Early universe cosmology with the stochastic gravitational wave background

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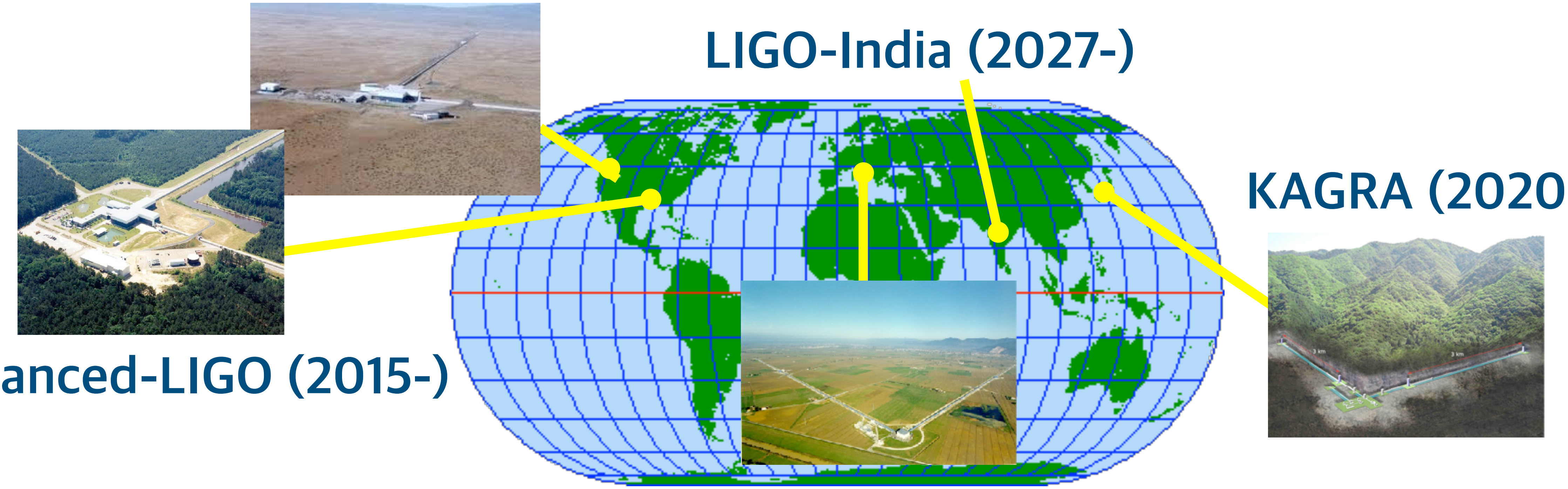
8 Dec 2022

Gravitational wave (GW) observation

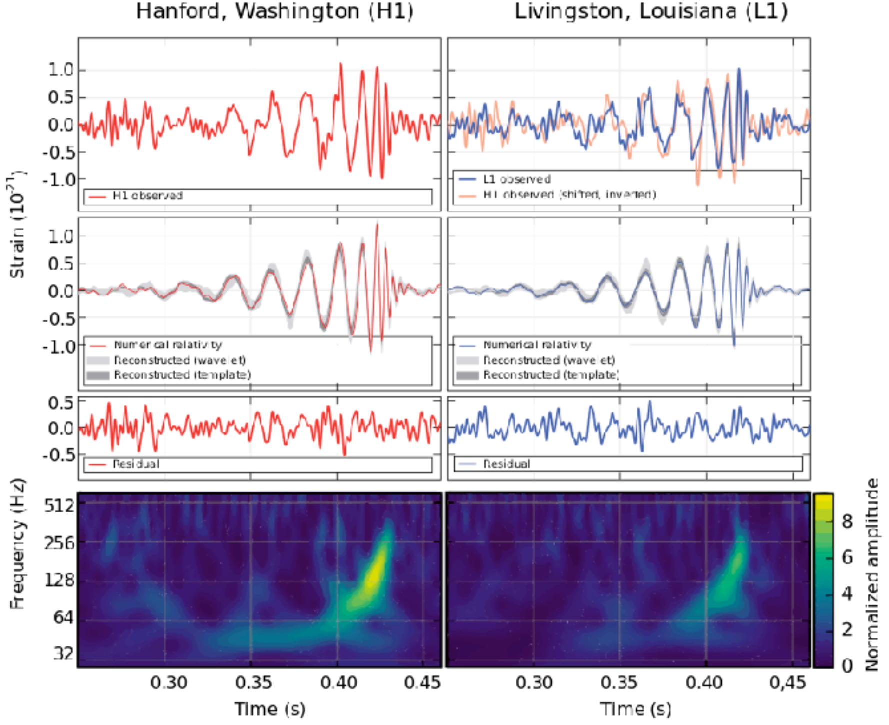


LIGO-India (2027-)

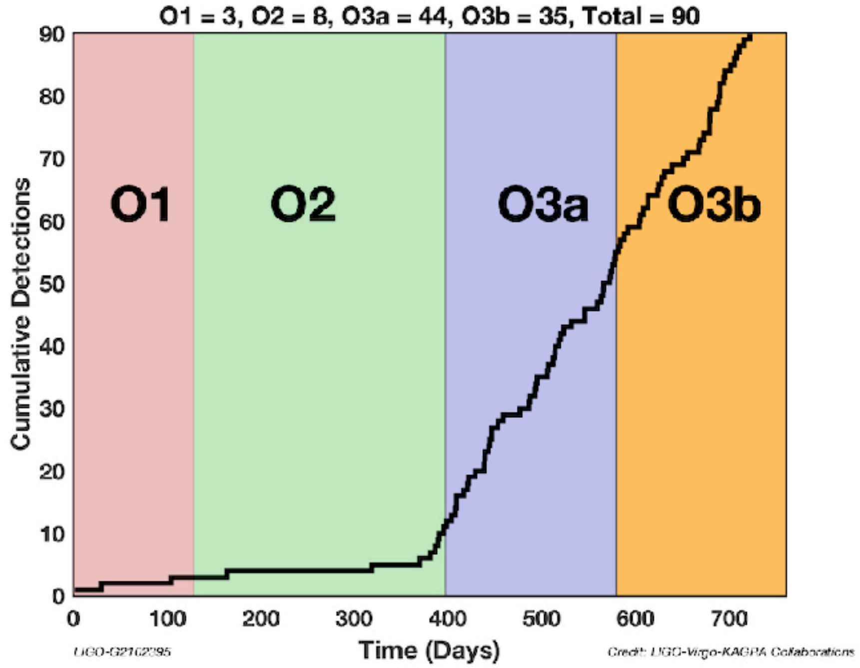
KAGRA (2020-)

Advanced-LIGO (2015-)

Advanced-VIRGO (2017-)



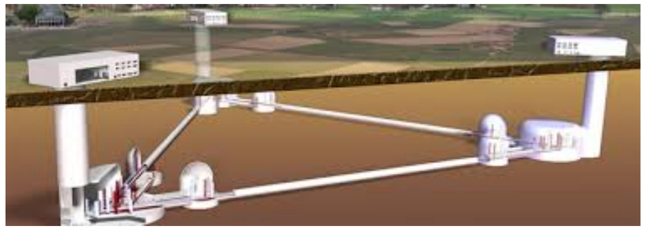
The first detection: GW150914



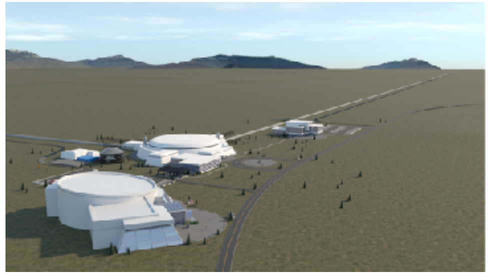
O4 starts in Mar 2023

Future projects

- Einstein Telescope

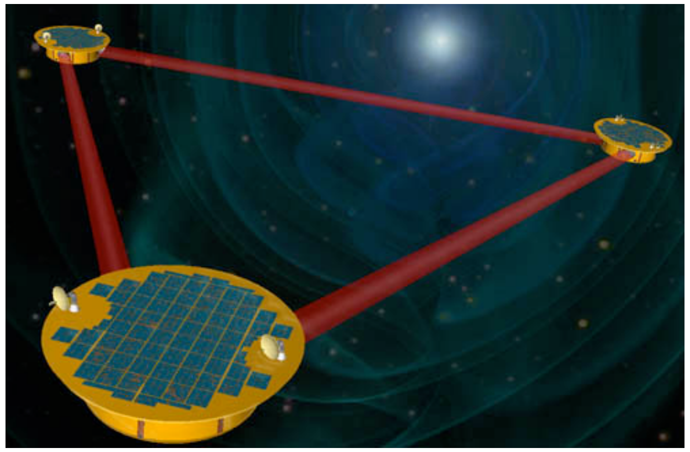


- Cosmic Explorer



etc.

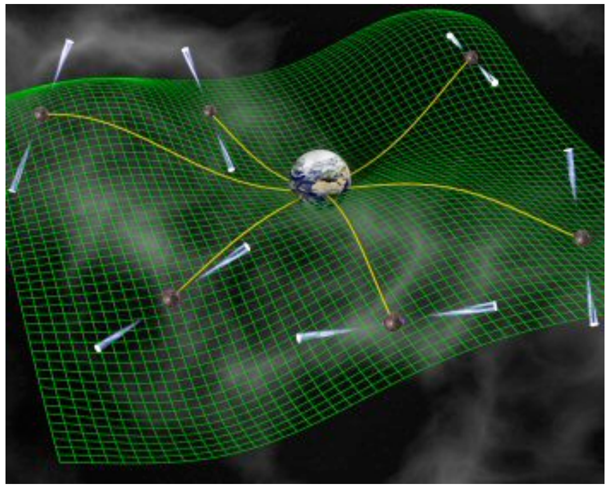
Other GW experiments



Space missions

LISA (2035)   DECIGO (20??)

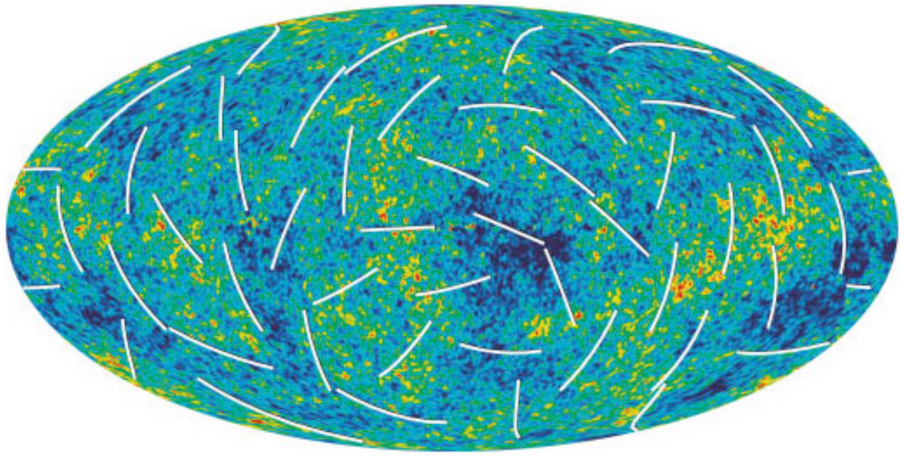
TianQin (2035), Taiji (2033)



Pulsar timing array

ongoing: NANOGrav, EPTA, PPTA

SKA (construction phase: 2021-2029)

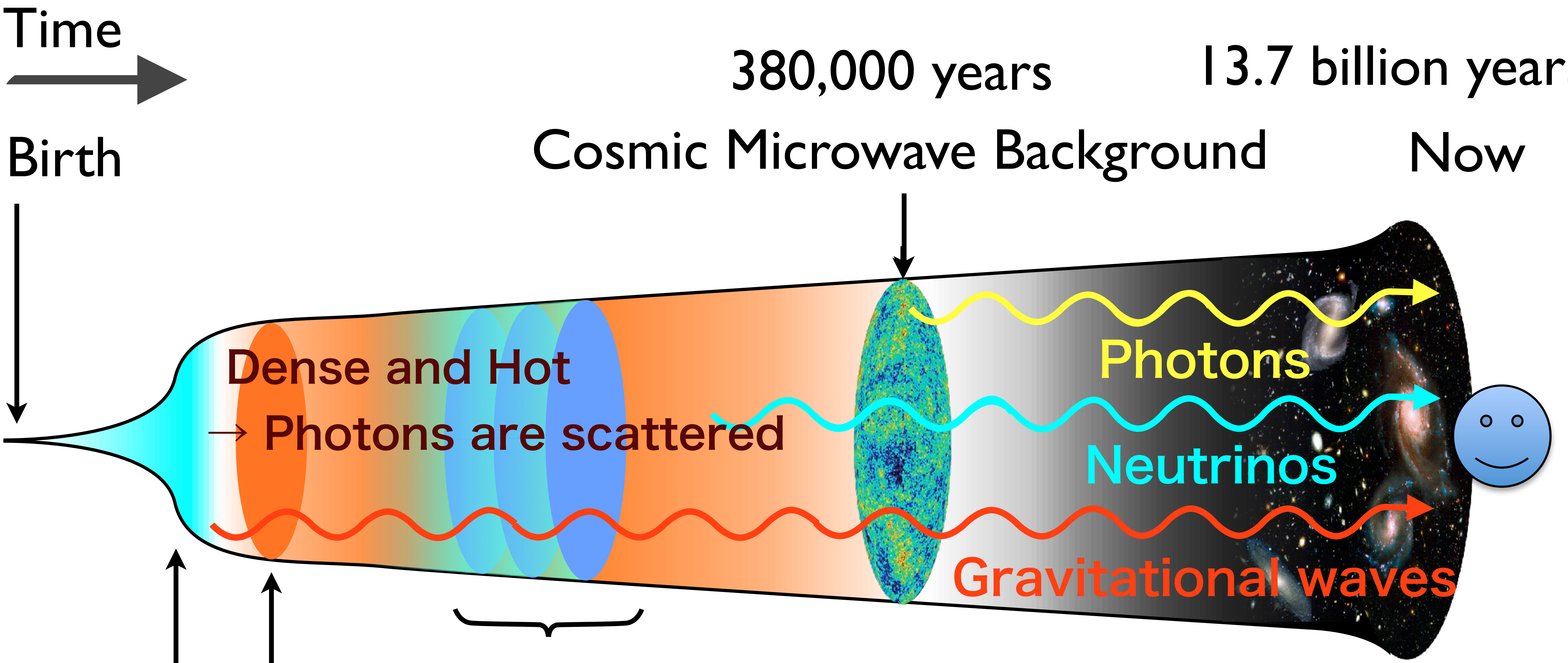


B-mode polarization in CMB

Ground-based experiments, CMB S4

LiteBIRD (2029-)

GWs allow us to directly observe the early universe!



Time

Birth

380,000 years

Cosmic Microwave Background

13.7 billion years

Now

Dense and Hot

→ Photons are scattered

Photons

Neutrinos

Gravitational waves

Cosmic phase transitions

Reheating

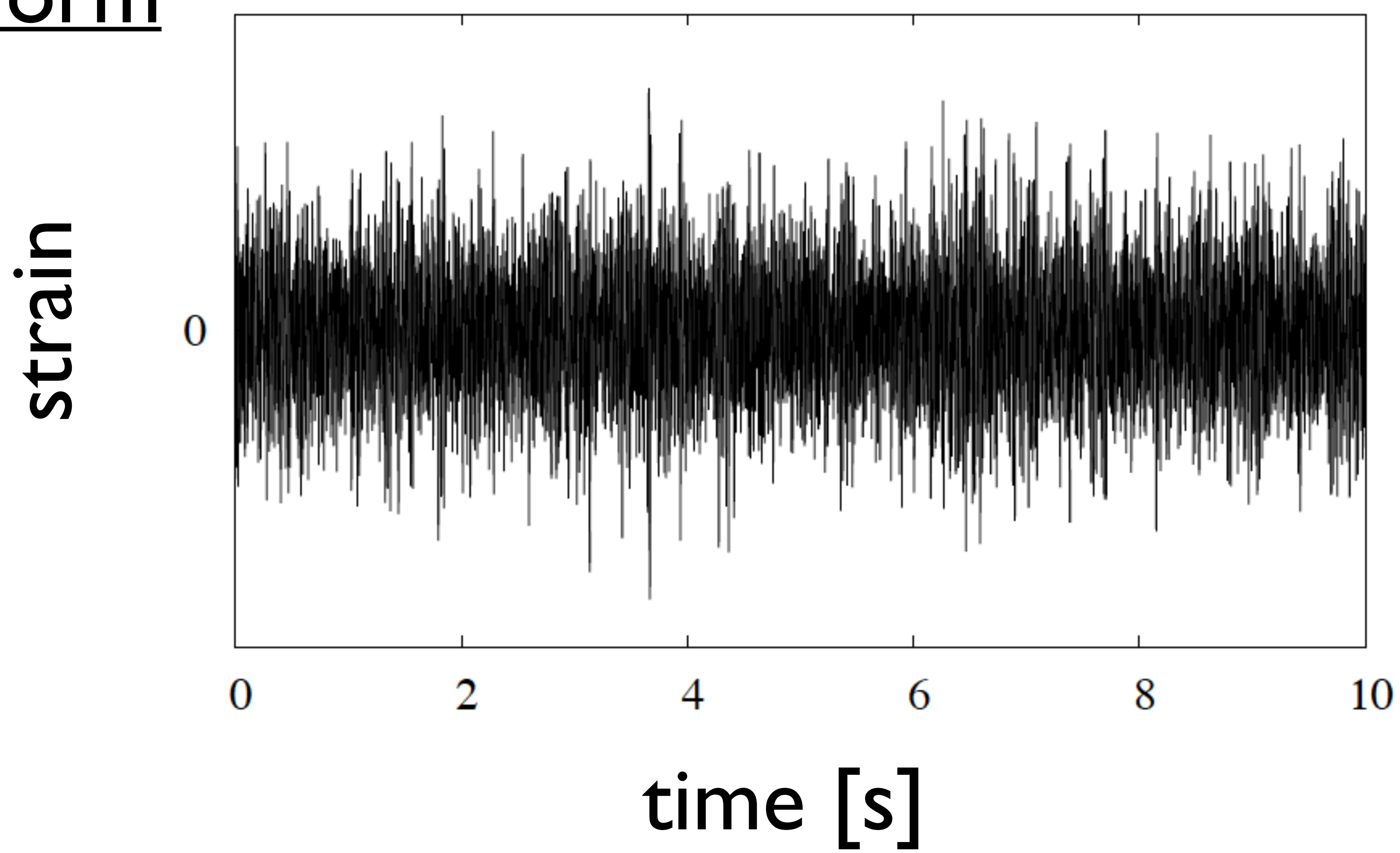
→ generate stochastic GWs

Inflation

→ a unique test of high energy theories

Stochastic GW background

Waveform



Continuous and random 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 signal
h: gravitational waves
n: noise

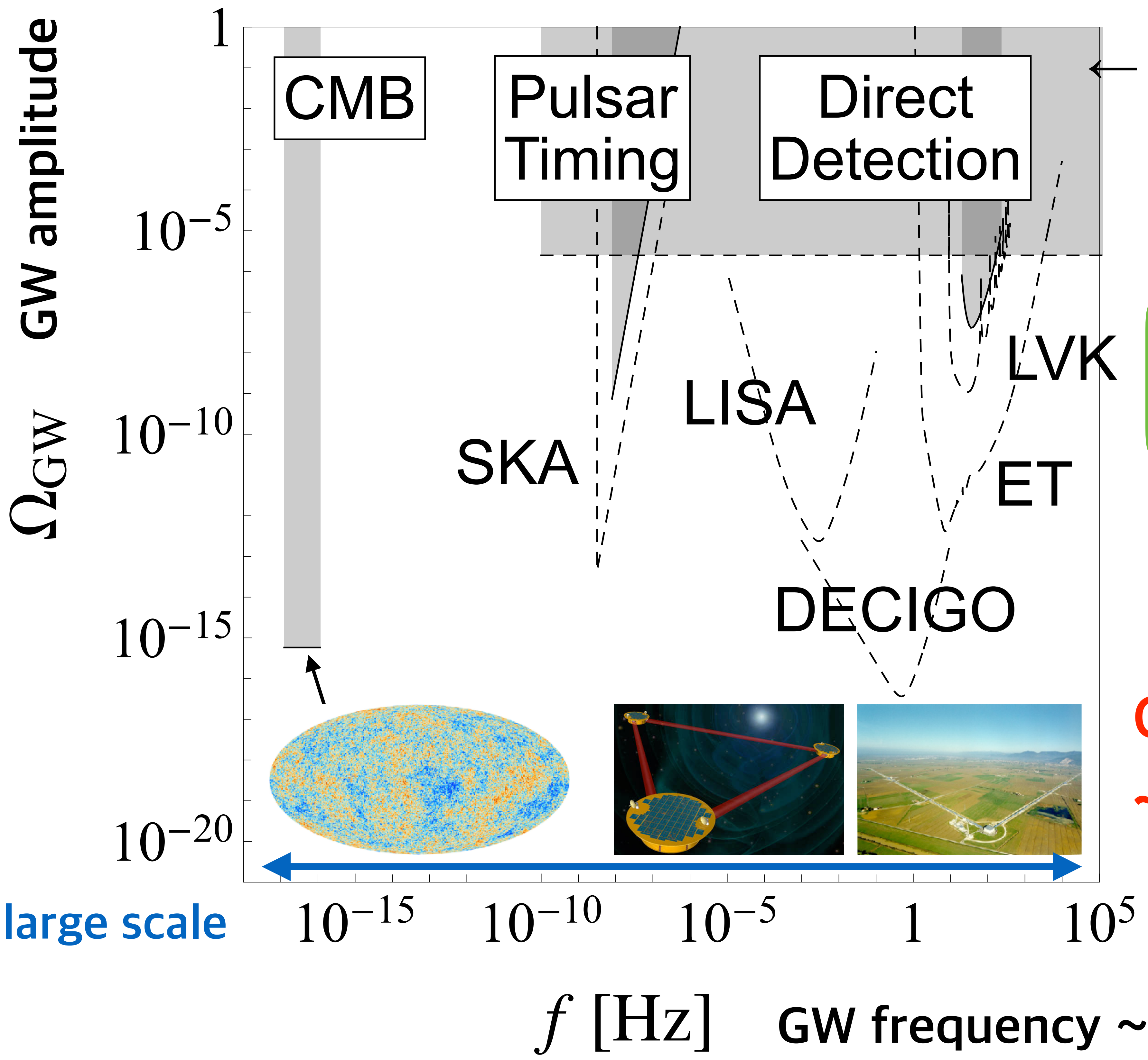
$$\langle S\rangle = \int_{-T/2}^{T/2} dt\, \langle s_1(t)s_2(t)\rangle$$

$$= \int_{-T/2}^{T/2} dt\, \langle h^2(t) + \underbrace{h(t)n_2(t)+n_1(t)h(t)+n_1(t)n_2(t)\rangle}_{\text{no correlations } \rightarrow\ 0}$$

$$= \int_{-T/2}^{T/2} dt\, \underbrace{\langle h^2(t)\rangle}_{\text{GW signal}}$$

(for detectors at the same location)

GW experiments probe different scales!



← BBN bound

Energy density of GWs

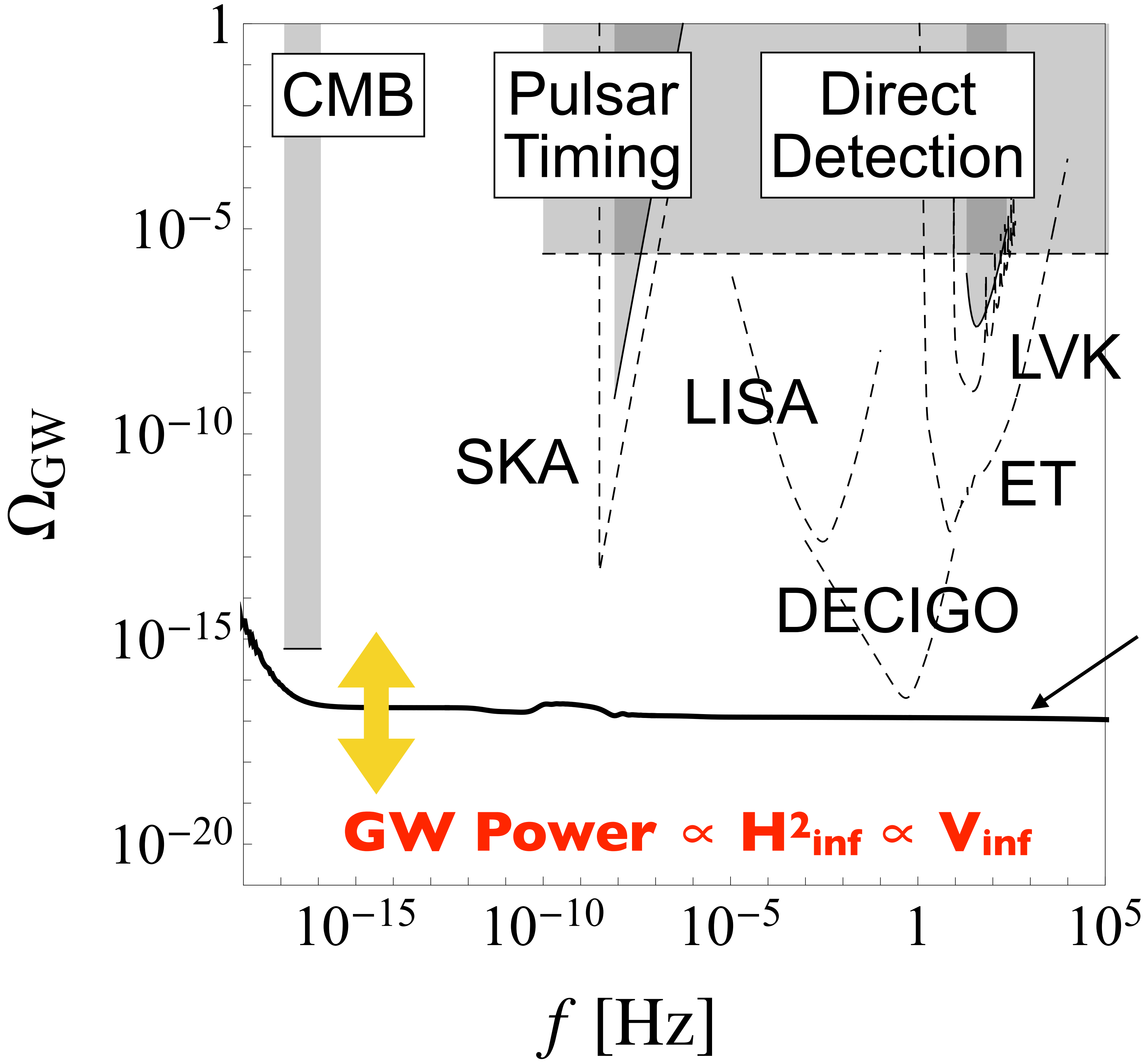
$$\Omega_{\rm GW} \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln k}$$

Critical density of the Universe

GW wavelength
~ laser arm length

small scale

GWs from inflation



GW Power ∝ H^2_{inf} ∝ V_{inf}

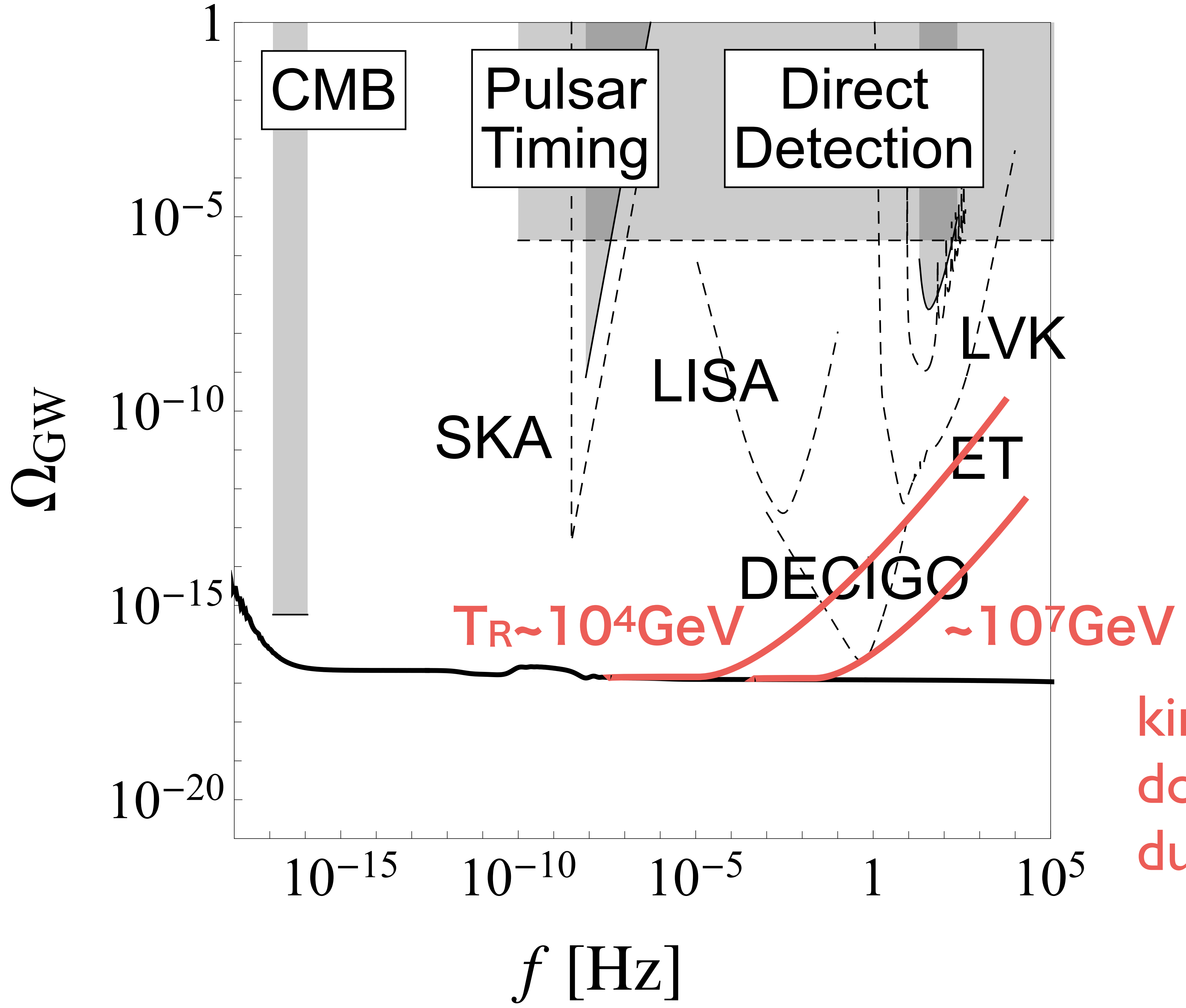
GWs from inflation

R^2 model: $r \sim 10^{-3}$

→ not detectable by interferometers

S. Kuroyanagi et al., PRD 79, 103501 (2009); PRD 90, 063513 (2014)

Effect of non-standard Hubble expansion

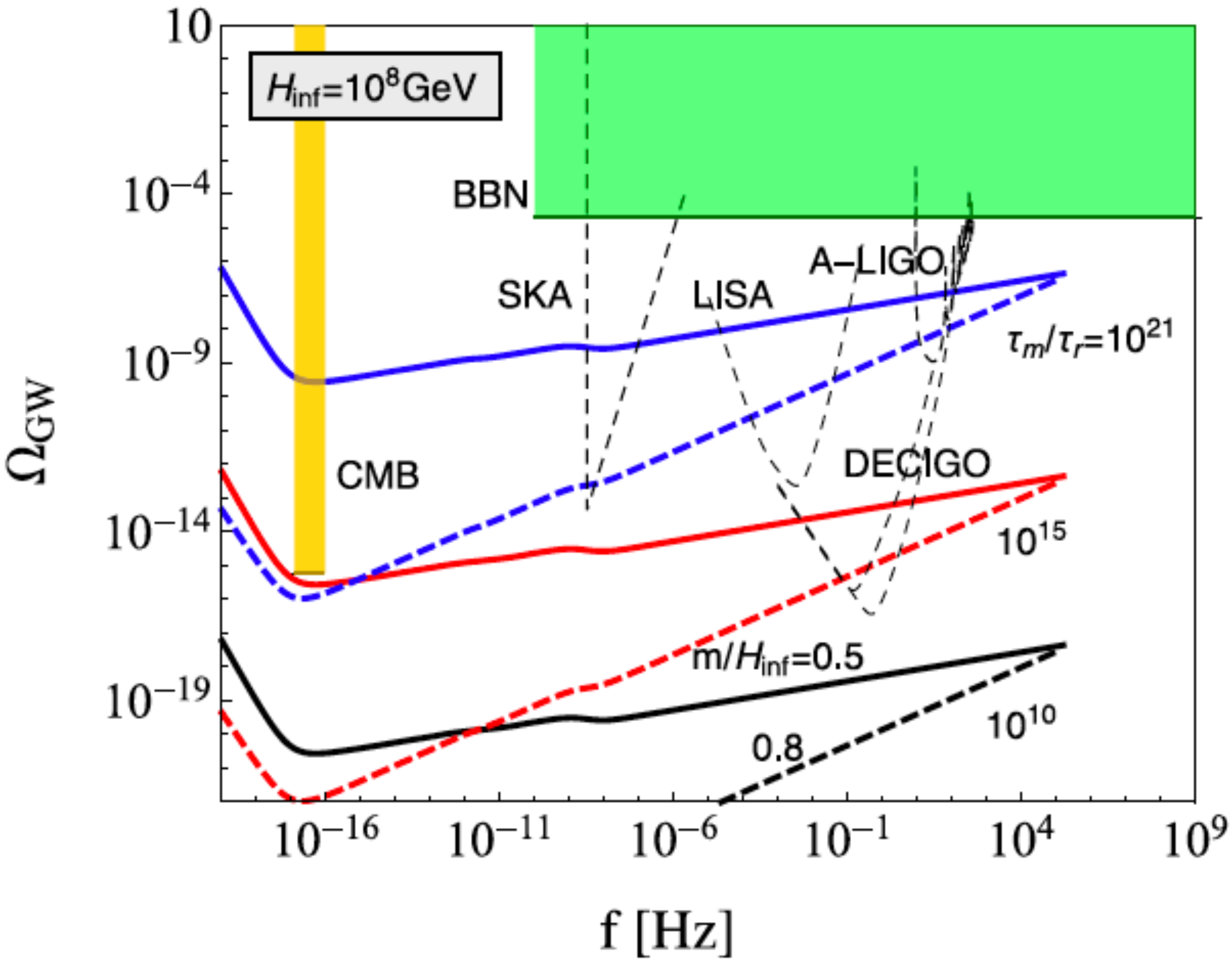


kinetic energy domination during reheating

S. Kuroyanagi et al., PRD 84, 123513 (2011)

Inflation with massive graviton

Massive graviton during and after inflation

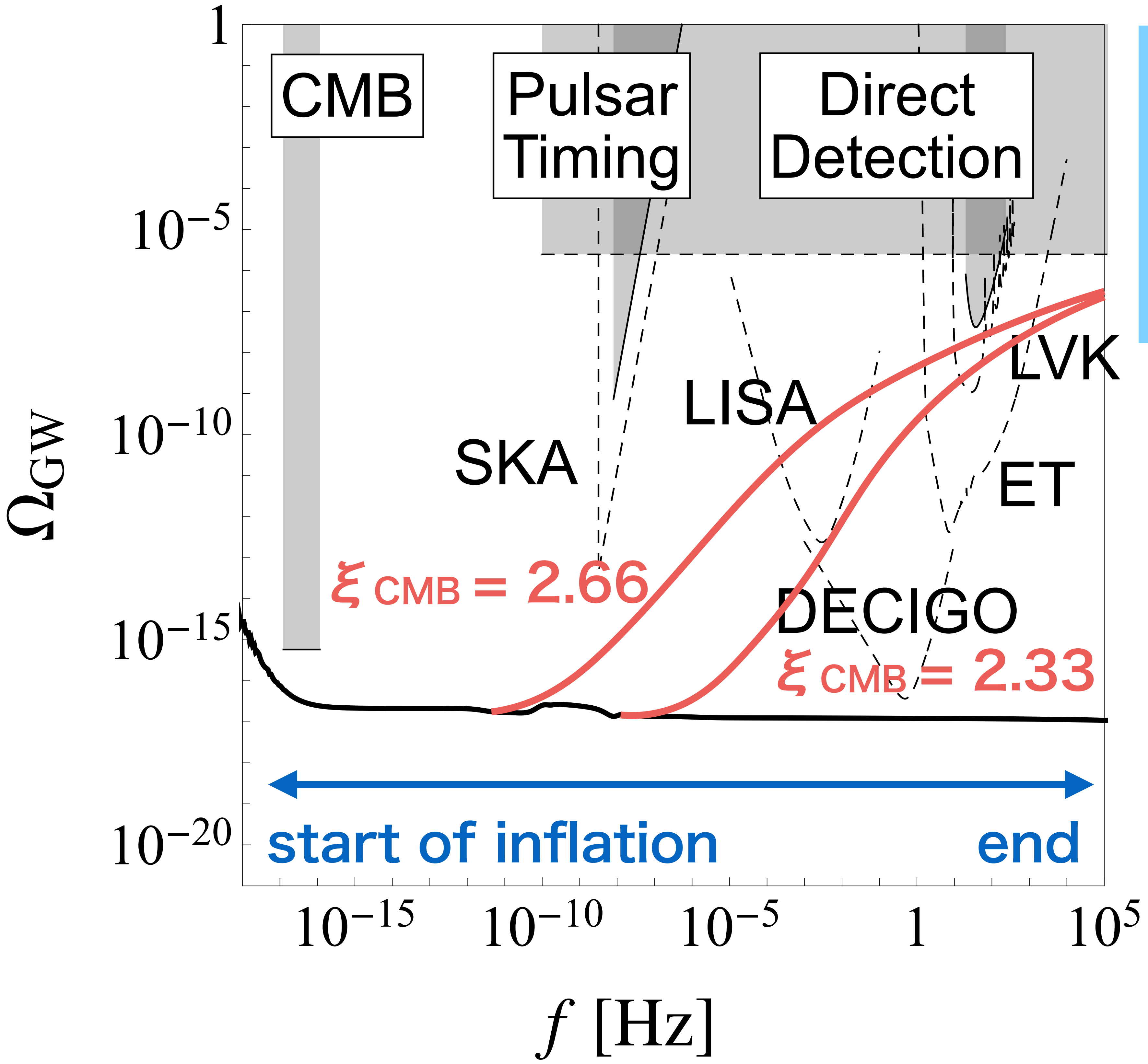


mass during inflation → blue tilt

mass after inflation → slower decay (enhancement of the amplitude)

Fujita et al. (+SK), PLB 789 (2019) 215-219

Gauge field production during inflation



N. Barnaby et al., PRD 85 023525 (2012)

Coupling between gauge field and inflaton

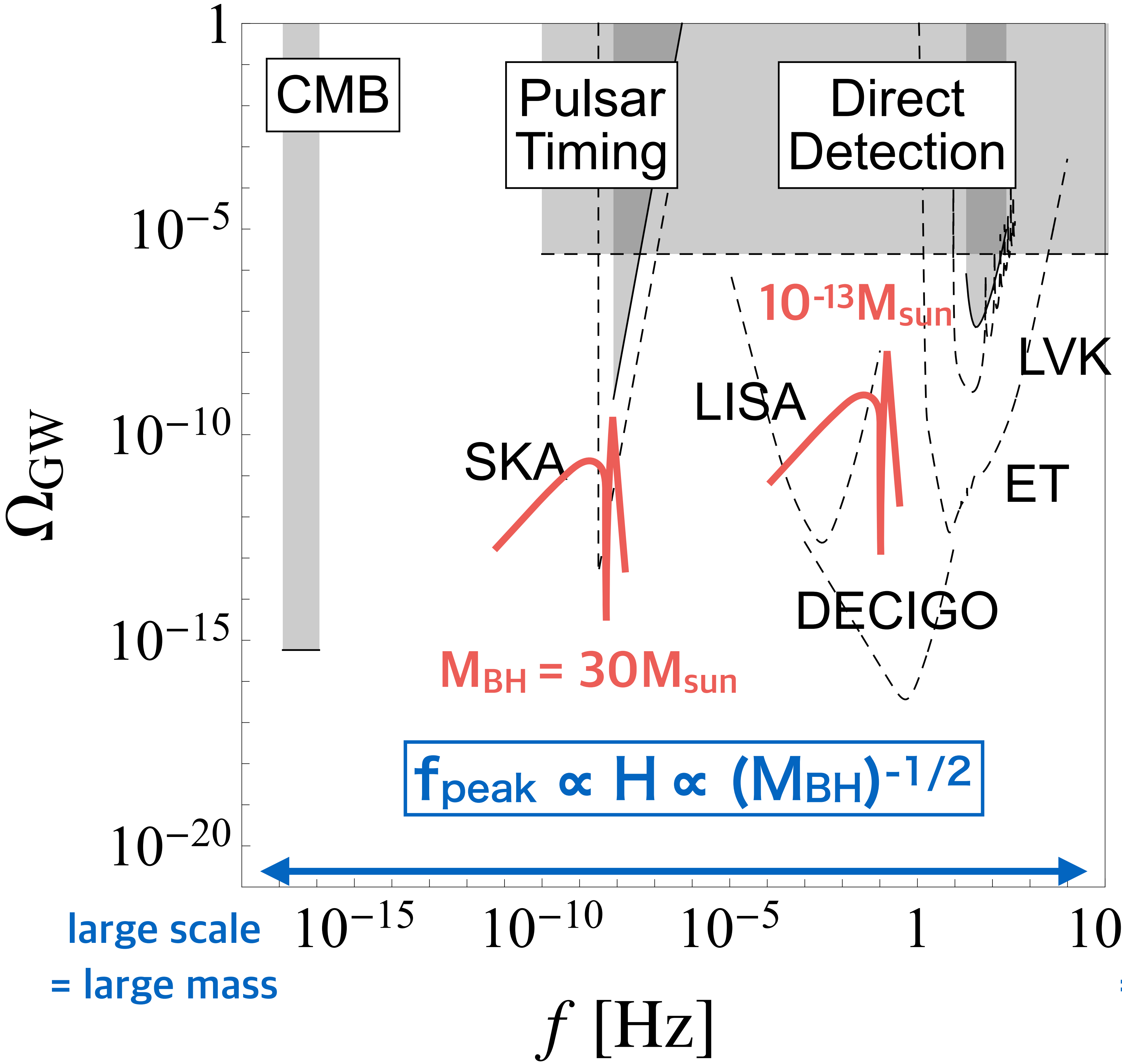
$$\Delta\mathcal{L}_{\rm int} = -\frac{1}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

→ the gauge field is amplified by $\sim e^{\pi\xi}$

$$\xi \equiv \frac{\dot{\phi}}{2fH}$$

larger ξ: stronger coupling

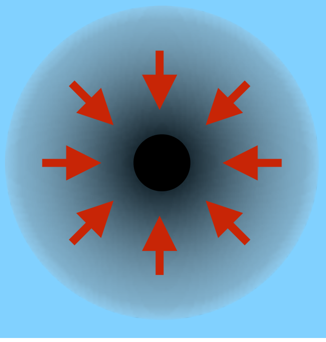
GWs associated with PBH formation



large scale
= large mass

small scale
= small mass

GWs are generated when large curvature perturbation collapse into PBHs

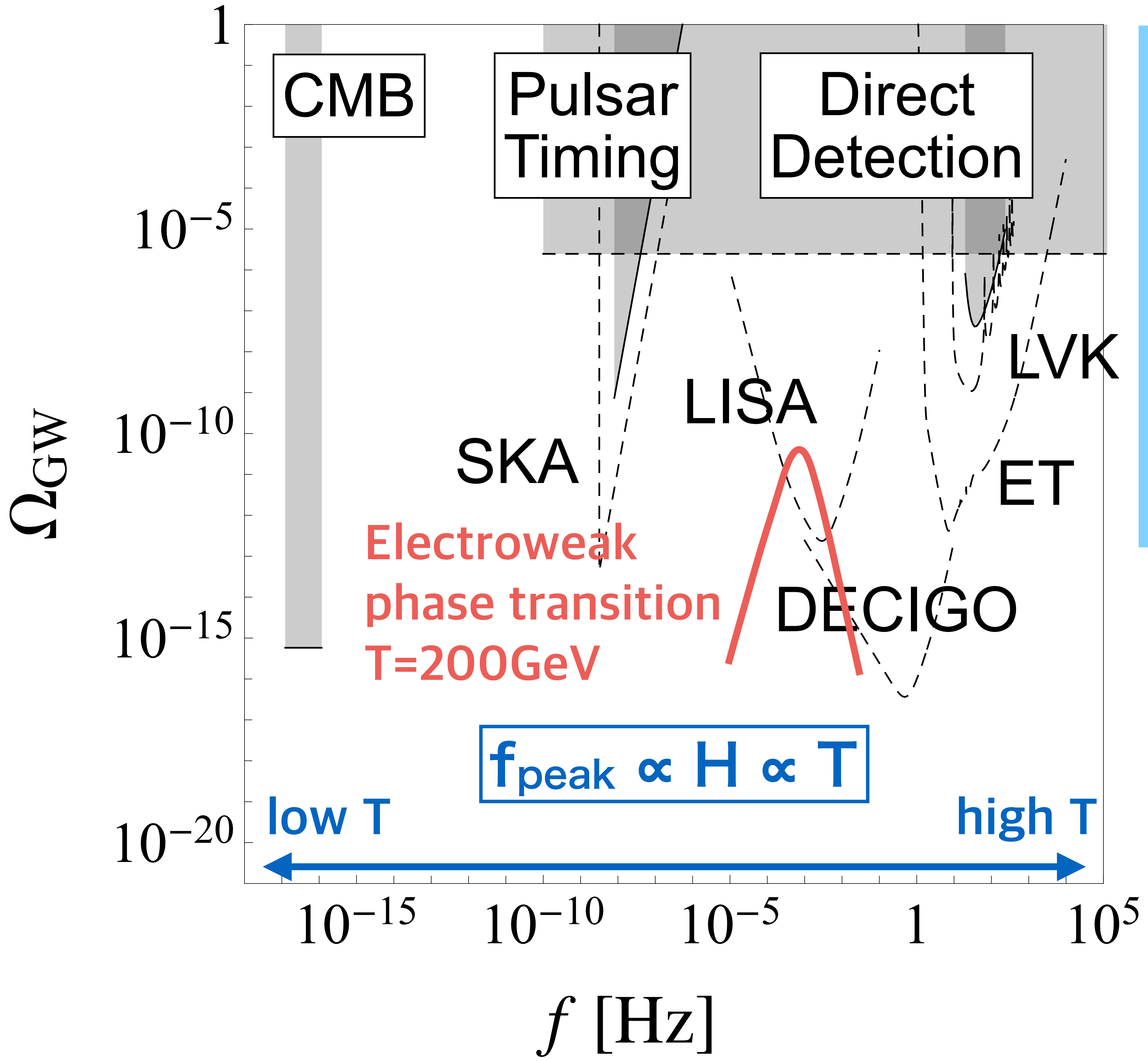


δ function peak is assumed

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

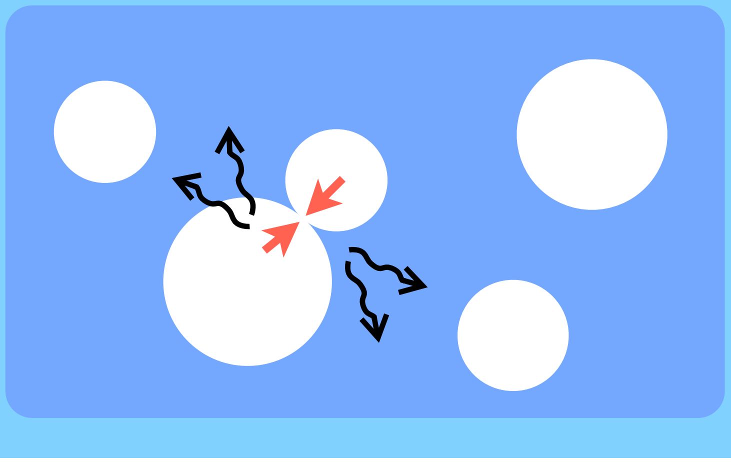
R. Saito & J. Yokoyama, PRL 102, 161101 (2009)

Cosmic phase transitions

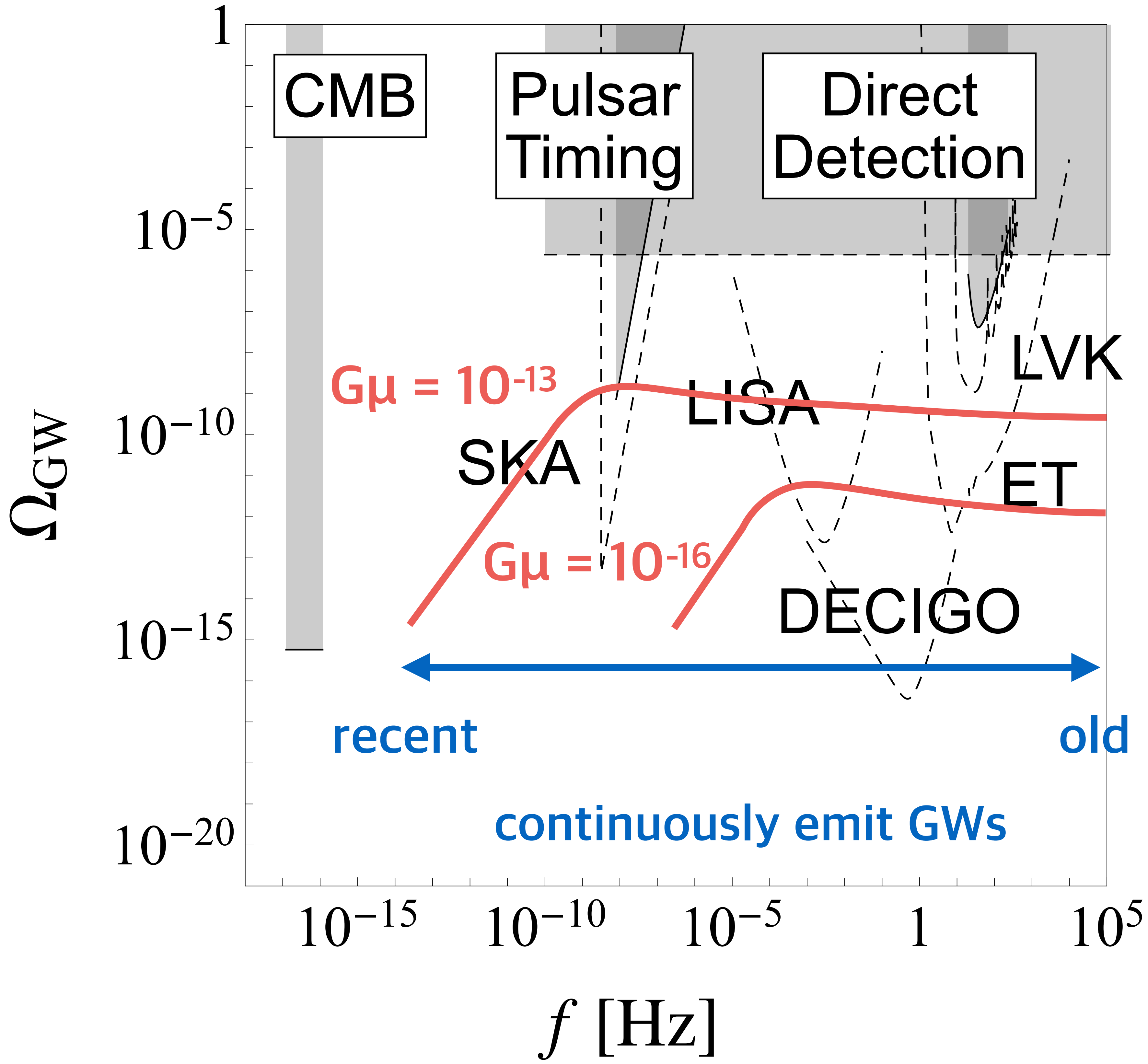


C. Caprini et al. (LISA CosWG), JCAP 03 (2020) 024

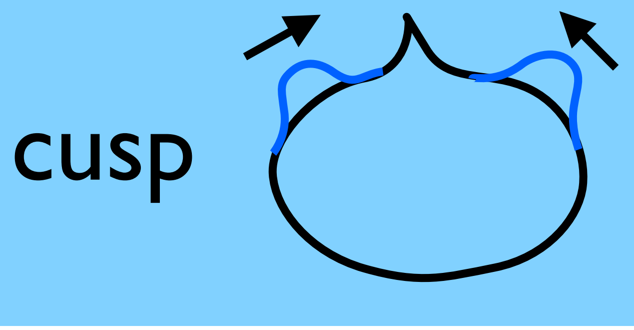
Bubble collisions during a first order phase transition



Cosmic strings (cusps on loops)



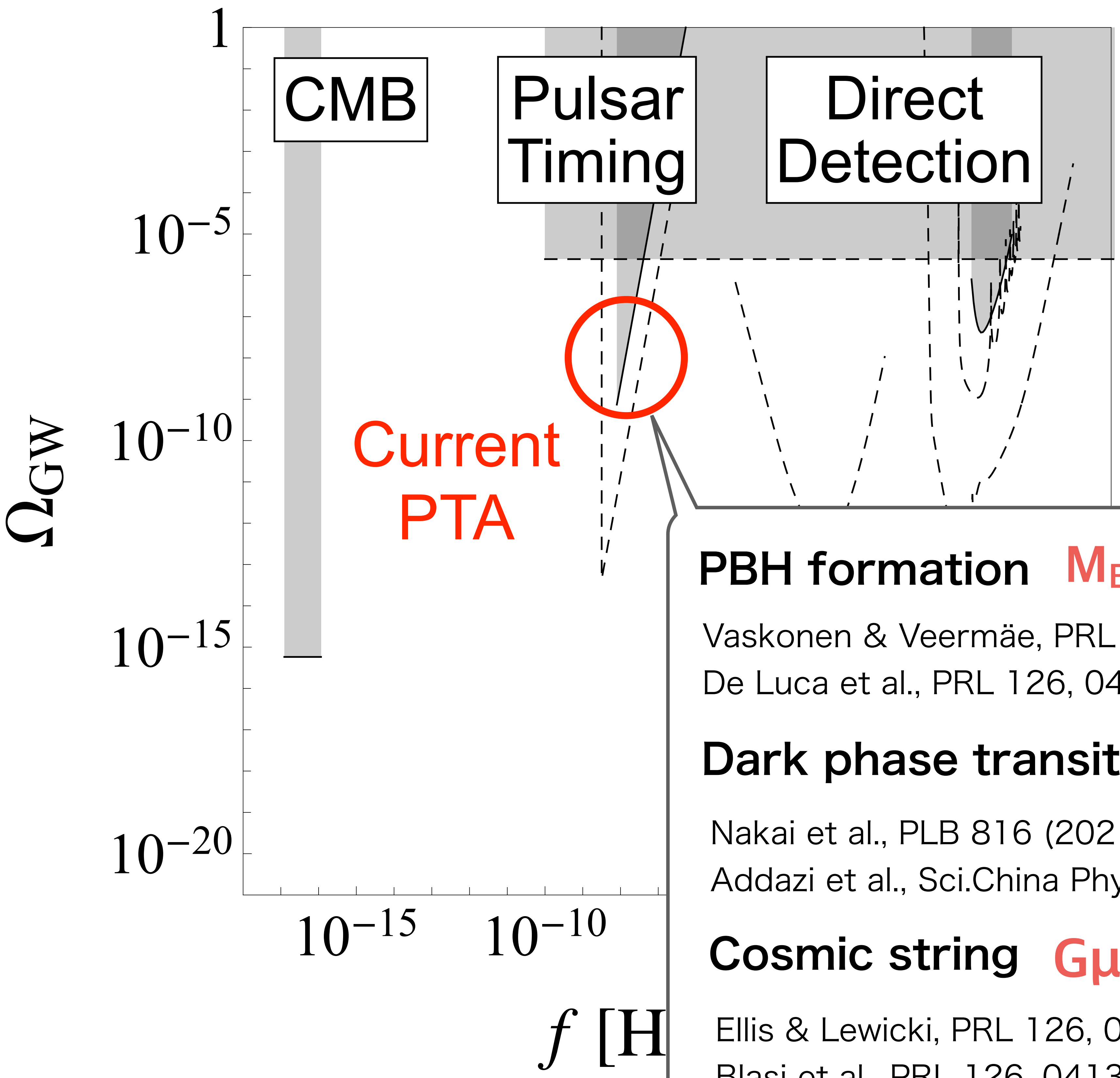
One dimensional topological defects generated during phase transition



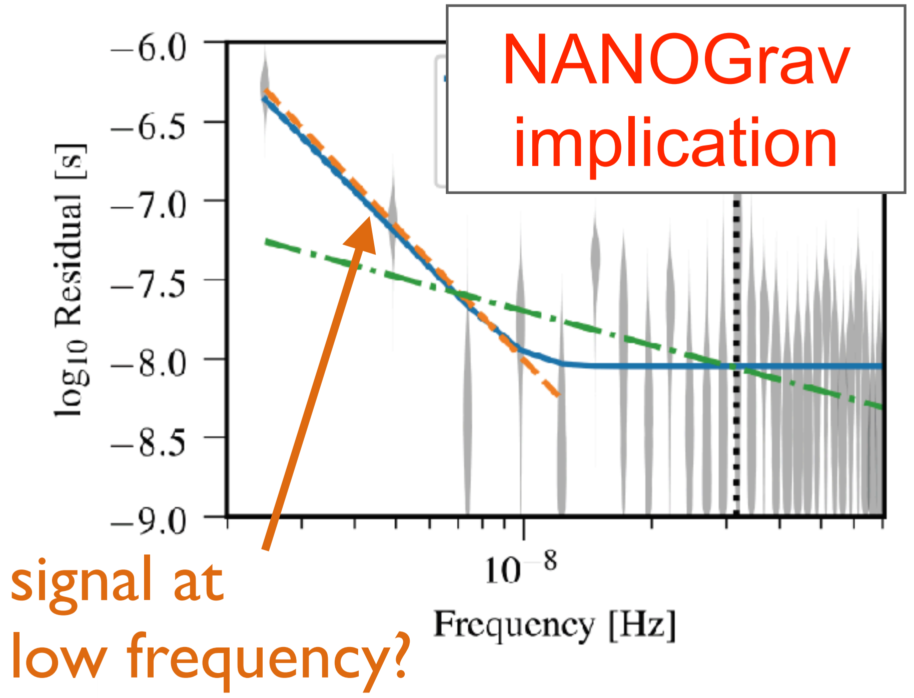
tension $G\mu$
= line density
~ $(E_{string}/m_{Pl})^2$

P. Auclair et al. (LISA CosWG), JCAP 04 (2020) 034

Current constraints



Arzoumanian et al., ApJ , 905, L34 (2020)



PBH formation $M_{BH} = 30M_{sun}$

Vaskonen & Veermäe, PRL 126, 051303 (2021)
De Luca et al., PRL 126, 041303 (2021)

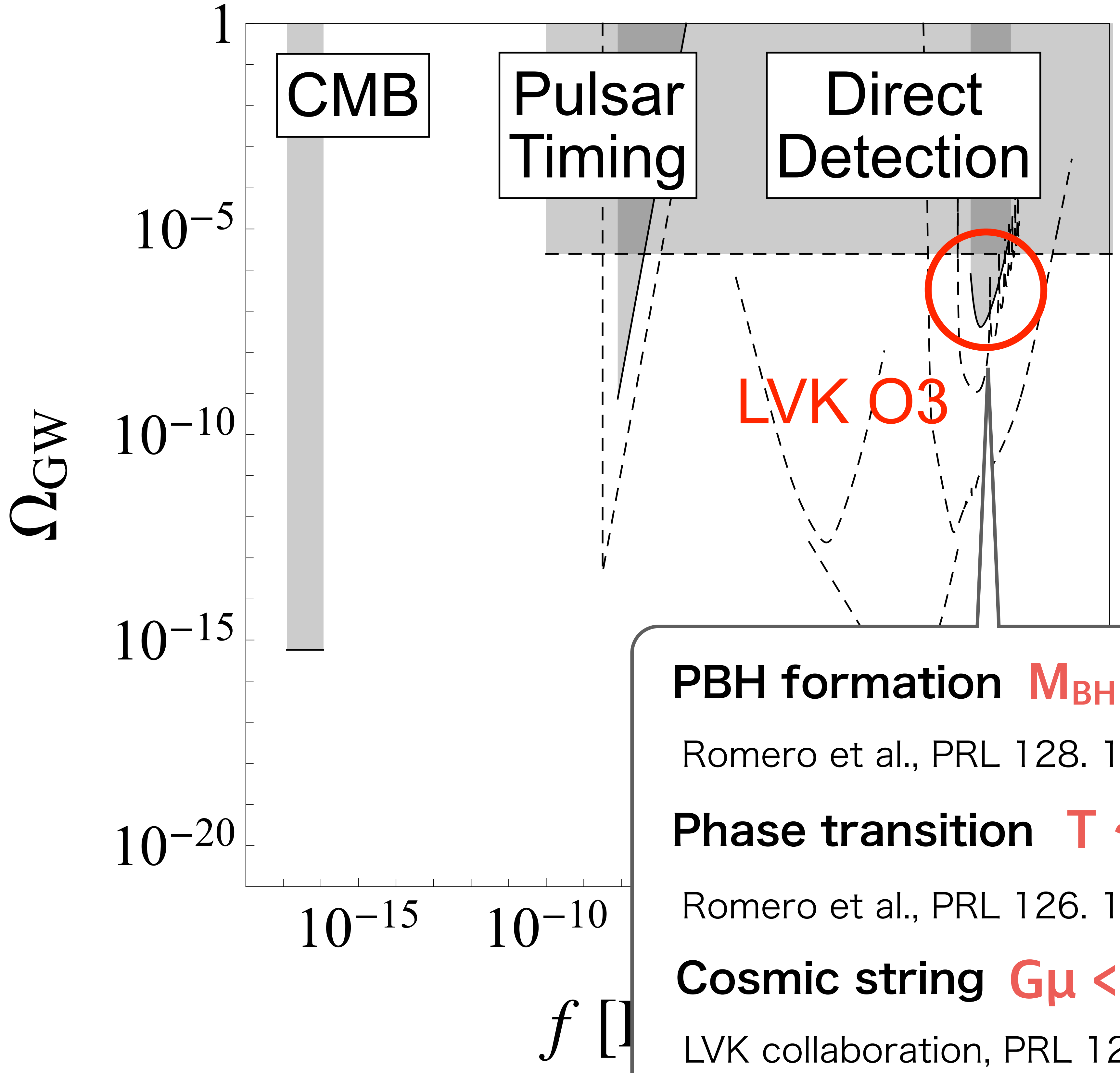
Dark phase transition T ~ O(1-100) MeV

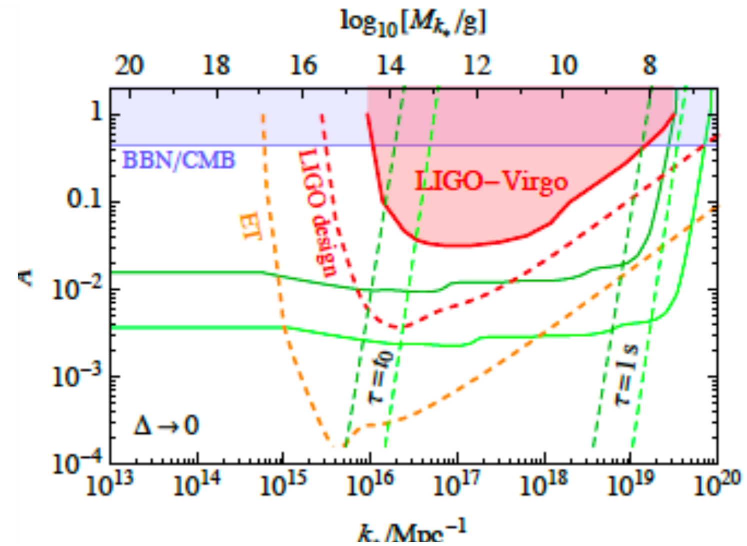
Nakai et al., PLB 816 (2021) 136238
Addazi et al., Sci.China Phys.Mech.Astron. 64, 290411 (2021)

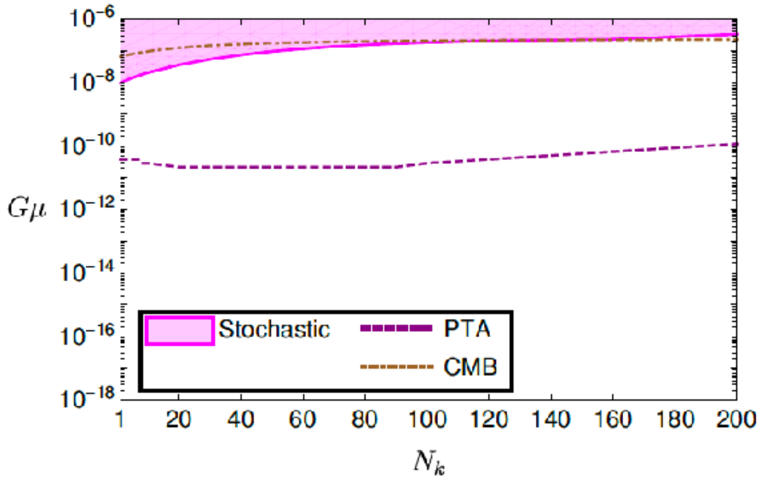
Cosmic string $G\mu \sim 10^{(-10)\,-\,(-11)}$

Ellis & Lewicki, PRL 126, 041304 (2021)
Blasi et al., PRL 126, 041305 (2021)

Current constraints







PBH formation $M_{BH} = 10^{10\text{-}14}$ g , A < 0.02

Romero et al., PRL 128. 151301 (2022)

Phase transition T ~ $10^{7\text{-}10}$ GeV, $\Omega_{\rm ref} < 10^{-8}$

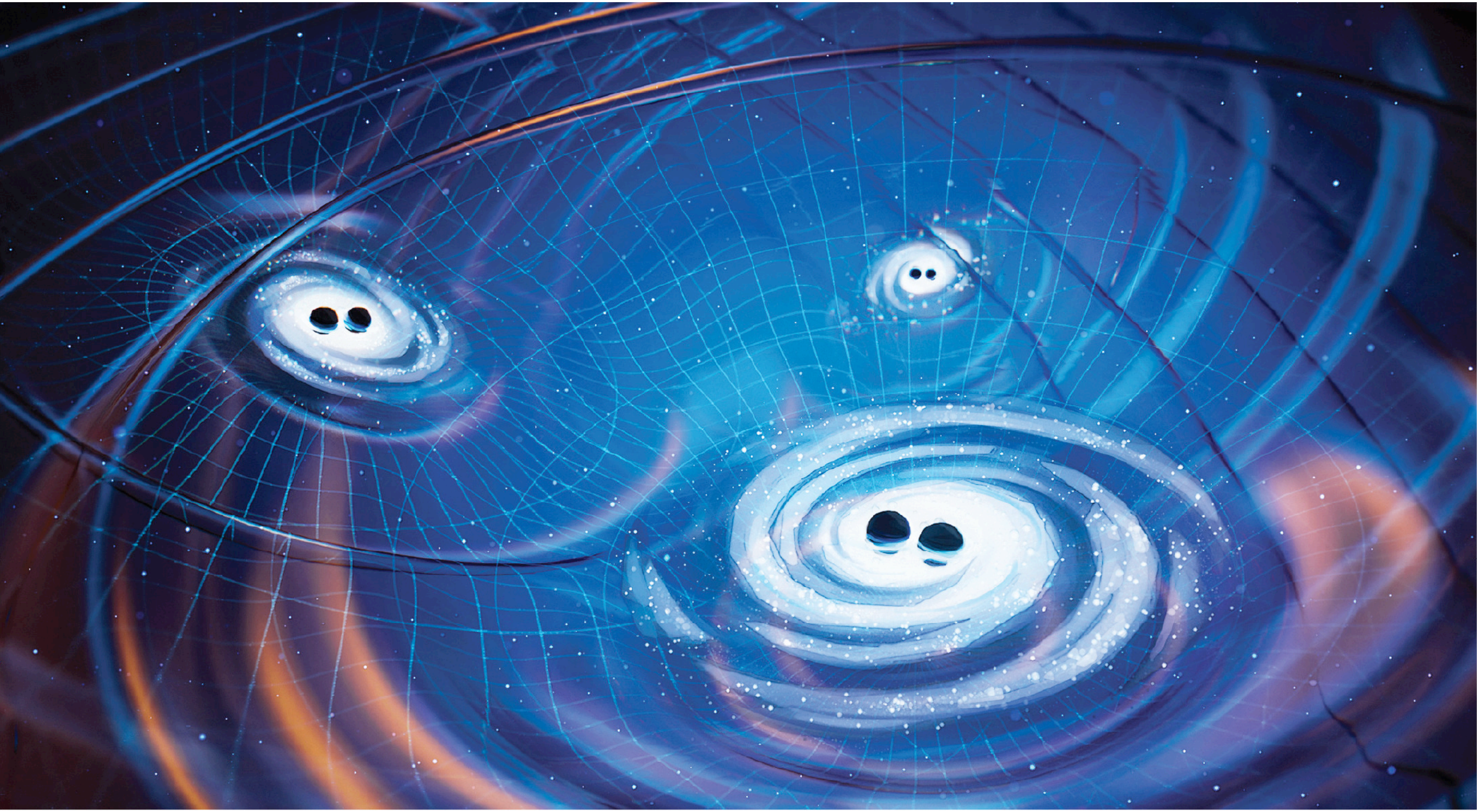
Romero et al., PRL 126. 151301 (2021)

Cosmic string $G\mu < 10^{-7}$

LVK collaboration, PRL 126, 241102 (2021)

Future prospect

Detection of the astrophysical GW background in 2020's?

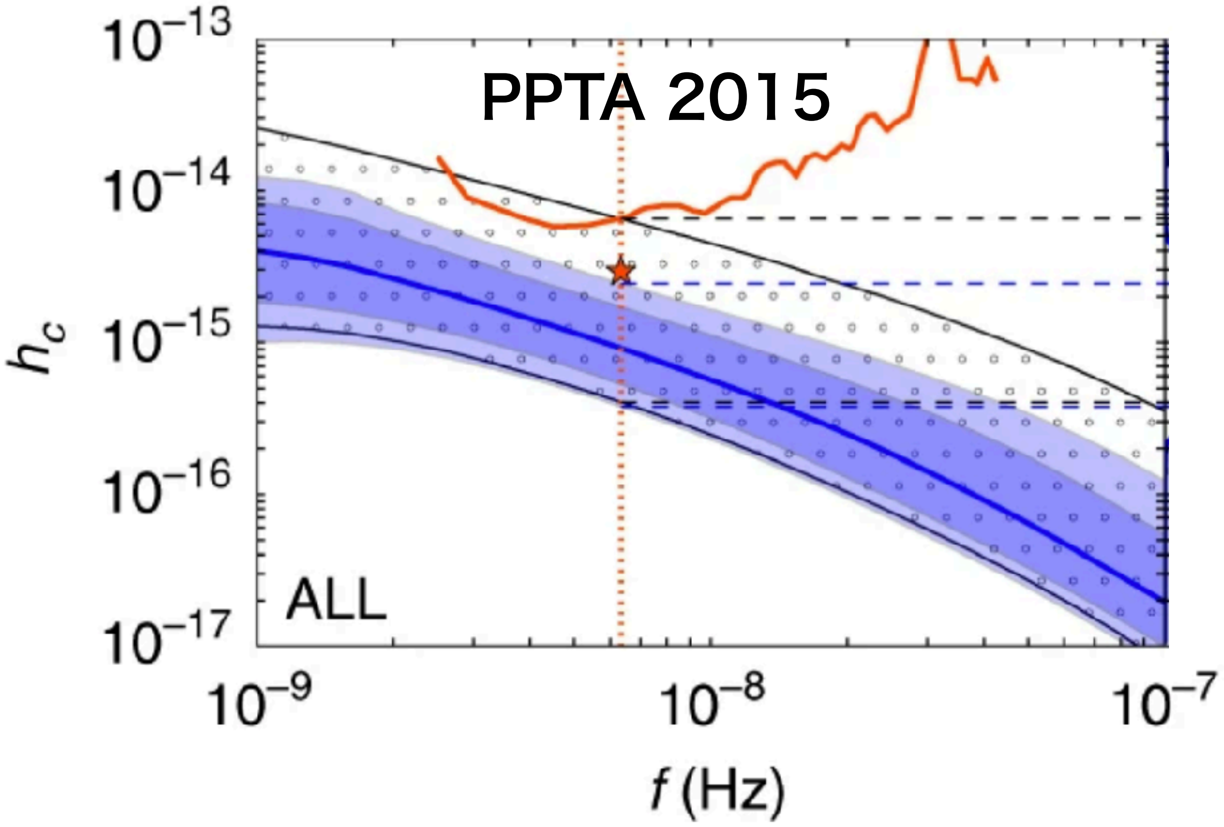


Superposition of individual GWs form a stochastic GW background

Future prospect

Detection of the astrophysical GW background in 2020's?

Pulsar timing array

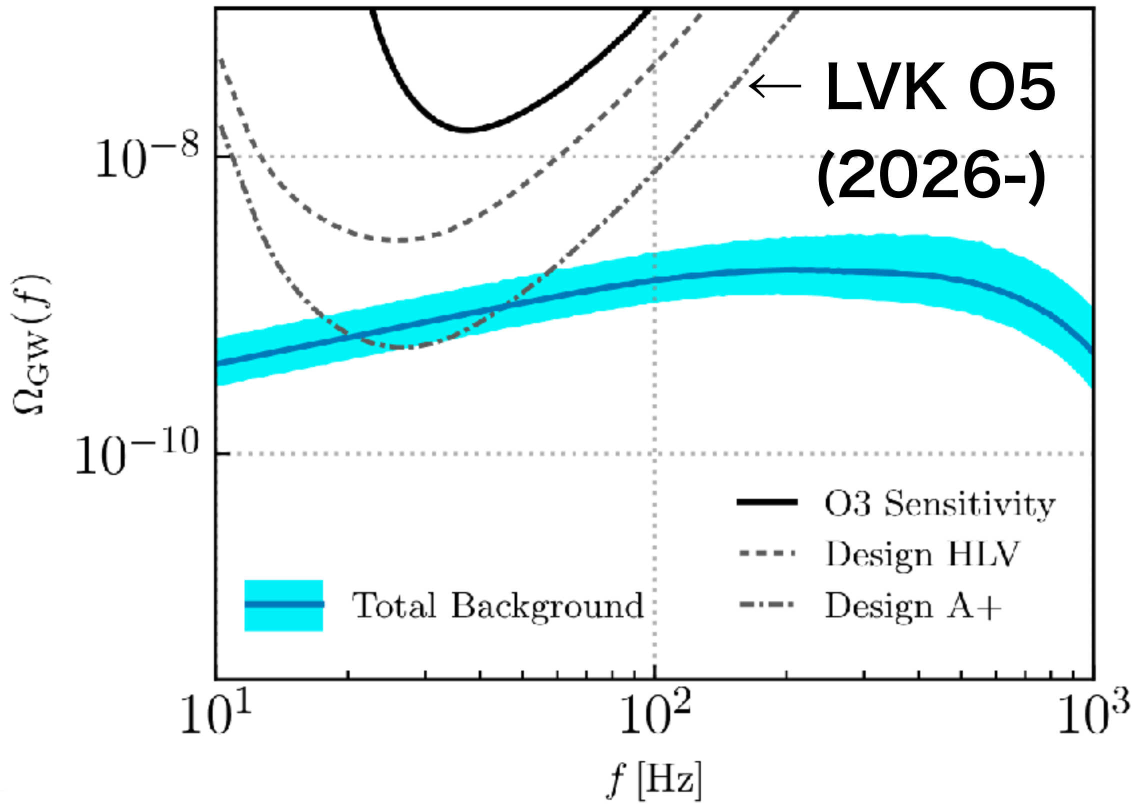


Super massive BH binaries

Implication of GW detection by NANOGrav, EPTA, PPTA

Middleton et al., Nat. Commun. 9, 573 (2018)

Ground-based interferometers



← LVK O5 (2026-)

O(10) solar-mass BH binaries

Supported by observation of individual binaries

BBH event rate (17.3 - 45 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$)

LVK collaboration, arXiv:2111.03634

How can we distinguish the astrophysical foreground and cosmological background?

1. Spectral shape

→ The BBH background has characteristic frequency dependence $\Omega_{GW} \propto f^{2/3}$ 👍

2. Anisotropy

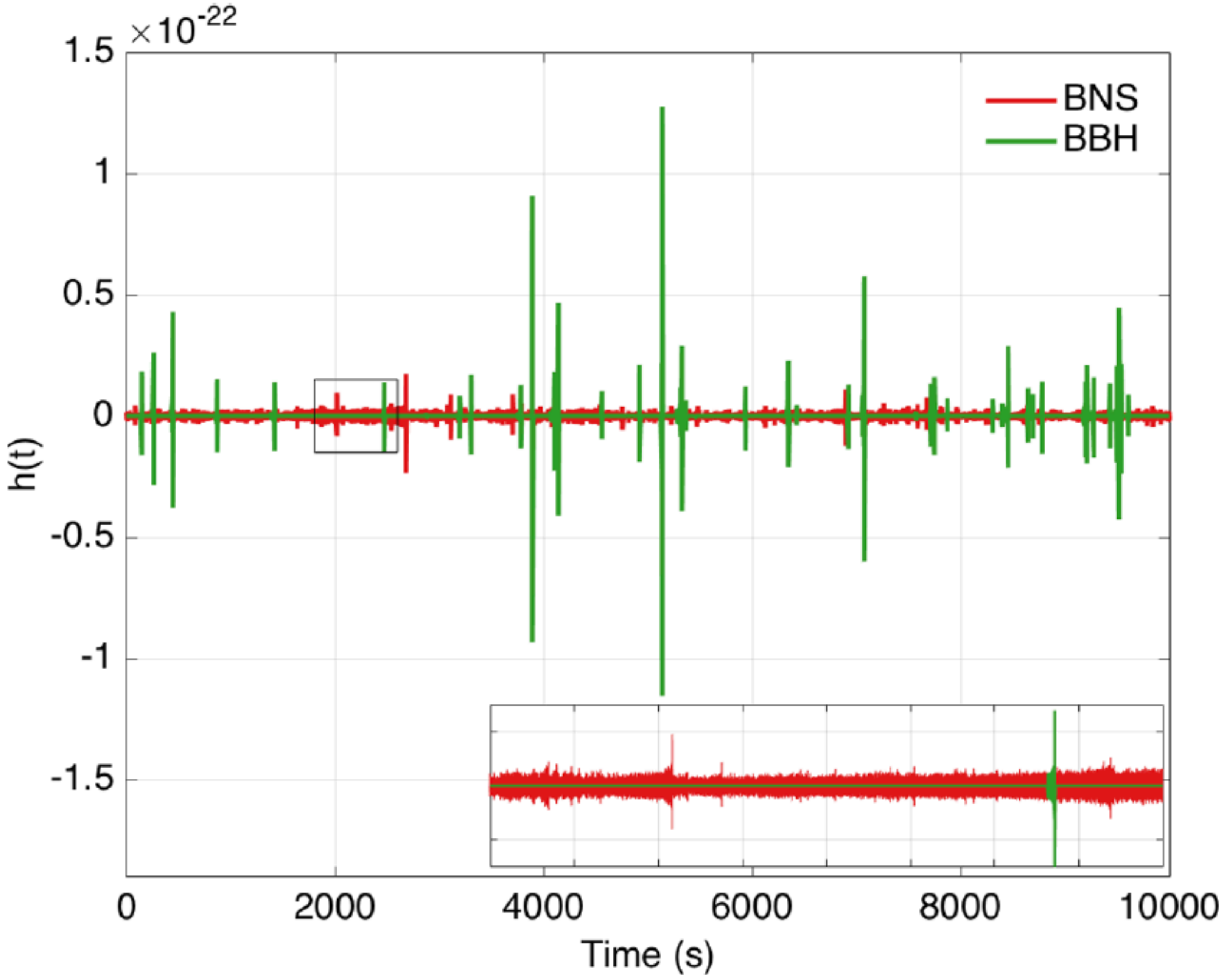
→ Astrophysical background has an anisotropy but GW detectors do not have good angular resolution 😟

3. Non-Gaussianity (in time series)

→ Cosmological background is typically Gaussian while astrophysical background can be highly non-Gaussian 🙄

Astrophysical GW background

Simulated stochastic background at LVK frequency

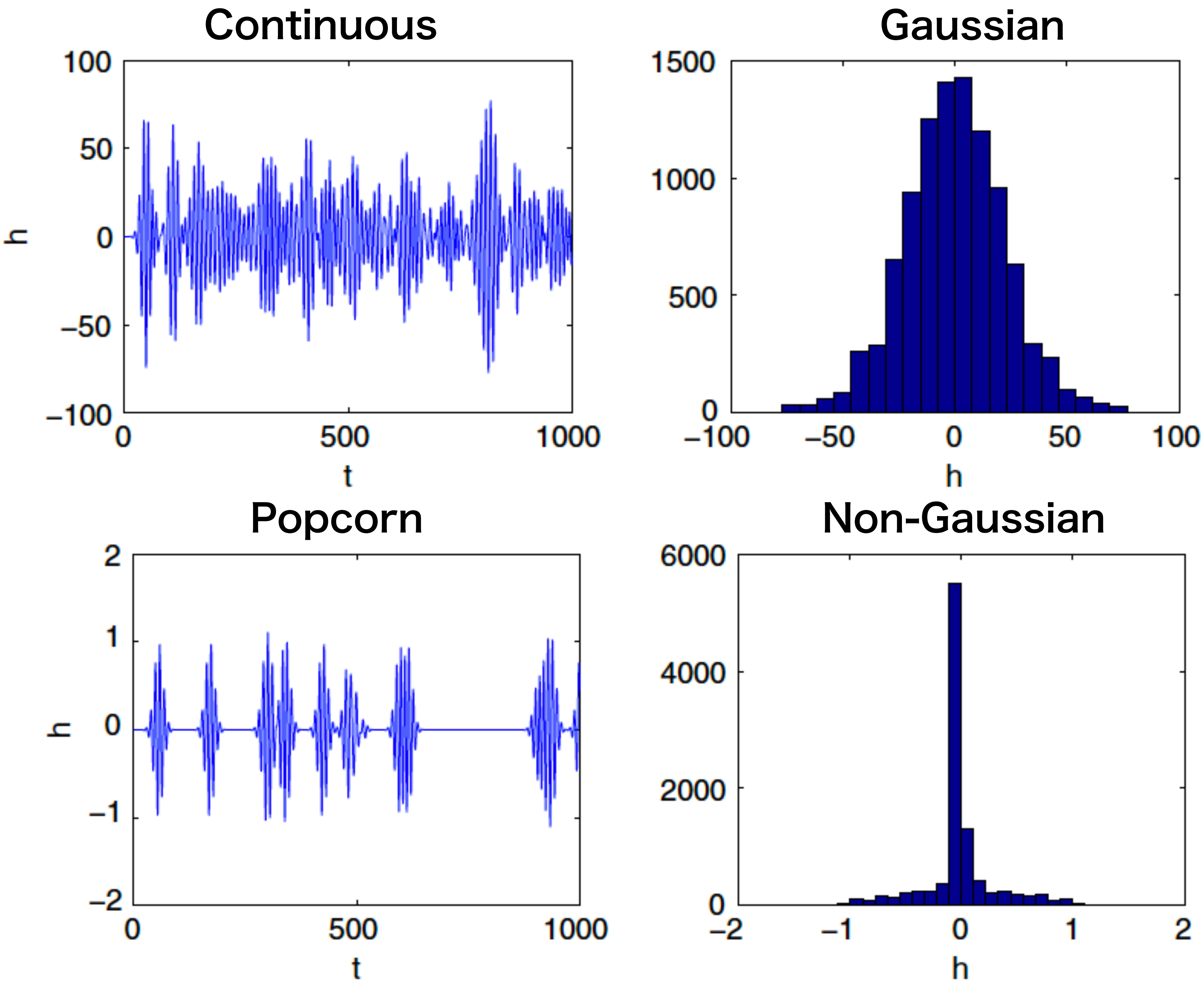


BBHs events do not overlap.

LV collaboration, PRL 120, 091101 (2018)

Signal is strongly non-Gaussian

Figure from Thrane, PRD 87, 043009 (2013)



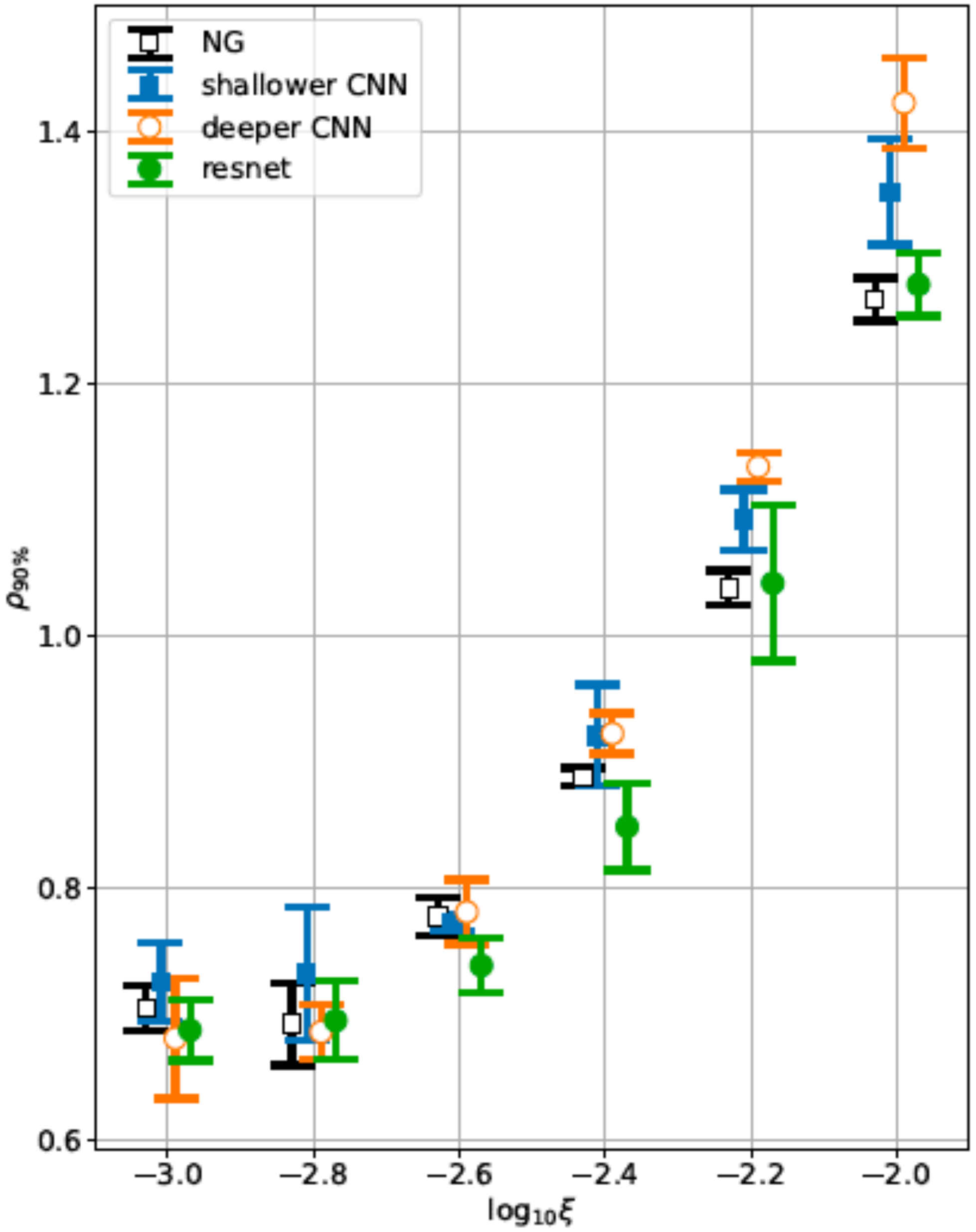
→ helps to distinguish astrophysical and cosmological origin

How do we detect the non-Gaussian GWB?

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: Yamamoto, SK, Liu, arXiv:2208.13156

Result

Minimum detectable SNR



Duty cycle

- NG (non-Gaussian statistics = CCI)
- Shallower CNN (fewer layers)
- Deeper CNN (more layers = resnet)
- Reset (Residual network)

→ shows comparable performance compared to the CCI

Advantage of Machine Learning

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:** Yamamoto, SK, Liu, arXiv:2208.13156

CCI: Optimal detection statistics

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

search in 4 dim.

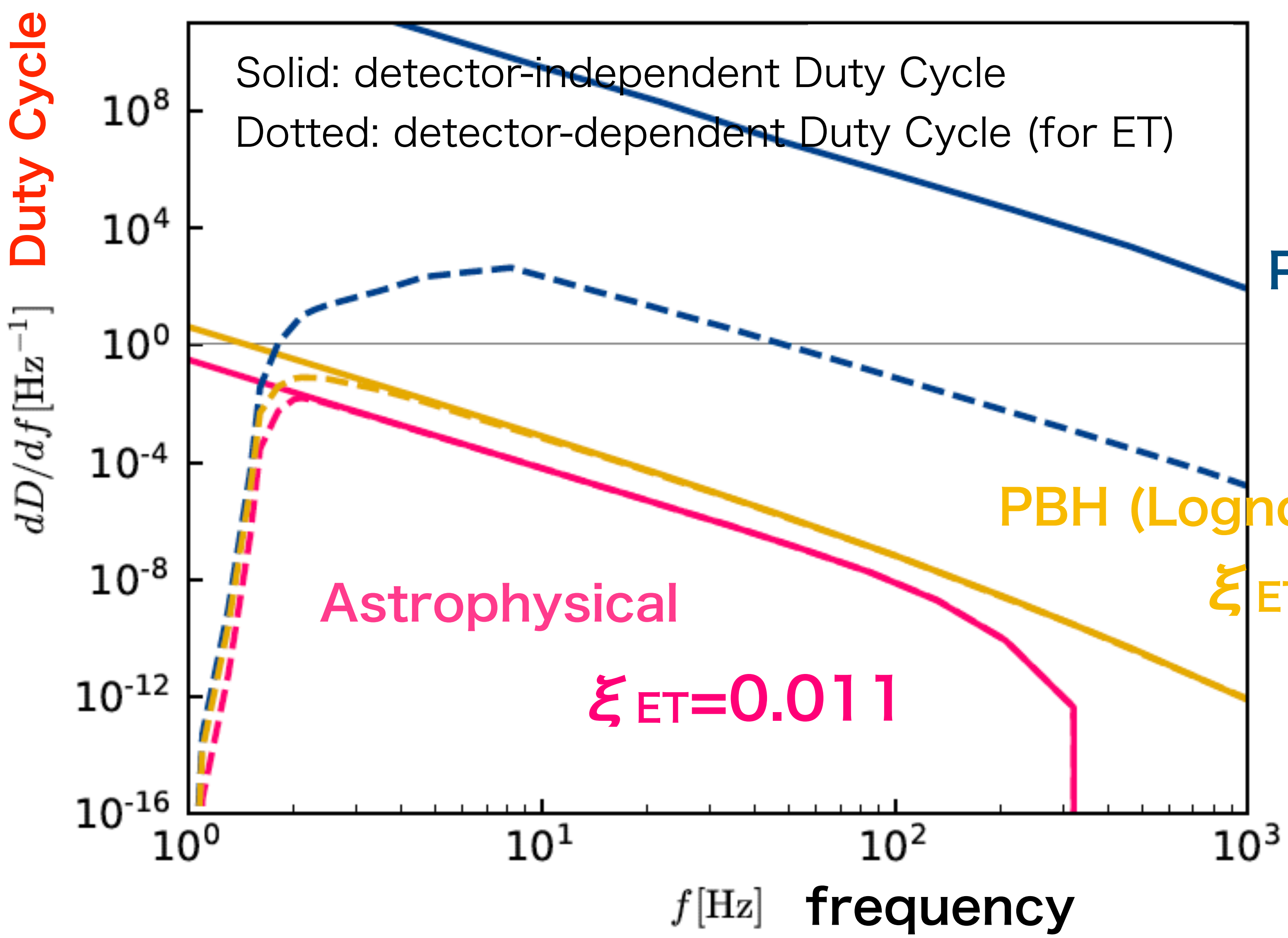
cf. standard cross-correlation detection statistics $\Lambda_{\mathrm{CC}}(h)=\frac{\hat{\alpha}^2}{\bar{\sigma}_1\bar{\sigma}_2}$

→ ML is O(10^4-10^5) 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

Non-Gaussianity also helps to infer the BH origin

Braglia et al. (+SK), arXiv: 2201.13414



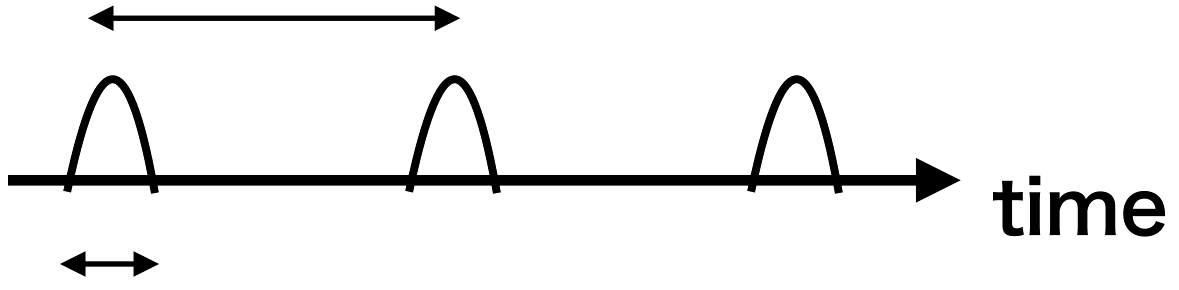
PBH (Thermal history)

$\xi \gg 1$: continuous

PBH (Lognormal)

$\xi_{\mathrm{ET}}=0.096$

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

Summary

GWs provide unique opportunities for testing the early universe.

- Once it is detected, it will bring a breakthrough in the understanding of our Universe.
- The first detection would be the astrophysical background. We will need a solid foreground separation method to further search the cosmological background.
- Non-Gaussianity is one of the key characteristics which could help to distinguish the astrophysical and cosmological origin. It could also provide a hint for the origin of binary BHs.