Searches for stochastic gravitational-wave backgrounds

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Abstract

These lecture notes provide a brief introduction to detection methods used to search for a stochastic background of gravitational radiation—a superposition of gravitational-wave signals either too weak or too numerous to individually detect. The lectures are divided into two main pieces: (i) an overview, consisting of a description of different types of gravitational-wave backgrounds and an introduction to the correlation method using multiple detectors; (ii) details, extending the previous discussion to non-trivial detector response, what to do in the absence of correlations, and a recently proposed Bayesian method to search for the gravitational-wave background produced by stellar-mass binary black hole mergers throughout the universe. Some suggested exercises for the reader are given throughout the text.

Contents

1 Motivation

A stochastic background of gravitational radiation is a superposition of gravitational-wave signals either too weak or too numerous to individually detect. The individual signals making up the background are thus *unresolvable*, unlike the large signal-to-noise binary black-hole (BBH) and binary neutron-star (BNS) merger signals recently detected by the advanced LIGO and Virgo detectors. But despite the fact that the individual signals are unresolvable, we shall see below that the detection of a stochastic gravitational-wave background (GWB) will be able to provide information about the statistical properties of the source.

1.1 Comparison with the CMB

The ultimate goal of gravitational-wave background searches is to produce the GW analogue of Figure **??**. Figure **??** is a sky map of the temperature fluctuations in the CMB blackbody radiation, relative to the $T_0 = 2.73$ K isotropic component. (The dipole contribution due to our motion with respect to the cosmic rest frame has also been subtracted out.) Recall that the CMB is a background of electromagnetic radiation, produced at the time of last scattering, roughly 380,000 yr after the Big Bang. At that time, the universe had a temperature of ~ 3000 K, roughly one thousand times larger than the temperature today, but cool enough for neutral hydrogen atoms to first form and photons to propagate freely. The temperature fluctuations in the CMB radiation tell us about the density of matter on the surface of last scattering and also about the integrated ...

For perspective, this map of the temperature fluctuations in the CMB was produced by the Planck mission in 2013, almost 50 years after its initial detection by Penzias and Wilson in 1965. It took many years and many more improved experiments (COBE, Boomerang, WMAP, Planck to name a few) to get to the high-precision measurements that we have now of the CMB. So its somewhat sobering to realize that right now, in 2018, we have not yet detected even the isotropic component of the GWB. So we have a long road ahead of us.

1.2 The background of BBH and BNS mergers in the LIGO band

But fortunately, as mentioned above, the advanced LIGO and Virgo detectors have detected other gravitational-wave signals from several individual BBH and BNS mergers. These were very strong signals, having matched-filter signal-to-noise ratios $\gtrsim 10$, and false alarm probabilities $< 2\times10^{-7}$—i.e., 5-sigma "gold-plated" events. Similar detections are expected in the upcoming observing run O3, which is scheduled to start in early 2019.

But we also expect many more signals, corresponding to more distant mergers or smaller mass systems, which are individually undetectable (i.e., *subthreshold* events). This weaker background of gravitational radiation is nonetheless detectable as a collectivity via the common influence of the gravitational waves on multiple detectors.

To get an idea of the statistical properties of this GWB, we note that the local rate estimate from these first detections of BBH mergers in the LIGO band (9-240 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$) lead to predictions of the total rate of such mergers throughout the universe to between ~ 1 per minute to a few per hour. (Exercise: 1: Verify the above values for the total rate.) Since the duration of BBH merger signals in band is ~ 1 s, the combined signal is highly-nonstationary (or *popcorn*-like).

One can do similar calculations for BNS mergers: The predicted total rate for such events is roughly one event every 15 s, while the duration of a BNS signal in band is roughly 100 s. Thus, the signals overlap leading to a continuous (or *confusion-limited*) background.

The combined signal from BBH and BNS mergers is potentially detectable with advanced LIGO and Virgo, shortly after reaching design sensitivity (3-σ, correspond to a 1/1000 false alarm probability).

This estimate of time to detection is based on the standard cross-correlation search, which assumes a Gaussian-stationary background.

But there is a better method, proposed by Smith and Thrane, which we will discuss at the end of these lectures.

2 Different types of stochastic backgrounds

Stochastic backgrounds can be of either astrophysical or cosmological origin:

(i) A potential astrophysical background for the current generation of ground-based interferometers is the combined signal from the population of stellar-mass BBH and BNS mergers throughout the universe. We will discuss the prospects of detecting this potential background throughout these lectures; the last section is devoted to a recently proposed detection method that targets this particular source.

(ii) A potential cosmological background is formed from *relic gravitational waves*—that is, quantum fluctuations in the geometry of space-time, driven to macroscopic scales by a period of rapid expansion (e.g., inflation) a mere $\sim 10^{-32}$ s after the Big Bang. This relic background is too weak to be detected by advanced LIGO, Virgo, etc., but is potentially detectable by its effect on the polarization of the cosmic microwave background (CMB) radiation. The Planck satellite and BICEP experiment (located at the South Pole) are searching for this signal.

3 Mathematical characterization of a stochastic background

4 Correlation methods - basic idea

5 Some simple examples

We now apply the above correlation method

6 Non-trivial detector response

7 Non-trivial correlations

8 What to do in the absence of correlations?

9 Searching for the background of binary black-hole mergers

References

A few references, which you might find helpful. *Disclaimer: This list is not in anyway complete, and there may be better references that you already know of.*

1. B. Allen - "The stochastic gravitational-wave background: sources and detection," from Les Houches School in Oct 1995
2. M. Maggiore - "Gravitational-wave experiments and early universe cosmology" (2000)
3. C. Caprini, D. Figueroa - "Cosmological backgrounds of gravitational waves" (2018)
4. T. Regimbau - "The astrophysical stochastic gravitational-wave backgrounds" (2011)
5. J. Romano, N. Cornish - "Detection methods for stochastic gravitational-wave backgrounds: a unified treatment" (2017)
6. R. Smith, E. Thrane - "Optimal search for an astrophysical gravitational-wave background" (2018)
7. Plus recent observational papers from LIGO, Virgo, pulsar timing arrays, etc., quoting upper limits on the strength of stochastic gravitational-wave backgrounds