Tracking the origin of black holes with the stochastic gravitational wave background popcorn signal

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arXiv: 2201.13414

in collaboration with

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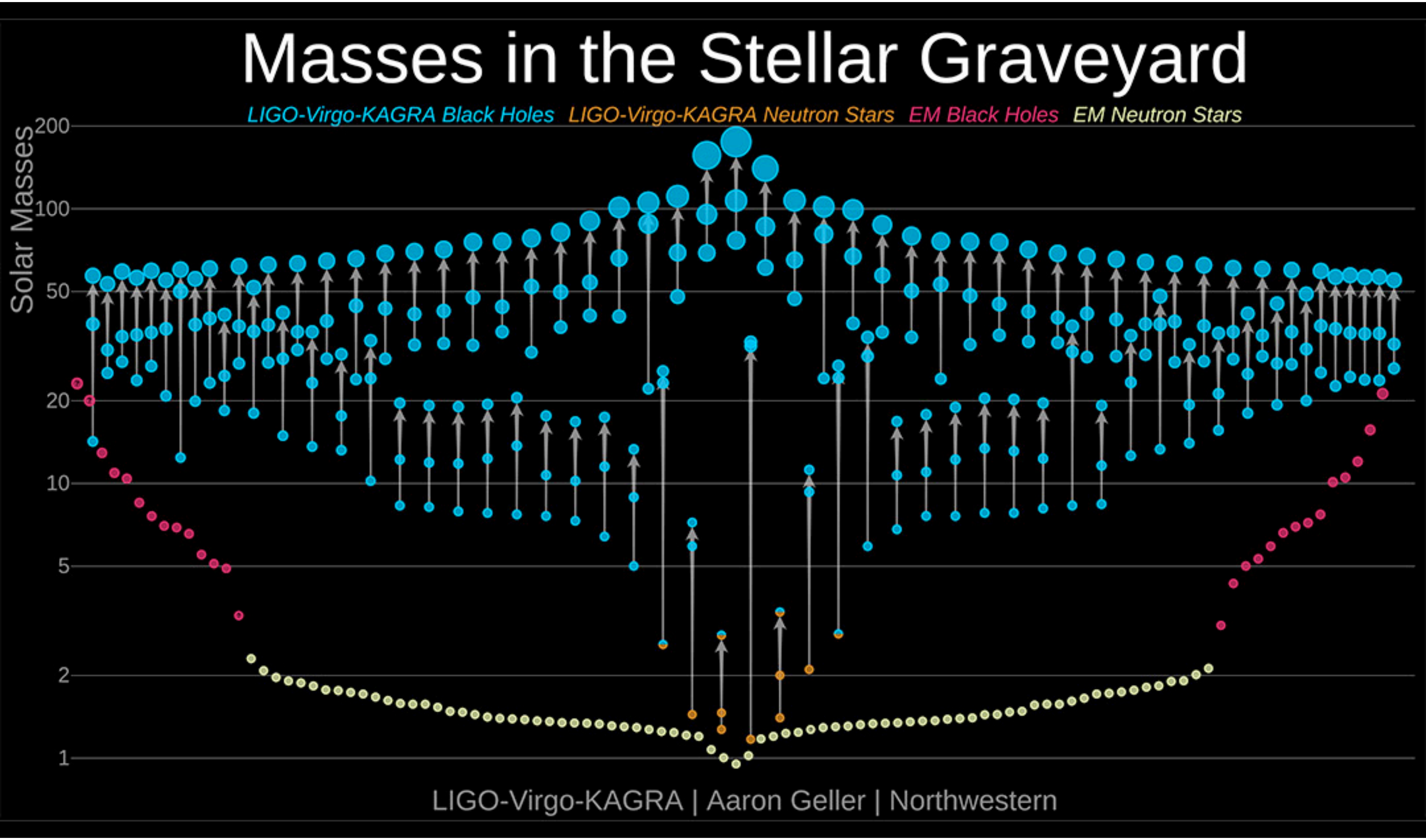
GWs from Binary Black Holes (BBHs)

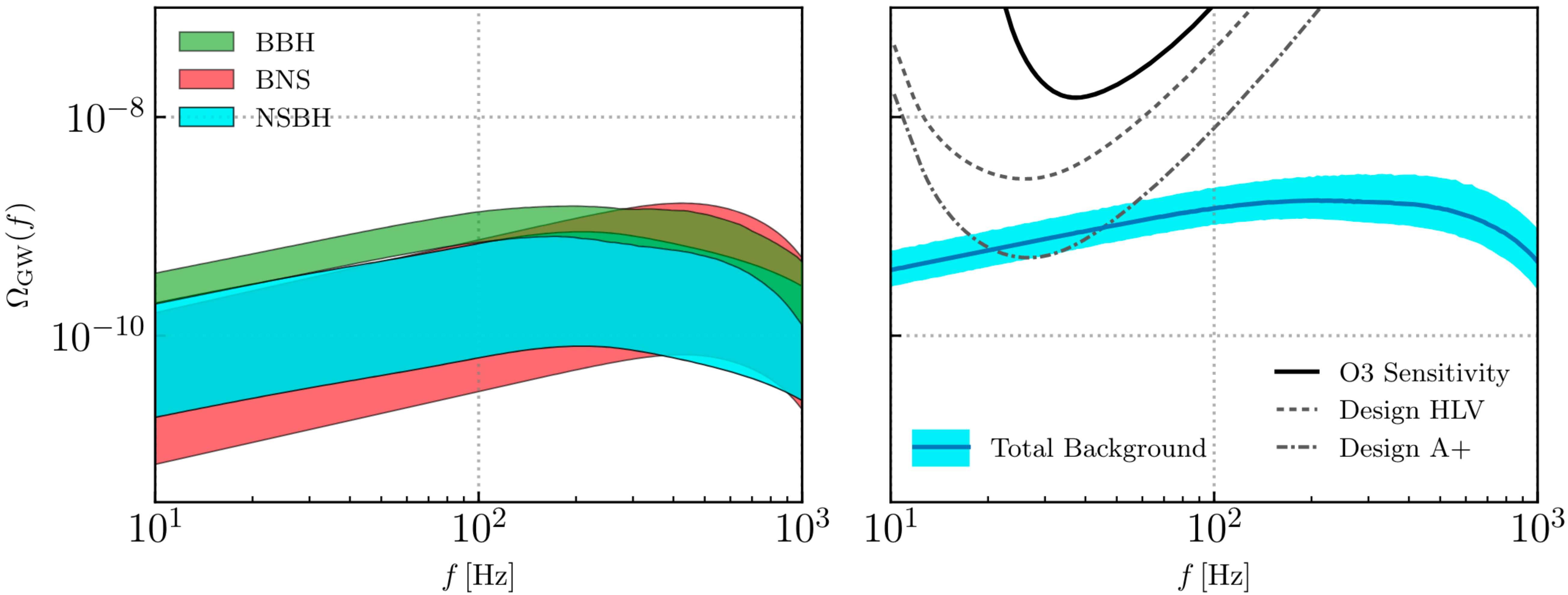


90 BBHs have been observed!

Event rate: 17.3 - 45 $Gpc^{-3}\ yr^{-1}$

Stochastic GW background from BBHs

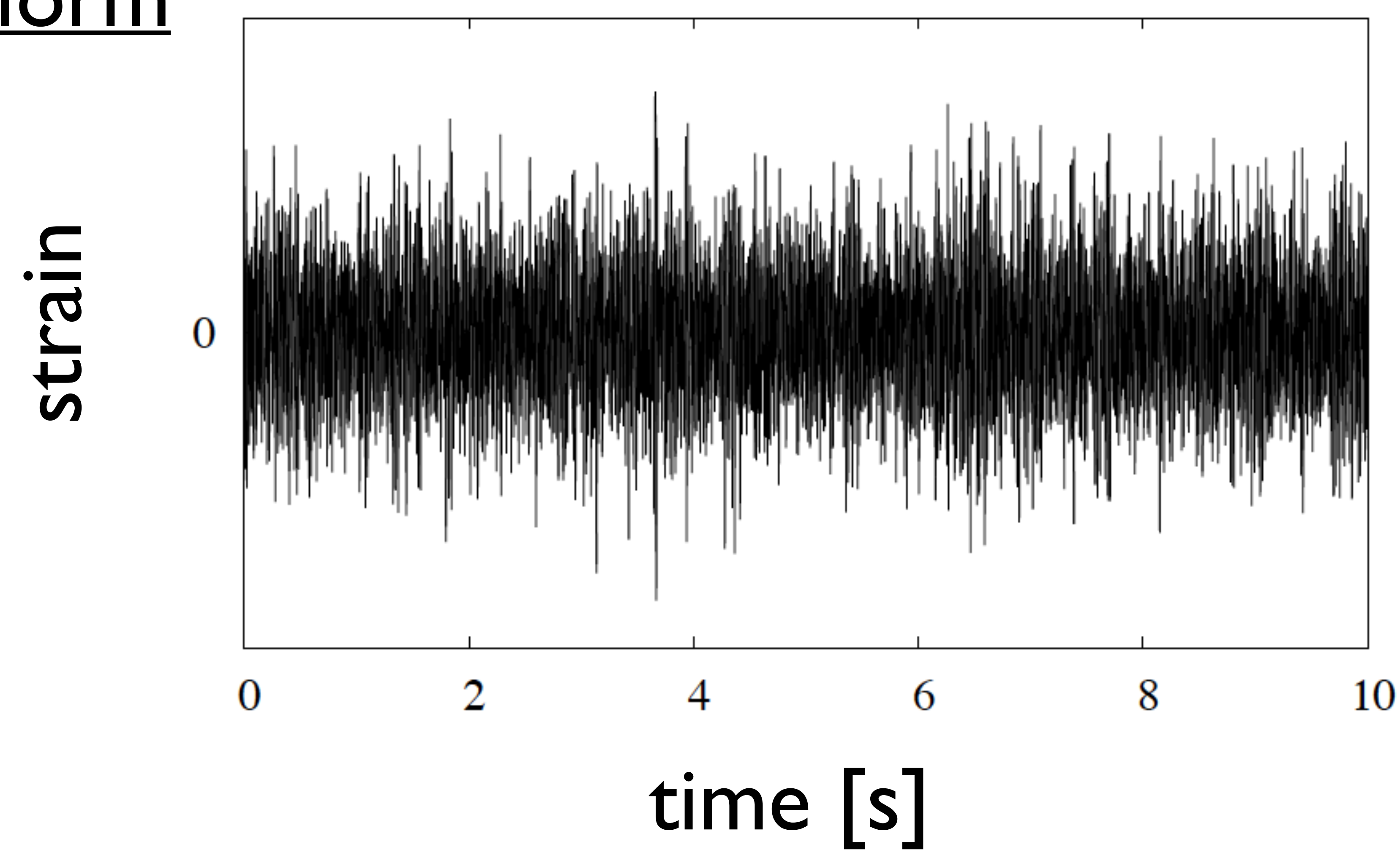
BBH event rate indicates the existence of
the stochastic GW background (SGWB)
possibly detectable by upgraded LVK detectors



LVK collaboration, arXiv:2111.03634

Stochastic GW background

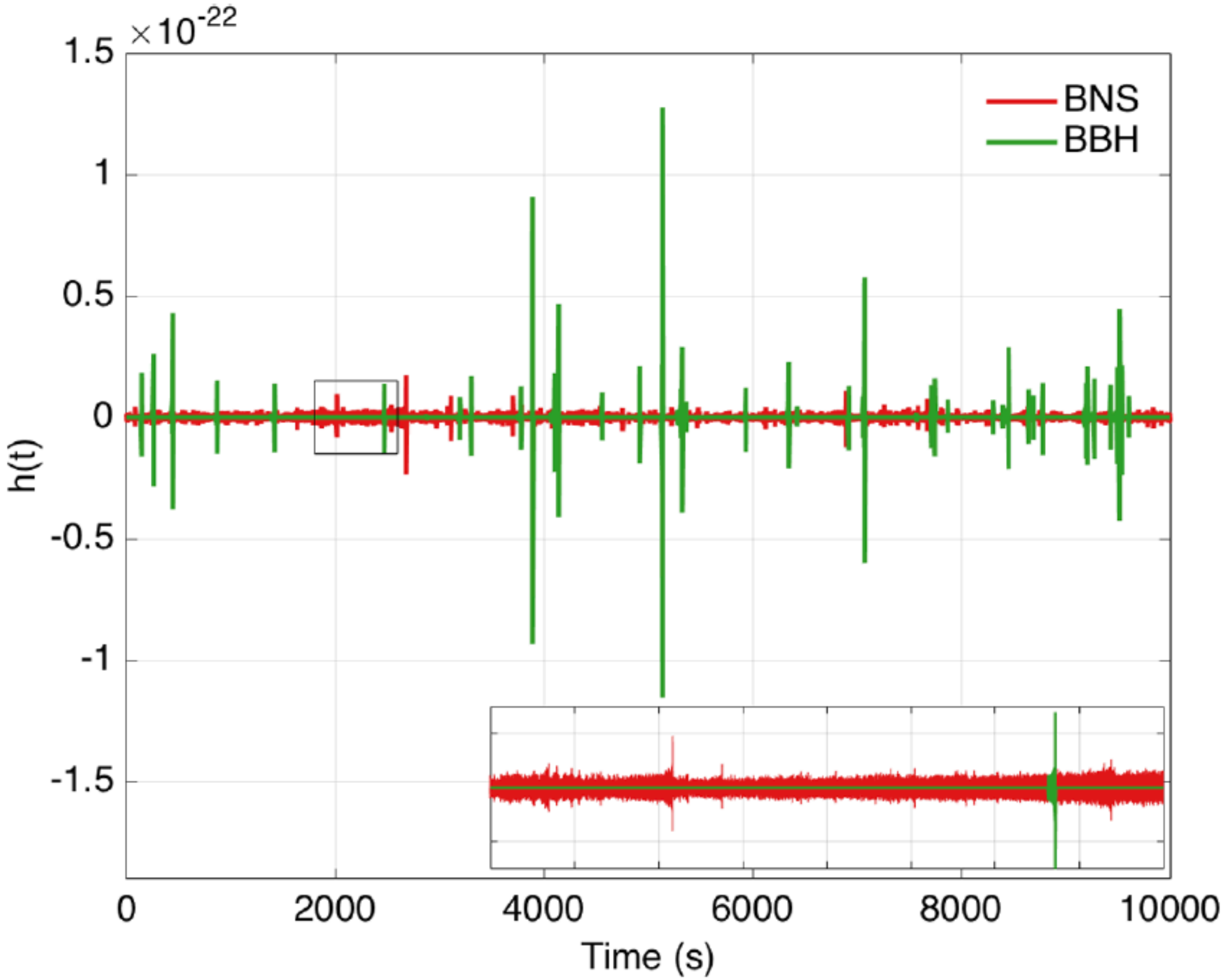
Waveform



Continuous and random gravitational wave (GW) signal coming from all directions → very similar to noise

Popcorn GW background

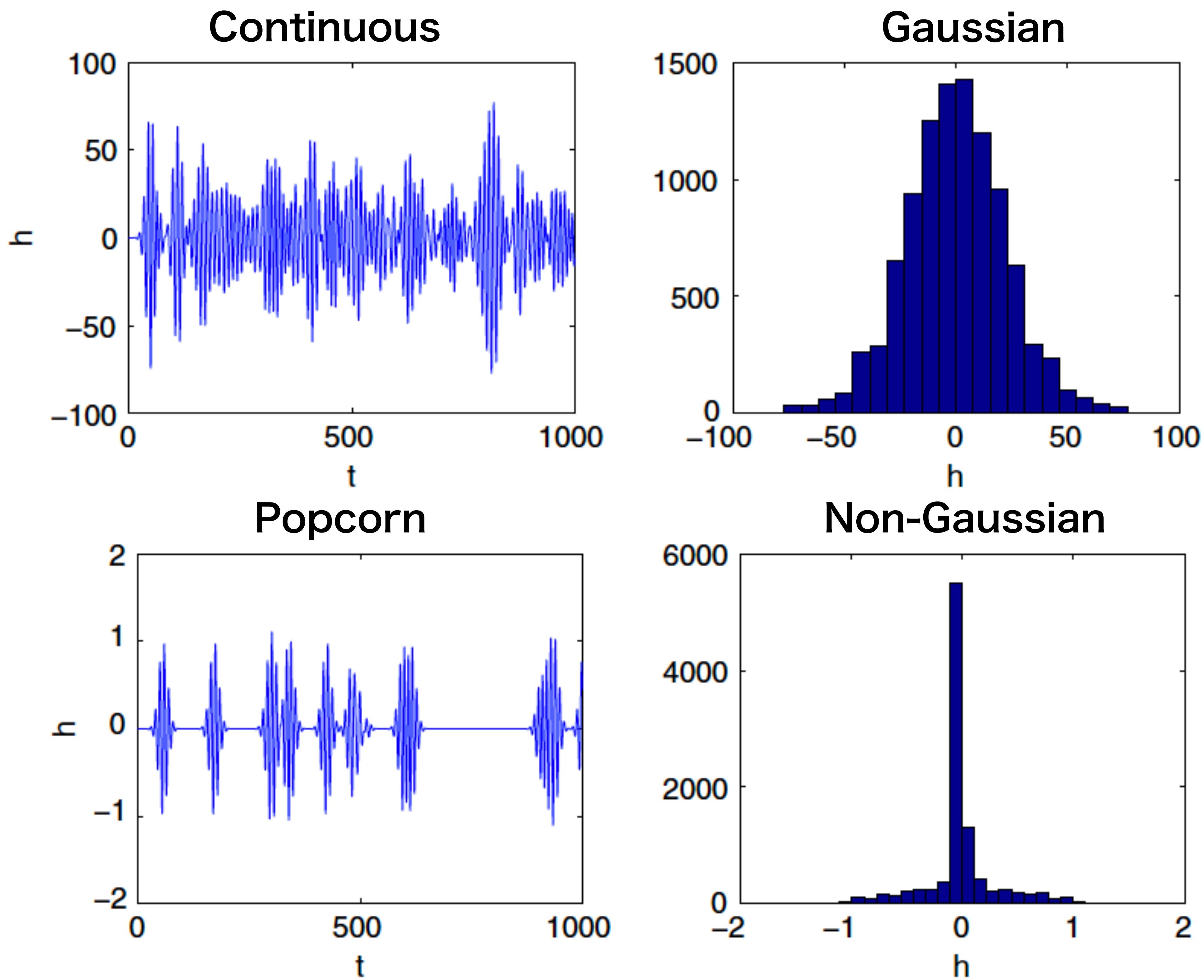
BBHs events do not overlap.



LV collaboration, PRL 120, 091101 (2018)

Popcorn = Non-Gaussian background

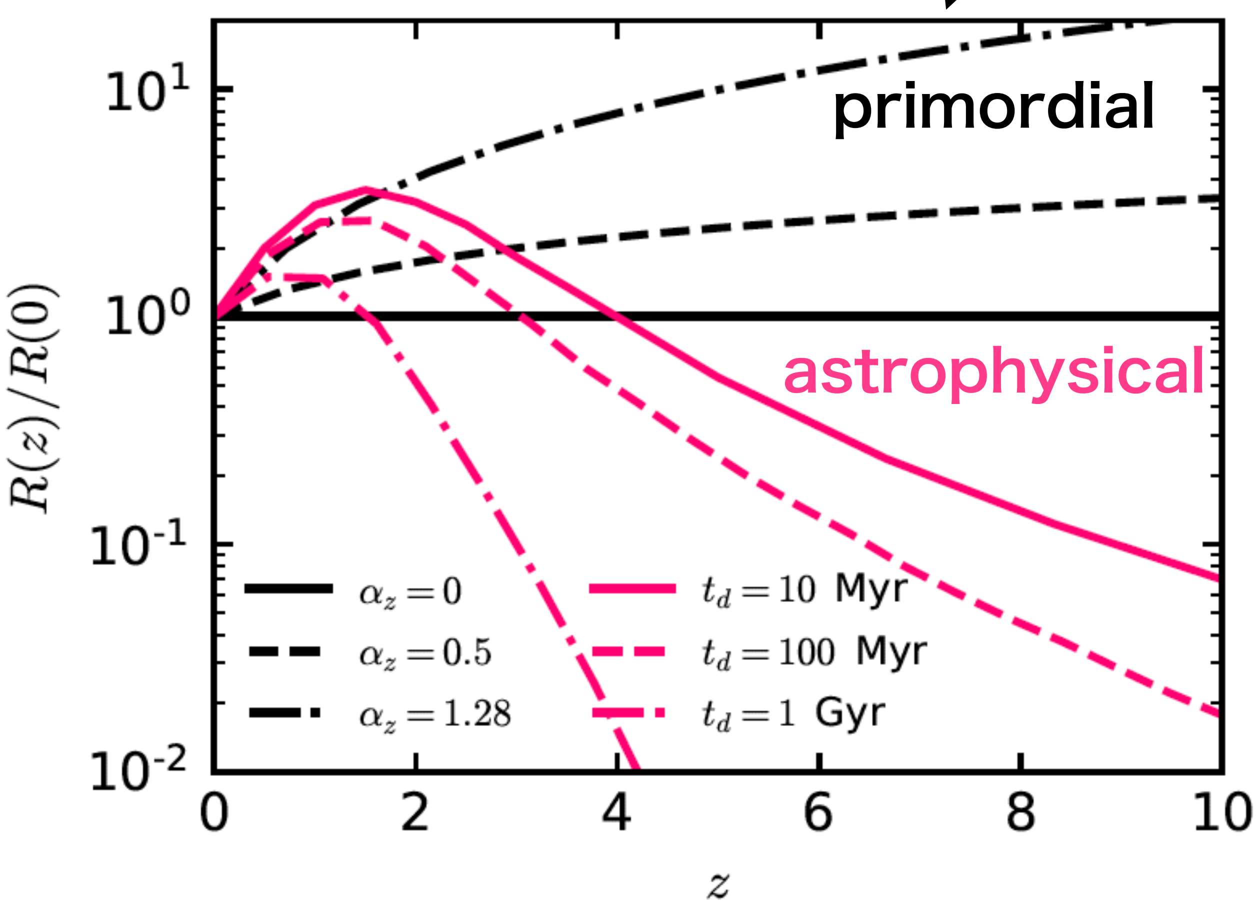
Figure from Thrane, PRD 87, 043009 (2013)

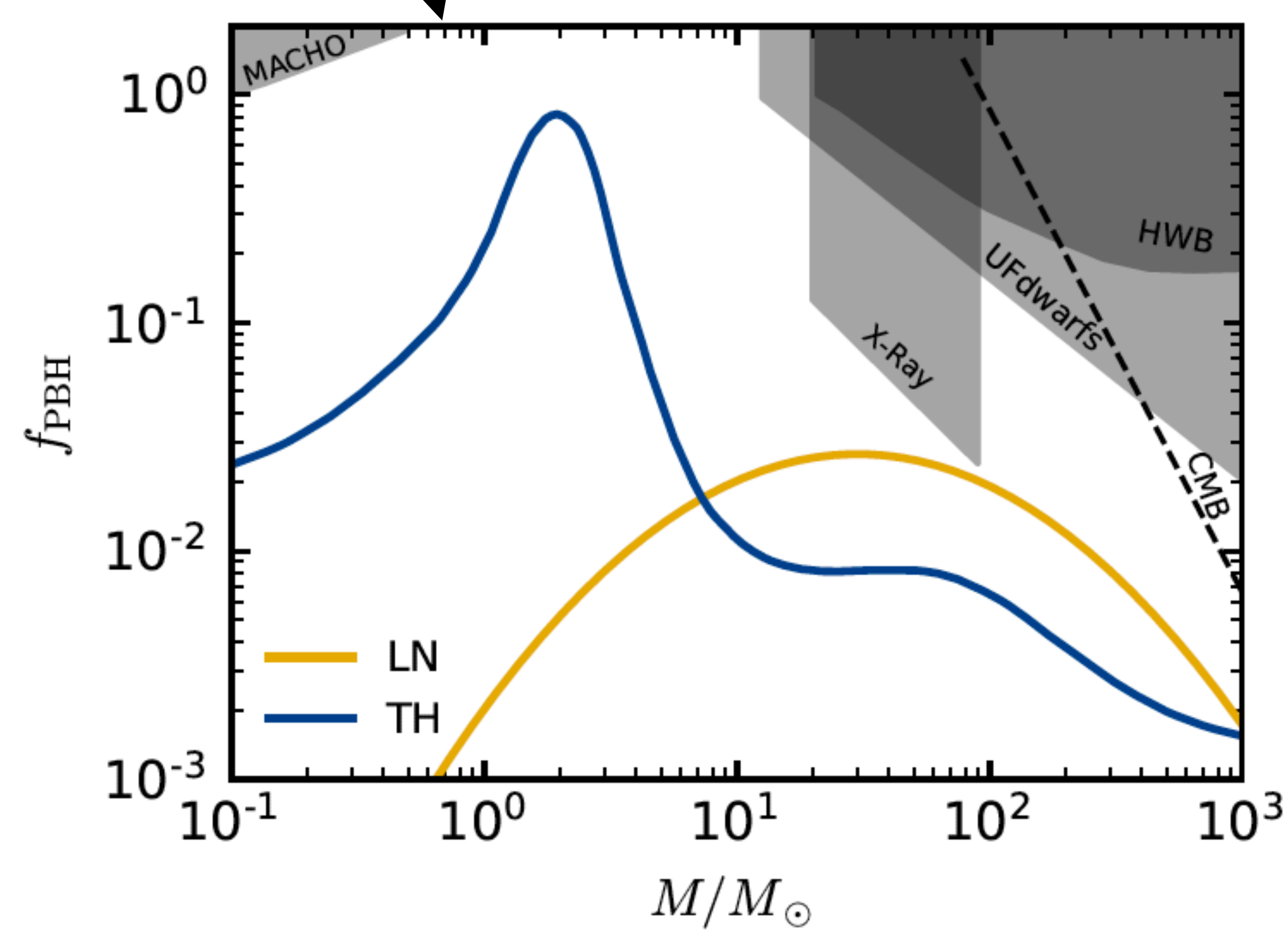


Does it help to tell whether the SGWB is astrophysical or primordial BBH origin?

Primordial Black Holes (PBHs)

The difference from astrophysical BHs (ABHs) can be seen in the merger rate and mass function





For PBH mass function, we consider

1. Lognormal (LN)
2. Standard-Model Thermal history (TM)

For ABHs, we use

$$P_1(m_1) \propto 1/m_1^{2.3}$$

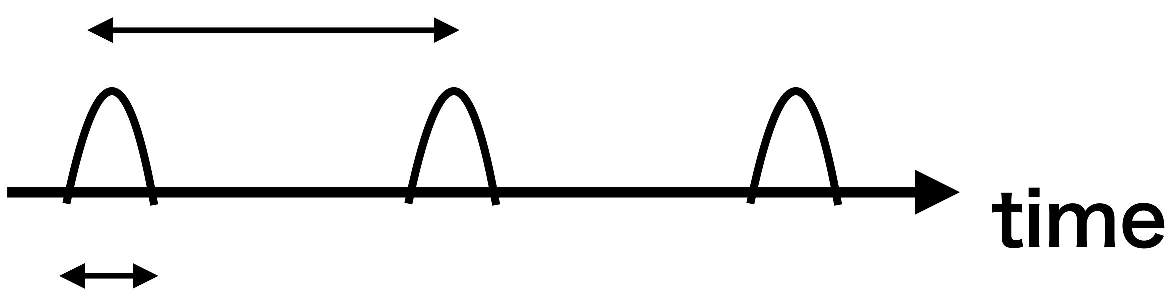
$$P_2(m_2) \propto 1/m_2$$

(Primary and Secondary mass)

Astrophysical Duty Cycle

How do we characterize a popcorn background?

ΔT : average time interval between two events



$\Delta\tau$: duration of the signal

Duty Cycle $\equiv \dfrac{\Delta\tau}{\Delta T}$

$DC \ll 1$ events do not overlap

$DC \gg 1$ events overlap

For BBH, we define

$$\frac{\mathrm{d}D}{\mathrm{d}f} = \int \mathrm{d}z \frac{\mathrm{d}R}{\mathrm{d}z}\frac{\mathrm{d}\bar{\tau}}{\mathrm{d}f}$$

$\Delta T \sim \left(\dfrac{\mathrm{d}R}{\mathrm{d}z}\right)^{-1}$ merger rate

$\Delta\tau \sim \dfrac{\mathrm{d}\bar{\tau}}{\mathrm{d}f} = \dfrac{5}{96\pi^{8/3}}(G\mathcal{M}_c^z)^{-5/3} f^{-11/3}$

chirp mass

Total duty cycle $\xi = \displaystyle\int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} \mathrm{d}f \frac{\mathrm{d}D}{\mathrm{d}f}$

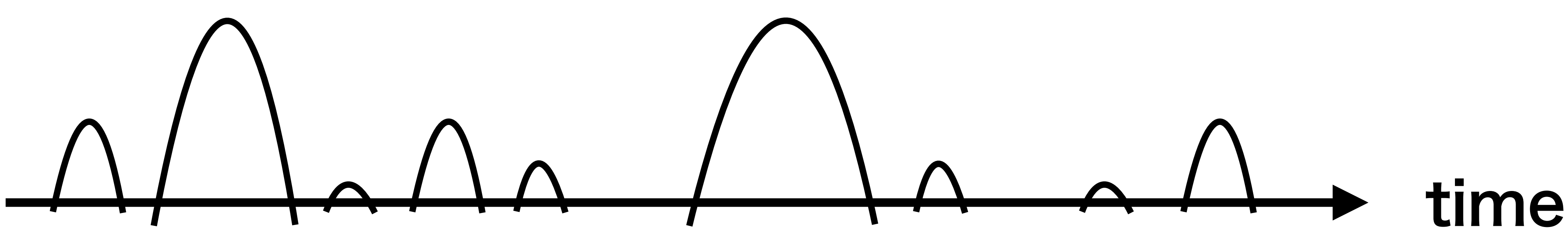
$\xi \ll 1$ **popcorn**

$\xi \gg 1$ **continuous**

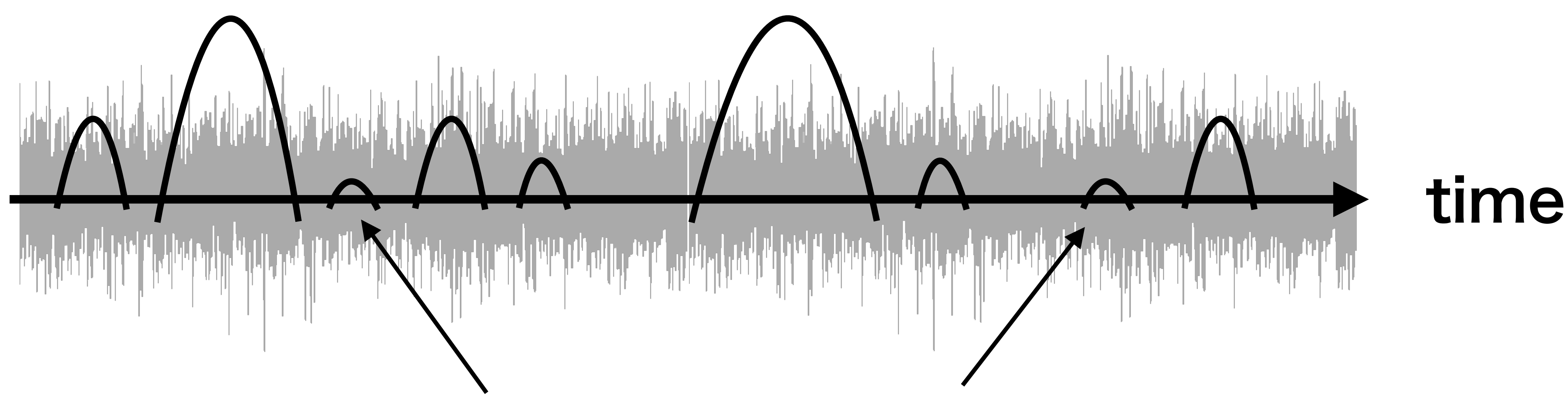
Detector-dependent Duty Cycle

Things to take into account for real data

1. Mixture of large and small events



2. Existence of noise



Do they contribute to the Duty Cycle? → No

Detector-dependent Duty Cycle

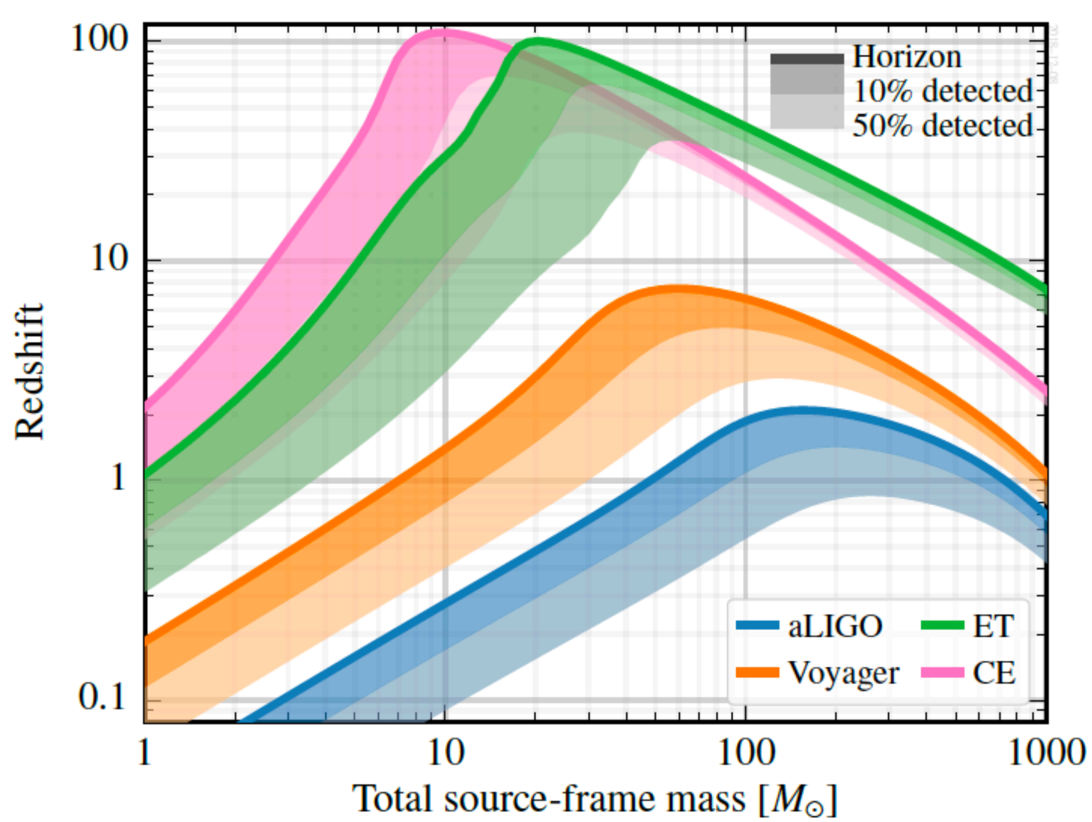
New definition

$$\xi_{\rm det} = \int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f \frac{{\rm d}D_{\rm det}}{{\rm d}f} = \int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f \int_0^{z_{\rm up}} {\rm d}z \frac{{\rm d}R}{{\rm d}z} \frac{{\rm d}\bar{\tau}}{{\rm d}f}$$

remove high redshift events with SNR < 1

z_{up} is determined by the horizon distance

$$R_{\rm det}(f, m_1, m_2, z) = \frac{4c\pi^{-2/3}}{{\rm SNR_{th}} \times 2.26} \sqrt{\frac{5}{96}} \left(\frac{G\mathcal{M}_c^z}{c^3}\right)^{5/6} \left(\int_{f_{\rm min,\,det}}^{f_{\rm max}(f)} df' \frac{f'^{-7/3}}{S_h(f')}\right)^{-1/2}$$



depends on the detector sensitivity

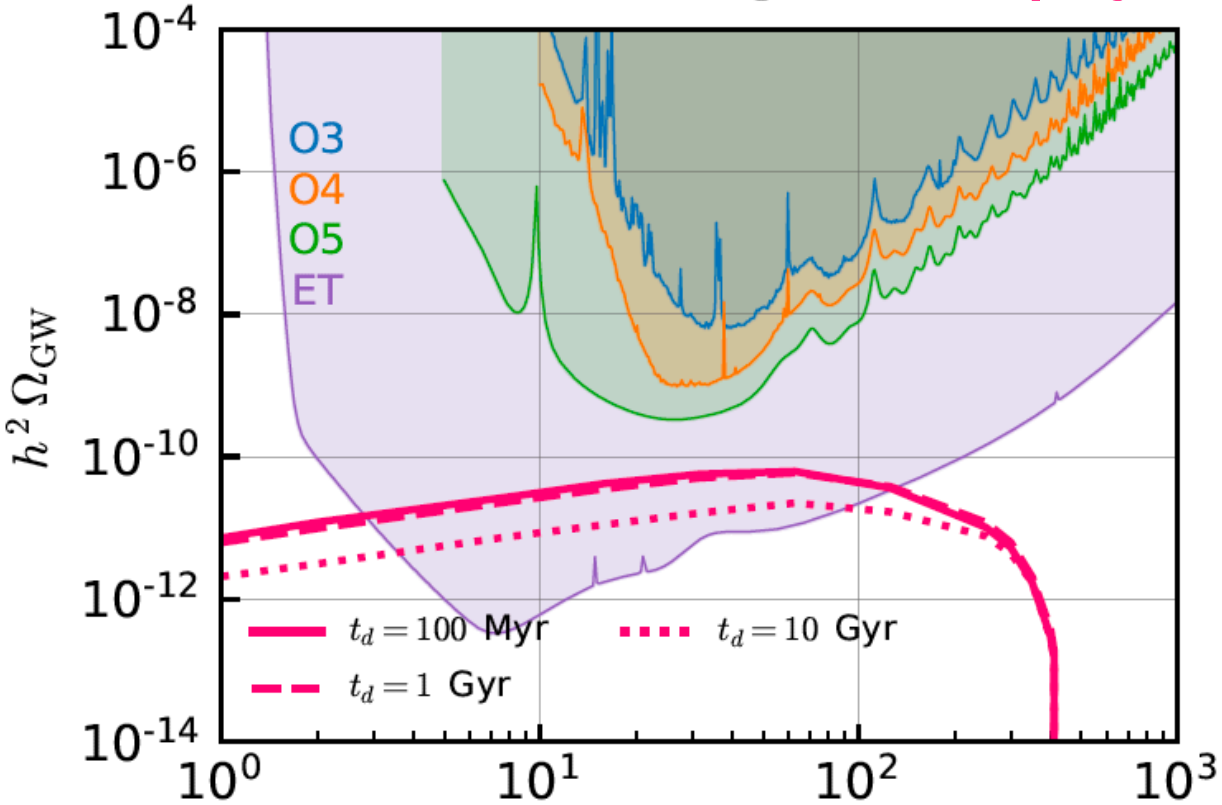
Note: $\xi_{\rm det}$ can be used only for a popcorn background (ξ<<1)

When ξ>>1, even events with SNR < 1 could accumulate and overcome the noise

Figure from
Hall and Evans, CQG 36 225002 (2019)

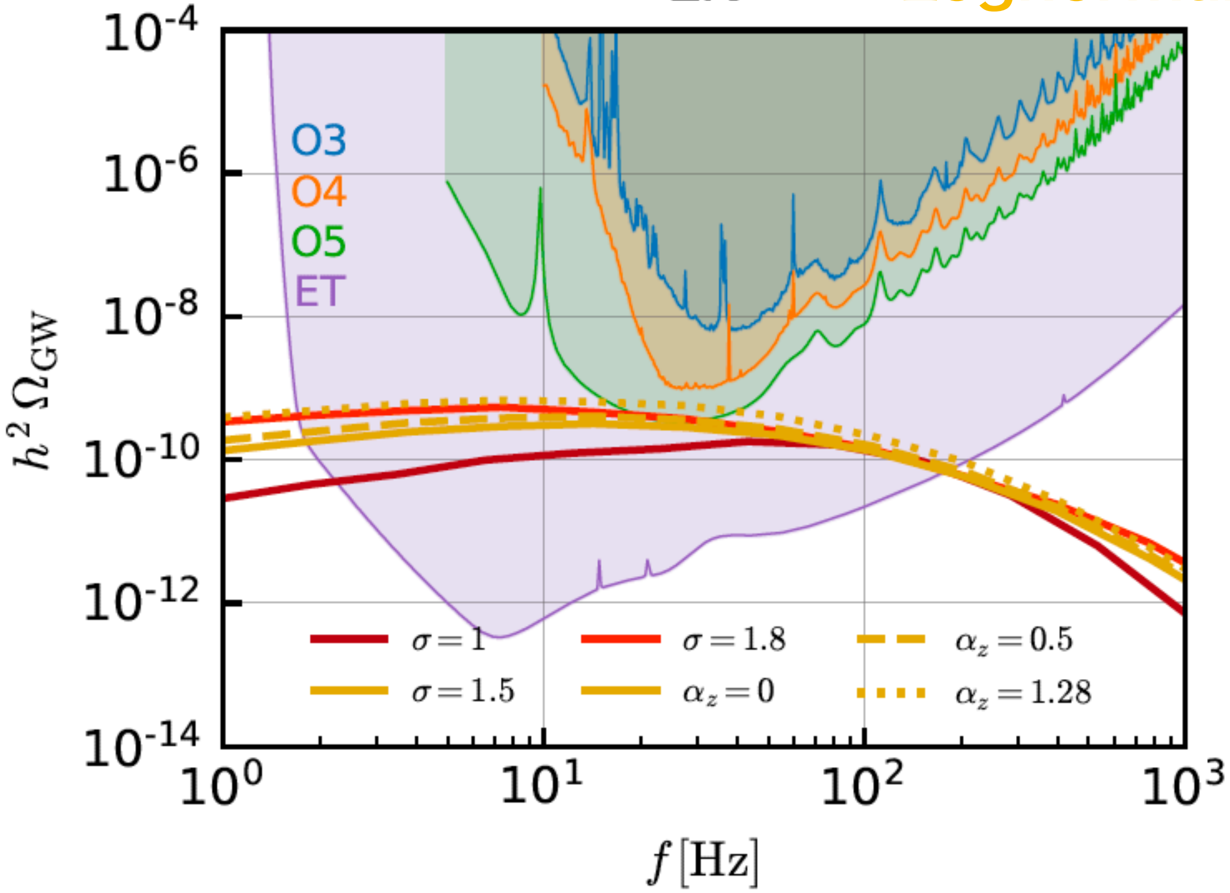
Result: SGWB spectrum

ABHs Astrophysical

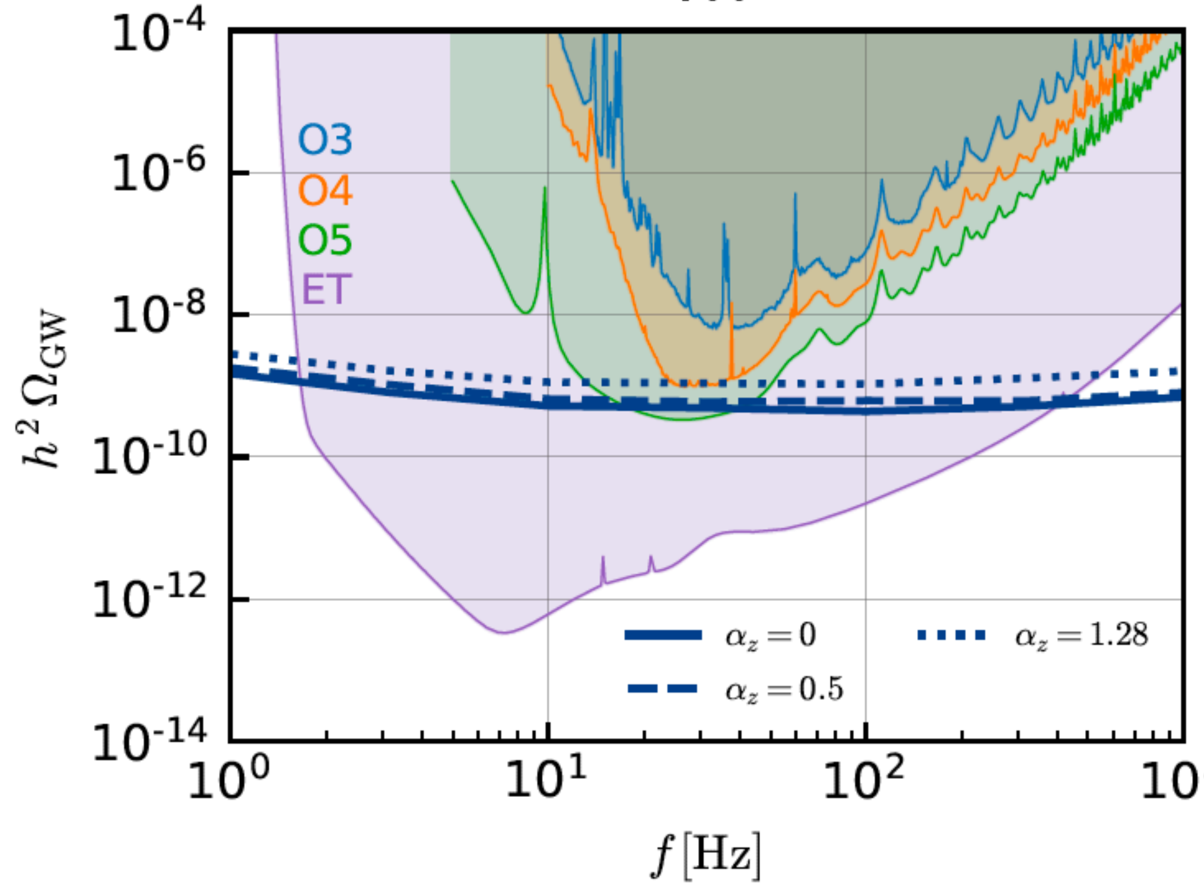


Note: normalization is taken to explain the rate of individual BBH events ($45\ {\rm Gpc}^{-3}\,{\rm yr}^{-1}$)

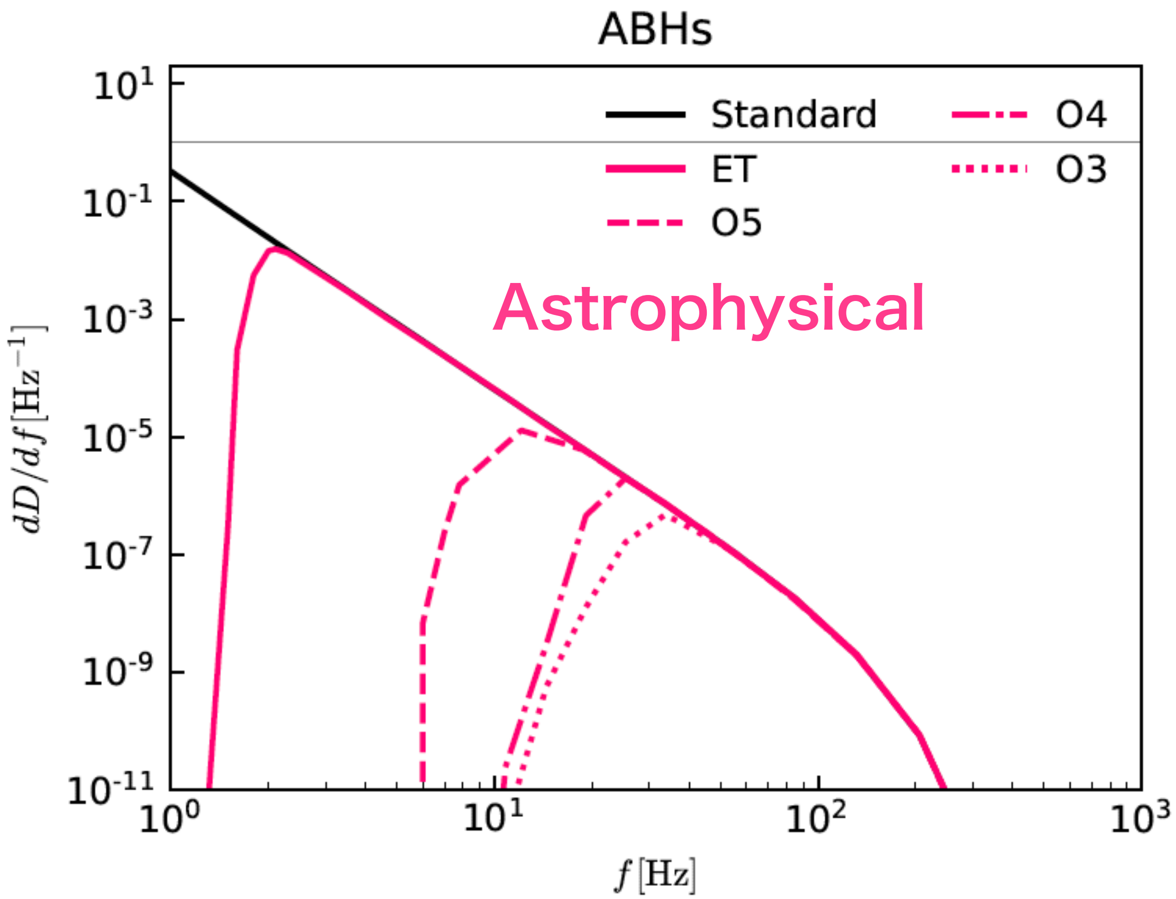
LN Lognormal



TH Thermal history



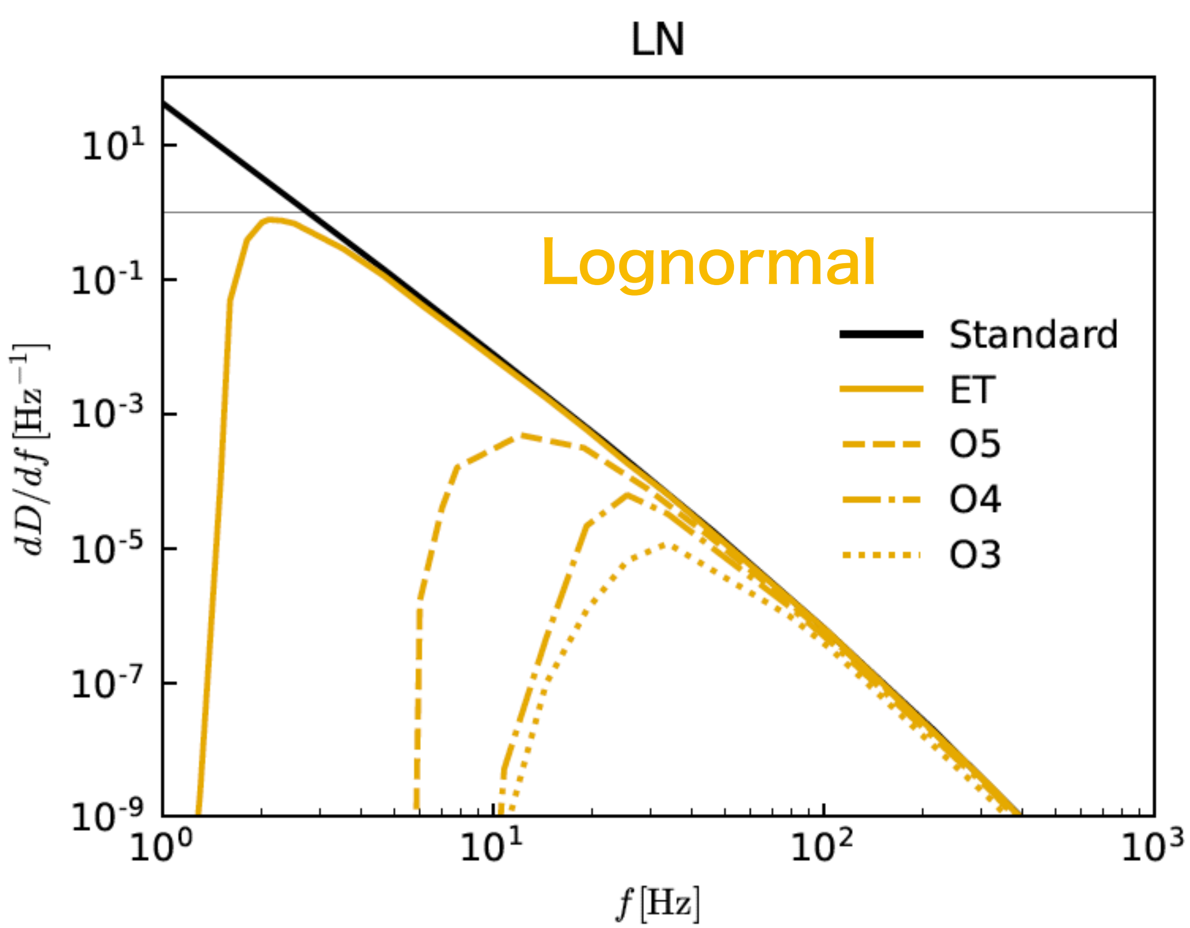
Result: Duty Cycle (dD/df)

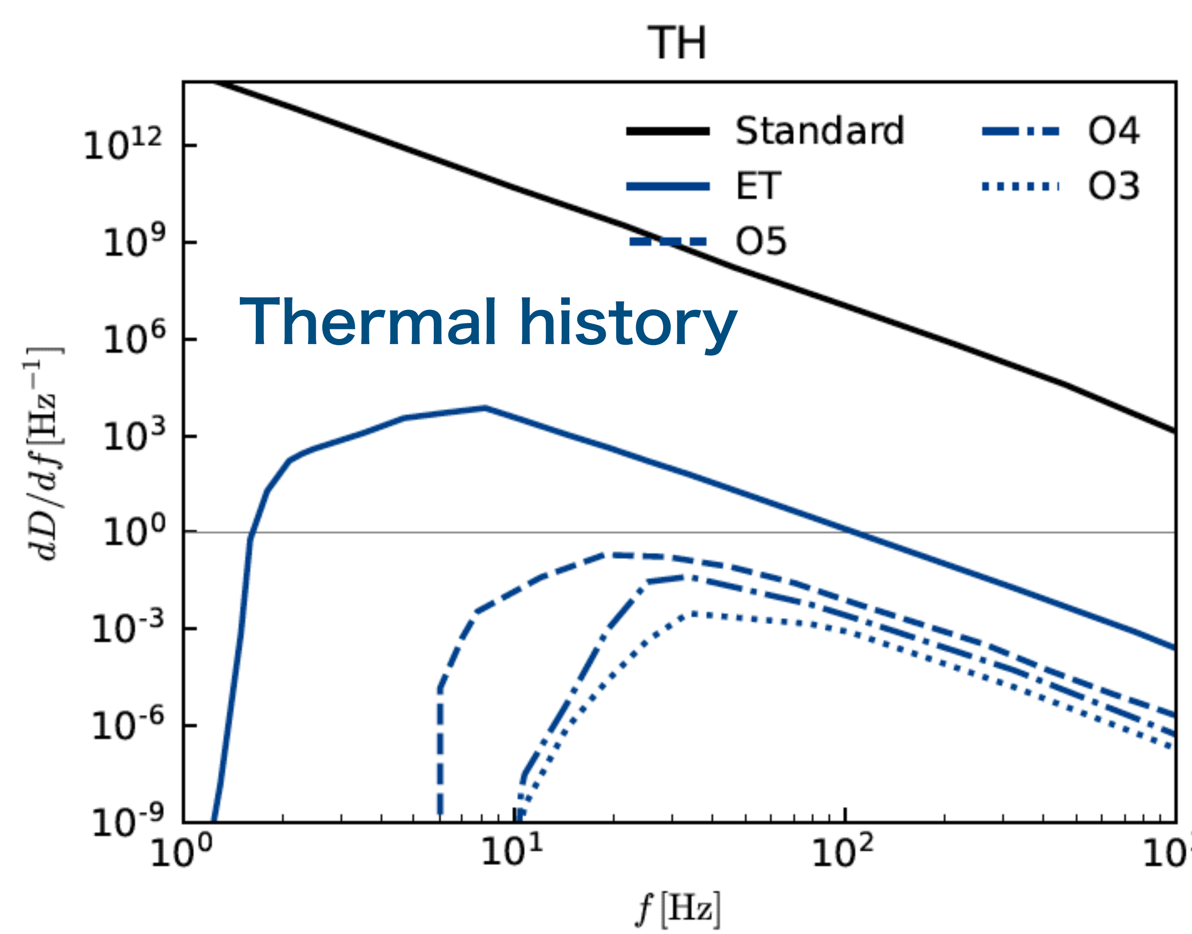


Black: detector-independent Duty Cycle
Colored: detector-dependent Duty Cycle

Total Duty Cycle ($\xi_{\rm det}$)

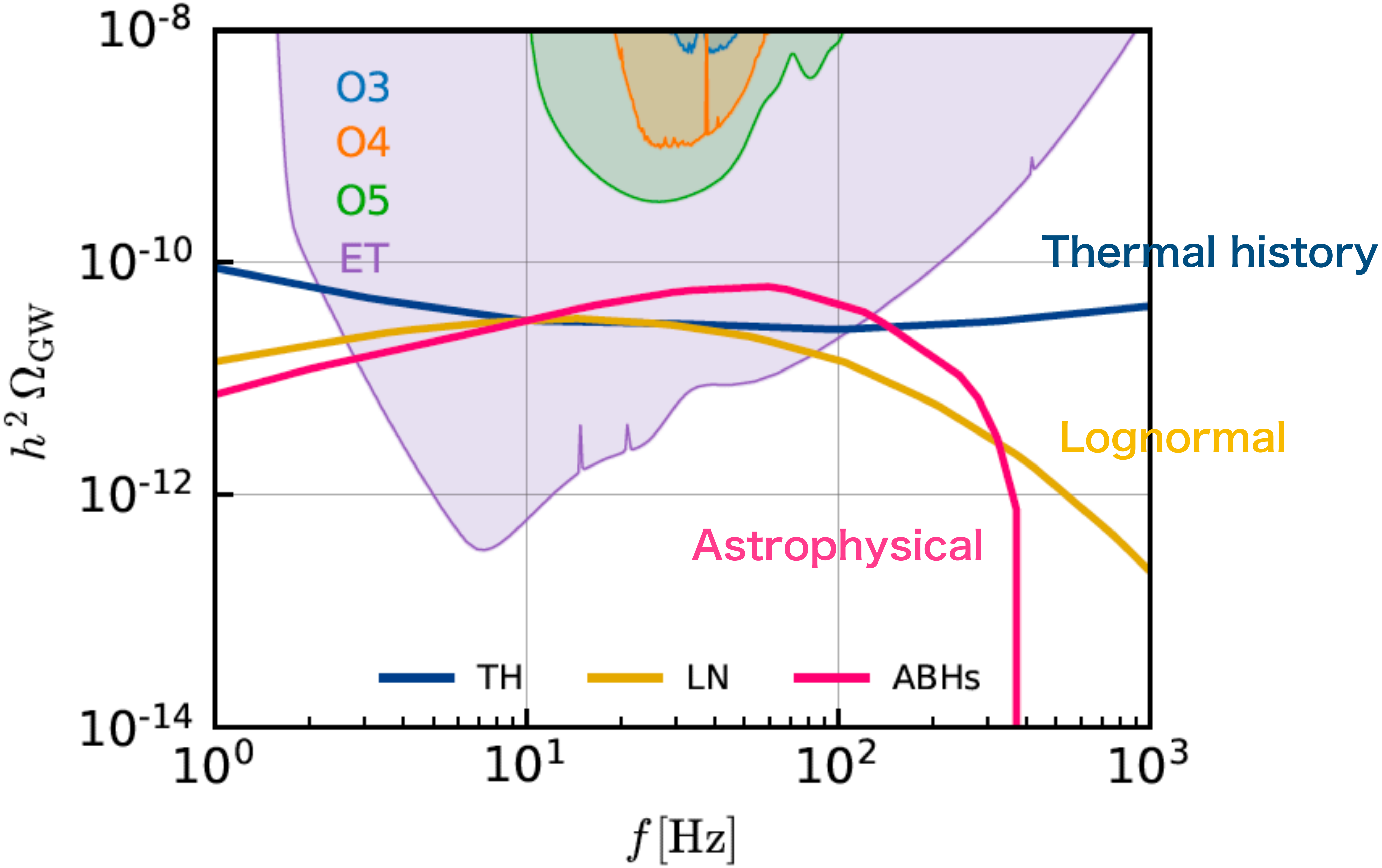
	O3	O4	AdvLIGO	ET
LN	3.5×10^{-4}	1.1×10^{-3}	1.8×10^{-3}	1.1
TH	0.2	1.9	7.3	5.2×10^{4}
ABHs	10.2×10^{-6}	2.1×10^{-5}	1.0×10^{-4}	1.3×10^{-2}





Imagine the situation…

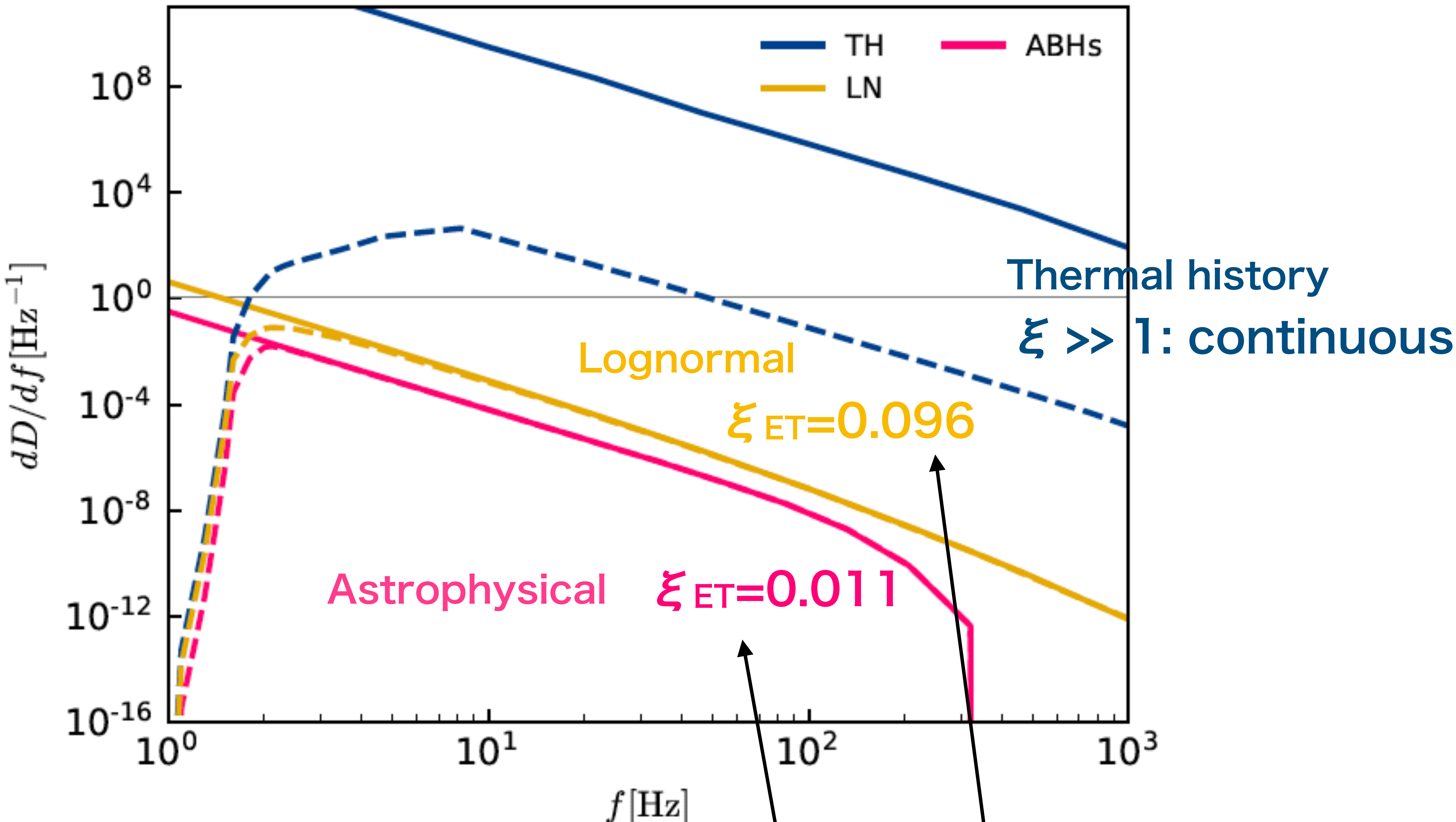
We detect a GW background by ET, but many models can predict similar amplitude by tuning the model parameters.



→ Can we distinguish them by measuring the Duty Cycle?

Yes, Duty Cycle helps

Solid: detector-independent Duty Cycle
Dotted: detector-dependent Duty Cycle (for ET)

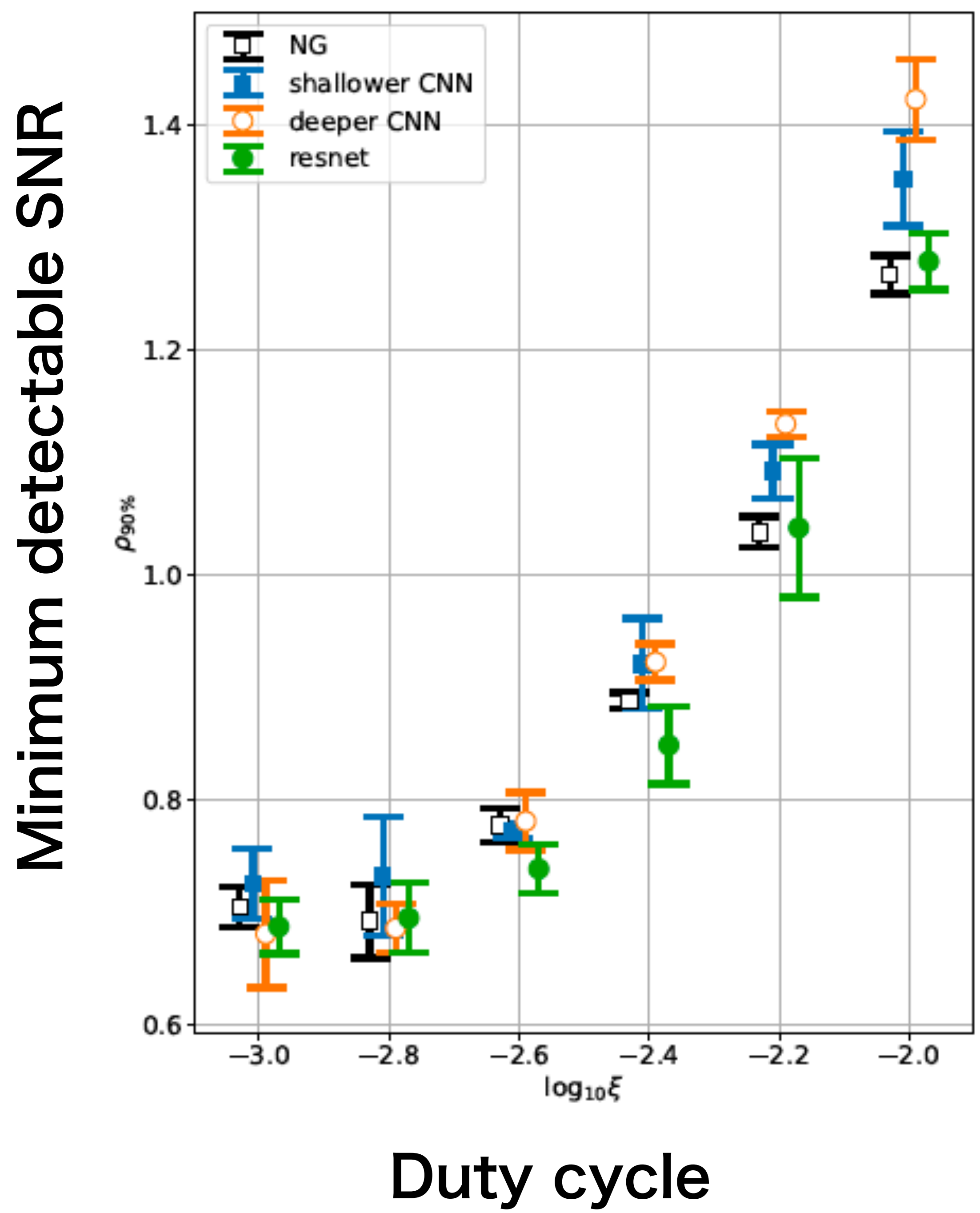


Almost an order of magnitude difference

→ can be distinguished by GW experiments

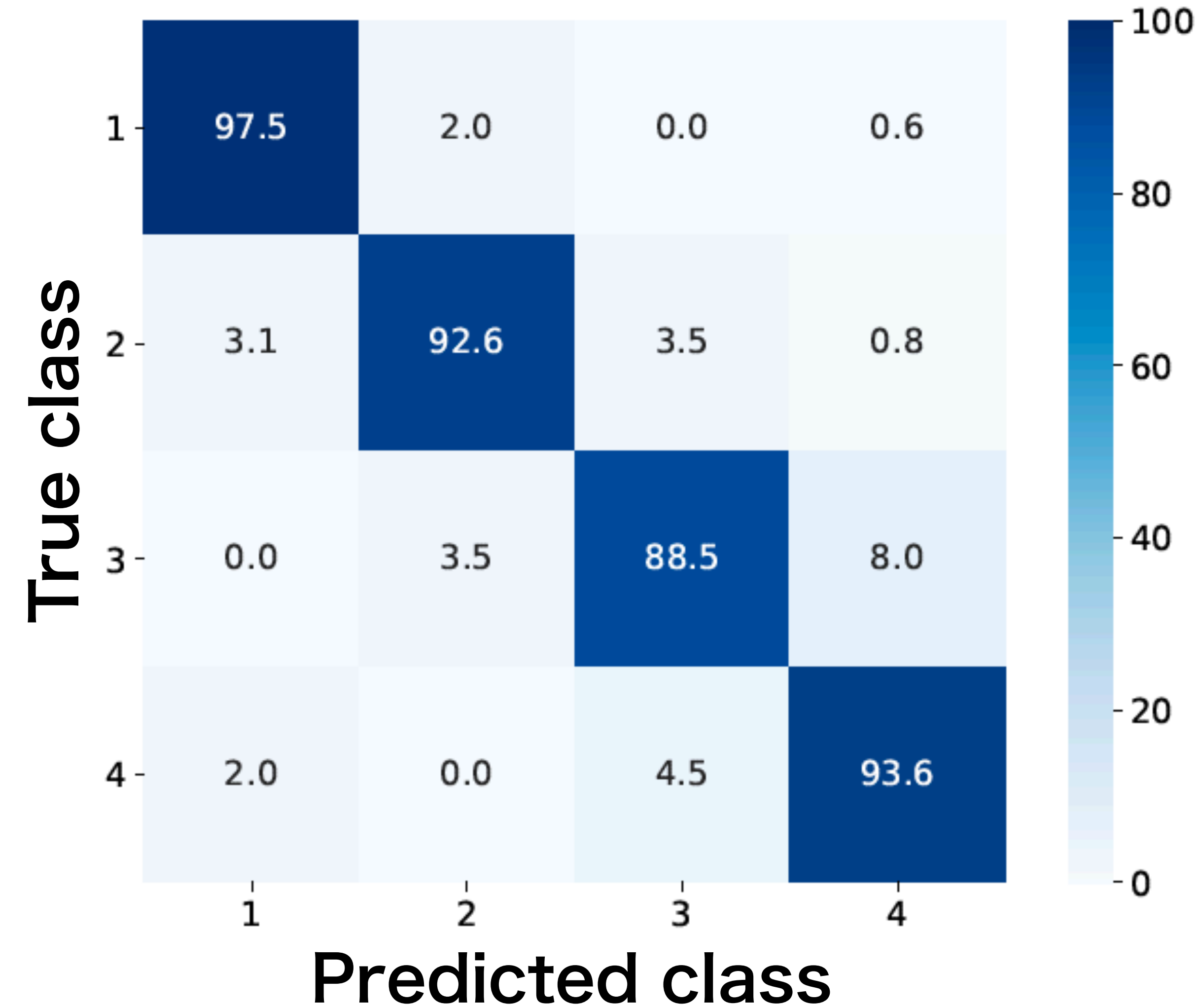
How do we measure the Duty Cycle?

1. CCI (Cross-Correlation search for Intermittent backgrounds): Drasco & Flanagan 2003
2. Use of sub-threshold events in template search: Smith & Thrane 2018
3. Machine Learning: with T. Yamamoto & G.G. Liu (paper in preparation)



Duty cycle estimation (classification)

$$\text{class index} = \begin{cases} 1 & (-1 \le \log_{10}\xi < 0) \\ 2 & (-2 \le \log_{10}\xi < -1) \\ 3 & (-3 \le \log_{10}\xi < -2) \\ 4 & (-4 \le \log_{10}\xi < -3) \end{cases}$$



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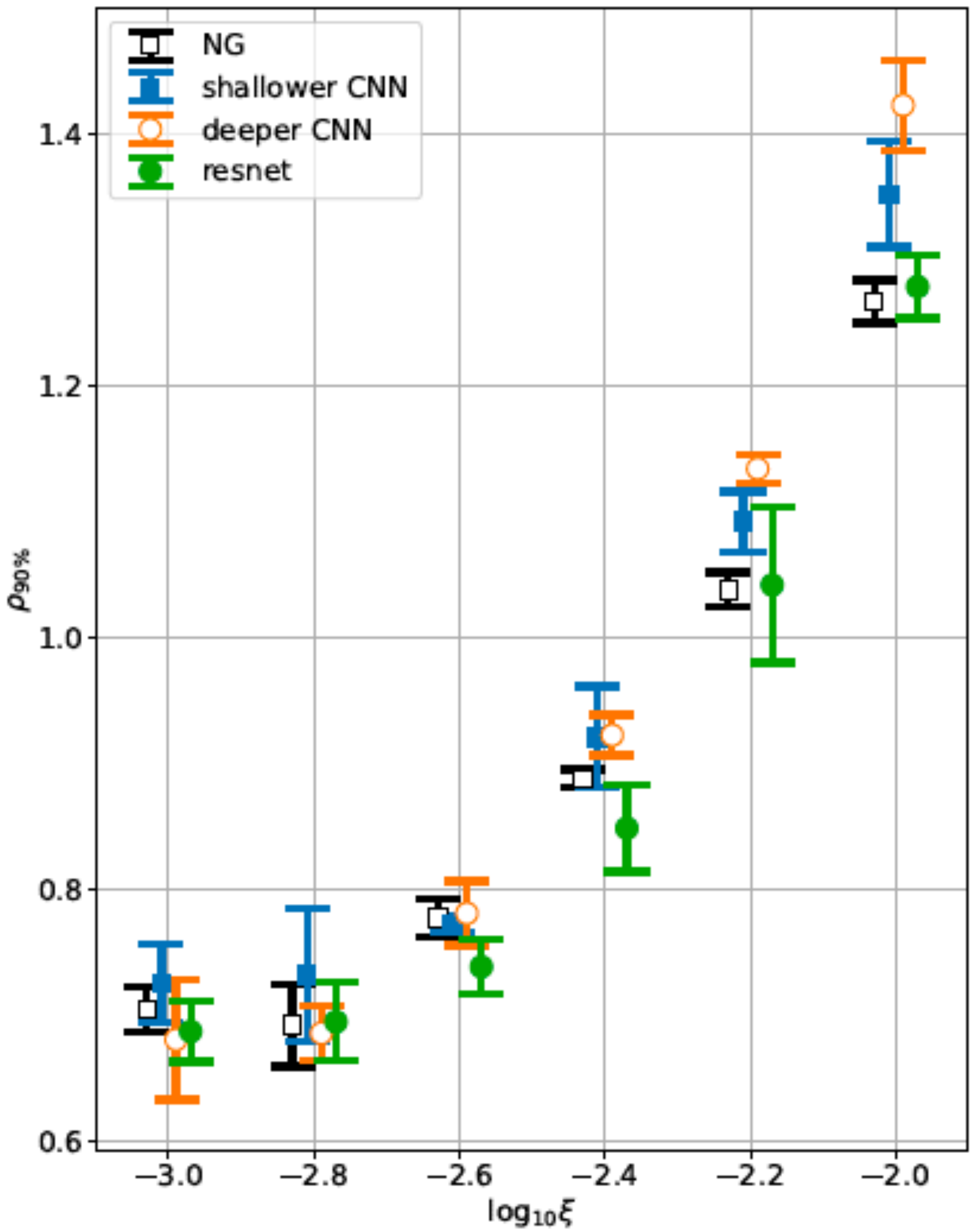
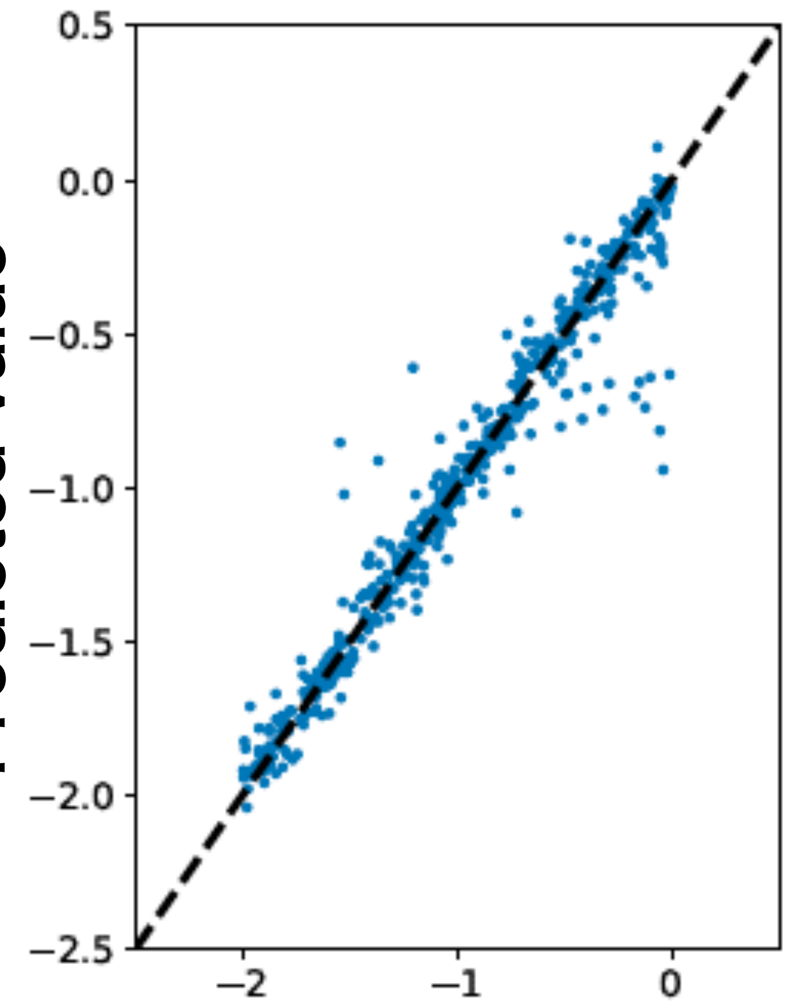
Minimum detectable SNR



Duty cycle

Duty cycle estimation (direct prediction) → works well for $\xi > 10^{-2}$

Predicted value



True value

Advantage

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CCI: Optimal detection statistics

$$\Lambda_{\mathrm{ML}}^{\mathrm{NG}}(h)=\max_{0<\xi\leq 1}\max_{\alpha>0}\max_{\sigma_1\geq 0}\max_{\sigma_2\geq 0}\prod_{k=1}^{N}\left\{\frac{\bar{\sigma}_1\bar{\sigma}_2\xi}{\sqrt{\sigma_1^2\sigma_2^2+\sigma_1^2\alpha^2+\sigma_2^2\alpha^2}}\exp\left[\frac{\left(\frac{h_1^k}{\sigma_1^2}+\frac{h_2^k}{\sigma_2^2}\right)^2}{2\left(\frac{1}{\sigma_1^2}+\frac{1}{\sigma_2^2}+\frac{1}{\alpha^2}\right)}-\frac{(h_1^k)^2}{2\sigma_1^2}-\frac{(h_2^k)^2}{2\sigma_2^2}+1\right]+\frac{\bar{\sigma}_1\bar{\sigma}_2}{\sigma_1\sigma_2}(1-\xi)\exp\left[-\frac{(h_1^k)^2}{2\sigma_1^2}-\frac{(h_2^k)^2}{2\sigma_2^2}+1\right]\right\}$$

search in 4 dim.

cf. standard cross-correlation detection statistics $\Lambda_{\mathrm{CC}}(h)=\frac{\hat{\alpha}^2}{\bar{\sigma}_1\bar{\sigma}_2}$

→ ML is $O(10^4\text{-}10^5)$ faster!

Method	Speed-up factor
Maximum likelihood	1
Shallower CNN	1.6 x 10^5
Deeper CNN	4.8 x 10^4
Residual network	5.9 x 10^4

Summary

GWs from BBHs form a popcorn stochastic background

Astrophysical and Primordial origin predicts different redshift distributions and mass functions of BBHs, which make a difference in popcorn characteristics and help us to distinguish the origin of BBHs.

- M. Braglia et al. arXiv: 2201.13414
  We have estimated the duty cycle for different BBH populations and found that PBH tends to predict a larger duty cycle than astrophysical BHs. **The difference is sufficiently large to be distinguished by the future GW observation.**

- T. Yamamoto et al. in prep.
  We have applied machine learning for the detection of a popcorn background and estimation of the duty cycle. It performs as well as the conventional method and dramatically speed-up the computation!