THE QUEST FOR THE GRAVITATIONAL-WAVE STOCHASTIC BACKGROUND

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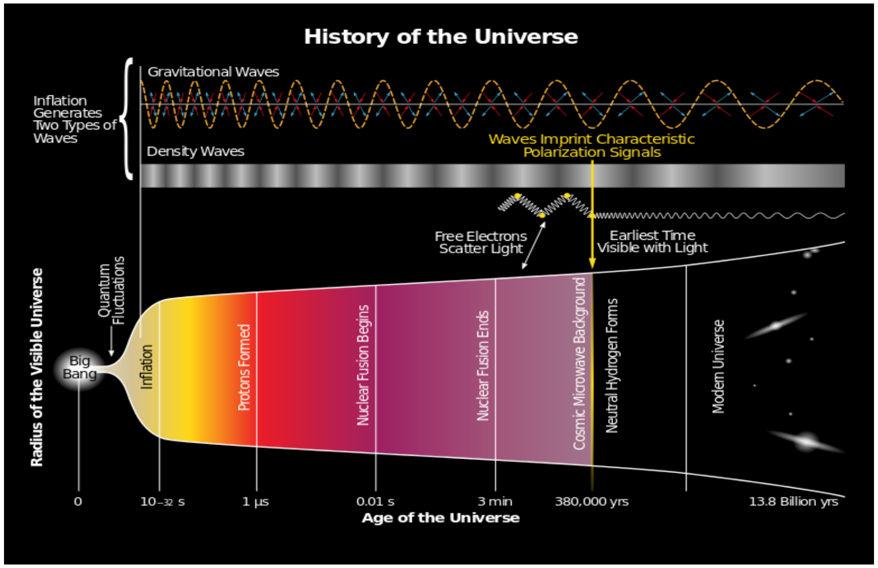
Probing the Early Universe with Gravity,
APC, Paris, 24/11/2016

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.

- **Cosmological:** signature of the early Universe
- **Astrophysical:** since the beginning of stellar activity



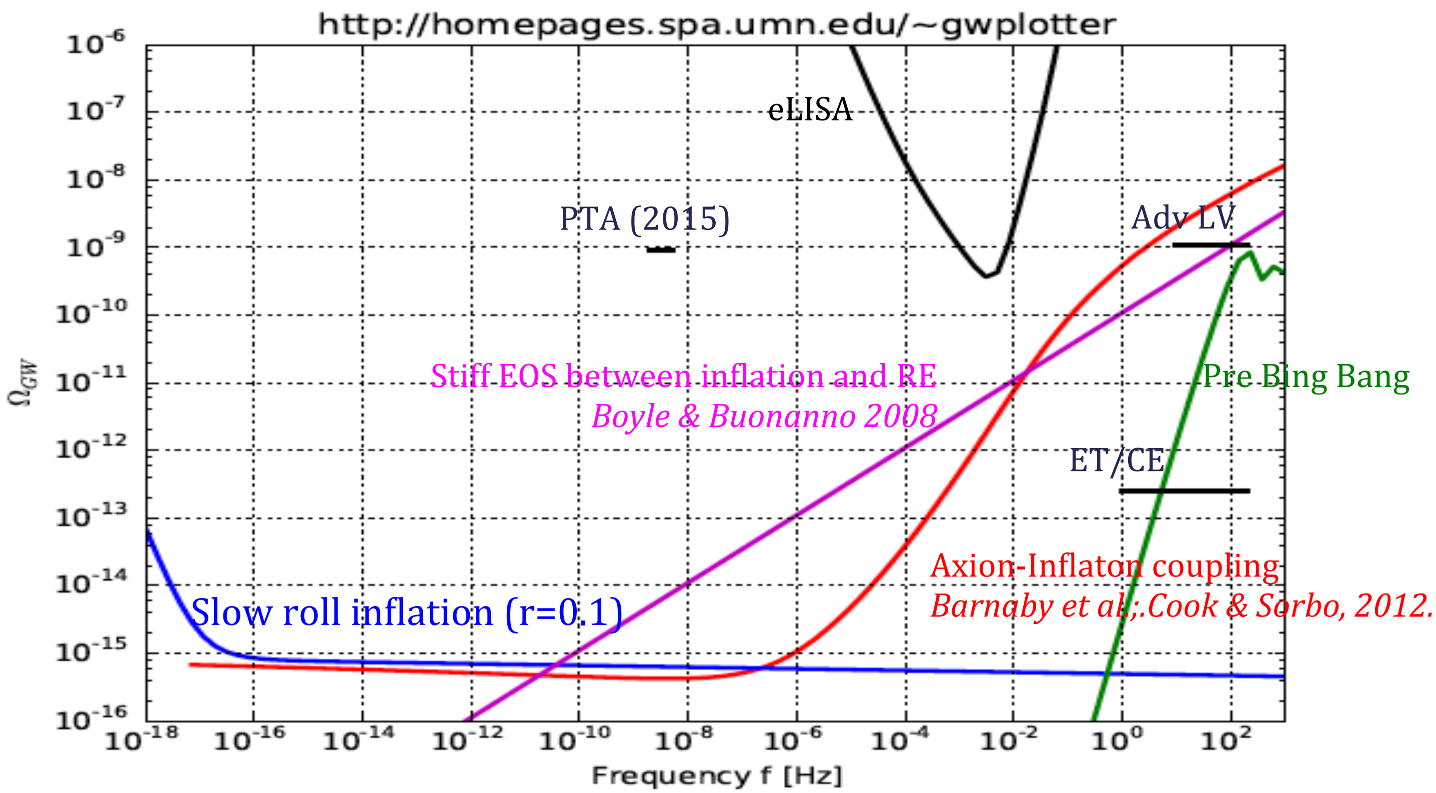
Cosmological background

- 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).

- The amplification of vacuum fluctuations during inflation, as well as on additional GW radiation produced in the final stages of inflation.

- Other models include phase transitions, cosmic (super)string models, and string theory pre-Big Bang models.

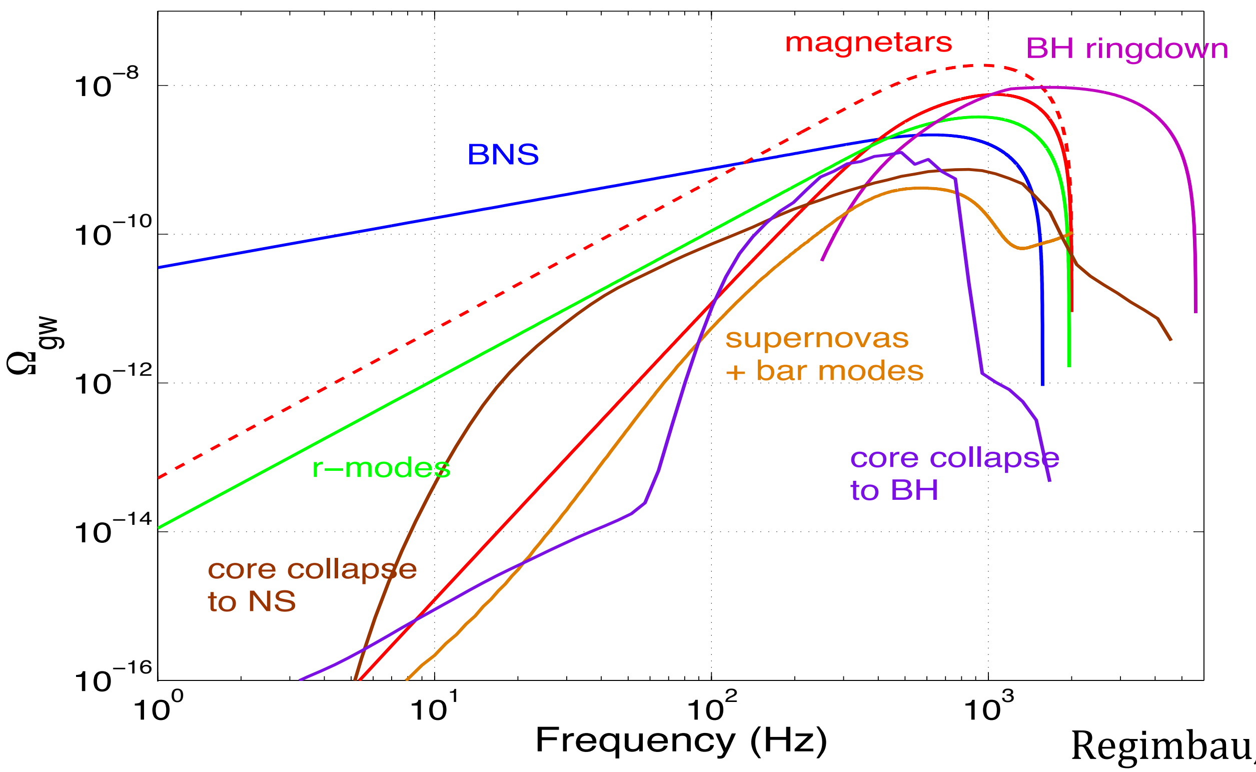
Background from inflation



Astrophysical Backgrounds

- All the sources that cannot be resolved individually (overlapping or below threshold)
- 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

Data Analysis Principle

- Assume stationary, unpolarized, isotropic and Gaussian stochastic background

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

$$s_i = h_i + n_i$$

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

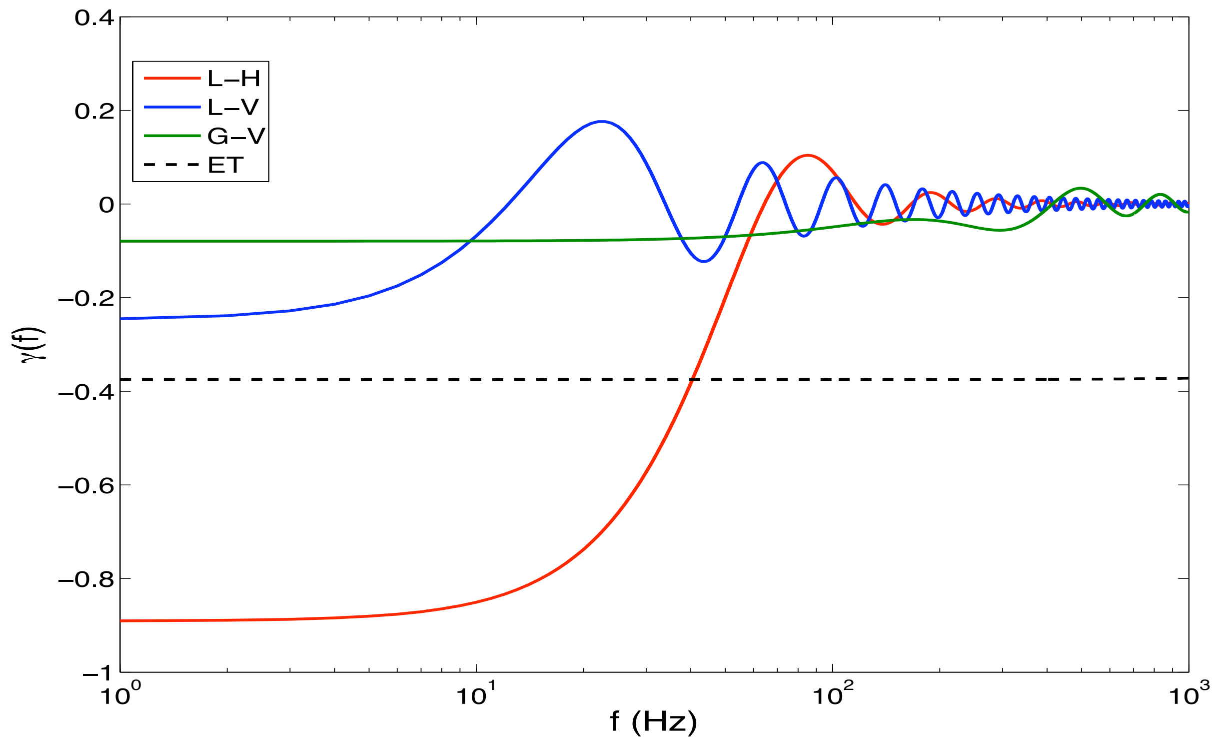
Cross Correlation Statistics

- Standard CC statistic (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

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

Overlap Reduction Function

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



What did we learn from the first Advanced LIGO run?

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. *PhysRevLetter.116.061102*

- 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 ($m_{1,2} \sim 30 M_{\odot}$) 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 $\theta=(m_1,m_2,\chi_{eff})$

$$\Omega_{gw}(f,\theta) = \frac{f}{\rho_c}\int_0^{20} \frac{dR_m^{\theta}}{dz}(z,\theta)\frac{\frac{dE_{gw}}{df}(\theta,f(1+z))}{4\pi r^2(z)}dz$$

- 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 (*arXiv:1602.03840*)
- Local merger rate: $R_0=16^{+38}_{-13}$ $Gpc^{-3}yr^{-1}$ (*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.

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

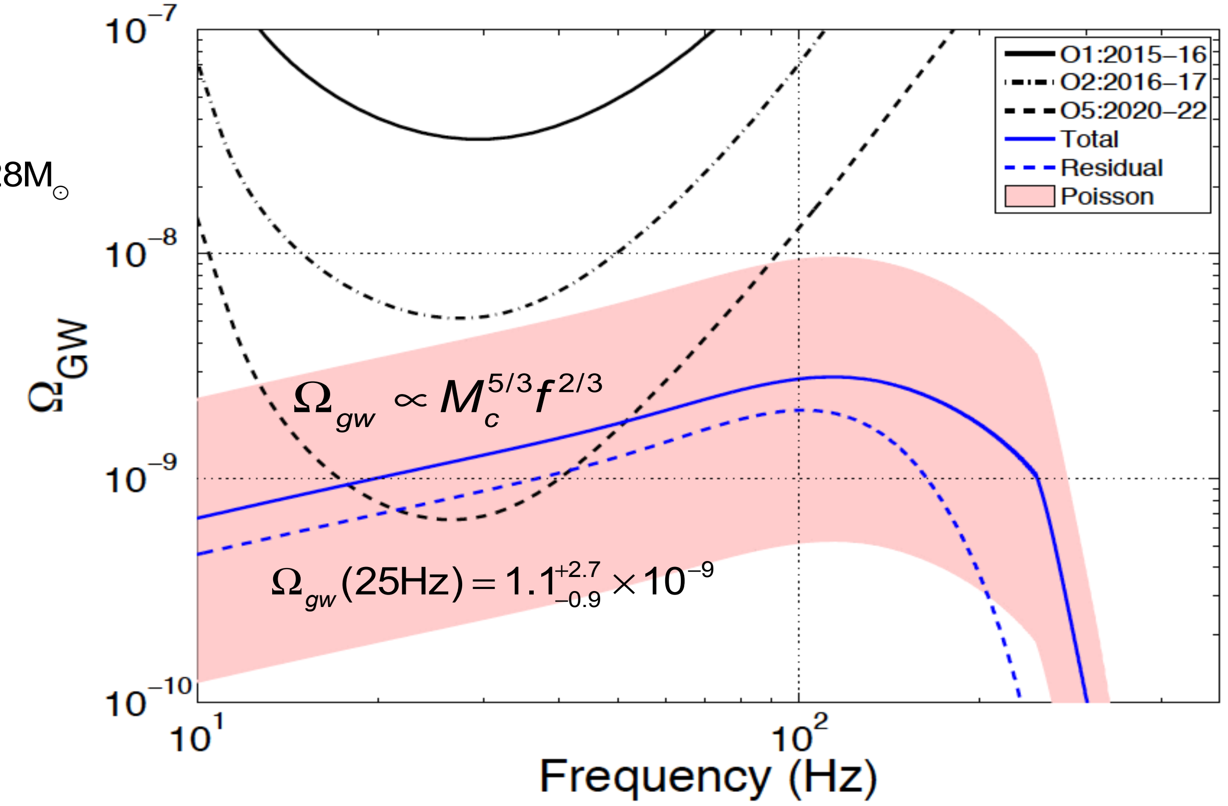
- Short delay time: $P(t_d) \propto t_d^{-1}$ with $t_d > 50$ Myr

PhysRevLetter.116.131102

Fiducial Model

chirp mass:

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



Alternative models

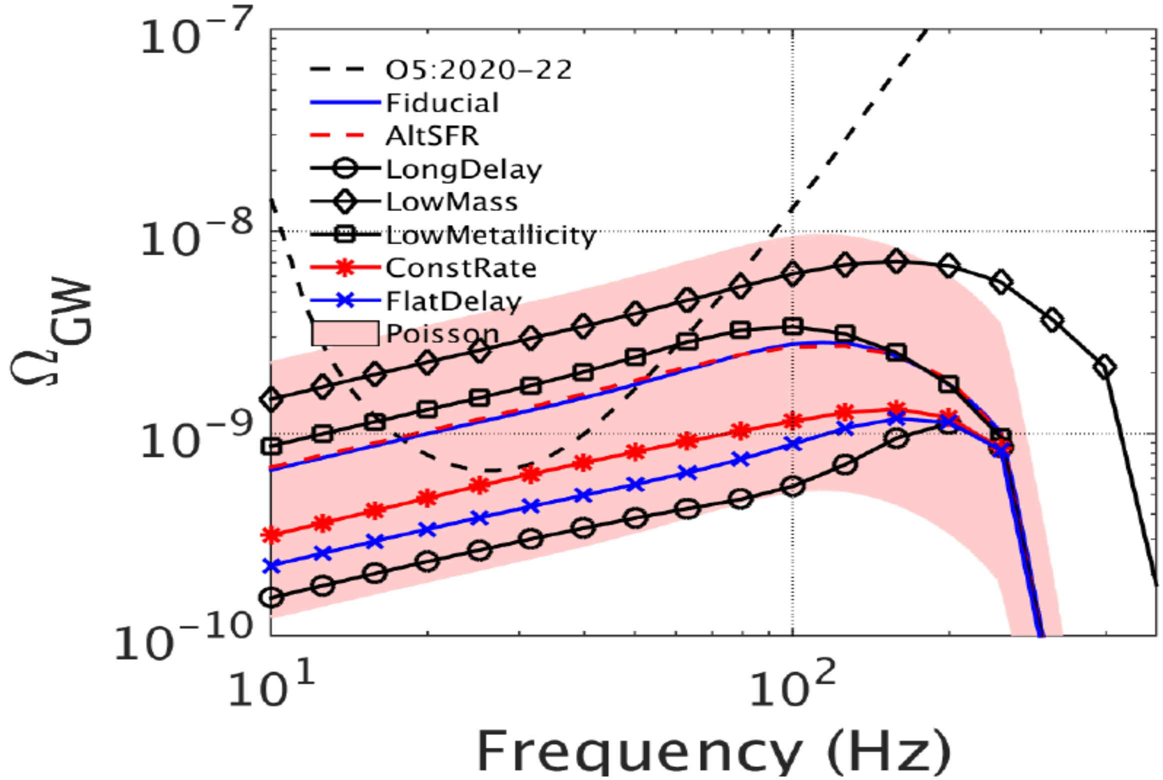
We investigated the impact of possible variations to the fiducial model

- **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 $Gpc^{-3}yr^{-1}$

PhysRevLetter.116.131102

Alternative models

All these variations are smaller than the Poisson uncertainty.



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Update using all of O1

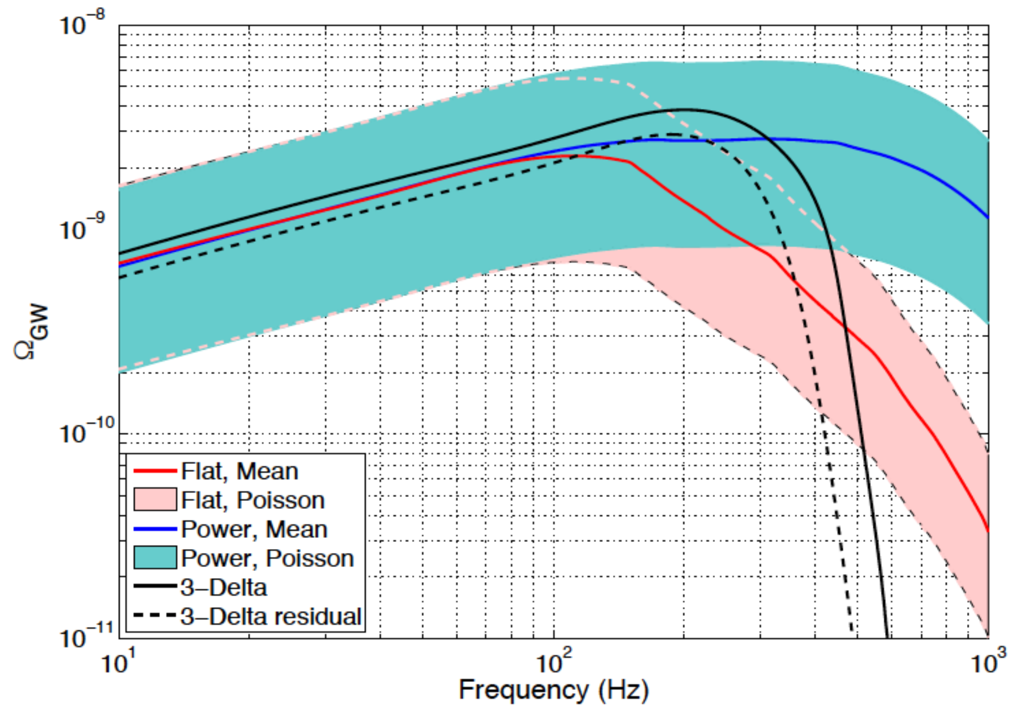
- 3 events GW150914 ($M_c \sim 28 M_\odot$), GW151226($\sim 15\ M_\odot$) and LVT151012 ($\sim 9\ M_\odot$)

- No significant difference in the median value for f<100 Hz.

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

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

- Slight improvement of the error



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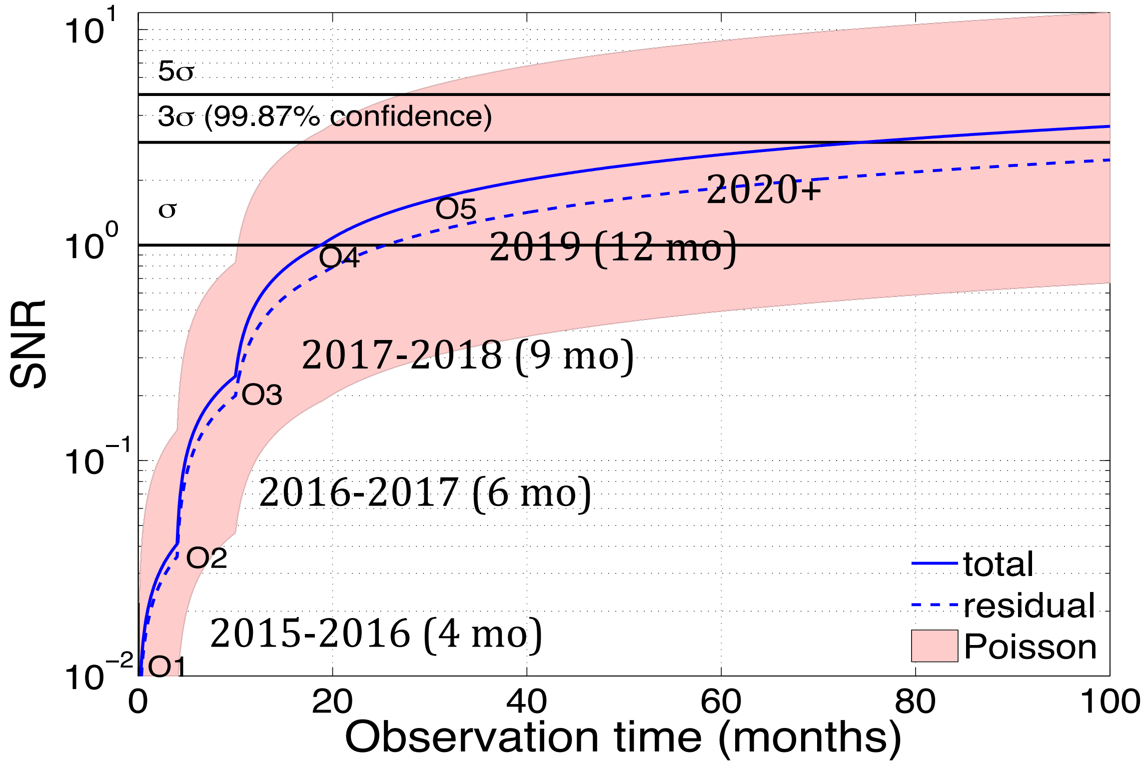
Evolution of the SNR

The background from BBHs could be detected before the detectors reach design sensitivity!



O1 results

- No evidence for a stochastic background
- But set upper limit on the energy density

α	99% sens. band	Ω_α	95% UL	S6 UL
0	$20 - 85.8$ Hz	$(4.4 \pm 5.9) \times 10^{-8}$	1.7×10^{-7}	5.6×10^{-6}
$\frac{2}{3}$	$20 - 98.2$ Hz	$(3.5 \pm 4.4) \times 10^{-8}$	1.3×10^{-7}	–
3	$20 - 305$ Hz	$(3.7 \pm 6.5) \times 10^{-9}$	1.7×10^{-8}	3.5×10^{-8}

- For α=0, 33x better than initial LIGO/Virgo

What next?

Context and Goal

- We are bathed in a stochastic primordial gravitational-wave background (PGWB) produced in the very early stages of the Universe.

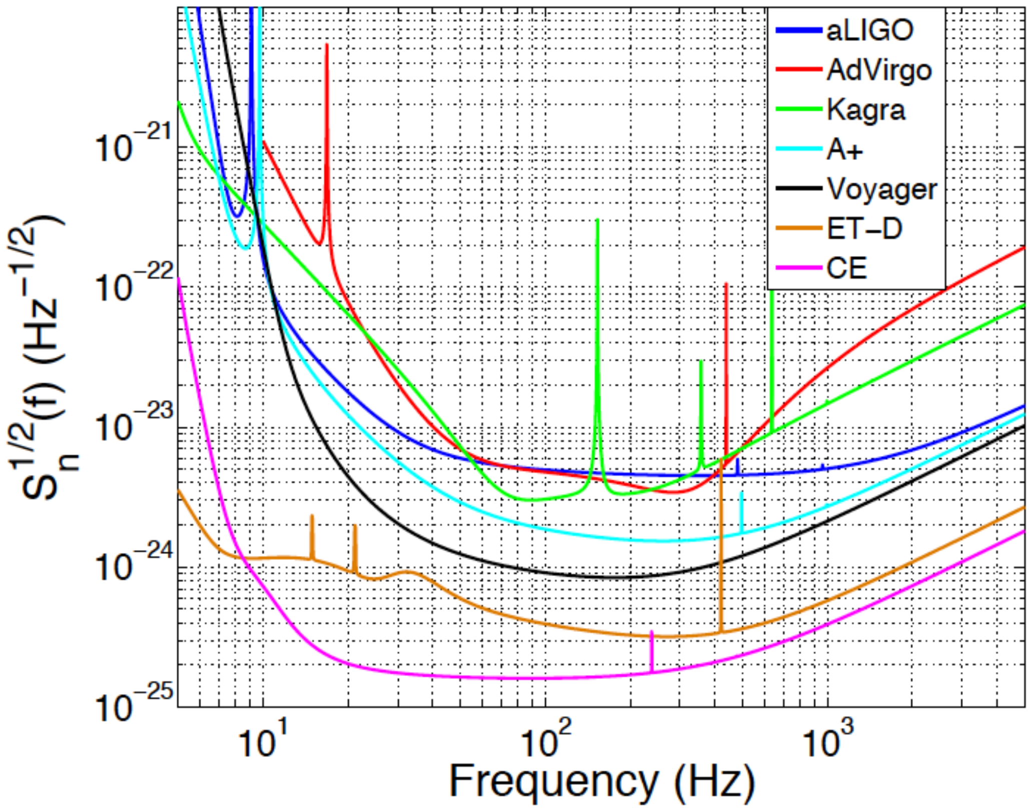
- Its detection would have a profound impact on our understanding of the evolution of the Universe, as it represents a unique window on the first instant, up to the limits of the Planck era, and on the physical laws that apply at the highest energy scales

- An astrophysical background is expected to result from the superposition of a large number of **unresolved sources** since the beginning of stellar activity.

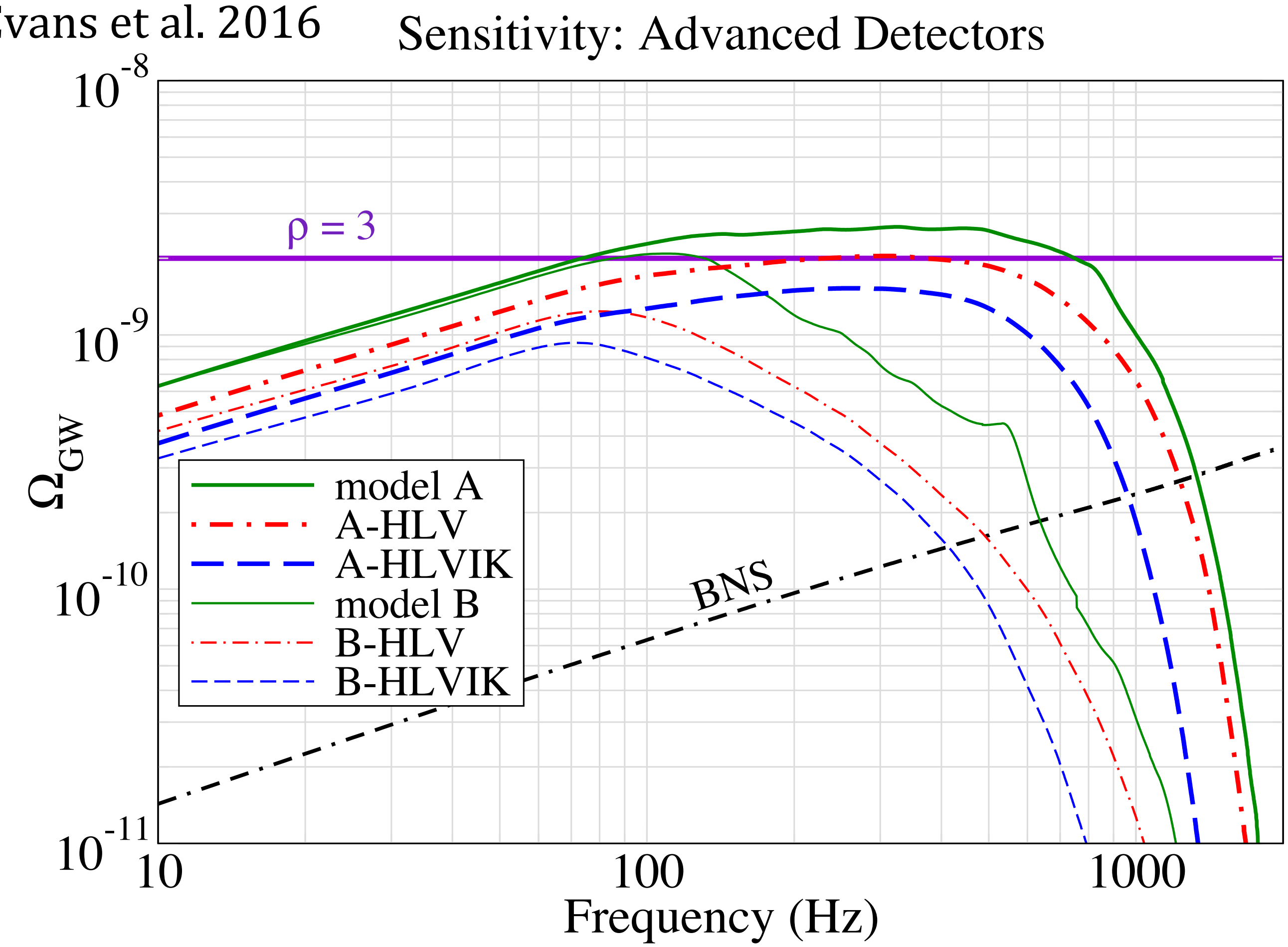
- The background from BBHs is expected to dominate in the LIGO/Virgo frequency band, resulting in an **astrophysical confusion background**.

- **How well can the future generation of detector remove the confusion background and recover the primordial background ?**

3rd generation



Regimbau, Evans et al. 2016



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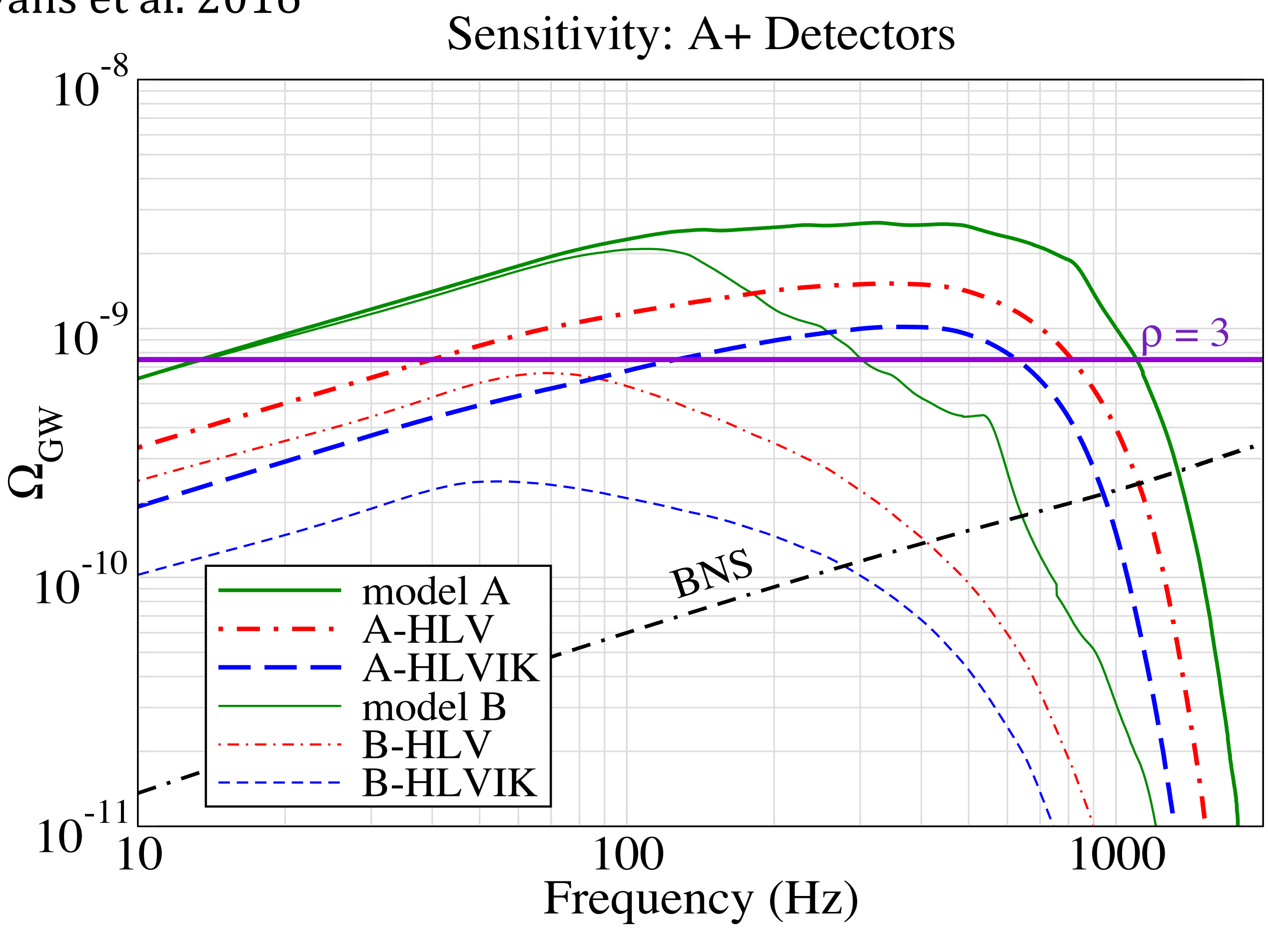

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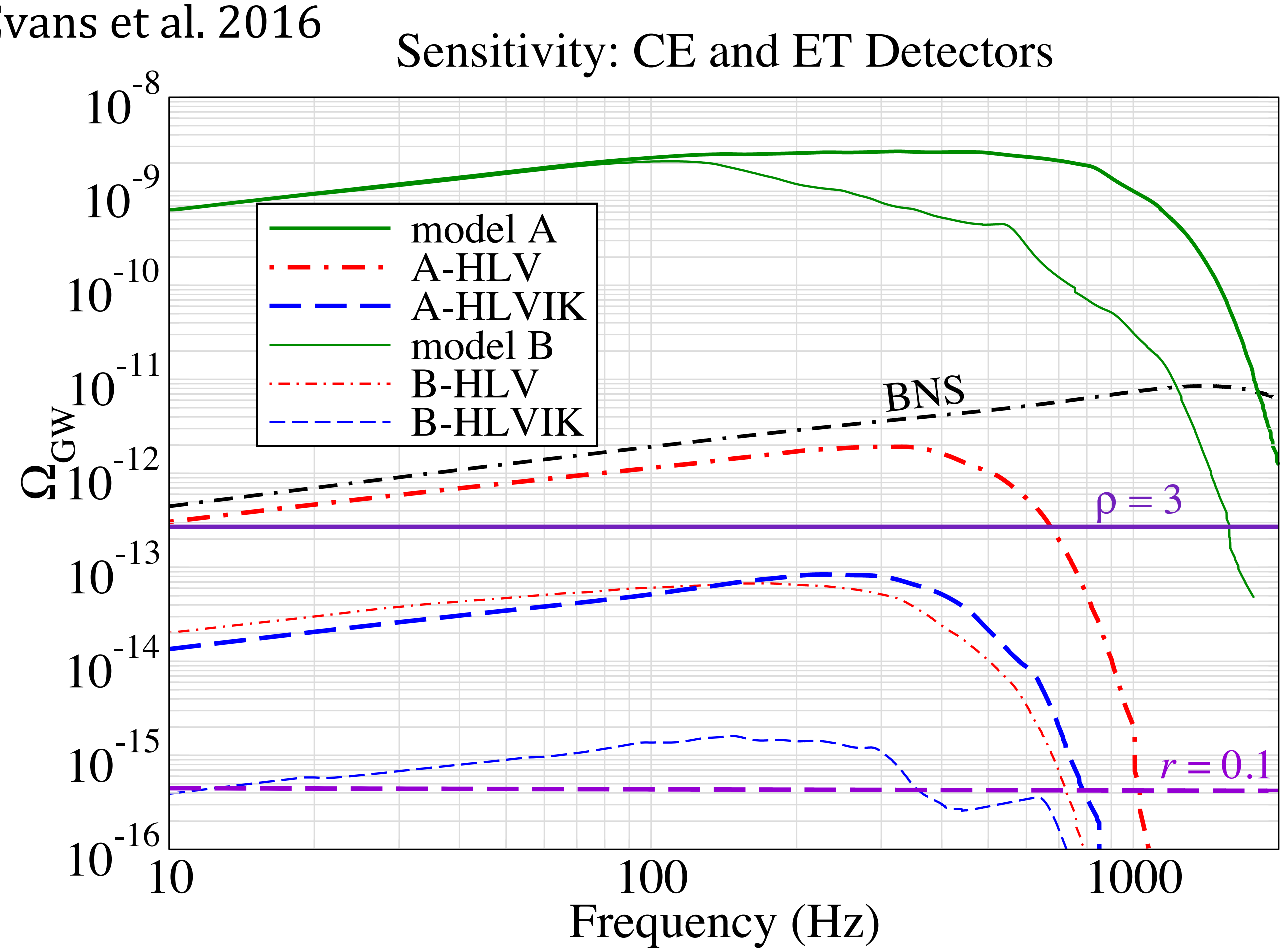

Results

- The confusion noise from BBHs can be decreased below the minimal detectable flat spectrum expected to mimic most of the cosmological backgrounds, using a network of five detectors

- This minimal detectable value is above the prediction for the standard inflation model, even for third generation detectors $\Omega_{min}=2.10^{-13}$ (same as LISA)

- The sensitivity should be improved by at least another factor of about 10 in the future to reach a level of $\Omega_{min}=2.10^{-15}$.

- An improvement of a factor of 3 in sensitivity would permit to remove all the binary sources of neutron stars and black holes.

Summary

- Exciting time for GW astronomy: first detection by LIGO, success of LISA pathfinder
- In addition to close individual searches, the astrophysical background from all the binaries at high redshift has a chance to be detected in the next few years
- The ultimate goal is to remove the astrophysical foreground and observe the cosmological background