Nuclear Instruments and Methods in Physics Research A 1068 (2024) 169721

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Search for gravitational waves using a network of RF cavities

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ARTICLE INFO

Keywords:
GravNet
Axion
Gravitational wave
GW
Primordial black hole
PBH
Cavity
Haloscope

ABSTRACT

The concept of detecting gravitational waves using RF-cavities in strong magnetic fields has gained considerable interest, using setups currently running axion searches. We propose a novel analysis approach for detecting GHz-regime gravitational waves, potentially from primordial black hole mergers, through synchronous measurements from multiple, distant cavities. While individual cavities may detect gravitational wave signatures, isolating them from noise is challenging since the strain (and thereby power deposition in a cavity) of such mergers is expected to be very small and short-lived. By correlating signals from several geographically separated cavities, we can significantly improve the signal-to-noise ratio and potentially investigate the sources of these waves. A demonstration experiment with a superconducting cavity is currently underway, forming the basis for our data analysis methods and outlining the prospects for the GravNet project. This project should be seen as an effort to bring the axion community together and collaborate in the context of gravitational wave physics.

1. Motivation

In 2015, the observation of gravitational waves (GW) by LIGO and Virgo marked a huge breakthrough in fundamental physics. While the frequencies detectable by large interferometers are limited to the kHz range, there are potential GW sources that could emit at much higher frequencies. These include primordial black hole (PBH) mergers, superradiance of boson clouds such as axion in the presence of black holes, or even a stochastic GW background analogous to the cosmic microwave background (CMB). These sources are expected to produce GWs in the GHz regime, a frequency range that is actively monitored by axion and dark photon haloscope experiments using radio frequency (RF) cavities. These haloscopes can be used in a slightly altered readout and analysis mode to search for PBH merger signals. By combining the time- and phase-aligned data from several experimental setups, a much higher sensitivity can be achieved compared to what could be reached with a single setup.

2. Using axion halocopes as HFGW detctors

RF-cavity based haloscopes, typically used to search for halo dark matter such as axions, enhance the axion signal through the cavity resonance. Axions can convert into photons by interacting with an external magnetic field, measurable as power access at the frequency corresponding to the axion mass. These haloscopes can also be repurposed to search for High Frequency Gravitational Wave signatures from PBH mergers. Some axion haloscope experiments already recast their axion limits into GW strain limits, but a common oversight is the limitation on integration time. Signals from PBH mergers are often fractions of a second long, so using several minutes or hours of integrated data is not appropriate. Therefore, when recasting limits, it is crucial to consider the signal coherence time during the analysis of integrated data in the frequency domain, as is customary in axion searches.

The nature and orientation of the excited cavity eigenmode differ for axions and GW signals from PBH mergers. For axions, the mode is a dipole and always aligned with the axis of the external magnetic field, while for GW signals, the ideal mode is a quadrupole, oriented along the propagation direction of the GW and therefore not having a preferred axis [1]. Axions convert into photons via the Primakoff effect, whereas GW signals convert via the inverse Gertsenshtein effect; both mechanisms involve interaction with an external magnetic field. This is practical, as it utilizes the magnets already inherent to axion haloscope experiments. For both types of signals, the signal strength is proportional to the cavity quality factor (Q_0) and the square of the external magnetic field (B_{ext}). However, the signal duration differs significantly, as mentioned above. Axions produce a coherent signal at a constant frequency corresponding to the axion rest mass, while GW signals from PBH mergers are transient and move through the frequency band. Signals from mergers in the GHz regime are expected

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https://doi.org/10.1016/j.nima.2024.169721
Received 30 June 2024; Received in revised form 5 August 2024; Accepted 8 August 2024

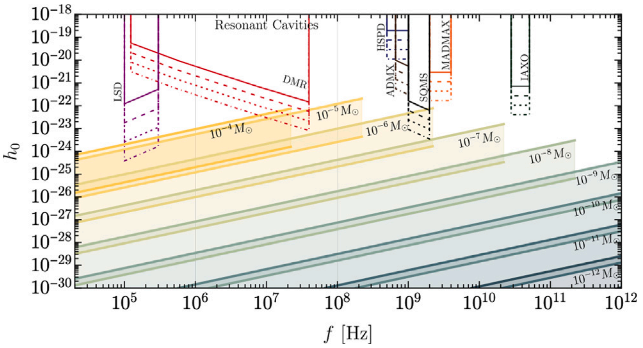

Fig. 1. Expected sensitivity of different experiments and strain of PBH mergers of different masses. The sensitivity of experiments using different integration time is shown with dashed lines. For ADMX and SQMS the assumed integration times correspond to PBH signals of mass $m_{\mathrm{PBH}} = (10^{-9}, 10^{-10}, 10^{-11}, 10^{-12})M_\odot$ and $m_{\mathrm{PBH}} = (10^{-10}, 10^{-11}, 10^{-12}, 10^{-13})M_\odot$ respectively from top to bottom [2].

to remain within the cavity bandwidth for a maximum of a few seconds, likely much less.

3. Sensitivity of existing cavity experiments

As can be seen in Fig. 1 the expected sensitivities to the GW strain h_0 in the GHz regime (SQMS, ADMX, etc.) are several orders of magnitude away what we would need to reach the required sensitivity derived from theoretical models.

While the development of detector hardware, such as increasing the quality factor, increasing the external B-fields used, lowering ambient temperature and increasing the effective volume will help to get closer to the necessary sensitivity, it is unlikely to cover 10 or more orders of magnitude just by detector improvement - especially considering that leading experiments are already employing superconductors to reach $Q_0 \sim 10^7$ and higher, magnets in the $\sim 10\,\mathrm{T}$ regime and dilution fridges with $< 100\,\mathrm{mK}$. To cover such a gap a new approach to analysis might be necessary.

4. The GravNet approach

The principle idea of GravNet is using time-correlated data from multiple RF-cavities, ideally not in one lab, but scattered across the globe. By correlating signals from several geographically separated cavities, one can significantly improve the signal-to-noise ratio, enhancing the strain sensitivity. As part of the GravNet proposal two scenarios have been considered. GravNet-1 and GravNet-2, one might think of them as two generations, the first as a proof of concept and the second as a larger project, dedicated to gain best-in-class sensitivity to PBH mergers.

GravNet-1 is proposed using mainly existing read-out hardware such as spectrum analyzers being used in many axion haloscope experiments. We assume an external B-field in a $r = 4\,\mathrm{cm}$ and $h = 24\,\mathrm{cm}$ cylindrical volume, containing three spherical cavities of $r = 4\,\mathrm{cm}$. The readout system is based on Josephson Parametric Amplifiers (JPAs) with system temperatures of $100\,\mathrm{mK}$, a setup already in use in many RF-halocopes with dilution fridges. Starting from $N = 10$ setups across the globe, each hosting three cavities, the sensitivity on the GW- strain h will improve by a factor $\sqrt{N}$ reaching $h_0 < 1.7 \cdot 10^{-23}$. This requires a phase-aligned combination of the time-series data from each setup, resulting in a linear increase in the SNR as the number of setups increases. To accomplish this, the direction of the incoming GW must be known to calculate the relative phase differences between the geographically separated setups. This can be achieved by scanning through both angles that define the GW's direction when combining the data.

The second generation of GravNet, **GravNet-2**, will concentrate on improving sensitivity by employing novel read-out techniques such as single photon detection below the quantum noise limit, a technique currently being developed for application in axion halocopes. We shall now assume $N = 10$ distinct setups, with a total of $N = 20$ cavities. The single RF photon detection efficiency is taken to be 50%, a dark count rate of 10 Hz and a time resolution of 0.2 ms are assumed. For the full set of assumptions see [3]. From here we can think of two possible scenarios. GravNet-a assumes all set-ups to be similar to the existing SUPAX [4] setup: an effective volume $V_{\mathrm{eff}} = 6 \cdot 10^{-4}\ \mathrm{m}^3$ and magnetic field of $B = 14\,\mathrm{T}$. With these assumptions one can reach a strain of $h_0 = 1.6 \cdot 10^{-22}$. GravNet-b assumes larger NMR-type magnets with $V_{\mathrm{eff}} = 0.25\ m^3$ and $B = 9\,\mathrm{T}$. The advantage in volume becomes clear with a nearly 50x better strain sensitivity of $h_0 = 3.4 \cdot 10^{-24}$.

Concluding, GravNet has the potential to reach the parameter space of PBH mergers. Currently the first two detector stations of GravNet are being built at Mainz and Bonn.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to thank the Graduate School: Particle Detectors for future Experiments for supporting this work. This work would have not been possible without the ERC-Grant "LightAtTheLHC" as well as the continuous support from the PRISMA+ Cluster of Excellence at the University of Mainz.

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