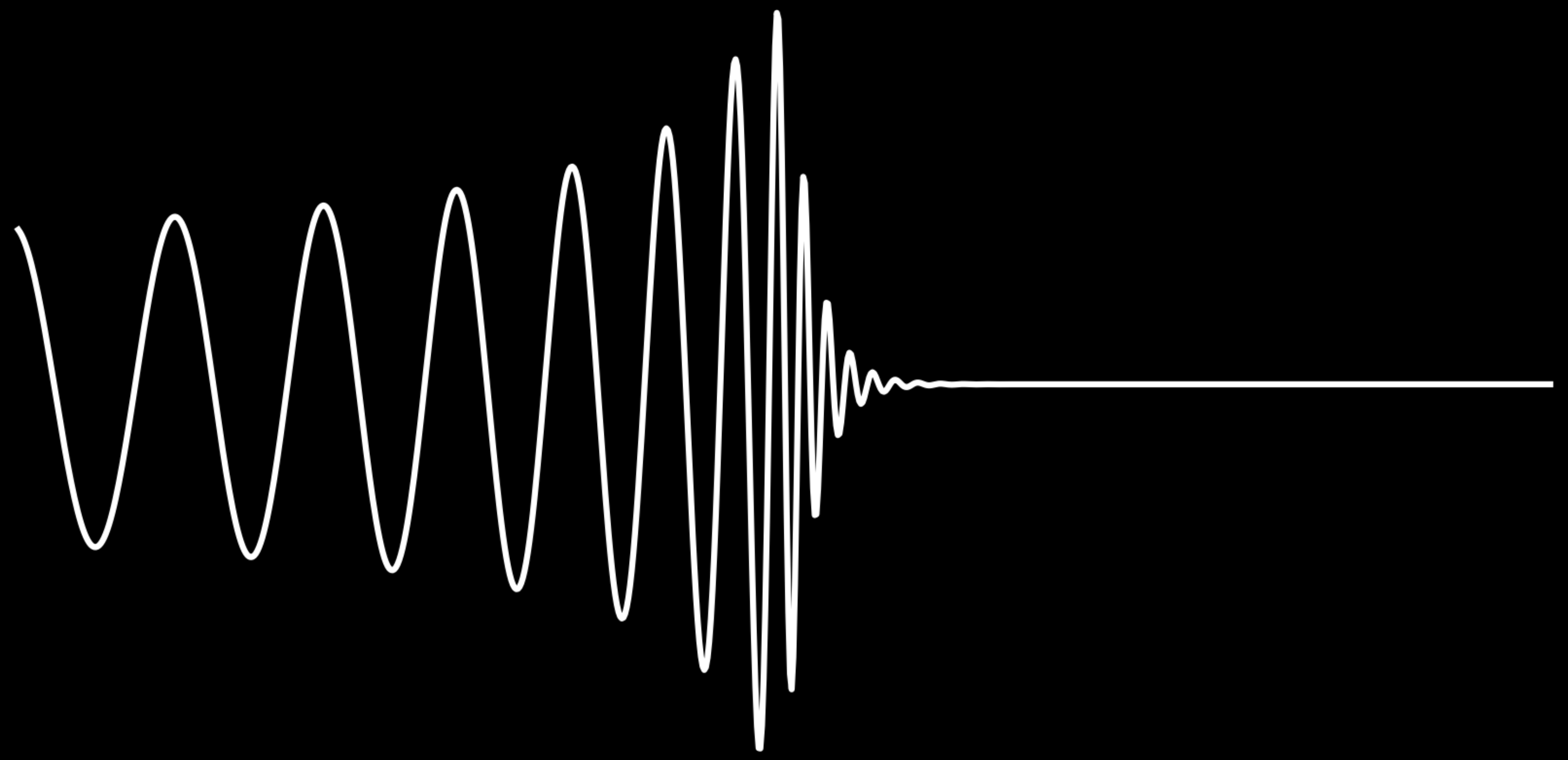
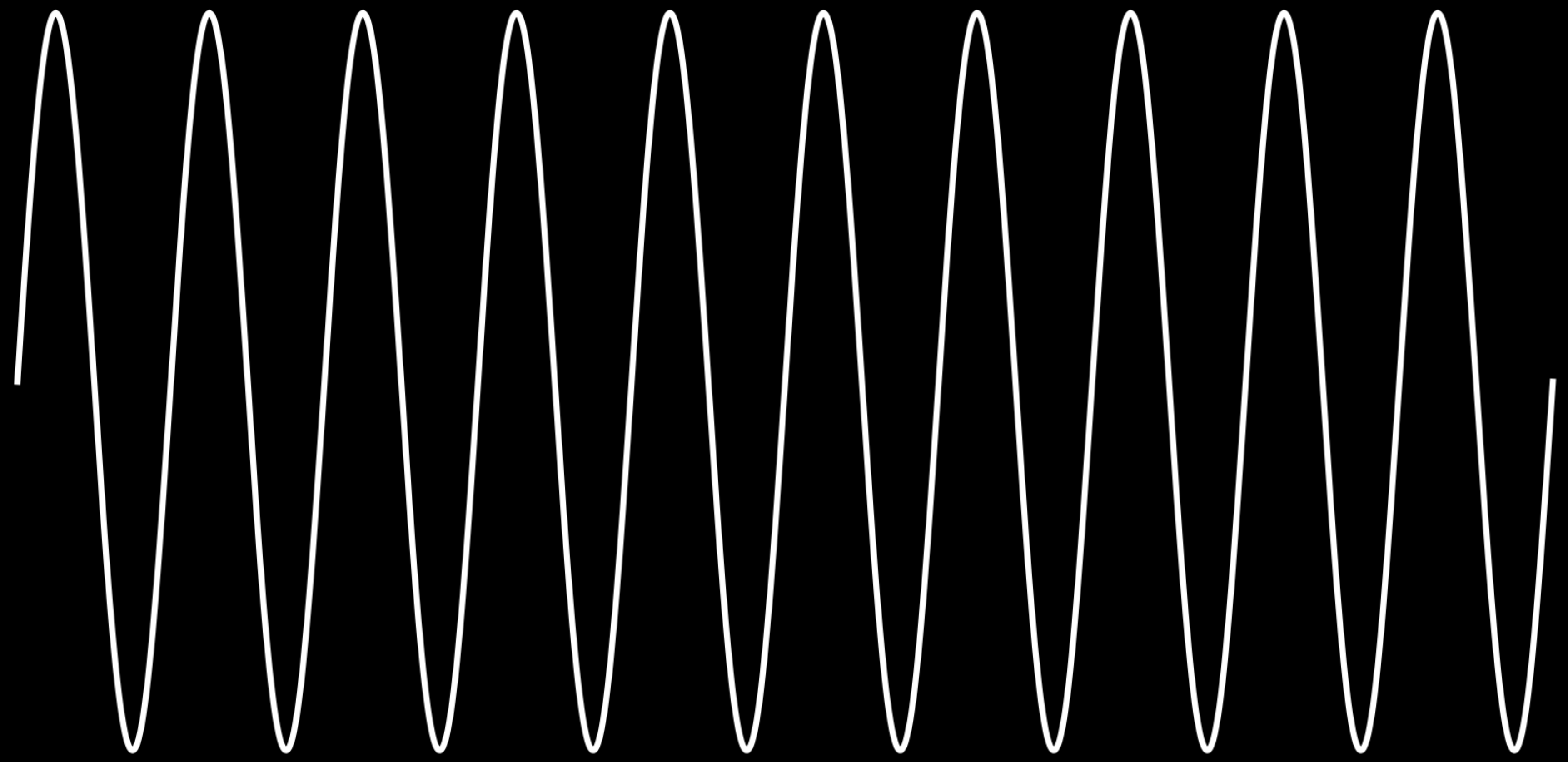
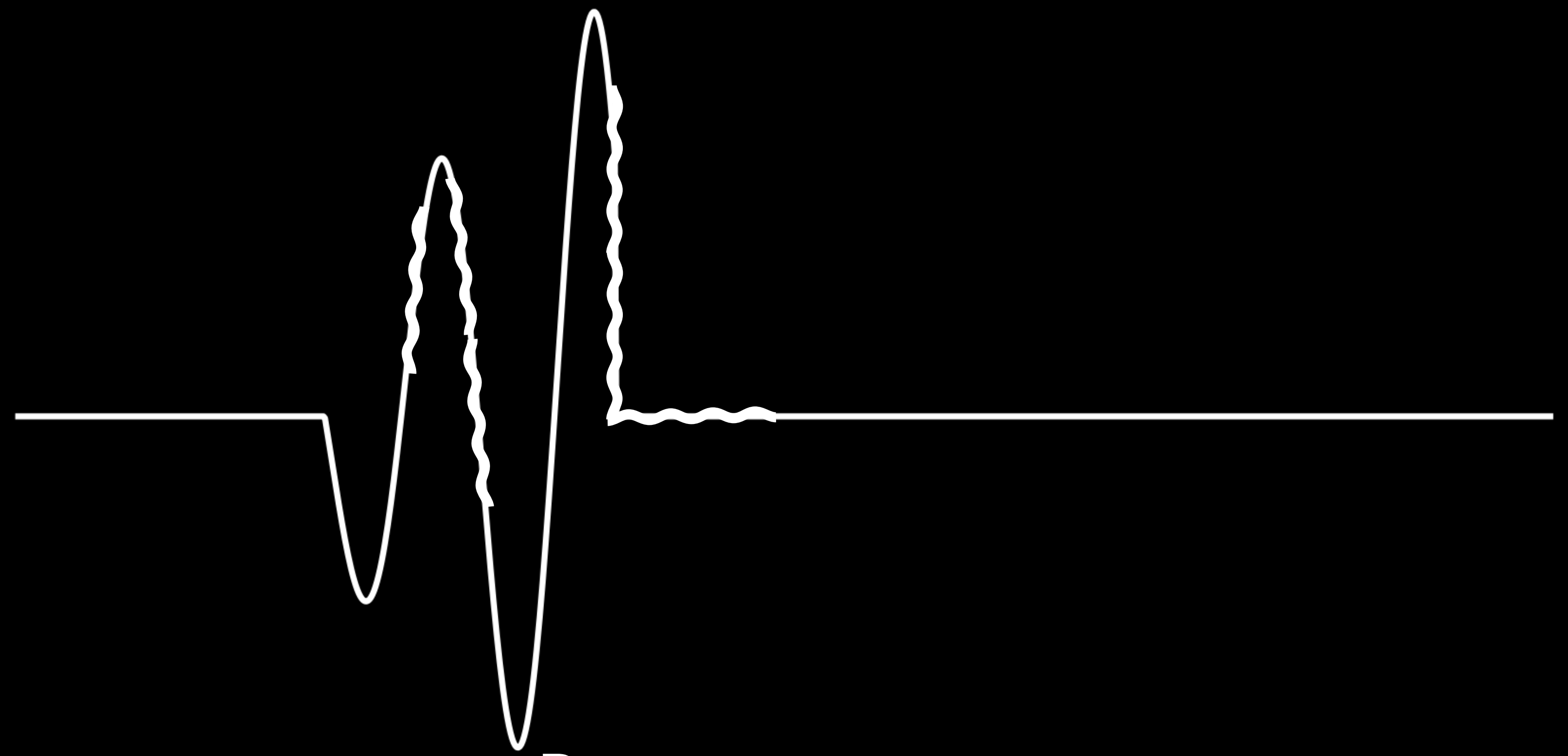
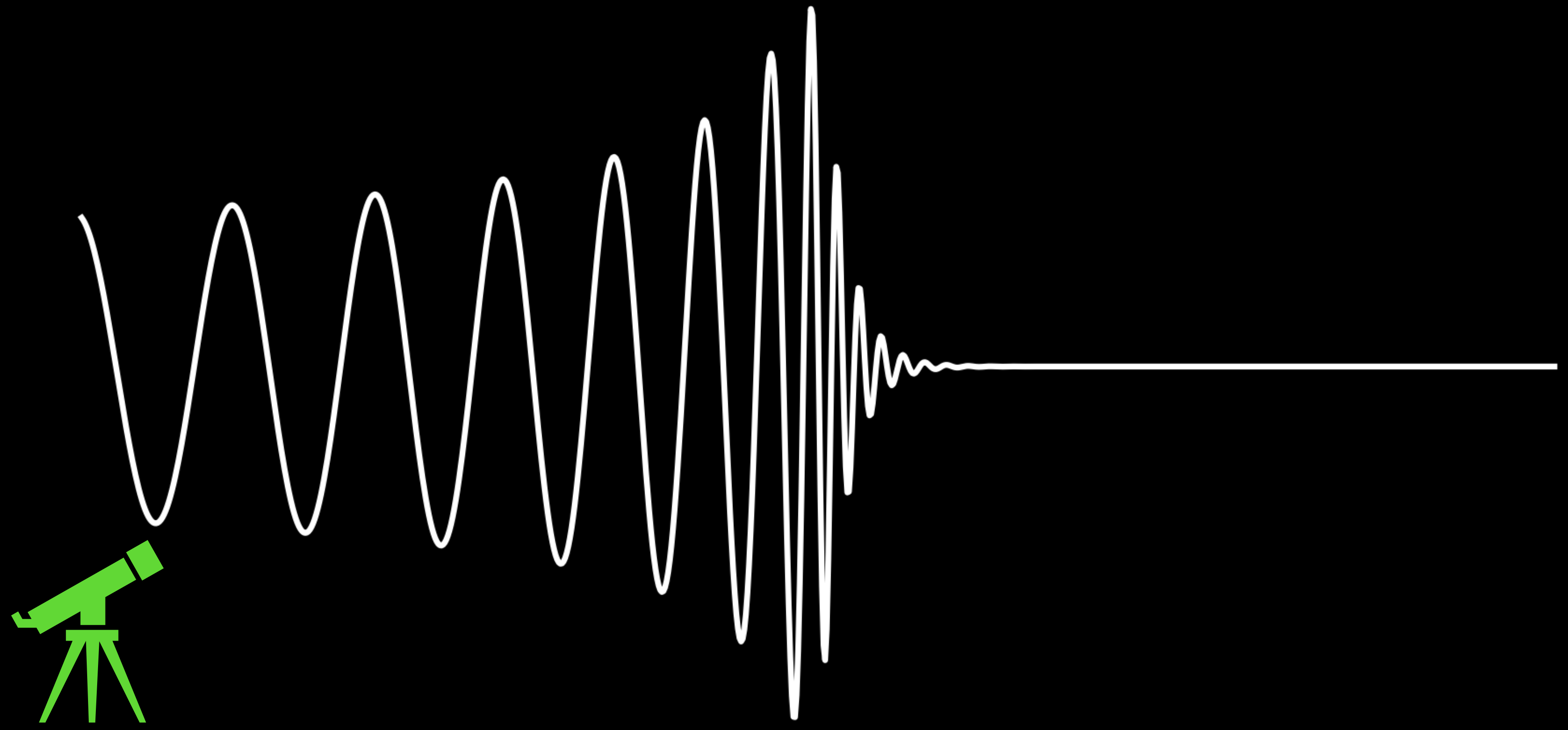
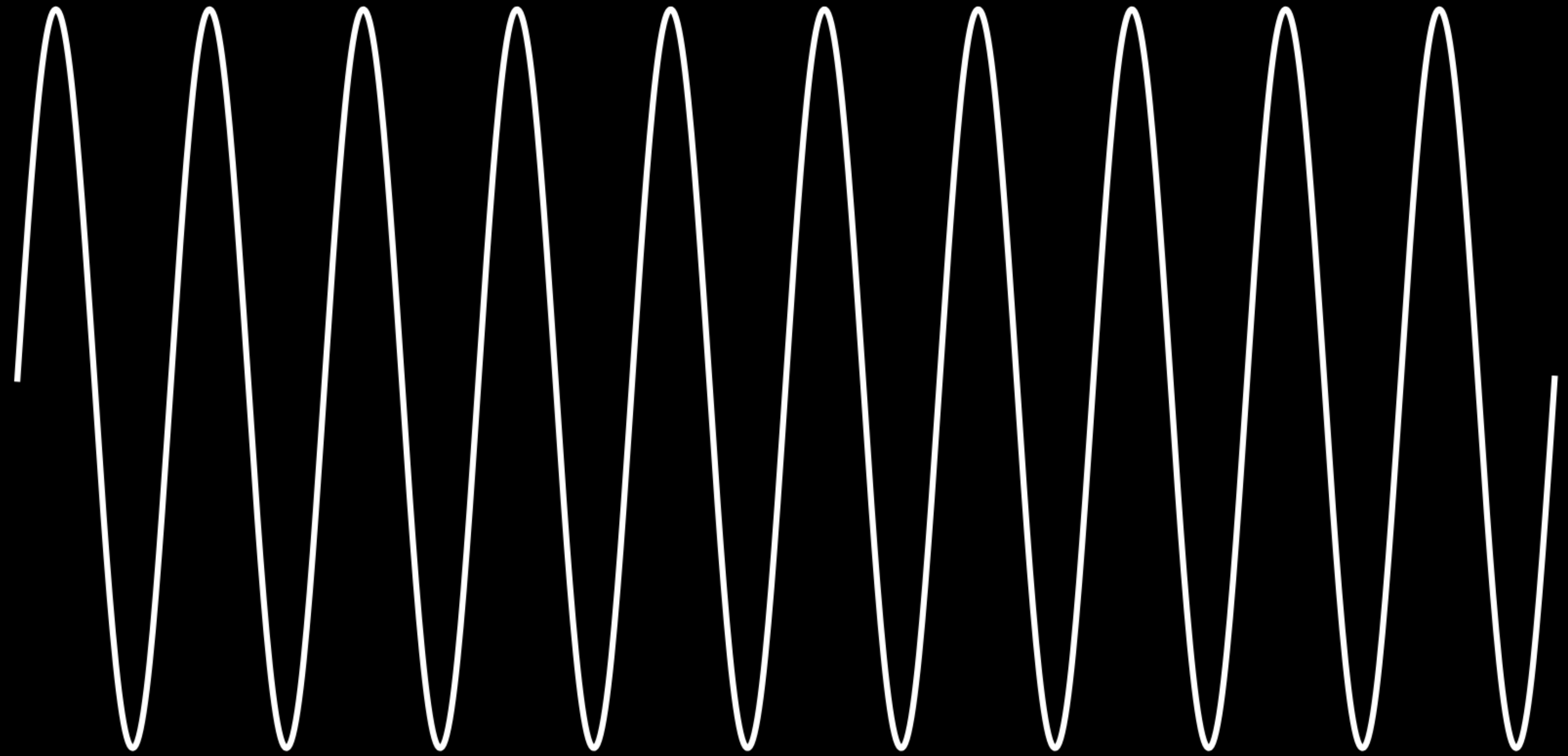
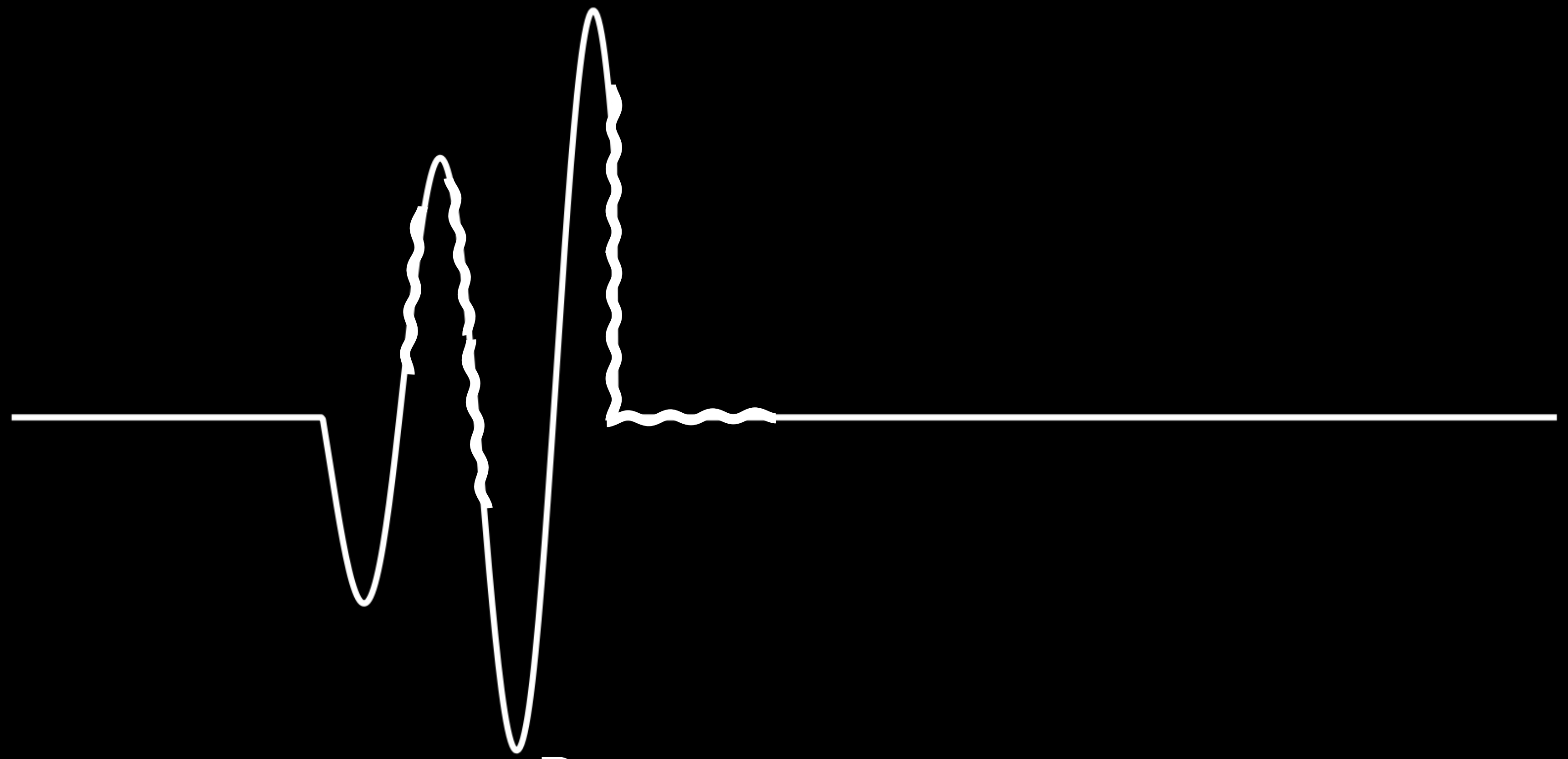
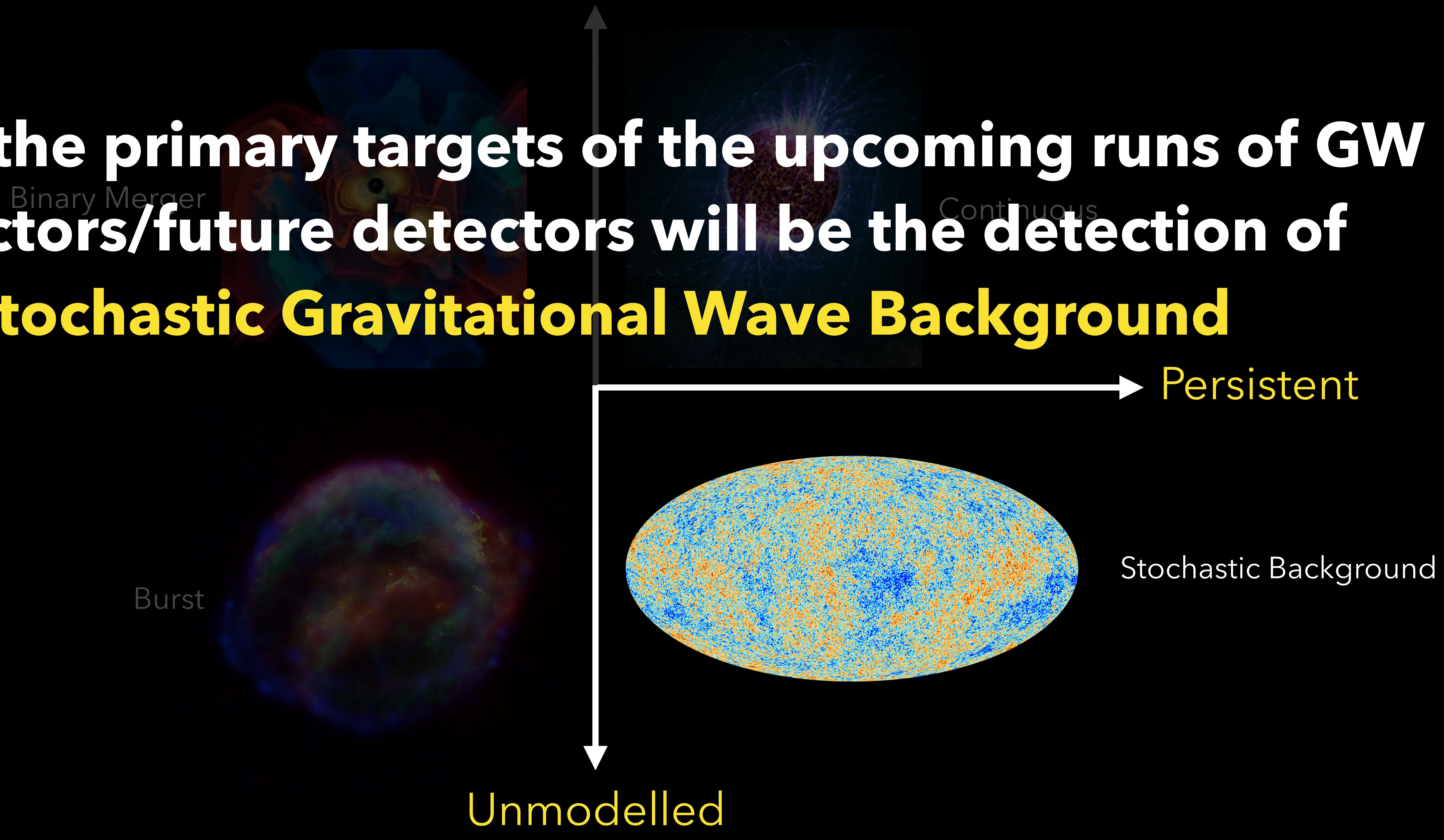
Searching for the Stochastic Gravitational-Wave Background With Ground-Based Detectors

Jishnu Suresh
Université catholique de Louvain

	Transient	Persistent
Phase modelled	Binary Merger 	Continuous Wave 
Phase unmodelled	 Burst	 Stochastic Background

	Transient	Persistent
Phase modelled	Binary Merger 	Continuous Wave 
Phase unmodelled	 Burst	 Stochastic Background

One of the primary targets of the upcoming runs of GW detectors/future detectors will be the detection of **Stochastic Gravitational Wave Background**

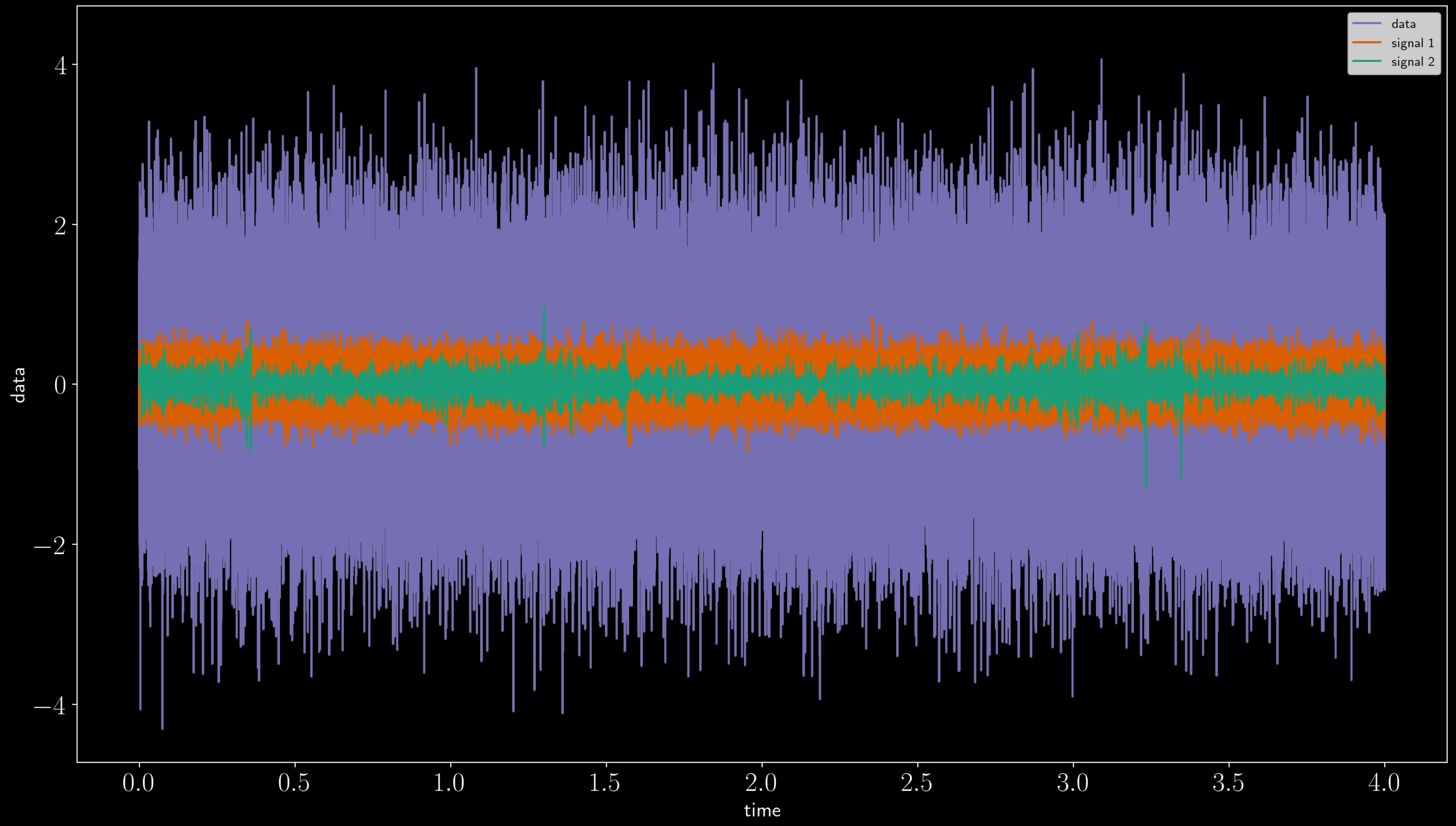


OPERATIONAL DEFINITION

Superposition of signals too weak or too numerous to individually detect

Looks like noise in a single detector

Characterized statistically in terms of ensemble averages of the metric perturbations



WHY SHOULD WE CARE ABOUT SGWB ?

Weakness of gravity relative to other forces ⟹ provides an unprecedented tool to explore the physics of the early universe.

High red shift universe

Lack of SGWB detection ⟶ Bounds on the high-redshift Universe

WHAT DETECTION METHODS CAN WE USE?

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

What can be done:

- Identify features that distinguish between the expected signal and noise.
  - Measure our detector's noise sources well enough in amplitude and spectral shape.
- Detectors with uncorrelated noise: cross-correlation separates the signal from the noise.

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

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

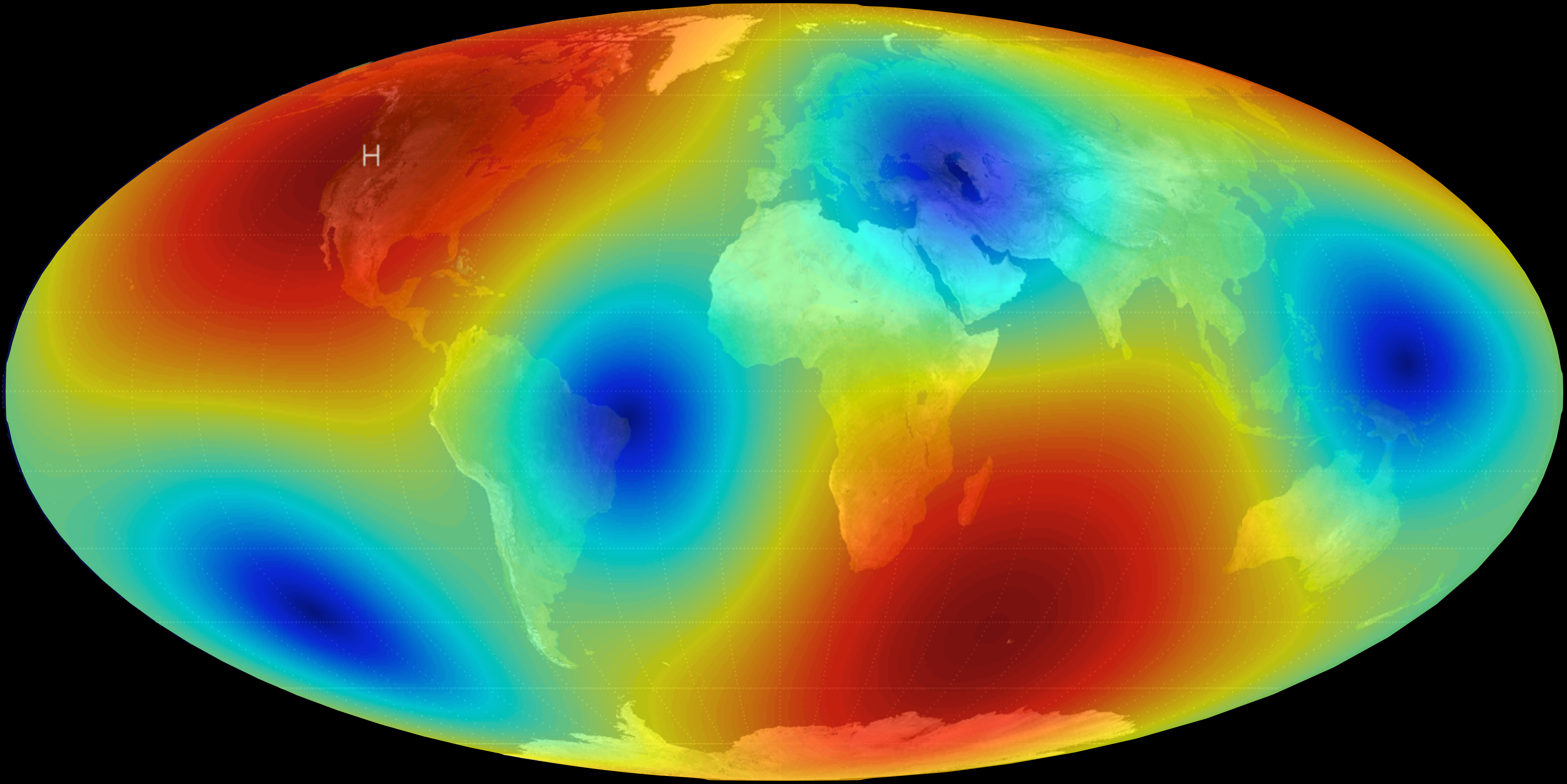
Assuming detector noise is uncorrelated*: $\langle d_1 d_2 \rangle = \langle h^2 \rangle + \cancelto{0}{\langle n_1 n_2 \rangle}$

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

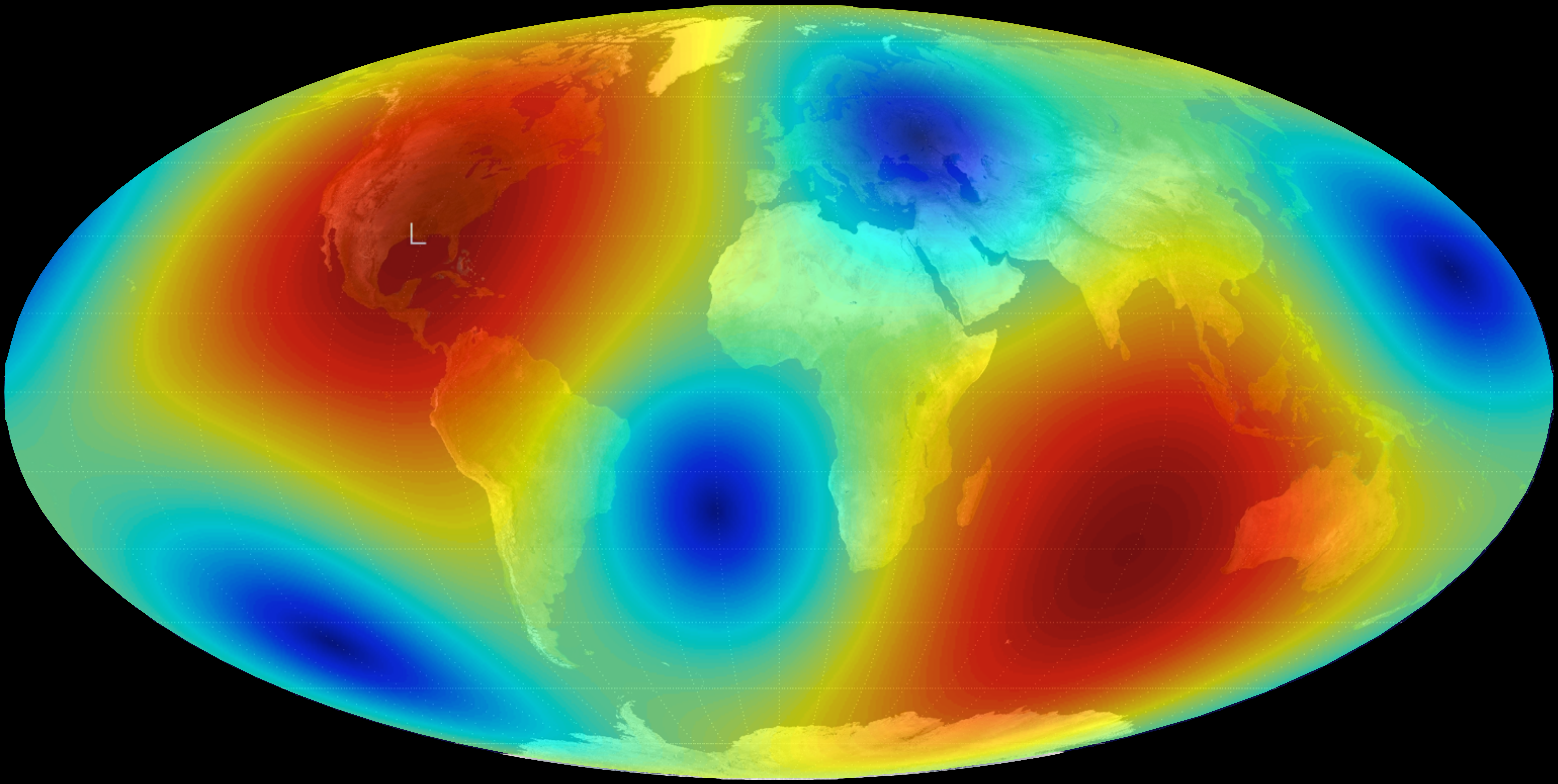
Cross-correlation separates the signal from the noise

Intensity of the background

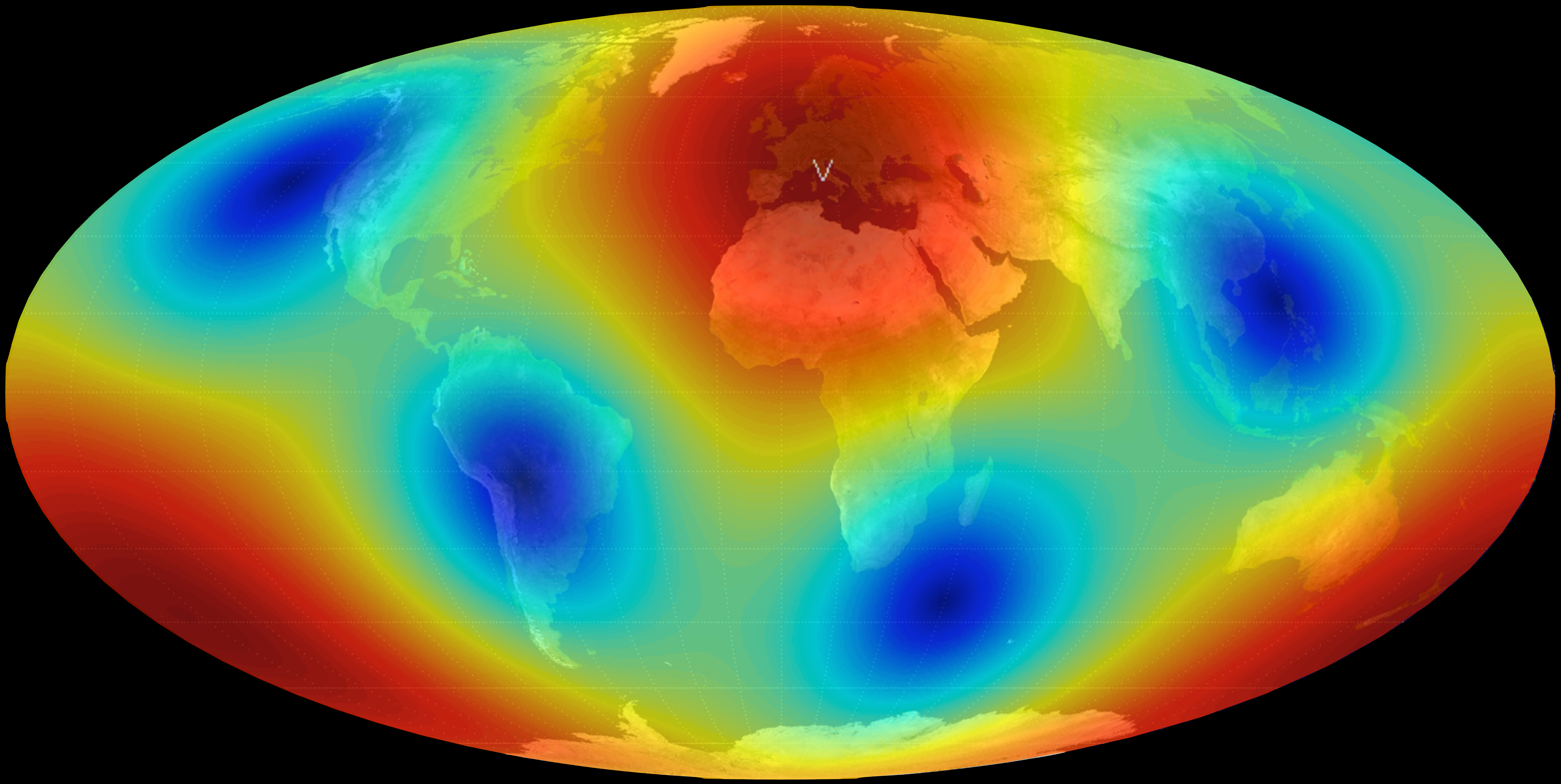
DETECTOR RESPONSE



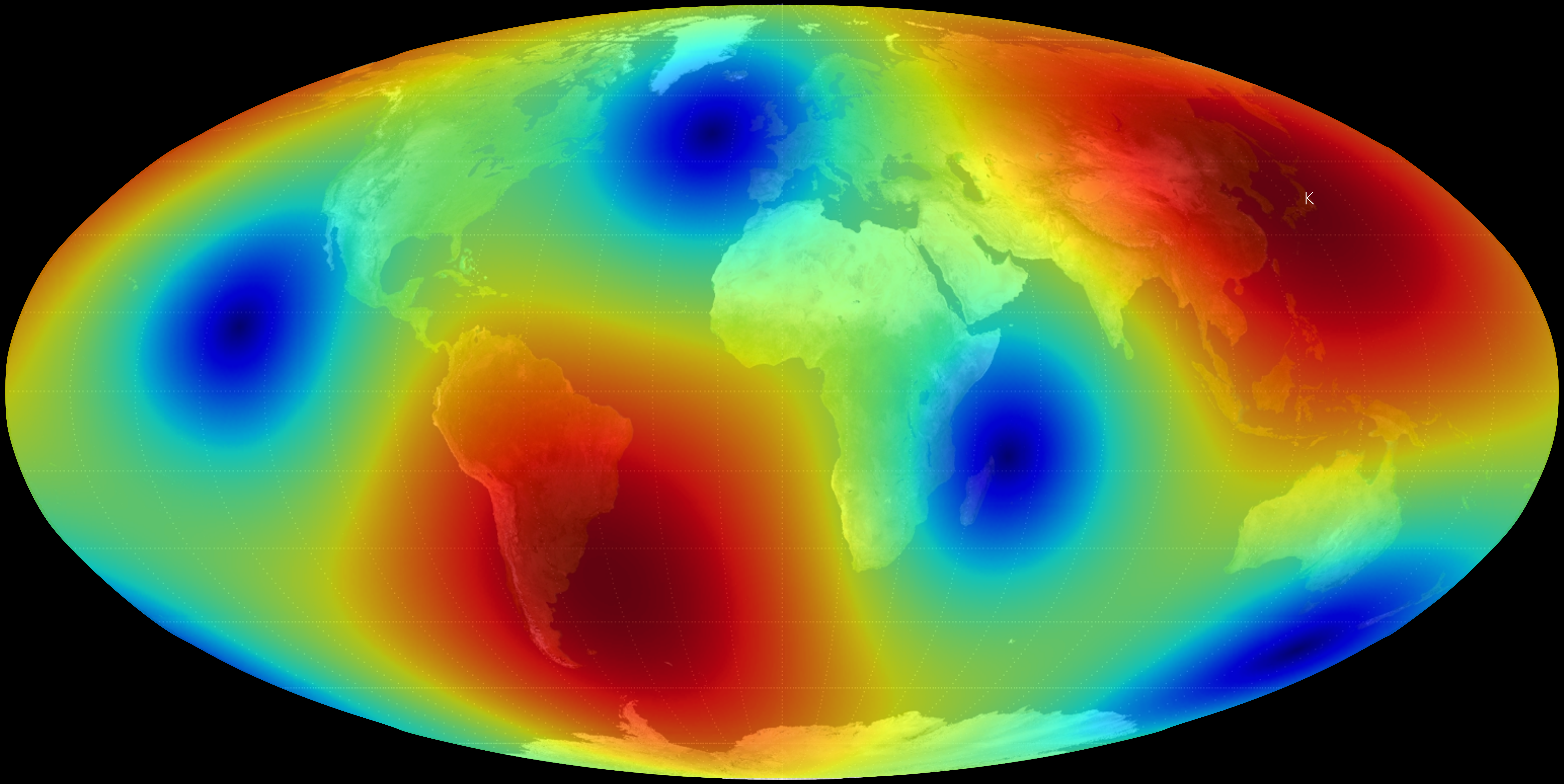
DETECTOR RESPONSE



DETECTOR RESPONSE

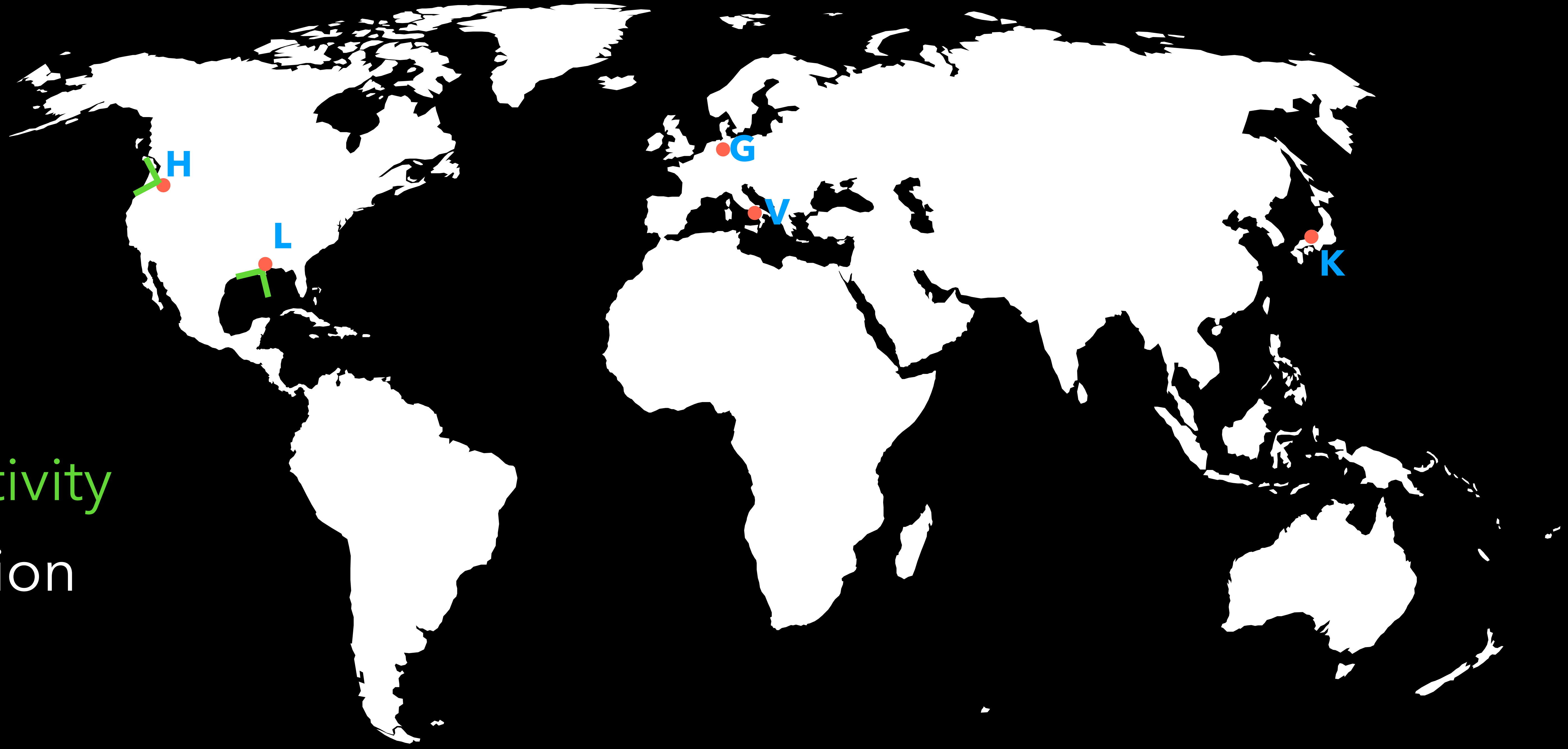


DETECTOR RESPONSE



OVERLAP REDUCTION FUNCTION

Detectors in different locations and with different orientations respond differently to a passing GW.



Overlap function encodes reduction in sensitivity of a cross-correlation analysis due to separation and misalignment of the detectors.

$$\gamma^{IJ}_{ft,p} = \sum_{A} F^A_I(\hat{\Omega}, t)\, F^A_J(\hat{\Omega}, t)\, e^{2\pi i f\, \hat{\Omega}\cdot\mathbf{\Delta x}_{\mathscr{J}}(t)/c}$$

WHAT DETECTION METHODS CAN WE USE?

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

Cross-correlation estimator

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

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

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

expected signal spectrum

Overlap reduction function

de-weight correlation when noise is large

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

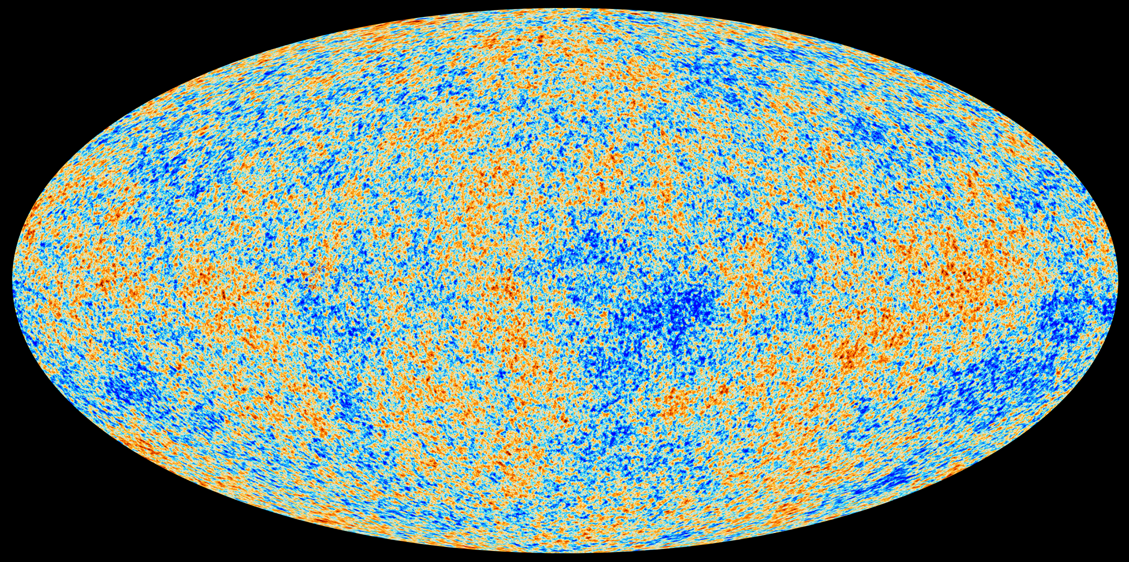
$$\Omega_{\mathrm{t}}(f) = \Omega_{\mathrm{ref}} \left(\frac{f}{f_{\mathrm{ref}}} \right)^{\alpha}$$

WHICH SGWBs WE ARE SENSITIVE TO?

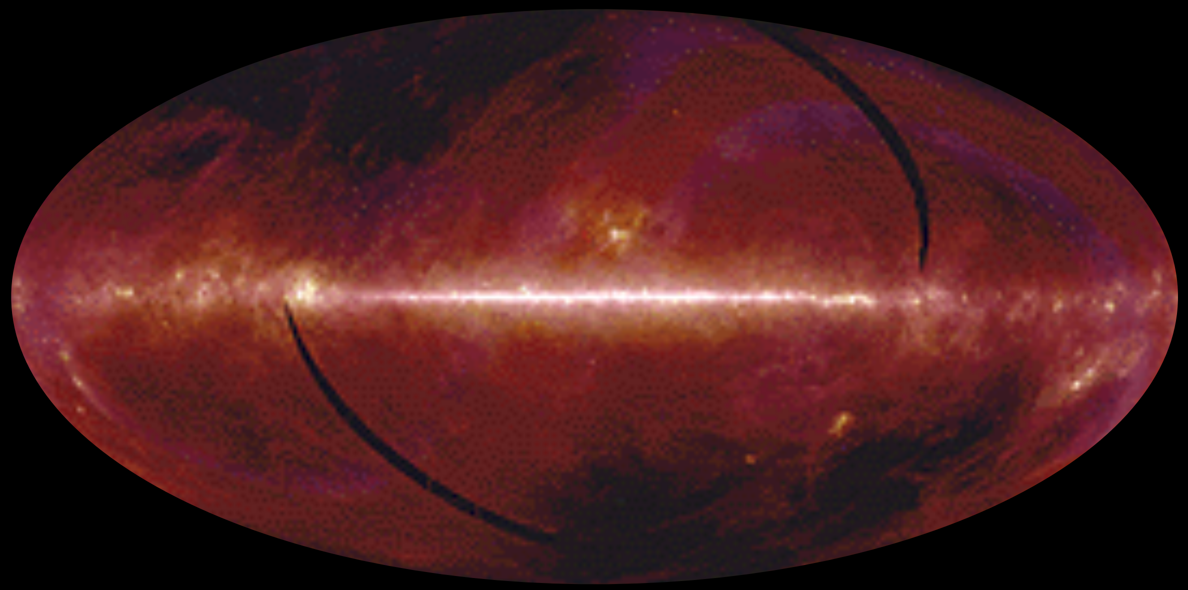
Cosmological Origin

Astrophysical Origin

EM

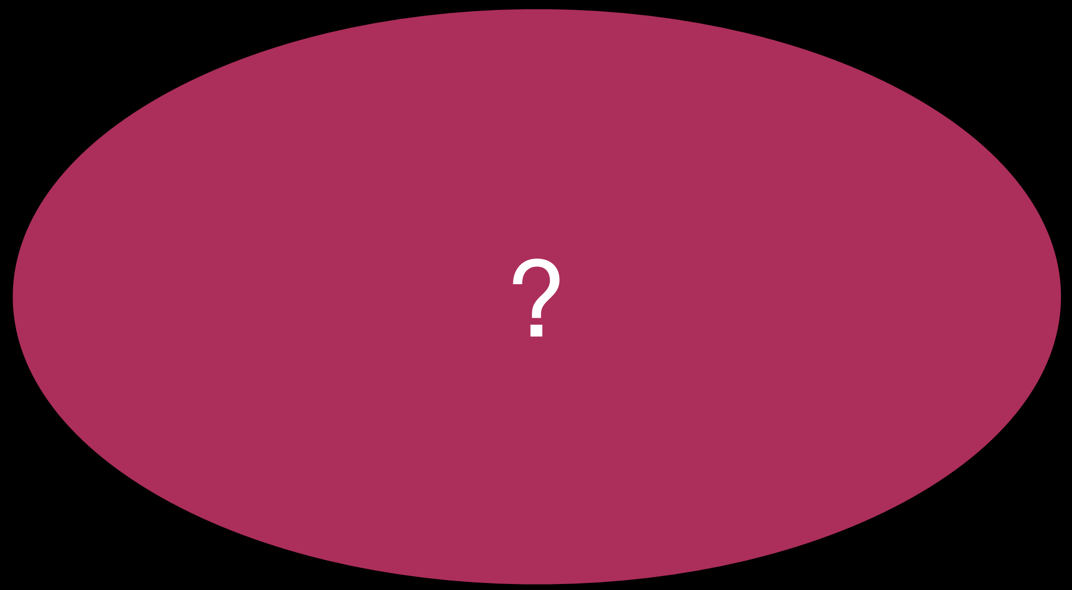


PLANCK CMB MAP

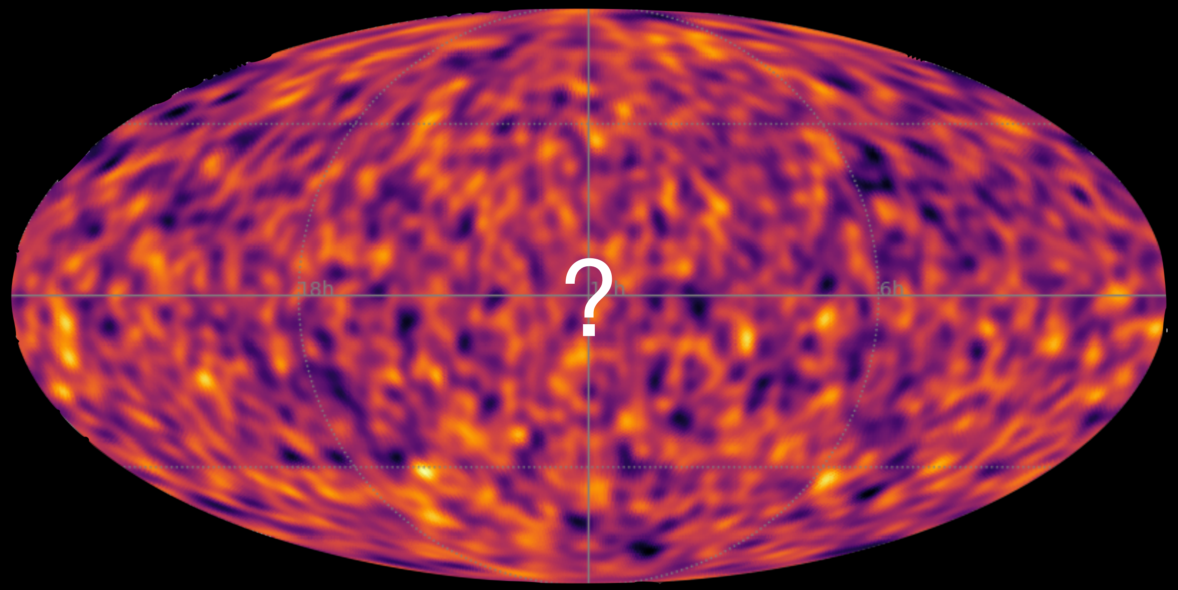


PLANCK IR MAP

GW



COSMOLOGICAL SGWB



ASTROPHYSICAL SGWB

WHICH SGWBs WE ARE SENSITIVE TO?

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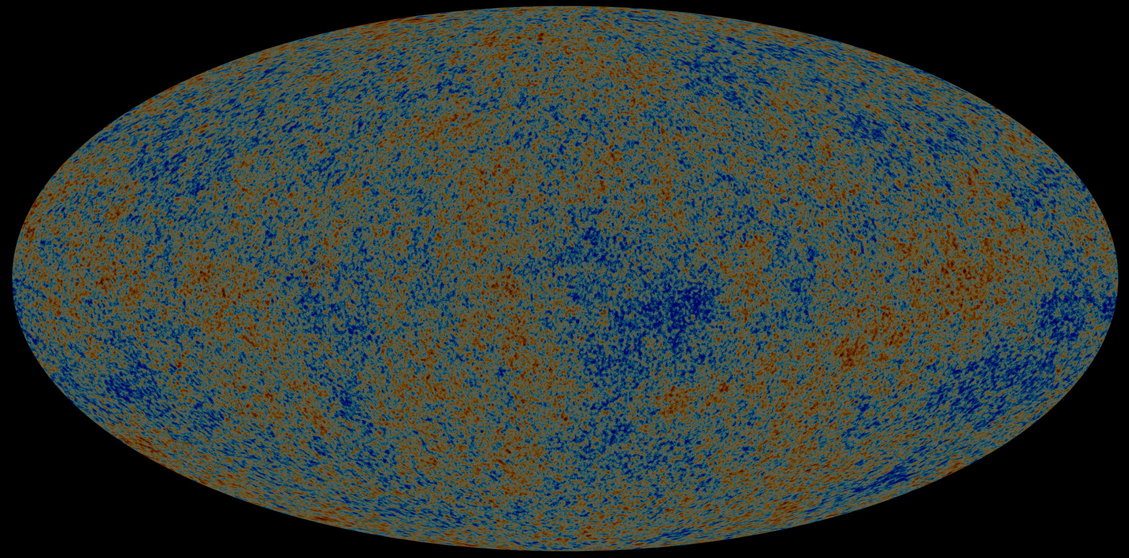
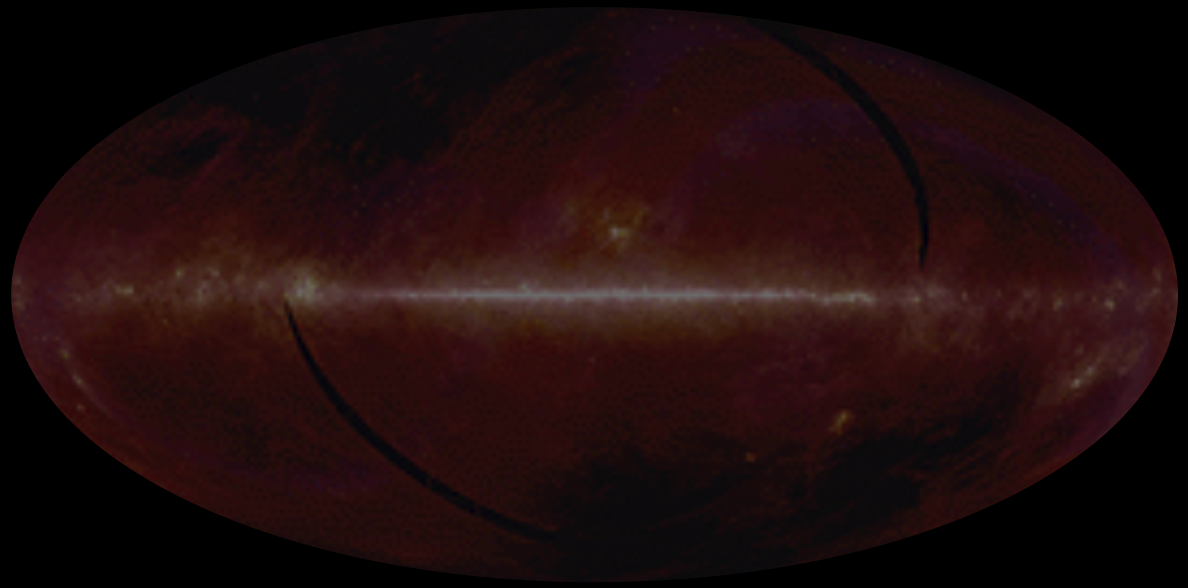


PLANCK CMB MAP

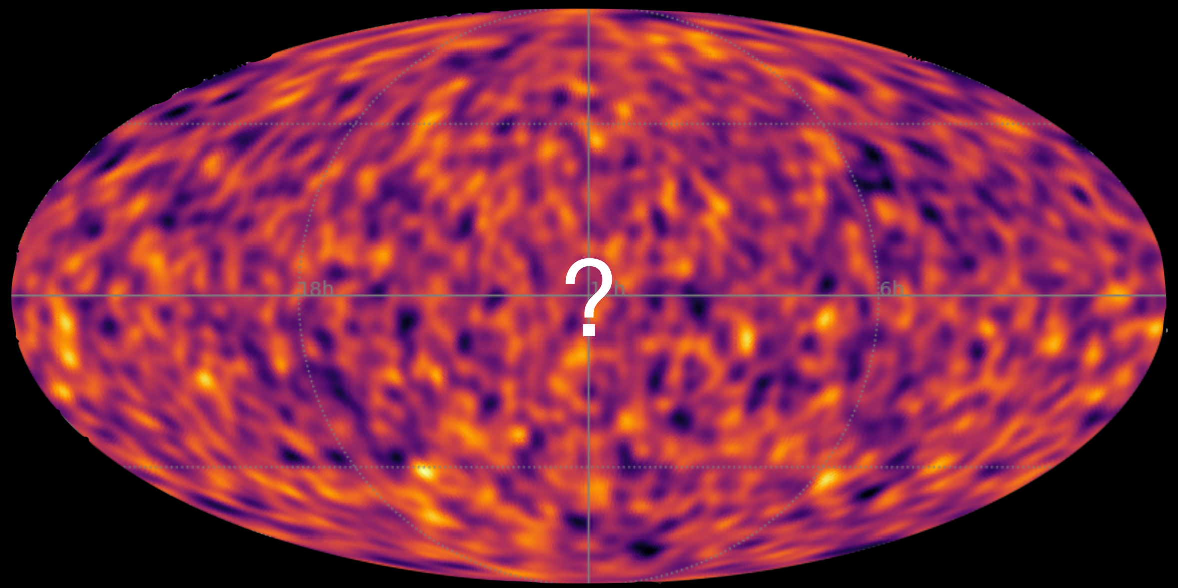


PLANCK IR MAP

GW

?

COSMOLOGICAL SGWB



ASTROPHYSICAL SGWB

ASTROPHYSICAL STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

For a collection of sources:

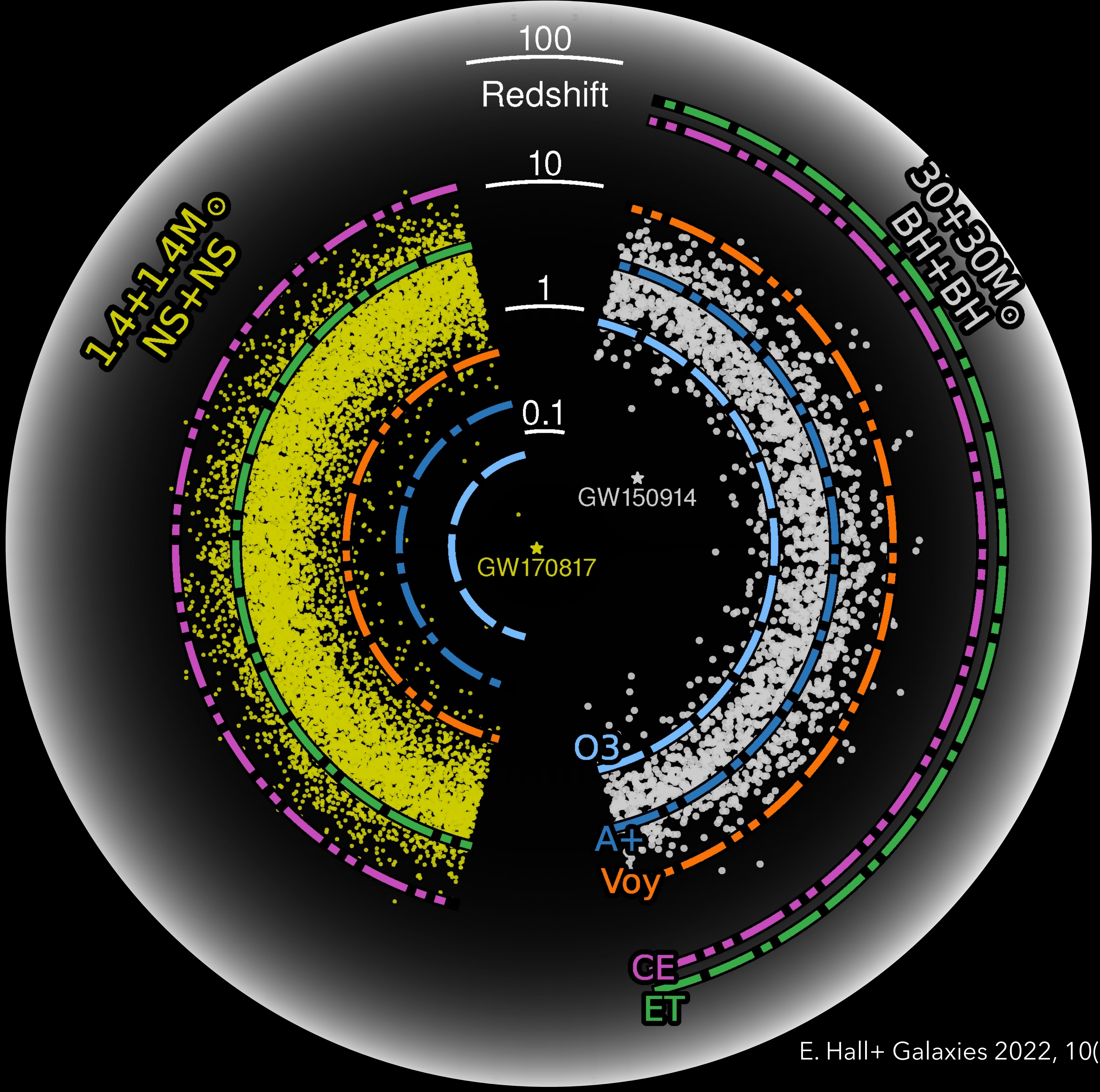
$\Omega_{\mathrm{gw}}(f) \propto$ <GW energy per source> x <source rate> dt

$$\Omega_{\mathrm{gw}}(f) \propto \int_0^\infty \mathrm{d}z\, R(z) \frac{1}{(1+z)E(z)} f_s \left(\frac{\mathrm{d}E_{\mathrm{gw}}}{\mathrm{d}f_s}\right)$$

Event rate

$E(z) = \sqrt{\Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda}$ –> cosmology

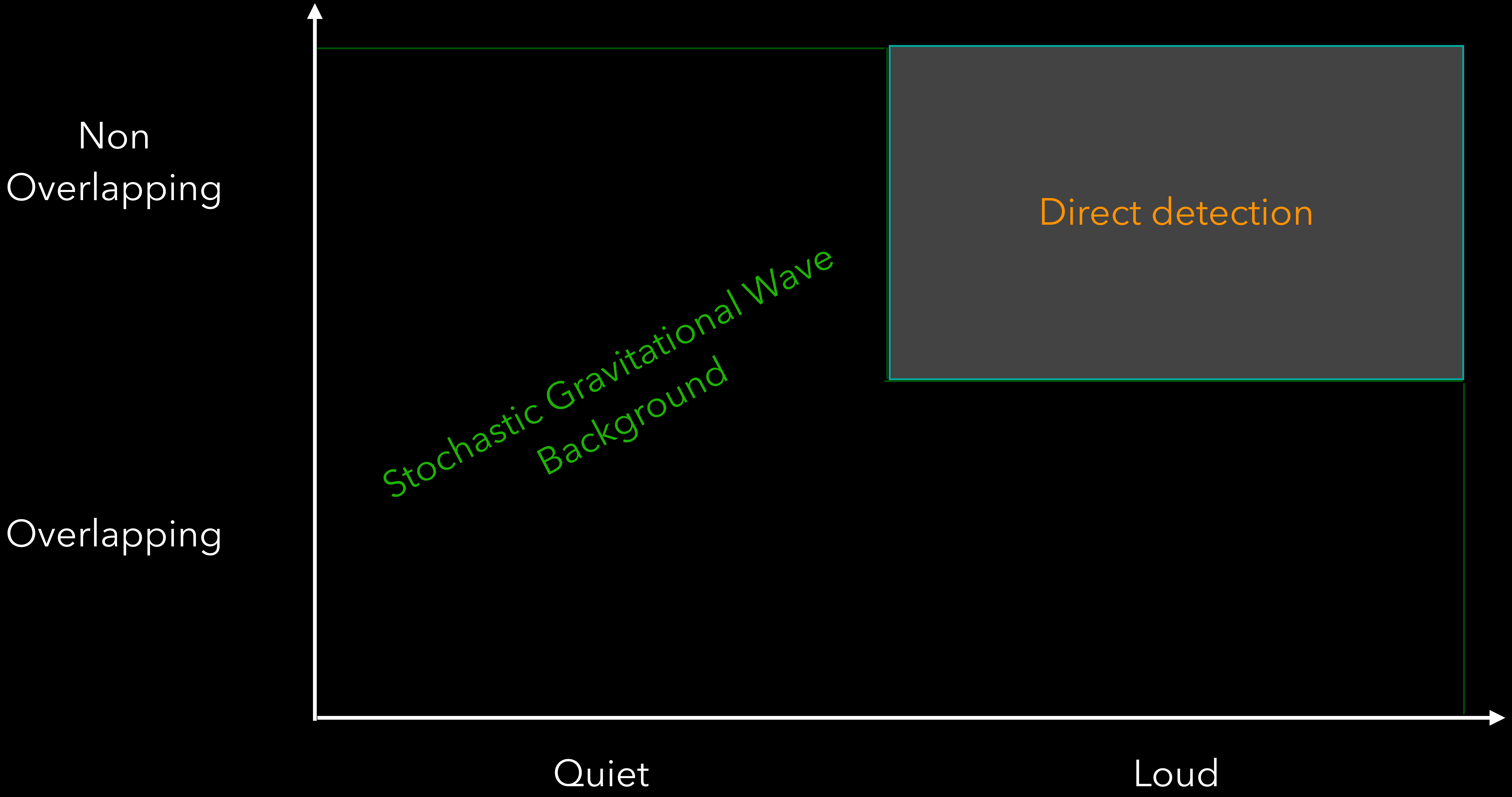
(redshifted) energy radiated per event per source-frame frequency



E. Hall+ Galaxies 2022, 10(4), 90

$$\Omega_{\mathrm{gw}}(f) \equiv \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{gw}}}{\mathrm{d}\ln f} = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{gw}}}{\mathrm{d}f} \qquad \rho_{gw} = \frac{c^2}{32\pi G}\langle \dot{h}_{ab}(t,\vec{x})\dot{h}^{ab}(t,\vec{x})\rangle$$

ASTROPHYSICAL STOCHASTIC GRAVITATIONAL WAVE BACKGROUND



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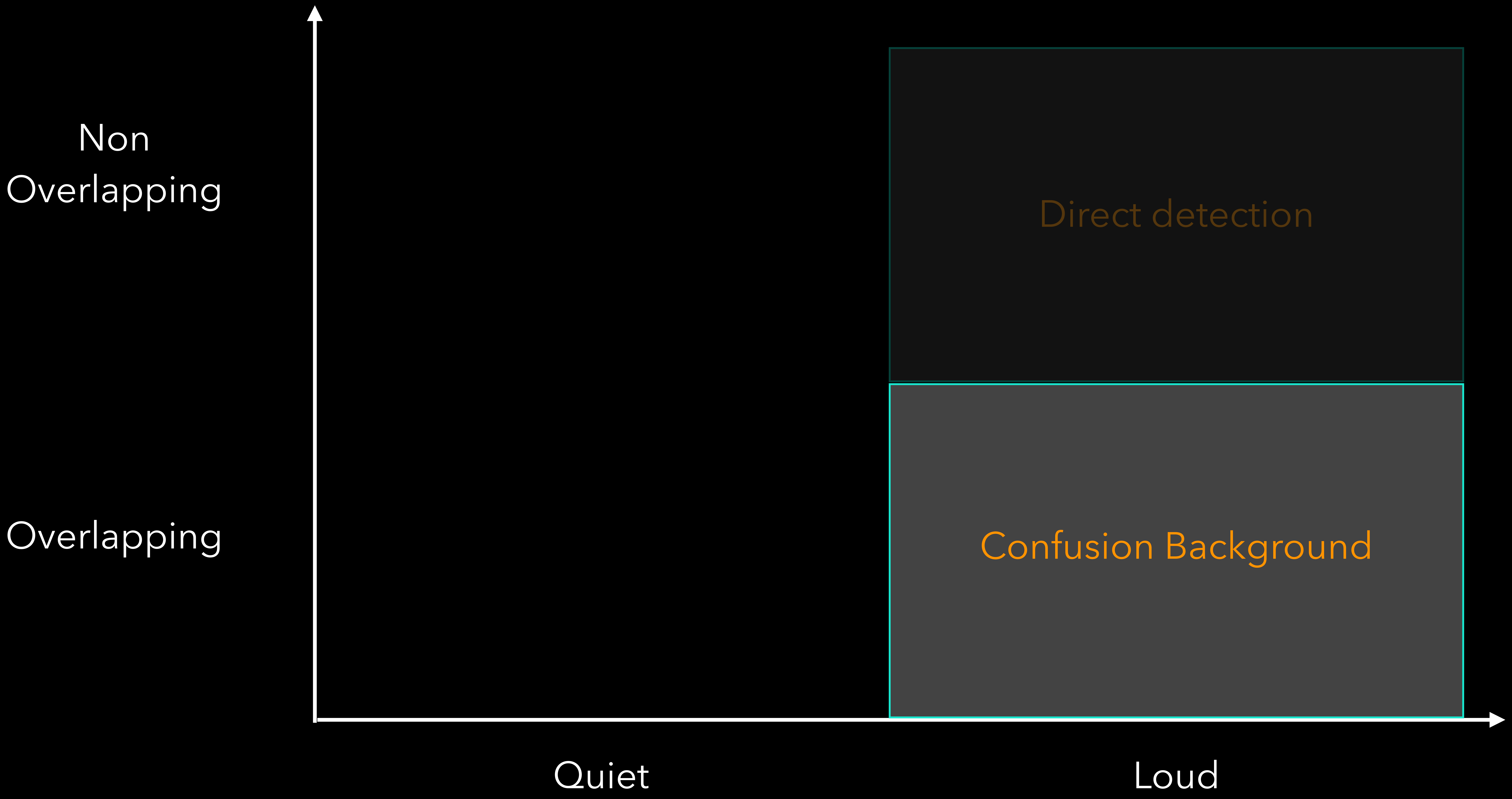

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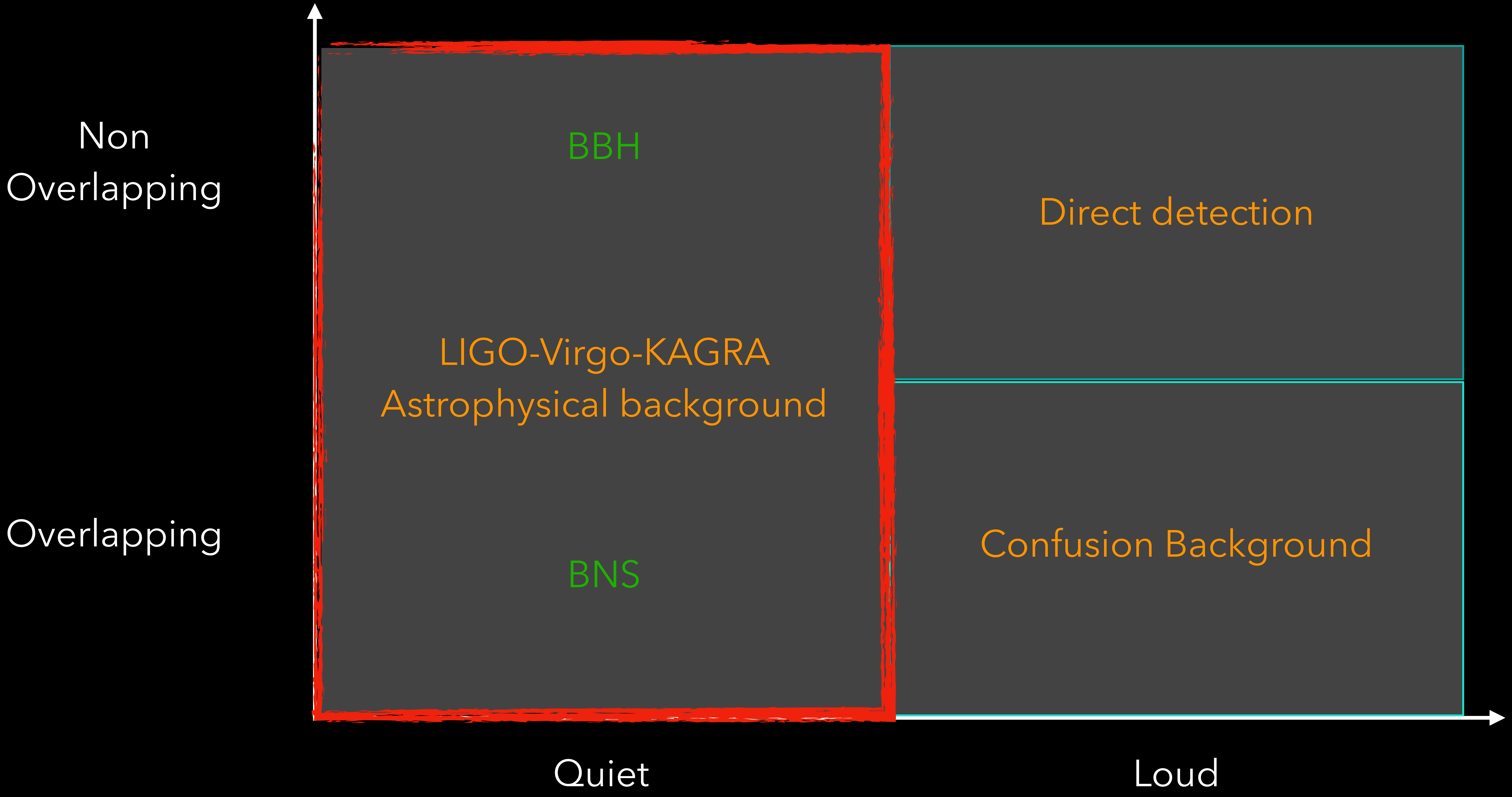


Non Overlapping

Overlapping

BBH

LIGO-Virgo-KAGRA Astrophysical background

BNS

Direct detection

Confusion Background

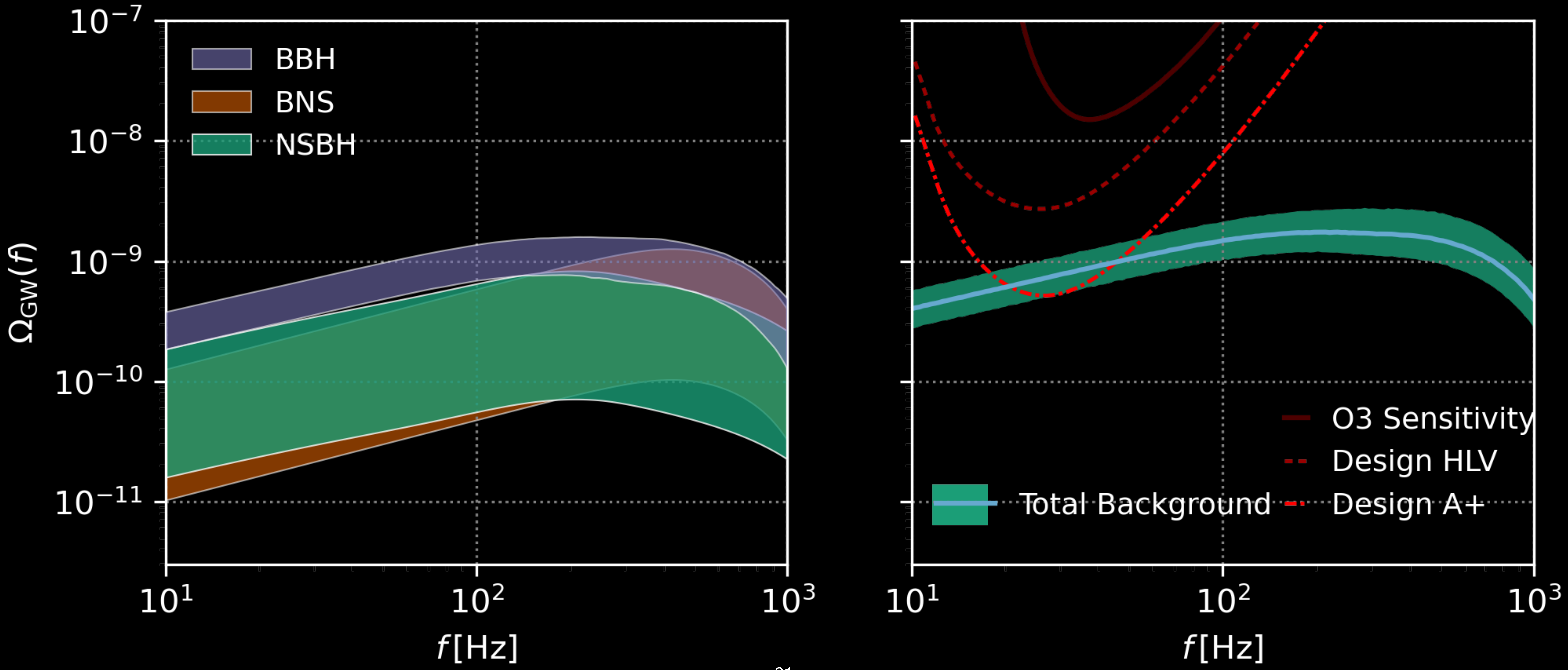
Quiet

Loud

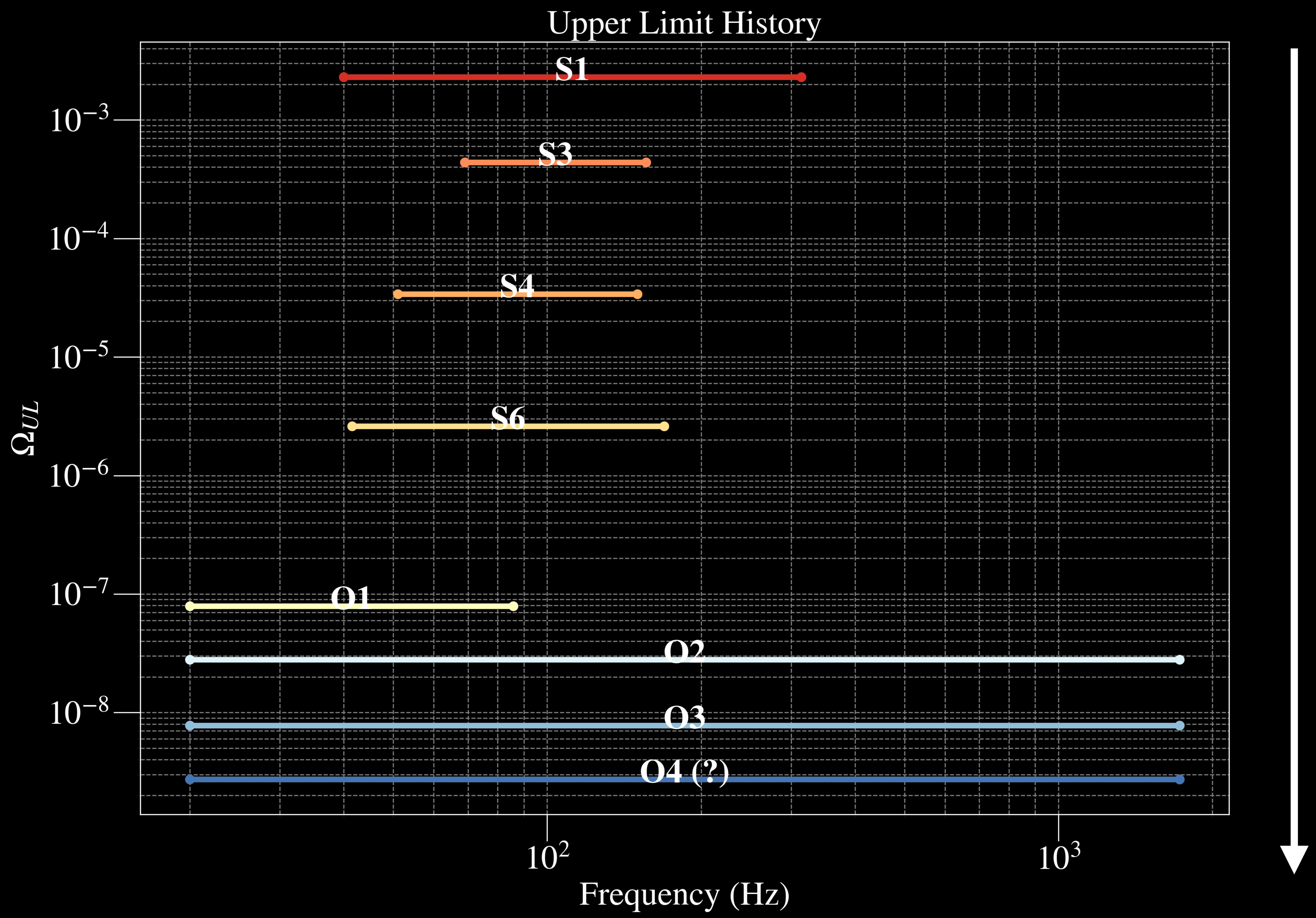
SENSITIVITY PROJECTION

LVK PRX:13, 011048 (2023)

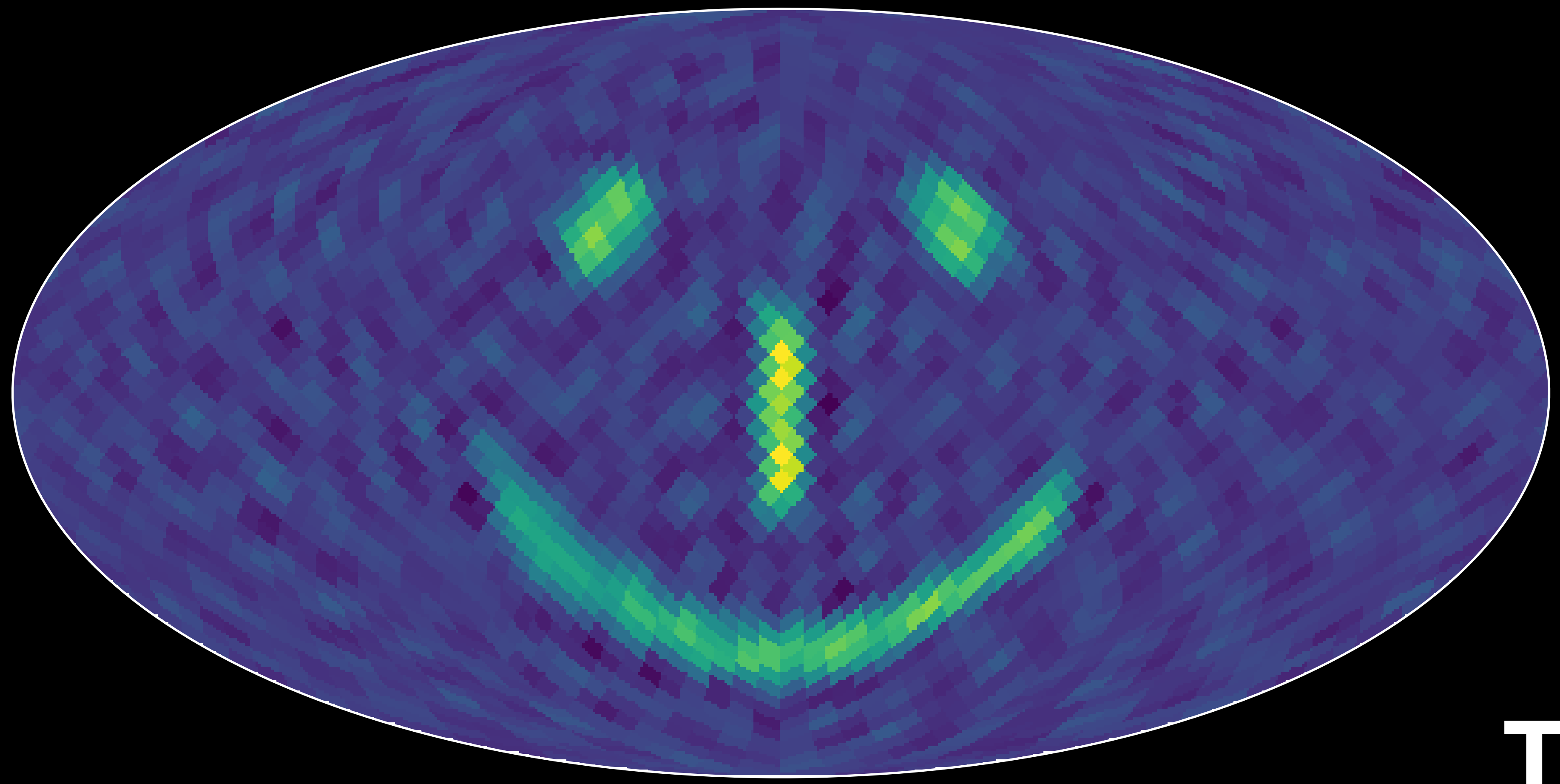
$$\Omega_{\mathrm{CBC}}(f) \propto \int_0^\infty \mathrm{d}z\, R(z) \frac{1}{(1+z)E(z)} f_s \left(\frac{\mathrm{d}E_{\mathrm{gw}}}{\mathrm{d}f_{\mathrm{s}}} \right)$$



WE ARE NOW AT:



We are reaching there…



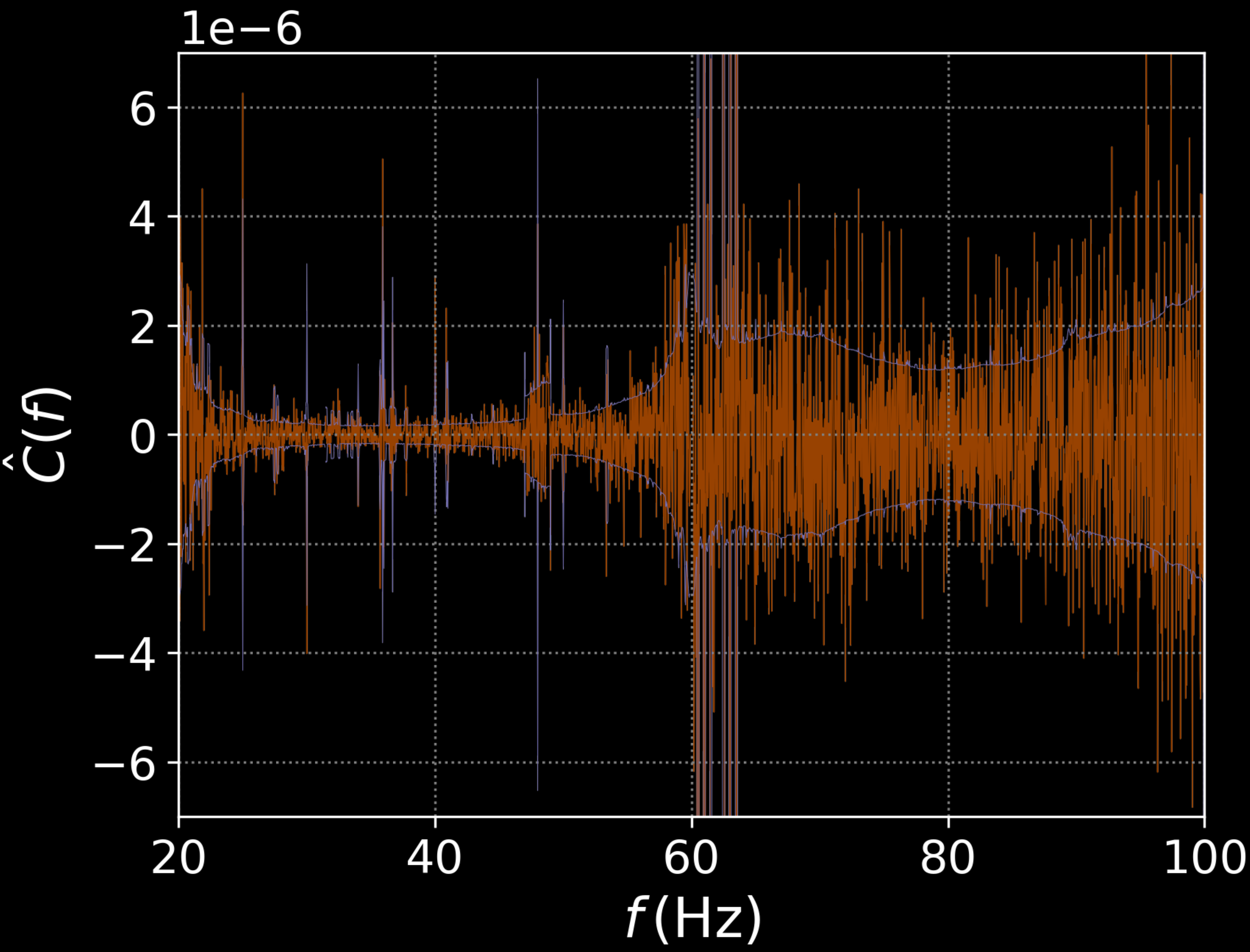
Thank you!

O3 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.

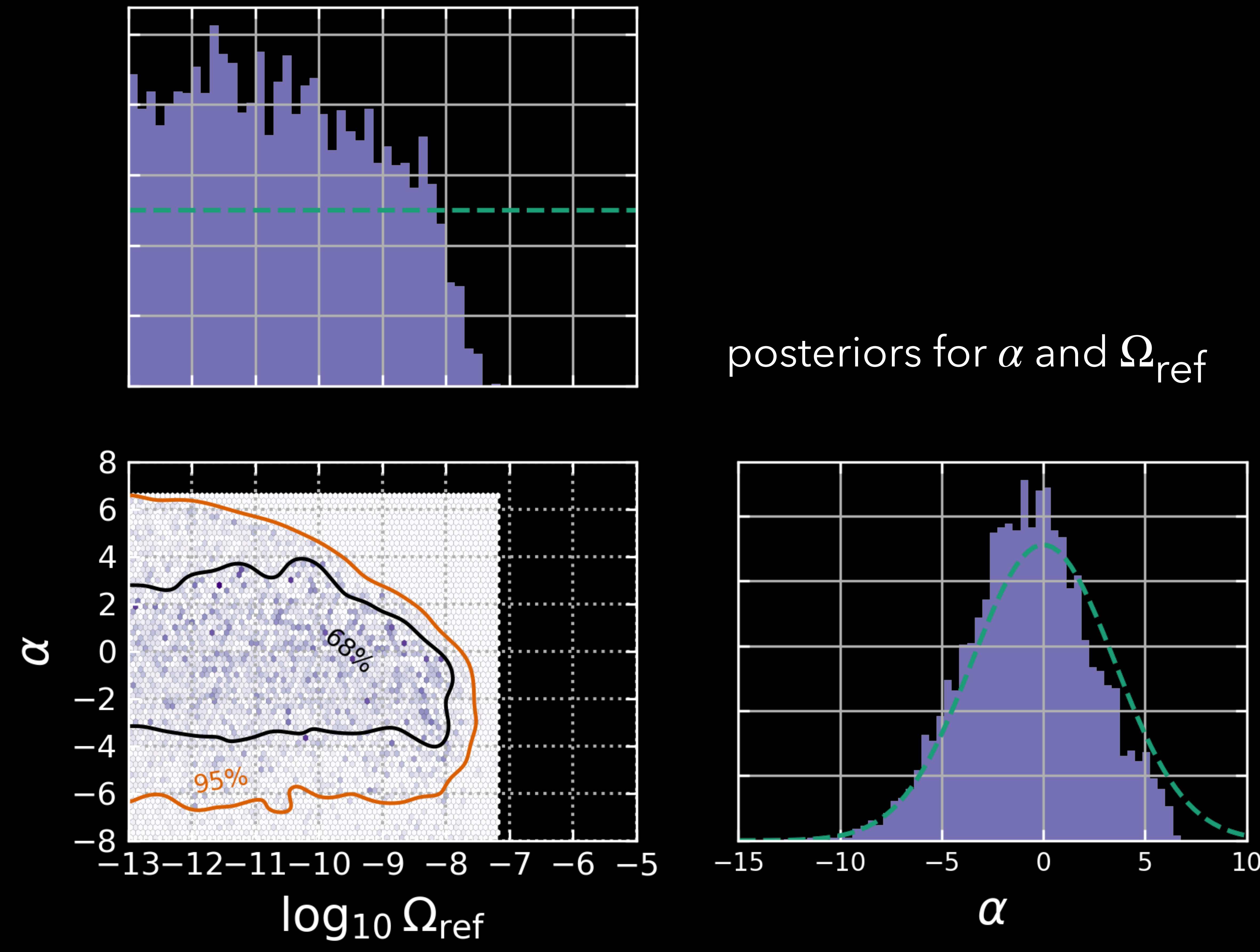


O3 RESULTS

PRD104, 022004 (2021)

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	$1.7\text{x}10^{-8}$	$6.0\text{x}10^{-8}$	3.6	$5.8\text{x}10^{-9}$	$3.5\text{x}10^{-8}$	6.0
2/3	$1.7\text{x}10^{-8}$	$4.8\text{x}10^{-8}$	4.0	$3.4\text{x}10^{-9}$	$3.0\text{x}10^{-8}$	8.8
3	$1.3\text{x}10^{-9}$	$7.9\text{x}10^{-9}$	5.9	$3.9\text{x}10^{-10}$	$5.1\text{x}10^{-9}$	13.1



posteriors for α and Ω_{ref}