The stochastic GW Background in the advanced detector era

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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.

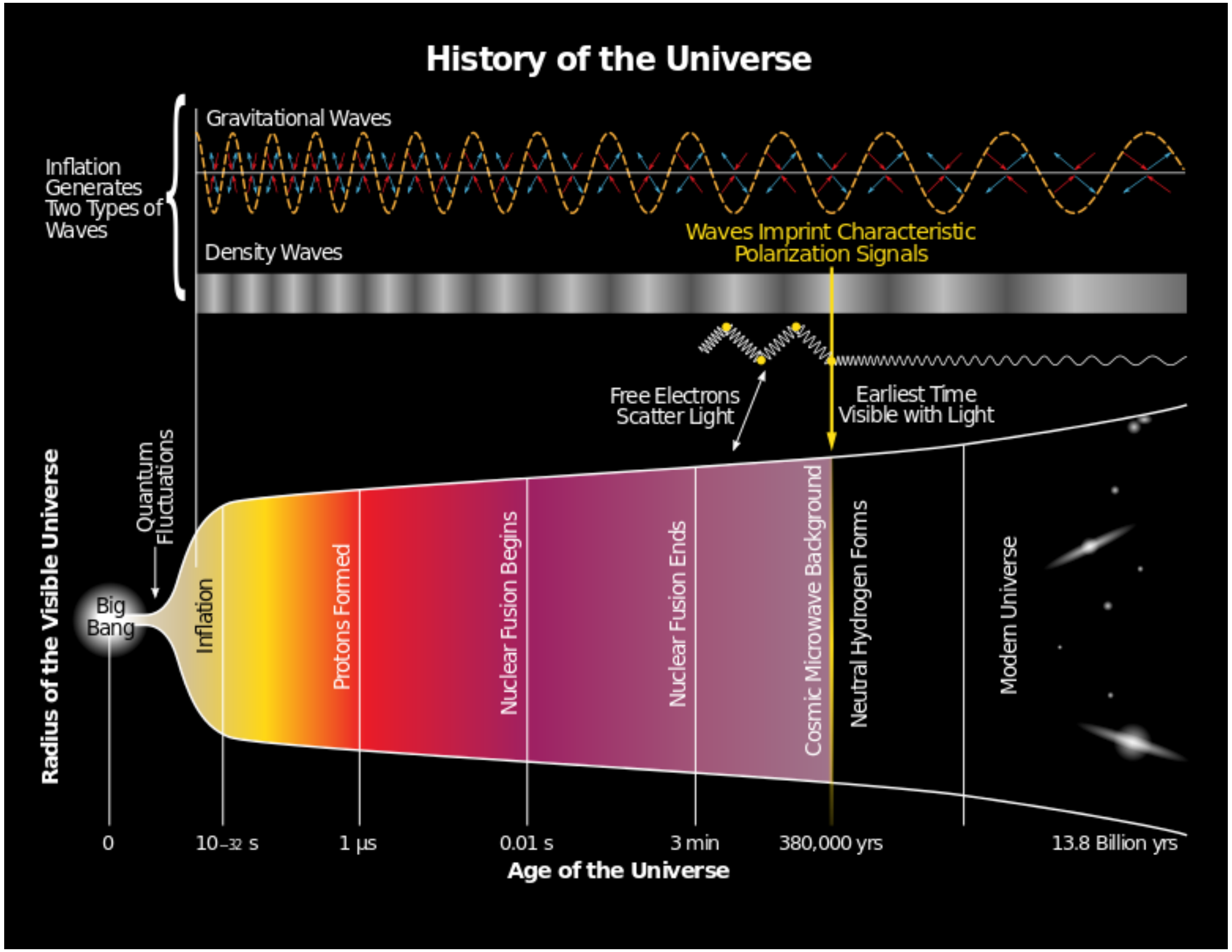
- The energy density in GW in the Universe :

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

- The sources can be either :

- Cosmological: signature of the early Universe near the Big Bang
inflation, cosmic strings, phase transitions…

- Astrophysical: from the beginning of stellar activity
compact binaries, core-collapse supernovas to NSs or BHs, rotating neutron stars, capture by supermassive BHs…


History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

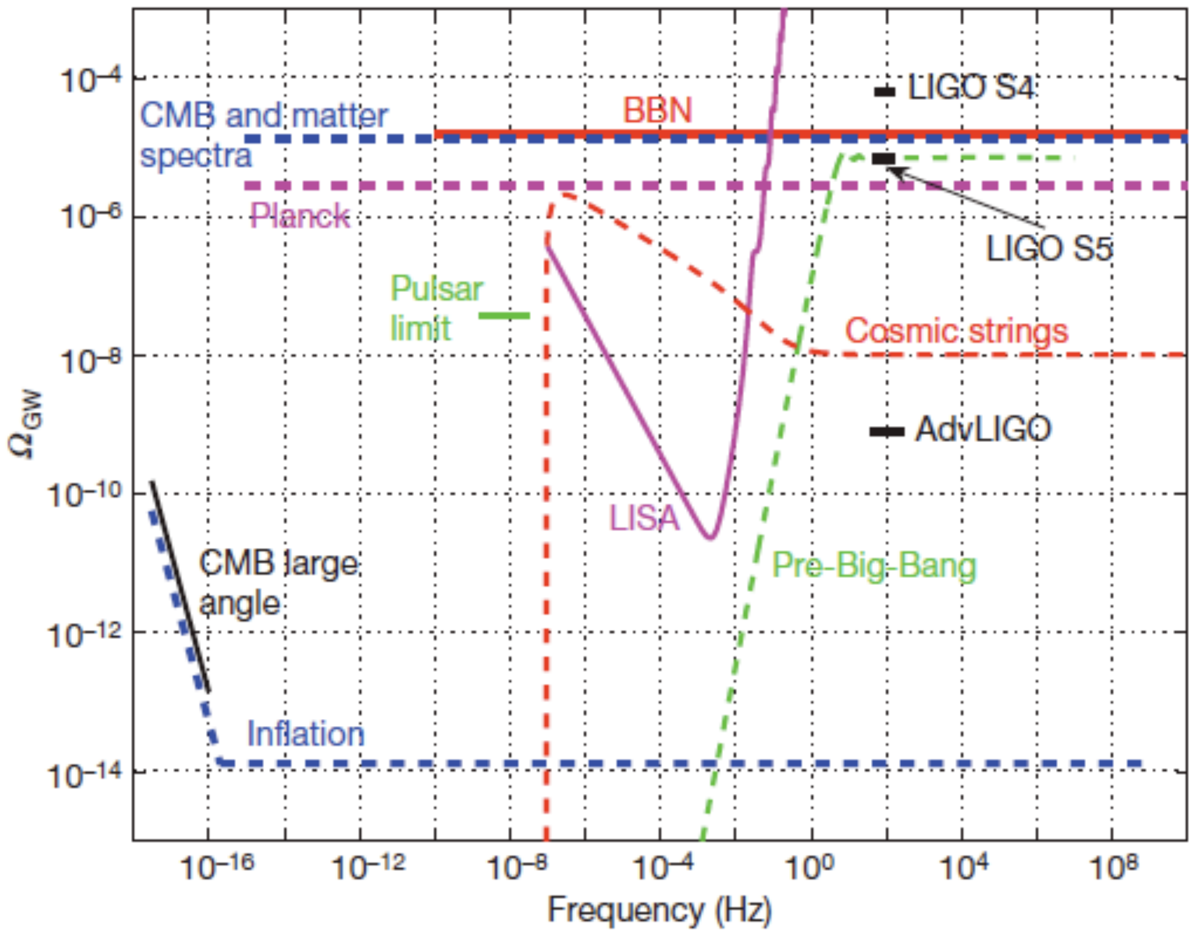
Cosmological Sources

- amplification of vacuum fluctuations during inflation, as well as on additional GW radiation produced in the final stages of inflation (for example in preheating models or models of axion inflation).

- detection of this background would have a profound impact on our understanding of the evolution of the Universe, as it represents a 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.

- other models of cosmological GW background include phase transitions, cosmic (super)string models, and string theory pre-Big Bang models.

Cosmological Sources



From the LIGO&Virgo Collaboration, 2009, Nature

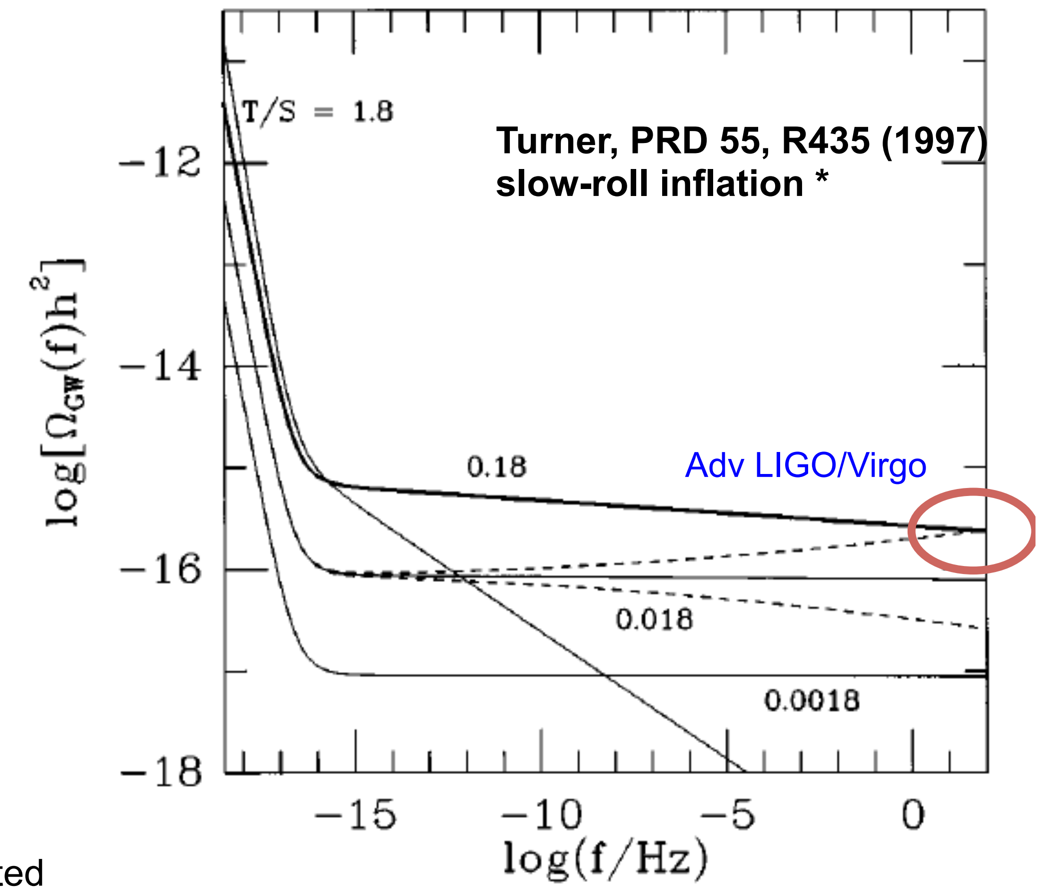
Implication of BICEP2 results (if…)

- Measurement of the CMB tensor-to-scalar ratio : *r = 0.16-0.2*

- The amplitude and the power index depend on *r:*

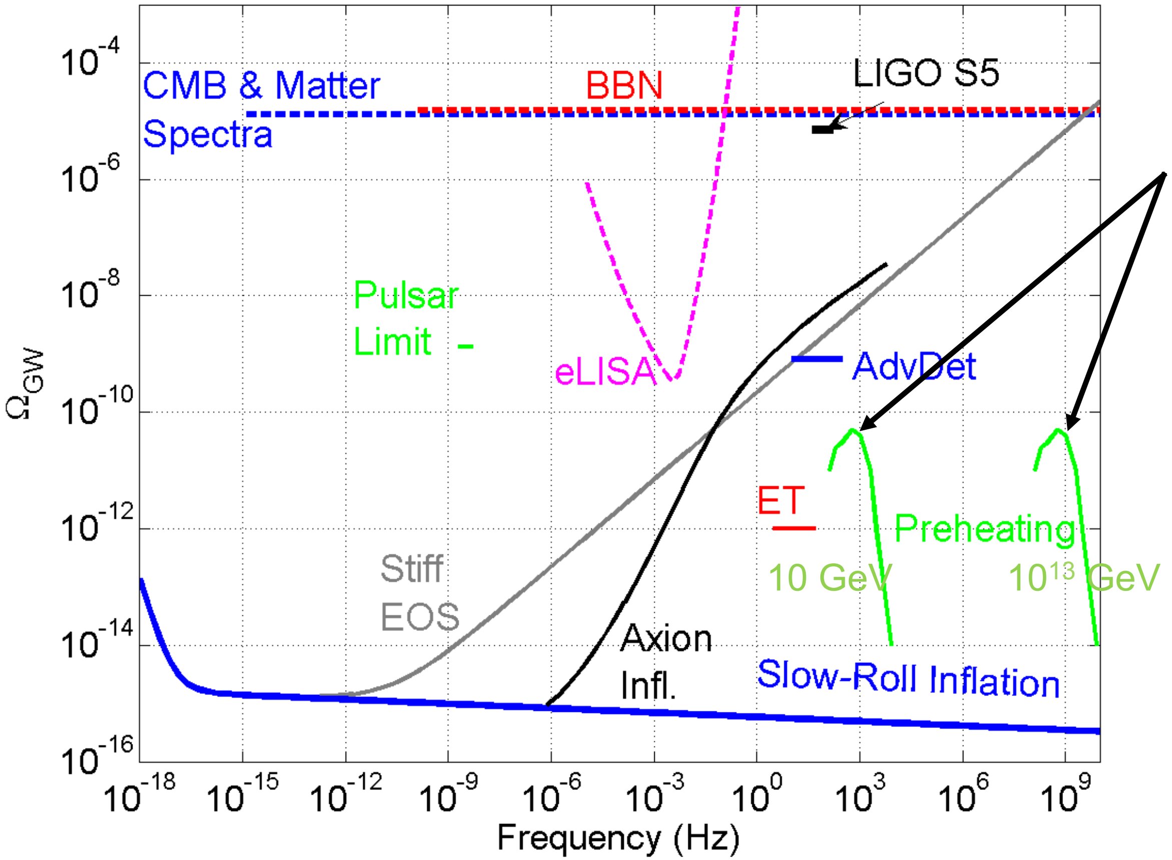
$$\Omega_{gw}(f) \approx 5\times10^{-16}\left(\frac{f}{100}\right)^{n_T} \text{ with } n_T = -r/8$$

- Slow-roll inflation out of reach of advanced detectors by 6-7 orders of magnitude



* the inflaton field drives a period of accelerated expansion by rolling toward the minimum of V (φ).

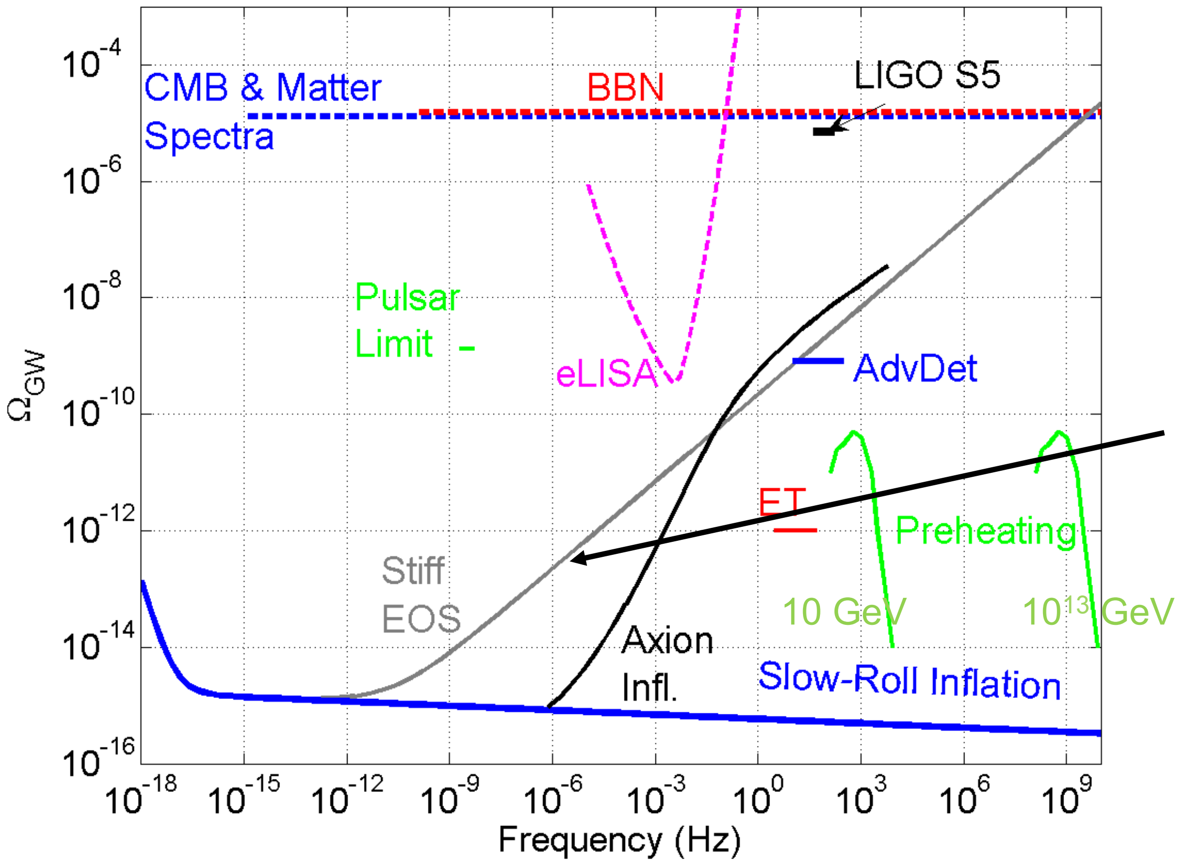
More promising…



- If inflation ends with a preheating resonant phase, inflaton energy is efficiently transferred to other particles.
- Can have significant increase in GW background.
- Peak depends on energy scale.

Slide provided by V. Mandic

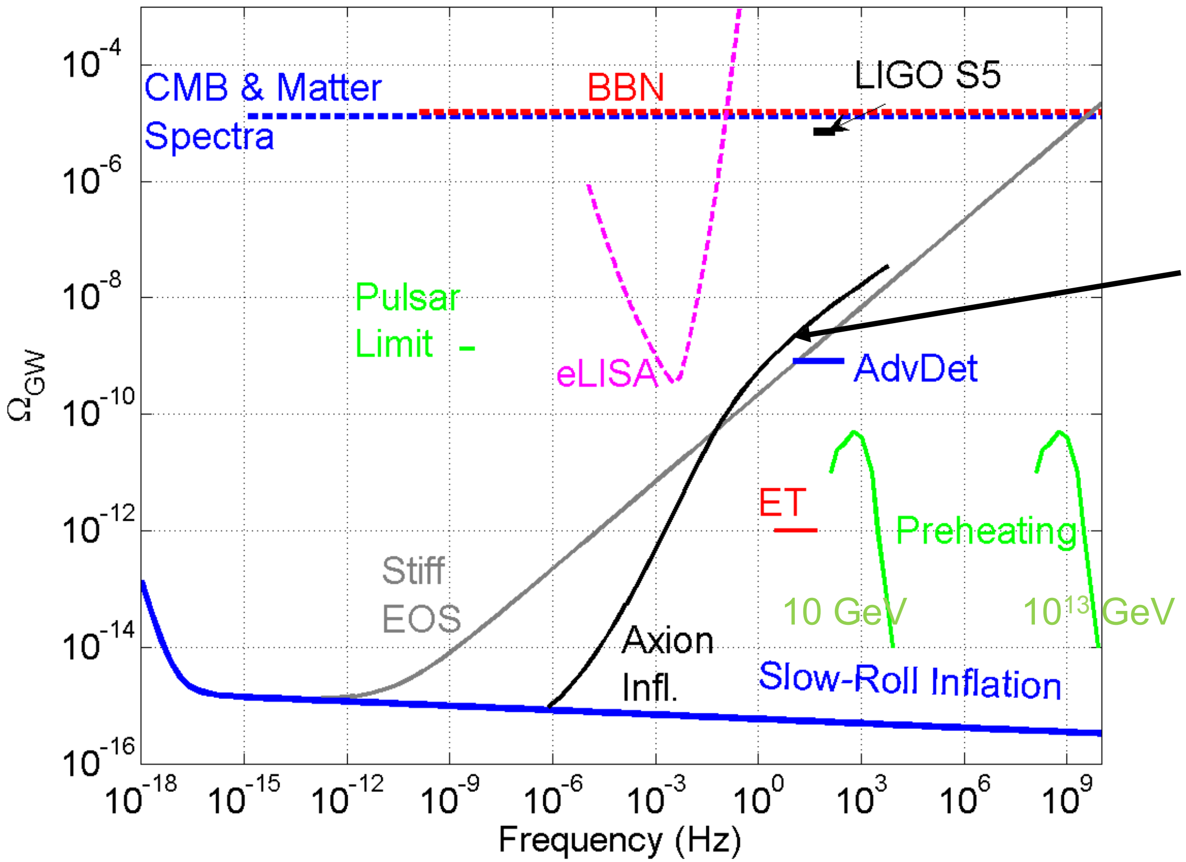
More promising…



- if EOS is stiff at the transition to the radiation era, the spectrum could increase with frequency and be potentially detectable by advanced detectors.

Slide provided by V. Mandic

More promising…



- Axion-based inflation models include axion-gauge couplings.
- Gauge backreaction on the inflaton extends inflation.
- This late inflationary phase increases GW production at high frequencies.

Slide provided by V. Mandic

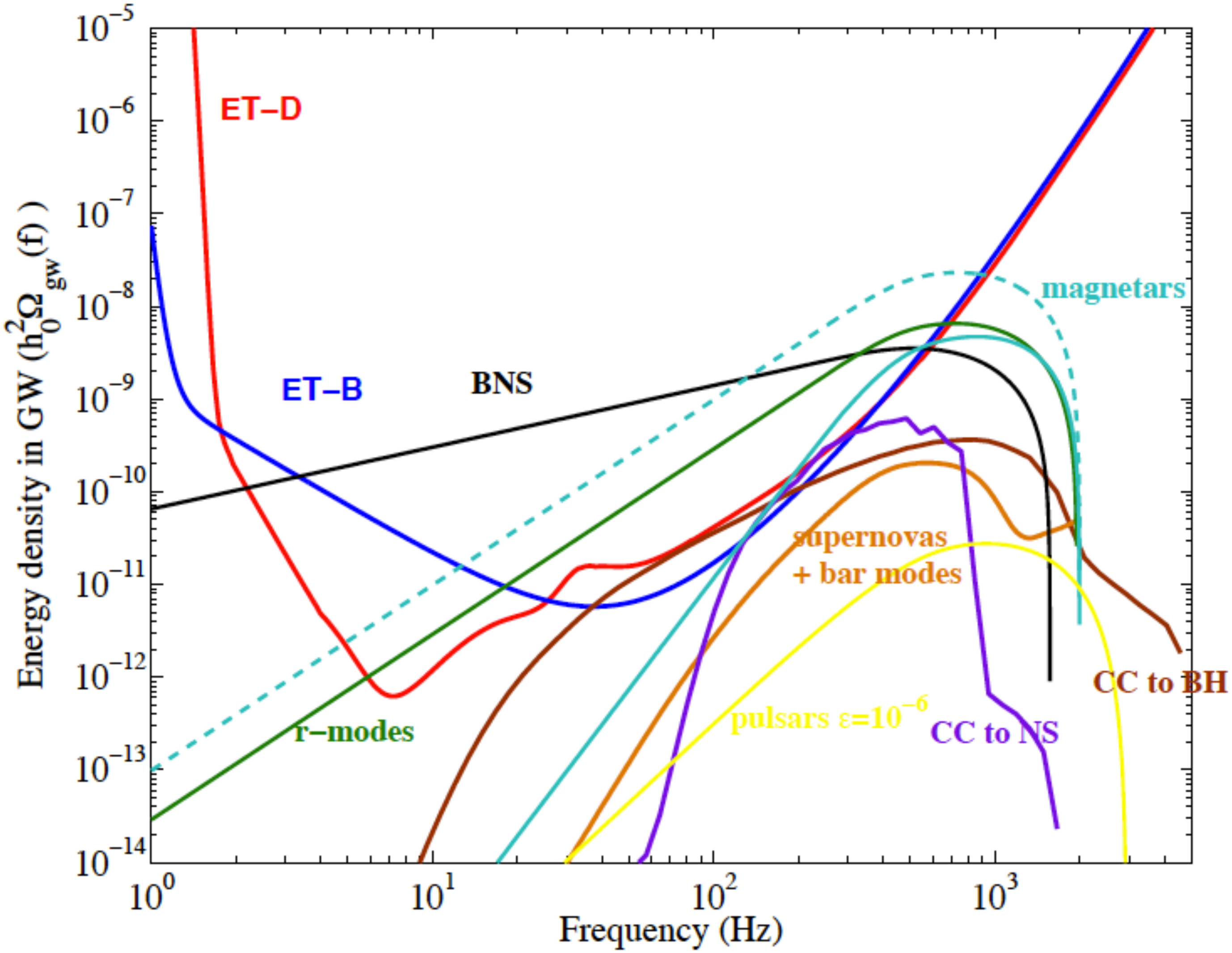
Astrophysical Sources

Neutron stars and black holes emit GW at different stages of their evolution, either because they rotate or oscillate. The superposition of all the extra-galactic sources, up to z~10, create an astrophysical backgroung.

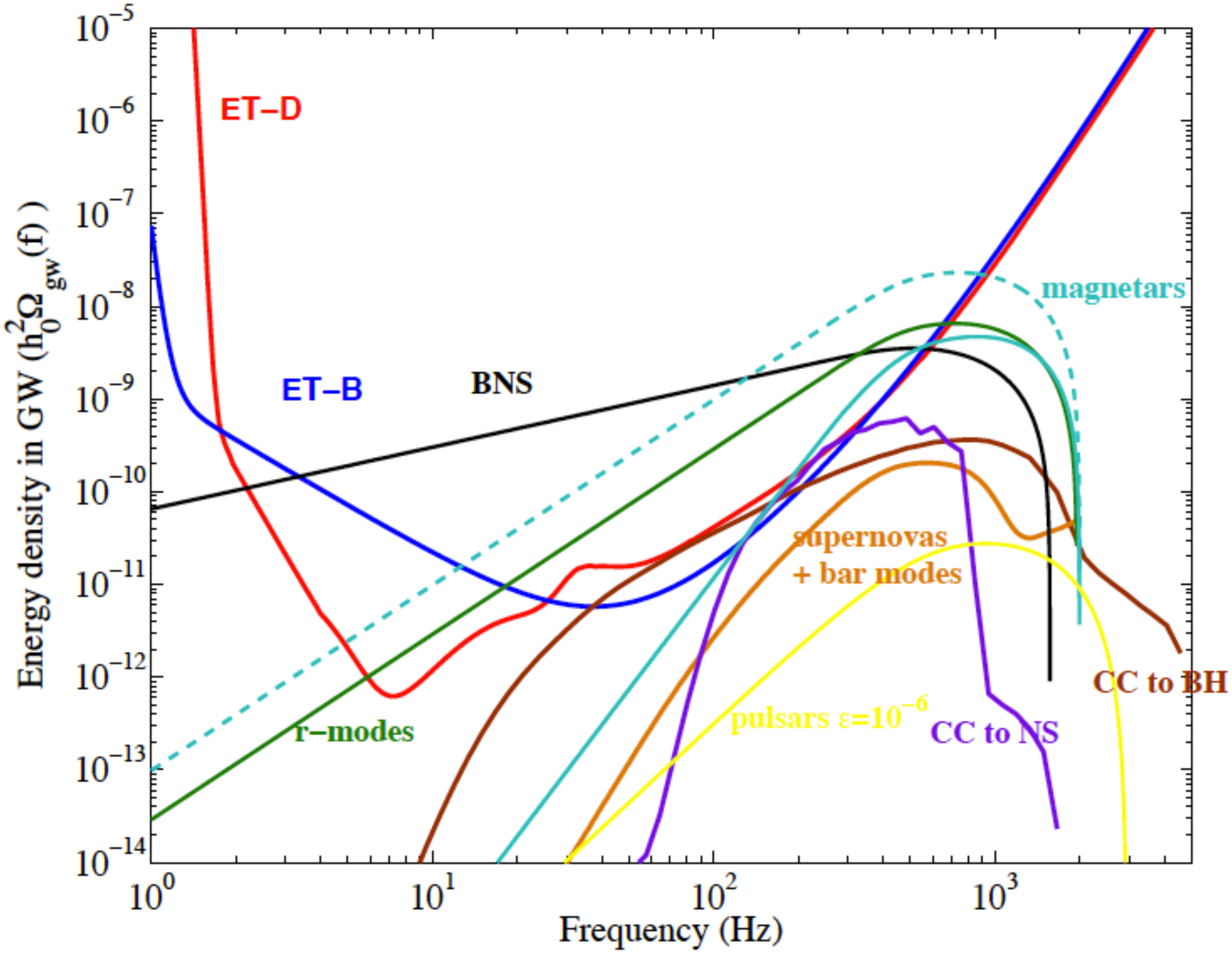
- Core-collapse to NS or BH
- Rotating neutron stars and initial instabilities
- NS phase transitions
- Oscillation modes in NS
- Compact binary coalescences
- Captures by SMBH

This background can be a foreground for the cosmological background but its detection would provide crucial information on the physical properties of NS and BH, their evolution with redshift, the star formation history, the initial mass fuction or the metallicity.

Astrophysical Sources



Astrophysical Sources



Data Analysis principle

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

$$h_i = s_i + n_i$$

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

- Existing searches (isotropic/spherical harmonics) assume stationary, unpolarized and Gaussian stochastic background

- Standard CC statistic

- Frequency domain cross product: $Y = \int \tilde{s}_1^*(f) \tilde{Q}(f) \tilde{s}_2(f)\, df$

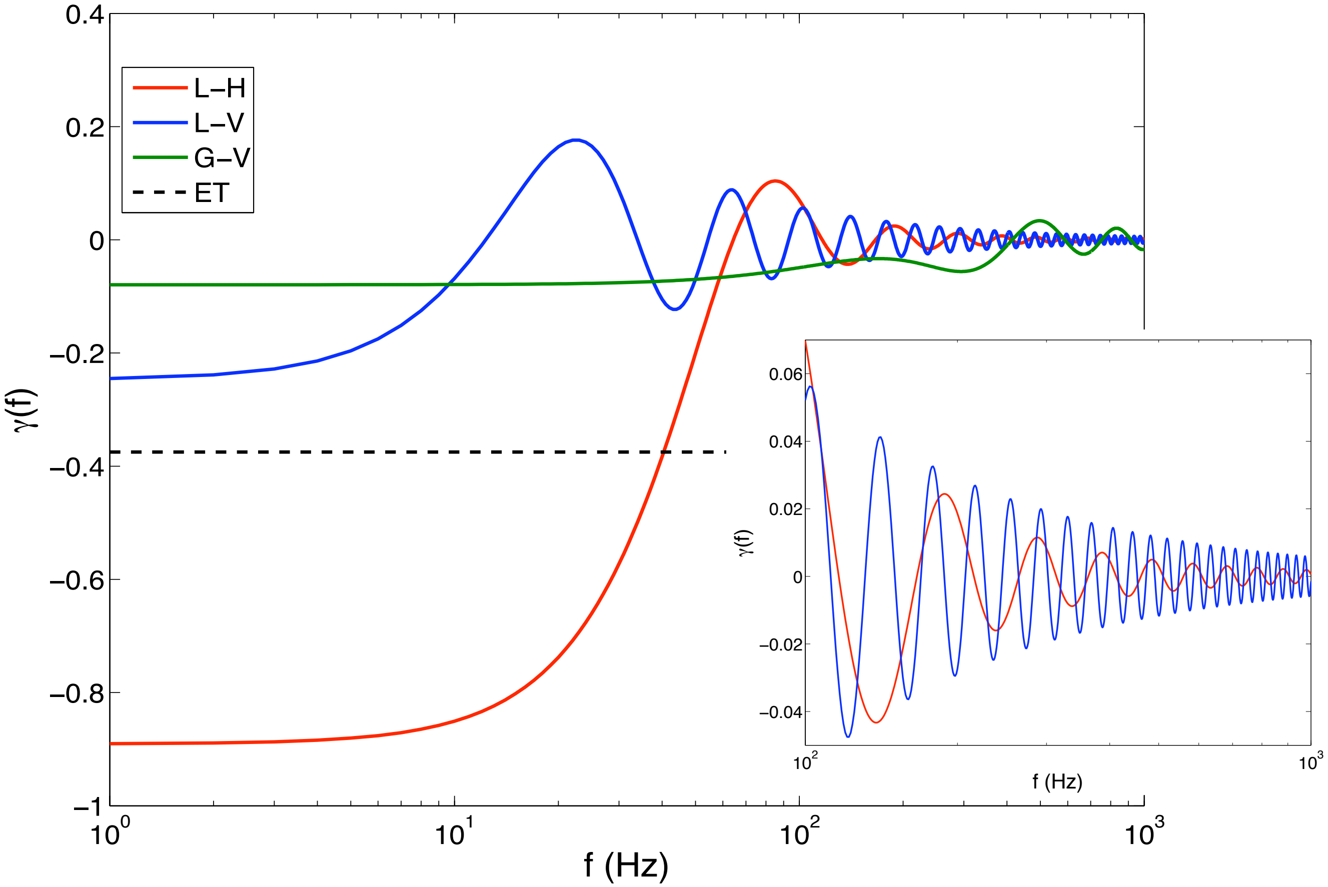
- optimal filter: $\tilde{Q}(f) \propto \dfrac{\gamma(f)\Omega_{gw}(f)}{f^3 P_1(f) P_2(f)}$ with $\Omega_{gw}(f) \equiv \Omega_0 f^\alpha$

- in the limit noise >>GW signal

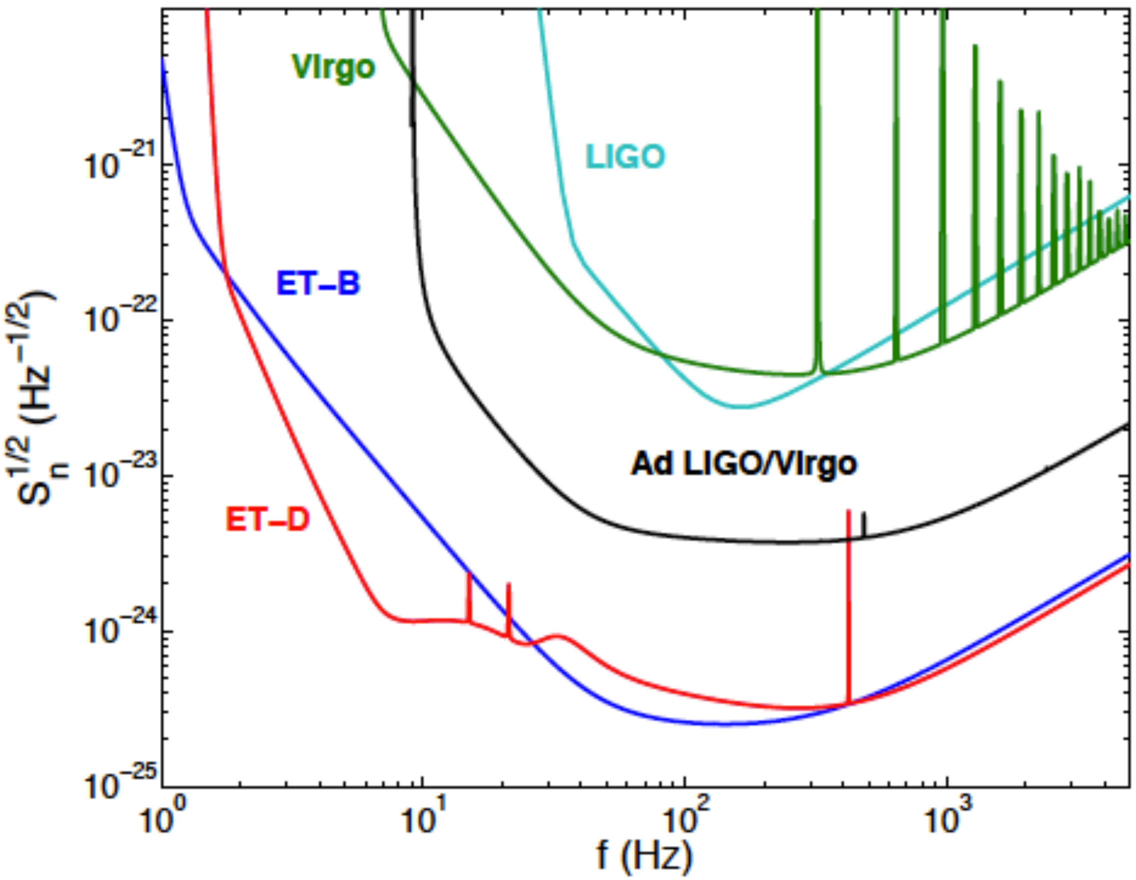
$$\mathrm{Mean}(Y) = \Omega_0 T,\ \mathrm{Var}(Y) \equiv \sigma^2 \propto T,\ \mathrm{SNR} \propto \sqrt{T}$$

Overlap Reduction Function

Reduction in sensitivity due to the separation and relative orientation of the detectors.



Noise Curves



Previous Upper Limits

run	Frequency band	Upper limit (90%)
S1* (51h H2-L)	40-314	23
S3* (218 h H1-L)	69-156	$8.4\ 10^{-4}$
S4* (350 h H-L)	51-150	$6.5\ 10^{-5}$
S5* (H-L)	40-170	$6.9\ 10^{-6}$
S5-VSR1** (H-L-V-G)	600-1000	H-L-V=2.5 H-L H-L-V-G: +10%

$^{*}\Omega_{gw}(f) = \Omega_0$ $^{**}\Omega_{gw}(f) = \Omega_0 f^3$

Latest Upper Limits

- LIGO S6 and Virgo VSR2-3 (*)

- direct 95% confidence level upper limits on the energy density of the background in each four frequency bands spanning 41.5-1726 Hz. The limits in these four bands are the lowest direct measurements to date on the stochastic background.

- Compared to S5 we have an improvement of 20% at low frequencies using the LIGO pair H-L, and of a factor 2.5 at higher frequencies using the LIGO/Virgo pairs.

- **41.5-169.25 Hz : Omega_GW(f) < 5.6e-6.**
- 600-1000 Hz band, Omega_GW(f) <0.14(f/900 Hz)^3
- 170-600 Hz : Omega_GW(f) <1.8e-4
- 1000-1726 Hz : Omega_GW(f) <1.0(f/1300 Hz)^-3

(*) arXiv:1406.4556

Other stochastic search pipelines

- Coincident detector analysis using noise identification and mitigation techniques (based on PEM-coherence and time shift analysis)

- Anisotropic search based on spherical harmonic decomposition

- Non Gaussian methods

Mock Data Challenge for the ADE

- A few astrophysical and cosmological models may be accessible by the Advanced detector network

- The background due to binary coalescences could be detected in a large range of the parameter space

- We initiated a Mock data challenge in order to study:

- the ability of the actual pipeline to recover the GW signal
- optimize the search parameters
- develop more specific data analysis methods
- test parameter estimation techniques
- prepare interpretation of the results in term of astrophysics and cosmology

Mock Data

We used the MDC Generation Code initially developed for ET to produce time series at the output of a network of Ad detectors.

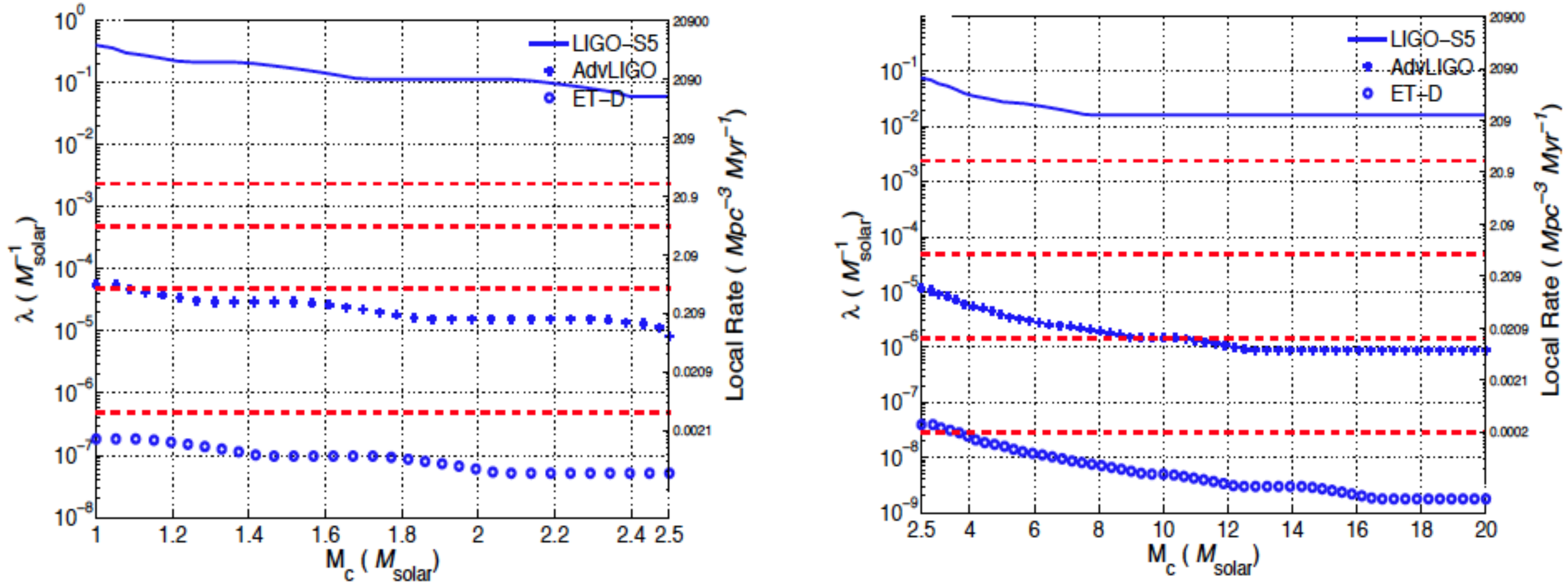
Gaussian colored instrumental noise is generated in the frequency domain and spliced to avoid discontinuities at frame boundaries. There is no instrumental correlation between detectors (but environmental noise can be included)

Gaussian, isotropic stochastic backgrounds are generated in the frequency domain from a power law spectral density ~f^a, and FFT to the time domain.

Astrophysical GW signals (CBC, bursts) are generated in the time domain. Parameters are realistically distributed in time (Poisson process), redshift (SFR +delay), position in the sky, orientation, masses etc…

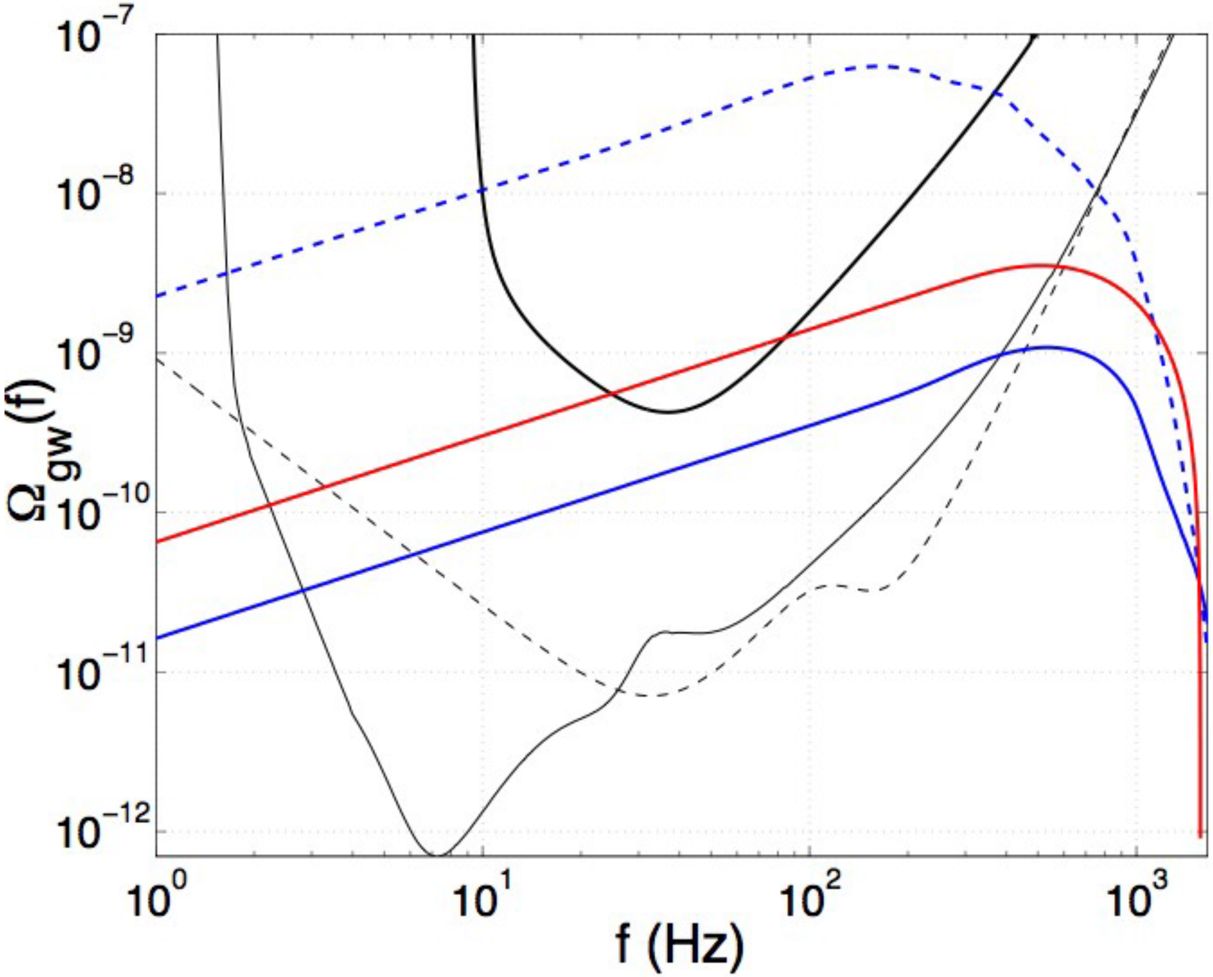
The simulated data are analyzed by the standard stochastic pipeline (isotropic cross correlation statistics) using a f^a filter to produce an estimate of the energy density of the total GW signal.

Accessibility of CBC background



Wu, Mandic & Regimbau, 2012, PRD,85, 104024

Models

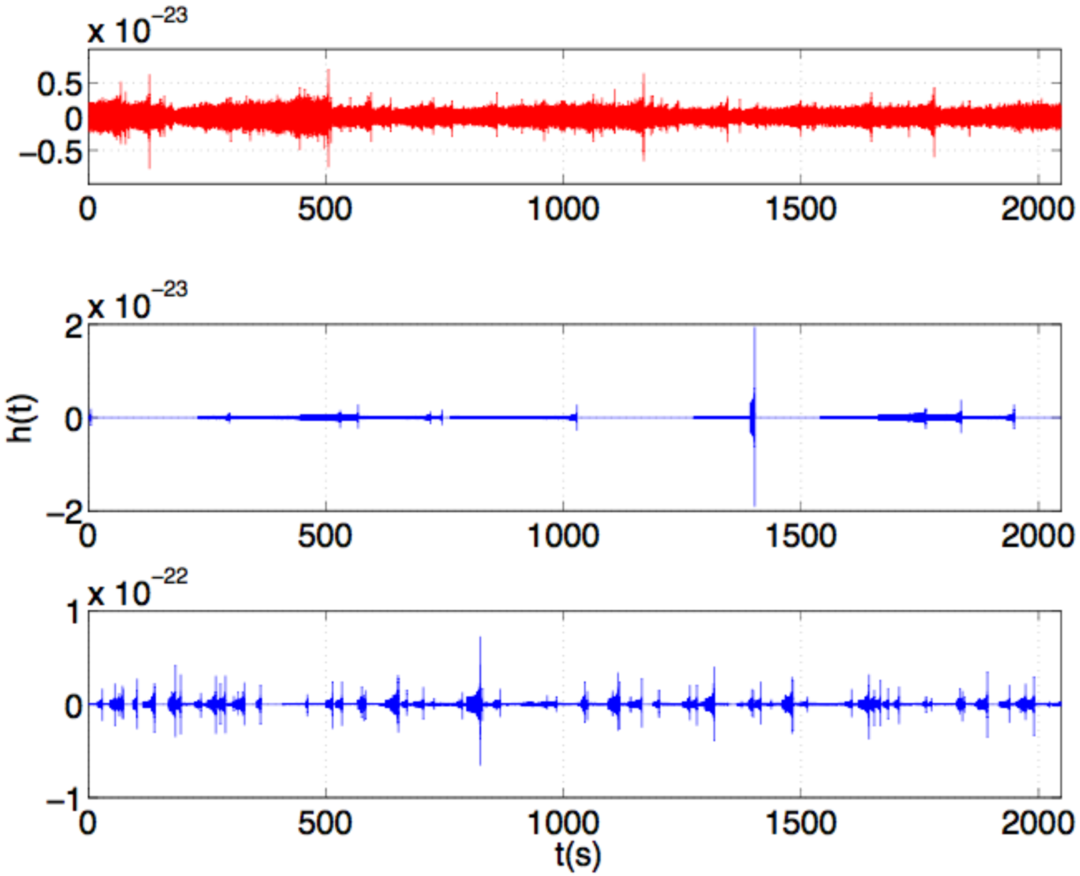


Kowalska, Regimbau, Bulik, Dominik, Belczynski, arXiv:1205.4621

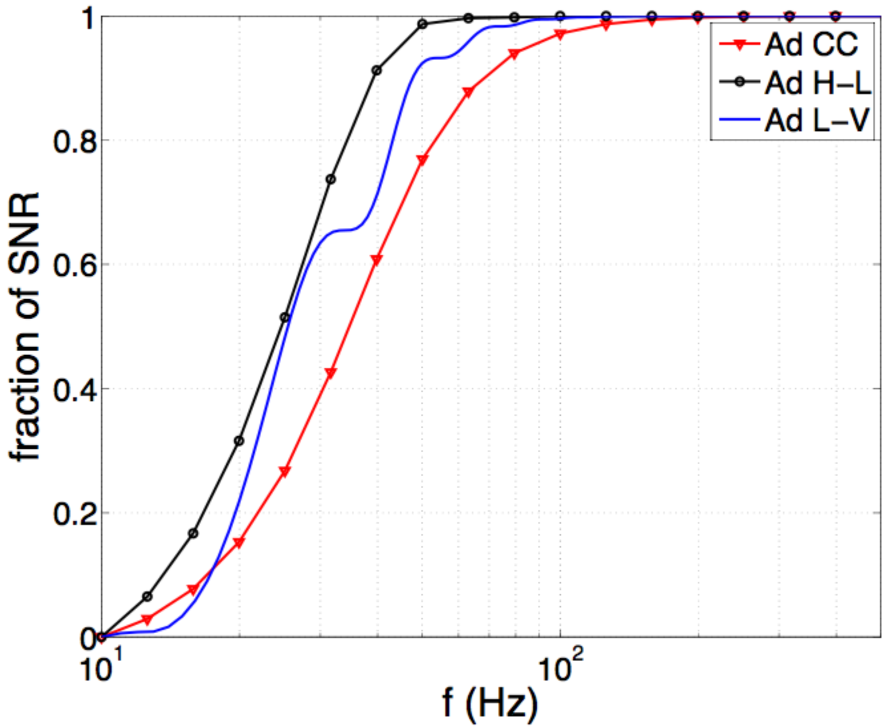
Time series

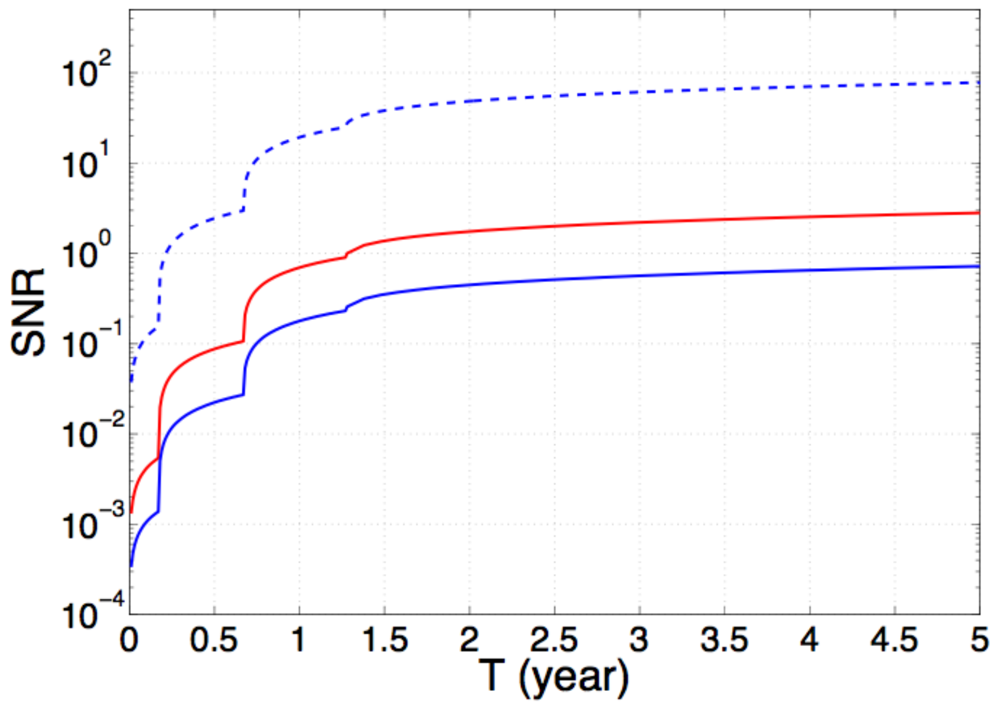
Depending on the time interval between events and the duration of the events, the waveforms may overlap or not and the GW signal may result in a continuous (Λ>1) or popcorn (Λ<1) background.

- simple MC :Λ~15
- ST BZK:Λ~1
- ST BZK: Λ~0.2



Evolution of SNR during ADE





➢The SNR of the network HLV is 50% the SNR of a coincident/colocated detector pair (H1H2)

➢The improvement from combining HLV is ~20% on the best performing pair H-L

Other Mock Data Challenge

- non-gaussian noise
- Schuman resonnances
- The background due to binary coalescences could be detected in a large range of the parameter space
- We initiated a Mock data challenge in order to study:

- the ability of the actual pipeline to recover the GW signal
- optimize the search parameters
- develop more specific data analysis methods
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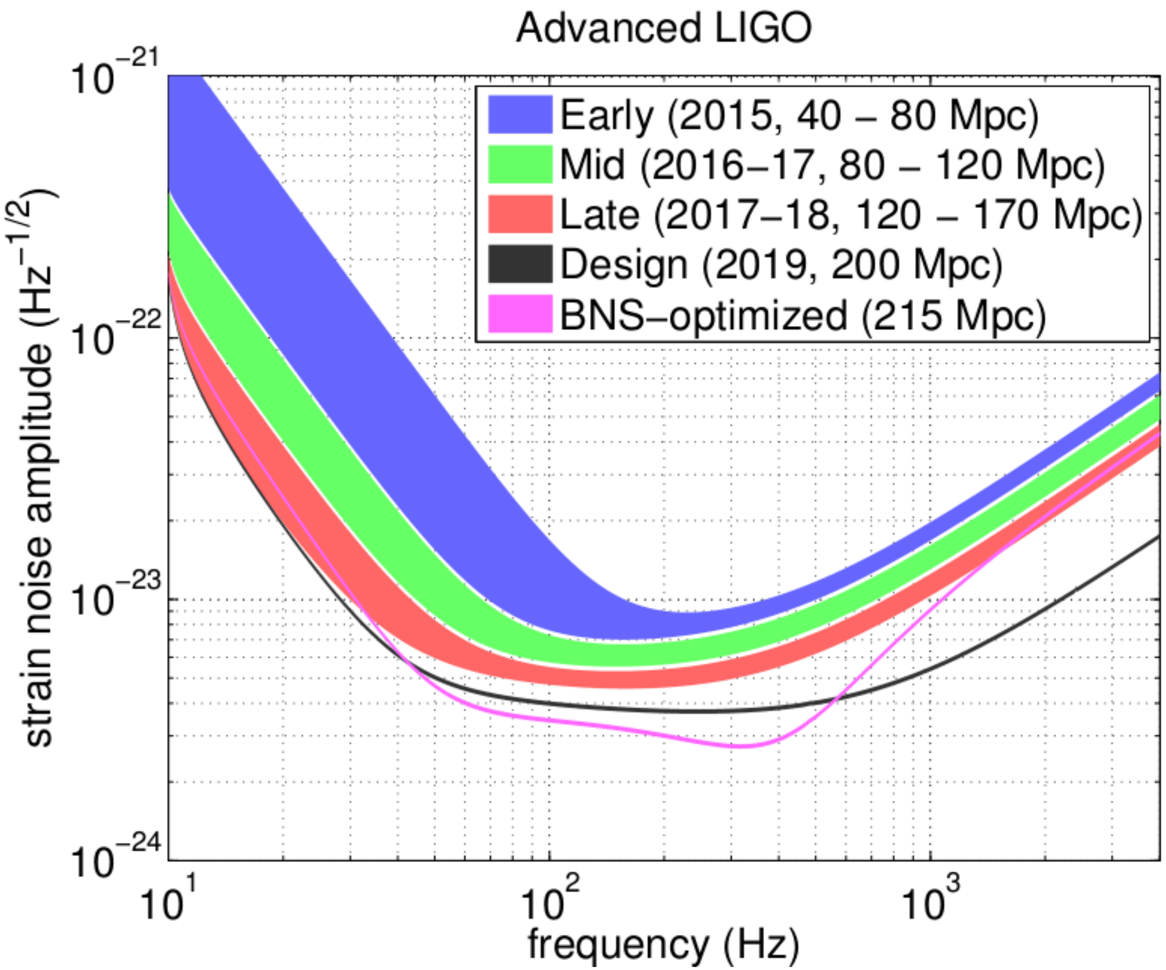
Evolution of the sensitivity



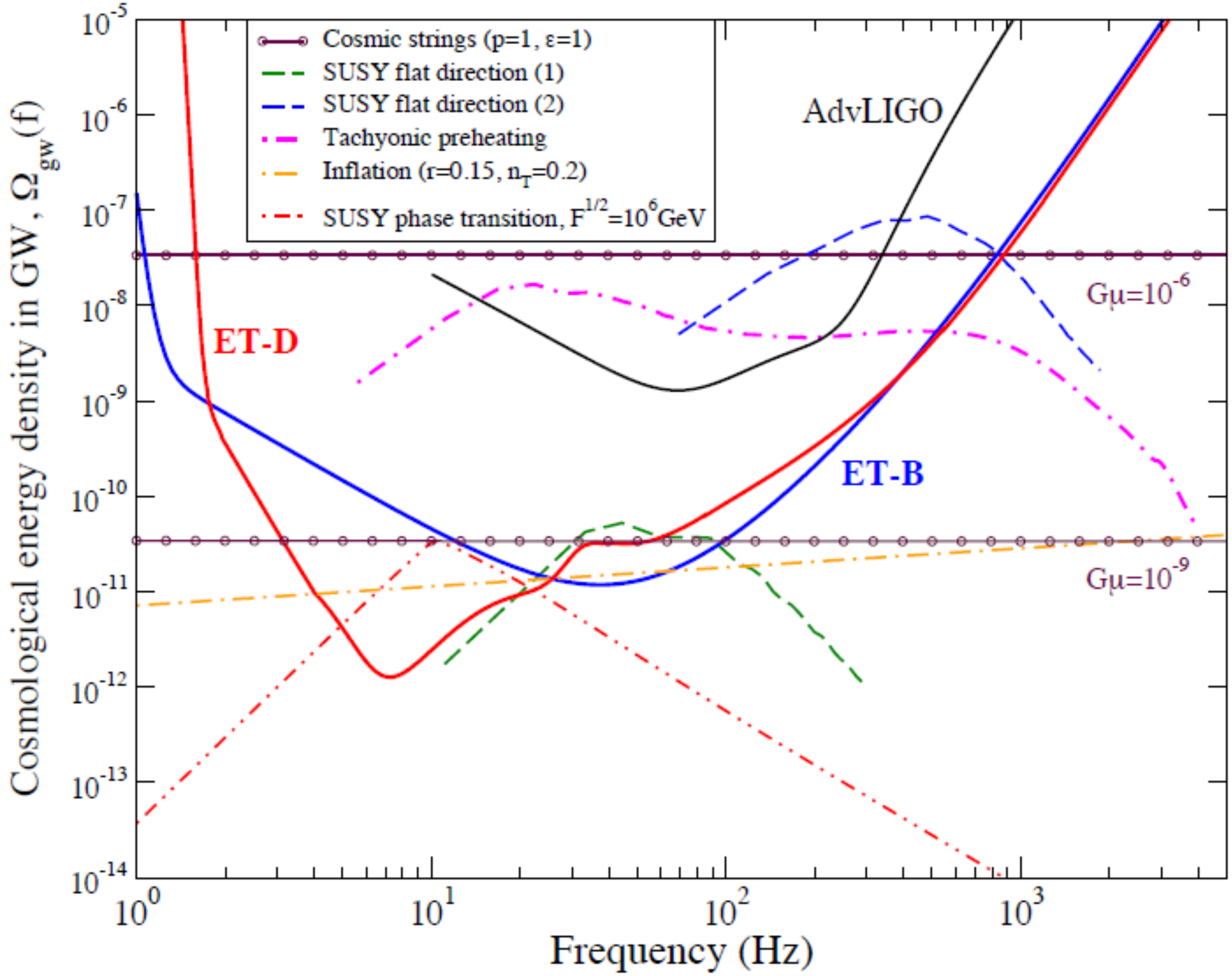
GW online plotter, Wu, Mandic, Regimbau, http://homepages.spa.umn.edu/~gwplotter/

Conclusions

- Many models are potentially be detected by the next generation of LIGO/ Virgo detectors and ET
- The cosmological background is a unique way to probe the very early Universe
- Astrophysical sources may create a foreground but can also provide very valuable informations
- A Mock data challenge is ongoing to optmize the chance of an early detection with Advanced LIGO/Vigo

EXTRA

Typical Landscape



Observational constraints

- Nucleosynthesis: large GW energy density at the time of BBN would alter the abundances of the light nuclei produced in the process.

$$\Omega_{BBN} = \int \Omega_{gw}(f) d(\ln f) < 1.1 \times 10^{-5} (N_{\nu} - 3)$$

- CMB matter power spectra:

- CMB large angle fluctuations : constrain the possible redshift of CMB photons due to the SGWB, and therefore limit the amplitude of the SGWB at smallest frequencies $\propto f^{-2}$ in $[10^{-18} - 10^{-16}]$

- Pulsar timing array : fluctuations in the radio pulse arrival times limit the amplitude of a GW passing between the pulsar and the Earth at around 10^{-8} Hz.

- Initial LIGO/VIrgo detectors