QUaerere AXion - QUAX
a haloscope for 10 GHz

Mainz, 2025

GravNet Symposium

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(on behalf of the QUAX collaboration)

The axion

- The axion is a **light pseudoscalar boson**, introduced in the 70s to solve the strong CP problem (Peccei and Quinn 1977)

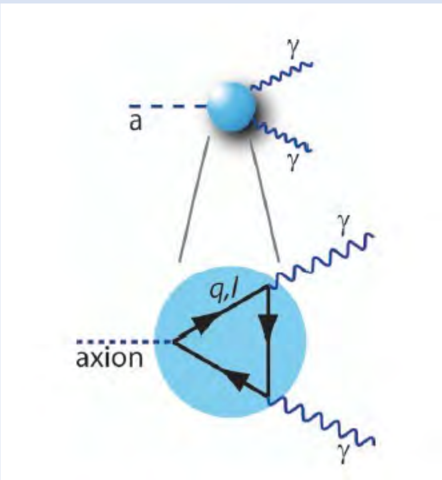
$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

- f_a is the axion decay constant, related to the scale of spontaneous breaking of the PQ simmetry
- the strong CP problem is solved regardless of the value of f_a
- f_a is the quantity that determines all the low energy phenomena of the axion

- **Axion couplings** with ordinary matter depends on the model implementing the PQ simmetry

Axion photon

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

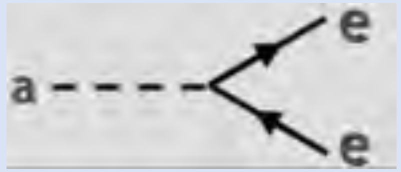


$g_\gamma = 0.36$ (DFSZ)

$g_\gamma = -\,0.97$ (KSVZ)

Axion electron

$$L_{aee} = -g_e \bar{e} i\gamma_5 e a$$



$g_e \approx \frac{m_a m_e}{m_\pi f_\pi} = 4.07\times 10^{-11} m_a$ (DFSZ)

$g_e \sim 0$ (Strongly suppressed) (KSVZ)

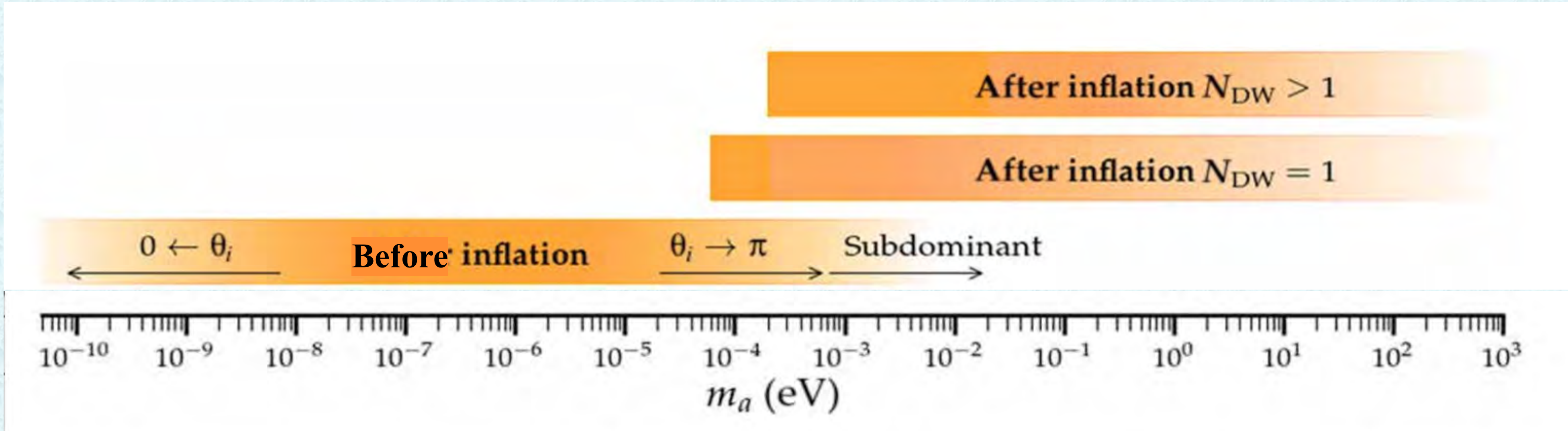
KSVZ – Kim 1979, Shifman-Vainshtein-Zakharov 1980
DFSZ – Dine-Fischler-Srednicki 1981, Zhitnitsky 1980

Dark matter axion

- Non-thermal mechanisms in the early Universe could have produced axions: the *vacuum realignment mechanism* and the *decay of topological defects* (axion strings and domain walls) → **Cold dark matter (GOOD)**
- *Vacuum realignment mechanism*: relaxation of the axion field after breakdown of the PQ symmetry → The expected cosmic mass density of axions depends on whether inflation happens after or before PQ breakdown

Allowed regions of mass (decay constant)

- These regions obtained by **assuming axion saturate DM density**. Lower values of m_a would overproduce DM while higher masses would lead to subdominant amount of axion DM
- If axions exist at least a fraction of DM are axions



The pre- and post- inflationary scenarios

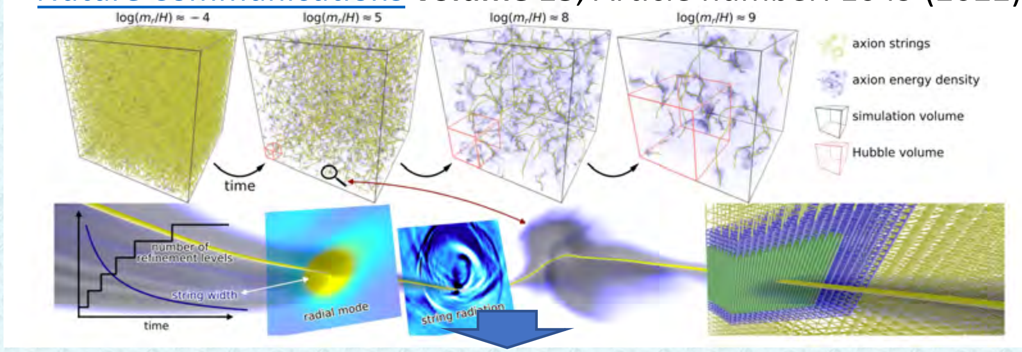
- Difference between the pre- and post- inflationary scenarios is **predictability**:
  - In **pre-inflationary** there are **two continuous free parameters**, an angle θ and the mass m_a, to obtain the observed dark matter density
  - In **post-inflationary** there is one continuous parameter, m_a, and a discrete one N.
    - ➢ **In principle the observed DM density predicts the value of m_a**
    - ➢ Due to nonlinearities, computing this mass accurately is a real challenge
    - ➢ Recent works make use of large static lattice simulations

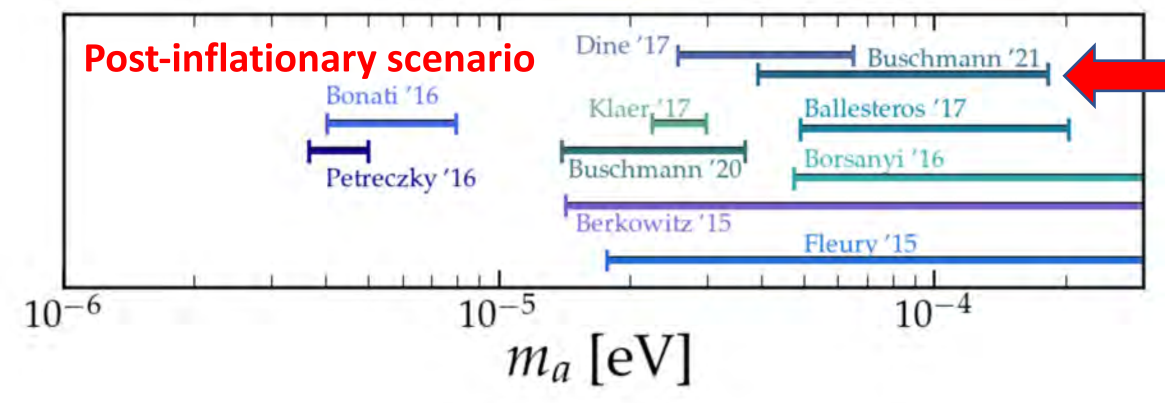
SciPost Select — SciPost Phys. 10, 050 (2021)

More axions from strings

Marco Gorghetto[1], Edward Hardy[2] and Giovanni Villadoro[3]

Nature Communications **volume 13**, Article number: 1049 (2022)





ARTICLE

https://doi.org/10.1038/s41467-022-28669-y OPEN

Dark matter from axion strings with adaptive mesh refinement

Malte Buschmann[1], Joshua W. Foster[2,3,4], Anson Hook[5], Adam Peterson[6], Don E. Willcox[6], Weiqun Zhang[6] & Benjamin R. Safdi[3,4]

$m_a \in (40, 180)$ **microeV**

Axions in the galactic halo

- In order to explain galaxy rotation curves, a **halo of dark matter** is hypothesized

- Accepted value for local dark matter **density**

$$\rho_{DM} \approx 0.3 \; - 0.45 \;\; \text{GeV/cm}^3$$

- Cold dark matter component is **thermalized** and has a Maxwellian velocity distribution, with a dispersion $\sigma_v \approx 270$ km/s

- There might be a non-thermalized component with sharper velocity distribution

- **Axion can be a dominant component of the galactic DM halo**

- Its **occupation number** is large

$$n_a \approx 3\times10^{14}\left(\frac{10^{-6}\, eV}{m_a}\right) \quad \text{axions/cm}^3$$

- It can be treated as a classical oscillating field with frequency given by the axion mass

$$\frac{\omega_a}{2\,\pi} = 2.4\left(\frac{10^{-6}\, eV}{m_a}\right) \quad \text{GHz}$$

- It has **coherence length** and **time**

$$\lambda = 1400\left(\frac{10^{-6}\, eV}{m_a}\right) \text{ m}$$

$$t = 5\left(\frac{10^{-6}\, eV}{m_a}\right) \text{ ms}$$

Haloscopes – Galactic axions – Sikivie Type

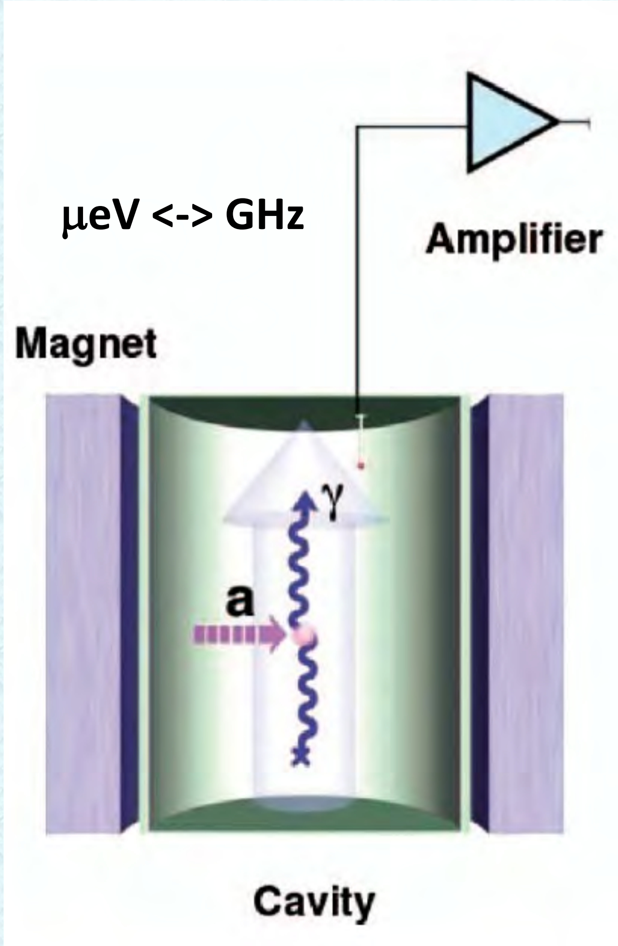
- Search for axions as cold dark matter constituent
- Original proposal by P. Sikivie (1983)
- **DM particles converted into photons inside a magnetic field (Primakoff effect), sensitivity to $g_{a\gamma\gamma}$**

  - **The mass** of the DM particle determines **the frequency of the photons** to be detected. For axions we are in the **microwave range**.

$$h\nu = E_a = m_a c^2\left(1 + \frac{1}{2}\beta_a^2\right) = m_a c^2(1 + O(10^{-6}))$$

$\beta_a \sim 10^{-3}$ axion velocity

  - **Use a microwave cavity** to enhance signal. Cavity must be tuned to axion mass. Being this unknown, **tuning is necessary**: very time consuming experiment!



Haloscopes – Galactic axions

- Search for axions as cold dark matter constituent
- Original proposal by P. Sikivie (1983)
- **DM particles converted into photons inside a magnetic field (Primakoff)**
    - Expected signal a **nearly monochromatic line**. Broadened by the **thermal distribution** of DM in the Milky Way

      $$\frac{\Delta E}{E} \approx 10^{-6} = 1/Q_a$$

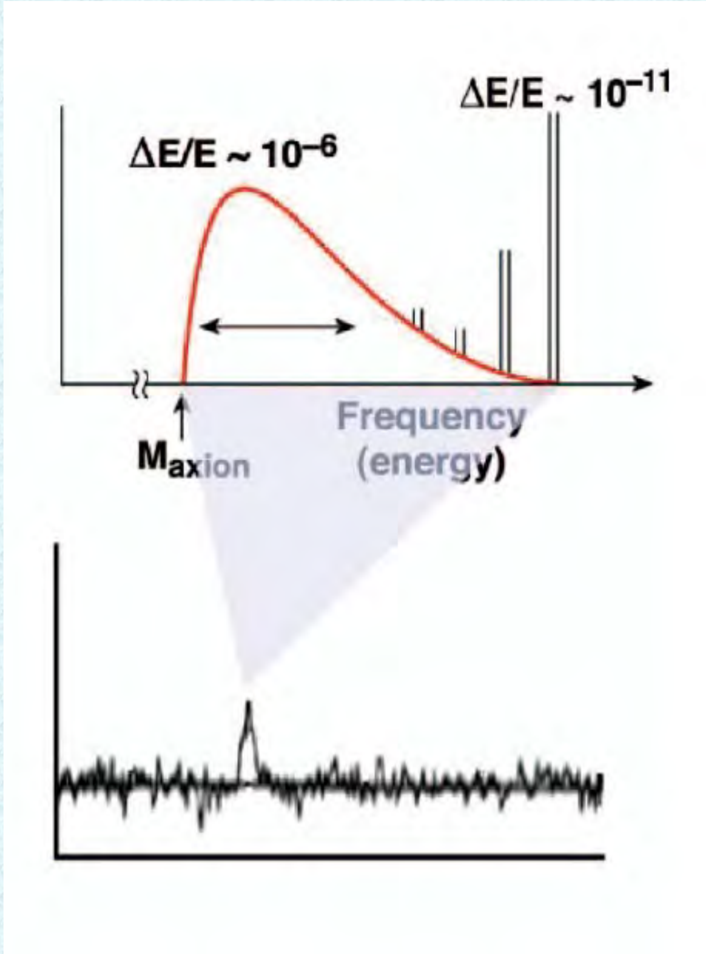
    - Possible **very sharp component due to non-thermalised** axion falling in and out of the Milky Way

      $$\frac{\Delta E}{E} \approx 10^{-11}$$

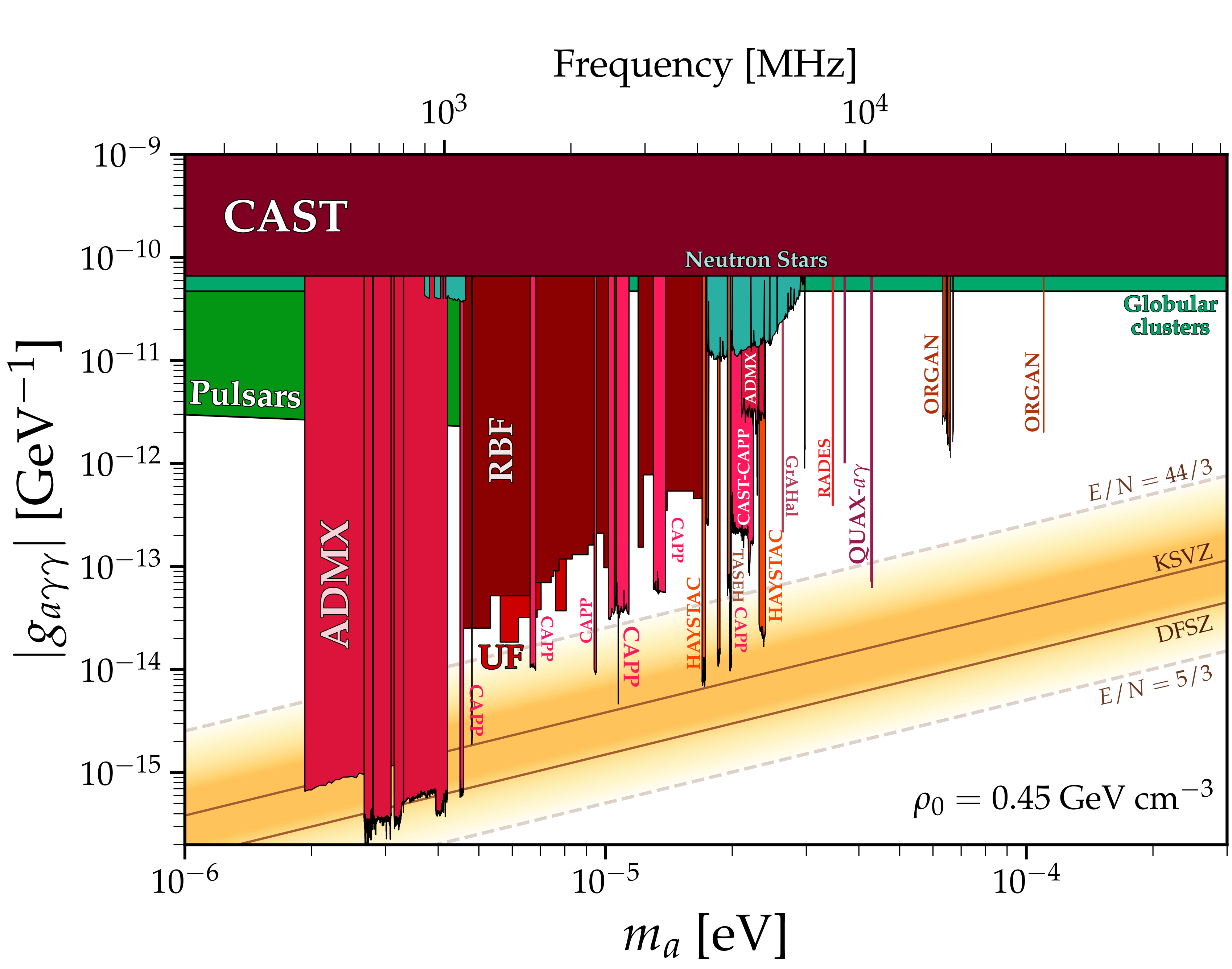
    - **Power** proportional to the number density and the square of the axion-photon coupling

      $$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right).$$

    - Typical powers to be measured below 10^{-23} W



Current limits – Sikivie's haloscopes



AxionLimits by **cajohare**.

Haloscopes – Galactic axions

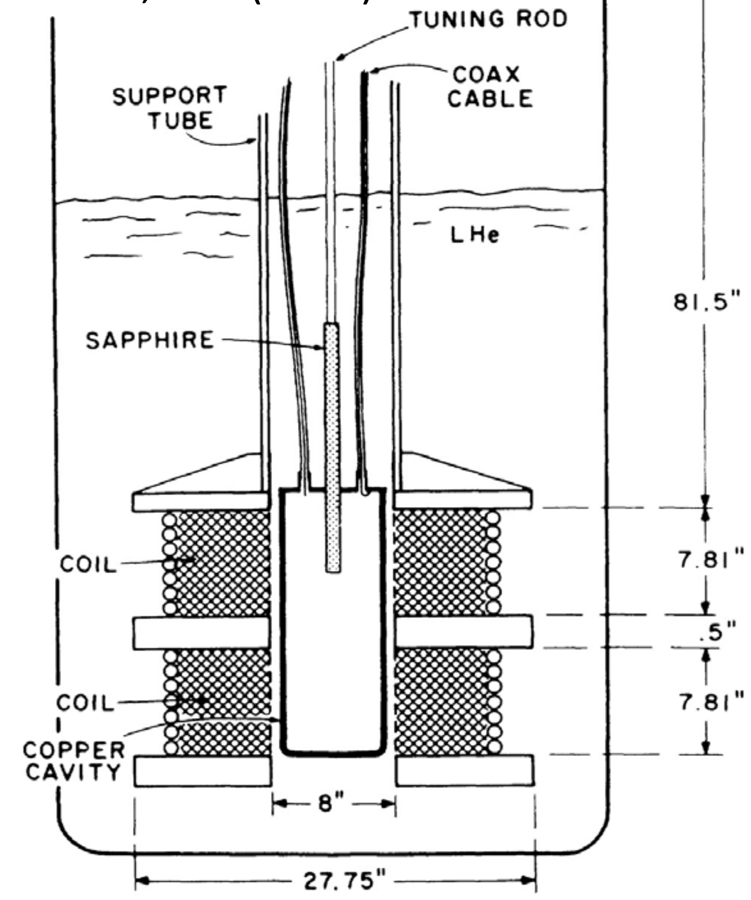
- Resonant detection of DM axions in a magnetic field. One measurement explores **only sharp cavity linewidth**.
  Scanning is necessary.

Figure of merit for scanning (mass or frequency)

$$\frac{\Delta f}{\Delta t} \propto V^2 B^4 C^2 T_{sys}^{-2}\ Q$$

- **High Q** microwave cavity operating inside a **strong magnetic field B**
- **Large volume *V*** cavity at **high rf frequency *f***
- **Low noise T_{sys}** radio frequency receiver
- Use cavity modes with **large form factor *C***

PRL 59, 840 (1987)



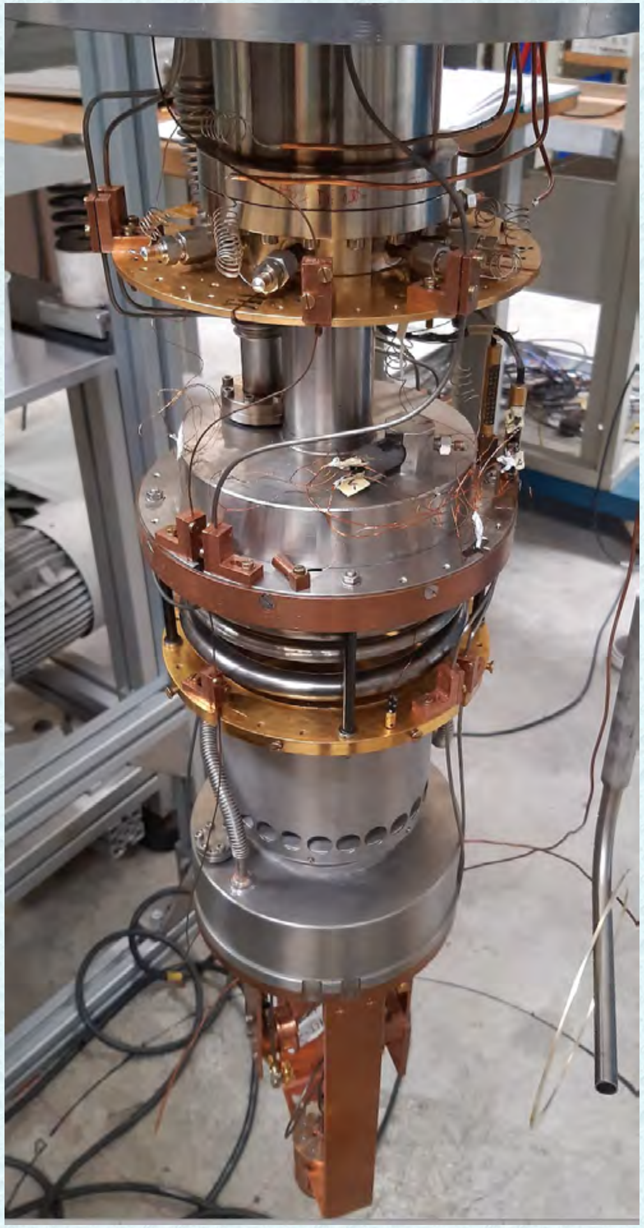
Schematic diagram of the RBF apparatus (1987)

- Scanning to high mass – high frequency very difficult due to reduced cavity volumes
- Scanning to low mass – low frequency implies large cavities and thus very big magnets

! All current limits assumes axion/ALPs saturate the local DM density

Main components of cavity haloscopes

Refrigeration system



Base temperature T

Microwave cavity

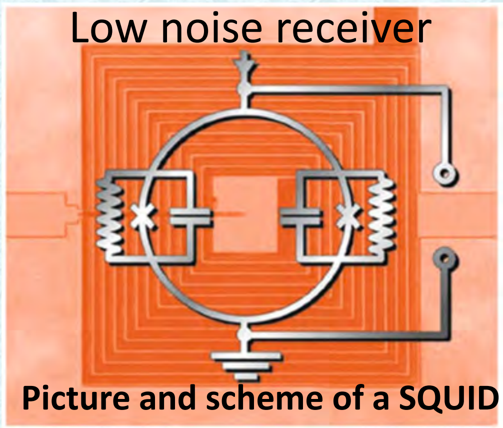
Quality Factor Qc

Form factor C_{mnl}

Volume V

Resonance frequency f

Tuning



Noise temperature T_n

Magnetic source

Magnetic energy B^2 V

Sensitivity

- When the frequency of the axion induced photon matches the frequency of the **cavity eigenmode**, the conversion power is **resonantly enhanced** via cavity Q_c *(Q_c << Q_a)* $Q_L = Q_c/(1+\beta)$

$$P_{\mathrm{axion}} = 1.1\times10^{-23}\,\mathrm{W}\left(\frac{g_\gamma}{1.92}\right)^2\left(\frac{\rho_a}{0.45\,\mathrm{GeV/cm^3}}\right)\left(\frac{\nu_a}{1\,\mathrm{GHz}}\right)\left(\frac{B_0}{10\,\mathrm{T}}\right)^2\left(\frac{V}{1\,\mathrm{liter}}\right)\left(\frac{C_{mnl}}{0.69}\right)\left(\frac{Q_L}{10^5}\right)\frac{\beta}{(1+\beta)}$$

- The **power is picked up by an antenna** with coupling β and read by an amplifier. Extremely low power levels are detected by sensitive amplifiers
- In the absence of a signal, the output of a receiver is noise measured on a **bandwidth B_a** corresponding to the axion linewidth

$$P_{\mathrm{noise}} = Gk_B(T_{\mathrm{cav}} + T_{\mathrm{ampl}})B_a = Gk_B T_{\mathrm{sys}} B_a$$

Cavity noise + amplifier noise

T_{ampl} = amplifier noise temperature
G – gain ; k_B – Boltzmann constant
T_{sys} = total system noise temperature

- The **SNR** can be calculated with **Dicke's radiometer equation** for a **measurement time t_m**

$$\mathrm{SNR} = \frac{P_{\mathrm{axion}}}{k_B T_{\mathrm{sys}}}\sqrt{\frac{t_m}{B_a}}$$

- Since all the frequencies within a cavity bandwidth can be scanned simultaneously, we can calculate a **scanning rate** as

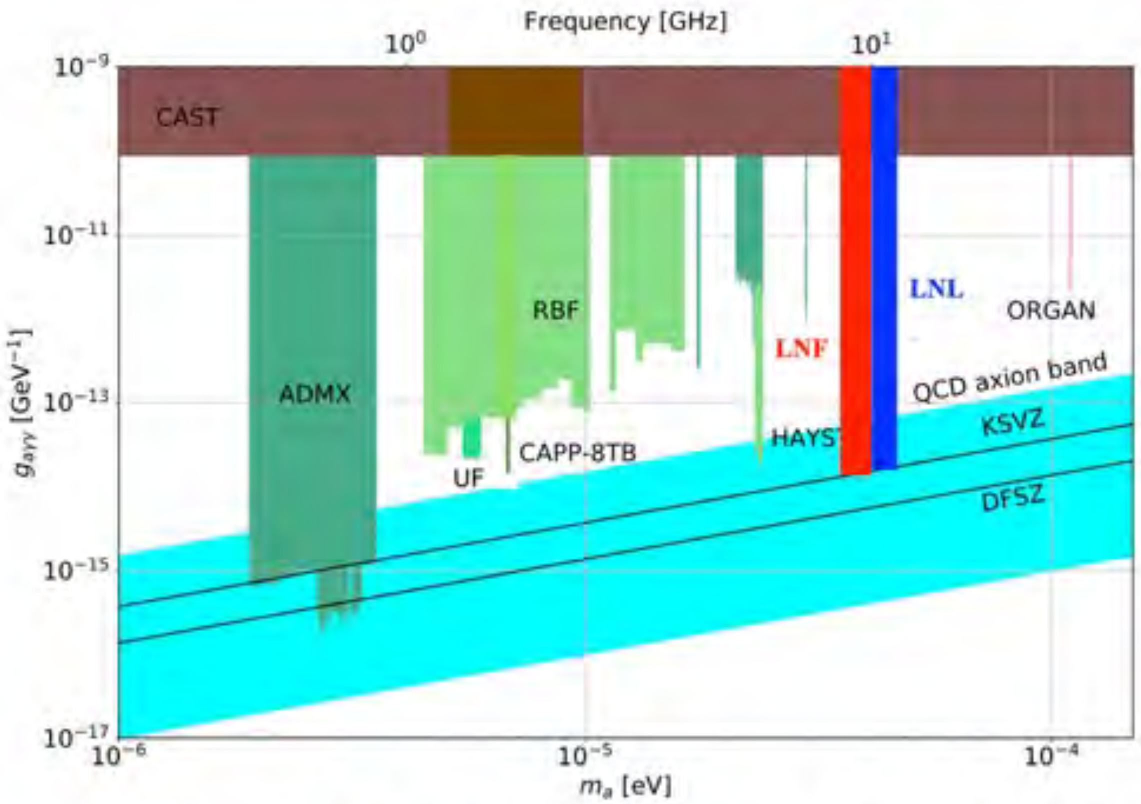
$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2}\frac{P^2_{\mathrm{axion}}}{k_B^2 T^2_{\mathrm{sys}}}\frac{Q_a}{Q_L}$$

Major R&D efforts are made to **increase $B_0^2\ V\ C_{mnl}\ Q_c$** and **minimizing T_{sys}**

QUAX experiment

- In 2020 INFN **has financed the QUAX experiment** to run an observatory for searching axion via the **axion-photon coupling in the unexplored region around 10 GHz**

- **QUAX is based on two haloscopes**: one in **Legnaro (LNL)** and the other in Frascati (**LNF)**



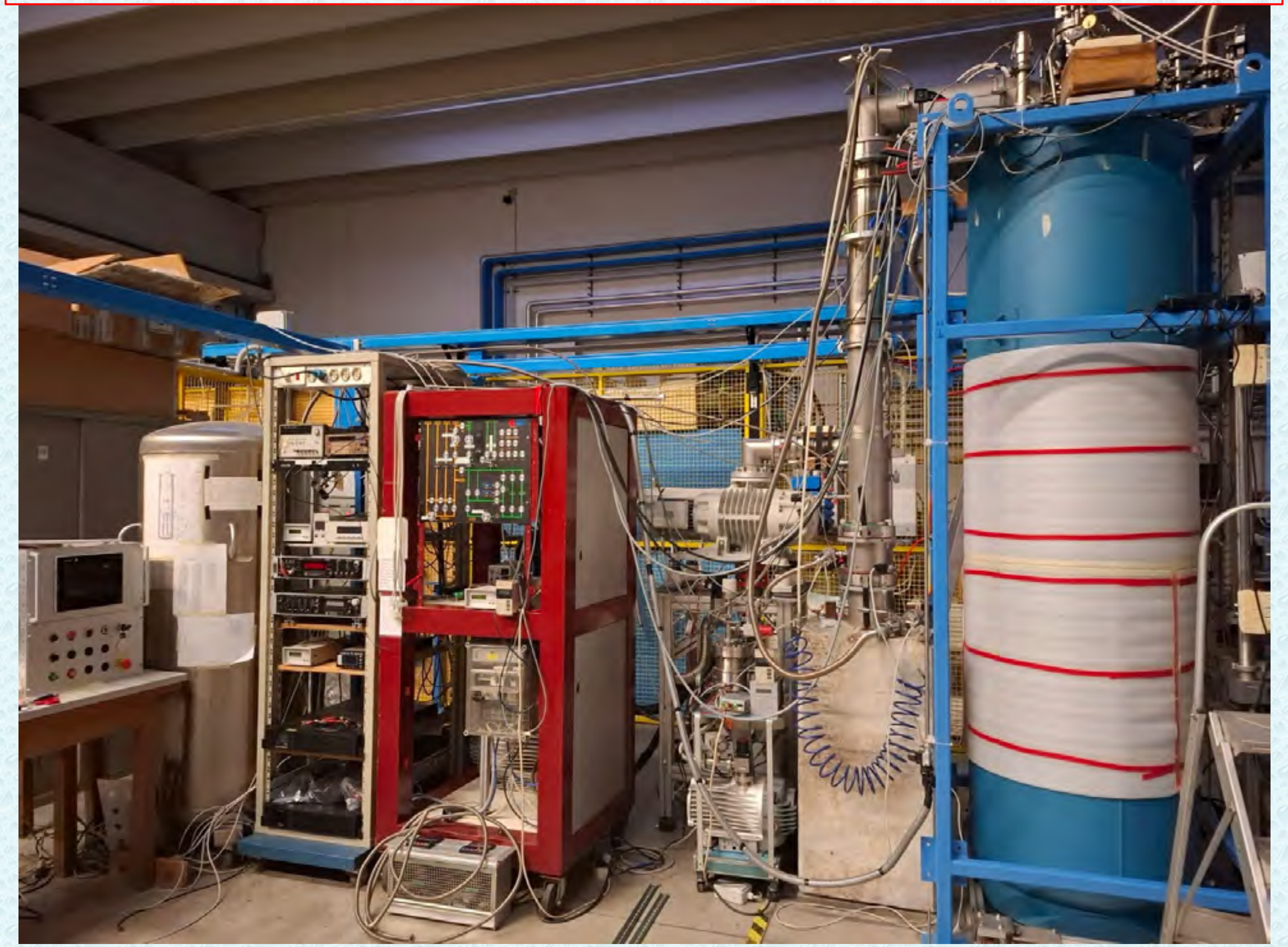
	LNF	LNL
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	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

- The **LNL haloscope** will be based on dielectric loaded cavities, traveling wave parametric amplifiers and 14 T magnet

- Cryogenic system a dilution refrigerator to work below 60 mK

Refrigeration system

QUAX main criostat with gas handling system and safety control

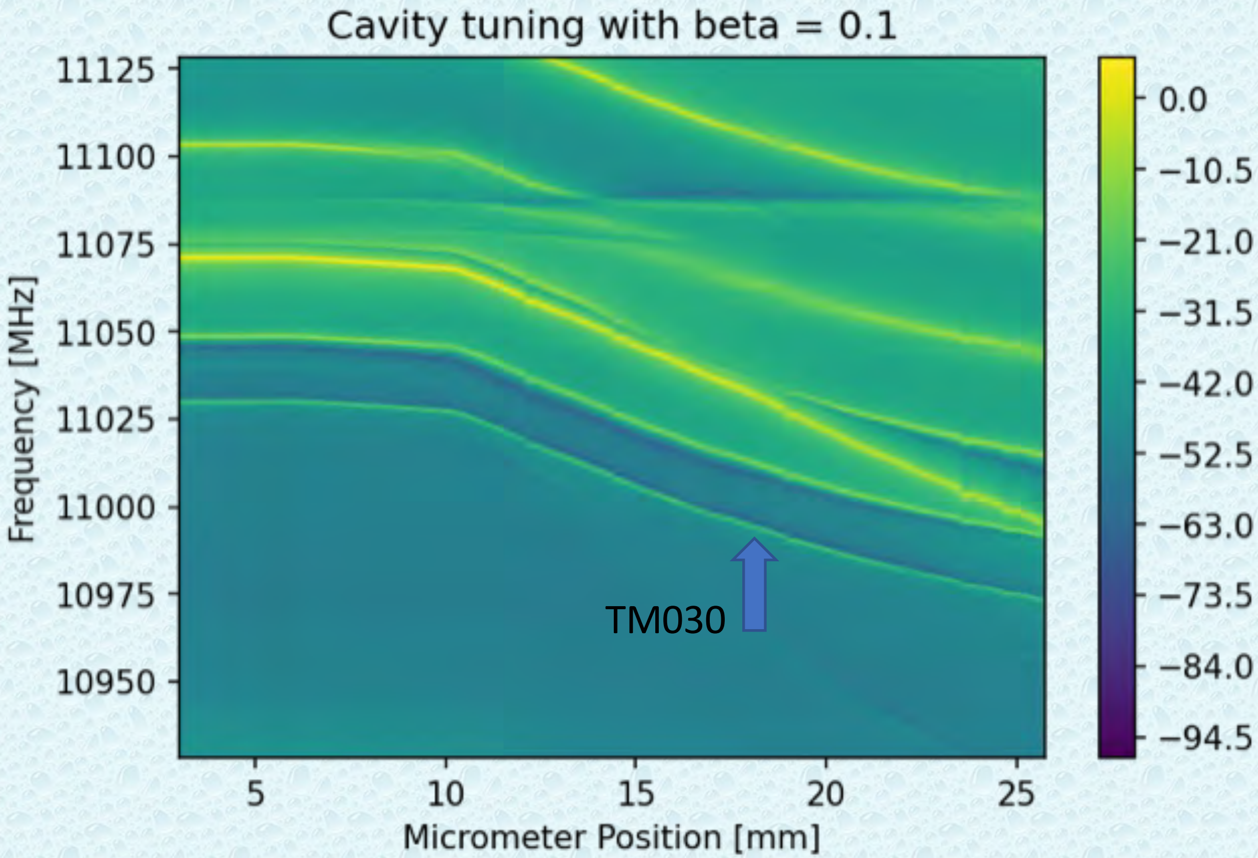


- Refurbished wet dilution unit from AURIGA experiment
- Base temperature @ MC 50 mK
- Cavity and electronics kept @ 100 mK

Gold Plated heat shield

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
- Good coupling to axion field (C factor)
- Bead pulling measurements



Dedicated test station for cavity characterization @ 4 K

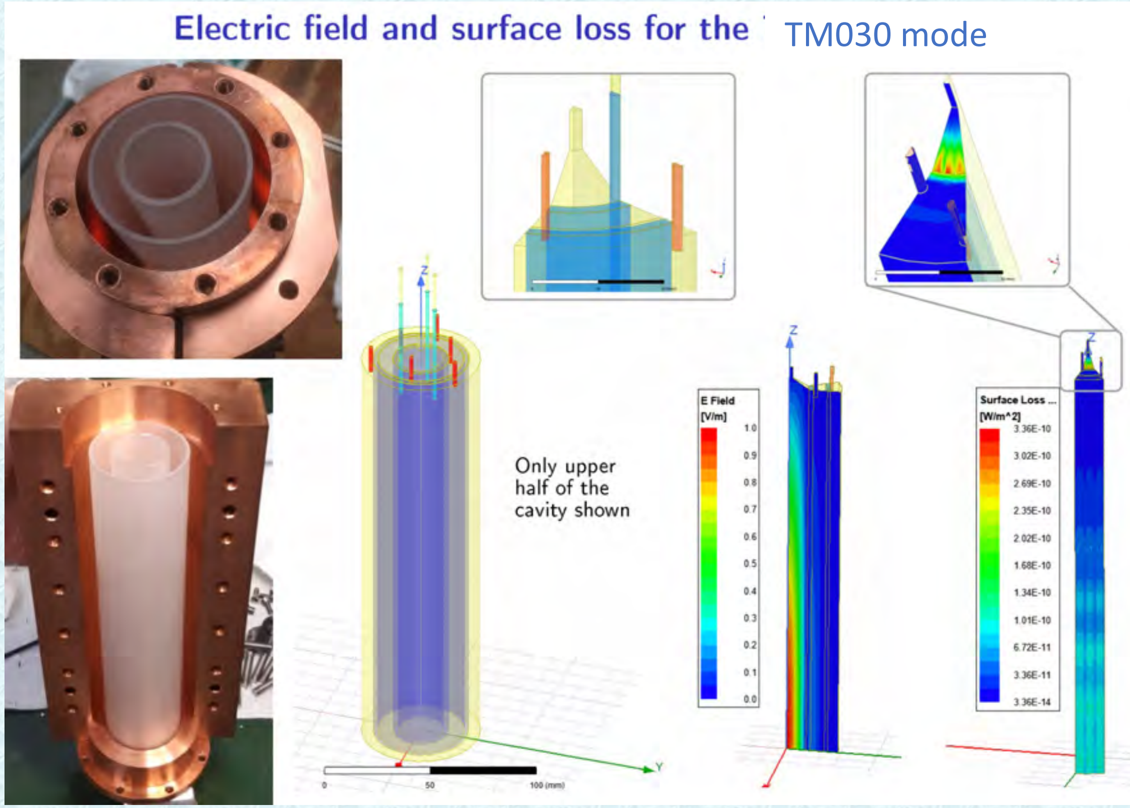
Q_0 ~ 200 k
Maximum tuning ~ 100 MHz

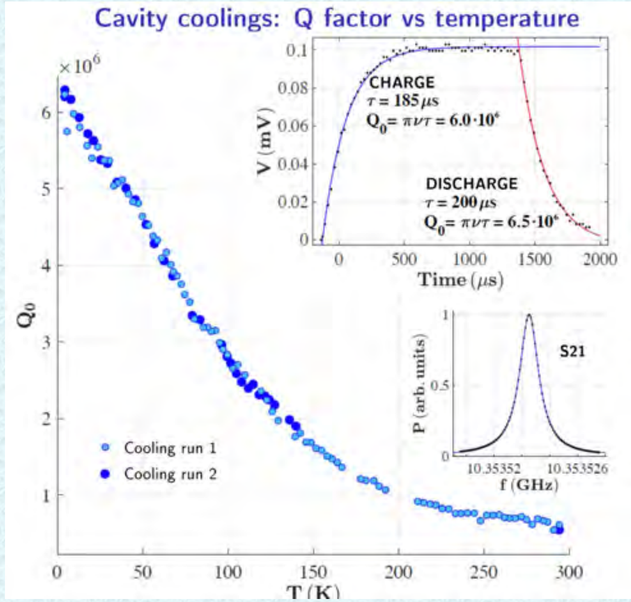
QUAX publications on cavities
- **A new class of axion haloscope resonators: the polygonal coaxial cavity – PRApplied,** 23, 034047 (2025)
- **A tunable large volume dielectric cavity at 11 GHz – under review on Rev Sci Instrum**
- A tunable clamshell cavity for wavelike dark matter searches - RSI 2023
- 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

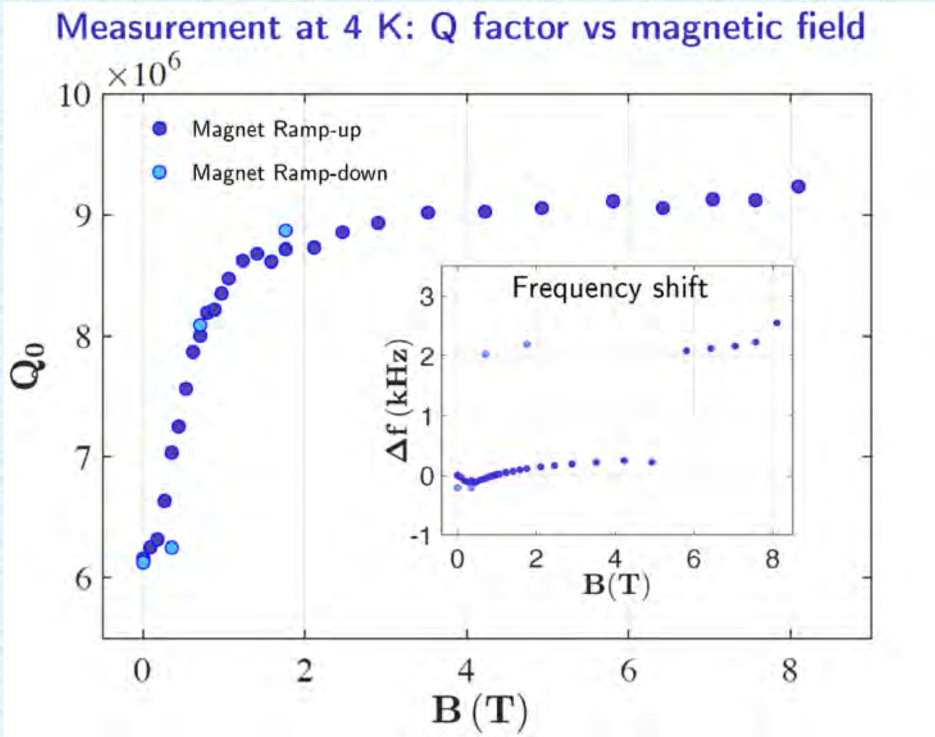
Dielectrically loaded cavity – High Q

First realization of a **dielectrically loaded cavity** made by **two concentric sapphire cylinders** to operate in a strong magnetic field

Exceptional Q value ~ 10 Million in an 8 T field







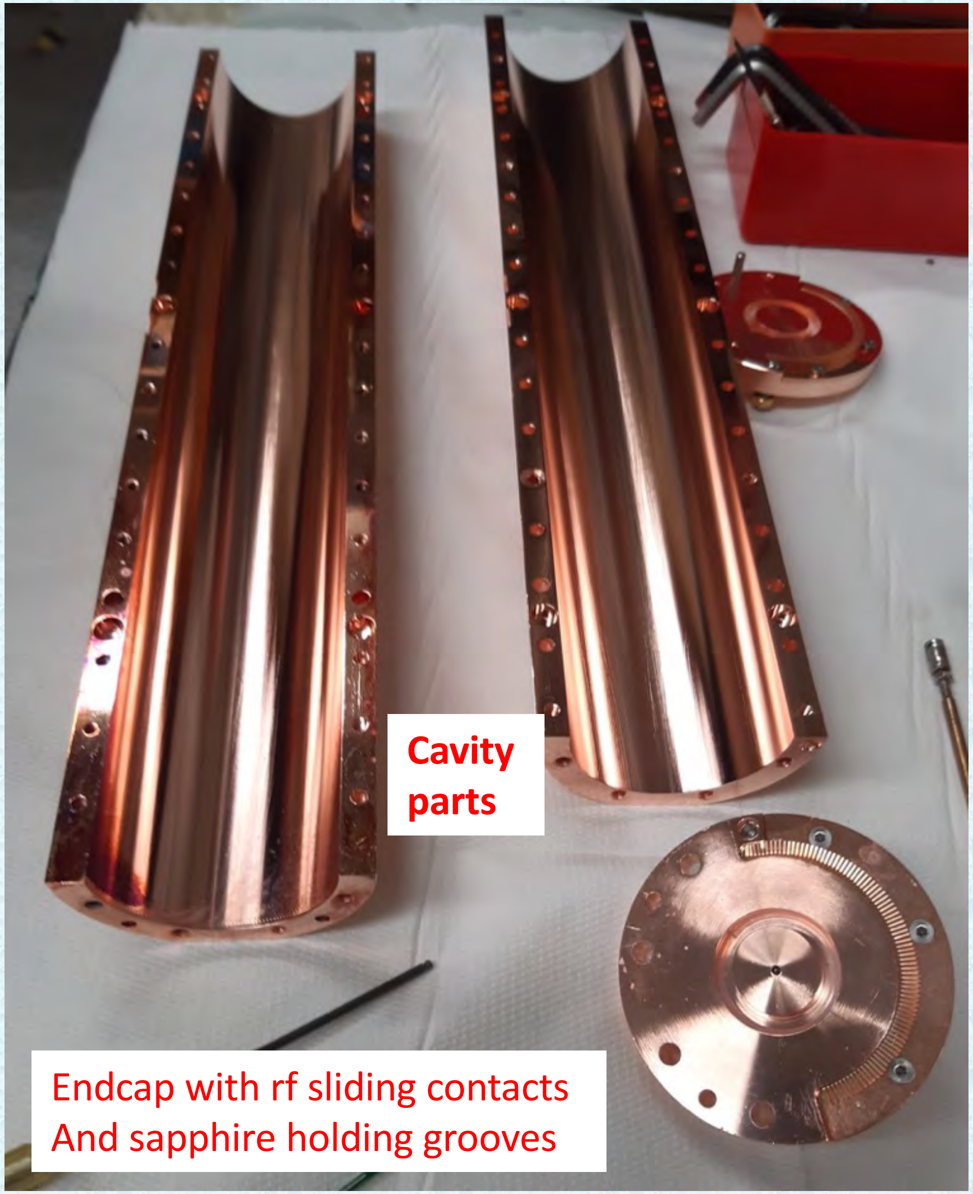
- Limited tuning of ~ 1.5 MHz
- Very poor coupling to axion field C_{mnl} = 0.034

Pilot run PRD 106, 052007 (2022)

Dielectrically loaded tunable cavity – single sapphire

Right cylindrical hybrid cavity

Copper shell
Sapphire cylinder inside



Clamshell mechanism for tuning

Base frequency 10.2 GHz

LAMED TC

(Phoenician: Goad)

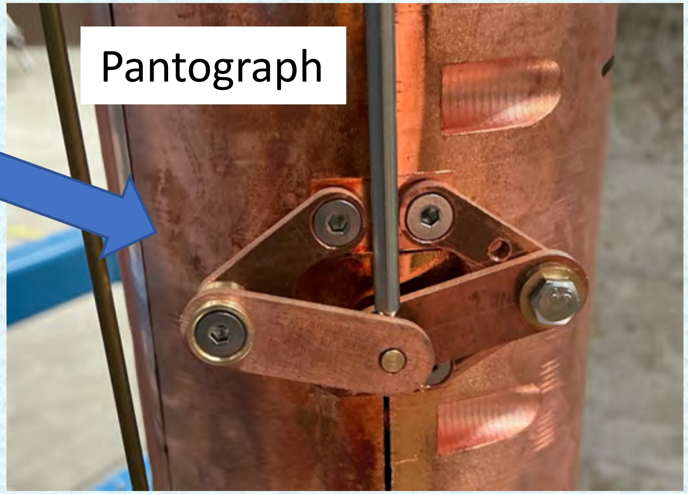
𐤋

Inner length = 413.4 mm
Inner diameter = 60.5 mm
Volume = 1.17 liters

Dielectrically loaded tunable cavity – single sapphire

LAMED TC

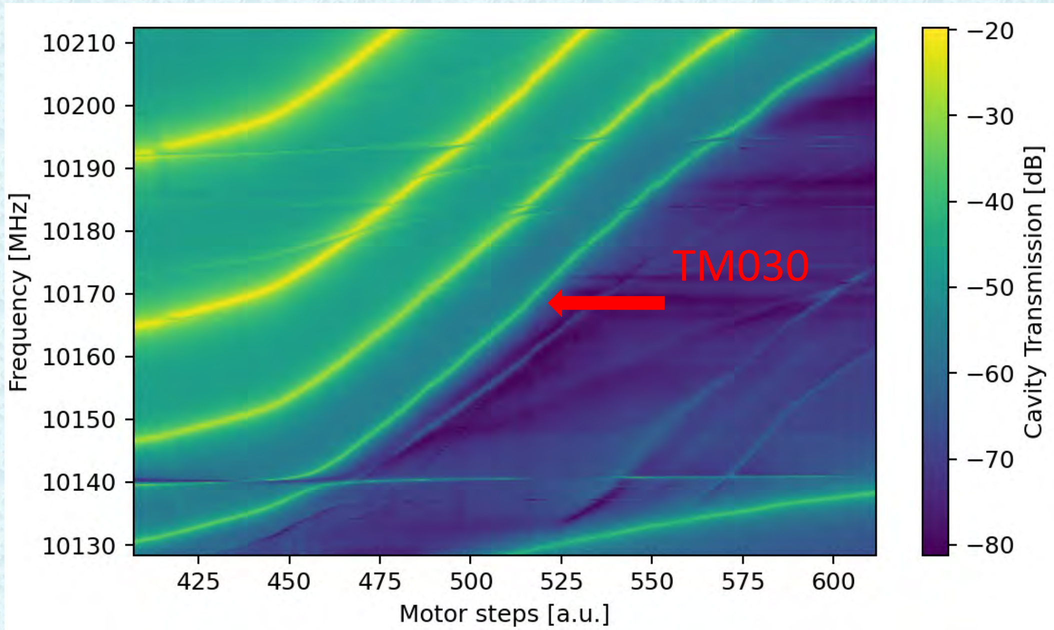
(Phoenician: Goad)



Inner length = 413.4 mm
Inner diameter = 60.5 mm
Volume = 1.17 liters, C_{mnl} = 0.43

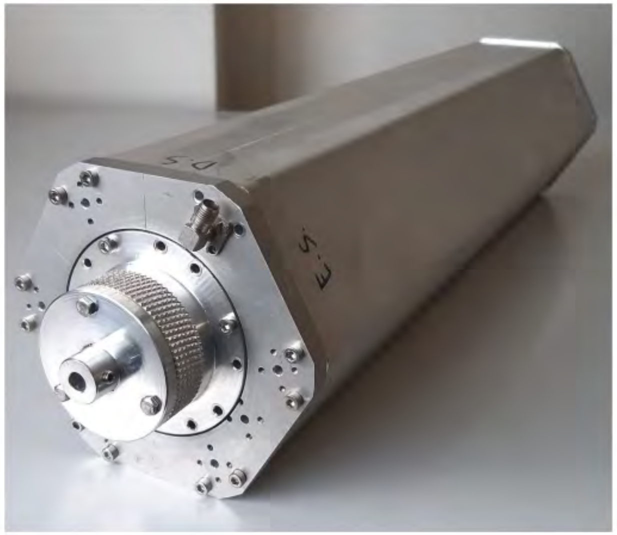
- Rame OFHC Copper
- L = 420 mm sapphire cylinder (from Armenia)
- Movable side wall - clamshell mechanism
- Single body endcaps
- Endcaps with 5.3 mm deep grooves for sapphire holding
- Copper Rf sliding contacts
- Motor actuated pantograph-like aperture mechanism
- Teflon 1.1 mm diameter to keep sapphire centered
- Tuning 85 MHz
- Q0 ~ 80 000

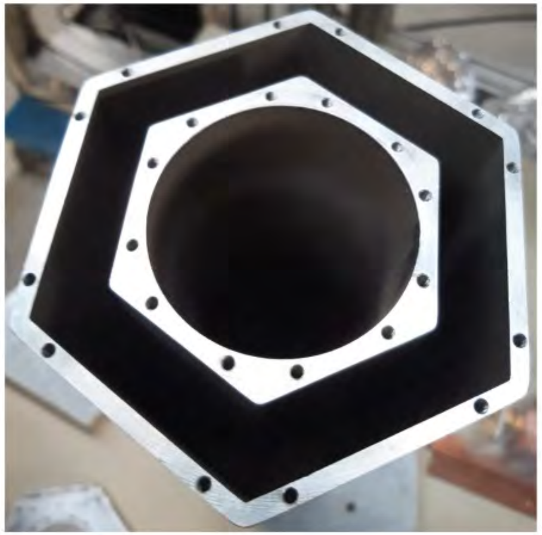
Tuning

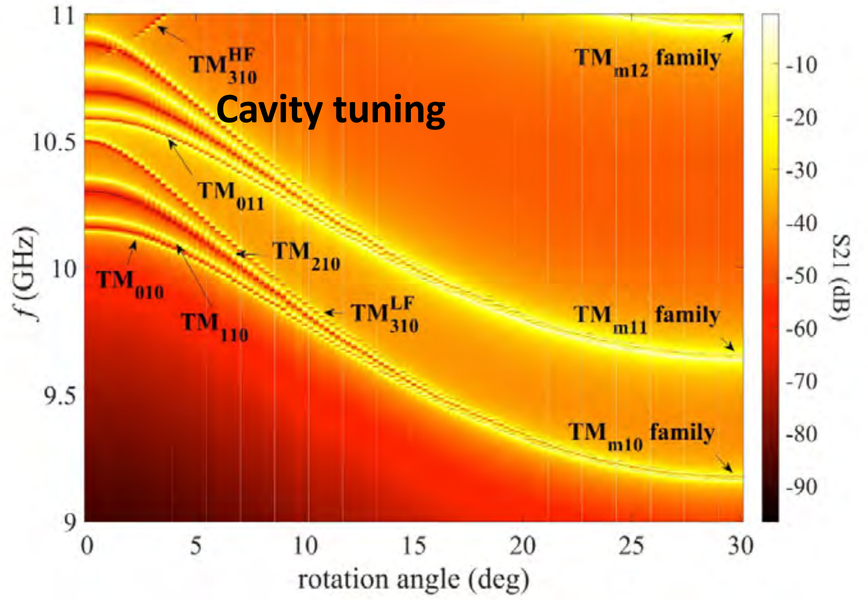


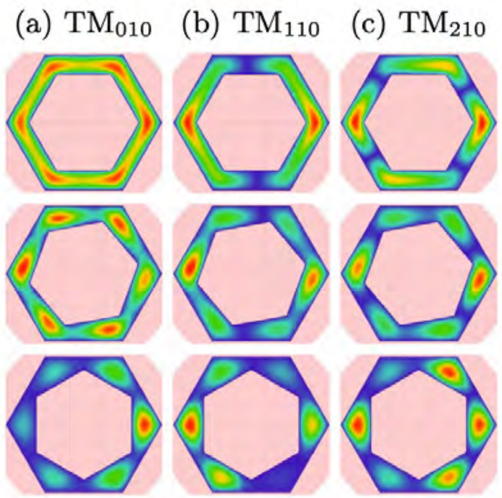
LNL Haloscope – High Frequency Tunable Cavities

A new class of axion haloscope resonators: the polygonal coaxial cavity









0 deg

10 deg

30 deg

For L = 420 mm effective volume = 2 liters * 0.8 = 1.6 liters

Available tuning about 5% of maximum frequency

R. Di Vora et al, Phys. Rev. Appl. 23, 034047 (2025)

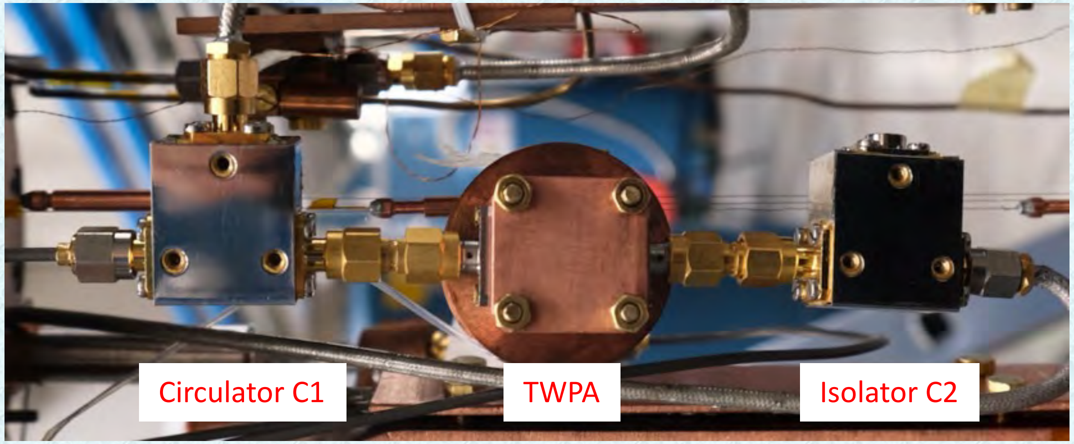
Magnetic field

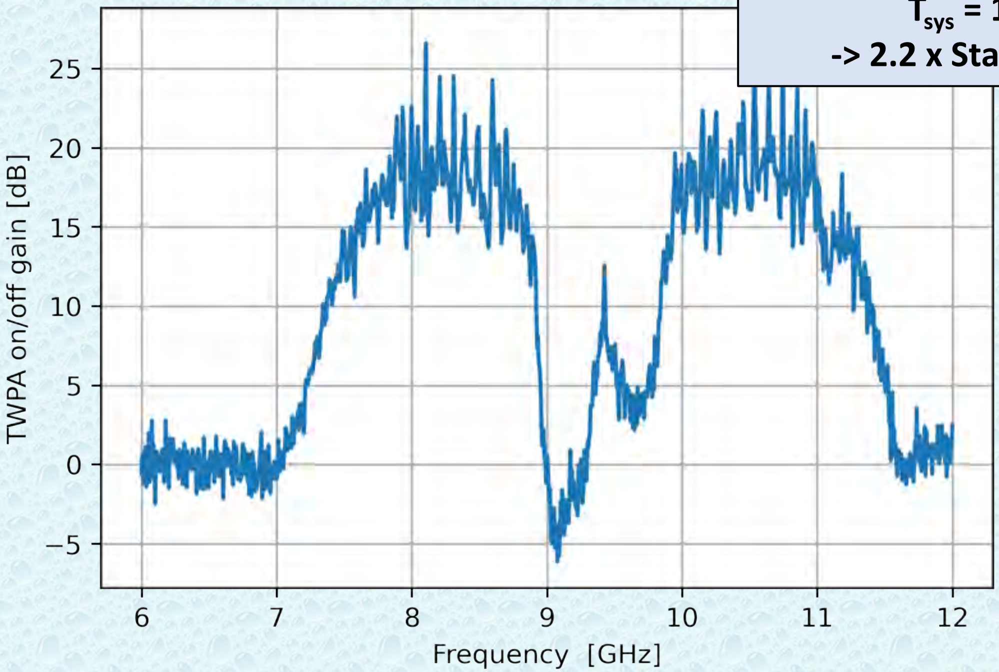
- Counter field magnet, NbTi superconducting coil
- Inner diameter 150 mm, height 250 mm
- Same driving current of main magnet
- Reduces stray field below 40 mT on sensitive electronics (passively shielded too!)

- Main magnet, NbTi superconducting coil
- 450 mm length, 150 mm inner diameter
- Peak field 8.0 T @ 92 A current
- Square field integral 50.2 T^2 m

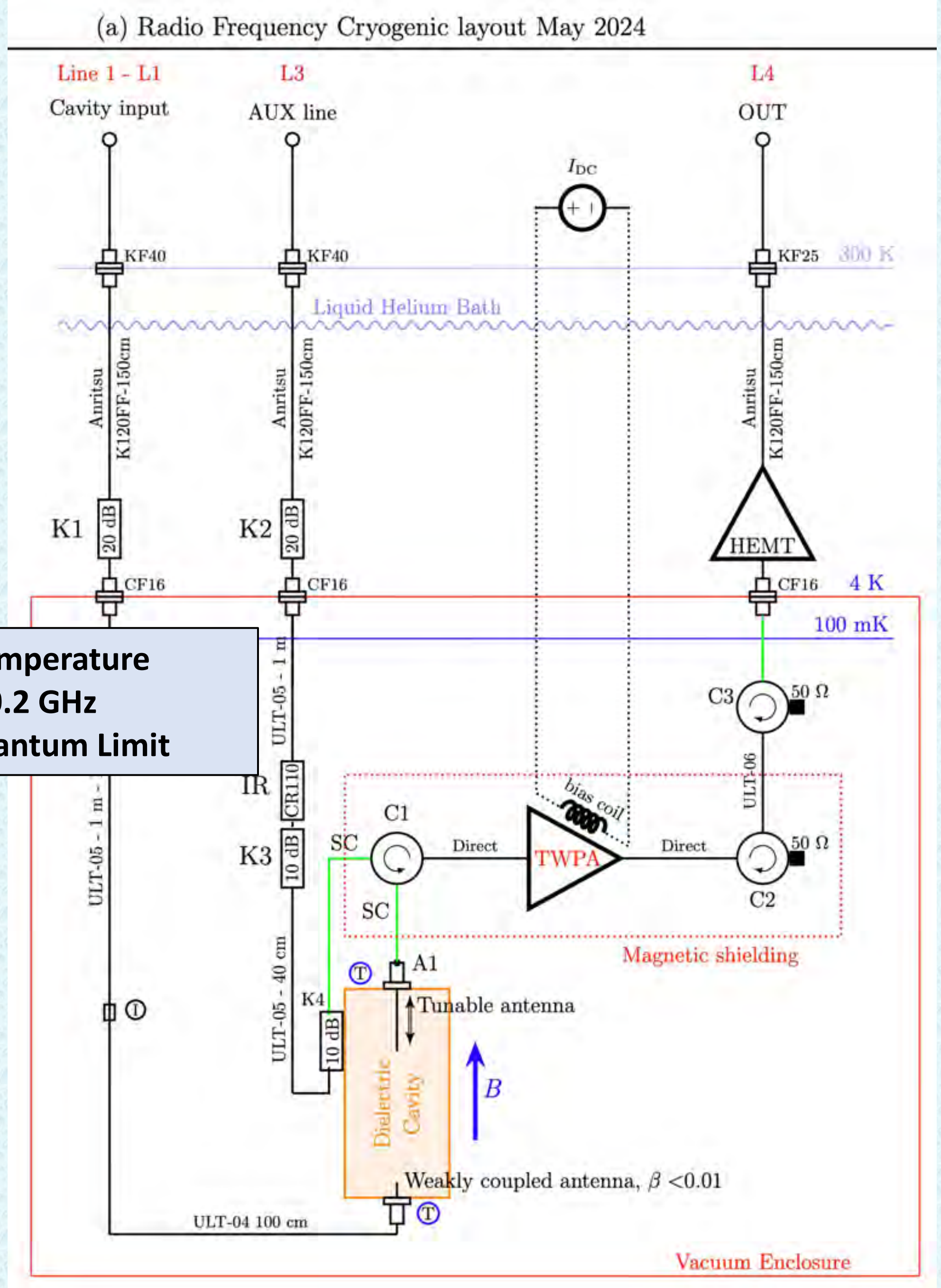
RF Receiver

The 10 GHz low noise receiver is based on a Traveling Wave Parametric Amplifier (TWPA - from N. Roch (Grenoble))





Measured Noise Temperature
T_{sys} = 1.1 K @ 10.2 GHz
-> 2.2 x Standard Quantum Limit

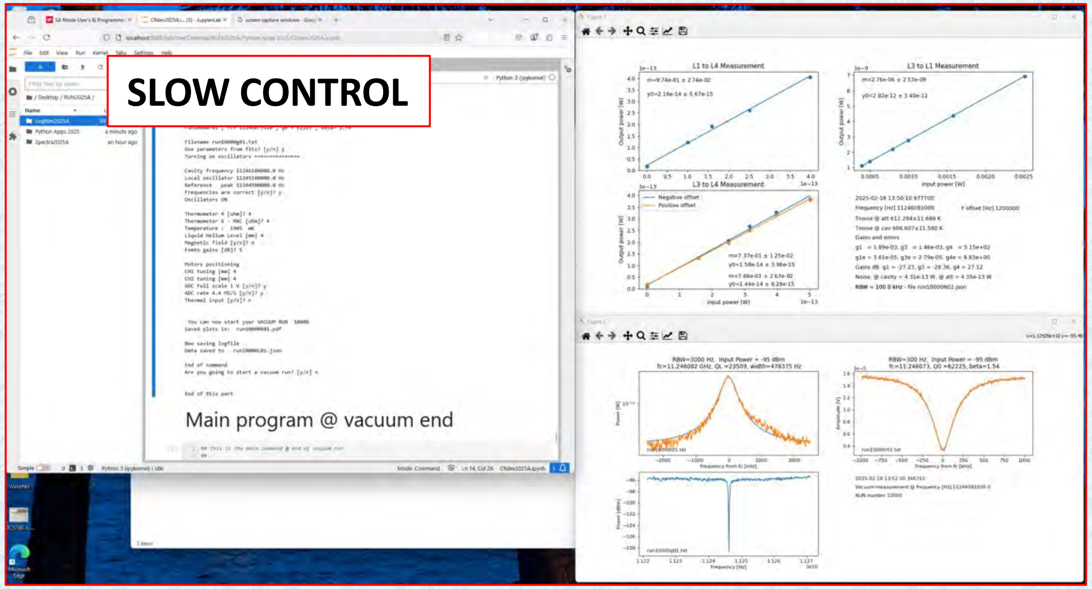


Run control

Run steps:

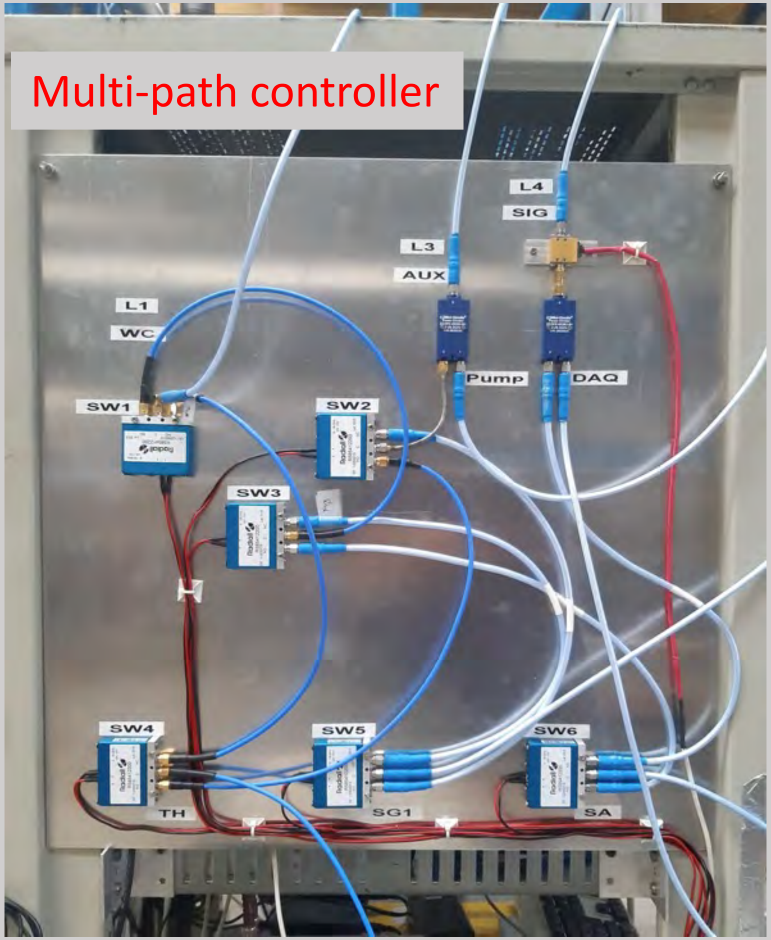
1. Cavity tuning (manual)
2. TWPA amplifier optimization (manual)
3. Measurement of Tsys and Gain (2 m)
4. Measurement of f_c, Q_L, Q_0 , gain profile (2 m)
5. Short data acquisition with thermal input (2 m)
6. Repeat steps 3-4 (4 m)
7. Long data acquisition with no input (65 m)
8. Repeat steps 3-4 (4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

Time for a single point 80 - 100 minutes



All measured parameters, data and spectra saved to Logfiles

Noise Temperature Measurement @ every step



Original idea published in

A haloscope amplification chain based on a traveling wave parametric amplifier – Rev. Sci. Instrum. 2022

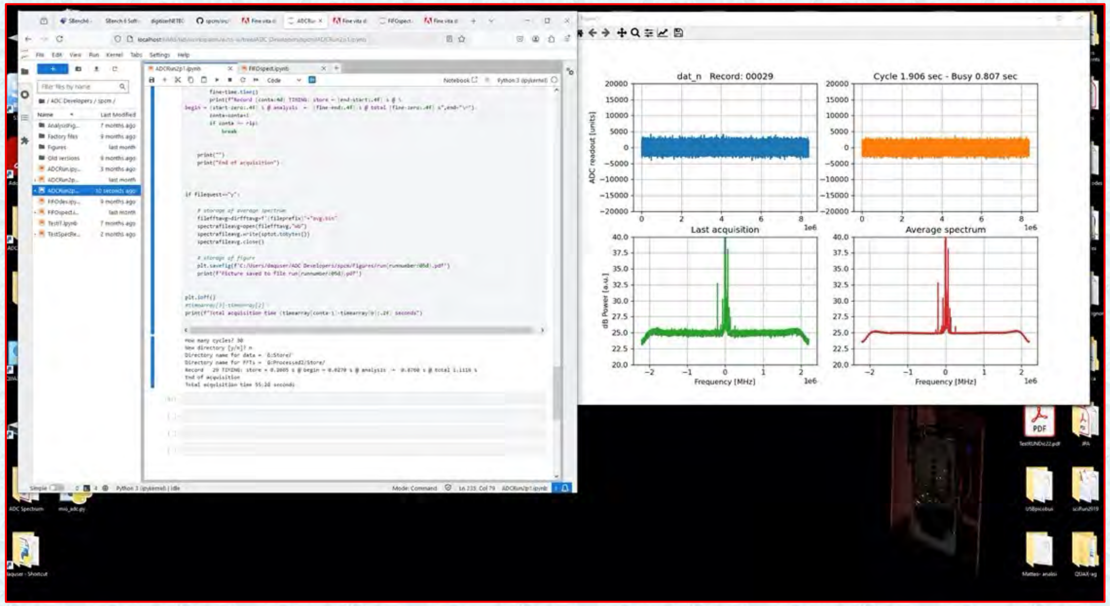
Data acquisition

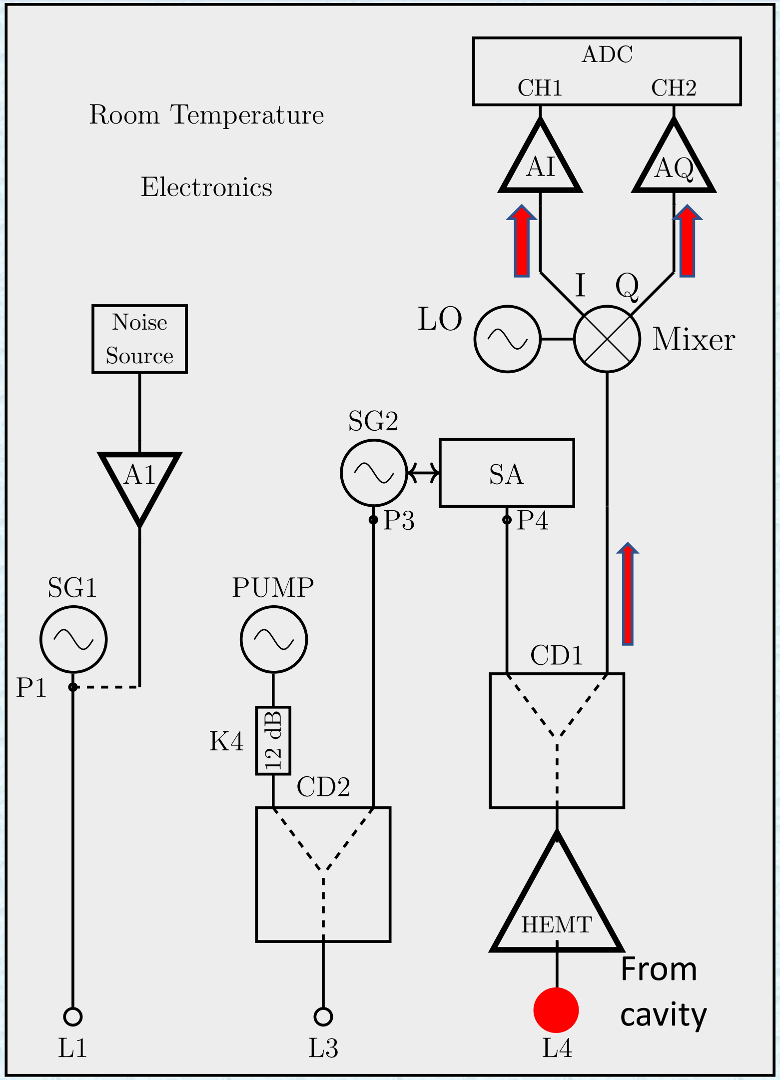
- 2- channel acquisition (I, Q from Mixer)
- **Sampling rate** = 4.4 MS/s
- Single block length 2^23 = 8 388 608 samples
- Single block length = 1.908 s

- **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**

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

ADC CONTROL





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

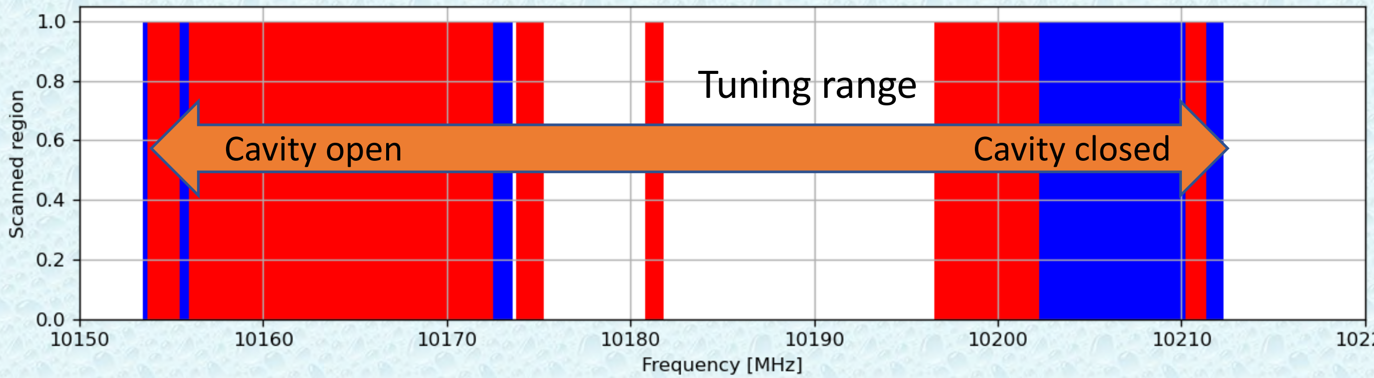
Total memory storage up to about 20 TByte

QUAX RUN 2024

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 = 1.16 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**



Spring session

Autumn session

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

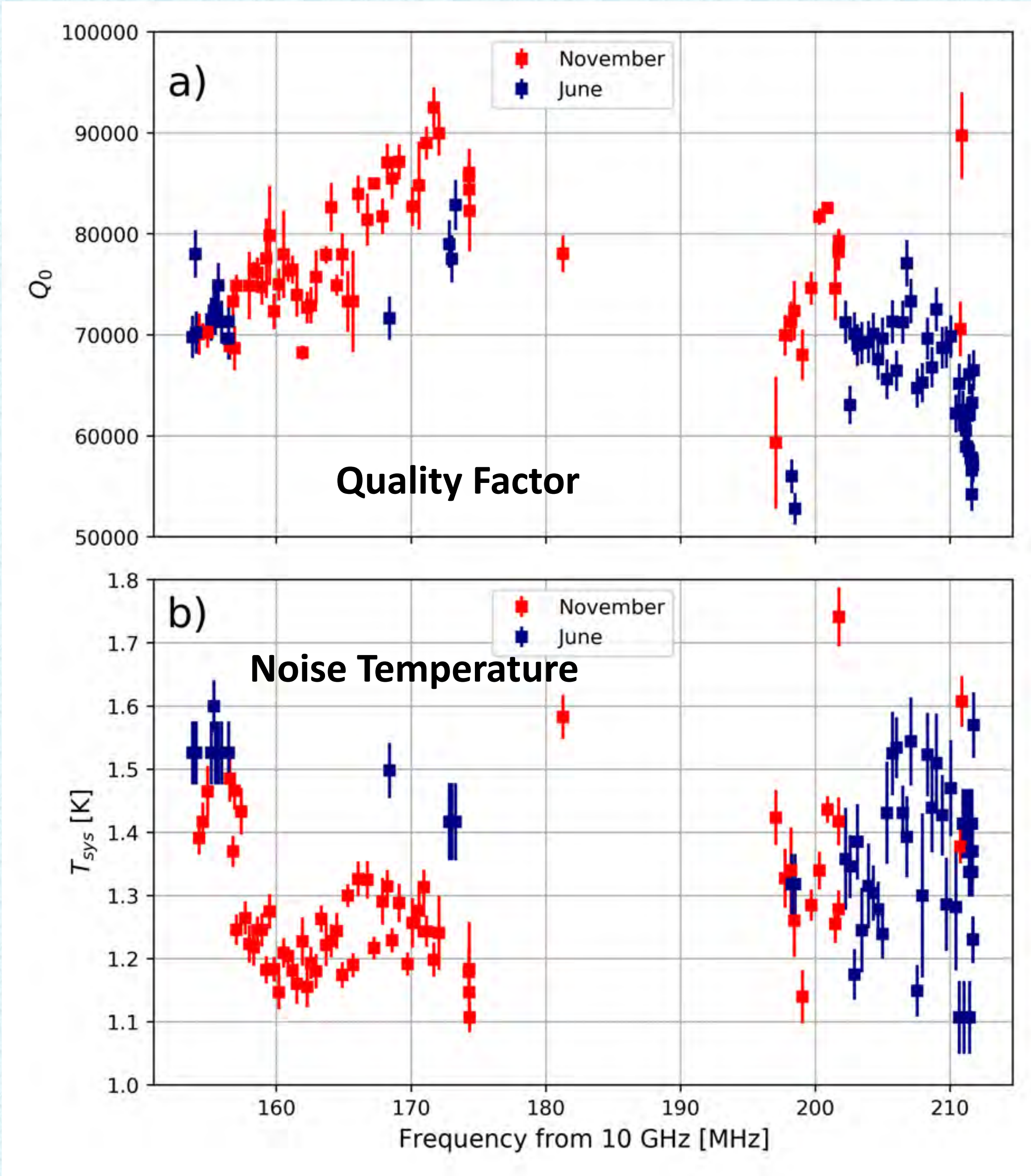
Ratio: 65% of available scan

Duty cycle 50%

Effective scan rate about

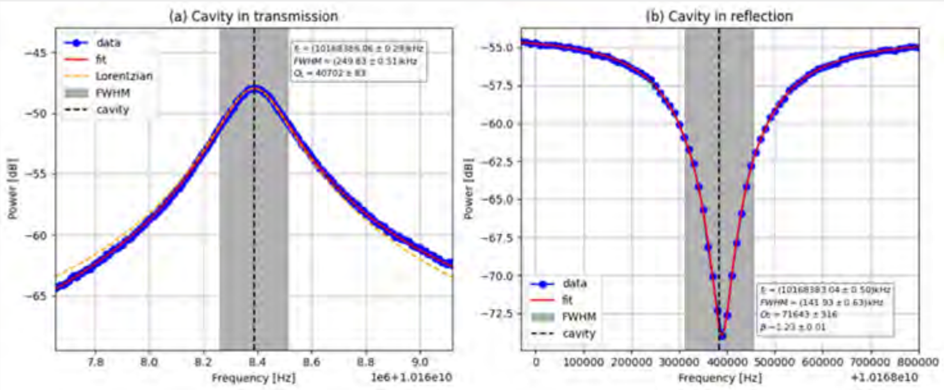
100 kHz/hour

2.5 MHz/day



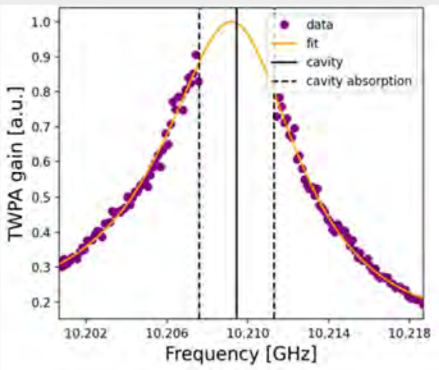
Data analysis

Parameter evaluation (β, f_c, Q_0, Q_L)

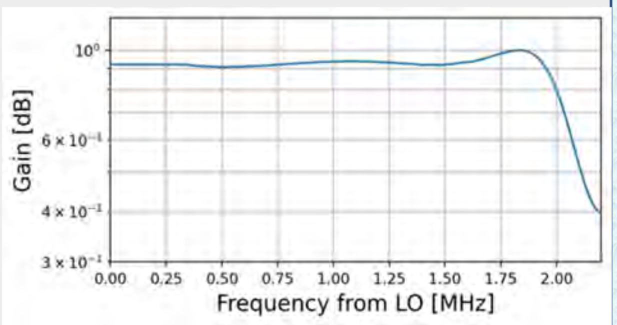


Remove freq-dependent

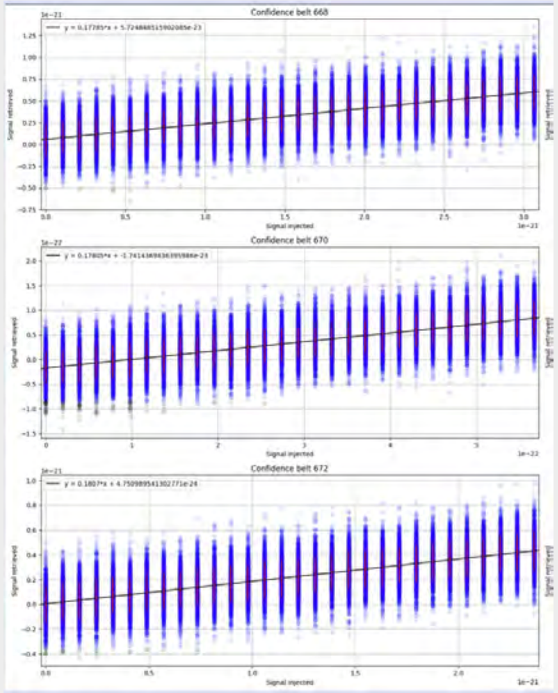
TWPA



Filters



- Average FFT of single frequency steps (bin = 268 Hz)
- Baseline removal with Savitzy Golay filtering
- Monte Carlo simulations to build confidence belts and look for excess power



$$P_{\rm in}^{a}(\nu,\nu_a) = g_{a\gamma\gamma}^2 \frac{\hbar^3 c^3 \rho_a}{m_a^2} \frac{2\pi\nu_a}{\mu_0} f_a(\nu,\nu_a)$$

Axion power

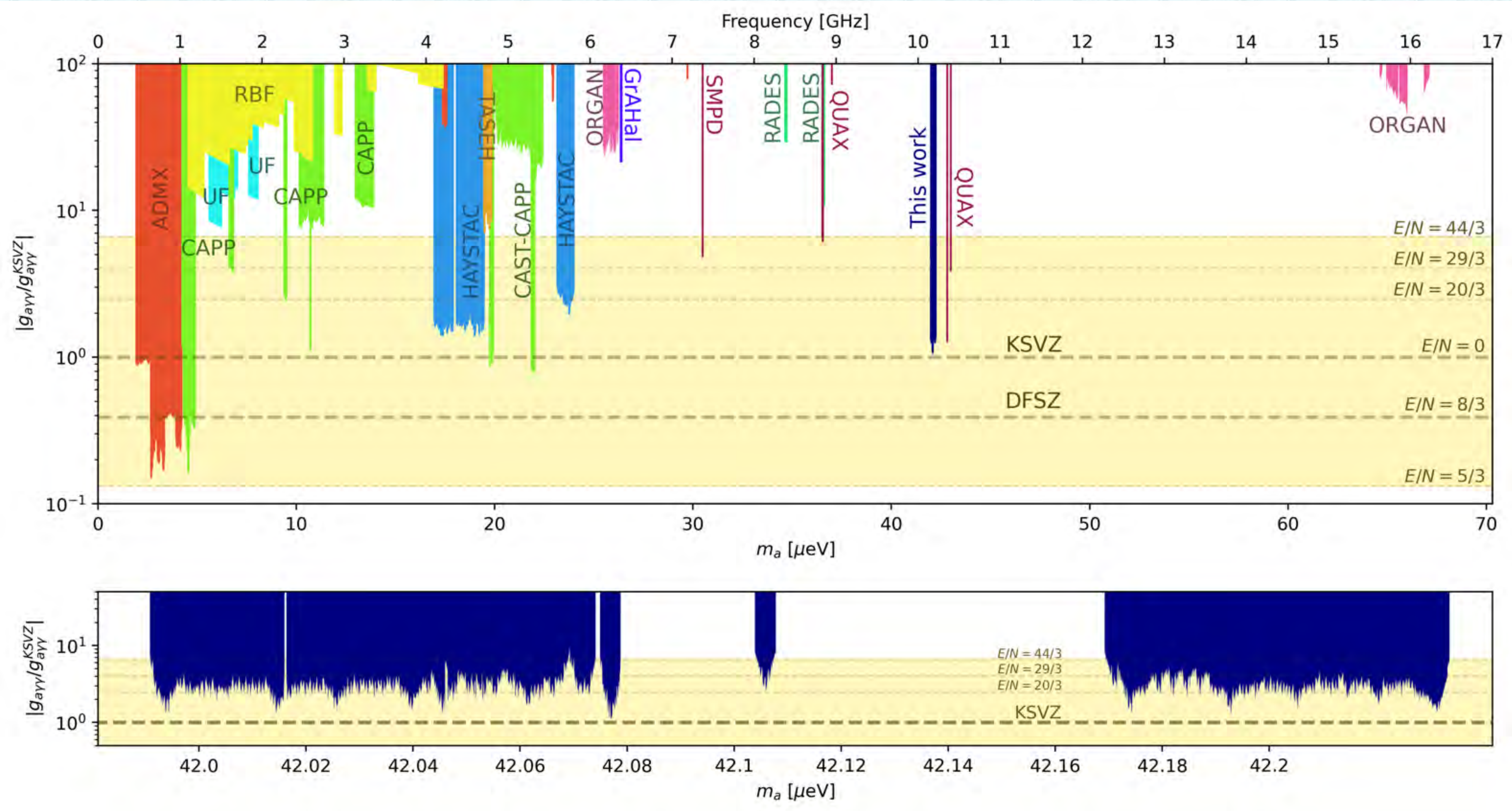
$$f_a(\nu,\nu_a) = \frac{2}{\sqrt{\pi}}\sqrt{\nu-\nu_a}\left(\frac{3}{1.7\nu_a\langle\beta_a^2\rangle}\right)^{3/2} e^{-\frac{3(\nu-\nu_a)}{1.7\nu_a\langle\beta_a^2\rangle}},$$

Maxwell Boltzmann distribution

QUAX RUN 2024

No candidate signal have been detected with **threshold 4.5 σ**

Axion-photon limits at 90% C.L.

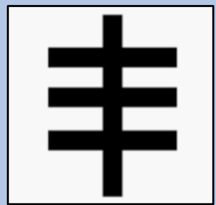


QUAX – the next future

- **Complete scanning of current cavity**
- **Improve run automation**
- **Install** **new cavity with larger tuning**

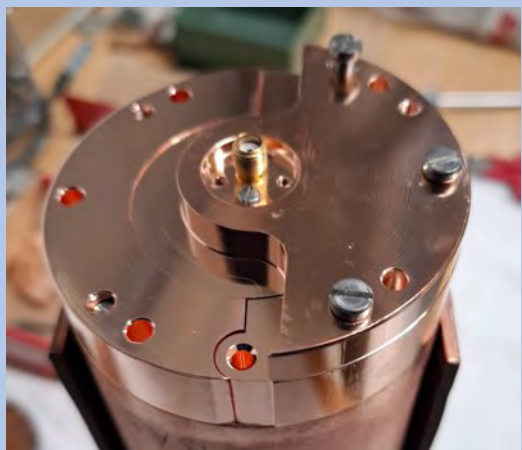
SAMEK 2G

(Phoenician: Pillar)



- New endcaps – two sliding parts
- No rf sliding contacts
- New aperture mechanism

Preliminary result: tuning range 240 MHz (9.96 – 10.20 GHz)



Gravitational waves with QUAX?

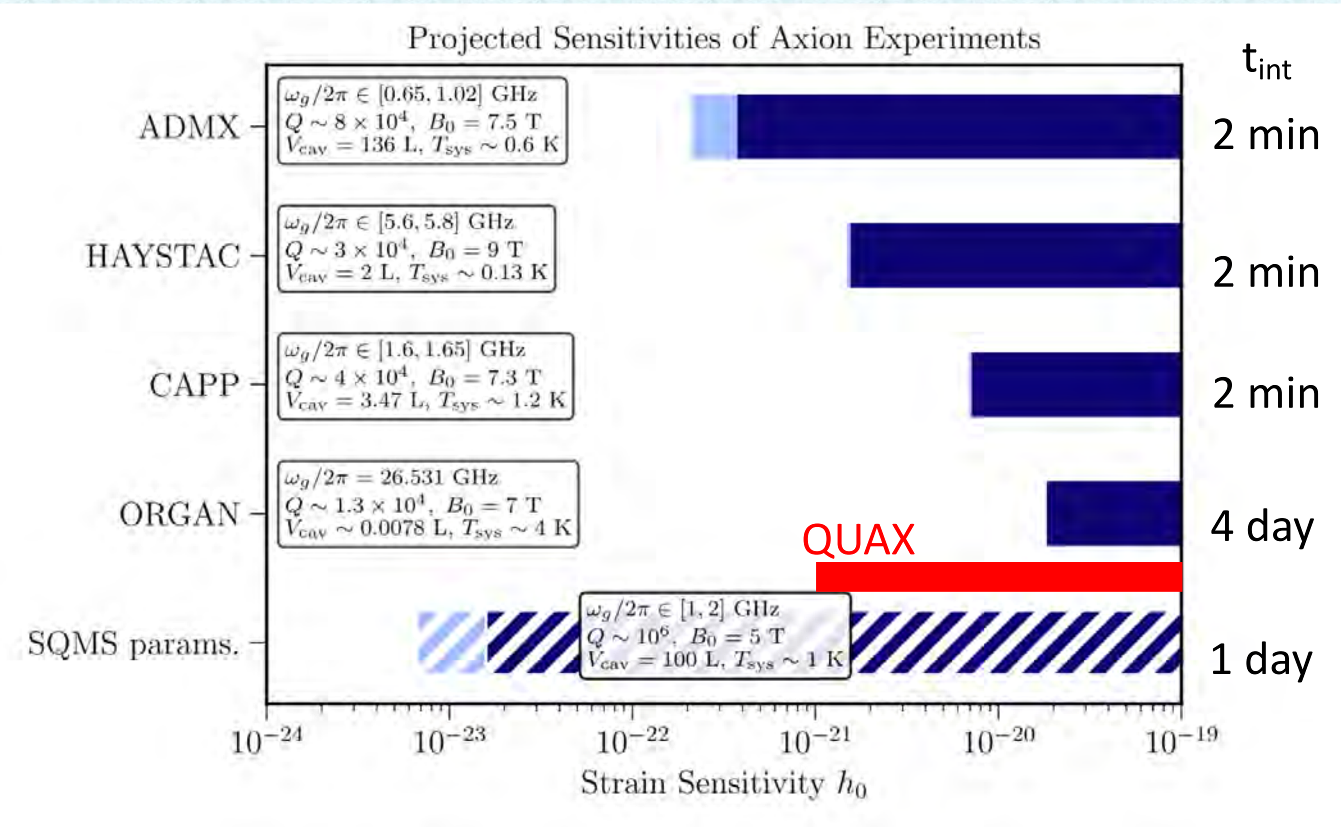
PHYSICAL REVIEW D **105**, 116011 (2022)

Detecting high-frequency gravitational waves with microwave cavities

Asher Berlin,[1,2,3] Diego Blas,[4,5] Raffaele Tito D'Agnolo,[6] Sebastian A. R. Ellis,[7,6]
Roni Harnik,[2,3] Yonatan Kahn,[8,9,3] and Jan Schütte-Engel[8,9,3]

$$h_0 \gtrsim 3\times 10^{-22} \times \left(\frac{1\ \mathrm{GHz}}{\omega_g/2\pi}\right)^{3/2}\left(\frac{0.1}{\eta_n}\right)\left(\frac{8\ \mathrm{T}}{B_0}\right)\left(\frac{0.1\ \mathrm{m}^3}{V_{\mathrm{cav}}}\right)^{5/6}\left(\frac{10^5}{Q}\right)^{1/2}\left(\frac{T_{\mathrm{sys}}}{1\ \mathrm{K}}\right)^{1/2}\left(\frac{\Delta\nu}{10\ \mathrm{kHz}}\right)^{1/4}\left(\frac{1\ \mathrm{min}}{t_{\mathrm{int}}}\right)^{1/4}$$

The GW-cavity coupling coefficient is fixed to η_n = 0.1 for each experiment



QUAX

f = 10 GHz
Q ~ 8 10^4
B_0 = 8 T
V_{cav} = 1 l = 0.001 m^3
T_{sys} ~ 1.1 K
Δν = 250 kHz

η_n ~ 0.04 (?)

Integration time

1 hour

Gravitational waves with QUAX?

- **Coupling coefficient**
  - QUAX uses the TM030 mode
  - Tuning does NOT change the mode shape (what happens in other experiments?)

- **Data taking**
  - I/Q down converted data read with 4.4 MS/s sampling rate
  - Continuos streaming of temporal data are recorded and can be analysed offline

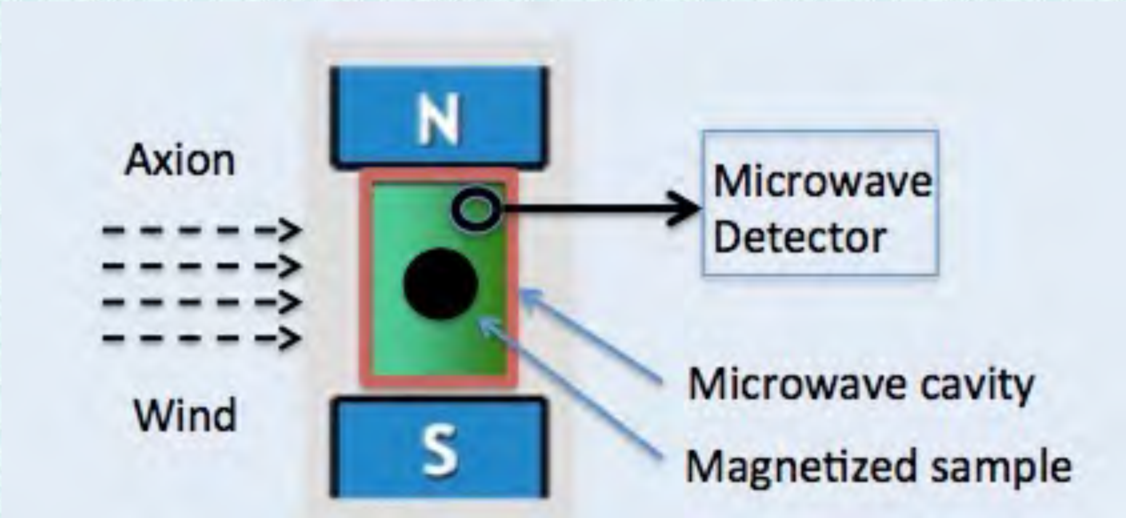
- **Timing**
  - A GPS disciplined oscillator is used as time base and could also provide absolute reference time

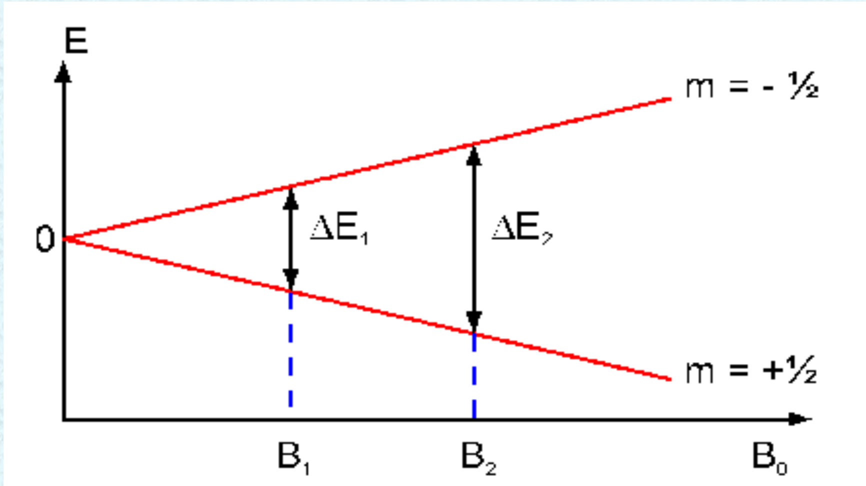
- **Detection chain**
  - TWPA amplifier is wide bandwidth and the detection chain can be easily tuned to different cavity modes in the 8 GHz to 12 GHz (Limited by other components like circulators)

- Standard operation will be ONLY at the axion coupled mode TM030

The ferrimagnetic QUAX: sensing the axion wind

- **Due to the motion of the solar system** in the galaxy, the axion DM cloud acts as an **effective RF magnetic field on electron spin**
- This field excites **magnetic transition in a magnetized sample** (Larmor frequency) and produces a detectable signal



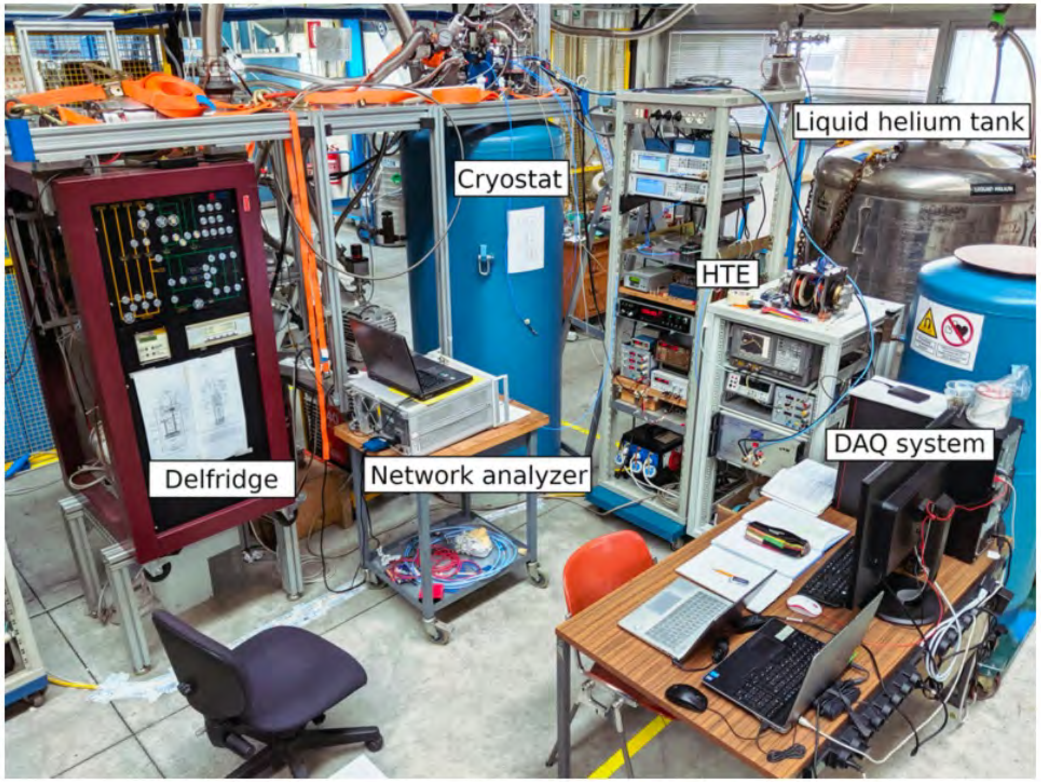


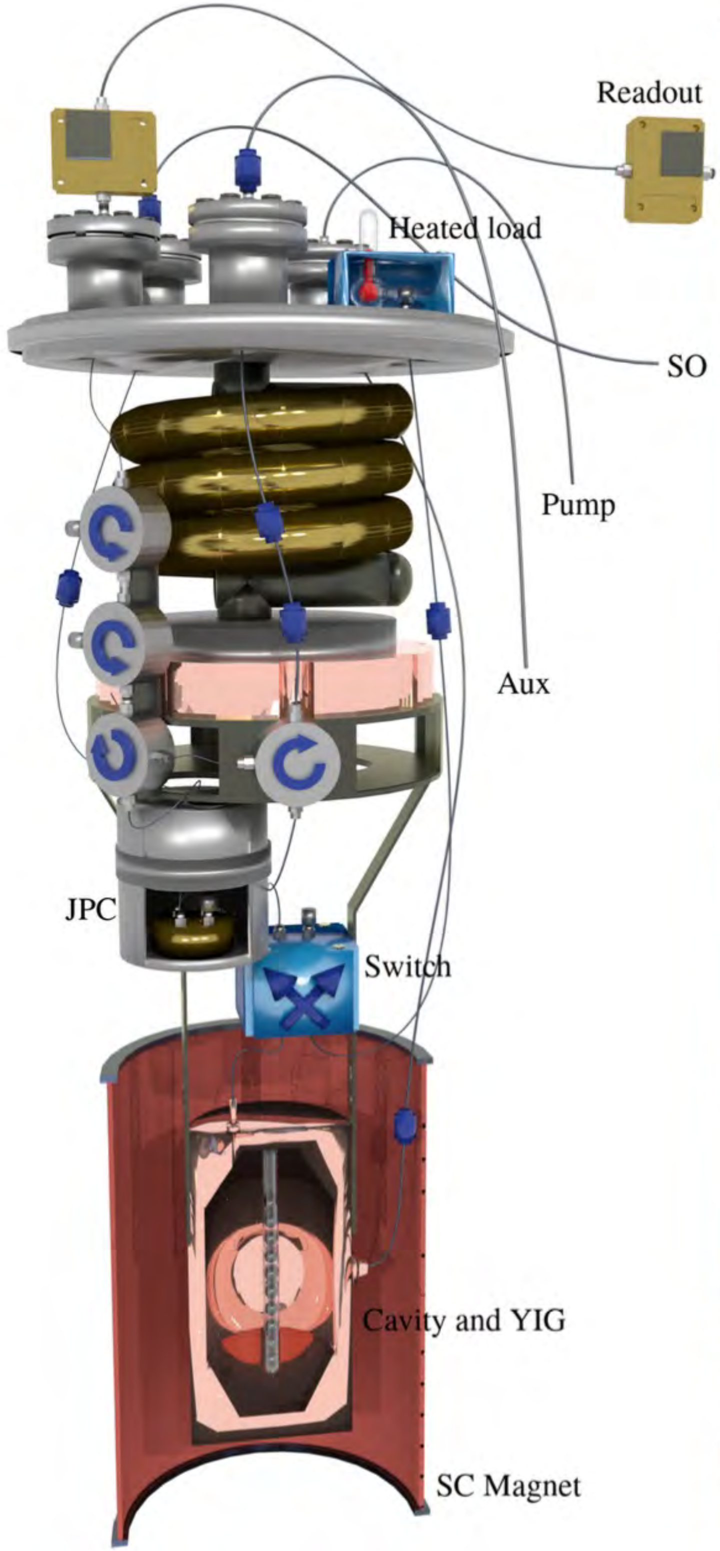
Idea comes from **several old works**:

- L.M. Krauss, J. Moody, F. Wilczeck, D.E. Morris, "Spin coupled axion detections", HUTP-85/A006 (1985)
- R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B 226, 357 (1989)
- F. Caspers, Y. Semertzidis, "Ferri-magnetic resonance, magnetostatic waves and open resonators for axion detection", Workshop on Cosmic Axions, World Scientific Pub. Co., Singapore, p. 173 (1990)
- A.I. Kakhizde, I. V. Kolokolov, Sov. Phys. JETP 72 598 (1991)

Ferrimagnetic QUAX

- **Large volume**
  10 YIG sphere 2.1 mm diameter
- **Reduced noise**
  Quantum limited amplifier (JPC)
  Dilution refrigerator (100 mK)
- **Scan axion mass range**
  Magnetic field tuning

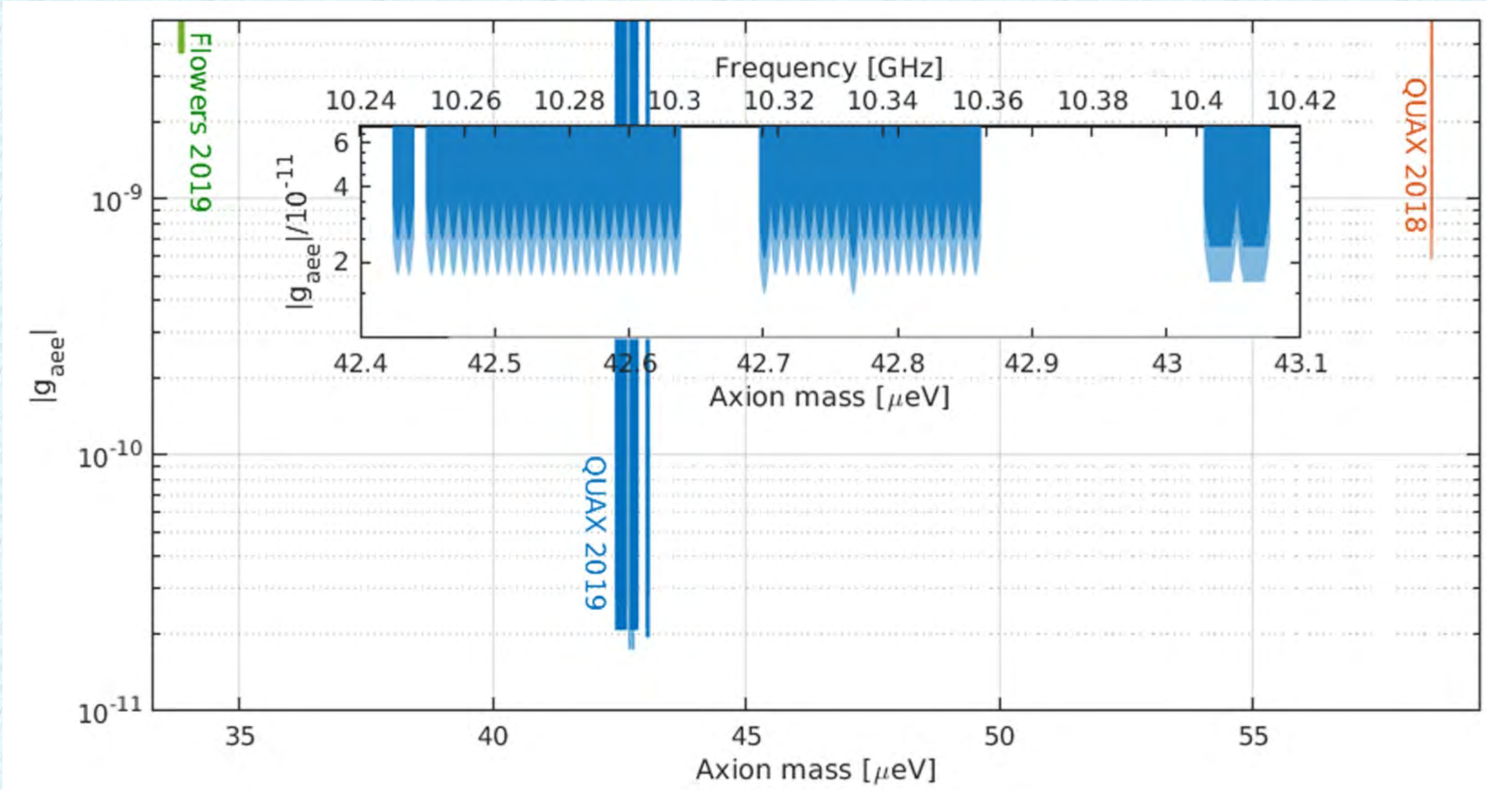




Results

- FFT the data with a 100 Hz resolution bandwidth to identify and remove biased bins and disturbances
- Rebin the FFTs with a resolution bandwidth **RBW ≃ 5 kHz** to look for axion signal
- Look for fluctuations from thermal spectrum
- **The measured fluctuations σ_P compatible with the estimated noise in every run**
- **Assuming DM is 100% made by ALPs ->> 95% CL plot**

$$g_{aee} < \frac{e}{\pi m_a v_a}\sqrt{\frac{k_{ac} \times 2\sigma_P}{2\mu_B \gamma_e n_a N_s \tau_s}}$$



PRL **124**, 171801 (2020)

For the longest run (9 h)
best power sensitivity **σ_P = 5.1 10^{-24} W** → Axion effective field **B_a = 5.5 10^{-19} T**

Gravitational Waves

Eur. Phys. J. C (2020) 80:179
https://doi.org/10.1140/epjc/s10052-020-7735-y

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Probing GHz gravitational waves with graviton–magnon resonance

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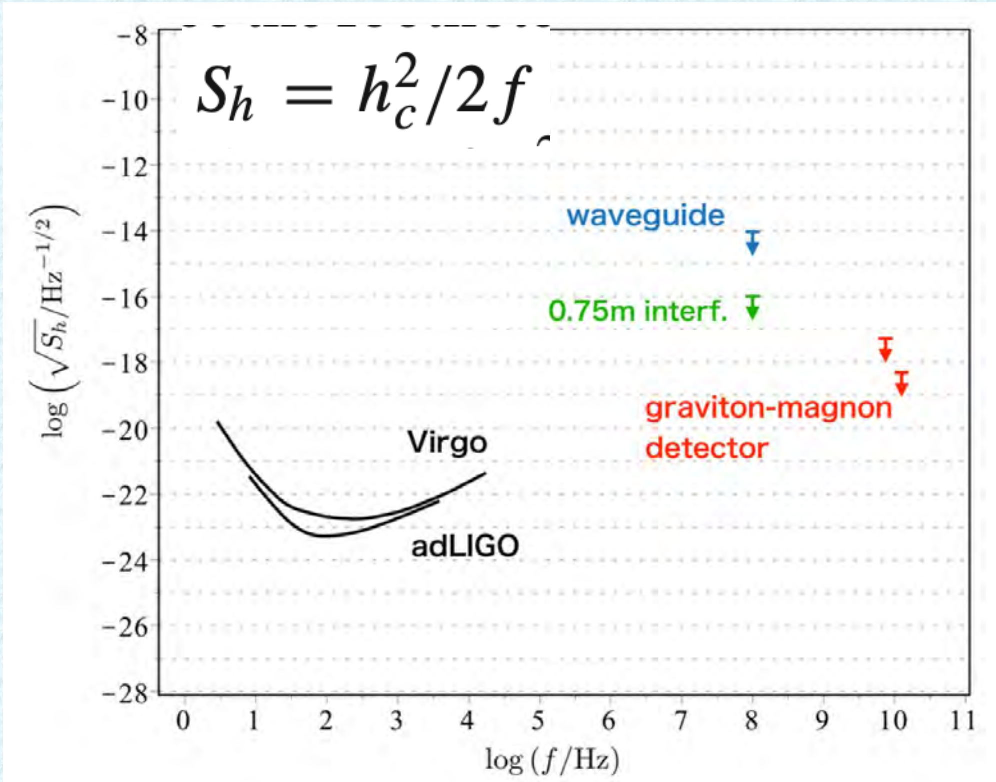
continuous gravitational waves
coming from Cygnus
no linear and circular polarizations
$h_c = h^{(+)} = h^{(\times)}$

Graviton-magnon effective coupling

$$g_{eff} = \frac{1}{4\sqrt{2}} \mu_B B_z \sin\theta \sqrt{N} \left[\cos^2\theta \left(h^{(+)}\right)^2 + \left(h^{(\times)}\right)^2 \right]^{1/2}$$

Bz – external field, N – number of spins

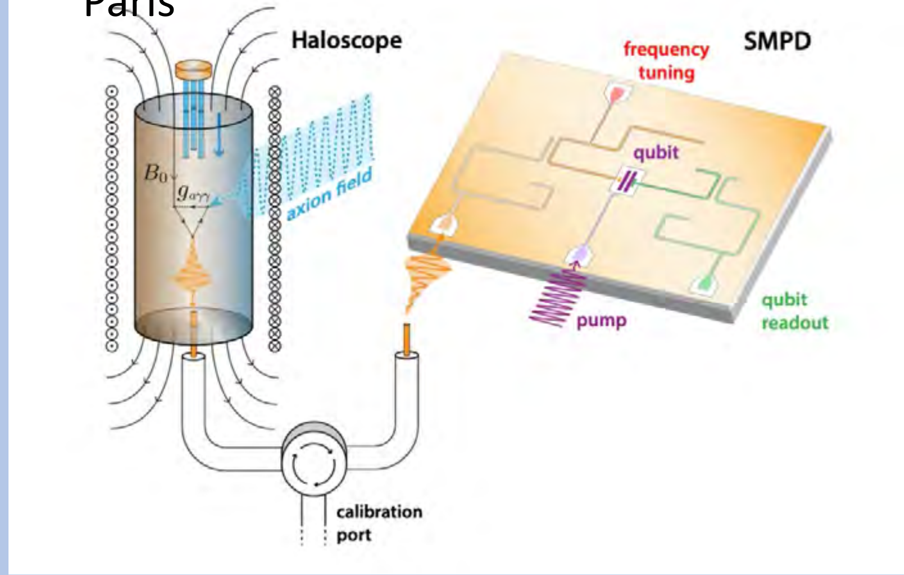


QUAX @ LNL long term future

- Installation of a **14 T magnet**
  - Expected mid 2026

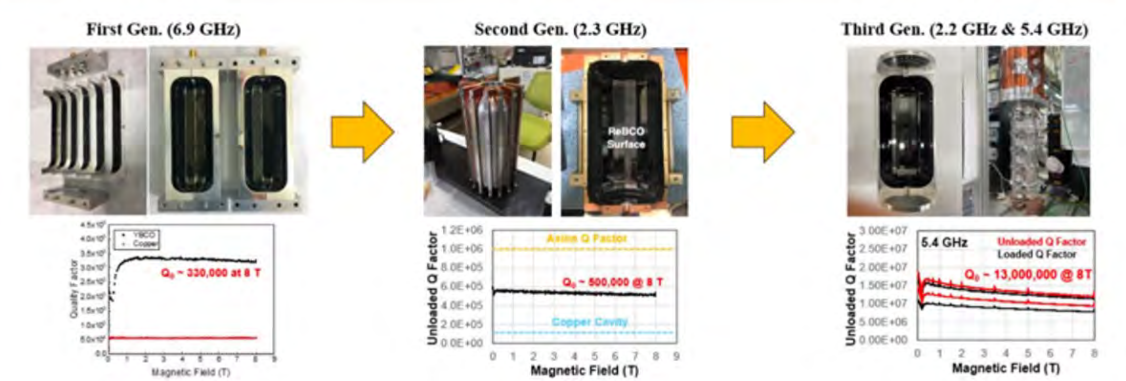
Model	: JMTA-14T103
Coil configuration	: Solenoid coil
Maximum central field	: 14 Tesla
Free bore diameter	: 103 mm
Outer diameter of the solenoid	: 400 mm excluding protrusion (tentative)
Total height of the solenoid	: 500 mm excluding protrusion (tentative)
Total weight (approximately)	: 250 kg (tentative)
Field direction	: Vertical two-way
Operating current (nominal)	: 185 A (tentative)
Inductance	: 64 Henries (tentative)
Maximum sweep rate	: 14 Tesla / 60 minutes (tentative)
Field homogeneity (designed value)	: More than 9 Tesla in a cylindrical area of 60mm diameter and 420 mm height

- Installation of a Single Photon Microwave Detector (SMPD) – Help of Quantronics Group Paris



- Develop high Q cavities based on HTS (With the help of Korea – CAPP)

Summary of HTS Cavity Development



- Installation of **new cryogenic system**
  - Wet assembly for magnet
  - Dry unit for cavity and rf detection

This will allow for longer and safer operation

People

QUAX Padova / Legnaro

G. Ruoso, R. Di Vora, C. Braggio, G. Carugno,
A. Lombardi
E. Berto, F. Calaon, M. Tessaro

L. Di Luzio (Guest), A. Ortolan,
D. Maiello, G. Sardo Infirri

QUAX Frascati
D. Alesini, A. D'Elia, D. Di Gioacchino, C. Gatti, C. Ligi, G. Maccarrone,
A. Rettaroli, and S. Tocci

QUAX Grenoble
G. Cappelli, M. Esposito, A. Ranadive, N. Roch

QUAX Trento
P. Falferi

QUAX Salerno
U. Gambardella, D. D'Agostino

null

QUAX – QUaerere AXion – QUest for AXion

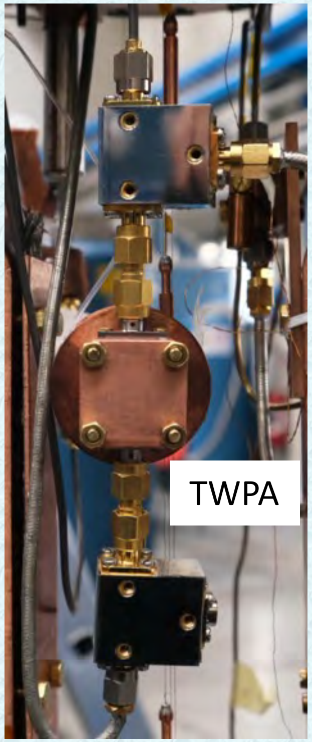
Experiment designed to look for dark matter axion in the 10 GHz region

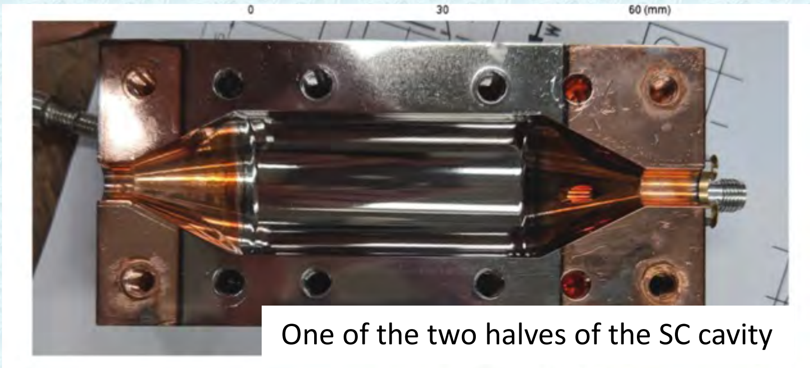
- **First apparatus to use a superconducting cavity** in a strong magnetic field   Q0 = 4.5 10^5 @ 2 T
- Operation of a quantum limited JPA at high frequency
- Operation of a near quantum limited TWPA at high frequency
- Use of **hybrid cavity design (copper-sapphire)** to get high Q and large volume
- First haloscope employing a cavity with Qc > Qa

INFN LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

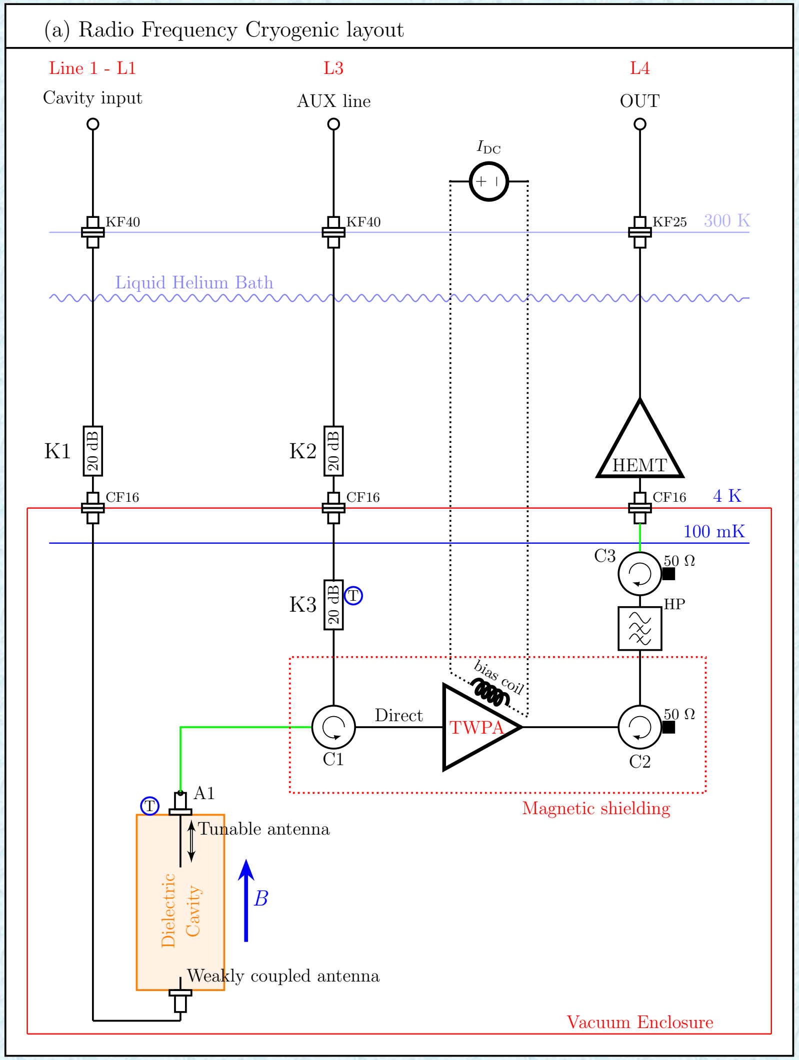
INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Layout with novel calibration scheme





One of the two halves of the SC cavity

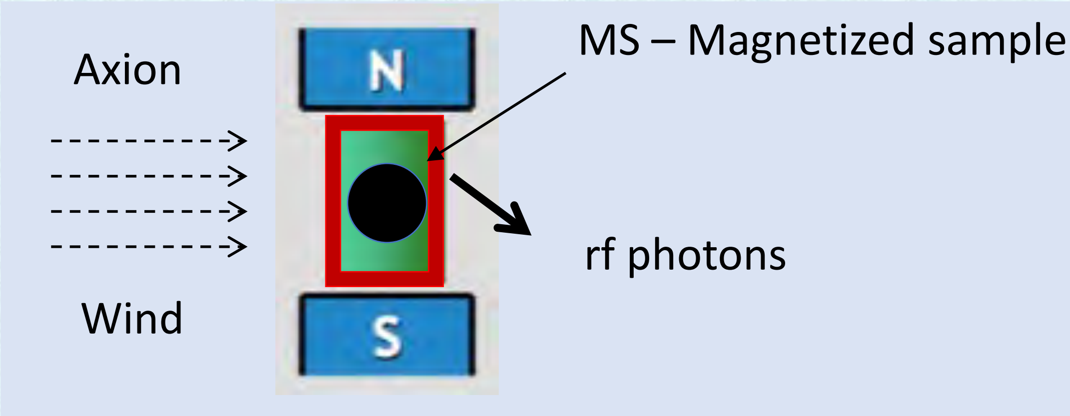


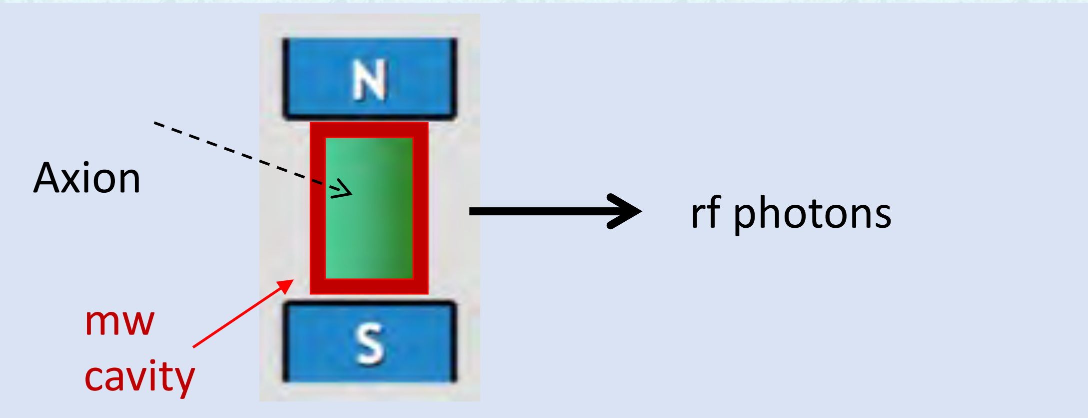
Achieved Tsys = 1.1 K @ 10.2 GHz
Reached QCD axion models sensitivity

CSN2 – QUaerere AXion - QUAX

- Detection of **cosmological axions** through their **coupling to electrons or photons**

- **Electron coupling: Due to the motion of the solar system** in the galaxy, 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**





- **Photon coupling: DM axion** are converted into **rf photons** inside a **resonant cavity** immersed in a **strong magnetic field**