FY2023 "What is dark matter?
- Comprehensive study of the huge discovery space in dark matter"

Primordial black holes and stochastic GW background

Sachiko Kuroyanagi

(Group A3 "macroscopic dark matter")

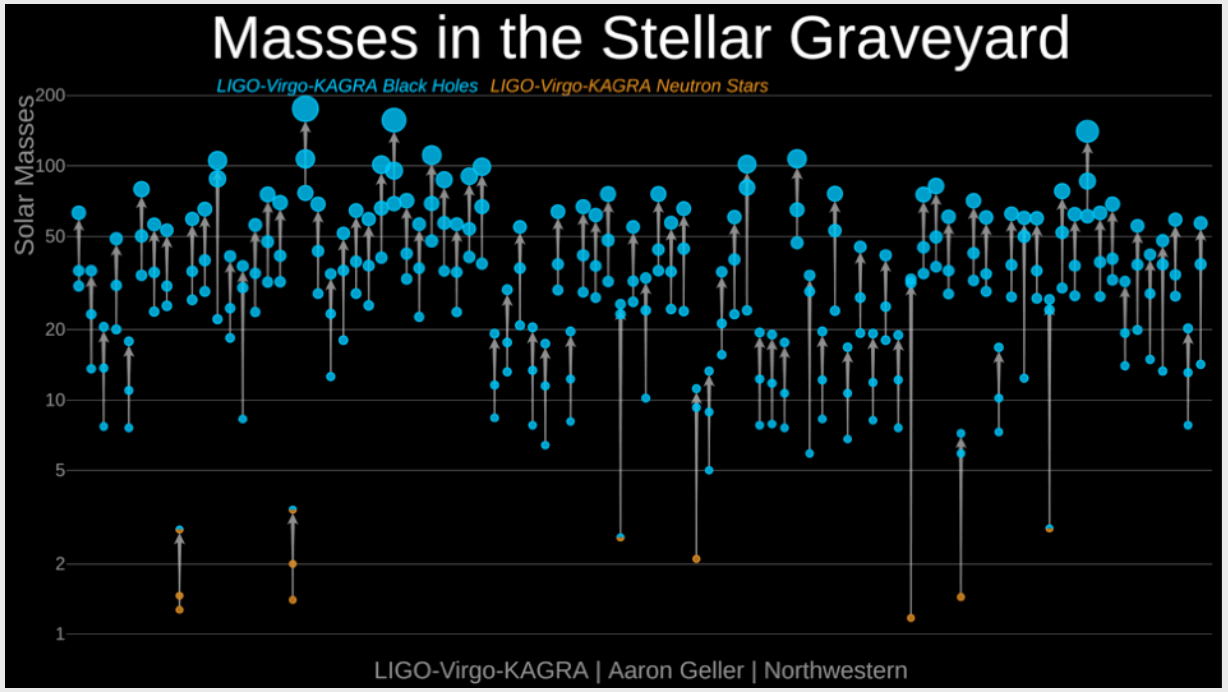
IFT UAM-CSIC / Nagoya University

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.



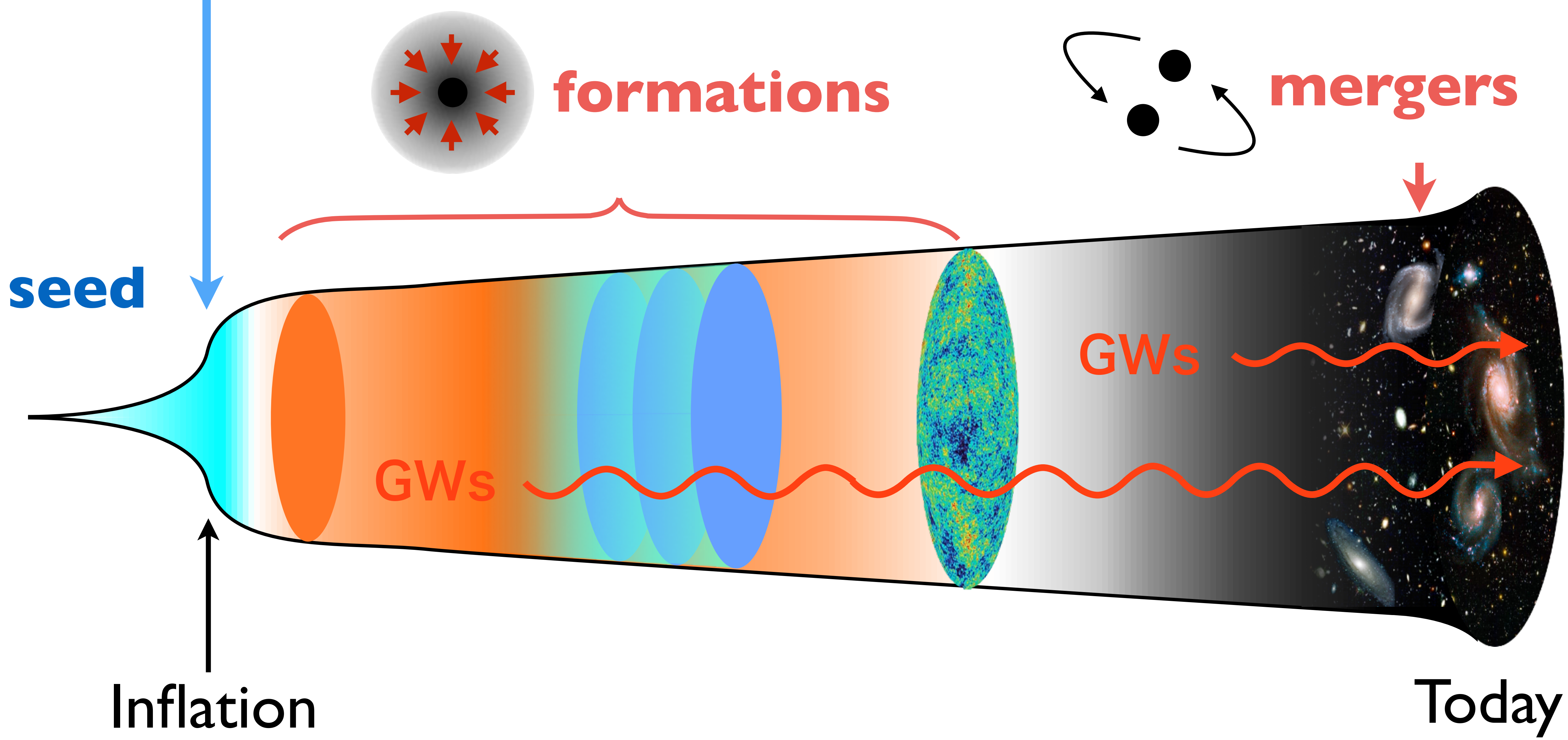
Origin of the observed BBHs could be primordial.

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

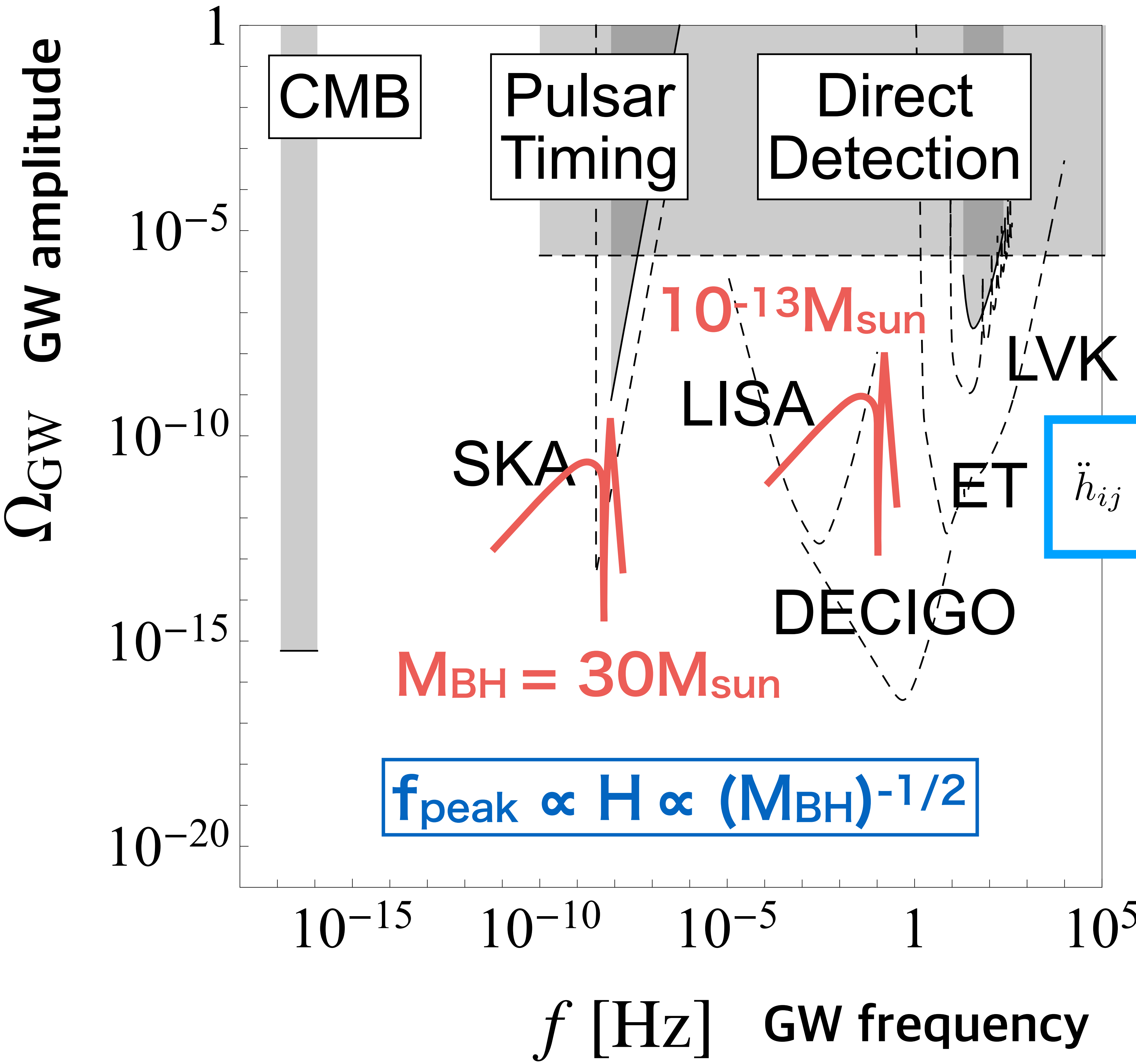
GW background as a probe of PBHs

large primordial curvature perturbations at small scale can be produced by changing the dynamics of the inflaton

GWs are generated through

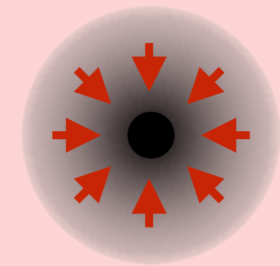


GW associated with PBH formation



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

GWs generated when



PBHs form

in the RD era

EOM for GWs

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G \Pi_{ij}$$

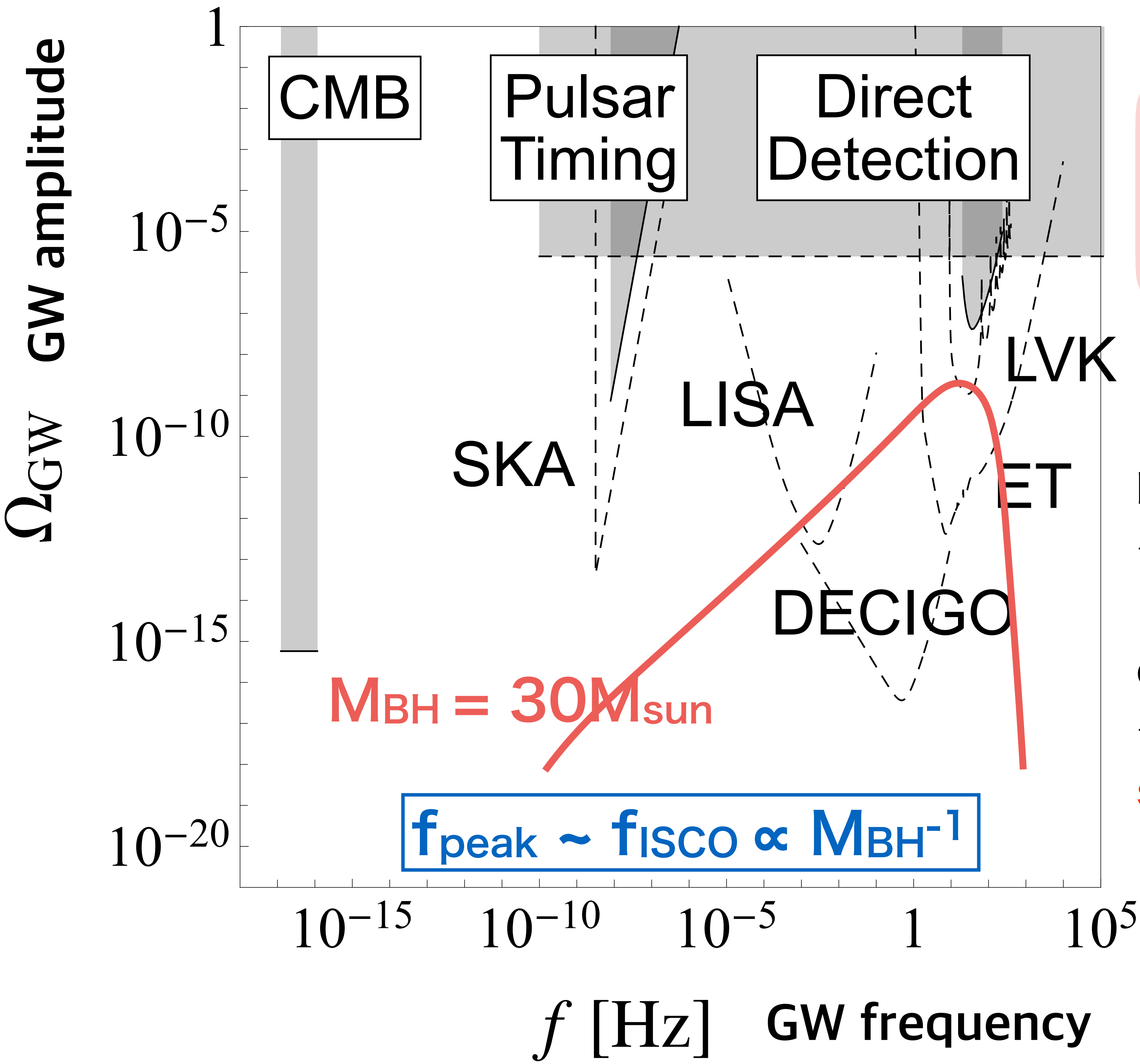
GWs sourced by scalar perturbations at 2nd order

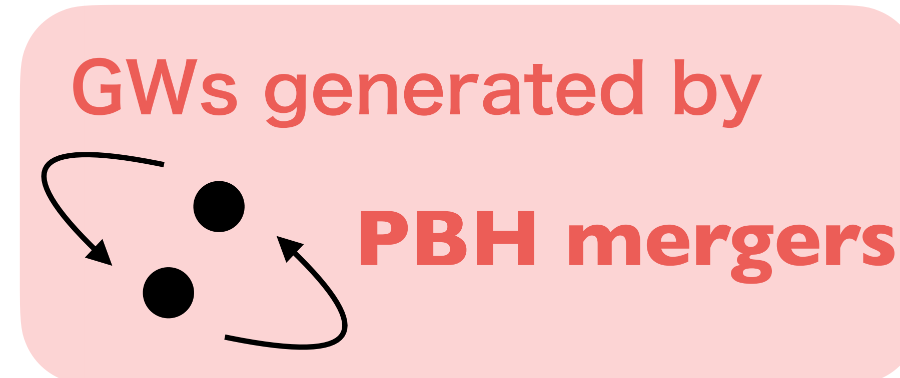
Energy density of GWs

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

Critical density of the Universe

GW background from PBH mergers



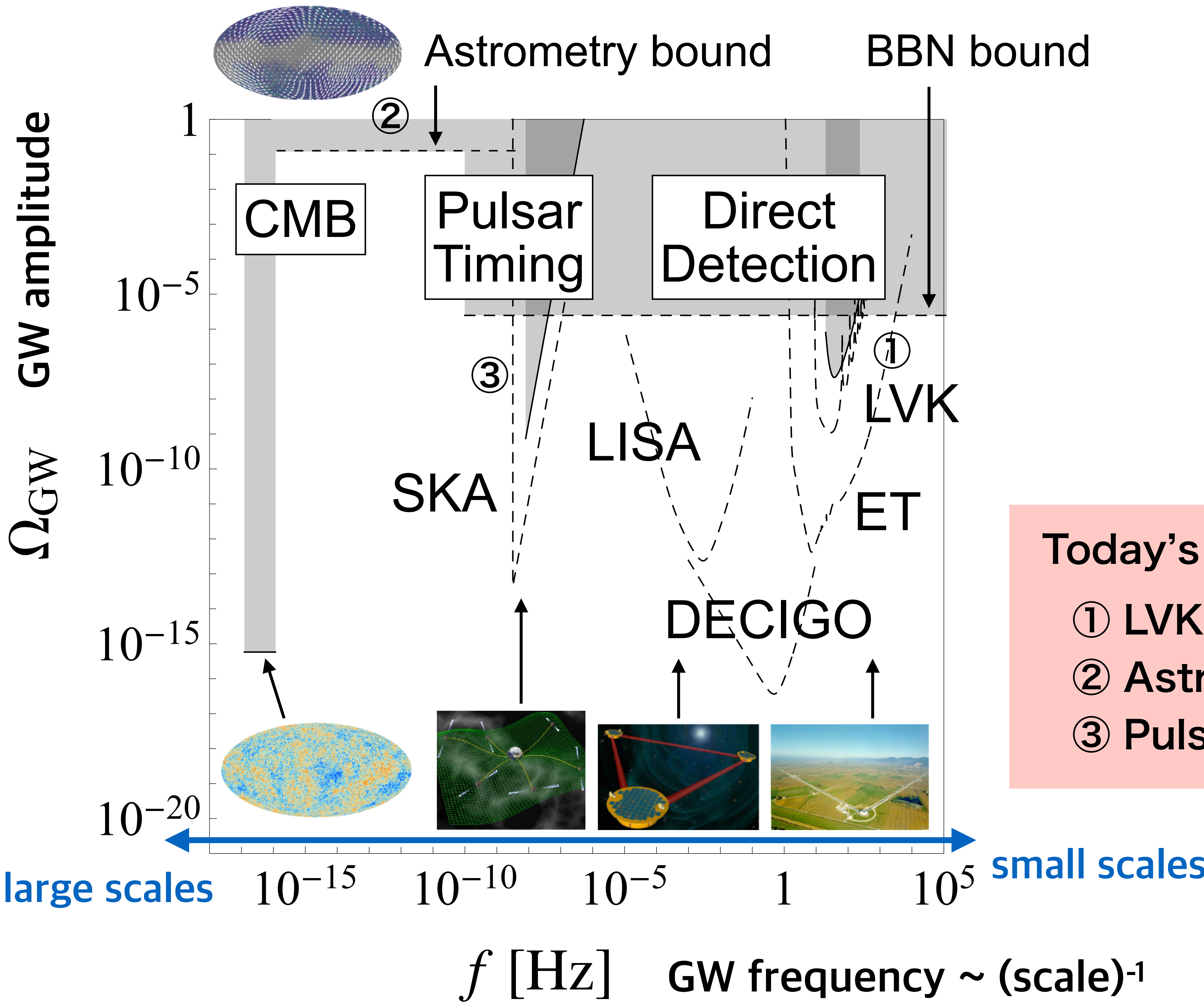


loud (nearby) events
→ individually detectable

distant events
→ detectable as a
stochastic GW background

S. Clesse & J. García-Bellido, PDU (2017) 105–114

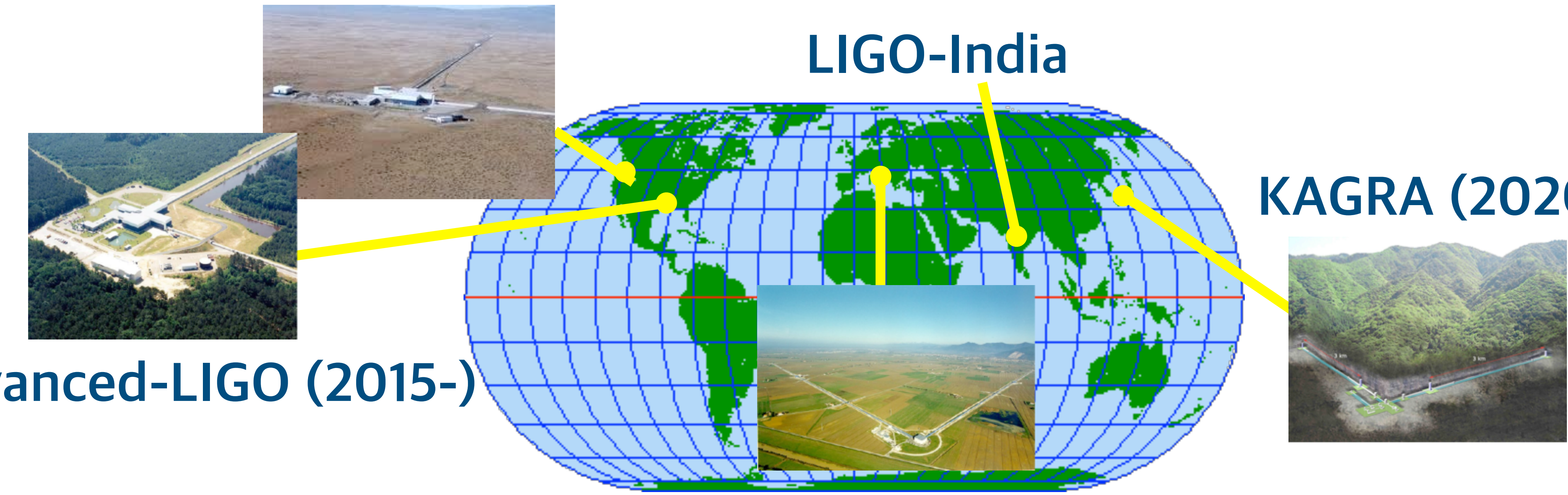
GW observatories cover a wide range of scales!



Today's talk

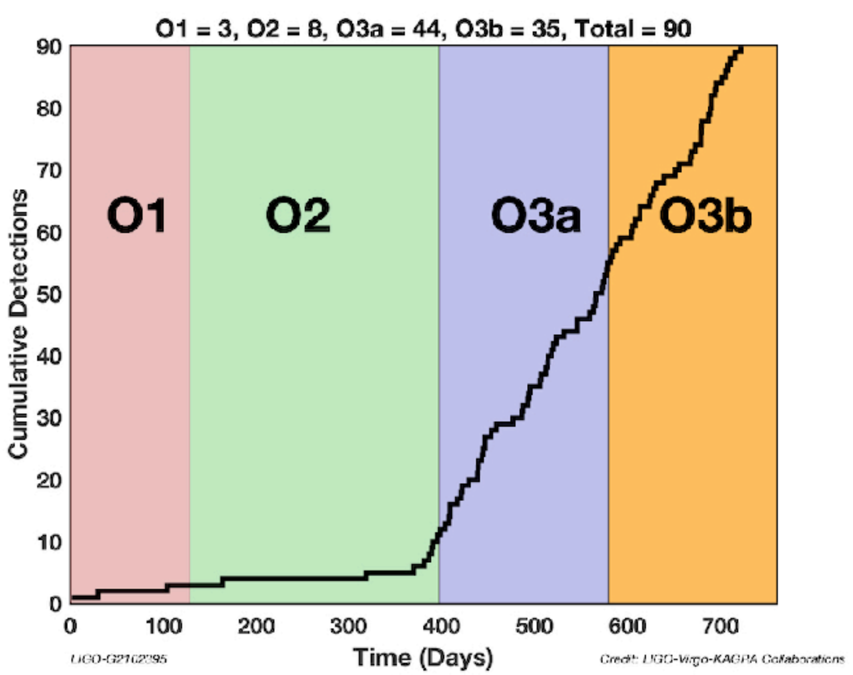
① LVK O3
② Astrometry
③ Pulsar timing

① LIGO-Virgo-KAGRA (LVK) O3 run

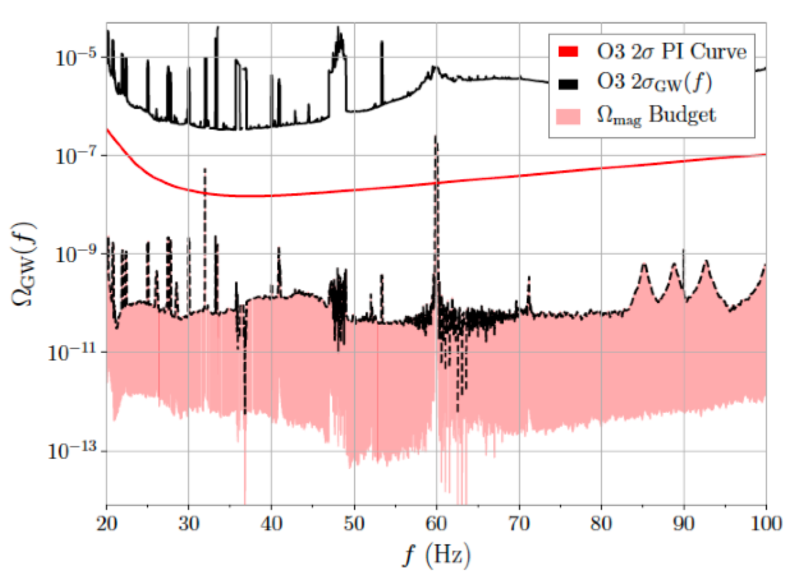


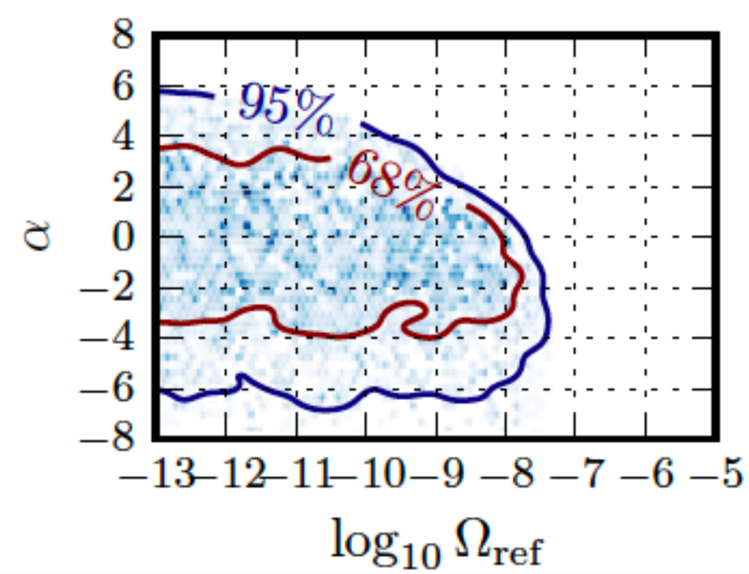
Most recent public data: O3 (April 2019 - March 2020)

- 90 BBH events



- Upper bound on a stochastic GW background
  $\Omega_{GW} < 5.8 \times 10^{-9}$ for a flat spectrum (95%CL)

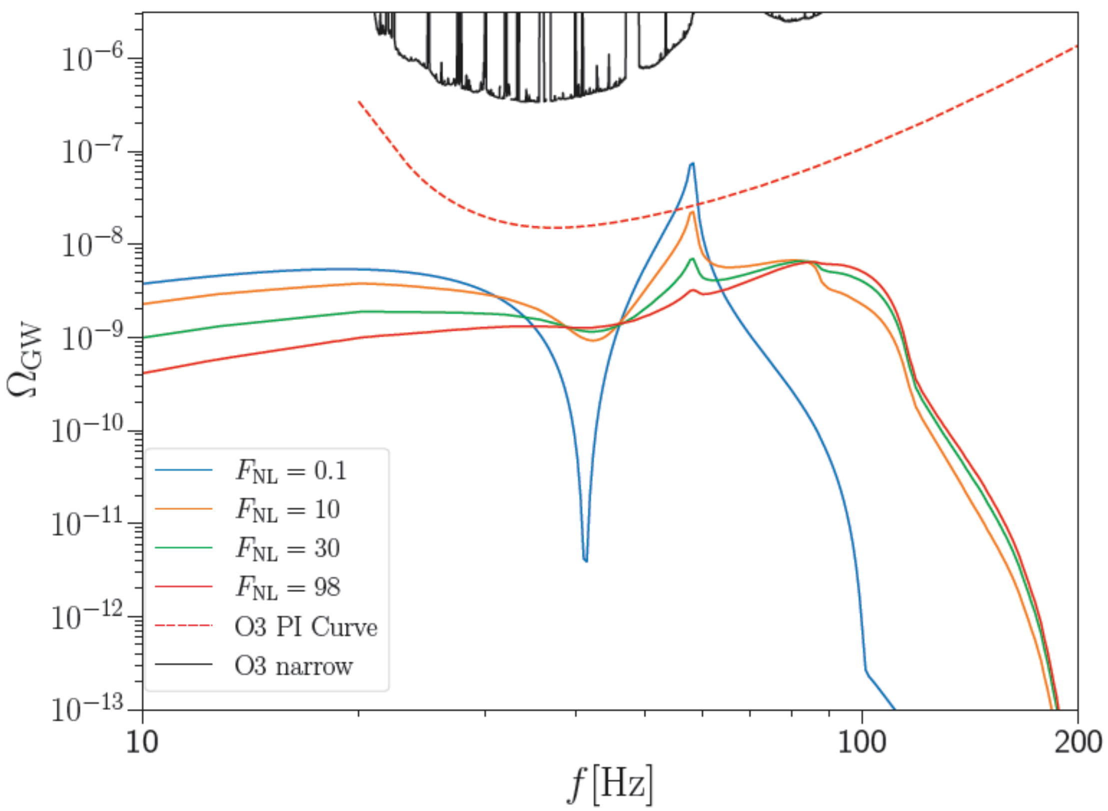




① LVK O3 constraint on 2nd order GWs

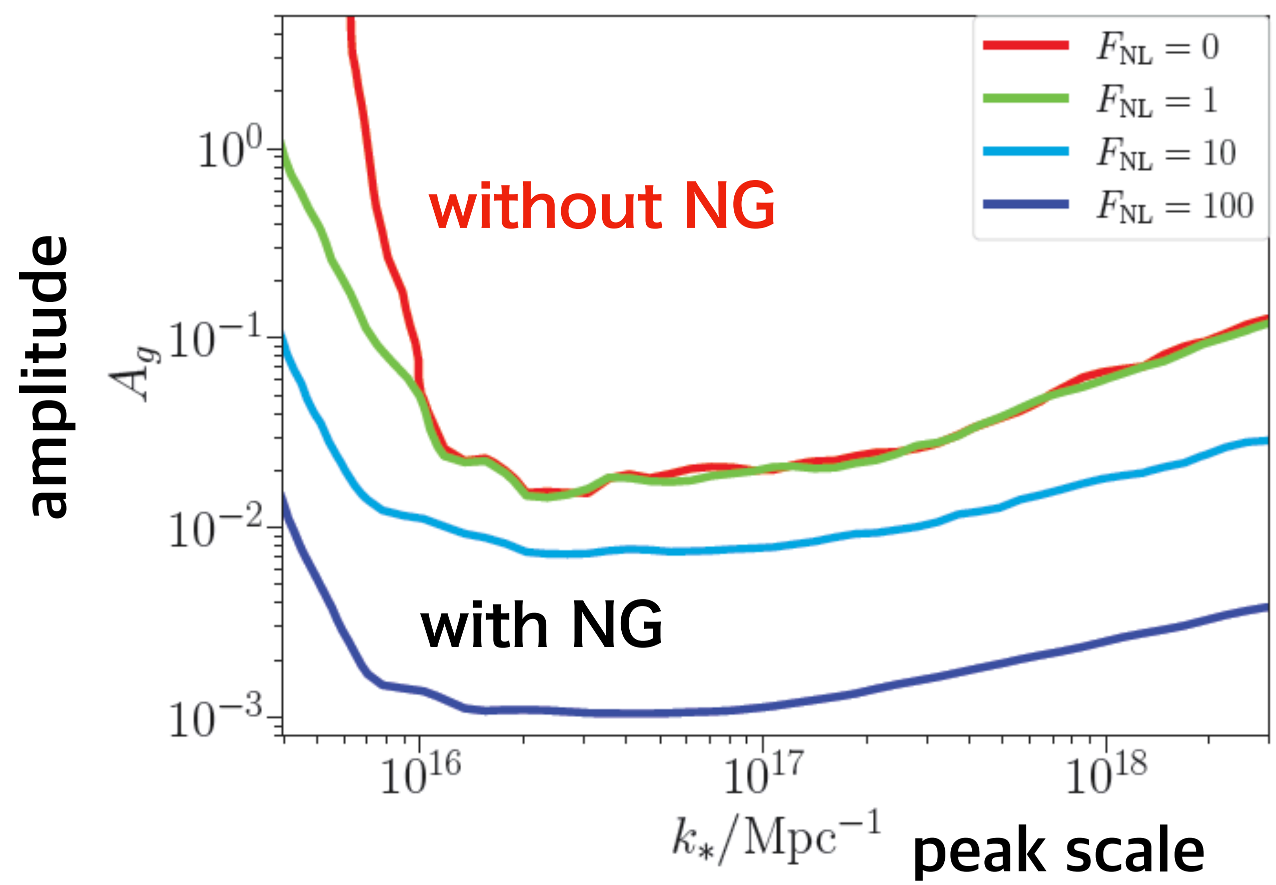
R. Inui, S. Jaraba, SK, S. Yokoyama, arXiv: 2311.05423

GW spectrum



Non-Gaussianity appears in many inflationary models predicting large curvature perturbations

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



Assumption:
local type non-Gaussianity

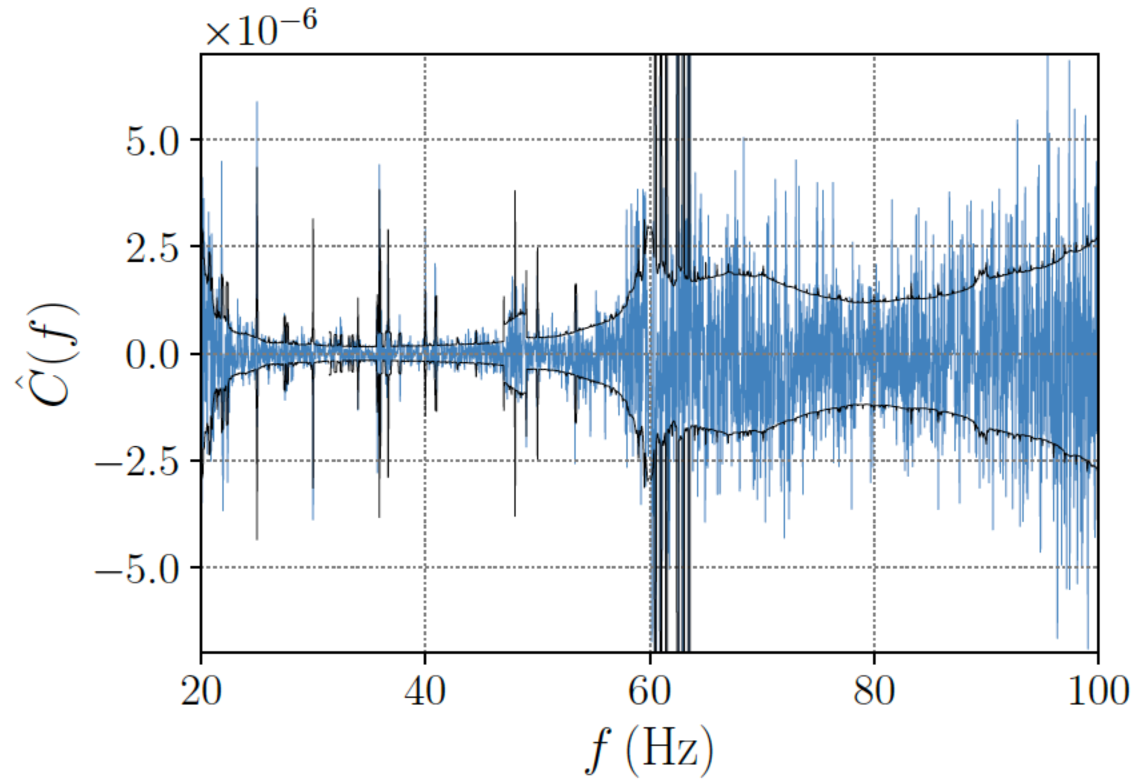
$$\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + F_{\rm NL}\zeta_g^2(\mathbf{x})$$

Note: Parametrization with F_{NL} covers limited cases

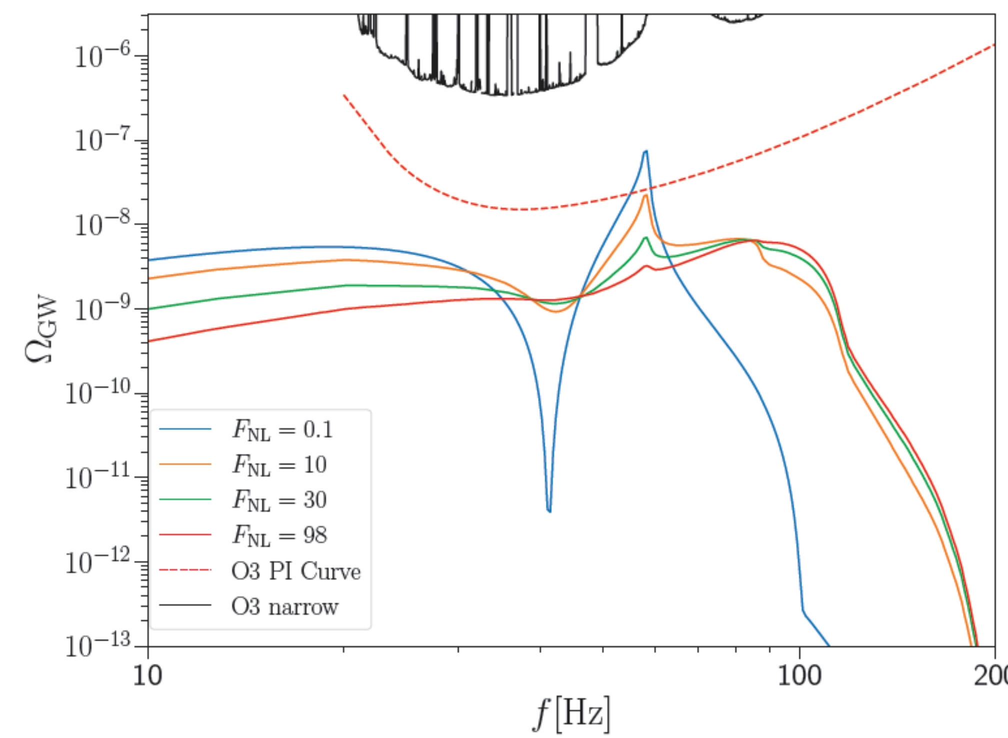
→ constraining $M_{BH} = 10^{-10} \sim 10^{-14} M_{sun}$

How do we obtain constraints?

data (cross-correlated spectrum)



Your model



Likelihood

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

variance

(calculated from the detector noise)

Prior

Posterior distribution

$$p(\boldsymbol{\Theta}|C_k^{IJ}) \propto p(C_k^{IJ}|\boldsymbol{\Theta})p(\boldsymbol{\Theta})$$

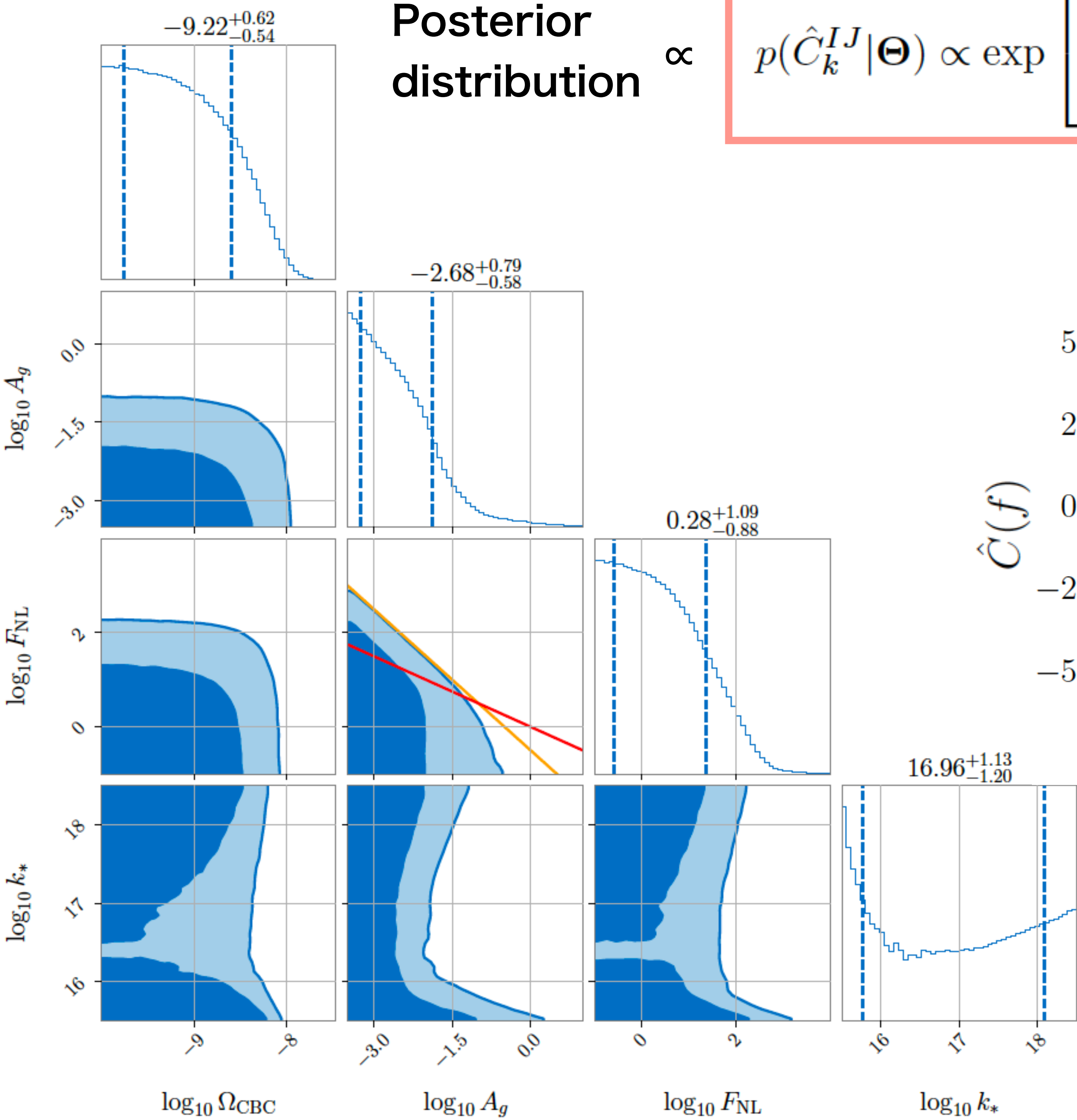
Likelihood analysis

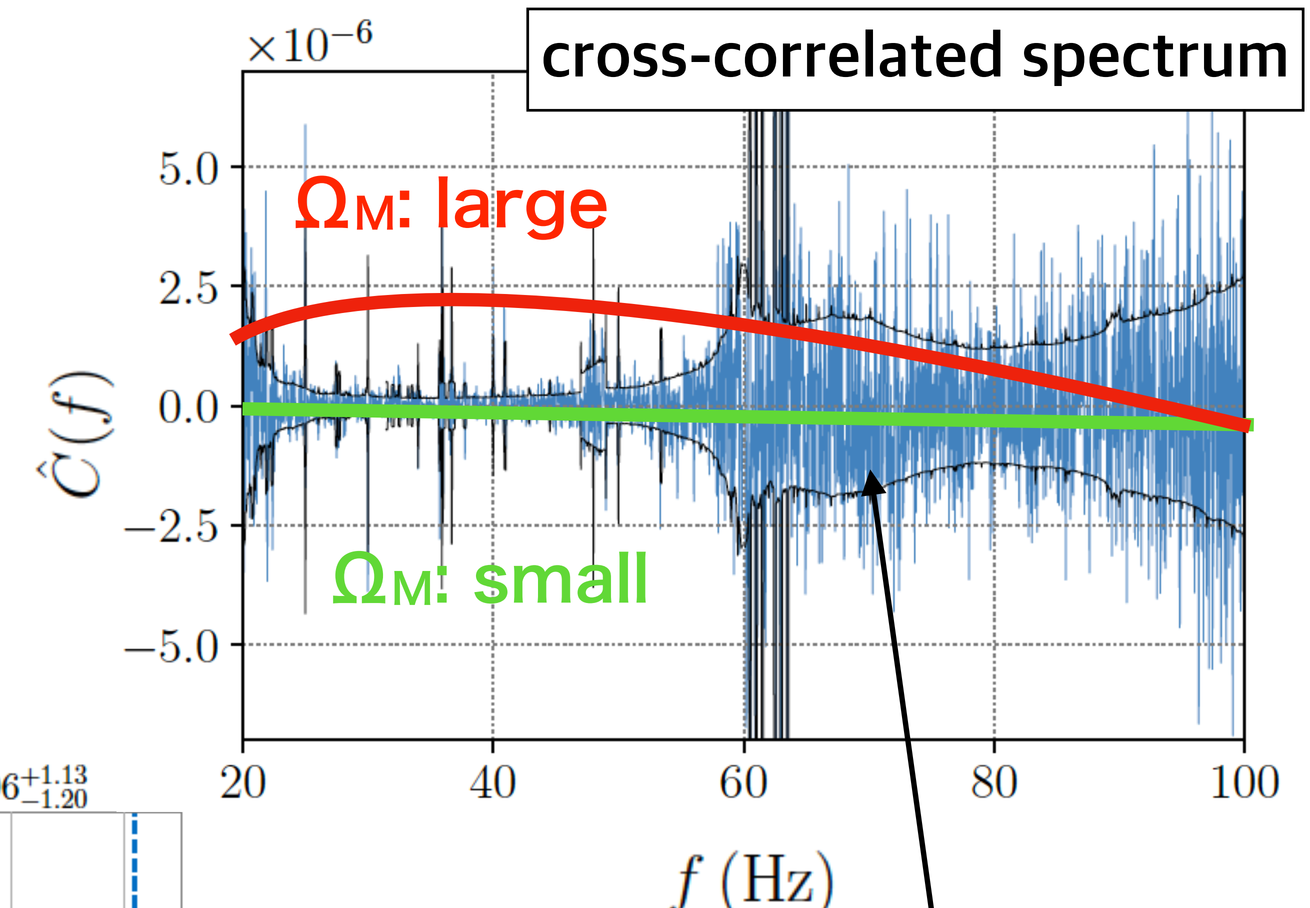
IJ: detector combinations
k: frequencies

Posterior distribution ∝

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

(for a flat & infinite-range prior)





fluctuating because of
the detector noise
with the variance $\sigma^2_{{\rm GW},f}$

More details will be in...

Springer textbook on PBH

Editorial board: Chris Byrnes, Gabriele Franciolini, Tomohiro Harada, Paolo Pani, Misao Sasaki

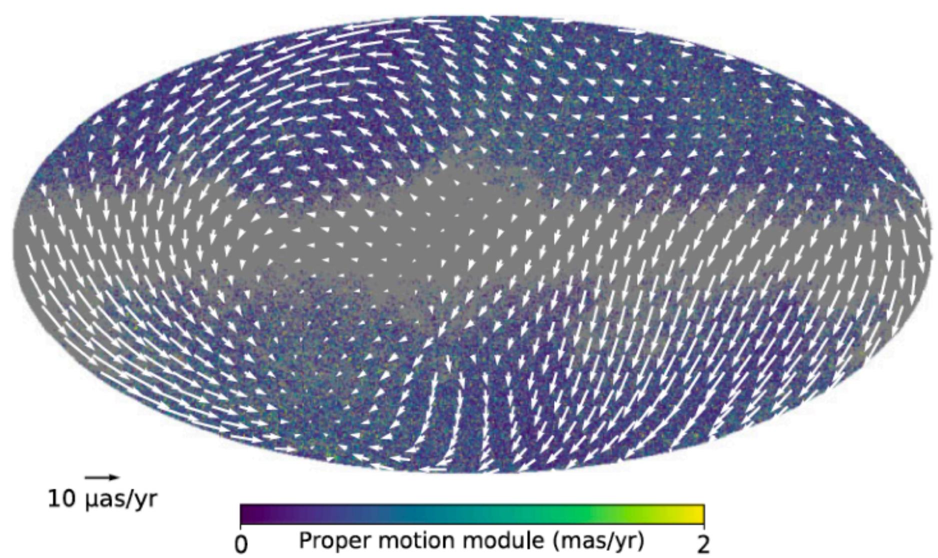
LVK constraints on PBHs from stochastic gravitational wave background searches

Alba Romero-Rodríguez and Sachiko Kuroyanagi

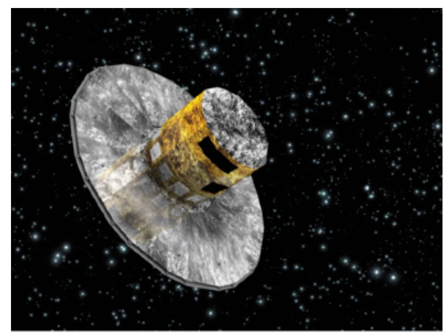
Abstract Primordial black holes (PBHs) may have left an imprint in the form of a stochastic gravitational wave background (SGWB) throughout their evolution in the history of the Universe. This chapter highlights two types of SGWB: those generated by scalar curvature perturbations associated with PBH formation in the early Universe and those composed of ensembles of GWs emitted during PBH mergers. After describing detection methods and a brief introduction on Bayesian inference, we discuss current constraints imposed by LIGO-Virgo-KAGRA (LVK) observations through the non-detection of the SGWBs and discuss their physical implications.

② Astrometry upper bound

S. Jaraba et al. (+SK) MNRAS 524, 3609-3622 (2023)



GWs induce fluctuations in location and proper motion of stars



Gaia satellite (2013-) provides precise measurements of star motions

Upper bound obtained by fitting l=2 multipole mode

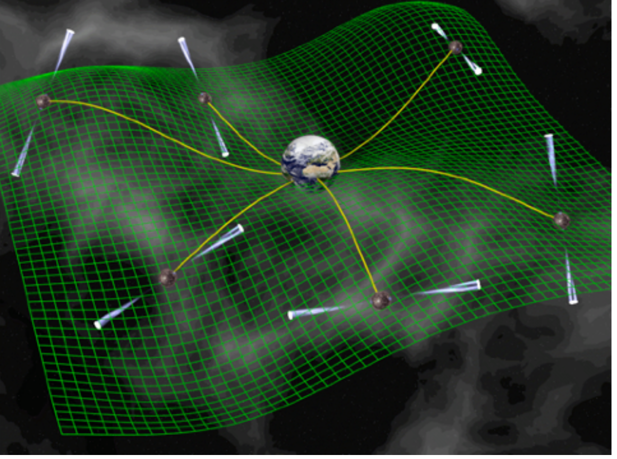
$$\Omega_{\rm GW} = \frac{6}{5}\frac{1}{4\pi}\frac{P_2}{H_0^2} = 0.000438\frac{P_2}{(1\ \mu{\rm as/yr})^2}h_{70}^{-2}$$

Valid frequency range

$$4.2\times10^{-18}\ {\rm Hz} \lesssim f \lesssim 1.1\times10^{-8}\ {\rm Hz}$$

Data set	$\sqrt{P_2}$ (μas/yr)	Z_2	$\ln \mathcal{B}_1^{12}$	$h_{70}^2\Omega_{\rm GW}$	$h_{70}^2\Omega_{\rm GW}^{\rm up}$ (95 percent)
Masked	12.51(1.81)	4.19	−17.2	0.069(0.021)	0.114
Pure	23.15(2.01)	10.21	34.4	0.235(0.040)	0.295
Astrometric	10.13(1.73)	3.10	−23.2	0.045(0.017)	0.089
Intersection	9.53(1.73)	2.68	−23.5	0.040(0.017)	0.087
VLBA	2.73(1.23)	−1.93	−42.3	0.0033(0.0056)	0.024
VLBA+Gaia DR1	5.30(1.36)	0.57	−14.7	0.0123(0.0077)	0.034
SDSS+Gaia EDR3	52.48(10.88)	4.70	69.6	1.21(0.54)	2.43

Obs. time
2.84yr
22.2yr

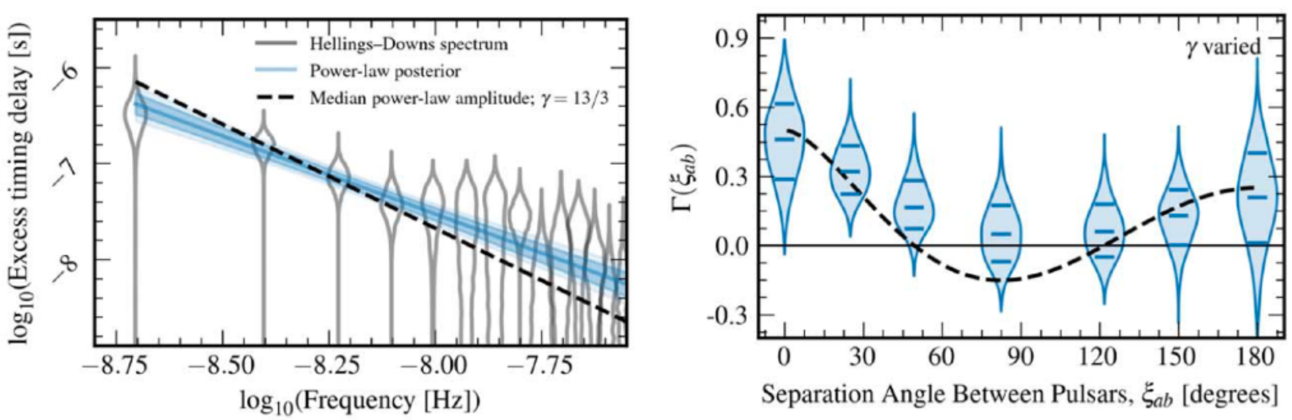


③ Pulsar timing

“Evidence” of GWs at nano-Hz frequencies

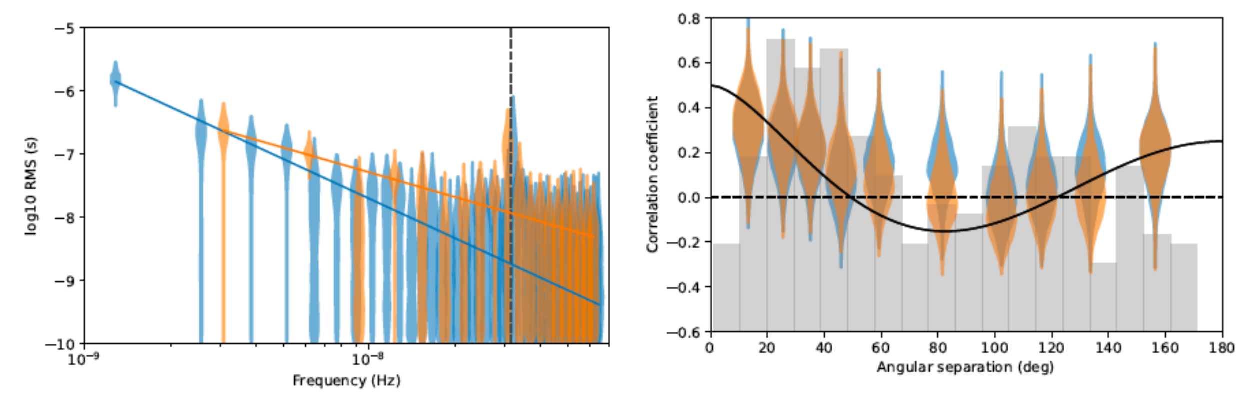
NANOGrav G. Agazie et al. (2023)

finding $p = 10^{-3}$ ($\approx 3\sigma$) for the observed Bayes factors



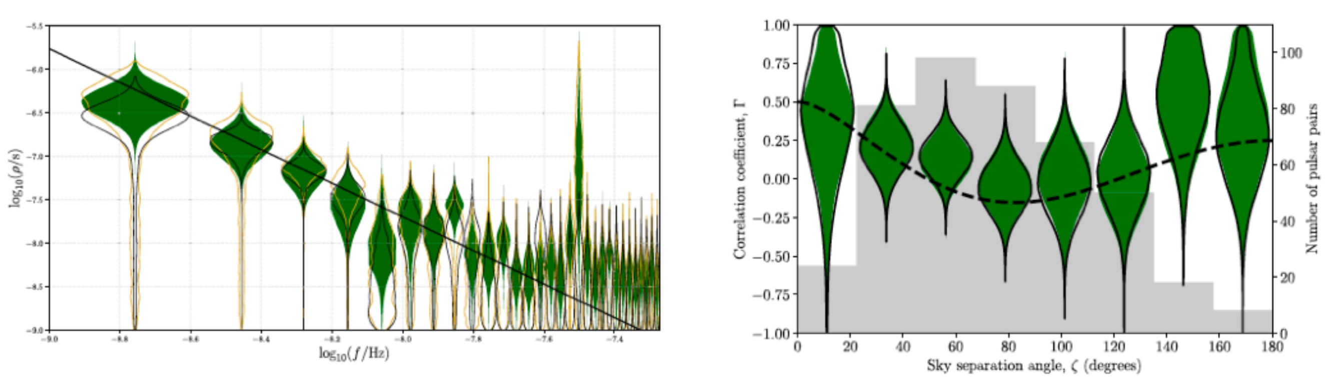
EPTA+IPTA J. Antoniadis et al. (2023)

a false alarm probability of about 0.1% ($\gtrsim 3\sigma$ significance)



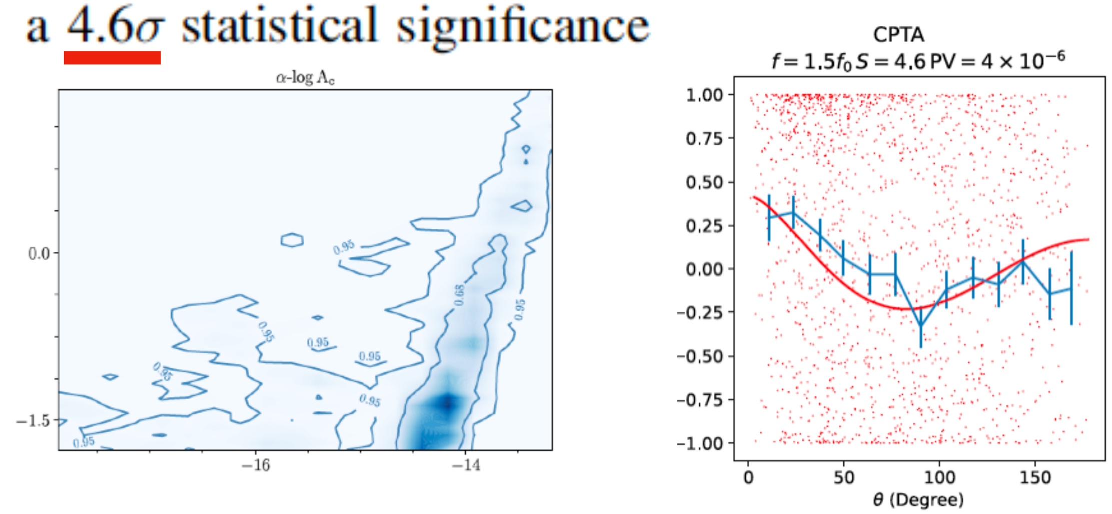
PPTA D. Reardon et al. (2023)

false-alarm probability of $p \lesssim 0.02$ (approx. 2σ)



CPTA H. Xu et al. (2023)

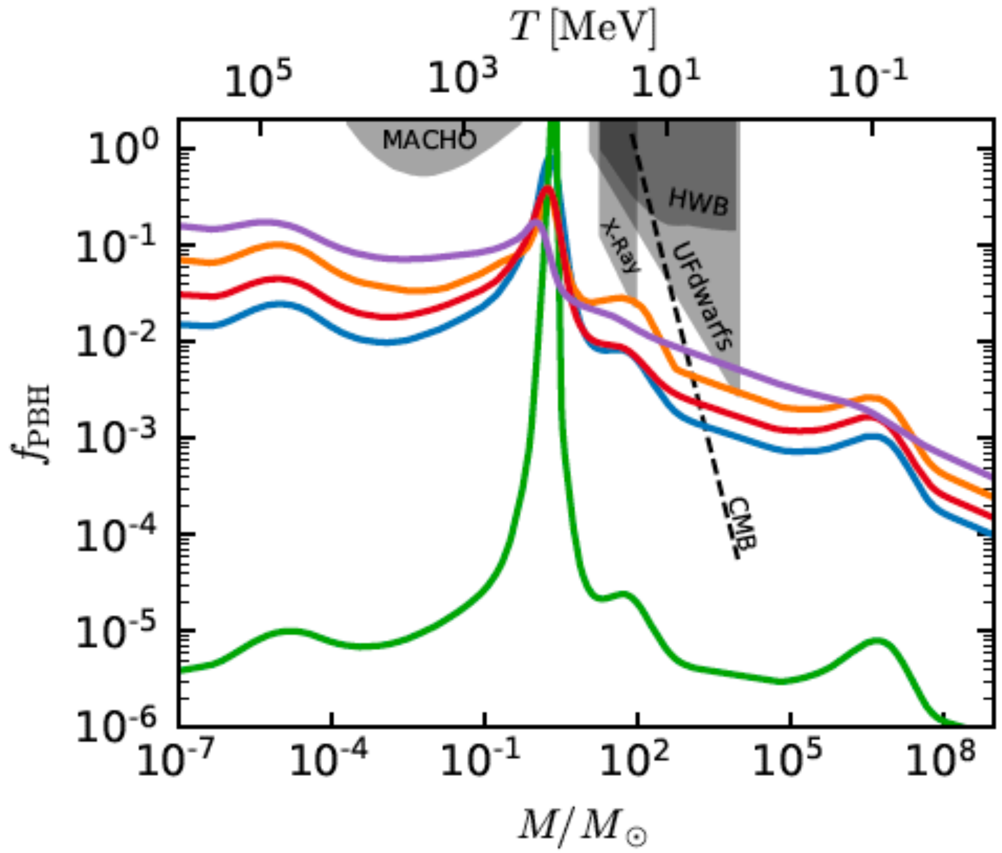
a 4.6σ statistical significance



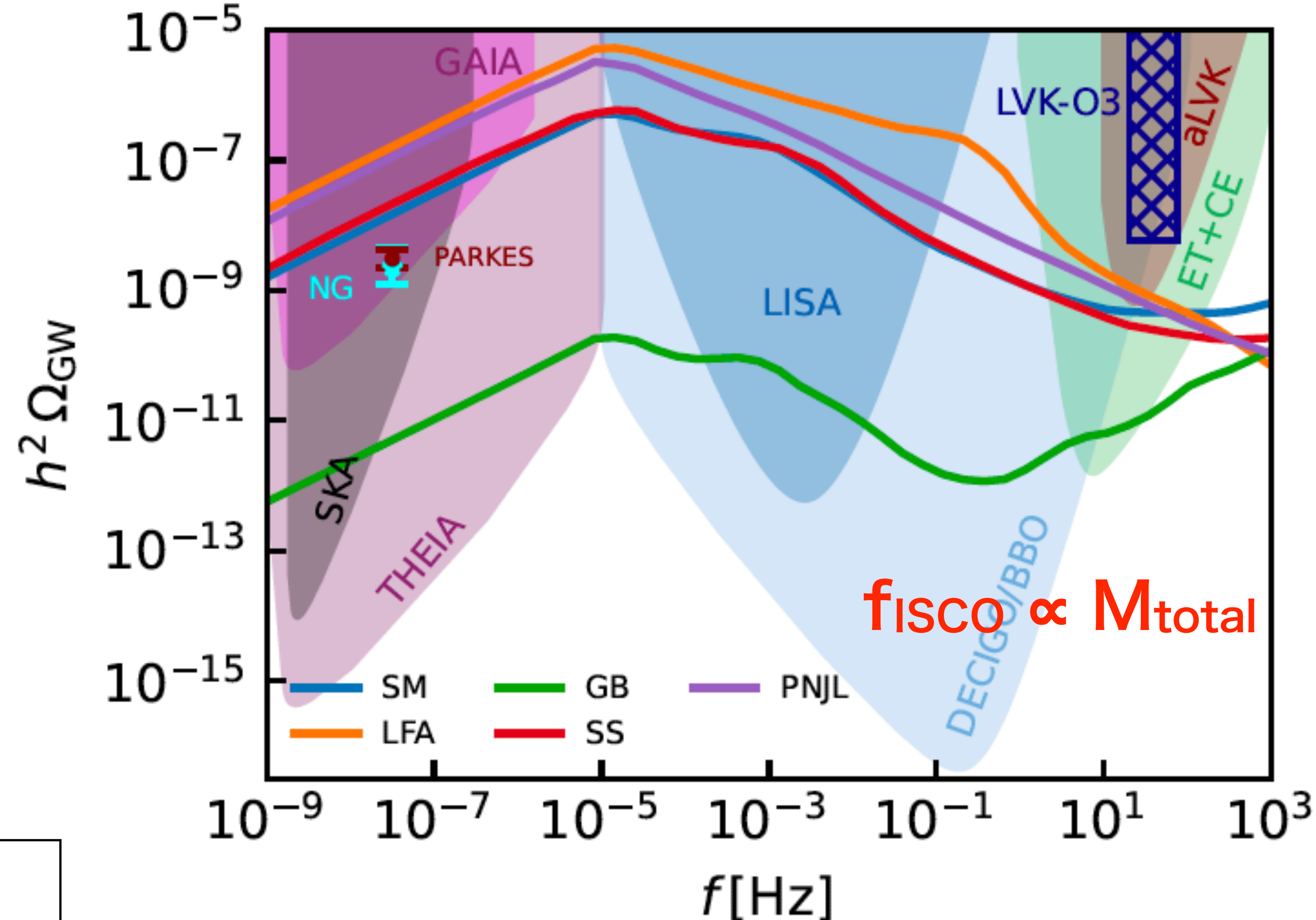
GW spectrum from PBH mergers

M. Braglia, J. Garcia-Bellido, SK, JCAP12, 012 (2021)

Thermal mass PBH mass function



GW spectrum



Assumption:
binary formation by dynamical capture

cross section

$$\sigma = \pi b^2 = \pi \left(\frac{GM}{v_0^2} \right)^2 (e^2 - 1)$$

event rate

$$\tau_{\rm ind} = \sigma v_{\rm PBH} n(m)$$

Wide mass range
→ Wide frequency

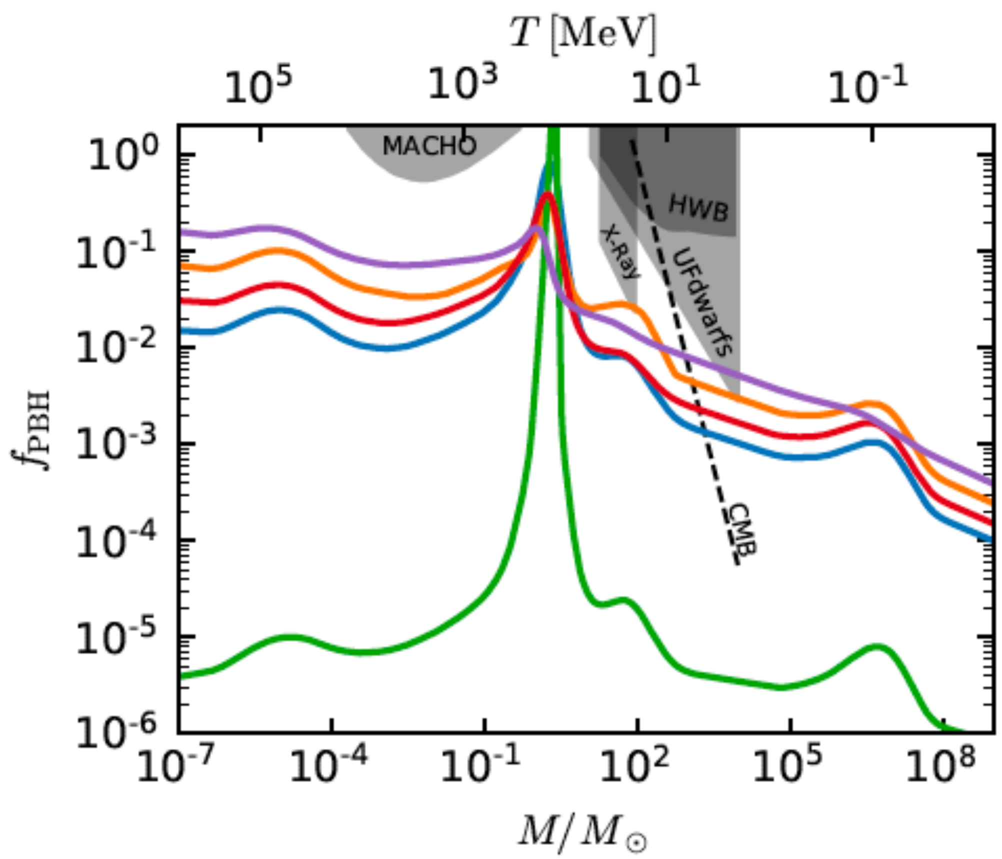
Primordial spectrum with n_s=0.97

Normalization of the merger rate is taken to explain all the individual events in GWTC-2 (38 /Gpc^3/yr)

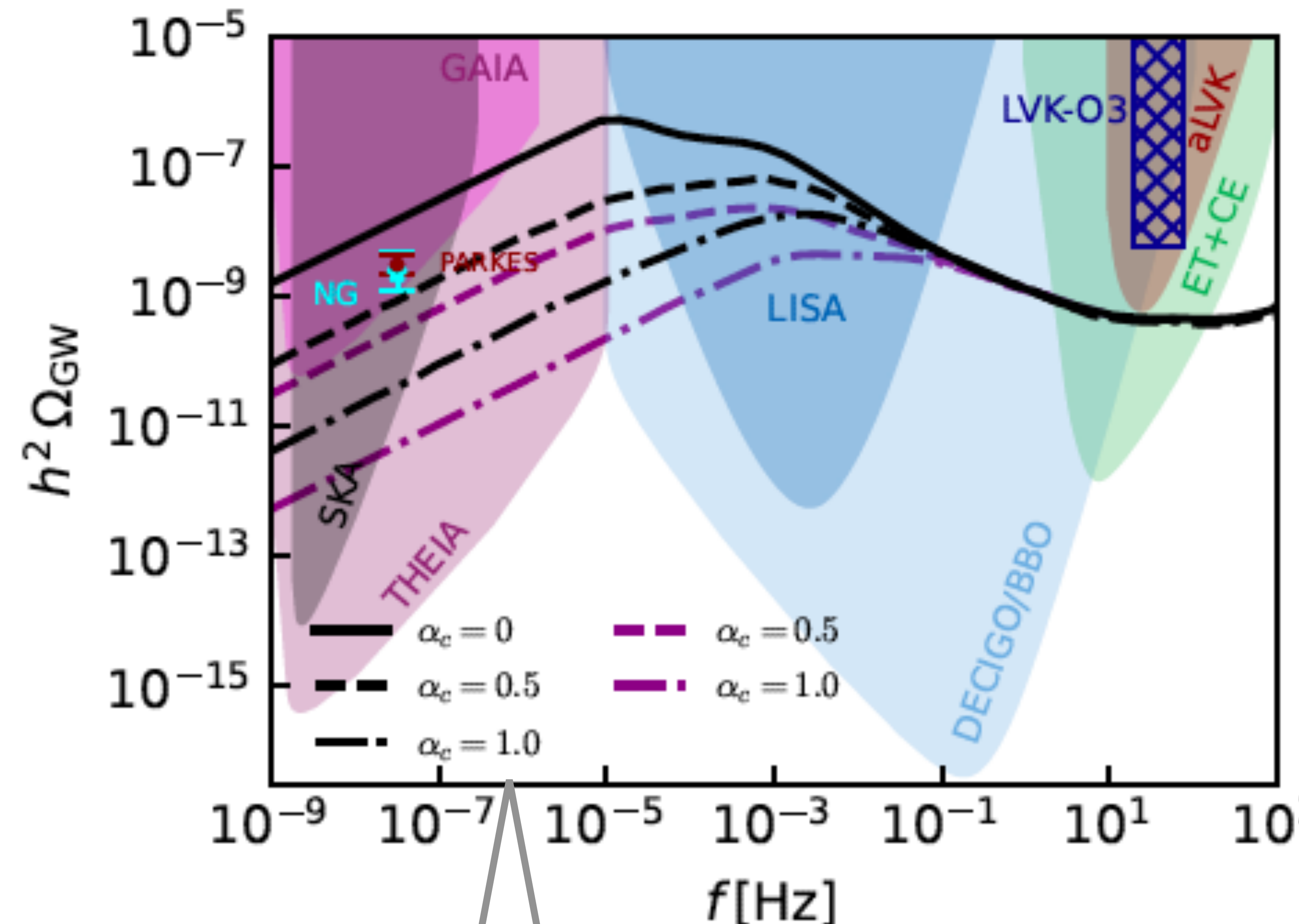
Prediction for pulsar timing?

M. Braglia, J. Garcia-Bellido, SK, JCAP12, 012 (2021)

Thermal mass PBH mass function



GW spectrum



Suppression of the merger rate of large mass BHs (more difficult to form binaries)

→ introduced by introducing a cutoff in mass function $1/\left[1+(M_{\rm tot}/M_*)\right]^{\alpha_c}$

Better way to provide prediction for pulsar timing?

Summary

Stochastic GW background is a useful tool to probe signature of PBHs.

Possible PBH signals and its peak frequency

2nd order GW $$f \sim 5.6 \times 10^{-9} \left(\frac{M_{\rm PBH}}{M_\odot} \right)^{-1/2} {\rm Hz}$$

PBH mergers $$f \sim 8.3 \times 10^{3} \left(\frac{M_\odot}{M_{\rm PBH}} \right)^{-1} {\rm Hz}$$

→ Multi-frequency GW observations
(Astrometry, Pulsar timing,
Space-borne/Ground-based interferometers)
help to explore a wide range of PBH mass scales!