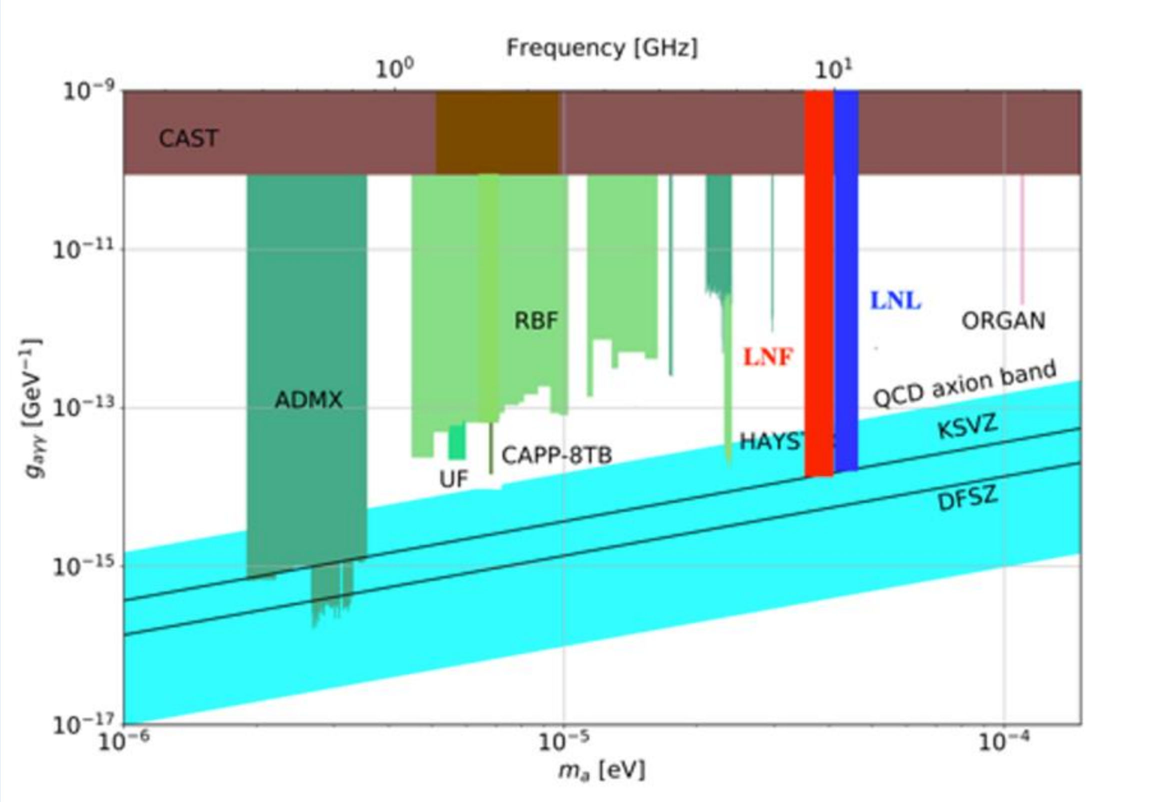
QUAX Experiment

- The **CSN2 has approved the QUAX experiment in 2020 for a 3 + 2 years** to run an observatory for searching axion via the **axion-photon coupling**
- The R&D activity on the axion – electron coupling will proceed with low priority
- **Two haloscopes** will be built: one in **Legnaro** and the other in **Frascati**

	LNF	LNL
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	pseudoTM030
Single volume	$1.5 \cdot 10^{-4}$ m^3	$1.5 \cdot 10^{-4}$ m^3
Total volume	7⊗0.15 liters	0.15 liters
Q_0	300 000	1 000 000
Single scan bandwidth	630 kHz	30 kHz
Axion power	$7 \otimes 1.2 \cdot 10^{-23}$ W	$0.99 \cdot 10^{-22}$ W
Preamplifier	TWJPA/INRIM	DJJAA/Grenoble
Operating temperature	30 mK	30 mK



- The **LNL haloscope** will be based on hybrid copper-dielectric cavities, travelling wave parametric amplifiers and 14 T magnet
- The **LNF haloscope** will be based on multiple-copper cavities, JPA/TWPA amplifier and 9 T magnet

LNL Haloscope – RUN 2024

- **Major renovations on dilution unit**
  - New connection for Cold Plate
  - New input lines for Mixing Chamber
  - New flexible line from cold plate to mixing chamber
  - Gold coating of heat shield

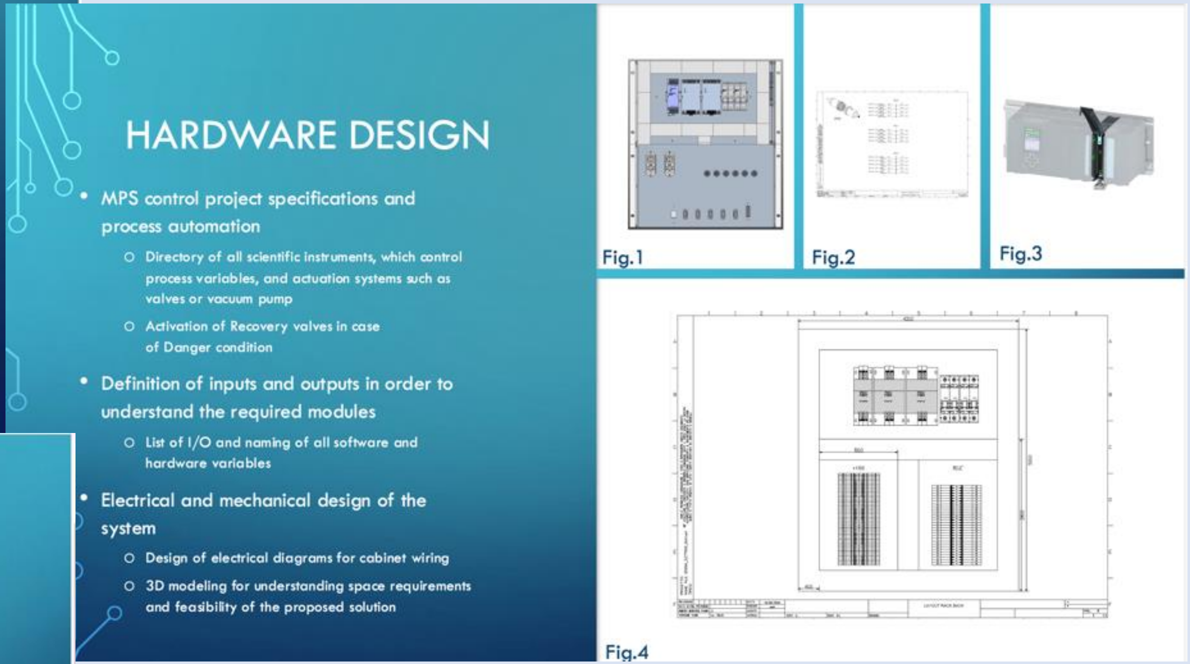
- **Installation of a large tuning range cavity**
  - Tuning about 60 MHz
  - Large effective volume
  - Q factor up to 80 000

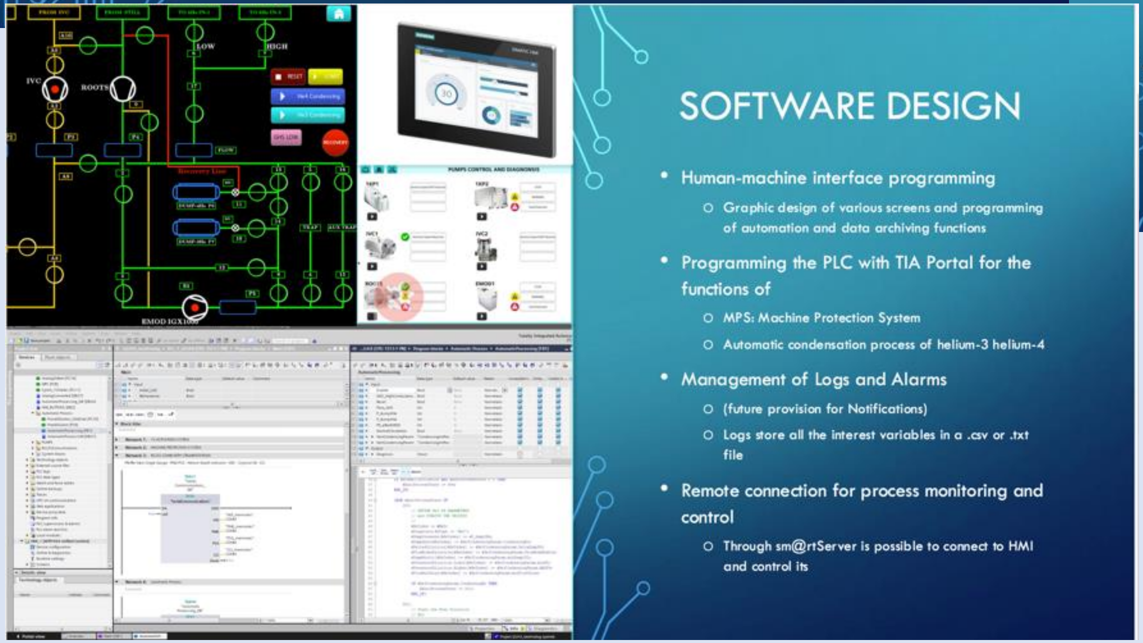
- **TWPA in operation with partially automated control system**

- **Dilution unit performed well**, mixing chamber @ 50 mK, cavity temperature at 100 mK
- **Magnet working** at 8 T as usual
- **TWPA amplifier working** fine in strong magnetic field ambient
- **Installed automations working** as expected
- **Performed scanning** of about 40 MHz with almost KSVZ sensitivity

Dilution unit control system

In order to allow **long term operation** of the dilution system a PLC-based control system of the dilution unit is currently being built





Tunable cavity

LamedNew

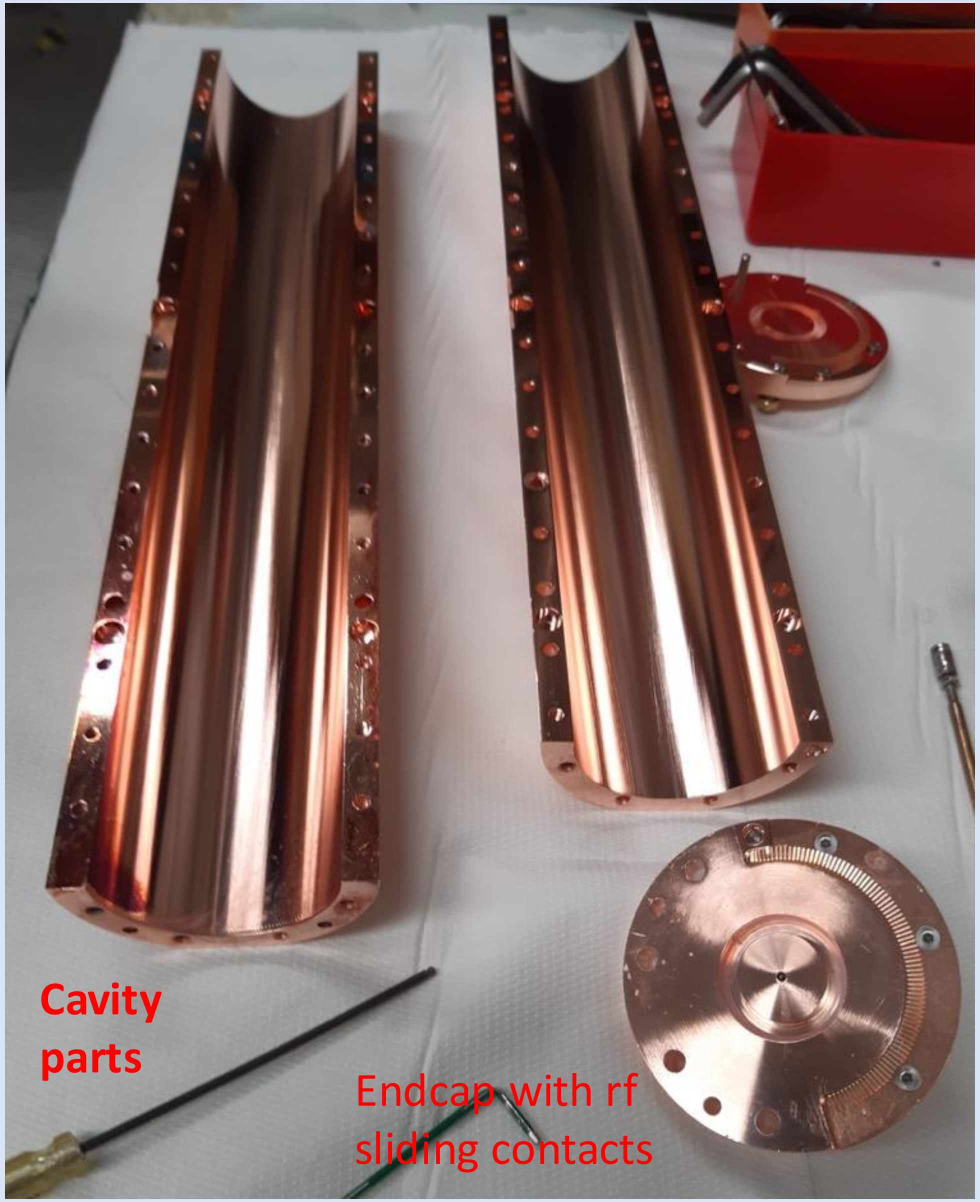
Right cylindrical hybrid cavity

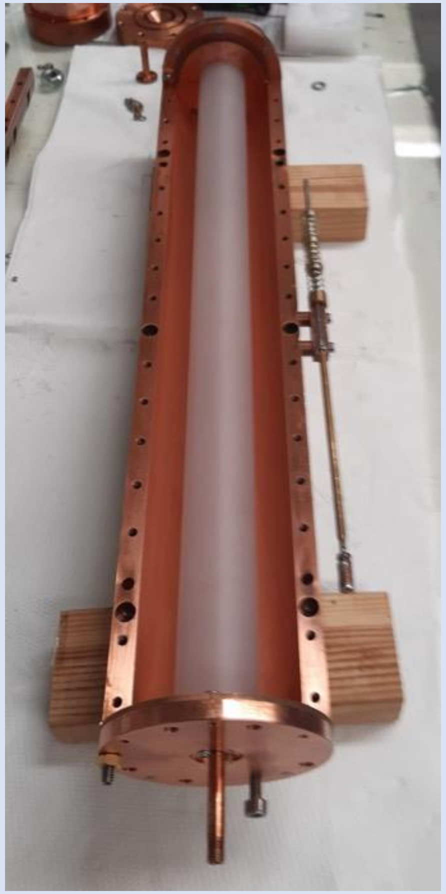
Copper shell
Sapphire cylinder inside

Clamshell mechanism for tuning

Base frequency 10.2 GHz

Q factor at about 80 000 at cryogenic temp




Open cavity with sapphire cylinder


Cavity in the dilution insert


Antenna

LAMED TC

(fenicio: Pungolo)

𐤋

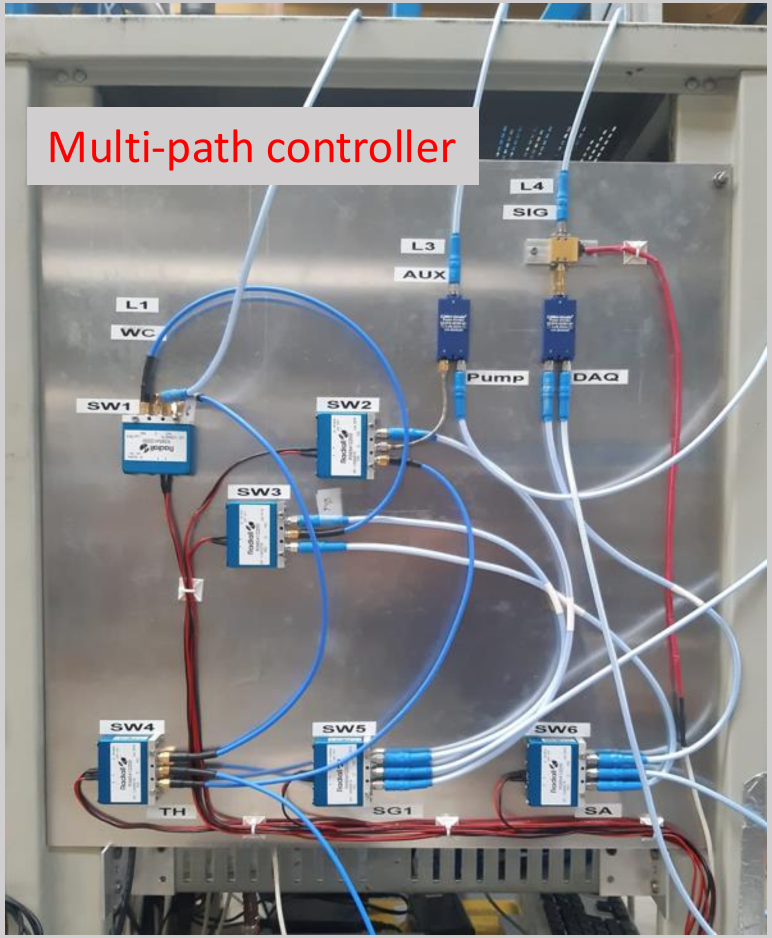
- Rame OFHC
- Zaffiro armeno L = 420 mm
- Tuning con parete laterale
- Tappi singolo pezzo
- Tappi con scanalatura profondità 5.3 mm per zaffiro
- Contatti tappi parete mobile in rame elastico
- Movimento con pantografo, motore lineare vs molle di richiamo
- Teflon in scanalatura d=1.6 mm

Q0 ~ 70.000 – 80.000
Accoppiamento variabile
Tuning massimo ca 55 MHz

Lunghezza interna 413.4 mm
Diametro 60.5 mm

Devices for automation

Installed the new **automatic system for Noise Temperature Measurement**



Original idea published in
A haloscope amplification chain based on a traveling wave parametric amplifier - RSI 2022

Long runs require automatization of all procedures: antenna coupling, cavity tuning, noise temperature measurement

Computer controlled motors for **cavity tuning** and **antenna coupling optimization**

Devices for automation

Python based programming for run control and data acquisition

New ADC board with up to 20 MS/s sampling rate – run rate 4.4 MS/s

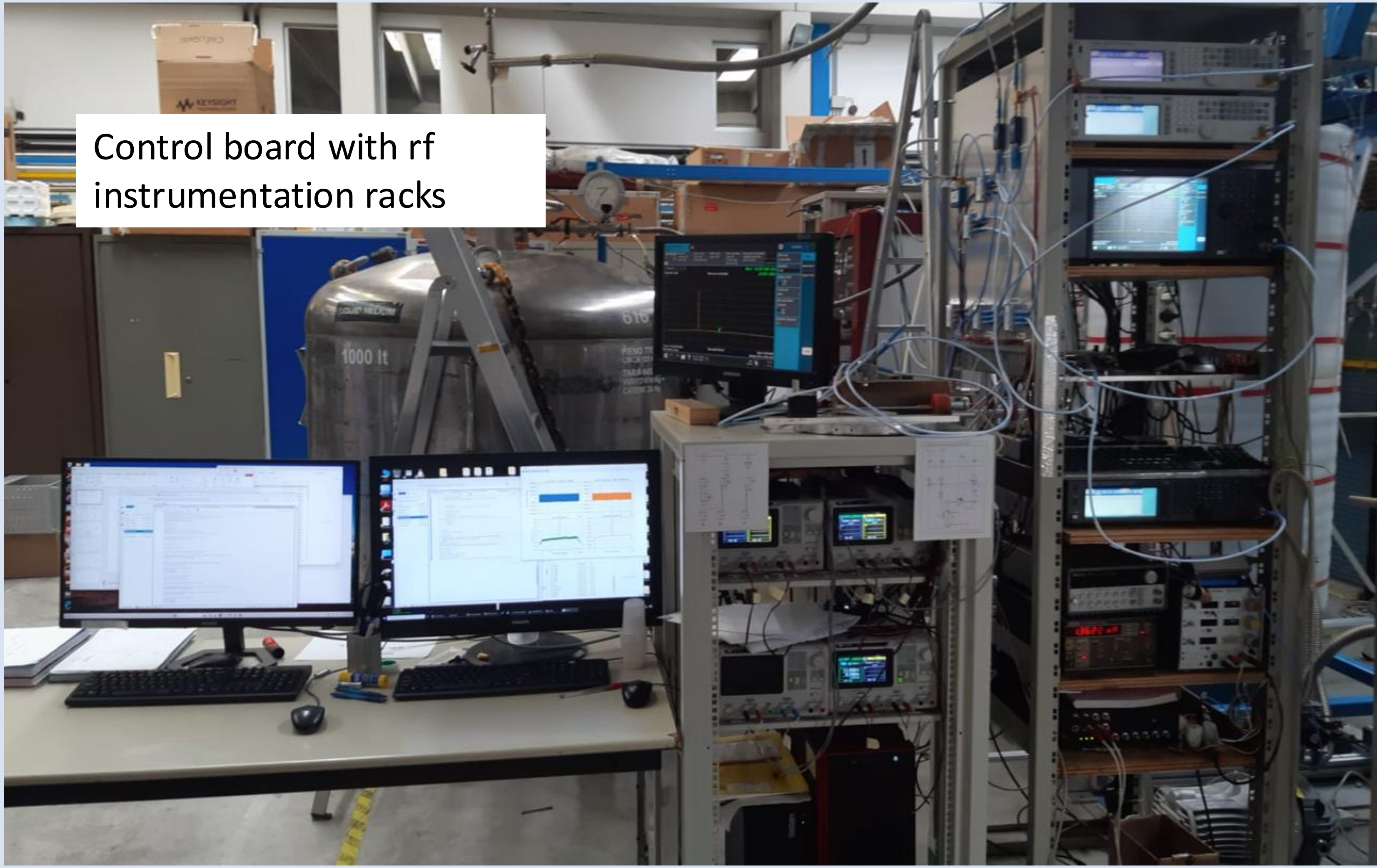
Semi-automatic run control:

By Operator:

- Cavity tuning
- TWPA amplifier tuning

Computer controlled:

- Cavity mode characterization (Q_0, beta)
- RF characterization (gain, noise)
- Data acquisition and storage



Control board with rf instrumentation racks

Data are transferred to INFN Cloud for offline analysis

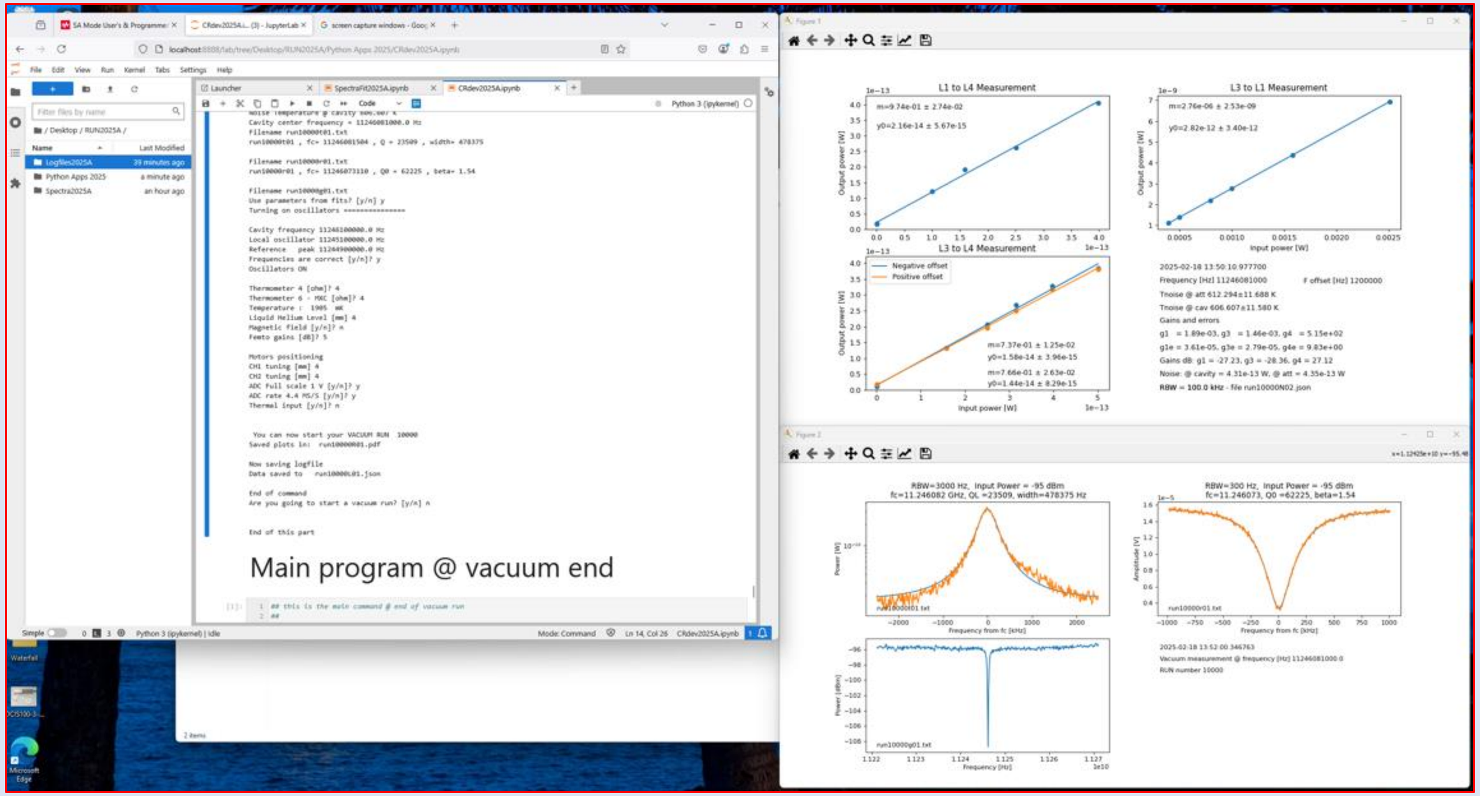
Run control

Run steps:

1. Cavity tuning (manual)
2. TWPA amplifier optimization (manual)
3. Measurement of Tsys and Gain (2 m)
4. Measurement of f_c, Q_L, Q_0 , gain profile (2 m)
5. Short data acquisition with thermal input (2 m)
6. Repeat steps 3-4 (4 m)
7. Long data acquisition with no input (65 m)
8. Repeat steps 3-4 (4 m)
9. Start over

Time for a single point 80 - 100 minutes

SLOW CONTROL



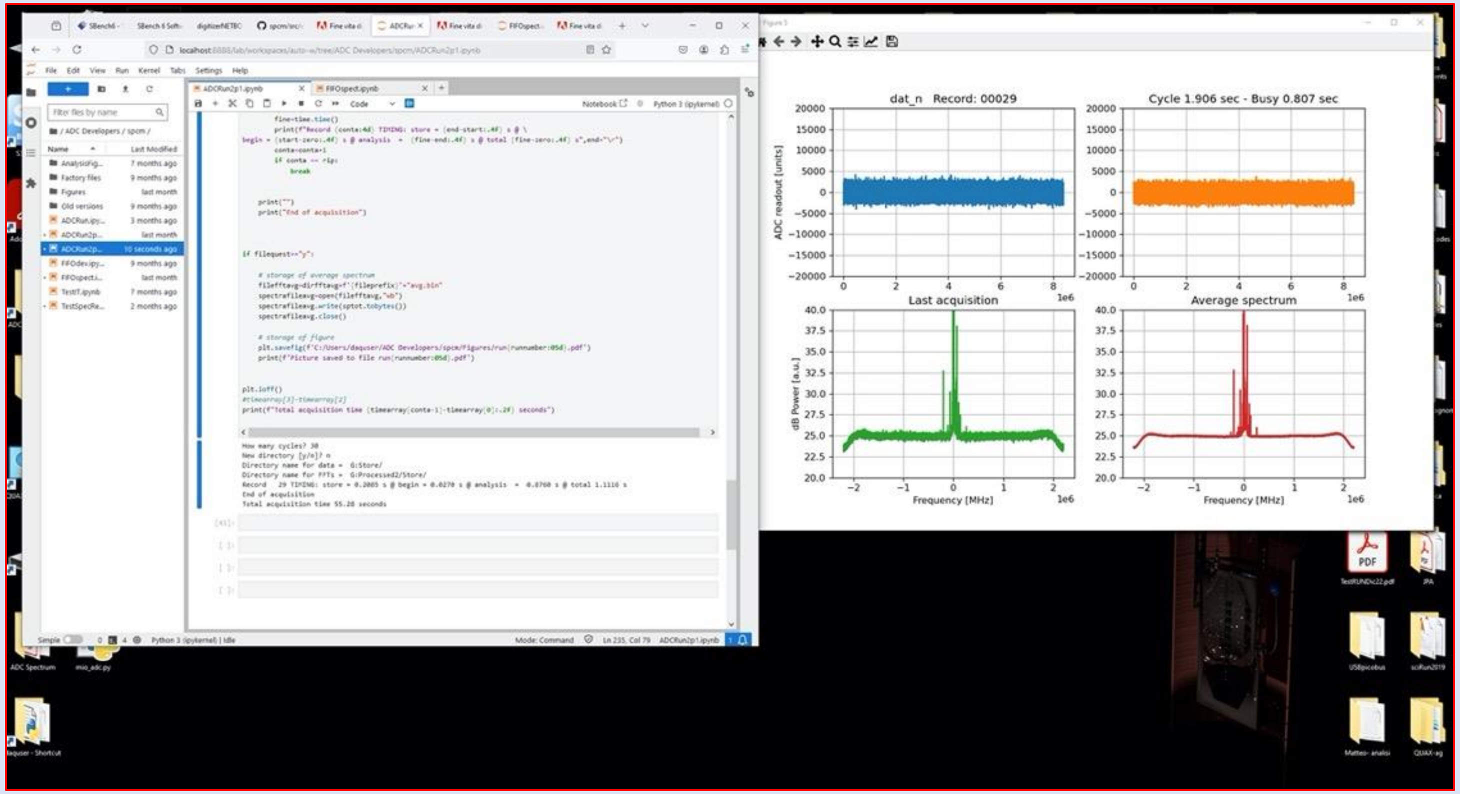
All measured parameters, data and spectra saved to Logfiles

Data acquisition

- 2- channel acquisition (I, Q from Mixer)
- Sampling rate = 4.4 MS/s
- Single block length 2^23 = 8 388 608 samples
- Single block length = 1.908 s

- FFT of each block during acquisition
- $f_{LO} \sim f_c - 1$ MHz
- Spectral window [f_{LO} – 2.2 MHz, f_{LO} + 2.2 MHz]
- 16384 bins of 268.6 Hz width

ADC CONTROL



Raw data and FFTs stored locally during acquisition
Data copied to cloud once per day

Data file size 33.6 MByte
Typical run 65 GByte
Daily request 600 GByte

Total memory storage up to about 20 TByte

QUAX RUN 2024 - Parameters

Magnetic field ON
Cavity frequency **f_c= 10.15– 10.21 GHz**
Noise temperature **T_{sys} = 1.1 – 1.5 K**
Quality factor **Q_0 = 60000 - 80000**
Antenna coupling **β = 1.4 – 1.8**
Cavity Volume **V = 1.06 liters**
Estimated efficiency **C_{030}= 0.4**
Effective field **B^2=50.89 T^2**
Axion mass **m_a = 44.9 μeV**
Typical Integration time **t_m = 3800 s**

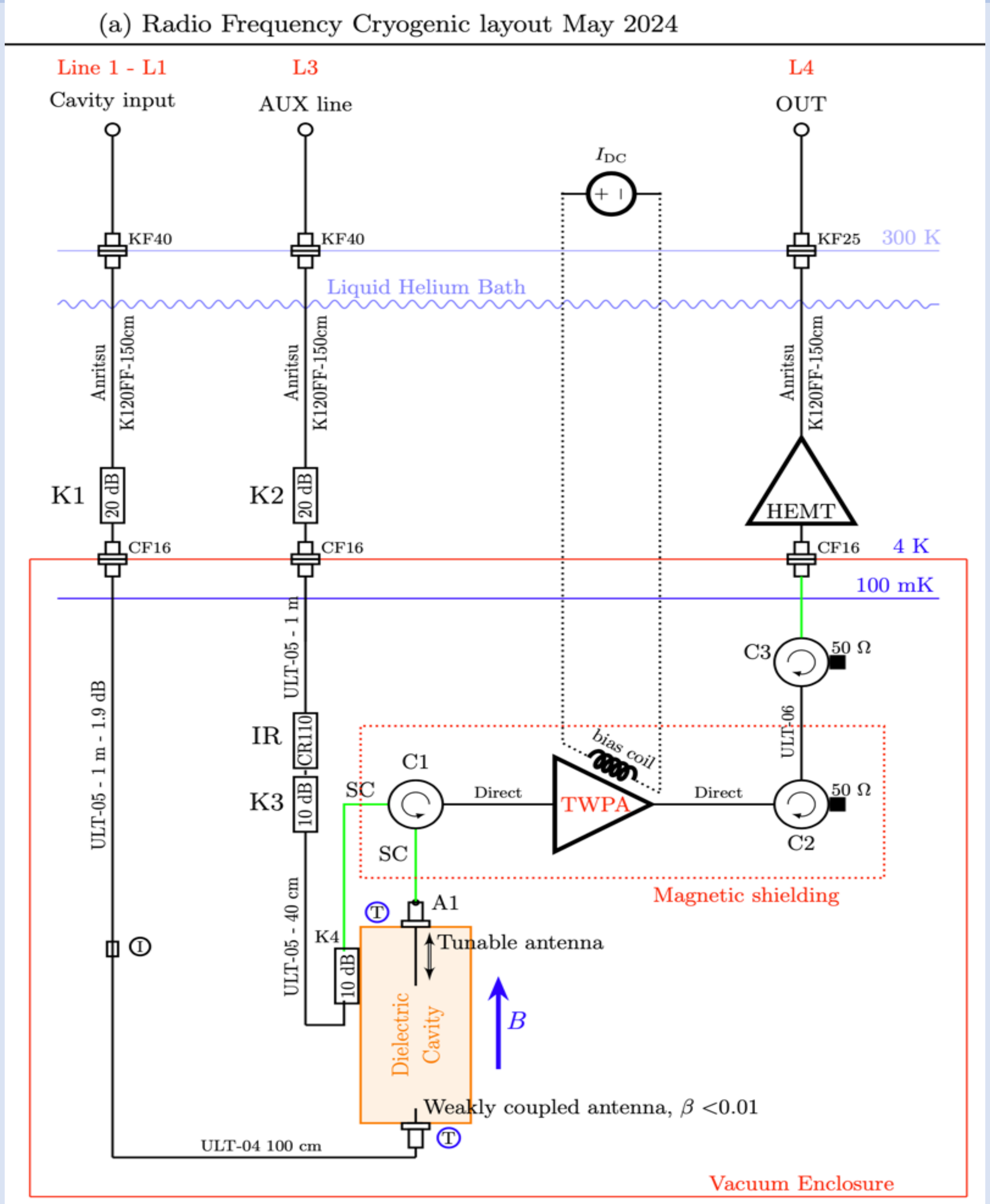
Expected axion power in a 10 kHz window **Pa = 6.0e-24 W**

Expected sensitivity (Dicke) in a 10 kHz window **σ_P= 2.5e-23 W**

Improved RF set-up

Key changes for a lower noise temperature

- Reduced losses on the read-out line
- Better isolation of the auxiliary line
- Better thermalization of critical elements
- Increase gain of TWPA amplifier



QUAX RUN 2024 – Spring and autumn sessions

Spring session

Total run time 3 weeks

2 separate weeks for data taking

May 28th to May 30th - 48 h of field ON

June 11th to June 14th - 90 h of field ON

Autumn session

Total run time 2 weeks

Nov 7th to Nov 13th - 138 h of field ON

Break due to power failure

Nov 19th to Nov 21th - 42 h of field ON

Covered span:

~40 MHz with 225 h vacuum data taking

Maximum tuning: 58.45 MHz

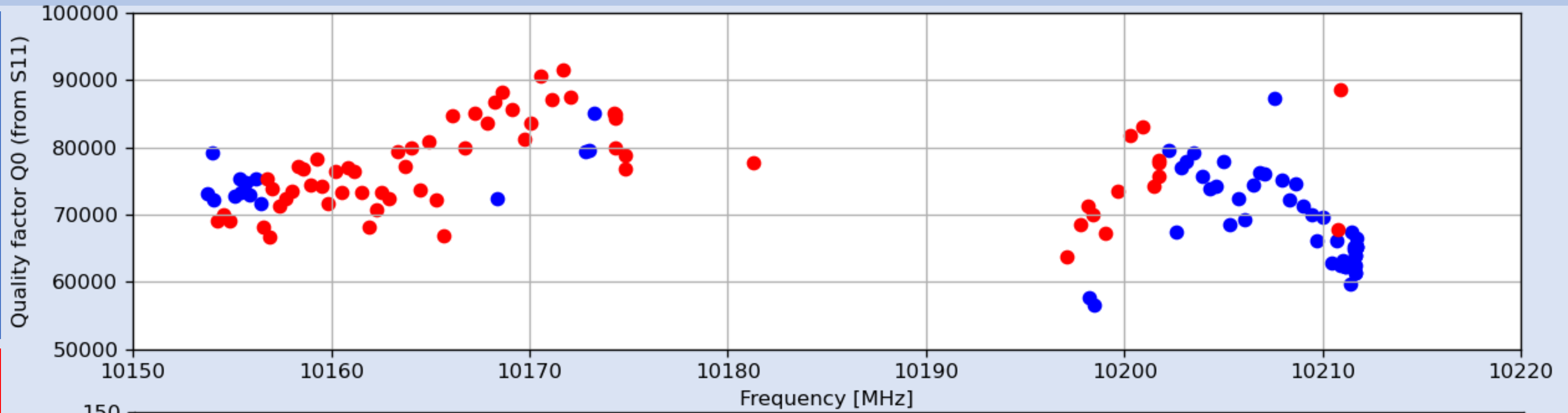
Ratio: 65% of available scan

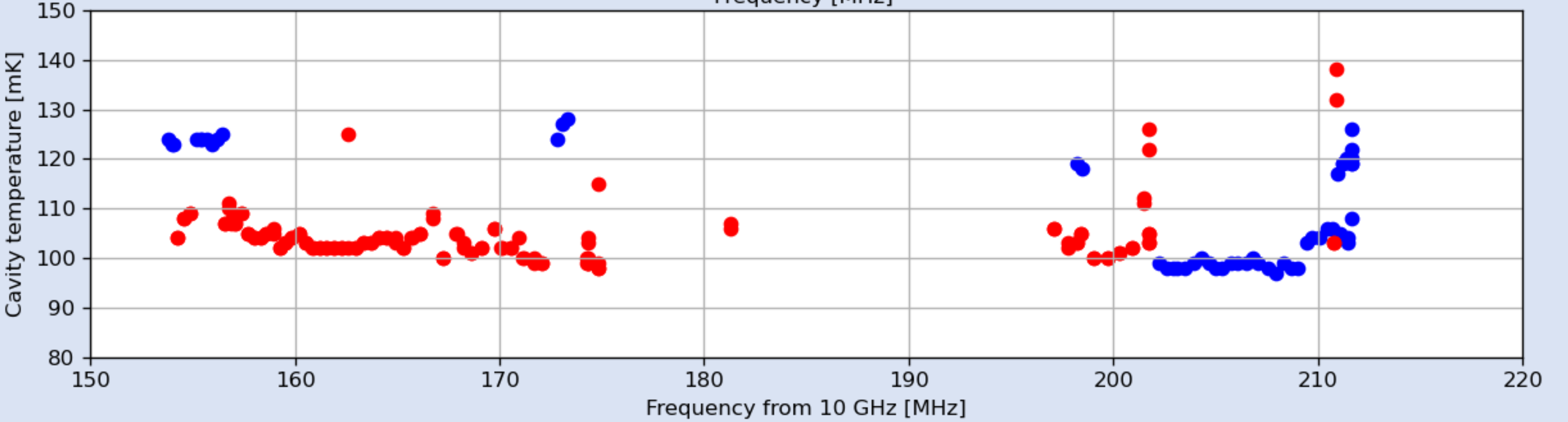
Duty cycle 50%

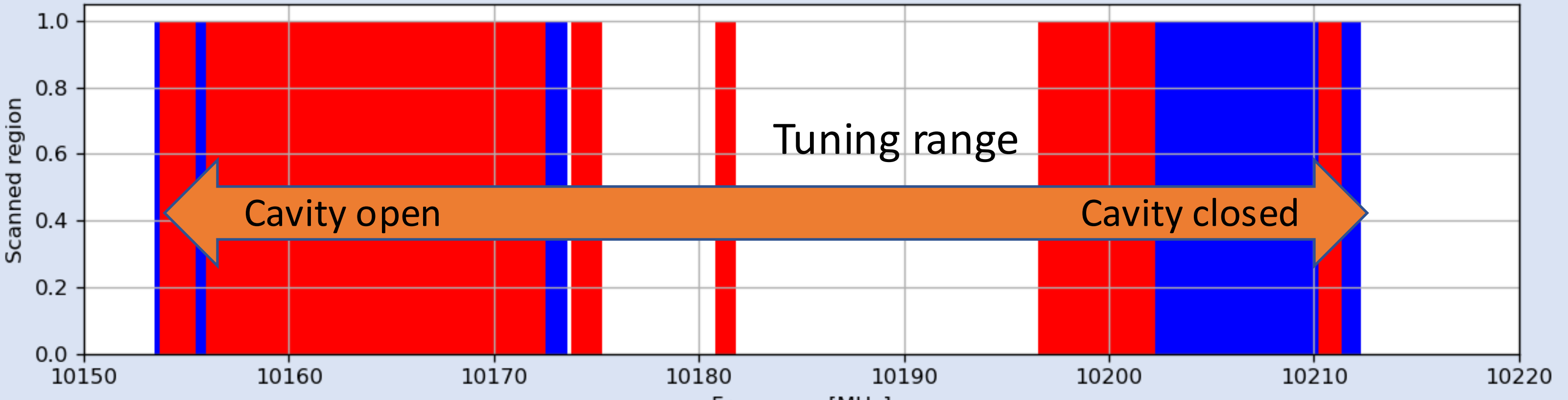
Effective scan rate about

100 kHz/hour

2.5 MHz/day





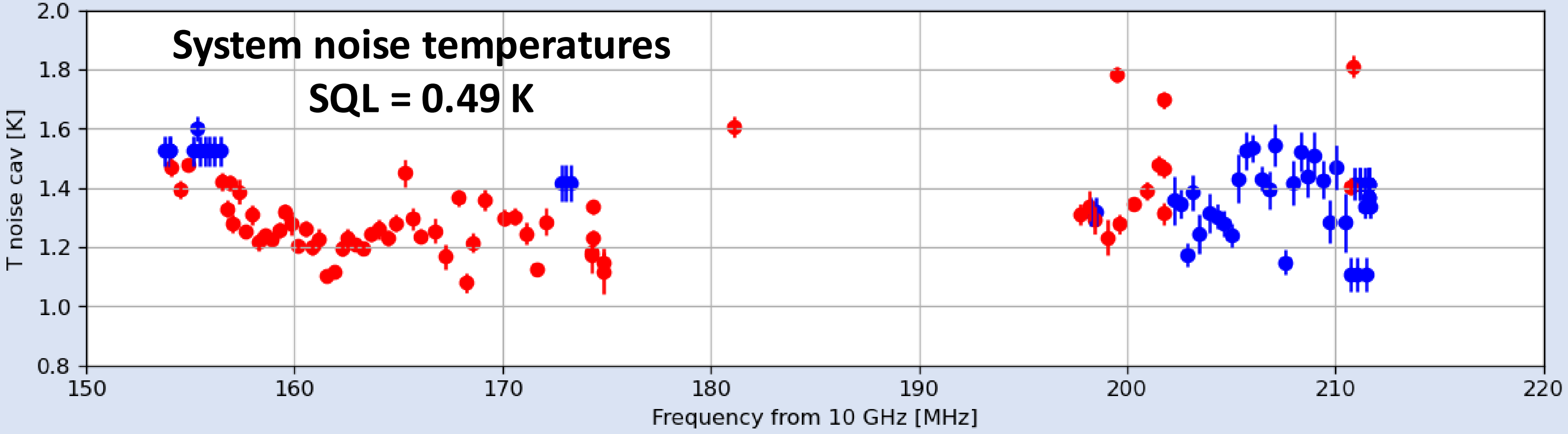


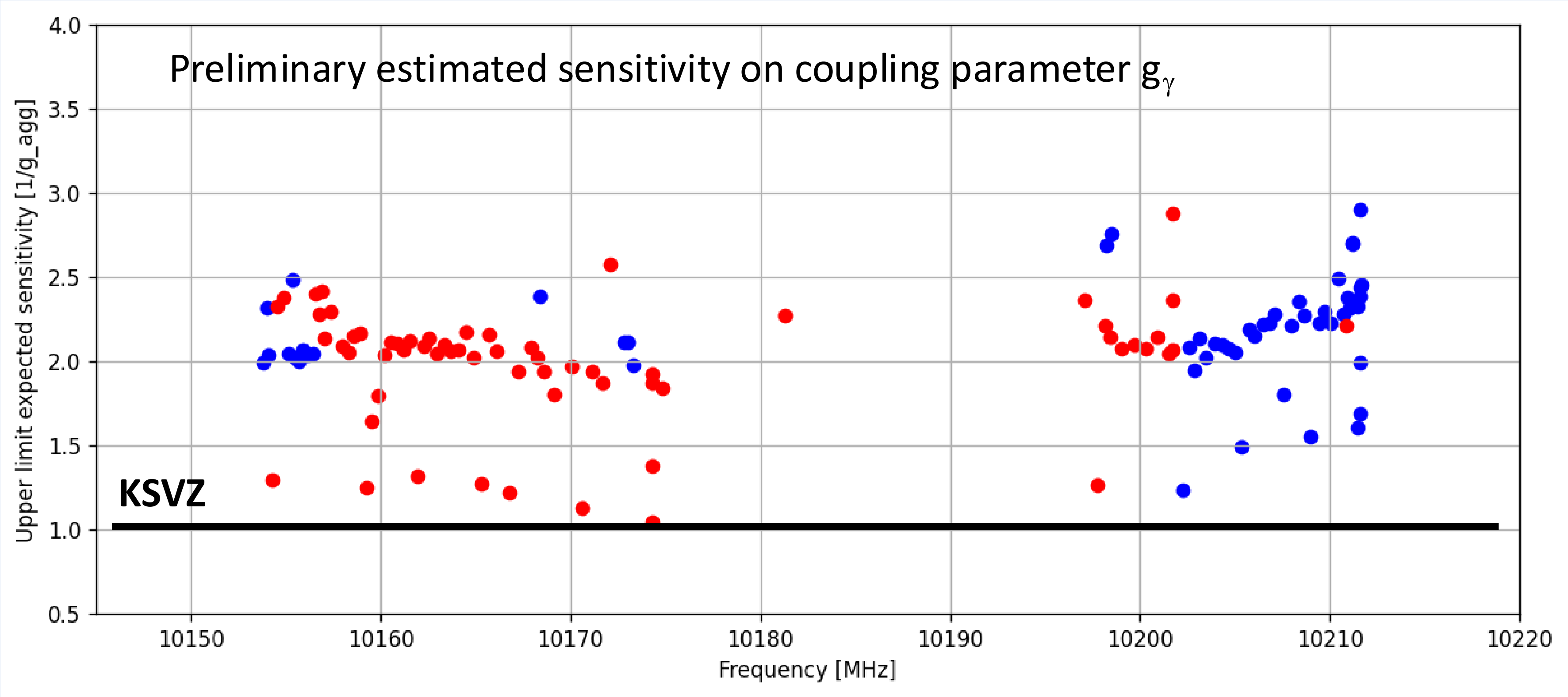
QUAX RUN 2024

Analysis in progress

Expected sensitivity with measured parameters in axion coupling normalized to KSVZ model

Formule scaling

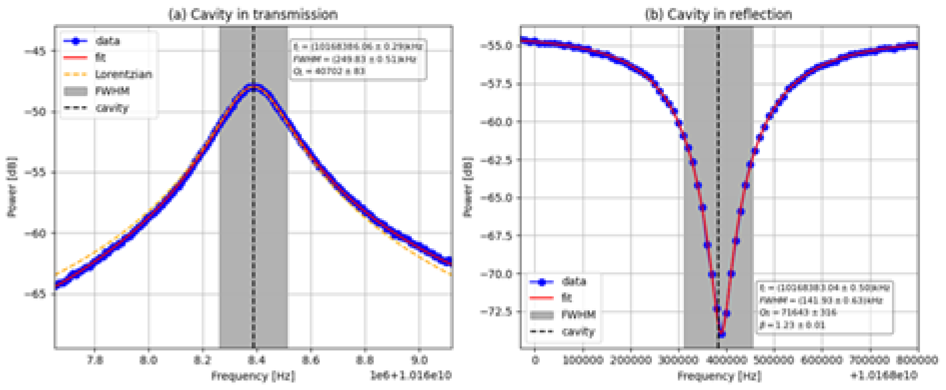




This result shows that with the expected improvements on the cavity and field the QUAX design sensitivity is within reach

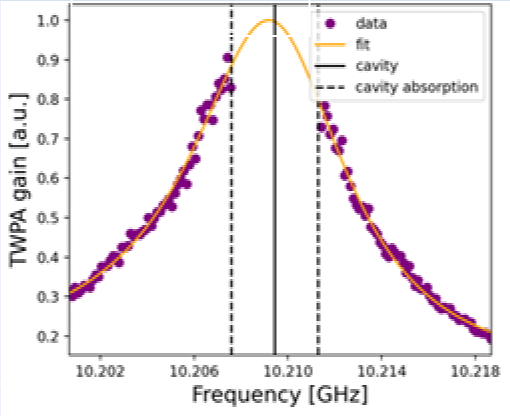
QUAX Data Analysis Checks

Parameter evaluation (β, f_c, Q_0, Q_L)

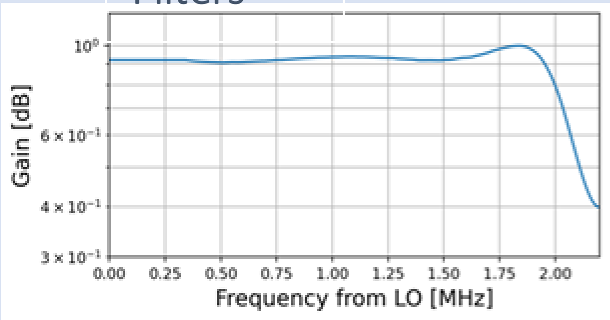


Remove freq-dependent

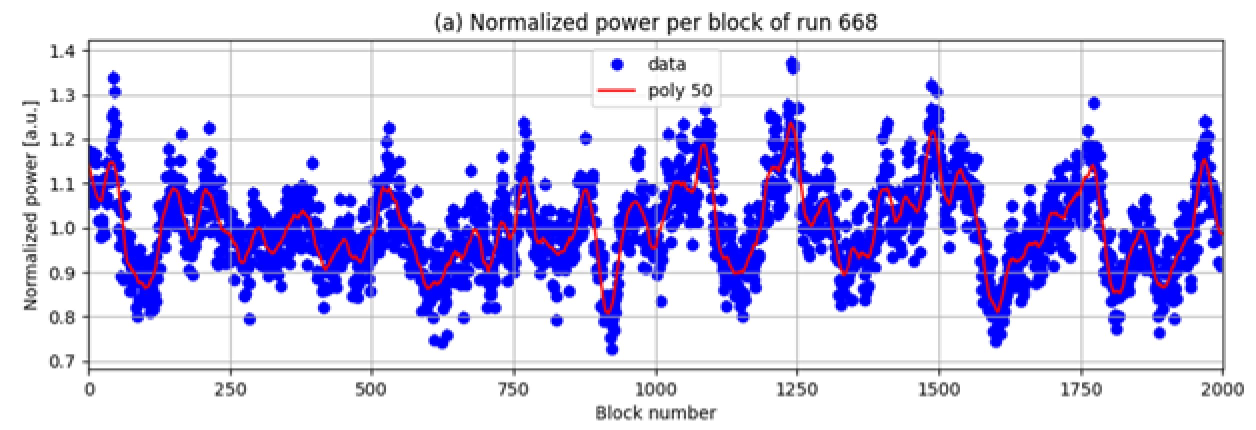
TWPA



Filters

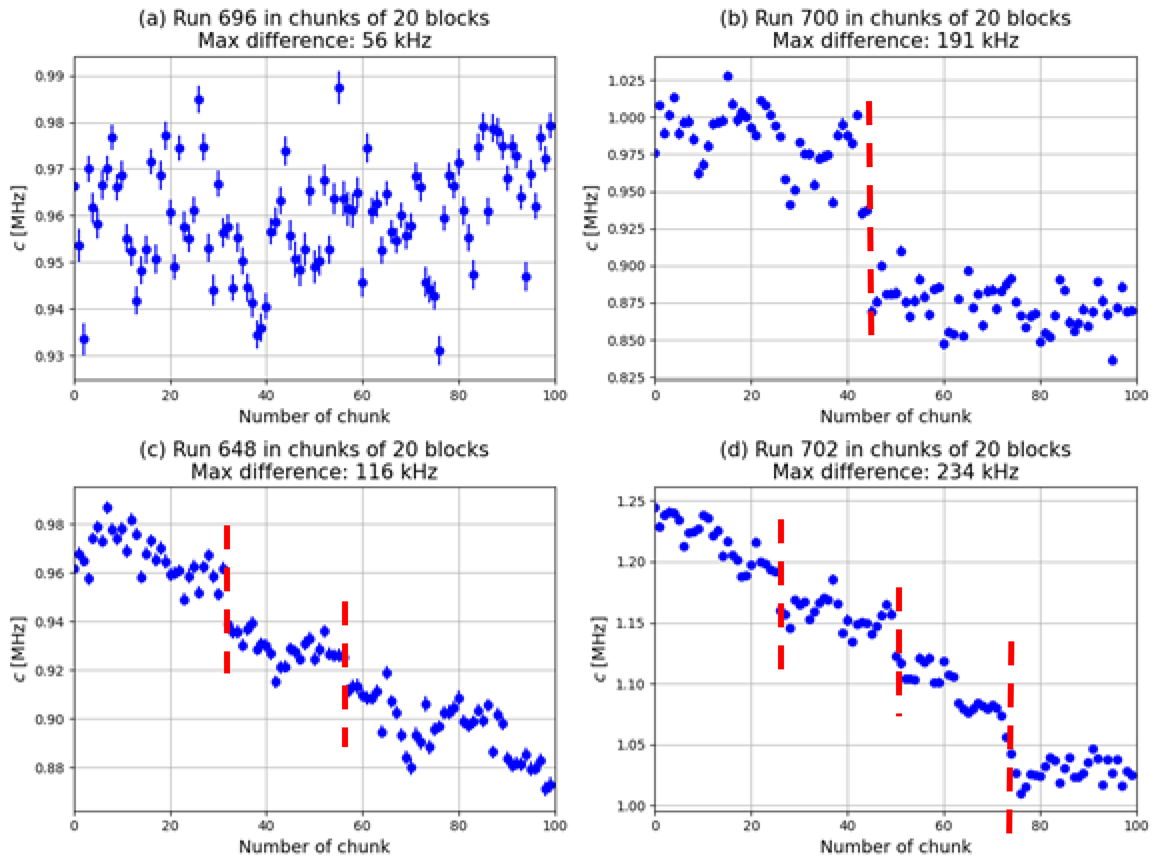


Remove time-dependent

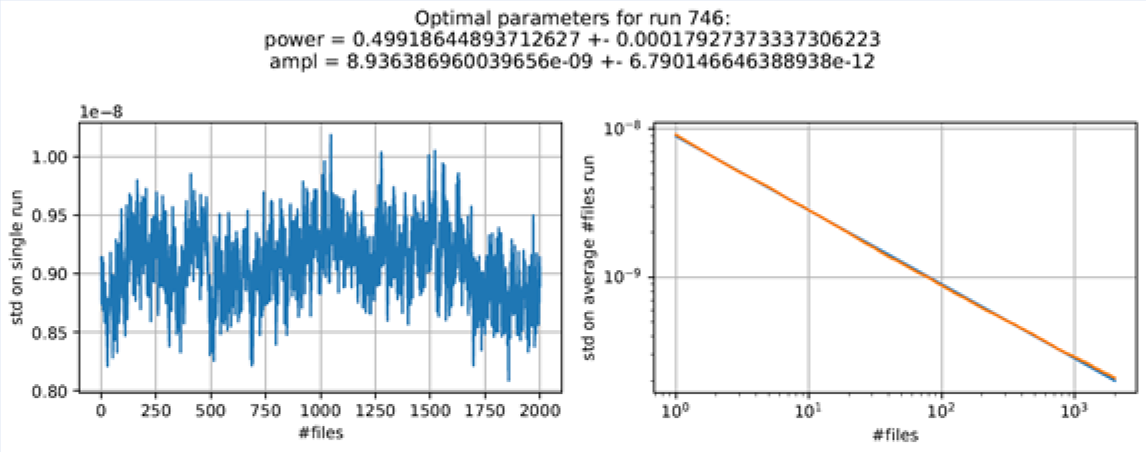


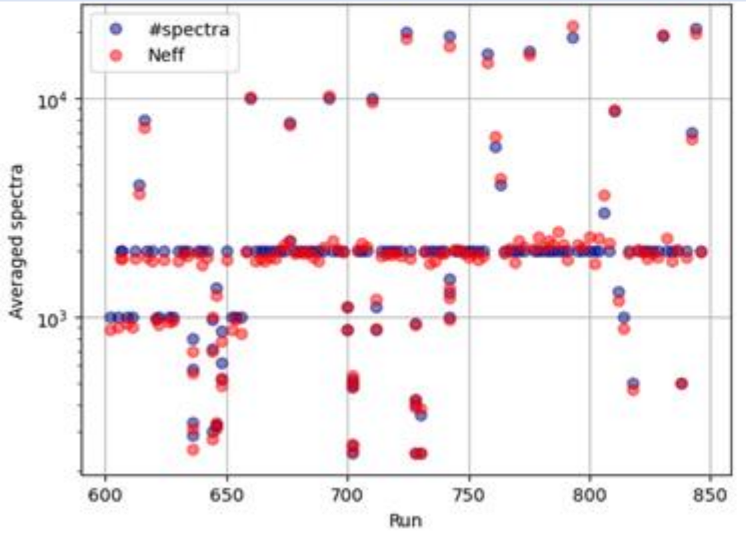
QUAX Data Analysis Checks

Spectra division based on behaviour over time @ cavity

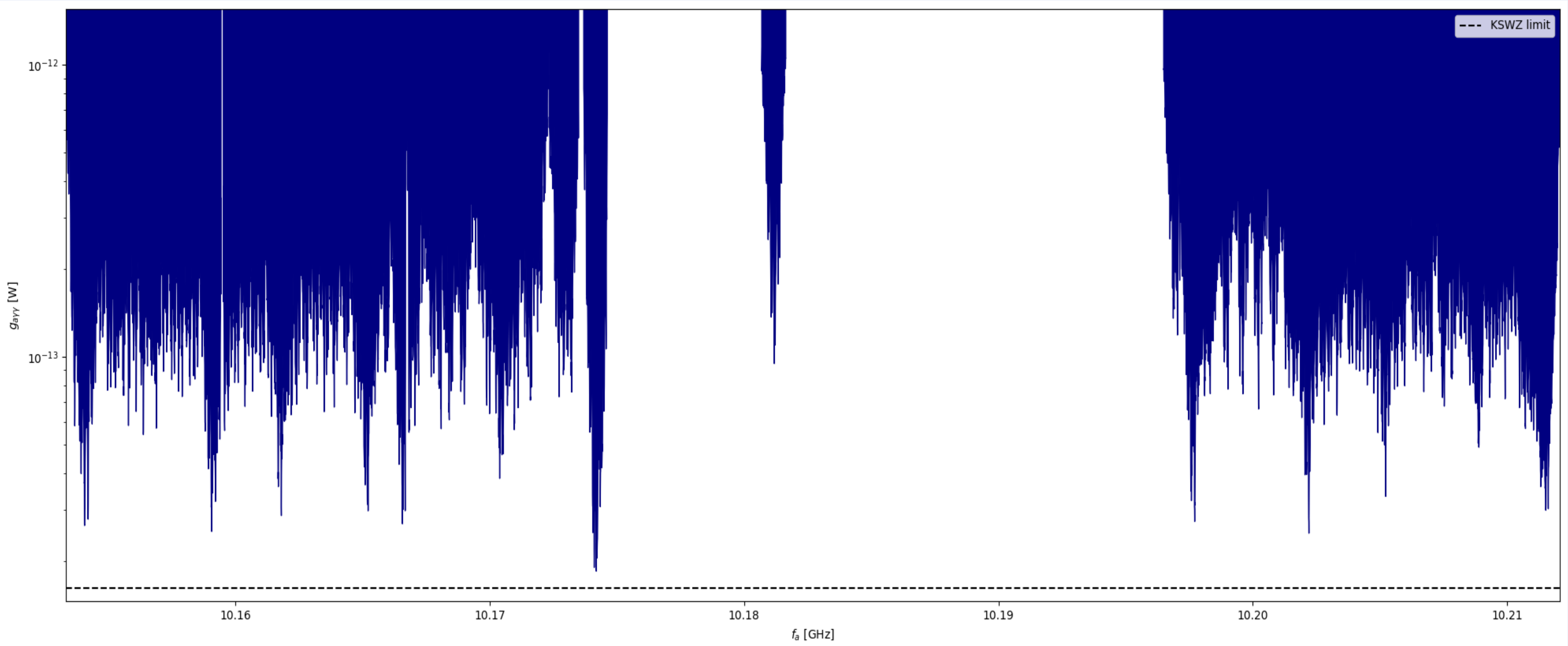


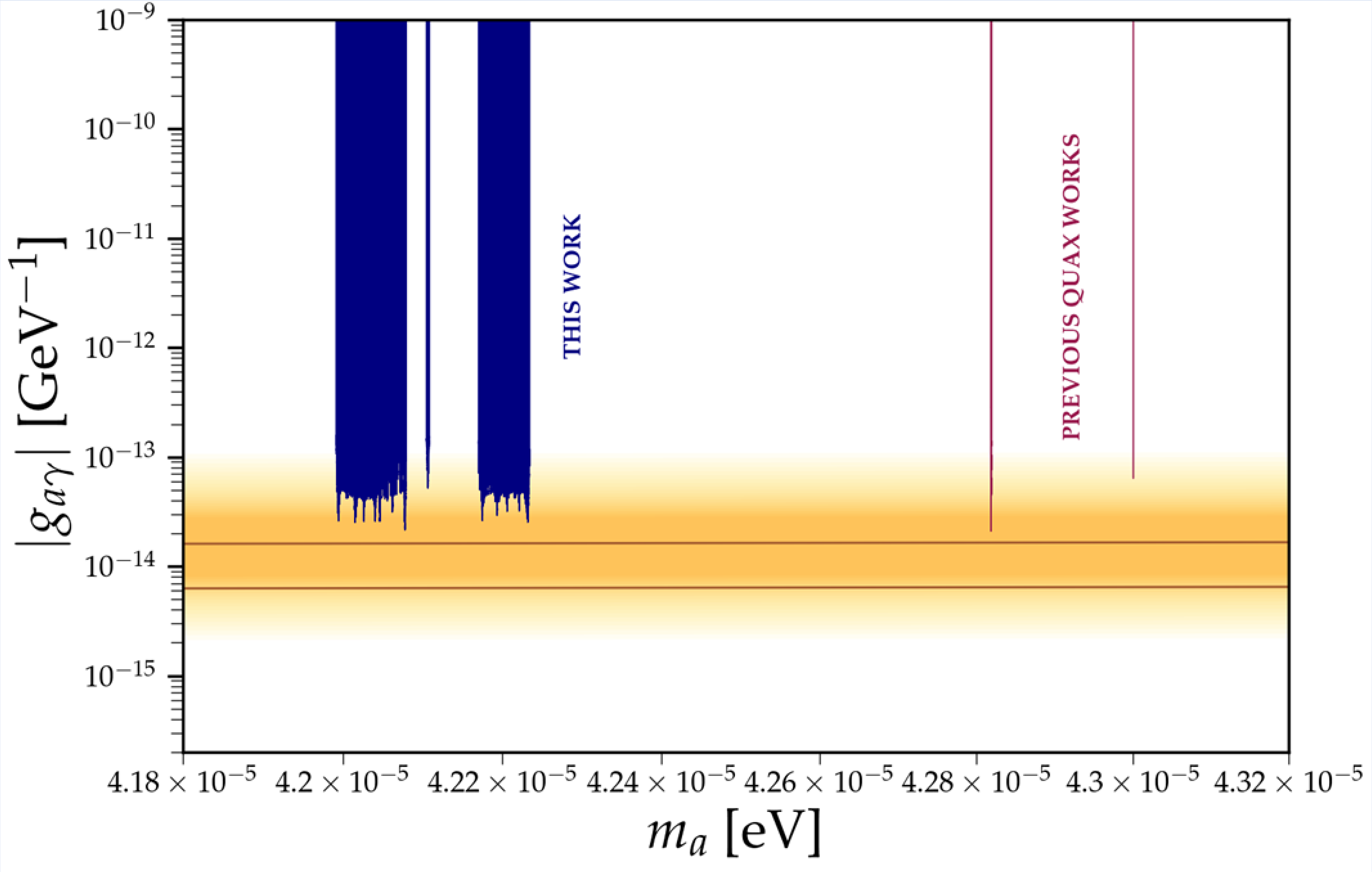
Dicke check for every data run





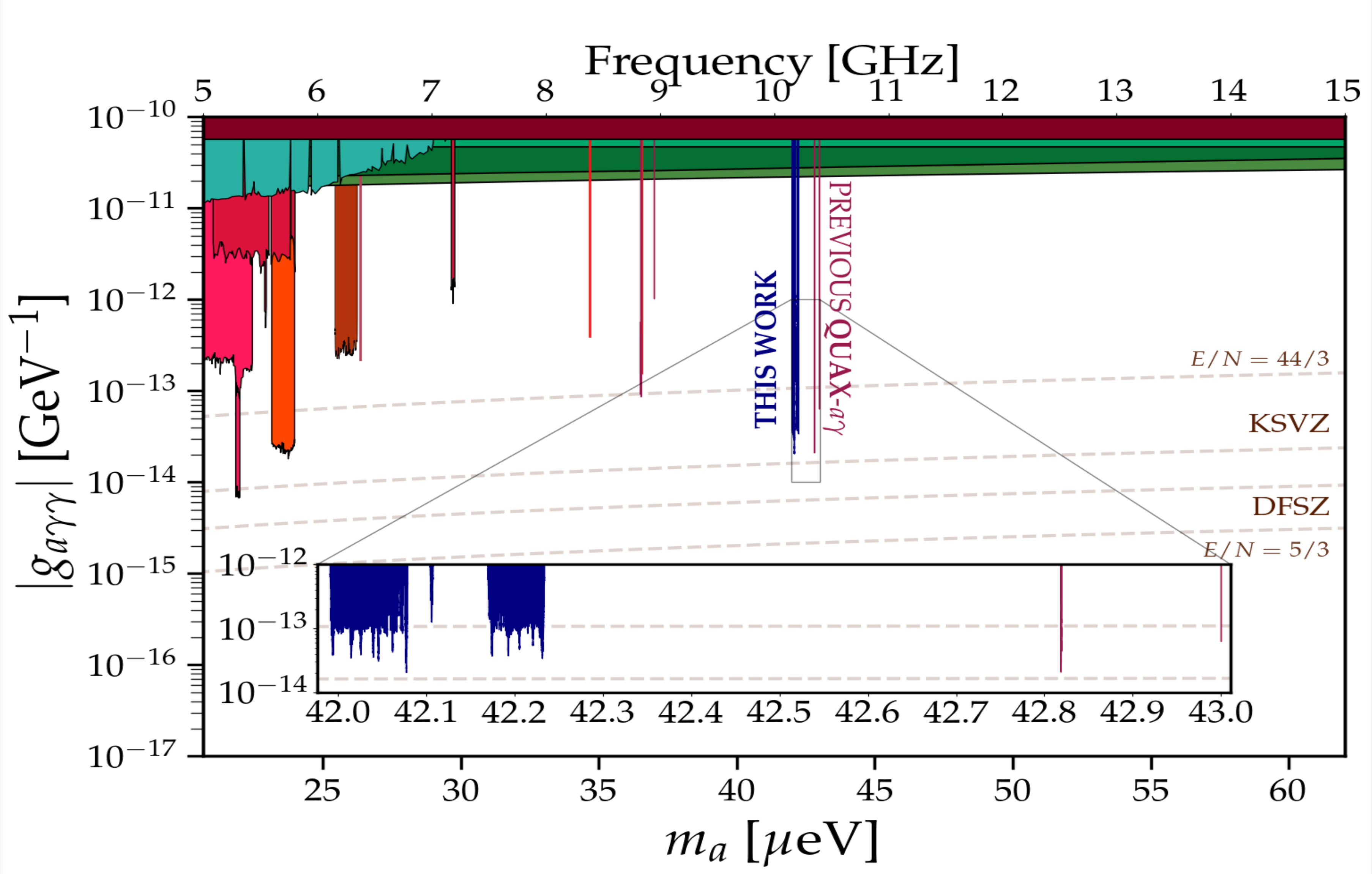
QUAX RESULTS





THIS WORK
PREVIOUS QUAX WORKS
$|g_{a\gamma}|$ [GeV^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
4.18×10^{-5}
4.2×10^{-5}
4.22×10^{-5}
4.24×10^{-5}
4.26×10^{-5}
4.28×10^{-5}
4.3×10^{-5}
4.32×10^{-5}
m_a [eV]

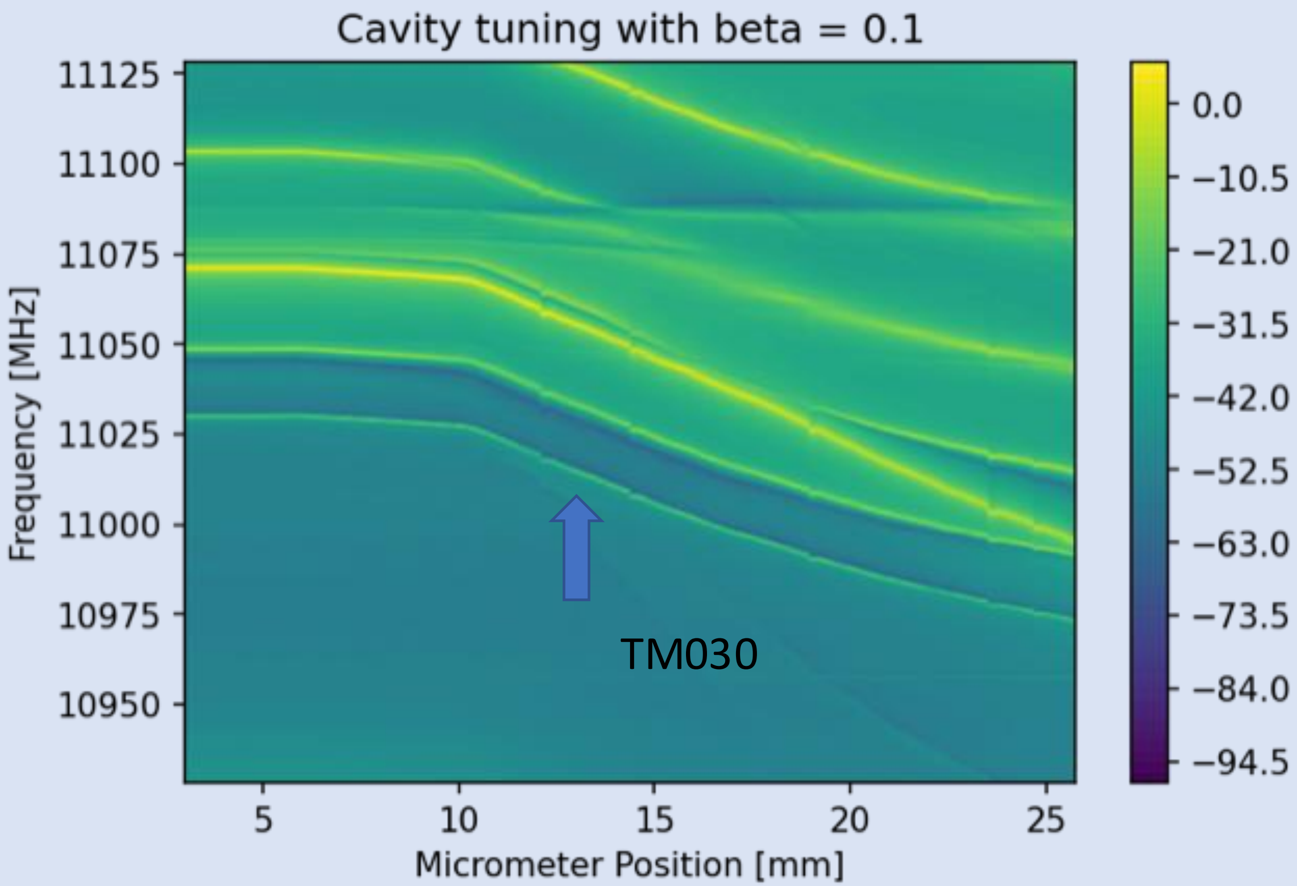
QUAX comparison



LNL Haloscope – High Frequency Tunable Cavities

Objectives:
- Resonance frequency above 10 GHz
- Tunable with range 100 MHz
- Large Volume
- High Q over the entire tuning range
- Limited spurious modes
- Operation in strong B field
- Bead pulling measurements

Dedicated test station for cavity characterization @ 4 K



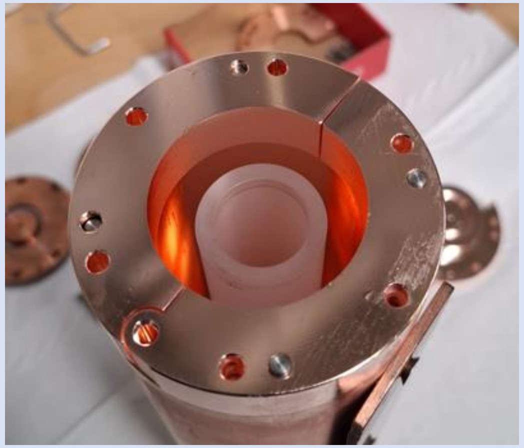
Q0 ~ 200 k

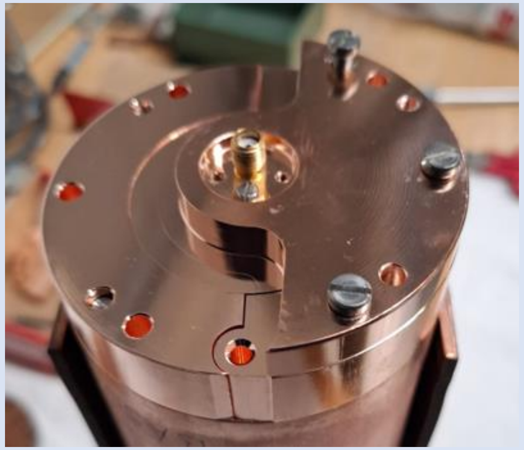
Maximum tuning ~ 100 MHz

QUAX publications on cavities
- **A new class of axion haloscope resonators: the polygonal coaxial cavity – 2nd turn on PRApplied**
- **A tunable large volume dielectric cavity at 11 GHz – in preparation 2024**
- A tunable clamshell cavity for wavelike dark matter searches - RSI 2023
- High- Q Microwave Dielectric Resonator for Axion Dark-Matter Haloscopes - PRAppl 2022
- Realization of a high quality factor resonator with hollow dielectric cylinders for axion searches - NIMA 2021
- High quality factor photonic cavity for dark matter axion searches - RSI 2020

SAMEK 2G

(fenicio: Pilastro)





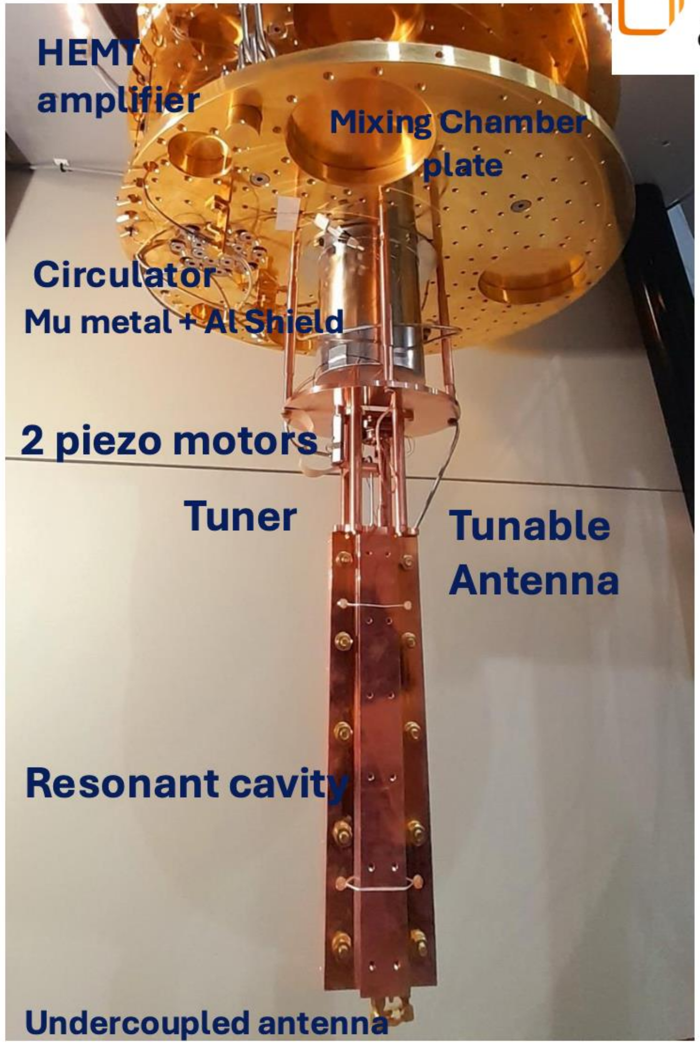
Lunghezza interna 243.4 mm
Diametro 60.5 mm

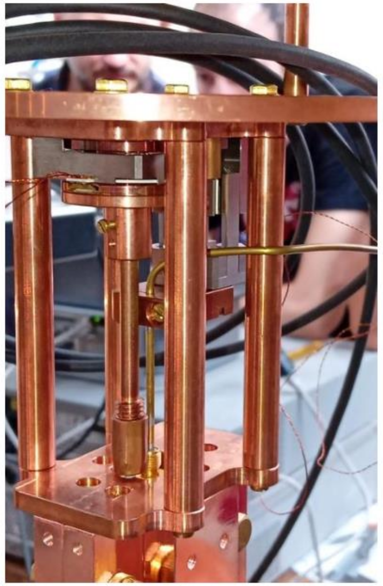
- Rame OFHC - electropolishing
- Zaffiro lituano L = 250 mm
- No tuning yet
- Tappi doppio pezzo - apribili
- Tappi con scanalatura profondità 5.3 mm per zaffiro
- Tappi con scanalatura ove campo nullo per apertura
- No contatti elastici fra pezzi mobili
- Previsto movimento con vite su tappo superiore
- Teflon in scanalatura d=1.2 mm

Future steps @ LNL-PD

- **Proceed with automation of data acquisition and control**
- **Proceed with installation of safety controls of dilution unit based on PLC**
- **Optimize dilution pumping system**
- **Improve mechanics of present cavity to allow tuning up to 90 MHz**
- **RUN with TWPA @ about 10.1 GHz, with T_n = 1.2 K and complete scanning of cavity Lamek (March – April)**
- **Realization of improved cavity design based on experience with Samek**

LNF Haloscope – RUN 2024



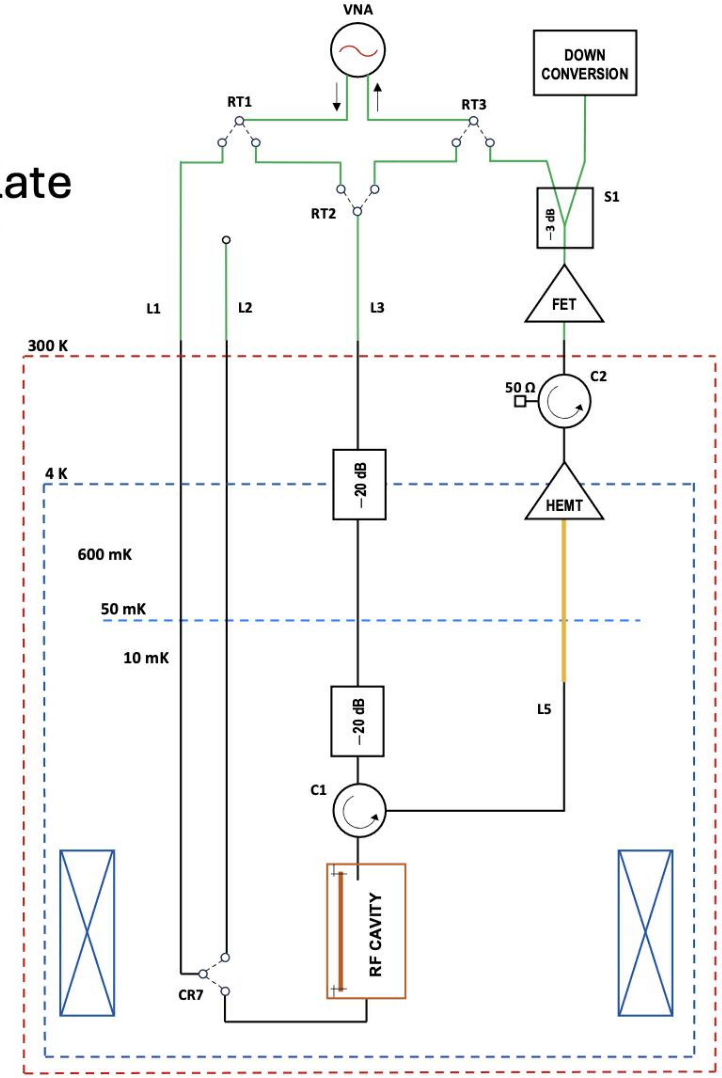


Temp. of 10 mK plate

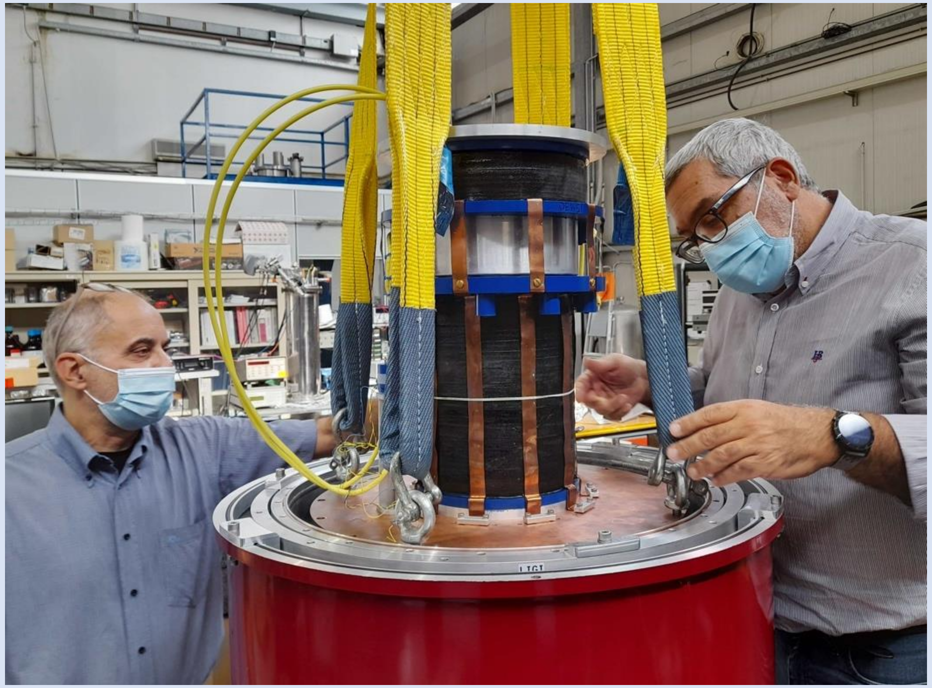
$T_{base} \simeq 20\ mK$

Target next run QUAX:

To take data on about 50 MHz frequency range



LNF 9 T SC Magnet



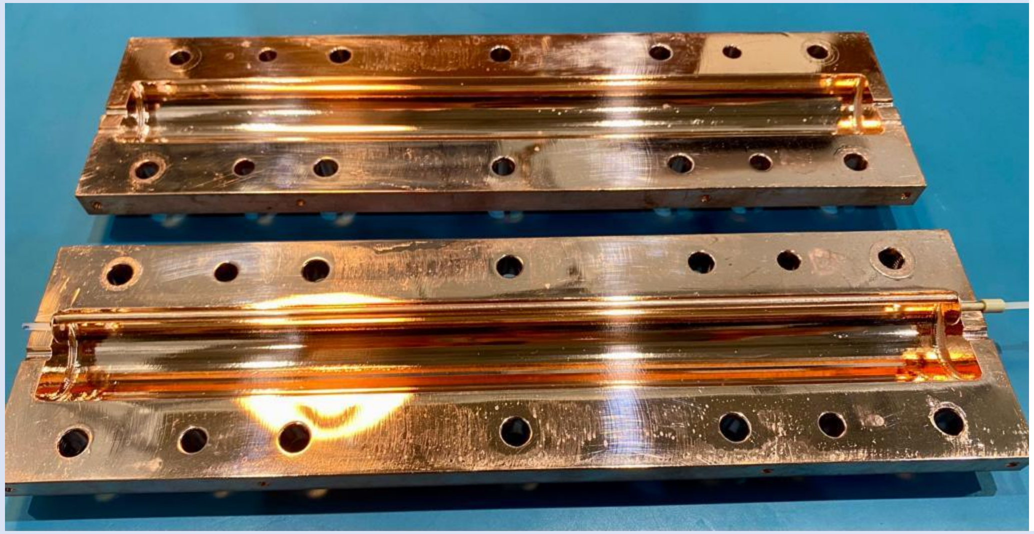
Anchored to 4 K stage

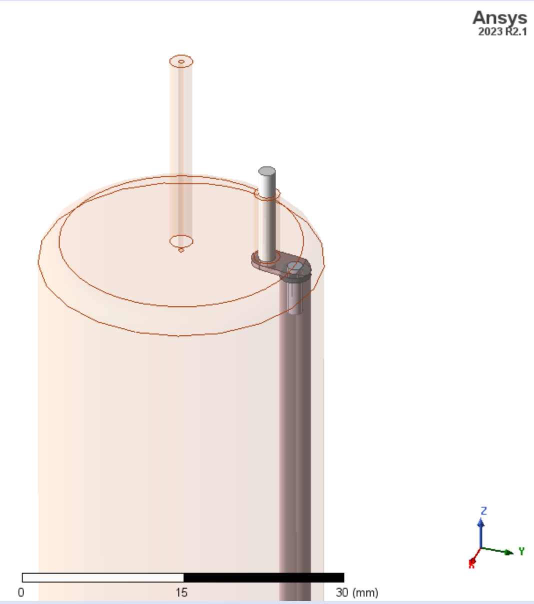
- Reached 9 T
- Took data at one freq with 9 T
- Quench
- Ramp to 8 T ok
- Took data with 8 T stably for 2 weeks

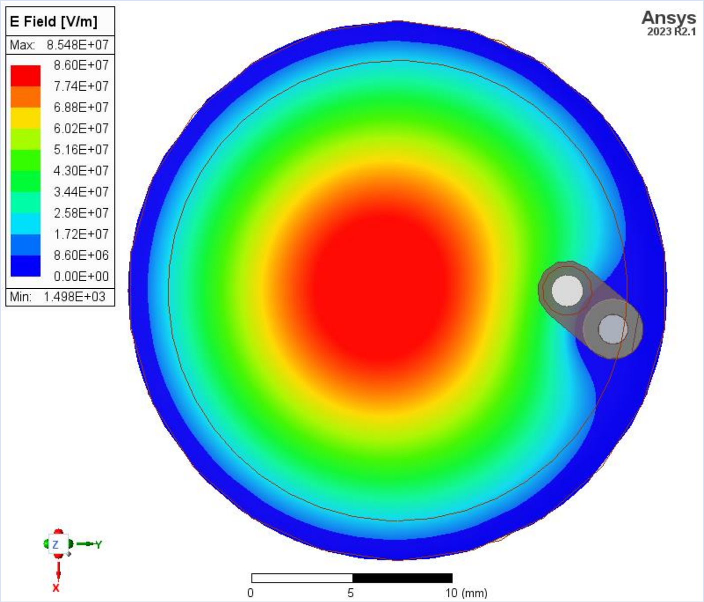
➡ Update mid 2024: Problem solved, ready to reach 9T

Microwave cavity + tuning

HFSS simulations by Simone Tocci





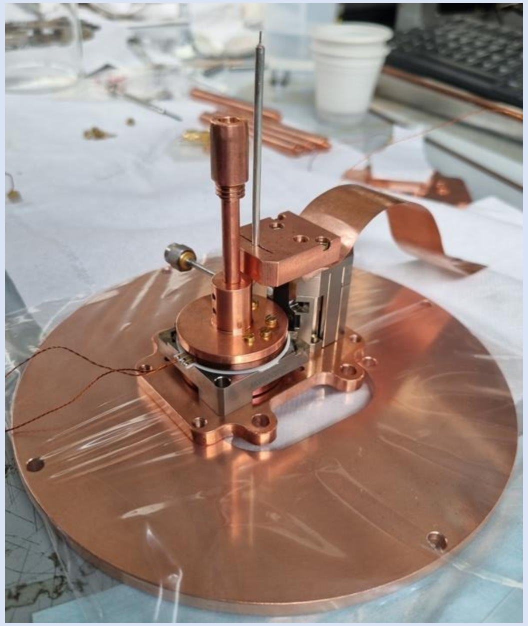


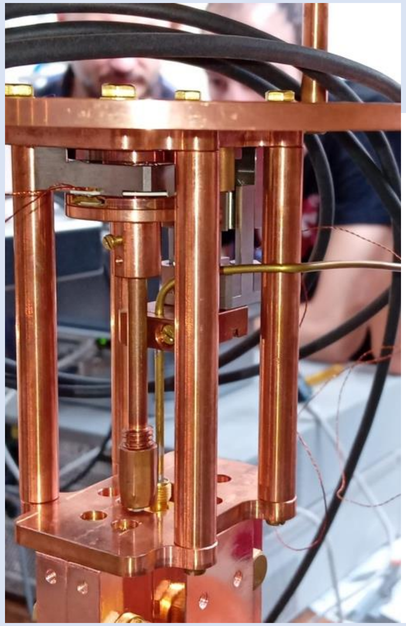
- **OFHC Copper**
- **Radius = 13.5 mm, height = 246 mm**
- **TM010 mode**

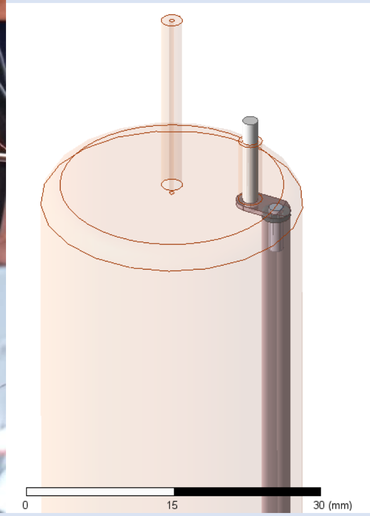
- **Starting frequency ($\alpha = 0°$): 8.83 GHz**
- **Tuning ~ 300 MHz with $\Delta\alpha \sim 80°$**

Rod and Antenna Movements

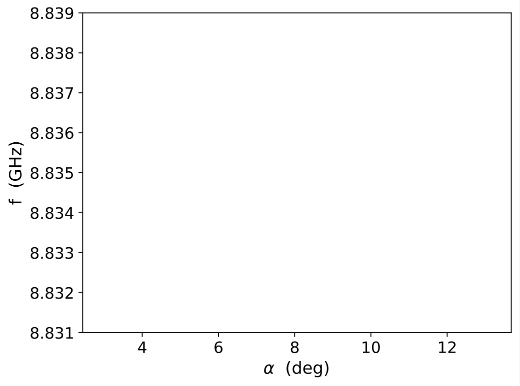
Operated at 20 mK





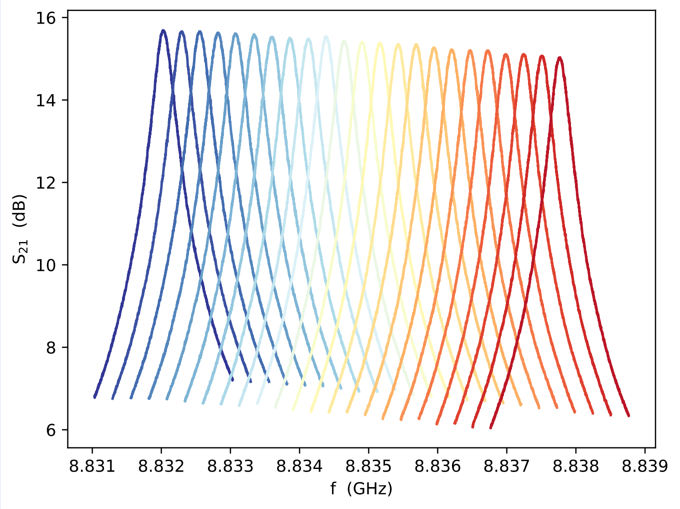


Frequency vs rod position



6 MHz scan

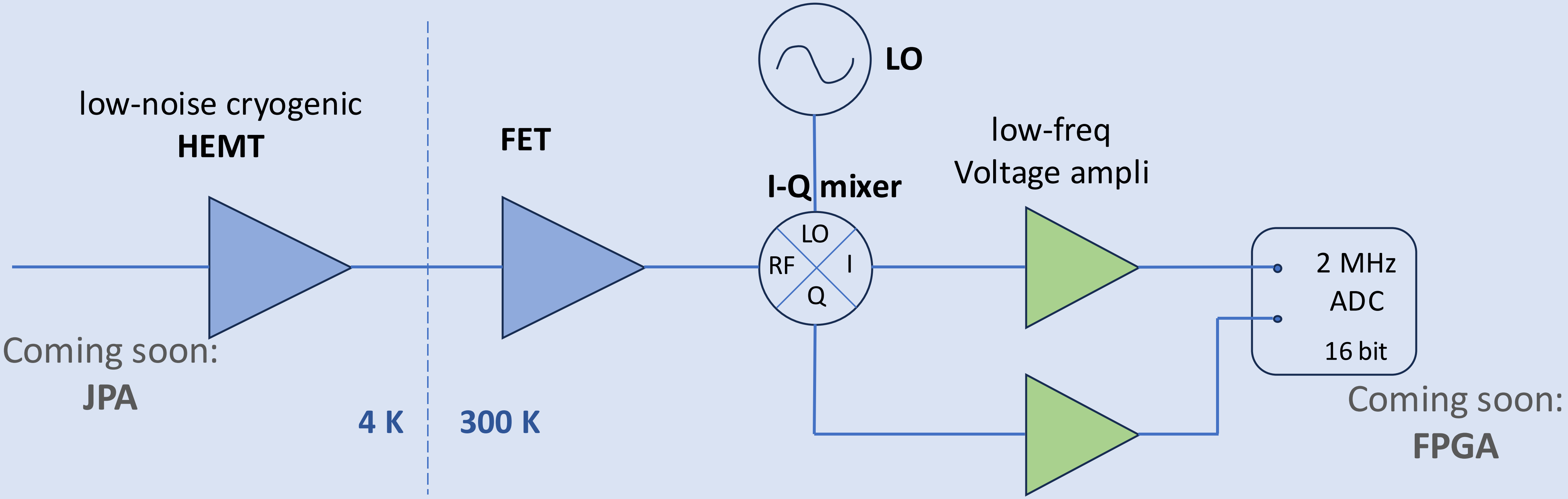
$\Delta m_a = 25\, neV$



Q_0, β and $Gain$ remain stable

- 1 linear motor for Antenna
- 1 rotative motor for Rod

Amplification Chain



$G^{HEMT} \simeq 37\ dB$

$T_n^{HEMT} \simeq 3\ K$

$G^{FET} \simeq 36\ dB$

$T_n^{FET} \simeq 80\ K$

$G^{V} \simeq \times\, 1000$

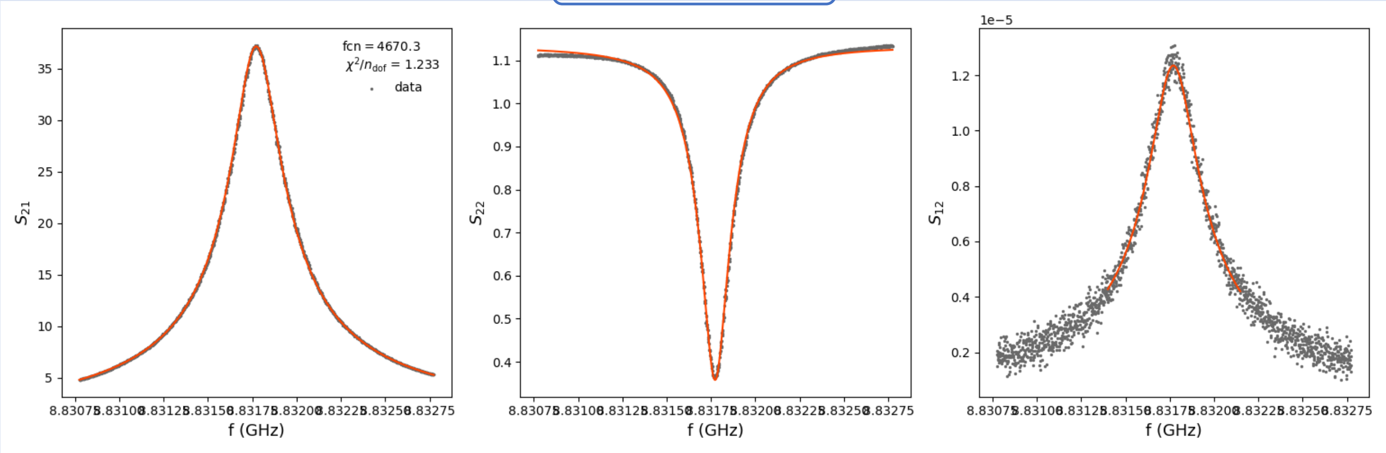
$V_n = 2.3\ nV/\sqrt{Hz}$

Tot eff. Gain = 116 dB

Noise Temp = 4.5 K

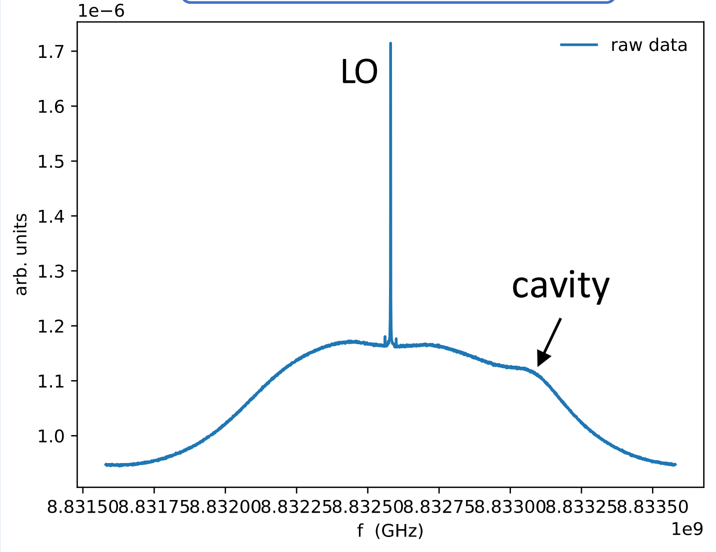
Calibration + spectrum

Fit procedure



Fits by Gianluca Vidali (student)

Raw power spectrum



From fit we extract

$\nu_c, Q_0, \beta, Gain$

for each frequency step

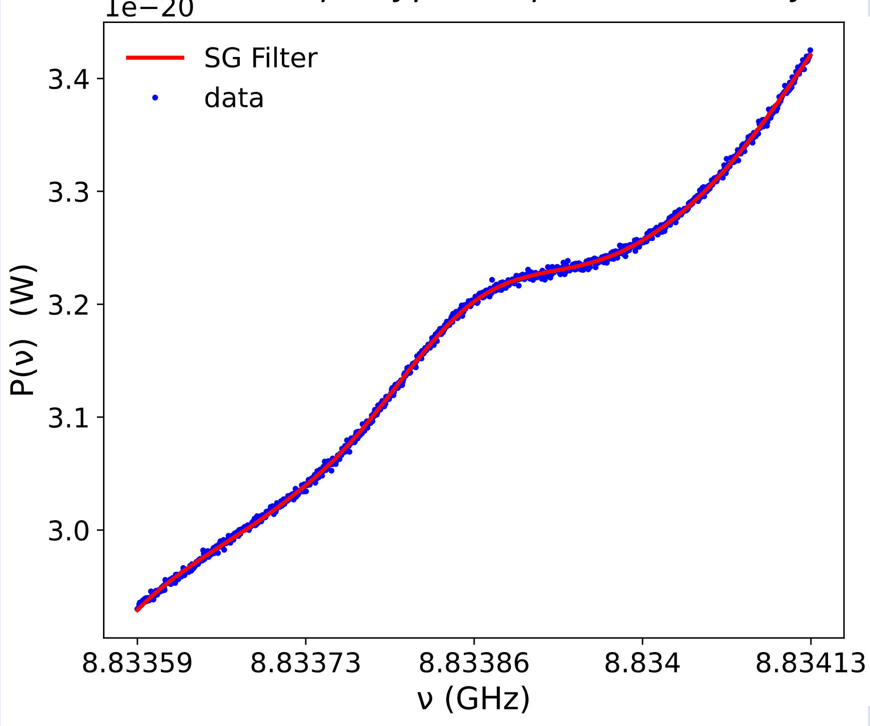
- $V = 0.141\ l$
- $f_{start} = 8.83$ GHz
- $m_a = 36.5\ \mu eV$
- $Q_0 = 50000$
- β = 0.5
- C_{010} = 0.667
- $B_0 = 8$ T (B_{av}=6.5 B_0)
- $\Delta t = 3760\ s$
- $T_{cav} = 40$ mK

From calibrated power spectrum
we extract the noise temp
$T_n \simeq 4.5\ K$

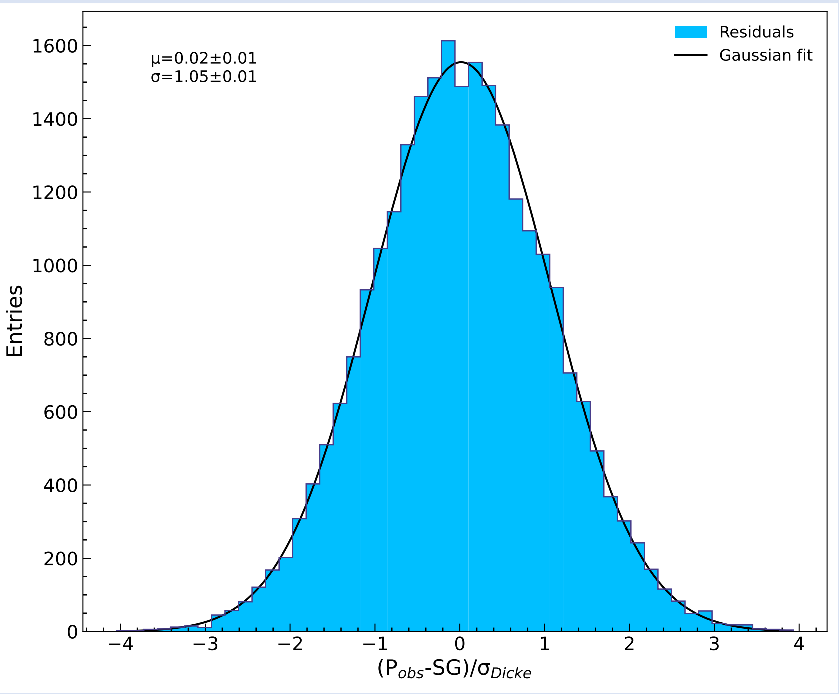
Analysis

Analysis procedure by Alessandro D'Elia

Example of power spectrum with SG fit



Cumulative normalized residuals over all scans



- Fit to power spectra with **Savitzky-Golay** filter to calculate residuals

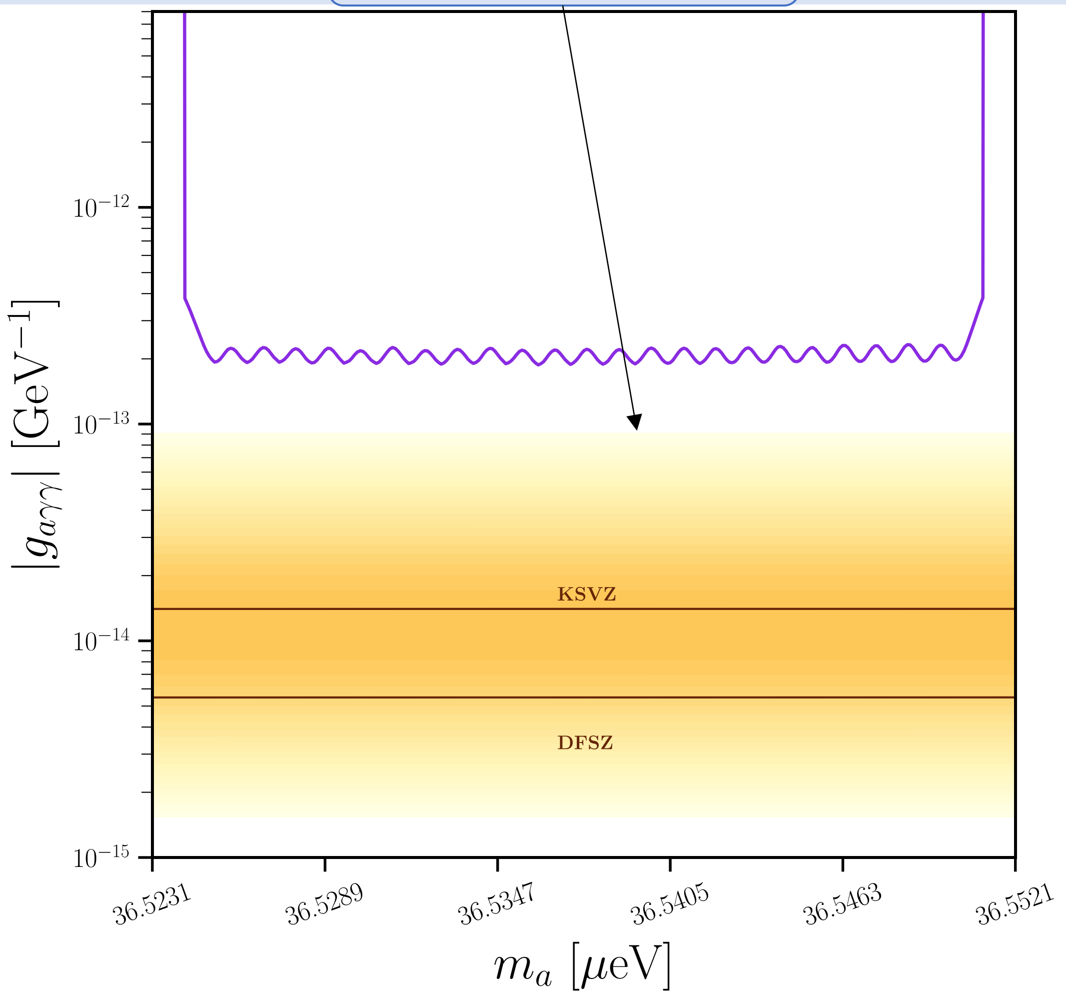
- **Maximum likelihood** over all scans to estimate the best value $\hat{g}_{a\gamma\gamma}$

$$\chi^2 = \sum_{\alpha=1}^{N_{\rm scan}} \sum_{i=1}^{N_{\rm bin}} \left[\frac{R_i^{(\alpha)} - S_i^{(\alpha)}(m_a, g_{a\gamma\gamma}^2)}{\sigma_{\rm Dicke}^{(\alpha)}} \right]^2$$

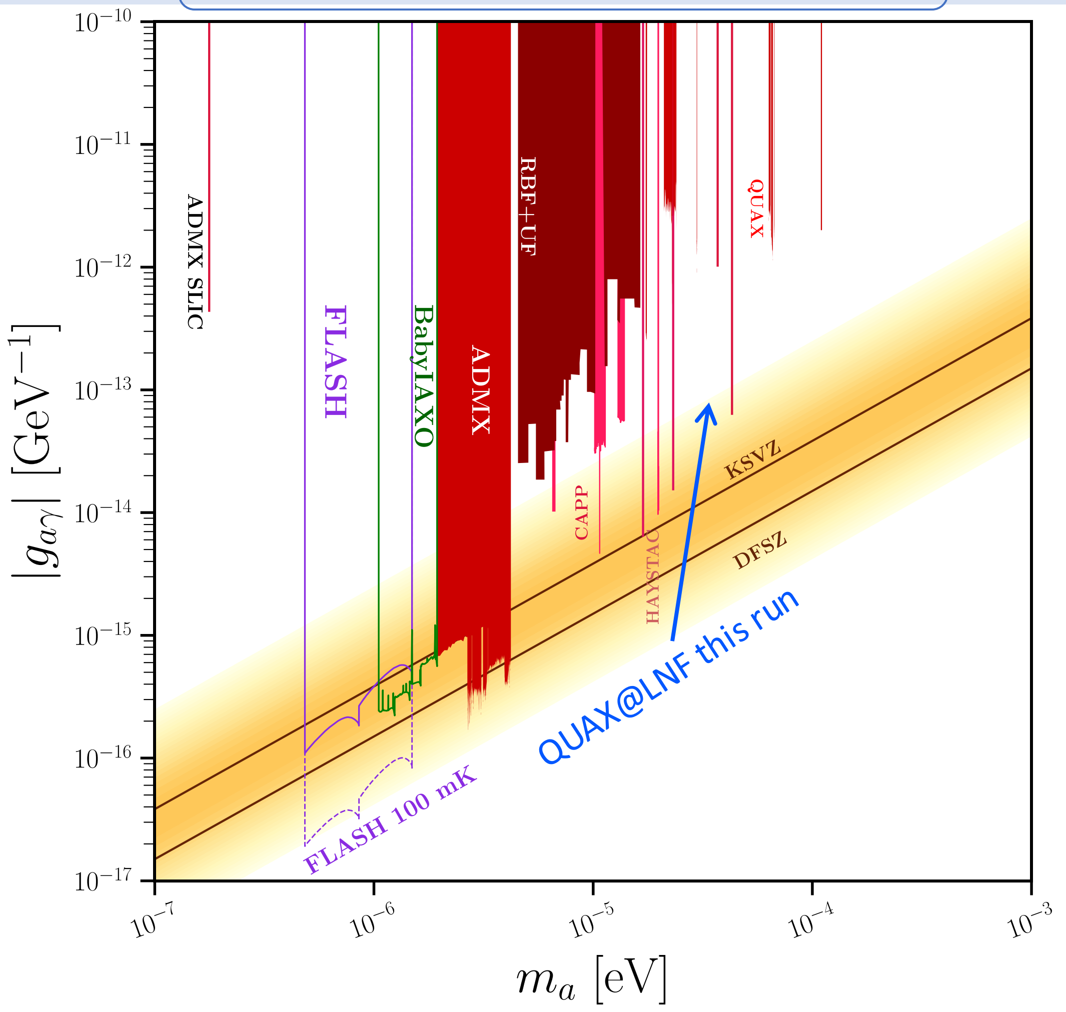
- Calculate the **efficiency** of the SG filter by Monte Carlo simulations with fake axion signal ($\varepsilon = 0.84$)

Final plot - $g_{a\gamma\gamma}$

Touched the QCD line



Avg value $g_{a\gamma\gamma} = 2 \times 10^{-13}\ GeV^{-1}$

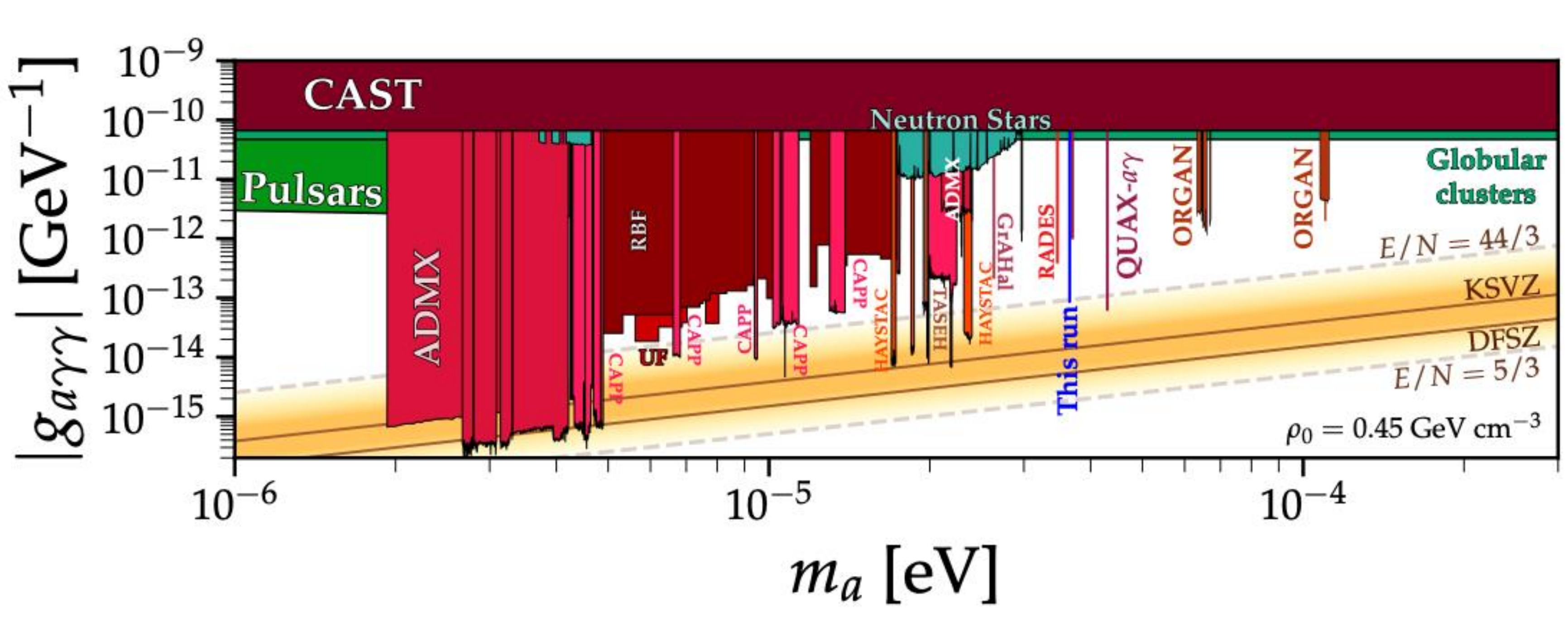


PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Search for axion dark matter with the QUAX–LNF tunable haloscope

A. Rettaroli, D. Alesini, D. Babusci, C. Braggio, G. Carugno, D. D'Agostino, A. D'Elia, D. Di Gioacchino, R. Di Vora, P. Falferi, U. Gambardella, A. Gardikiotis, C. Gatti, C. Ligi, A. Lombardi, G. Maccarrone, A. Ortolan, G. Ruoso, S. Tocci, and G. Vidali (QUAX Collaboration)

Phys. Rev. D **110**, 022008 – Published 23 July 2024

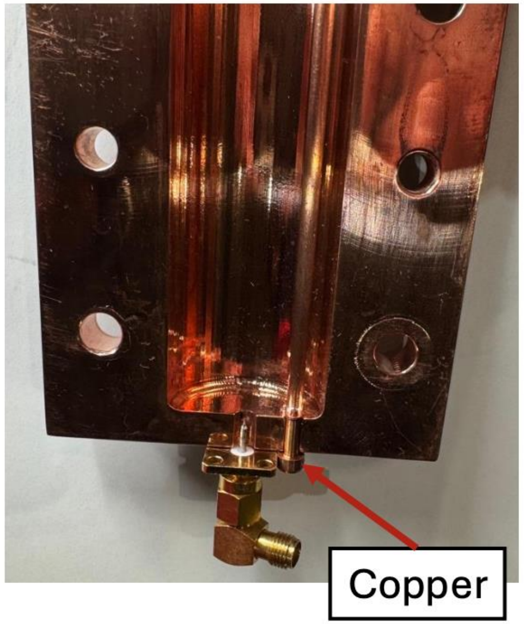


LNF Next Steps

- Finish the optimization of the tuning rod mechanics and complete the relevant tests for Cavity control
- Assembly of the haloscope and configuration/calibrations of the DRY-DU for the acquisition with TWPA improvements
- New Run planned for September with scanning larger then 50 MHz

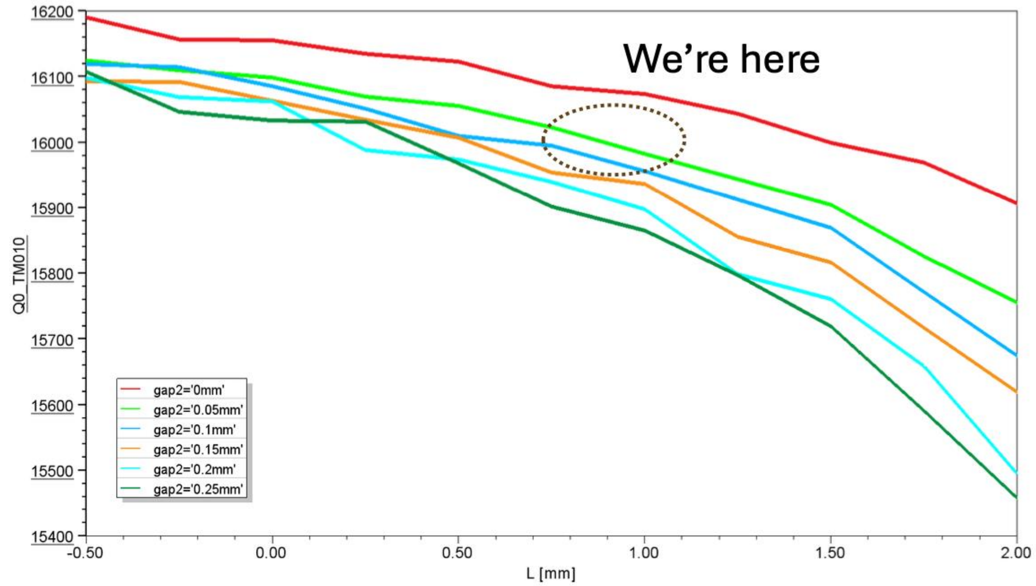
Mechanical Improvements to Cavity Tuning System

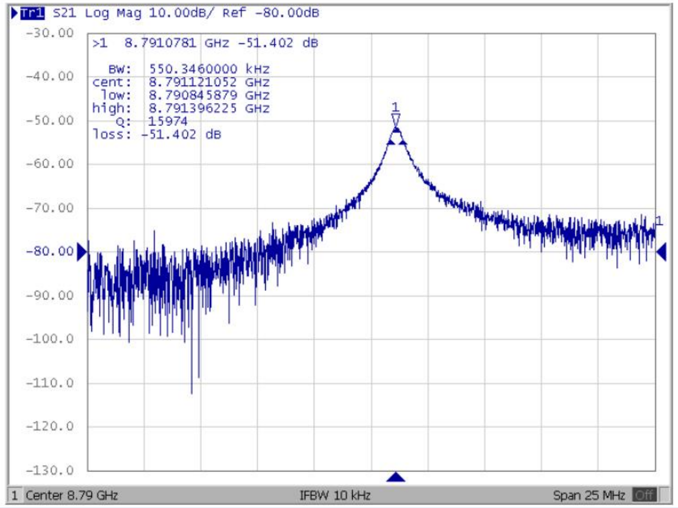
- Optimise the positioning of the rod inside the cavity
  - Reduce the space between the rod and the cavity end caps
  - Reduce the space between the rod and the cavity sidewall
- Improve the thermal coupling of the rod
- General improvements to the manufacturing process of the rod and its supports

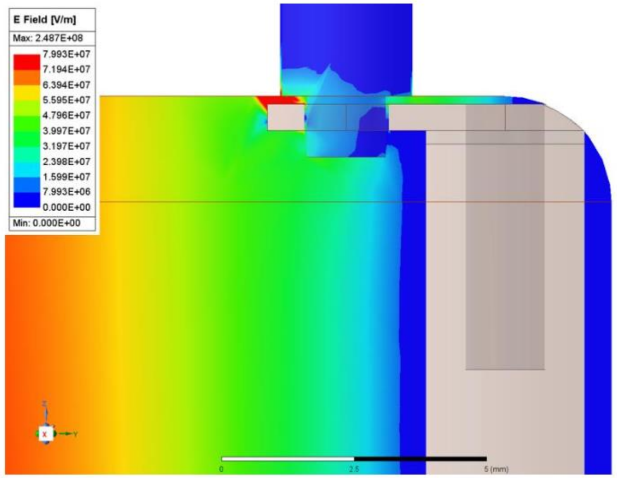


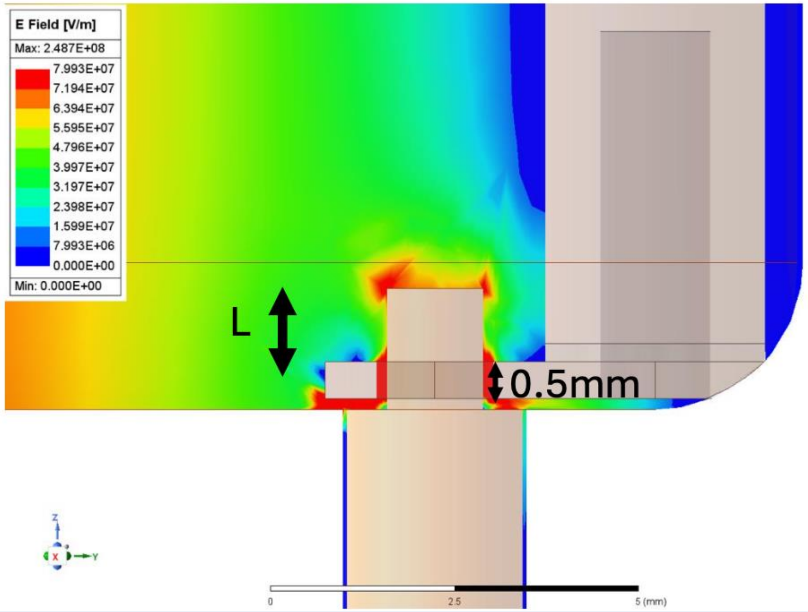
Mechanical improvements have been made in the LNF workshop.
To date, everything has been assembled. The first tests have been carried out at room temperature.

EM Simulations and First Tests Results







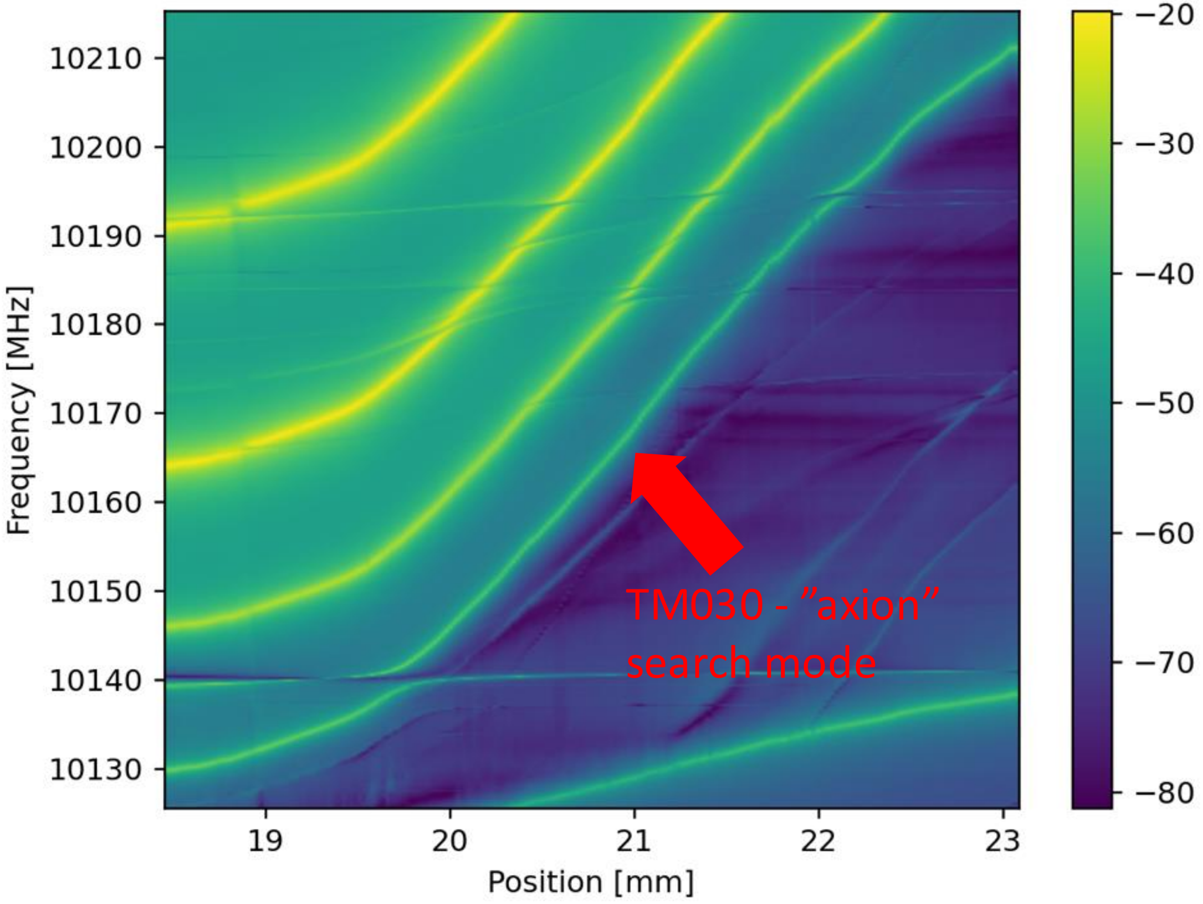


LNL Haloscope – RUN 2025 A

Objectives:

- New mechanics for tuning
- Extend search window
- Improvements on dilution unit

Cavity transmission spectra
Tuning vs motor position



Run started on April 3rd

Cavità QUAX

	Samek2G	SamekF2	SamekFG	Samek	Samek	LamedTC	LamedT A	LamedT E	LamedShort2 E	LamedShort2 A	LamedShort A	LamedShort E	LamedNew E	LamedNew E	LamedNew A	Lamed A	Lamed E	Gimel R	Gimel A	Gimel E	Aleph E	Aleph A	Aleph R
Copper tube diameter (mm)	60.5			60.5?		60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	57.2	57.2	57.2
Length from endcaps (mm)	238			238??		413.4	413.4	413.4	413.4	413.4	413.4	413.4	449	413.4	413.4	412.4	412.4	411.6	411.6	411.6	423	423	423
End caps type	Groove+groove, 1.2 mm teflon spacer	Flat+Groove **No Teflon Top**	Flat+Groove	Groove+groove	Groove+groove	Flat w/groove 5.3 mm	Flat w/ groove 5.3mm	Flat w/ groove 5.3mm	Flat w/ groove 5.3mm	Flat w/ groove 5.3mm	Flat w/ groove 4.8mm	Flat w/groove	FLAT	reentrant w/ groove	reentrant w/ groove	w/ groove	w/ groove	w/ groove	w/ groove	w/ groove	Flat	Flat	Flat
End caps gap	no gap	No gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	no gap	gap	gap	gap
Tuning		No	no	no	no	Yes	Yes	Yes	no	no	no	no	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES
Tuning type	No tuning, **electropolished copper**, endcaps for upper tuning					Movable side,w/spheres,inverted V, Copper RF contact	Movable side, w/spheres	Movable side, w/spheres													Side wall	Side wall	Side wall
Main antenna	Fixed	Fixed	Fixed	Fixed	Fixed	Movable	Movable	Movable	Movable	Movable	Movable	Movable	Movable	Movable	Movable	Fixed	Fixed	Movable	Movable	Movable	Movable	Movable	Movable
Sapphire type	Lituanian	Lituanian	Lituanian	Lituanian	NO	Armenian	Armenian	NO	NO	Armenian	Armenian	NO	NO	NO	Armenian	Armenian	NO	Russian	Armenian	NO	NO	Armenian	Russian
Measurements at 300 K	**Single cylinder**	**Single cylinder**	**Single cylinder**	**Single cylinder**	**Single cylinder**	**5 mm open**	**1 mm open**	**at no tune**								Spurio							
TM030 frequency (GHz)	10.1505	10.1618	10.161	10.162	??	10.149	10.1247	13.621	13.6756/spur?	10.162/Spur?	10.164/spur?	13.635	13.646	13.632	10.164	10.169/10.174	13.633	10.692	10.167	13.626	?	10.75	10.96
TM030 Q0	34000	31500	22000	35000		42600	37000	32700	39000	98500	71000	35000	42300	36000	54000	26500/40000	25000	85000	40000	42000		35000	50000
Maximum beta top	fixed 0.1	low beta					>1						>1	0.2	0.6	fixed	fixed	>1	1.2			<1	1 (low Q0)
Maximum beta bottom	fixed 0.05	negligible					fixed low		fixed low		fixed 0.0017			fixed low	fixed low				>1				>1 (High Q0)
Tuning range (MHz)						60 MHz	>85 MHz																55
TM020 frequency (GHz)	7.7709	7.779	7.778	7.779			7.8191			7.8485	7.846	8708	8.693		7.847	7.847			7.8406				9.032
TM020 Q0	33000	44000	41200	31700			45000			48500	46000	37000	32200		44000	45000			46000				16000
TM010 frequency (GHz)		1.9296	1.929	1.917	3.778	1.939	1.93868	3.7818	3.7859	1.94598	1.9457	3.786	3.789	3.784	1.945	1.945	3.785		1.944		3.997		
TM010 Q0		18700	18000	4100	7500	21300	21000	18500	22300	22200	22400	22200	22800	8000	18500	18500	10500		19500		3700		
Measurements at 4 K	**Chiusa**	**Chiusa**	**Chiusa**			**chiusa**																	
TM030 frequency (GHz)	10.202429	10.2116/10.2172	10.216	10.2153		10.2145			13.704 (?)	10.22374	10.2233				10.2213			10.732	10.215			10.8	11.028
TM030 Q0	106500	72000/230000	31000 (??)	67500		81000			86000	100000	51000				74000			170000	90000			100000	200000
Maximum beta top	fixed 0.33	.069/.265		0.037						1.4	stuck				.2 (stuck)			>1	?			0.7	1 (Low Q0)
Tuning range (MHz)																							60
TM020 frequency (GHz)	7.8191	7.8251	7.825	7.858		7.8851			8.7664 (?)	7.8922	7.89196				7.892			?	7.898			8.11	
TM020 Q0	76000	131300	72000	50000		175000			97000	140000	136000				145000			?	110000			58000	
TM010 frequency (GHz)	1.9345	1.9513	1.951	1.933		1.966			3.7994	1.9679	1.9678				1.9675			1.938	1.965				
TM010 Q0	6500	60900	42700	8700		12300			61000	72000	63000				56000			1200	10700				

RUN 2024

LNL Haloscope – High Frequency Tunable Cavities

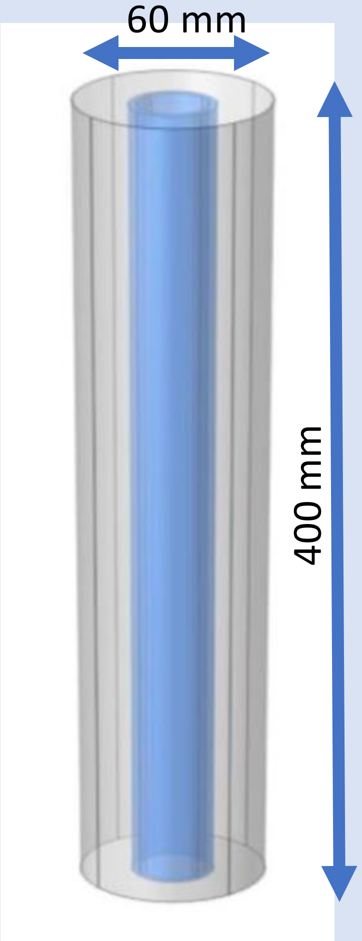
Single crystal dielectric - copper cavity

Gap on top plate for safety

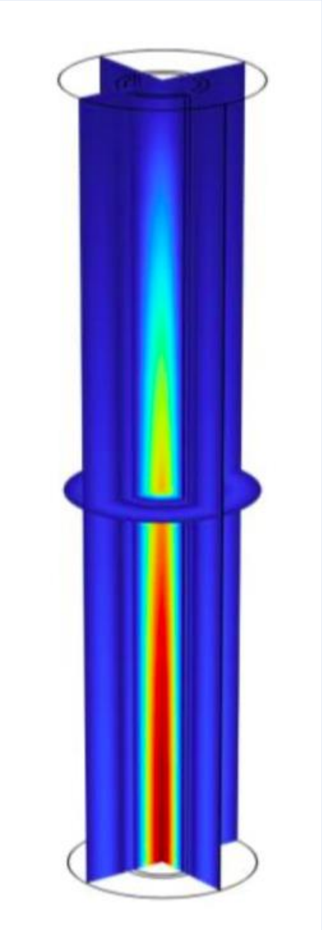
Close with tuning mechanism

Open with sapphire view

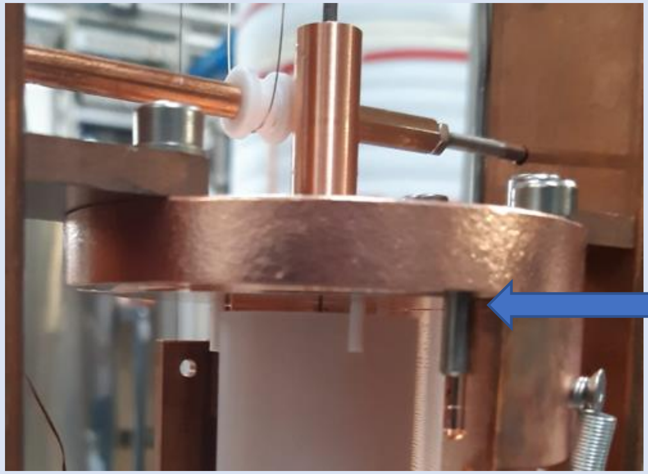
General layout



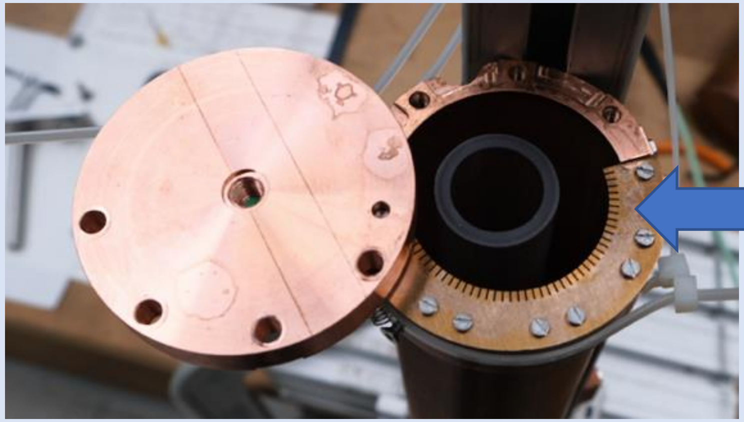
Simulated Map of E field TM030 mode



Upper end cap details



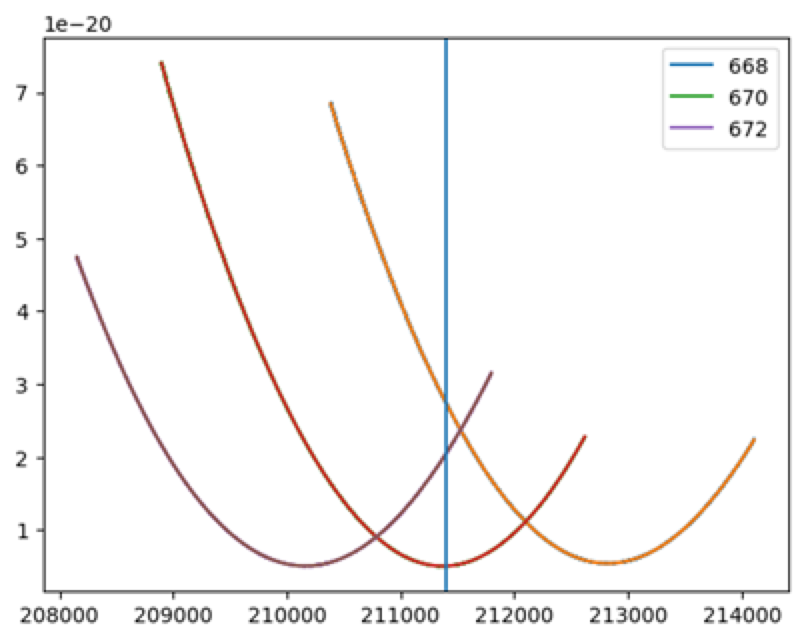
GAP



Rf sliding contact

QUAX data analysis (preliminary Monte Carlo)

Overlapping spectra w. different axion sensitivity



Creation of Confidence Belt and ROC for every detector