Gravitational Wave Orchestra; Being Sensitive is Crucial!

Jishnu Suresh,
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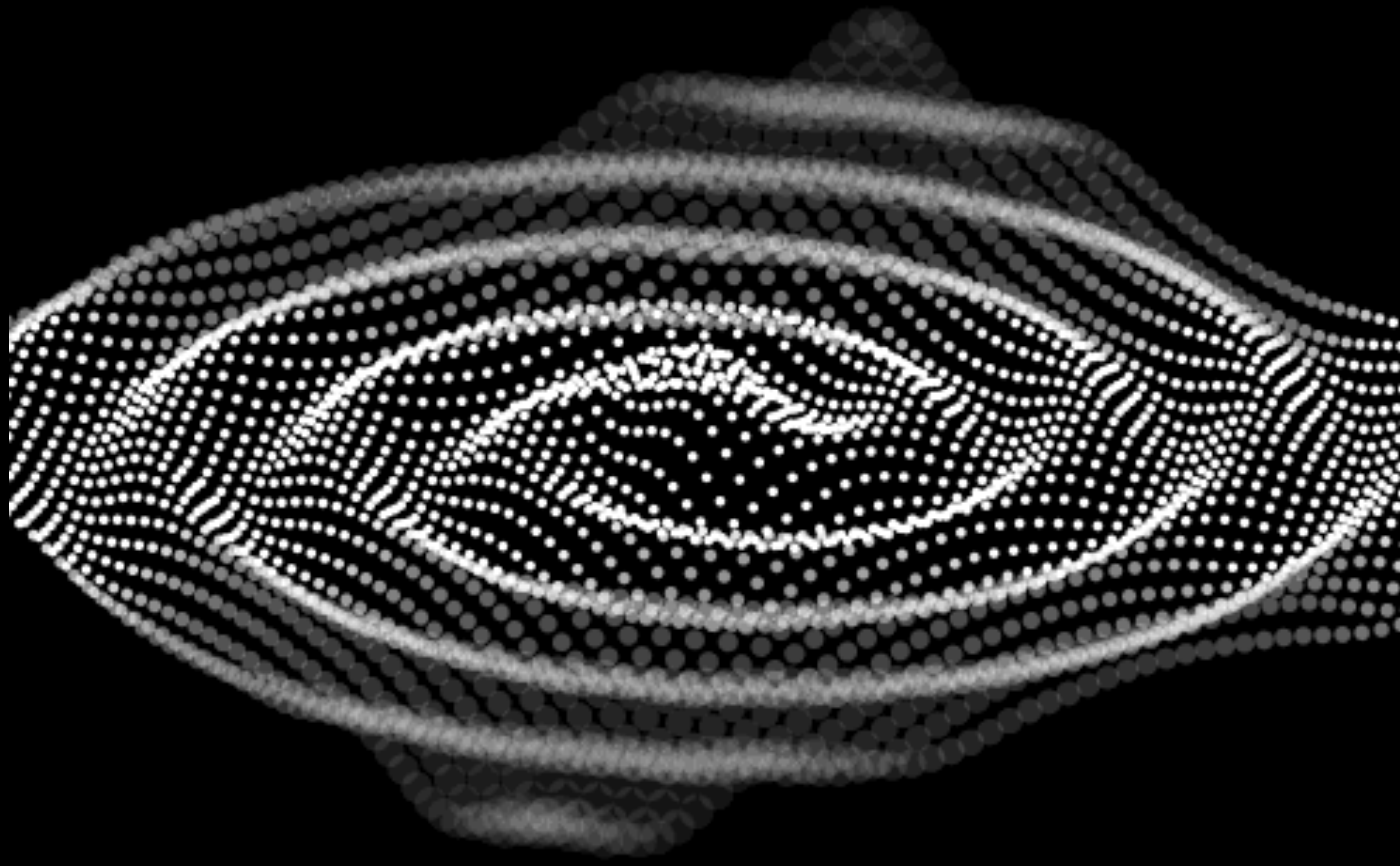
GRAVITATIONAL WAVES

The universe is not static! Nor is space time!

GWs are freely propagating oscillations in the geometry of spacetime - ripples in the fabric of spacetime.

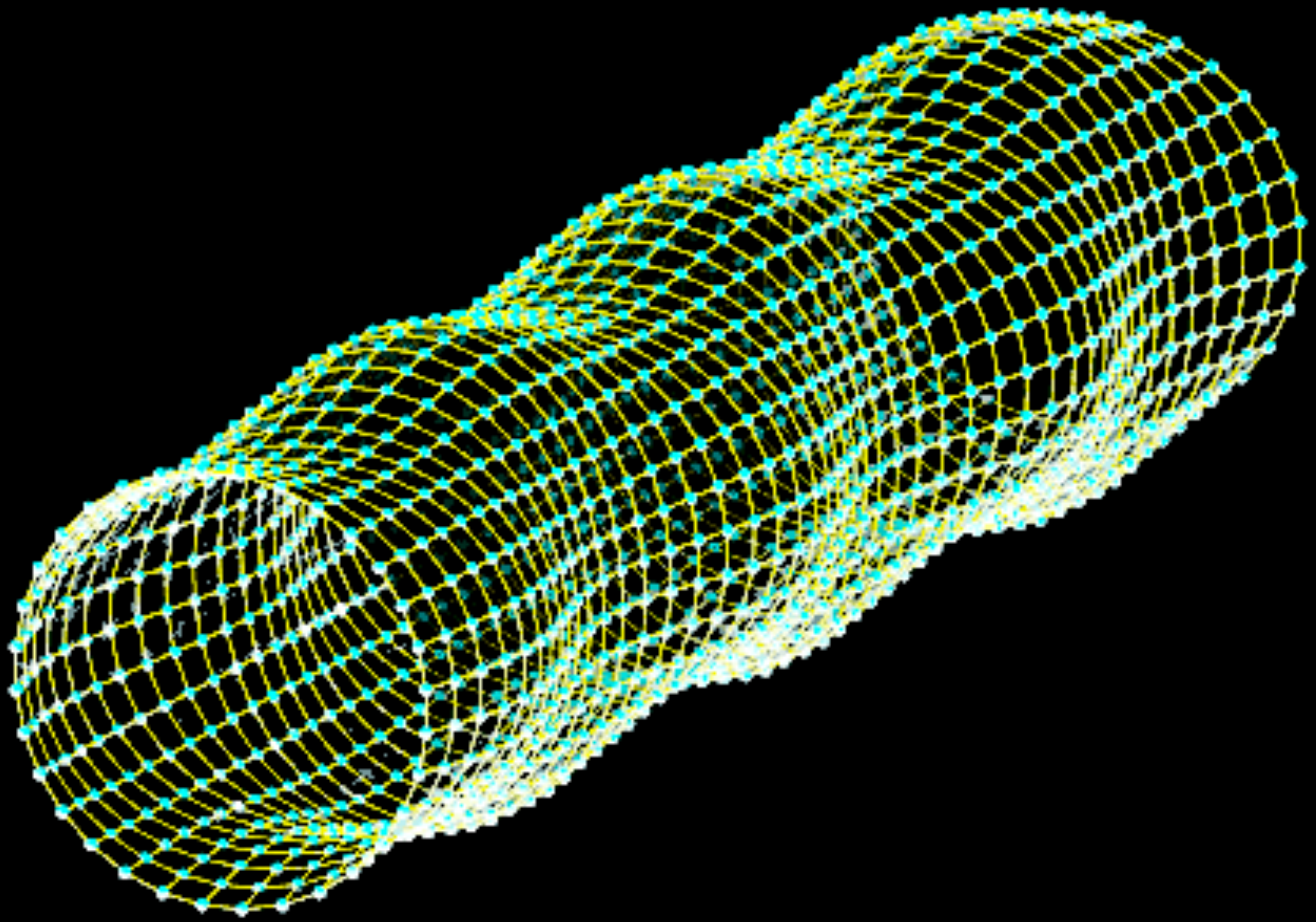
accelerating charges ⟹ Electromagnetic Waves

accelerating masses ⟹ Gravitational Waves



GRAVITATIONAL WAVES

GW produce a time-dependent change in the geometry of the space-time.



credit: Einstein online info

Stretching and squeezing of space

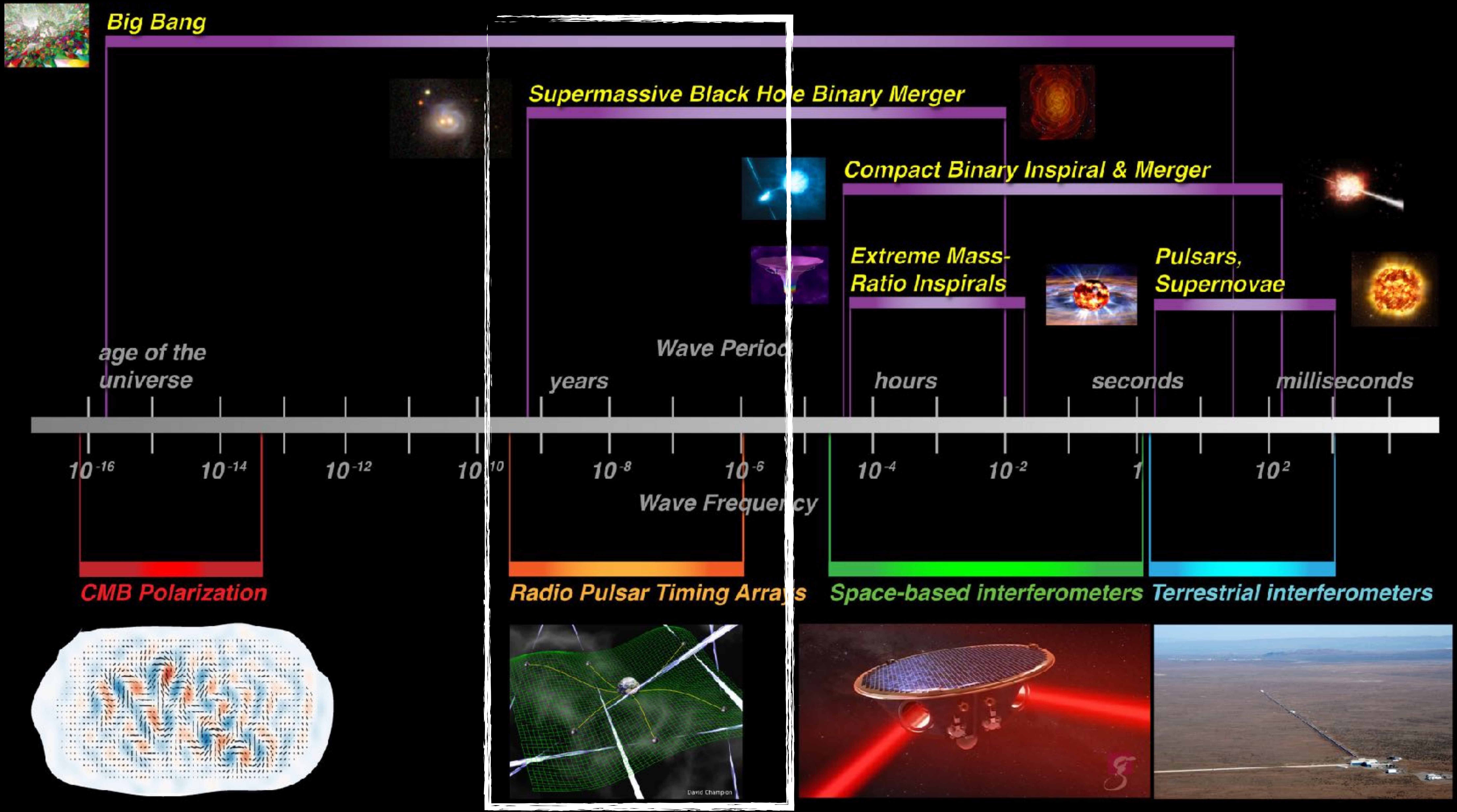
Gravitational waves are ‘strains’:
Changes in length per unit length,
$\Delta L/L$

Space-time is very stiff

Strain from astrophysical sources*
on earth is $h \approx 10^{-21}$

* Two compact object, each 10 times mass of the sun, revolving around each other and merging!

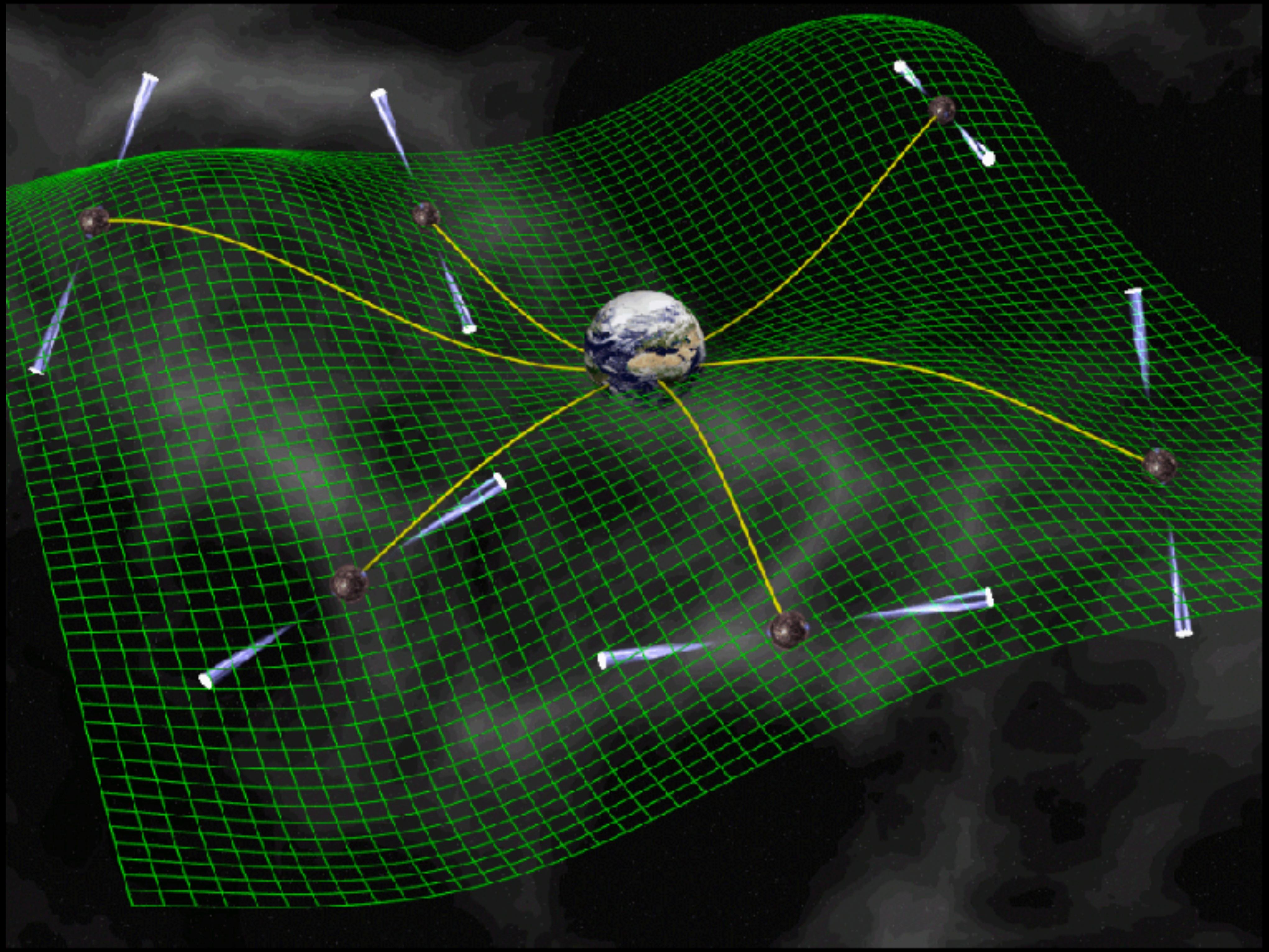
GW ACROSS THE SPECTRUM



credit: NASA/J. I.Thorpe

nHz BAND

- Pulsars; rapidly rotating neutron stars
- Measure radio pulse arrivals
- Can predict pulse arrival time to nano-second precision
- GWs cause change in expected arrival time
- That delay is correlated between different pulsars



GWs perturb the arrival times of pulses -> look for the presence of GWs in the timing residuals

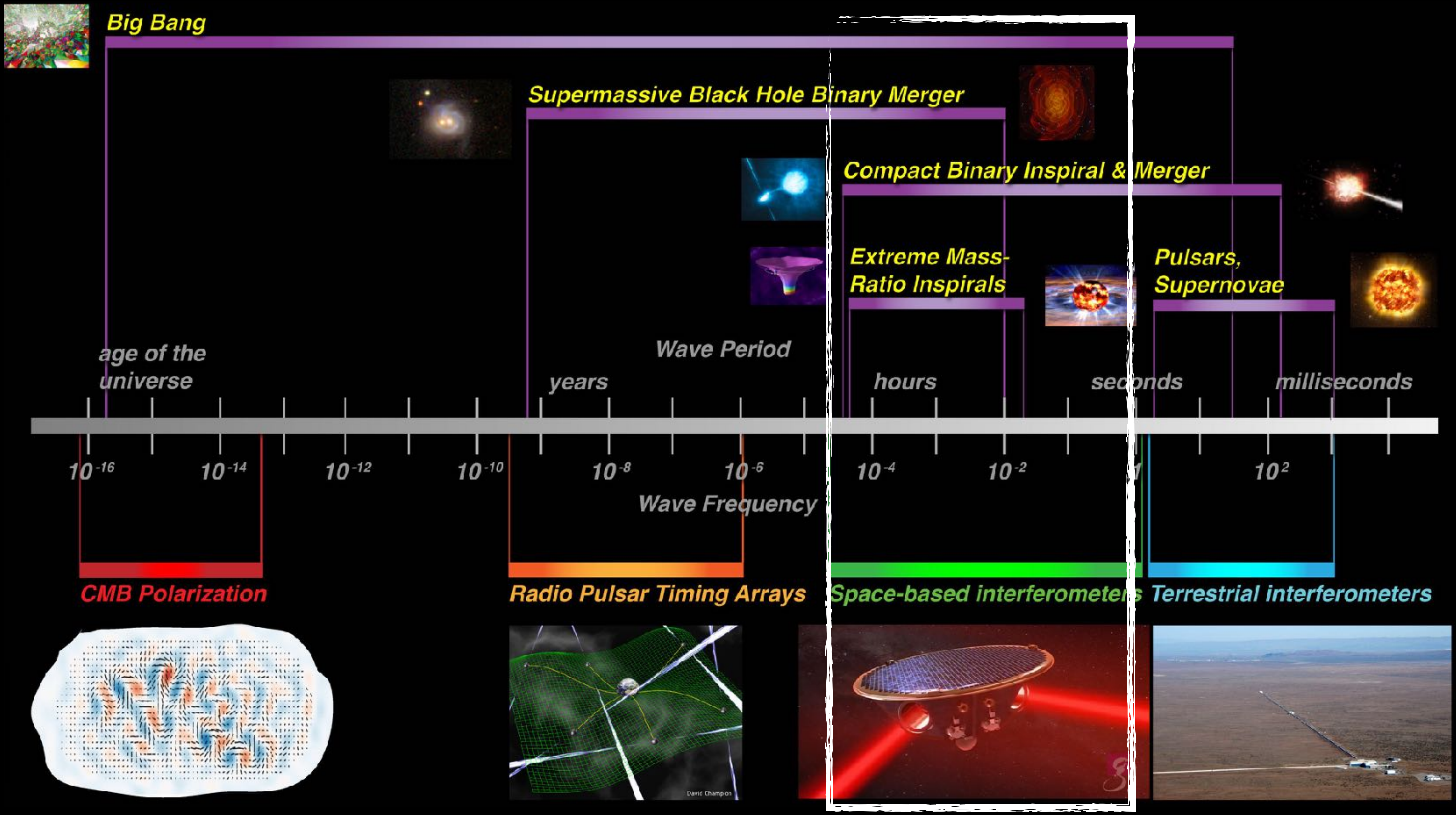
nHz BAND

Exciting news from June 2023

Evidence for a GW signal that is correlated among different pulsars

Collaboration	Paper	Link
NANOGrav	GWB Paper	https://arxiv.org/abs/2306.16213
EPTA	GWB Paper	https://arxiv.org/abs/2306.16214
PPTA	GWB Paper	https://arxiv.org/abs/2306.16215
CPTA	GWB Paper	https://arxiv.org/abs/2306.16216
NANOGrav	Data Paper	https://arxiv.org/abs/2306.16217
NANOGrav	Noise Model Paper	https://arxiv.org/abs/2306.16218
NANOGrav	New Physics Paper	https://arxiv.org/abs/2306.16219
NANOGrav	SMBH Binary Paper	https://arxiv.org/abs/2306.16220
NANOGrav	Anisotropy Paper	https://arxiv.org/abs/2306.16221
NANOGrav	Continuous GW Paper	https://arxiv.org/abs/2306.16222
NANOGrav	Code Review Paper	https://arxiv.org/abs/2306.16223
EPTA	Data Paper	https://arxiv.org/abs/2306.16224
EPTA	Noise Model Paper	https://arxiv.org/abs/2306.16225
EPTA	Continuous GW Paper	https://arxiv.org/abs/2306.16226
EPTA	Implications Paper	https://arxiv.org/abs/2306.16227
EPTA	Ultralight Dark Matter	https://arxiv.org/abs/2306.16228
PPTA	Noise Model Paper	https://arxiv.org/abs/2306.16229
PPTA	Data Paper	https://arxiv.org/abs/2306.16230

GW ACROSS THE SPECTRUM

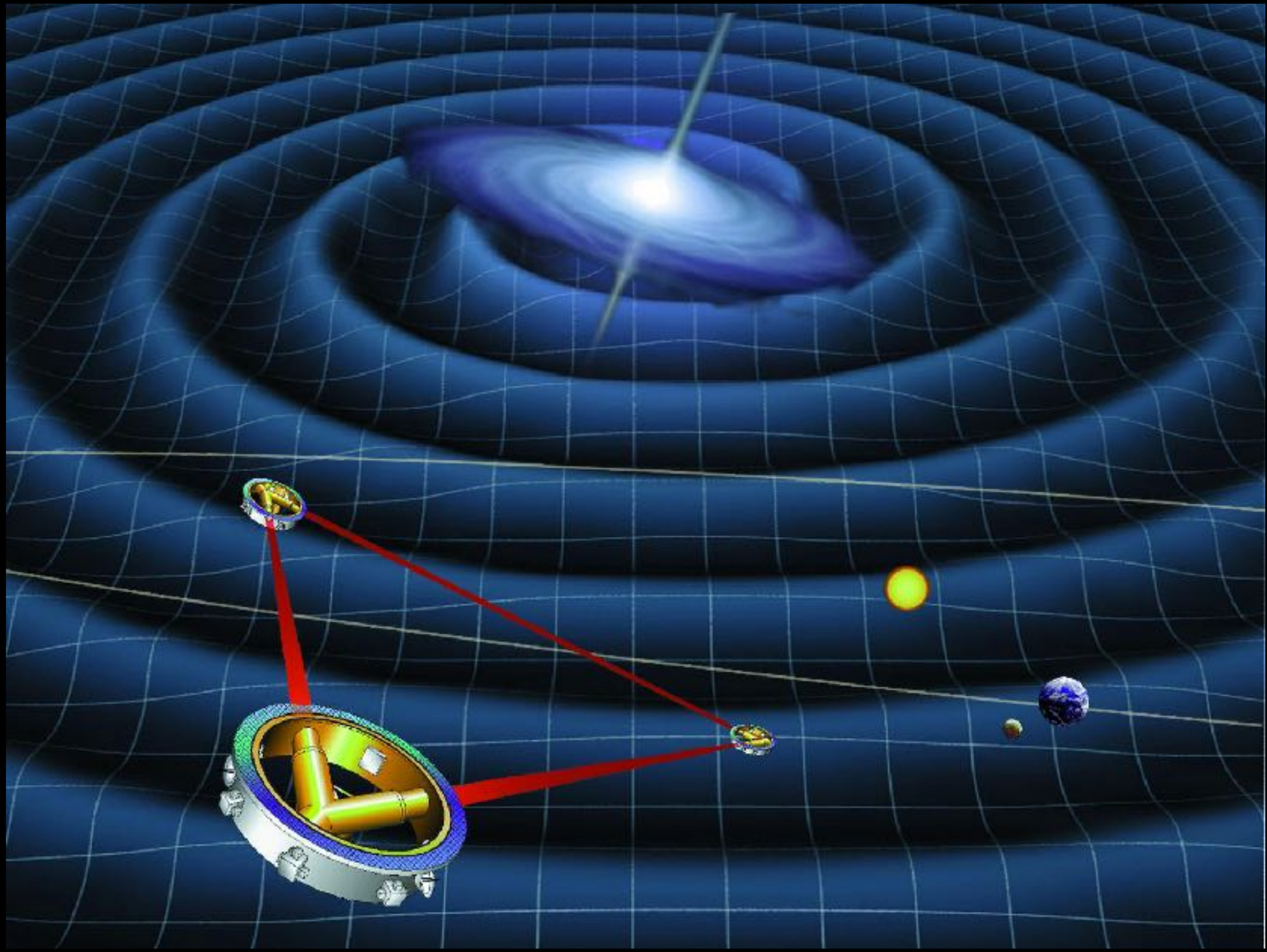


credit: NASA/J. I.Thorpe

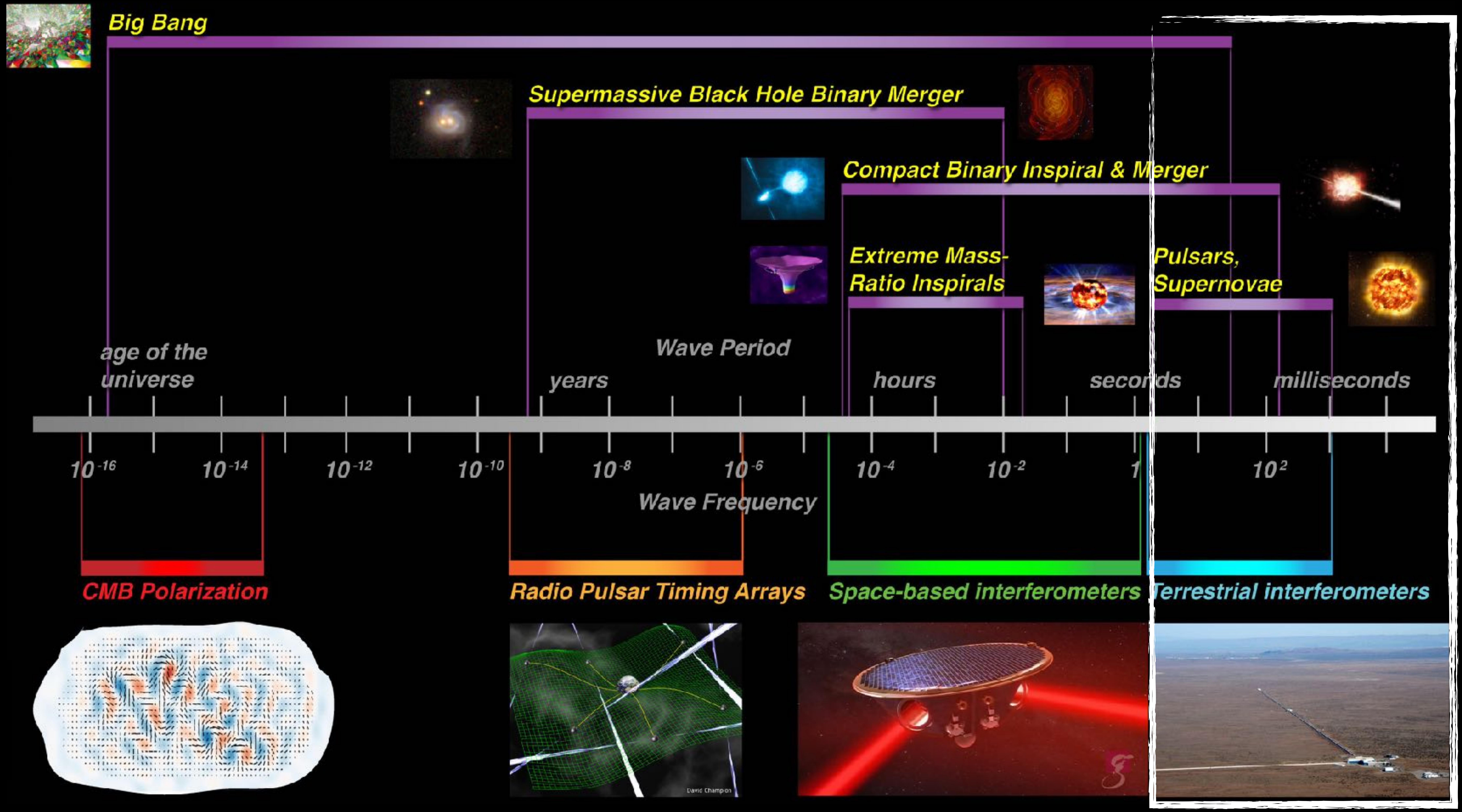
mHz BAND

Laser Interferometer Space Antenna (LISA)

- Constellation of satellites 2.5 million km apart
- uses different type of interferometry
- dominated by white dwarf binaries in the galaxy
- Planned launch date ~2034
- Potential sources to detect: Massive black hole binaries, galactic white dwarf binaries, extreme mass ratio inspirals, ….

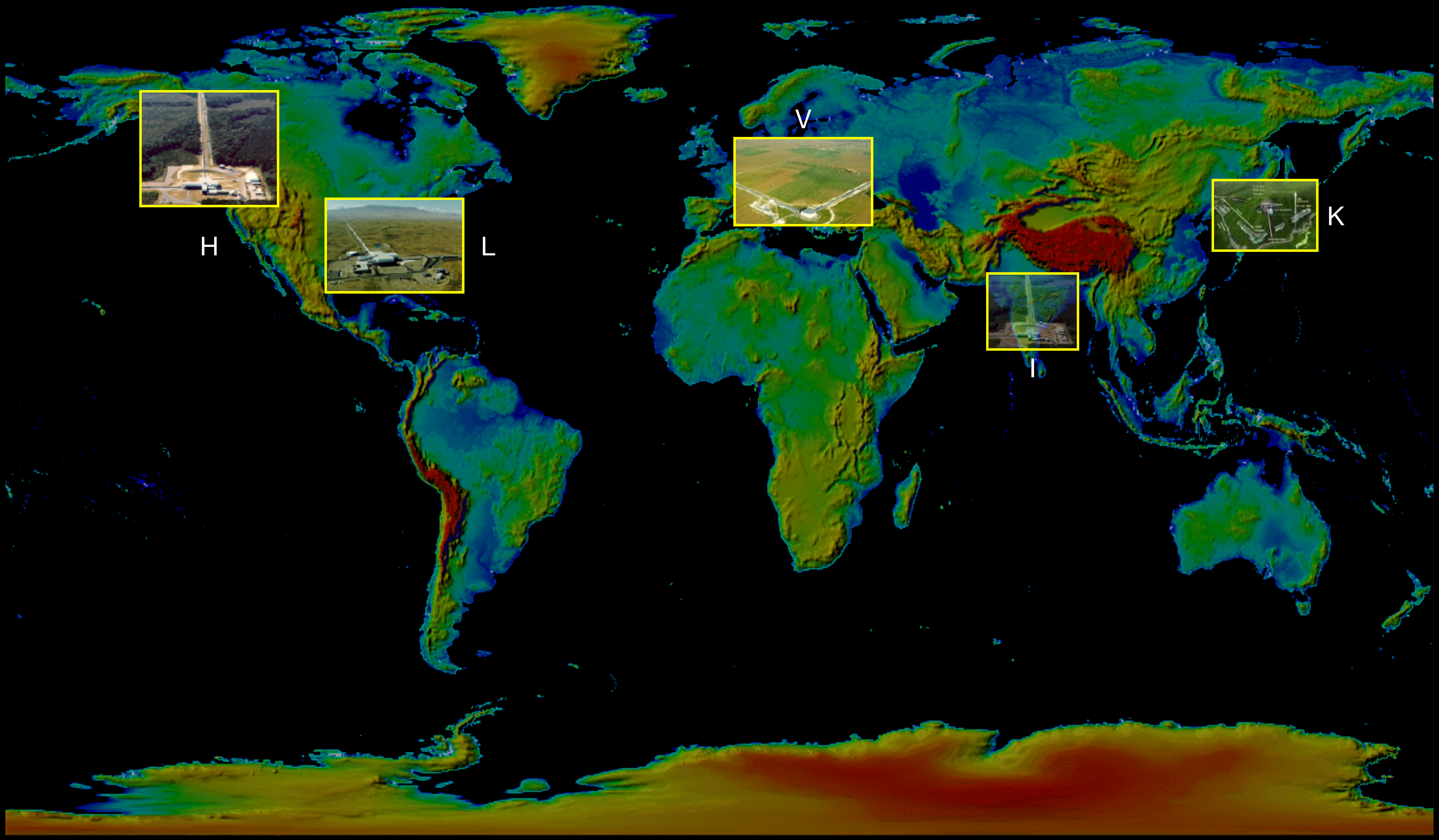


GW ACROSS THE SPECTRUM



credit: NASA/J. I.Thorpe

GRAVITATIONAL WAVE DETECTOR NETWORK



LIGO and Virgo

LIGO and Virgo observatories started constructions in ‘90s, and…

…Observed with the initial detectors 2005-2011,
and saw…

LIGO and Virgo

~~nothing~~

We saw no gravitational-wave signals.

But we learned how to build and commission detectors.

We learned how to analyze the data.

1.3 Billion years after the Black Holes merged.. (and multicellular life started on earth…)

100 years after Einstein predicted gravitational waves…

50 years after Rai Weiss invented the detectors...

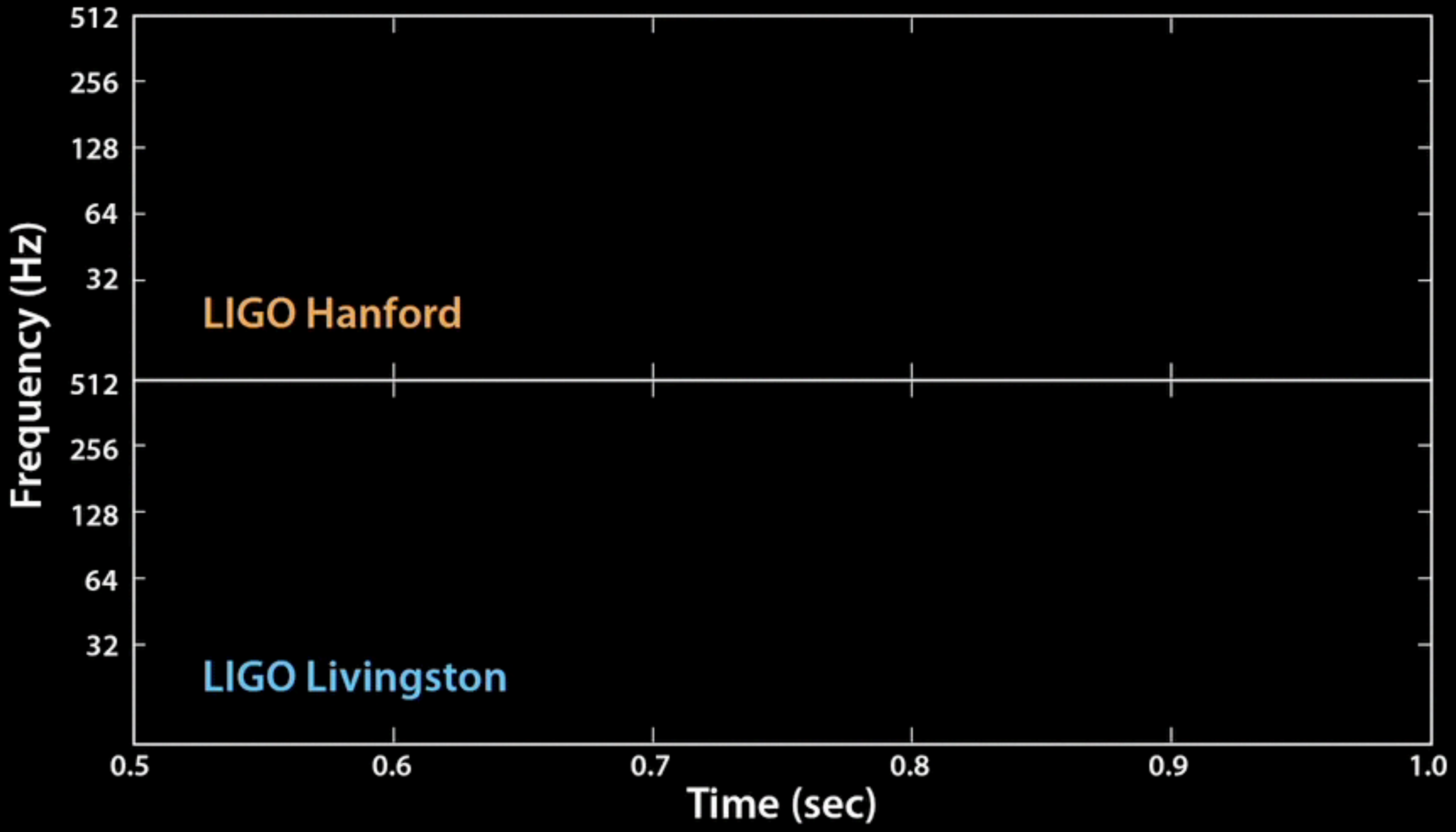
20 years after LIGO and Virgo were build…

10 years after Advanced LIGO and Virgo got the ok...

6 months after starting detector tuning...

Two days after we started observing...

September 14, 2015 at 09:50 UTC: Cosmic Rendezvous



LIGO-Virgo-KAGRA observations so far..

3 GW detection during O1

- First direct detection of GW
- From coalescing binary systems of black holes

8 GW detection during O2

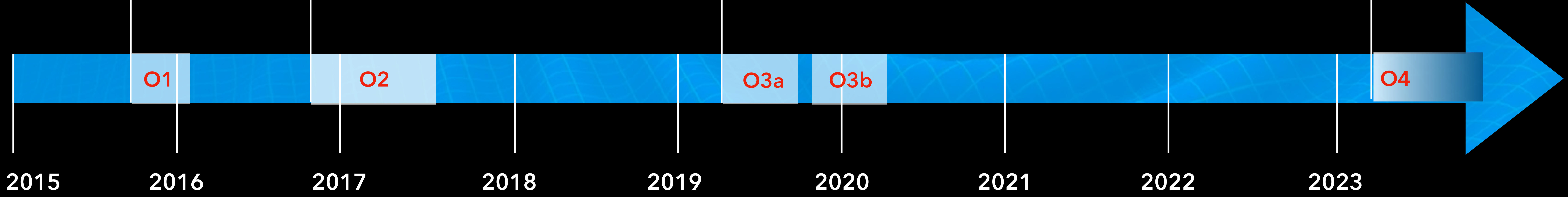
- 1 coalescing binary system of neutron stars: electromagnetic counterpart detected

79 GW detection during O3

- 44 during O3a, including 1 confirmed binary system of neutron stars
- 35 during O3b, including 2 confirmed systems of neutron stars - black holes
- No electromagnetic counterpart

O4

- 51 significant Detection Candidates

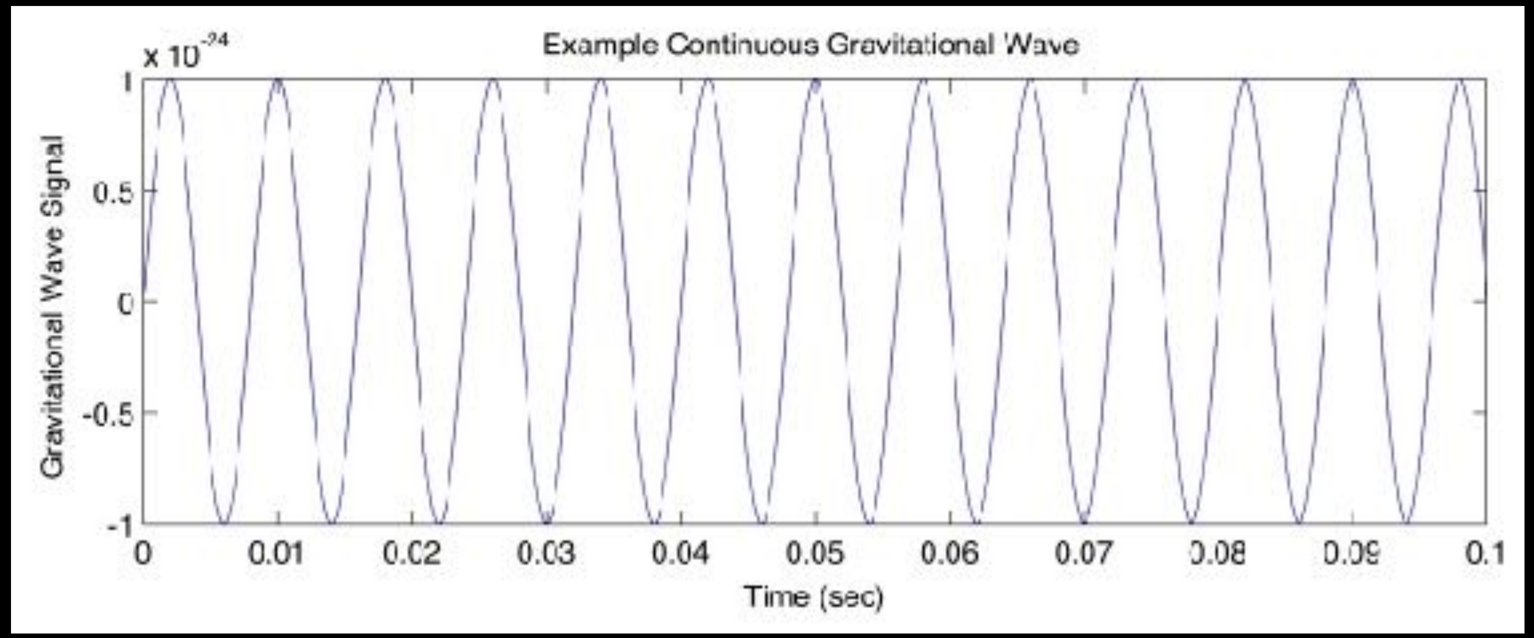


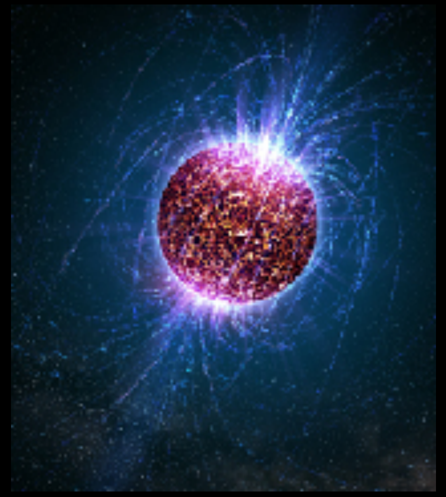
~ 140 GW events/candidates

Adapted from: Leïla Haegel for the LVK collaboration [2022]

WHAT'S NEXT

Continuous

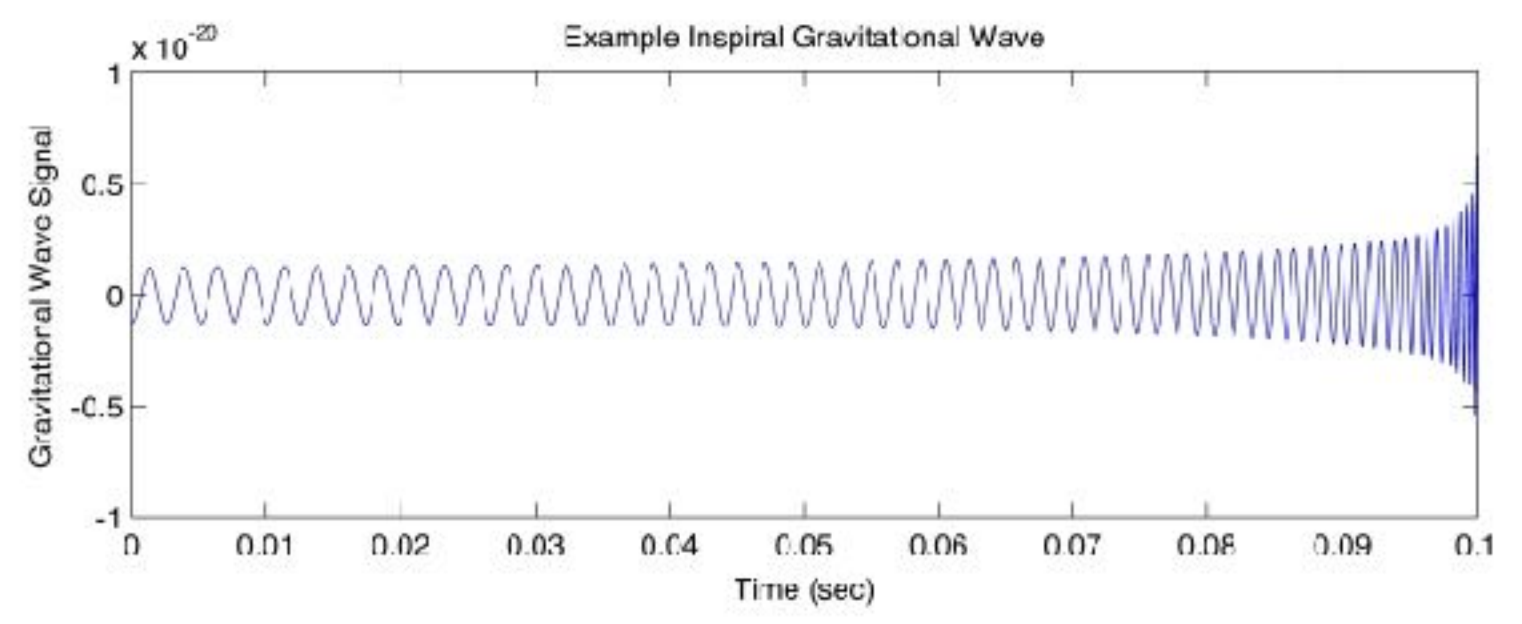


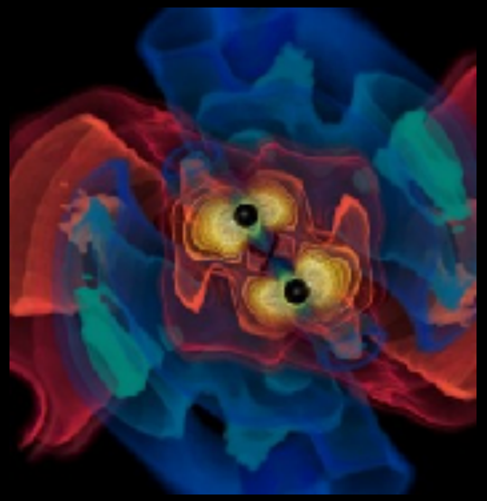


A single star swiftly rotating about its axis with a large mountain or other irregularity on it

Expected to produce comparatively weak gravitational waves

Binary Merger

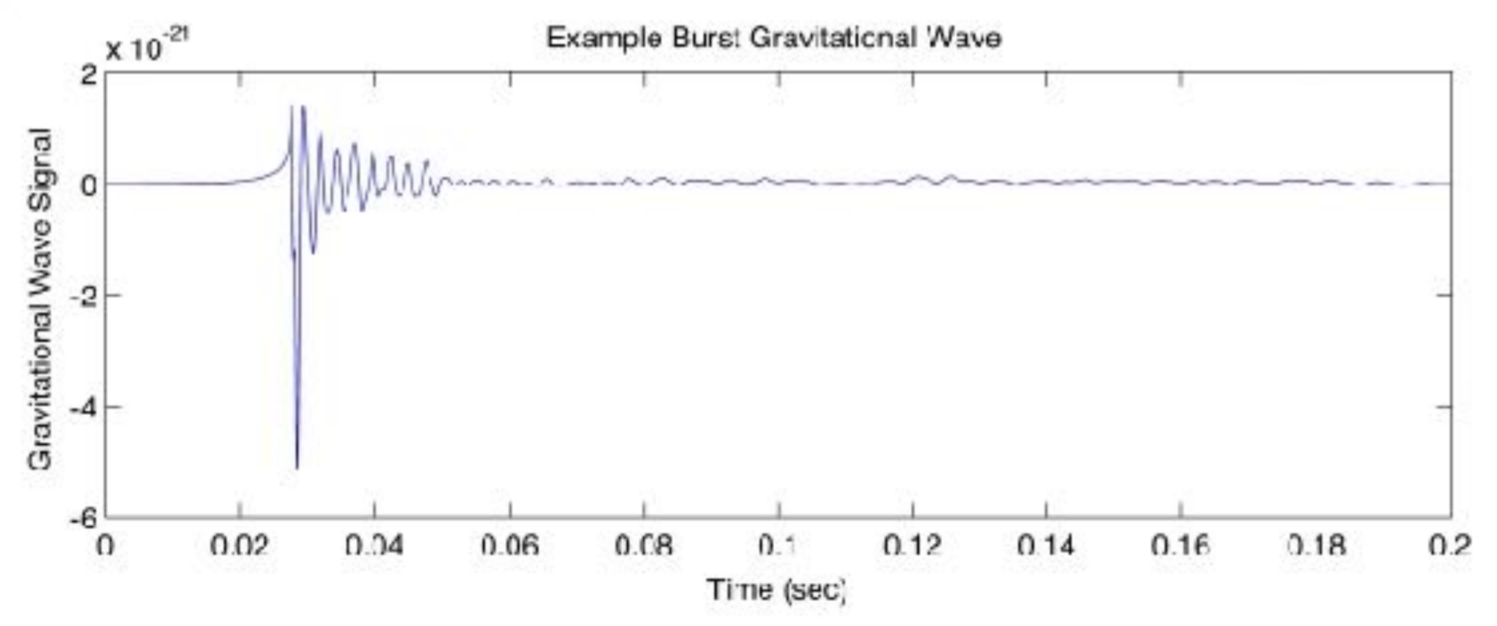


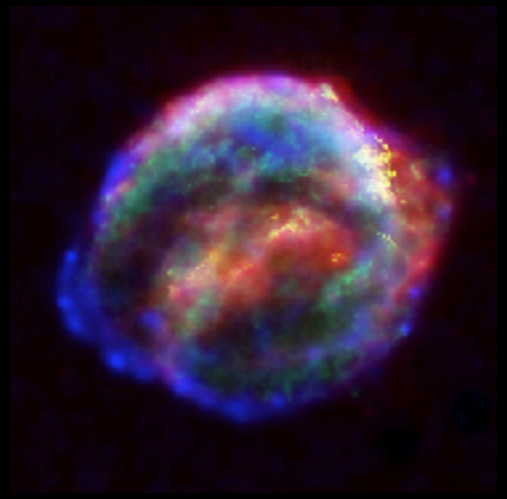


Generated during the end-of-life stage of binary systems where the two objects merge into one.

These systems are usually two neutron stars, two black holes, or a neutron star and a black hole

Burst

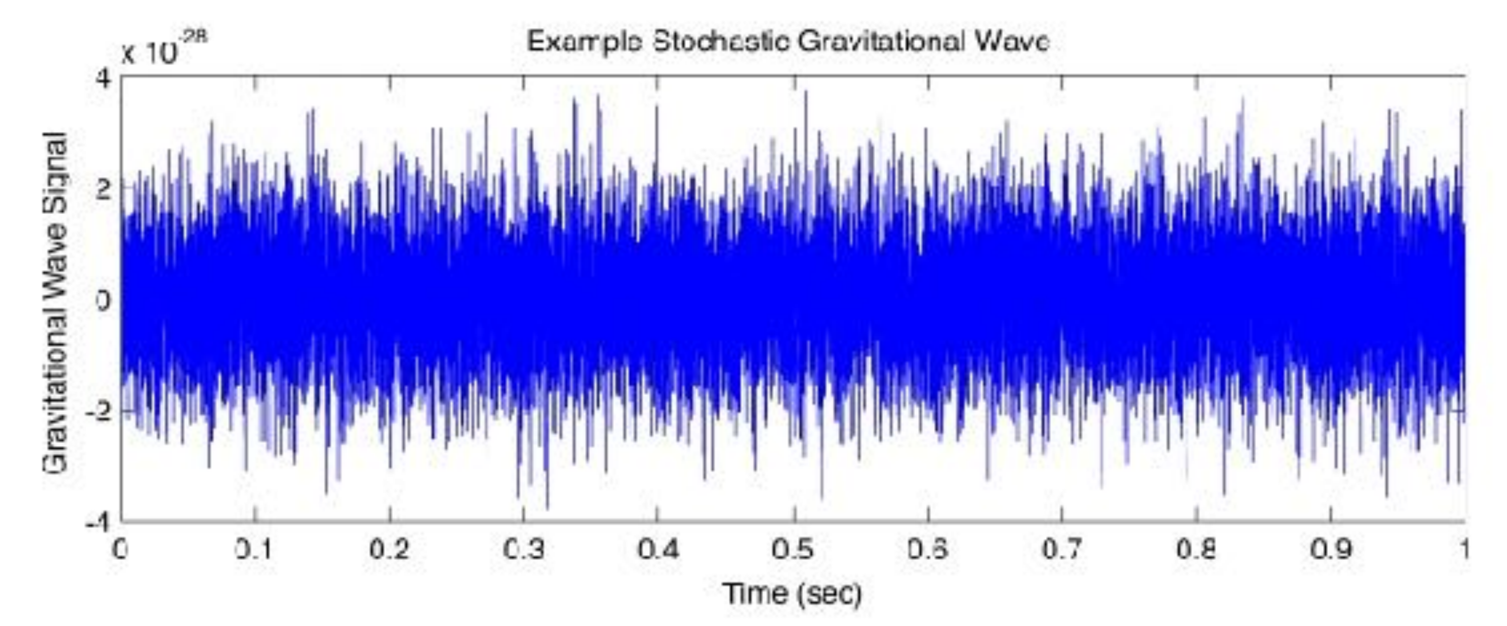


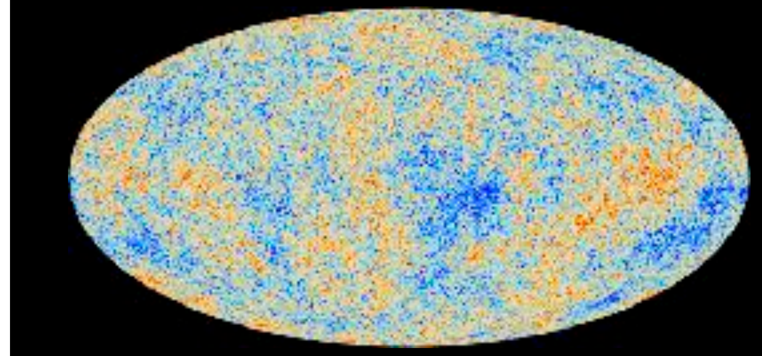


From short-duration unknown or unanticipated sources

There are hypotheses that some systems such as supernovae or gamma ray bursts may produce burst gravitational waves, but too little is known about the details of these systems to anticipate the form these waves will have

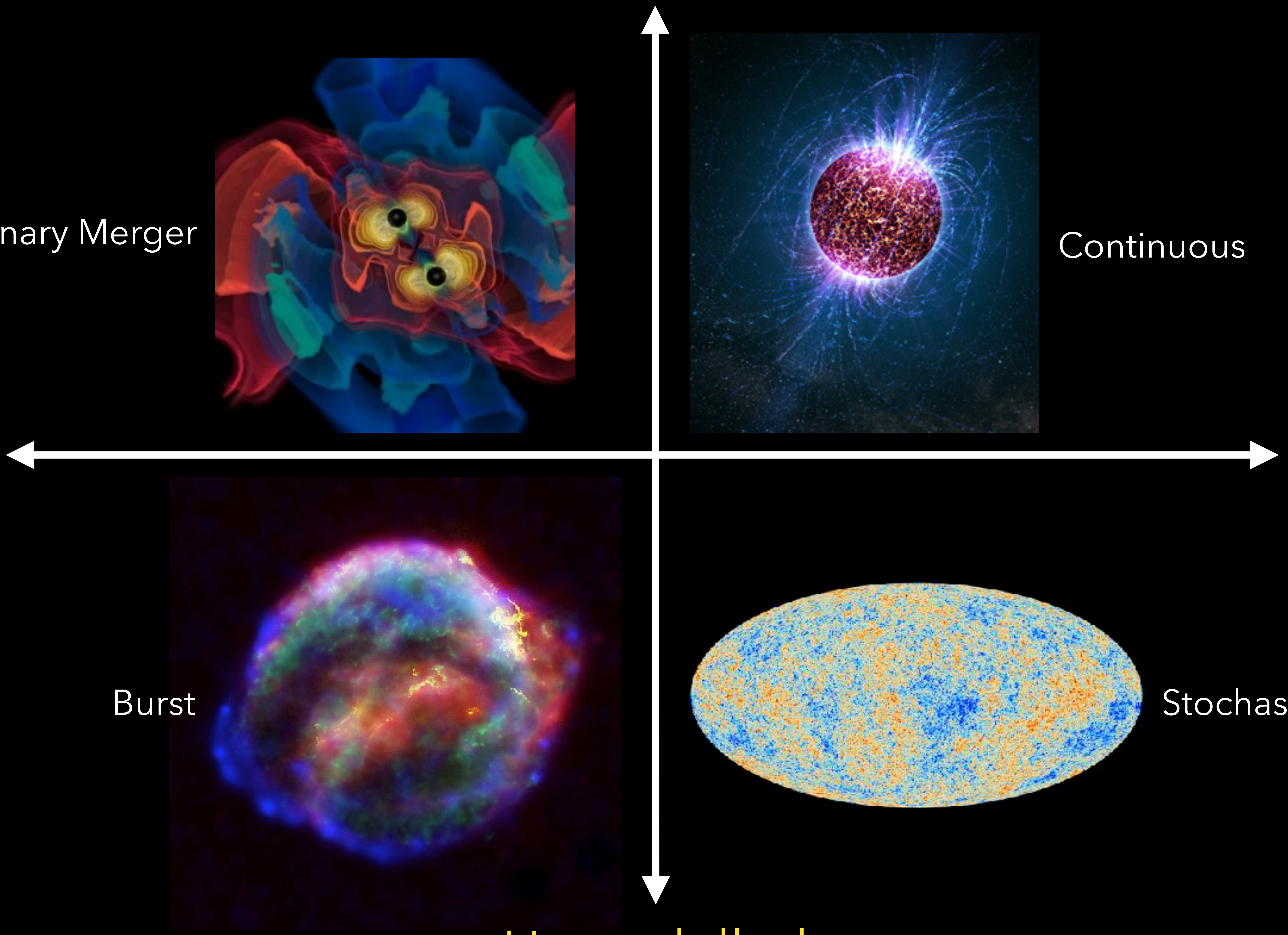
Stochastic Background





Incoherent superposition of many GW sources. It could be cosmological (for example, vacuum fluctuation from the early universe) and/or astrophysical (for example, adding contribution from all binary black hole coalescence in the universe).

WHAT'S NEXT



Modeled

Binary Merger

Continuous

Transient

Persistent

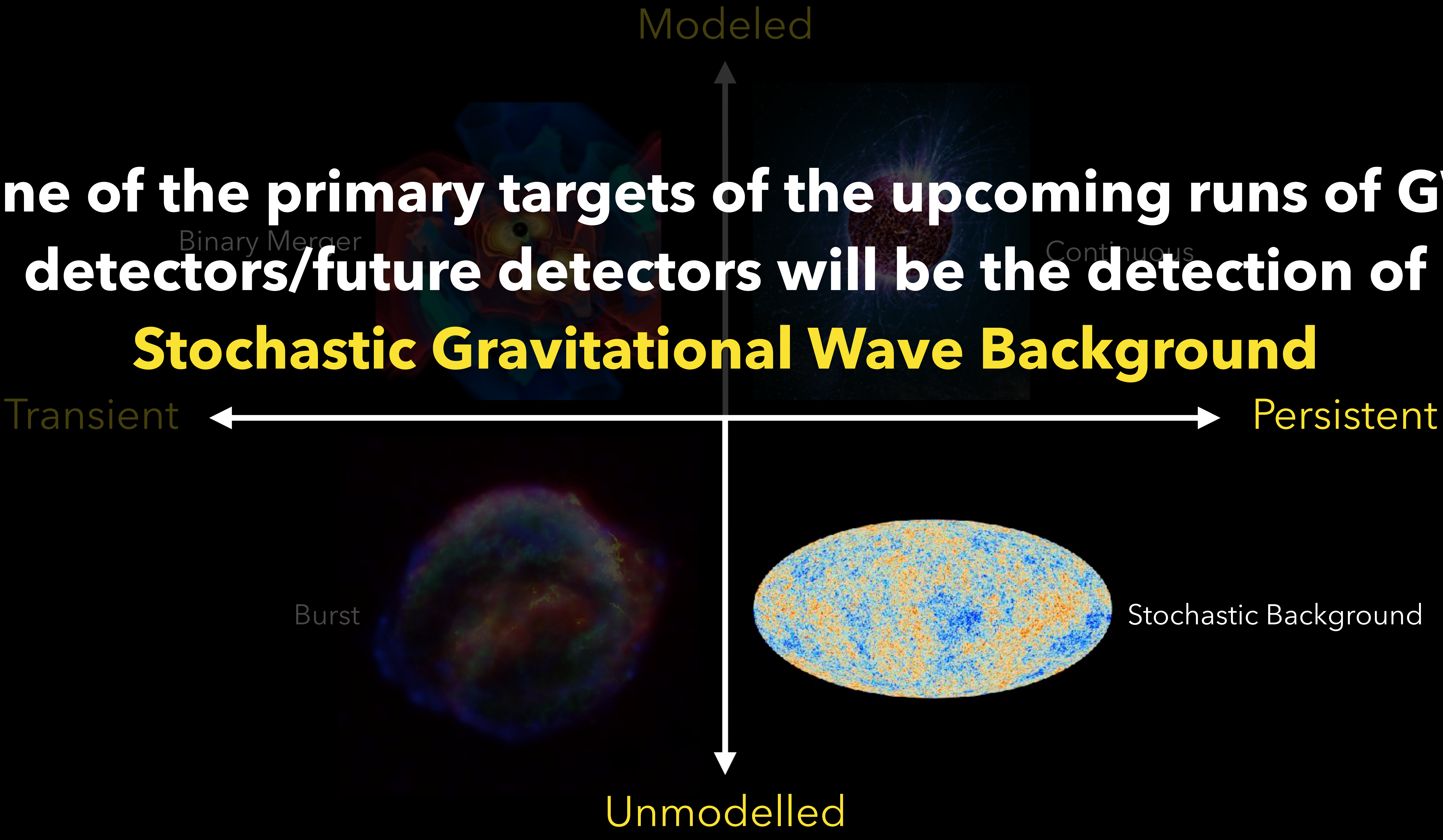
Burst

Stochastic Background

Unmodelled

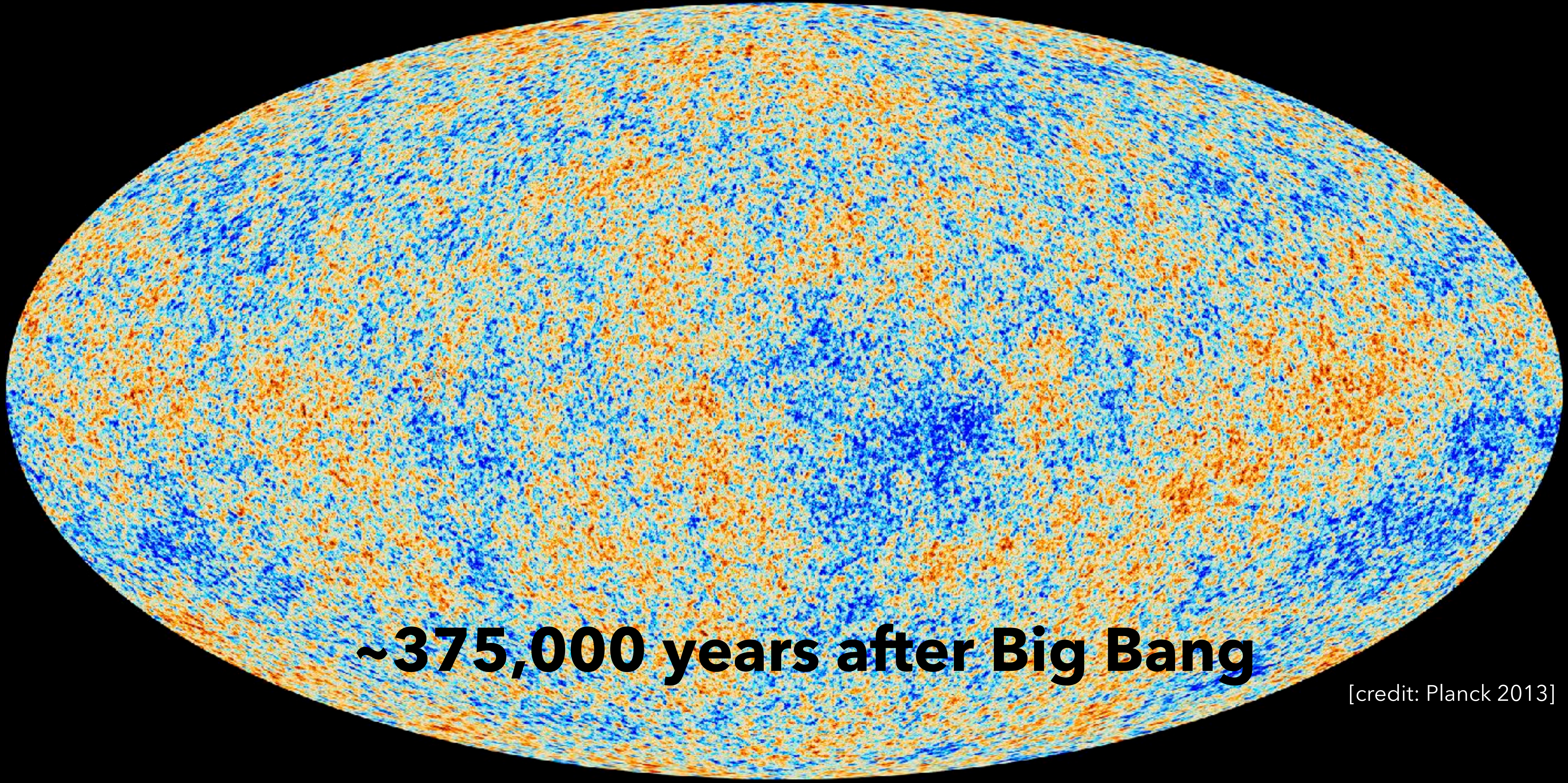
WHAT'S NEXT

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



WHY SHOULD WE CARE ABOUT SGWB ?

Stochastic background of **EM** radiation



[credit: Planck 2013]

The observation of CMB and its anisotropies has revolutionized our understanding of the universe

WHY SHOULD WE CARE ABOUT SGWB ?

Stochastic background of **GW** radiation

??

$\sim 10^{-32}$ seconds after Big Bang

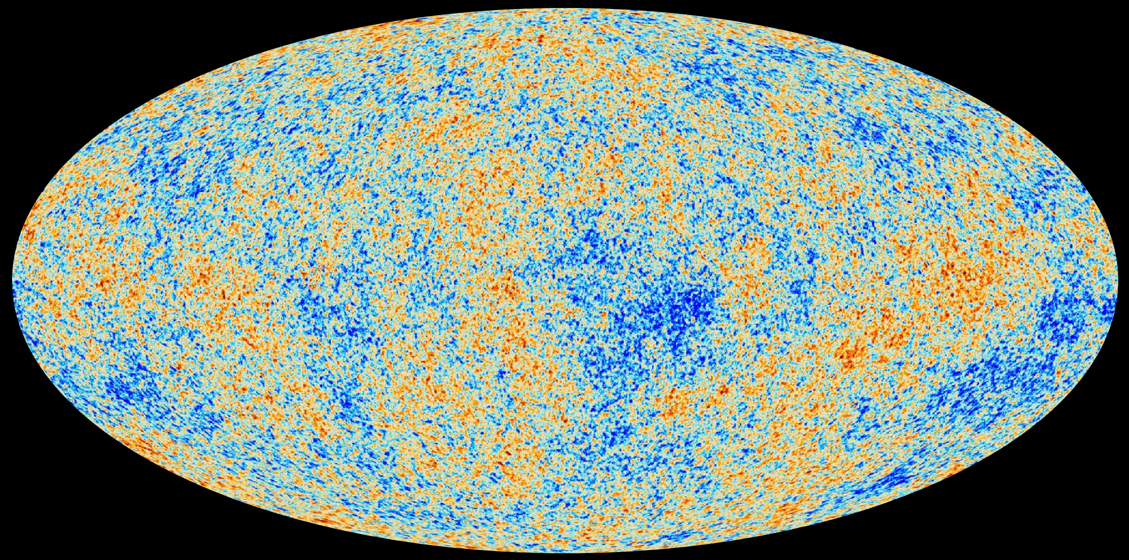
Weakness of gravity relative to other forces ⟹ provide an unprecedented window to the physics of the early universe.

WHICH SGWBs WE ARE SENSITIVE TO?

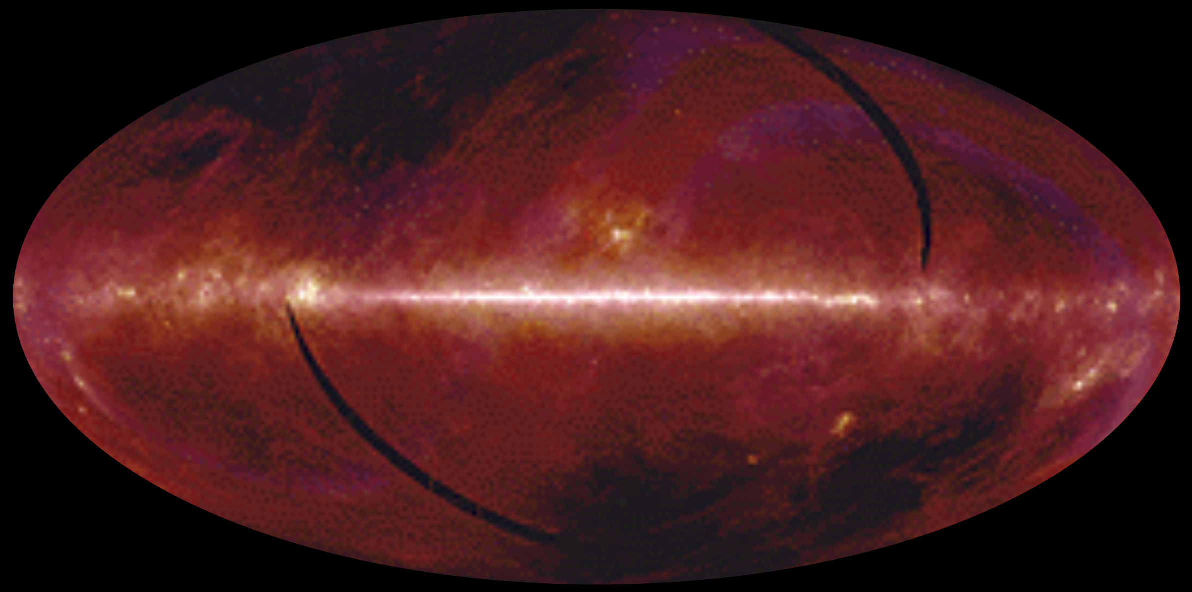
Cosmological Origin

Astrophysical Origin

EM

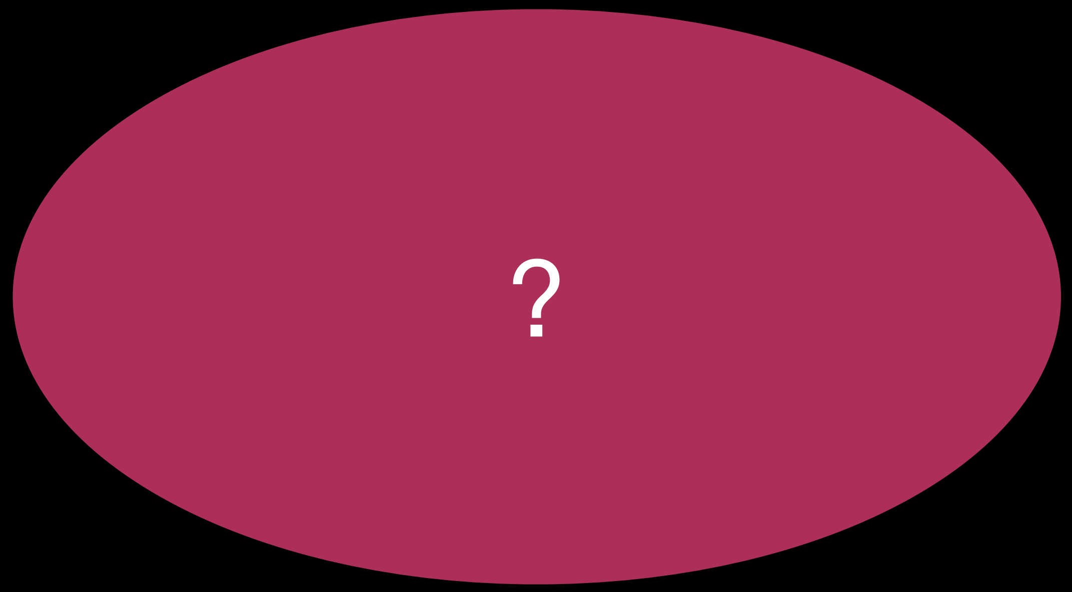


PLANCK CMB MAP

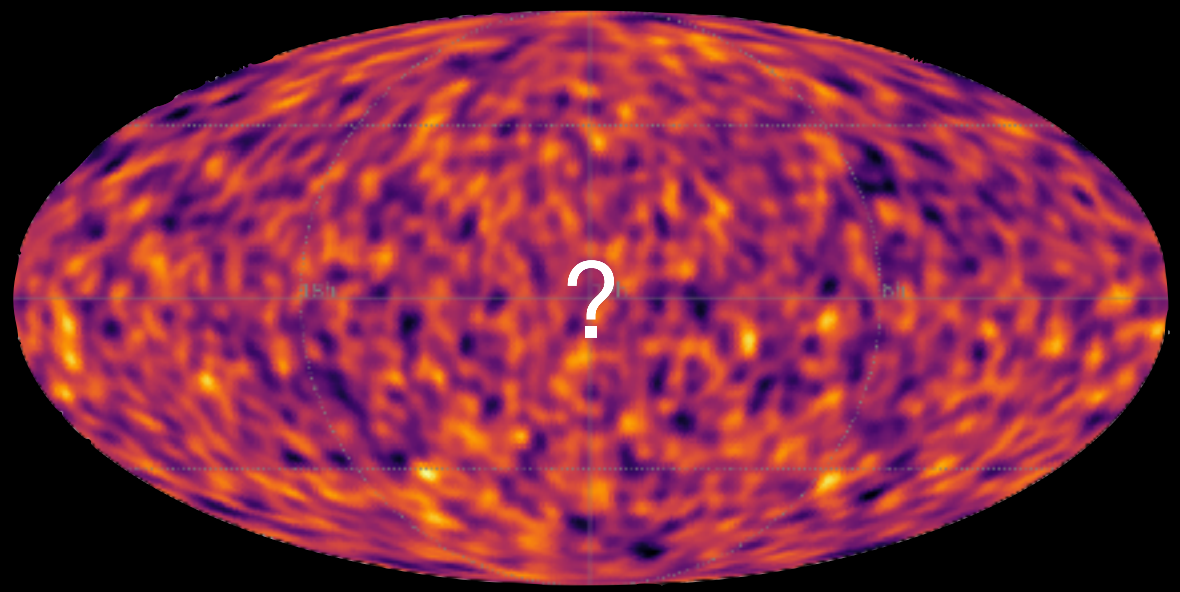


PLANCK IR MAP

GW



COSMOLOGICAL SGWB



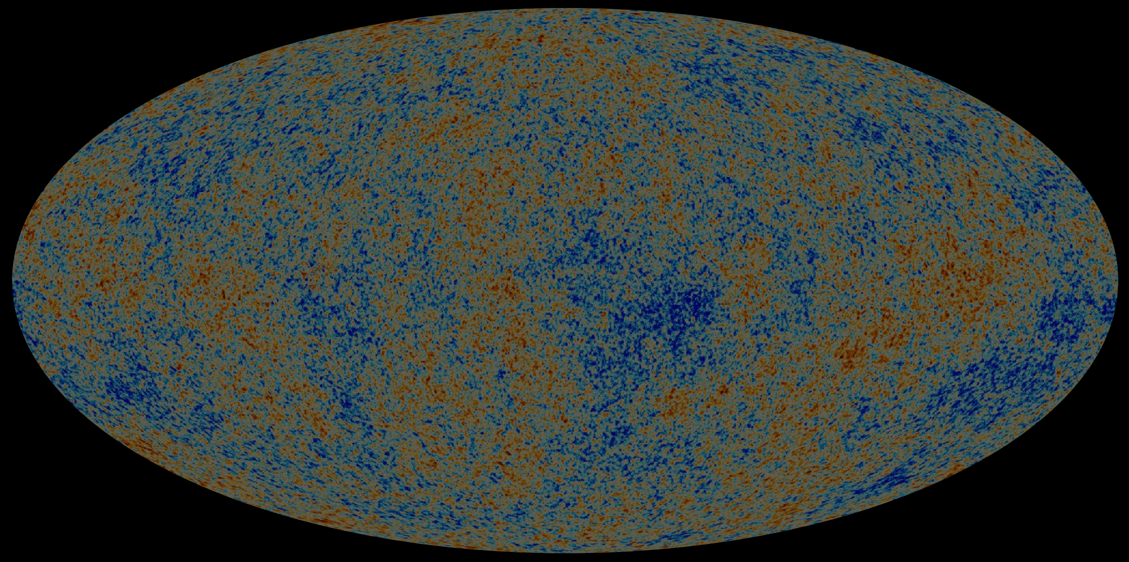
ASTROPHYSICAL SGWB

WHICH SGWBs WE ARE SENSITIVE TO?

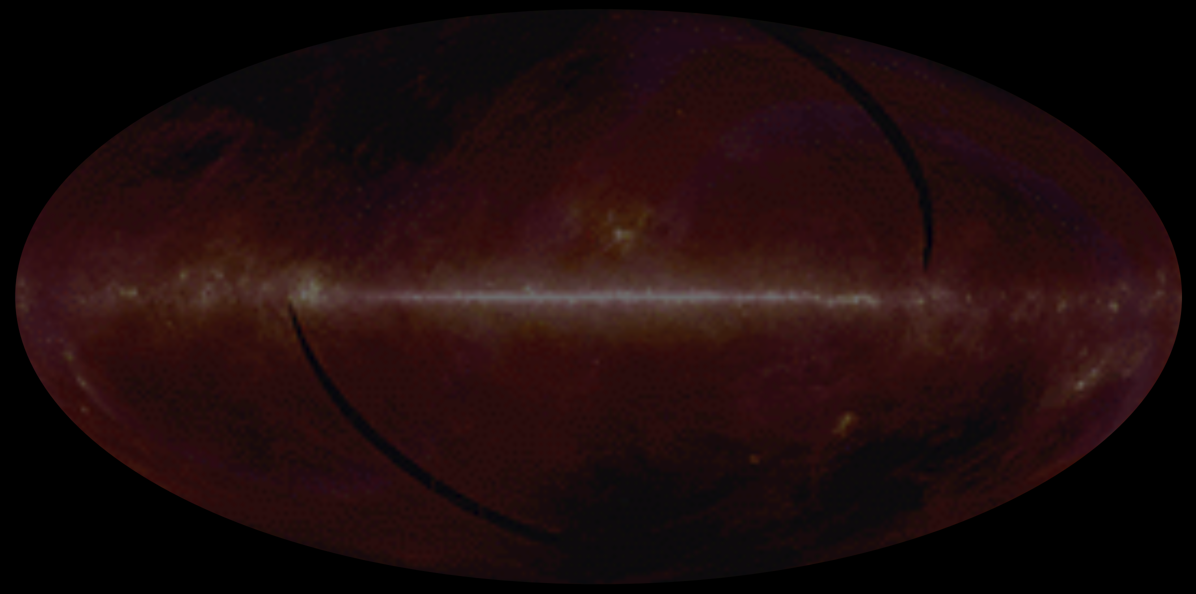
Cosmological Origin

Astrophysical Origin

EM



PLANCK CMB MAP

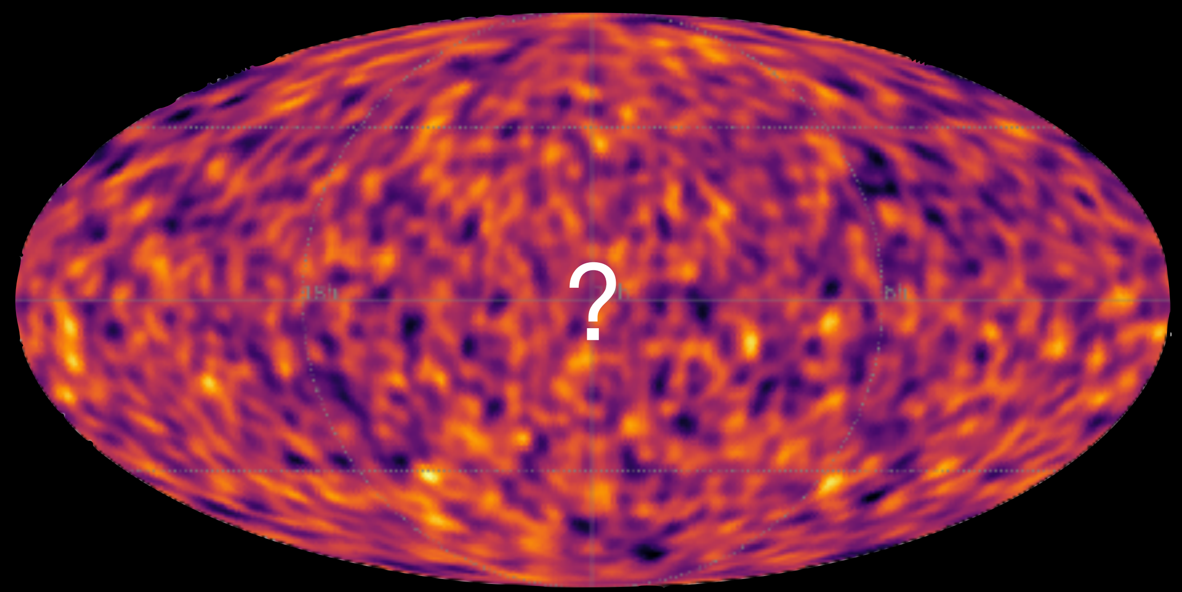


PLANCK IR MAP

GW

?

COSMOLOGICAL SGWB



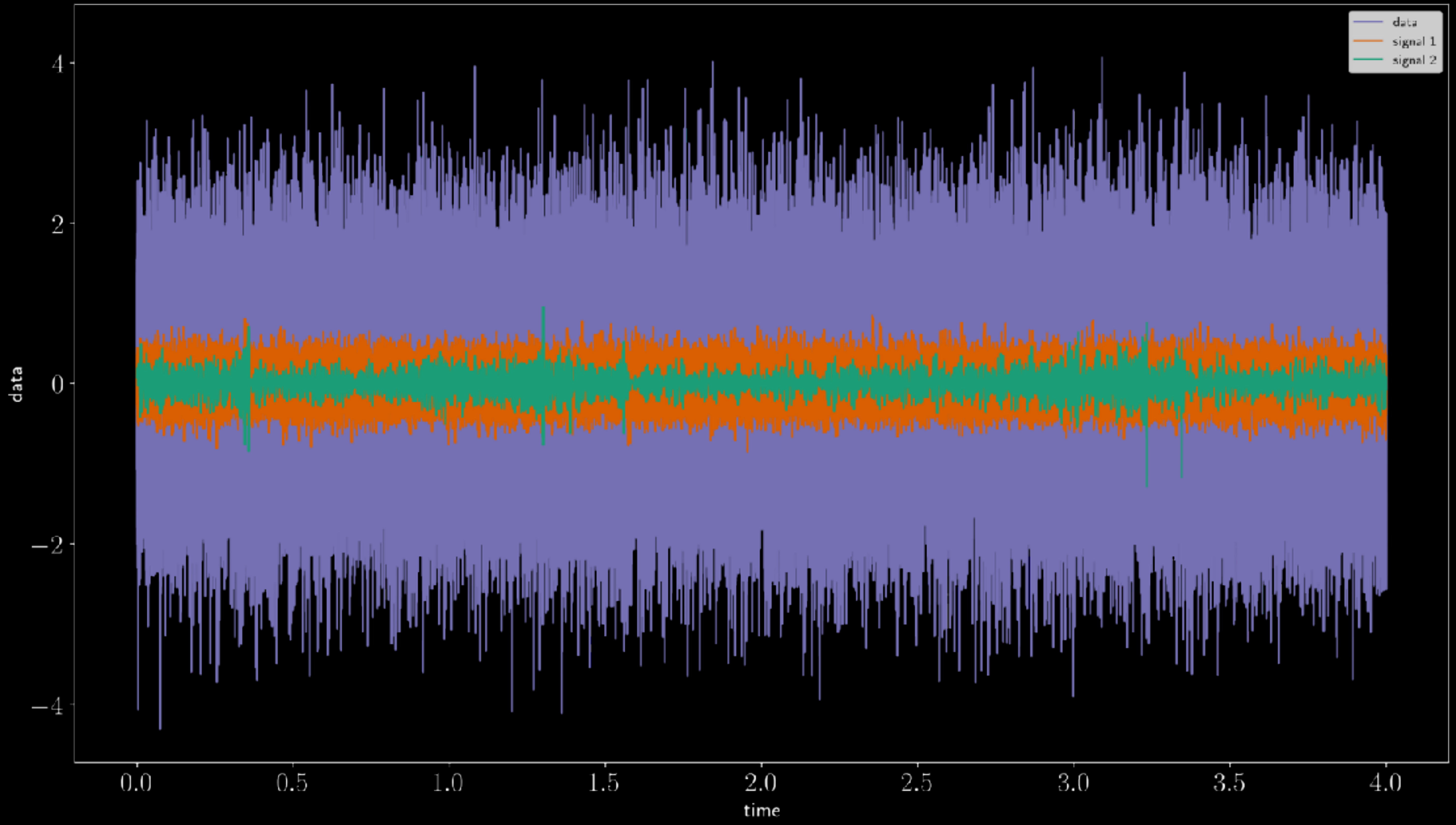
ASTROPHYSICAL SGWB

WHAT ARE THESE SGWBs ?

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

Plane wave expansion of metric perturbations

$$h_{ab}(t,\vec{x}) = \int_{-\infty}^{\infty} \mathrm{d}f \int \mathrm{d}^2\Omega_{\hat{n}} \sum_{A=+,\times} h_A(f,\hat{n})\, e^A_{ab}(\hat{n})\, e^{i2\pi f(t+\hat{n}\cdot\vec{x}/c)}$$

Strain

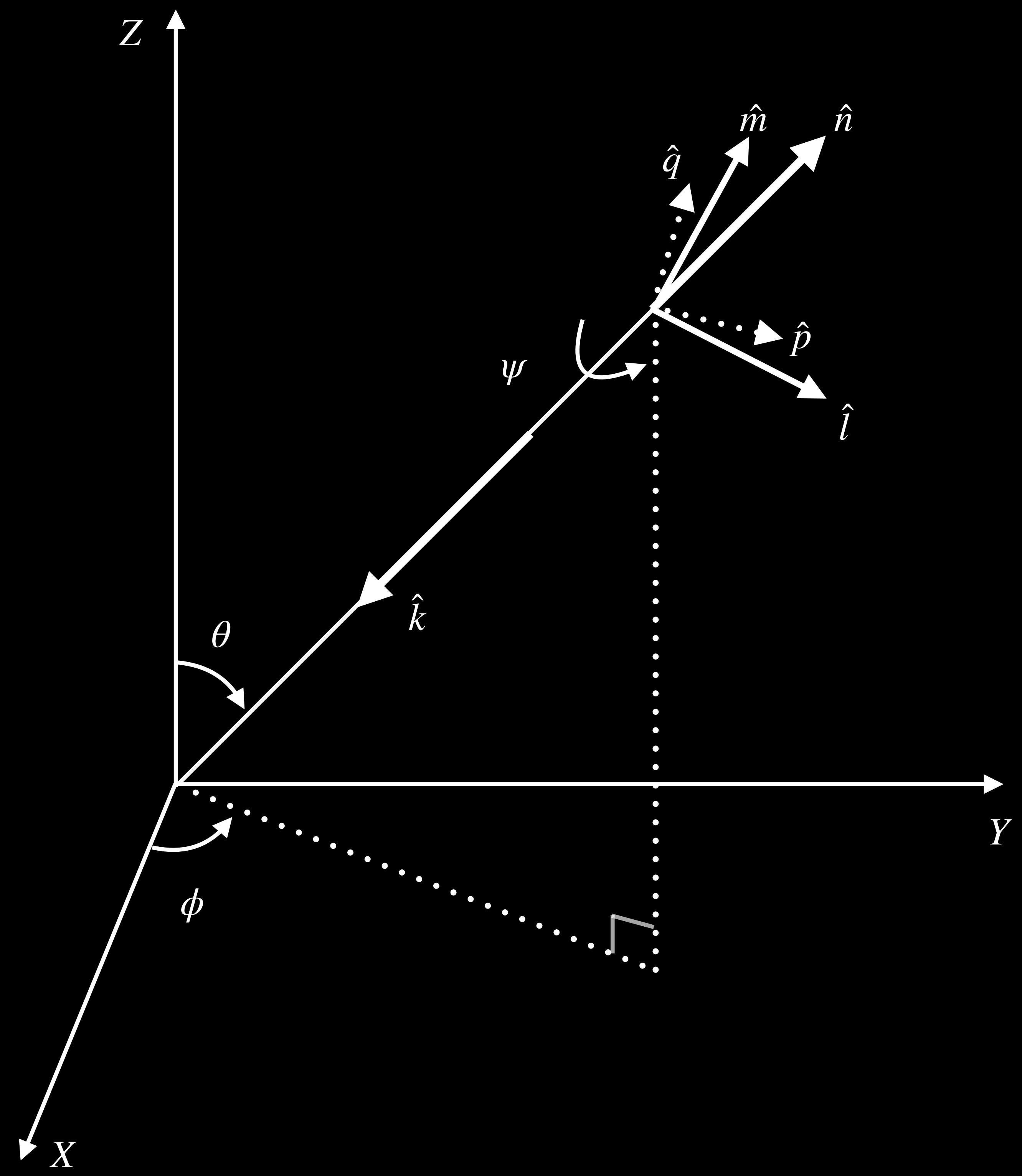
Measured at $\vec{x}$

Integrate over all frequency

Integrate over all sky direction

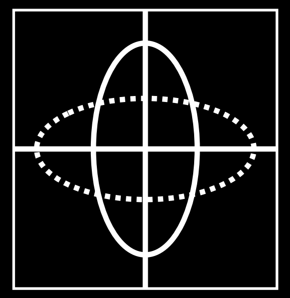
Plane wave coefficients

Plane wave phase



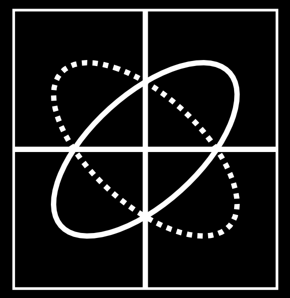
Polarization tensors:

$$e^{+}_{ab}(\hat{n}) = \hat{l}_a\hat{l}_b - \hat{m}_a\hat{m}_b$$



$A = +$

$$e^{\times}_{ab}(\hat{n}) = \hat{l}_a\hat{m}_b + \hat{m}_a\hat{l}_b$$



$A = \times$

STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

Statistical properties are encoded in:

$$\cancel{\langle h_A(f,\hat{n})\rangle}\,, \quad \langle h_A(f,\hat{n})h_{A'}(f',\hat{n}')\rangle\,, \quad \cancel{\langle h_A(f,\hat{n})h_{A'}(f',\hat{n}')h_{A''}(f'',\hat{n}'')\rangle}\,, \quad \cancel{\cdots}$$

0

(no loss of generality)

in terms of quadratic expectation values (if Gaussian)

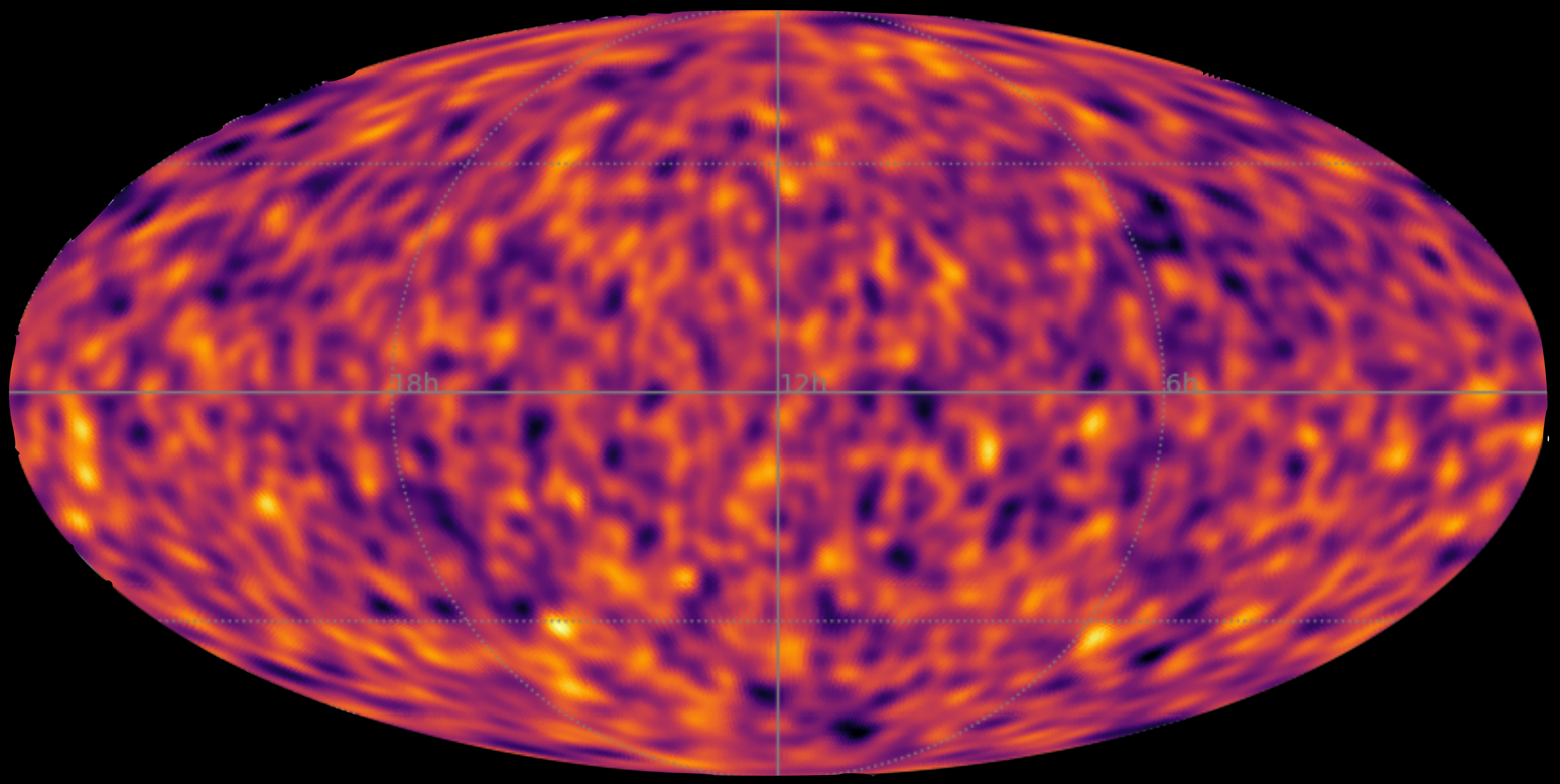
ensemble averages over all realisations of the field

If $h_A(f,\hat{n})$ are mean-zero Gaussian fields, the signal is fully described by its second moment.

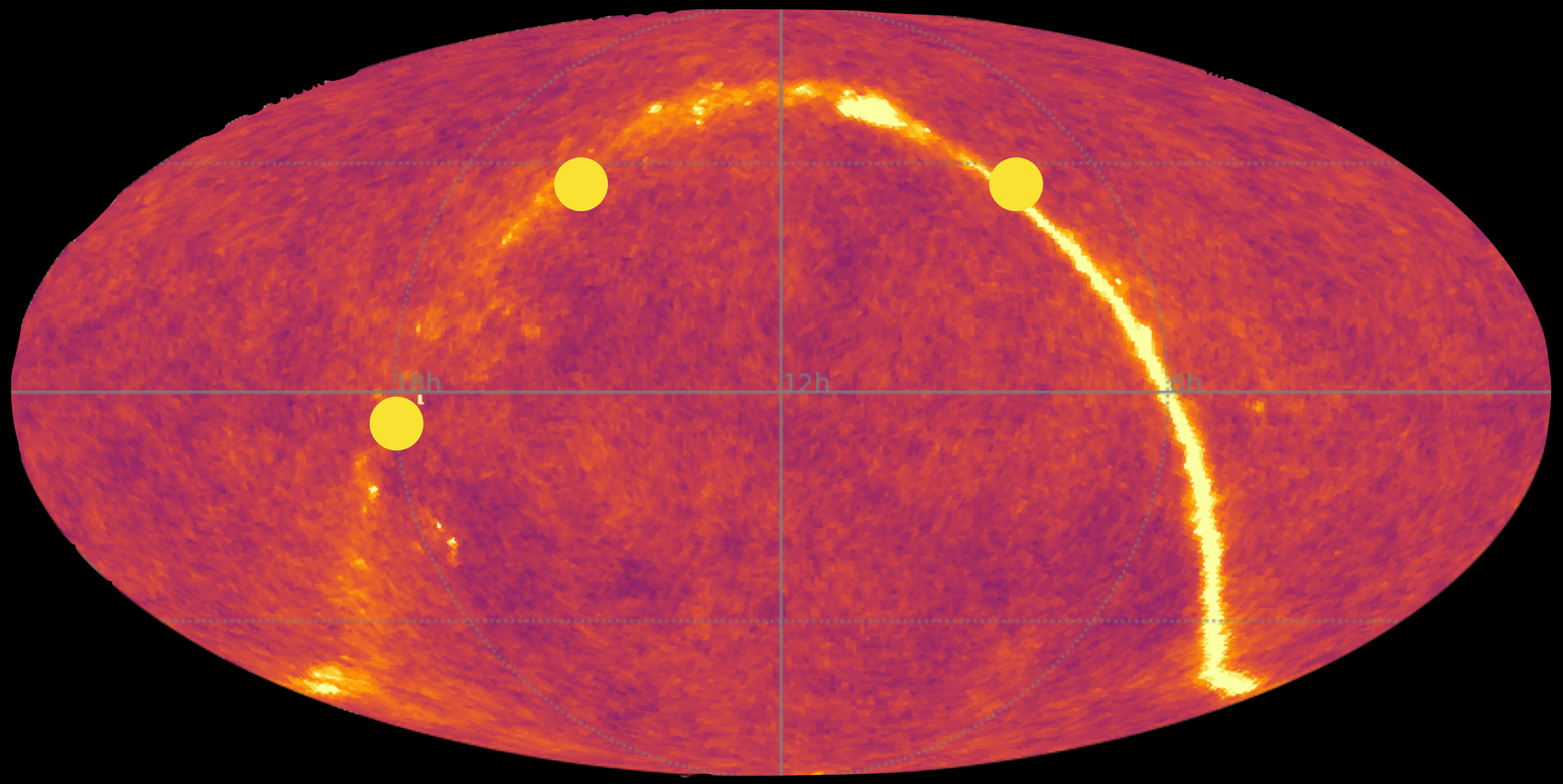
TYPES OF STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

(1) Spatial distribution

isotropic



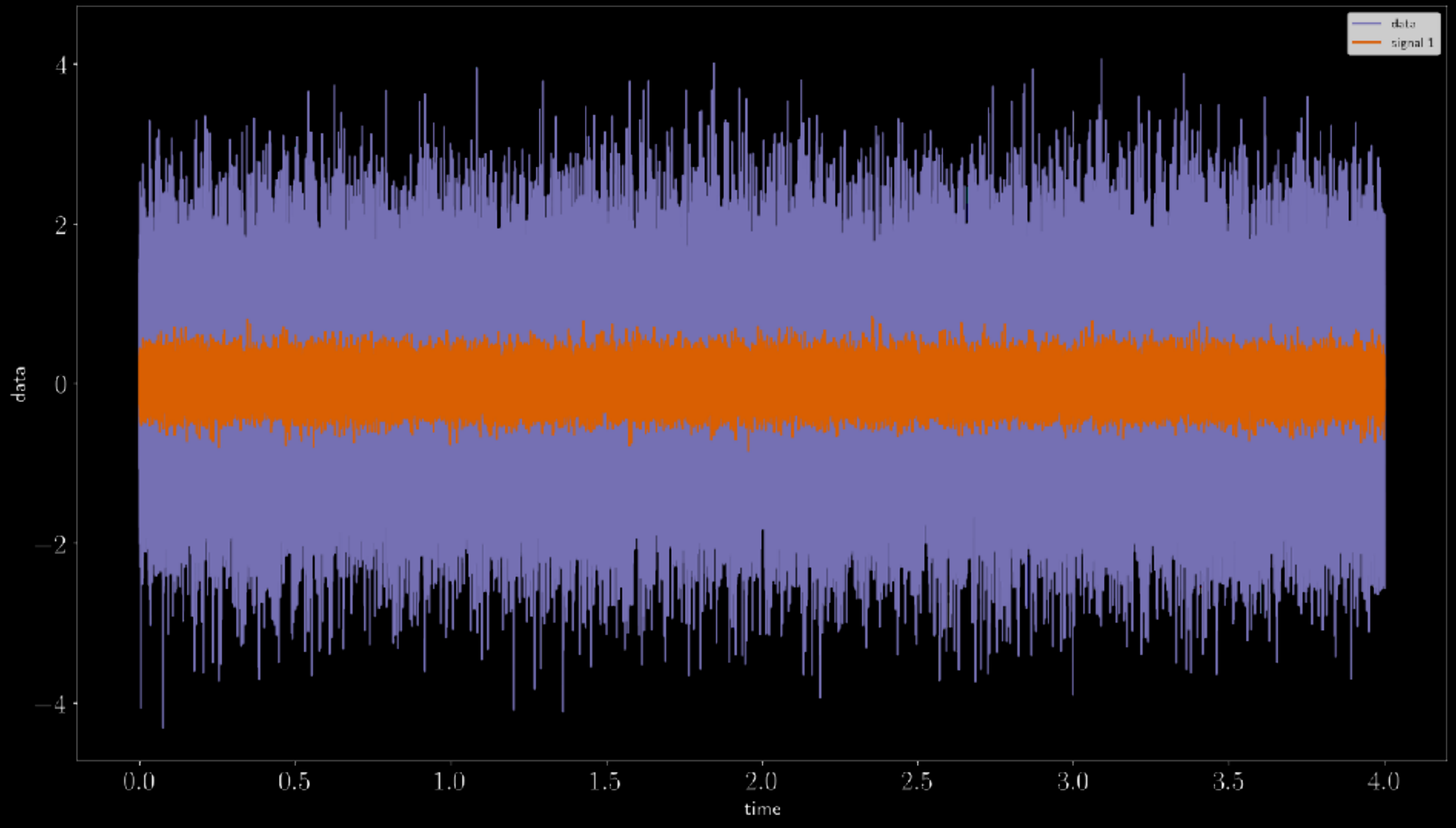
anisotropic



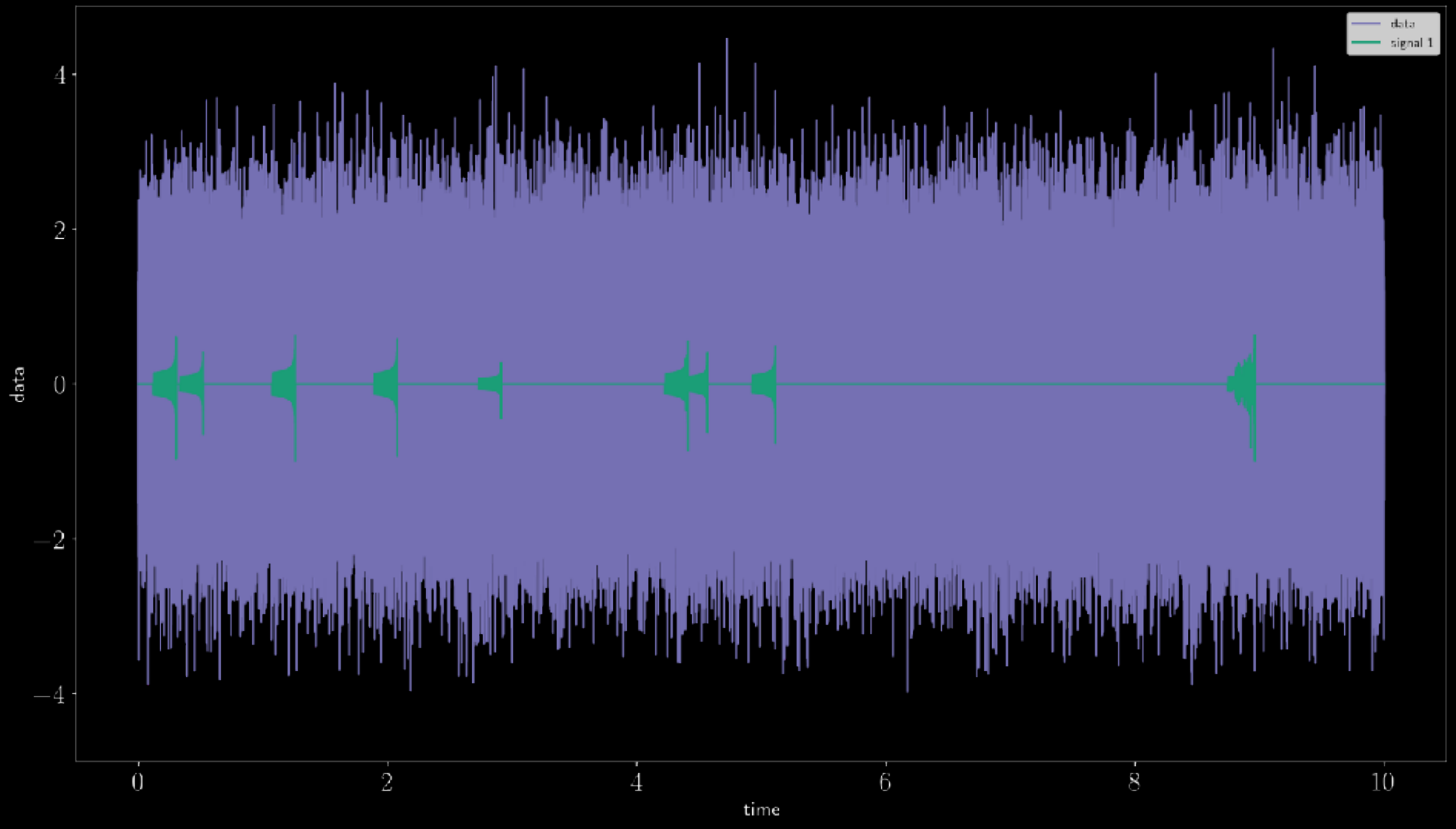
TYPES OF STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

(2) Temporal distribution

Stationary Gaussian

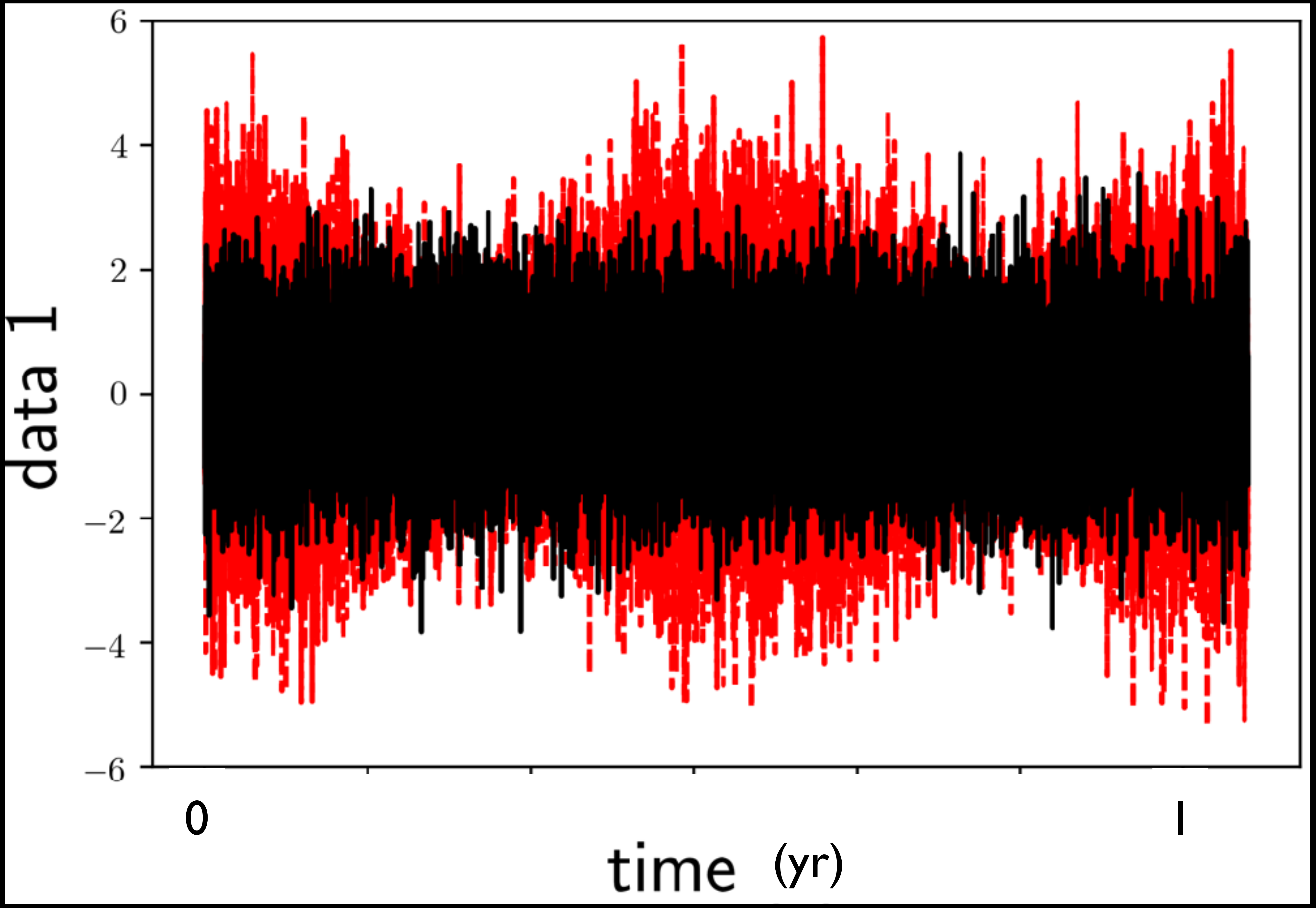


Non-stationary (non-gaussian)



TYPES OF STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

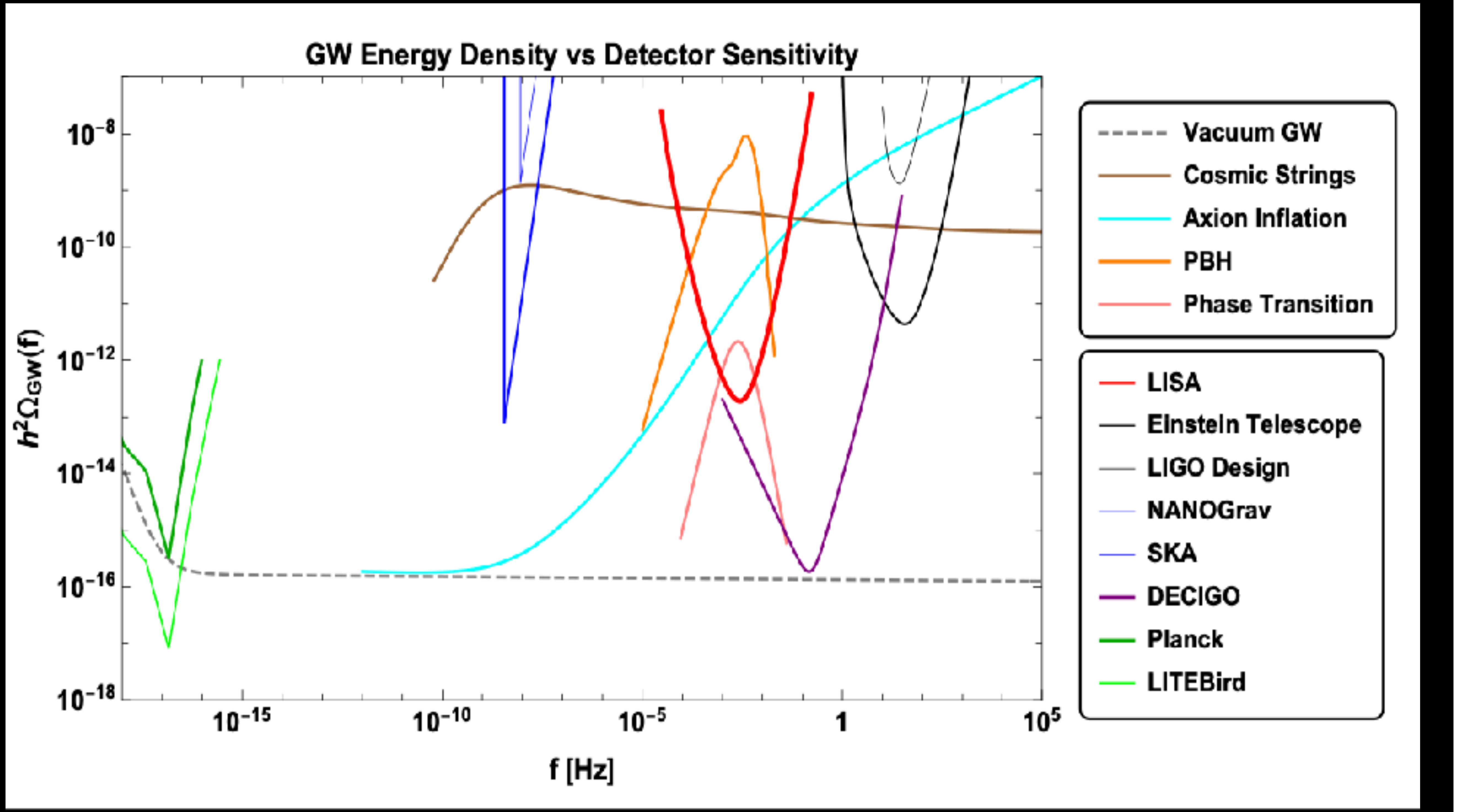
(2) Temporal distribution



(e.g., from galactic white dwarf binaries; modulated by LISA's orbital motion)

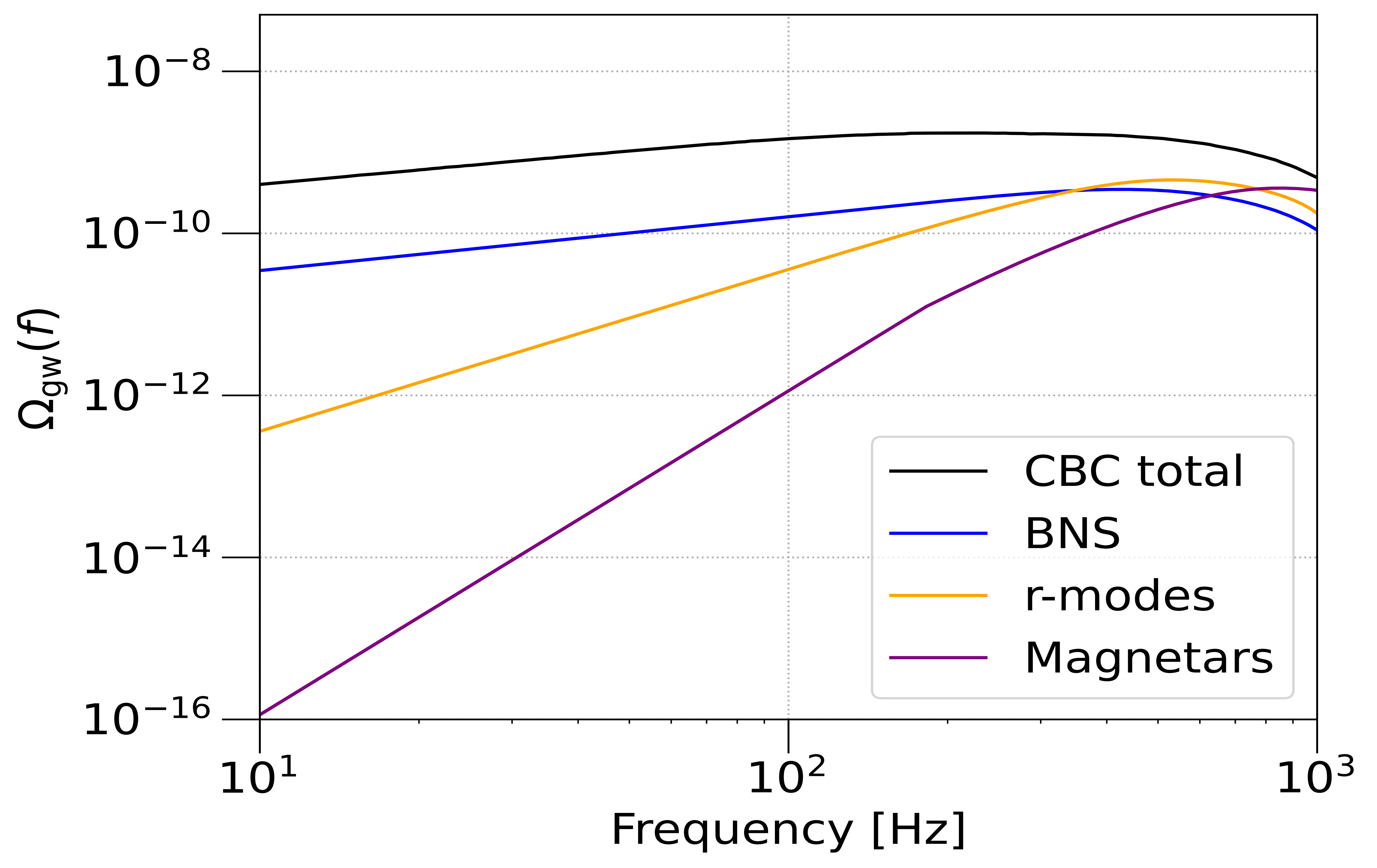
TYPES OF STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

(3) Different Power Spectra



Overview of several proposed model spectra for cosmic SGWB and different experiments' sensitivities.

arXiv:2204.05434



Taxonomy of astrophysical SGWB within the frequency range of ground-based detectors.

F. DeLillo, JS arXiv:2310.05823

TYPES OF STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

(4) Different Polarization

So far we have assumed that the gravitational-wave power in the + and × polarization modes are equal (on average) and are statistically independent of one another.

↓

no correlations between the + and × polarization modes

some processes in the early Universe to give rise to parity violations, which would manifest themselves as an *asymmetry in the amount of right and left circularly polarized gravitational waves*

STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

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(no loss of generality)

in terms of quadratic expectation values (if Gaussian)

ensemble averages over all realisations of the field

If $h_A(f,\hat{n})$ are mean-zero Gaussian fields, the signal is fully described by its second moment.

STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

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ensemble averages over all realisations of the field

If $h_A(f,\hat{n})$ are mean-zero Gaussian fields, the signal is fully described by its second moment.

Unpolarized, stationary, isotropic:

$$\langle h_A(f,\hat{n})\,h^*_{A'}(f',\hat{n}')\rangle = \frac{1}{16\pi}S_h(f)\,\delta(f-f')\delta_{AA'}\,\delta^2(\hat{n},\hat{n}')$$

Unpolarized, stationary, anisotropic:

$$\langle h_A(f,\hat{n})\,h^*_{A'}(f',\hat{n}')\rangle = \frac{1}{4}\mathscr{P}(f,\hat{n})\,\delta(f-f')\delta_{AA'}\,\delta^2(\hat{n},\hat{n}')$$

where

$$S_h(f) = \frac{3H_0^2}{2\pi^2}\frac{\Omega_{\rm gw}(f)}{f^3}$$

$$\boxed{\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\rm gw}}{\mathrm{d}\ln f} = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{\rm gw}}{\mathrm{d}f}}$$

energy density spectrum (dimensionless)

ASTROPHYSICAL STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}\ln f} = \frac{f}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}f}$$

$$\rho_{gw} = \frac{c^2}{32\pi G}\langle \dot{h}_{ab}(t,\vec{x})\dot{h}^{ab}(t,\vec{x})\rangle$$

For a collection of sources:

Phinney formula

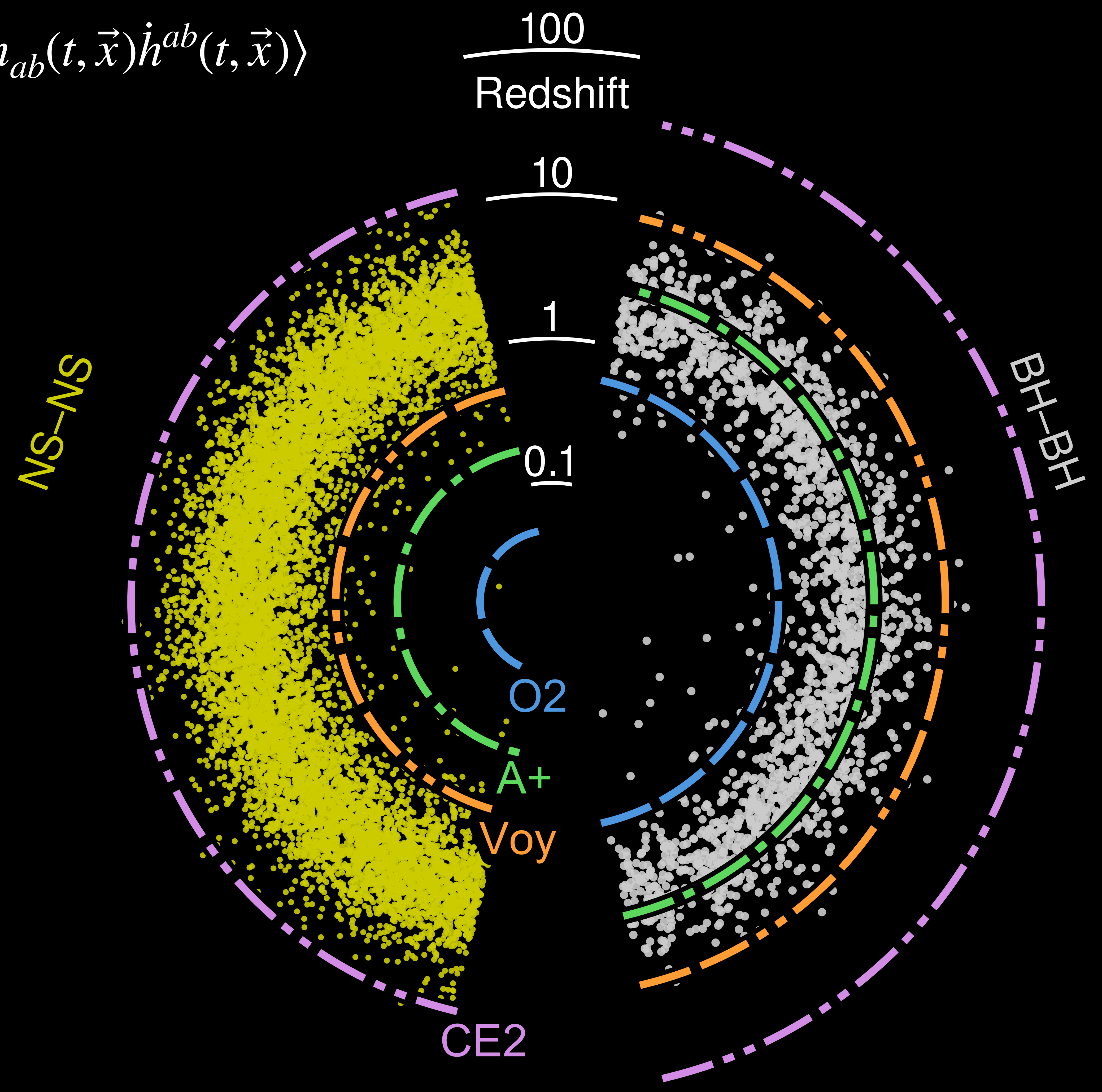
$\Omega_{\rm gw}(f) \propto$ <GW energy per source> x <source rate> dt

$$\Omega_{\rm gw}(f) = \frac{f}{\rho_{\rm c}H_0}\int_0^\infty {\rm d}z\, R(z)\,\frac{1}{(1+z)E(z)}\left(\frac{{\rm d}E_{\rm gw}}{{\rm d}f_{\rm s}}\right)\Bigg|_{f_{\rm s}=f(1+z)}$$

Event rate

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

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



E. Hall & S. Vitale, LIGO-G1900803

ASTROPHYSICAL STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln f} = \frac{f}{\rho_c}\frac{d\rho_{\rm gw}}{df}$$

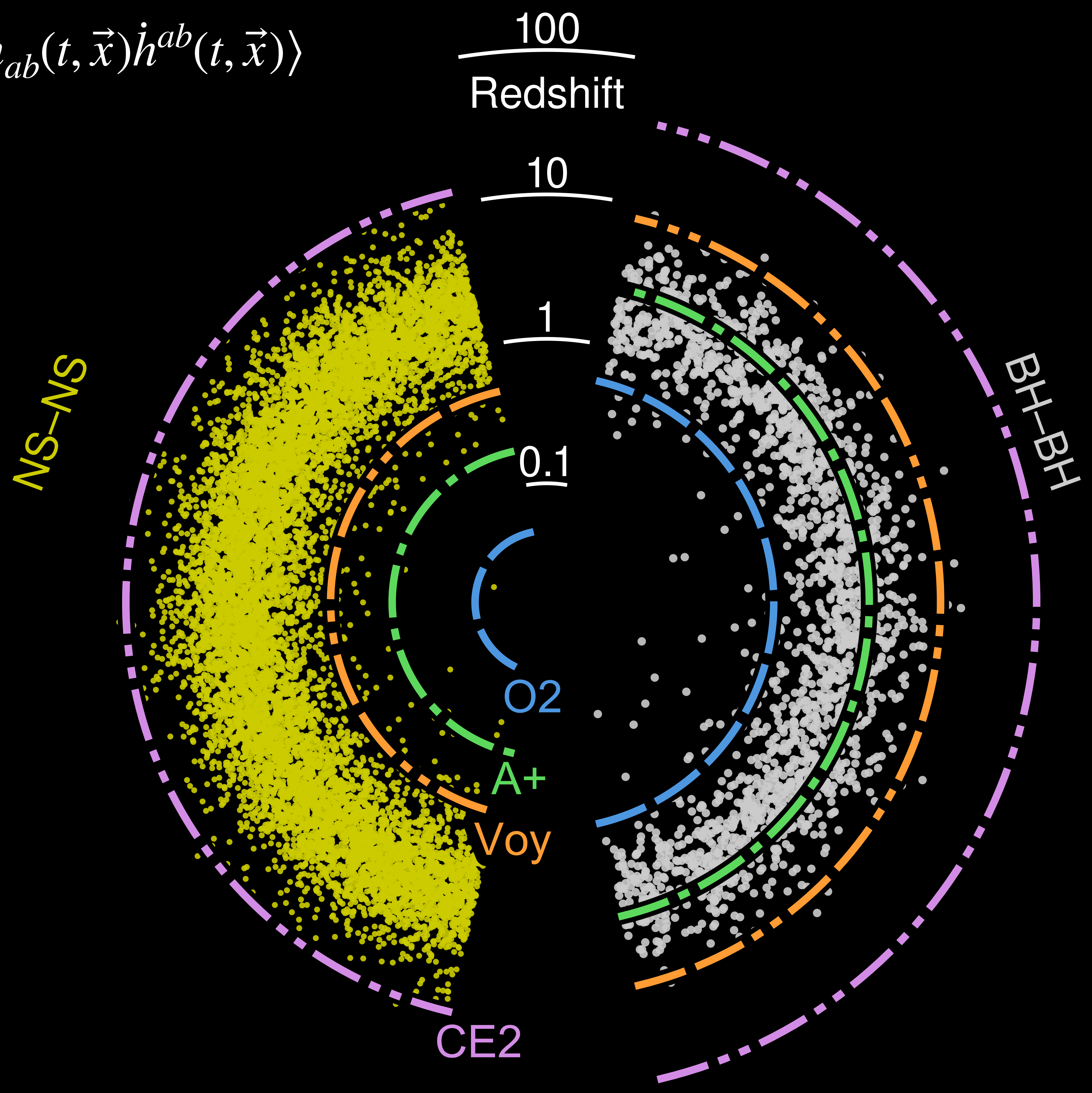
$$\rho_{gw} = \frac{c^2}{32\pi G}\langle \dot{h}_{ab}(t,\vec{x})\dot{h}^{ab}(t,\vec{x})\rangle$$

For a collection of sources:

Phinney formula

Compact Binaries: $\Omega_{\rm gw}(f) \propto f^{2/3}$

Isolated Neutron star: $\Omega_{\rm gw}(f) \propto f^{4}$



E. Hall & S. Vitale, LIGO-G1900803

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.
- Detectors with uncorrelated noise: cross-correlation separates the signal from the noise.

WHAT DETECTION METHODS CAN WE USE?

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What can be done:

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

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

Cross-correlation separates the signal from the noise

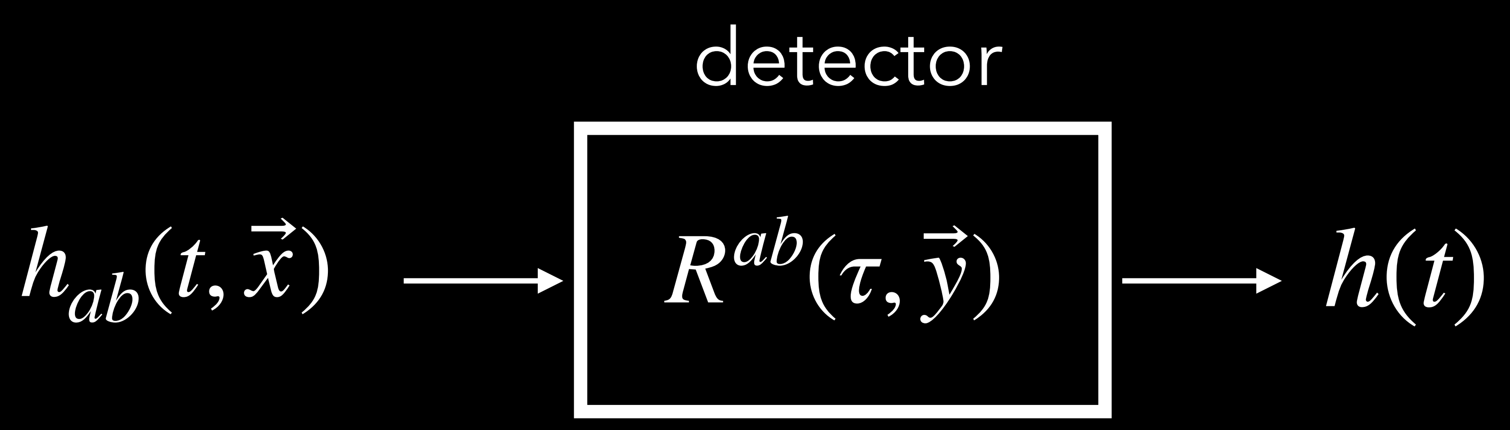
Intensity of the background

*Correlated noise and anisotropy SV,FDL, JS+ (in-preparation)

DETECTOR RESPONSE

(Slide credit: J. Romano)

detector acts as a linear system, which converts metric perturbations to detector output



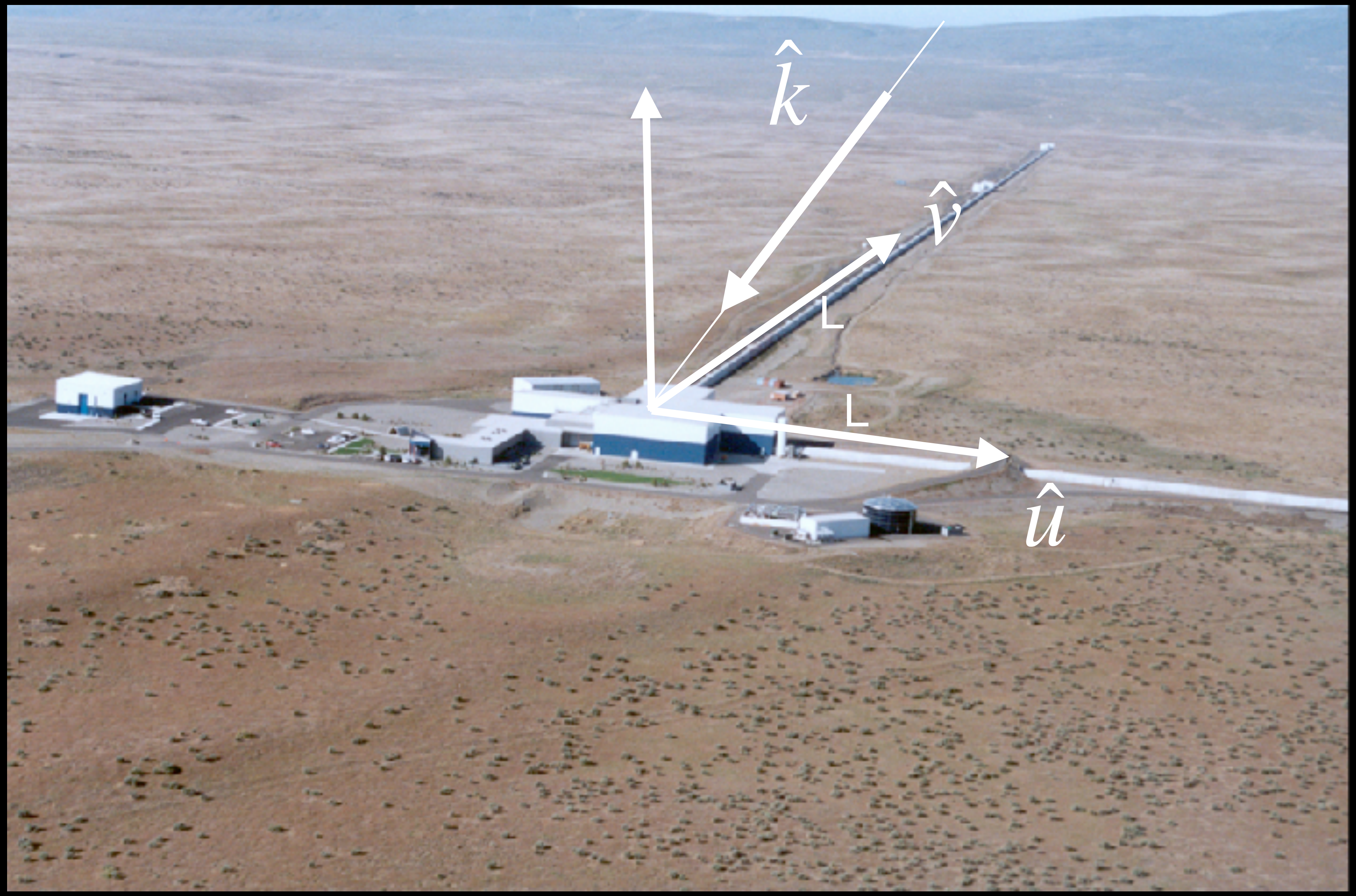
detector

$$h_{ab}(t,\vec{x}) \longrightarrow \boxed{R^{ab}(\tau,\vec{y})} \longrightarrow h(t)$$

detector output

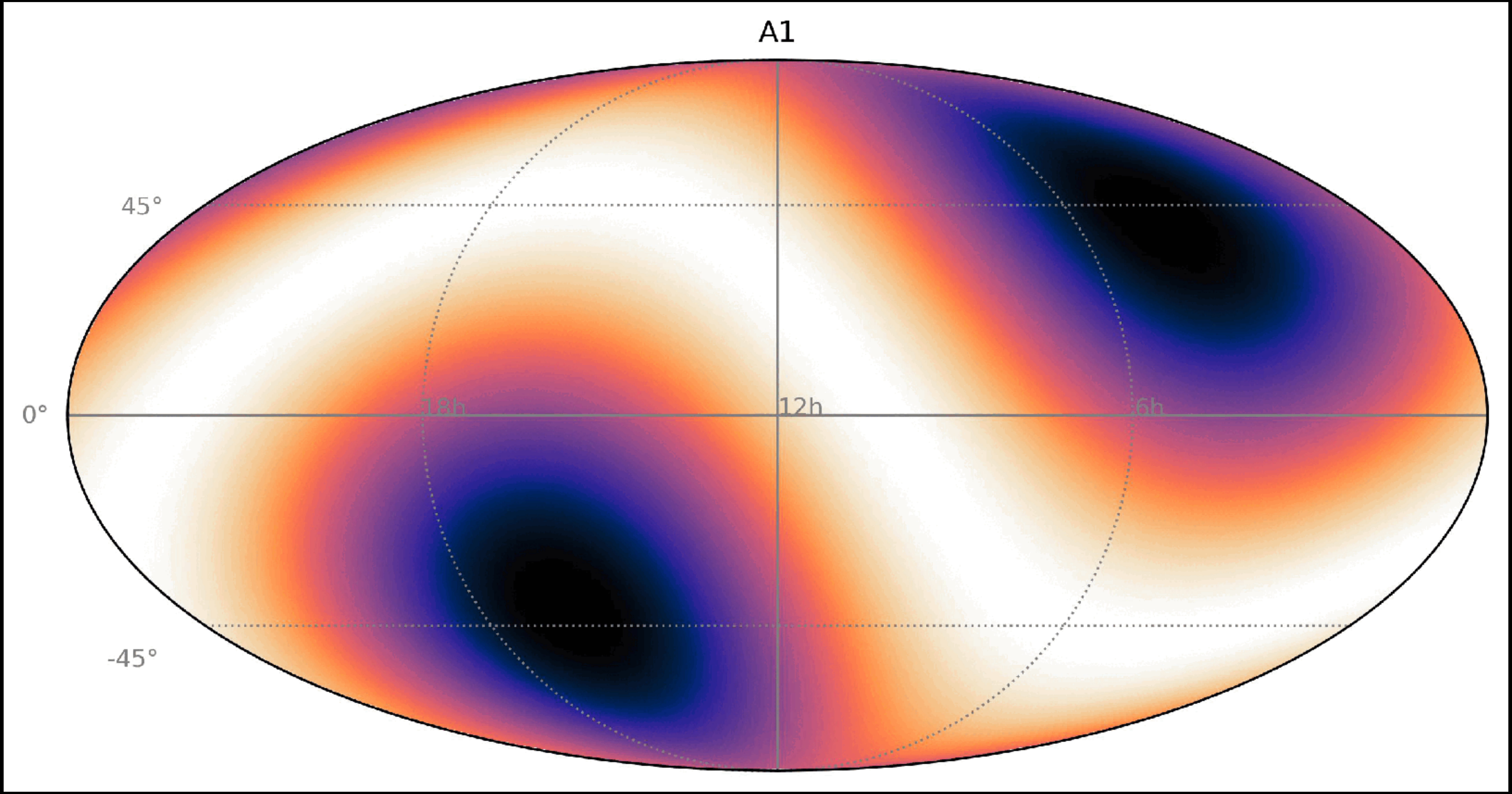
$$\tilde{h}(f) = \int \mathrm{d}^2\Omega_{\hat{n}} \sum_A \underbrace{R^A(f,\hat{n})}_{\uparrow} h_A(f,\hat{n})$$

detector response for a plane-wave
with frequency f, direction n, polarization A



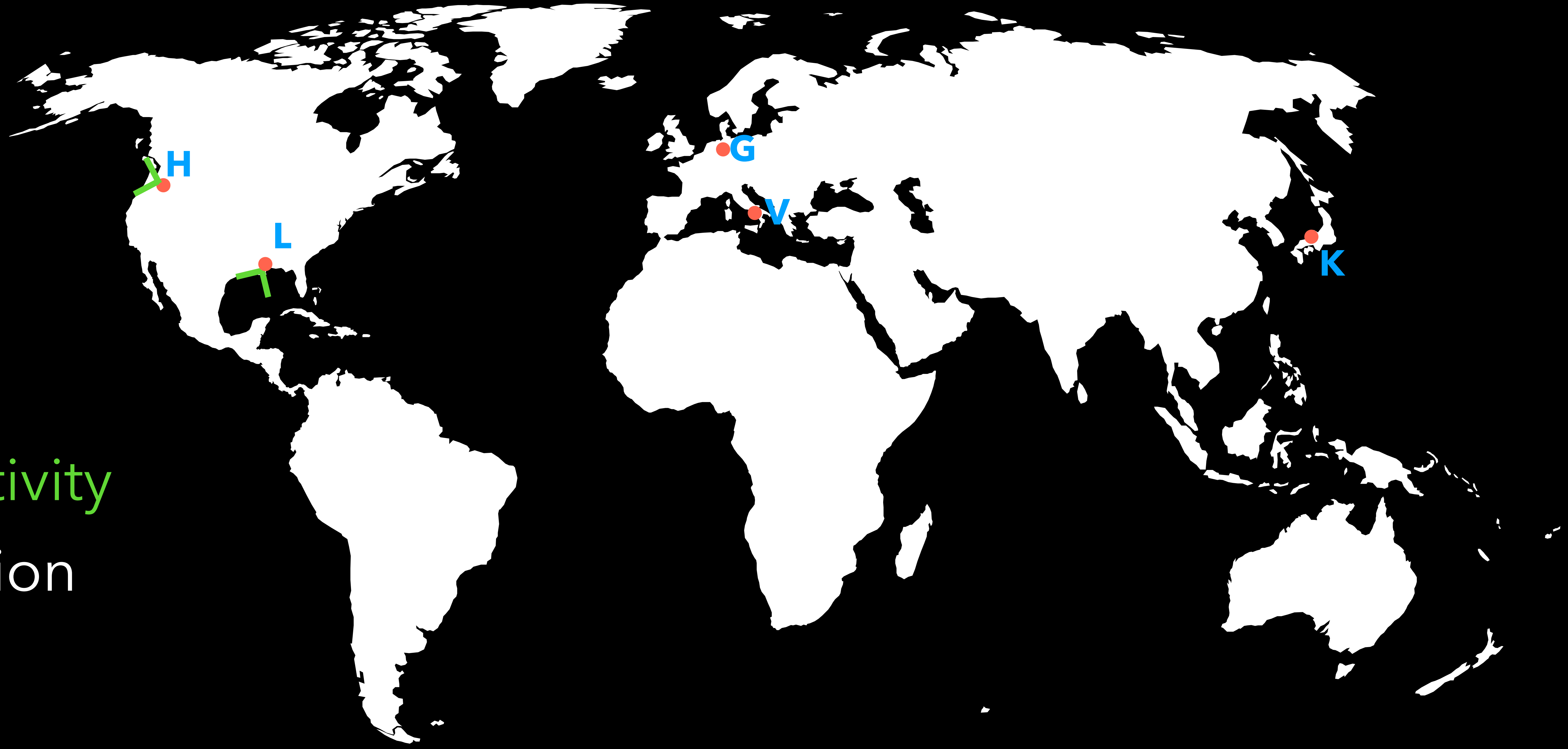
$$R^A(f,\hat{n}) \simeq \frac{1}{2}\left(u^a u^b - v^a v^b\right)\, e^A_{ab}(\hat{n})$$

BEAM PATTERN FUNCTIONS



OVERLAP REDUCTION FUNCTION

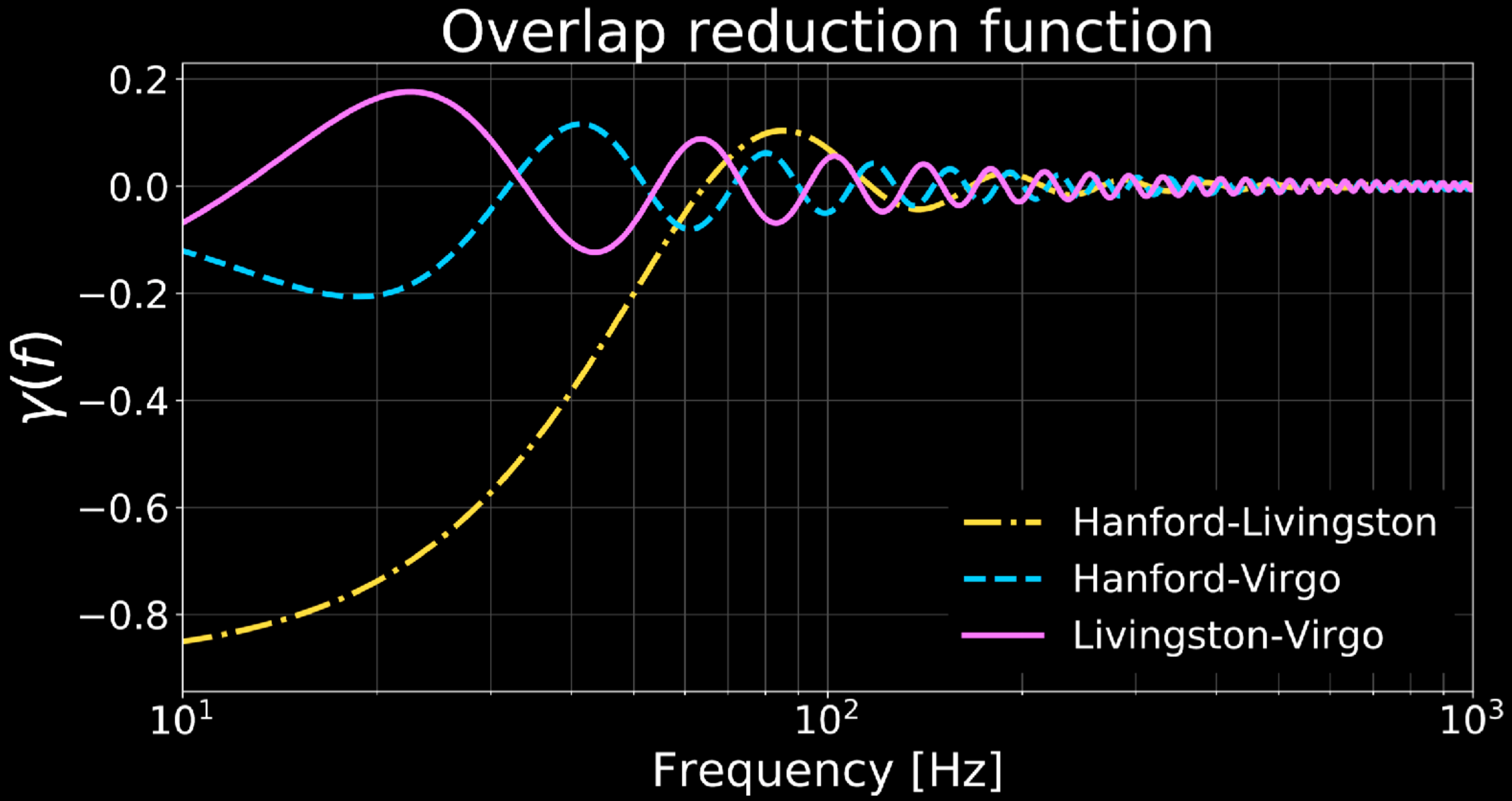
Detectors in different locations and with different orientations respond differently to a passing GW.



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

$$\gamma^{\mathcal{I}}_{ft,p} = \sum_A F^A_{\mathcal{I}_1}(\hat{\mathbf{n}}_p, t)\, F^A_{\mathcal{I}_2}(\hat{\mathbf{n}}_p, t)\, e^{2\pi i f\, \hat{\mathbf{n}}_p \cdot \Delta\mathbf{x}_{\mathcal{I}}(t)/c}$$

OVERLAP REDUCTION FUNCTION



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

expected
signal spectrum

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

Overlap reduction function

de-weight correlation
when noise is large

OPTIMAL FILTERING

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

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

SGWB SEARCHES IN O3

- No detections were made –
  - Used ~200 days of data from 2019-2020
- Set limits on Ω_α for a few values of α.
  - $\alpha = 2/3$ –> Unresolved CBCs
  - $\alpha = 3$ –> Flat in energy density
  - $\alpha = 0$ –> Flat in GW power
- Combine with binary black hole detections to set limits on merger rate vs. redshift
- SGWB searches are useful for constraining high redshifts
- New limits are, in general, 6-12 times better than previous ones.

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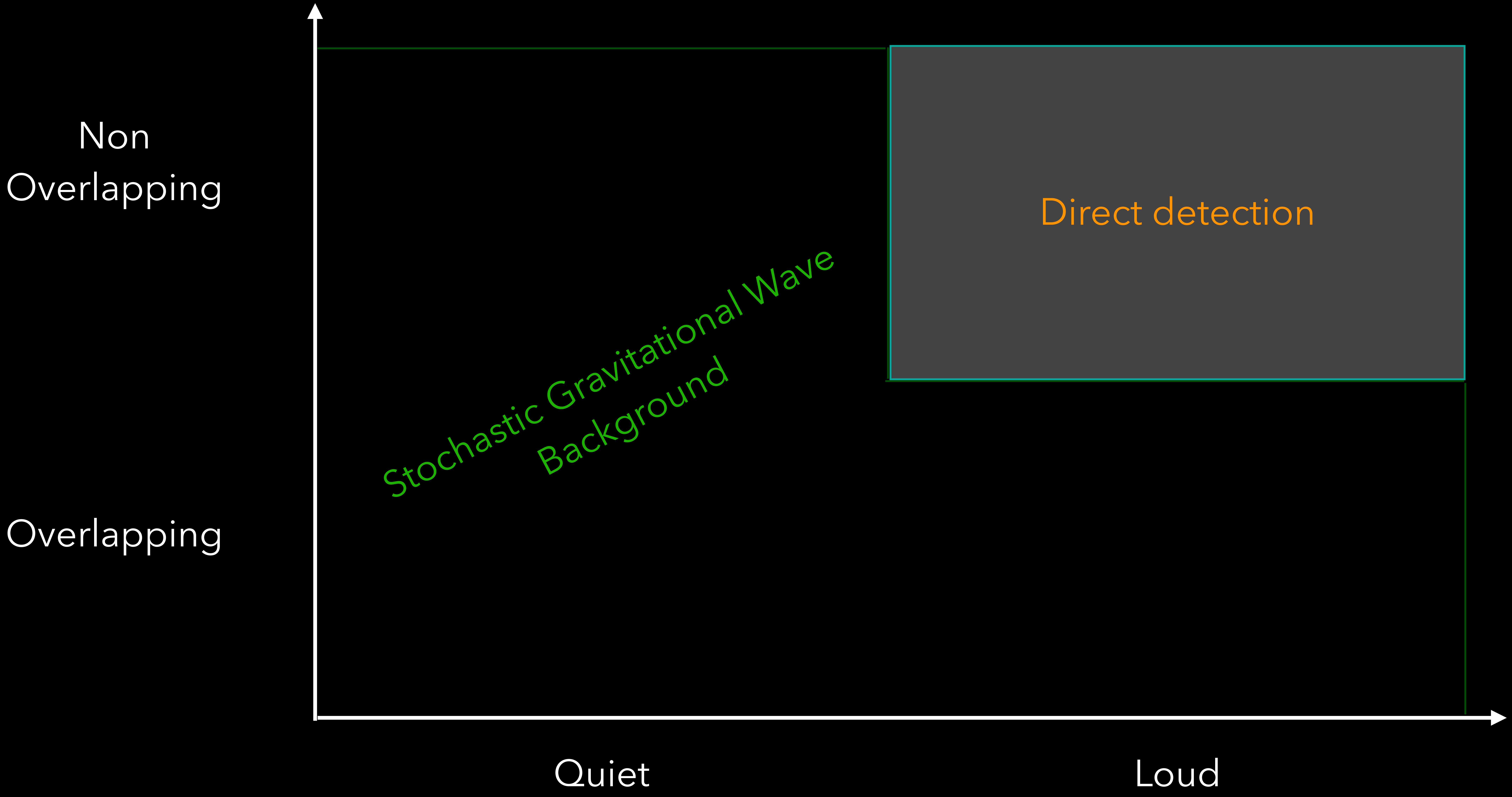
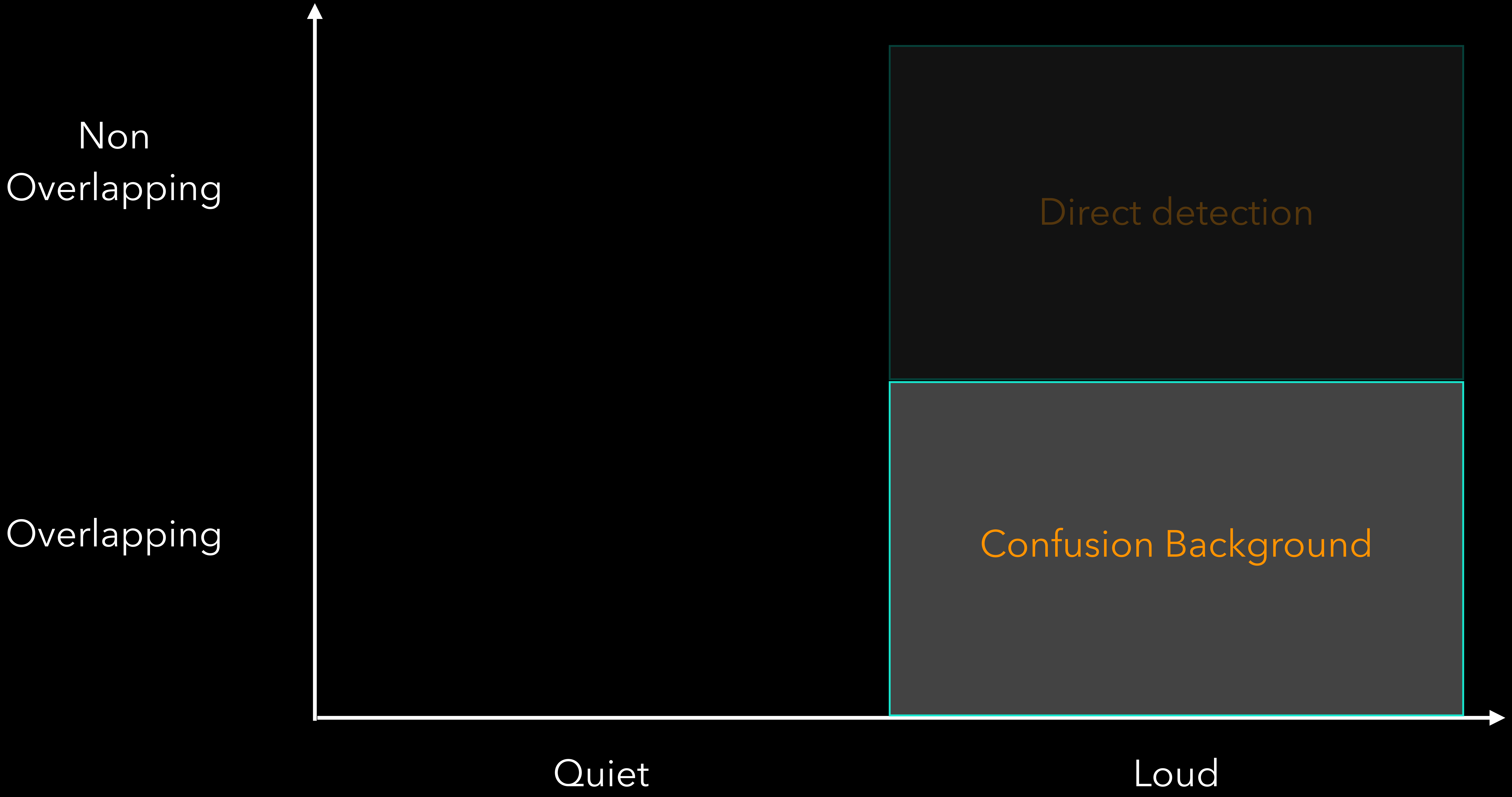
ASTROPHYSICAL STOCHASTIC GRAVITATIONAL WAVE BACKGROUND



ASTROPHYSICAL STOCHASTIC GRAVITATIONAL WAVE BACKGROUND



Non Overlapping

Overlapping

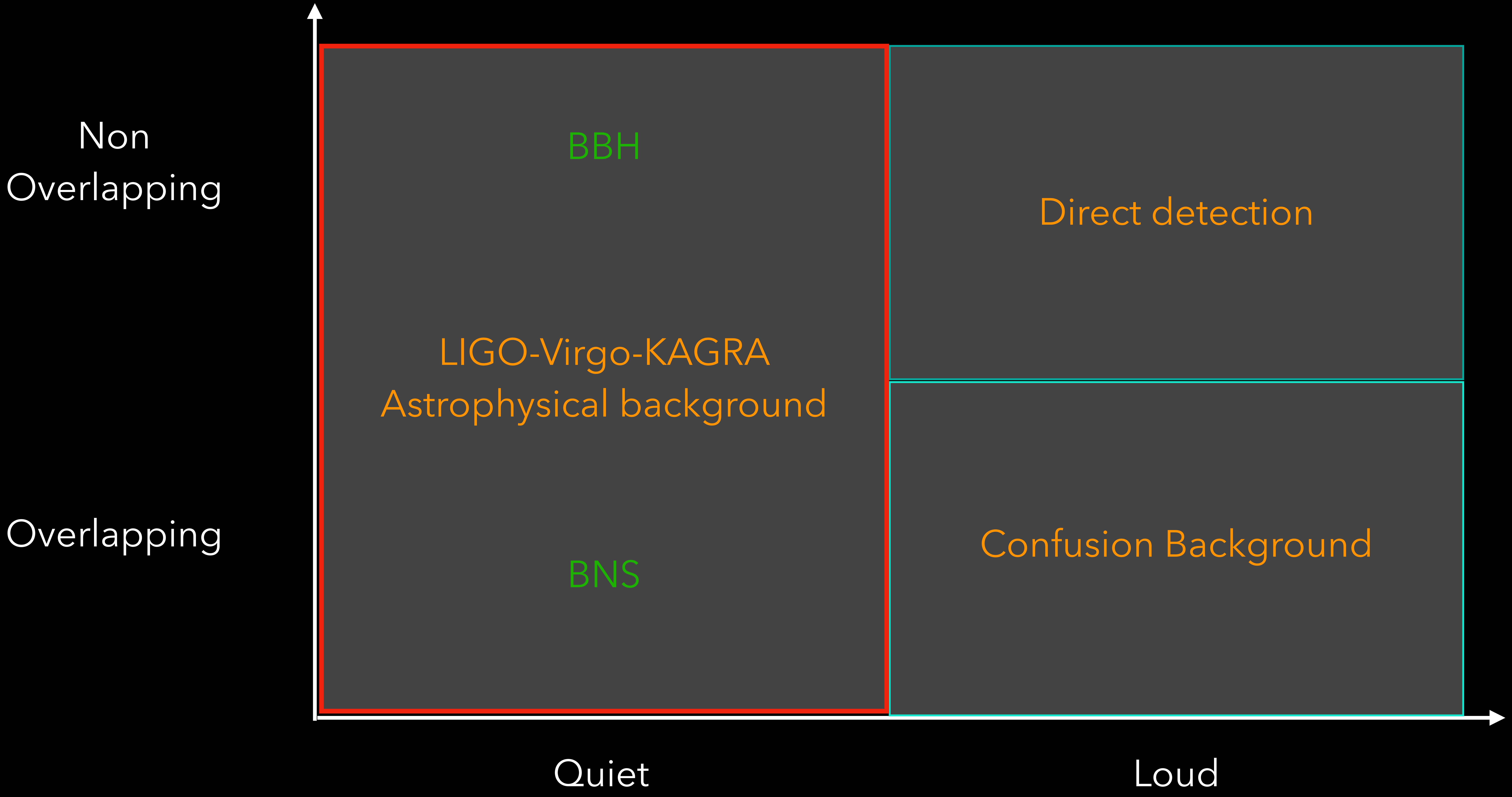
Direct detection

Confusion Background

Quiet

Loud

ASTROPHYSICAL STOCHASTIC GRAVITATIONAL WAVE BACKGROUND



Non Overlapping

Overlapping

BBH

LIGO-Virgo-KAGRA Astrophysical background

BNS

Direct detection

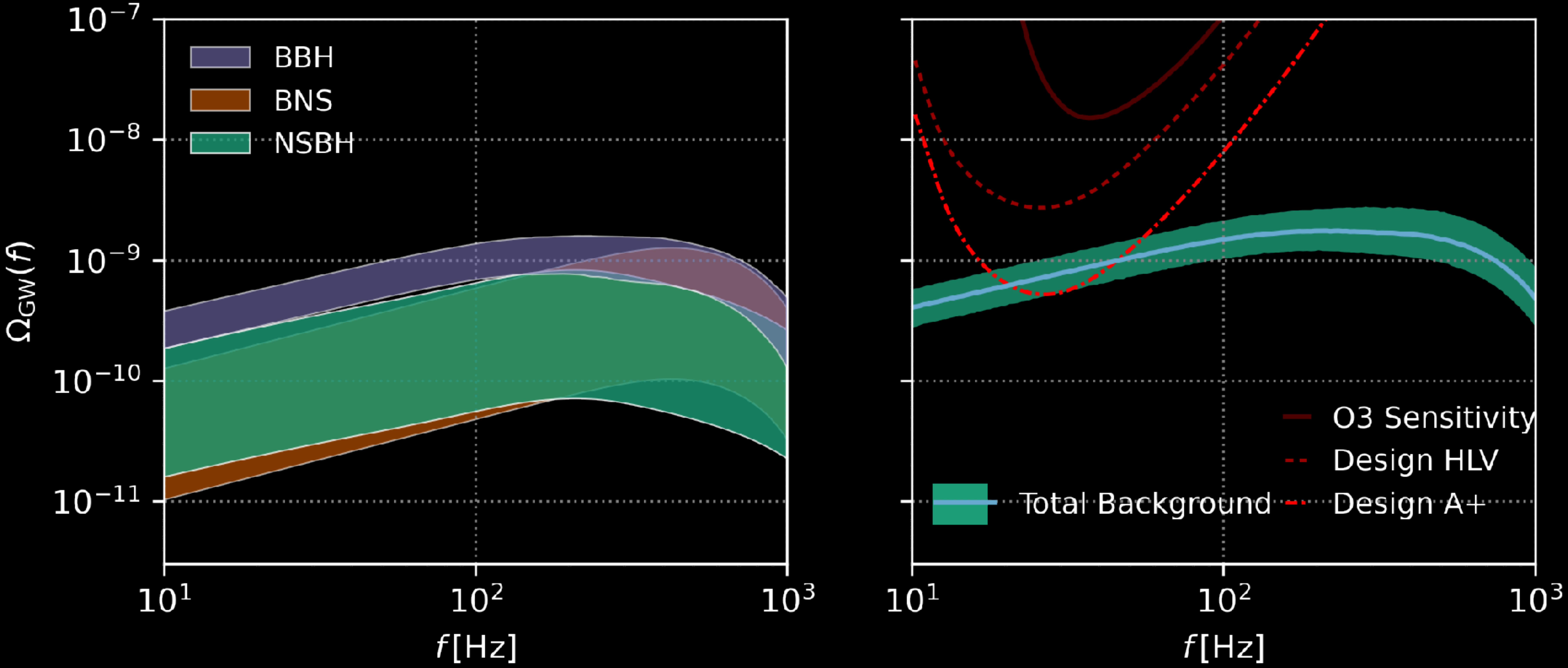
Confusion Background

Quiet

Loud

SENSITIVITY PROJECTION

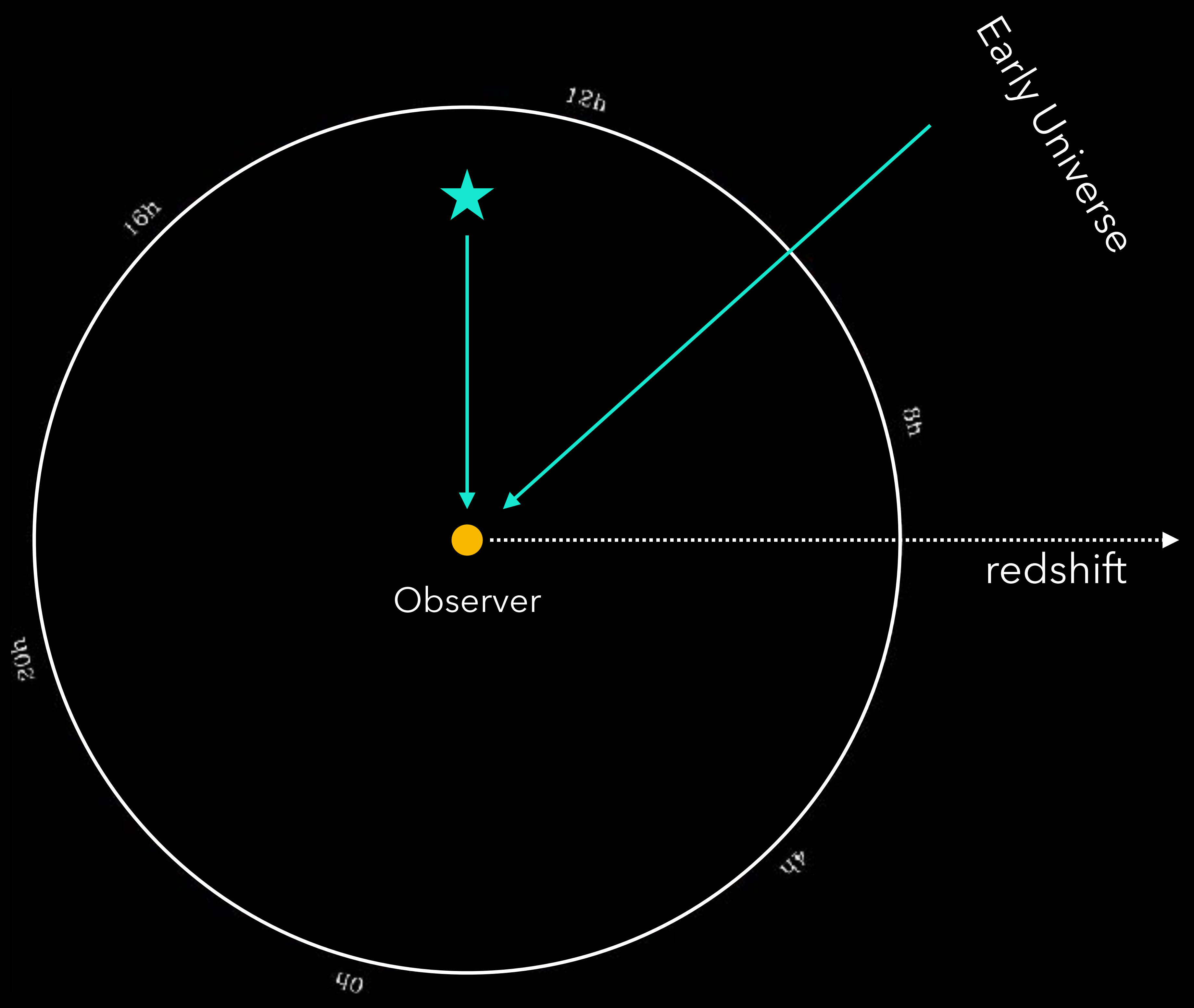
LVK arXiv:2111.03634



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)

ANISOTROPIC SEARCH

$\Omega_{\rm gw}(f)$



- sources isotropically distributed
- propagation along straight line
- no anisotropy in received flux

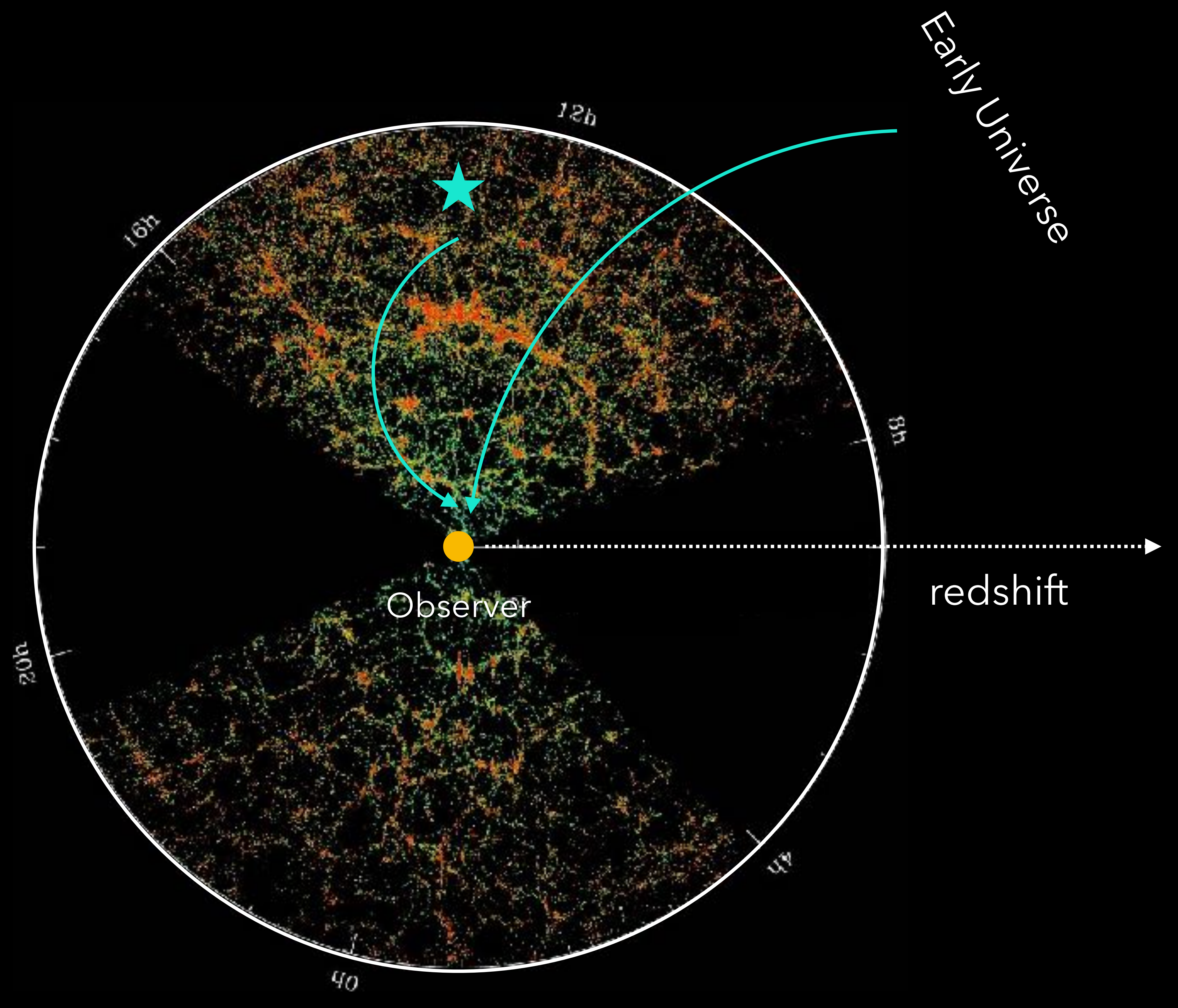
Slide inspired from G. Cusin's talk

ANISOTROPIC SEARCH

A more realistic description

$$\Omega_{\mathrm{gw}}(f, \hat{n})$$

- Anisotropic distribution of the emitting sources.
- Due to propagation: as gravitational-wave propagate, they accumulate line-of-sight effects, crossing different matter density fields which are inhomogeneously distributed in the Universe.

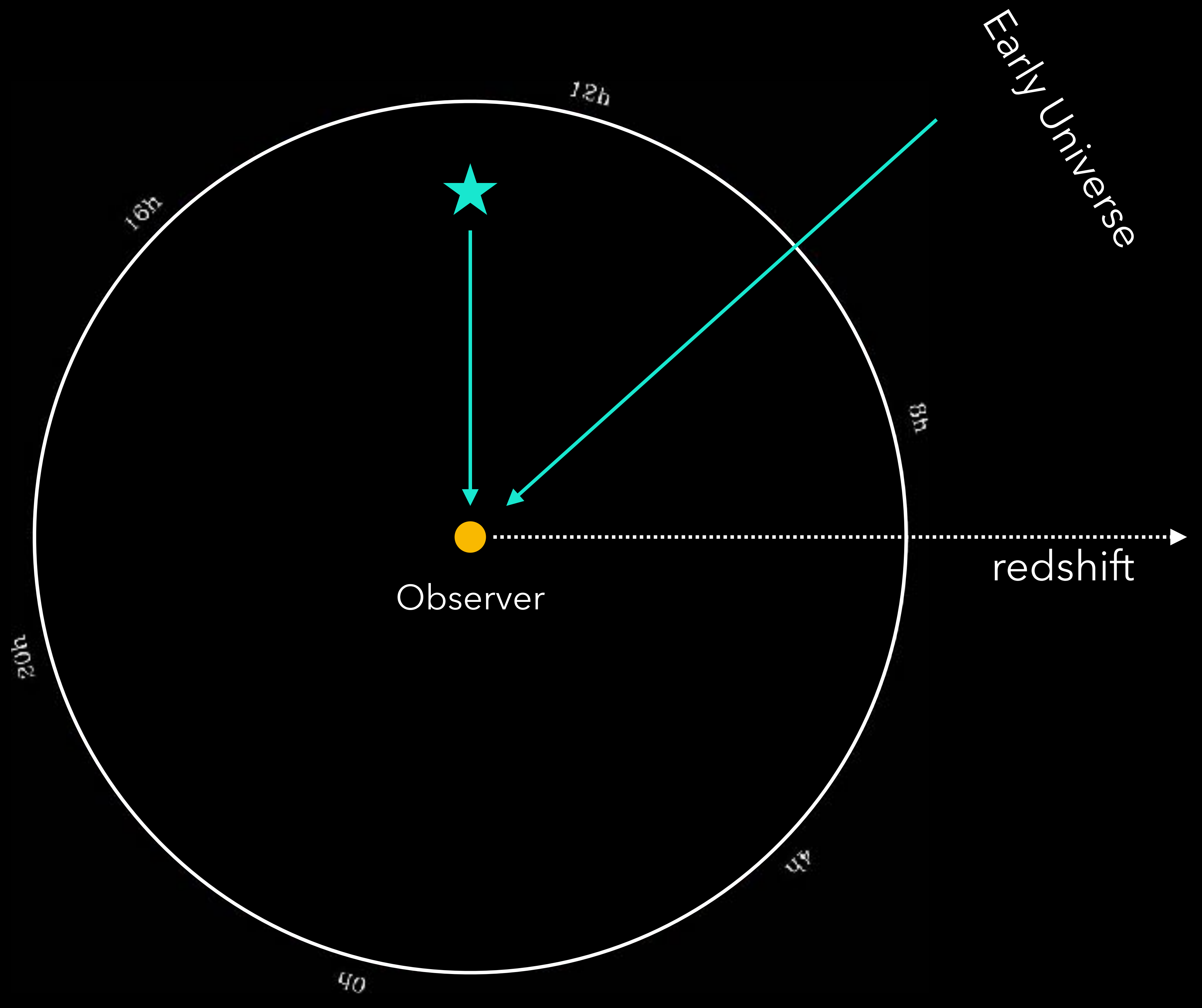


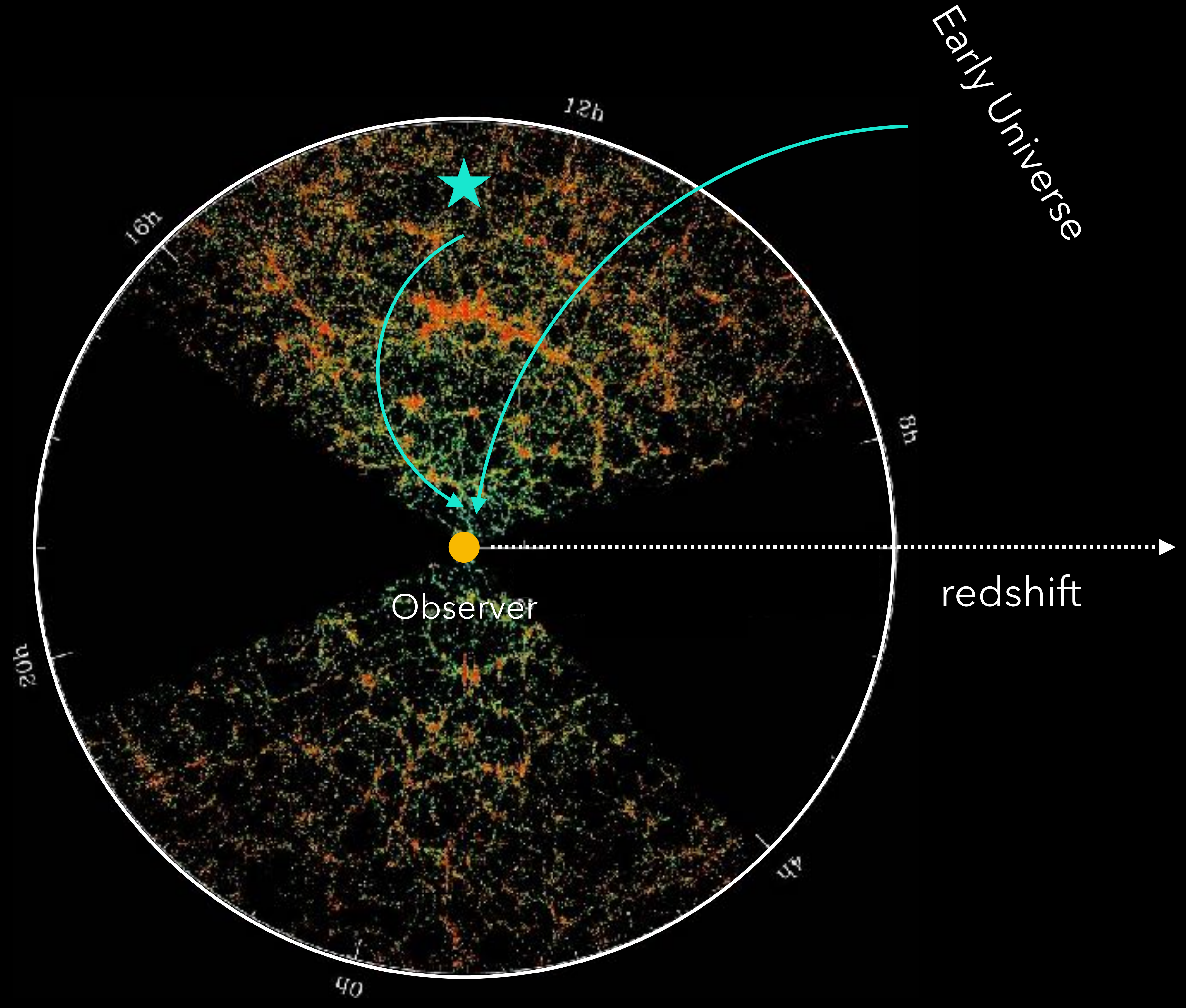
Slide inspired from G. Cusin's talk

ANISOTROPIC SEARCH

A more realistic description

$$\Omega_{\mathrm{gw}}(f) \longrightarrow \Omega_{\mathrm{gw}}(f, \hat{n})$$





Slide inspired from G. Cusin's talk

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.

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

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

Anisotropy can be expanded in pixel or spherical harmonic basis

$$\mathscr{P}(f,\hat{\mathbf{n}}) = \sum_p \mathscr{P}_p(f)\, e_p(\hat{\mathbf{n}})$$

HOW DO WE MAP THE SGWB SKY?

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

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

$-\hat{\Omega}$

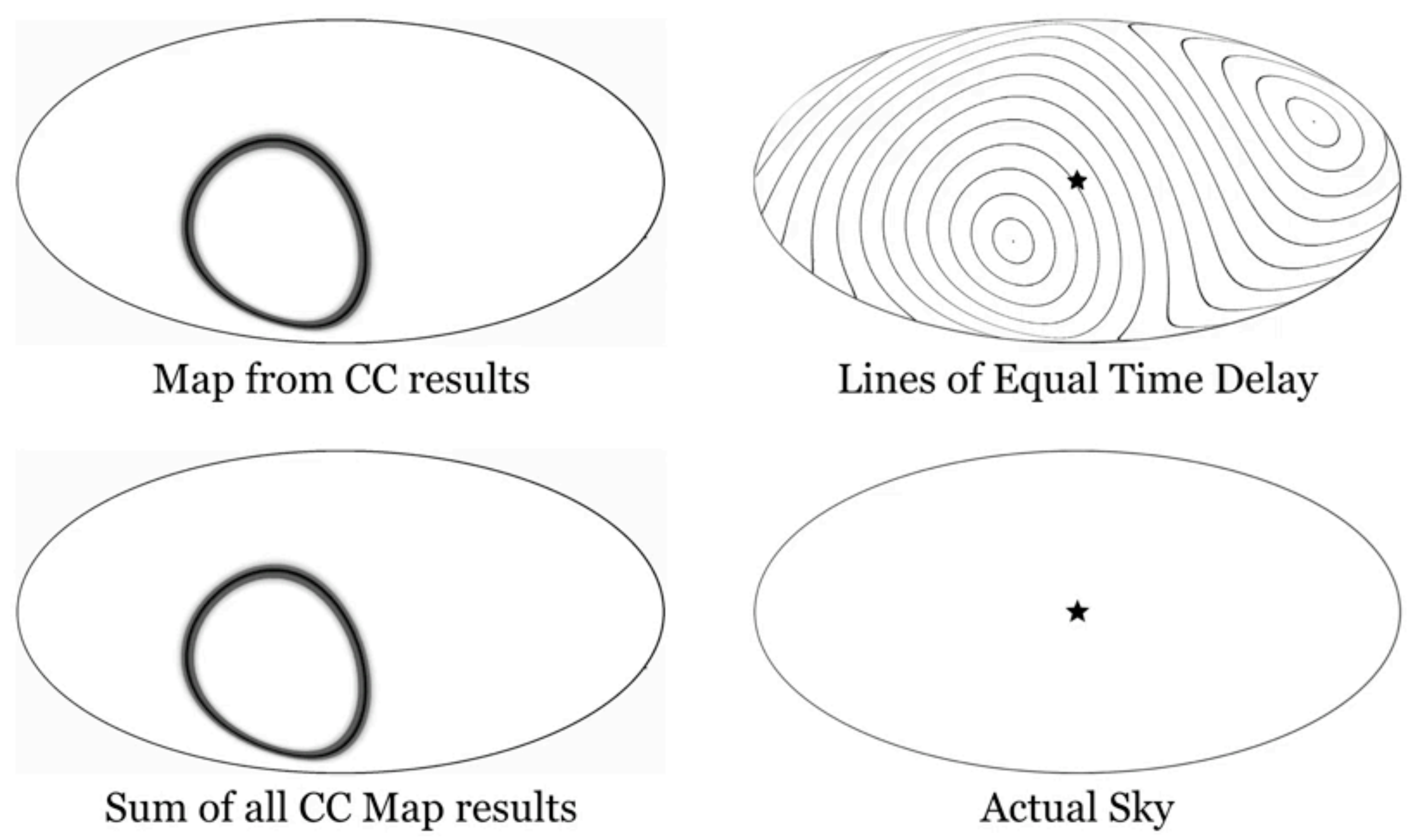
Most of the analysis performed so far assumes that the frequency and direction dependence can be separated: $\mathscr{P}(f, \hat{\mathbf{n}}) = P(\hat{\mathbf{n}})\, H(f)$

Where the common choic [illegible] spectral shape is $H(f) = \left(\frac{f}{f_{\mathrm{ref}}}\right)^{\beta}$

We will perform a model-independent search

ANISOTROPIC SEARCH

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

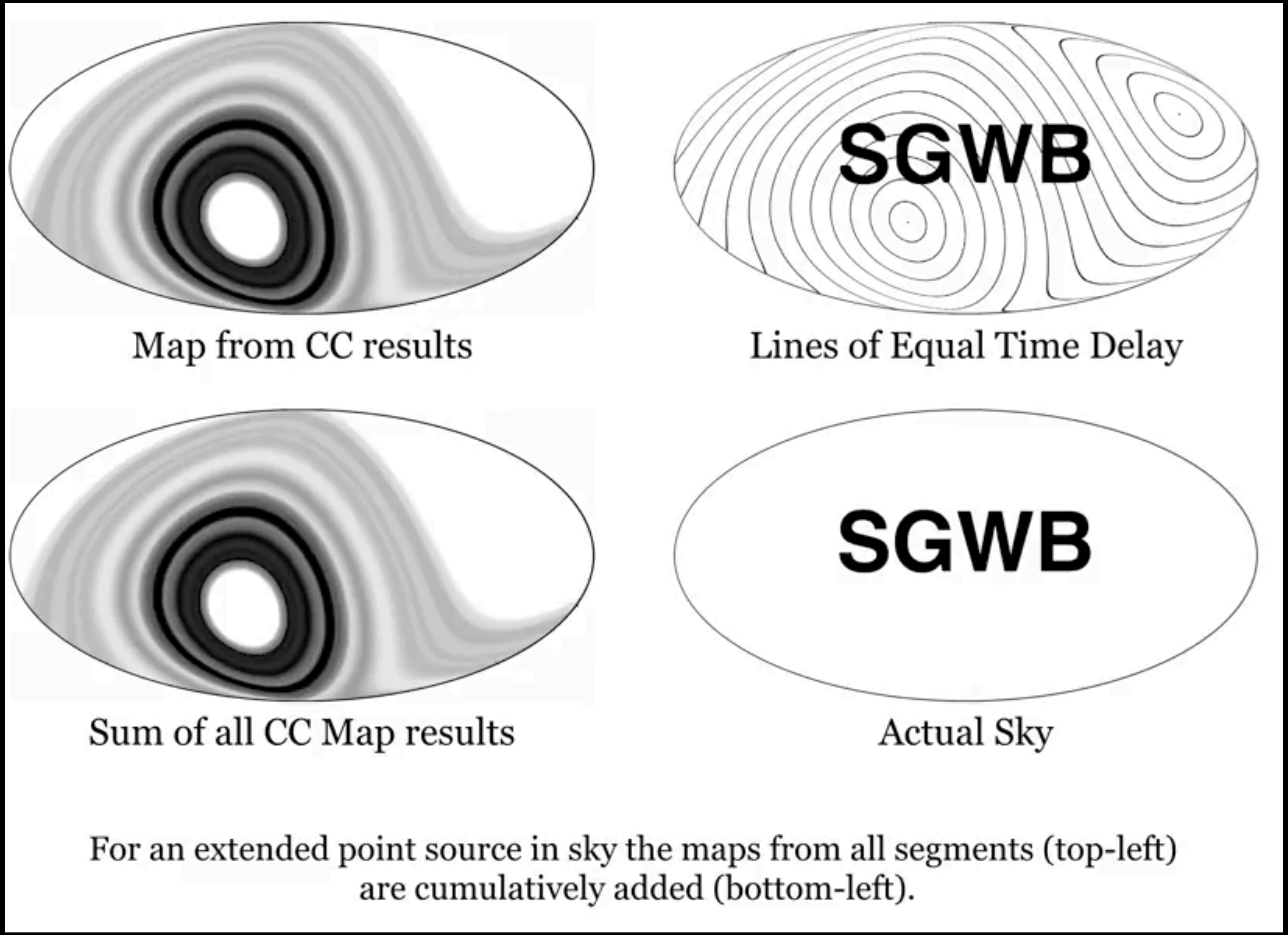


For a point source in sky the maps from all segments (top-left) are cumulatively added (bottom-left).

Animation Credit: A. Ain

ANISOTROPIC SEARCH

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



Map from CC results

Lines of Equal Time Delay

Sum of all CC Map results

Actual Sky

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

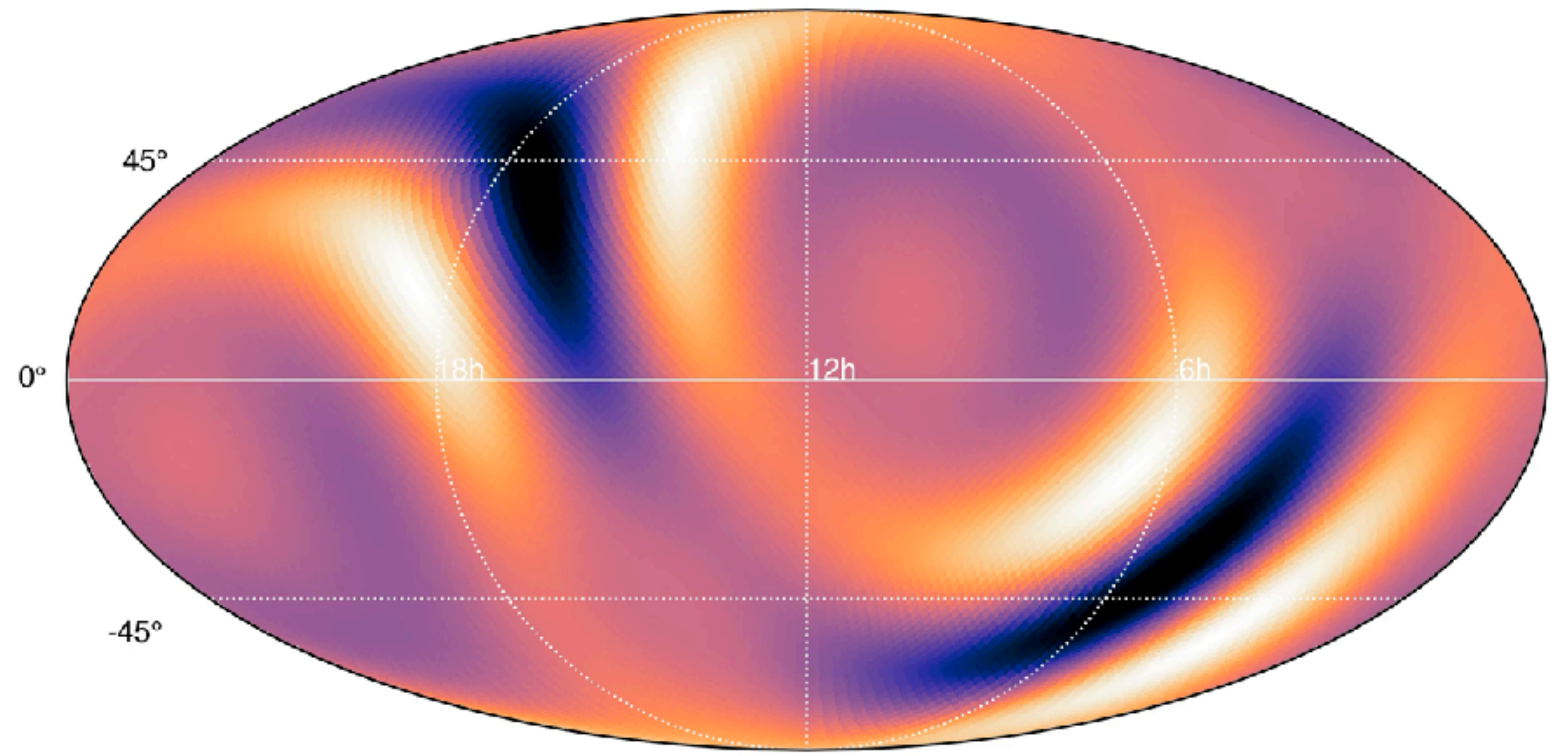
Animation Credit: A. Ain

DIRECTIONAL OVERLAP REDUCTION FUNCTION

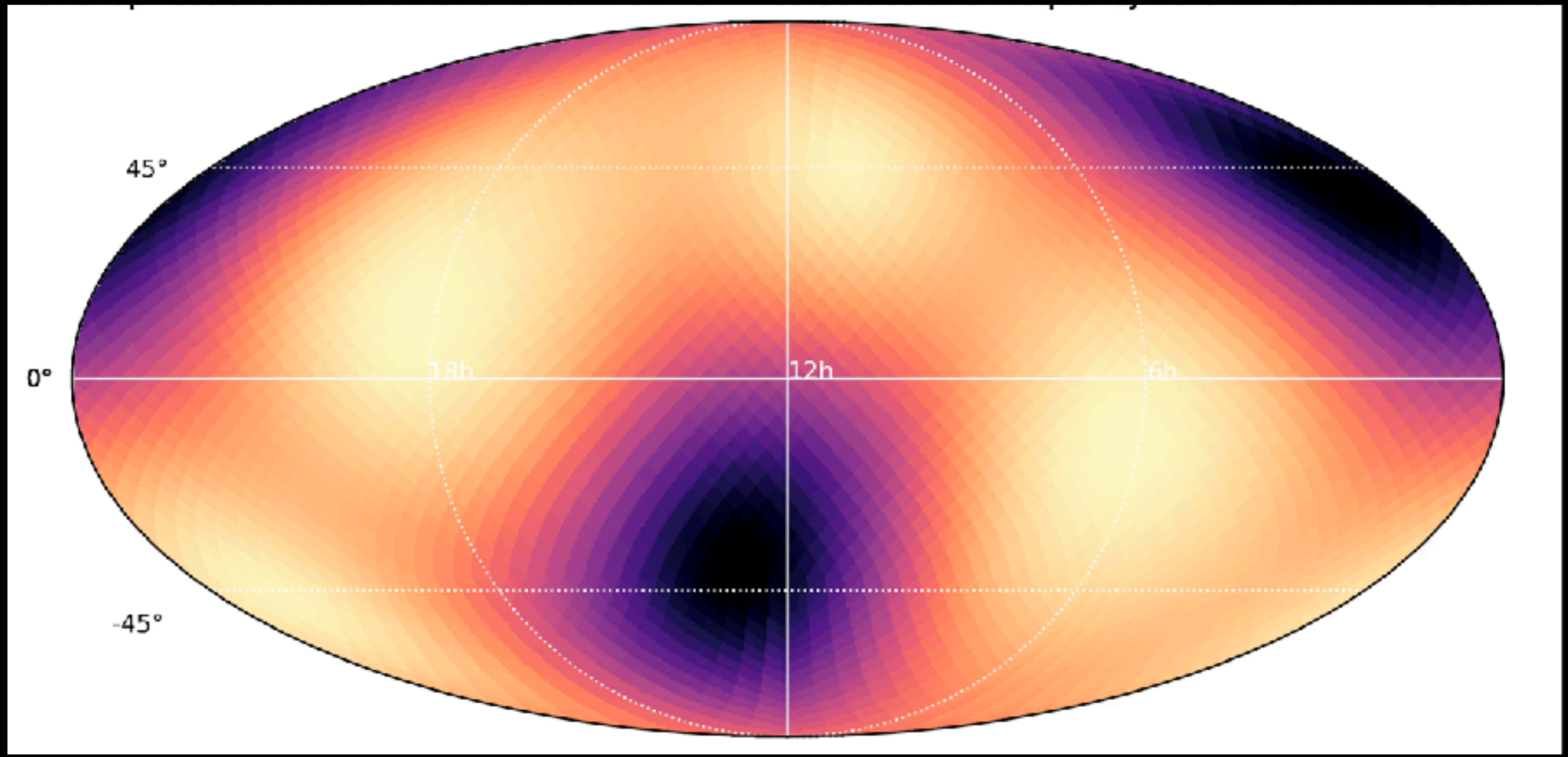
Recall:

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

$$\gamma_{ft,n} :\equiv \sum_A F_1^A(\hat{n}, t)\, F_2^A(\hat{n}, t)\, e^{2\pi i f\ \hat{n}\cdot\Delta x(t)\ /c}$$



$\gamma_{t,n}\Big|_{f=100\text{Hz}}$



$\gamma_{f,n}\Big|_{t=1326542418}$

PyStoch: MAP-MAKING PIPELINE

Ain, Suresh, Mitra PRD 98, 024001 (2018)
Suresh, Ain, Mitra 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

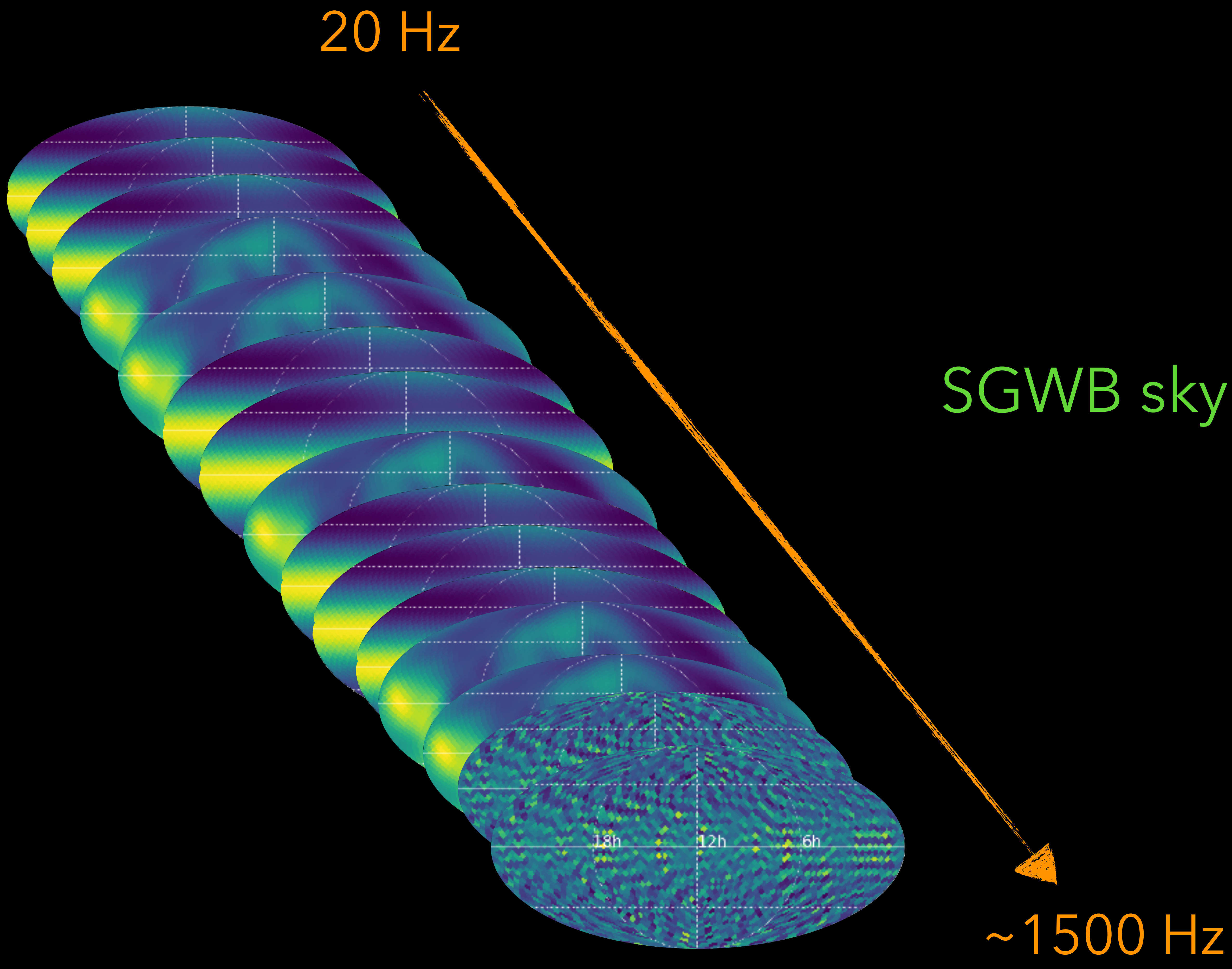
so separate search for different frequency spectra becomes redundant

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

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

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

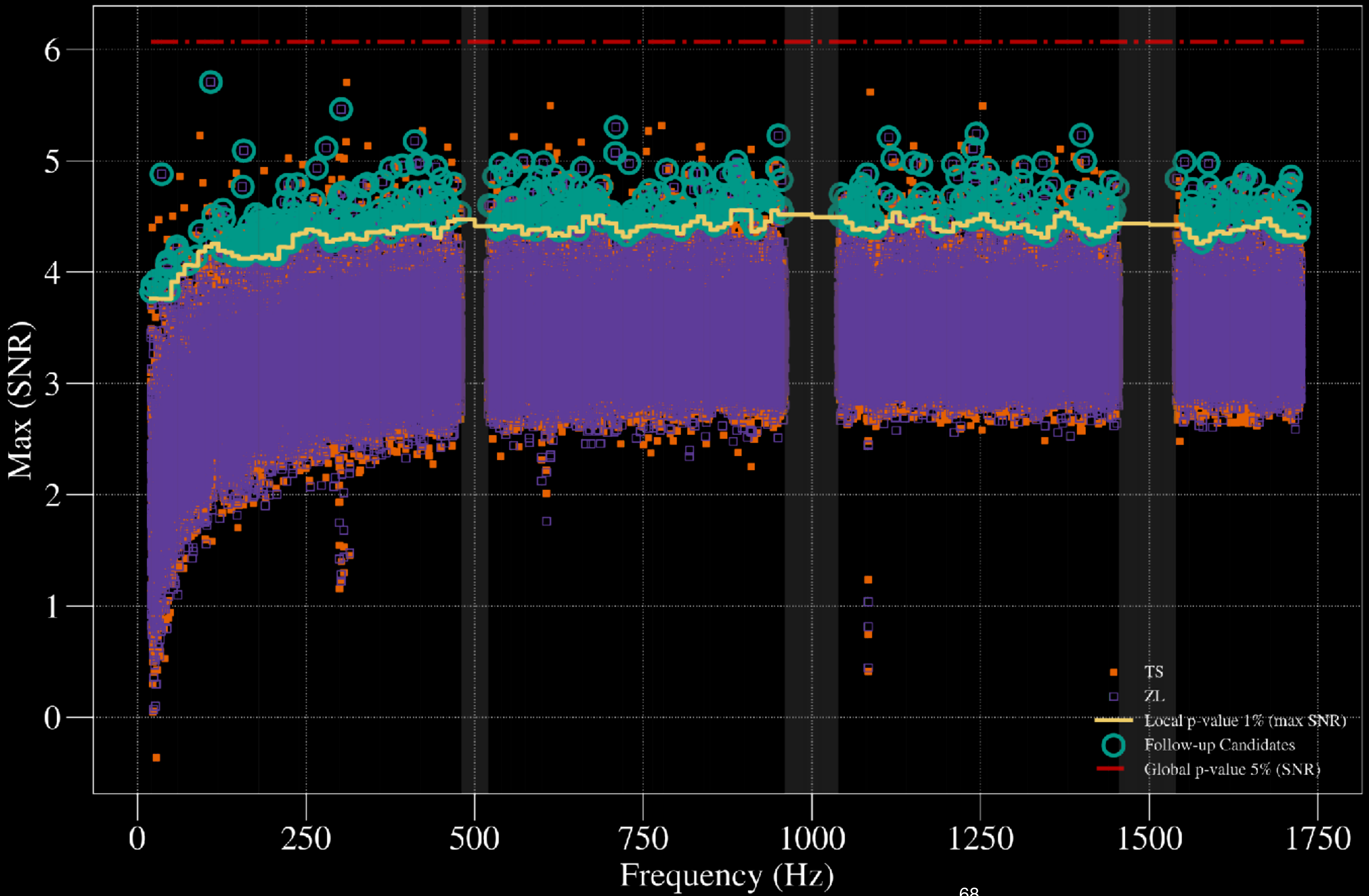


SGWB sky maps at every frequency bins

ALL-SKY ALL-FREQUENCY SEARCH

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

Distribution of maximum SNRs



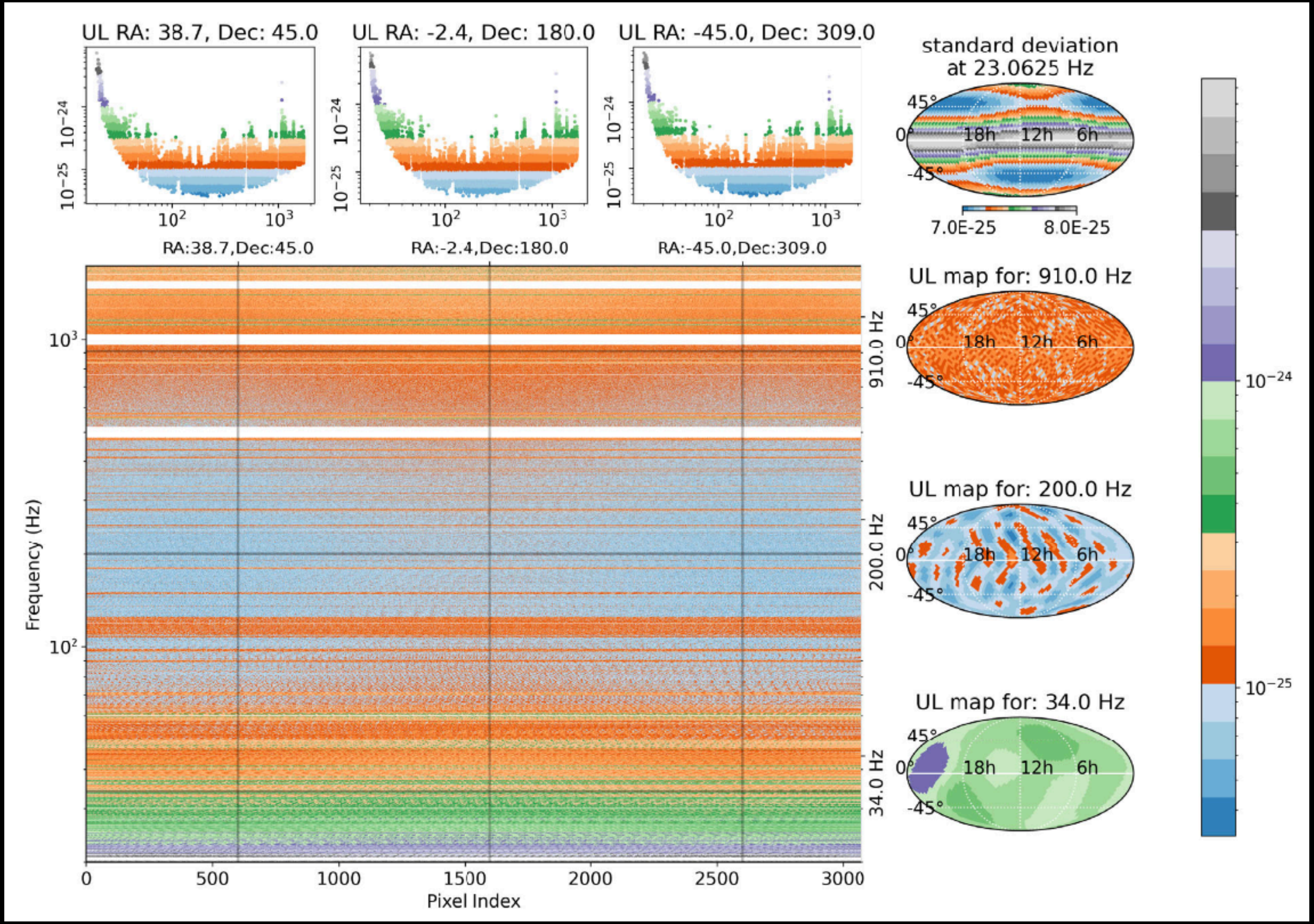
- The yellow curve shows the 99th percentile of maximum SNR for every 10 Hz frequency bin in TS, smoothed over three neighbouring 10 Hz bins.
- The red line delineates the trials-factor-corrected, one-sided global p-value of 5%
- The points above the yellow curve marked with teal circles are the identified candidates for follow-up studies.

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 effective strain*:

$$h(f,\hat{\mathbf{n}}) = \sqrt{\mathscr{P}(f,\hat{\mathbf{n}})\,df}$$



- 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.

*circular polarisation without Doppler correction

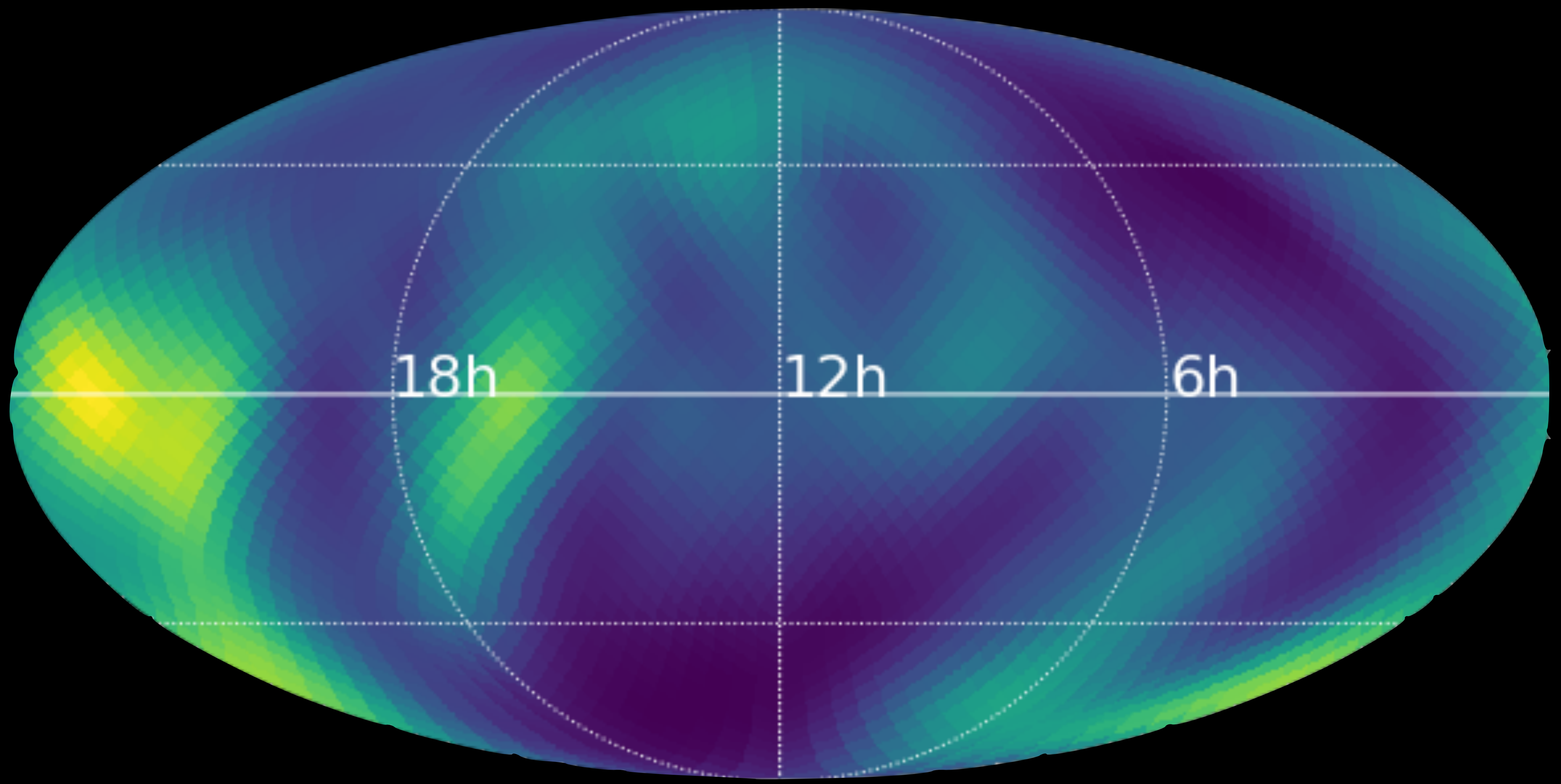
ALL-SKY ALL-FREQUENCY RESULTS

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

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

$$\hat{\mathscr{P}}(\hat{\mathbf{n}}) = \frac{\sum_f \hat{\mathscr{P}}(f,\hat{\mathbf{n}})\,\sigma_{\hat{\mathbf{n}}}^{-2}(f)\,H(f)}{\sum_f \sigma_{\hat{\mathbf{n}}}^{-2}(f)\,H^2(f)}$$

$$\sigma_{\hat{\mathbf{n}}} = \left[\sum_f \sigma_{\hat{\mathbf{n}}}^{-2}(f)\,H^2(f)\right]^{-1/2}$$

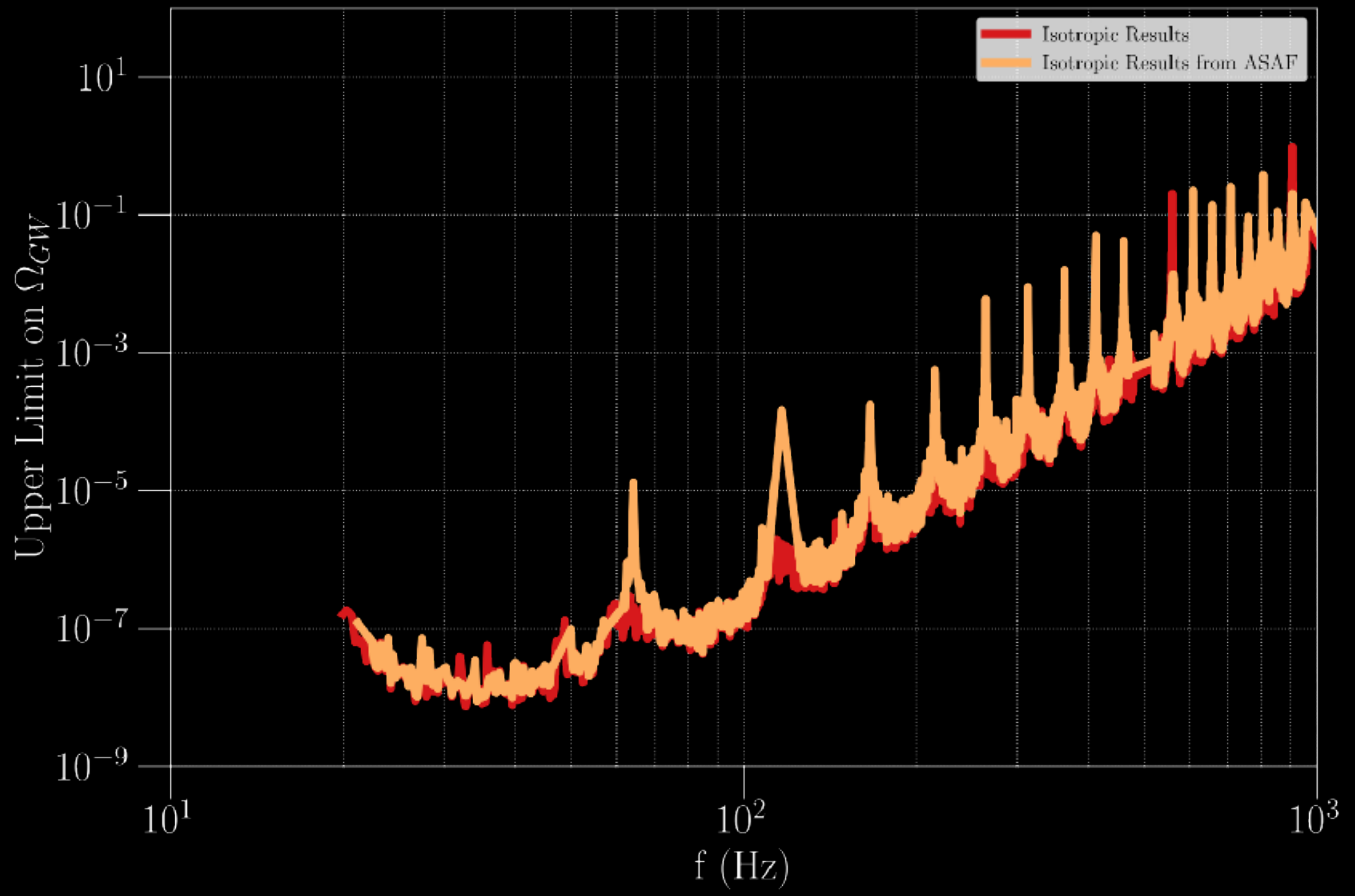


$\alpha = 0$, spectral shape

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

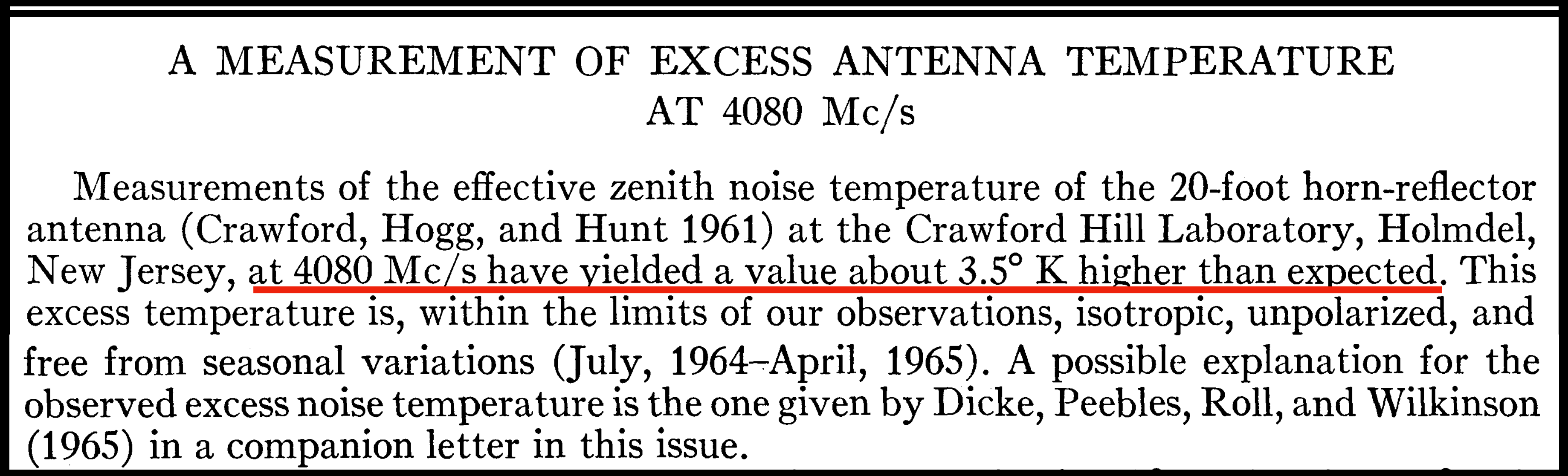
$$\hat{\mathscr{P}}_{\rm iso}(f)\,\sigma_{\rm iso}^{-2}(f) = \frac{5}{4\pi}\int d\hat{\mathbf{n}}\,\hat{\mathscr{P}}(f,\hat{\mathbf{n}})\,\sigma_{\hat{\mathbf{n}}}^{-2}(f)$$

$$\sigma_{\rm iso}^{-2}(f) = \left(\frac{5}{4\pi}\right)^2\int d\hat{\mathbf{n}}\int d\hat{\mathbf{n}}'\,\Gamma_{\hat{\mathbf{n}},\hat{\mathbf{n}}'}(f)$$



WE ARE NOW AT:

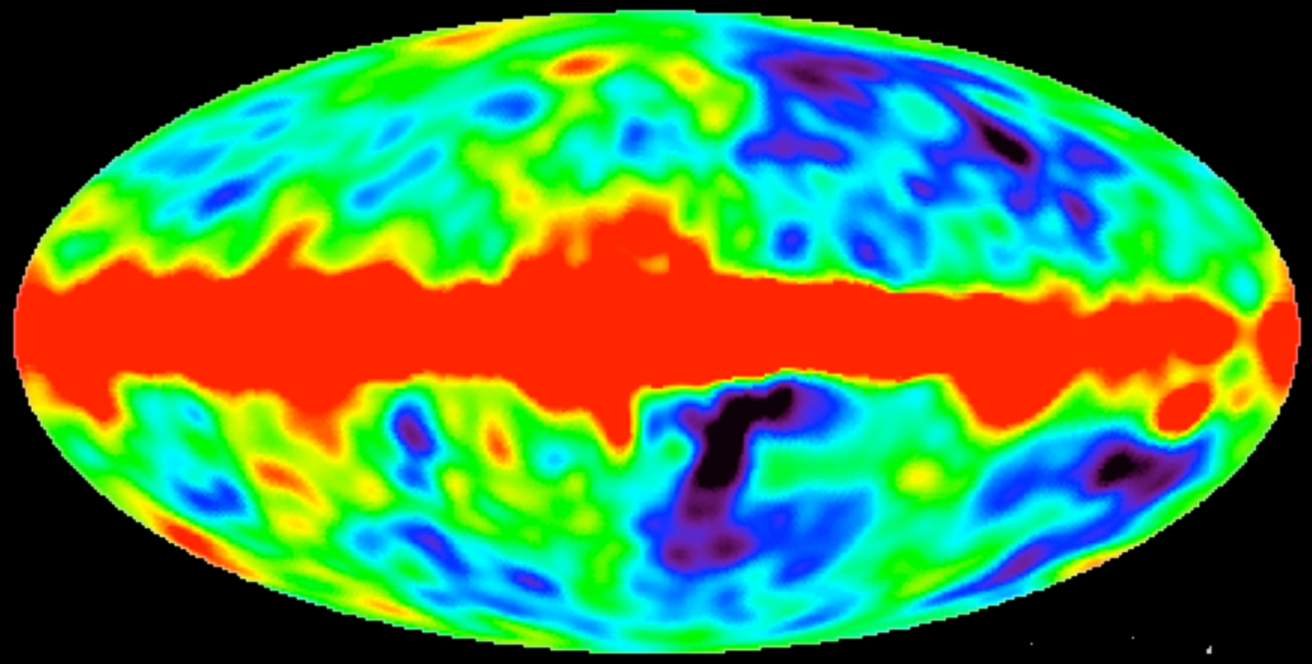
1965: Penzias & Wilson



A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

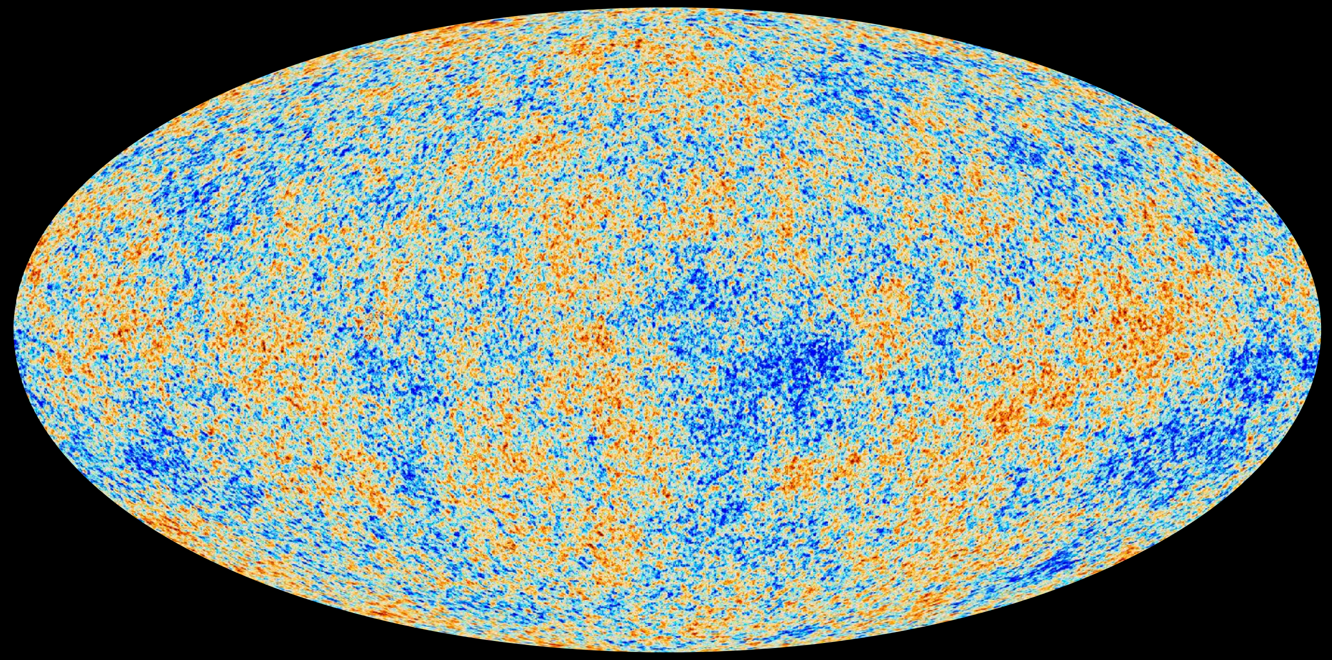
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

1992: COBE



(ang resolution: ~10 degrees)

2013: WMAP, Planck



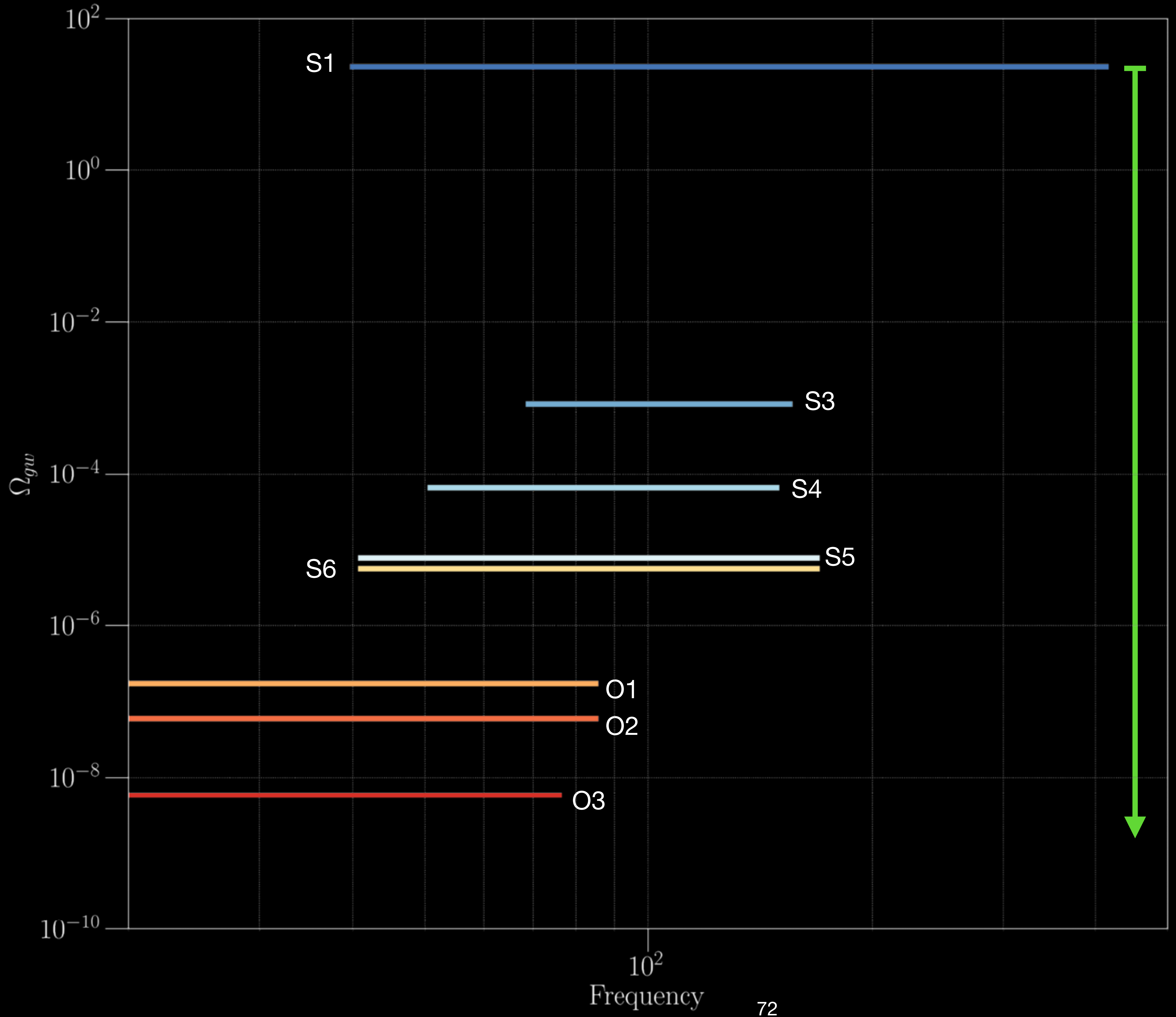
(ang resolution: ~10 arcmin)

2023: We are yet to detect the isotropic SGWB component

Long road ahead.....

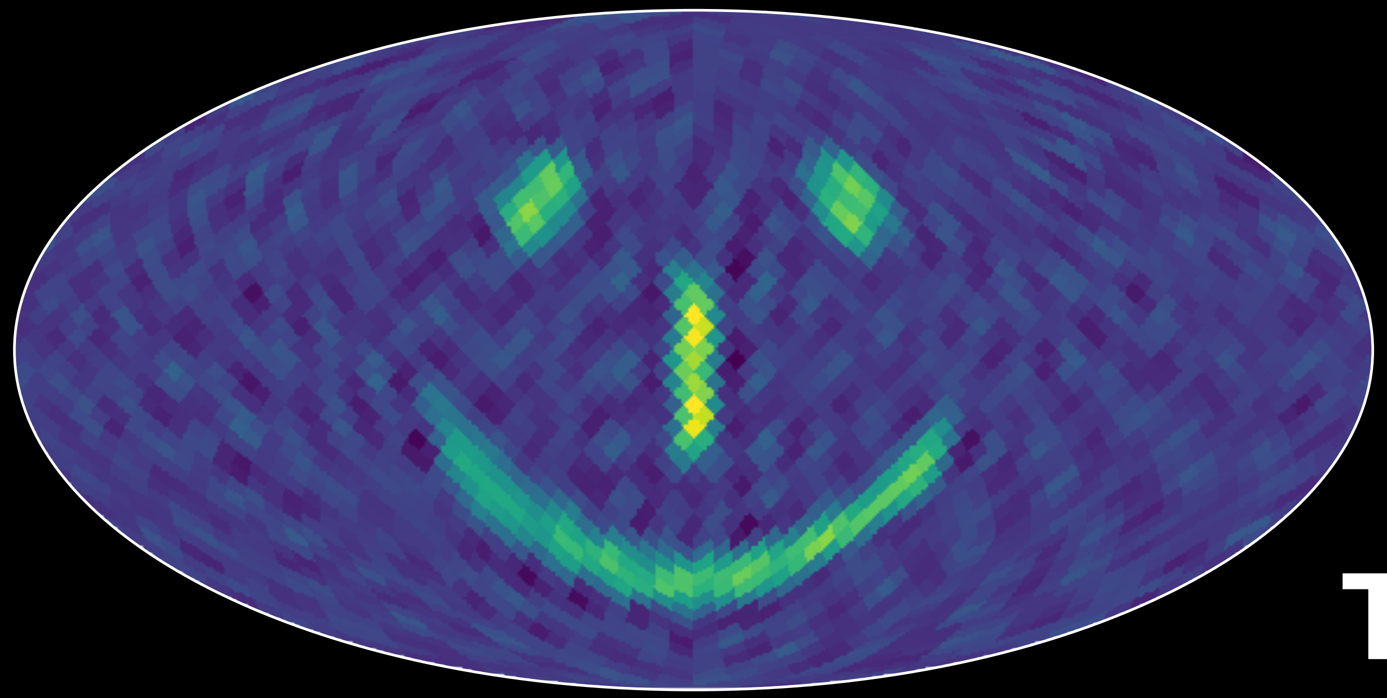
WE ARE NOW AT:

adapted from LIGO S4 paper: APJ 659:918, 2007



We are reaching there…

- ☐ 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!