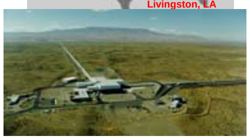
LIGO-G060595-00-D

Searching for Stochastic Gravitational-wave Background with LIGO

Vuk Mandic, Caltech
Texas06 Symposium
Melbourne, December 2006

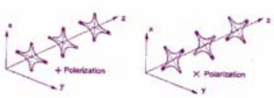
LIGO Observatories

- LIGO has built 3 interferometers at two sites:
  - H1: 4 km at Hanford, WA
  - H2: 2 km at Hanford, WA
  - L1: 4 km at Livingston, WA

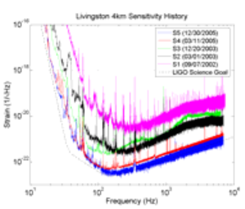


- Locations 3000 km apart.
  - Minimizes instrumental correlations.

- Main idea: gravitational wave effectively stretches one interferometer arm while compressing the other.
  - Two polarizations



- Many possible sources:
  - Transient (bursts, inspirals)
  - Periodic (e.g. pulsars)
  - Stochastic: incoherent supperposition of many sources, astrophysical or cosmological in nature
- Sensitivity improved $10^4\times$ over 4 years!
- Reached design sensitivity
  - 1-year long run has started in November 2005



LIGO Scientific Collaboration Search for Isotropic Stochastic Background

Cross-correlation estimator

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

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

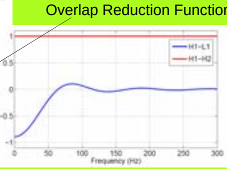
Theoretical variance

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

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



Template Spectrum

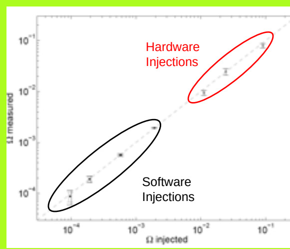
$$\Omega_t(f) = \Omega_\alpha (f/100\ \mathrm{Hz})^\alpha$$

Choose *N* such that

$$<Y> = \Omega_\alpha T$$

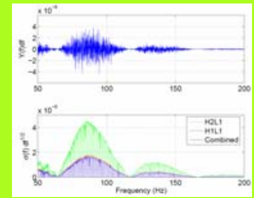
Recovery of Signal Injections

- Software injections:
  - Signal added to data in software.
  - Successfully recovered down to $\Omega \sim 10^{-4}$.
  - Theoretical error agrees with the standard error over 10 trials.
- Hardware injections:
  - Physically moving the mirrors.
  - Successfully recovered (within errors).

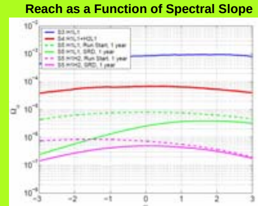


Recent Results

- S4 Science Run:
  - Feb. 22 – Mar. 23, 2005.
- Combined H1L1 + H2L1:
  - $\Omega_0 \pm \sigma_\Omega = (-0.8 \pm 4.3) \times 10^{-5}$
  - H_{100} = 72 km/s/Mpc
  - Frequency range: 51-150 Hz
- Bayesian 90% UL:
  - Prior on Ω: S3 Posterior
  - Marginalize over calibration errors
    - 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



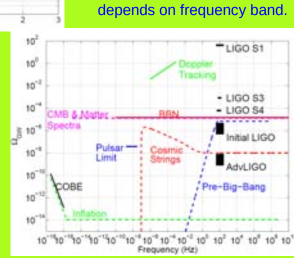
$$\Omega_t(f) = \Omega_\alpha (f/100\ \mathrm{Hz})^\alpha$$

- 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.

Landscape of Stochastic Gravitational-Wave Background

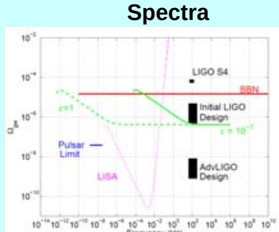


Cosmic Strings Models

- 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 Siemens, Mandic & Creighton, astro-ph/0610920
  - Update on 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.

Siemens, Mandic & Creighton, astro-ph/0610920

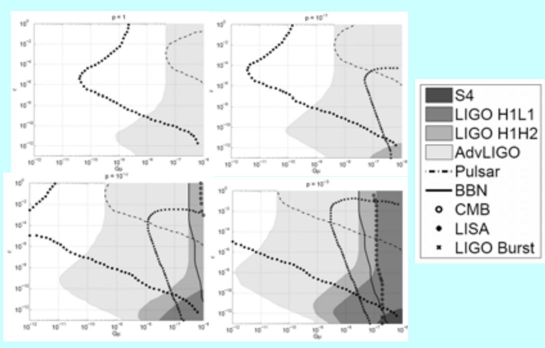
Typical Gravitational-wave Spectra



Small-loop Case
$p = 5\times 10^{-3}$
$G\mu = 10^{-7}$

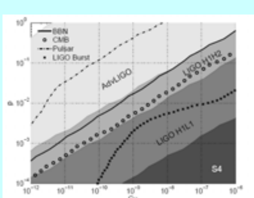
Small-loop Case

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



Large-loop Case

- Recent simulations indicate that loops could be large at formation, and therefore long-lived.
- The loop distribution as a function of time is more complex, and with typically larger amplitudes of gravitational-wave spectra.
- The free parameters are:
  - 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.



Conclusions

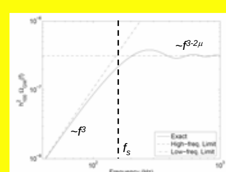
- Small-loop case:
  - Experiments already probe parameter space
  - LIGO is already more sensitive than the BBN bound in some parts of the parameter space
  - There is significant complementarity between LIGO and other experiments/observations
  - LIGO stochastic and burst searches are partly complementary and partly overlap
  - Future experiments are expected to explore a large part of this parameter space
- Large-loop case:
  - Current experiments explore an even larger fraction of the parameter space
  - Pulsar limit currently most constraining, but Advanced LIGO and LISA are expected to overcome this limit.

Pre-Big-Bang Models

Mandic & Buonanno, Phys. Rev. D73, 063008, (2006).

- Mechanism for production of gravitational waves: 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:
    - $f << (2\pi\,\Delta T)^{-1}$ or $\lambda >> 2\pi\, H^{-1}$ - i.e. super-horizon modes!
- This mechanism appears in inflationary models:
  - Inflation phase / Radiation phase / Matter phase.
- The phases in Pre-Big-Bang models are different:
  - Dilaton-dominated phase: Universe is large and shrinking
  - Stringy phase: not well understood
  - Standard radiation, matter phases.

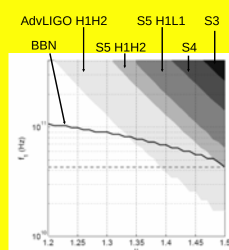
Typical Gravitational-wave Spectrum



- 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: $0 – f_1$

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

- But: High-frequency amplitude goes as f_1^4.
  - 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.



- 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:

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

- 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).