The Quest for the Gravitational-Wave stochastic Background with LIGO/Virgo

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GW Astronomy

- GWs are space-time perturbations created by asymmetric acceleration of masses **or non stationary fields.**

- GWs propagate at the speed of light, minimally interacting with the matter they encounter.

- The binary pulsar discovered by Hulse & Taylor in 1974 provided the first indirect evidence for the existence of GWs

- In March 2014, the Bicep2 experiment identified B-modes polarization in CMB (imprint of SGWB at 10^{-16} Hz or more likely dust)

- Direct detection expected in the next few years (Adv LIGO/Virgo, 1 Hz-10kHz)

- Other experiments include the space antenna eLISA (0.1 mHz-0.1 Hz) or pulsar timing (10^{-8} Hz, difference in pulse arrival time)

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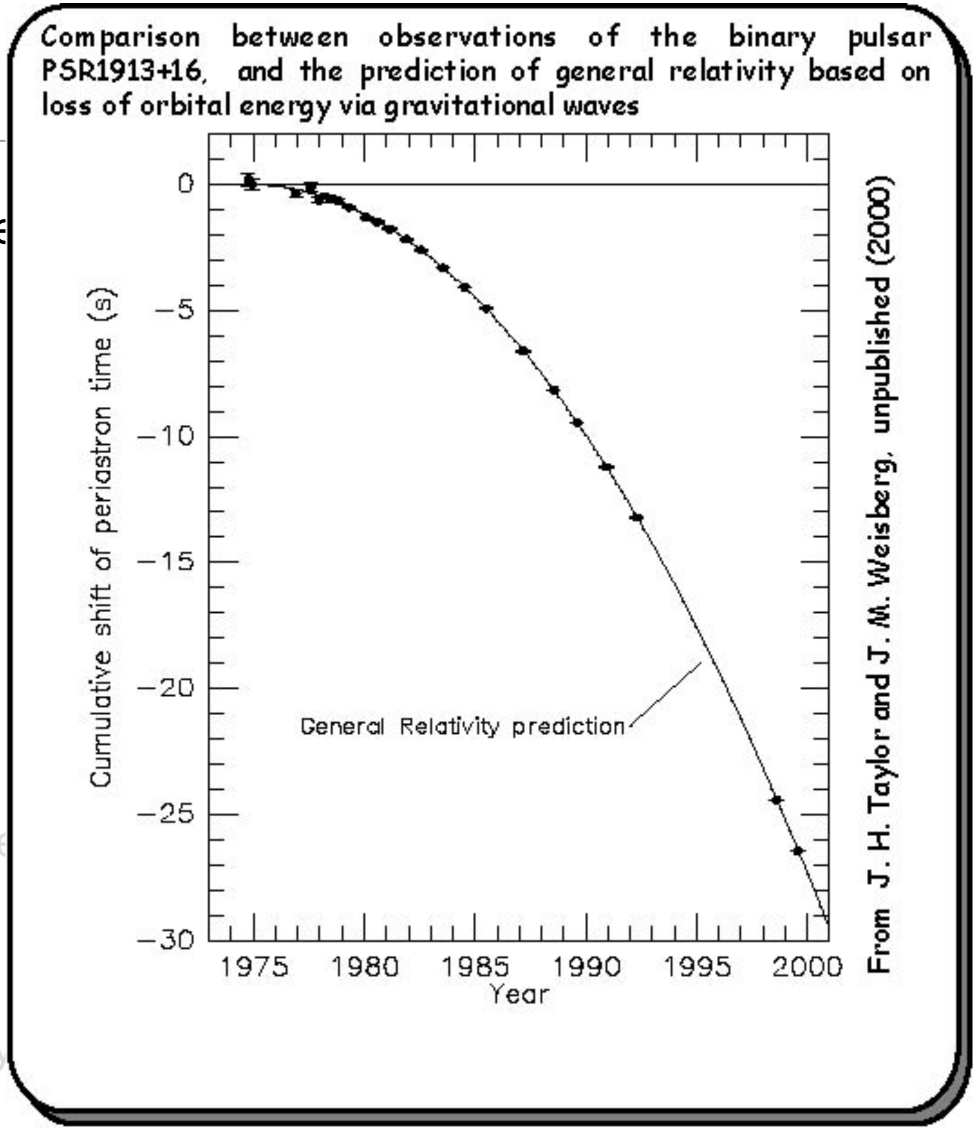

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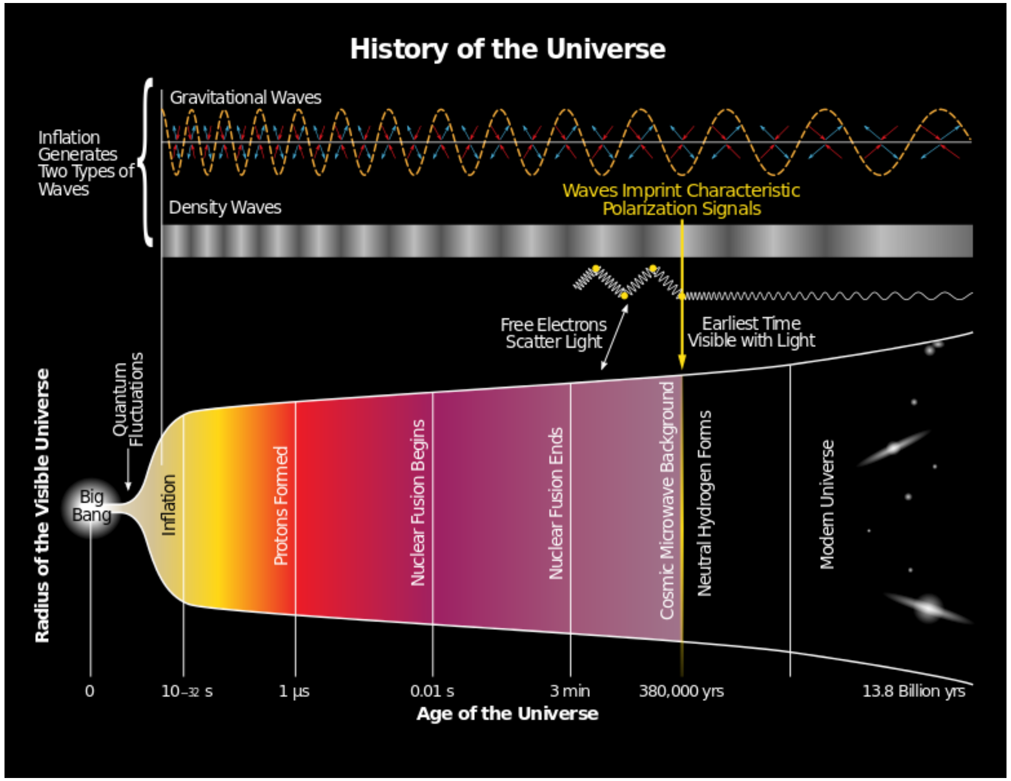
GW Stochastic Background

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.

The source can be either :

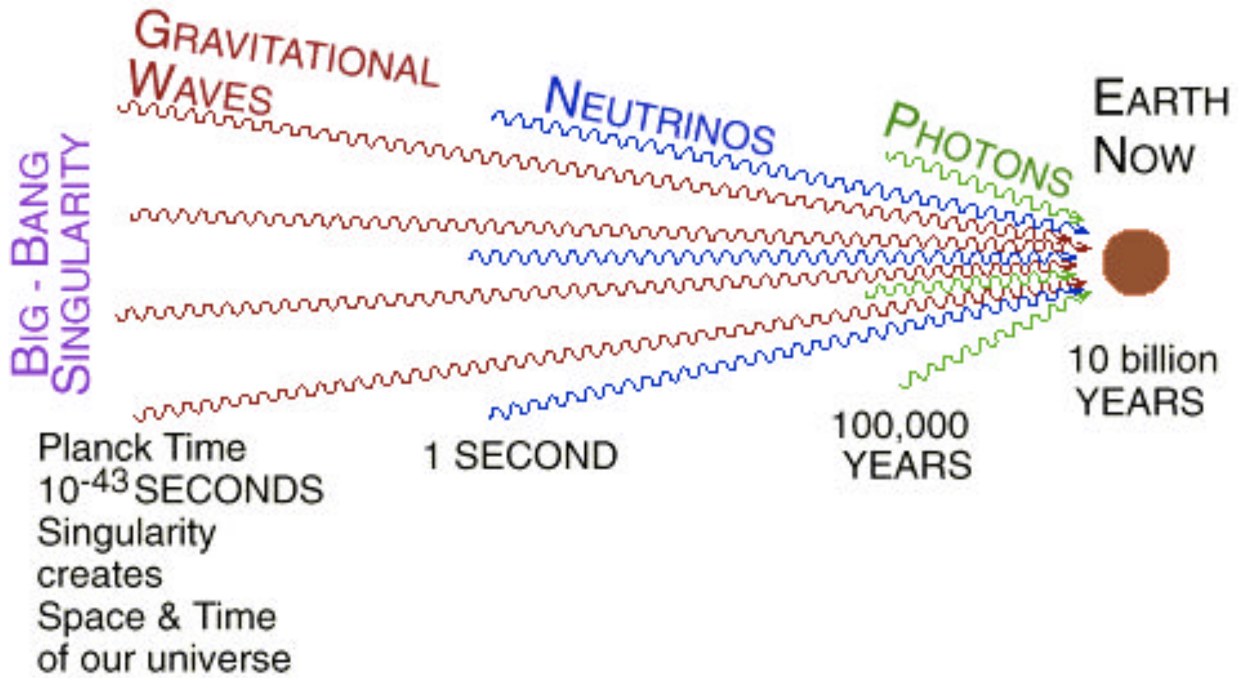
- **Cosmological:** signature of the early Universe near the Big Bang *inflation, cosmic strings, phase transitions…*
- **Astrophysical:** since the beginning of stellar activity *compact binary coalescences, core-collapse supernovas, rotating neutron stars, capture by SMBHs…*



Primordial GW Stochastic Background

- Gravitons decoupled from the original plasma below the Planck scale

$$\frac{\Gamma}{H} > 1 \text{ for } T < T_{\text{dec}} \quad (\Gamma \sim n\sigma v)$$



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- 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 $T_{dec} \sim 10^{16}$ GeV

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

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

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Relating BICEP2 results to the SGWB

- Energy density in GWs :

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

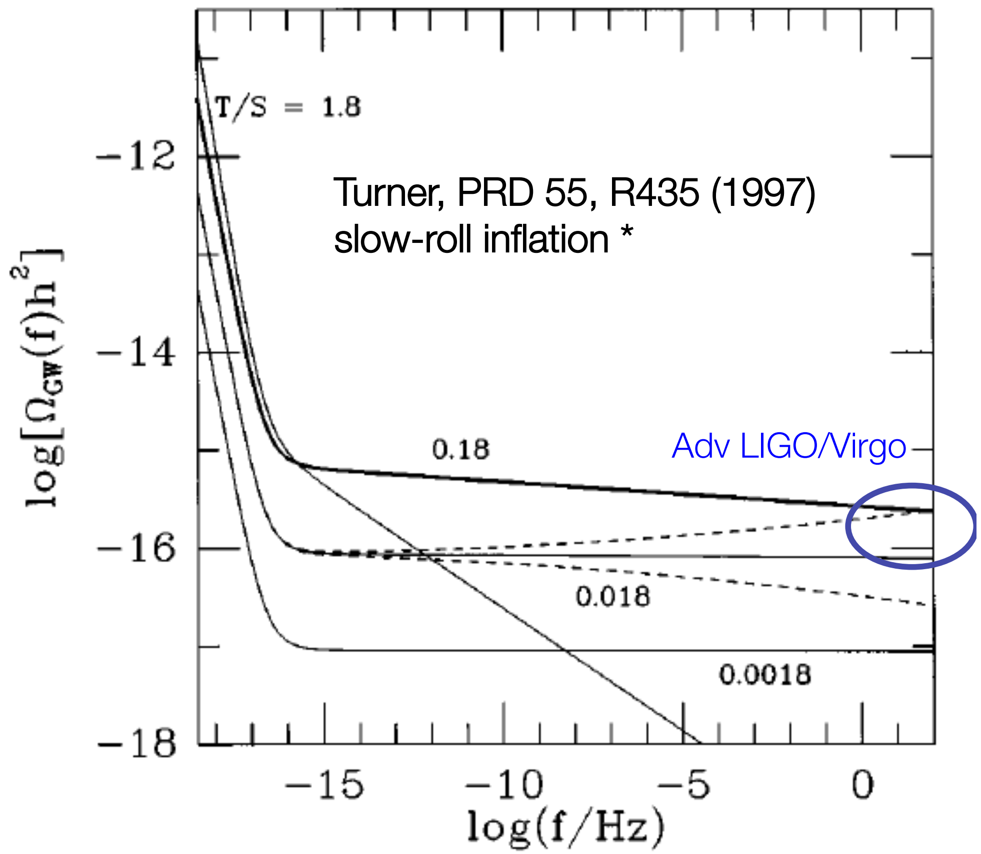
- Scales with the tensor-to-scalar ratio *r=T/S*

- The spectral shape depends on *r:*

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

- Bicep2 : r=0.2

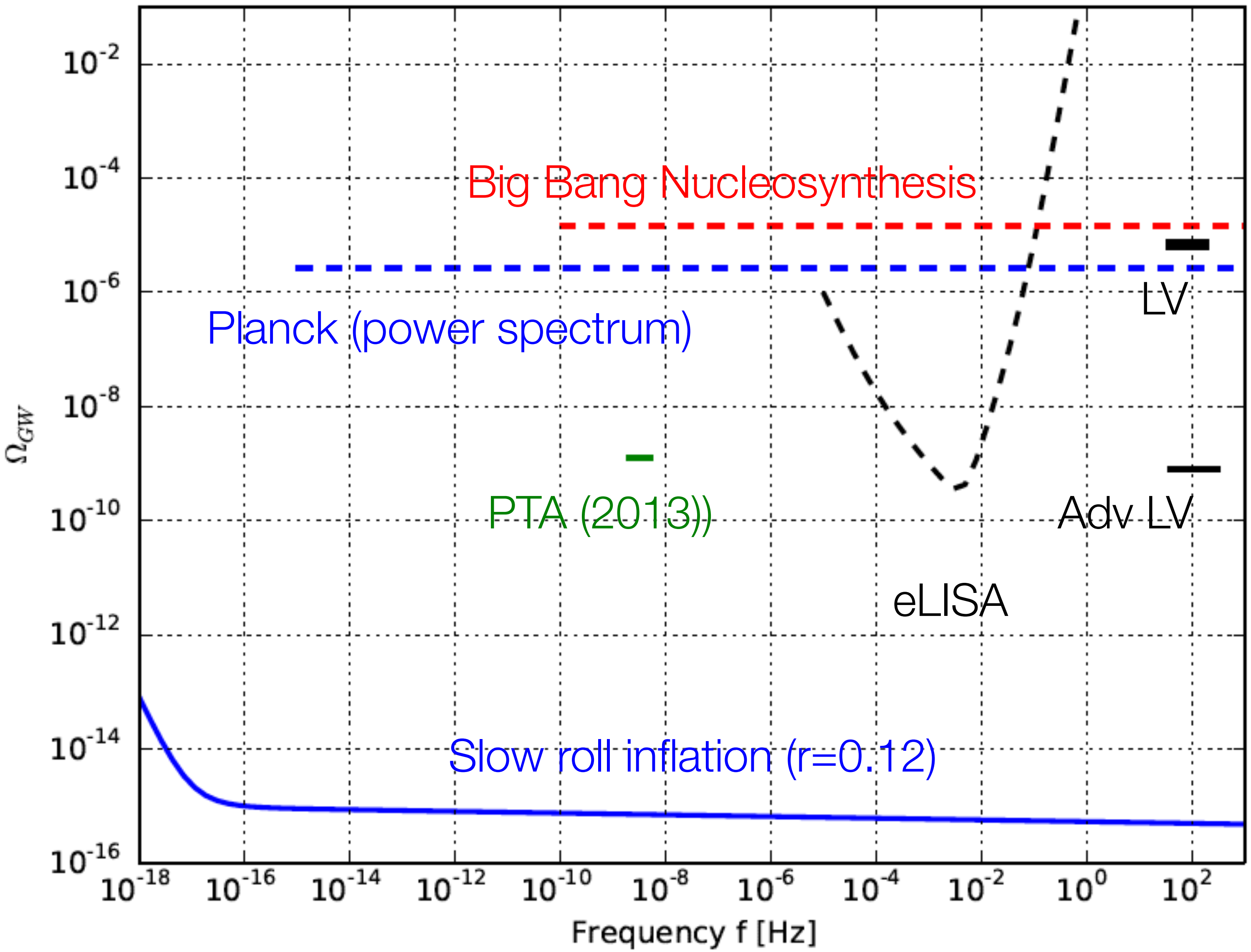
- Bicep2/Keck/Planck : r<0.12 at 95% confidence



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

Bounds on the SGWB

http://homepages.spa.umn.edu/~gwplotter/



Possible enhanced contributions at high frequencies

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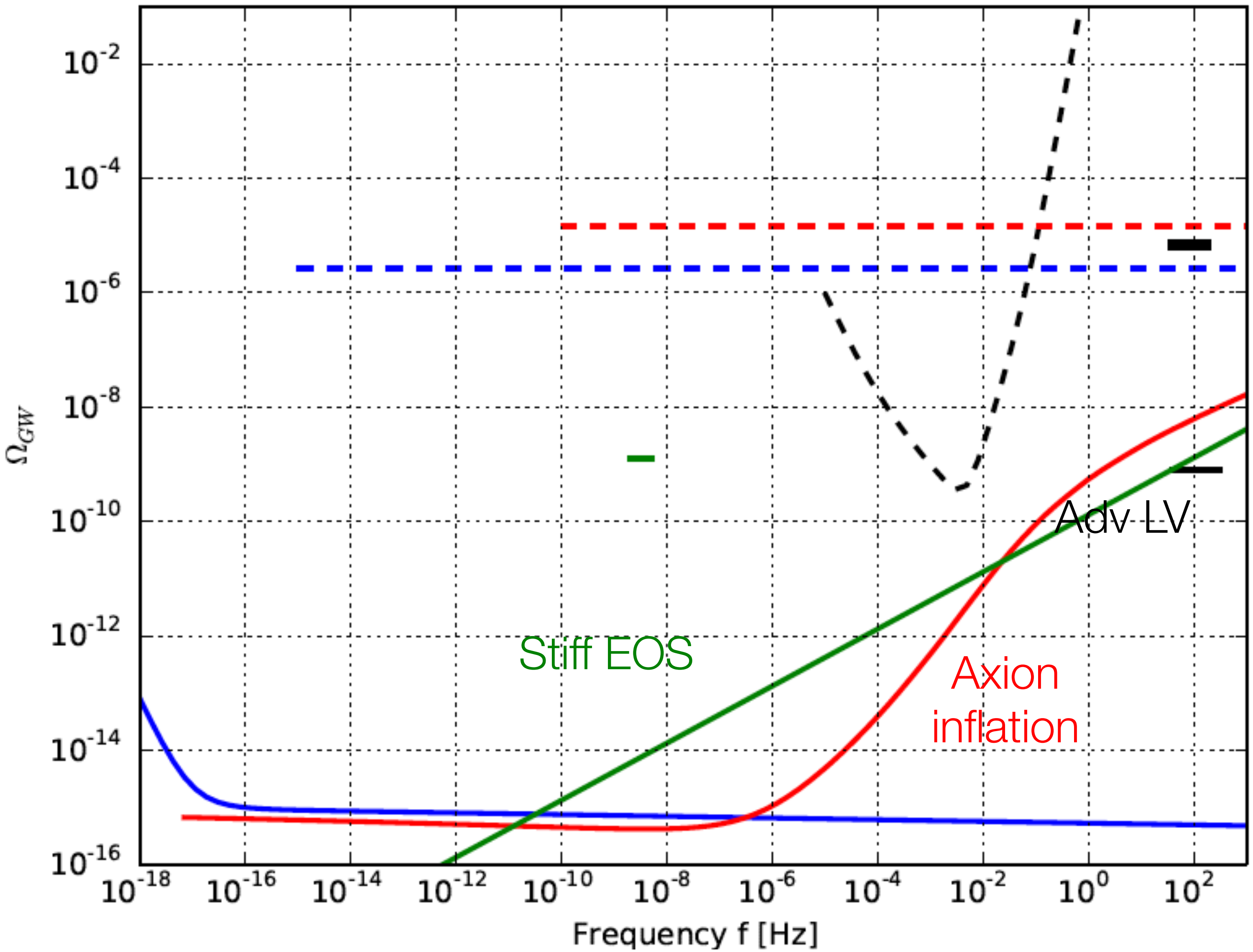
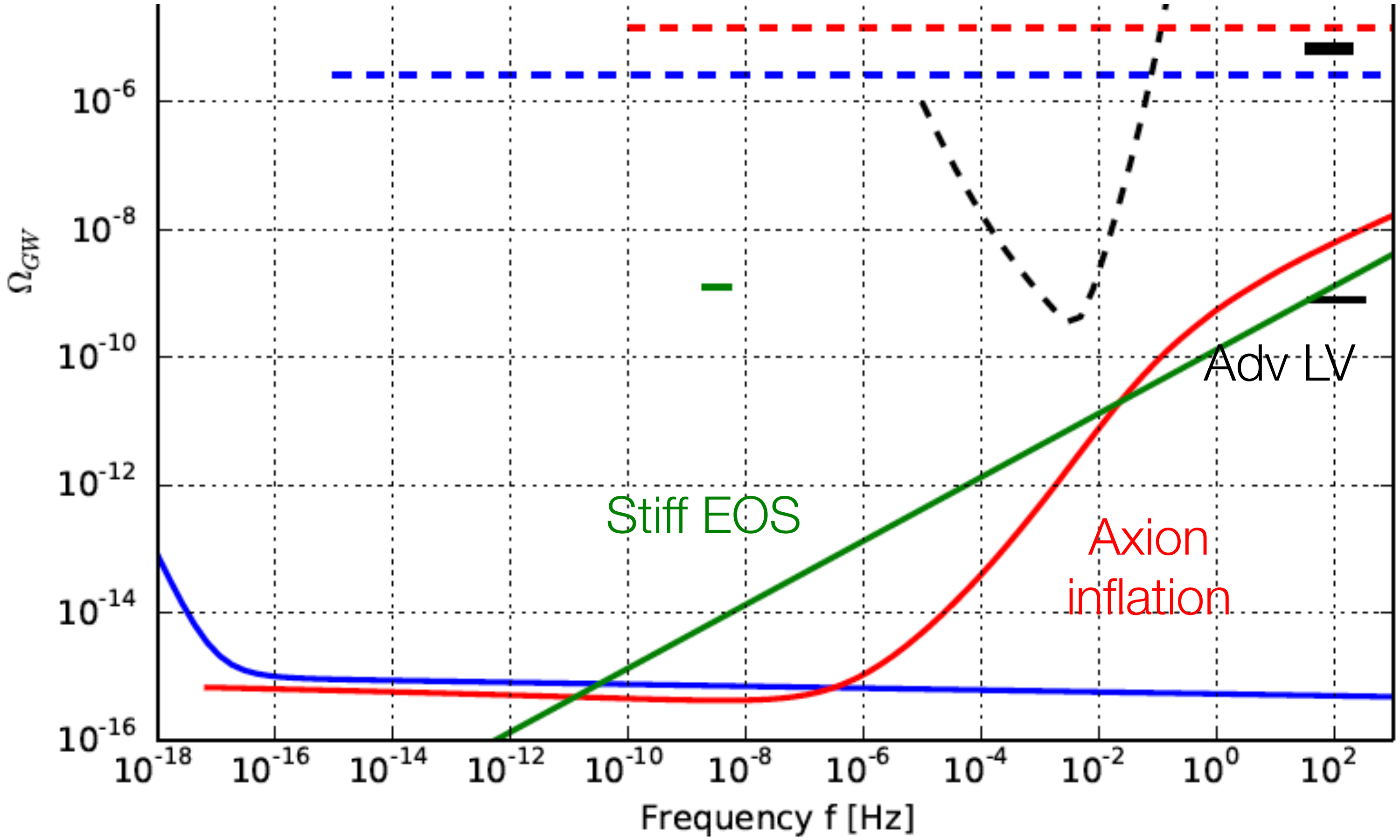


Possible enhanced contributions at high frequencies

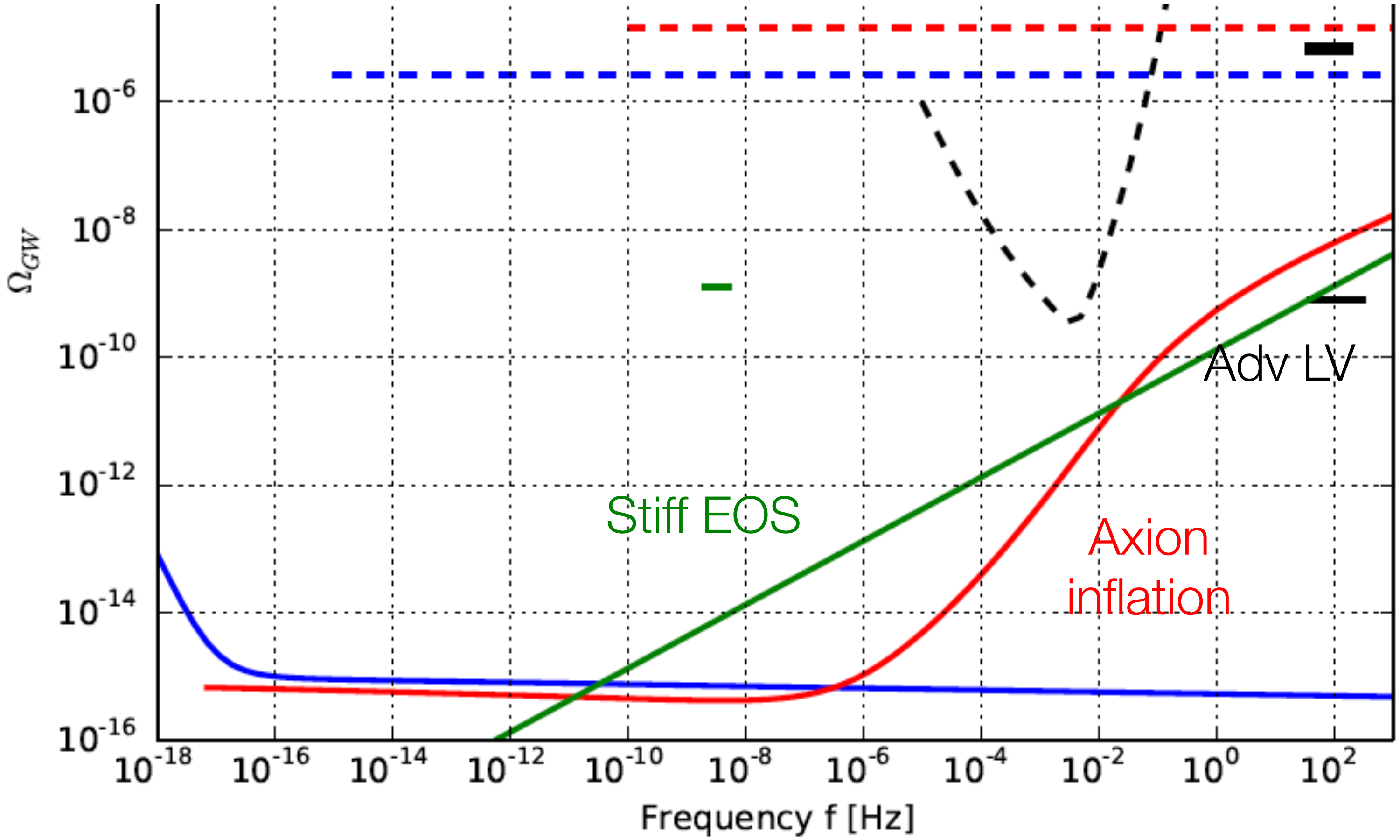
If the equation of state between inflation and radiation era is stiff, the spectrum could increase with frequency and be potentially detectable by advanced detectors.
Boyle & Buonanno, PRD 78, 043531 (2008).



Possible enhanced contributions at high frequencies

Axion-based inflation models include axion-gauge couplings. Gauge backreaction on the inflaton extends inflation.

Barnaby et al, Phys. Rev. D. 85, 023525 (2012).Cook & Sorbo, Phys. Rev. D85, 023534 (2012).



Other Predictions

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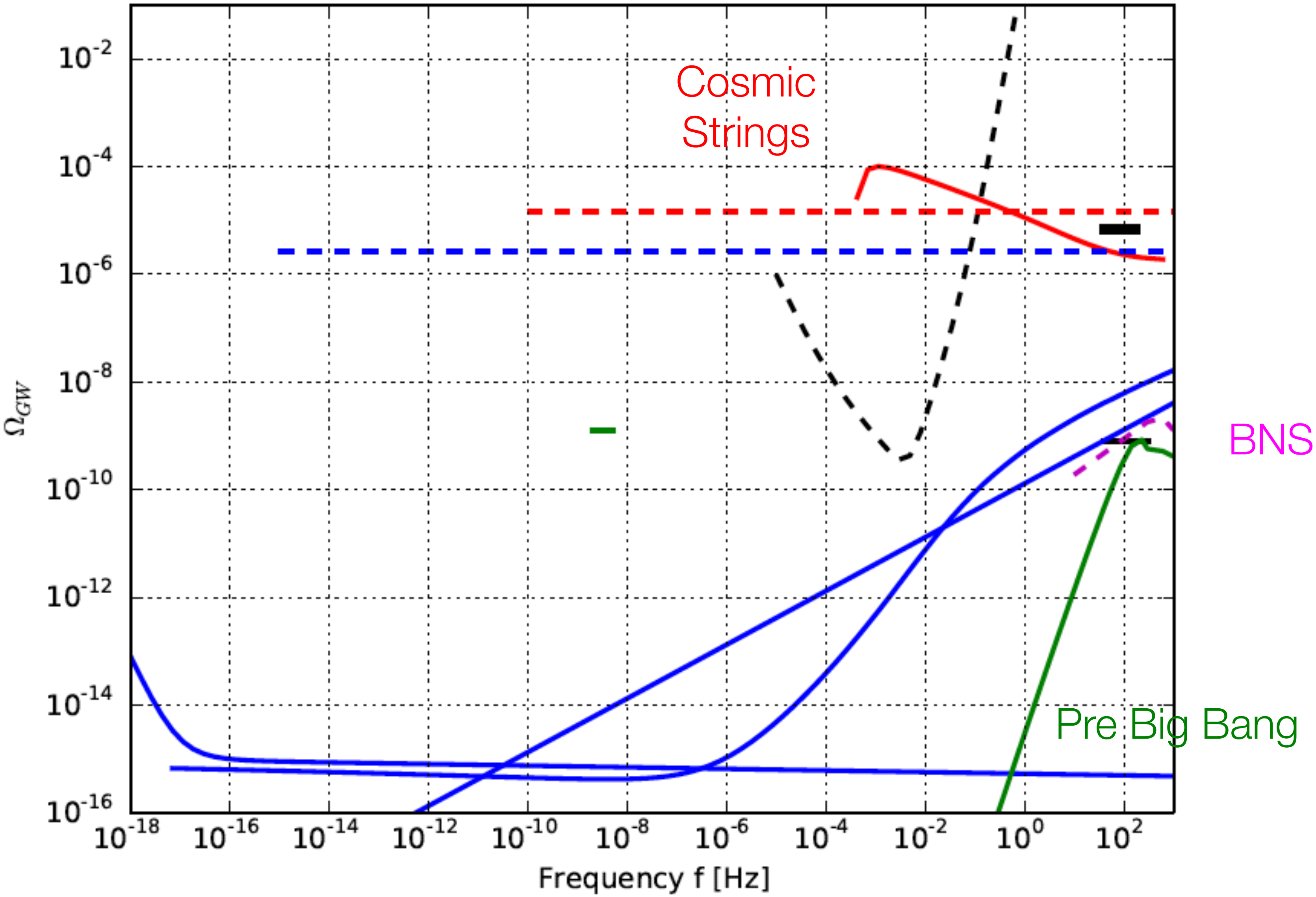


Data Analysis Principle

- Assume stationary, unpolarized, isotropic and Gaussian stochastic background

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

$$h_i = s_i + n_i$$

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

- Current upper limit and future sensitivity:

- Initial LIGO/Virgo: $\Omega_{gw} = 5.6 \times 10^{-6}$ in [40-170] Hz (Nature, 460,990 (2009))

- Avanced LIGO/Virgo: $\Omega_{gw} \approx 10^{-9}$

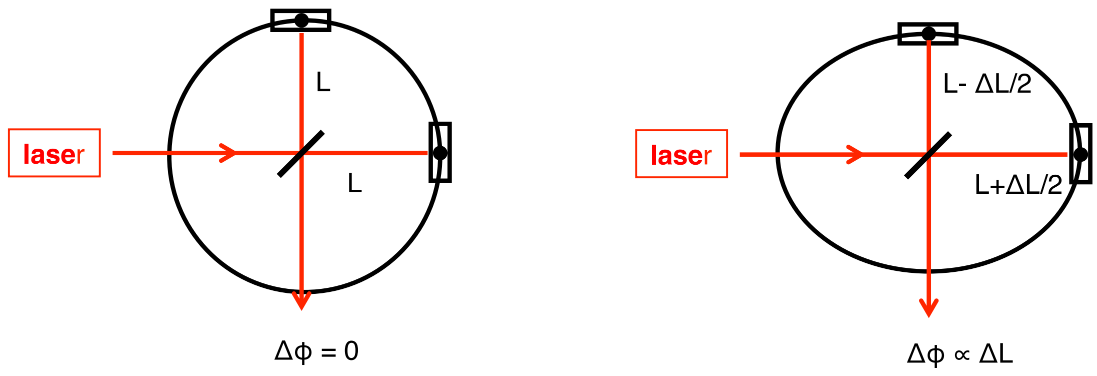
- 3rd generation Einstein Telescope: $\Omega_{gw} \approx 10^{-12}$

Conclusion

- Many models of SGWB can potentially be detected by the next generation of LIGO/Virgo detectors
- 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
- Complementary to CMB and other experiments measurements in other frequency bands

GW Interferometry Principle (in a nutshell)

- GW interferometers measure the phase difference caused by passing GWs which stretch one arm as they compress the other.



- The gravitationnal-wave strain amplitude is: $h = \frac{\Delta L}{L}$

- The effect is expected to be extremelly small (less than $h \sim 10^{-21}$)

- LIGO/Virgo (2001-2012, *proof of principle. Upper limits) ;* Advanced LIGO/Virgo (2015, *first detections ;* Einstein Telescope (2025, *precision astronomy and cosmology)*

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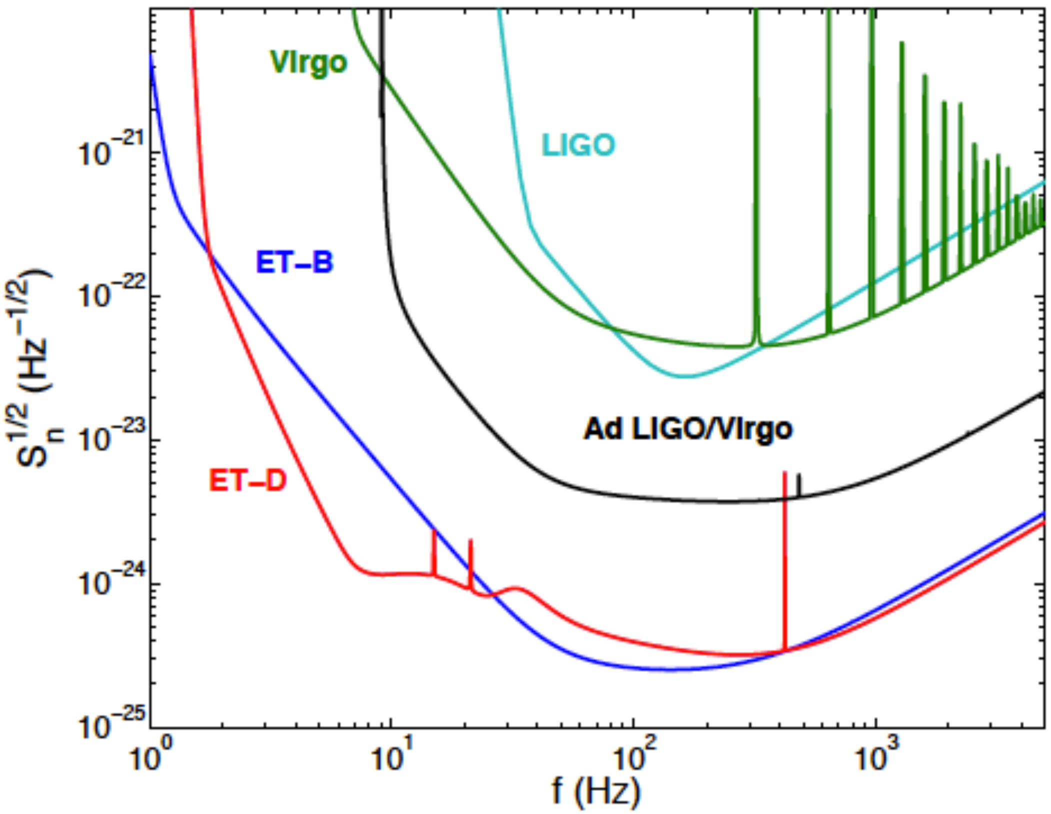

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Astrophysical Backgrounds

- All the sources that cannot be resolved individually

- The spectrum depends on the rate and the individual spectral properties

$$\Omega_{gw}(f) = \frac{8\pi G}{3c^3 H_0^2} f F(f) \simeq \frac{8\pi G}{3c^3 H_0^2} f \int_{z_h}^{z_{\max}} \frac{dR(z)}{dz} \frac{d\bar{E}}{df_e}(f(1+z)) \frac{dz}{4\pi r(z)^2}$$

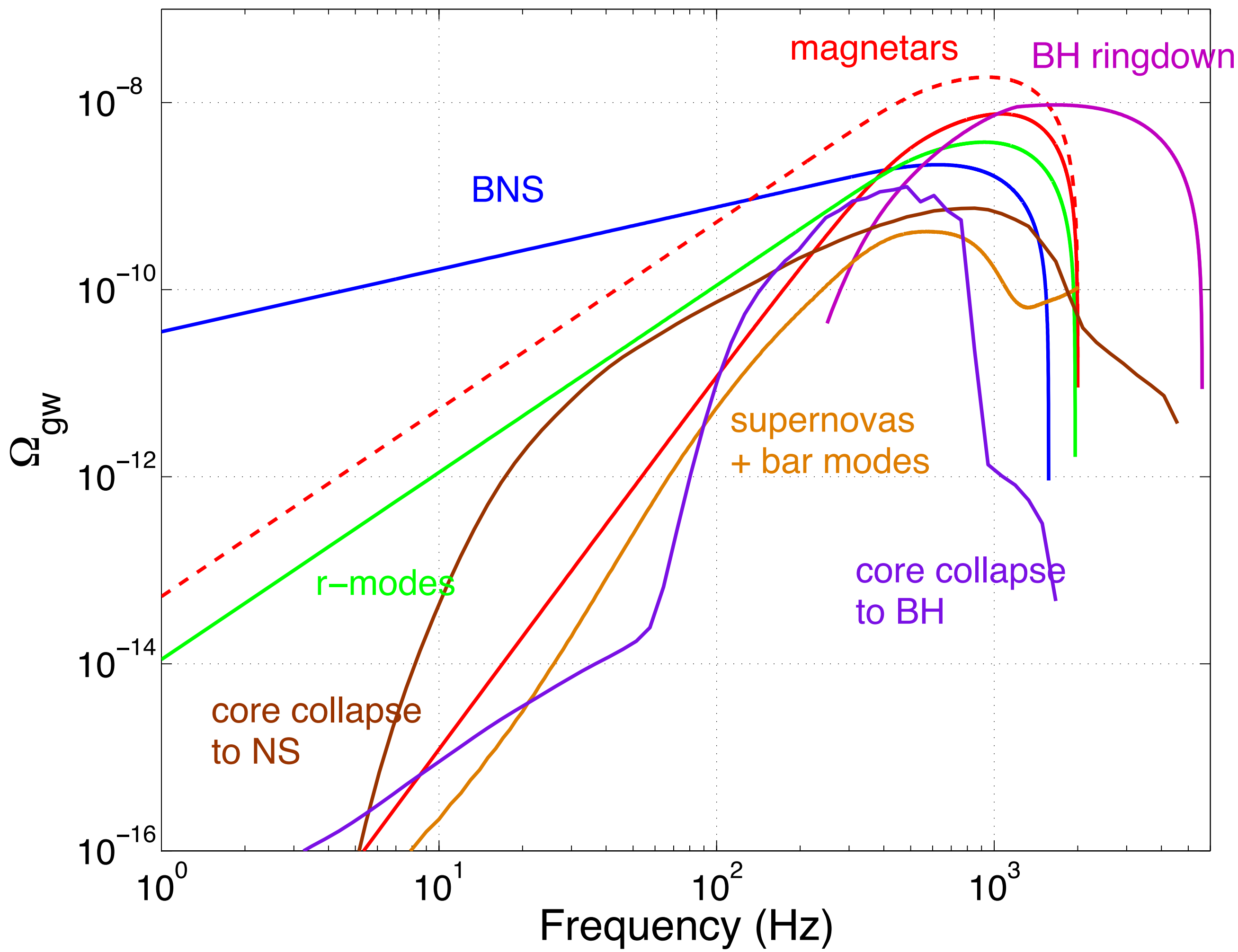
- Carry lots of informations about the star formation history, the metallicity evolution, the distribution of the source parameter.

- But can be a noise for the cosmological background

- May have different statistical properties : non continuous, non-Gaussian, non isotropic

Astrophysical Backgrounds

Regimbau, RAA, 11, 369 (2011)



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- Standard CC statistic

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

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

\- in the limit noise >>GW signal $\text{Mean}(Y) = \Omega_0 T,\ \text{Var}(Y) \equiv \sigma^2 \propto T,\ \text{SNR} \propto \sqrt{T}$

Joint BICEP2/Keck Array/Planck analysis

- Re-analized BICEP2 data using Planck maps of galactic dust polarization rather than models.

- A new joint analysis fits the CMB polarization measurements to an improved model of galactic dust and a possible contribution from primordial gravitational waves generated by inflation.

- This new analysis yields a new upper limit for the contribution from primordial gravitational waves, but no longer disfavours a zero contribution at high statistical significance.

- $r < 0.12$ at 95% confidence