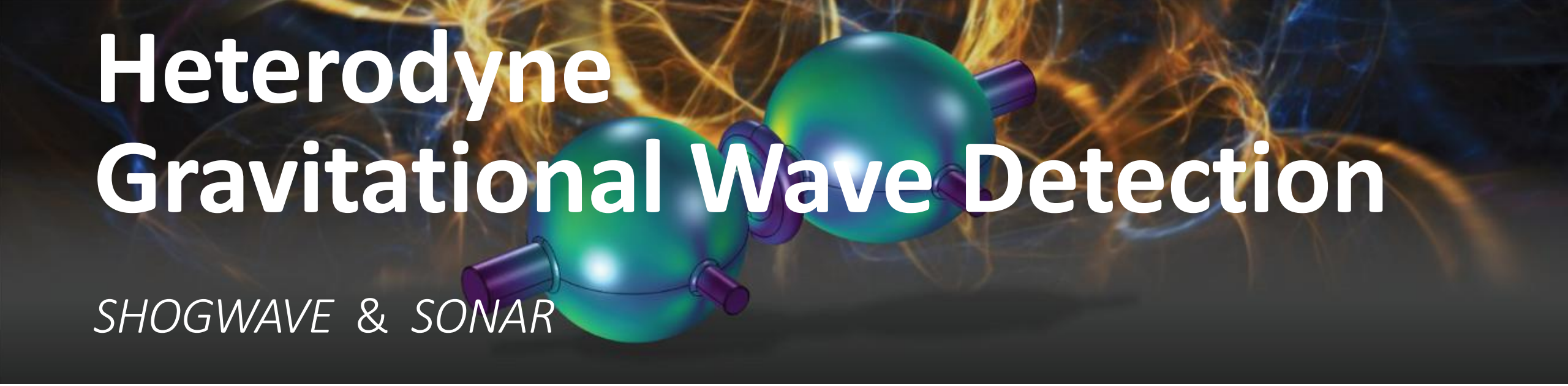
Heterodyne Gravitational Wave Detection

SHOGWAVE & SONAR



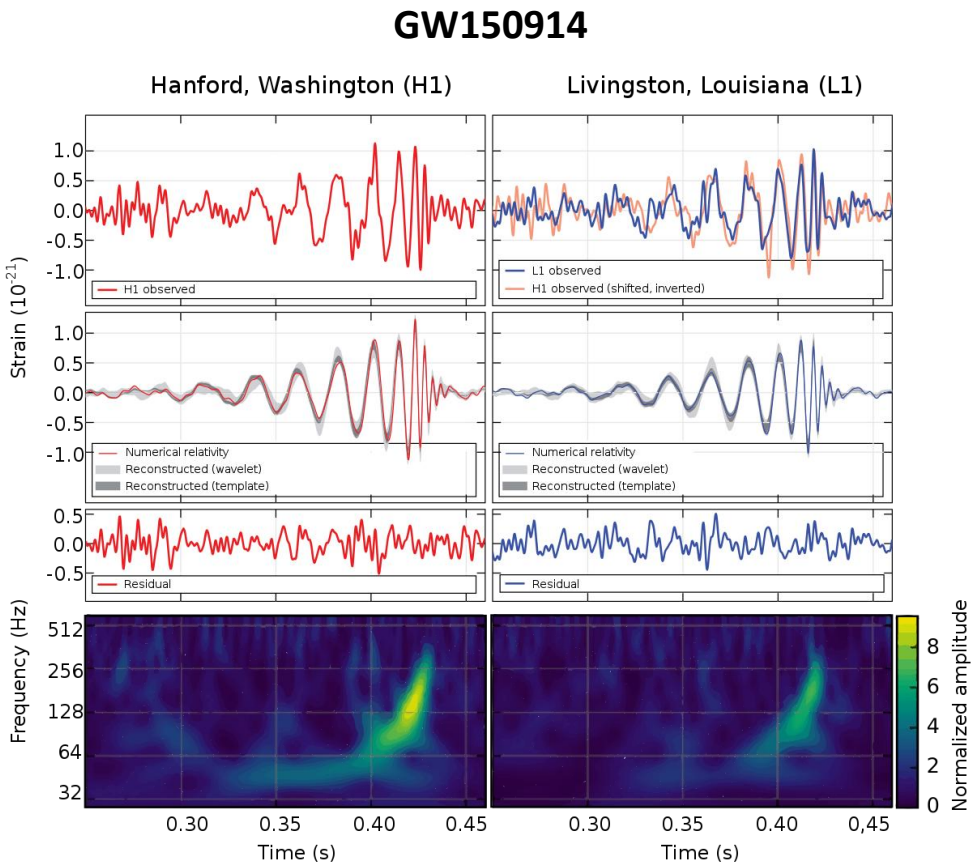
Marc Wenskat

With: Julien Branlard, Vijay Chouhan, Can Docuyucu, Bianca Giaccone, Mona Eberenz, Sebastian Ellis, Lars Fischer, Ivan Gonin, Anna Grassellino, Wolfgang Hillert, Matthias Hoffmann, Timergali Khabiboulline, Tom Krokotsch, Frank Ludwig, Giovanni Marconato, Uros Mavric, Paolo Neri, Gudrid Moortgat-Pick, Yuriy Orlov, Sam Posen, Oleg Pronitchev, Andreas Ringwald, Udai Singh

Extend detection reach beyond interferometers

Extend detection reach beyond interferometers

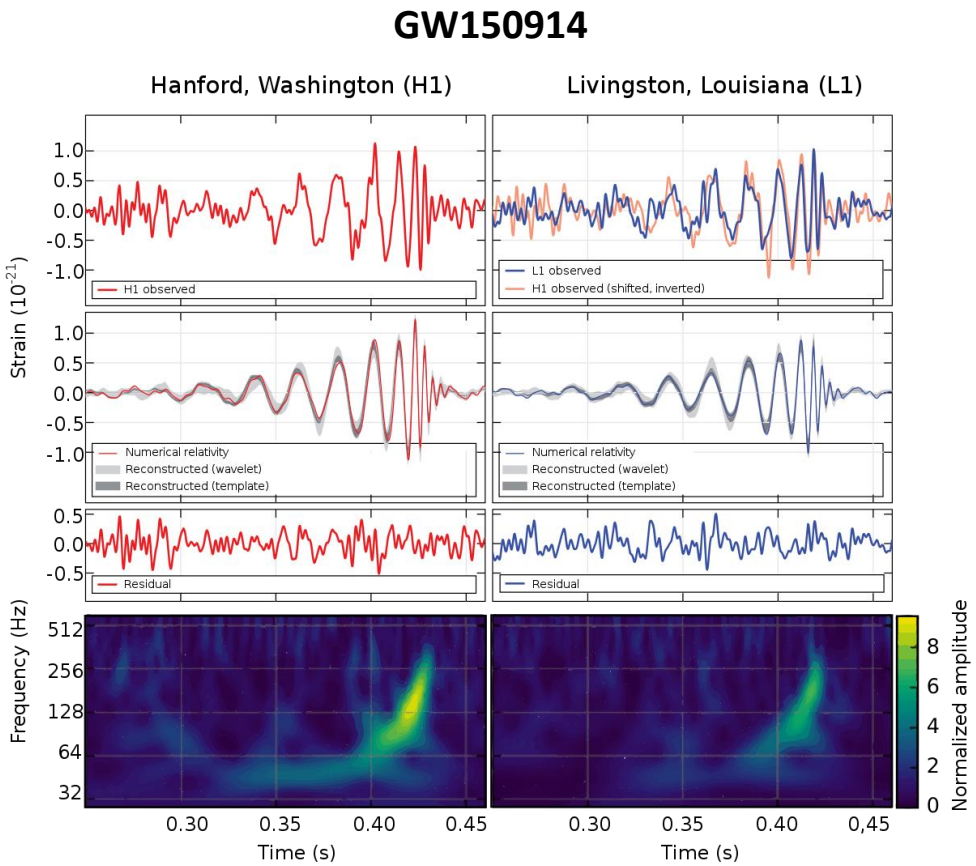
$$h_c = \frac{\Delta L}{L}$$



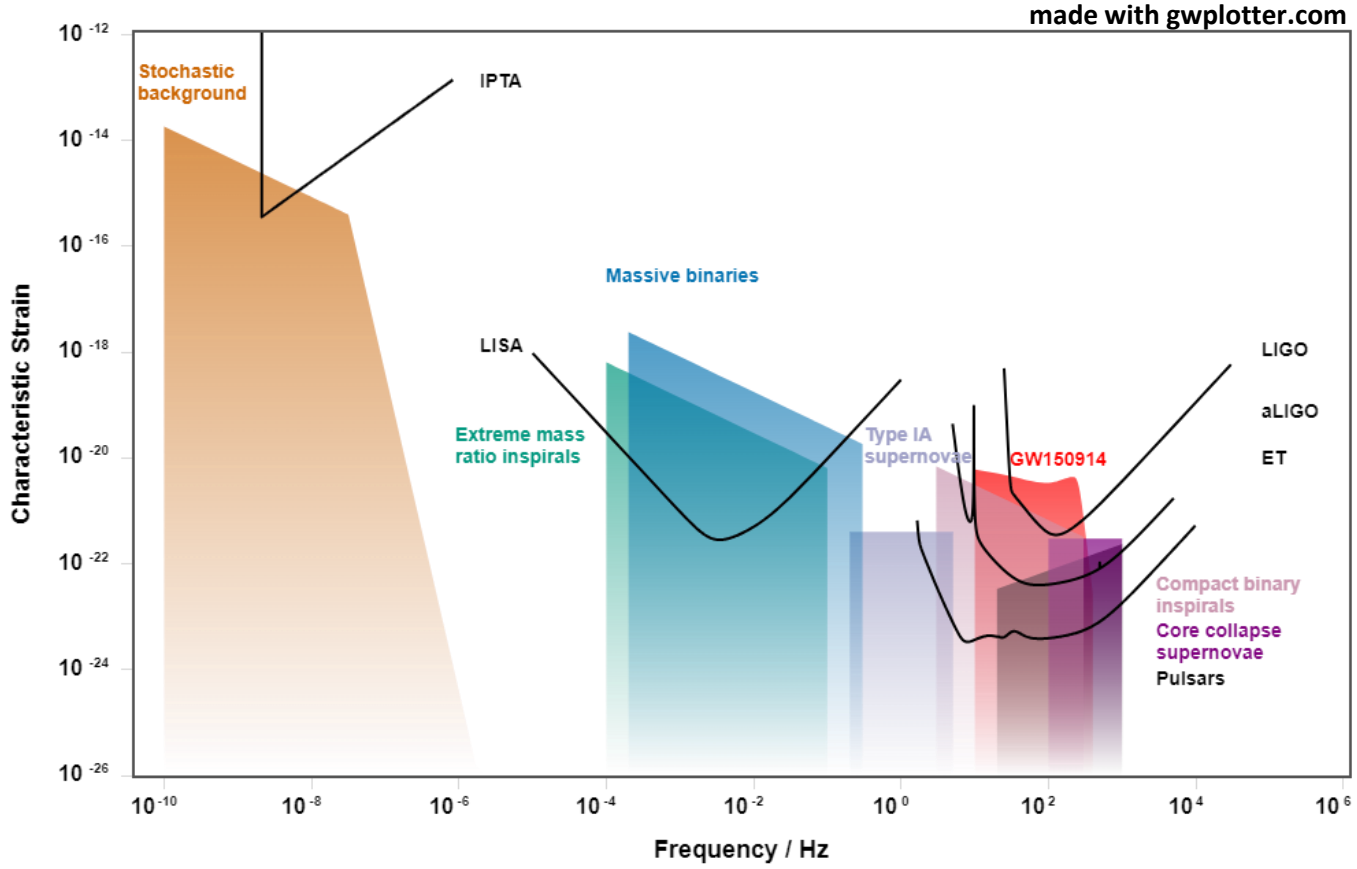
[Abbott et al., Phys. Rev. Lett. 116, 061102 (2016)]

Extend detection reach beyond interferometers

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

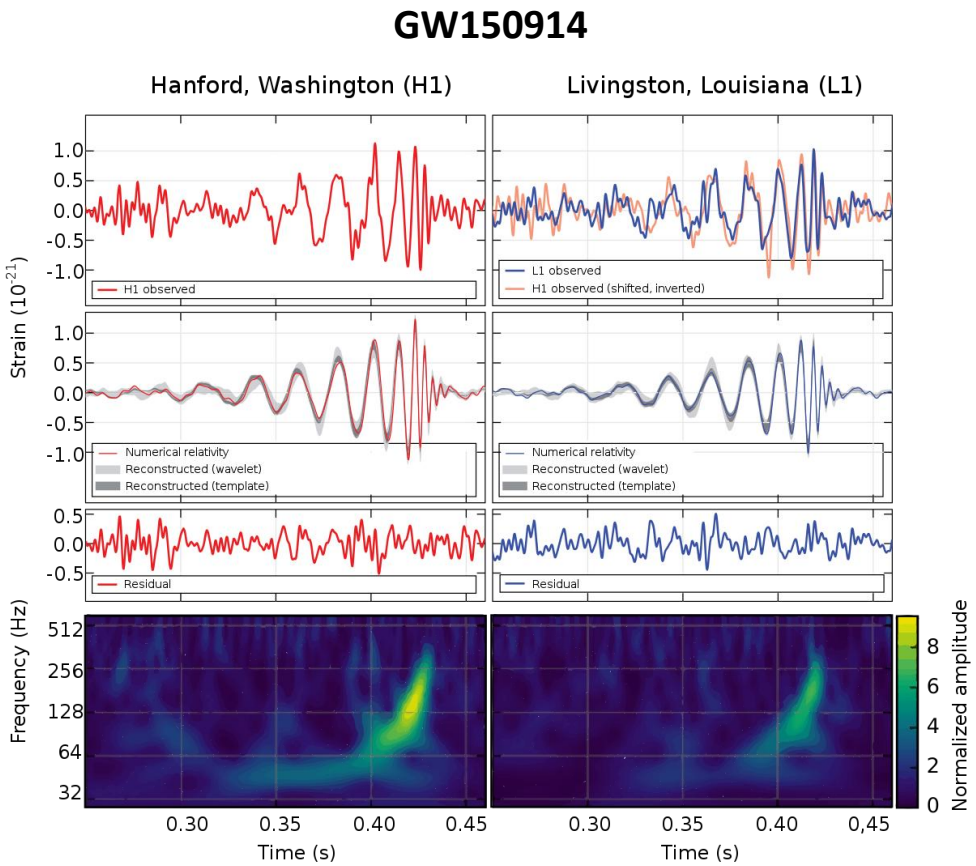


[Abbott et al., Phys. Rev. Lett. 116, 061102 (2016)]

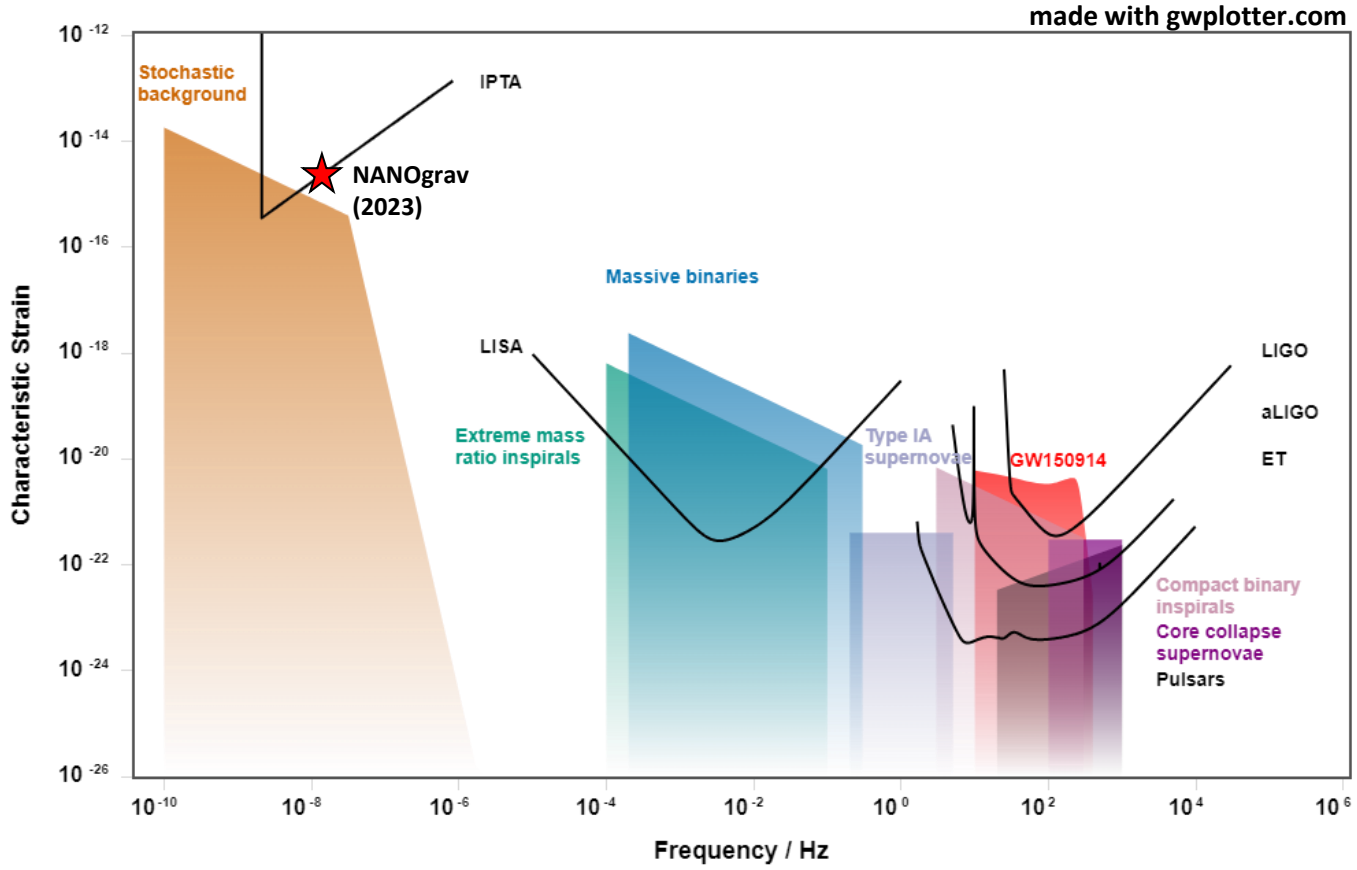


Extend detection reach beyond interferometers

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

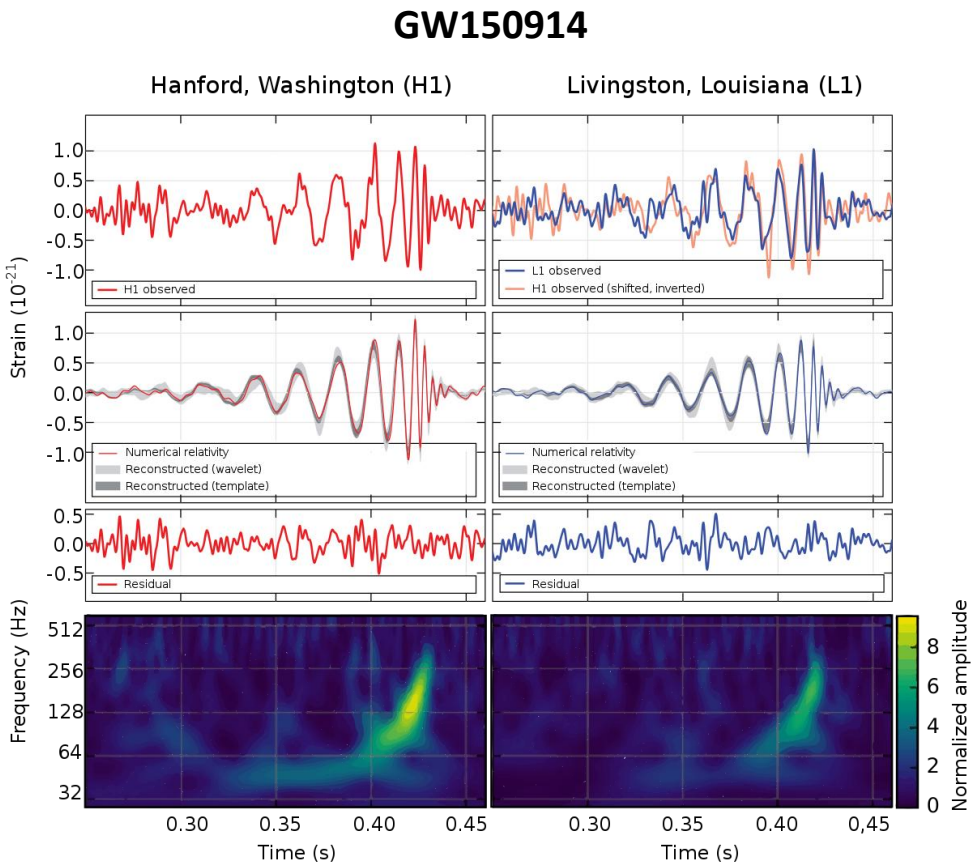


[Abbott et al., Phys. Rev. Lett. 116, 061102 (2016)]

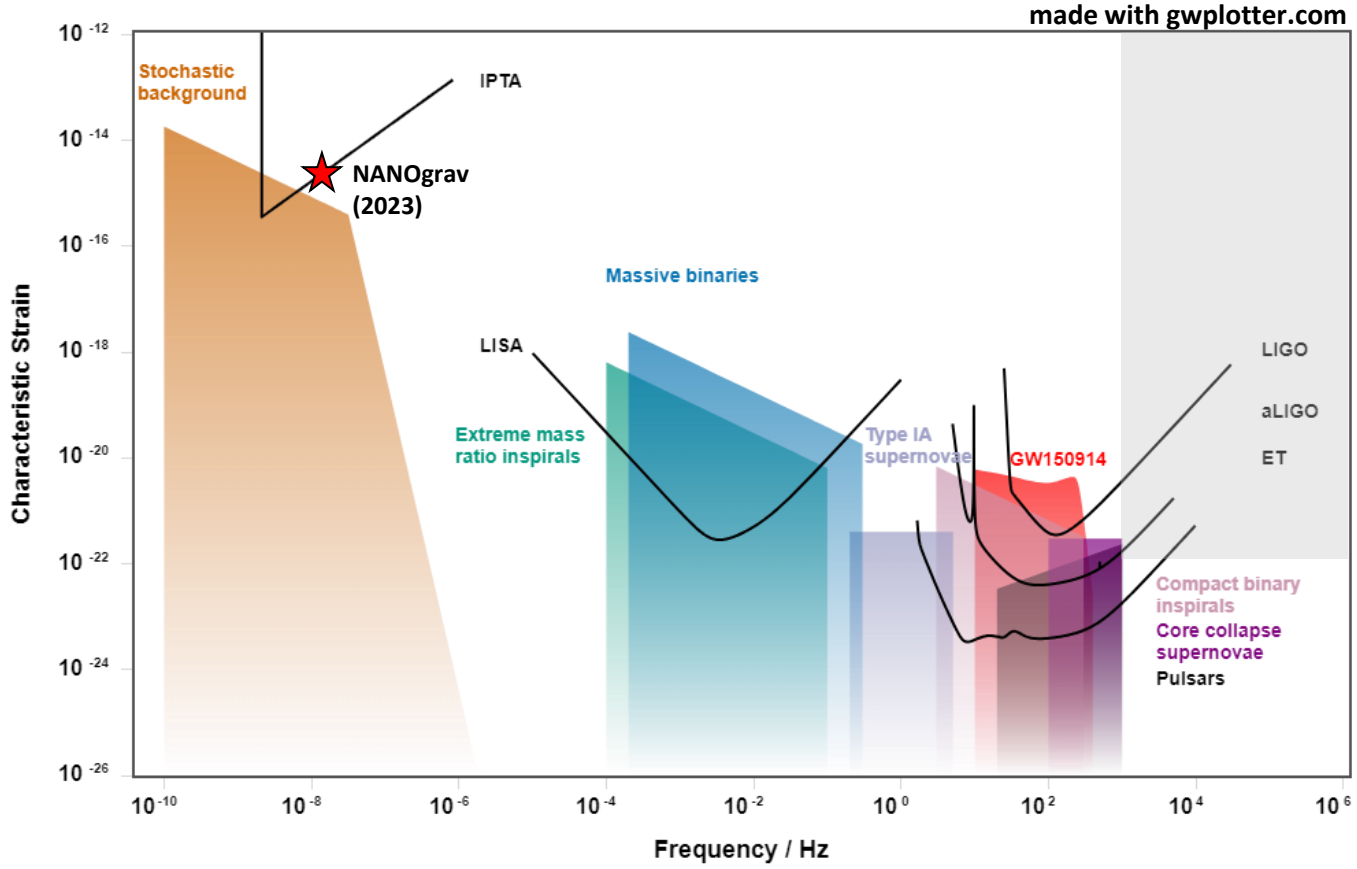


Extend detection reach beyond interferometers

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

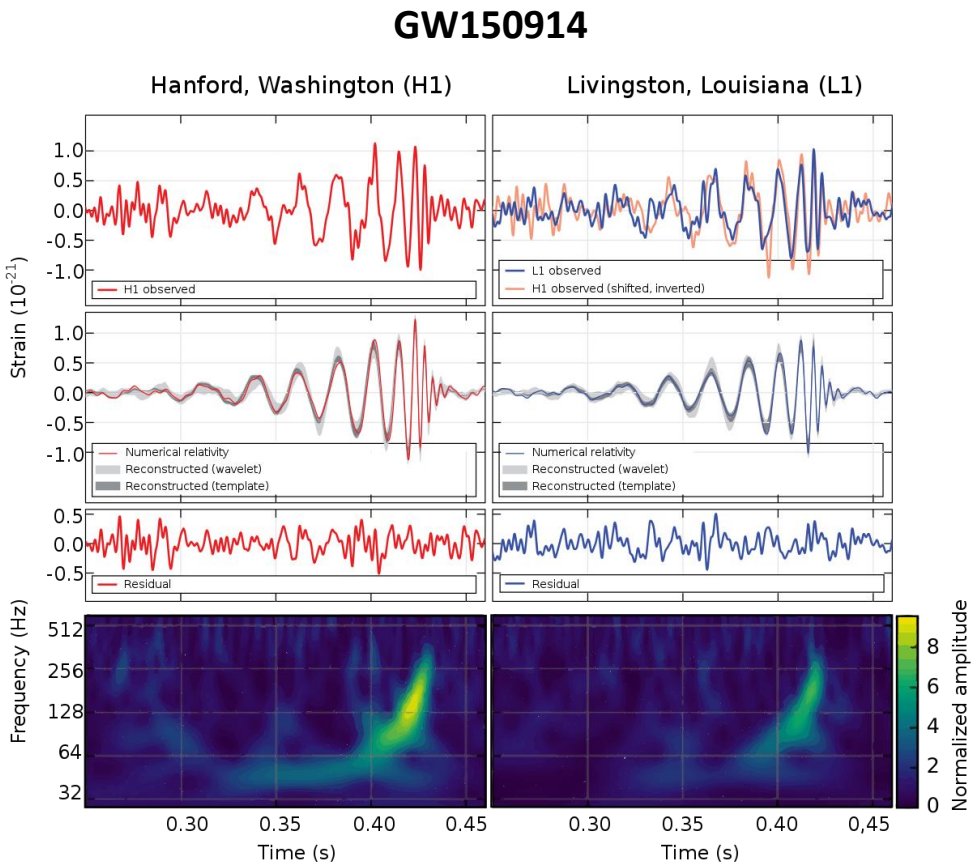


[Abbott et al., Phys. Rev. Lett. 116, 061102 (2016)]

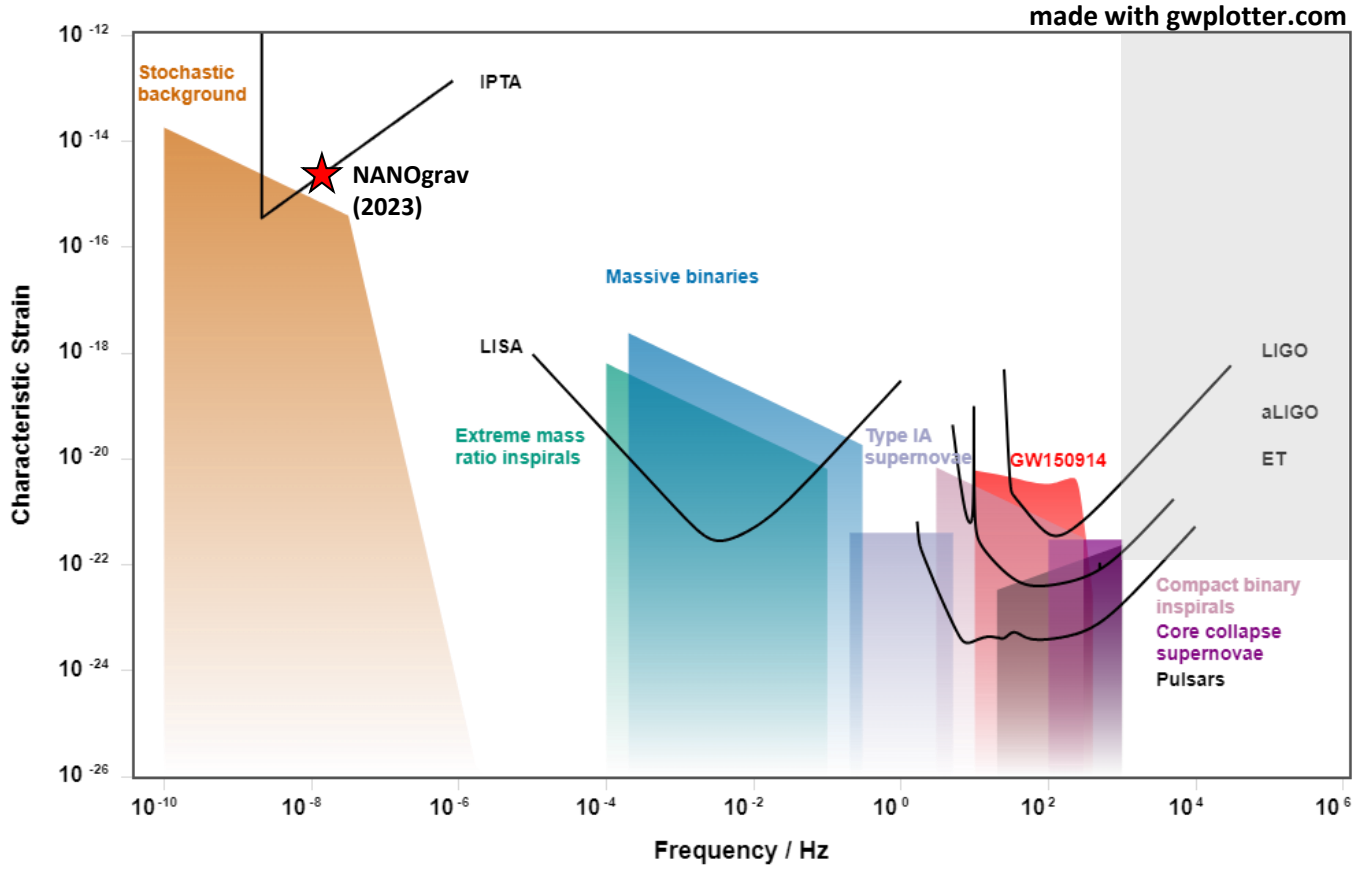


Extend detection reach beyond interferometers

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



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

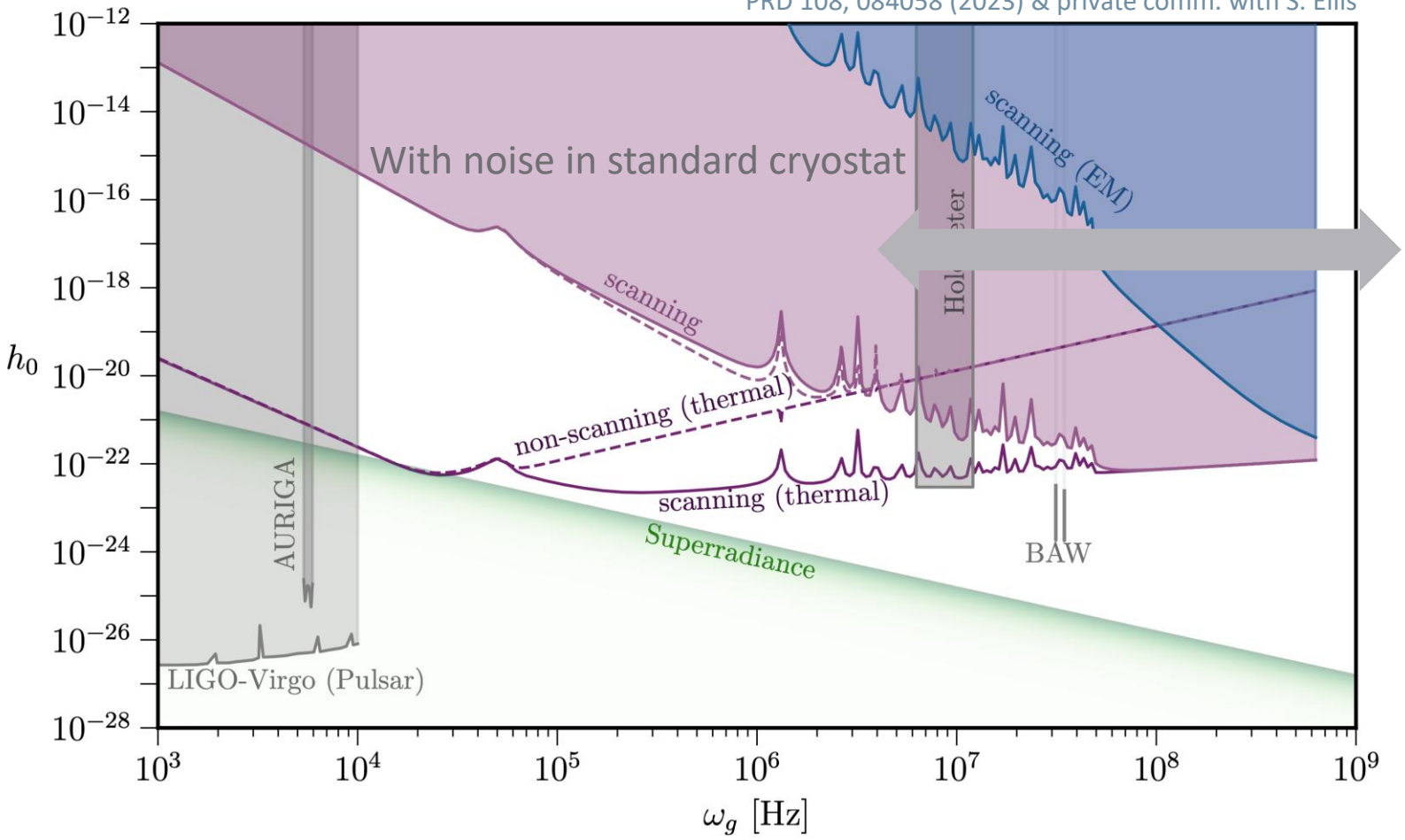


Any GW signal would be a spectacular discovery

Promising experimental reach

Unique broadband sensitivity

PRD 108, 084058 (2023) & private comm. with S. Ellis

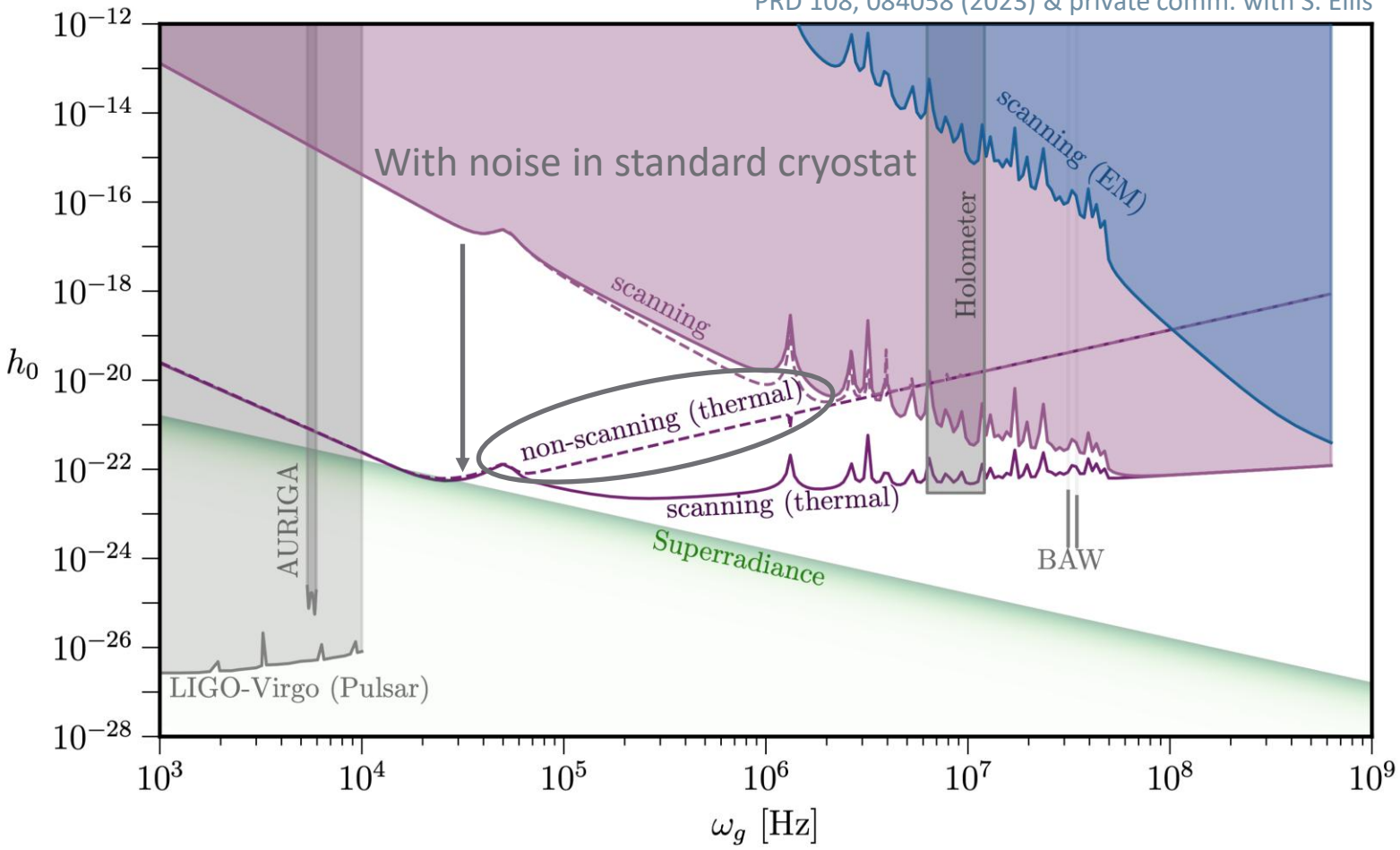


Even with a standard cryostat, novel frequency ranges can be explored, albeit with limited sensitivity

Promising experimental reach

Unique broadband sensitivity

PRD 108, 084058 (2023) & private comm. with S. Ellis



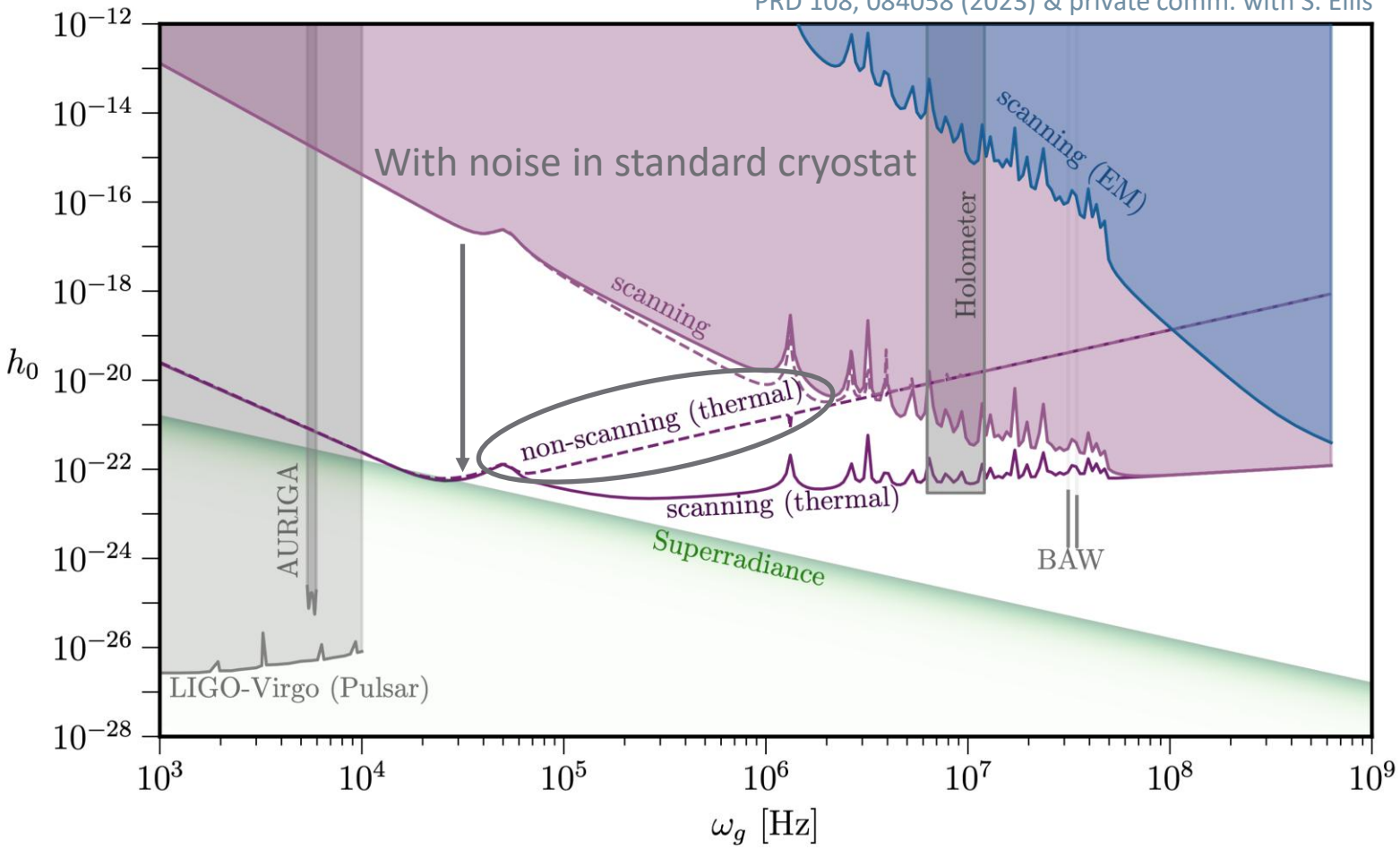
Even with a standard cryostat, novel frequency ranges can be explored, albeit with limited sensitivity

Strongly improve reach by attenuating vibrational noise

Promising experimental reach

Unique broadband sensitivity

PRD 108, 084058 (2023) & private comm. with S. Ellis



Even with a standard cryostat, novel frequency ranges can be explored, albeit with limited sensitivity

Strongly improve reach by attenuating vibrational noise

Unique broadband sensitivity!

Indirect measurement using heterodyne detection

STEP 1

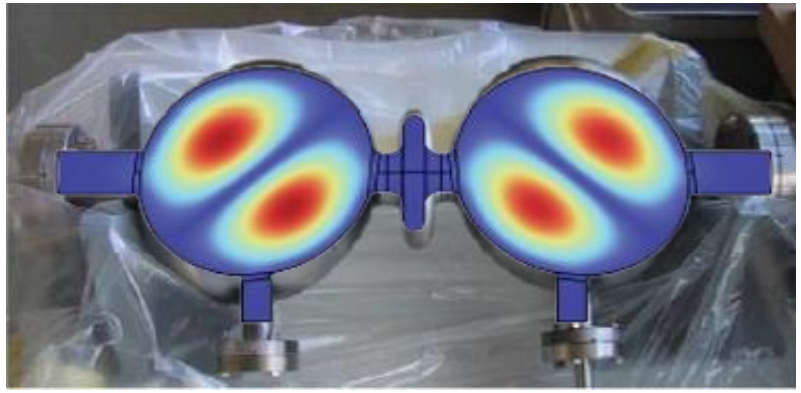
632 mm



Indirect measurement using heterodyne detection

STEP 1

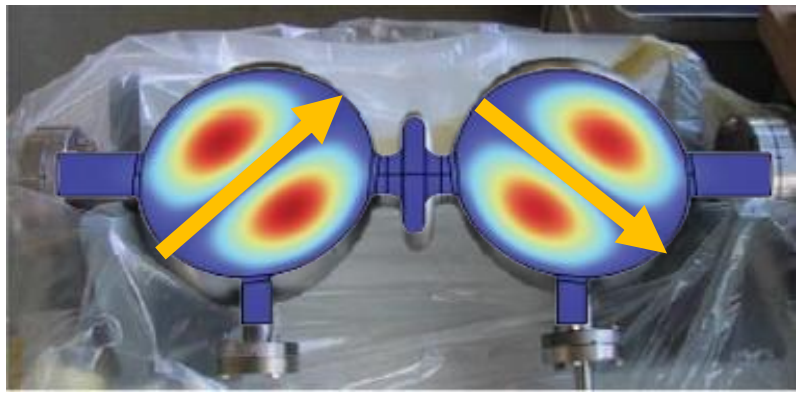
632 mm

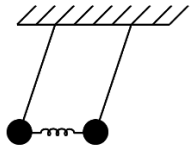


Indirect measurement using heterodyne detection

STEP 1

632 mm

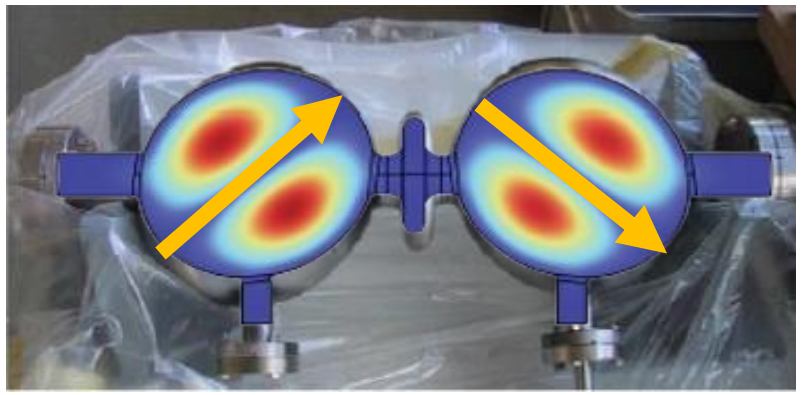


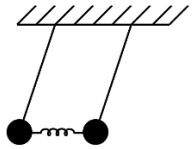


Indirect measurement using heterodyne detection

STEP 1

632 mm

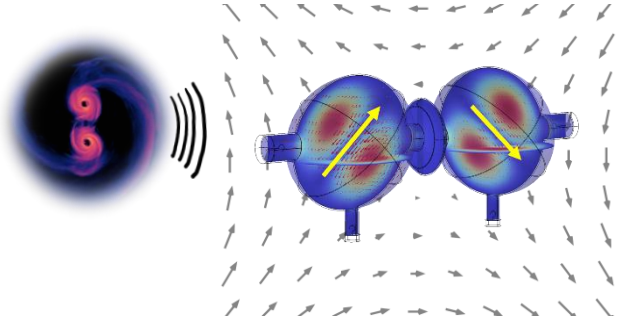




STEP 2

GW → Mechanical → RF

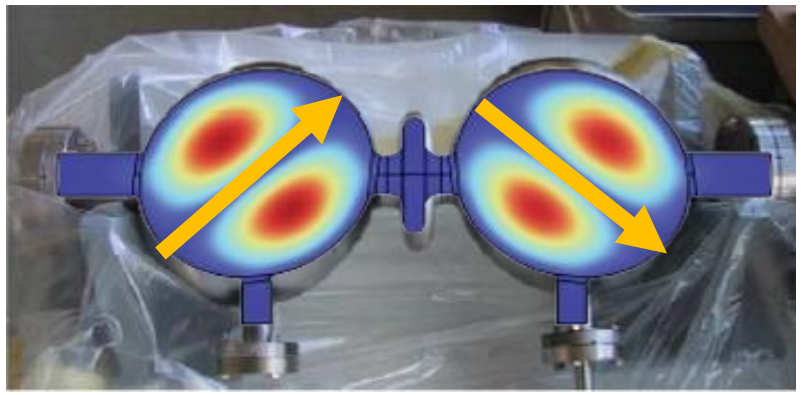
The **vibration** of the walls from **GW** produces an **upconversion of** the **RF signal** to a higher frequency

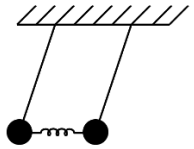


Indirect measurement using heterodyne detection

STEP 1

632 mm

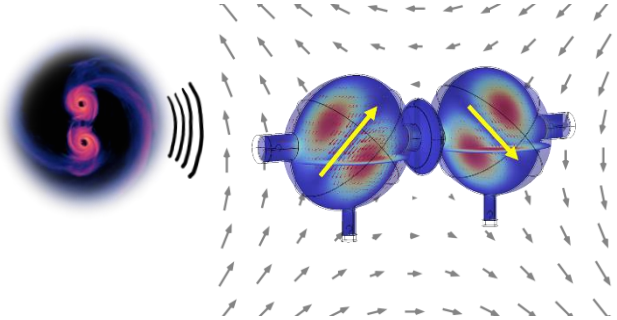




STEP 2

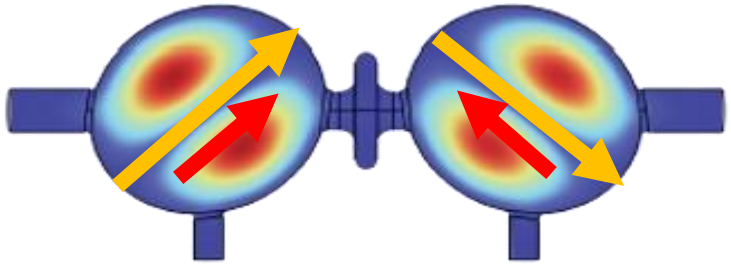
GW → Mechanical → RF

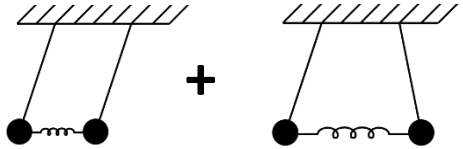
The **vibration** of the walls from **GW** produces an **upconversion of** the **RF signal** to a higher frequency



STEP 3

Read only the **signal mode**

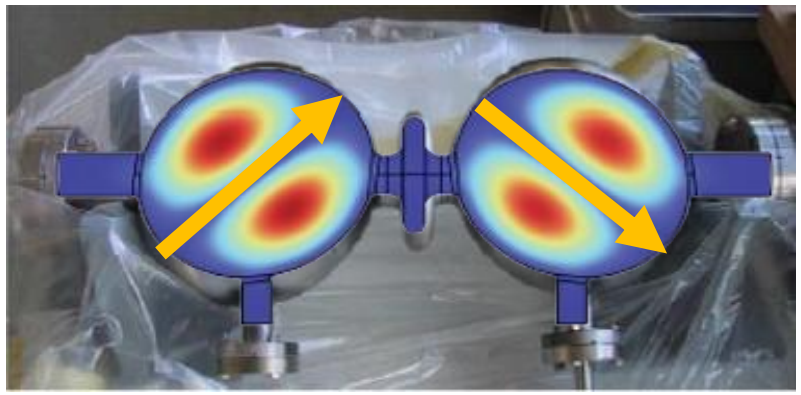


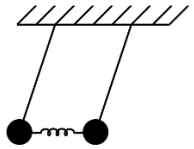


Indirect measurement using heterodyne detection

STEP 1

632 mm

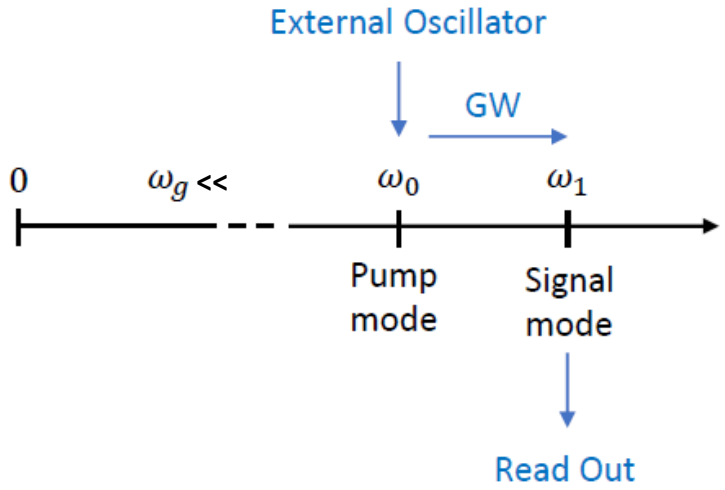




STEP 2

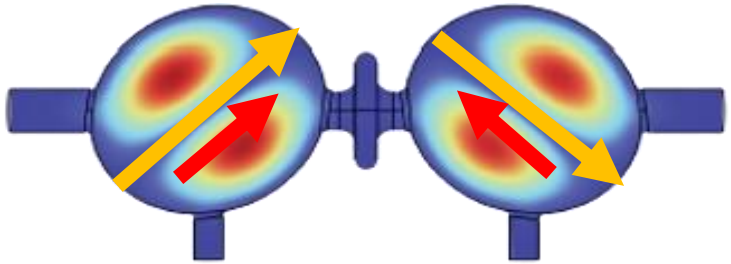
GW → Mechanical → RF

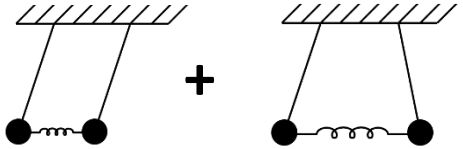
The **vibration** of the walls from **GW** produces an **upconversion of** the **RF signal** to a higher frequency



STEP 3

Read only the **signal mode**

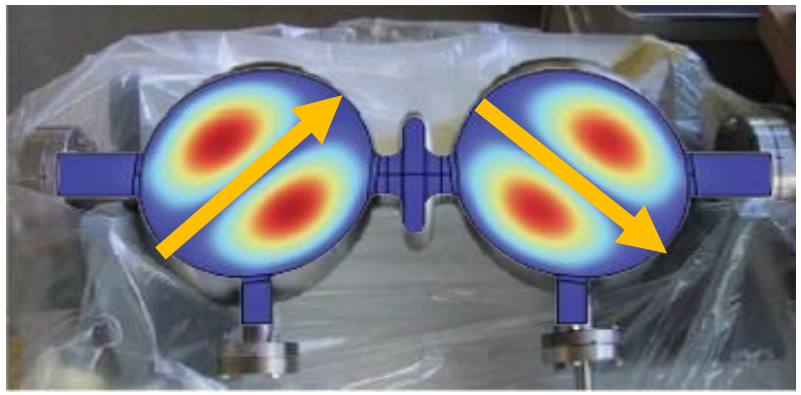


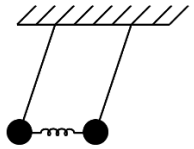


Indirect measurement using heterodyne detection

STEP 1

632 mm

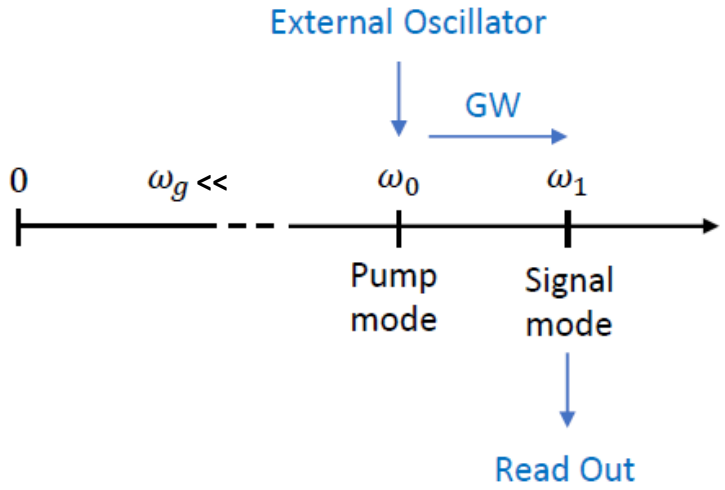




STEP 2

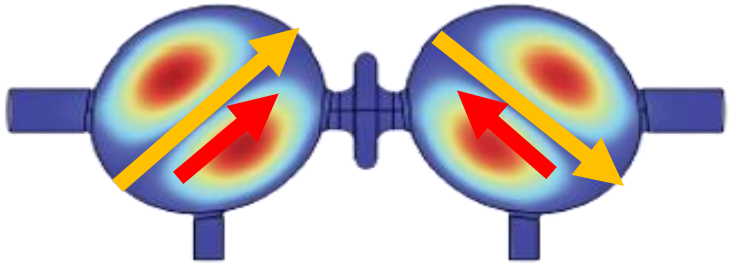
GW → Mechanical → RF

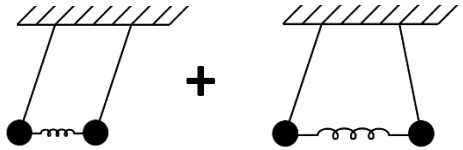
The **vibration** of the walls from **GW** produces an **upconversion of** the **RF signal** to a higher frequency



STEP 3

Read only the **signal mode**





$$k_{cc} = 2\frac{\omega_1 - \omega_0}{\omega_1 + \omega_0} \approx \frac{kHz}{GHz} = 10^{-6}$$

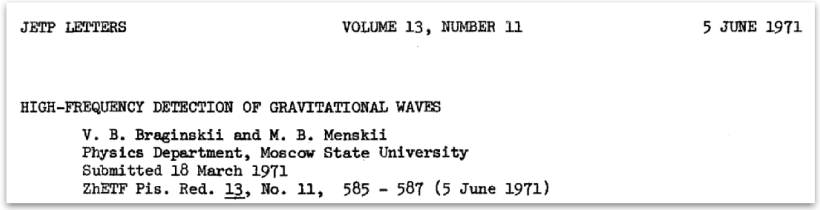
The MAGO proposal

… and the PACO cavities

The MAGO proposal

… and the PACO cavities

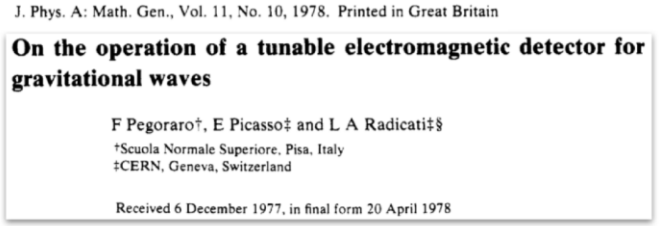
Initial idea from the 70s, which led to the MAGO proposal



JETP LETTERS VOLUME 13, NUMBER 11 5 JUNE 1971

HIGH-FREQUENCY DETECTION OF GRAVITATIONAL WAVES

V. B. Braginskii and M. B. Menskii
Physics Department, Moscow State University
Submitted 18 March 1971
ZhETF Pis. Red. 13, No. 11, 585 - 587 (5 June 1971)

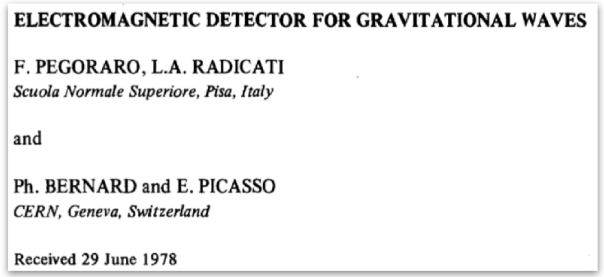


J. Phys. A: Math. Gen., Vol. 11, No. 10, 1978. Printed in Great Britain

On the operation of a tunable electromagnetic detector for gravitational waves

F Pegoraro†, E Picasso‡ and L A Radicati‡§
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978



ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

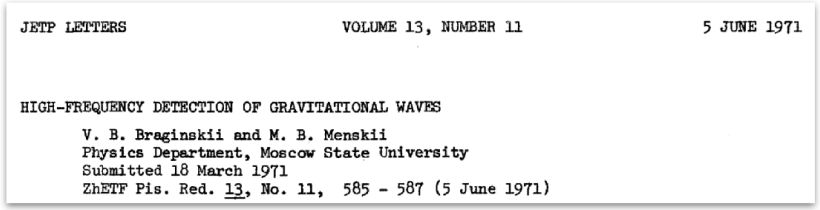
Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

Received 29 June 1978

The MAGO proposal

… and the PACO cavities

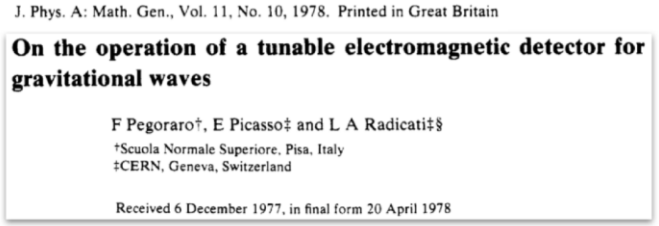
Initial idea from the 70s, which led to the MAGO proposal



JETP LETTERS VOLUME 13, NUMBER 11 5 JUNE 1971

HIGH-FREQUENCY DETECTION OF GRAVITATIONAL WAVES

V. B. Braginskii and M. B. Menskii
Physics Department, Moscow State University
Submitted 18 March 1971
ZhETF Pis. Red. 13, No. 11, 585 - 587 (5 June 1971)

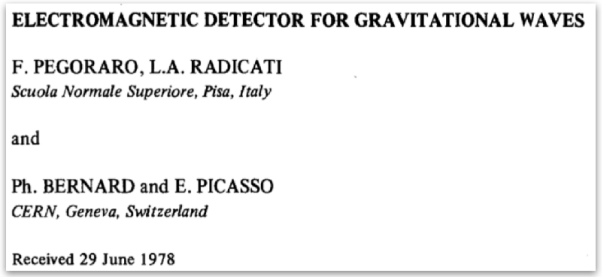


J. Phys. A: Math. Gen., Vol. 11, No. 10, 1978. Printed in Great Britain

On the operation of a tunable electromagnetic detector for gravitational waves

F Pegoraro†, E Picasso‡ and L A Radicati‡§
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978



ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

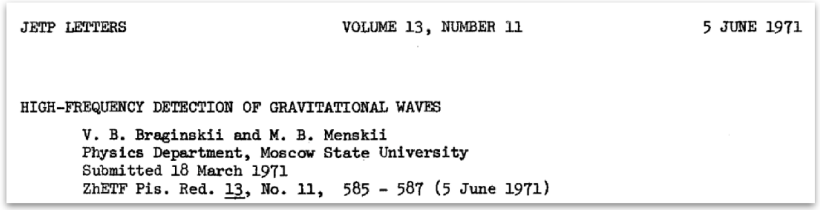
Received 29 June 1978

MAGO was a proposal for a scaled-up experiment with 500 MHz cavities targeting the kHz GW frequency range (project not funded)

The MAGO proposal

… and the PACO cavities

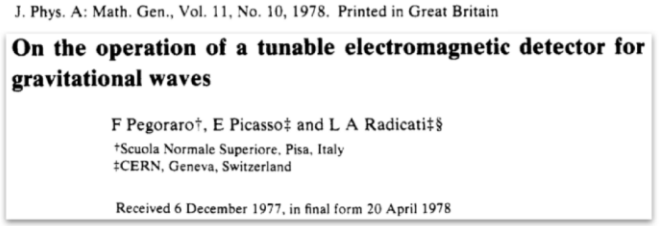
Initial idea from the 70s, which led to the MAGO proposal



JETP LETTERS VOLUME 13, NUMBER 11 5 JUNE 1971

HIGH-FREQUENCY DETECTION OF GRAVITATIONAL WAVES

V. B. Braginskii and M. B. Menskii
Physics Department, Moscow State University
Submitted 18 March 1971
ZhETF Pis. Red. 13, No. 11, 585 - 587 (5 June 1971)

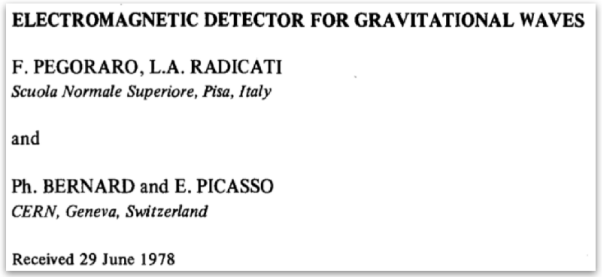


J. Phys. A: Math. Gen., Vol. 11, No. 10, 1978. Printed in Great Britain

On the operation of a tunable electromagnetic detector for gravitational waves

F Pegoraro†, E Picasso‡ and L A Radicati‡§
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978



ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

Received 29 June 1978

MAGO was a proposal for a scaled-up experiment with 500 MHz cavities targeting the kHz GW frequency range (project not funded)

During the R&D activities 3 superconducting cavities were built

The MAGO proposal

… and the PACO cavities

Initial idea from the 70s, which led to the MAGO proposal

JETP LETTERS VOLUME 13, NUMBER 11 5 JUNE 1971

HIGH-FREQUENCY DETECTION OF GRAVITATIONAL WAVES

V. B. Braginskii and M. B. Menskii
Physics Department, Moscow State University
Submitted 18 March 1971
ZhETF Pis. Red. 13, No. 11, 585 - 587 (5 June 1971)

J. Phys. A: Math. Gen., Vol. 11, No. 10, 1978. Printed in Great Britain

On the operation of a tunable electromagnetic detector for gravitational waves

F Pegoraro†, E Picasso‡ and L A Radicati‡§
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978

ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

Received 29 June 1978

MAGO was a proposal for a scaled-up experiment with 500 MHz cavities targeting the kHz GW frequency range (project not funded)

During the R&D activities 3 superconducting cavities were built

1. PACO-3GHz-pillbox

- 2-cell cylindrical pillbox-cavity @ 3GHz as proof-of-principle experiment
- Low Q, test of RF system, excitation of signal mode



The MAGO proposal

… and the PACO cavities

PACO-2GHz-fixed

- 2-cell cavity with optimised geometry
- Underwent chemistry and cold test to obtain $Q_0(U)$ for TE011



Figure 5. Niobium spherical cavities (fixed coupling).

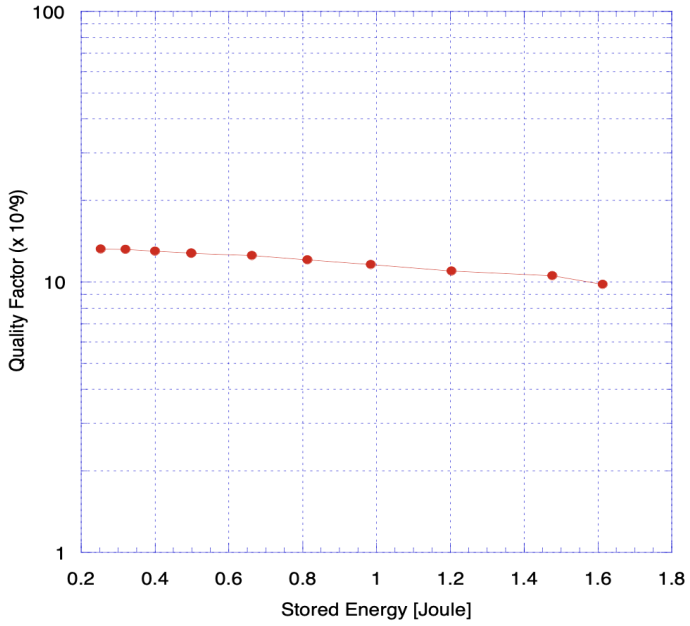


FIG. 11: Quality factor vs. stored energy for the fixed–coupling cavity

The MAGO proposal

… and the PACO cavities

PACO-2GHz-fixed

- 2-cell cavity with optimised geometry
- Underwent chemistry and cold test to obtain $Q_0(U)$ for TE011

PACO-2GHz-variable

- 2-cell cavity with same geometry but variable coupling
- Never treated nor tested – on shelf for >15y @ INFN Genova





Figure 5. Niobium spherical cavities (fixed coupling).

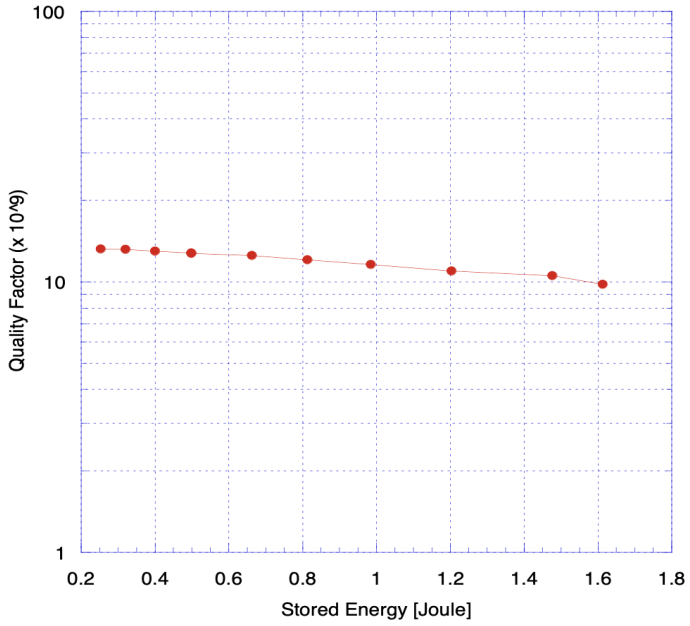


FIG. 11: Quality factor vs. stored energy for the fixed–coupling cavity

R&D efforts with the MAGO cavity

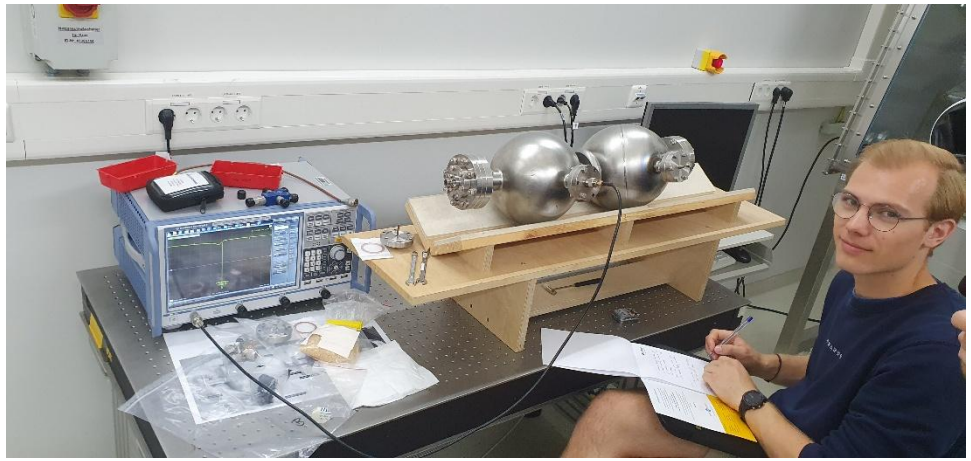
DESY/UHH - FNAL collaboration

R&D efforts with the MAGO cavity

DESY/UHH - FNAL collaboration

Cavity at DESY (2023)

- Mechanical characterization and RF measurements at room temperature



R&D efforts with the MAGO cavity

DESY/UHH - FNAL collaboration

Cavity at DESY (2023)

- Mechanical characterization and RF measurements at room temperature

Cavity at FNAL (2024)

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

Fischer et al., Class. Quantum Grav. 42 115015 (2025)



R&D efforts with the MAGO cavity

DESY/UHH - FNAL collaboration

Cavity at DESY (2023)

- Mechanical characterization and RF measurements at room temperature

Cavity at FNAL (2024)

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

Fischer et al., Class. Quantum Grav. 42 115015 (2025)

Cavity at DESY (2025)

- Cryogenic tests for LLRF system development

Dokuyucu et al., submitted to Rev.Sci.Inst.
arXiv:2607.02476



R&D efforts with the MAGO cavity

DESY/UHH - FNAL collaboration

Cavity at DESY (2023)

- Mechanical characterization and RF measurements at room temperature

Cavity at FNAL (2024)

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

Fischer et al., Class. Quantum Grav. 42 115015 (2025)

Cavity at DESY (2025)

- Cryogenic tests for LLRF system development

Dokuyucu et al., submitted to Rev.Sci.Inst. arXiv:2607.02476

Cavity at FNAL – right now

- Test with all four antennas assembled & optimal coupling



R&D efforts with the MAGO cavity

DESY/UHH - FNAL collaboration

Cavity at DESY (2023)

- Mechanical characterization and RF measurements at room temperature

Cavity at FNAL (2024)

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

Fischer et al., Class. Quantum Grav. 42 115015 (2025)

Cavity at DESY (2025)

- Cryogenic tests for LLRF system development

Dokuyucu et al., submitted to Rev.Sci.Inst. arXiv:2607.02476

Cavity at FNAL – right now

- Test with all four antennas assembled & optimal coupling

???? (202?)

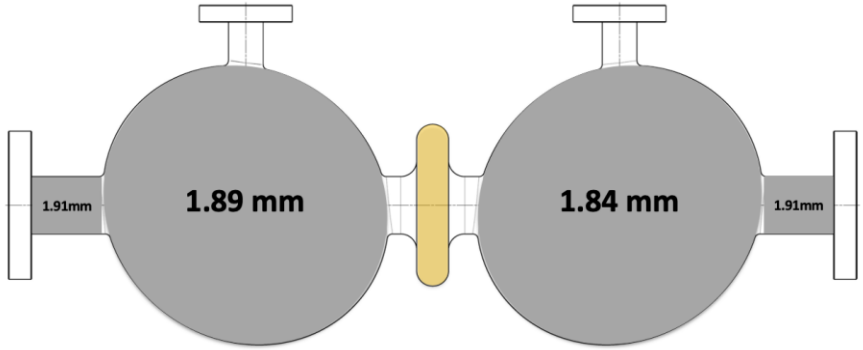
- Physics run: search for a signal



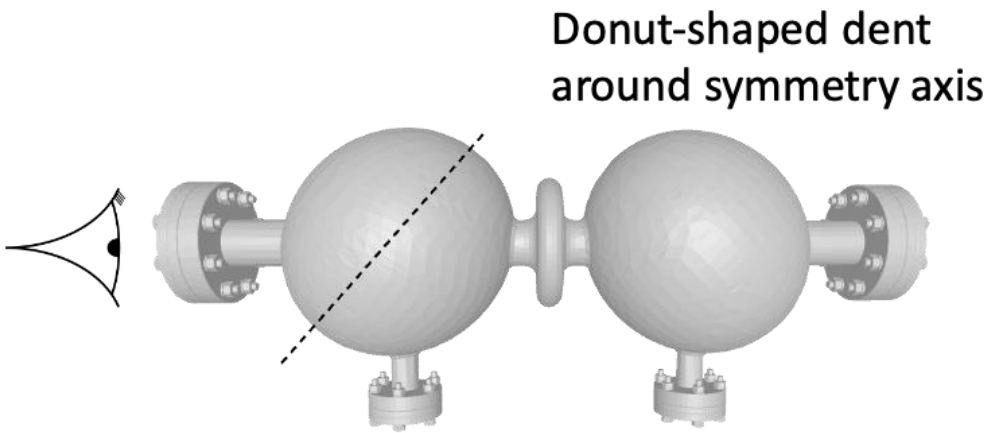
Cavity is out of shape

Mechanical survey

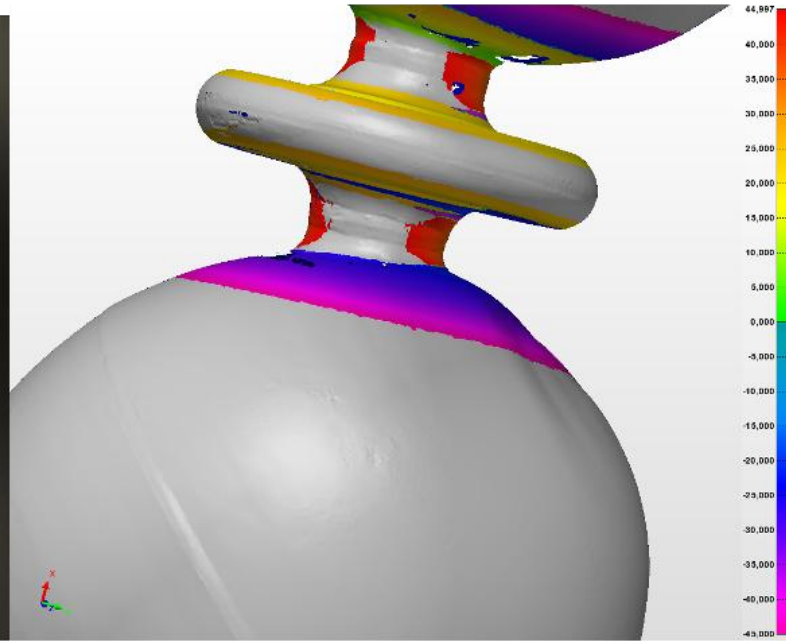
Measurement of the cavity geometry at arrival at DESY with a laser line scan and an ultrasonic wall thickness measurement (expected wall thickness 2mm)



Measured wall thickness
10 points per cell, 4 per tube, average values shown

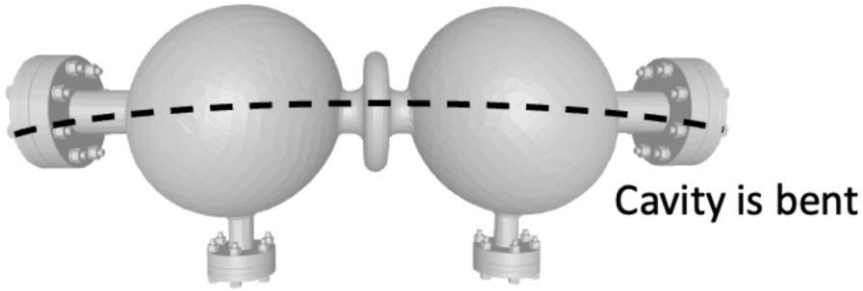


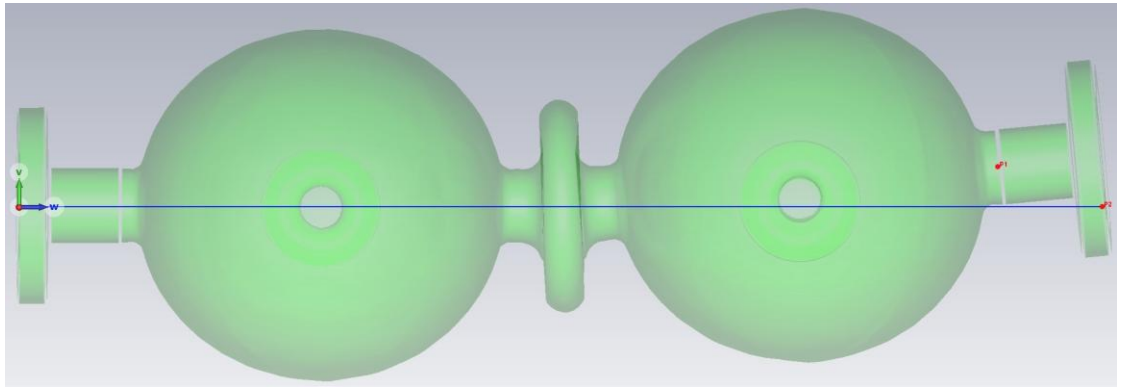


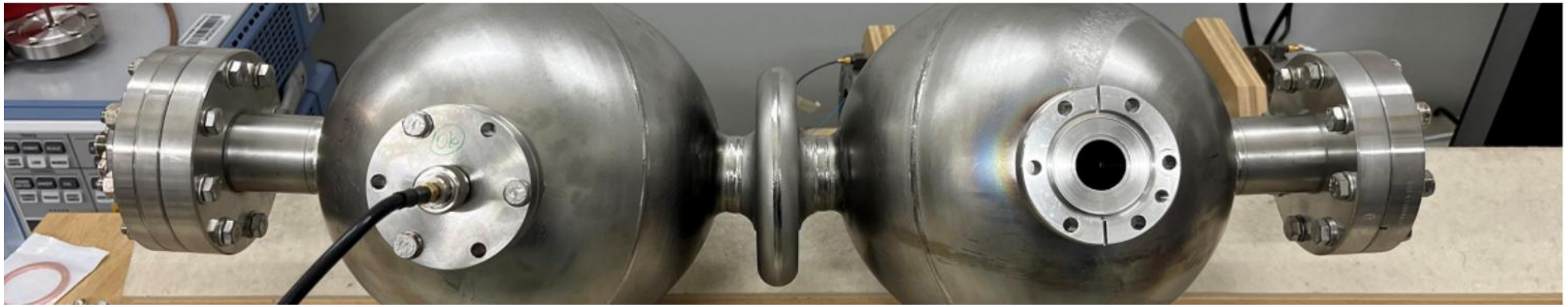


Cavity is out of shape

Mechanical survey





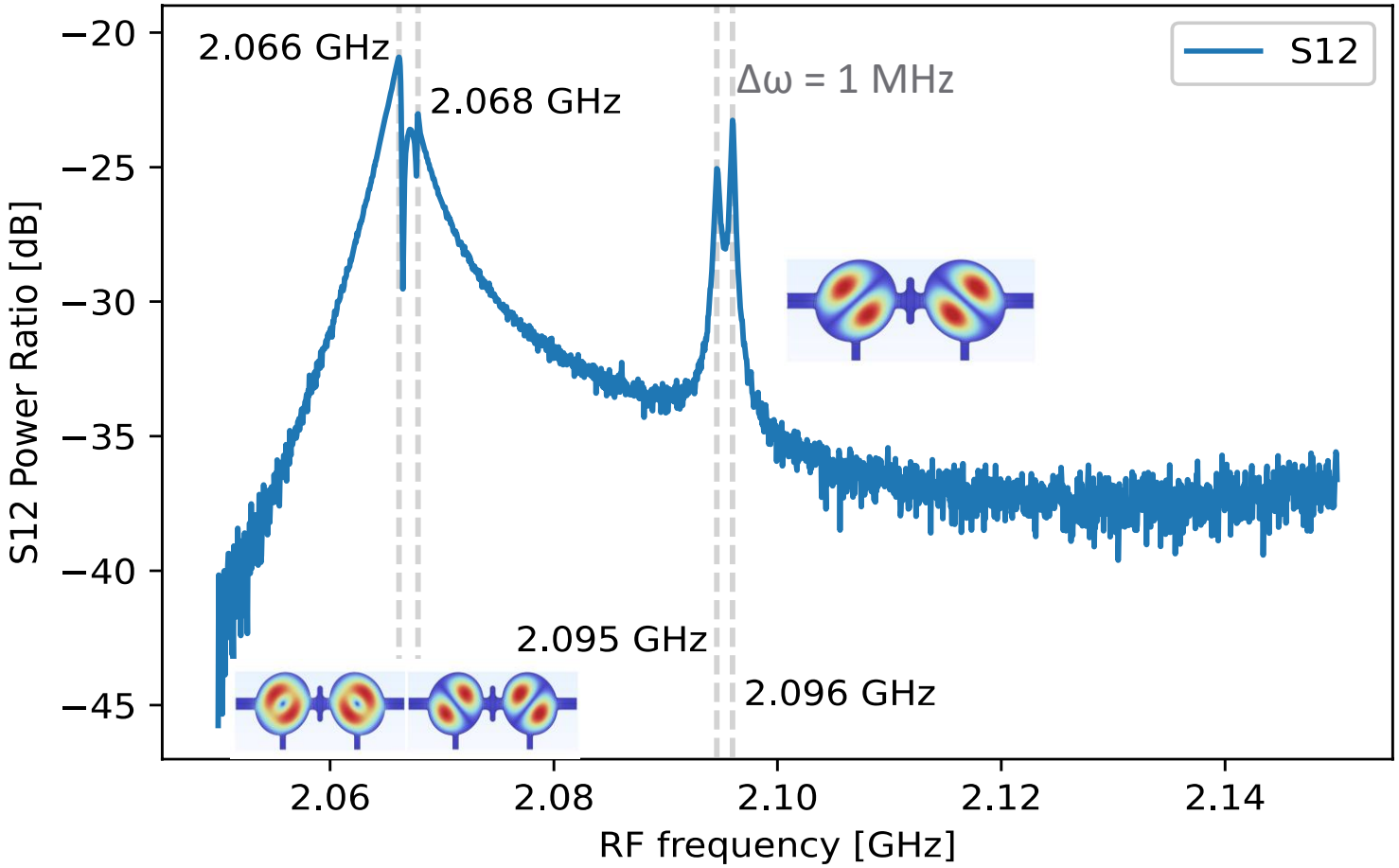


No damage to flanges or sealing surface, cavity leaktight

RF measurements worrisome

Not what expected from ideal geometry at room temperature

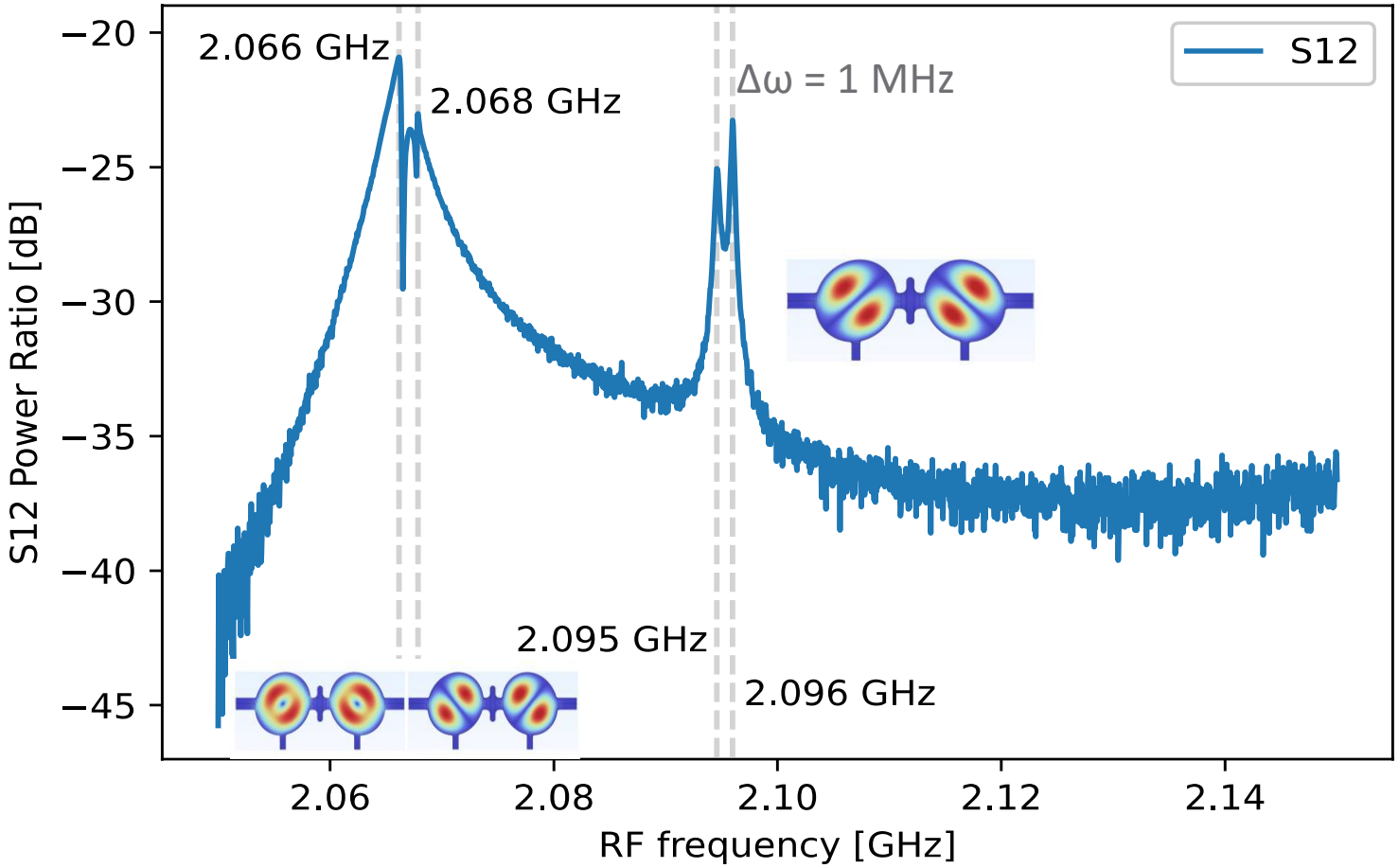
Transmission spectrum from one cell to the other



RF measurements worrisome

Not what expected from ideal geometry at room temperature

Transmission spectrum from one cell to the other



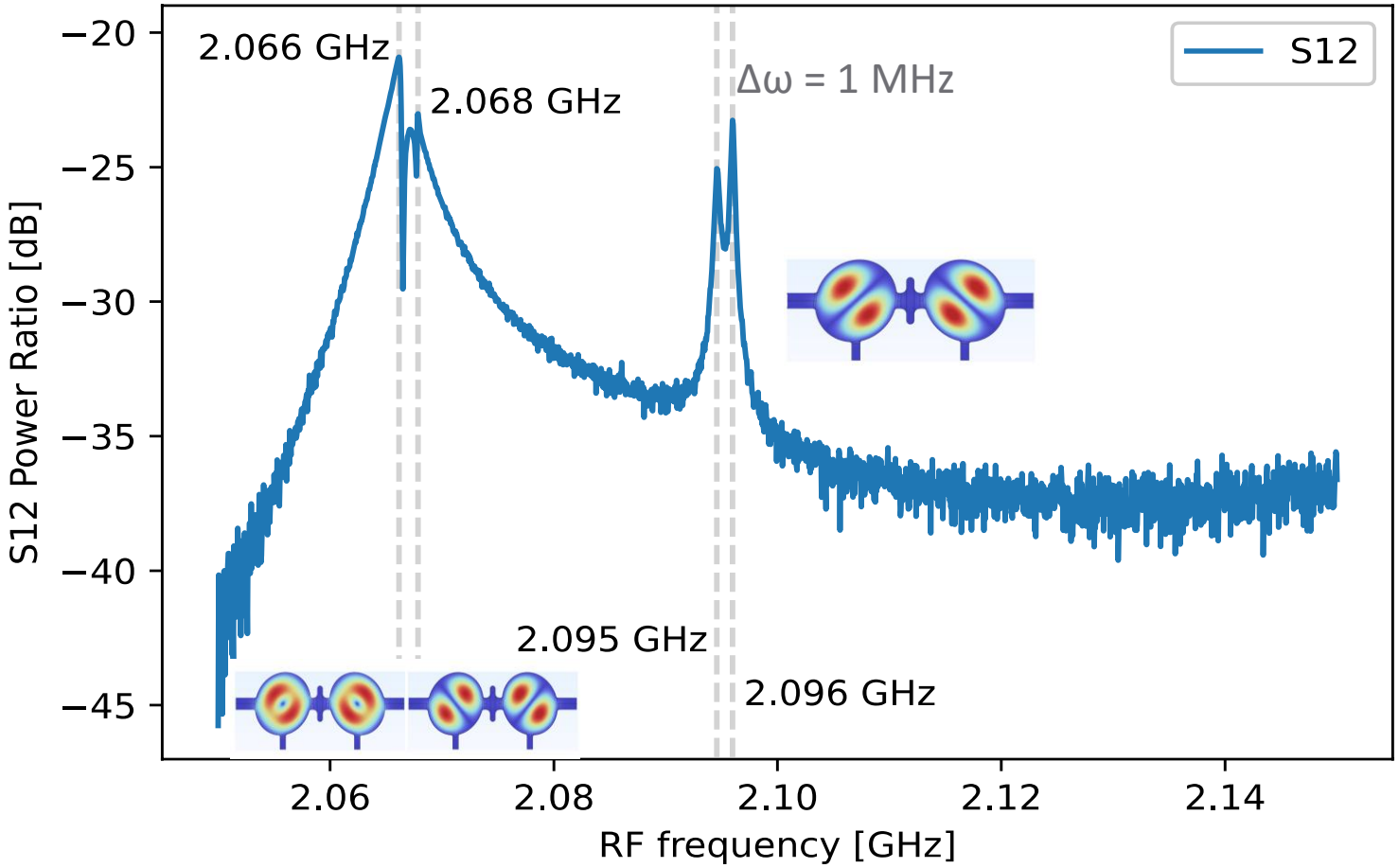
Verified with an equivalent circuit fitting:

The eigenfrequencies of the individual cells too far apart for given k_{cc}.

RF measurements worrisome

Not what expected from ideal geometry at room temperature

Transmission spectrum from one cell to the other



Verified with an equivalent circuit fitting:

The eigenfrequencies of the individual cells too far apart for given k_{cc}.

Remember the pendulum? The spring is too weak for to different pendulum lengths

Cavity needs mechanical tuning

Limit single cell frequency differences

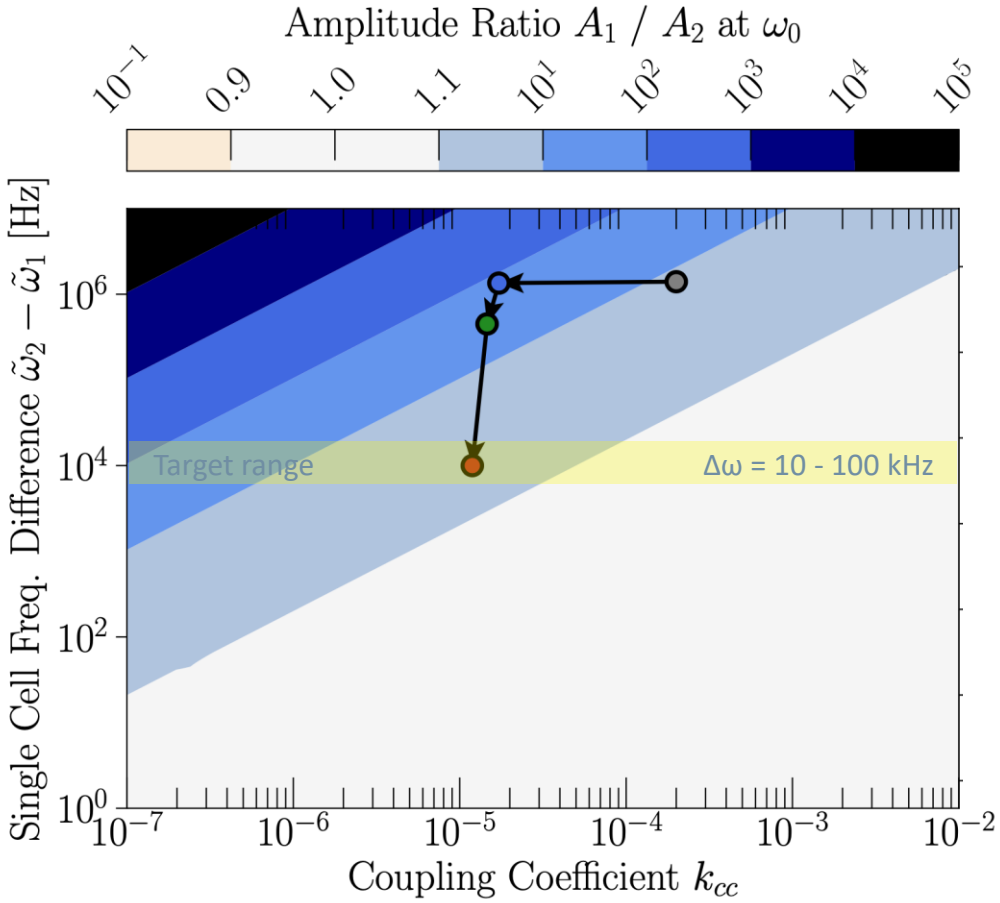
$\Delta\omega = \omega_\pi - \omega_0$ depends on the **tuning cell geometry** (coupling coefficient k_{cc}) and on the **single cell frequency difference**

Cavity needs mechanical tuning

Limit single cell frequency differences

$\Delta\omega = \omega_\pi - \omega_0$ depends on the **tuning cell geometry** (coupling coefficient k_{cc}) and on the **single cell frequency difference**

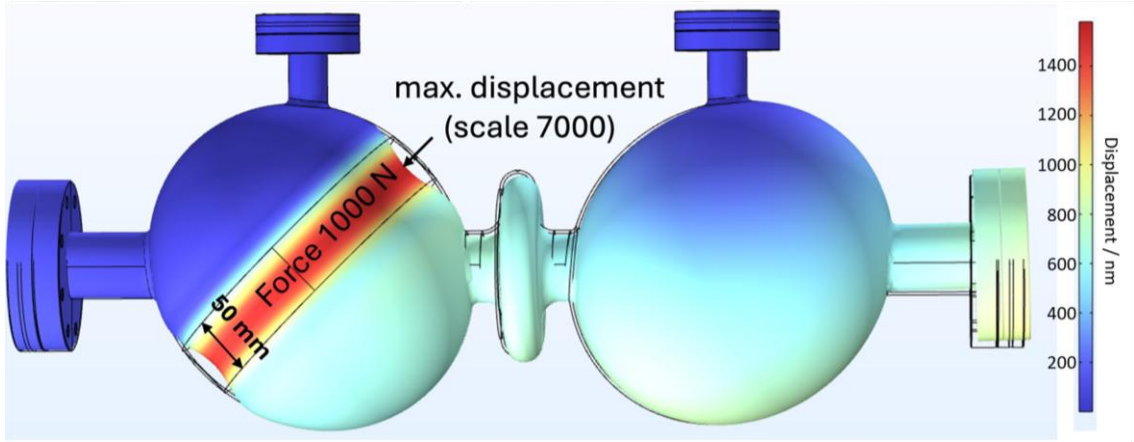
Need to tune cavity cells to achieve wanted Δω



Cavity Inelastic Tuning at Room Temperature

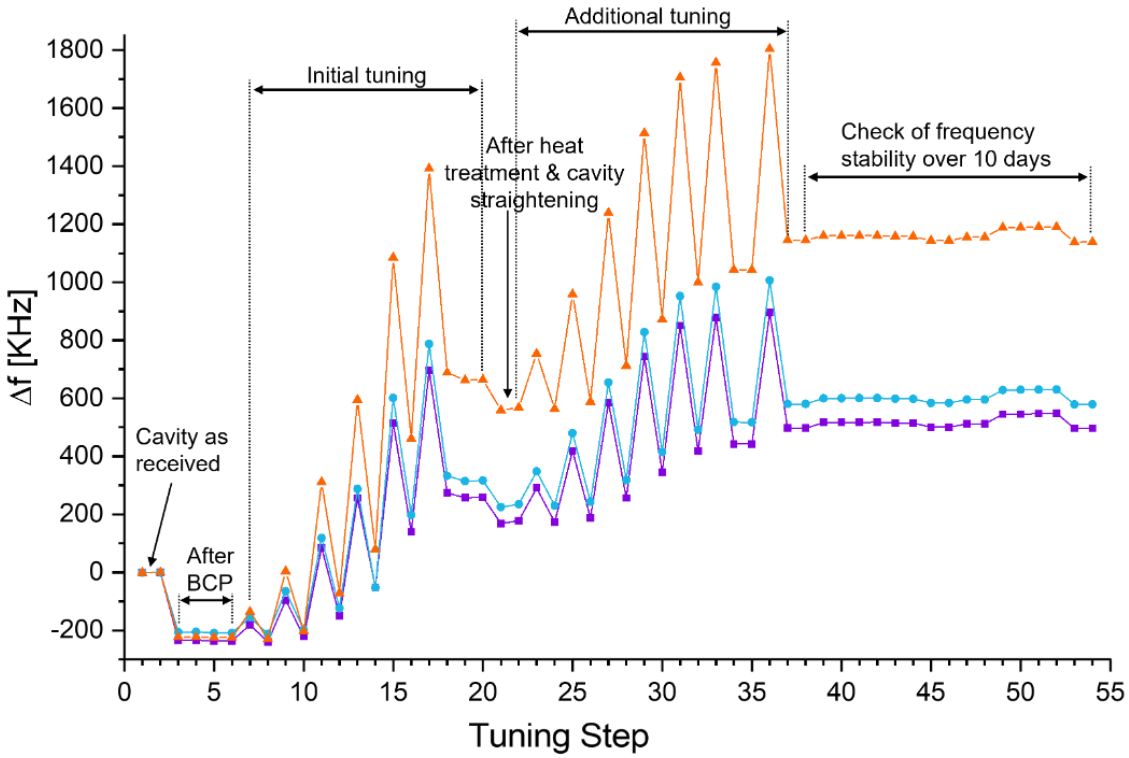
Straightening and Frequency Tuning

- First straighten cavity to eliminate bend and fit in mechanical frame that will be used for all following steps to support and constrain the cavity
- Then install chain tuner and slowly compress lowest frequency cell. Alternate compression and relaxation to assess elastic vs inelastic tuning. Repeat until cells frequency is matched (within limits of RT measurement)



Cavity Frequency History and Final Room Temperature Results

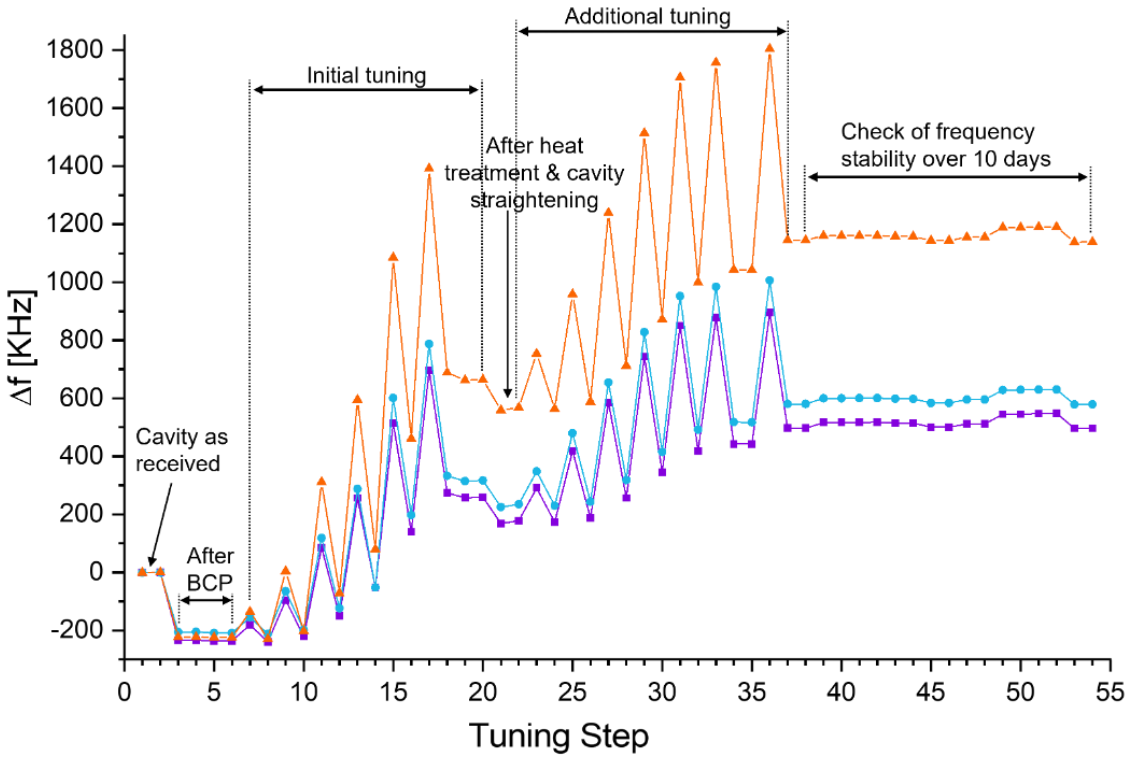
Achieved frequency difference at room temperature ≈ (4-7) kHz



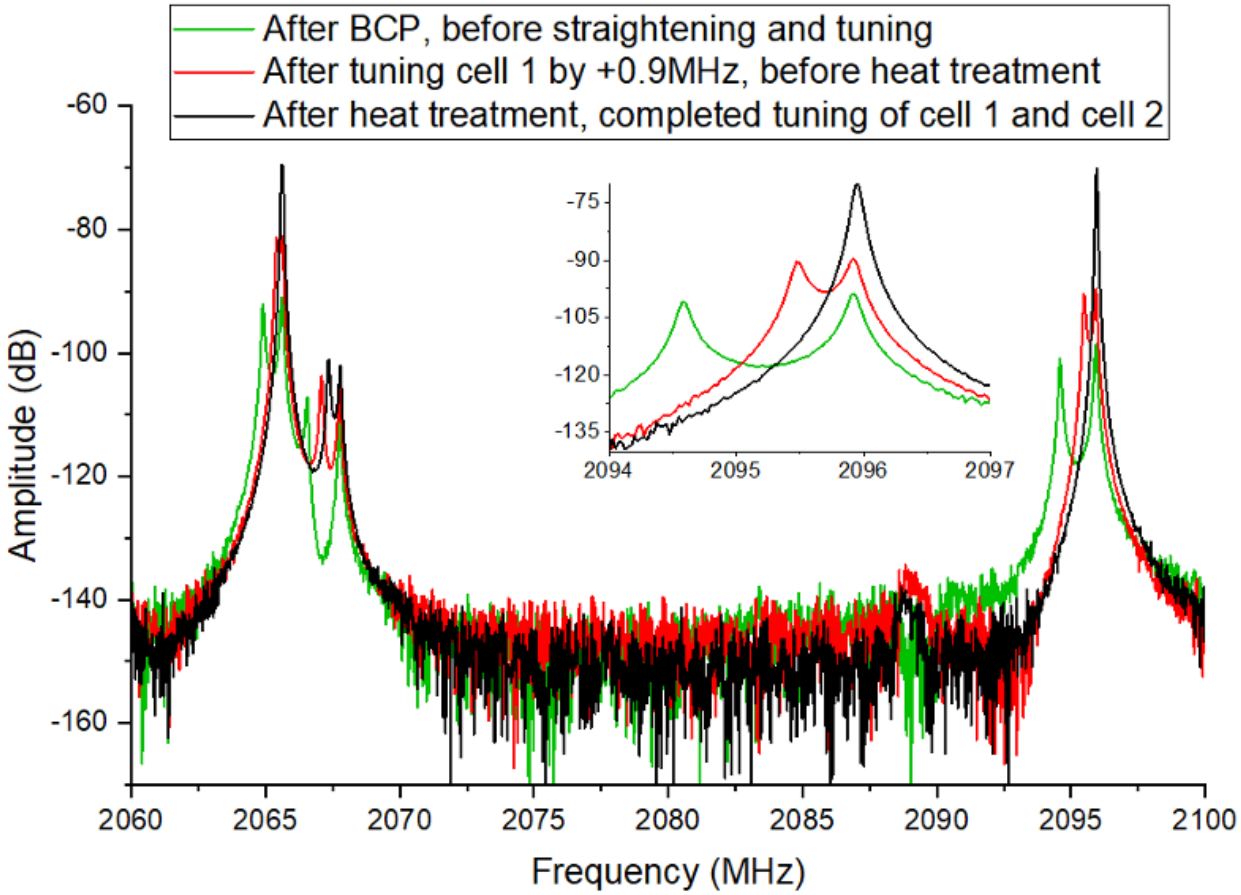
Frequency history of the cavity at room temperature. Tuning pattern of compression and relaxation is clearly visible.

Cavity Frequency History and Final Room Temperature Results

Achieved frequency difference at room temperature ≈ (4-7) kHz

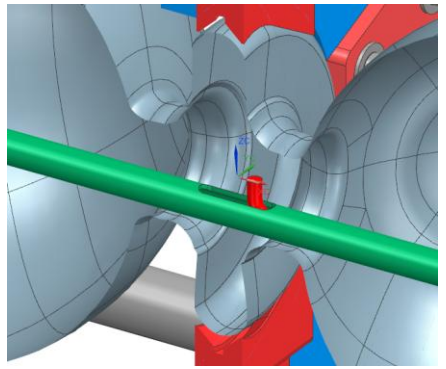


Frequency history of the cavity at room temperature. Tuning pattern of compression and relaxation is clearly visible.

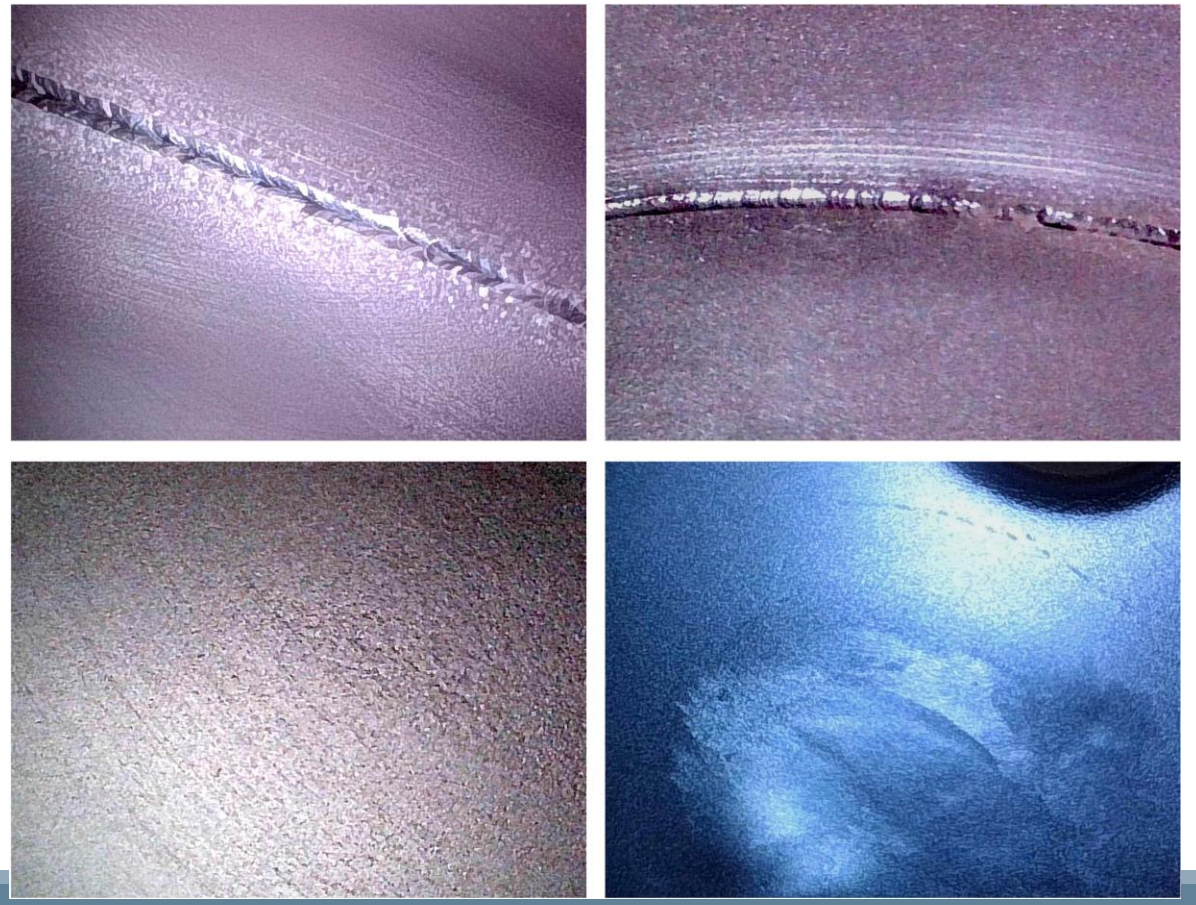


RF spectrum at room temperature at different steps of the cavity frequency history. After tuning the two peaks appear as one due to the broad RT bandwidth.

Cavity Surface Inspection



- Typical Optical Inspection tool was not compatible with this cavity
- Used Boroscope supported via rigid wand to photograph inner surface
- Found several imperfections (dents) and remaining traces of fabrication on the surface such as scratches and rolling marks
- Normally fabrication is followed by bulk EP/BCP to remove damaged layer → here probably not conducted yet

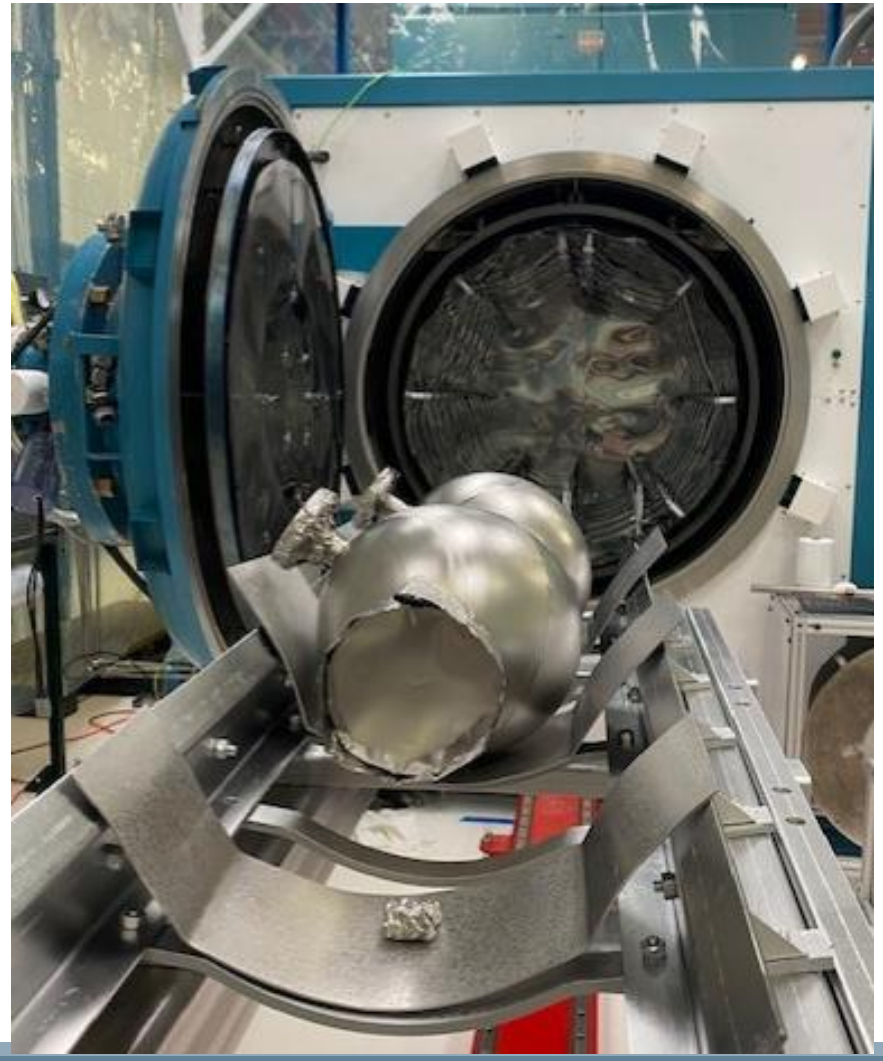


Cavity Surface Processing

Surface Removal and Heat Treatment

- Conducted only flash BCP (few µm) at ANL to avoid further decreasing the thickness of the coupling cell (already <1mm thick!)
- Heat treatment temperature limited to 600C due to stainless steel flanges to prevent contamination of cavity and furnace





First RF Cold Tests @ FNAL & DESY

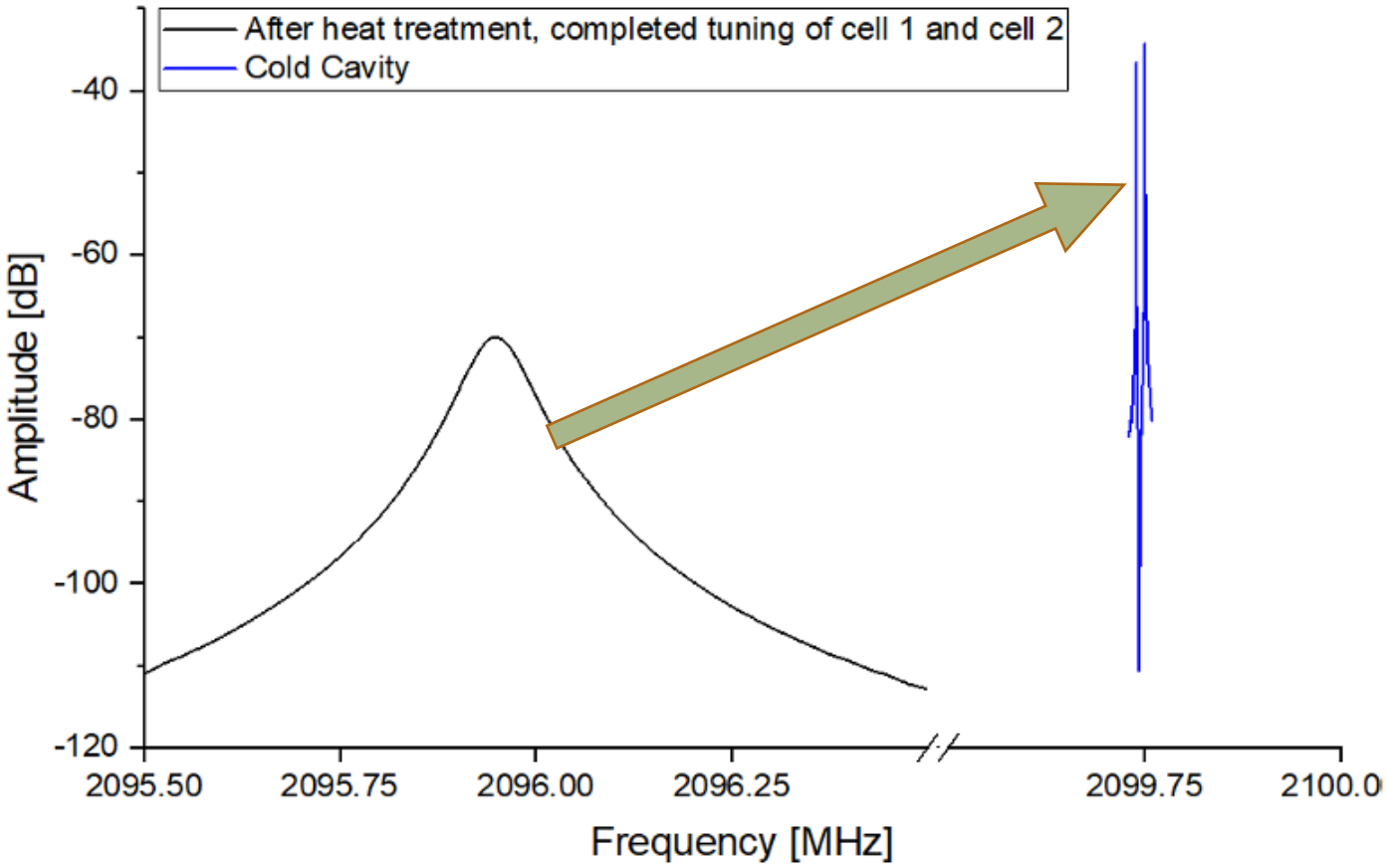
Preparation and plan

- RF setup oriented for cavity characterization, not for search
  - 1 input coupler (critical coupling), 2 pick up antennas (weak coupling)
- Goals:
  - Track frequency behavior during cooldown (thermal and pressure effects)
  - Characterize cavity performance (Q vs U)



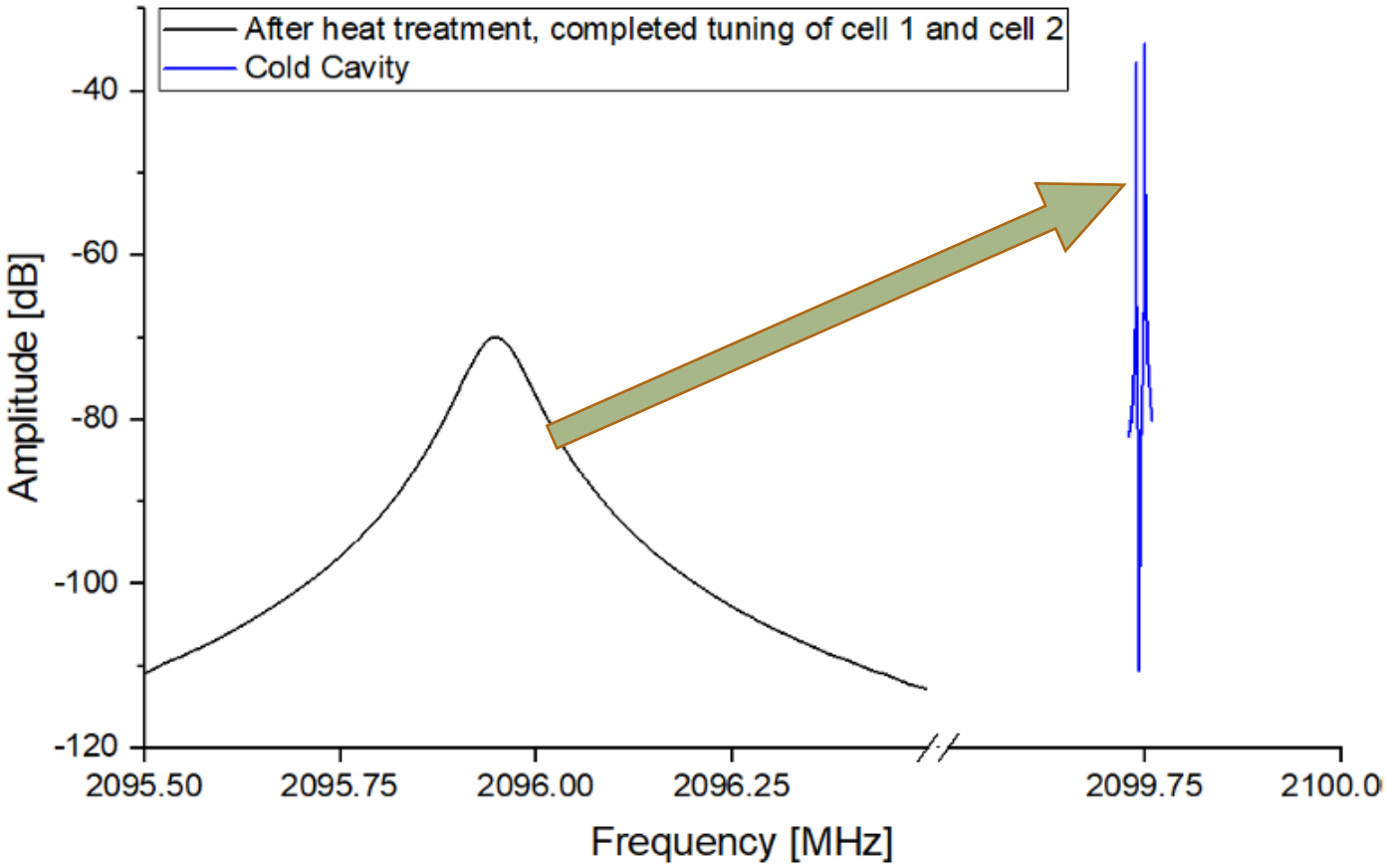
First RF Cold Test

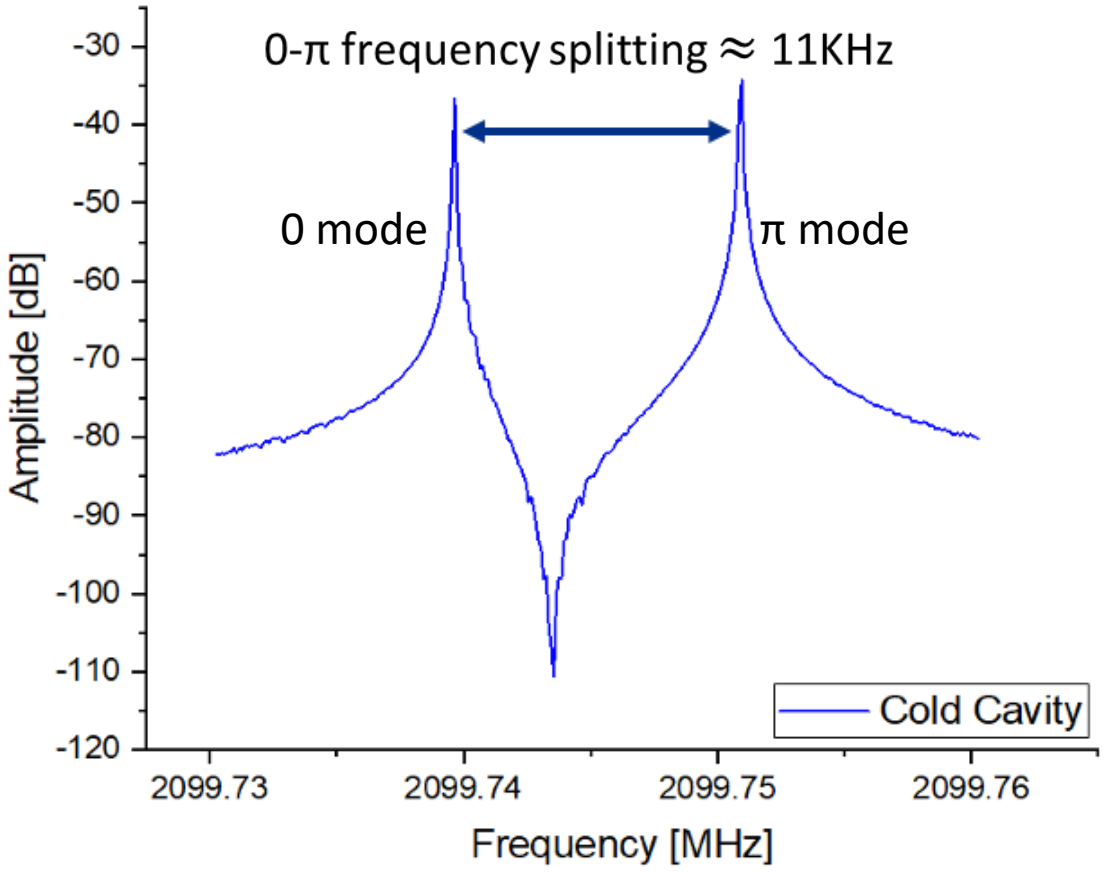
Frequency Behavior



First RF Cold Test

Frequency Behavior

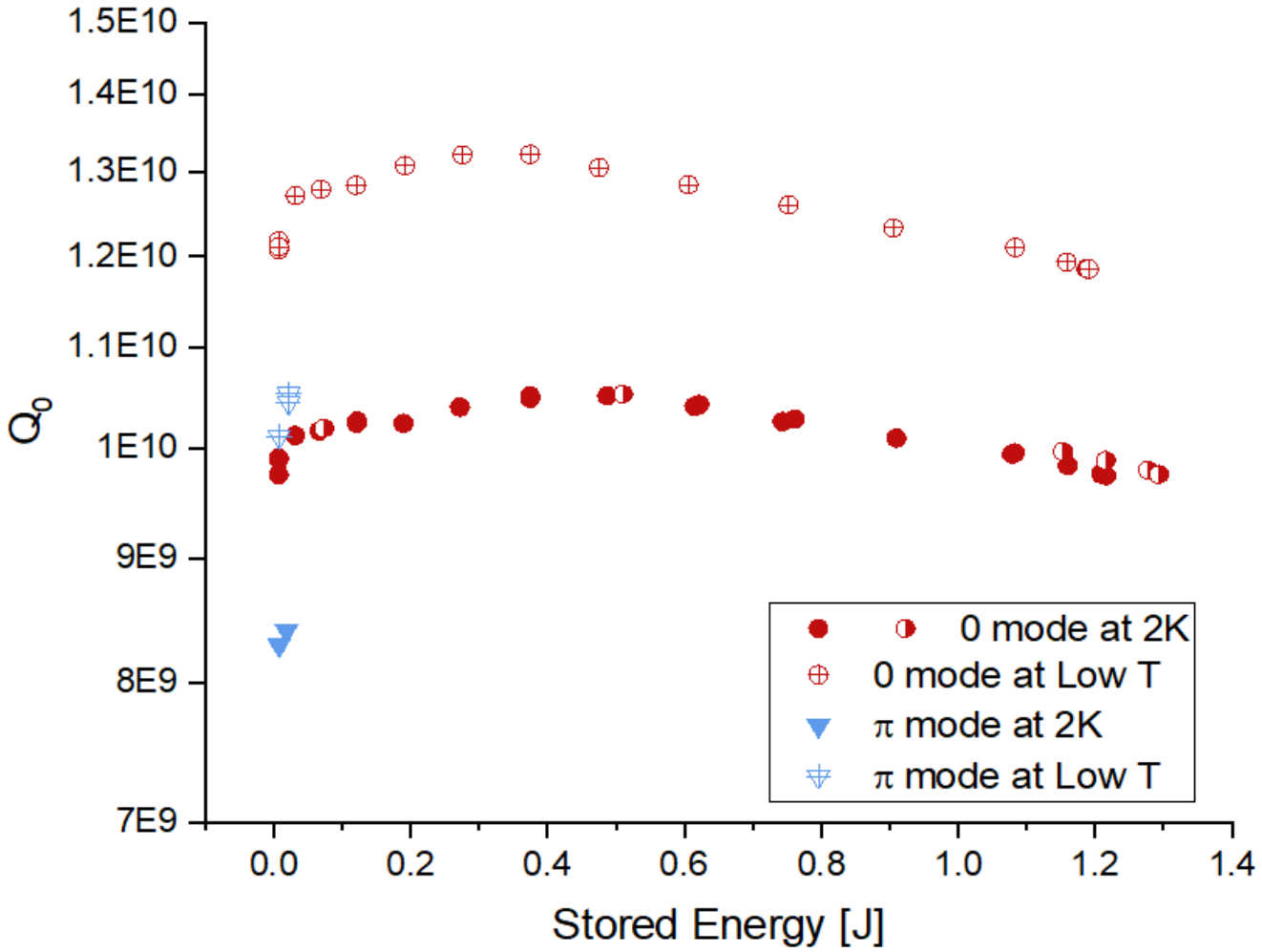




First RF Cold Test

Q vs U Results

- Despite surface imperfections cavity quality factor $Q_0 \approx 1 \times 10^{10}$ at 2 K (high Geometric Factor$\approx$ 800 Ω and low surface fields)
- Cavity quenched at lower U value than hoped → probably due to surface defects?



First RF Cold Test

Q vs U comparison with previous PACO prototype

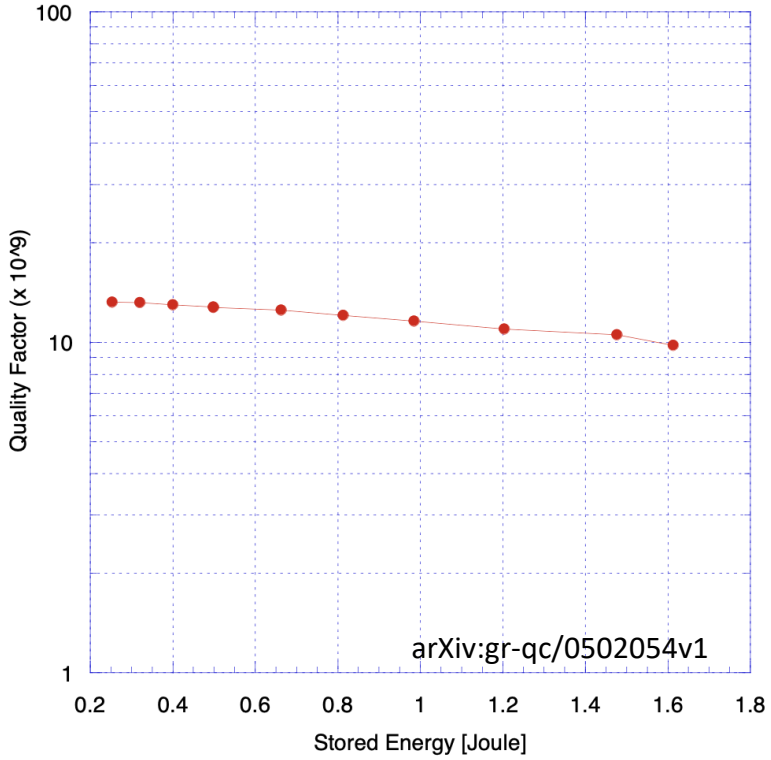
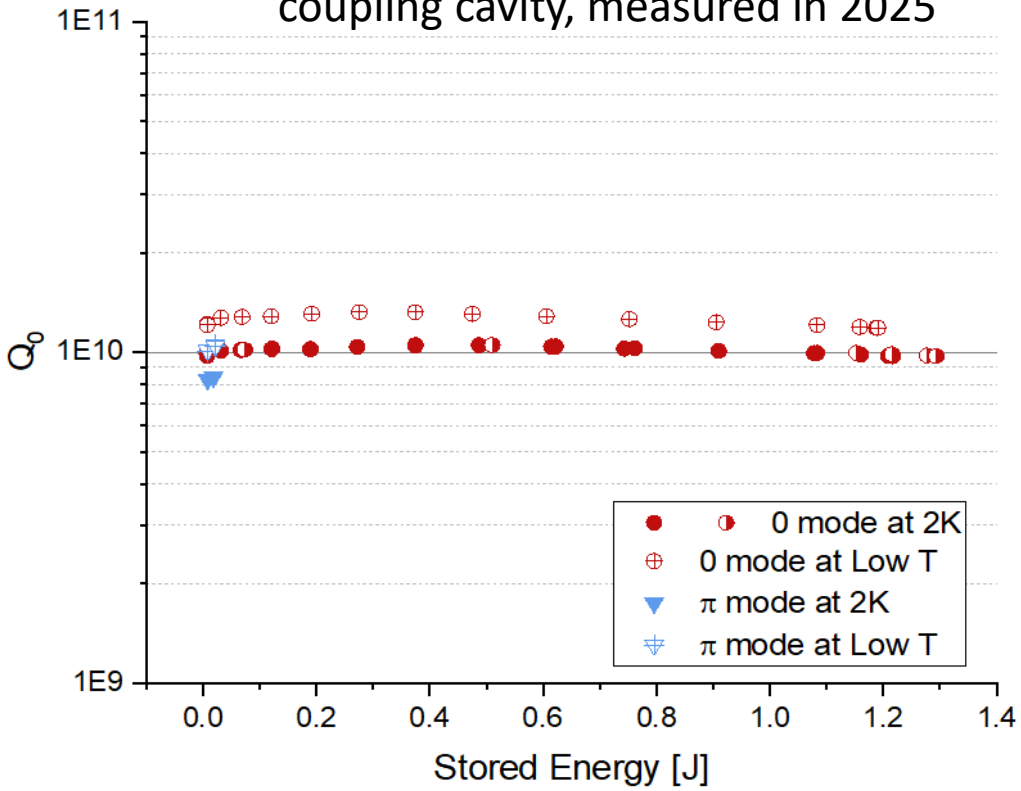


FIG. 11: Quality factor vs. stored energy for the fixed–coupling cavity



Quality factor vs Stored Energy for the variable coupling cavity, measured in 2025



1-point Multipacting quenches the cavity

and excites the 0-mode when driving the π mode

- Quench field in both cavities close to each other
  Coincidence?

1-point Multipacting quenches the cavity

and excites the 0-mode when driving the π mode

- Quench field in both cavities close to each other
  Coincidence?

- We saw excitation of 0-mode when driving π-mode

1-point Multipacting quenches the cavity

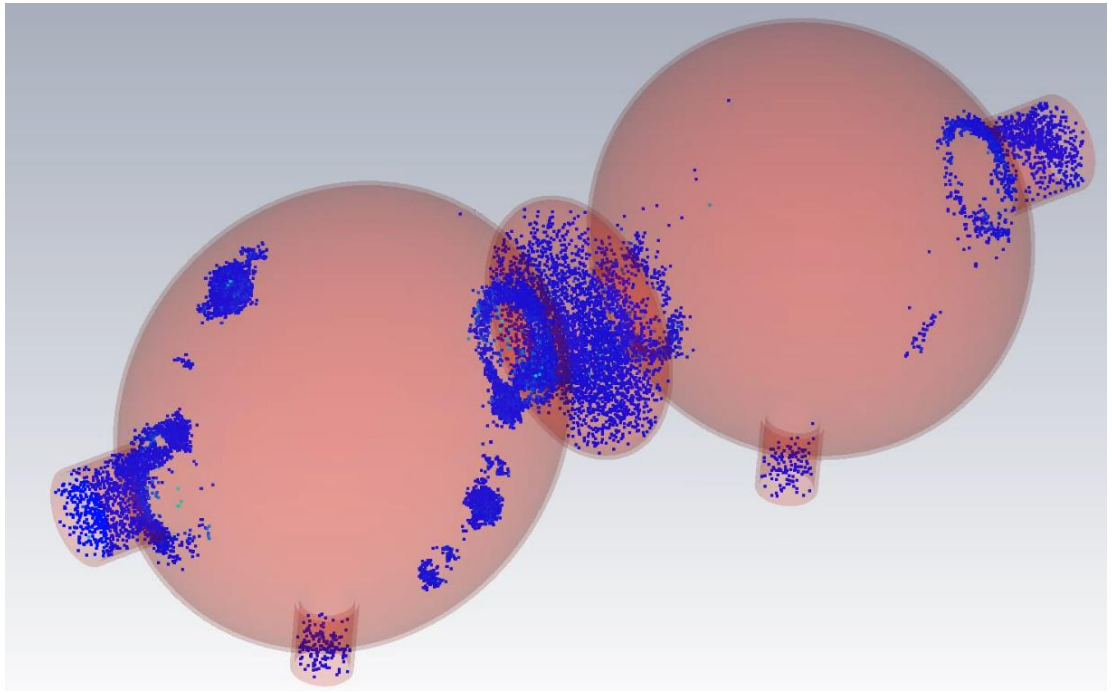
and excites the 0-mode when driving the π mode

- Quench field in both cavities close to each other
  Coincidence?
- We saw excitation of 0-mode when driving π-mode
- Single explanation would be MP

1-point Multipacting quenches the cavity

and excites the 0-mode when driving the π mode

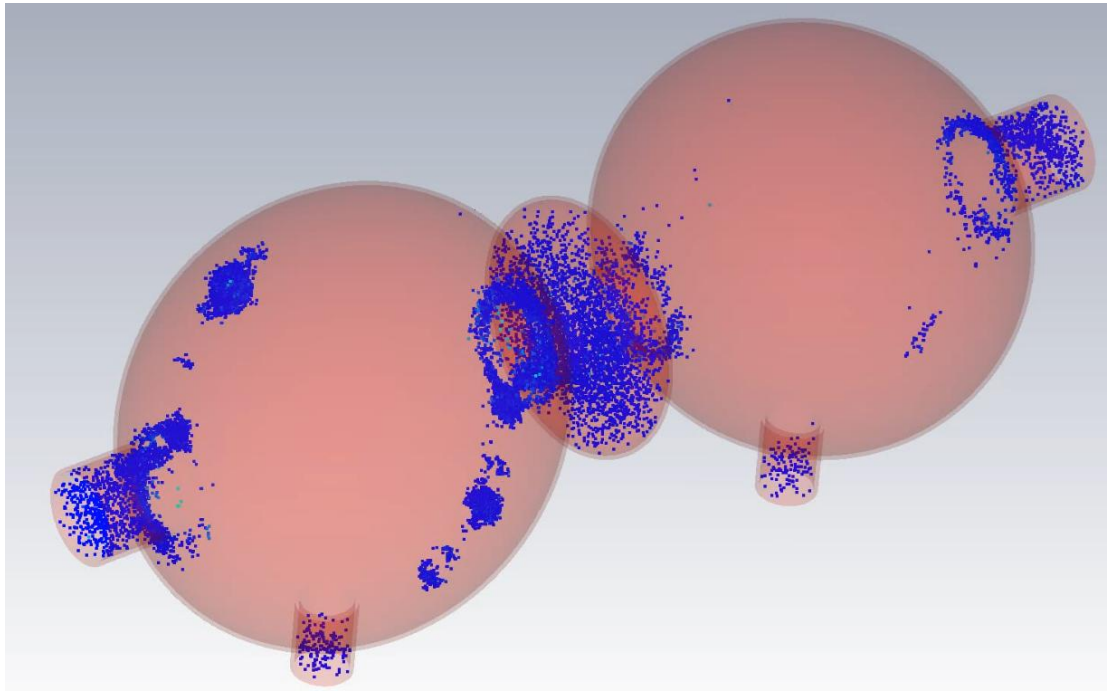
- Quench field in both cavities close to each other Coincidence?
- We saw excitation of 0-mode when driving π-mode
- Single explanation would be MP
- Numerical simulations confirm existance of 1-point MP



1-point Multipacting quenches the cavity

and excites the 0-mode when driving the π mode

- Quench field in both cavities close to each other Coincidence?
- We saw excitation of 0-mode when driving π-mode
- Single explanation would be MP
- Numerical simulations confirm existance of 1-point MP
- Proof by measuring current on antenna in next test

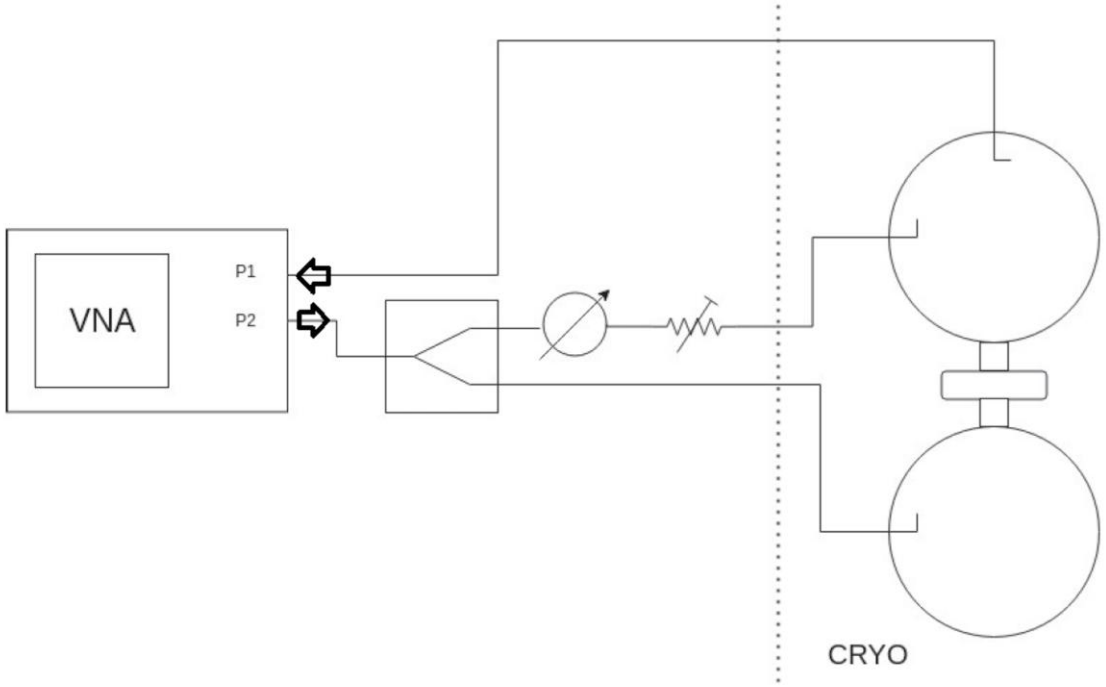


Mode rejection scheme for the input signal

PACO detection scheme (separately for drive and readout)

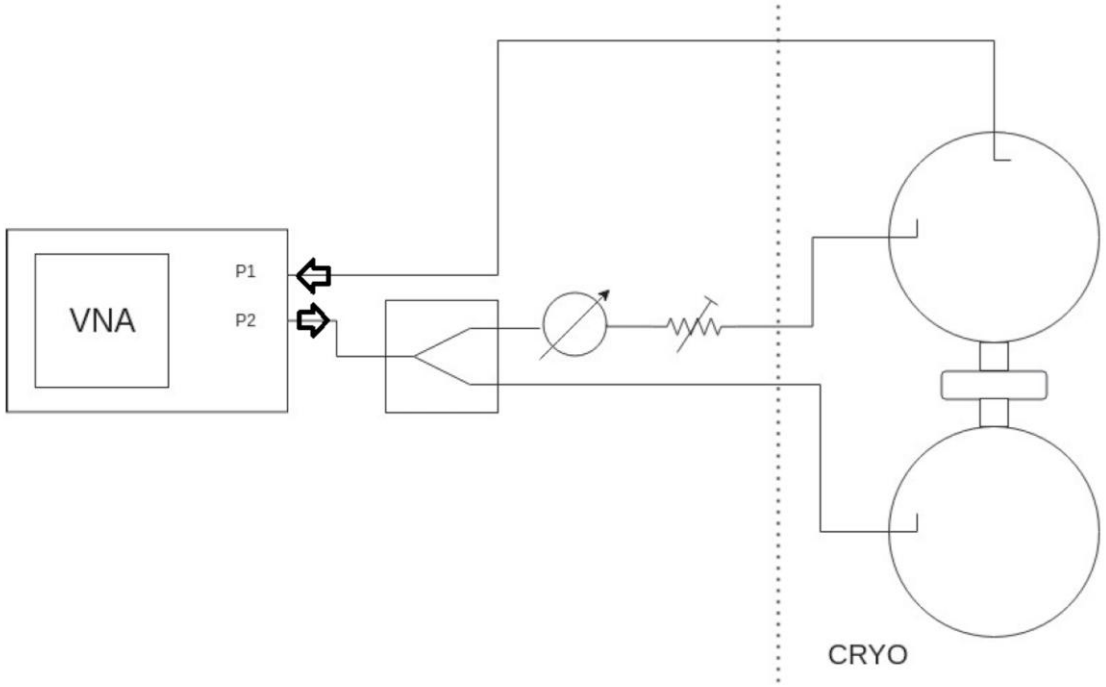
Mode rejection scheme for the input signal

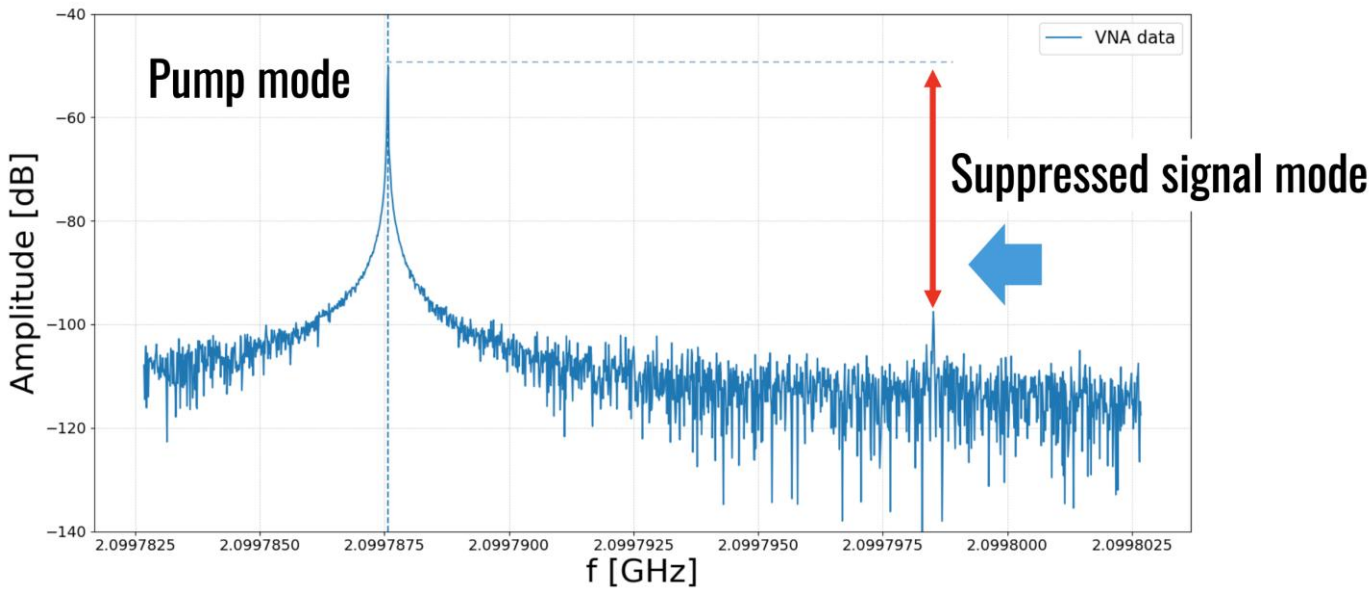
PACO detection scheme (separately for drive and readout)



Mode rejection scheme for the input signal

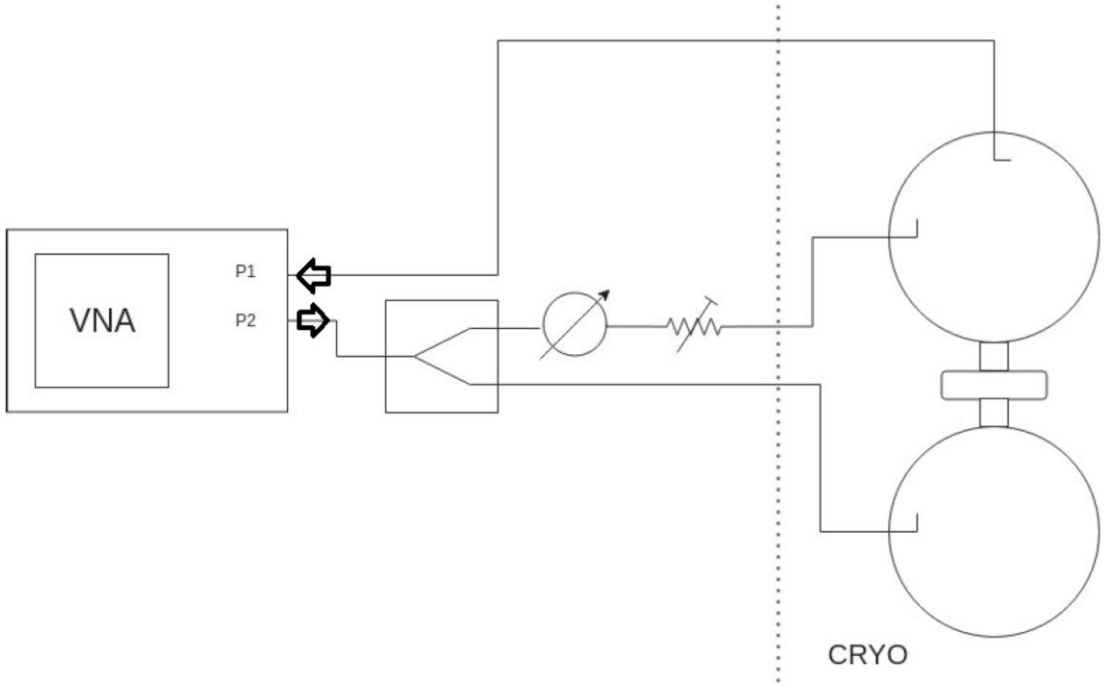
PACO detection scheme (separately for drive and readout)

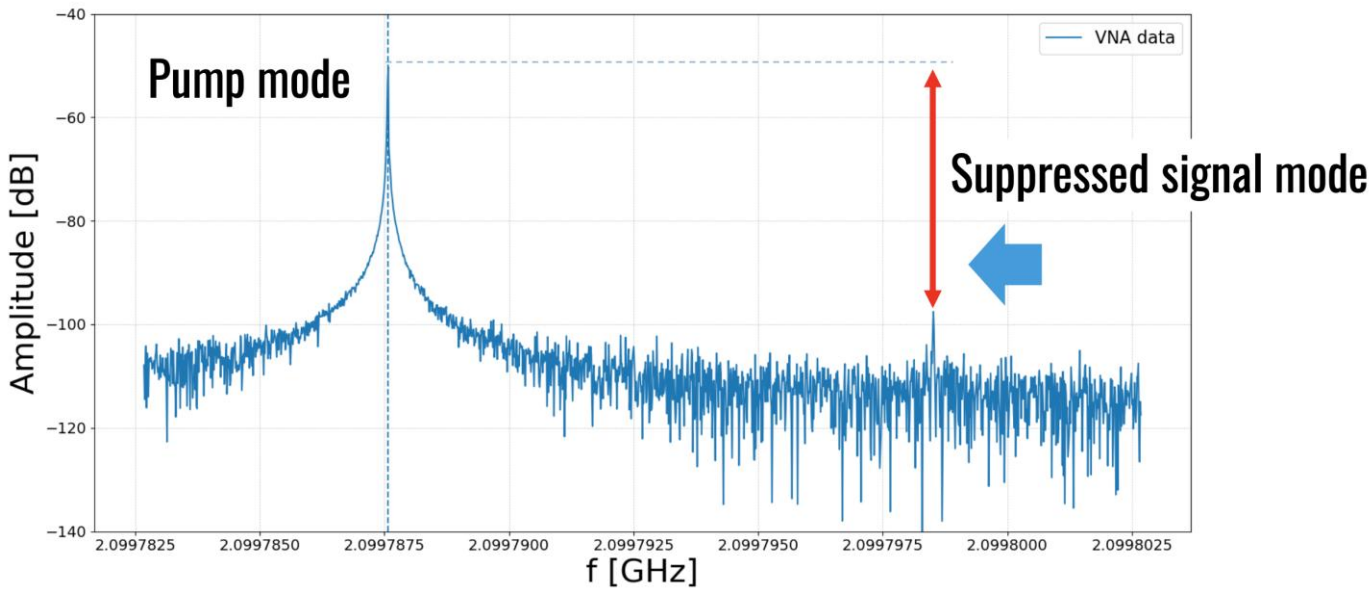




Mode rejection scheme for the input signal

PACO detection scheme (separately for drive and readout)

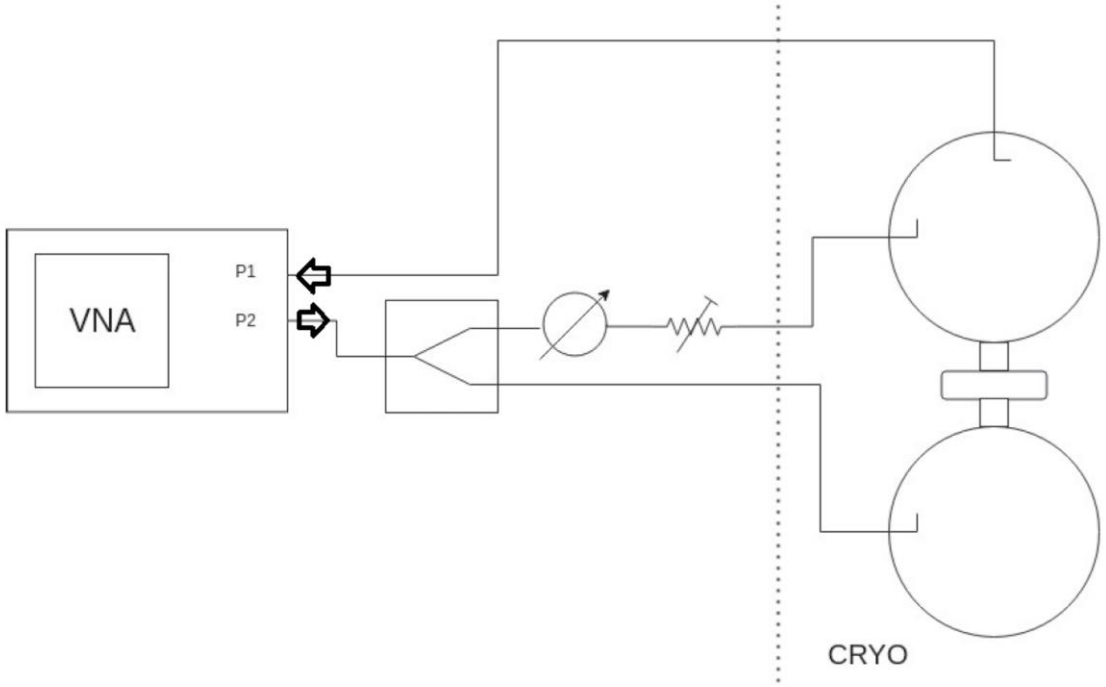


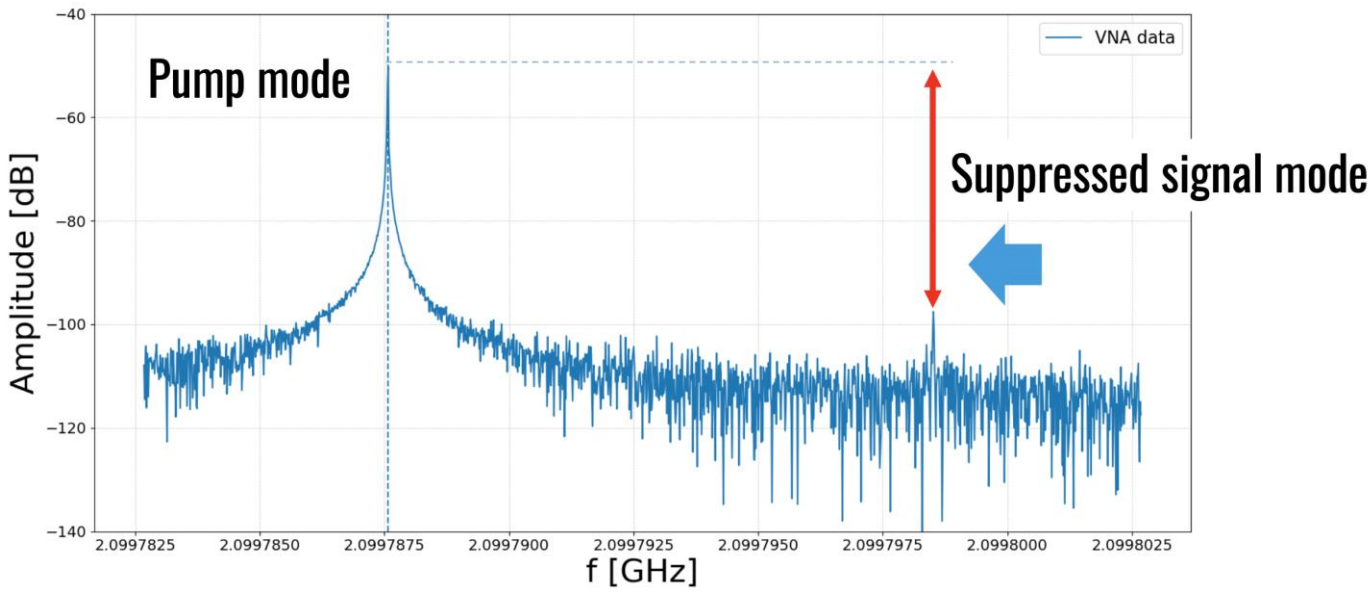


Avoid excitation of signal mode by driving signal

Mode rejection scheme for the input signal

PACO detection scheme (separately for drive and readout)



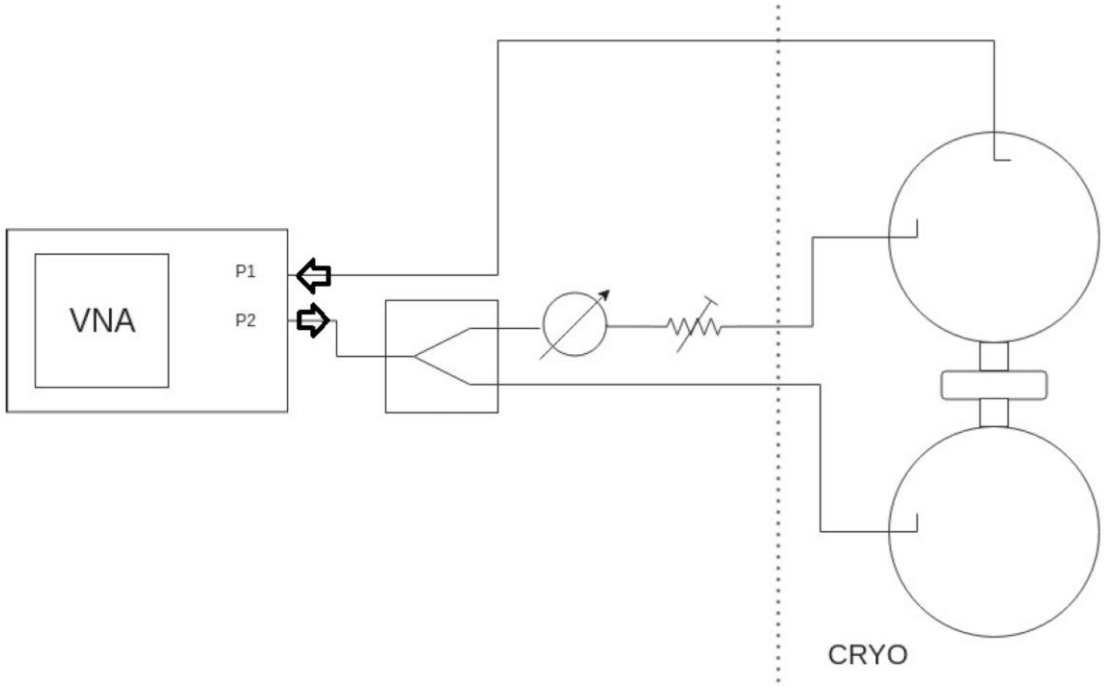


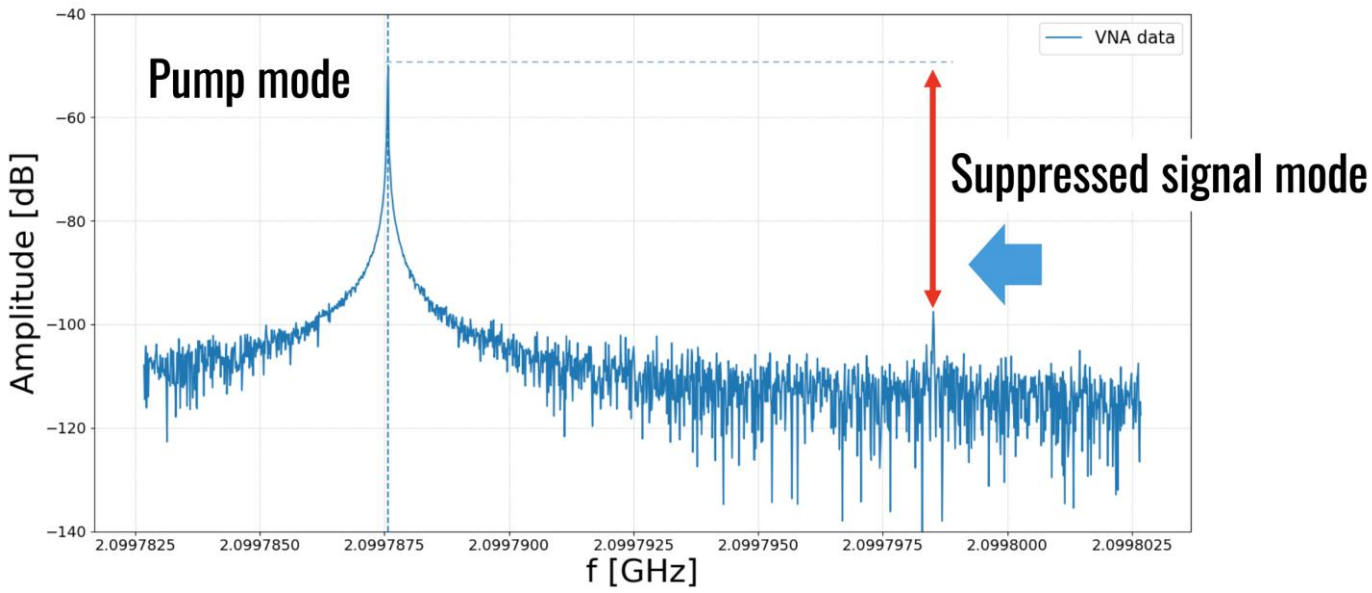
Avoid excitation of signal mode by driving signal

- **With a non-optimized setup achieved a -50 dB suppression (on average) using a VNA to drive the cavity**

Mode rejection scheme for the input signal

PACO detection scheme (separately for drive and readout)





Avoid excitation of signal mode by driving signal

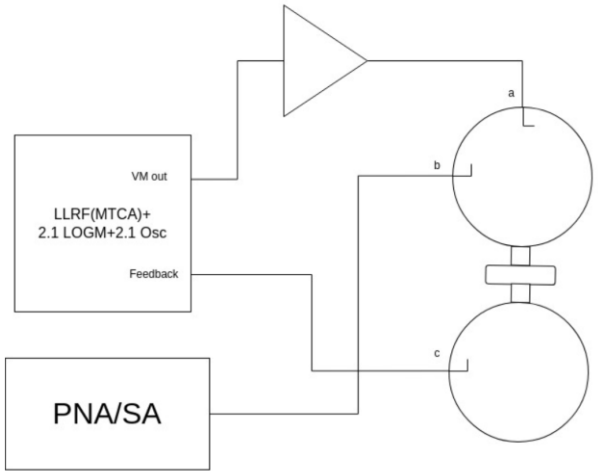
- **With a non-optimized setup achieved a -50 dB suppression (on average) using a VNA to drive the cavity**
- **PACOs optimized setup achieved -70dB using a narrow band amplifier to drive the cavity**

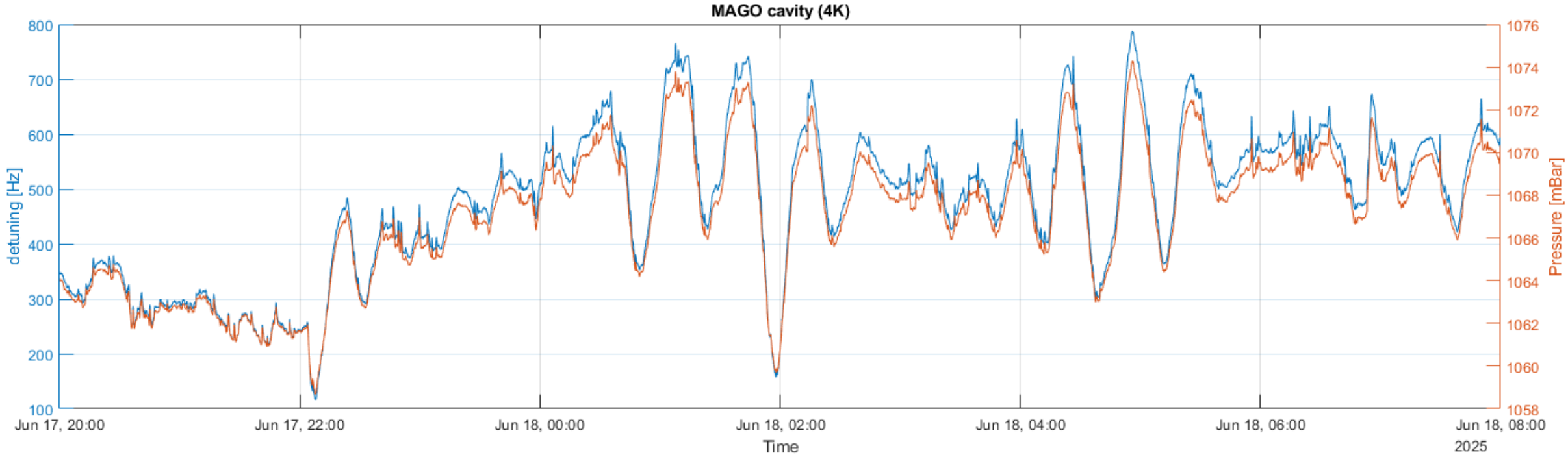
Frequency tracking configuration

Big step towards a functioning LLRF system

Large pressure variations in the cryostat lead to significant frequency change of the pump mode

Tracking the cavity for 13 hours worked

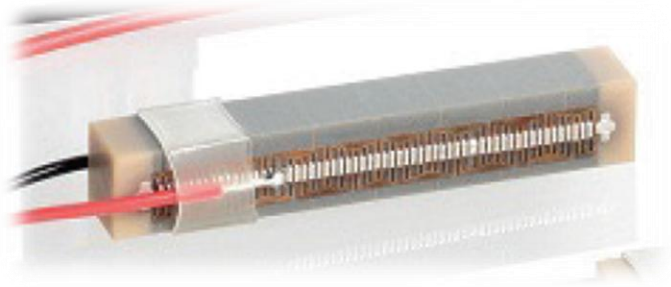




Cryogenic mechanical characterization



- Install piezoelectric actuators to:
  - Excite mechanical vibrations at desired frequency
  - Study mechanical to RF conversion
  - Read out vibrations of cavity & correlate with pressure fluctuations & microphonics

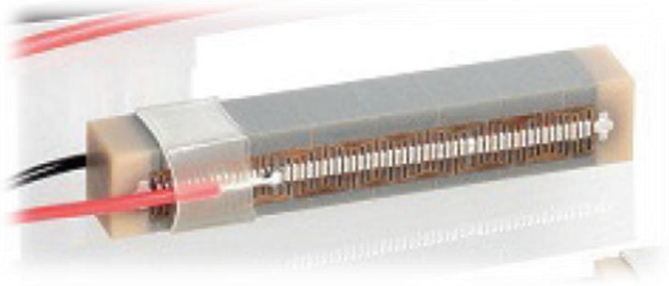


Cryogenic mechanical characterization

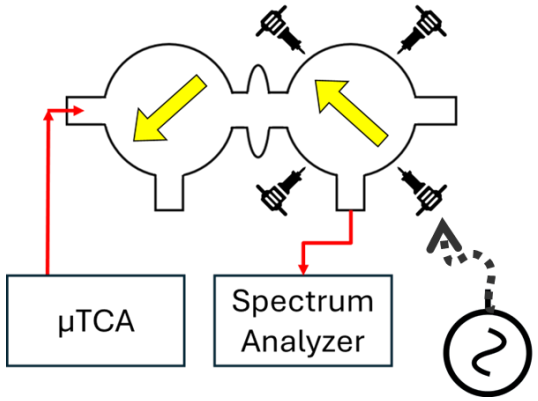


- Install piezoelectric actuators to:
  - Excite mechanical vibrations at desired frequency
  - Study mechanical to RF conversion
  - Read out vibrations of cavity & correlate with pressure fluctuations & microphonics

- **Fake Gravitational Wave!** for system calibration

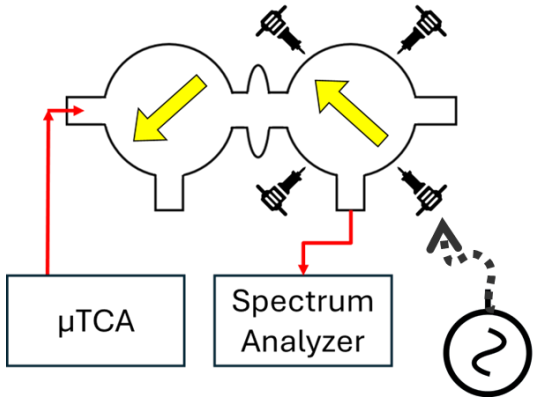


Mechanical to RF signal

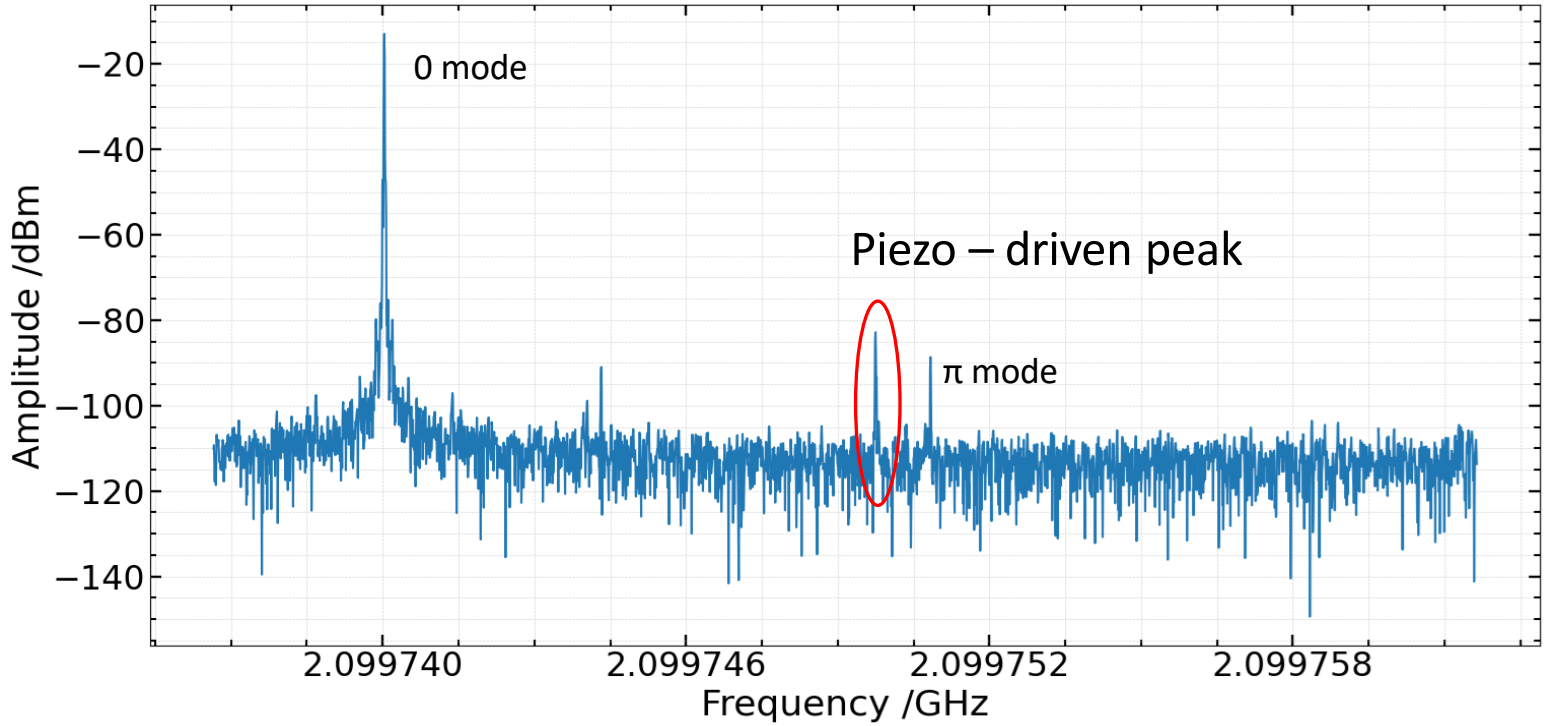


- Drive 0 mode with µTCA (LLRF system)
- Drive piezos with signal generator
- Readout spectrum analyzer

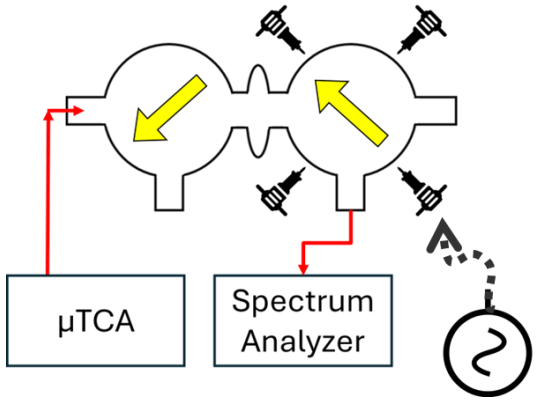
Mechanical to RF signal

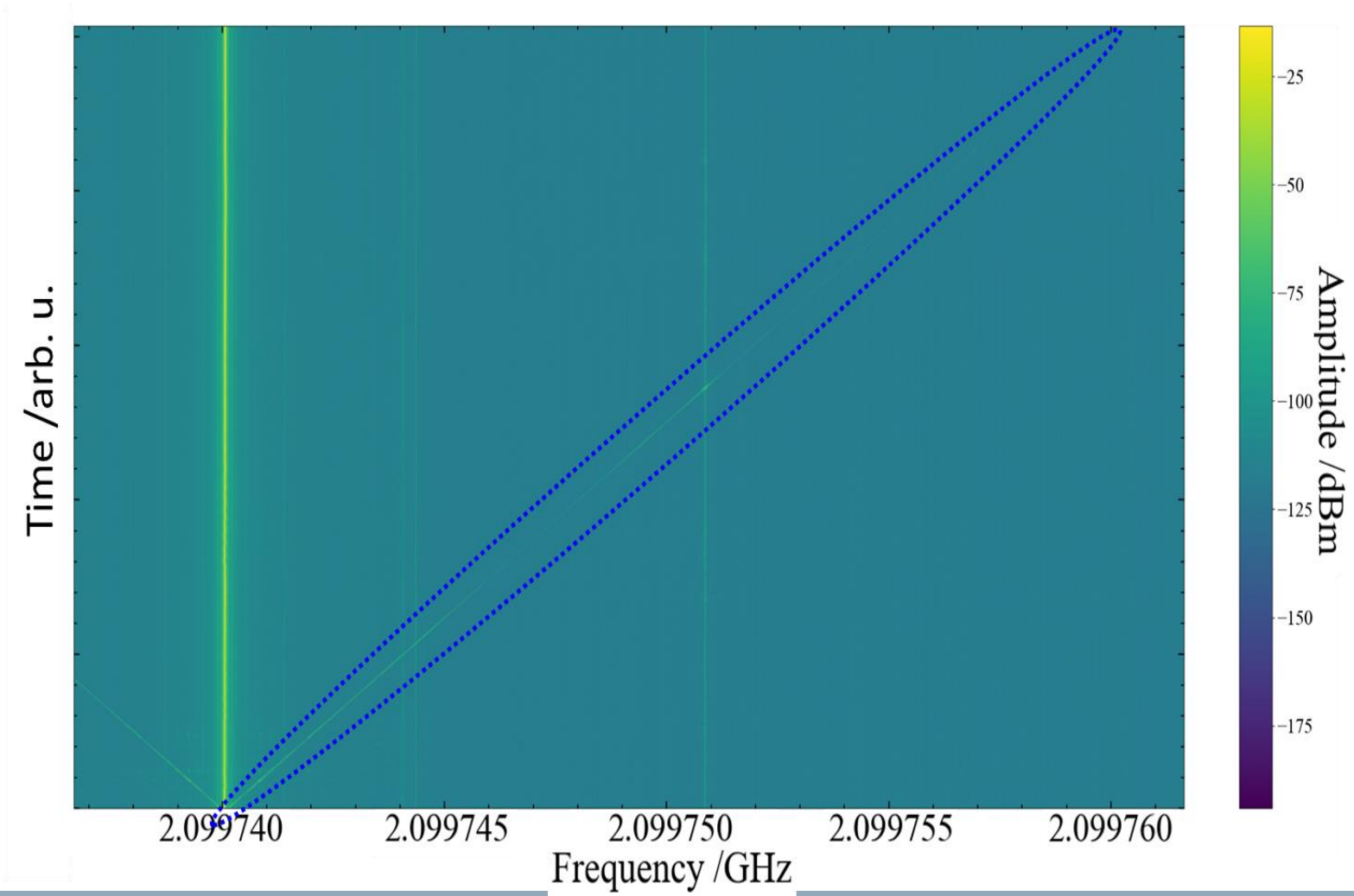


- Drive 0 mode with µTCA (LLRF system)
- Drive piezos with signal generator
- Readout spectrum analyzer

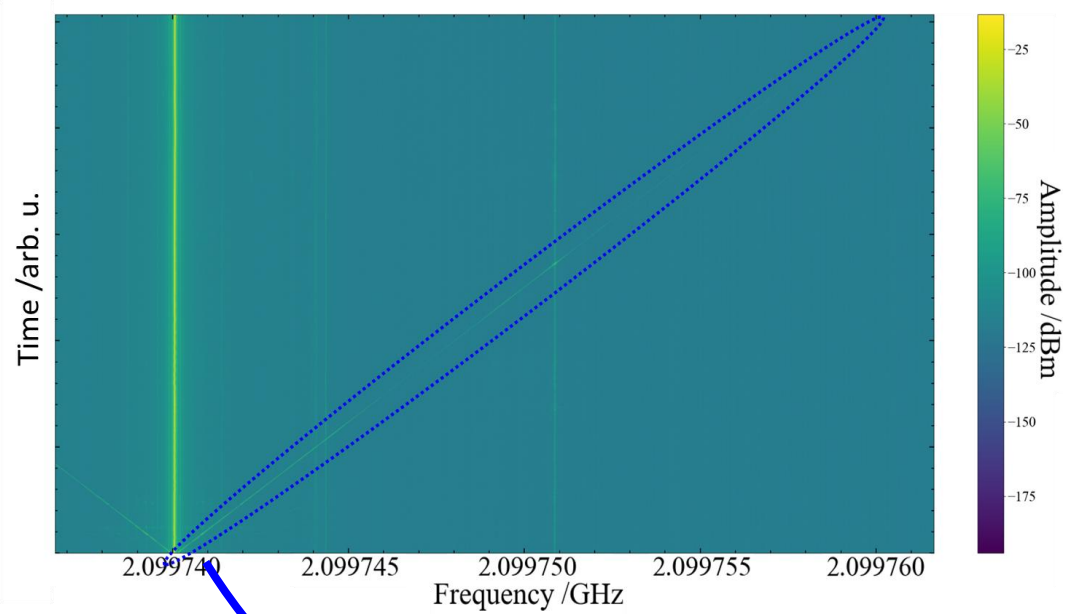


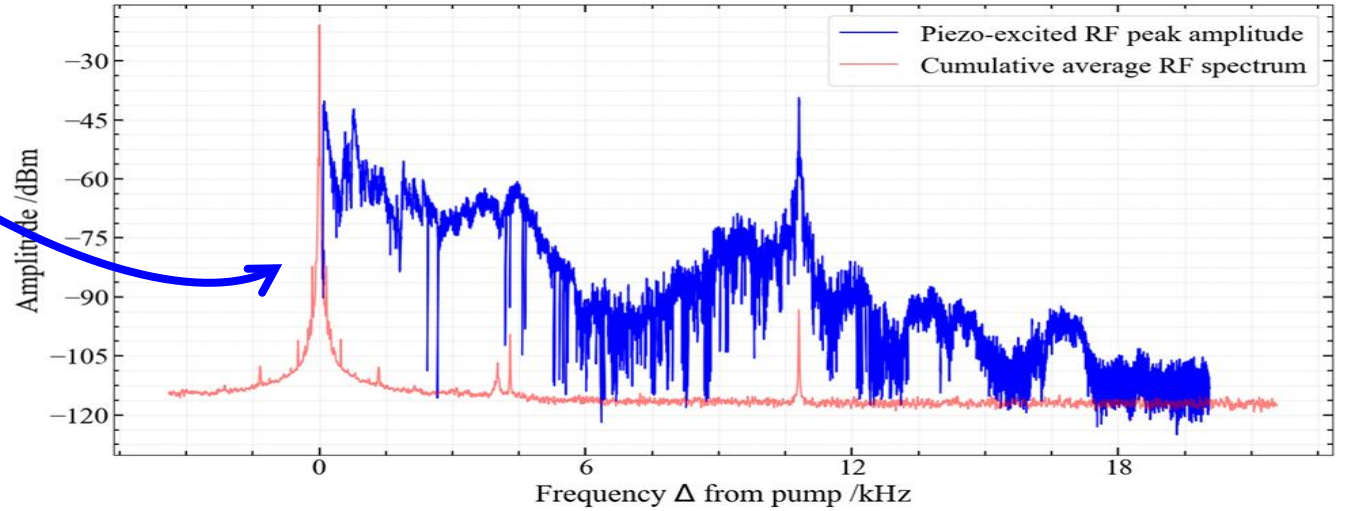
Mechanical to RF signal



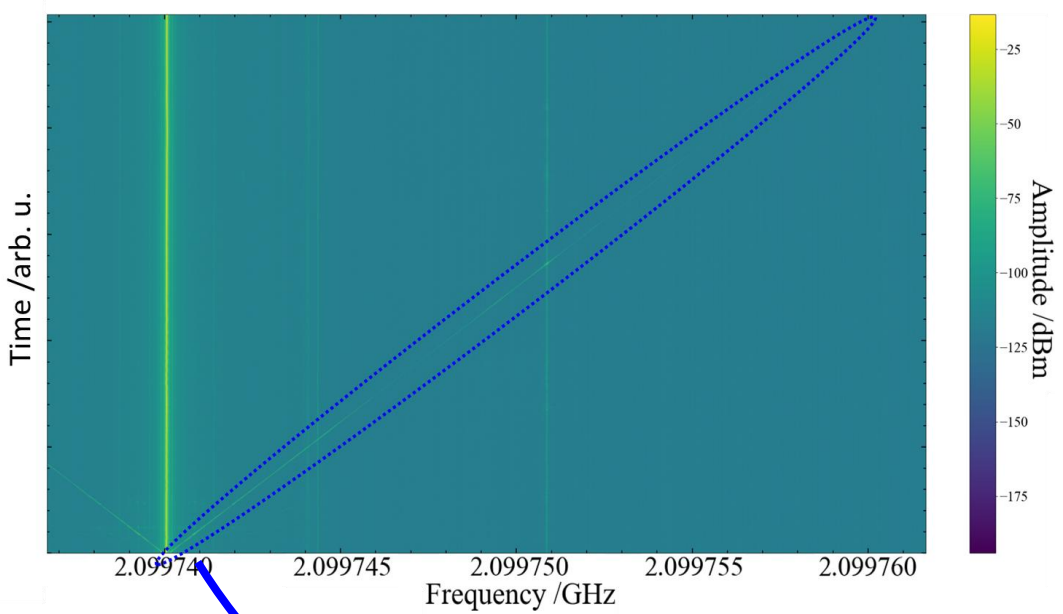


The role of piezoelectric actuators





The role of piezoelectric actuators



Amplite of response is combination of

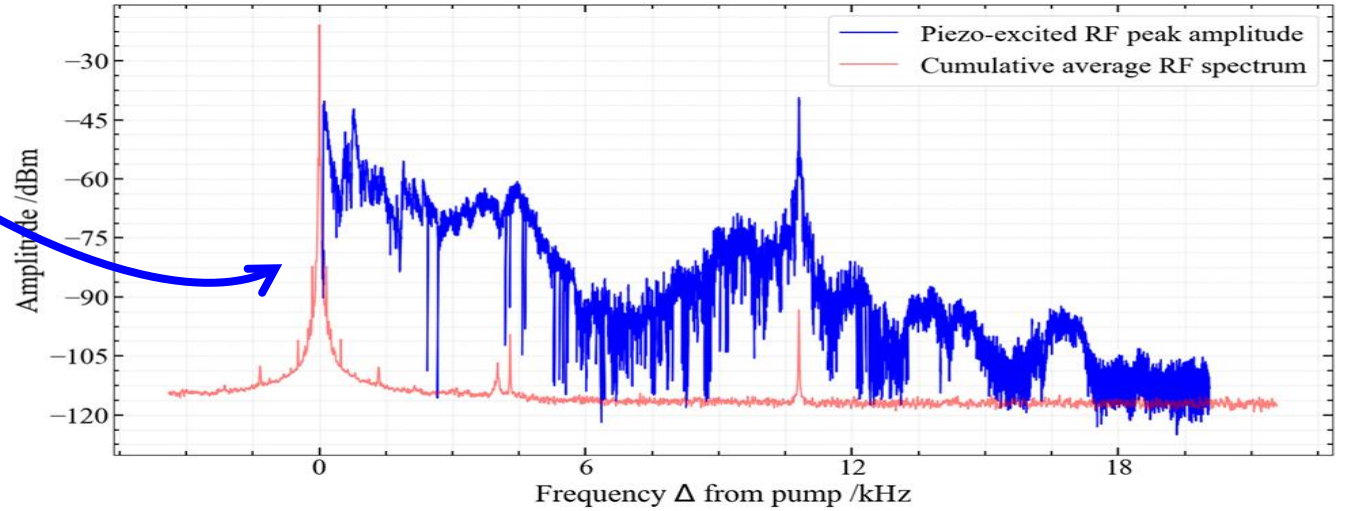
Piezo response to AC

+

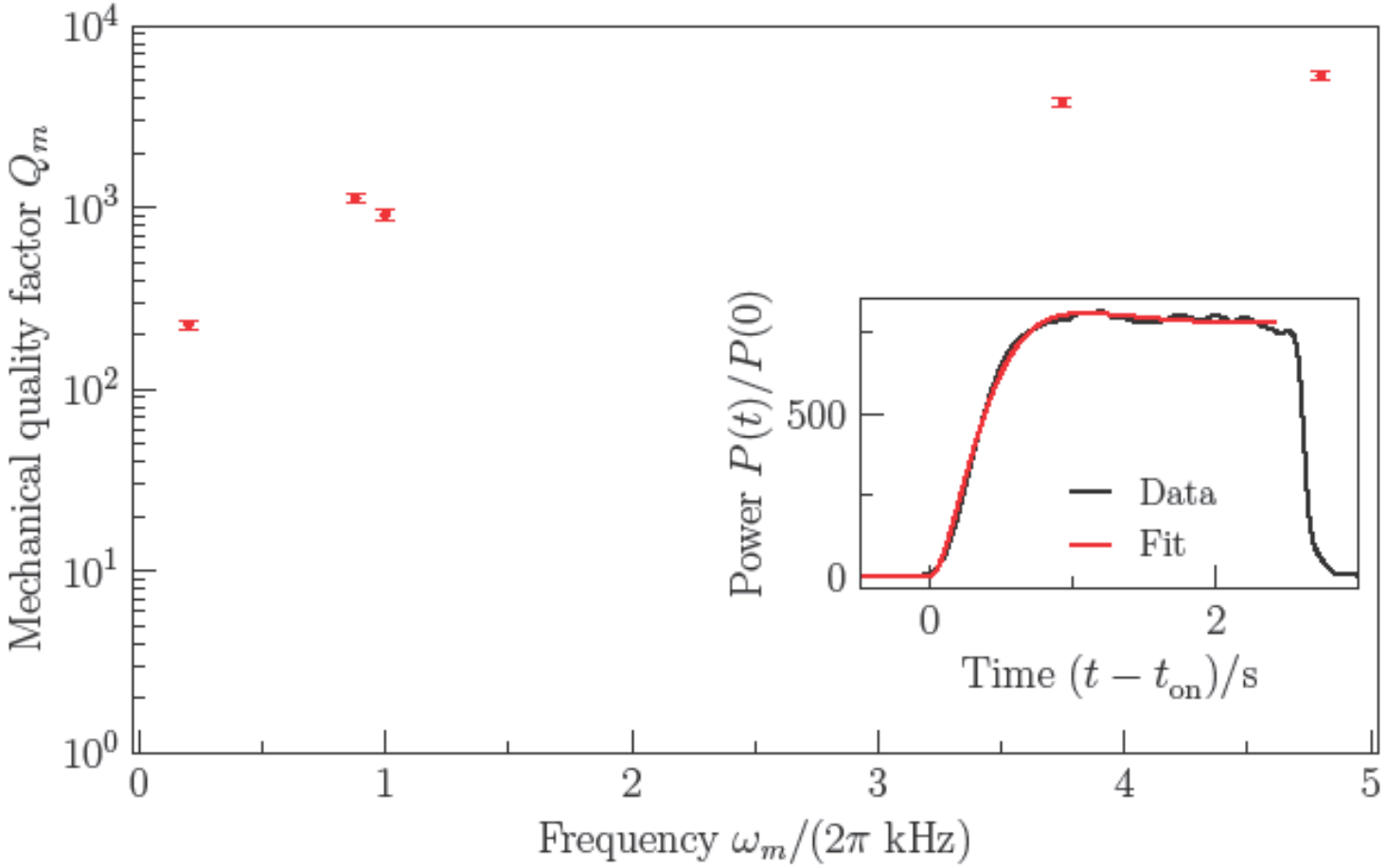
Mechanical cavity response

+

RF response to cavity deformation



Mechanical Quality factor



- Theoretical calculation assume $Q_m = 10^5$
- Measurement reflects contributions of the whole system

How to realise a dedicated experiment

Four key challenges

How to realise a dedicated experiment

Four key challenges



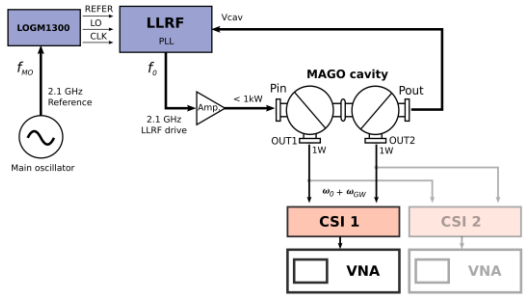
Based on the experience with MAGO, develop and fabricate **new cavities** with optimised geometry

How to realise a dedicated experiment

Four key challenges



Based on the experience with MAGO, develop and fabricate **new cavities** with optimised geometry



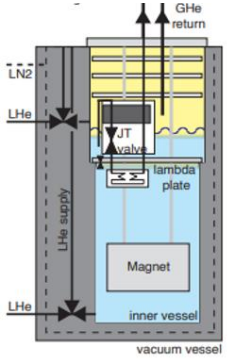
LLRF system to drive and read-out the cavity with highest possible sensitivity

How to realise a dedicated experiment

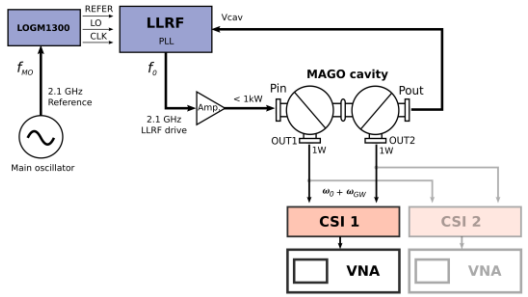
Four key challenges



Based on the experience with MAGO, develop and fabricate **new cavities** with optimised geometry



Find a cryostat with required thermal properties and which minimises acoustic noise in the He bath



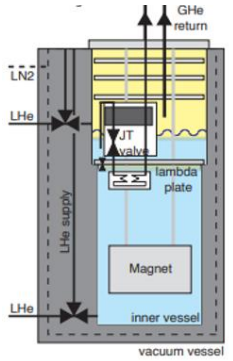
LLRF system to drive and read-out the cavity with highest possible sensitivity

How to realise a dedicated experiment

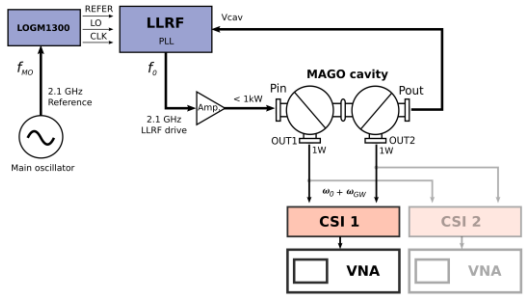
Four key challenges



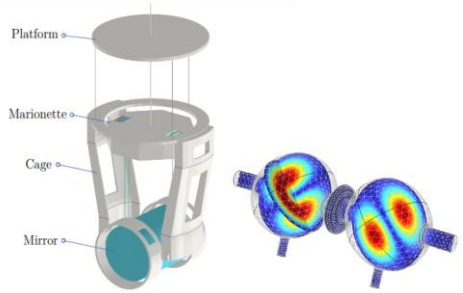
Based on the experience with MAGO, develop and fabricate **new cavities** with optimised geometry



Find a cryostat with required thermal properties and which minimises acoustic noise in the He bath



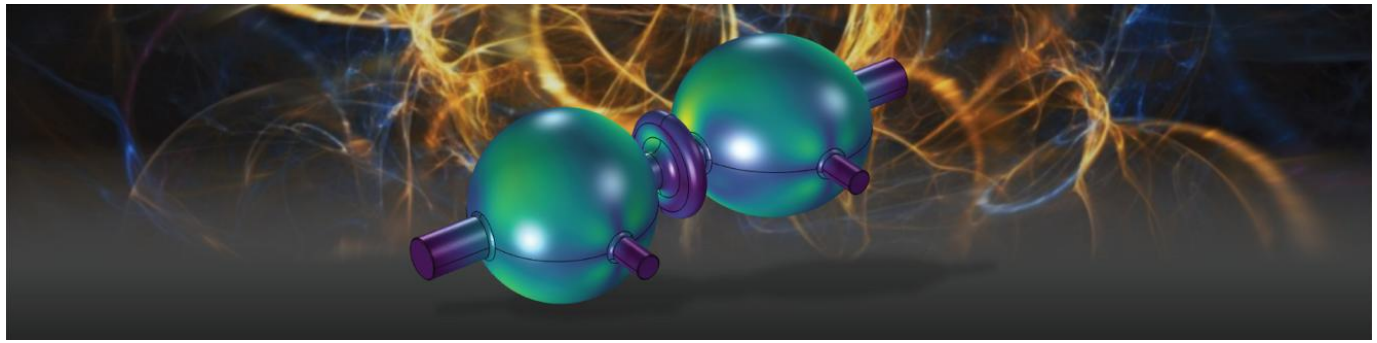
LLRF system to drive and read-out the cavity with highest possible sensitivity



Suspension system to eliminate mechanical noise (from environment and ground motion)

Conclusions and next steps

Successful cryogenic tests at Fermilab and DESY, the cavity can be used for a first physics run!

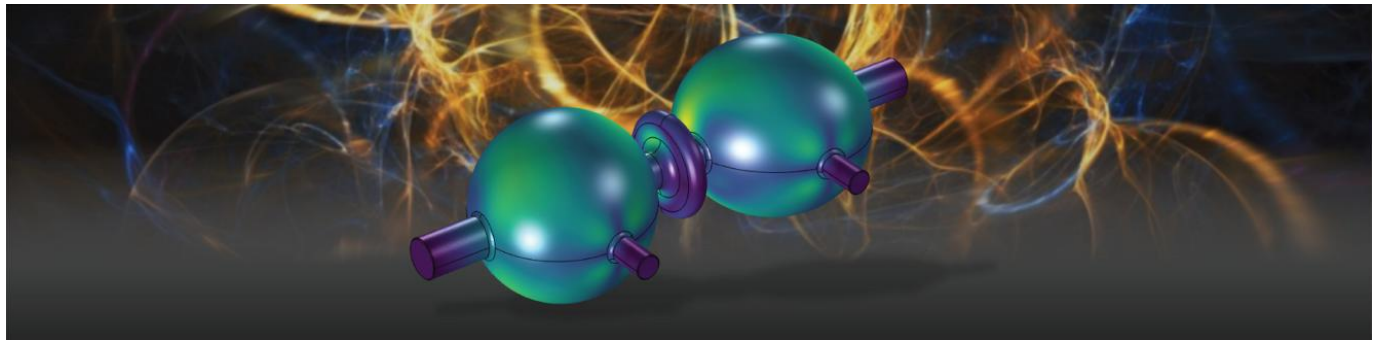


Conclusions and next steps

Successful cryogenic tests at Fermilab and DESY, the cavity can be used for a first physics run!

Future plans:

0. Finalize initial LLRF system development.



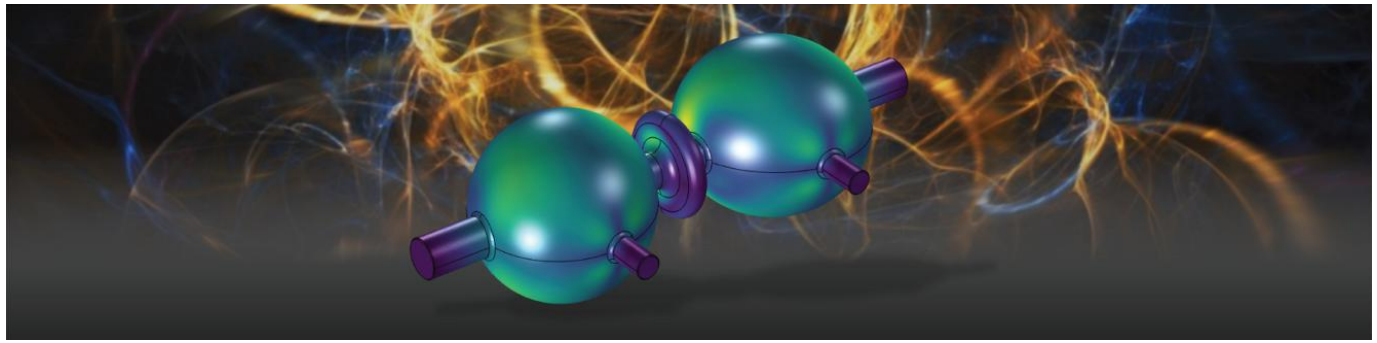
Conclusions and next steps

Successful cryogenic tests at Fermilab and DESY, the cavity can be used for a first physics run!

Future plans:

0. Finalize initial LLRF system development.

1. Proof-of-principle measurement: HFGW search with MAGO cavity in existing cryostat



Conclusions and next steps

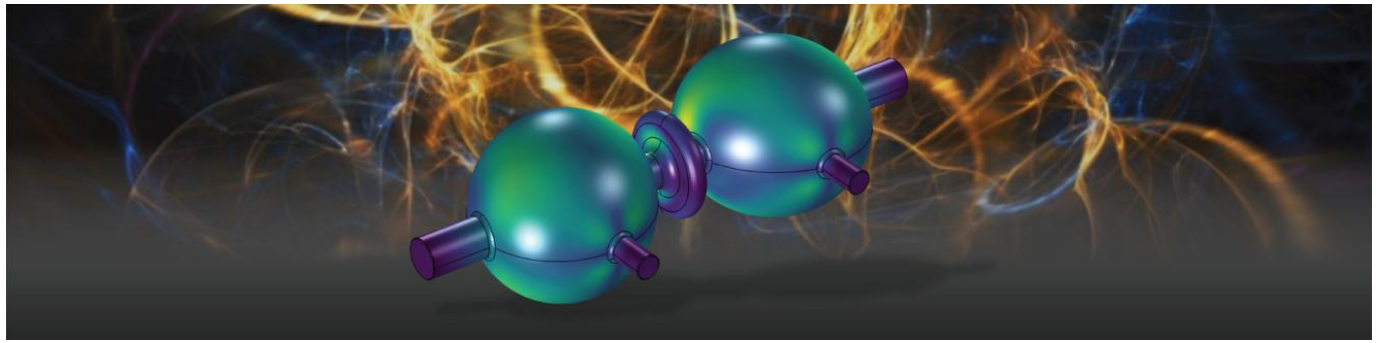
Successful cryogenic tests at Fermilab and DESY, the cavity can be used for a first physics run!

Future plans:

0. Finalize initial LLRF system development.

1. Proof-of-principle measurement: HFGW search with MAGO cavity in existing cryostat

2. Demonstrator experiment: improve reach with **new cavities** and construction of **suspension system**, still measure in existing cryostat



Conclusions and next steps

Successful cryogenic tests at Fermilab and DESY, the cavity can be used for a first physics run!

Future plans:

0. Finalize initial LLRF system development.

1. Proof-of-principle measurement: HFGW search with MAGO cavity in existing cryostat

2. Demonstrator experiment: improve reach with **new cavities** and construction of **suspension system**, still measure in existing cryostat

3. If successful, repeat with **scaled up cavities** and **dedicated cryostat**

