Searching for stochastic GW backgrounds across the GW spectrum - overview

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Thursday, 8 Sep 2022

(GWO2022 Workshop)

Outline

1. Why should we care about detecting a stochastic GW background?
2. What sorts of sources / signals do we expect to detect?
3. What detection methods can we use?
4. What are the current observational constraints / limits on stochastic GW backgrounds?

Highlight subsequent talks on related topics!

("teasers" of what others will describe in more detail)

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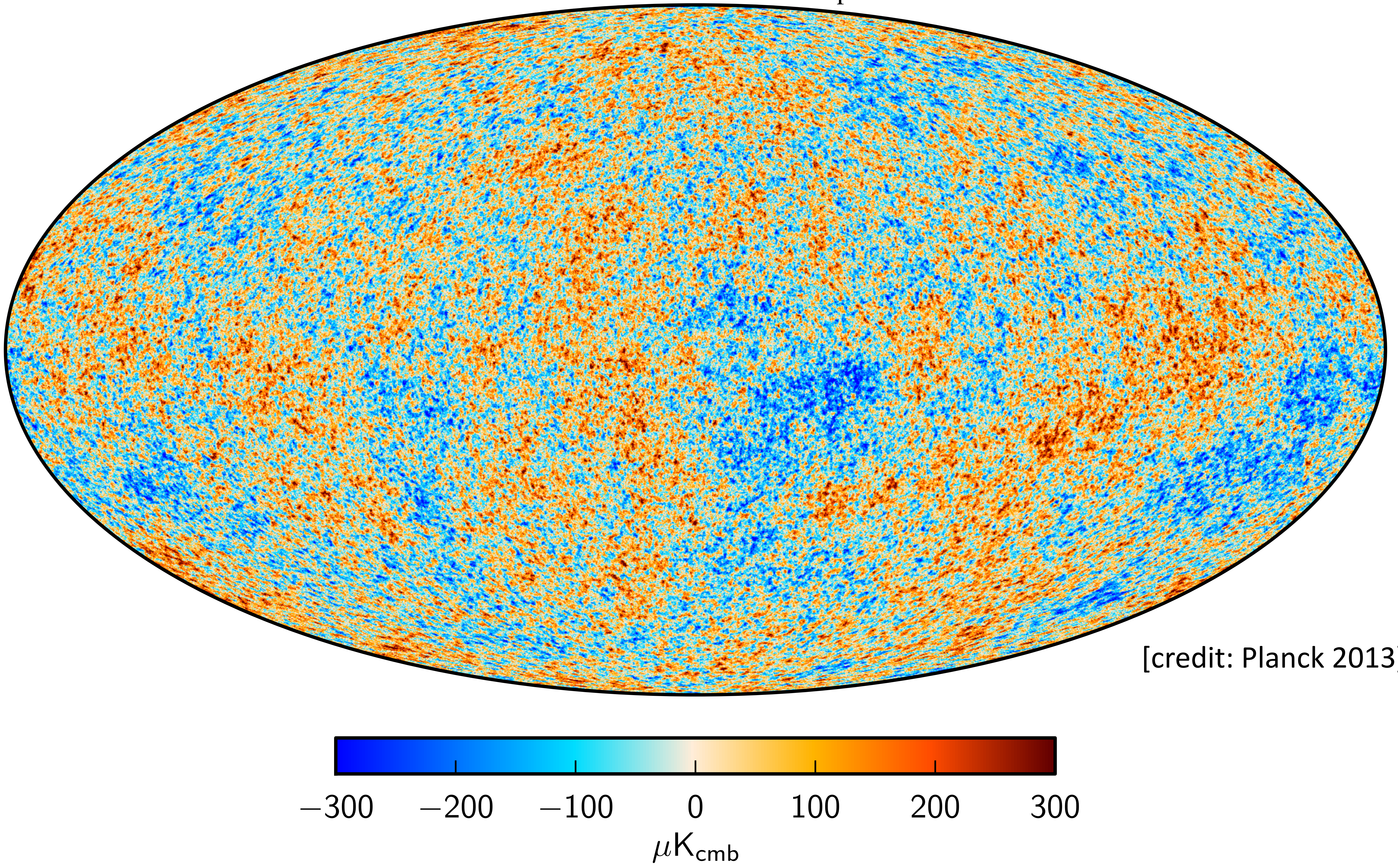
  - definition is detector dependent
- "Operational definition": a signal is stochastic if it is best searched for using a signal model described by statistical properties (as opposed to deterministic waveforms)

1. Why should we care?

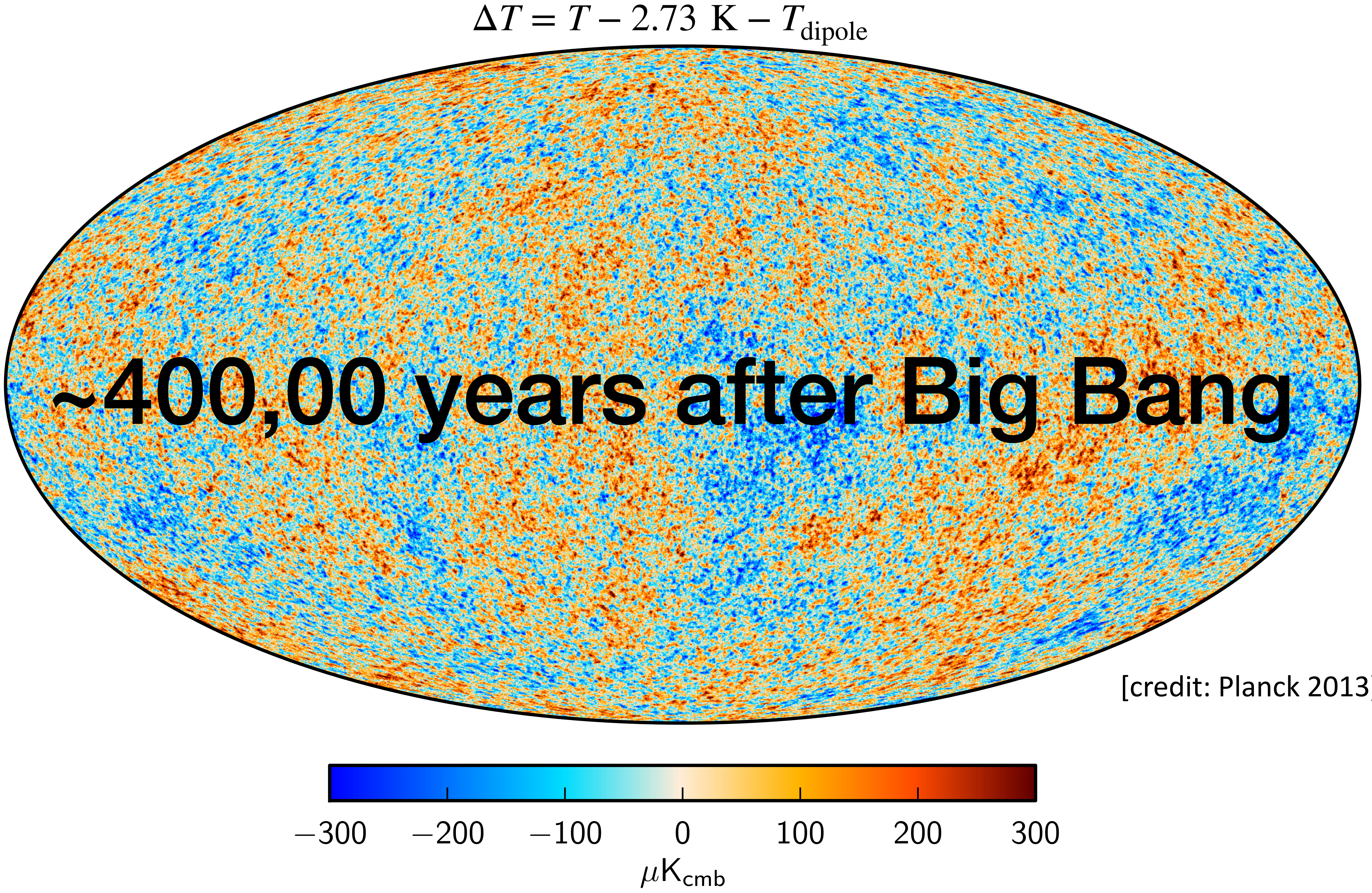
A stochastic background of EM radiation

$\Delta T = T - 2.73\ \mathrm{K} - T_{\mathrm{dipole}}$



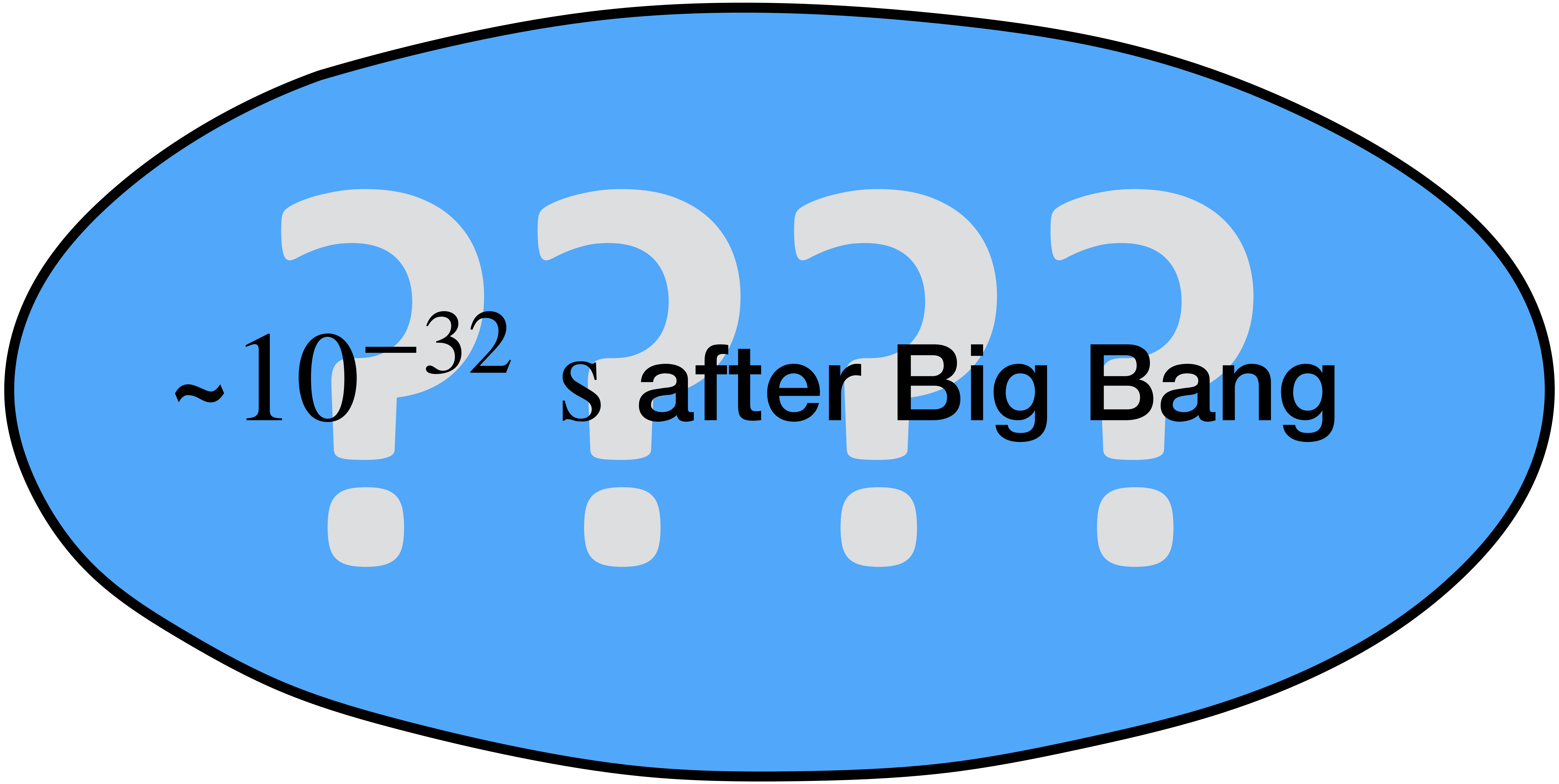
[credit: Planck 2013]

A stochastic background of EM radiation



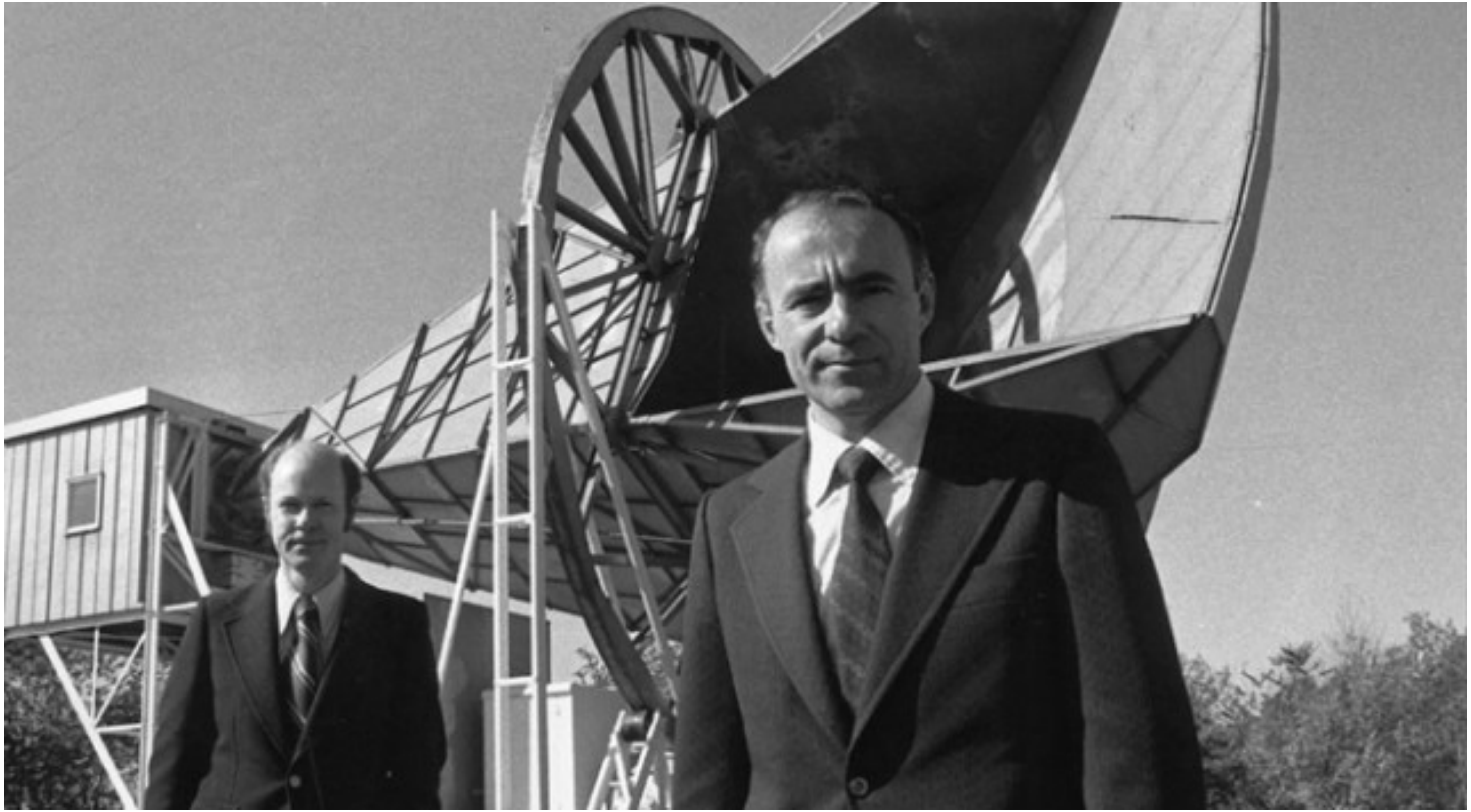
[credit: Planck 2013]

A stochastic background of GWs



weakness of gravity relative to other forces $\Longrightarrow$
see back much earlier into the history of the Universe

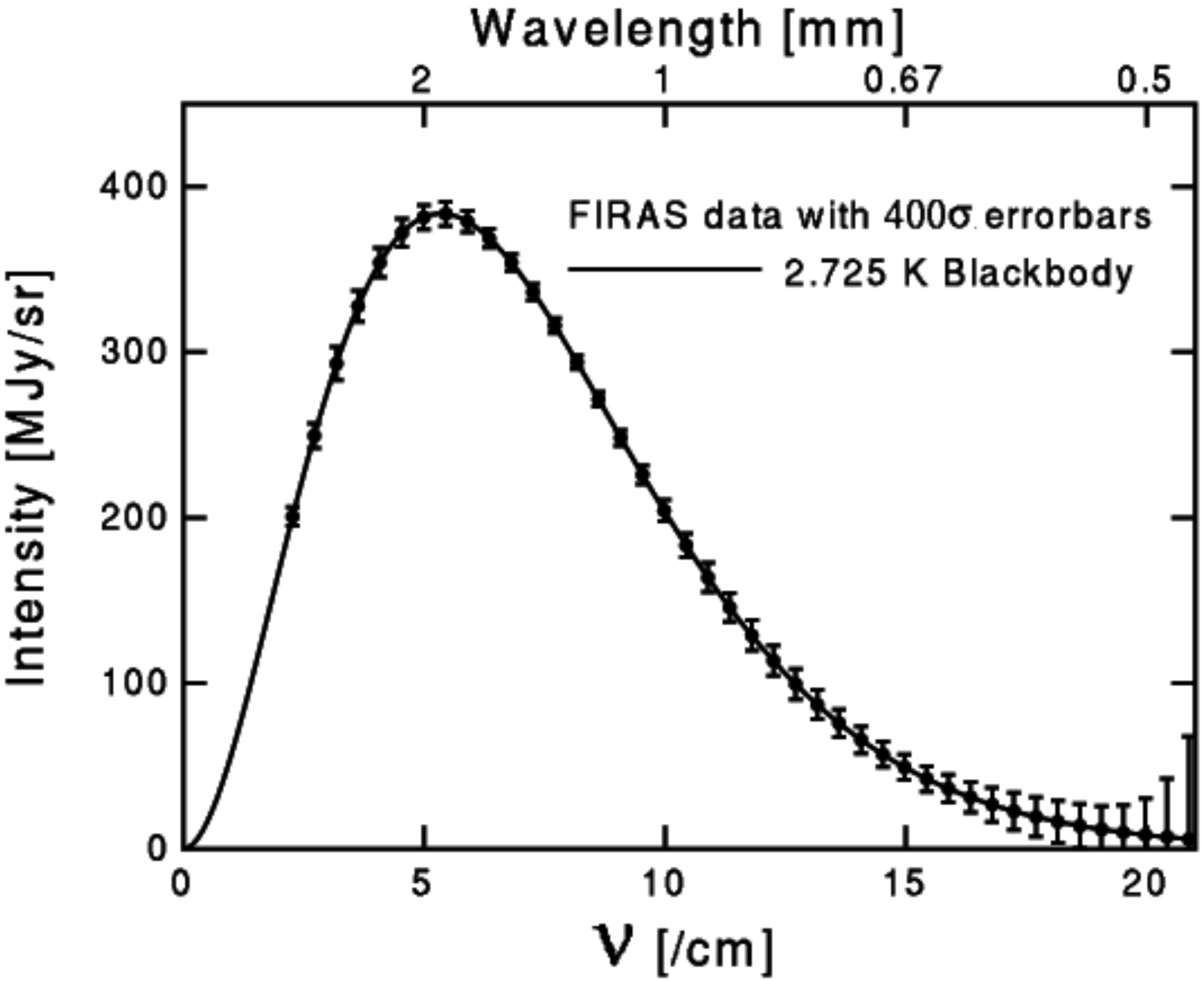
CMB detection - 1965 (Penzias and Wilson)



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.

COBE satellite - 1992



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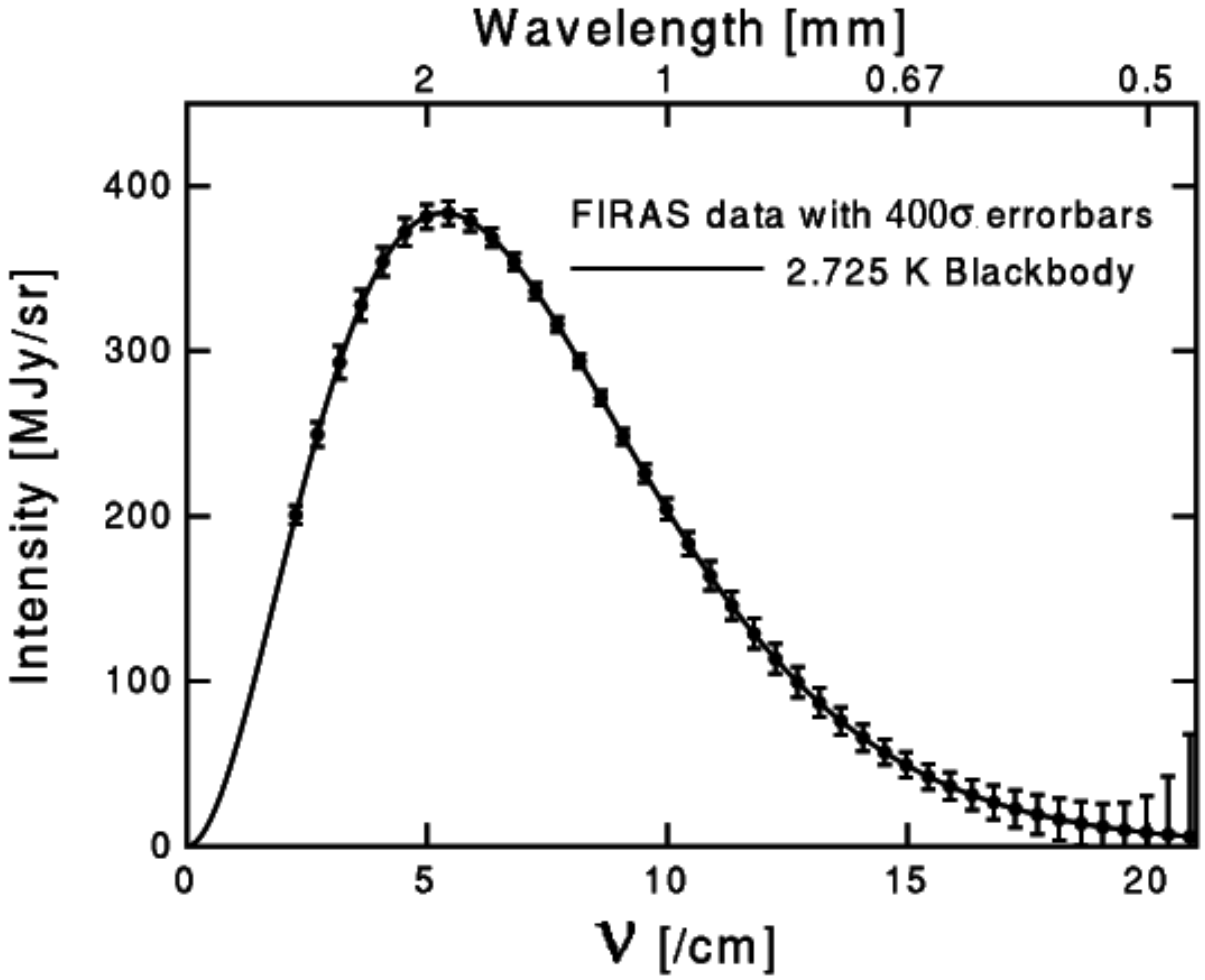
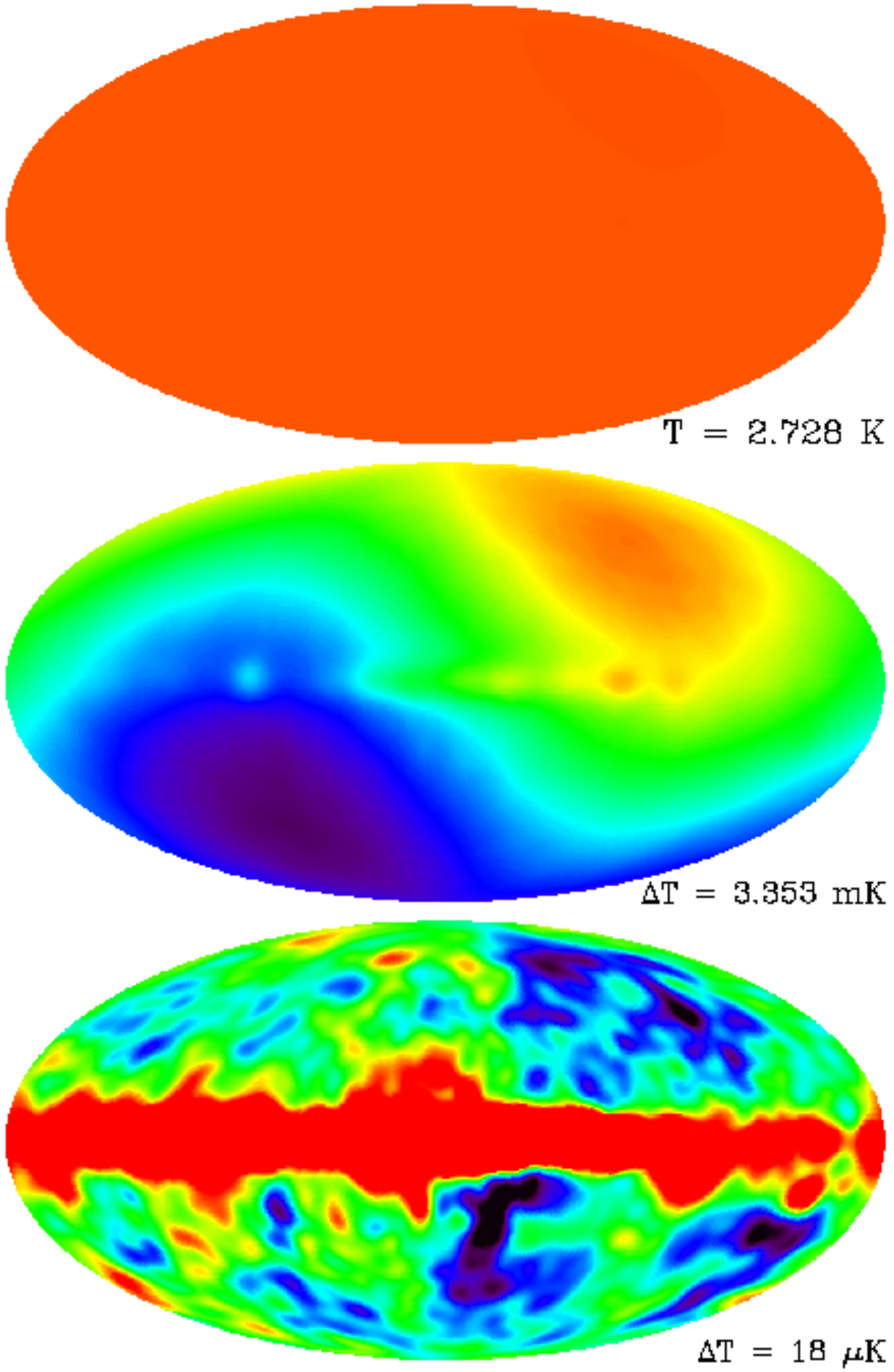
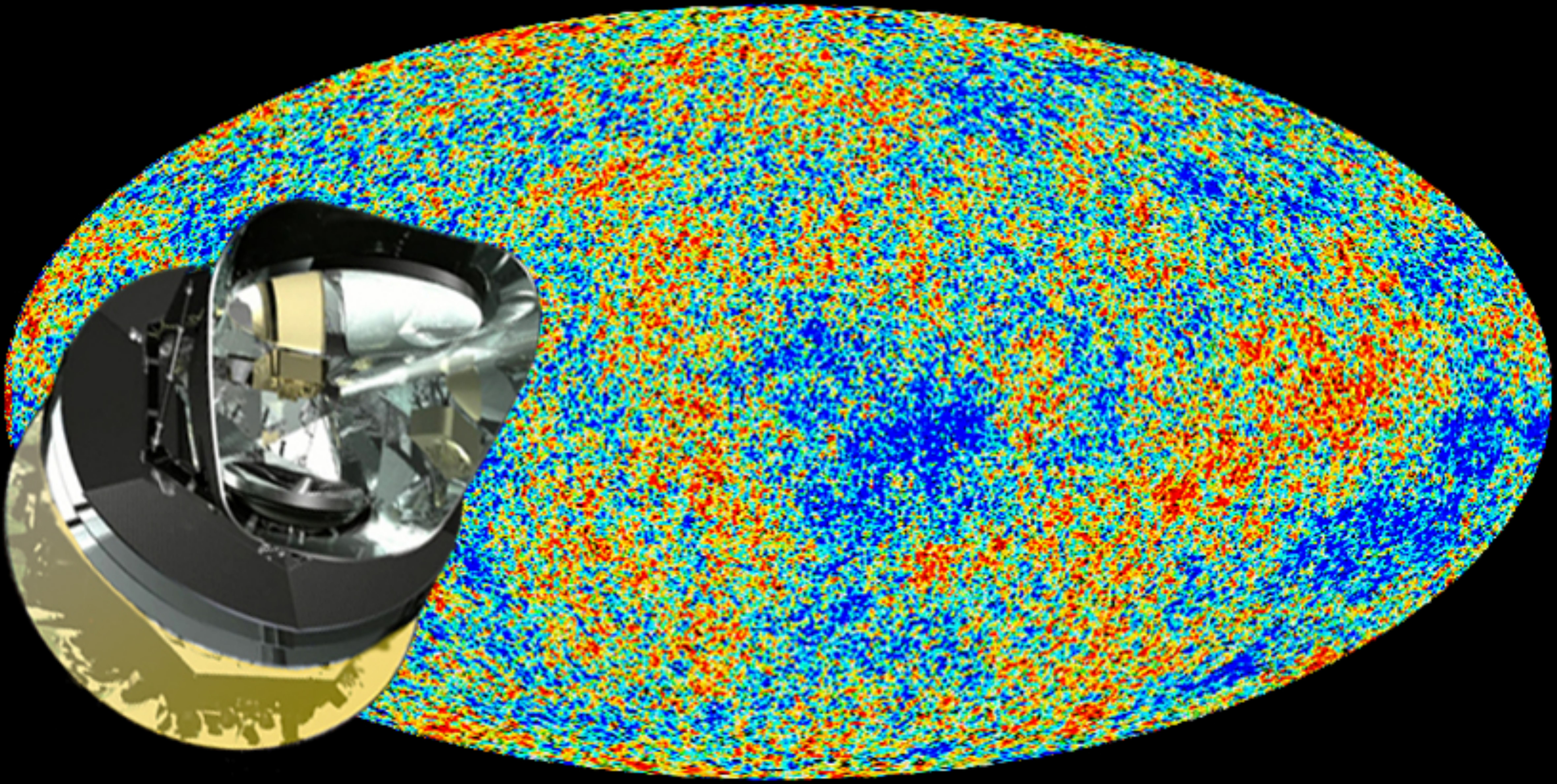




Planck - 2013



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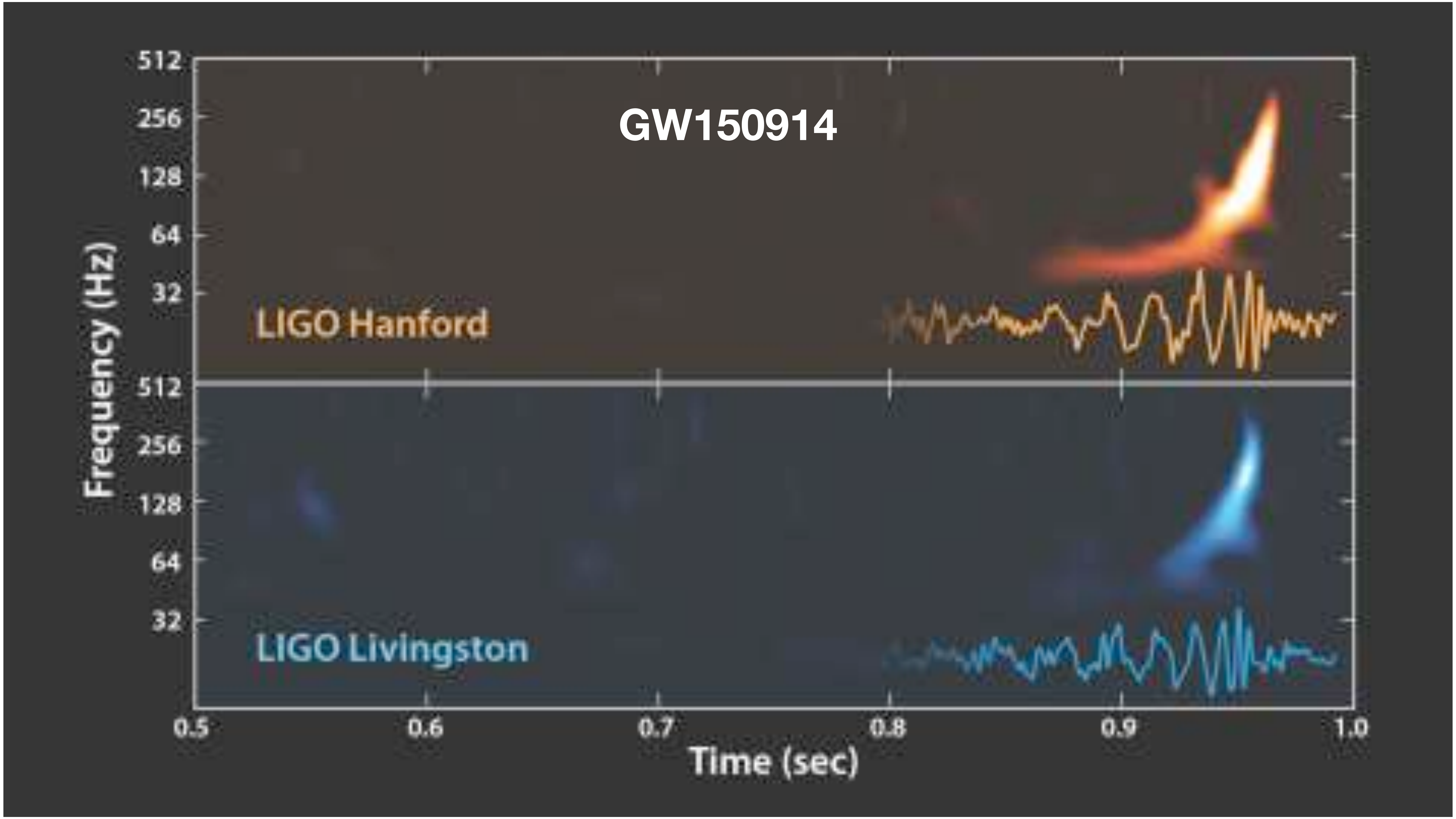
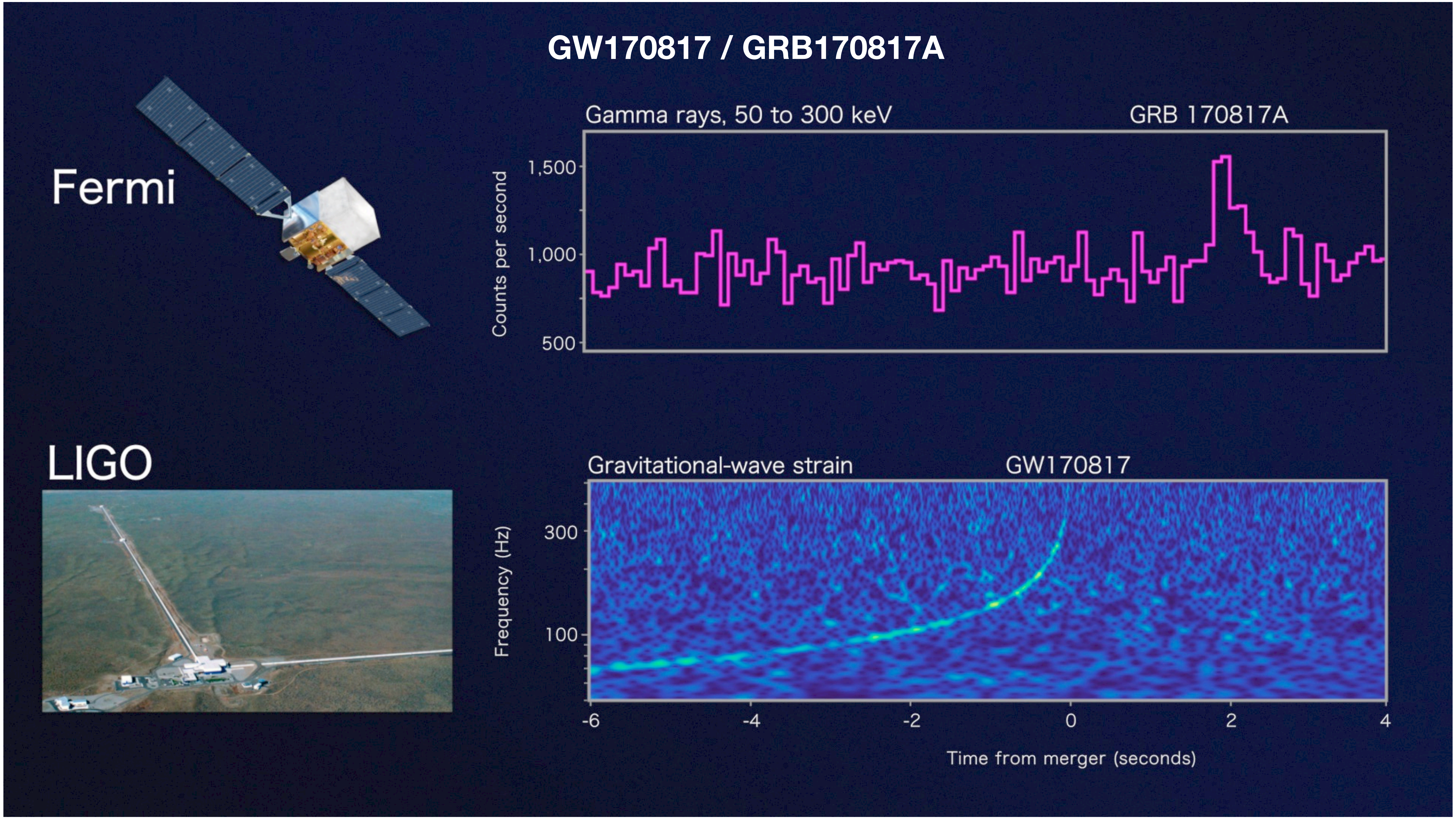
- we have not yet detected the isotropic component of the GWB!!

2. What sources / signals?

~100 BBH mergers

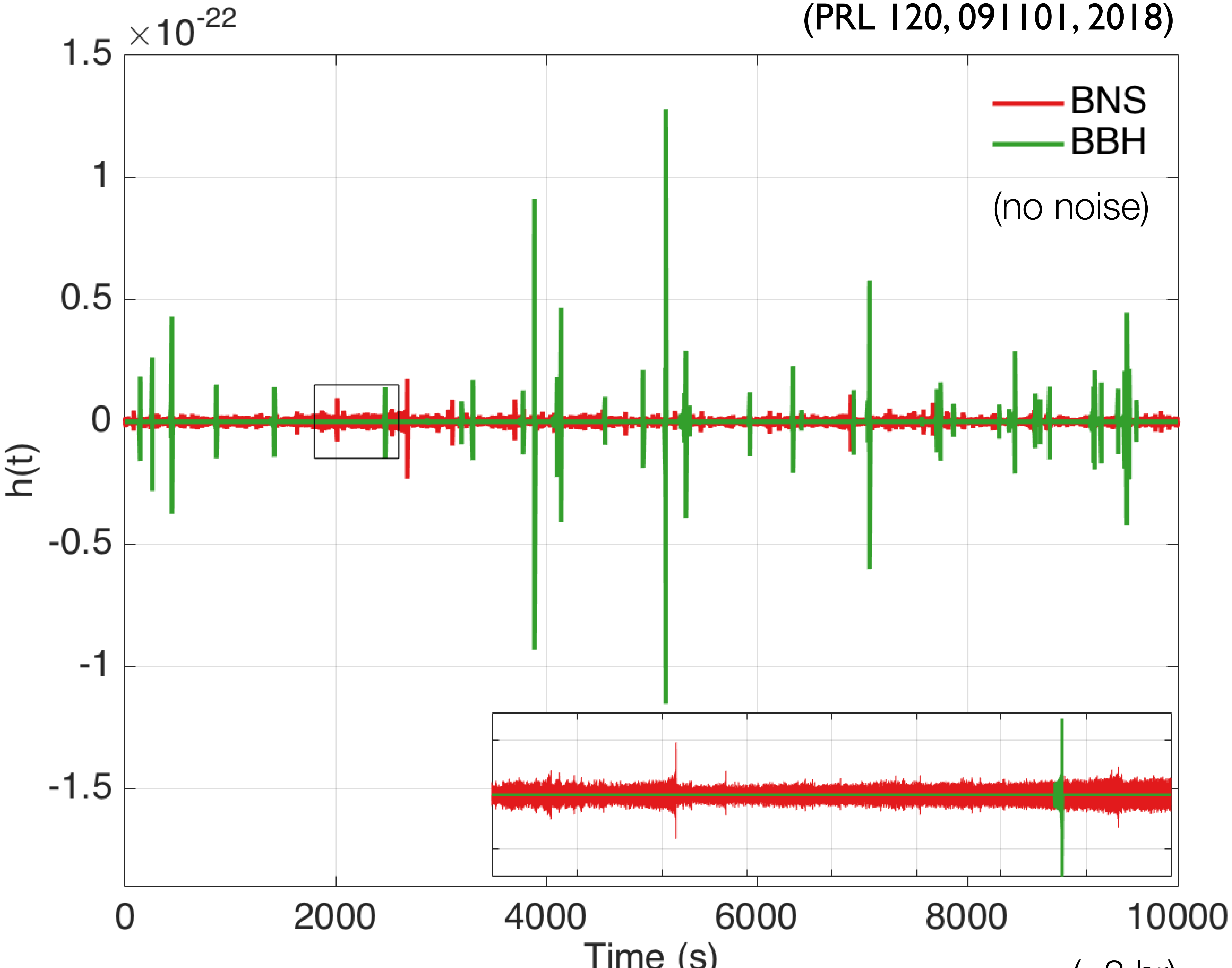


a couple of BNS mergers



Expect many more weaker signals

(PRL 120, 091101, 2018)



(~3 hr)

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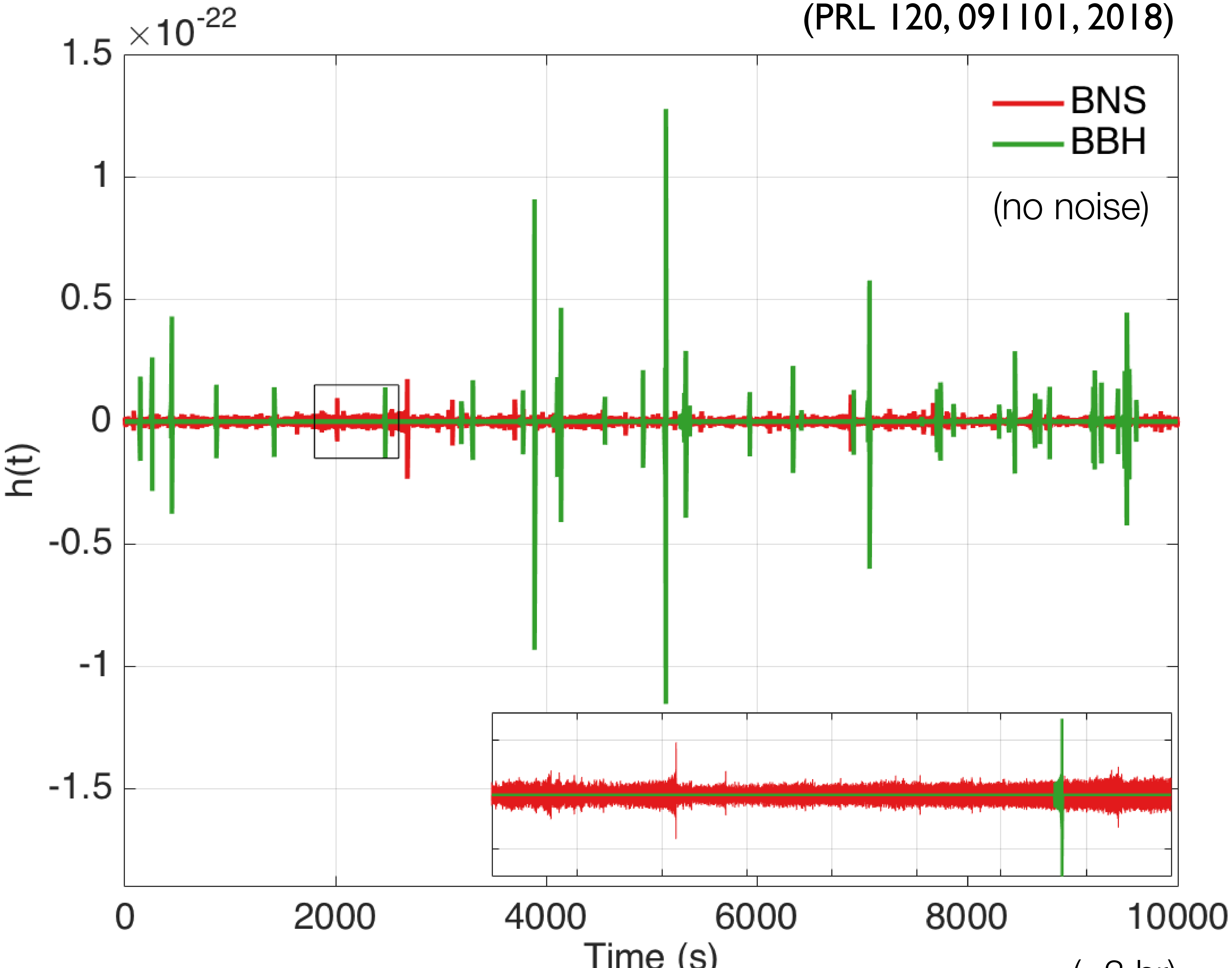
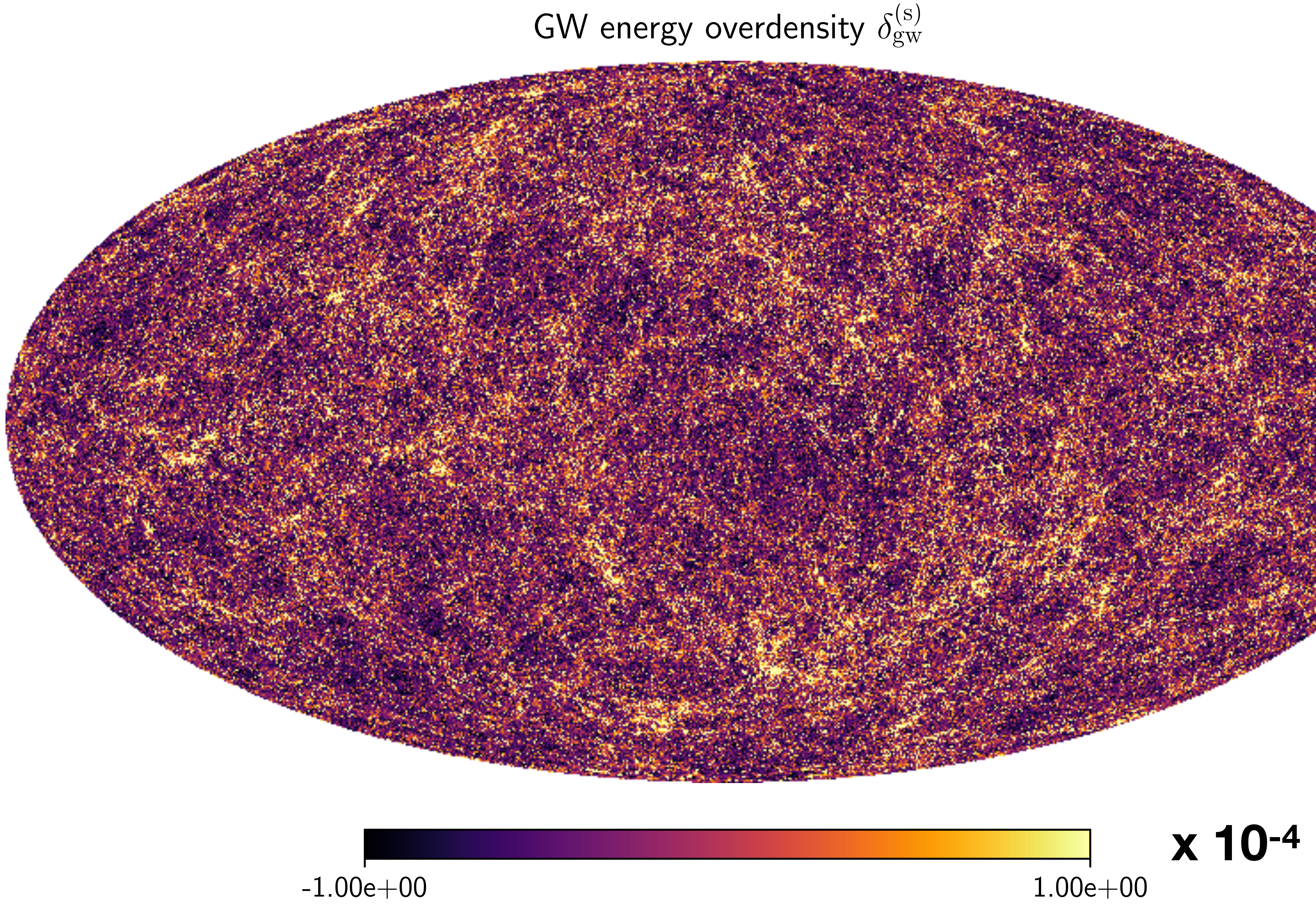


(~3 hr)

BBH background potentially detectable in O4 or O5 using searches that model intermittent nature of the signal!!

Vuk's talk

Predicted sky map for binary BH and/or NS mergers

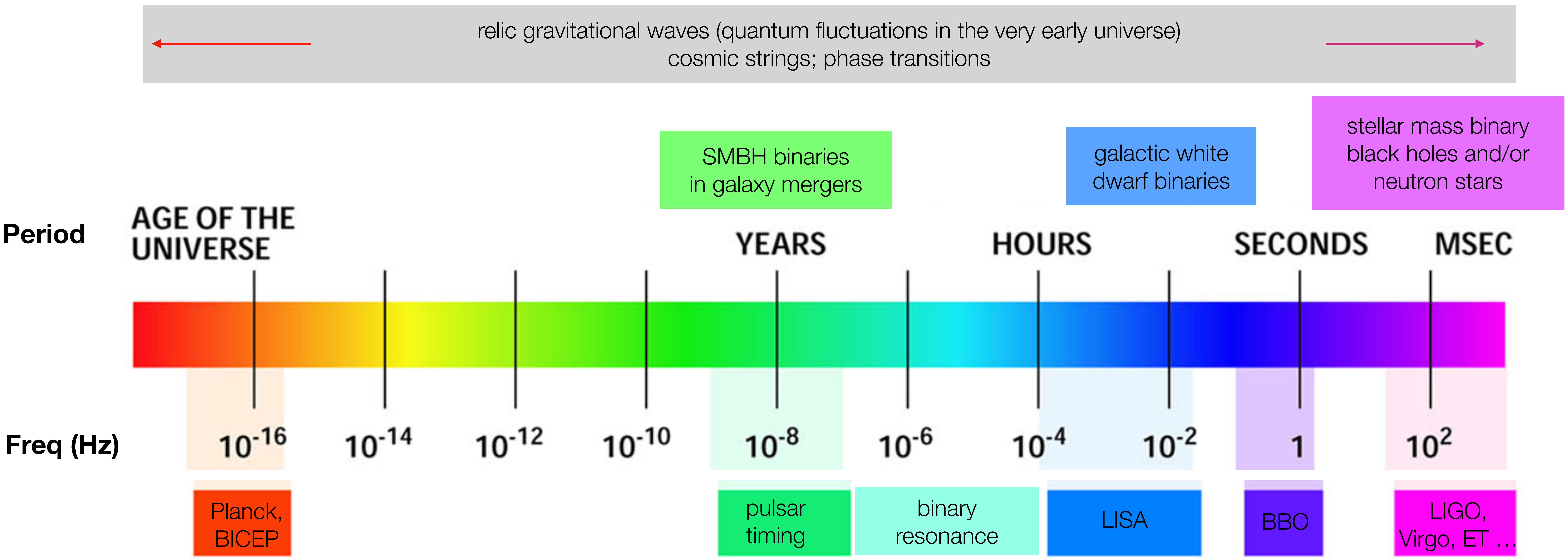


Giulia's talk

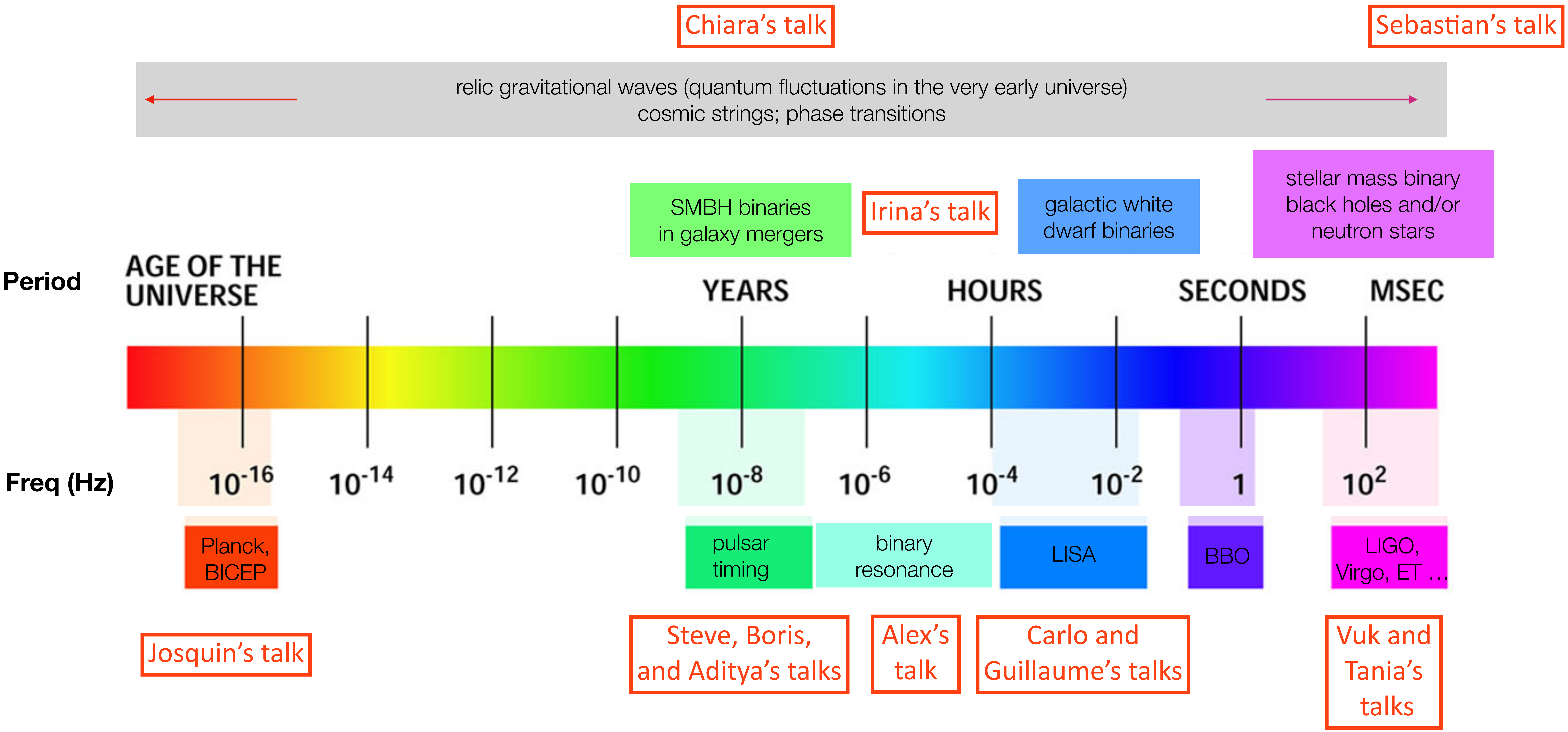
Sanjit's talk

[Jenkins et al., PRD98, 063501 (2018)]

Potential stochastic backgrounds across the GW spectrum



GWO-2022 talks across the GW spectrum!!



3. How to detect?

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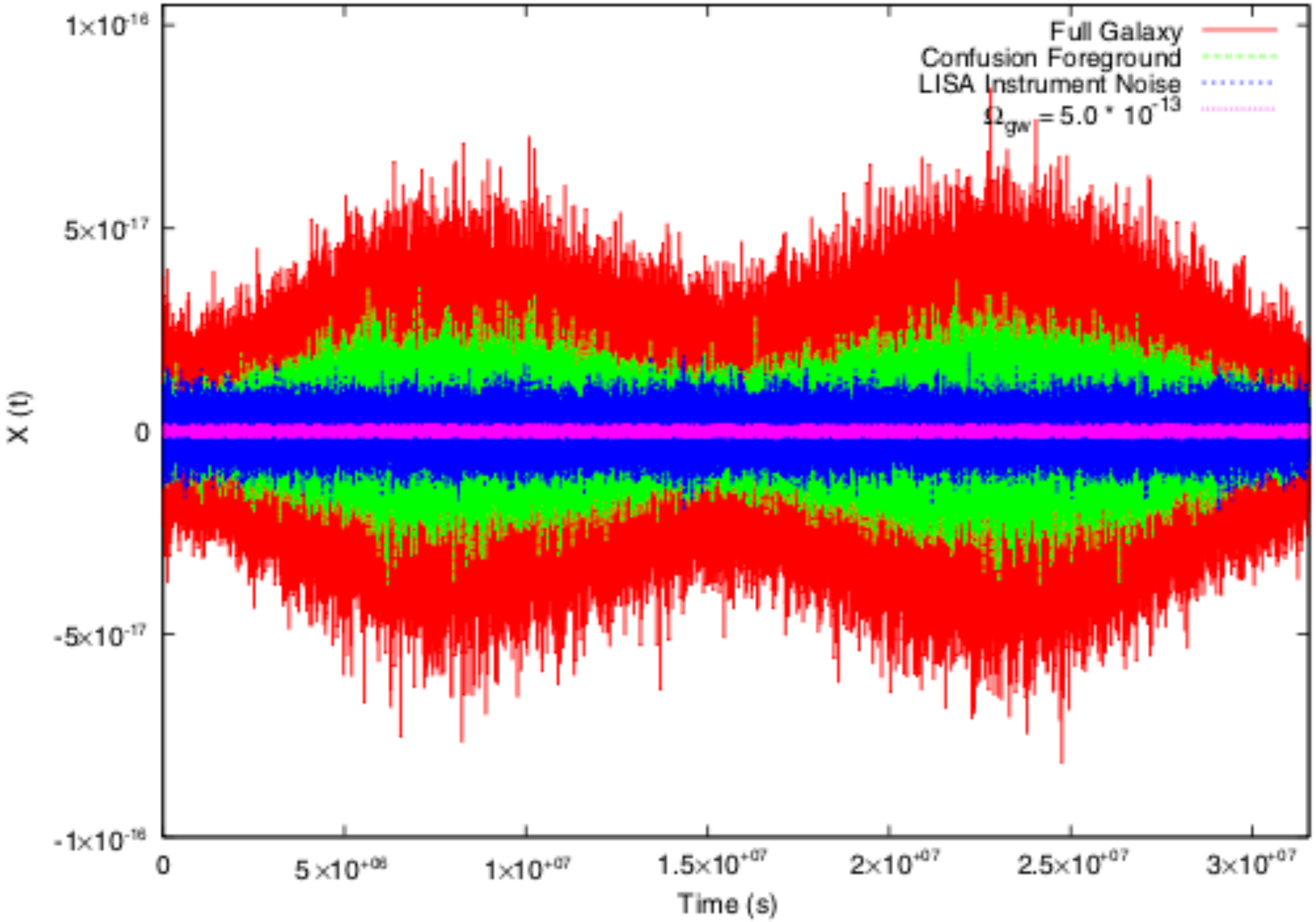
Kamiel's talk

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

LISA acts like a single detector for stochastic GWB searches

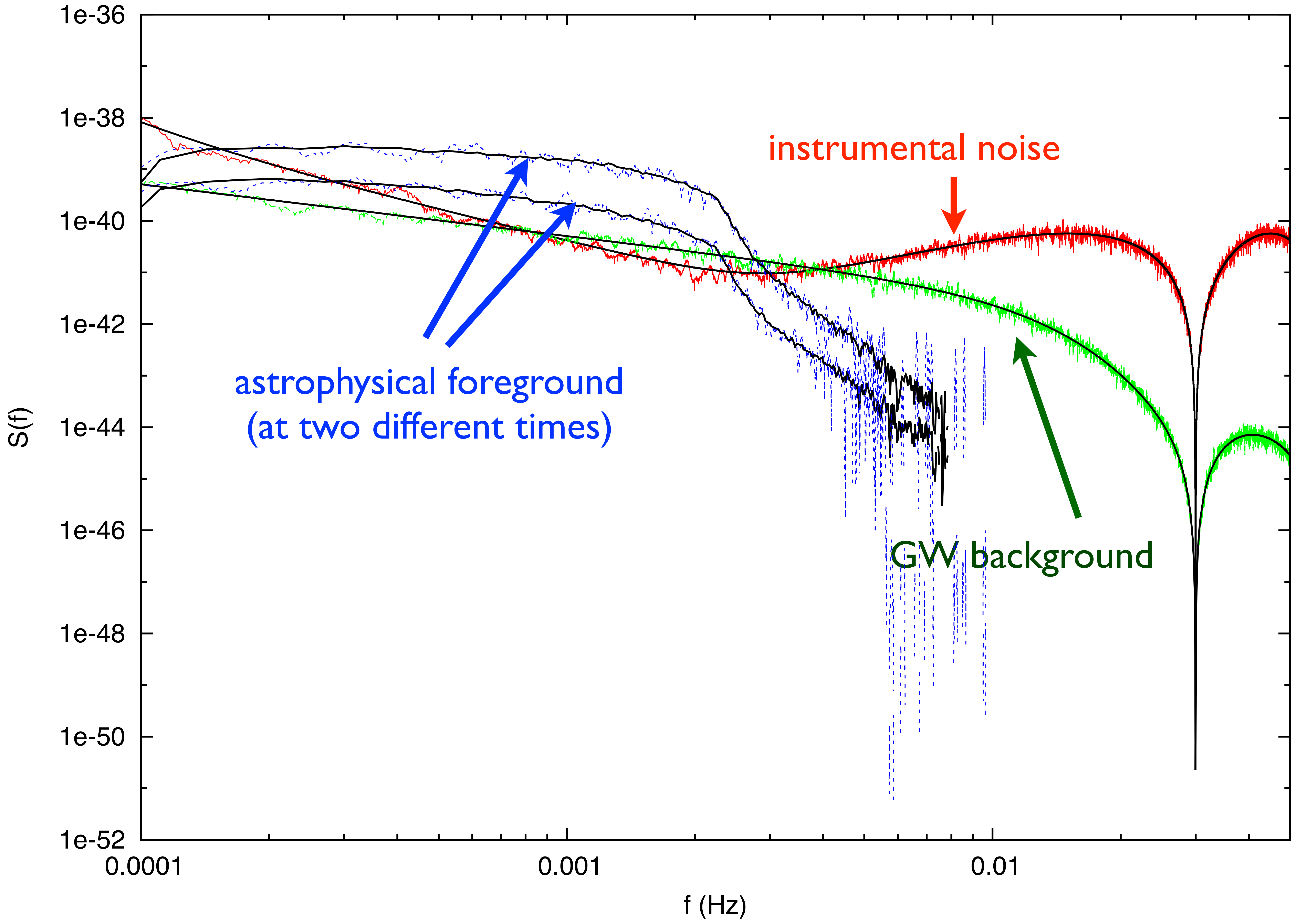
Carlo and Guillaume's talks

Temporal differences between the signals and noise



Guillaume’s talk

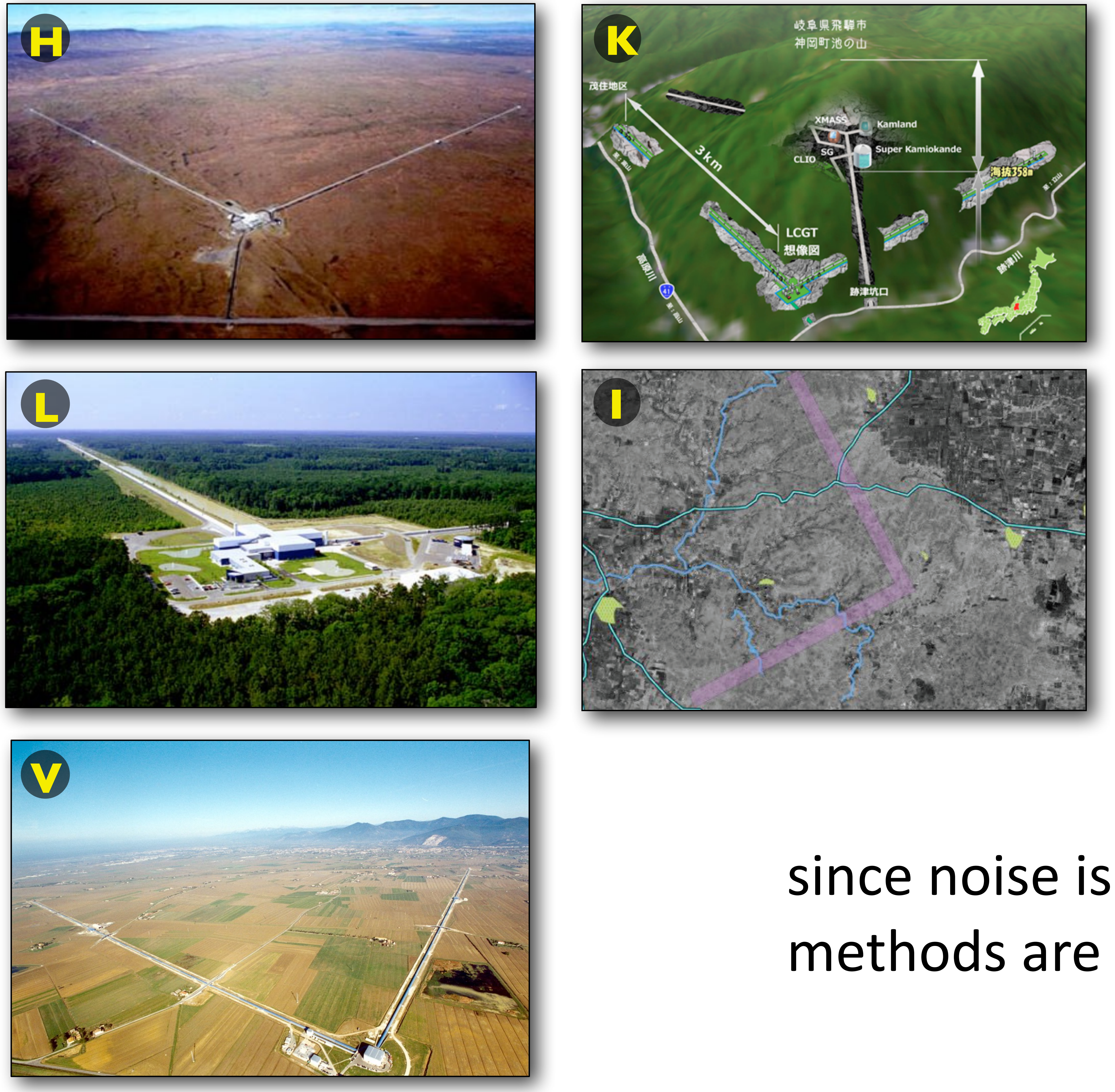
Spectral differences between the signals and noise



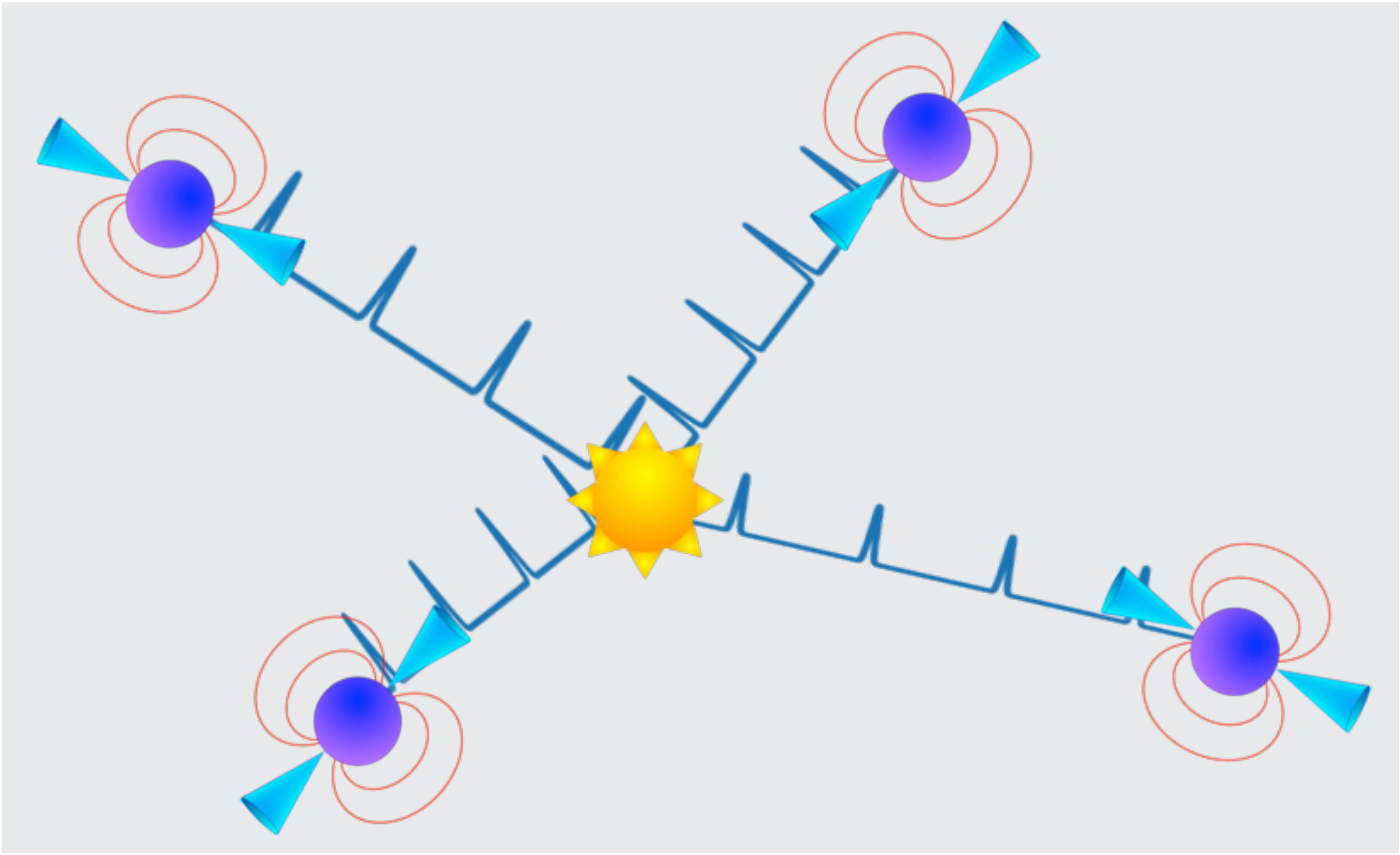
Guillaume's talk

Networks of multiple detectors

Ground-based detectors



Pulsar timing array



since noise is (mostly) uncorrelated, cross-correlation methods are possible for these searches

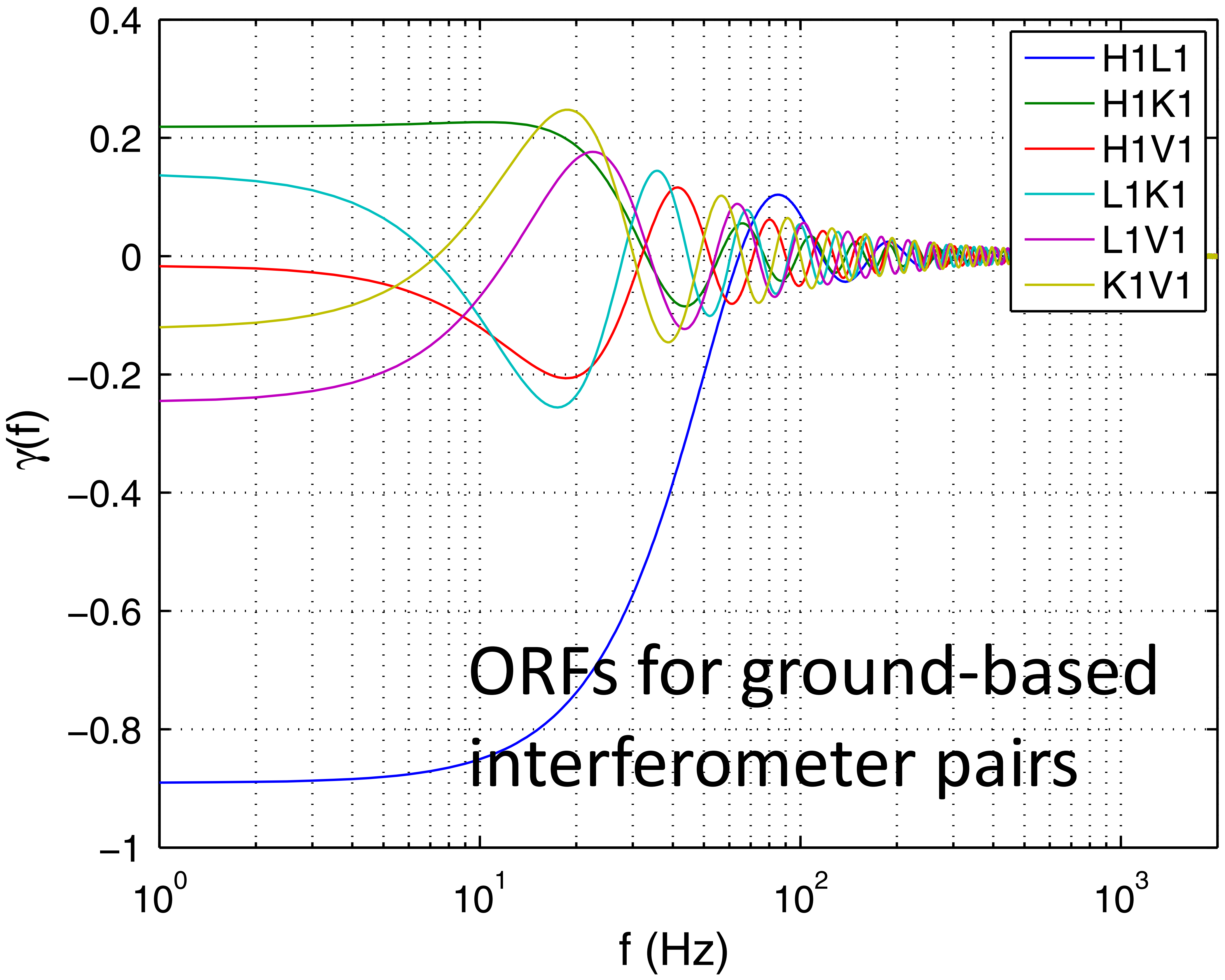
Overlap reduction functions

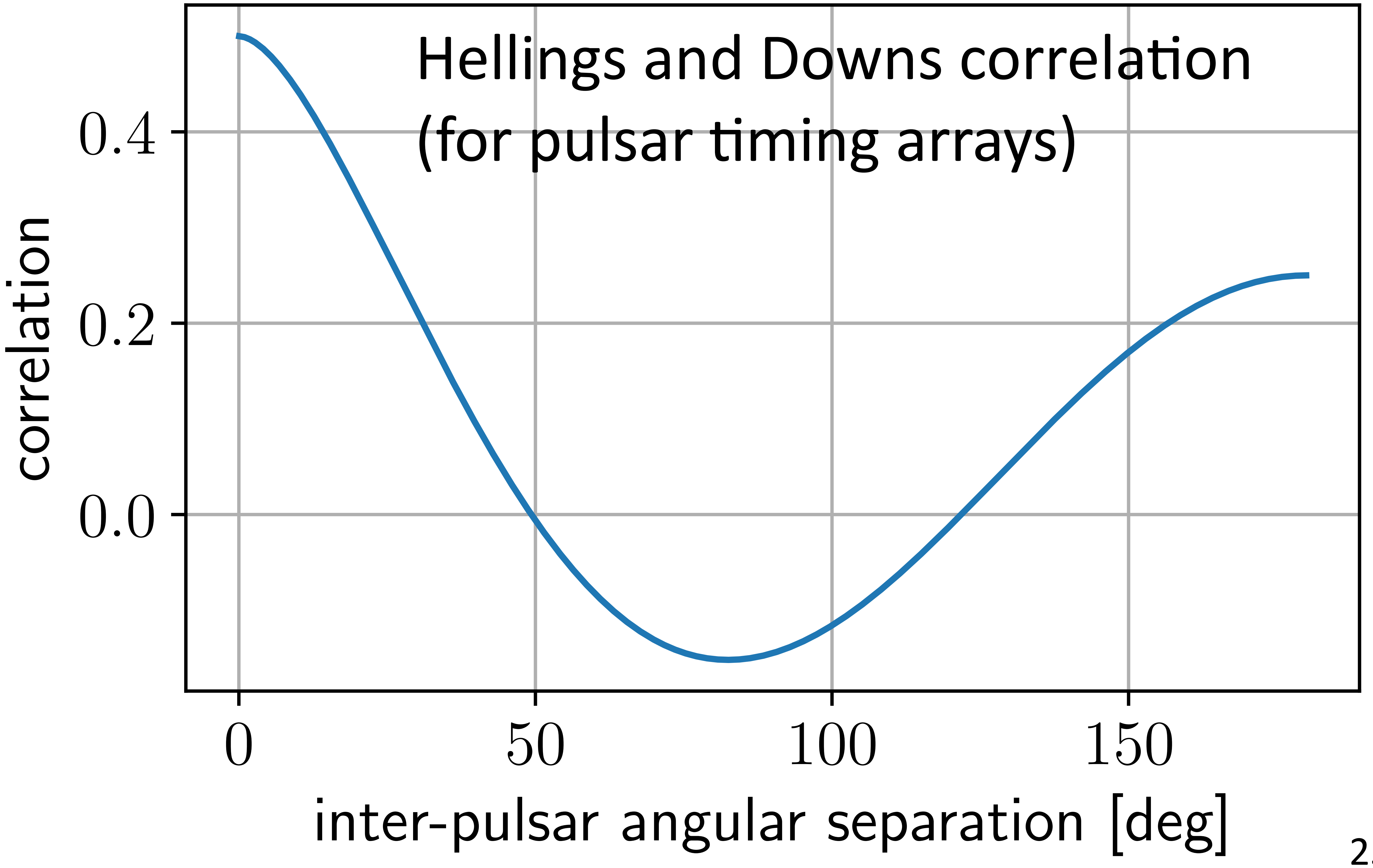
Quantifies the reduction in sensitivity due to physical separation and misalignment of a pair of detectors

$$C_{IJ}(f) = \gamma_{IJ}(f)\, P_{\rm gw}(f)$$

cross-correlated GWB power

auto-correlated power in GWB





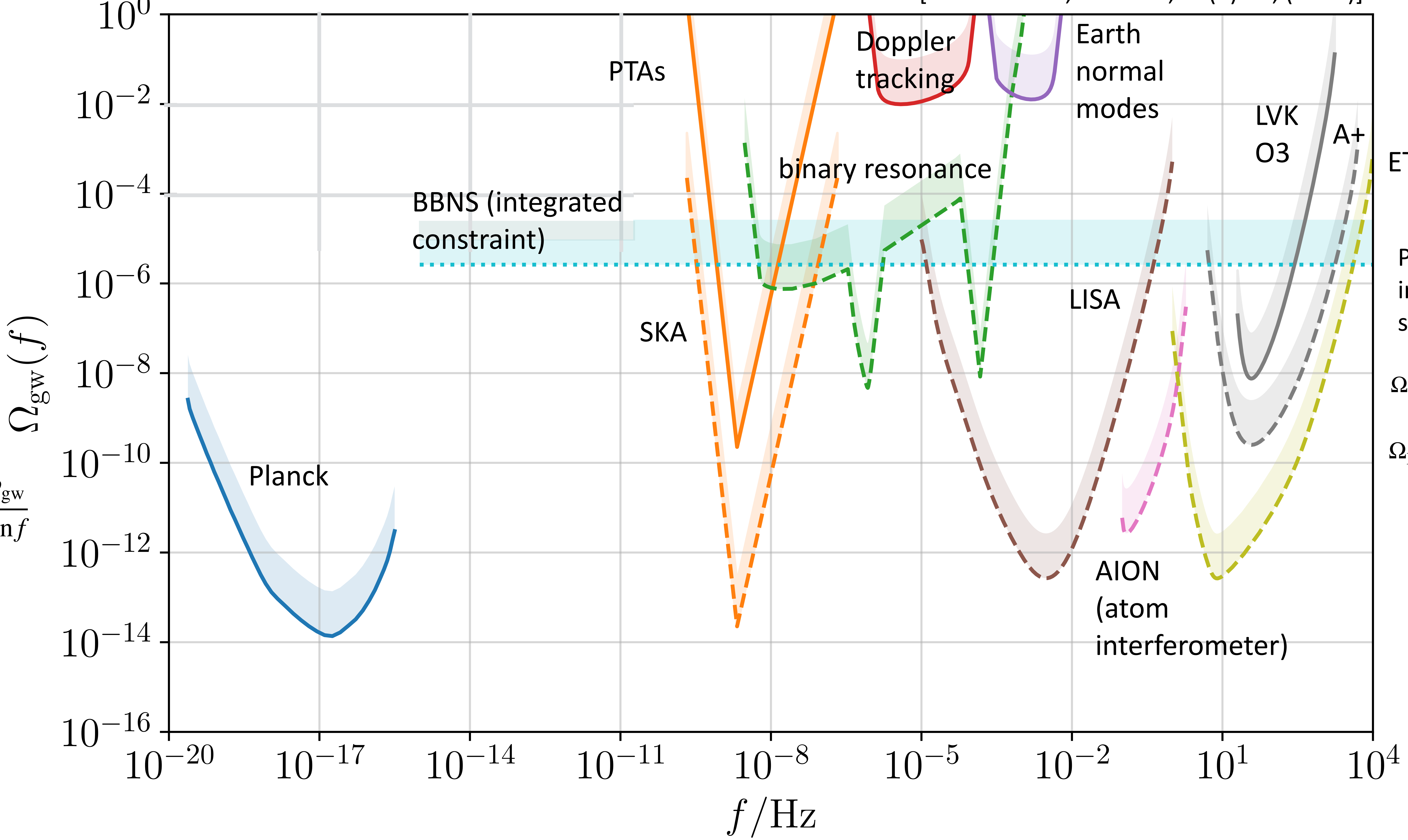
4. What are the current observational constraints?

Current and projected 95% upper limits

[Renzini et al., Galaxies, 10(1):34, (2022)]

Dimensionless energy-density spectrum

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

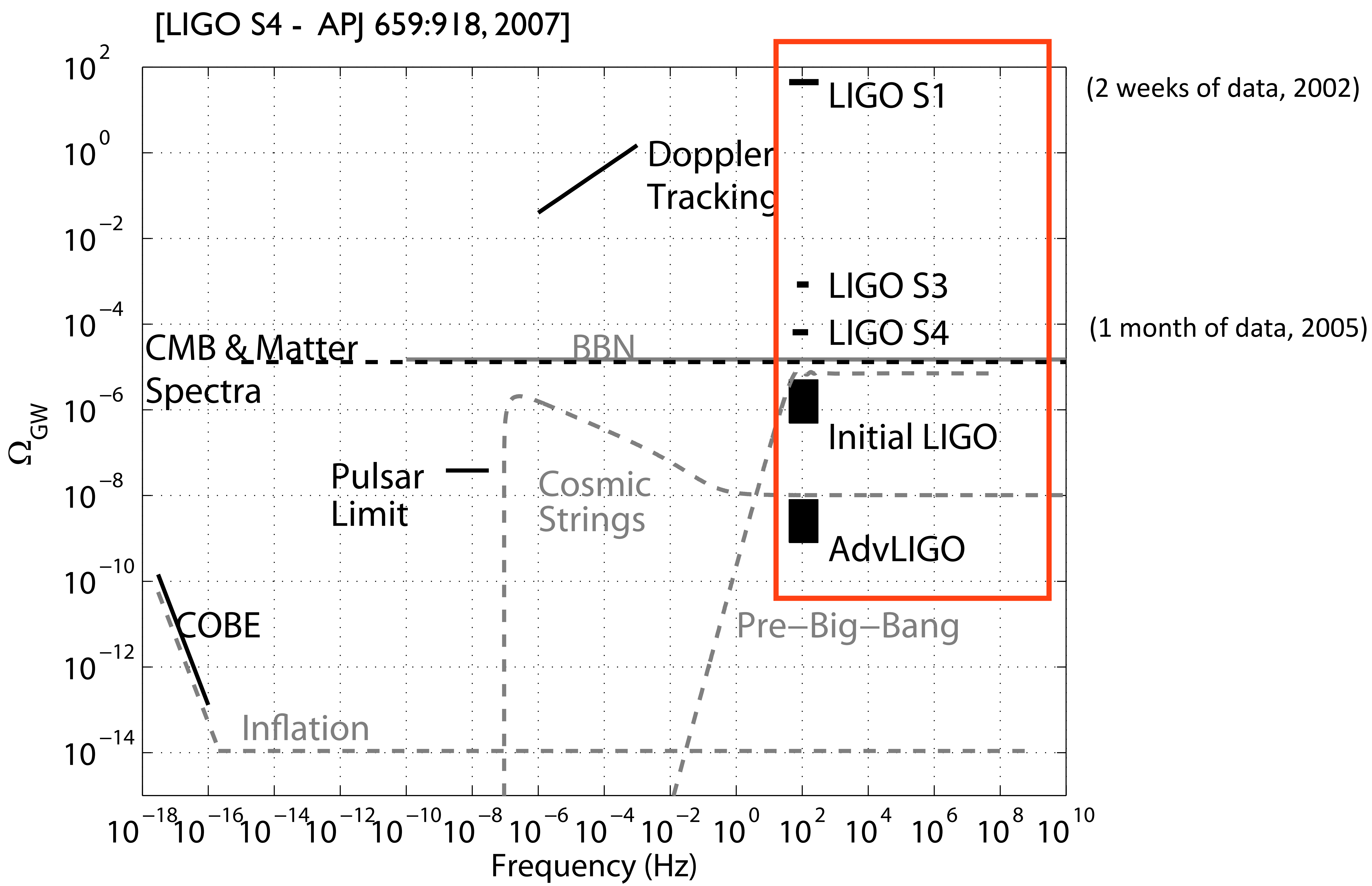


Power-law integrated sensitivity curves

$$\Omega_{\rm gw}(f) \equiv \Omega_\alpha \left(\frac{f}{f_{\rm ref}}\right)^\alpha$$

$$\Omega_{\rm PI}(f) \equiv \max_\alpha \Omega_{\rm gw}(f)$$

Improvement in ULs over the last ~20 yrs



A "hint" of a possible detection!!??

The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background

THE ASTROPHYSICAL JOURNAL LETTERS, 905:L34 (18pp), 2020 December 20

ABSTRACT

We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5-year pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars. Under our fiducial model, the Bayesian posterior of the amplitude for an $f^{-2/3}$ power-law spectrum, expressed as the characteristic GW strain, has median 1.92×10^{-15} and 5%–95% quantiles of 1.37–2.67×10^{-15} at a reference frequency of $f_{\rm yr} = 1\ {\rm yr}^{-1}$; the Bayes factor in favor of the common-spectrum process versus independent red-noise processes in each pulsar exceeds 10,000. However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with general relativity. We find that the process has neither monopolar nor dipolar correlations, which may arise from, for example, reference clock or solar system ephemeris systematics, respectively. The amplitude posterior has significant support above previously reported upper limits; we explain this in terms of the Bayesian priors assumed for intrinsic pulsar red noise. We examine potential implications for the supermassive black hole binary population under the hypothesis that the signal is indeed astrophysical in nature.

Steve and Boris's talk

On the Evidence for a Common-spectrum Process in the Search for the Nanohertz Gravitational-wave Background with the Parkes Pulsar Timing Array
THE ASTROPHYSICAL JOURNAL LETTERS, 917:L19 (8pp), 2021 August 20 (PPTA)

Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: inferences in the stochastic gravitational-wave background search (EPTA)
MNRAS **508,** 4970–4993 (2021)

The International Pulsar Timing Array second data release: Search for an isotropic Gravitational Wave Background
arXiv:2201.03980v1 [astro-ph.HE] 11 Jan 2022 (IPTA)

questions??

extra slides

Potential GWB signals and 95% ULs

[Renzini et al., Galaxies, 10(1):34, (2022)]

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

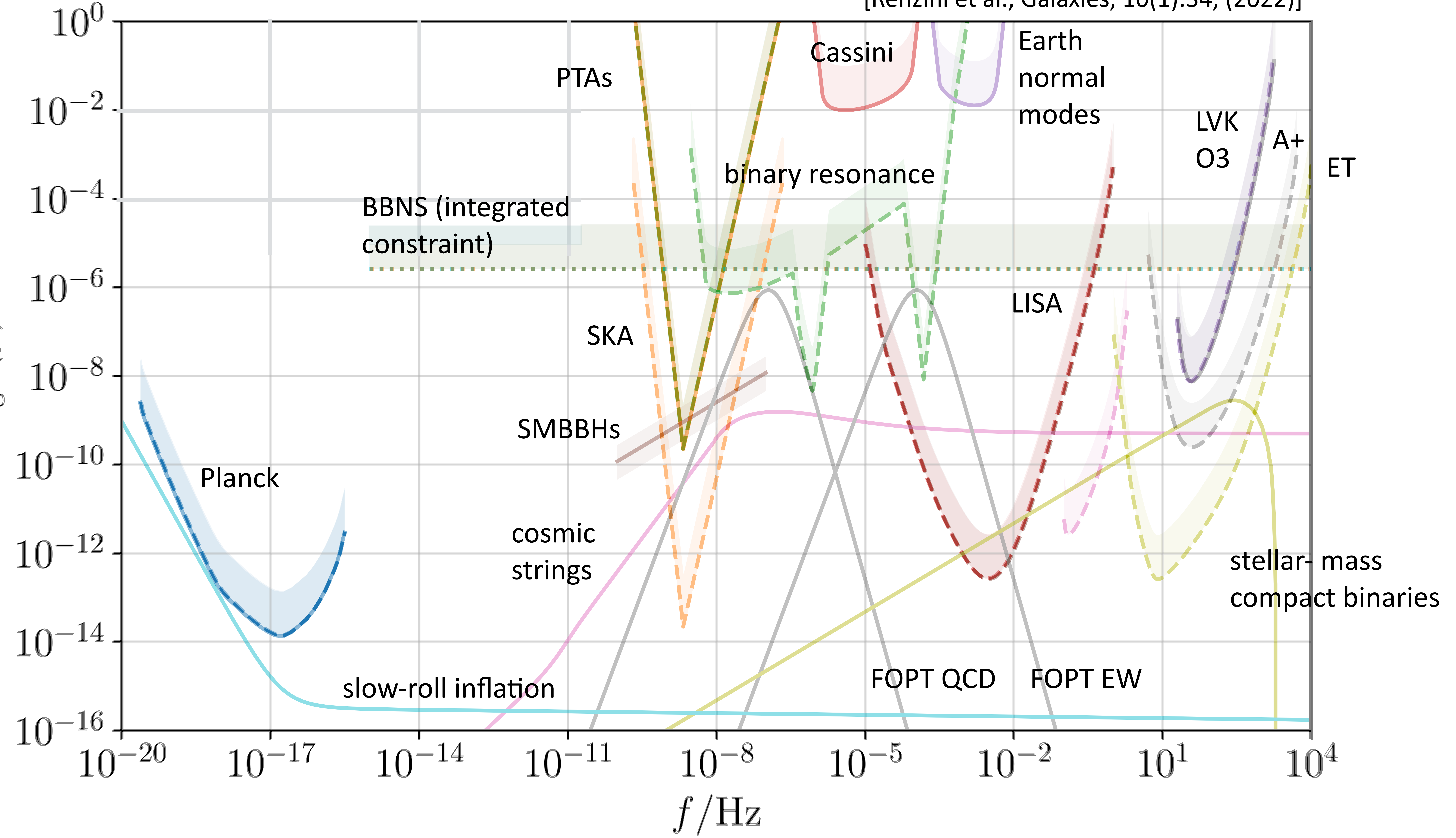


Figure 1. An overview of potential GWB signals across the frequency spectrum. The light blue curve shows the prediction for single-field slow-roll inflation with a canonical kinetic term, with tensor-to-scalar ratio $r_{0.002} = 0.1$ [52]. The pink curve shows a GWB from Nambu–Goto cosmic strings, using "model 2" of the loop network, with a dimensionless string tension of $G\mu = 10^{-11}$ [53]. The brown curve shows a GWB from inspiralling supermassive BBHs, with the amplitude and shaded region shown here corresponding to the common noise process in the NANOGrav 12.5-year data set [54]. The two grey curves show GWBs generated by first-order phase transitions at the electroweak scale (∼200 GeV) and the QCD scale (∼200 MeV), respectively [55]. The yellow curve shows a GWB generated by stellar-mass compact binaries, based on the mass distributions and local merger rates inferred by LVK detections [56]. The dashed curves show various observational constraints, as described further in Section 5 (this includes the PPTA constraint, which intersects the possible NANOGrav SMBBH signal); the dotted curve shows the integrated constraint from measurements of N_{eff}, which cannot be directly compared with the frequency-dependent constraint curves but is shown here for indicative purposes.

Figure 7. A survey of constraints (all at 95% confidence) on the GWB across the frequency spectrum. Solid curves indicate existing results from LIGO/Virgo's first three observing runs [56], monitoring of the Earth's normal modes [221], Doppler tracking of the Cassini satellite [222], pulsar timing observations by the PPTA [223], and CMB temperature and polarisation spectra measured by Planck [223,224]. Dashed curves are forecast constraints for LIGO at A+ sensitivity, Einstein Telescope [14], AION-km [225], LISA [29], binary resonance searches [226,227], and pulsar timing with the Square Kilometre Array [228]. The dotted curve indicates the level of the integrated constraint from measurements of N_{eff} [38]; note that this is a constraint on the total GW energy density over a broad frequency range and *cannot* be directly compared to the other constraints. Note also that both the Planck and N_{eff} constraints apply only to primordial GWs emitted before the epoch of BBN. See Figure 1 for various GWB signal predictions in relation to these constraints.