Gravitational wave background: LVK analysis, implications and challenges

Presented By
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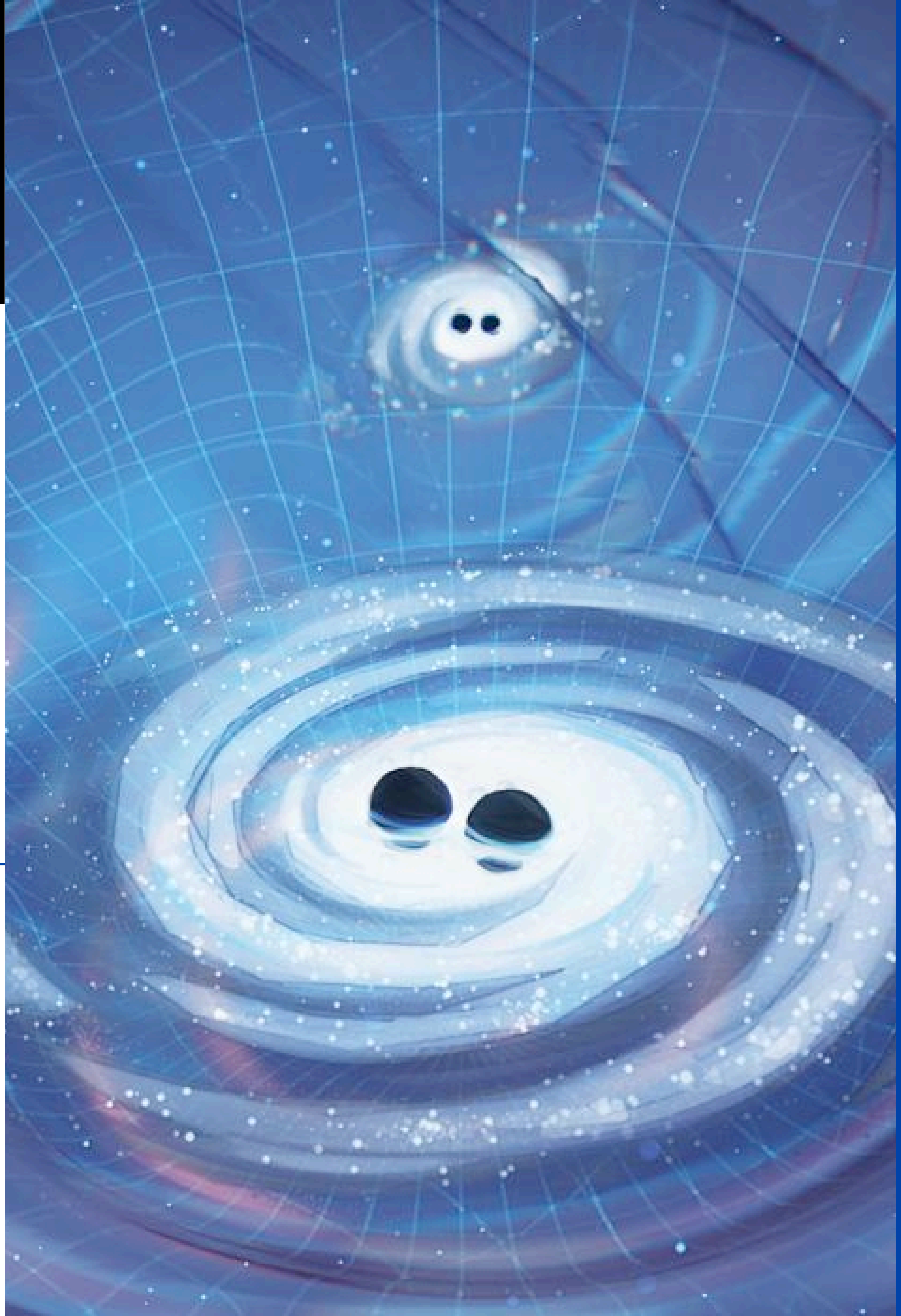
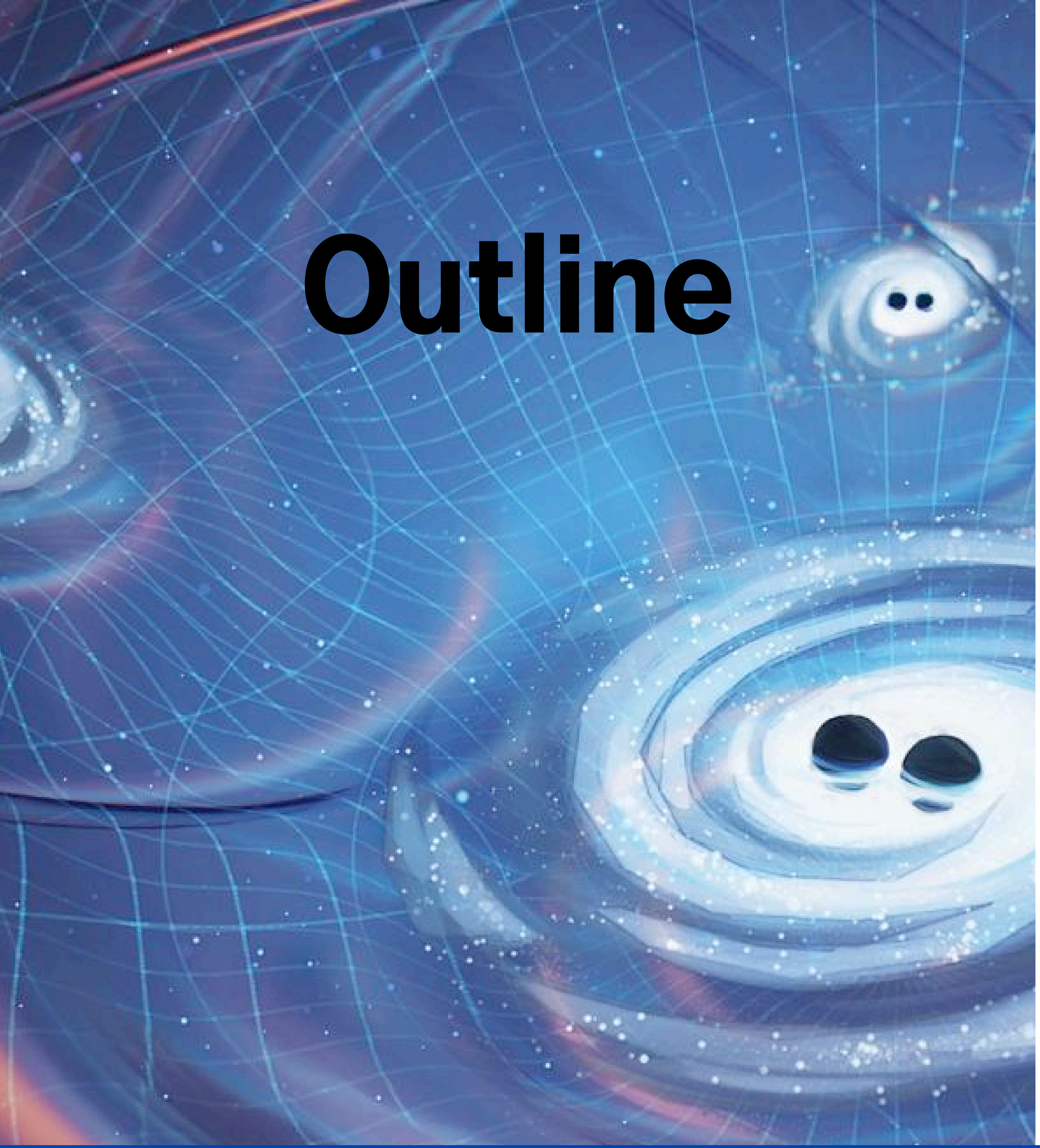
VRIJE UNIVERSITEIT BRUSSEL

GEMMA 2
16th of September 2024





Outline

1 Sources of gravitational waves

2 Gravitational wave background (GWB)

3 GWB characterization

4 LVK search for an isotropic GWB

5 Current LVK constraints_on the GWB

6 Astrophysical implications

7 Cosmological implications

8 Challenges

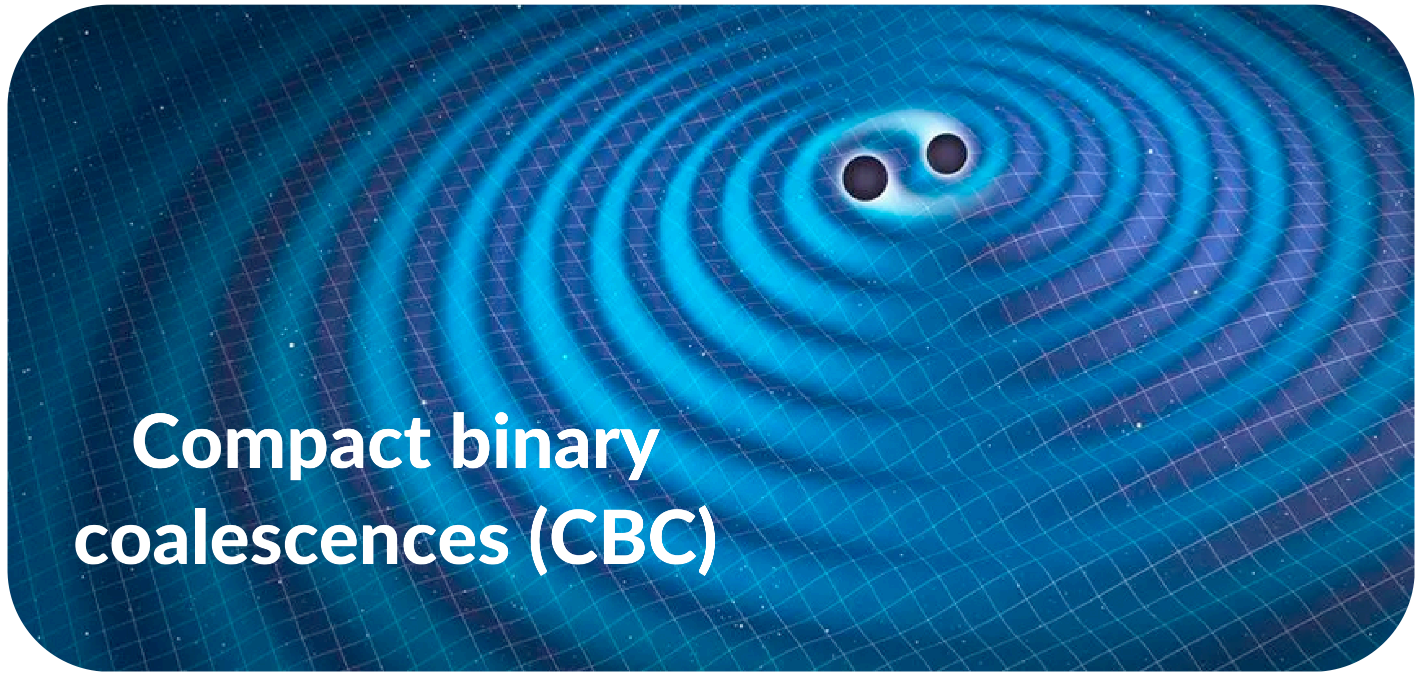
9 Other experiments and future

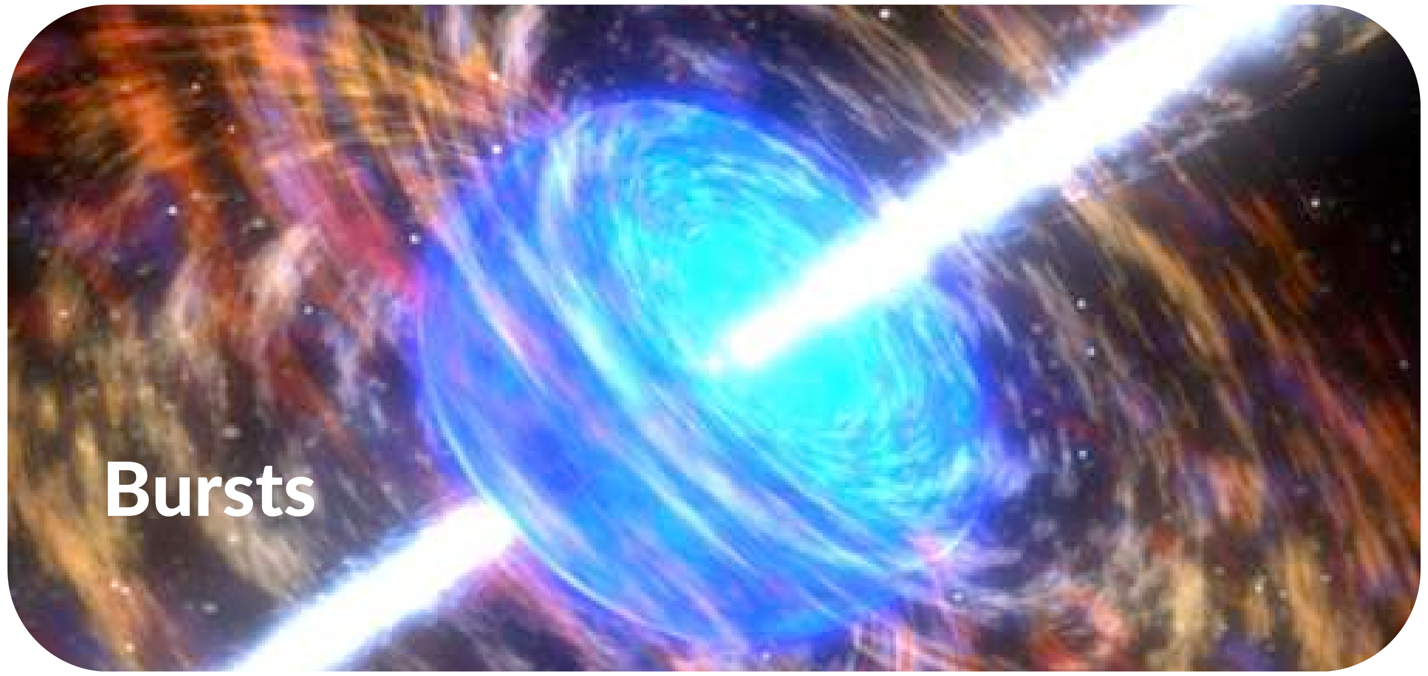
Sources of GWs

Modelled

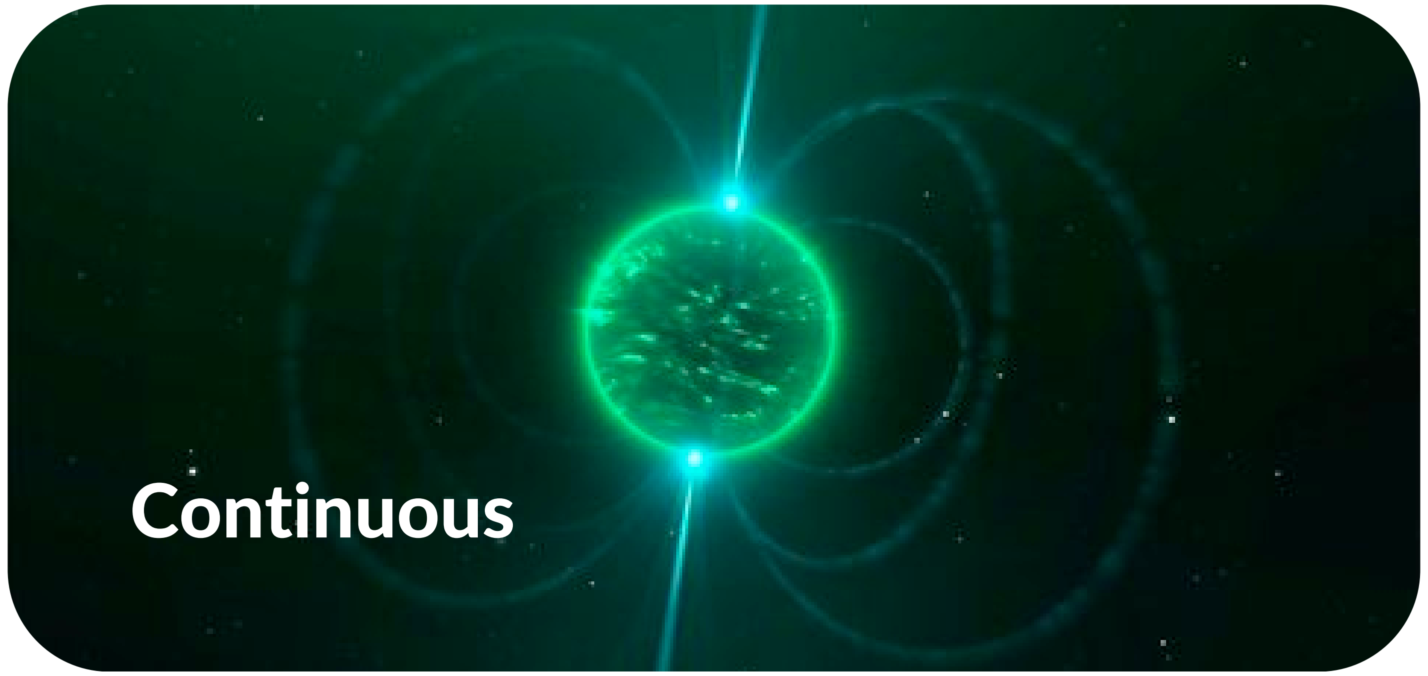
Unmodelled

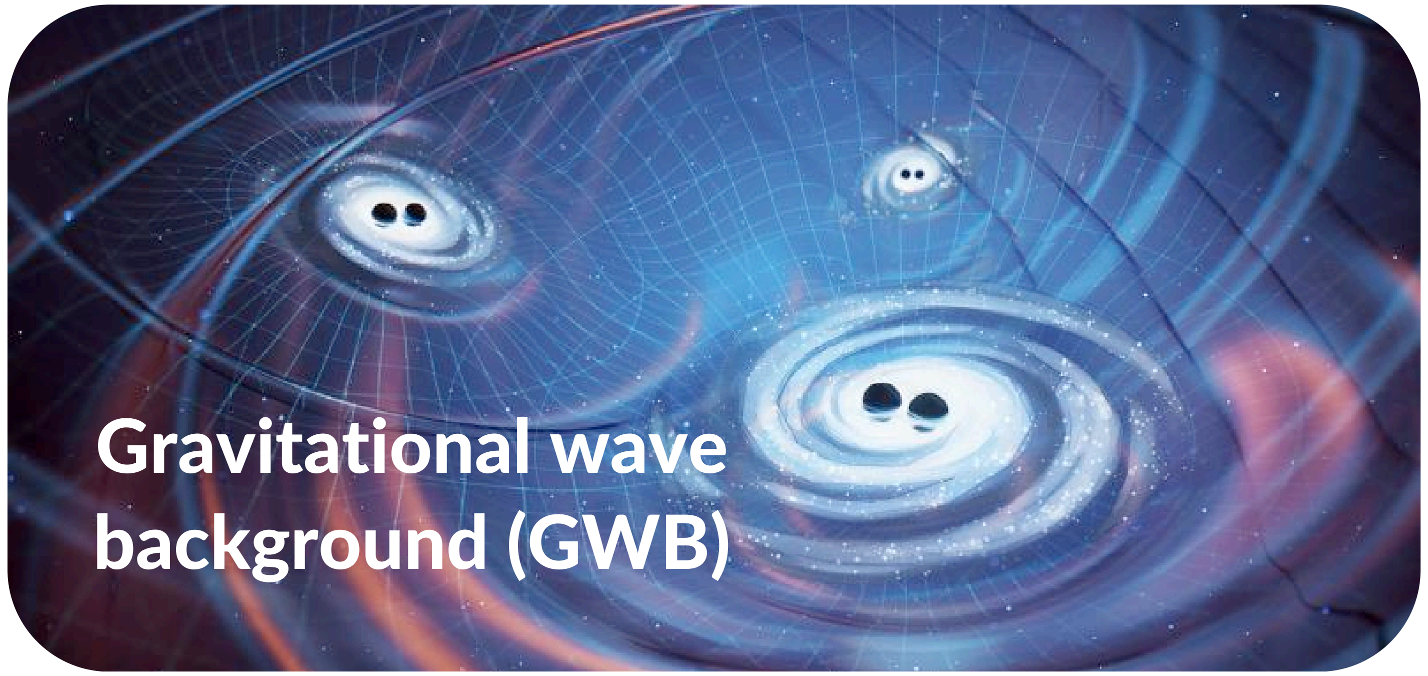
Short duration





Long duration





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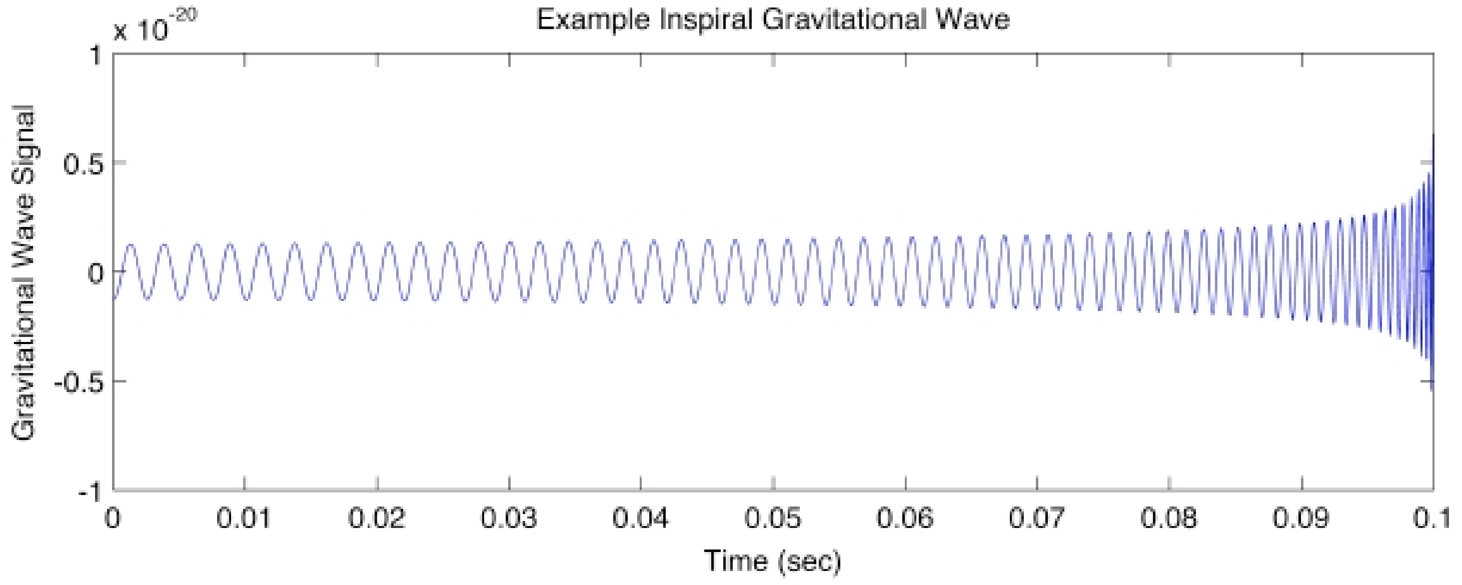

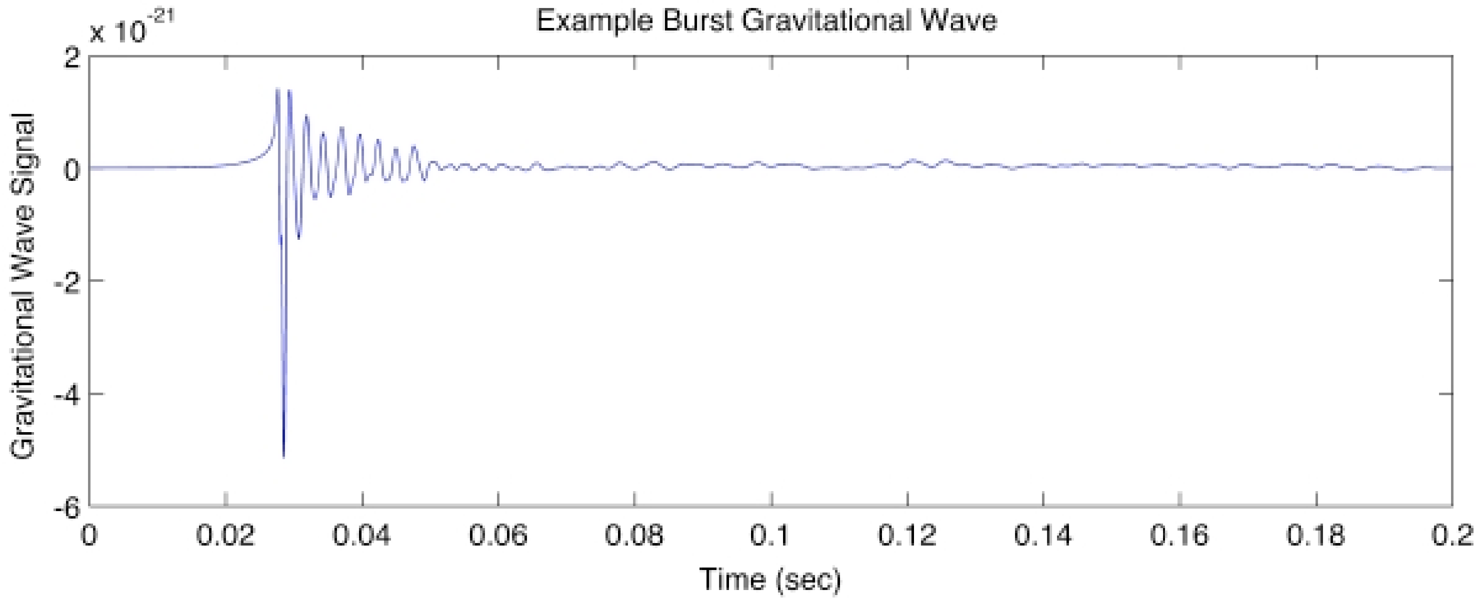

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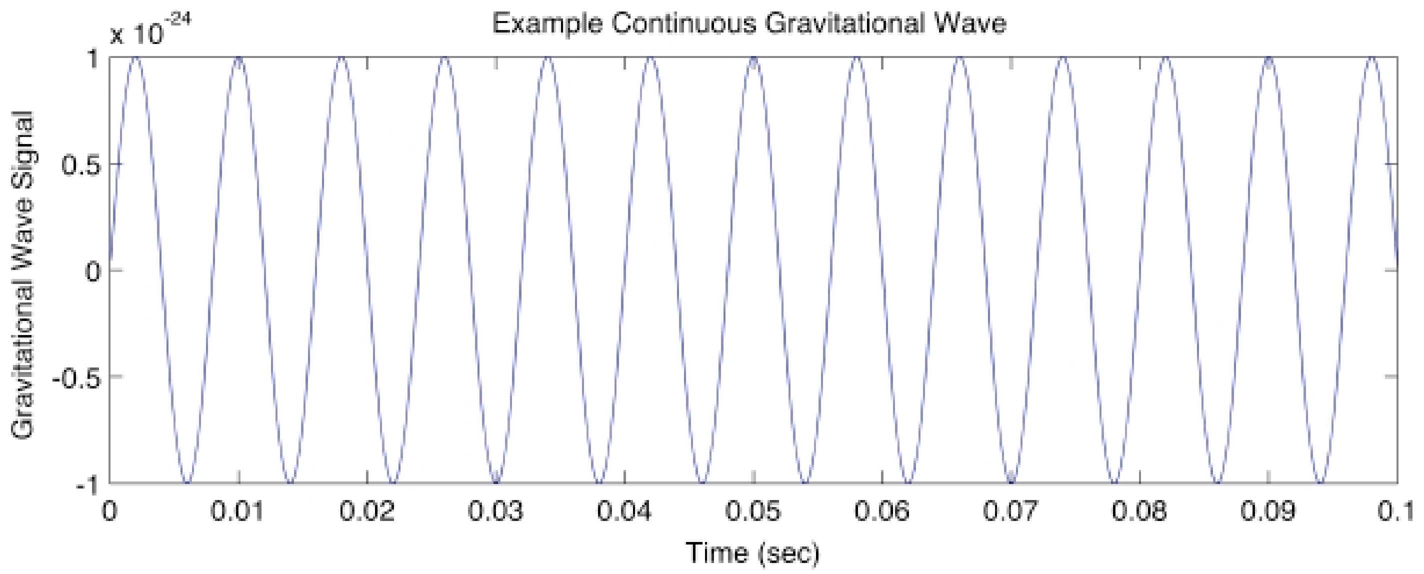

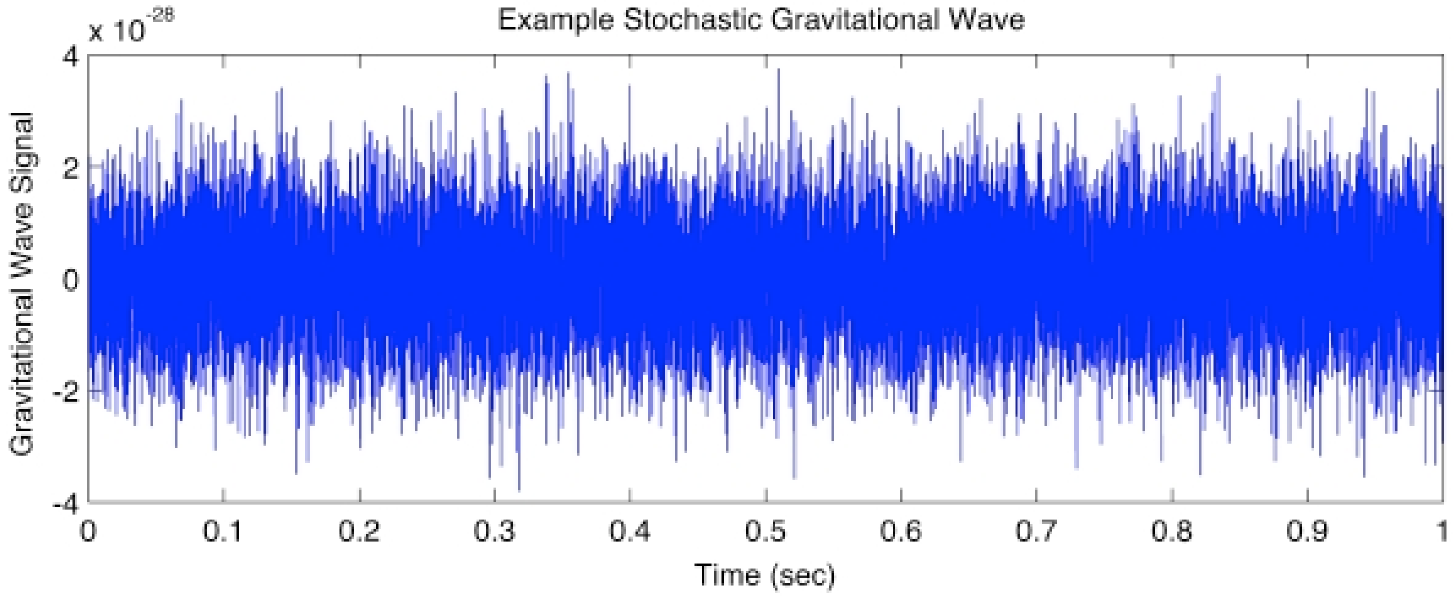

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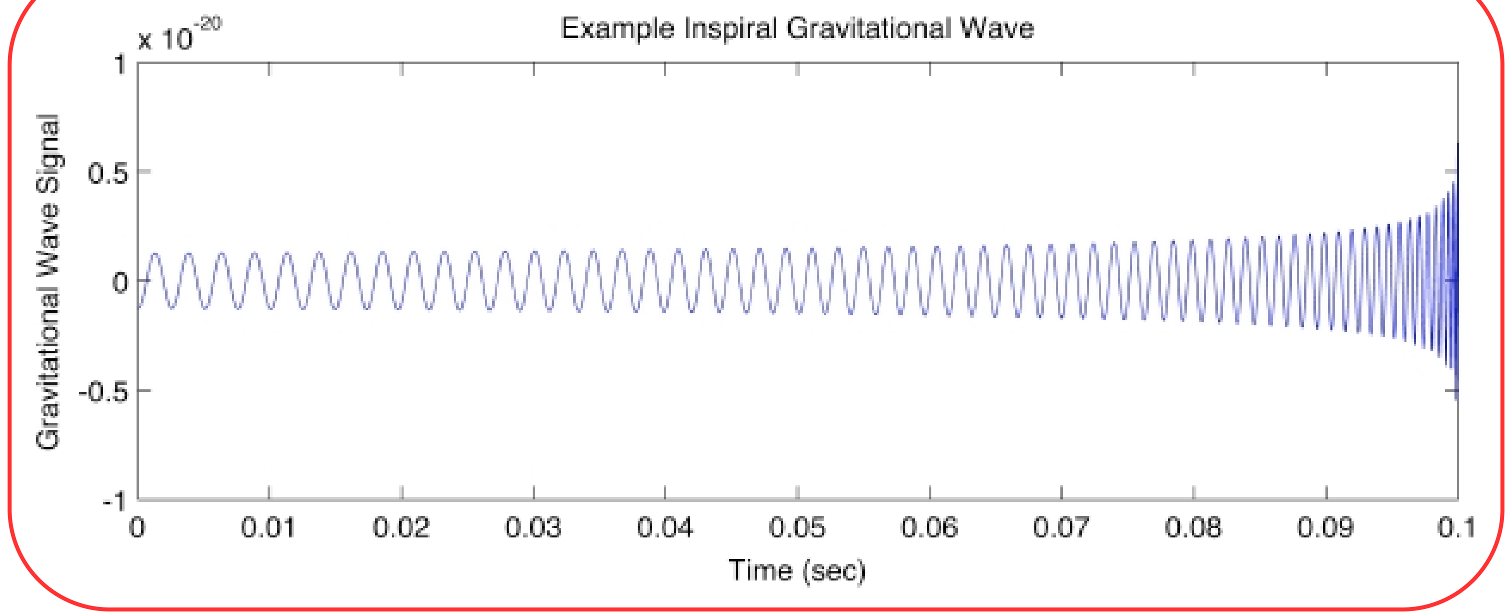

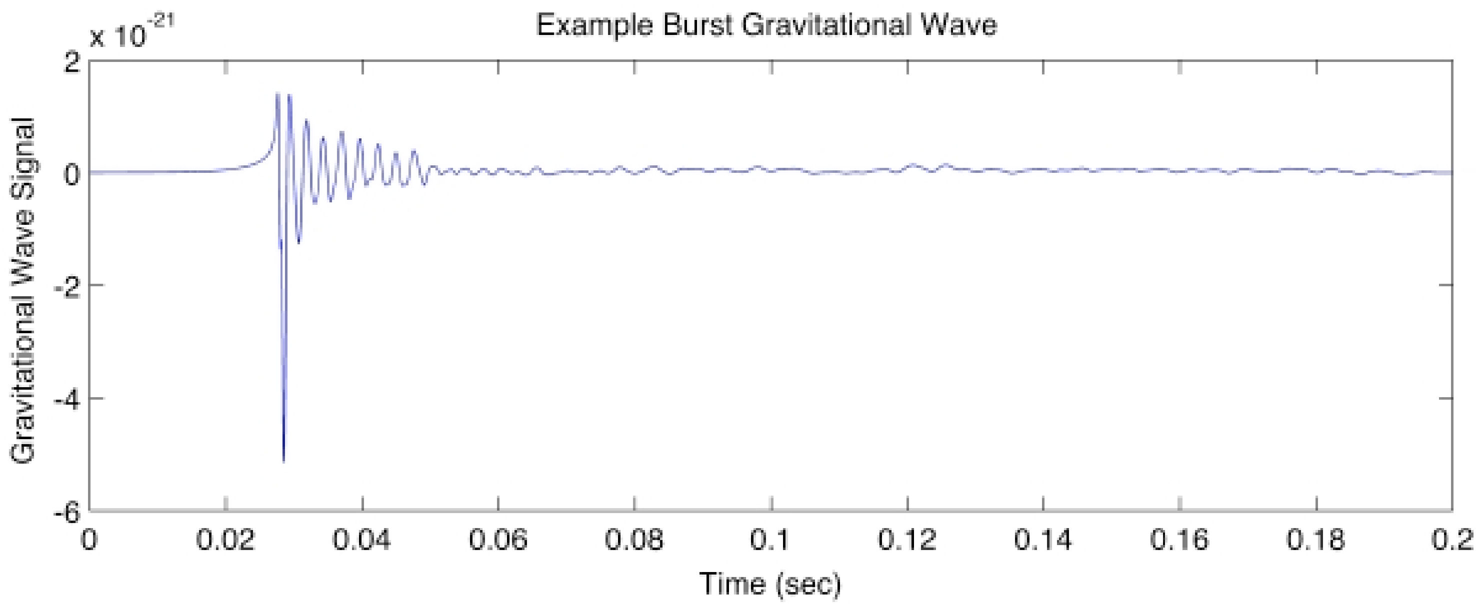

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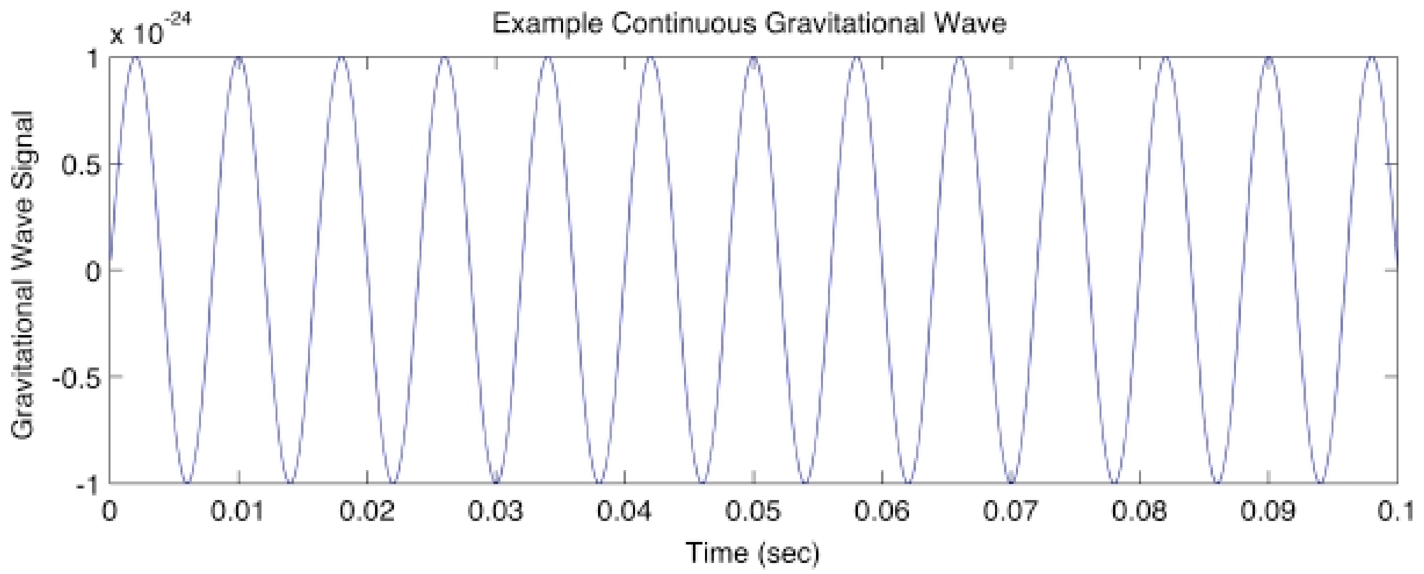
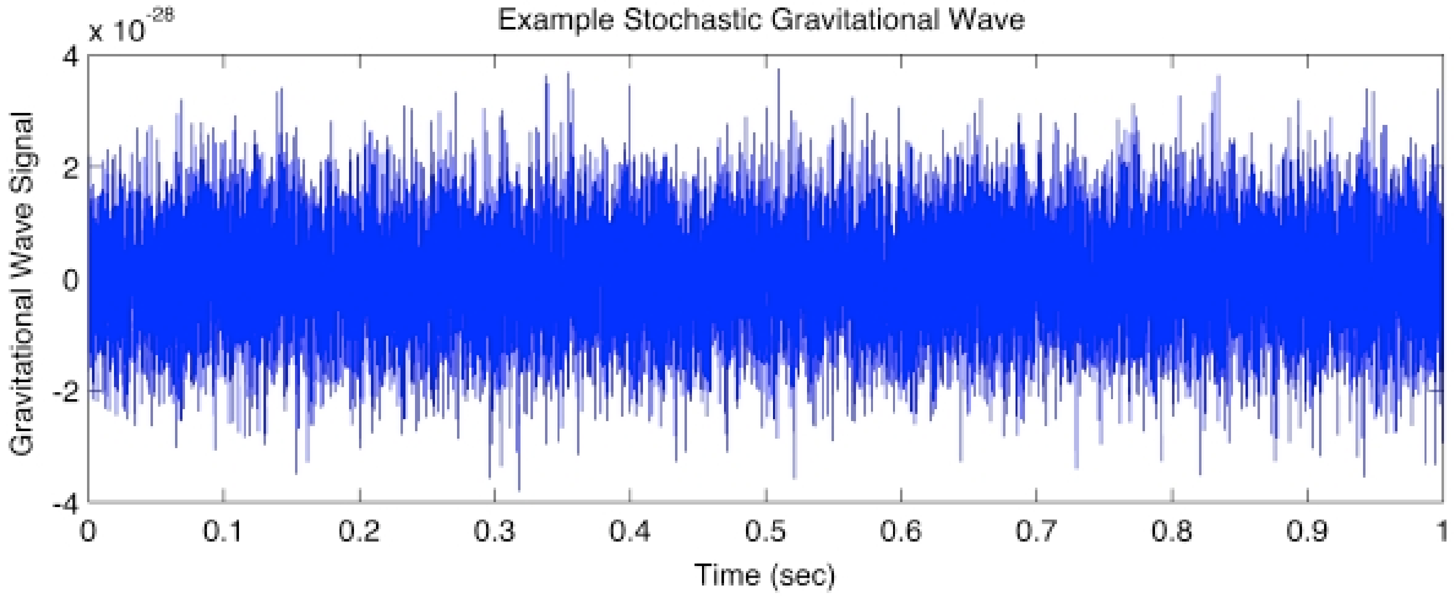
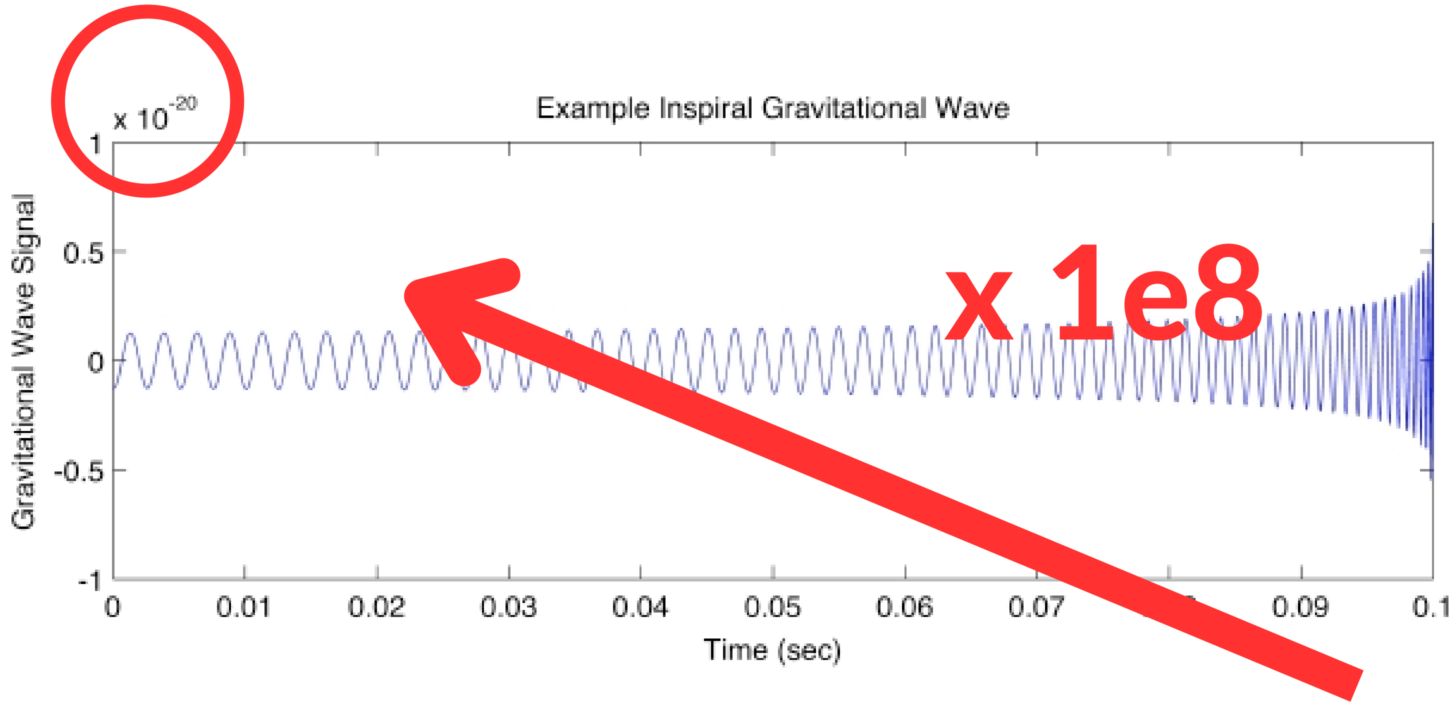


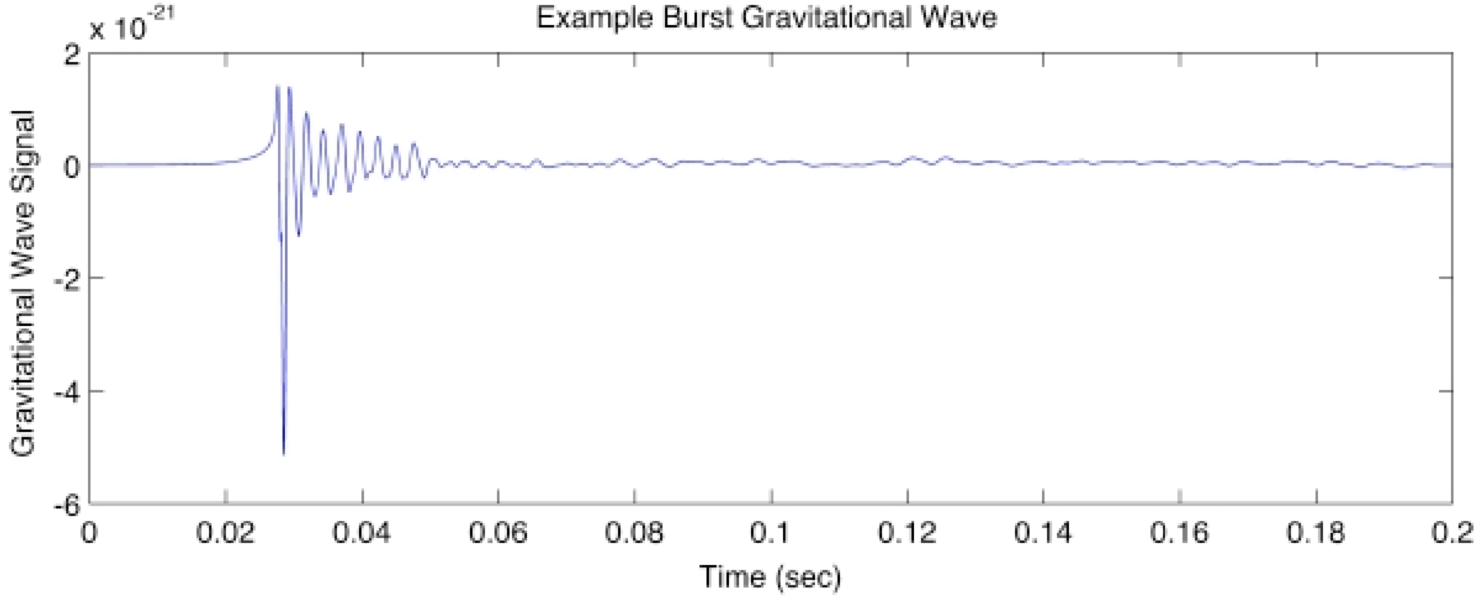


Sources of GWs

Modelled | Unmodelled

Short duration





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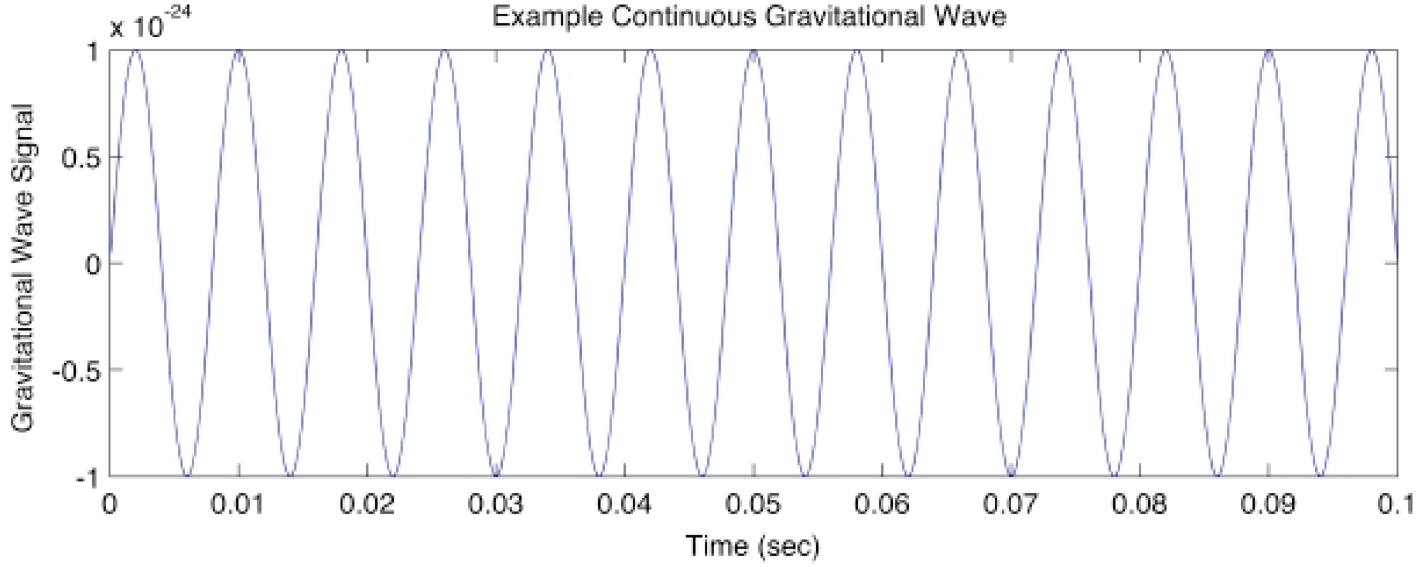

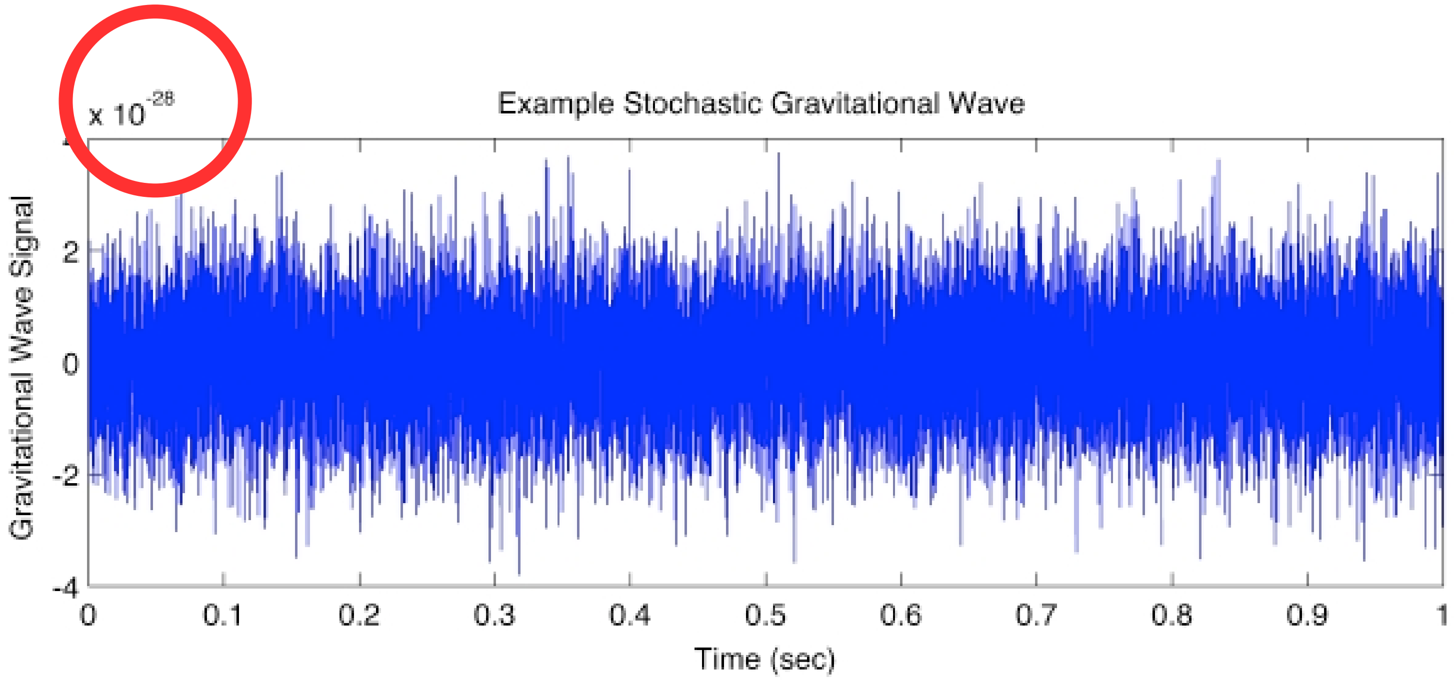

Sources of GWs

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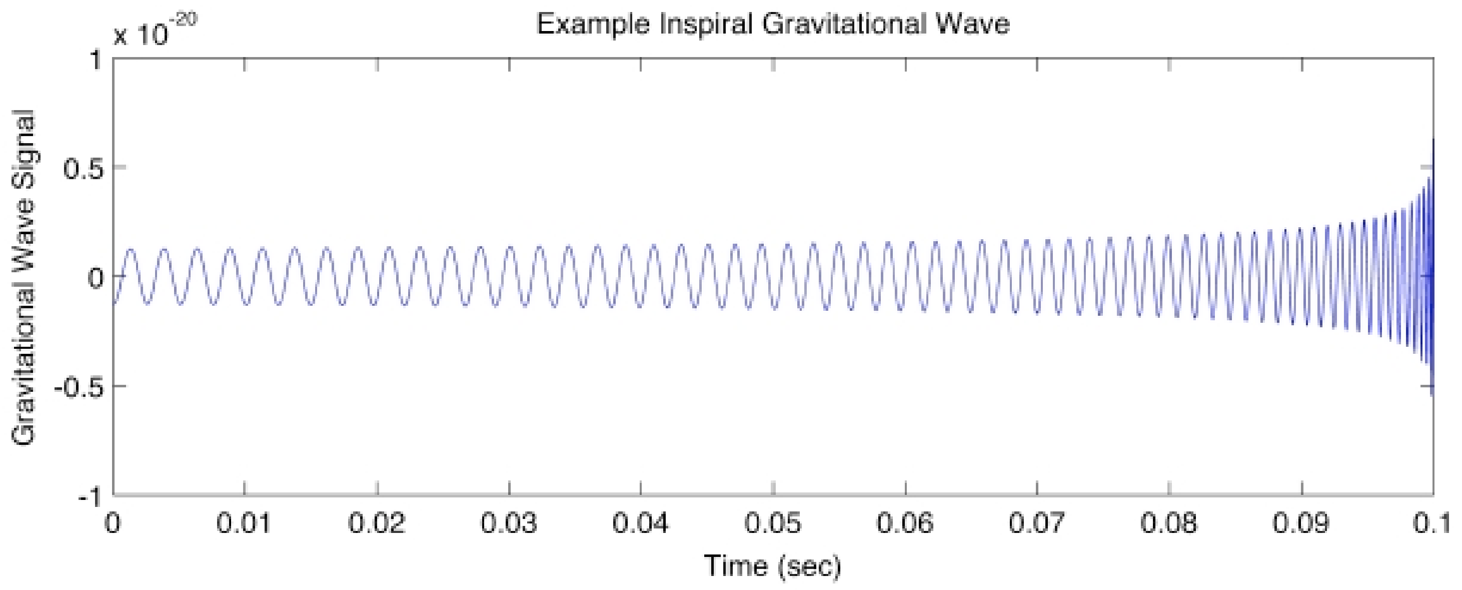

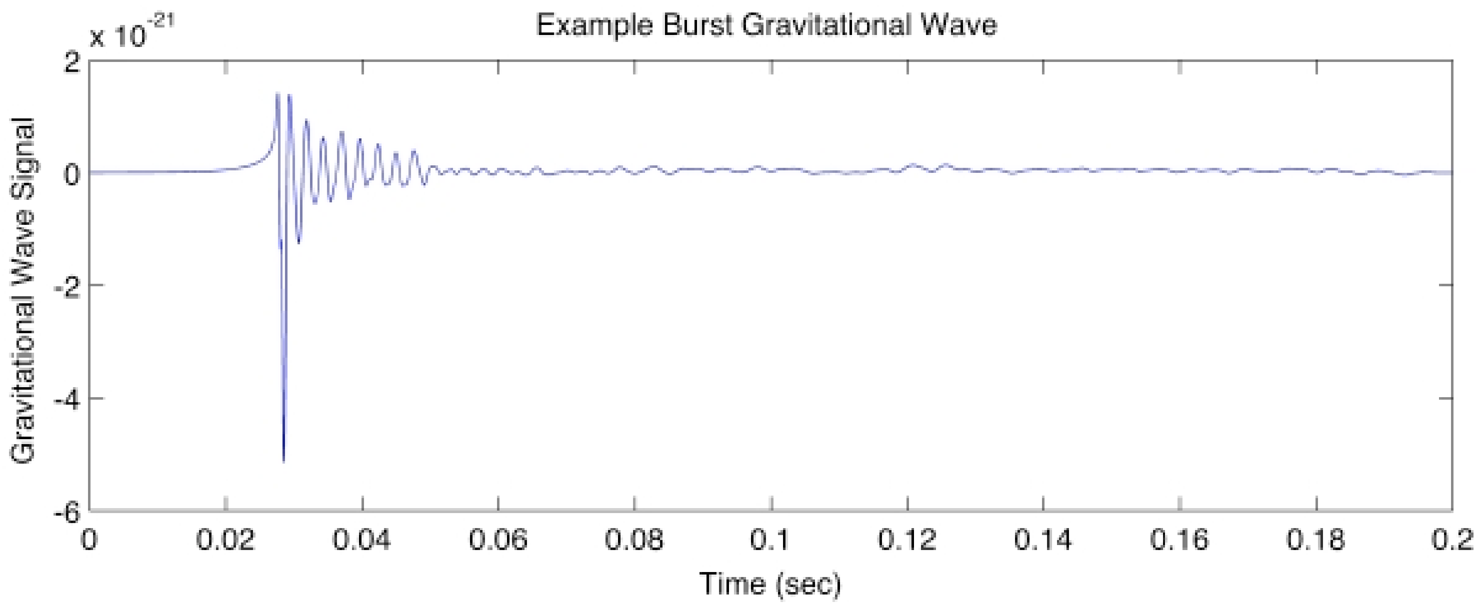

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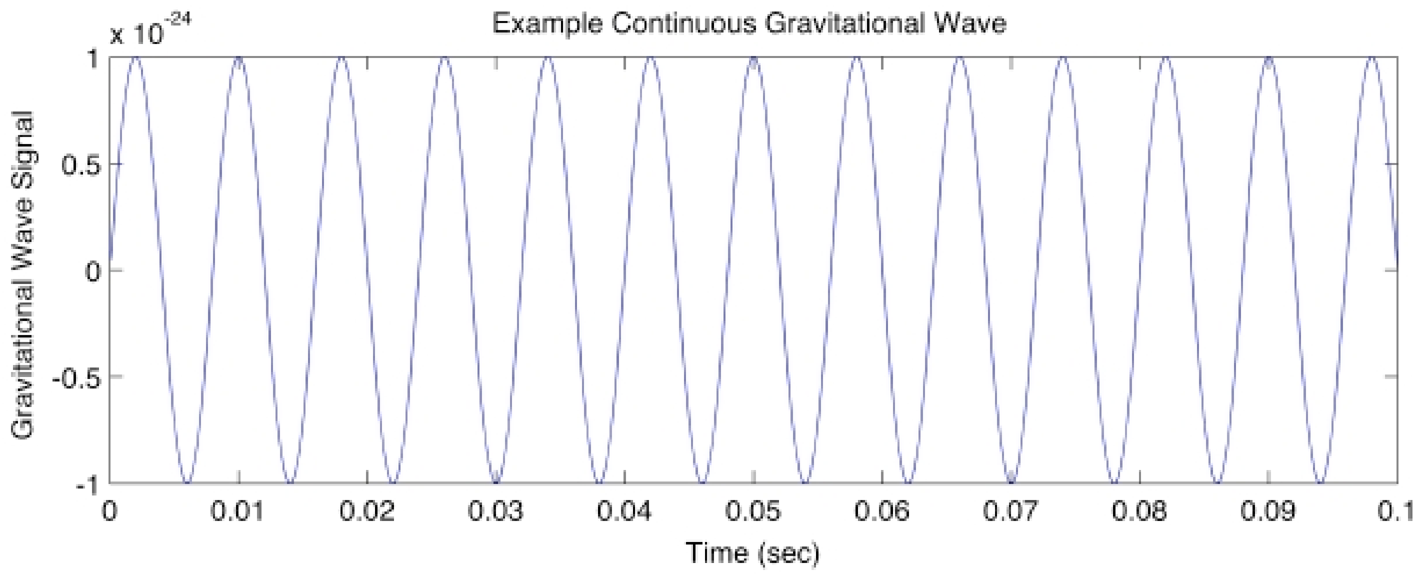
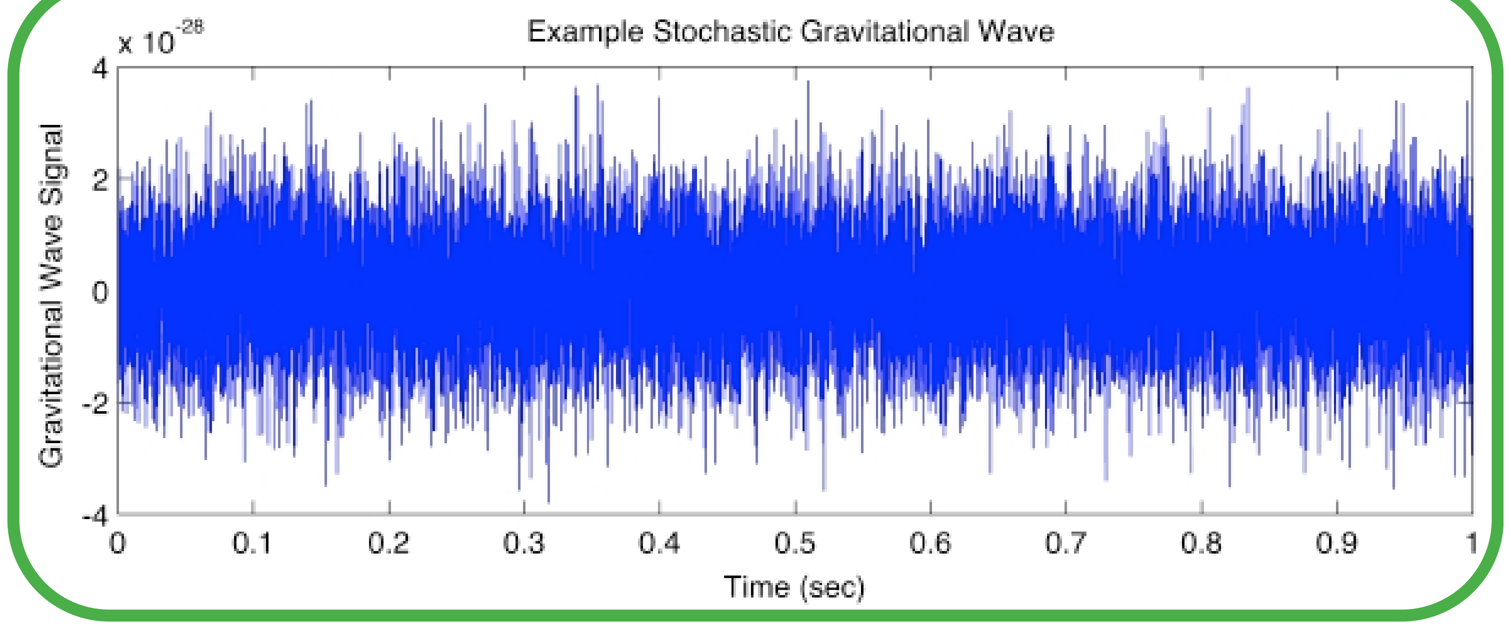
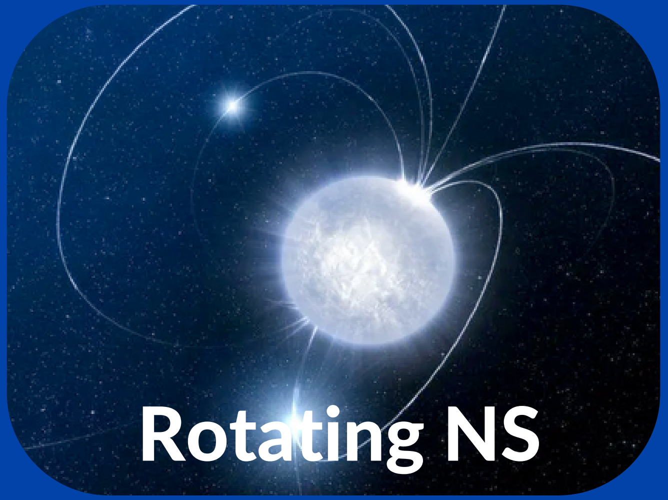
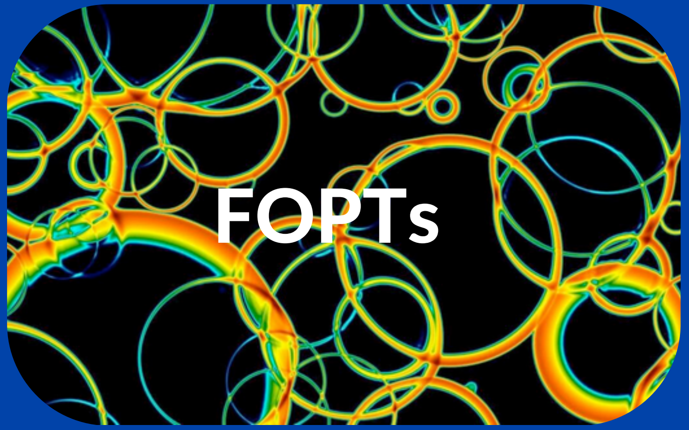


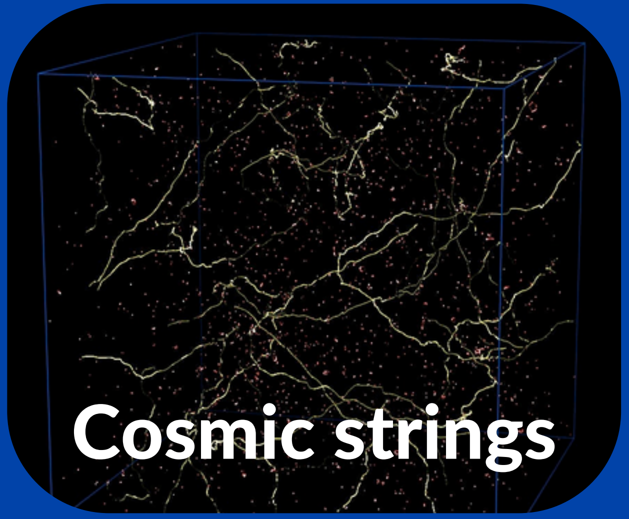


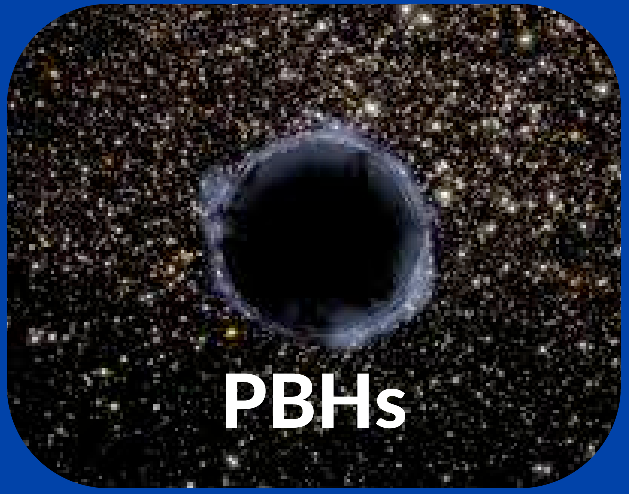
Gravitational wave background

Superposition of random GW signals produced by a large number of weak, independent and unresolved sources

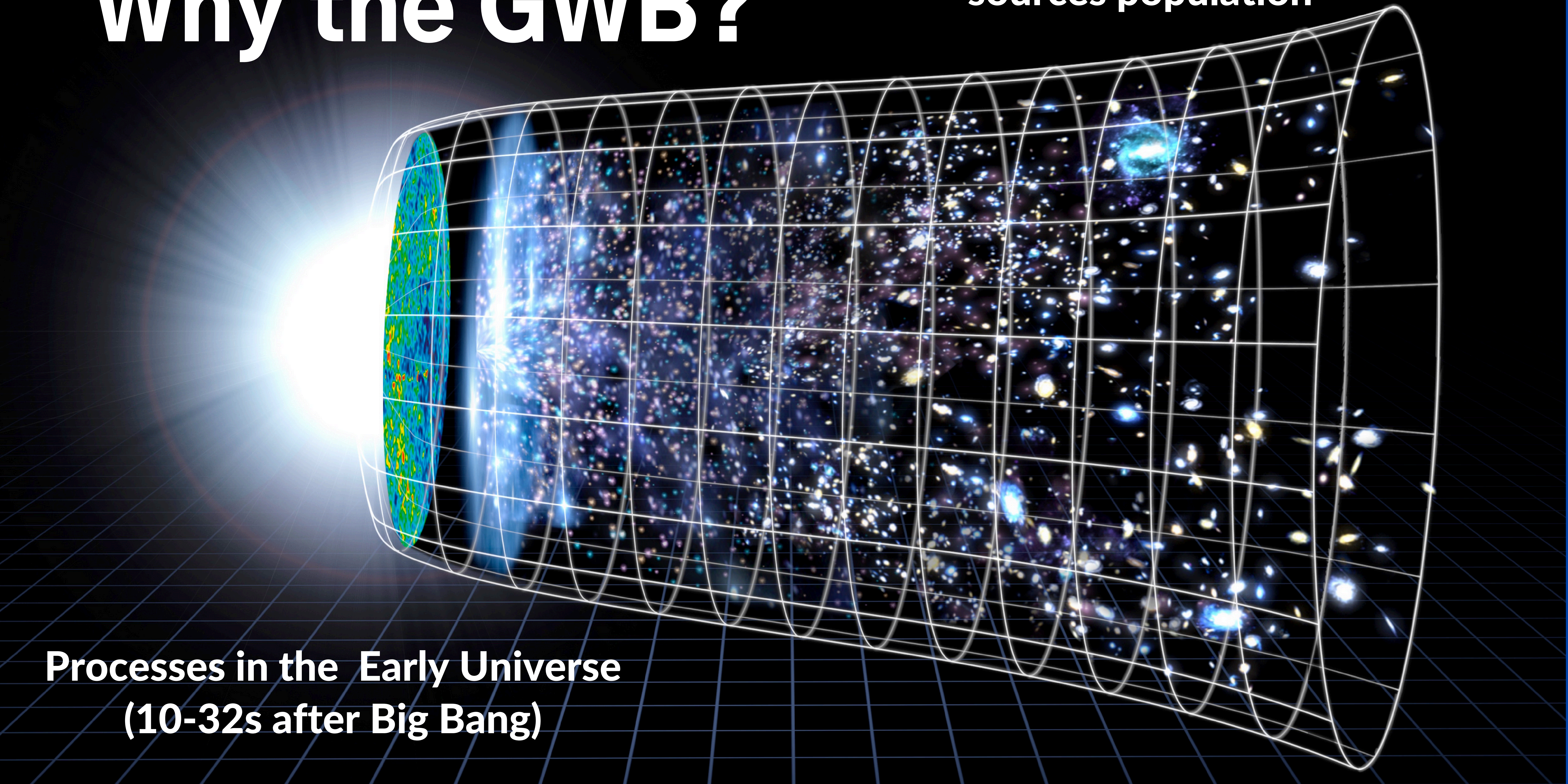








Why the GWB?


Astrophysical sources population
Processes in the Early Universe (10-32s after Big Bang)

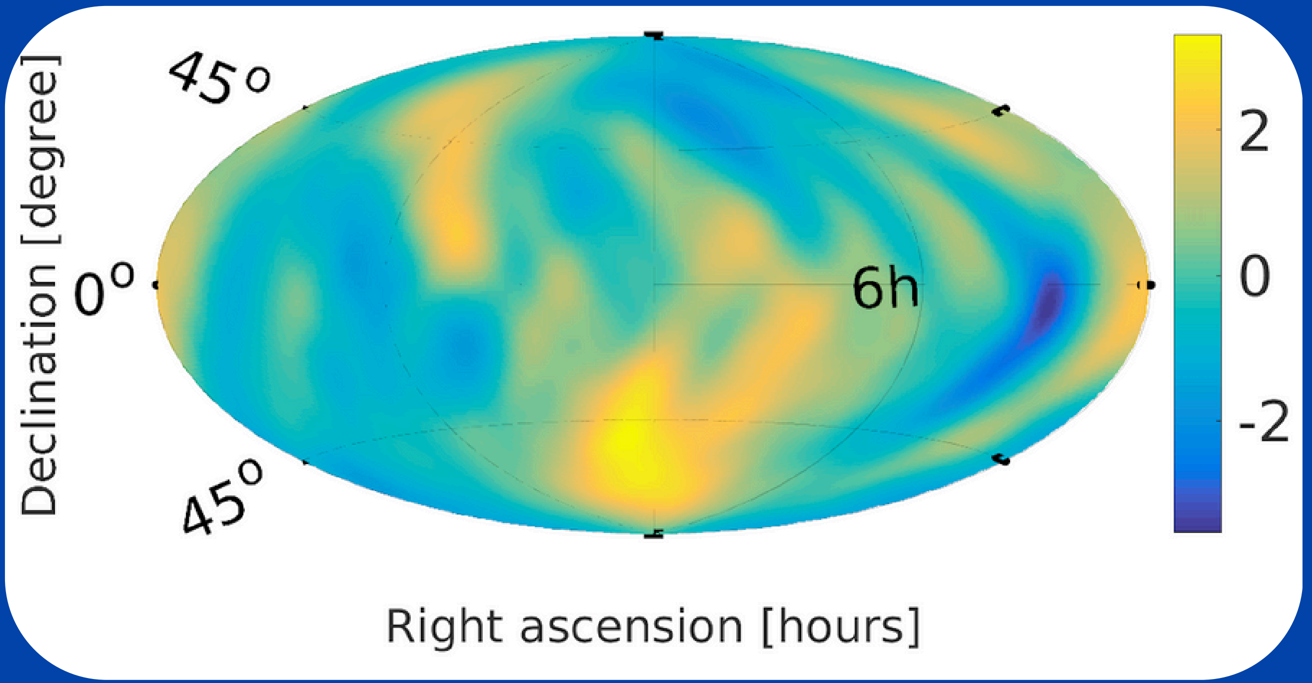
GWB characterization

- Statistically: probability distribution or moments
- Large number of independent sources: GWB is Gaussian

$$\langle h_{ab}(t,\vec{x})\rangle, \quad \langle h_{ab}(t,\vec{x})h_{cd}(t',\vec{x}')\rangle$$

Assumptions

- Isotropic
- Stationary
- Unpolarized
- Gaussian



$$\left\langle h_A(f,\hat{n})h^*_{A'}(f',\hat{n}')\right\rangle = \frac{1}{16\pi}S_h(f)\delta(f-f')\delta_{AA'}\delta^2(\hat{n},\hat{n}')$$

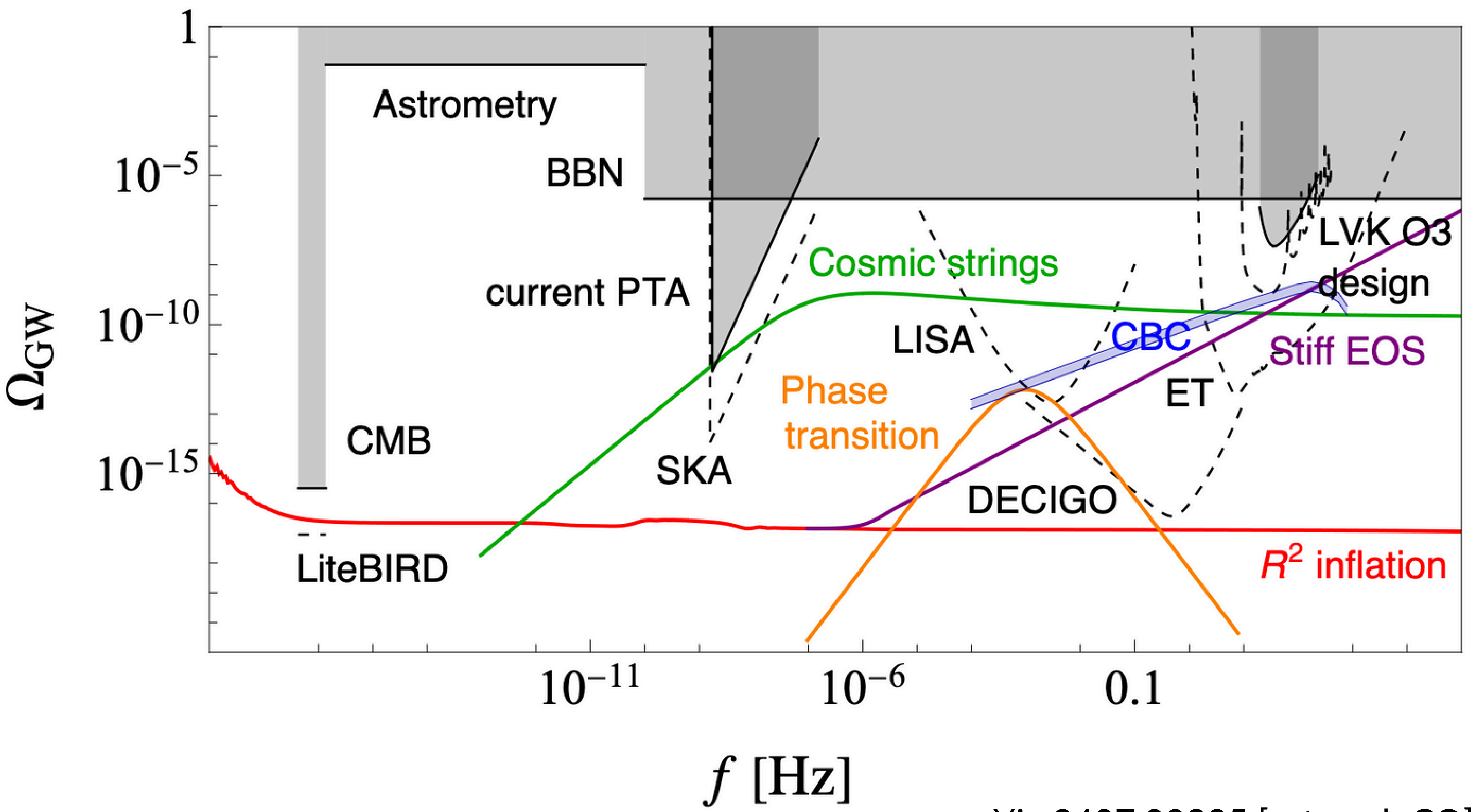
GWB characterization

Fractional energy density spectrum in GWs

$$\Omega_{gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{gw}}{d\ln f}$$

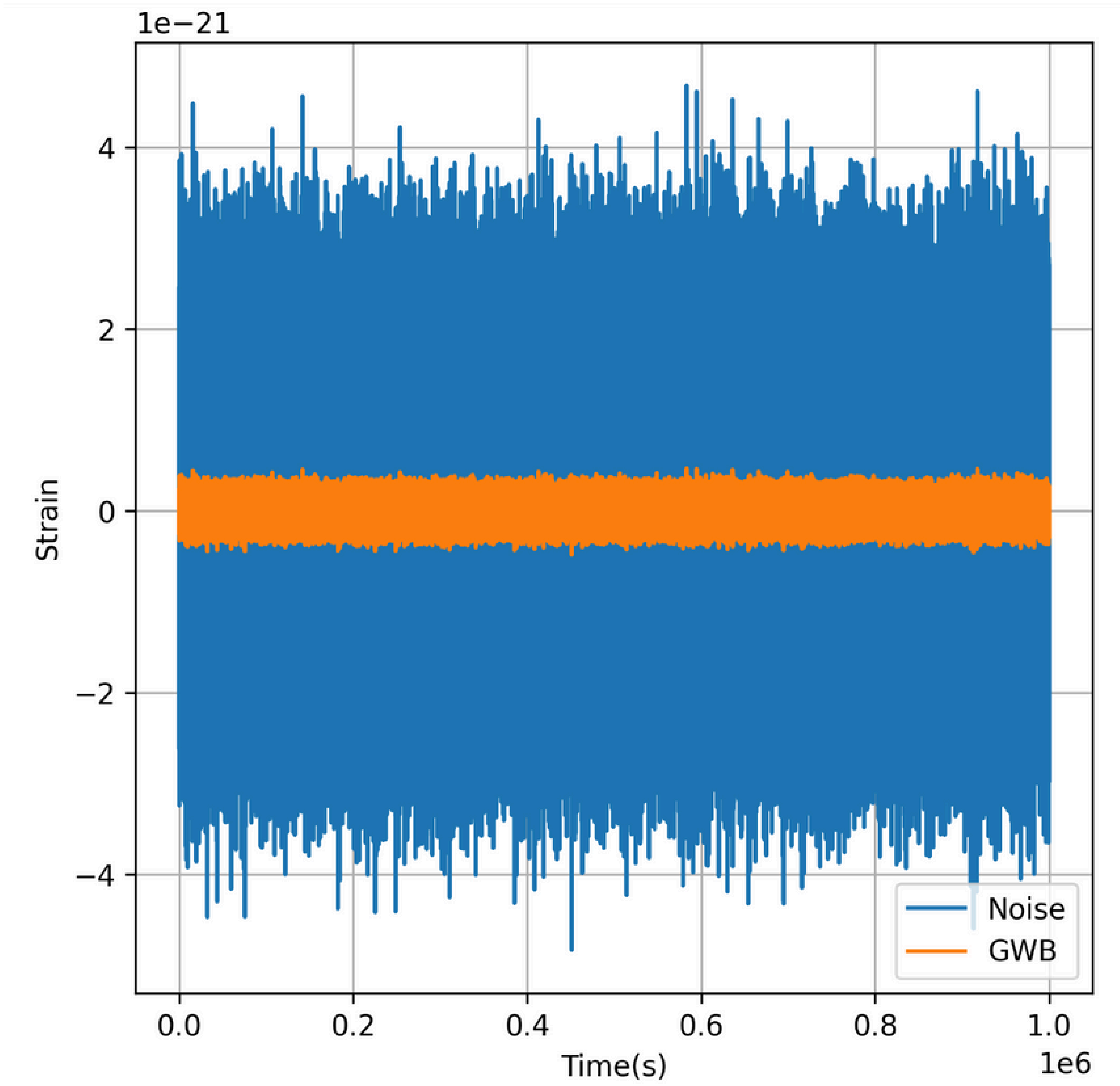
$$\rho_{GW} = \frac{c^2}{32\pi G}\langle \dot{h}_{ab}(t,\mathbf{x})\dot{h}^{ab}(t,\mathbf{x})\rangle$$

$$\Omega_{GW}(f) = \frac{2\pi^2}{3H_0^2} f^3 S_h(f)$$



arXiv:2407.00205 [astro-ph.CO]

LVK search for an isotropic GWB



Cross correlation search

$$s_1(t) = n_1(t) + h_1(t),$$
$$s_2(t) = n_2(t) + h_2(t)\,.$$

$$\mathrm{SNR} = \frac{3H_0^2\sqrt{T}}{10\pi^2}\left(\int_{-\infty}^{\infty} \mathrm{d}f\, \frac{\Omega_{\mathrm{GW}}^2(|f|)\gamma_{12}^2(|f|)}{|f|^6 P_1(|f|)P_2(|f|)}\right)^{1/2}$$

Cross correlation search

$$\mathrm{SNR} = \frac{3H_0^2\sqrt{T}}{10\pi^2}\left(\int_{-\infty}^{\infty} \mathrm{d}f\, \frac{\Omega_{\mathrm{GW}}^2(|f|)\gamma_{12}^2(|f|)}{|f|^6 P_1(|f|)P_2(|f|)}\right)^{1/2}$$

T : observation time

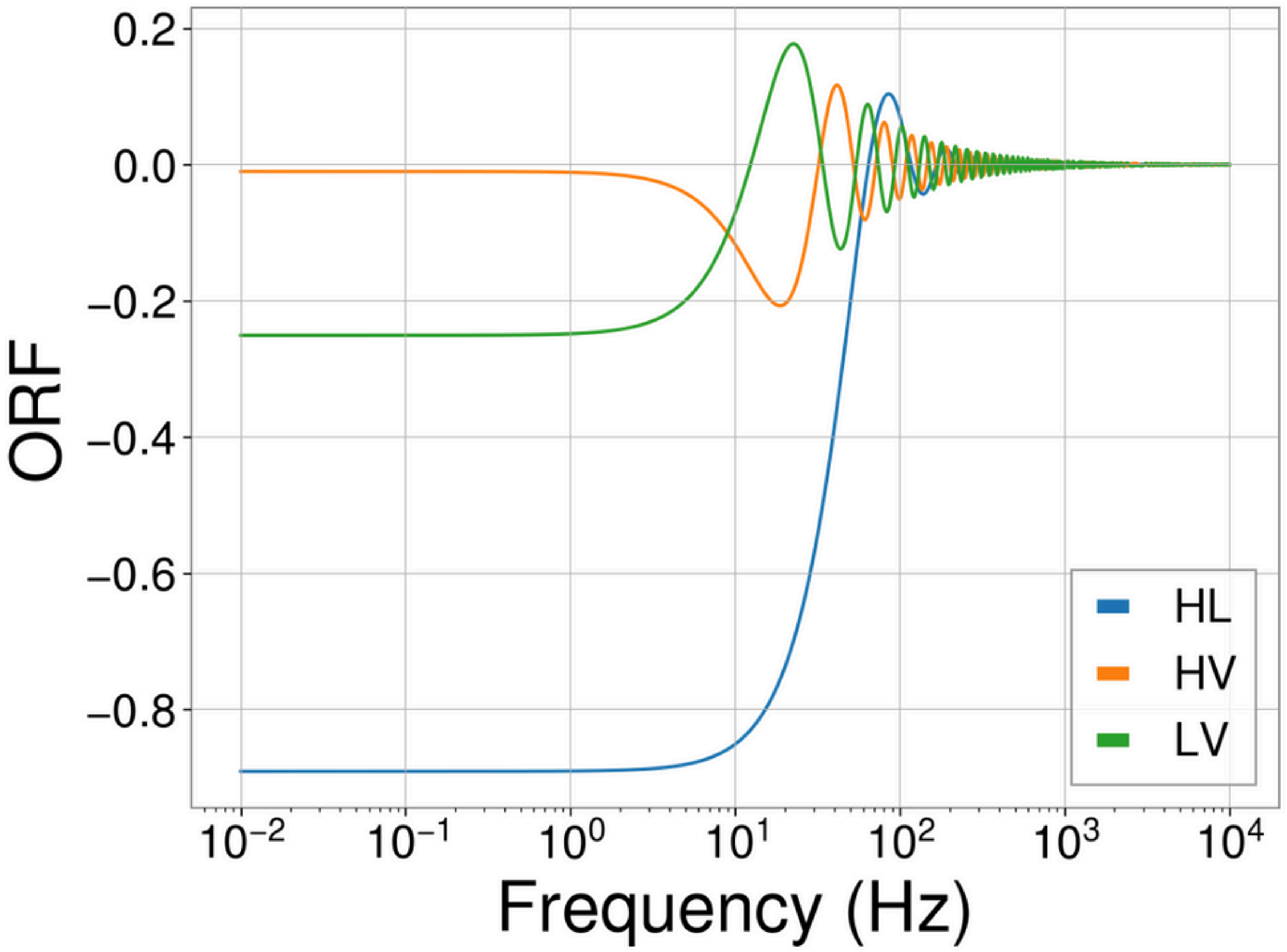
Cross correlation search

$$\mathrm{SNR} = \frac{3H_0^2\sqrt{T}}{10\pi^2}\left(\int_{-\infty}^{\infty} \mathrm{d}f \frac{\Omega_{\mathrm{GW}}^2(|f|)\gamma_{12}^2(|f|)}{|f|^6 P_1(|f|)P_2(|f|)}\right)^{1/2}$$

Cross correlation search

Overlap reduction function (ORF)

$$\mathrm{SNR} = \frac{3H_0^2\sqrt{T}}{10\pi^2}\left(\int_{-\infty}^{\infty} \mathrm{d}f\, \frac{\Omega_{\mathrm{GW}}^2(|f|)\gamma_{12}^2(|f|)}{|f|^6 P_1(|f|)P_2(|f|)}\right)^{1/2}$$



Cross correlation search

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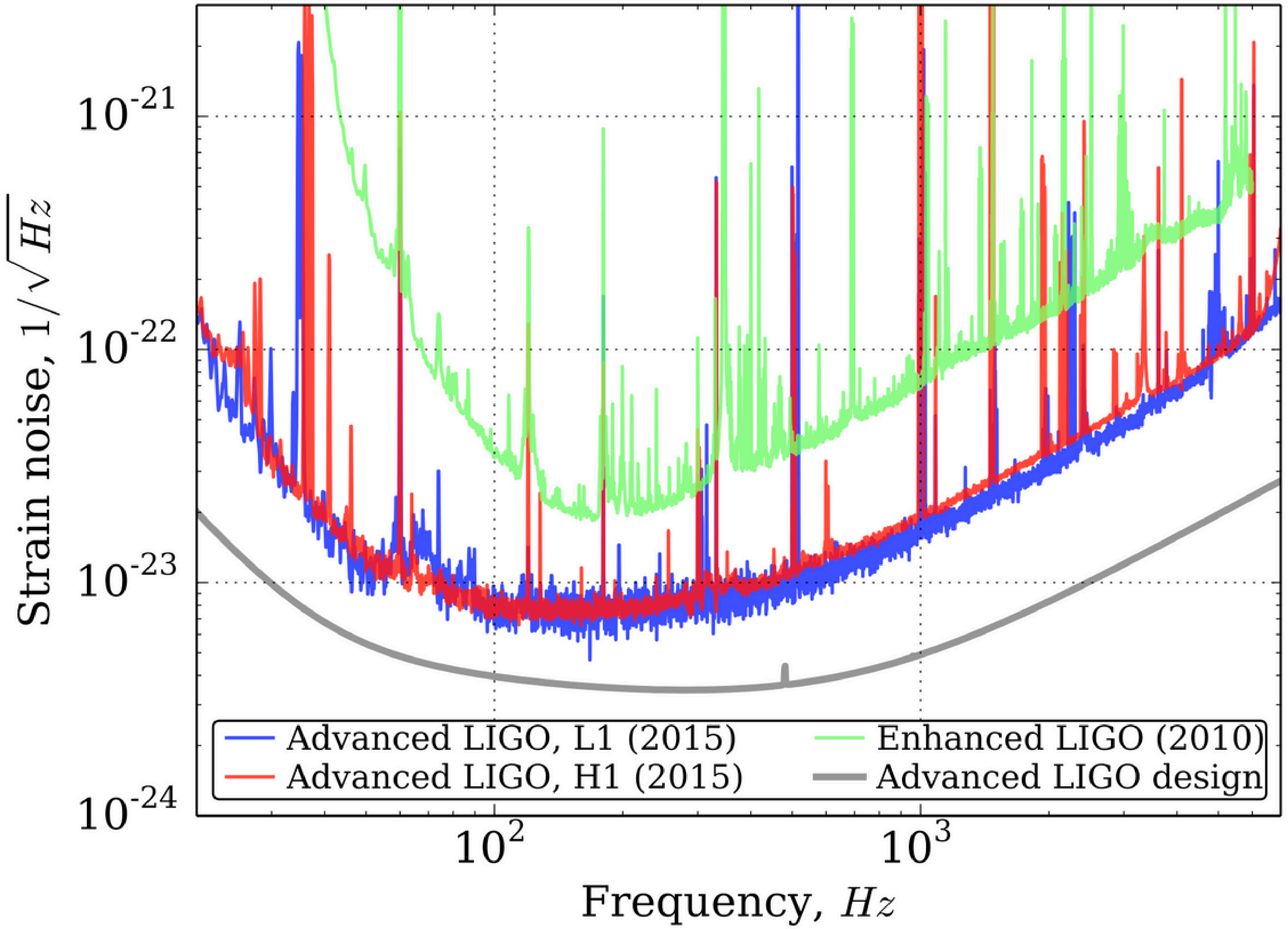
Noise power spectra



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$$\Omega_{\mathrm{GW}}(f) = \Omega_\alpha\left(\frac{f}{f_{\mathrm{ref}}}\right)^\alpha$$

- $f$ref = 25 Hz
- α = 0 : inflation, cosmic strings
- α = 2/3 : inspiral phase of CBCs
- α = 3 : supernovae

Bayesian inference

Gaussian likelihood

$$p(\{\hat{Y}_f\}|\Theta) \propto \exp\left[-\sum_f \frac{(\hat{Y}_f - Y(f|\Theta))^2}{2\sigma^2_{\hat{Y}_f}}\right]$$

Bayesian inference

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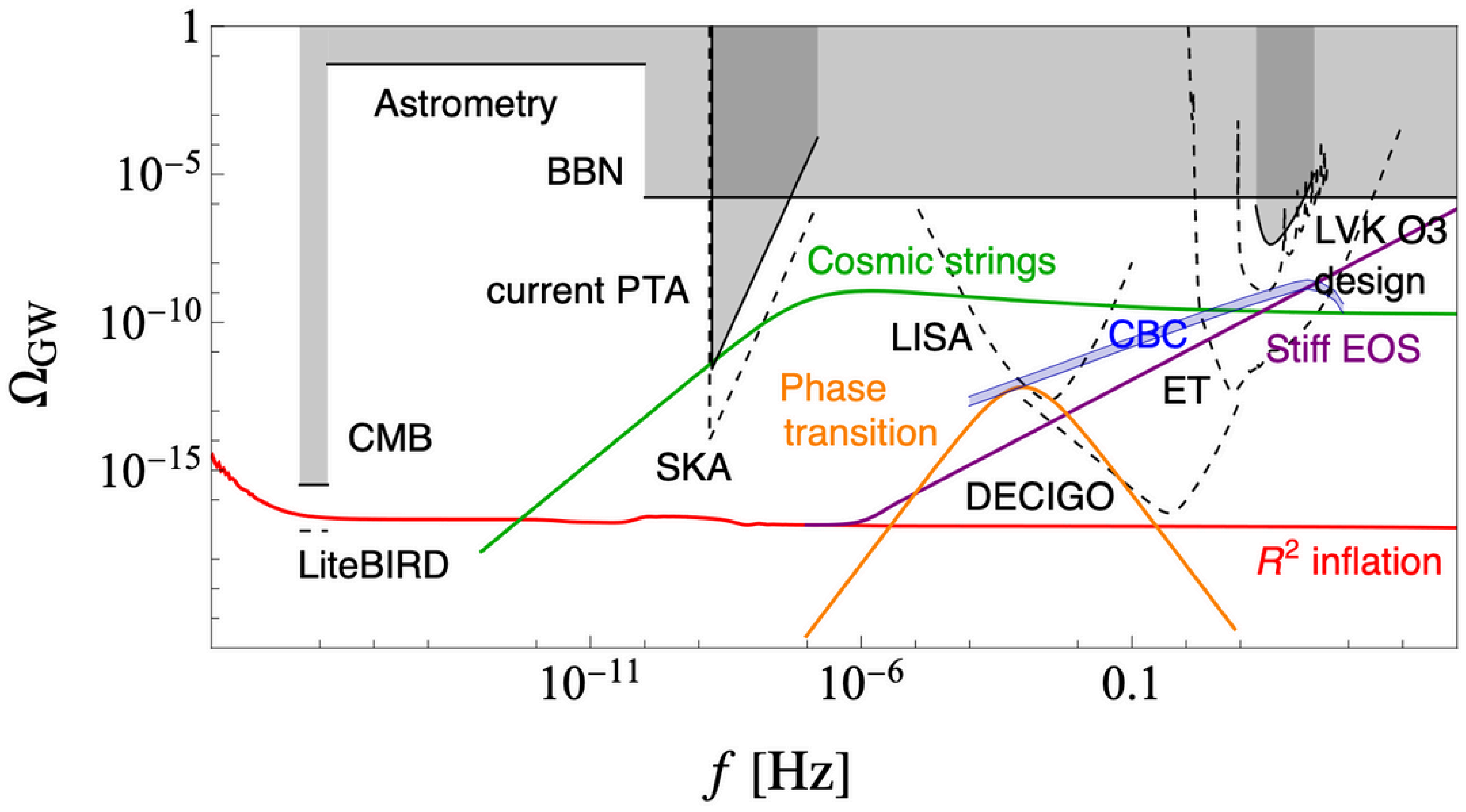
$$p(\{\hat{Y}_f\}|\Theta) \propto \exp\left[-\sum_f \frac{(\hat{Y}_f - Y(f|\Theta))^2}{2\sigma^2_{\hat{Y}_f}}\right]$$

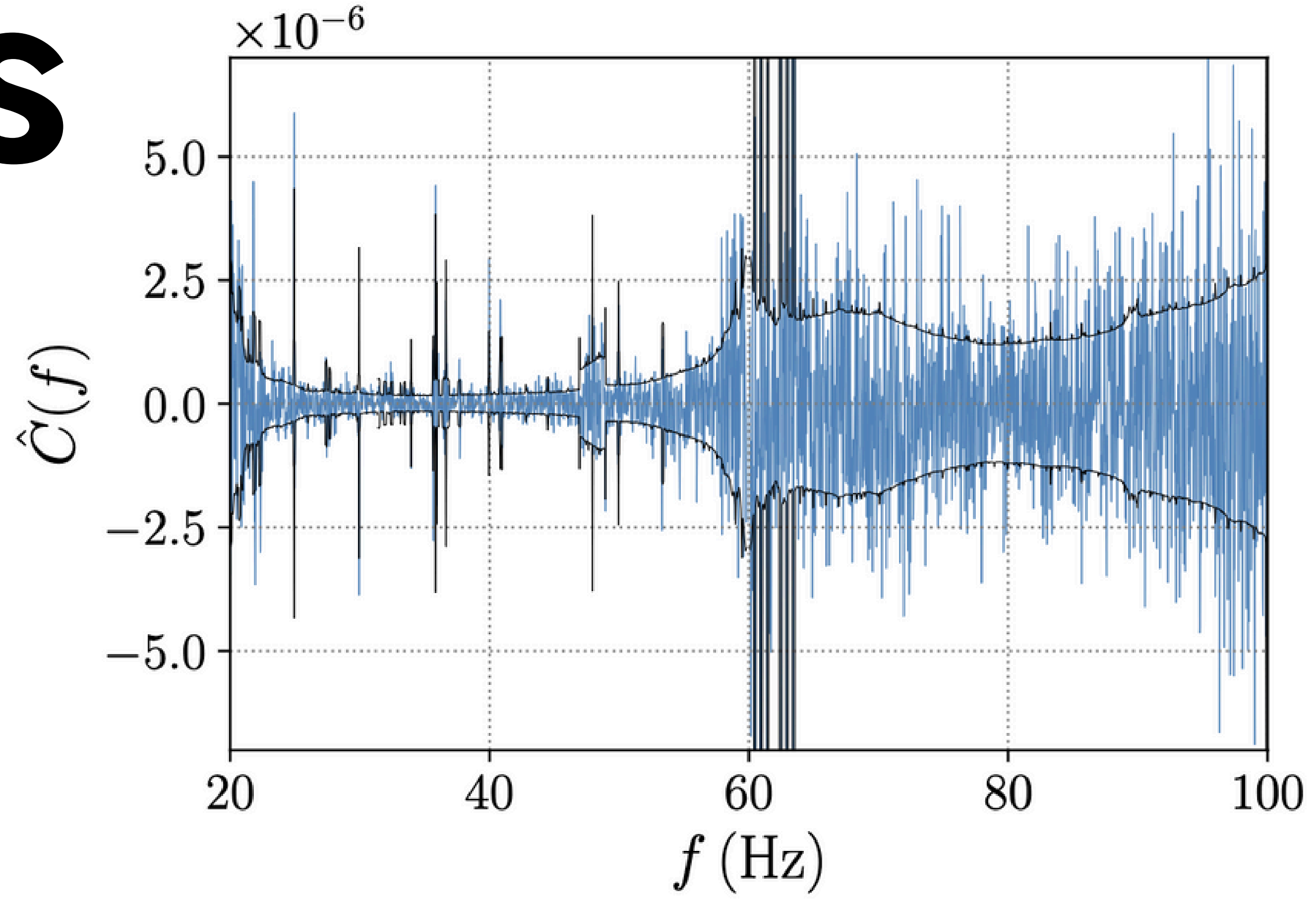
Model assumed to describe the GWB



arXiv:2407.00205 [astro-ph.CO]

Current LVK results

- Data from O1-O3
- H1, L1 and V1 data
- Frequency range: 20-1726Hz



R. Abbott et al. (LVK), Phys. Rev. D 104, 022004

Power law	$f_{99\%}^{HL}$ [Hz]	$\hat{C}^{HL}/10^{-9}$	$f_{99\%}^{HV}$ [Hz]	$\hat{C}^{HV}/10^{-9}$	$f_{99\%}^{LV}$ [Hz]	$\hat{C}^{LV}/10^{-9}$	$f_{99\%}^{O1+O2+O3}$ [Hz]	$\hat{C}^{O1+O2+O3}/10^{-9}$
0	76.1	-2.1 ± 8.2	97.7	229 ± 98	88.0	-134 ± 63	76.6	1.1 ± 7.5
2/3	90.2	-3.4 ± 6.1	117.8	145 ± 60	107.3	-82 ± 40	90.6	-0.2 ± 5.6
3	282.8	-1.3 ± 0.9	375.8	9.1 ± 4.1	388.0	-4.9 ± 3.1	291.6	-0.6 ± 0.8

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Negative point estimates

Power law	$f^{HL}_{99\%}$ [Hz]	$\hat{C}^{HL}/10^{-9}$	$f^{HV}_{99\%}$ [Hz]	$\hat{C}^{HV}/10^{-9}$	$f^{LV}_{99\%}$ [Hz]	$\hat{C}^{LV}/10^{-9}$	$f^{O1+O2+O3}_{99\%}$ [Hz]	$\hat{C}^{O1+O2+O3}/10^{-9}$
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HL is the most sensitive baseline

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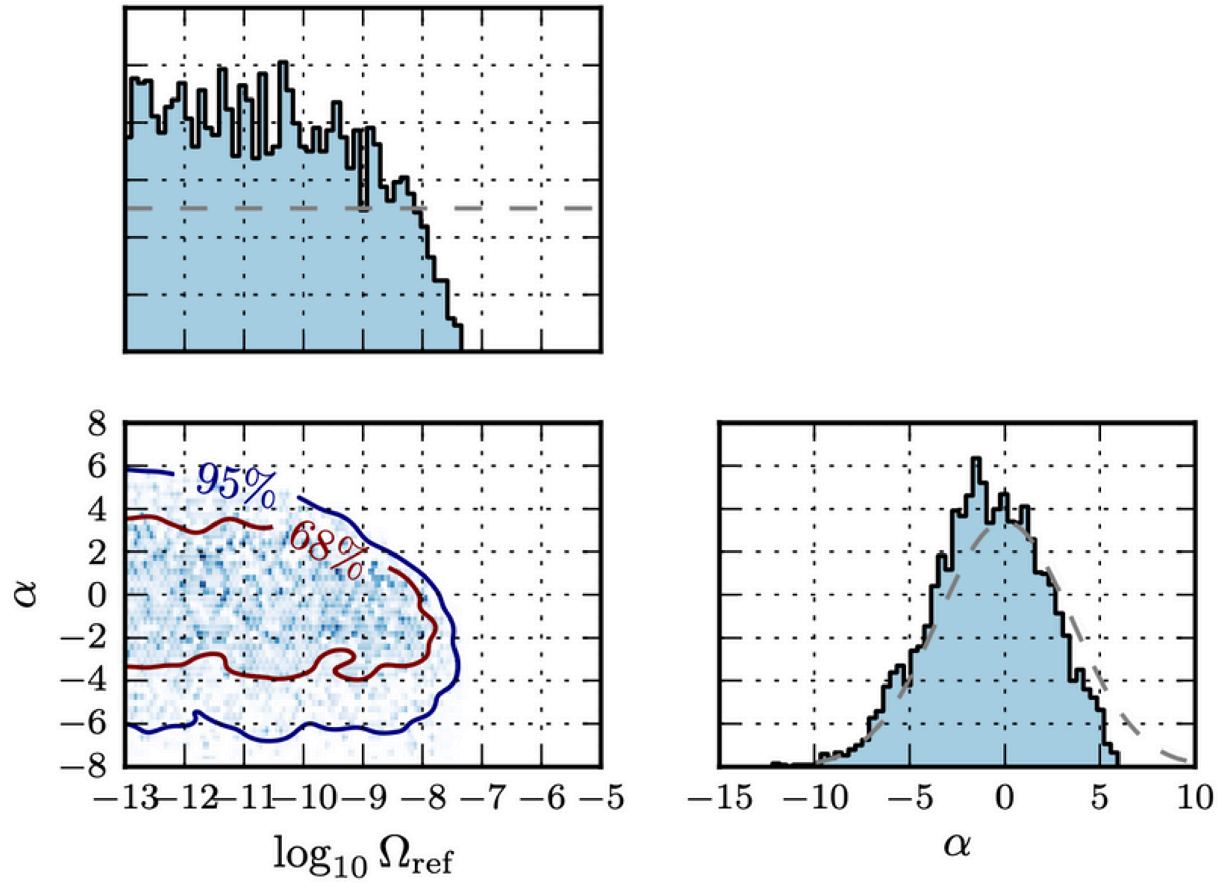
Current LVK results

Upper limits at 95% CL

	Log-uniform prior		
α	O3	O2 [43]	Improvement
0	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	3.4×10^{-9}	3.0×10^{-8}	8.8
3	3.9×10^{-10}	5.1×10^{-9}	13.1
Marg.	6.6×10^{-9}	3.4×10^{-8}	5.1



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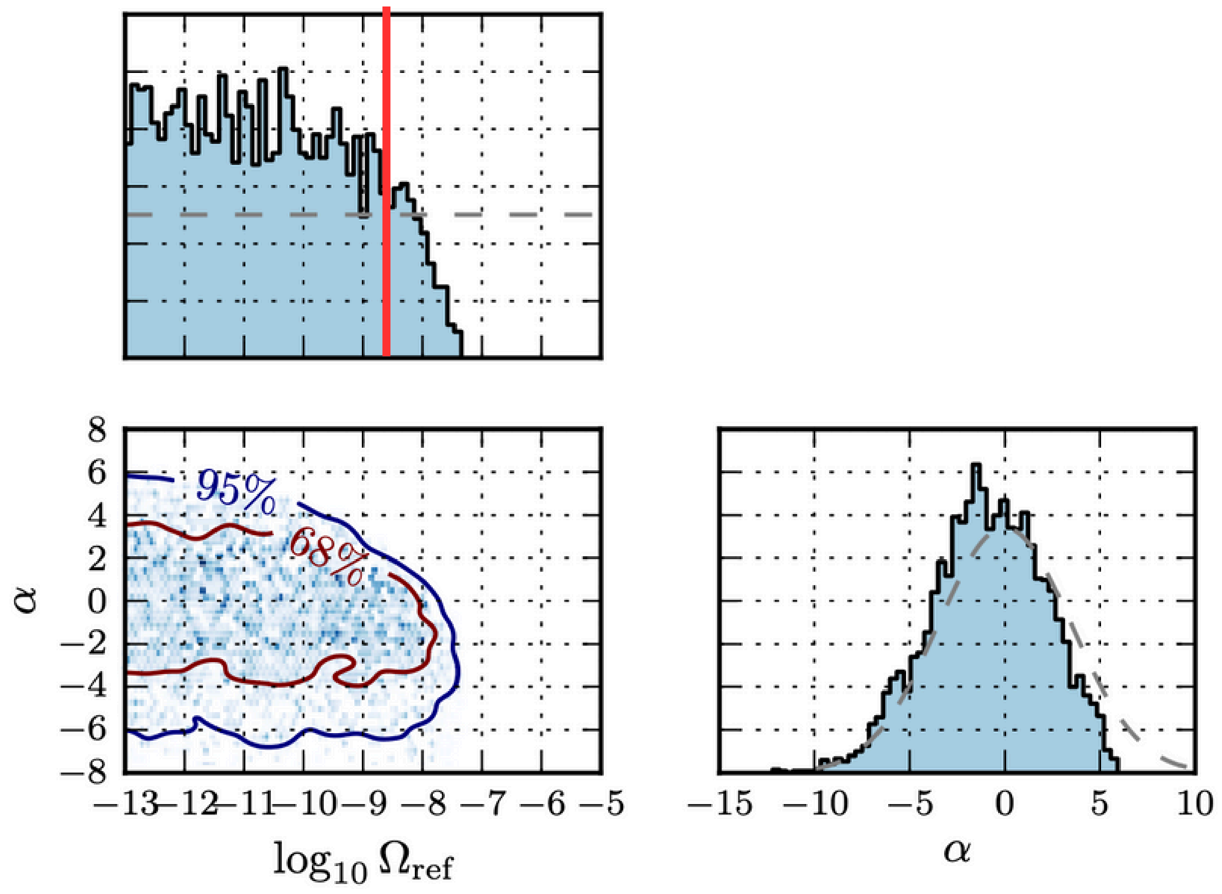
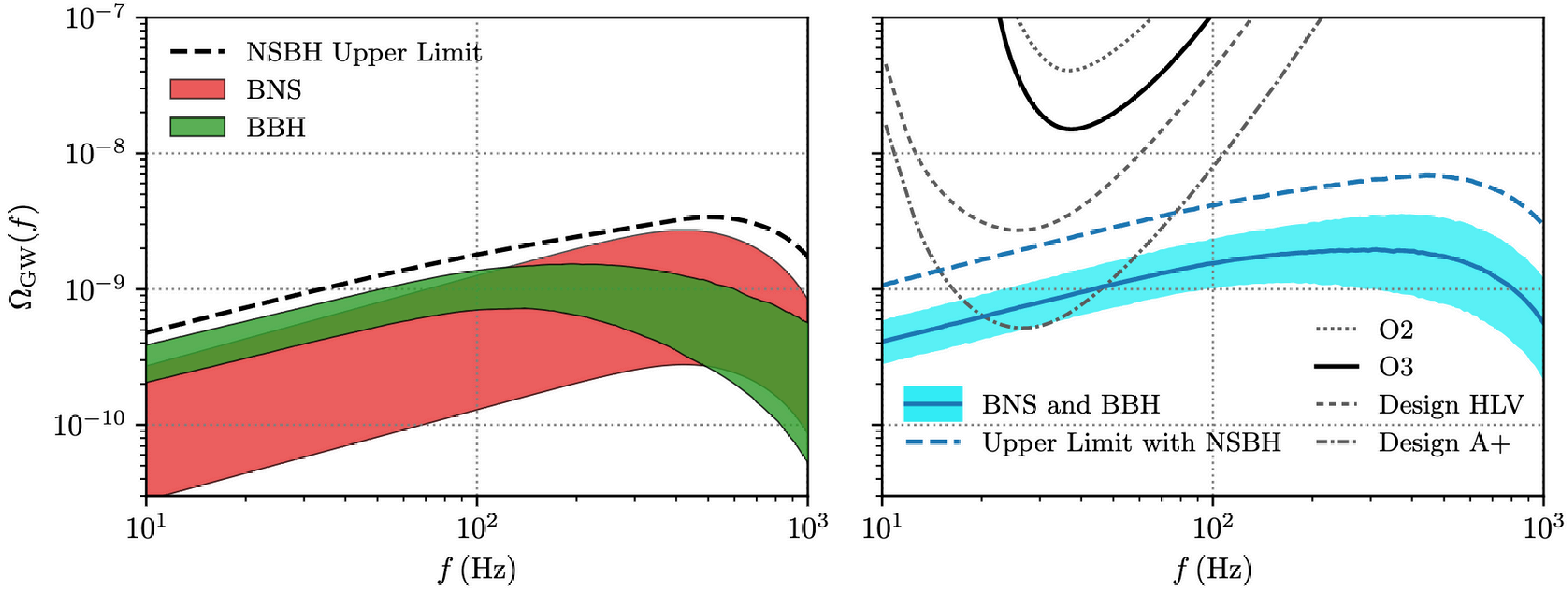


R. Abbott et al. (LVK), Phys. Rev. D 104, 022004

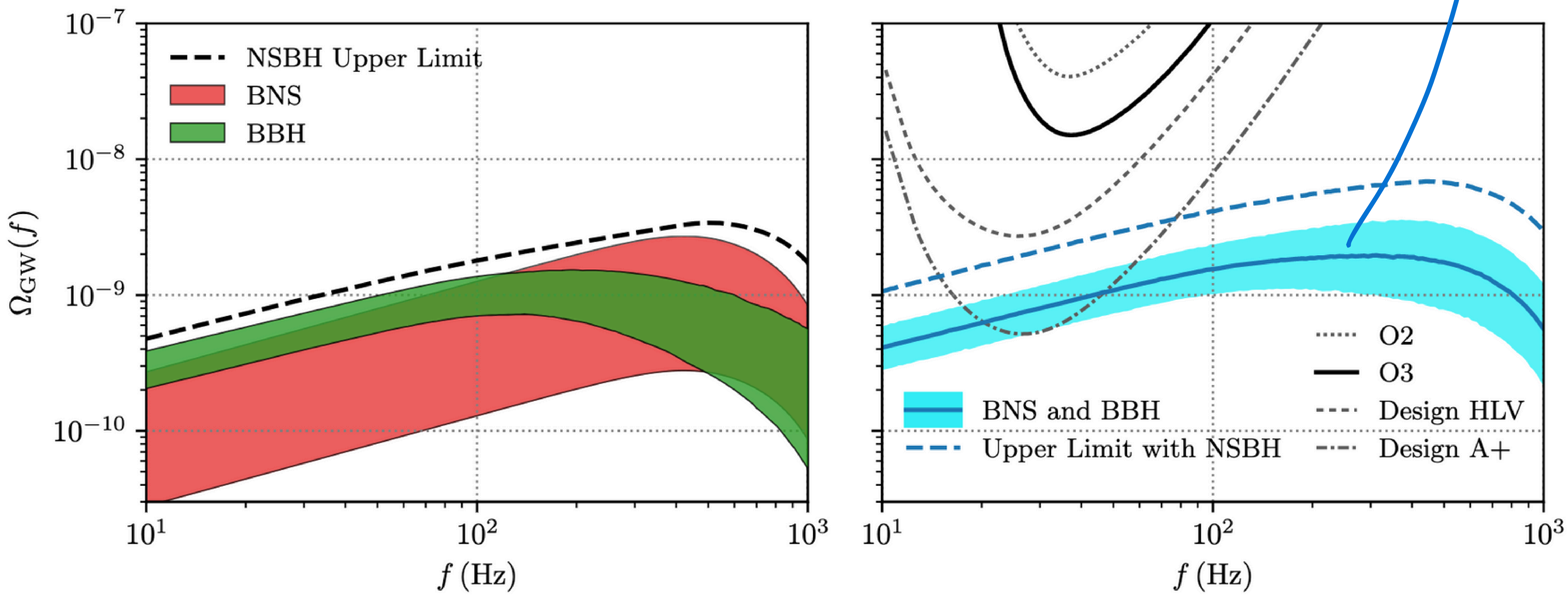
LVK results – astrophysical implications



R. Abbott et al. (LVK), Phys. Rev. D 104, 022004

LVK results – astrophysical implications

$$\Omega_{\mathrm{BBH+BNS}}(25\mathrm{Hz}) = 7.2^{+3.3}_{-2.3} \times 10^{-10}$$



R. Abbott et al. (LVK), Phys. Rev. D 104, 022004

LVK results – astrophysical implications

Detectable in A+?

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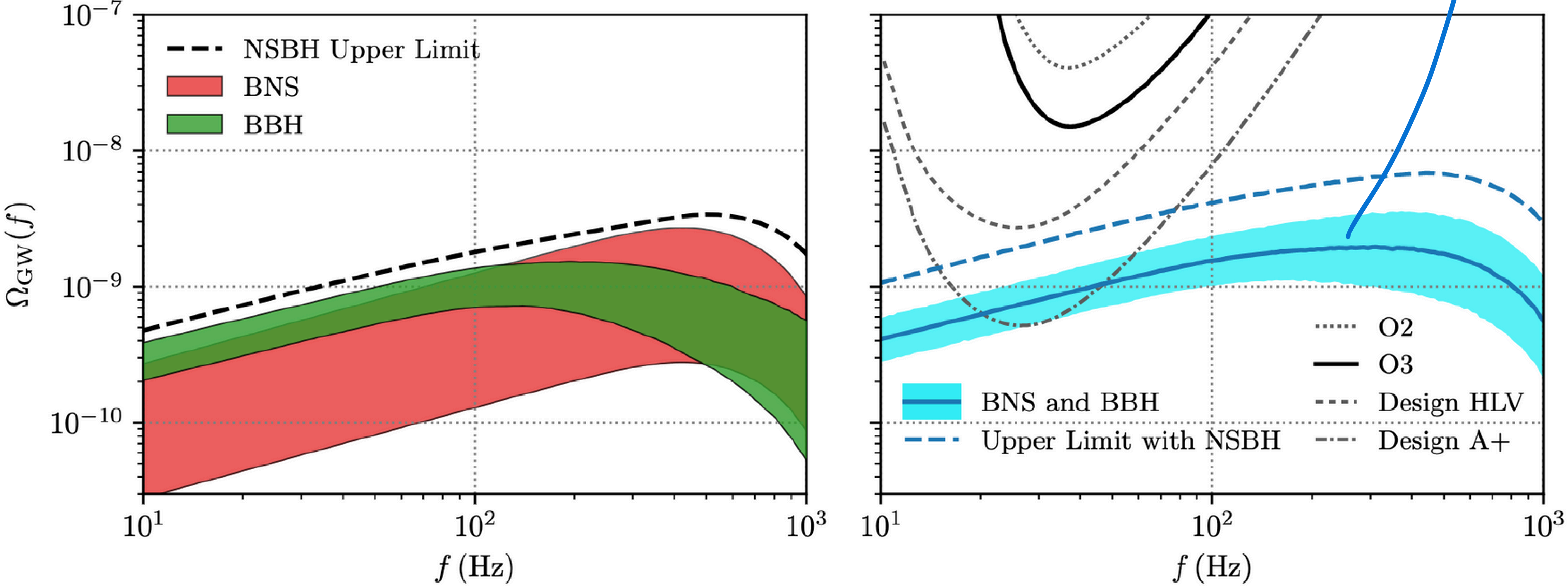
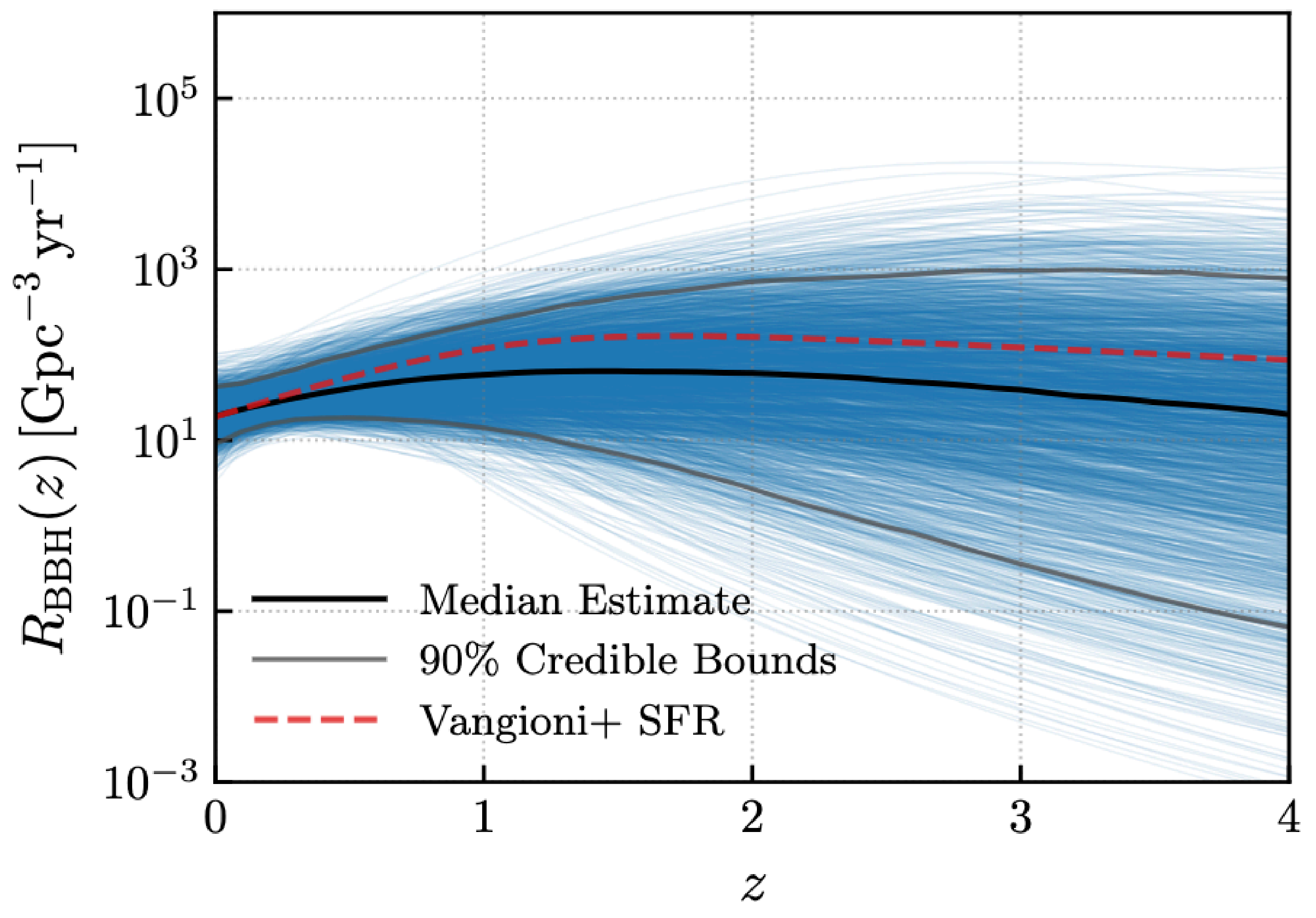


R. Abbott et al. (LVK), Phys. Rev. D 104, 022004

Constraints on the CBC merger rate

UL on the BBH merger rate beyond z ≃ 2 at 90% credibility:

$$\sim 10^3\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$



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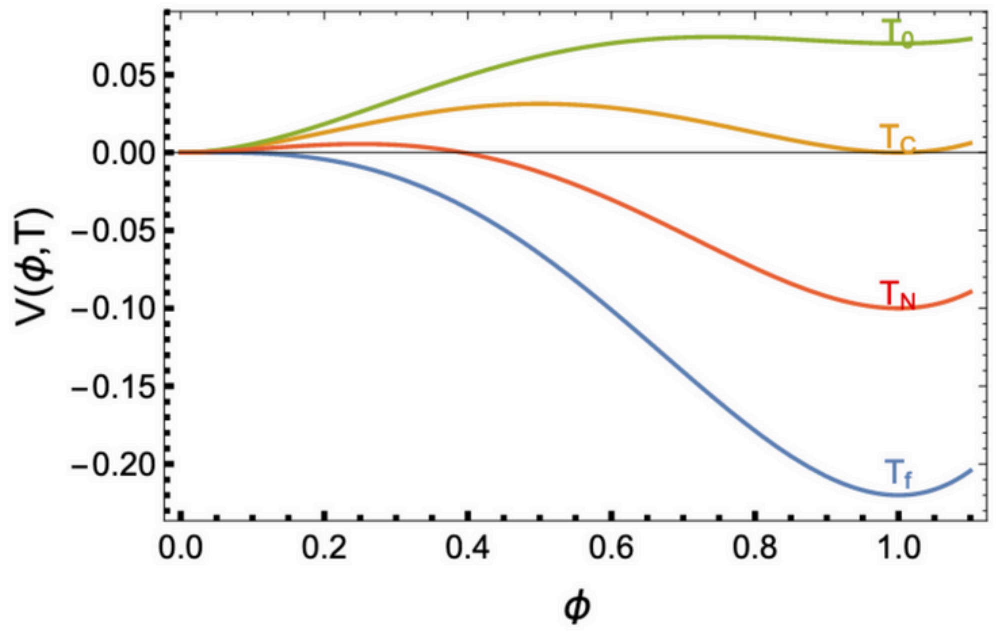
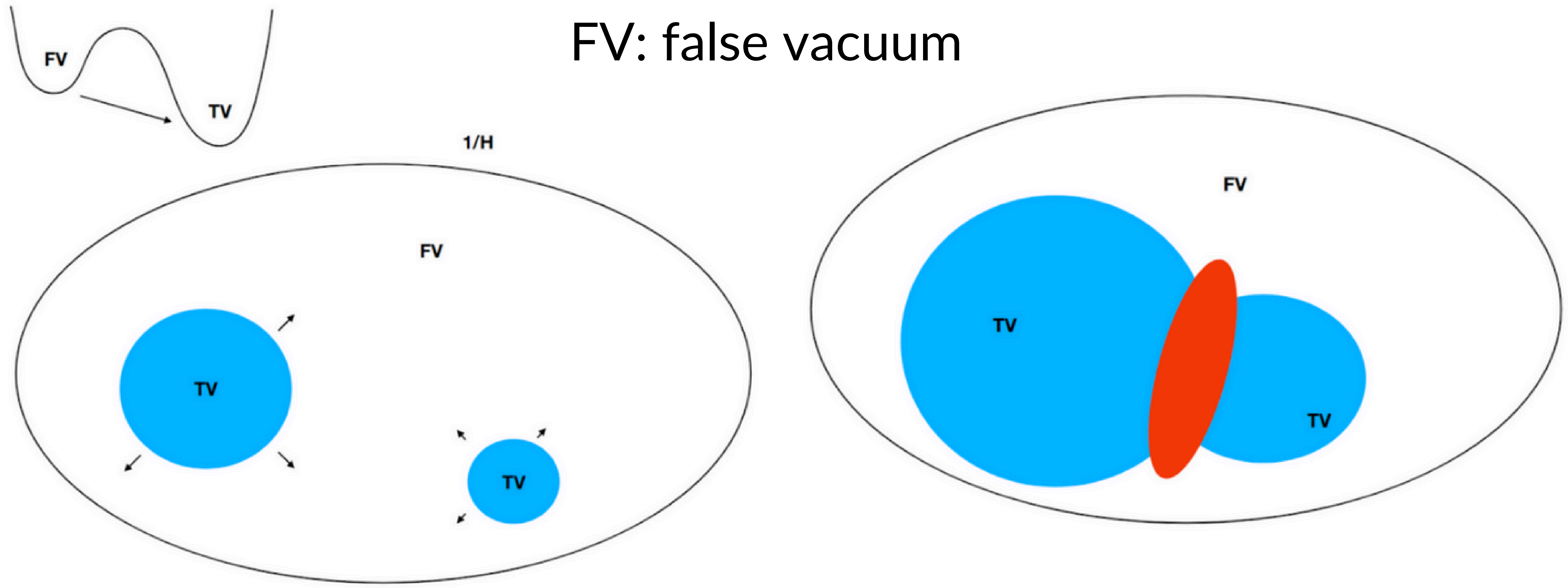
Implications on FOPTs

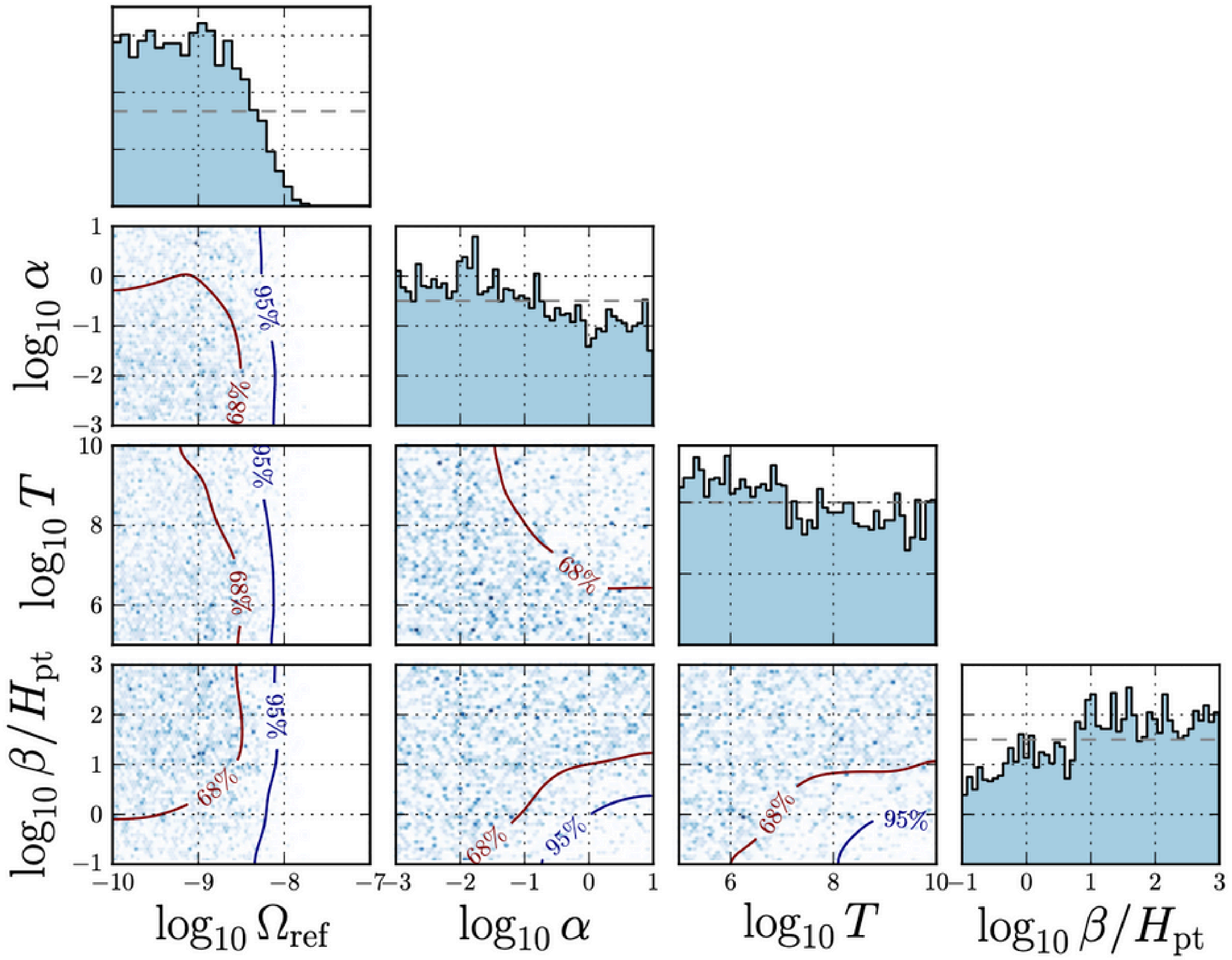


TV: true vacuum
FV: false vacuum



Implications on FOPTs

- Nucleation temperature: T_{pt}
- Inverse duration of the transition: β/H_{pt}
- Strength of the FOPT: α
- Bubble wall velocity: vw = c



ARR et. al., Phys. Rev. Lett. 126, 151301

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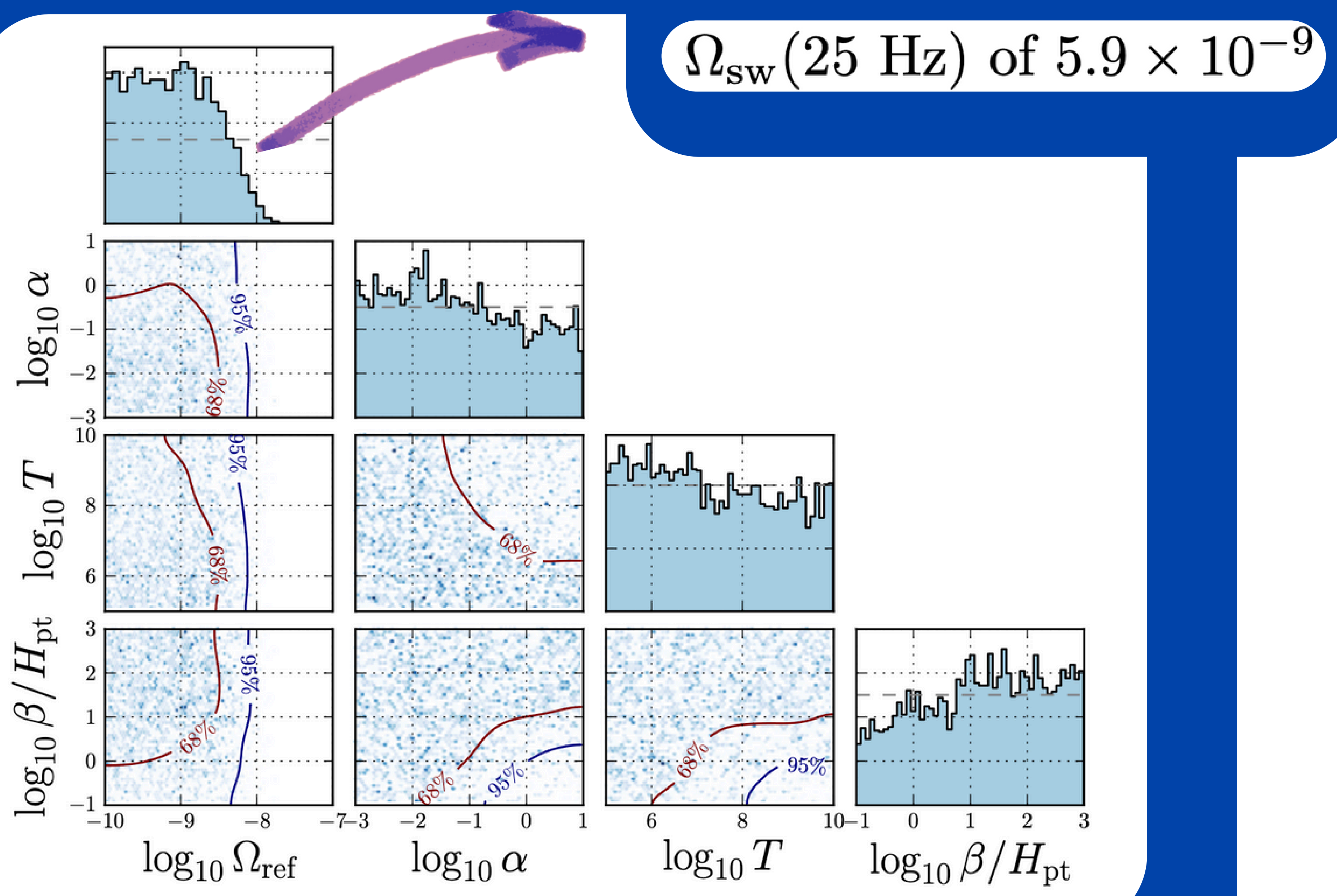

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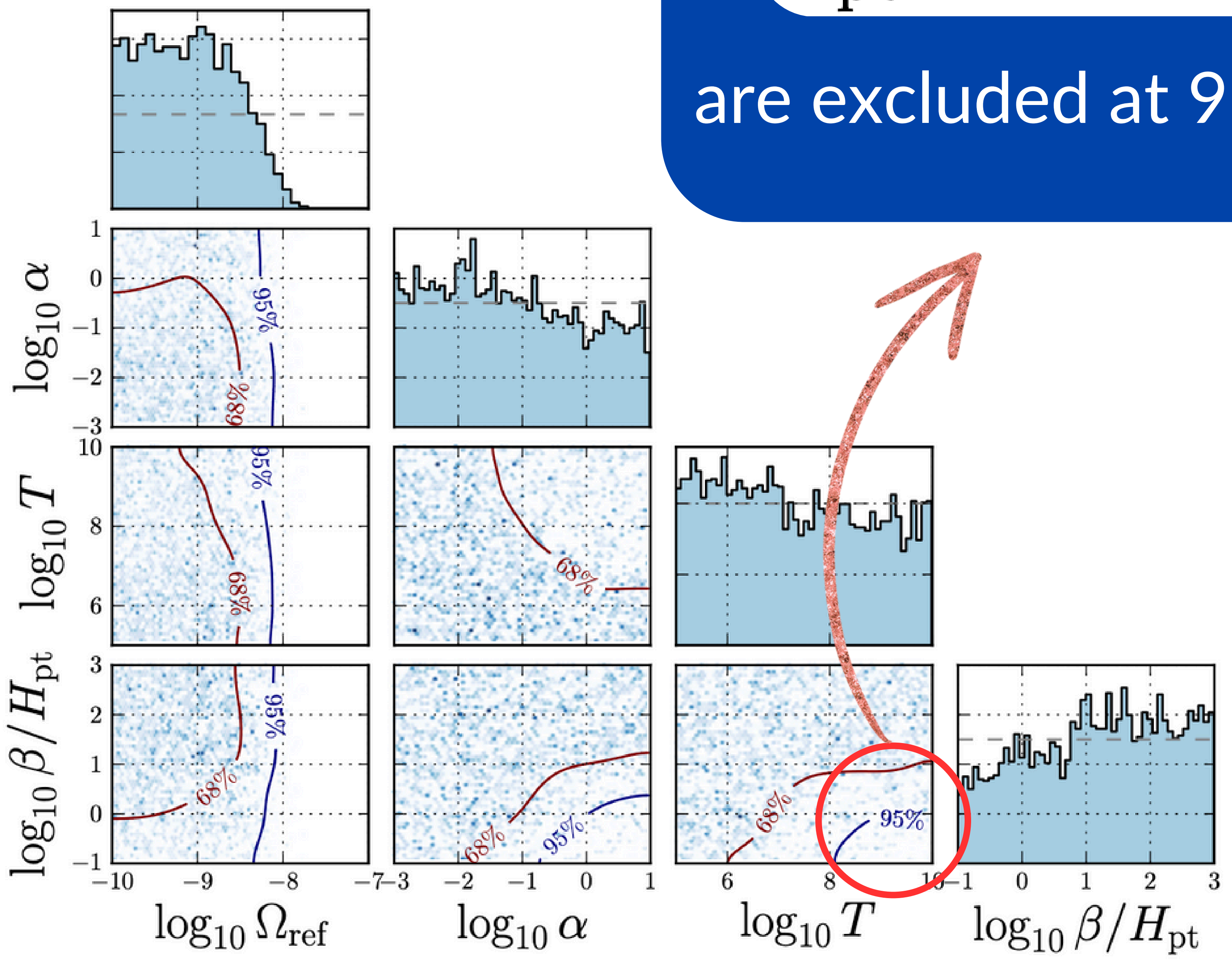


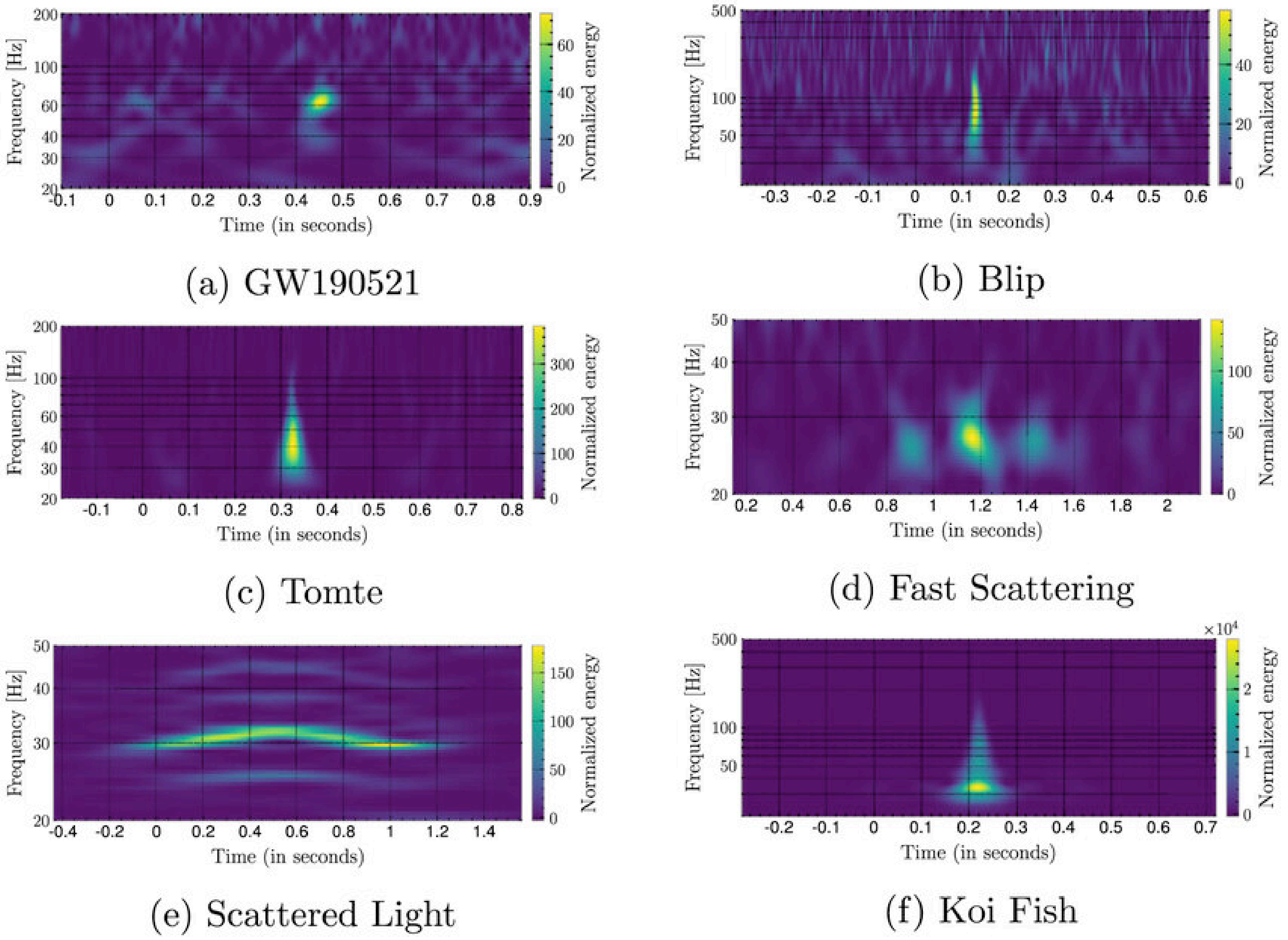
$T_{\rm pt} > 10^8$ GeV

are excluded at 95% CL

ARR et. al., Phys. Rev. Lett. 126, 151301

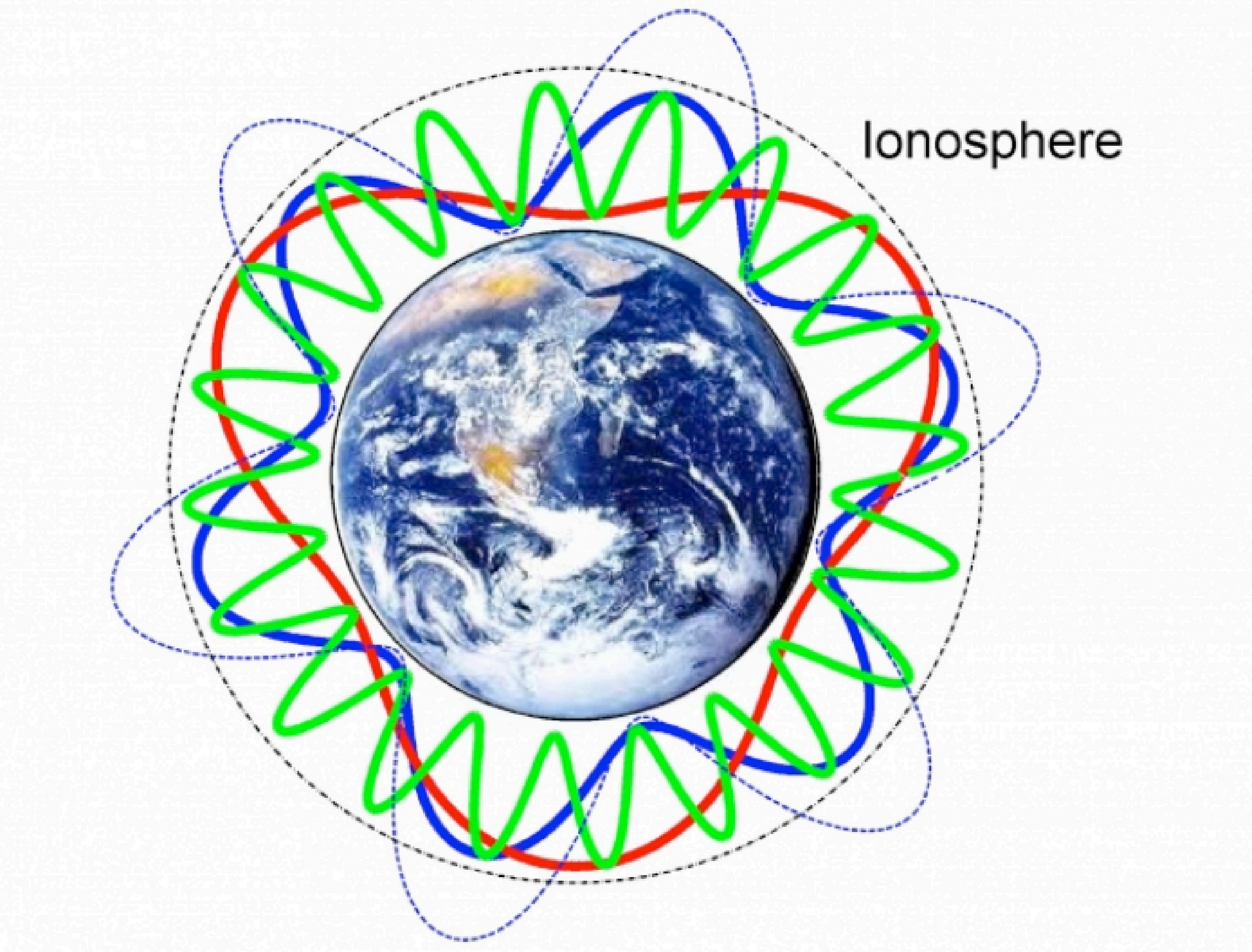
Challenges in LVK

- Data are not stationary nor Gaussian: glitches



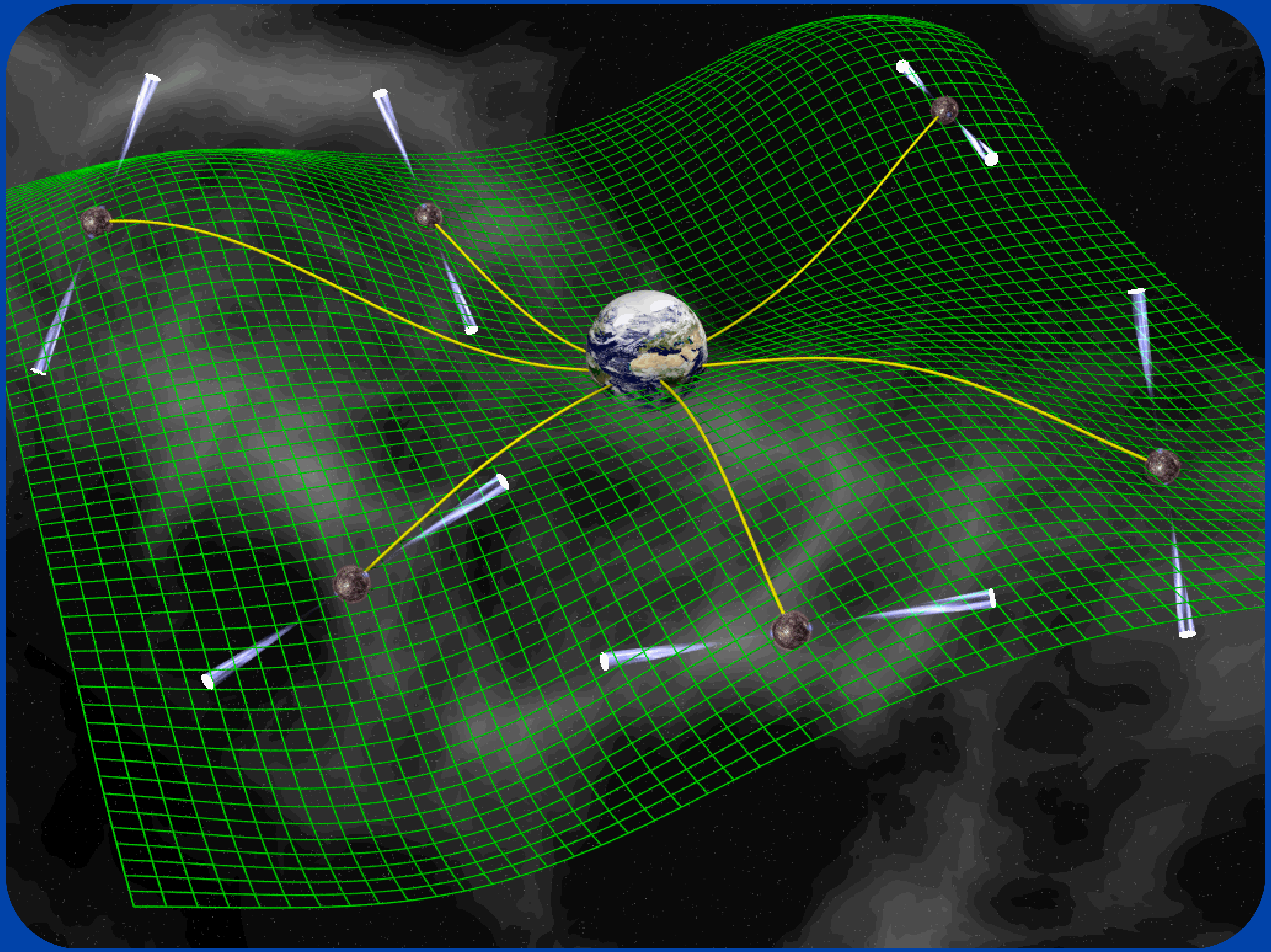
Challenges in LVK

- Data are not stationary nor Gaussian: glitches
- Correlated magnetic noise
  - Electronic mains
  - Synchronisation to GPS
  - Schumann resonances



Other experiments and future

Pulsar timing arrays



Other experiments and future

Pulsar timing arrays

THE ASTROPHYSICAL JOURNAL LETTERS

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The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

Gabriella Agazie[1], Akash Anumarlapudi[1], Anne M. Archibald[2], Zaven Arzoumanian[3], Paul T. Baker[4], Bence Bécsy[5], Laura Blecha[6], Adam Brazier[7,8], Paul R. Brook[9], Sarah Burke-Spolaor[10,11] Show full author list

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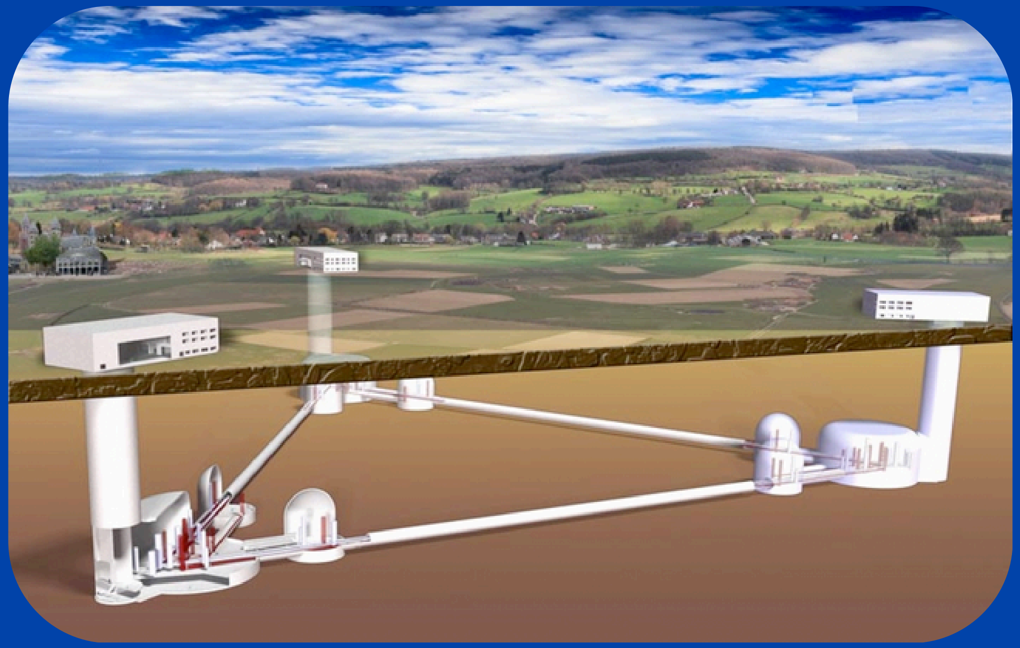
Focus on NANOGrav's 15 yr Data Set and the Gravitational Wave Background

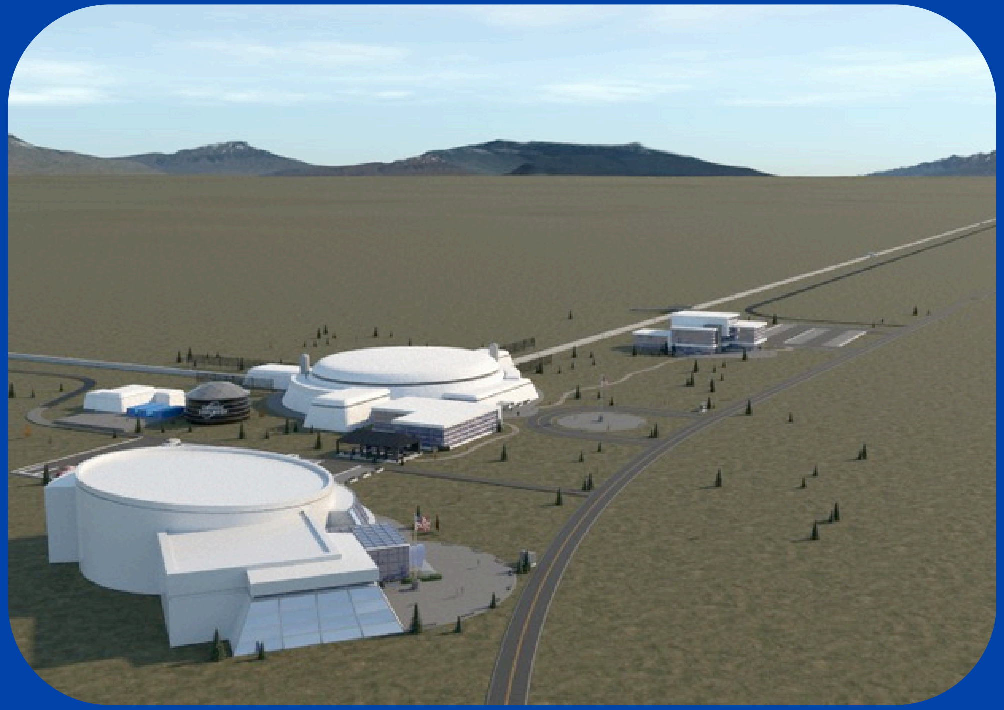
Citation Gabriella Agazie *et al* 2023 *ApJL* **951** L8

DOI 10.3847/2041-8213/acdac6

Other experiments and future

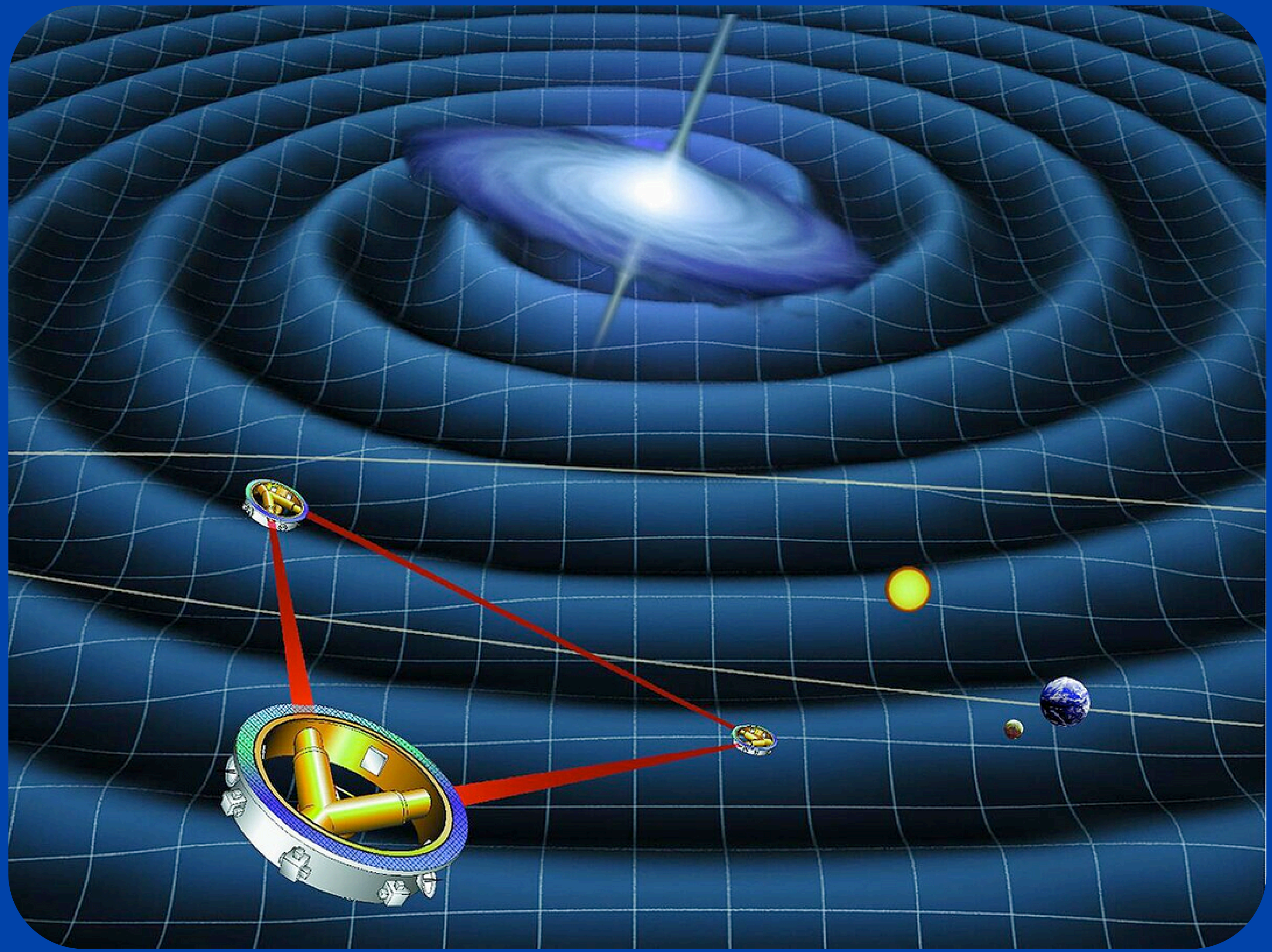
Einstein Telescope (ET) and Cosmic Explorer (CE)



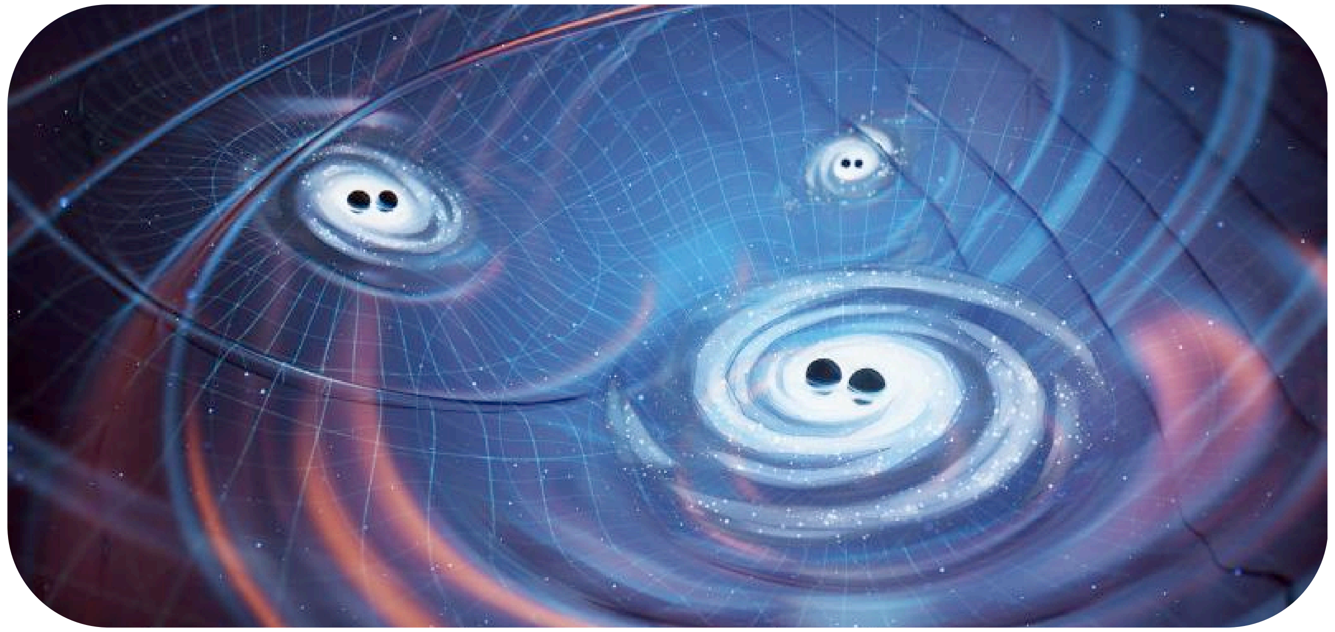


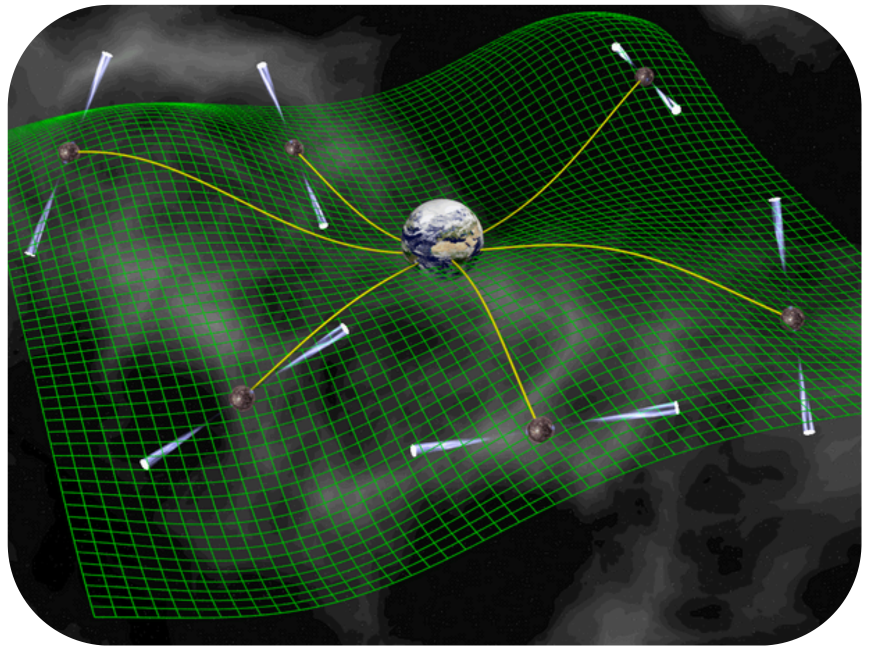
Other experiments and future

LISA

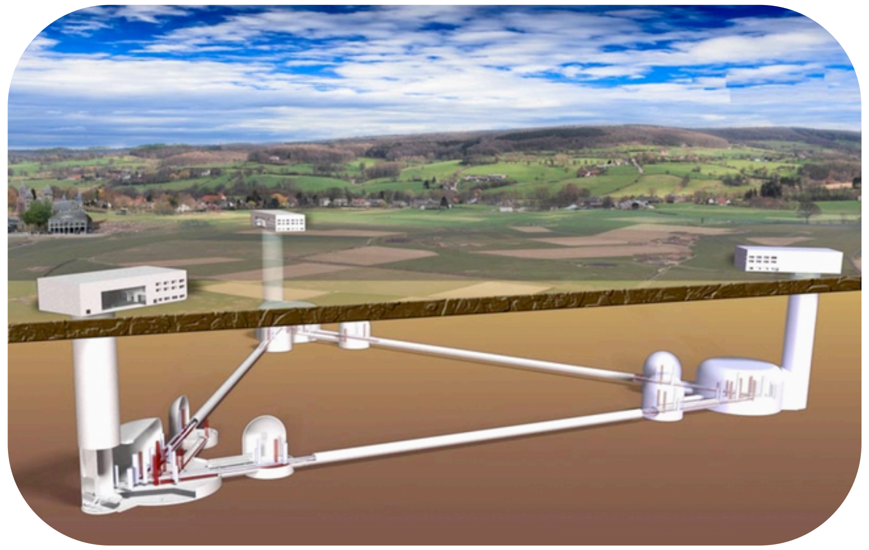


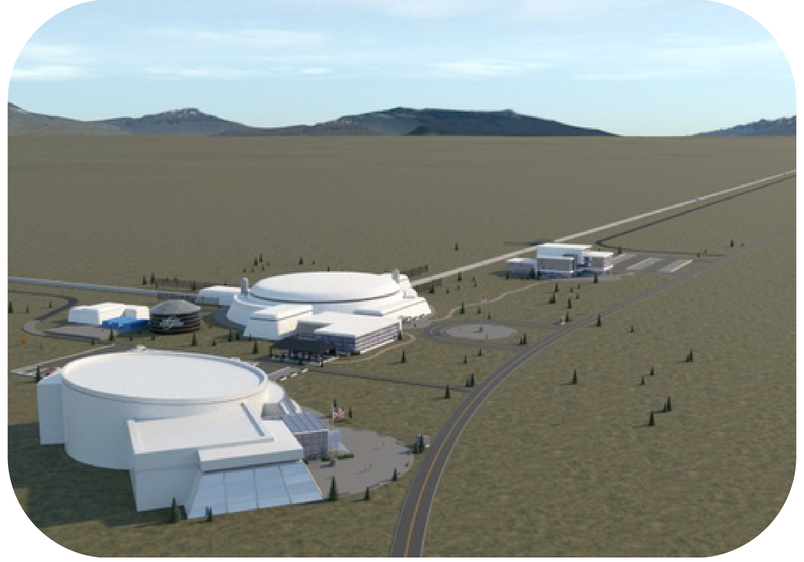
Summary

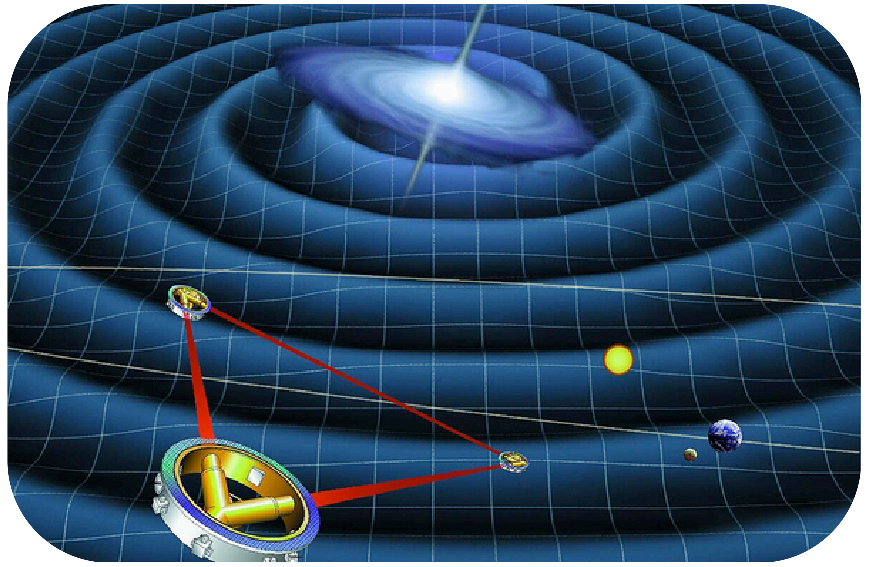




- Gravitational wave background (GWB) provides info. as early as 10-30 s after Big Bang
- Many challenges to detect it
- No evidence for a GWB at LVK
- Evidence for a GWB in Nanograv
- Bright future ahead







BACKUP

Narrowband/broadband analysis

Cross spectral density

$$C_{12}(f) := \frac{2}{T} s_1^*(f) s_2(f')$$

Cross-correlation estimator

$$\hat{Y}_f = \frac{\mathrm{Re}[C_{12,f}]}{\gamma_{12}(f) S_0(f)}$$

Variance

$$\sigma^2_{\hat{Y}_f} = \frac{1}{2T\Delta f} \frac{P_{1,f} P_{2,f}}{\gamma^2_{12}(f) S^2_0(f)}$$

Broadband analysis

$$\hat{Y} := \frac{\sum_f H^2(f) \sigma^{-2}_{\hat{Y}_f} \hat{Y}_f}{\sum_f H^2(f) \sigma^{-2}_{\hat{Y}_f}},$$

$$\sigma^{-2}_{\hat{Y}} := \sum_f H^2(f) \sigma^{-2}_{\hat{Y}_f}.$$

Current LVK results

- Data from O1-O3
- H1, L1 and V1 data
- Frequency range: 20-1726Hz

Smaller uncertainty for α = 3

Power law	$f_{99\%}^{HL}$ [Hz]	$\hat{C}^{HL}/10^{-9}$	$f_{99\%}^{HV}$ [Hz]	$\hat{C}^{HV}/10^{-9}$	$f_{99\%}^{LV}$ [Hz]	$\hat{C}^{LV}/10^{-9}$	$f_{99\%}^{O1+O2+O3}$ [Hz]	$\hat{C}^{O1+O2+O3}/10^{-9}$
0	76.1	-2.1 ± 8.2	97.7	229 ± 98	88.0	-134 ± 63	76.6	1.1 ± 7.5
2/3	90.2	-3.4 ± 6.1	117.8	145 ± 60	107.3	-82 ± 40	90.6	-0.2 ± 5.6
3	282.8	-1.3 ± 0.9	375.8	9.1 ± 4.1	388.0	-4.9 ± 3.1	291.6	-0.6 ± 0.8

Current LVK results

Upper limits at 95% CL

	Log-uniform prior		
α	O3	O2 [43]	Improvement
0	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	3.4×10^{-9}	3.0×10^{-8}	8.8
3	3.9×10^{-10}	5.1×10^{-9}	13.1
Marg.	6.6×10^{-9}	3.4×10^{-8}	5.1

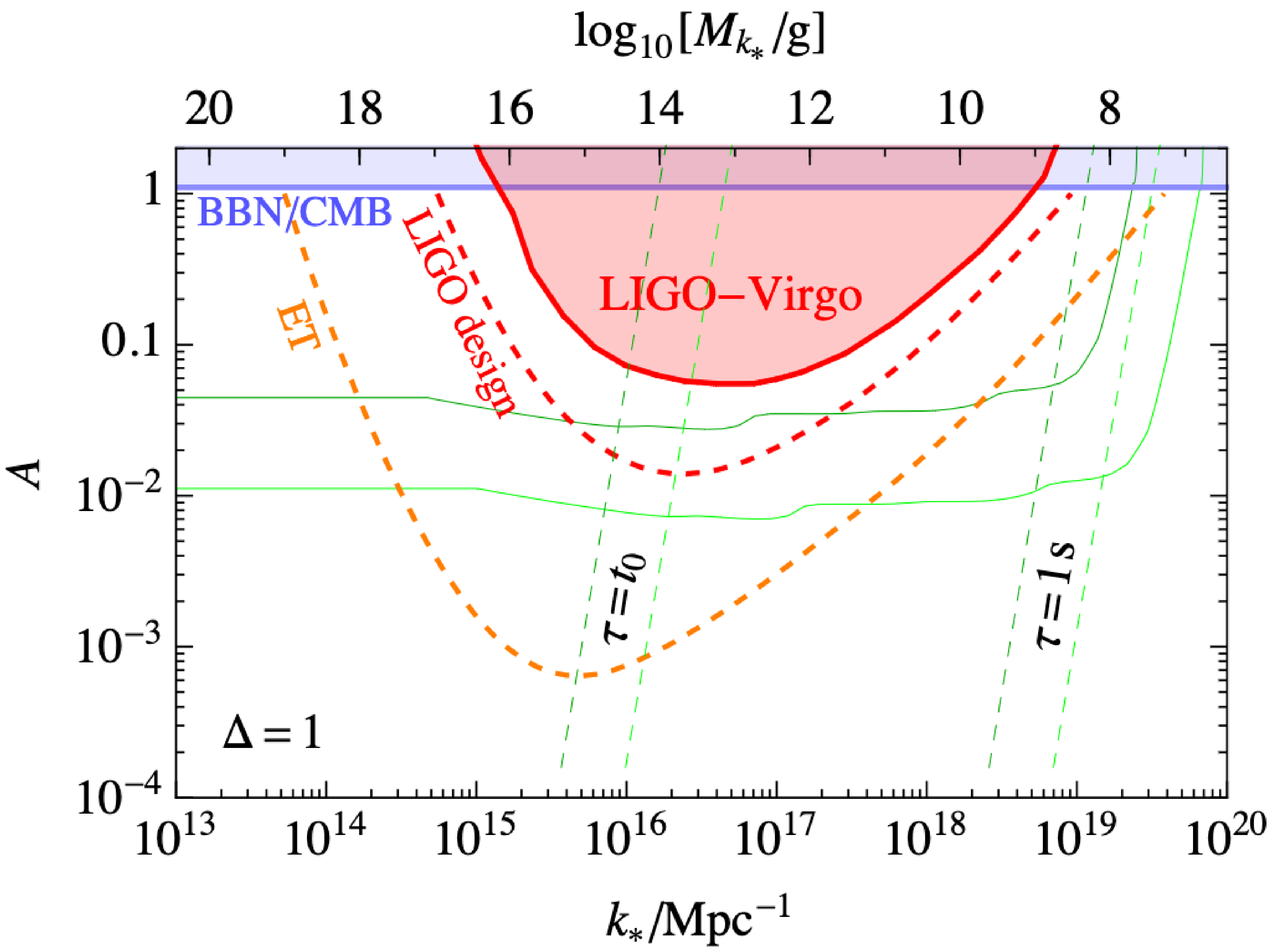
Best improvement for α = 3 :

- Signal recycling
- Addition of V1?

Implications on the formation of PBHs

Formation of PBHs from inflationary fluctuations is accompanied by a scalar induced GWB

$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$



ARR et al., Phys. Rev. Lett. 128, 051301

LVK results astrophysical implications

$$\Omega_{\mathrm{Total}}(25\,\mathrm{Hz}) \leq 1.9 \times 10^{-9}$$