Searching for the Stochastic Gravitational-Wave Background with Ground-Based Detectors

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Université catholique de Louvain

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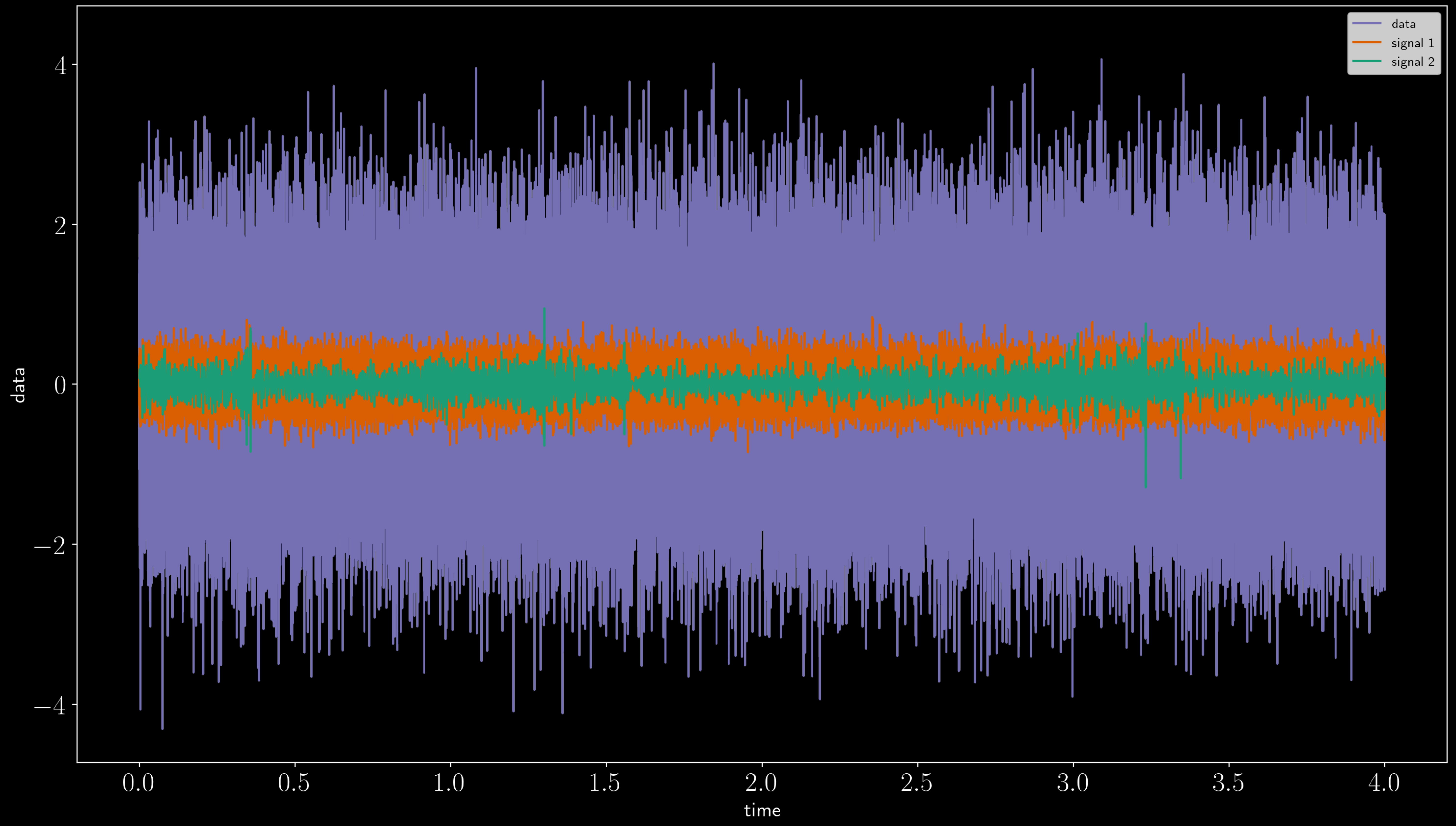
STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

Superposition of signals too weak or too numerous to individually detect

Looks like noise in a single detector

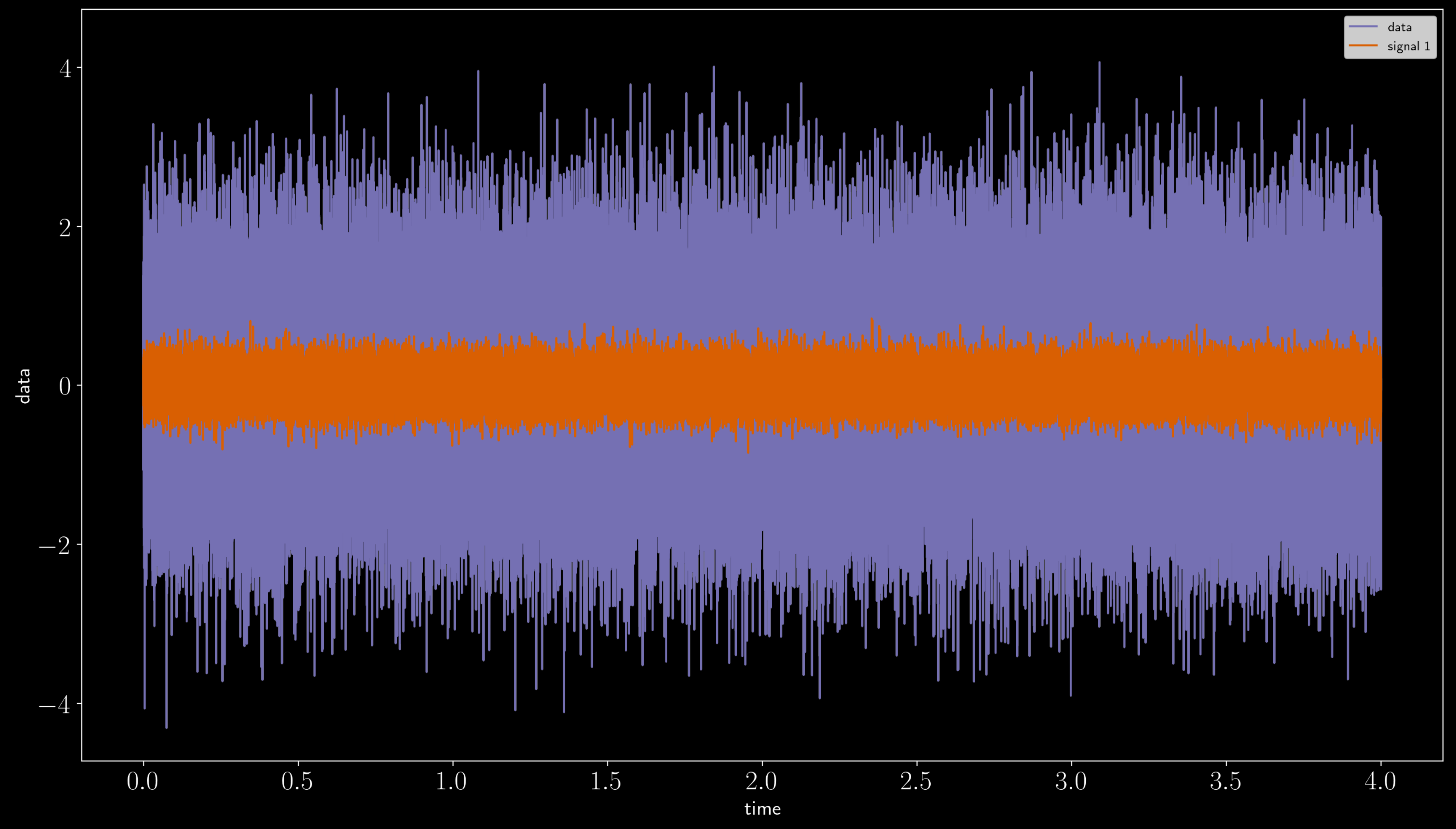
Characterized statistically in terms of moments (ensemble averages) of the metric perturbations



STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

In this talk, we will only consider the following cases

Unpolarized,



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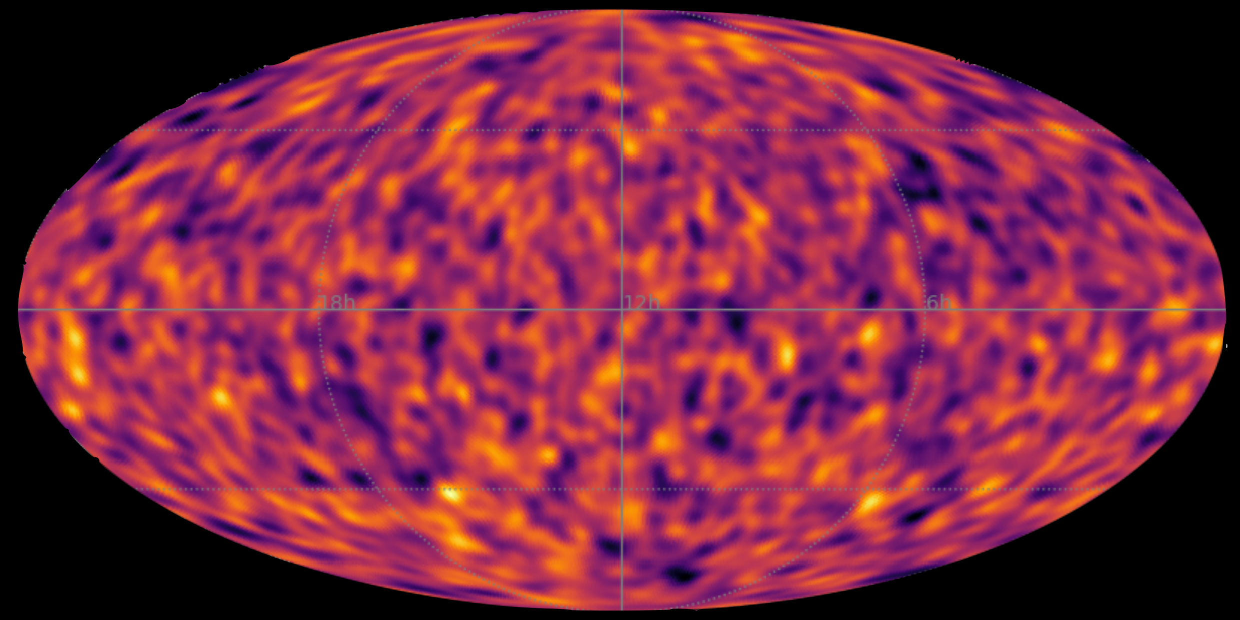

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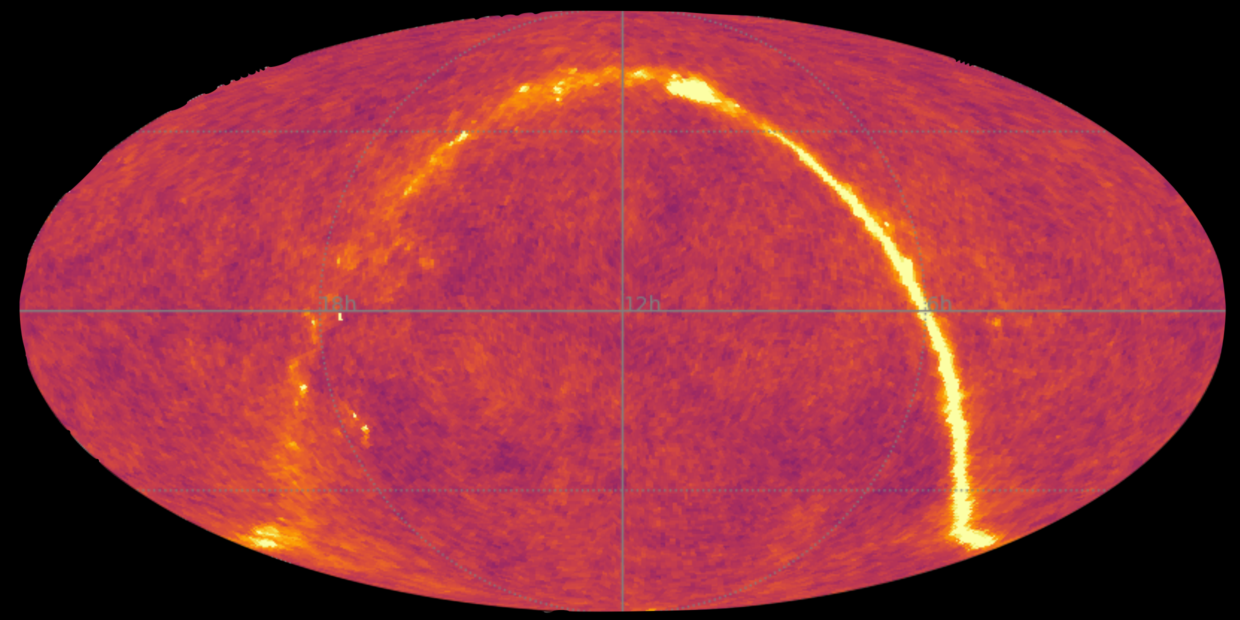

WHAT DETECTION METHODS CAN WE USE?

Problem: The stochastic signal looks more like noise in a single detector.

Solutions:

- Identify features that distinguish between the expected signal and noise.
  - Know our GW detector's noise sources well enough in amplitude and spectral shape.
- For multiple detectors having uncorrelated noise: cross-correlation separates the signal from the noise.

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— For multiple detectors having uncorrelated noise: cross-correlation separates the signal from the noise.

Data from two detectors: $d_1 = h + n_1 \qquad d_2 = h + n_2$ h -> common GW signal component

Cross-correlation: $\langle d_1\, d_2 \rangle = \langle h^2 \rangle + \langle n_1\, n_2 \rangle + \cancelto{0}{\langle h\, n_2 \rangle} + \cancelto{0}{\langle n_1\, h \rangle} = \langle h^2 \rangle + \langle n_1\, n_2 \rangle$

Assuming detector noise is uncorrelated: $\langle d_1\, d_2 \rangle = \langle h^2 \rangle + \cancelto{0}{\langle n_1\, n_2 \rangle}$

$$\langle d_1\, d_2 \rangle = \langle h^2 \rangle \equiv S_h$$

Cross-correlation separates the signal from the noise

Intensity of the background

OPTIMAL FILTERING

What is the optimal way to correlate data from two physically separated and misaligned detectors to search for a SGWB

Cross-correlation estimator $$\hat{S}_h \simeq \int_{-\infty}^{\infty} \mathrm{d}f \int_{-\infty}^{\infty} \mathrm{d}f' \, \delta_T(f-f')\, \tilde{d}_1(f)\, \tilde{d}_2^*(f')\, \tilde{Q}^*(f')$$

Variance $$\sigma^2 \simeq \frac{T}{2} \int_0^{\infty} \mathrm{d}f \, P_1(f)\, P_2(f)\, |\tilde{Q}(f)|^2$$

What we meant by optimal: Choose Q to maximize SNR for fixed spectral shape

$$\tilde{Q}(f) \propto \frac{\Gamma_{12}(f)\, \Omega_t(f)}{P_1(f)\, P_2(f)}$$

expected signal spectrum

Overlap reduction function

de-weight correlation when noise is large

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$$\tilde{Q}(f) \propto \frac{\Gamma_{12}(f)\,\Omega_{\mathrm{t}}(f)}{P_1(f)\,P_2(f)}$$

Overlap reduction function

de-weight correlation
when noise is large

We often choose a power-law functional form for the SGWB template spectrum

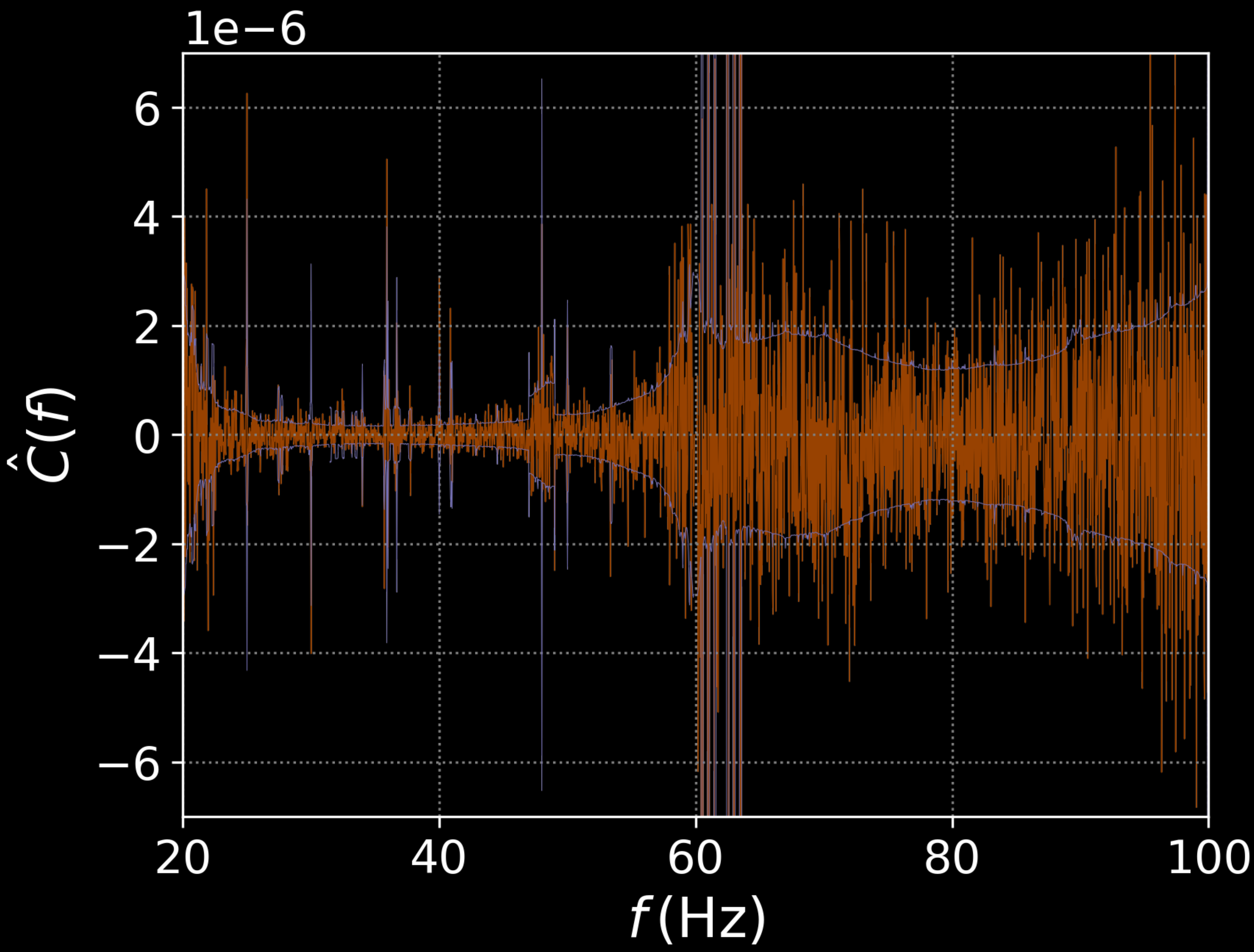
$$\Omega_{\mathrm{t}}(f) = \Omega_{\mathrm{ref}}\left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$$

O3 ISOTROPIC RESULTS

PRD104, 022004 (2021)

O1+O2+O3 RESULTS

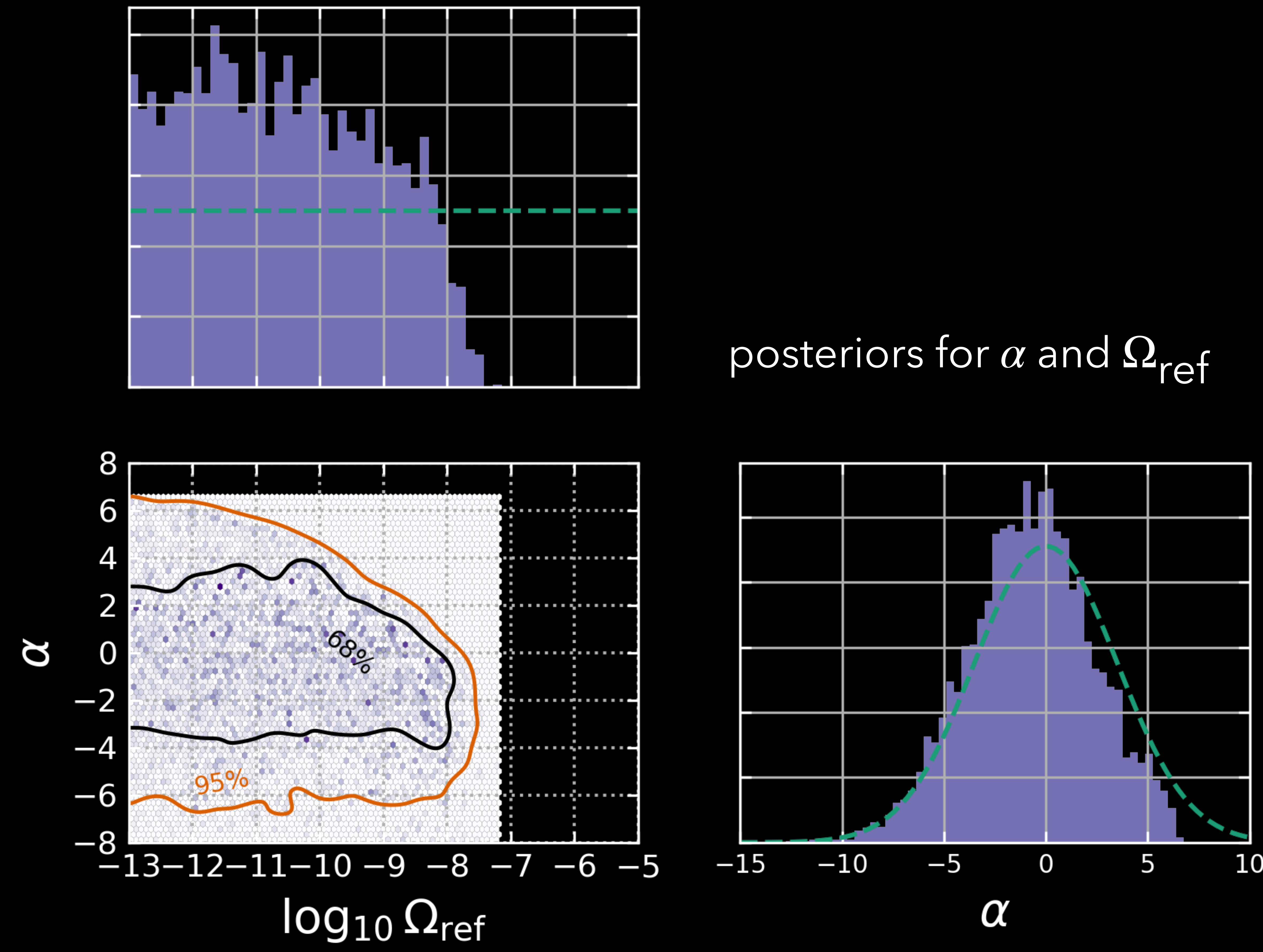
The observed cross-correlation spectra combining data from all three baselines in O3, as well as the HL baseline in O1 and O2. The spectrum is consistent with expectations from uncorrelated, Gaussian noise.



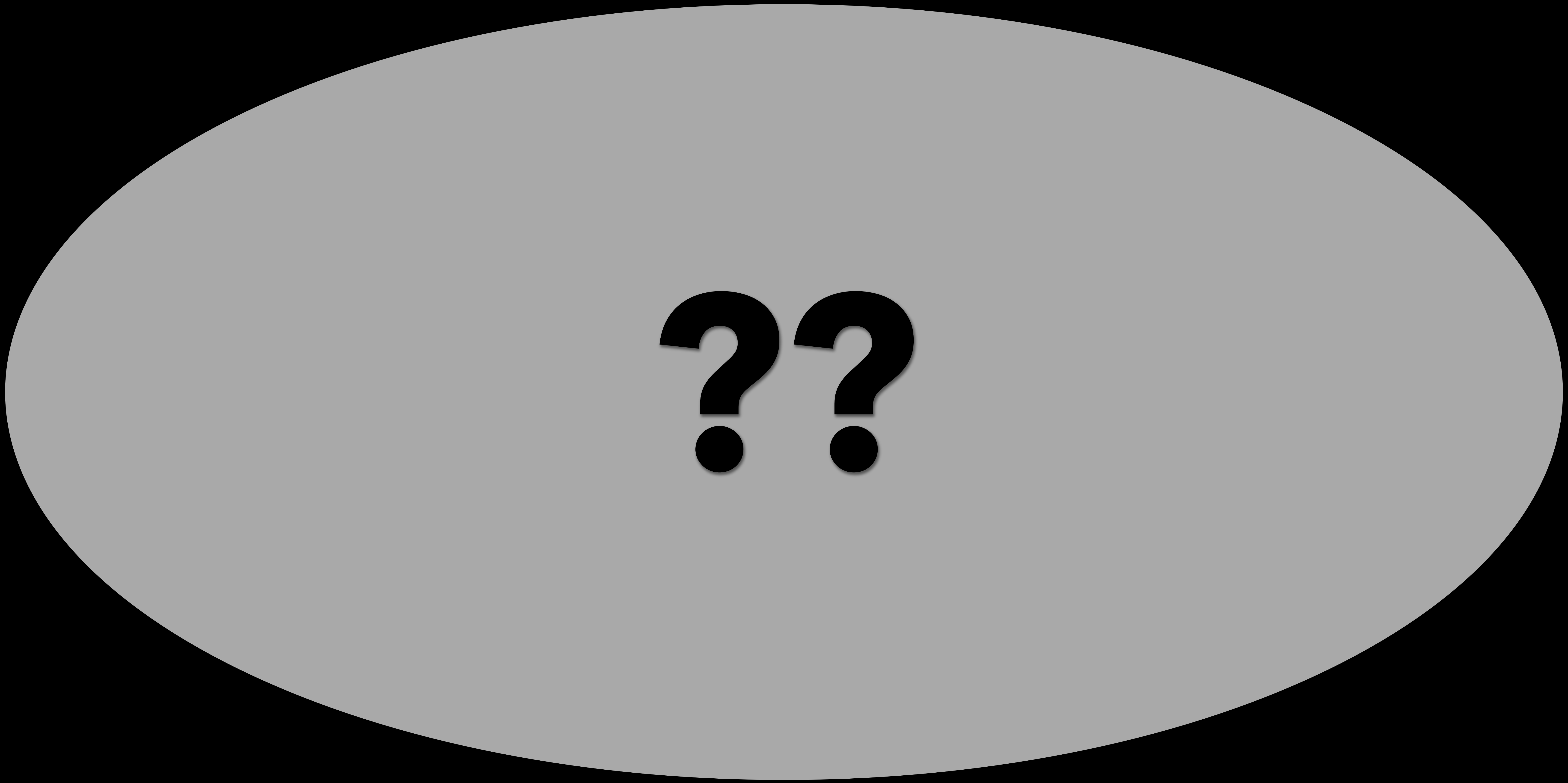
O3 ISOTROPIC RESULTS

Since there was no evidence of an isotropic signal, we placed upper limits on Ω_α for different power-law indices α.

	Uniform prior			Log-uniform prior		
α	O3	O2	Improv.	O3	O2	Improv.
0	1.7×10^{-8}	6.0×10^{-8}	3.6	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	1.7×10^{-8}	4.8×10^{-8}	4.0	3.4×10^{-9}	3.0×10^{-8}	8.8
3	1.3×10^{-9}	7.9×10^{-9}	5.9	3.9×10^{-10}	5.1×10^{-9}	13.1



HOW DO WE MAP THE SGWB SKY?



HOW DO WE MAP THE SGWB SKY?

Cross-correlation is essentially a one-dimensional map of the sky

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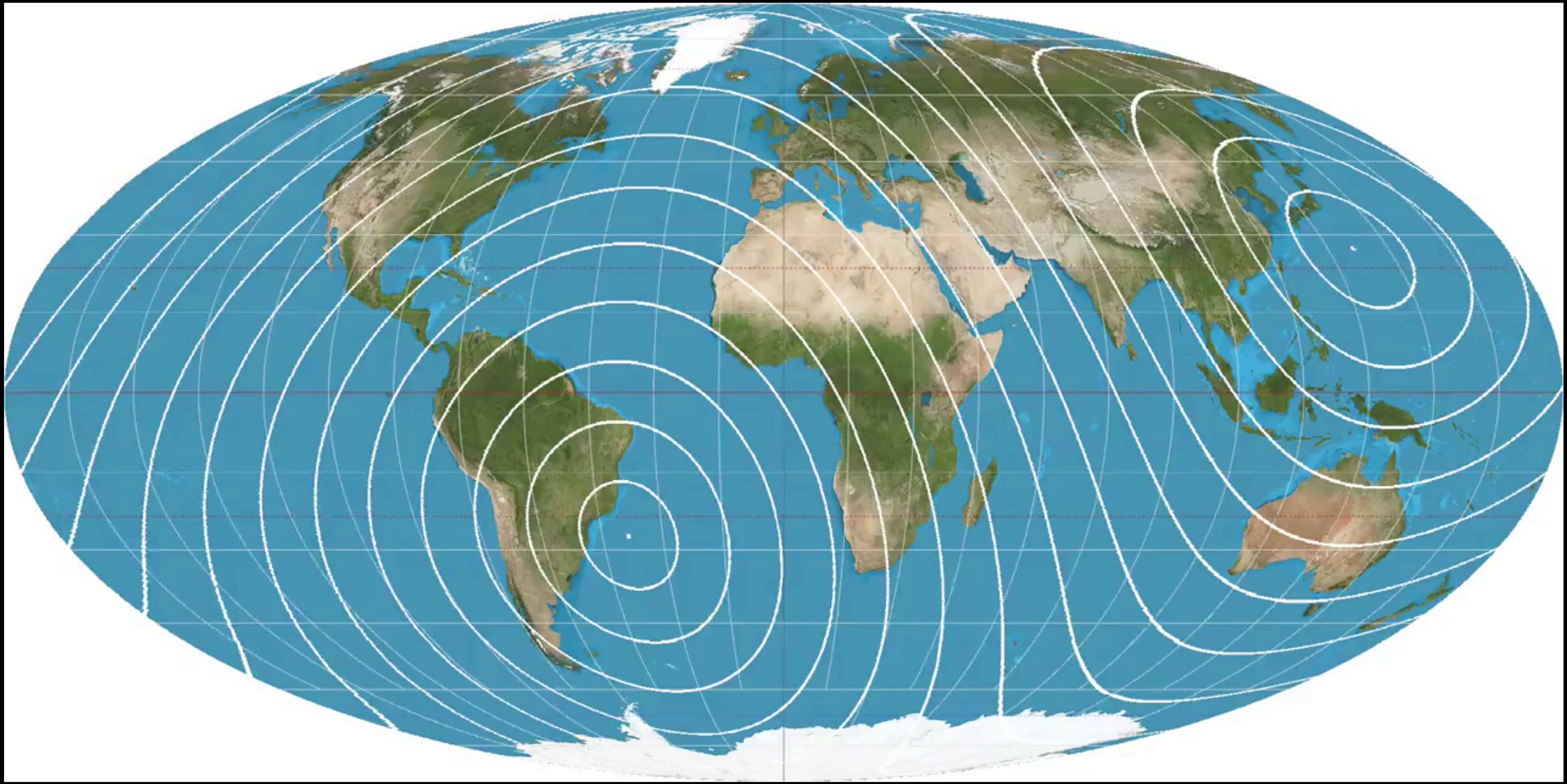
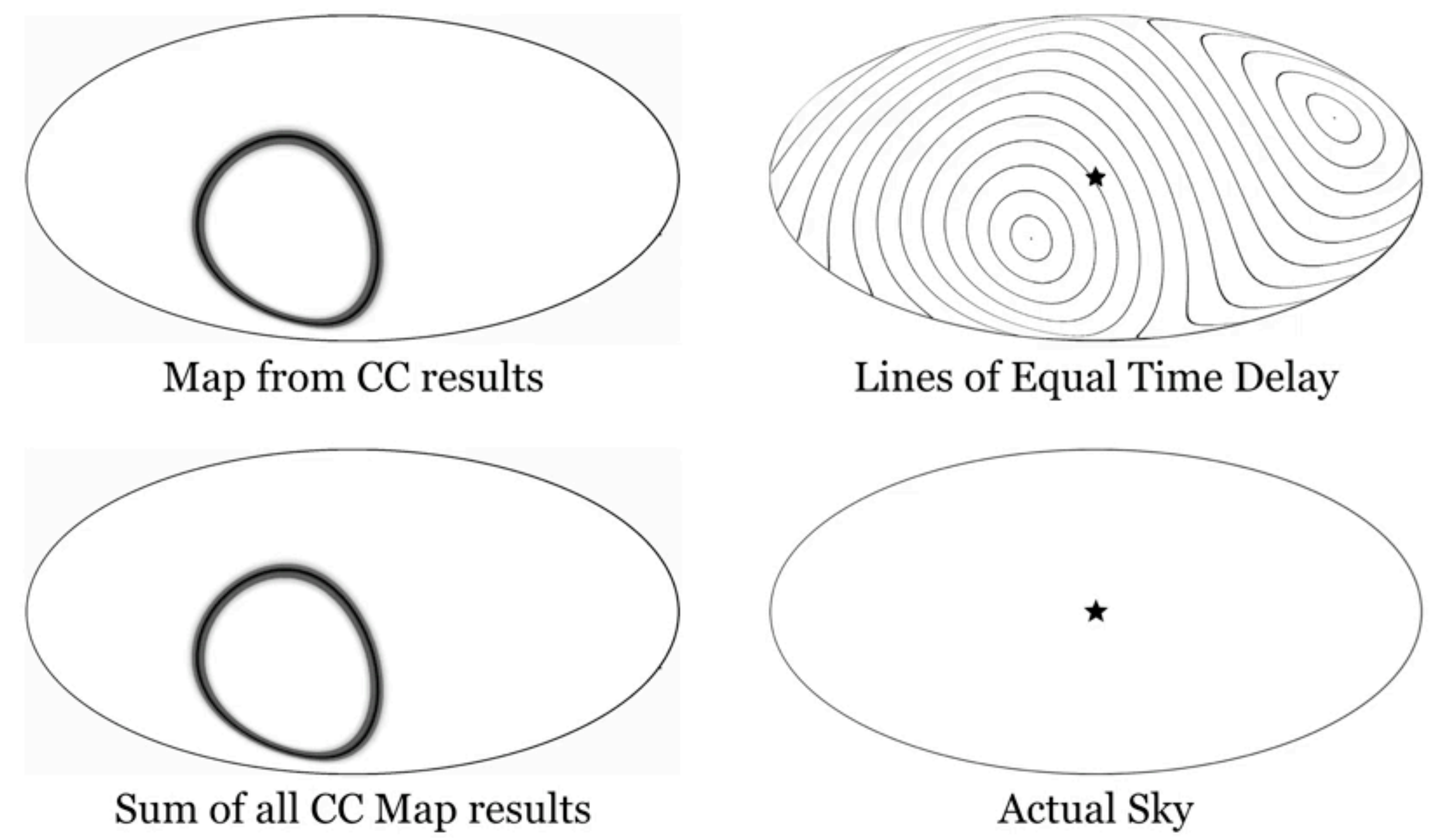


The white circles indicate positions in the sky map that will have equal time/phase delay when the signal from that part of the sky arrives in the LIGO Hanford and Livingston detectors.

SGWB MAPPING

Cross-correlation is essentially a one-dimensional map of the sky.

When we consider the time delay between two detectors and the Rotation of the earth.



For a point source in sky the maps from all segments (top-left) are cumulatively added (bottom-left).

Animation Credit: A. Ain

- LIGO Hanford-Livingston baseline.
- Assume that the detector has perfect sky coverage.
- All the processes are in the time domain.
- No detector noise.
- Strong monochromatic signal.

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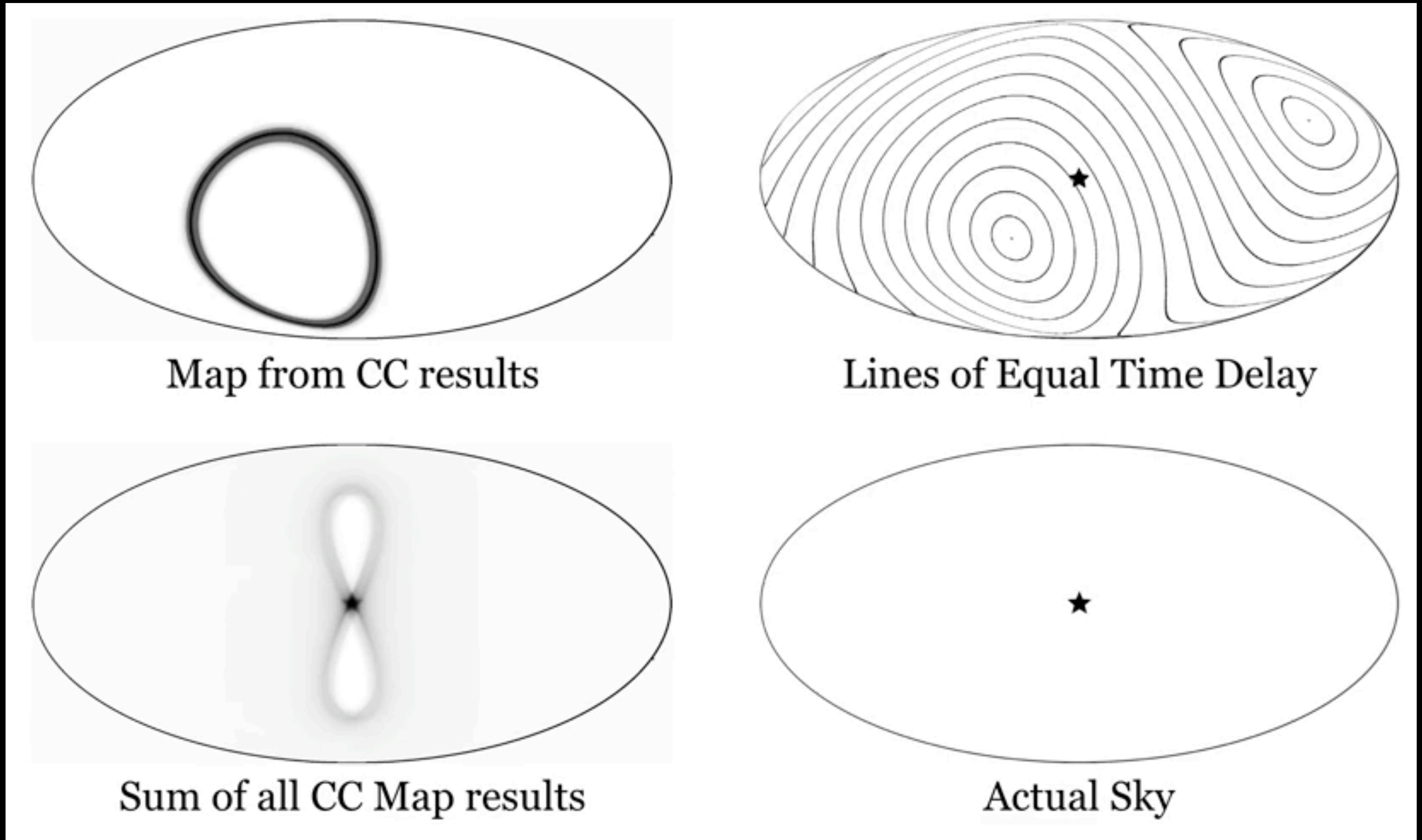

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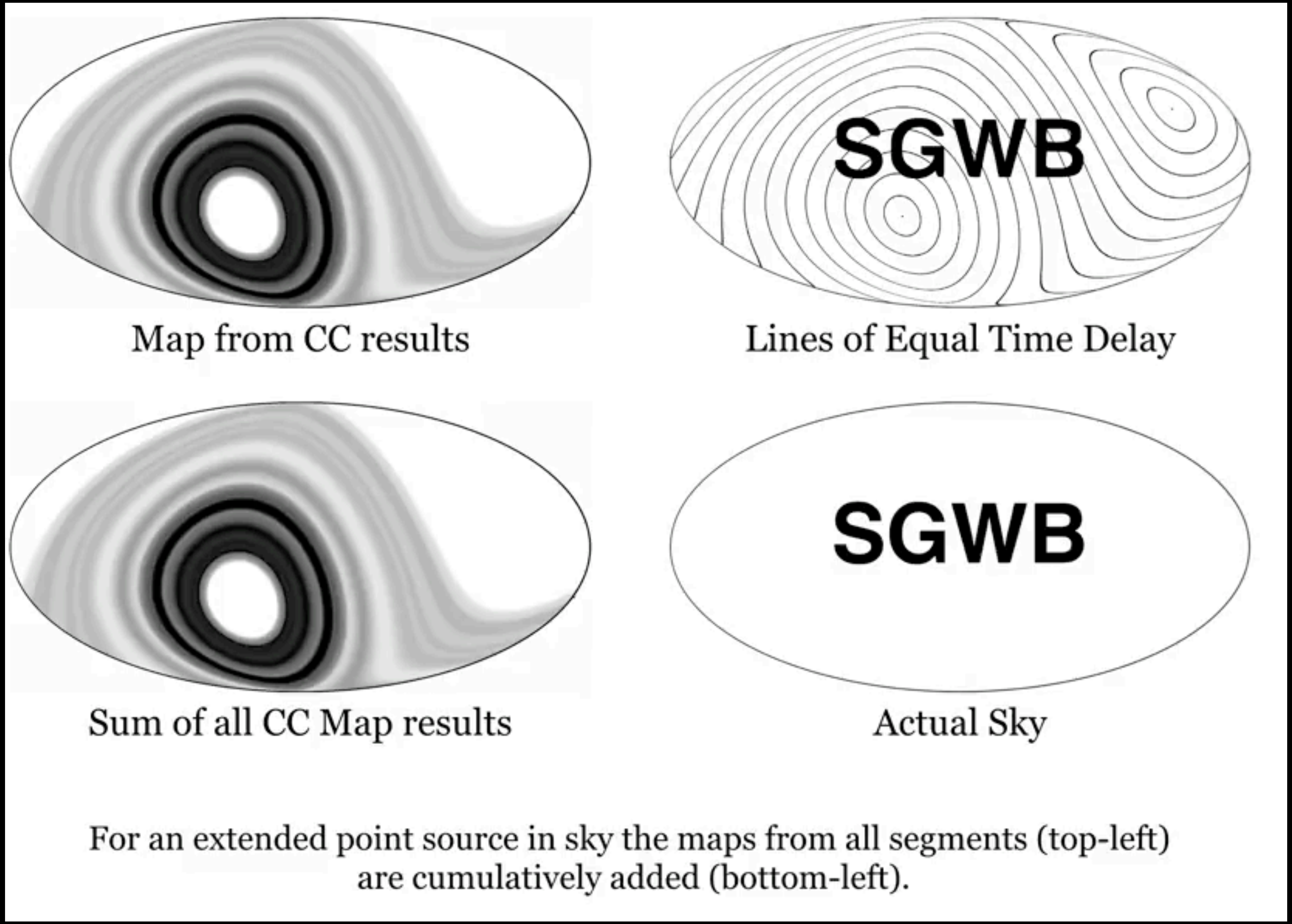

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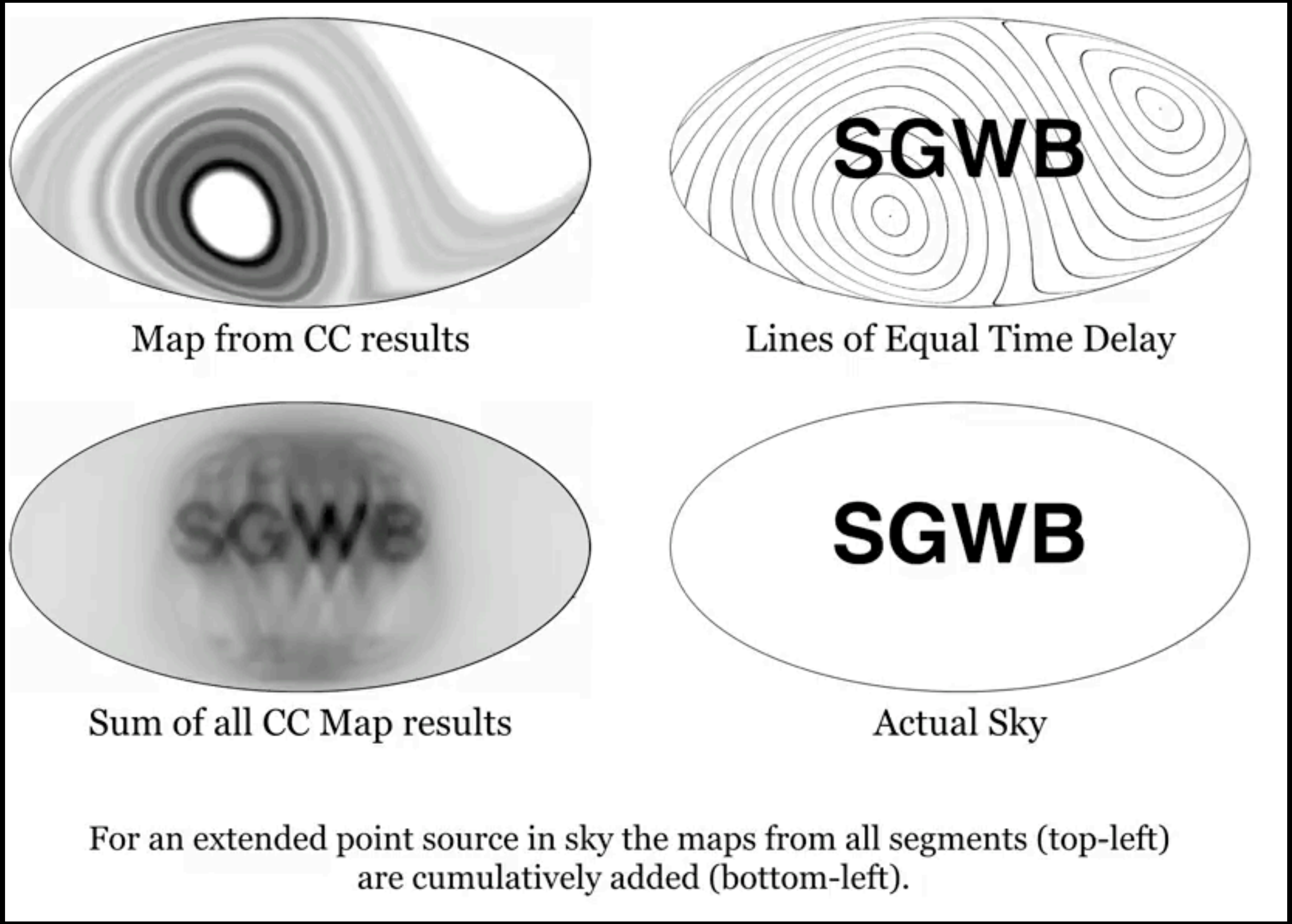

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ANISOTROPIC SEARCH

Anisotropic search tries to measure the direction of the sky from where the signal comes.
In this mapping process, we consider:

- The time delay between two detectors
- Rotation of the earth.

Recall: the SGWB energy density $\Omega_{\rm GW}(f, \hat{\mathbf{n}}) \equiv \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df} = \frac{2\pi^2}{3H_0^2} f^3 \mathscr{P}(f, \hat{\mathbf{n}})$

Cross-correlation is essentially a one-dimensional map of the sky.

Anisotropy can be expanded in pixel or spherical harmonic basis

HOW DO WE MAP THE SGWB SKY?

The anisotropy of the SGWB can be characterized using the dimensional energy density parameter

$$\Omega_{\mathrm{GW}}(f, \hat{\mathbf{n}}) \equiv \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df} = \frac{2\pi^2}{3H_0^2} f^3 \mathscr{P}(f, \hat{\mathbf{n}})$$

Most of the analysis performed so far assumes that the frequency and direction dependiecs can be separated: $\mathscr{P}(f, \hat{\mathbf{n}}) = P(\hat{\mathbf{n}})\, H(f)$

Where the common choice of spectral shape is $H(f) = \left(\frac{f}{f_{\mathrm{ref}}}\right)^{\beta}$

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We will perform a model-independent search

PyStoch: MAP-MAKING PIPELINE

Ain+ PRD 98, 024001 (2018)
Suresh+ PRD 103, 083024 (2021)

PyStoch : fast HEALPix based SGWB mapmaking

↓

perform the whole analysis on a laptop in a few minutes*

↓

Produces the narrowband maps as an intermediate result

so separate search for different frequency spectra becomes redundant

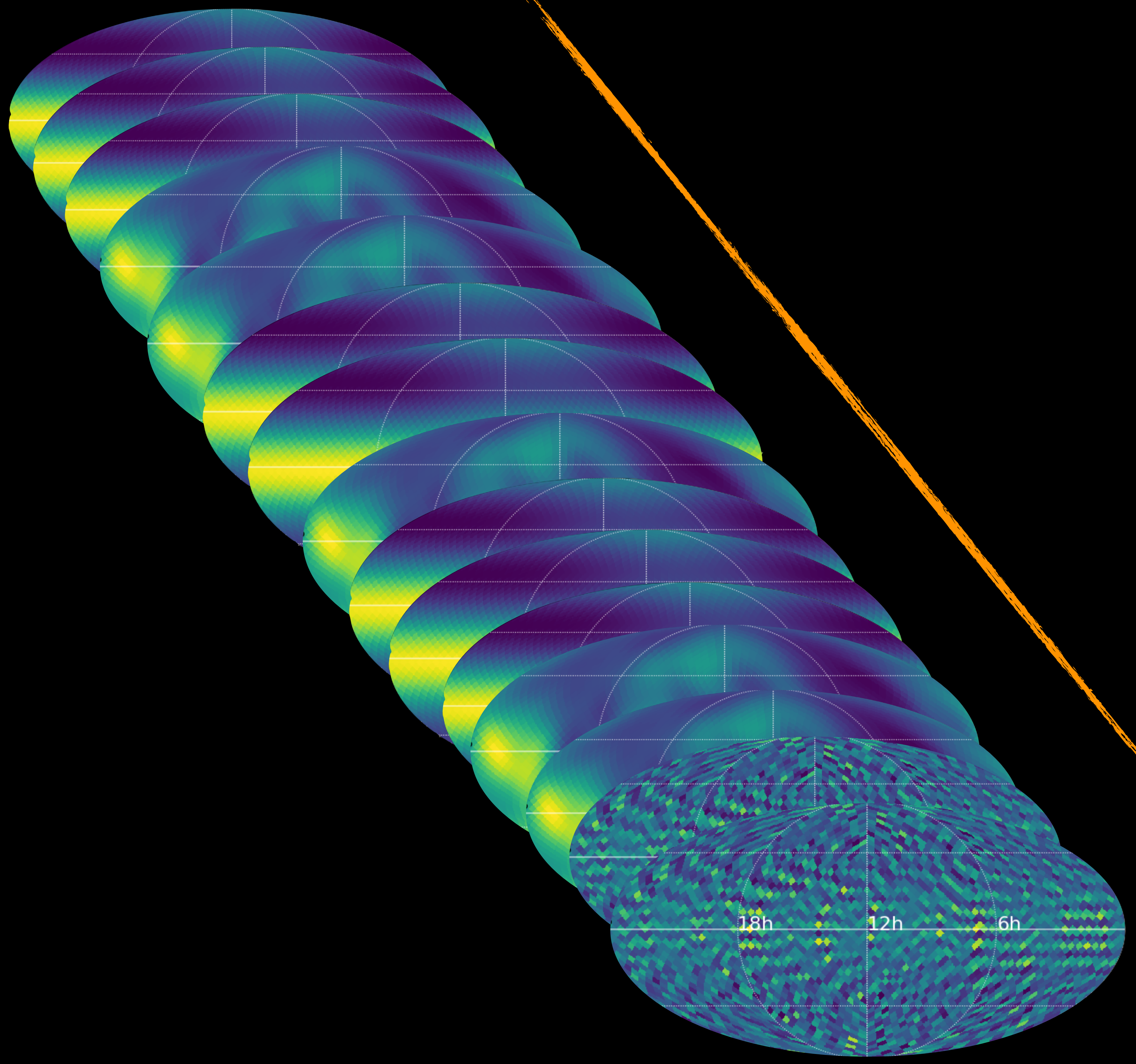
* We have used sidereally folded data (PRD 92, 022003 2015) set for this analysis

https://git.ligo.org/stochastic-public/stochastic.git

ALL-SKY ALL-FREQUENCY SEARCH

Now we have all the ingredients to perform an all-sky, all-frequency search, which assumes **no** specific power-law model for the SGWB

20 Hz



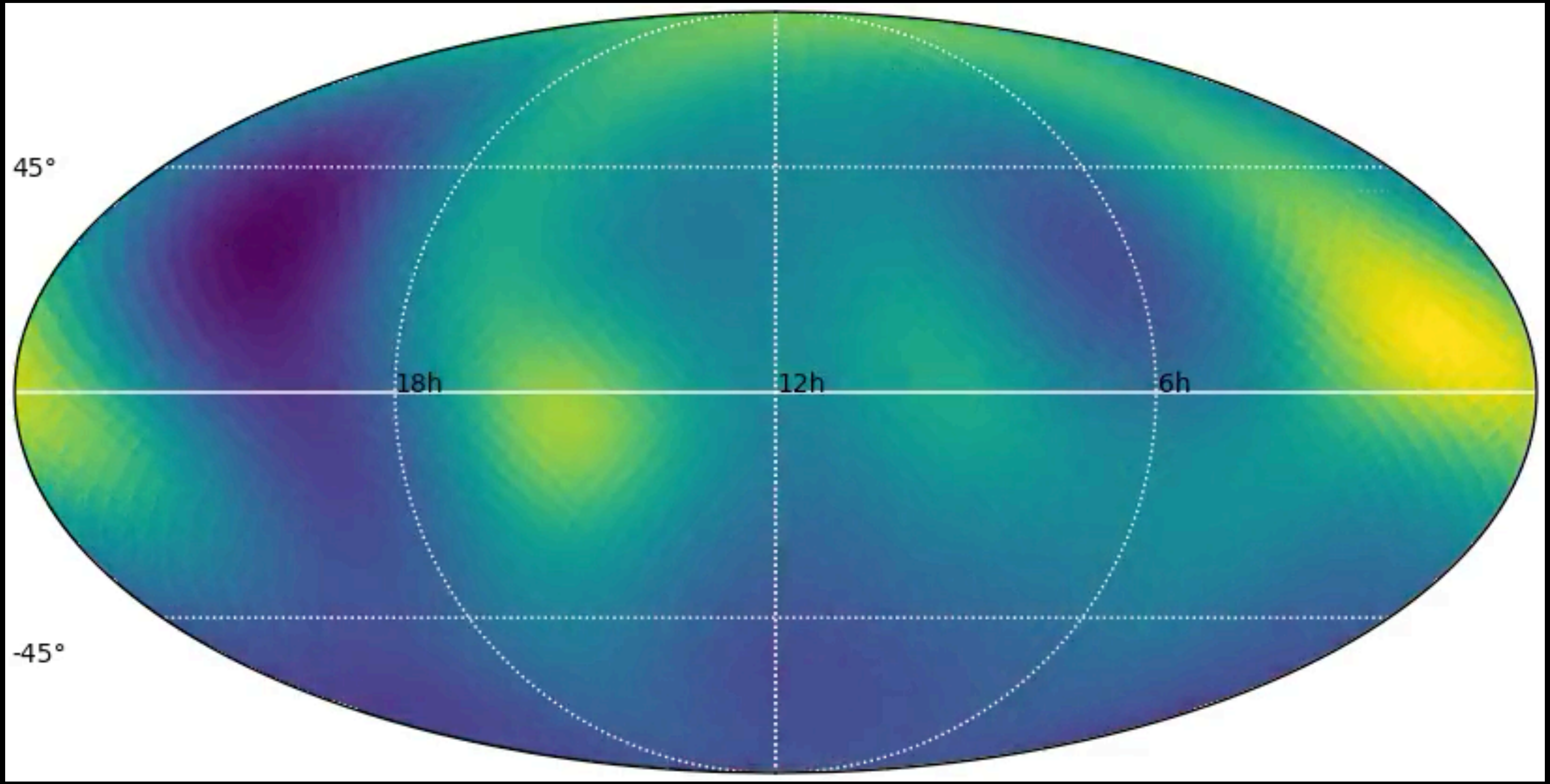
~1500 Hz

SGWB sky maps at every frequency bins

ALL-SKY ALL-FREQUENCY SEARCH

Now we have all the ingredients to perform an all-sky, all-frequency search, which assumes **no** specific power-law model for the SGWB

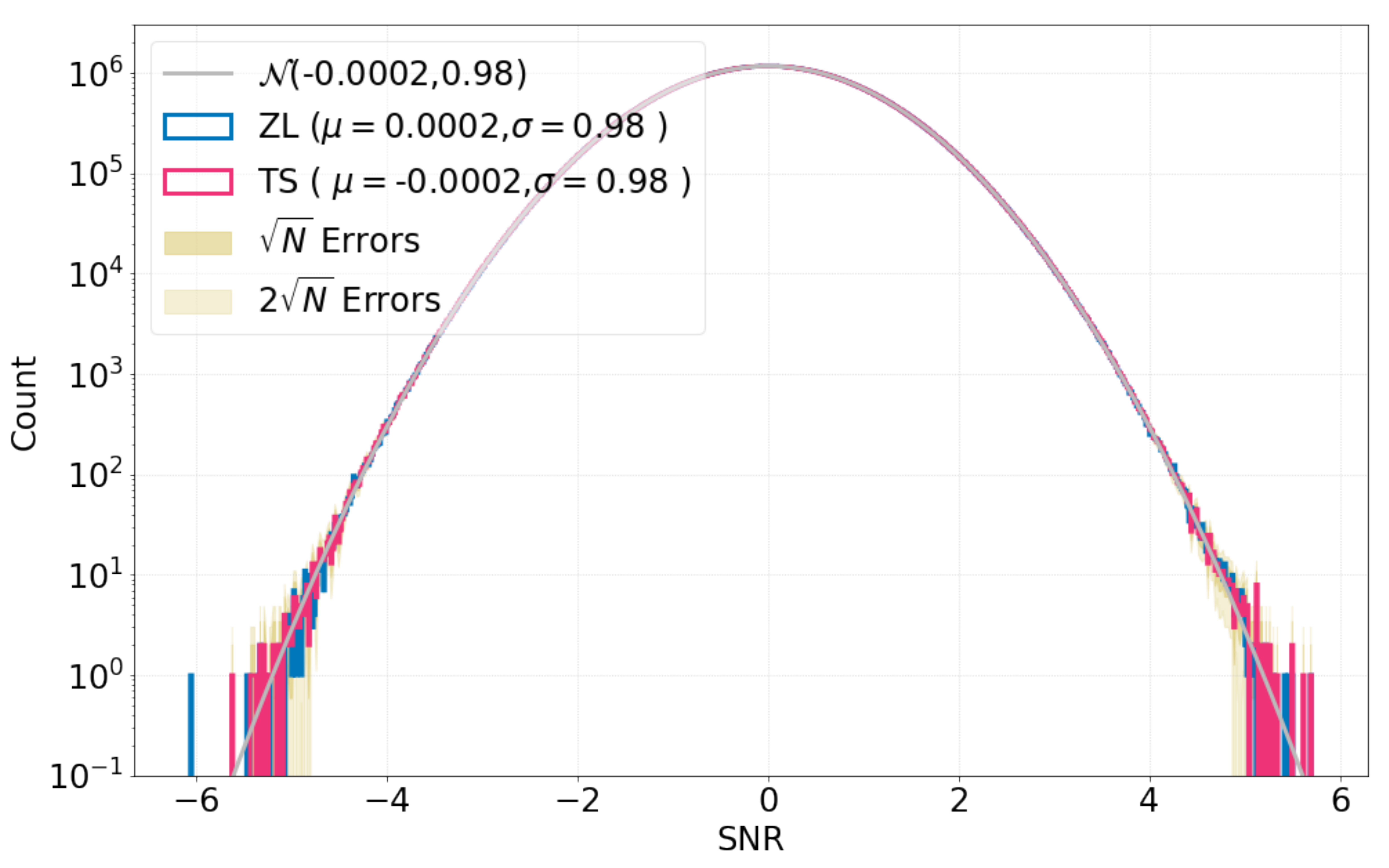
We presented the **first atlas** of SGWB sky from this analysis.



ALL-SKY ALL-FREQUENCY SEARCH

Phys.Rev.D 105 (2022) 10, 102001

GW data from LIGO-Virgo-KAGRA's first three observing runs (O1 + O2 + O3)



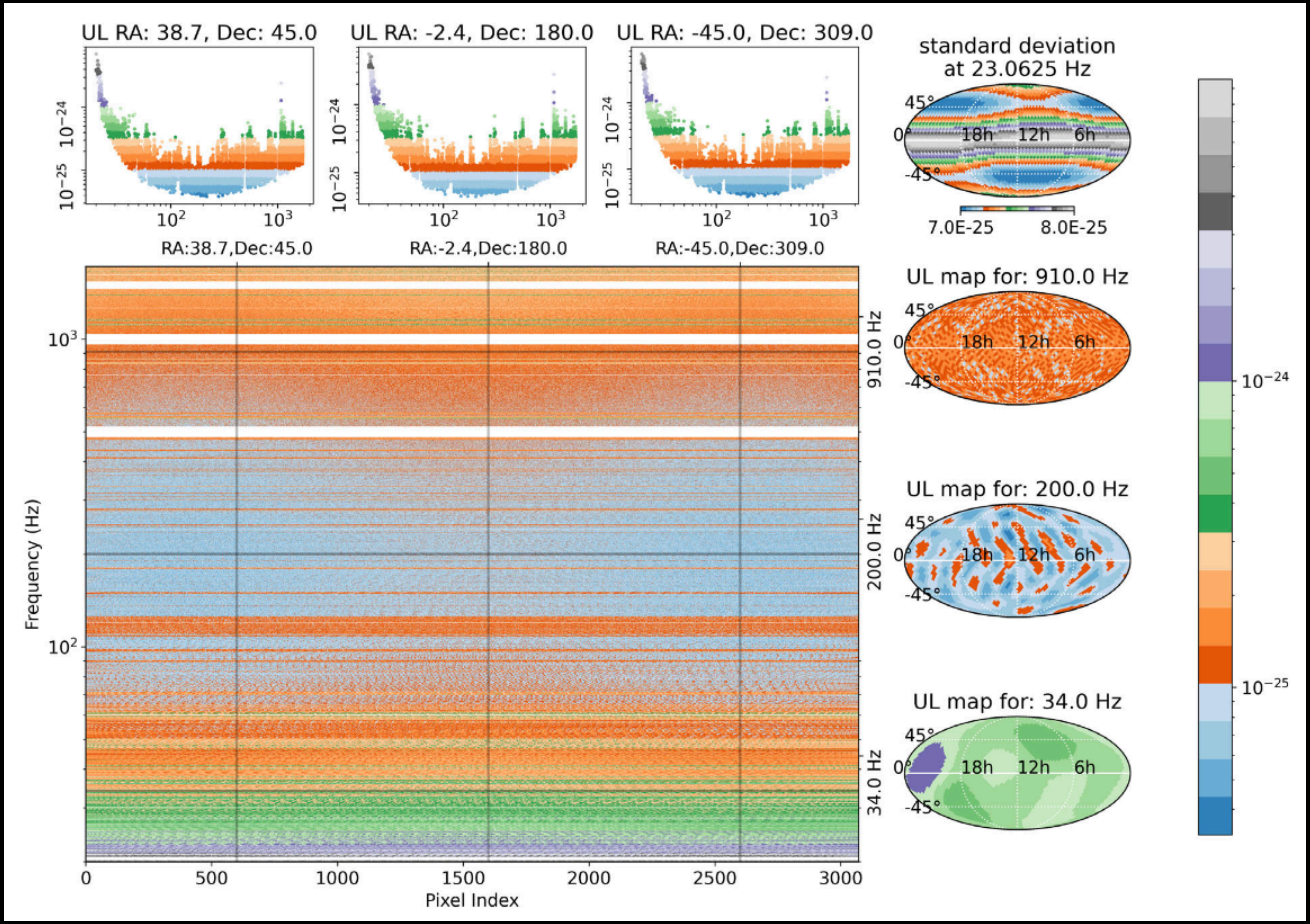
The zero-lag (ZL) data is consistent with the time-shifted (TS) data within 2-sigma error bars.

We did follow-up studies on the outlier (SNR <-6) and found no astrophysical motivated channels. This outlier is also statistically insignificant, given the trial factors corrected p-value >5%

ALL-SKY ALL-FREQUENCY SEARCH

Phys.Rev.D 105 (2022) 10, 102001

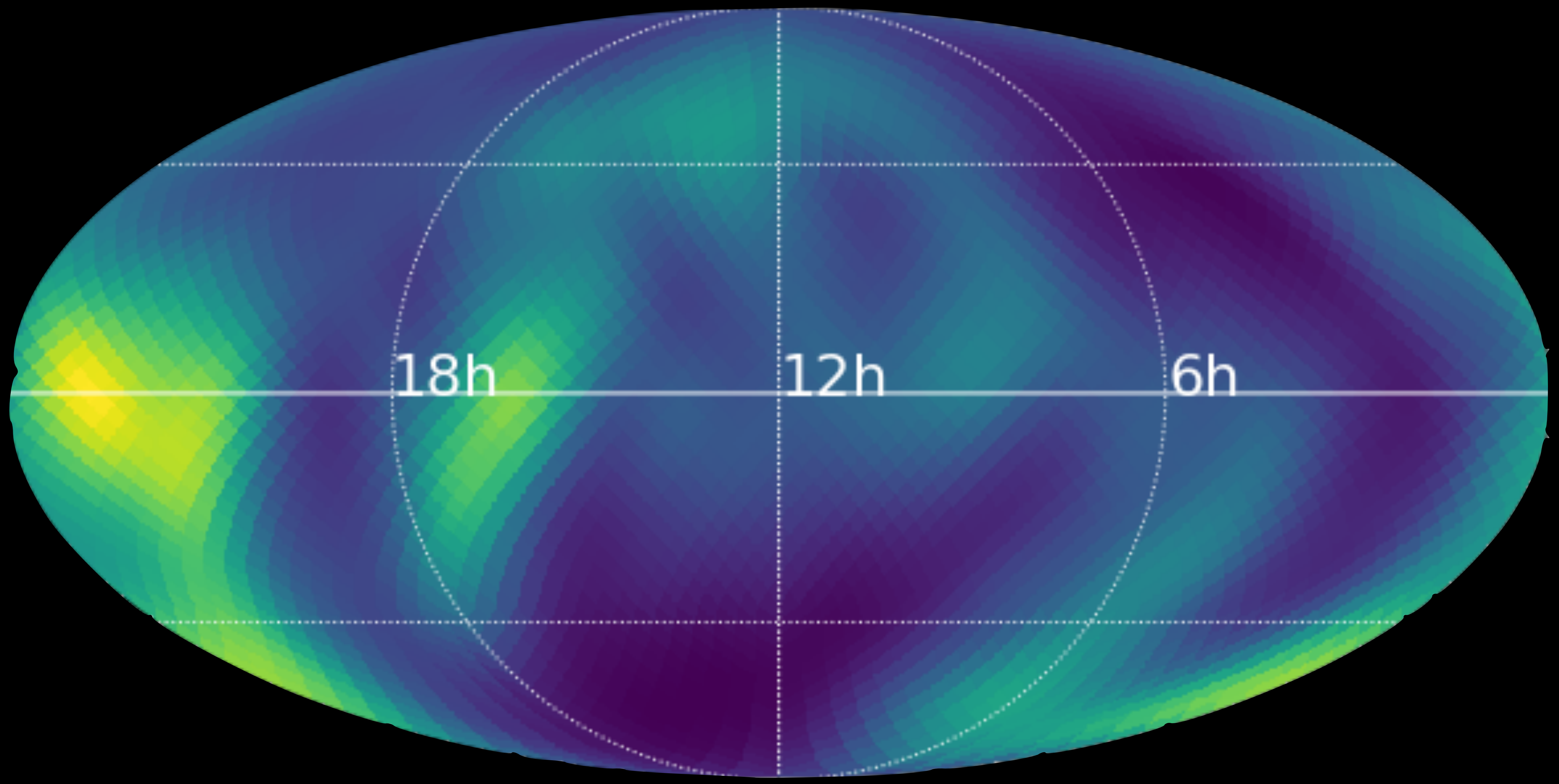
Given no detection, we set the all-sky all-frequency upper limits on the SGWB strain



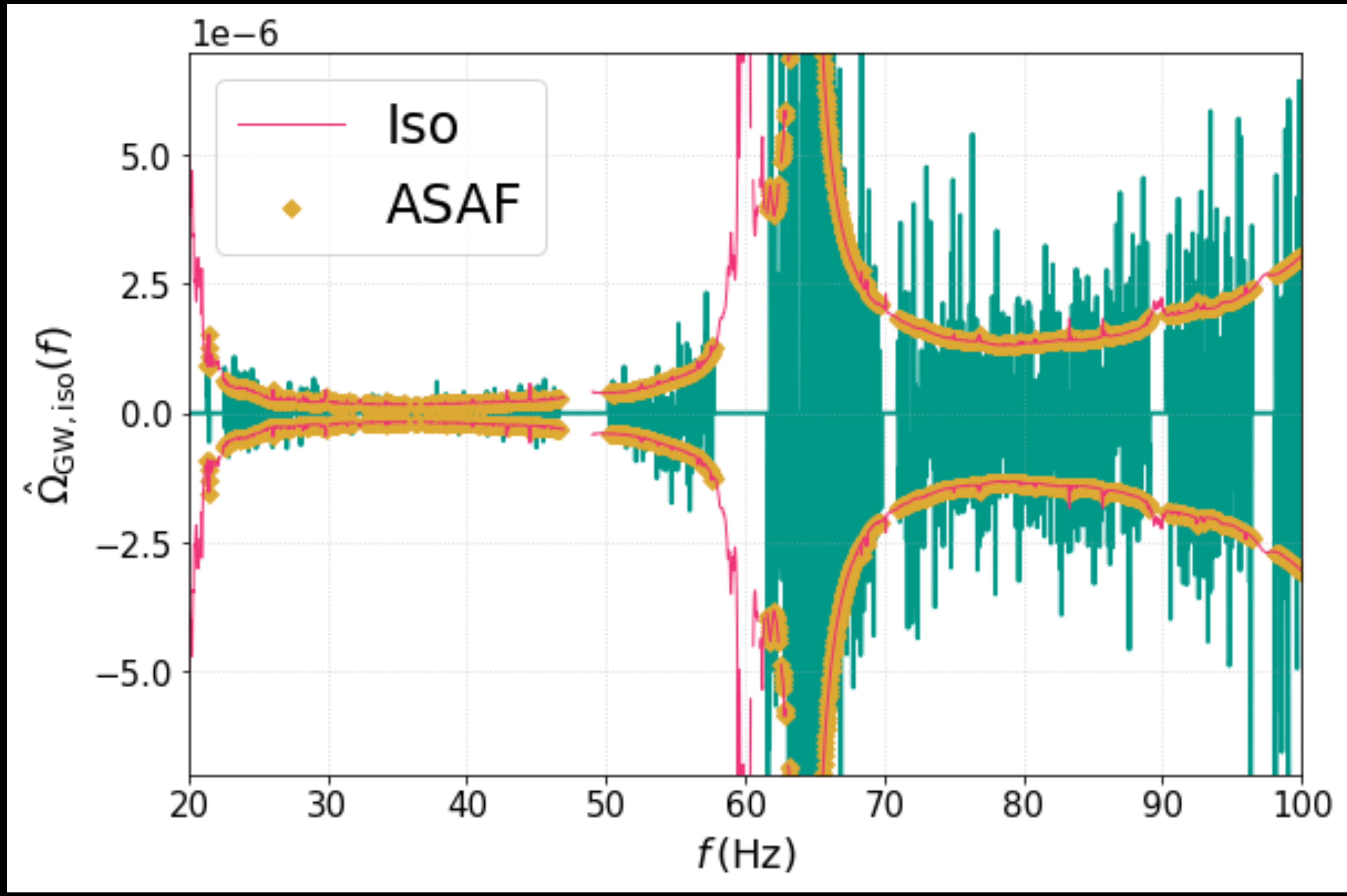
- The colour bar here denotes the range of upper limit variations.
- The vertical cross-section in this diagram shows the frequency-dependent upper limit in a particular direction.
- The Horizontal cross-sections form a map of upper limits in a particular frequency.
- Notched frequencies in a baseline appear as horizontal white bands in the plot.

ALL-SKY ALL-FREQUENCY RESULTS

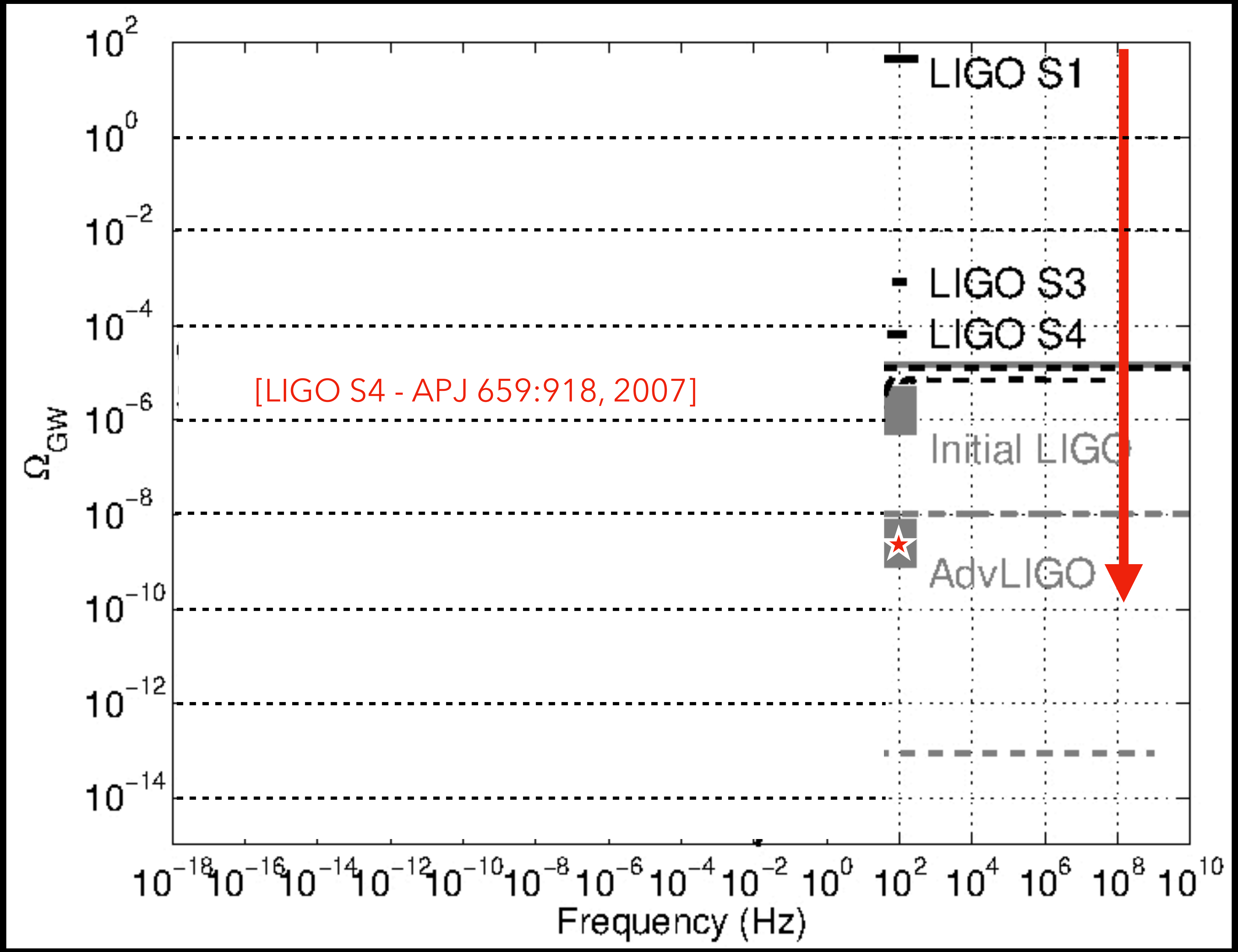
Assume a power law and combine these narrowband maps to obtain the 'usual' broadband results

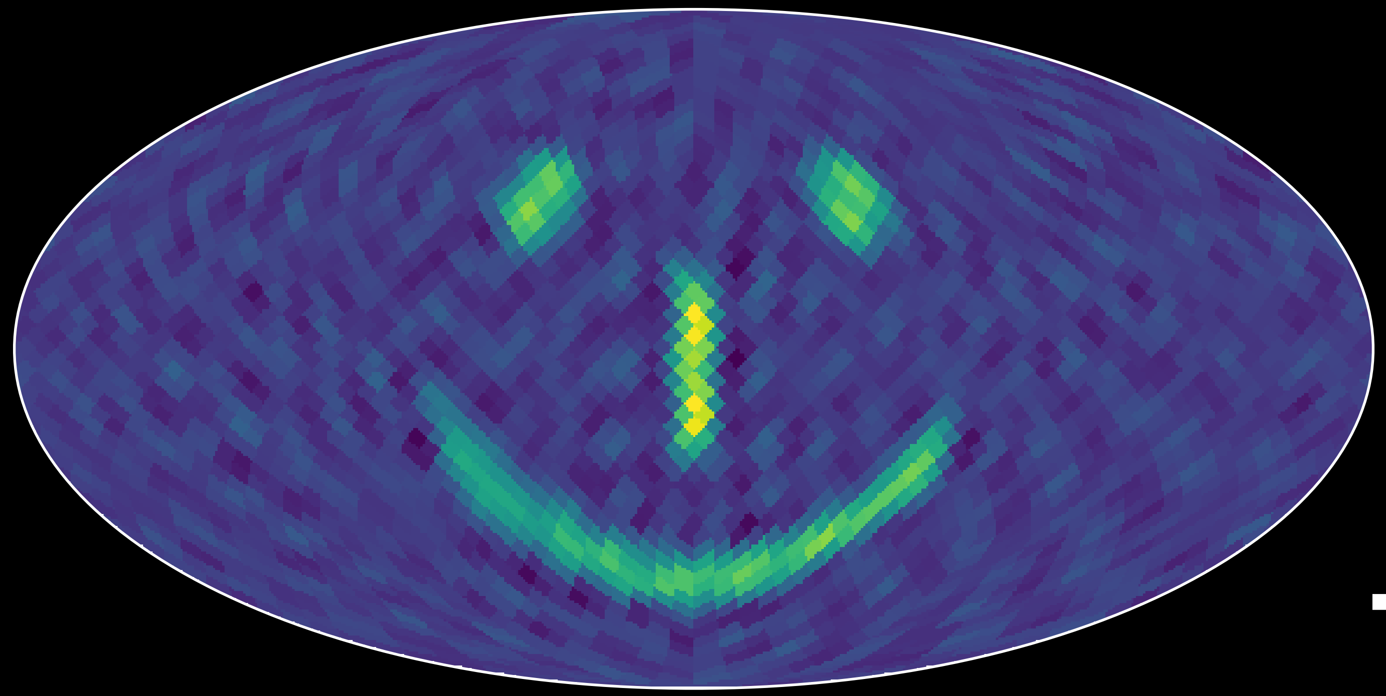


Assume a power law and sum over all the directions of these narrowband maps to obtain the 'usual' isotropic results



- New searches and techniques are opening up efficient ways to probe the dark universe.
- Plenty more work to do!
  - More detectors, More signals, More systems, and Dealing with real data…..



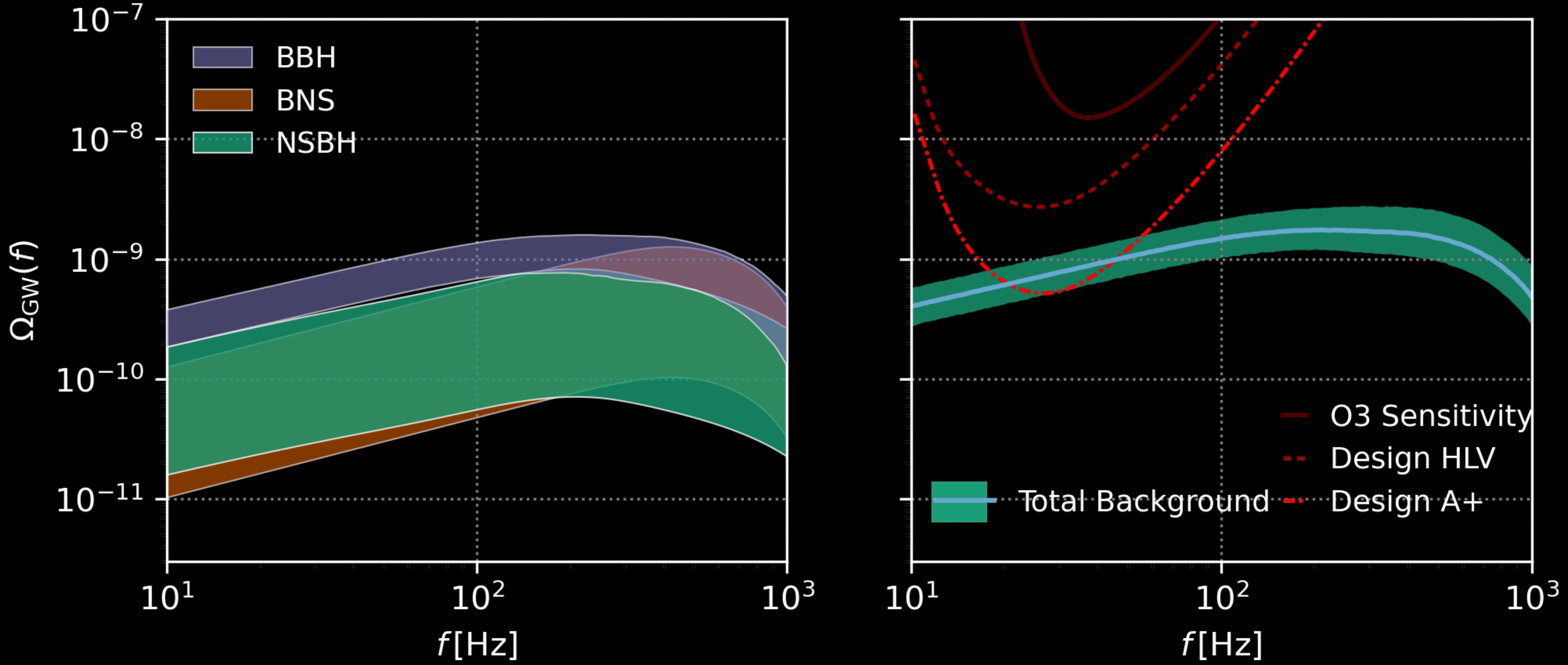


Thank you!

BACKUP

SENSITIVITY PROJECTION

LVK arXiv:2111.03634



The individual contributions expected from the collection of BNS, NSBH, and BBH mergers. While uncertainties on the energy density due to BNS and NSBH are due to Poisson uncertainties in their merger rates, our forecast for the SGWB due to BBHs includes systematic uncertainties associated with their imperfectly known mass distribution. (Right): Estimate of the total gravitational-wave background (green), as well as our current experimental sensitivity (red)

O3 ANISOTROPIC RESULT

- Broadband: point sources with different power-law spectra.
- Narrowband: point sources having narrow GW frequency band (SN 1987A, ScoX-1, GC)
- Spherical harmonics search: Extended or diffuse sources - measure angular power spectra

All-sky BBR Results			**Max SNR (% p-value)**				**Upper limit ranges** (10^{-8})	
α	Ω_{GW}	$H(f)$	**HL(O3)**	**HV(O3)**	**LV(O3)**	O1 + O2 + O3 **(HLV)**	O1 + O2 + O3 **(HLV)**	O1 + O2 **(HL)**
0	Constant	$\propto f^{-3}$	2.3 (66)	3.4 (24)	3.1 (51)	2.6 (23)	1.7–7.6	4.4–21
$2/3$	$\propto f^{2/3}$	$\propto f^{-7/3}$	2.5 (59)	3.7 (14)	3.1 (62)	2.7 (24)	0.85–4.1	2.3–12
3	$\propto f^{3}$	Constant	3.7 (32)	3.6 (47)	4.1 (12)	3.6 (20)	0.013–0.11	0.046–0.32

O3 ANISOTROPIC RESULT

PRD 104, 022005 (2021)

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Narrow band Radiometer Results					
Direction	Max SNR	p-value (%)	Frequency (Hz) (± 0.016 Hz)	Best upper limit (10^{-25})	Frequency band (Hz)
Scorpius X-1	4.1	65.7	630.31	2.1	189.31–190.31
SN 1987A	4.9	1.8	414.0	1.7	185.13–186.13
Galactic Center	4.1	62.3	927.25	2.1	202.56–203.56

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SHD Results

			Max SNR (% p-value)				Upper limit range (10^{-9})	
α	Ω_{GW}	$H(f)$	HL(O3)	HV(O3)	LV(O3)	O1 + O2 + O3 (HLV)	O1 + O2 + O3 (HLV)	O1 + O2 (HL)
0	Constant	$\propto f^{-3}$	1.6 (78)	2.1 (40)	1.5 (83)	2.2 (43)	3.2–9.3	7.8–29
$2/3$	$\propto f^{2/3}$	$\propto f^{-7/3}$	3.0 (13)	3.9 (0.98)	1.9 (82)	2.9 (18)	2.4–9.3	6.4–25
3	$\propto f^{3}$	Constant	3.9 (12)	4.0 (10)	3.9 (11)	3.2 (60)	0.57–3.4	1.9–11