Detecting Signatures of the Cosmic Thermal History through Pulsar Observations

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Cosmological Gravitational Waves

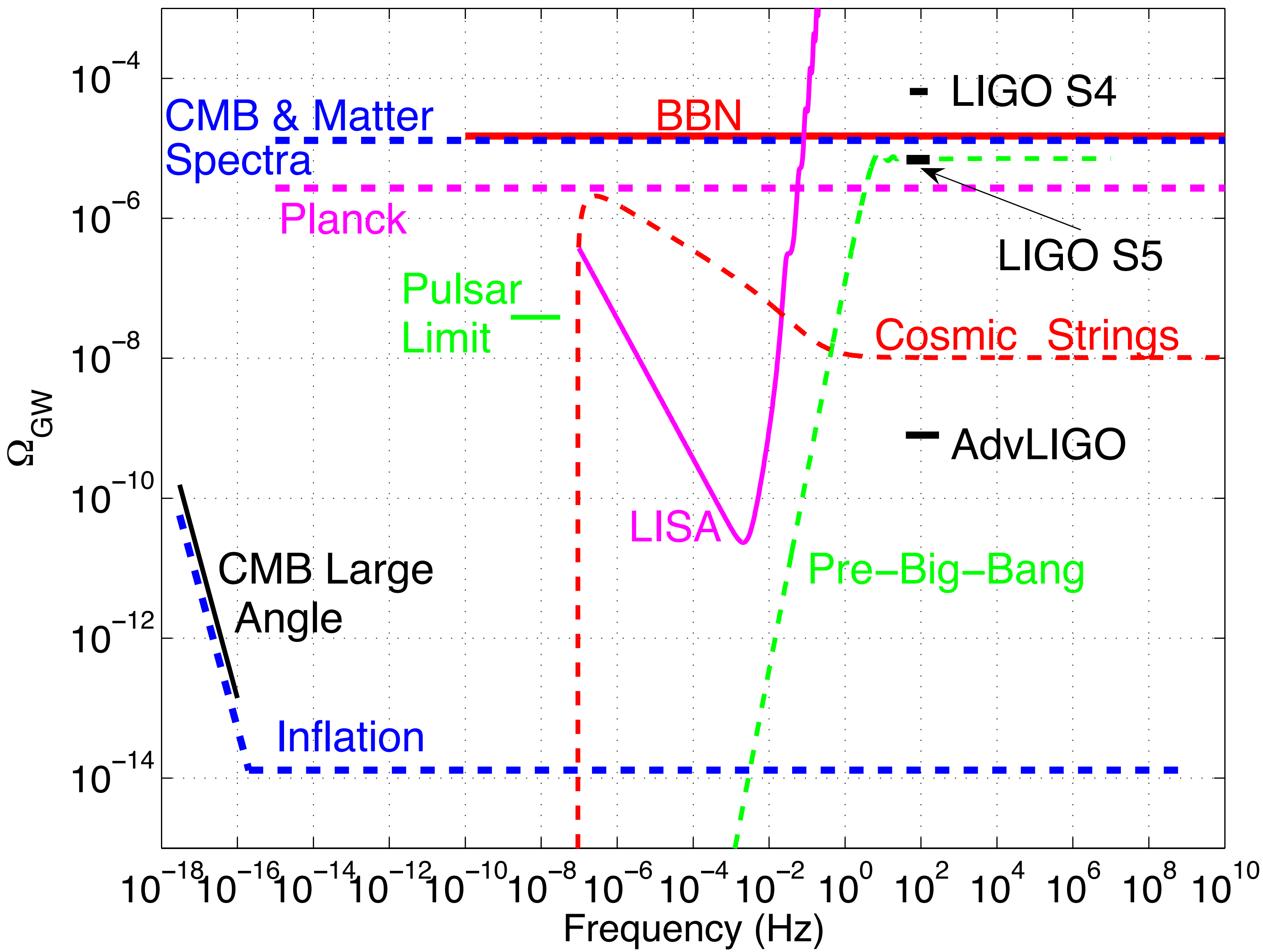
The detection of cosmological gravitational waves (GW) produced in the early Universe would be a major breakthrough in cosmology and high-energy physics.

The basic reason for this is that GWs decouple from the primordial plasma at $T \sim M_{Pl} \sim 10^{19}$ GeV, and thus give a "snapshot" of the Universe as it was at the time of their production (since this usually occurs at $T < M_{Pl}$!).

Several scenarios of the early Universe predict the production of gravitational waves, through a variety of physical processes:

- **Inflation** (amplification of vacuum fluctuations)
- **String Cosmology** (amplification of vacuum fluctuations)
- **Cosmic strings** (oscillation of closed string loops)
- **Phase transitions** (bubble collisions, turbolence)

Cosmological Gravitational Waves



LIGO and VIRGO collaborations, Nature 460, 990 (2009)

Interaction of GWs with cosmological neutrinos

- The GW spectrum has to be propagated until the present time

$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 16\pi G a^2 \Pi_{ij}$$

- The source term on the RHS of Einstein eqn. is the anisotropic part of the stress tensor, and vanishes in the case of a perfect fluid. It is thus a (at least) first order quantity in the framework of cosmological perturbation theory.

- As a rule of thumb, we have that π_{ij} is proportional to the mean free path of particles.

- Then the main contribution to the anisotropic stress (AS) is due to neutrinos, since they are the most weakly interacting particles. The Universe is filled by neutrinos, with a number density of the order of the number density of the CMB photons.

- Weinberg (*Phys. Rev. D* **69**, 023503, 2004) has computed the effect of neutrino AS on the propagation of gravitational waves on a FRW background, *for frequencies relevant to the CMBR*.

- In that regime, neutrinos are effectively collisionless, i.e. C[f] = 0.

- We want to explore the regime in which collisions should be taken into account.

Interaction of GWs with cosmological neutrinos

$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 16\pi G a^2 \Pi_{ij}$$

$$\dot{F}_\nu + i(\vec{k}\cdot\hat{n})F_\nu + 2\dot{h}_{ij}n_i n_j = \frac{4\pi}{a^4\bar{\rho}}\int dq q^3 \left(\frac{\partial f}{\partial\tau}\right)_C$$

Mathematical Procedure:

- Write the distr. function of neutrinos as an equilibrium, zeroth order part + a small perturbation δf(**x**, **q**, t)
- Fourier transform the spatial dependence;
- Integrate to eliminate the dependence from the neutrino momentum;
- Expand the Boltzmann equation over Legendre polynomials in order to eliminate the residual angular dependence;

Interaction of GWs with cosmological neutrinos

$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 4Ga^2\bar{\rho}_\nu G^{(0)}_{ij}$$

$$\dot{G}^{(0)}_{ij} = -k\,G^{(1)}_{ij} - \frac{8\pi}{15}\dot{h}_{ij} - \frac{G^{(0)}_{ij}}{\tau},$$

$\tau_{weak} = 1/(G_F^2\, T^5)$

$$\dot{G}^{(2)}_{ij} = -\frac{k}{5}\left[3G^{(3)}_{ij} - 2G^{(1)}_{ij}\right] - \frac{16\pi}{105}\dot{h}_{ij} - \frac{G^{(2)}_{ij}}{\tau},$$

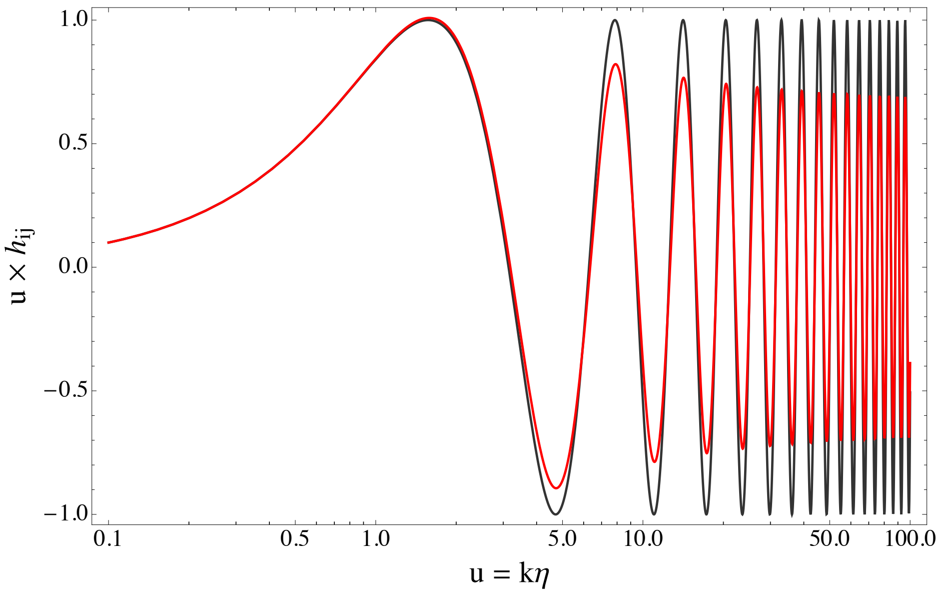
$$\dot{G}^{(4)}_{ij} = -\frac{k}{9}\left[5G^{(5)}_{ij} - 4G^{(3)}_{ij}\right] - \frac{8\pi}{315}\dot{h}_{ij} - \frac{G^{(4)}_{ij}}{\tau},$$

$$\dot{G}^{(\ell)}_{ij} = -\frac{k}{2\ell+1}\left[(\ell+1)G^{(\ell+1)}_{ij} - \ell\,G^{(\ell-1)}_{ij}\right] - \frac{G^{(\ell)}_{ij}}{\tau} \qquad (\ell \neq 0, 2, 4).$$

Interaction of GWs with cosmological neutrinos

- The main effect of the interaction is that the amplitude of the wave is damped by a factor *D*
- The damping depends on two parameters: the neutrino density $f_\nu = \rho_\nu / \rho_{tot}$ and the frequency of collisions $1/\tau_c$
- In the early Universe, in the case of constant f_ν and without collisions, *D* is indepedent from the frequency of the GW.
- Neutrino collisions set up at T~1 MeV, i.e $\nu \sim 6 \times 10^{-10}$ Hz
- In general, $h_c(f) \rightarrow D(f)\, h_c(f)$ and $\Omega_{gw}(f) \rightarrow D(f)^2\, \Omega_{gw}(f)$

For $f_\nu = 0.4$, the amplitude of wave is damped by 10% (20% in intensity) wrt to vacuum propagation. For $f_\nu = 1$, the damping is 25% (50% in intensity).



Neutrino Thermal History

- At T~1 MeV, the Universe undergoes a “phase transition”

- For T>> 1 MeV, the Universe is a plasma of photons, electrons, positrons and neutrinos that are kept in thermal equilibrium by the electromagnetic and weak interactions;

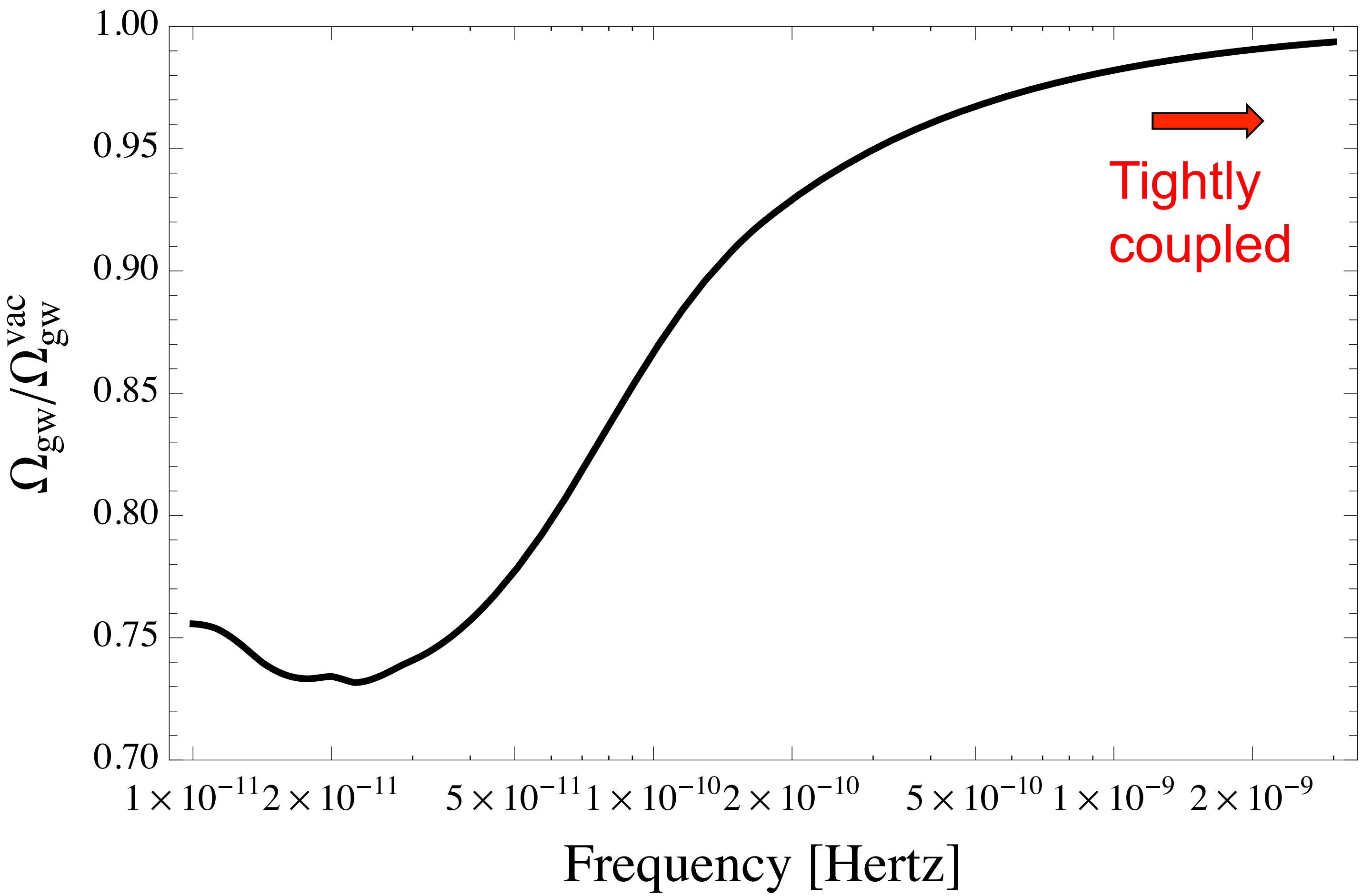
- At T ~ 1 MeV, the weak interactions “freeze-out” and the cosmological fluid is made by two components: a photon,e+e- plasma on one side, and the neutrino (collisionless) gas on the other; the two components, althoug not in thermal contact, have the same temperature

- Sligthly below, 1 MeV, the e+ and e- annihilate mainly to photons and heat the photon component that is then hotter than the neutrinos;

- The frequency of a wave entering the horizon at T~1 MeV is between 10^{-10} and 10^{-9} Hertz

- The region between 10^{-9} and 10^{-7} Hz can be probed by pulsar timing techniques.

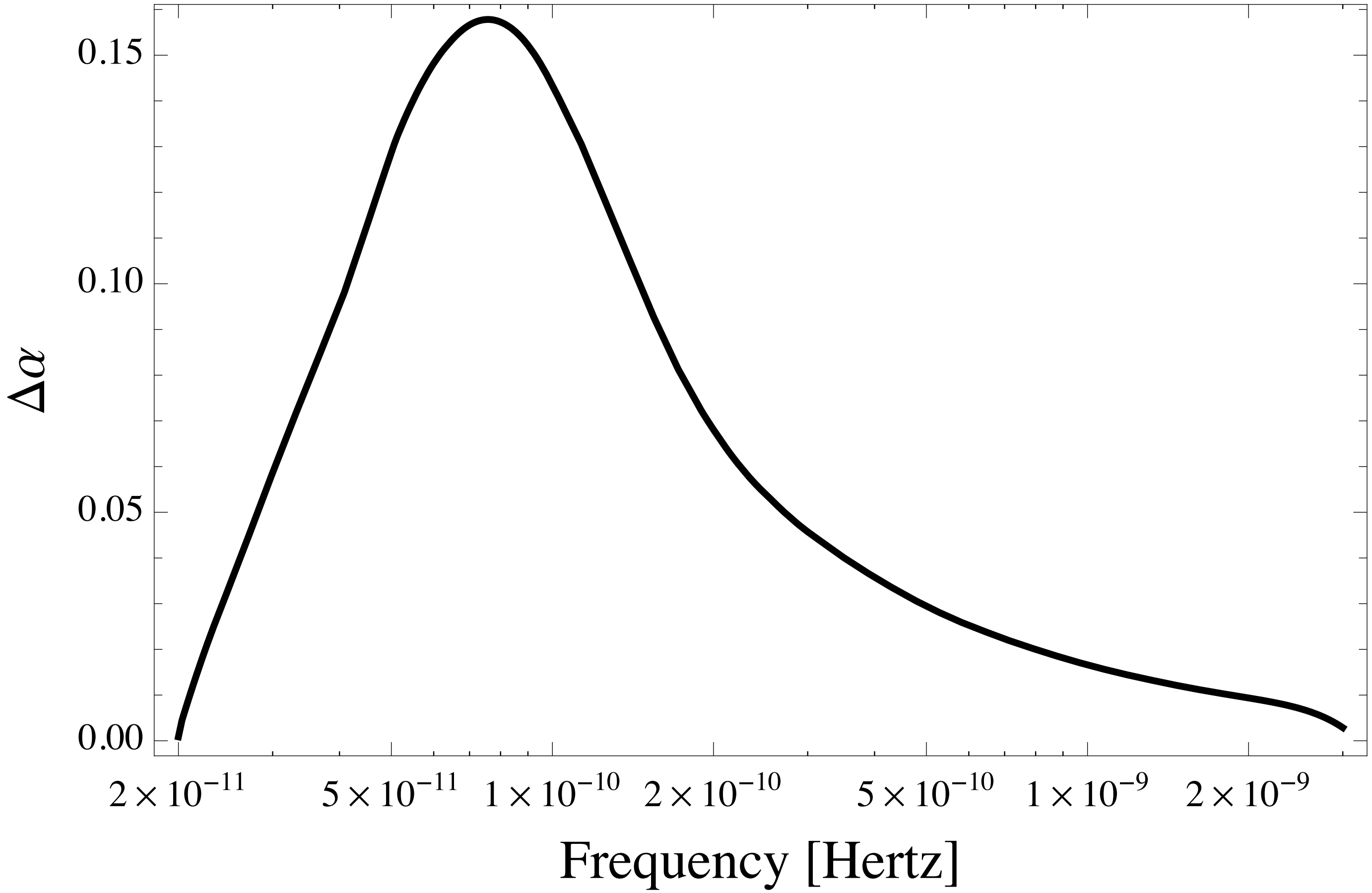
Signatures of the Neutrino Thermal History



This is how a flat spectrum at the source (normalized to high frequencies) would appear now, after GW propagation across the Universe.

Signatures of the Neutrino Thermal History

Deviation from a power law behaviour



$\Omega_{gw}(f) = D(f)^2\ \Omega^0{}_{gw}(f) = D(f)^2\ A\ f^{\alpha}$

$\Delta\alpha = d\log[D(f)^2]/d\log[f]$

Signatures of the Neutrino Thermal History

Can we see this feature? (A theorist's view)

- A large enough cosmological signal should be present in the nHz range (cosmic strings?);
- An independent confirmation at larger frequencies (interferometers) would be useful (also to "normalize" the signal);
- The cosmological GW background should be larger than the astrophysical background (BH binaries); or, the latter should be removed;
- Frequencies below 1 nHz should be measured, the smaller the better. At f=1/(100 years), the damping is just 5%. The largest change in slope occurs at f ~ 0.1 nHz ~ ~ 1/(300 years). Large times of observations would also introduce problems related to the timing stability;
- One should have enough frequency resolution and sensitivity to the signal to do a proper characterization of the spectrum.

SUMMARY

- The production of gravitational waves is a prediction of several early Universe scenarios.
- The spectra predicted from these scenarios differ very much.
- Cosmological GWs DO NOT propagate in vacuum, since they interact with the anisotropic stress of the cosmological fluid (i.e. its effective viscosity). A source of anisotropic stress are the free streaming background neutrinos.
- The interaction of GWs with cosmological neutrinos results in a damping of the wave intensity, amounting to 50% at most. This damping is not so severe to prevent primordial GWs to be detected today.
- The thermal evolution around T ~ 1 MeV (z ~ 10^{10}) (i.e. neutrino decoupling and e^+e^- annihilation) would leave a distinct imprint on any cosmological signal in the sub-nHz range.
- To explore that frequency range with PTAs would require ~ 100 years.
- However, neutrinos are not the only possible source of anisotropic stress (e.g. magnetic fields)....
- .... and the thermal history of the Universe is largely unknown!!!

BACKUP SLIDES

Theoretical predictions:

- **De Sitter Inflation**

Flat spectrum for $f > f_{eq} \sim 10^{-16}$ Hz

$1/f^{2}$ spectrum for $f < f_{eq}$

Typical intensity: $h_0^2\Omega_{gw} \sim 10^{-13} (H / 10^{-4} M_{Pl})^2$

Correction for slow-roll:

Small tilt $|n_T|$~1 in the "flat" region: $n_T = -\frac{1}{7}\frac{A_T}{A_S}$

- **String Cosmology**

Almost flat spectrum for $f > f_s \sim$?

f^3 spectrum for $f < f_s$

Typical intensity: $h_0^2\Omega_{gw} \sim 10^{-13} - 10^{-4}$

Theoretical predictions:

Phase Transitions

The spectrum is usually peaked at a single frequency f_0 (e.g., $f_0 \sim 4 \times 10^{-3}$ Hz for EW phase transition)

Strongly first order transitions are needed

$\varepsilon \sim 1$ is excluded (optimistically, $\varepsilon \sim 10^{-2}$)

Typical peak intensity: $h_0^2 \Omega_{gw} \sim 10^{-5} \varepsilon^2$ x suppression factors

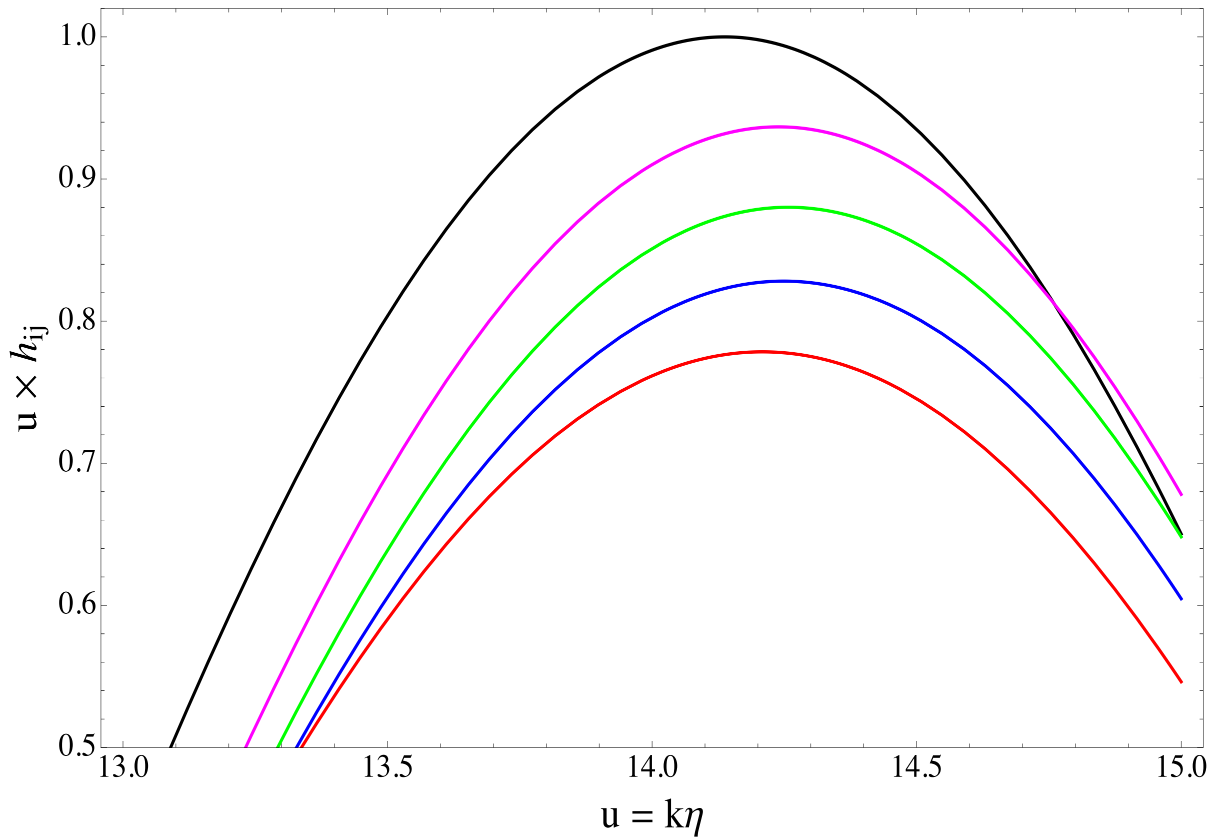
Cosmic Strings

Flat spectrum for 10^{-8} Hz < f < 10^{10} Hz

Peak in the region $f \sim 10^{-12}$ Hz

Typical intensity: $h_0^2 \Omega_{gw} \sim 10^{-8} - 10^{-7}$

Interaction of Cosmological GWs with neutrinos



Decreasing τ

$1/(k\,\tau) = 0.1, 0.5, 1, 2$

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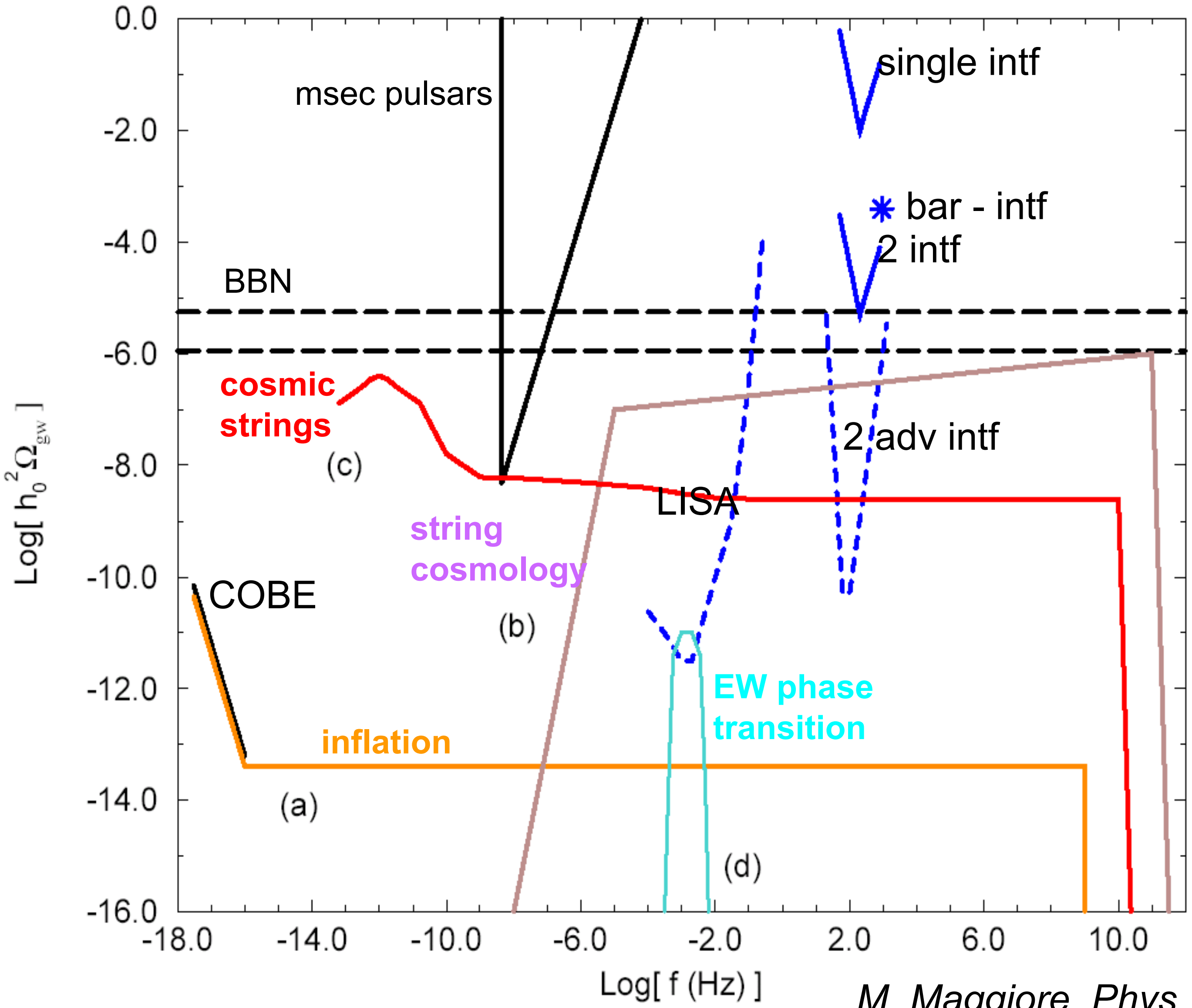
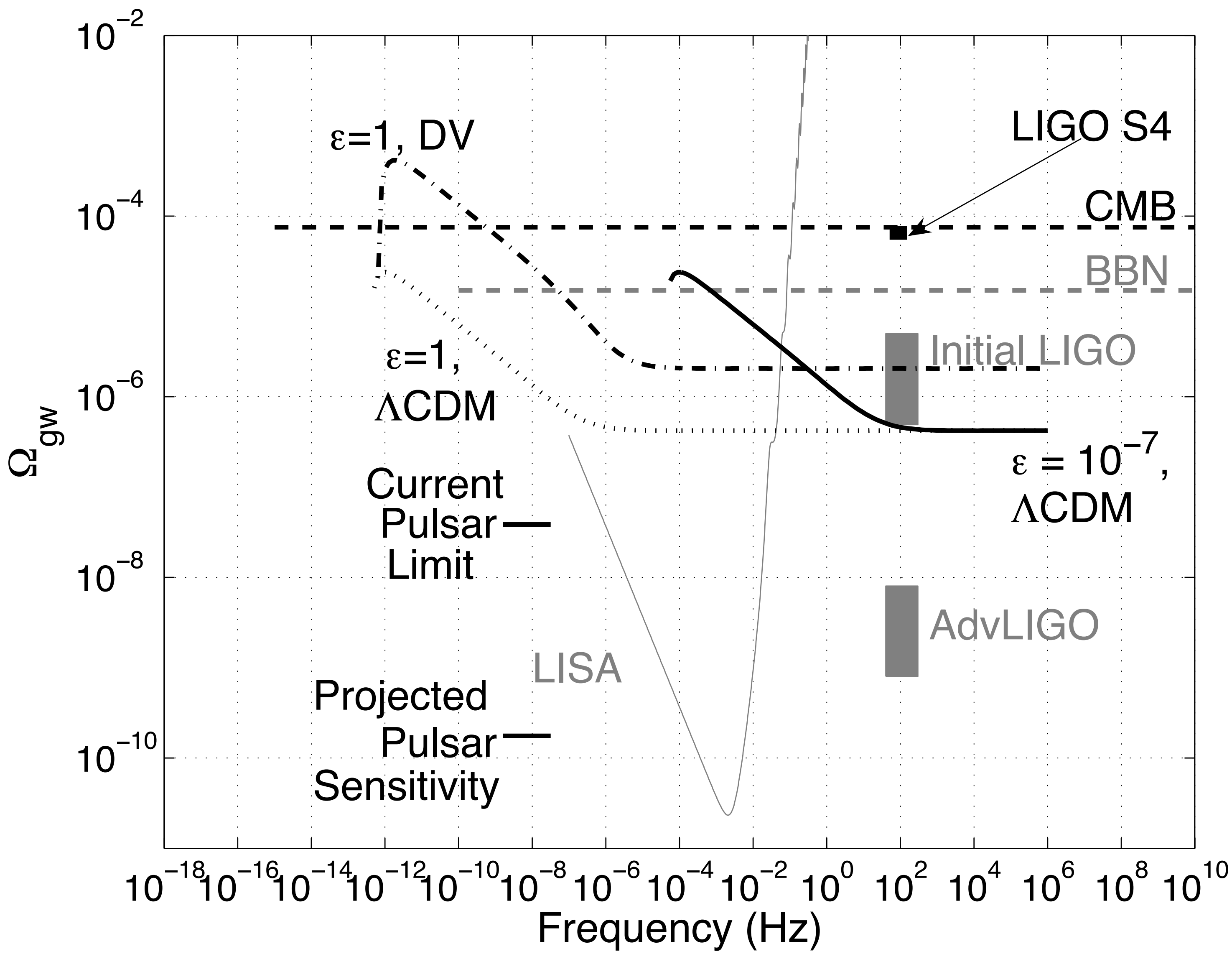


M. Maggiore, Phys. Rept. 331 (2000), 283

Cosmological Gravitational Waves



Siemens, Mandic & Creighton, PRL 98, 111101 (2007)