Probing primordial black holes through the stochastic gravitational wave background

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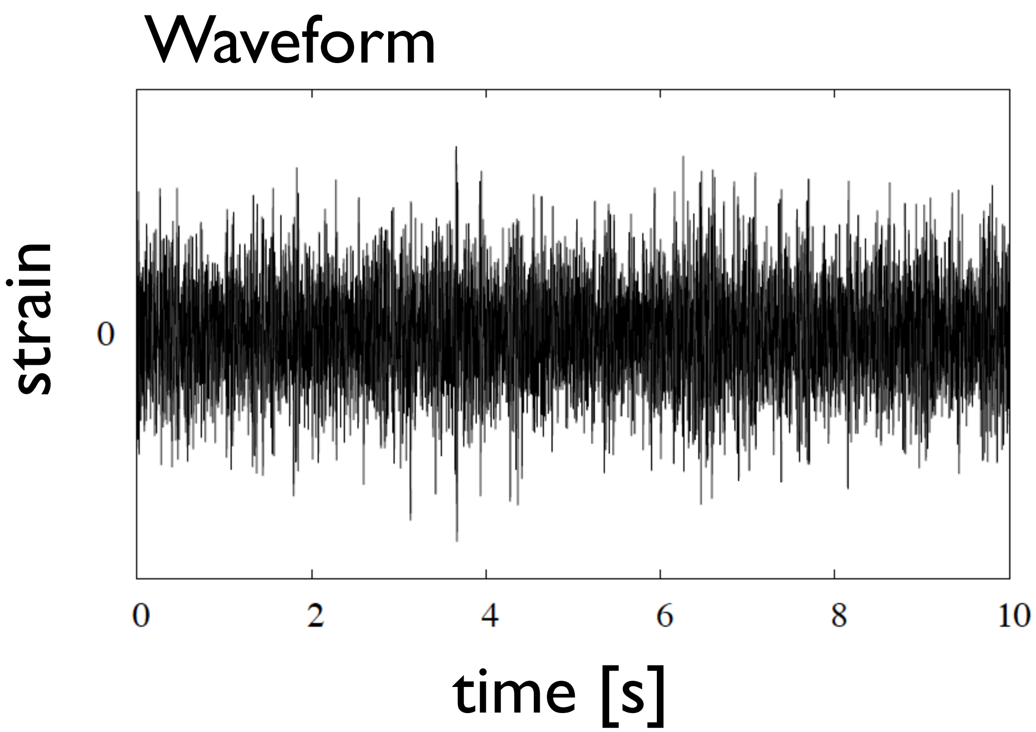
Progress in FY2021

1. “The stochastic gravitational wave background from close hyperbolic encounters of primordial black holes in dense clusters”
Juan García-Bellido, Santiago Jaraba, Sachiko Kuroyanagi
arXiv:2109.11376 [gr-qc], accepted by DSU

2. "Testing Primordial Black Holes with multi-band observations of the stochastic gravitational wave background”
Matteo Braglia, Juan Garcia-Bellido, Sachiko Kuroyanagi
arXiv:2110.07488 [astro-ph.CO], JCAP 12, 012 (2021)

3. "Tracking the origin of black holes with the stochastic gravitational wave background popcorn signal”
Matteo Braglia, Juan Garcia-Bellido, Sachiko Kuroyanagi
arXiv:2201.13414 [astro-ph.CO]

Stochastic GW background



Continuous and random gravitational wave (GW) signal coming from all directions

→ Cross-correlation of two detectors is needed to distinguish it from noise

Generation mechanisms

Astrophysical origin

generated by distant sources (faint and numerous)

- Black holes
- Neutron stars
- White dwarfs
- Supernovae

etc.

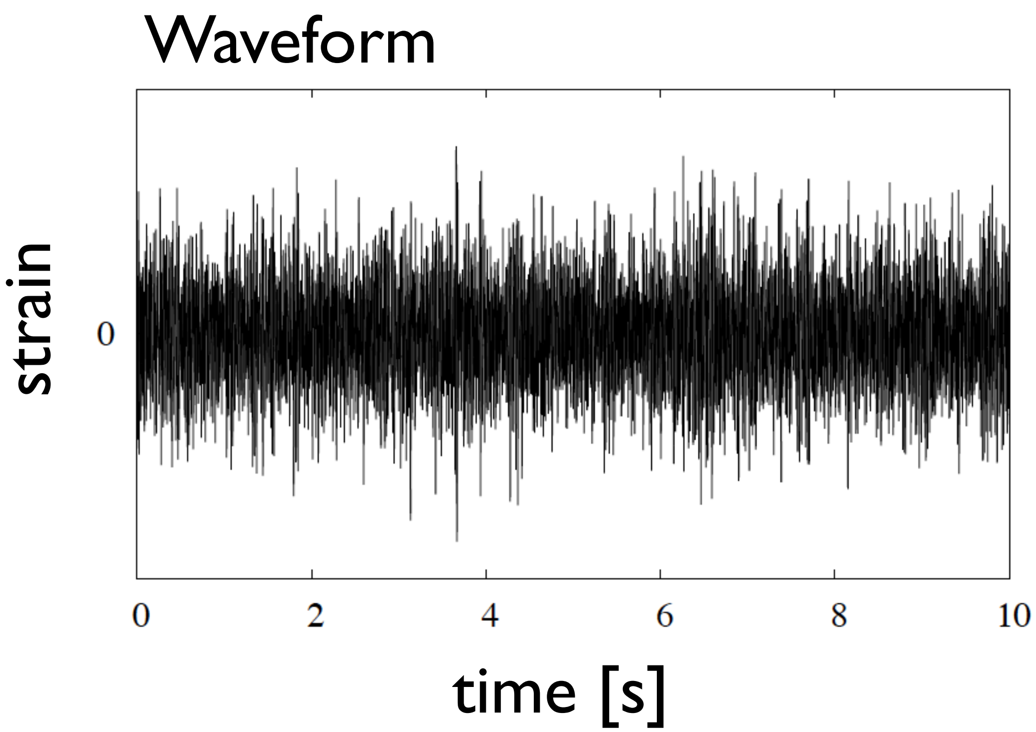
Cosmological origin

generated in the early Universe

- Inflation
- Preheating
- Phase transitions
- Gauge fields

etc.

Stochastic GW background



Continuous and random gravitational wave (GW) signal coming from all directions

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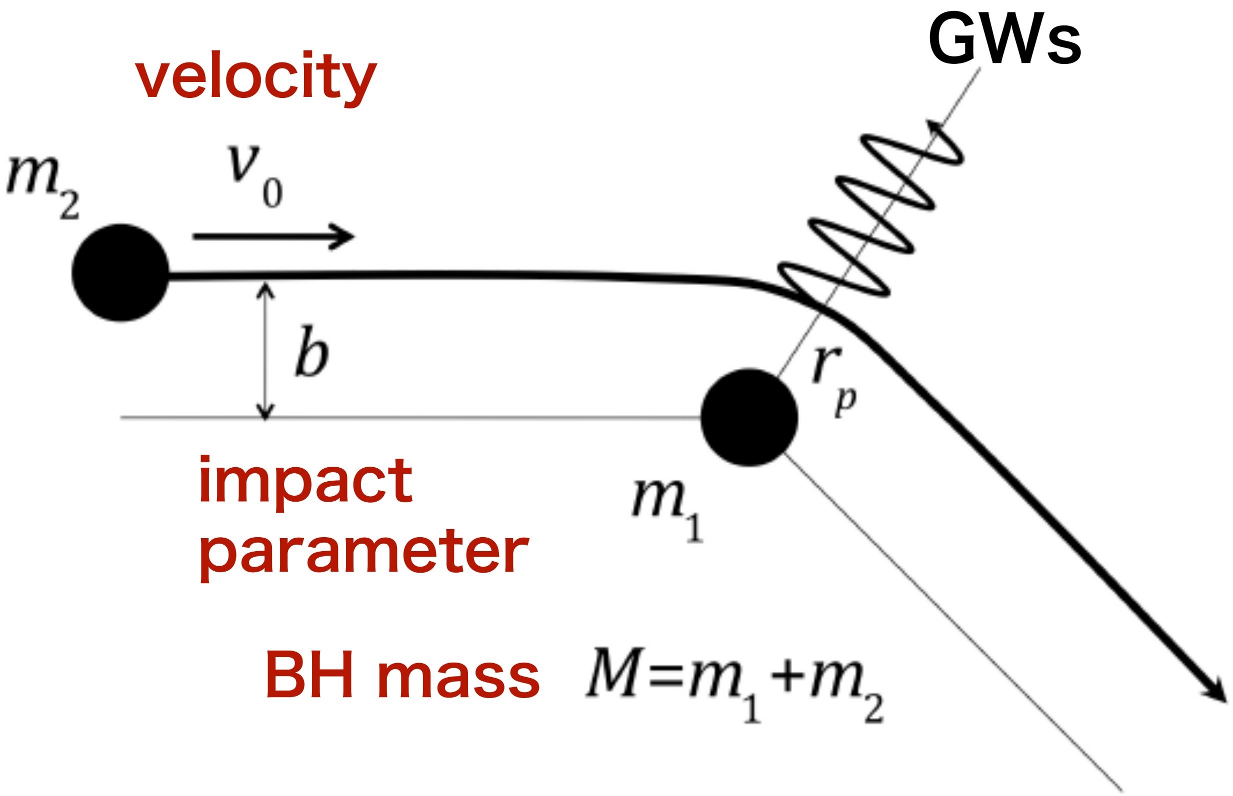
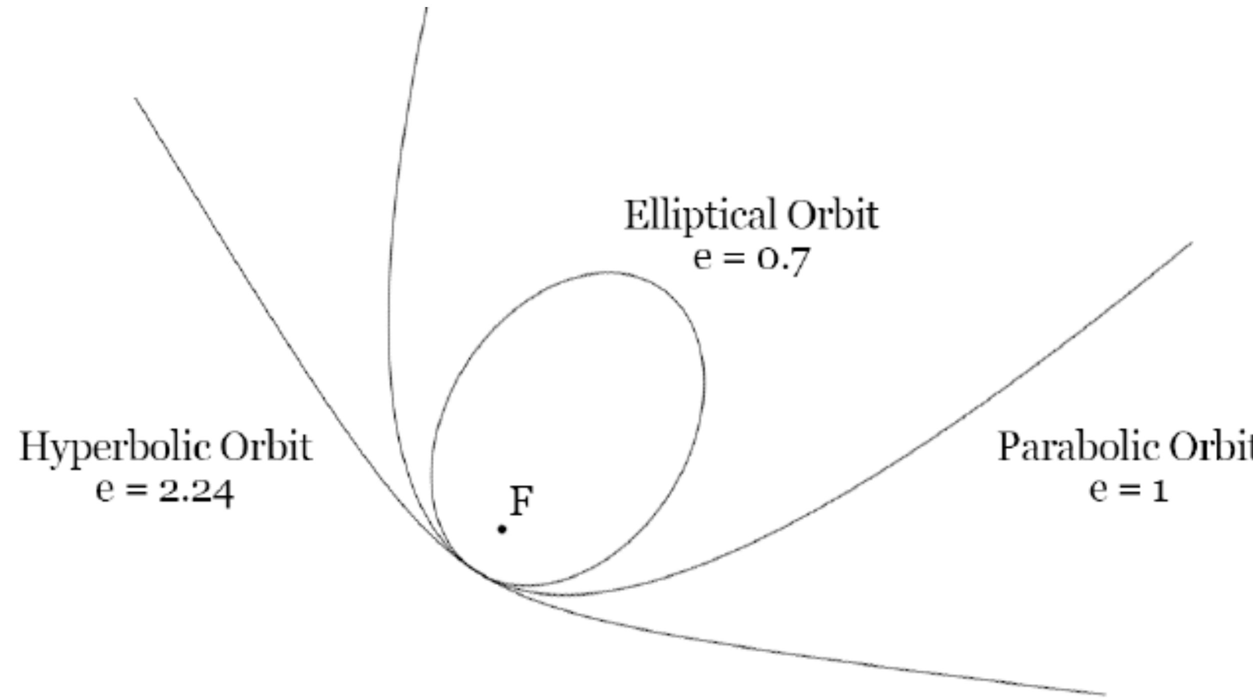
1. GWs from a close hyperbolic encounter

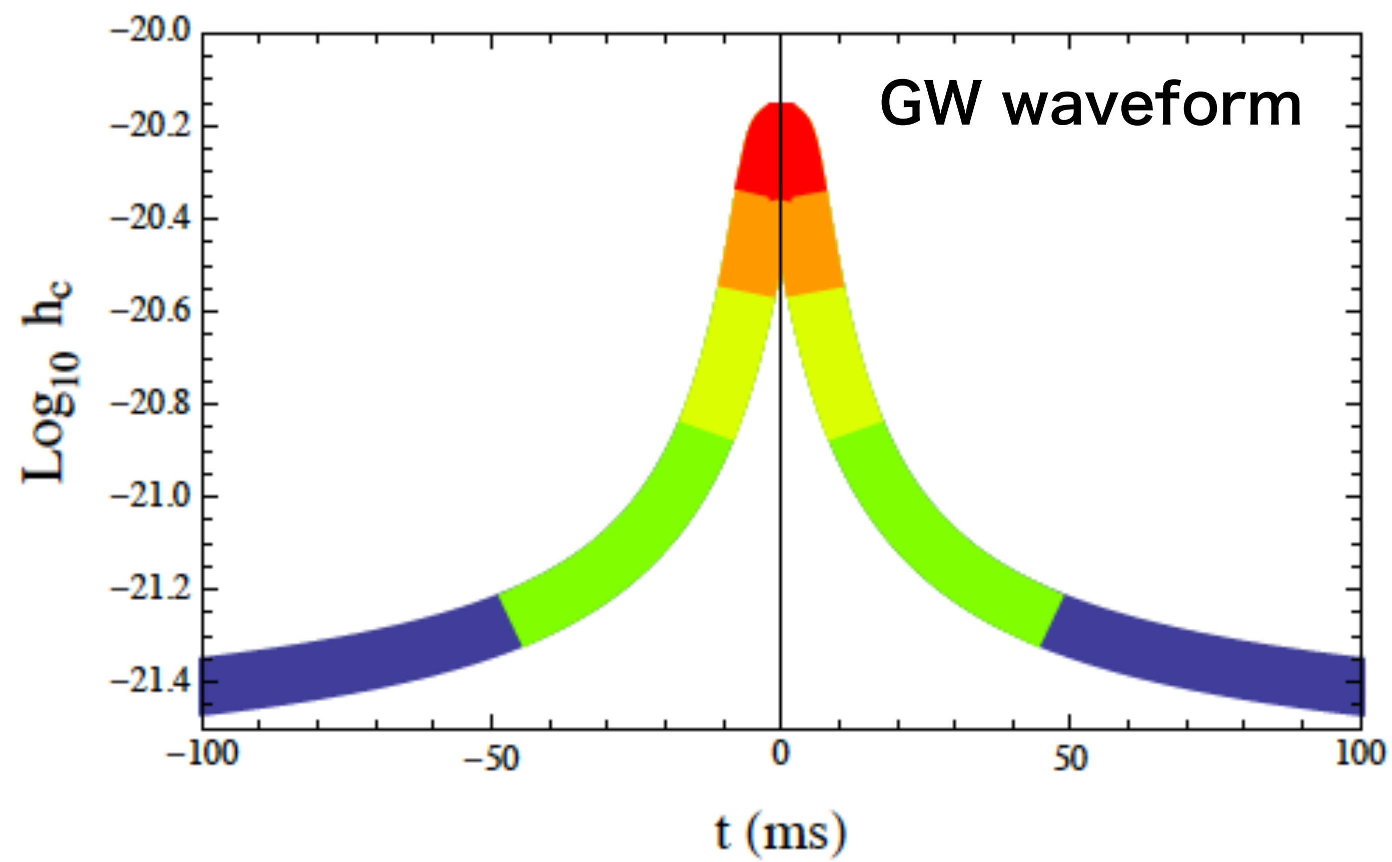




parameters

- semi-major axis $a = \frac{GM}{v_0^2}$
- eccentricity $e > 1$

$$y = \sqrt{e^2 - 1} = \frac{b v_0^2}{GM} = \frac{b}{a}$$



Garcia-Bellido & Nesseris, Phys. Dark Univ., 18 (2017) 123-126

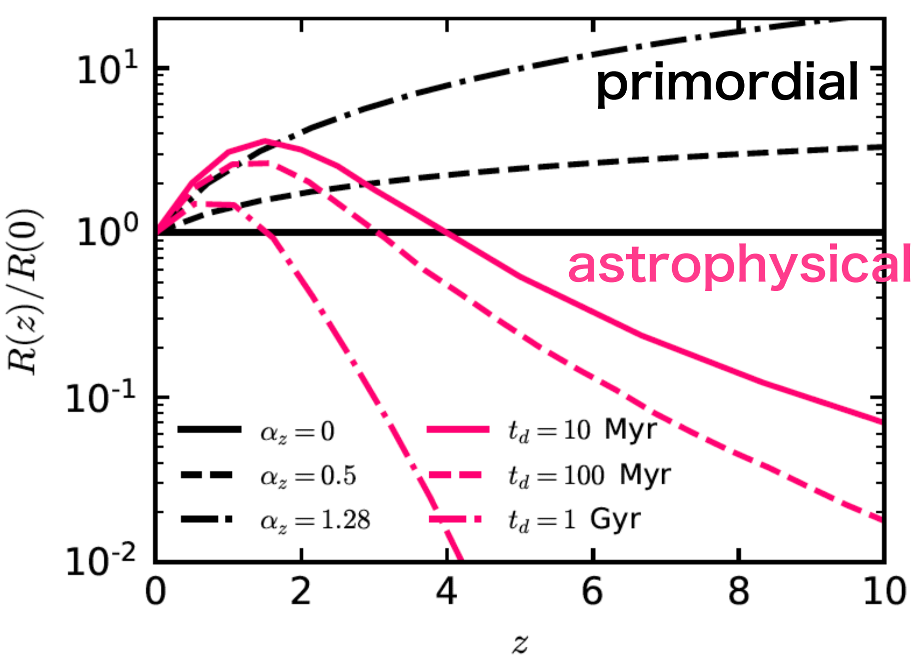
GW spectrum

GW amplitude

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

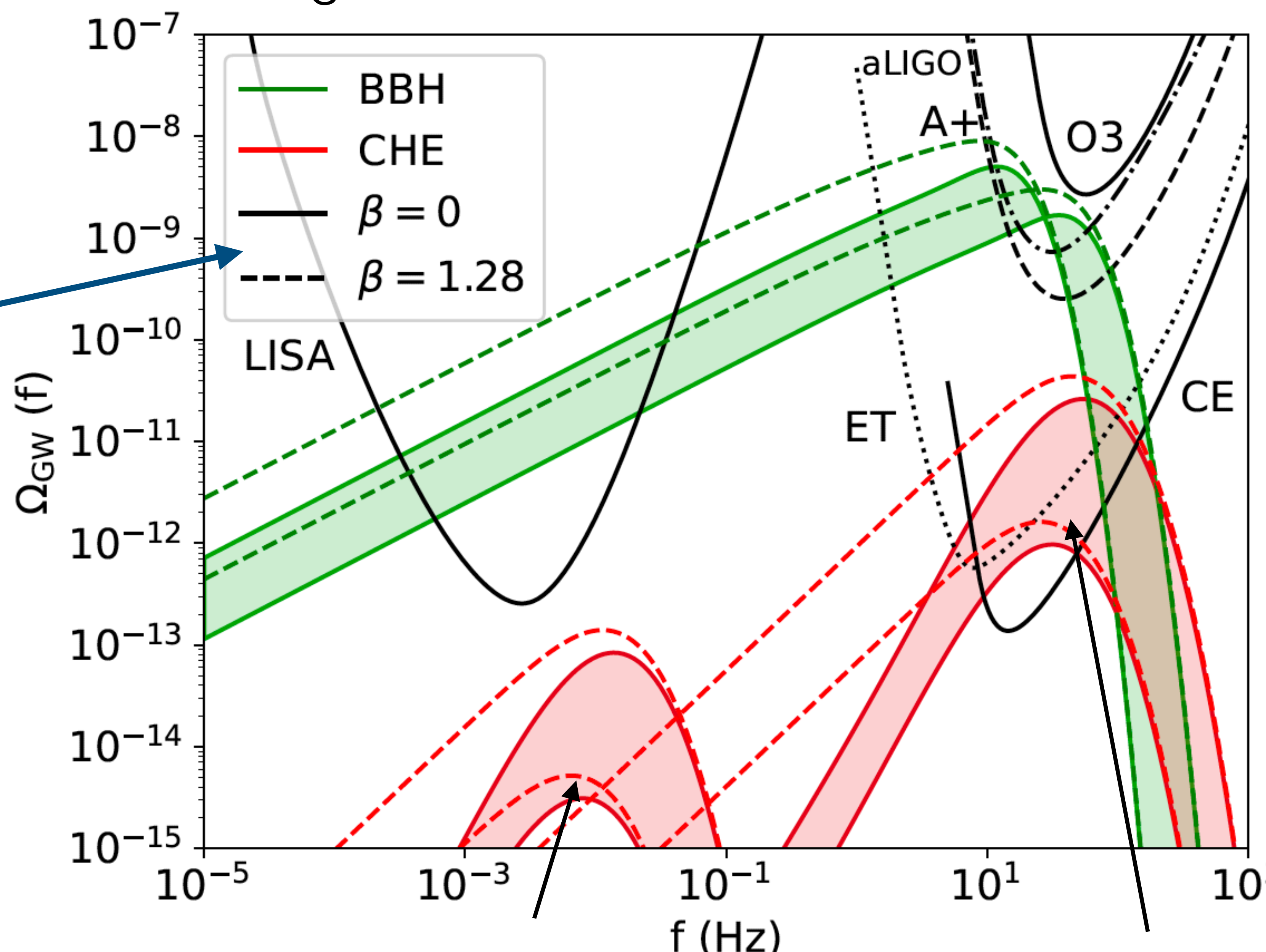
merger rate

$$\propto (1+z)^{\beta}$$



$m_1 = m_2 = 100\text{-}300 M_\odot$

Lognormal mass function with **$\sigma_m = 0.5$**



a = 5×10⁷ AU → $a = 5\times10^{7}$ AU

$y = 10^{-5}$

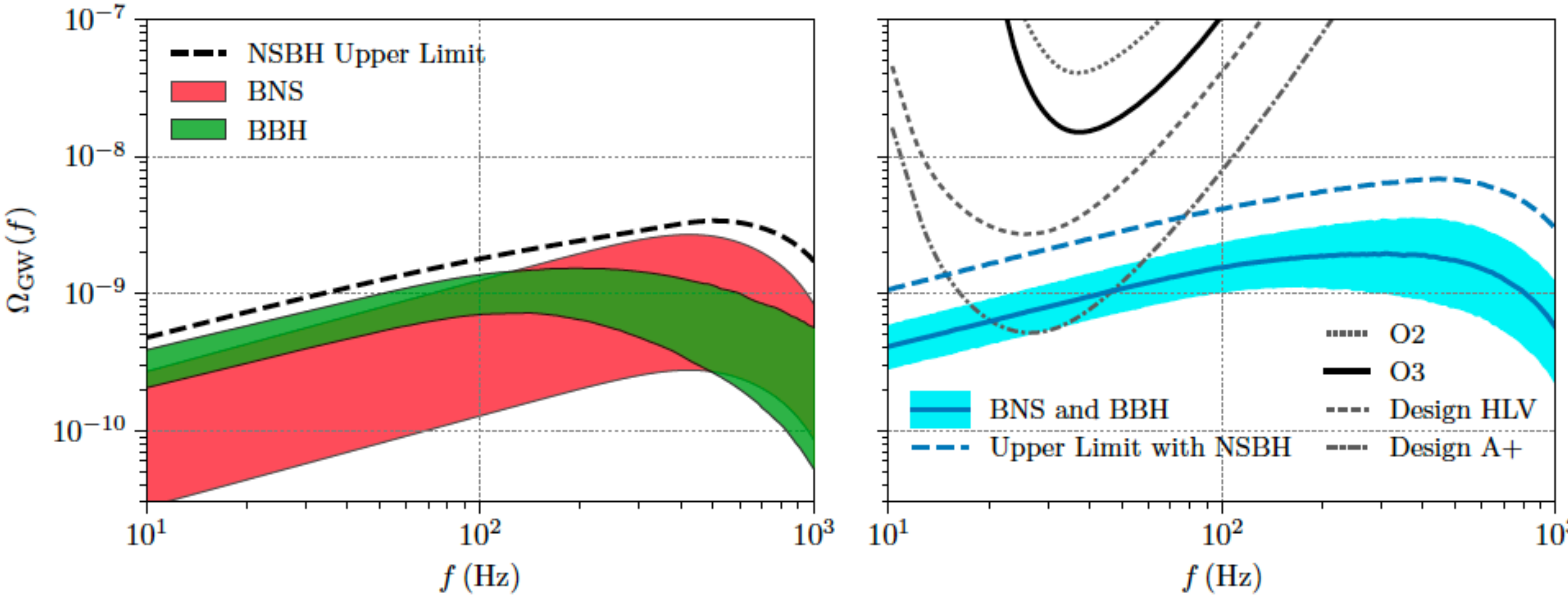
a = 5 AU

y = 0.002

Jaraba, Garcia-Bellido, Kuroyanagi, arXiv:2109.11376

2. GWs from BBHs

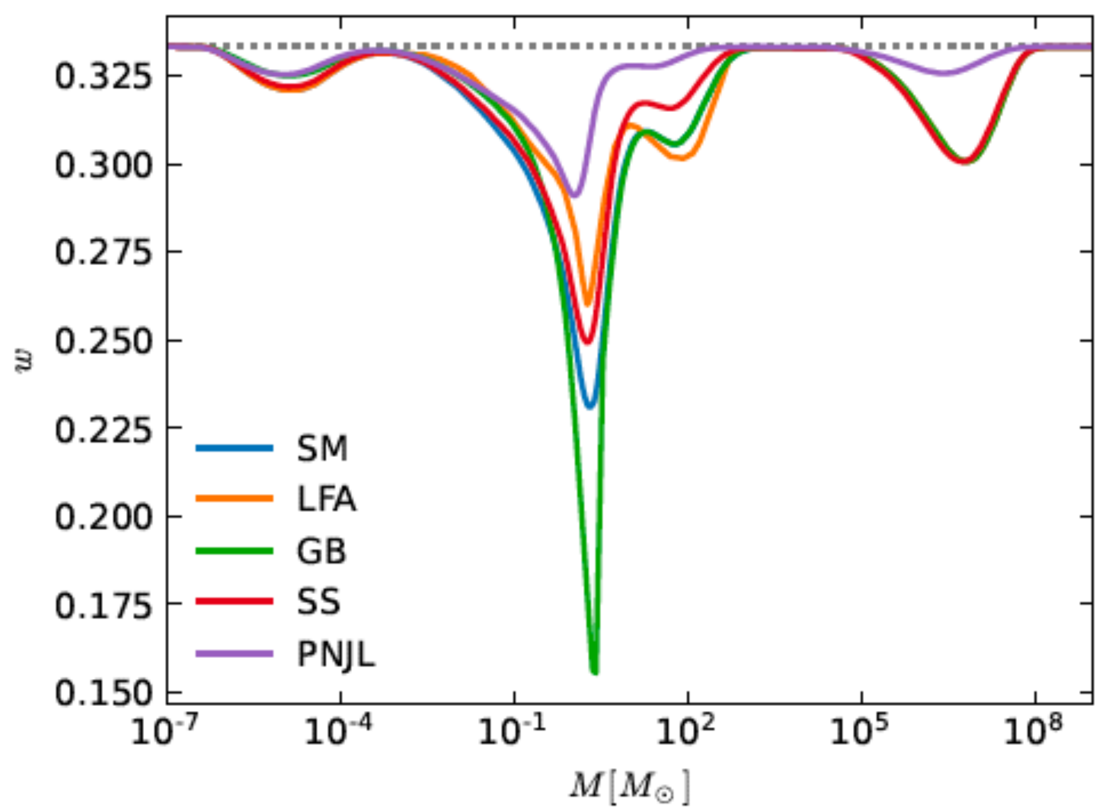
Individual Binary Black Hole (BBH) event rate indicates the existence of the stochastic GW background (SGWB) possibly detectable by upgraded LVK detectors

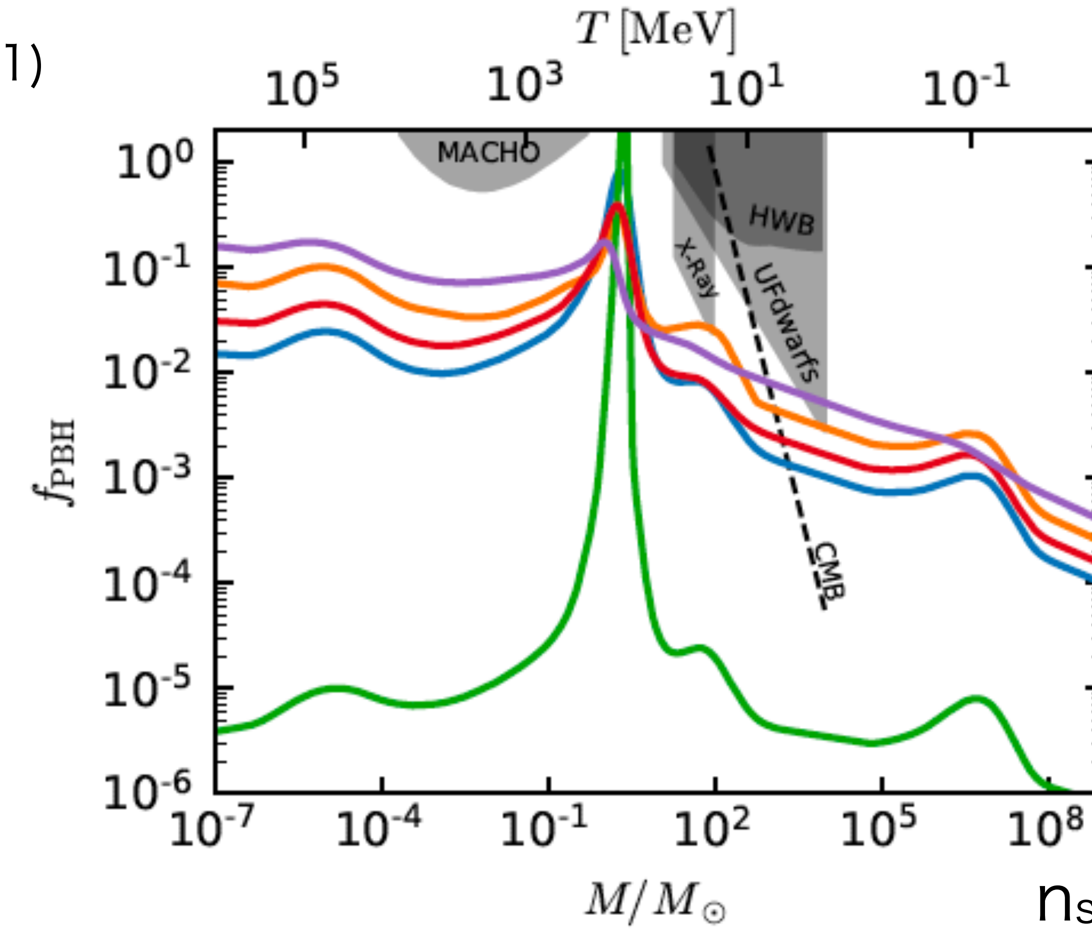


LVK collaboration, PRD 104, 022004 (2021)

Thermal history mass function

Jedamzik, Phys. Rev. D, 55, 5871(1997)
Garcia-Bellido, Murayama, White, JCAP12, 023 (2021)





n_s=0.97

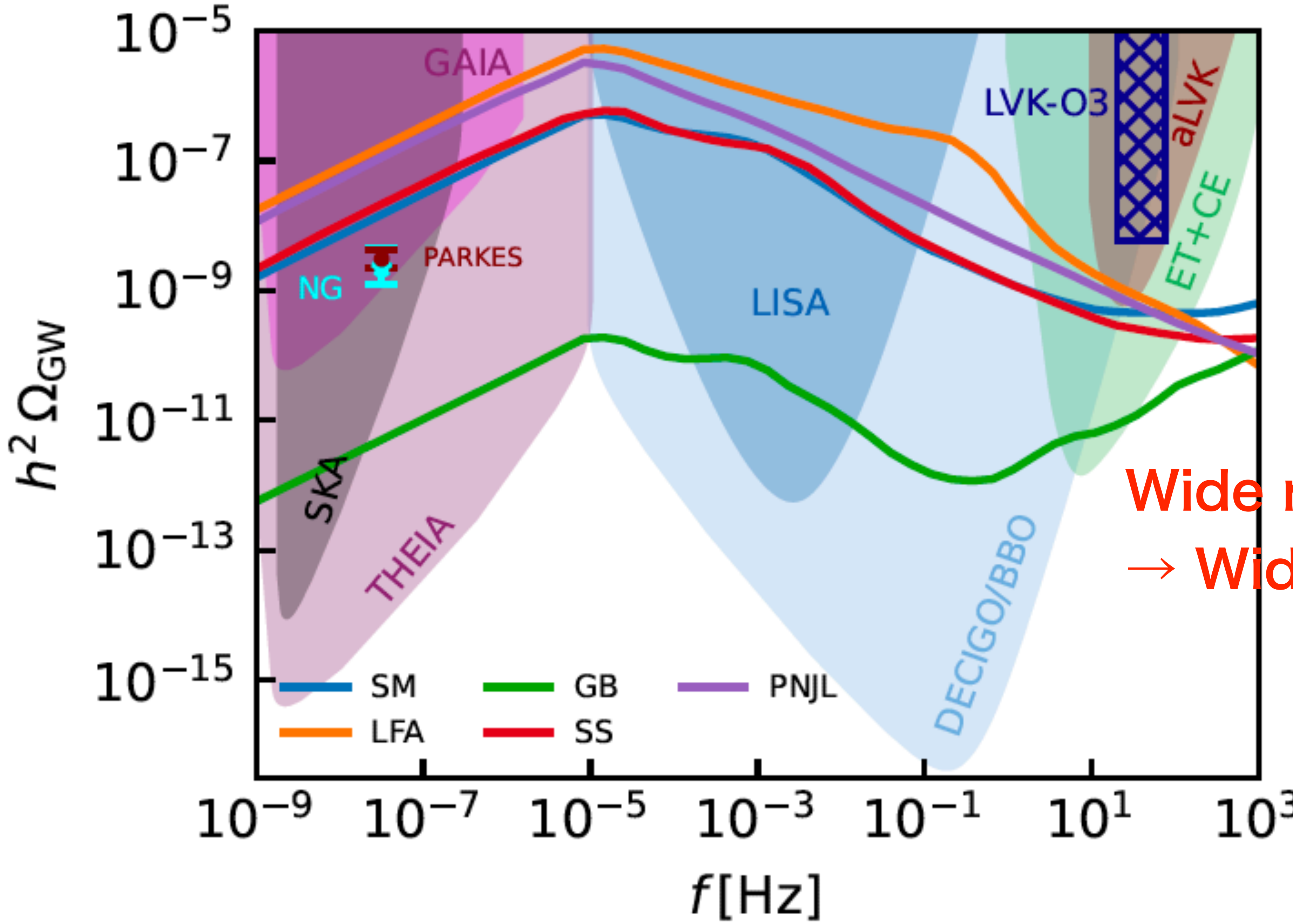
Equation of motion (w) changes during QCD phase transition

PBH abundance changes depending w(T)

Changes the critical density of PBH formation

$$\beta(M) \approx \mathrm{erfc}\left[\frac{\delta_c(w[T(M)])}{\sqrt{2}\,\delta_{\rm rms}(M)}\right]$$

GW spectrum



n_s=0.97

Wide mass range

→ Wide frequency

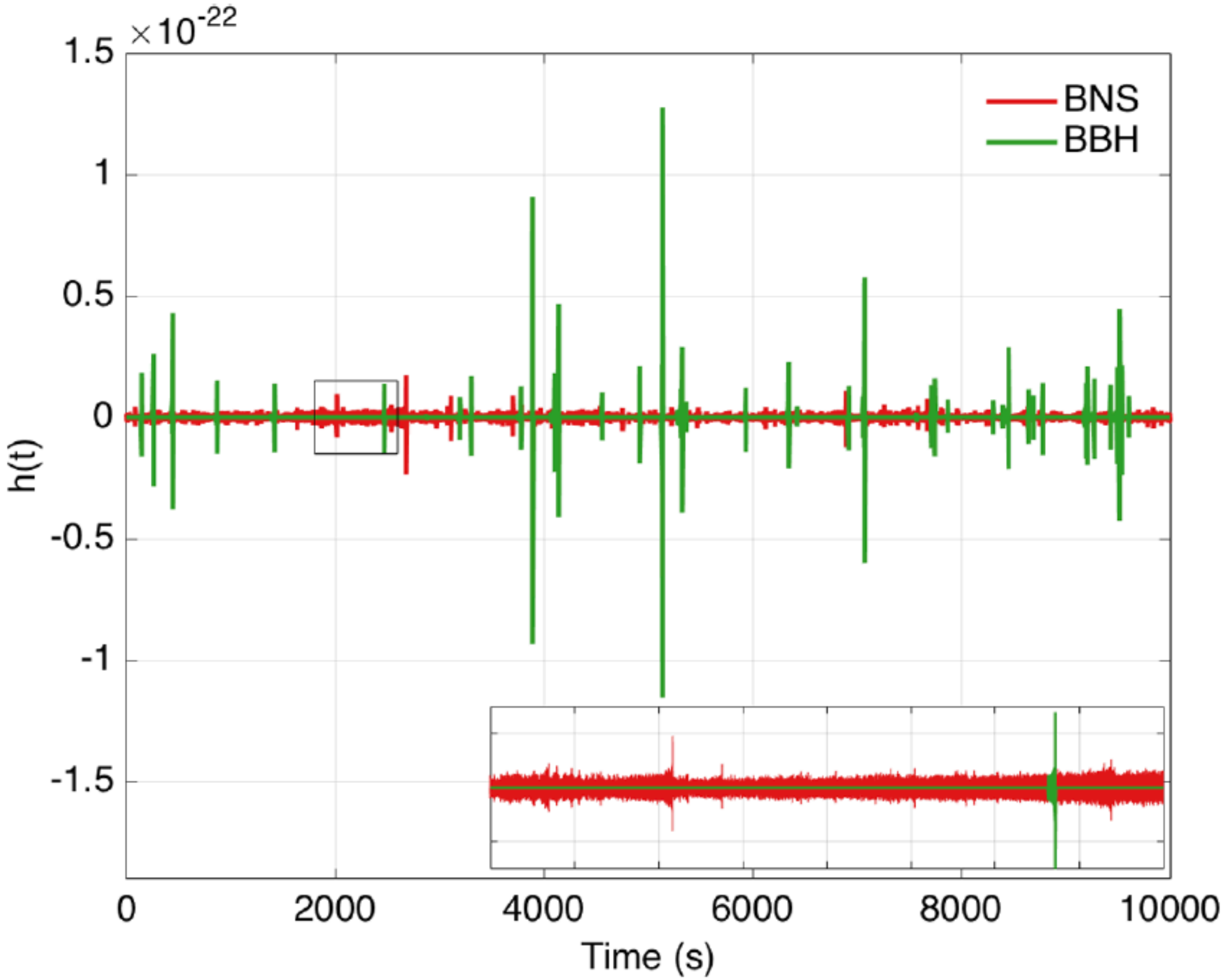
$f_{ISCO} \propto M_{total}$

Note: normalization is taken to explain all the events in GWTC-2 (merger rate = 38 /Gpc^3/yr)

Braglia, Garcia-Bellido, Kuroyanagi, JCAP12, 012 (2021)

3. Popcorn GW background

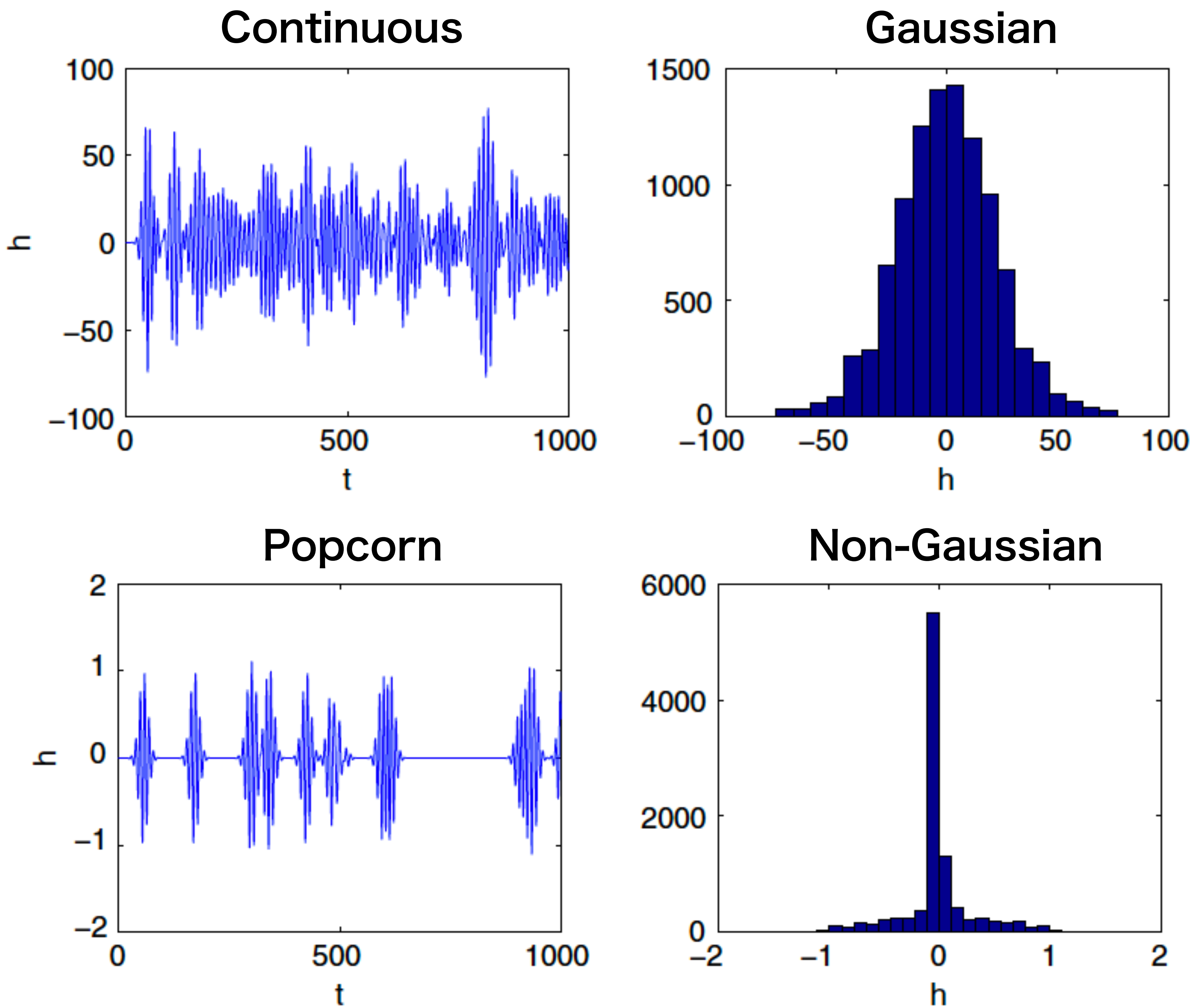
BBHs events do not overlap one another.



LV collaboration, PRL 120, 091101 (2018)

Popcorn = Non-Gaussian background

Thrane, PRD 87, 043009 (2013)

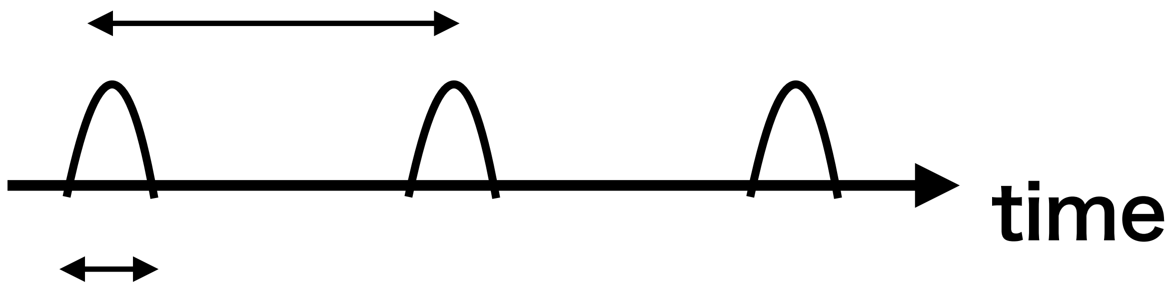


→ Can we use this to distinguish BH models?

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

$DC \gg 1$ events overlap

$DC \ll 1$ events do not overlap

For BBH, we define

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

$$\Delta T \sim \left(\frac{\mathrm{d}R}{\mathrm{d}z}\right)^{-1} \qquad \Delta \tau \sim \frac{\mathrm{d}\bar{\tau}}{\mathrm{d}f} = \frac{5}{96\pi^{8/3}} (G\mathcal{M}_c^z)^{-5/3} f^{-11/3}$$

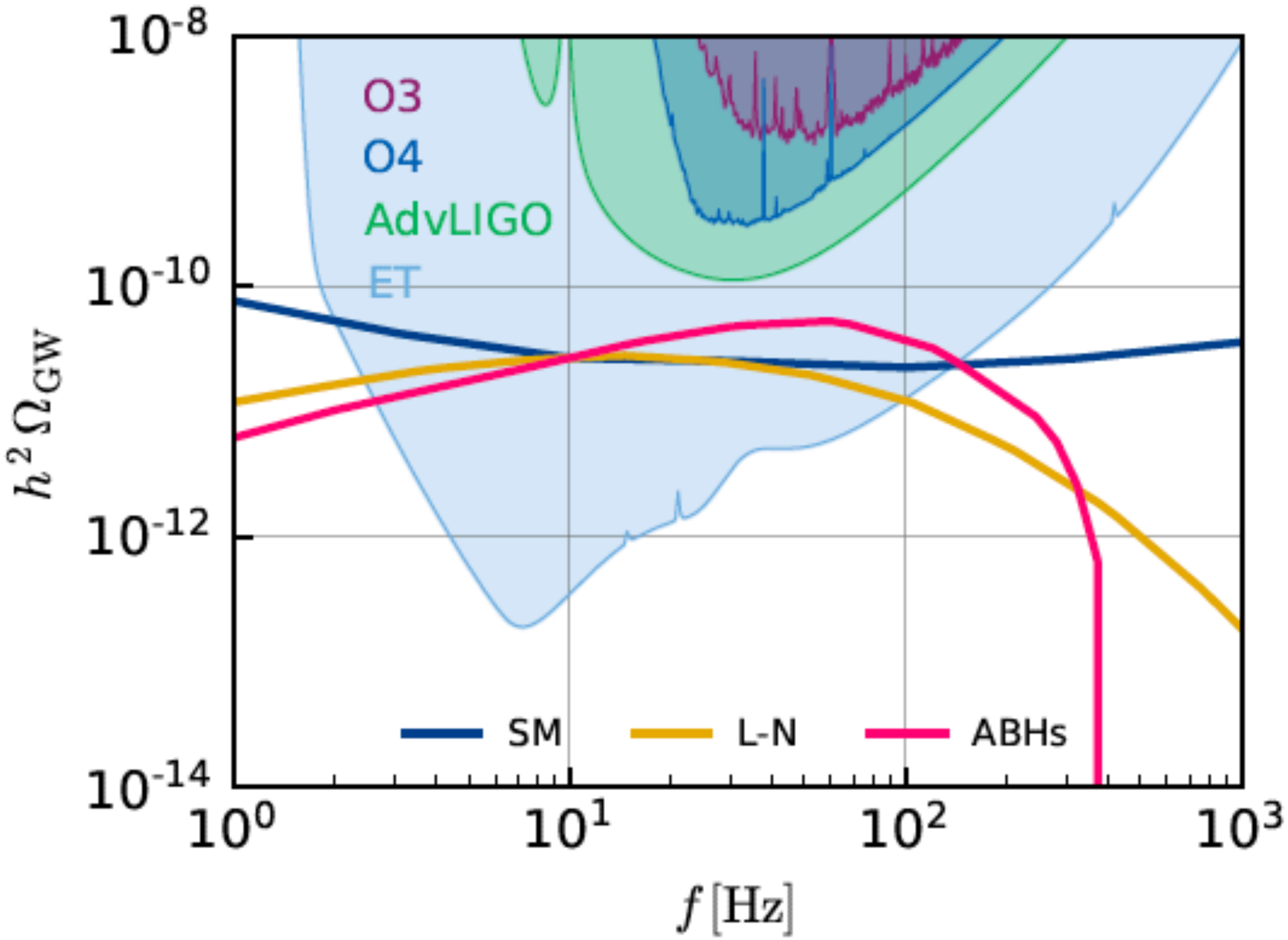
Total duty cycle $\xi = \displaystyle\int_{f_{\rm min}}^{f_{\rm max}} \mathrm{d}f \frac{\mathrm{d}D}{\mathrm{d}f}$

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

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

Imagine the situation...

We detect a GW background by ET, but many models can predict similar amplitude by tuning the normalization of the merger rate.

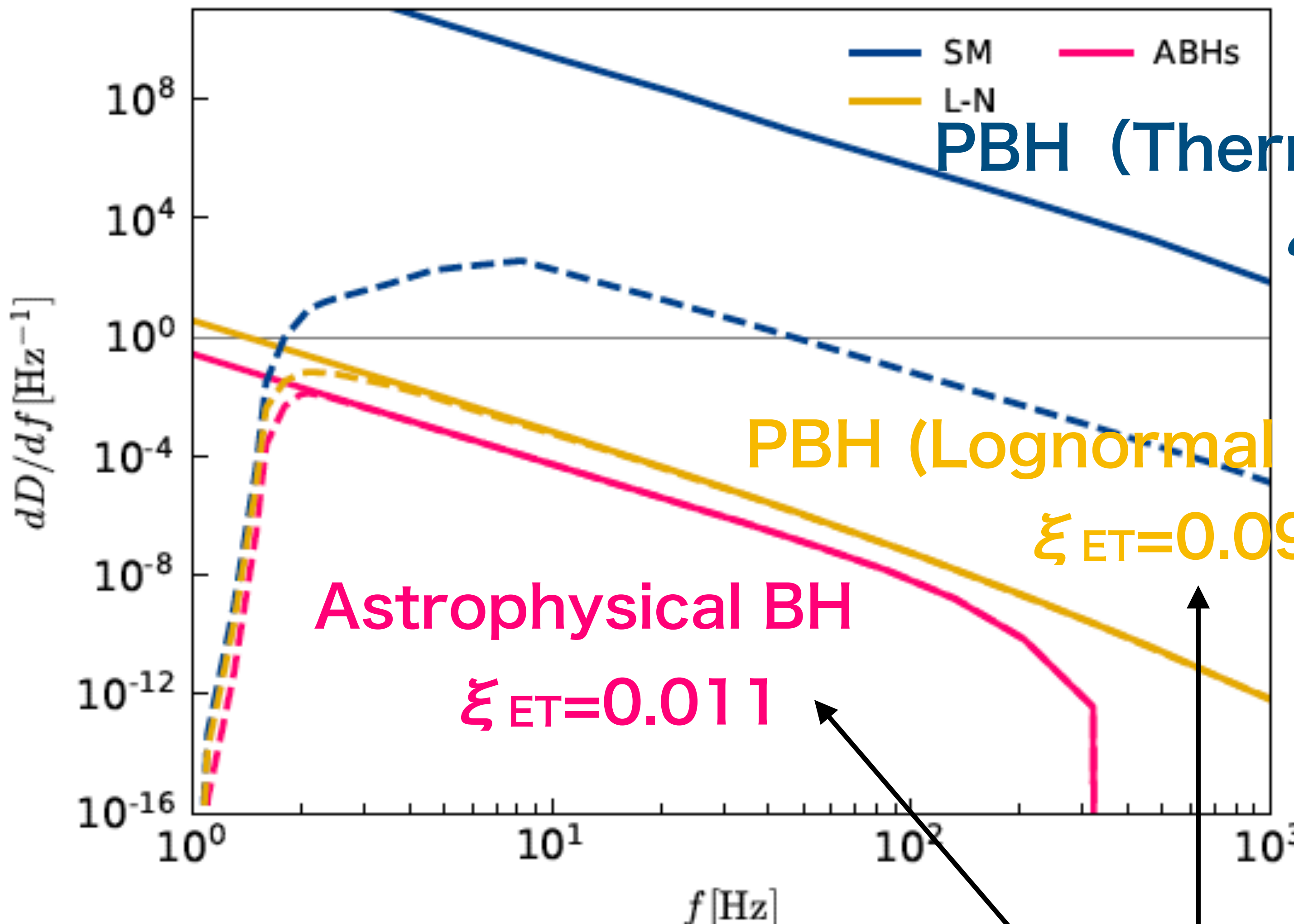


→ Can we distinguish them by measuring the Duty Cycle?

Yes, Duty Cycle helps

Solid: counting all events

Dotted: counting only SNR>1 events in ET



PBH (Thermal history model)

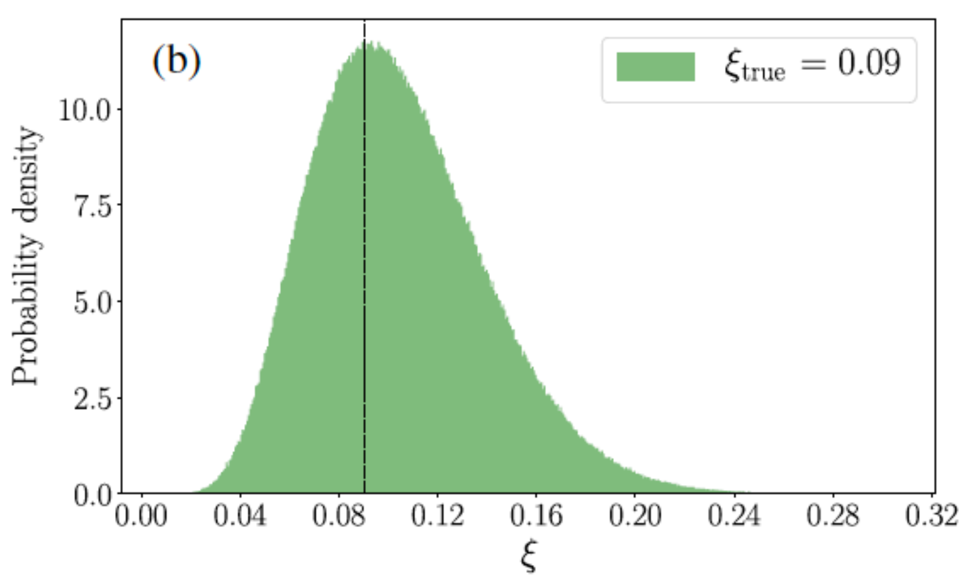
ξ >> 1: continuous

PBH (Lognormal σ_m=1.5)

ξ_{ET}=0.096

Astrophysical BH

ξ_{ET}=0.011



Almost an order of magnitude difference

→ It may be possible to distinguish

Simulation by Smith and Thrane,
PRX 8, 021019 (2018)

Summary

Stochastic GW background is an interesting observable for probing PBHs.

1. We made the first estimation of the stochastic GW background from **close hyperbolic encounters**
2. We calculated the GW background from BBHs for the **thermal history mass function**
3. We estimated the duty cycle of the BBH GW background for different origins (astrophysical/Lognormal/Thermal history) and found that three different models can be distinguished by measuring **duty cycle**