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Global Network of Cavities to Search for Gravitational Waves: GravNet

Kristof Schmieden[a,*] **and Matthias Schott**[a]

[a] *PRISMA+ Cluster of Excellence, Institute of Physics, Johannes Gutenberg University, Mainz, Germany*

E-mail: kschmied@uni-mainz.de, mschott@uni-mainz.de

The idea of searching for gravitational waves using cavities in strong magnetic fields has recently received significant attention. In particular, cavities with rather small volumes that are currently used to search for axions are discussed in this context. We propose here a novel experimental scheme enabling the search for gravitational waves with MHz frequencies and above, which could be caused for example by primordial black hole mergers. The scheme is based on synchronous measurements of cavity signals from several devices operating in magnetic fields at distant locations. Although signatures of gravitational waves may be present as identifiable signals in a single cavity, it is highly challenging to distinguish them from noise. By analysing the correlation between signals from multiple, geographically separated cavities, it is not only possible to increase substantially the signal over noise ratio, but also to investigate the nature and the source of those gravitational wave signatures. The prospects of GravNet (Global Network of Cavities to Search for Gravitational Waves) are outlined in this presentation.

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[*]Speaker

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1. Introduction

The first observation of a gravitational wave in 2015 by the LIGO and VIRGO collaborations [1] marked the beginning of a new era of gravitational wave astronomy. The observed merging of two 30 solar mass black holes about 1.3 billion light years from earth produced a gravitational wave strain h_0 in the order of 10^{-21}. The recorded signals spans a frequency range from 30 – 500 Hz. This is shown in the iconic picture released in [1] which is presented here in Fig. 1. The sensitive frequency range of such gravitational wave detectors ranges up to 10^3 Hz. However, there exist many astrophysical models which predict additional sources of gravitational waves at much larger frequencies. Among those are the merging of sub-solar mass primordial black holes (PBH) [2] and boson clouds around black holes exhibiting superradiance instabilities [3]. Both could lead to the emission of gravitational waves in the GHz regime. Hence it certainly is very interesting to study the possibilities of detecting these ultra high frequency gravitational waves (UHFGW). As classical interferometers are not sensitive at those frequencies alternative detection methods are needed. To this end the well known concept of magnetised haloscopes can be utilised. Originally developed to search for axions [4–6] they also exhibit sensitivity to UHFGW, as will be discussed in the next section. Recent reviews of sources of UHFGWs and the challenges detecting them can be found in Refs. [2, 7].

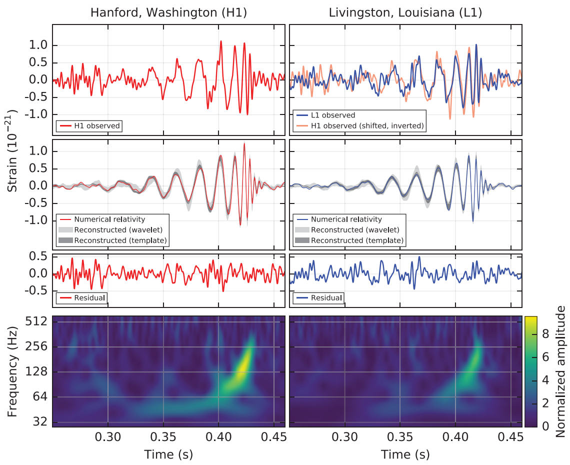

Figure 1: The first gravitational wave event (GW150914) observed by the LIGO Hanford and Livingston detectors, as presented in Ref. [1]. The observed strain is in the order of 10^{-21} and the signal spans a frequency range from 30 – 500 Hz.

2. Detection Principle

Given a radio frequency (RF) cavity which is placed inside a magnetic field, a gravitational wave will excite an electromagnetic (EM) field with the same frequency of the gravitational wave. Two effects contribute to the generation of the EM field. The first being the mechanical deformation of the cavity itself, leading to a periodic change in the magnetic flux through the cavity and hence inducing an EM signal. A similar effect is exploited by the MAGO experiment [8]. There a system of coupled cavities is used where one cavity is pumped with RF power and the mechanical oscillation will lead to an energy transfer to the second cavity, without the need for an external magnetic field.

The second effect of interest is the direct coupling of the gravitational wave to the EM field via the inverse Gertsenshtein effect [9]. For the remainder of this paper only the direct coupling is considered. The generated RF power P_{sig} is calculated to be $P_{sig} = \frac{1}{2}Q\omega_g^3 V^{5/3}(\eta_n h_0 B_0)^2 \frac{1}{\mu_0 c^2}$, depending on GW frequency ω_g, its incoming direction w.r.t. the direction of the magnetic field, the properties of the detection cavity (Volume V and Quality factor Q) and the external magnetic field strength B as well as the overlap of the excited EM field with the cavity resonant mode η.

This has many similarities with the detection of axions in RF cavities. One important difference, as discussed in [2], is the structure of the excited effective electrical current in the cavity. While axions will excite a dipole EM field, a gravitational wave will excite an EM field with a quadrupole structure. Hence the standard TM010 mode exploited by most axion searches will show no to very little sensitivity to the EM field excited by a GW, which has the largest overlap with a T020 mode. A recast of the sensitivity of several experiments optimised to search for axions to the respective sensitivity to UHFGWs is shown in [2]. It turns out that existing experiments reach a strain sensitivity of few times 10^{-22} at integration times of 120 seconds. Thus lacking several orders of magnitude to the strain PBHs are expected to produce of up to 10^{-23} at best. It should be pointed out that the strongest PBH signals are highly transient, with signal life-times in the order of milliseconds within the bandwidth of a typical cavity. Thus the approach of integrating the RF signals from UHFGW over hundreds of seconds is not applicable, leading to reduction of sensitivity by one orders of magnitude compared to the value stated above.

To be able to detect highly transient signal either the sensitivity has to be drastically increased, or the detection approach has to be changed altogether. The signal power calculation is giving the knobs to increase the generated RF signal power. Increasing the magnetic field and the overlap of the generated EM field with the cavity mode η enters squared into the signal power. However, B is limited by the available magnets, where at best an increase by a factor of two can be expected with the available magnet technology. The overlap factor η can be significantly improved when utilising a cavity optimised for the detection of GWs. Where cavities optimised for axion searches exhibit values of $\eta \sim 0.1$, a cavity optimised for GWs will show values of order 1. The volume of a cavity is constrained by the resonance frequency. To increase the volume the resonance frequency has to be decoupled from the geometry of the cavity, which can be achieved by utilising meta-materials inside the cavity. Lastly, the quality factor Q of the cavity can be increased by using cavities coated with a superconducting layer instead of bare copper. This can improve Q by several orders of magnitude. However, at the same time the resonance width of the cavity is reduced, decreasing the integration time usable for detecting transient signals. All of the above is part of current R& D efforts within several research groups around the world, including ours [10]. A different approach to drastically increase the sensitivity is presented in the next section.

3. How to improve the Sensitivity?

As alternative to increasing the sensitivity of any individual setup, we present here the idea to combine multiple setups and explain the impact on the sensitivity depending on the chosen readout scheme. The following study was first published in [11].

3.1 Phase aligned combination of multiple cavities

The RF voltage signals from multiple cavities can be summed $U_{comb} = \frac{it\omega}{\sqrt{N}} \sum_i^n U_i e^{i\phi_i} \propto \sqrt{N} U_0$, with $U_i = U_0$ and $\phi_i = \phi$, leading to an increase in the measured power $P \propto U^2$ scaling linearly with the number of cavities n. The strain sensitivity will hence scale with $\sqrt{n}$. Assuming the combination of signals from 3 identical spherical cavities with a resonance frequency of $f_0 = 5\,\text{GHz}$, a quality factor of $Q = 10^6$ at a system temperature of $0.1\,K$ inside a $14\,T$ B-field and 1 second integration time a sensitivity to strains $h_0 > 5 \cdot 10^{-23}$ is reached [11].

The difficulty i this approach is to phase align the cavities. This can be facilitated by performing the combination of the recorded time-series of the digitised RF signals offline. This is similar to the approach used in radio astronomy for the offline combination of data from several telescopes. It requires a real-time digitisation of the RF waveform from each cavity and storage of large amounts of data. The data rate is in the order of 100 MB/s, depending of the resonance frequency and sampled bandwidth. This approach would allow the combination of signals from experimental setups which are geographically separated, allowing for a larger number of cavities and the inclusion of different setups. Assuming 10 cavities, which the same properties as before, the strain sensitivity is increased to $h_0 > 10^{-23}$. Two aspects of the search for PBH mergers are important to point out. Those events will produce transient signals, sweeping over a relatively broad range of frequency with varying emitted GW strain. Therefor the detector can operate at a fixed frequency, eliminating the need for complicated tuning mechanism of the resonance frequency of the cavities. Signals from detectors at different locations will exhibit an unknown phase difference of the GW signal, depending on the unknown incident direction of the GW itself. Hence a scan over all possible incoming directions within the angular resolution of the setup has to be performed during the signal combination, which is a significant computational effort.

For GW signals which are constant in frequency, like superradiance of bosonic clouds, the integration time can be increase. However, the sensitivity only scales with the integration time like $t^{1/4}$. Thus a two hour integration and combination of signals from ten cavities yields a sensitivity of $h_0 > 10^{-24}$.

3.2 Coincidence measurements

As alternative to the time-series measurement of the RF signal discussed above the read-out scheme of a cavity based haloscope can be altered to detect individual photons. This requires very low temperatures in the order of 10 mK to suppress the thermal noise as well as single photon detectors sensitive to RF photons in the GHz regime. In the recent years significant progress has been achieved in the development of such detectors. Techniques employed include current biased Josephson Junctions [12], Kerr Josephson Parametric Amplifiers [13] as well as transmon Q-bits [14] for which a single photon detection efficiency of 43% for 7 GHz photons at a dark count rate below 90 Hz has been shown.

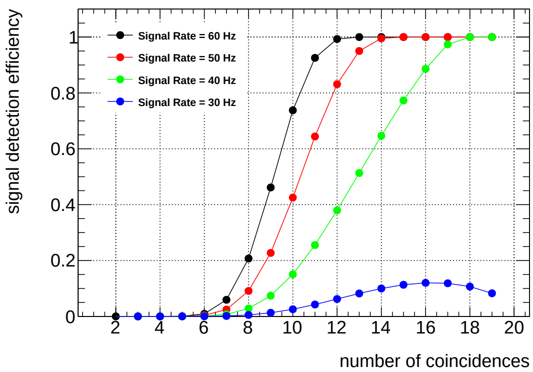

Figure 2: Signal efficiency in dependence of the number of coincidences for various assumptions on the signal photon rate. The coincidence window is set to limit the number of accidental coincidences to < 1 per year for a total noise rate of 10 Hz. A total of 20 independent detectors is assumed.

These developments allow a paradigm change in the cavity based haloscope experiments. Instead of combining the RF signals of several setups phase aligned and integrating the measured RF power continuously over longer time periods, a coincidence counting approach can be used.

In this approach each photon is tagged with a timestamp and coincidences between measurements from several setups can be performed trivially. The sensitivity of the coincidence measurement is defined by the chosen coincidence window, number of contributing detectors and the individual detector noise rates and single photon efficiencies. The detection efficiency for a coincidence measurement is given by $\epsilon_{\text{tot}} = \sum_{i\geq k} \binom{N}{i} \epsilon^{i}_{\text{indiv}}$ where k is the number of required coincidences, N is the number of detectors and $\epsilon_{\text{indiv}} = \epsilon_{det} \Delta t_{\text{coincidence}} \phi_{\text{sig}}$ is the detection efficiency of a GW signal of a single setup. ϵ_{det} is the quantum efficiency of the detector, $\Delta t_{\text{coincidence}}$ is the coincidence time window and ϕ_{sig} refers to the signal photon flux. Figure 2 shows the sensitivity to a gravitational wave signal in dependence of the number of coincidences required assuming a total noise rate of 10 Hz, 20 independent detectors and $\epsilon_{det} = 0.5$. The coincidence window is chosen for each point so that the rate of accidental coincidences is below one per year. This shows that a detection efficiency of 1 can be achieved with 20 detectors for a signal photon flux of 40 Hz and above with coincidence window of 32 ms. Hence such a system is sensitive to very short signals, ideally suited for the hunt for PBH mergers.

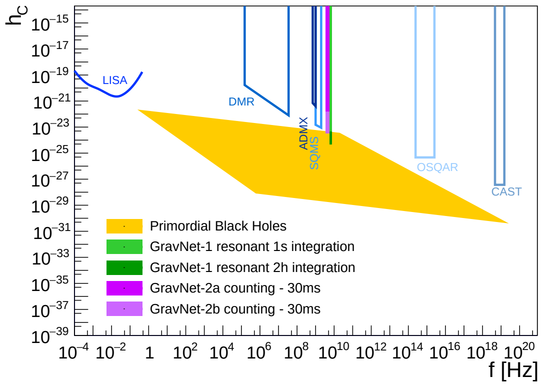

Figure 3: Estimated sensitivity on the GW strain h when combining several cavity based haloscopes using the phase aligned integration (GravNet-1) and coincidence measurement (GravNet-2) approaches, assumed 10 individual cavities. For GravNet-2 sensitivities for two cavity dimensions with volumes of (a) $V = 6 \cdot 10^{-4} m^3$ and (b) $V = 0.25 m^3$ are shown. The figure is adapted from [11] using the expected range of PBH merger signals sensitivity of similar experiments as summarised in [15].

The signal photon rate depends on the used cavities. Assuming a standard 5 GHz cavity with a volume of $6 \cdot 10^{-4}\ m^3$, $Q = 10^5$ in a 14 T magnetic field a photon flux of 40 Hz corresponds to a strain of 10^{-22}. Such a basic setup yields plenty of room for improvements in particular in terms of cavity volume, number of detectors and single detector photon efficiency. Hence sensitivities to strains of 10^{-24} and smaller seem in reach. This is well within the range of strains where PBH merging event are believed to be found, as is shown in Fig. 3 adapted from [6, 11].

4. Conclusions

While it is very challenging to increase the sensitivity of an individual cavity based UHFGW detector, the combination of signals from many such detectors provides a new approach in increasing the overall sensitivity. In particular when targeting fast transient signals a paradigm change towards photon counting coincidence measurements can significantly improve the reach. There are many advantages in combining efforts in the hunt for UHFGW in a coordinated way. One could rely on relatively cheap, commercial magnet systems, costs would be automatically shared in a world-wide collaboration and any R&D results can be swiftly distributed at all detector sites, to name a few. A global network of UHFGW detectors (the GravNet initiative) [11] would exploit all those advantages.

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References

[1] LIGO Scientific Collaboration and Virgo Collaboration collaboration, *Observation of gravitational waves from a binary black hole merger*, *Phys. Rev. Lett.* **116** (2016) 061102.

[2] A. Berlin, D. Blas, R. Tito D'Agnolo, S.A.R. Ellis, R. Harnik, Y. Kahn et al., *Detecting high-frequency gravitational waves with microwave cavities*, *Phys. Rev. D* **105** (2022) 116011 [2112.11465].

[3] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, *String Axiverse*, *Phys. Rev. D* **81** (2010) 123530 [0905.4720].

[4] ADMX collaboration, *Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range*, *Phys. Rev. Lett.* **127** (2021) 261803 [2110.06096].

[5] K. Schmieden and M. Schott, *Supax: A new axion search experiment using superconductive cavities*, *PoS* **EPS-HEP2021** (2021) 141.

[6] A. Berlin et al., *Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities*, 2203.12714.

[7] N. Aggarwal et al., *Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies*, *Living Rev. Rel.* **24** (2021) 4 [2011.12414].

[8] R. Löwenberg and G. Moortgat-Pick, *Lorentz Force Detuning in Heterodyne Gravitational Wave Experiments*, 2307.14379.

[9] Y.B. Zel'dovich, *Electromagnetic and gravitational waves in a stationary magnetic field*, *Zh. Eksp. Teor. Fiz* **65** (1973) 1311.

[10] T. Schneemann, K. Schmieden and M. Schott, *First results of the SUPAX Experiment: Probing Dark Photons*, 2308.08337.

[11] K. Schmieden and M. Schott, *The Global Network of Cavities to Search for Gravitational Waves (GravNet): A novel scheme to hunt gravitational waves signatures from the early universe*, 2308.11497.

[12] A. D'Elia et al., *Stepping Closer to Pulsed Single Microwave Photon Detectors for Axions Search*, *IEEE Trans. Appl. Supercond.* **33** (2023) 1500109 [2302.07556].

[13] K. Petrovnin, J. Wang, M. Perelshtein, P. Hakonen and G.S. Paraoanu, *Microwave photon detection at parametric criticality*, 2308.07084.

[14] L. Balembois, J. Travesedo, L. Pallegoix, A. May, E. Billaud, M. Villiers et al., *Practical Single Microwave Photon Counter with* $10^{-22}\mathrm{W}/\sqrt{\mathrm{Hz}}$ *sensitivity*, 2307.03614.

[15] G. Franciolini, A. Maharana and F. Muia, *The Hunt for Light Primordial Black Hole Dark Matter with Ultra-High-Frequency Gravitational Waves*, 2205.02153.

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