Is it still intersting to look at the gravitational-wave background with NG detectors?

Tania Regimbau

GW Orchestra – Louvain-la-Neuve

Two Questions

Q1. Does the background have an interest compared to individual detections?

- intrinsic parameter distribution? (masses, spins etc…)
- redshift distribution?
- sky distribution?

Q2. Will we be able to get rid of the correlated noise (see Kamiel's talk) and astrophysical foreground from CBCs?

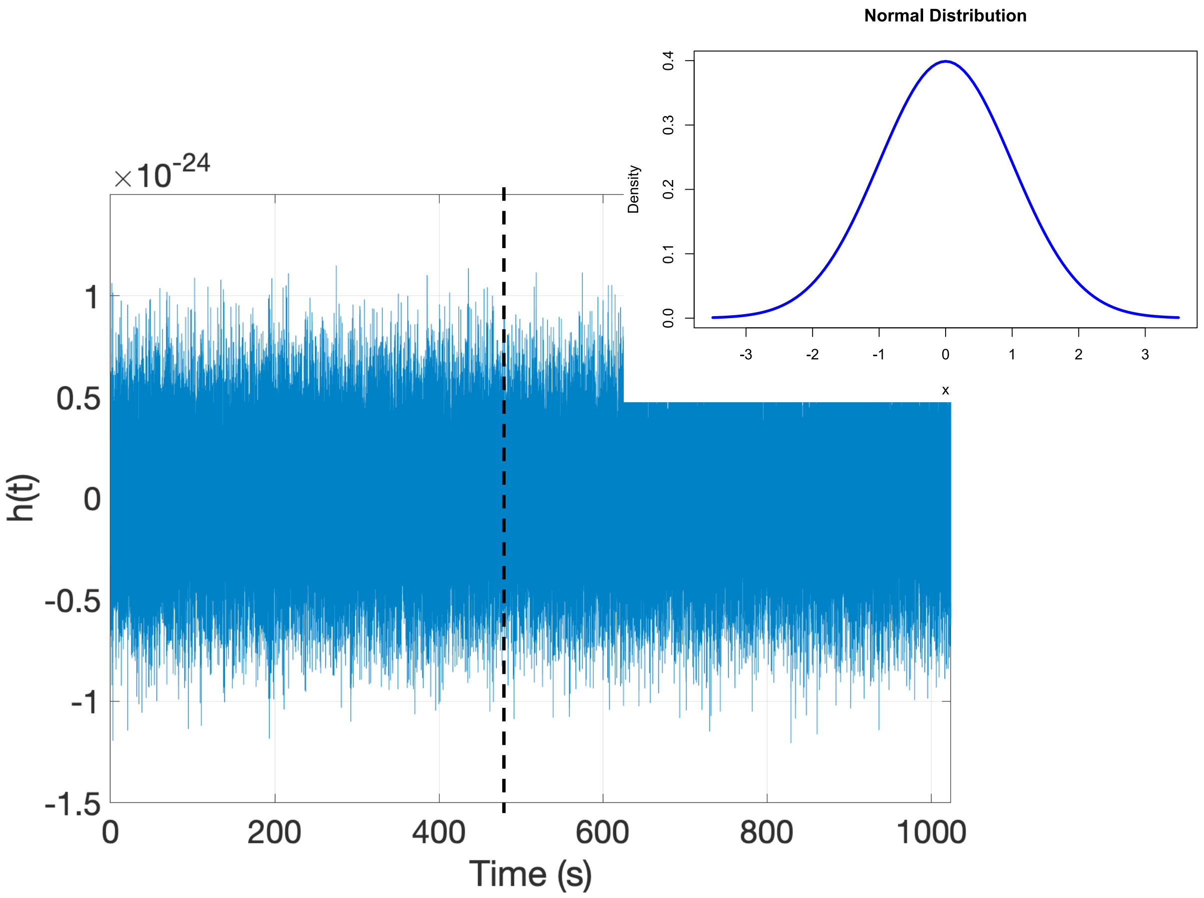
What sources contribute to the background

Definition: A stochastic background of gravitational waves has resulted from the superposition of a large number of independent unresolved sources.

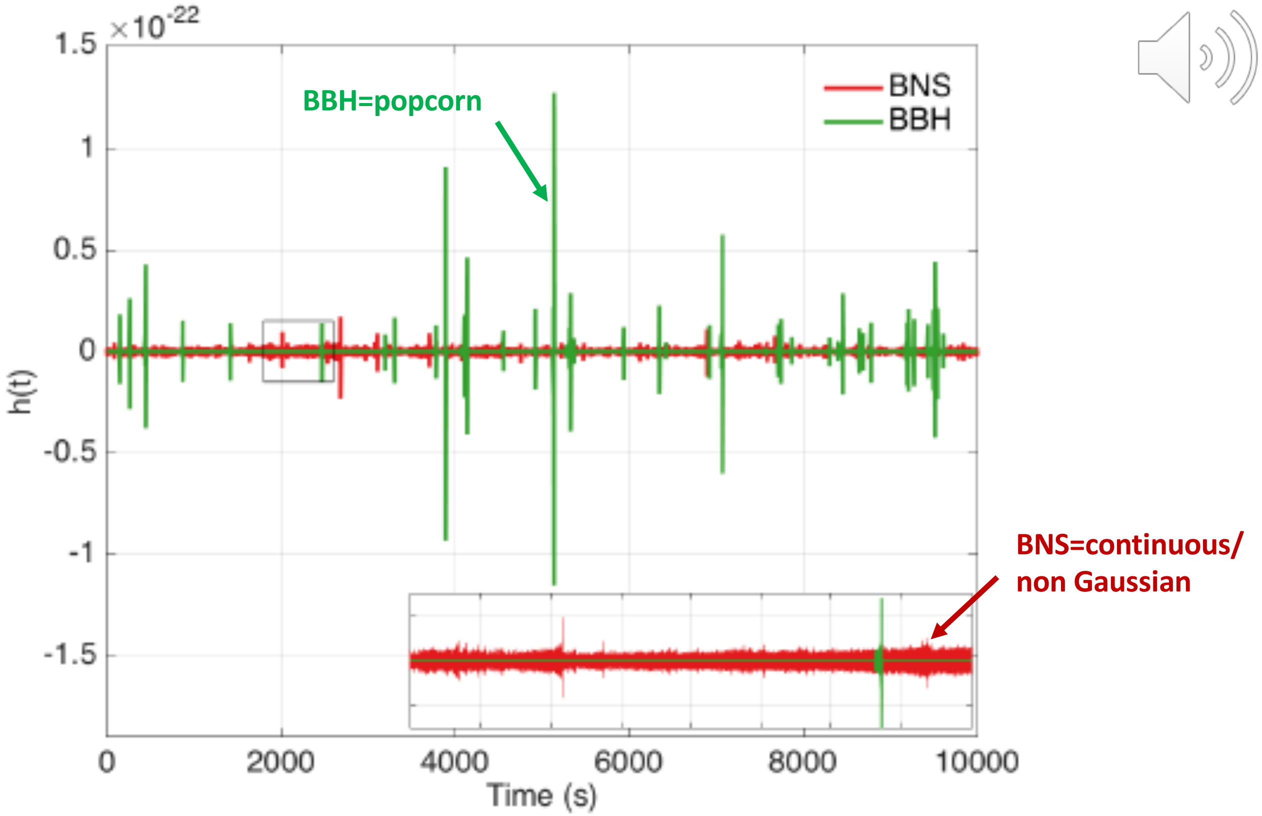
- Sources that overlap and cannot be separated individually.

- Sources that are below the sensitivity of the detectors.

The case of a cosmological background



The case of the CBC background



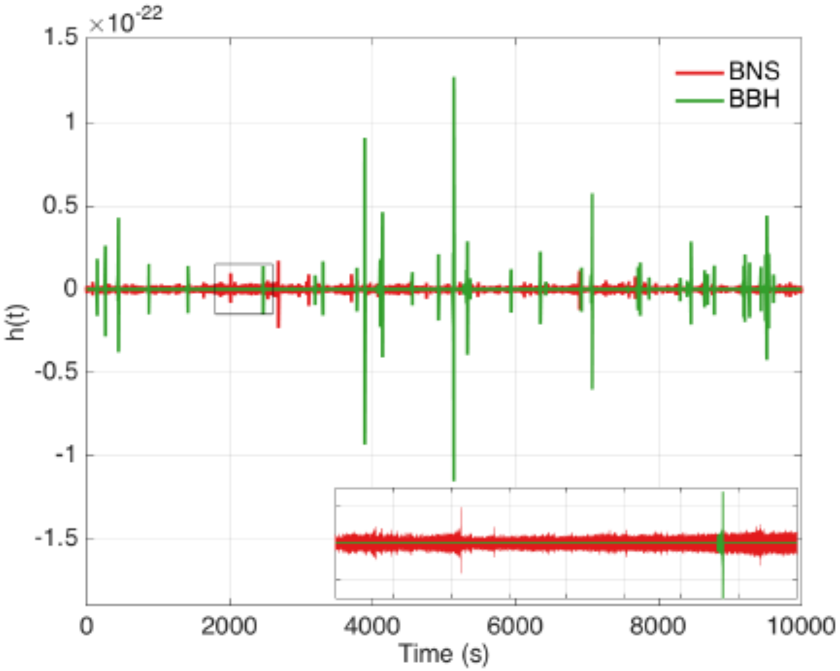
LVC, 2018, [PhysRevLett.120.091101]

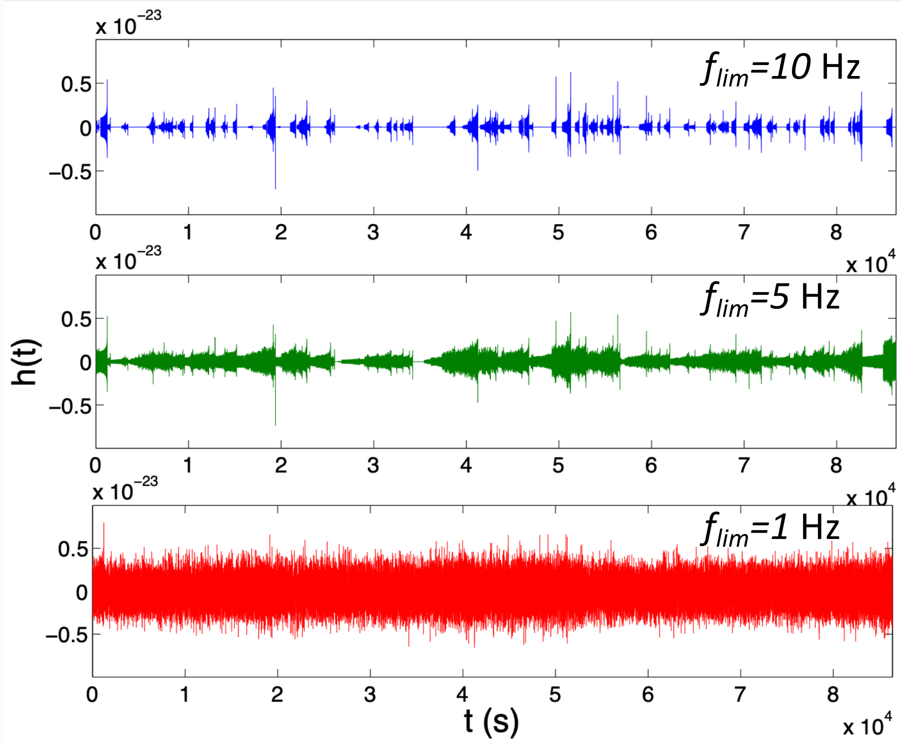
Detection methods for non-Gaussian gravitational wave stochastic backgrounds

Steve Drasco* and Éanna É. Flanagan†
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Dated: November 1, 2018)

A gravitational wave stochastic background can be produced by a collection of independent gravitational wave events. There are two classes of such backgrounds, one for which the ratio of the average time between events to the average duration of an event is small (i.e., many events are on at once), and one for which the ratio is large. In the first case the signal is continuous, sounds something like a constant *hiss*, and has a Gaussian probability distribution. In the second case, the discontinuous or intermittent signal sounds something like popcorn popping, and is described by a non-Gaussian probability distribution. In this paper we address the issue of finding an optimal detection method for such a non-Gaussian background. As a first step, we examine the idealized situation in which the event durations are short compared to the detector sampling time, so that the time structure of the events cannot be resolved, and we assume white, Gaussian noise in two collocated, aligned detectors. For this situation we derive an appropriate version of the maximum likelihood detection statistic. We compare the performance of this statistic to that of the standard cross-correlation statistic both analytically and with Monte Carlo simulations. In general the maximum likelihood statistic performs better than the cross-correlation statistic when the stochastic background is sufficiently non-Gaussian, resulting in a gain factor in the minimum gravitational-wave energy density necessary for detection. This gain factor ranges roughly between 1 and 3, depending on the duty cycle of the background, for realistic observing times and signal strengths for both ground and space based detectors. The computational cost of the statistic, although significantly greater than that of the cross-correlation statistic, is not unreasonable. Before the statistic can be used in practice with real detector data, further work is required to generalize our analysis to accommodate separated, misaligned detectors with realistic, colored, non-Gaussian noise.

The case of the BNS background

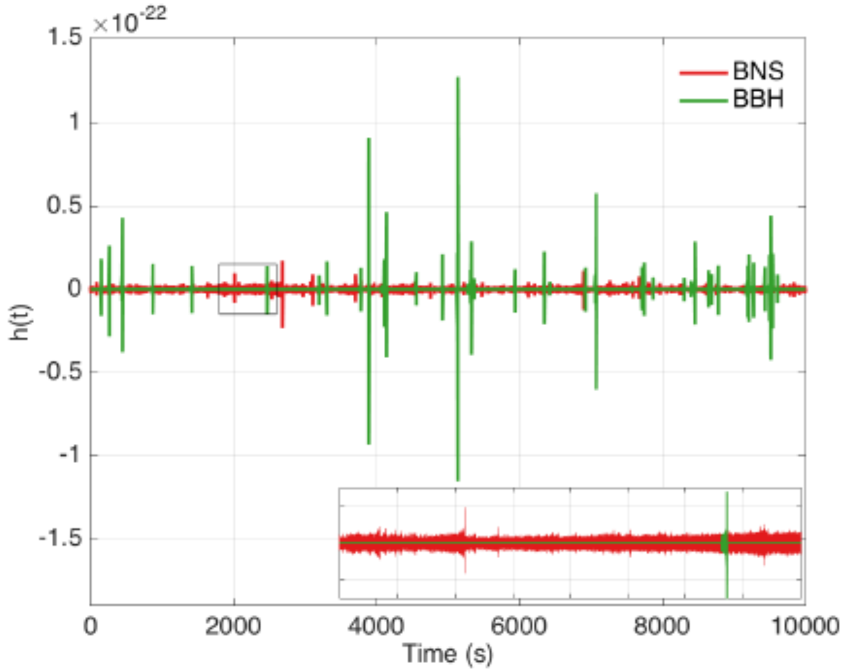


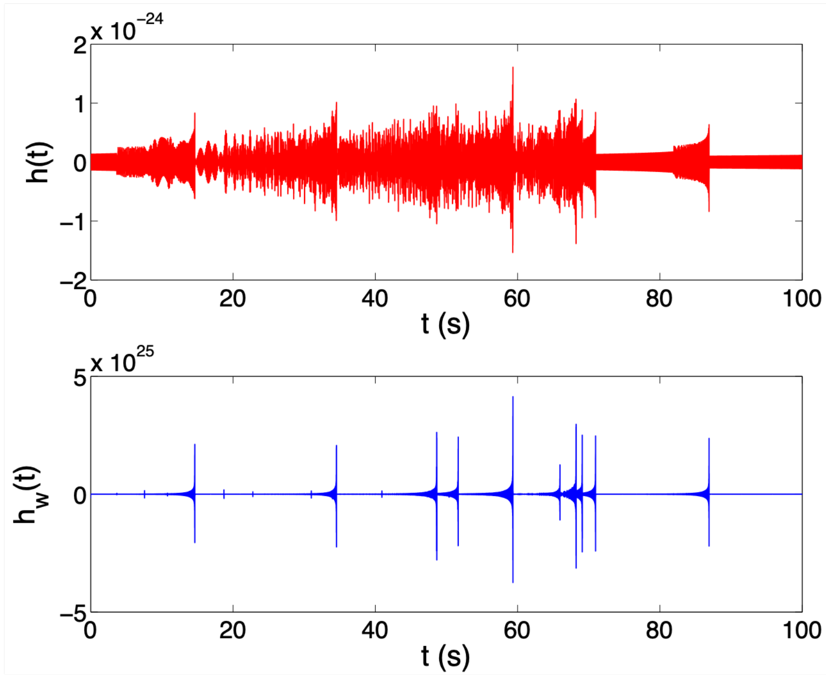


LVC, 2018, [PhysRevLett.120.091101]

Regimbau and Meacher, MDC Generation Package, LIGO-T1400401

The case of the BNS background



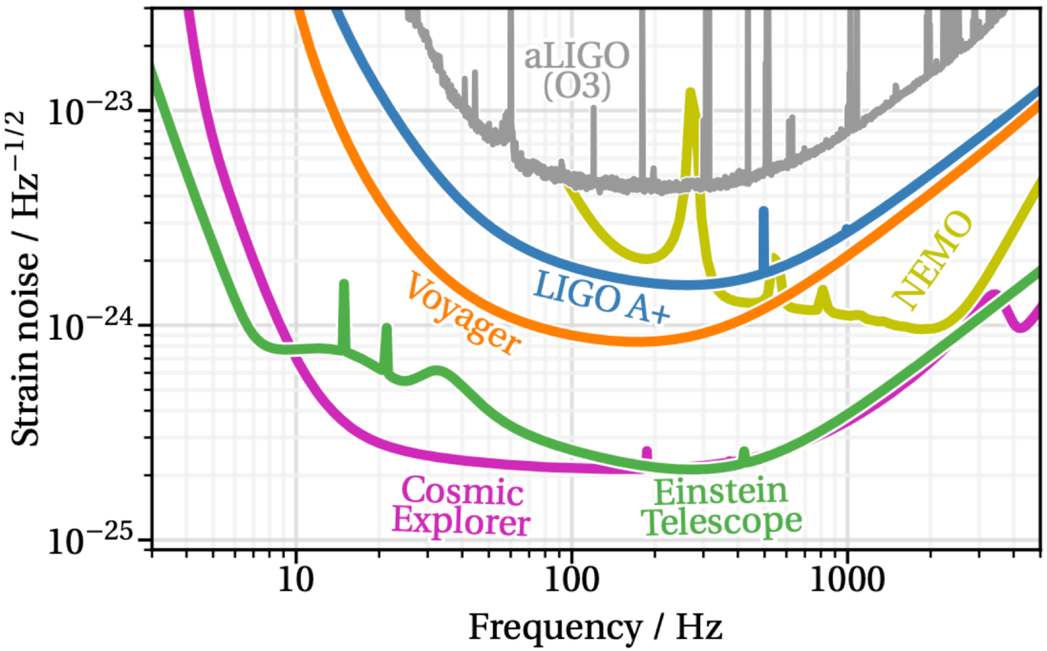


LVC, 2018, PhysRevLett.120.091101
simulated with MDC_Generation package (Regimbau 2012)

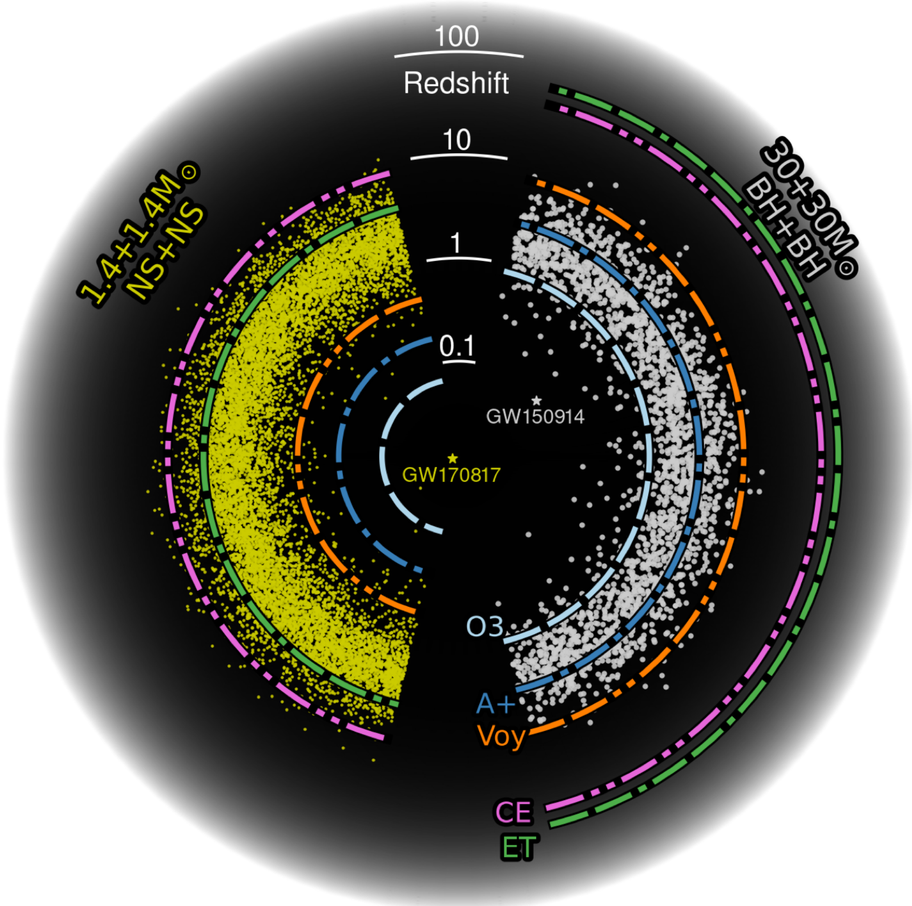
Regimbau, 2018, PhysRevD.86.122001

Q1: Does the background have an interest compared to individual detections?

Individual detections

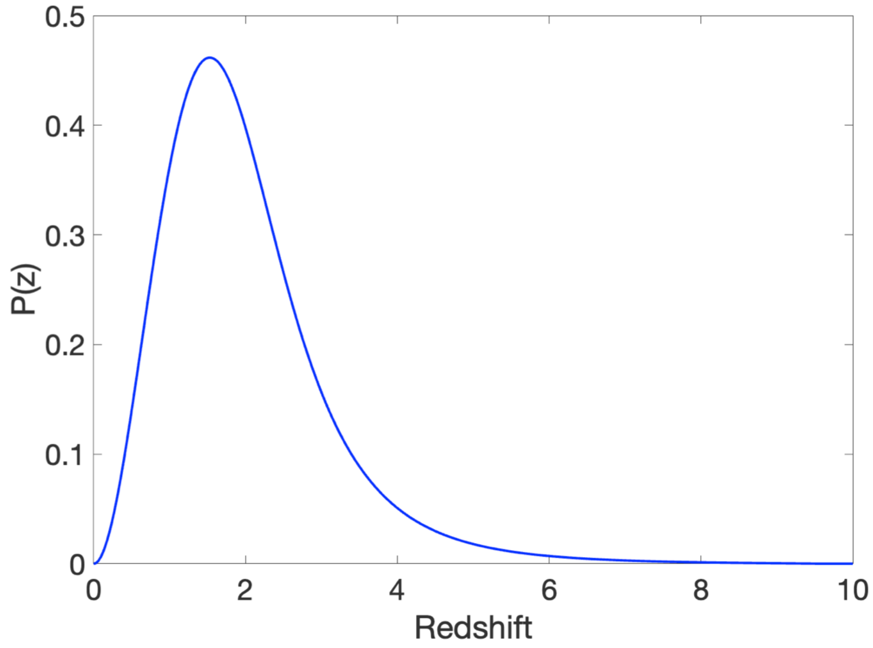


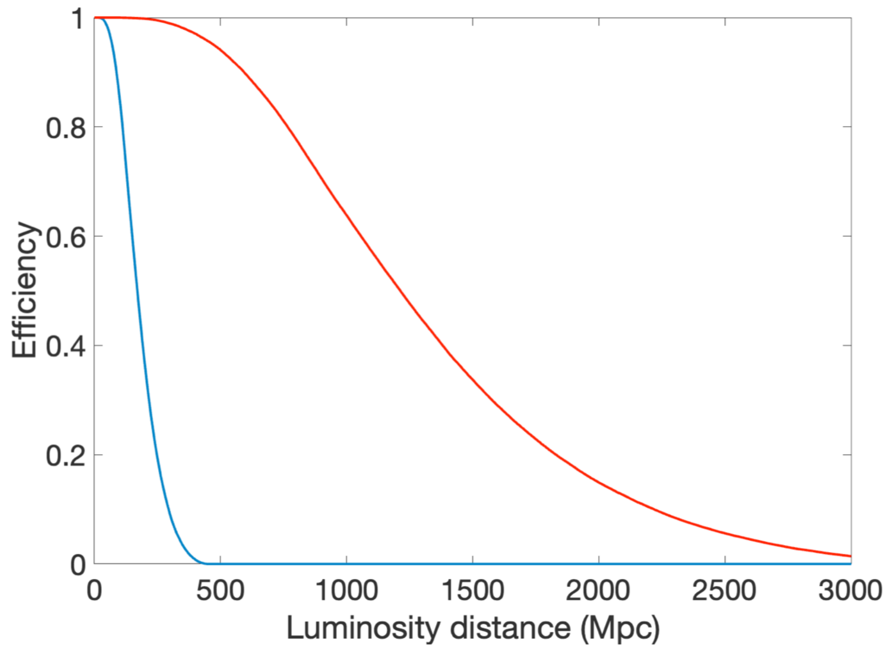
http://cosmicexplorer.org/



With 2G detectors

Individual detections and background probe different redshifts.





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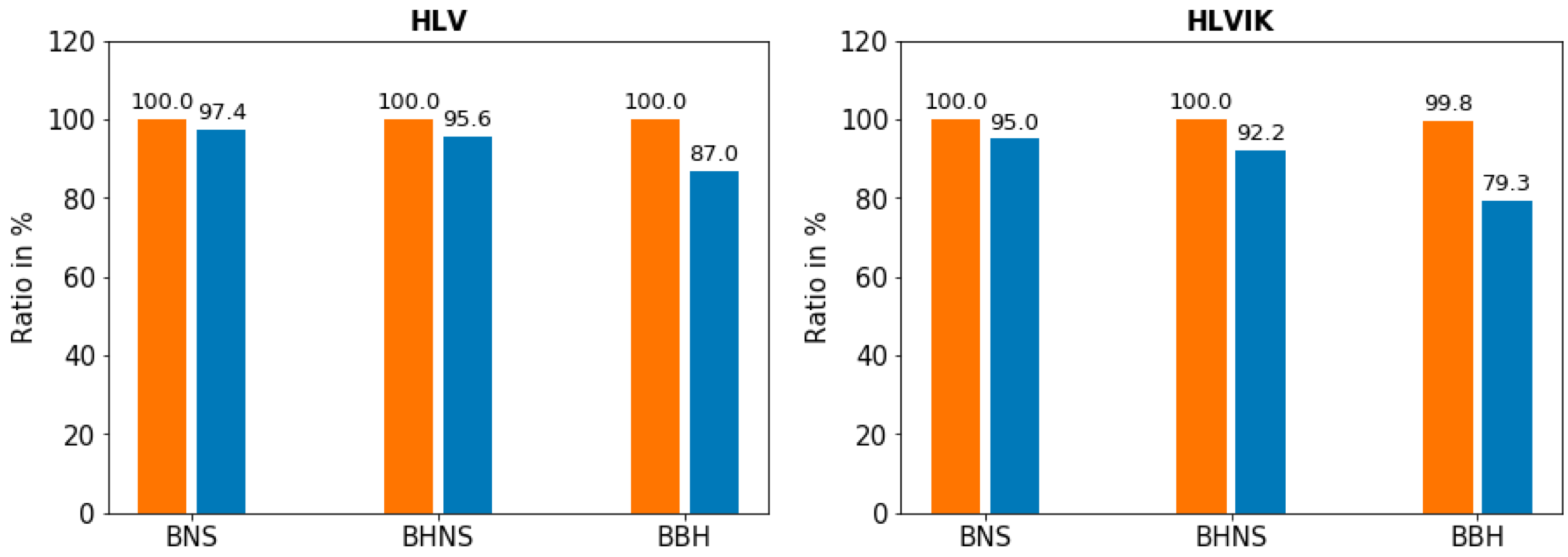


Périgois et al., 2021, PhysRevD.103.043002

With 2G detectors

- The sources that are detected now are the closest and the loudest sources
- The sample of individual detections is strongly biased toward small redshift and large masses
- The background contains informations about average values.

Astrophysical background

The integrated GW flux is the sum of all the individual contributions:

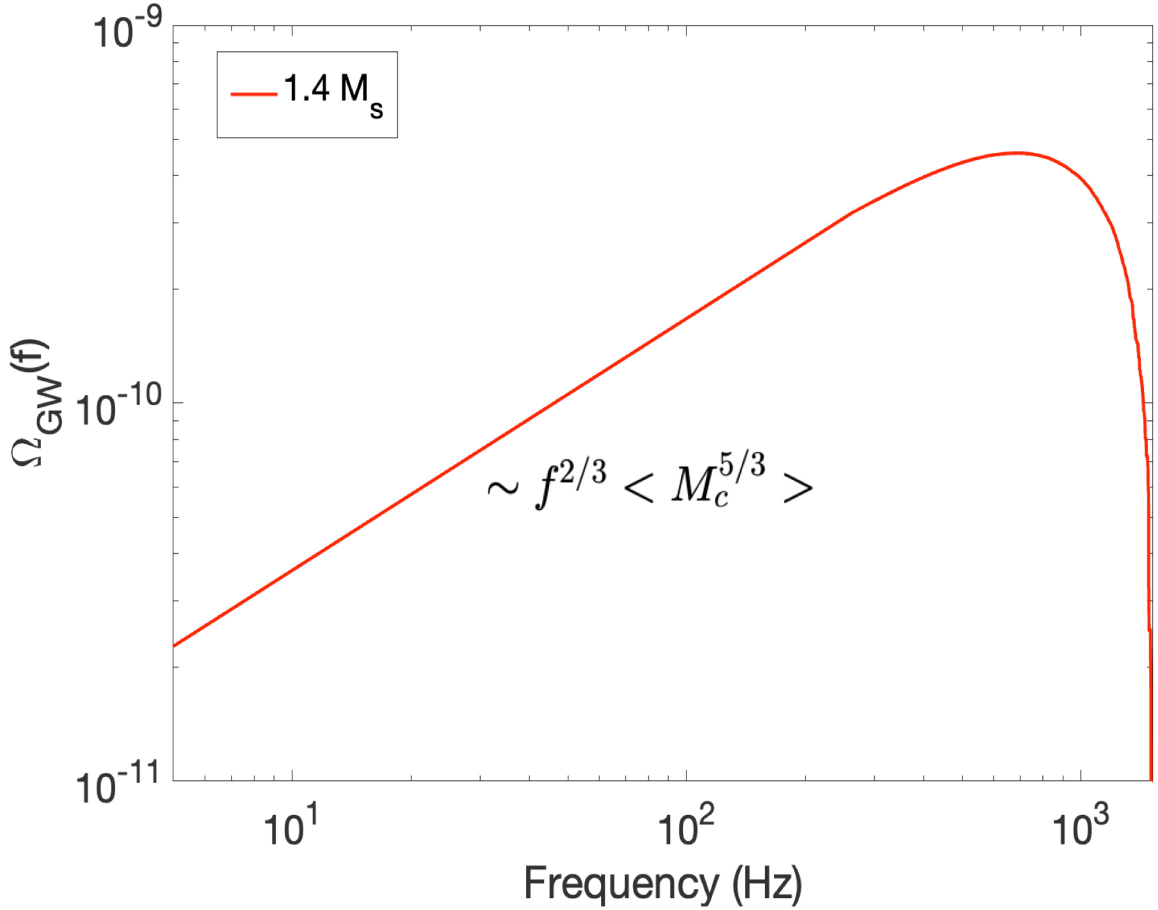
$$F_{GW}(f) = \int_{\Theta} p(\theta) d\theta \int_{z_{\min}(\theta)}^{z_{\max}(\theta)} dz \frac{dR_z}{dz}(\theta, z) \frac{1}{4\pi r(z)^2} \frac{dE_{GW}}{df_s}(\theta, f_s)$$

Rate

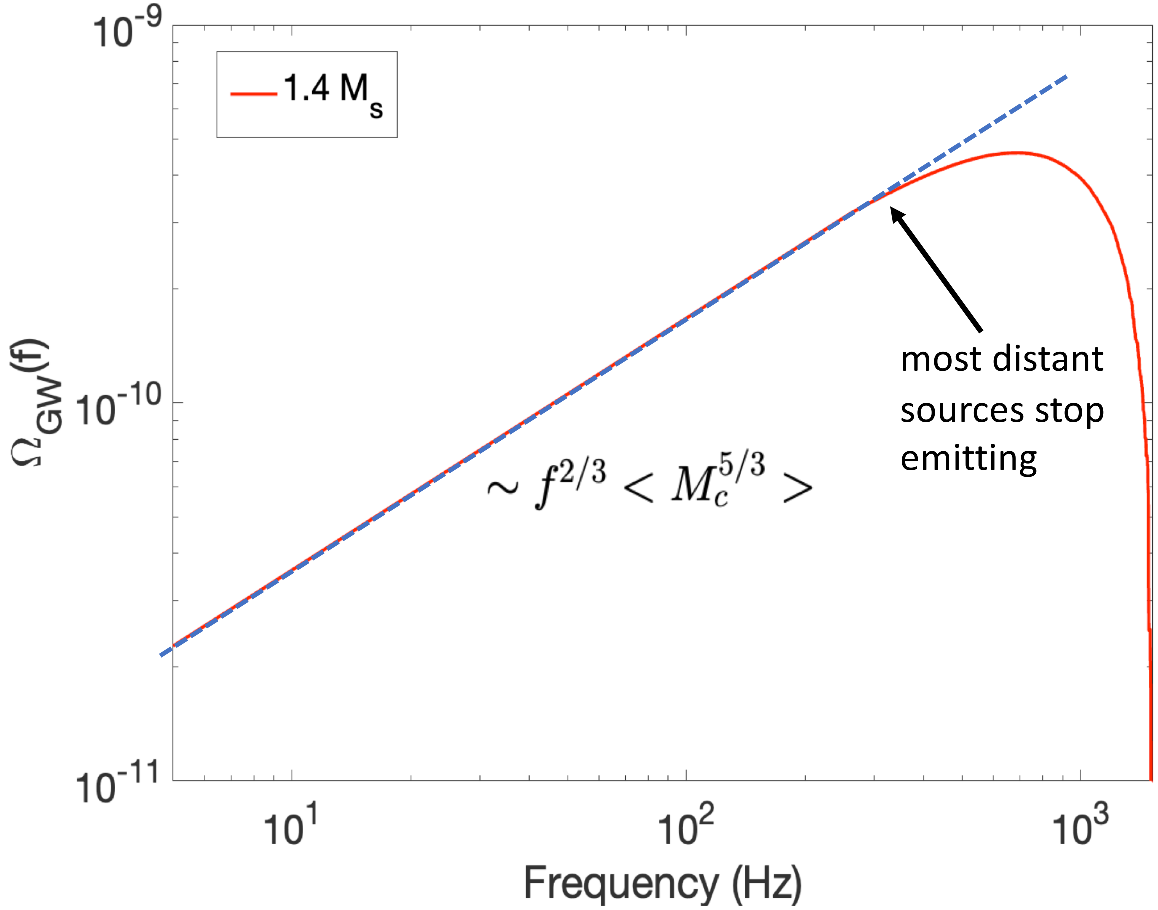
Spectral properties of individual sources

with the individual fluence: $$\frac{1}{4\pi r^2} \frac{dE_{gw}}{df_s}(f_s) = \frac{\pi c^3}{2G} f_s^2 (H_+^2(f_s) + H_\times^2(f_s))$$

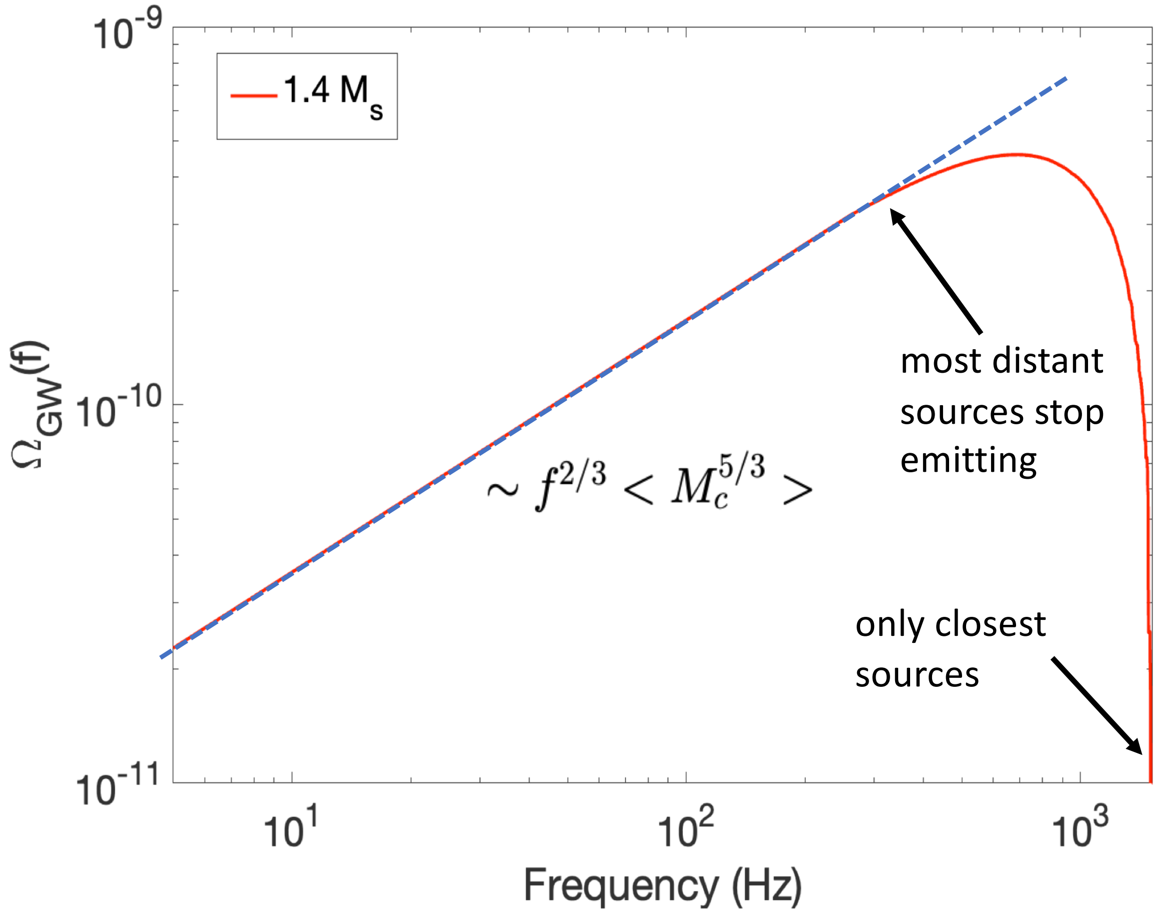
With 2G detectors



With 2G detectors

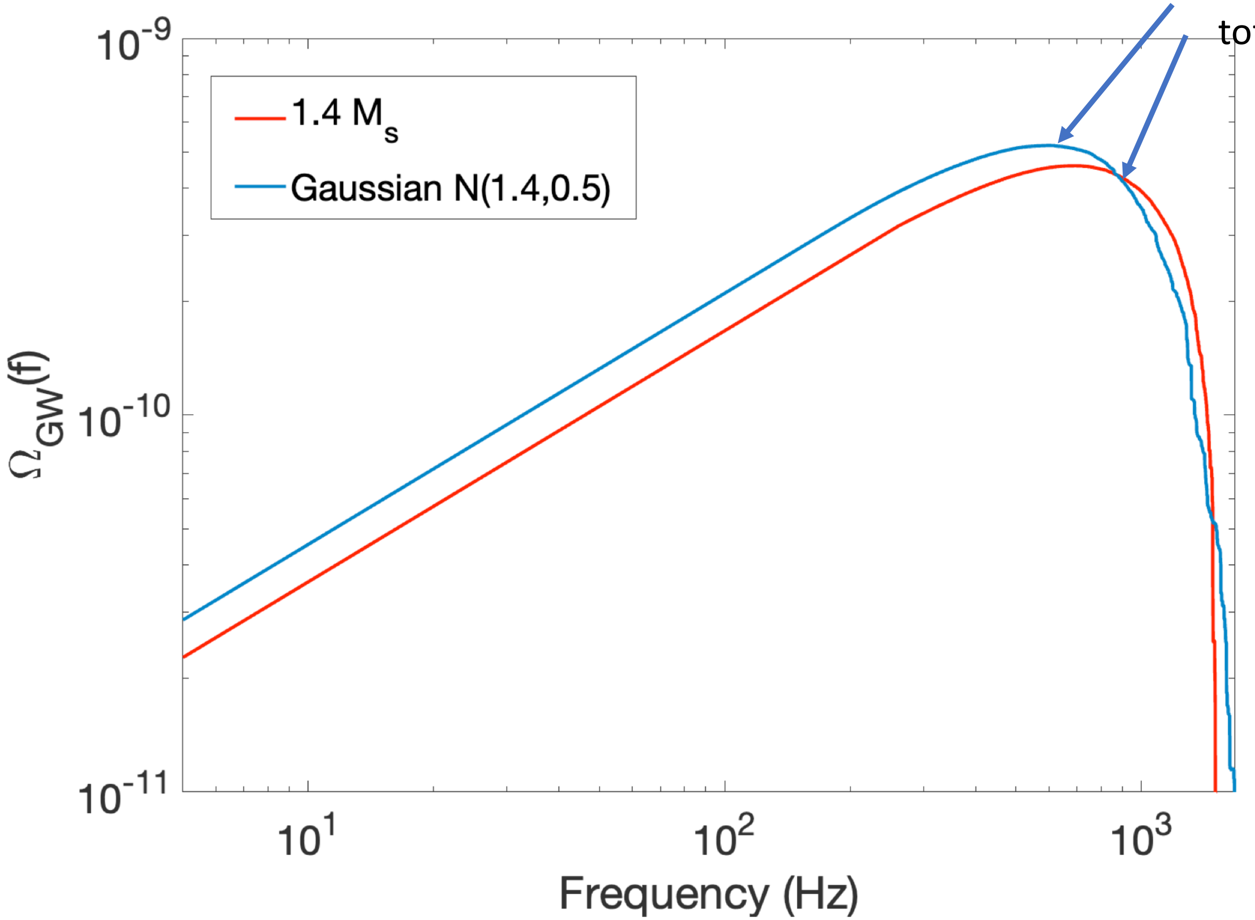


With 2G detectors



With 2G detectors

Peak related to the average redshifted total mass

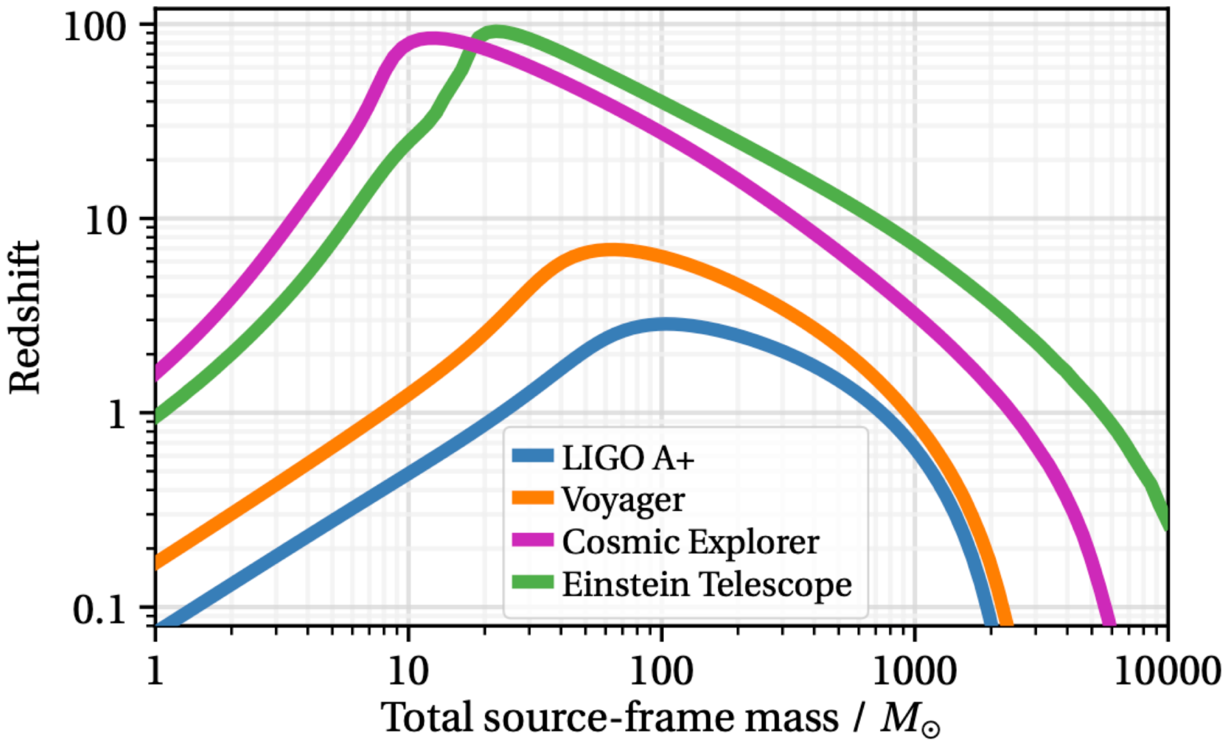


With 2G detectors

- The sources that are detected now are the closest and the loudest sources
- The sample of individual detections is strongly biased toward small redshift and large masses
- The background contains informations about average values.
- What is it with next generations ?

With 3G detectors

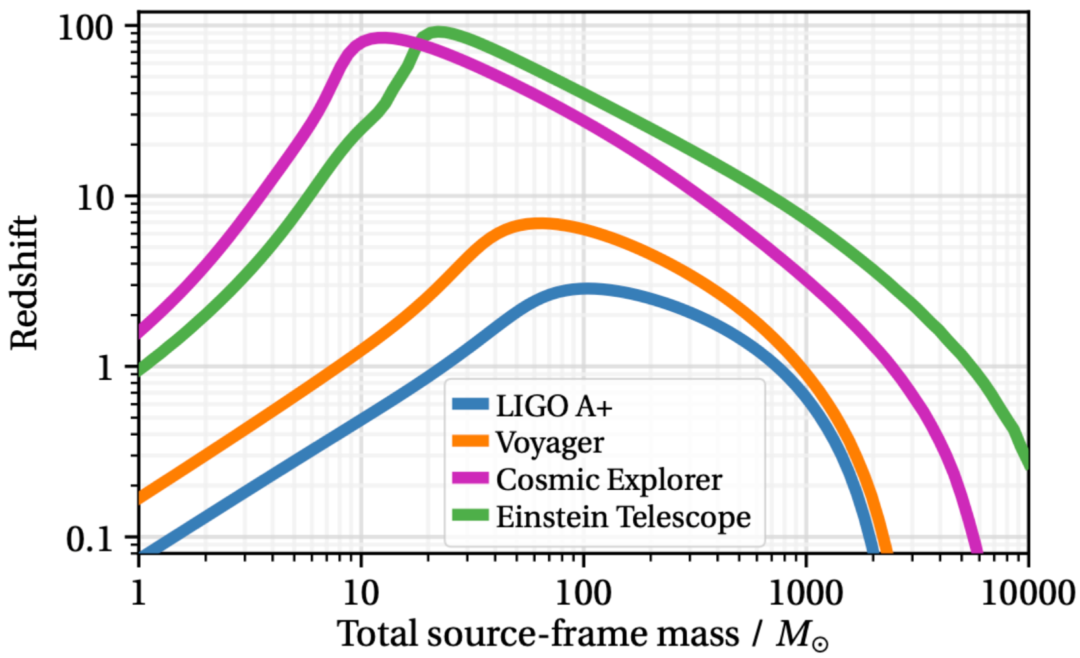
Individual detections and background probe different redshifts?

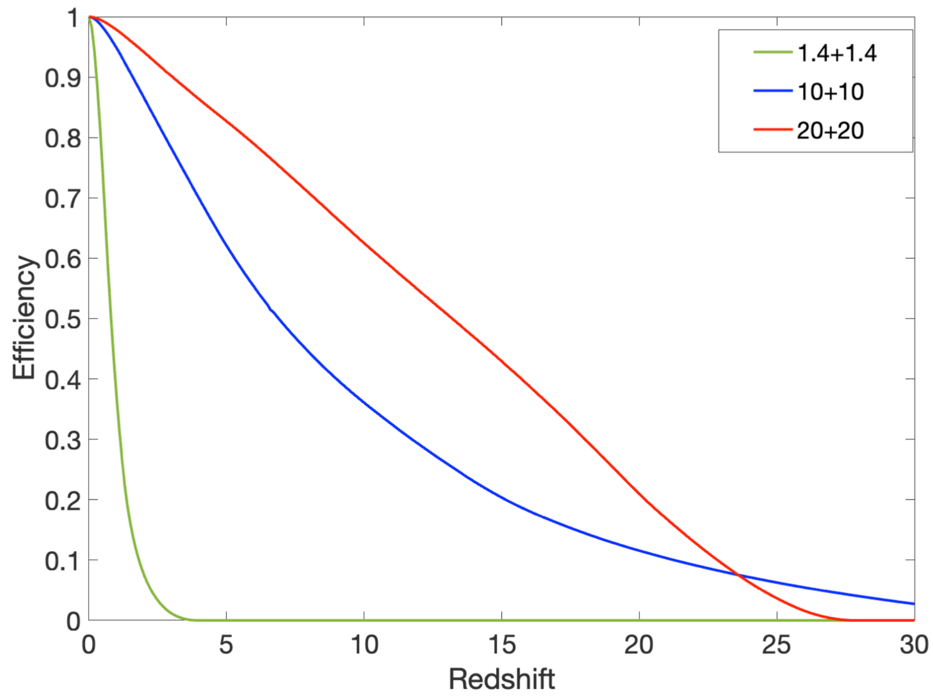


http://cosmicexplorer.org/

With 3G detectors

Individual detections and background probe different redshifts?





Q2. Will we be able to get rid of the astrophysical foreground from CBCs with NG

What do we have in the background?

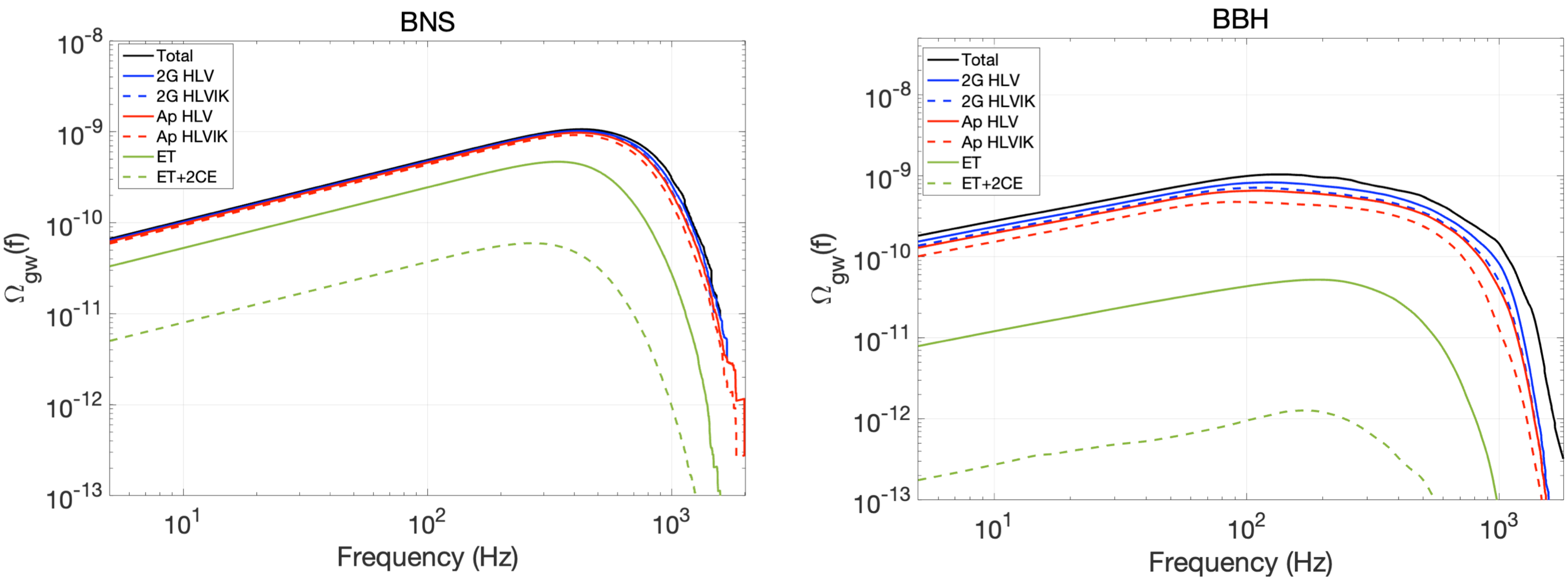
The total background is the sum of different contributions:

$$\Omega_{\mathrm{GW}} = \Omega_{\mathrm{astro,\ r}} + \Omega_{\mathrm{cosmo}} + \Omega_{\mathrm{cbc}}.$$

The total background from CBCs is formed by resoved and unresolved sources:

$$\Omega_{\mathrm{cbc}} = \Omega_{\mathrm{cbc,res}} + \Omega_{\mathrm{cbc,unres}}$$

Residual background



Régimbau et al., 2017, PhysRevLett.118.151105; 2022 Symmetry

Subtracting the background from CBCs

The total background is the sum of different contributions:

$$\Omega_{\rm GW} = \Omega_{\rm astro,\ r} + \Omega_{\rm cosmo} + \Omega_{\rm cbc}.$$

The background from CBCs is formed by resoved and unresolved sources:

$$\Omega_{\rm cbc} = \Omega_{\rm cbc,res} + \Omega_{\rm cbc,unres}$$

Errors on parameters estimation:

$$\Omega_{\rm cbc} = \Omega_{\rm cbc,\ rec} + \Omega_{\rm error} + \Omega_{\rm cbc,\ unres}$$

Effect of errors on parameter estimation

In addition to non resolved sources the residual contains a contribution due to waveforms non perfectely removed:

$$\Omega_{\mathrm{cbc}} = \Omega_{\mathrm{cbc,\ rec}} + \Omega_{\mathrm{error}} + \Omega_{\mathrm{cbc,\ unres}}$$

The contribution from parameter estimation erros is:

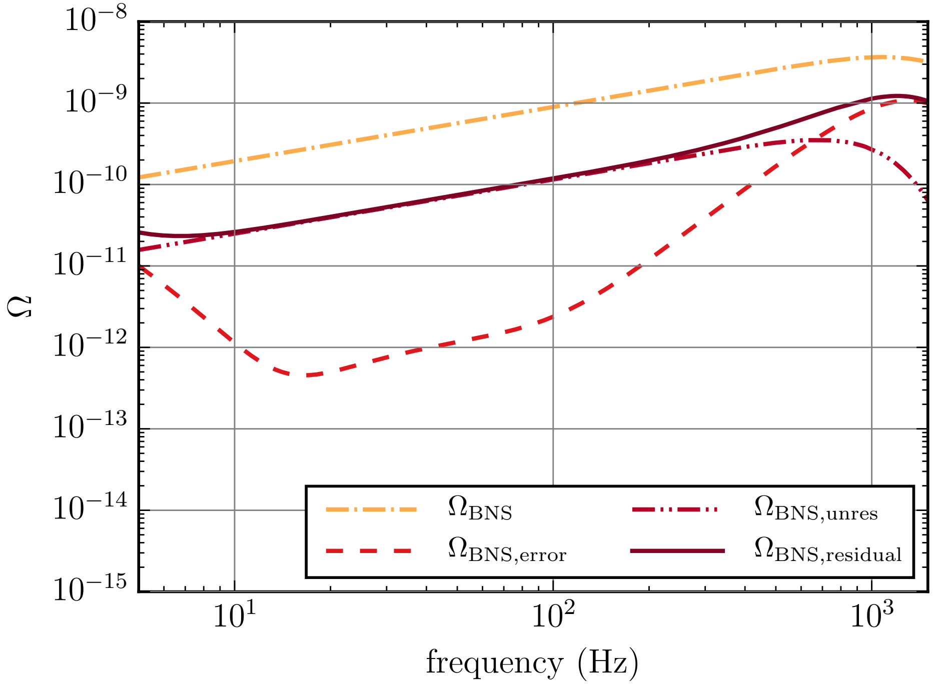
$$\Omega_{\mathrm{error}} = \frac{1}{\rho_c c} f F_{\mathrm{error}}(f)$$

$$F_{\mathrm{error}}(f) = T^{-1}\frac{\pi c^3}{2G} f^2 \sum_{k=1}^{N} ((\tilde{h}^{\mathrm{true}}_{+,k}(f) - \tilde{h}^{\mathrm{recovered}}_{+,k}(f))^2 + (\tilde{h}^{\mathrm{true}}_{\times,k}(f) - \tilde{h}^{\mathrm{recovered}}_{\times,k}(f))^2)$$

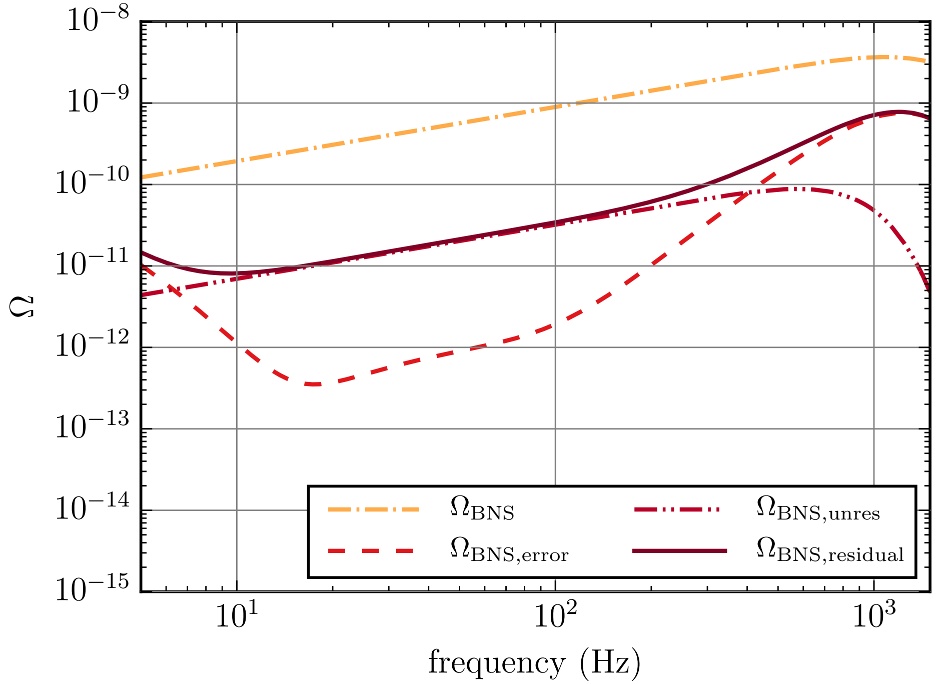
Sachdev et al., PhysRevD.102.024051

Effect of errors on parameter estimation

$\vec{\theta} = (f_0 t_c, \phi_c, \ln \mathcal{M})$.



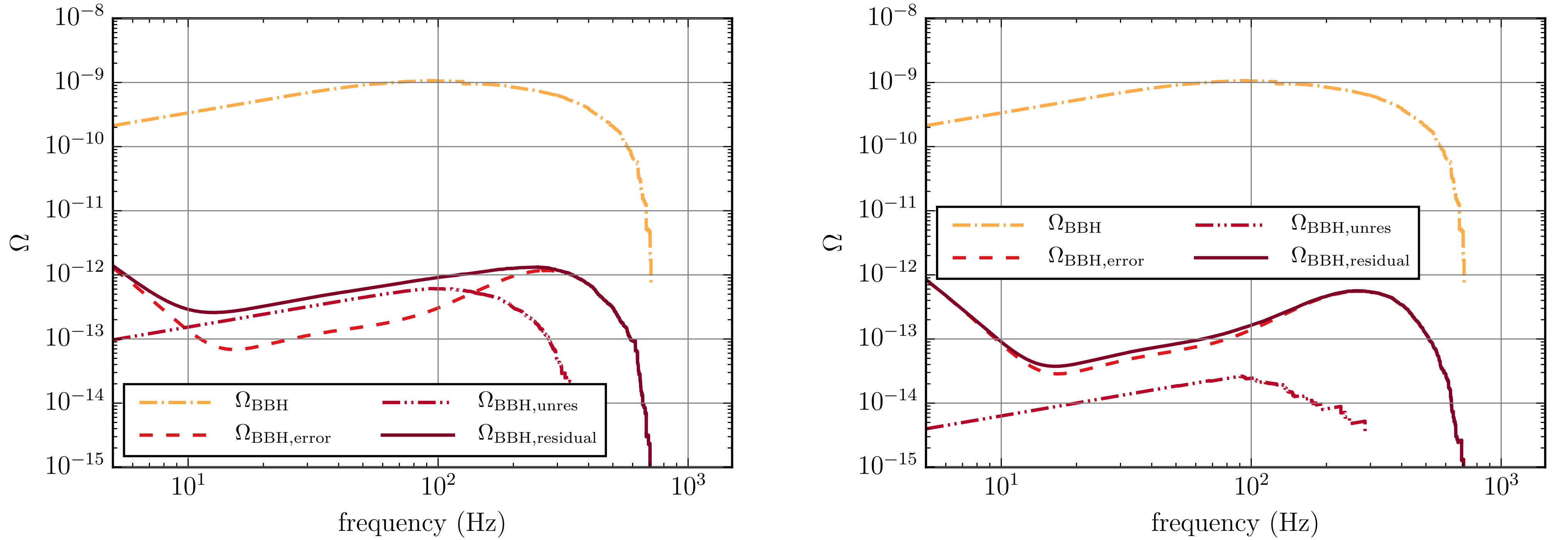
(c) BNS, HLV network



(d) BNS, HLVIK network

Sachdev et al., [PhysRevD.102.024051]

Effect of errors on parameter estimation

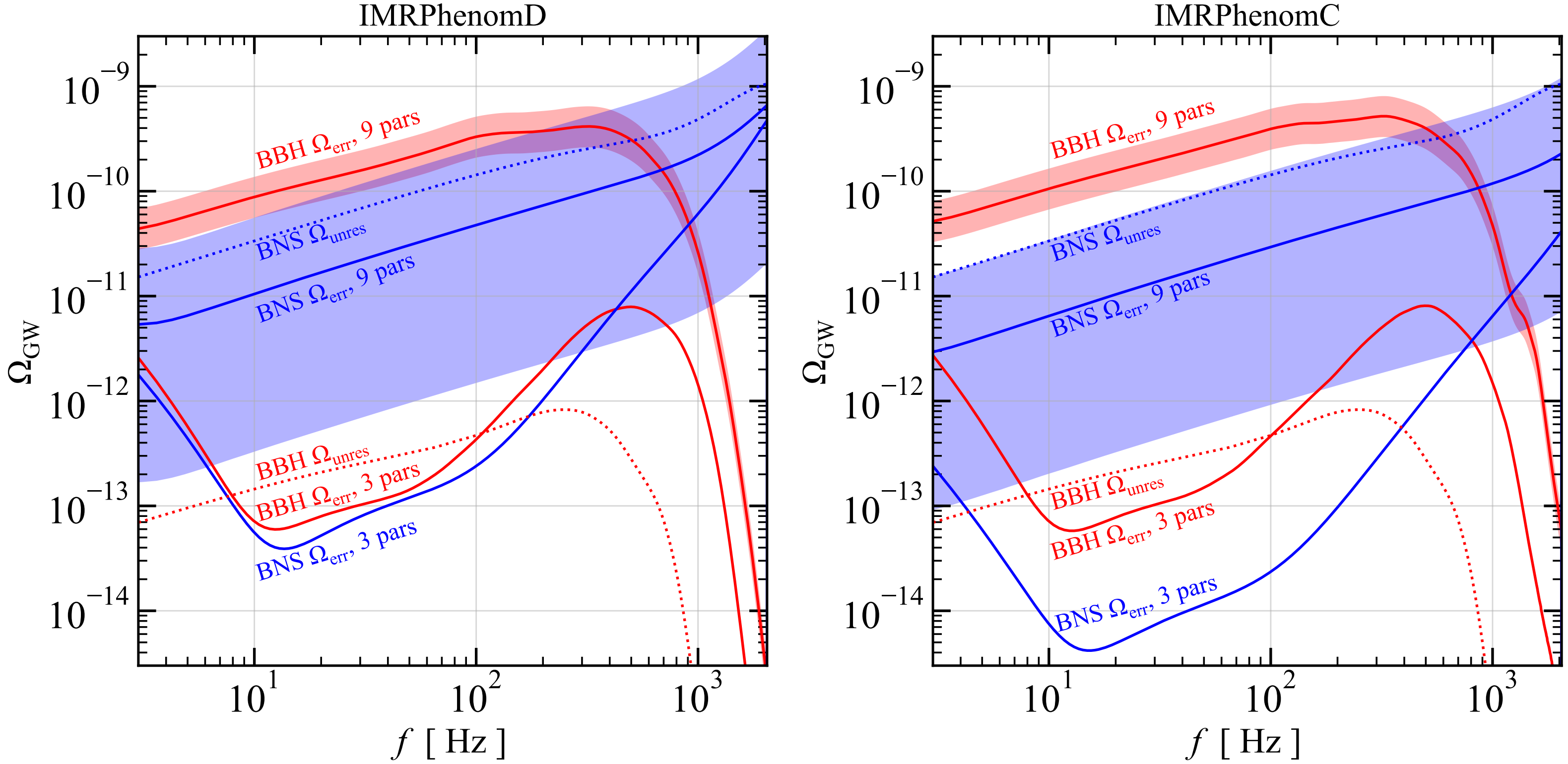


(a) BBH, HLV network

(b) BBH, HLVIK network

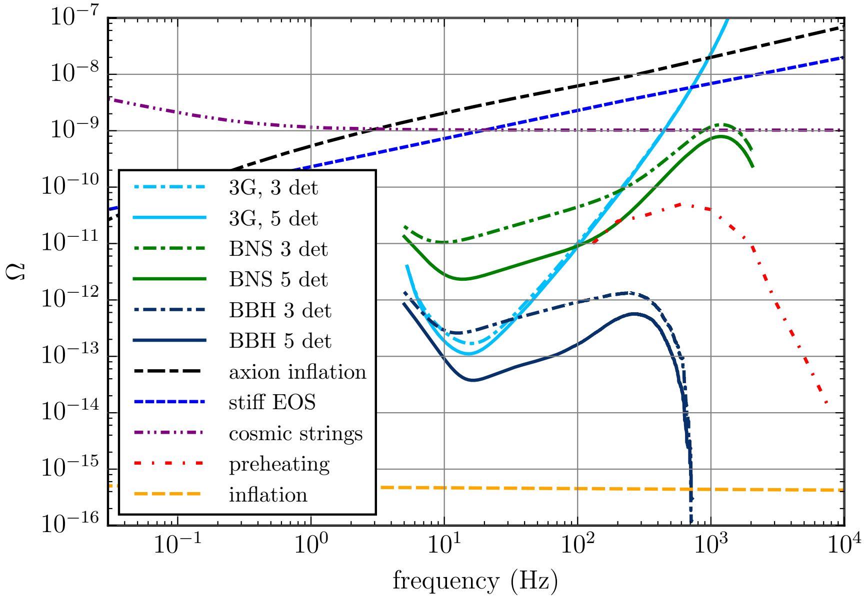
The situation get worse with 9 parameters

$$\boldsymbol{\theta} = \left\{ \ln\left(\frac{\mathcal{M}_z}{M_\odot}\right), \eta, \ln\left(\frac{D_L}{\mathrm{Mpc}}\right), \cos\iota, \cos\delta, \alpha, \psi, \phi_c, t_c \right\}$$

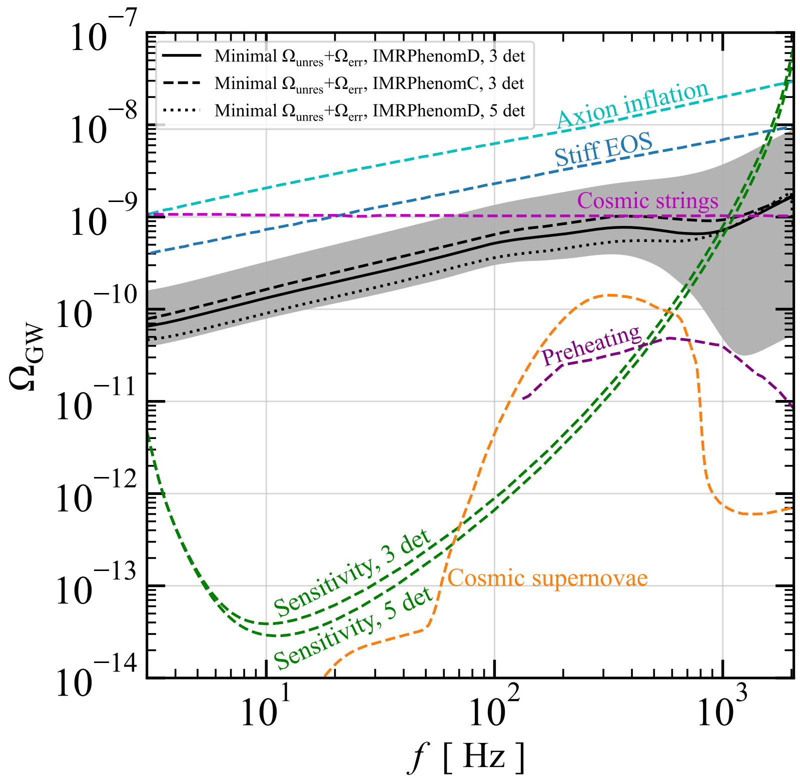


Zhou et al., [arXiv:2209.01310](https://arxiv.org/abs/2209.01310)

A foreground for other backgrounds



Sachdev et al., 2021, [PhysRevD.102.024051]

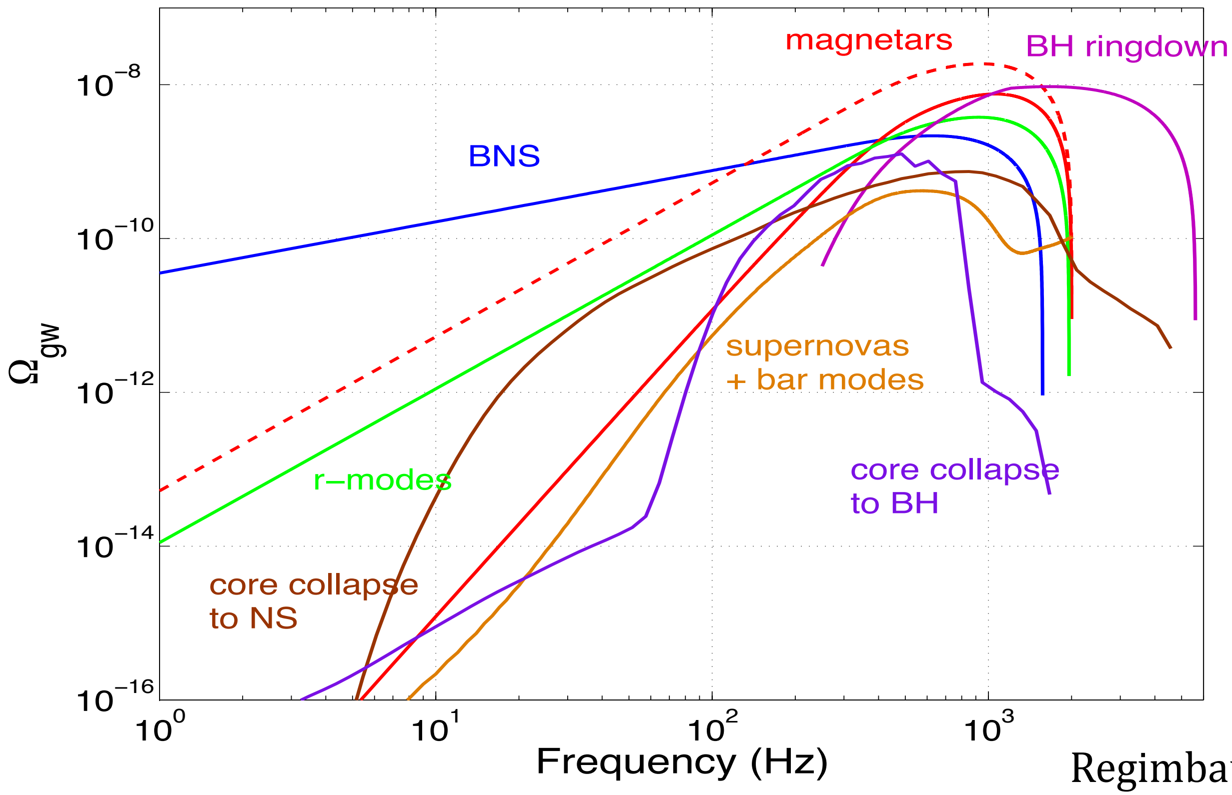


Zhou et al., 2022, submitted

What can we do ?

- Projection methods (Cutler and Harms 2006; Sharma et al. 2020)
- Bayesian method (Biscoveanu et al. 2020)
- Notching in the time frequency plan (Zhong et al. 2022)
- For ET, use the null stream

Other backgrounds : astrophysical predictions



Regimbau, arXiv:1101.2762

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Constraints on young pulsars/magnetars

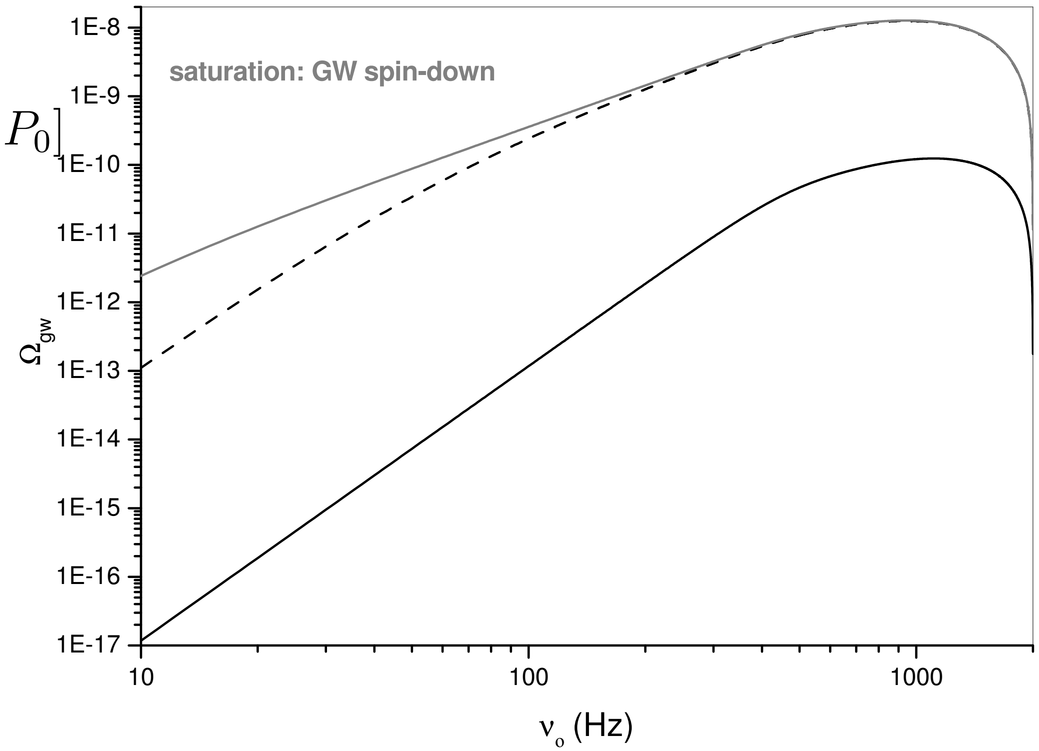
Spectral energy density:

$$\frac{dE_{gw}}{d\nu} = K\nu^3(1 + \frac{K}{\pi^2 I_{zz}}\nu^2)^{-1} \ \text{with} \ \nu \in [0 - 2/P_0]$$

$$K = \frac{192\pi^4 G I^3}{5c^2 R^6} \frac{\varepsilon^2}{B^2 \sin^2 \alpha}$$

Ellipticity:

$$\varepsilon_B = \beta \frac{R^8 B^2 \sin^2 \alpha}{4 G I_{zz}^2}$$



Regimbau and Mandic, 2008

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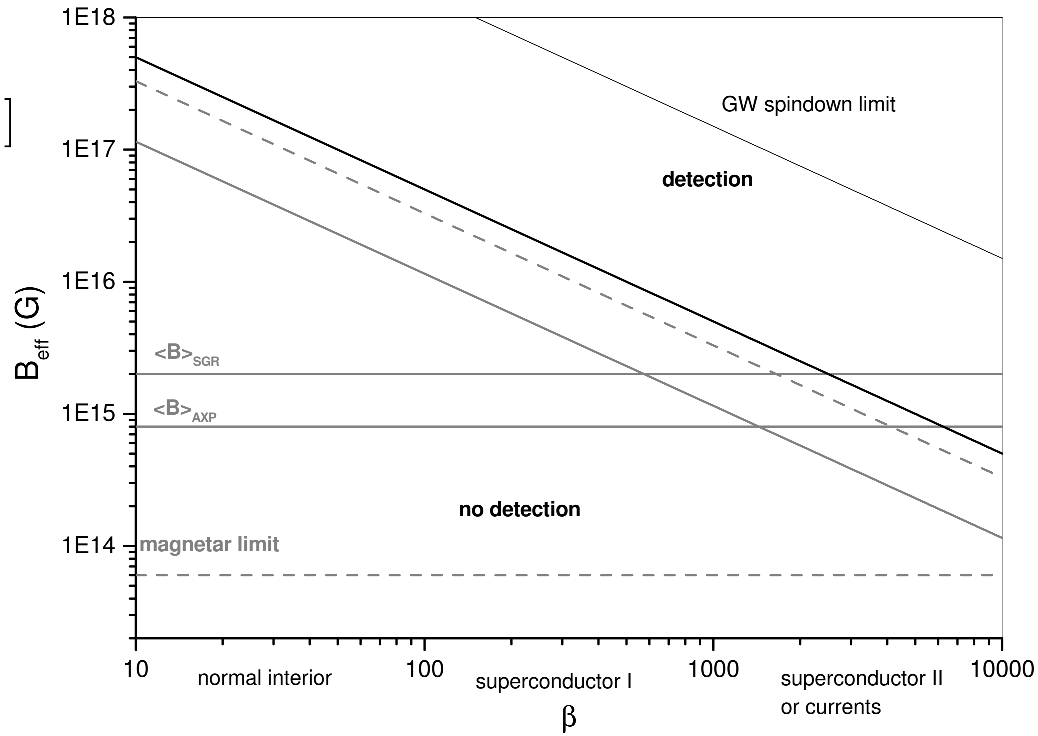

Regimbau and Mandic, 2008

Conclusion

- It is not clear that the background will bring extra informations compared to individual detection for CBCs
- The situation is different for other astrophysical background or the cosmological background
- Parameter estimation errors jeopardize the chance to observe any other background in NG detectors