16th Patras Workshop on Axions, WIMPs and WISPs

14-18 June 2021

Probing the axion-photon interaction with QUAX experiment: status and perspectives

Alessio Rettaroli

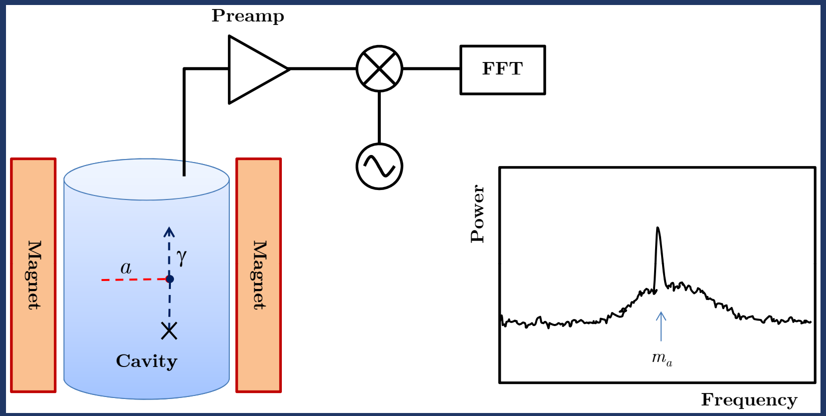
on behalf of the QUAX collaboration

CONTENTS

- Brief introduction
- QUAX-$a\gamma$ latest result
- Future developments

INTRODUCTION

- QCD axions, μeV mass range
- Velocity dispersion
  $v \simeq 270\ km/s$
- Axion figure of merit
  $Q \sim 2\times10^6\ ,\ \ Q_{lab} \sim 10^6$

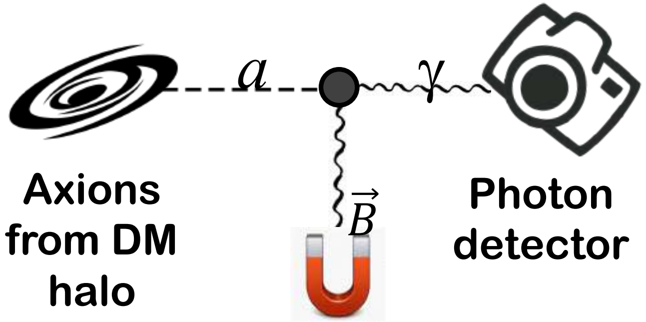


(image stolen from Irastorza-Redondo)

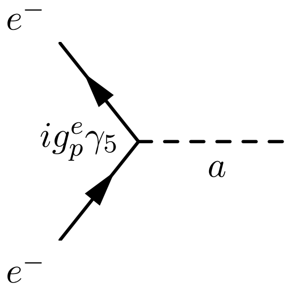
INTRO: QUAX a-e *and* QUAX a-γ

LNF (Frascati)

- R&D on resonant cavities
- Incoming *classical haloscope* for axion-photon coupling (QUAX a-γ)



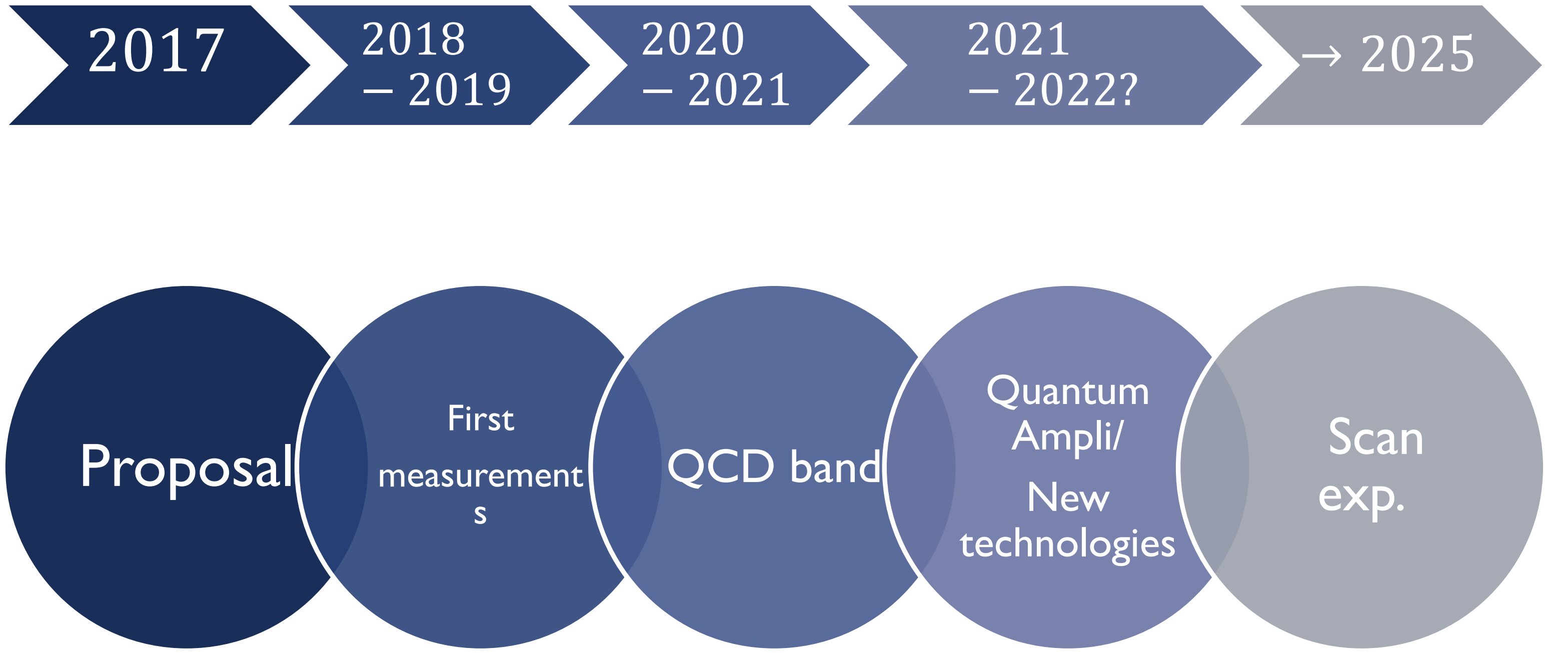
LNL (Legnaro)



- Axion-electron coupling with *ferromagnetic haloscope* (QUAX a-e)
- Axion-photon coupling with *classical haloscope* (QUAX a-γ)

Main results:

- **Proposal**
  Phys. Dark Univ. **15**, 135-141 (2017)
- **QUAX a-e 2018**
  Eur. Phys. J. C **78,** 703 (2018)
- **QUAX a-γ 2019**
  Phys. Rev. D **99**, 101101(R) (2019)
- **QUAX a-e 2020**
  Phys. Rev. Lett. **124**, 171801 (2020)
- **QUAX a-γ 2021**
  Phys. Rev. D **103**, 102004 (2021)



LATEST AXION SEARCH WITH QUAX-$a\gamma$

LATEST RESULT

PHYSICAL REVIEW D **103**, 102004 (2021)

Search for invisible axion dark matter of mass $m_a = 43\ \mu eV$ with the QUAX–$a\gamma$ experiment

D. Alesini,[1] C. Braggio,[2,3] G. Carugno,[2,3] N. Crescini,[4,3,*] D. D'Agostino,[5,6] D. Di Gioacchino,[1] R. Di Vora,[2,7,†] P. Falferi,[8,9] U. Gambardella,[5,6] C. Gatti,[1] G. Iannone,[5,6] C. Ligi,[1] A. Lombardi,[4] G. Maccarrone,[1] A. Ortolan,[4] R. Pengo,[4] A. Rettaroli,[1,10,‡] G. Ruoso,[4] L. Taffarello,[2] and S. Tocci[1]

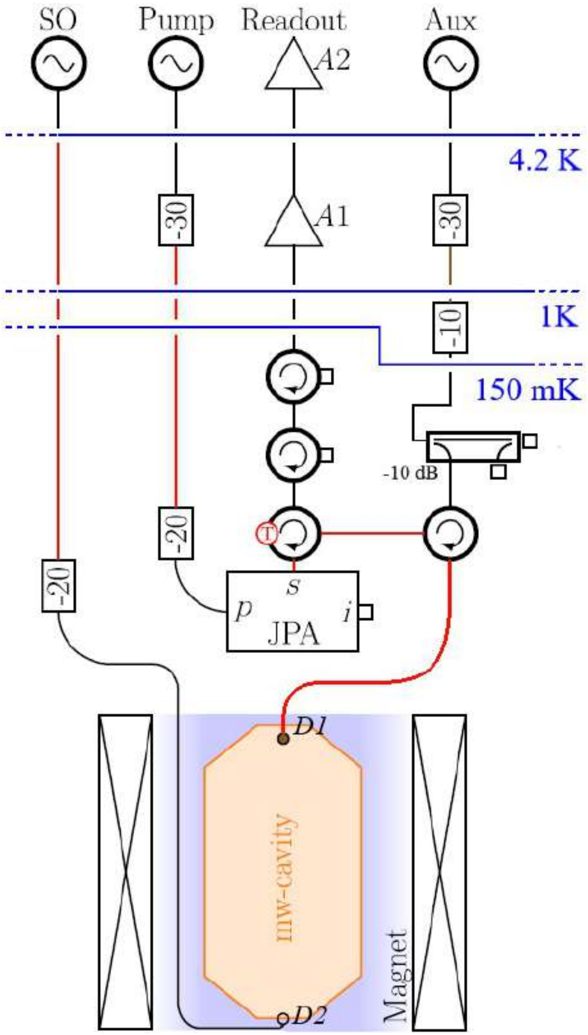
Data taken in January 2020

with the haloscope at Legnaro

Finally the paper is available on PRD since May 2021

10.1103/PhysRevD.103.102004

EXPERIMENTAL SETUP

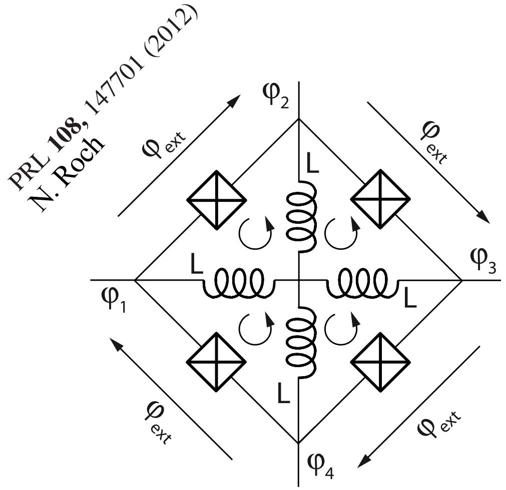


Dilution refrigerator
$T_{base} = 90\ mK$

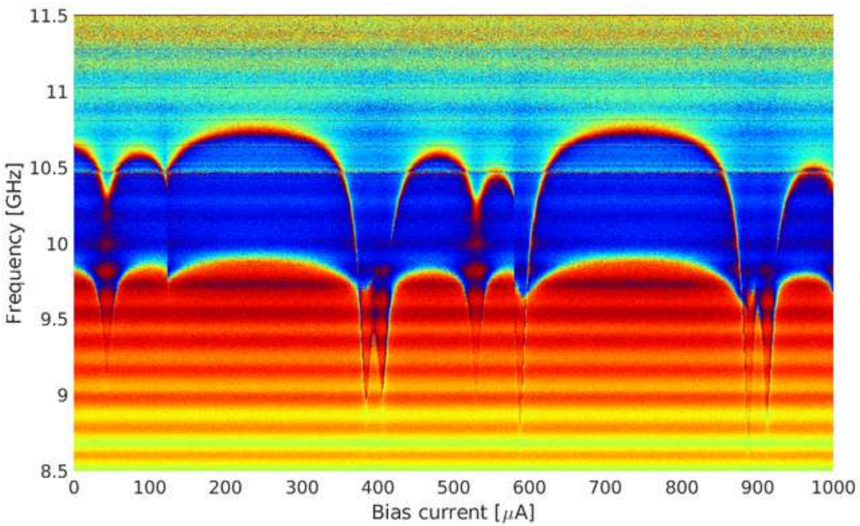
SC magnet
$B = 8.1\ T$
Bore: $150\ mm$
Length: $500\ mm$

Amplifiers
JPA
Cryogenic HEMT
Room-temp. HEMT

JPA

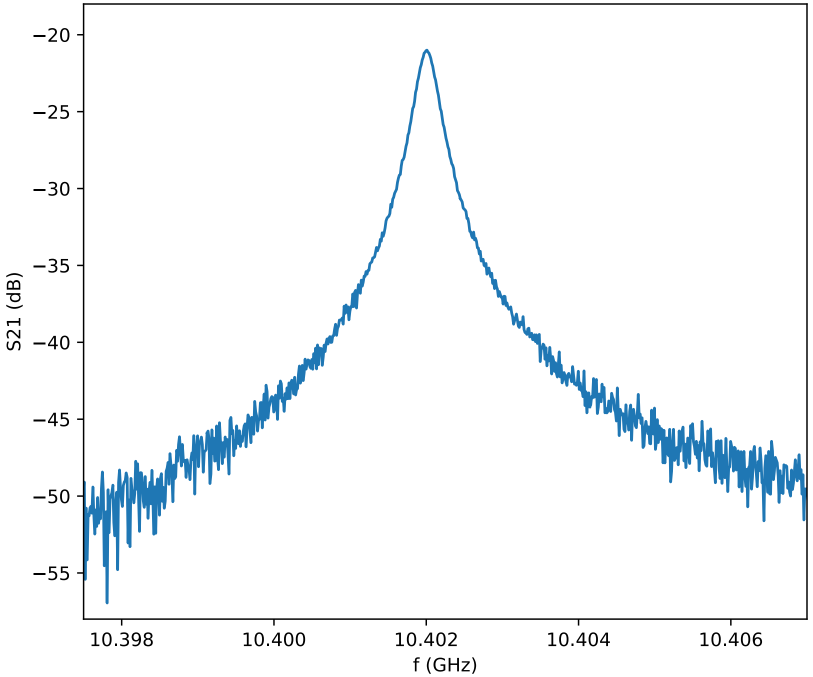


- **Tunability**: between 10.2 and 10.5 GHz
- **Gain**: 18 dB (up to 25 dB) in a 10 MHz bandwidth centered at 10.4 GHz
- **Noise** at Standard Quantum Limit (0.5K)



RESONANT CAVITY

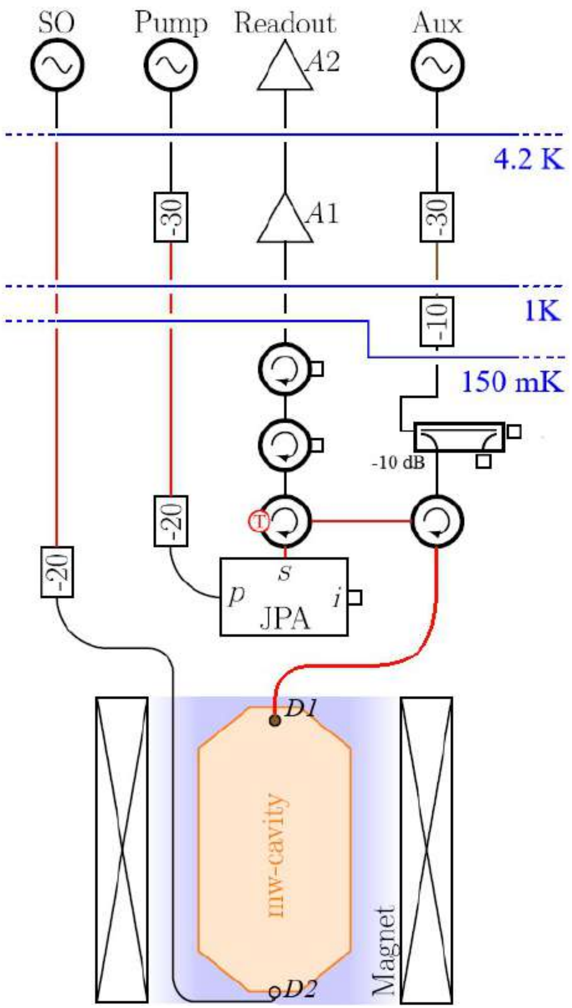
- OFHC Copper cavity
- Cilindrical, $r = 11.05\ mm$
- Lenght $210\ mm$



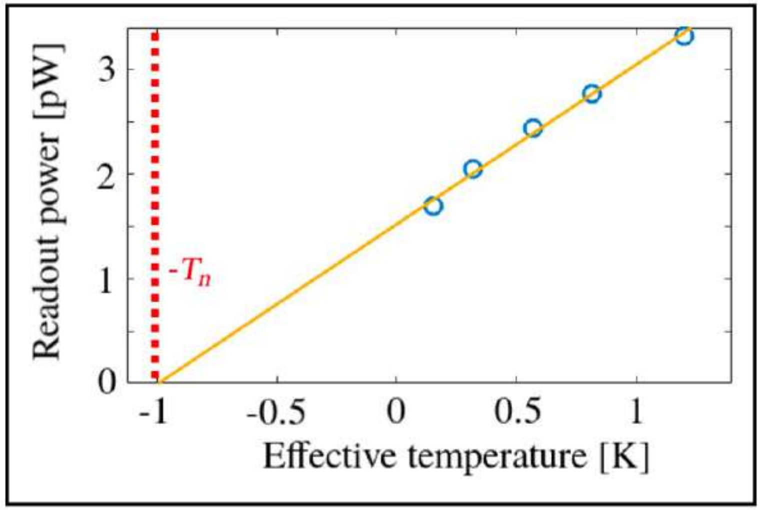
$\nu = 10.4018\ GHz$
$Q_0 = 76\ 000$
$Q_L = 36\ 000$

$TM010$ mode measured at $T = 150\ mK$

CALIBRATION



1) Transmittivity measurement of rf lines
2) Υ-measurement to obtain gain and noise temperature

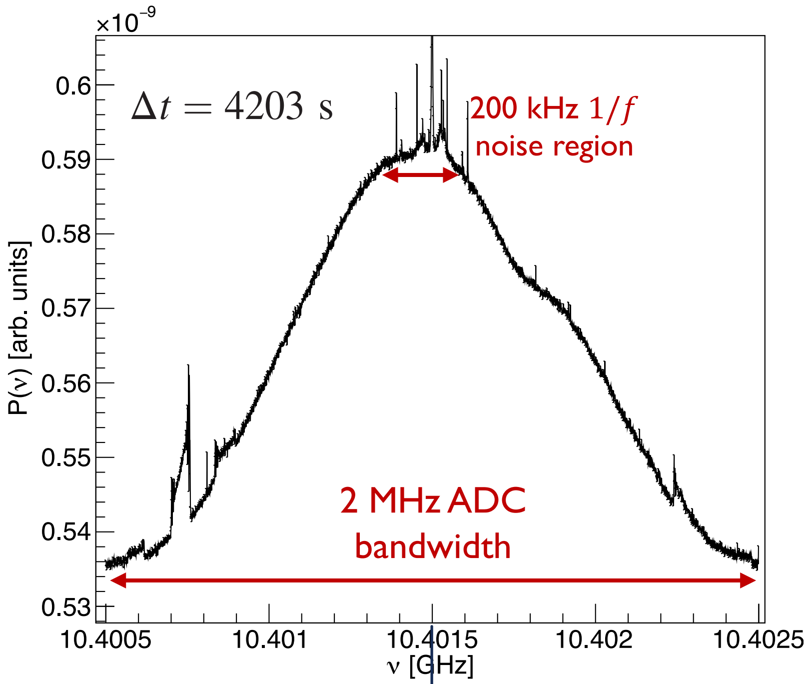


$$T_n = (0.99 \pm 0.15_{\text{cal}} \pm 0.04_{\text{stab}})\ \text{K}$$

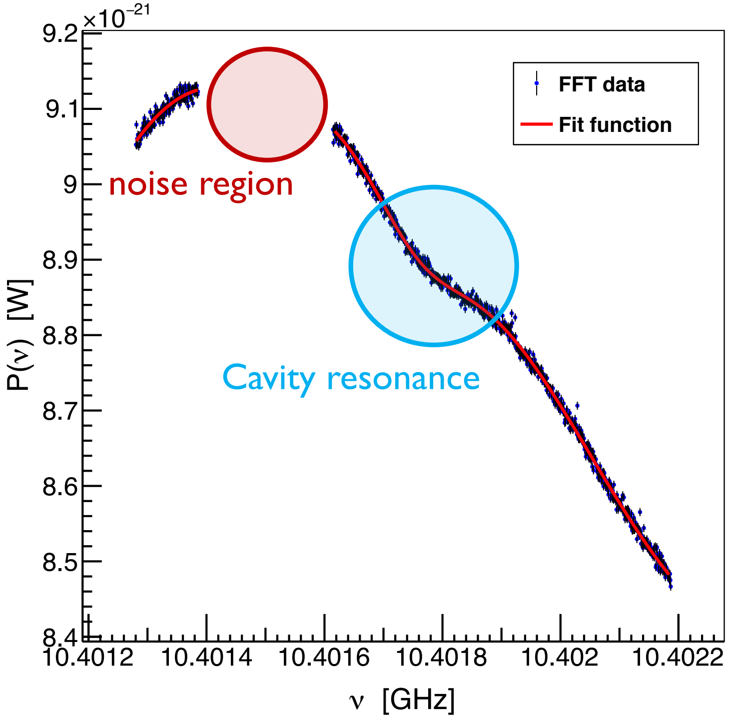
16% uncertainty due to limited tunability of the coupling

Systematic due to temperature instability during data-taking

DATA TAKING AND QUALITY CUT



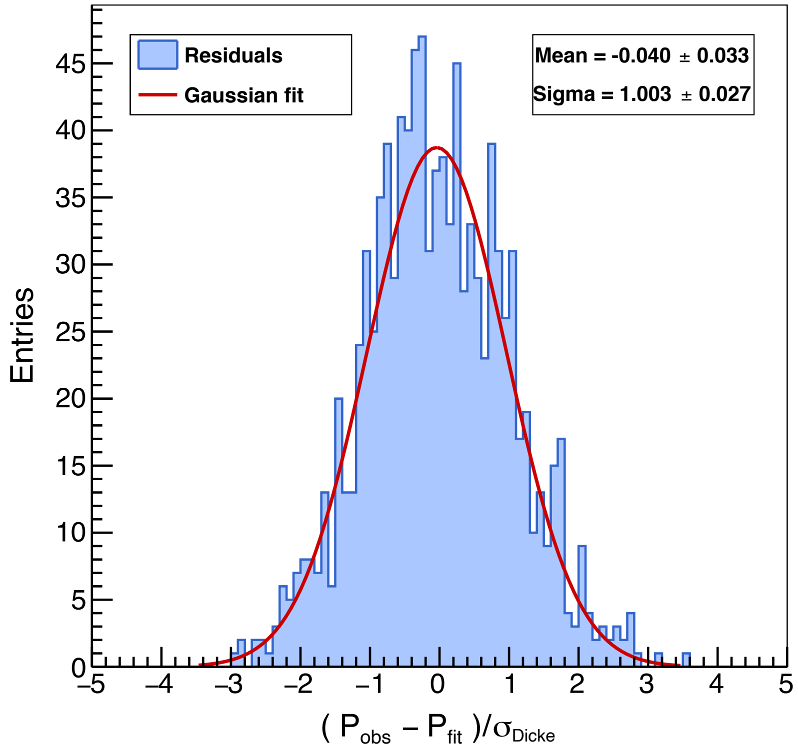
$$\nu_{LO} = 10.4015\ GHz$$



Fitted cavity parameters
$\nu_c = 10.40176\ GHz$
$Q_L = 35\ 000$

ANALYSIS PROCEDURE

Residuals normalized to
$\sigma_{\text{Dicke}} = 5.38 \times 10^{-24}$ W



1) Discovery candidate claimed if power is in excess of 5σ (bins > 5 in the normalized residuals)

(actually account for the *look-elsewhere effect*, resulting in $Z > 6.2$ in our case)

2) Maximum likelihood method to etimate $g_{a\gamma\gamma}$

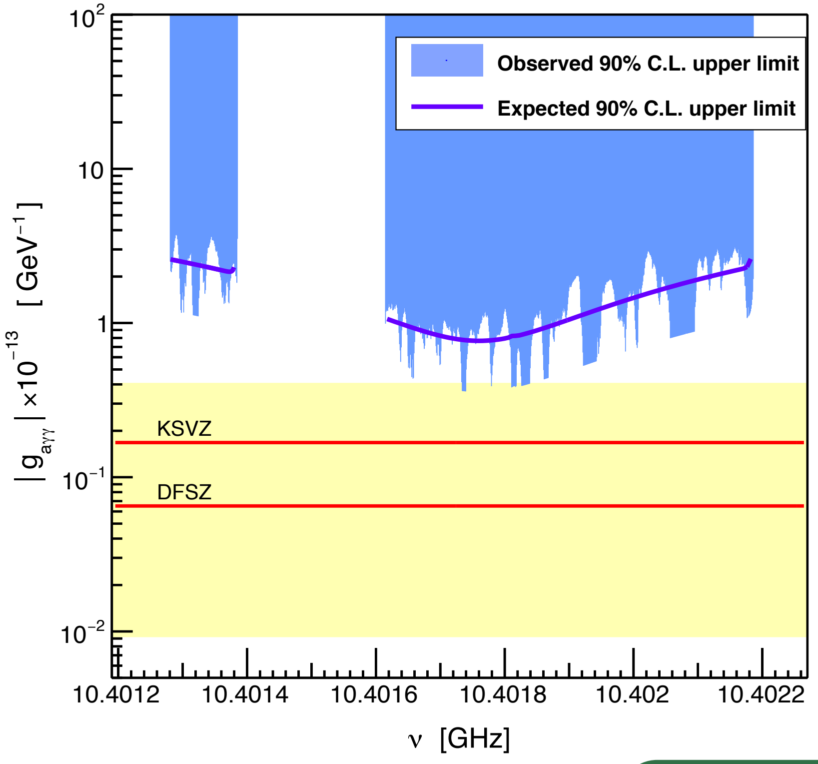
$$-2 \ln \mathcal{L}(m_a, g^2_{a\gamma\gamma}) = \sum_{i=0}^{N_{\text{bin}}} \frac{(R_i - S_i(m_a, g^2_{a\gamma\gamma}))^2}{(\sigma^{\text{max}}_{\text{Dicke}})^2}$$

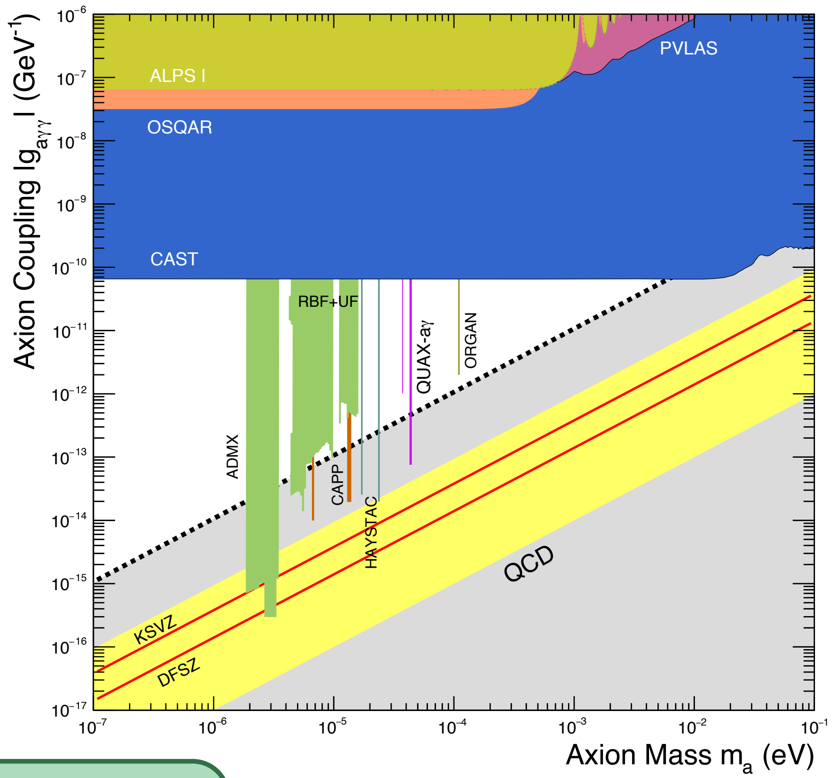
R_i residuals, S_i expected power x Standard Halo Model*

3) Then, 90% CL: $g^{\text{CL}} = \sqrt{\hat{g}^2 + 1.28\,\hat{\sigma}_{\hat{g}^2}}$

*Turner, Phys. Rev. D 42, 3572 (1990)

AXION-PHOTON COUPLING RESULT





$$g_{a\gamma\gamma} < 0.766 \times 10^{-13}\ \mathrm{GeV}^{-1}$$

$$(\, m_a = 43.0182\ \mu eV \,)$$

FUTURE PLANS

QUAX PLAN TO 2025

About (9 – 11) GHz span to KSVZ line

Different cavity schemes

Quantum amplification

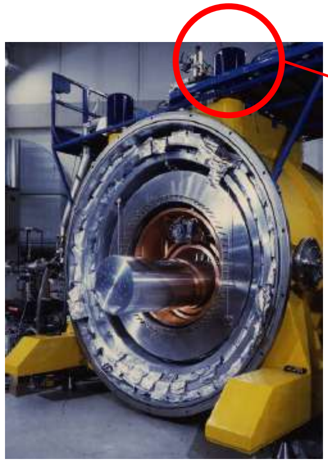
	LNF	**LNL**
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	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
Performance for KSVZ model at 95% c.l. with $N_A = 0.5$		
Noise Temperature	0.43 K	0.5 K
Single scan time	3100 s	69 s
Scan speed	18 MHz/day	40 MHz/day
Performance for KSVZ model at 95% c.l. with $N_A = 1.5$		
Noise Temperature	0.86 K	1 K
Single scan time	12500 s	280 s
Scan speed	4.5 MHz/day	10 MHz/day

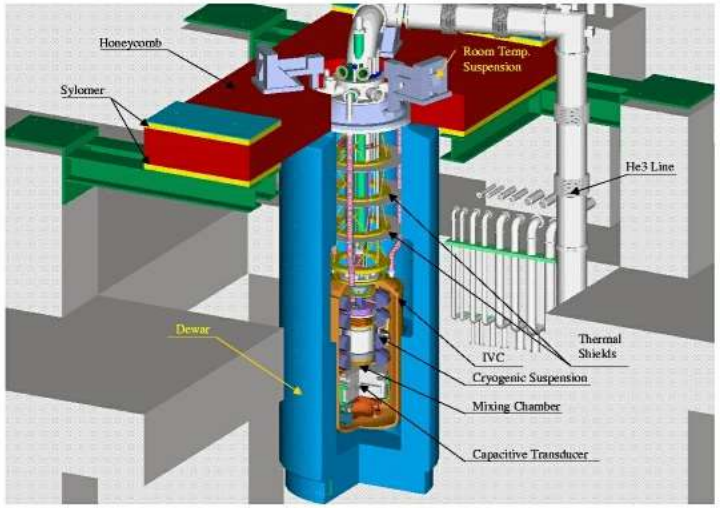
LNL HALOSCOPE

- Refurbished dilution from Auriga

$$T_{base} = 70\ mK$$

$$1\ mW\ @\ 100\ mK$$





- Use of the tunable sapphire resonator with $Q > 10^6$
- Start with 8 T magnet → possible upgrade to 14 T magnet – same length: 40 cm

LNF HALOSCOPE

Horizon 2020
European funding

SUPERGALAX

$T_{base} = 8\ mK$

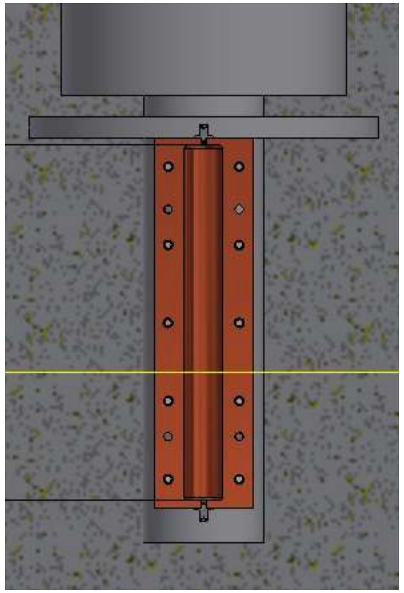
$500\ \mu W\ @\ 100\ mK$

5 rf lines

LEIDEN CRYOGENICS

SC magnet, $9\ T$

Lenght $325\ mm$

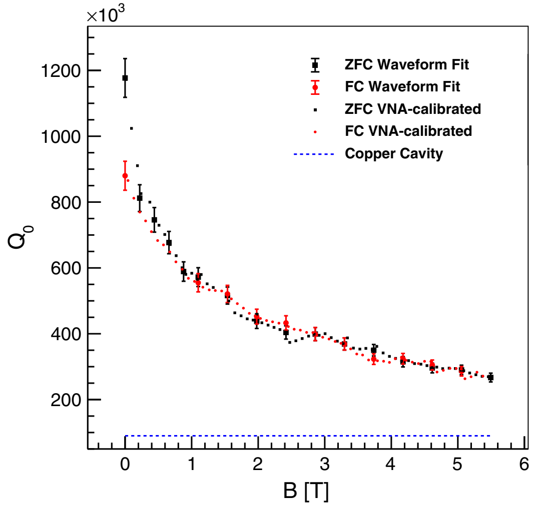


Bore $100\ mm$

➤ $9\ T$ magnet + tunable cavity expected for the beginning of 2022

LNF SUPERCONDUCTING CAVITIES

Sputtered $NbTi$



10.1103/PhysRevD.99.101101

YBCO tapes

(pending)

For interesting results refer to CAPP/KAIST talks

Bulk Nb_3Sn

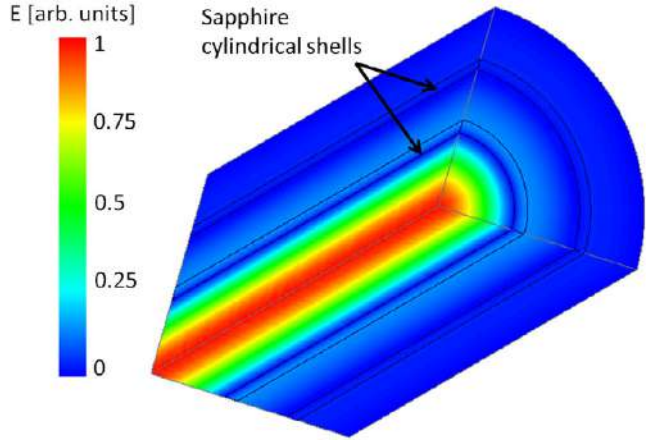
SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

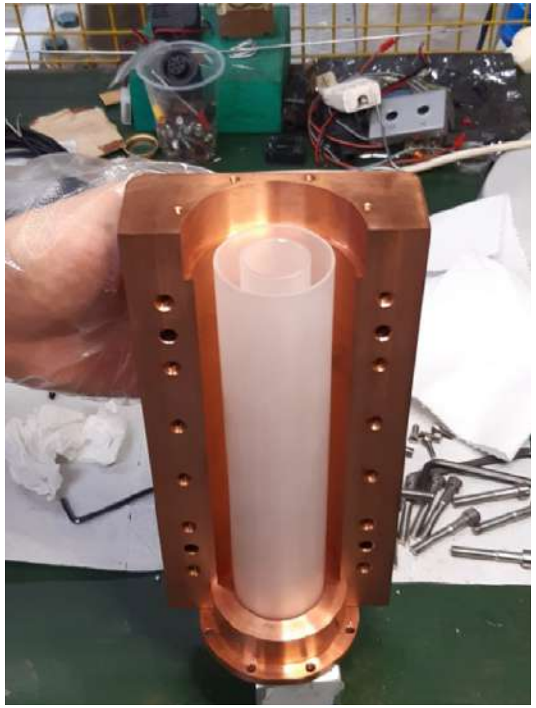
Bulk Nb_3Sn in fabrication at FNAL

Promising results from simulations

LNL DIELECTRIC CAVITIES

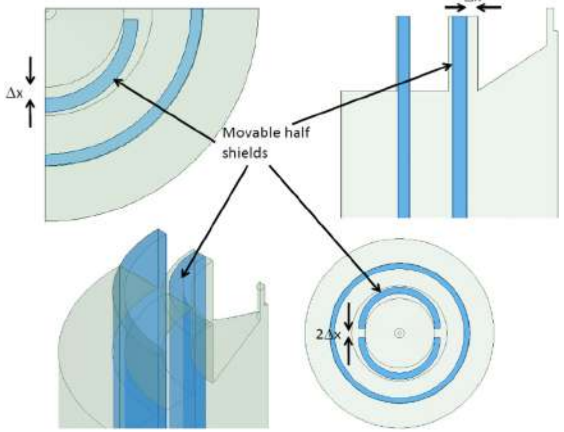
- Concentric sapphire hollow-tubes housed in a copper cavity





$\nu_{030} = 10.916\ GHz$
$Q_0 = 720\ 000$
at $T = 5.4\ K$

Tuning simulations: $500\ MHz$ with $\Delta x = 1.5\ mm$



See the new outstanding results from

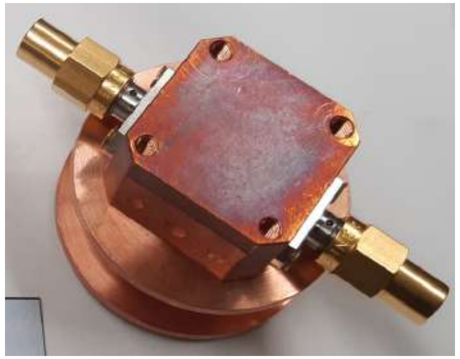
Raffaele di Vora

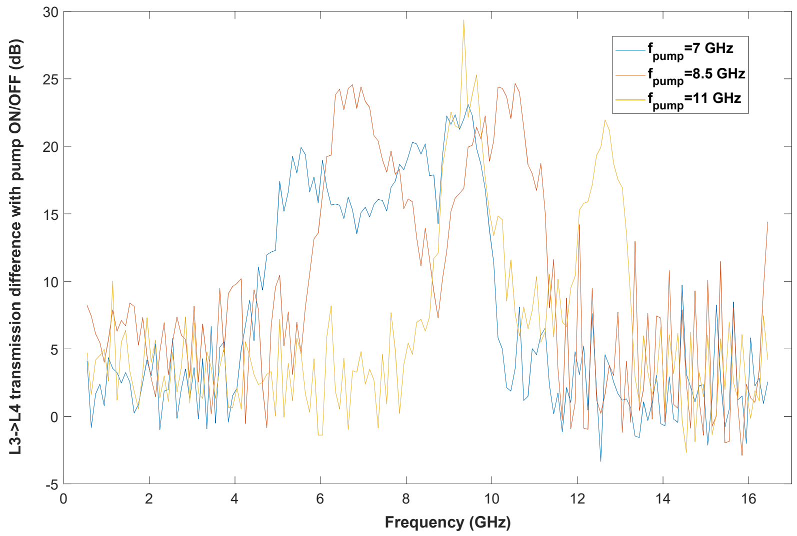
Wednesday, 16 June 2021 16:15

DOI: 10.1016/j.nima.2020.164641

LNL AMPLIFICATION

- Employment of a TWPA provided by collaborating group of Nicolas Roch (Grenoble), based on superconducting nonlinear asymmetric inductive elements (SNAIL) arXiv:2101.05815





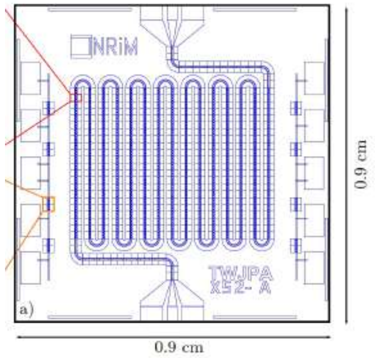
about
20 dB gain

- Amplification over a large bandwidth ($> 1\ GHz$)
- Noise temperature of about 2 photons

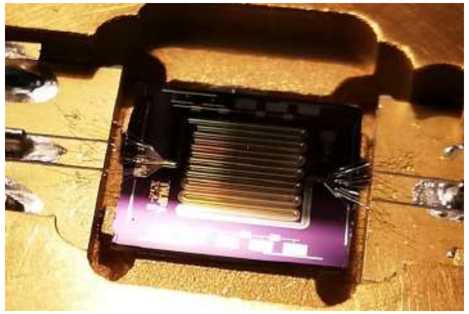
LNF AMPLIFICATION and MULTICAVITY SCHEME

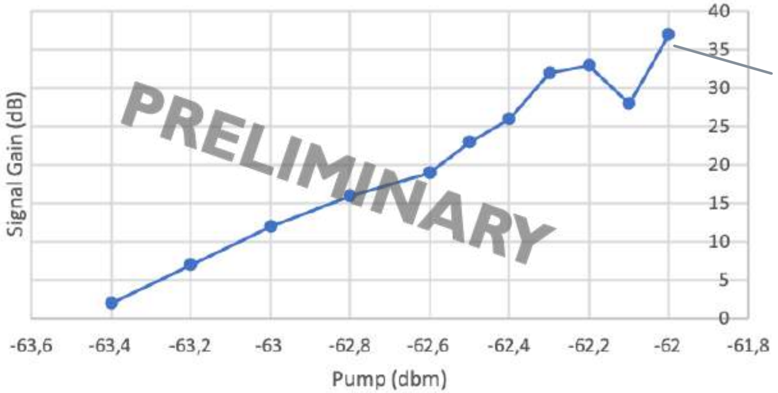
Traveling Wave Josephson Parametric Amplifier

TL + SQUIDs array

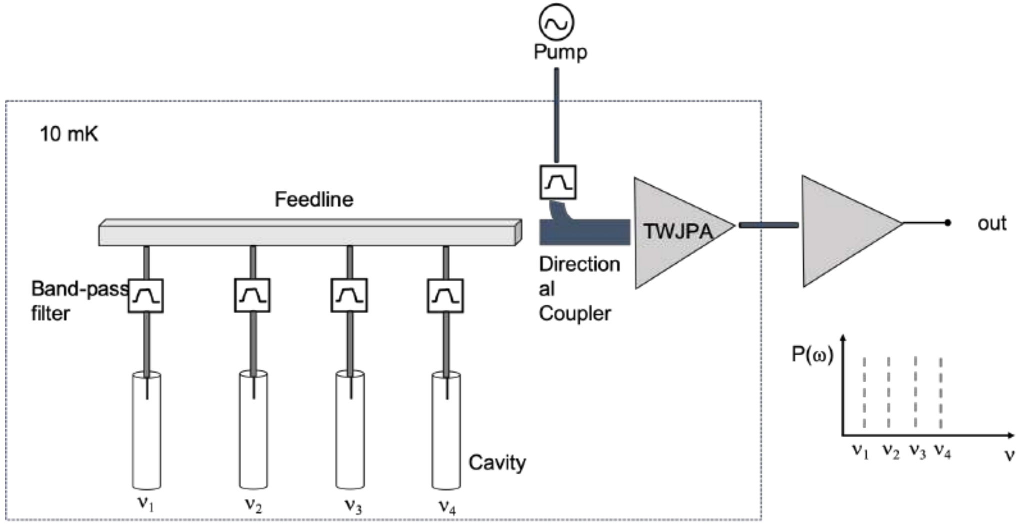


Fabricated by INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA



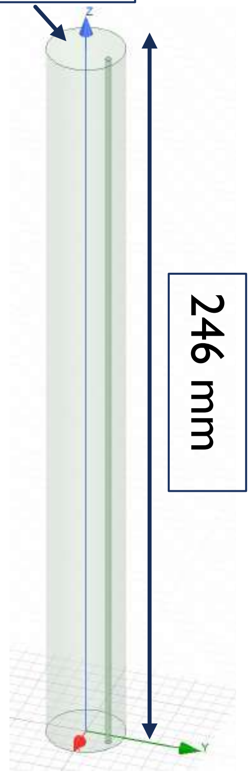


Almost
40 db gain
(at single freq)

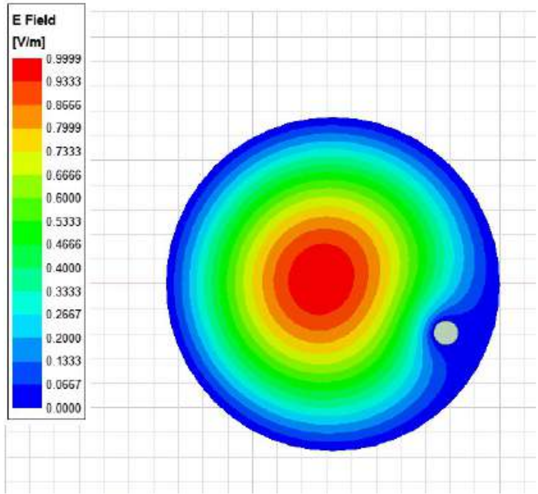


TUNABLE CAVITIES

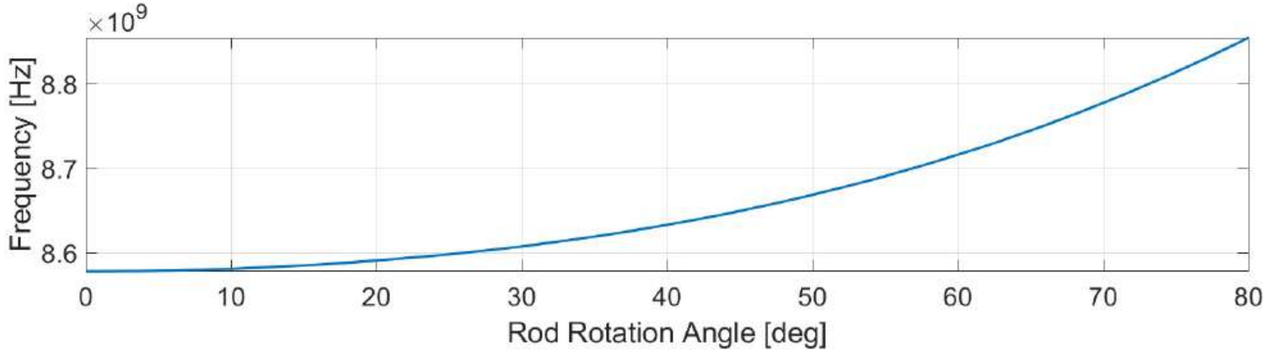
R 13.51 mm



Simulation of Copper cavity tuned with a conductive rod

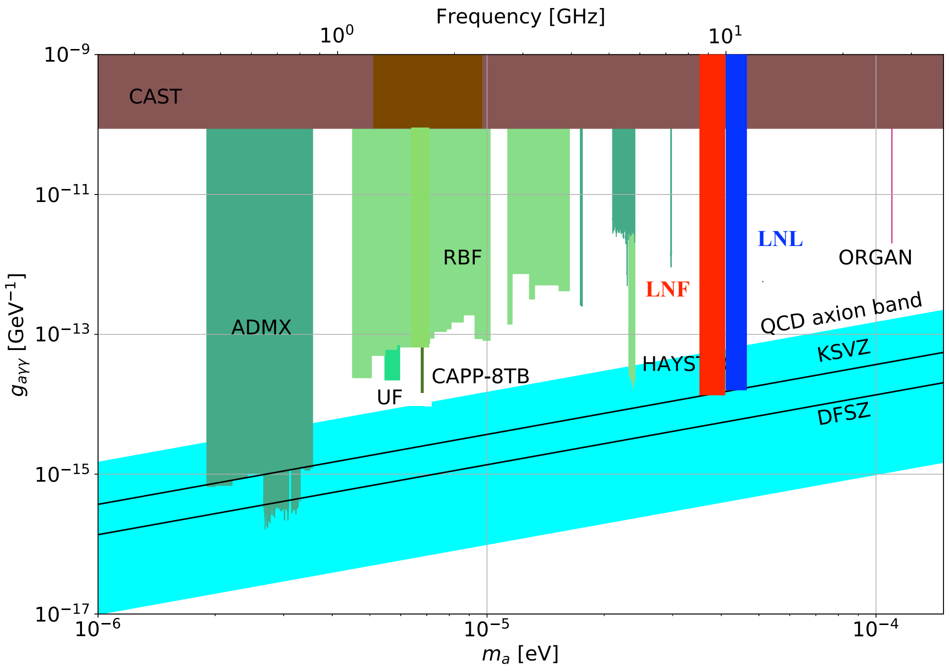


Mode: **TM010**
Frequency: **8.578 GHz (at 0 deg)**
Rod Rotation: **from 0° to 80°**
Frequency Shift: **from 8.578 GHz to 8.854 GHz**
Tuning: **~ 276 MHz**



- QUAX a-γ has recently menaged to reach the QCD band
- We're at work to:
  - Develop new resonant cavities
  - Handle quantum amplification
  - Improve cryogenics and magnets

CONCLUSIONS



Quax 2025 projection: 2 GHz scan to the KSVZ line

THANK YOU!