Probing the axion-photon coupling with the QUAX haloscope

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INFN
On behalf of the QUAX collaboration

UCLA Dark Matter 2023

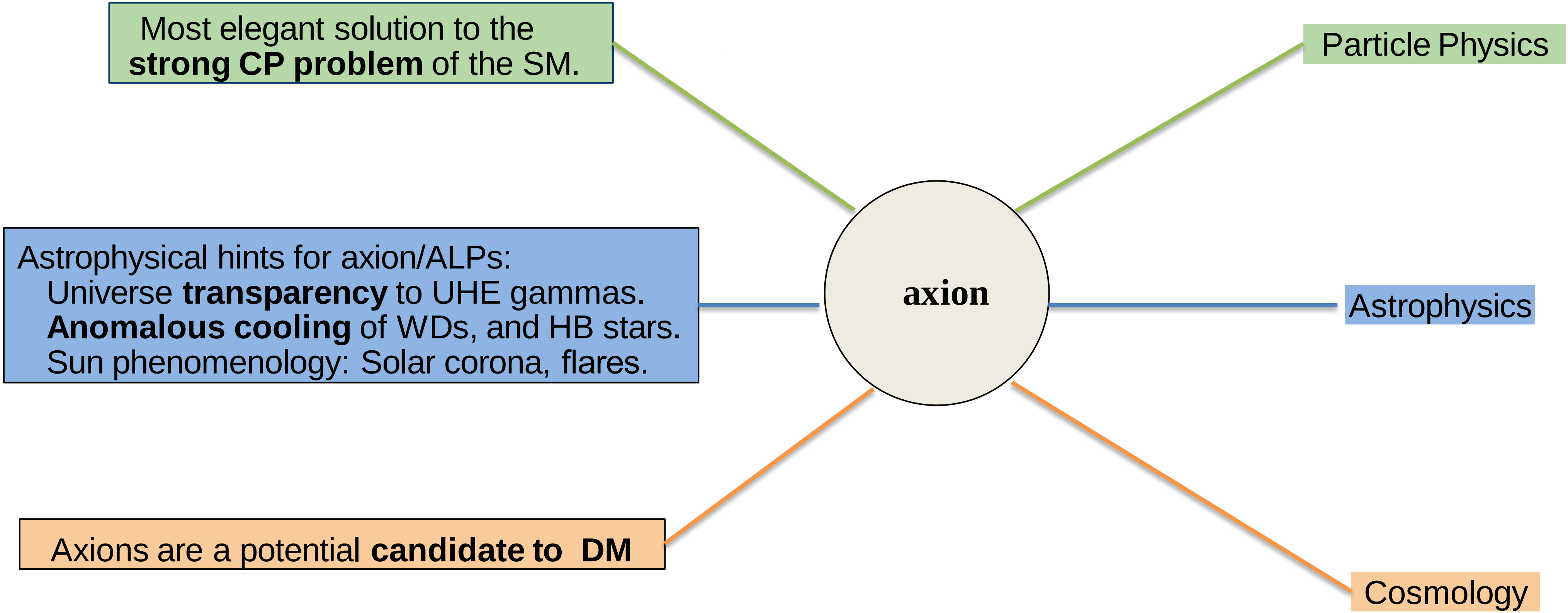
Istituto Nazionale di Fisica Nucleare

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Quantronics Group
Research Group in Quantum Electronics, CEA-Saclay, France

NÉEL institut

Axion research motivation



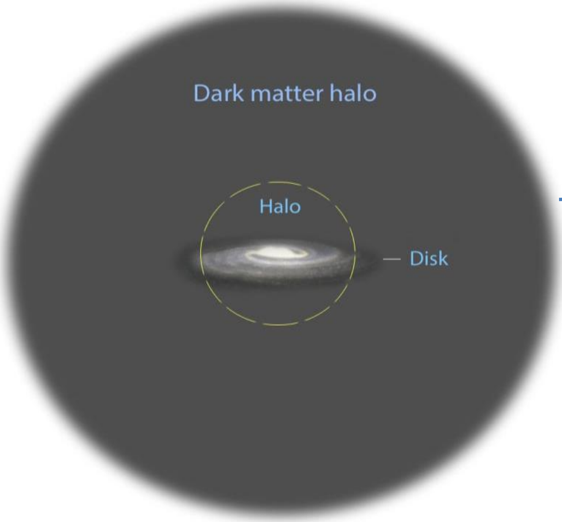
Most elegant solution to the **strong CP problem** of the SM.

Astrophysical hints for axion/ALPs:
- Universe **transparency** to UHE gammas.
- **Anomalous cooling** of WDs, and HB stars.
- Sun phenomenology: Solar corona, flares.

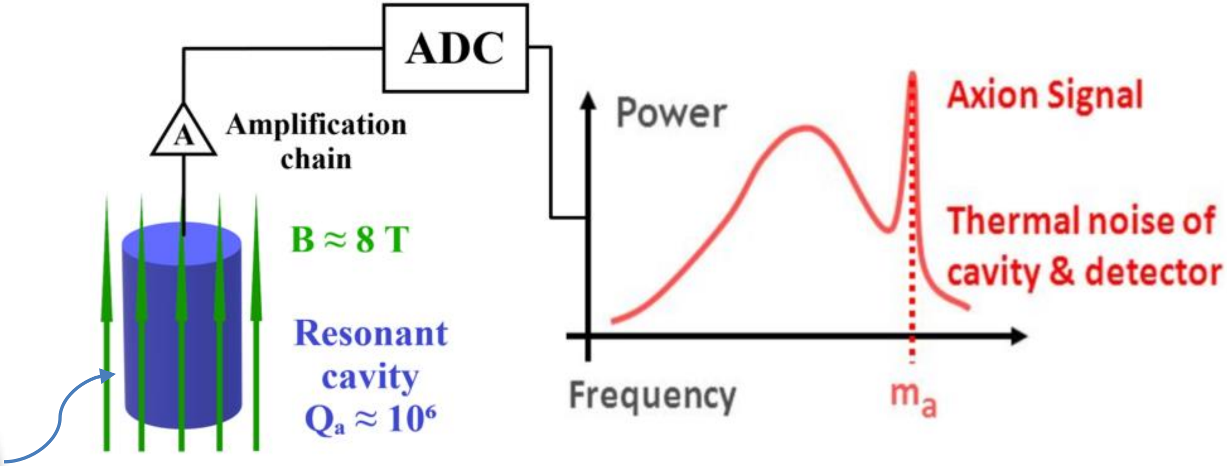
Axions are a potential **candidate to DM**

Axion detection with Haloscopes

—original proposal by P. Sikivie -PRL 51:1415 (1983)



Milky Way model



$$1\ \mu eV < m_a < 10\ meV$$

$$P_{\alpha\to\gamma} = \left(g^2_{\alpha\gamma\gamma}\frac{\rho_\alpha}{m_\alpha}\right)\left(\frac{\beta}{1+\beta}B_0^2\boldsymbol{VCQ_L}\right)$$

$$\delta P_{noise} = k_B T_{sys}\sqrt{\frac{\Delta\nu}{\Delta t}}$$

QUAX (QUaerere Axion) Experiment - Collaboration

DM axion search (axion-photon coupling) by scanning
(8.5 — 11) GHz frequency range at KSVZ sensitivity

LNL and **LNF** INFN laboratories will work in synergy, operating in different mass ranges and using **different low noise amplifiers** and **single microwave photon detectors.**

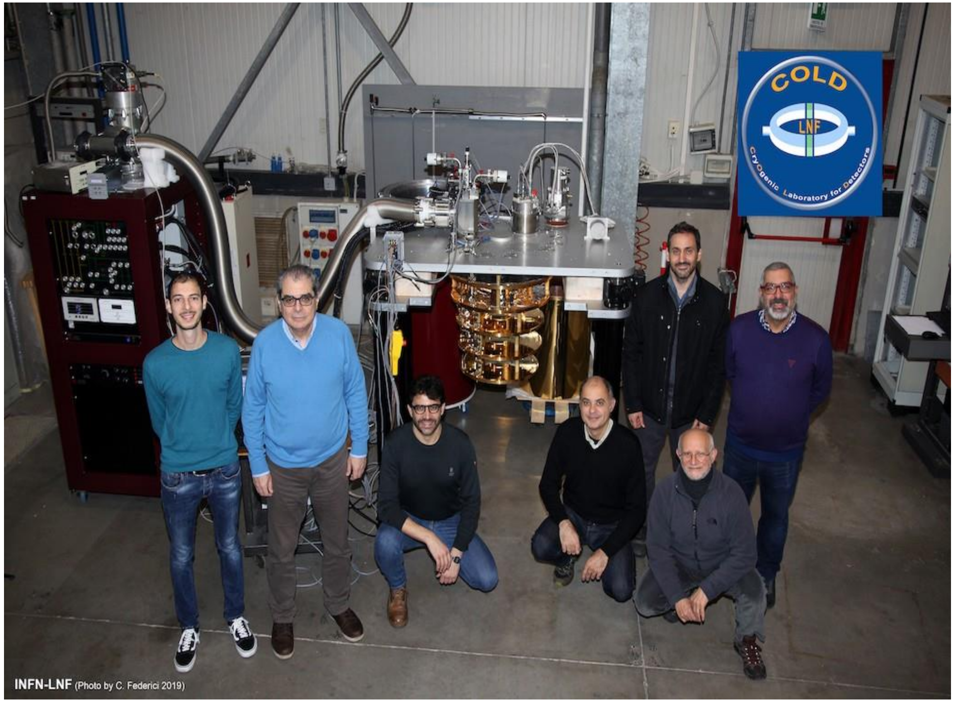
EU and US collaborations for the integration of:

1. **high-Q cavities** (SQMS, Fermilab)
2. state-of-the-art **itinerant microwave photon counters** (Quantronics group, Saclay)
3. **TWPA** (N. Roch group, Neel Institute in Grenoble)

QUAX Collaboration

LNL

LNF



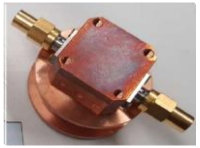
Funded program to run an axion observatory with two Haloscopes : One in **LNL** & one in **LNF**

QUAX (QUaerere Axion) Experiment

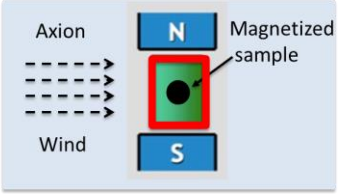
Outline

- **High Q** dielectric resonators / novel tuning mechanisms and geometries

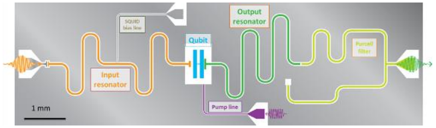
- **TWPA** – based amplification chain characterization and measurements



- **Ferrimagnetic** axion Haloscope project



- **Single Microwave Photon Detectors** (**SMPD**) for “itinerant” photons

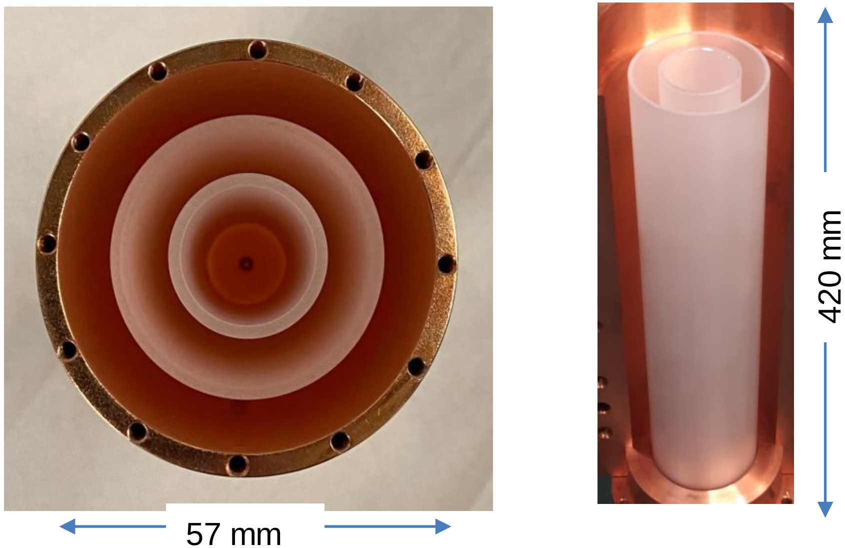


trasmon-based SMPD

High–Q sapphire cavities to catch dark matter

Tunable cavity with dielectric shells

"**dielectric boosted**" resonator

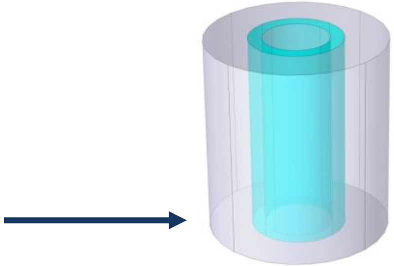


High purity aluminum oxide (99.99% Al_2O_3)

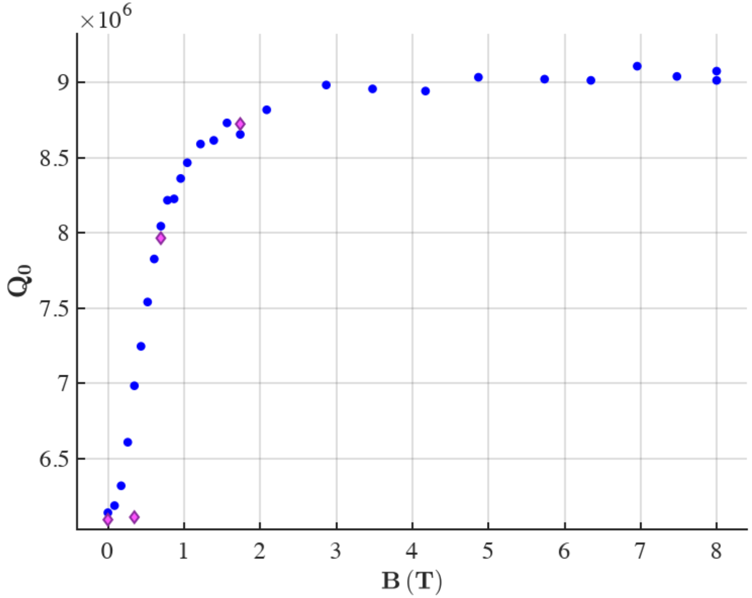
TM_{030} higher order mode for axion detection

2 shells → $C_{030} = 0.03$

1 shell → **$C_{030} = 0.49$**



$Q_0 \sim 9 \cdot 10^6$ @ **10.3** GHz – 4.2 K



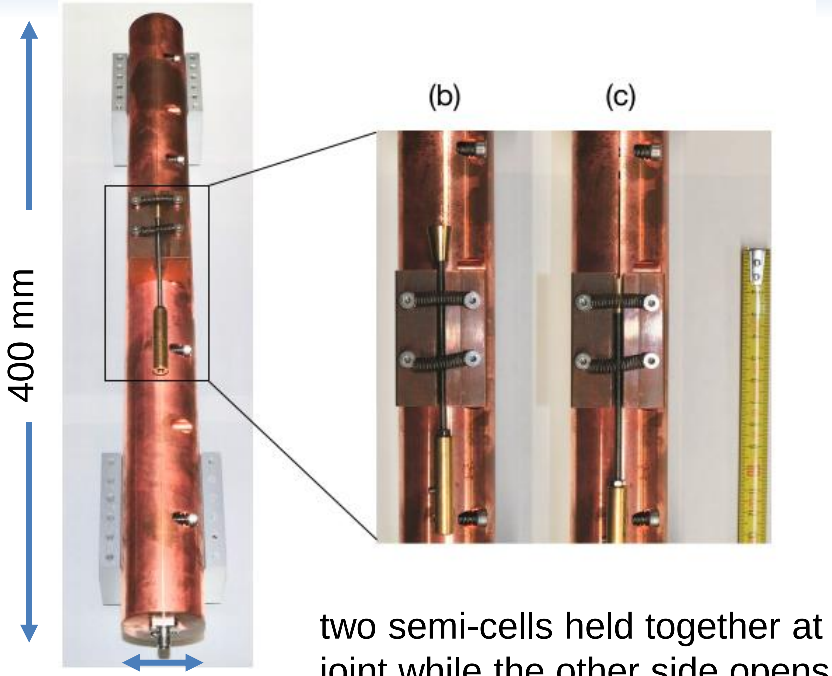
paramagnetic impurities in sapphire :

@ high B-fields they are completely swept away

Phys. Rev. Appl. 17, 054013 (**2022**)

Nucl. Instrum. Methods A **985**, 164641 (**2021**)

A tunable clamshell cavity for wavelike dark matter searches

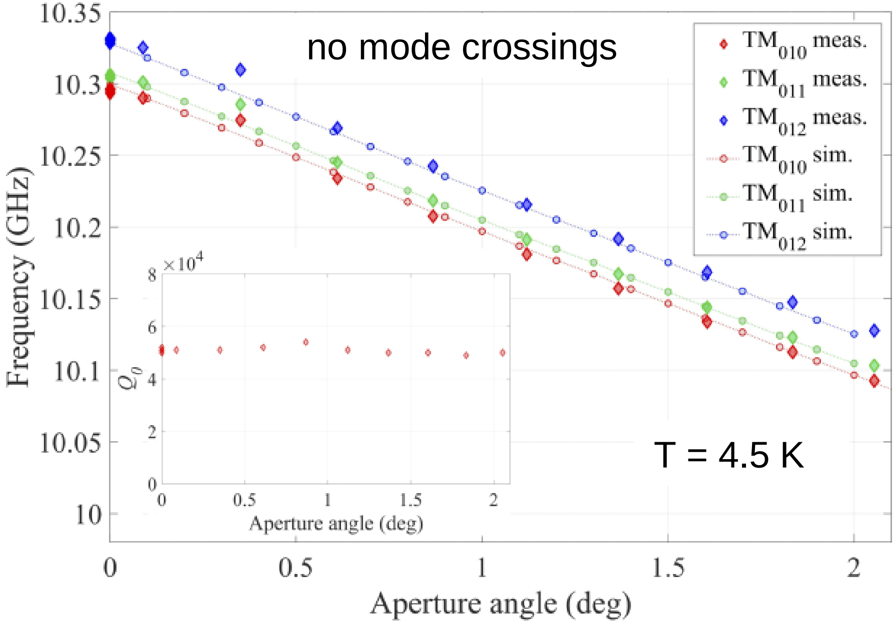


V=0.158 liters
$Q_0 \approx 50000$

two semi-cells held together at a fixed joint while the other side opens to tune the frequency of the resonant mode

maximum aperture of ~ 2 degrees, is equivalent to a 2% increase in effective volume

Measurements and finite elements method simulations



Tuning a range of at least 200 MHz for the fundamental mode TM_{010}

Search for Galactic axions with a high-Q dielectric cavity

July 2021 run

High-Q dielectric cavity

TM_{030} mode ($C_{030} = 0.03$)

$Q_L \sim 3 \cdot 10^5$ ($\beta \geq 14$, i.e., $Q_L \ll Q_a$)

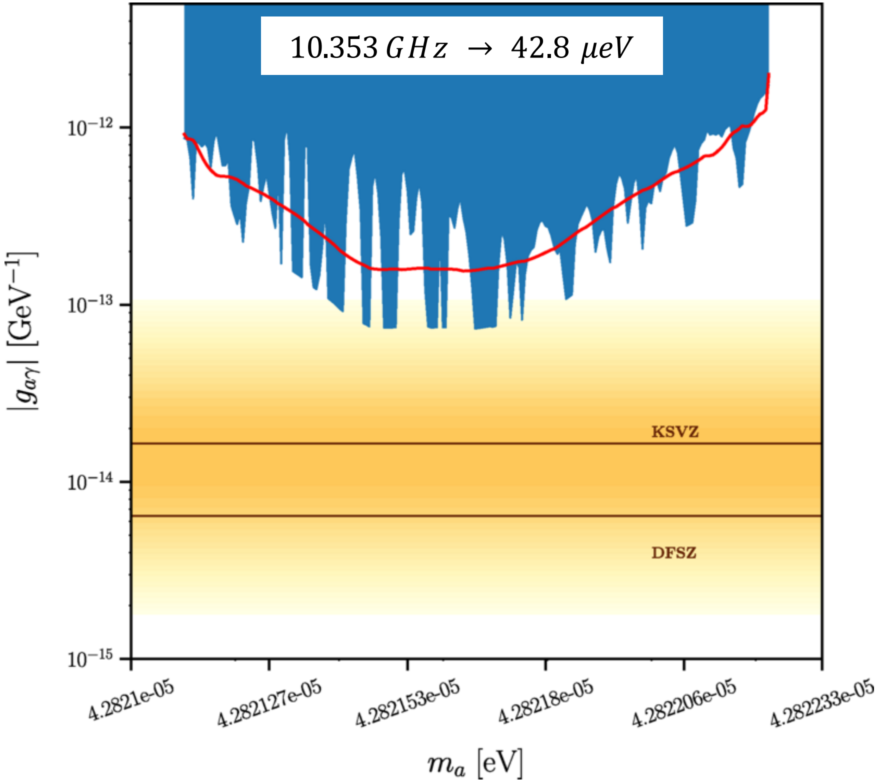
$T_{sys} = 17.3 \pm 1$ K (*problematic* HEMT)

Scanned axion mass not accessible to other running experiments

$$\frac{d\nu}{dt} = \frac{1}{\mathrm{SNR}^2}\left(\frac{\beta P_{a\to\gamma}}{k_B T_{sys}}\right)^2 \frac{1}{(1+\beta)Q_0}$$

A scan rate of ~2 MHz /day using a quantum-limited readout (T_{sys}=0.5 K)

Phys. Rev. D 106, 052007 2022



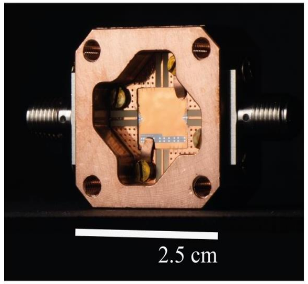
We set a limit for the axion-photon coupling a factor about 4 from the benchmark axion-QCD band

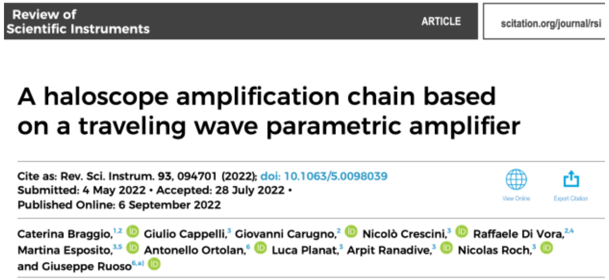
TWPA: applications to SC quantum science & technologies

In axion DM research we need:

- **quantum-limited noise performance**
- **GHz amplification bandwidth**

TWPA parametric amplifiers from Néel *





Review of
Scientific Instruments

ARTICLE

scitation.org/journal/rsi

A haloscope amplification chain based on a traveling wave parametric amplifier

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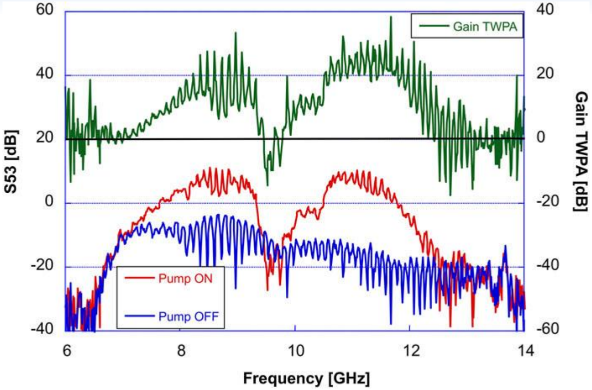
A. Renadive et al, Nat. Commun. 13, 1737 (2022) *

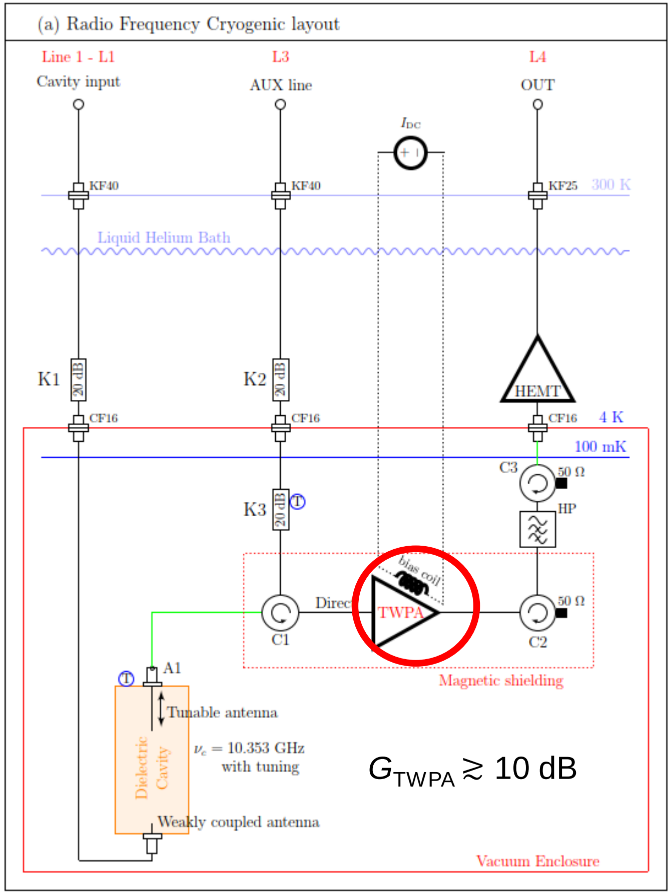


Integration of TWPA into QUAX

No B-field

$$\boxed{T_{sys} = 3.3 \pm 0.1\, K}$$

Novel, reliable calibration scheme to measure T_{sys} exactly at the cavity output and without the need for switches nor heated load.



$G_{TWPA} \gtrsim 10$ dB

Measuring TWPA performance in a haloscope setup

- He^3-He^4 “wet” dilution refrigerator (refurbished) ! recovery system + compressor at LNL
- Cooling power of 1 mW at 120 mK

8 T field

base temperature of 50 mK after ~ 9 hours

QUAX$_{\alpha\gamma}$ TWPA-based amplification measurement

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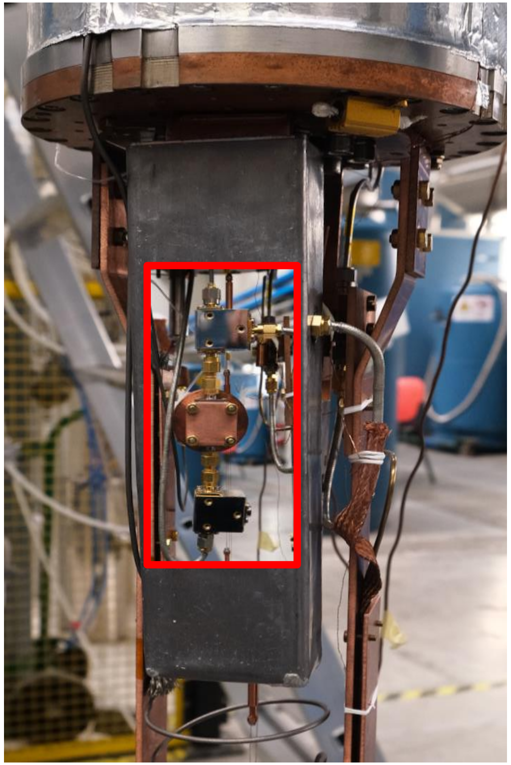
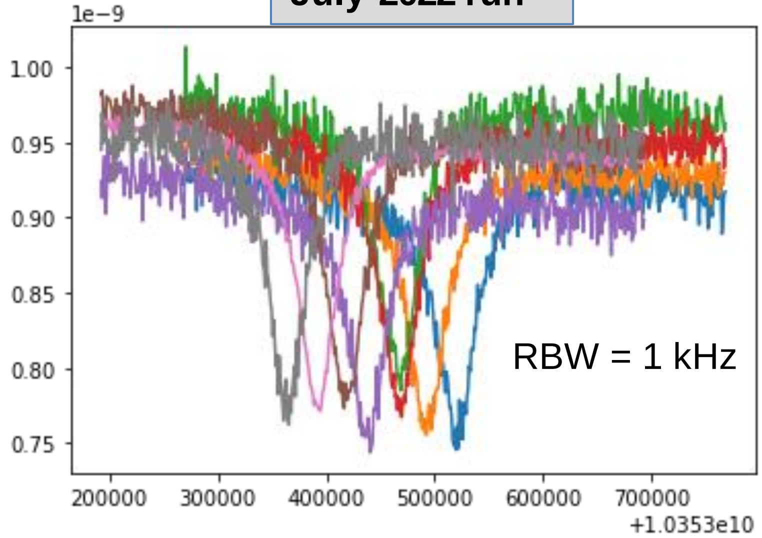
TWPA with circulators
inside the shielding box



- Mixing chamber @ 50 mK
- Cavity @ 110 mK

July 2022 run

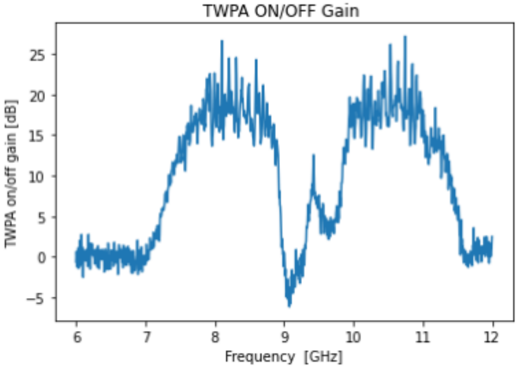


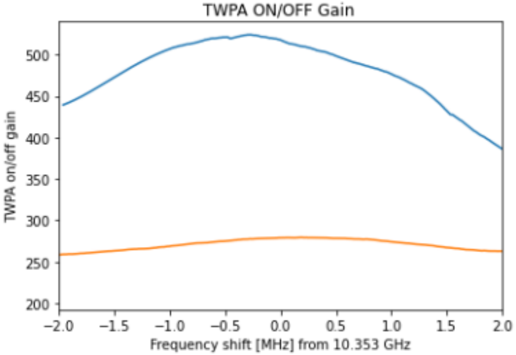
$$\boxed{\boldsymbol{T_{sys} = 2.01 \pm 0.06\ K}}$$

$$N_{sys} = \frac{k_B}{h\nu_s} T_{sys} = 4.2 \pm 0.3\ photons$$

Data taking for 17 hours
-- 8 T magnetic field
-- ν_c =10.353 GHz
-- Q ~ 2.5•10^5

data analysis and
Publication in progress





in-situ **tunability of amplification bandwidth** over an unprecedented wide range

Quantum-limited spin magnetometer → axion Haloscope

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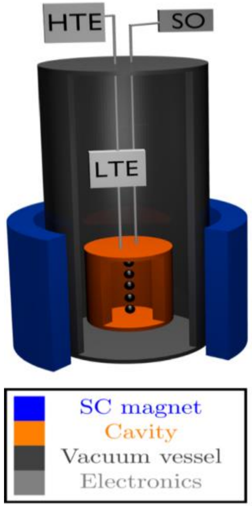
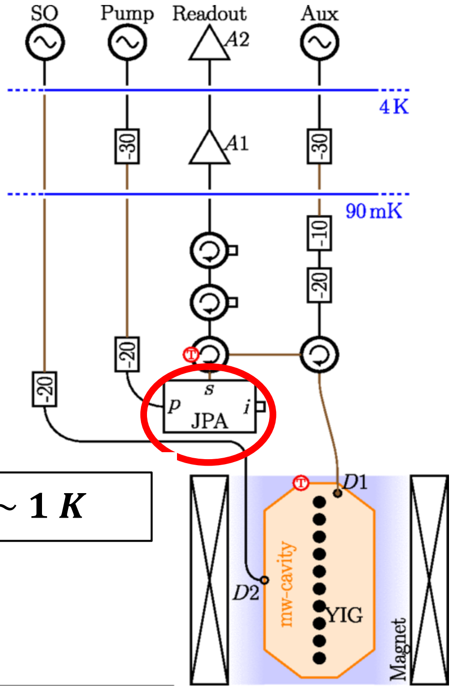
Electron coupling: the axion DM cloud acts as an **effective magnetic field** on electron spin exciting magnetic transitions in a magnetized sample and **producing rf photons** ⟹

$$B_a \equiv \left(\frac{g_{\alpha ee}}{2e}\right)\nabla a$$

$$P_a = \gamma_e \mu_B N_s \omega_a B_a^2 \tau_s$$

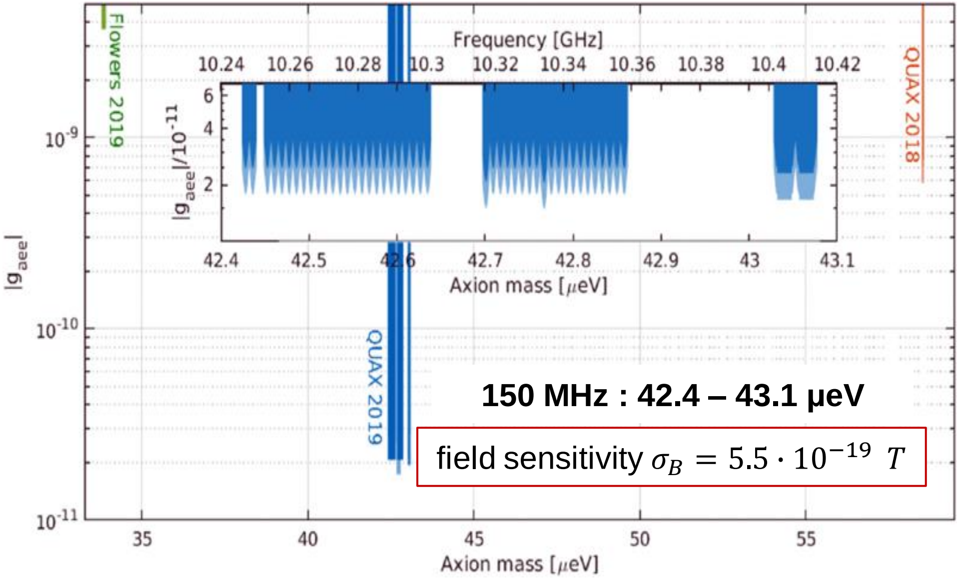




$T_{sys} \sim 1\ K$

- TM110 mode @ 10.7 GHz
- ten 2.1 mm diameter spheres of **YIG**

[Phys. Rev. Lett. 124, 171801 (2020)](#)



150 MHz : 42.4 – 43.1 μeV

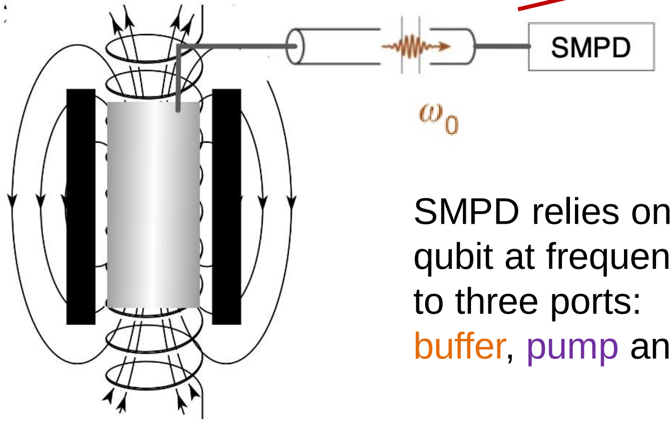
field sensitivity $\sigma_B = 5.5 \cdot 10^{-19}\ T$

Eur. Phys. J. Plus 137, 338 (2022)
Phys. Rev. B 104, 064426 (2021)

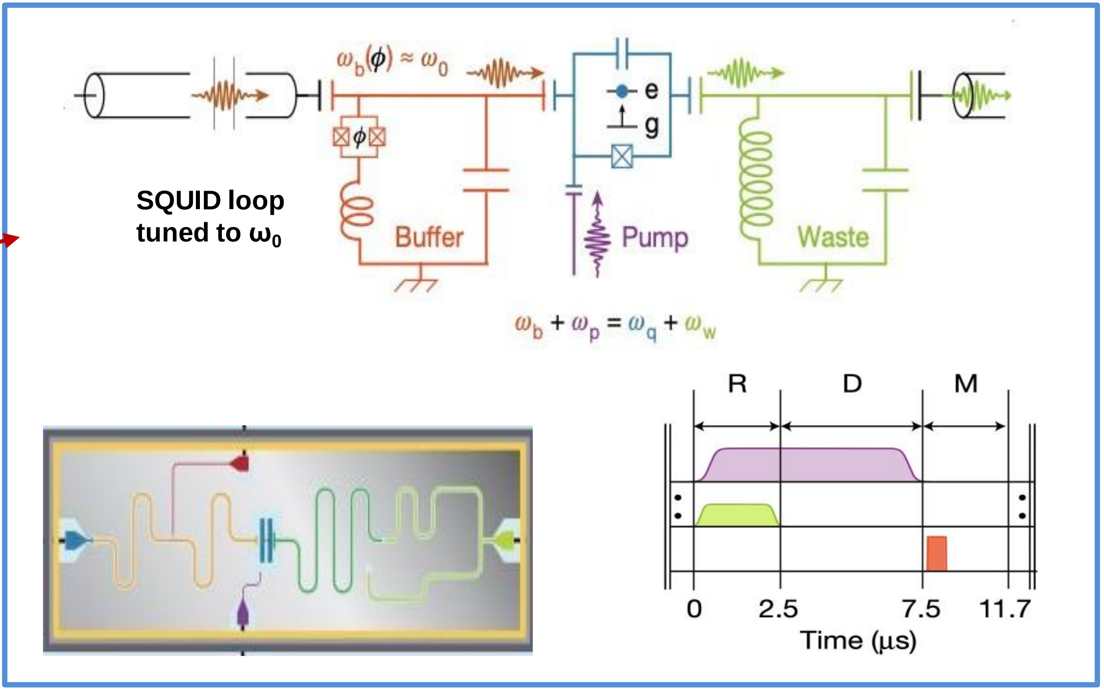
Detecting dark matter through quantum science

Single Microwave Photon Detector (SMPD):
a transmon-based counter (**artificial atom**) that can employ quantum nondemolition (QND) techniques to count photons

cavity photons ≠ itinerant photons



SMPD relies on a transmon qubit at frequency ω_q coupled to three ports:
buffer, pump and waste



a three-step process repeated continuously
-- qubit reset (R) performed by turning on the pump pulse
+ weak resonant coherent pulse to the waste port
-- detection (D) step with the pump pulse on
-- measurement (M) step probes the dispersive shift of the buffer resonator to infer the qubit state

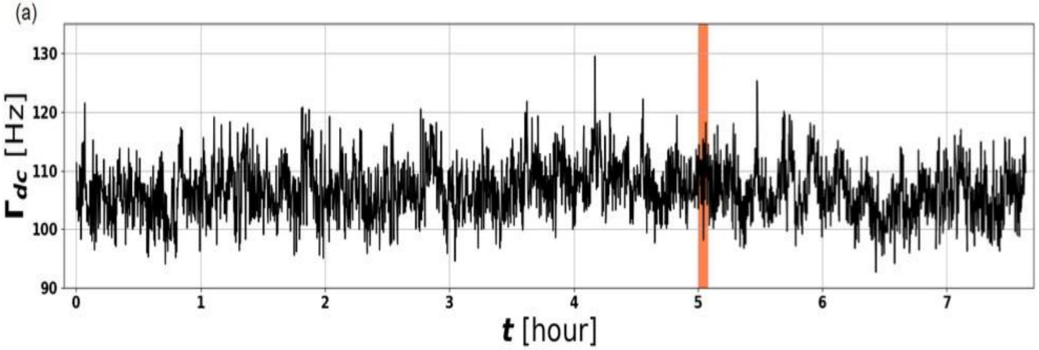
R. Lescanne et al, Phys. Rev. X 10, 021038 (2020)
E. Albertinale , Nature 600, 434 (2021)

SMPD in axion dark matter search

single microwave photon detectors (SMPDs) developed in the context of quantum information science have the potential to **greatly improve the search speed at haloscopes**

A pilot experiment is ongoing with researchers from **INFN** (Padova, **LNL**) and the **Quantronics group** (CEA Saclay)

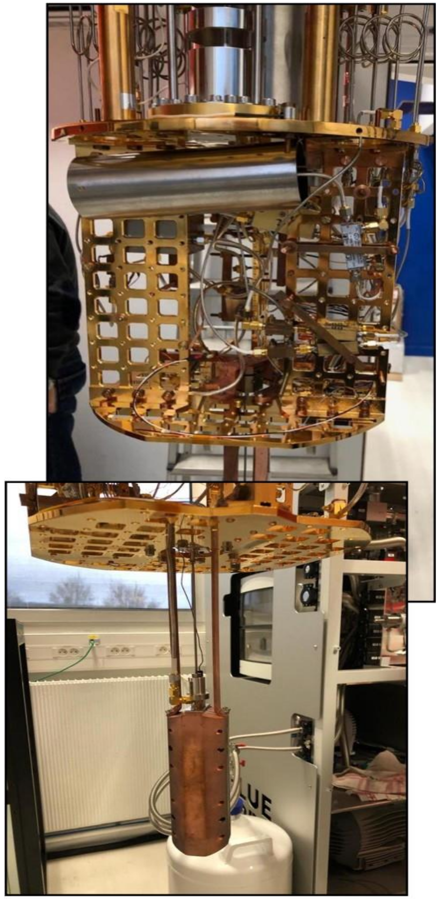
- tunable, high quality factor cavity
- TM_{010} mode $\nu_c \rightarrow 7.3\ \mathrm{GHz}$ is readout by a SMPD



Unwanted photons: false-positive events

Detector bandwidth	~	1 MHz
Tunabilty range	~	200 MHz
Dark count rate	~	100-120 Hz
Efficiency	~	0.4

data analysis→ in progress



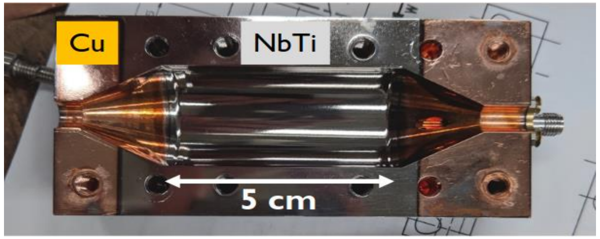
Operating temperature = 10 mK

Study of SMPD in Legnaro-Padova lab

New dilution unit → 7 mK base Temperature

Paris run was successful so the SMPD device will be transferred to Italy for haloscope developments in INFN-LNL:

- $\text{QUAX}_{\alpha\gamma\gamma}$
- $\text{QUAX}_{\alpha e}$
- Superconductive cavity
  (copper cavity sputtered with **NbTi**)



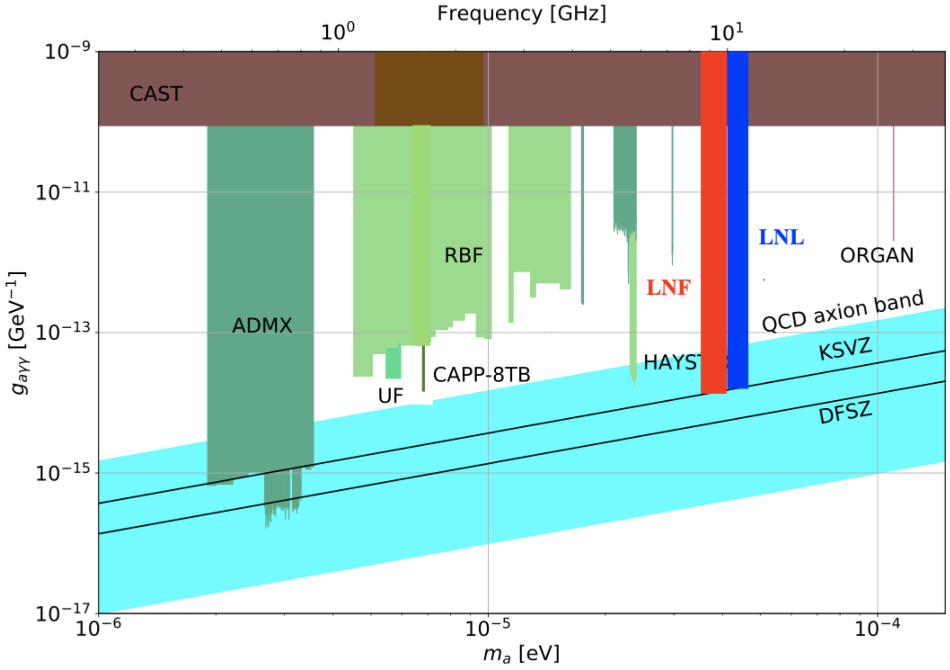
Conclusions

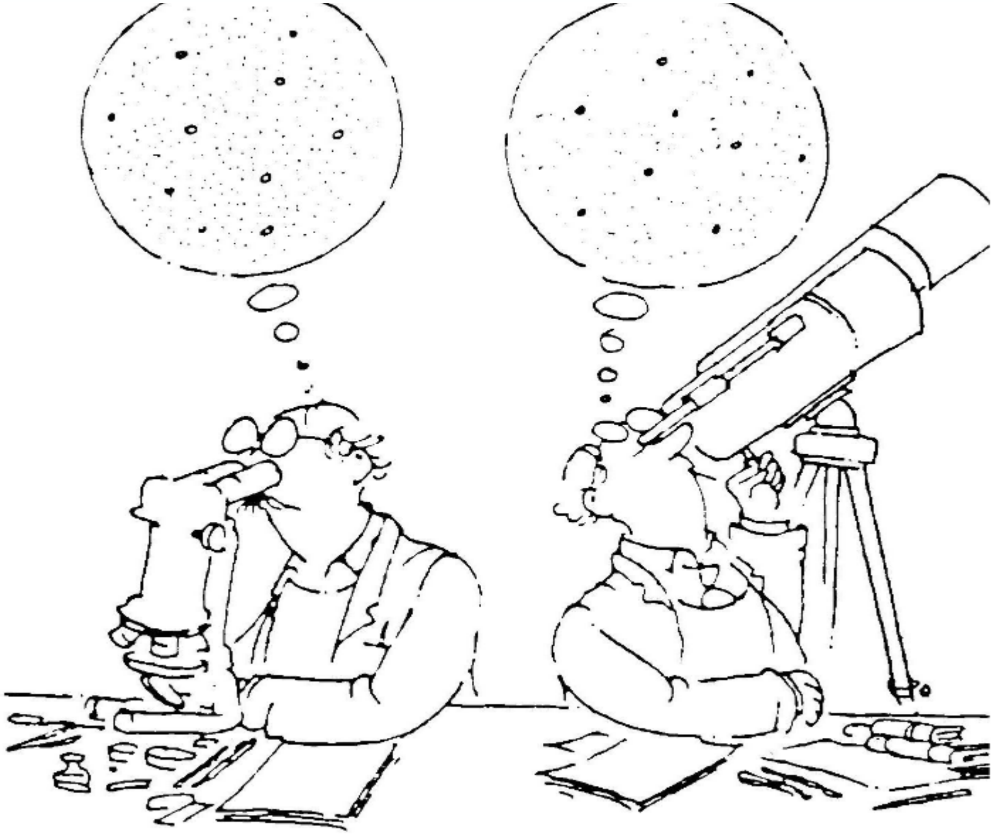
Ongoing R&D on High-Q cavities for high frequency axion search (with dielectrics , HTSC strips)

Implementation of SQL noise amplifiers (TWPA) in our setups (Characterization and measurements)

First in the world axion measurement with SMPD (QND detection of an itinerant microwave photon)

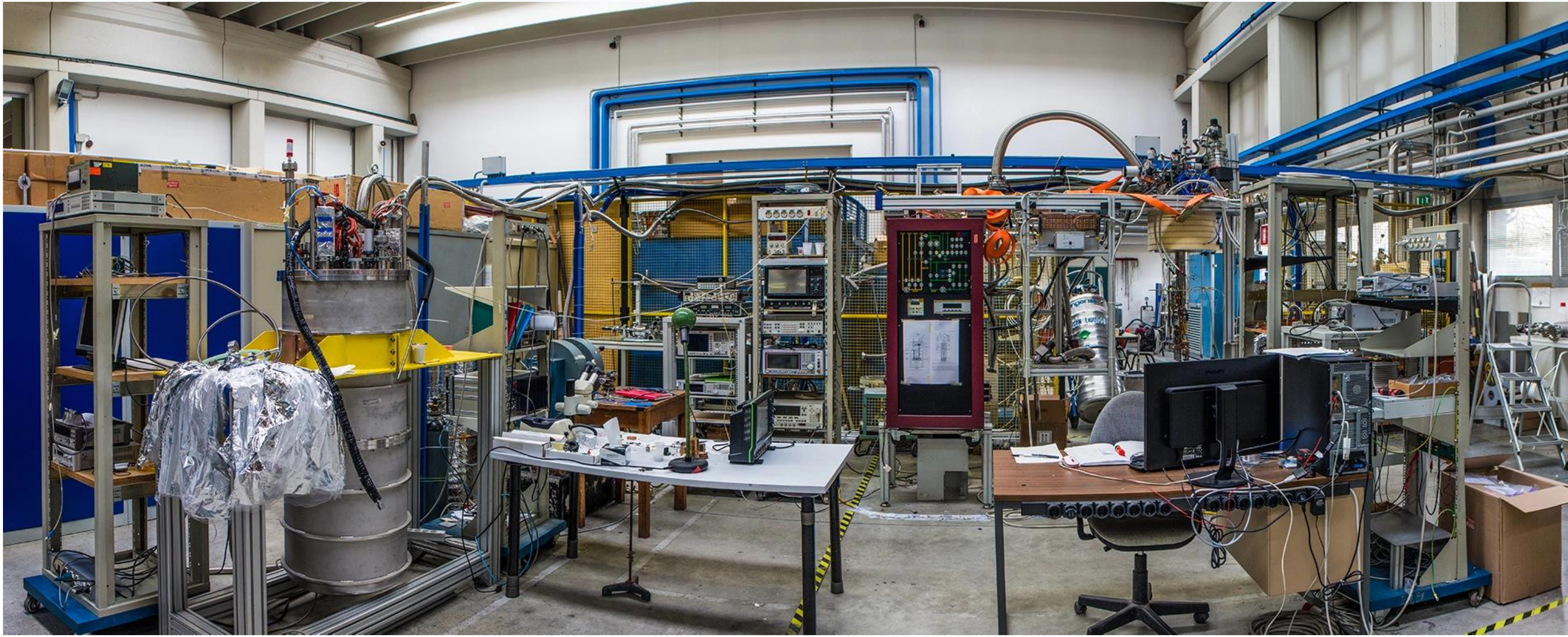
New dilution unit at 7 mK for the new setups (using SMPD and TWPA)





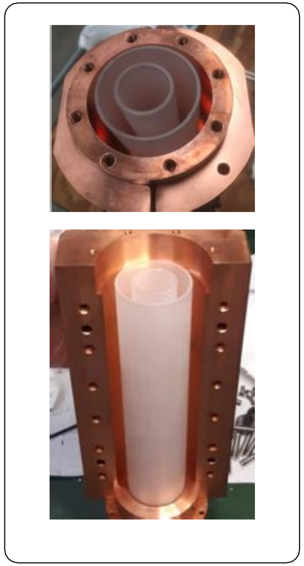
Thank you

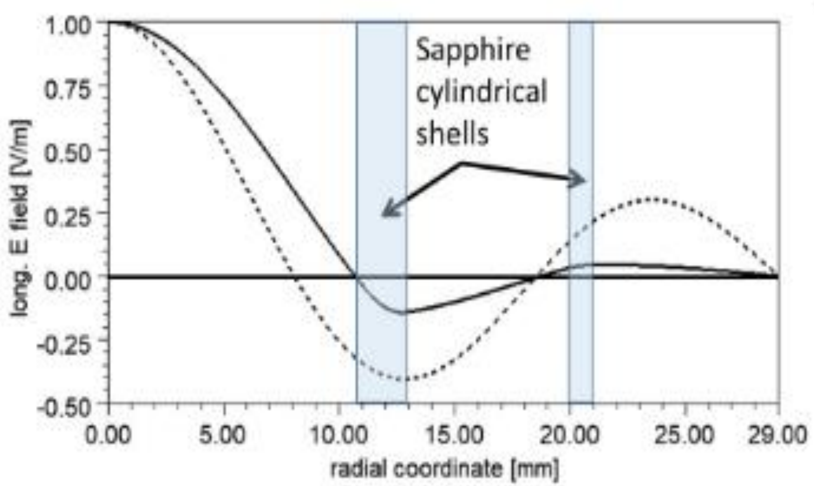
QUAX laboratory at Legnaro

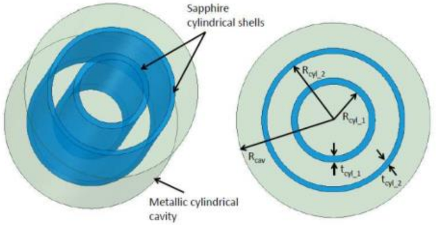


High-Q Microwave Dielectric Resonator for Axion Dark-Matter Haloscopes

QUAX a-γ

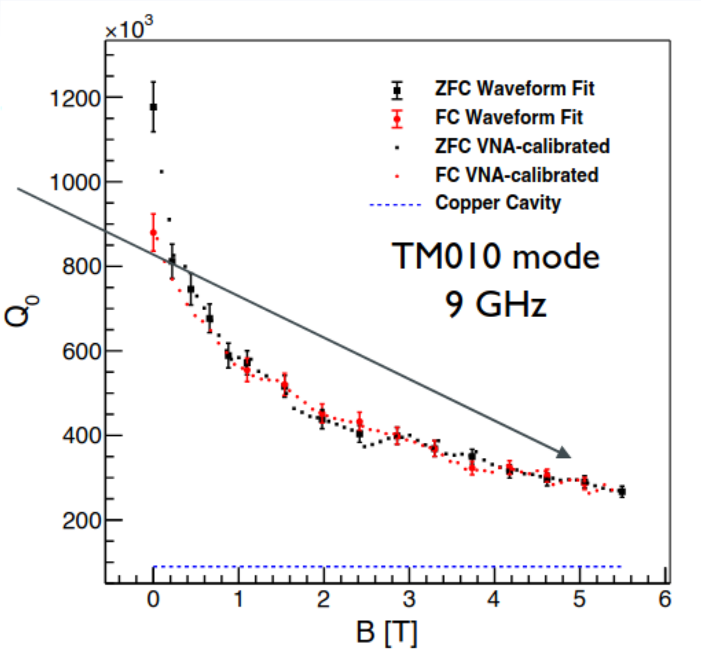






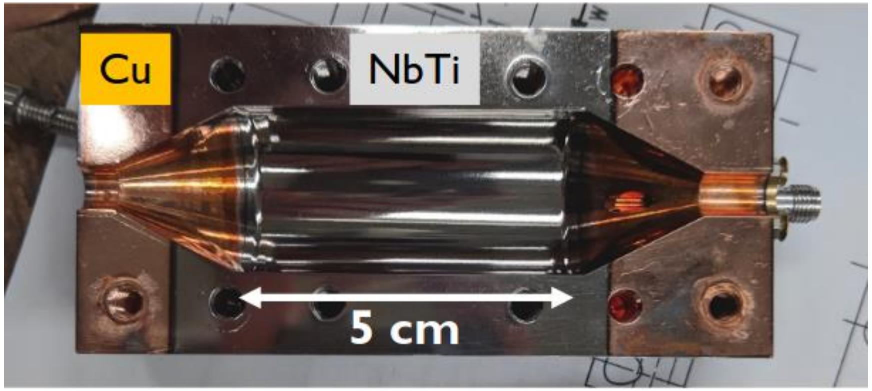
Physical Review Applied 17 (5), 054013, 2022

Improving Q of Resonant Cavity with **Superconducting** NbTi



Cavity coated with 4 μm NbTi layer and copper end-caps

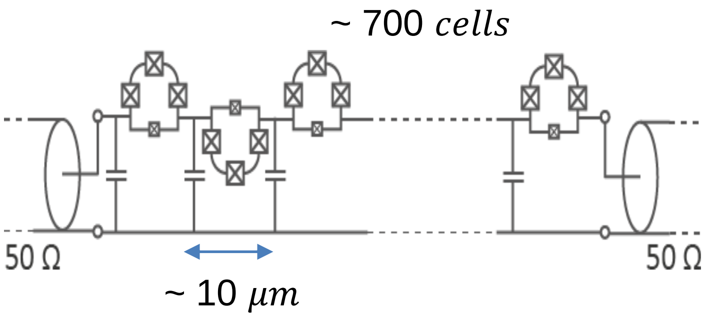
Experimental Setup	
B [T]	2
Frequency [GHz]	9
NbTi cavity Q (mode TM010)	400,000
T_{cavity} [K]	5.0
T amplifier [K] (HEMT)	11



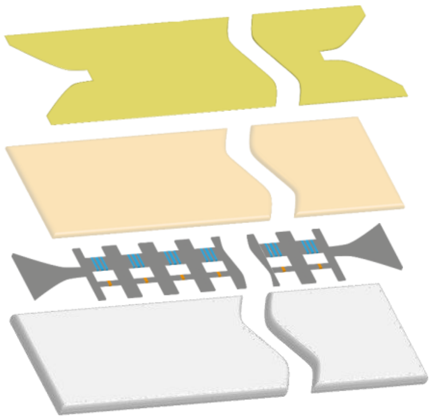
magnetron sputtering in INFN-LNL

SQMS is currently developing experiments using tunable SRF cavities that will search through a broader range of parameter space

TWPA Fabrication



Josephson
Junction

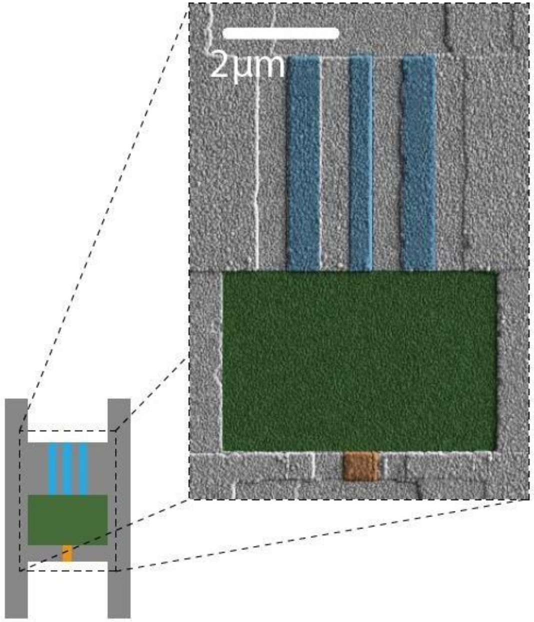


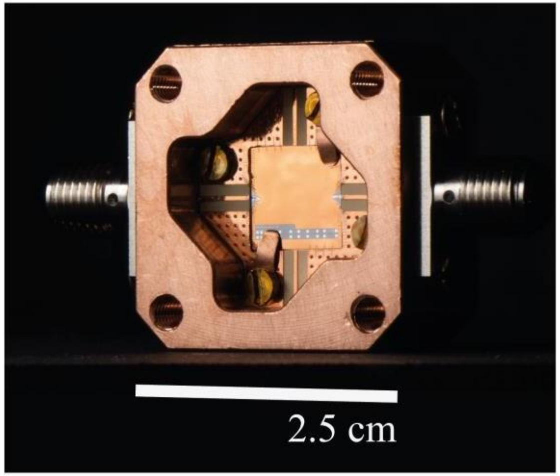
Top ground (Copper)

Dielectric (Alumina)

JJ composite chain

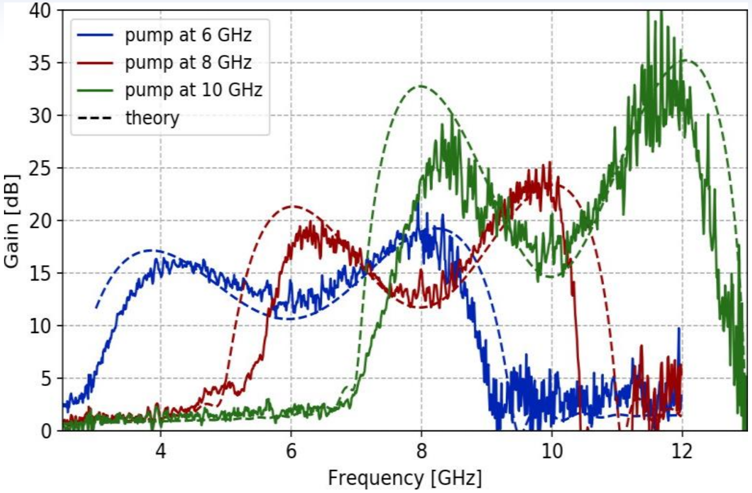
Substrate (Silicon)

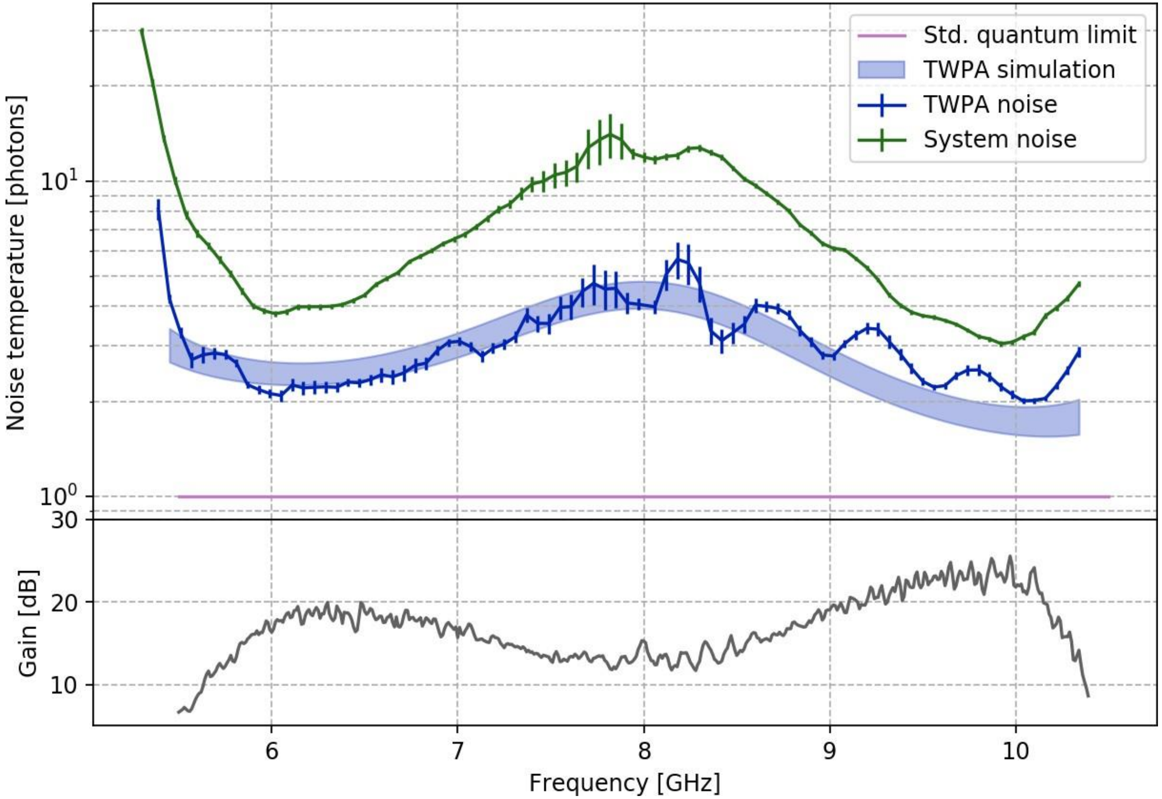




- Ranadive, A. *et al.* ***Nat Commun*** **13, 1737 (2022)**

Reversed Kerr TWPA Gain & noise

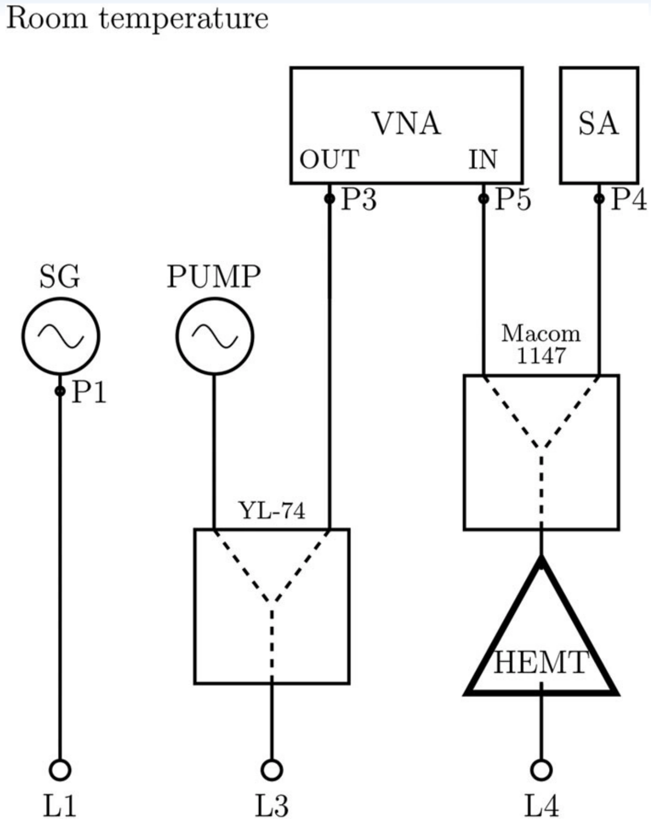




- **No gap in the gain profile**
- **BW > 3.5 GHz**
- **Dynamic tunability~8 GHz**

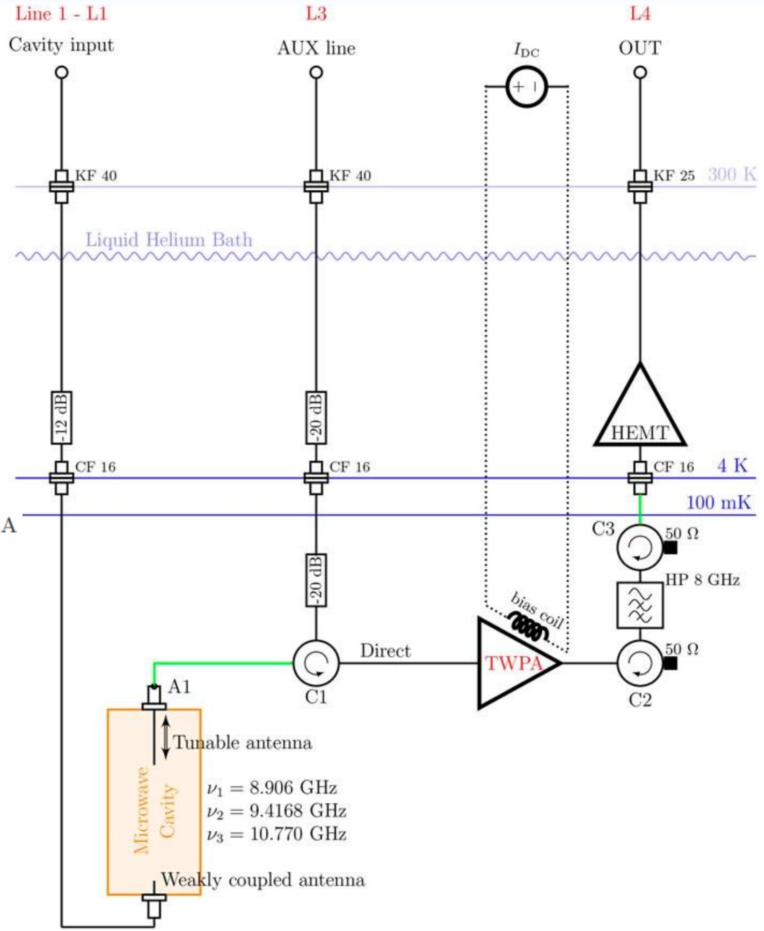
TWPA amplifier

A haloscope amplification chain based on a traveling wave parametric amplifier



$$P_{out}^{xy} = P_{n}^{xy} + G_{xy} \cdot P_{in}$$

$$P_{n}^{xy} = g_4 k_B T_{sys} B + \mathrm{Noise}_{\mathrm{SA}}$$



A system noise temperature of (3.3 ± 0.1) K has been measured at a frequency of 10.77 GHz /G_{TWPA}(dB) = 24

Review of Scientific Instruments **93**, 094701 (2022)

LNL & LNF INFN laboratories in collaborations

➢ **SQMS Center**

The Superconducting Quantum Materials and Systems Center, led by Fermi lab, funded by the U.S. Department of Energy to develop and deploy the world's most powerful quantum computers and sensors.

Using :

- **Ultrahigh-Q superconducting resonators**
- **Superconducting transmon qubits and processors**
- **Quantum sensing for fundamental physics**

➢ **Quantronics group** (CEA, Saclay)

-single spin flip detection with SMPDs/ transmon-based SMPD

➢ **Néel Institute (**Grenoble, France)

-quantum sensing and continuous variable quantum computing

-TWPA

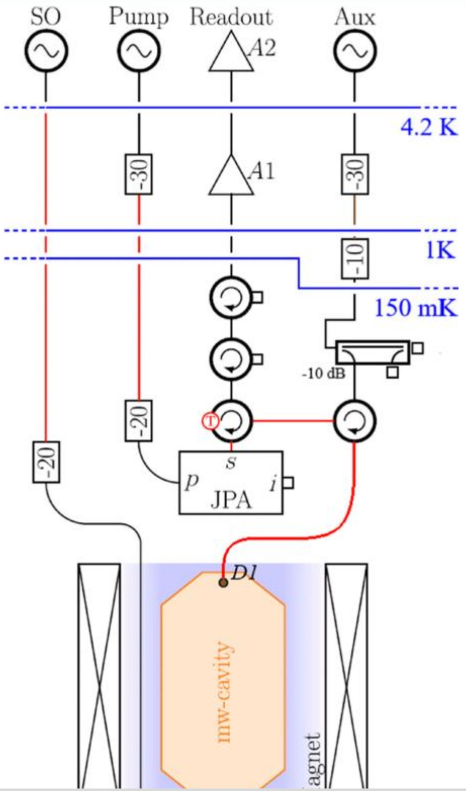
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Quantronics Group

Research Group in Quantum Electronics, CEA-Saclay, France

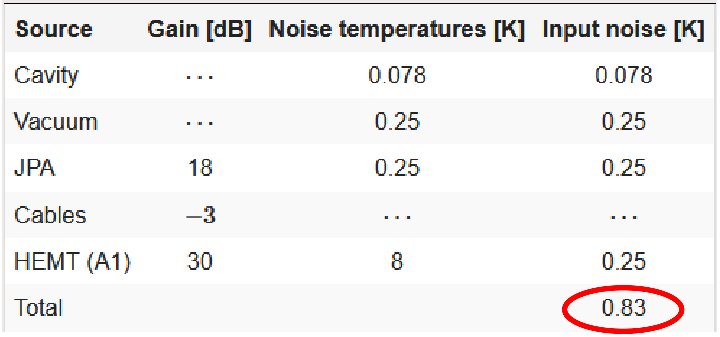
NÉEL institut

QUAX a-γ: Reached the Sensitivity to QCD Axions

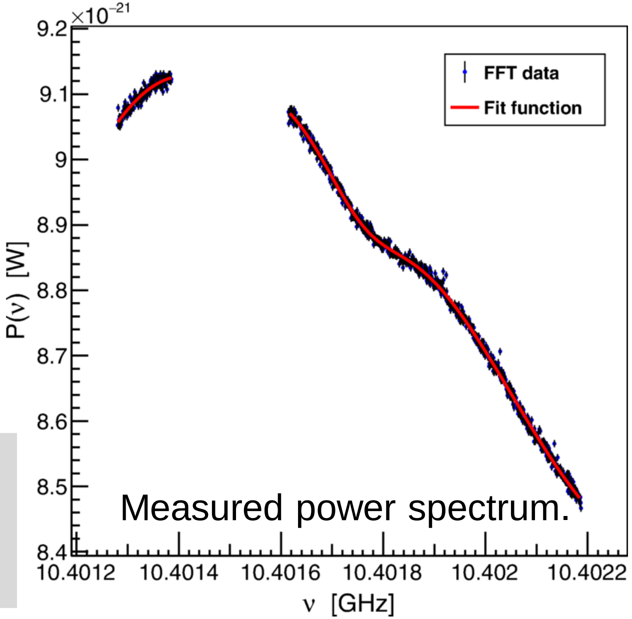


B=8 T

Cu cavity Q (mode TM010)	76.000
T amplifier [K] (JPA)	0.5
T cavity [mK]	100

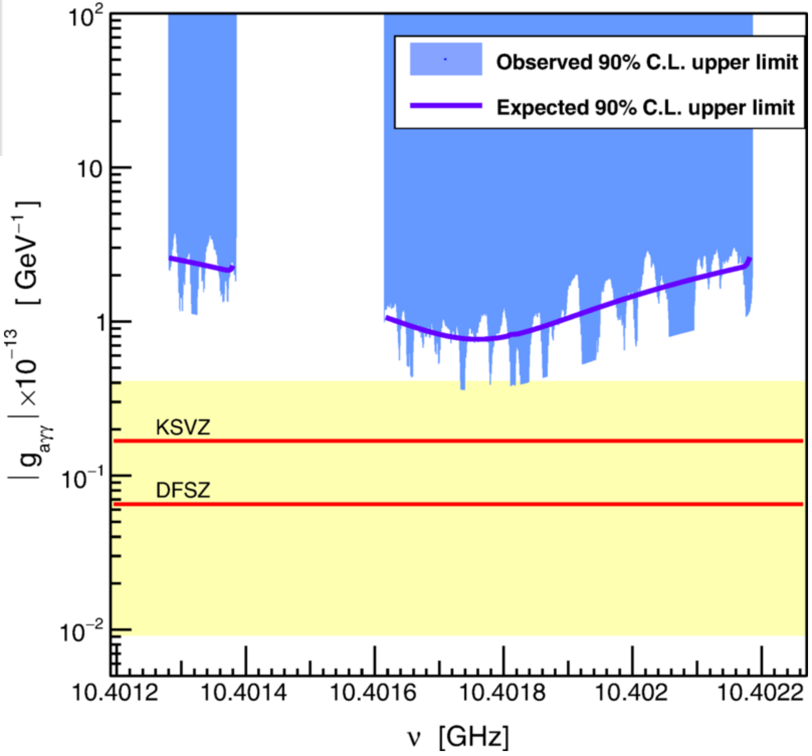


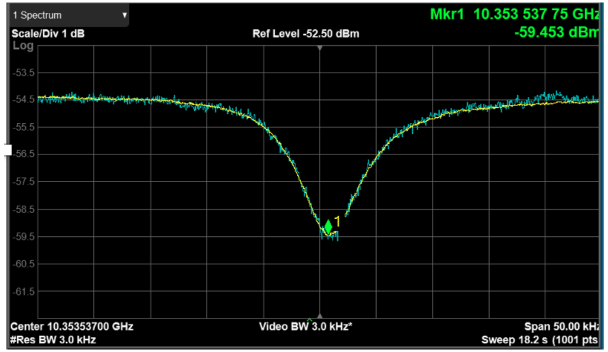
Source	Gain [dB]	Noise temperatures [K]	Input noise [K]
Cavity	...	0.078	0.078
Vacuum	...	0.25	0.25
JPA	18	0.25	0.25
Cables	−3	...	...
HEMT (A1)	30	8	0.25
Total			0.83

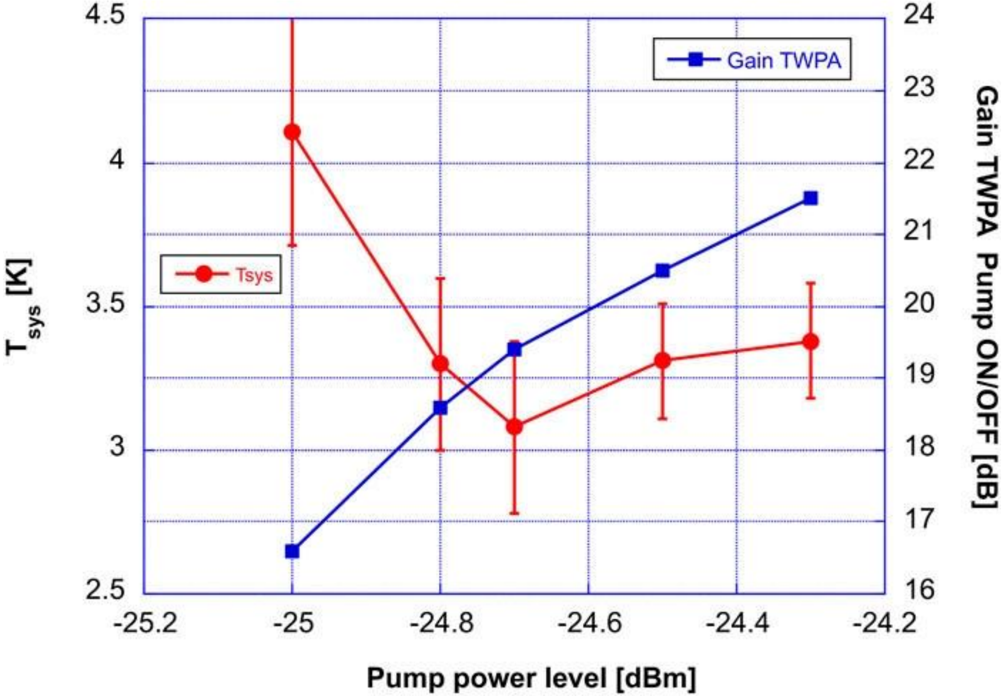


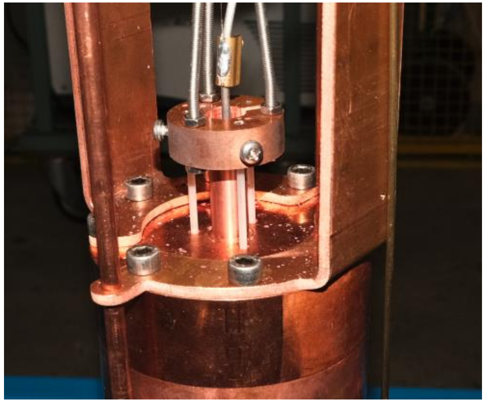
Measured power spectrum.

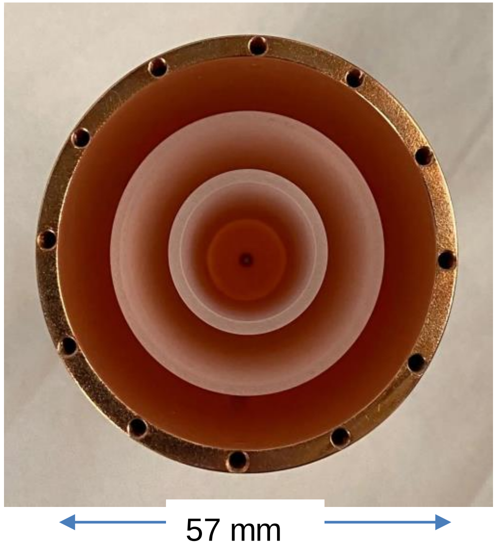
m_a=43 μeV



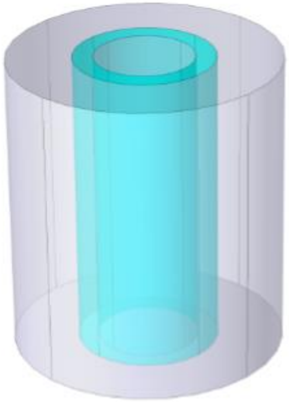

1 Spectrum
Mkr1 10.353 537 75 GHz
-59.453 dBm
Scale/Div 1 dB
Log
Ref Level -52.50 dBm
-53.5
-54.5
-55.5
-56.5
-57.5
-58.5
-59.5
-60.5
-61.5
1
Center 10.35353700 GHz
#Res BW 3.0 kHz
Video BW 3.0 kHz*
Span 50.00 kH
Sweep 18.2 s (1001 pts


Gain TWPA
Tsys
T_{sys} [K]
4.5
4
3.5
3
2.5
Gain TWPA Pump ON/OFF [dB]
24
23
22
21
20
19
18
17
16
-25.2
-25
-24.8
-24.6
-24.4
-24.2
Pump power level [dBm]

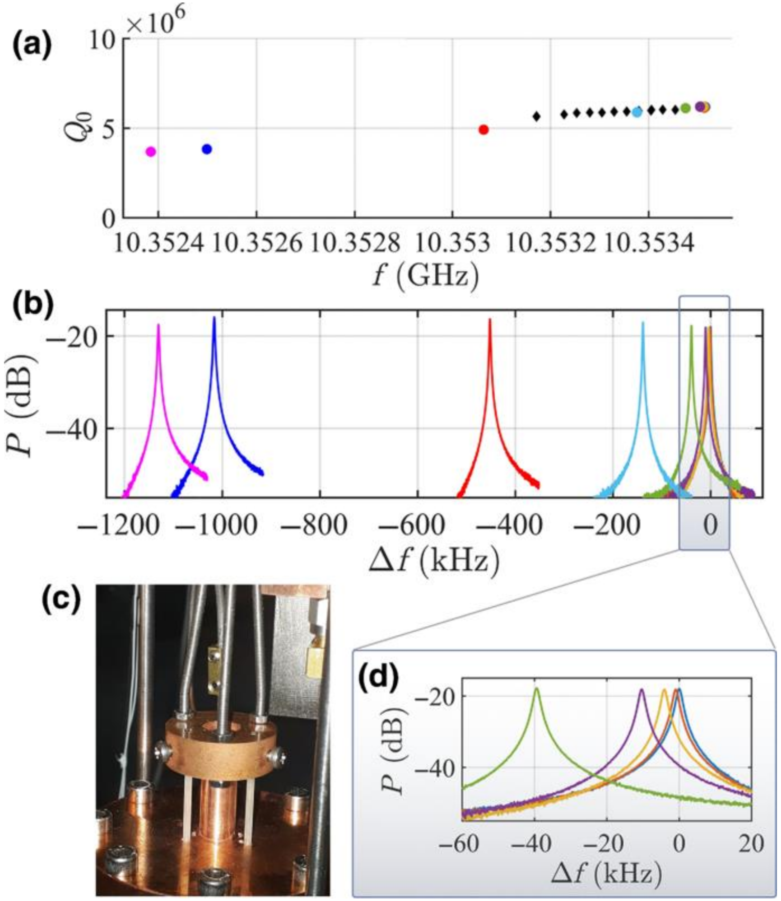


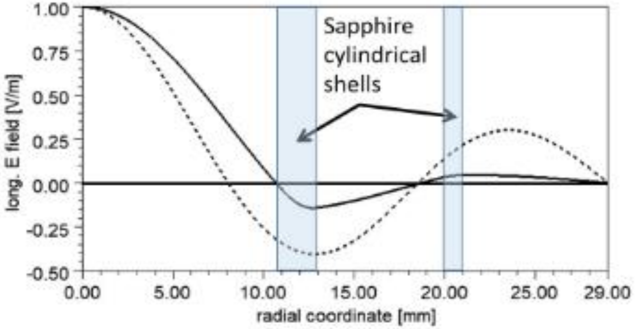

57 mm

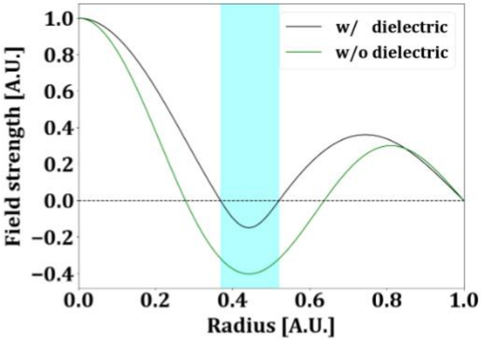
Q ~ 10^6



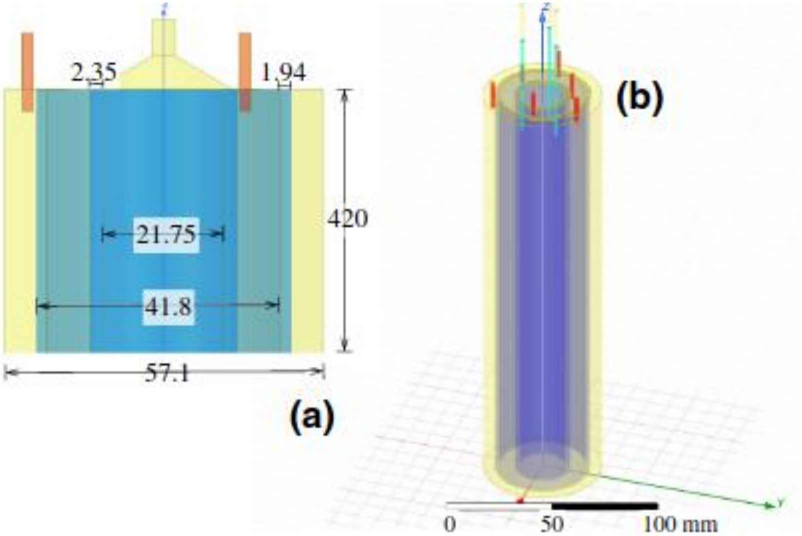
Q ~ 10^4


(a)
$\times 10^6$
10
5
0
Q_0
10.3524
10.3526
10.3528
10.353
10.3532
10.3534
f (GHz)
(b)
−20
−40
P (dB)
−1200
−1000
−800
−600
−400
−200
0
Δf (kHz)
(c)
(d)
−20
−40
P (dB)
−60
−40
−20
0
20
Δf (kHz)

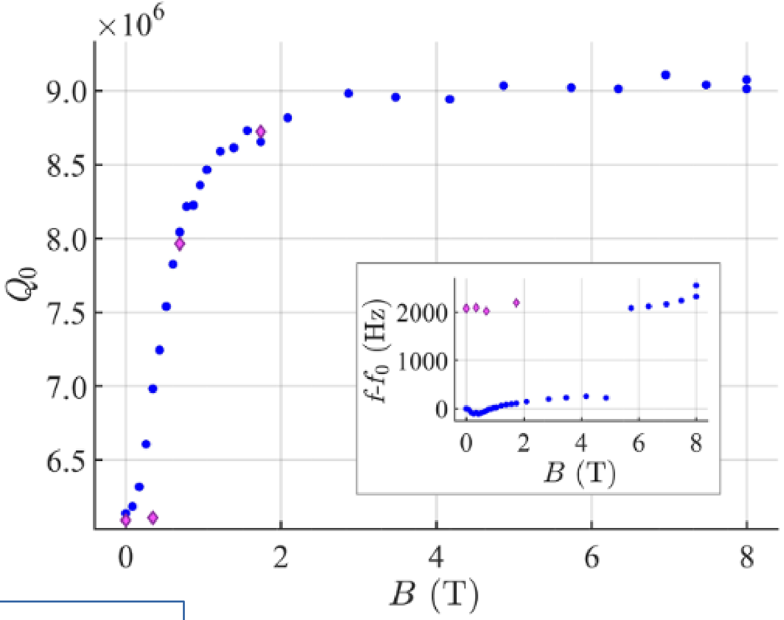

1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
long. E field [V/m]
0.00
5.00
10.00
15.00
20.00
25.00
29.00
radial coordinate [mm]
Sapphire
cylindrical
shells


1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
Field strength [A.U.]
0.0
0.2
0.4
0.6
0.8
1.0
Radius [A.U.]
w/ dielectric
w/o dielectric

QUAX a-γ Dielectric cavity simulations and measurements



Measurement of Q_0 at 4 K



Simulations of the cavity at 4.2 K

ϵ_r	f (GHz)	C_{030}	Q_{Cu}	Q_{Sapph}	Q_0
11.44	10.4556	0.0324	1.14×10^7	4.98×10^9	1.11×10^7
11.3	10.4666	0.0322	1.10×10^7	4.96×10^9	1.10×10^7
11.2	10.4745	0.0321	1.09×10^7	1.03×10^9	1.08×10^7
11.1	10.4825	0.0319	1.07×10^7	1.21×10^9	1.06×10^7

$$\frac{1}{Q_0} = \frac{1}{Q_{\mathrm{Cu}}} + \frac{1}{Q_{\mathrm{Sapph}}}$$

scan rates exceeding 2 MHz/day using a quantum limited receiver

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