CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

MAGO

Detecting high-f gravitational waves with SRF cavities

Giovanni Marconato on behalf of the "MAGO" team

Outline

- The goal
  - Parameters' space exploration
  - Sources we might see
- The physics
  - GW – Cavity interaction
    - From GW to mechanical excitation
    - From mechanical excitation to RF
  - The detection scheme
- The history
  - Past
  - Present

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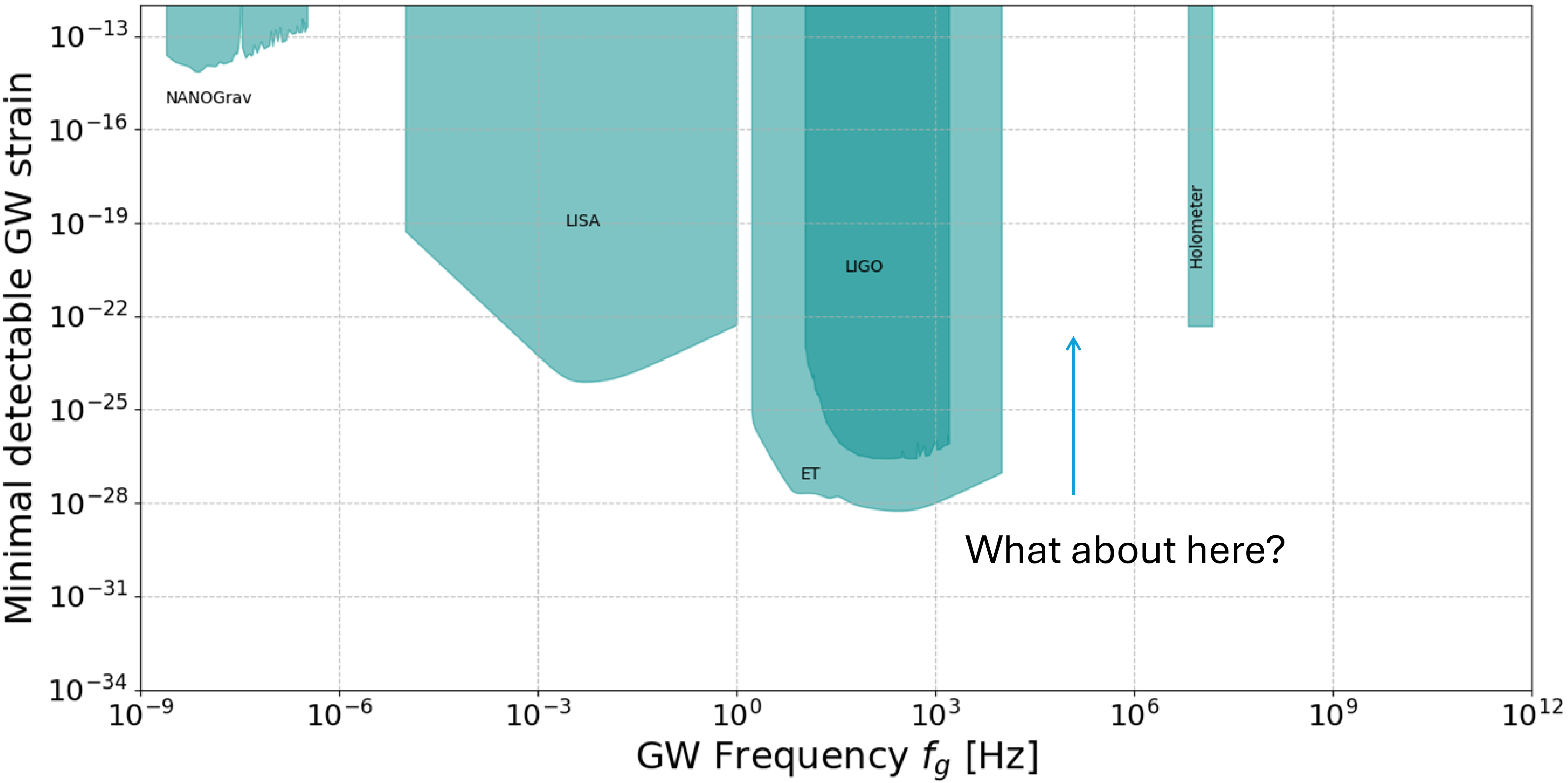
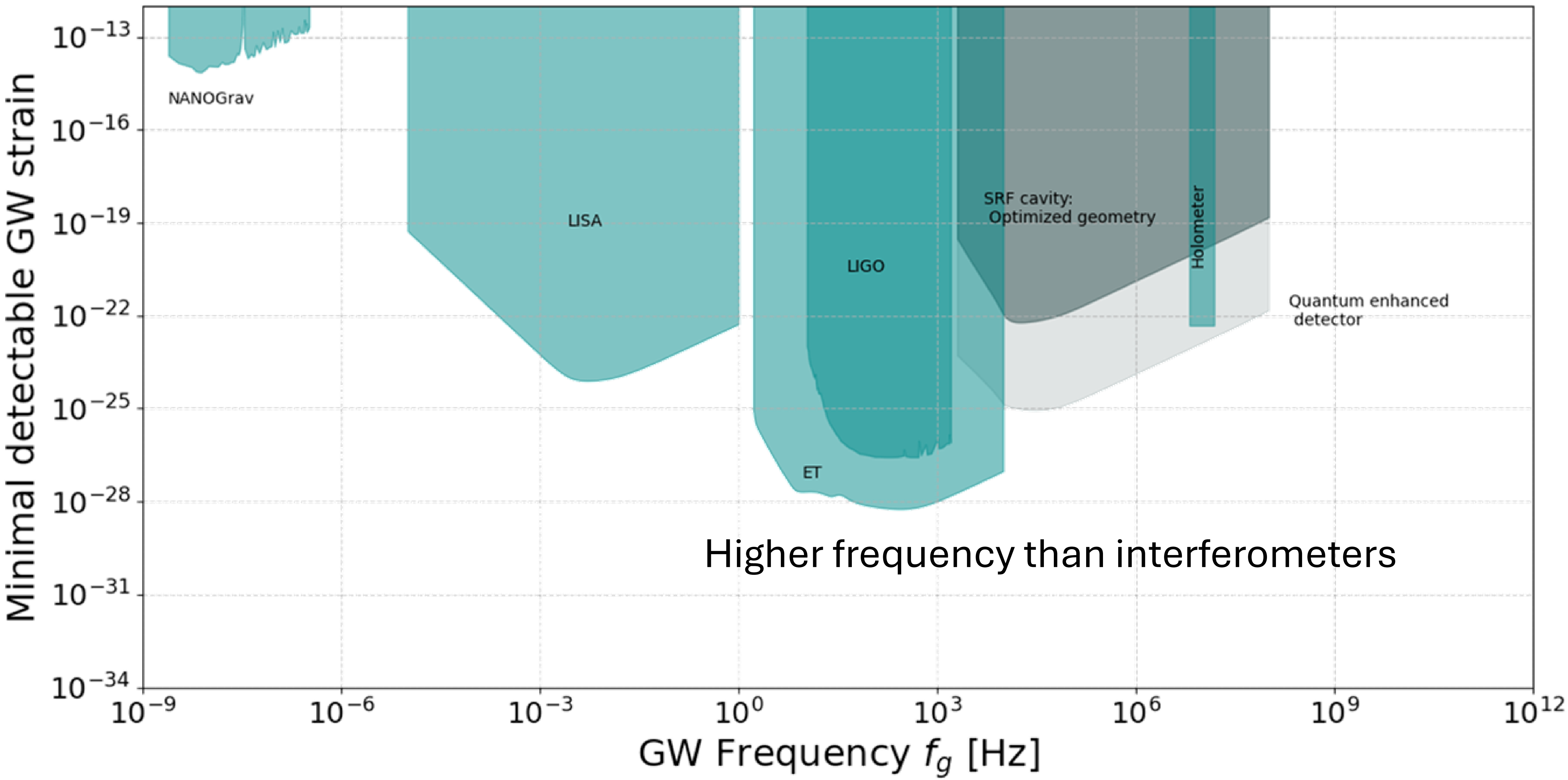
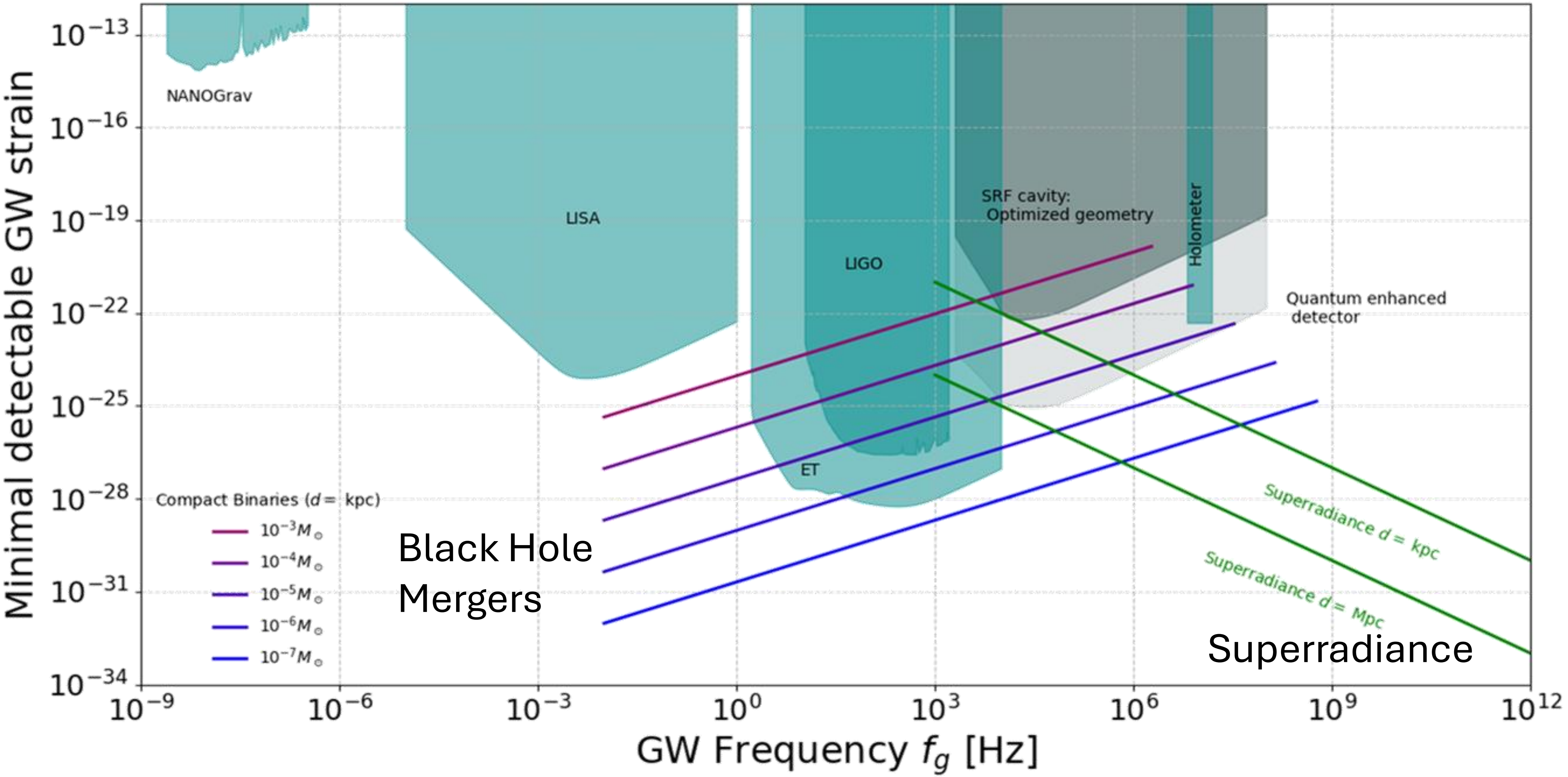
Parameters' space exploration



Parameters’ space exploration



Sources we might see



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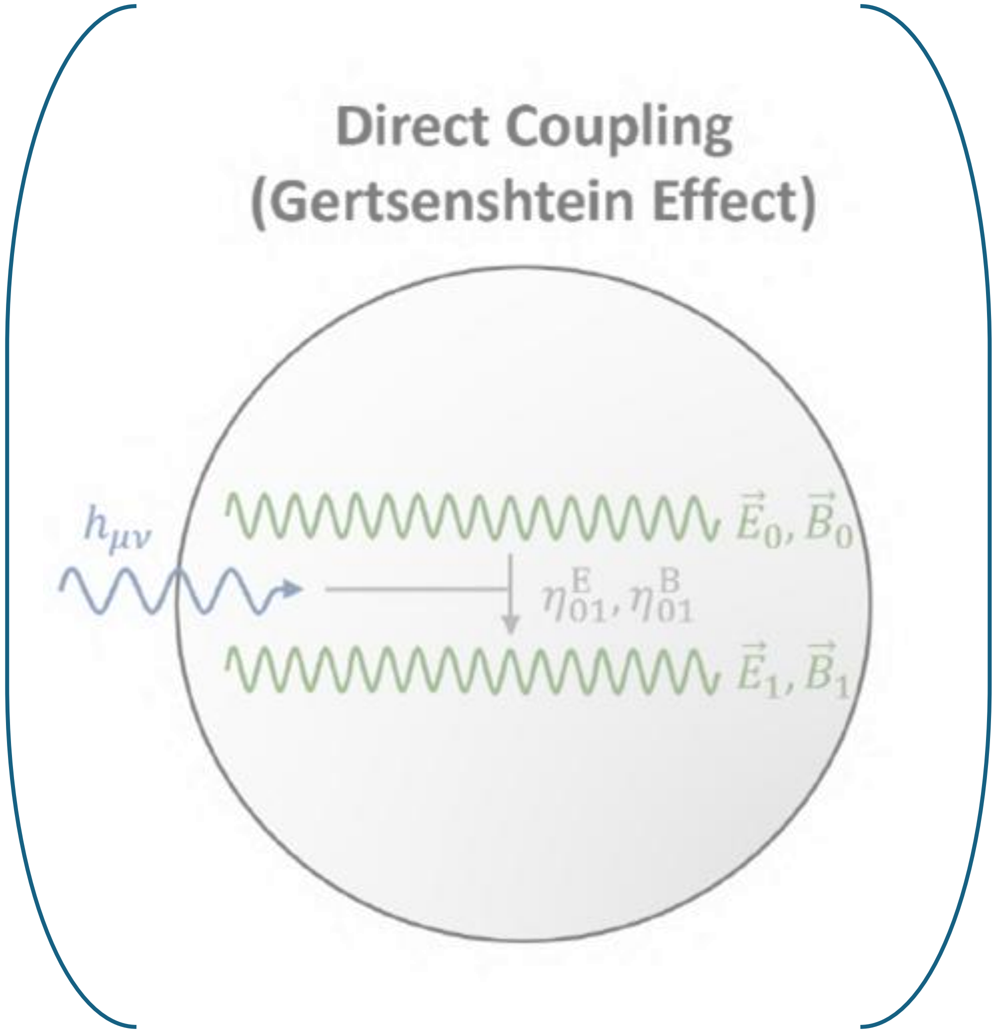
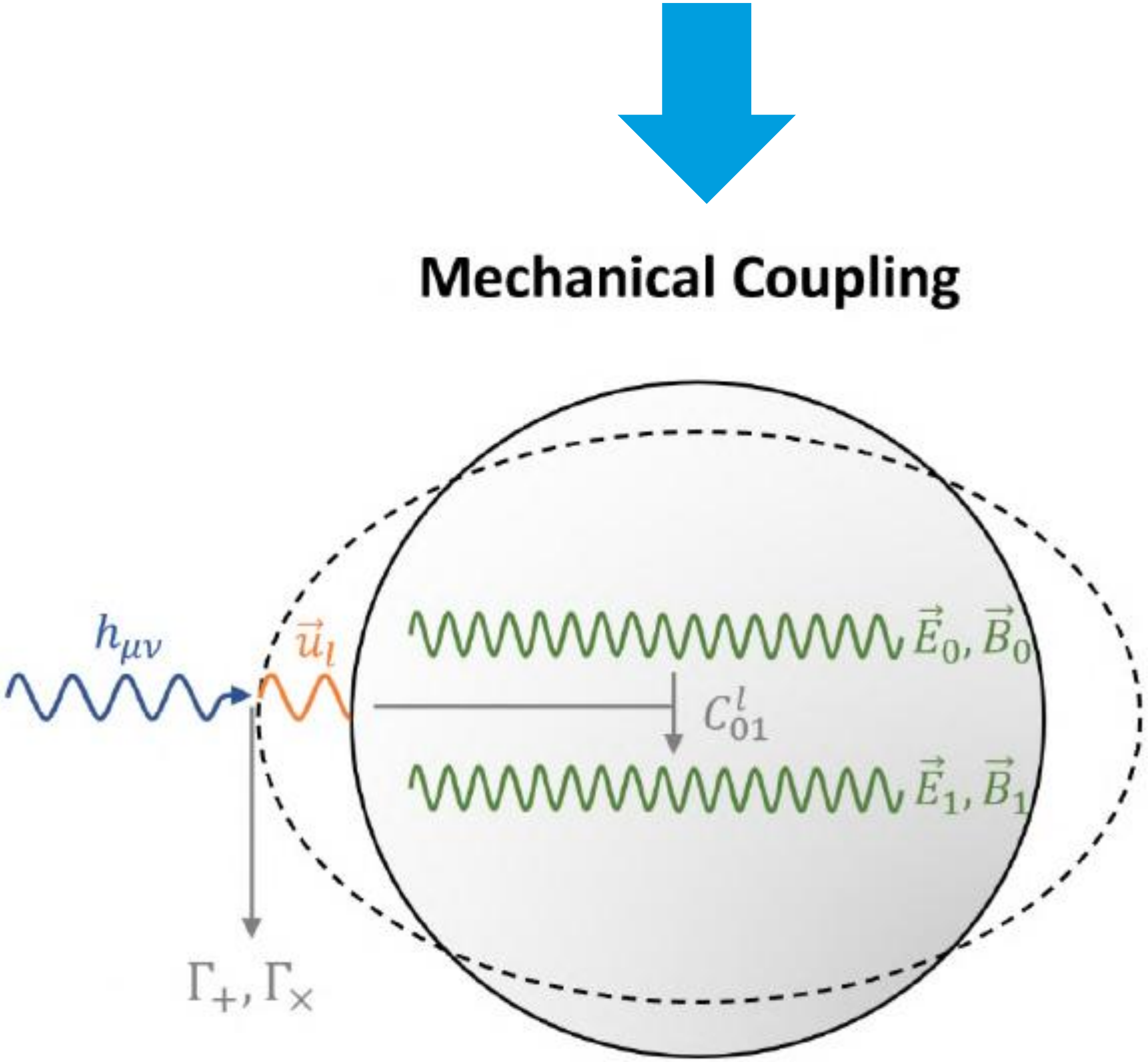
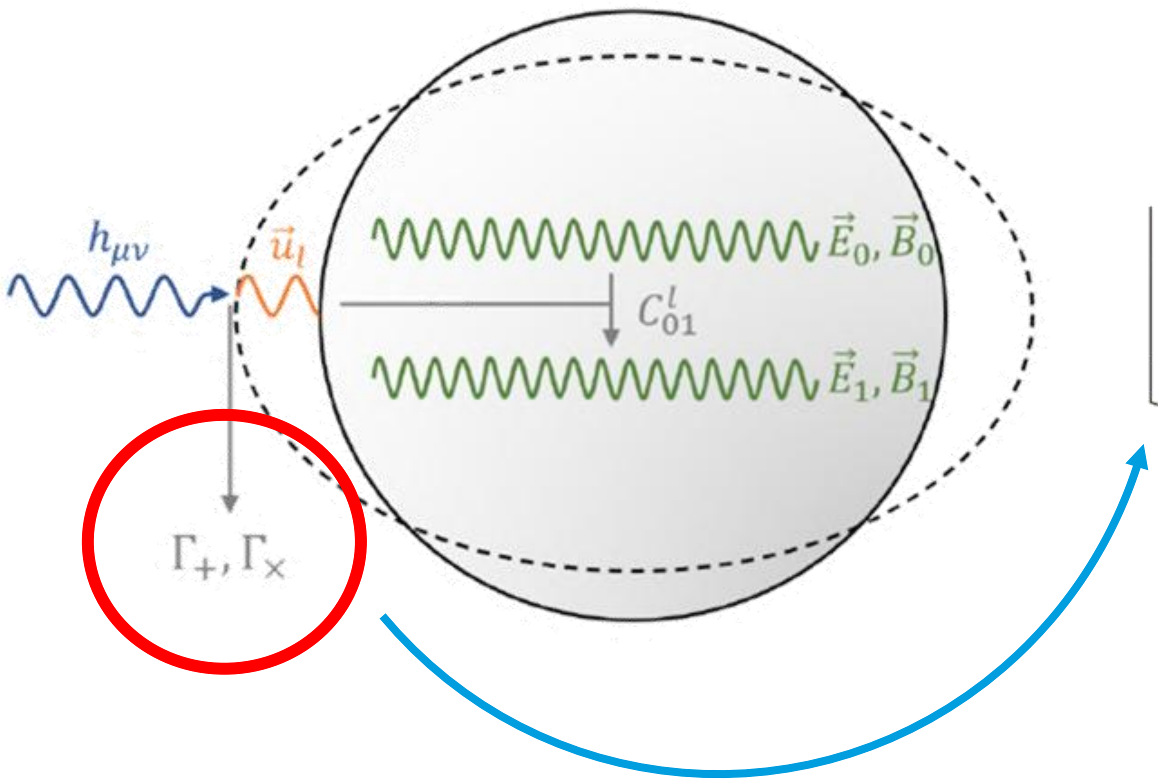
GW – Cavity interaction

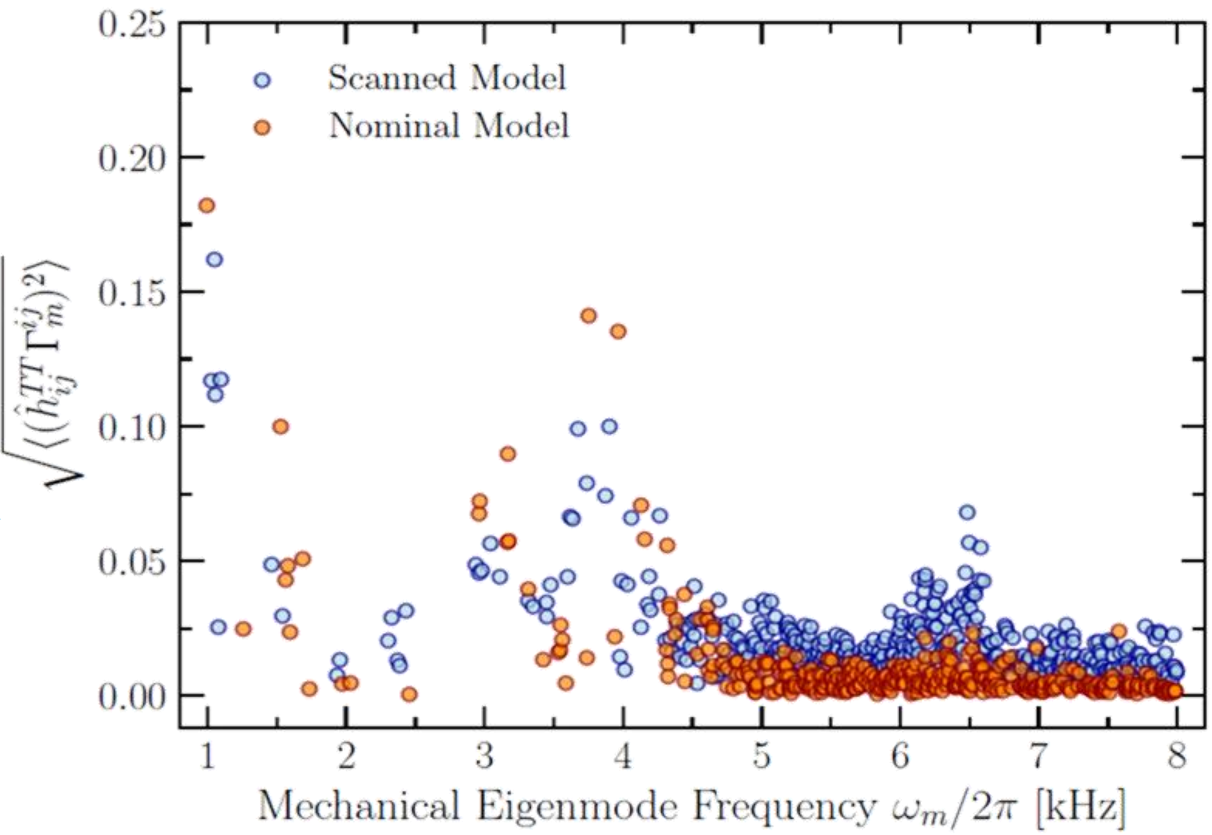




Relevant for higher GW frequencies ~ GHz

From GW to mechanical excitation





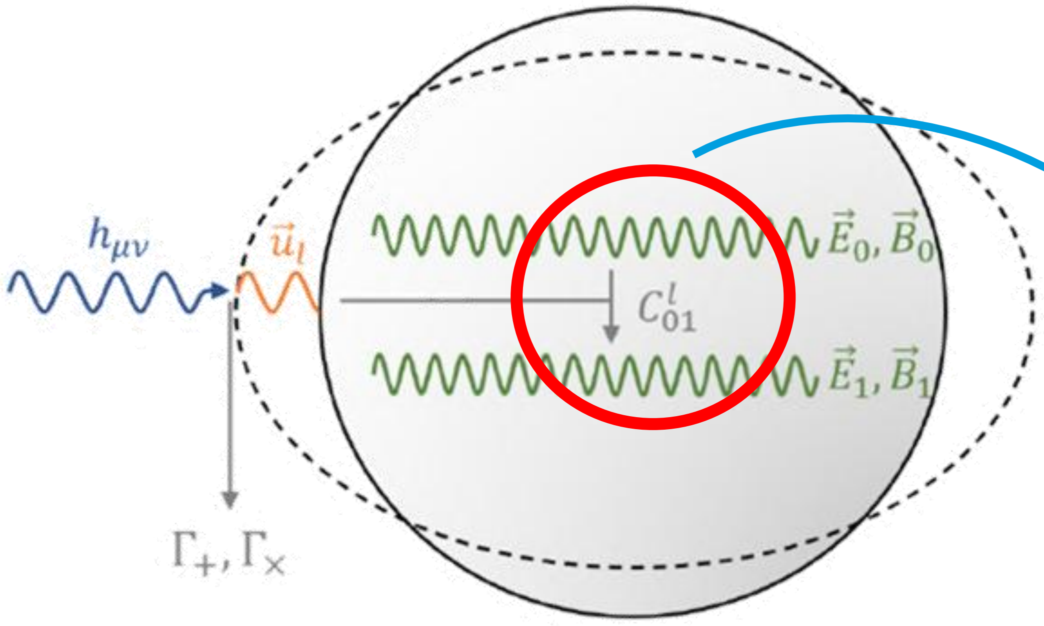
L. Fischer et al., "First characterisation of the MAGO cavity, a superconducting RF detector for kHz–MHz gravitational waves," Class. Quantum Grav., vol. 42, no. 11, May 2025

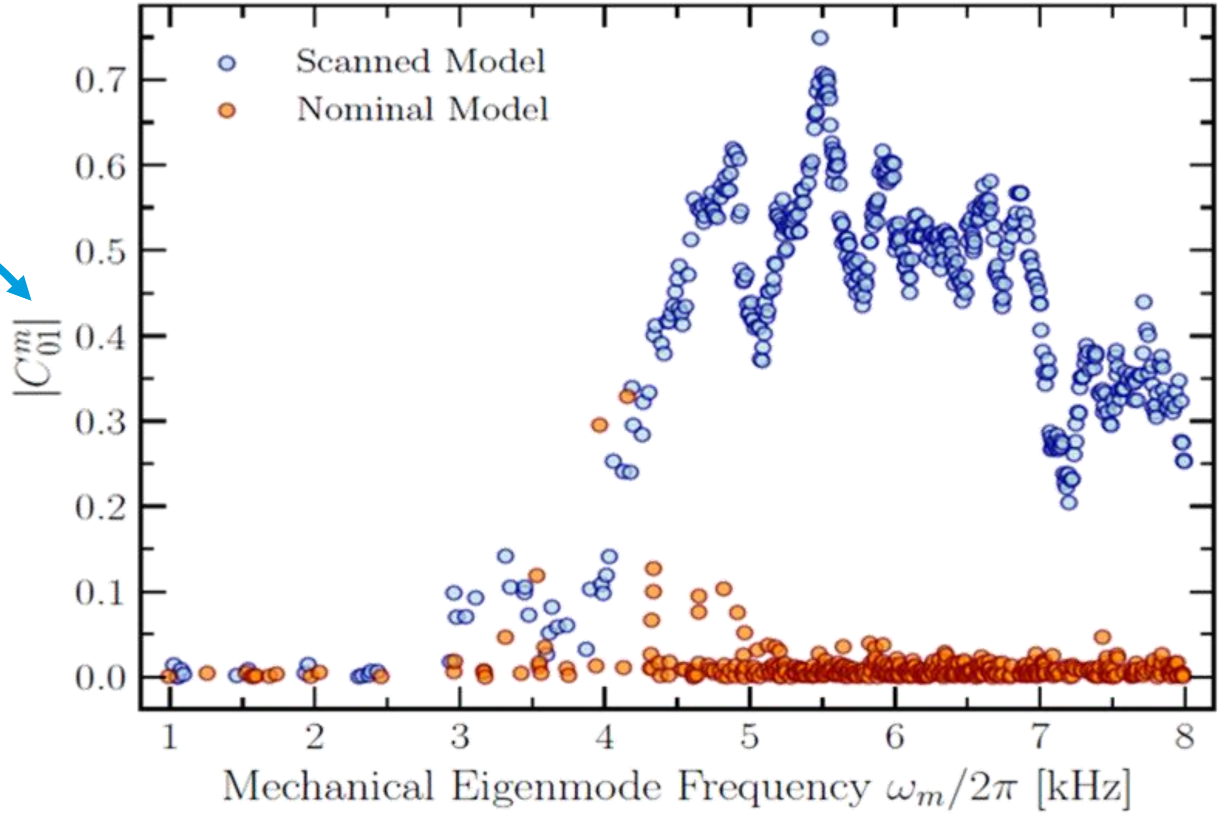
Each mechanical mode couples differently to the GW based on the **shape** of the mode.

→

Based on GW symmetry the first best guess is **quadrupole** shape.

From mechanical excitation to RF





L. Fischer et al., "First characterisation of the MAGO cavity, a superconducting RF detector for kHz–MHz gravitational waves," Class. Quantum Grav. 42(11), May 2025

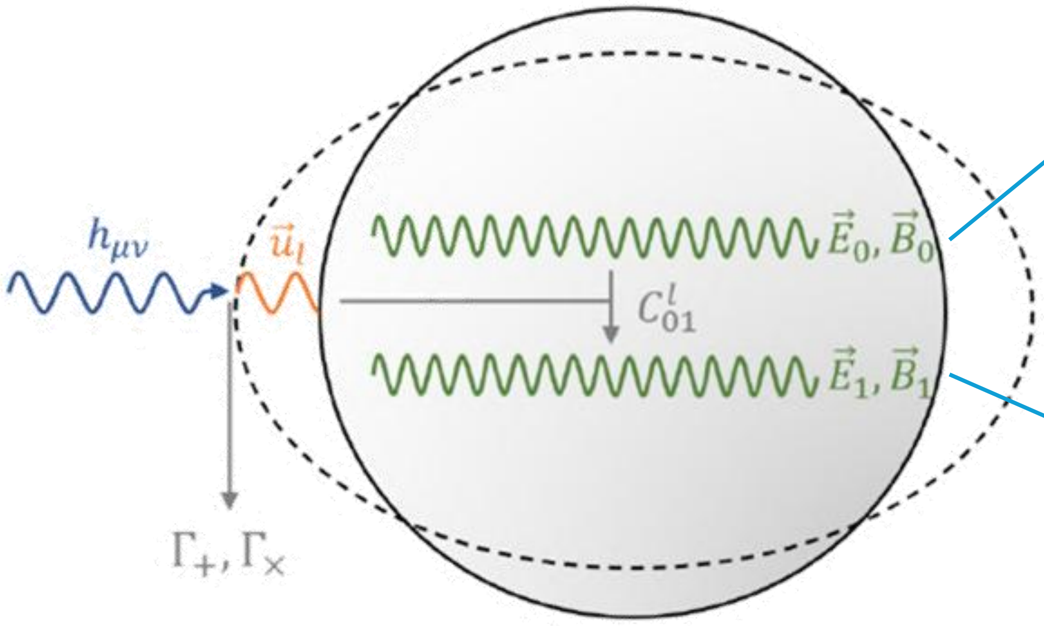
Each mechanical mode couples differently to the EM eigenmodes based on the **spatial distribution** of each mode

$$C^l_{01} \propto B_0 B_1 - E_0 E_1$$

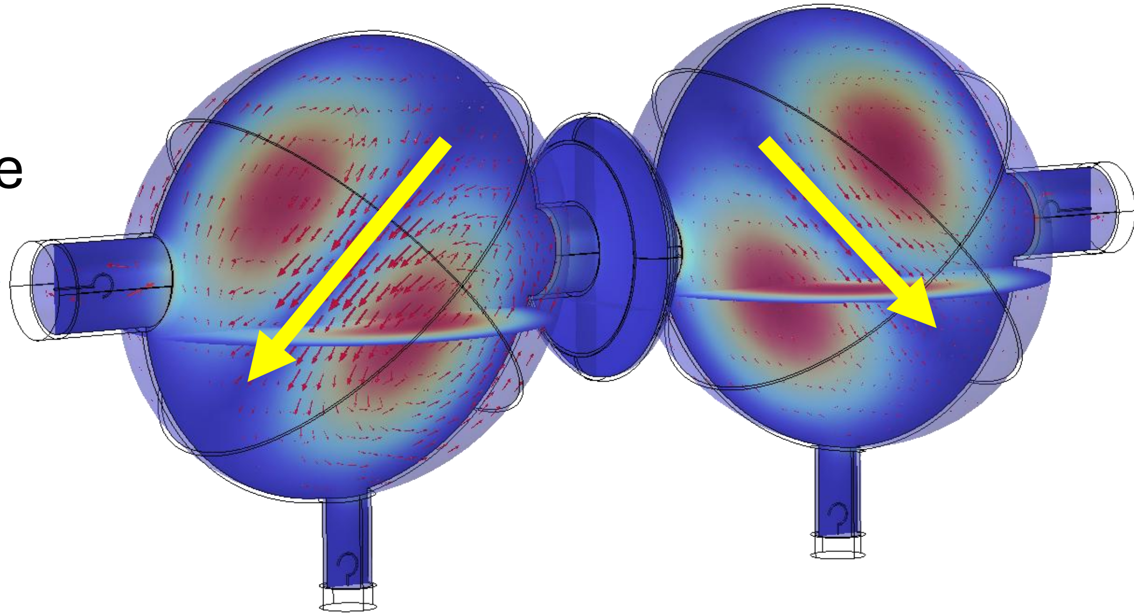
Best EM mode found so far is TE_{011}

At least dipole symmetry and parallel fields between modes

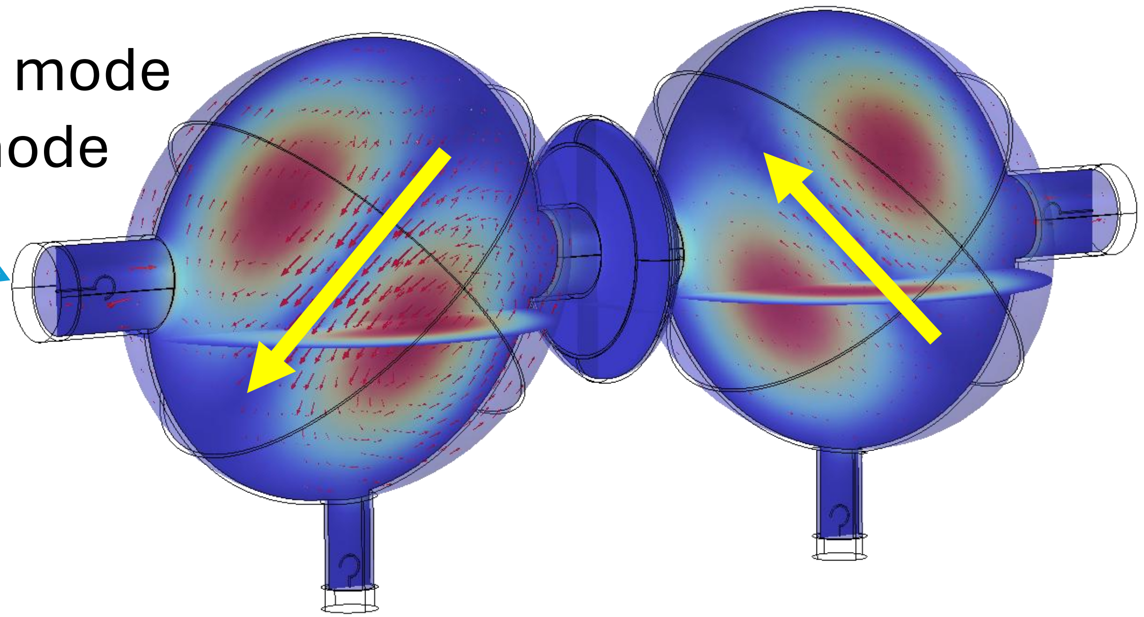
From mechanical excitation to RF



Pump mode
or 0 mode



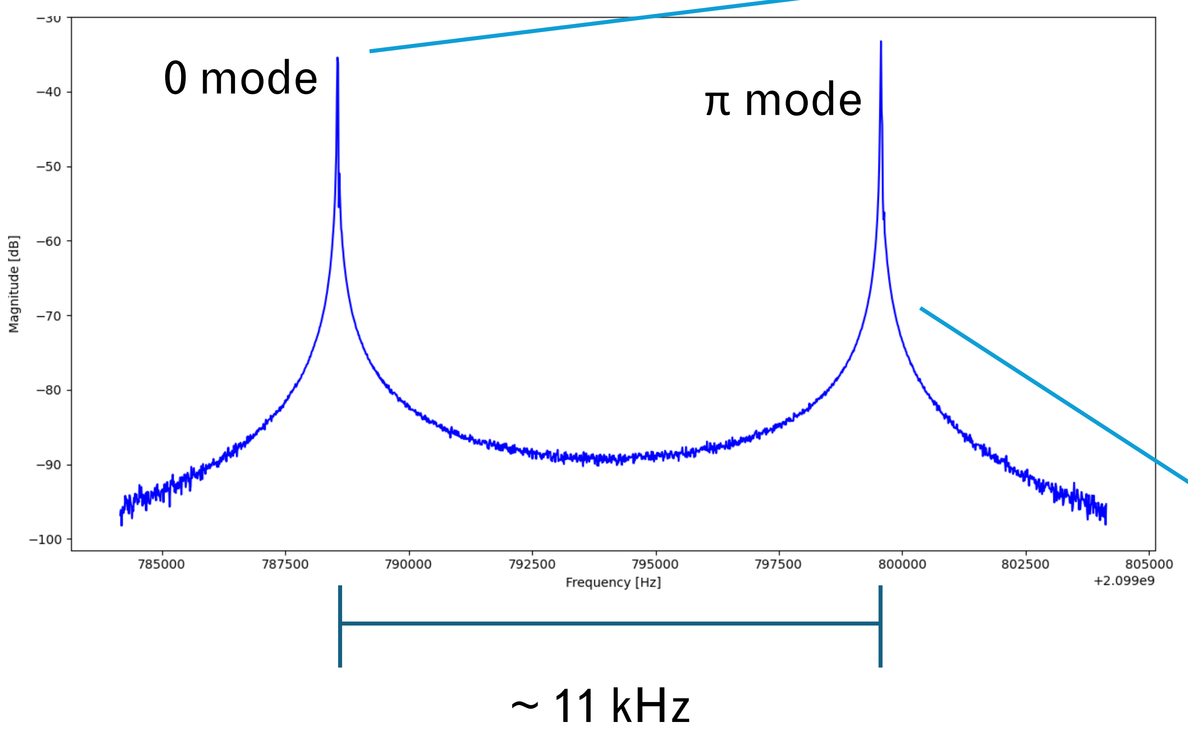
Signal mode
or π mode

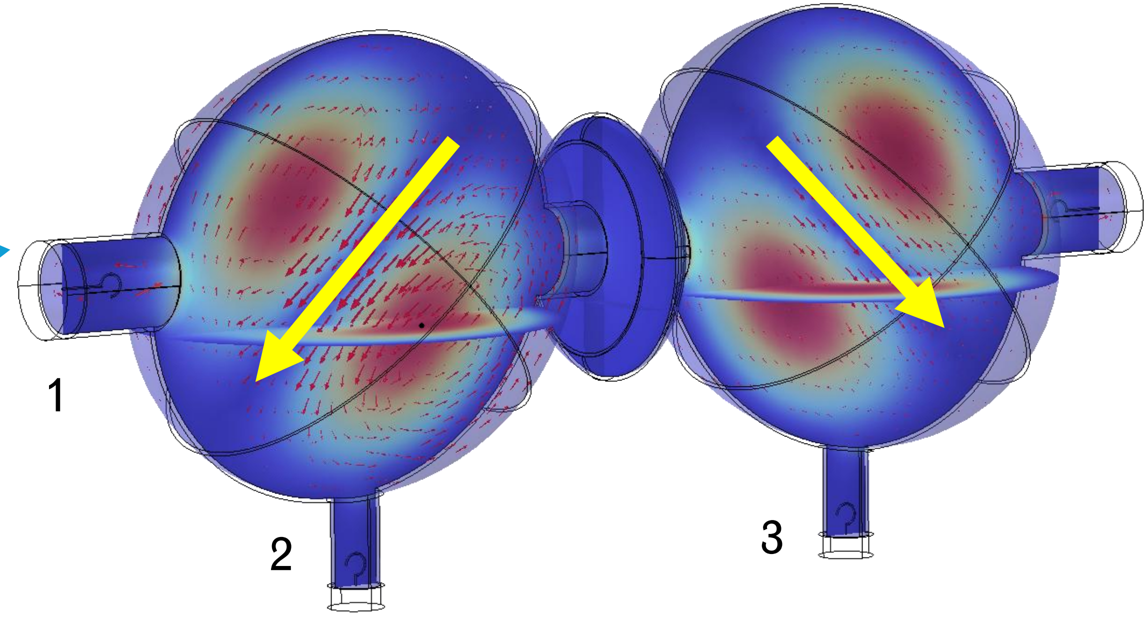


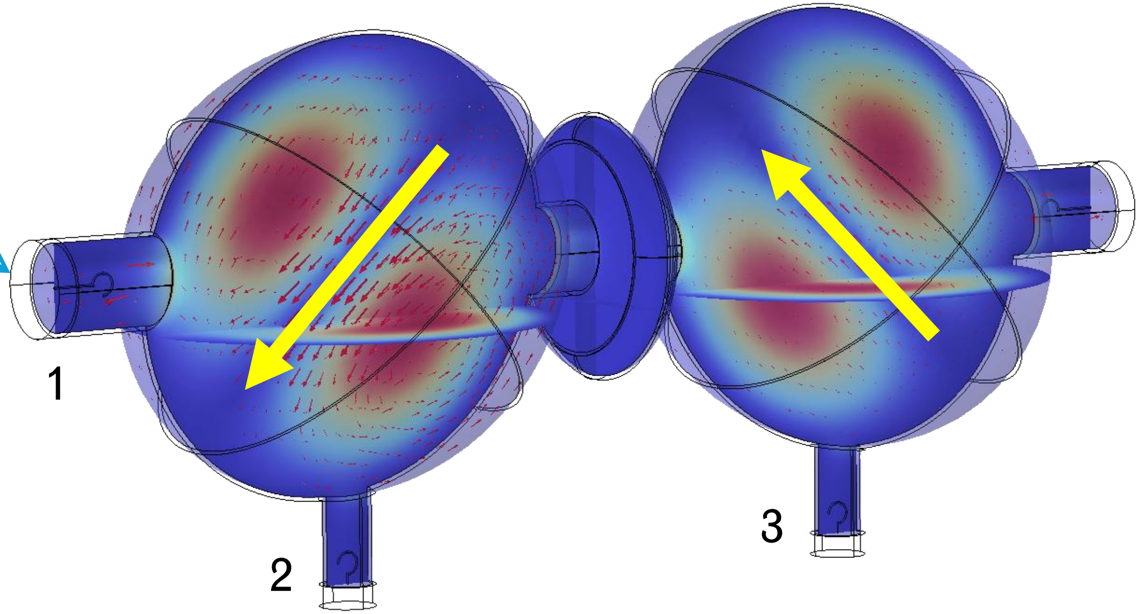
(But maybe there are better modes!)

From mechanical excitation to RF

S31 real measurement

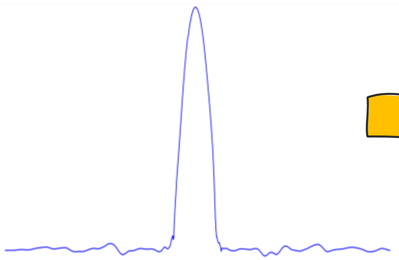


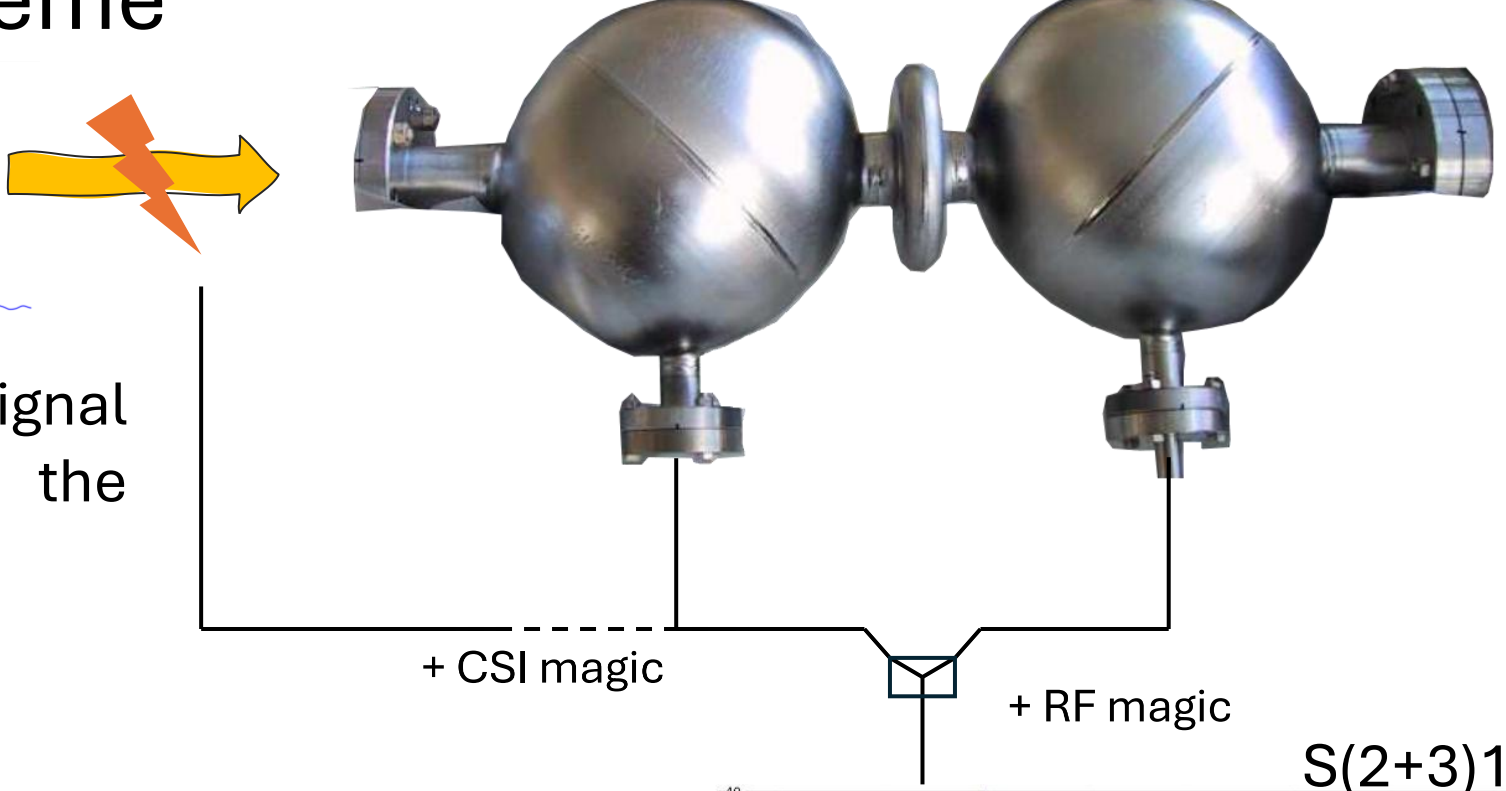




$Q_0 \approx 10^{10}$ @ 2 K

The detection scheme

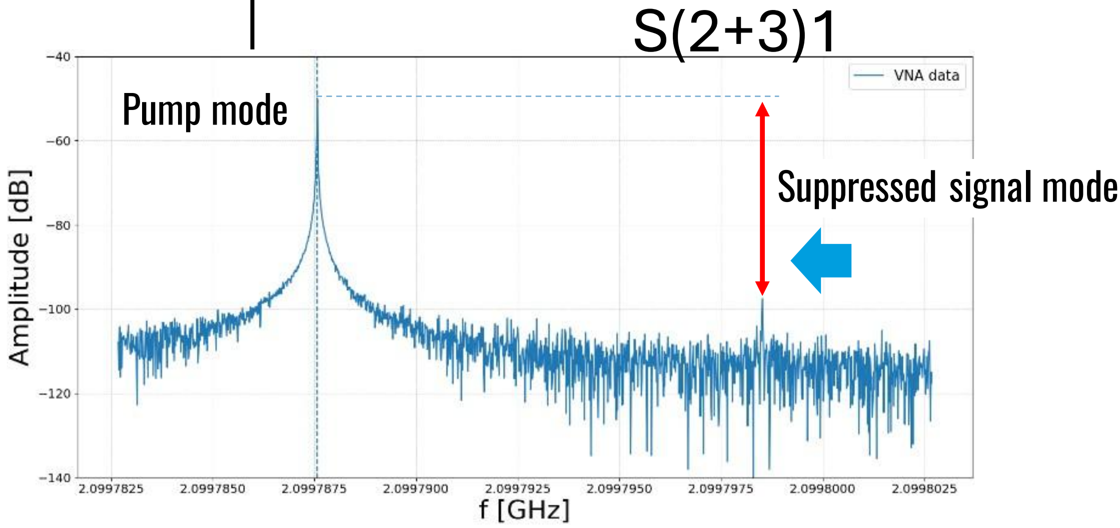




Bandwidth of the input signal is large compared with the peaks spacing

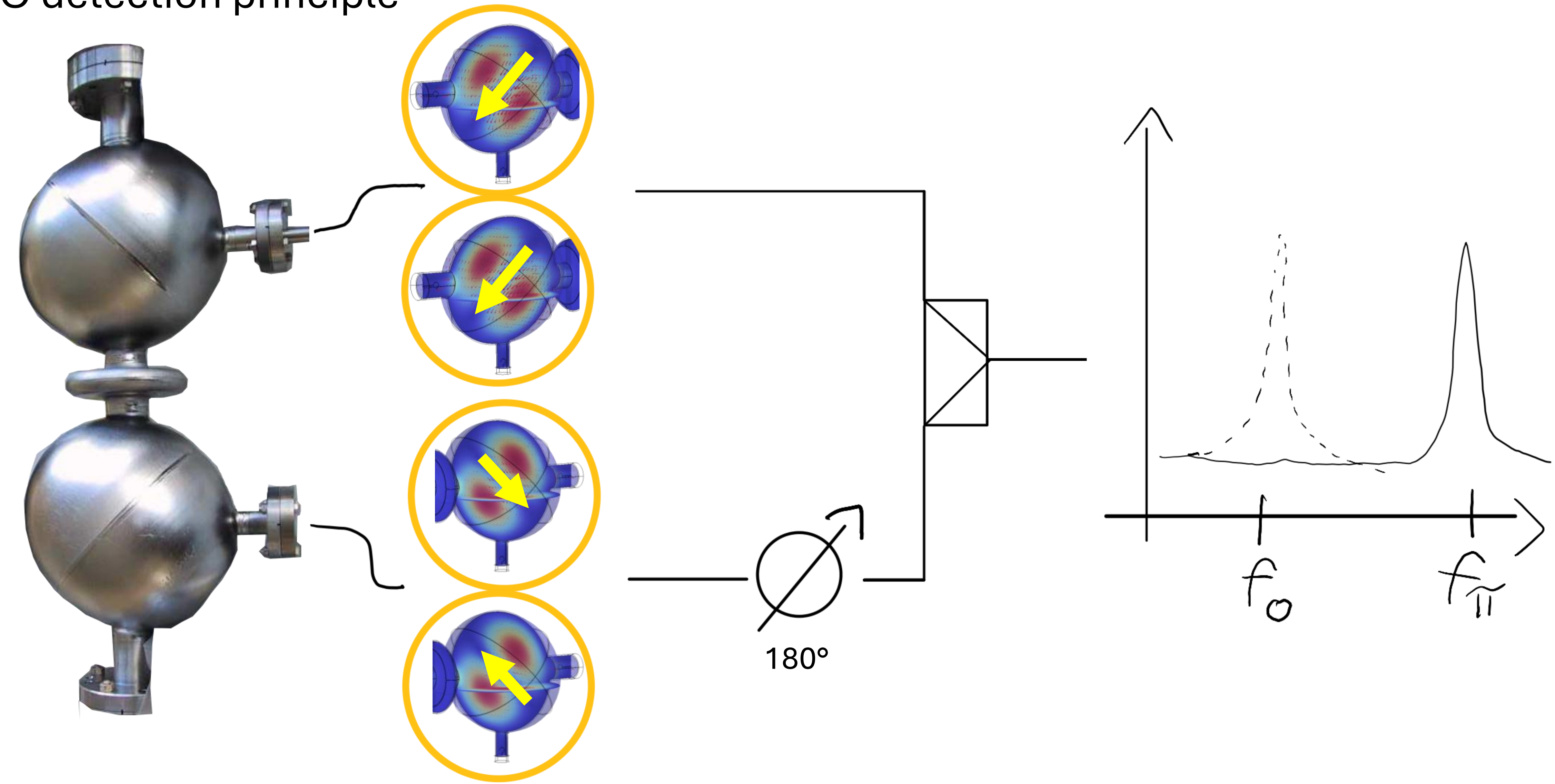
Need multiple strategies to suppress the unwanted excitation of the signal mode

Suppress the pump mode in the output



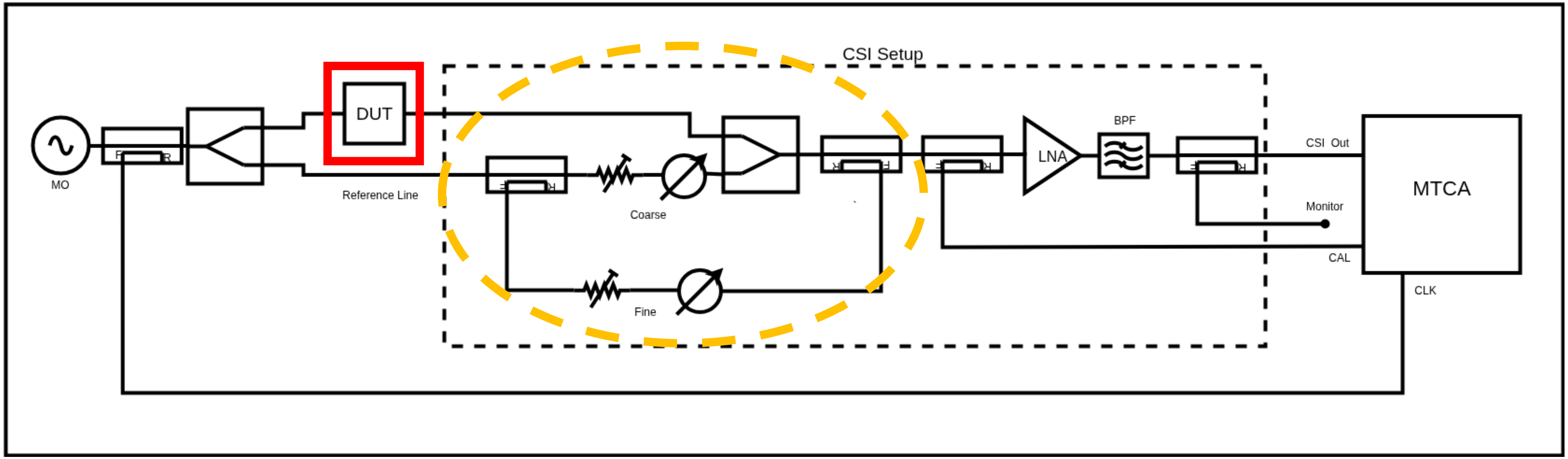
The detection scheme

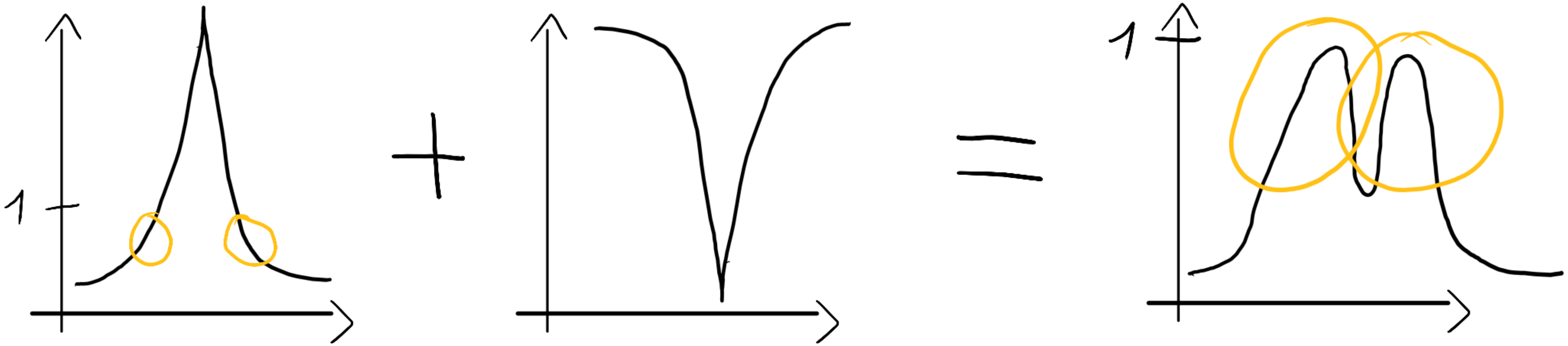
PACO detection principle



The detection scheme

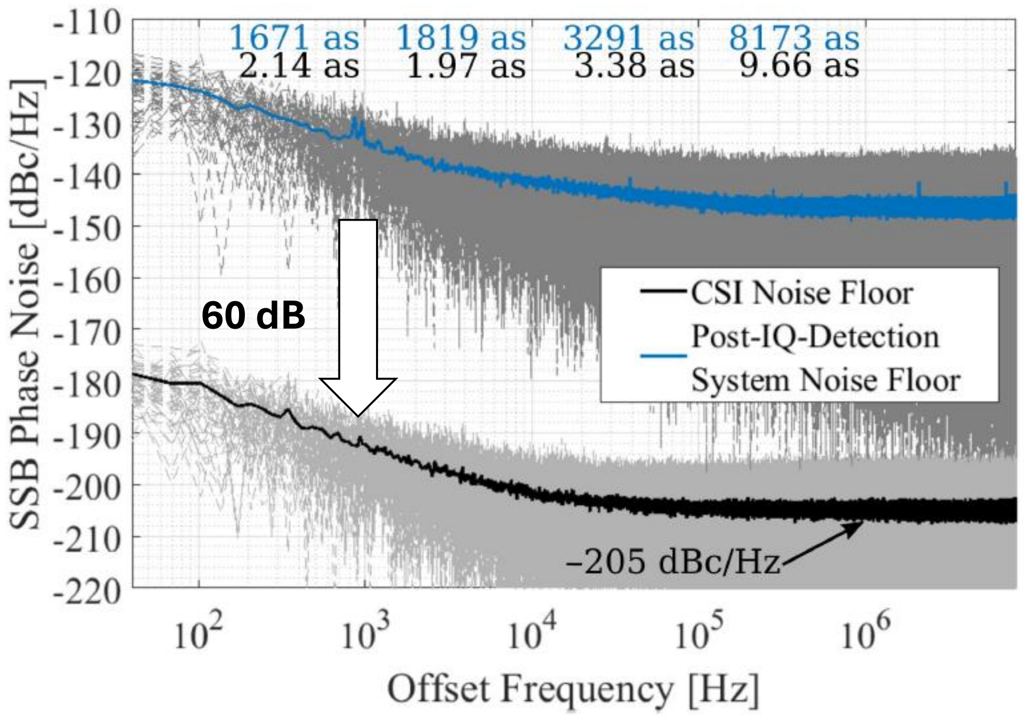
Quick look at CSI

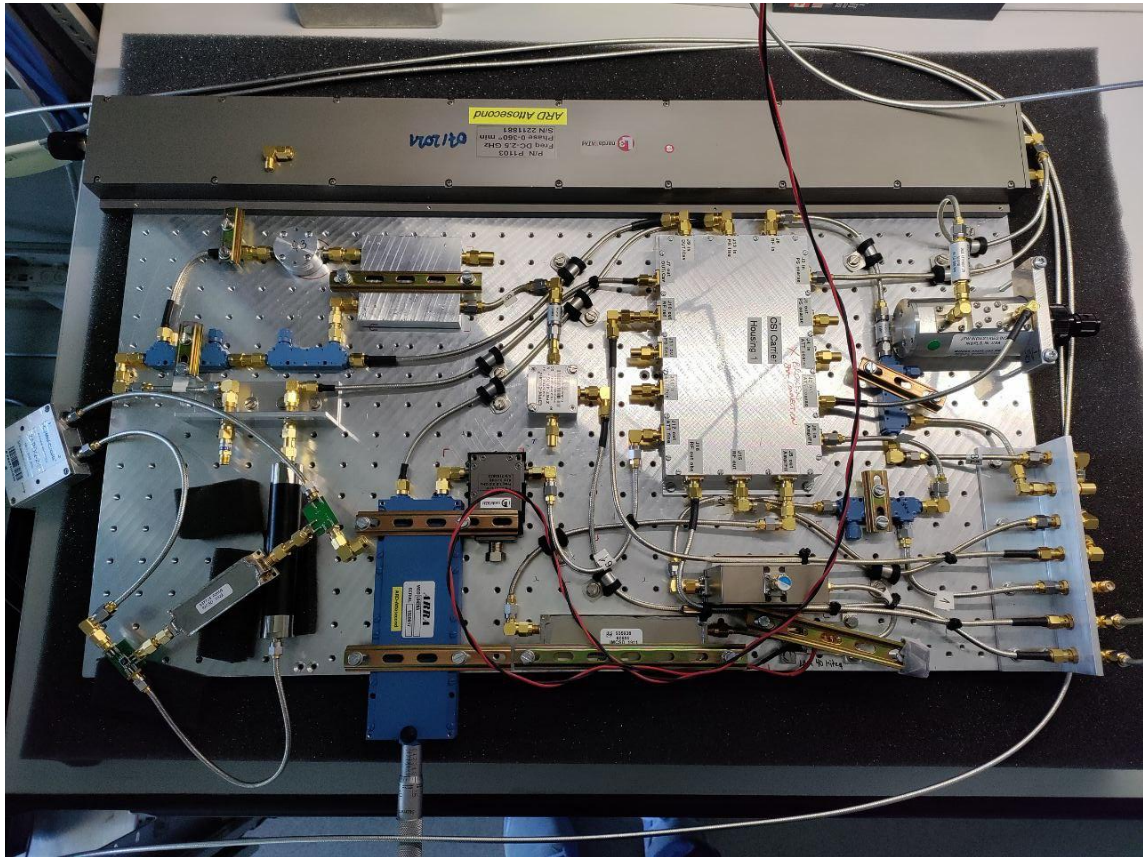




The detection scheme

Quick look at CSI





L. Springer *et al.*, "Phase Noise Measurements for L-Band Applications at Attosecond Resolution," in IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-7, 2022, Art no. 8003307, doi: 10.1109/TIM.2022.3170975.

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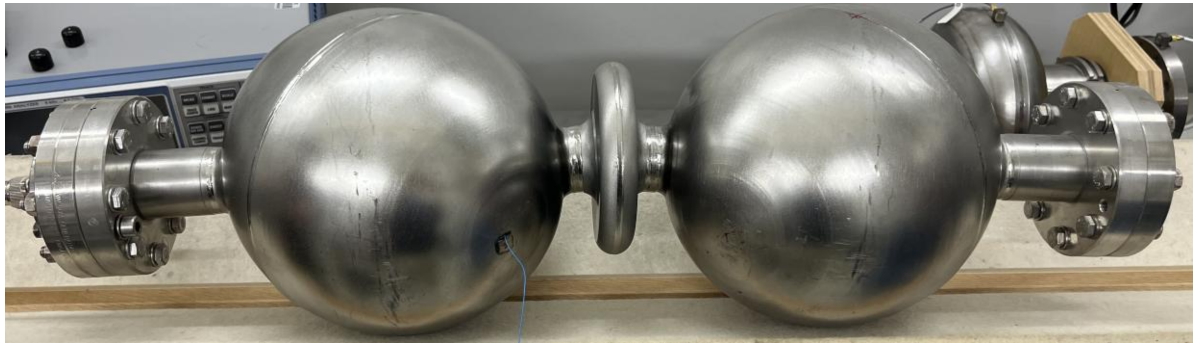
Past



We revived an INFN project and borrowed their prototype

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

INFN GENOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Genova

The cavity was deformed and detuned from sitting in a museum for 10 years

It’s now restored and tested both at FNAL and at DESY

Present

Use the already-made prototype to learn as much as possible

- What parameters really matter?
- Where is our bottleneck now?
- Is the detection scheme working?

How do we optimize?

New cavity

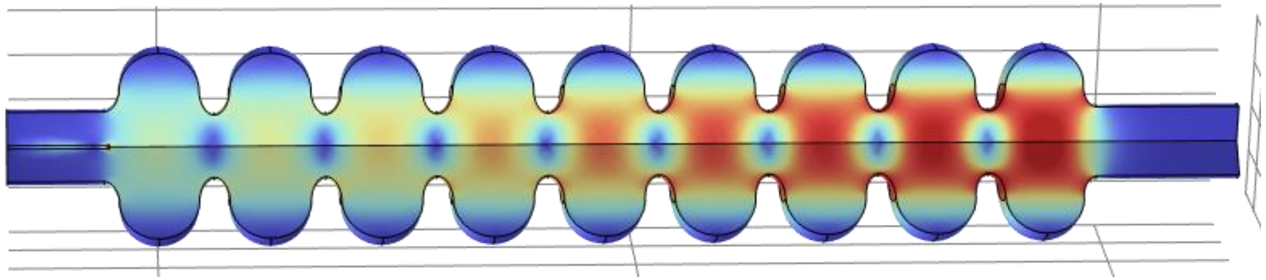
Present

MAXIMIZE

Parameter	Meaning
$\Gamma_{+/\times}$	Coupling of the GW to the mechanical modes of the cavity
C_{01}^{l}	Coupling of the mechanical modes to the EM modes upconversion
B_s	Surface magnetic field (limited by superconductor)
Q_0	Internal quality factor of the cavity
U	Maximum energy stored in the cavity ($\sim E_{acc}^2$ but we have no acceleration)

Present

Simulations using COMSOL



Some results but many questions:

- What's the optimal mesh size → huge impact on results; huge impact on time consumption
- Quantify the distortion of the modes in the cells
- Evaluate the thermal losses → Helium perturbations & back-action
- Optimize antenna couplings
- Mechanical simulation of eigenmodes
- ...

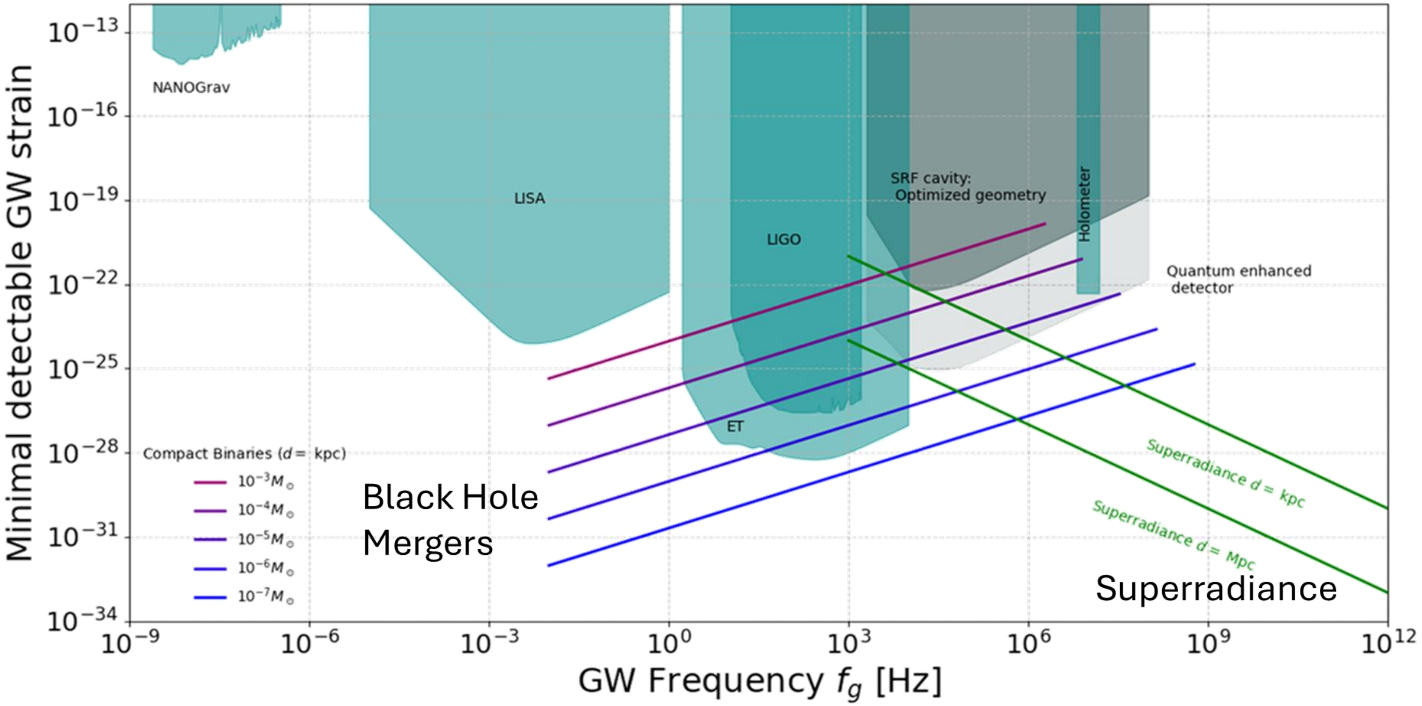
Present

Measurements so far

We have successfully tested the cavity at 2 K @ Fermilab and at 4 K @ DESY

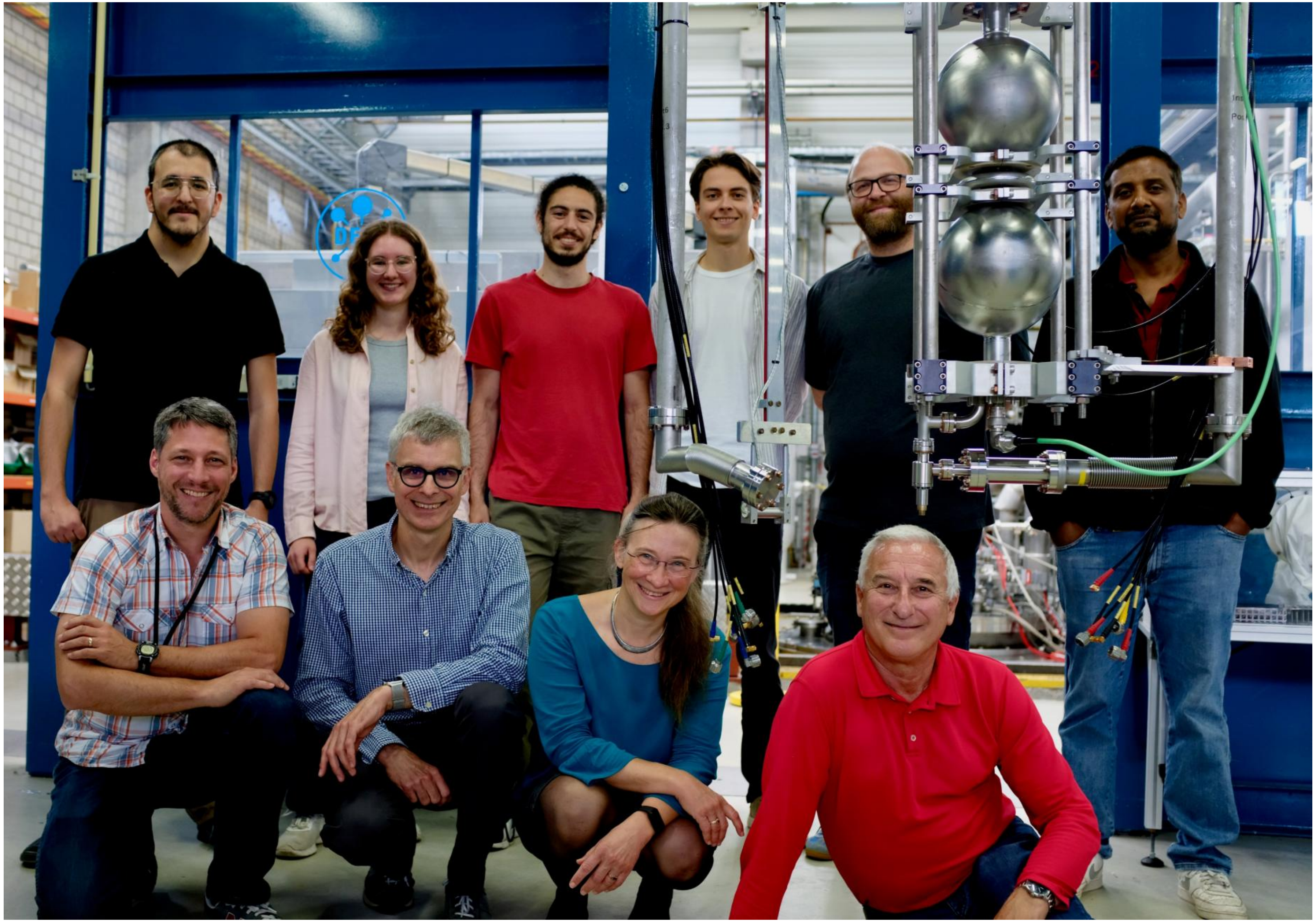
- Design of LLRF system at 2 GHz is almost complete
- PACO principle is working but requires fine tuning → like CSI
- Influence of microphonics and vibration under investigation
- Sensitivity of the π mode to phase noise is under investigation
- Implementation of CSI in discussion
- Do we really want a fast-response frequency control?

Conclusions



- The LLRF requirements for the MAGO project are extremely high but development is ongoing and promising!
- We expect to be able to do a first GW search with this prototype next year
- Optimization of the design is ongoing in parallel and a new cavity will be produced

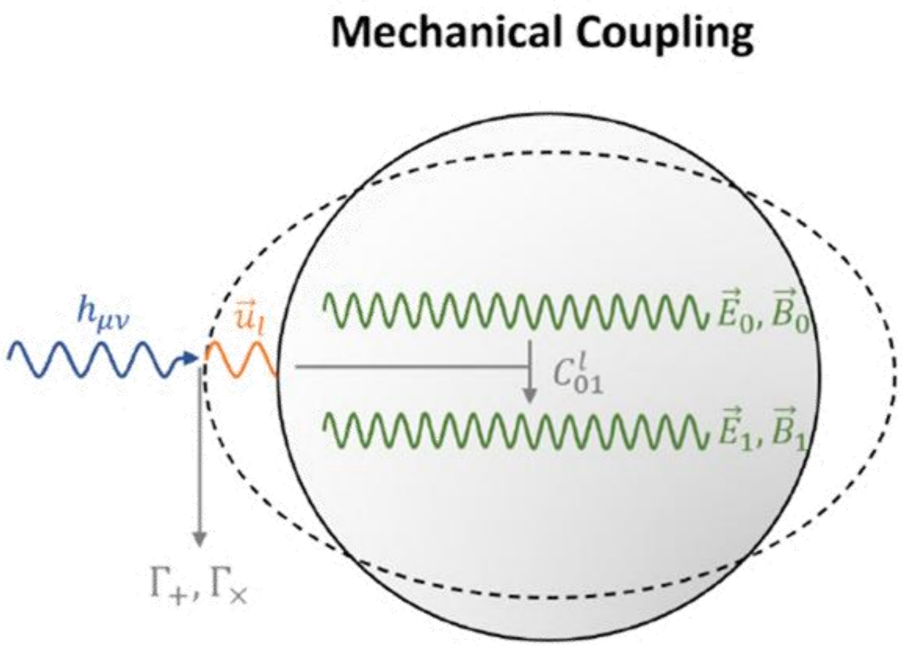
The team



THANK YOU

BACKUP

Hey... Do you want some equations?



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

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

$$C_{01}^l = \frac{V_{cav}^{1/3}}{2\sqrt{U_0 U_1}} \int_{\partial V_{cav}} \mathrm{d}\vec{S} \cdot \vec{\xi}_l(\vec{x}) \left[\frac{1}{\mu_0} \overrightarrow{B_0}(\vec{x}) \overrightarrow{B_1}(\vec{x}) - \varepsilon_0 \overrightarrow{E_0}(\vec{x}) \overrightarrow{E_1}(\vec{x}) \right]$$

Hey... Do you want some equations?

About noise and sensitivity

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

Cavity transfer function GW → signal
$$|T(w_g)|^2 \sim \frac{\beta_{in}\beta_{0ut}}{(1+\beta_{\mathrm{in}})^2}\cdot\frac{\omega_0}{Q_0}\cdot V_{cav}\cdot B_{eff}^2\cdot|C_{01}^m\Gamma_m|^2\cdot\frac{\omega_1^4}{(\omega_1^2-\Delta\omega^2)^2+\left(\frac{(\omega_0+\omega_g)\omega_1}{Q_1}\right)^2}$$

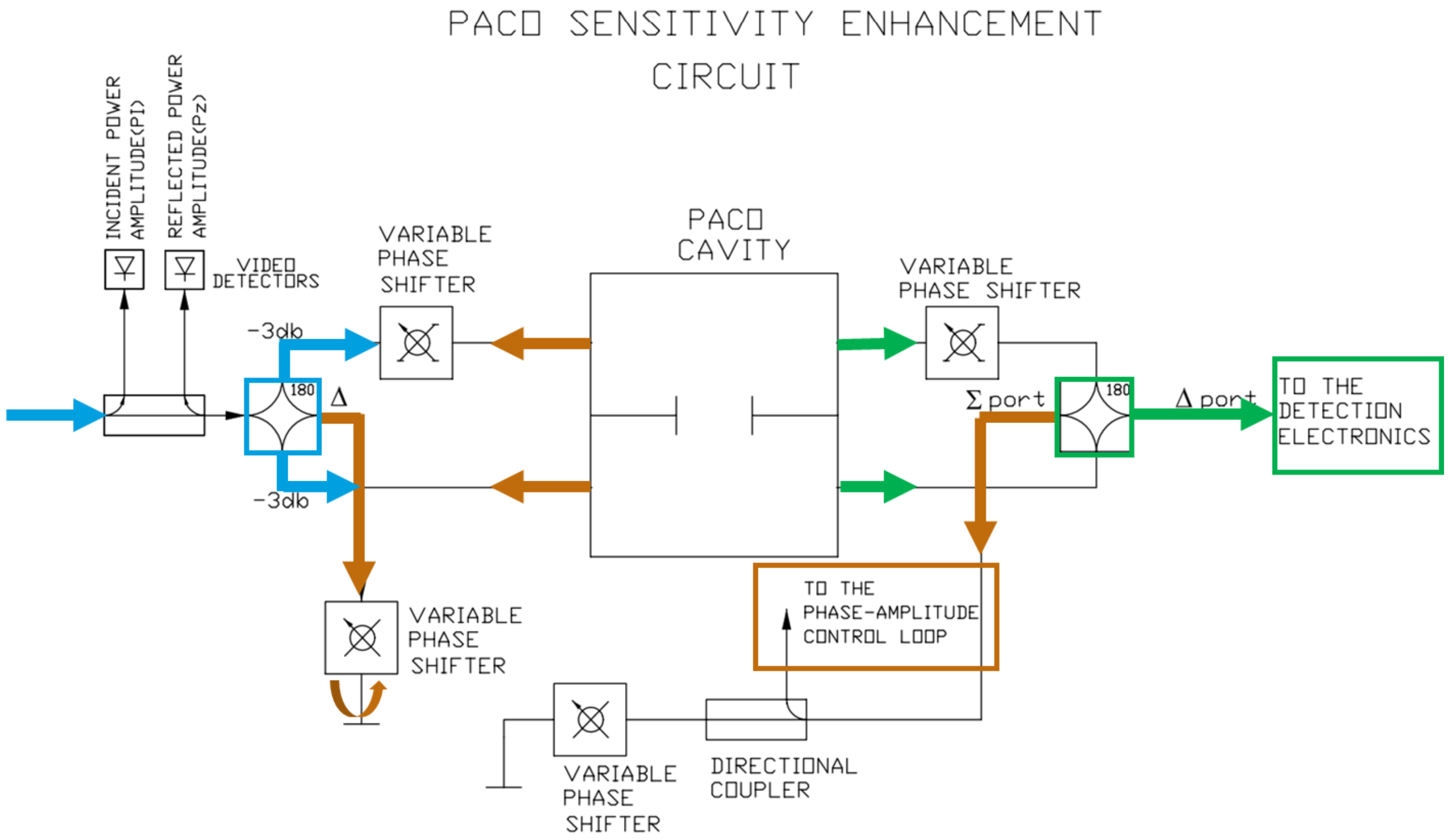
Mechanical noise
$$\sqrt{S_{mech}(\omega_g)} \sim \Gamma^{-1}\cdot q_{rms}\cdot Q_{mech}^{-\frac{1}{2}}\cdot\left(\frac{\omega_{mech}}{\omega_g}\right)^{\frac{3+\alpha}{2}}\cdot\omega_g^{-\frac{1}{2}}$$

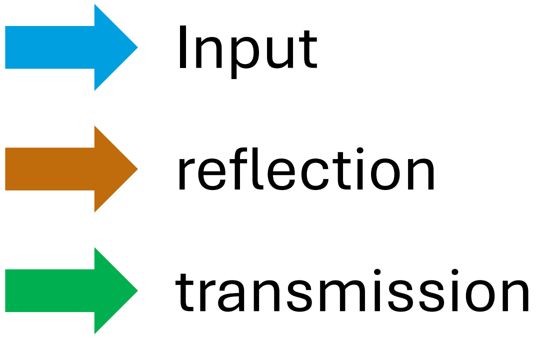
Thermal noise
$$\sqrt{S_{th}(\omega_g)} \sim \frac{1+\beta_{in}}{\sqrt{\beta_{\mathrm{in}}\beta_{\mathrm{out}}}}\cdot B_{eff}\cdot Q_0^{\frac{1}{2}}\cdot(C_{01}^m\Gamma_m)^{-1}\cdot(\omega_g-\Delta\omega)$$

The PACO detection scheme

The final setup is still in discussion after the recent tests @ DESY

This is the previous setup by PACO collaboration:





Courtesy of Julien Branlard, MSK, DESY

Heat dissipation

- Evaluate the thermal losses

→ Helium perturbations

Heat dissipation on the surface of the cavity might cause turbulence in the helium bath

→ Is there a back-action of the helium on the cavity?

If so, how big is the displacement caused?

Compares with the displacement induced by mechanical modes → nm

Parameters' first guess

DISCUSS

Parameter	Meaning
$\omega_{0,1}$	Frequency of the two eigenmodes and **TYPE** of mode
$\Delta\omega$	Spacing between the modes
$Shape$	There is no argument against changing the shape to something different
k_{cc}	Coupling between the cells → linked to previous parameters
$Dimensions$	The only real limit to the cavity dimensions is the cryostat

Distortion

- Quantify the distortion of the modes in the cells

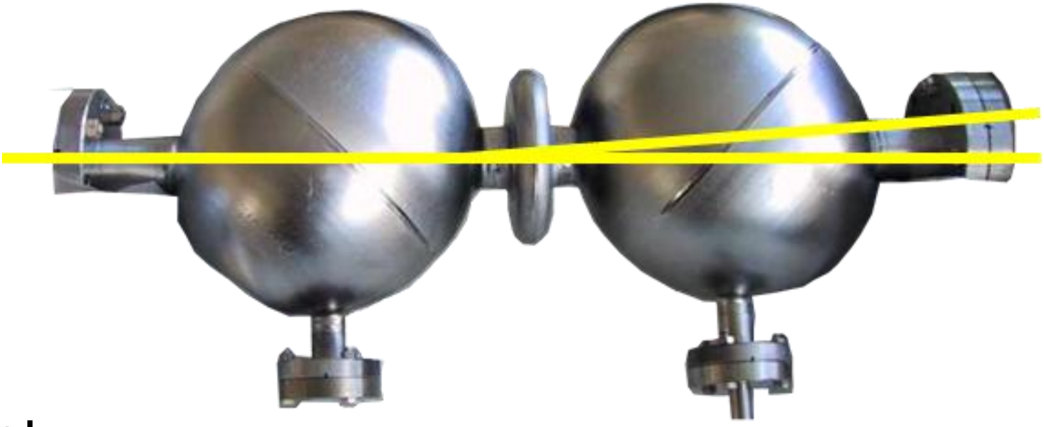
➡ Impact on the coupling to the antennas and on the LLRF system

Caused by?

➡ Difference in the two cells geometry

One cell has a “dent”

Even after tuning the cells have different eigenfrequencies



The cavity is bent