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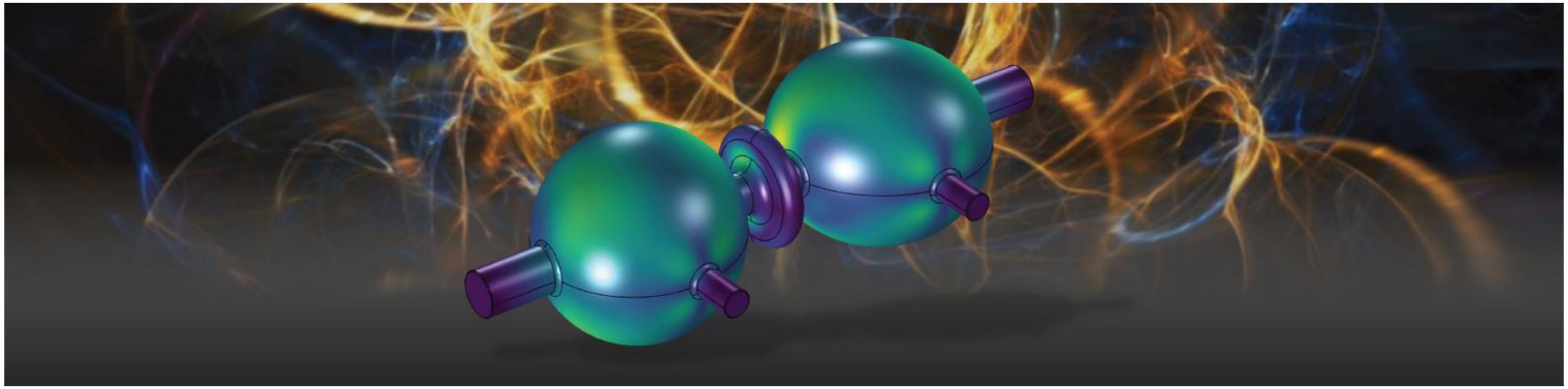
SHOGWAVE

Superconducting cavities for t**h**e **o**bservation of **g**ravitational **wave**s



The project team:

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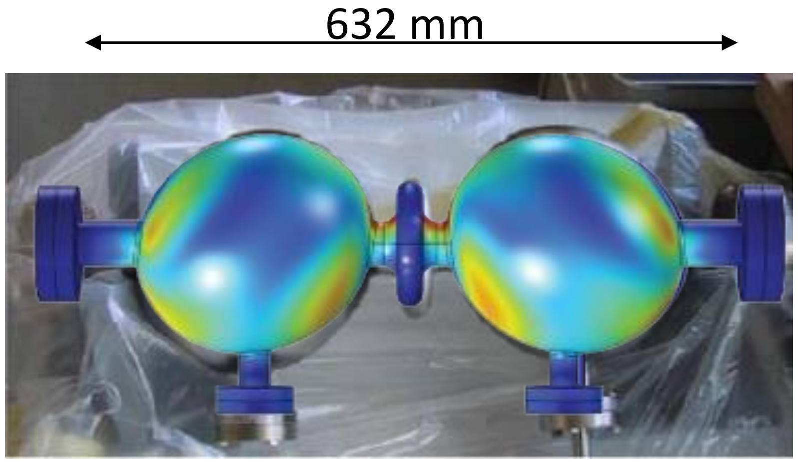
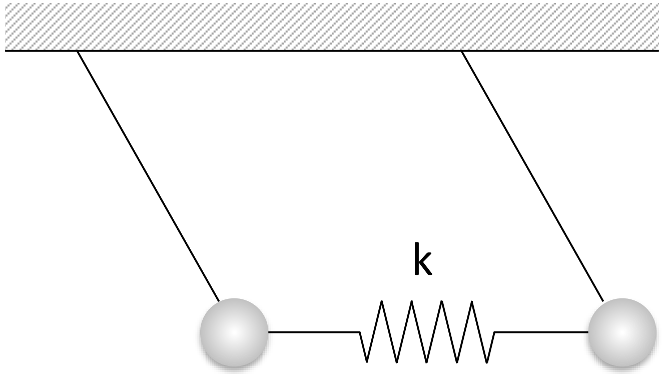
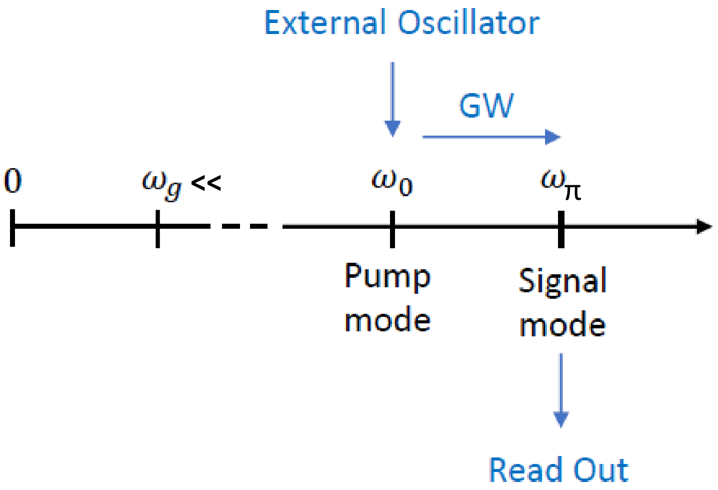
DESY.

Gravitational Waves & Cavity – How does it work?

Indirect measurement using heterodyne detection



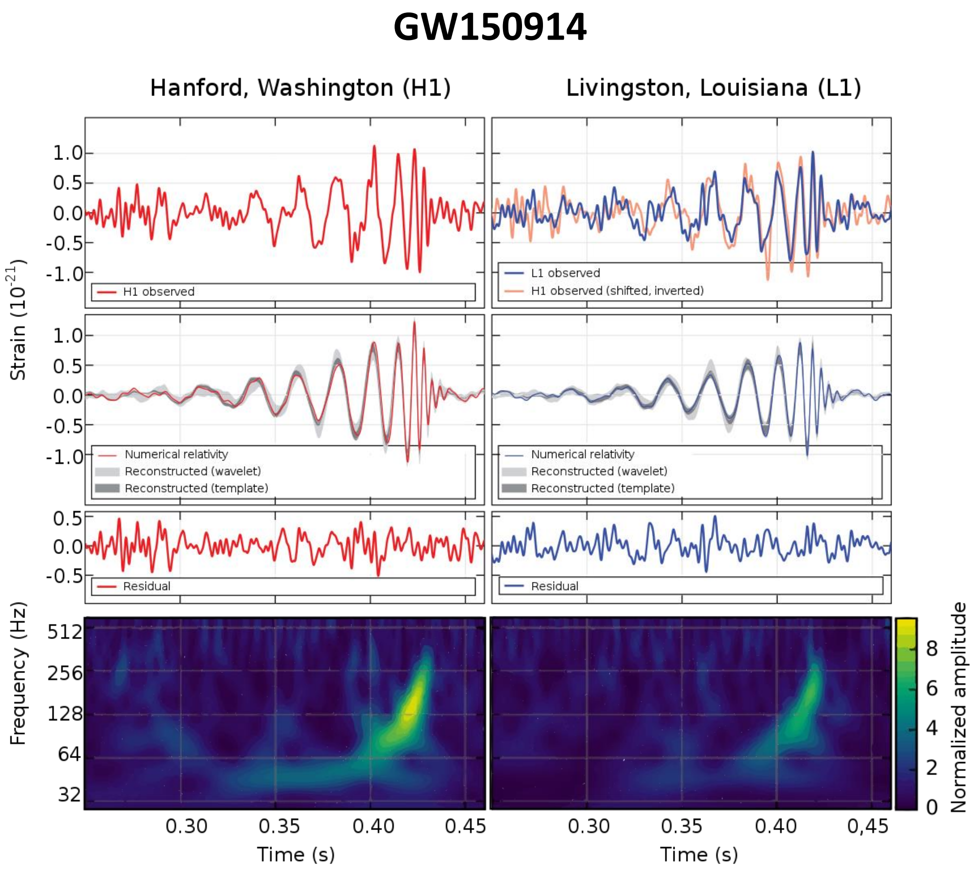




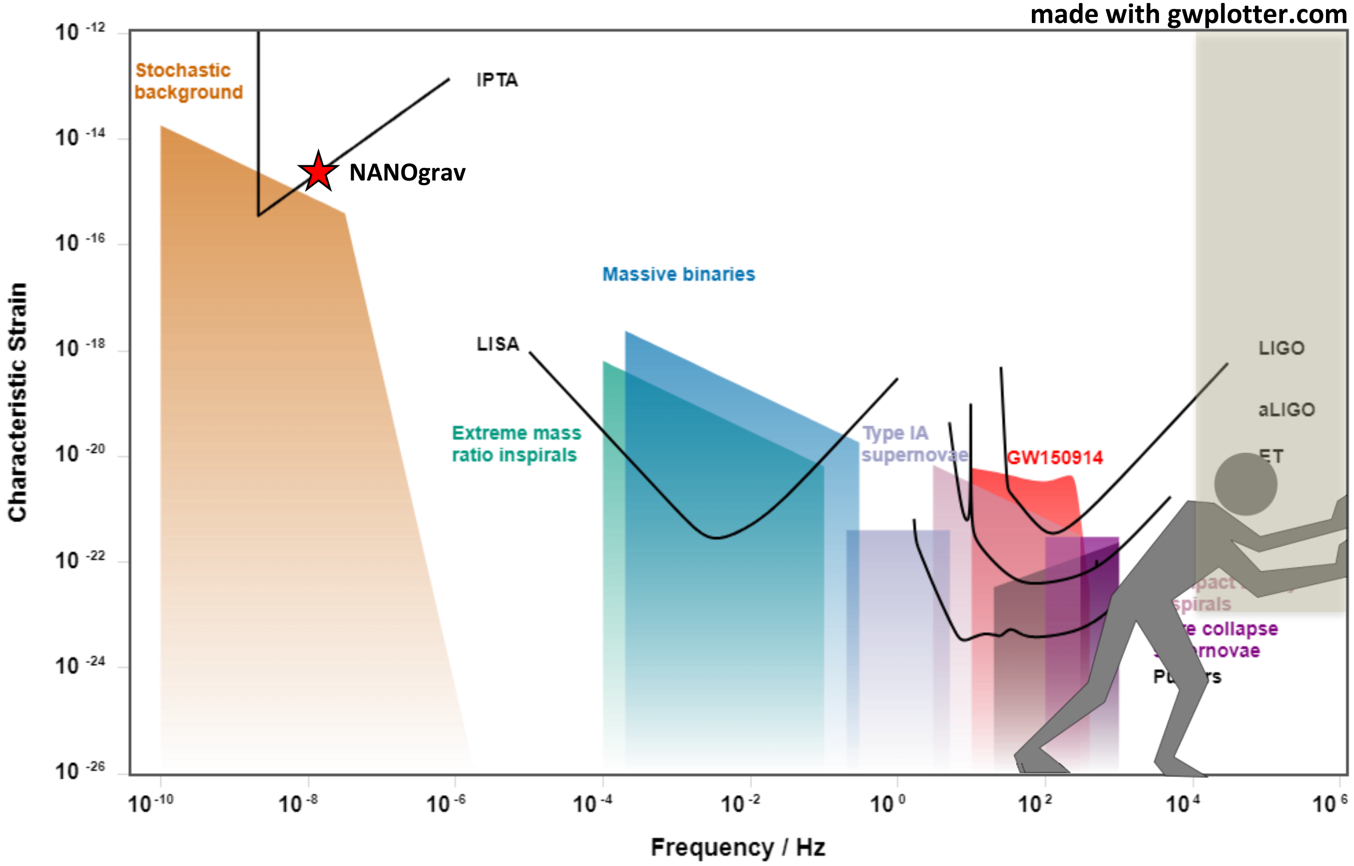
- Energy transfer from pump mode with ω_0 to signal mode with ω_π due to (resonant) GW deformation of cavity
- Heterodyne = GW is in resonance with frequency difference of two cavity modes (here: pump and signal mode)
- $\Delta\omega = \omega_\pi - \omega_0$ is tunable by spring constant k aka cavity geometry
- Highest sensitivity: GW frequency $\omega_g \approx$ mechanical resonance ω_m & mechanical resonance $\omega_m \approx$ rf frequency difference $\Delta\omega$
- Not just frequencies, but patterns matter: GW couples to modes with quadrupole symmetry

Extend detection reach beyond interferometers

$$h_c = \frac{\Delta L}{L}$$



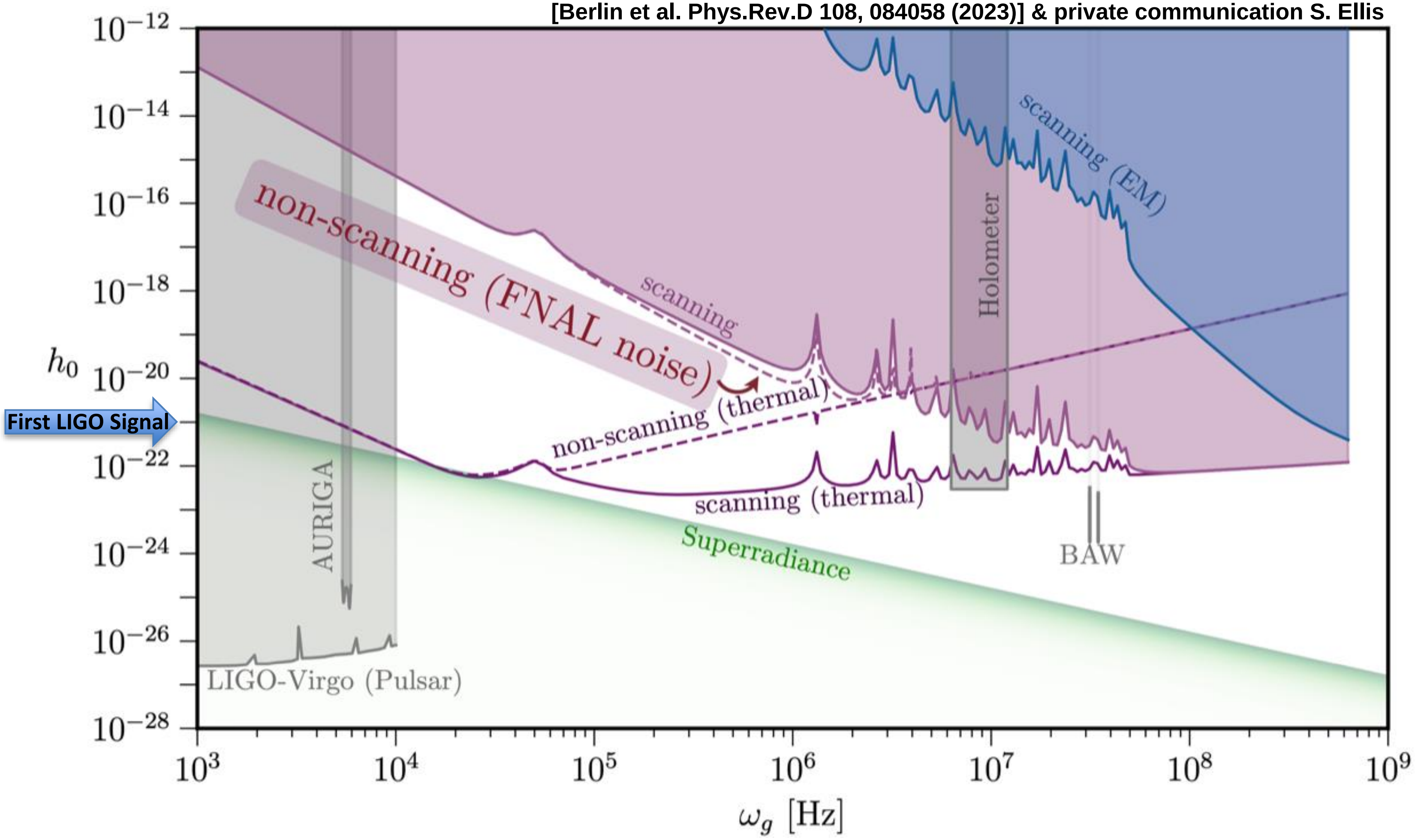
[Abbott et al., Phys. Rev. Lett. 116, 061102 (2016)]

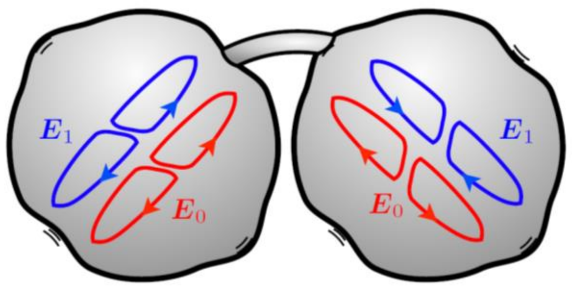


Any GW signal would be a spectacular discovery

Reach of a MAGO-like Cavity

[Berlin et al. Phys.Rev.D 108, 084058 (2023)] & private communication S. Ellis





„MAGO“-like cavity – two spherical cells

- T = 1.8 K
- E_{acc} = 30 MV/m
- $Q_0 = 10^{10}$
- TE_{011} $\omega_0 \approx$ 2 GHz
- $\omega_m = \Delta\omega$ = 20 kHz
- $Q_{mech} = 10^6$

scanning = on-resonance signal: $\omega_g = \omega_m = \Delta\omega$
non-scanning = off-resonance signal: $\omega_g > \omega_m = \Delta\omega$

(thermal) = if mechanical noise can be neglected ∝ T/Q^2

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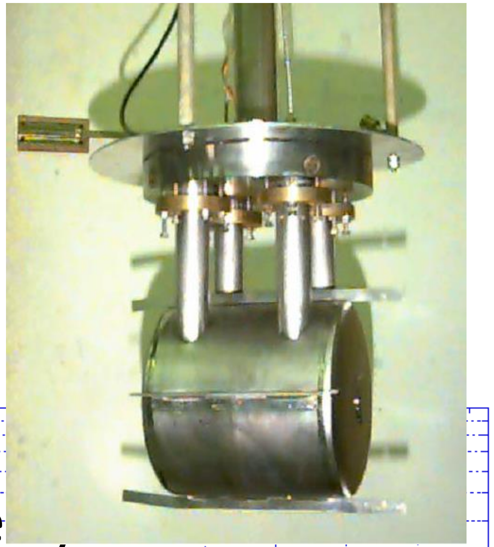
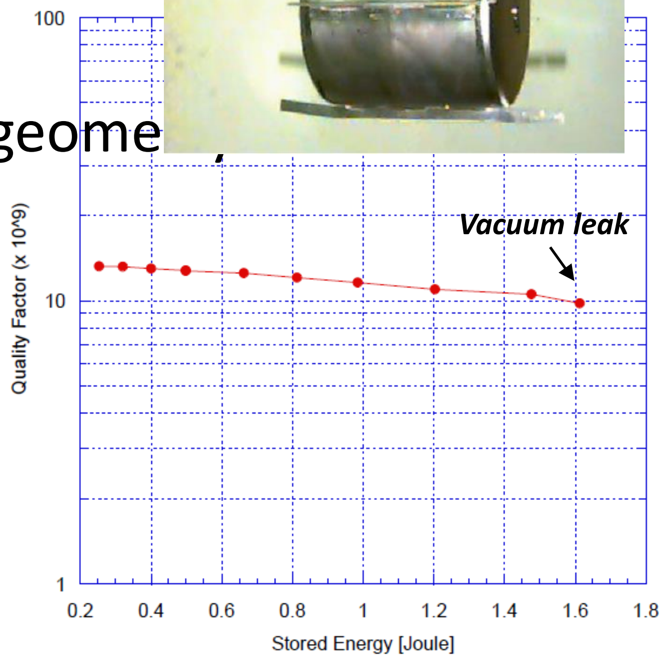
The MAGO Cavity

What was PACO/MAGO

[Ballantini et al., arXiv:gr-qc/0502054 2005]

- PACO (1999)
  - 2-cell pillbox-cavity @ 3GHz as proof-of-principle experiment
  - Low Q, test of RF system, excitation of signal mode
- MAGO (2000s)
  - 1st Cavity: 2-cell cavity with optimized geometry
  - Underwent chemistry and cold test to obtain Q_0 (U) for TE_{011}
  - 2nd Cavity: 2-cell cavity with variable coupling and optimized geome
  - Never treated nor tested – on shelf for >15y @ INFN Genova
- Collaboration betwe   revive MAGO





Continuation of R&D efforts

June 2023

Cavity at DESY

- Mechanical characterisation and RF measurements at room temperature (done)

Cavity at FNAL

Today

- Treatment of cavity, RF antenna design, cavity tuning and first cryogenic characterisation

End 2024

Cavity back at DESY

- Cryogenic test with (initial) LLRF system

Beginning 2025

Cavity back at FNAL

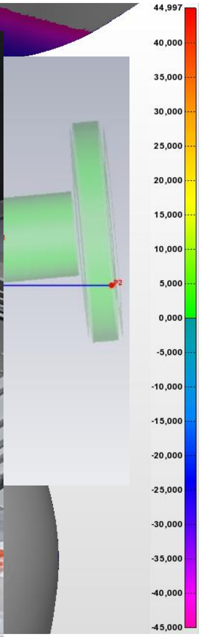
- First GW search in existing cryostats at Fermilab

University Genova

Result from warm commissioning

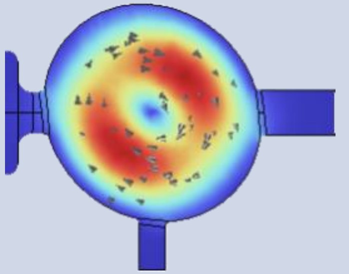
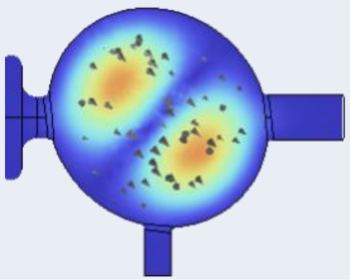
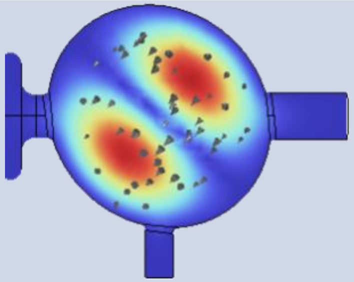
Cavity is out of shape

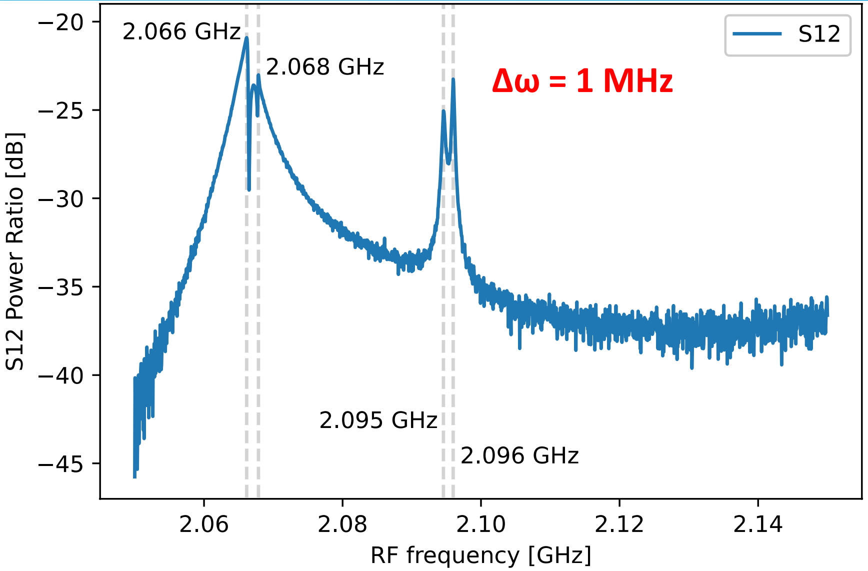
Donut shaped dent

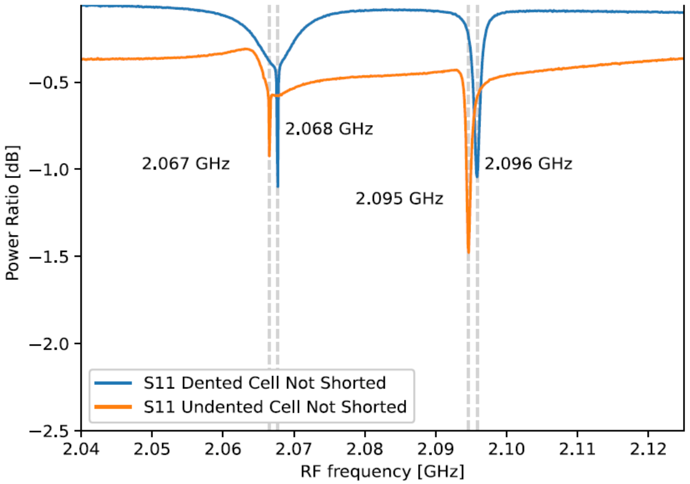


No damage to flanges / sealing surface.
Leaktight at RT.

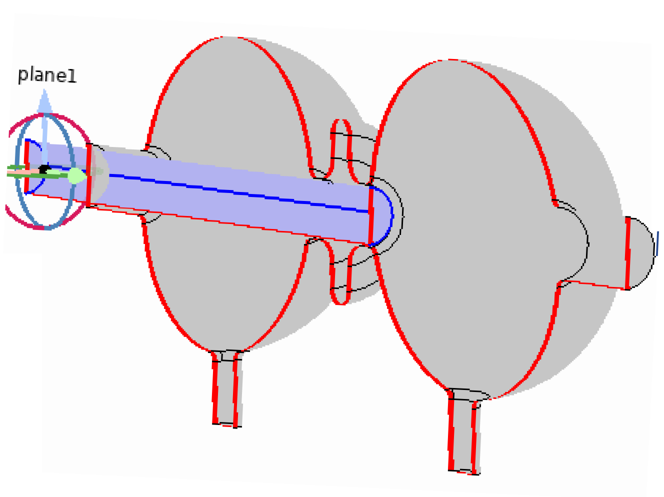
RF measurement is worrysome

Simulated Eigenfrequency	Electric Field Distributions
2.073 GHz (2 merged peaks)	
2.077 GHz (2 merged peaks)	
TE_{011} **0-mode: 2.10381 GHz** **π-mode: 2.10390 GHz** **Δω ≈ 9 kHz** **→ @RT: 2 merged peaks**	





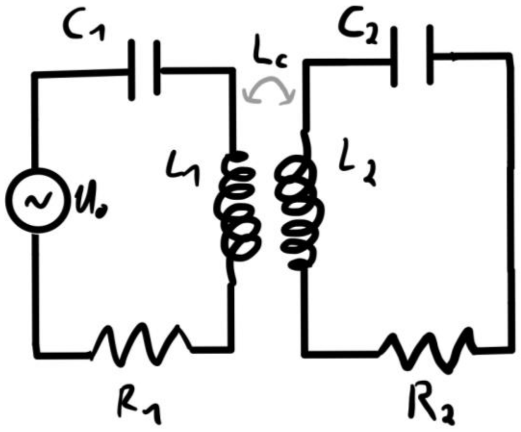
Idea:
Short one cell and measure the other



Results:
- Measurements ≠ Simulations
- Eigenfrequencies of „single-cells" $\Omega_1 \neq \Omega_2$
- Eigenfrequencies Ω_i of „single-cells" ≈ eigenfrequencies ω_i of cavity

Not wanted nor expected!
Remember the coupled pendulum?

Explanation of warm rf measurements: RLC circuits



- Model the two MAGO cells as inductively coupled RLC circuits
- External oscillator U(t) in circuit 1
- Mechanical analogue: double pendulum (small angles)
- E.o.Ms:

$$L_1 \ddot{I}_1 + R_1 \dot{I}_1 + \frac{1}{C_1} I_1 = -L_c \ddot{I}_2 + \dot{U}$$

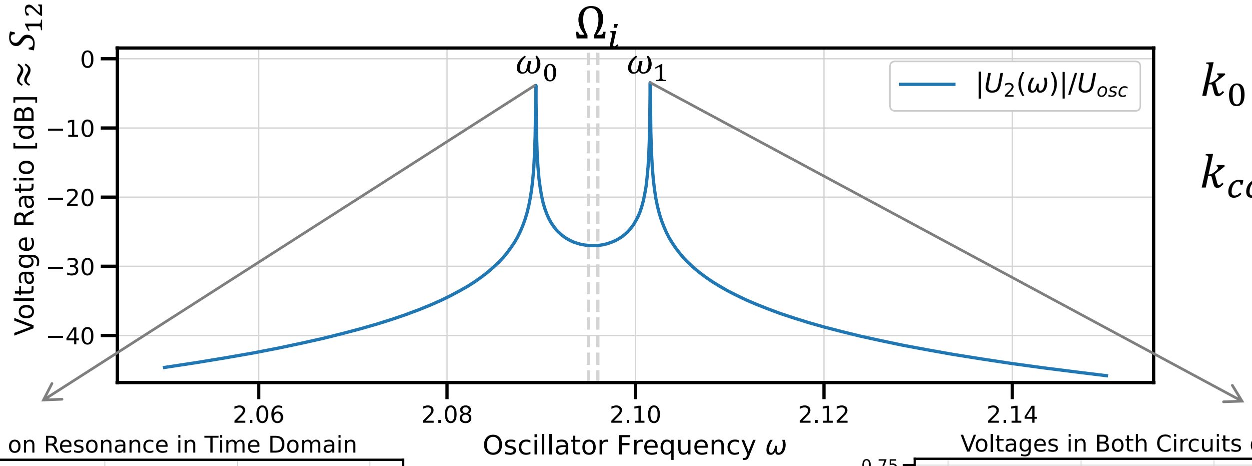
$$L_2 \ddot{I}_2 + R_2 \dot{I}_2 + \frac{1}{C_2} I_2 = -L_c \ddot{I}_1$$

$$\Omega_i = \frac{1}{\sqrt{L_i C_i}}$$

$$k_0 = \frac{L_c}{\sqrt{L_1 L_2}}$$

Solution of the coupled E.o.Ms

Fourier transform spectrum assuming
$U_0 = U_{osc}\sin(\omega_i t)$

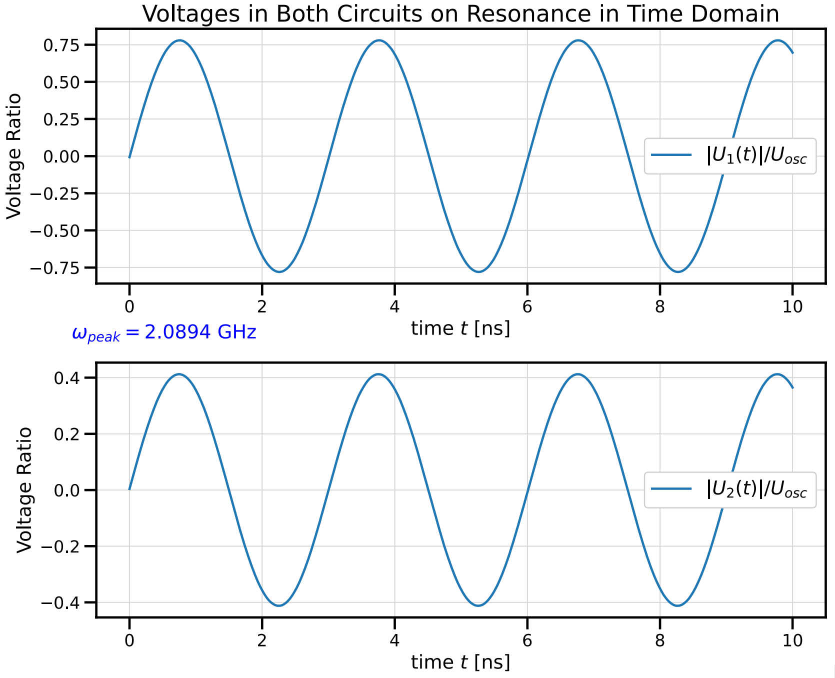


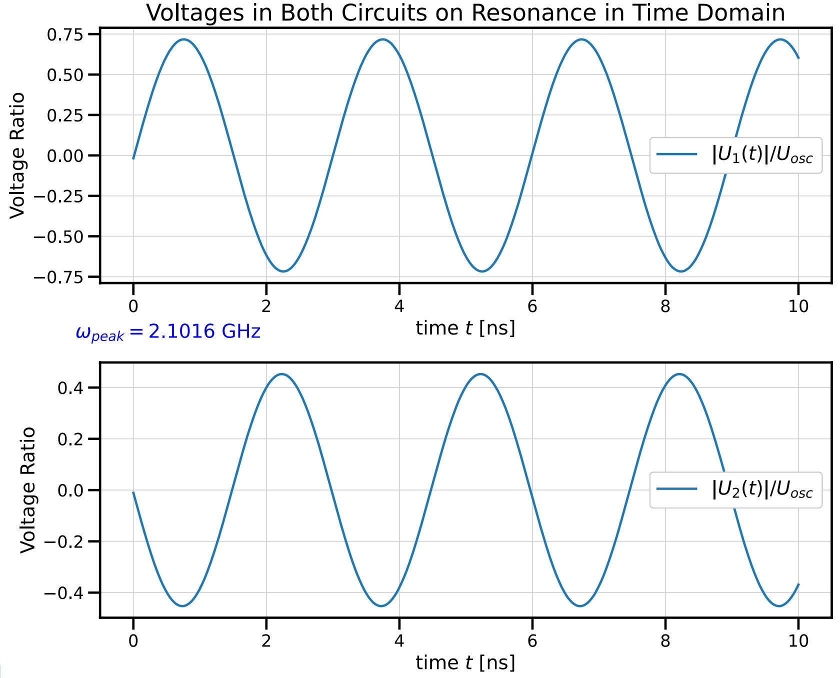
$k_0 = 10^{-2}$, $\Delta\Omega = 1$ MHz

$k_{cc,TESLA}$ = 1.5 % = 1.5 x 10^{-2}

Cell 1

Cell 2

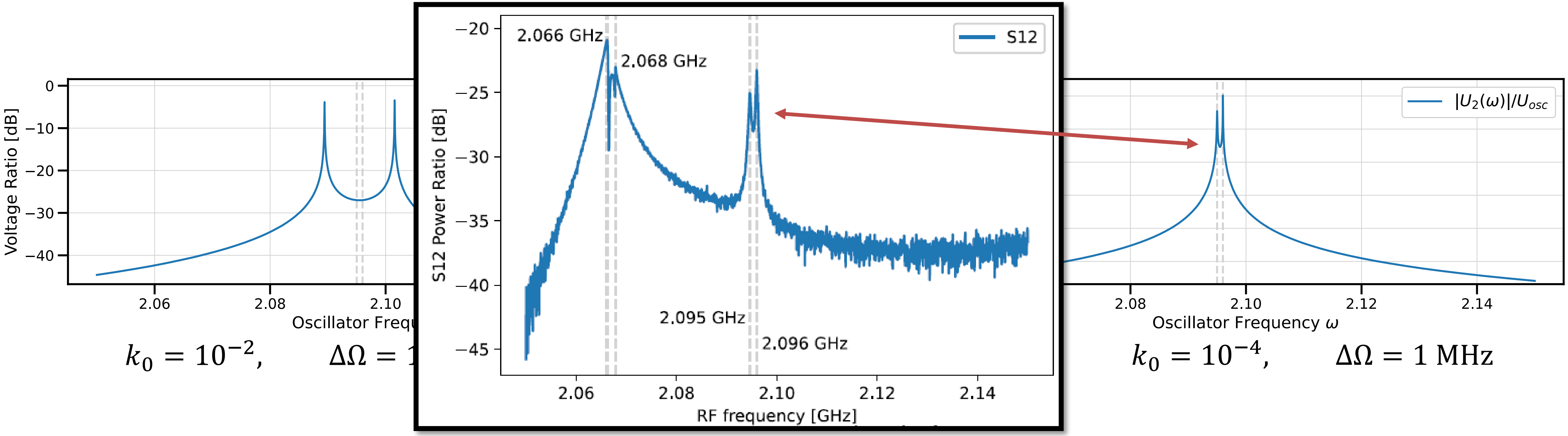




Symmetric

Antisymmetric

Varying coupling parameter k



$k_0 = 10^{-2}$, $\Delta\Omega = 1$

$k_0 = 10^{-4}$, $\Delta\Omega = 1\ \mathrm{MHz}$

Weak coupling is inherent!

$$k_{cc} = 2\frac{\omega_1 - \omega_0}{\omega_1 + \omega_0}$$

$\Delta\Omega = 1\ MHz\,;k_0 = 10^{-4}$

Only weakly coupled 0/π mode

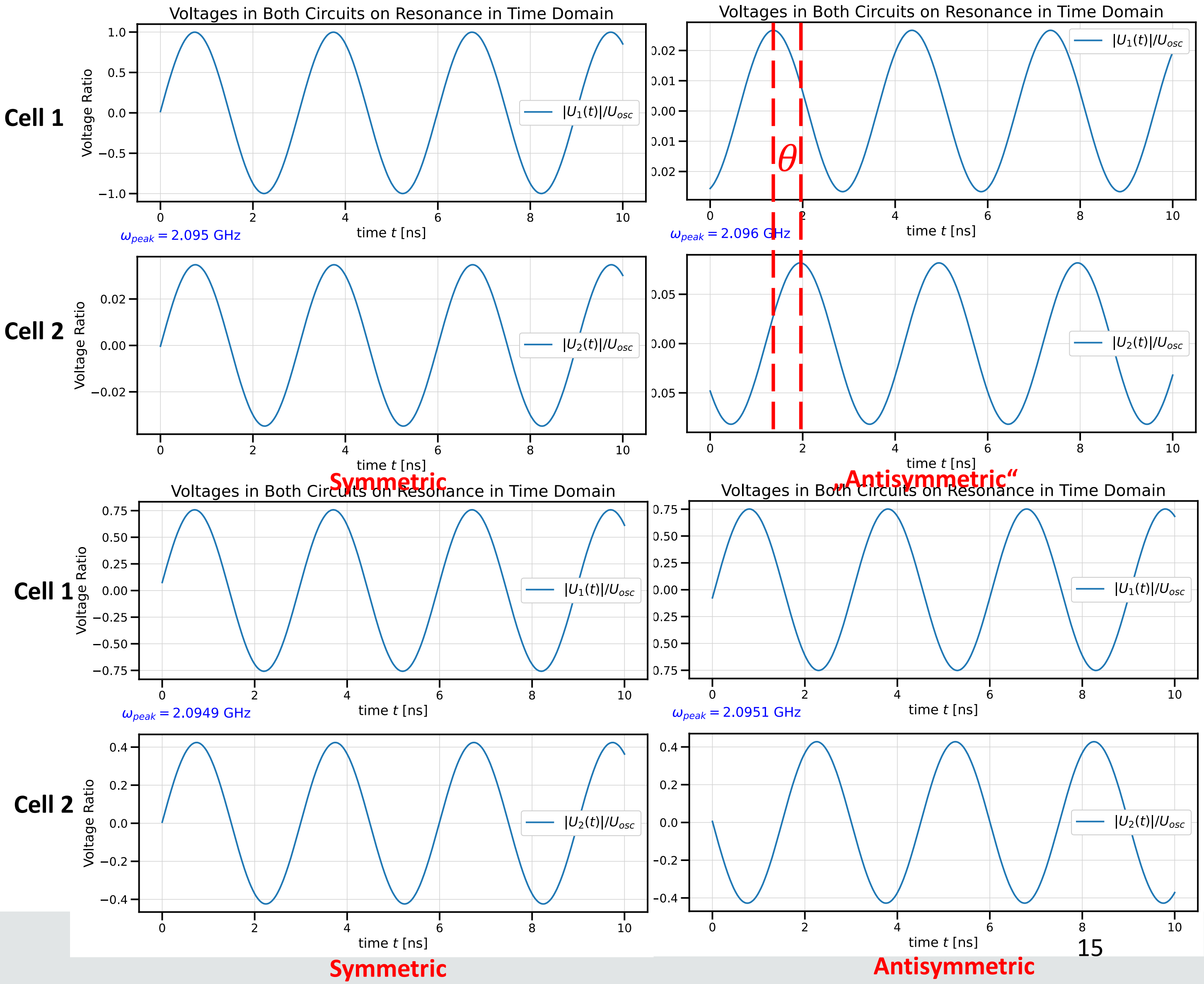
- Why is this bad?

  $Sensitivity\ \propto \vec{E}_0 \cdot \vec{E}_1 = \hat{E}_0\hat{E}_1\cos(\theta)$

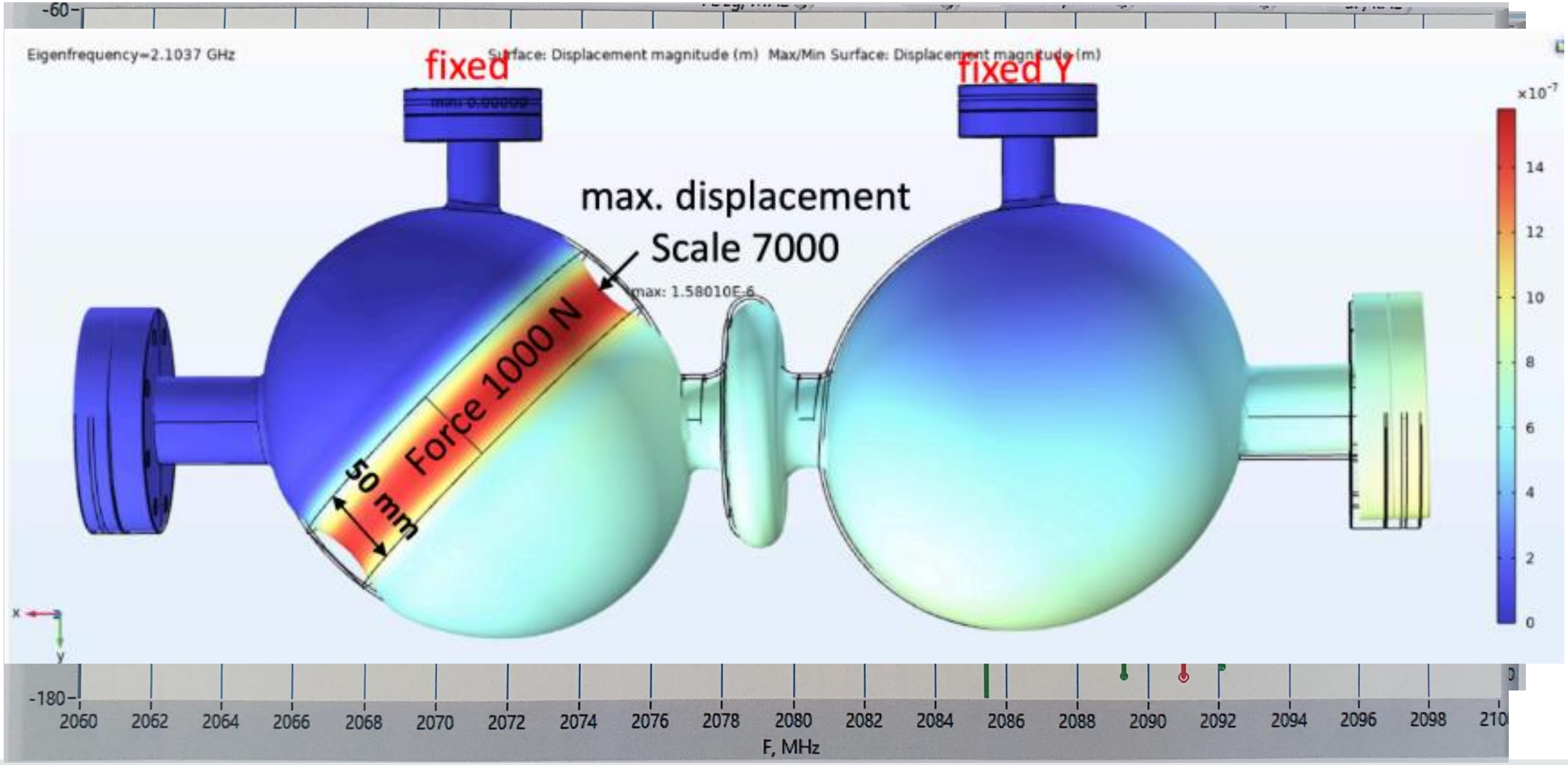
- Recover by bringing ΔΩ closer together

  $\Delta\Omega = \mathbf{1\ kHz}\,;k_0 = 10^{-4}$

- Need to **tune** cavity/cells to achieve wanted ΔΩ



Tuning done at FNAL 2 weeks ago



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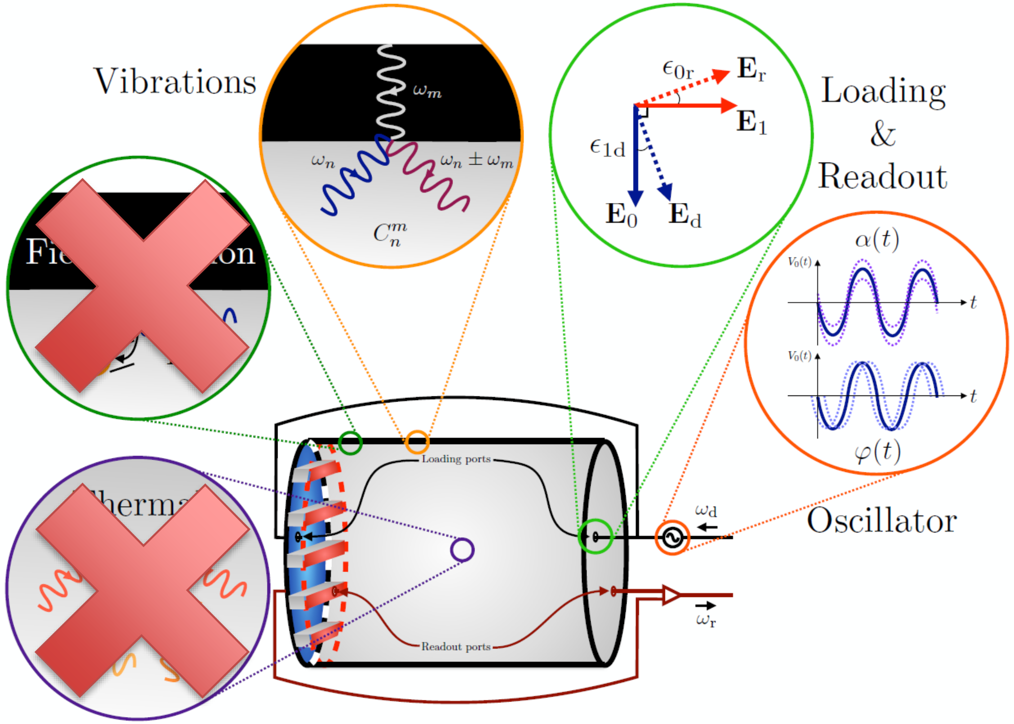
DESY.

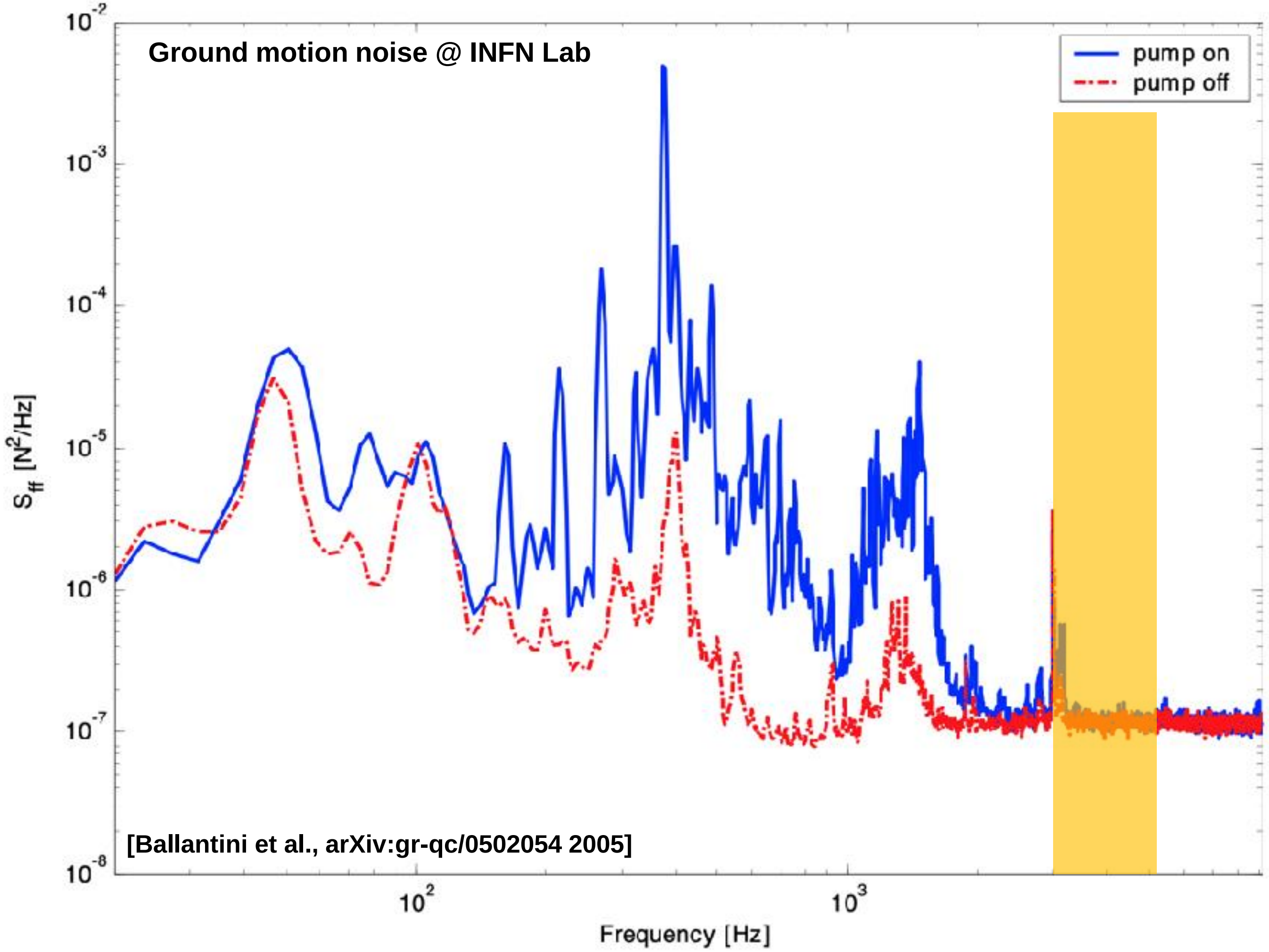
Major research topics – kill the noise!

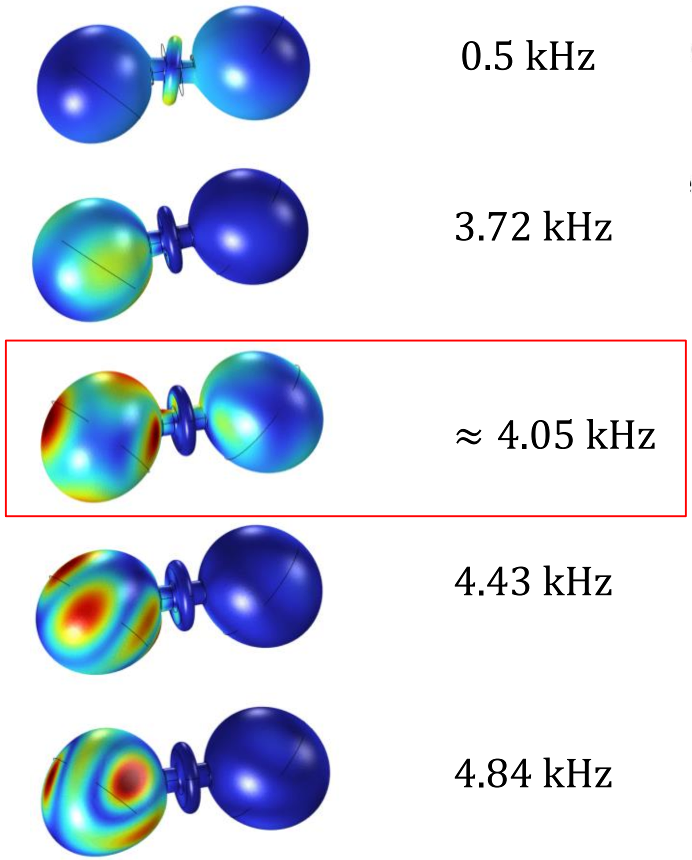
Noise sources



[Berlin et al., *arXiv:hep-ph/1912.11048v1 (2019)]*

What is the noise spectrum in the cryostats?

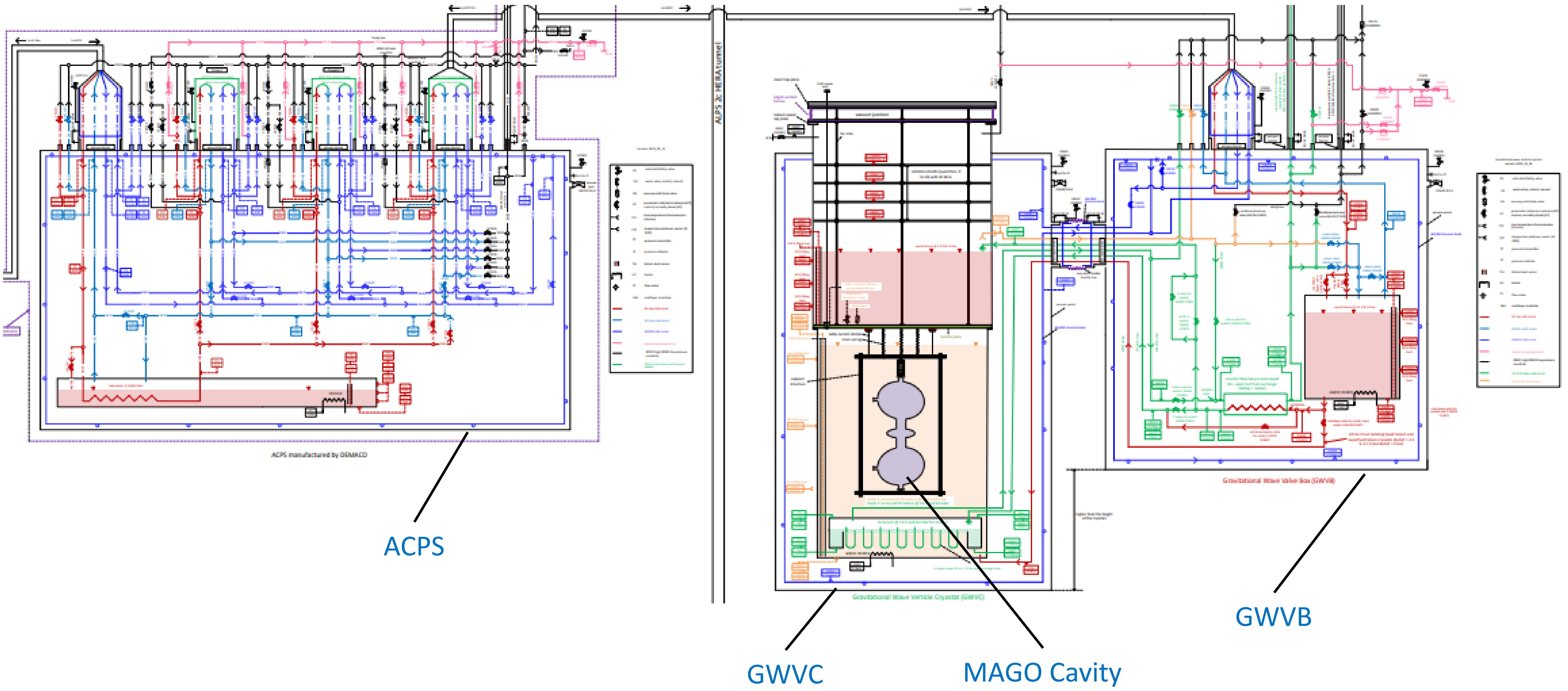




dungsverstärker

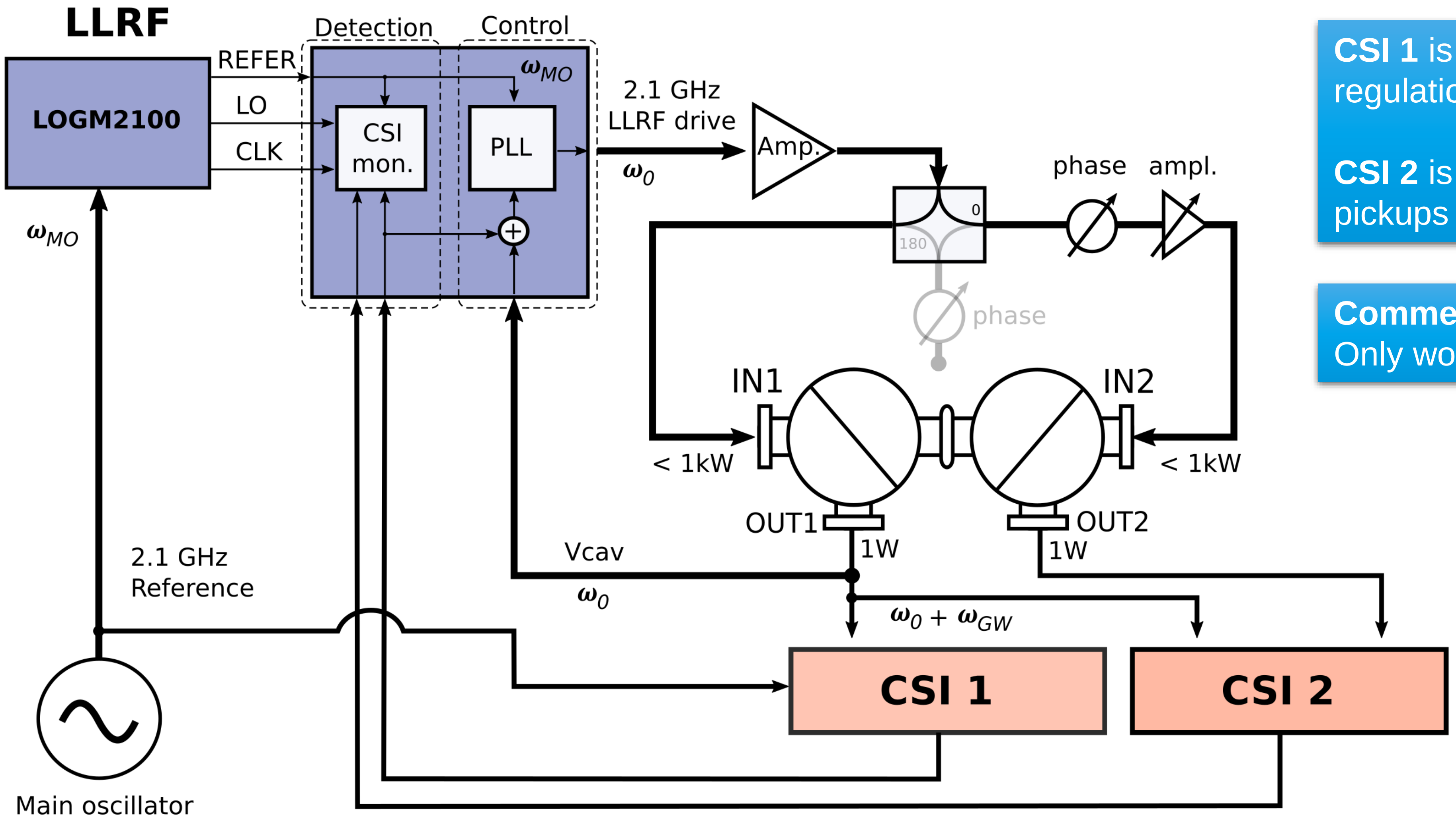
nsorpositionen

Flow scheme of GW vertical cryostat (GWVC) and GW valve box (GWVB)



LLRF setup for MAGO

Proposal 2



CSI 1 is used to improve field regulation

CSI 2 is used to compare the pickups

Comment:
Only works in GDR

Summary

- SRF cavities for GW detection opens up a frequency range currently not probed
- Broadband potential makes this approach so interesting
- >50y of GW search – first prototype studies and physics run with MAGO are a pathfinder
- Significant overlap with LLRF development for accelerators
- Need of „silent“ environment and cryogenic infrastructure
  → we can operate parasitically at a cold accelerator

Thank you

Thanks to

Asher Berlin (FNAL), Thorsten Büttner (DESY), Sergio Callatroni (CERN), Ralph Doermann (DESY), Sebastian Ellis (U Geneva), Erika Garutti (UHH), Gianluca Gemme (INFN), Oliver Gerberding (UHH), Bianca Giaccone (FNAL), Michael Grefe (UHH), Ivan Gonin (FNAL), Roni Harnik (FNAL), Beate Heinemann (DESY), Matthias Hoffmann (DESY), Timergali Khabiboulline (FNAL), Frank Ludwig (DESY), Norbert Meyners (DESY), Cornelius Martens (UHH), Andrea Muhs (DESY), Sam Posen (FNAL), Yuri Pischalnikov (FNAL), Jörn Schaffran (DESY), Tobias Schnautz (DESY), Udai Singh (DESY), Louise Springer (DESY), Jan-Hendrick Thie (DESY), Patrik Wiljes (DESY) and many more to come

Questions?