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Synergies between earthbound and space gravitational wave detectors

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Abstract. The usual approach for the search of a stochastic background of gravitational waves relies on correlating data from different detectors that share common sensitivity bands. This method leverages the overlapping frequency ranges to enhance the signal-to-noise ratio and improve detection confidence. However, here an alternative approach will be explored: detecting and characterizing a stochastic background using a network of detectors with non-overlapping sensitivity bands, such as the Einstein Telescope (ET) and the Laser Interferometer Space Antenna (LISA). We will delve into the theoretical and practical conditions under which this method is viable, including the mathematical framework for cross-correlating data from detectors operating in different frequency ranges. The role of the non-Gaussianity of the stochastic background will be a focal point, as non-Gaussian features can provide additional information about the sources and the nature of the background. We will discuss how non-Gaussian statistics can be used to distinguish between different types of stochastic backgrounds, such as those arising from astrophysical sources like binary black hole mergers and those from cosmological sources like primordial gravitational waves.

Keywords: gravitational waves, stochastic background, data analysis, detection, Gaussian statistic

Introduction. Detecting a stochastic background of gravitational waves involves several sophisticated techniques and methodologies. The most common method used is cross-correlation statistic. It involves correlating the data from multiple detectors to enhance the signal-to-noise ratio. By comparing the signals from different detectors, it is possible to identify common patterns that indicate the presence of a stochastic background [1]. Both Bayesian and frequentist statistical methods are employed to analyze the data. Bayesian methods use prior probability distributions to update the likelihood of a signal being present, while frequentist methods rely on the frequency of observed data to make inferences [1].

Conventional methods for detecting a stochastic background of gravitational waves involve correlating data from multiple detectors that operate within overlapping sensitivity bands. This technique takes advantage of the shared frequency ranges to boost the signal-to-noise ratio, thereby enhancing the confidence in detection. In this presentation an innovative approach is introduced: detecting and characterizing a stochastic background using a network of detectors with non-overlapping sensitivity bands, such as the Einstein Telescope (ET) and the Laser Interferometer Space Antenna (LISA).

Methods and materials; results. Starting from [2, 3], where “importance sampling” is used to determine relevant statistical parameters, the theoretical and practical conditions necessary for a multiband detection method to be effective will be investigated. A mathematical framework for cross-correlating data from detectors that operate in different frequency ranges will be presented. A key aspect of this approach is the consideration of the non-Gaussianity of the stochastic background. Non-Gaussian features can reveal additional information about the sources and the nature of the background. We will discuss how non-Gaussian statistics can be employed to improve detection and parameter estimation, and to differentiate between various types of stochastic backgrounds, such as those originating from astrophysical sources like binary black hole mergers and those from cosmological sources like primordial gravitational waves. The case of an astrophysical stochastic background generated by a superposition of multi-band gravitational waves will be considered in detail. Multi-band gravitational waves refer to gravitational wave signals that can be detected across multiple frequency bands by different observatories. These waves originate from astrophysical sources, such as binary black hole mergers, neutron star collisions, and extreme mass-ratio inspirals.

The significance of multi-band gravitational wave astronomy [4, 5] in the case of a resolved source lies in its ability to track the evolution of compact binary systems over extended periods. For example, a binary black hole system first detected in the millihertz range by LISA could later be observed in the hertz range by LIGO/Virgo. This allows for more precise parameter estimation, better constraints on general relativity, and insights into black hole formation and population dynamics [6–8]. Multi-band observations also help test modifications to gravity theories, as deviations from general relativity might be more pronounced at different frequencies. As future detectors like the Einstein Telescope and Cosmic Explorer become operational, multi-band gravitational wave astronomy is expected to play a crucial role in advancing our understanding of the universe. It will be shown that these advantages can be generalized in the case of unresolved sources (stochastic background) in a way which depends on the level of non-Gaussianity.

Conclusion. The possibility of improving the detection and the characterization of a stochastic background of gravitational waves on a multi-band detector is connected to the non Gaussianity of the background. For a Gaussian stochastic background measurement on different bands are essentially statistically independent. When non-Gaussian contributions are present, it is possible to take advantage of them to extract relevant information from a multiband analysis. We think that conceptually the same approach could be used for multimessenger observations of backgrounds, but details still need to be investigated.

References

- [1] Romano J.D., Cornish N.J. Detection methods for stochastic gravitational-wave backgrounds: a unified treatment. *Living Rev Relativ*, 2017, vol. 20. <https://doi.org/10.1007/s41114-017-0004-1>

- [2] Buscicchio R., Ain A., Ballelli M., Cella G., Patricelli B. Detecting non-Gaussian gravitational wave backgrounds: A unified framework. *Physical Review D*, 2023, vol. 107 (6), art. no. 063027. <https://doi.org/10.1103/PhysRevD.107.063027>
- [3] Ballelli M., Buscicchio R., Patricelli B., Ain A., Cella G. Improved detection statistics for non-Gaussian gravitational wave stochastic backgrounds. *Physical Review D*, 2023, vol. 107 (12), art. no. 124044. <https://doi.org/10.1103/PhysRevD.107.124044>
- [4] Sesana A. The promise of multi-band gravitational wave astronomy. *Physical Review Letters*, 2016, vol. 116 (23), art. no. 231102. <https://doi.org/10.1103/PhysRevLett.116.231102>
- [5] Sesana A. Prospects for multiband gravitational-wave astronomy after GW150914. *Physical Review Letters*, 2016, vol. 116, art. no. 231102. <https://doi.org/10.1103/PhysRevLett.116.231102>
- [6] Grimm S., Harms J. Multiband gravitational-wave parameter estimation: A study of future detectors. *Physical Review D*, 2020, vol. 102, art. no. 022007. <https://doi.org/10.1103/PhysRevD.102.022007>
- [7] Vitale S. Multiband gravitational-wave astronomy: Parameter estimation and tests of general relativity with space-and ground-based detectors. *Physical Review Letters*, 2016, vol. 117, art. no. 051102. <https://doi.org/10.1103/PhysRevLett.117.051102>
- [8] Baker T. et al. Testing gravitational wave propagation with multiband detections. *Journal of Cosmology and Astroparticle Physics*, 2023, vol. 03, art. no. 044. <https://doi.org/10.1088/1475-7516/2023/03/044>
- [9] Carson Z., Yagi K. Multi-band gravitational wave tests of general relativity. *Classical and Quantum Gravity*, 2019, vol. 36 (21), art. no. 215007. <https://doi.org/10.1088/1361-6382/ab5c9a>
- [10] Gupta A. et al. Multiparameter tests of general relativity using multiband gravitational-wave observations. *Physical Review Letters*, 2020, vol. 125, art. no. 201101. <https://doi.org/10.1103/PhysRevLett.125.201101>
- [11] Colpi M., Sesana A. Gravitational wave sources in the era of multi-band gravitational wave astronomy. *Astrophysics and Space Science Library*. Springer, 2017. https://doi.org/10.1142/9789813141766_0002
- [12] Gerosa D. et al. Multiband gravitational-wave event rates and stellar physics. *Physical Review D*, 2019, vol. 99, art. no. 103004. <https://doi.org/10.1103/PhysRevD.99.103004>
- [13] Isoyama S., Nakano H. Observing binary inspirals with a decihertz detector, B-DECIGO. *Progress of Theoretical and Experimental Physics*, 2018, vol. 7, art. no. 073E01. <https://doi.org/10.1093/ptep/pty063>
- [14] Ng K.K.Y. et al. Multiband gravitational-wave searches for ultralight bosons. *Physical Review D*, (2020), vol. 102, art. no. 083020. <https://doi.org/10.1103/PhysRevD.102.083020>