SEARCHING FOR THE STOCHASTIC GRAVITATIONAL-WAVE BACKGROUND WITH ADVANCED LIGO AND ADVANCED VIRGO

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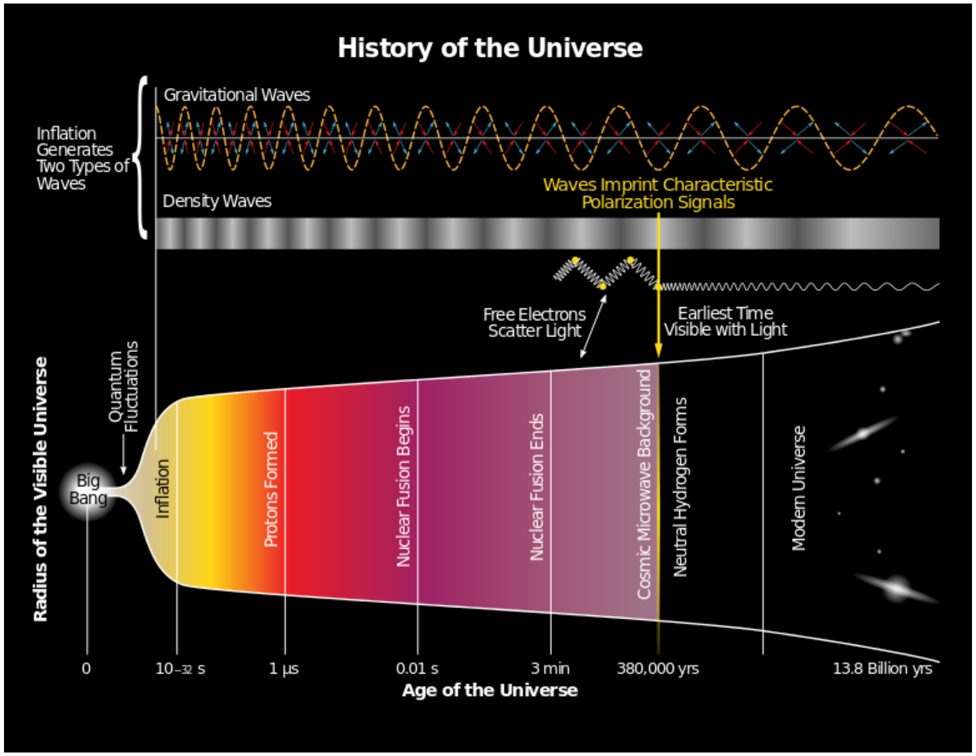
GW Stochastic Background

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.

- **Cosmological:** signature of the early Universe near the Big Bang *inflation, cosmic strings, phase transitions…*
- **Astrophysical:** since the beginning of stellar activity *compact binary coalescences, core-collapse supernovas, rotating neutron stars, capture by SMBHs…*



Implications of LIGO first detections

- On Sept 14th 2015 LIGO detected for the first time the GW signal from a stellar binary black hole (BBH) at z~0.1 (GW150914). *PhysRevLetter.116.061102*

- Another event (GW151226), likely two (LVT151012), were detected in the LIGO first observational run. *arXiv:1606.04856*

- Besides the detection of loud individual sources at close distances, we expect to see the background formed by all the sources from the whole Universe (up to z~20)

- GW150914 told us that black hole masses ($m_{1,2}$~$30M_{\odot}$) can be larger than previously expected in the close Universe.

- Revised previous predictions of the GW background from BBHs, assuming various formation scenarios. *PhysRevLetter.116.131102*

The Background from BBHs

- Energy density spectrum in GWs characterized by:

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

- Contribution of BBHs with parameters $\theta_k=(m_1,m_2,\chi_{eff})$

$$\Omega^k_{gw}(f,\theta_k) = \frac{f}{\rho_c}\int_0^{20}\frac{dR^k_m}{dz}(z,\theta_k)\frac{\frac{dE_{gw}}{df}(\theta_k,f(1+z))}{4\pi r^2(z)}dz$$

- Total population:

$$\Omega_{gw}(f) = \int d\theta P(\theta)\Omega_{gw}(f,\theta)$$

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(*PRL.116.241102*)
- Local merger rate: R_0= 16^{+38}_{-13} $\mathrm{Gpc^{-3}yr^{-1}}$ (*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.

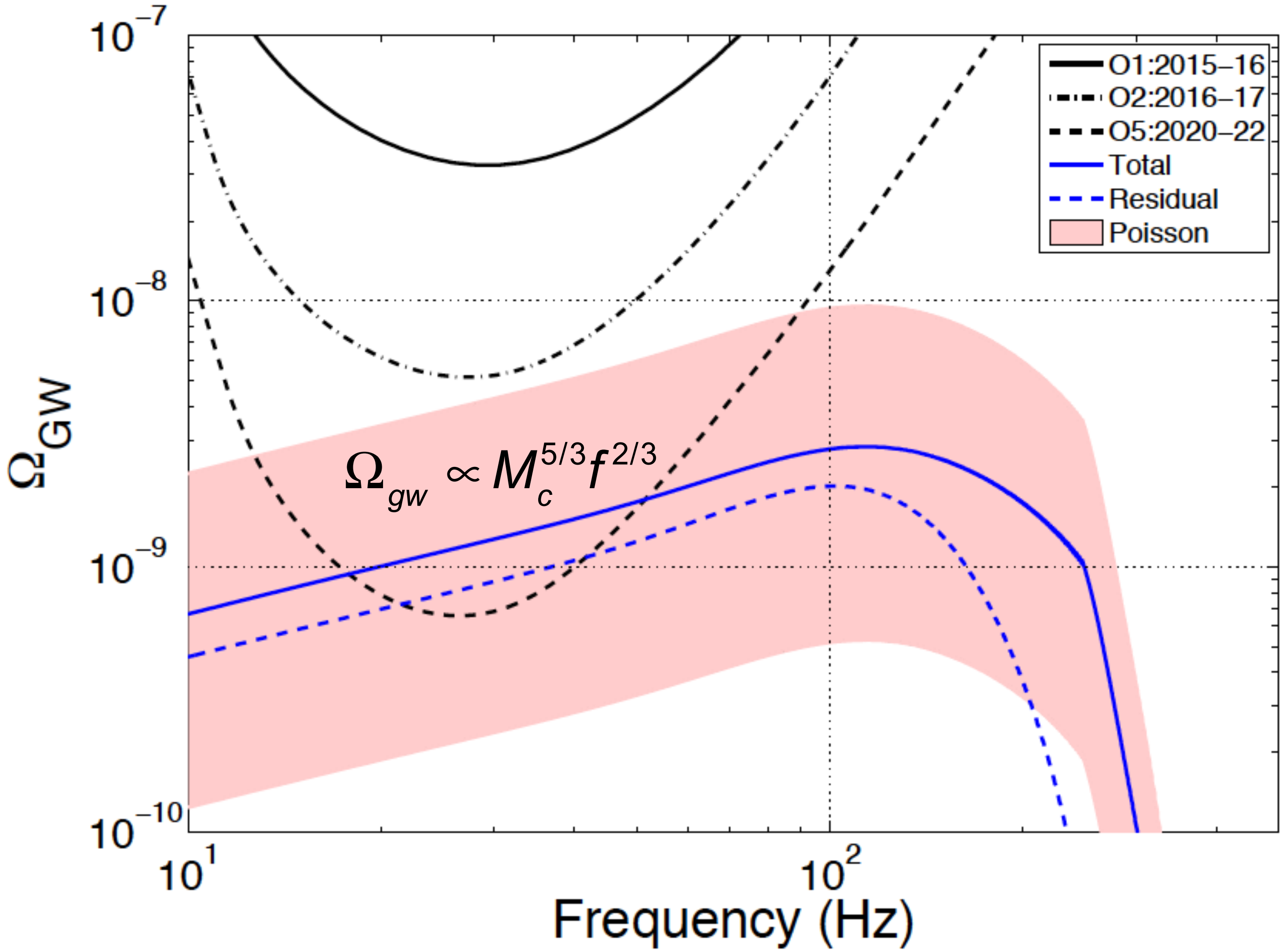
$$R_m(z,\theta_k) = \int_{t_{\min}}^{t_{\max}} R_f(z,\theta_k) P(t_d,\theta_k)\, dt_d$$

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

Fiducial Model

PhysRevLetter.116.131102

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



Alternative models

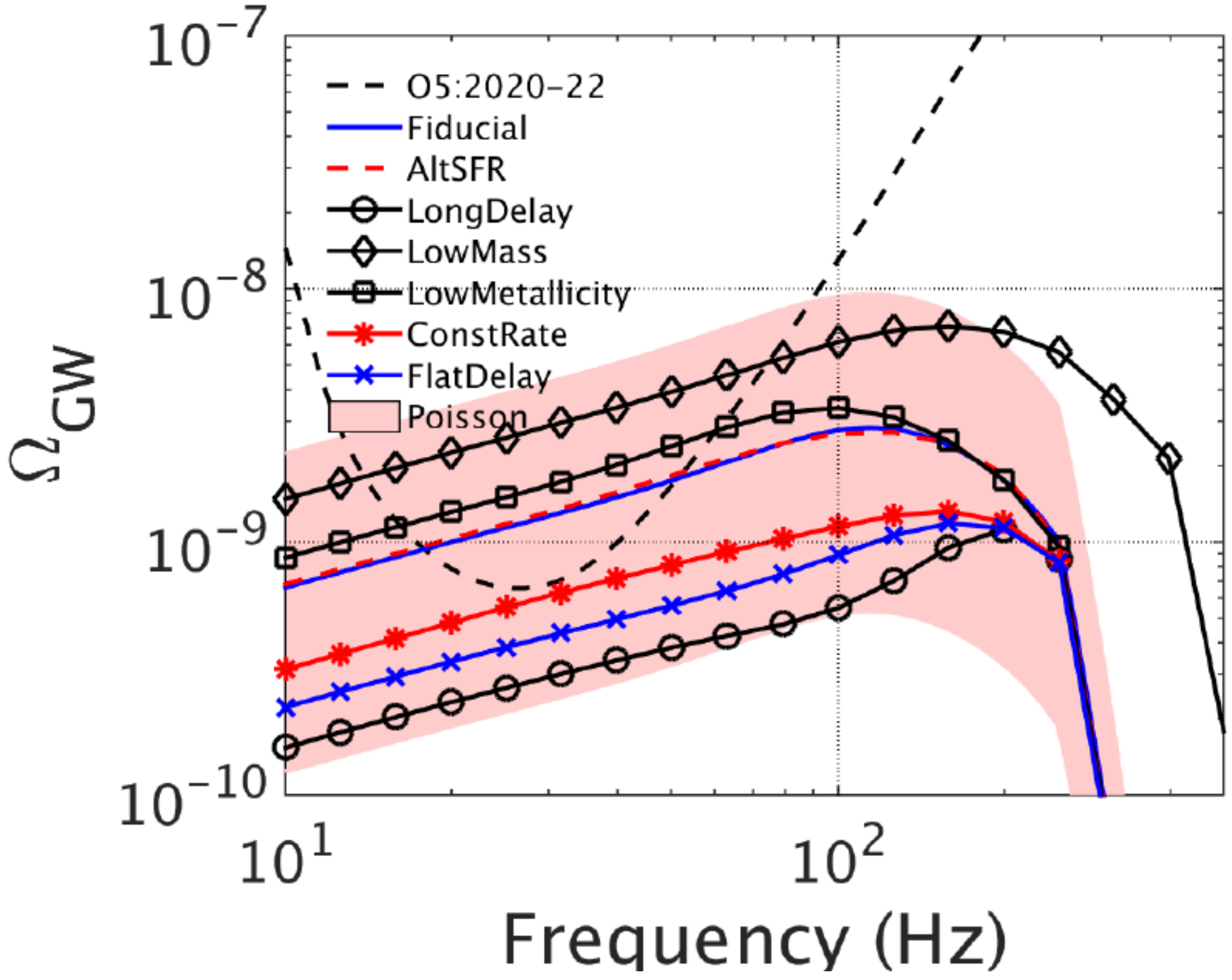
We investigated the impact of possible variations to the fiducial model

- **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 signicant event (LVT151012) with $M_c=15M_{\odot}$, $R_0= 61$ $Gpc^{-3}yr^{-1}$

All these variations are smaller than the Poisson uncertainty.

PhysRevLetter.116.131102

Alternative models



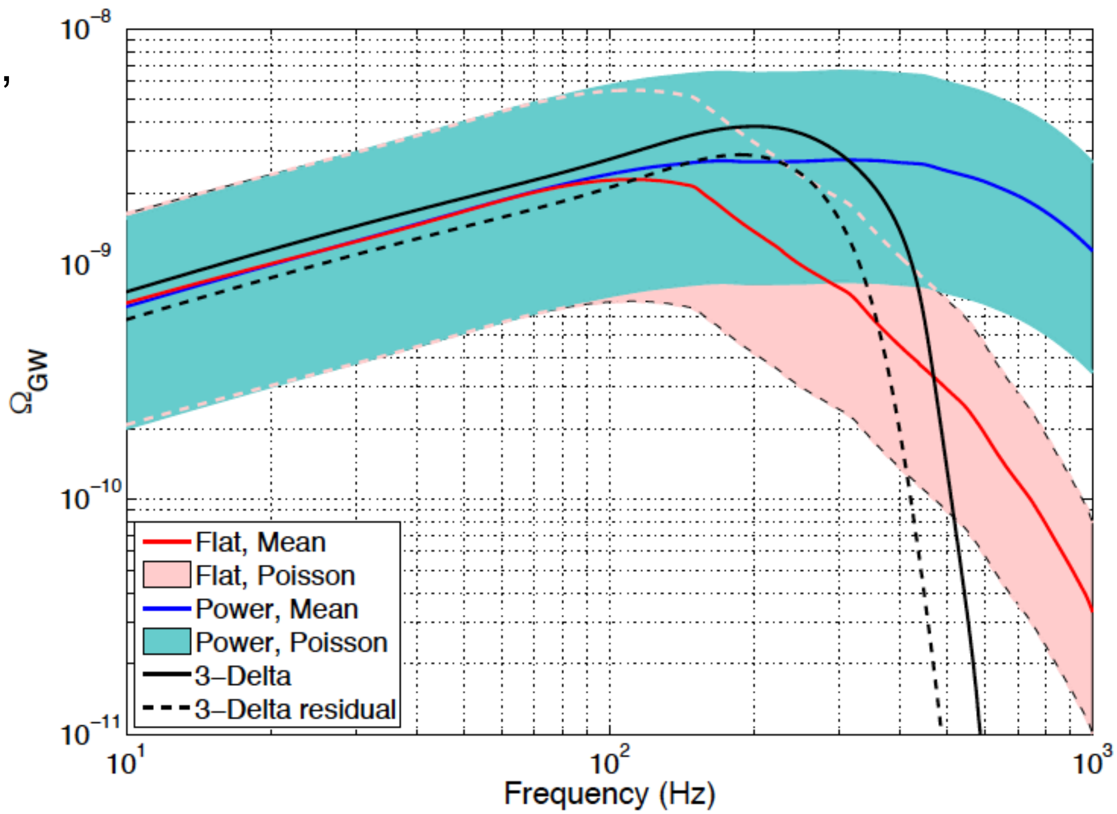
arXiv:1606.04856

Update using all of O1

- 3 events GW150914 (M_c~28 $M_\odot$), GW151226(~15 $M_\odot$) and LVT151012 (~9 $M_\odot$)
- No significant difference in the median value for f<100 Hz.
- Slight improvement of the error

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

$$\Omega_{gw}^{new}(25\text{Hz}) = (1.1-1.3)^{+1.8}_{-0.8} 10^{-9}$$



Data Analysis Principle

- Assume stationary, unpolarized, isotropic and Gaussian stochastic background

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

$$s_i = h_i + n_i$$

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

Isotropic search

- Frequency domain cross product:

$$Y = \int \tilde{s}_1^*(f)\tilde{Q}(f)\tilde{s}_2(f)df$$

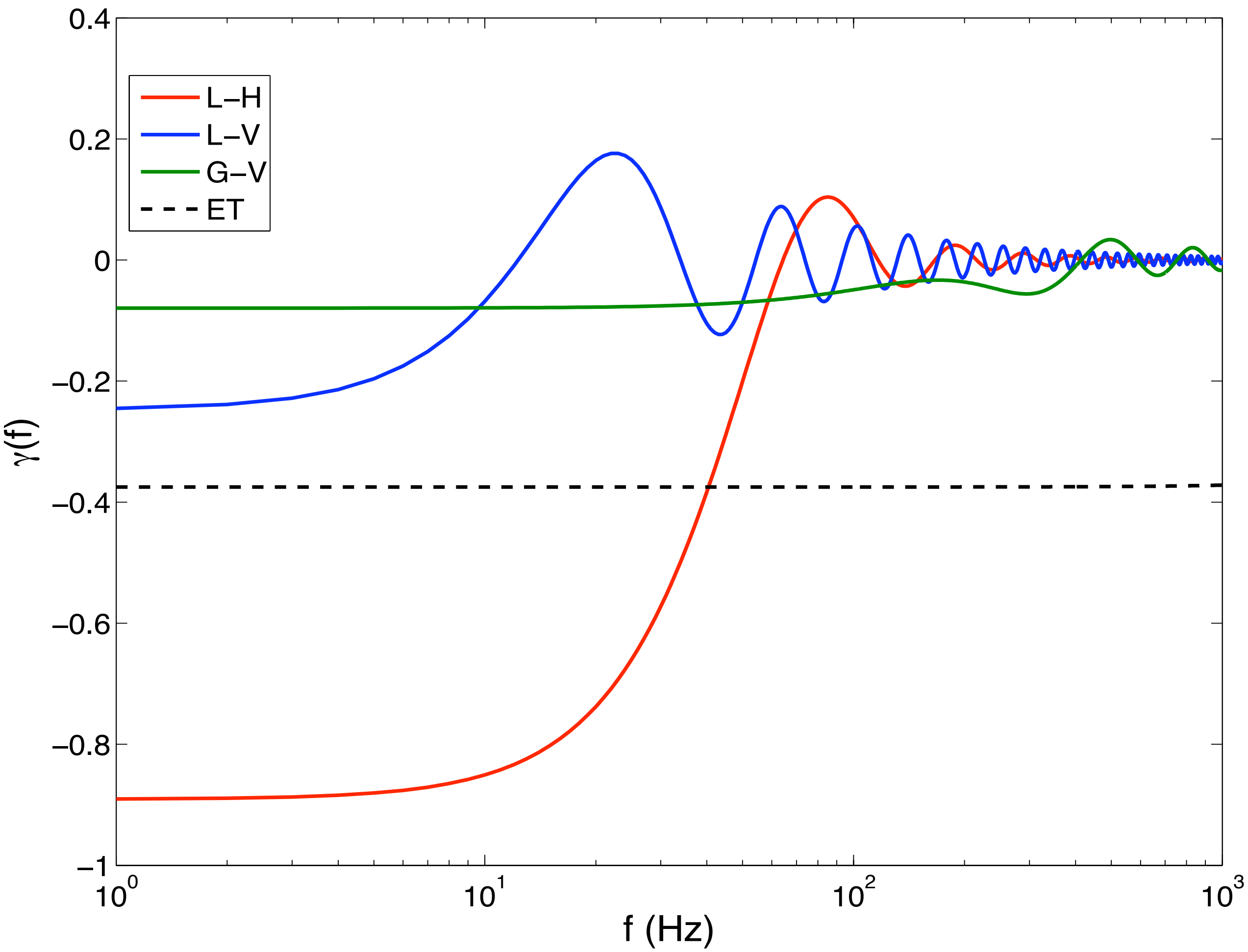
- optimal filter:

$$\tilde{Q}(f) \propto \frac{\gamma(f)\Omega_{gw}(f)}{f^3 P_1(f)P_2(f)} \text{ with } \Omega_{gw}(f) \equiv \Omega_\alpha f^\alpha$$

- in the limit noise >>GW signal

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

Overlap reduction function



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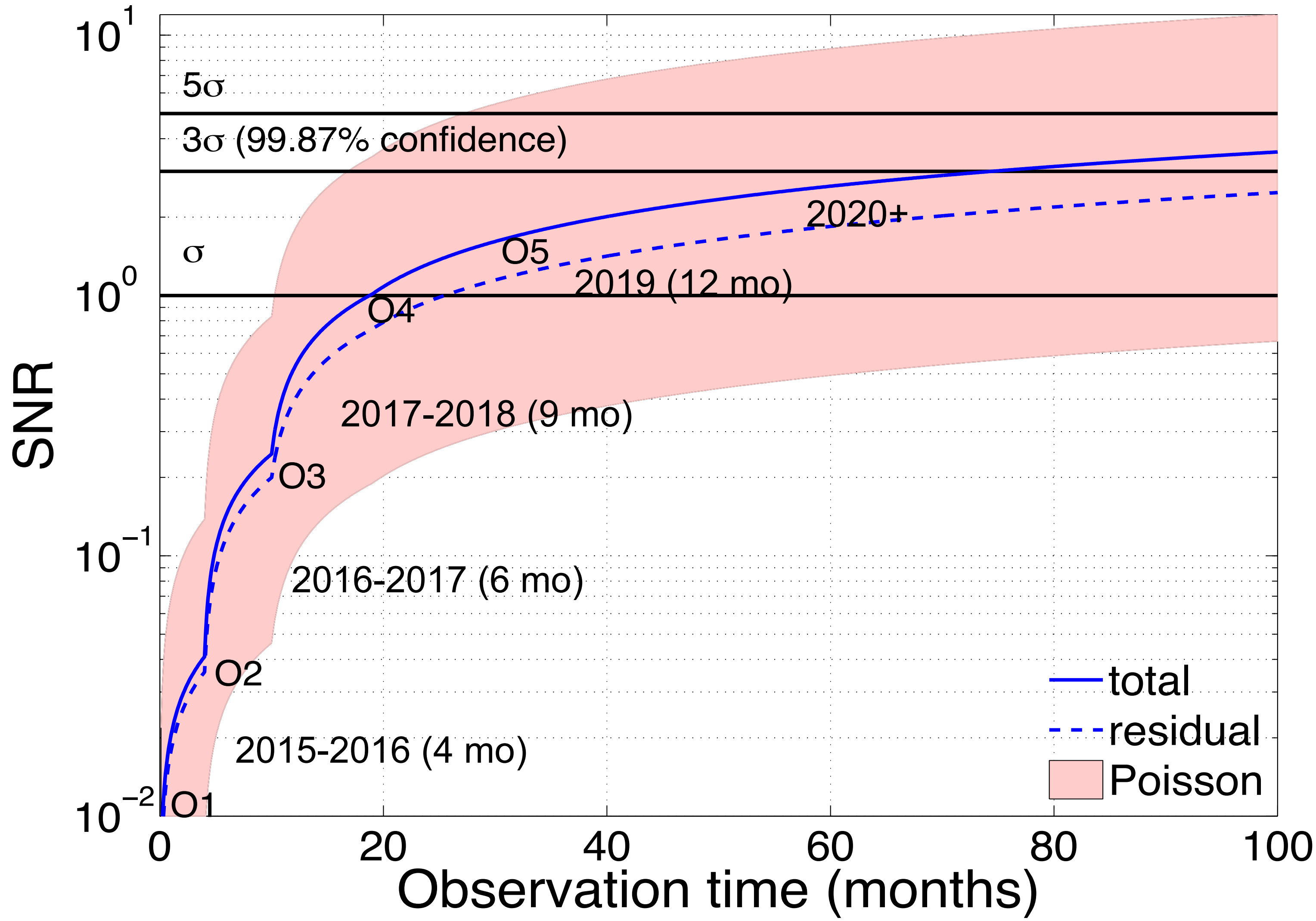
Evolution of the SNR



O1 results

Papers in preparation

PRELIMINARY

- No evidence for a stochastic background for both the isotropic and direction searches

- But upper limits on the energy density for different power indices

- For α=0, the isotropic bound is 33x better than with initial LIGO/Virgo

$$\Omega_{gw}(25\text{Hz}) < 1.7 \times 10^{-7}$$

Slide from Letizia Sammut

Directional searches

- relax assumption of isotropy and generalize the search for a stochastic signal to the case of arbitrary angular distribution.

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

$$\mathcal{P}(\hat{\Omega}) = \mathcal{P}_\alpha \mathbf{e}_\alpha(\hat{\Omega})$$

Radiometer Analysis

Spherical Harmonic Decomposition

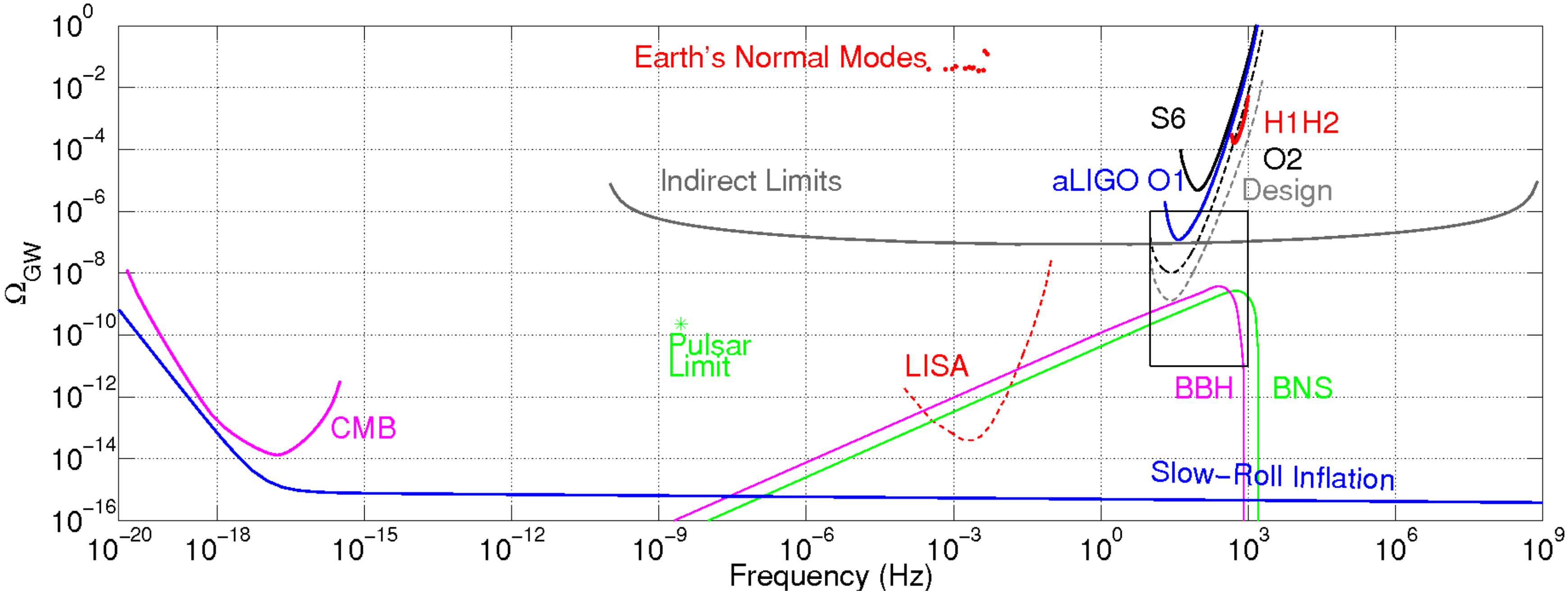
$$\mathcal{P}(\hat{\Omega}) \equiv \eta(\hat{\Omega}_0)\delta^2(\hat{\Omega}, \hat{\Omega}_0)$$

$$\mathcal{P}(\hat{\Omega}) \equiv \sum_{lm} \mathcal{P}_{lm} Y_{lm}(\hat{\Omega})$$

Summary/Conclusion

- The GW stochastic background from BBHs is expected to be in the higher end of previous predictions
- The background may be measured by LIGO/Virgo operating at or near design sensitivity.
- No evidence for a stochastic background in O1.
- Upper limit on a flat spectrum 33x better than with initial LIGO/Virgo

O1 isotropic paper, in preparation



Indirect limits: PhysRevX.6.011035
"CMB temperature and polarization power spectra, lensing, BAOs and BBN"

PI integrated sensitivity curves: PhysRevD.88.124032
"The LISA sensitivity curve corresponds to an autocorrelation measurement in a single detector assuming perfect subtraction of instrumental noise and/or any unwanted astrophysical foreground."