Cosmology2025 @ ICISE

# Constraining primordial black holes using gravitational wave observations

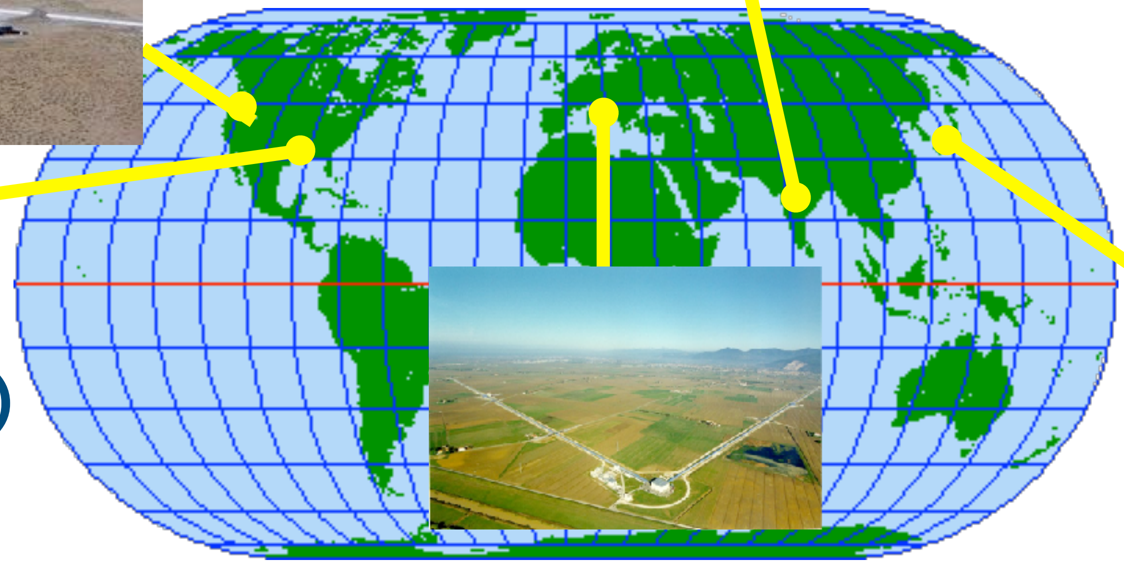

Sachiko Kuroyanagi

IFT UAM-CSIC / Nagoya University

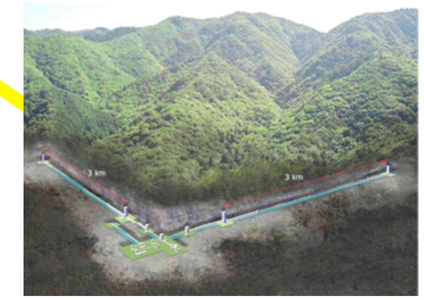

12 Aug 2025

# Gravitational wave (GW) observation

LIGO-India (2027-)



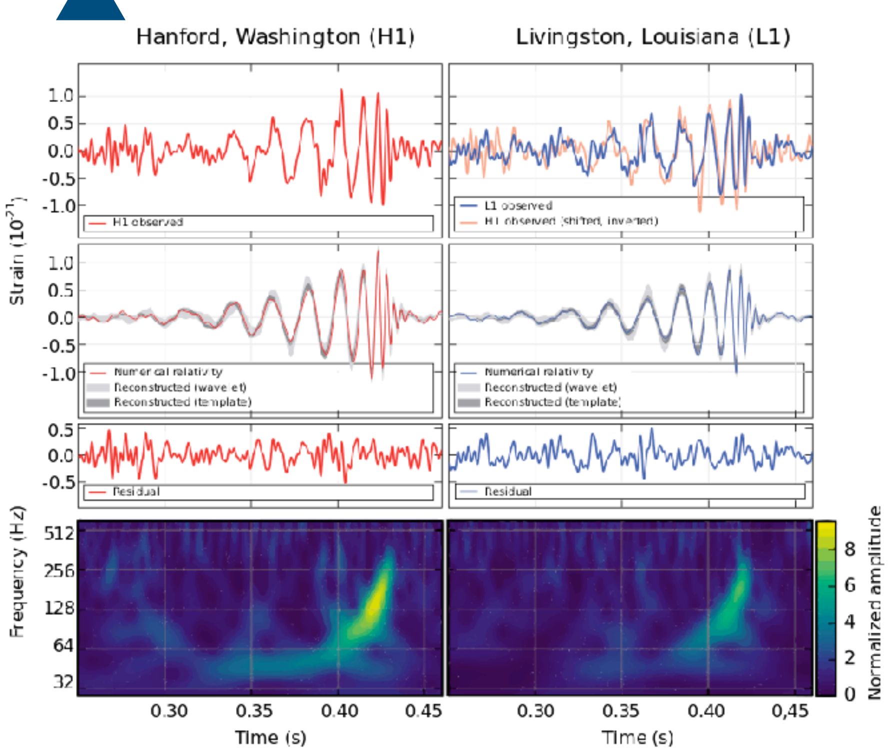
KAGRA (2020-)



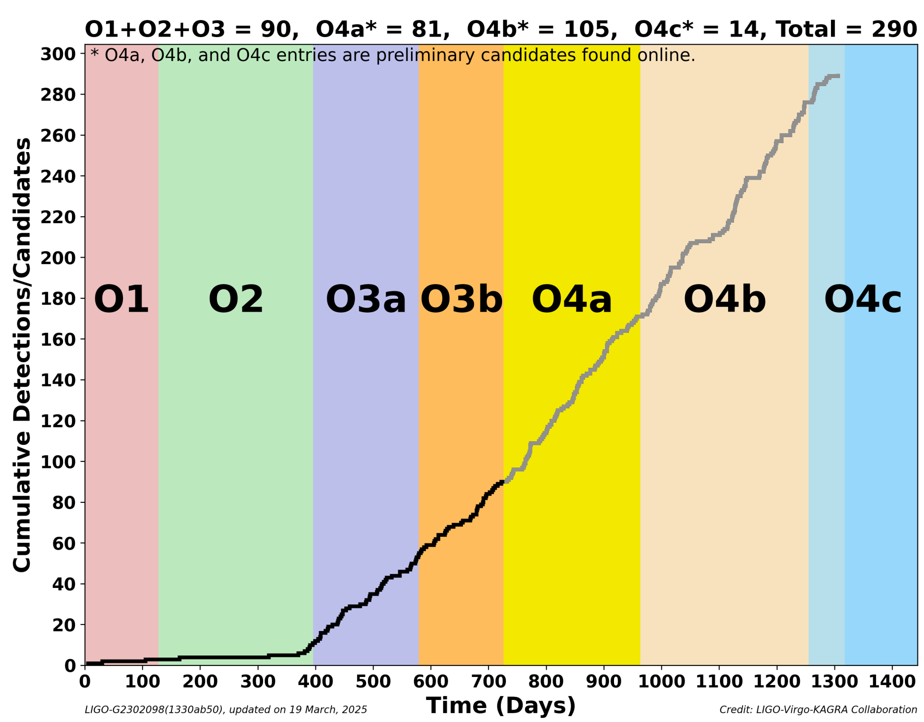
Advanced-LIGO (2015-)

Advanced-VIRGO (2017-)

2015 2020' 2030'



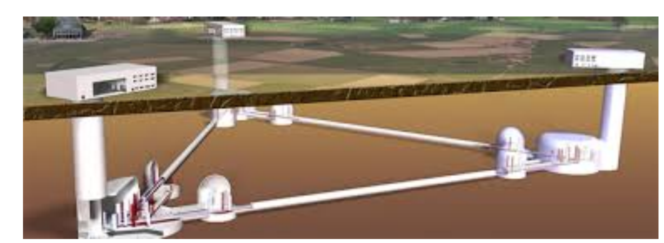

The first detection: GW150914




200th detection in O4 19/03/2025

Future projects

- Einstein Telescope

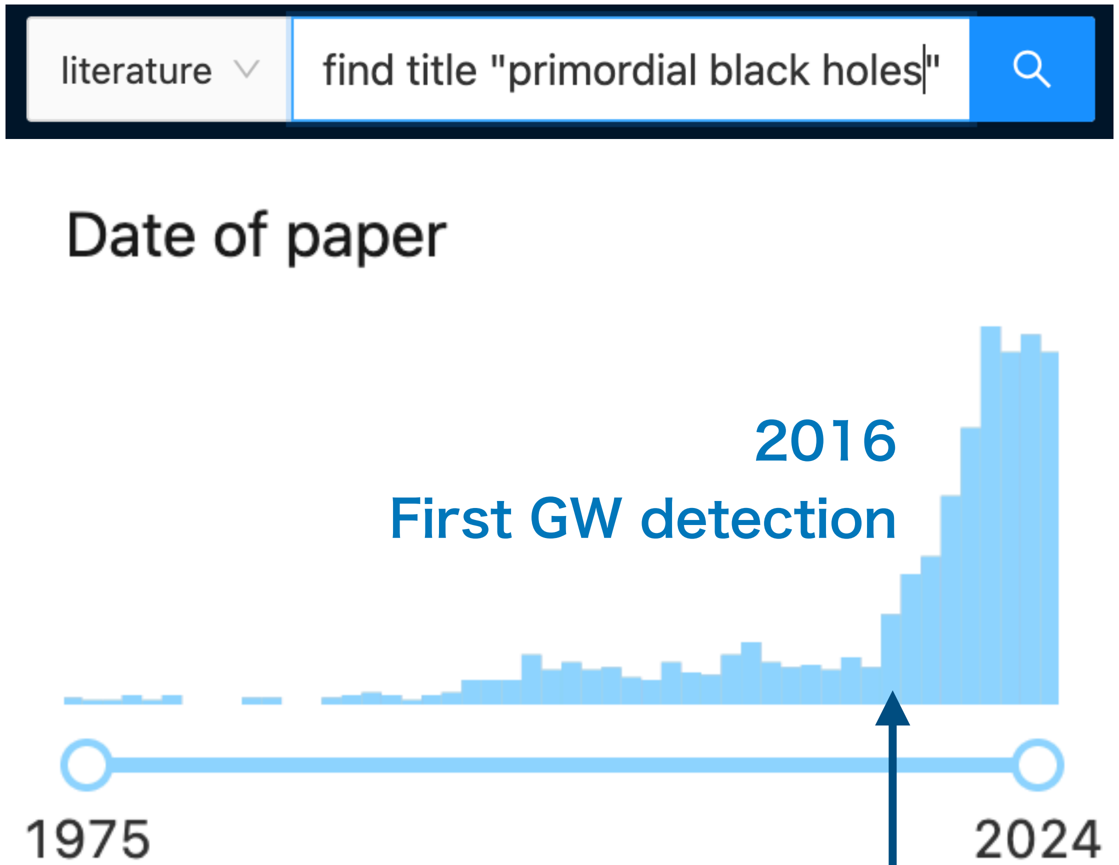


- Cosmic Explorer

etc.

# Primordial Black Holes (PBHs)

= Black holes generated in the early universe




could originate from

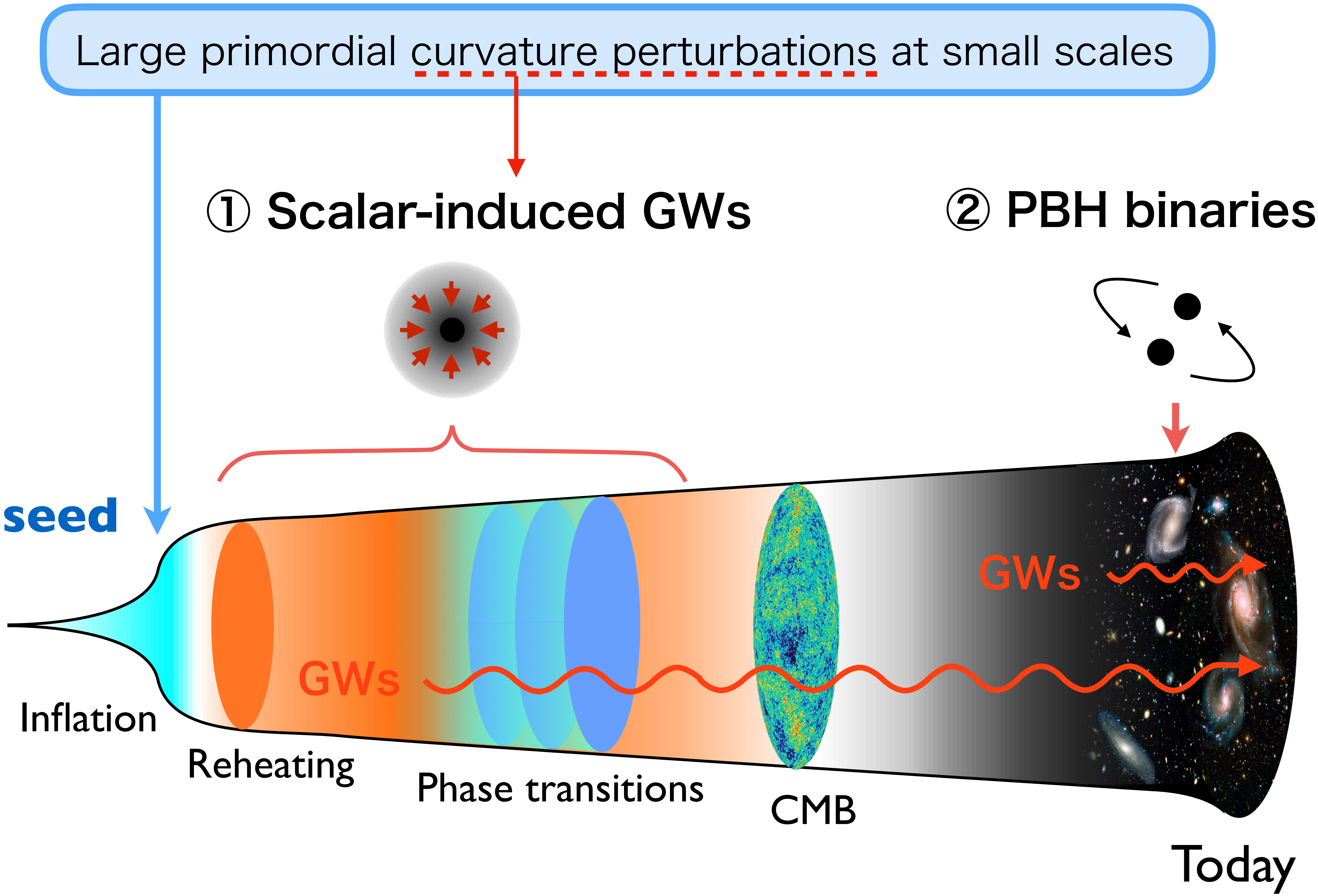
- **Inflation**
- Reheating
- Phase transitions
- Collapse of cosmic strings
- Scalar field instabilities

etc.

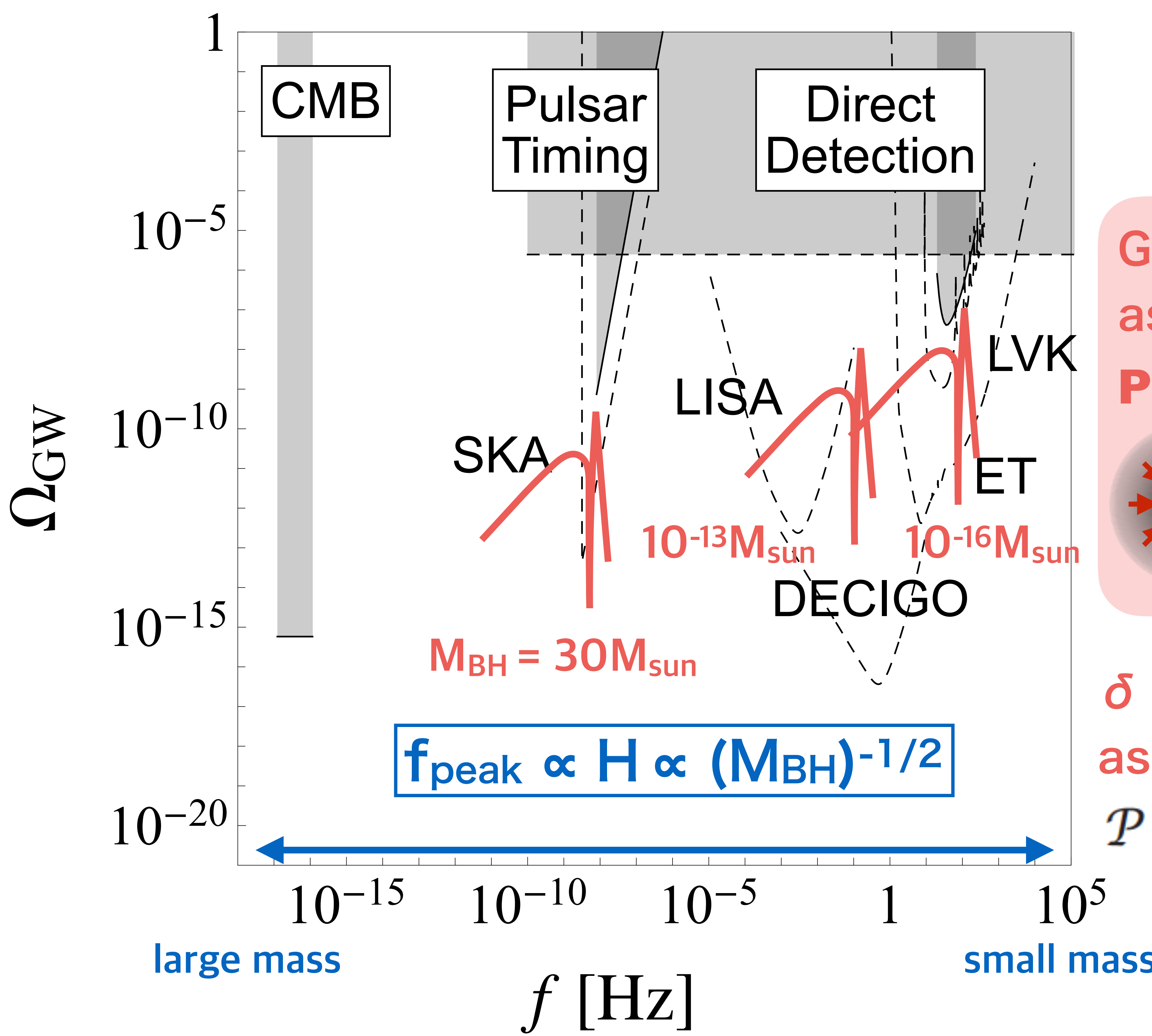
**Origin of the observed 30 $M_\odot$ BBHs could be primordial.**

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

# GWs as a probe of PBHs

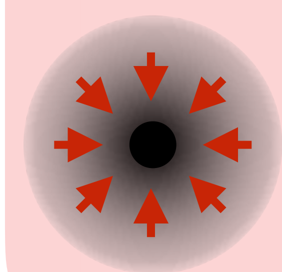


# ① Scalar-induced GWs




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

GWs are generated associated with **PBH formation** in the RD era

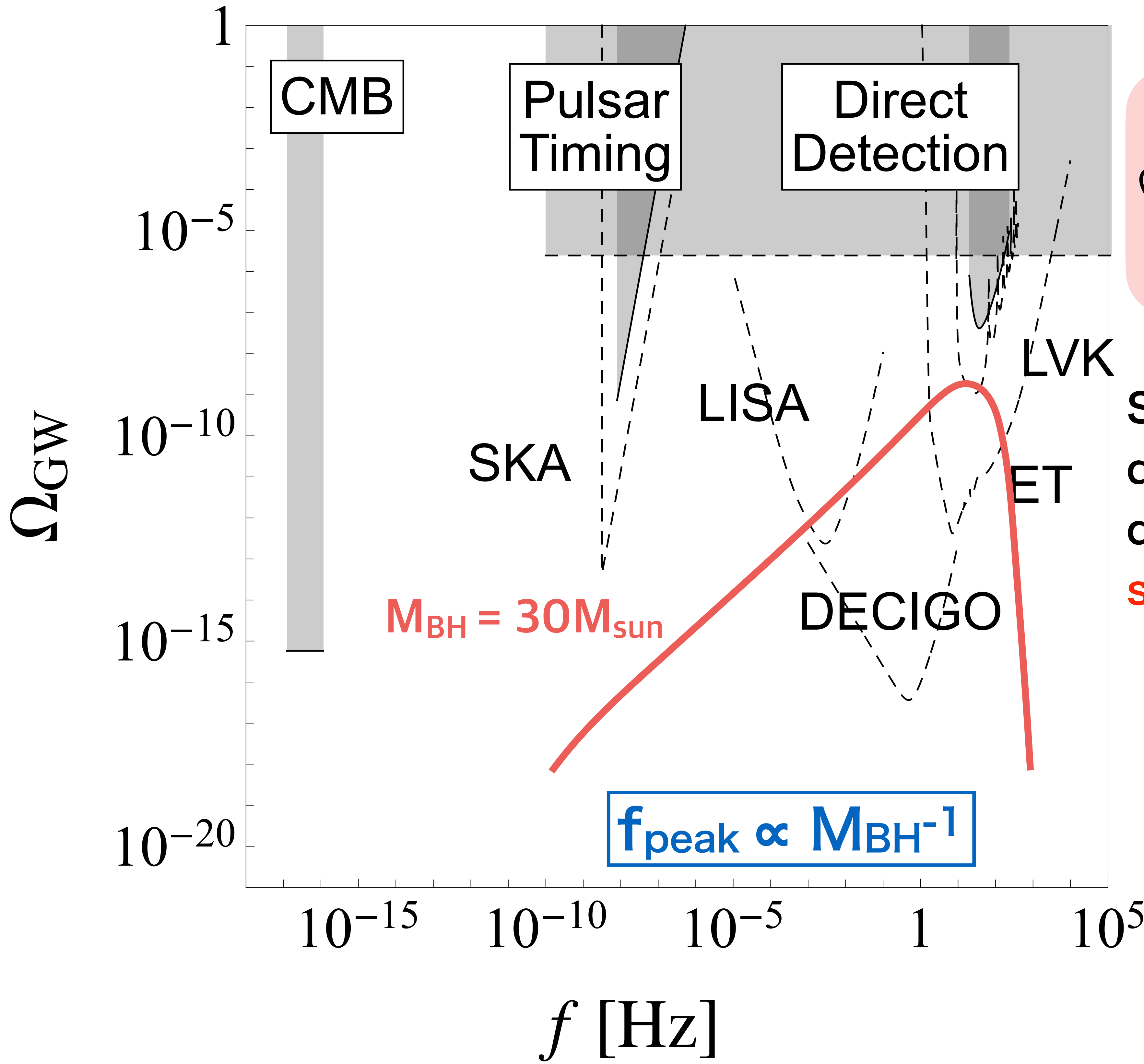


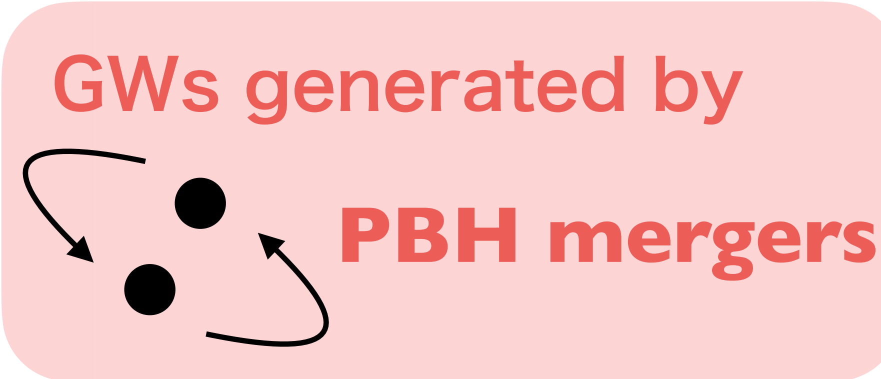
$\delta$ function peak is assumed

$$\mathcal{P}_\Psi(k) = \mathcal{A}^2\delta_D(\ln(k/k_p))$$

R. Saito & J. Yokoyama, PRL 102, 161101 (2009)

# ② GWs from PBH binaries




Superposition of distant events are detectable as a stochastic GW background

S. Clesse & J. García-Bellido, Phys. Dark Univ. 18, 105 (2017)

# 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**

**Chirp time (at Newtonian order)**

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

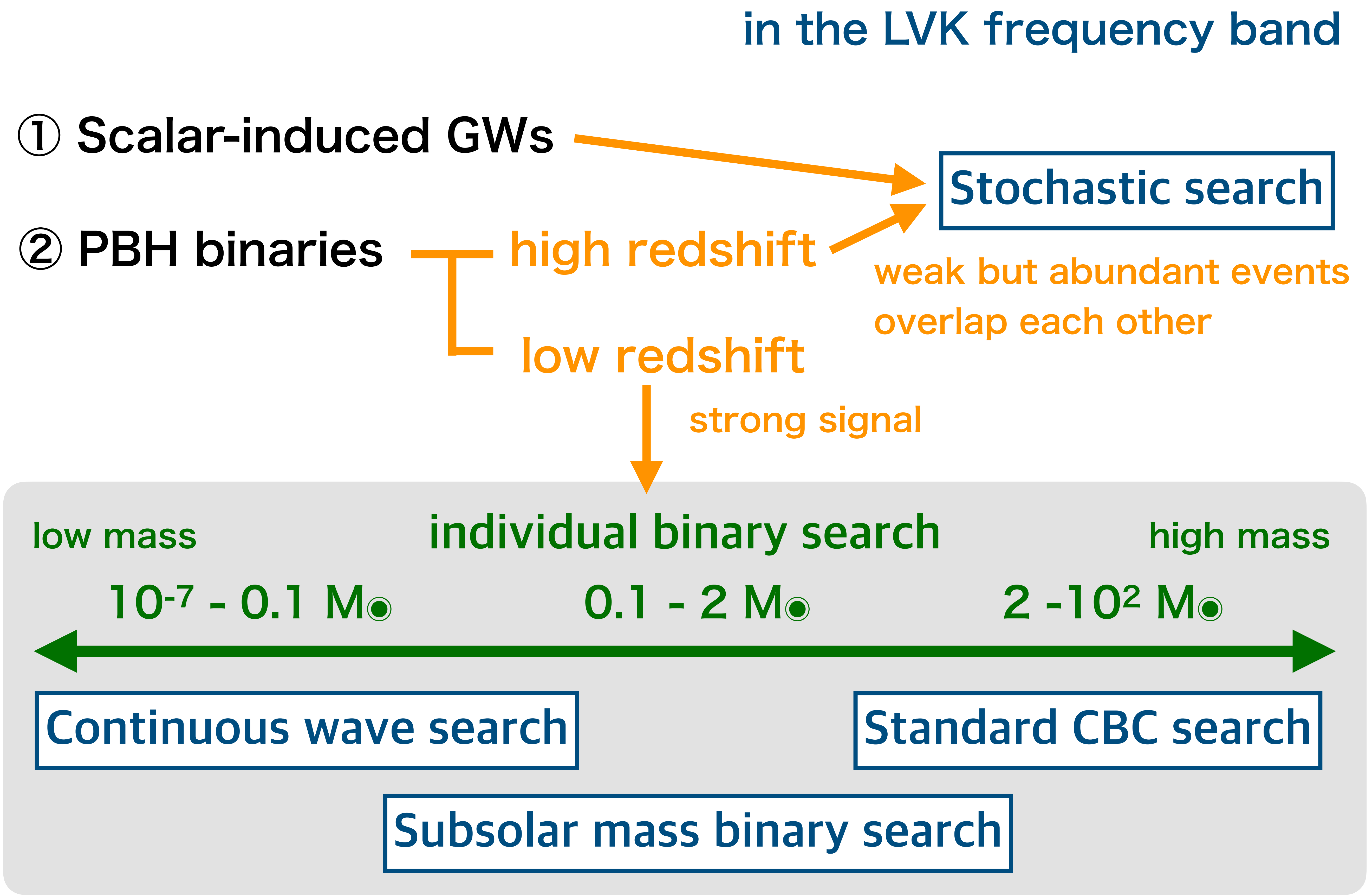
Total mass: $M = m_1 + m_2$

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

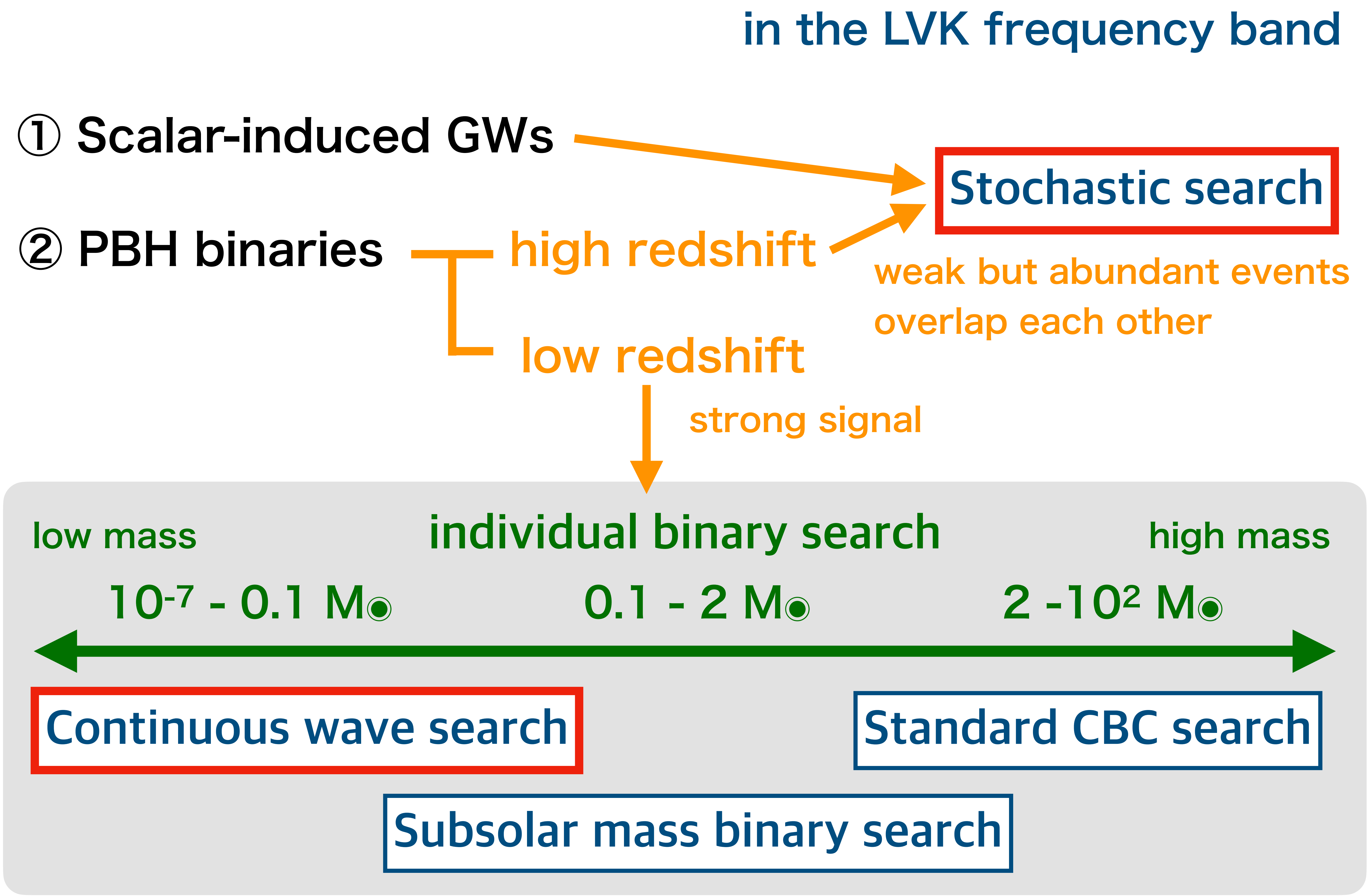
Lowest frequency: $f_0$

smaller mass → longer duration of the signal

# Various ways to search PBHs



# Various ways to search PBHs



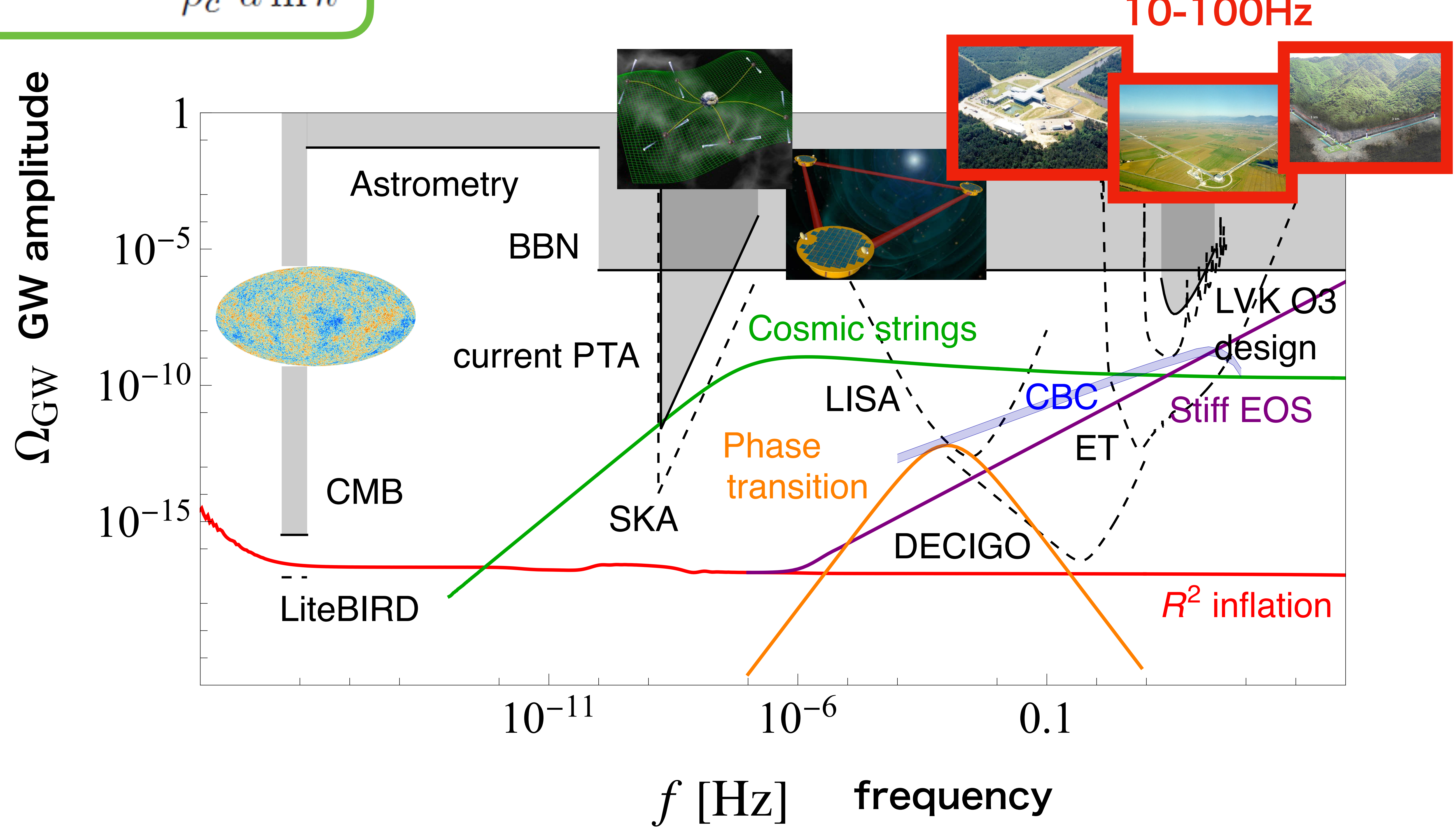
# Stochastic GW background search

# GW background as a probe of the early universe

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

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

$\rho_c$: Critical density of the Universe



# Upper bounds on stochastic background

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

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

$\rho_c$ : Critical density of the Universe

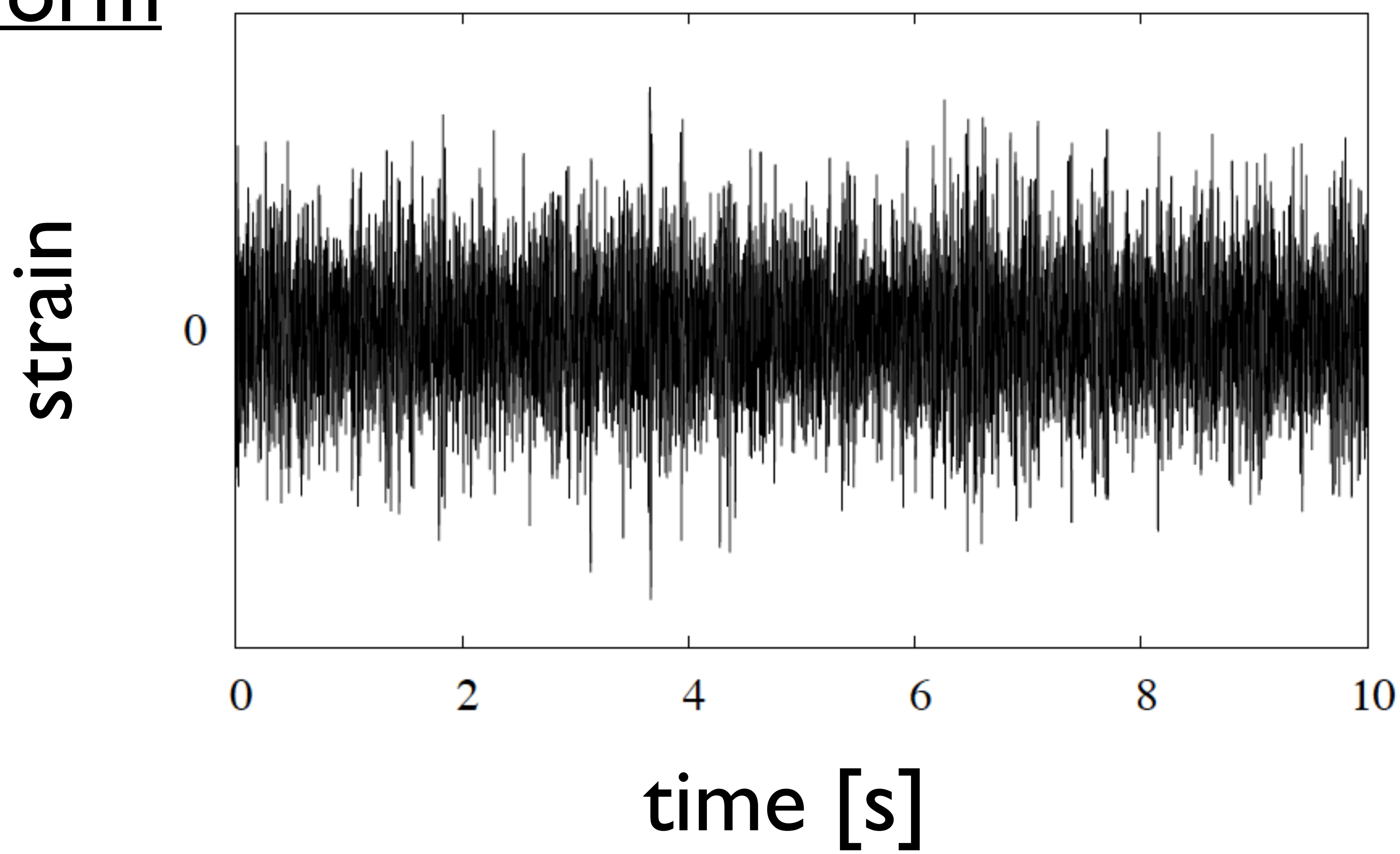
BBN + CMB bound:
$\Omega_{\rm GW} < 2.7 \times 10^{-6}$

| **Observation run** | **Year** | **95% Upper bound** (for a flat spectrum) |
|---|---|---|
| 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 | $\Omega_{\rm GW} <$ ??? |

→ becoming a competitive tool to constrain early universe models

# How to detect a stochastic background

Waveform




Continuous and random gravitational wave (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

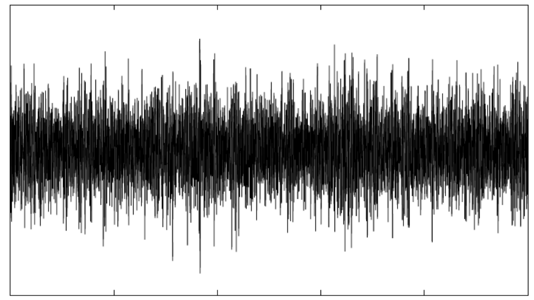
$$= \int_{-T/2}^{T/2} dt \, \underline{\langle h^2(t) \rangle}$$

GW signal

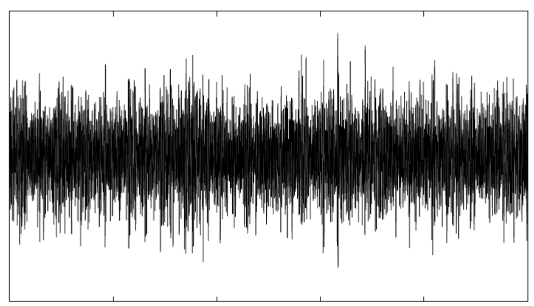
(for detectors at the same location)

# What we do in the LVK stochastic search

Renzini et al., ApJ 952, 25 (2023)



strain data 1



strain data 2

strain data in discrete Fourier space

$$\tilde{s}_f \equiv \sum_{t_k=0}^{T-\delta t} s(t_k)\, e^{-i2\pi m t_k/T}$$

for every T = 192 s

cross-correlated spectrum

$$C_{IJ,f} = \frac{2}{T} \tilde{s}^*_{I,f} \tilde{s}_{J,f}$$

IJ: detector combinations

estimator

$$\hat{\Omega}_{\mathrm{GW},f} = \frac{\mathrm{Re}[C_{IJ,f}]}{\gamma_{IJ}(f) S_0(f)}$$

overlap reduction function

takes into account

the detector's locations and orientations

$$S_0(f) = \frac{3H_0^2}{10\pi^2} \frac{1}{f^3}$$

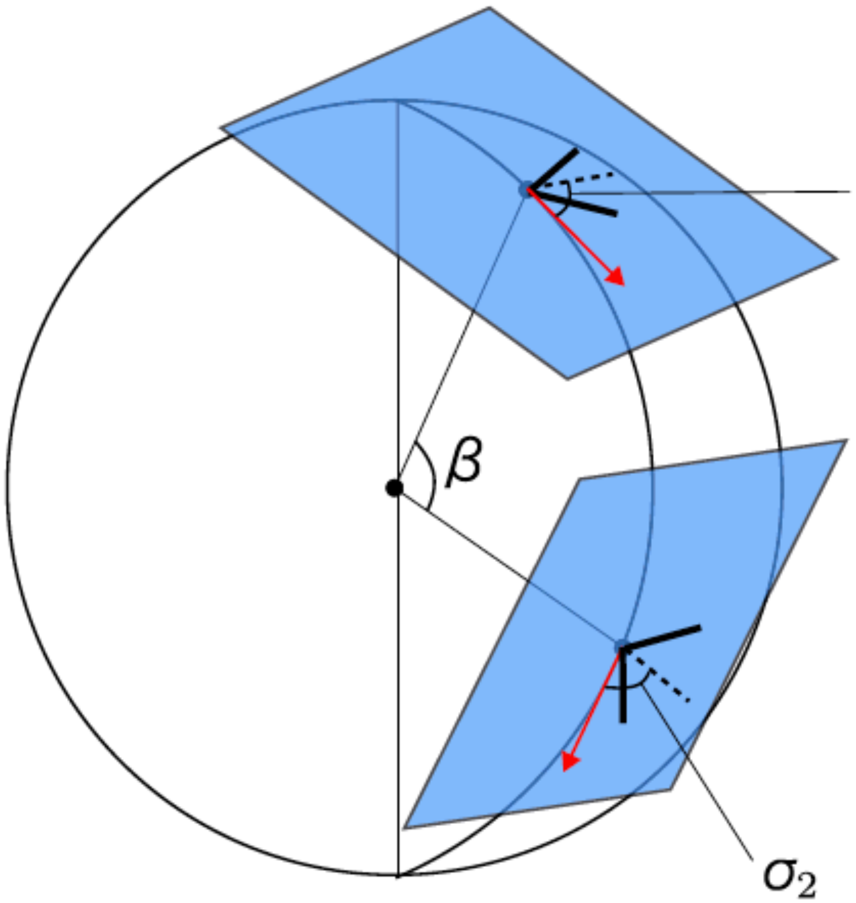
c.f. $g_{ab} = \eta_{ab} + h_{ab}$

$$\langle h_{ab}(t) h^{ab}(t) \rangle = 2 \int_{-\infty}^{\infty} \mathrm{d}f\, S_h(f)$$

$$\Omega_{\mathrm{gw}}(f) = (4\pi^2/3H_0^2) f^3 S_h(f)$$

# Overlap reduction function

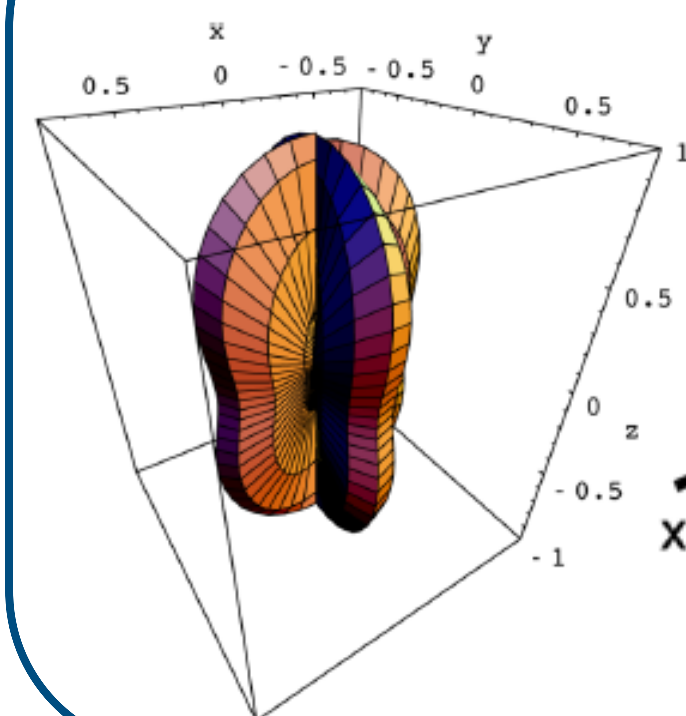
Detectors are located at different site and facing different direction



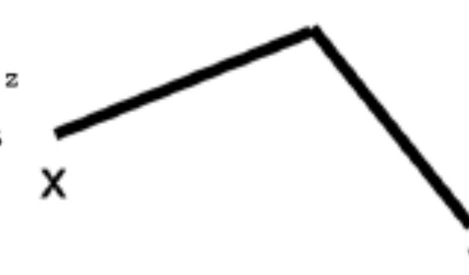

① Time difference

② Antenna pattern

+ mode




detector arms




× mode

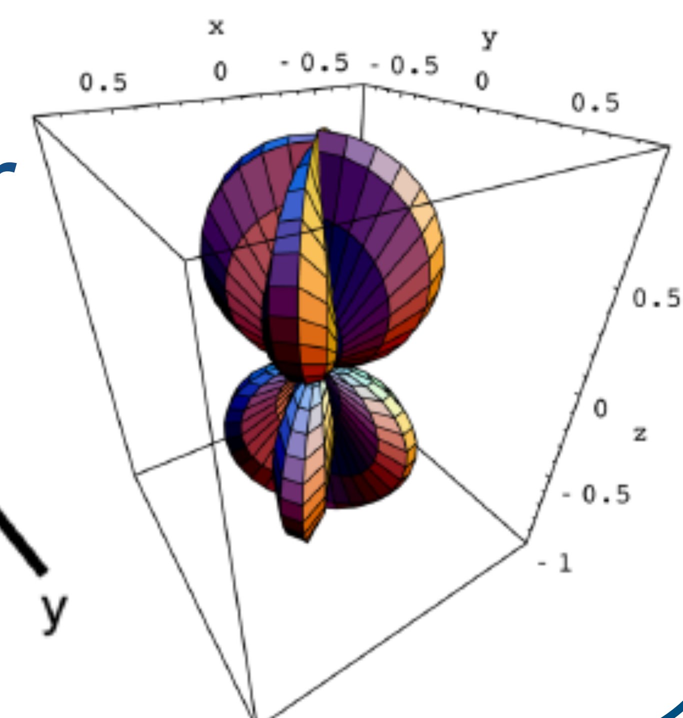



Figure from A. Nishizawa et al. PRD 79, 082002 (2009)

# Overlap reduction function

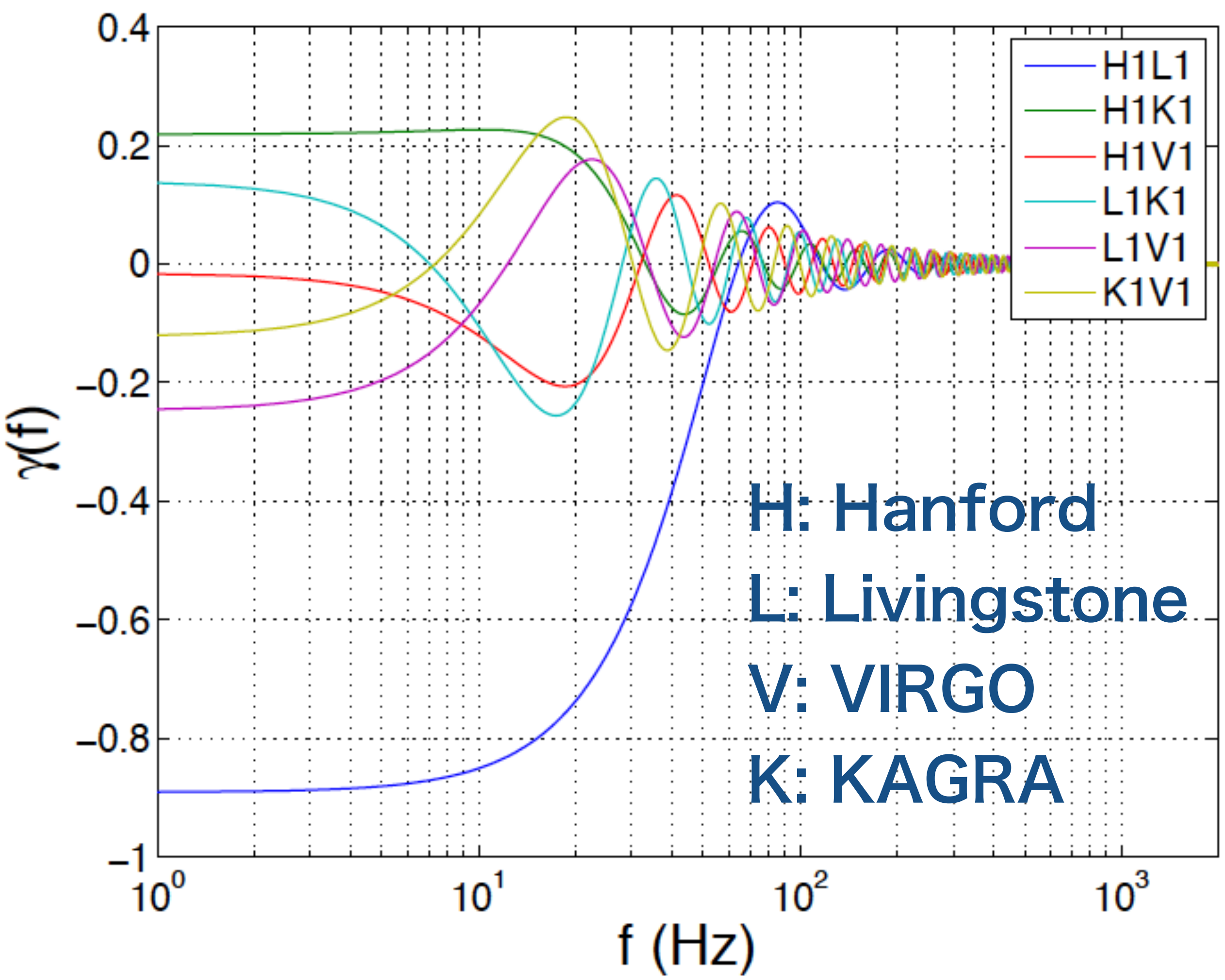
For a stochastic GW background, we construct

$$\gamma_{IJ}^{T}(f) \equiv \frac{5}{2}\int_{S^2}\frac{d\hat{\Omega}}{4\pi}e^{2\pi i f\hat{\Omega}\cdot\Delta\vec{X}/c}(F_I^{+}F_J^{+} + F_I^{\times}F_J^{\times})$$

integration over the whole sky

① Time difference ② Antenna pattern

I and J denote different detectors




→ represents reduction in sensitivity due to the separation/orientation of the detectors

Figure from E. Thrane & J. D. Romano, PRD 88, 124032 (2013)

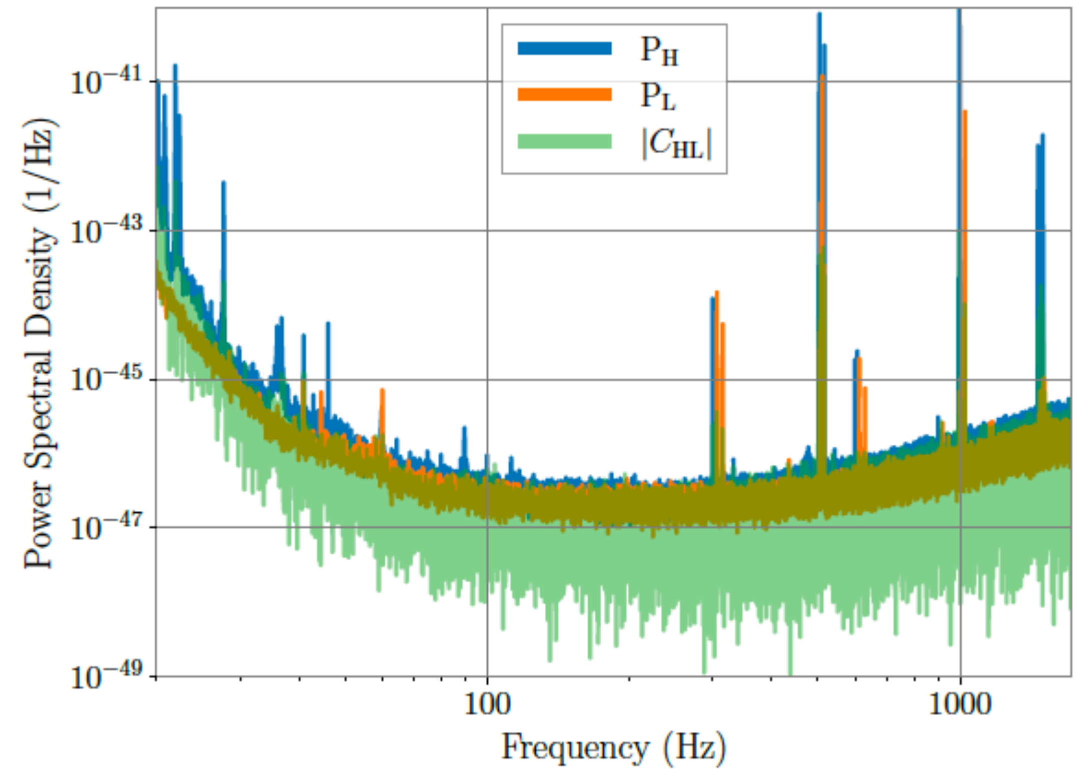
# Variance: level of noise

**strain data in discrete Fourier space**

signal ↓ noise ↓

$$\tilde{s}_{I,f} = F_I \tilde{h}_f + \tilde{n}_{I,f}$$

↑ antenna pattern for + and x → gives $\gamma_{IJ}(f)$




**cross-correlation**

$$C_{IJ,f} = \frac{2}{T} \tilde{s}^*_{I,f} \tilde{s}_{J,f}$$

→ dominated by $\langle \tilde{h}^2_f \rangle$ signal

**estimator**

$$\hat{\Omega}_{\mathrm{GW},f} = \frac{\mathrm{Re}[C_{IJ,f}]}{\gamma_{IJ}(f) S_0(f)}$$

**auto-correlation**

$$P_{I,f} = \frac{2}{T} |\tilde{s}_{I,f}|^2$$

→ dominated by $\langle \tilde{n}^2_{I,f} \rangle$ noise

**variance**

$$\sigma^2_{IJ,k} = \frac{1}{2T\Delta f} \frac{P_{I,f} P_{J,f}}{\gamma^2_{IJ}(f) S^2_0(f)}$$

→ an indicator of the level of noise

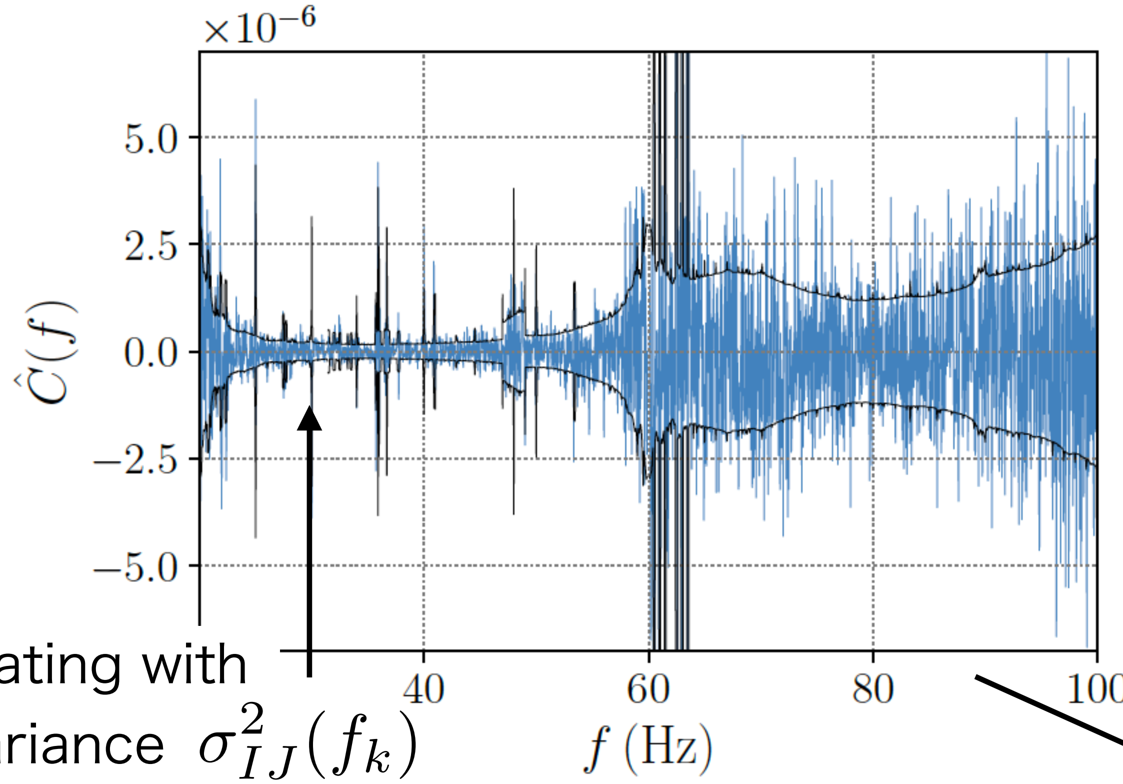
# Likelihood analysis

Renzini et al., ApJ 952, 25 (2023)

pygwb 1.5.1

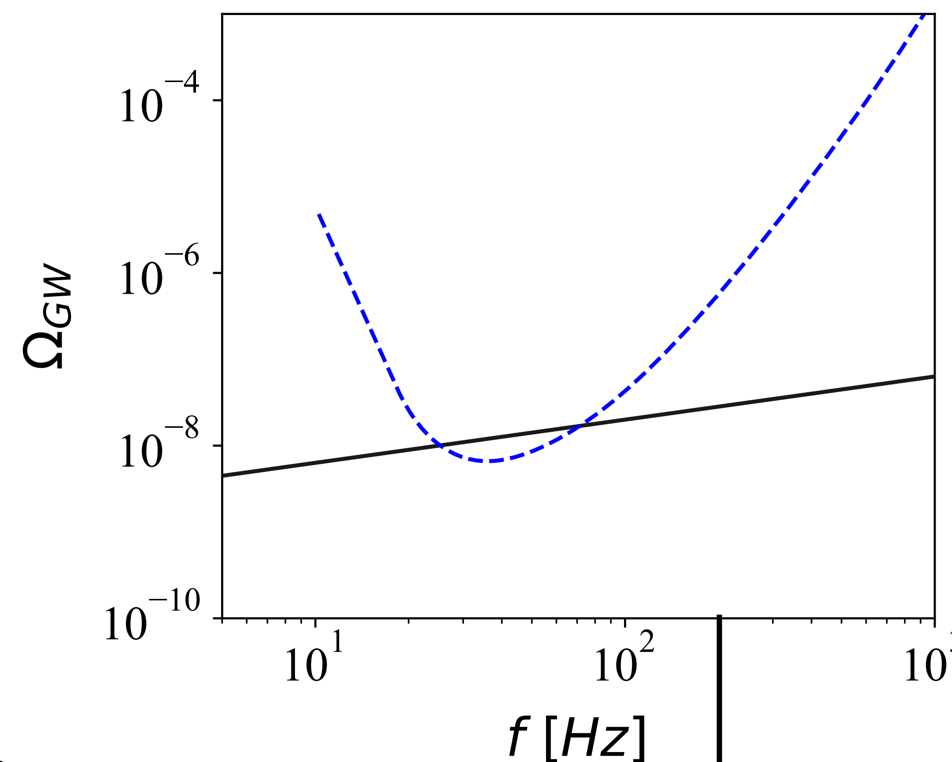
pip install pygwb

**data (cross-correlated spectrum)**




fluctuating with the variance $\sigma^2_{IJ}(f_k)$

**Your model**




**Likelihood**

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

variance

IJ: detector combinations

k: frequencies

Prior

**Posterior distribution**

$$p(\mathbf{\Theta}|C^{IJ}_k) \propto p(C^{IJ}_k|\mathbf{\Theta})p(\mathbf{\Theta})$$

# Likelihood analysis

Posterior distribution $\propto$

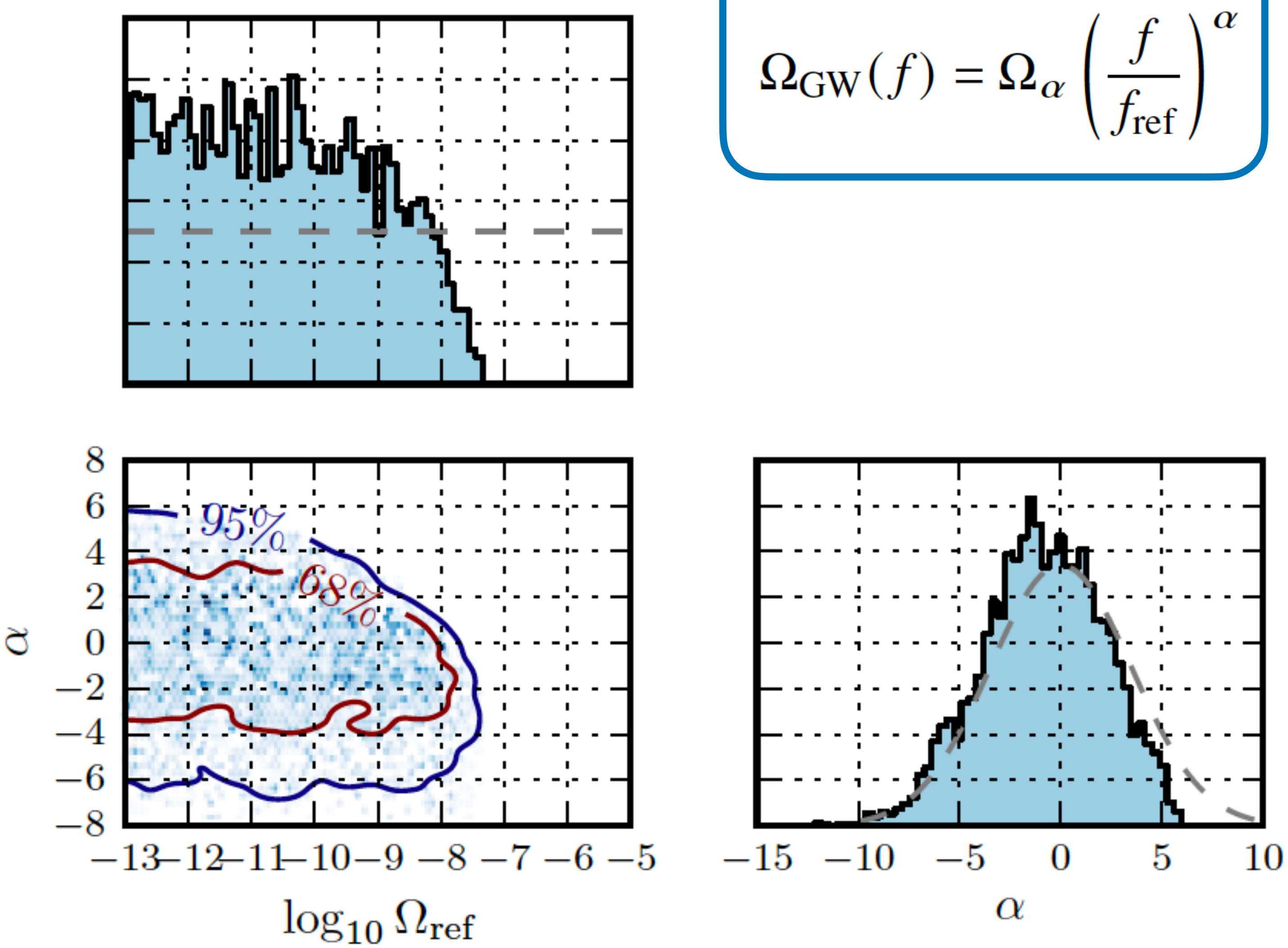
$$p(\hat{C}_k^{IJ}|\boldsymbol{\Theta}) \propto \exp\left[-\frac{1}{2}\sum_{IJ}\sum_{k}\left(\frac{\hat{C}_k^{IJ}-\Omega_{\rm M}(f_k|\boldsymbol{\Theta})}{\sigma_{IJ}^2(f_k)}\right)^2\right]$$

IJ: detector combinations

k: frequencies

(for a flat & infinite-range prior)

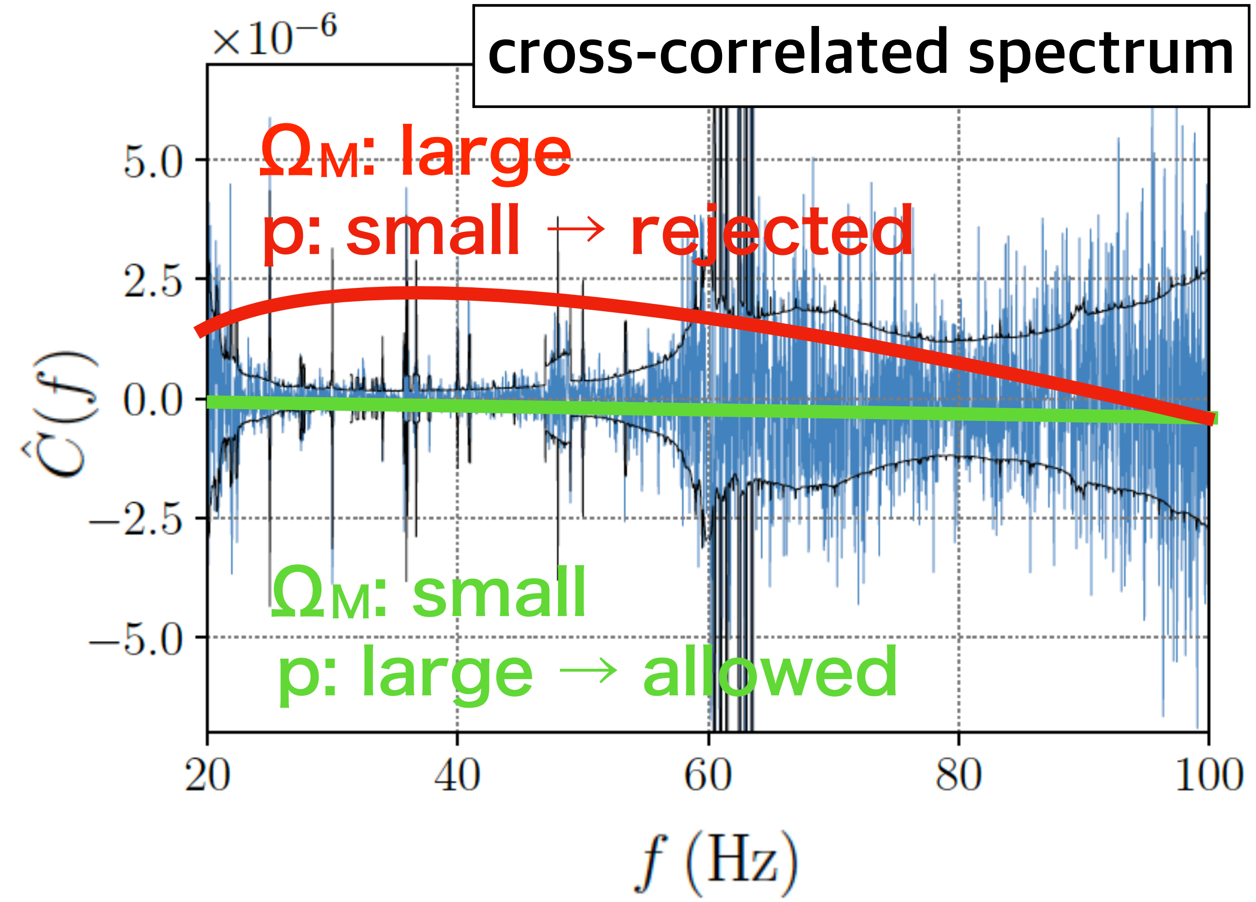
Constraint by O3 data




**Model = power-law**

$$\Omega_{\rm GW}(f) = \Omega_\alpha\left(\frac{f}{f_{\rm ref}}\right)^\alpha$$

cross-correlated spectrum




LVK collaboration, PRD 104, 022004 (2021)

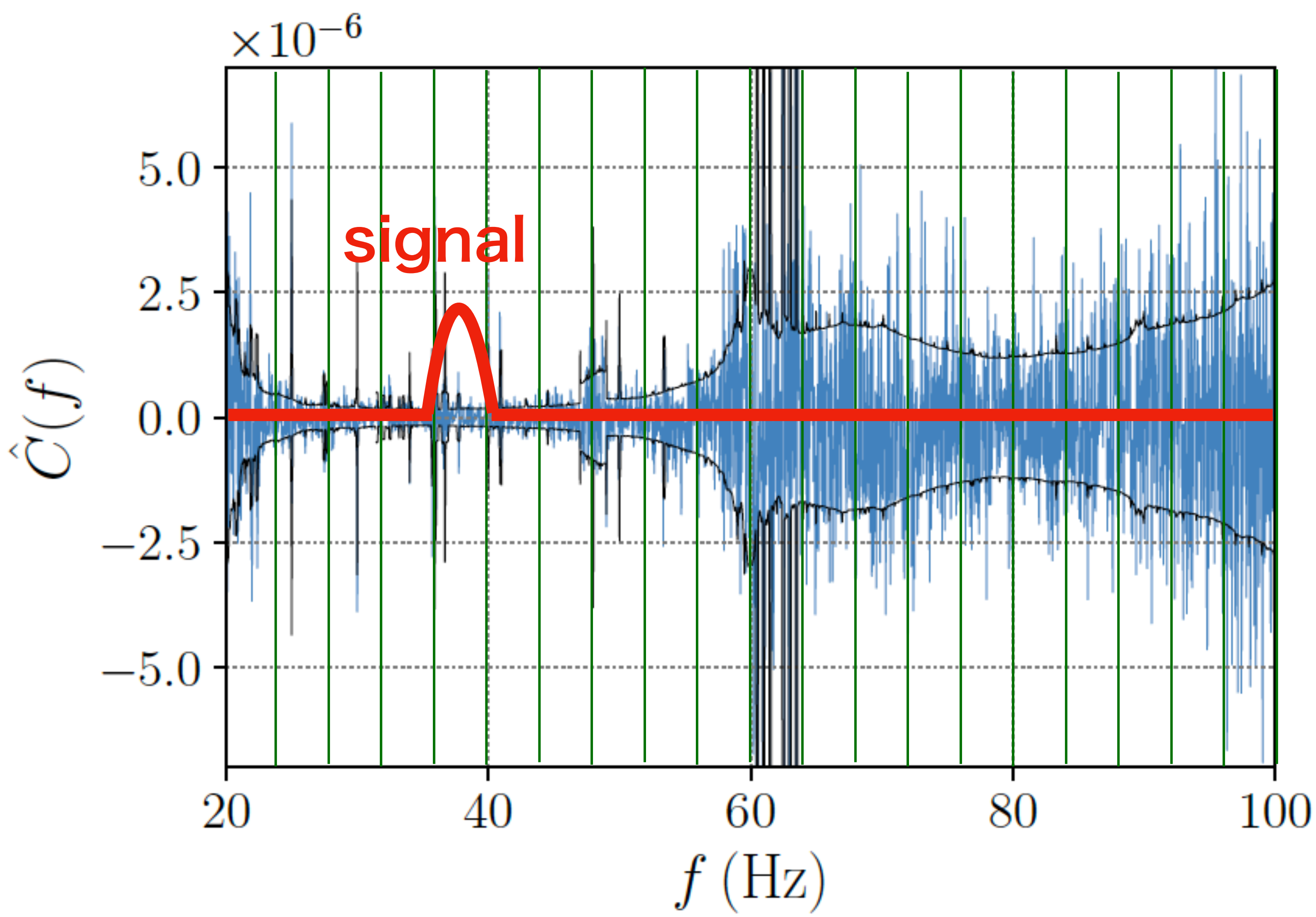
# FAQ: Can we detect features in GW background?

Likelihood

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

f: frequencies

→ Yes, features can be detected if the signal has high enough SNR (>> 1) in the corresponding frequency bin.




narrower bin
→ fine feature

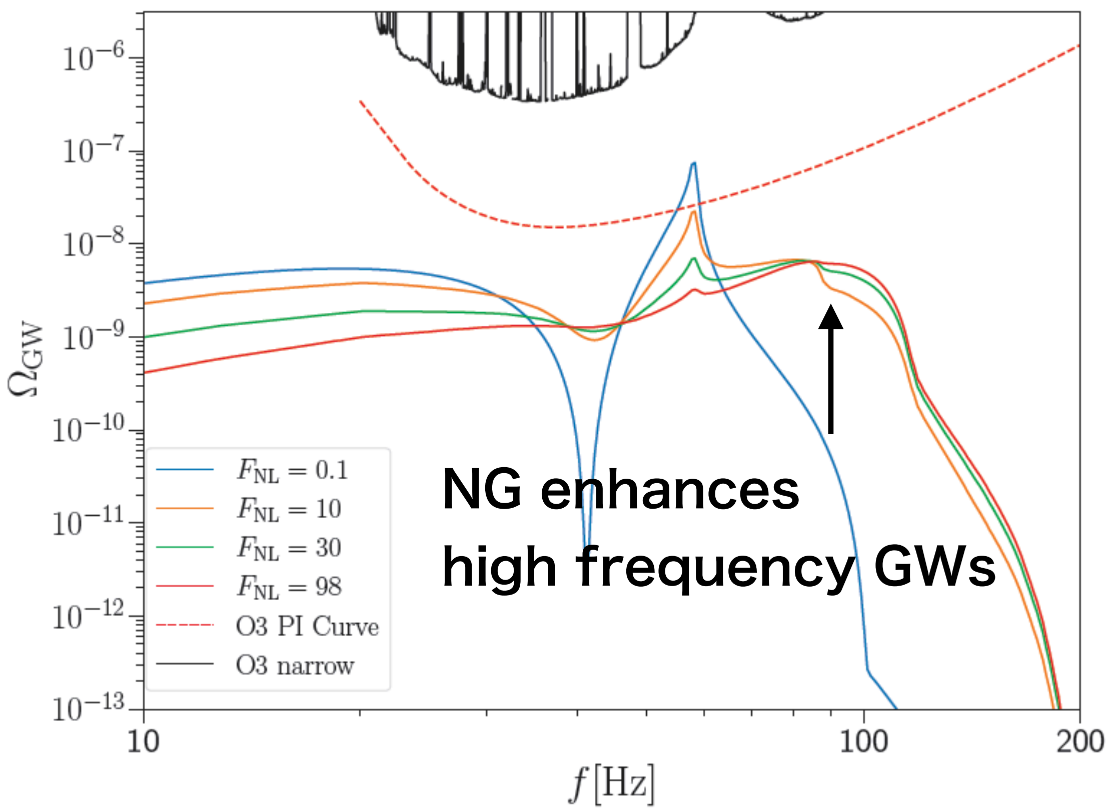
wider bin
→ high SNR in the bin
+ stable noise estimation

LVK analysis

Frequency resolution
1/32Hz

# ① LVK O3 constraint on scalar induced GWs

GW spectrum



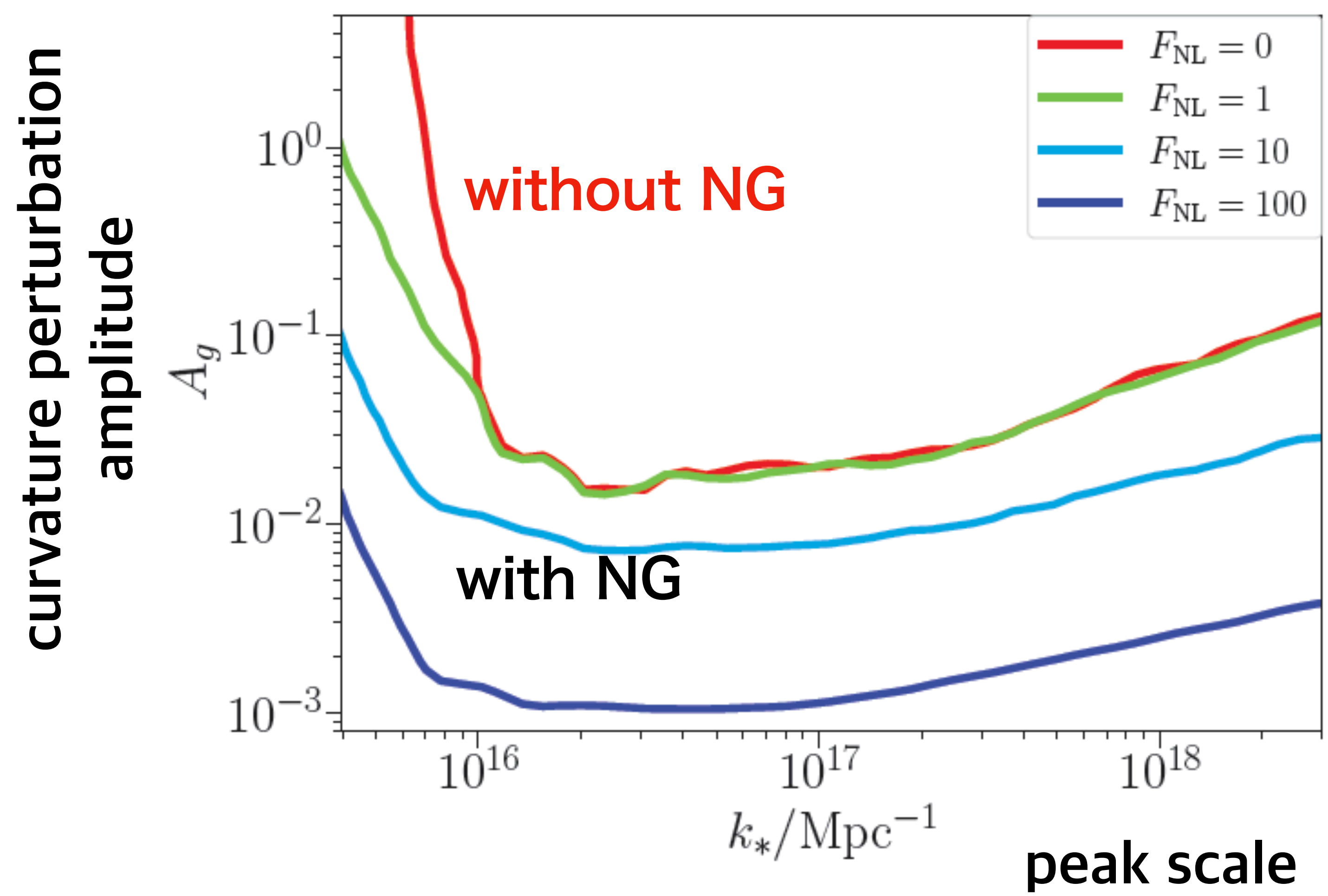

Many inflationary models predicting large curvature perturbations (and producing PBHs) exhibit Non-Gaussianity (NG)

- ultra slow roll inflation
- multi field inflation
- couplings leading to particle production, etc.

**Assumption:**
**local type non-Gaussianity**

$$\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + F_{NL}\zeta_g^2(\mathbf{x})$$

Note: Parametrization with $F_{NL}$
covers limited cases




R. Inui, S. Jaraba, SK, S. Yokoyama, JCAP 05 (2024) 082

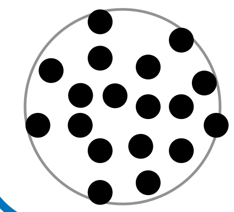
# ② LVK O3 constraint on PBH binaries

**Superpositions of PBH binaries form a stochastic background**

## Early binary formation

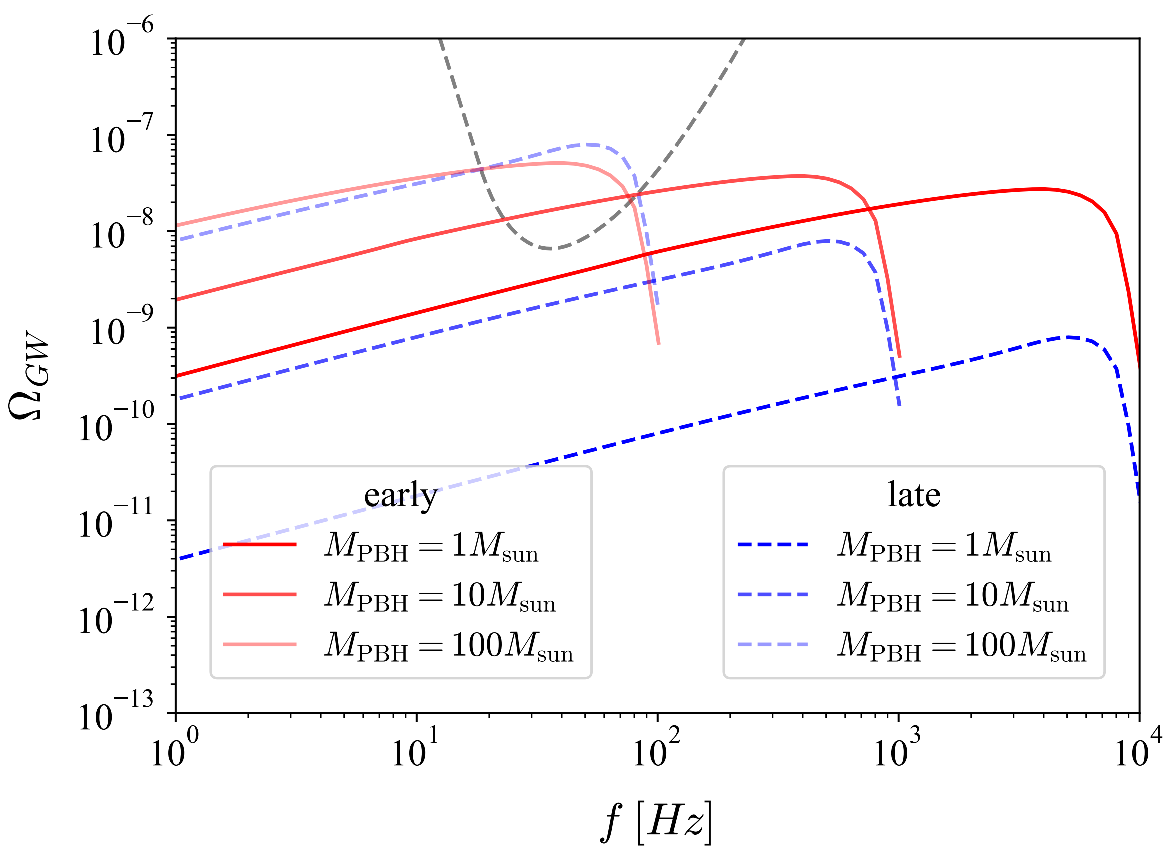
tidal torque

## Late binary formation

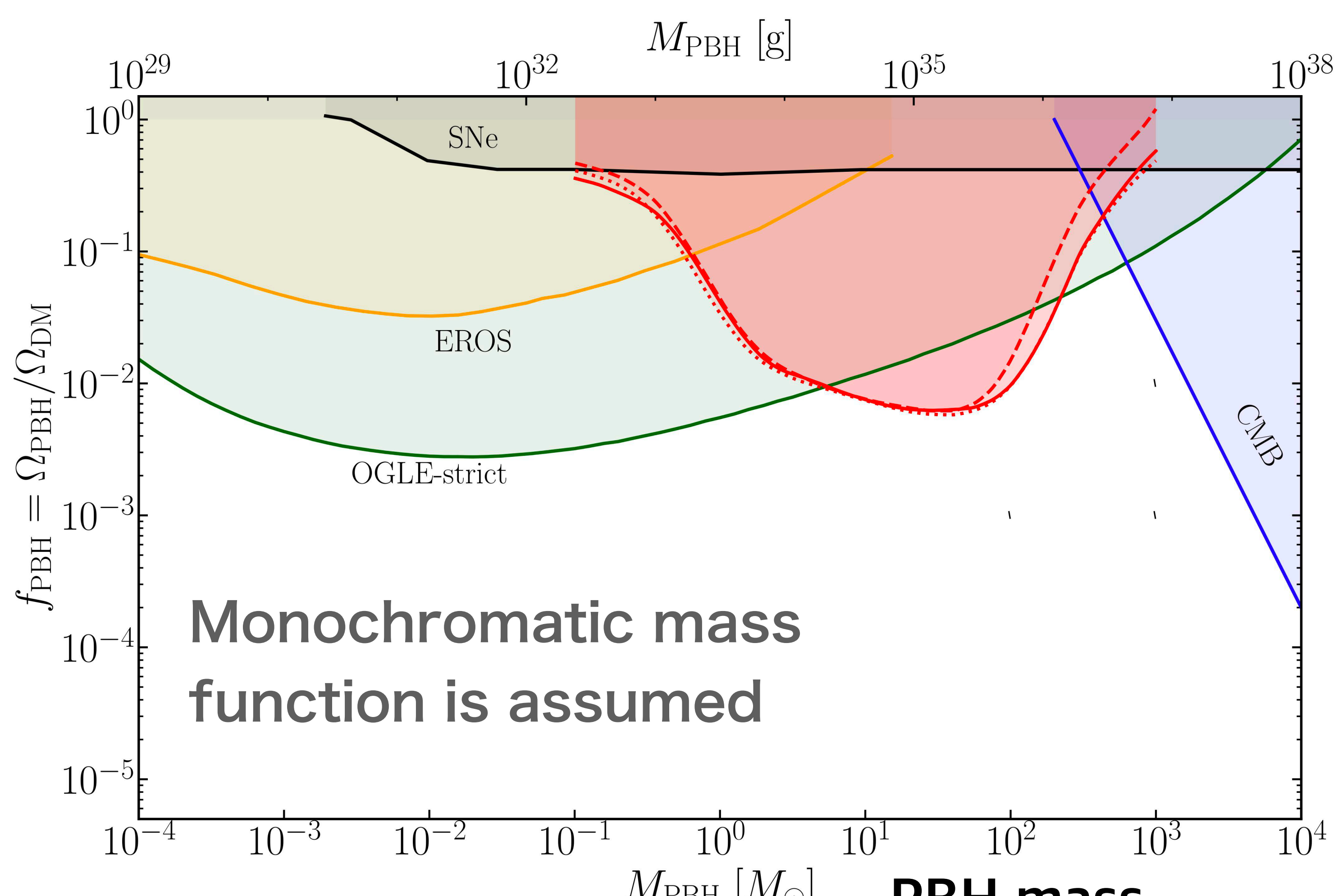


dynamical capture
in a cluster

### GW spectrum




### Constraint on PBH fraction



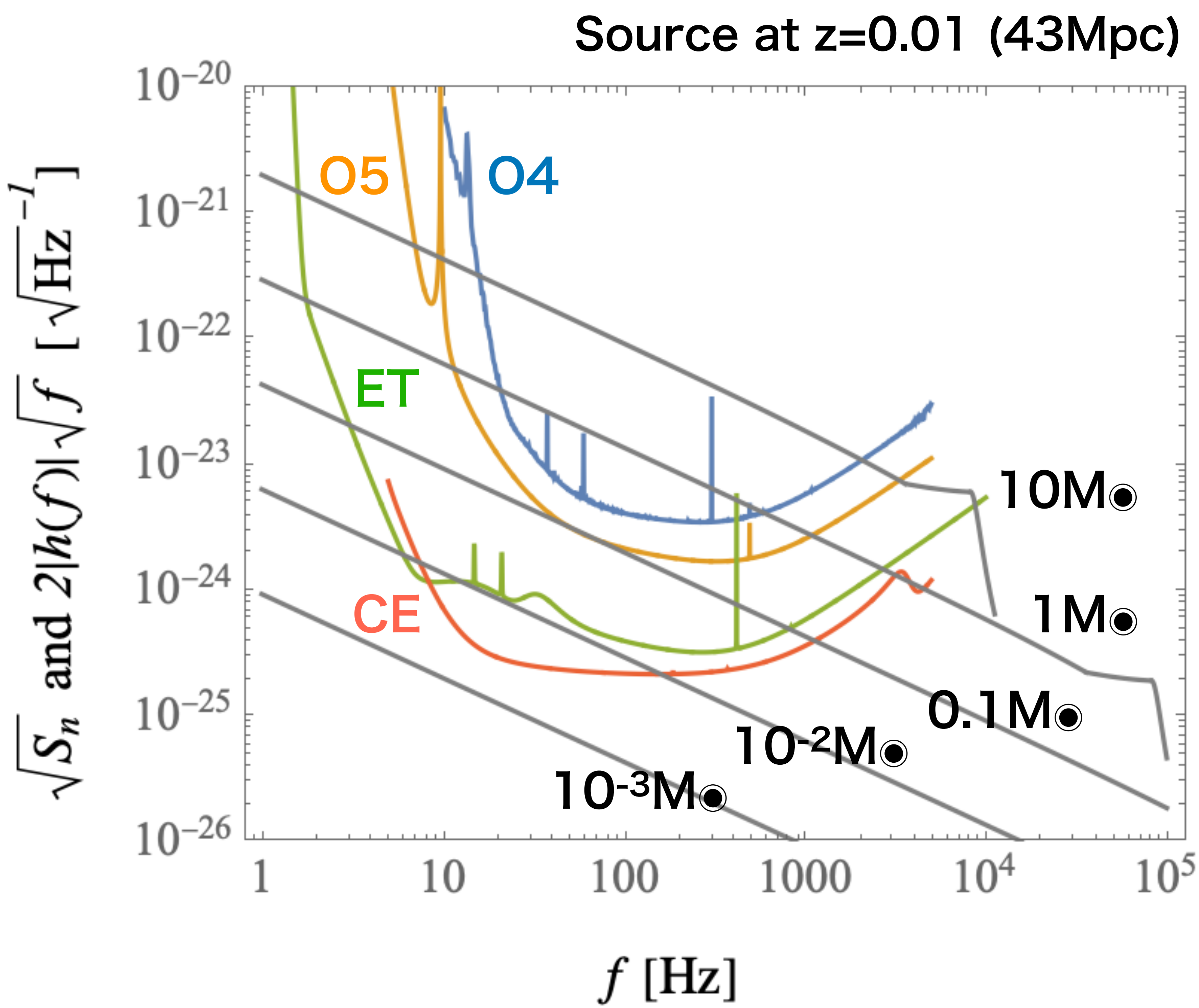

**PBH mass**

T. Boybeyi, S. Clesse, SK, M. Sakellariadou, PRD 112, 023551 (2025)

# Individual binary search
# (Continuous wave like signal)

# Searching primordial black holes

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

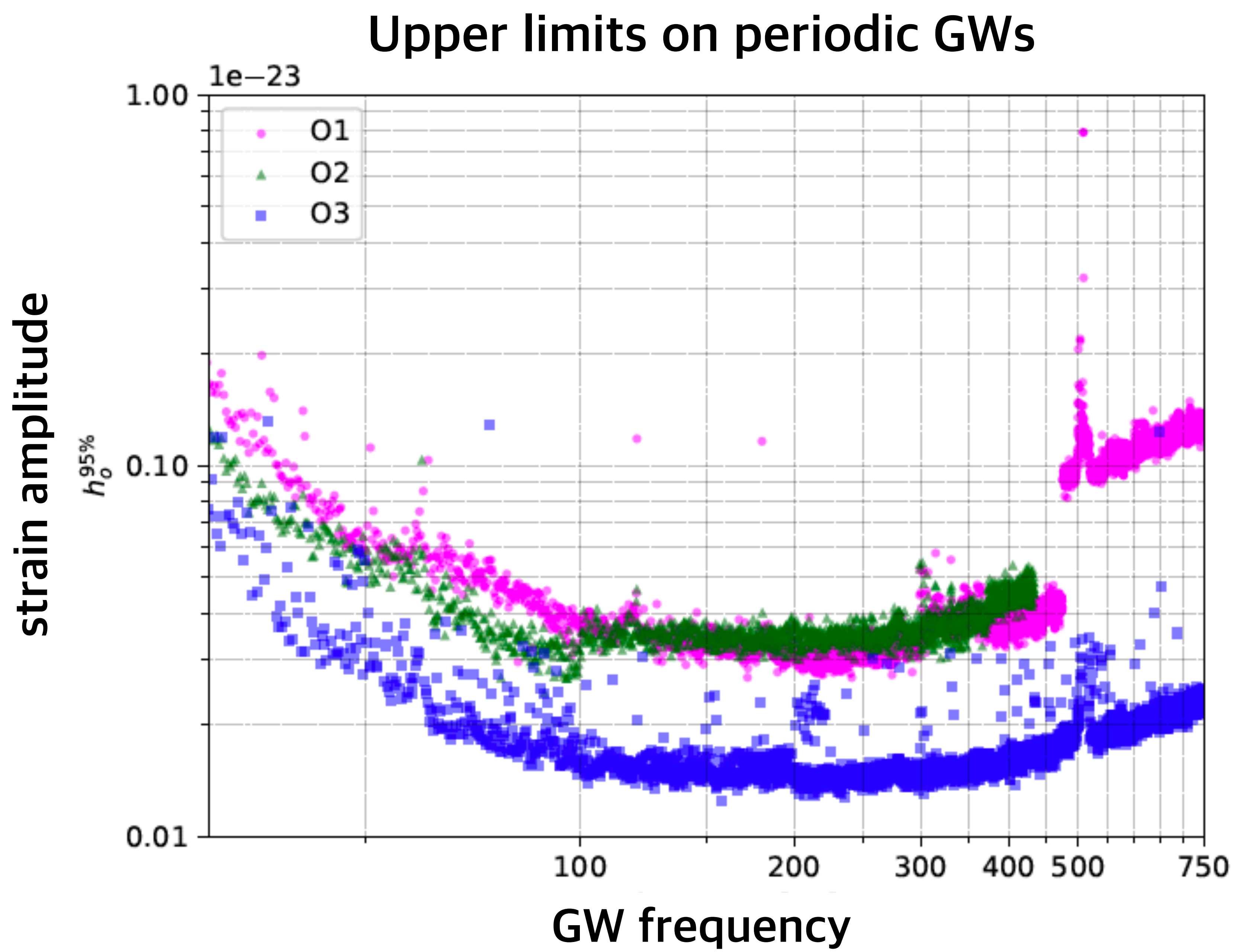


# Applying traditional CW search

LVK collaboration, PRD 106, 102008 (2022)

## <u>Continuous wave (CW) search</u>

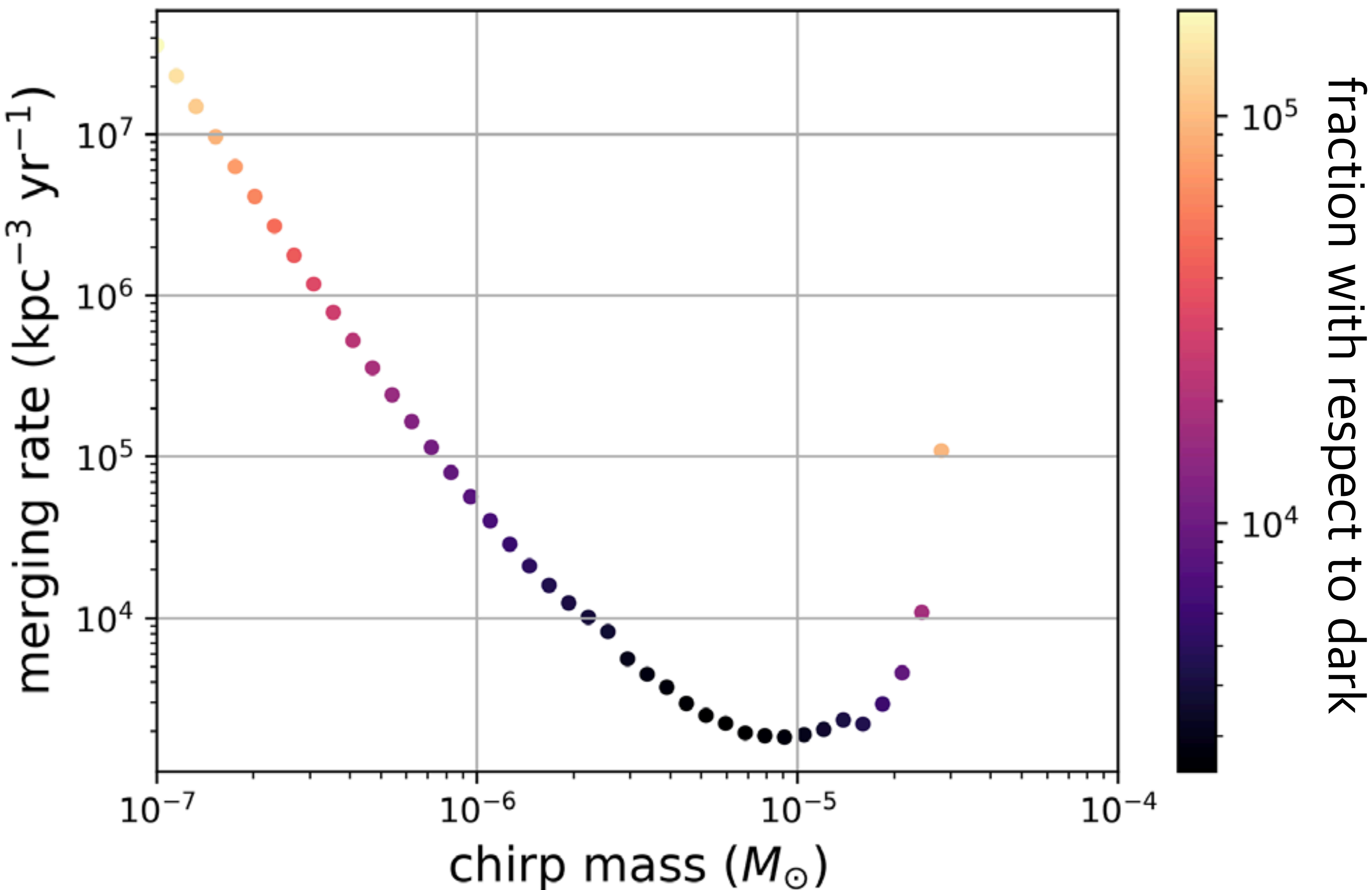
Initial target: spinning neutron star with mass asymmetry




→ can be used to constrain small mass PBH binaries with small frequency change

# Applying traditional CW search

Miller et al., PDU 32, 100836 (2021)
PRD 105, 062008 (2022)




strain amplitude is too small | $\dot{f}$ is too large

**Frequency evolution**

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

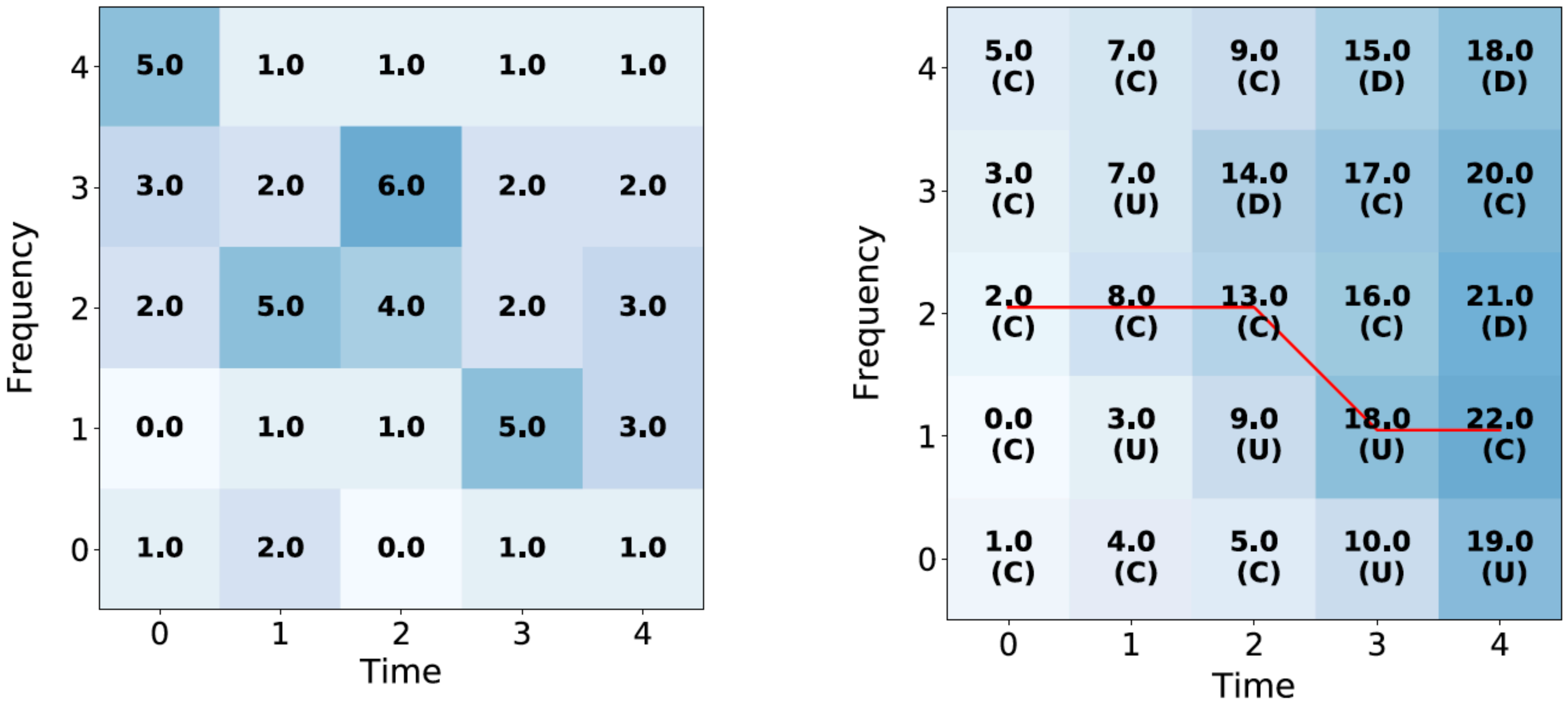
**<u>Powerflux pipeline</u>**

→ searched periodic signal allowing spin-up of $\dot{f} \leq 1.00 \times 10^{-9}\ \mathrm{Hz/s}$

# Let us explore > $10^5 M_\odot$

## Application of Viterbi algorithm

### Step-by-step scan for most probable signal location




(a) The input data

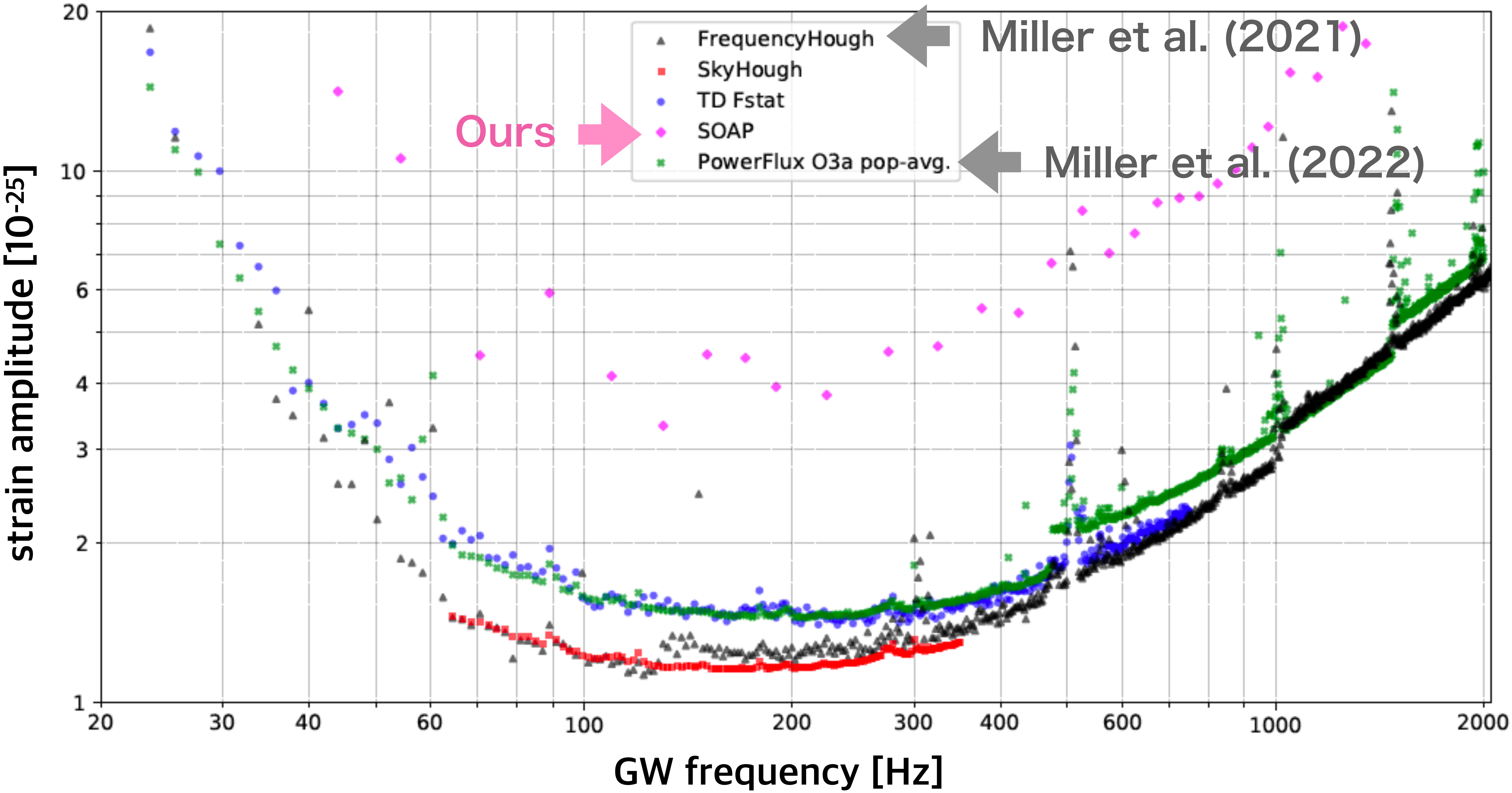
(b)The log-probabilities, jumps, and most probable path

**Tracking amplitude excess in the frequency-time plane**

Figure from Bayley et al. PRD 100, 023006 (2019)

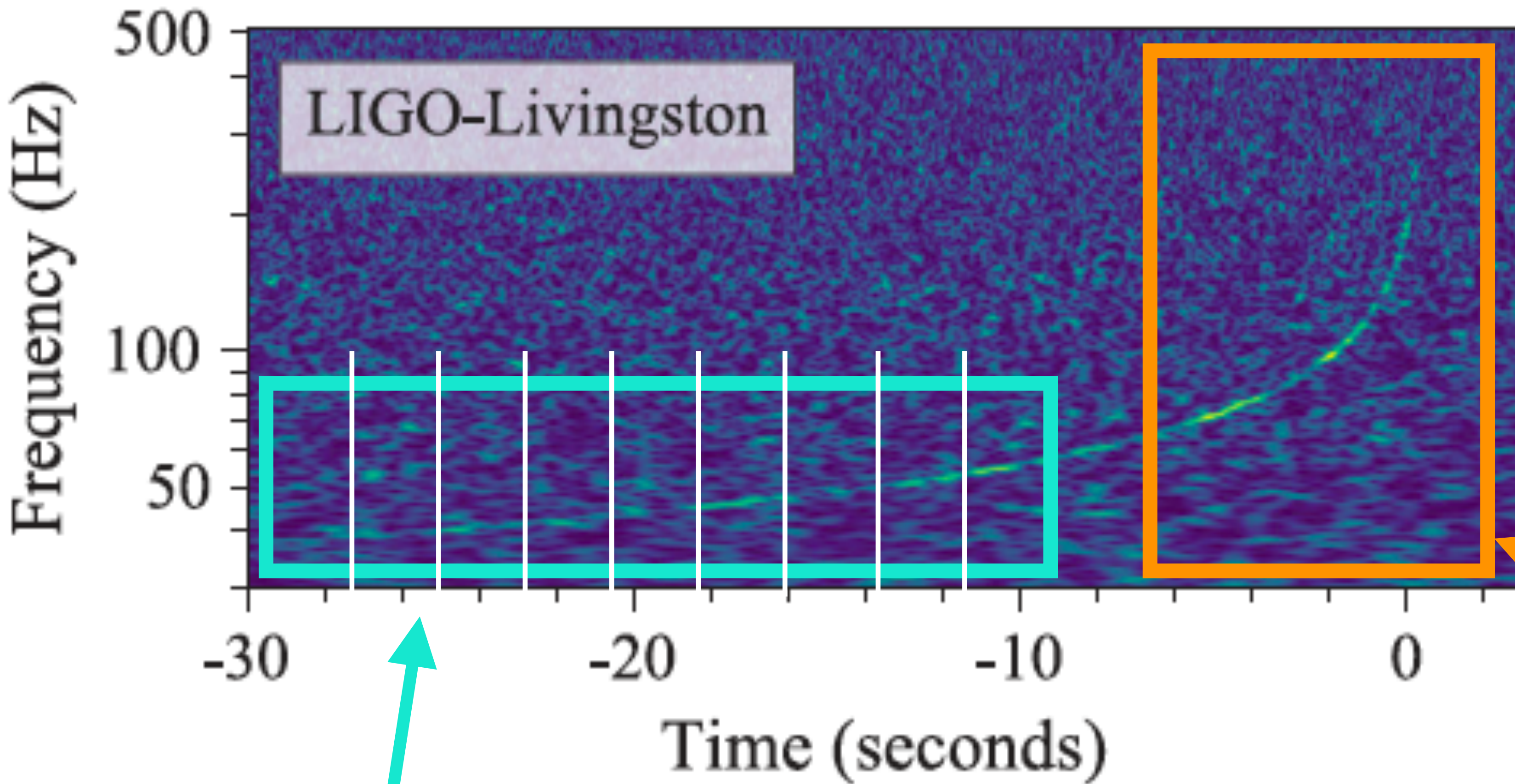
# O3 continuous wave search

Already used in CW search




Not very sensitive, but fast and agnostic

# Search method




We are interested in slowly evolving part

Example:
Spectrogram for
chirp signal of NS binary

We don't observe this part if < 1M$_\odot$

**Finding optimal SFT length (time resolution) is essential**

SFT: short Fourier transform

Time resolution is too small
→ amplitude excess is not enough

Time resolution is too large
→ the signal do not stay in one frequency bin →

Frequency evolution

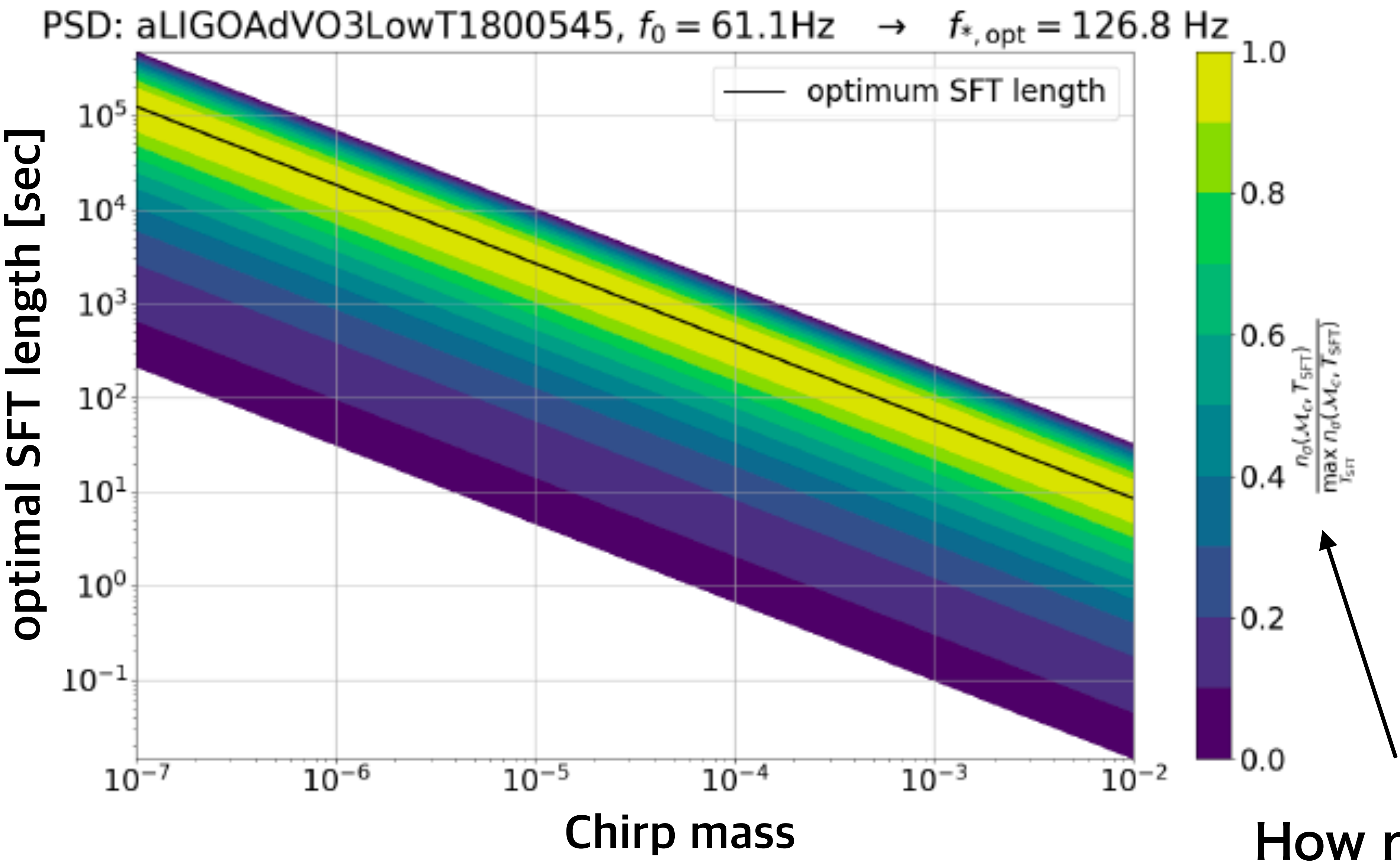
$$\dot{f}_{\rm gw} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f_{\rm gw}^{11/3}$$

depends on the mass

# Optimal SFT length

SFT to maximize detection efficiency

condition: signal has to stay in a single frequency bin of the SFT




How much it loses SNR
if we use different length

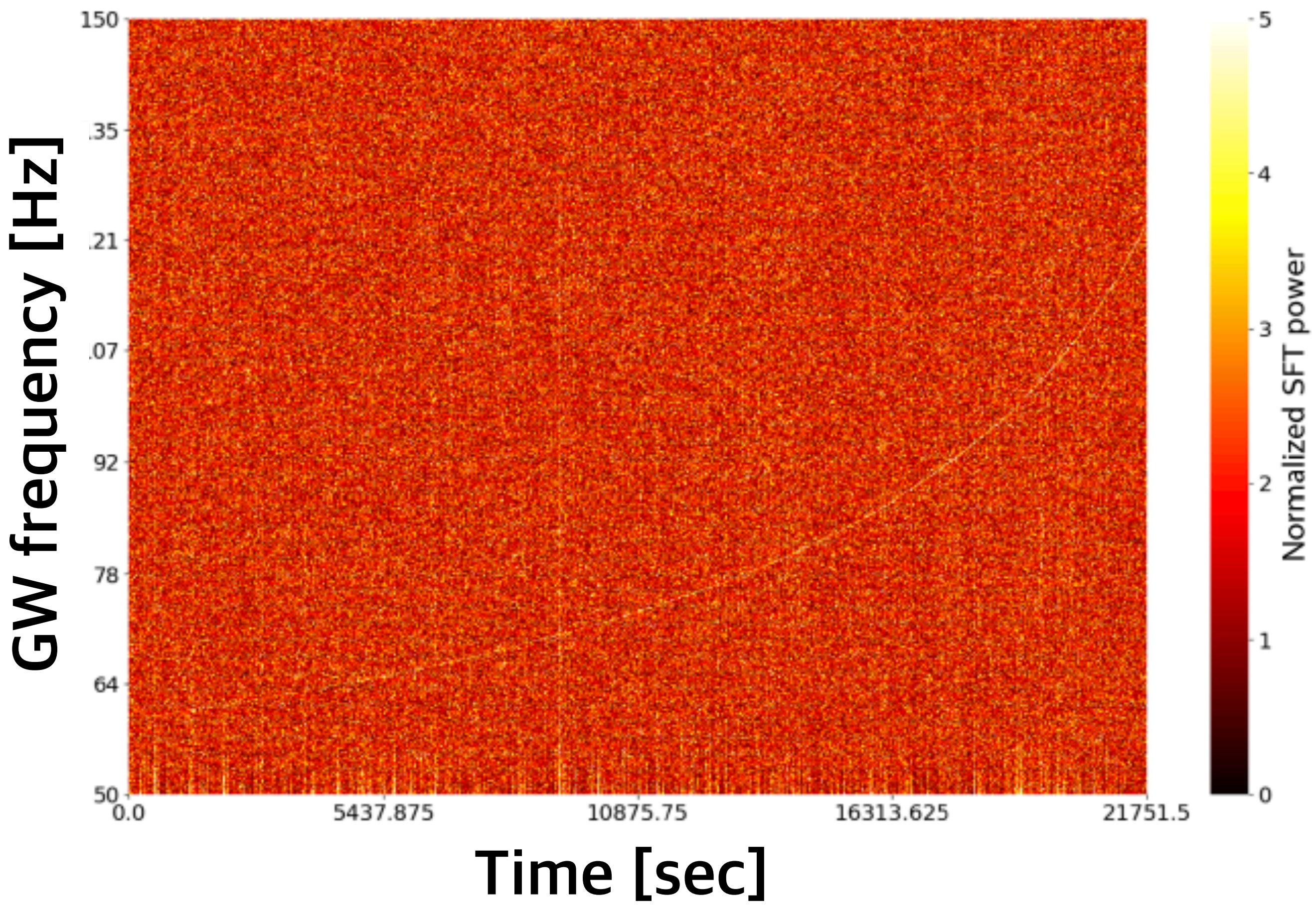
G. Alestas et al. (+SK), PRD 109, 123516 (2024)

# Working example

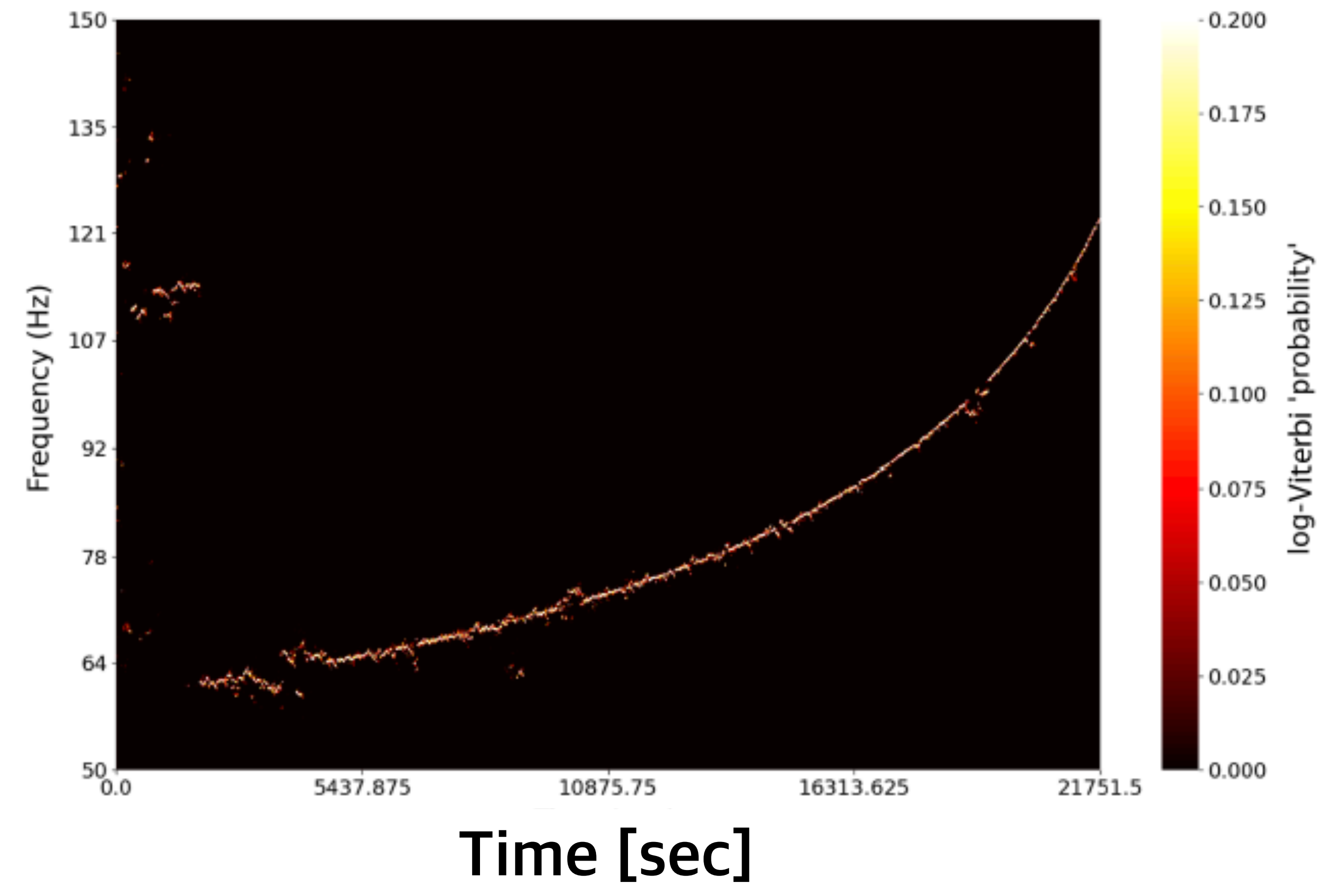
O3 Gaussian noise is assumed

$$[\mathcal{M}_c, d_L] = [10^{-2} M_\odot, 147\mathrm{Kpc}]$$

<u>Injeccted signal</u>




<u>Recovery by Viterbi</u>

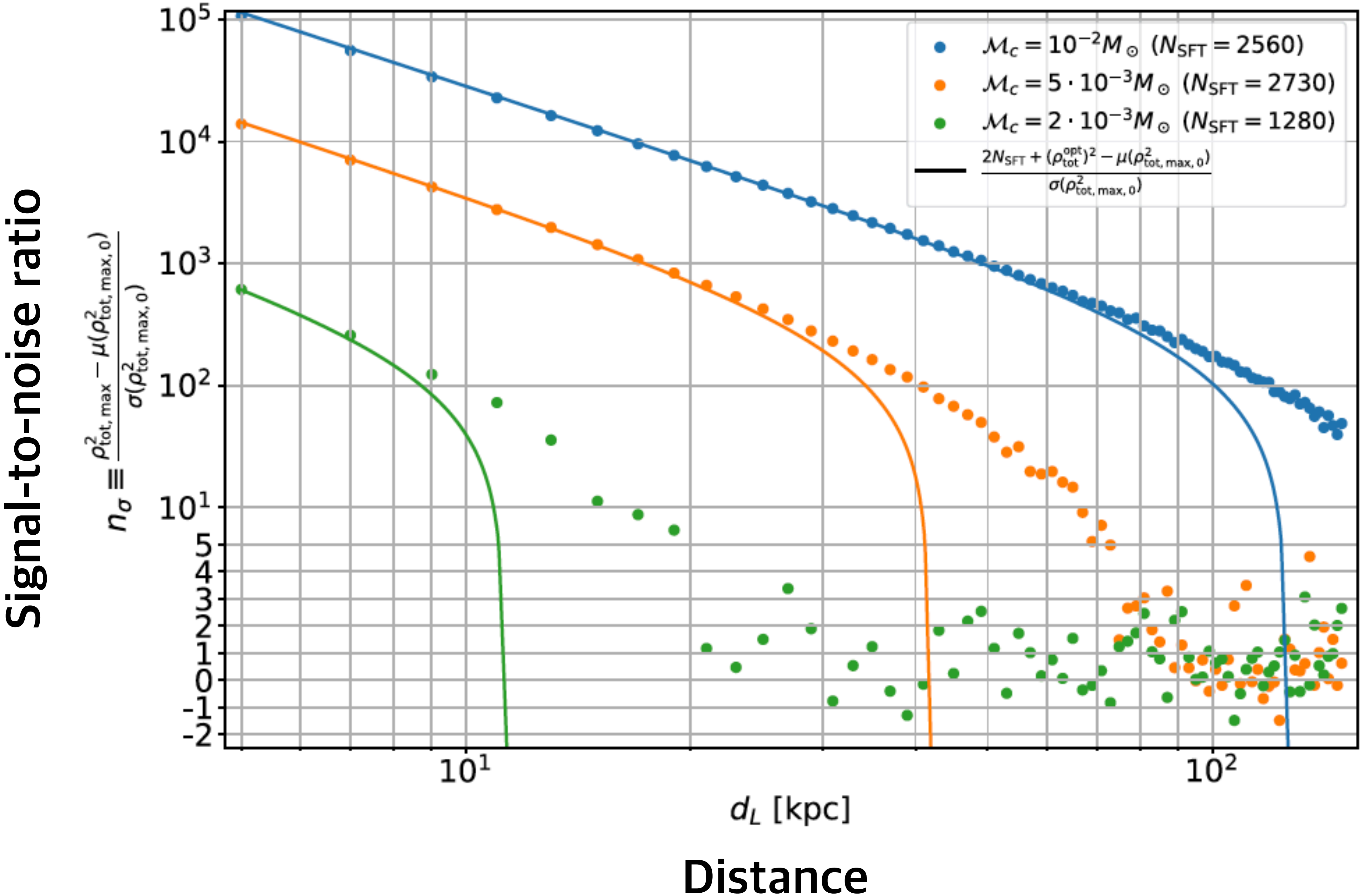



G. Alestas et al. (+SK), PRD 109, 123516 (2024)

# Sensitivity

for equal mass binary

Solid: analytic estimation
Dots: simulation




G. Alestas et al. (+SK), PRD 109, 123516 (2024)

# Summary

## Gravitational wave is a unique probe of primordial black hole scenarios

### Stochastic search

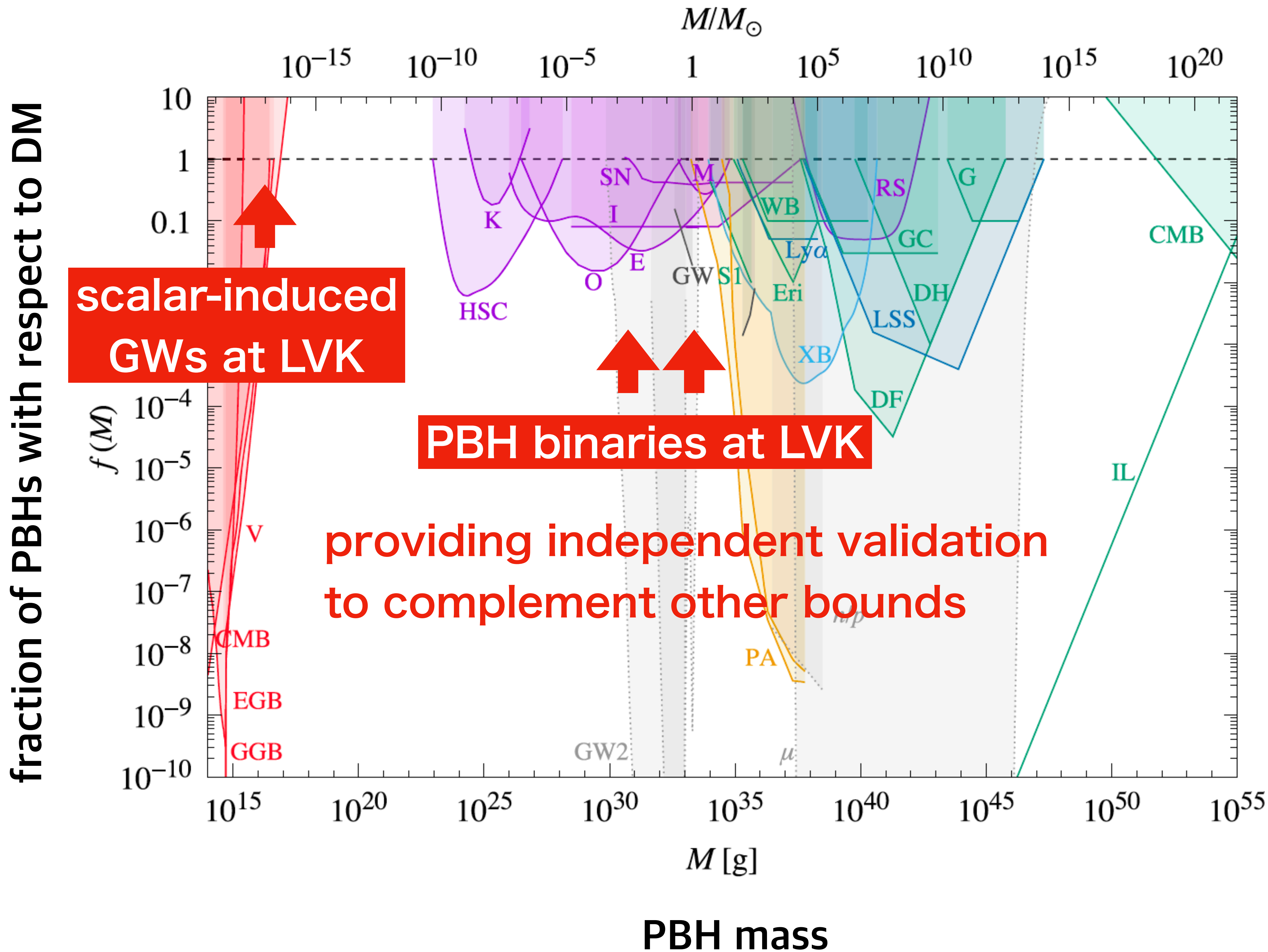
- **Inui et al. (+SK) JCAP 05, 082 (2024)**
  We have provided constraint on scalar-induced GWs using LVK O3 data, by taking into account the effect of non-Gaussianity in curvature perturbations.

- **Boybeyi et al. (+SK), PRD 112, 023551 (2025)**
  We have provided constraint on PBH binaries using LVK O3 data by considering both early and late binary formation.

### Continuous wave search

- **Alestas et al. (+SK) PRD 109, 123516 (2024)**
  We have formulated a method to search planetary mass ($10^{-2}$ - $10^{-5} M_\odot$) PBH with the application of Viterbi algorithm.

# PBH constraints across a wide mass range




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