High frequency gravitational wave sensing with superconducting microwave cavities

G. Marconato, T. Krokotsch, C. Dokuyucu, K. Peters, J. Branlard, G. Moortgat-Pick, A. Ringwald, W. Hillert, B. Giaccone, M. Wenskat

Universität Hamburg — DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
DESY.
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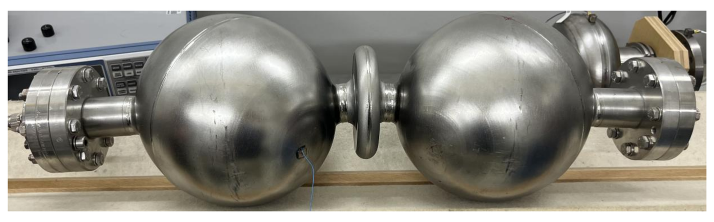
STORY OF A LONELY CAVITY

INFN GENOVA — Istituto Nazionale di Fisica Nucleare, Sezione di Genova

PACO project → MAGO



R. Ballantini *et al*, "Microwave apparatus for gravitational waves observation," Feb. 11, 2005

→ DESY. Universität Hamburg + Fermilab

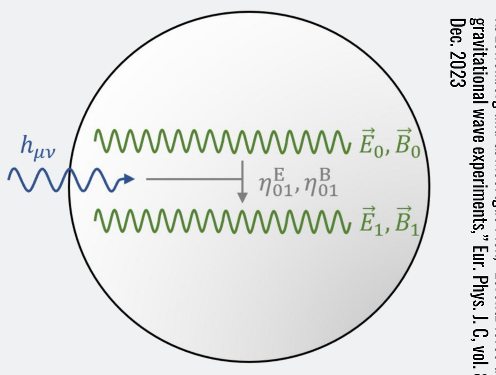
DETECTION PRINCIPLE

There are two ways a gravitational wave (GW) can interact with a SRF cavity:

GERTSENSHTEIN effect

Best for GHz

The GW couples directly to the RF field inside the cavity producing an upconversion of the signal to a higher frequency.

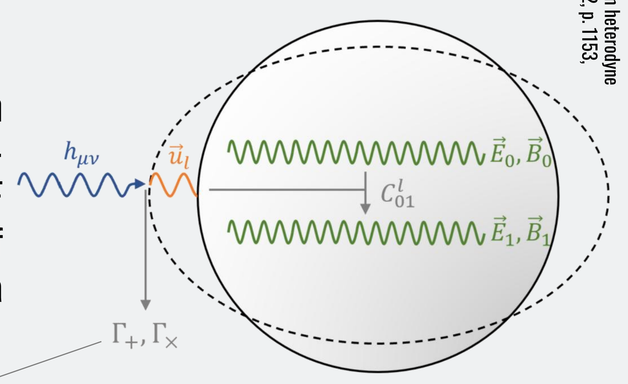


R. Löwenberg and G. Moortgat-Pick, "Lorentz force detuning in heterodyne gravitational wave experiments," Eur. Phys. J. C, vol. 83, no. 12, p. 1153, Dec. 2023

MECHANICAL coupling

Best for kHz - MHz

The GW couples to a mechanical vibration of the cavity which generates time-varying boundary conditions for the RF field. This produces an upconversion of the signal to a higher frequency through a mechanical - EM coupling.

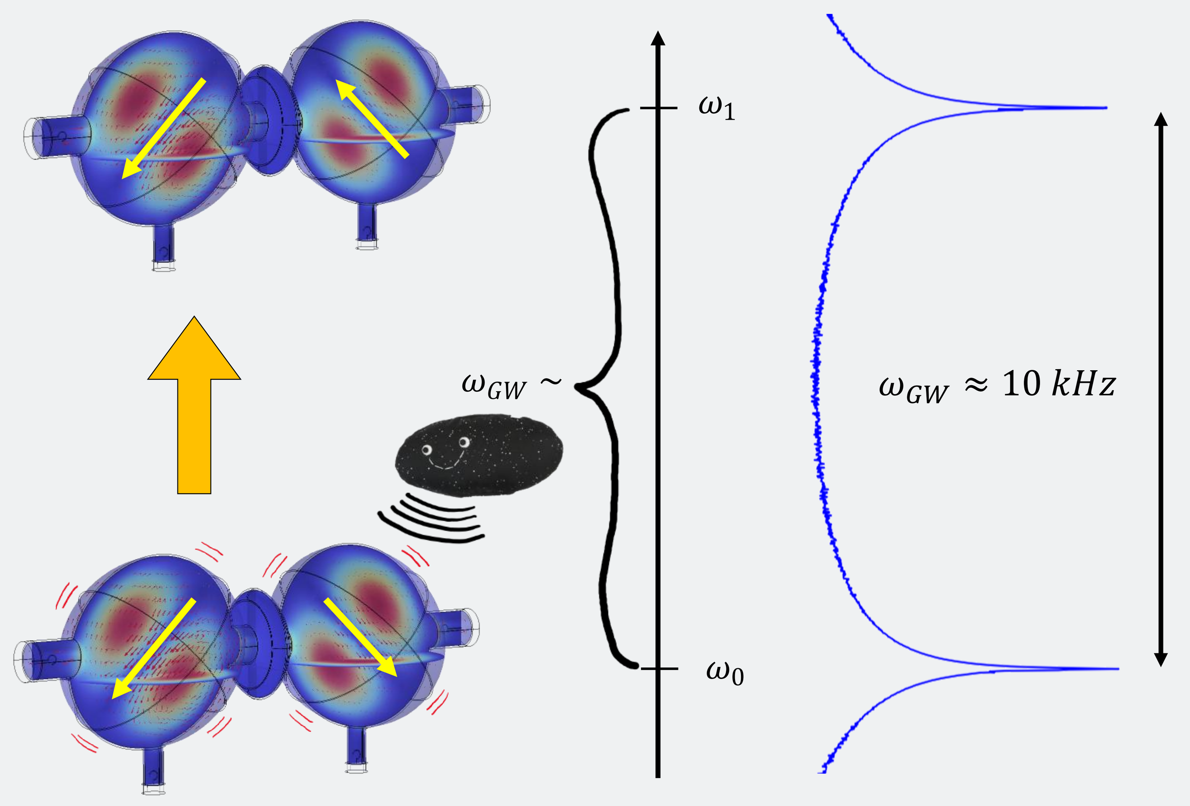


$$\Gamma_+^l := V_{cav}^{-1/3} \cdot M_{cav}^{-1} \int_{V_{cav}} d^3x\, \rho(\vec{x}) \left(x\vec{\xi}_{l,x}(\vec{x}) - y\vec{\xi}_{l,y}(\vec{x}) \right)$$

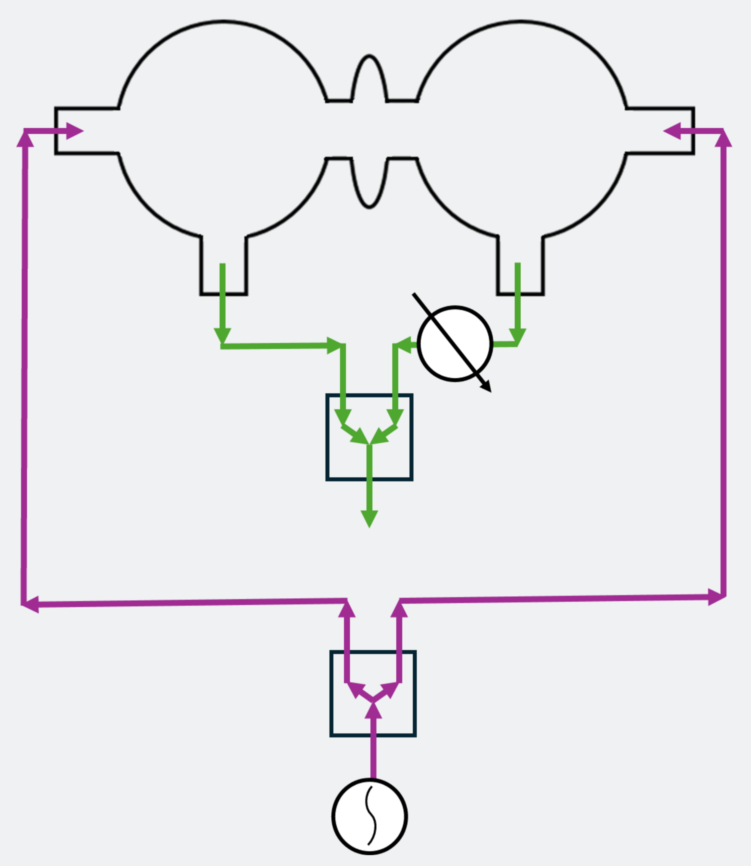
$$\Gamma_\times^l := V_{cav}^{-1/3} \cdot M_{cav}^{-1} \int_{V_{cav}} d^3x\, \rho(\vec{x}) \left(x\vec{\xi}_{l,y}(\vec{x}) - y\vec{\xi}_{l,x}(\vec{x}) \right)$$

$$C_{01}^l = \frac{V_{cav}^{1/3}}{2\sqrt{U_0 U_1}} \oint_{\partial V_{cav}} d\vec{S} \cdot \vec{\xi}_l(\vec{x}) \left[\frac{1}{\mu_0} \vec{B}_0(\vec{x})\vec{B}_1(\vec{x}) - \varepsilon_0 \vec{E}_0(\vec{x})\vec{E}_1(\vec{x}) \right]$$

Our focus is the kHz – MHz range, therefore our setup will be optimized to maximize the mechanical coupling.



DETECTION SCHEME



Leveraging the symmetry difference in the modes we can achieve:

- Signal mode suppression in input
- Pump mode suppression in readout

Further improvements:

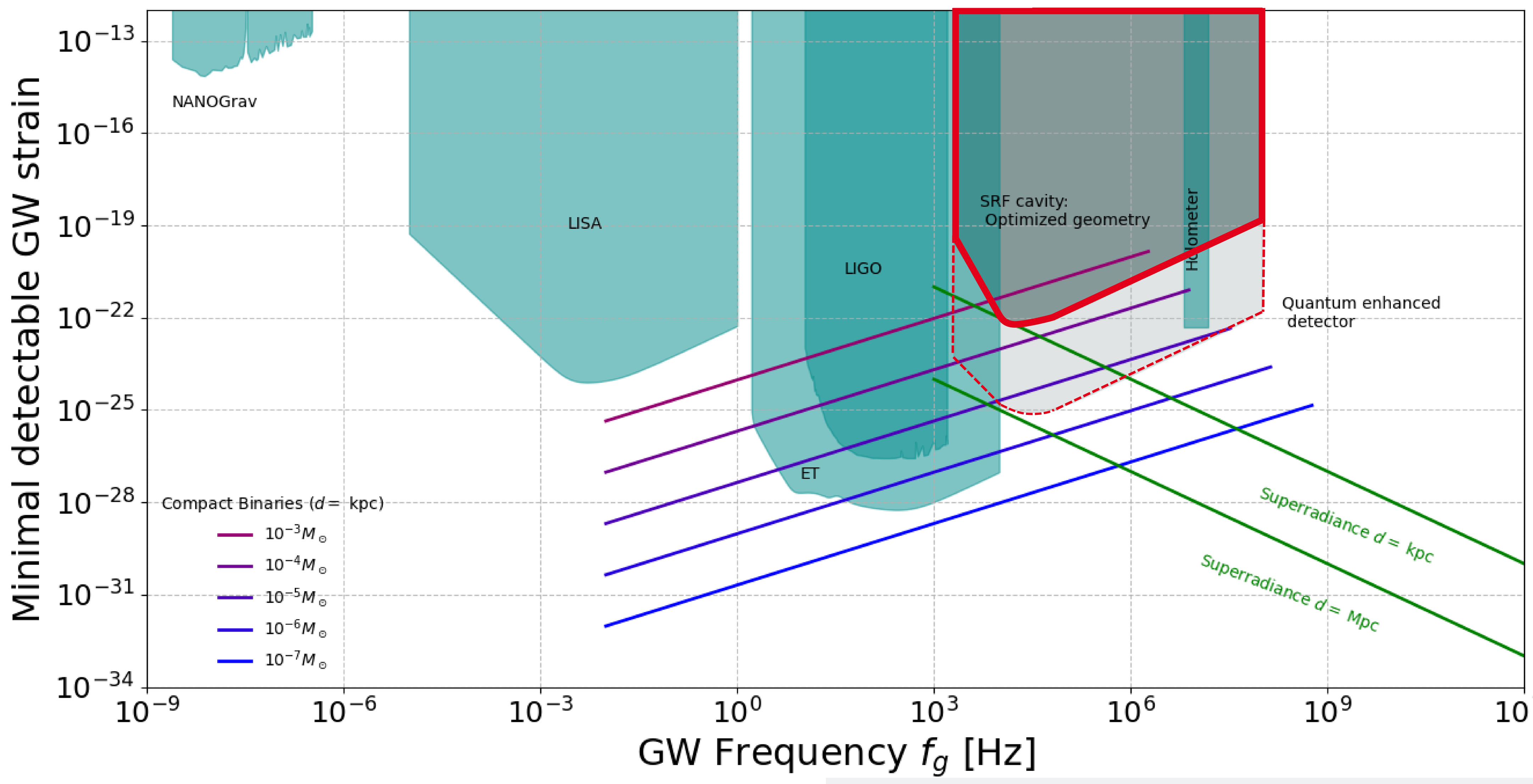
- Carrier suppression interferometry in readout

L. Springer et al., "Phase Noise Measurements for L-Band Applications at Attosecond Resolution," IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1–7, 2022

- Quantum enhancement techniques to amplify and improve the readout

The scheme shows a very simplified version of the drivinig / readout system we want to implement.
The first idea of this scheme was introduced by the PACO collaboration.

P. Bernard, et al., "The rf control and detection system for PACO the parametric converter detector," Apr. 17, 2000



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," Aug. 22, 2023
Z. Arzoumanian et al., "The NANOGrav 12.5 yr Data Set: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries," ApJL, vol. 951, no. 2, p. L28, Jul. 2023
T. L. S. Collaboration et al., "Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs," ApJ, vol. 935, no. 1, p. 1, Aug. 2022

PREDICTED SENSITIVITY

A way to define the sensitivity is by using the noise strain power spectral density S_n. This can be interpreted as the power spectral density (PSD) of the noise if it was mistaken for strain generated by a GW.
We found that the minimum detectable strain for our setup is:

$$h_{min}(\omega_g) \sim \sqrt{S_n(\omega_g)} := \sqrt{\frac{S_{noise}(\omega_0 + \omega_g)}{|T(\omega_g)|^2}}$$

$$|T(\omega_g = \Delta\omega)|^2 \sim \frac{\beta_{in}\beta_{out}}{(1+\beta_{in})^2} \cdot \frac{\omega_0}{Q_0} \cdot V_{cav} \cdot B_{eff}^2 \cdot |C_{01}^m \Gamma_m|^2 \cdot Q_L^2$$

The main noise sources are:

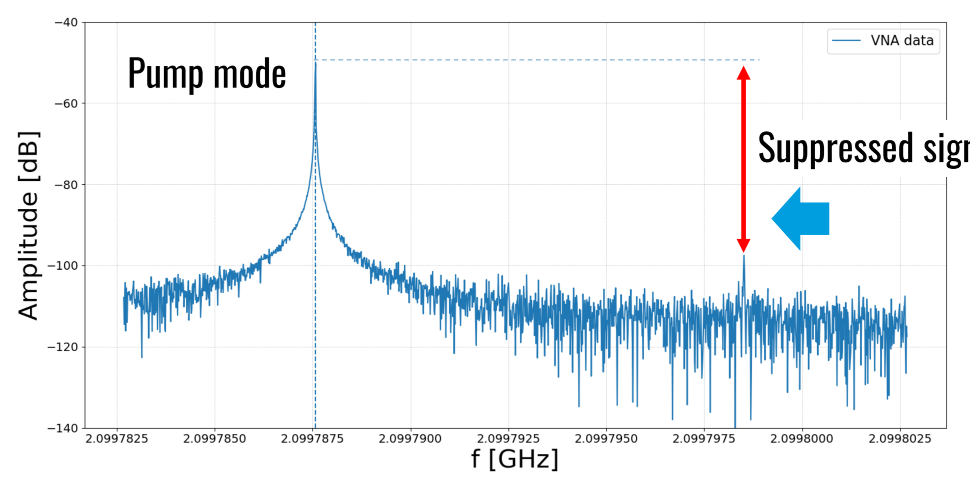
- Mechanical $\sqrt{S_{mech}(\omega_g)} \sim \Gamma^{-1} \cdot q_{rms} \cdot Q_{mech}^{-\frac{1}{2}} \cdot \left(\frac{\omega_{mech}}{\omega_g}\right)^{\frac{3+\alpha}{2}} \cdot \omega_g^{-\frac{1}{2}}$
- Thermal $\sqrt{S_{th}(\omega_g)} \sim \frac{1+\beta_{in}}{\sqrt{\beta_{in}\beta_{out}}} \cdot B_{eff} \cdot Q_0^{\frac{1}{2}} \cdot (C_{01}^m \Gamma_m)^{-1} \cdot (\omega_g - \Delta\omega)$
- RF Dependent on instrumentation

L. Fischer et al., "First characterisation of the MAGO cavity, a superconducting RF detector for kHz-MHz gravitational waves," Nov. 27, 2024

Many parameters play a role in both increasing the sensitivity but the noise as well:

- Q_L quality factor of the SRF cavity. Increasing this paremeter increases the sensitivity on resonance.
- The coupling coefficients determine the efficiency of conversion from GW to detectable signal, but this also means that any other source of mechanical vibration that excites a mechanical mode with the correct shape gets enhanced as well.
- $B_{eff}^2 := \frac{1}{V_{cav}} \int_{V_{cav}} dV \cdot B_0^2$ The effective magnetic field shows how efficiently the pump mode stores energy in the cavity. The higher the stored energy, the higher the sensitivity but also the noise. This quantity is also intrinsically limited by the superheating field of the superconductor the cavity is made of.
- The couplings of the input and output ports determine the sensitivity in and out of resonance. A lower coupling would enhance greatly the sensitivity in a very narrow region around the resonances. On the other hand a larger coupling in output broadens the resonance peaks, increasing the sensitivity out of resonance.

EXPERIMENTAL RESULTS



We tested the mode rejection scheme for the input signal with a non optimized setup and obtained a **50 dB** suppression of the signal mode using a VNA.

SOURCES

Some plausible sources of signal in the range of frequencies of our interest are:

- Primordial Black Holes mergers (PBH)
- Black hole superradiance
- Cosmic Gravitational Microwave Background (CGMB)

G. Franciolini, et al. "Hunt for light primordial black hole dark matter with ultrahigh-frequency gravitational waves," Phys. Rev. D, vol. 106, no. 10, p. 103520, Nov. 2022
N. Aggarwal et al., "Challenges and Opportunities of Gravitational Wave Searches above 10 kHz," Jan. 20, 2025

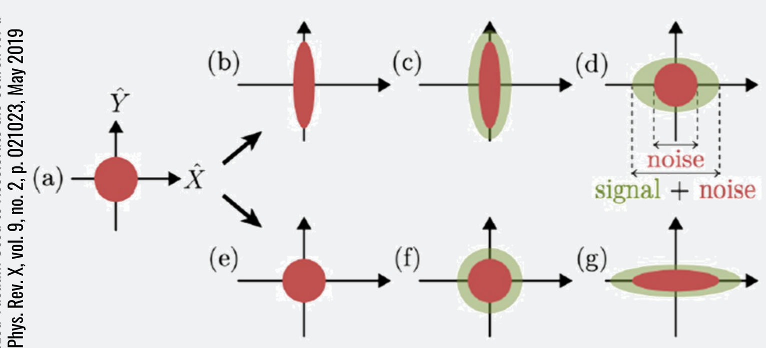
The sensitivity required to measure the signal coming from the CGMB is still out of reach, but since this is a very likely signal motivated within the Standard Model, it's natural to aim to detect it with future upgrades of the system.

QUANTUM ENHANCEMENT

Quantum enhancement techniques can improve the broadband sensitivity by lowering the noise level out of resonance.

We have to keep in mind that all these technologies require the readout system to be at least partially at millikelvin temperature!

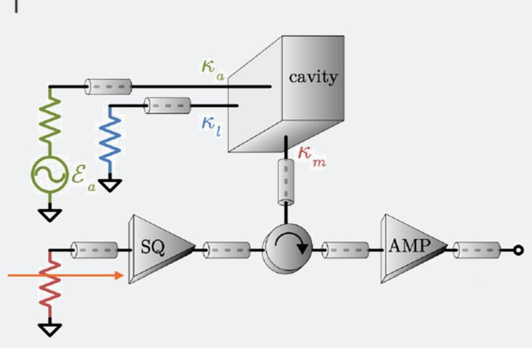
SQUEEZING



Increase the noise in the Y quadrature to reduce it in the X quadrature.

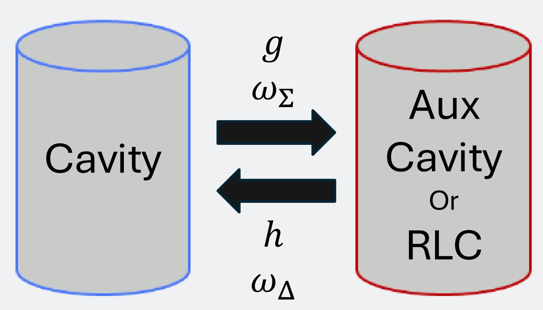
M. Malnou, et al. "Squeezed Vacuum Used to Accelerate the Search for a Weak Classical Signal," Phys. Rev. X, vol. 9, no. 2, p. 021023, May 2019

The Josephson parametric amplifier (JPA) as non-linear element allows to the squeeze of one component with respect to the other.



$\frac{\Delta\omega_{sq}}{\Delta\omega_0} \simeq G$ = gain of the JPA denoted as SQ

BACK-ACTION EVADING AMPLIFICATION



Use a second cavity or RLC circuit coupled to the main cavity with couplings g and h.

Modulating g with frequency $\omega_\Sigma = \omega_{cav} + \omega_{aux}$

Modulating h with frequency $\omega_\Delta = \omega_{cav} - \omega_{aux}$

K. Wurtz, et al. "Cavity Entanglement and State Swapping to Accelerate the Search for Axion Dark Matter," *PRX Quantum*, vol. 2, no. 4, p. 040350, Dec. 2021

ω_Σ Modulation of coupling leads to **parametric amplification** $\propto g$

ω_Δ Modulation of coupling leads to **back-action free** amplification (with $h = g$)

$$\frac{\Delta\omega_{BAE+sq}}{\Delta\omega_0} \sim 2 \cdot 2^{\frac{1}{3}} \cdot G^{\frac{1}{3}} \left(g \frac{Q_0}{\omega_1} \right)^{\frac{2}{3}}$$

For MAGO-like cavity it's possible to obtain a 10^4 improvement in the sensitivity!