THE QUEST FOR THE SGWB WITH LIGO/VIRGO

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SB of GW, HEP@VUB Brussels, 14/11/2019

Stochastic GW Background

- A stochastic background of gravitational waves has resulted from the superposition of a large number of independent unresolved sources from different stages in the evolution of the Universe.

- Either cosmological (signature of the early Universe) or astrophysical (since the beginning of stellar activity)

- Usually characterized by the energy density in GWs:

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

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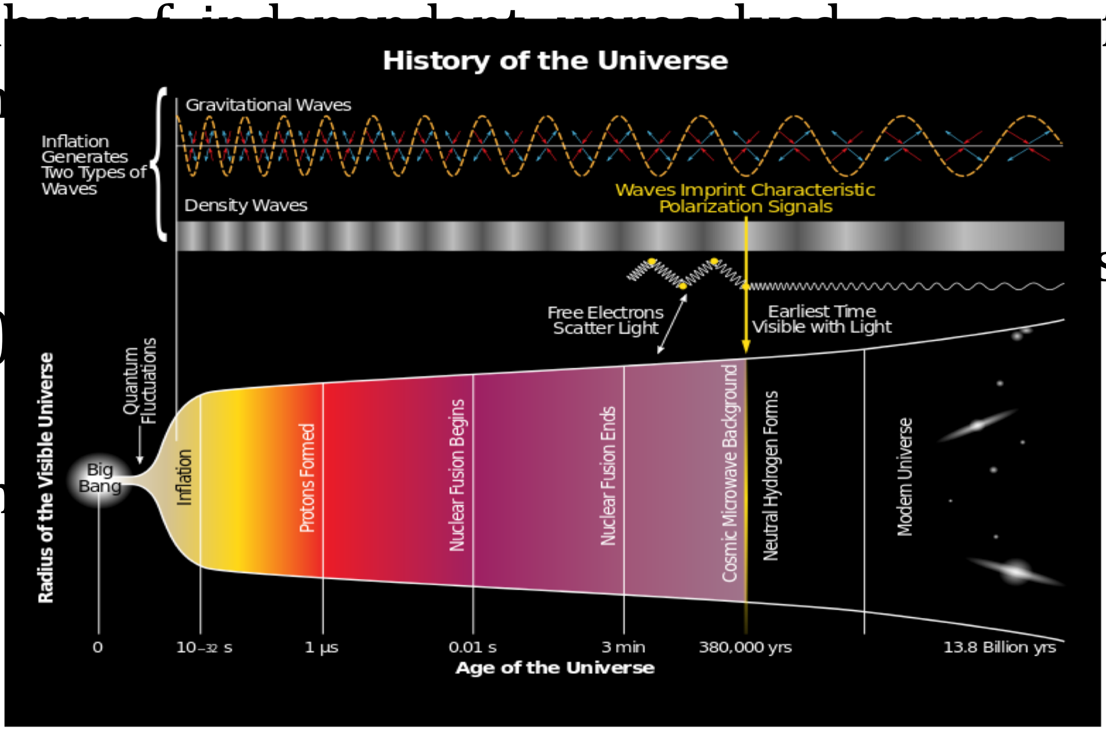


SGWB = noise

Family dinner

Cocktail party

SGWB = symphony of the Universe

SGWB = symphony of the Universe

?

Cosmological background

- Unique window on the very early stages and on the physical laws that apply at the highest energy scales (potentially up to the Grand Unified Theory (GUT) scale 10^{16} GeV).

- An *irreductible background* has resulted from the amplification of vacuum metric fluctuations during inflation (arXiv:1610.06481)

- Active sources could have enhanced GW production at the end of inflation (particle production, reheating, spectator fields, primordial black holes)

- Other models include cosmic phase transitions (first order electroweak in LISA), topological defects (cosmic (super)strings)

Relating CMB results to the SGWB

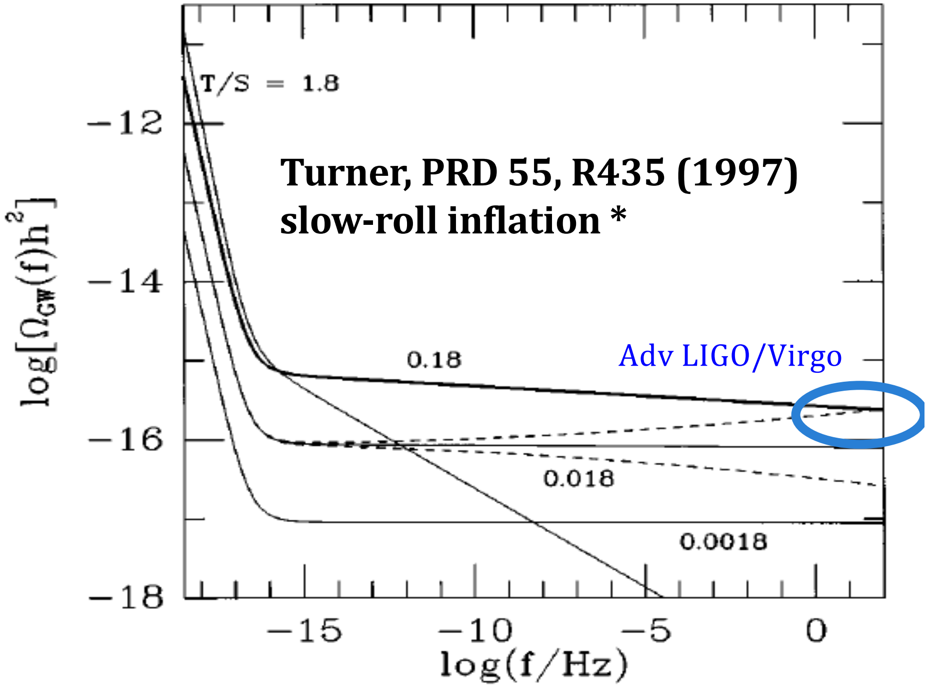
- Energy density in GWs :

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

- Amplitude scales with *r=T/S*

- Spectral shape depends on *r:*

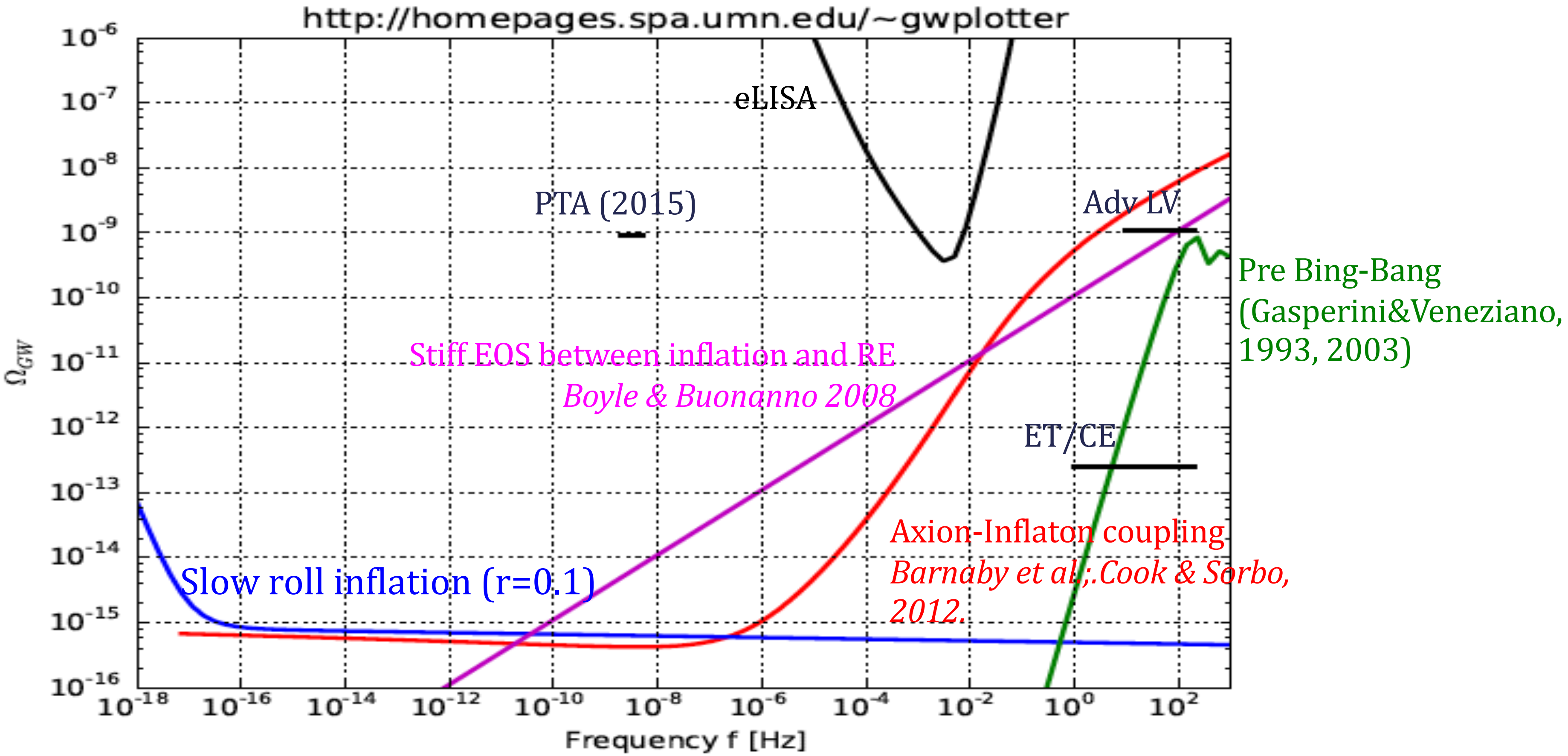
$$\Omega_{gw}(f)\approx f^{n_T} \text{ with } n_T=-r/8$$



Turner, PRD 55, R435 (1997)
slow-roll inflation *

- Bicep2/Keck/Planck gives r<0.1 at 95% confidence (arXiv:1510.09217)

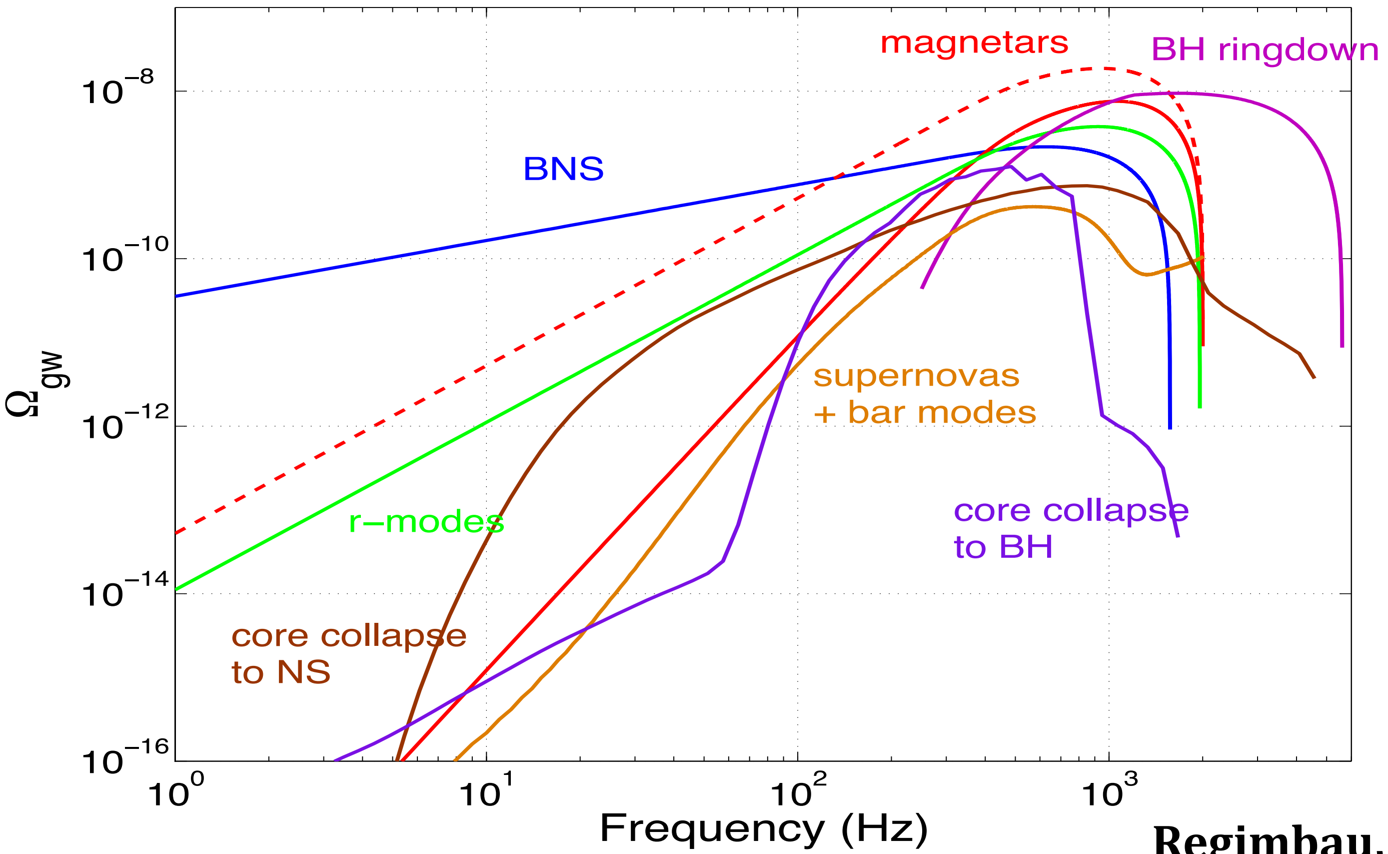
Background from inflation



Astrophysical Backgrounds

- All the sources not resolved individually (overlapping/subthreshold)
- Complementary to individual detections (probe the high redshift population)
- Carry lots of information about the star formation history, the metallicity evolution, the average source parameters.
- May have different statistical properties: non continuous, non-Gaussian, non isotropic
- But can be a noise for the cosmological background

Astrophysical Backgrounds



Regimbau, arXiv:1101.2762

Implications of the first LIGO/Virgo detections

- LIGO and Virgo have already observed 10 BBHs and 1 BNS in O1/O2 (˜40 alerts in O3).
- The events we detect now are loud individual sources at close distances ($z \sim 0.1$-0.5 for BBHs and $z \sim 0.01$ for the BNS). Many more sources at larger distances contribute to create a stochastic background.
- Using mass distributions and local rates derived from the first observations, we were able to revise previous predictions of the GW background from BBHs and BNSs.
- The detection of this background could be the next milestone for LIGO/Virgo.

Stochastic background from CBCs

Energy density in GWs for a population k (BBH, BNS or BH-NS)

$$\Omega_{GW}(f,\theta_k) = \frac{f}{\rho_c}\int d\theta_k P(\theta_k)\int_0^{10} dz R_m^k(z,\theta_k)\frac{\frac{dE_{gw}}{df}(\theta_k, f(1+z))}{4\pi r^2(z)}$$

Rate

Spectral properties
of individual sources

with distribution $P(\theta_k)$ in the parameter space $\theta_k=(m_1,m_2,\chi_{eff})$

Contribution of GW150914-like BBHs

- The analysis of GW150914 provides :
- Masses and spin: m_1=36$M_\odot$, m_2=29$M_\odot$, χ_{eff}~0 (arXiv:1602.03840)
- Local merger rate: $R_0 = 16^{+38}_{-13}$ $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ (arXiv:1602.03842)

- We also assume (fiducial model):
- BBHs with m~30$M_\odot$ form in low metallicity environment Z<1/2 $Z_\odot$
- The formation rate is proportional to the SFR (Vangioni et al. 2015)
- The merger rate tracks the formation rate, albeit with some delay t_d.

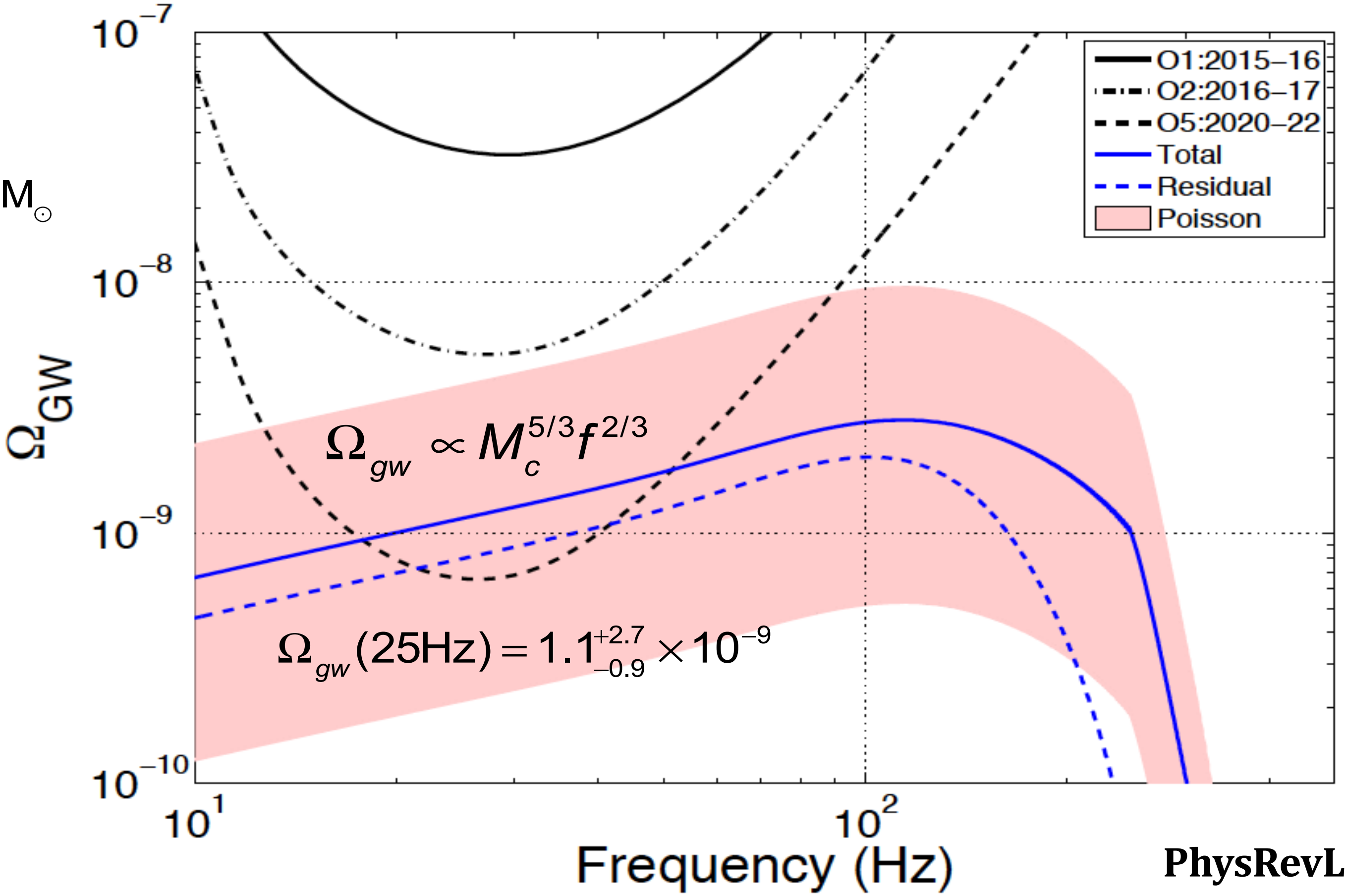
$$R_m(z,\theta_k) = \int_{t_{\min}}^{t_{\max}} R_f(z,\theta_k) P(t_d,\theta_k)\, dt_d$$

- Short delay time: $P(t_d) \propto t_d^{-1}$ with $t_d > 50$ Myr

GW150914: Fiducial Model

chirp mass:

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \simeq 28M_\odot$$



$$\Omega_{gw} \propto M_c^{5/3} f^{2/3}$$

$$\Omega_{gw}(25\text{Hz}) = 1.1^{+2.7}_{-0.9} \times 10^{-9}$$

PhysRevLetter.116.131102

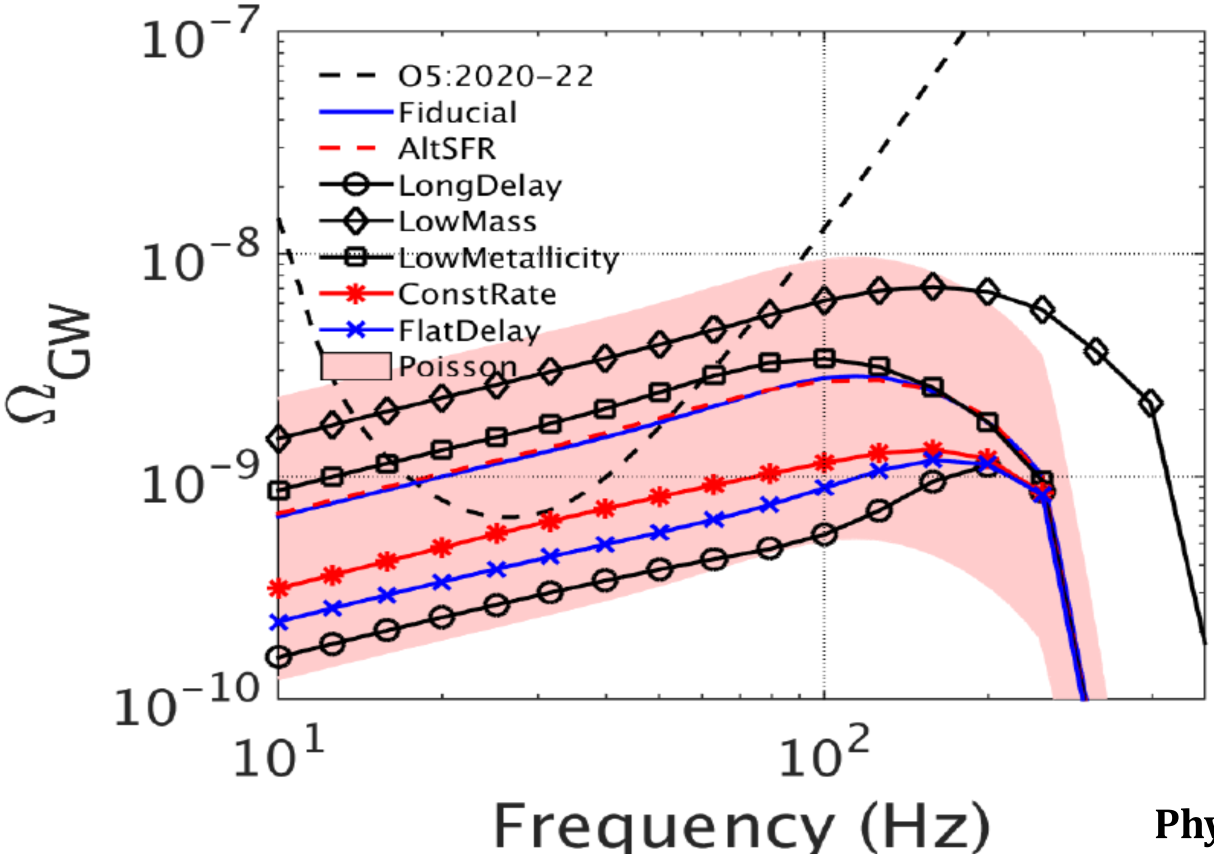
Alternative models

We investigated the impact of possible variations to the fiducial model

- **AltSFR:** SFR of Madau et al. (2014), Tornatore et al. (2007)
- **ConstRate:** redshift independent merger rate
- **LowMetallicity:** metallicity of $Z<Z_\odot/10$ required to form heavy BHs
- **LongDelay:** t_d>5 Gyr
- **FlatDelay:** uniform distribution in 50Myr-1Gyr (dynamical formation)
- **LowMass:** add a second class of lower-mass BBHs sources corresponding to the second most significant event (LVT151012) with M_c=15$M_\odot$, R_0= 61 Gpc^{-3}yr^{-1}

Alternative models

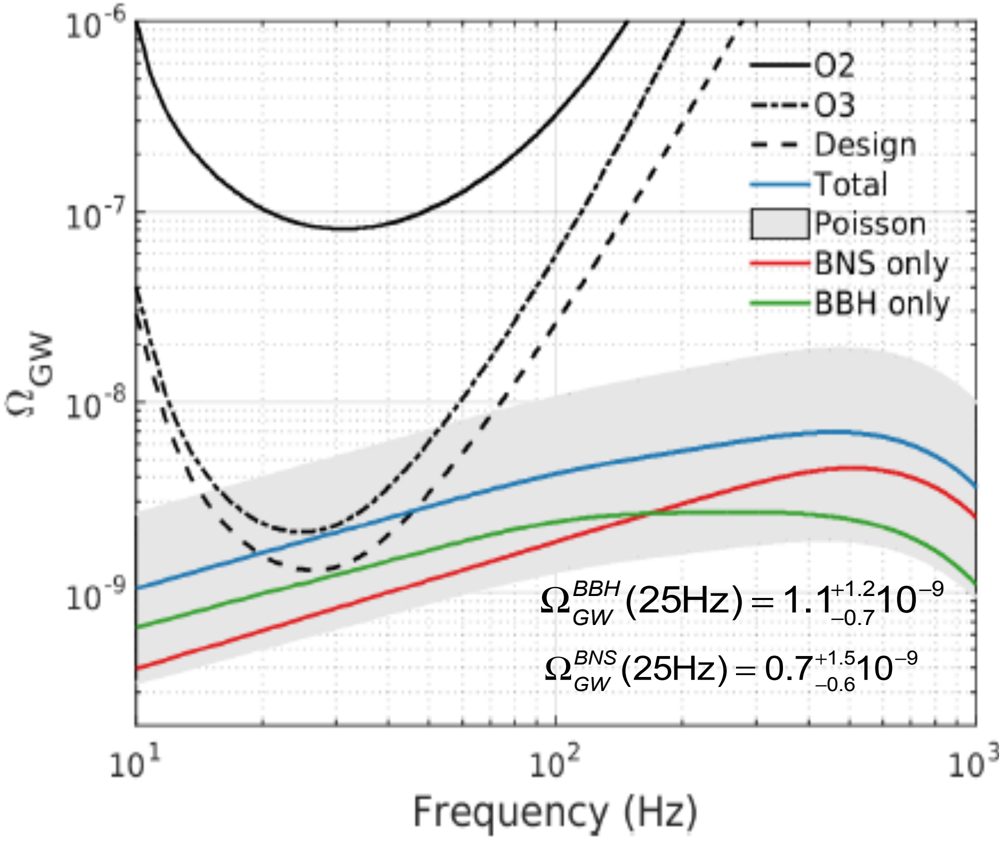
All these variations are smaller than the Poisson uncertainty.

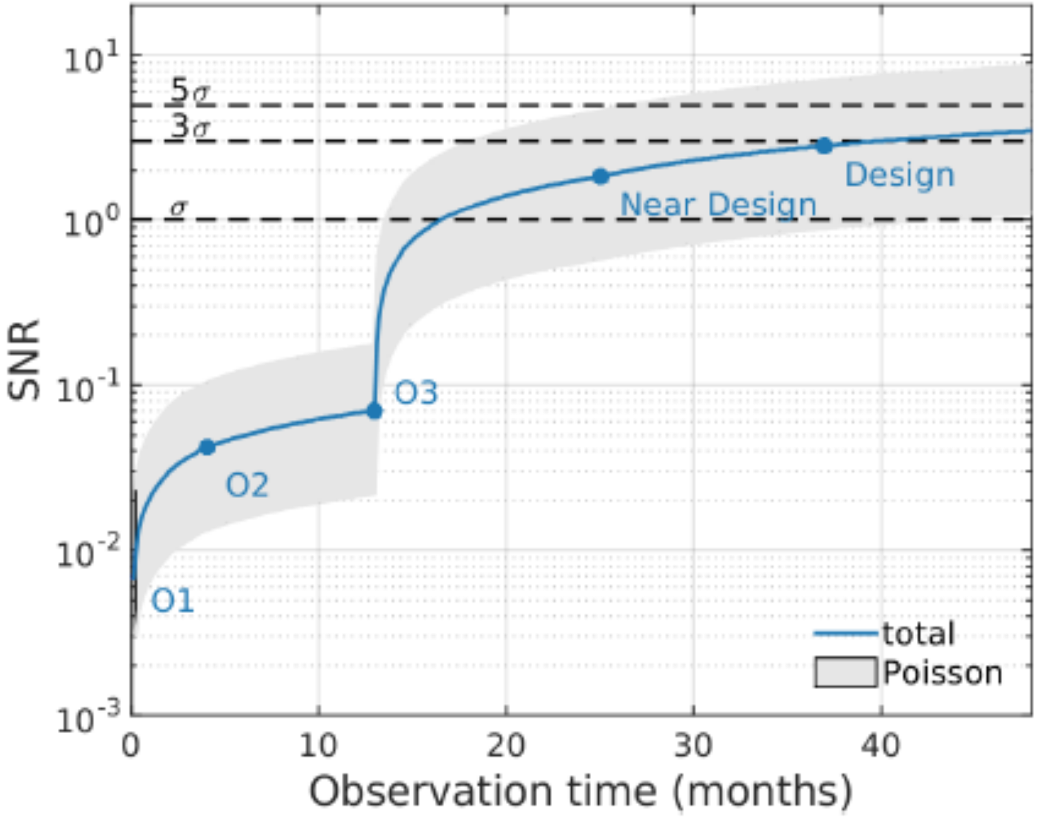


PhysRevLetter.116.131102

Estimate after the first BNS

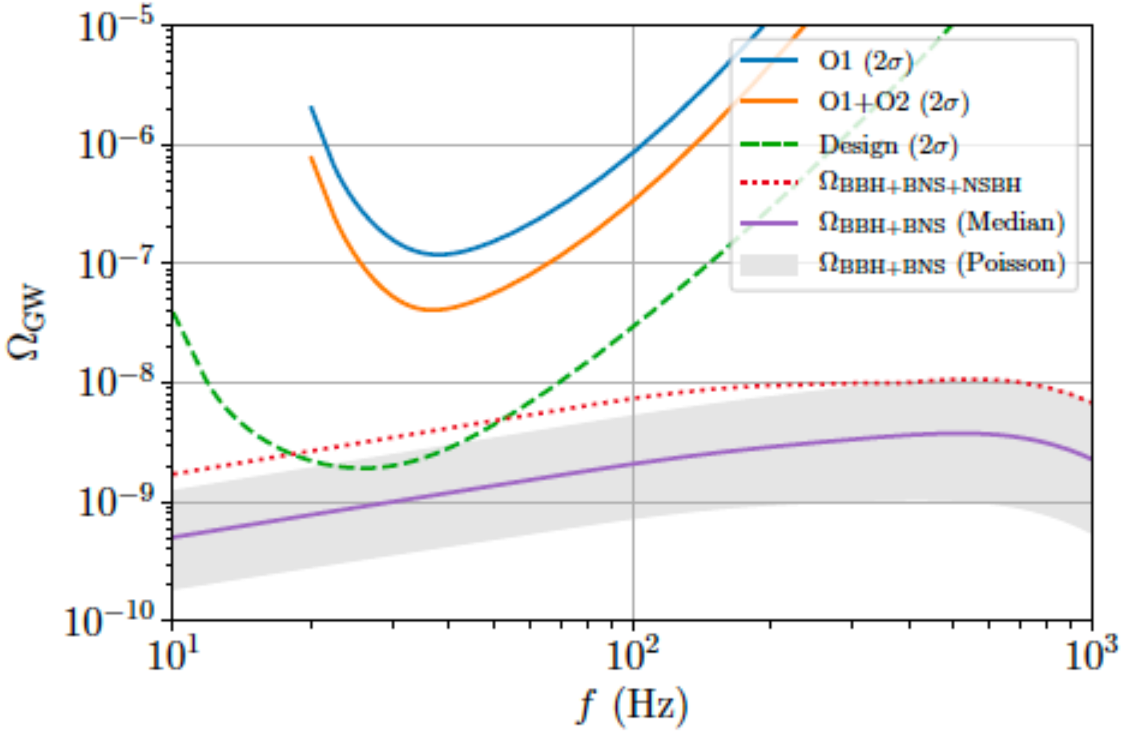
Abbott et al. PRL, 120.091101 (2017)





Revision at the end of O2

The predicted amplitude of BBH+BNS has been reduced by half as compared to previous estimations.

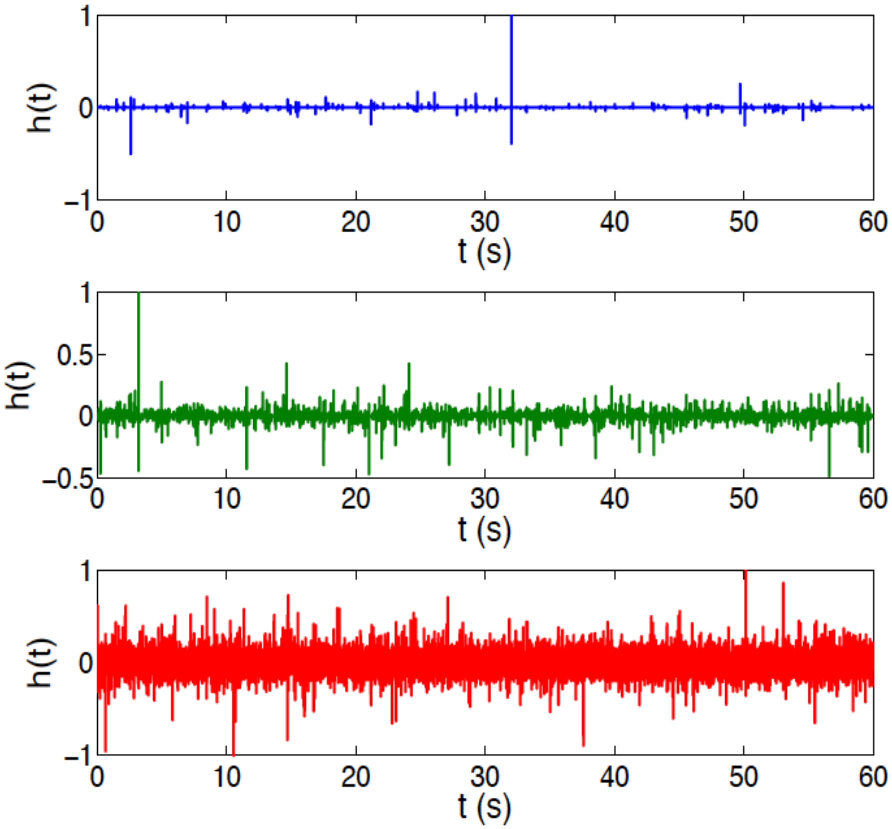


arXiv:1903.02886

Detection Regime

- **Continuous/popcorn**: Depending on the ratio between the ***duration*** of the events and the ***time interval*** between successive events, the waveforms may overlap or not and the GW signal may result in a continuous (Λ>1) or popcorn (Λ<1) background.

- **Gaussian/non Gaussian:** even if it's continuous a background may not be necessarily Gaussian. The signal can be continuous at some frequencies but not over the full frequency range (pulsars, CBCs).

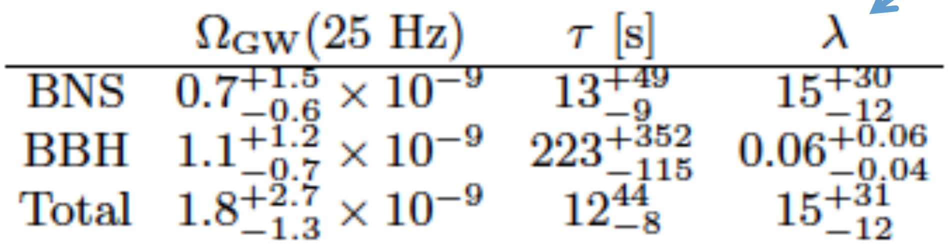


Time domain behavior

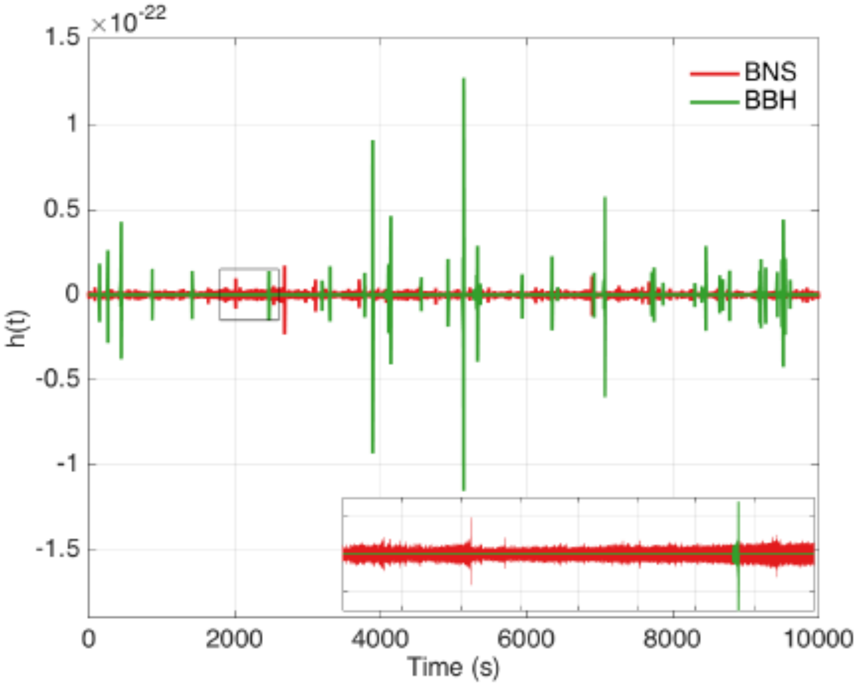
BNS = continuous and BBH = popcorn like

Abbott et al. PRL, 120.091101 (2017)

Duty cycle



	$\Omega_{\rm GW}(25\ {\rm Hz})$	τ [s]	λ
BNS	$0.7^{+1.5}_{-0.6} \times 10^{-9}$	13^{+49}_{-9}	15^{+30}_{-12}
BBH	$1.1^{+1.2}_{-0.7} \times 10^{-9}$	223^{+352}_{-115}	$0.06^{+0.06}_{-0.04}$
Total	$1.8^{+2.7}_{-1.3} \times 10^{-9}$	12^{44}_{-8}	15^{+31}_{-12}



Data Analysis Principle

Search for excess of coherence in the cross correlated data streams from multiple detectors with minimal assumptions on the morphology of the signal.

- Assume stationary, unpolarized, isotropic and Gaussian stochastic background.

- Cross correlate the output of detector pairs to eliminate the noise:

$$s_i = h_i + n_i$$

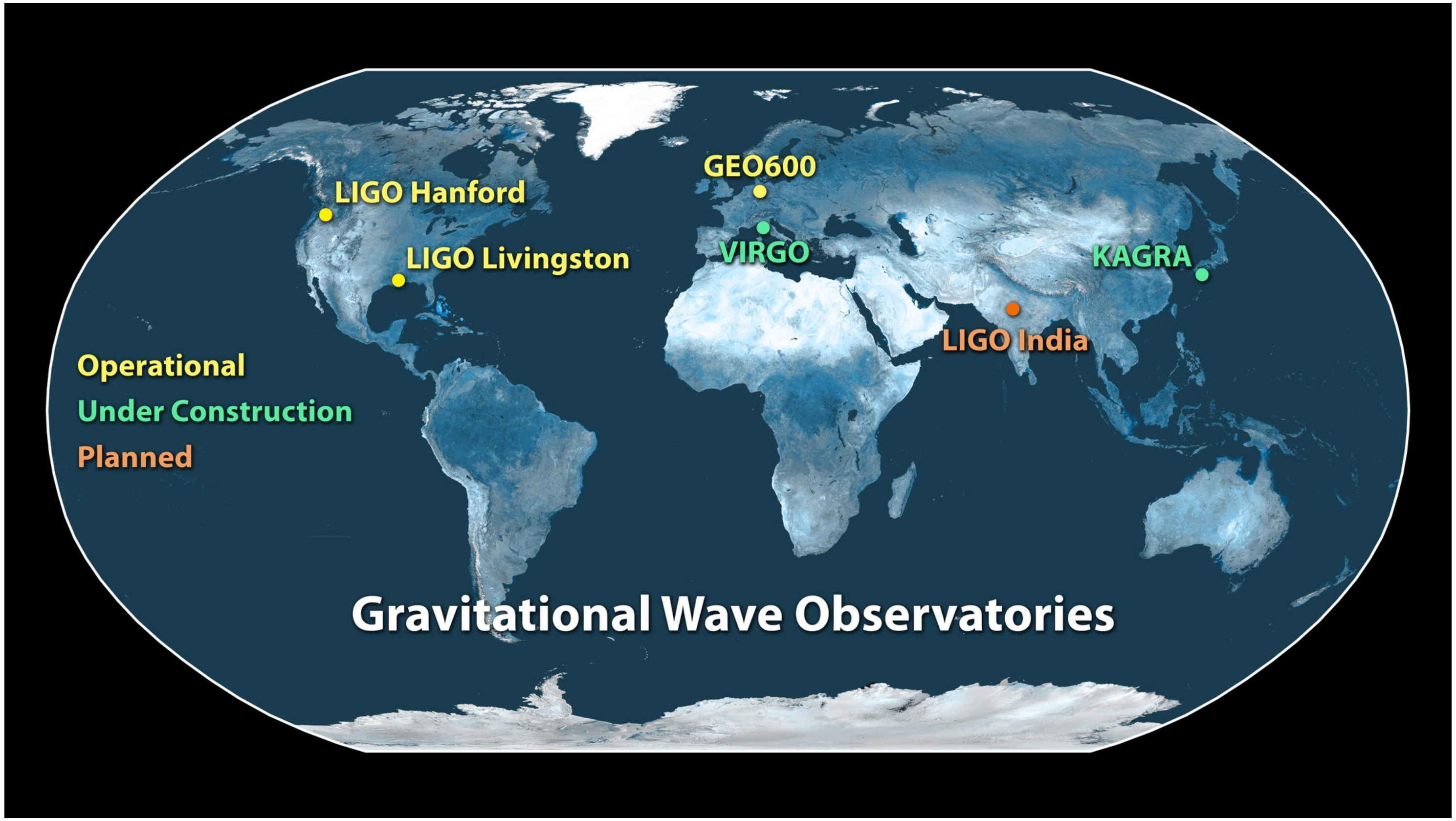
$$< s_1 s_2 > = < h_1 h_2 > + \underbrace{\cancel{< n_1 n_2 >}}_{0} + \underbrace{\cancel{< h_1 n_2 >}}_{0} + \underbrace{\cancel{< n_1 h_2 >}}_{0}$$

Cross Correlation Statistics

- Standard CC statistics (Allen & Romano, 1999, PRD, 59, 102001)
- Frequency domain cross product: $Y = \int \tilde{s}_1^*(f)\tilde{Q}(f)\tilde{s}_2(f)df$
- optimal filter: $\tilde{Q}(f) \propto \frac{\gamma(f)\Omega_{gw}(f)}{f^3 P_1(f) P_2(f)}$ with $\Omega_{gw}(f) \equiv \Omega_0 f^{\alpha}$
- in the limit noise >> GW signal

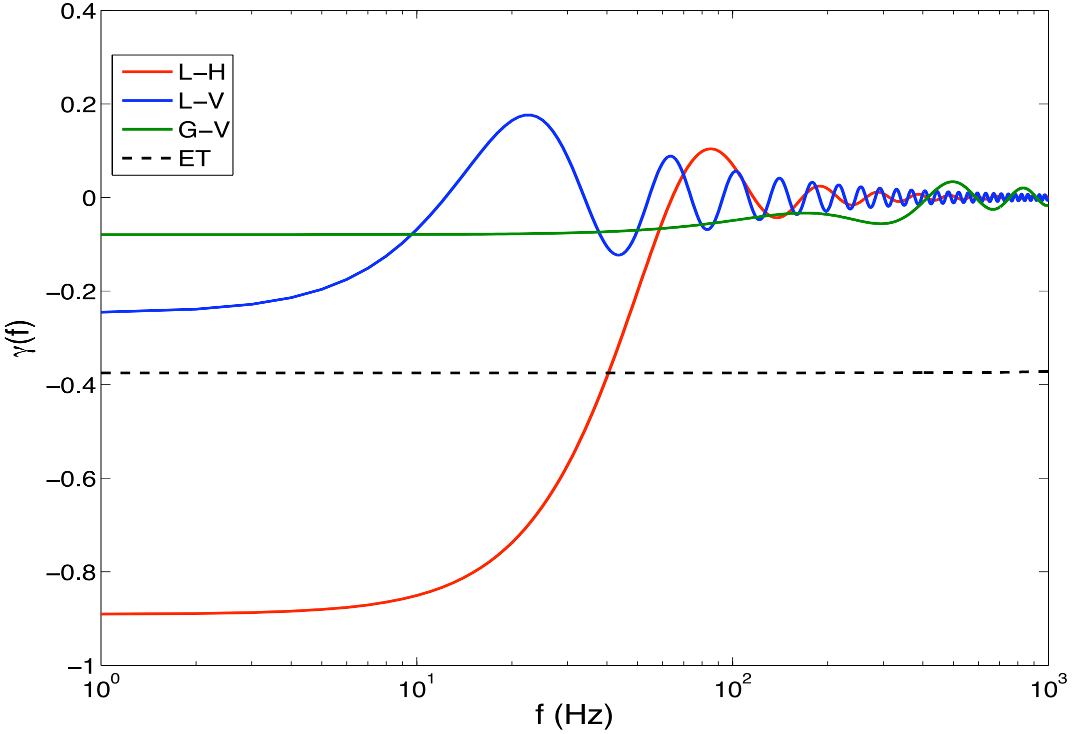
$$\text{Mean}(Y) = \Omega_0 T,\ \text{Var}(Y) \equiv \sigma^2 \propto T,\ \text{SNR} \propto \sqrt{T}$$

Gravitational-wave detector network



Overlap Reduction Function

Loss of sensitivity due to the separation and the relative orientation of the detectors.



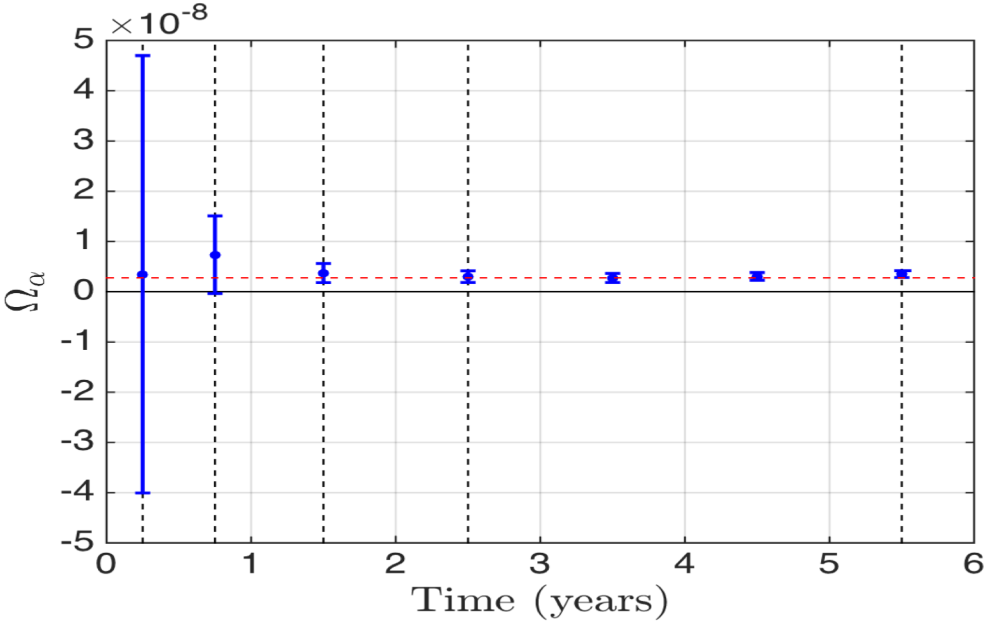
Time delay

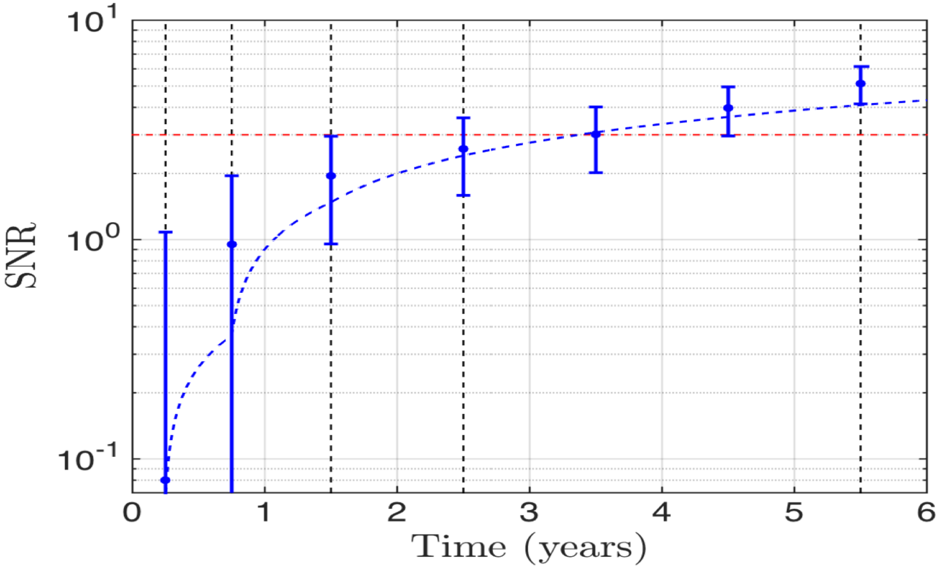
$$\gamma(f)=\frac{5}{8\pi}\sum_{A=\{+,\times\}}\int e^{2\pi i f\hat{\Omega}\Delta\vec{x}/c}F_1^A(\hat{\Omega})F_2^A(\hat{\Omega})d\Omega$$

Detector response

Non Gaussian case

Mock Data Challenges for ALV and Einstein Telescope (ET) have shown that the background from compact binary coalescences could be detected with no bias using the CC statistics even if it is non-continuous and non-Gaussian. Regimbau et al. arXiv:1404.1134,1201.3563, Meacher et al. arXiv:1506.06744)

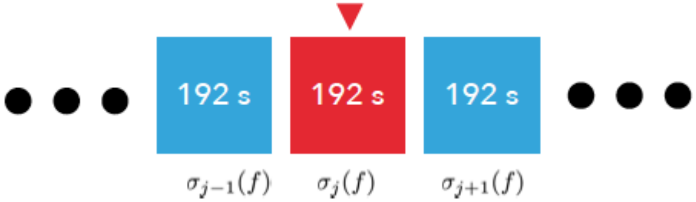




Pre-analysis: data cut

- data split into half-overlapping 192s segments, downsampled to 1024 Hz, Hann windowed, HPF, Fourier transformed and coarse grained to 0. 03125 Hz.

- remove time segments where the noise is non stationary



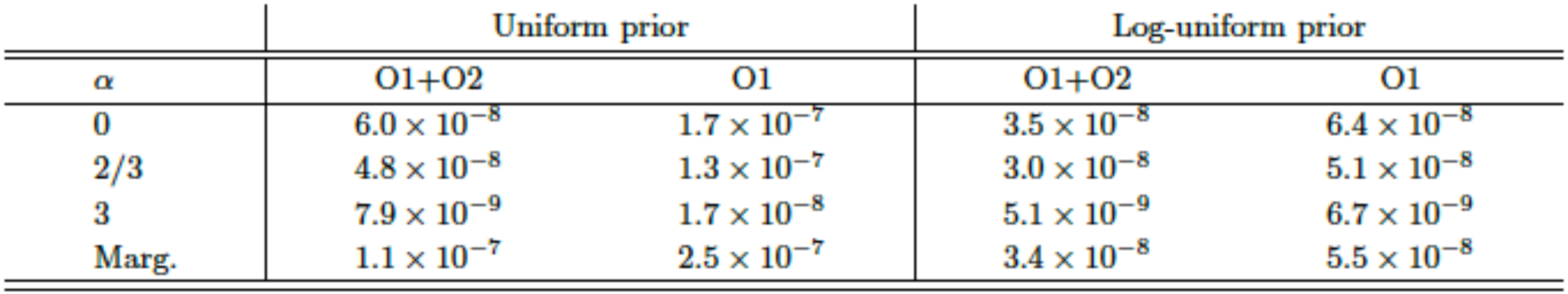
$$\boxed{\left|\sigma_j - \frac{\sigma_{j+1}+\sigma_{j-1}}{2}\right| \leq 0.2\sigma_j}$$

- remove frequency bins which display coherence with auxiliary chanels (power mains, GPS timing, Schuman resonances).

- assume ˜5% calibration uncertainty.

Constraints on the GW energy density

- No evidence for a stochastic background (cosmological or astrophysical).
- But set upper limits on the total energy density:



	Uniform prior		Log-uniform prior	
α	O1+O2	O1	O1+O2	O1
0	6.0×10^{-8}	1.7×10^{-7}	3.5×10^{-8}	6.4×10^{-8}
2/3	4.8×10^{-8}	1.3×10^{-7}	3.0×10^{-8}	5.1×10^{-8}
3	7.9×10^{-9}	1.7×10^{-8}	5.1×10^{-9}	6.7×10^{-9}
Marg.	1.1×10^{-7}	2.5×10^{-7}	3.4×10^{-8}	5.5×10^{-8}

arXix:1903.02886

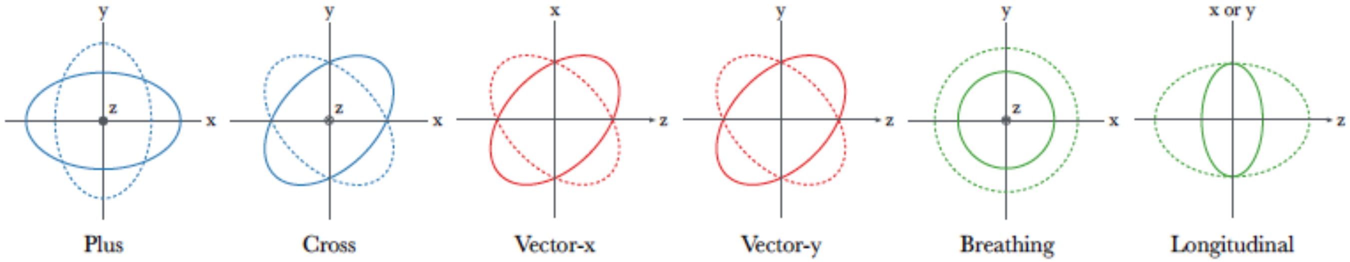
- For α=0, O1 33x better than initial LIGO/Virgo, O2 3x better than O1.
- strong constraints on the CS tension of Nambu- Goto models

($G\mu < 10^{-12}$ for Ringeval et al.)

Search for extra polarization

- Most alternative theories of gravity have extra scalar and vector polarization modes and gi e SGWB.

- Assume that t modes

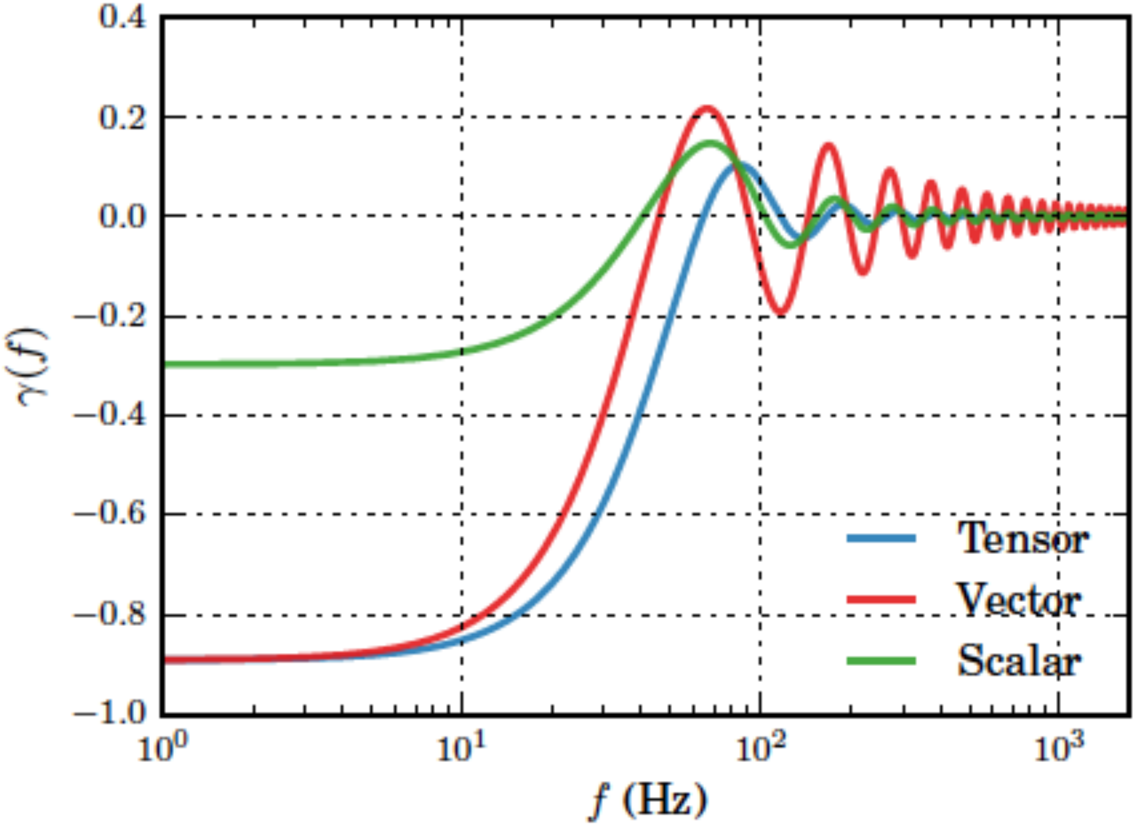


$$\langle \tilde{s}_1(f)\tilde{s}_2^*(f')\rangle = \delta(f-f')\sum_A \gamma_A(f)H^A(f)$$

Overlap reduction functions

- Compute Bayesian evidence for various hypothesis : (N): Gaussian noise only, (SIG): SGWB present of any polarization, (GR): SGWB present purely tensor-polarized, (NGR): SGWB present with tensor and/or scalar polarizations.

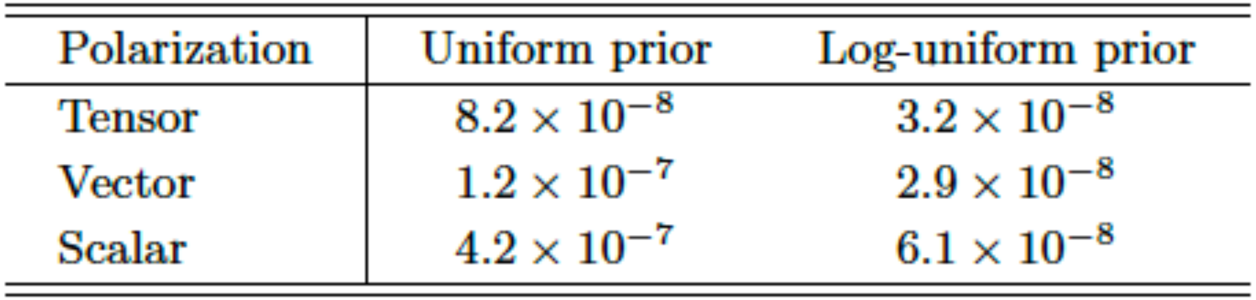
Search for extra polarization



Callister et al., PhysRevX.7.041058

Search for extra polarization

O1+O2 results



Polarization	Uniform prior	Log-uniform prior
Tensor	8.2×10^{-8}	3.2×10^{-8}
Vector	1.2×10^{-7}	2.9×10^{-8}
Scalar	4.2×10^{-7}	6.1×10^{-8}

arXix:1903.02886

Directional searches

- relax assumption of isotropy and generalize to arbitrary angular distribution.

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df} = \frac{2\pi^2}{3H_0^2} f^3 H(f) \int_{S^2} d\hat{\Omega}\, \mathcal{P}(\hat{\Omega})$$

- by applying appropriate time varying delays between detectors it is possible to map the angular power distribution in a pixel or spherical harmonic basis

  - radiometer for point-like sources: $\mathcal{P}(\hat{\Omega}) \equiv \eta(\hat{\Omega}_0)\delta^2(\hat{\Omega}, \hat{\Omega}_0)$

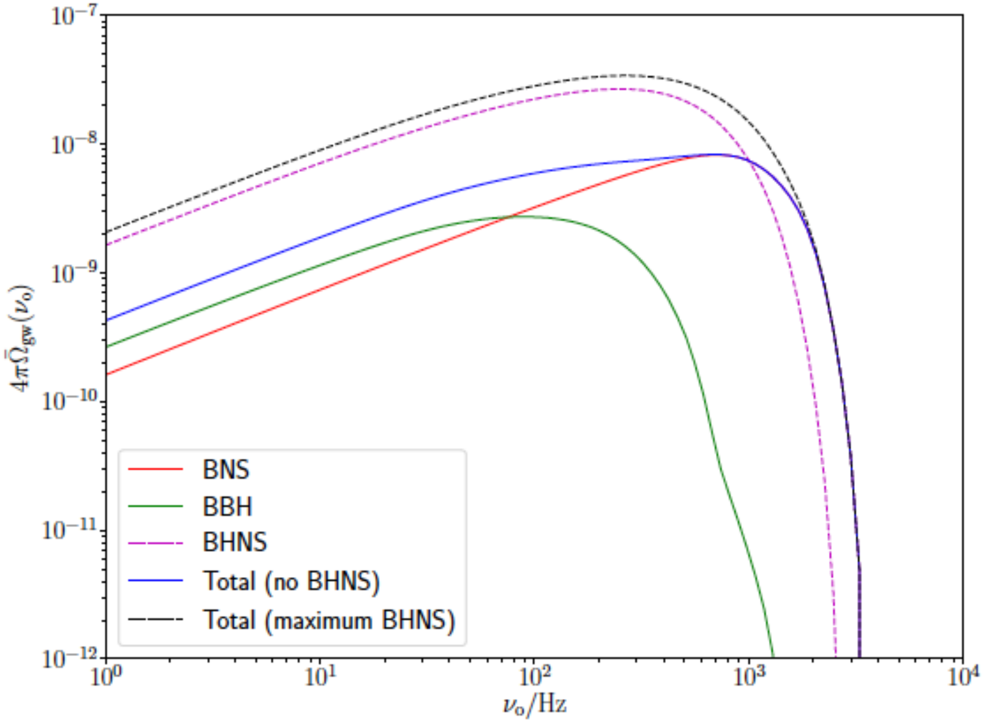
  - spherical harmonic decomposition : $\mathcal{P}(\hat{\Omega}) \equiv \sum_{lm} \mathcal{P}_{lm} Y_{lm}(\hat{\Omega})$

- anisotropy due to the finitness of the number of sources, the nature of spacetime along the line of sight, and for astrophysical models the local distribution of matter.

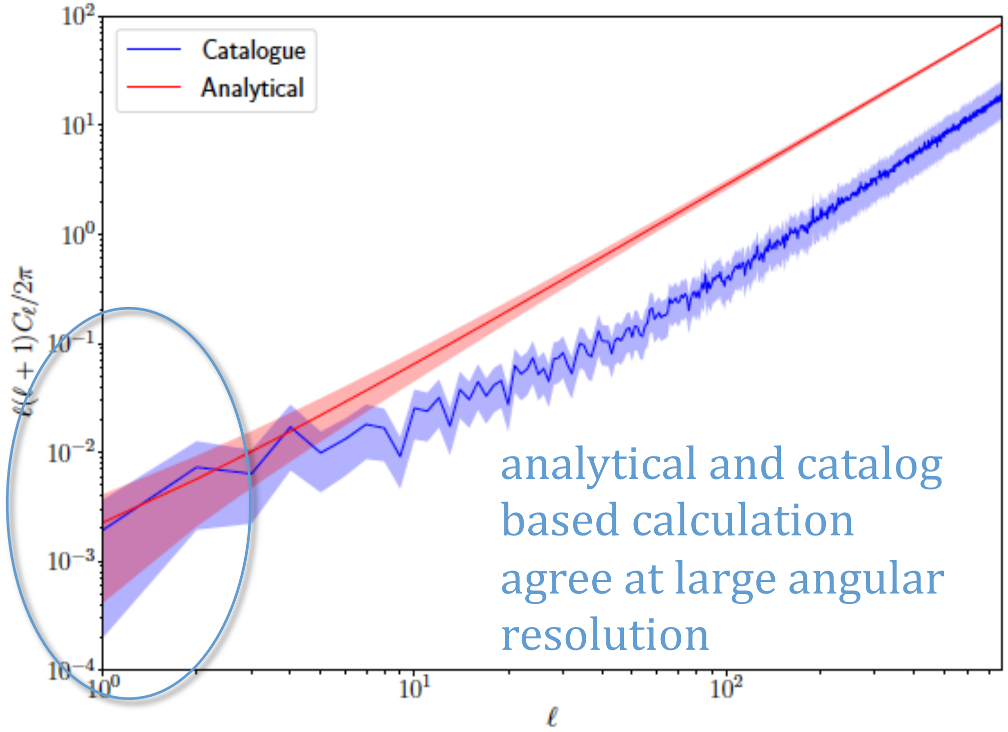
Jenkins & Sakellariadou, arXiv:1802.06046

Anisotropies from Compact Binary Mergers

Monopole



Overdensity



analytical and catalog based calculation agree at large angular resolution

Jenkins & Sakellariadou, arXiv:1802.06046

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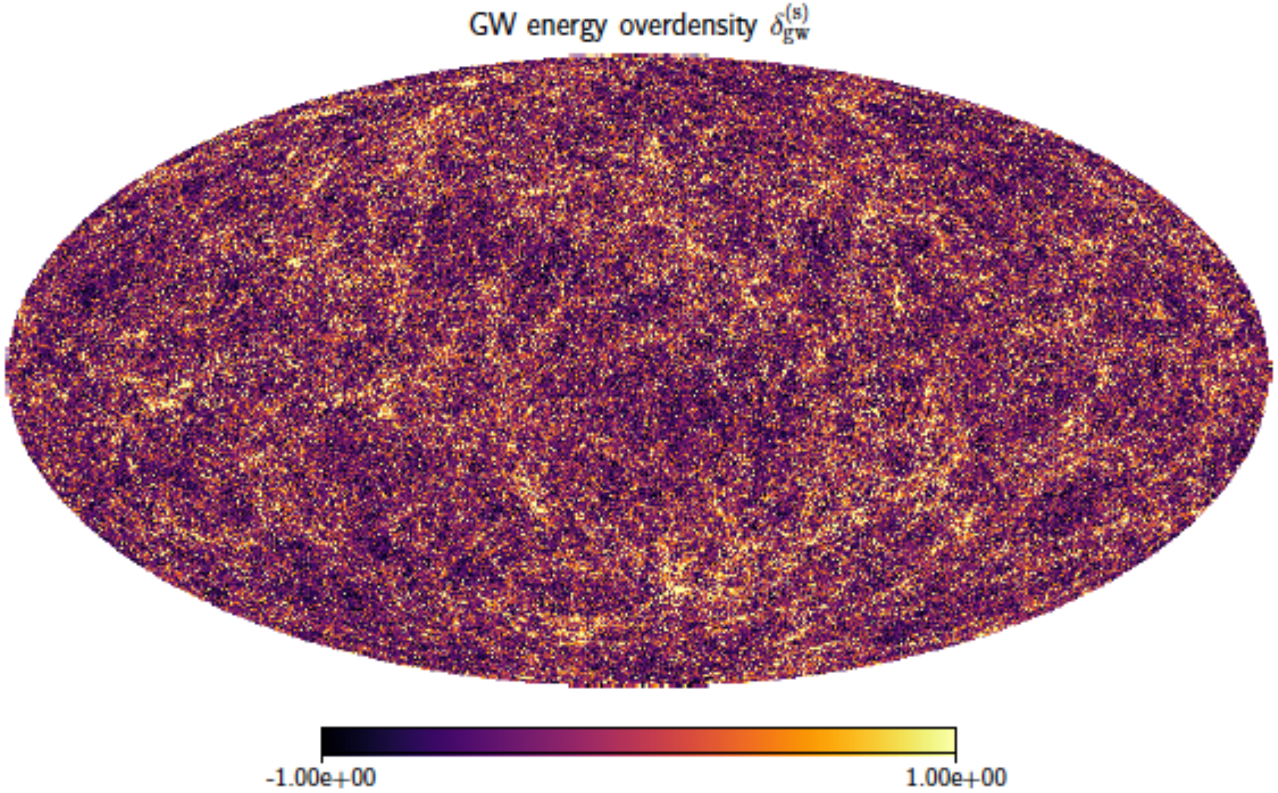
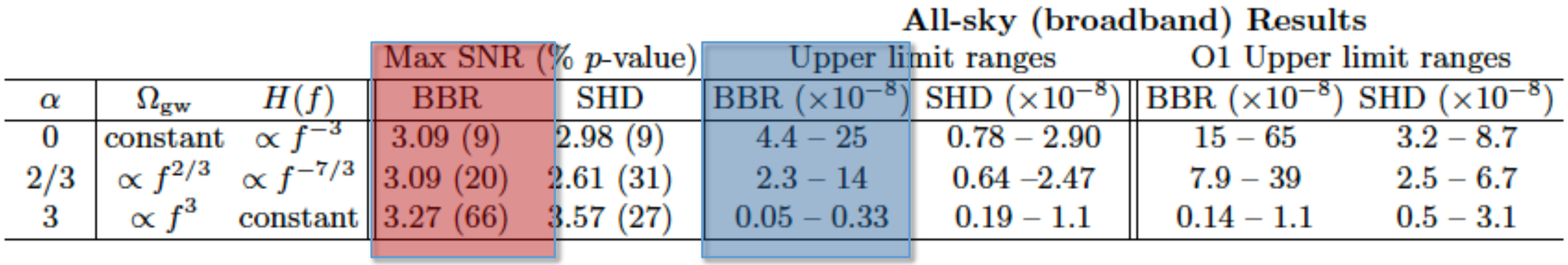


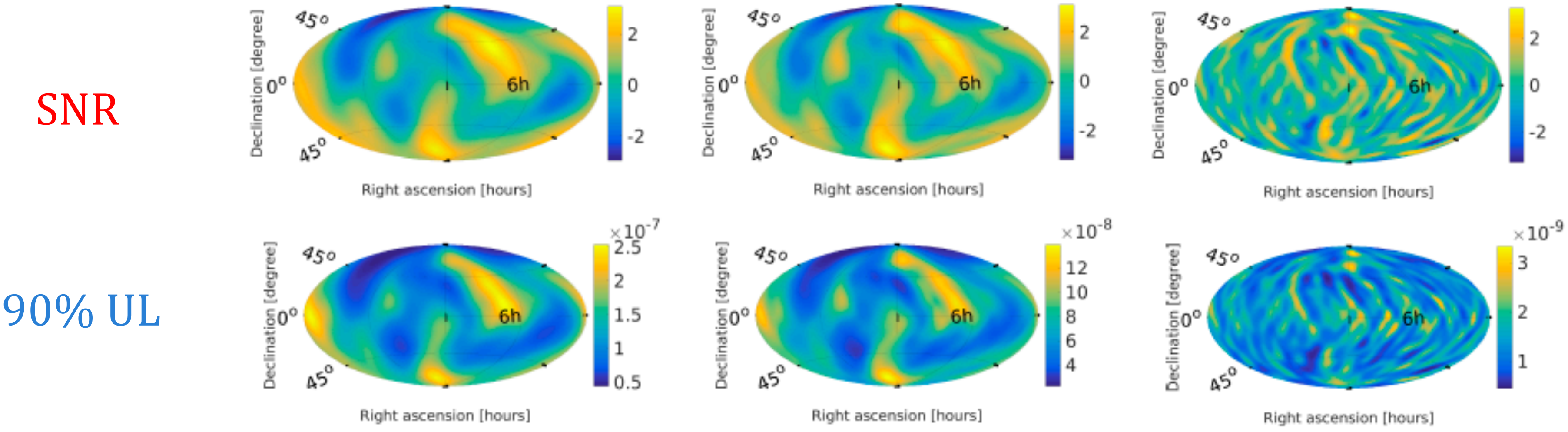
Abbott et al, Phys.Rev.Lett. 118 (2017)

Radiometer: O1/O2 results



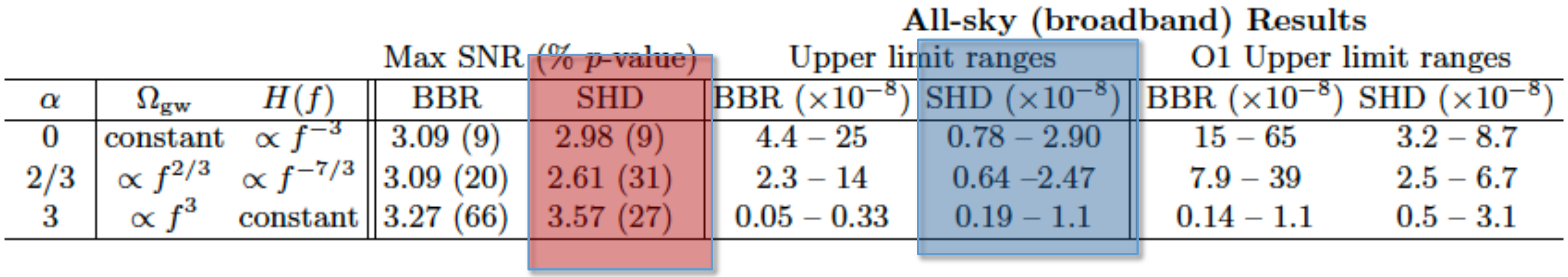
All-sky (broadband) Results

			Max SNR (% p-value)		Upper limit ranges		O1 Upper limit ranges	
α	Ω_{gw}	$H(f)$	BBR	SHD	BBR ($\times 10^{-8}$)	SHD ($\times 10^{-8}$)	BBR ($\times 10^{-8}$)	SHD ($\times 10^{-8}$)
0	constant	$\propto f^{-3}$	3.09 (9)	2.98 (9)	4.4 – 25	0.78 – 2.90	15 – 65	3.2 – 8.7
2/3	$\propto f^{2/3}$	$\propto f^{-7/3}$	3.09 (20)	2.61 (31)	2.3 – 14	0.64 –2.47	7.9 – 39	2.5 – 6.7
3	$\propto f^{3}$	constant	3.27 (66)	3.57 (27)	0.05 – 0.33	0.19 – 1.1	0.14 – 1.1	0.5 – 3.1



Abbott et al, Phys.Rev.Lett. 118 (2017)

SHD: O1/O2 results



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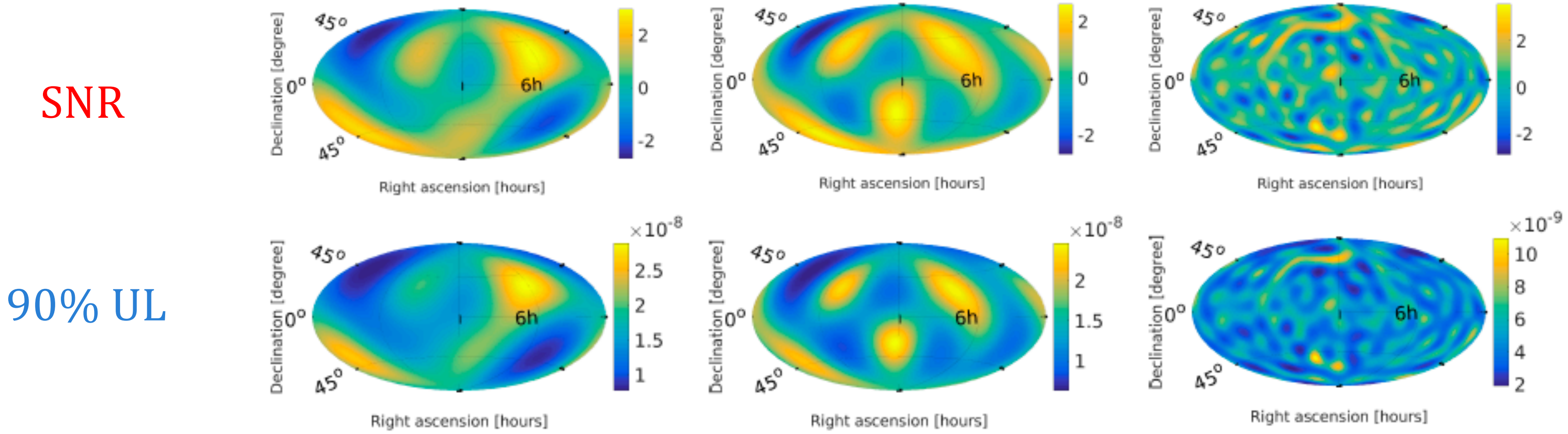

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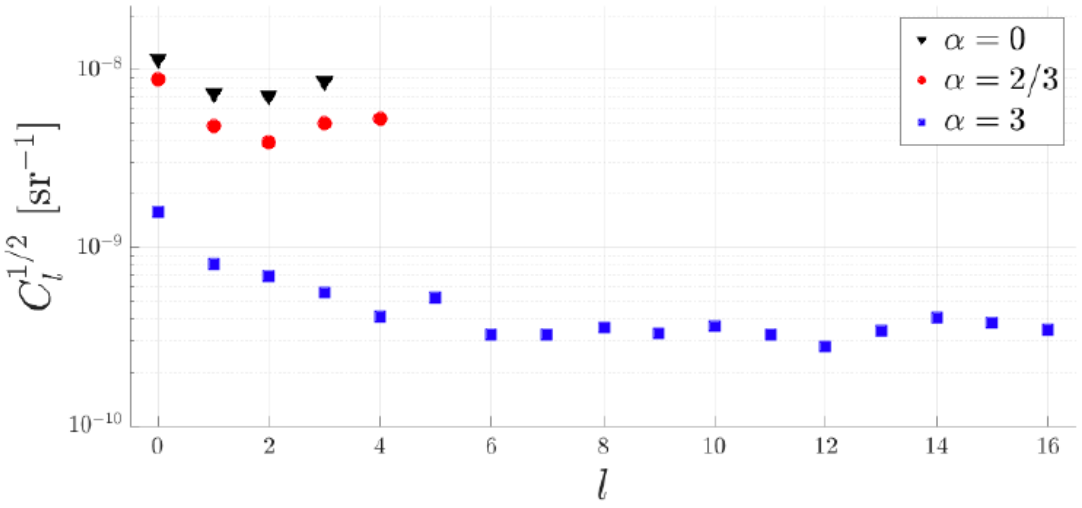
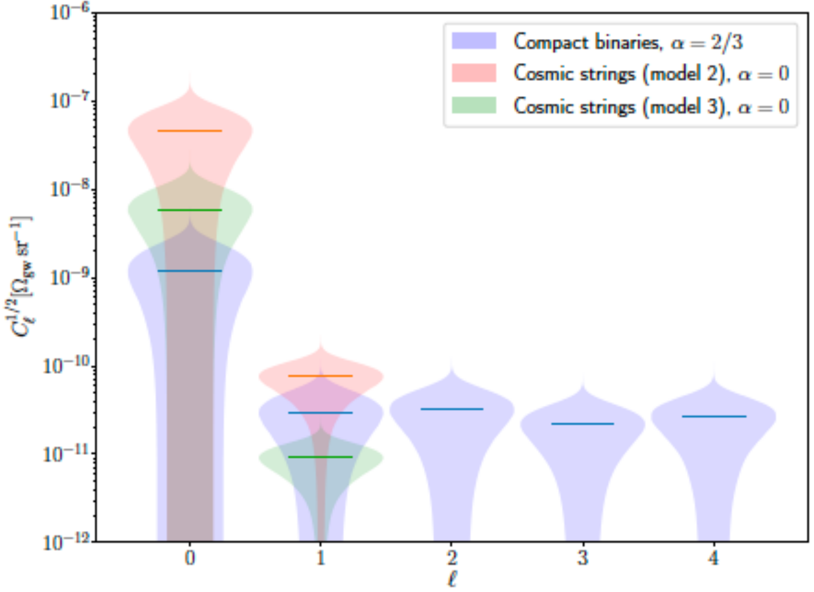
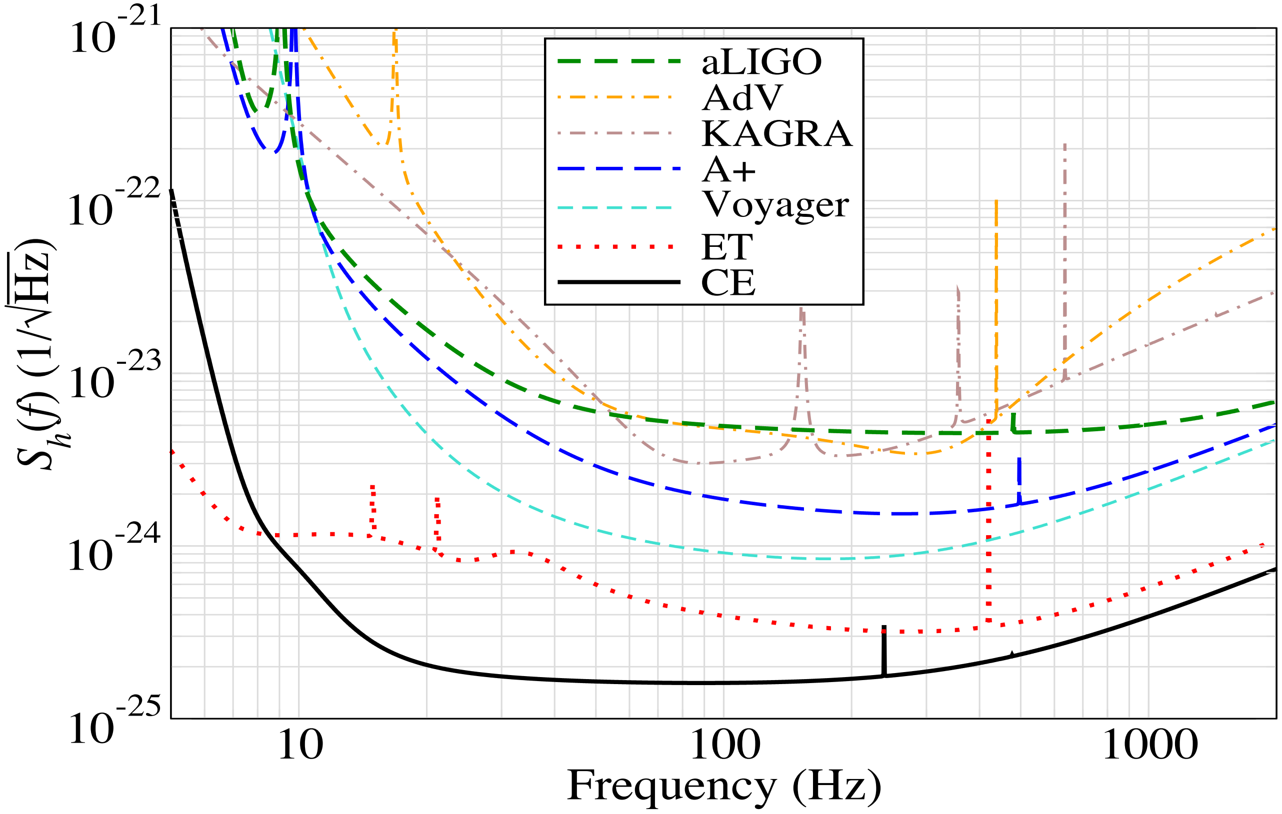


Jenkins & Sakellariadou



Still above theoretical predictions. But could be possible with O3.

Next Generation of Detectors



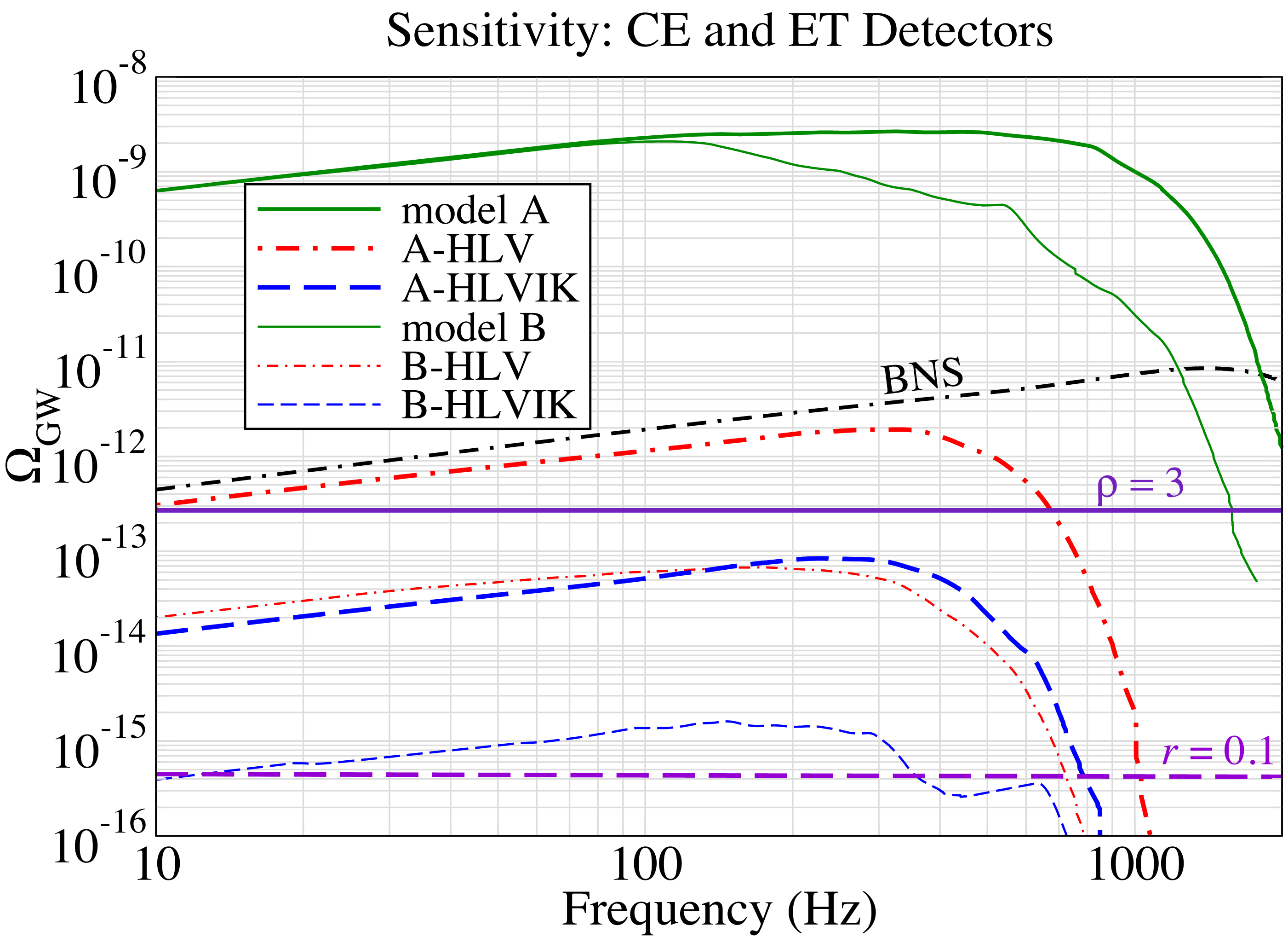
Remove the astrophysical background

- 3G detectors, such as the Einstein Telescope and the Cosmic Explorer, will be able to observe binary black hole mergers throughout the universe

- The foreground can be subtracted to observe the cosmological background at the level of $\Omega_{gw} = 2\times10^{-13}$ (Regimbau et al., PhysRevLett.118.151105)

- Need to perform intensive mock data challenges (in both LISA and LIGO/Virgo band) to develop efficient subtraction methods

- An improvement of a factor of 5 in sensitivity is required to remove all the low mass binaries and a factor of 10 to reach the background from inflation



PhysRevLett.118.151105

Conclusion

- The preliminary goal of the LIGO/Virgo stochastic group is to measure the isotropic SGWB.

- The background from CBCs have a good chance to be detected in the next few years.

- With 3G the goal wil be to subtact it to recover the cosmological background below

- Many new searches can lead to very interesting results (non-isotropic, non standard polarization, non Gaussian). These searches could be extended to LISA.

Other directional searches

- Narrow band radiometer for persistent GW in a specific directions in the sky (Sco-X1, SN1987A, galactic center)

- Probing the Fermi-LAT GeV excess with gravitational waves. A serious candidate is a population of subthreshold MSP in the bulge (Calore, Regimbau and Serpico, PhysRevLett.122.081108)

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