Search For Axion Dark Matter With The QUAX Haloscopes

C GATTI

OUTLINE

- Axion Dark Matter
- Haloscope
- QUAX Experiment
  - QUAX ae
  - QUAX aγ
- Quax 2021-2025
  - R&D on resonant cavities
  - R&D on signal amplification
- Conclusion

Axion Dark Matter

Local Dark Matter density

$$\rho \simeq 0.3GeV/cm^3$$

Axion density

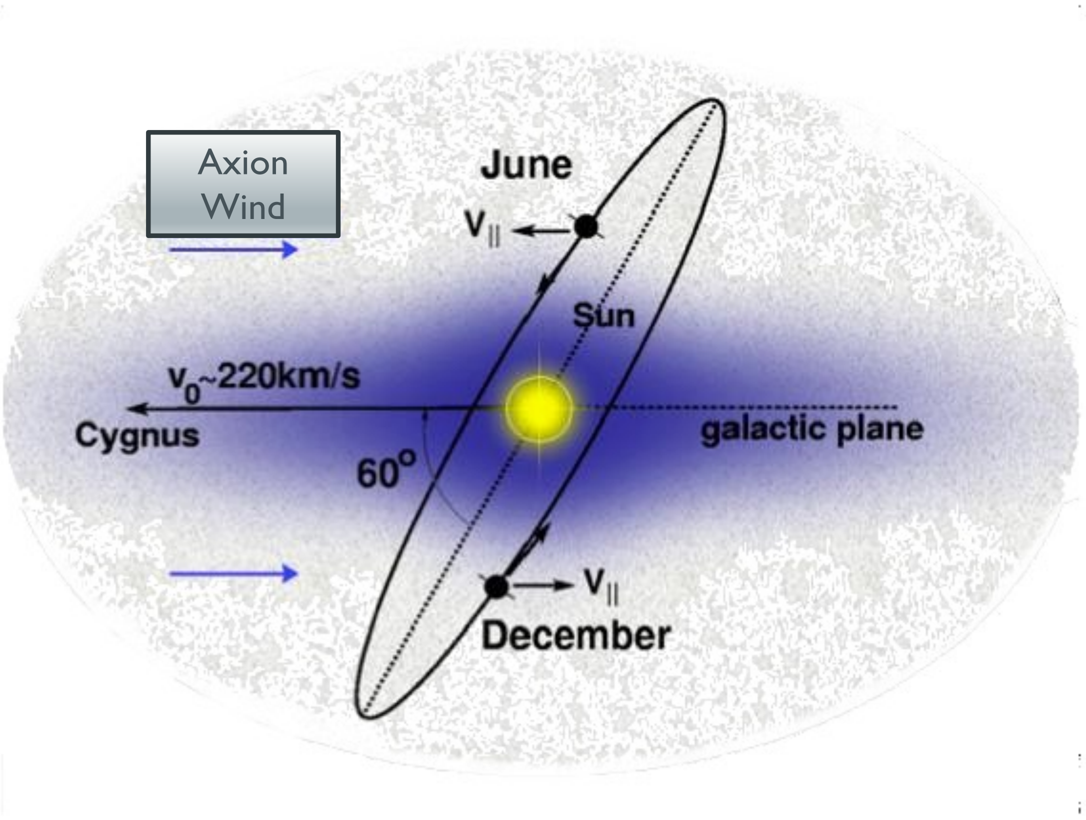
$$n_a \simeq 3 \times 10^{12} \left(\frac{100\mu eV}{m_a}\right) 1/\mathrm{cm}^3$$

Axion-Earth relative speed

$$\beta_a \sim 10^{-3} \qquad \hbar\omega \simeq m_a c^2$$

Treat axion as a classical field

$$a = a_0 \cos(\omega t - kx) \quad a_0 = \sqrt{\frac{n_a \hbar^3}{m_a c}}$$



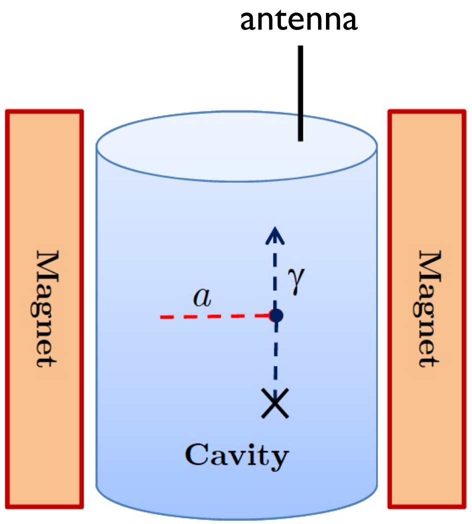
$$v_a = v_{Halo} - v_{Earth}$$

Sikivie Haloscope

In presence of a strong magnetic field, cavity modes are excited by a resonant axion field

$$\nabla^2 E - \partial_t^2 E = -g_{a\gamma\gamma} B_0 \partial_t^2 a$$

$$P_{\text{sig}} = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \times \left(\frac{\beta}{1+\beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mnl} Q_L \right)$$



Sikivie Phys. Rev. D 32,11 (1985)

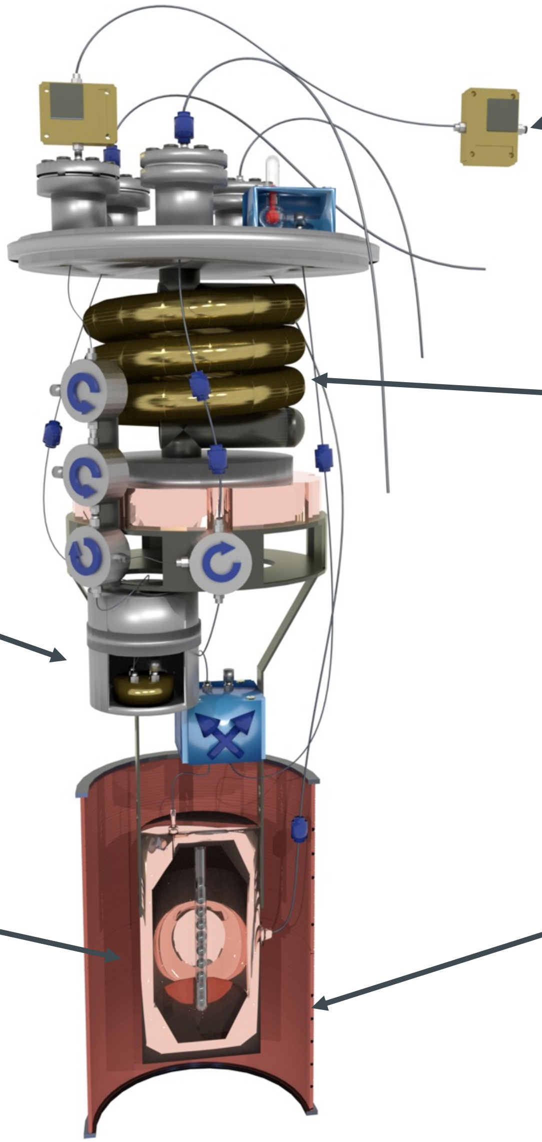
β antenna coupling to cavity

V cavity volume

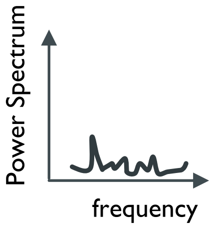
C_{mnl} mode dependent factor about 0.6 for TM010

Q_L cavity "loaded" quality factor

State of Art Sikivie's Haloscope



Room Temperature Amplifiers



Dilution Refrigeretor T<100 mK

Cryogenic Amplifier (noise at SQL)

Scan rate

$$\frac{df}{dt} \propto \frac{B^4 V^2 Q_L}{T_{sys}^2}$$

Resonant cavity

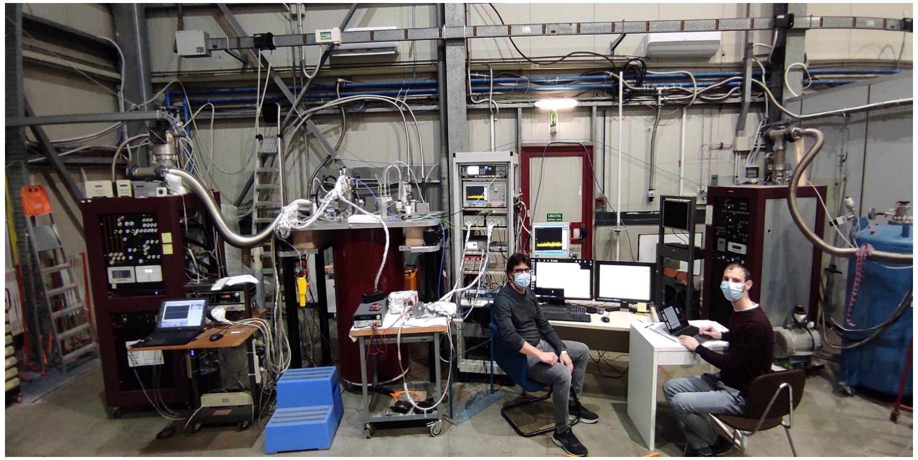
SC magnet (~10 T)

Sikivie Phys. Rev. D 32,11 (1985)

QUAX Collaboration

Laboratori Nazionali di Frascati (LNF)

EPS Historic site: AdA first e+e- collider (1961)

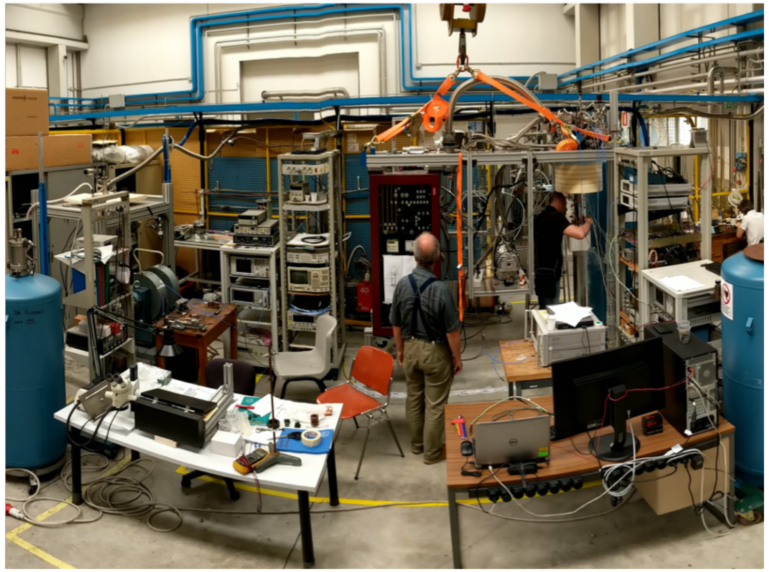


INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

TIFPA
Trento Institute for Fundamental Physics and Applications

INFN
Gruppo Collegato di Salerno
Sezione di Napoli
Istituto Nazionale di Fisica Nucleare

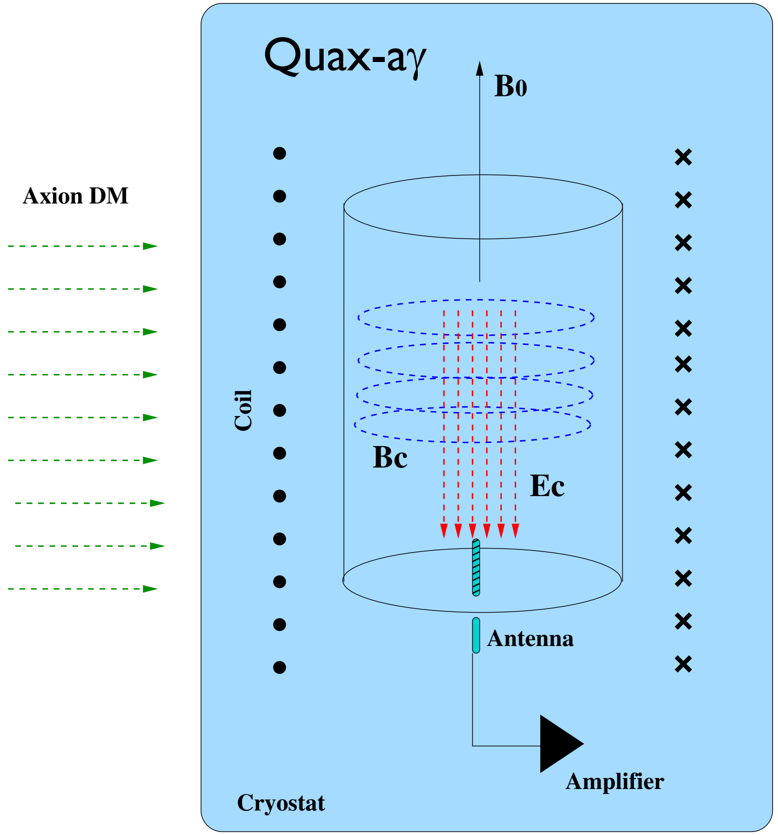
Laboratori Nazionali di Legnaro (LNL)

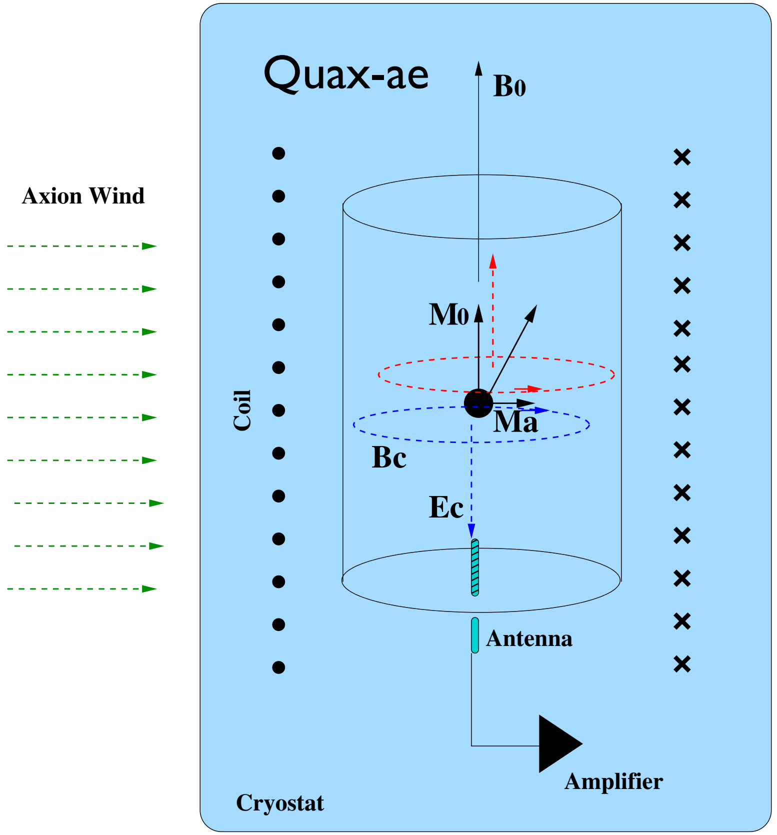


In collaboration with Birmingham University

QUAX: Quest for Axions

$$\mathcal{L} = i\frac{g_d}{2}a\left(\bar{N}\sigma_{\mu\nu}\gamma^5 N\right)F^{\mu\nu} + i\frac{g_{aNN}}{2m_N}\partial_\mu a\left(\bar{N}\gamma^\mu\gamma^5 N\right) + i\frac{g_{aee}}{2m_e}\partial_\mu a\left(\bar{e}\gamma^\mu\gamma^5 e\right) + g_{a\gamma\gamma}aE\cdot B$$

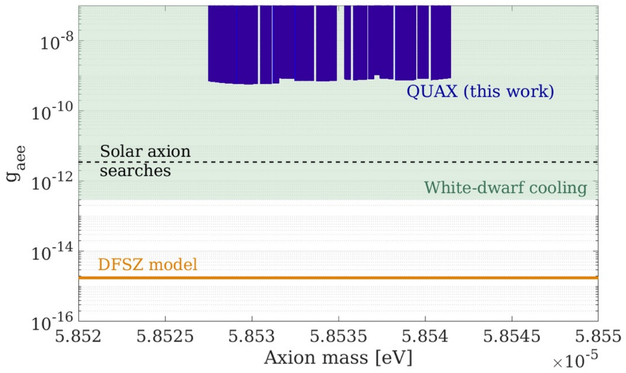




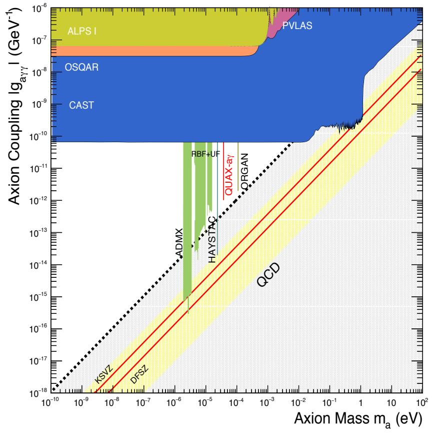
QUAX RESULTS 2018-2021

- QUAX-ae result with Ferromagnetic Axion Haloscope at m_a = 58 meV, EPJC (2018) 78:703.
- QUAX-aγ Result with Superconductive Resonant Cavity at m_a = 37.5 meV, Phys. Rev. D **99**, 101101(R) (2019).
- QUAX-ae with Quantum-Limited Ferromagnetic Haloscope, Phys. Rev. Lett. **124**, 171801 (2020).
- Search for Invisible Axion Dark Matter of mass m_a = 43 meV with the QUAX-ag Experiment, Phys. Rev. D 103, 102004 (2021).

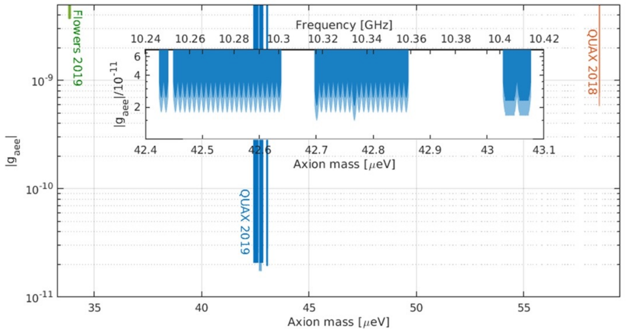
Quax-ae 2018



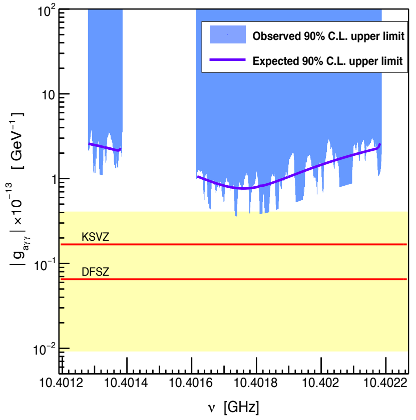
Quax-aγ 2019



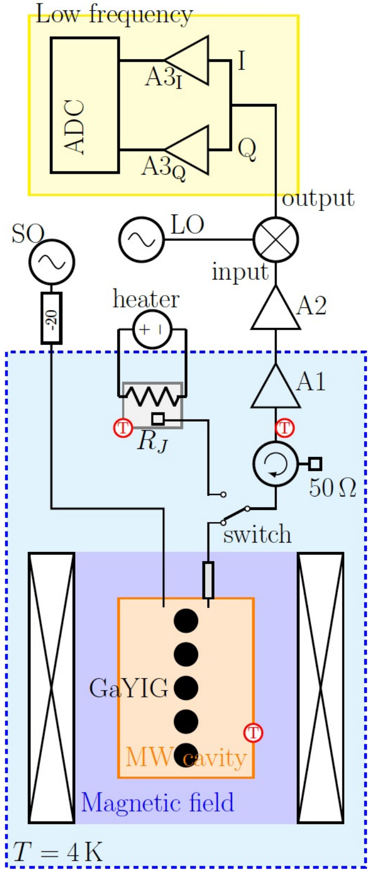
Quax-ae 2020



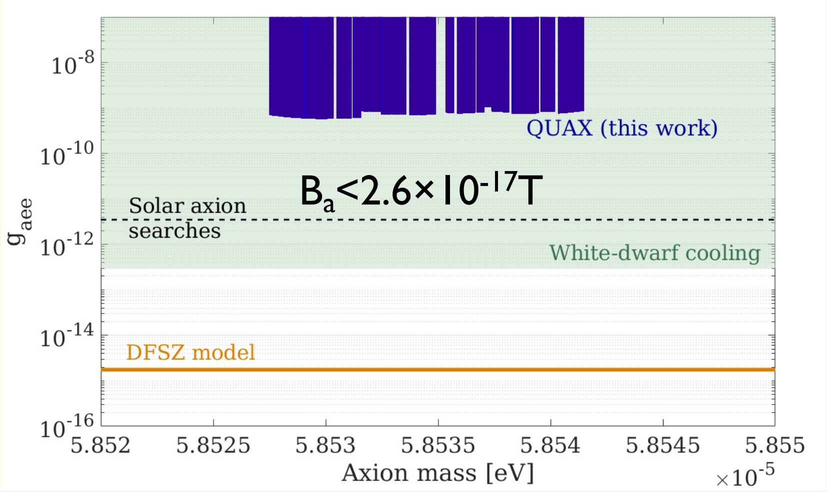
Quax-aγ 2021

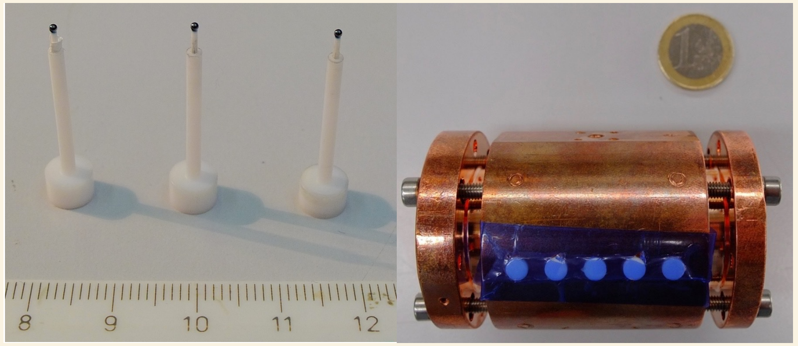


QUAX-ae First Ferromagnetic Axion Haloscope at m_a = 58μeV



Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =1 mm)	5
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.11
Frequency [GHz]	13.98
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [K]	5.0
T amplifier [K] (HEMT)	11



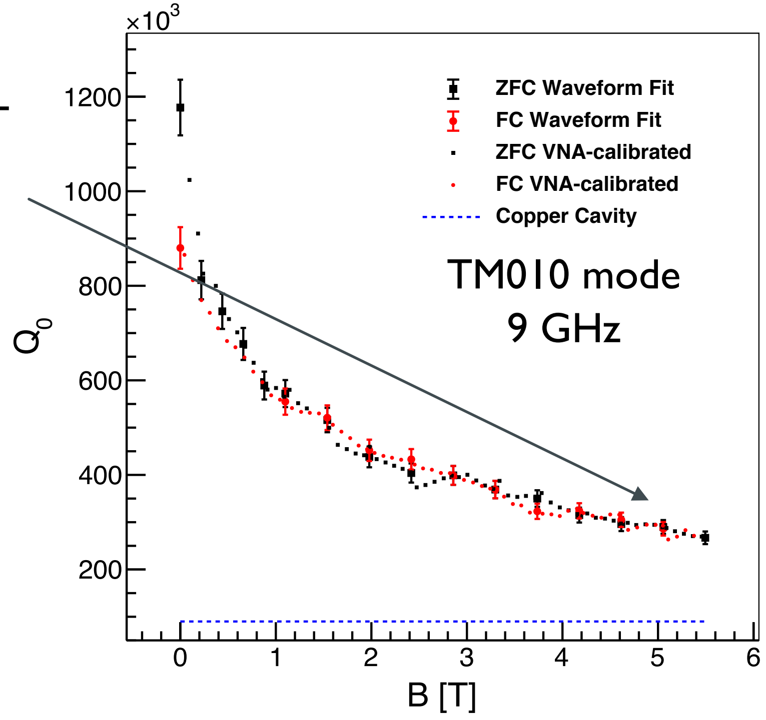


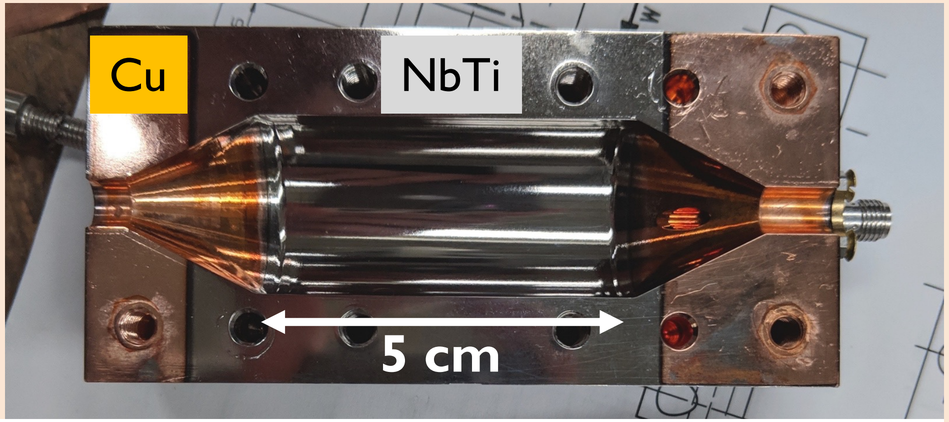
EPJC (2018) 78:703

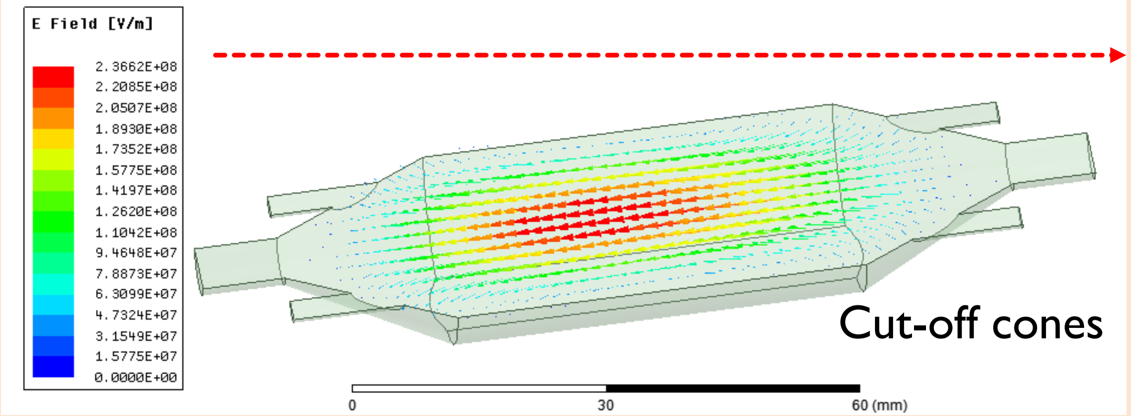
Improving Q of Resonant Cavity with Superconducting NbTi

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

$Q_0=3\times10^5$ at 5 T gain a factor 3.3 wrt (simulated) Cu cavity

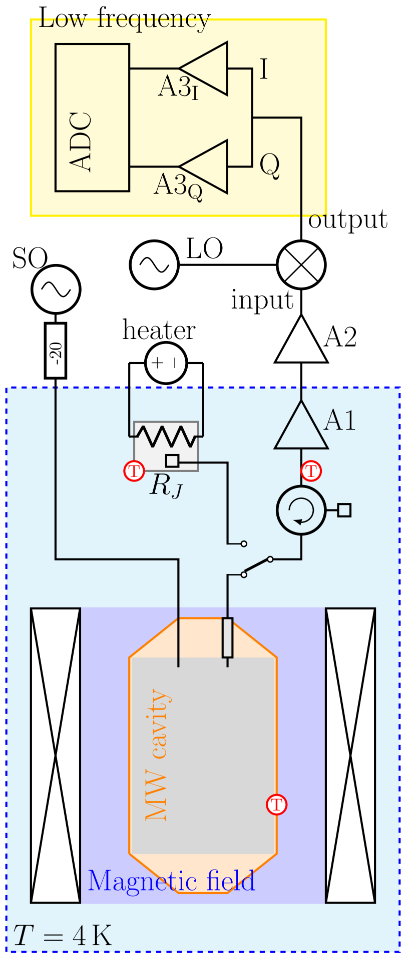




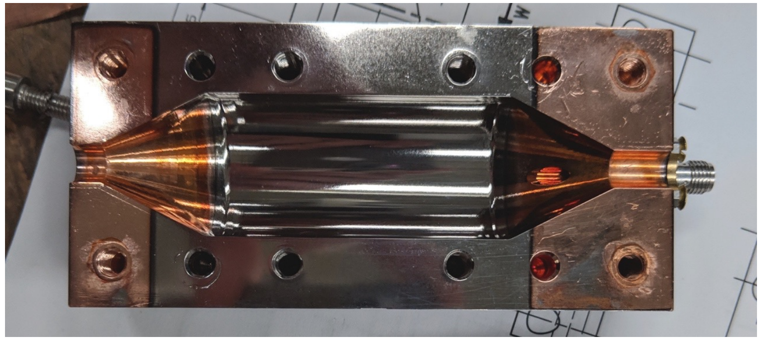


IEEE TRANS. APP. SUPERCOND. 29, 5 (2019)

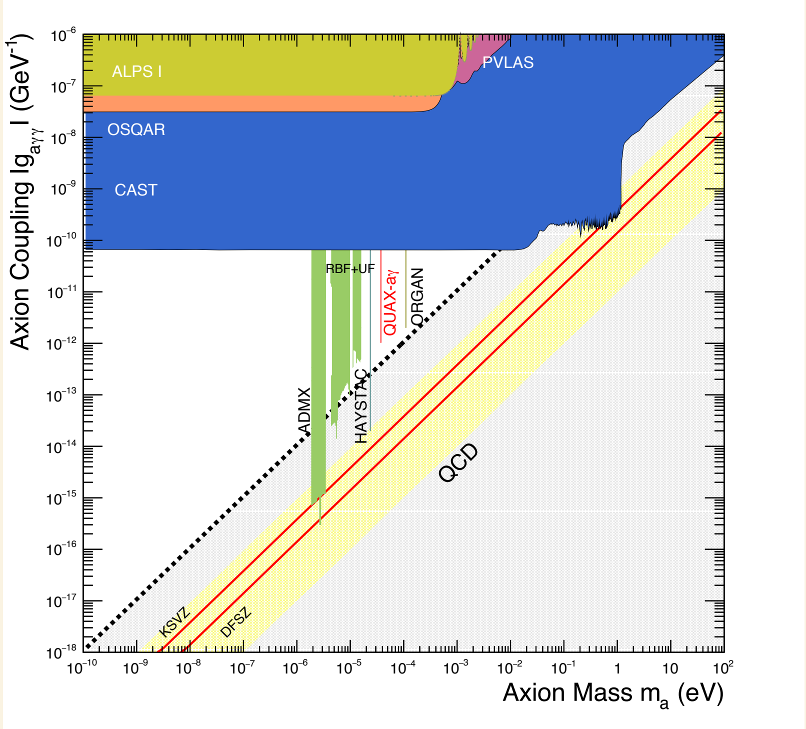
QUAX-aγ Result with Superconductive Resonant Cavity at m_a = 37.5 μeV



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

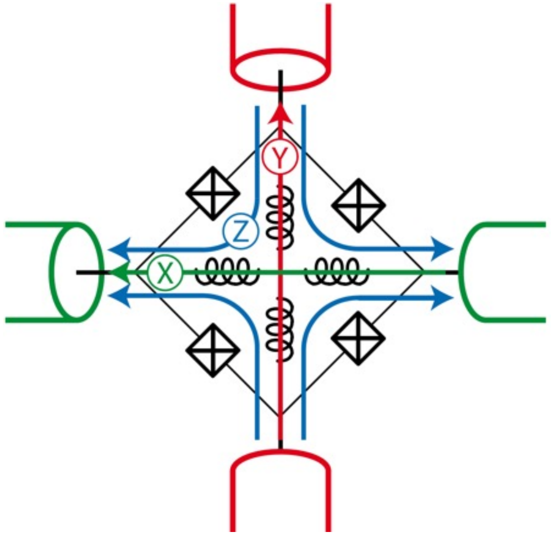


$$g_{a\gamma\gamma} < 1.03 \times 10^{-12}\,\text{GeV}^{-1}$$

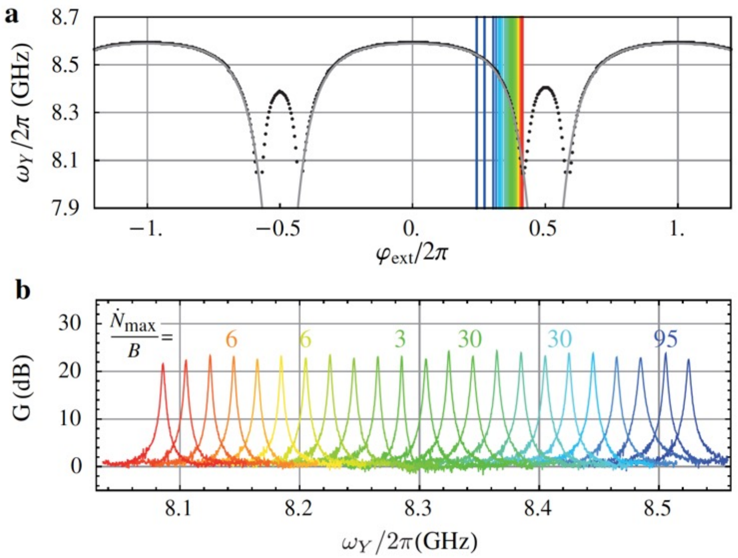


Phys. Rev. D **99**, 101101(R) (2019)

Reducing Noise with Quantum Amplifier: Ring JPA

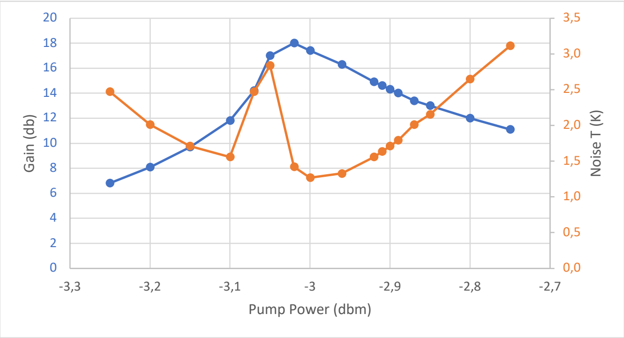


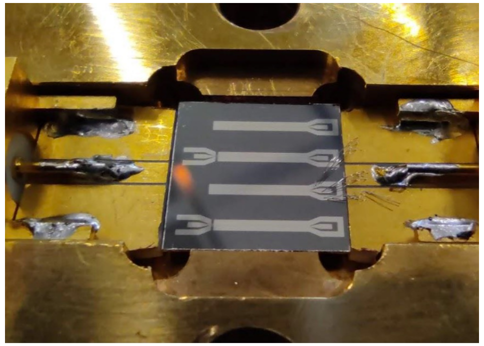
N Roch et al. PRL 108, 147701 (2012)



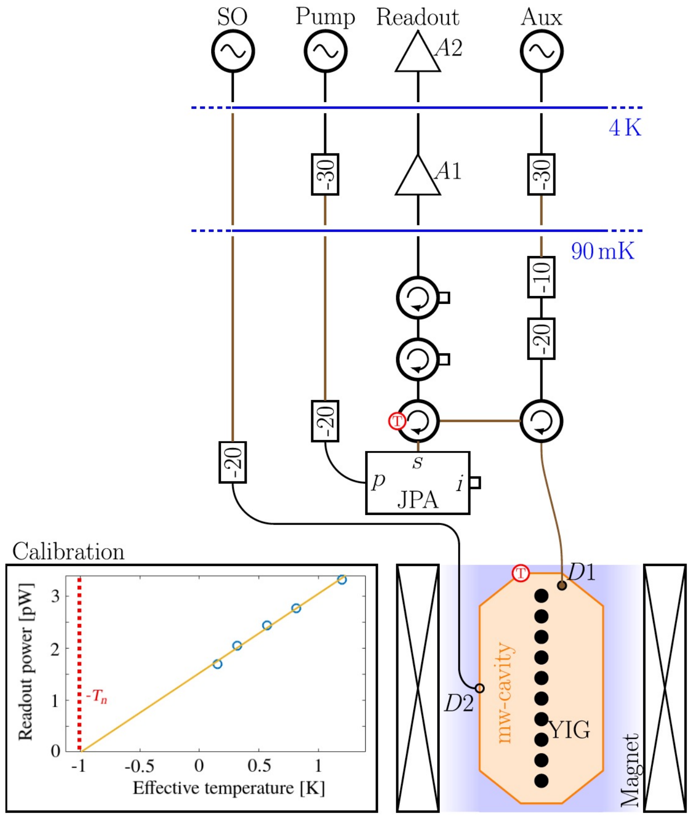
T_{noise}	0.5-1 hν
mixing	3 wave
Gain	21 dB
BW	10 MHz
Tunability	0.5 GHz

First test of JPA fabrication within INFN project SIMP



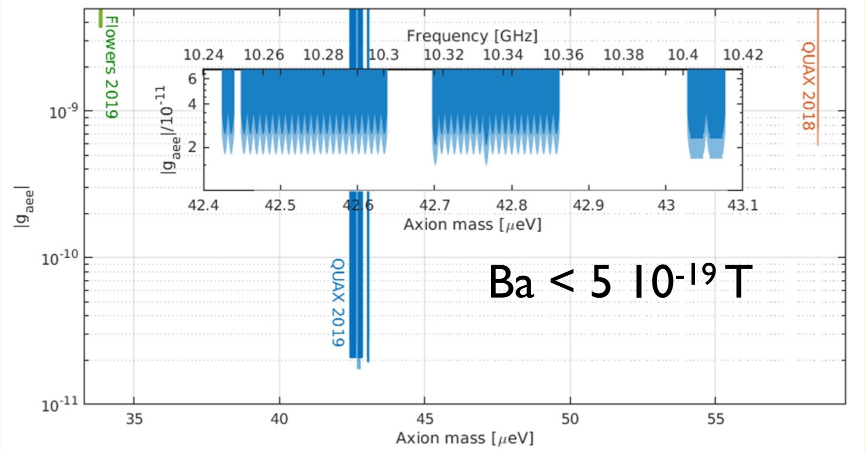


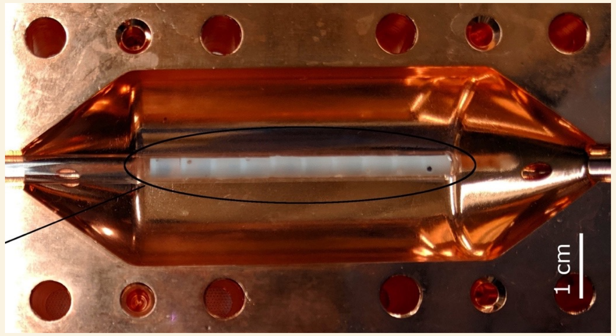
QUAX-ae Result with Quantum-Limited Ferromagnetic Haloscope



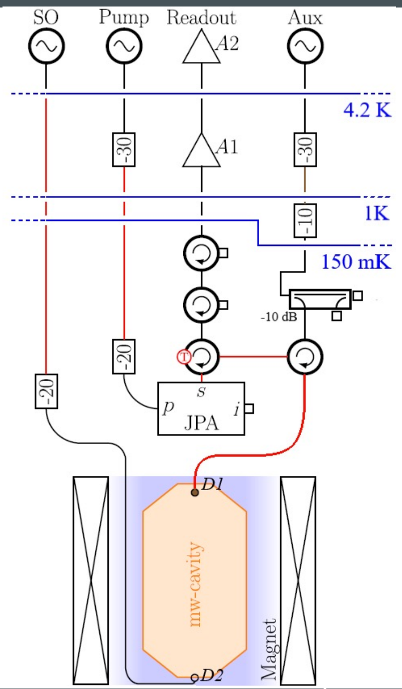
Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =2.1 mm)	10
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.1
Frequency [GHz]	10.7
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [mK]	90
T amplifier [K] (JPA)	0.5-1

Phys. Rev. Lett. **124**, 171801 (2020)



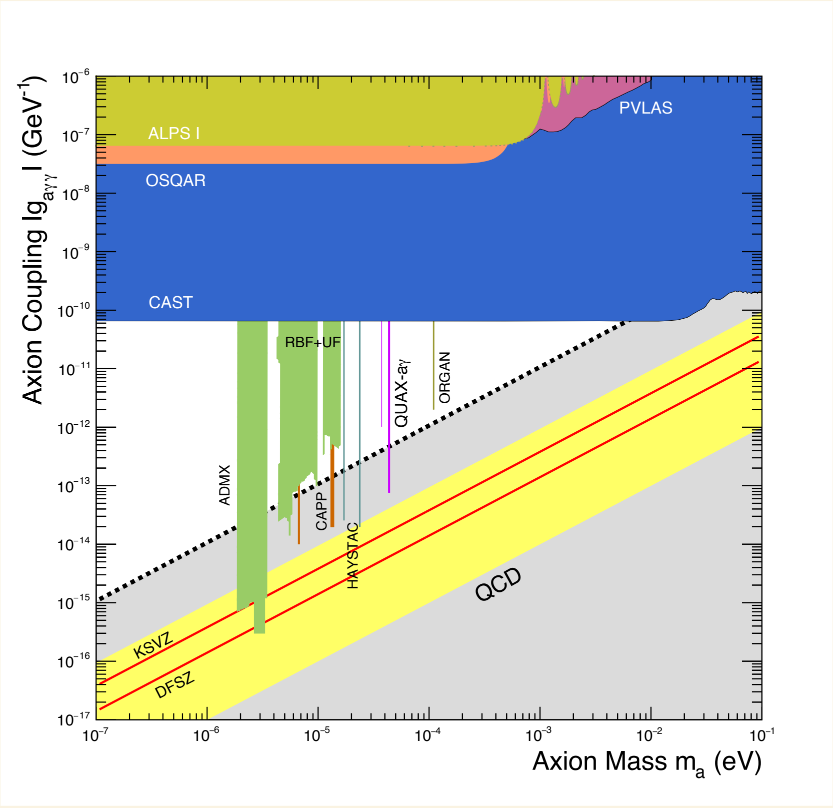


QUAX-aγ Reached the Sensitivity to QCD Axion m_a=43 μeV



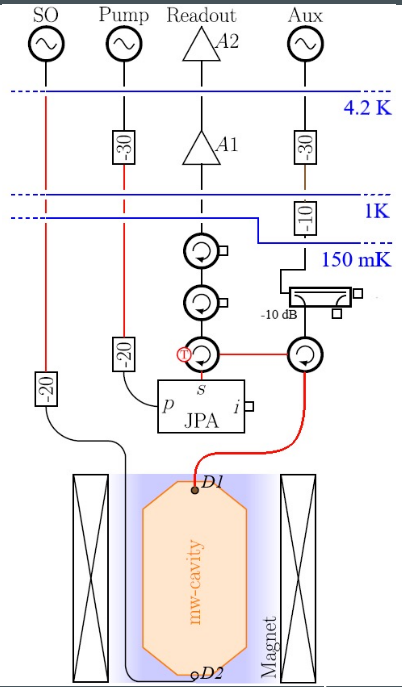
Experimental Setup	
B [T]	8
Frequency [GHz]	10.4
Cu cavity Q (mode TM010)	76,000
T_{cavity} [mK]	100
T amplifier [K] (JPA)	0.5

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



Phys. Rev. D 103, 102004 (2021)

QUAX-aγ Reached the Sensitivity to QCD Axion m_a=43 μeV



Experimental Setup	
B [T]	8
Frequency [GHz]	10.4
Cu cavity Q (mode TM010)	76,000
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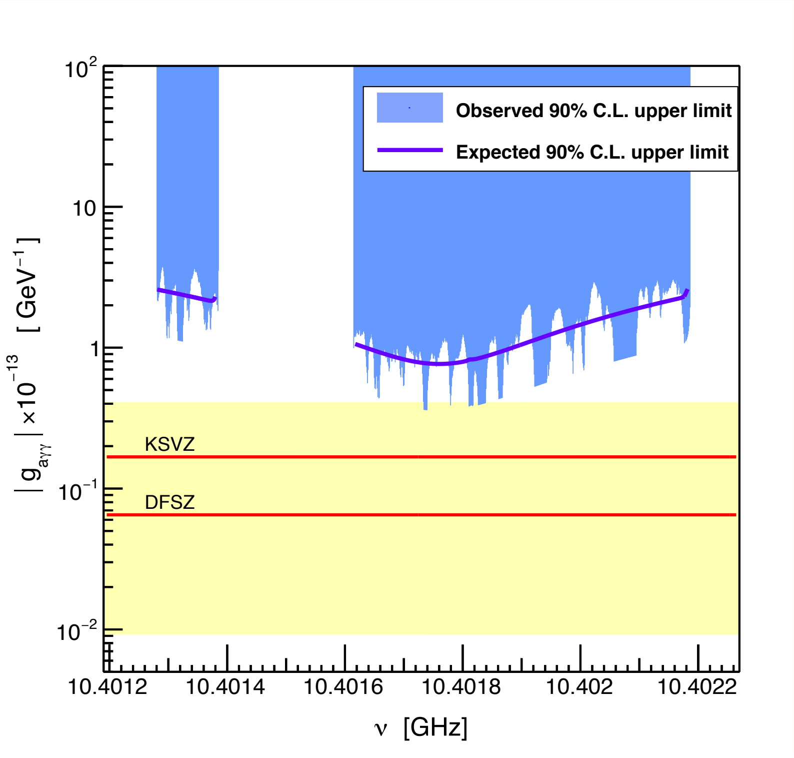
T amplifier [K] (JPA)	0.5

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



Phys. Rev. D 103, 102004 (2021)

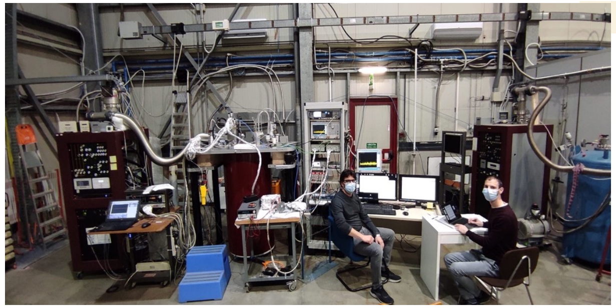
QUAX 2021-2025

2021	2022	2023	2024	2025

Assembly of haloscopes at LNL and LNF

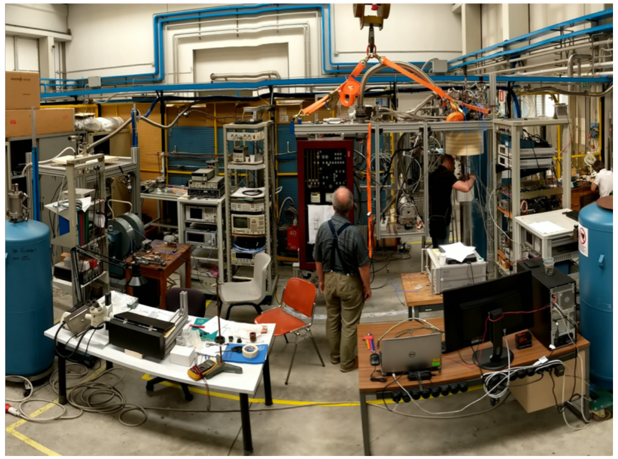
Data Taking

Scan in range 8.5 - 11 GHz



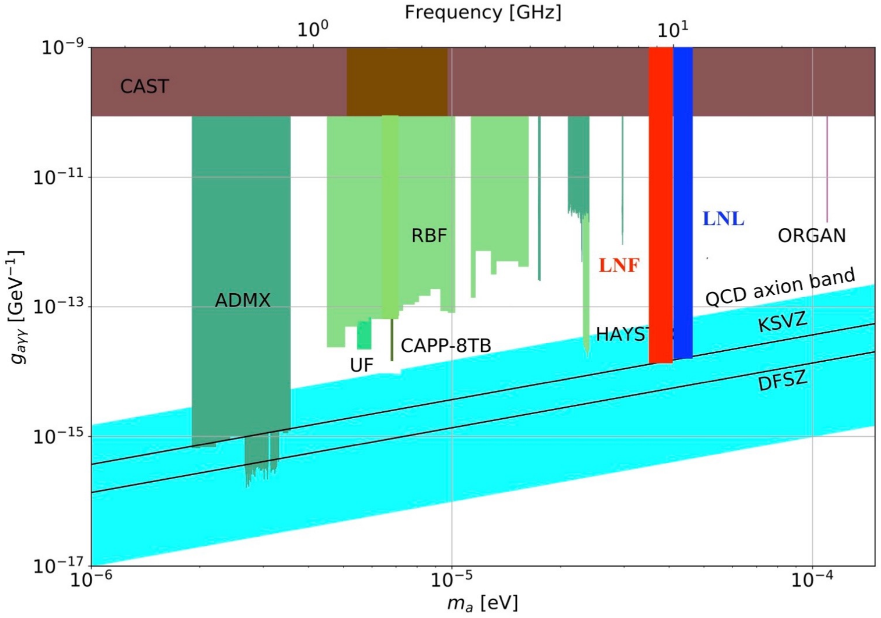
LNF:

- Superconducting cavity $Q_0 > 3\times10^5$
- B=9T
- Multicavity



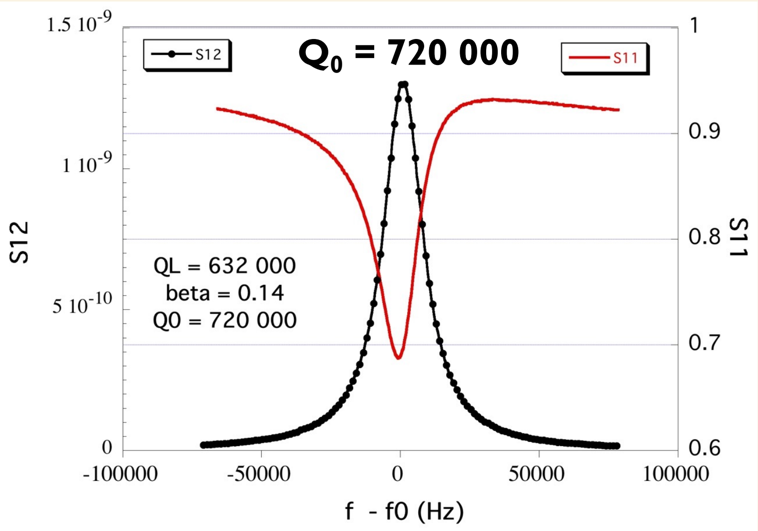
LNL:

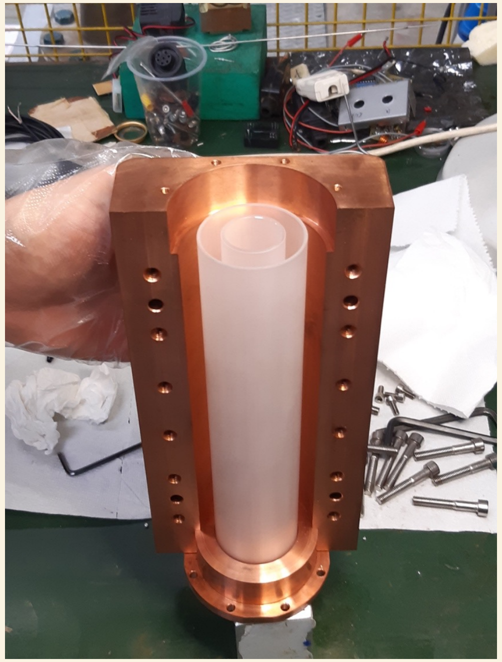
- Dielectric cavity $Q_0 > 10^6$
- B=14T
- Single cavity



High Quality Factor Dielectric Cavity

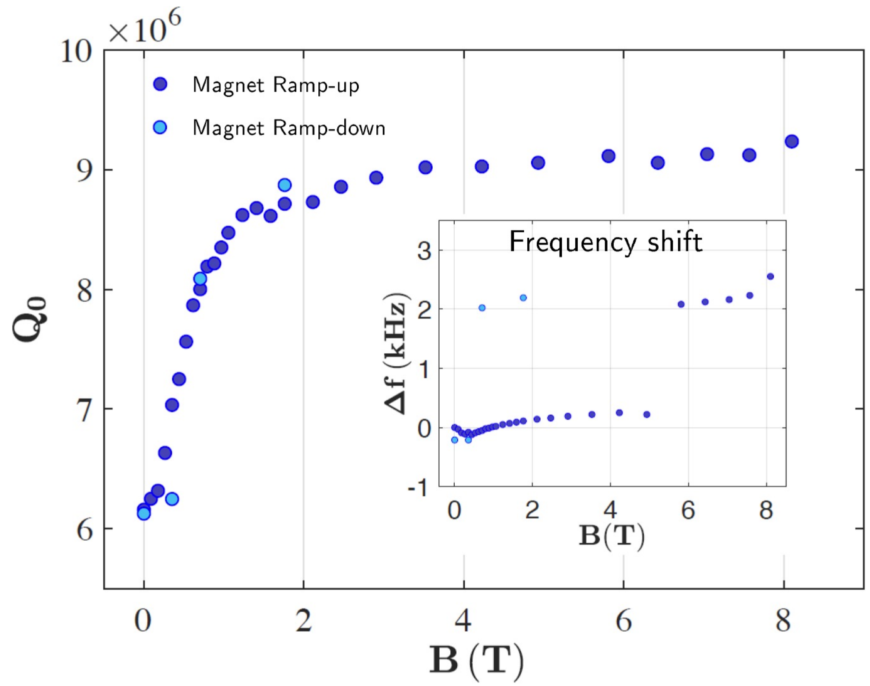
High quality factor photonic resonator with hollow dielectric cylinders





10.1016/j.nima.2020.164641

New longer cavity of 50 cm height tested in 8T magnetic field at 4 K



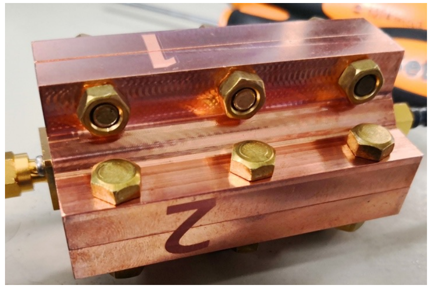
Superconducting Cavities

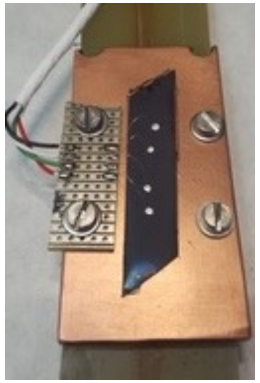
- NbTi

Sputtering of longer cavity and test in dilution refrigerator with 9T magnetic field.

- YBCO Tapes

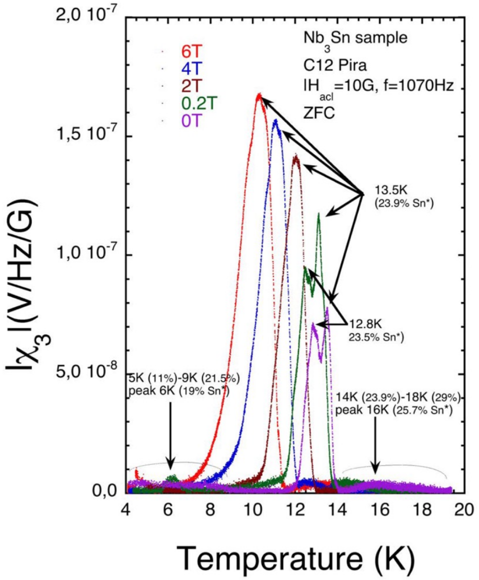
R&D ongoing in collaboration with ENEA Frascati





- Nb3Sn

a. Characterization of Nb3Sn samples produced in LNL by multiharmonic AC susceptibility



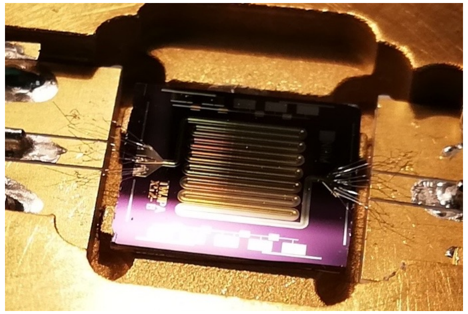
b. Promising results of Q factor calculation from vortex dynamics simulation for a 9 GHz cavity in multi Tesla field (M.Checchin)

PHYSICAL REVIEW APPLIED 14, 044018 (2020)

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

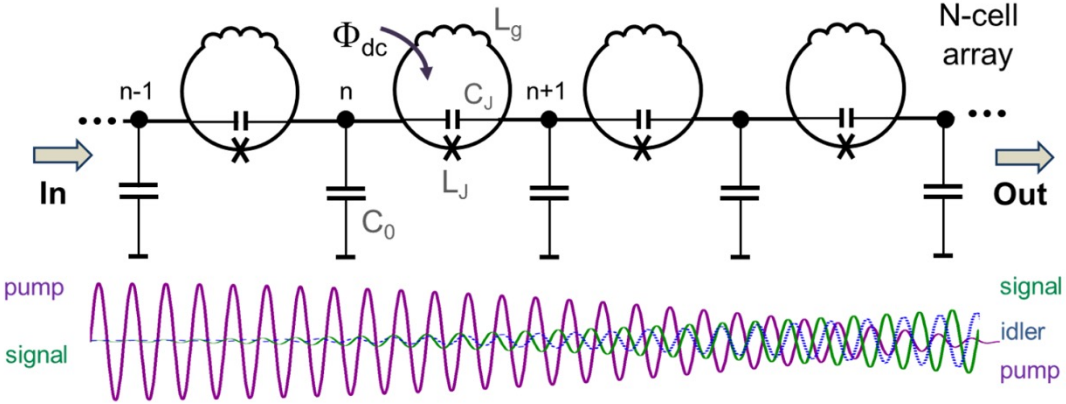
Traveling Wave JPA

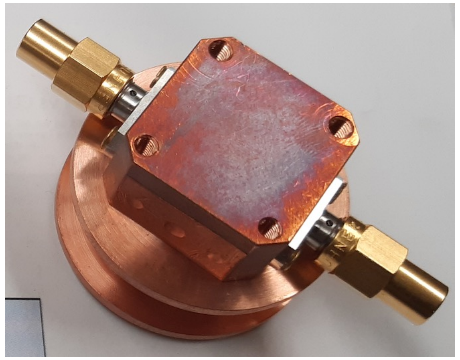
Traveling Wave Josephson Parametric Amplifiers amplify microwave signal over a broad range (GHz) adding the minimum noise set by quantum mechanics. We are testing both 3-wave and 4-wave mixing devices.



3-wave mixing device

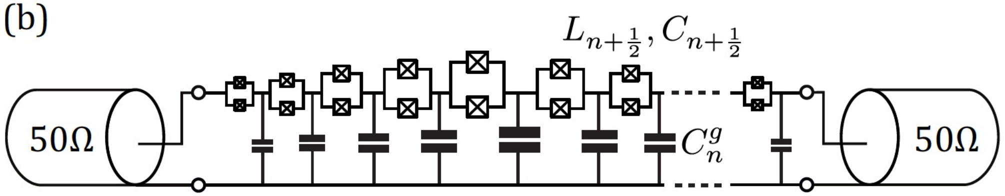
Phys. Rev. Applied 6, 034006 (2016)





4-wave mixing device

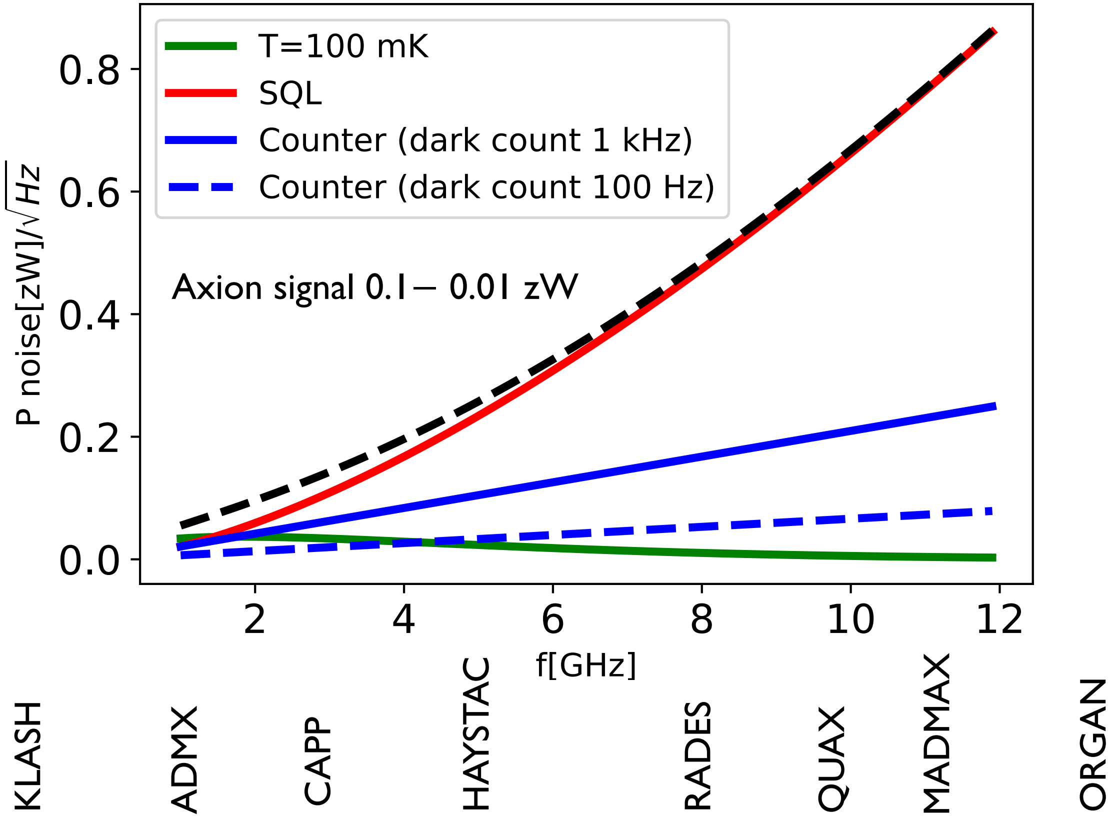
Phys. Rev. X 10, 021021 (2020)



Noise in Haloscopes

Energy spread of galactic axion

$$\frac{\Delta\nu_a}{\nu_a} \sim 10^{-6}$$



Quantum limited amplifiers

$$\hbar\omega\sqrt{\Delta\nu_a}$$

Photon counters

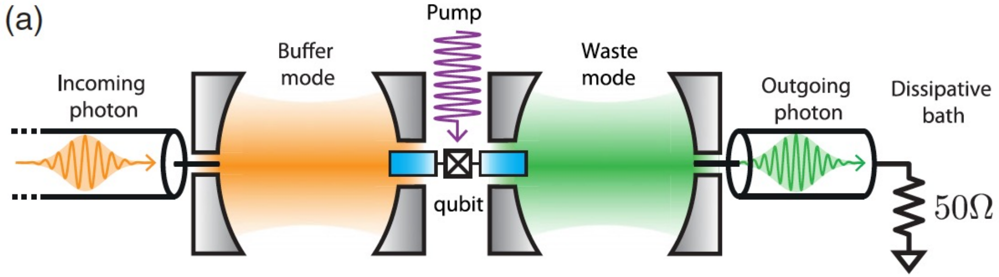
$$\hbar\omega\sqrt{\Delta\nu_{dark}}$$

Thermal noise

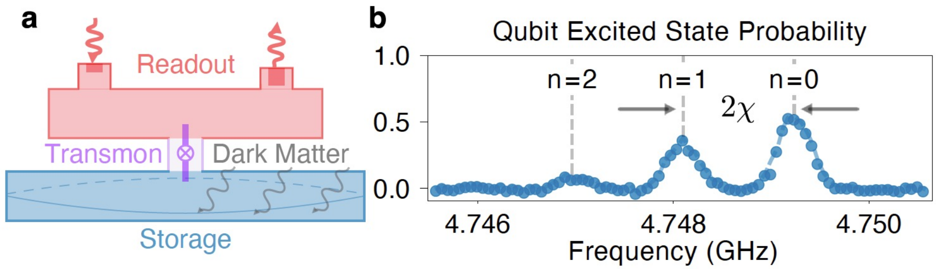
$$n_{th}\sqrt{\Delta\nu_a}$$

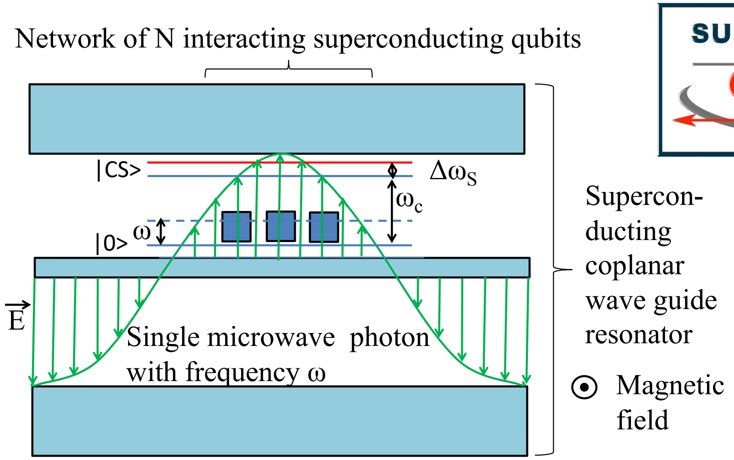
Single Photon Detection

PHYS. REV. X 10, 021038 (2020)

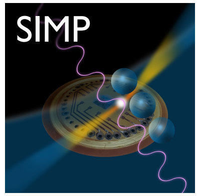


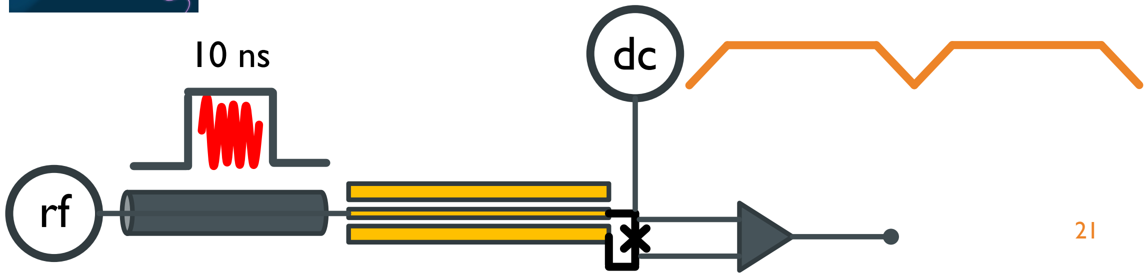
Dixit et al arXiv:2008.12231





SUPERGALAX





Conclusion

- The first QUAX haloscope in LNL reached the sensitivity for QCD axions with mass 40 μeV
- In the next years QUAX will take data with two haloscopes:
  I. LNL: dielectric cavity in 14 T field in a dilution refrigerator
  II. LNF: multiple superconducting-cavities in 9T field in dilution refrigerator
- Probe a region O(1 GHz) wide between 9 and 11 GHz within 2025
- Continue R&D on quantum amplifiers, resonant cavities and single photon detectors