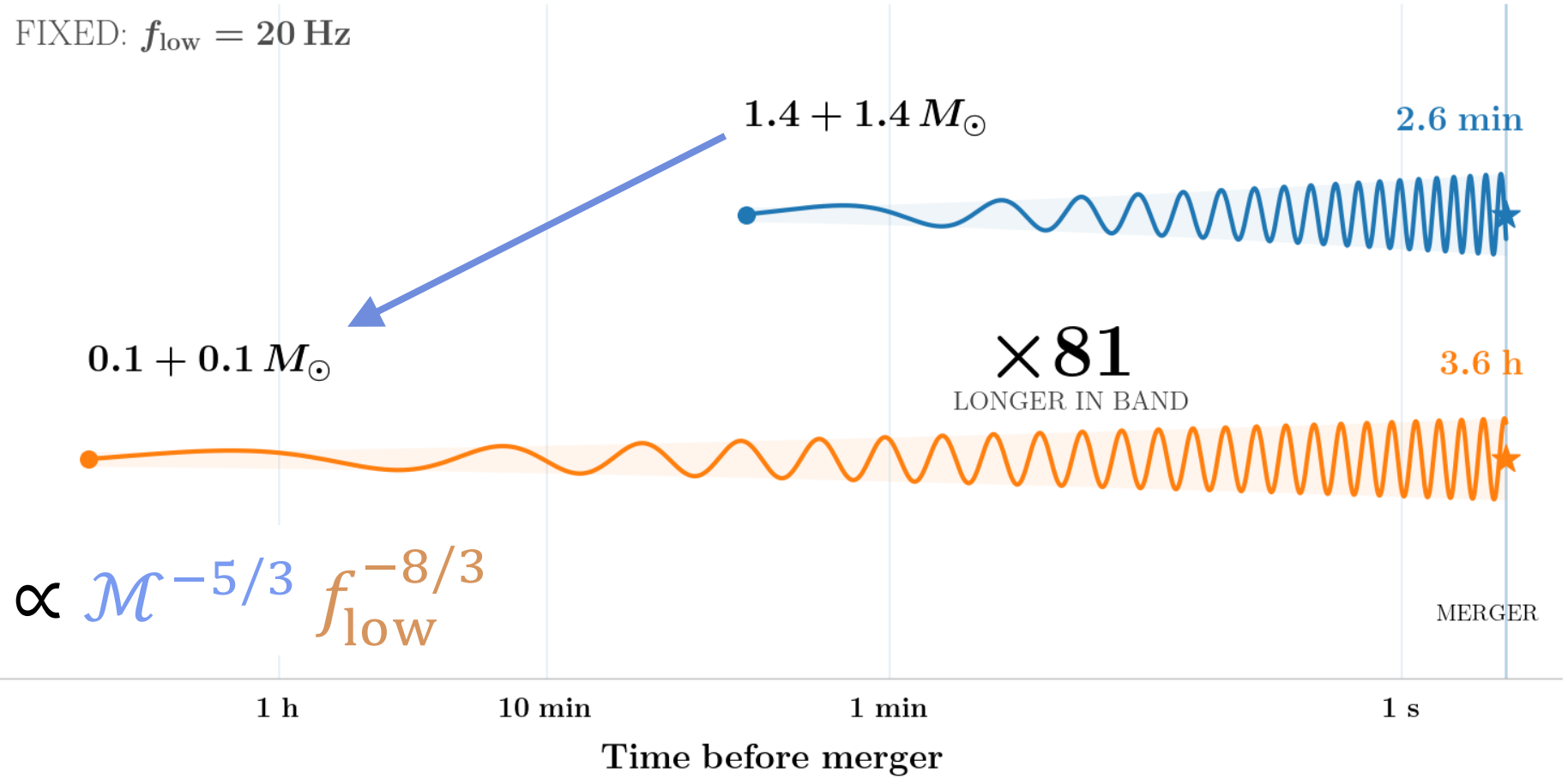
Matched filtering to find Gravitational Waves



$$\mathrm{SNR}(t) = 4\left|\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{d}(f)\,\tilde{h}^{*}(f)}{S_n(f)}\, e^{2\pi i f t}\,\mathrm{d}f\right|$$

Noise Power Spectral Density (PSD)

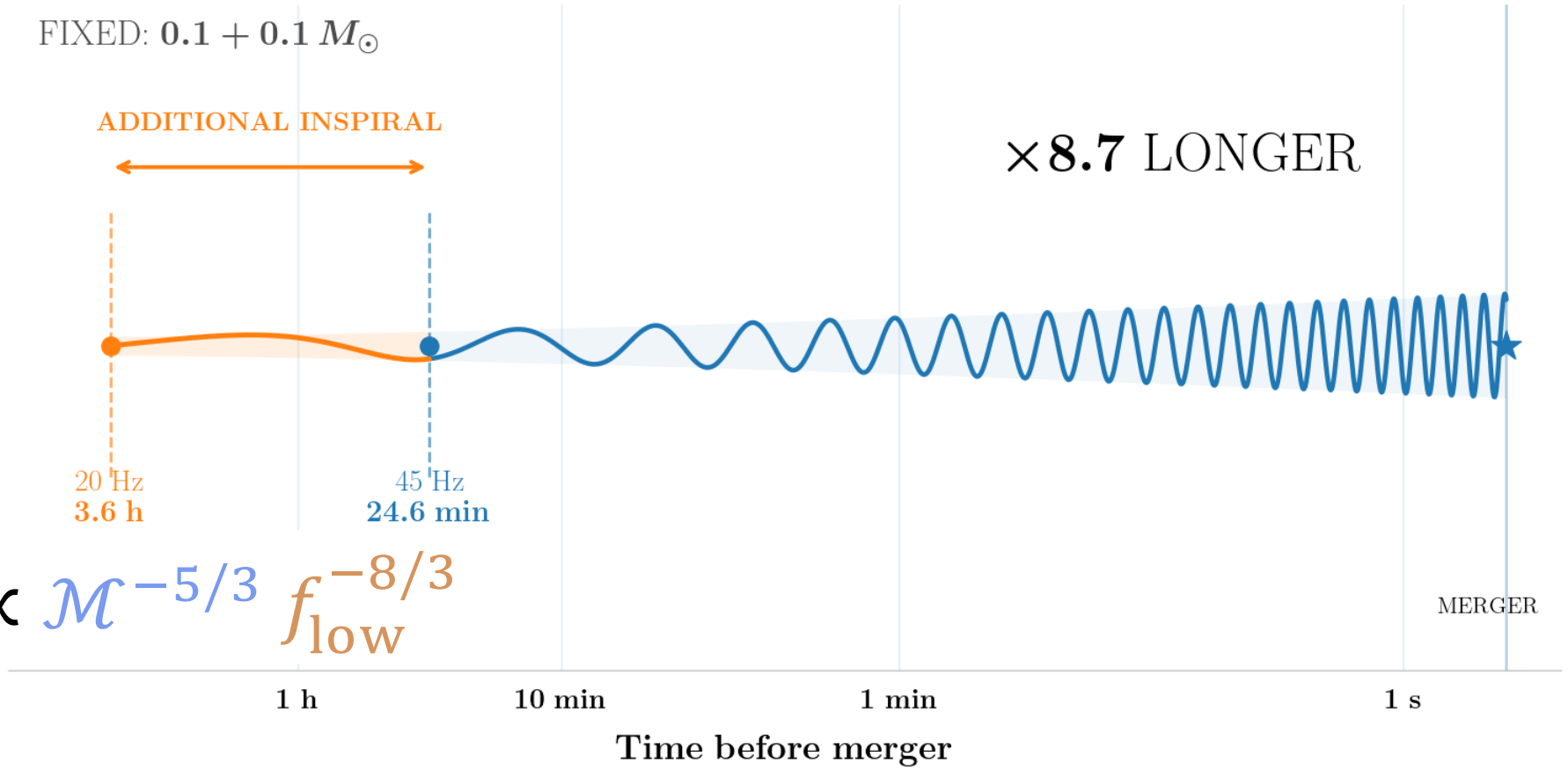
Challenge of sub-solar search



Time to merger $\propto \mathcal{M}^{-5/3}\, f_{\rm low}^{-8/3}$

Longer waveform → More memory / larger FFT / larger template bank

Current searches limit the low-frequency cutoff

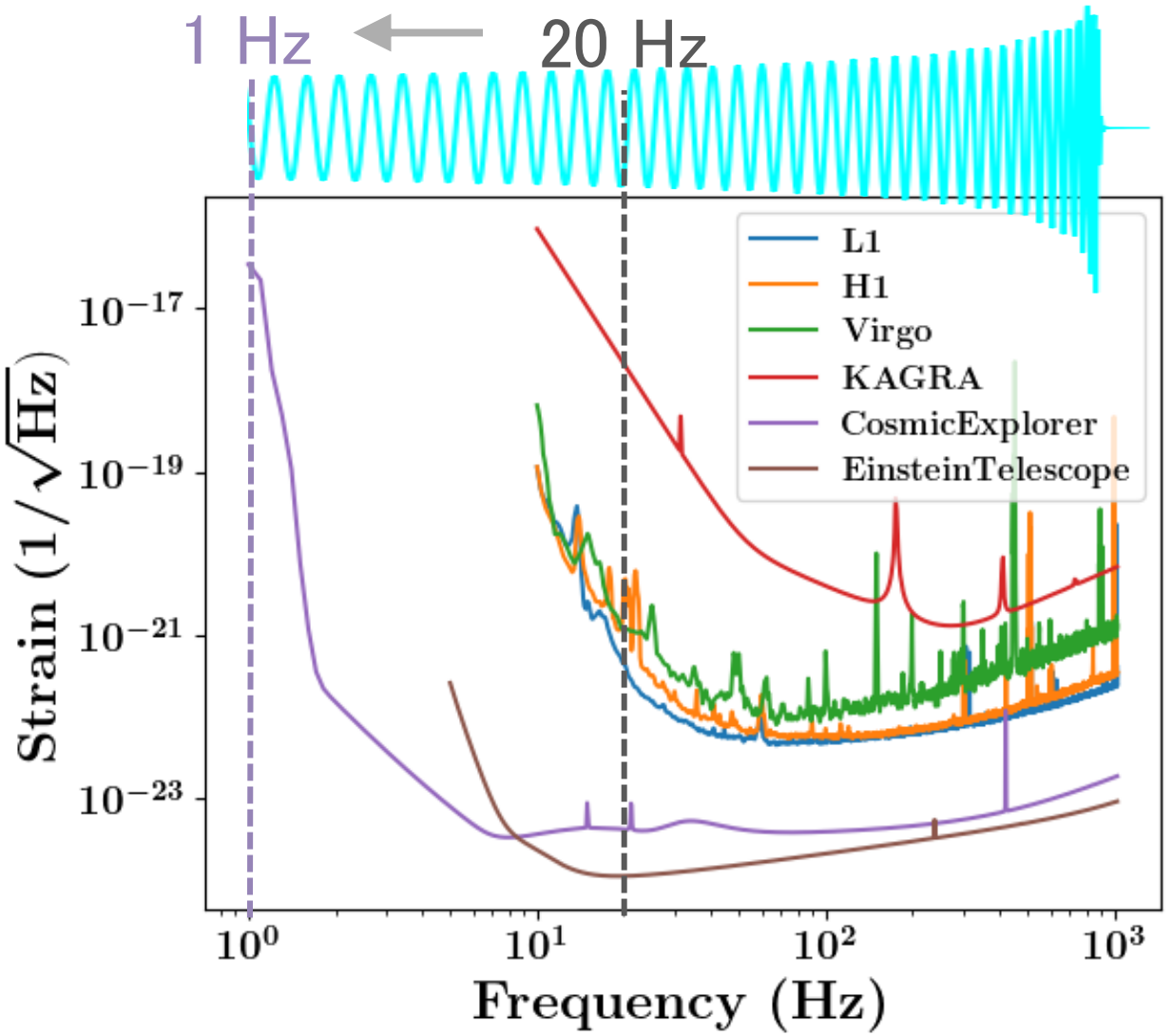


Time to merger $\propto \mathcal{M}^{-5/3}\ f_{\rm low}^{-8/3}$

Longer $f_{\rm low}$ ➡ shorter waveform ➡ This leads to a loss of sensitivity.

Future detectors will extend their sensitivity to lower frequency

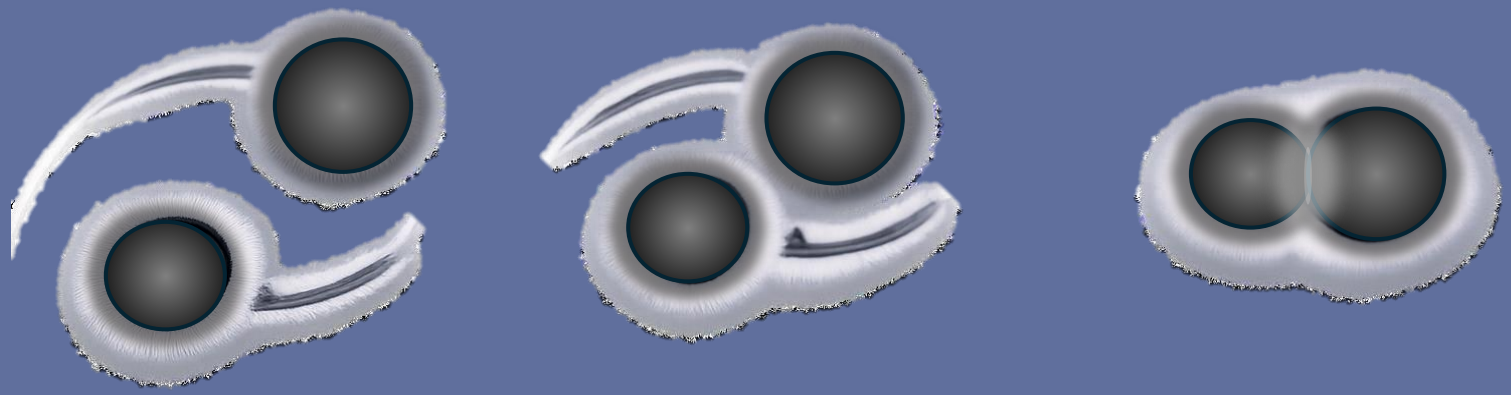
Longer waveforms
are **inevitable**
in future detectors.



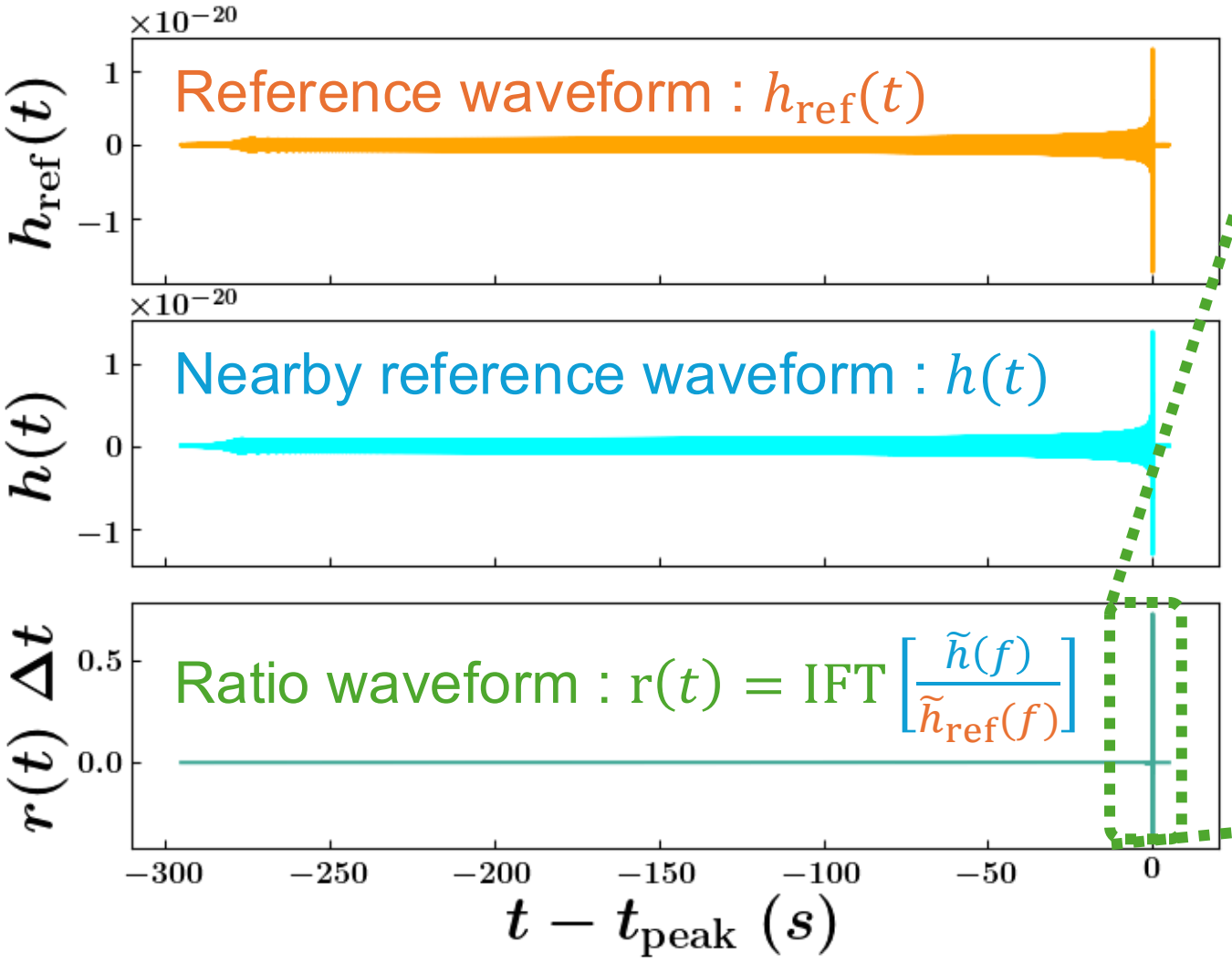
OUR APPROACH: RATIO FILTER

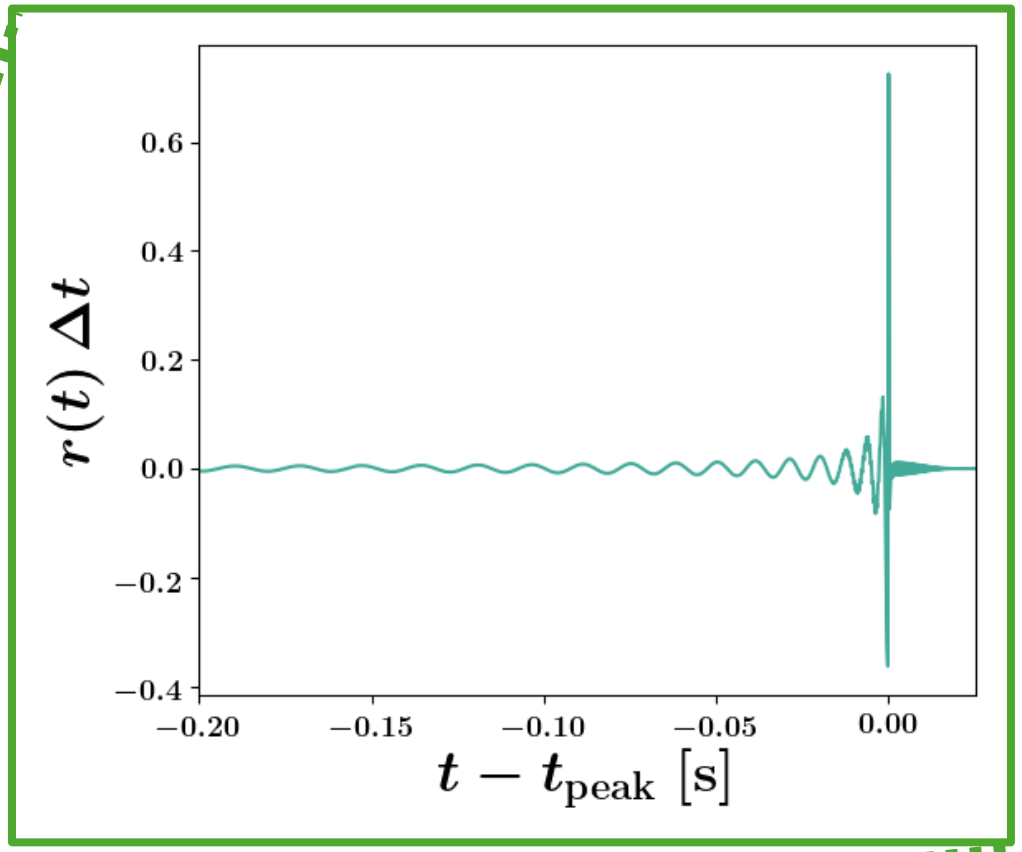
(PRD:113, 064006 (2026))

SCAN ME



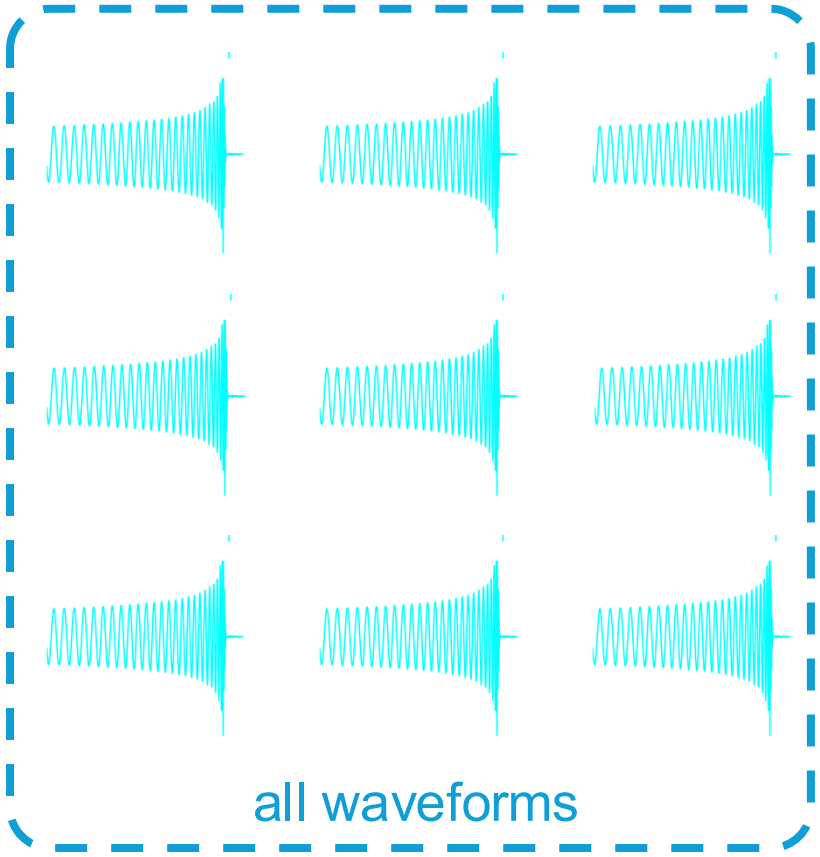
The ratio waveform is as long as the duration difference

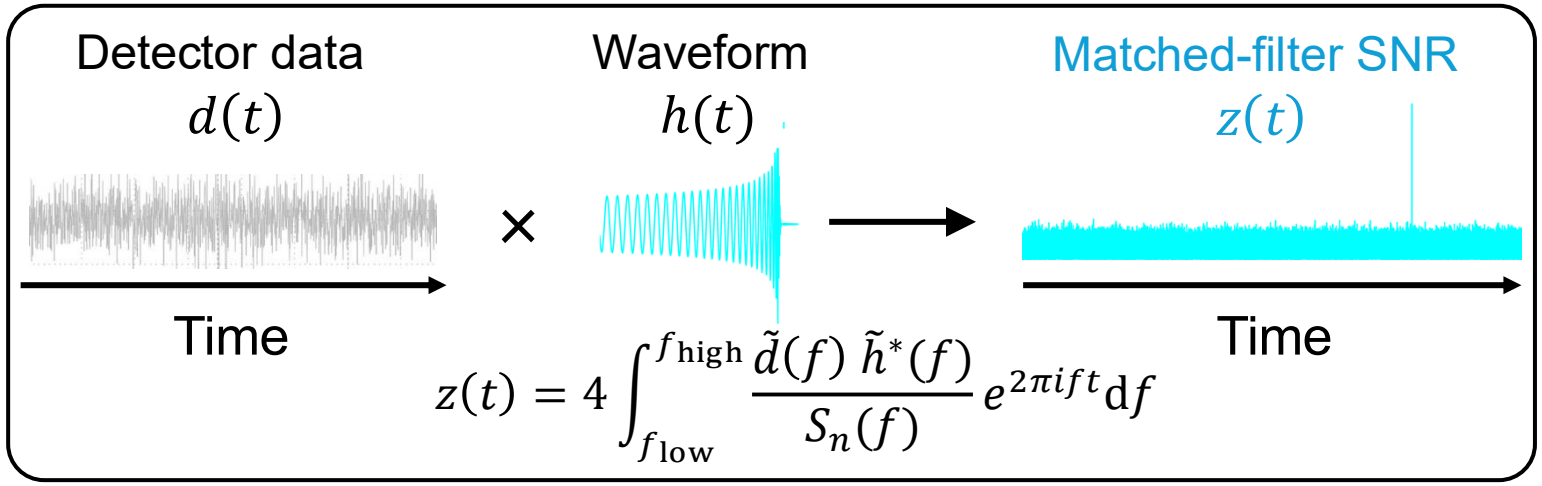




Heterodyning / relative binning
[Cornish 2010; Zackay+ 2018]

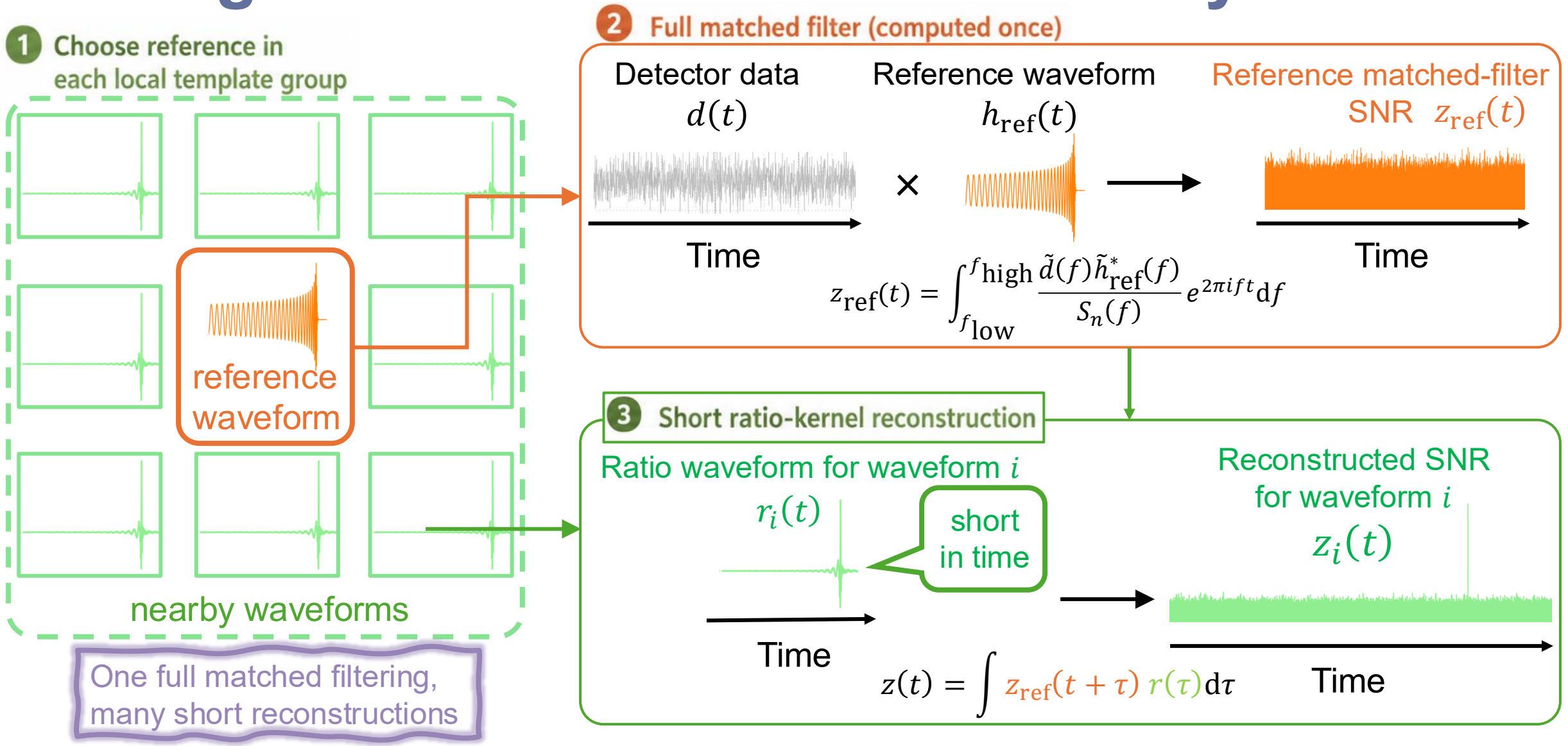
Conventional matched filtering





Full matched filtering for all waveforms

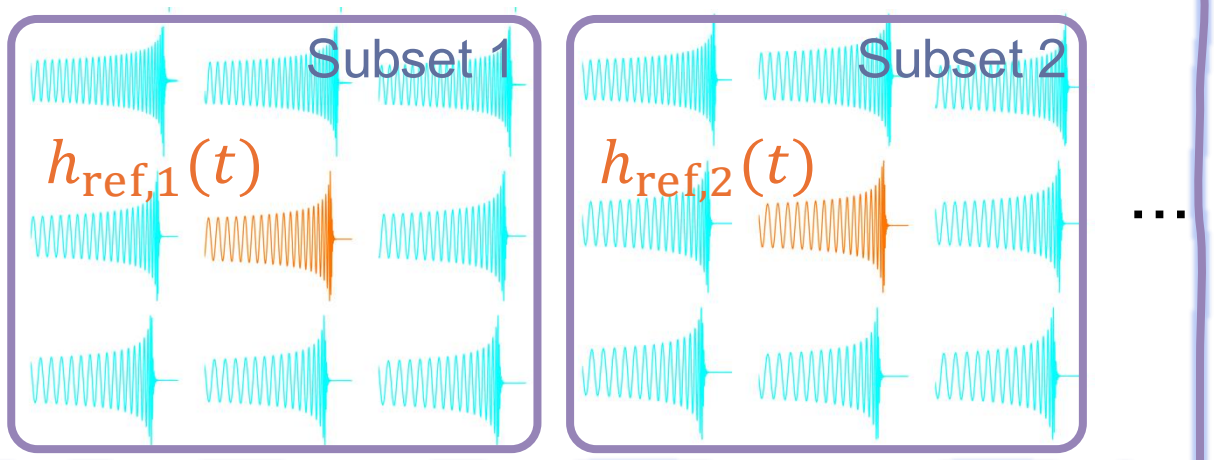
Reusing one reference SNR for nearby waveform



Ratio filter on simulated data

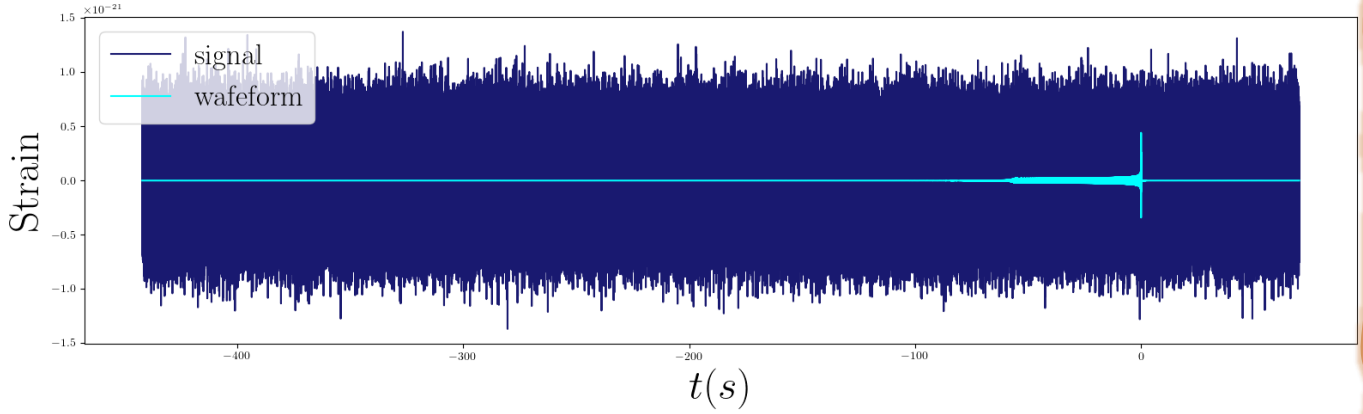
Non-spinning template bank

- $m_{1,2} \in [1, 3]\ M_{\odot}$
- Number of templates: 51,588
- Number of reference waveforms: 131

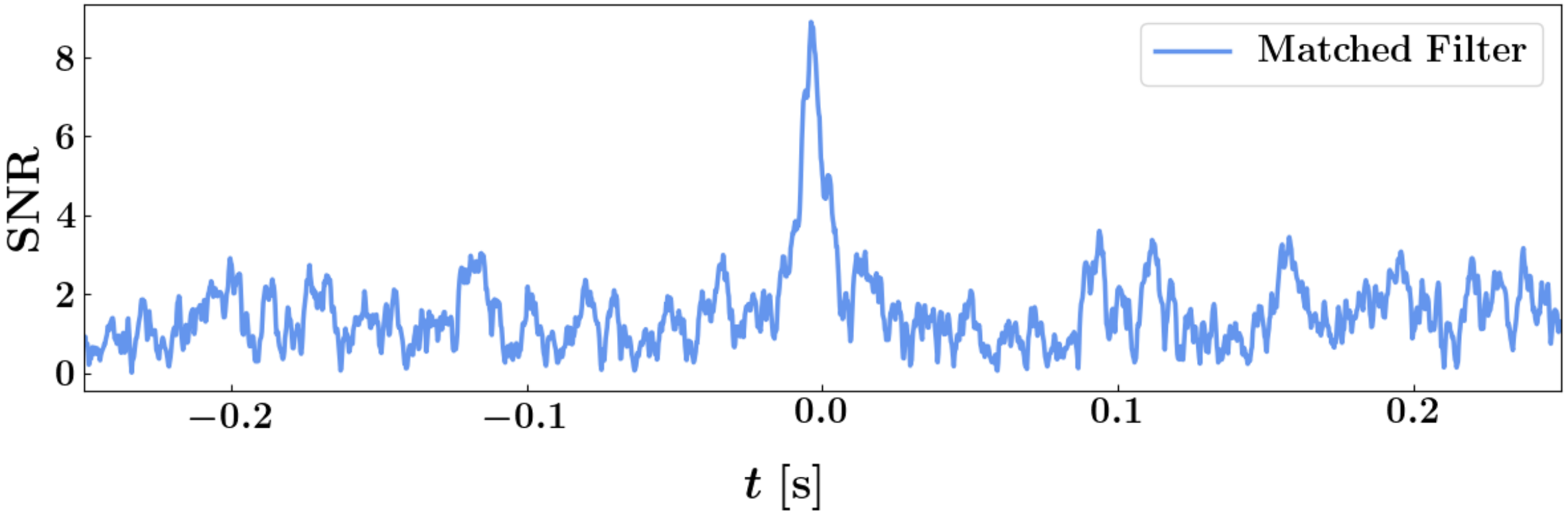


Simulation data

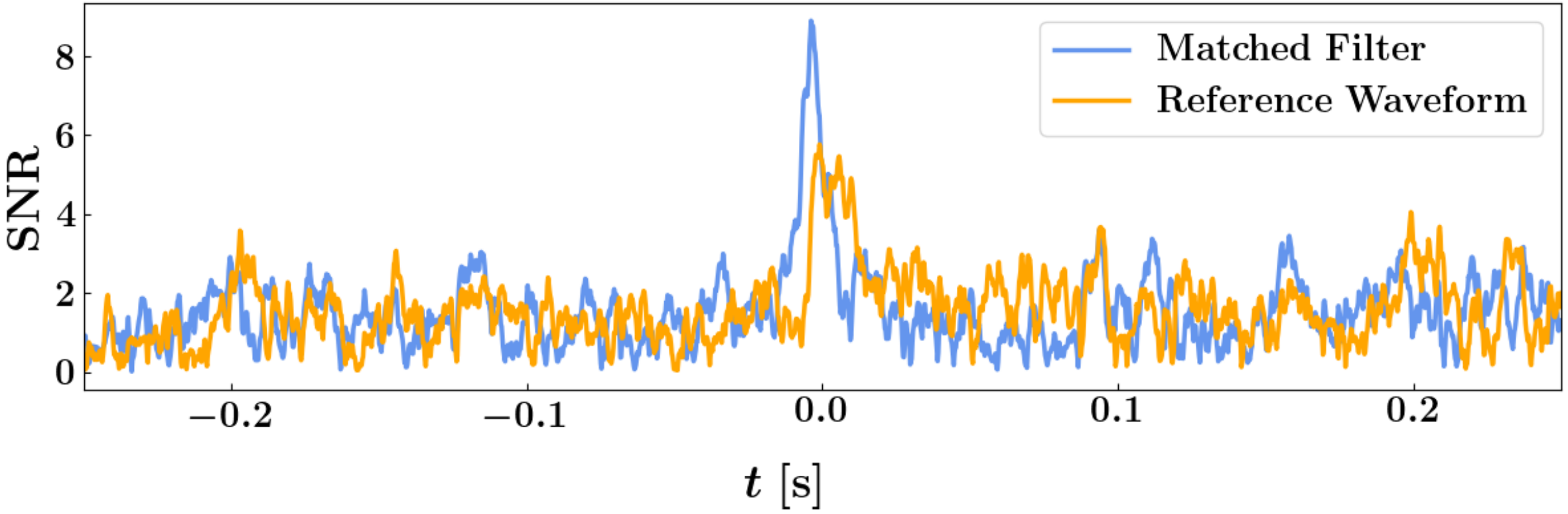
- Duration : 512 s
- Sampling rate : 4096 Hz
- PSD : aLIGO designed sensitivity
- Injection mass: (1.67 + 1.67) $M_{\odot}$



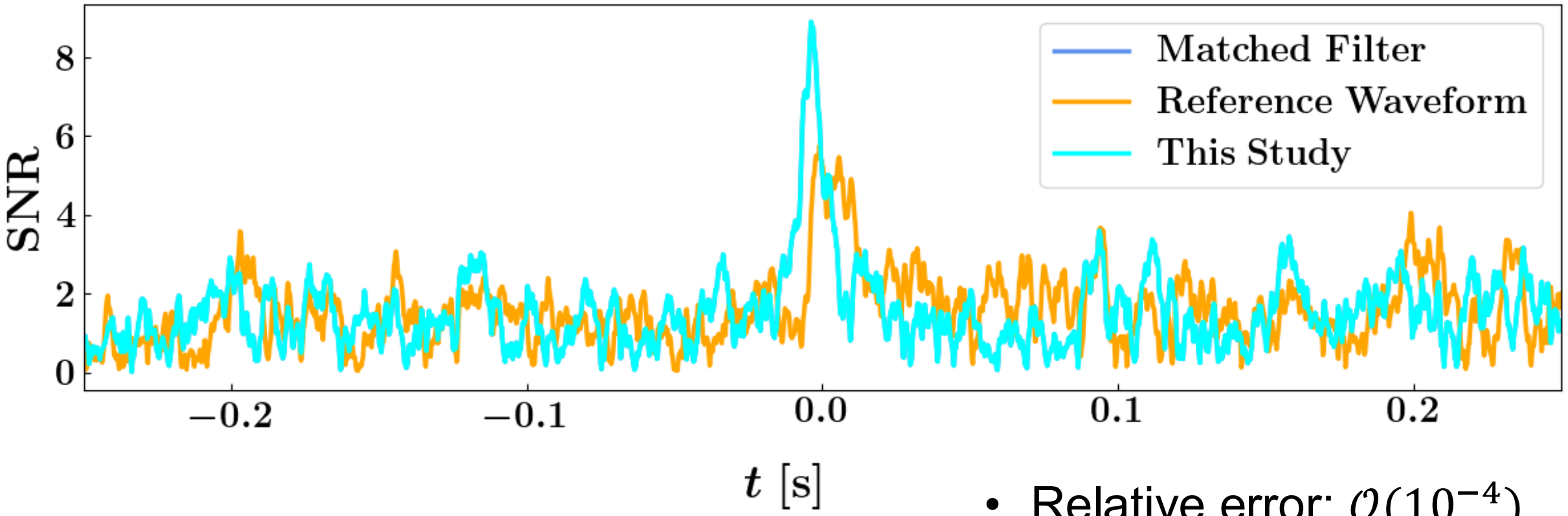
SNR time series for the loudest template



SNR time series for the loudest template

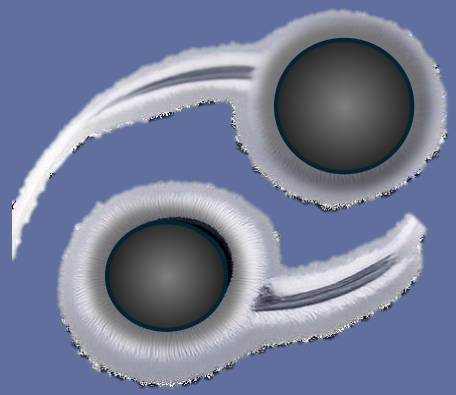


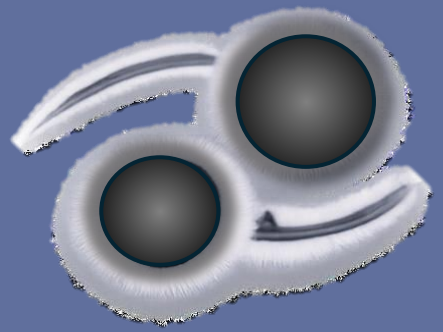
SNR time series for the loudest template

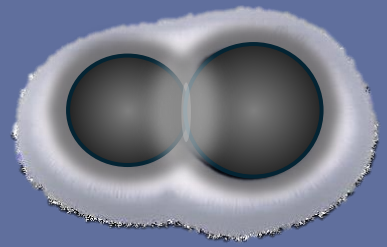


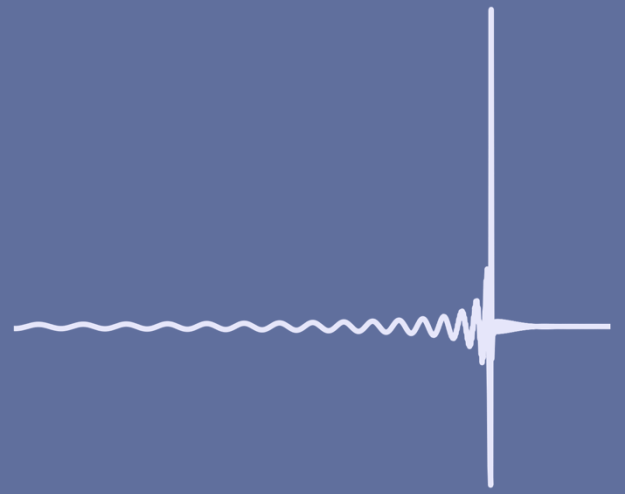
- Relative error: $\mathcal{O}(10^{-4})$
- Speed up gain: 25~30%

REAL DATA TEST

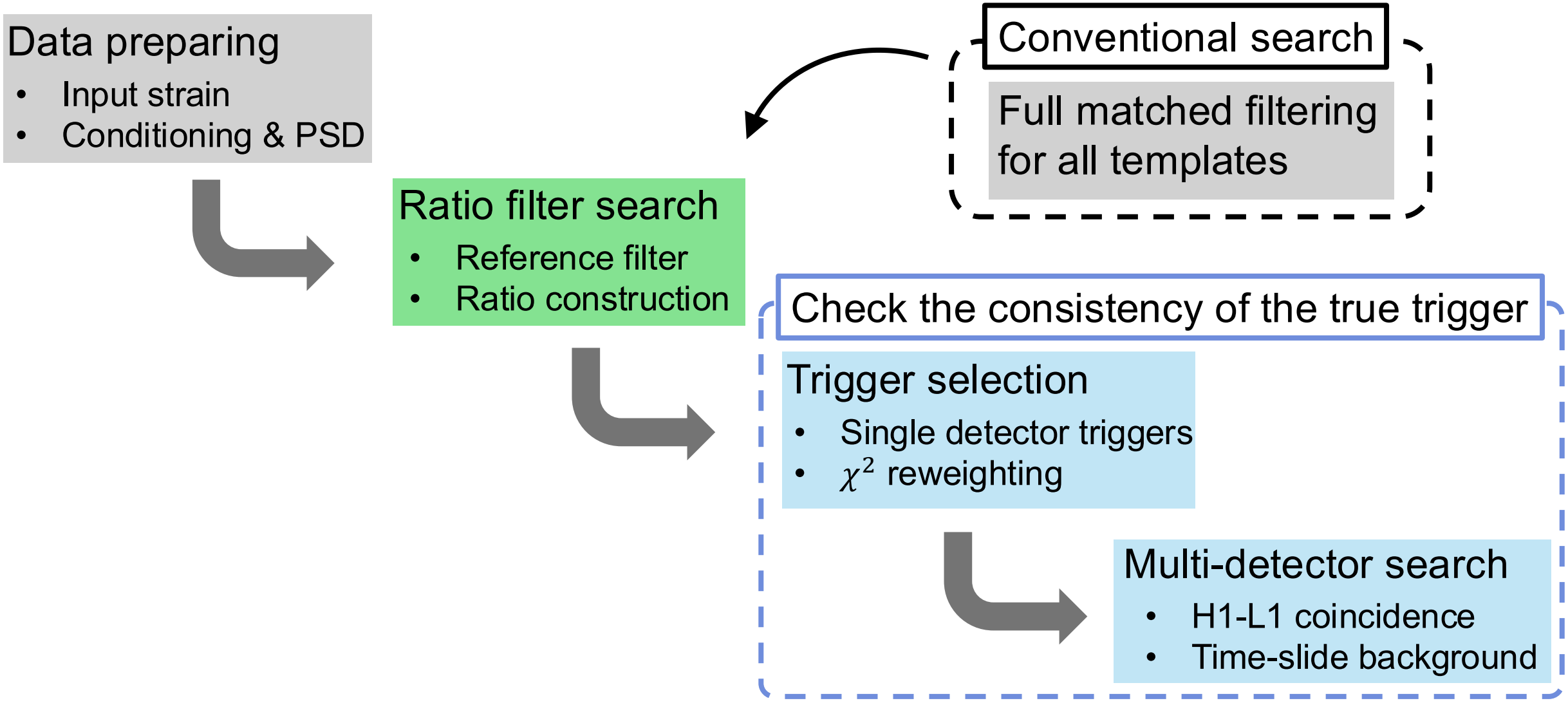




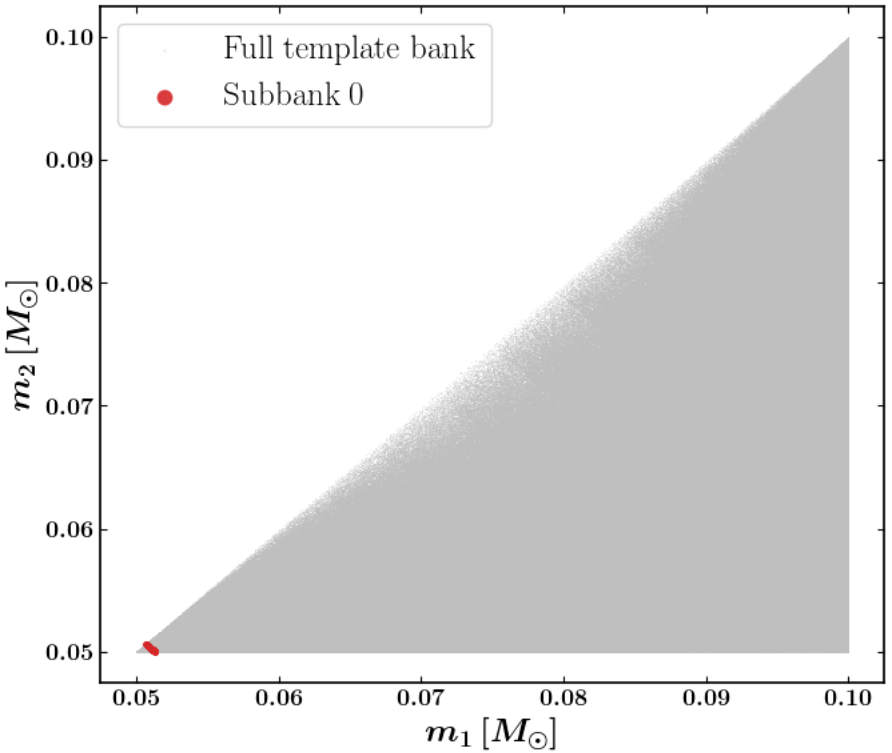




Where the ratio filter enters the pipeline



First real-data demonstration: one subbank

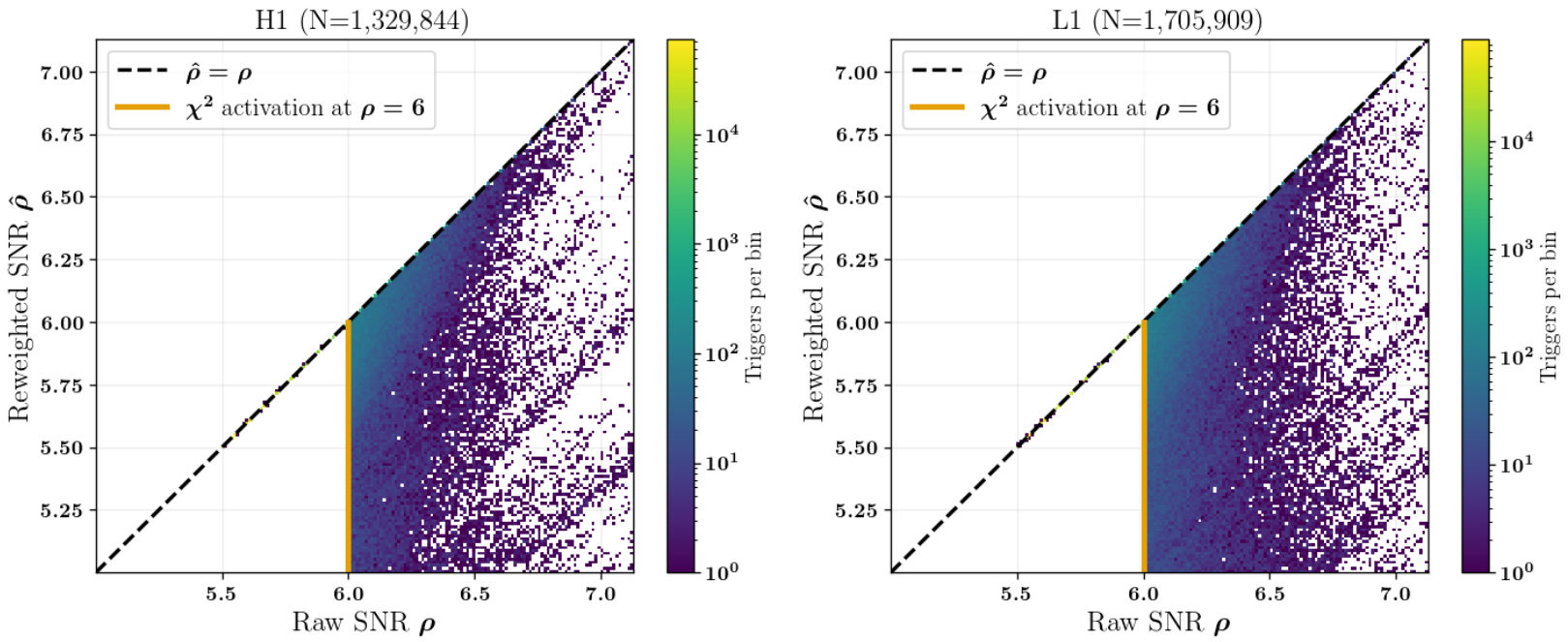


- One reference group / one subbank: 811 templates
  - Reference template:
    m1: 0.051 $M_\odot$, m2: 0.050 $M_\odot$,
    chi1: -0.94, chi2: -0.80

- LIGO Livingston and Hanford during O1
  - H1: 2015-09-12 05:51:43 ~ 2015-11-10 16:38:07 (live time: 34.3 days)
  - L1: 2015-09-12 04:43:27 ~ 2015-11-24 03:45:51 (live time: 36.8 days)

→ No candidate

χ^2 down-ranks inconsistent triggers



$$\hat{\rho} = \rho \left[\frac{1 + (\chi_r^2)^3}{2} \right]^{-1/6}$$

$$\chi_r^2 = \frac{\chi^2}{2p - 2}$$

p = the degree of freedom

- Signal like: $\tilde{\rho} \approx \rho$
- Noise-inconsistent: down ranked
- Removed by new SNR cut

- Raw-SNR ρ threshold: 5.5
- New SNR $\tilde{\rho}$ threshold: 5

Conclusions

- The problem
  - Sub-solar and future-detector signals are very long
- The method
  - One reference matched filter + short ratio convolutions (ratio filter)
- The result
  - Accurate SNR reconstruction + first real-data subbank analysis

Future work

- Complete the search for sub-solar mass region and find sub-solar mass candidates or constraint on the existence of PBH

Ratio filter: reconstructs the new SNR via convolving with the reference SNR

$$\mathrm{SNR}(t) = 4\left|\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{d}(f)\,\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t}\,\mathrm{d}f\right| \longleftarrow \text{SNR for nearby waveform}$$

$$= \left|\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} 4\frac{\tilde{d}(f)\tilde{h}^*_{\mathrm{ref}}(f)}{S_n(f)} \left(\frac{\tilde{h}(f)}{\tilde{h}_{\mathrm{ref}}(f)}\right)^* e^{2\pi i f t}\,\mathrm{d}f\right|$$

$$= \left|\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \tilde{z}_{\mathrm{ref}}(f)\,\tilde{r}^*(f)\, e^{2\pi i f t}\,\mathrm{d}f\right| \quad \text{The ratio waveform}: r(t) = \mathrm{IFT}\left[\frac{\tilde{h}(f)}{\tilde{h}_{\mathrm{ref}}(f)}\right]$$

$$= \left|\int z_{\mathrm{ref}}(t+\tau)\, r(\tau)\,\mathrm{d}\tau\right| \quad \text{SNR for the reference waveform}$$

The number of triggers