A Radiometer for a Stochastic Background of Gravitational Radiation

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GW Radiometer Motivation

- Stochastic GW Background due to Astrophysical Sources?
  - Not isotropic if dominated by nearby sources
  - Do a *Targeted Stochastic Search* with LIGO

- Source position information from
  - Signal time delay between different sites (sidereal time dependent)
  - Sidereal variation of the single detector acceptance

⇒ Time-Shift and Cross-Correlate!

⇒ Effectively a Radiometer for Gravitational Waves
The Radiometer

\[ Y(\Omega) = \int dt \int dt' s_1(t)s_2(t') \tilde{Q}_{t_{\text{sidereal}}}(t-t') \]

\[ \sigma^2(\Omega) \approx \frac{T}{4} (Q_{t_{\text{sidereal}}}, Q_{t_{\text{sidereal}}}) \]

\[ Q_{t_{\text{sidereal}}}(f) \propto \frac{H(f)\gamma_{t_{\text{sidereal}}}(f)}{P_1(f)P_2(f)} \]

\[ H(f) \text{ is the source spectrum} \]

Detailed description in gr-qc/0510096
Data Analysis Flow

**Detector 1**
60 sec data segments

- Downsample, HP filter, Calibrate, Mask Freq: 60 Hz, 120 Hz, …; Pulsars, …
- Estimate PSD (data from \(i-1, i+1\) intervals)
  - Hann window, FFT
- Compute optimal filter \(Q_i\) and theoretical variance \(\sigma_i^2\)
  - Compute Cross Correlation spectrum & InvFFT (=CC time series)
  - Read out CC time series for each pixel (time shifted and scaled)
  - Optimally combine data from all segments for each pixel

**Detector 2**
60 sec data segments

- Downsample, HP filter, Calibrate, Mask Freq: 60 Hz, 120 Hz, …; Pulsars, …
- Estimate PSD (data from \(i-1, i+1\) intervals)
  - Hann window, FFT
- Inject simulated signal into data

\(i = 1, 2, 3, \ldots\)
LIGO’s Fourth Science Run (S4)

\[ H_{\beta=-3}(f) \propto \left( \frac{100 \text{Hz}}{f} \right)^3 \]

(corresponds to scale-invariant primordial perturbation spectrum)

FIG. 6: **S4 Result:** Map of the 90% confidence level Bayesian upper limit on \( H_\beta \) for \( \beta = -3 \). The upper limit varies between \( 1.2 \times 10^{-48} \text{Hz}^{-1} \left(100 \text{ Hz}/f\right)^3 \) and \( 1.2 \times 10^{-47} \text{Hz}^{-1} \left(100 \text{ Hz}/f\right)^3 \), depending on the position in the sky. All fluctuations are consistent with the expected noise.
FIG. 7: **S4 Result:** Map of the 90% confidence level Bayesian upper limit on $H_\beta$ for $\beta = 0$. The upper limit varies between $8.5 \times 10^{-49}$ Hz$^{-1}$ and $6.1 \times 10^{-48}$ Hz$^{-1}$ depending on the position in the sky.

$$H_{90\%} = (0.85 - 6.1) \times 10^{-48} \text{ Hz}^{-1}$$
Narrowband Radiometer
Sco-X1 (nearest LMXB), S4

FIG. 9: S4 Result for Sco-X1: The 90% confidence Bayesian upper limit as a function of frequency - marginalized over the calibration uncertainty. The standard deviation (one sigma error bar) is shown in blue.

Consistent with no signal
But the maps are convolved

\[ \propto \langle Y_\Omega Y_{\Omega'} \rangle \]
Point Spread Function
Convolution: Inject a diffuse source map
Deconvolution:
Invert the covariance matrix to get a maximum likelihood map
Or use a Spherical Harmonic Basis: Maximum Likelihood Estimation

- Rotational Symmetry $\Rightarrow$ covariance $= 0$ for $m \neq m'$
- different l’s at the same m are correlated
- Symmetry broken due to diurnal sensitivity variations

Advantage of a smaller (tens instead of thousands), block diagonal, covariance matrix $\Rightarrow$ lower computational cost.

Being actively pursued by the stochastic analysis group.
**Blinded Data from S5**

time shift the detector streams by more than the light travel time between detectors → no true gw signal remains

With only the first 4 months of S5, upper limit sensitivity bound can reach (for $H(f) = \text{const (}\beta=0)\) :

$$H_{90\%} = (0.82 - 9.9) \times 10^{-49} \text{ Hz}^{-1}$$

already 10x better than S4 result

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Finding for another detection metric: autocorrelation at each declination

- NOT a standard 2-point correlation function
  - Can’t because of variability of point spread function with sky position
- $X(\Delta RA)$ at each declination (integral is over RA)
- $Y_i$’s are point estimates of GW strain
- $w_i$’s are statistical weights of each point on the sky (1st attempt: use reciprocal of theoretical sigma)
- Overall normalization is $X(0)$

For all $i,j$ separated by $\Delta RA$

$$X(\Delta RA) = \sum_{i,j} w_i Y_i Y_j w_j$$

$$w_i = \frac{\langle \sigma \rangle_i}{\sigma_i}$$
Autocorrelation at each declination

- First 4 months of S5, blinded
- $H(f) = \text{const}$
- Working on a “detection metric”—what quantifies absence/presence of signal?
Average the autocorrelations at each declination, over all declinations

In the absence of signal, this can tell us about the resolving power of the instrument; consistent with other estimates.

\[ \frac{\lambda}{D} \frac{500\,Hz}{3000\,km} \Rightarrow 11^\circ \]

diffraction limited gw astronomy

Robert Ward, Caltech

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Because the IFOs still work better at night, the region of best sensitivity moves across the sky as the earth goes around the sun.
The Near Future

- Projected sensitivity increase and longer run time means we should surpass BBN bound during S5
- Narrowband searches from more directions (Virgo cluster, galactic plane)
- Continue development of maximum likelihood analysis, in both point-source (pixel) basis and spherical harmonic basis.
some questions for reviewers

- I’ve included still-blind results from the first 4 months of S5, which reveal sensitivity and data quality. If I redo these results with more data (longer averaging for better sensitivity), can I replace them in the slides?
- Can I add a blinded narrow-band result (repeat of Sco-X1 search) to show sensitivity increase?
- should I add some more general introduction/motivation at the beginning?
- advice on what to cut first if this is too long
The End
Sigma Ratio DQ cut

- Don’t include any 60 second segments whose PSD gives a 20% larger sigma than neighboring PSD’s to reduce effects of nonstationarity.
- This rejects 1.80% of the data
- 1st 4 months of S5