First upper limit analysis and results from LIGO science data: stochastic background

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Stochastic GW Background

- Random BG produced in early universe (cosmological) and/or by many unresolved sources (astrophysical)
- Strength defined by $\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_{\mathrm{crit}}} \frac{d\rho_{\mathrm{GW}}}{d \ln f} = \frac{f}{\rho_{\mathrm{crit}}} \frac{d\rho_{\mathrm{GW}}}{df}$
- Measure $h_{100}^2 \Omega_{\mathrm{GW}}(f)$ to factor out dep of ρ_{crit} on H_0
- Work w/assumption $\Omega_{\mathrm{GW}}(f) = \Omega_0$ =const across freq band
- Look for cross-correlation btwn GW detector outputs

Optimally Filtered Cross-Correlation Statistic

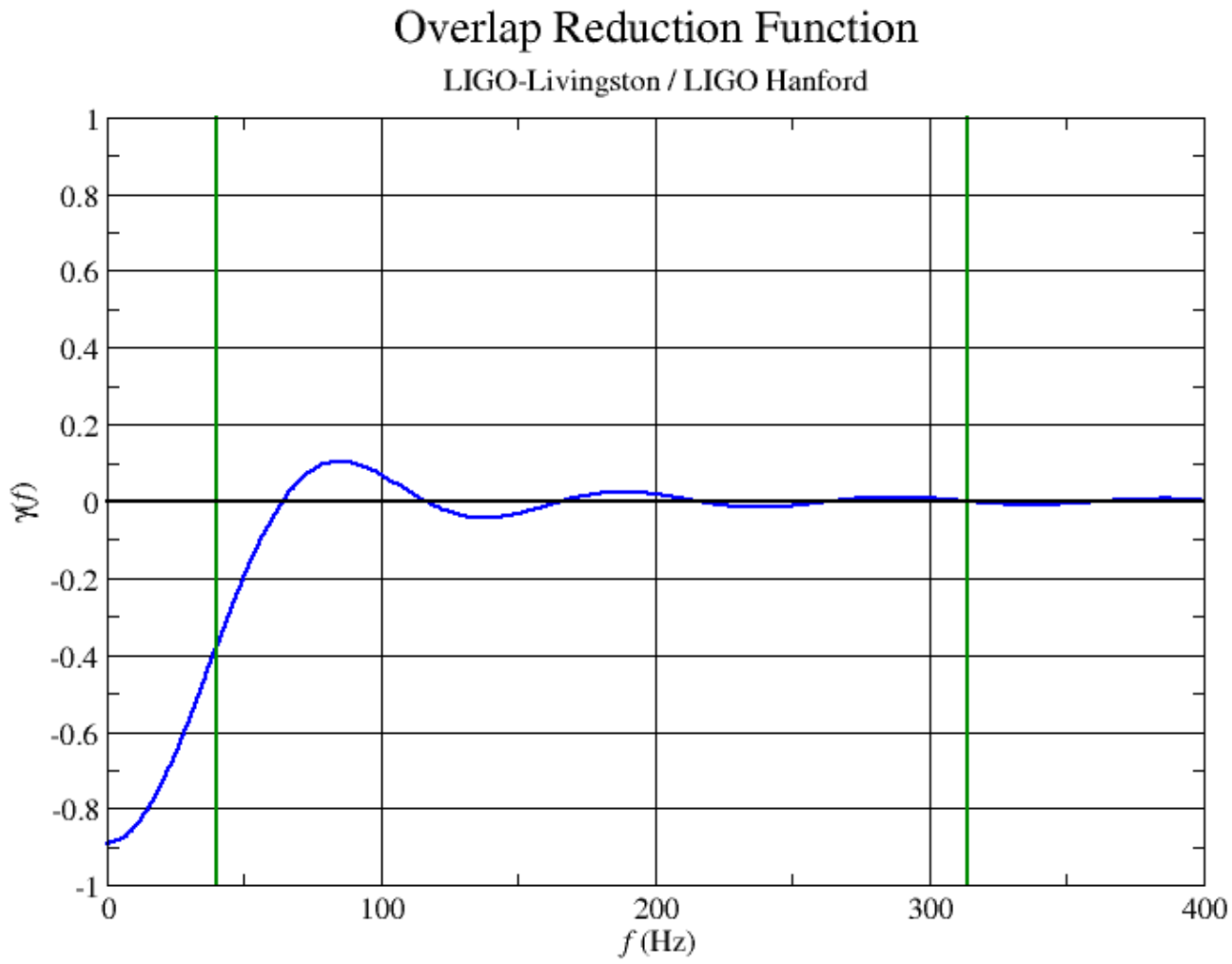
$$Y_Q = \int df\, \tilde{h}_1^*(f)\, \tilde{Q}(f)\, \tilde{h}_2(f)$$

- Optimal filter (maximizes SNR for $\Omega_{\rm GW}(f)$ =const):

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

- Choose normalization s.t. $\langle Y \rangle = h_{100}^2 \Omega_0 T$

- Overlap reduction fcn $\gamma(f)$ encodes geometry



(For correlations between LHO 2km & LHO 4km, $\gamma(f) \equiv 1$)

Previous Upper Limits

- Best published upper limit: correlation between EXPLORER & NAUTILUS bars (Astone et al, 1999): $h_{100}^2 \Omega_{\rm GW}(920\,{\rm Hz}) \leq 60$
- Correlation between Garching & Glasgow prototype IFOs (Compton et al, 1994): $h_{100}^2 \Omega_{\rm GW}(f) \lesssim 3 \times 10^5$
- Correlation between 70 hrs of LIGO Hanford & Livingston engineering (E7) data (Tech Doc LIGO-T020115-00-Z): $h_{100}^2 \Omega_{\rm GW}(f) \lesssim 8 \times 10^4$
- Cosmological constraint (Big-Bang Nucleosynthesis)

$$\int_{10^{-8}\,{\rm Hz}}^{\infty} \frac{df}{f} h_{100}^2 \Omega_{\rm GW}(f) \lesssim 10^{-5}$$

Highlights of Analysis Method: Frequencies

- Analyze LLO 4 km (L1), LHO 4 km (H1) & LHO 2 km (H2)

- Frequency band is 40-314 Hz for L1-H1 & L1-H2,
  40-300 Hz for H1-H2

- Zero out bins ($\Delta f = 0.25$ Hz) at freq likely to give CC noise:
  - $n \cdot 60$ Hz (AC power) & $n \cdot 16$ Hz (GPS)
  - Overall coherence $> 10^{-2}$
    (250 Hz for L1-H2; 168.25 Hz & 168.5 Hz for H1-H2)

Highlights of Analysis Method: Statistics

- Divide coïncident clean data into 900-sec blocks;
  Assume noise & calibration constant over each block

- Pt estimate $h_{100}^2 \hat{\Omega}_0$ is weighted average of $\frac{Y}{T}$

- Calculate CC stat for 10 90-second segments in each block
  - stat error from std dev of 10 meas in each block
  - also use to find error due to cal & noise variations

  appropriate average of these over the run gives
  "standard error" $\hat{\sigma}_{\rm tot}$ assoc w/$h_{100}^2 \Omega_0$ measurement

- 90% CL upper limit is $h_{100}^2 \Omega_0 \leq h_{100}^2 \hat{\Omega}_0 + 1.28\, \hat{\sigma}_{\rm tot}$

Results

IFO Pair	obs time (h:mm)	$h_{100}^2 \hat{\Omega}_0$	$\hat{\sigma}_{\text{tot}}$	90% CL UL
H2-L1	51:15	0.2	18	23
H1-L1	64:00	32	18	55
H1-H2	100:15	-8.3	0.9	N/A

- Additional overall 20% uncertainty due to calibration
- Evidence of instrumental correlation between Hanford IFOs
- Time-shift analysis & χ^2 of spectrum show
  - H1-H2 corr inconsistent w/const-$\Omega_{\text{GW}}(f)$ stoch BG ($\chi^2 = 5$)
  - L1-H1 & L1-H2 pass consistency checks b/c of low SNR

Summary

- Optimally filtered cross-corr of 50–100 hrs of LIGO S1 data
- Assume $\Omega_{\mathrm{GW}}(f) \equiv \Omega_0$ across $40\,\mathrm{Hz} \leq f \leq 314\,\mathrm{Hz}$
- LLO-LHO measurements:

$$\boxed{\mathbf{h_{100}^2 \Omega_0 \leq 23 \pm 4.6}}$$

  $\longrightarrow$ factor of 2–3 improvement over previous observations (over 1000 times better than previous IFO measurements)

- LHO 2 km-4 km shows instrumental anti-correlation equivalent to $-9.9 \pm 2.0 \leq h_{100}^2 \Omega_0 \leq -6.8 \pm 1.4$