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High Frequency Gravitational Wave Detection with Superconducting Microwave Cavities

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So far, high frequency gravitational waves (GWs) remain unexplored messengers of new physics. Proposed sources in the MHz - GHz band include primordial black hole mergers, black hole superradiance and several stochastic backgrounds.
Our collaboration is working on tapping into this source by employing superconducting microwave cavities for high precision measurements of harmonic displacements.
The detection principle is to load an electromagnetic mode of a cavity so that a GW-induced vibration of the cavity walls up-converts some power into another, unloaded EM mode. The power in the unloaded mode is then taken to be the GW signal.
This summary outlines the ongoing work and future plans of our project in Hamburg. Specifically, the potential sources, the cavity design, and the signal readout mechanism are discussed.

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1. Why search for high frequency gravitational waves?

Almost a decade has passed since gravitational wave observatories have started to receive astrophysical signals. These tiny oscillations of spacetime have opened up an entirely new window to events in the universe that were previously nearly impossible to probe. Apart from detections of the interferometers in the LIGO-Virgo-KAGRA (LVK) collaboration [1], there has been evidence for the detection of a stochastic gravitational wave background from the pulsar timing array (PTA) method used by NANOGrav [2].

When combined with the major future planned detectors such as LISA [3], GW observatories will soon be able to measure an impressive frequency range from nHz up to kHz. The reason that almost all focus has been on such frequencies is that GW signals were guaranteed to exist there given our previous understanding of the universe. For the most part, *proven* astrophysical objects are not expected to emit gravitational waves at much higher frequencies with considerable energies [4]. But precisely here lies the opportunity. Extending our sensitivity to *high frequency gravitational waves* (HFGWs) (i.e. $\omega_{GW} \gg$ kHz) will allow testing a number of phenomena *beyond* our so far observed universe [5]. In the past, exploring new frequency ranges in the electromagnetic spectrum has also led to major unexpected discoveries. The field of gravitational wave astronomy is still young, so we should not pass on the opportunity to explore it in all facets and look where no one else has looked.

2. Selection of high frequency gravitational wave sources

In order to get an impression of the kind of processes that can create high frequency gravitational waves, we will discuss a few common ideas. However, a HFGW search will also always be an explorative search for unpredicted and unexpected features of our universe.

2.1 Compact binaries

Binaries of compact objects such as black holes or neutron stars emit gravitational waves at frequencies that grow over time, as the objects approach each other. The highest frequency the binary reaches depends on the frequency at the innermost stable orbit. For two black holes of mass M, this frequency is around $\sim 2\,(M_\odot/M)$ kHz [6]. Thus, only black hole binaries with $M < M_\odot$ will emit significantly at high frequencies. However, such black hole masses are not expected from the collapse of stars [7]. Nevertheless, *primordial black holes* (PBHs) of masses down to $10^{-19}\,M_\odot$ could be stable and exist since their creation from density fluctuations in the early universe and explain part or even all the observed dark matter in the universe [8].

Therefore, in case a transient signal matching a compact binary coalescence were to be observed at frequencies $\gg$ kHz, this would constitute strong evidence for the existence of primordial black holes in our galaxy and perhaps even solve part of the dark matter mystery.

2.2 Black hole superradiance

Superradiance is an effect that occurs when a massive spinning body transfers energy to much lighter particles scattering off it. A case of this can occur if a cloud of massive scalar bosonic matter surrounds a rapidly spinning black hole [9]. In order for such clouds to build up, the wavelength of the scalar particles needs to be of the size of the black hole radius. The dominant way in which such

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a system can emit GWs is by bosons annihilating into gravitons at twice the Compton frequency of the boson [10]. This means that a black hole of mass M can emit GWs through superradiance at a frequency around

$$\omega_{GW} \sim 0.3\,(M_\odot/M)\,\text{MHz}\,. \tag{1}$$

Black hole superradiance can produce a continuous monochromatic GW signal for multiple years with negligible frequency drift [11]. This is a huge benefit for experimental searches which can exploit a long integration time to improve the signal resolution.

However, no particles that could take part in such superradiance are part of the standard model. Therefore, a search for superradiance would be probing scalar particles beyond the standard model such as axions [12]. Primordial black holes are equally suited to exhibit GW superradiance as astrophysical black holes. Their lighter masses can generate GWs of much higher frequencies according to equation (1).

However, the chance of particles beyond the standard model accumulating around a black hole whose radius their wavelength matches are slim. Still, a highly monochromatic GW signal at frequencies above kHz would be strong evidence for matter beyond the standard model.

2.3 Primordial gravitational waves

Maybe the biggest promise of gravitational wave astronomy is the ability to receive information from further in the universe's past than electromagnetic radiation can provide. There are a great amount of stochastic gravitational wave backgrounds predicted from speculative, but also standard model sources. This includes cosmic strings, cosmic phase transitions and remnants of inflation [5]. Many of these GW backgrounds are also present and sometimes stronger at lower frequencies probed by PTAs and LVK. However, there is a guaranteed astrophysical foreground of unresolved binary mergers that might be much stronger than most cosmological sources [13]. Resolving a stochastic background in the presence of another much stronger background is only possible if they can be discriminated by e.g. anisotropies. This is why primordial gravitational wave searches benefit from happening at frequencies where binary mergers can not drown out cosmological signals. This is a unique promise of high frequency gravitational wave detection.

Unfortunately, current proposals for high frequency gravitational wave detectors can not claim sensitivity to primordial backgrounds yet [5]. Still, it is even more reason to continue research on high frequency gravitational wave detection.

3. How to use microwave cavities for gravitational wave detection

Gravitational waves exert a quadrupolar tidal force on any massive body they encounter. The principle of a *Weber bar detector* was to directly read out the resonant vibration of heavy metal cylinders caused by gravitational waves [6]. The idea presented here is to use a microwave cavity in place of a solid cylinder. Oscillating electromagnetic fields in the cavity are very sensitive to mechanical perturbations of the cavity walls. If an electromagnetic eigenmode (*pump mode*) of the cavity is excited at a frequency ω_0, any vibration of the cavity walls at frequency ω_g will cause some power to be up-converted to a frequency $\omega_0 + \omega_g$. If the cavity also supports another eigenmode (*signal mode*) at the frequency $\omega_1 \cong \omega_0 + \omega_g$ and the geometry of the wall vibration couples well between the pump and signal modes, the effect of the wall vibration can be resonantly enhanced.

For such a detector to have considerable gravitational wave sensitivity, there are several further requirements. First, the cavity needs to be cooled down to cryogenic temperatures ~ 2 K. This improves the experiment in several ways. Niobium cavities like those developed for particle acceleration are superconducting at such temperatures and turn into extremely efficient resonators with quality factors $Q > 10^{10}$ [14]. This allows for power to be stored more efficiently in the pump mode and a stronger resonant enhancement of a signal at $\omega_g = \omega_1 - \omega_0$. Further, it leads to lower thermal dissipation in the cavity walls, and in the readout electronics.

A second requirement is to suppress any vibrations of the cavity walls not caused by gravitational waves, as they can induce the same power up-conversion. This can be achieved with a dedicated suspension system of the cavity [15]. However, a certain level of vibrations coming from the thermal energy in the cavity walls sets an irreducible noise level.

The last major challenge to the experiment is power from the pump mode leaking into the signal readout without any perturbation of the cavity walls. Neither should the oscillator of the drive excite the signal mode at $\omega_0 + \omega_g$ nor should the signal readout pick up the phase noise of the pump mode at $\omega_0 + \omega_g$. Both of these issues can be mitigated by exploiting the symmetry difference between the pump and signal mode fields imprinted by the quadrupolar gravitational wave. This principle is made more explicit in the next section.

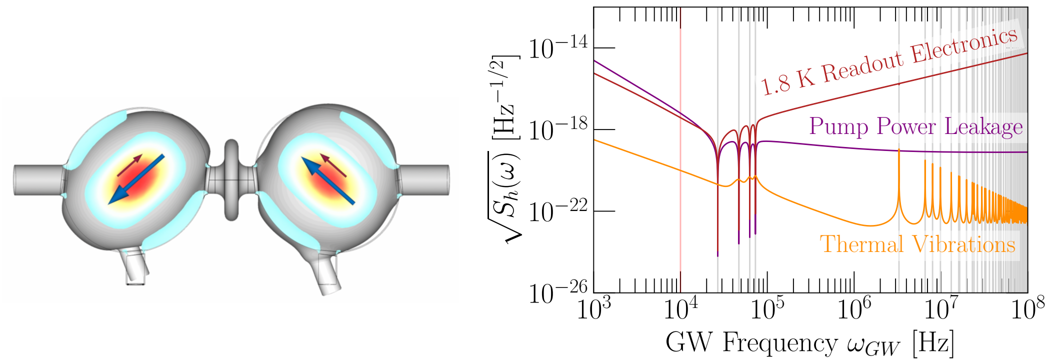

Figure 1: Left: An illustration of the vibrating MAGO cavity with its pump (blue) and signal (red) magnetic field. Right: The amplitude power spectrum of the noise sources discussed in the text. The resonance at $\omega_1 - \omega_0$ is marked with a red line and the quadrupole vibrations of a spherical cavity with grey lines. Mechanical vibrations are assumed to be successfully mitigated. For more details see [15] and [16].

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4. The design of the MAGO cavity and its future use

The idea to use superconducting microwave cavities for GW detection was first proposed in [17] and first successful tests of the concept were conducted independently in [18] and [19]. The latter collaboration went on designing a prototype cavity that could be used to set first limits on gravitational waves in the 10 kHz range, the *Microwave Apparatus for Gravitational Waves Observation* (MAGO) [15]. However, the project was put on hold before the cavity could be fully prepared and tested. This was until recent work [16] pointed out that, while not competitive with interferometers at lower frequencies, the MAGO detection principle is much better suited for *high* frequency GW detection. Another benefit is that extensive expertise and infrastructure for fabricating and operating high-Q superconducting microwave cavities exists in accelerator laboratories around the world and setting up a MAGO detector requires significantly less resources than GW interferometers. This is why DESY and the University of Hamburg have partnered with FNAL to use the existing MAGO cavity and start a dedicated search for high frequency gravitational waves. The remainder of this section will first present the design of the MAGO cavity and then explain how we plan to use it in the near future.

The MAGO cavity consists of two coupled spheroidal niobium cavities whose major axes are oriented at a right angle to each other. The almost spherical cavities were chosen to allow for sensitivity to GWs from as many angles as possible. However, spherical cavities do not support a pair of eigenmodes with $\omega_1 - \omega_0 \sim$ kHz between which a GW can efficiently convert power. However, a system of two weakly coupled identical cavity resonators supports eigenmodes close in frequency where each individual cavity mode oscillates in both cavities either in phase or 180° out of phase.

The two cavity cells are oriented at a right angle because the direction of the quadrupolar tidal force from the GW is anti-symmetric under a 90° rotation. Therefore, a GW induced vibration will be out of phase between the two cavity cells and is able to drive a transition between a symmetric and anti-symmetric mode pair. For this purpose, the symmetric oscillation of the TE_{011} mode is best used as pump mode and its anti-symmetric oscillation as signal mode.

This is exactly the symmetry difference that can be used to suppress the pump power leakage noise. By driving both cavity cells with identical antennas *in phase*, the phase noise driving the signal mode is further suppressed. If the readout also consists of one antenna per cavity cell, and their output is interfered with each other at a 180° phase shift, any symmetric component is subtracted out. This ensures that phase noise from the pump mode in the readout is reduced. In principle, both tasks can be achieved with the same two antennas as in [18]. However, it turns out that a better performance can be achieved if two antennas per cavity cell are used [15].

Implementing this idea successfully requires a sophisticated RF system which is currently under development at DESY. Furthermore, the design of a dedicated cryostat for microwave cavity GW detection has been started. However, a first GW search can also be conducted in a regular cryostat used for accelerator cavity tests albeit with reduced sensitivity.

After a survey of the mechanical properties of the cavity in Hamburg, the MAGO cavity was sent to FNAL where it underwent surface treatments and a tuning of the cavity cell coupling. As soon as the cavity and the detection system has been thoroughly tested at 1.8 K and the RF system has been finalized, the MAGO cavity will be ready for a first GW observing run. Certain parameters like the coupling strength of the signal pickup antennas need to be adjusted depending on the type of signal we are looking for. For instance, transient sources require a strong coupling, which broadens the bandwidth while monochromatic waves are best observed with less power leaking into the readout as this improves the sensitivity at the resonant frequency.

5. Conclusion and outlook

High frequency gravitational waves open a unique window into the universe which has remained mostly unexplored so far. The focus of large scale GW observatories lays rightfully at lower frequencies where astrophysical sources are guaranteed. However, superconducting microwave cavity detectors are much smaller-scale experiments with comparable gravitational wave sensitivity in the high frequency regime. This will allow our team to set first limits in a new frequency range using the MAGO cavity in the near future. However, the MAGO cavity is still only a prototype and the same detection concept can reach significantly better sensitivities in principle. By optimising the cavity geometry, making it larger and heavier and improving the readout system, many more orders of magnitude in strain sensitivity can be obtained. The long-term goal of our efforts is to exploit the full potential of HFGW detection with microwave cavities until new physics of our universe has either been constrained as far as possible or a discovery has been made.

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