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Searching for the stochastic gravitational-wave background with Advanced LIGO and Advanced Virgo

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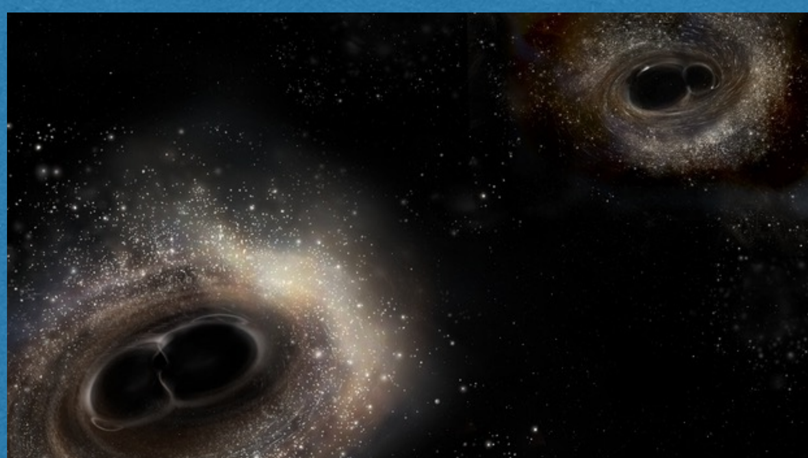
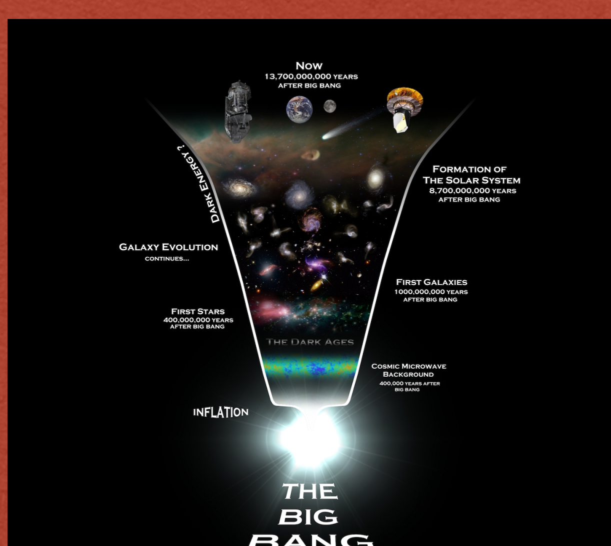
Stochastic gravitational wave background

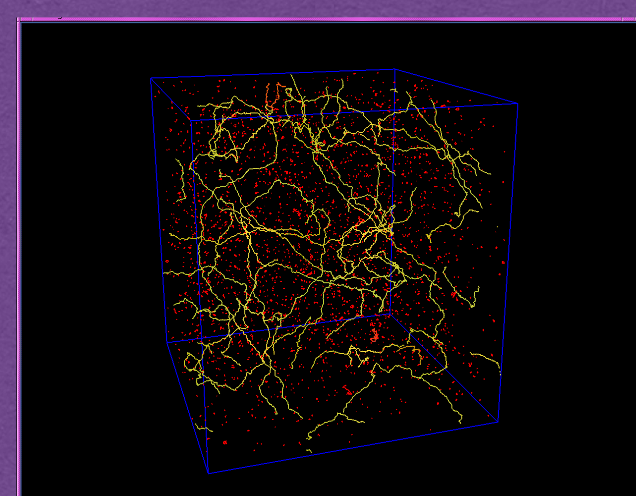
A superposition of astrophysical and cosmological sources, including…



Unresolved astrophysical sources (binaries, supernovae, NS, ...)

Early Universe
(inflation, pre big-bang, ...)





Cosmic Strings

Cosmological
Phase Transitions

Data analysis technique

Cross correlate the time series from 2+ detectors

The signal is long duration and non-deterministic

$$s_1 = h_1 + n_1$$
$$s_2 = h_2 + n_2$$

signal and noise
are uncorrelated

$$\langle s_1 s_2 \rangle = \boxed{\langle h_1 h_2 \rangle} + \langle h_2 n_1 \rangle + \langle h_1 n_2 \rangle + \langle n_1 n_2 \rangle$$

signal

noise at 2 widely
separated detectors is
uncorrelated

Allen and Romano, Phys.Rev. D59 (1999) 102001

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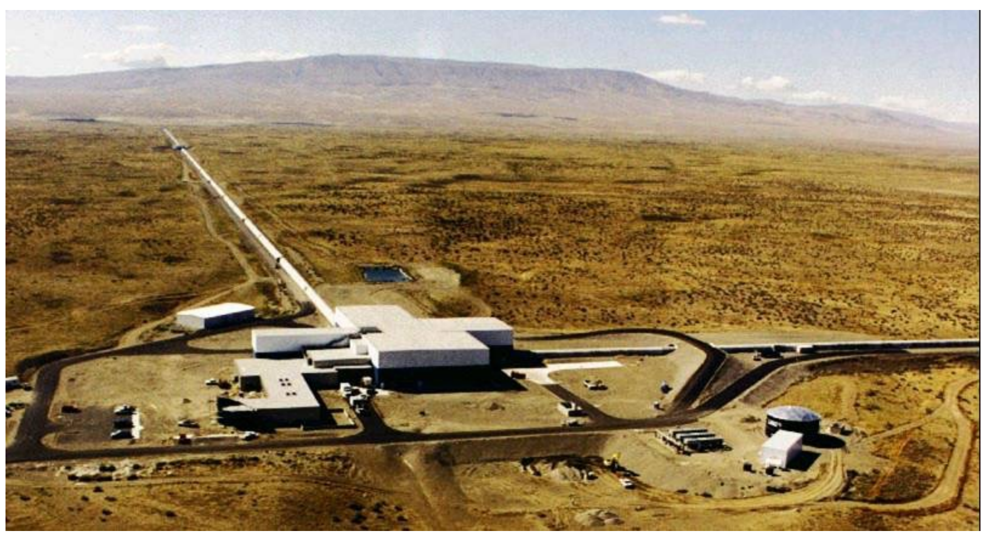
Analysis of LIGO's first two observing runs

We analyzed data at H1 and L1 from the first two observing runs
(O1) September 2015—January 2016
(O2) December 2016-August 2017



Hanford, Washington (H1)

O2 Results papers

Abbott *et al*, 1903.02886
Abbott *et al*, 1903.08844

Livingston, Louisiana (L1)

Image credit: LIGO Lab

Analysis cuts

Abbott *et al,* Phys.Rev.Lett. 118 (2017) no.12, 121101

Abbott *et al,* 1903.02886

1. We remove times where data is known to be corrupt (for example: interferometer not operational)

2. We remove time segments where noise is non-stationary

● ● ● | 192 s | 192 s | 192 s | ● ● ●

$\sigma_{j-1}(f)$ $\sigma_j(f)$ $\sigma_{j+1}(f)$

$$\boxed{\left|\sigma_j - \frac{\sigma_{j+1}+\sigma_{j-1}}{2}\right| \leq 0.2\sigma_j}$$

3. We remove frequency bins which display coherence with instrumental (auxiliary) channels

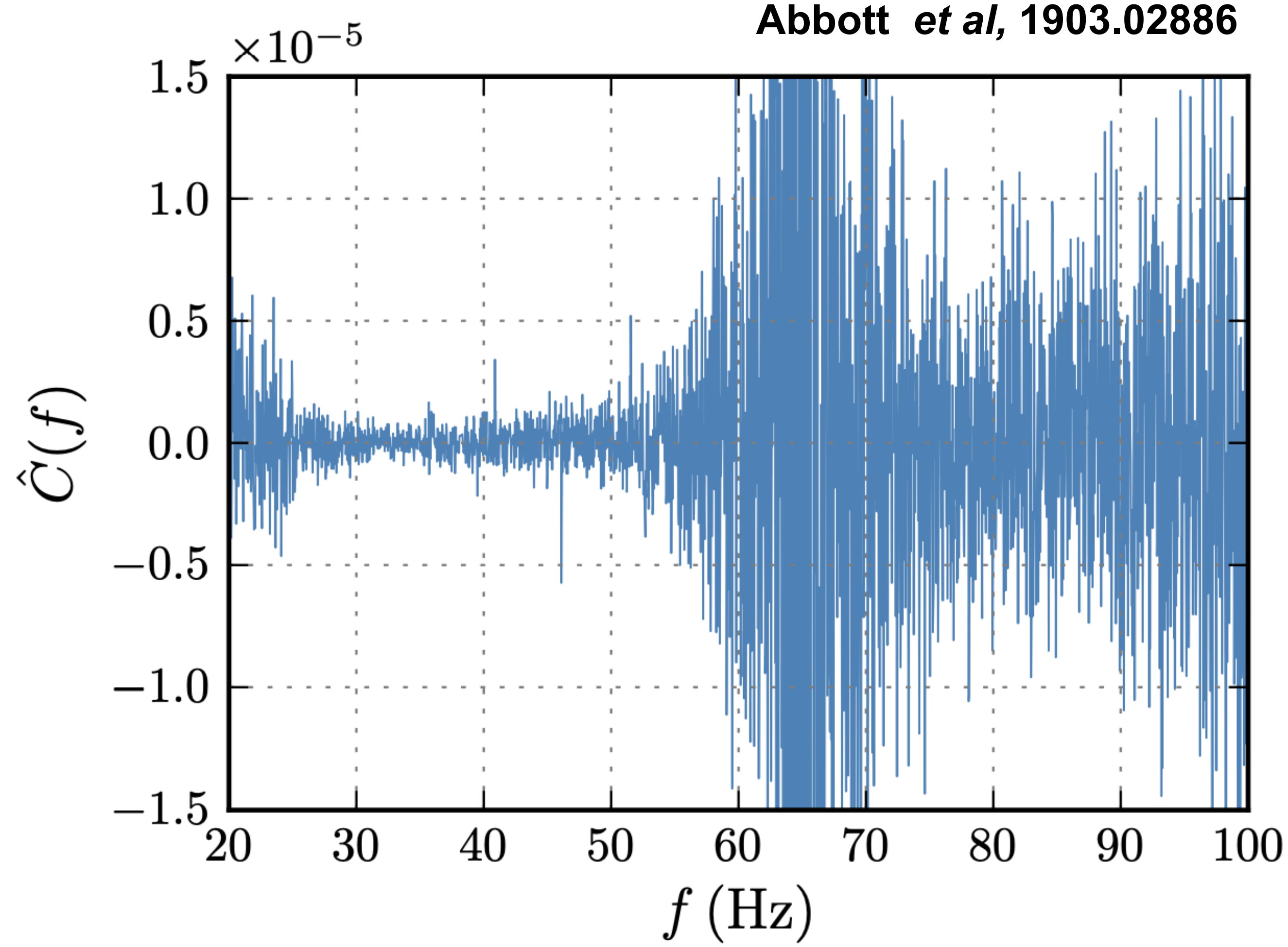
Covas et al, Phys.Rev. D97 (2018) no.8, 082002

Cross-correlation spectrum

Representation of data in form useful for stochastic searches

Spectrum consistent with Gaussian, un-correlated noise

Abbott *et al*, 1903.02886

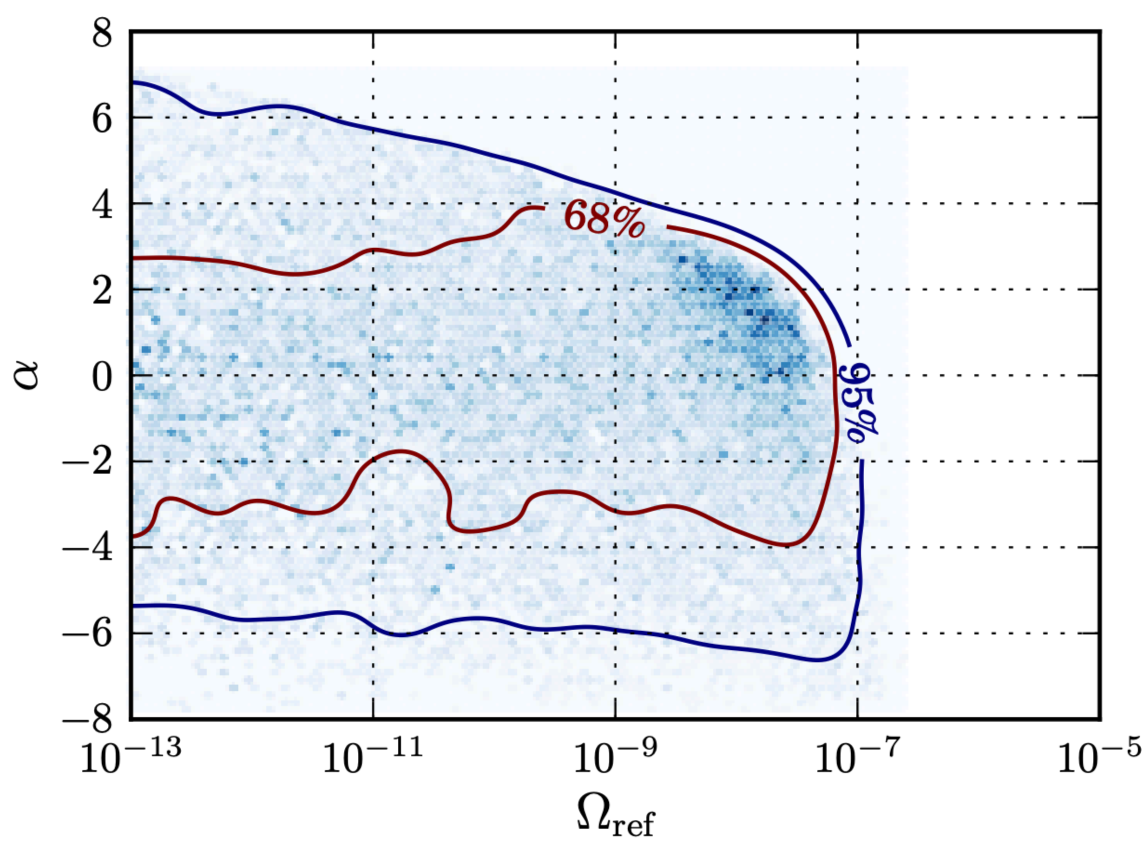


α	$\hat{\Omega}_{\rm ref}$ (O2)	$\hat{\Omega}_{\rm ref}$ (O1)	O2 Sensitive band
0	$(2.2 \pm 2.2) \times 10^{-8}$	$(4.4 \pm 6.0) \times 10^{-8}$	20-85.8 Hz
2/3	$(2.0 \pm 1.6) \times 10^{-8}$	$(3.5 \pm 4.4) \times 10^{-8}$	20-98.2 Hz
3	$(3.5 \pm 2.8) \times 10^{-9}$	$(3.7 \pm 6.6) \times 10^{-9}$	20-305 Hz

* Increase in sensitivity is more than "O1 + longer integration time"

Upper limits

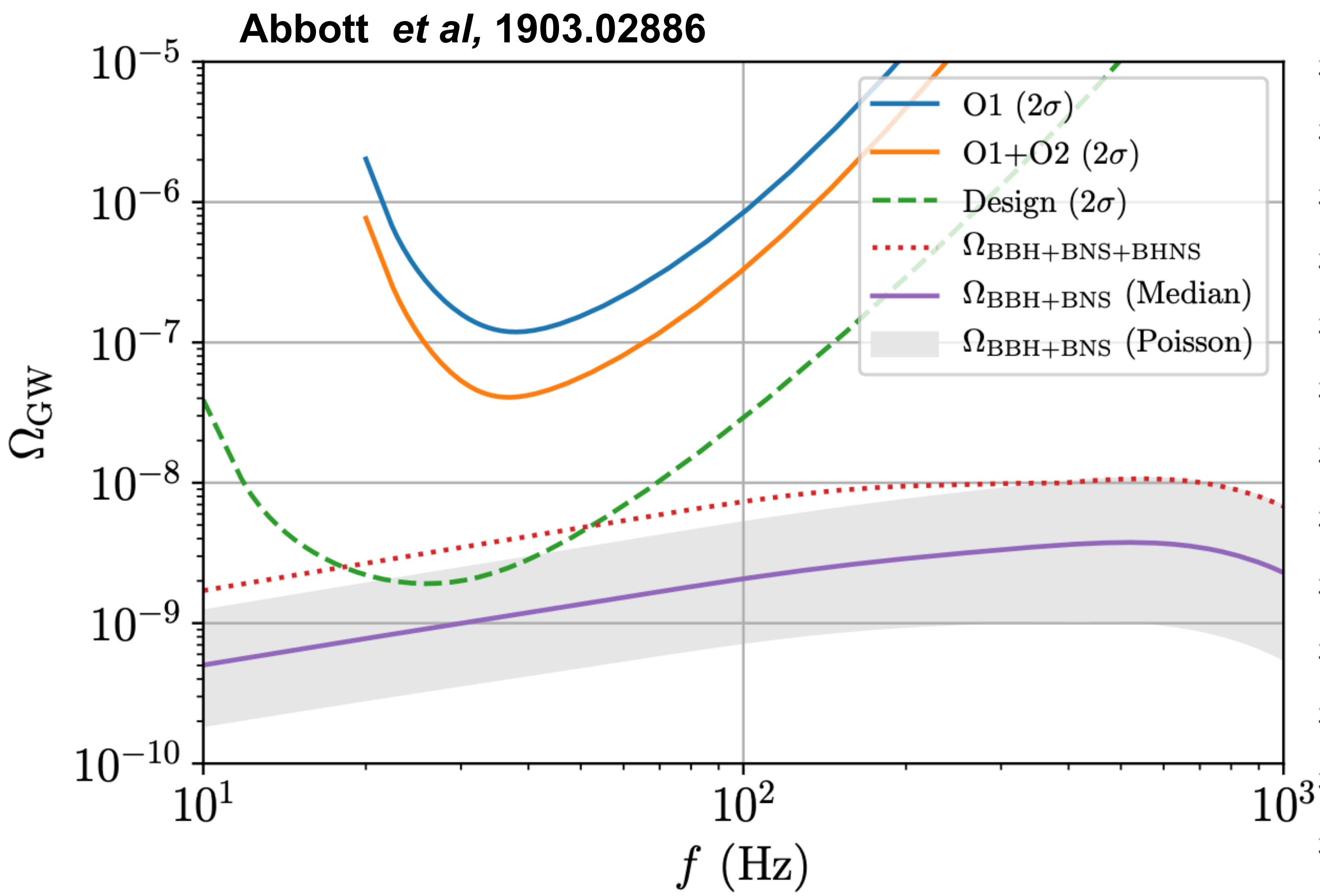
	Uniform prior		Log-uniform prior	
α	O1+O2	O1	O1+O2	O1
0	6.0×10^{-8}	1.7×10^{-7}	3.5×10^{-8}	6.4×10^{-8}
2/3	4.8×10^{-8}	1.3×10^{-7}	3.0×10^{-8}	5.1×10^{-8}
3	7.9×10^{-9}	1.7×10^{-8}	5.1×10^{-9}	6.7×10^{-9}
Marg.	1.1×10^{-7}	2.5×10^{-7}	3.4×10^{-8}	5.5×10^{-8}



* Improvement over O1 by about a factor of 2.8

Abbott *et al*, 1903.02886

Implications for CBC background



predictions

$$\Omega_{\rm BBH}(25\ {\rm Hz}) = 5.3^{+4.2}_{-2.5} \times 10^{-10}$$

$$\Omega_{\rm BNS}(25\ {\rm Hz}) = 3.6^{+8.4}_{-3.1} \times 10^{-10}$$

$$\Omega_{\rm BBH+BNS}(25\ {\rm Hz}) = 8.9^{+12.6}_{-5.6} \times 10^{-10}$$

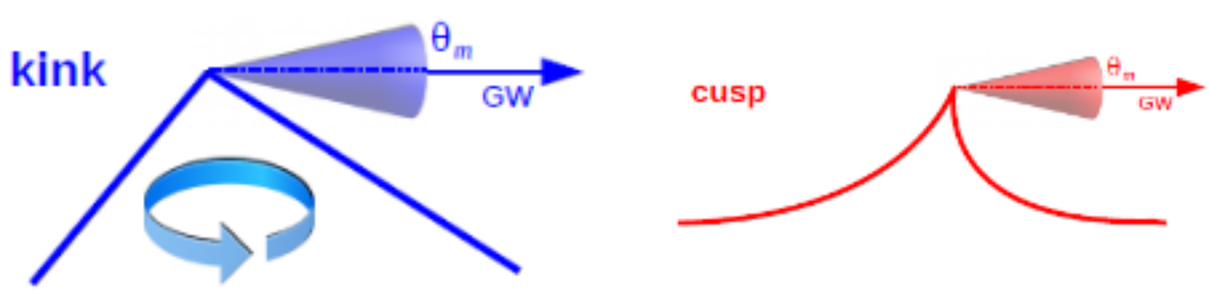
upper limit $\Omega_{\rm BHNS}(25\ {\rm Hz}) = 9.1 \times 10^{-10}$

$$\Omega_{\rm GW}(f,\theta_k) = \frac{f}{\rho_c H_0} \int_0^{z_{\rm max}} {\rm d}z \frac{R_m(z,\theta_k)\frac{{\rm d}E_{\rm GW}(\theta_k)}{{\rm d}f}}{(1+z)E(\Omega_M,\Omega_\Lambda,z)}$$

May detect background at design sensitivity

Implications for cosmic string background

- Cusps and kinks in network of cosmic strings can produce gravitational waves



c/o Florent Robinet

- Place upper limits on string tension within the context of 2 different models of string network

Blanco-Pillado et al $G\mu/c^2 \leq 1.1 \times 10^{-6}$

Lorenz et al $G\mu/c^2 \leq 2.1 \times 10^{-14}$

Abbott *et al*, 1903.02886

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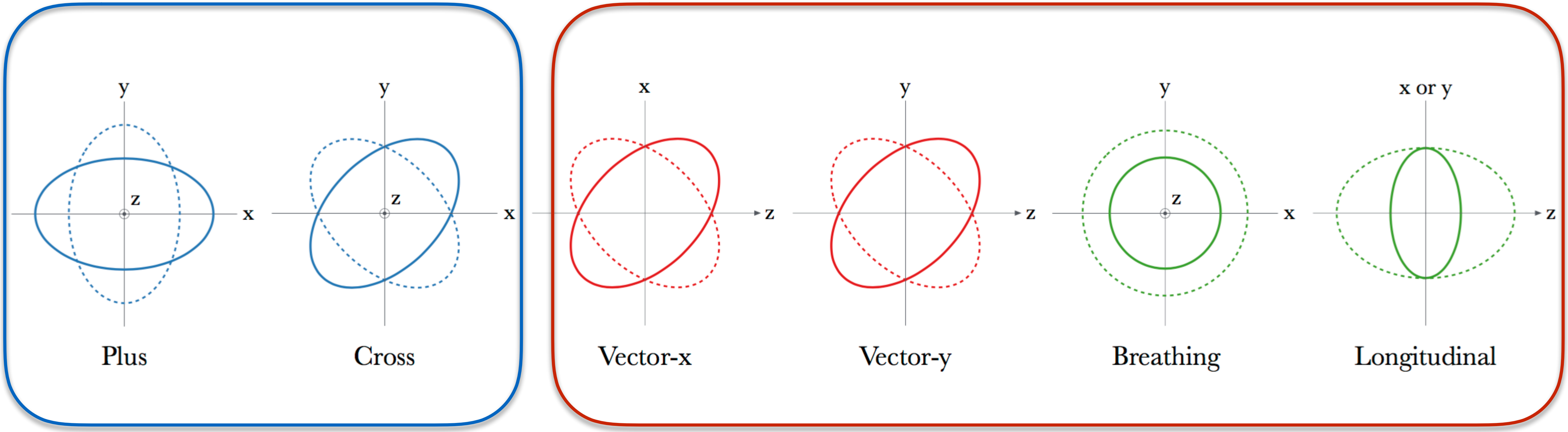
Non-tensor polarizations

Abbott *et al*, 1903.02886

6 polarizations for a symmetric 3x3 tensor



Predicted by GR **Modification of GR**

With uniform prior, obtain limits on backgrounds of each polarization

$$\Omega_T < 8.2 \times 10^{-8} \qquad \Omega_S < 4.2 \times 10^{-7}$$

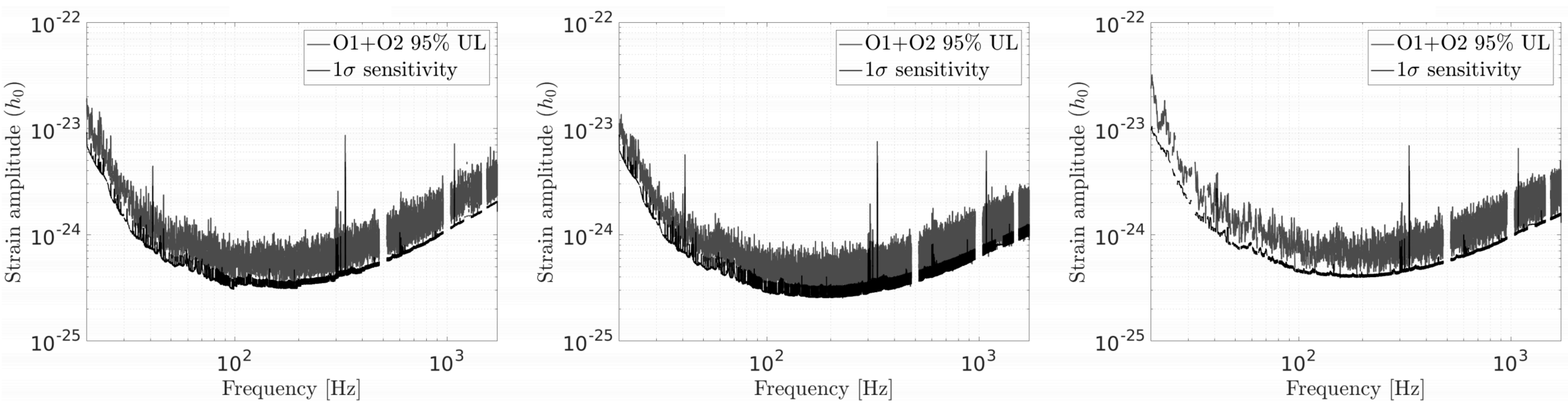
$$\Omega_V < 1.2 \times 10^{-7}$$

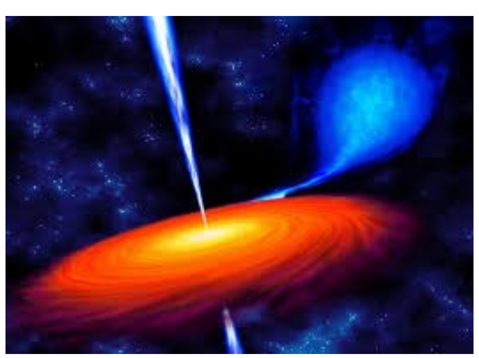
Directional searches: narrowband sources

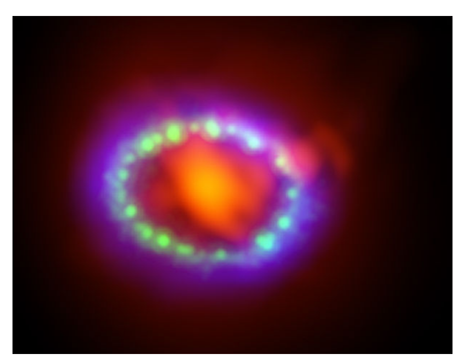
Abbott *et al*, 1903.08844

Narrowband Radiometer Results

Direction	Max SNR	p-value (%)	Frequency (Hz) ($\pm$ 0.016 Hz)	Best UL ($\times 10^{-25}$)	Frequency band (Hz)
Sco X-1	4.80	4.5	1602.09	4.2	183.6 – 184.6
SN 1987A	4.95	1.7	181.81	3.6	247.75 – 248.75
Galactic Center	3.80	98	20.28	4.7	156.8 – 157.8







36.06 Hz frequency bin marginally significant in ScoX-1 direction in O2 (but not O1+O2)

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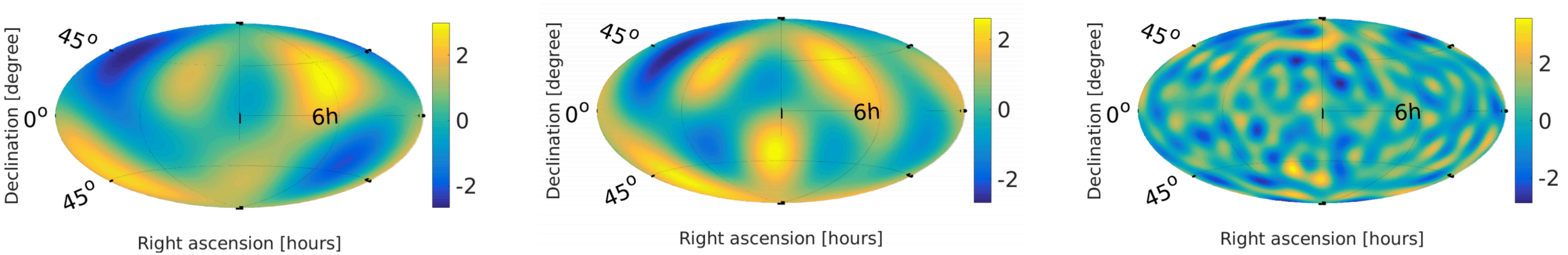
Directional search: broadband sources

All-sky (broadband) Results

α	$\Omega_{\rm gw}$	$H(f)$	Max SNR (% p-value) BBR	Max SNR (% p-value) SHD	Upper limit ranges BBR ($\times 10^{-8}$)	Upper limit ranges SHD ($\times 10^{-8}$)	O1 Upper limit ranges BBR ($\times 10^{-8}$)	O1 Upper limit ranges SHD ($\times 10^{-8}$)
0	constant	$\propto f^{-3}$	3.09 (9)	2.98 (9)	4.4 – 25	0.78 – 2.90	15 – 65	3.2 – 8.7
2/3	$\propto f^{2/3}$	$\propto f^{-7/3}$	3.09 (20)	2.61 (31)	2.3 – 14	0.64 –2.47	7.9 – 39	2.5 – 6.7
3	$\propto f^{3}$	constant	3.27 (66)	3.57 (27)	0.05 – 0.33	0.19 – 1.1	0.14 – 1.1	0.5 – 3.1



Abbott *et al*, 1903.08844

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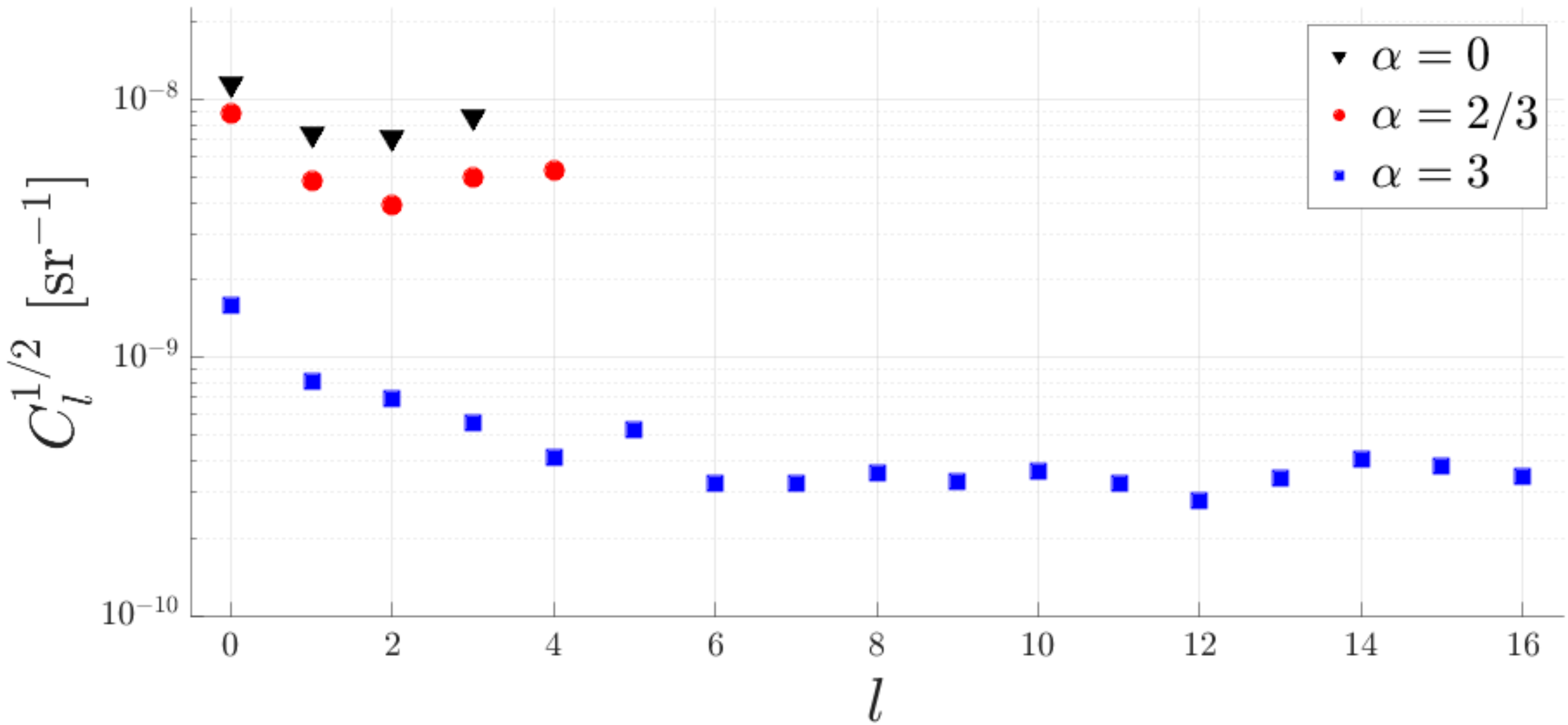
Directional searches: Upper limits on CL



Abbott *et al*, 1903.08844

Magnetic noise

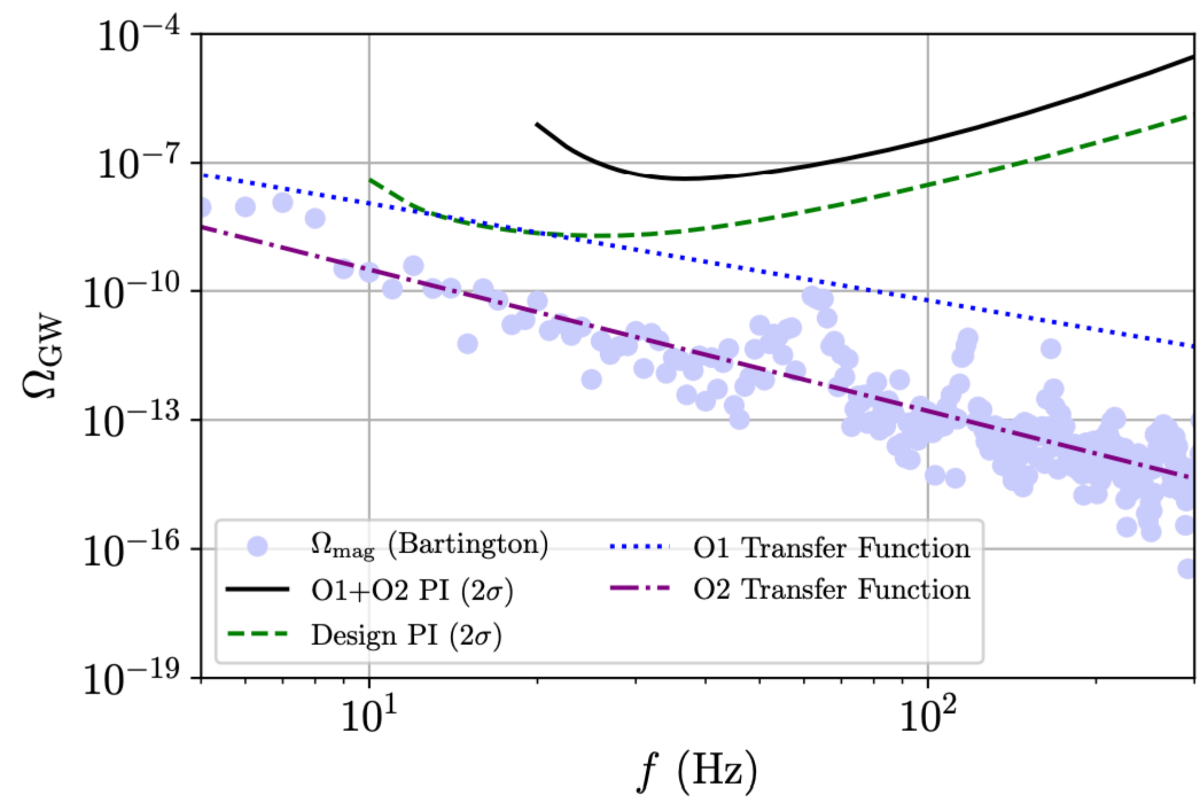
* Global scale Schumann resonances lead to correlated magnetic noise.

* We construct budget using magnetic transfer functions and cross-correlation spectrum between magnetic fields

$$\Omega_{\rm mag}(f) = \frac{|T_1(f)||T_2(f)|{\rm Re}[M_{12}(f)]}{\gamma_T(f) S_0(f)}$$

* Upper limits indicate that this is not an issue in O2, could be in issue in future runs.

* Mitigation strategies being developed including Wiener filtering and Bayesian estimation.



Abbott *et al*, 1903.02886

Summary

- Searched O1 and O2 data for stochastic background, did not detect
- Upper limits placed on the stochastic background
  - isotropic for different spectral shapes
  - non-tensor modes
- Studied implications of results for cosmic string and CBC models
- Detection of CBC background possible at design sensitivity

Extras

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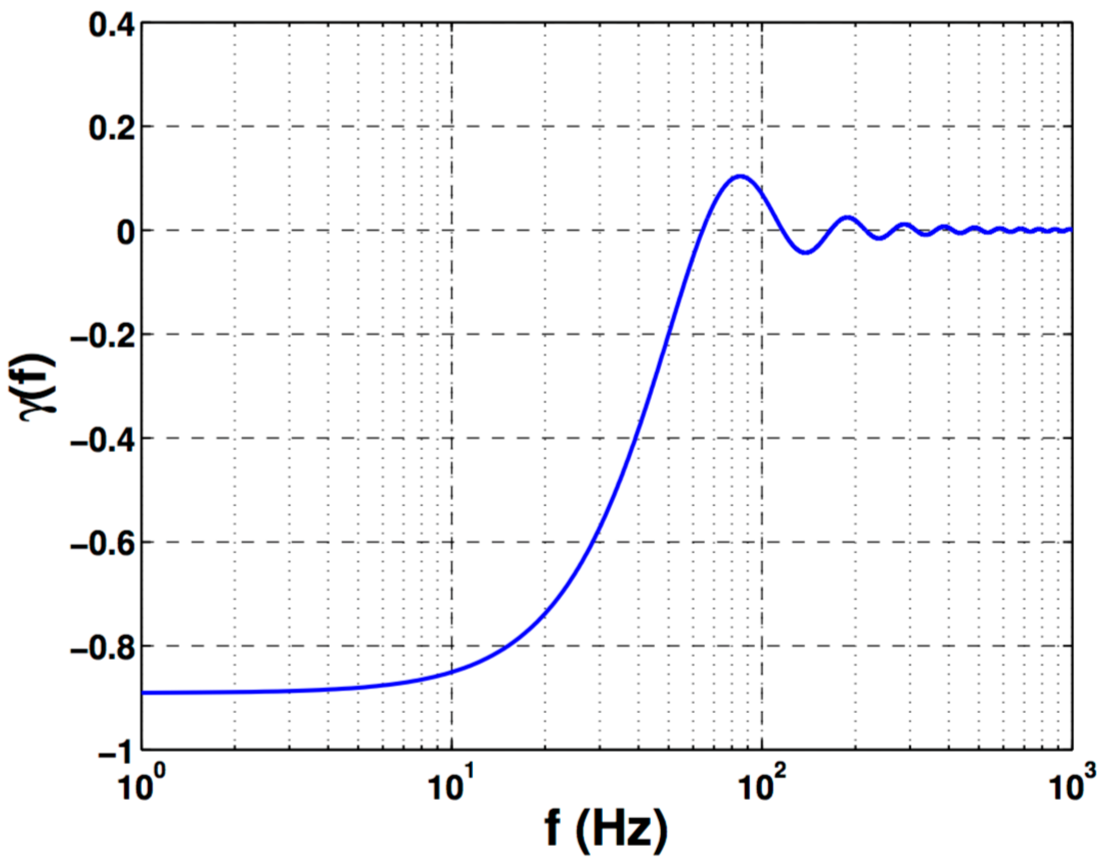
Overlap reduction function

Cross correlation of detector outputs is related to $\Omega_{\rm GW}$

$$\langle \tilde{s}_1(f)^\star \tilde{s}_2(f) \rangle = \frac{3H_0^2}{20\pi^2}\delta(f-f')|f|^{-3}\Omega_{\rm GW}(|f|)\gamma(|f|)$$



Allen and Romano, Phys.Rev. D59 (1999) 102001

Overlap reduction function

$$\gamma(f) := \frac{5}{8\pi}\sum_A \int_{S^2} d\hat{\Omega}\, \underbrace{e^{i2\pi f\hat{\Omega}\cdot\Delta\vec{x}/c}}_{\text{time delay}}\, \underbrace{F_1^A(\hat{\Omega})F_2^A(\hat{\Omega})}_{\text{detector response}}$$

Geometric factor controlling sensitivity

Anisotropic background

$$\langle h_A^*(f,\hat{\Omega}) h_{A'}(f',\hat{\Omega}')\rangle = \frac{1}{4}\boxed{\mathcal{P}(f,\hat{\Omega})}\,\delta(f-f')\delta_{AA'}\delta(\hat{\Omega},\hat{\Omega}')$$

Typically assume $\mathcal{P}(f,\hat{\Omega}) = \mathcal{P}(\hat{\Omega})\bar{H}(f)$

Expand $\mathcal{P}(\Theta)$ in a basis

$$\mathcal{P}(\Theta) = \mathcal{P}_\alpha \mathbf{e}_\alpha(\Theta)$$

$$\mathbf{e}_\alpha(\Theta) = \delta^2(\Theta,\Theta_\alpha)$$

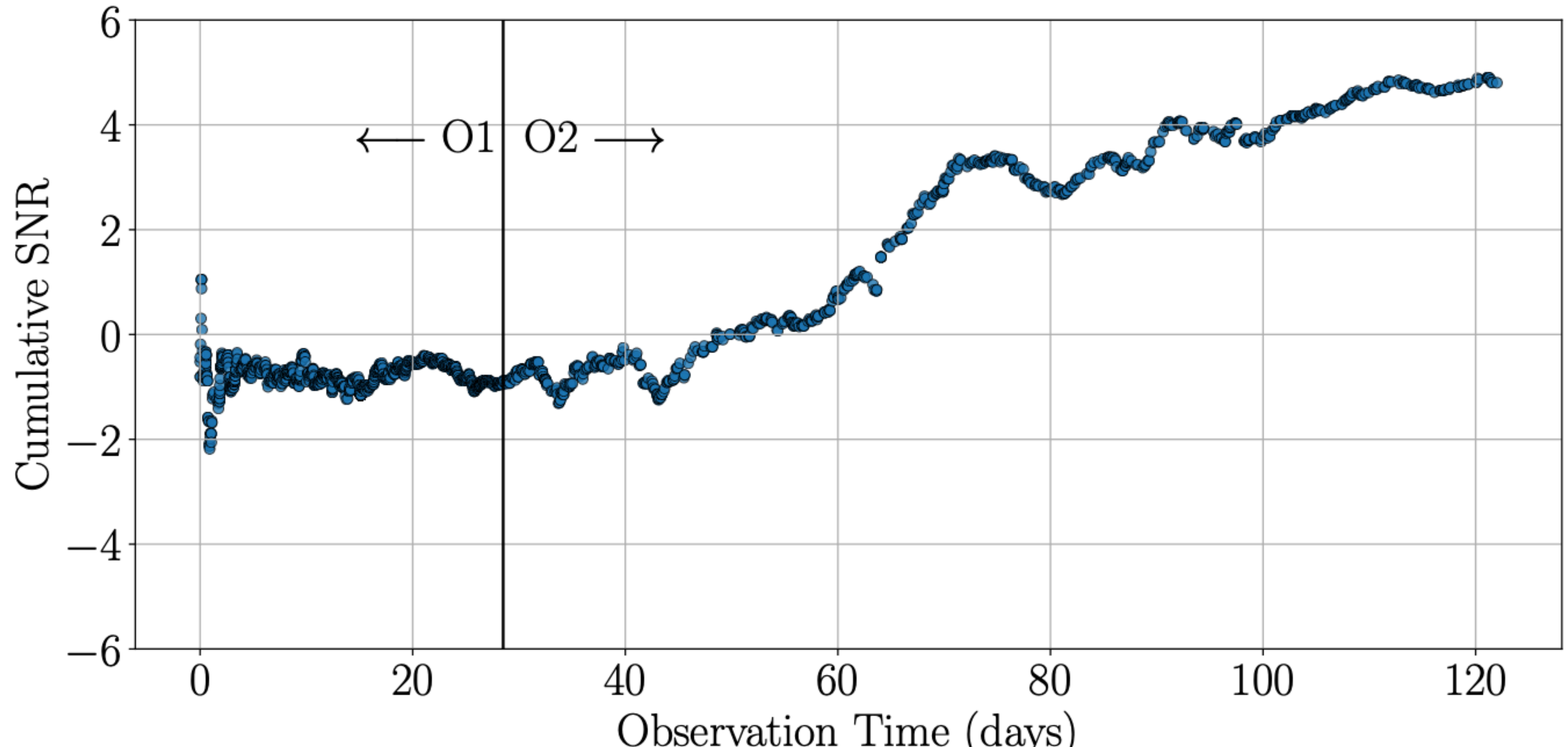
Radiometer search
point sources

$$\mathbf{e}_\alpha(\Theta) = Y_{\ell m}(\Theta)$$

Spherical harmonic search

Abbott *et al,* 1903.08844

Radiometer outlier



- 1 frequency bin at 36.06Hz in direction of SN1987A with marginal significance (3 sigma) in O2
- Not significant combining O1 and O2 (we will learn more in O3)
- If we interpret result as a neutron star at distance of SN1987A, infer ellipticity 3×10^{-2}

Abbott *et al,* 1903.08844