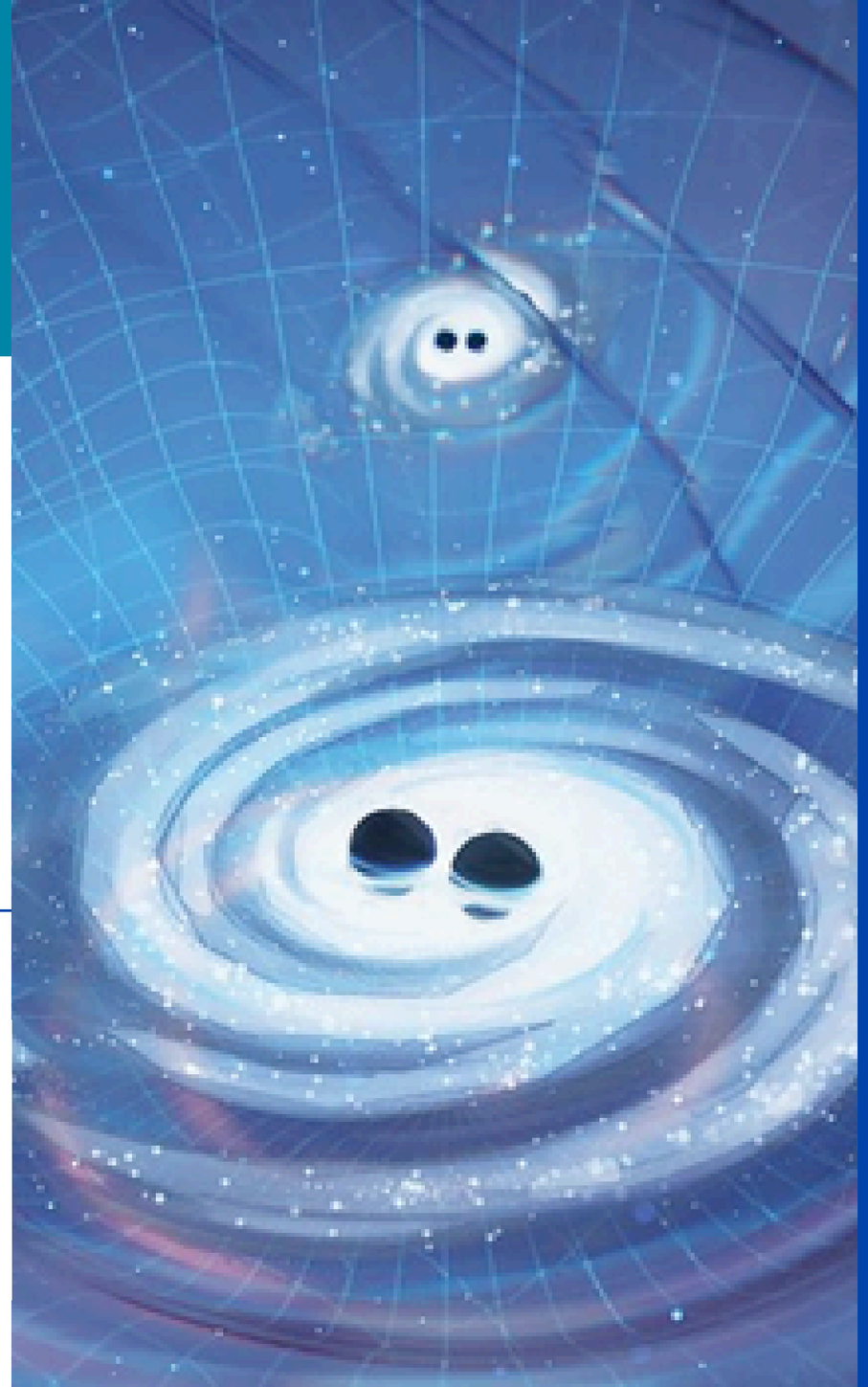
TAUP 2025

19TH INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS

Gravitational wave background: LVK analysis, implications and challenges



Presented By

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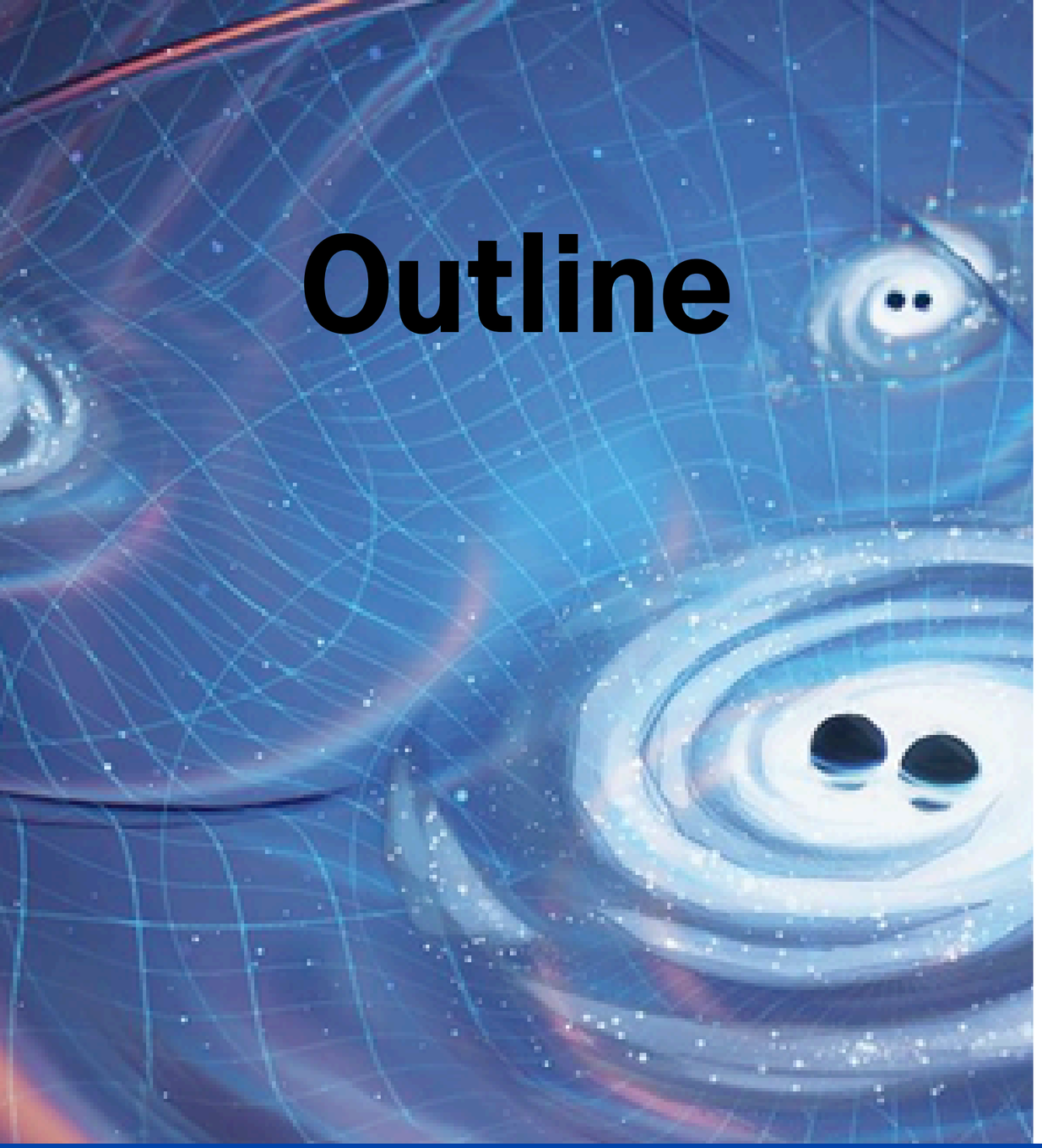
Laboratoire d'Annecy de Physique des Particules

TAUP 2025

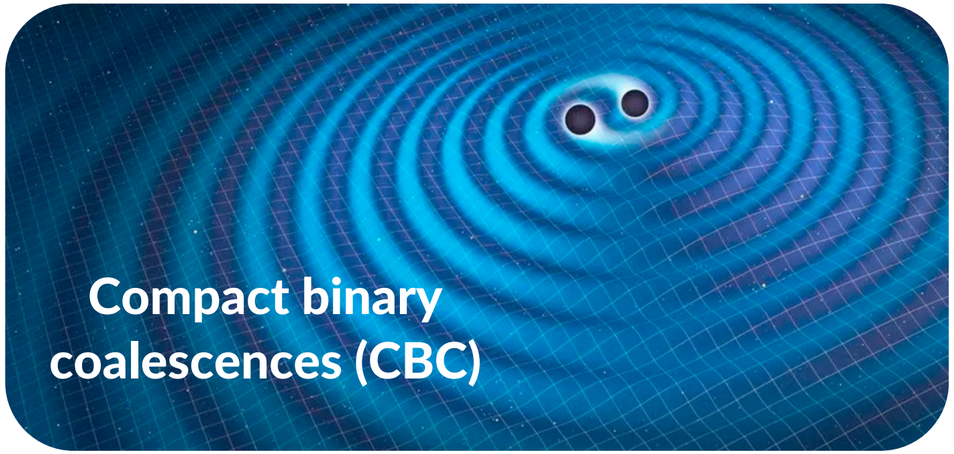
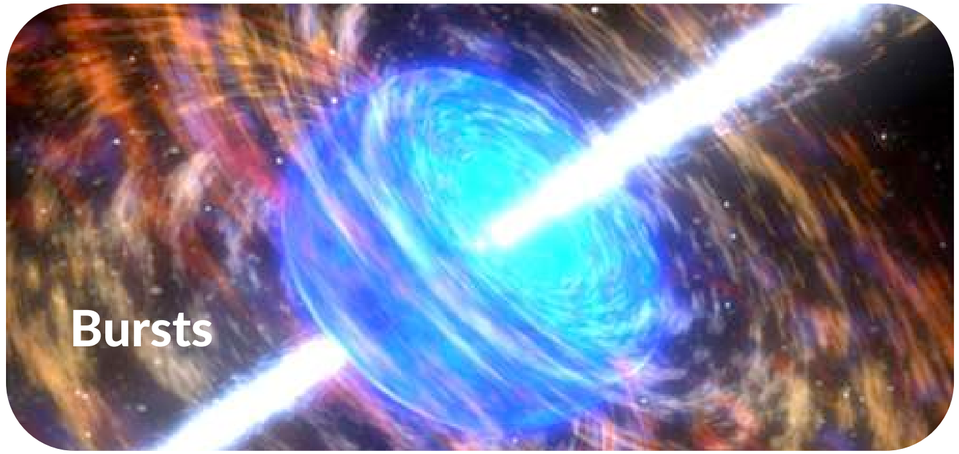
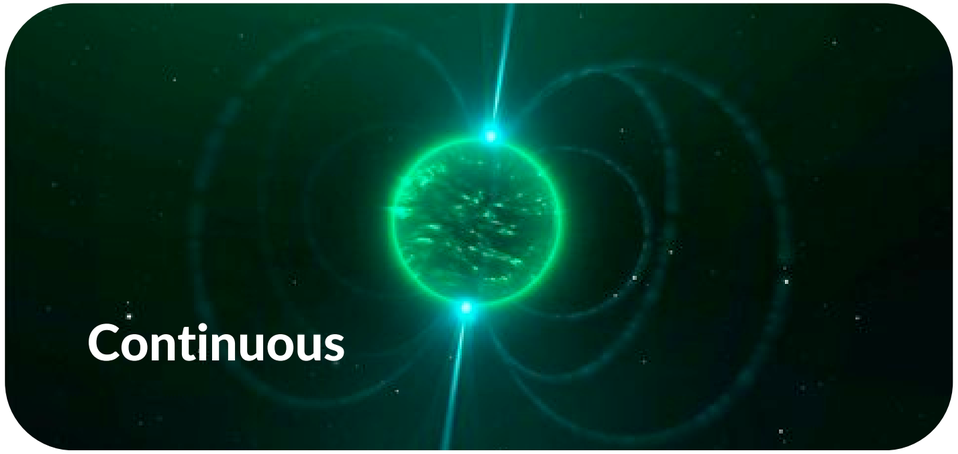
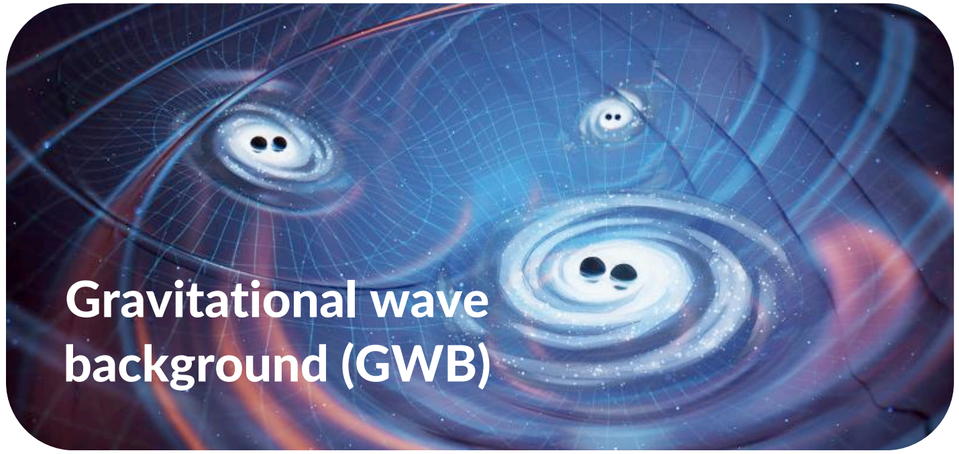
27th of August 2025



Outline

1. Gravitational wave background (GWB)
2. LIGO-Virgo-KAGRA collaborations (LVK) search for an isotropic GWB
3. Current LVK results on the isotropic search for a GWB
4. Implications on cosmological sources to the GWB
5. Analysis challenges in LVK
6. Future analysis challenges

Sources of GWs

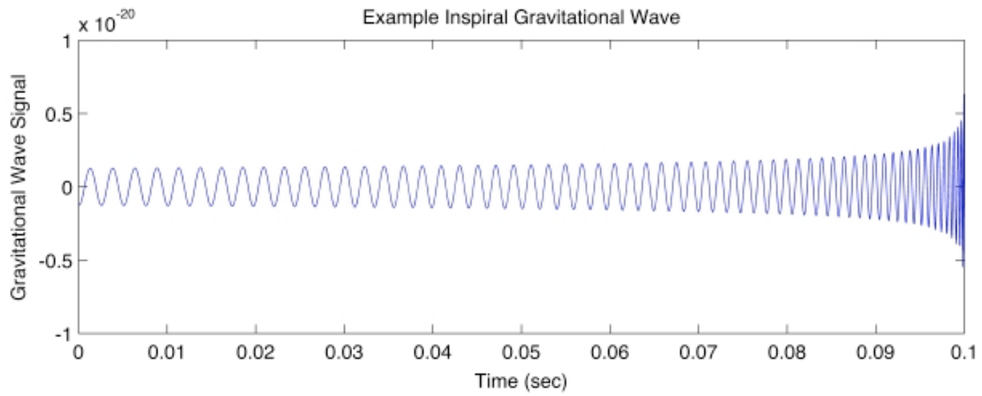
	Modelled	Unmodelled
Short duration		
Long duration		

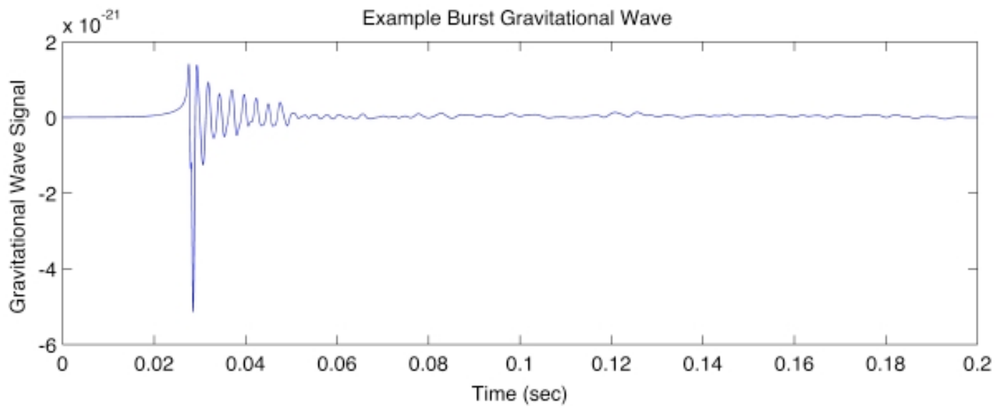
Sources of GWs

Modelled

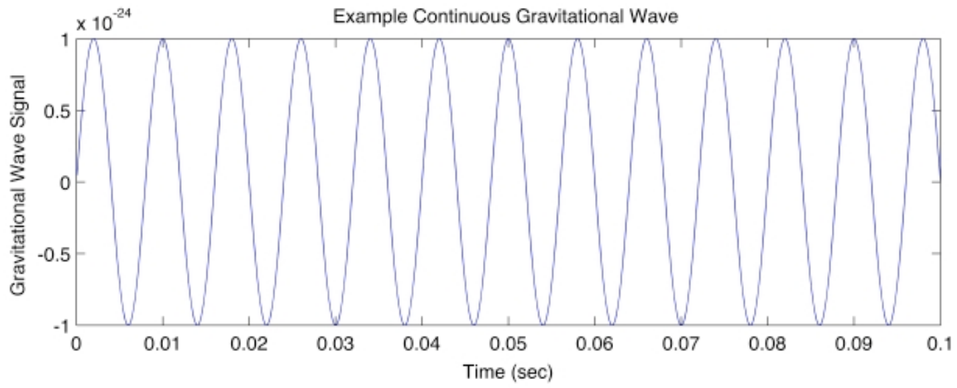
Unmodelled

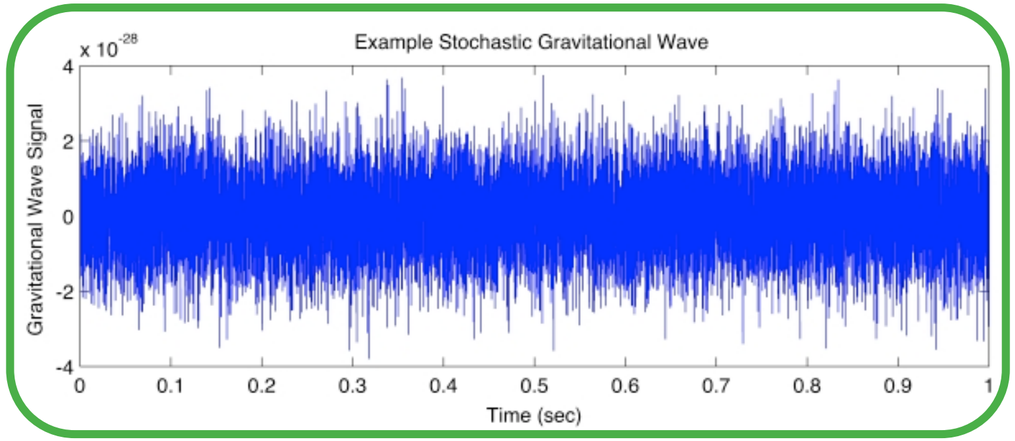
Short duration





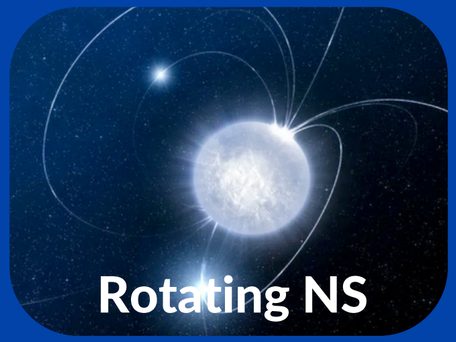
Long duration

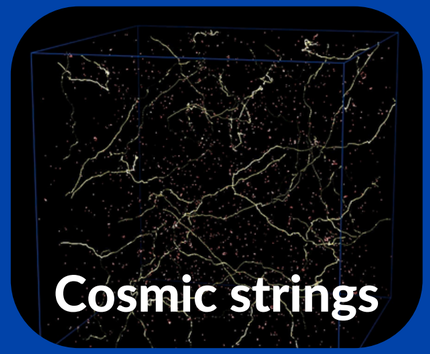


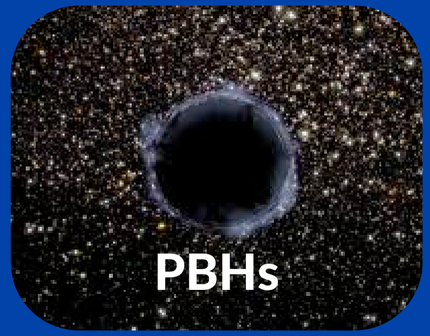


Gravitational wave background

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







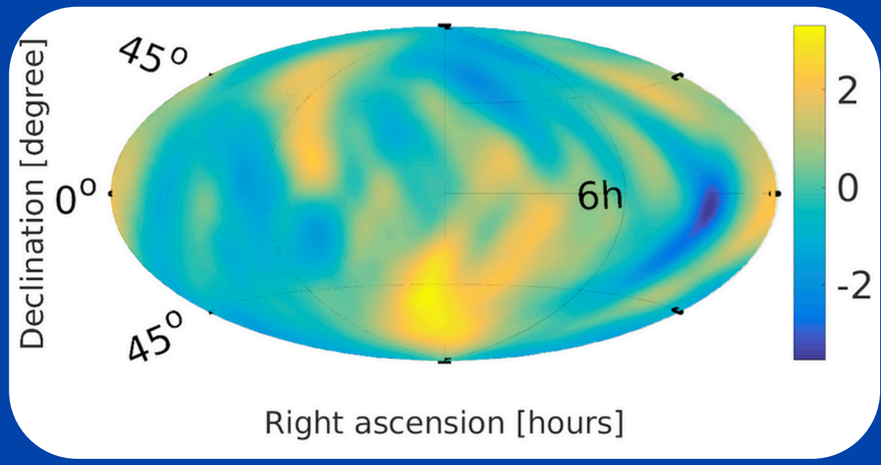
GWB characterization

- 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



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

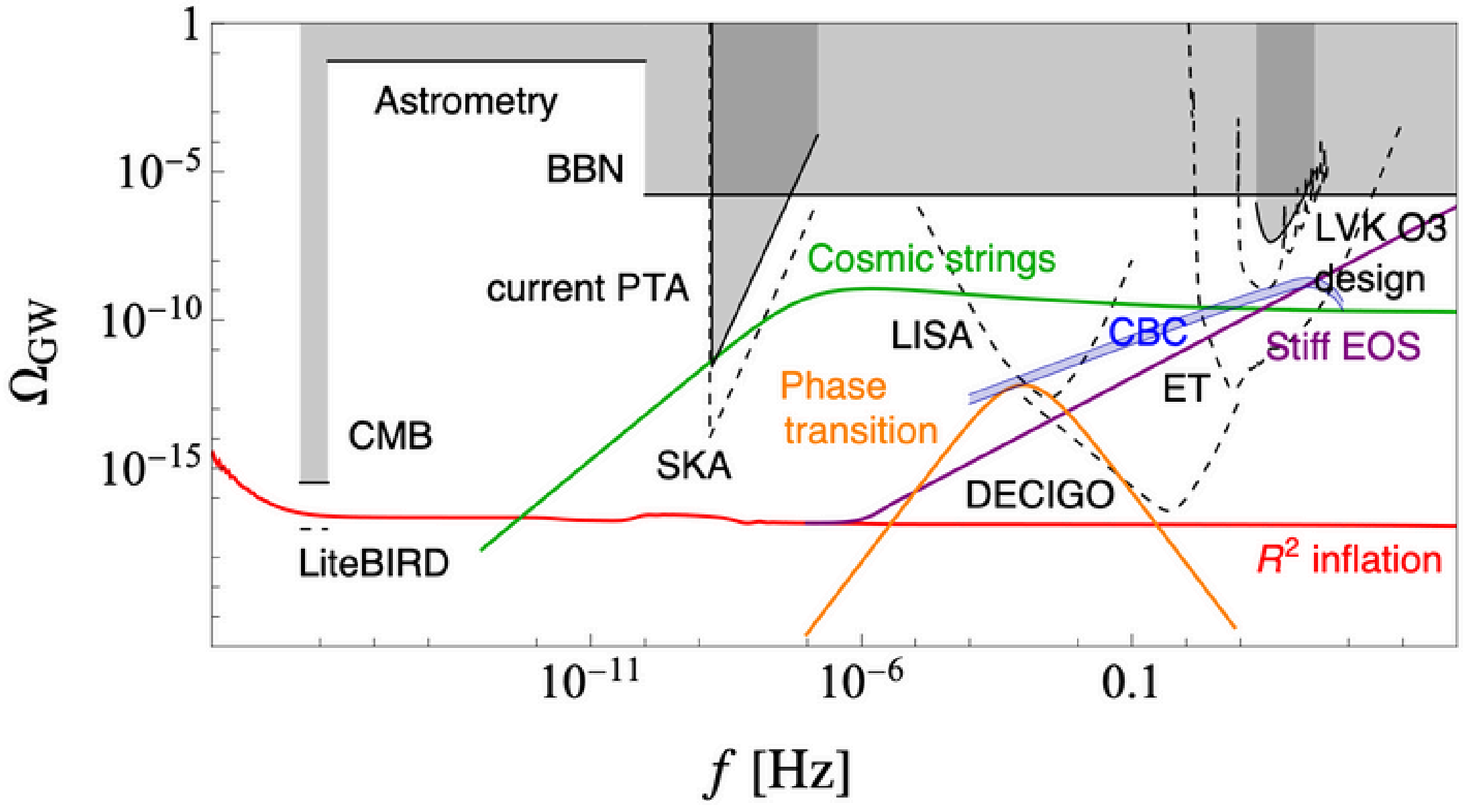
GWB characterization

Fractional energy density spectrum in GWs

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

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

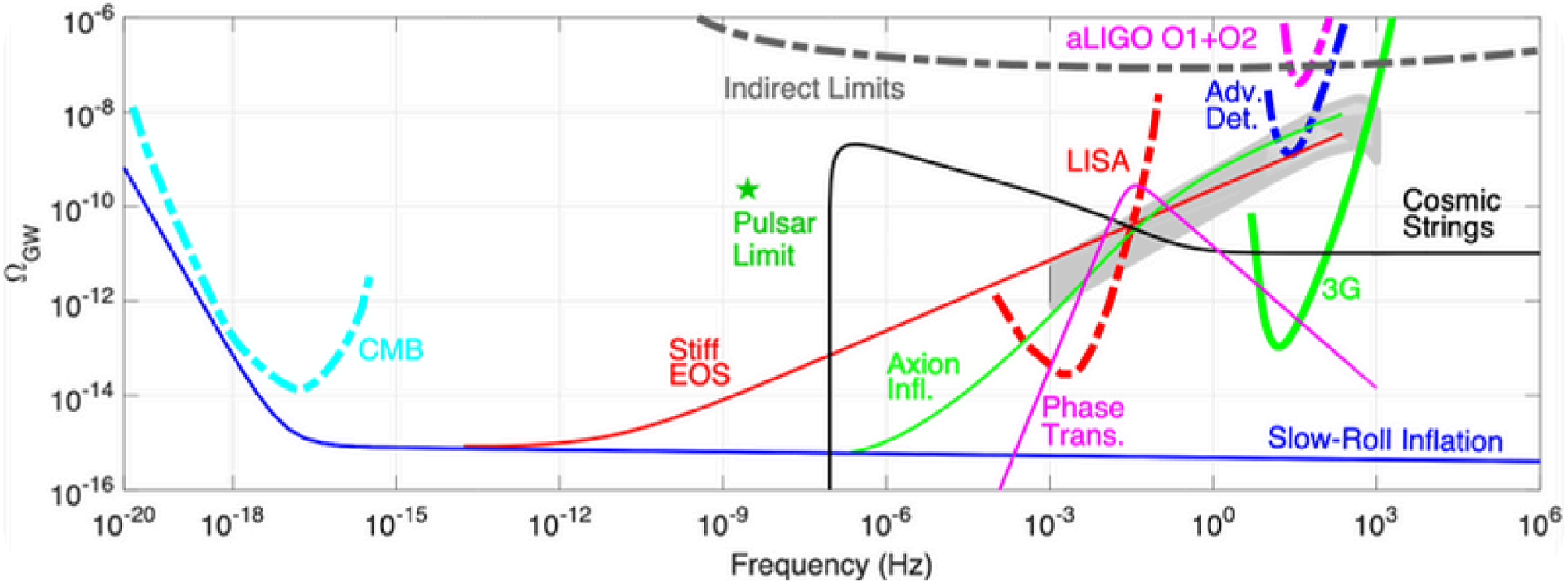
$$\Omega_{\rm GW}(f) = \frac{2\pi^2}{3H_0^2} f^3 S_h(f)$$



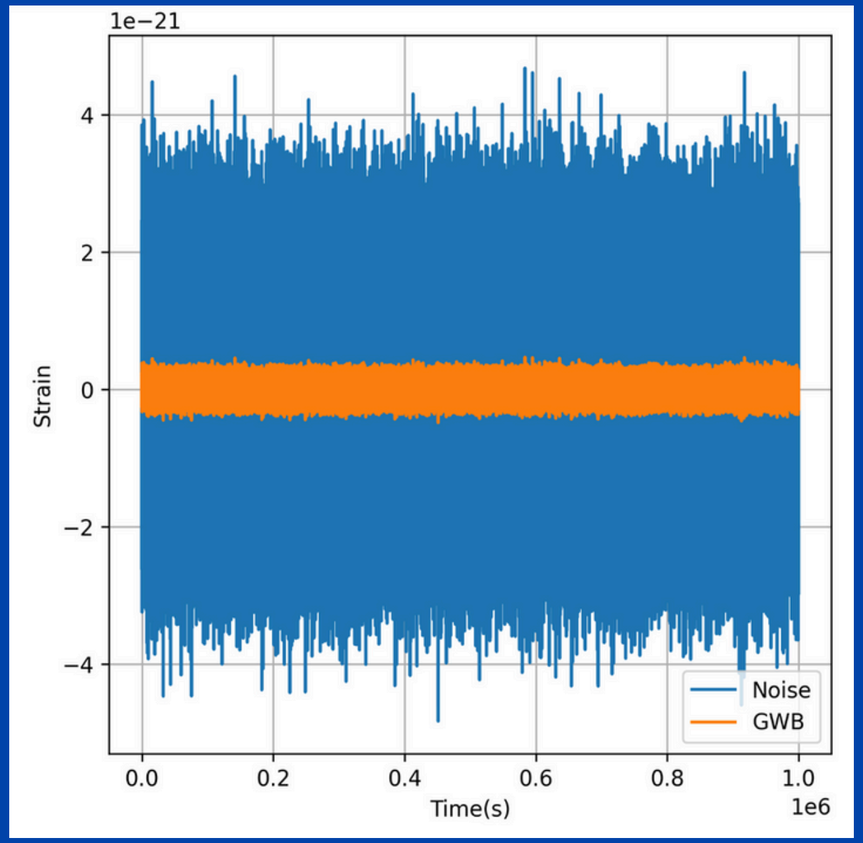
ARR, and S. Kuroyanagi. 2024. *Primordial Black Holes*. Chap. 27. Springer (link). Arxiv: https://doi.org/10.48550/arXiv.2407.00205.

LVK search for an isotropic GWB

Hybrid search → Frequentist
Hybrid search → Bayesian



LVK search for an isotropic GWB

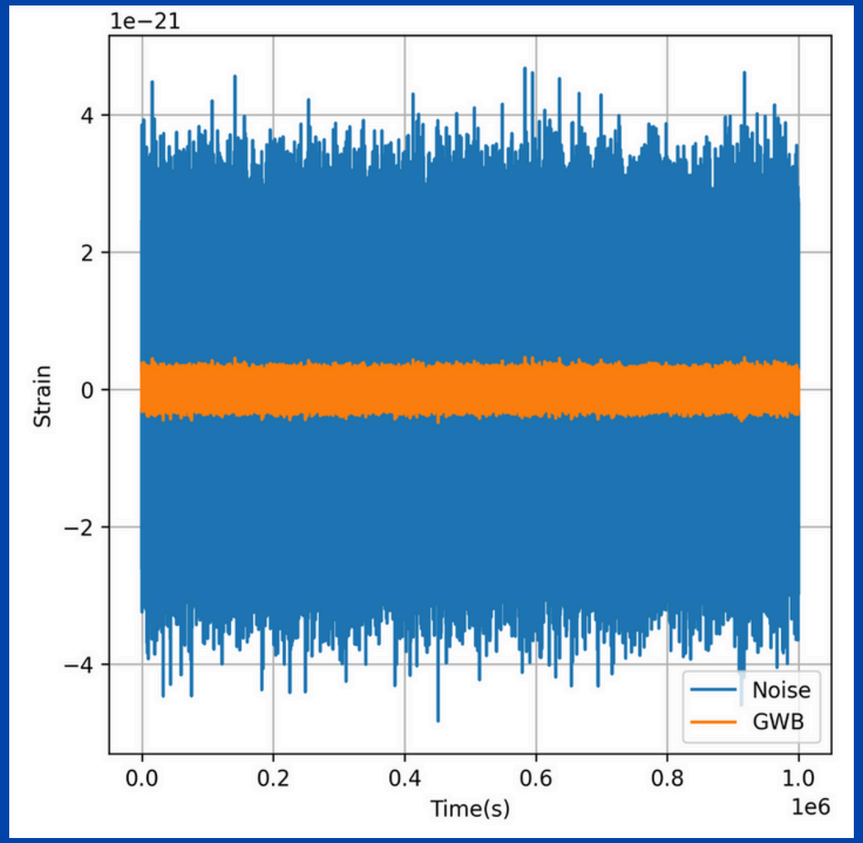


Cross correlation search

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

$$\left\langle s_1^*(f)\, s_2(f') \right\rangle$$

LVK search for an isotropic GWB



Cross correlation search

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

$$\langle s_1^*(f)\, s_2(f') \rangle$$

$$\langle n_i^*(f)\, h_j(f') \rangle = 0$$

$$\langle n_i^*(f)\, n_j(f') \rangle = \delta_{ij}$$

LVK search for an isotropic GWB

$$\langle s_1^*(f) s_2(f') \rangle$$

Cross correlation estimator and variance

$$\hat{C}^{IJ}(f) = \frac{2}{T} \frac{\mathrm{Re}[\tilde{s}_I^\star(f)\tilde{s}_J(f)]}{\gamma_{IJ}(f) S_0(f)}$$

$$\sigma^2_{IJ}(f) \approx \frac{1}{2T\Delta f} \frac{P_I(f) P_J(f)}{\gamma^2_{IJ}(f) S_0^2(f)}$$

LVK search for an isotropic GWB

Cross correlation spectrum (frequentist analysis)

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T : observation time

LVK search for an isotropic GWB

Cross correlation spectrum (frequentist analysis)

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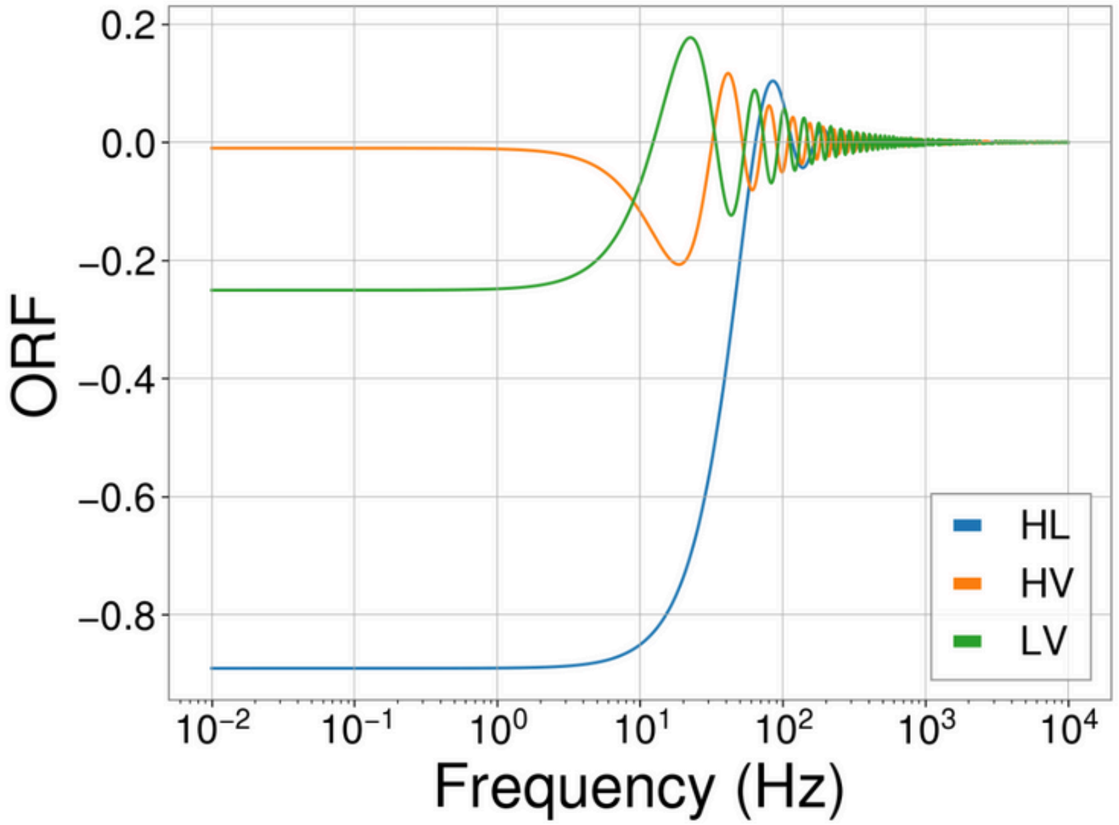
Overlap reduction function (ORF)



LVK search for an isotropic GWB

Cross correlation spectrum (frequentist analysis)

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$$\sigma^2_{IJ}(f) \approx \frac{1}{2T\Delta f}\frac{P_I(f)P_J(f)}{\gamma^2_{IJ}(f)S_0^2(f)}$$

$$S_0(f) = \frac{3H_0^2}{10\pi^2}\frac{1}{f^3}$$

LVK search for an isotropic GWB

Cross correlation spectrum (frequentist analysis)

$$\hat{C}^{IJ}(f) = \frac{2}{T}\frac{\mathrm{Re}[\tilde{s}_I^{\star}(f)\tilde{s}_J(f)]}{\gamma_{IJ}(f)S_0(f)}$$

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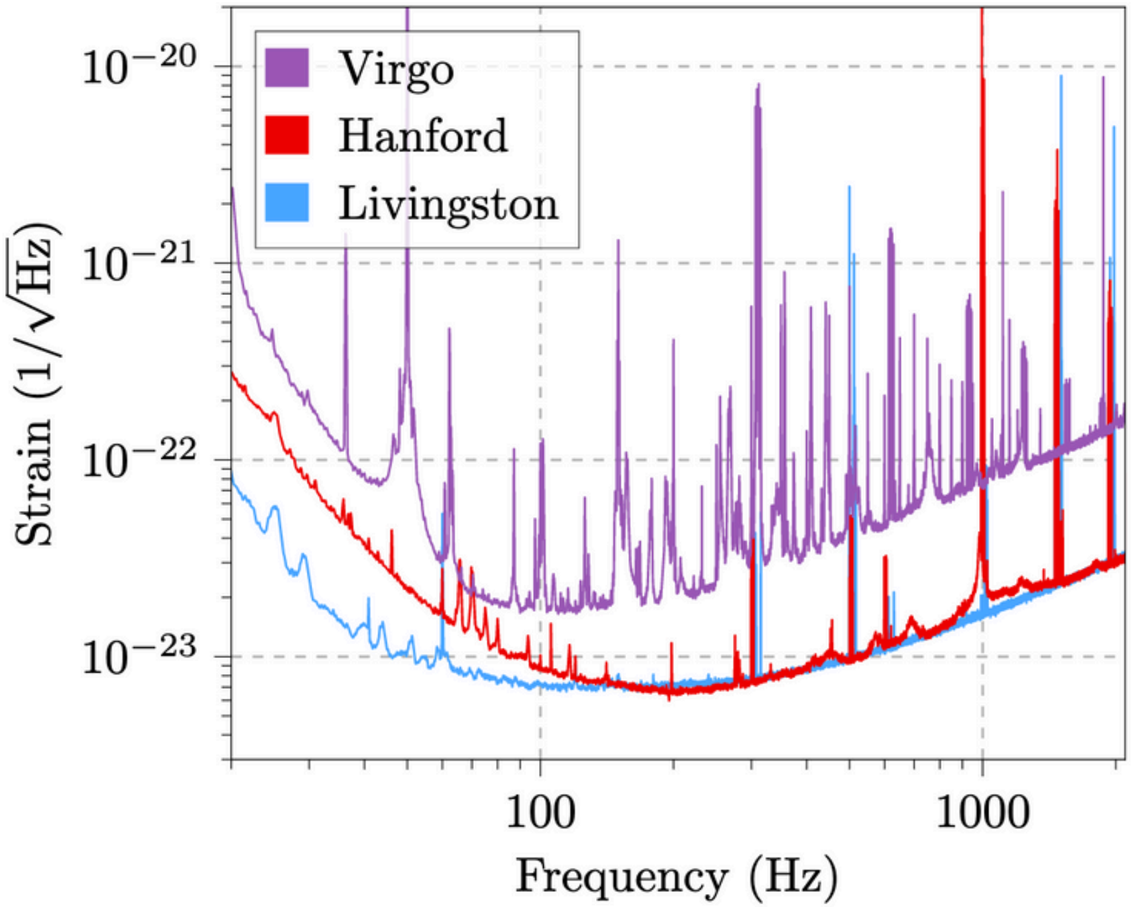
Noise power spectra



B. P. Abbott et al. (LVK), Phys. Rev. Lett. 119, 141101

LVK search for an isotropic GWB

Signal to noise ratio

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

LVK search for an isotropic GWB

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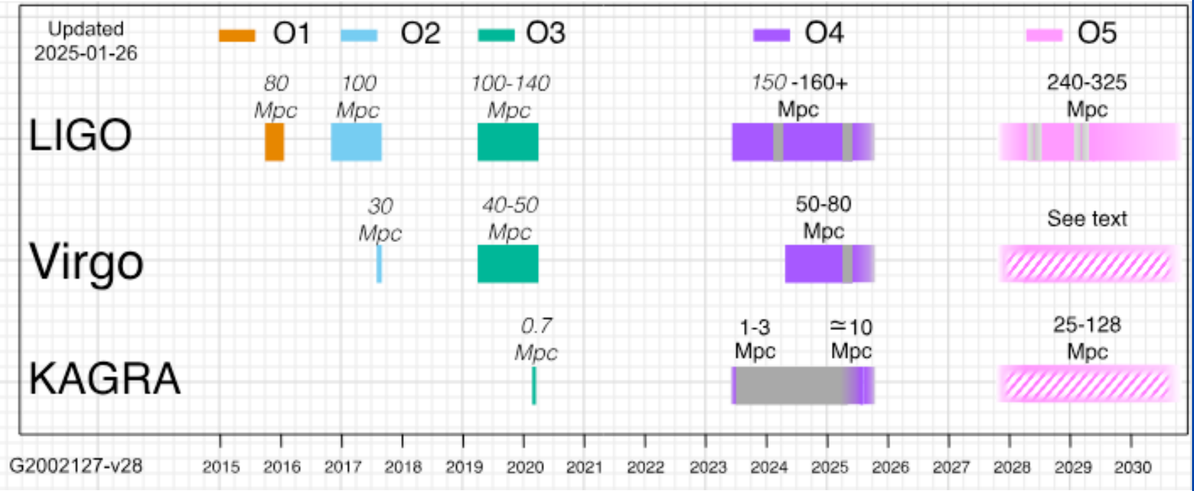

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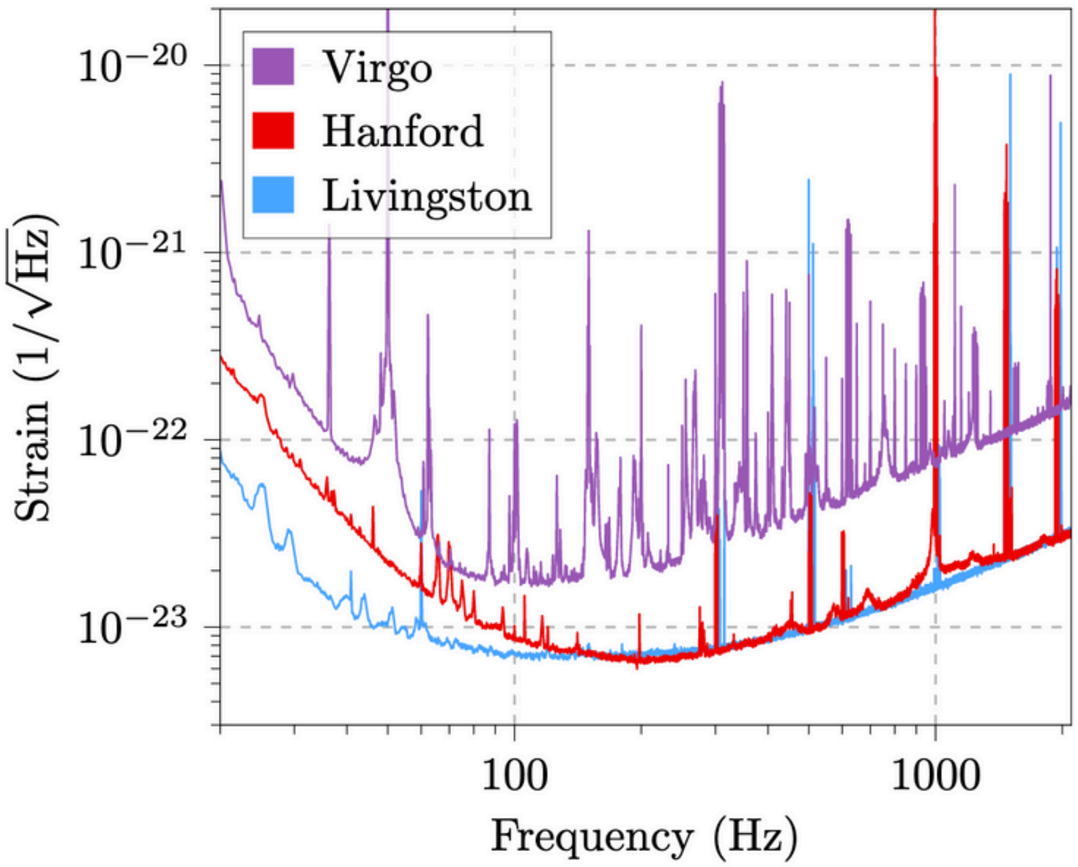

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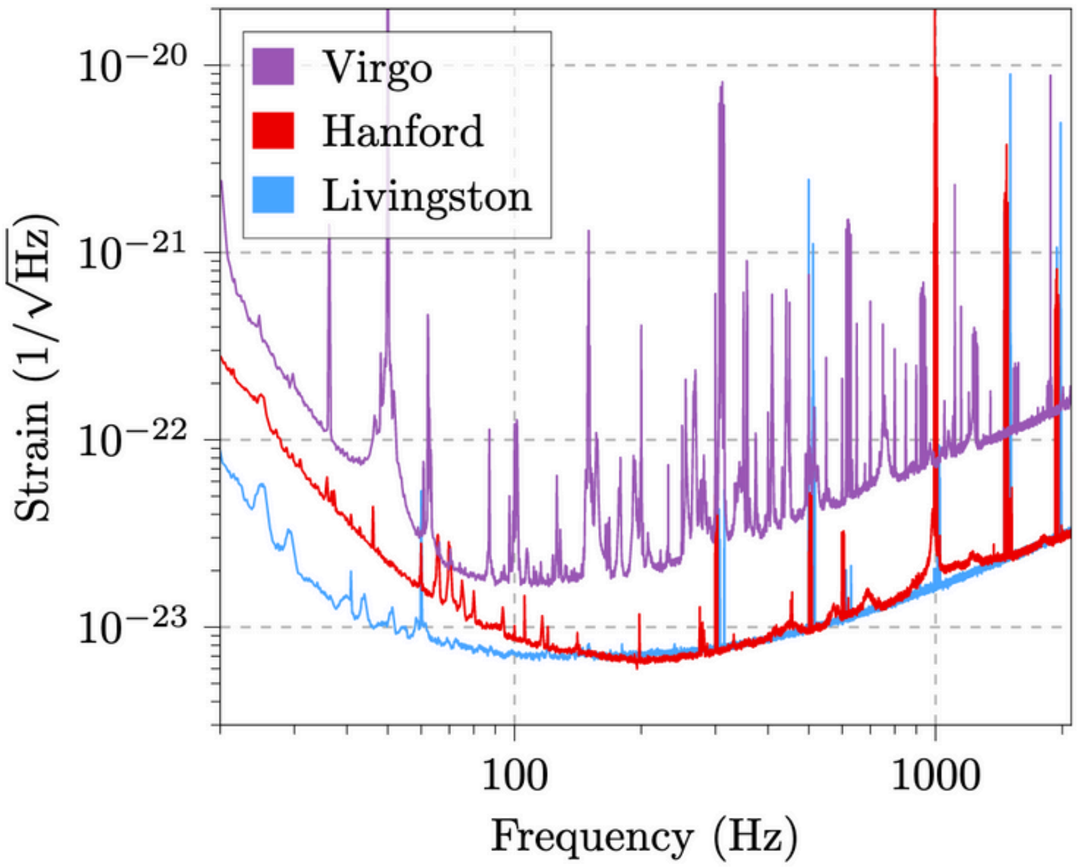

LVK search for an isotropic GWB

Signal to noise ratio

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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

LVK search for an isotropic GWB

Gaussian likelihood

$$p(\hat{\Omega}_0|\Theta,\Lambda) \propto \exp\left[-\frac{1}{2}\sum_f \frac{(\hat{\Omega}_0(f) - \Lambda\Omega_{\rm GW}(f;\Theta))^2}{\sigma_0^2(f)}\right]$$

LVK search for an isotropic GWB

Gaussian likelihood

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Frequentist versus Bayesian analyses: Cross-correlation as an approximate sufficient statistic for LIGO-Virgo stochastic background searches

AM and JR, Phys. Rev. D 103, 062003

LVK search for an isotropic GWB

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Frequentist results

LVK search for an isotropic GWB

Gaussian likelihood

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Calibration uncertainties

LVK search for an isotropic GWB

Gaussian likelihood

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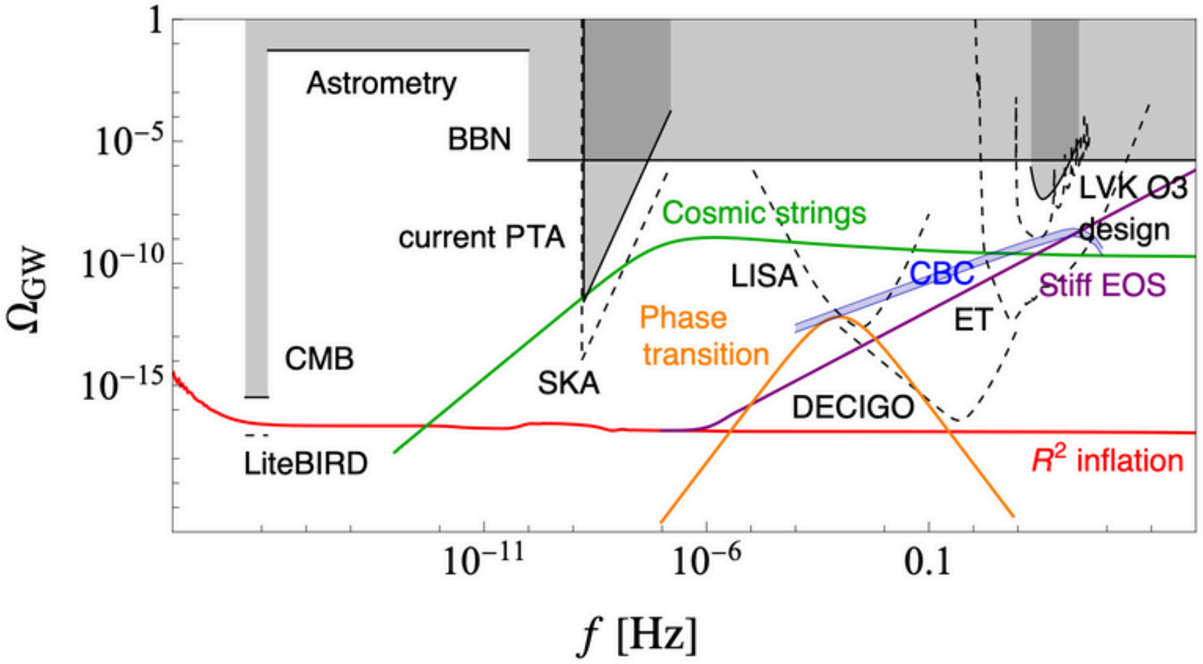
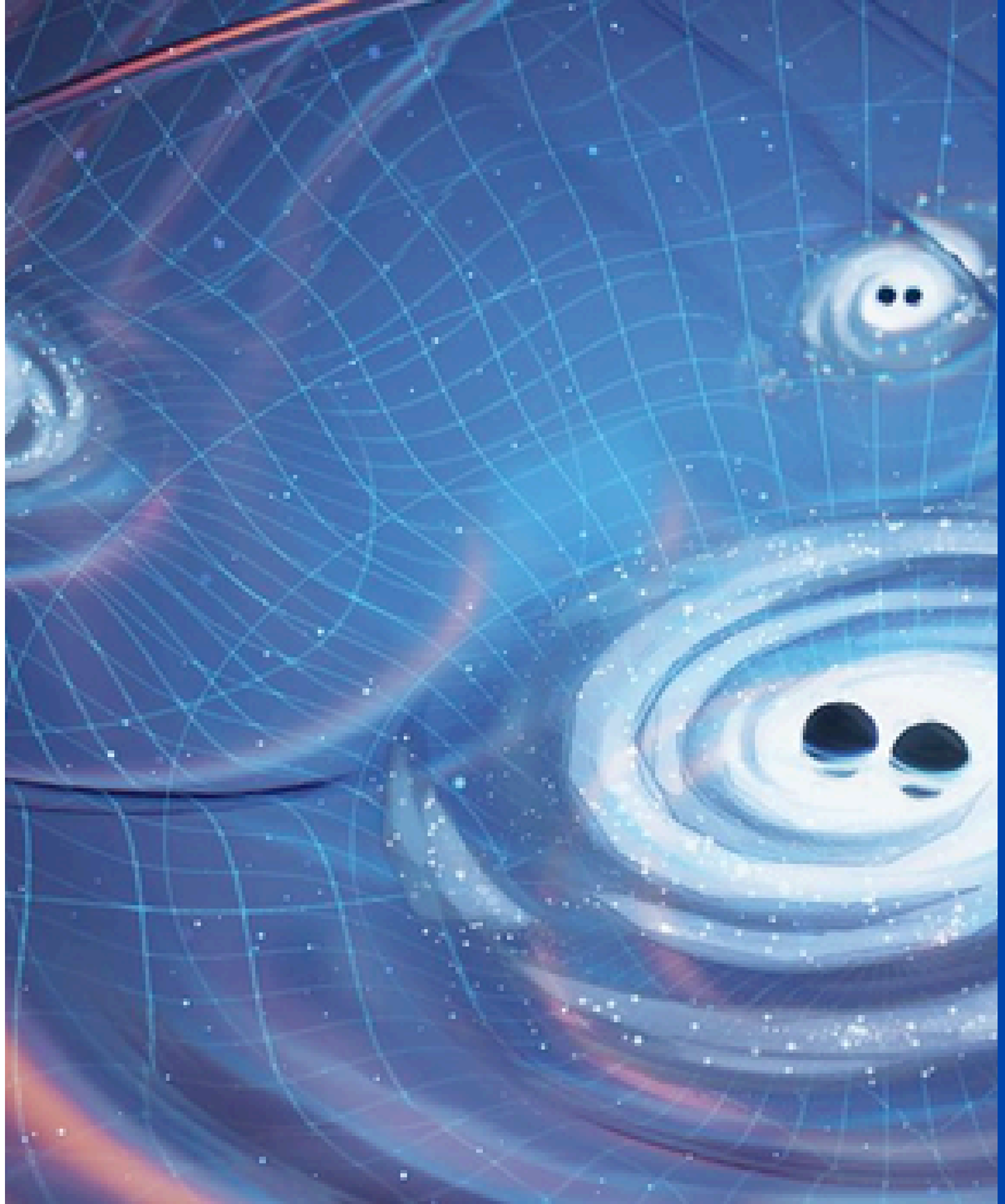
Model assumed to describe the GWB



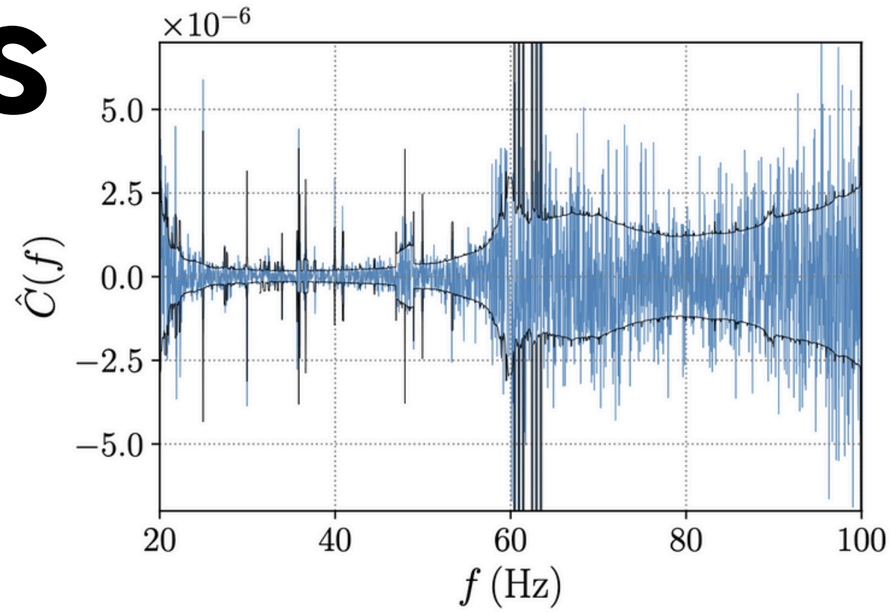
ARR, and S. Kuroyanagi. 2024. *Primordial Black Holes*. Chap. 27. Springer (link). Arxiv: https://doi.org/10.48550/arXiv.2407.00205.

O1-O3 LVK results on the search for an isotropic GWB



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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HL is the most sensitive baseline

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]	$\hat{C}^{O1+O2+O3}/10^{-9}$
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Current LVK results

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Search is most sensitive to 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]	$\hat{C}^{O1+O2+O3}/10^{-9}$
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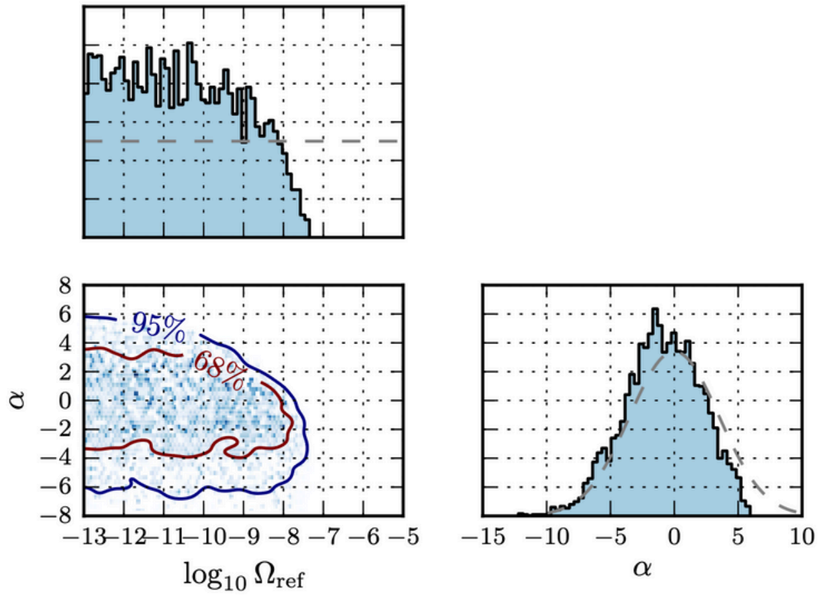
Current LVK results

$$\Omega_{\rm GW}(f) = \Omega_\alpha F_\alpha(f)$$

$$F_\alpha(f) = \left(\frac{f}{25\,\mathrm{Hz}}\right)^\alpha$$

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



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

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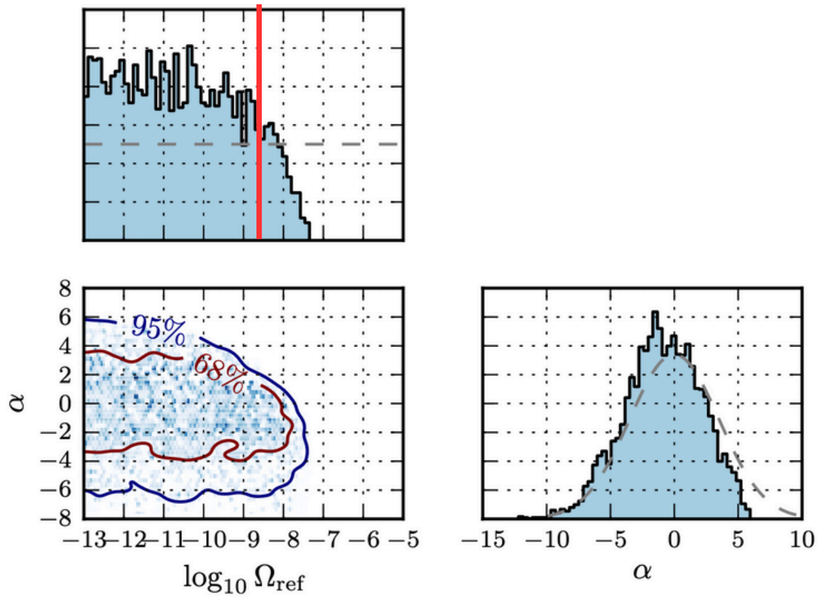
Marg.	6.6×10^{-9}	3.4×10^{-8}	5.1

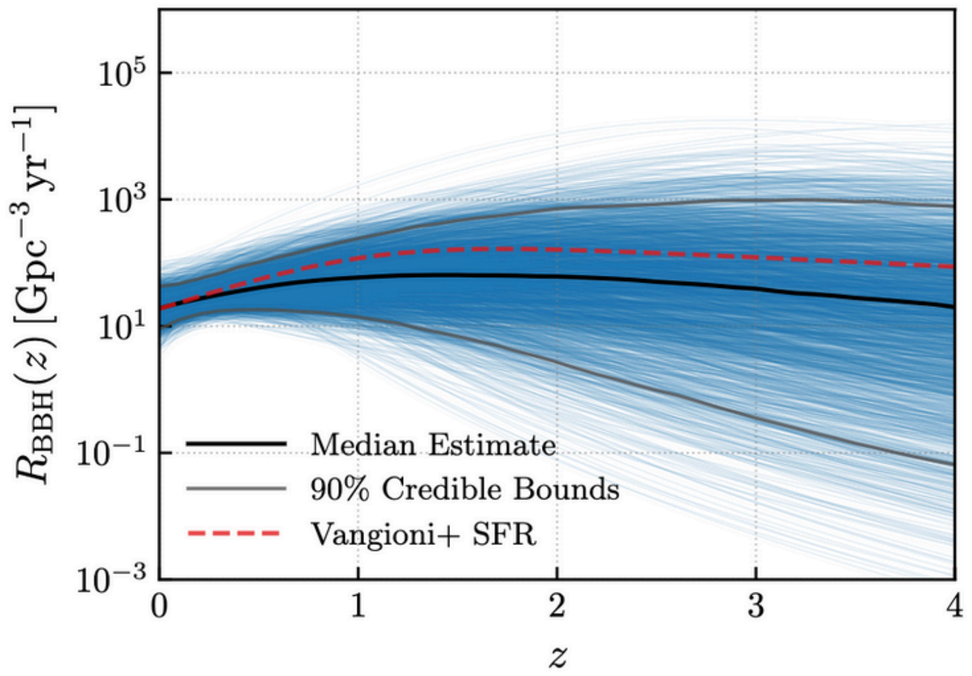


R. Abbott et al. (LVK), Phys. Rev. D 104, 022004

Constraints on the CBC merger rate

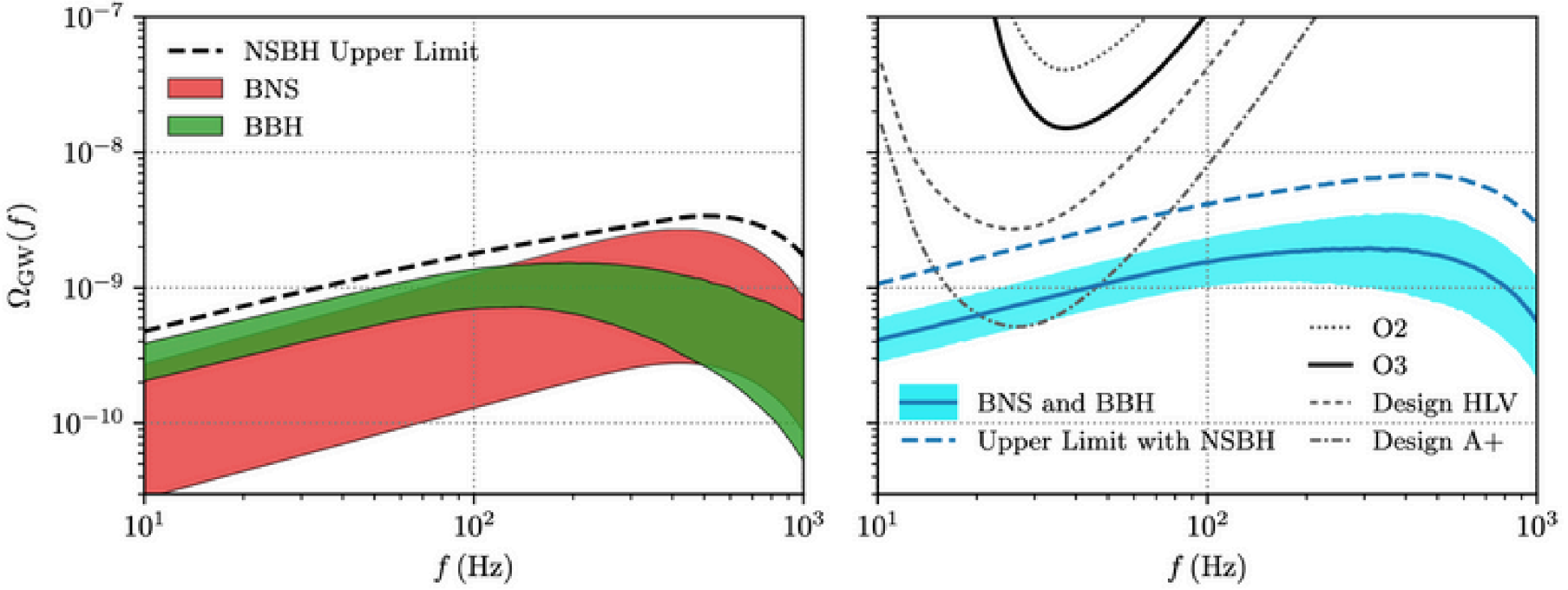
UL on the BBH merger rate beyond z ≃ 2 at 90% credibility:

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



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

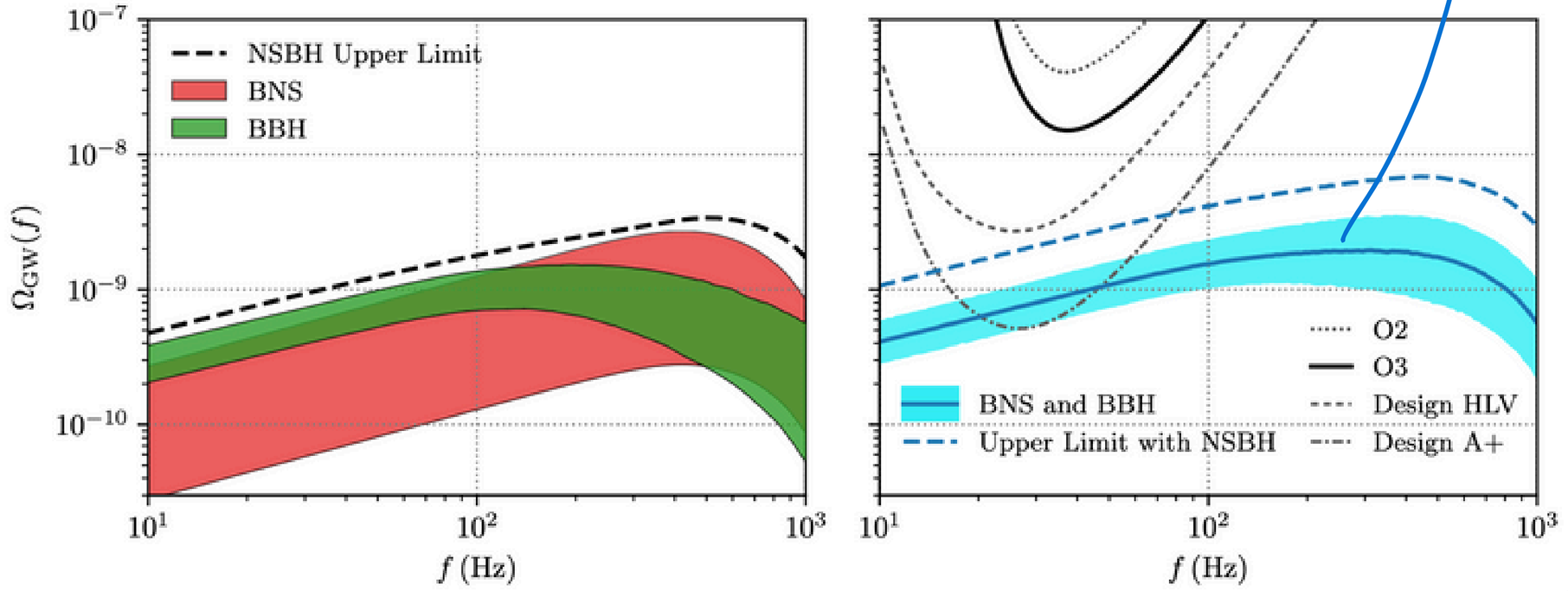
LVK results – astrophysical implications



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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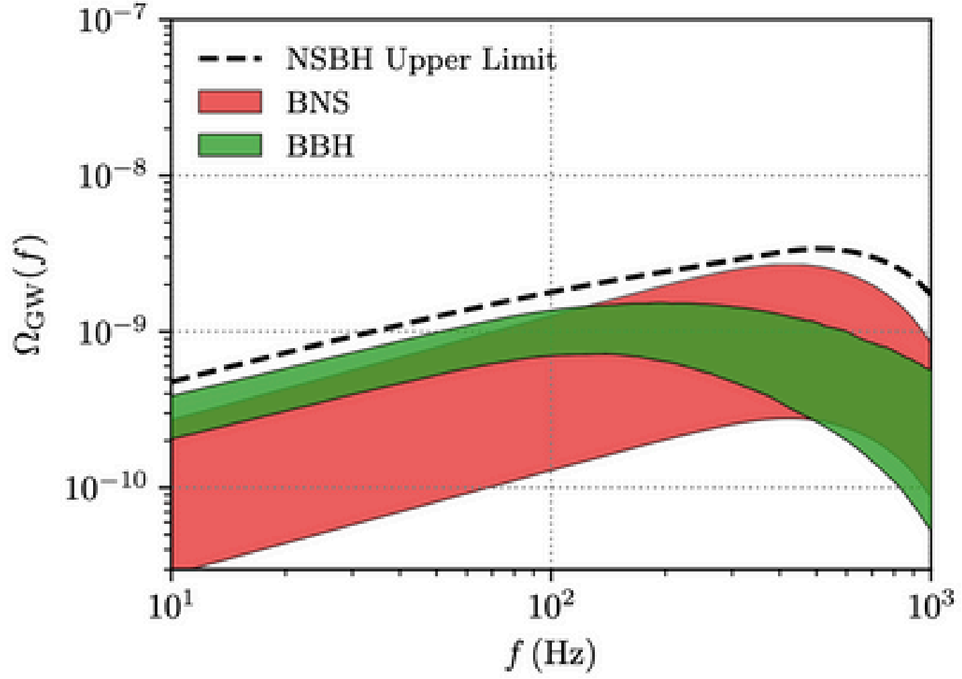
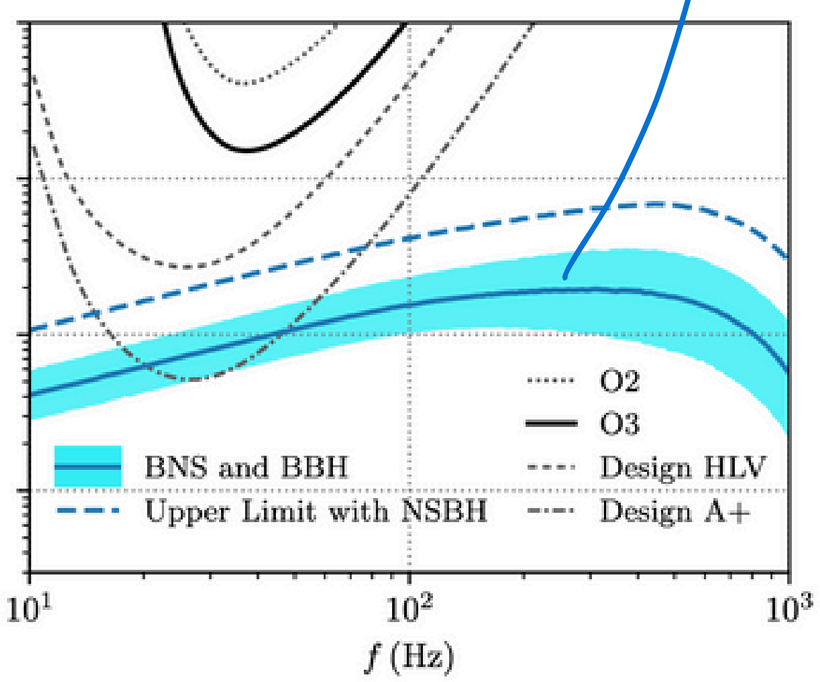
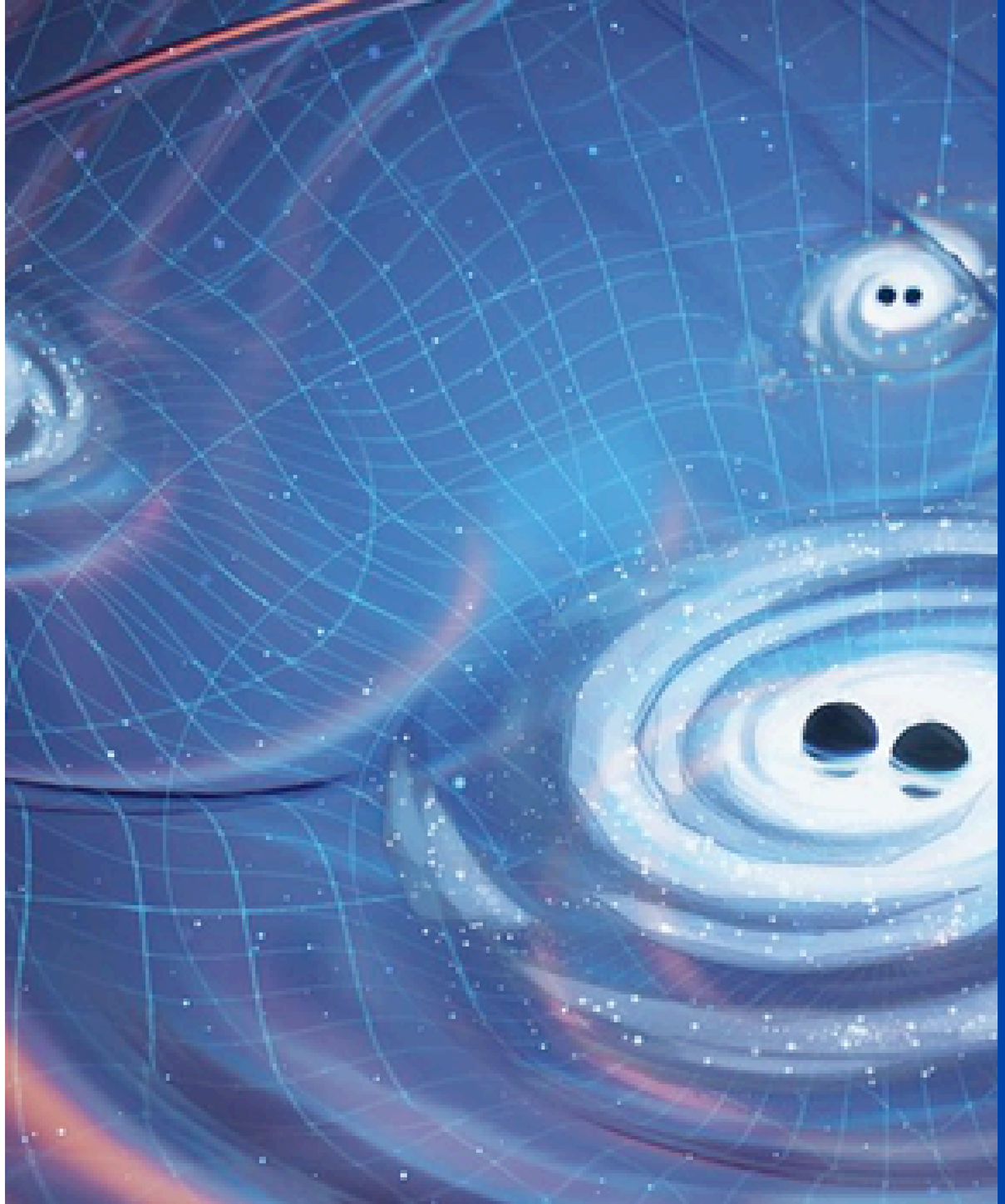




R. Abbott et al. (LVK), Phys. Rev. D 104, 022004

Implications on cosmological sources



Implications on cosmo sources

- Cosmic strings (LVK papers):
  - Phys. Rev. D 97, 102002,
  - Phys. Rev. Lett. 126, 241102
- First Order Phase Transitions (FOPTs):
  - ARR et al. Phys. Rev. Lett. 126, 151301,
  - CB et al. Phys. Rev. D 107, 023511
- Scalar Induced GWB (SIGWB):
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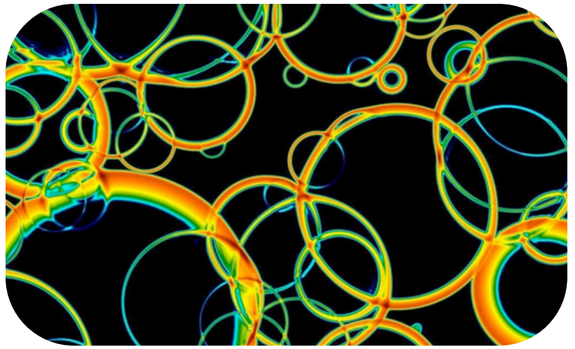
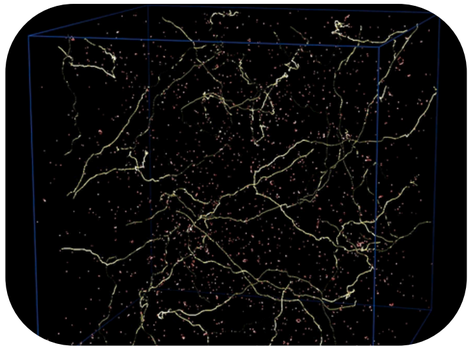
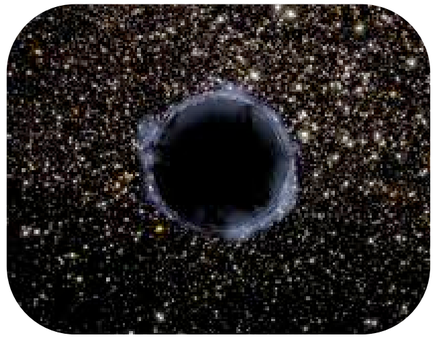
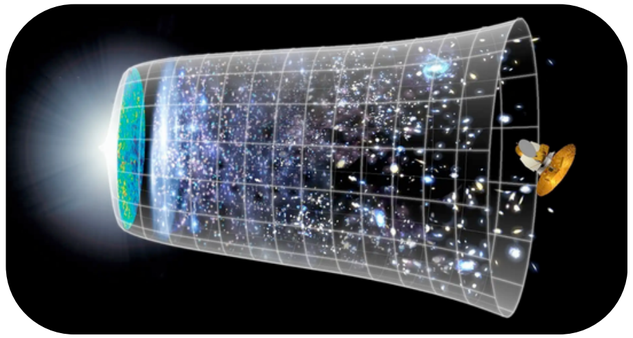
- Stiff equation of state:
  - HD et al. Phys. Rev. D 110, 103503
- Inflation:
  - CB et al. Phys. Rev. D 110, 084063
- Domain walls:
  - SB et al JCAP04(2023)008









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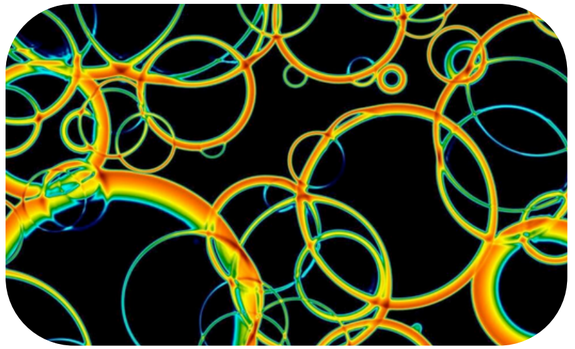
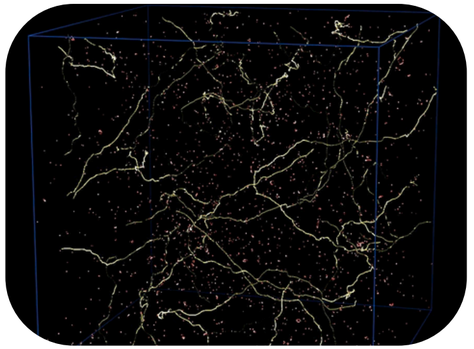
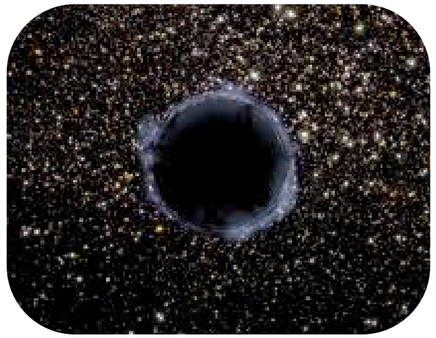
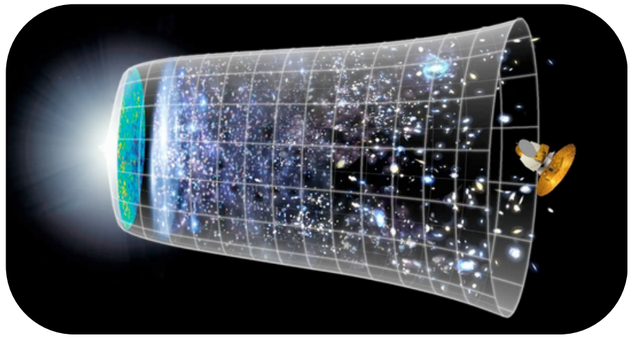
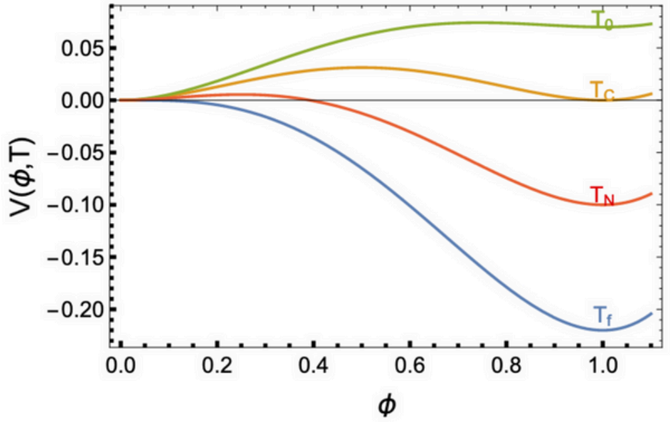




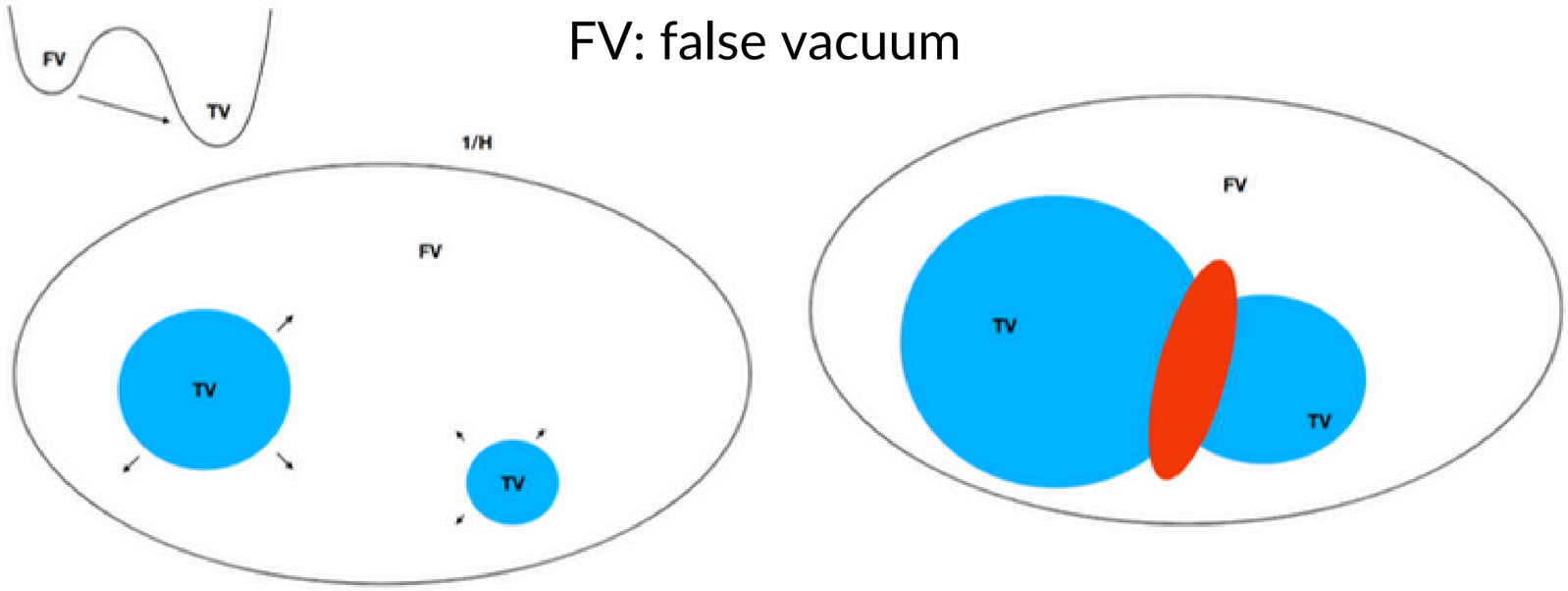




Implications on FOPTs

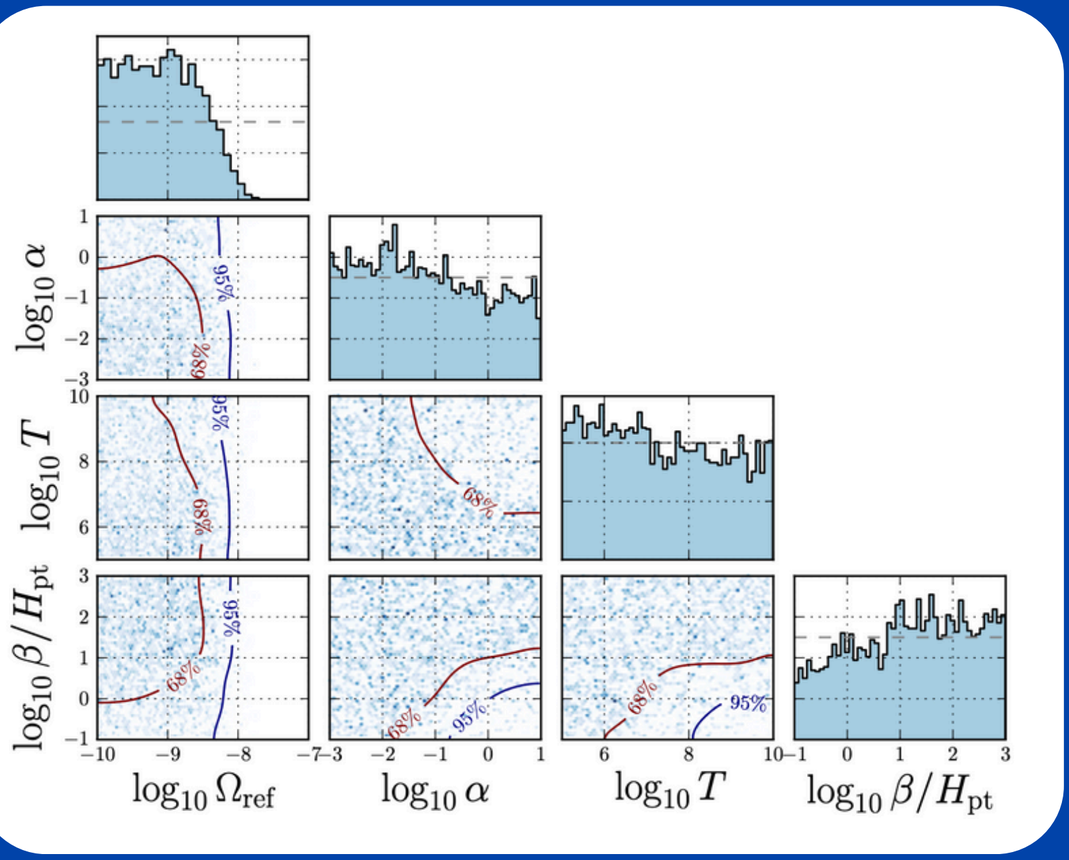


TV: true vacuum
FV: false vacuum



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

Implications on FOPTs

$$\Omega_{\rm cbc} = \Omega_{\rm ref}(f/f_{\rm ref})^{2/3}$$

- Nucleation temperature: T_{pt}
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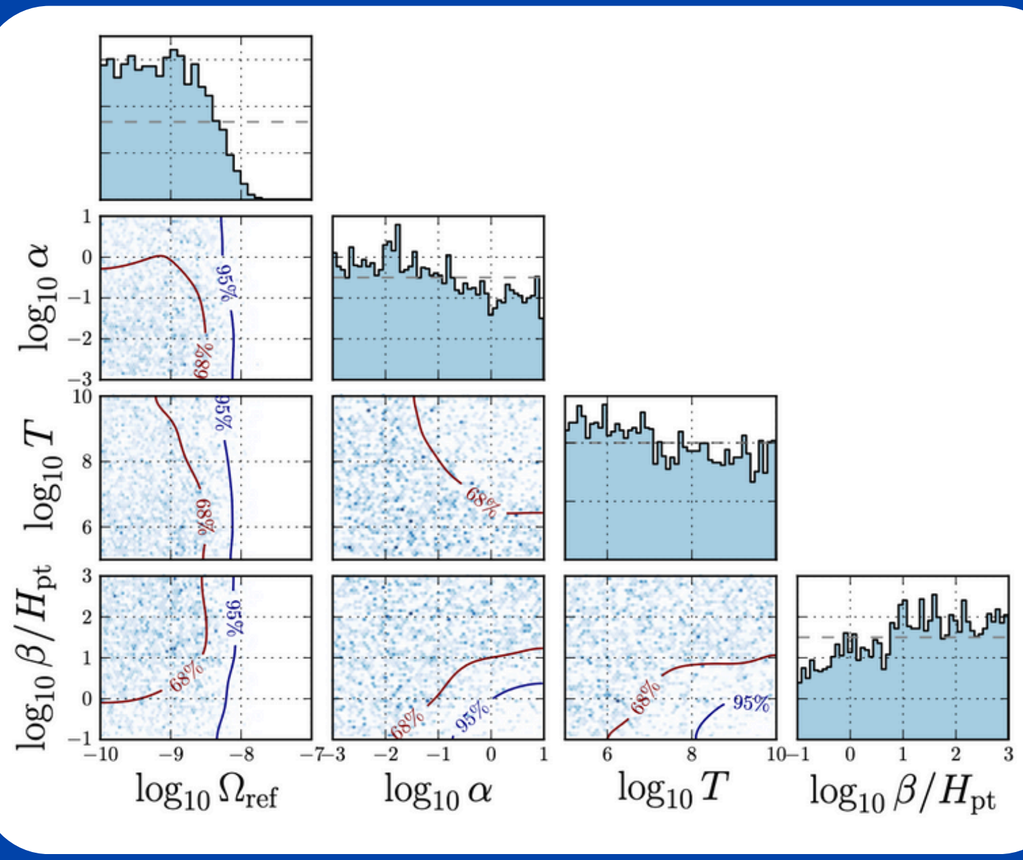

ARR et. al., Phys. Rev. Lett. 126, 151301

Implications on FOPTs

- Nucleation temperature: T_{pt}
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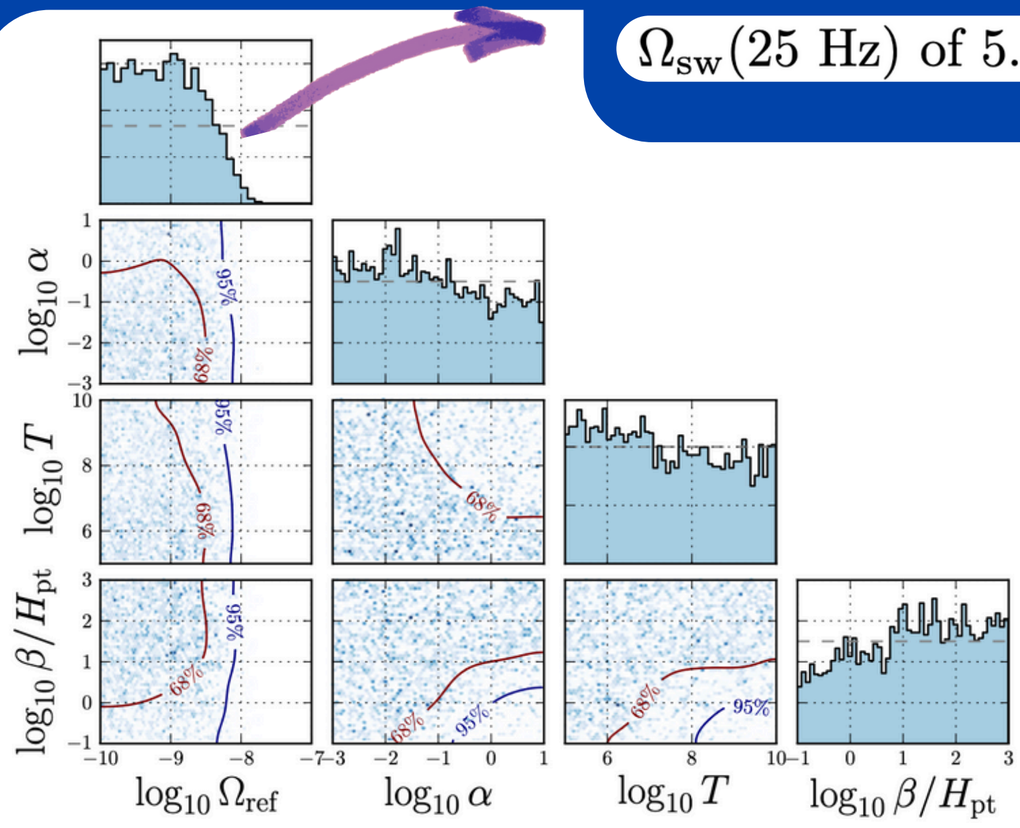
- Bubble wall velocity: vw = c

UL at 95% CL on

$\Omega_{\rm sw}(25\ {\rm Hz})$ of 5.9×10^{-9}



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

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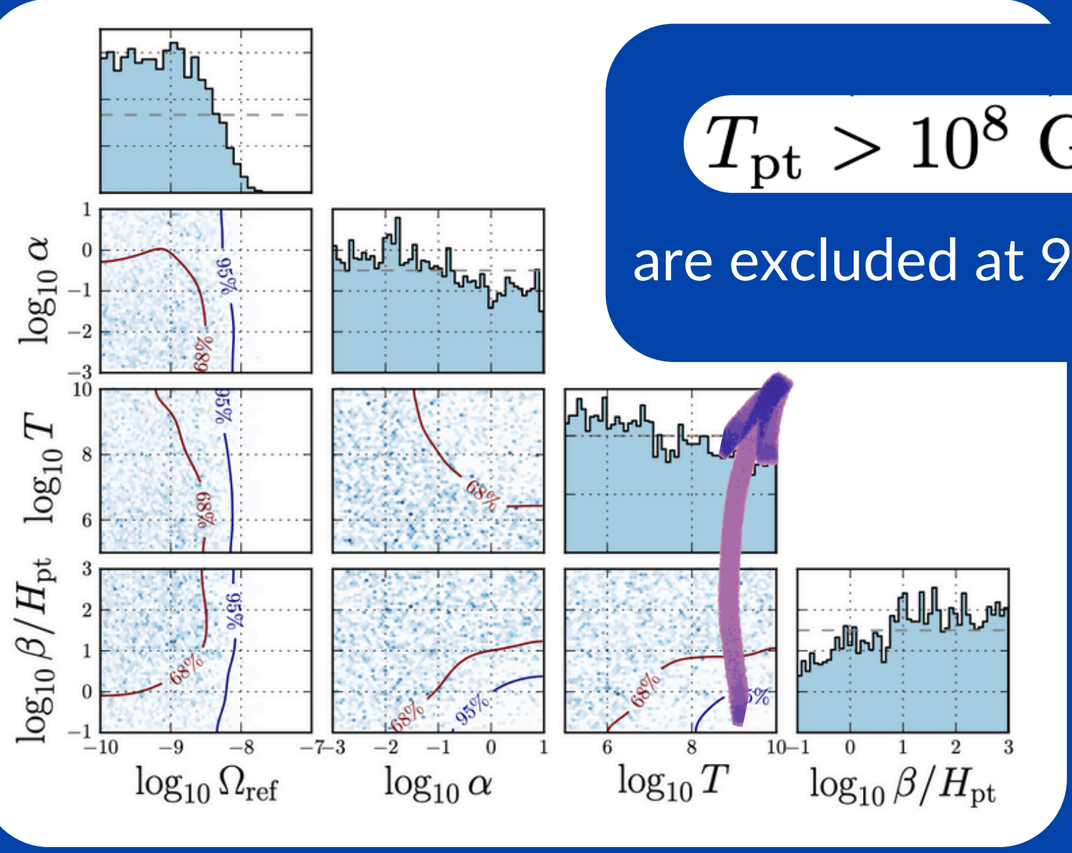

$T_{\rm pt} > 10^8$ GeV

are excluded at 95% CL

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

Implications on FOPTs

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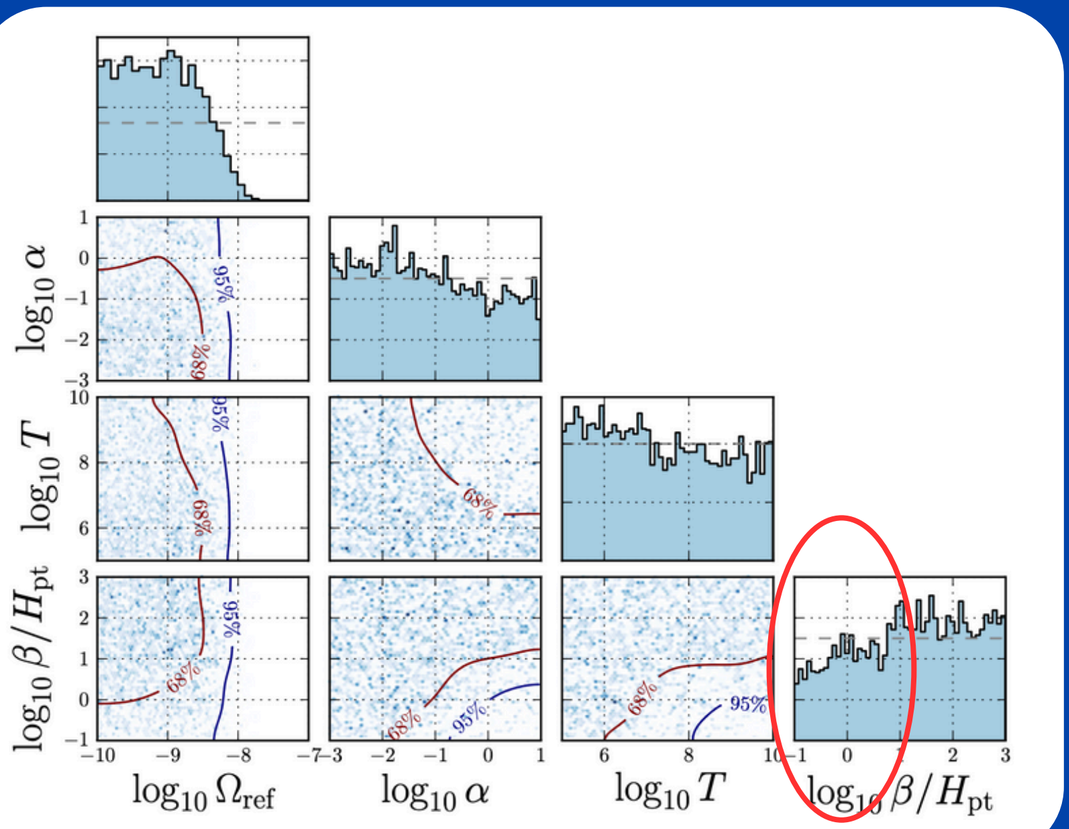
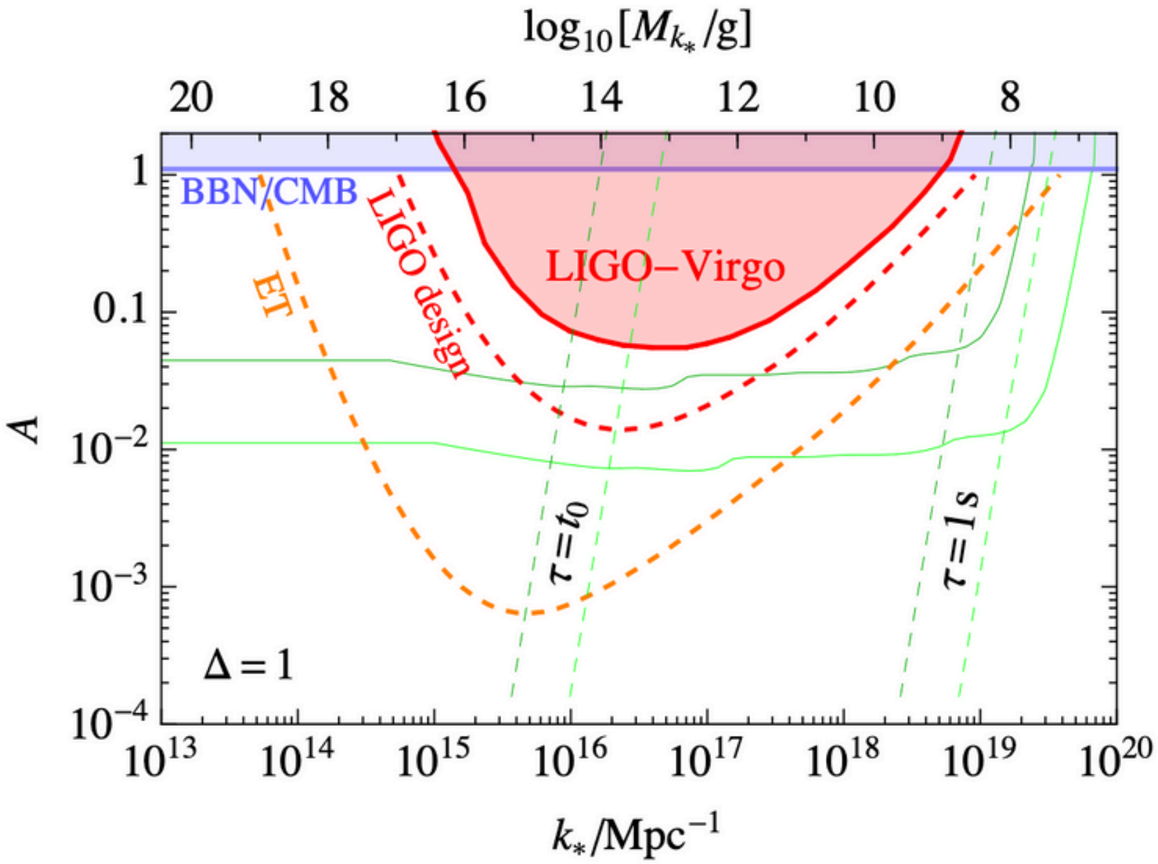


ARR et. al., Phys. Rev. Lett. 126, 151301

Implications on the formation of PBHs

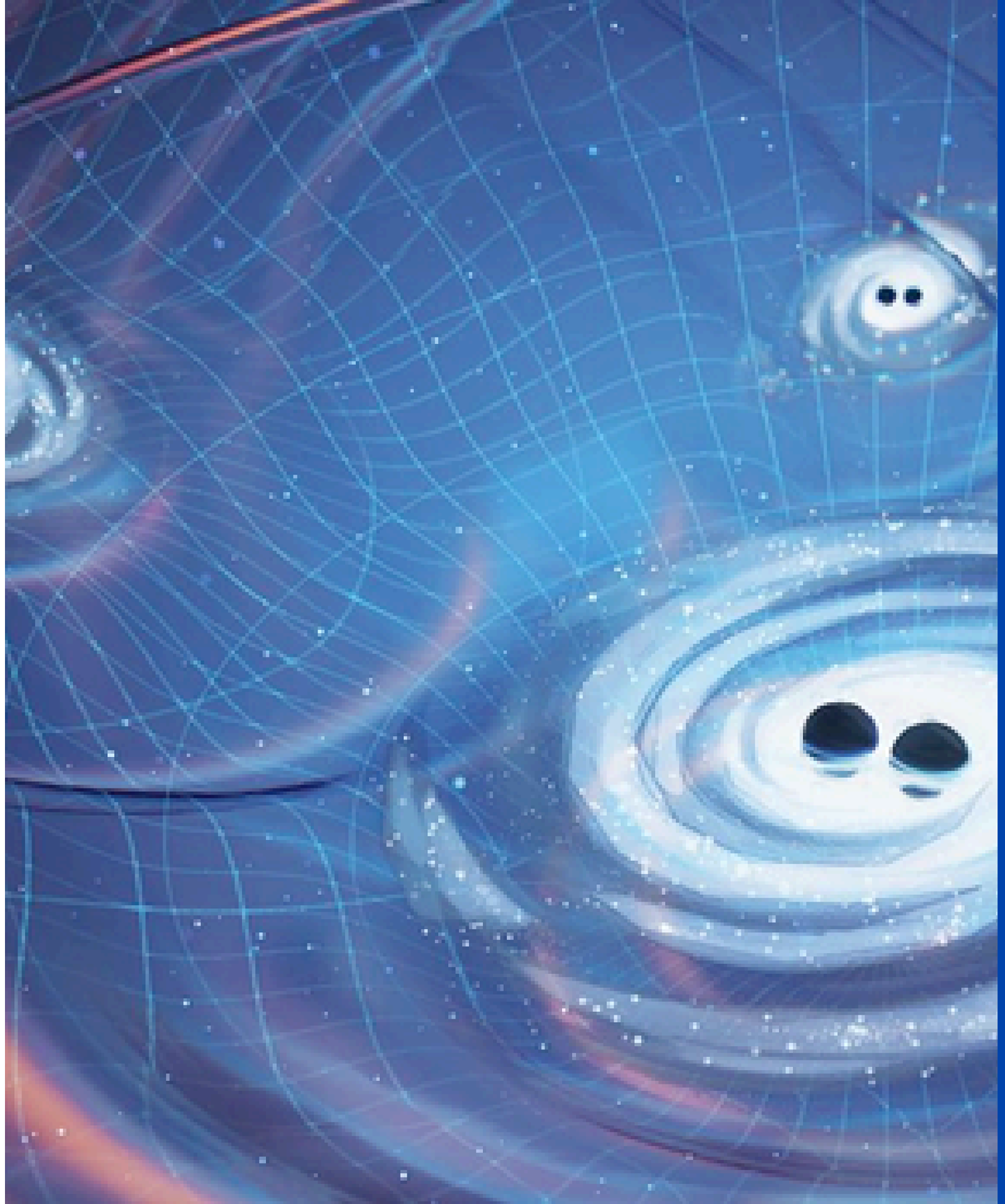
Formation of PBHs from inflationary fluctuations is accompanied by a scalar induced GWB

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



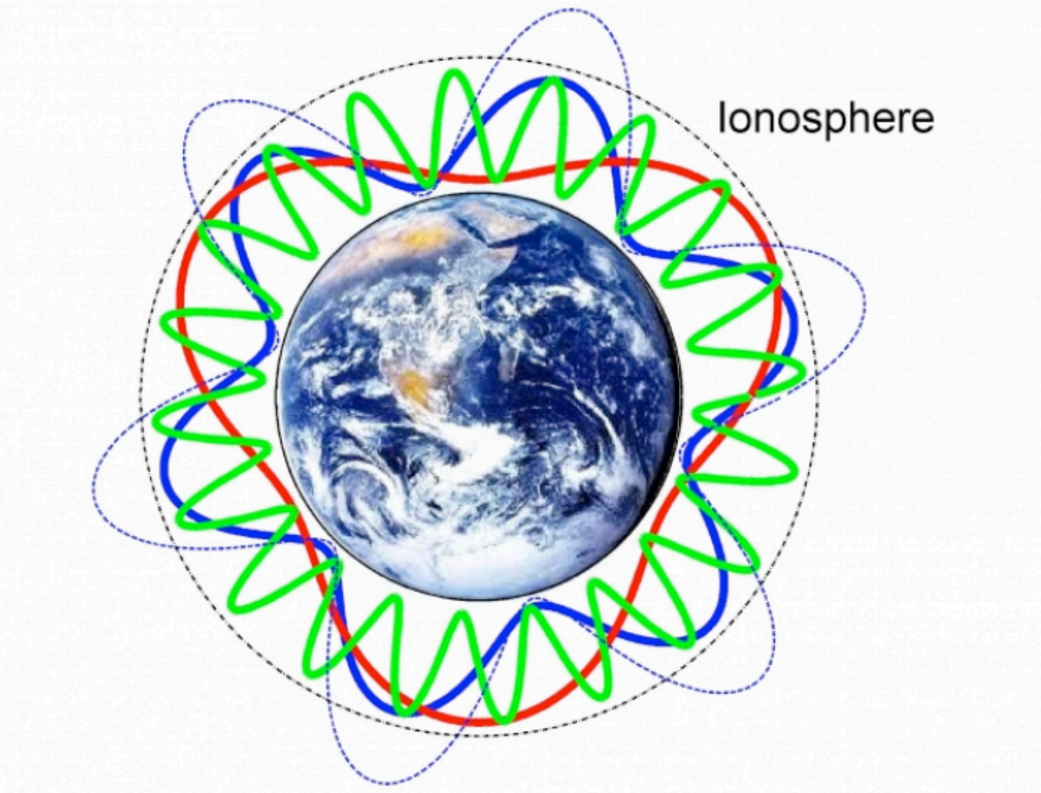
ARR et al., Phys. Rev. Lett. 128, 051301

Challenges in the search for a GWB



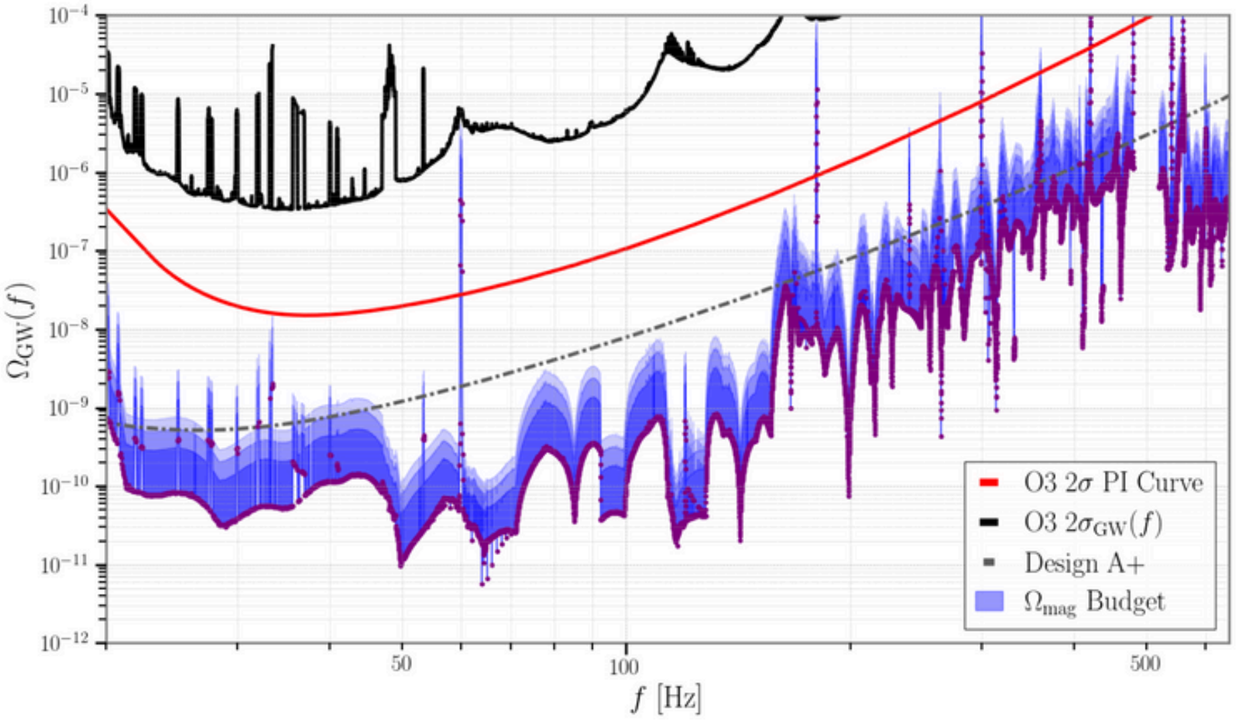
Some challenges in LVK

- Correlated magnetic noise:
  - Electronic mains
  - Synchronisation to GPS
  - Schumann resonances



Some challenges in LVK

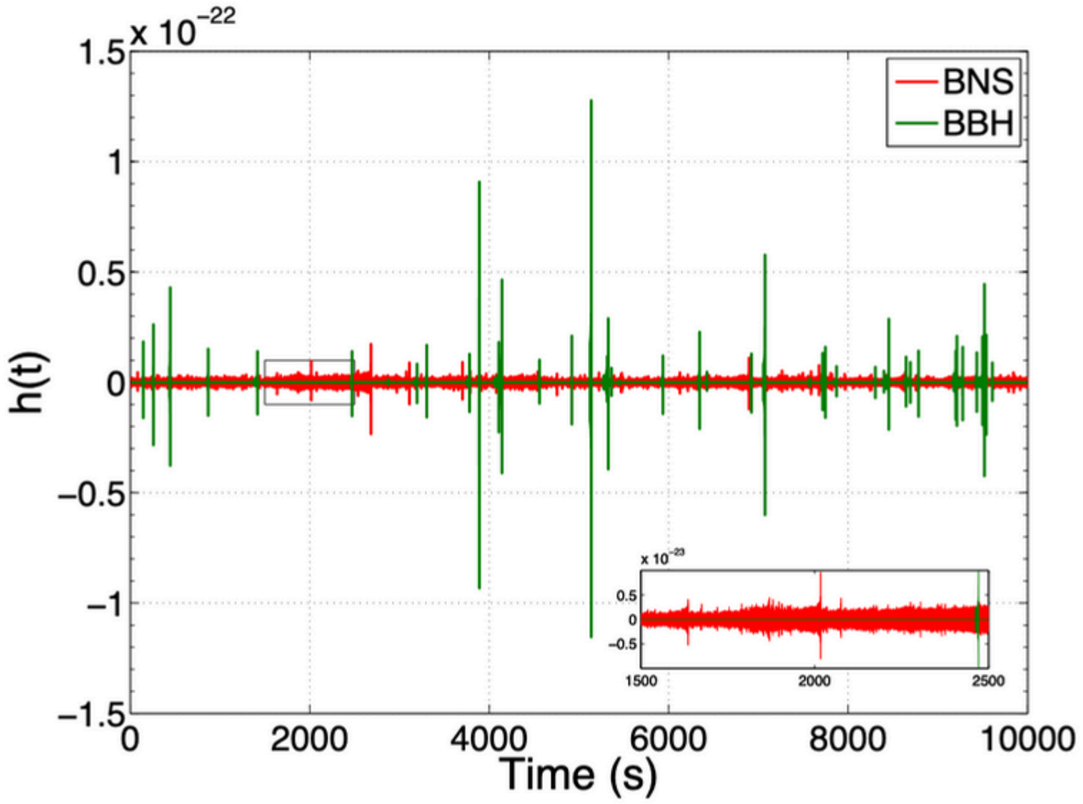
- Correlated magnetic noise:
  - Magnetic noise budget: not harmful for current searches



KJ et al. Phys. Rev. D 107, 022004

Some challenges in LVK

- Correlated magnetic noise:
  - Magnetic noise budget: not harmful for current searches
- Non-persistent background:



LVK collab. Phys. Rev. Lett. 120, 091101

Some challenges in LVK

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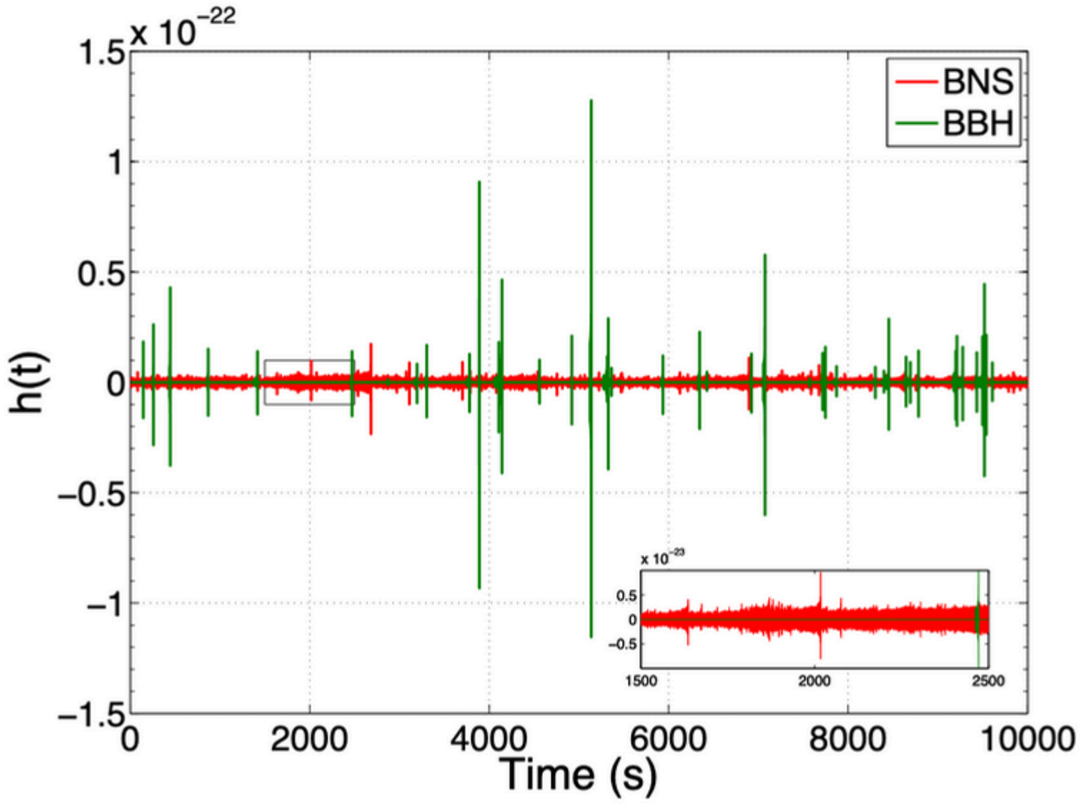
  - SSI : JL et al. Phys. Rev. D 107, 103026



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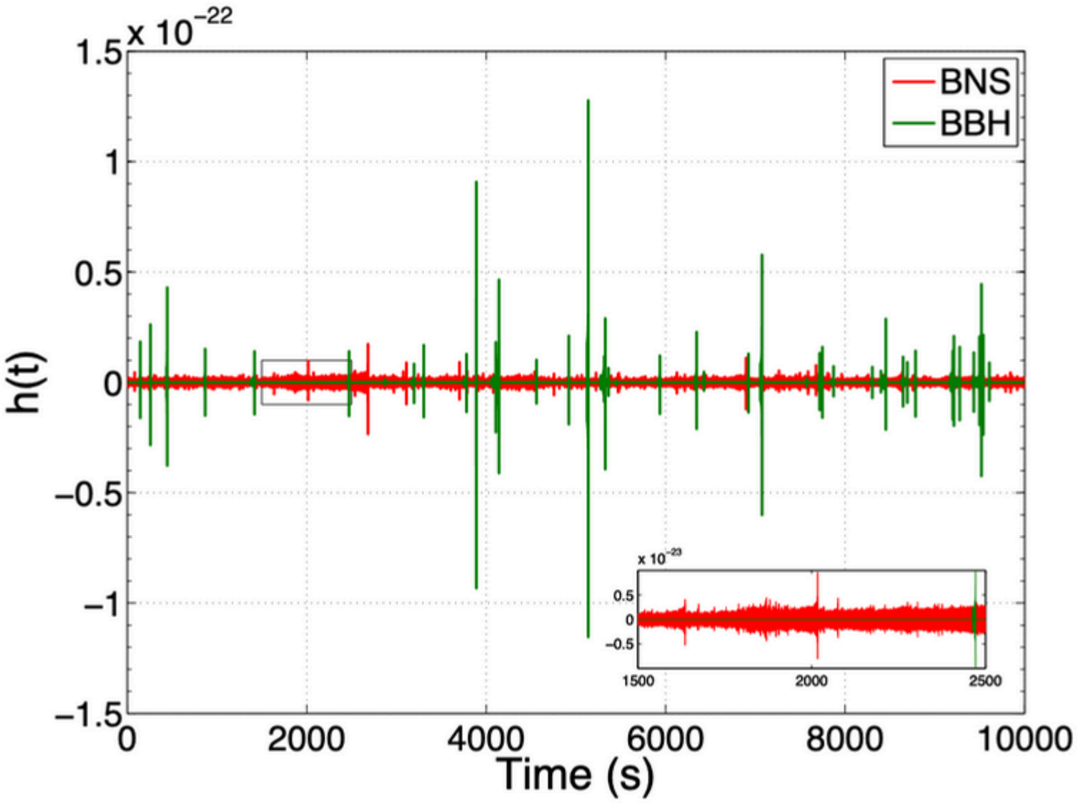
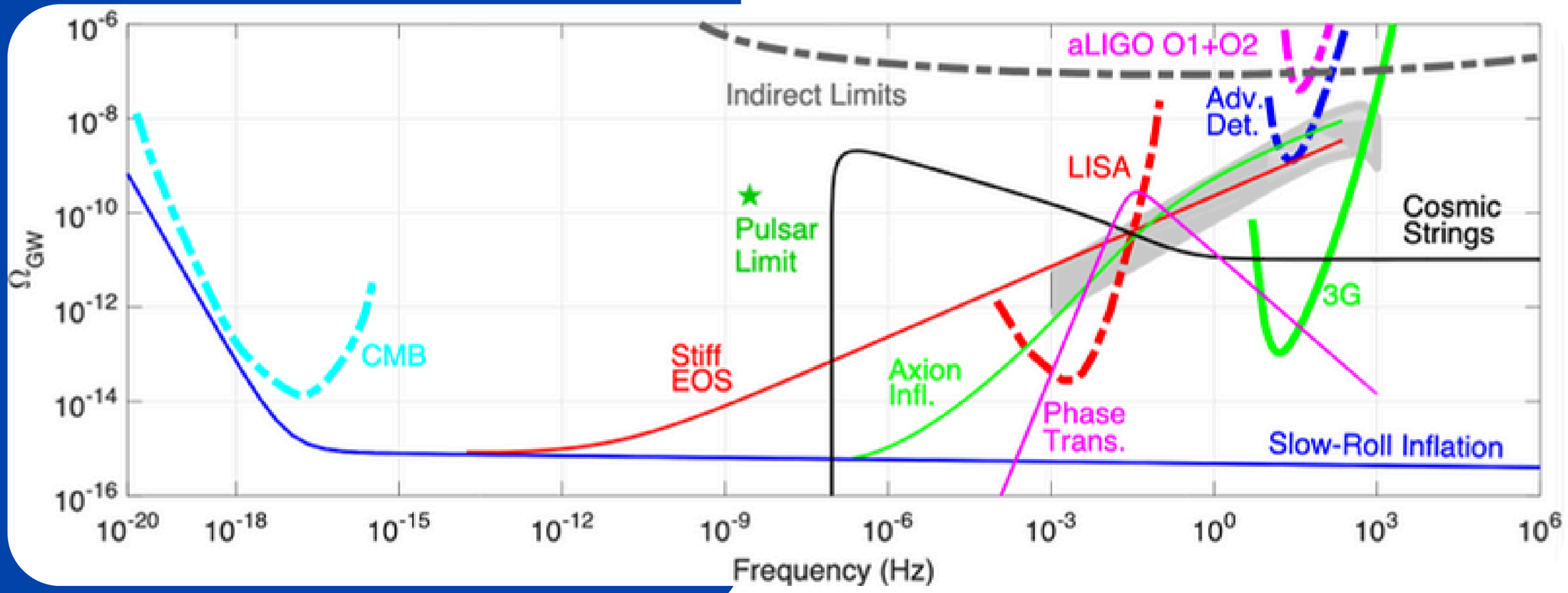
  - TBS: https://dcc.ligo.org/LIGO-G2500161



LVK collab. Phys. Rev. Lett. 120, 091101

Future challenges in GWB search

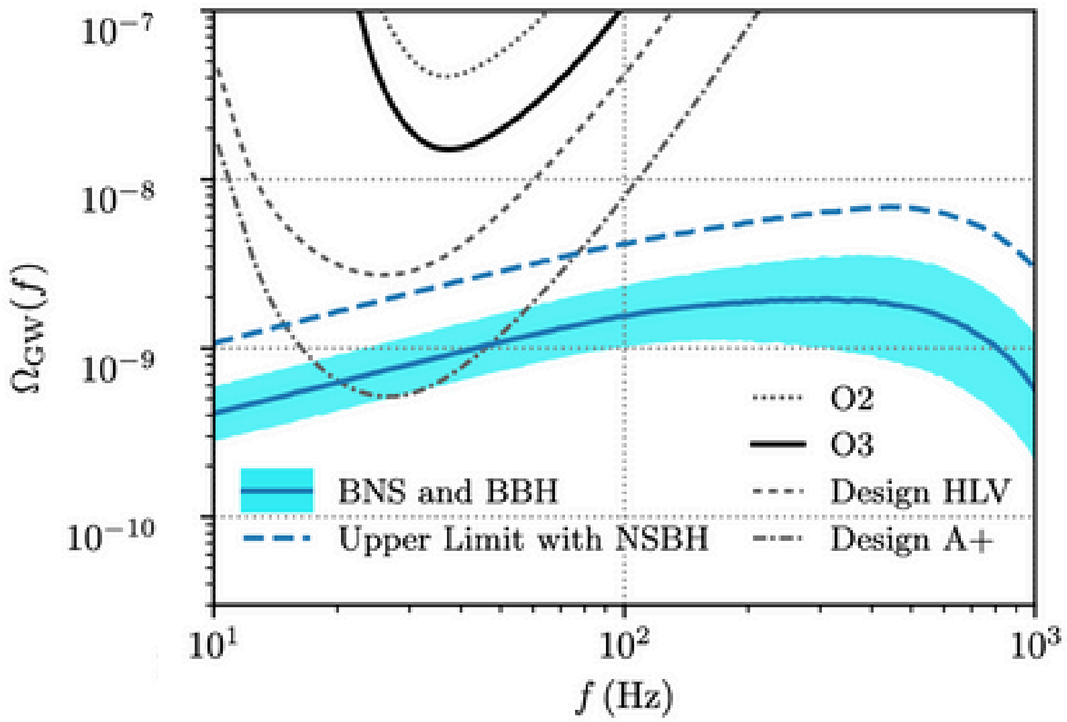
- Cross-correlation method assumes weak signal



VK et al. The Next Generation Global Gravitational Wave Observatory: The Science Book. 2021.

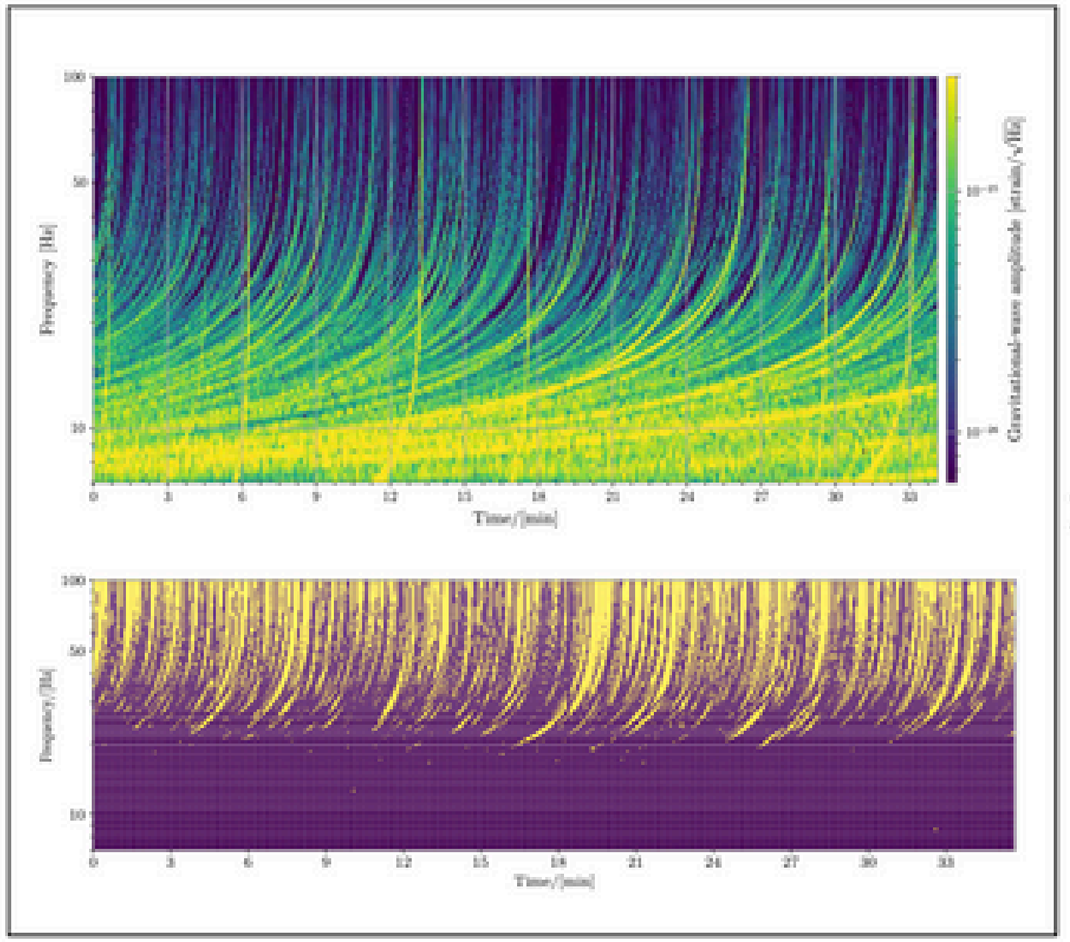
Future challenges in GWB search

- Cross-correlation method assumes weak signal
- Astrophysical foreground masking the cosmological background



Future challenges in GWB search

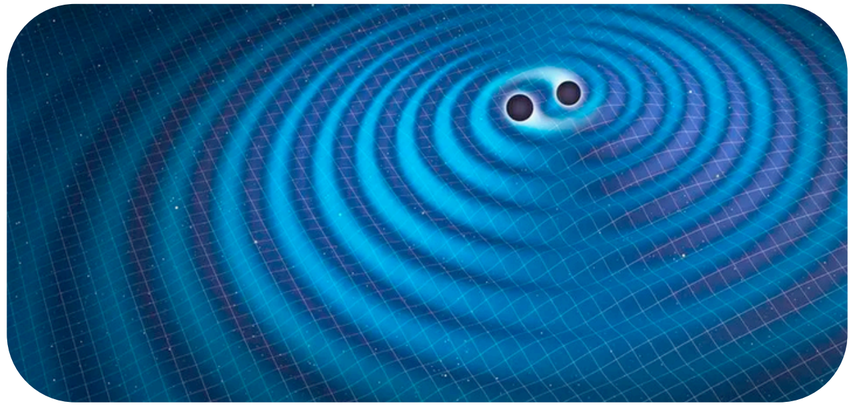
- Cross-correlation method assumes weak signal
- Astrophysical foreground masking the cosmological background
  - Removal techniques

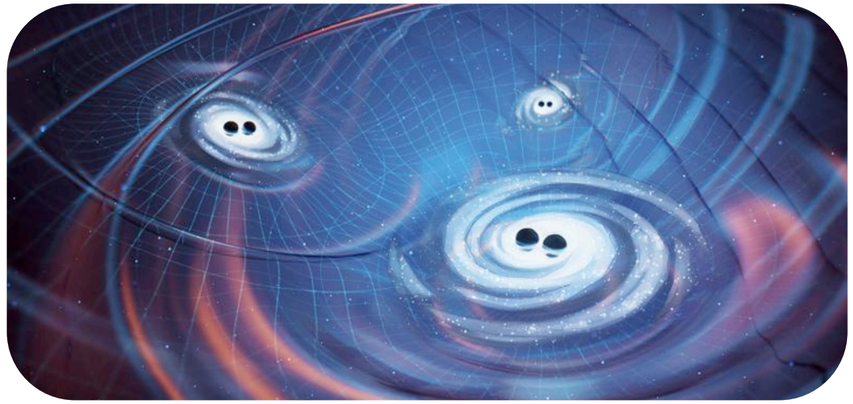


HZ, Phys. Rev. D 108, 089902

Future challenges in GWB search

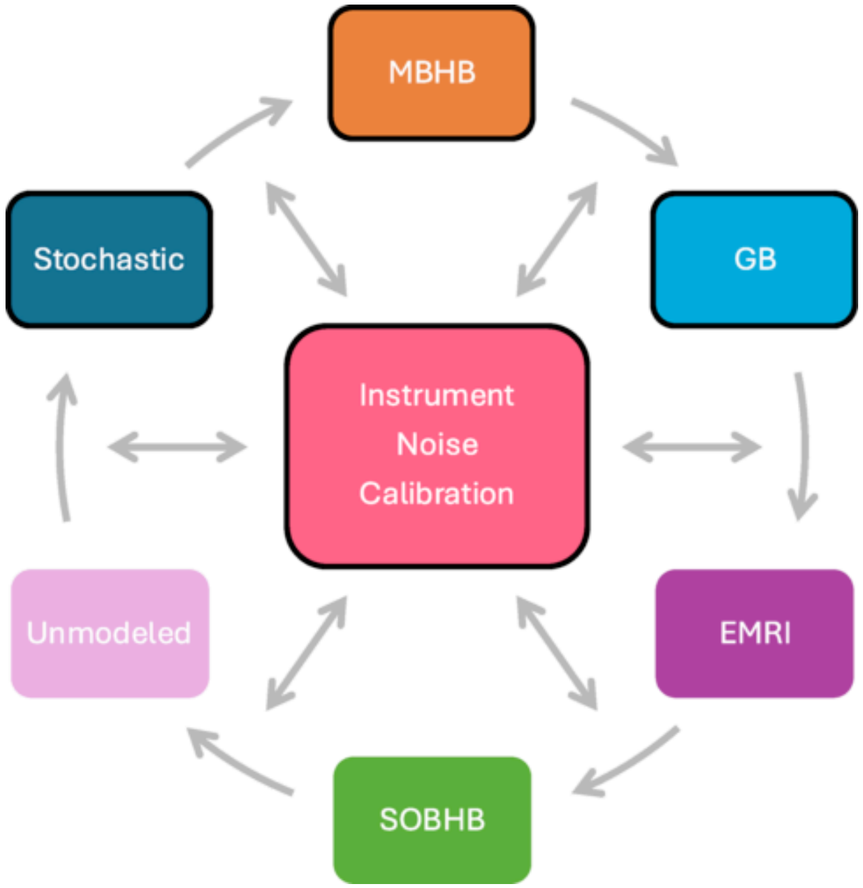
- Cross-correlation method assumes weak signal
- Astrophysical foreground masking the cosmological background
  - Removal techniques
  - Astrophysical and cosmological models have large uncertainties





Future challenges in GWB search

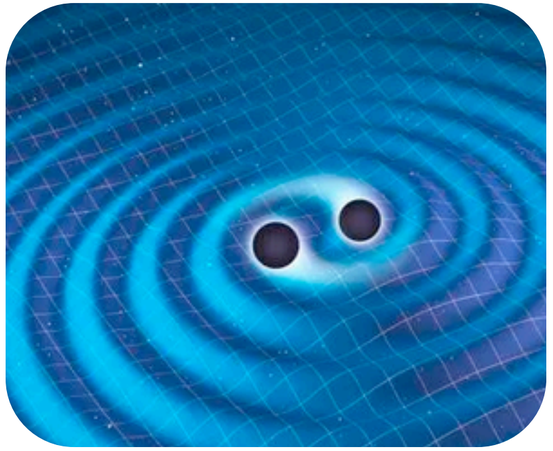
- Cross-correlation method assumes weak signal
- Astrophysical foreground masking the cosmological background
  - Removal techniques
  - Astrophysical and cosmological models have large uncertainties
- Computational challenges: e.g.: global fit in LISA

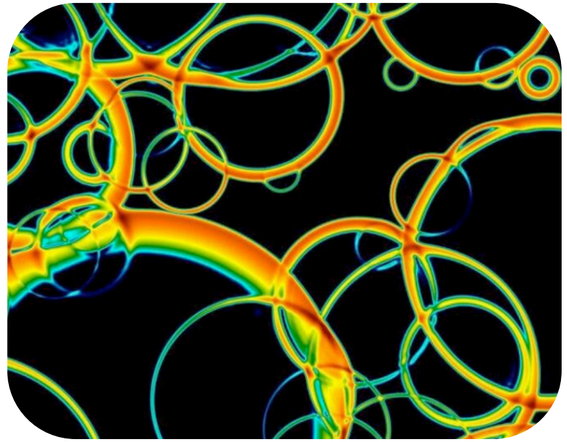


MLK, Phys. Rev. D 111, 024060

Summary

- Isotropic searches in LVK
  - Cross correlation search
  - Bayesian inference
- No detection yet → upper limits:
  - Agnostic model
  - Cosmological models
- Estimation of the astrophysical foreground → possible detection with A+
- Future challenges to be further studied





News: GWTC-4 papers released

1. arXiv:2508.18083 [pdf, ps, other] astro-ph.HE gr-qc

GWTC-4.0: Population Properties of Merging Compact Binaries

Authors: The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration

Abstract: We detail the population properties of merging compact objects using 158 mergers fro which includes three types of binary mergers: binary neutron star, neutron star--black hole binar and under-densities in the black hole mass distribution: features persist at primary masses of... ▽

Submitted 25 August, 2025; **originally announced** August 2025.

Comments: As part of the Astrophysical Journal Letters Focus Issue on the Gravitational Wave Transient Catalog

Report number: LIGO-P2400004

2. arXiv:2508.18082 [pdf, ps, other] gr-qc astro-ph.HE

GWTC-4.0: Updating the Gravitational-Wave Transient Catalog with Observa Virgo-KAGRA Observing Run

Authors: The LIGO Scientific Collaboration, The Virgo Collaboration, the KAGRA Collaboration

Abstract: Version 4.0 of the Gravitational-Wave Transient Catalog (GWTC-4.0) adds new candidate through the first part of the fourth observing run (O4a: 2023 May 24 15:00:00 to 2024 January 16 data, we find 128 new compact binary coalescence candidates that are identified by at least one

Submitted 25 August, 2025; **originally announced** August 2025.

Comments: As part of the Astrophysical Journal Letters Focus Issue on the Gravitational Wave Transient Catalog

Report number: LIGO-P2400386

3. arXiv:2508.18081 [pdf, ps, other] gr-qc astro-ph.HE

GWTC-4.0: Methods for Identifying and Characterizing Gravitational-wave Transients

Authors: The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, A. G. Abac, I. Aboue D. Adhikari, N. Adhikari, R. X. Adhikari, V. K. Adkins, S. Afroz, D. Agarwal, M. Agathos, M. Aghaei Abchouyeh, O. D. A Ajith, S. Akcay, T. Akutsu, S. Albanesi, R. A. Alfaidi , et al. (1787 additional authors not shown)

Abstract: The Gravitational-Wave Transient Catalog (GWTC) is a collection of candidate gravitational-wave transier the LIGO-Virgo-KAGRA Collaboration. Producing the contents of the GWTC from detector data requires complex a techniques to model the signal; identify the transients in the data; evaluate the quality of the data and mitigate...

Submitted 25 August, 2025; **originally announced** August 2025.

Comments: As part of the Astrophysical Journal Letters Focus Issue on the Gravitational Wave Transient Catalog

Report number: LIGO-P2400300

4. arXiv:2508.18080 [pdf, ps, other] gr-qc astro-ph.HE

GWTC-4.0: An Introduction to Version 4.0 of the Gravitational-Wave Transient Catalog

Authors: The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, A. G. Abac, I. Aboue D. Adhikari, N. Adhikari, R. X. Adhikari, V. K. Adkins, S. Afroz, D. Agarwal, M. Agathos, M. Aghaei Abchouyeh, O. D. A Ajith, S. Akcay, T. Akutsu, S. Albanesi, R. A. Alfaidi , et al. (1785 additional authors not shown)

Abstract: The Gravitational-Wave Transient Catalog (GWTC) is a collection of short-duration (transient) gravitation KAGRA Collaboration in gravitational-wave data produced by the eponymous detectors. The catalog provides info such as the arrival time and amplitude of the signal and properties of the signal's source as inferr... ▽ More

Submitted 25 August, 2025; **originally announced** August 2025.

Comments: As part of the Astrophysical Journal Letters Focus Issue on the Gravitational Wave Transient Catalog

Report number: LIGO-P2400293

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?

LVK results astrophysical implications

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