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Searching for the stochastic background with advanced ground based detectors

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Albert Einstein Institute, Potsdam
Dark Odyssey 2020, Seoul National University, 6 January 2020

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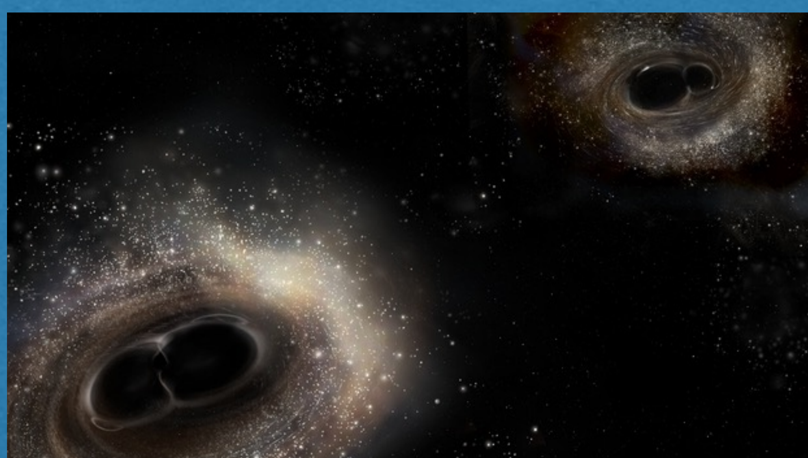
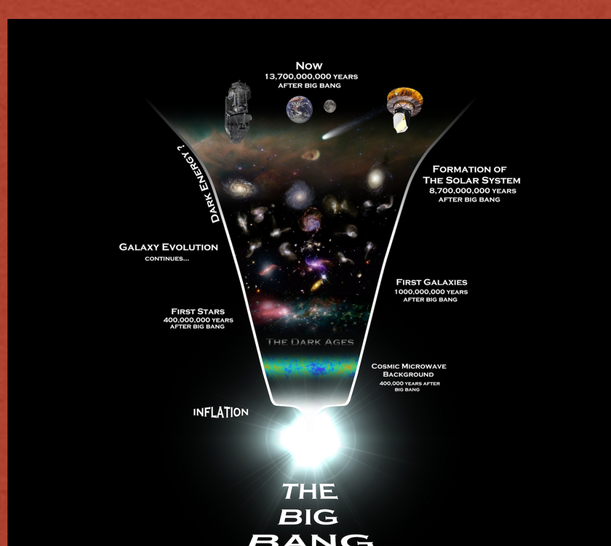
Stochastic gravitational wave background

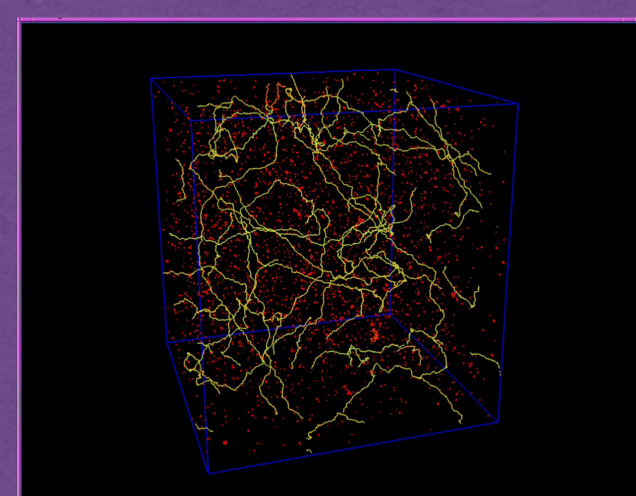
A superposition of astrophysical and cosmological sources, including…



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

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





Cosmic Strings

Cosmological
Phase Transitions

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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

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

signal

noise at 2 widely separated detectors is uncorrelated

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

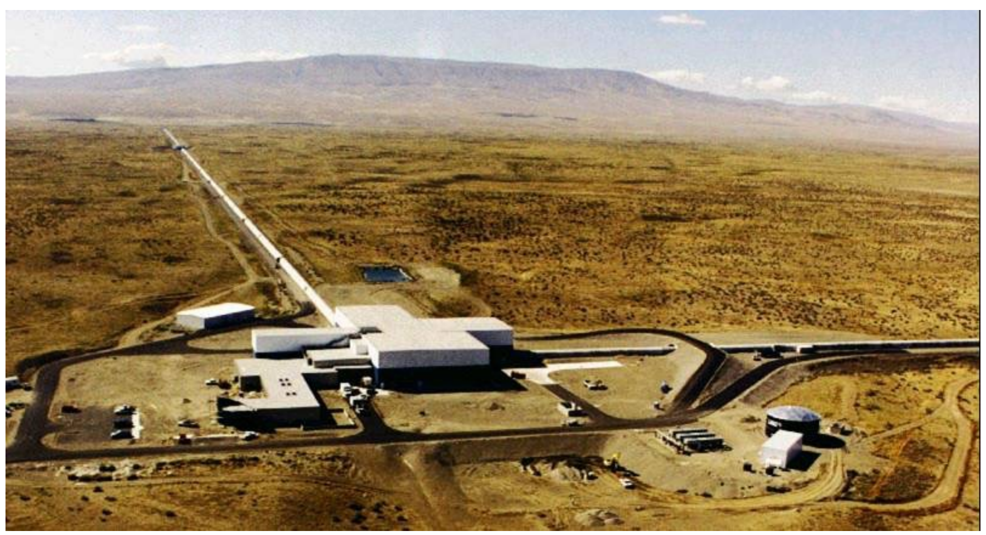
Analysis of LIGO's first two observing runs

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

O2 Results papers

Abbott *et al,* Phys.Rev. D100 (2019) no.6, 061101

Abbott *et al,* Phys.Rev. D100 (2019) no.6, 062001



Hanford, Washington (H1)

Livingston, Louisiana (L1)

Image credit: LIGO Lab

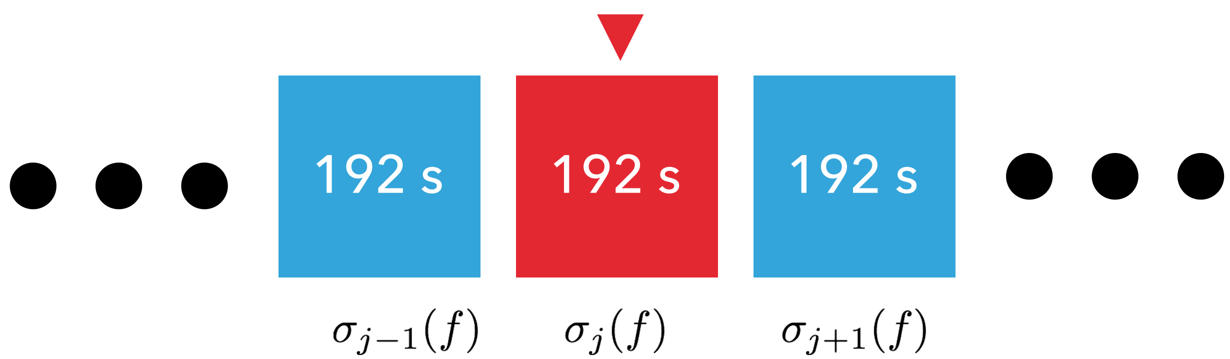
Analysis cuts

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

Abbott *et al,* Phys.Rev. D100 (2019) no.6, 061101

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



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

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

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

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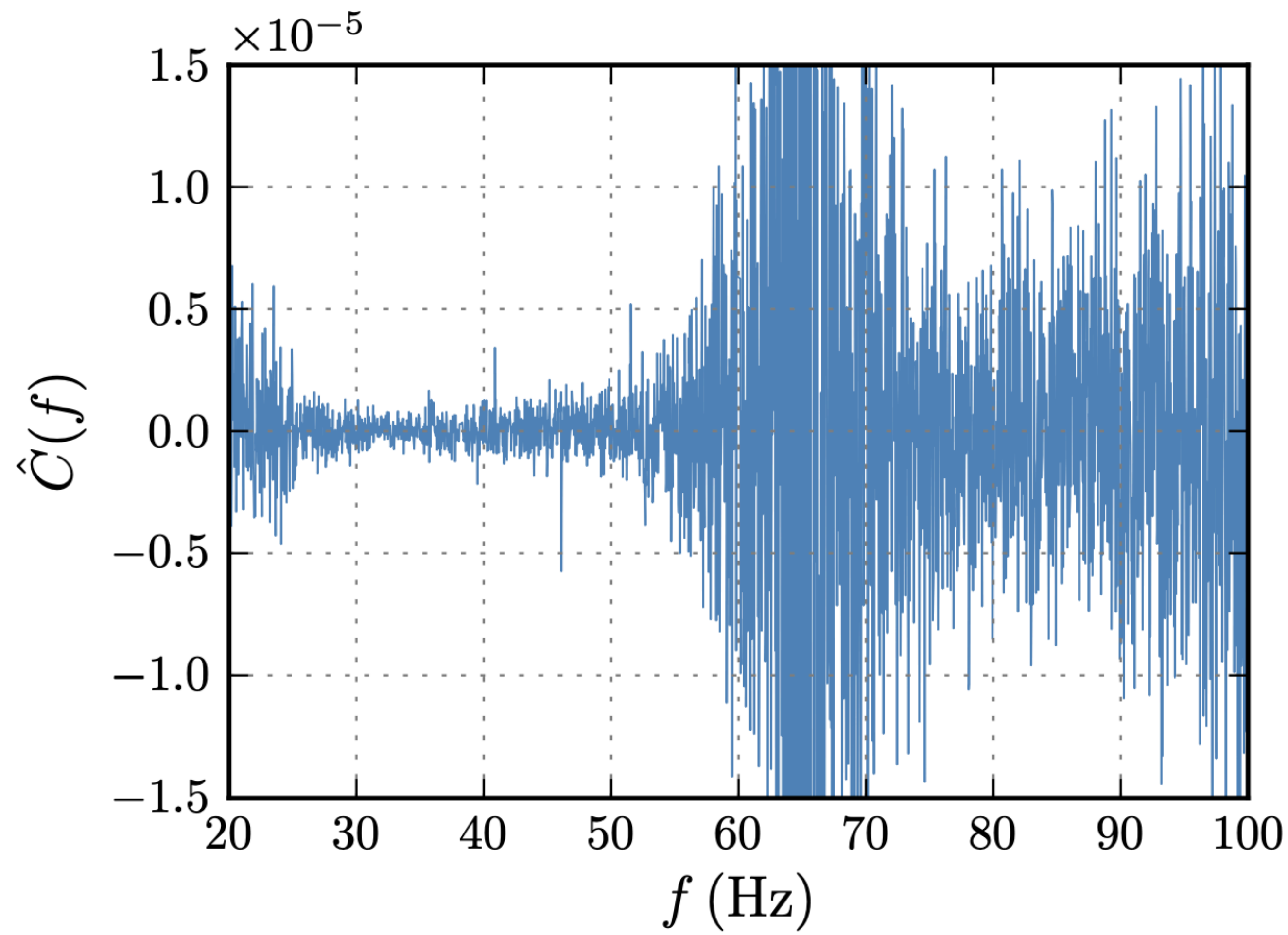
Cross-correlation spectrum

Abbott *et al*, Phys.Rev. D100 (2019) no.6, 061101



Representation of data in form useful for stochastic searches

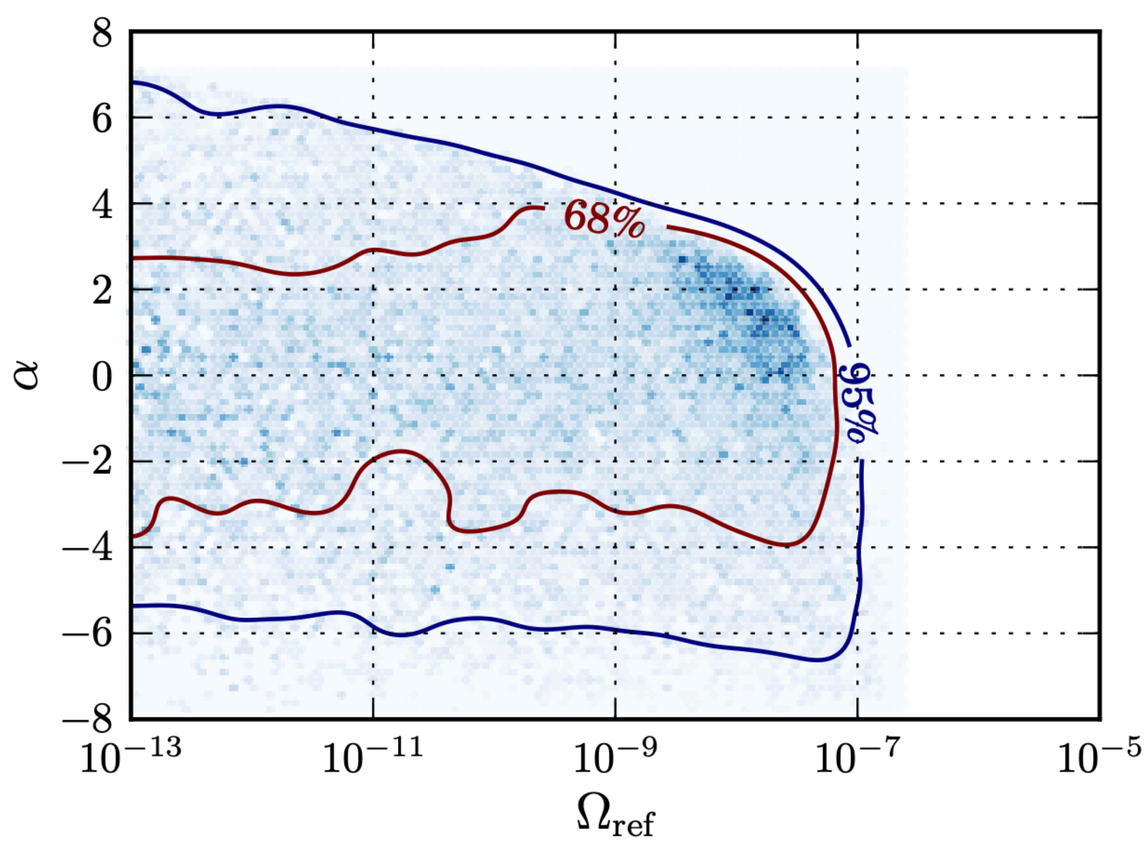
Spectrum consistent with Gaussian, un-correlated noise

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}

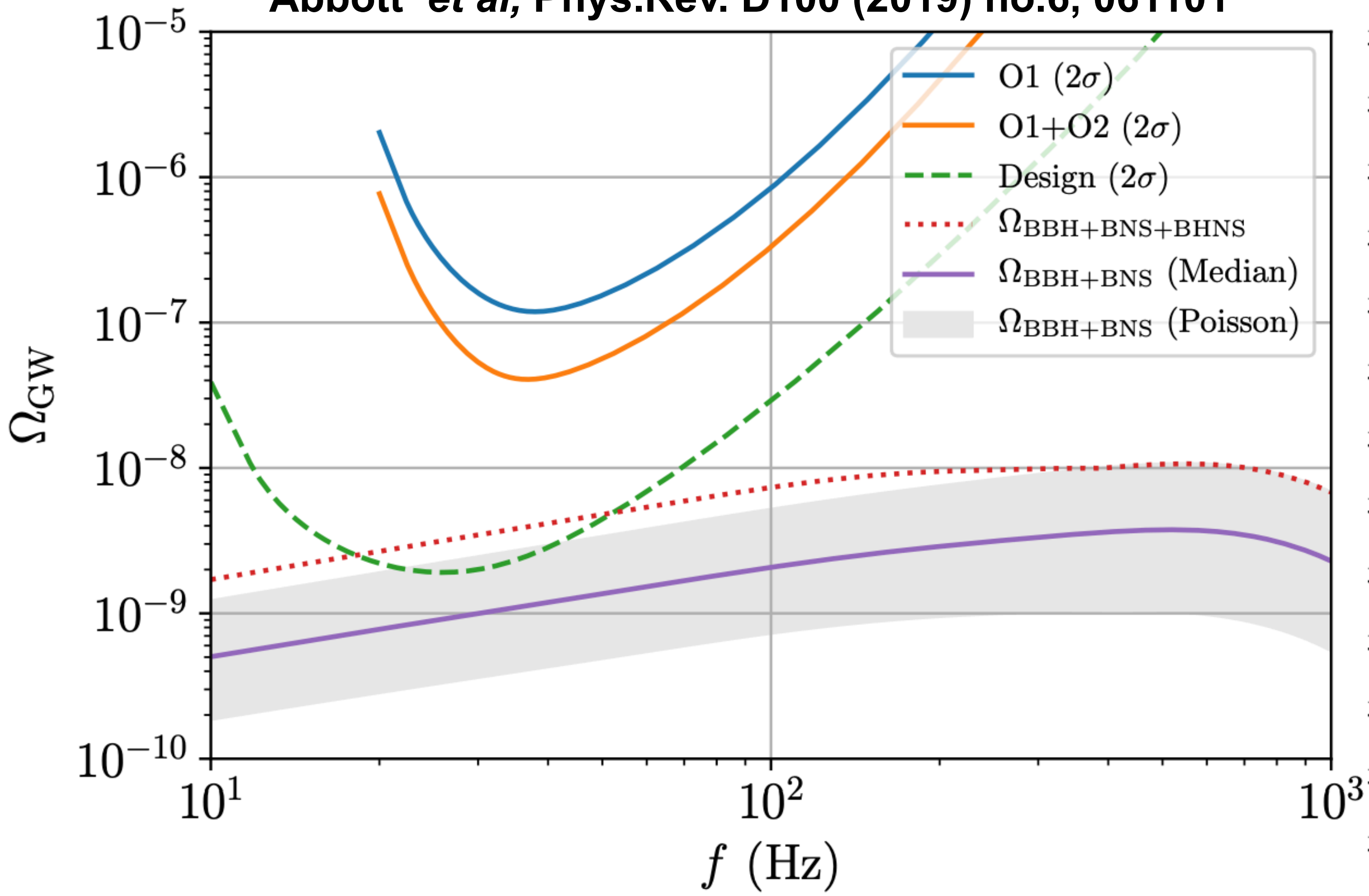


* Improvement over O1 by about a factor of 2.8

Abbott *et al,* Phys.Rev. D100 (2019) no.6, 061101

Implications for CBC background

Abbott *et al,* Phys.Rev. D100 (2019) no.6, 061101



predictions

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

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

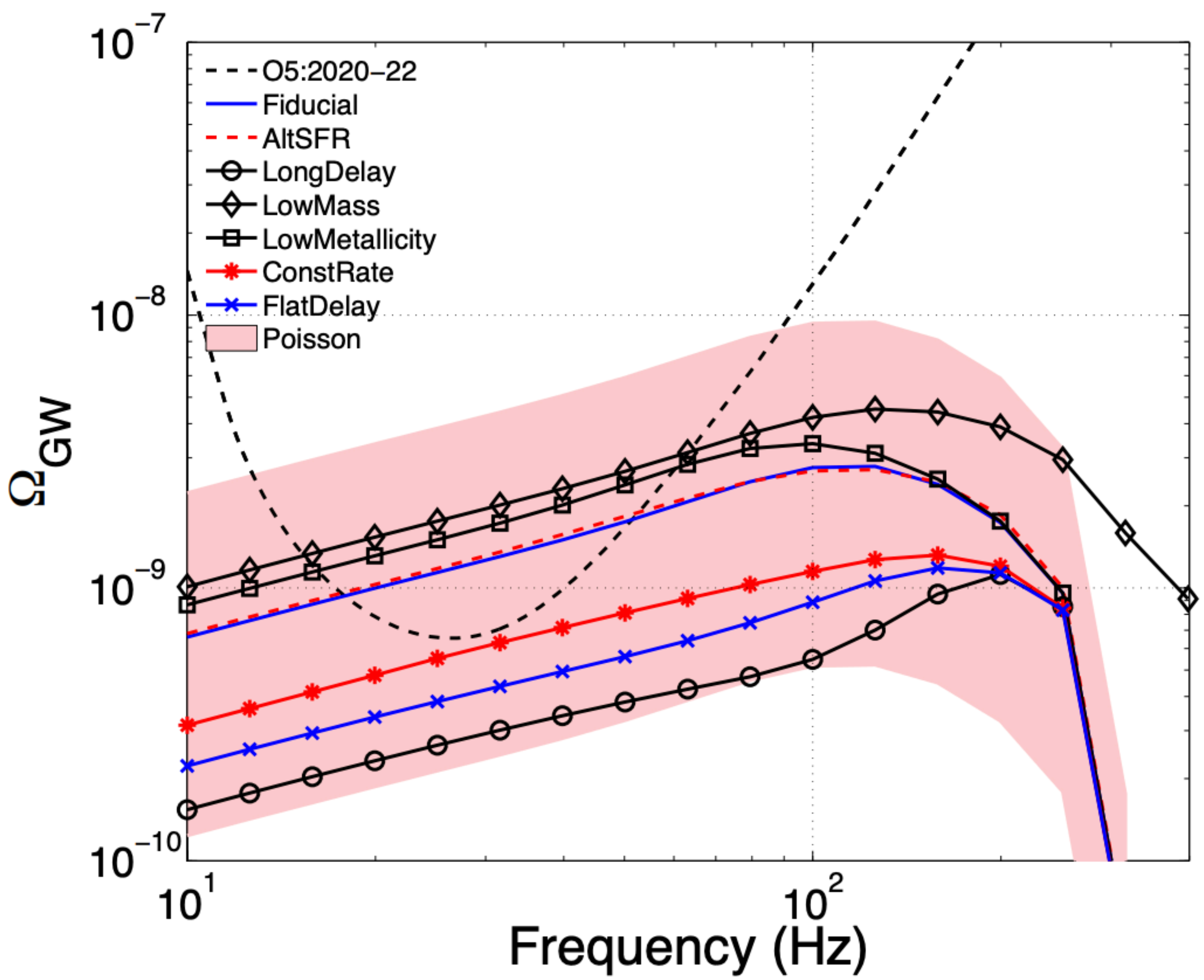
$$\Omega_{\rm BBH+BNS}(25\ {\rm Hz}) = 8.9^{+12.6}_{-5.6} \times 10^{-10}$$

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

Model variations



Abbott et al, Phys.Rev.Lett. 116 (2016) no.13, 131102

Fiducial: Mass distribution centered on 150914 mass parameters

AltSFR: use star formation rate from Tonnotore et al

LongDelay: minimum time delay 5 Gyr

LowMass: add component

LowMetallicity: Metallicity to form heavy BH

$$Z_c = Z_{\odot}/10$$

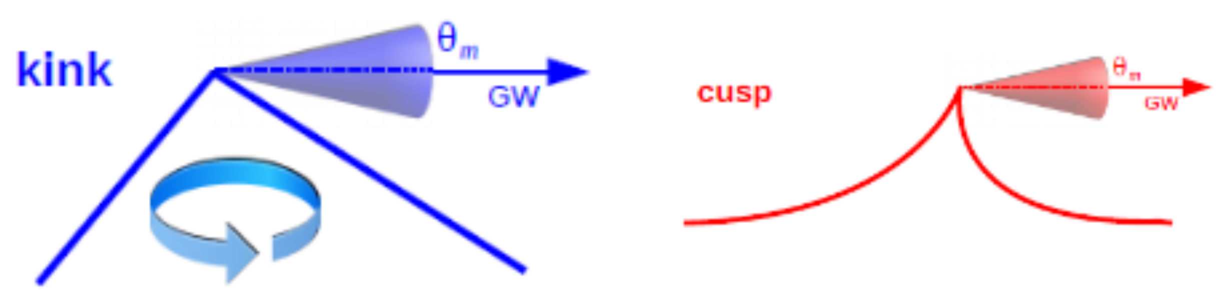
ConstRate: z-independent merger rate

FlatDelay: Assume flat time delay distribution

Model variations contained in Poisson errors

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,* Phys.Rev. D100 (2019) no.6, 061101

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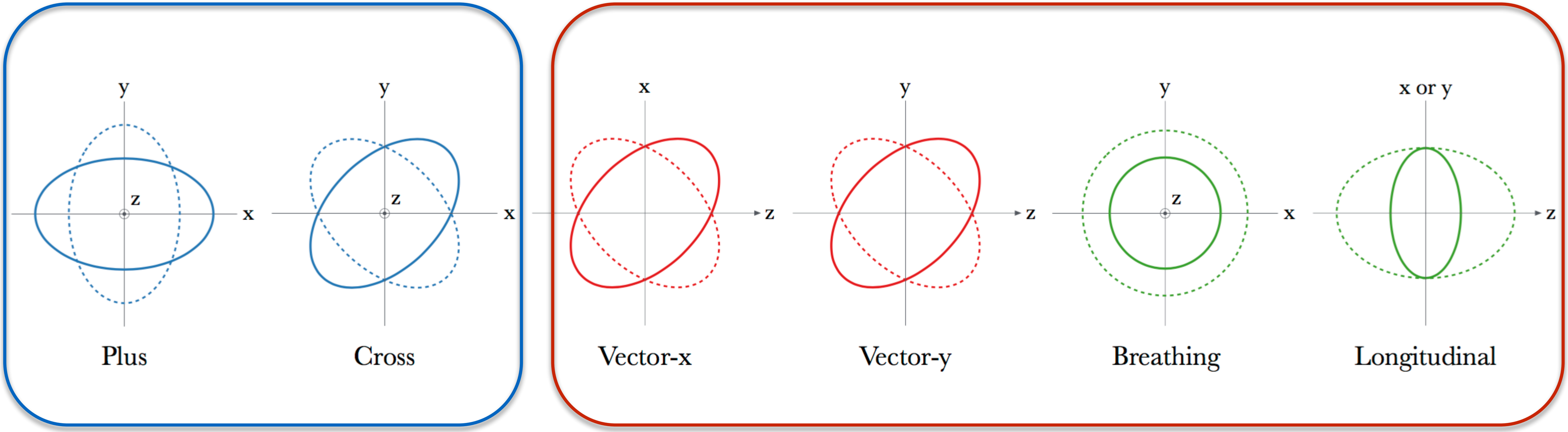
Non-tensor polarizations

Abbott *et al,* Phys.Rev. D100 (2019) no.6, 061101

6 polarizations for a symmetric 3x3 tensor



Predicted by GR **Modification of GR**

With uniform prior, obtain limits on backgrounds of each polarization

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

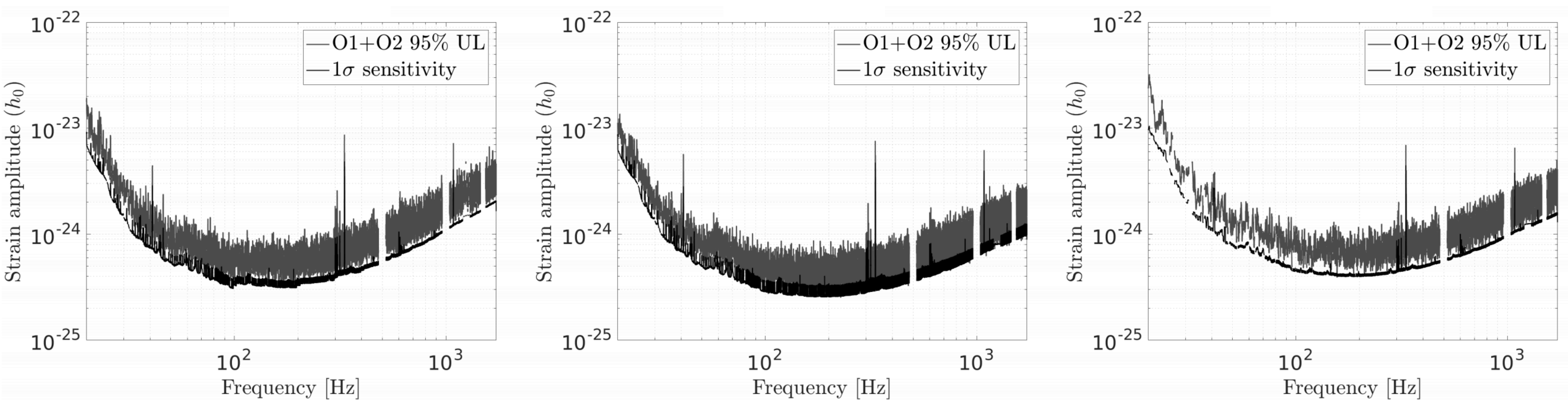
$$\Omega_V < 1.2 \times 10^{-7}$$

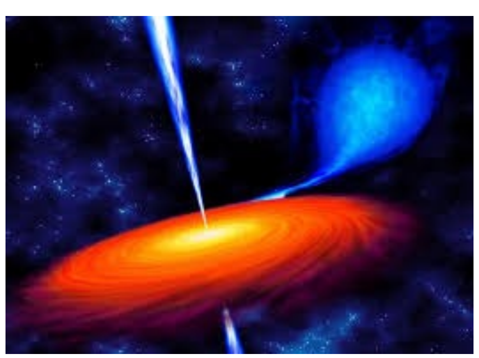
Directional searches: narrowband sources

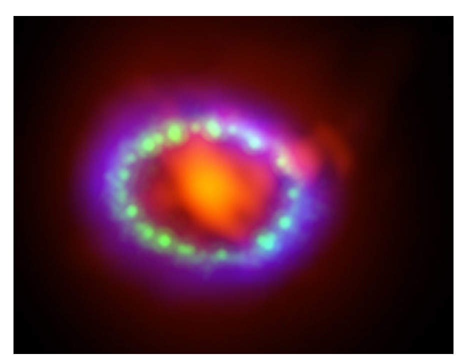
Abbott *et al*, Phys.Rev. D100 (2019) no.6, 062001

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



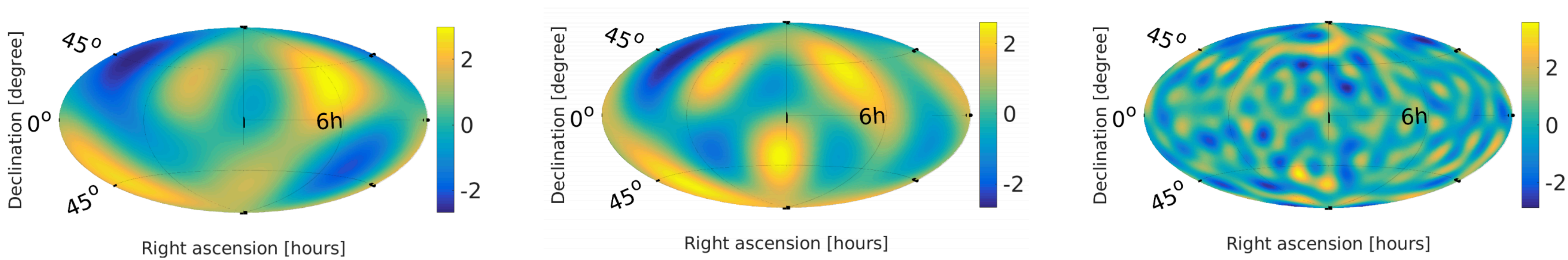




36.06 Hz frequency bin marginally significant in ScoX-1 direction in O2 (but not O1+O2)

Directional search: broadband sources

			Max SNR (% p-value)		Upper limit ranges		O1 Upper limit ranges	
					All-sky (broadband) Results			
α	$\Omega_{\rm gw}$	$H(f)$	BBR	SHD	BBR ($\times 10^{-8}$)	SHD ($\times 10^{-8}$)	BBR ($\times 10^{-8}$)	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,* Phys.Rev. D100 (2019) no.6, 062001

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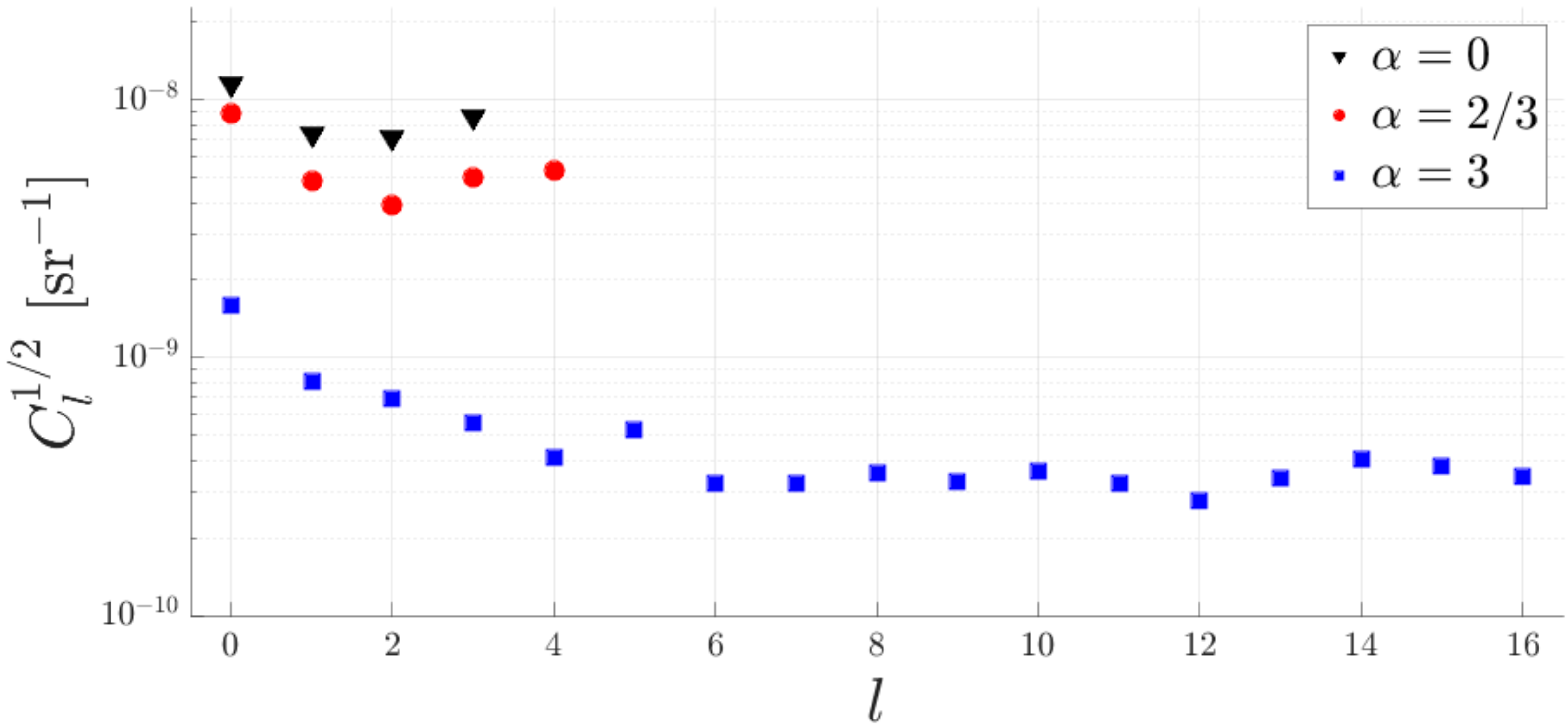
Directional searches: Upper limits on CL



Abbott *et al,* Phys.Rev. D100 (2019) no.6, 062001

Approaching esign sensitivity for detector network

- At design sensitivity, expect sensitivity to a flat background to be ~1e-9 at 25 Hz
- Including more detectors in the network can…
  - Improve sensitivity to isotropic background for larger power laws **Thrane and Romano, Phys.Rev. D88 (2013) no.12, 124032**
  - Reduce bias in constructing sky maps **Thrane et al, Phys.Rev. D80 (2009) 122002**
  - Distinguish between non-GR polarizations

    Callister et al, Phys.Rev. X7 (2017) no.4,

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Magnetic noise

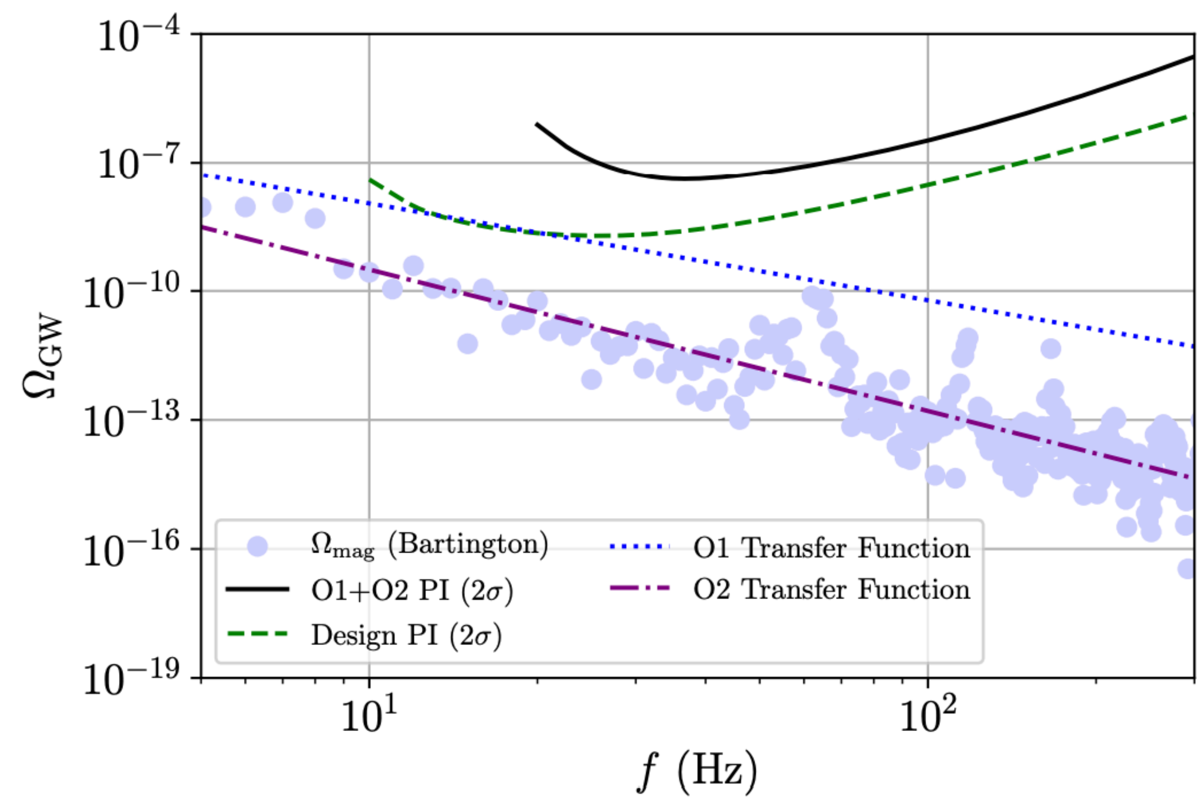
* Global scale Schumann resonances lead to correlated magnetic noise.

* 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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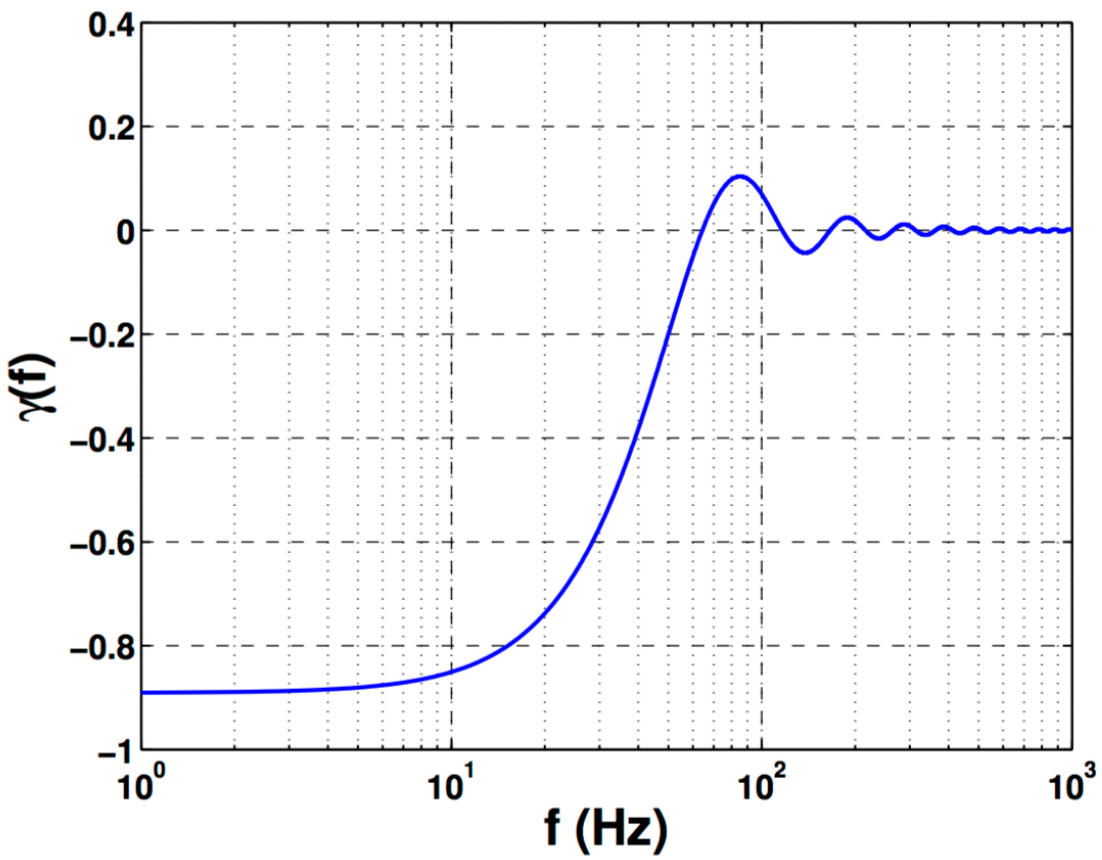
Overlap reduction function

Cross correlation of detector outputs is related to Ω_{GW}

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



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

Overlap reduction function

time delay

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

detector response

Geometric factor controlling sensitivity

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Anisotropic background

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

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

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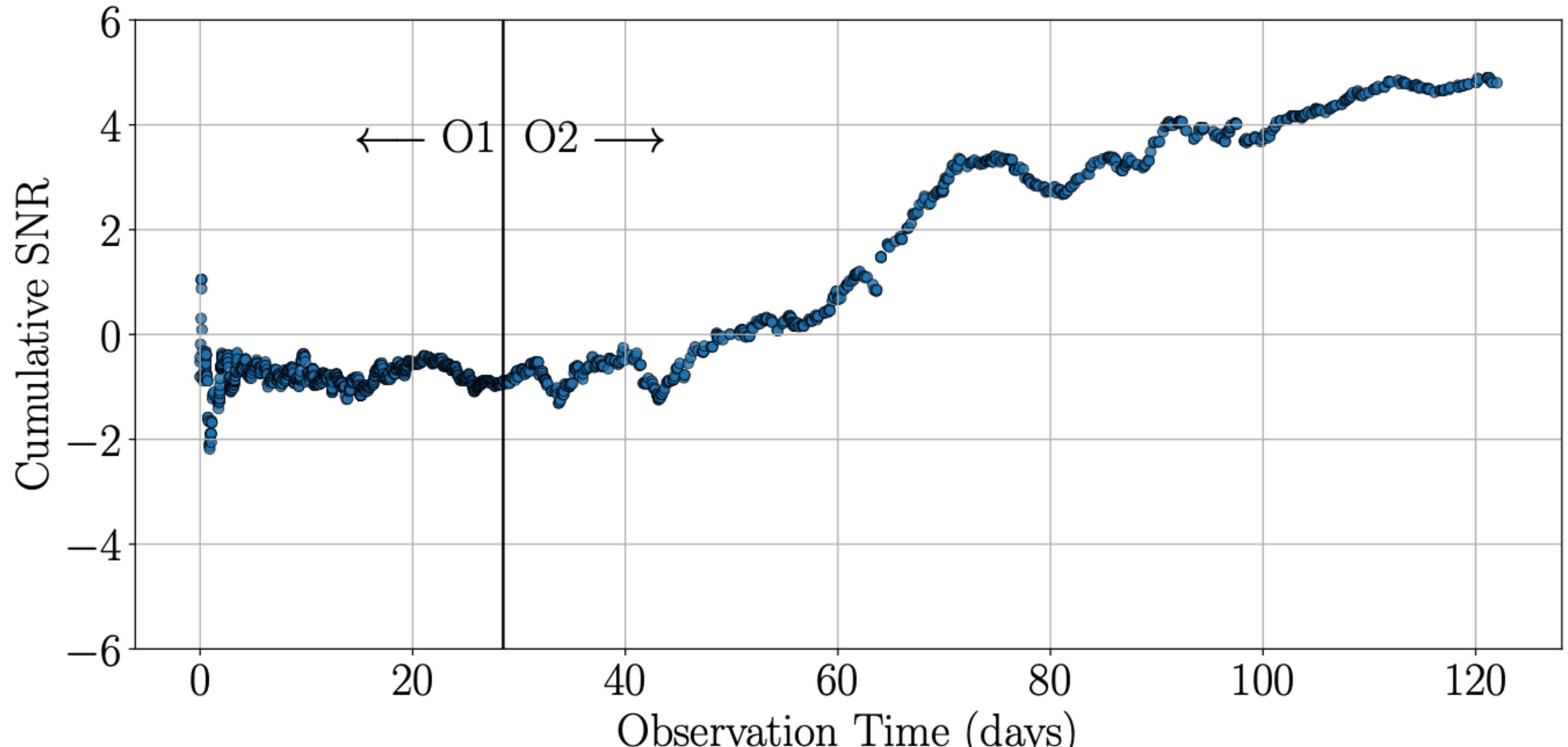
Radiometer outlier



- 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