Searching for Stochastic Gravitational Radiation with LIGO: Recent Results and Implications

Vuk Mandic

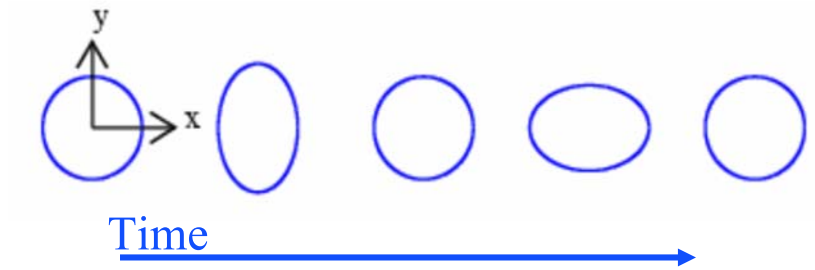
SUSY06

Irvine, 06/16/06

LIGO-G060288-00-D

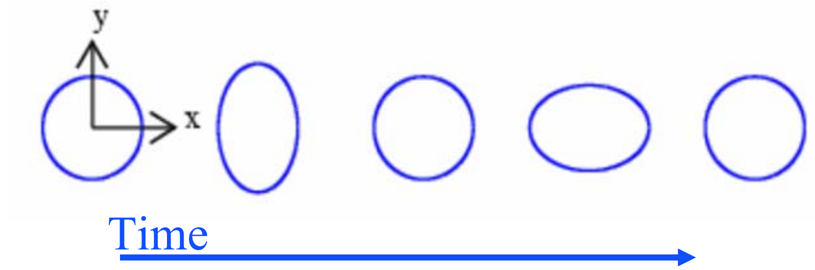
Detecting Gravitational Waves

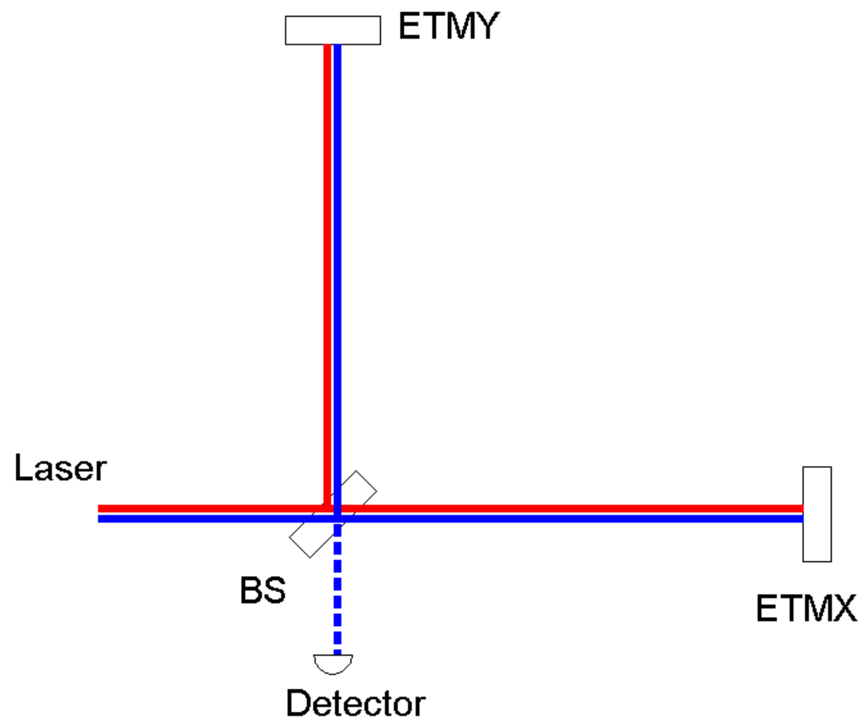
- Gravitational wave effectively stretches one arm while compressing the other.



Detecting Gravitational Waves

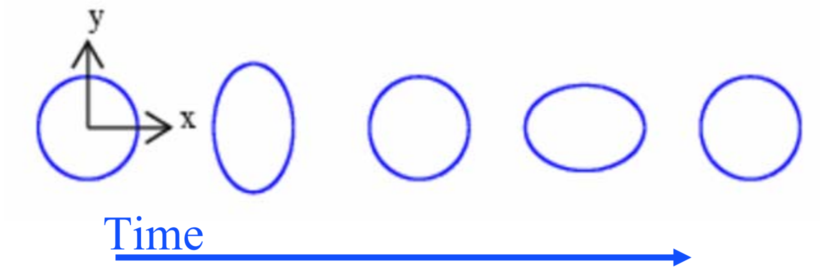
- Gravitational wave effectively stretches one arm while compressing the other.
- Interferometer measures the arm-length difference.
  - » All masses are free.
  - » Dark fringe at the detector.

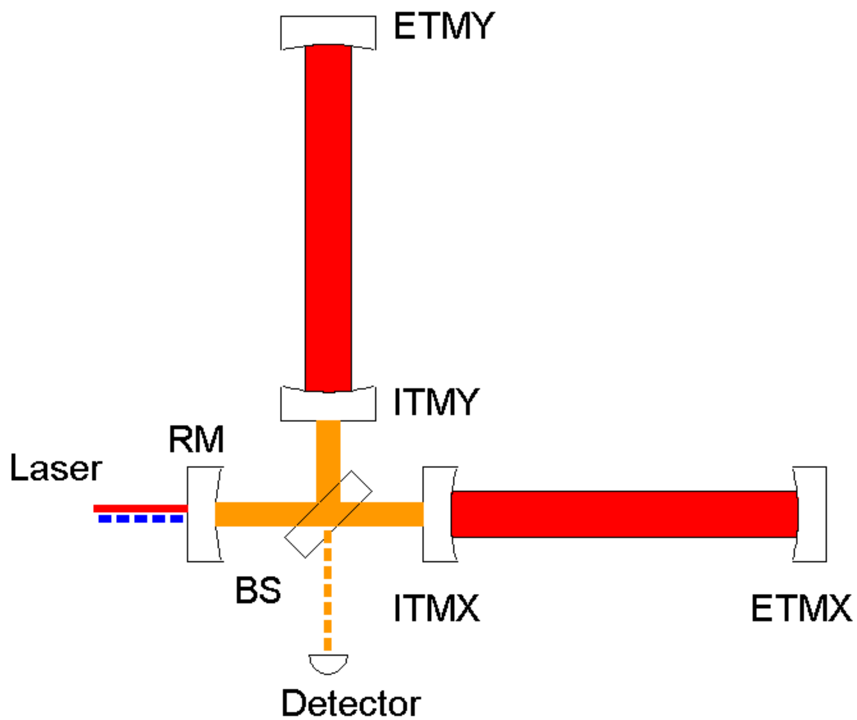




Detecting Gravitational Waves

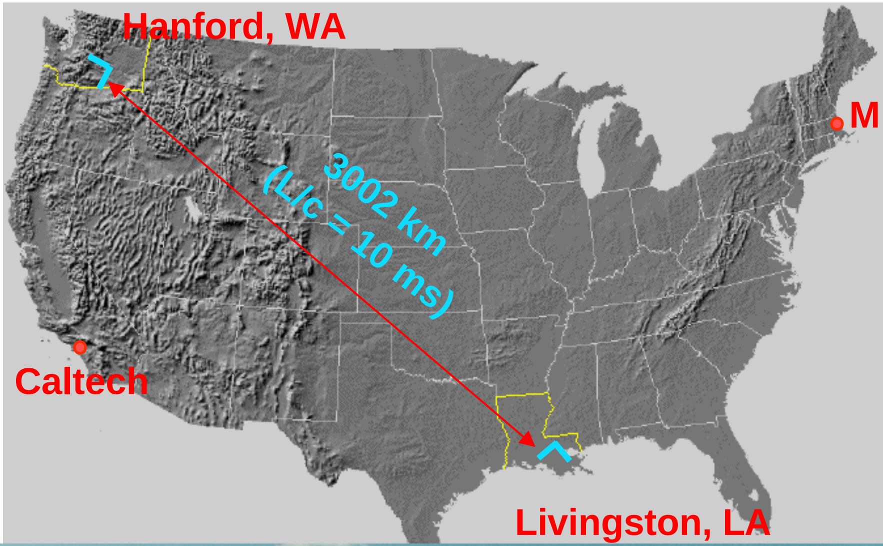
- Gravitational wave effectively stretches one arm while compressing the other.
- Interferometer measures the arm-length difference.
  - » All masses are free.
  - » Dark fringe at the detector.
- Fabry-Perot cavities in the arms
  - » Effectively increase arm length ~100 times.
- Power-recycling mirror
  - » Another factor of ~40 in power.

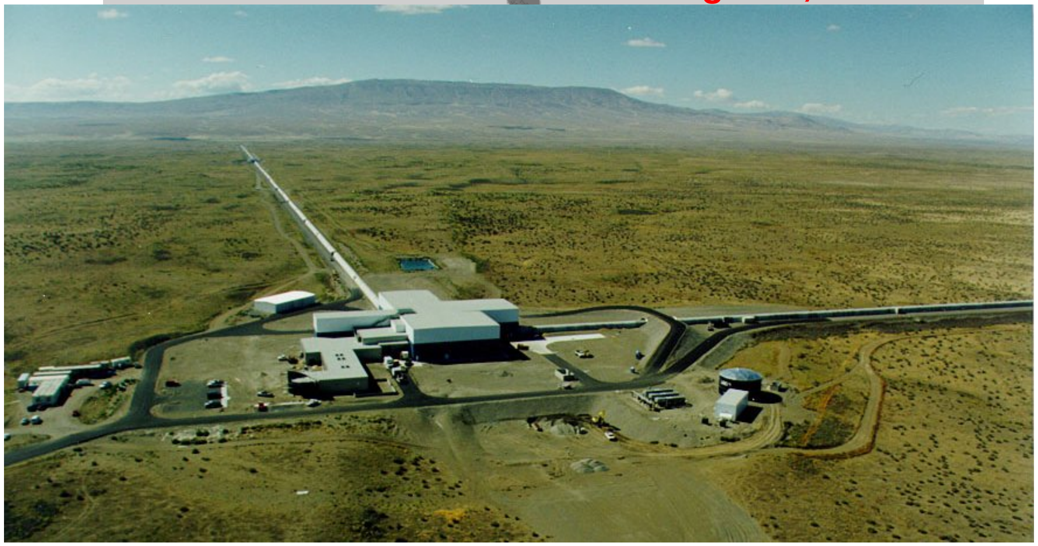




LIGO Observatories

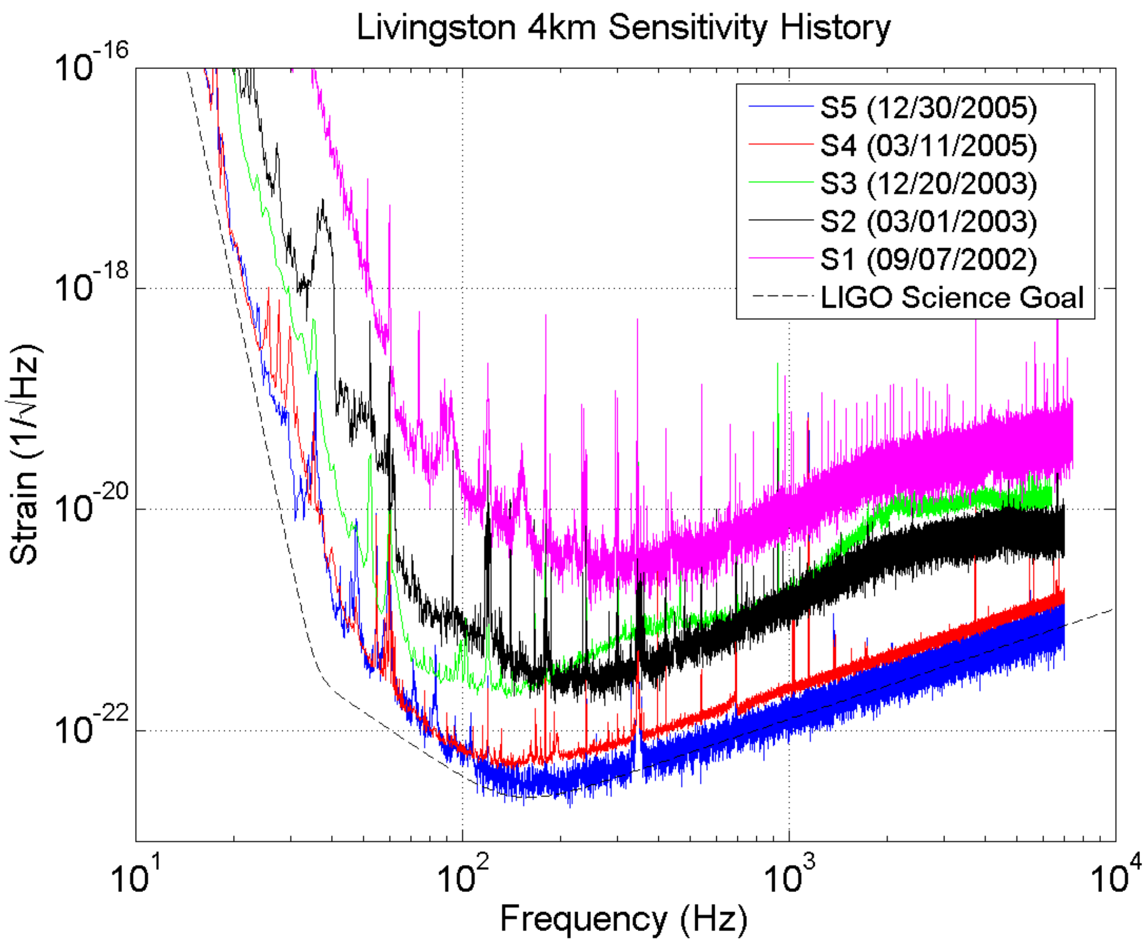
- 2 sites, 3 interferometers:
  - » H1: 4 km at Hanford, WA
  - » H2: 2 km at Hanford, WA
  - » L1: 4 km at Livingston, WA
- Locations 3000 km apart.
  - » Minimizes instrumental correlations.
- Reached design sensitivity
  - » 1-year long run has started: S5





Interferometer Sensitivity

- Sensitivity steadily improved over time.
- Reached design sensitivity.
- Started 1-year long run in November 2005.



Stochastic Background of Gravitational Waves

- Energy density:

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\, \dot{h}^{ab} >$$

- Characterized by log-frequency spectrum:

$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f}$$

- Related to the strain power spectrum:

$$S(f) = \frac{3H_0^2}{10\pi^2} \frac{\Omega_{GW}(f)}{f^3}$$

- Strain scale:

$$h(f) = 6.3 \times 10^{-22} \sqrt{\Omega_{GW}(f)} \left(\frac{100\ \mathrm{Hz}}{f}\right)^{3/2} \mathrm{Hz}^{-1/2}$$

Detection Strategy

- Cross-correlation estimator

$$Y = \int_{-T/2}^{+T/2} dt_1 \int_{-T/2}^{+T/2} dt_2 \; s_1(t_1) \; s_2(t_2) \; Q(t_2 - t_1)$$

$$Y = \int_{-\infty}^{+\infty} df \; \tilde{s}_1^*(f) \; \tilde{s}_2(f) \; \tilde{Q}(f)$$

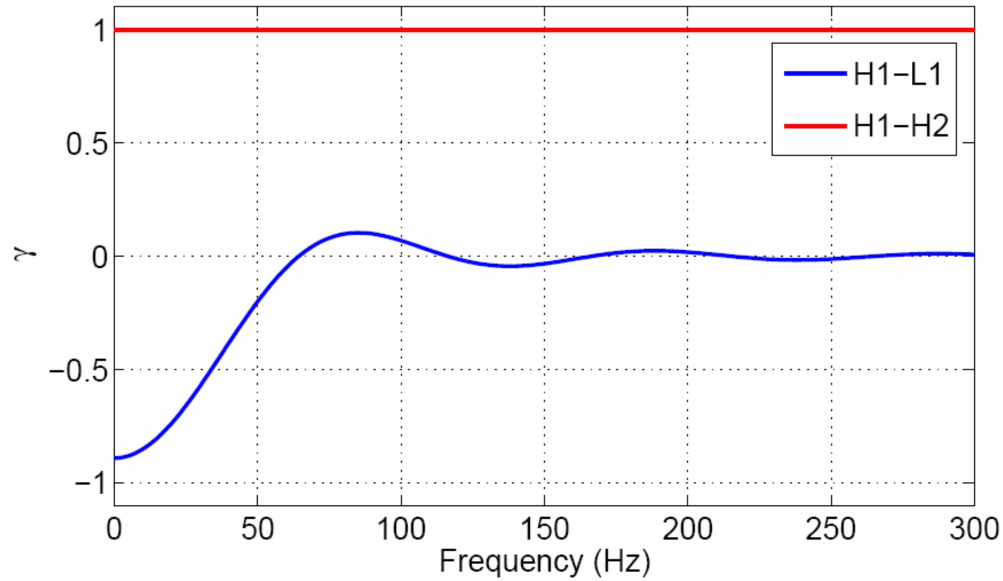
- Theoretical variance

$$\sigma_Y^2 \approx \frac{T}{2} \int_0^{+\infty} df \; P_1(f) \; P_2(f) \; | \; \tilde{Q}(f) \; |^2$$

- Optimal Filter

$$\tilde{Q}(f) = \frac{1}{N} \frac{\gamma(f) \; \Omega_t(f)}{f^3 \; P_1(f) \; P_2(f)}$$

Overlap Reduction Function

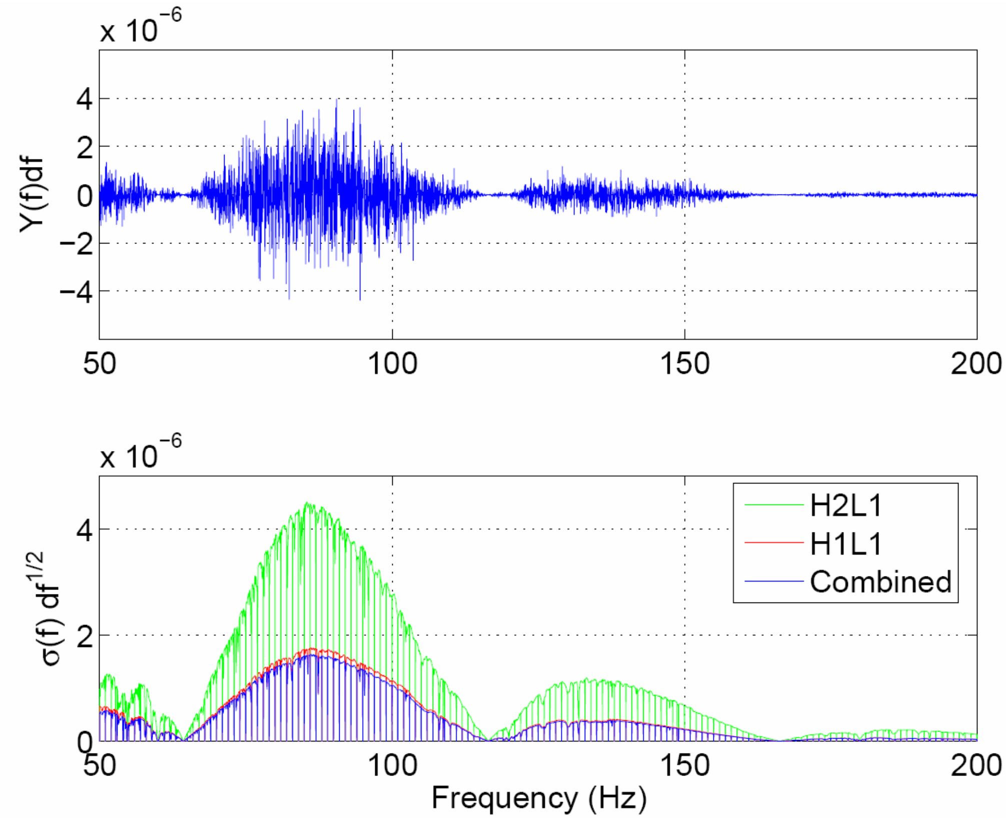


For template: $\Omega_t(f) = \Omega_\alpha (f/100 \text{ Hz})^\alpha$

Choose *N* such that: $< Y >= \Omega_\alpha T$

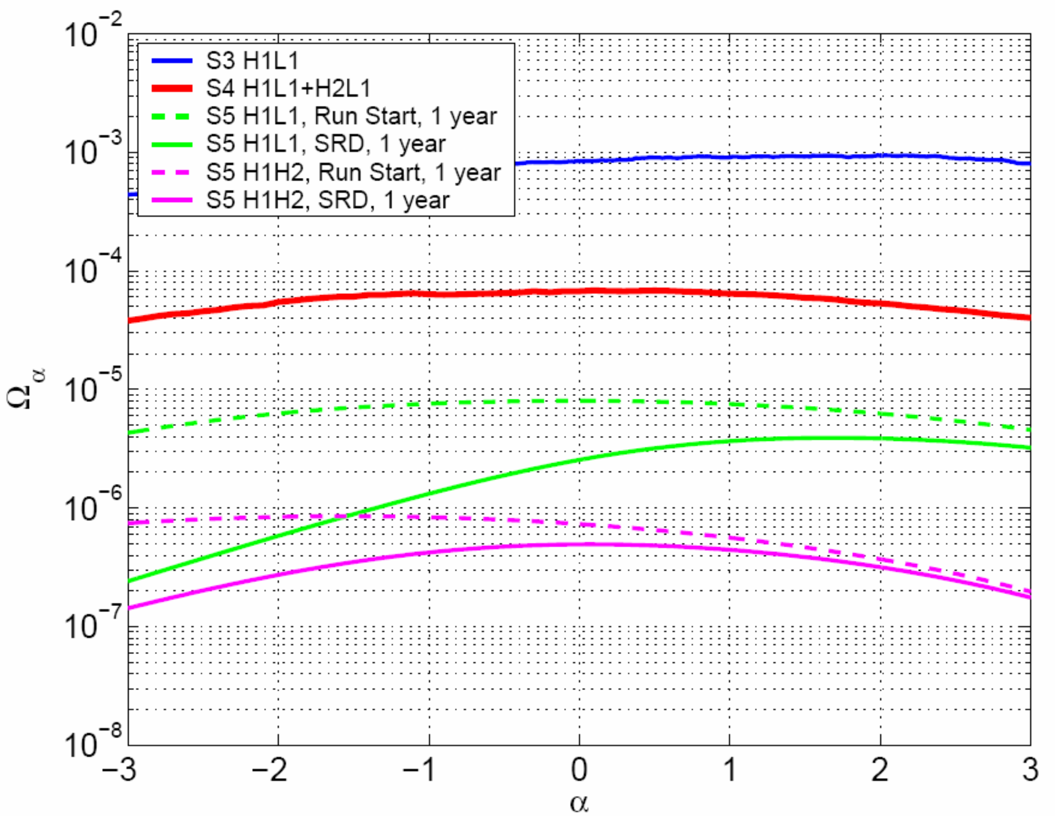
Recent Results

- S4 Science Run:
  - » Feb. 22 – Mar. 23, 2005.
- Combined H1L1 + H2L1:
  - » **$\Omega \pm \sigma_\Omega$ = (-0.8 ± 4.3) × 10^{-5}**
  - » h = 72 km/s/Mpc
  - » 51-150 Hz (includes 99% of inverse variance)
- Bayesian 90% UL:
  - » Prior on Ω: S3 Posterior
  - » Marginalize over calibration uncertainties
    - – Gaussian priors with standard deviation 5% for L1, 8% for H1 and H2.
  - » 90% UL: **6.5 × 10^{-5}**



Reach as a Function of Spectral Slope

$$\Omega_t(f) = \Omega_\alpha (f/100\ \text{Hz})^\alpha$$



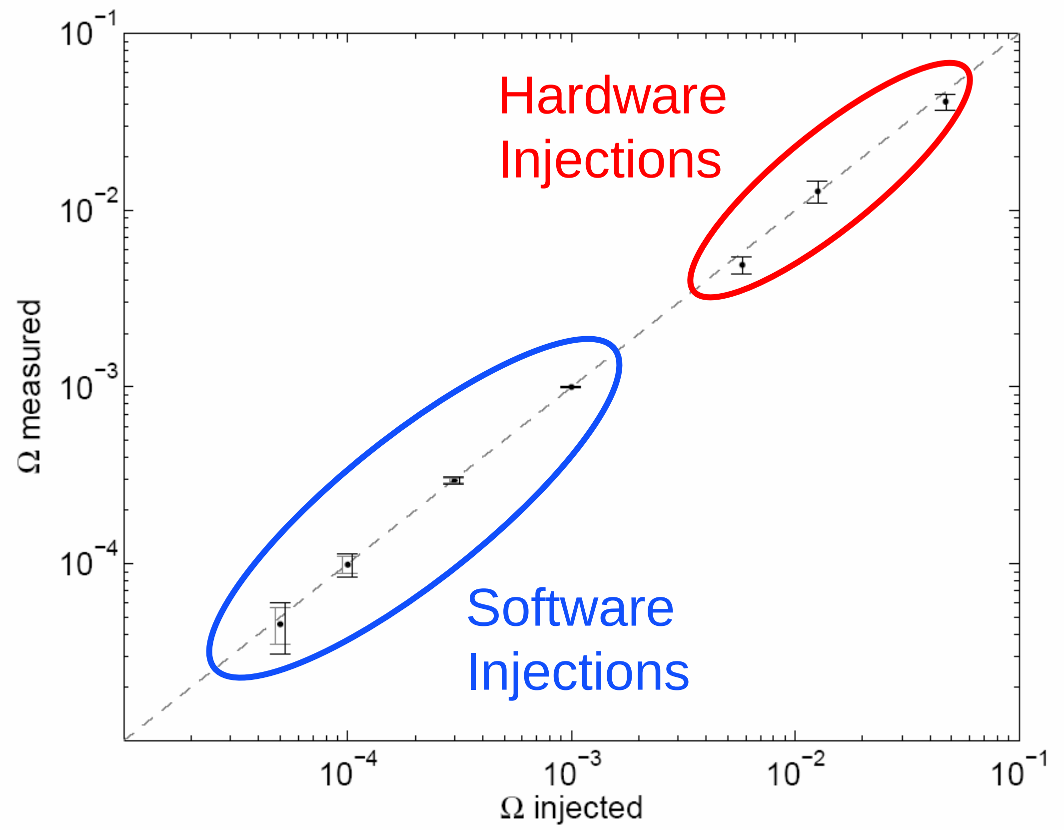
- S3 H1L1: Bayesian 90% UL.

- S4 H1L1+H2L1: Bayesian 90% UL.

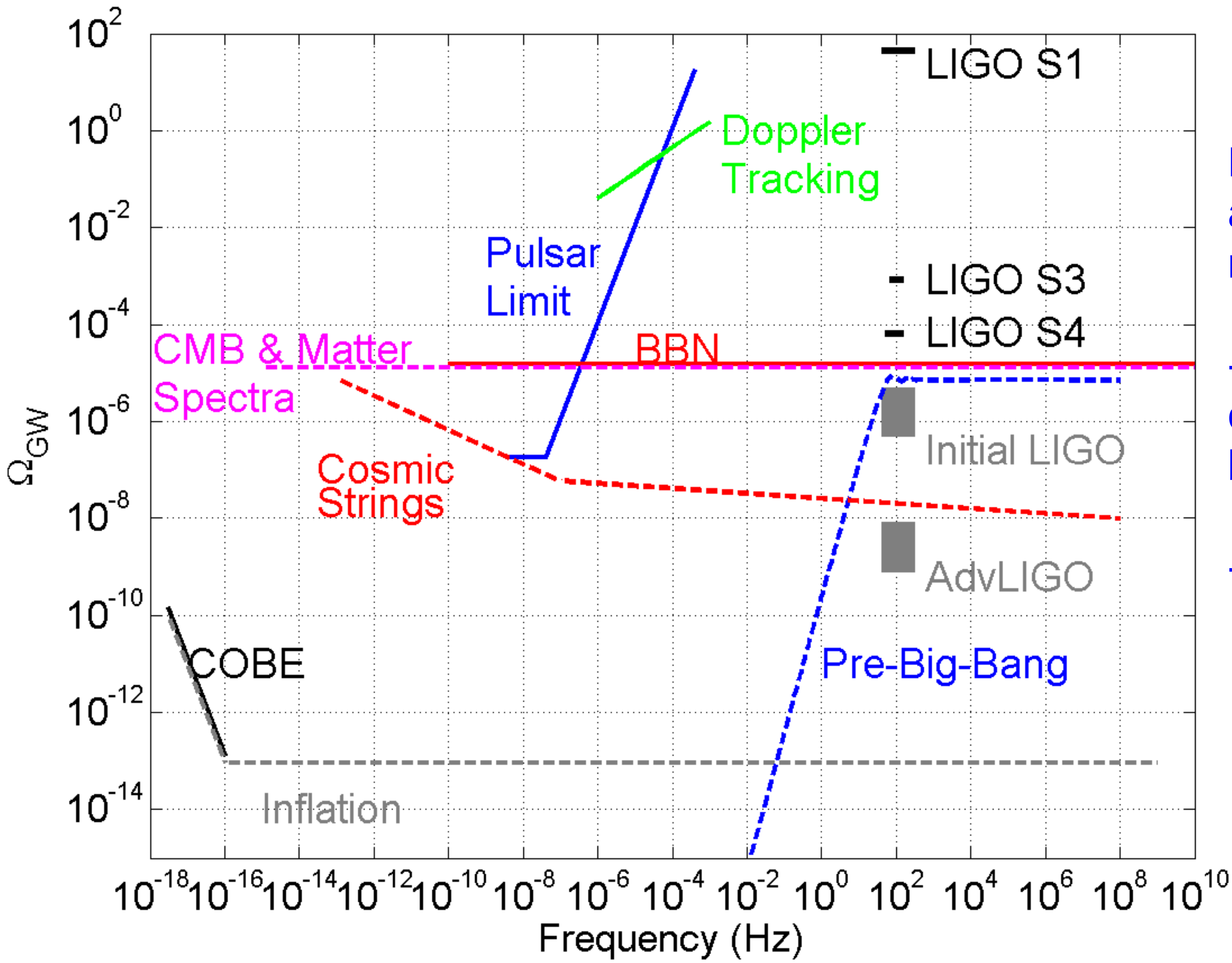
- Expected S5: design strain sensitivity and 1 year exposure.
    - For H1L1, sensitivity depends on frequency band.

Injections

- Software injections:
  - » Signal added to data in software.
  - » Successfully recovered down to $\Omega \sim 5\times10^{-5}$.
  - » Theoretical error agrees with the standard error over 10 trials.
- Hardware injections:
  - » Physically moving the mirrors.
  - » Successfully recovered (within errors).



Landscape



Pre-Big-Bang models and Cosmic Strings models:

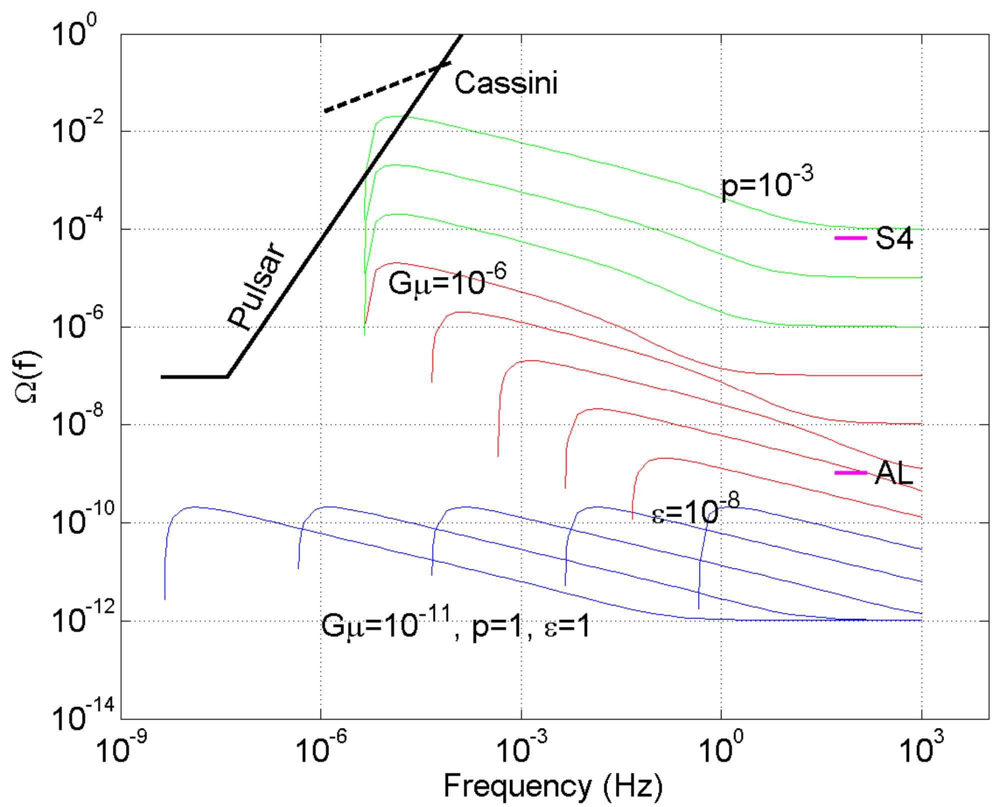
- can easily escape other experimental bounds

- accessible to LIGO.

Cosmic Strings: Model

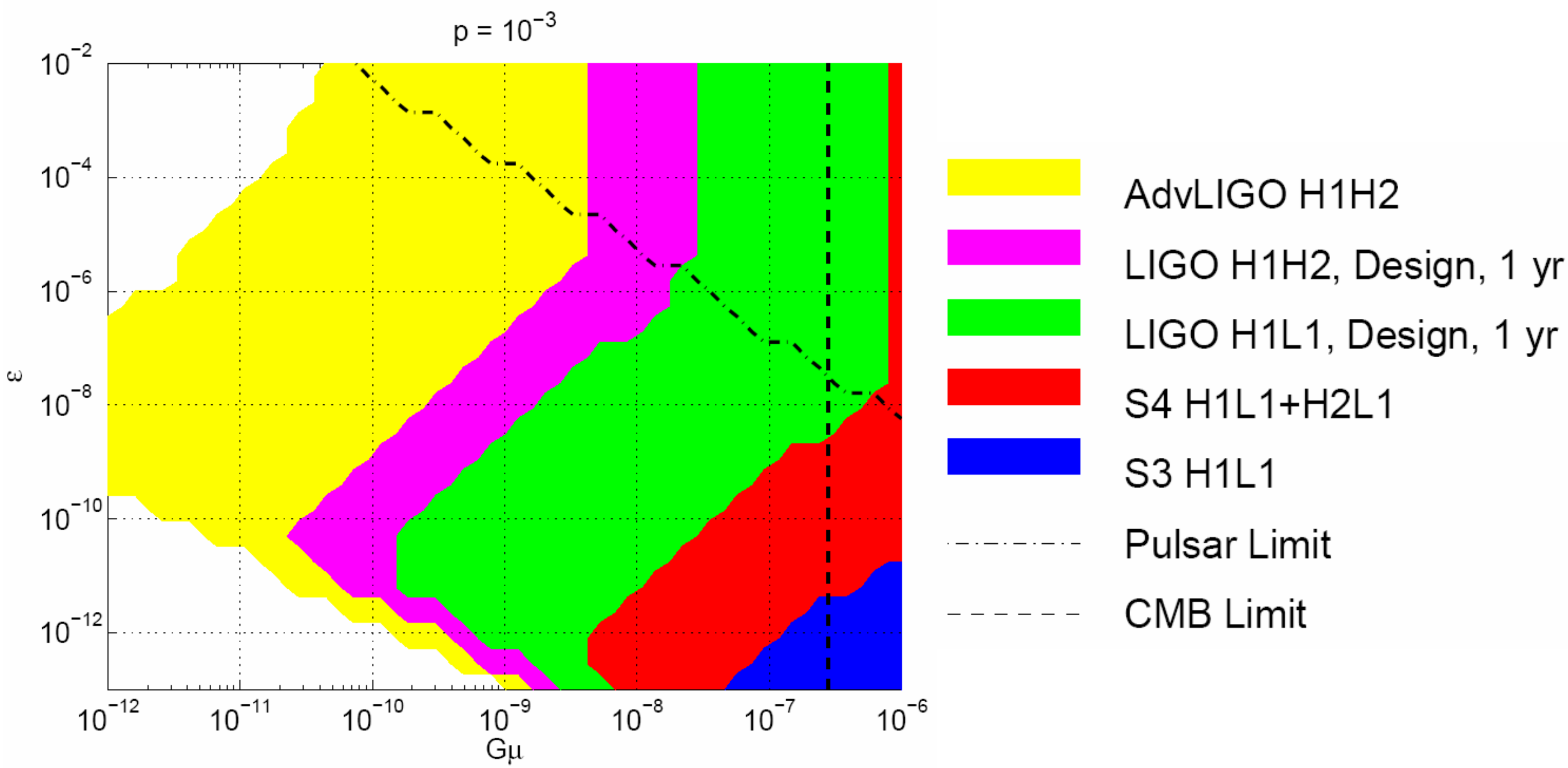
- Cosmic strings are topological defects formed during phase transitions in the early Universe.
- They can also be fundamental or Dirichlet strings (in string theory).
- Cosmic string cusps, with large Lorentz boosts, can create large GW signals.
- Look for the stochastic background created by superposing cusp signals throughout the Universe.
- Calculation done by Damour & Vilenkin, PRD71, 063510 (2005)
  - » There is a number of uncertainties in the calculation.
  - » Some of them can be resolved by improving the calculation (ongoing work with X. Siemens et al).
  - » Some of them require simulations.

Cosmic Strings: Results

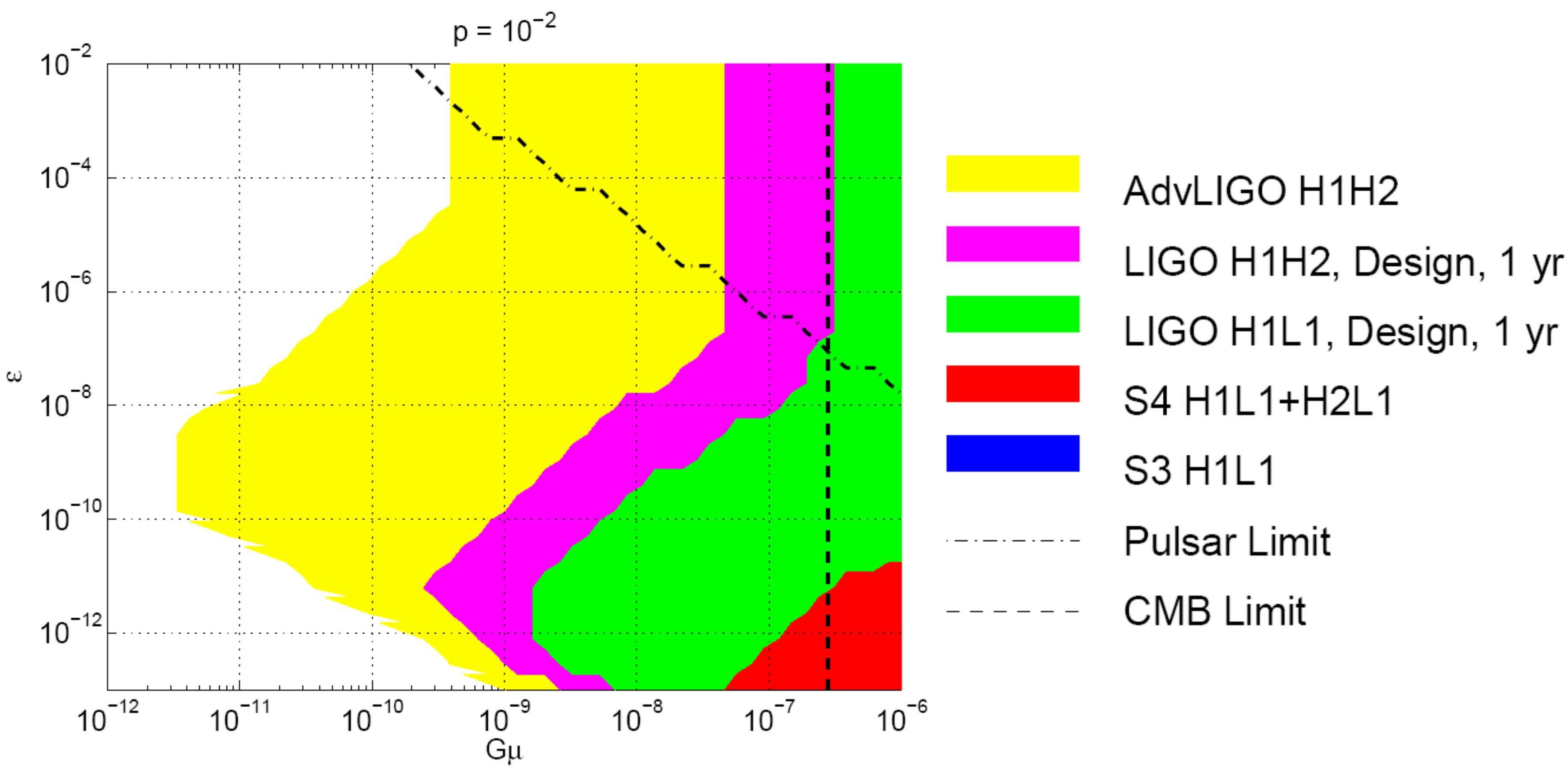


- String tension: $10^{-12} < G\mu < 10^{-6}$
- Reconnection probability: $10^{-3} < p < 1$
  - » Affects the density of strings and the amplitude of GW background.
- Efficiency of damping perturbations with GW radiation: $10^{-13} < \varepsilon < 10^{-2}$
  - » Defines the size of smallest structures in the string network.
- 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 $1/p$.

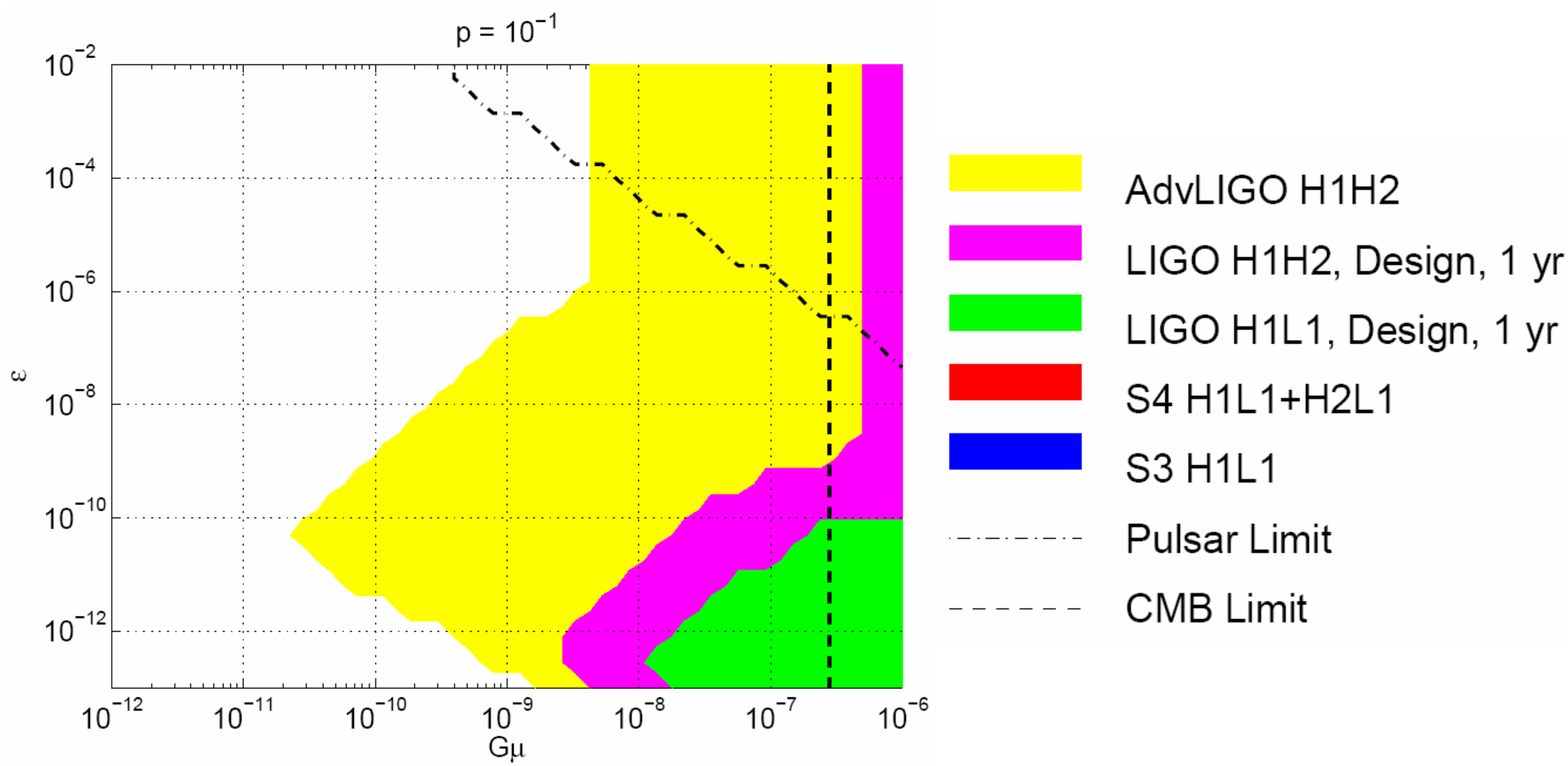
Cosmic Strings: Results



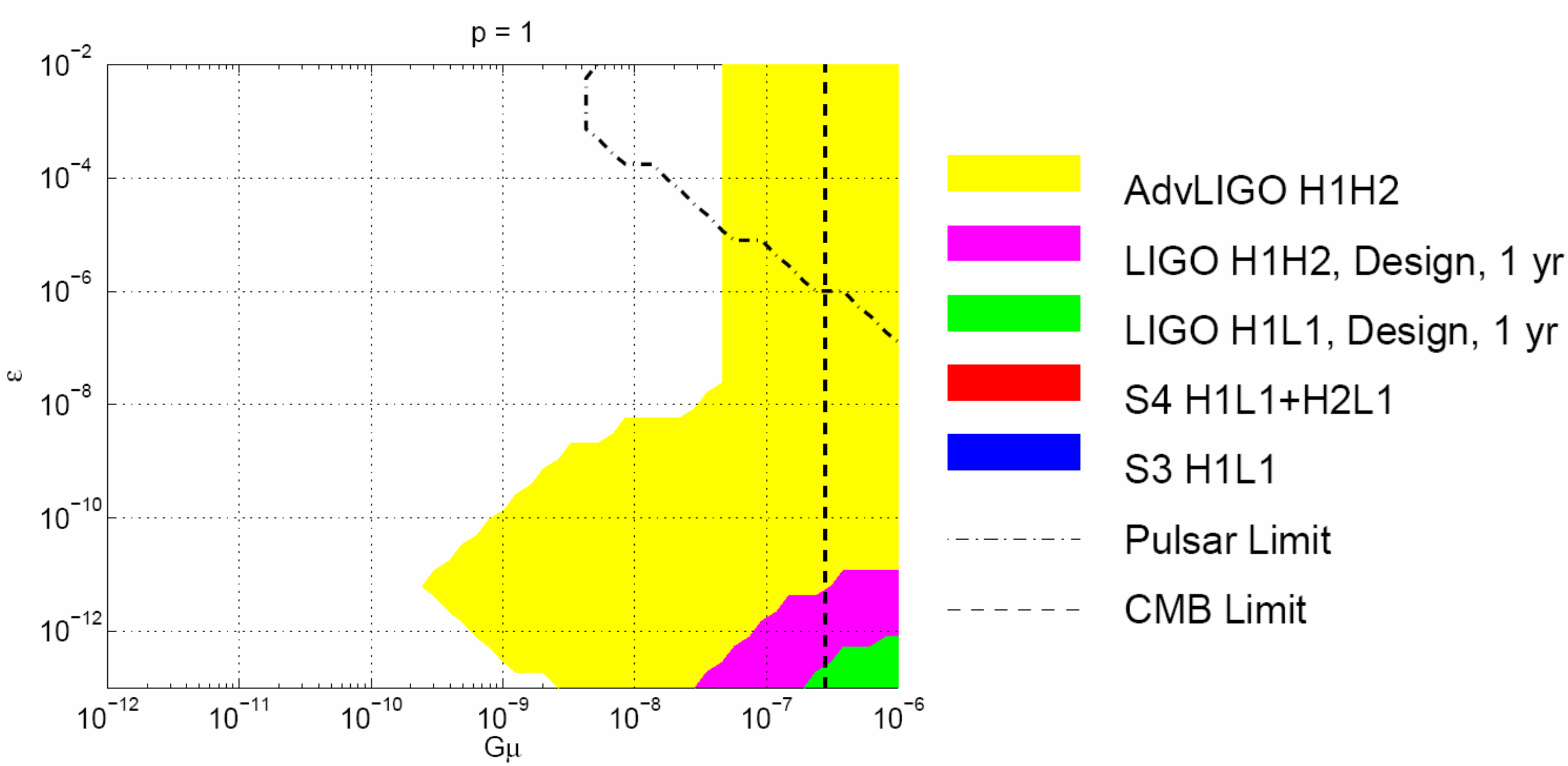
Cosmic Strings: Results



Cosmic Strings: Results



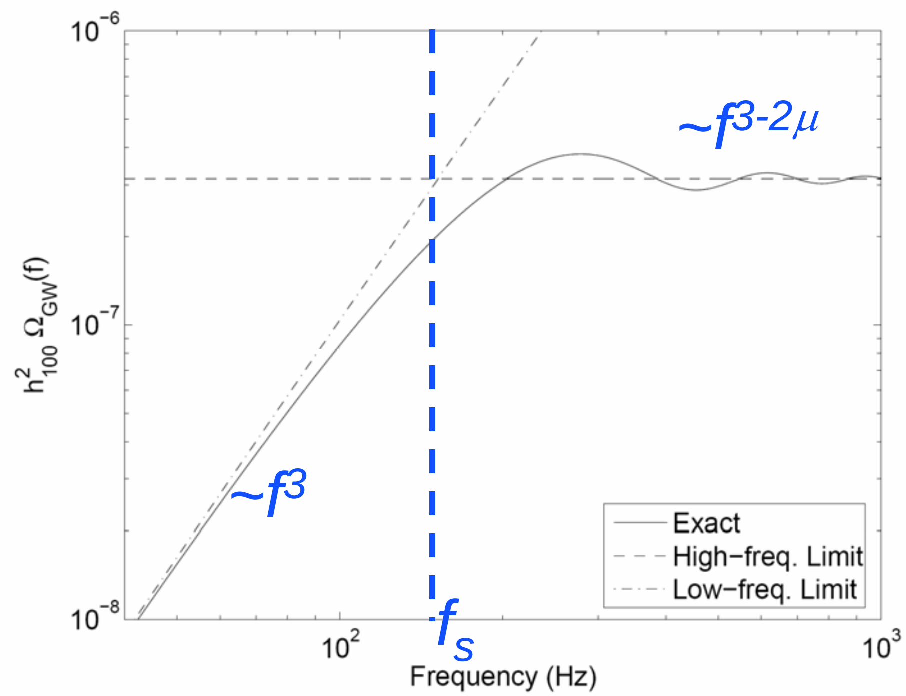
Cosmic Strings: Results



Pre-Big-Bang: Model

- Amplification of vacuum fluctuations
  - » Transition from one regime to another in the Universe (e.g. from inflation to radiation dominated) on time-scale ΔT
    - – For cosmological setting, $\Delta T \sim H^{-1}$.
  - » Vacuum fluctuations are amplified only if transition is fast:
    - – $f \ll (2\pi\, \Delta T)^{-1}$ or $\lambda \gg 2\pi\, H^{-1}$ - i.e. super-horizon modes!
- Inflation:
  - » De Sitter inflation phase
  - » Radiation-dominated phase
  - » Matter-dominated phase.
- Pre-Big-Bang Models:
  - » Dilaton-dominated phase
  - » Stringy phase
  - » Radiation, followed by matter phase.

Pre-Big-Bang: Parameters



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

- Typically, think of 2 free parameters:
  - » μ - determines the high-frequency slope
    - – Consider $1 < \mu < 1.5$.
  - » f_s – the "turn-over" frequency
    - – Essentially unconstrained: 0 – f_1
- But: High-frequency amplitude goes as f_1^4.

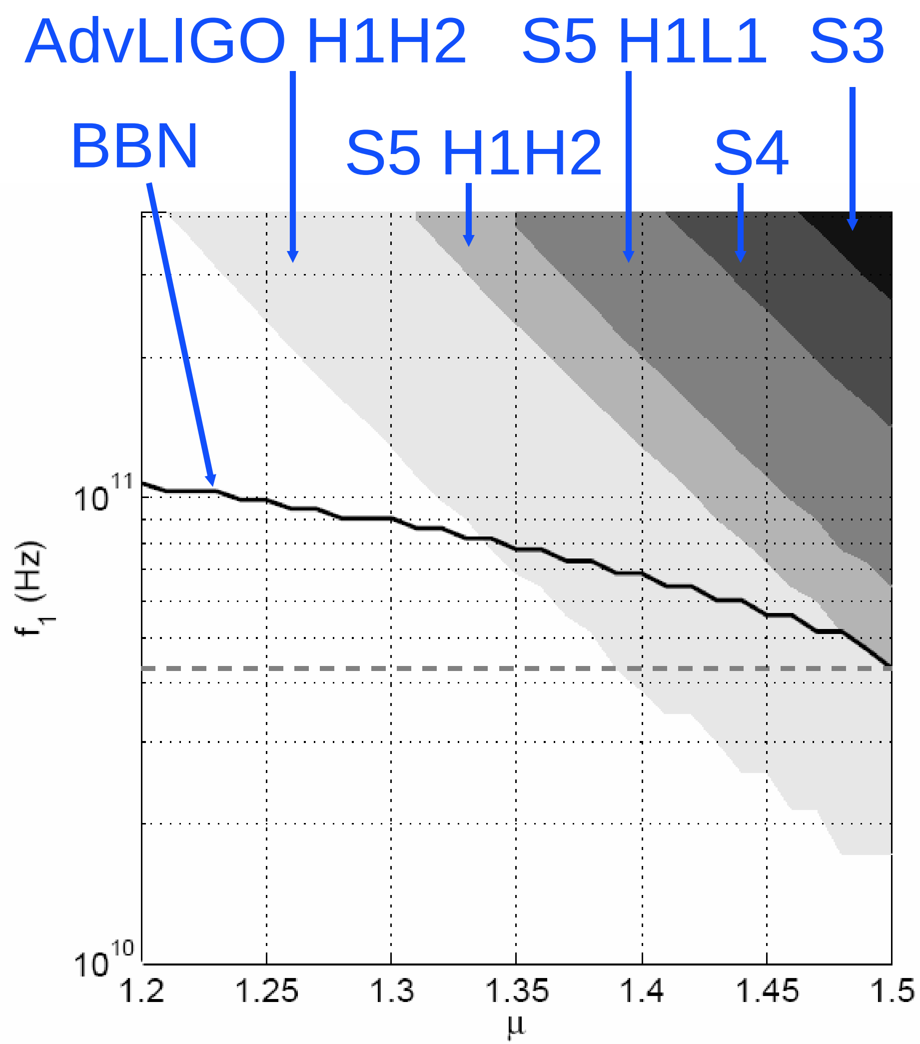
$$f_1 \simeq 4.3 \times 10^{10}\ \mathrm{Hz} \left(\frac{H_s}{0.15 M_{Pl}}\right)\left(\frac{t_1}{\lambda_s}\right)^{1/2}$$

  - » f_1 depends on string related parameters, which are not well known.
  - » So, treat it as another free parameter.
    - – Vary by factor of 10 around the most "natural" value.

Pre-Big-Bang: Results

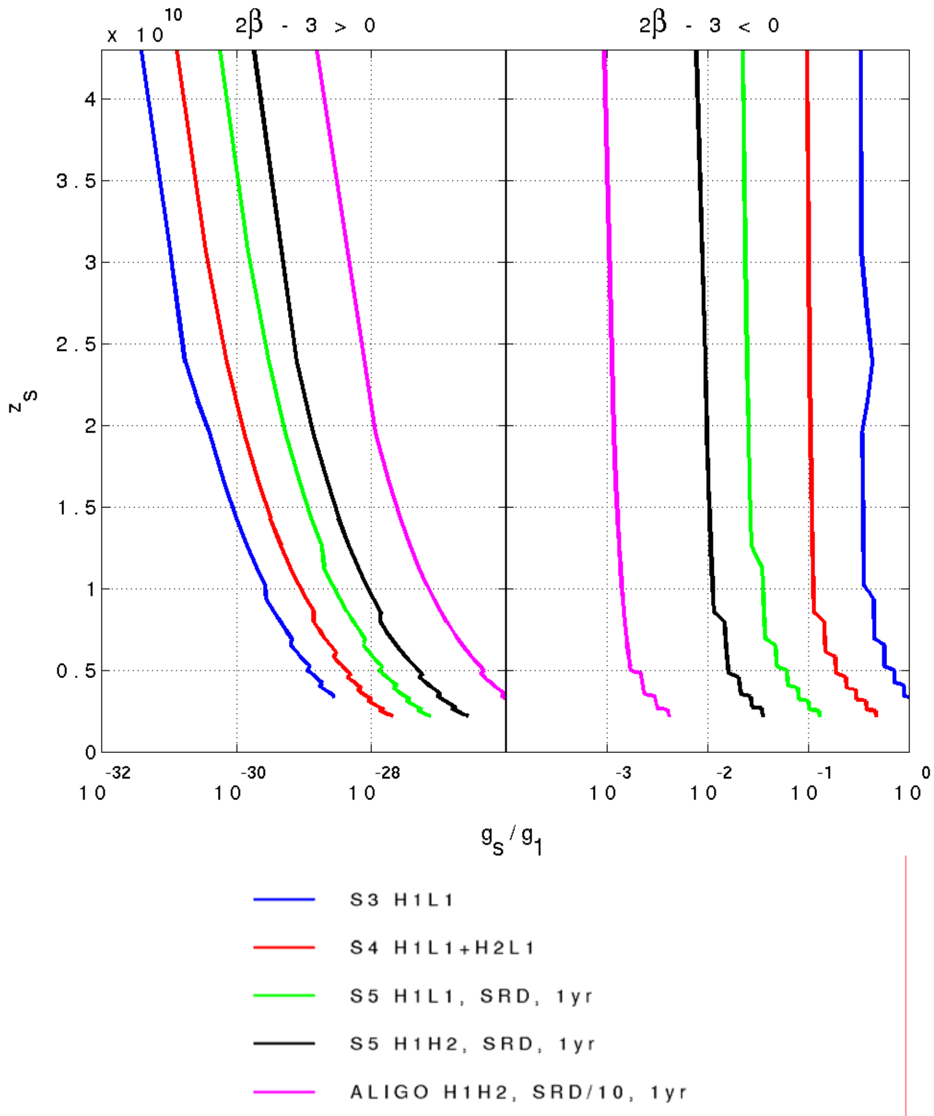
- Scan f_1 - μ plane for f_s=30 Hz.
- For each model, calculate $\Omega_{GW}(f)$ and check if it is within reach of current or future expected LIGO results.
- Beginning to probe the allowed parameter space.
- Currently sensitive only to large values of f_1.
- Sensitive only to spectra close to flat at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

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



Pre-Big-Bang: Results

- Can also define:
  - » $z_s = f_1/f_s$ is the total redshift in the stringy phase.
  - » $g_s/g_1 = (f_s/f_1)^\beta$, where $2\mu = |2\beta - 3|$
    - – g_s (g_1) are string couplings at the beginning (end) of the stringy phase
- Probe fundamental, string-related parameters, in the framework of PBB models.
- Assumed $f_1 = 4.3 \times 10^{11}$ Hz (relatively large).



Conclusions

- LIGO interferometers have reached design sensitivity.
- 1-year long science run on the way.
- Most recent result of the stochastic search:
  - » $\Omega < 6.5 \times 10^{-5}$, for the flat spectrum, 50-150 Hz.
- Comparable with other measurements and constraints on the GW background.
- Beginning to explore some of the theoretical models of GW background (examples are cosmic strings and pre-big-bang models)
- Potential to study string-theory motivated models.