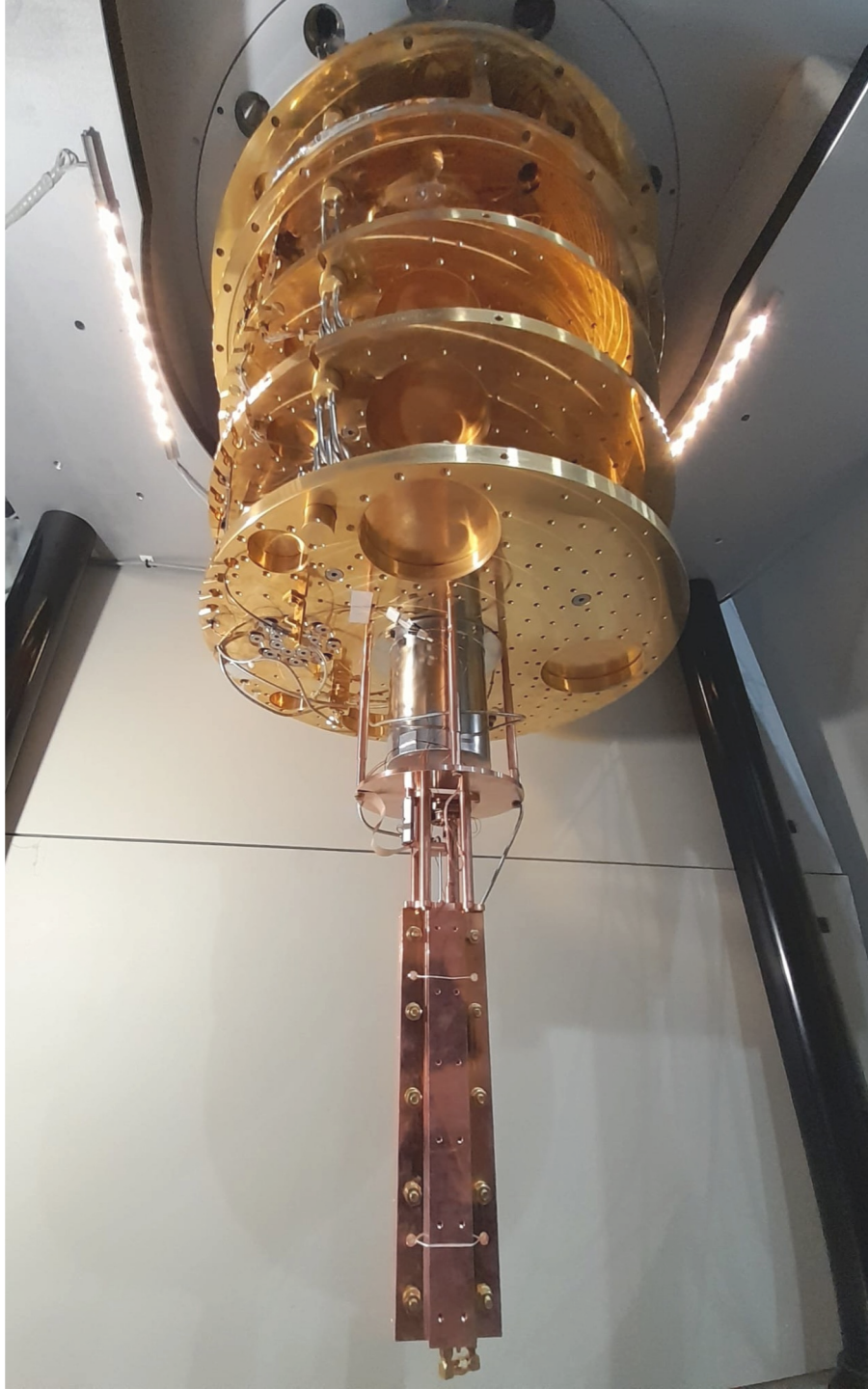
Recent results of QUAX @ LNF

Alessio Rettaroli
alessio.rettaroli@lnf.infn.it

COST Action COSMIC WISPers (CA21106) – Working Group Meeting
1 - 2 Feb 2024 – DESY, Hamburg

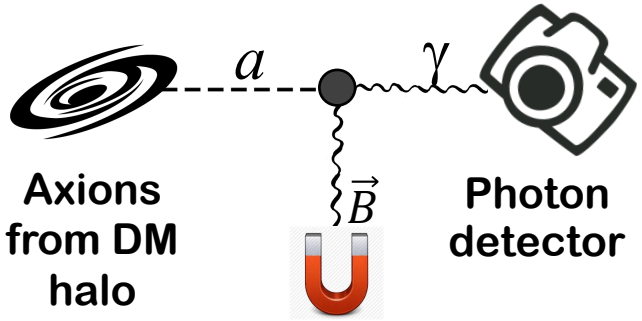


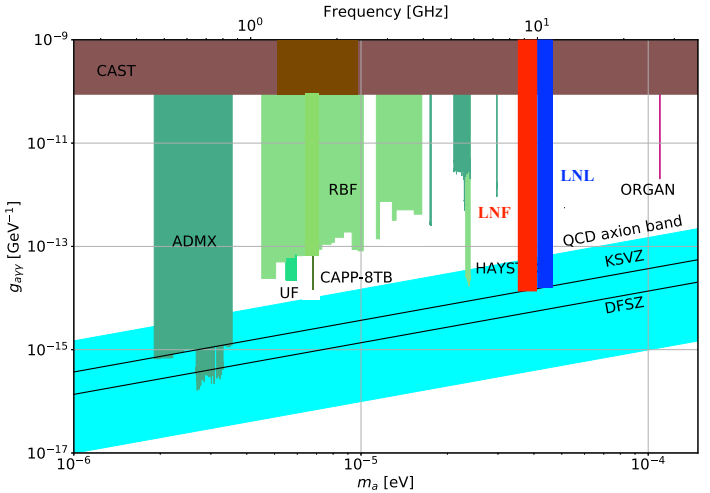
The QUAX experiment is a light DM hunt experiment

- **Classical haloscope (just like ADMX, HAYSTAC etc)**
- **Searching for QCD axions**
- **Between $8 - 10$ GHz**

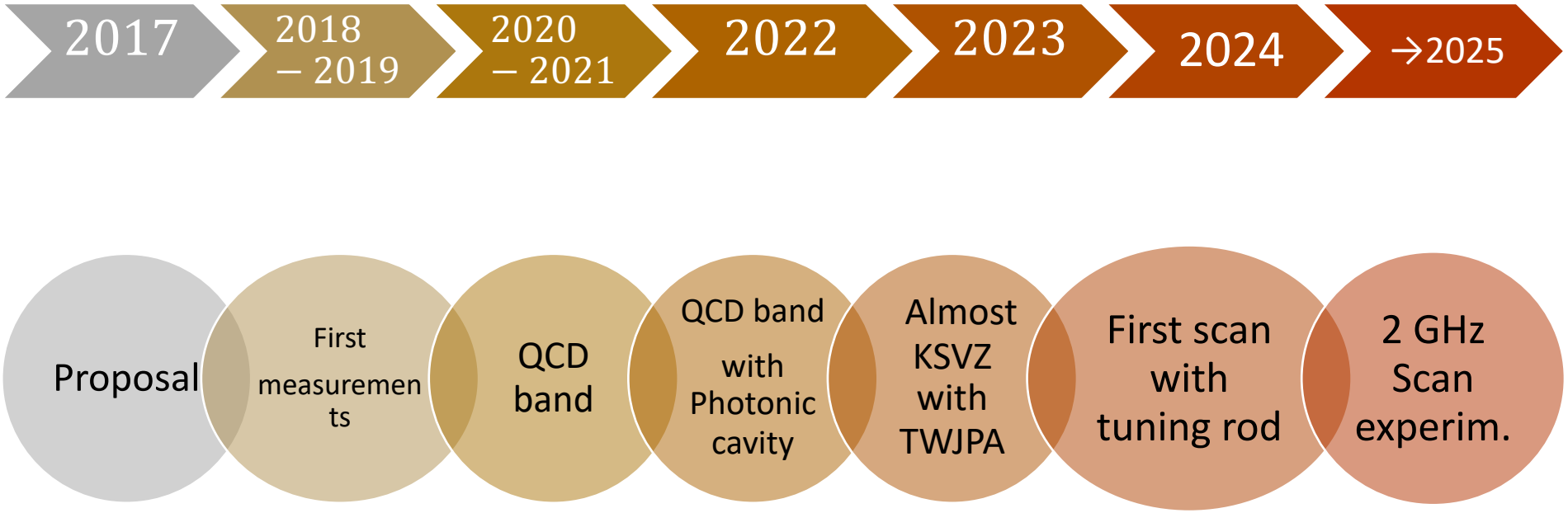
LNL (Legnaro)

LNF (Frascati)

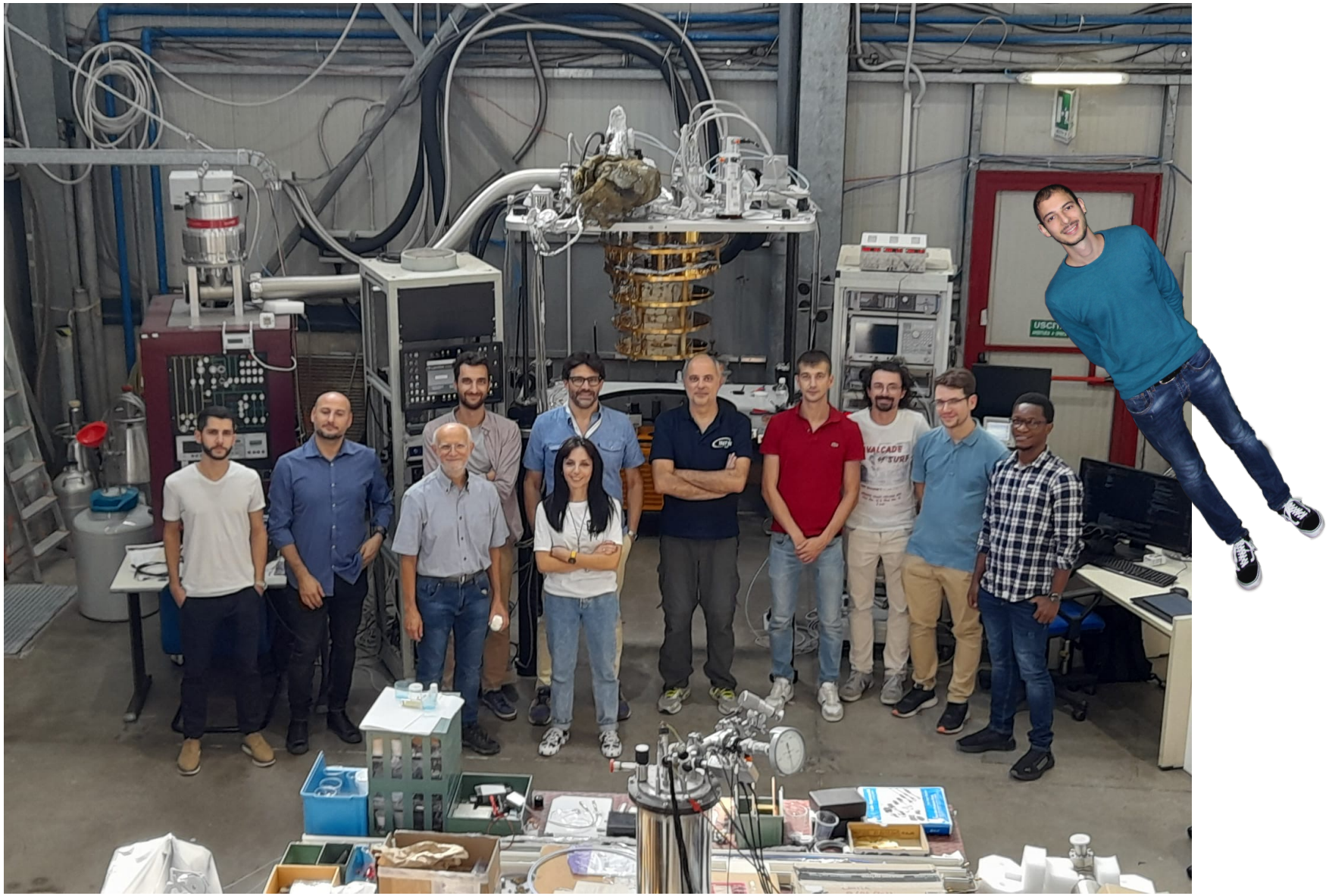




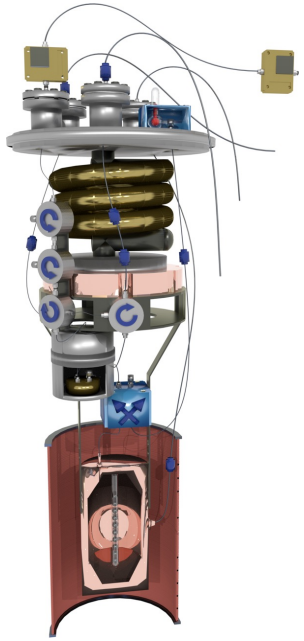
QUAX timeline



Group and lab are enlarging



Haloscope ingredients



Low noise receiver

Ongoing

SC magnet

Recent Achievements

Microwave resonant cavity

Tunable frequency

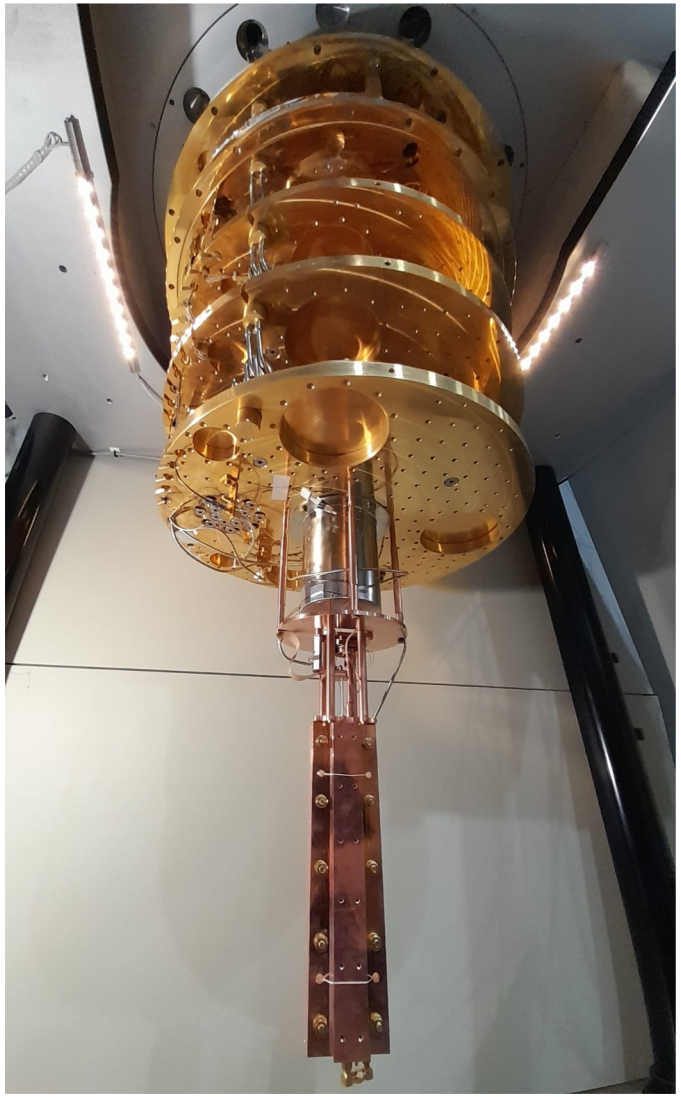
Recent Achievements

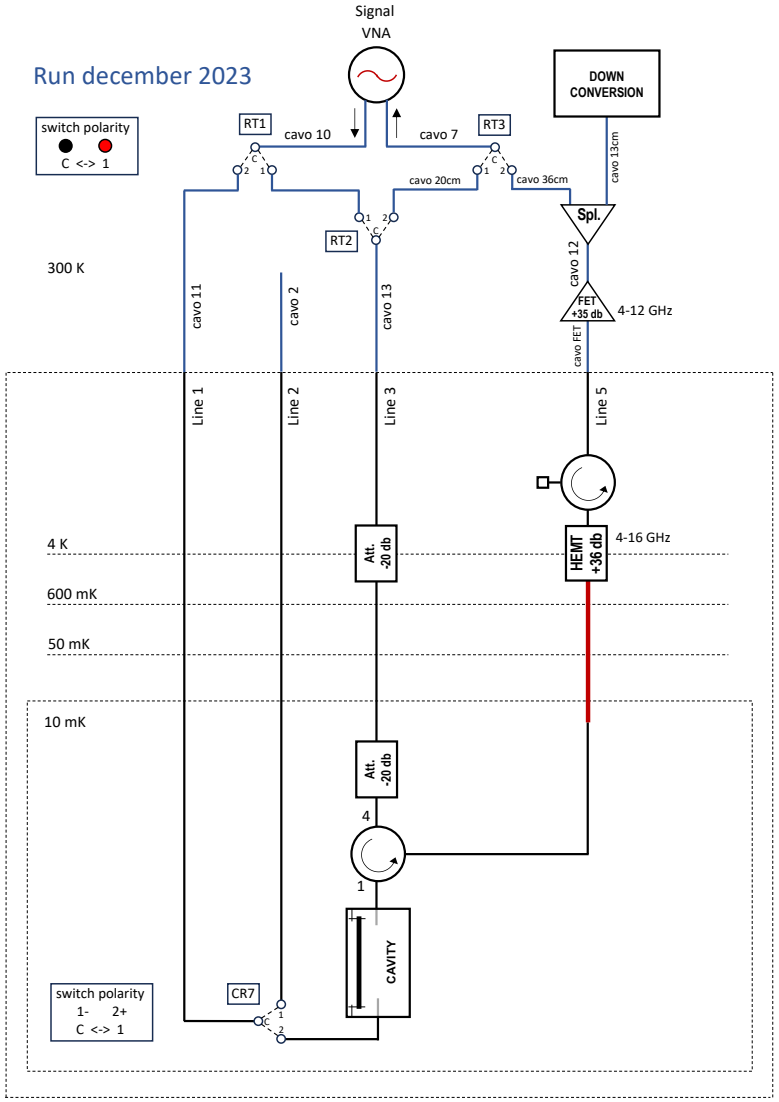
Dilution refrigerator

Already purchased

QUAX@LNF first axion search with tuning rod mechanism

Dilution refrigerator





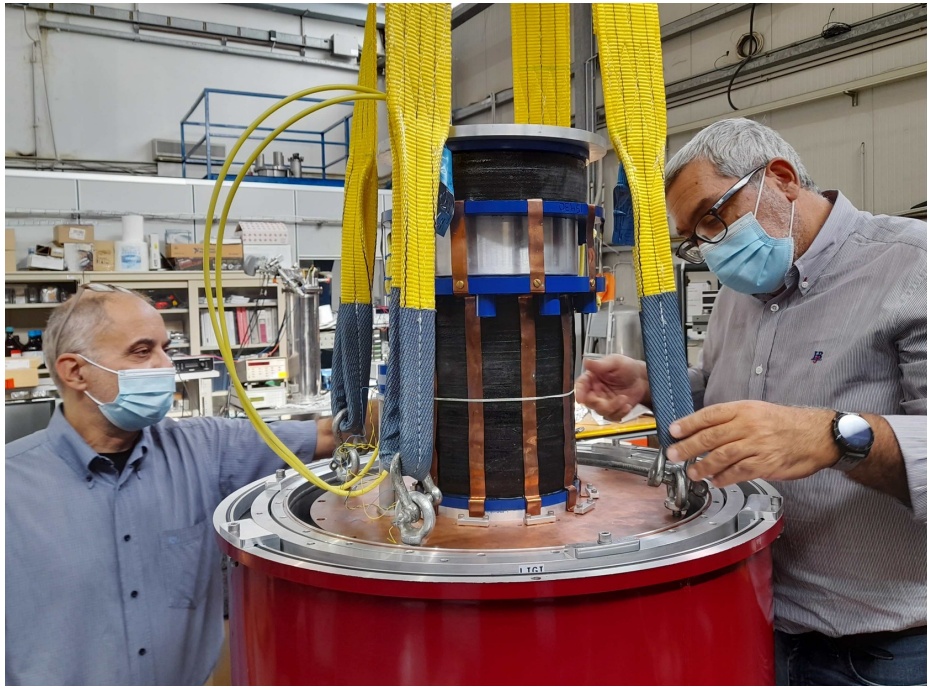
Leiden Cryogenics

Cooling power
$450\ \mu W\ @\ 100\ mK$

Temp. of 10 mK plate
$T_{base} \simeq 20\ mK$

Cavity temperature
$T_{cav} \simeq 30\ mK$

9 T magnet

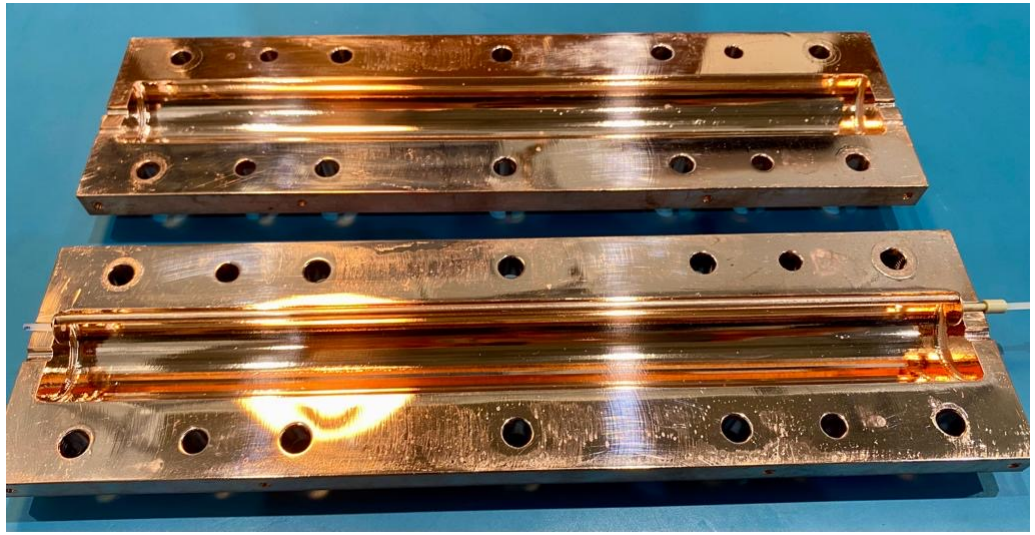


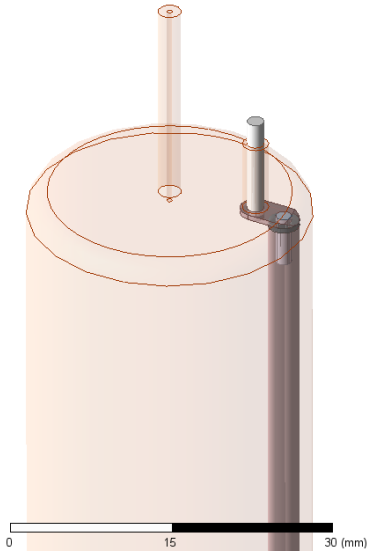
Anchored to 4 K stage

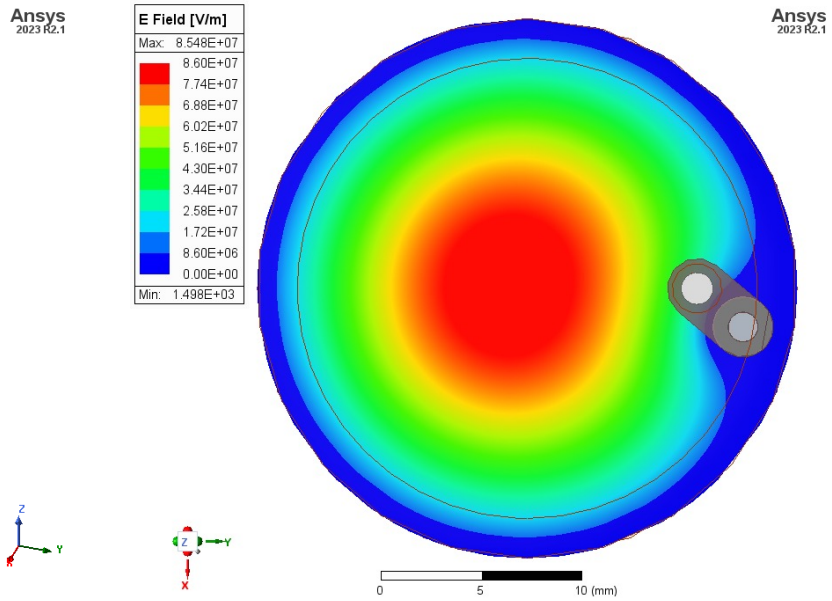
- Reached 9 T
- Took data at one freq with 9 T
- Quench
- Ramp to 8 T ok
- Took data with 8 T stably for 2 weeks

Microwave cavity + tuning

HFSS simulations by Simone Tocci



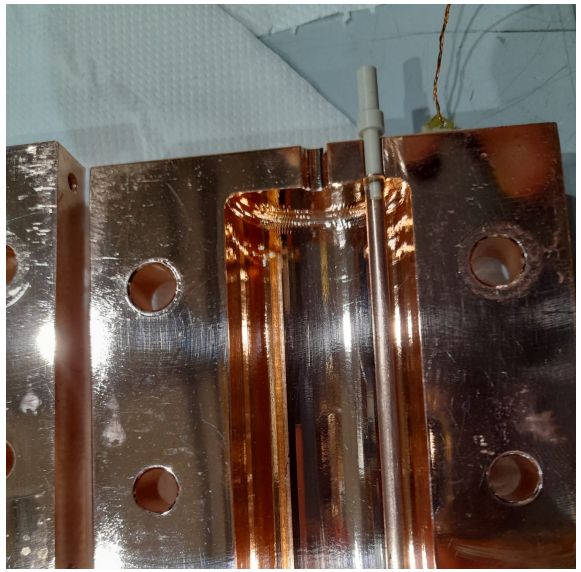


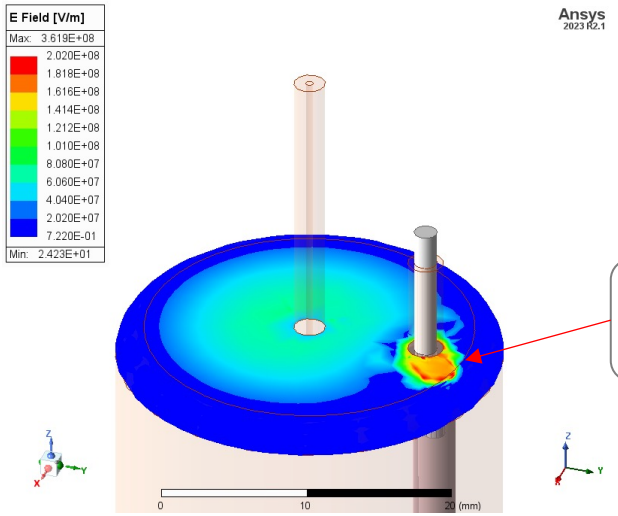


- **OFHC Copper**
- **Radius = 13.5 mm, height = 246 mm**
- **TM010 mode**

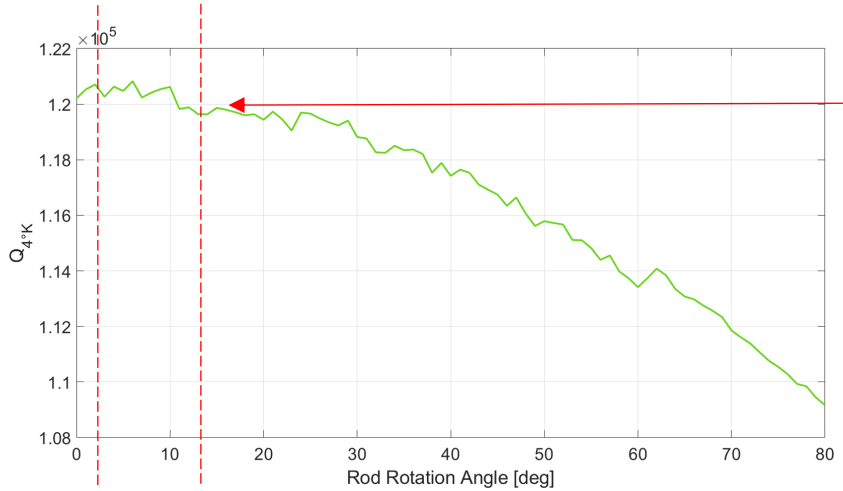
- **Starting frequency ($\alpha = 0°$): 8.83 GHz**
- **Tuning ~ 300 MHz with $\Delta\alpha \sim 80°$**

Microwave cavity + tuning





Trapped field between metallic disk and cavity endcap



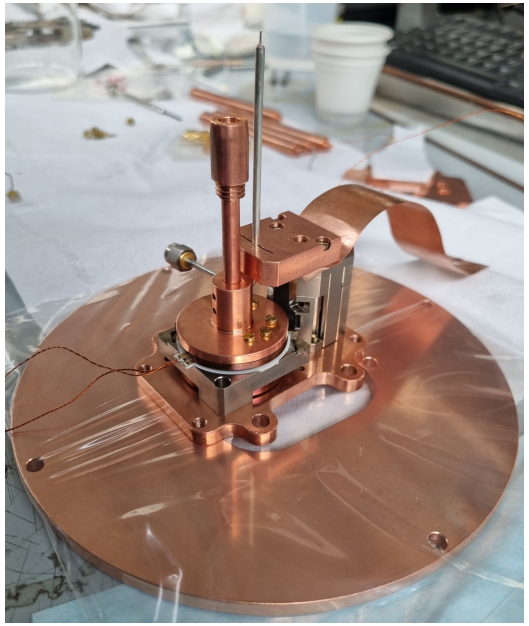
Expected $Q_0 \simeq 10^5$ from simulations, and measured w/out rod

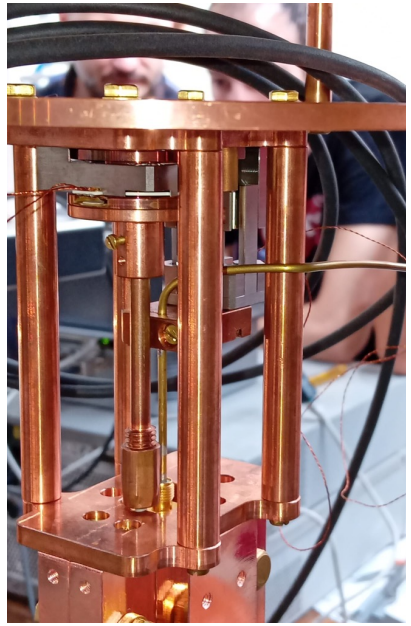
Measured $Q_0 \simeq 5{\times}10^4$ w/ rod

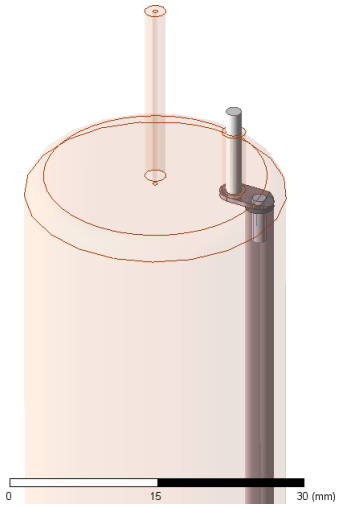
This is likely due to losses caused by the rod configuration and PEEK

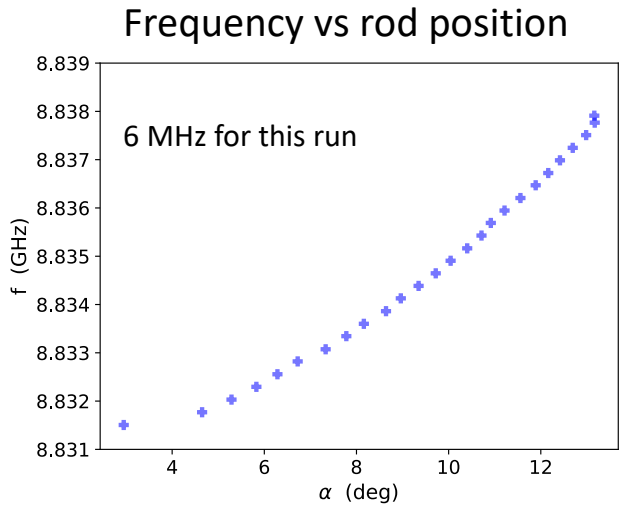
Rod and antenna movimentations

attocube
WITTENSTEIN Group



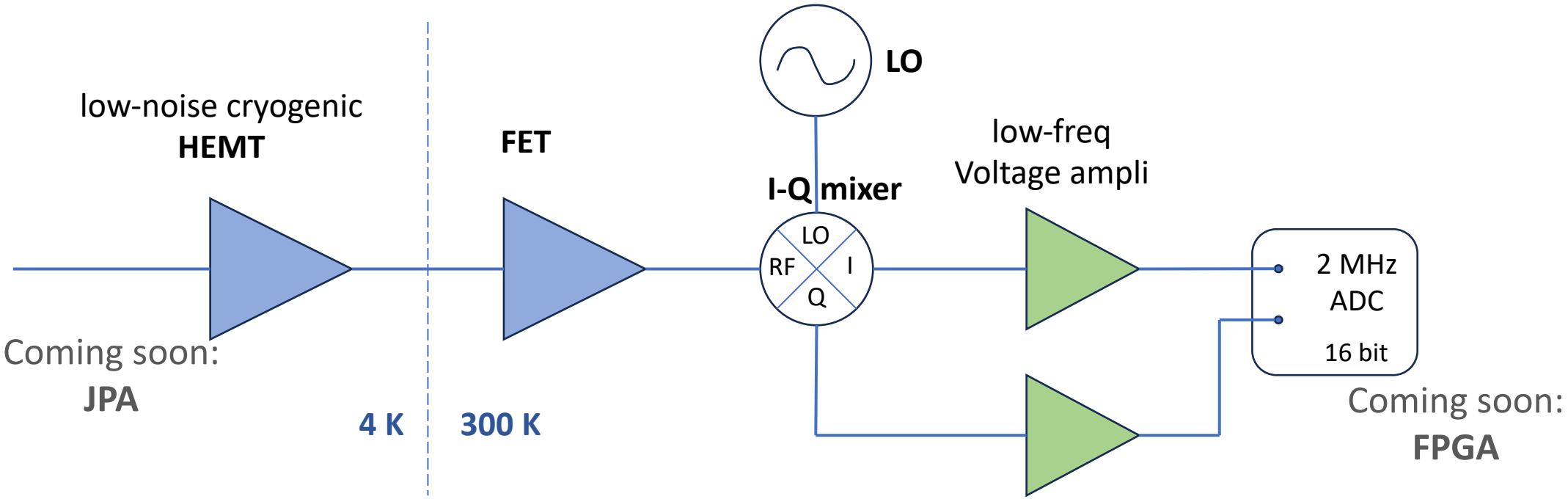






- **1 linear motor for Antenna**
- **1 rotative motor for Rod**

Amplification chain



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

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

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

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

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

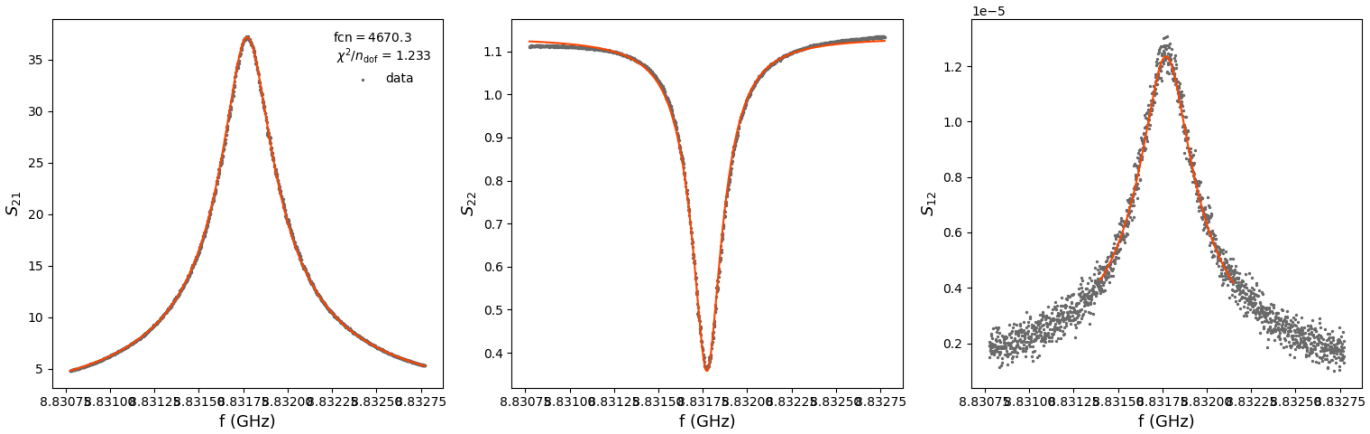
$V_n = 2.3\ nV/\sqrt{Hz}$

Tot eff. Gain = 116 dB

Noise Temp = 4.5 K

Calibration + spectrum

Fit procedure

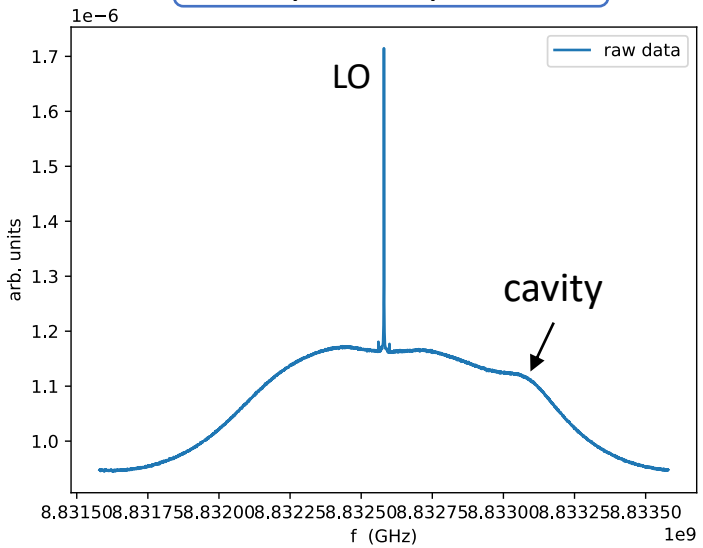


Fits by Gianluca Vidali (student)

From fit we extract
$\nu_c, Q_0, \beta, Gain$

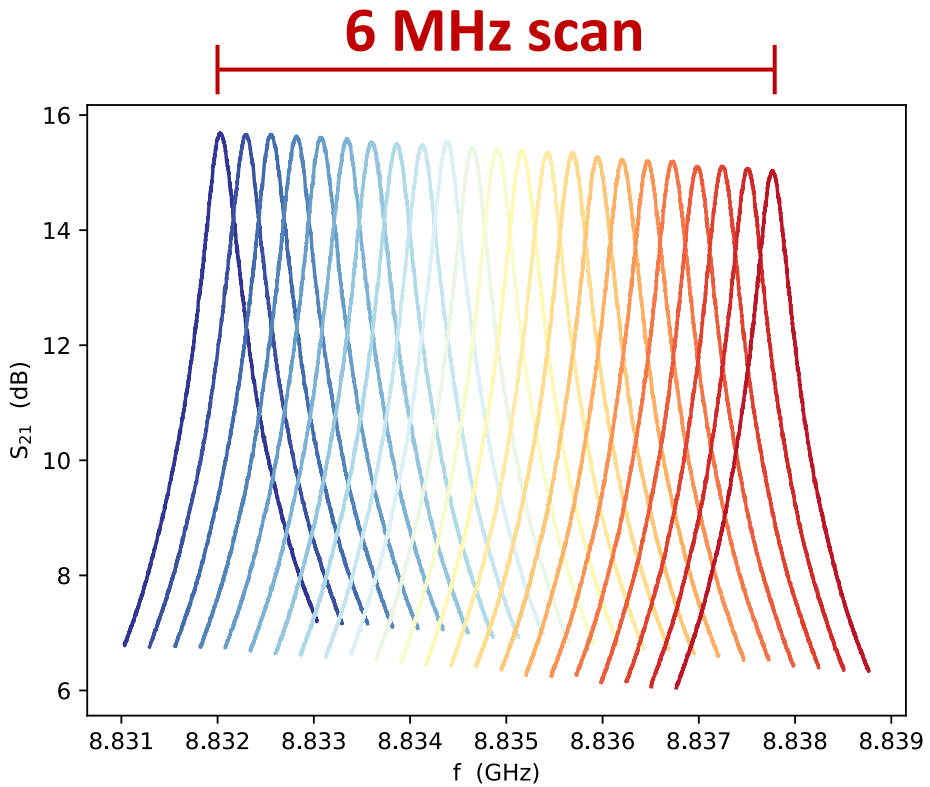
- $V = 0.141\ l$
- $f_{start} = 8.83$ GHz
- $m_a = 36.5\ \mu eV$
- $Q_0 = 50000$
- β = 0.5
- C_{010} = 0.667
- $B_0 = 8$ T (B_{av}=6.5 B_0)
- $\Delta t = 3760\ s$
- $T_{cav} = 40$ mK

Raw power spectrum



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

6 MHz tuning



Performed the same procedure on each run

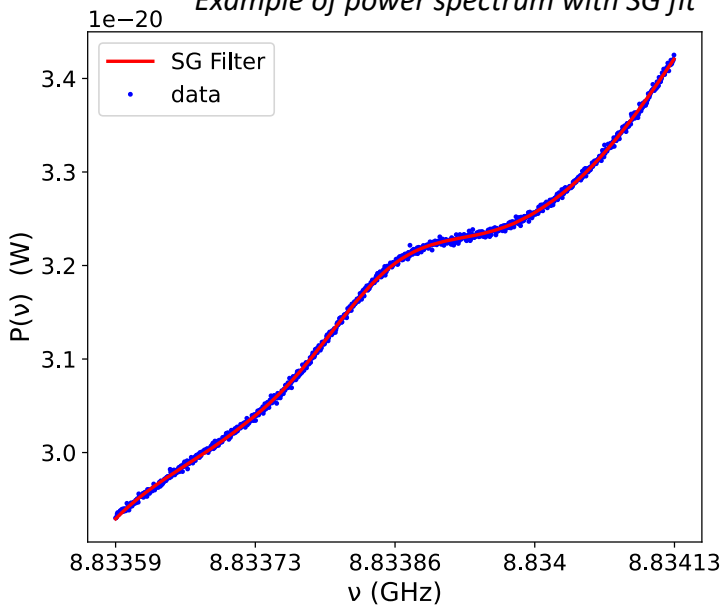
- $\boldsymbol{Q_0}$, $\boldsymbol{\beta}$ and $\boldsymbol{Gain}$ remain stable
- $\Delta m_a = \boldsymbol{25\ neV}$
- Effective scan rate in this test:

220 MHz/year

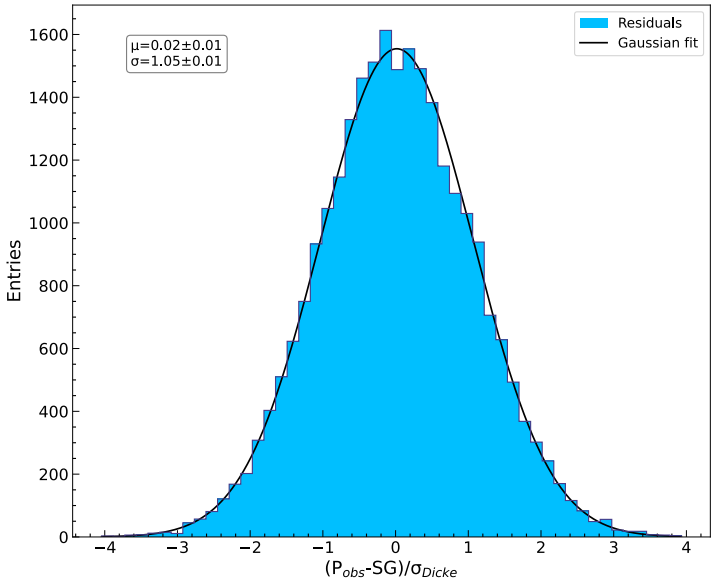
Analysis

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 $\hat{g}_{a\gamma\gamma}$

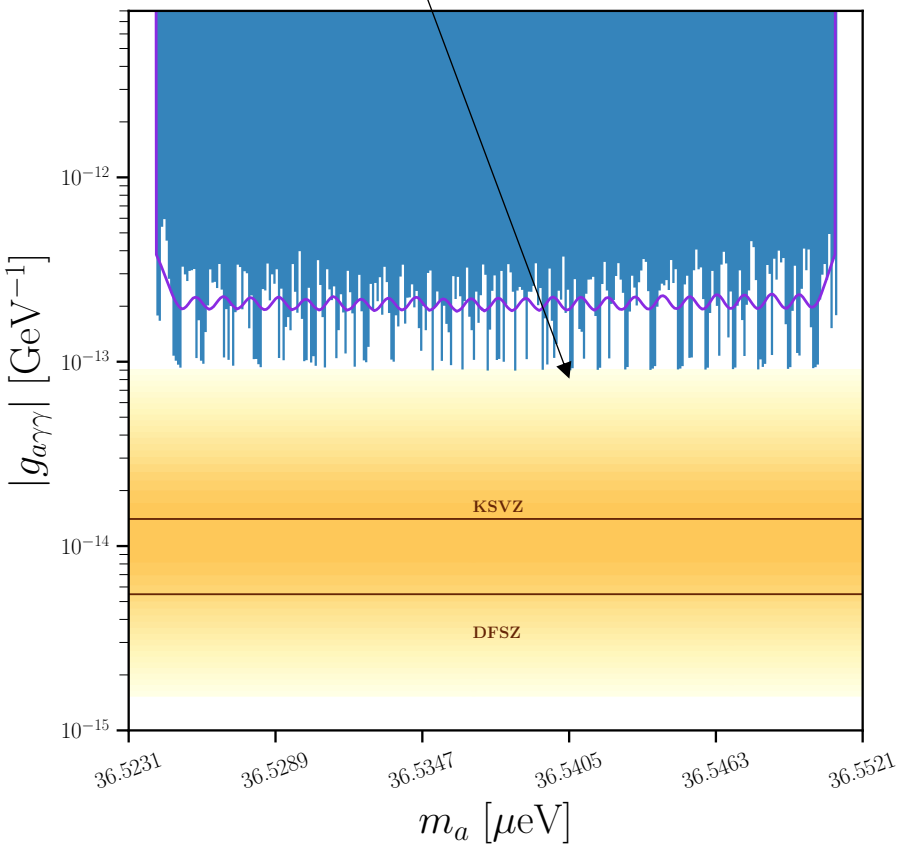
$$\chi^2 = \sum_{\alpha=1}^{N_{\text{scan}}} \sum_{i=1}^{N_{\text{bin}}} \left[\frac{R_i^{(\alpha)} - S_i^{(\alpha)}(m_a, g_{a\gamma\gamma}^2)}{\sigma_{\text{Dicke}}^{(\alpha)}} \right]^2$$

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

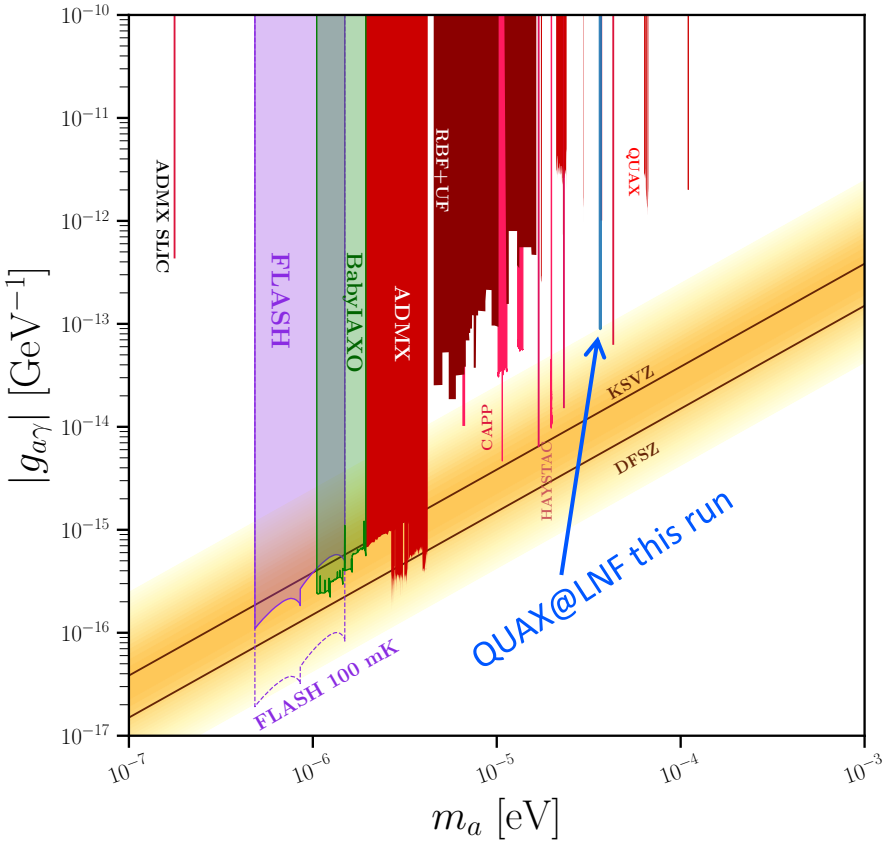
Final plot - $g_{a\gamma\gamma}$

PRELIMINARY

Touched the QCD line

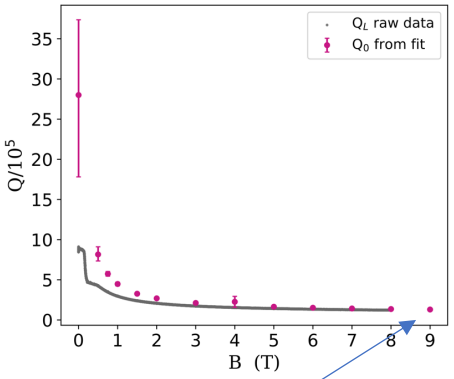


Avg value $g_{a\gamma\gamma} = 2\times10^{-13}\ GeV^{-1}$



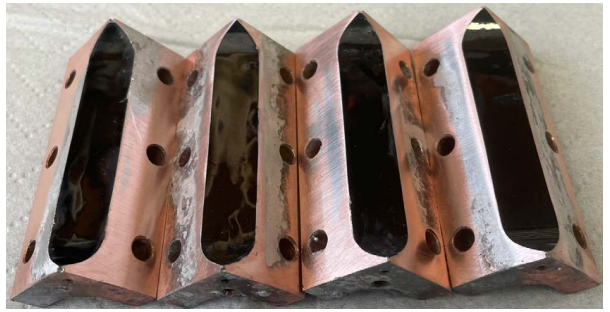
Bonus: superconducting cavities

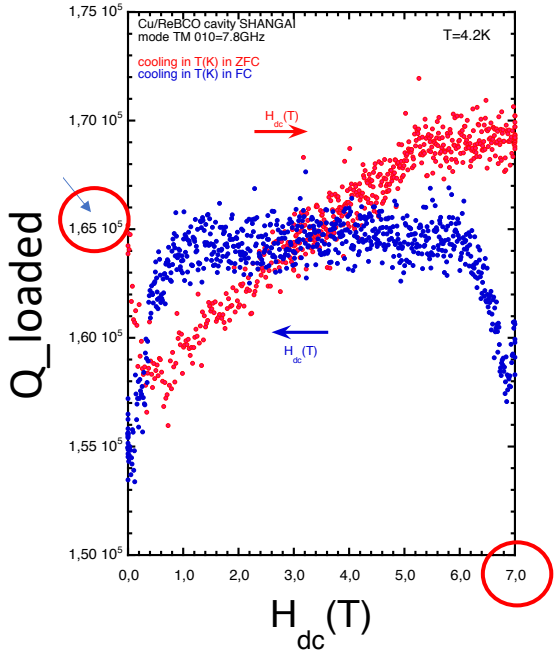
Nb_3Sn cavity by FNAL



$Q_0 \simeq 1.3\times10^5$ at 9T

ReBCO-tapes cavity





Next

- Qubit photon detector*
- JPA, fabrication by FBK
- Optimization of tuning rod
- Superconducting cavities
- FPGA for acquisition

*S. Kono et al; **Nature Phys 14, 546–549 (2018)**

Conclusions

- **First QUAX@LNF run with complete haloscope**
  - **2 weeks of data taking.**
  - **9 T magnet.** Operated at 8 T.
  - **Tuning rod to scan frequencies**.
- **Savitzky-Golay + Maximum Likelihood analysis.**
- **Still much room for improvements.**
- **QUAX competitive in the panorama**.