Stochastic GW searches and Cosmology with GWs

Giancarlo Cella (INFN Pisa) for the LIGO-VIRGO Collaboration

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INFN Istituto Nazionale di Fisica Nucleare

VIRGO

LSC LIGO Scientific Collaboration

Stochastic background in a nutshell

A stochastic background can be seen as

- a GW field which evolves from an initially random configuration
- the result of a superposition of many uncorrelated and unresolved sources

Two different kinds:

- Cosmological:

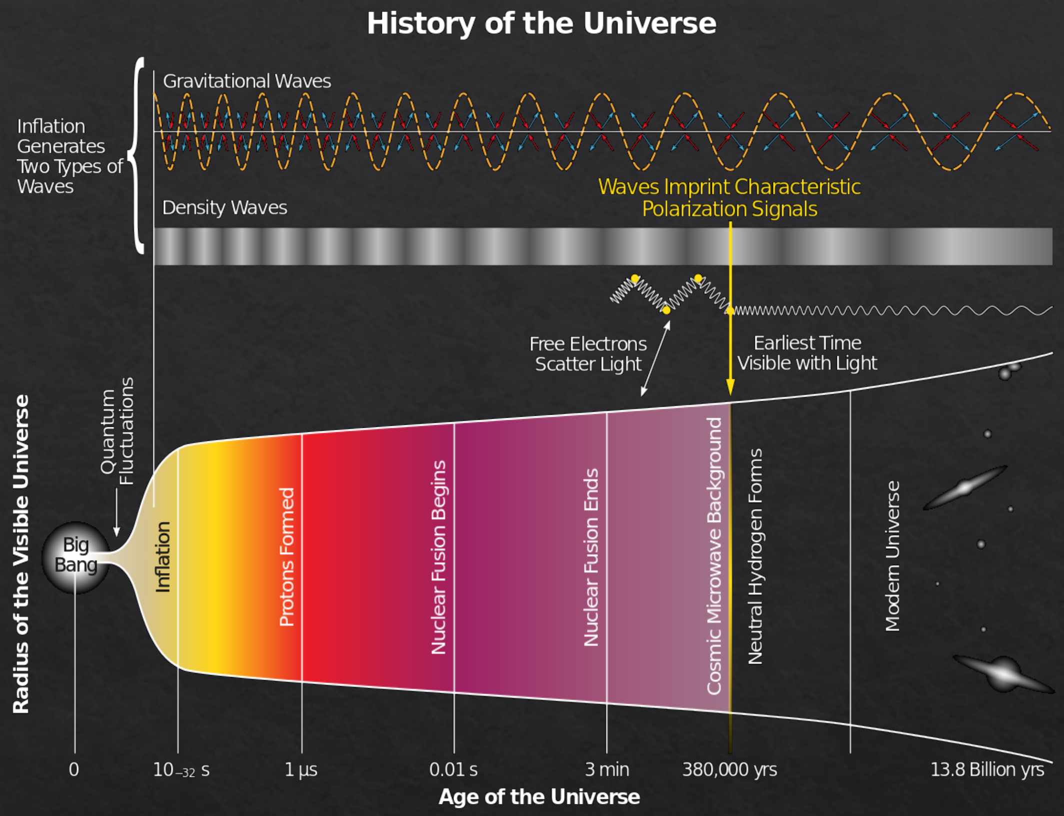
  signature of the early Universe

  inflation, cosmic strings, phase transitions...

- Astrophysical:

  sources since the beginning of stellar activity

  compact binaries, supernovae, rotating NSs, core-collapse to NSs or BHs, supermassive BHs...

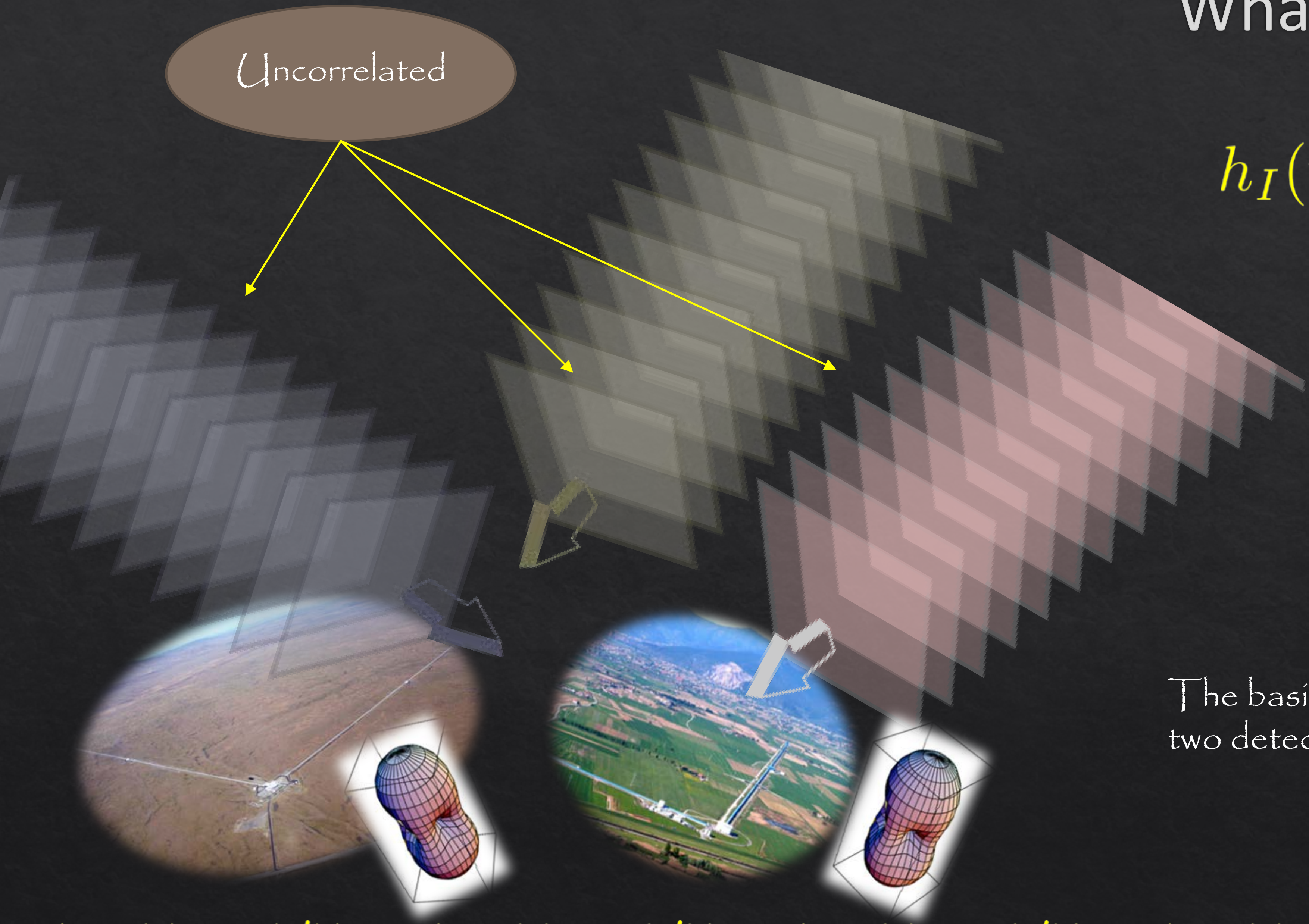


Typical «first approximations» :

1) Gaussian, because sum of many contributions
2) Stationary, because physical time scales much larger than observational ones
3) Isotropic (at least for cosmological backgrounds)

If these are true, SB is completely described by its power spectrum

What we observe



$$h_I(t) = D_I^{ij}(t) h_{ij}(\vec{x}_I, t)$$

$$S_1(t) = h_1(t) + n_1(t)$$

$$S_2(t) = h_2(t) + n_2(t)$$

The basic idea: correlate the output of two detectors.

$$\langle S_1(t) S_2(t') \rangle = \langle h_1(t) h_2(t') \rangle + \langle h_1(t) n_2(t') \rangle + \langle n_1(t) h_2(t') \rangle + \langle n_1(t) n_2(t') \rangle$$

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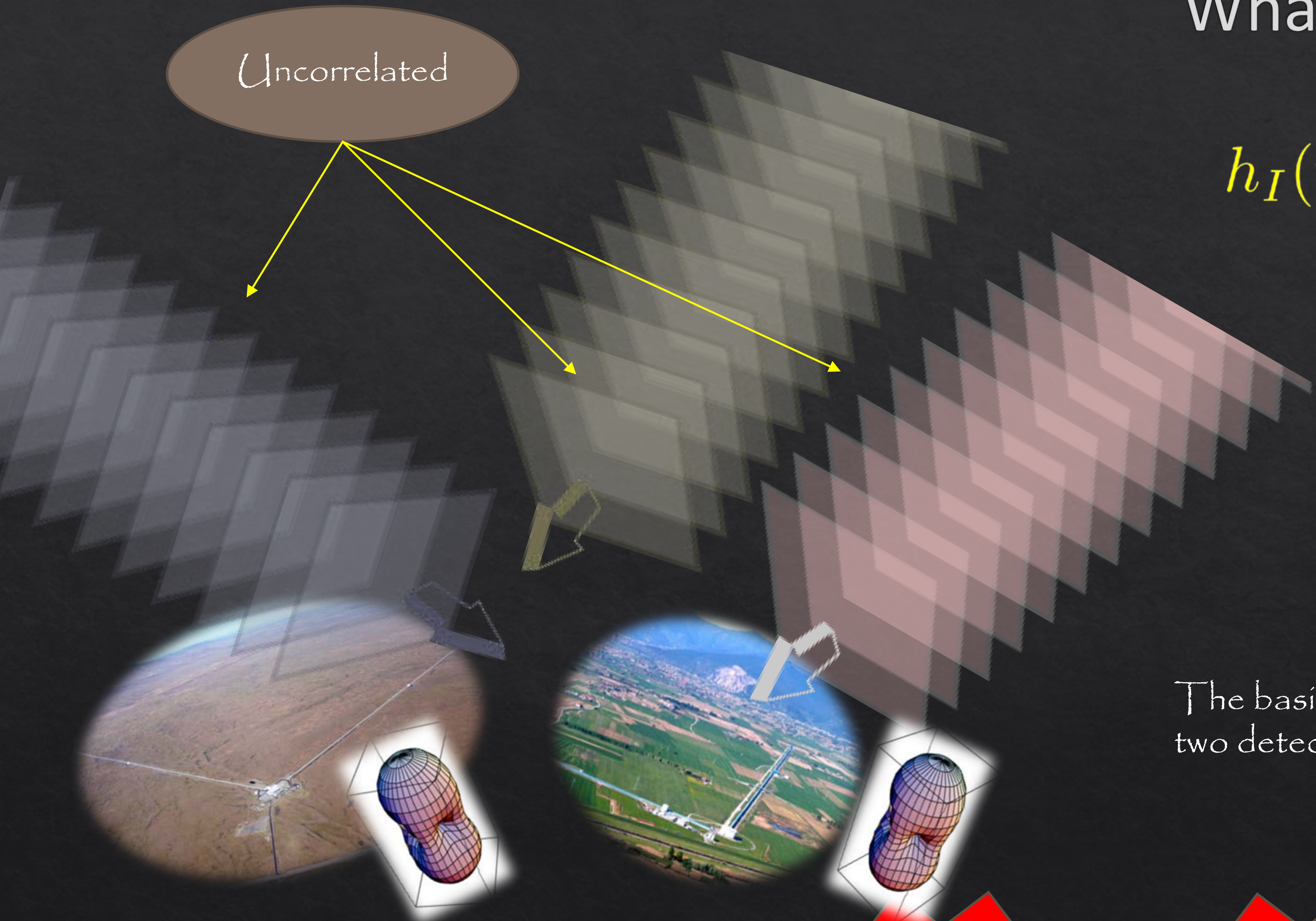

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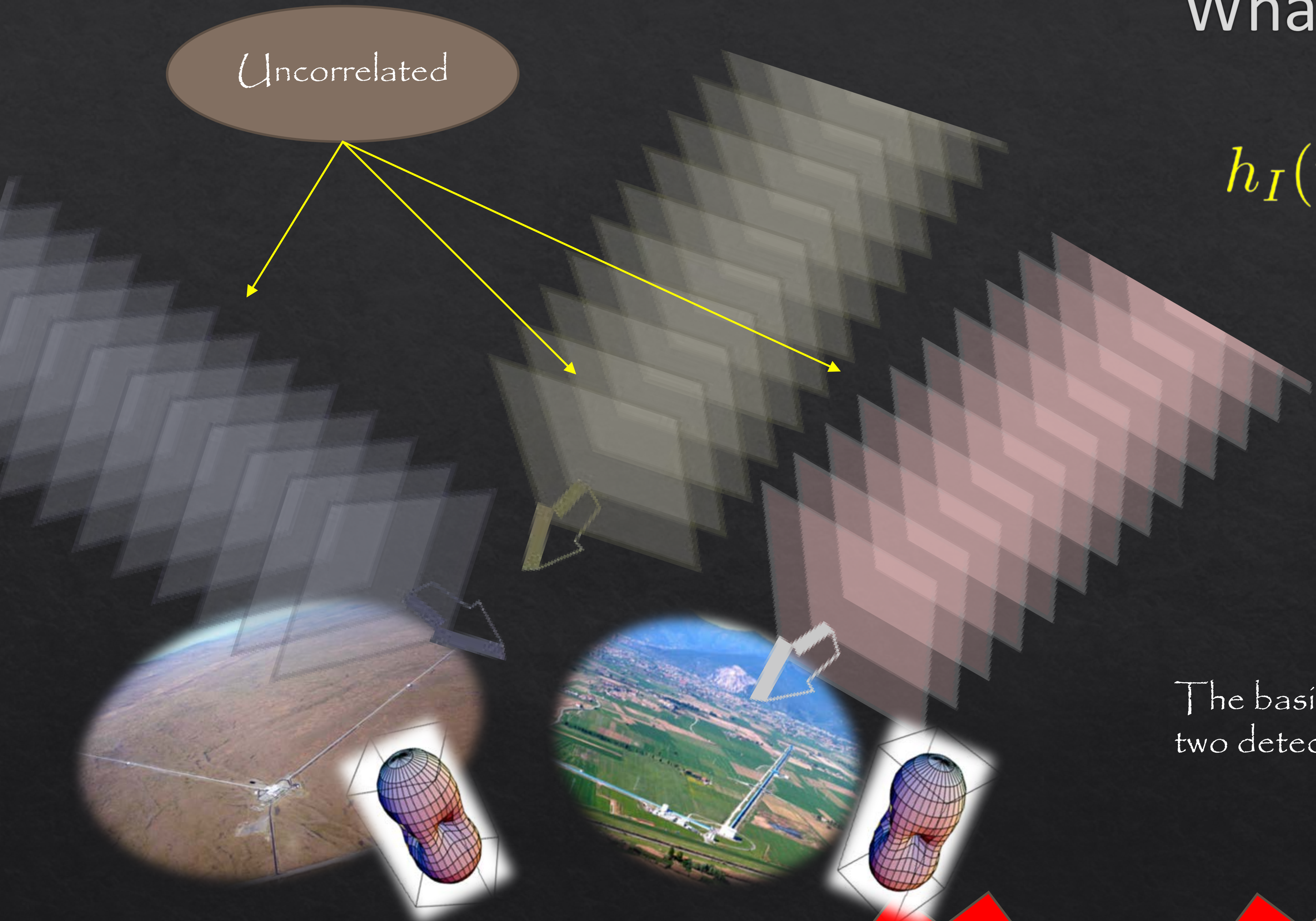

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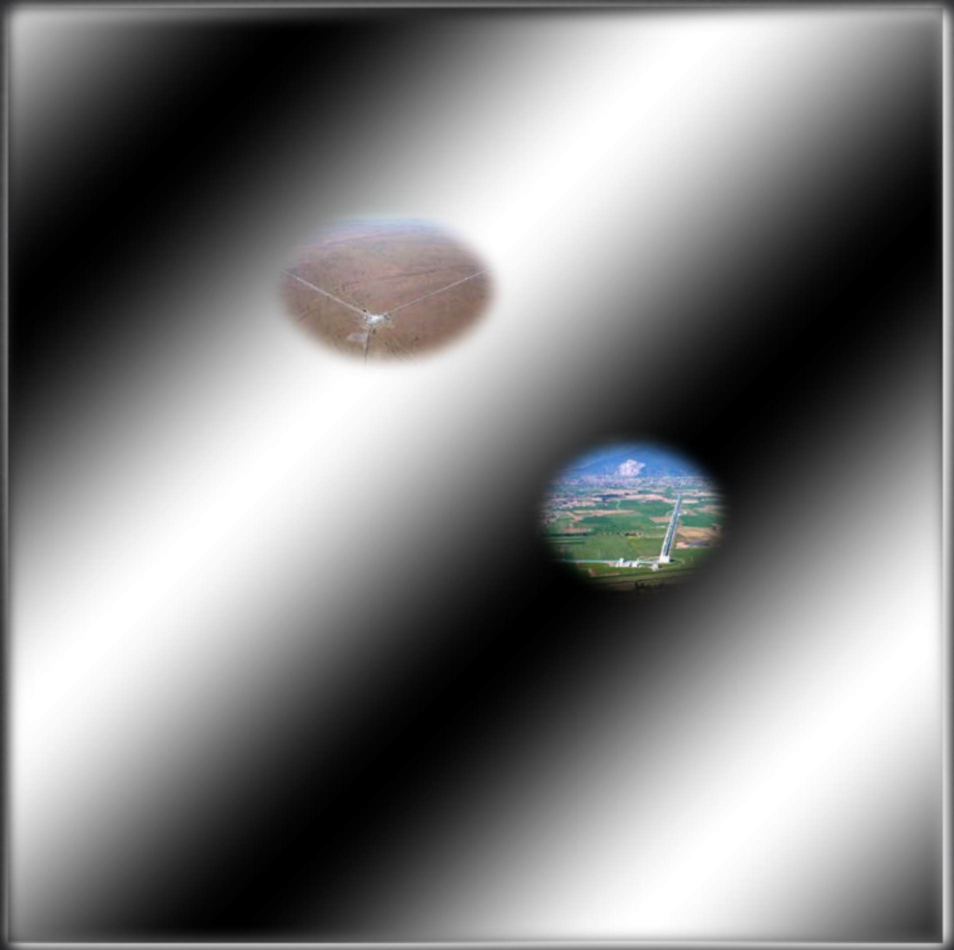
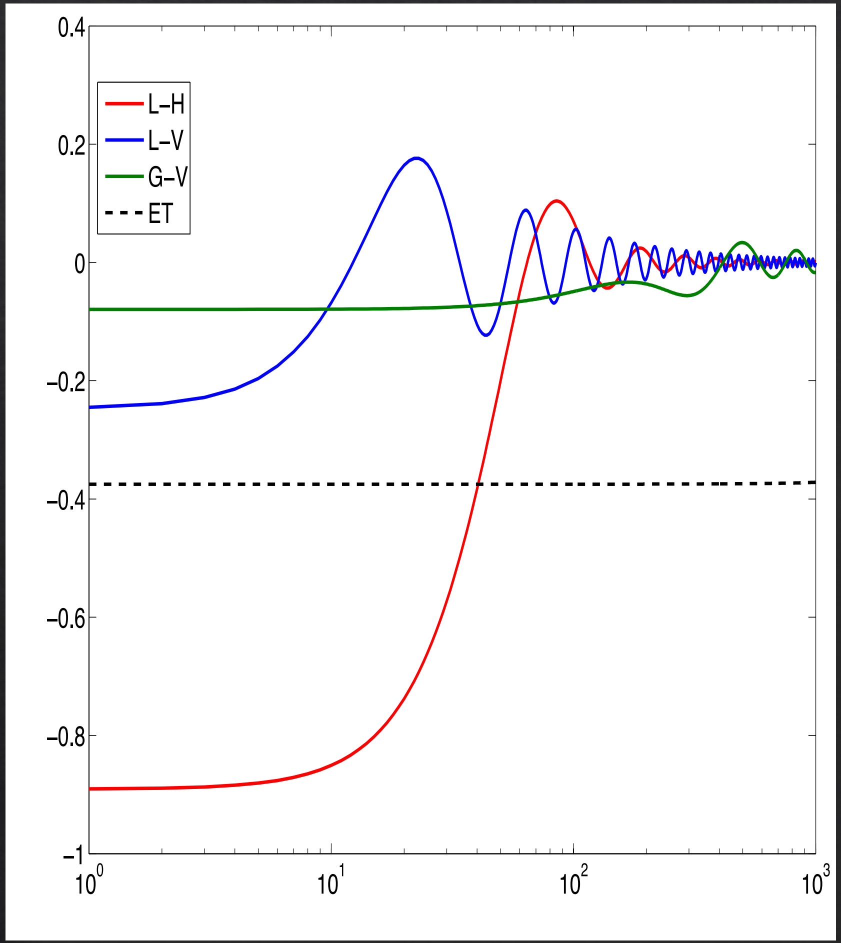
SNR & overlap reduction function (a.k.a. coherence)

$$Y = \lambda \int df \frac{\tilde{h}_1^\star(f)\tilde{h}_2(f)\gamma_{12}(f)S_h(f)}{S_{n,1}(f)S_{n,2}(f)} \qquad \mathrm{SNR}_Y^2 := \frac{\mu_Y^2}{\sigma_Y^2} = 2T\int_0^\infty S_h^2(f)\frac{\gamma_{12}^2(f)}{S_{n,1}(f)S_{n,2}(f)}\,df$$





Optimal statistic takes into account:

- The spectral distribution of the noise;
- The spectral distribution of the signal;
- The loss of coherence due to the fact that different detectors are coupled to a set of GW in different ways.

Overlap reduction function (a.k.a. coherence)

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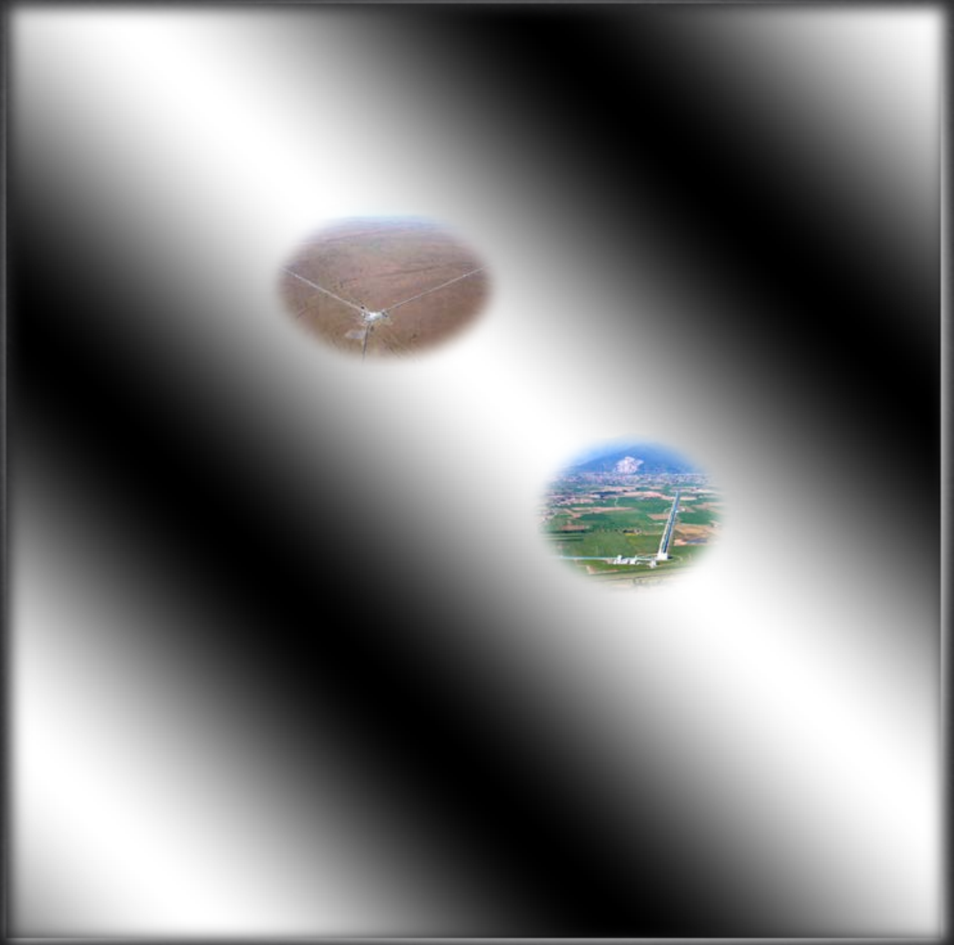

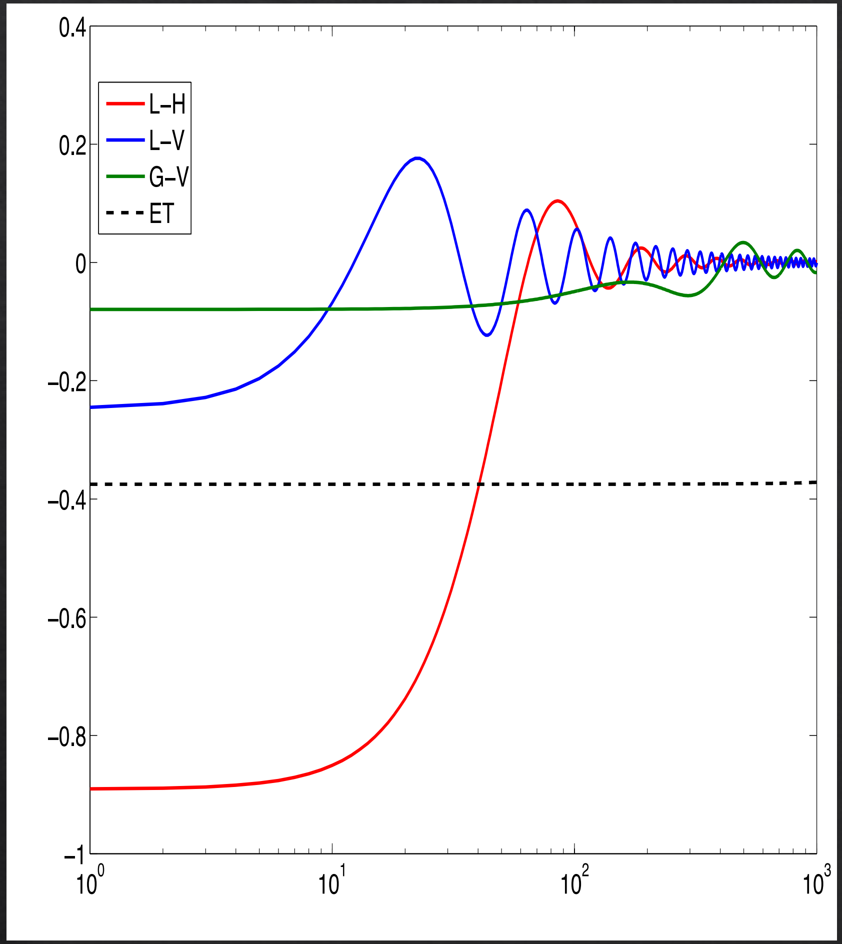

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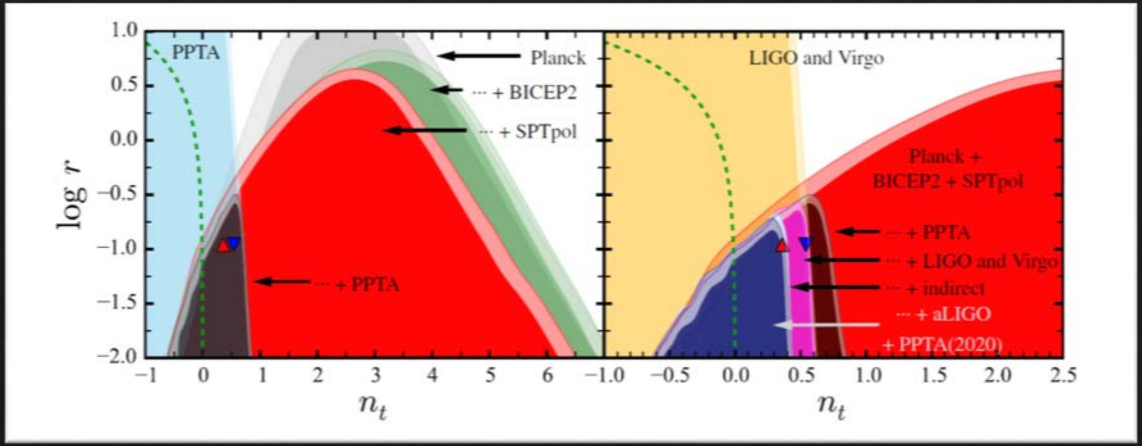
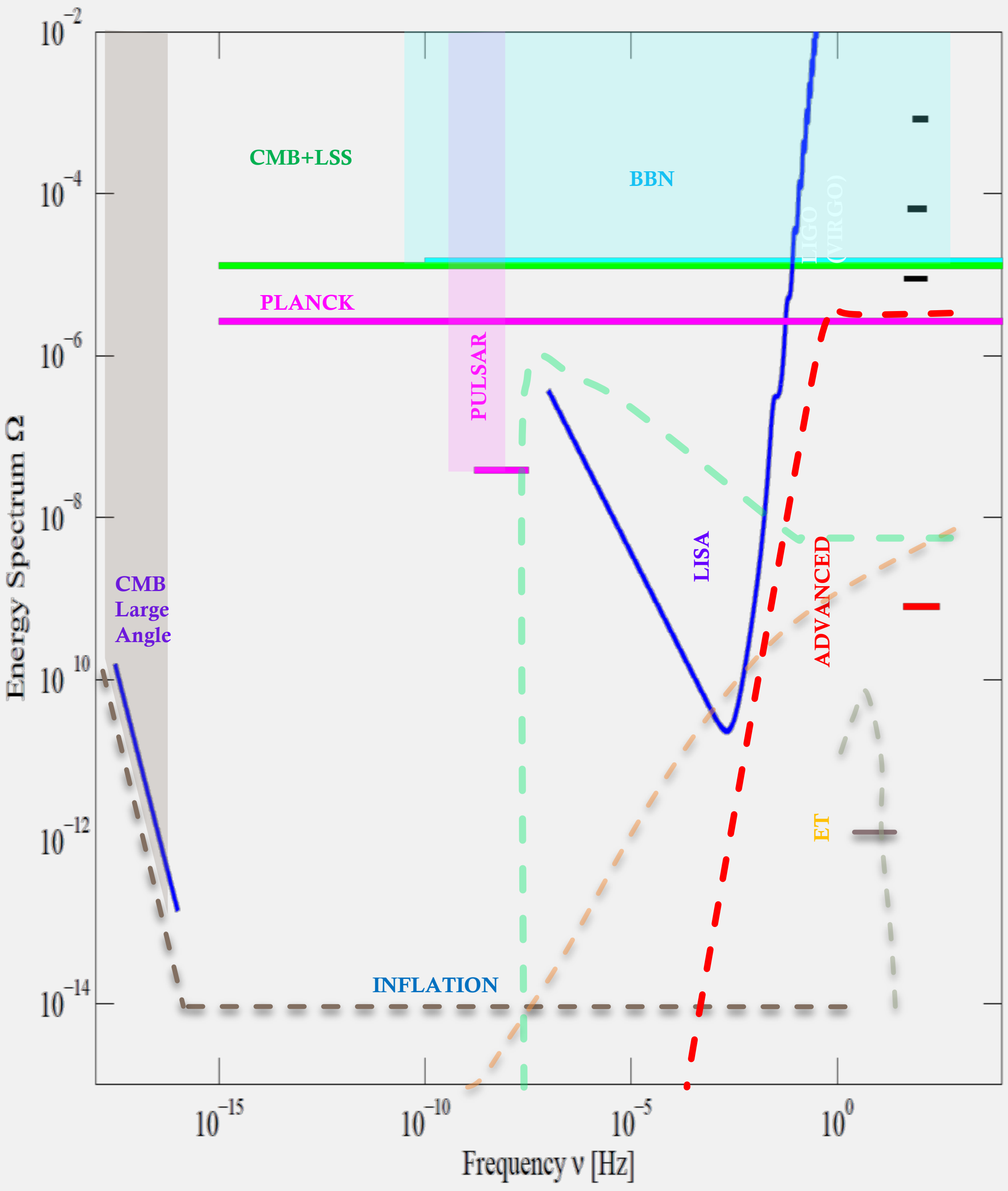
Upper limits & expected sensitivities

- **Big-Bang Nucleosynthesis model and observations** constrain the total GW energy at the time of BBN (integral bound)
- Similar bound from **CMB observations**
- Too much GW gives too much **large angle anisotropy** by the Sachs Wolfe effect
- Signal from **millisecond pulsars** works as a (big) interferometer

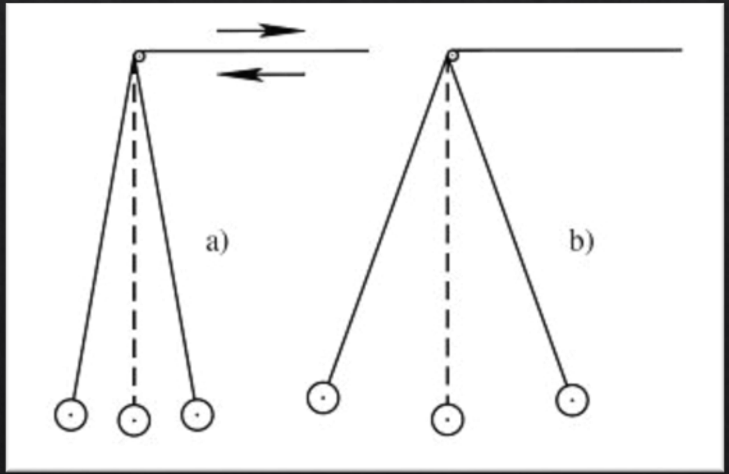
Complementary constraint in very different frequency regions: see Phys. Rev. X 6, 011035 (2016)

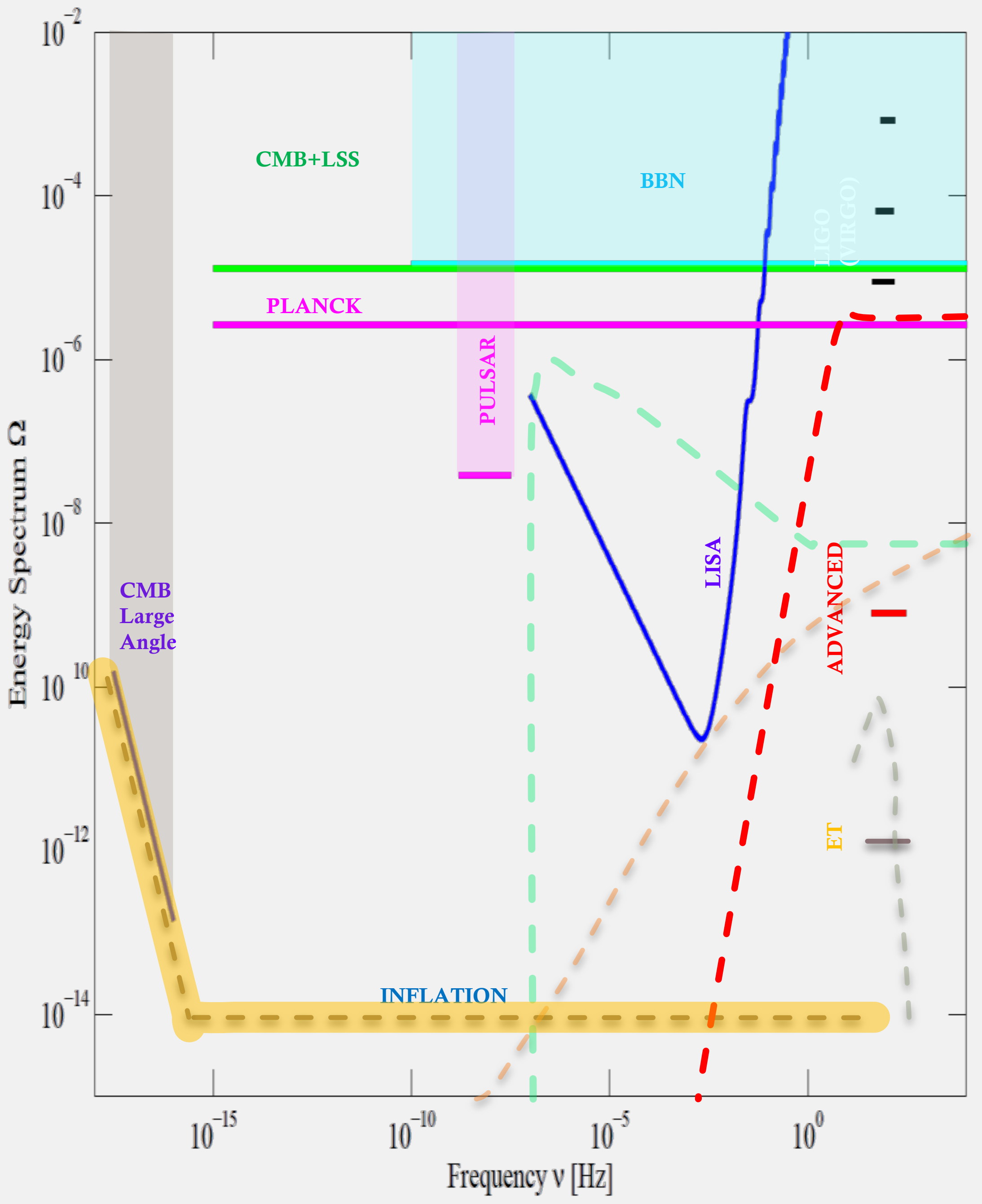




Inflation

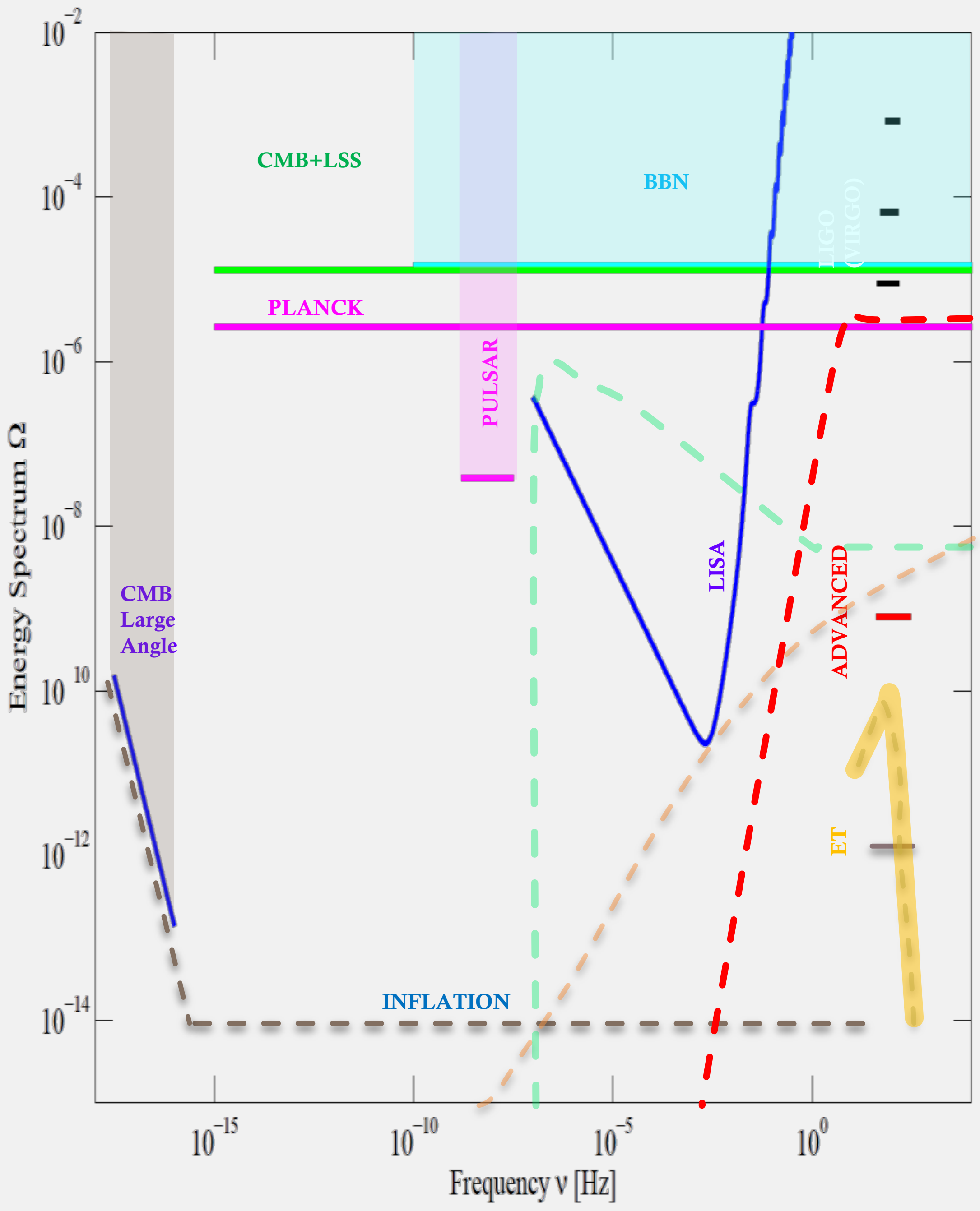
- Parametric amplification of vacuum quantum fluctuations
- Standard inflationary models are weakly dependent on frequency
- Tight bound: CMB large angle anisotropy
- Out of reach of advanced detectors by 5 orders of magnitude





Resonant preheating

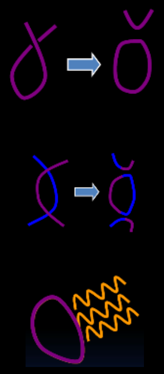
- During a resonant preheating phase at the end of the inflation, inflaton energy can be transferred efficiently to other particles
- Can produce a significant GW background
- Spectrum peak depends on energy scale (here 10 GeV, higher frequencies for a larger scale)



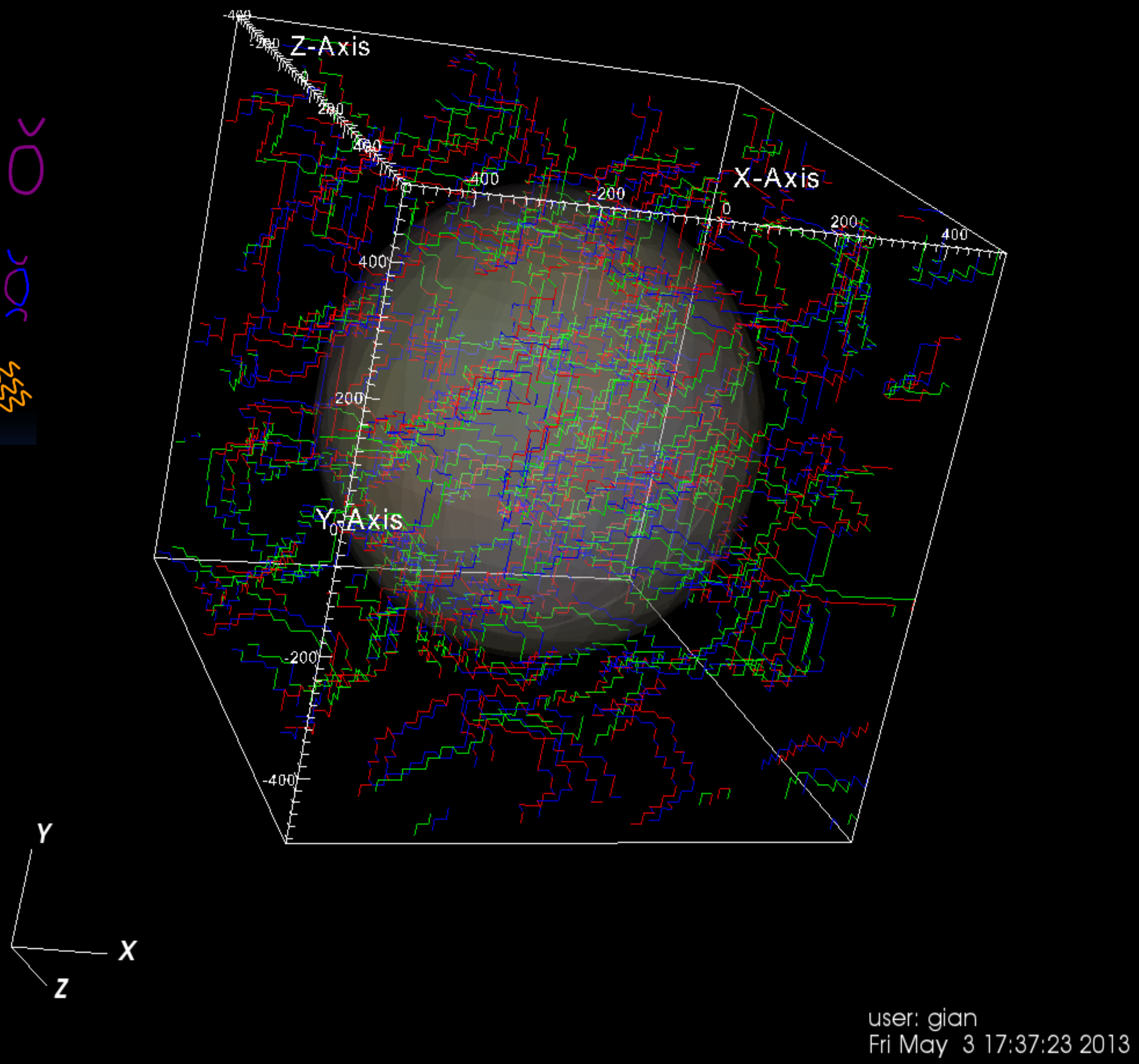
Easther & Lim, JCAP 0604, 010 (2006)
Easther et al., PLR 99, 221301 (2007)
Easther, Nucl. Phys. Proc. Suppl. 194, 33 (2009)

Cosmic (super)string models

- Dynamical network:
  - Strings entering in the horizon
  - Interconnection: loops generation
  - Radiation (GW and other fields): loop destruction



- Most efficient emission mechanisms: cusps and kinks
- Integrating over the whole universe leads to a GW background
- Large parameter space



Damour & Vilenkin, PRL 85, 3761 (2000)
Siemens et al., PRL 98, 111101 (2007)
Olmez et al., PRD 81, 104028 (2010)

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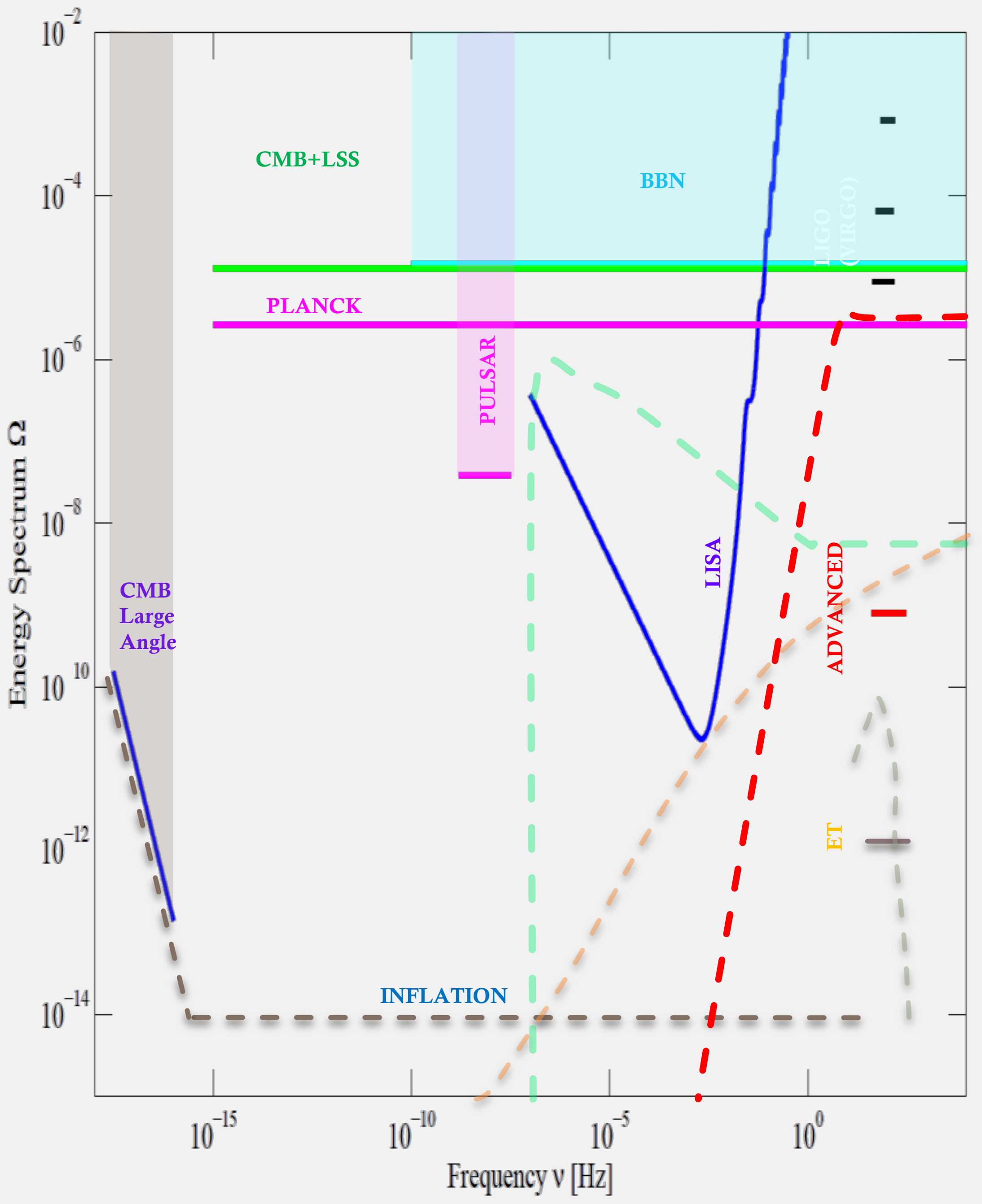

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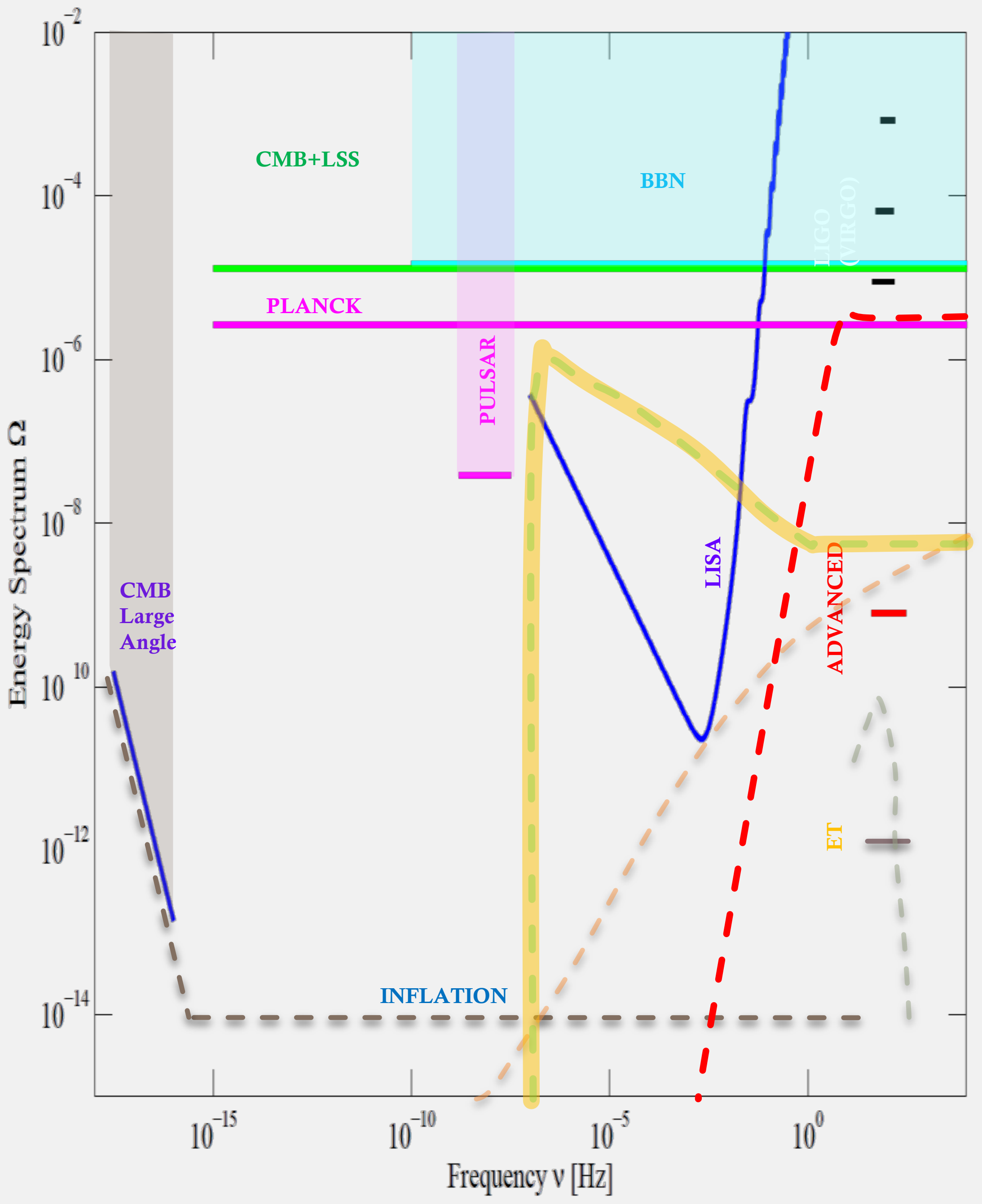
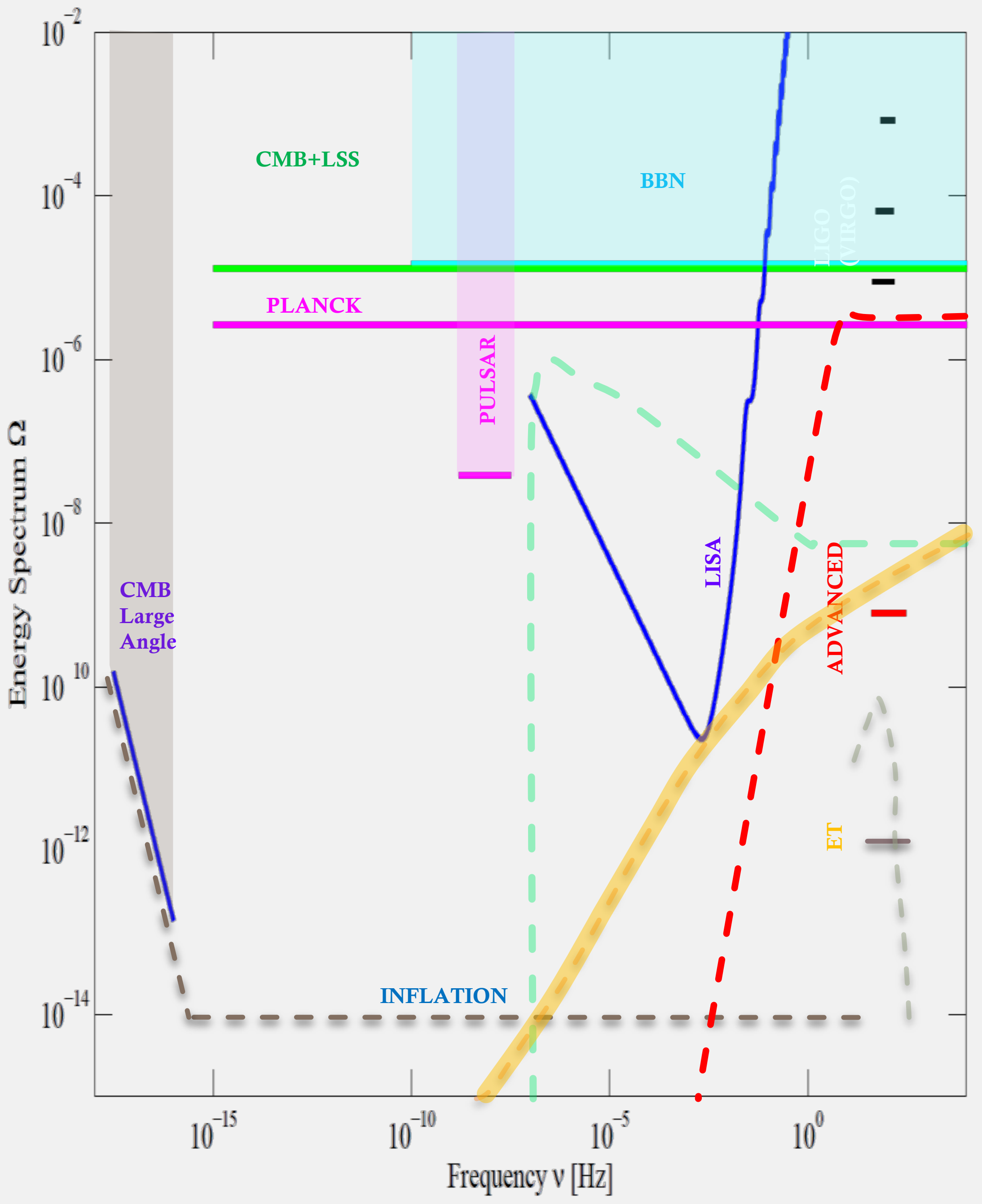


Axion-based inflation models

- Models include axion-gauge couplings
- Gauge back-reaction on the inflaton extends inflation
- The late inflationary phase increases GW production at high frequencies

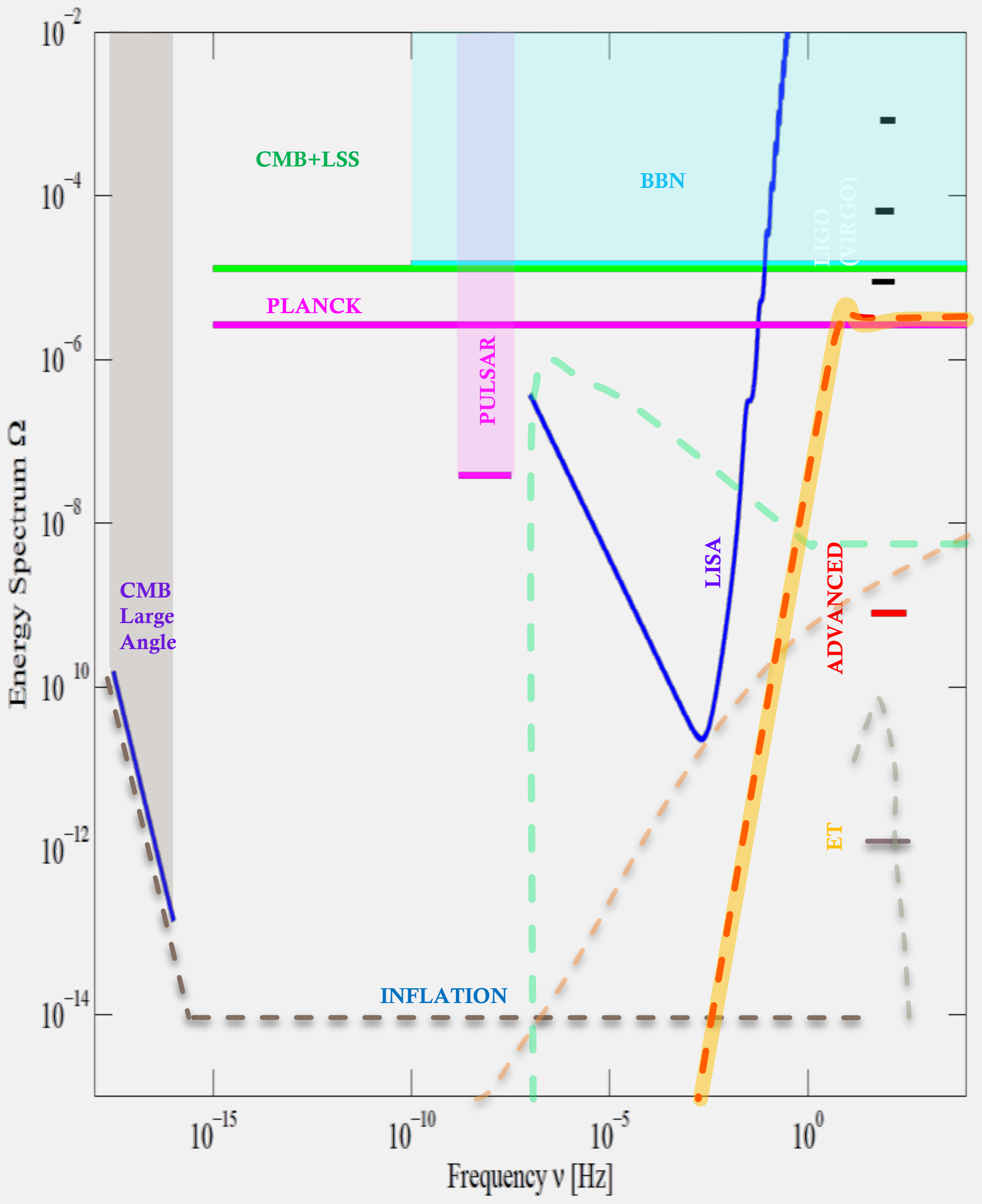
Barnaby, Pajer and Peloso - Phys. Rev. D 85, 023525



Pre-BB models

- Alternative cosmologies
- Evade the CMB large angle anisotropy bound
- Evade the BBN-CMB integral bound
- Can be significant at Virgo/LIGO frequencies

Gasperini & Veneziano, Phys. Rep. 373, 1 (2003)
Buonanno et al., PRD 55, 3330 (1997)



Isotropic upper limits

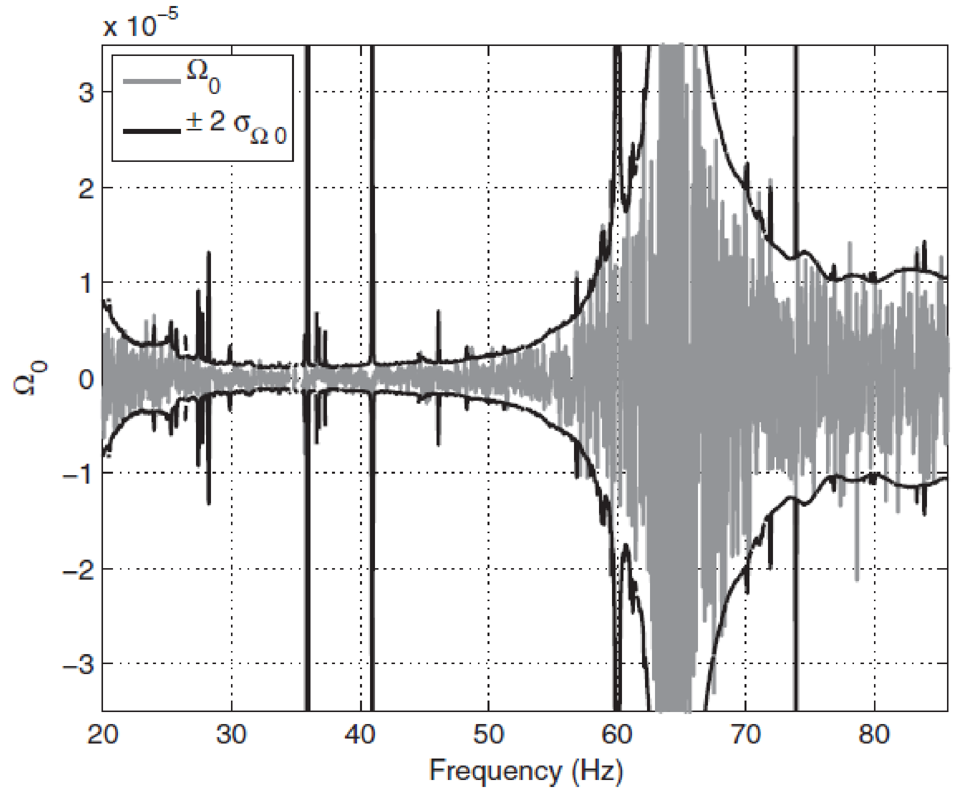


FIG. 1. We show the estimator for Ω_0 in each frequency bin, along with $\pm 2\sigma$ error bars, in the frequency band that contains 99% of the sensitivity for $\alpha = 0$. The loss of sensitivity at around 65 Hz is due to a zero in the overlap reduction function. There are several lines associated with known instrumental artifacts which do not lead to excess cross-correlation. The data are consistent with Gaussian noise, as described in the Results section.

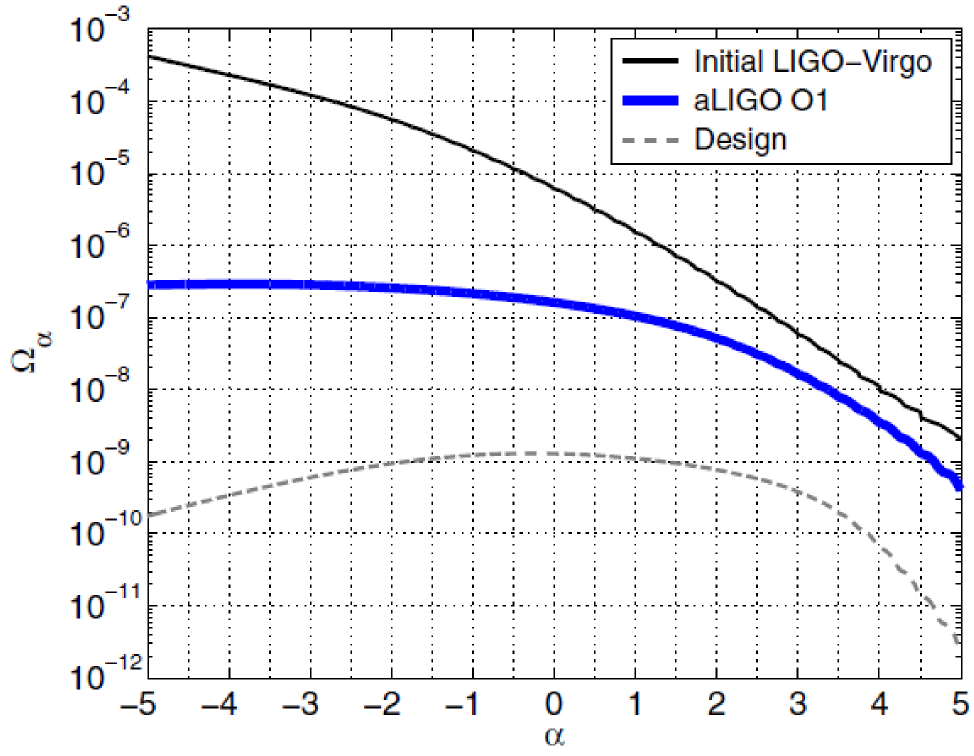


TABLE I. The frequency bands with 99% of the sensitivity are shown, along with the point estimate and standard deviation for the amplitude of the background, and 95% confidence level upper limits using O1 data for three values of the spectral index, $\alpha = 0, 2/3, 3$. We also show the previous upper limits using Initial LIGO-Virgo data.

Spectral index α	Frequency band with 99% sensitivity	Amplitude Ω_α	95% C.L. upper limit	Previous limits [36]
0	20–85.8 Hz	$(4.4 \pm 5.9) \times 10^{-8}$	1.7×10^{-7}	5.6×10^{-6}
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}	7.6×10^{-8}

Phys. Rev. Lett. 118, 121101

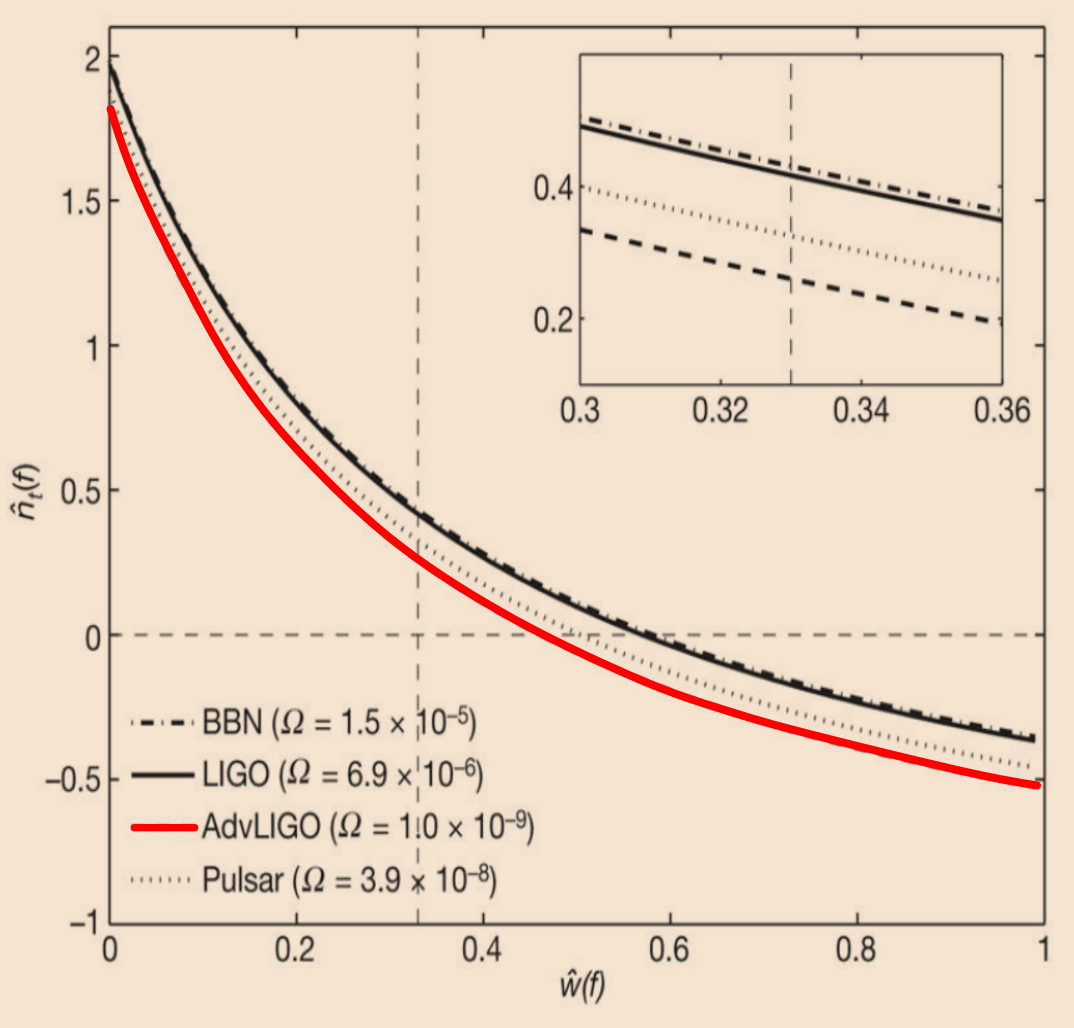
Constraint on early universe state equation

Spectrum parameterization:

$$\Omega_{GW}(f) = A f^{\hat{\alpha}(f)} f^{\hat{n}(f)} r$$

$$\hat{\alpha}(f) = 2\frac{3\hat{w}(f) - 1}{3\hat{w}(f) + 1}$$

- $\hat{n}_t(f)$ effective tensor tilt parameter
- r ratio of tensor and scalar perturbation amplitudes (here $r = 0.1$)
- $\hat{w}(f)$ equation of state parameter



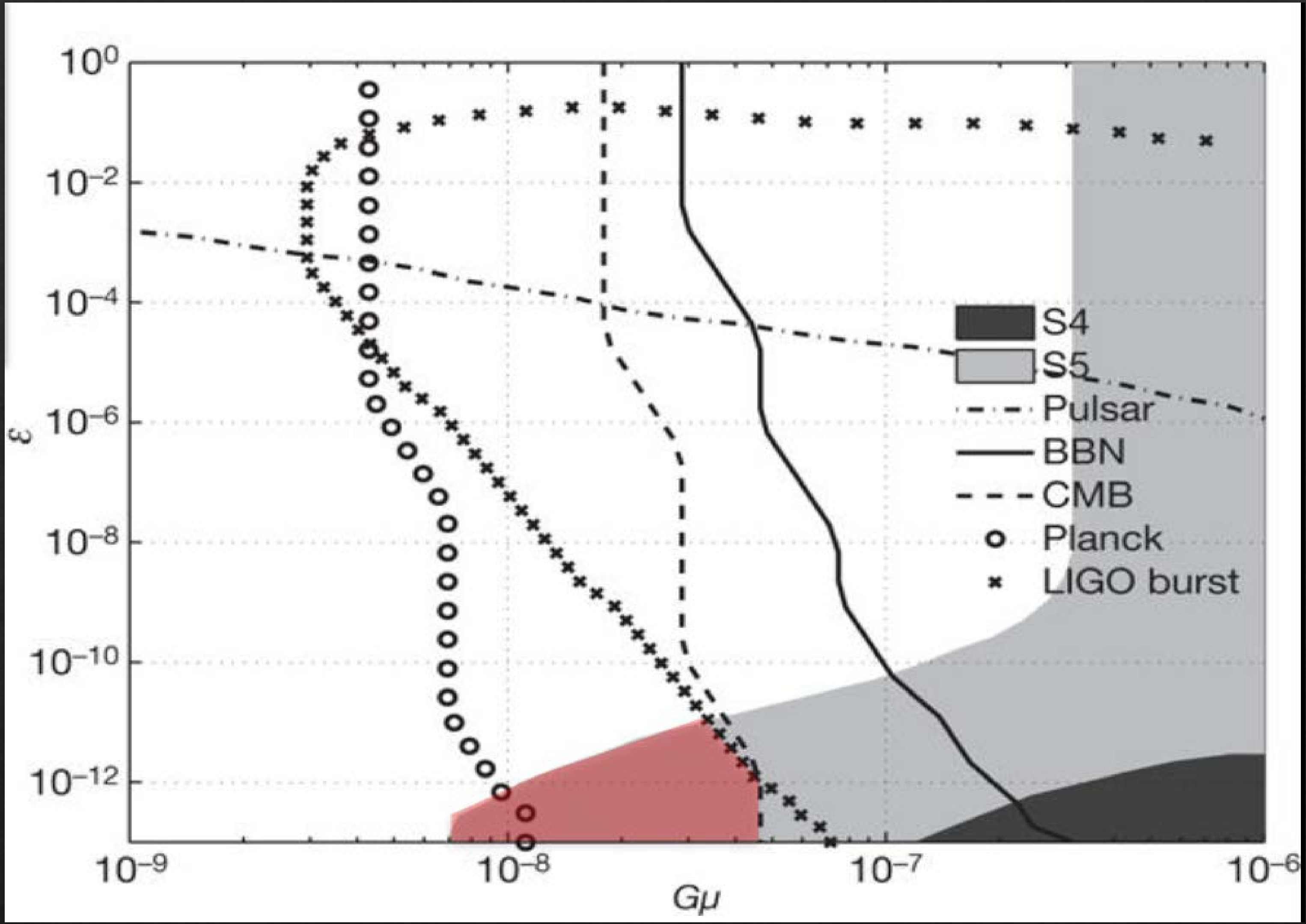
LSC/Virgo Collaboration, Nature 460, 990-994 (2009)
PRD 78, 043531 (2008)

Constraint on cosmic strings models

- Network of cosmic strings parameterized by:
- String tension μ
- Reconnection probability p
- Loop size (parameterized by ε)

- $G\mu < 10^{-6}$ (CMB observations)
- ε unconstrained
- $10^{-4} < p < 1$ ($p = 10^{-3}$ here)

Region excluded: entire plane will be probed by advanced detectors.



LSC/Virgo Collaboration, Nature 460, 990-994 (2009)
PRD 80, 062002 (2009)
PRL 98, 111101 (2007)

Constraints on pre-Big-Bang models

Spectrum:

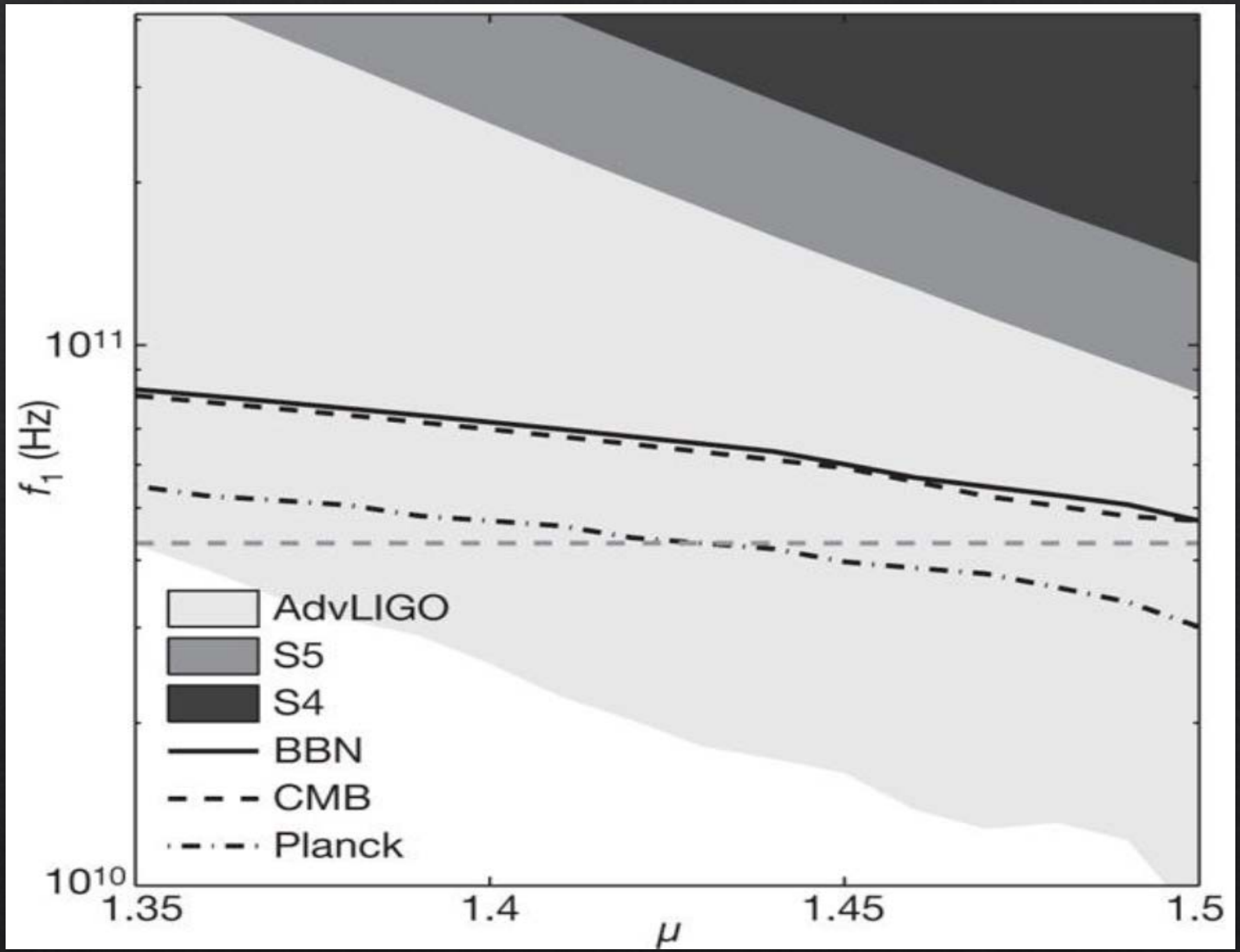
$$\Omega_{GW}(f) \propto f^3$$

below f_s , f_s = 30 Hz here

$$\Omega_{GW}(f) \propto f^{3-2\mu}$$

above f_s , f_s = 30 Hz here

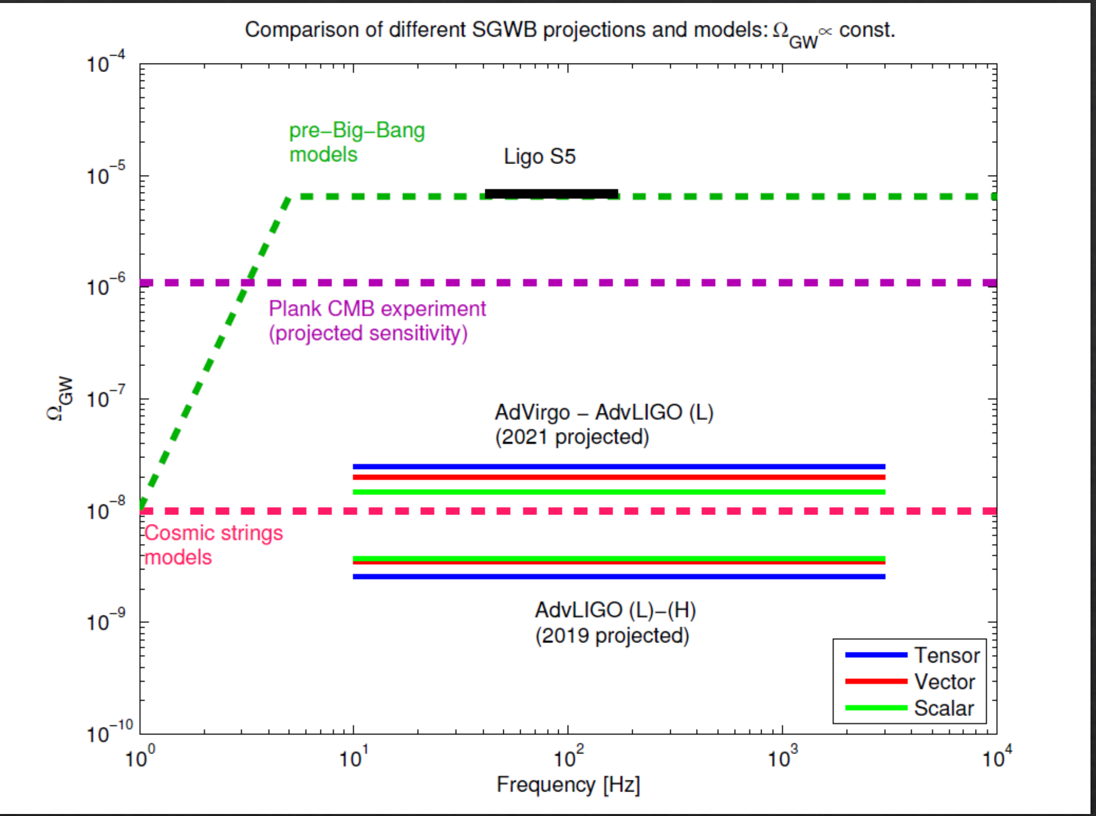
f_1 : cut off frequency
(a factor 10 from 4.3×10^{10})

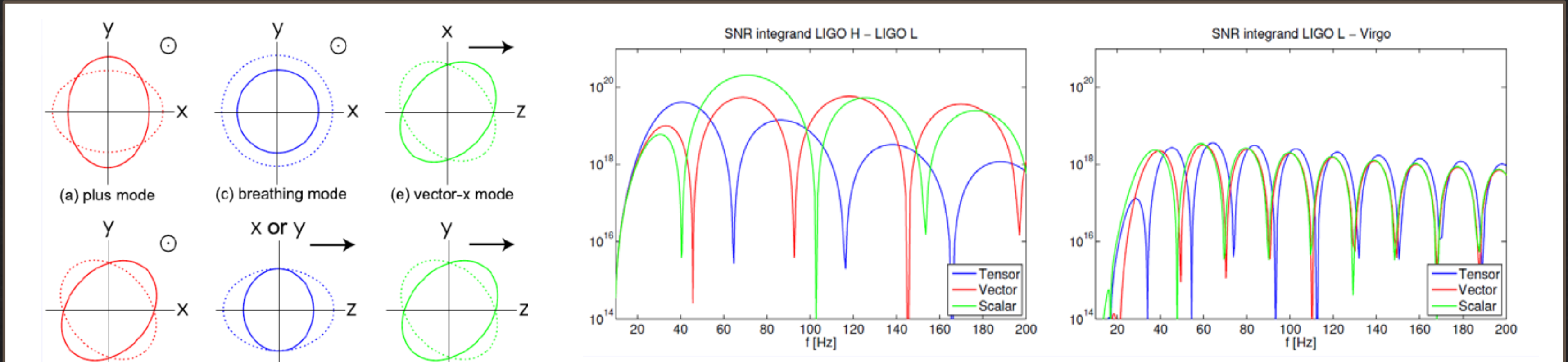


LSC/Virgo Collaboration, Nature 460, 990-994 (2009)
PRD 73, 063008 (2006)

Non standard polarizations

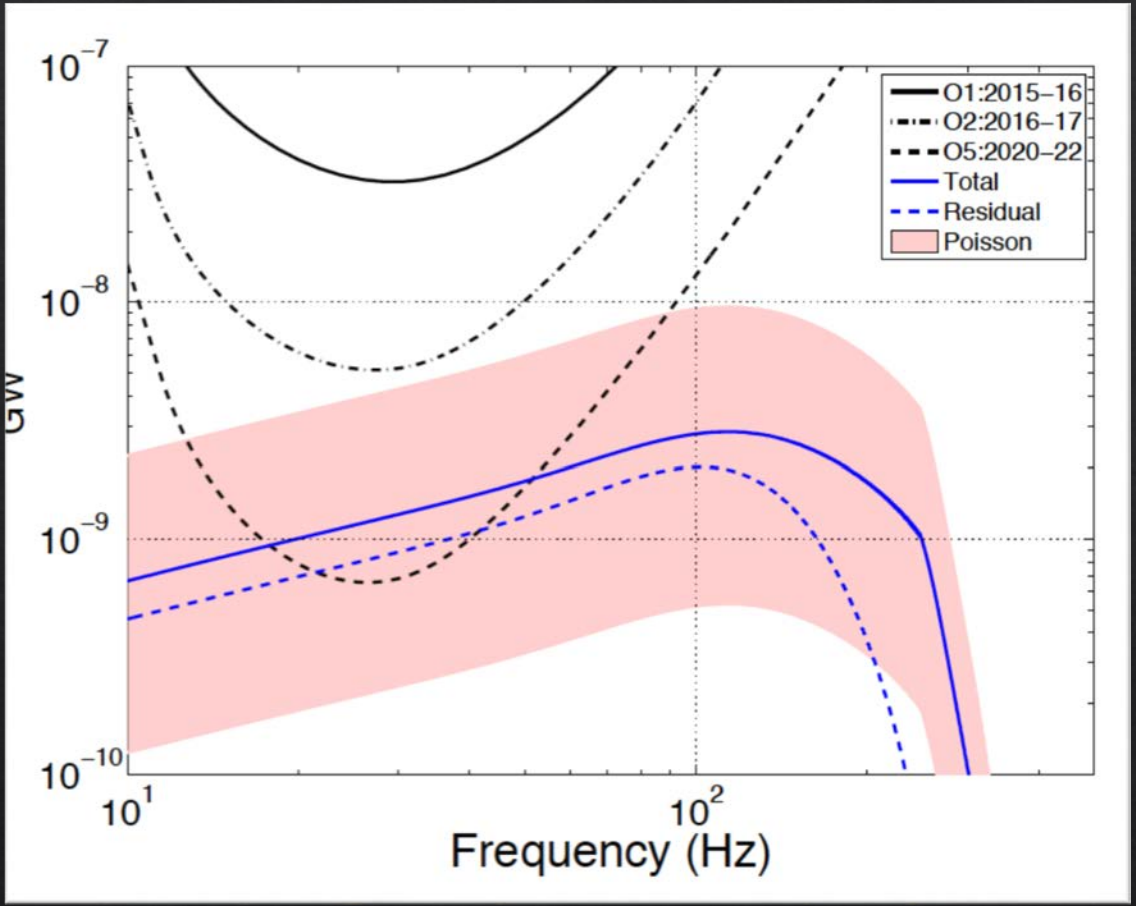
- Looking at alternative theories of gravity
- Indirect constraints on scalar modes
  - Binary pulsars
  - WMAP
- Need many detector pairs to disentangle different contributions





Nishizawa et al., 2009

Conclusions



- Stochastic background not yet measured
- Direct detection not excluded with some model in the advanced era, however
  - Astrophysical models can be detected also;
  - A cosmological contribution must be disentangled.
- Several interesting constraints on models start to be available, and will improve;
- In principle, possibility of testing alternate gravity models.
- Not discussed here:
  - Directional searches (maps of anisotropies)