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High frequency gravitational wave sensing with superconducting microwave cavities

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A promising way to probe physics beyond the Standard Model is to search for gravitational wave (GW) signals at high frequencies where known astrophysical sources can not obscure the signal. Similar to the search for dark matter, microwave cavity resonators can be used to detect faint effects from GWs. We will report on the progress of our project to operate such a detector and highlight improvements we are planning in the future. This includes quantum enhancement techniques like vacuum squeezing which will allow future detectors to operate beyond the standard quantum limit.

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1. Introduction

Superconducting resonant cavities' range of applications has greatly broadened going from particle accelerators to dark matter search [1–6] and to quantum computing [7, 8]. The very high quality factor of these cavities can be leveraged also in the search for gravitational waves (GWs) in frequency ranges scarcely explored by current experiments. Stemming from an idea proposed in the 1970s by Pegoraro et al. [9] and Caves [10] the MAGO proposal [11] in the end of 1990s aimed at using SRF cavities to detect gravitational waves in the lower kHz range, but the same concept can be applied to the detection of high frequency GWs in the kHz to MHz range. In this range of frequencies there are no known astrophysical sources of GWs, creating an ideal foreground-free search for new physics. Possible well motivated sources include primordial black hole mergers (PBH), one of the candidates for dark matter, and superradiance, another exotic phenomenon that would hint at the presence of additional light bosonic matter [12].

2. Detection principle

The MAGO proposal consists in a "heterodyne" detector with two nearly degenerate EM eigenmodes. The lower frequency one (0-mode) is loaded with RF power and the higher frequency one (π-mode) is used as detection mode. A GW interacting with the cavity's walls (mechanical interaction [13]) can cause an upconversion of the RF power at a frequency $\omega = \omega_0 + \omega_{GW}$.
The upconversion condition is resonantly enhanced when the resulting frequency coincides with the π-mode frequency, resulting in an enhanced sensitivity. This effect is even amplified if ω_g coincides also with a mechanical resonance. The device is generally more sensitive on resonance, but it is possible to broaden the read out sensitivity by strongly overcoupling to the cavity [14]. The coupling of a GW to the superconducting cavity's walls can be expressed as [15]:

$$\begin{aligned}\Gamma^l_+ &:= V_{\text{cav}}^{-\frac{1}{3}} \cdot M_{\text{cav}}^{-1} \int_{V_{\text{cav}}} d^3x\rho(\vec{r}) \left(x\vec{\xi}_{l,x}(\vec{r}) - y\vec{\xi}_{l,y}(\vec{r})\right), \\ \Gamma^l_\times &:= V_{\text{cav}}^{-\frac{1}{3}} \cdot M_{\text{cav}}^{-1} \int_{V_{\text{cav}}} d^3x\rho(\vec{r}) \left(x\vec{\xi}_{l,y}(\vec{r}) - y\vec{\xi}_{l,x}(\vec{r})\right),\end{aligned} \tag{1}$$

with $+, \times$ two polarizations of the GW, V_{cav},M_{cav},ρ respectively volume, mass and density of the cavity and $\xi_{l,x}$ displacement of the l mechanical eigenmode in the x direction. The second step of coupling between mechanical vibration and EM eigenmodes can be then described by the following coupling coefficient:

$$C^l_{01} = \frac{V_{\text{cav}}^{\frac{1}{3}}}{2\sqrt{U_0 U_1}} \int_{\partial V_{\text{cav}}} d\vec{S} \cdot \vec{\xi}_l(\vec{r}) \left[\frac{1}{\mu_0}\vec{B}_0(\vec{r})\vec{B}_1(\vec{r}) - \varepsilon_0\vec{E}_0(\vec{r})\vec{E}_1(\vec{r})\right], \tag{2}$$

with U_0,U_1 energy stored in both modes, $\vec{B}_{0,1}$,$\vec{E}_{0,1}$ magnetic and electric field distribution respectively in each mode.

3. Sensitivity predictions

In order to estimate the sensitivity to GWs it was decided to use as figure of merit the noise strain power spectral density (PSD) (S_n). The minimum detectable strain can be defined as:

$$h_\mathrm{min}(\omega_g) \sim \sqrt{S_\mathrm{n}(\omega_g)} := \sqrt{\frac{S_\mathrm{noise}(\omega_0+\omega_g)}{\left|T(\omega_g)\right|^2}}, \tag{3}$$

in which $T(\omega_g)$ is the transfer function of the SRF cavity that describes the signal response to a GW input in the form $S_\mathrm{sig}(\omega_0+\omega_g) = \left|T(\omega_g)\right|^2 S_h(\omega_g)$. It should be stressed that this kind of estimation does not take into consideration integration time and data analysis techniques.
Far from mechanical resonances the absolute value of the transfer function can be expressed as:

$$|T(\omega_g = \Delta\omega)|^2 = \frac{\beta_\mathrm{in}\beta_\mathrm{out}}{(1+\beta_\mathrm{in})^2}\cdot\frac{\omega_0}{Q_0}\cdot V_\mathrm{cav}\cdot B^2_\mathrm{eff}\cdot|C^m_{01}\Gamma_m|^2\cdot Q^2_\mathrm{L}, \tag{4}$$

here the magnetic field was redefined as an effective field averaging over the cavity volume $B^2_\mathrm{eff} := \frac{1}{V_\mathrm{cav}}\int_{V_\mathrm{cav}} B^2_0$ to measure how efficiently the pump mode stores energy in the cavity and $\Delta\omega$ is the frequency difference between pump and signal mode. The coefficients β_in,β_out are the couplings of the antennas to the two modes. Q_0 is the unloaded quality factor of the cavity relative to the pump mode at frequency ω_0, while Q_L is the loaded quality factor. It is reasonable to expect that the main contributing noise sources in the final detection experiment are going to be mechanical noise and thermal noise. When $\omega_g \approx \Delta\omega$ these can be described by the following equations:

$$\begin{gathered}\sqrt{S_\mathrm{th}(\omega_g)} \sim \frac{1+\beta_\mathrm{in}}{\sqrt{\beta_\mathrm{in}\beta_\mathrm{out}}}\cdot B_\mathrm{eff}\cdot Q_0^{1/2}\cdot\left(C^m_{01}\Gamma_m\right)^{-1}\cdot(\omega_g-\Delta\omega),\\ \sqrt{S_\mathrm{mech}(\omega_g)} \sim \Gamma^{-1}\cdot q_\mathrm{rms}\cdot Q^{-1/2}_\mathrm{mech}\cdot\left(\frac{\omega_\mathrm{mech}}{\omega_g}\right)^{\frac{3+\alpha}{2}}\cdot\omega_g^{-1/2},\end{gathered} \tag{5}$$

in which ω_mech is the frequency of a mechanical eigenmode, q_rms the root-mean-squared wall displacement and α source-dependent parameter [14]. From equations (3)(5) it can be seen that some parameters contribute to the sensitivity both increasing the transfer function absolute value and/or decreasing the noise PSD. For example higher Q_L values (decreased input coupling) will improve the sensitivity on resonance, while lower Q_L (increased coupling) will improve the out-of-resonance sensitivity, favoring a broadband search. A bigger coupling factor C_{01} produces a higher signal amplitude but independently from the source of mechanical deformations, therefore enhancing also mechanical noise. On the contrary larger coupling factors $\Gamma_+, \Gamma_\times$ only increase the deformation induced by the GW on the cavity walls and are therefore beneficial for the sensitivity. In figure 1 is shown an estimation for the minimum detectable strain as function on the GW frequency compared to already existing detectors and some future projects. This calculation assumes an "optimized" SRF cavity (solid grey background) with one year integration time. Possible GW sources like primordial black holes (PBH) mergers and superradiance predictions are also shown as lines with varying PBH mass or distance from Earth [19]. This sensitivity is calculated envisioning a broadband scan, meaning that the difference between pump and signal mode will be kept constant at $\sim$ 11 kHz, given by the geometry of the existing cavity prototype. Since the possible predicted

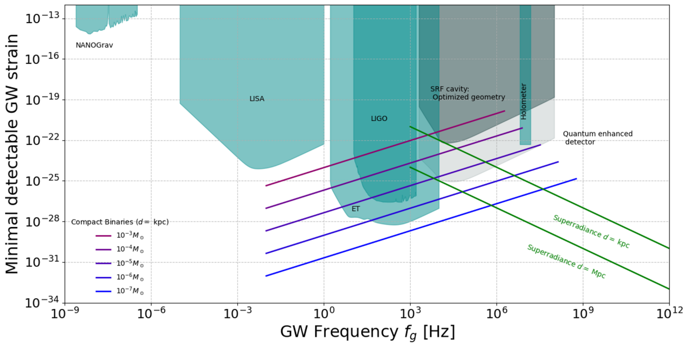

Figure 1: Sensitivity plot of minimal detectable GW strain vs frequency for different experiments and predicted sensitivities of approved projects[16–18]. The blue lines show the predicted signal coming from PBH mergers of different BH mass. The green lines show the predicted signal from superradiance effects.

GW signals are expected to be transient and broadband, it was chosen to not operate the detector on resonance but rather do a broadband search. A broadband scan implies a very high coupling to the signal mode that will increase the sensitivity off-resonance at the price of lowering Q_L.

4. Quantum enhancement

In a broadband scan a lot of sensitivity is lost due to the need of lowering Q_L to overcouple strongly to the signal mode. This loss can be compensated by implementing quantum enhancement techniques. The first and most known quantum enhancement technique is *squeezing* [20]. Given a signal with quadrature components $\hat{X}$ and $\hat{Y}$ it is possible to increase the uncertainty on one quadrature to reduce it on the other.

A second quantum enhancement technique that could be leveraged is the *Back-Action Evading amplification* (BAE) [21–24]. In this approach instead of reading out the signal from the main SRF cavity, a second auxiliary cavity or RLC circuit is coupled to the main cavity. The coupling of this second resonator to the principal detector is modulated at frequency $\omega_\Sigma = \omega_{\text{cav}} + \omega_{\text{aux}}$ and at frequency $\omega_\Delta = \omega_{\text{cav}} - \omega_{\text{aux}}$ at the same time. By doing so it is possible to avoid the transmission of noise from the auxiliary resonator to the main detector and amplify only the wanted signal. By applying these quantum enhancement techniques it was estimated that with optimized parameters the SRF cavity based GW detection could obtain a factor 10^4 improvement in sensitivity to broadband signals.

5. Conclusions

Superconducting cavities are a promising technology for high frequency GW detection in the range of kHz to MHz. In this range a foreground-free search for new physics is possible due to the absence of known astrophysical sources. The MAGO project shows a very appealing projected sensitivity in the range of interest, reaching the required minimum detectable strain to detect some well-motivated theoretical sources. The implementation of further quantum enhancements techniques would increase the sensitivity even more, though an experimental demonstration is still to be realized.

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