Cosmological Stochastic Backgrounds

Michele Maggiore
Département de Physique Théorique

UNIVERSITÉ DE GENÈVE

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How to characterize a SBGW

$$\rho_{\mathrm{GW}} = \int_0^\infty d(\log f)\ \frac{d\rho_{\mathrm{GW}}}{d\log f}$$

$$\Omega_{\mathrm{gw}}(f) = \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\log f} \qquad\qquad \rho_c = \frac{3H_0^2}{8\pi G_N}$$

I will rather use:

$$h_0^2\Omega_{\mathrm{gw}}(f)\,, \qquad h_0 = 0.73(3)$$

What we known about SBGW

BBN bound

- from the balance of H and Γ at nucleosynthesis, together with $H^2 = (8\pi G/3)\,\rho$
- is a bound on the total energy density, integrated over all frequencies.

$$\int_{f=f_{\rm min}}^{f=\infty} d(\log f)\; h_0^2 \Omega_{\rm gw}(f) \le 5.6 \times 10^{-6} (N_\nu - 3)$$

$f_{min} \approx 10^{-10}$ Hz fixed by the horizon size at BBN

- N_ν = effective number of neutrino species, parametrizes any extra energy contribution

- in the SM, N_ν =3.046 (due to residual interaction of neutrinos with $e^{\pm}$ and to finite temperature QED effects). So, more precisely,

$$\int_{f=f_{\rm min}}^{f=\infty} d(\log f)\; h_0^2\Omega_{\rm gw}(f) \leq 5.6\times 10^{-6}(N_\nu - 3.046)$$

- in order of magnitude, it says that at time of NS there were no more GWs than photons

- it can be translated into a bound on the integrand

- depending on assumptions about NS and priors,
  - $N_\nu < 4.4$ at 95% c.l. (η determined from BBN itself)
  - $N_\nu < 3.7$ at 95% c.l. (η taken from WMAP)

(Cyburt et al. 2004)

  - $N_\nu < 3.6$ at 95% c.l. (η from BBN itself)

  from updated analysis (Iocco, Mangano, Miele, Pisanti and Serpico, Phys Rept 2009)

  (more accurate determination of ^{4}He mass fraction)

- it can be further relaxed if there is a non-standard thermal history leading to non-thermal neutrinos
  - incomplete thermalization of neutrinos in low-scale reheating model ($T_{reheating}$ can be as low as O(1) MeV)

LIGO/VIRGO paper

(Nature, 2009, see talk by E. Thrane)

$$\Omega_{gw} < 6.9 \cdot 10^{-6}$$

at 95% c.l., in the band 41.5 Hz<f<169.25 Hz

In term of N_ν : $N_\nu < 4.0$

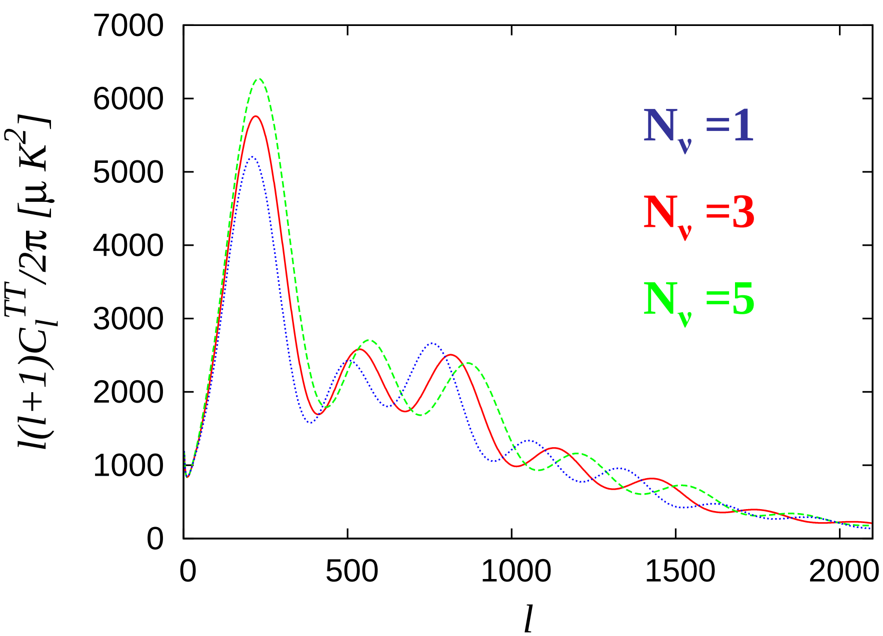
- comparable but not really better than BBN bound
- furthermore, a detection just below the BBN bound would be possible only if all extra radiation allowed by BBN were concentrated in the LIGO band
- for a spectrum that extends over many decades, the BBN bound is still much stronger

CMB bound on N_ν

- Adding radiation shifts the point of matter-radiation equality closer to the epoch of last scattering

→ increases the early ISW effect

→ more power close to the first acoustic peak



(from Ichikawa, Sekiguchi,Takahashi, PRD 2008)

Kneller et al 2001,

Hannestad 2001

Bowen et al 2002,

……

Hamann et al 2007

de Bernardis et al 2008,

Komatsu et al (WMAP) 2008,

Dunkley et al (WMAP) 2008

- until almost the 2nd/3rd peak the effect of increasing Ω_{rad} is degenerate with decreasing Ω_m
  - break the degeneracy using other cosmological data set (LSS, BAO, SNIa, Lyman-α, HST...).

Results depend on datasets, priors, ...

$N_\nu < 4.28$ at 95% cl (Smith, Pierpaoli and Kamionkowski, 2006)

(for non-adiabatic initial conditions)

Forecasts for Planck: $N_\nu < 3.3$ at 95% cl

CMBPol: $N_\nu < 3.13$ at 95% cl

- CMB only (WMAP+ACBAR+CBI+BOOMERANG)

$N_\nu < 7.9$ at 95% cl (Ichikawa, Sekiguchi,Takahashi, 2008)

Forecasts for Planck: $N_\nu < 3.4$ at 95% cl

- the CMB bound on N_ν holds for GWs present at last scattering (z=1100, T≈ 0.1 eV)

  the BBN bound holds at T≈ 1 MeV

- the CMB bound extend down to 10^{-15} -10^{-16} Hz

  (size of the horizon at last scattering),

  the BBN bound extend down to 10^{-10} Hz

- pulsar timing

relevant at $f \sim 1/(\text{observation time}) \sim 10^{-8}$ Hz

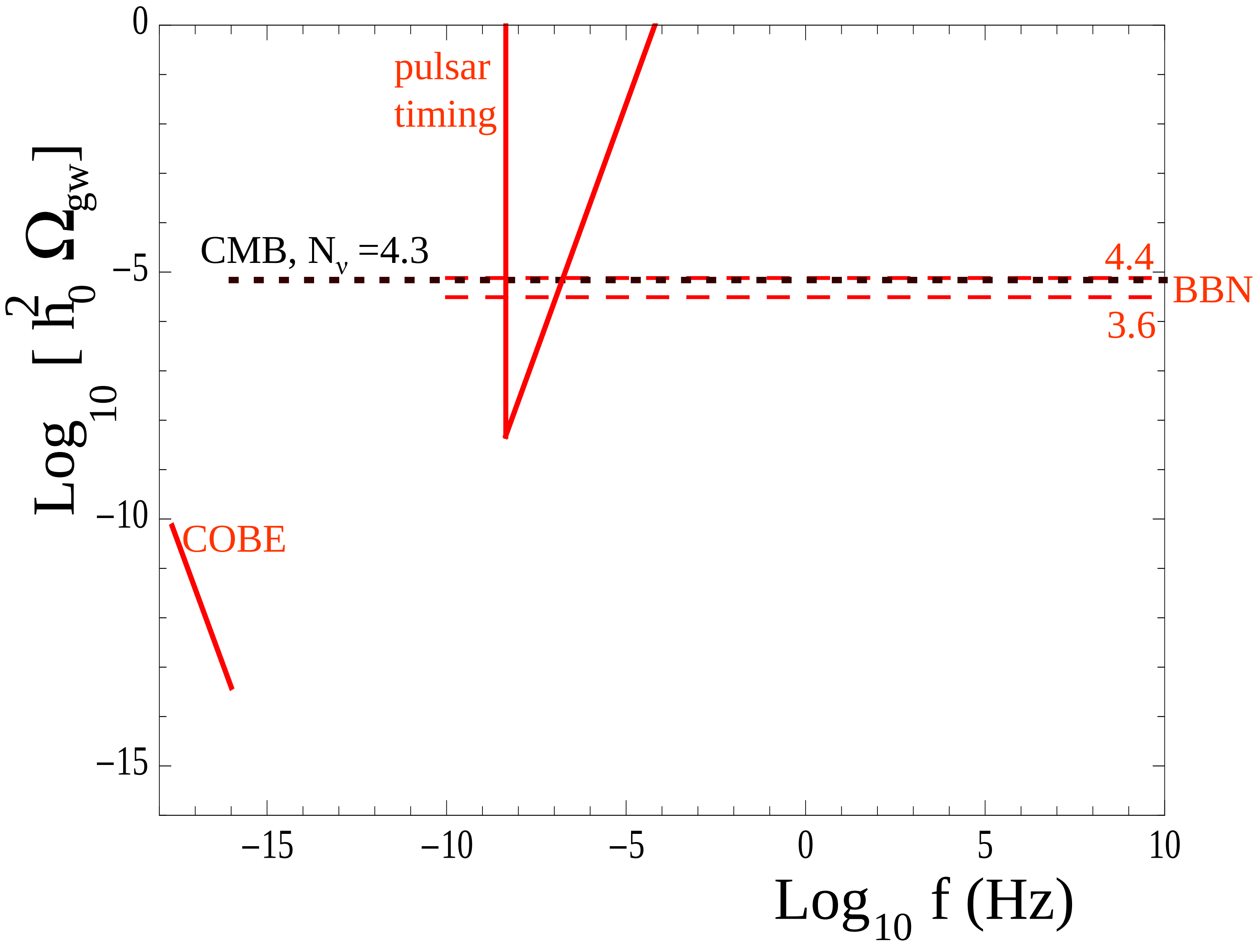
- CMB large-angle bound

relevant at $3 \cdot 10^{-18}$ Hz $< f <$ 10^{-16} Hz

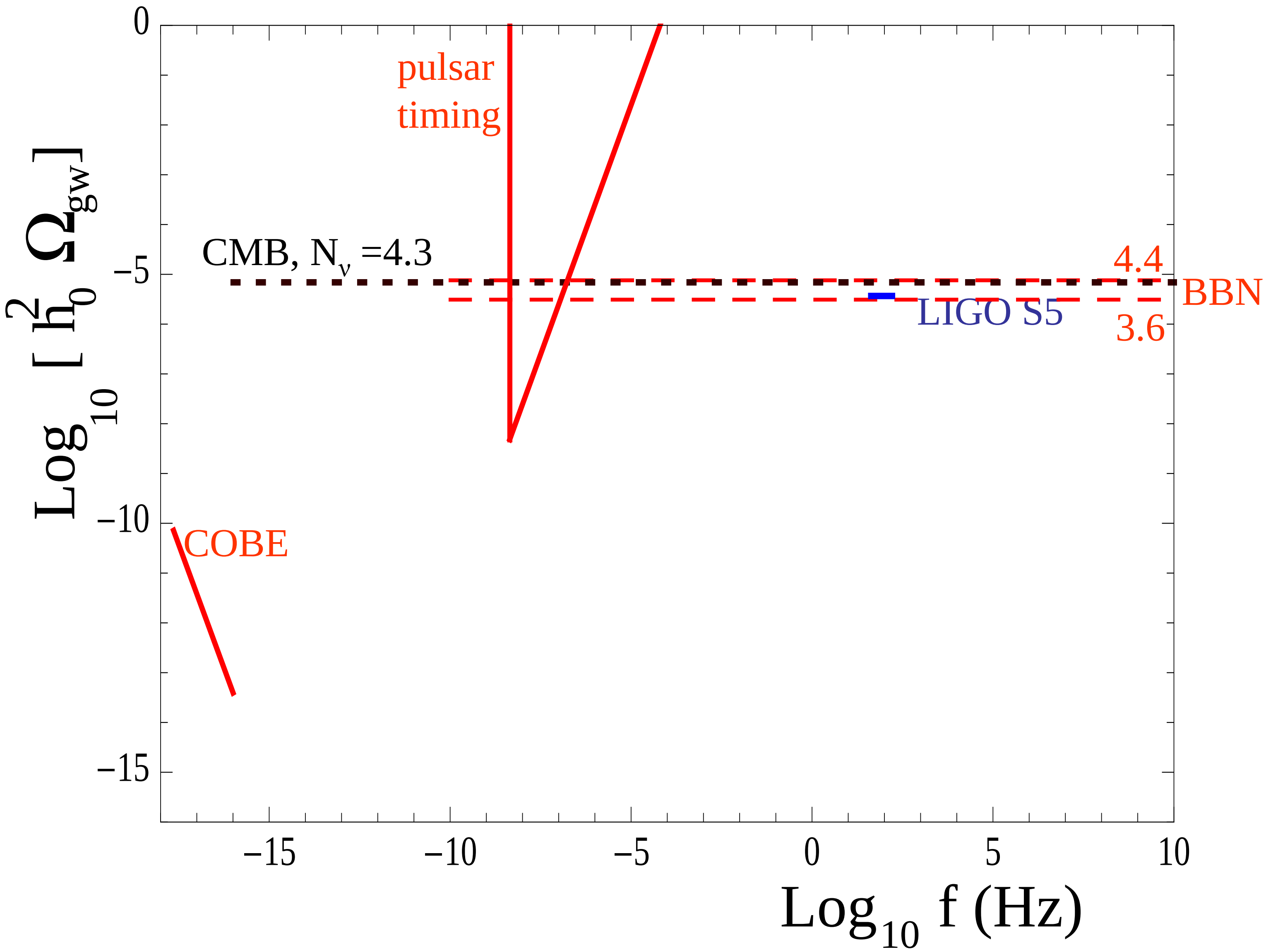
Inside the horizon today — Outside the horizon at last scattering

- once GWs enter the horizon, their amplitude decays
- inside the horizon microphysics dominate (acoustic peaks)

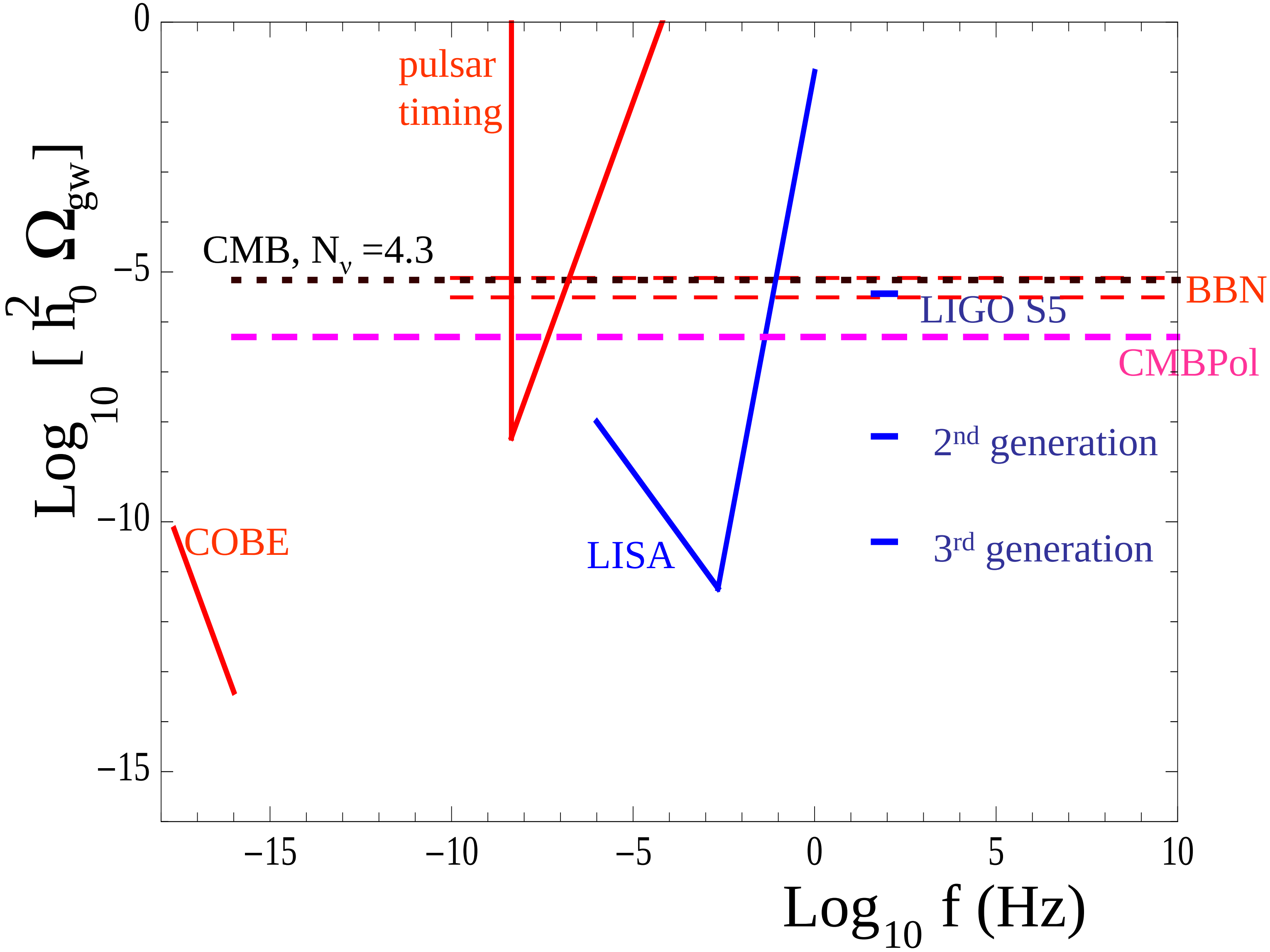
→ GWs affect only the low multipoles of CMB.



pulsar timing
CMB, N_ν =4.3
4.4
BBN
3.6
COBE
0
−5
−10
−15
−15
−10
−5
0
5
10
$\mathrm{Log}_{10}\,[\,h_0^2\,\Omega_{gw}]$
$\mathrm{Log}_{10}\,f$ (Hz)



0
−5
−10
−15
pulsar
timing
CMB, N_ν =4.3
4.4
BBN
3.6
LIGO S5
COBE
−15
−10
−5
0
5
10
Log_{10} f (Hz)
Log_{10} [h_0^2 Ω_{gw}]

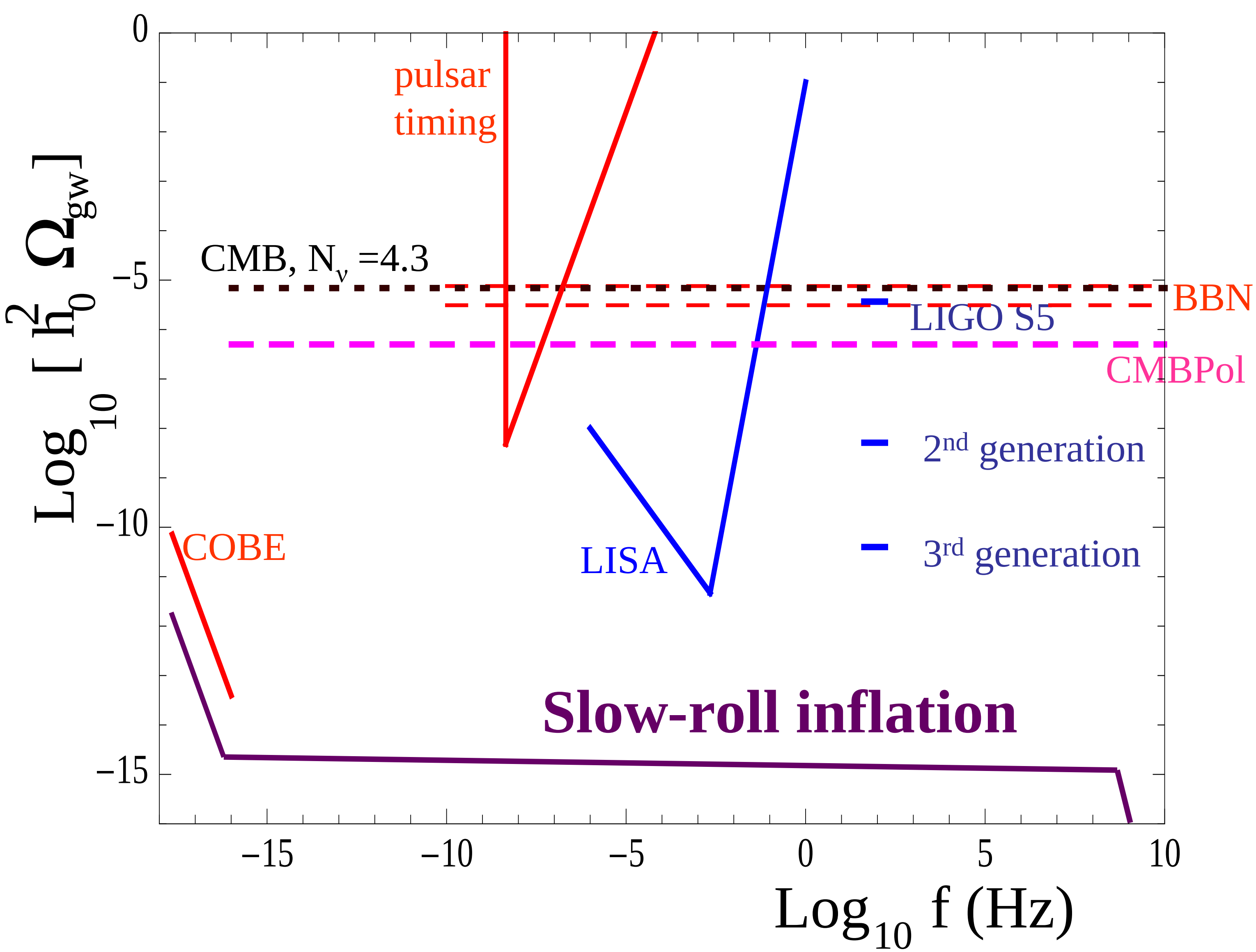


0
−5
−10
−15
Log10 [h0^2 Ωgw]
pulsar
timing
CMB, Nν =4.3
BBN
LIGO S5
CMBPol
2nd generation
3rd generation
COBE
LISA
−15
−10
−5
0
5
10
Log10 f (Hz)

Cosmological production mechanism

- amplification of vacuum fluctuations
  - inflation
  - pre-big-bang
- phase transition
  - bubble collisions, turbulence, magnetic fields
- preheating
- cosmic/fundamental strings
  - string network,
  - cusps
- supermassive BH-BH (see talk by A. Sesana)

Grishchuk 1975, Starobinski 1979,.....

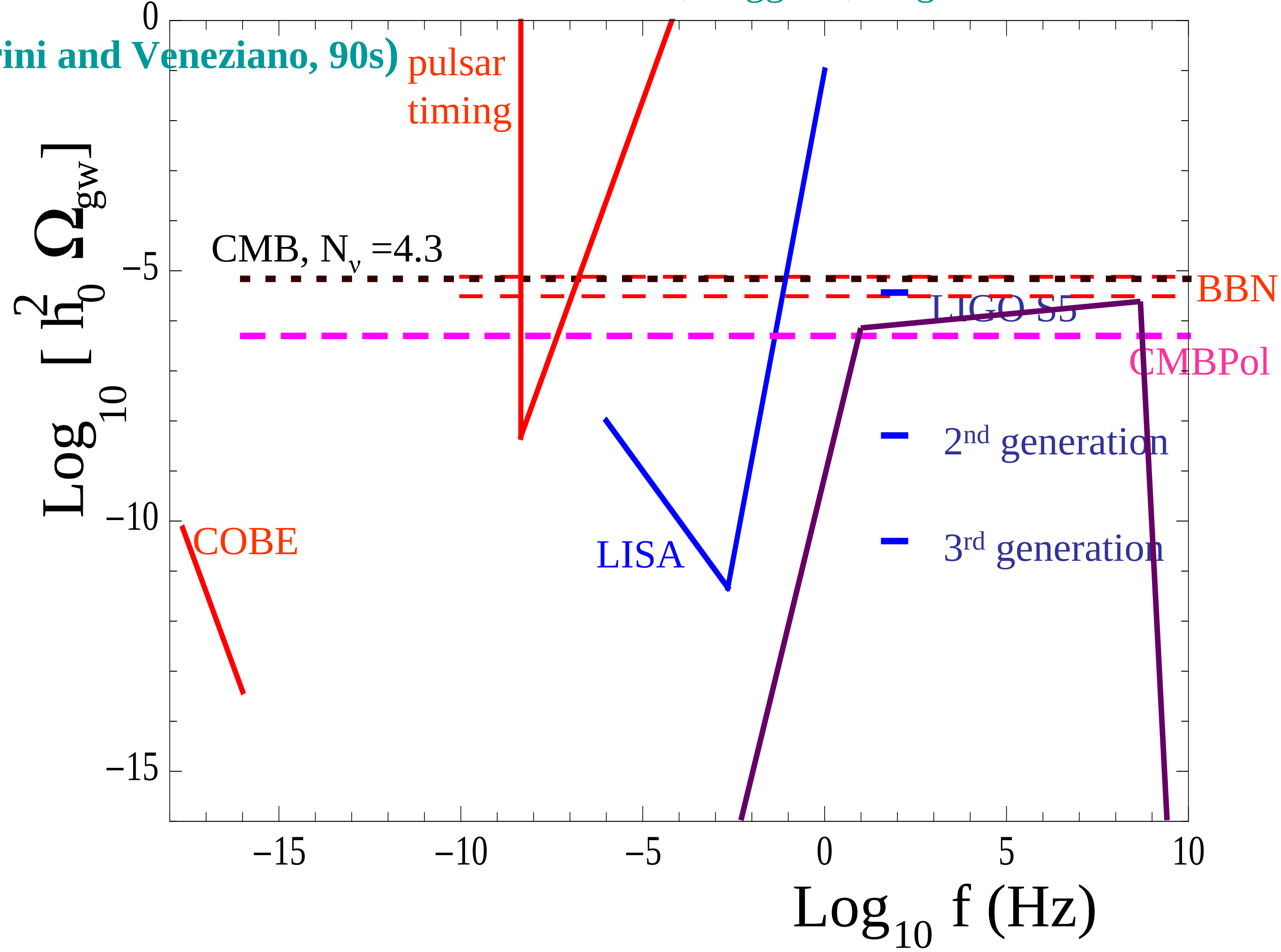


Pre-big-bang

Brustein, Gasperini, Giovannini and Veneziano 1996;

Buonanno,Maggiore, Ungarelli 1997

(Gasperini and Veneziano, 90s)



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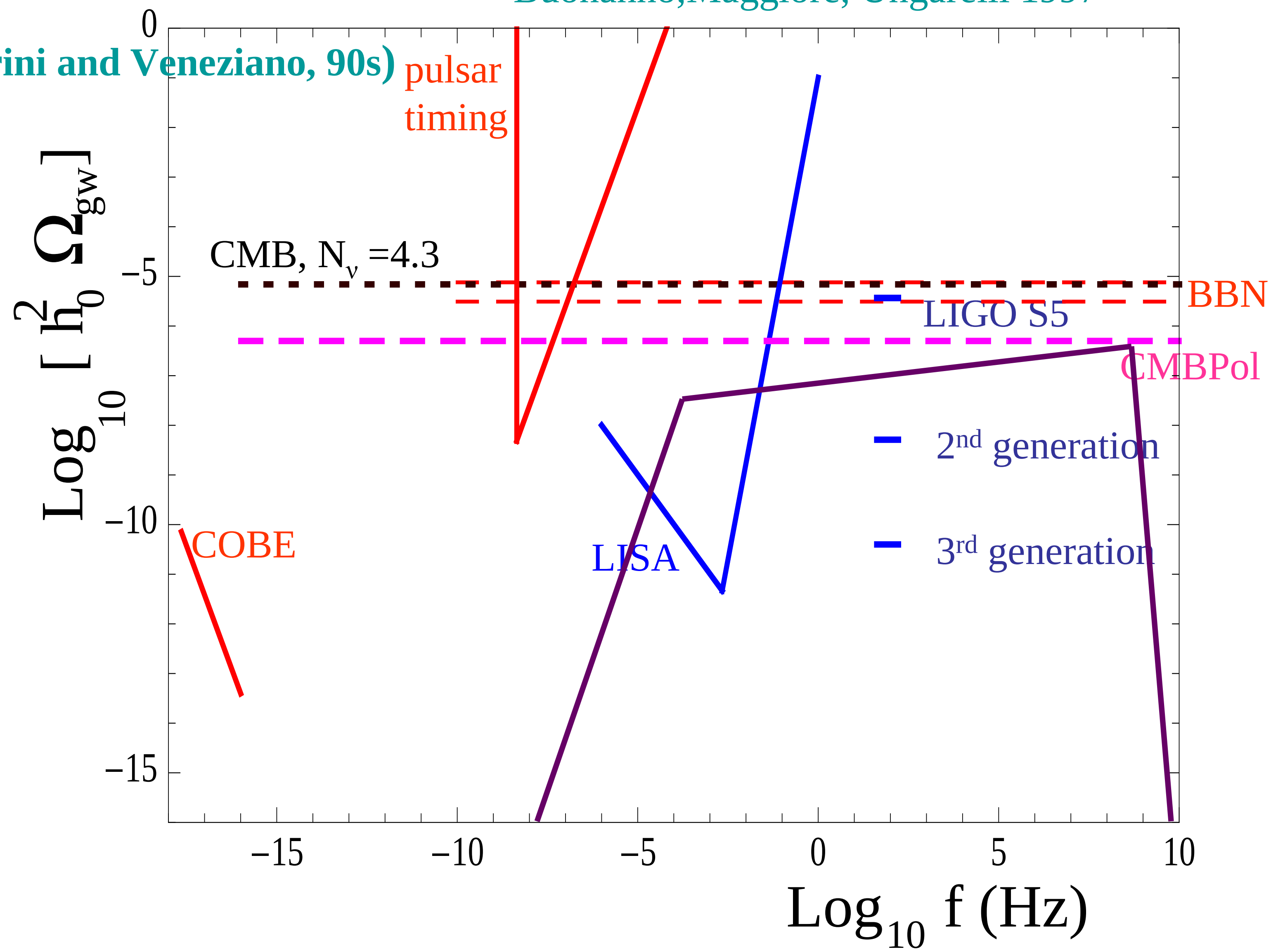

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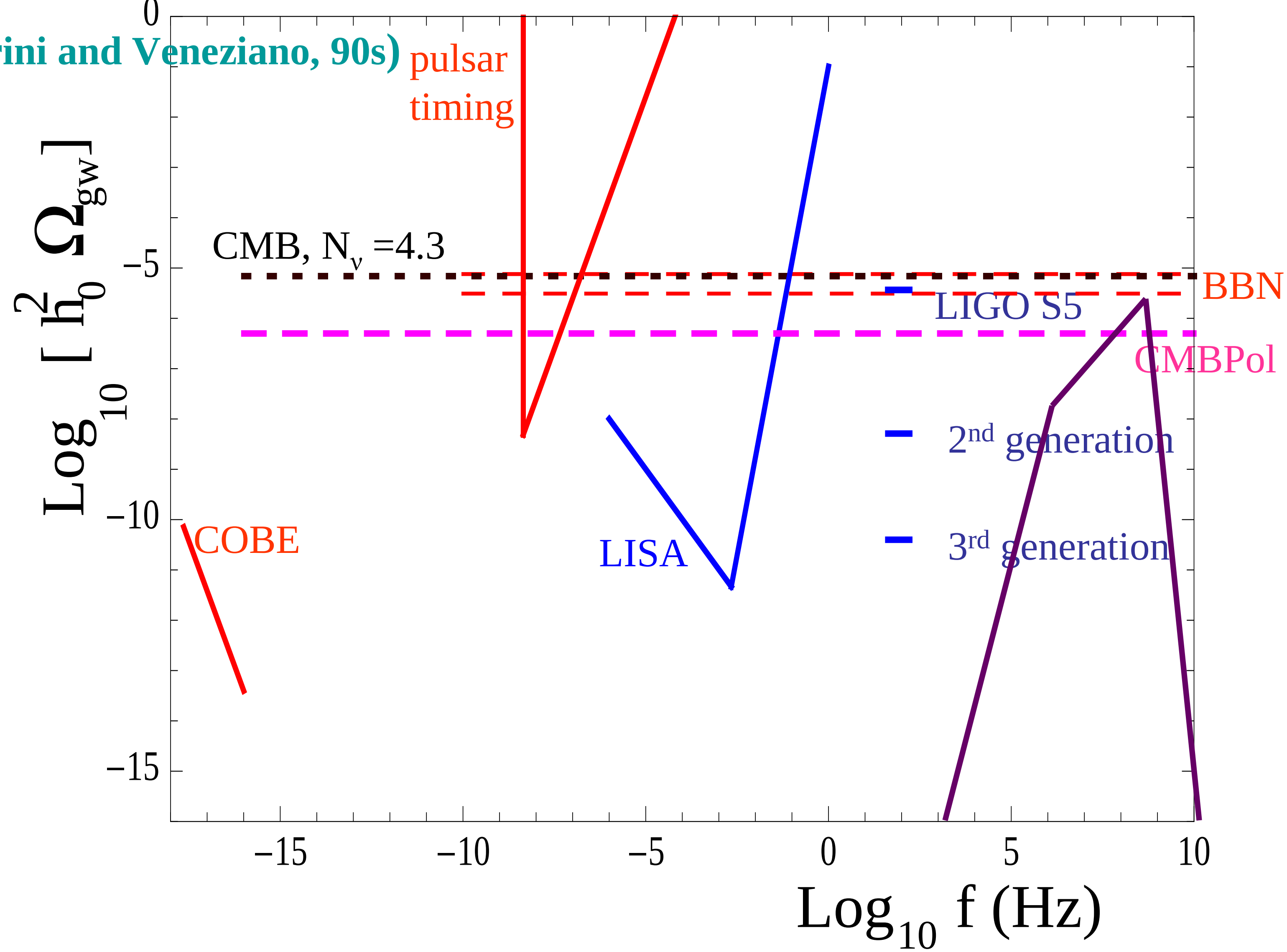
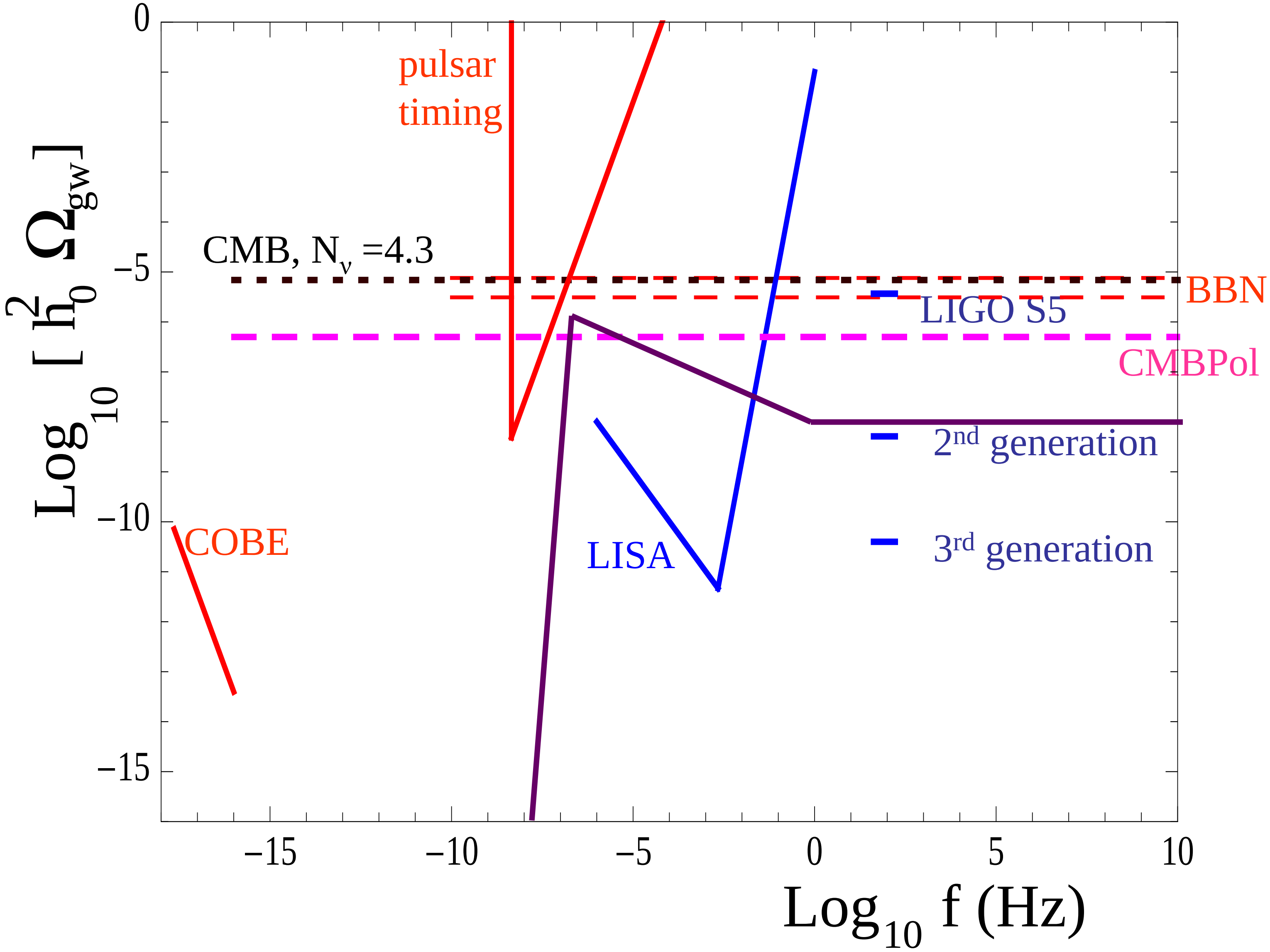


Cosmic strings (Vilenkin, 1981; Vilenkin and Shellard 1994)



Bubble collision in phase transitions

Kosowsky, Turner, Watkins, 1992
Kamionkowski, Kosowsky, Turner, 1993

- EW phase transition → LISA window !

however: need strongly first order.

  - in the SM is only a smooth crossover
  - supersym extension with non-minimal Higgs sector can have strongly first order in some corners of parameter space → $\Omega_{gw} \approx 10^{-10}$- 10^{-11}
  - the same condition provide EW baryogenesis!

(Apreda, Maggiore, Nicolis, Riotto 2002)

- turbulence at the EW phase transition also leads to GW production

Apreda,Maggiore, Nicolis, Riotto 2002,
Kosowsky, Mack, Kahniashvili 2002,
Dolgov, Grasso, Nicolis 2002,
Nicolis 2004

- recent developments:

  two sources of GWs

  – turbulent kinetic energy
  – turbulent magnetic fields

Caprini and Durrer 2005,
Megevand 2008,
Caprini, Durrer and Fenu 0905.0643
Caprini, Durrer and Servant, 0909.0622

turbulence lasts for many Hubble times after the phase transition is completed

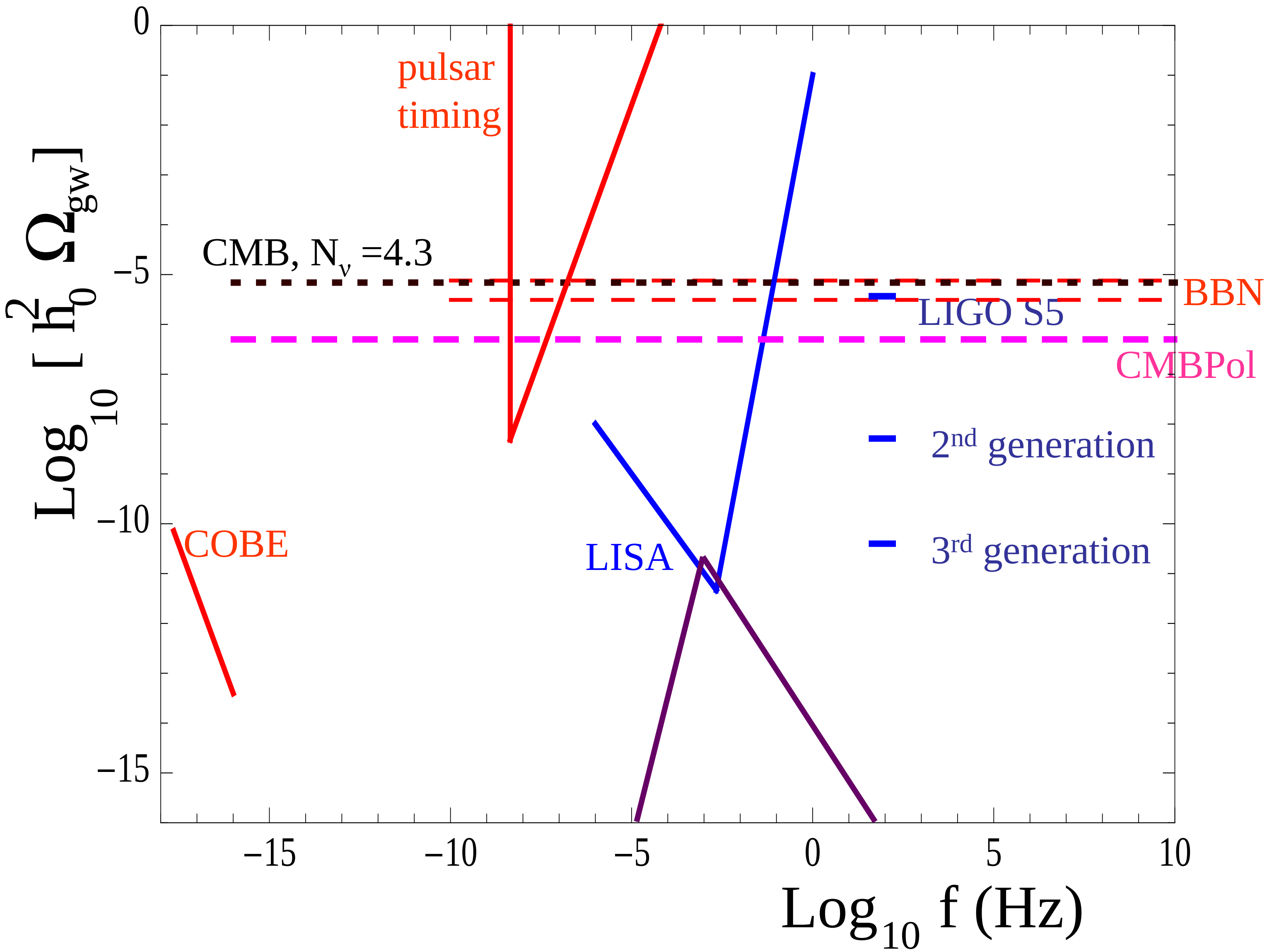
more accurate treatment of turbulent velocity field and turbulent magnetic field

- at $f=f_{peak}$ $h_0^2\,\Omega_{gw} \approx 10^{-11}$ (MHD turbulence somewhat higher than bubble collision)

- at $f<f_{peak}$ $\Omega_{gw} \sim f^3$
- at $f > f_{peak}$ $\Omega_{gw} \sim f^{-5/3}$ (turbulence)

  $\Omega_{gw} \sim f^{-3/2}$ (magnetic fields)

Caprini, Durrer and Servant, 0909.0622



pulsar
timing
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Log_{10} [h_0^2 Ω_{gw}]
Log_{10} f (Hz)

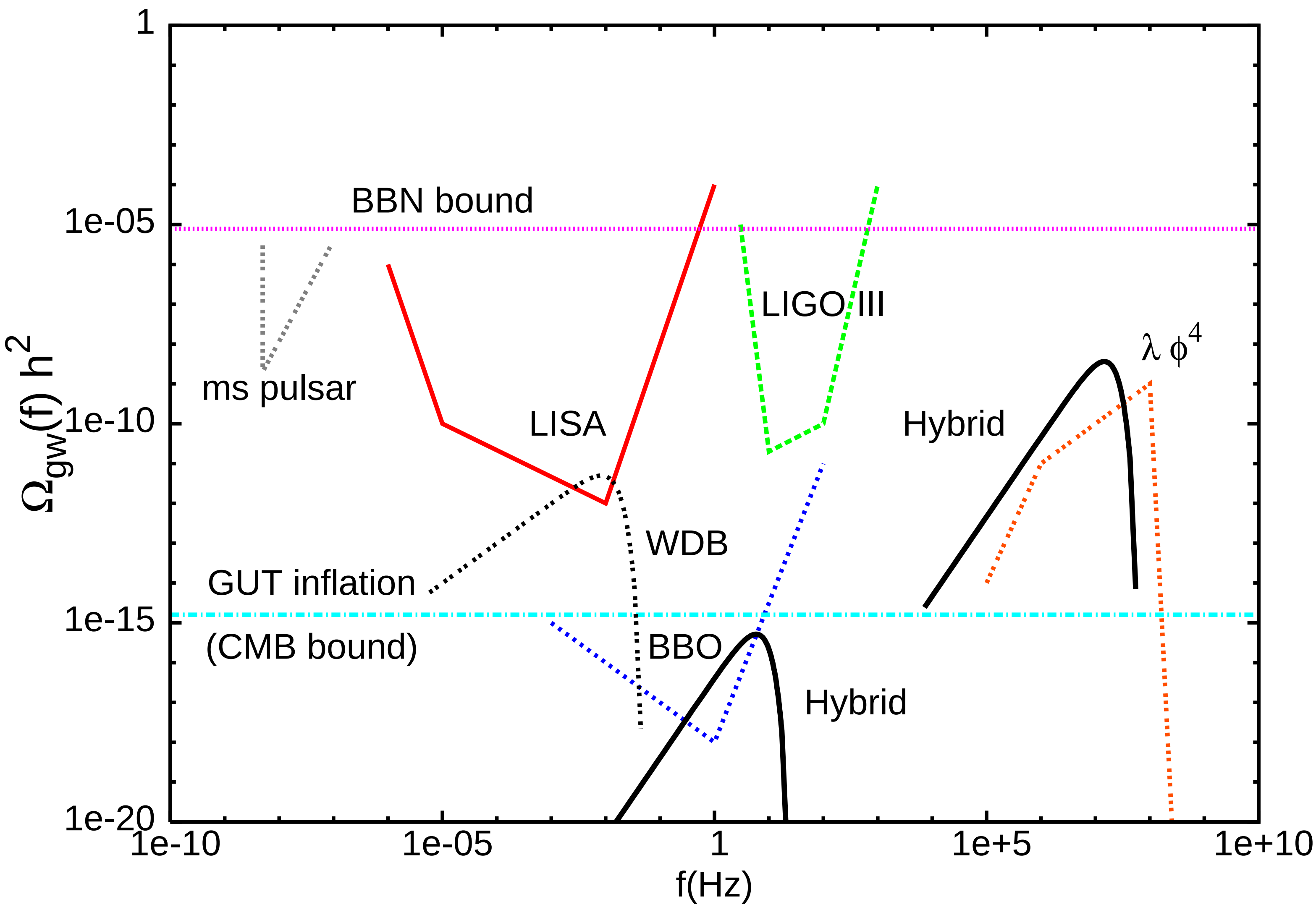
Reheating

- Is the process by which the energy density that drives inflation is converted into radiation and matter
- the first stage, preheating, is know to be explosive:
  - chaotic inflation: the inflaton oscillations generate waves of matter which collide, generating GWs. However, typically $f \sim 10^7 - 10^9$ Hz, too high

    Khlebnikov and Tkachev 1997,
    Easther and Lim 2006

  - hybrid inflation: symmetry-breaking instability triggers the end of inflation (tachyonic preheating)

Garcia-Bellido and Figueroa, PRL 2007



Various other mechanisms recently proposed

- 1^{st}-order density perturbations generate GWs at 2^{nd} order

  Mollerach, Harari and Matarrese 2004; Ananda, Clarkson and Wands 2007; Baumann, Steinhardt, Takahashi and Ichiki 2007; Assadullahi and Wands 2009

  potentially relevant for GW detection from CMB anisotropies
- large density fluctuations leading to primordial BHs also generate GWs

  → interesting bounds on the abundance of PBH with masses 10^{2}- 10^{4} $M_{\odot}$ from pulsar timing (Saito and Yokoyama, PRL 2009)

  – LISA, BBO, DECIGO could put bound on PBH with mass 10^{-13}- 10^{-7} $M_{\odot}$, which are potential DM candidates

- decay of condensates along supersymmetric flat directions:

scalar fields can develop large VEV along flat directions.

they start to oscillate when the Hubble rate $H \sim m_{susy\text{-}breaking}$

resonant effects lead to explosive decay of these coherent oscillations and GW production

Dufaux, PRL 2009

even possible $h_0^2 \, \Omega_{gw} \approx 10^{-8}$ at f= 100Hz-1kHz

- self-ordering of scalar fields at horizon entry

(potentially interesting for LISA)

Fenu, Figueroa, Durrer and Garcia-Bellido 2009

Conclusions

- GW interferometers start to put interesting experimental bounds on stochastic backgrounds
- Intense theoretical activity, suggesting many possible cosmological production mechanism
- Future sensitivities can probe deeply into an unknown and potentially interesting territory