Focus Week on Primordial Black Holes
@ Kavli IPMU

Searching for planetary-mass primordial black holes

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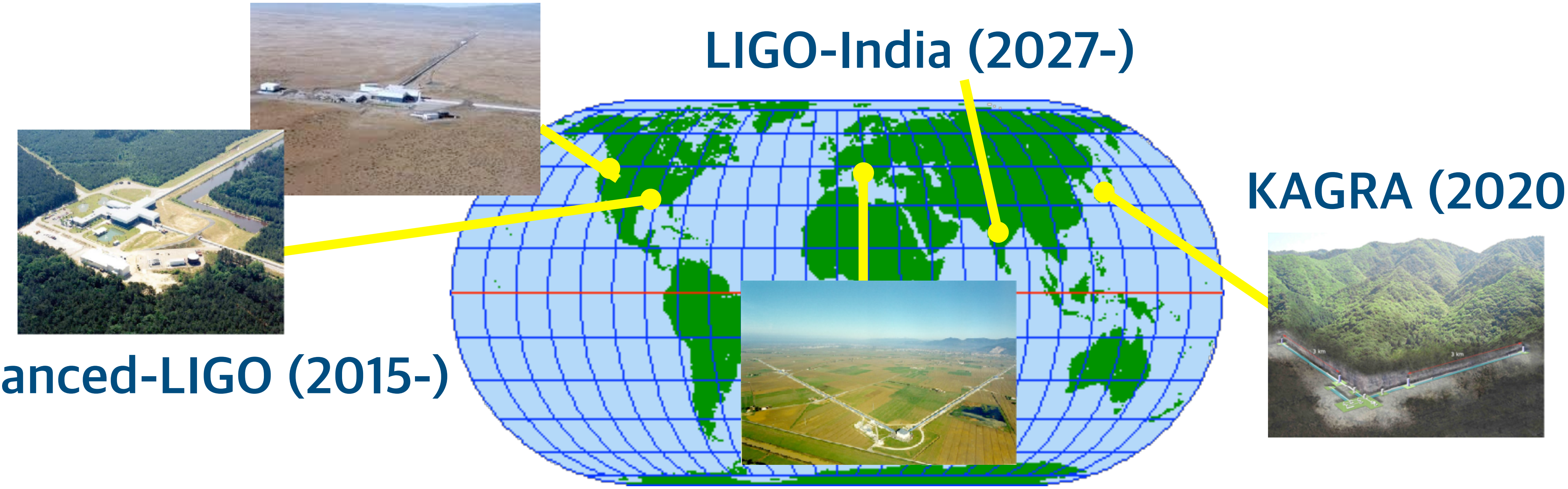
16 Nov 2023

Gravitational wave (GW) observation



LIGO-India (2027-)

KAGRA (2020-)

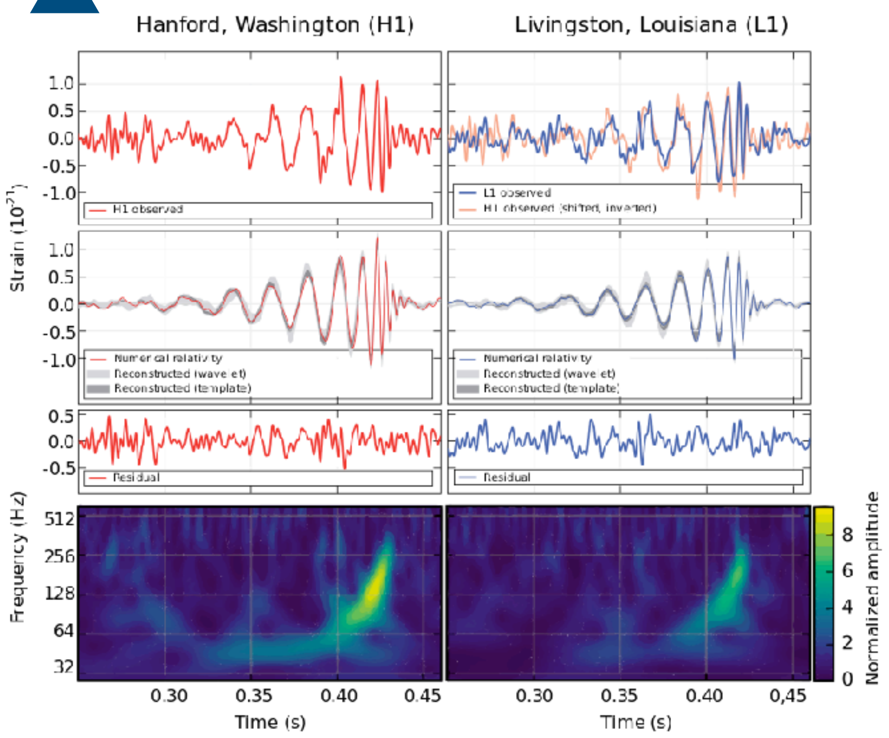
Advanced-LIGO (2015-)

Advanced-VIRGO (2017-)

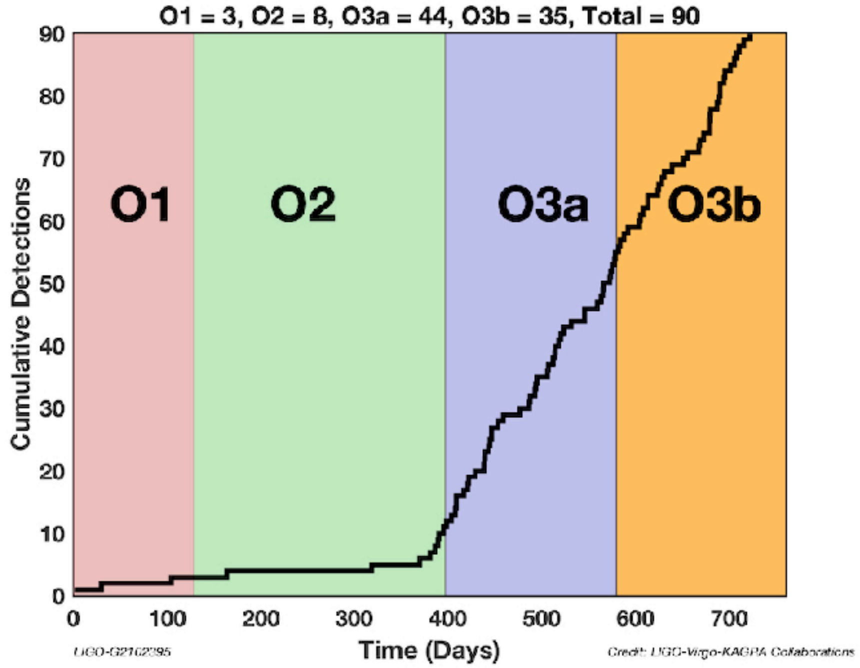
2015

2020'

2030'



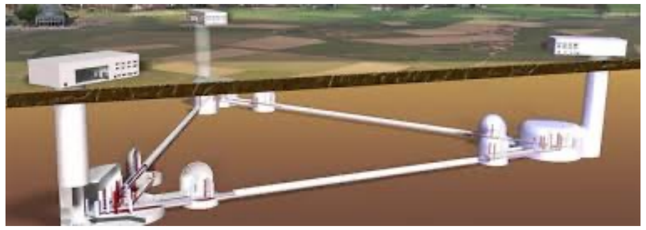
The first detection: GW150914



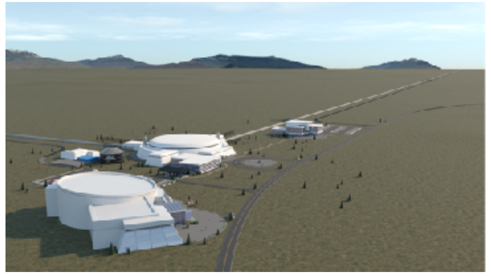
O4 started in May 2023

Future projects

- Einstein Telescope



- Cosmic Explorer

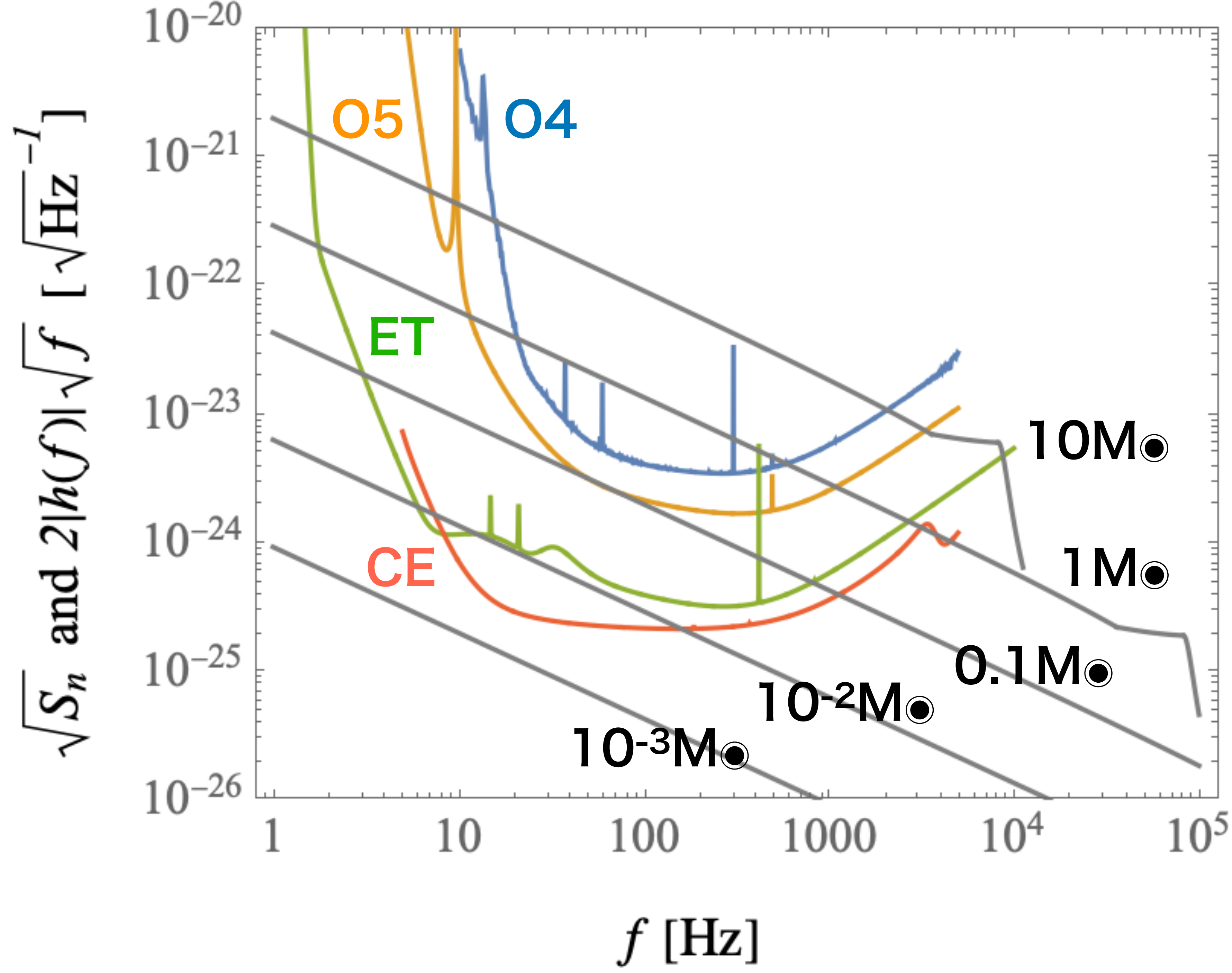


etc.

Searching primordial black holes

Detection of BH with < ~1$M_\odot$ can be a strong evidence of primordial origin

Source at z=0.01 (43Mpc)

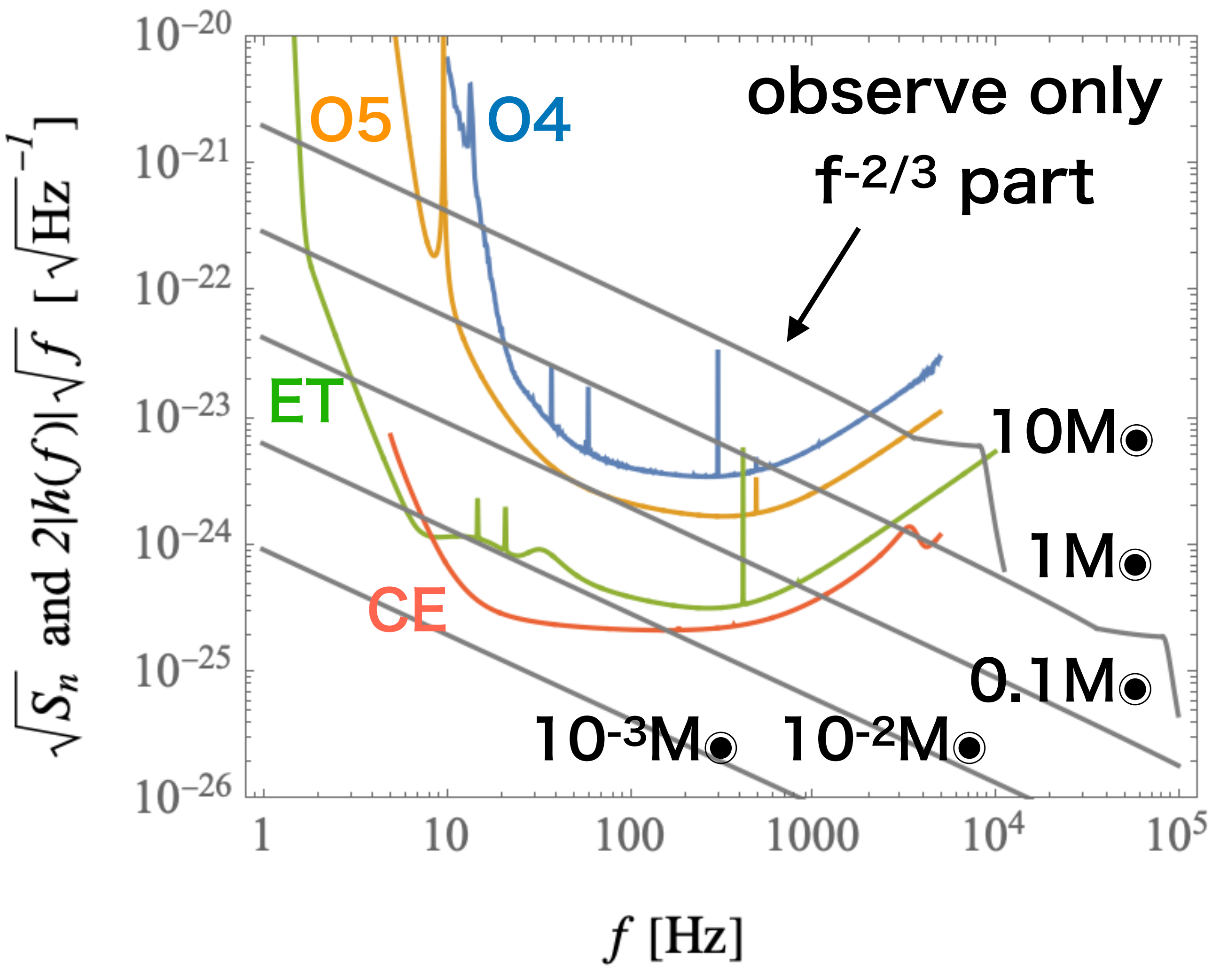


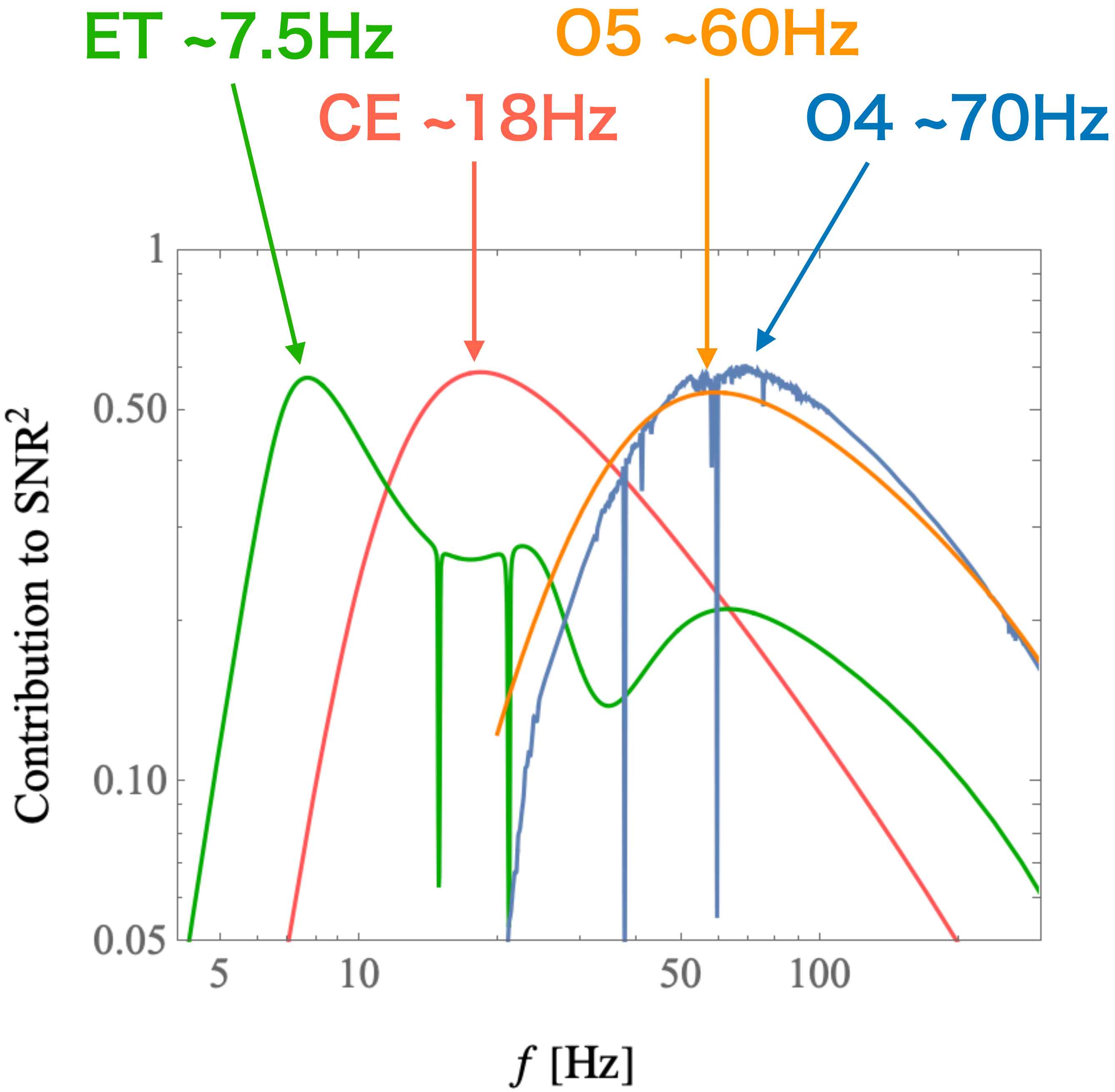
Searching primordial black holes

What frequency is important
for detecting sub-solar mass event?

Signal-to-noise ratio (SNR)

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





Search method

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

0.2 - 2 $M_\odot$ Subsolar mass search

LVK collaboration, PRL 121, 231103 (2018); PRL 123, 161102 (2019);
PRL 129, 061104 (2022); arXiv:2212.01477
Nitz & Wang, ApJ, 915, 54 (2021)
Phukon et al., arXiv:2105.11449
Morrás et al., PDU 42, 101285 (2023)

→ compact binary coalescence (CBC) search

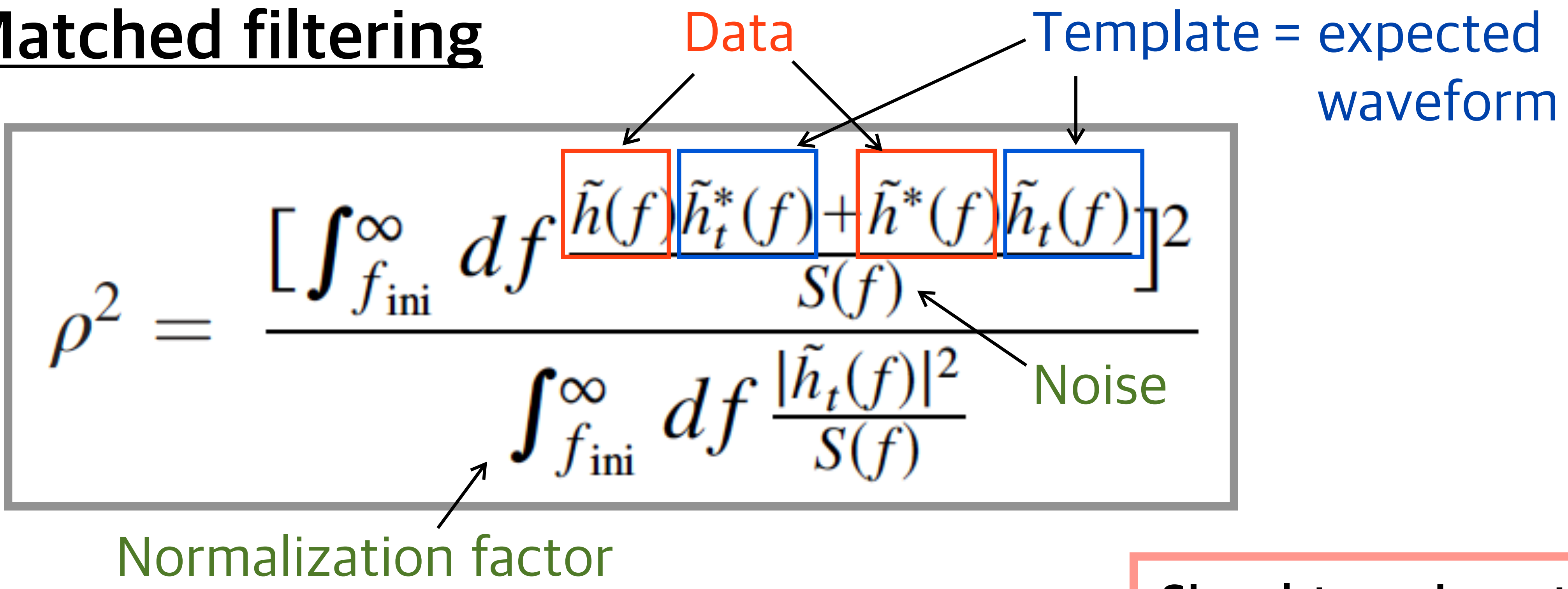
10^{-7} - 0.2 $M_\odot$ Planetary mass search

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

→ continuous wave (CW) search

Subsolar mass search

Matched filtering

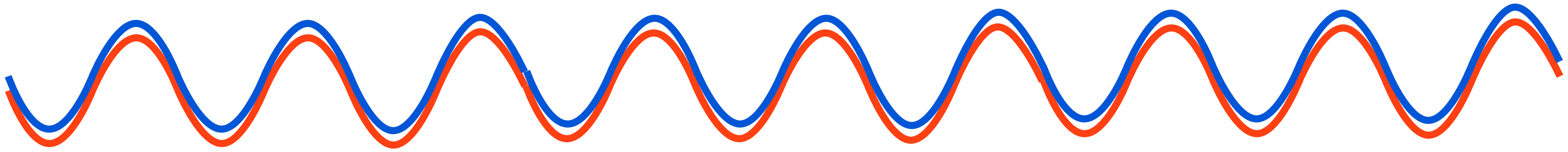


$$\rho^2 = \frac{\left[\int_{f_{\rm ini}}^{\infty} df\, \frac{\boxed{\tilde{h}(f)}\,\boxed{\tilde{h}_t^*(f)}+\boxed{\tilde{h}^*(f)}\,\boxed{\tilde{h}_t(f)}}{S(f)}\right]^2}{\int_{f_{\rm ini}}^{\infty} df\, \frac{|\tilde{h}_t(f)|^2}{S(f)}}$$

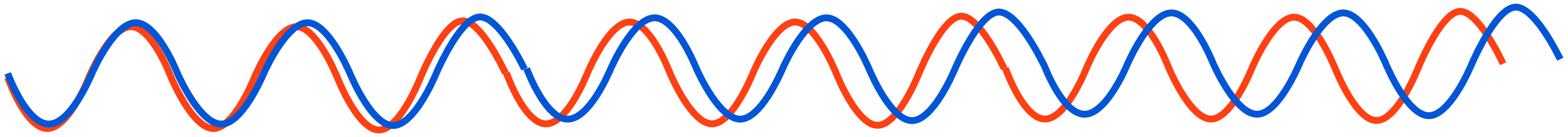
Assuming $\tilde{h}(f) = \tilde{h}_t(f)$ ➡

Signal-to-noise ratio (SNR)

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



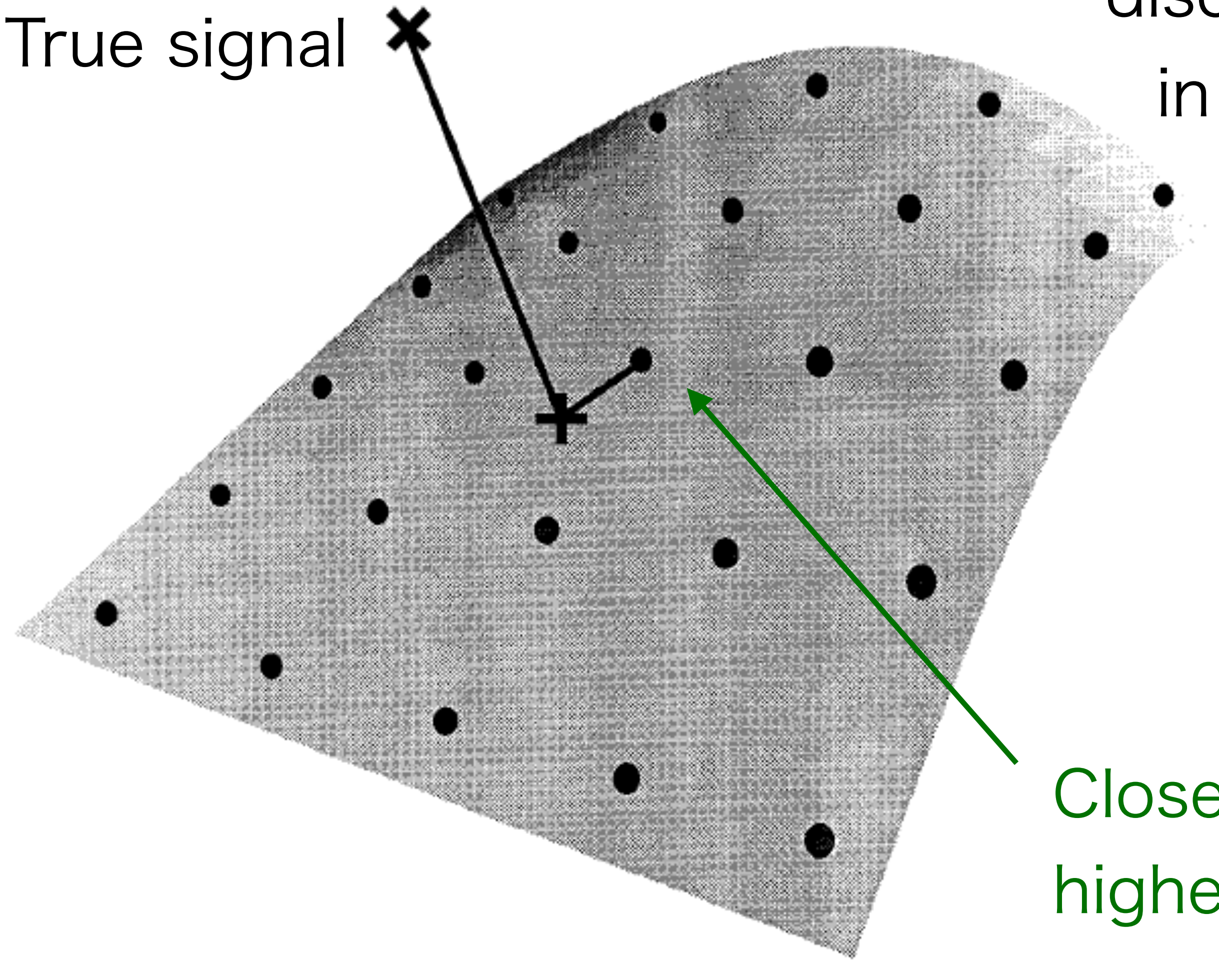
→ matched: SN is maximized



→ mismatch: SN is reduced

Template bank

How do we find the correct template?
→ We simply try many and search for parameter values that maximize the SNR.



True signal

discrete templates
in parameter space

Closest point gives
highest SNR

Typically, the discreteness of the template bank is selected in a way that ensures the loss of SNR is less than 3%

Figure from Owen, PRD 53, 6749 (1996)

Challenge in subsolar mass search

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

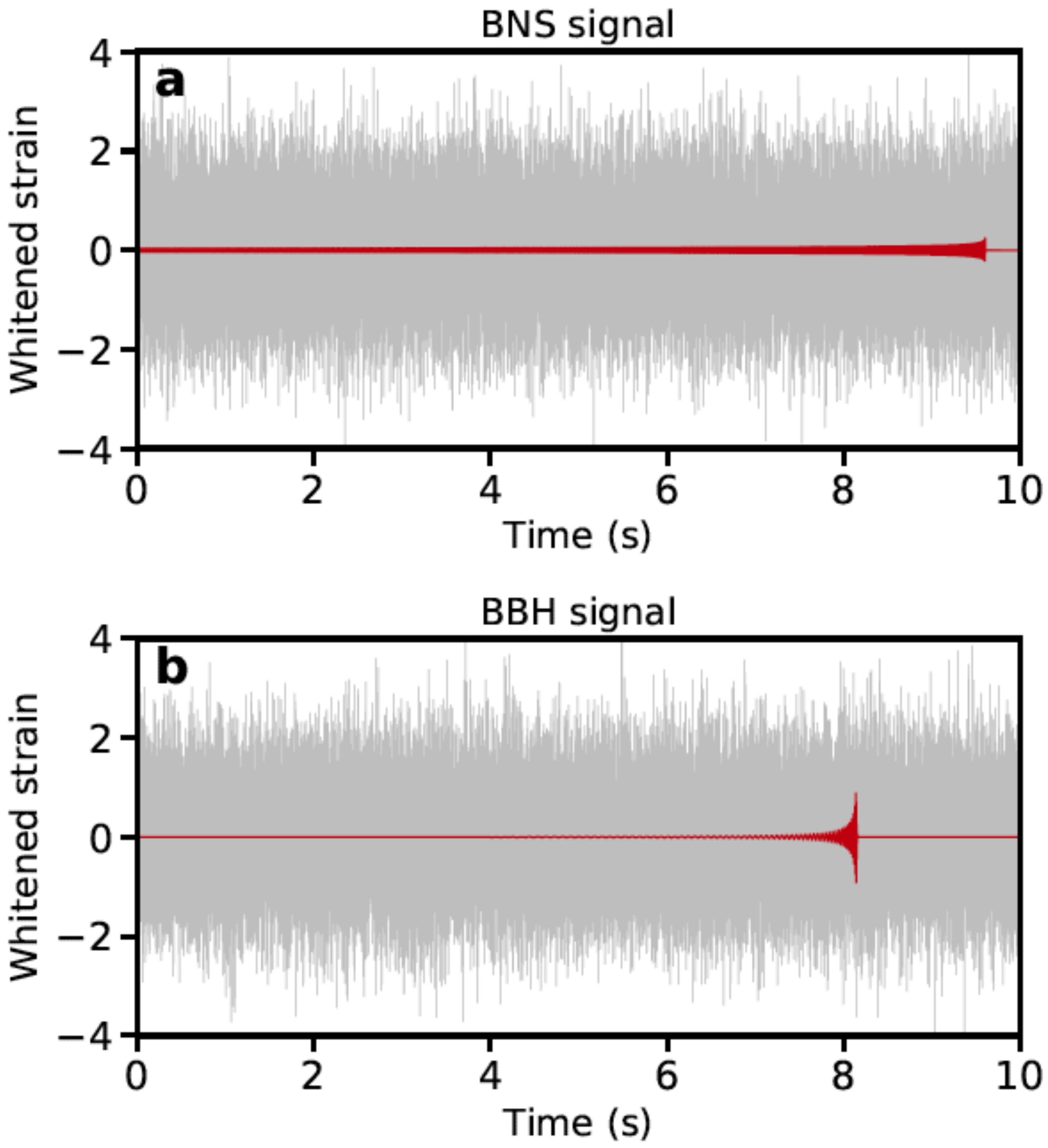
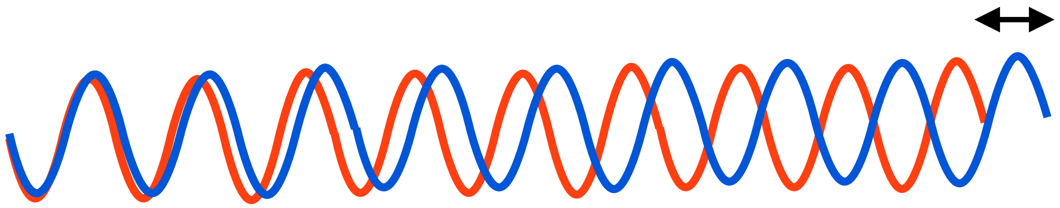
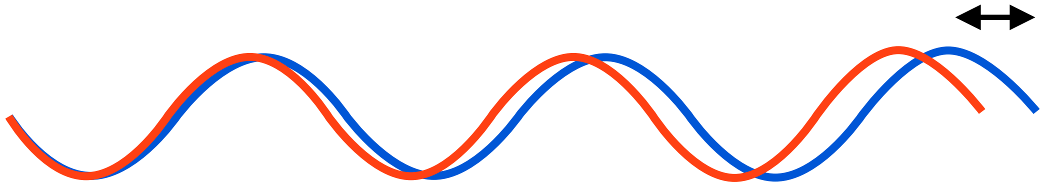


Figure from Krastev, PLB 803, 135330 (2020)



→ sensitive to small phase shift by variation of parameters



→ insensitive to small phase shift

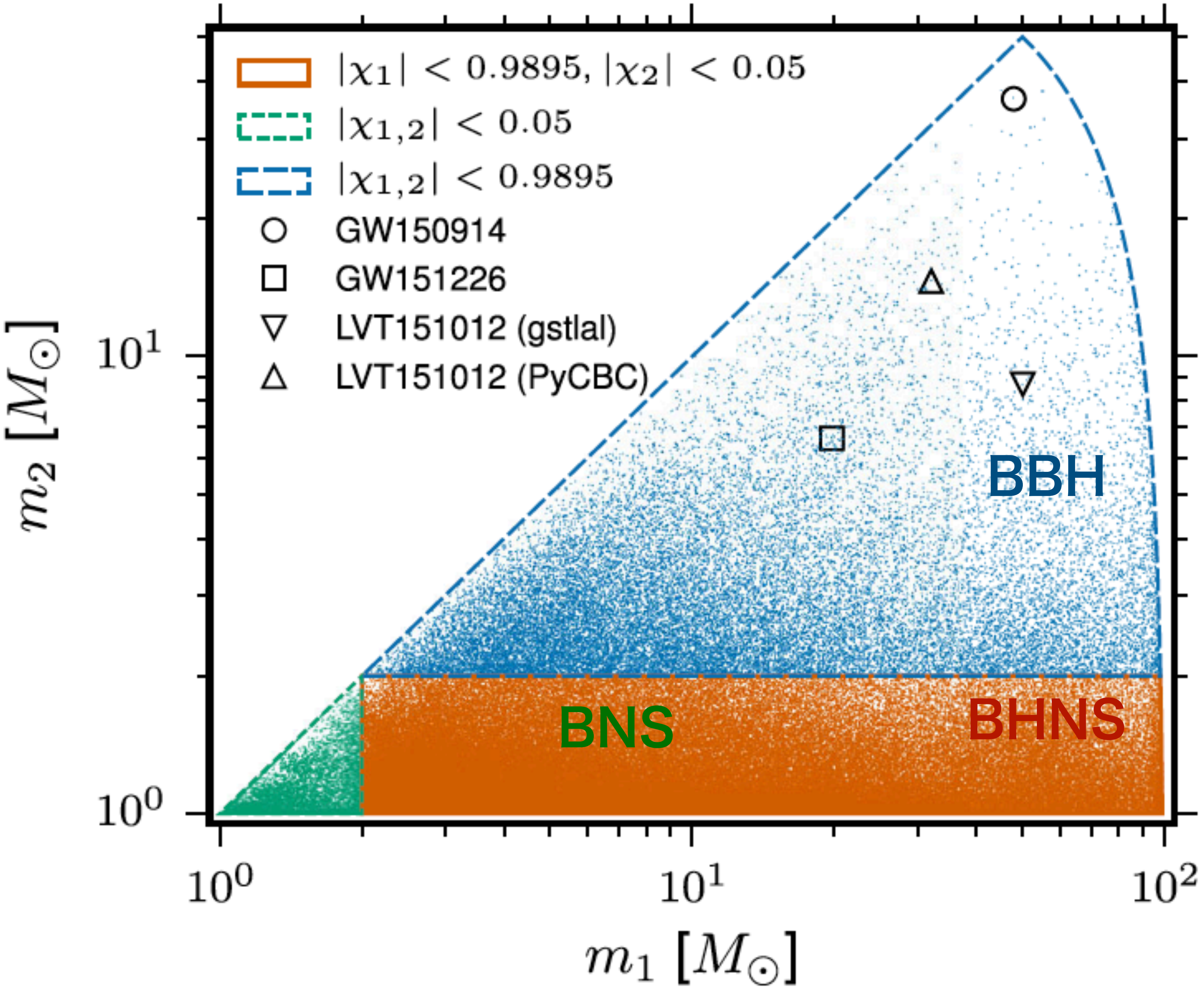
→ need to decrease the grid size of the template bank

→ more computation time

Challenge in subsolar mass search

Low mass event requires fine gridding to avoid mismatch.

Template used in O1 CBC search



denser

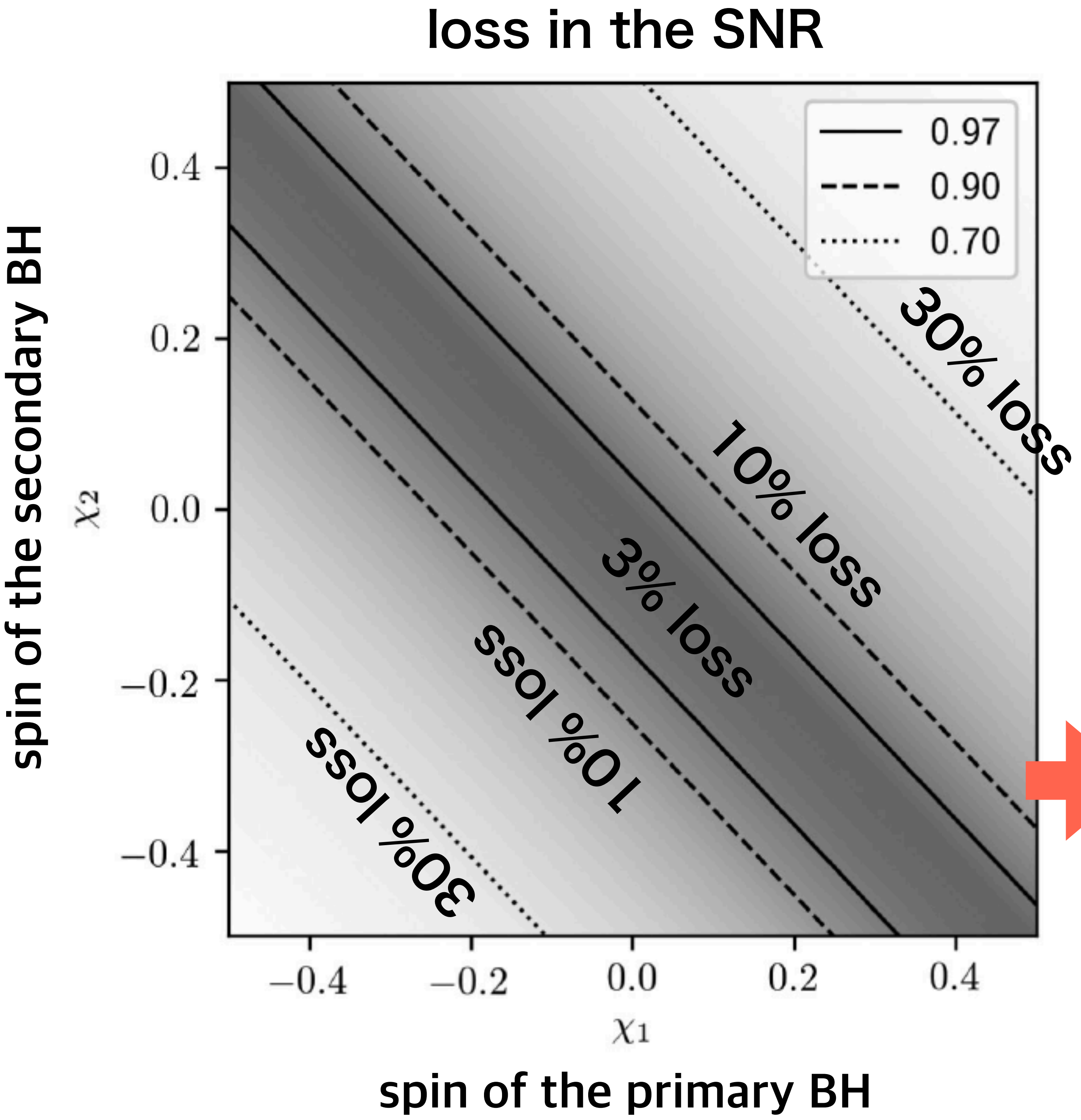
We want to explore this region!

LVK collaboration, PRX 6, 041015 (2016)

Study for spin parameter

Magee et al. PRD 98, 103024 (2018)

Non-spinning waveforms offer an easy way to reduce the computational cost by potentially 1–2 orders of magnitude.



Simulation with 10000 mock data

signal model

$0.5\ M_\odot$–$0.5\ M_\odot$ BBH events

with spin values of $|\chi_i| < 0.5$

search

Non-spinning template

with mass range of

$m_i \in (0.3\ M_\odot, 0.7\ M_\odot)$

Non-spinning template bank can recover the signals if effective spin is in the range of

$\chi_{\rm eff} > -0.08$ or $\chi_{\rm eff} < 0.02$

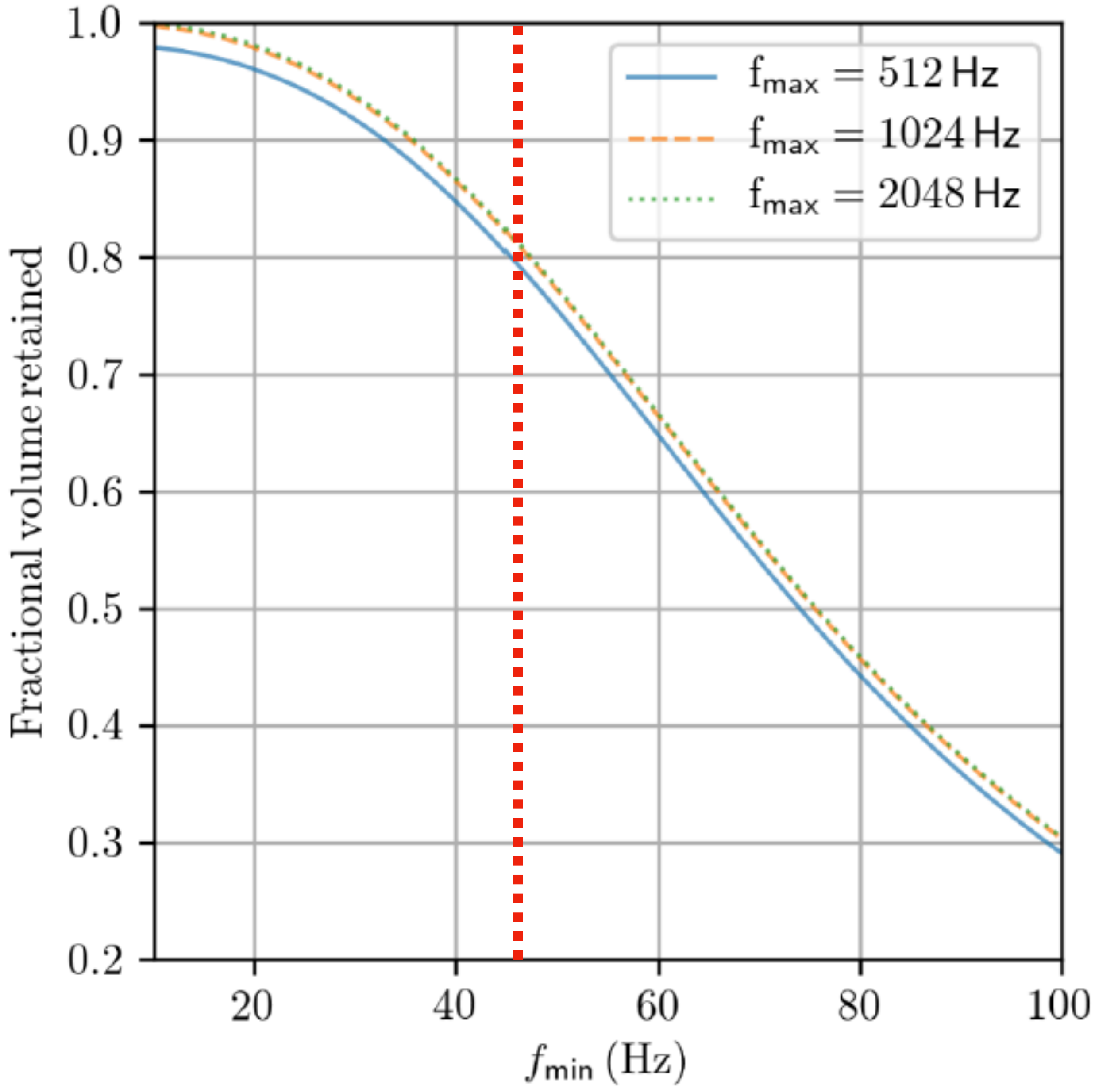
Remedy(?): cutting low frequency

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 in LVK

O3b $f_{\rm min} = 45{\rm Hz}$

LVK collaboration, arXiv:2212.01477

search range: $m_1 \in [0.2,\ 10\ ]\ M_\odot$

$m_2 \in [0.2,\ 1.0\ ]\ M_\odot$

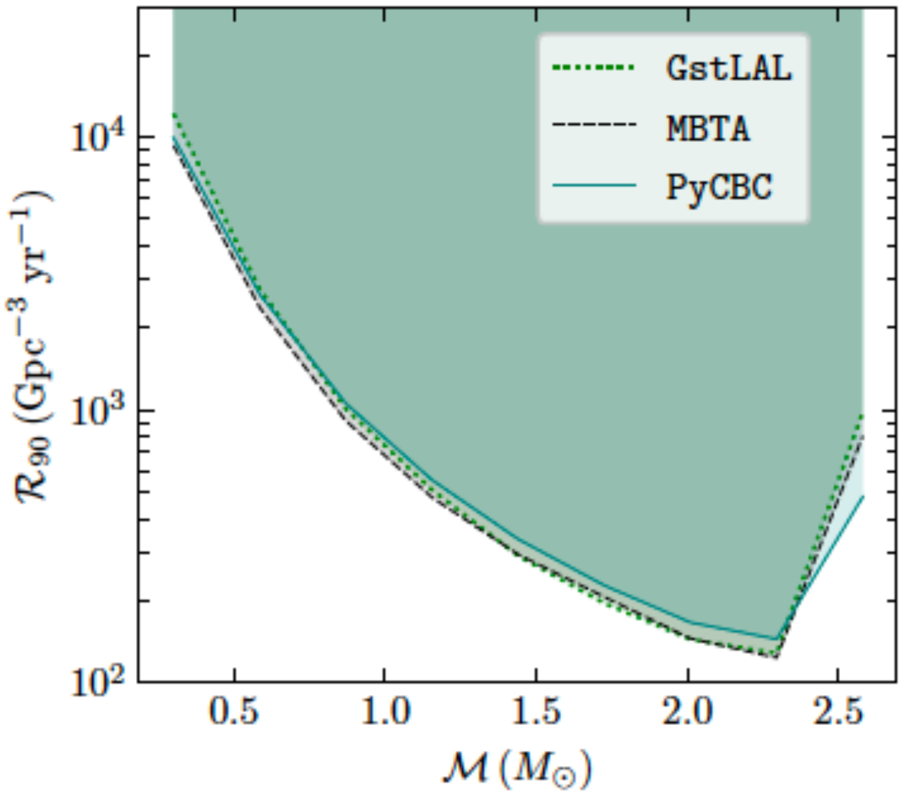
$0.1 < q < 1.0 \qquad q \equiv m_2/m_1$

$\chi_{1,2} < 0.9$

cf. number of templates
O1: 500332
O2: 992461
O3: ?

Triggers with FAR < 2 yr^{-1}

FAR [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

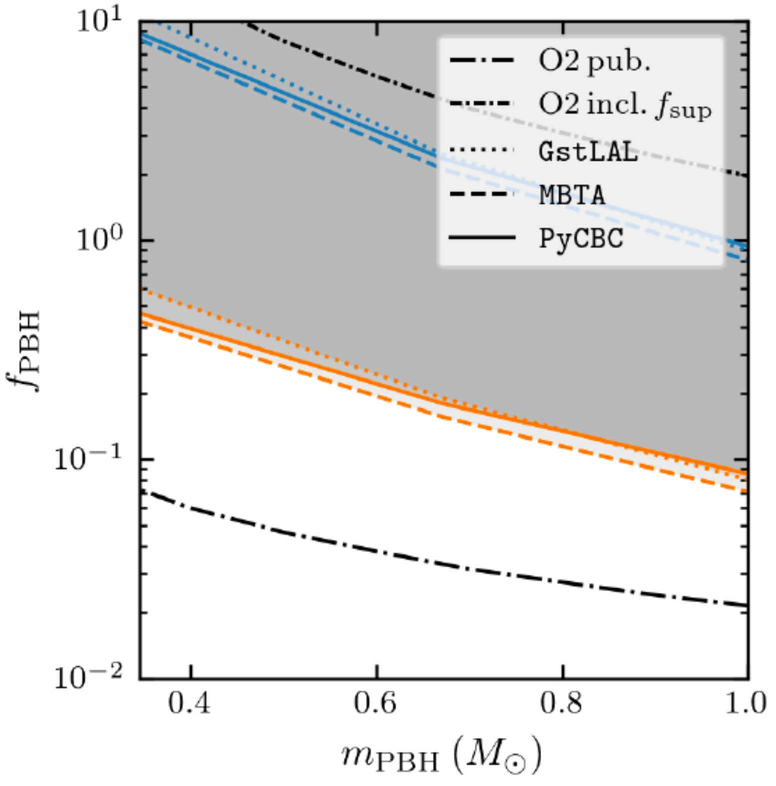


rate

chirp mass

Assumption:
early binary
formation
Sasaki et al. PRL
117, 061101 (2016)
Raidal et al.
JCAP 02, 018 (2019)

PBH fraction



PBH mass

Sub-solar mass search in LVK

O2 Extended search of O2 data (allowing large mass ratio)

Triggers with FAR < 2 yr⁻¹

Phukon et al., arXiv: 2105.11449

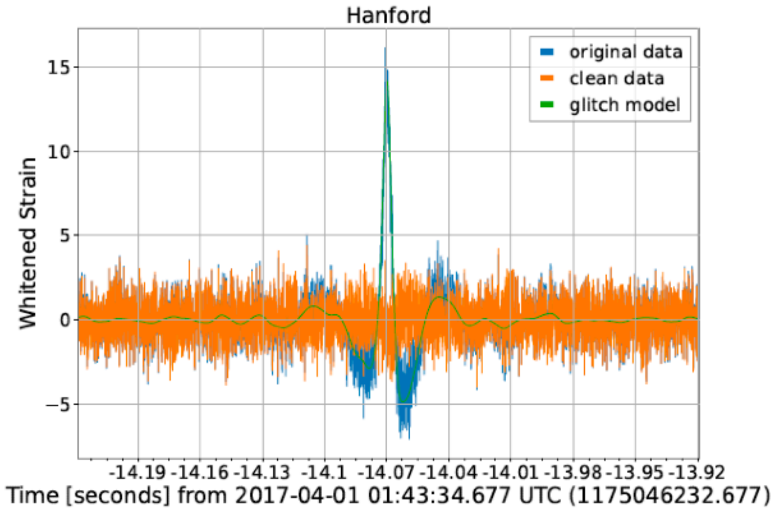
FAR [yr^{-1}]	$\ln \mathcal{L}$	UTC time	mass 1 [$M_\odot$]	mass 2 [$M_\odot$]	spin1z	spin2z	Network SNR	H1 SNR	L1 SNR
0.1674	8.457	2017-03-15 15:51:30	3.062	0.9281	0.08254	-0.09841	8.527	8.527	-
0.2193	8.2	2017-07-10 17:52:43	2.106	0.2759	0.08703	0.0753	8.157	-	8.157
0.4134	7.585	2017-04-01 01:43:34	4.897	0.7795	-0.05488	-0.04856	8.672	6.319	5.939
1.2148	6.589	2017-03-08 07:07:18	2.257	0.6997	-0.03655	-0.04473	8.535	6.321	5.736

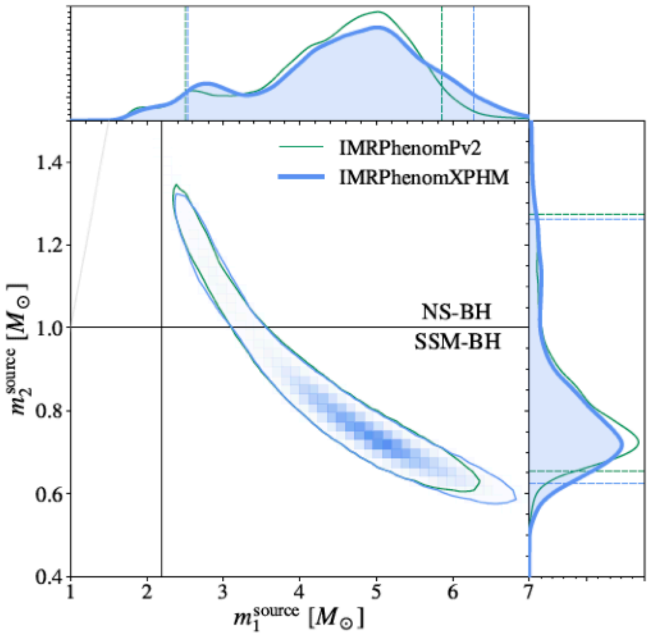
reanalysis by
removing a glitch
extending f_{min} to 20Hz
using more accurate waveform

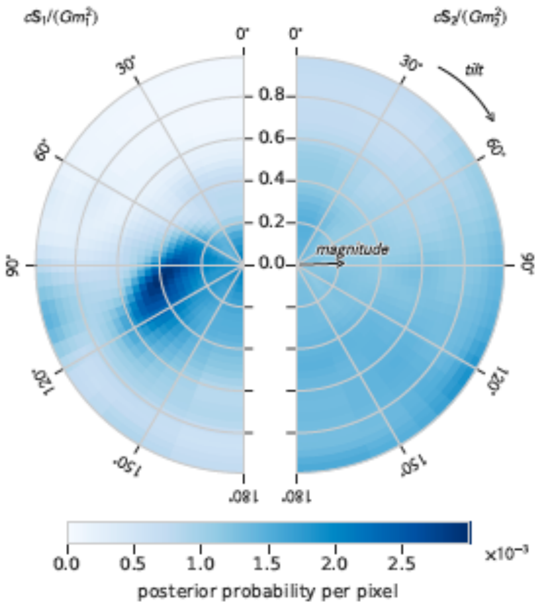
→ SNR is reduced

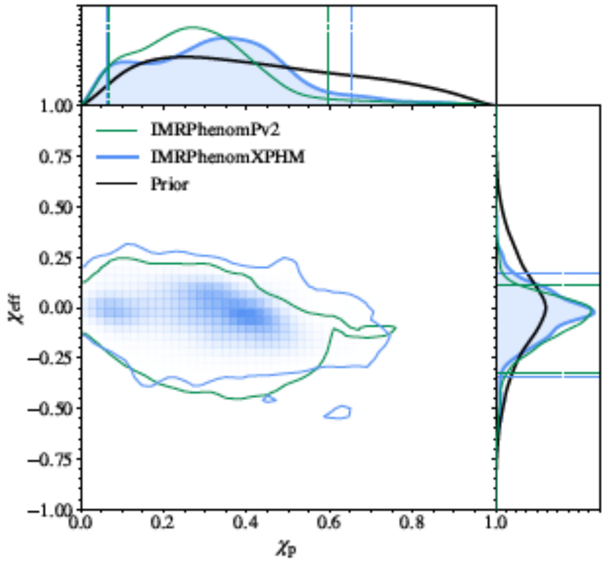
Morrás et al., PDU 42, 101285 (2023)

Parameter	IMRPhenomPv2	IMRPhenomXPHM
Signal to Noise Ratio	$7.98^{+0.62}_{-1.03}$	$7.94^{+0.70}_{-1.05}$
Primary mass ($M_\odot$)	$4.65^{+1.21}_{-2.15}$	$4.71^{+1.57}_{-2.18}$
Secondary mass ($M_\odot$)	$0.77^{+0.50}_{-0.12}$	$0.76^{+0.50}_{-0.14}$







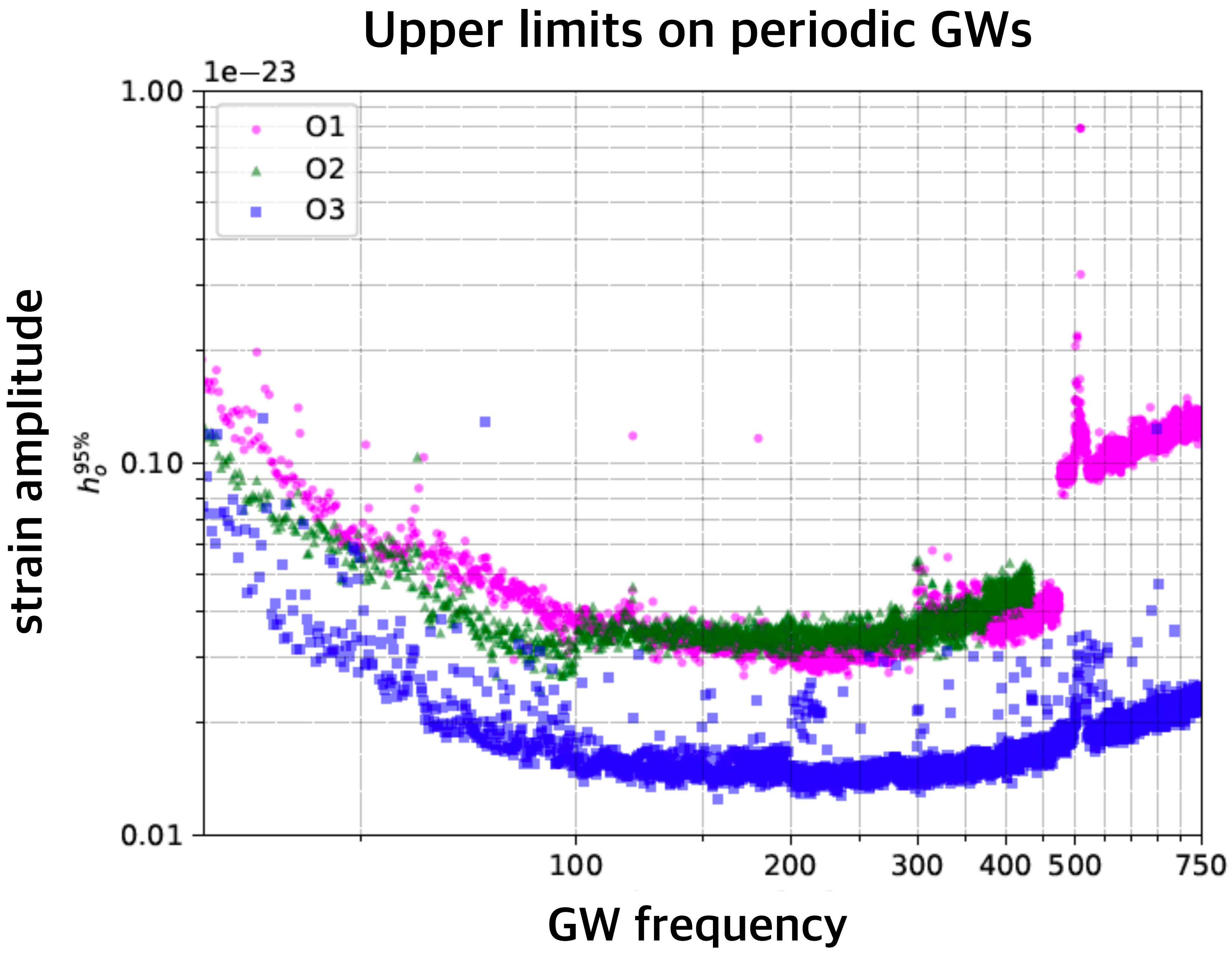


Planetary mass BH constraints

LVK collaboration, PRD 106, 102008 (2022)

Continuous wave (CW) search

Initial target: spinning neutron star with mass asymmetry



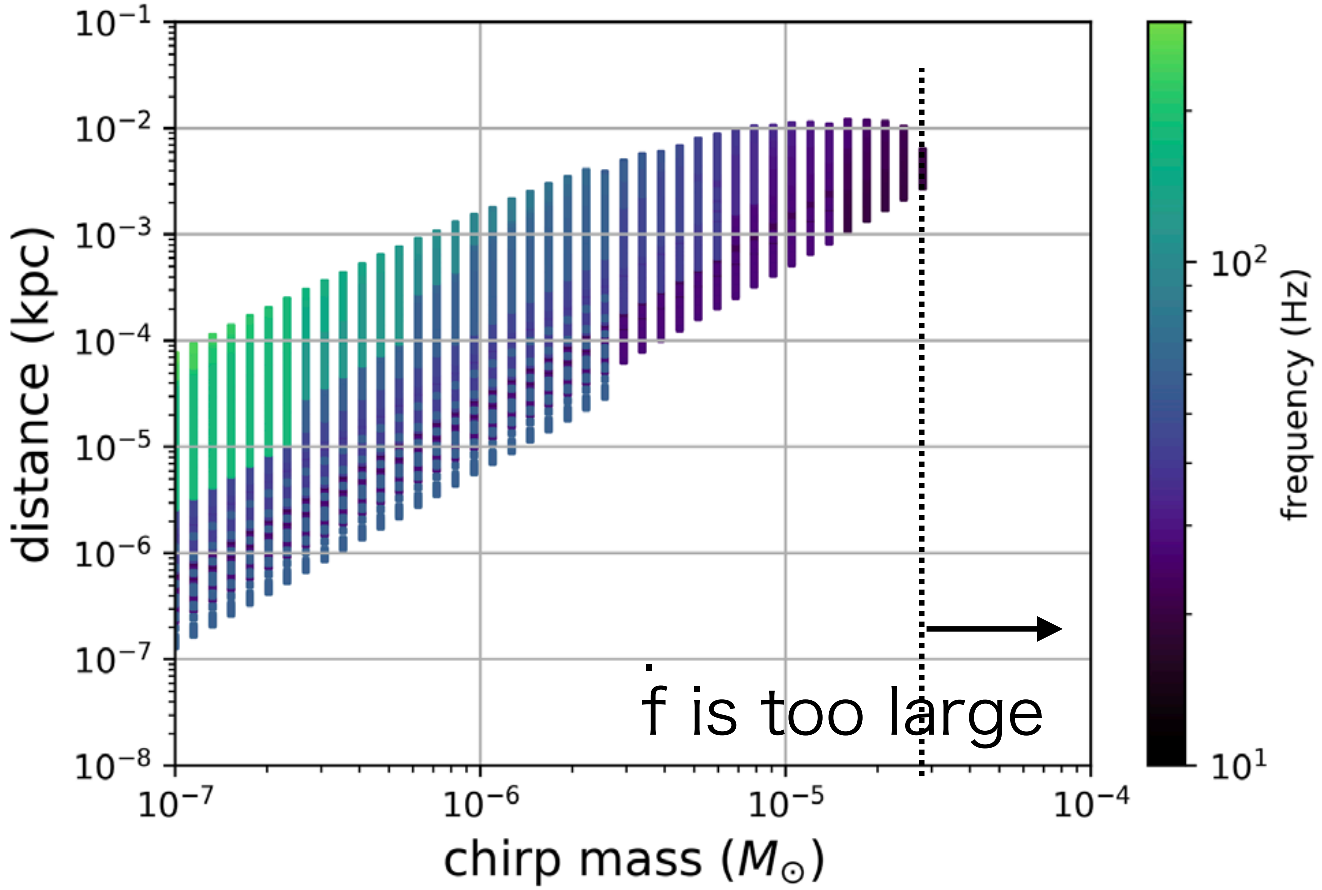
→ can be used to constrain small mass PBH binaries with small frequency change

Constraints from CW search

Miller et al., PRD 105, 062008 (2022)

Powerflux pipeline

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

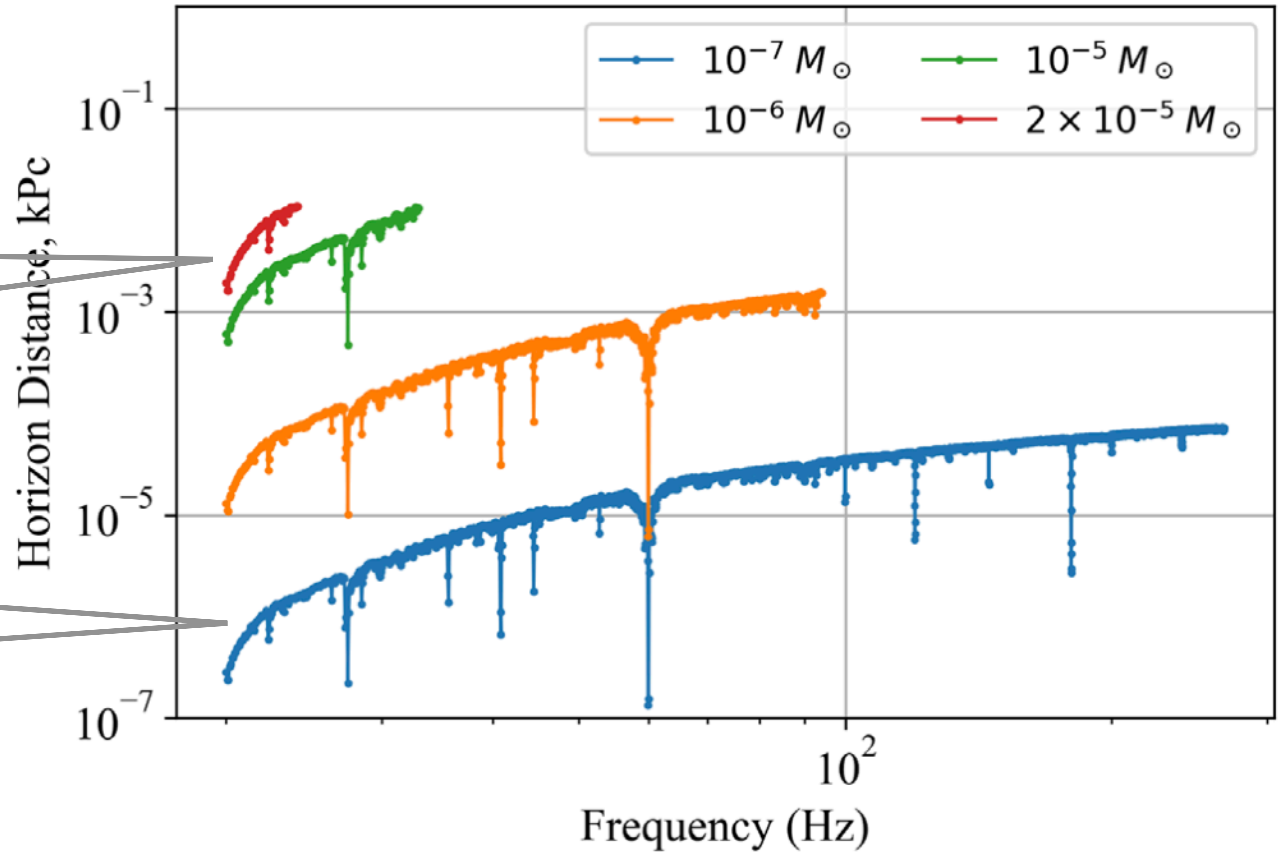


$\dot{f}$ is too large

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

$$\simeq 9.83 \times 10^{-11}\ \mathrm{Hz/s}\left(\frac{\mathcal{M}}{10^{-6}\ M_\odot}\right)^{5/3}\left(\frac{f_{\mathrm{gw}}}{50\ \mathrm{Hz}}\right)^{11/3}$$

→ grows too fast for
larger mass and larger frequency

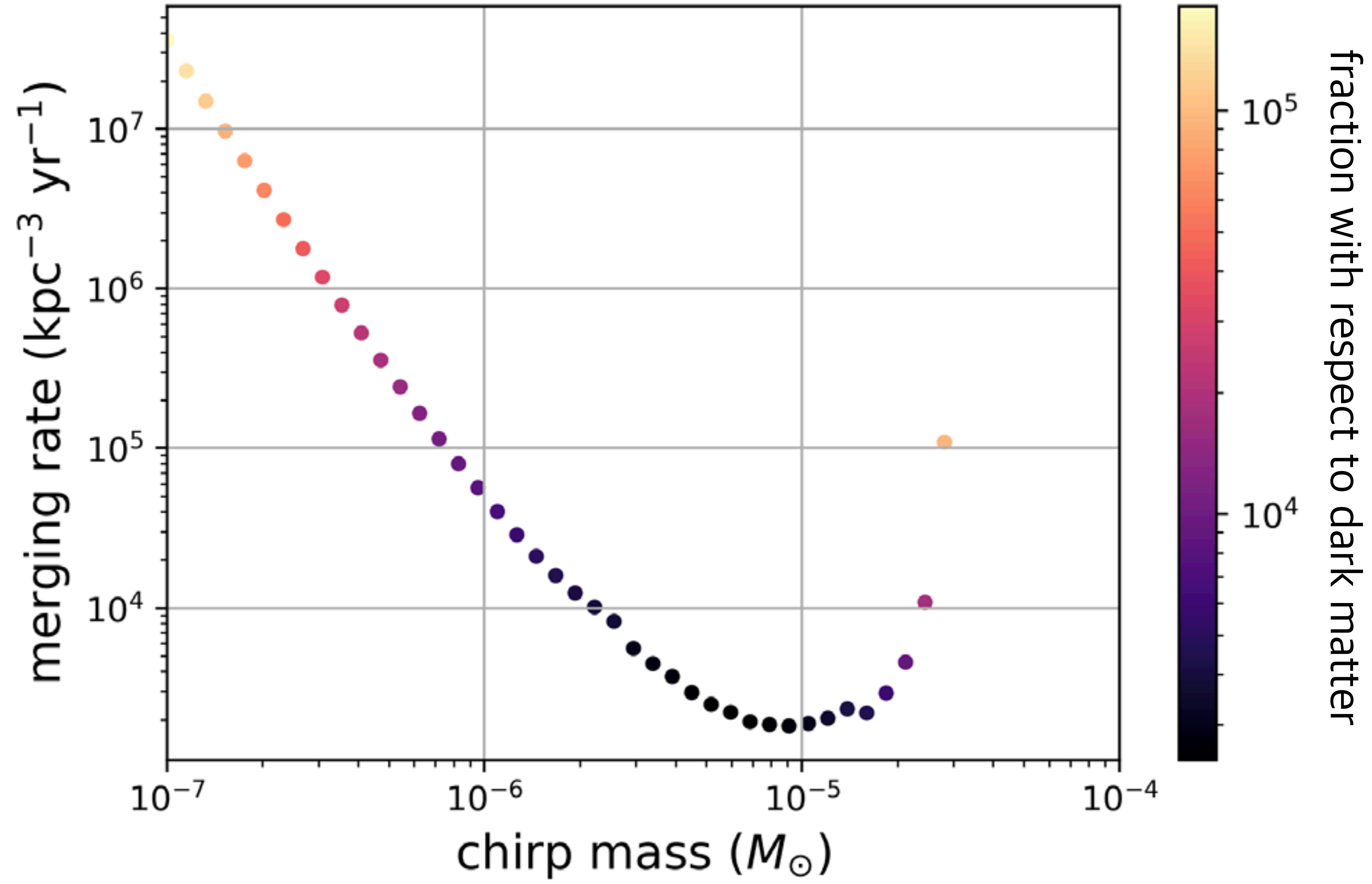


Large mass:
large strain amplitude
but $\dot{f}$ becomes too large for high frequencies

Small mass:
can be covered in wide frequency
but strain amplitude is small

Constraints from CW search

Miller et al., PRD 105, 062008 (2022)



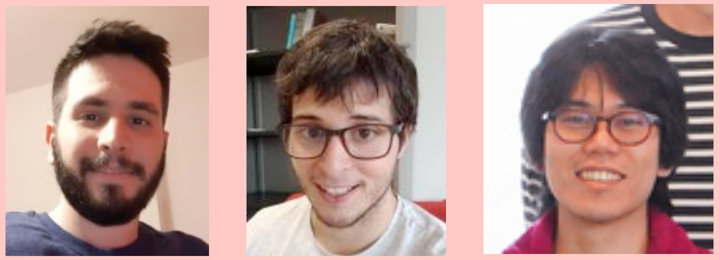
strain amplitude is too small

$\dot{f}$ is too large

Detection principle:
Miller et al., PDU 32, 100836 (2021)

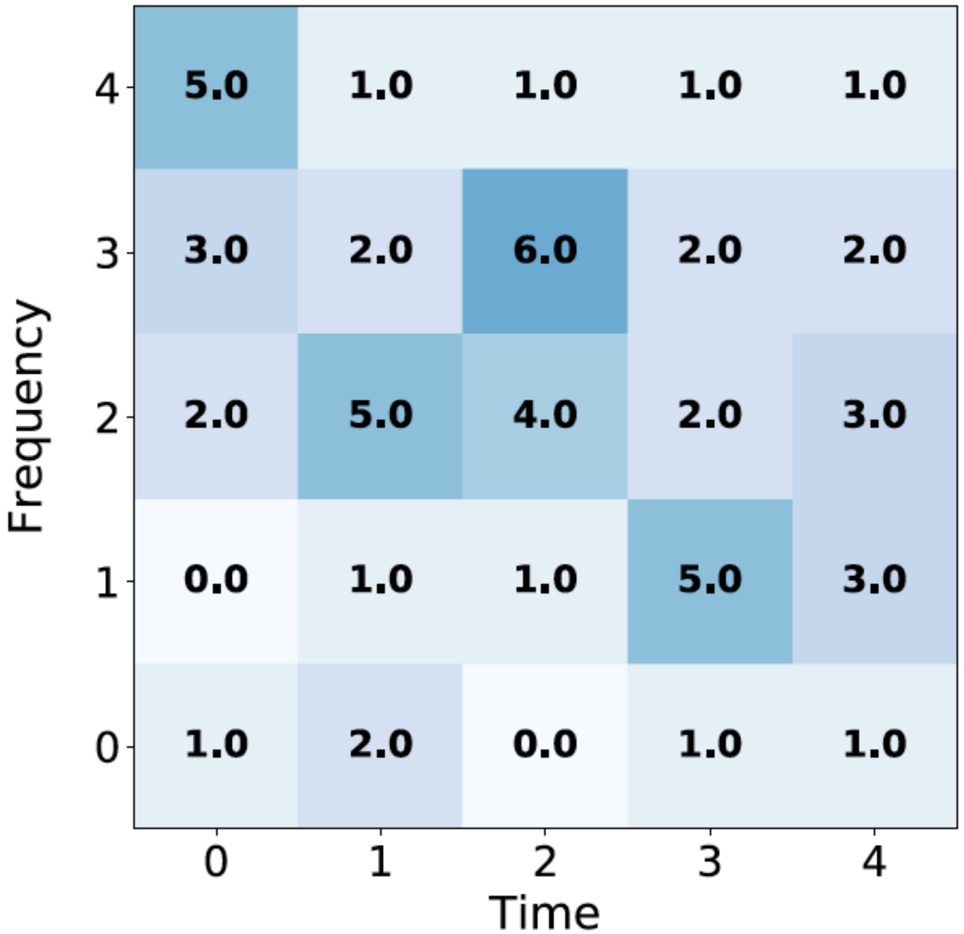
Planetary mass search

Paper in preparation with
George Alestas, Gonzalo Morras, Takahiro Yamamoto,
Juan Garcia-Bellido, Savvas Nesseris



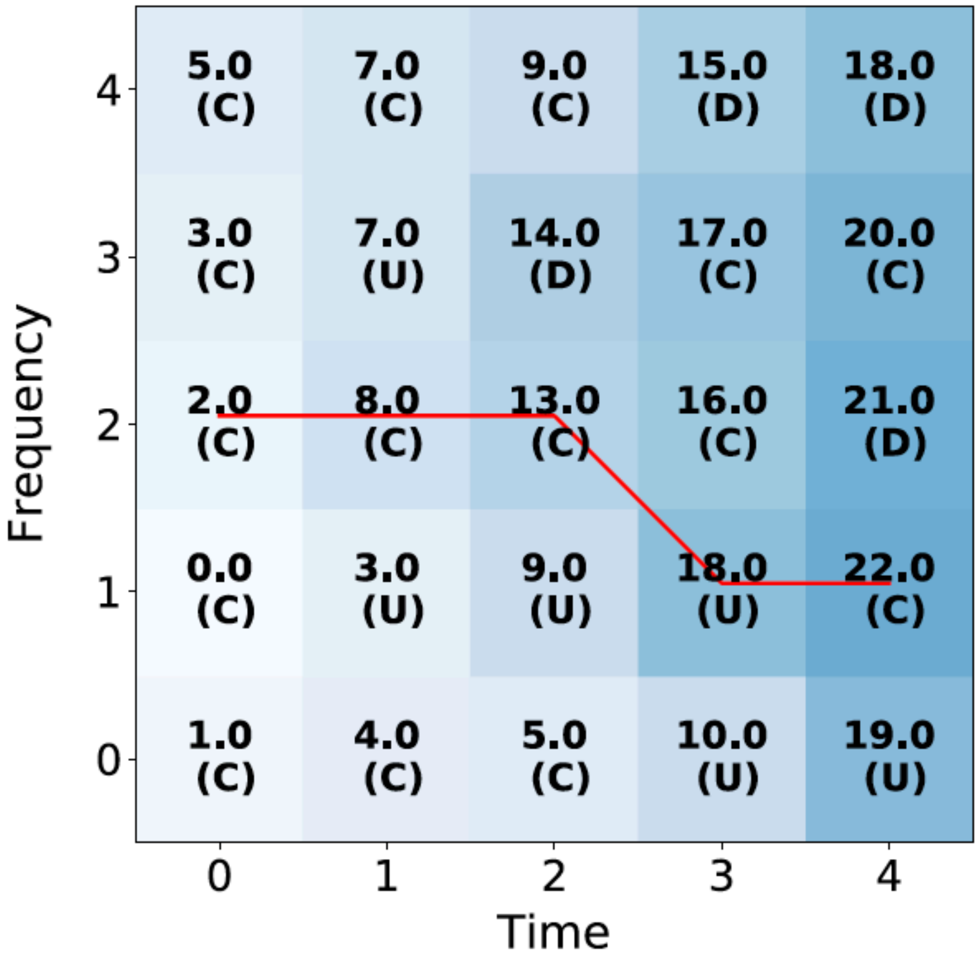
Viterbi algorithm

Step-by-step scan for most probable signal location



Frequency	0	1	2	3	4
4	5.0	1.0	1.0	1.0	1.0
3	3.0	2.0	6.0	2.0	2.0
2	2.0	5.0	4.0	2.0	3.0
1	0.0	1.0	1.0	5.0	3.0
0	1.0	2.0	0.0	1.0	1.0

(a) The input data



Frequency	0	1	2	3	4
4	5.0 (C)	7.0 (C)	9.0 (C)	15.0 (D)	18.0 (D)
3	3.0 (C)	7.0 (U)	14.0 (D)	17.0 (C)	20.0 (C)
2	2.0 (C)	8.0 (C)	13.0 (C)	16.0 (C)	21.0 (D)
1	0.0 (C)	3.0 (U)	9.0 (U)	18.0 (U)	22.0 (C)
0	1.0 (C)	4.0 (C)	5.0 (C)	10.0 (U)	19.0 (U)

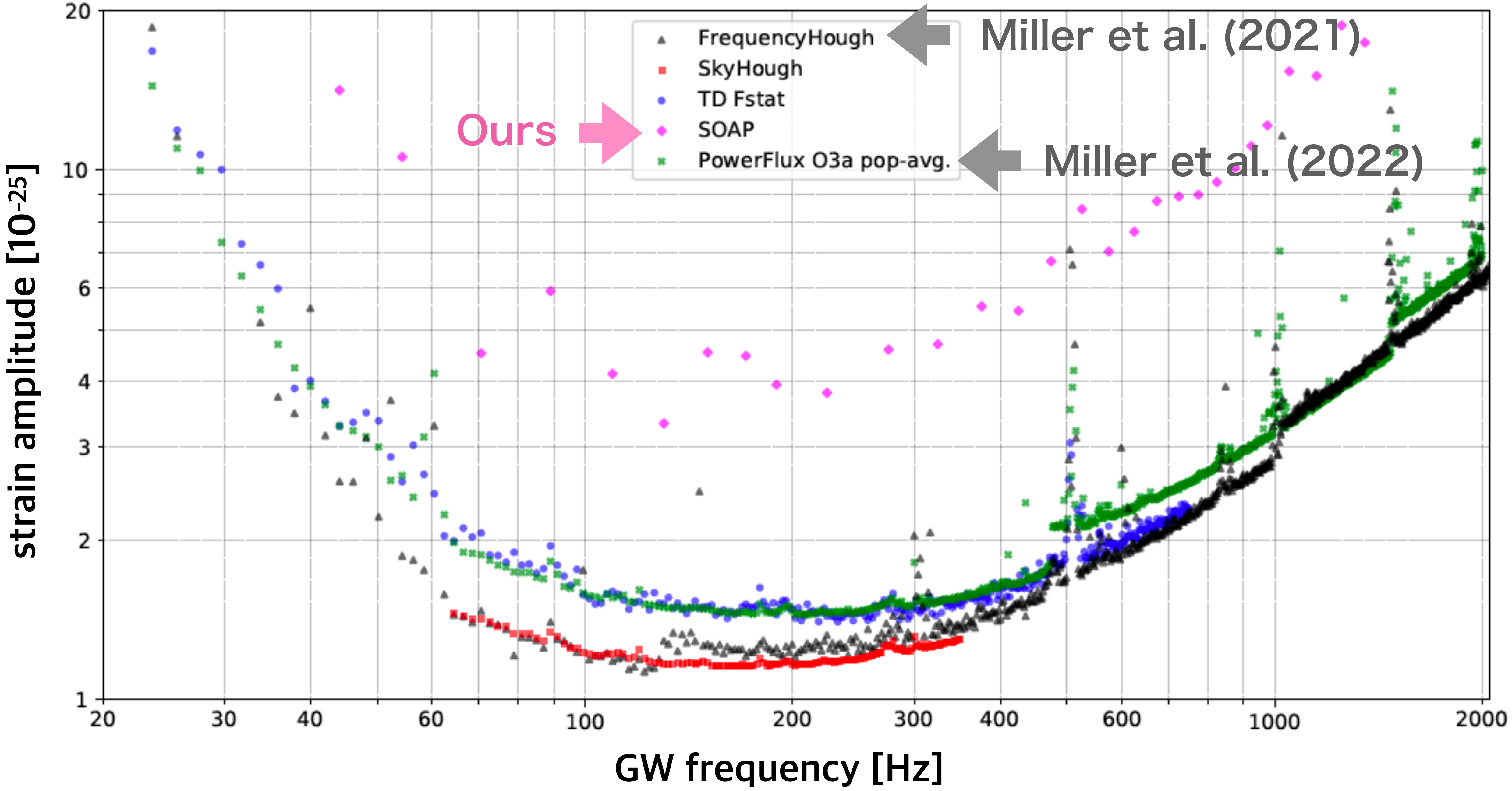
(b)The log-probabilities, jumps, and most probable path

amplitude excess in the f-t plane

Bayley et al. PRD 100, 023006 (2019)

Planetary mass search

Already used in CW search



Miller et al. (2021)

Ours

Miller et al. (2022)

Not very sensitive, but fast and agnostic

Optimal SFT length

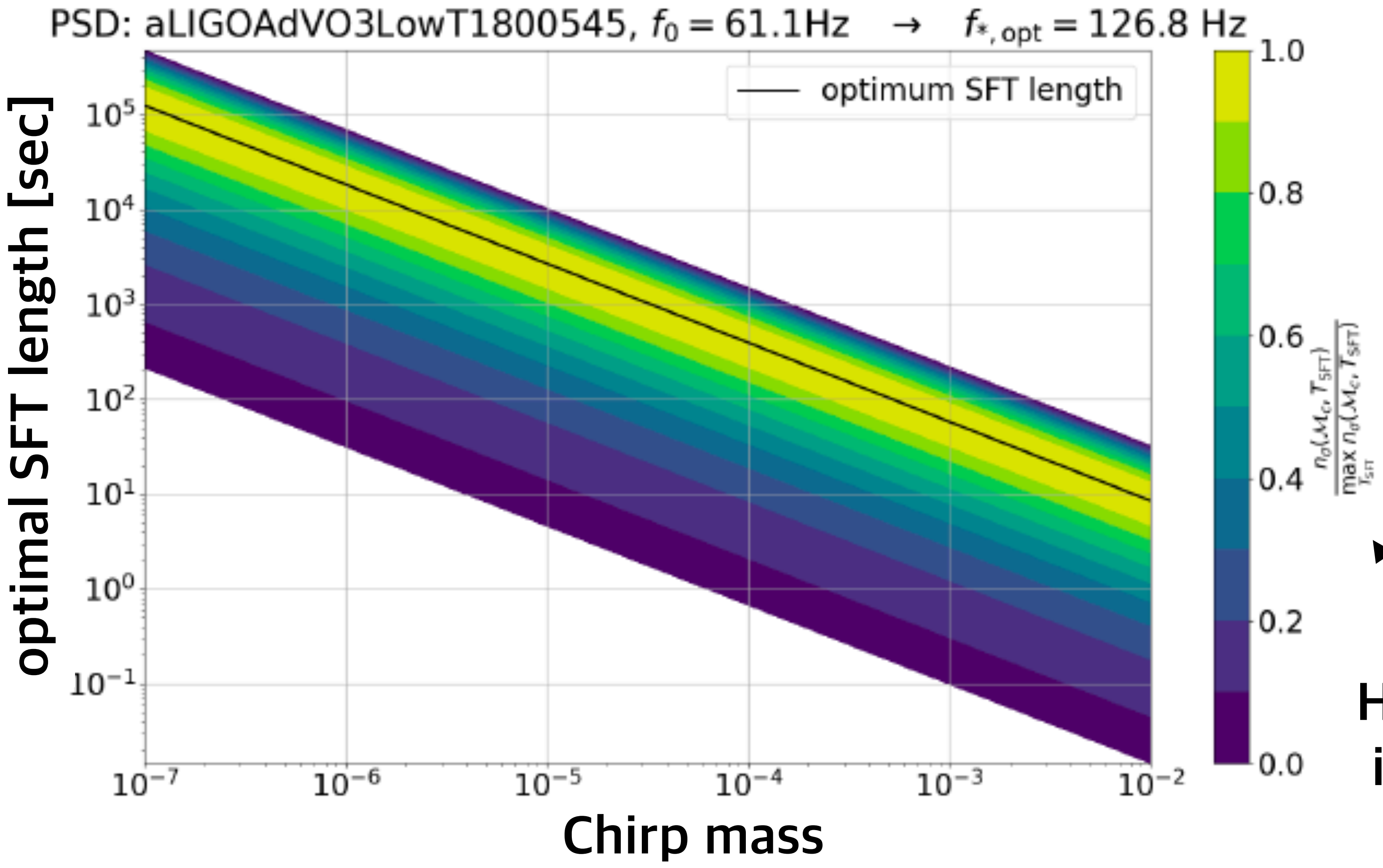
SFT (short time Fourier transformation)

$\dot{f}$ is relatively large so the signal do not stay in one frequency bin

→ We have to divide the data into optimal length

<u>SFT to maximize "sigma"</u>

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

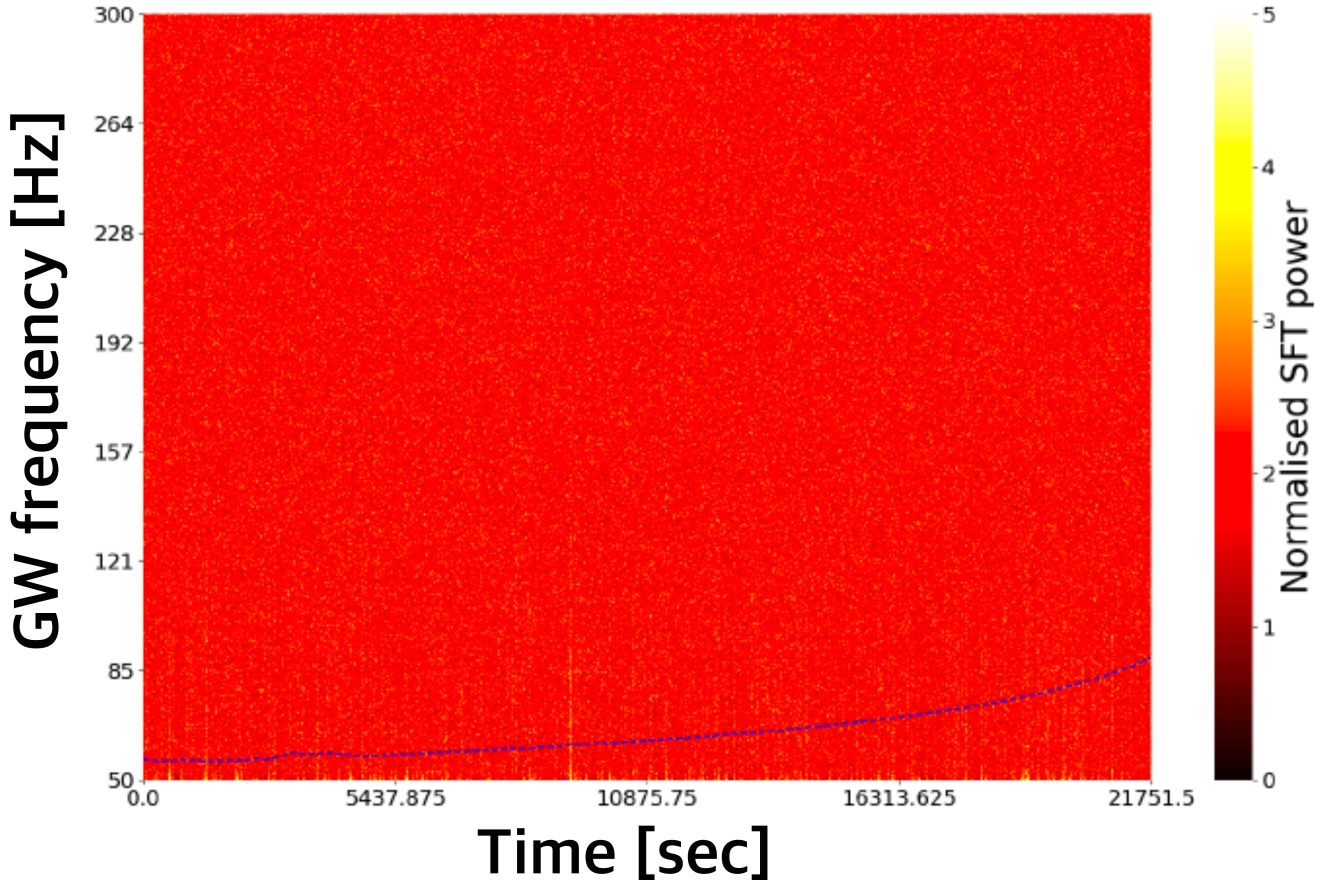


How much it loses "sigma"
if we use different length

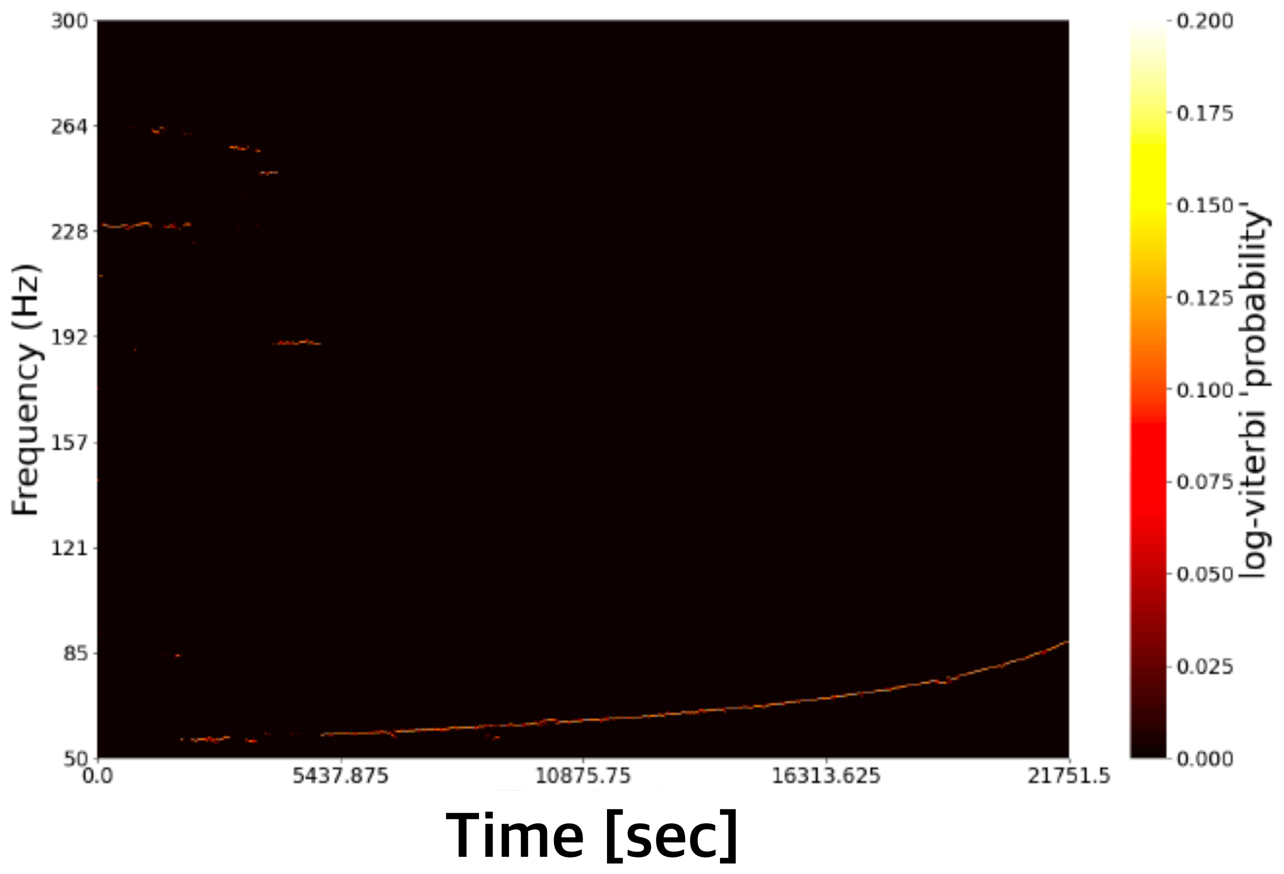
Working example

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

Injeccted signal

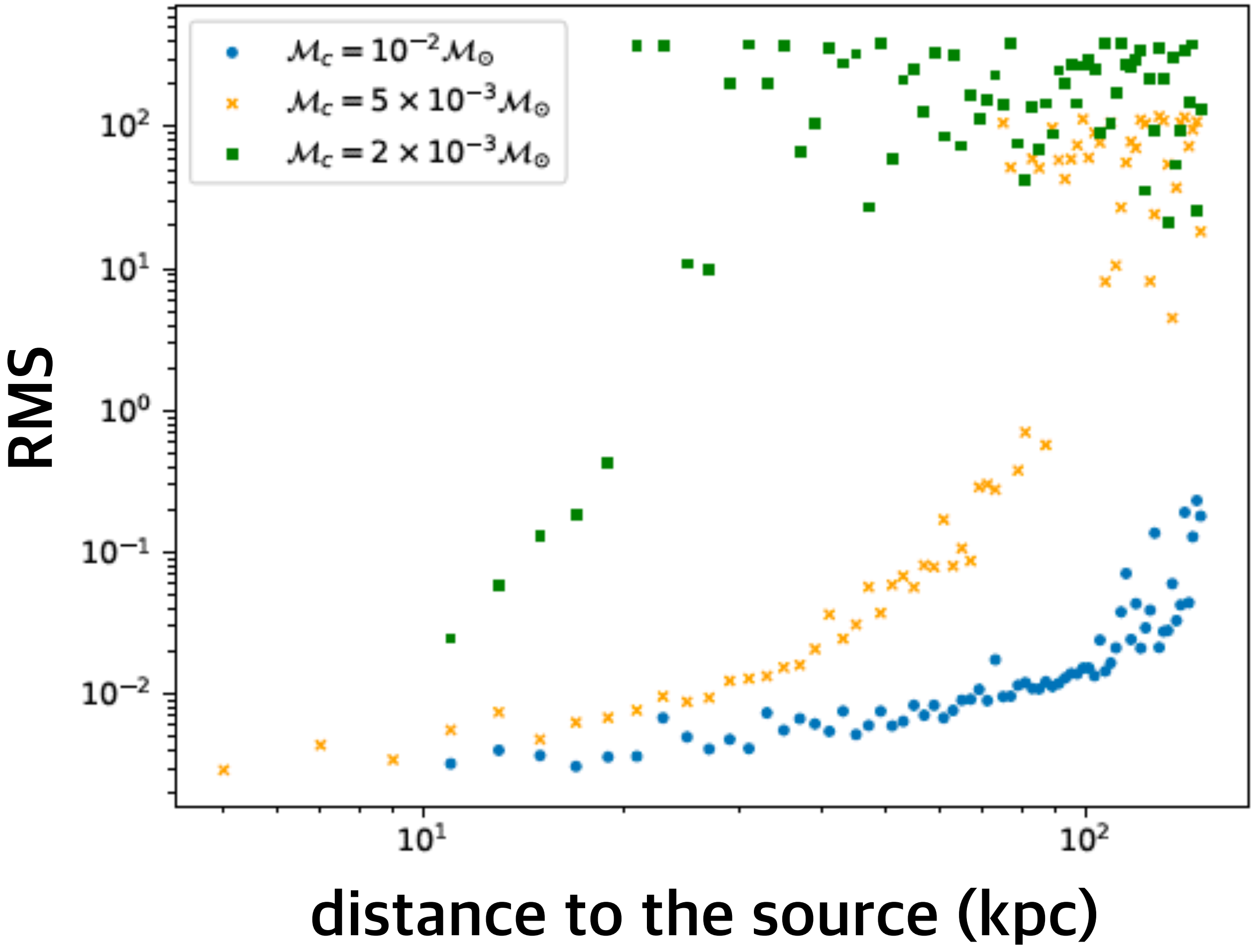


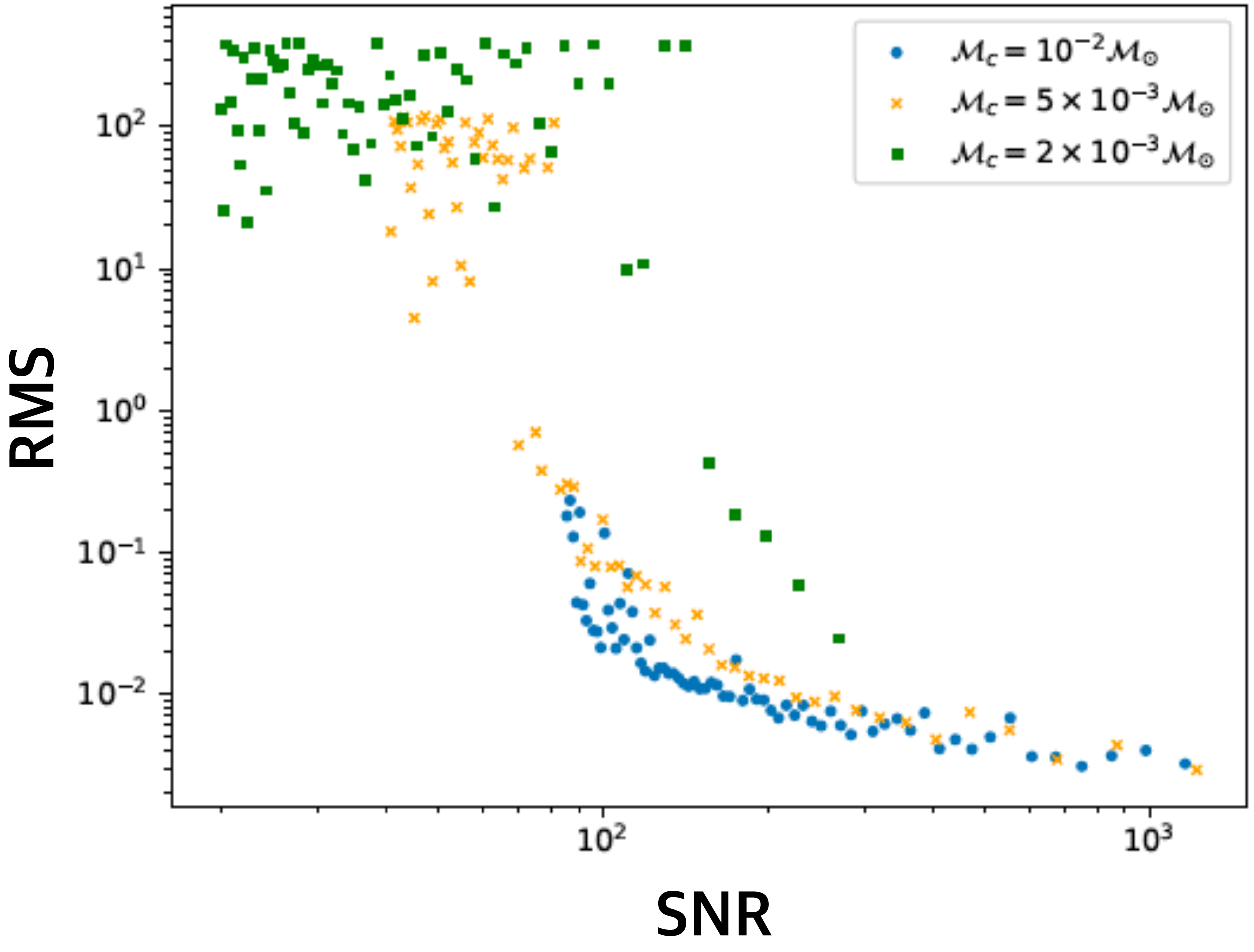
Recovery by Viterbi



Sensitivity

RMS: root mean square distance





of template search

Signal-to-noise ratio (SNR)

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

Summary

There are increasing attention to subsolar mass search.

Motivations (yesterday's talk by K. Kohri)

2nd order GW at NANOGrav indicates $\sim 10^{-5}$ - 10^{-3} $M_\odot$

OGLE microlensing event corresponds $\sim 10^{-6}$ - 10^{-4} $M_\odot$

- Single $< 1 M_\odot$ event will be a strong evidence for PBH.
- We are exploring application of Viterbi algorithm for planetary mass search
- The code runs very fast: ~8 sec with Macbook (SFT preparation not included)
- has advantage to detect unmodeled signal with non-trivial frequency evolution
- The method worked for Gaussian noise case. Next step is to test with more realistic data (with glitch and line noises)