LVK O4a Constraints on Primordial Black Holes

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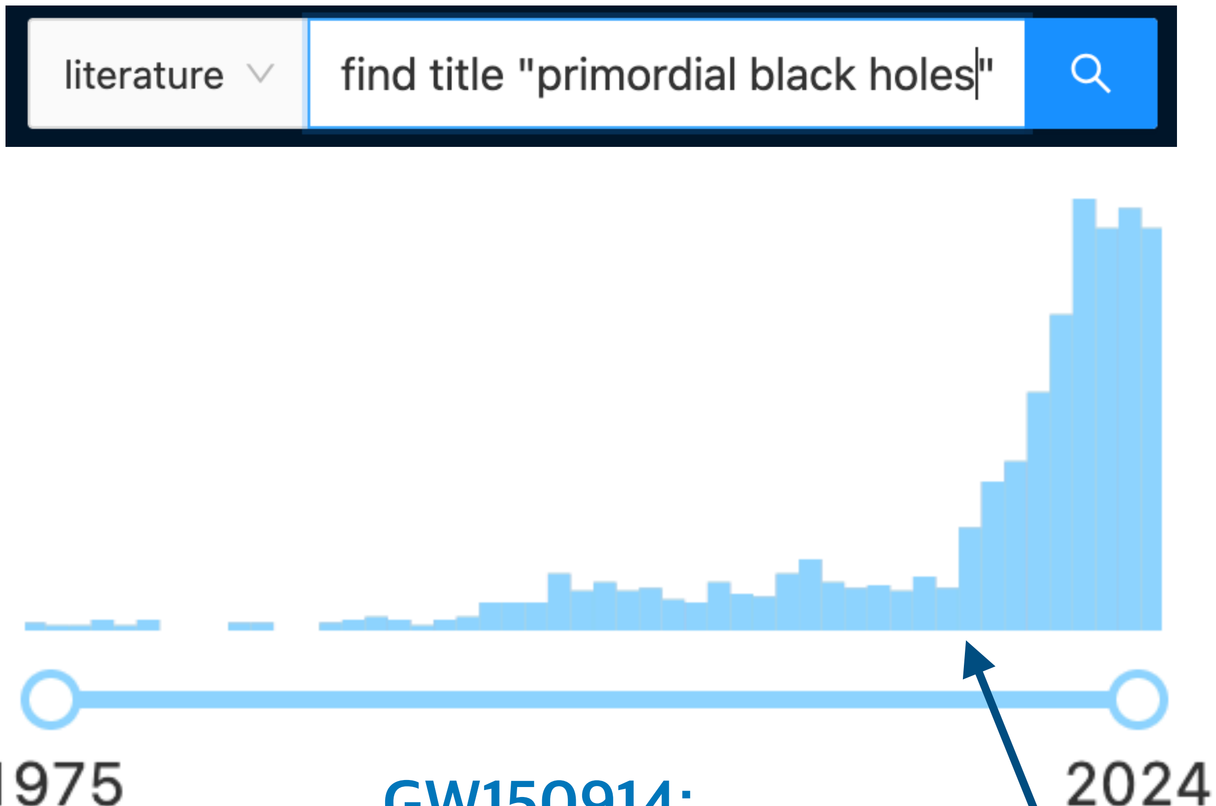
2 Dec 2025

Primordial Black Holes (PBHs)

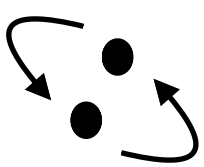
= Black holes generated in the early universe



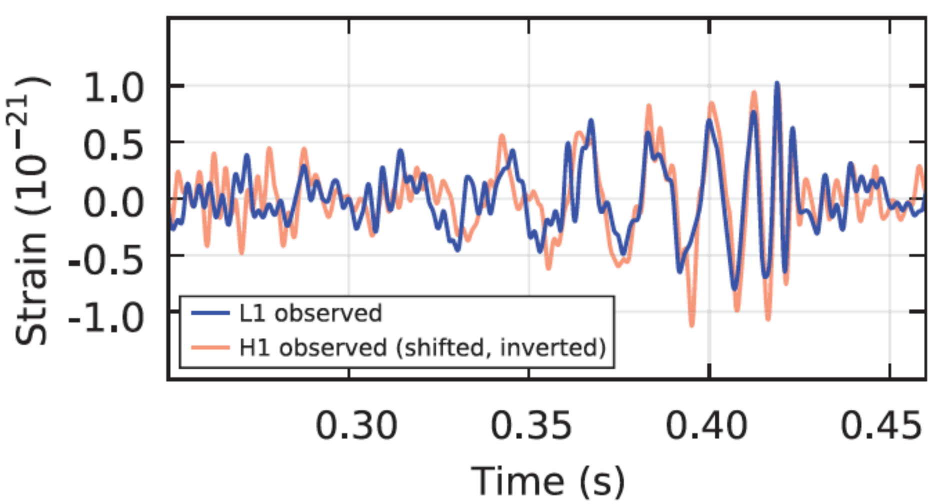
could originate from

- **Inflation**
- Reheating
- Phase transitions
- Collapse of cosmic strings
- Scalar field instabilities

etc.



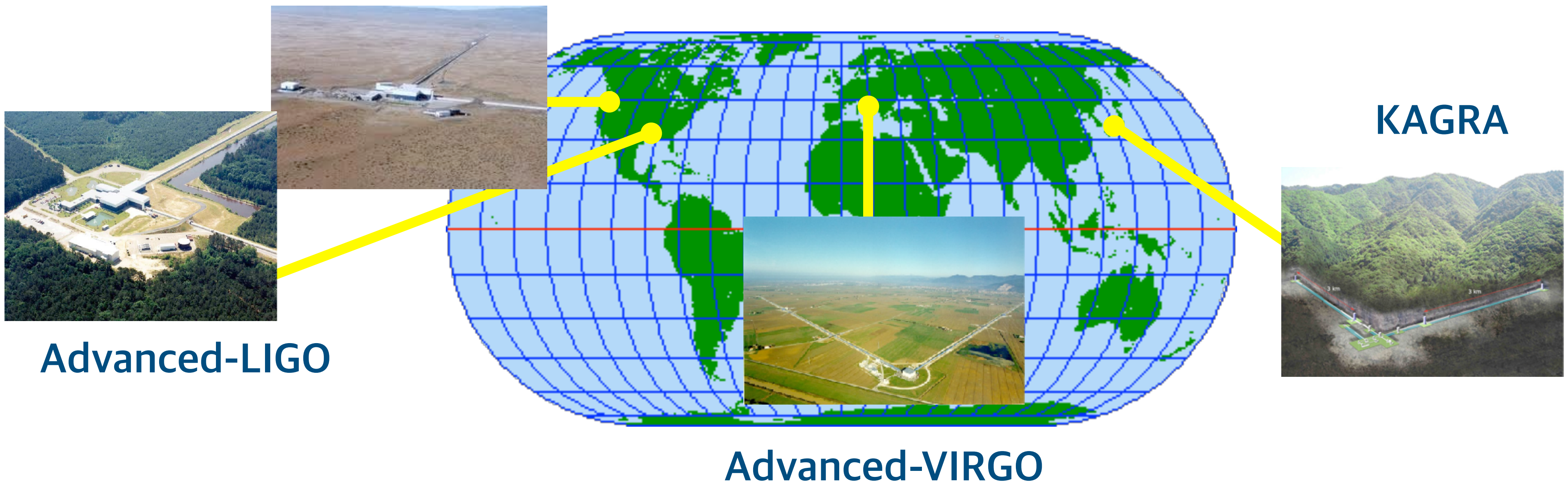
GW150914:
The first detection of a binary black hole

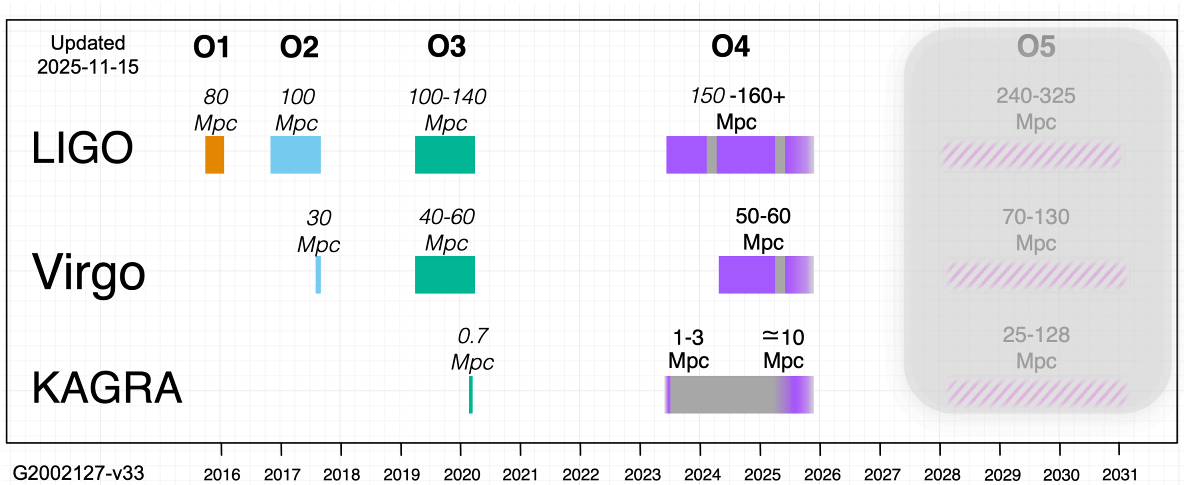


Origin of the observed 30 $M_\odot$ BBHs could be primordial.

Bird et al., PRL 116, 201301 (2016)
Clesse & Garcia-Bellido, PDU 10, 002 (2016)
Sasaki et al., PRL 117, 061101 (2016)

LVK O4 run observation



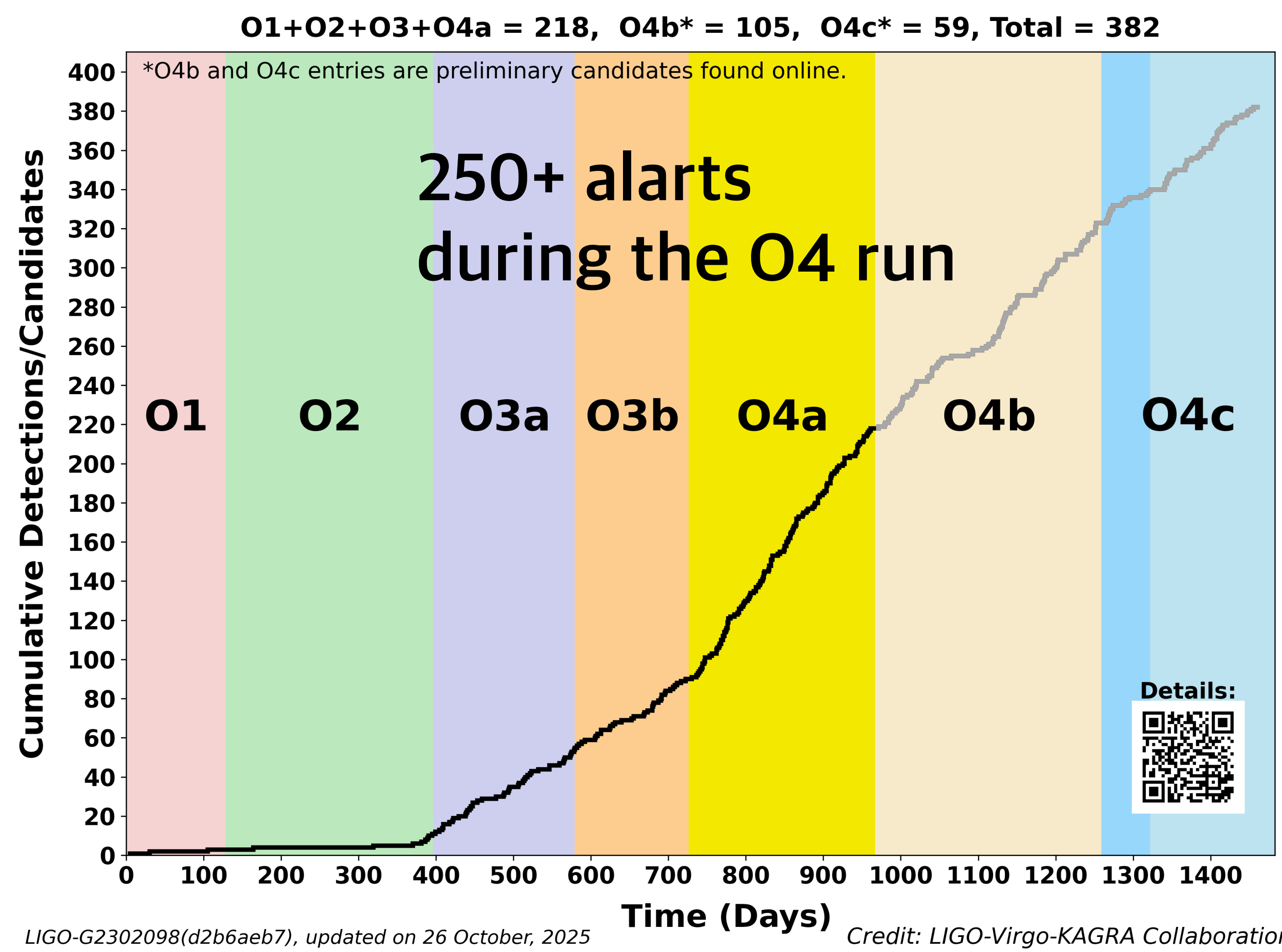


O4a: 237 days May 24, 2023 - Jan 16, 2024

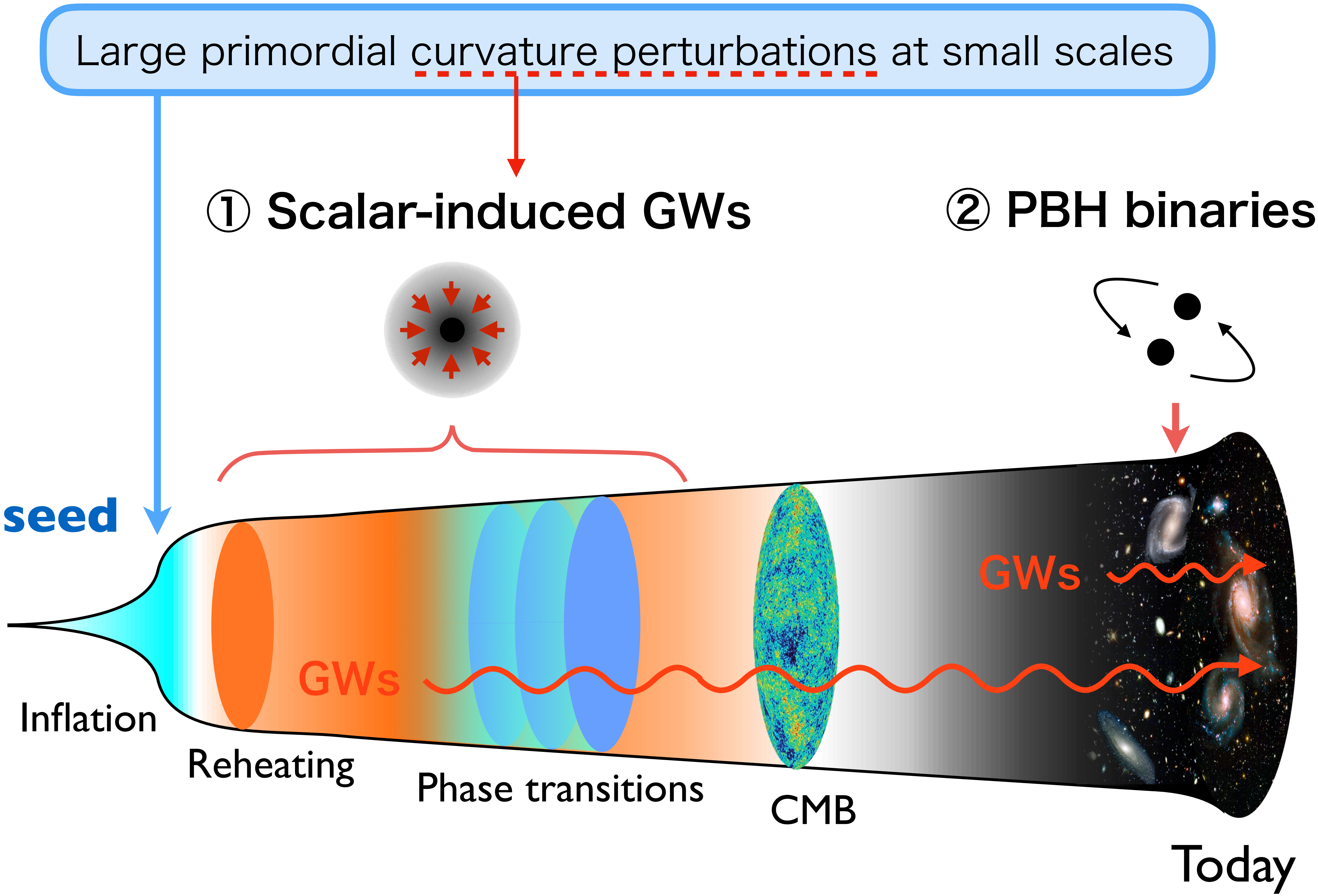
O4b: 356 days Apr 10, 2024 - Apr 1 2025

O4c: 160 days Jun 11 - Nov 18, 2025

O4a data release: Aug 26 2025



GWs as a probe of PBHs



Various ways to search PBHs

in the LVK frequency band

① Scalar-induced GWs → **Stochastic search**

② PBH binaries
- high redshift → **Stochastic search**
  - weak but abundant events overlap each other
- low redshift → strong signal → **individual binary search**

individual binary search

<u>Chirp time (at Newtonian order)</u>

$$\tau_0 = \frac{5}{256} M^{-5/3} (\pi f_0)^{-8/3} \eta^{-1}$$

Total mass: $M = m_1 + m_2$

Symmetric mass ratio: $\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$

Lowest frequency: f_0

smaller mass → longer duration of the signal

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  - weak but abundant events overlap each other
- low redshift → individual binary search
  - strong signal

individual binary search

low mass ⟷ high mass

10^{-7} - 0.1 $M_\odot$ | 0.1 - 2 $M_\odot$ | 2 - 10^2 $M_\odot$

Continuous wave search

Standard CBC search

Sub-solar mass binary search

Series of papers from LVK O4a run

(related to PBHs)

Stochastic search

arXiv:2508.20721, "Upper Limits on the Isotropic Gravitational-Wave Background from the first part of LIGO, Virgo, and KAGRA's fourth Observing Run"

arXiv:2510.26848, "Cosmological and High Energy Physics implications from gravitational-wave background searches in LIGO-Virgo-KAGRA's O1-O4a"

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arXiv:2508.18083, "GWTC-4.0: Population Properties of Merging Compact Binaries"

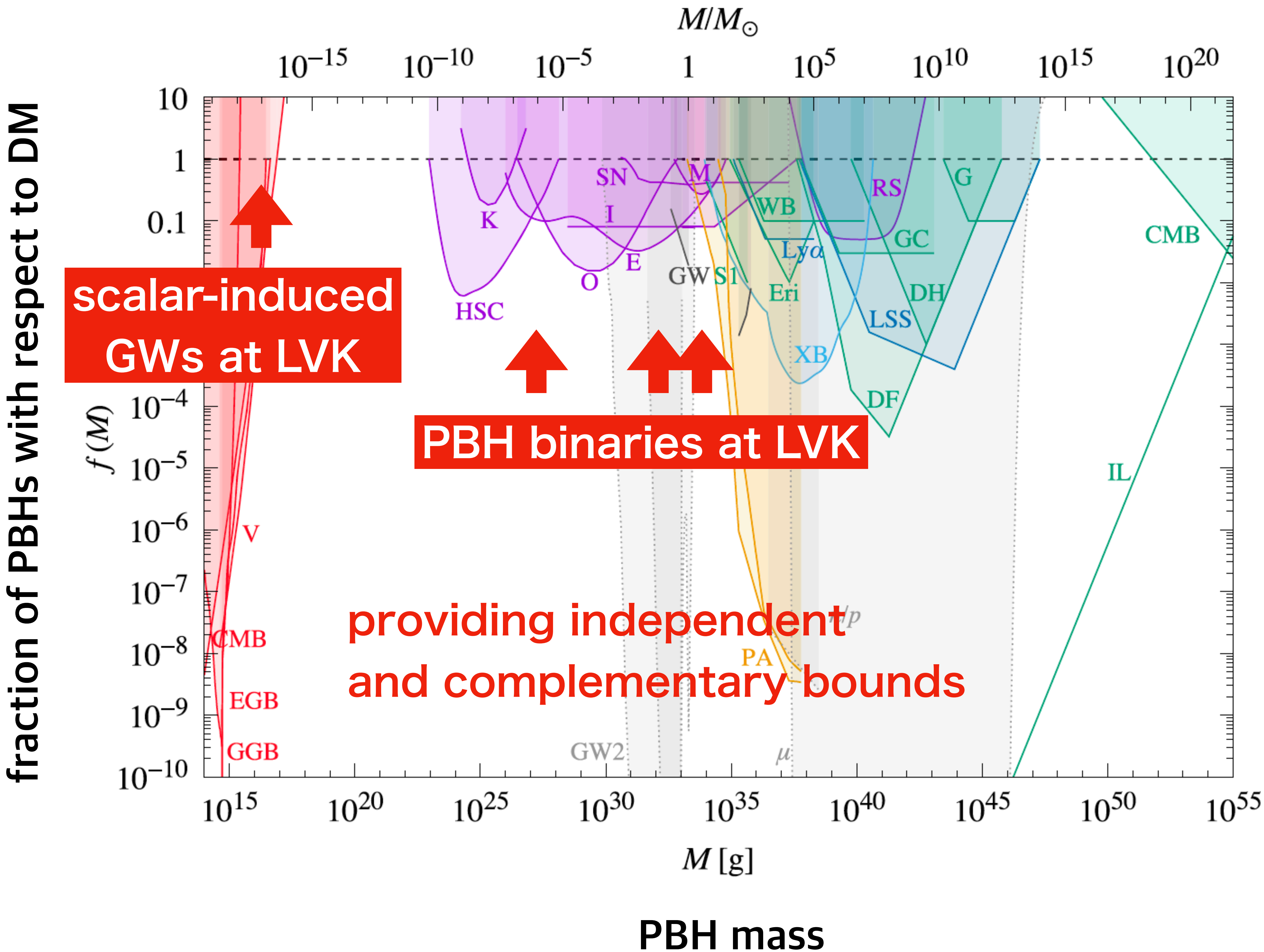
Sub-solar mass binary search

will be out soon

Continuous wave search

arXiv:2511.19911, "Search for planetary-mass ultra-compact binaries using data from the first part of the LIGO–Virgo–KAGRA fourth observing run"

PBH constraints across a wide mass range

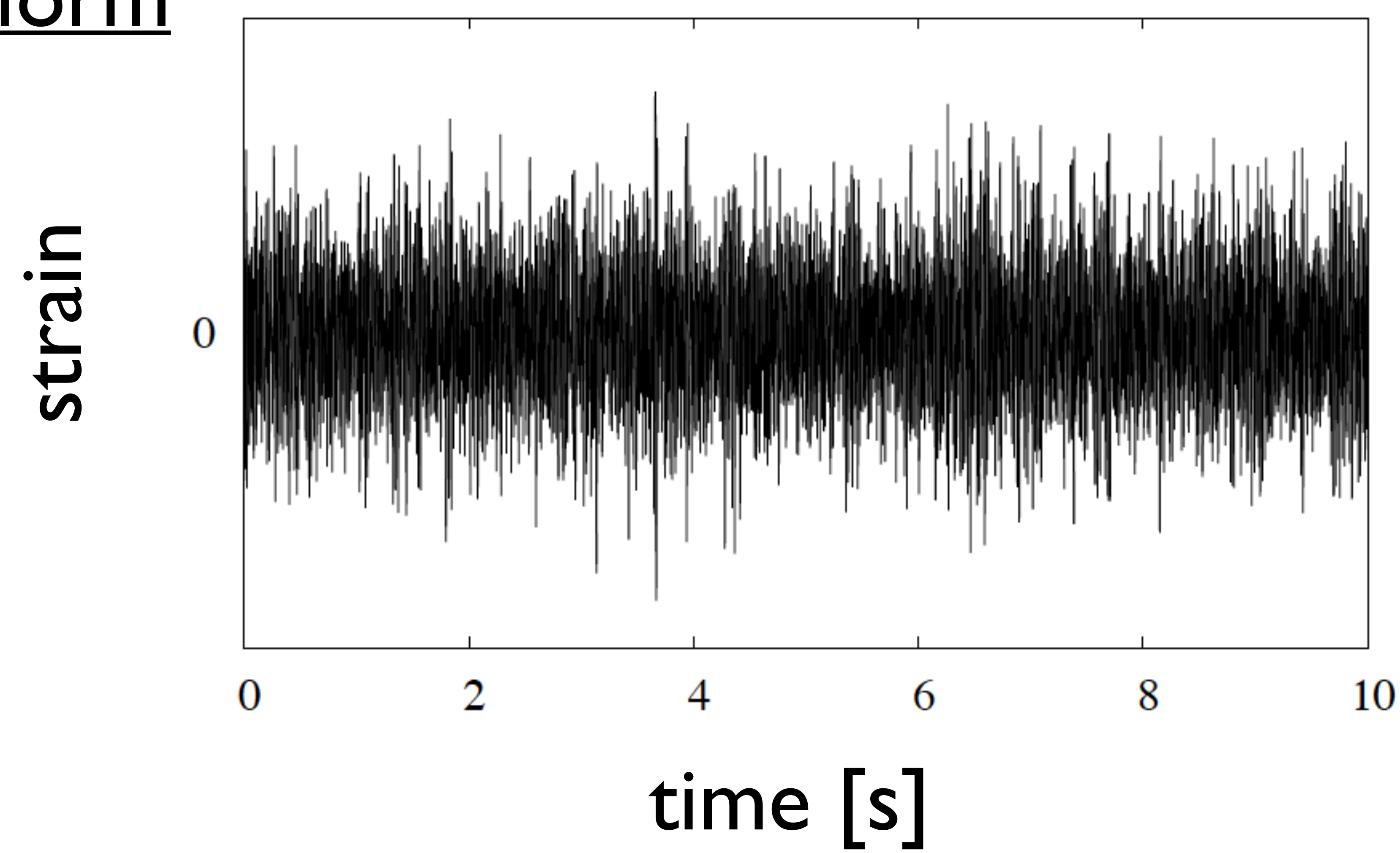


Carr et al. PRD 81, 104019 (2010), Rep. Prog. Phys. 84, 116902 (2021)

Stochastic search

Stochastic GW background

<u>Waveform</u>



Continuous and random GW signal
coming from all directions → very similar to noise

How to detect a stochastic background

Cross Correlation

detector1

$$s_1(t) = h(t) + n_1(t)$$

detector2

$$s_2(t) = h(t) + n_2(t)$$

s: observed data
h: gravitational waves
n: noise

$$\langle S \rangle = \int_{-T/2}^{T/2} dt \, \langle s_1(t) s_2(t) \rangle$$

$$= \int_{-T/2}^{T/2} dt \, \langle h^2(t) + \underline{h(t) n_2(t) + n_1(t) h(t) + n_1(t) n_2(t)} \rangle$$

no correlations → 0

$$= \int_{-T/2}^{T/2} dt \, \underline{\langle h^2(t) \rangle}$$

GW signal

(for detectors at the same location)

Upper bounds on stochastic background

arXiv:2508.20721, "Upper Limits on the Isotropic Gravitational-Wave Background from the first part of LIGO, Virgo, and KAGRA's fourth Observing Run"

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln k}$$

$\rho_{\rm GW}$: Energy density of GWs

ρ_c: Critical density of the Universe

Observation run	**Year**	**95% Upper bound** (for a flat spectrum at 25Hz)
LIGO S6	2009	$\Omega_{\rm GW} < 6.9 \times 10^{-6}$
Advanced LIGO O1	2016	$\Omega_{\rm GW} < 1.7 \times 10^{-7}$
Advanced LIGO O2	2019	$\Omega_{\rm GW} < 6.0 \times 10^{-8}$
Advanced LIGO O3 (+ Virgo)	2021	$\Omega_{\rm GW} < 5.8 \times 10^{-9}$
Advanced LIGO O4a	2025	$\Omega_{\rm GW} < 2.7 \times 10^{-9}$

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[illegible]	2019	$\Omega_{\mathrm{GW}} < 6.0 \times 10^{-8}$
Advanced LIGO O3 205 days	2021	$\Omega_{\mathrm{GW}} < 5.8 \times 10^{-9}$
Advanced LIGO O4a 126 days	2025	$\Omega_{\mathrm{GW}} < 2.7 \times 10^{-9}$

2.1

The sensitivity of the cross-correlation analysis improves as $\propto 1/\sqrt{T_{\mathrm{obs}}}$

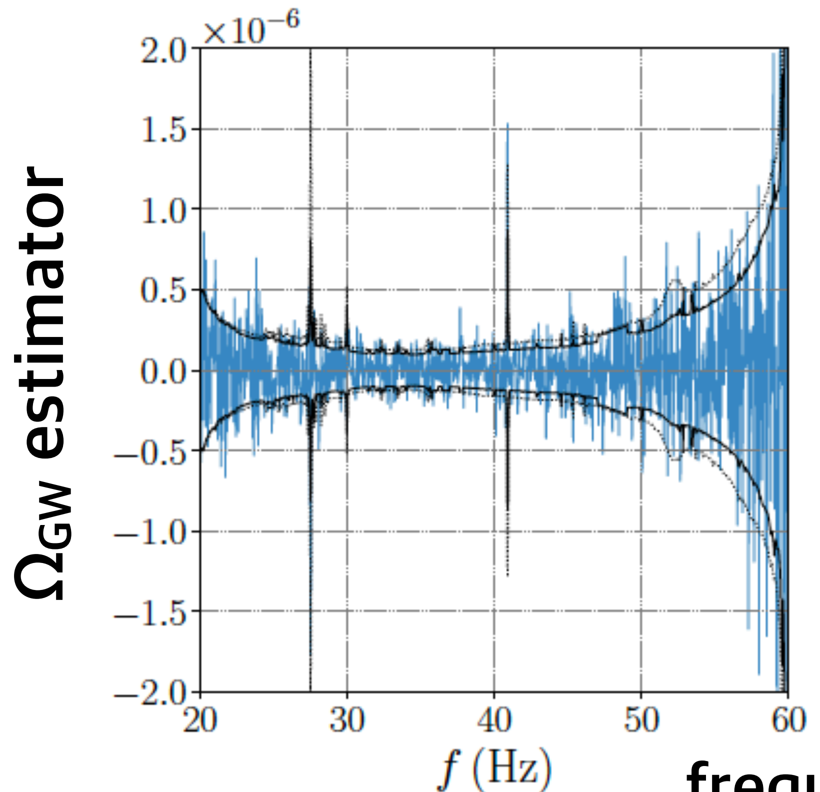
Cosmological implications

arXiv:2510.26848, "Cosmological and High Energy Physics implications from gravitational-wave background searches in LIGO-Virgo-KAGRA's O1-O4a"

Investigating 7 (+1) models of the early universe

SK in paper writing team

data (cross-correlated spectrum)



frequency

Theoretical models

① First-order phase transitions
② Cosmic strings
③ Domain walls
④ Stiff equation of state
⑤ Axion inflation
⑥ Second-order scalar perturbations
⑦ Primordial black holes
⑧ Parity Violation

Likelihood

$$p\left(\hat{\Omega}^{IJ}_{\mathrm{GW},f}|\mathbf{\Theta}\right) \propto \exp\left[-\frac{1}{2}\sum_{IJ}^{B}\sum_{f}\left(\frac{\hat{\Omega}^{IJ}_{\mathrm{GW},f}-\Omega_{\mathrm{M}}(f|\mathbf{\Theta})}{\sigma^{IJ}_{\mathrm{GW},f}}\right)^2\right]$$

Constraints on PBH scenarios

① Scalar-induced GWs

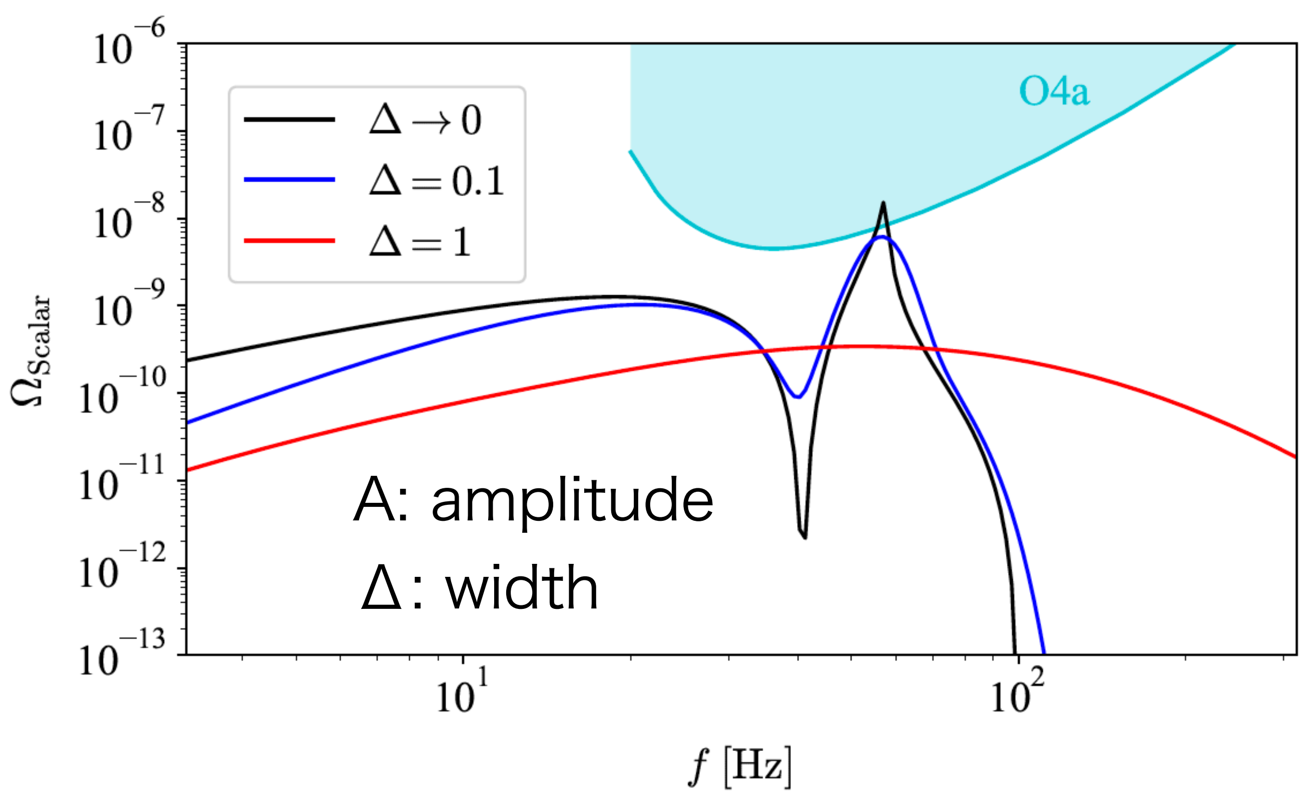
LVK collaboration, arXiv:2510.26848

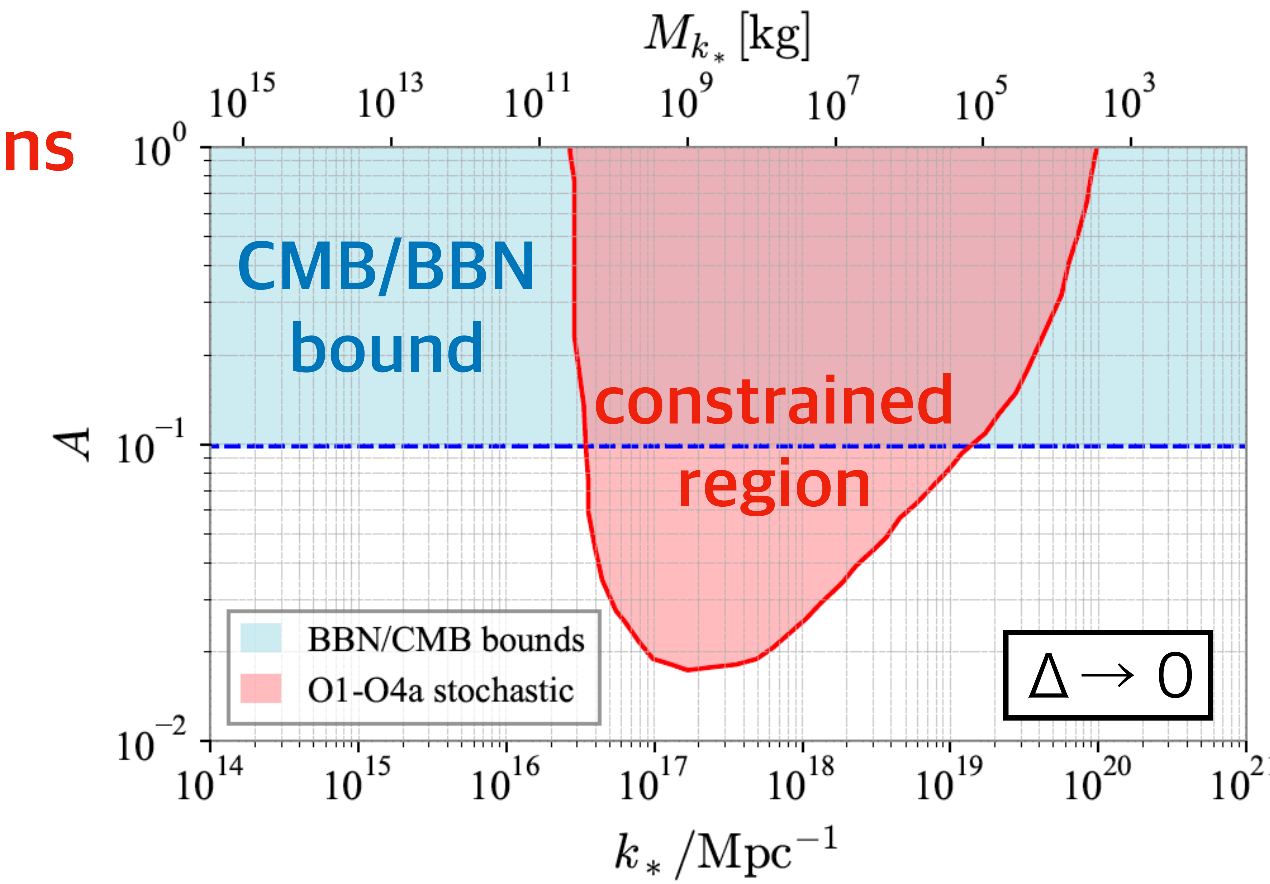
GWs induced by large scalar perturbations

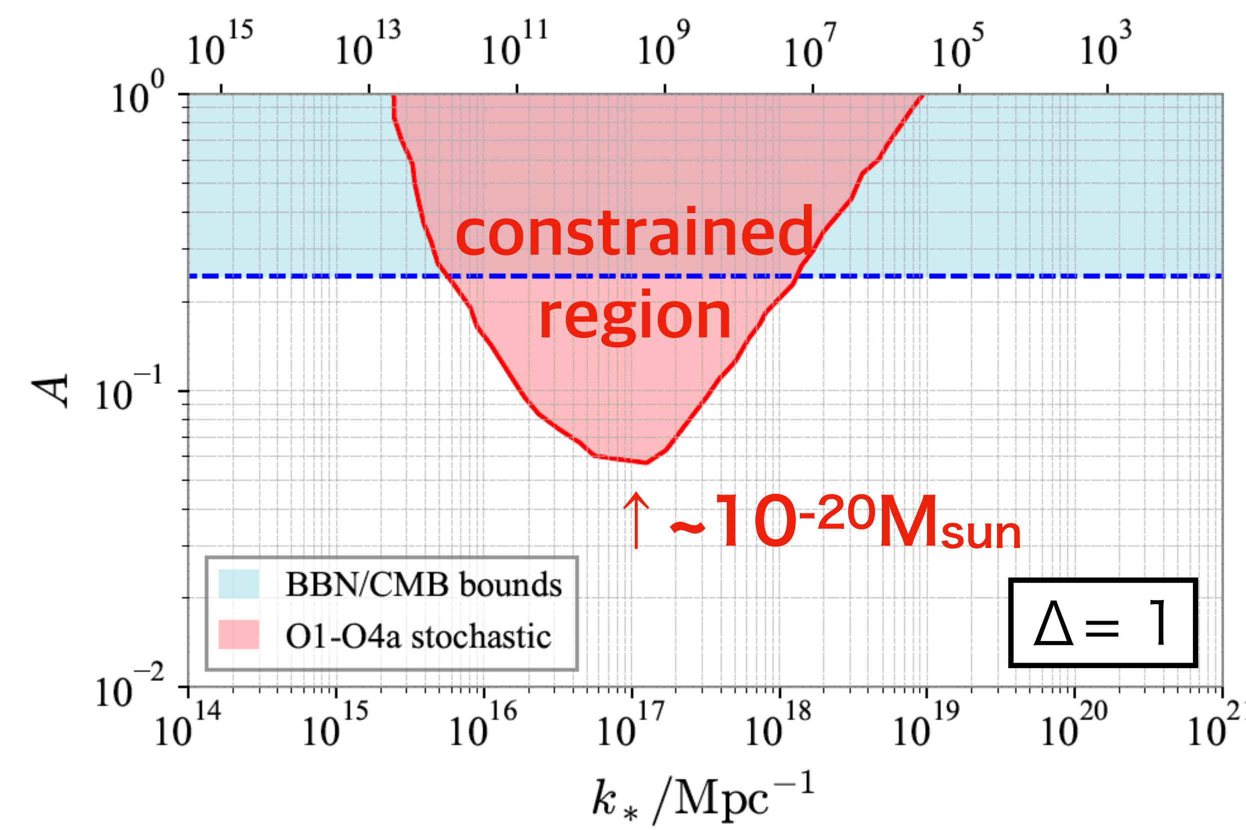
assumption: Log-normal curvature perturbation spectrum

$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

GW spectrum







Constraints on PBH scenarios

② PBH binaries

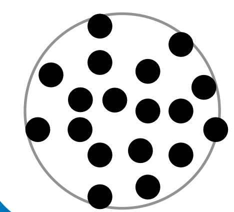
Superposition GWs of PBH binaries

assumption: monochromatic mass function, two binary formation scenarios

Early binary formation

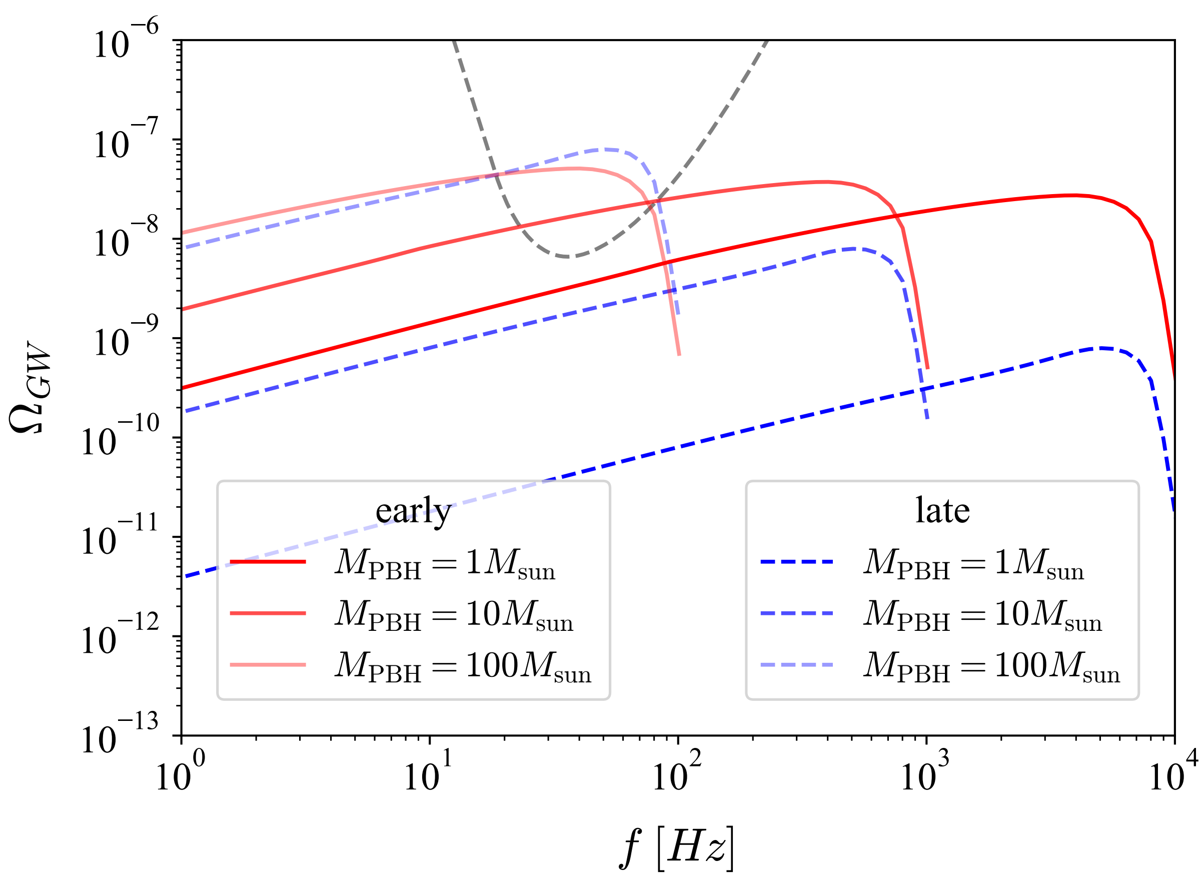
tidal torque

Late binary formation

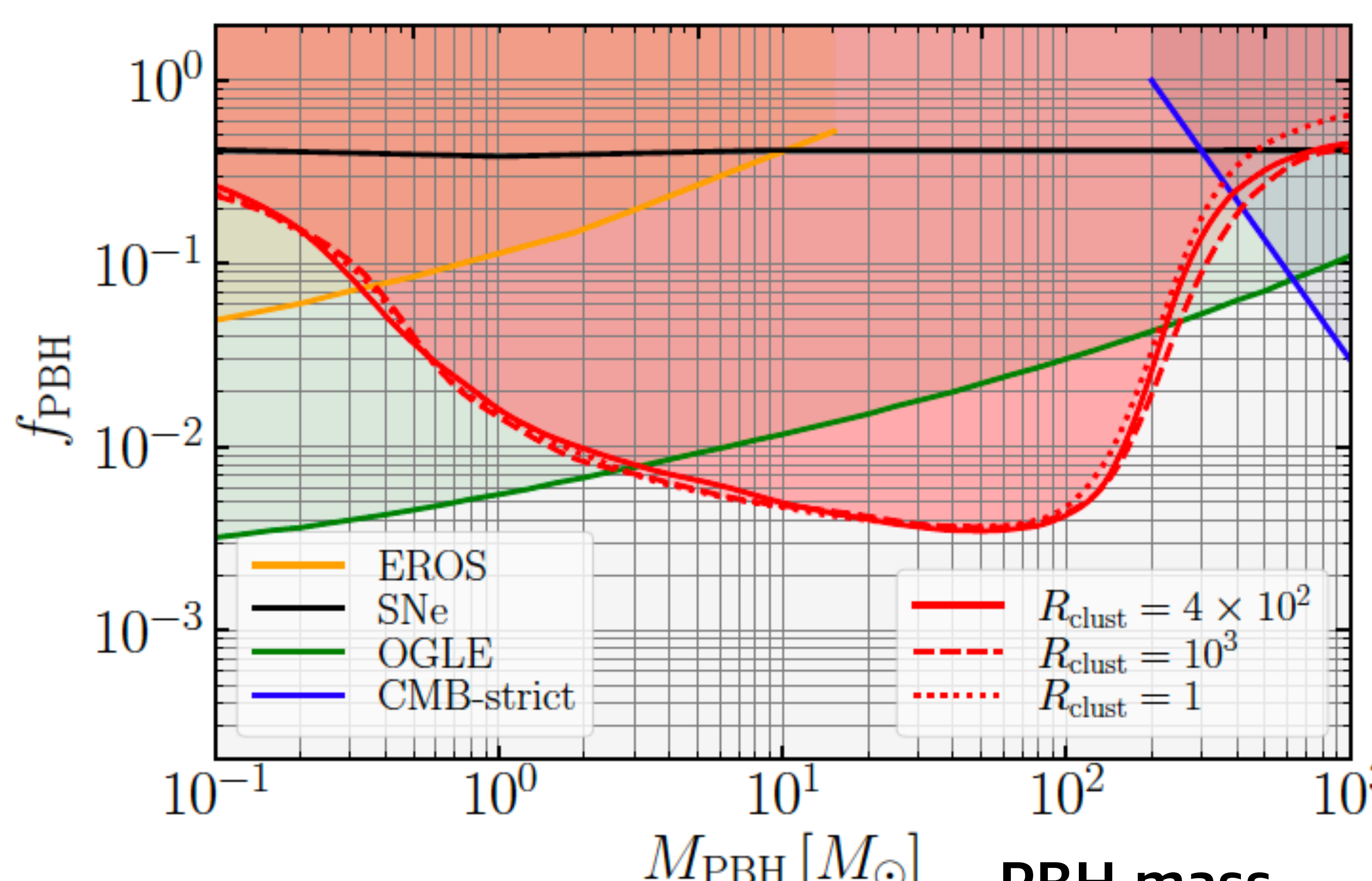


dynamical capture in a cluster

GW spectrum



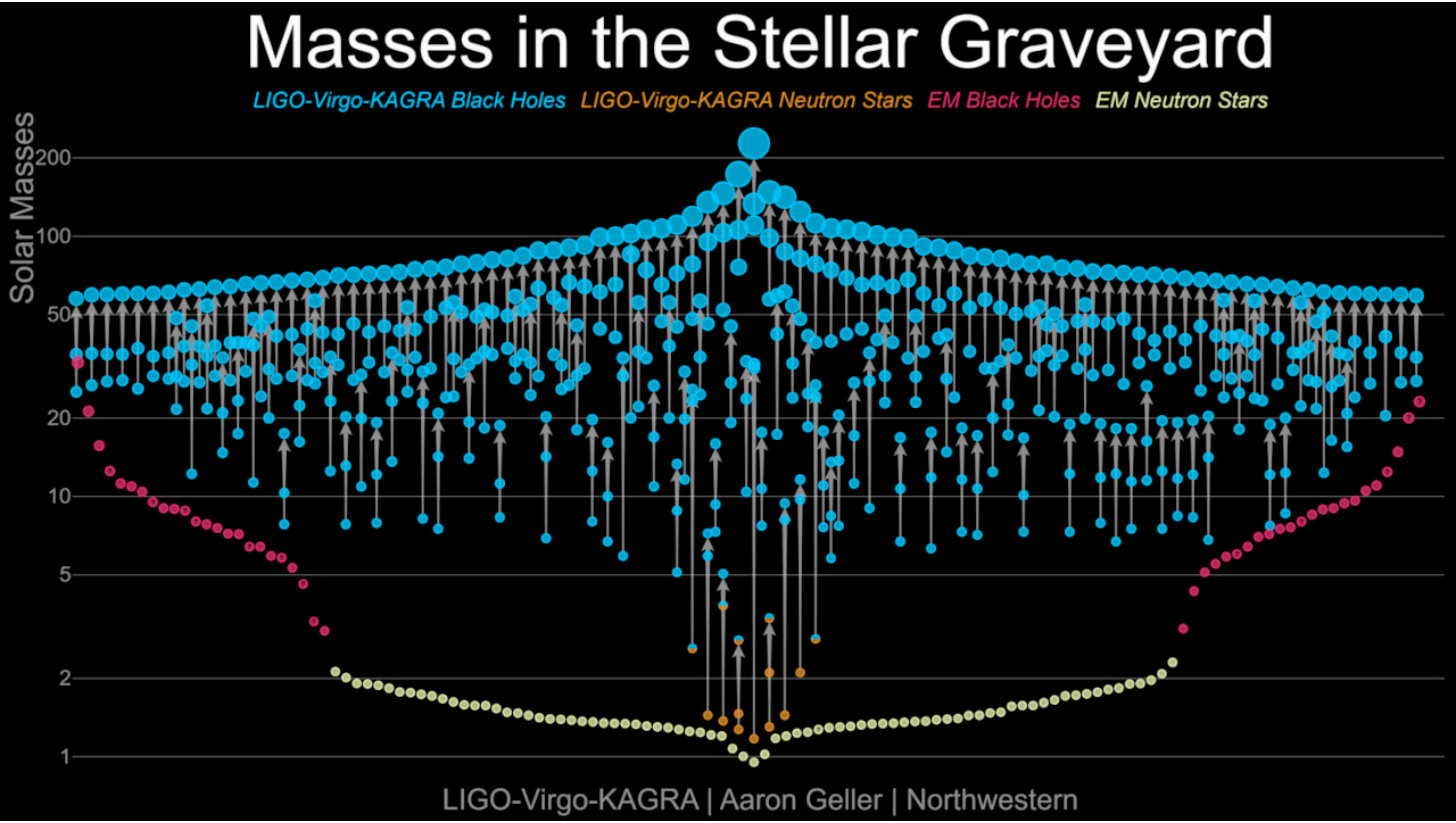
Constraint on PBH fraction



PBH mass

Standard CBC search

128 new merger events are identified



128 new merger events are identified

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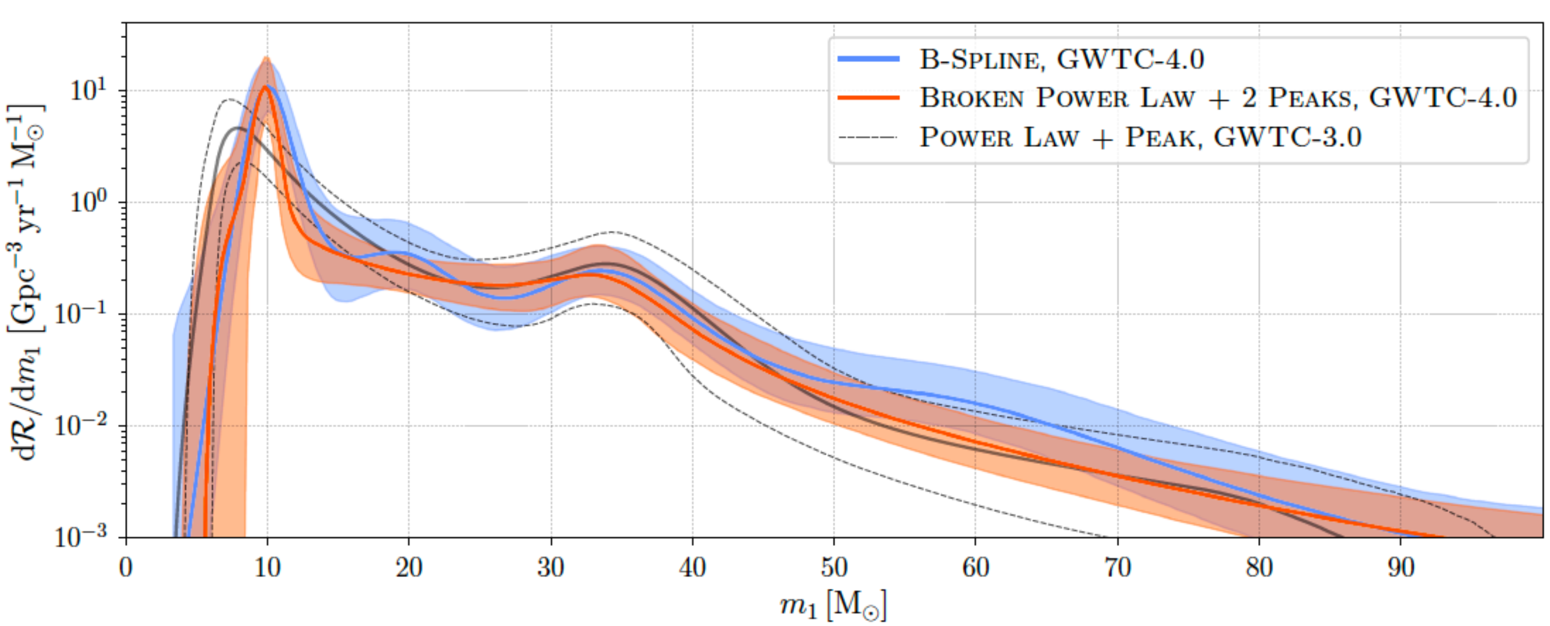
arXiv:2508.18083, “GWTC-4.0: Population Properties of Merging Compact Binaries”

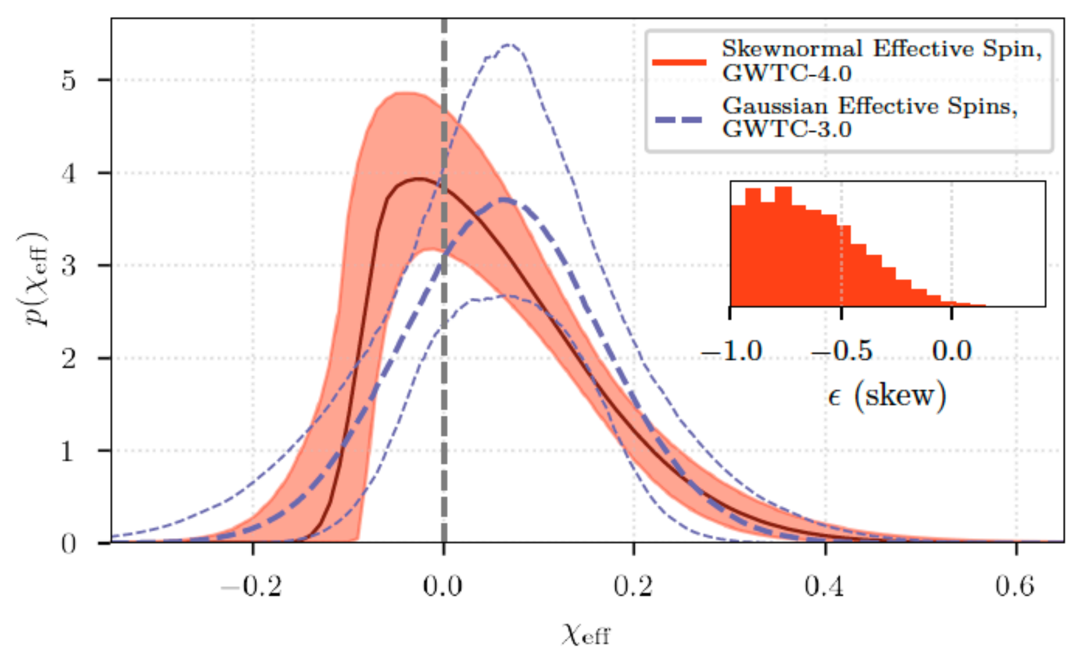
86 events with FAR < 1yr^{-1} was analyzed in details (84 BBHs and 2 BHNSs)

False Alarm Rate (FAR): the estimated rate at which the detector noise can mimic the real GW signal

BBH mass function



Effective spin parameter



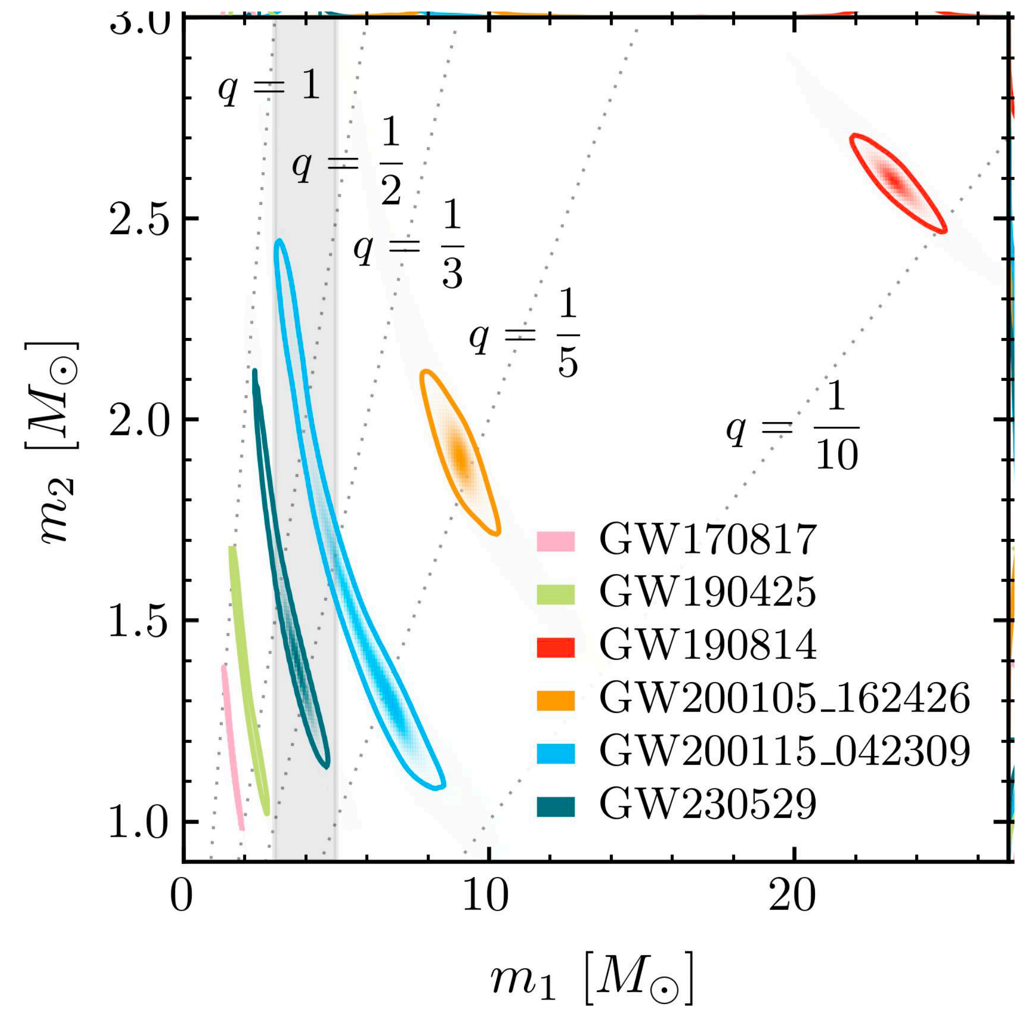
Picked up events

arXiv:2404.04248, "Observation of Gravitational Waves from the Coalescence of a 2.5–4.5 M⊙ Compact Object and a Neutron Star"

GW231123

Primary BH is in the NS — BH mass gap

Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$



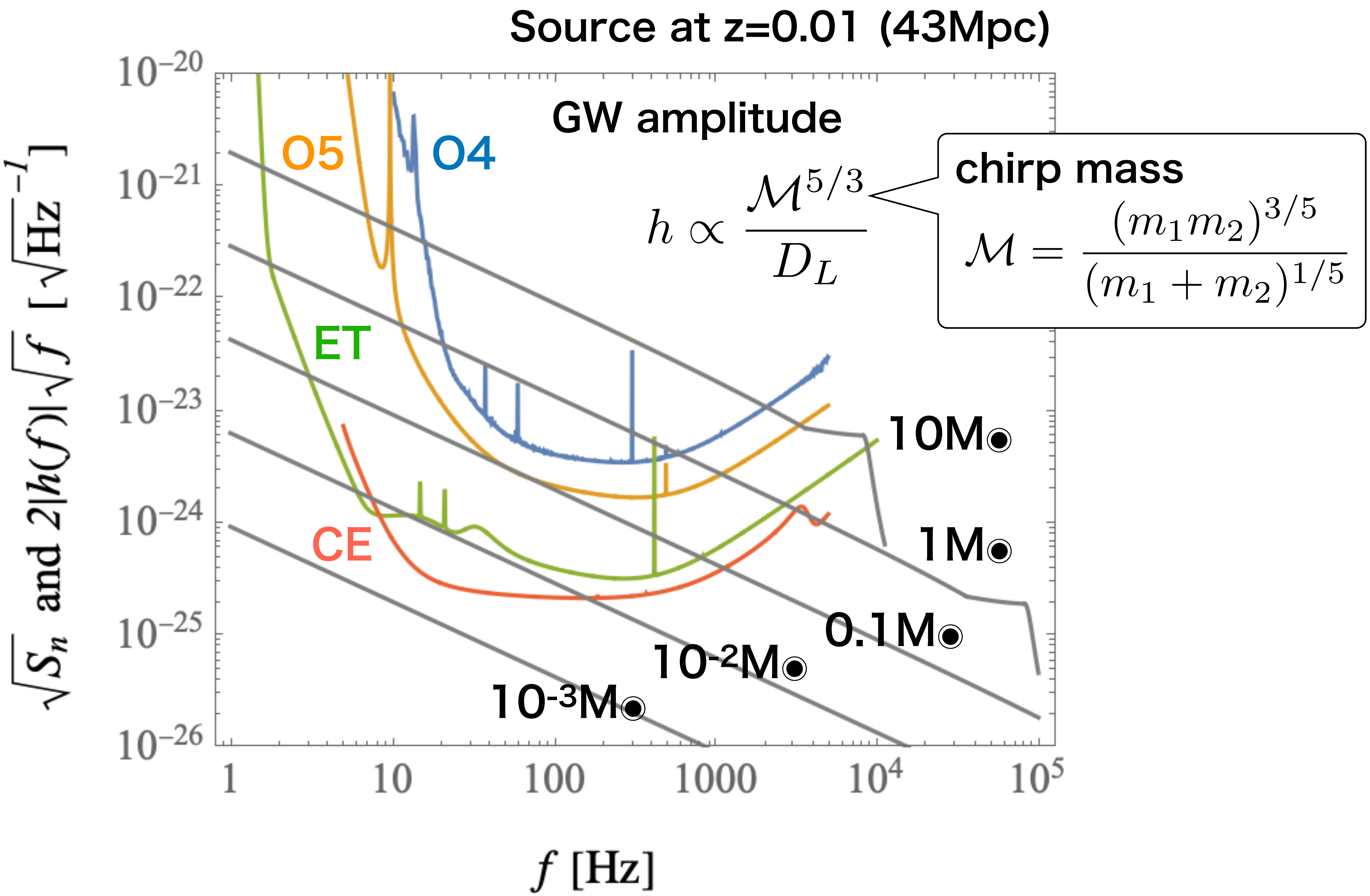
arXiv:2507.08219, "GW231123: a Binary Black Hole Merger with Total Mass 190-265 M⊙"

GW230529 **Both are in the super nova pair-instability mass gap**

$$M_1 = 137^{+22}_{-17}\,M_\odot \quad M_2 = 103^{+20}_{-52}\,M_\odot \qquad \sim [60, 130]\,M_\odot$$

Sub-solar mass binary search

Searching sub-solar mass binaries



Detection of BH with < ~1M⊙ can be a strong evidence of primordial origin

Matched filtering search

Signal-to-noise ratio (SNR)

Data

Template = expected waveform

$$\rho^2 = \frac{\left[\int_{f_{\rm ini}}^{\infty} df\, \frac{\tilde{h}(f)\tilde{h}_t^*(f) + \tilde{h}^*(f)\tilde{h}_t(f)}{S(f)}\right]^2}{\int_{f_{\rm ini}}^{\infty} df\, \frac{|\tilde{h}_t(f)|^2}{S(f)}}$$

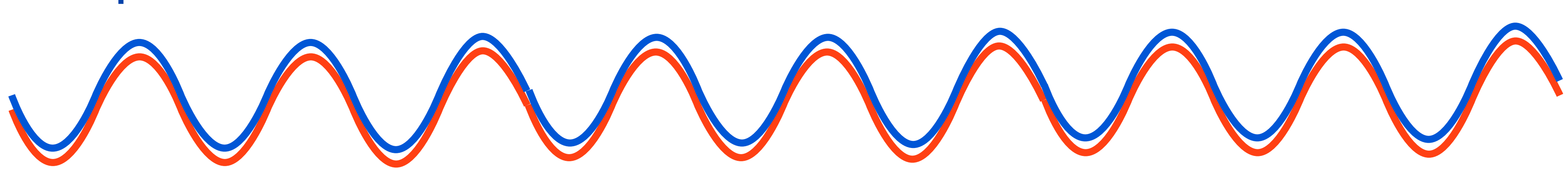
Noise

Normalization factor

Assuming $\tilde{h}(f) = \tilde{h}_t(f)$

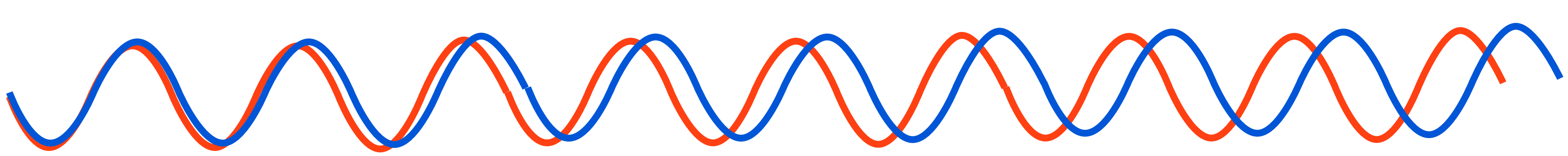
$$\rho^2 = \int_0^\infty \frac{(2|\tilde{h}(f)|\sqrt{f})^2}{S_n(f)}\, \mathrm{d}\ln(f)$$

Template



Data

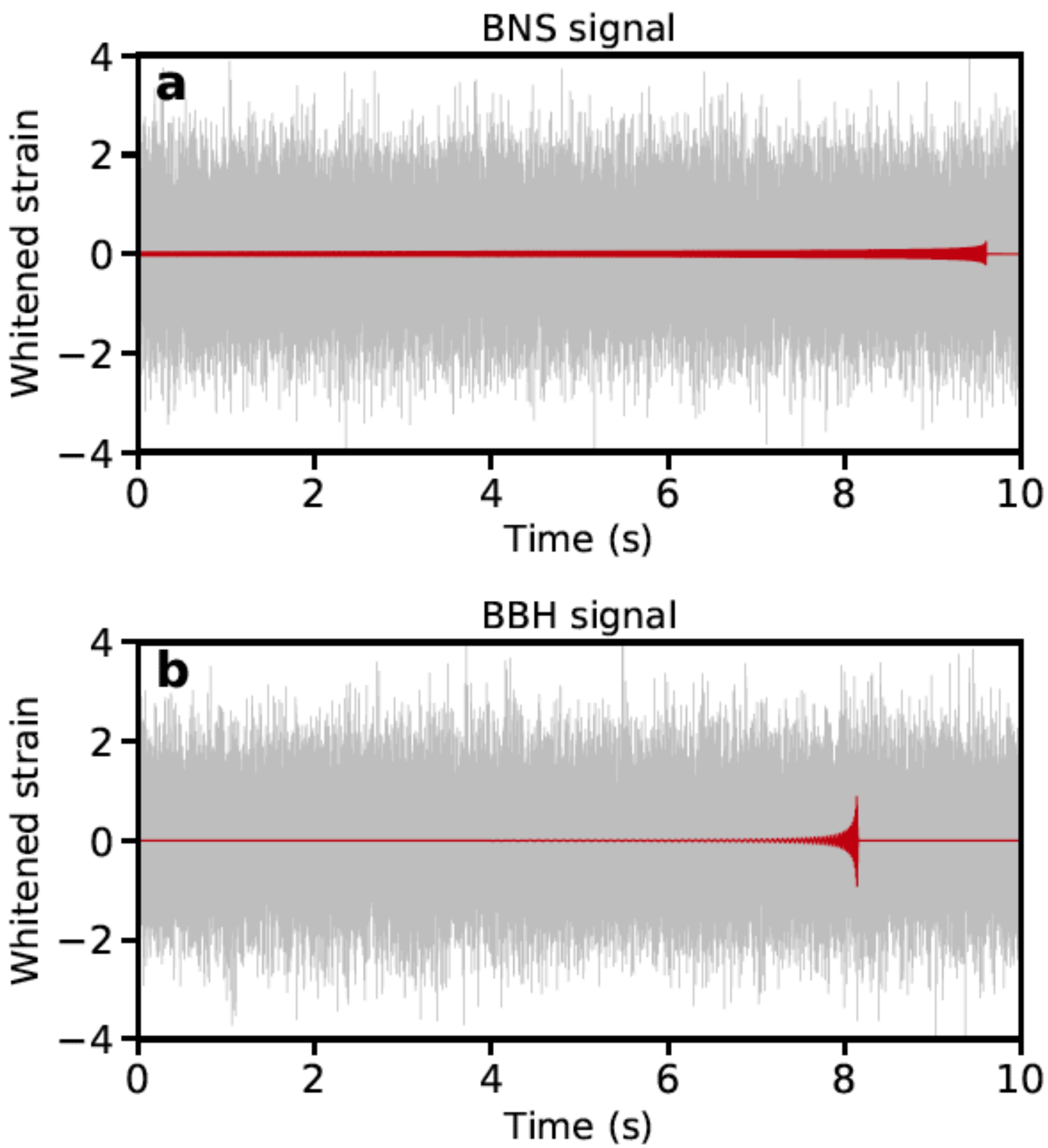
→ matched: SNR is maximized

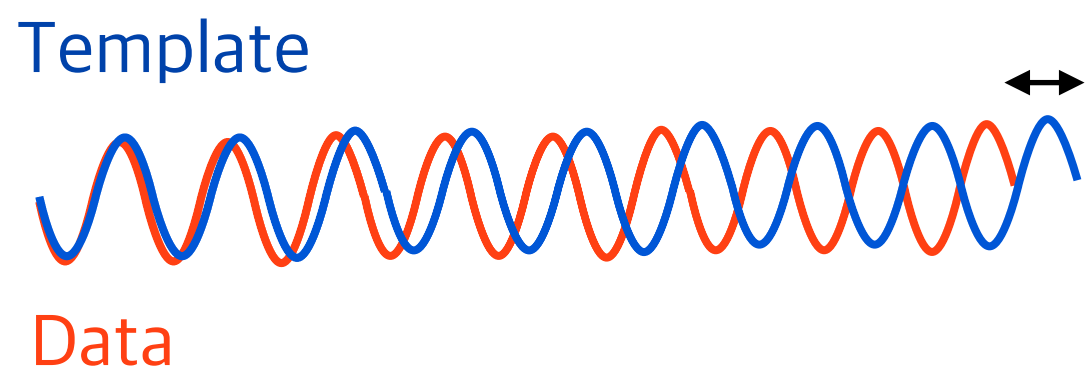


→ mismatch: SNR is reduced

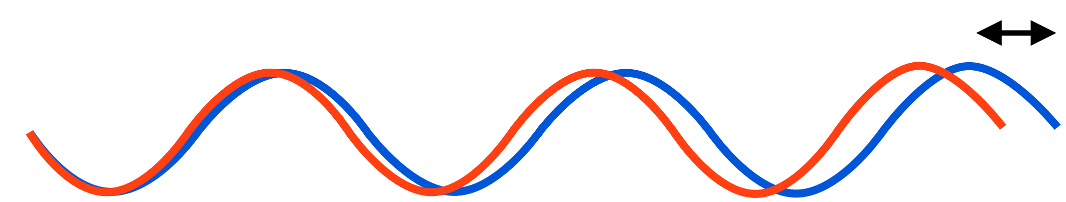
Challenge in sub-solar mass search

Low mass event continues long time and has more oscillation cycles.





→ sensitive to small phase shift by variation of parameters



→ insensitive to small phase shift

→ **need to increase resolution of the templates**

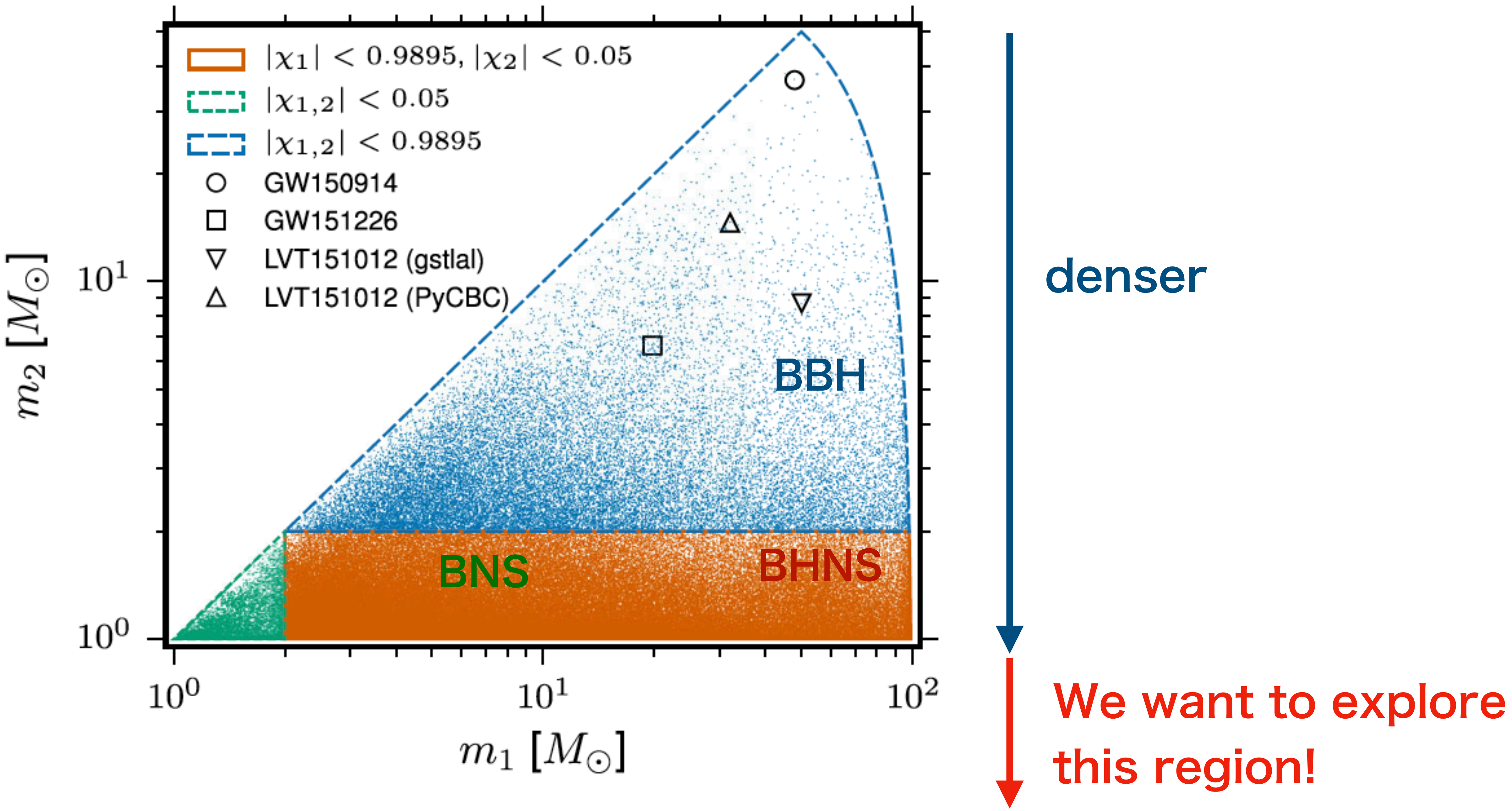
→ **more computation time**

Figure from Krastev, PLB 803, 135330 (2020)

Challenge in sub-solar mass search

Low mass event requires fine gridding to avoid mismatch.

Template bank used in the O1 CBC search



LVK collaboration, PRX 6, 041015 (2016)

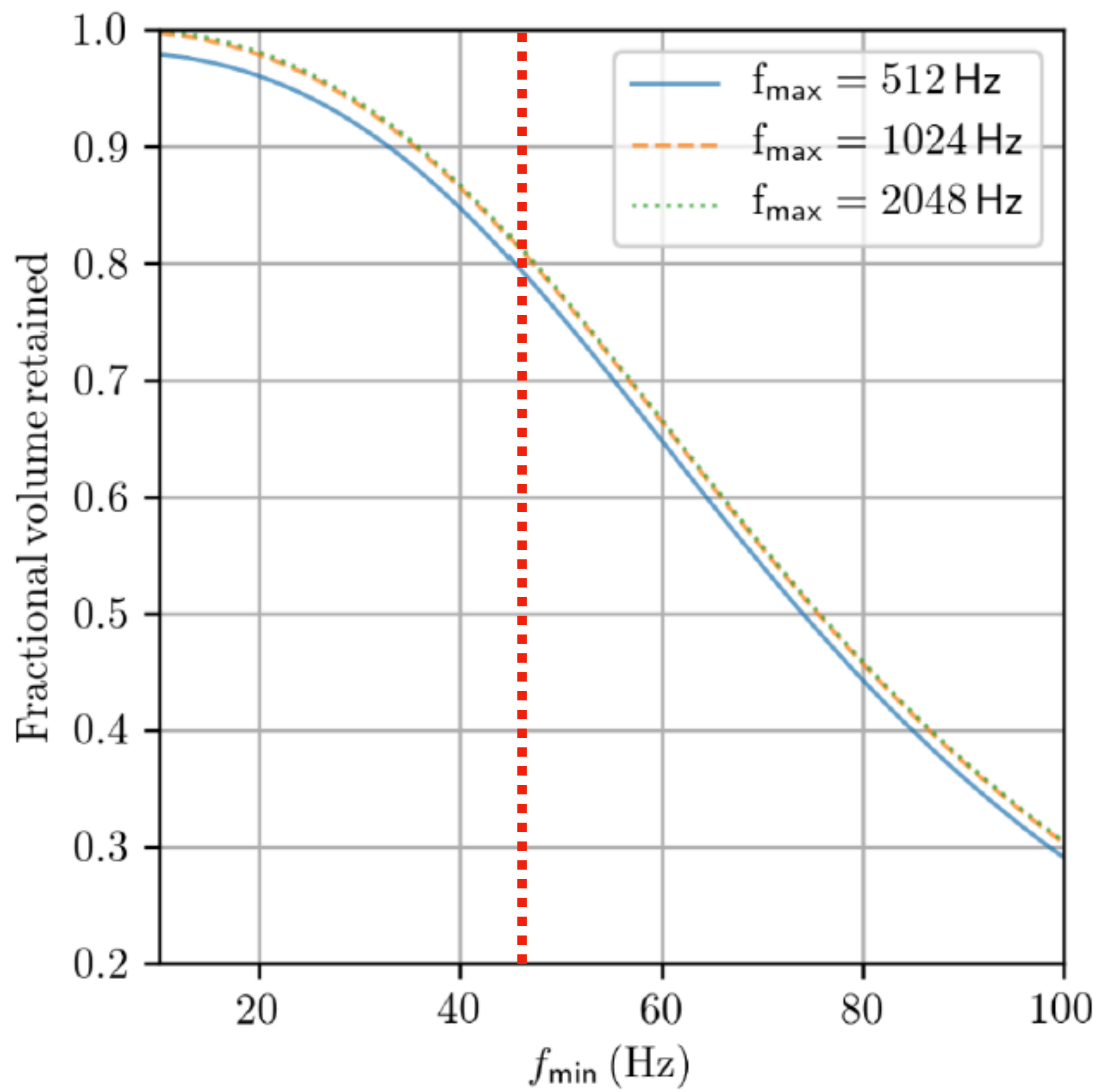
Cutting low frequency helps

Magee et al. PRD 98, 103024 (2018)

Number of template: $N \propto m_{\min}^{-8/3} f_{\min}^{-8/3}$

→ Increasing f_{min} helps to reduce computation time, but it reduces the SNR

Volume ∝ SNR^3

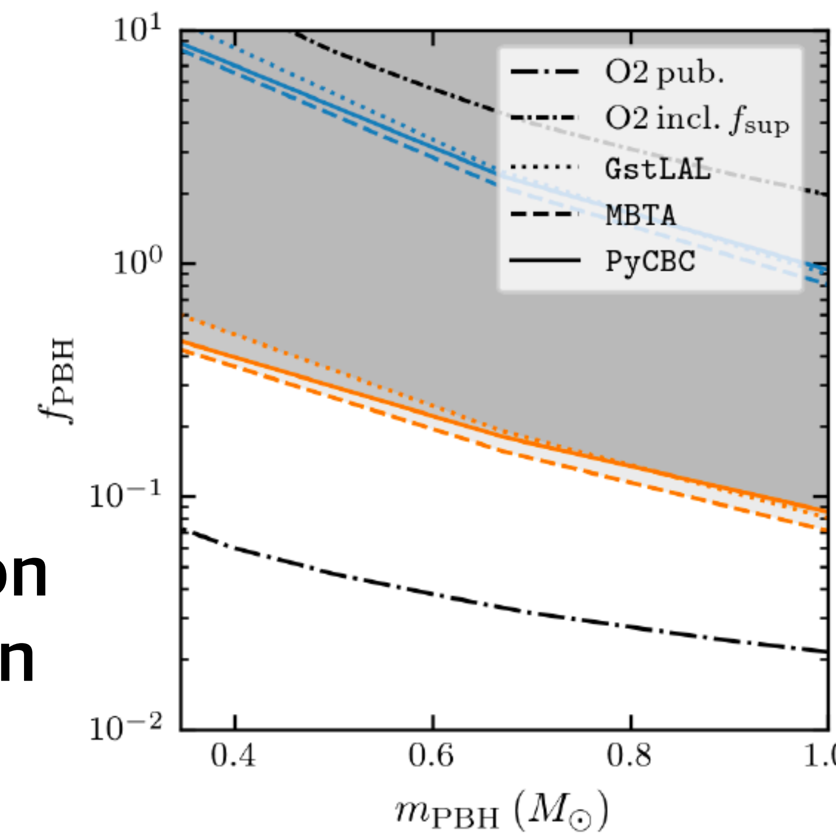


← f_{min} = 45Hz is commonly used in LVK search, allowing 20% loss in volume

Sub-solar mass search with LVK O3b

arXiv:2212.01477, "Search for subsolar-mass black hole binaries in the second part of Advanced LIGO's and Advanced Virgo's third observing run"

- ✔ low frequency cut off: $f_{\rm min} = 45{\rm Hz}$
- ✔ search range: $m_1 \in [0.2,\ 10\ ]\ M_\odot$
  $m_2 \in [0.2,\ 1.0\ ]\ M_\odot$
  $0.1 < q < 1.0 \qquad q \equiv m_2/m_1$
  $\chi_{1,2} < 0.9$
- ✔ No significant event was found → **Constraint on PBH fraction**



Triggers with FAR < 2 yr^{-1}

FAR $[{\rm yr}^{-1}]$	Pipeline	GPS time	$m_1\ [M_\odot]$	$m_2\ [M_\odot]$	χ_1	χ_2	H SNR	L SNR	V SNR	Network SNR
0.20	GstLAL	1267725971.02	0.78	0.23	0.57	0.02	6.31	6.28	-	8.90
1.37	MBTA	1259157749.53	0.40	0.24	0.10	−0.05	6.57	5.31	5.81	10.25
1.56	GstLAL	1264750045.02	1.52	0.37	0.49	0.10	6.74	6.10	-	9.10

FAR = 0.2 yr^{-1} → **p value = 6%**

The probability of observing a result as extreme as this event, assuming the null hypothesis (no signal in data) is true

$$p = 1 - e^{-{\rm FAR}\cdot T_{\rm obs}}$$

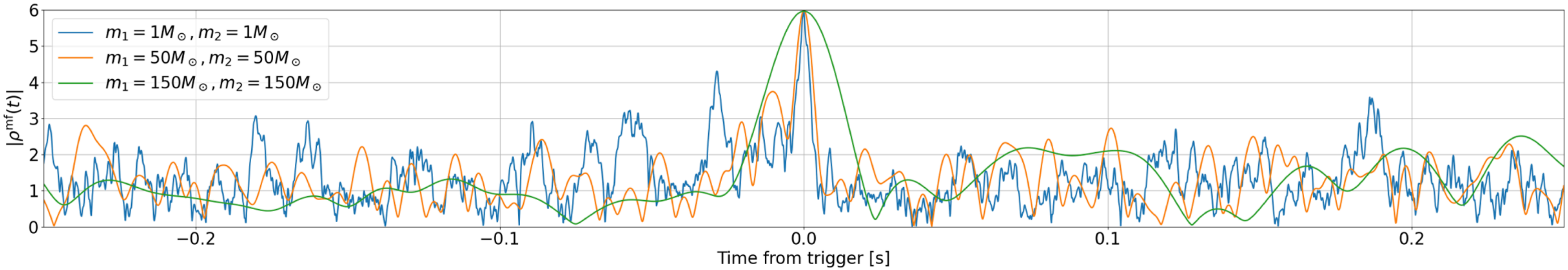
Challenge in sub-solar mass search

✔ We would require much more high significance to claim the first detection

cf. GW150914:

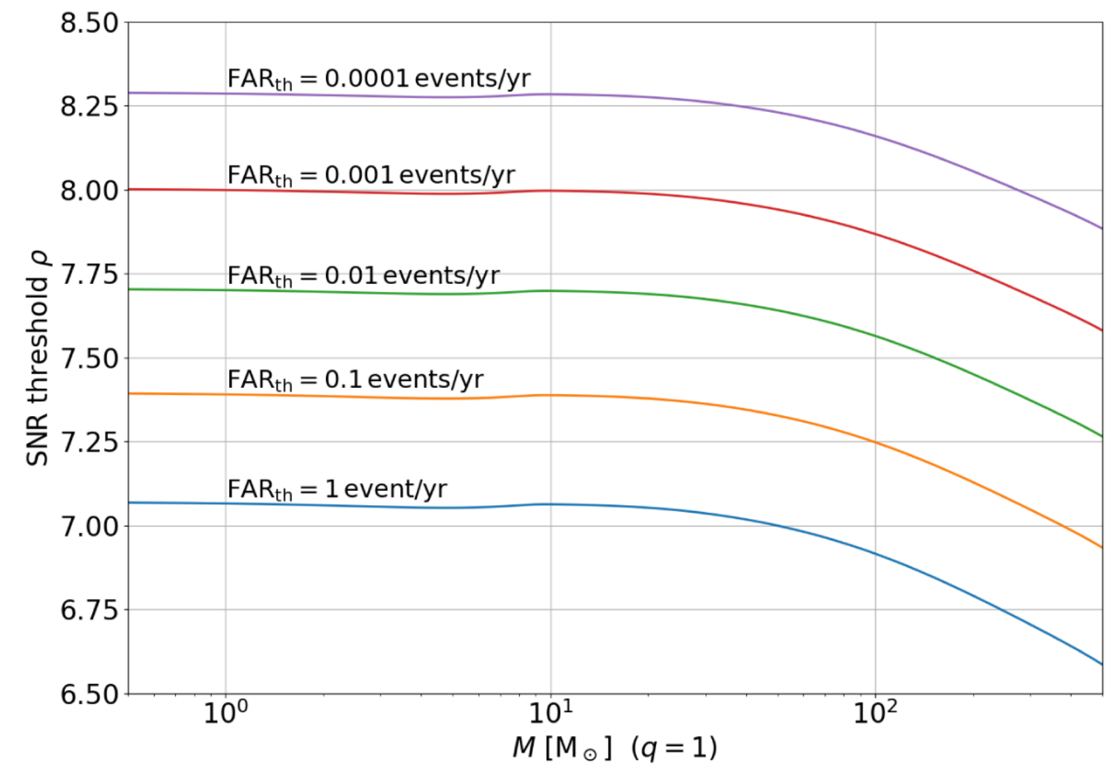
FAR = 5 × 10^{-6} yr^{-1} → False alarm probability = 2 ×10^{-7} %

✔ High-frequency sub-solar-mass signals show weaker time-series correlation, making them **easier to mimic with non-Gaussian noise**.



Even with Gaussian noise,
the same SNR leads to a higher
FAR for smaller mass binaries →

Morras et al. 107, 023027 (2023)



Continuous wave search

Planetary-mass search with LVK O3b

arXiv:2511.19911, "Search for planetary-mass ultra-compact binaries using data from the first part of the LIGO–Virgo–KAGRA fourth observing run"

✔ Inspiral phase has very slow evolution of frequency

$$\dot{f}_{\rm GW} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f_{\rm GW}^{11/3} \equiv k f_{\rm GW}^{11/3}$$

$$\simeq 1.25 \times 10^{-4}\ {\rm Hz/s}\left(\frac{\mathcal{M}}{10^{-3}\,M_\odot}\right)^{5/3}\left(\frac{f_{\rm GW}}{100\ {\rm Hz}}\right)^{11/3}$$

✔ and simple frequency evolution at the leading order

$$h_0(t) = \frac{4}{d}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\rm GW}(t)}{c}\right)^{2/3}$$

$$\simeq 2.56 \times 10^{-23}\left(\frac{1\ {\rm kpc}}{d}\right)\left(\frac{\mathcal{M}}{10^{-3}\,M_\odot}\right)^{5/3}\left(\frac{f_{\rm GW}(t)}{100\ {\rm Hz}}\right)^{2/3}$$

→ similar to continuous waves from spinning-up pulsars

Planetary mass search

Generalized frequency-Hough algorithm

Modified version of the one used in CW search

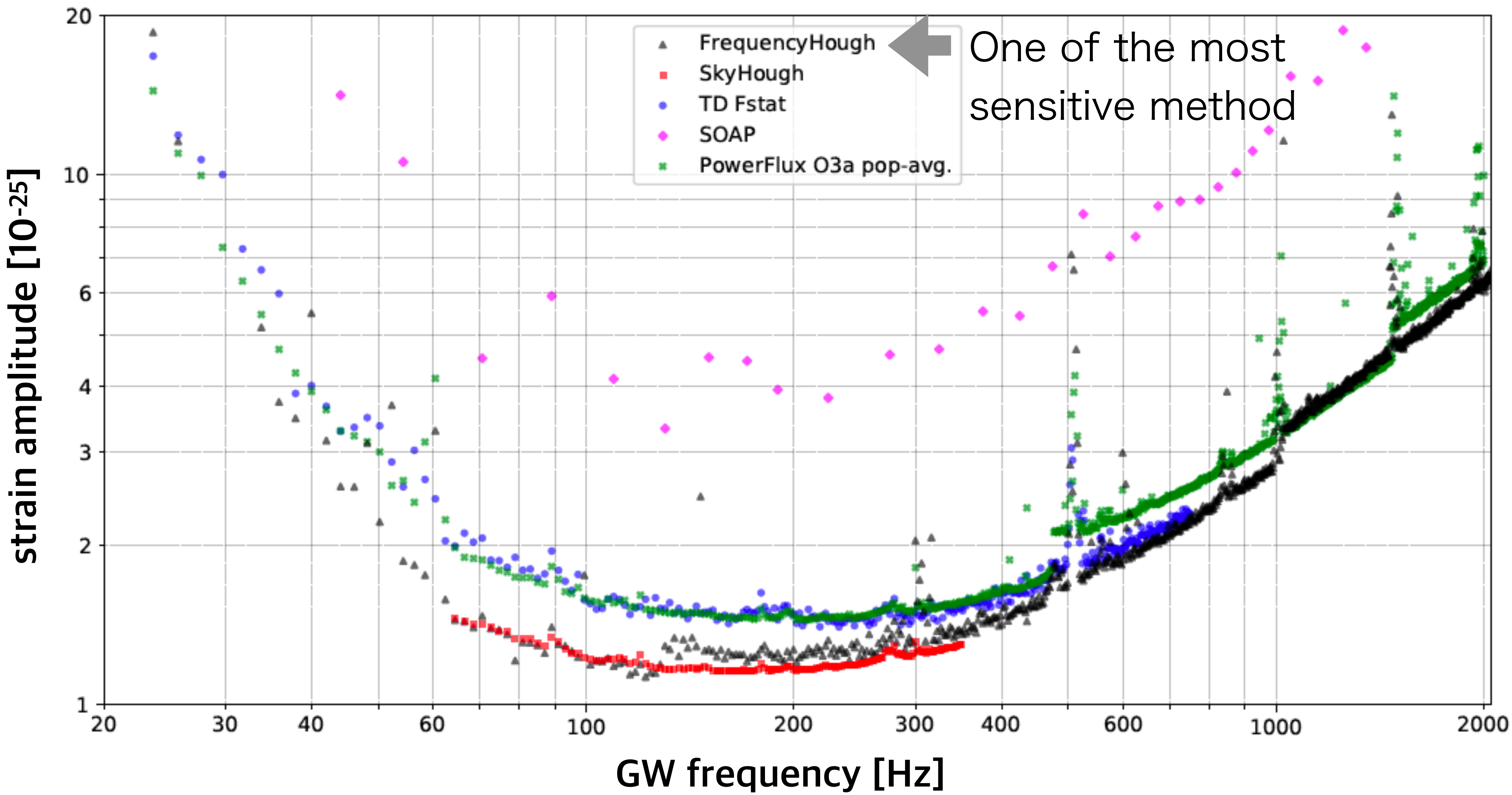


Figure from O3 pulsar constraints: LVK collaboration, PRD 106, 102008 (2022)

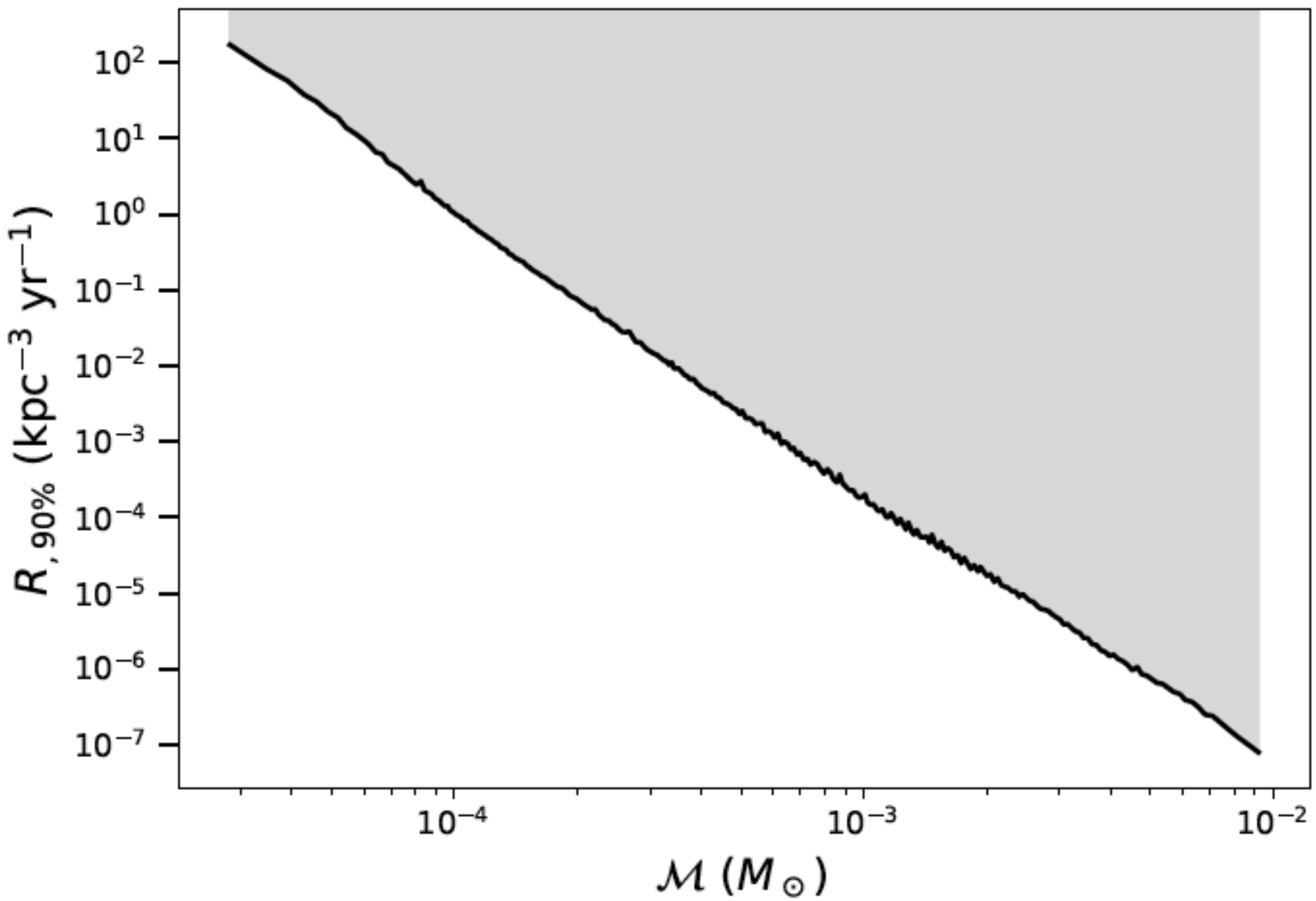
Event rate on equal mass binaries

✔ 5×10^5 candidates were followed up and no significant events were found

Upper bound on the event rate

↓ Chirp time larger than observation time

Event rate



Chirp mass

Considering non-equal mass binaries

Having large m_1 helps to enhance the signal amplitude

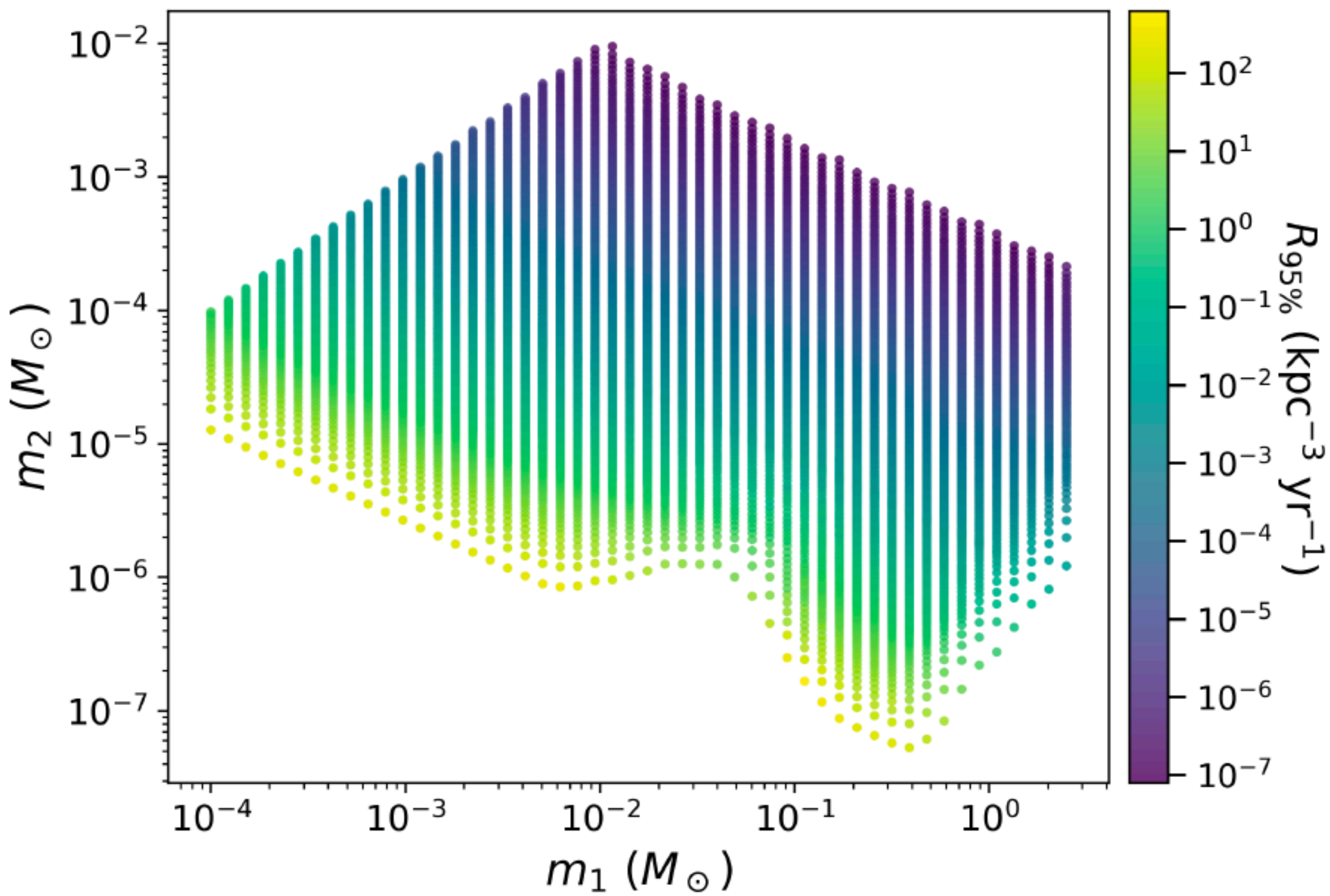
GW amplitude

$$h \propto \frac{\mathcal{M}^{5/3}}{D_L}$$

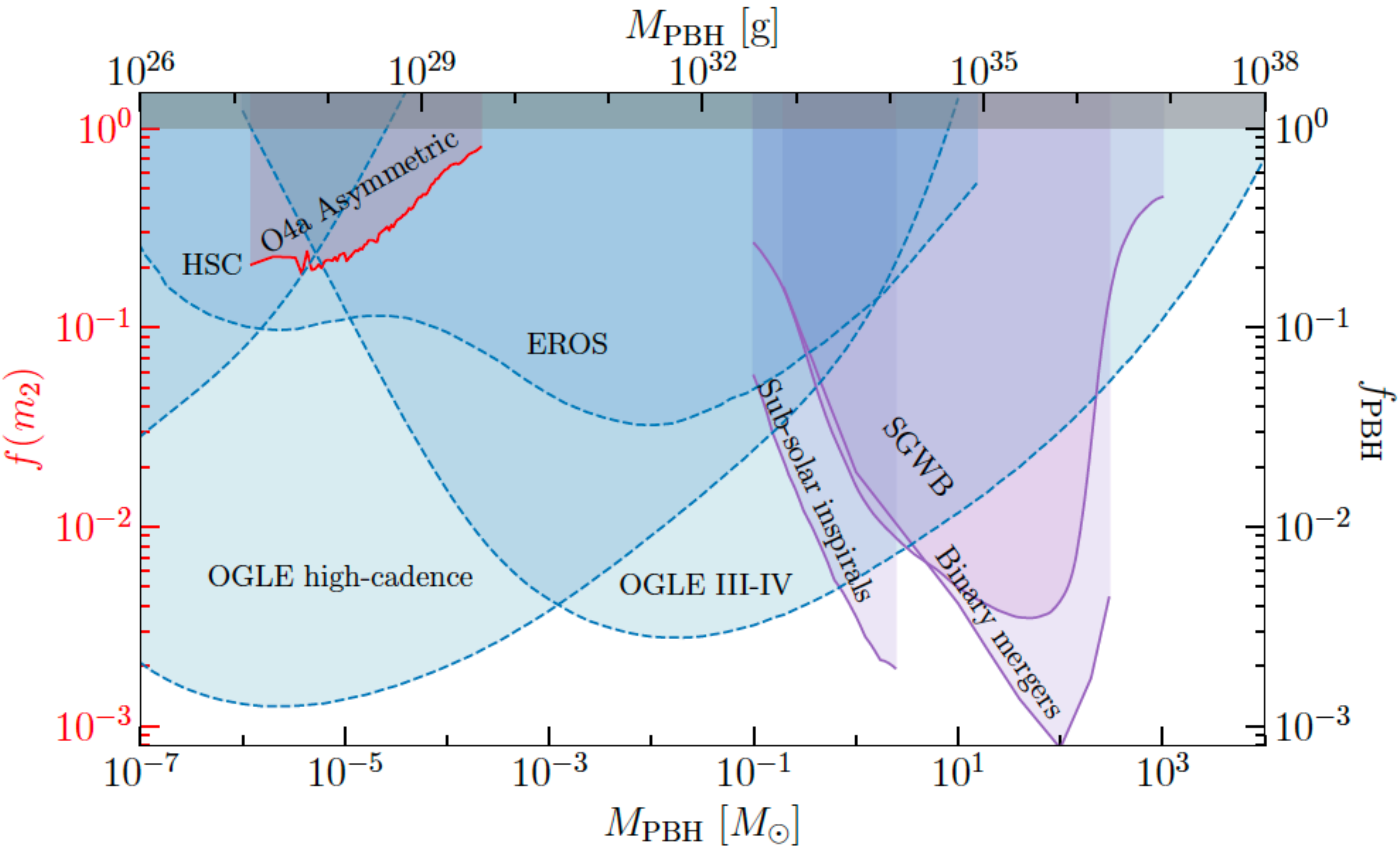
chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

→ better constraints on m_2



Summary of f_{PBH} constraints



Summary

Gravitational wave is a unique probe of primordial black hole scenarios

Stochastic search

Non-detection the stochastic background have provided constraint on scalar-induced GWs as well as superposition of GWs from PBH binaries.

CBC search

Some events fall in the mass-gap region (pair-instability and NS-BH), whose origin remains difficult to account for within standard astrophysical scenarios.

Sub-solar mass search

The paper is forthcoming. Stay tuned.

Continuous wave search

Planetary-mass binary event rates are constrained.