Cosmological Sources of Stochastic Gravitational-Wave Background

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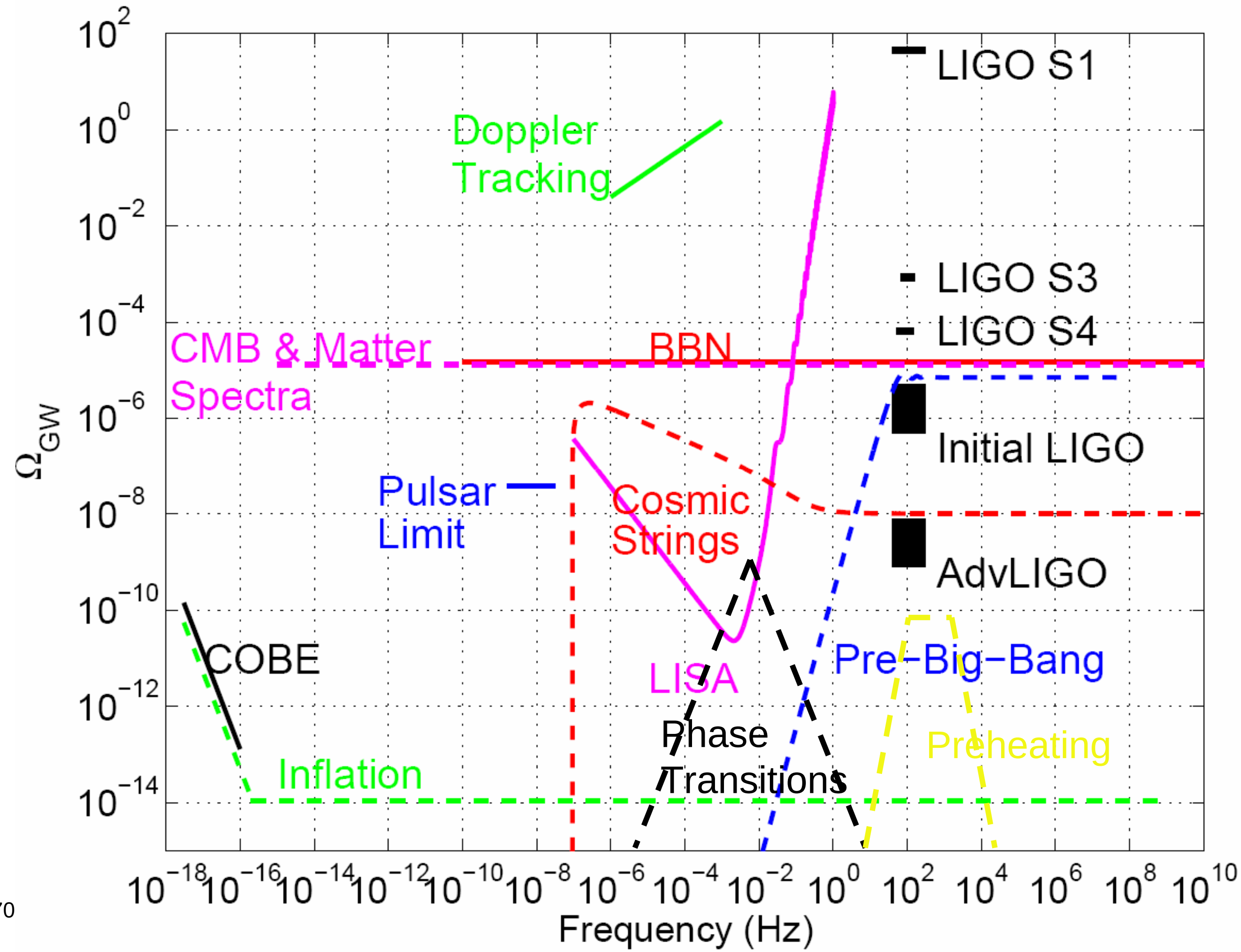
GWDAW-12, MIT, 12/14/07

LIGO-G070855-00-D

Landscape



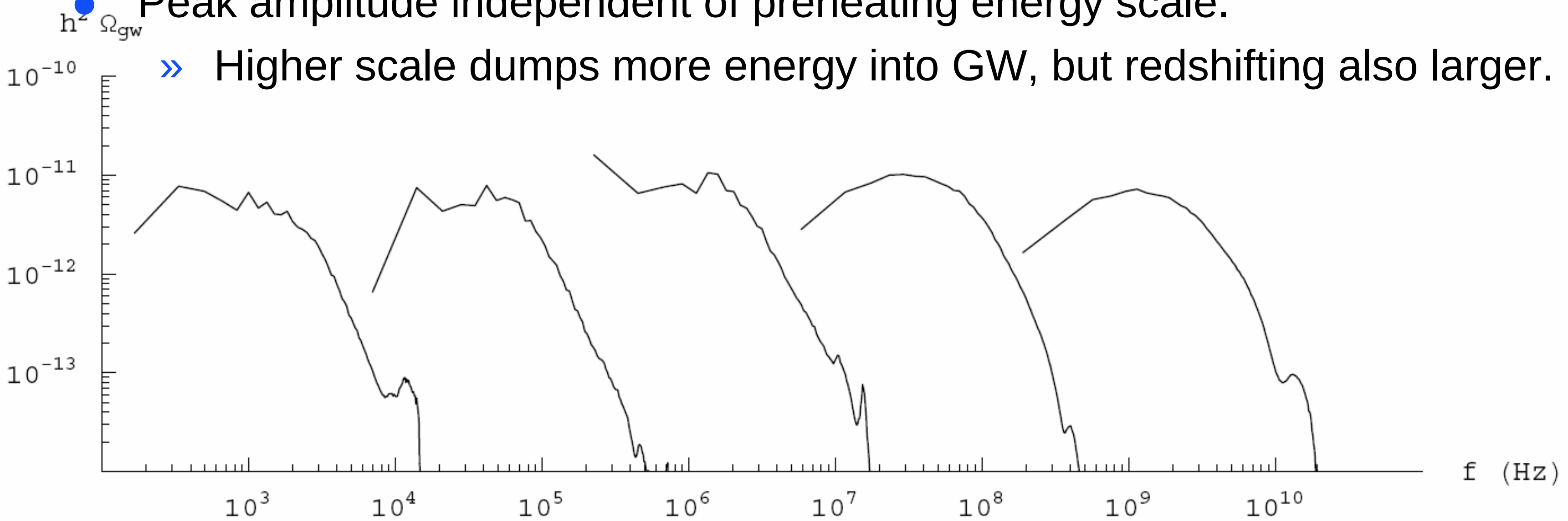
LIGO S1
Doppler Tracking
LIGO S3
LIGO S4
CMB & Matter Spectra
BBN
Initial LIGO
Pulsar Limit
Cosmic Strings
AdvLIGO
COBE
LISA
Pre−Big−Bang
Phase Transitions
Preheating
Inflation
Ω_{GW}
10^{2} 10^{0} 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14}
10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10}
Frequency (Hz)

Inflationary Models (1)

- Amplification of quantum vacuum fluctuations
  - » Modes larger than the horizon size are amplified as the Universe transitions from inflationary to radiation and matter phases.
- GW spectrum expected to be (nearly) flat.
  - » Tightest constraint comes from the CMB observations at large scales (small l): $\Omega_{GW} < 10^{-14}$.
- However, details of inflation epoch are not understood, and likely involve violent events.
  - » Such events could leave substantial GW signals, on top of the "vacuum fluctuation" background.
- Many inflationary models include a period of preheating:
  - » As the inflaton oscillates at the bottom of the potential well, it resonantly excites some momentum modes of other fields to which it is coupled: parametric resonance.
  - » There are at least two mechanisms for GW production during preheating.

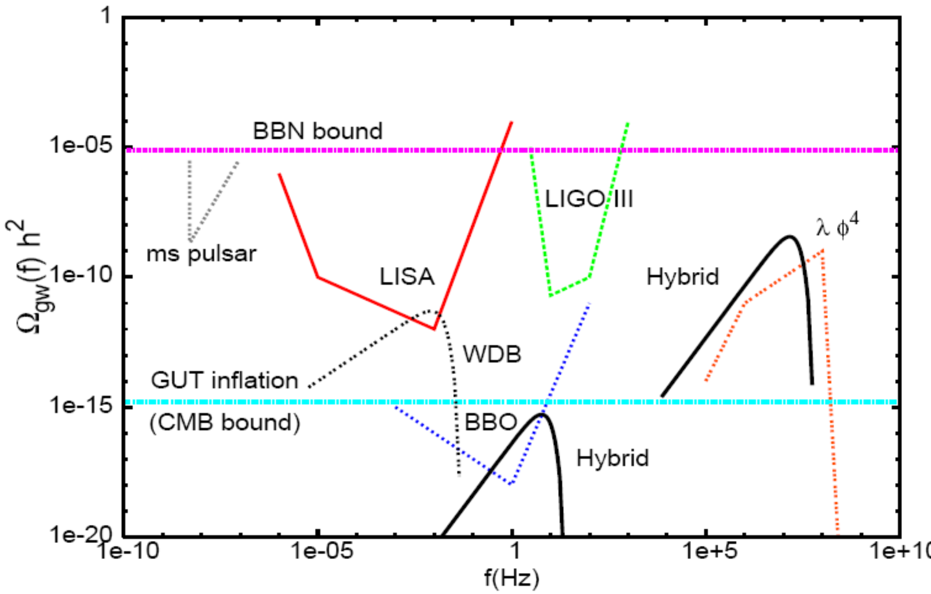
Inflationary Models (2)

- The excited modes render the Universe inhomogeneous, which sources GWs.
  - » Khlebnikov and Tkachev: PRD56, 653 (1997).
  - » Easther and Lim: JCAP 0604, 10 (2006); astro-ph/0612294.
- Highly nonlinear, simulations are required.
- Spectrum peaks at the frequency corresponding to preheating energy scale:
  - » ~TeV ⇒ LISA, 10^9 GeV ⇒ LIGO.
  - » Much lower than GUT scale, but are possible (hybrid inflation models etc).
- Peak amplitude independent of preheating energy scale.
  - » Higher scale dumps more energy into GW, but redshifting also larger.



Inflationary Models (3)

- Symmetry breaking at the end of inflation could lead to formation of bubble-like structures, corresponding to different vacua.
  - » Similar to 1st order phase transitions.
  - » Bubbles expand, travel, and collide, producing GWs
- Such situation can occur in hybrid inflationary models, which have symmetry breaking fields.
  - » Garcia and Figueroa, PRL98, 061302 (2007).
- Also involves preheating, so it is nonlinear and simulations are required.



- Both mechanisms could produce substantially larger GW background than the vacuum fluctuations model, potentially within reach of LIGO/LISA/BBO.

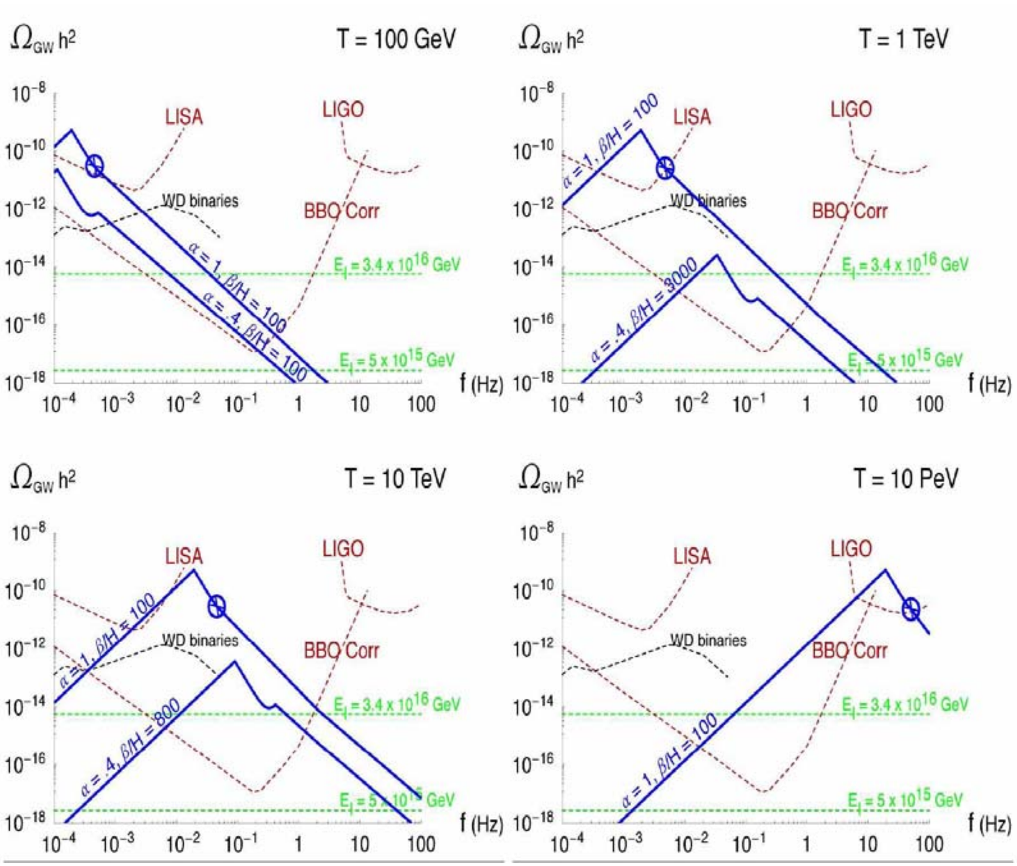
- Potentially new ways of probing inflationary physics.

Phase Transitions (1)

- 1st-Order Phase transitions could occur as the Universe cools.
  - » Symmetry-breaking process.
  - » Different parts of the Universe can take different vacua.
  - » Bubbles of different vacua are formed, they expand and collide.
- In the 1990's, GW spectrum due to bubble collisions was computed.
  - » Little interest: no 1st order transition due to EW symmetry breaking in the Standard Model.
  - » E.g. Kosowsky, Turner and Watkins, PRL69, 2026 (1992); PRD45, 4514 (1992).
- More recently: turbulence in the plasma can also produce GW background of similar scale.
  - » E.g. Kosowsky, Mack and Kahniashvili, PRD66, 024030 (2002).
- Also, 1st-order EW phase transition is possible in supersymmetric extensions of the Standard Model.
- Other possibilities:
  - » Turbulence in magnetic fields (dynamo effect) also produces GWs (Kosowsky, Mack and Kahniashvili, PRD66, 024030 (2002)).
  - » Helical turbulence can polarize GW background (Kahniashvili, Gogoberidze, and Ratra, PRL95, 151301 (2005)).
  - » Phase transitions possible in extra-dimensions models (Randall and Servant, JHEP 0705, 054 (2007)).

Phase Transitions (2)

- Recent extensive study: Grojean and Servant, hep-ph/0607107.
  - » Spectrum described by:
    - – α: fraction of the vacuum energy deposited into GWs.
    - – β^{-1}: duration of the transition.
  - » Amplitude, relative peak locations, slopes can be used to distinguish between models.
  - » Independent of the model (i.e. can be calculated for a given model).
  - » Includes both bubble collisions and turbulence mechanisms.
  - » Energy scale of the transition determines the peak of spectrum.
- There are models accessible to LIGO (10 PeV transitions).
- ~TeV scale phase transition would be observable with LISA.
  - » Complementary to LHC: constraining the Higgs sector.



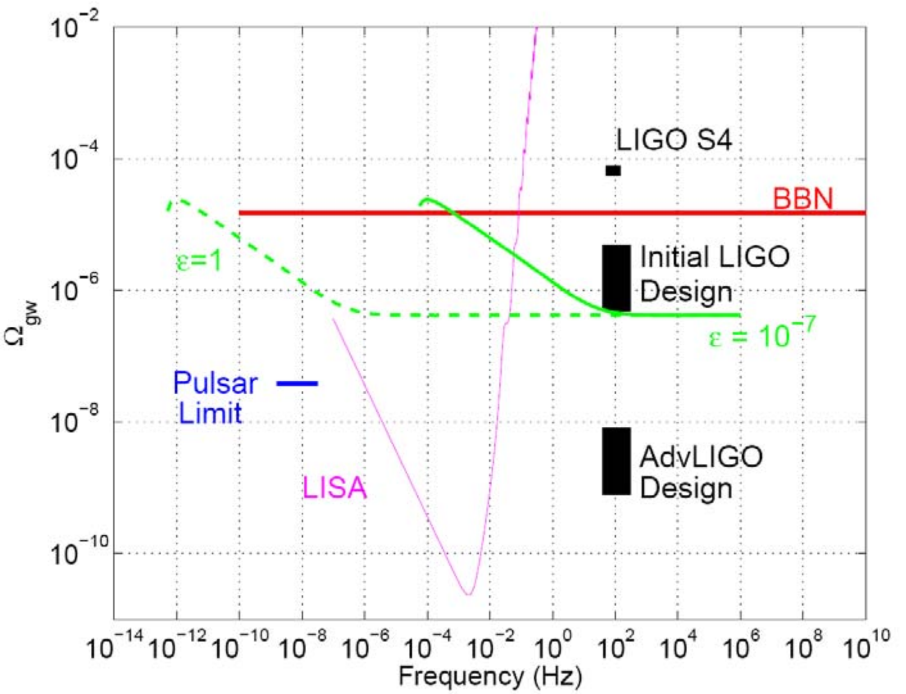
Cosmic Strings

- Topological defects formed during phase transitions in the early Universe.
- Recently realized that fundamental or Dirichlet strings could also have cosmological scale.
  - » Potential window into string theory!
  - » E.g.: N. Jones et al., JHEP 0207, 051 (2002); E.J. Copeland et al., JHEP 0406, 013 (2004); Dubath, Polchinski, Rocha, arXiv:0711.0994.
- Cosmic string cusps, with large Lorentz boosts, can create large GW signals.
- Look for the stochastic background created by superposing cusp signals throughout the Universe.
- Calculation done by Siemens, Mandic & Creighton, PRL98, 111101 (2007).
  - » Update on Damour & Vilenkin, PRD71, 063510 (2005).

Small-loop Case

$p = 5\times10^{-3}$

$G\mu = 10^{-7}$



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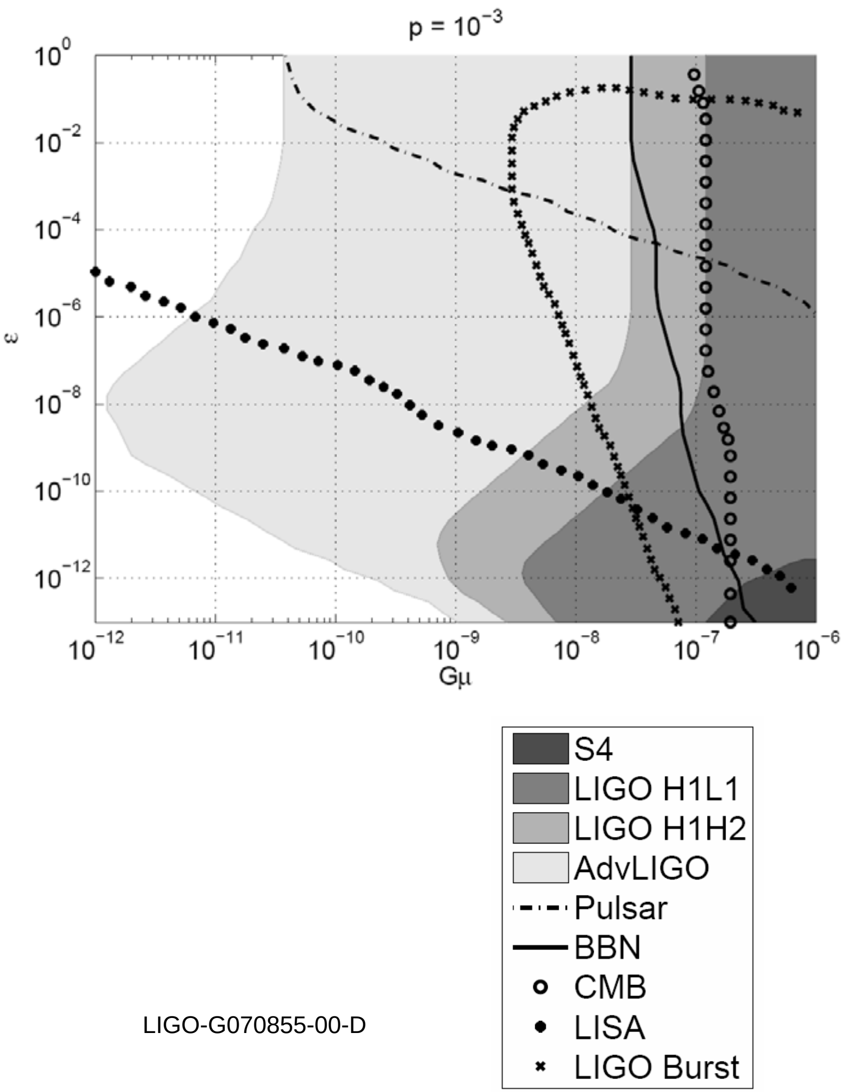

- If loop-size at formation is determined by gravitational back-reaction, the loops are small and of the same size.
- Parameters:
  - » Loop-size parametrized by: $10^{-13} < \varepsilon < 1$
  - » String tension: $10^{-12} < G\mu < 10^{-6}$
    - – Upper bound from CMB observations.
  - » Reconnection probability: $10^{-3} < p < 1$
    - – Determines the density of strings.
- Spectrum has a low-frequency cutoff.
  - » Determined by the string length and the angle at which we observe the cusp.
- Small ε or $G\mu$ push the cutoff to higher frequencies.
- Spectrum amplitude increases with $G\mu$ and with $1/p$.

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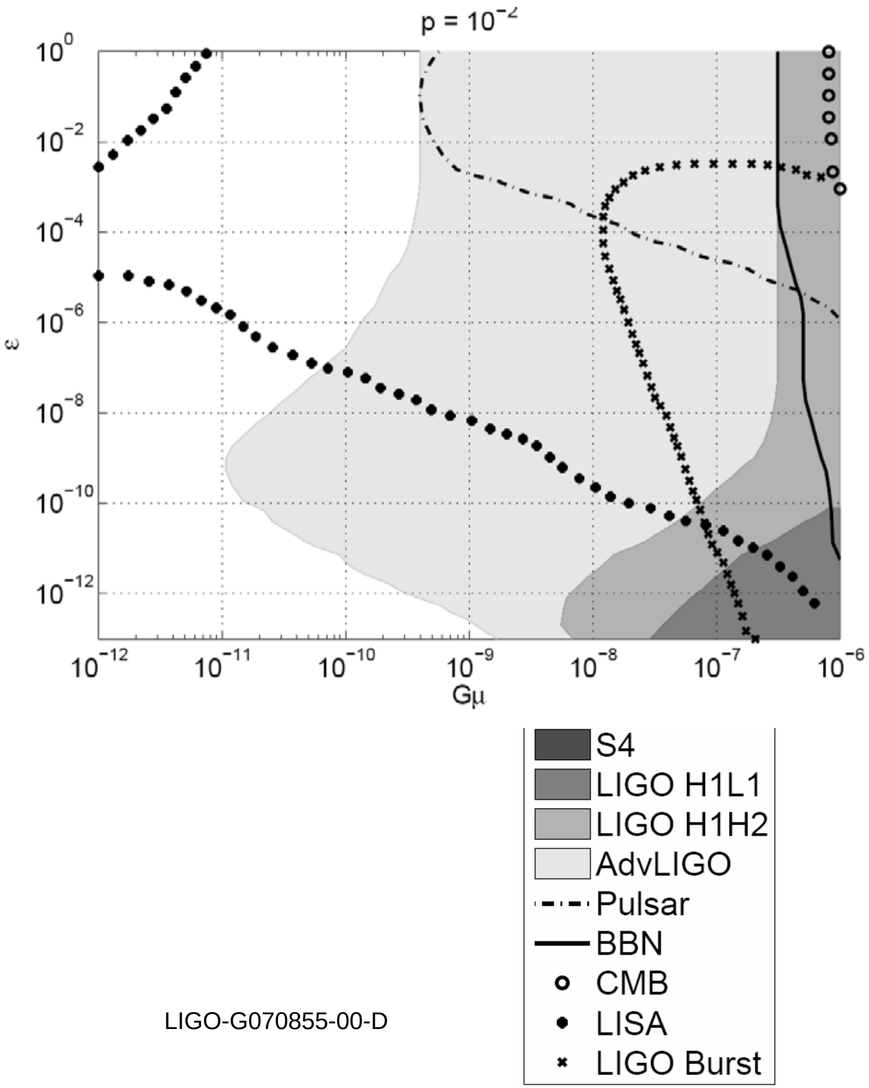

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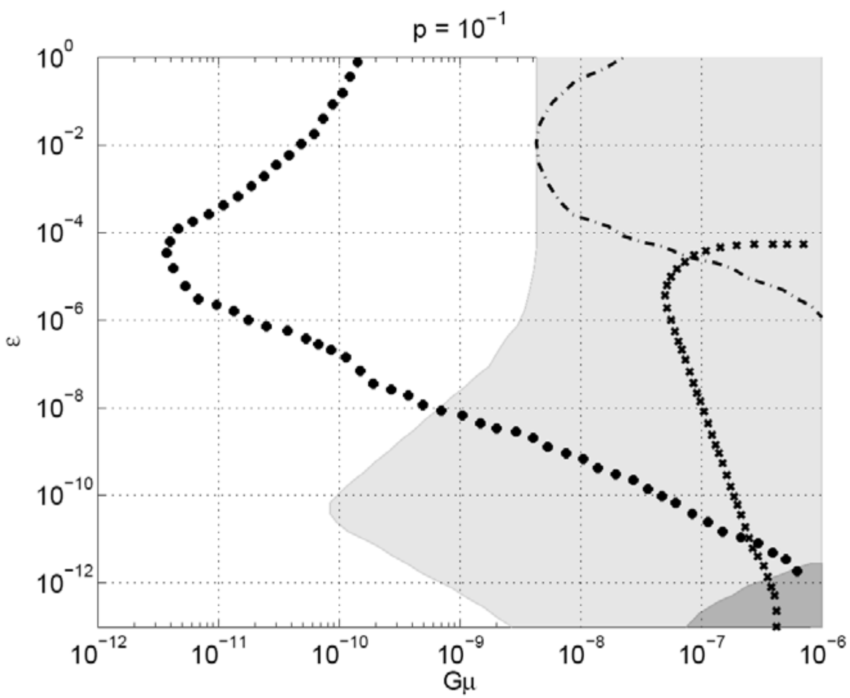

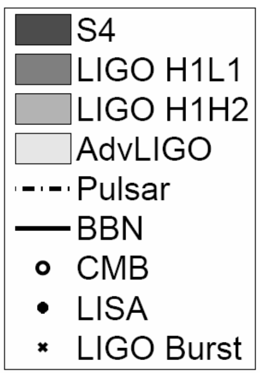

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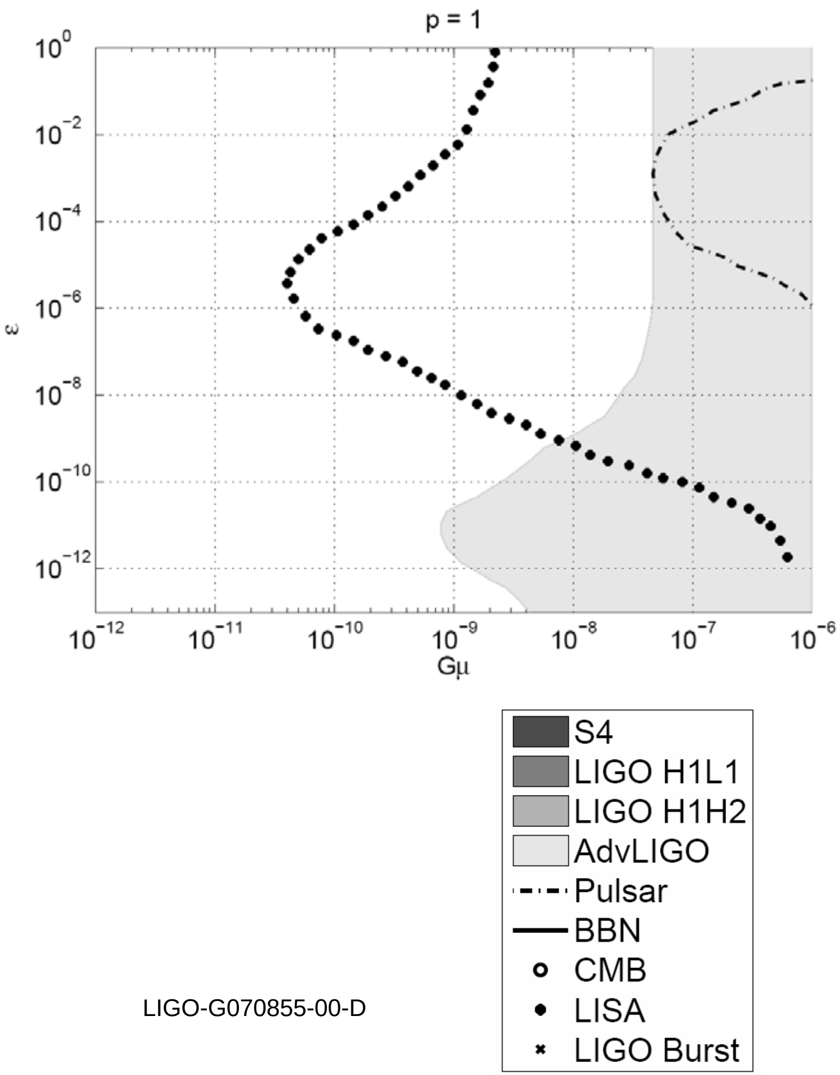

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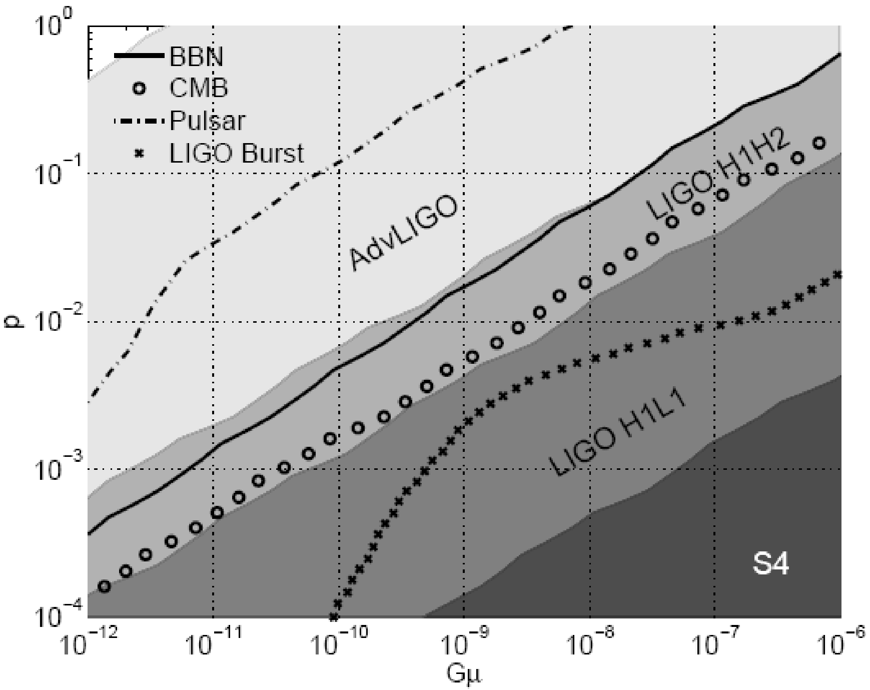
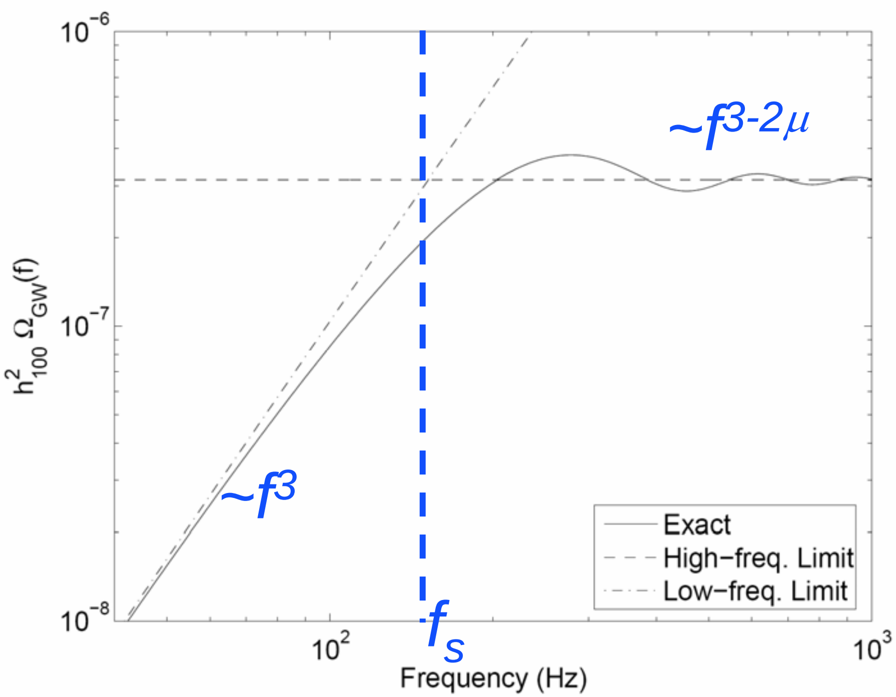
Large Loop Case



- Recent simulations indicate that loops could be large at formation, and therefore long-lived.
- Loop distribution more complex.
  - » Larger amplitudes of gravitational-wave spectra.
- Free parameters:
  - » String tension: $10^{-12} < G\mu < 10^{-6}$
  - » Reconnection probability: $10^{-4} < p < 1$
- Assuming that loop-size is 10% of the horizon at the formation time.
  - » Some simulations indicate that a more complicated distribution would be more accurate, involving both small and large loops.

Pre-Big-Bang Models (1)



Mandic & Buonanno, PRD73, 063008, (2006).

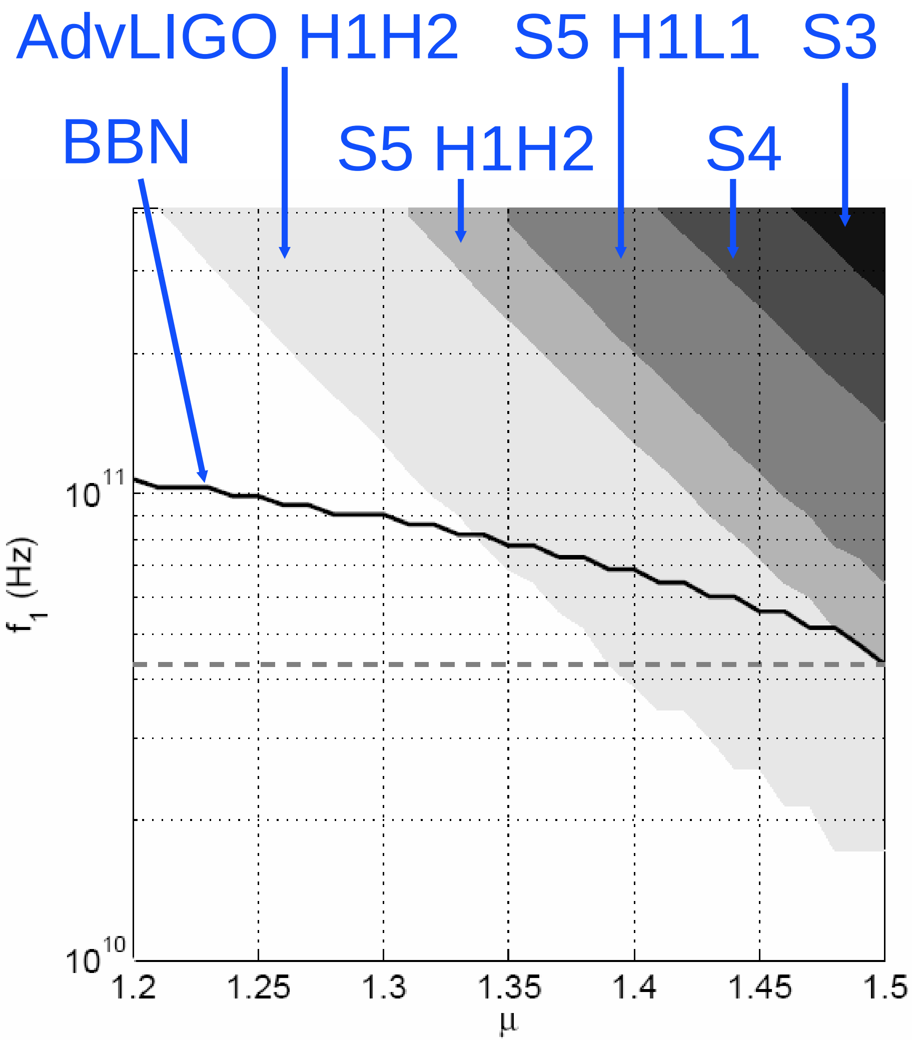
$$f_1 \simeq 4.3 \times 10^{10}\ \mathrm{Hz} \left(\frac{H_s}{0.15 M_{Pl}}\right)\left(\frac{t_1}{\lambda_s}\right)^{1/2}$$

- Mechanism similar to inflation:
  - Amplification of vacuum fluctuations
  - Super-horizon modes are amplified during transitions between phases.
- Universe goes through several phases:
  - Dilaton-dominated phase
  - Stringy phase
  - Radiation, followed by matter phase.
- 2 free parameters:
  - $1 < \mu < 1.5$
  - f_s – essentially unconstrained
- But: High-frequency amplitude goes as f_1^4.
  - f_1 depends on string related parameters, which are not well known.
  - We vary it by factor of 10 around the most “natural” value.

Pre-Big-Bang Models (2)

- Scan f_1 - μ plane for f_s=30 Hz.
- For each model, calculate $\Omega_{GW}(f)$ and check if it is within reach of current or future expected LIGO results.
- Beginning to probe the allowed parameter space.
- Currently sensitive only to large values of f_1.
- Sensitive only to spectra close to flat at high-frequency.
- But, not yet as sensitive as the BBN bound:

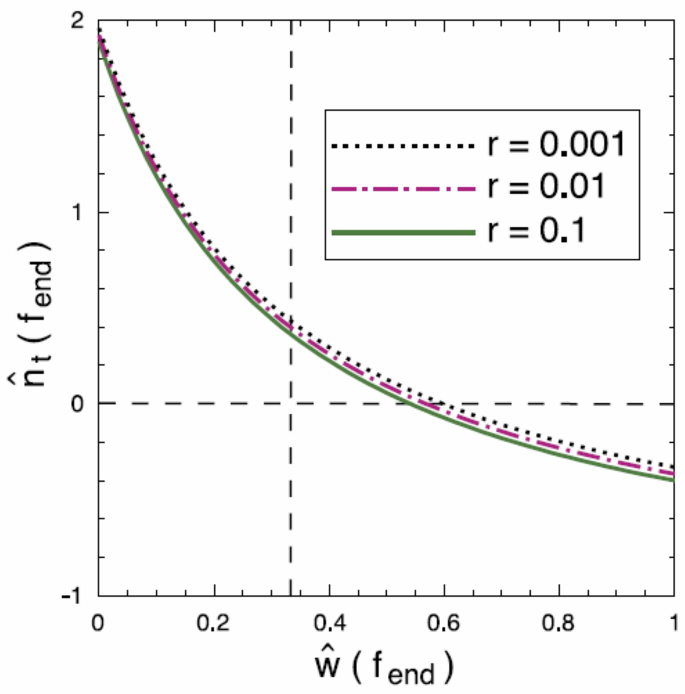
$$\int \Omega_{\rm GW}(f) h_{100}^2 d(\ln f) < 6.3 \times 10^{-6}$$



Spectral Shape

- Boyle and Buonanno, arXiv:0708.2279
  - Use the tensor-to-scalar ratio (to be measured by CMB B-mode) and the measurement of $\Omega_{GW}(f)$ by pulsar-timing and laser-interferometer experiments to constrain:
    - "effective" primordial tensor spectral index $n_t(f)$
    - "effective" equation of state parameter $w(f)$ (appearing in $\alpha(f)$)
  - Master Equation: $$\Omega_0^{gw}(f) = \left[A_1 A_2^{\hat{\alpha}(f)} A_3^{\hat{n}_t(f)}\right] r$$
- Model independent way to obtain new information about the early Universe!
- Can also examine the possibility of "stiff", w=+1/3, energy component in the early Universe (pre BBN).
  - May dominate the energy budget at sufficiently early times.

Combining CMB measurement of r and the BBN limit



Conclusions

- Variety of cosmological sources of GW background.
  - » Recently, much activity focused on inflationary, cosmic strings and phase transition models.
- Predicted backgrounds are often within reach of LIGO or LISA.
- Probing early Universe cosmology:
  - » Inflationary epoch, equation of state, alternative cosmologies.
- Probing high-energy physics:
  - » String theory, extra dimensions, Higgs sector (TeV scale phase transitions).
- Stay tuned – the coming decade should be very interesting!