MAGO

A GRAVITY CAVITY

Detecting high-f gravitational waves with SRF cavities

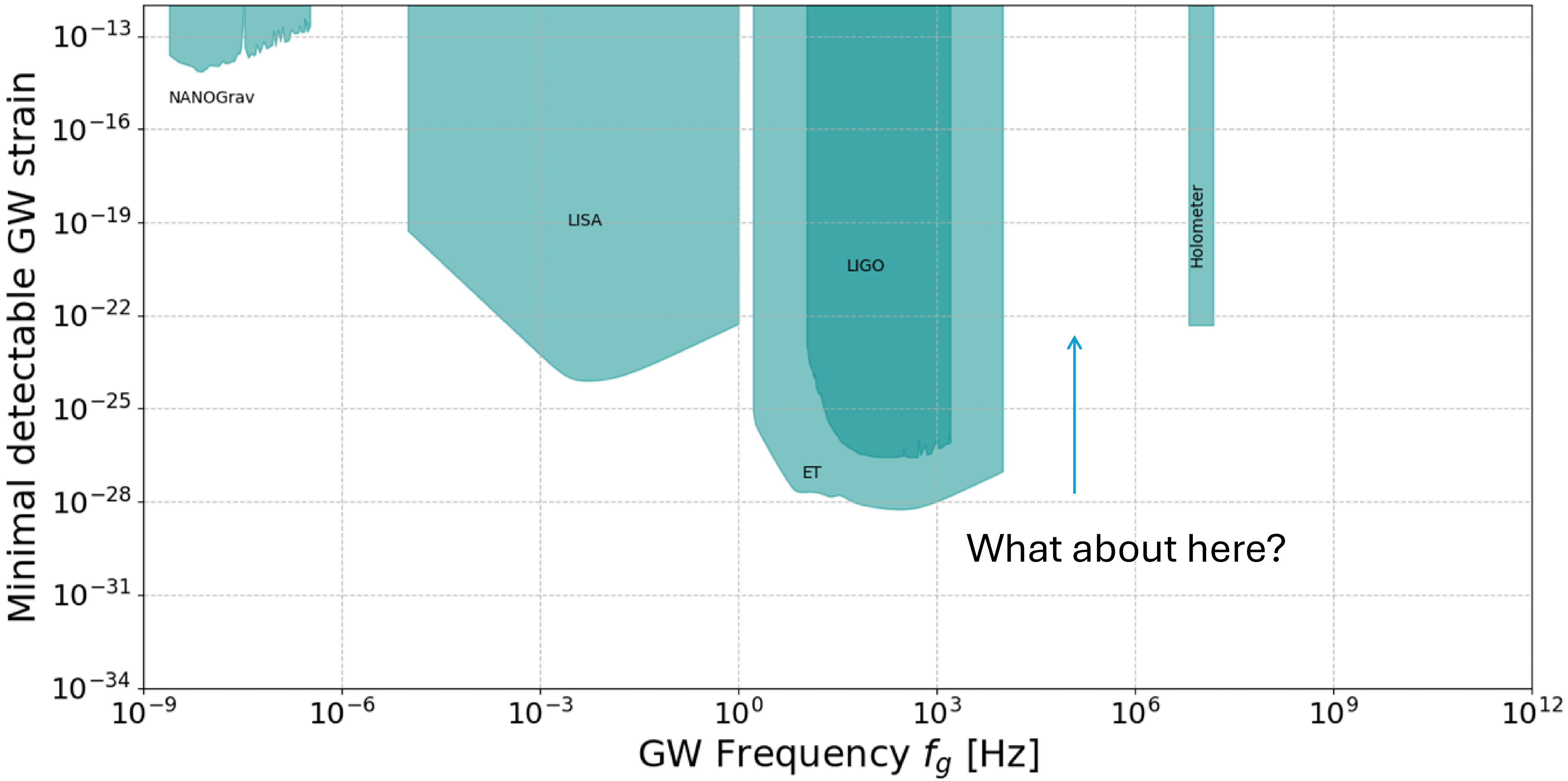
Giovanni Marconato

Outline

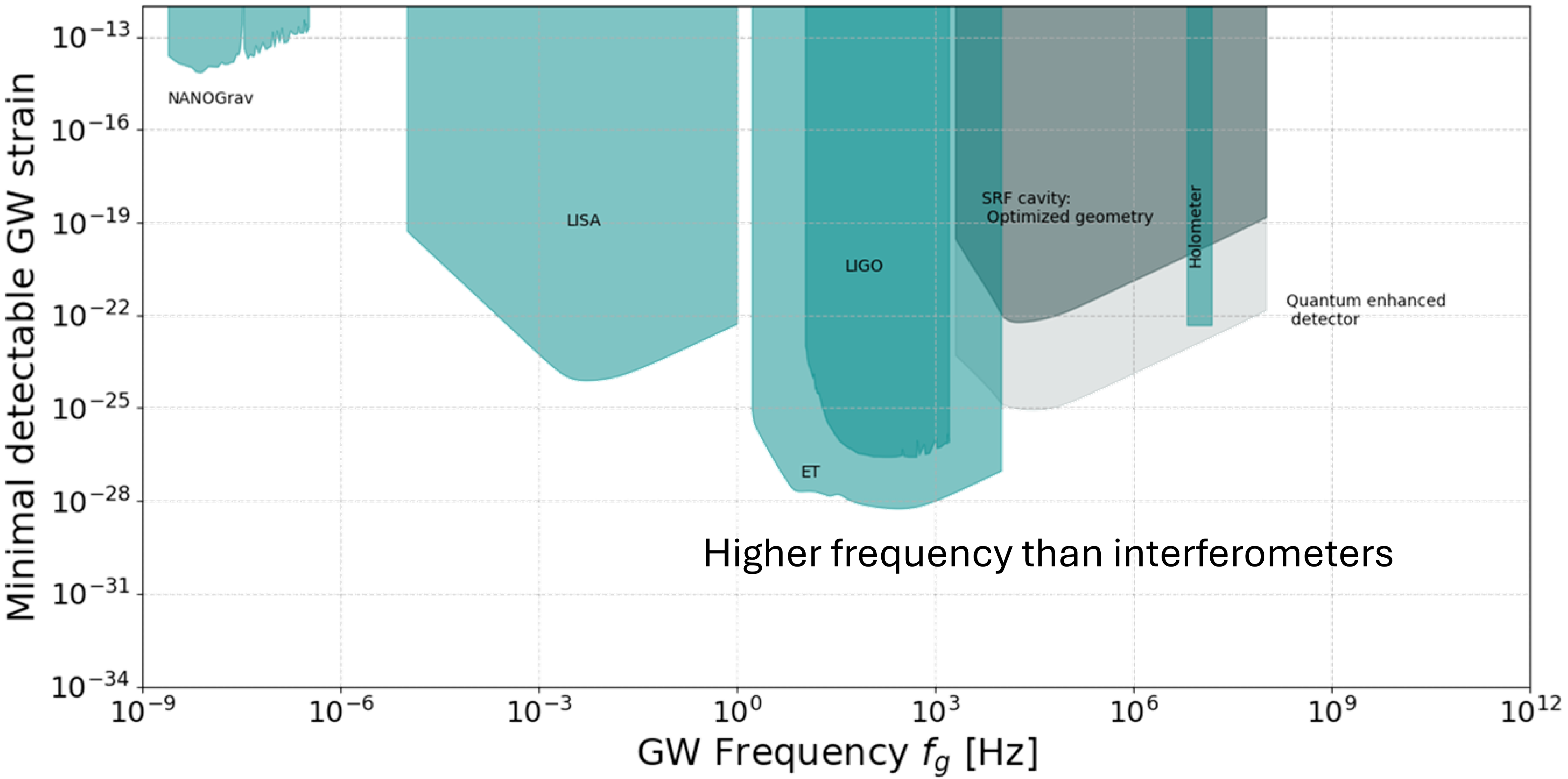
- The goal
- The physics
- The history
- The simulations

- The goal →
  - Parameters' space exploration
  - Sources we might see
- The physics
- The history
- The simulations

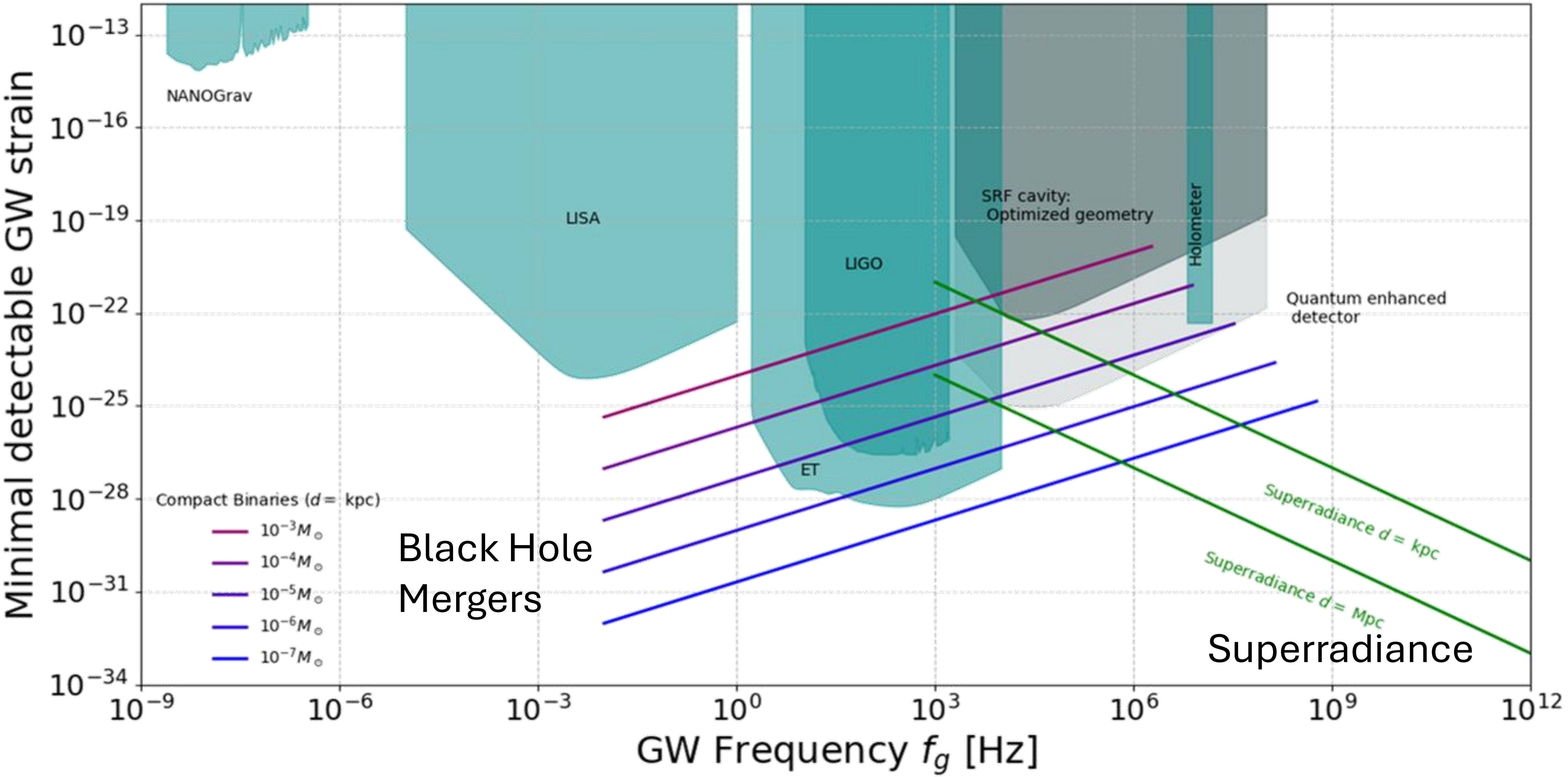
Parameters' space exploration



Parameters' space exploration



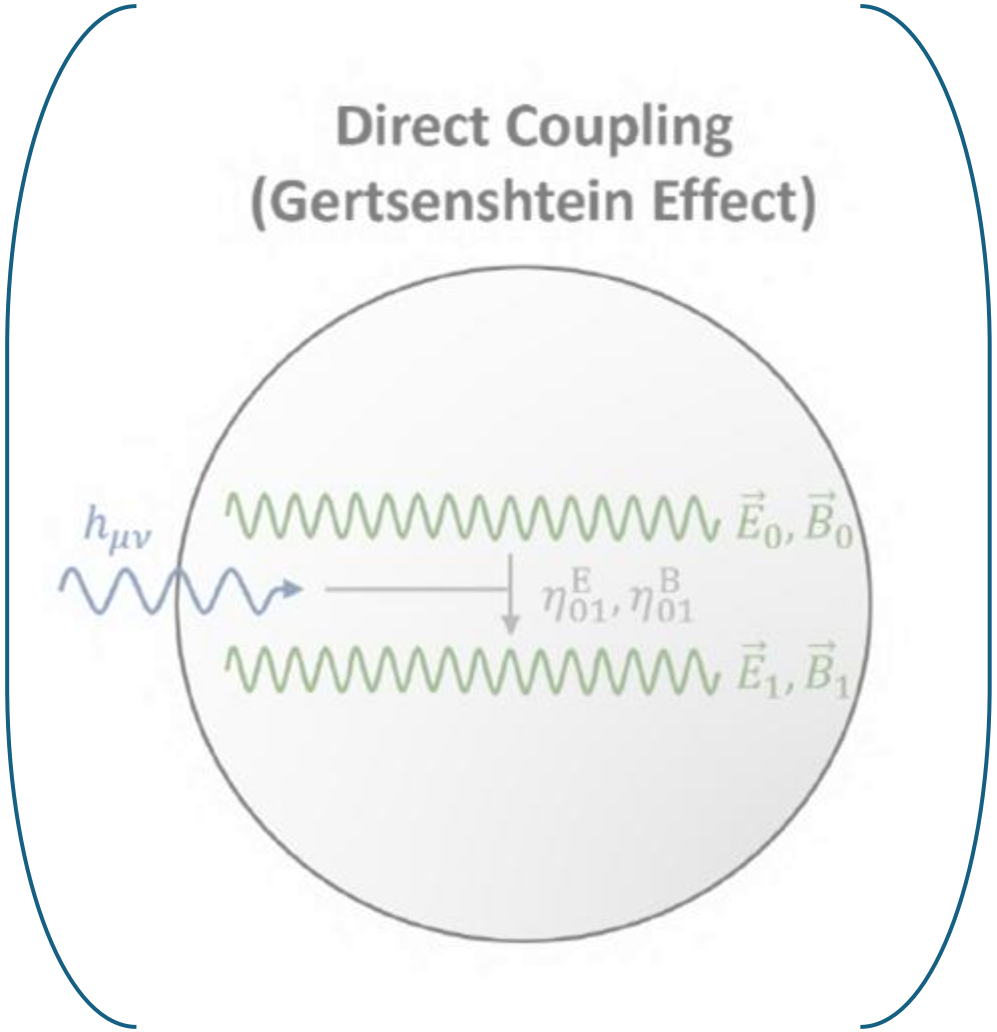
Sources we might see

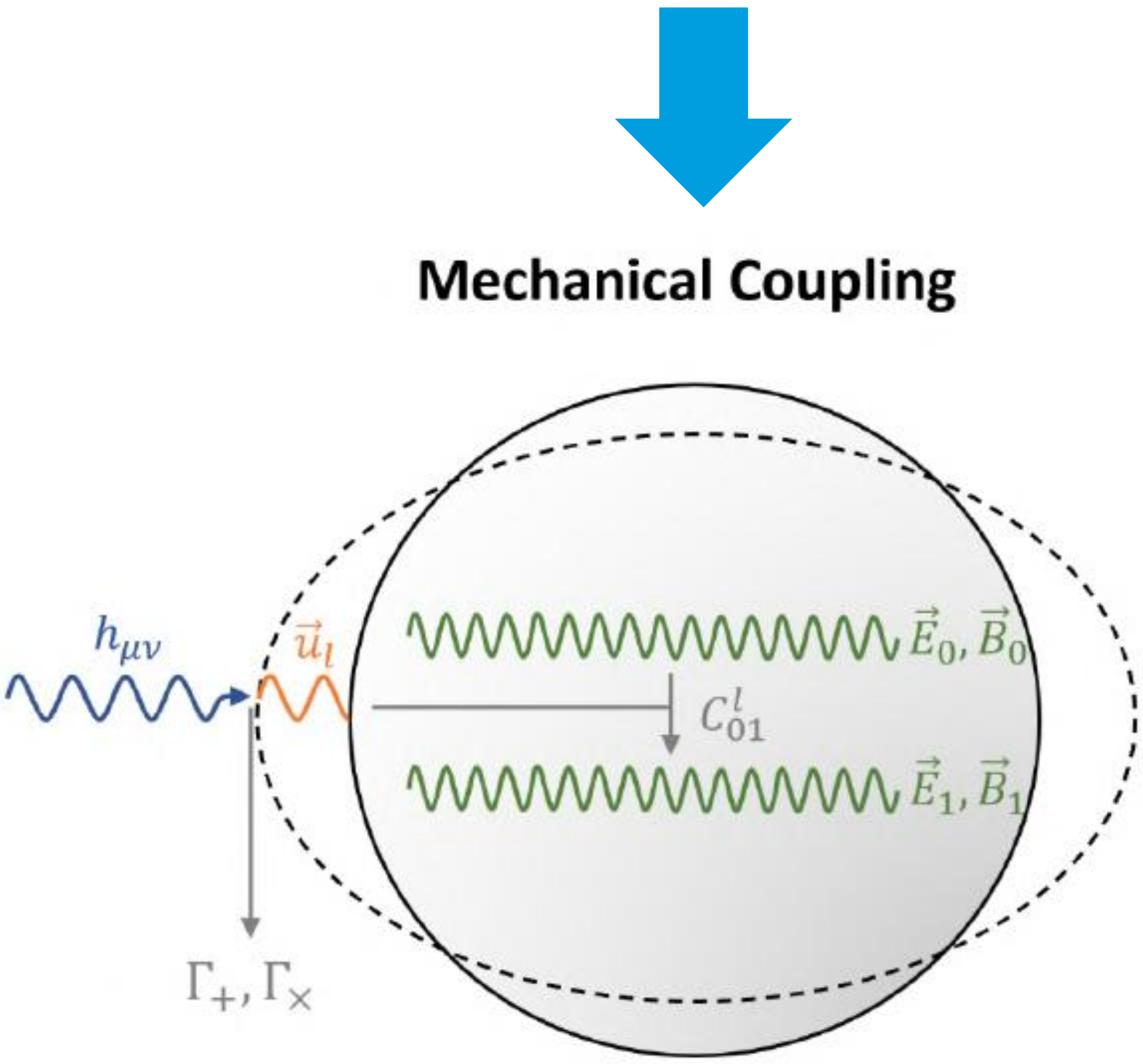


- The goal
- The physics
- The history
- The simulations

- GW – Cavity interaction
  - From GW to mechanical excitation
  - From mechanical excitation to RF
- Shaping RF smartly
- Looking at the modes
- The detection scheme

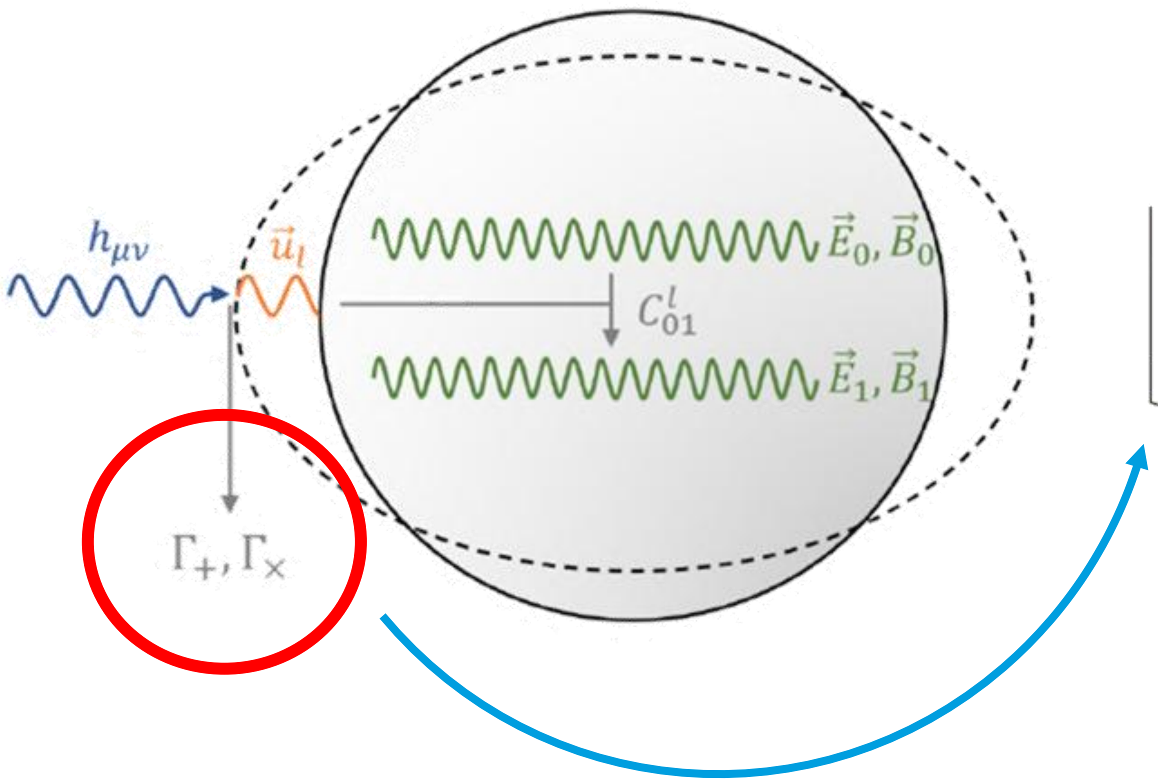
GW – Cavity interaction

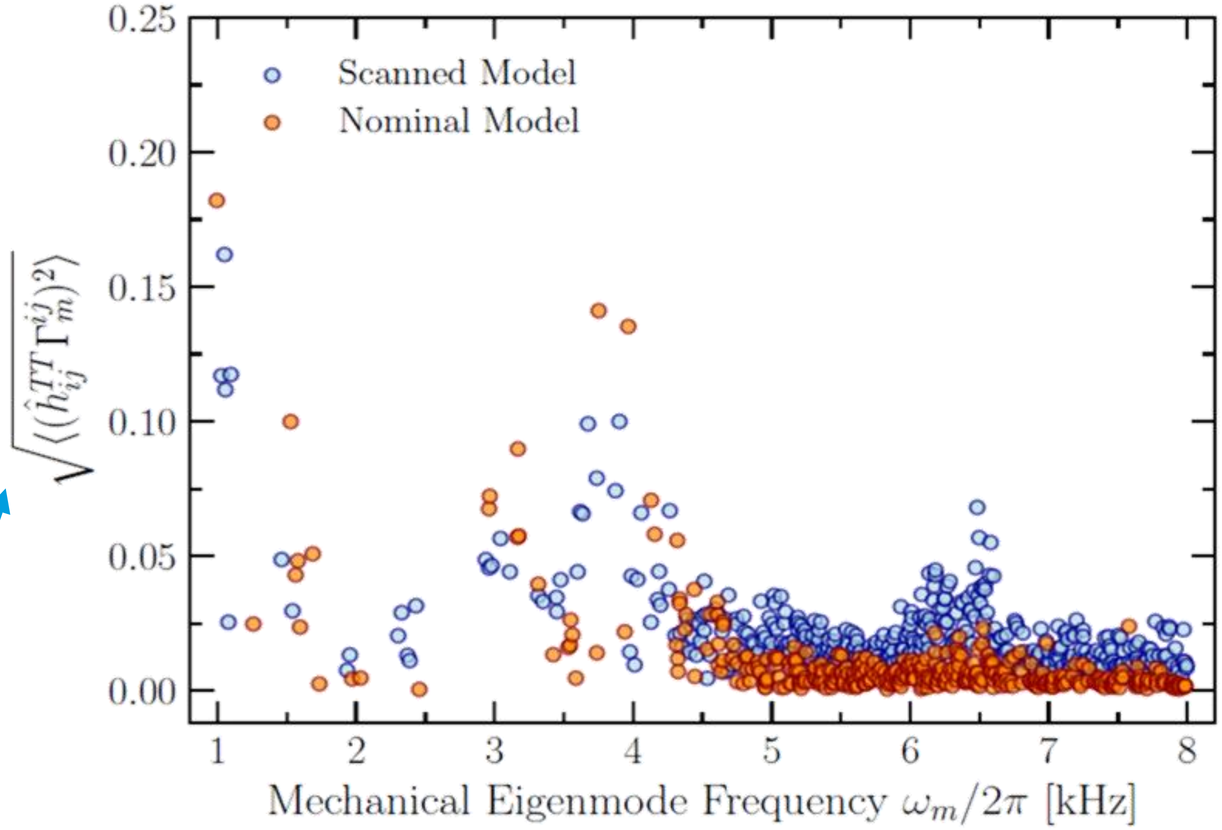




Relevant for higher GW frequencies ~ GHz

From GW to mechanical excitation



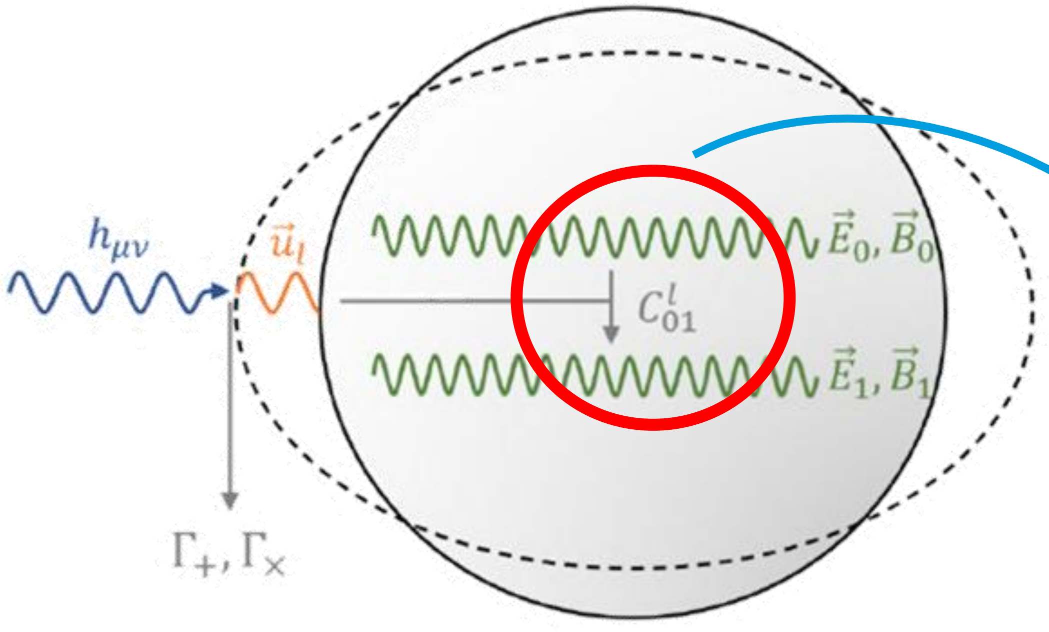


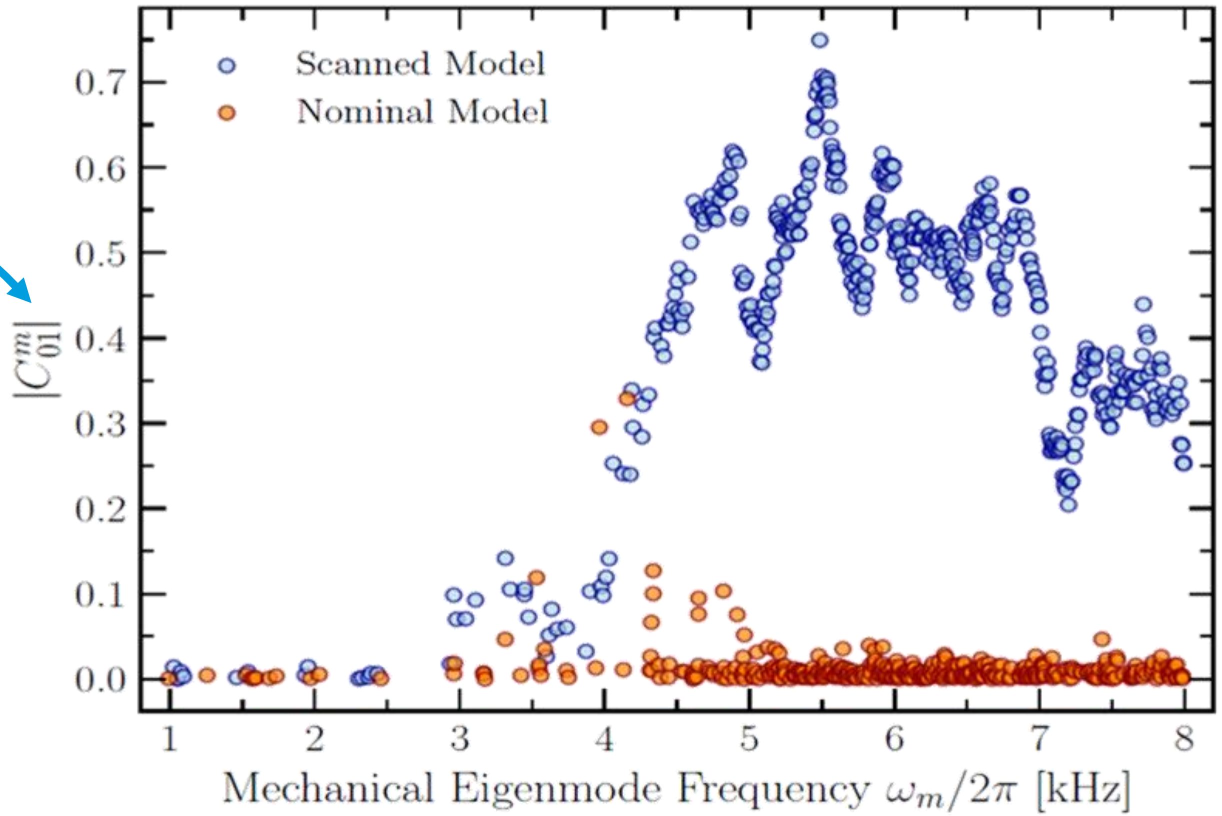
L. Fischer et al., "First characterisation of the MAGO cavity, a superconducting RF detector for kHz–MHz gravitational waves," Class. Quantum Grav., vol. 42, no. 11, May 2025

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

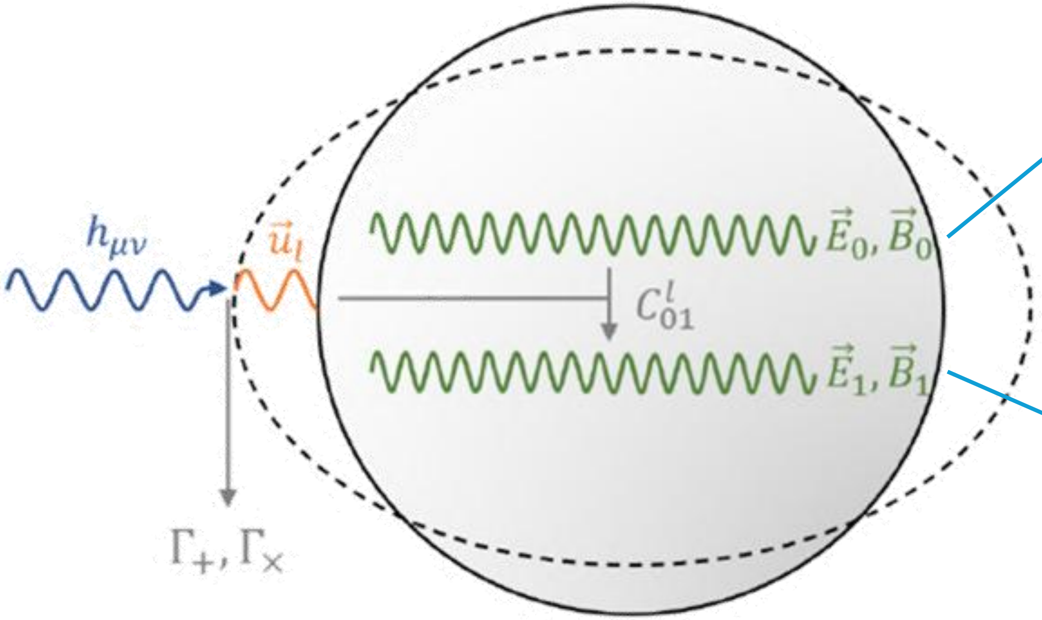
Each mechanical mode couples differently to the EM eigenmodes based on the **spatial distribution** of each mode

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

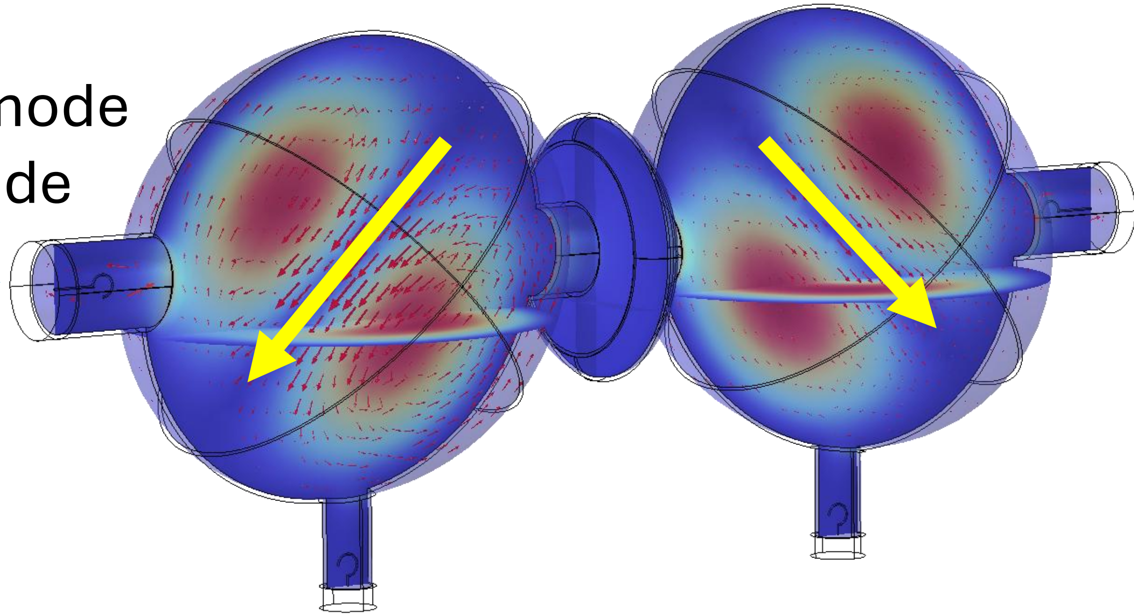
Best EM mode found so far is TE_{011}

At least dipole symmetry and parallel fields between modes

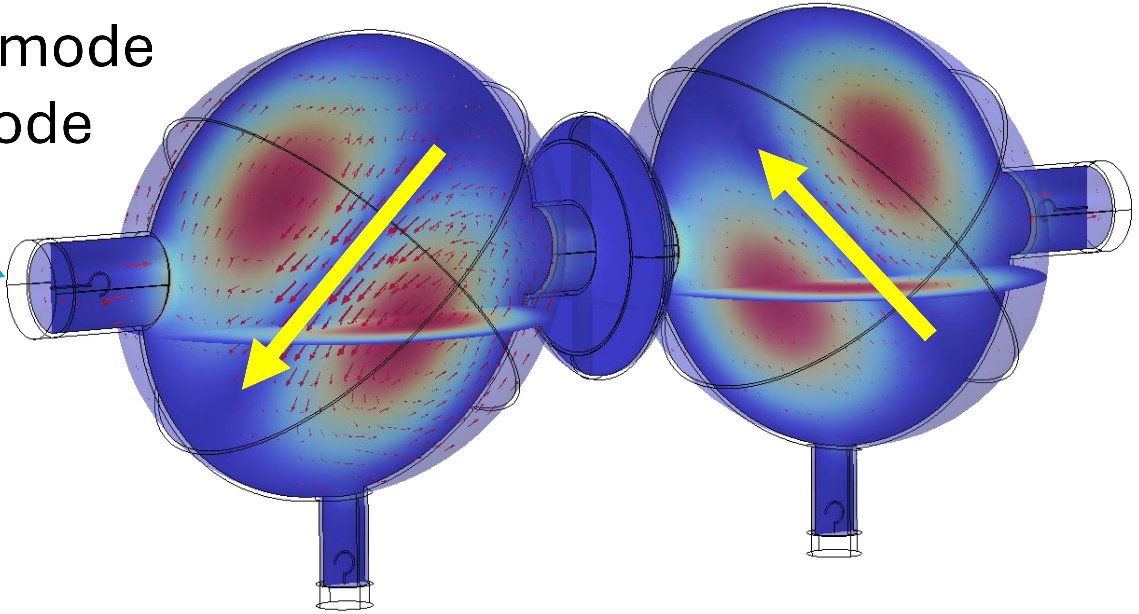
Shaping RF smartly



Pump mode
or 0 mode



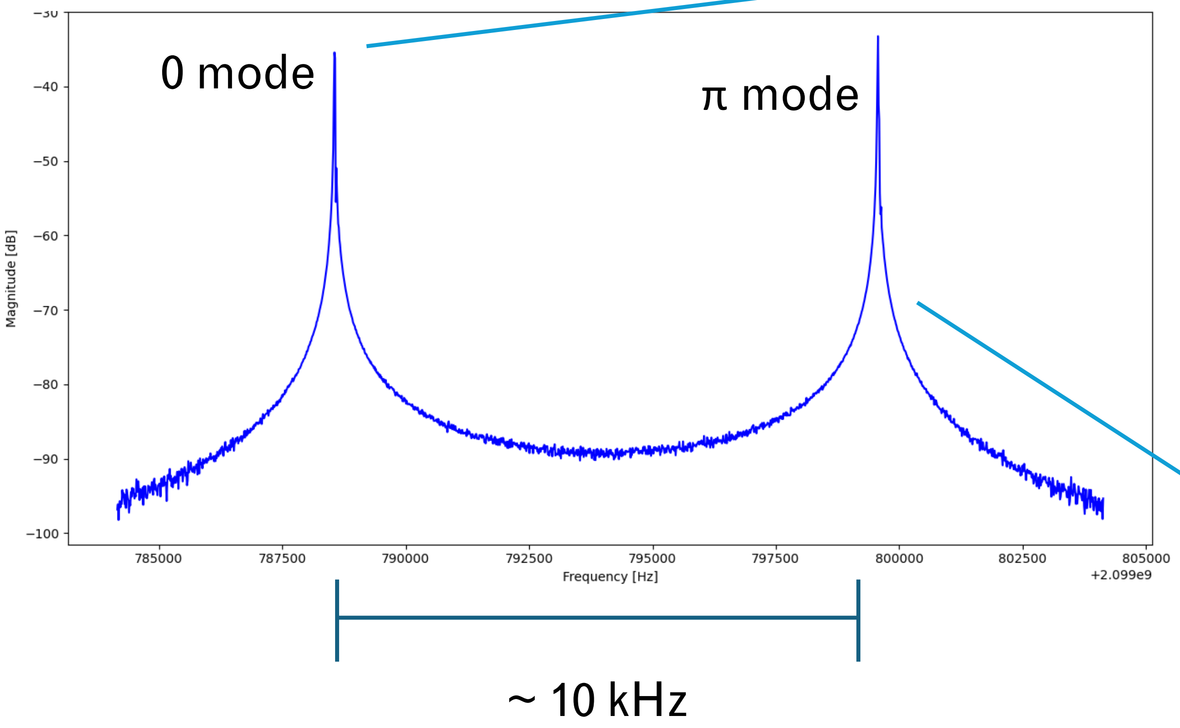
Signal mode
or π mode

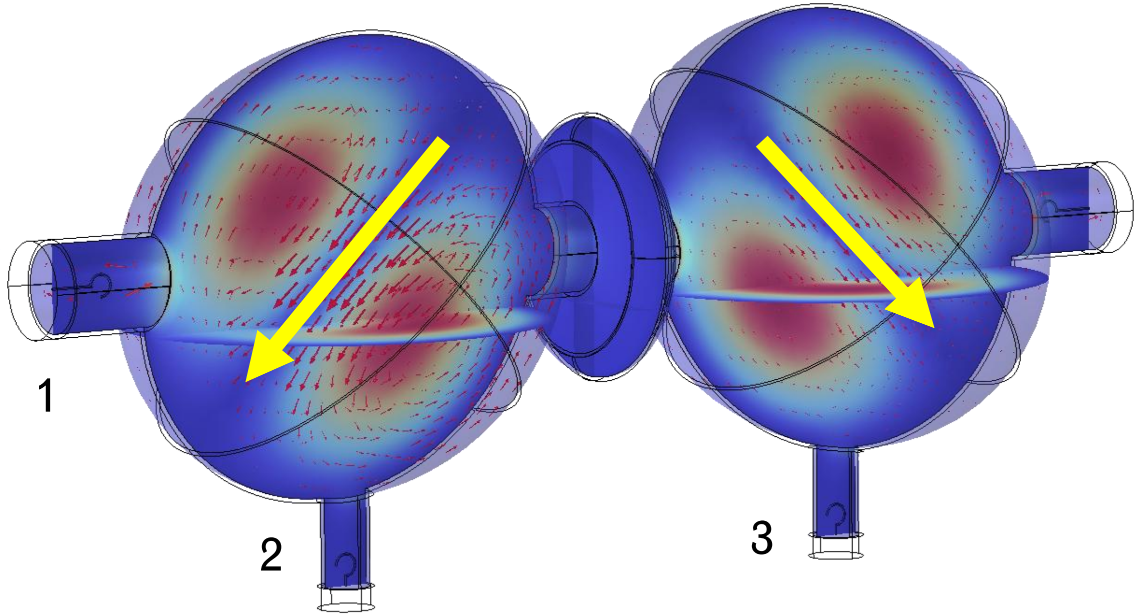


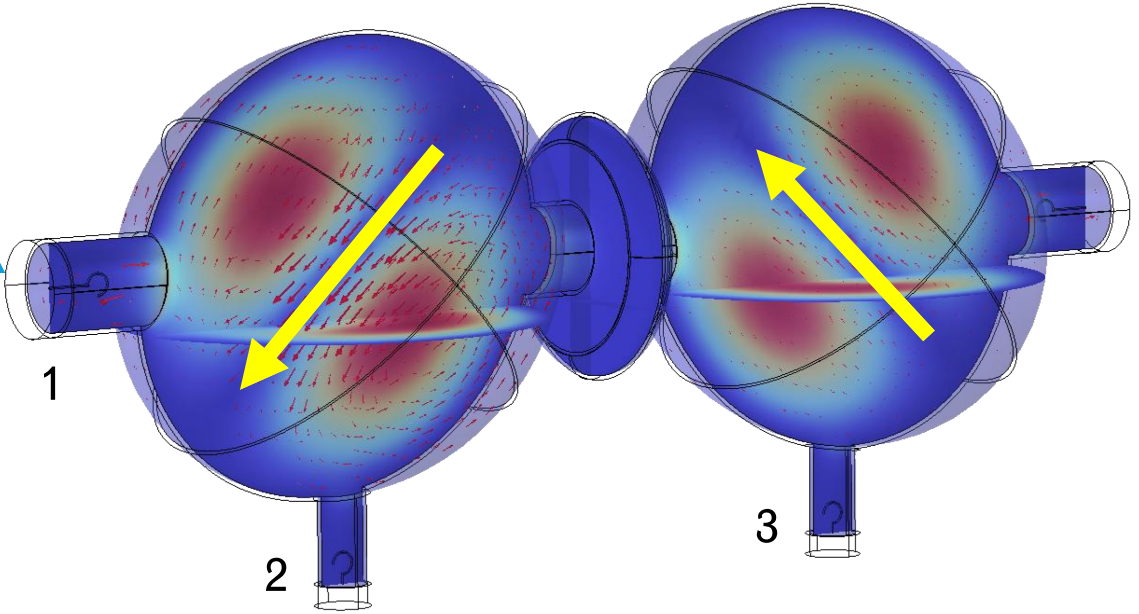
But maybe there are better modes!

Looking at the modes

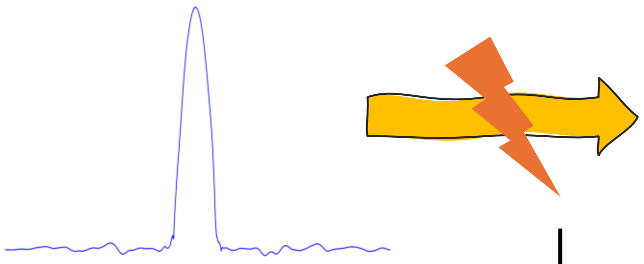
VNA experimental spectrum



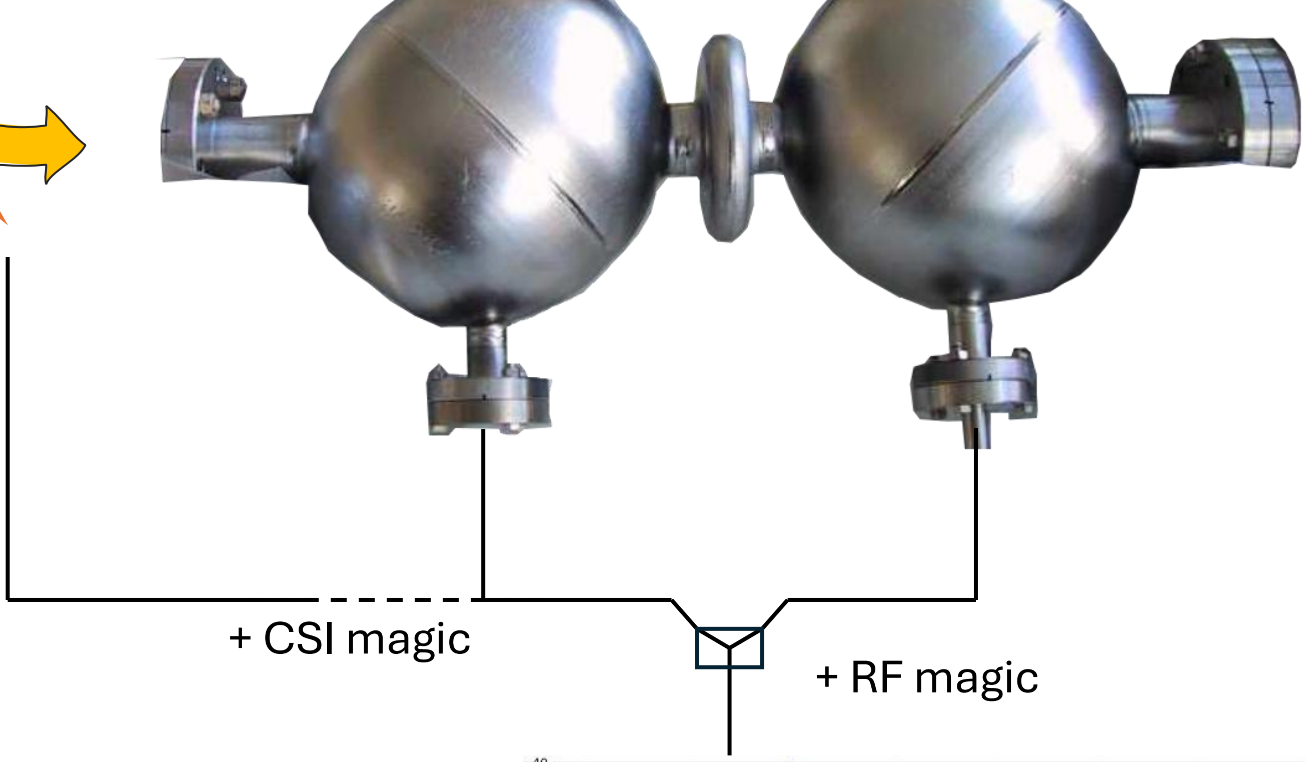




The detection scheme



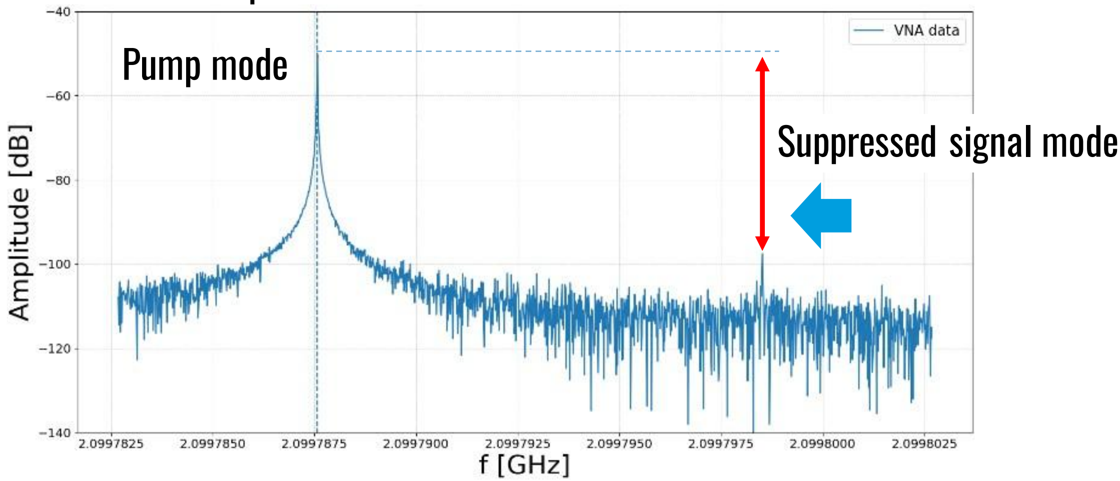
Bandwidth of the input drive is large compared with the peaks spacing



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

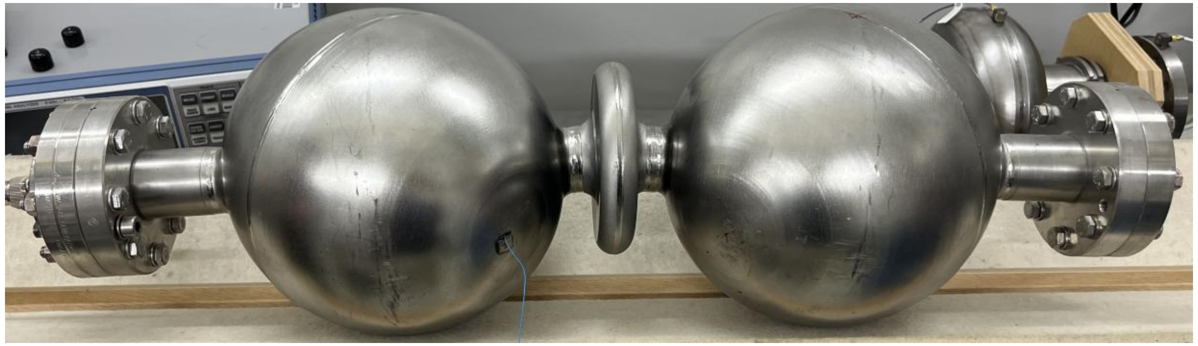
\+

Suppress the pump mode in the output



- The goal
- The physics
- The history
    - Past
    - Present
- The simulations

Past



We revived an INFN project and borrowed their prototype

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

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

- The goal
- The physics
- The history
- **The simulations**
    - Parameters' first guess
    - Open problems
        - Distortion
        - Heat dissipation
        - (Many) Couplings
    - Future

Parameters' first guess

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)

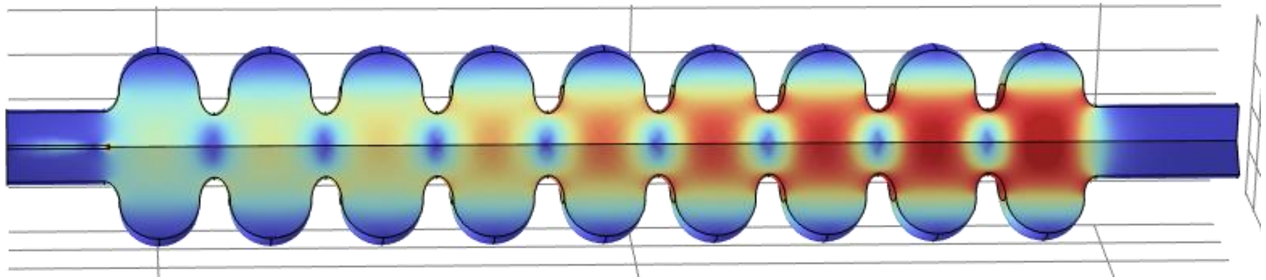
Parameters' first guess

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

Open problems

So far 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 coupling to multiple modes
- Mechanical simulation of eigenmodes
- …

Distortion

- Quantify the distortion of the modes in the cells

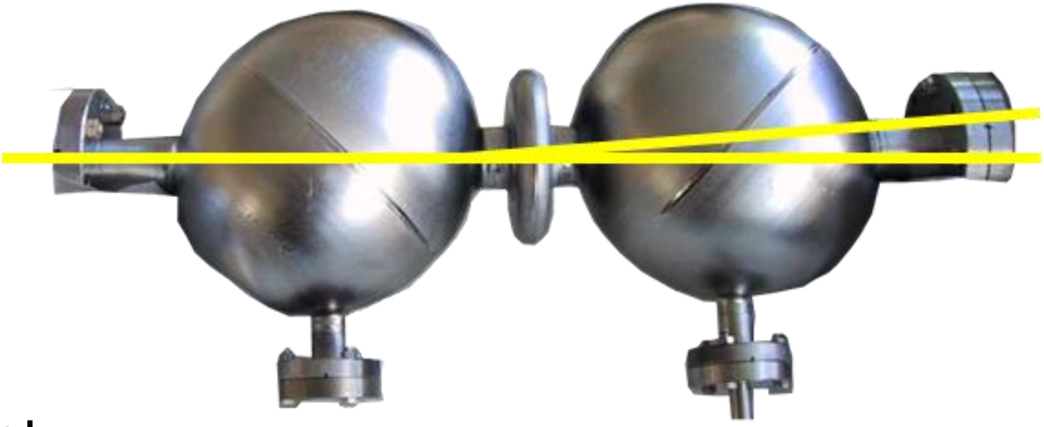
➡ Impact on the coupling to the antennas and on the LLRF system

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

(Many) Couplings

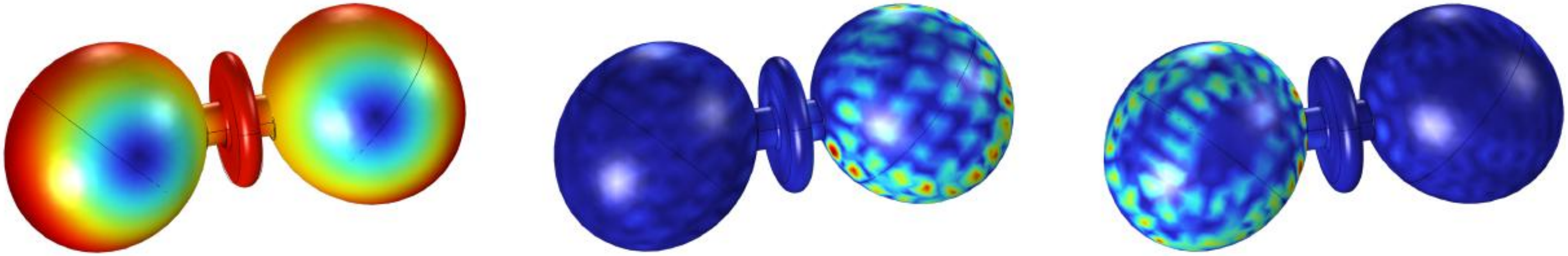
- Optimize antenna coupling to multiple modes

➡ We don't have to limit ourselves to one pair of modes!

The mode we chose might not be the optimal one

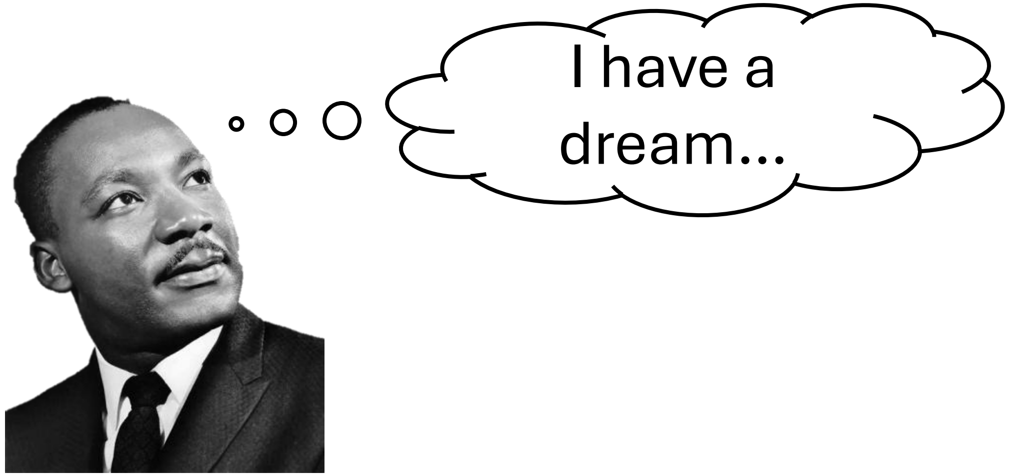
We are at the moment limited by the accuracy of mechanical simulations

➡ Simulate and verify mechanical spectrum



R. Lowenberg, "Revisiting Gravitational Wave Detection with SCRF Cavities at DESY," Master's Thesis, Hamburg University, 2023

Future



Coupling mechanical vibration and thermal effects to RF excitation

Mechanical simulation defines the moving boundary conditions for the RF simulation

noise

Future

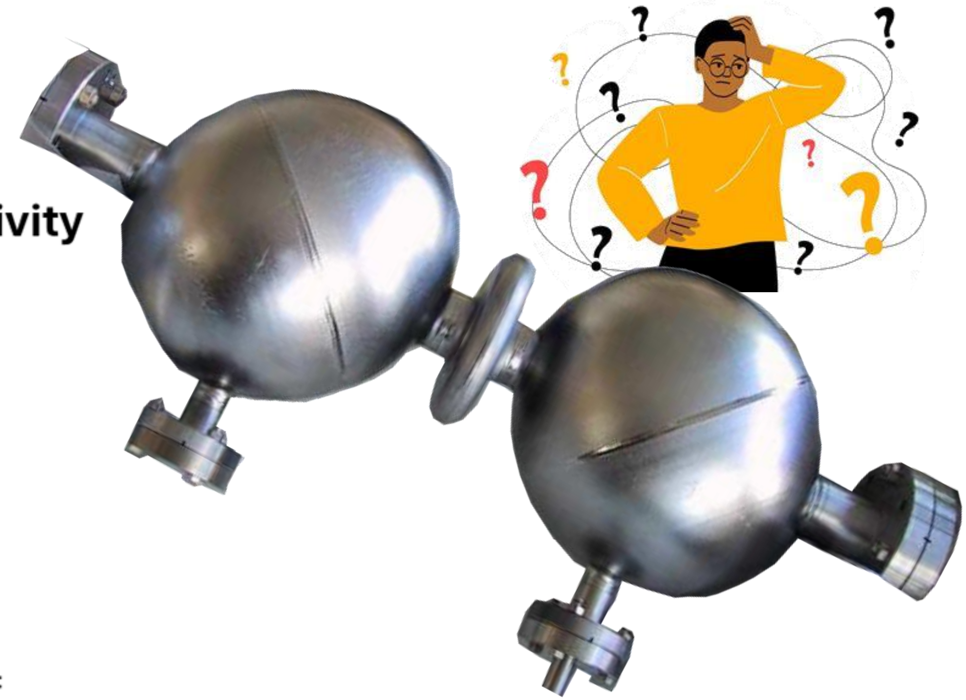
The final goal is the optimization of the geometry to have the **best sensitivity**

- What is the **best geometry**?
- Can we include all the effects of the readout system?
- Can we include the effect of thermal dissipation of the helium bath?

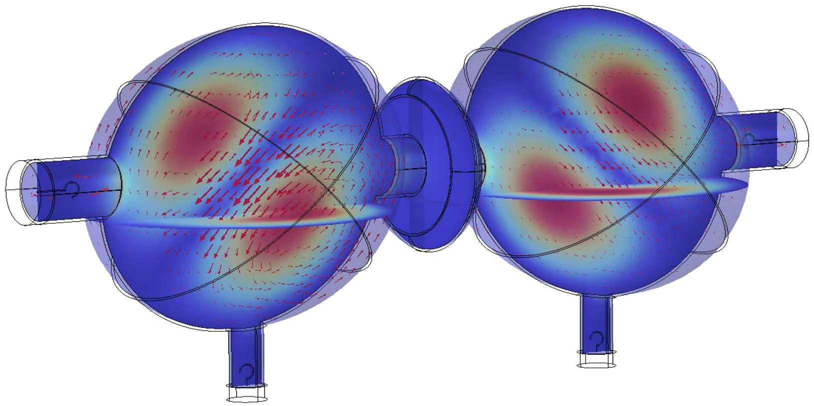
THANK YOU

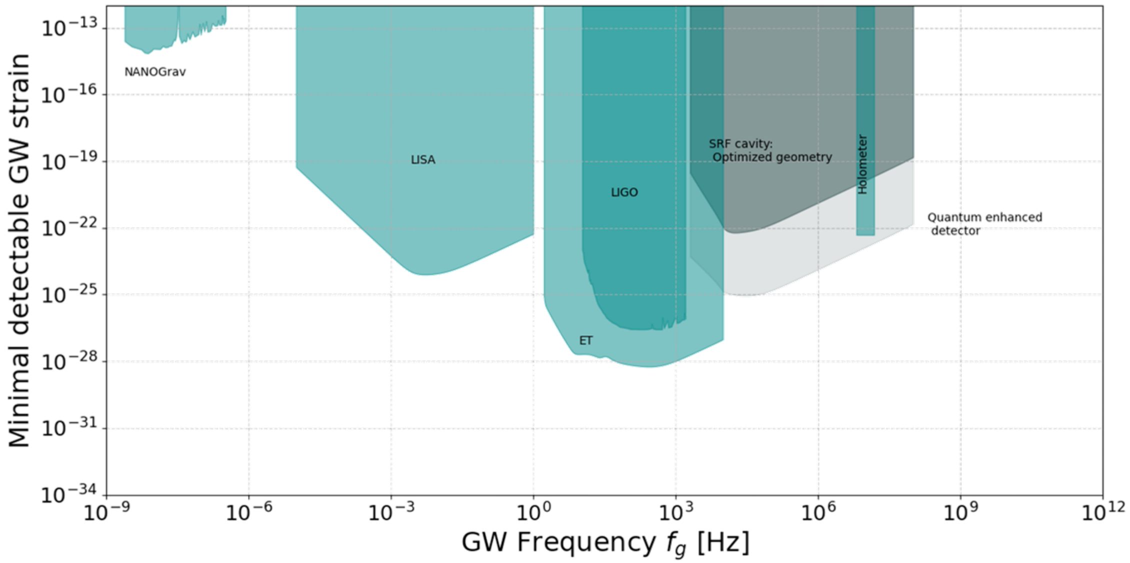
Future

The final goal is the optimization of the geometry to have the **best sensitivity**



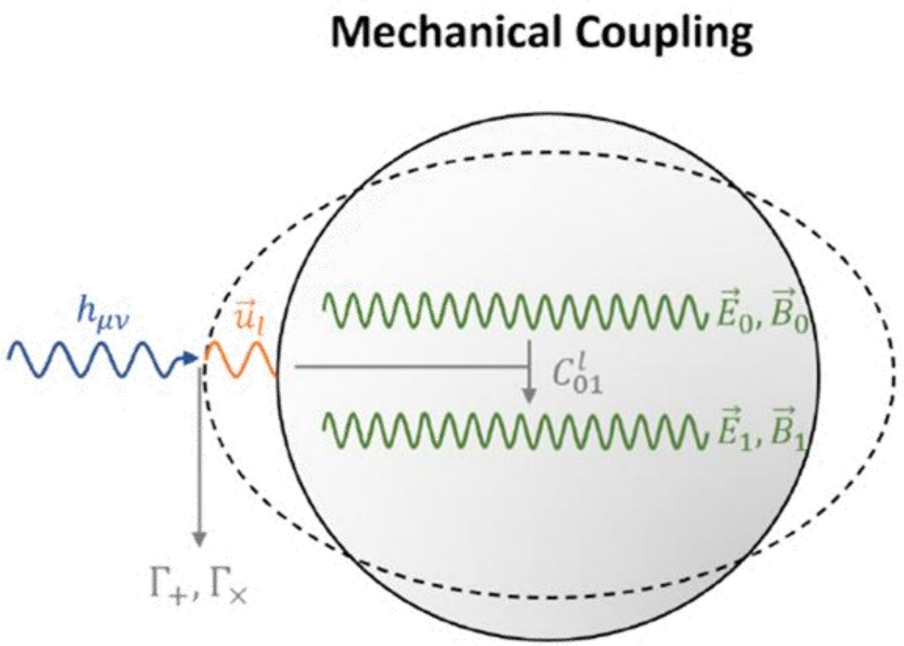
- What is the **best geometry**?
- Can we include all the effects of the readout system?
- Can we include the effect of thermal dissipation of the helium bath?





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

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

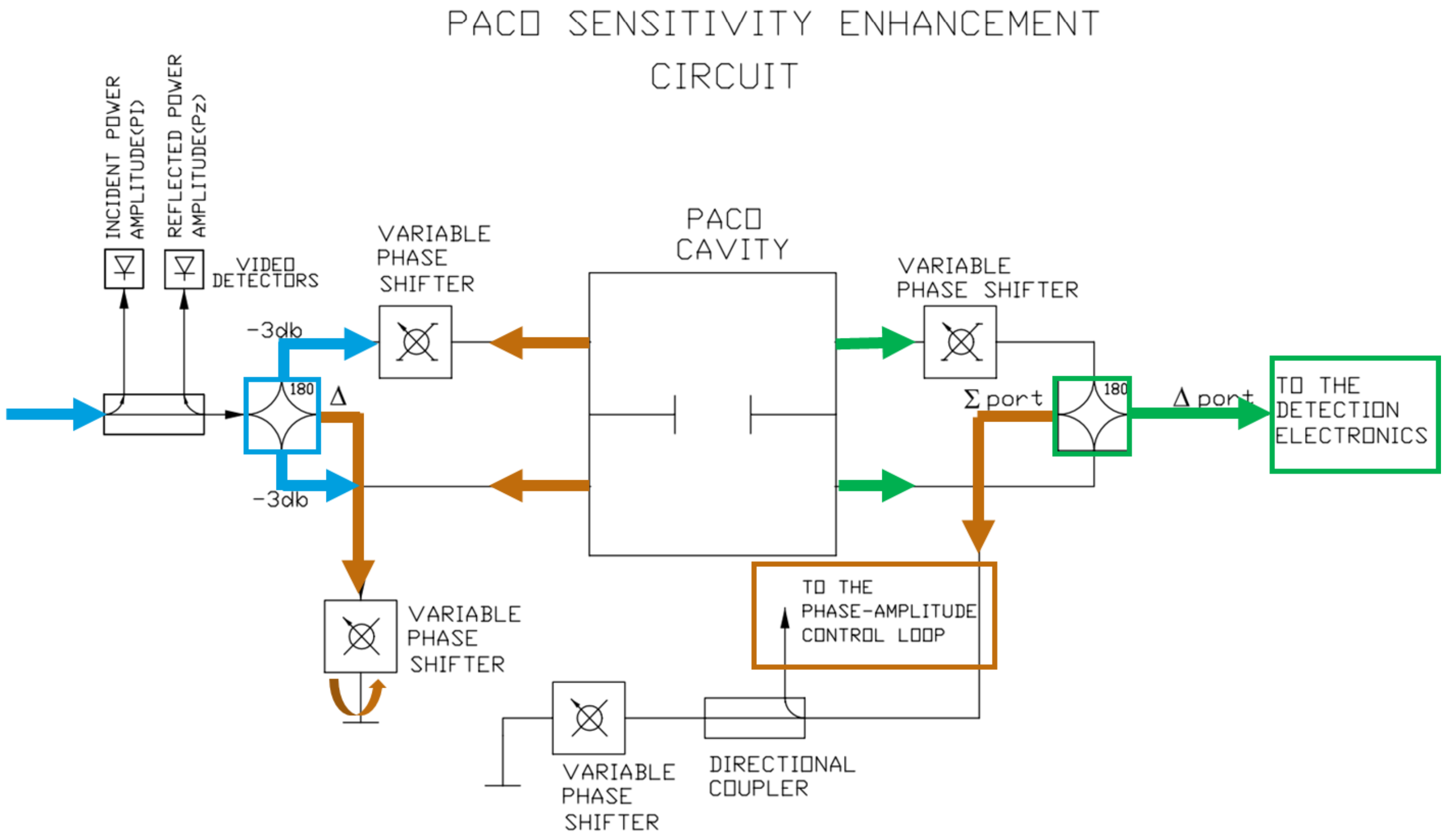
Mechanical noise
$$\sqrt{S_{mech}(\omega_g)} \sim \Gamma^{-1}\cdot q_{rms}\cdot Q_{\mathrm{mech}}^{-\frac{1}{2}}\cdot\left(\frac{\omega_{mech}}{\omega_g}\right)^{\frac{3+\alpha}{2}}\cdot\omega_g^{-\frac{1}{2}}$$

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 “real” RF setup

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