Searches for a Stochastic Background of Gravitational Waves

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Outline

1. Background
   - Stochastic Gravitational-Wave Backgrounds
   - Cross-Correlation Method
2. Partial S5 Results
   - Details of S5 Analysis
   - PRELIMINARY Upper Limit Result
   - Validation
3. Interpretation
   - Comparison to other Limits
   - Expected Sensitivity of Full S5 Analysis

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Sources of Stochastic Gravitational Waves

- Stochastic Gravitational-Wave background: superposition of unresolved GW sources
- "Cosmological" sources include inflation, pre-big-bang, phase transitions, cosmic strings
  - Probably $\sim$ isotropic
- "Astrophysical" sources include unresolved binaries, neutron star instabilities, LMXBs
  - Can show anisotropies if dominated by local universe

Characterization of Stochastic GW Background

- Focus on isotropic, unpolarized, stationary, Gaussian backgrounds. (We also search for backgrounds w/strong anisotropy, but beyond scope of this talk)
- One way of defining spectrum of isotropic background: via gravitational-wave contribution to $\Omega = \frac{\rho}{\rho_{\text{crit}}}$:

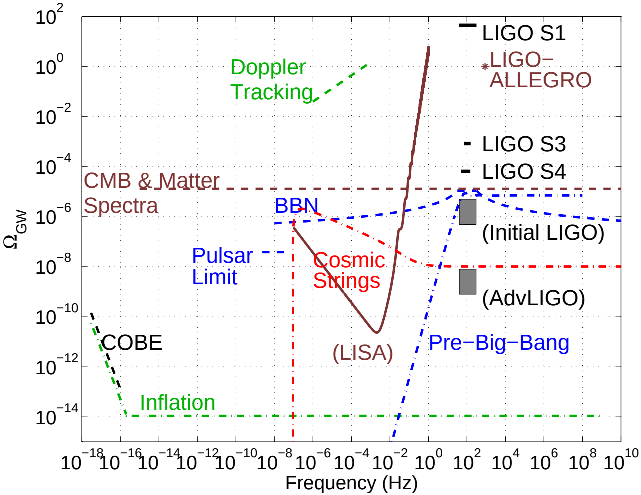
$$\Omega_{\text{gw}}(f) := \frac{1}{\rho_{\text{crit}}} \frac{d\rho_{\text{gw}}}{d\ln f} \equiv \frac{f}{\rho_{\text{crit}}} \frac{d\rho_{\text{gw}}}{df}$$

Note $\rho_{\text{crit}} \propto H_0^2$. Our results assume $H_0 = 72\,\text{km}/\text{s}/\text{Mpc}$

- Equivalent GW strain power (in interferometer w/$\perp$ arms)

$$S_{\text{gw}}(f) = \frac{3H_0{}^2}{10\pi^2} f^{-3}\,\Omega_{\text{gw}}(f)$$

Stochastic GW “Landscape”



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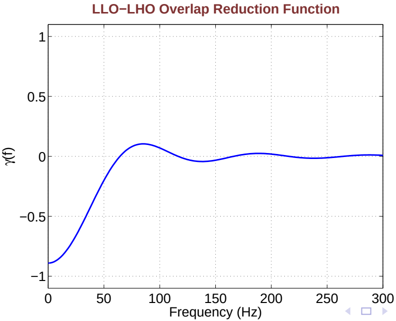
Expected Cross-Correlation

- Cross-correlation between GW signals in pair of detectors:

$$\langle \widetilde{s}_1(f)^* \widetilde{s}_2(f) \rangle = \gamma(f) S_{\text{gw}}(f)$$

- Geometry enters via Overlap Reduction Function $\gamma(f)$, depending on orientation & separation of detectors



Optimally Filtered Cross-Correlation Statistic

- Assume $\Omega_{\rm gw}(f)$ constant across band
- Cross-correlation gives point estimate of $\Omega_{\rm gw}(f)$:

$$\widehat{\Omega} = \int df \, \widetilde{s}_1^*(f) \, \widetilde{Q}(f) \, \widetilde{s}_2(f)$$

- Maximize sensitivity w/Optimal Filter

$$\widetilde{Q}(f) \propto \frac{\gamma(f)}{f^3 P_1(f) P_2(f)}$$

- Can estimate error bar from noise:

$$\sigma \propto \left(T \int df \, \frac{[\gamma(f)]^2}{f^6 P_1(f) P_2(f)} \right)^{-1/2}$$

- Short-time estimates $\{\widehat{\Omega}_i\}$ weighted by $\{\sigma_i^{-2}\}$ & averaged

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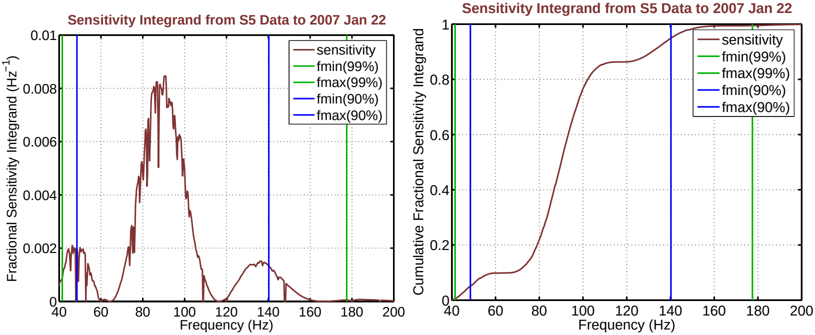
S5 Data

- LIGO Hanford Observatory (4 km H1, 2 km H2) observed 2005 Nov 4-2007 Sep 30
- LIGO Livingston Observatory (4 km L1) observed 2005 Nov 14-2007 Sep 30
- Preliminary, Partial result being presented here includes H1-L1 coïncident data up to 2007 Jan 22 378608 overlapped 60 sec segments $\approx$ 140 days effective observing time
- Duty cycles & sensitivity improved during run: Up to 2007 Jan 22 $\cong 1/2$ of coïncident observing time & $\sim 1/3$ of noise-weighted observing time (total sensitivity)
- Use preliminary calibration; will be revised for final result; H2-L1 correlation measurements will also be included

Frequency Range Determined by Sensitivity



Frequencies kept for analysis give 99% of sensitivity (measured by integrand of σ^{-2}): $41.5\,\text{Hz} < f < 177.5\,\text{Hz}$ (90% comes from range $48.5\,\text{Hz} < f < 140.25\,\text{Hz}$)

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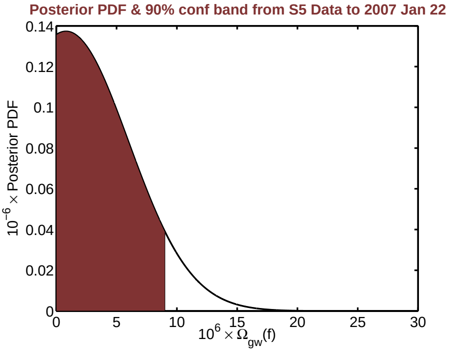
PRELIMINARY Cross-Correlation Result

- Optimally combined PRELIMINARY analysis of data to 2007 Jan 22 gives estimate on $\Omega_{\text{gw}}(f)$ (assumed to be constant over $41.5\,\text{Hz} < f < 177.5\,\text{Hz}$)

$$\widehat{\Omega} = 1.0 \times 10^{-6} \qquad \sigma = 5.2 \times 10^{-6}$$

- Null result; set upper limit on $\Omega_{\text{gw}}(41.5\,\text{Hz} < f < 177.5\,\text{Hz})$ by constructing Bayesian posterior:
  - S4 posterior as prior ($\sim$ Gaussian w/90% UL 6.5×10^{-5})
  - Marginalize over calibration errors (Gaussian priors) effectively adds systematic error of $\sigma^{\text{cal}} = 0.15\widehat{\Omega}$

Posterior PDF



90% confidence level upper limit is 9.0×10^{-6}

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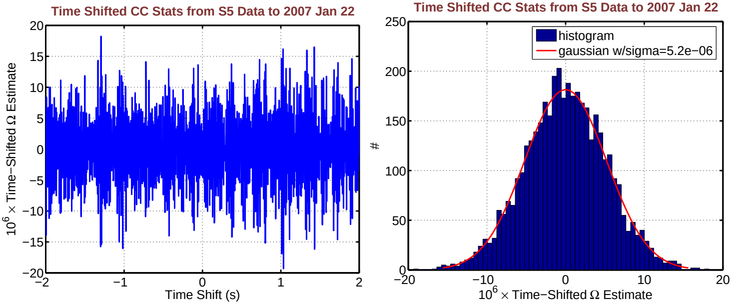
Time-Shift Analysis

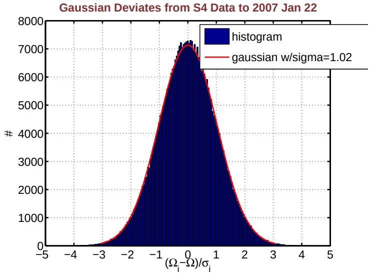
- Can simulate small time-shifts w/inverse Fourier transform of integrand of $\widehat{\Omega}$



- $\sim$ Gaussian; best fit has standard deviation 5.20×10^{-6} consistent w/independently calculated $\sigma = 5.21 \times 10^{-6}$

Distribution in Time

Measurement combined from 378608 independent numbers $\widehat{\Omega}_i$;
Can't quite histogram (different error bars σ_i)
Can construct Gaussian deviates $\frac{\widehat{\Omega}_i - \widehat{\Omega}}{\sigma_i}$

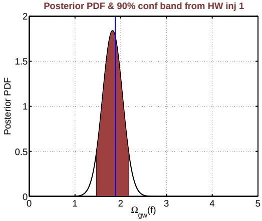


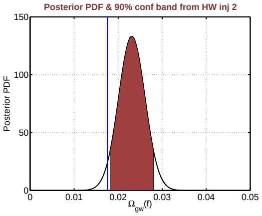
Injections of Simulated Signals

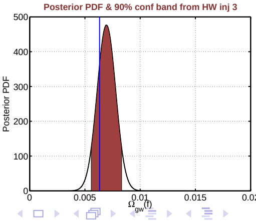
- Have added simulated signals (“software injections”)
  Can recover $\Omega_{\rm gw}(f) \sim 4 \times 10^{-5}$ from full data stream
- Did 3 “hardware injections”; varying strengths & durations
  - Inject into instruments w/known forces on end test mirrors
  - Some common unknown calibration factors
    systematic calibration error only $\sigma^{\rm cal} = 0.12\widehat{\Omega}$
  - Designed to have significant signal-to-noise;
    $\sigma^{\rm cal}$ bigger effect than statistical error bar σ

Hardware Injection Results

	inj 1	inj 2	inj 3
T_{eff} (min)	12.9	29.3	215.5
Ω_{gw}^{inj}	1.88	1.76×10^{-2}	6.3×10^{-3}
$\widehat{\Omega}$	1.82	2.31×10^{-2}	6.9×10^{-3}
σ (statistical)	0.05	0.13×10^{-2}	0.2×10^{-3}
σ^{cal}	0.21	0.27×10^{-2}	0.8×10^{-3}







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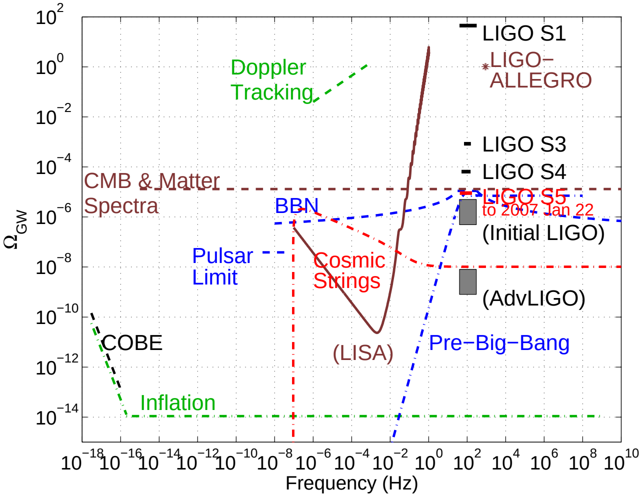
Stochastic GW "Landscape" Including New Result



Big-Bang Nucleosynthesis

- BBN constrains energy density present @ nucleosynthesis: $\Omega \lesssim 1.1 \times 10^{-5}$
- Total contribution from GW background

$$\Omega_{\text{gw}}^{\text{tot}} = \int \frac{df}{f} \Omega_{\text{gw}}(f)$$

- Our excluded background $\Omega_{\text{gw}}(f) = 9.0 \times 10^{-6}$ over $41.5\,\text{Hz} < f < 177.5\,\text{Hz}$ would have $\Omega_{\text{gw}}^{\text{tot}} = 1.3 \times 10^{-5}$ (Note 90% of sensitivity comes from $48.5\,\text{Hz} < f < 140.25\,\text{Hz}$; energy in BG confined to that range would be $\Omega_{\text{gw}}^{\text{tot}} = 9.6 \times 10^{-6}$)
- Direct limits from LIGO now comparible to BBN limit

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Projecting Sensitivity for Full S5 Run

- PRELIMINARY result through 2007 Jan 22:
  - $\widehat{\Omega} = 1.0 \times 10^{-6}$ & $\sigma = 5.2 \times 10^{-6}$
  - 90% upper limit $\Omega_{\mathrm{gw}}(41.5\,\mathrm{Hz} < f < 177.5\,\mathrm{Hz}) \leq 9.0 \times 10^{-6}$
  - Used $\sim 1/2$ of coïncident H1-L1 data in S5
- Expectations for full S5 analysis:
  - Error bar shrinks like square root of observing time
  - Sensitivity improved during S5; estimate $\sim 1.7\times$ improvement in error bar
  - Can think of partial result as $\sim 1/3$ of observing power

Summary

- Searched for stochastic GW background in LIGO S5 data through 2007 Jan 22
- Use optimally filtered cross-correlation technique; Look for correlations between 4km Livingston & Hanford detectors
- Analysis so far includes $\sim 1/2$ of coïncident observing time or $\sim 1/3$ of noise-weighted observing time (expect factor of ~ 1.7 increase in sensitivity for full S5)
- PRELIMINARY result (90% CL) $\Omega_{\mathrm{gw}}(41.5\,\mathrm{Hz} < f < 177.5\,\mathrm{Hz}) \leq 9.0 \times 10^{-6}$
- Direct LIGO measurements now comparable to constraints from big-bang nucleosynthesis