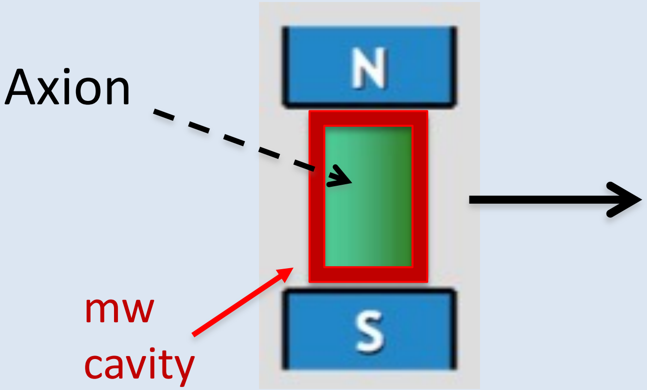
QUAX – QUaerere AXion

Main Activity

- **Photon coupling: Due to the motion of the solar system in the galaxy, Dark Matter axions** are converted into **rf photons** inside a **resonant cavity** immersed in a **strong magnetic field**

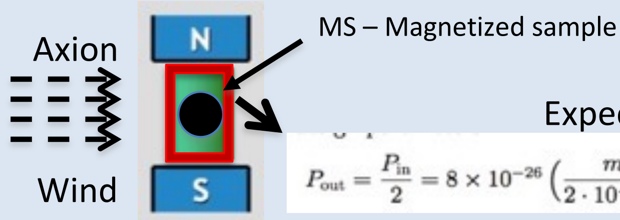


Expected rf power

$$P_a = 1.85\times 10^{-25}\,\mathrm{W}\left(\frac{V}{0.0361}\right)\left(\frac{B}{2\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{-0.97}\right)^2 \times\left(\frac{C}{0.589}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right)\left(\frac{Q_L}{201000}\right)$$

R&D Activity

- **Electron coupling:** the axion DM cloud acts as an **effective RF magnetic field** on electron spin exciting magnetic transitions in a magnetized sample and **producing rf photons**



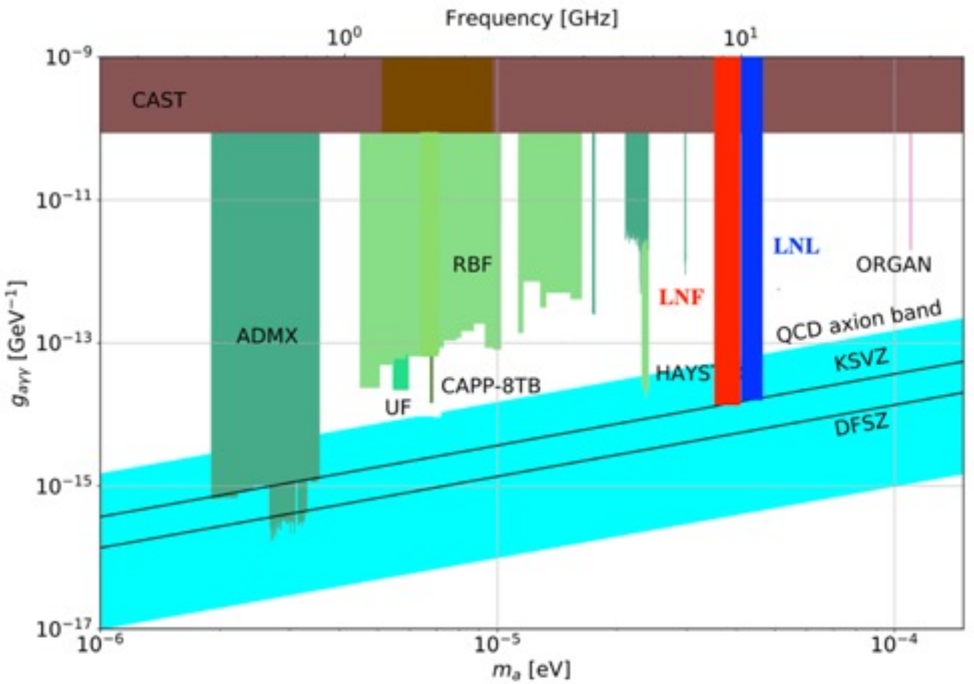
Expected rf power

$$P_{\mathrm{out}} = \frac{P_{\mathrm{in}}}{2} = 8\times 10^{-26}\left(\frac{m_a}{2\cdot 10^{-4}\,\mathrm{eV}}\right)^3\left(\frac{V_s}{1\ \mathrm{liter}}\right)\left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right)\left(\frac{\tau_{\mathrm{min}}}{10^{-6}\,\mathrm{s}}\right)\ \mathrm{W},$$

QUAX Experiment

- The **INFN has approved the QUAX experiment** 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 **LNF**

	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



Quax 2025 projection: 2 GHz scan to the KSVZ line

- The **LNL haloscope** will be based on dielectric cavities, travelling wave parametric amplifiers and 14 T magnet
- Cryogenic system: Dilution Refrigerator to work below 60 mK

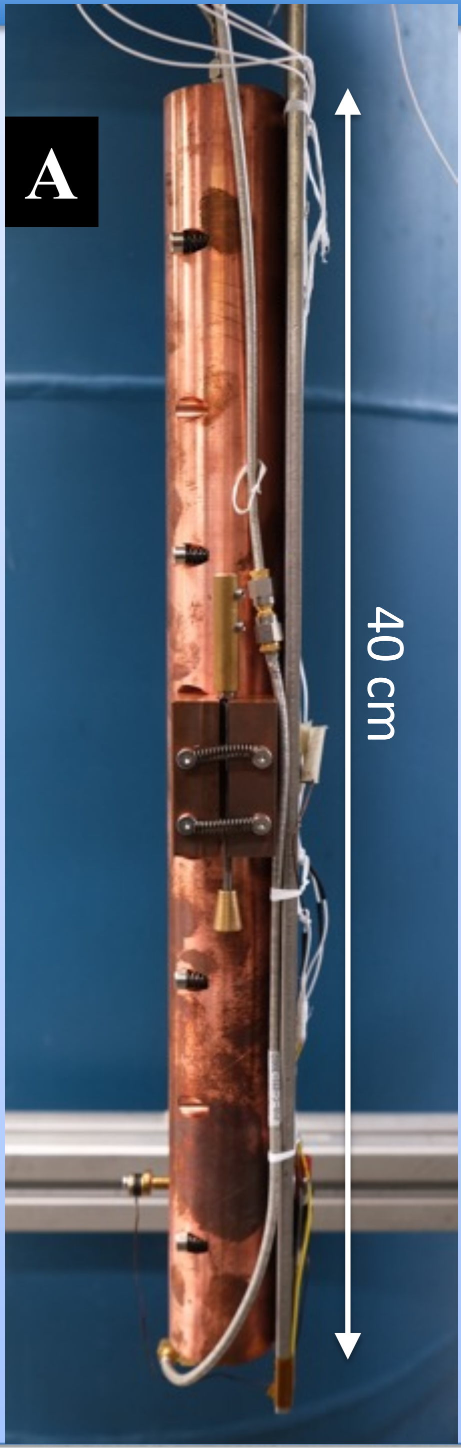
QUAX: PD-LNL RUN 2024 - Parameters

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**

Cavity Developments 1



Three different novel cavity designs are being studied to maximize **$C^2 V^2 Q$**:

A. Empty "double-shell" cylindrical cavity with simple tuning

B. High volume, high C factor single-shell dielectrical cavity

C. High volume, high C factor empty "polygonal" cavity

A tunable clamshell cavity for wavelike dark matter searches

Cite as: Rev. Sci. Instrum. 94, 045111 (2023); doi: 10.1063/5.0137621
Submitted: 4 December 2022 • Accepted: 31 March 2023 •
Published Online: 19 April 2023

View Online Export Citation CrossMark

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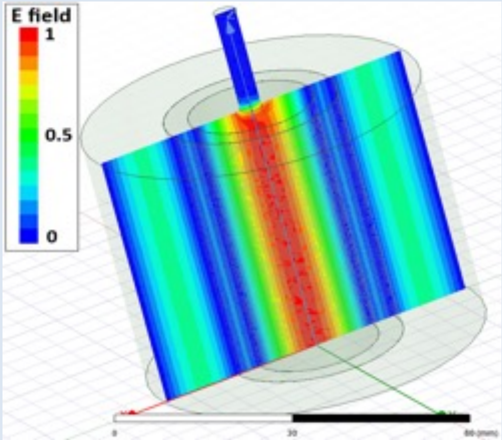
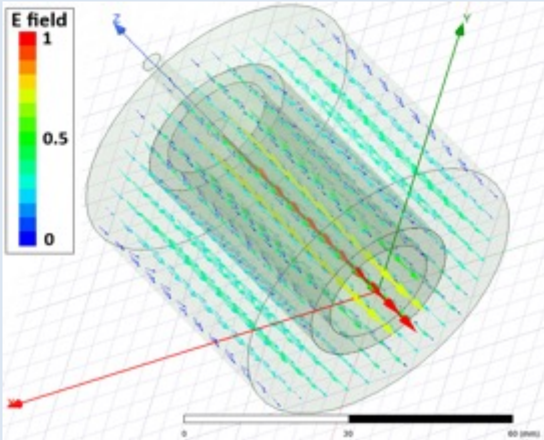
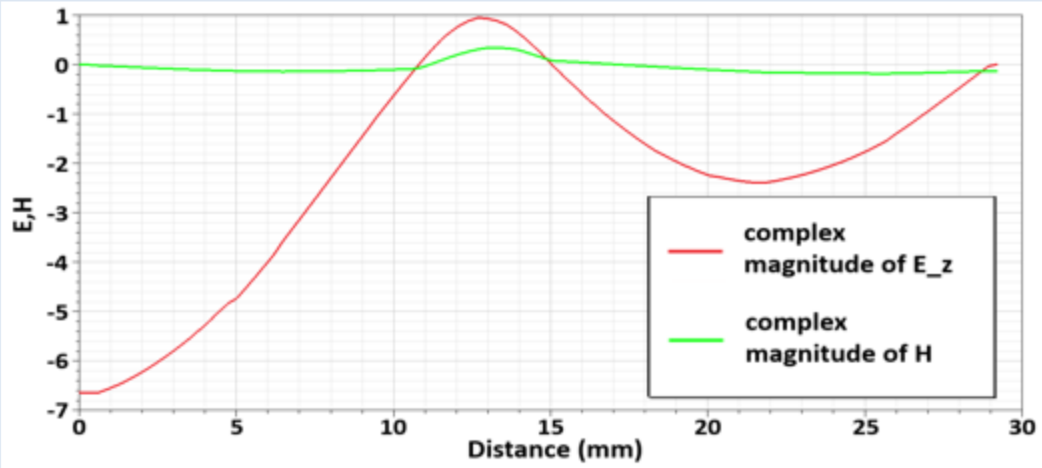
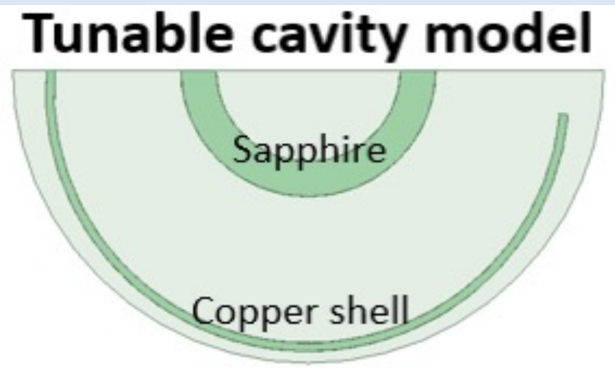
Cavity developments 2

B



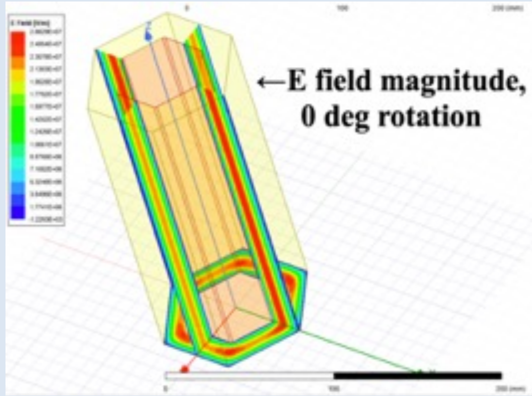




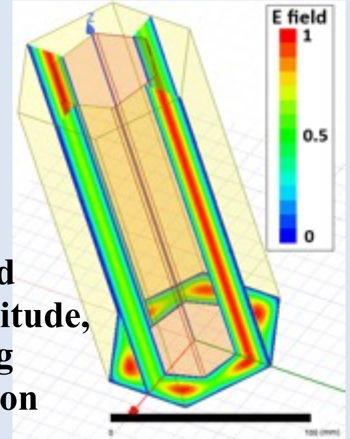


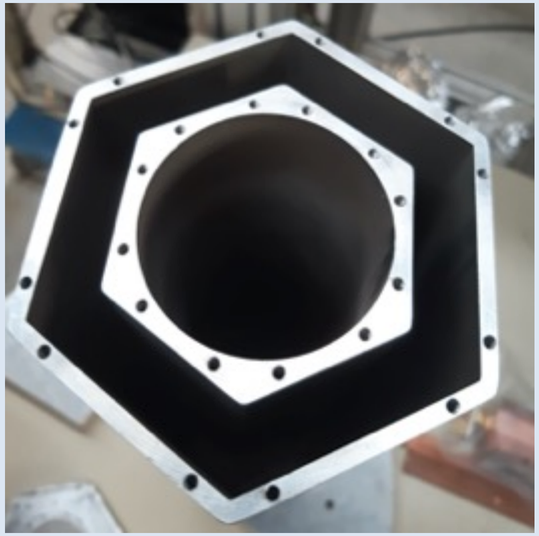
C ~ 0.47
V ~ 1.15 l
Q ~ 250000
Δf ~ 200 MHz

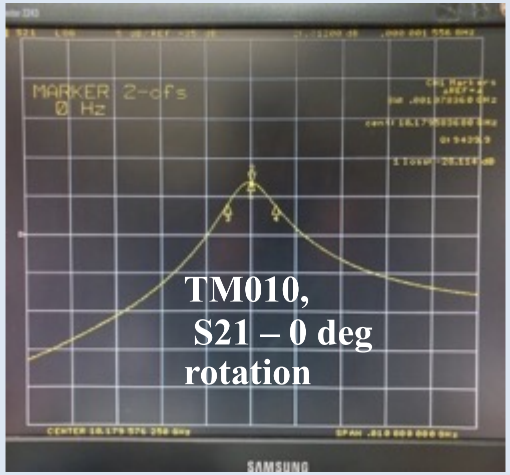
C

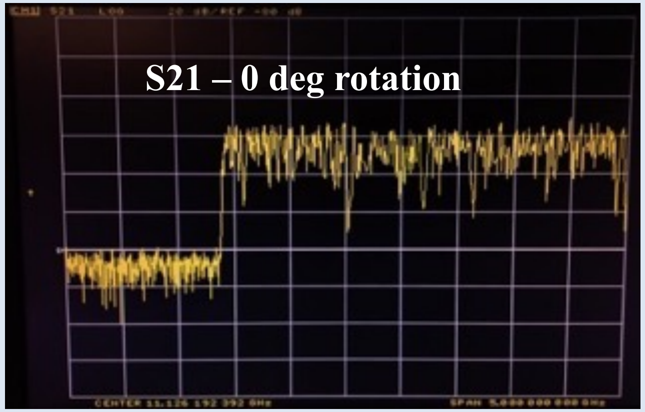


E field magnitude, 15 deg rotation









C ~ 0.8
V ~ 1.76 l
Q ~ 62000
Δf ~ 500 MHz

Tunable Cavity (B) in DU System

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

LamedNew

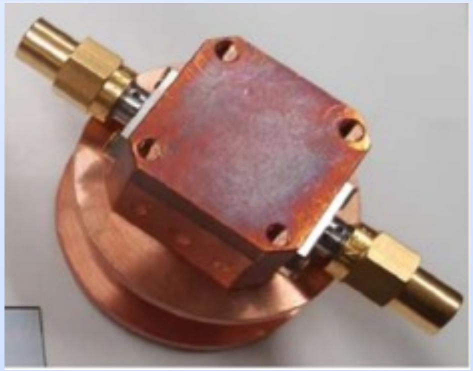
Open cavity with sapphire cylinder

Cavity in the dilution insert

Antenna

New Sliding RF contact under Tests

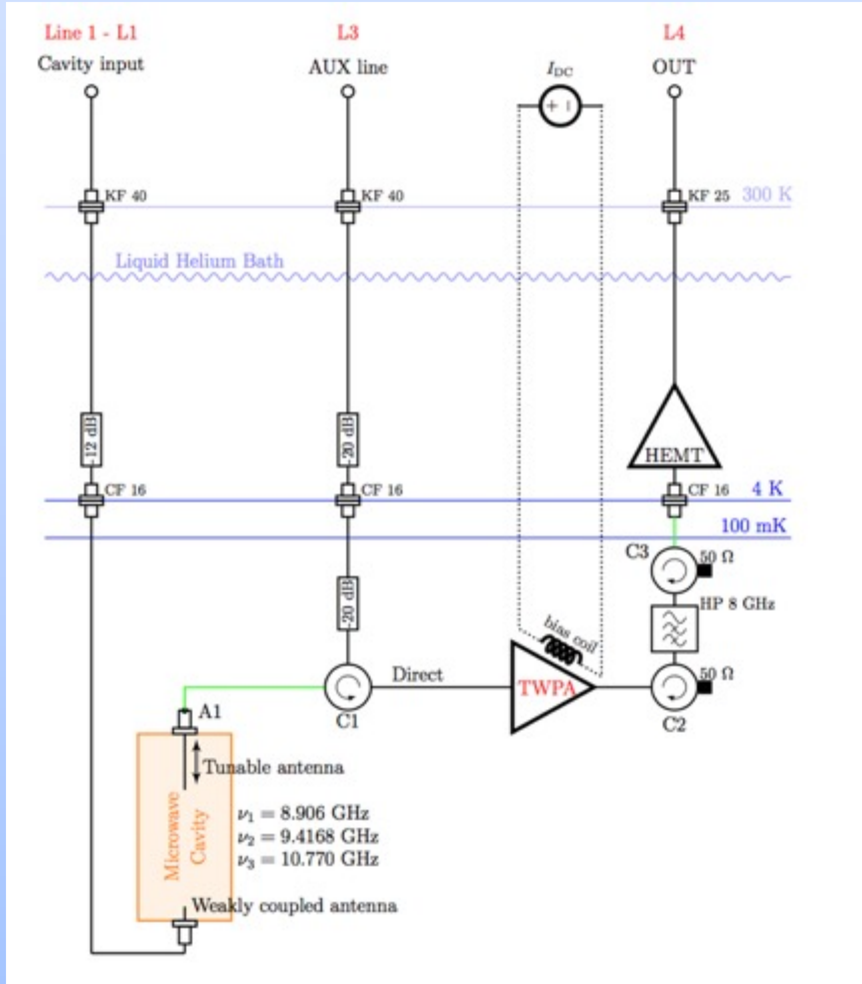
TWPA Amplifier

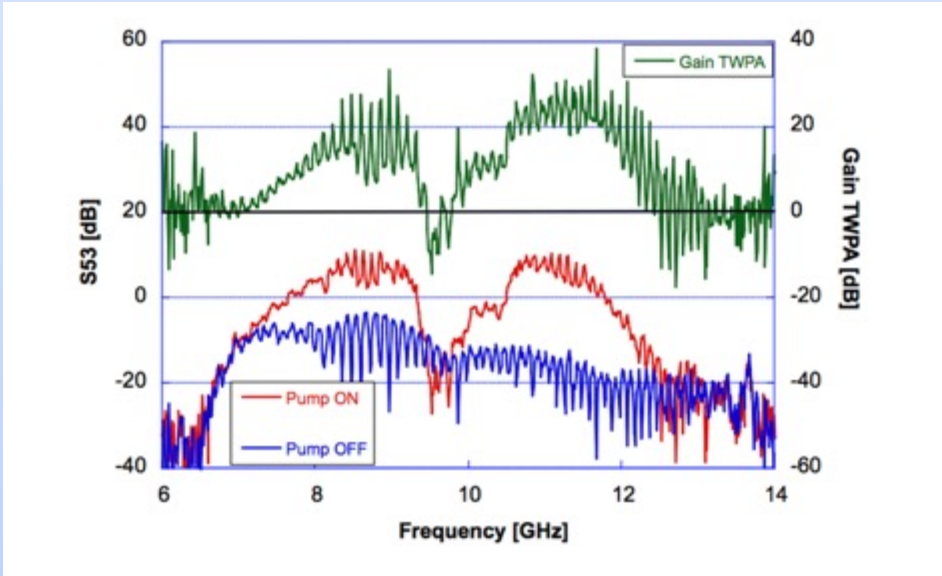


Large bandwidth ~ 1 GHz

Noise T ~ 1-2 photons

This allowed us to start testing **a new Quantum Limited rf amplifier** provided us from Nicholas Roch (Grenoble)





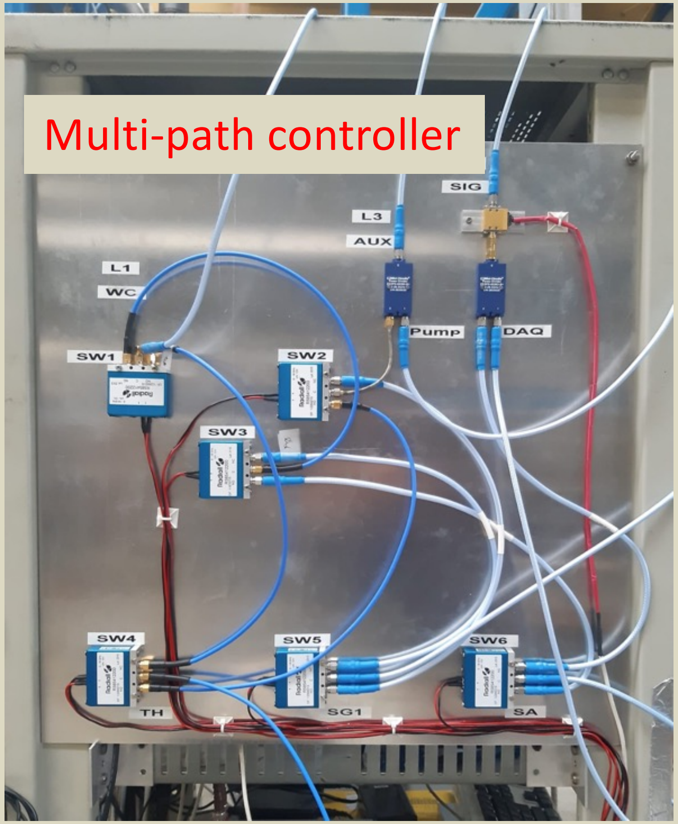
$$T_{\rm sys} \approx \frac{h\nu_c}{2k_B}\coth\frac{h\nu_c}{2k_B T_c} + \Lambda_1 T_{\rm TWPA} + \frac{\Lambda_2\Lambda_1}{G_{\rm TWPA}} T_{\rm HEMT}$$

T_{noise} = 1 – 1,5 Kelvin with 8 Tesla Field

@ 10 GHz

Devices for Automation

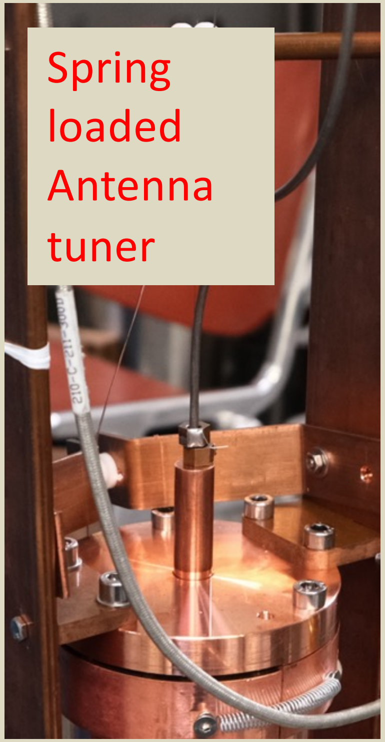
Installed the new **automatic system for Noise Temperature Measurement**



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

QUAX RUN 2024

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

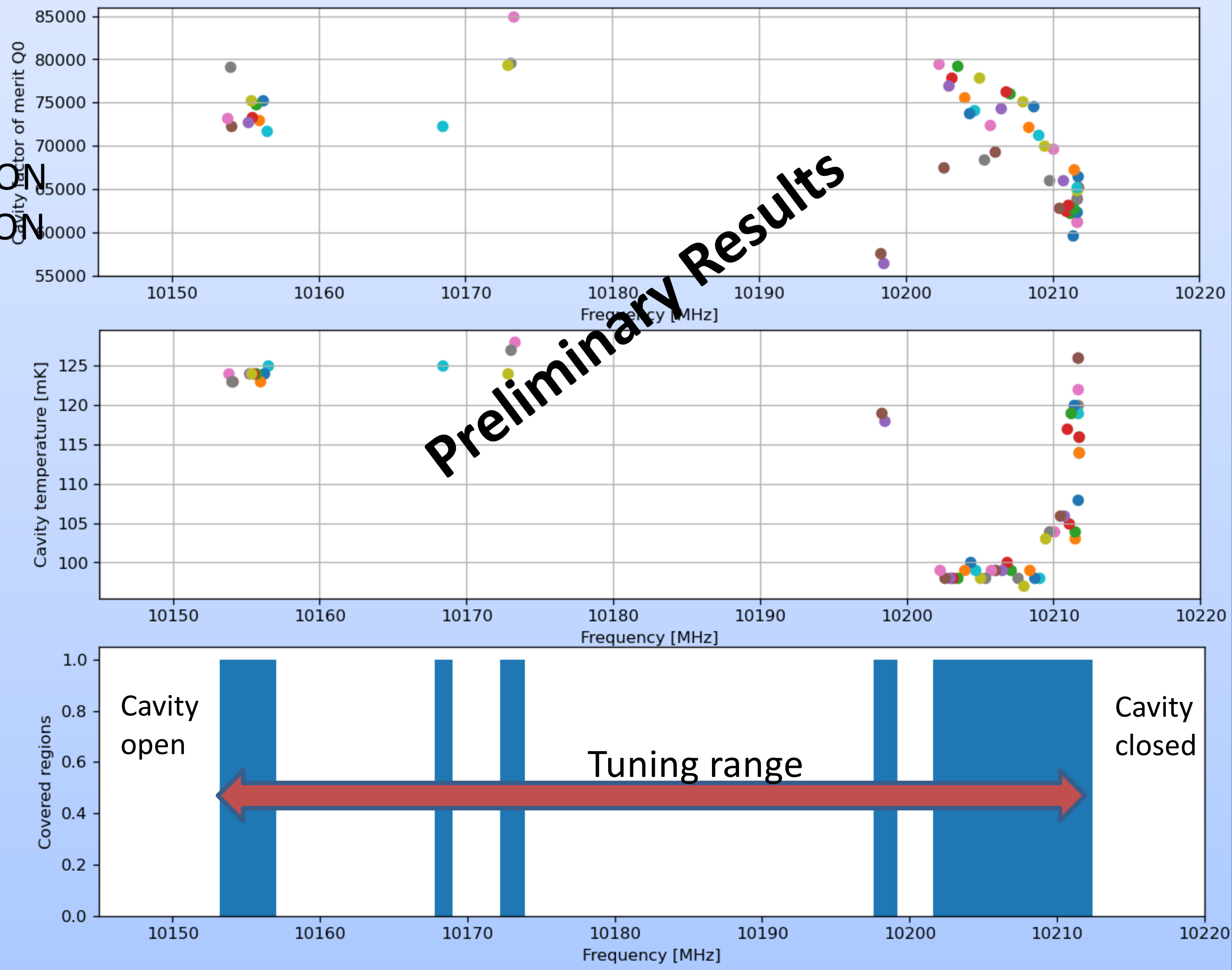
Dead intervals due to safety reasons and shift organization

Covered span: 14.7 MHz
Maximum tuning: 58.45 MHz
Ratio: 25% of available scan

Effective scan rate about

100 kHz/hour

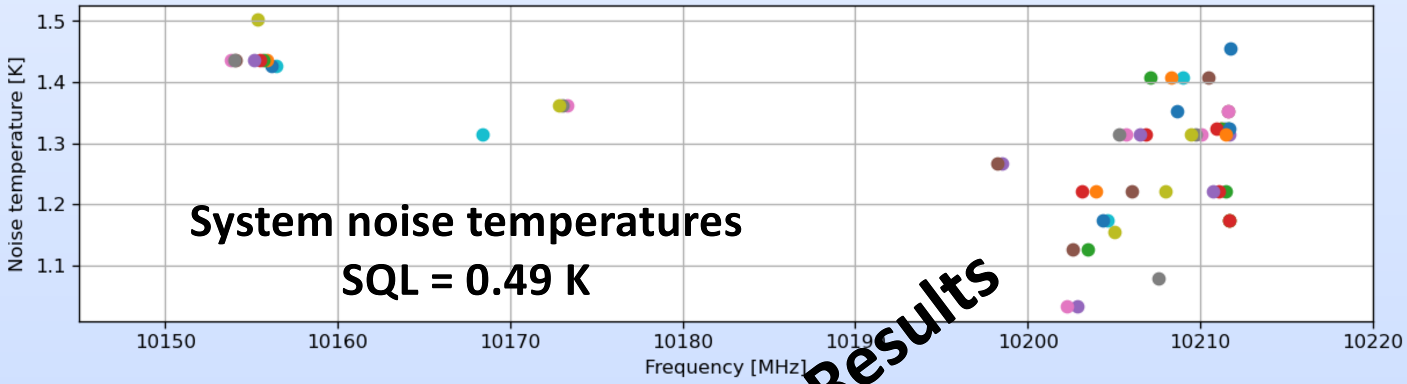
2.5 MHz/day



QUAX RUN 2024

Analysis in progress

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

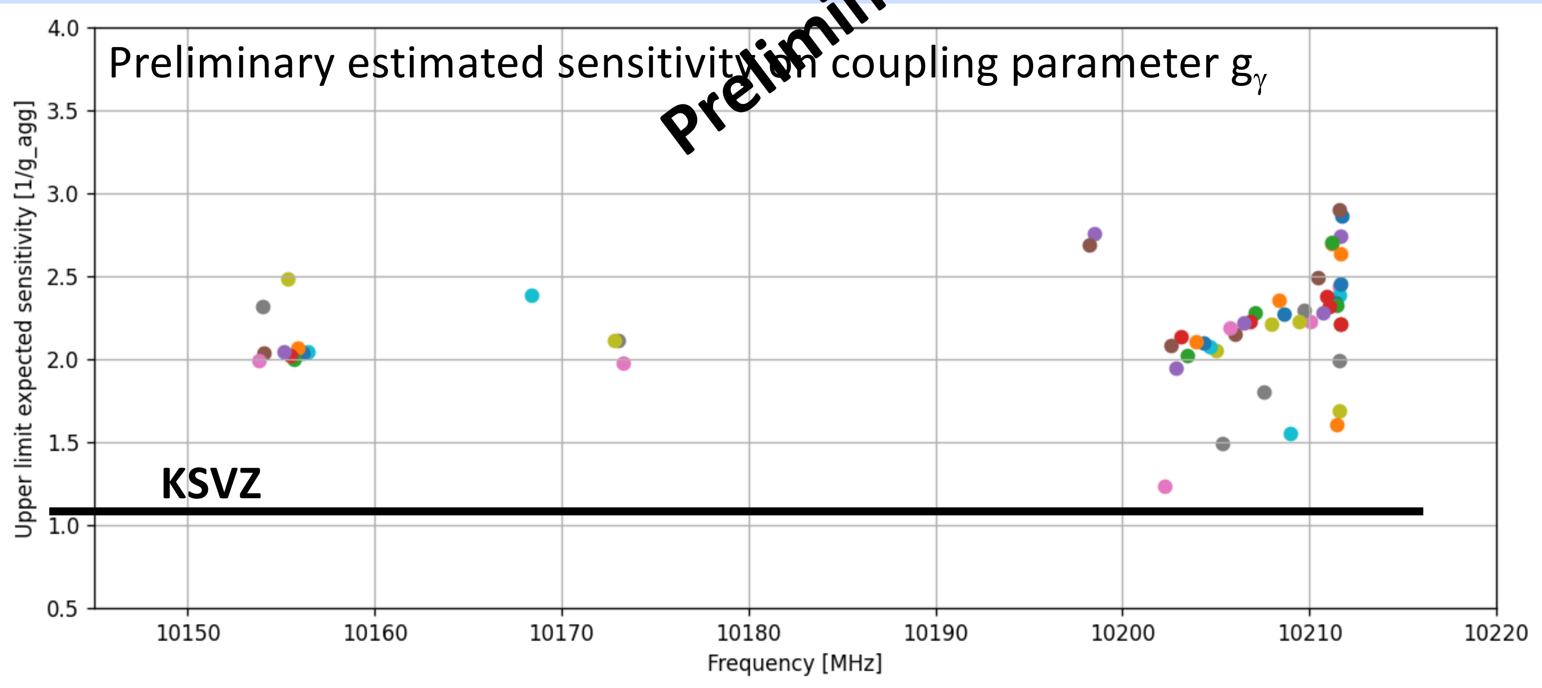


Preliminary Results

Scaling:

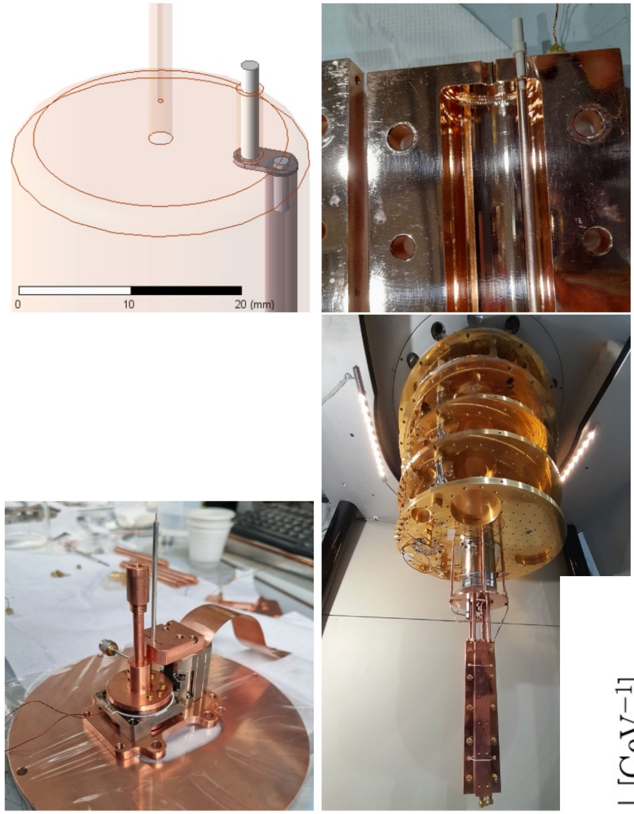
Linear B

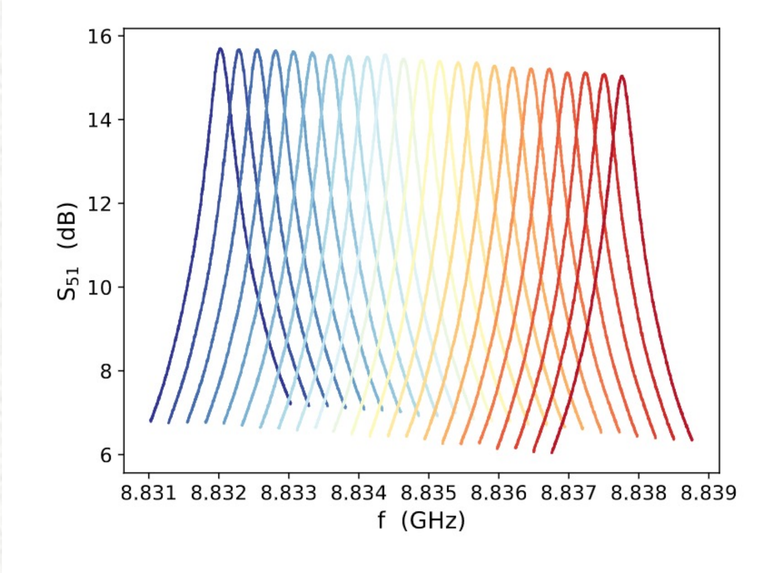
SQRT Q

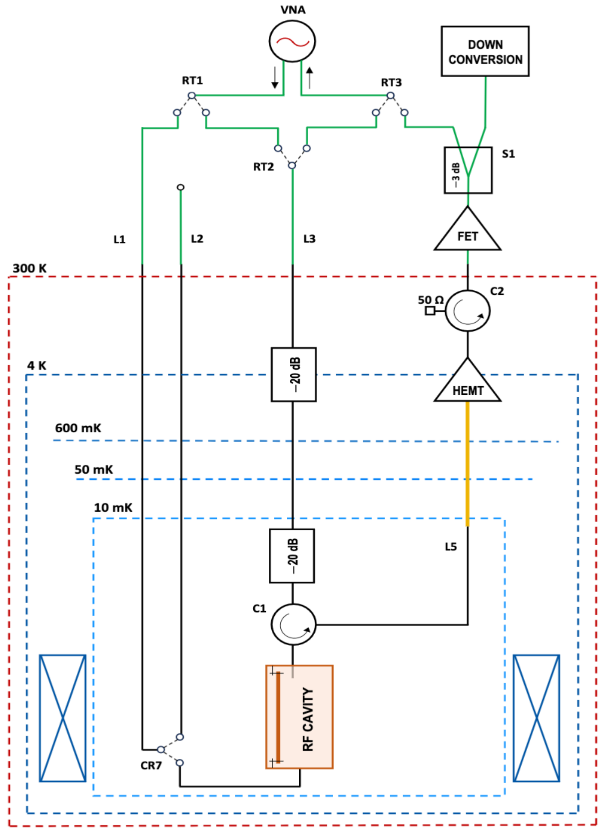


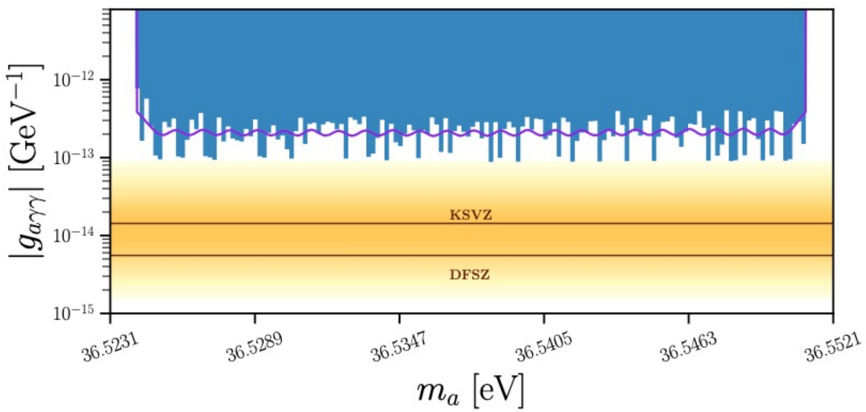
This result shows that with the expected improvements on the cavity and field the QUAX design sensitivity is within reach

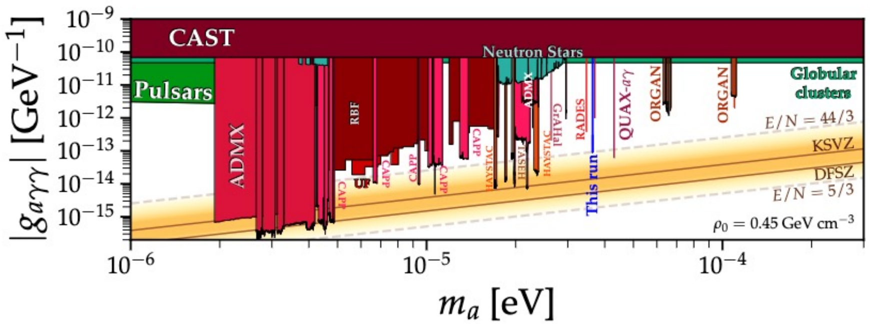
Search for Axion dark matter with the QUAX–LNF Tunable Haloscope











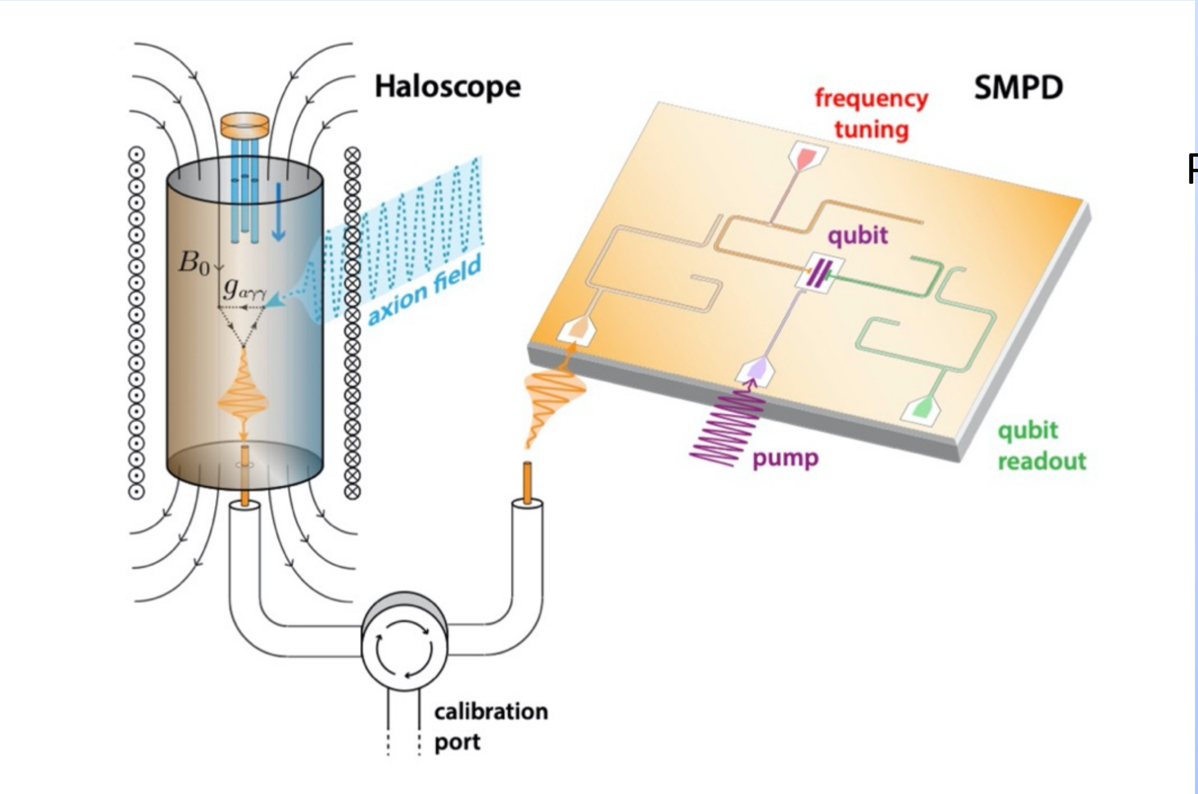
Autumn Run with JPA

Accepetd for Pub. Phys. Rev. D

Next Generation Haloscope – Single Photon Detection

Joint effort between QUAX (LNL, PD), Padova Dept. of Excellence, SQMS, Quantronics Group Saclay

Single Microwave Photon Detector (SMPD) as haloscope receiver



Linear amplifier irreducible limit
Standard Quantum Limit

$$P_{\mathrm{SQL}} = h\nu_a\sqrt{\Delta\nu_a/t}$$

$$\mathrm{SNR}_{\mathrm{SQL}} = \frac{P_a}{h\nu_a}\sqrt{\frac{t}{\Delta\nu_a}}$$

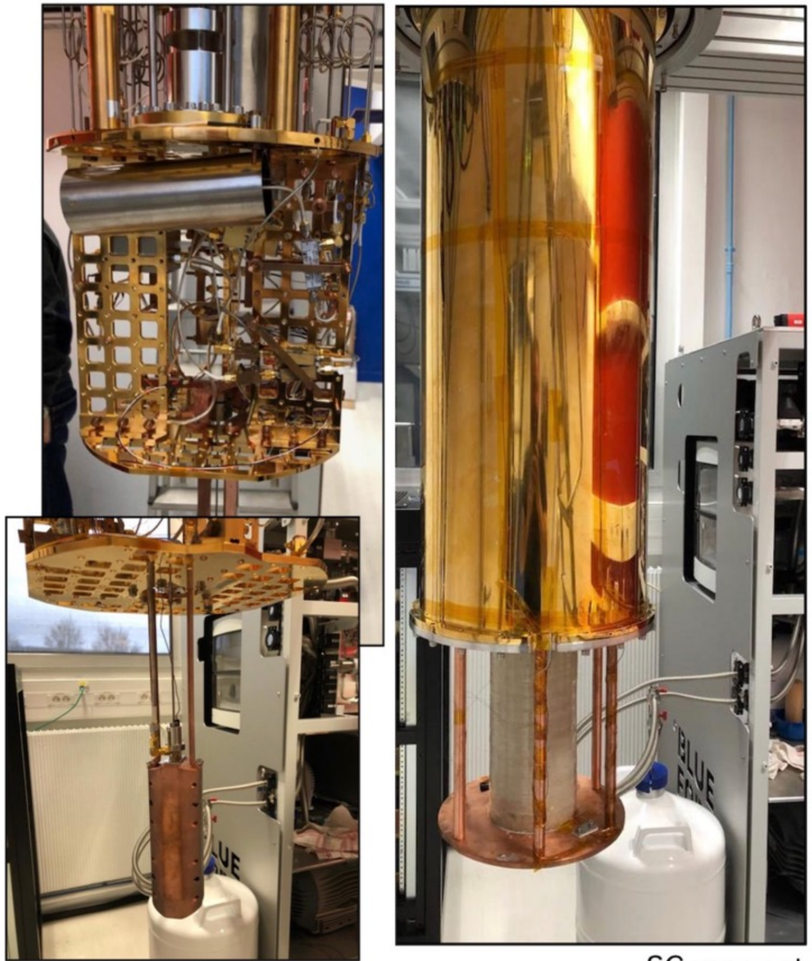
Photon Counter PC limited by **dark count** Γ_{DC} rate and **efficiency** η

$$\mathrm{SNR}_{\mathrm{PC}} \approx \frac{\eta P_a}{h\nu_a}\sqrt{\frac{t}{\Gamma_{\mathrm{dc}}}}$$

Improvement in scanning speed with SMPD

$$\eta^2\frac{\Delta\nu_a}{\Gamma_{\mathrm{dc}}}$$

Single Photon Detection – First Test @ Saclay

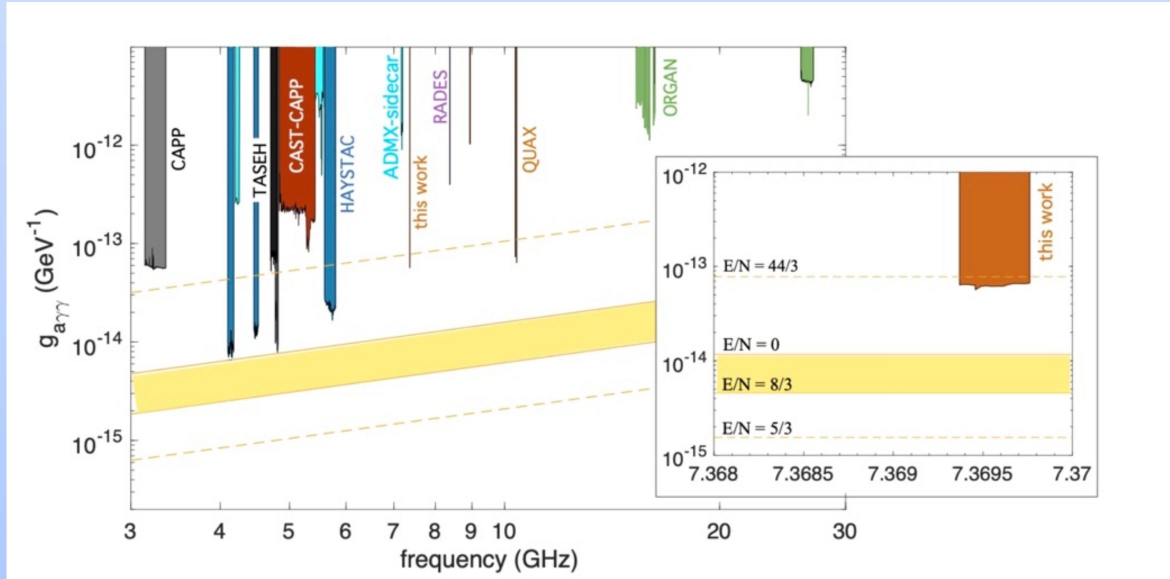


SMPD (top) and cavity

SC magnet

- hybrid (normal-superconducting) cavity 7.37 GHz, tunable, $Q_0 = 9 \times 10^5$
- T=14 mK delfridge base temperature @ Quantronics lab (CEA, Saclay)
- 2 T-field
- triplet of rods controlled by a nanopositioner mounted at the MC stage to probe for different axion masses
- passive protection by the B-field for SMPD and TWPA

- Developed a dedicated protocol
- Dark count at the 100 Hz level
- System stability up to 10 minutes



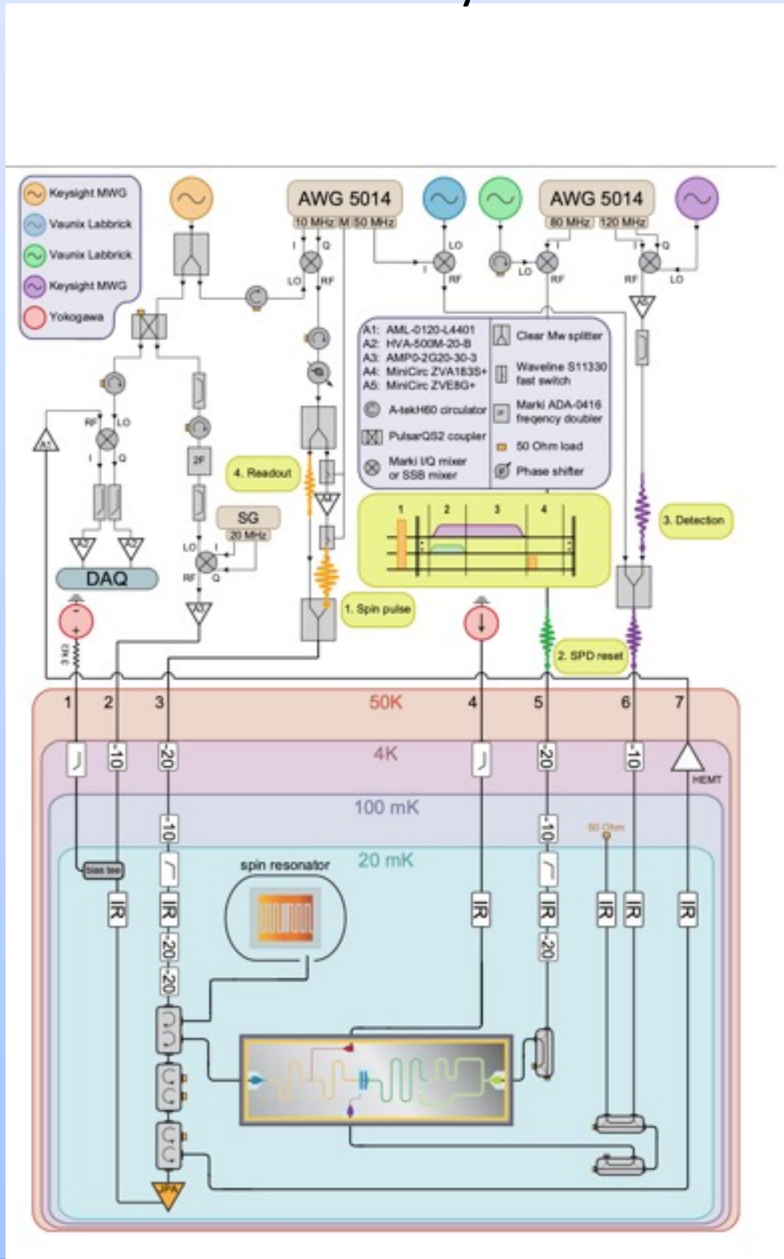
https://arxiv.org/abs/2403.02321

20 Times faster then SQL based Amplifier with a Dark Count @ 10 Hz (new Devices) 100

Haloscope with SMPD in Italy

Paris run was successful the device will be mounted @ LNL/PD

Electronics layout



DRY dilution unit

QUAX: LNL-LNF Future Steps

Short Term Program:

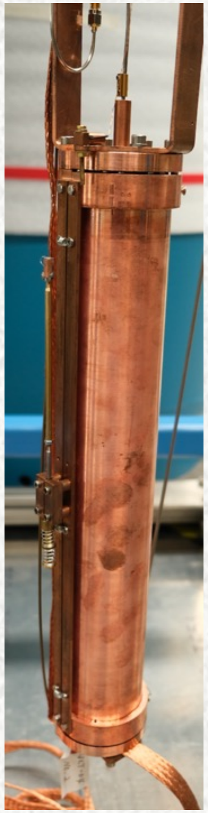
- Proceed with automation of data acquisition and control
- Proceed with installation of safety controls of dilution unit based on PLC
- LNL RUN with TWPA @ about 10.2 GHz, with T_n = 1.2 K and complete scanning with the remaining 40 MHz – AUTUMN 2024
- LNF RUN with JPA @ about 9 GHZ continuos scanning over 50 MHz – Autumn 2024
- Realization of improved cavities design, same scheme but different frequencies + REBCO Tapes
- New Cavity approach for large tuning range under test
- The 14 T magnet @ LNL competition has been completed, but Its installation only in 2025

PD-LNL Haloscope – High Frequency Tunable Cavities

Single crystal dielectric - copper cavity

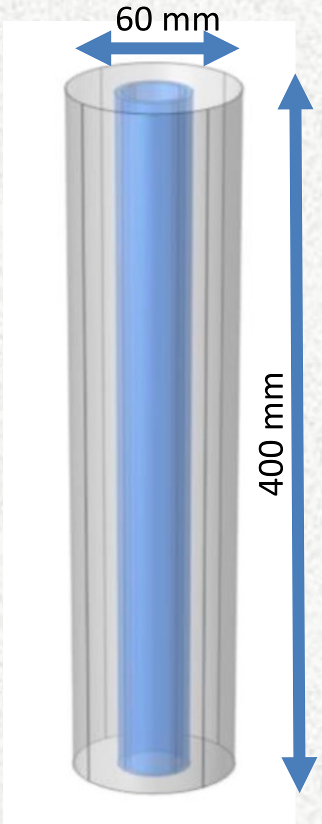
Gap on top plate for safety

Close with tuning mechanism

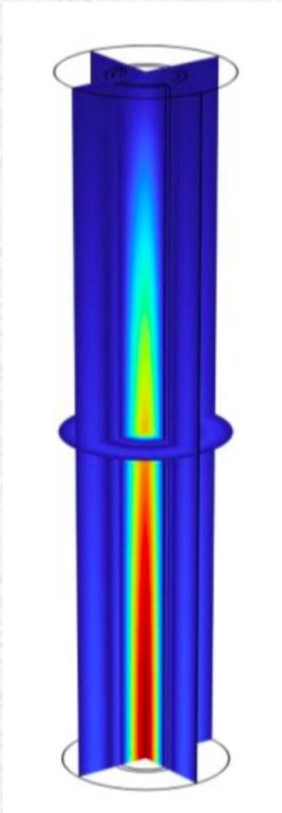


Open with sapphire view

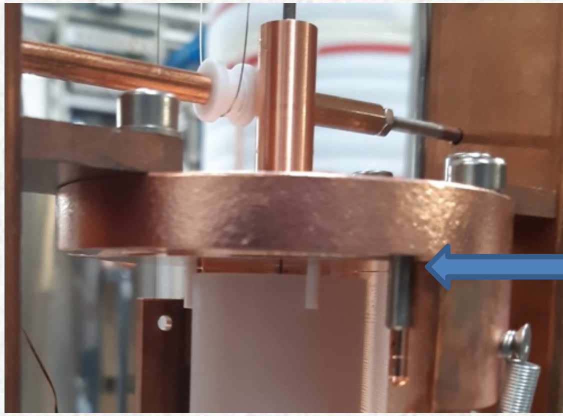
General layout



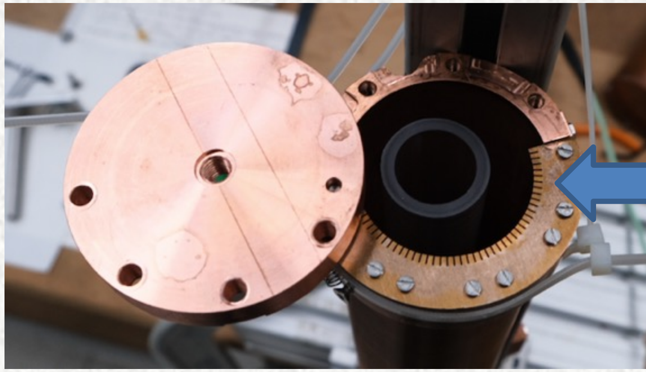
Simulated Map of E field TM030 mode



Upper end cap details



GAP



Rf sliding contact