Search for Axion Dark Matter with the QUAX Haloscopes

CLAUDIO GATTI – LNF INFN - QUAX COLLABORATION

International Workshop *Searching for Galactic Axions and Superconducting Devices with Quantum Efficiency*
October 2021

OUTLINE

- QUAX Experiment
  - QUAX ae
  - QUAX aγ
- Quax 2021-2025
  - LNL Haloscope
  - LNF Haloscope
- Conclusion

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

In collaboration with Birmingham University

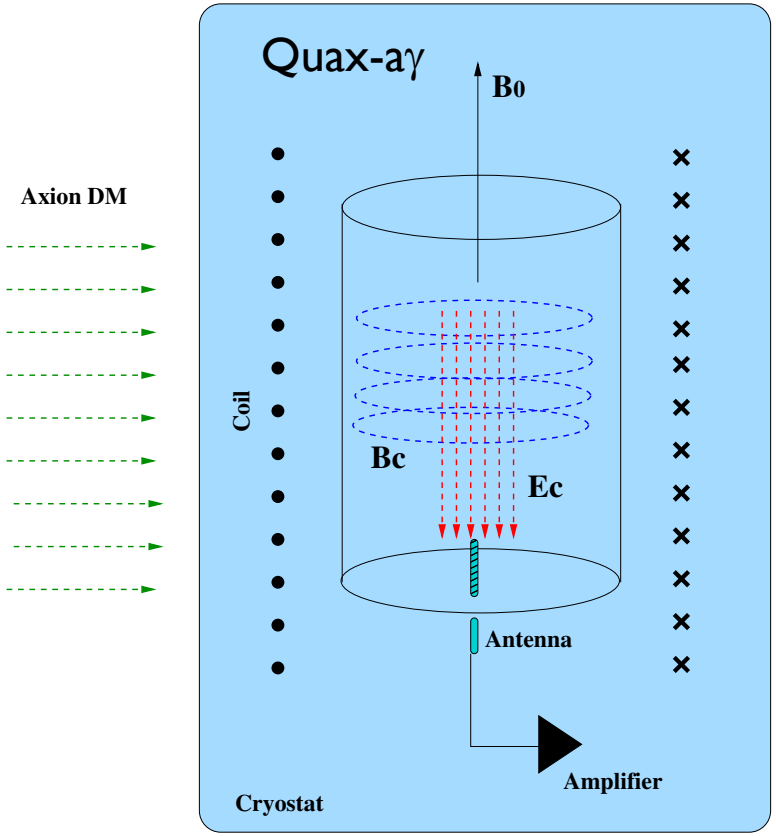
Laboratori Nazionali di Legnaro (LNL)

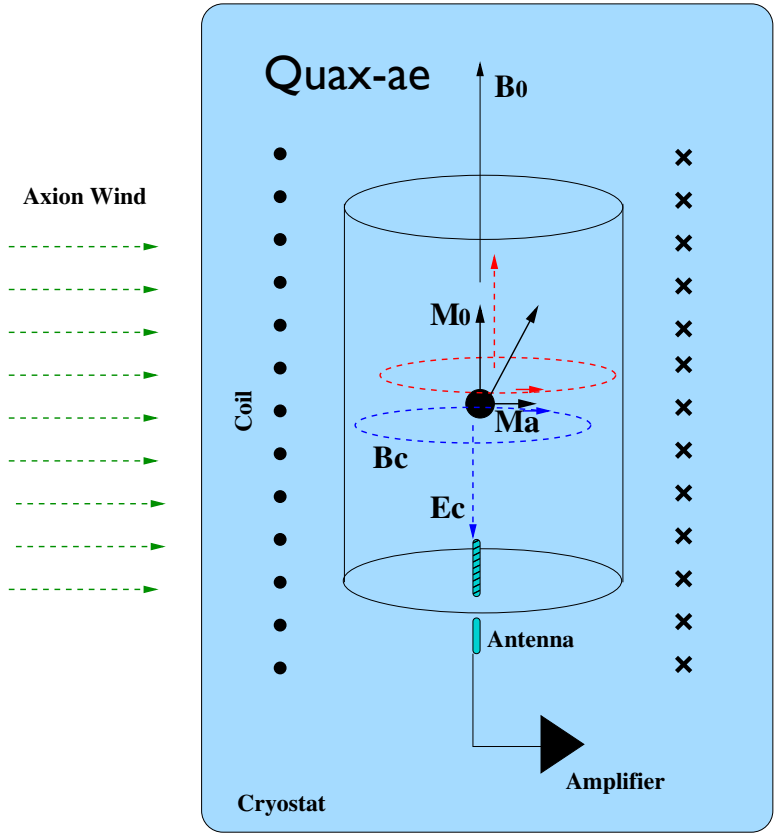




QUAX: Quest for Axions

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

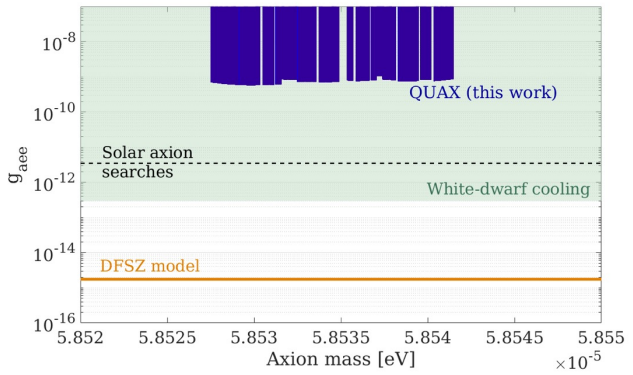




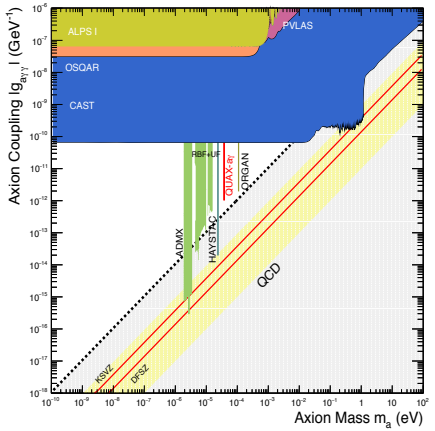
QUAX RESULTS 2018-2021

- 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).

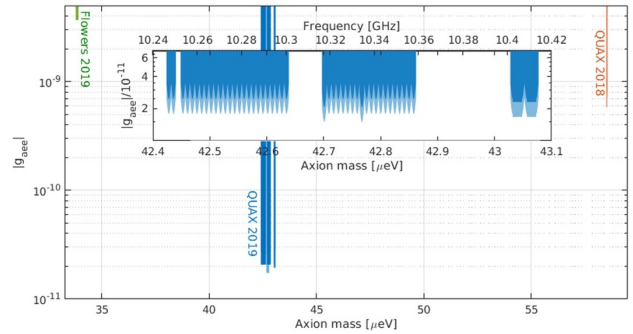
Quax-ae 2018



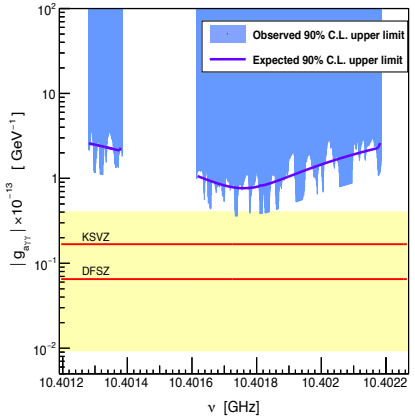
Quax-aγ 2019



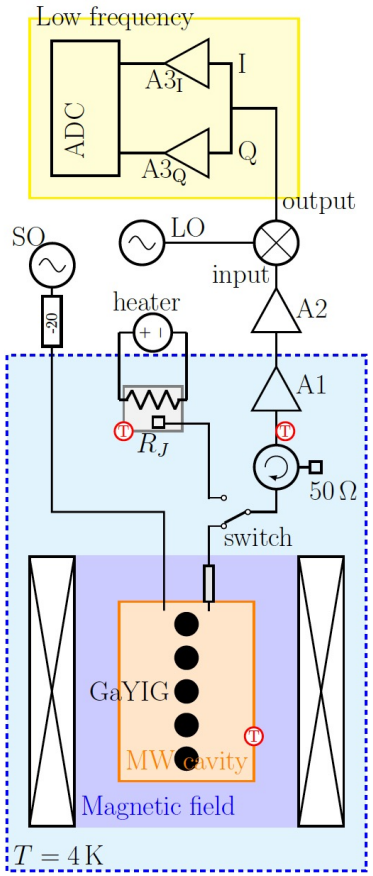
Quax-ae 2020



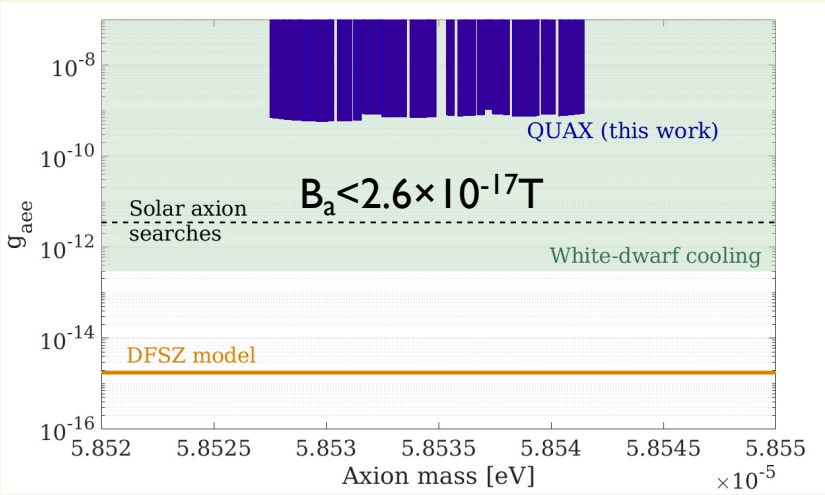
Quax-aγ 2021

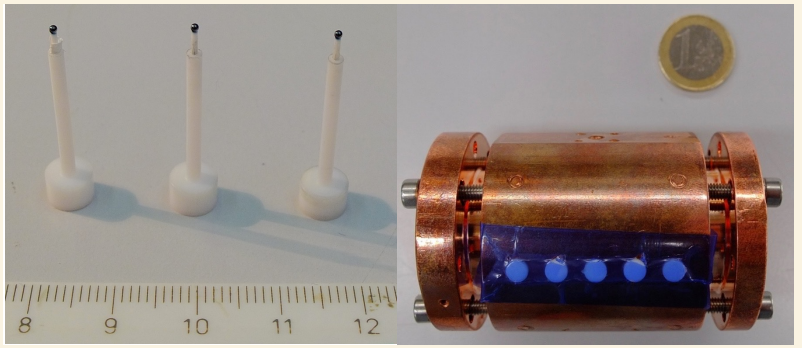


QUAX-ae First Ferromagnetic Axion Haloscope at m_a = 58μeV



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



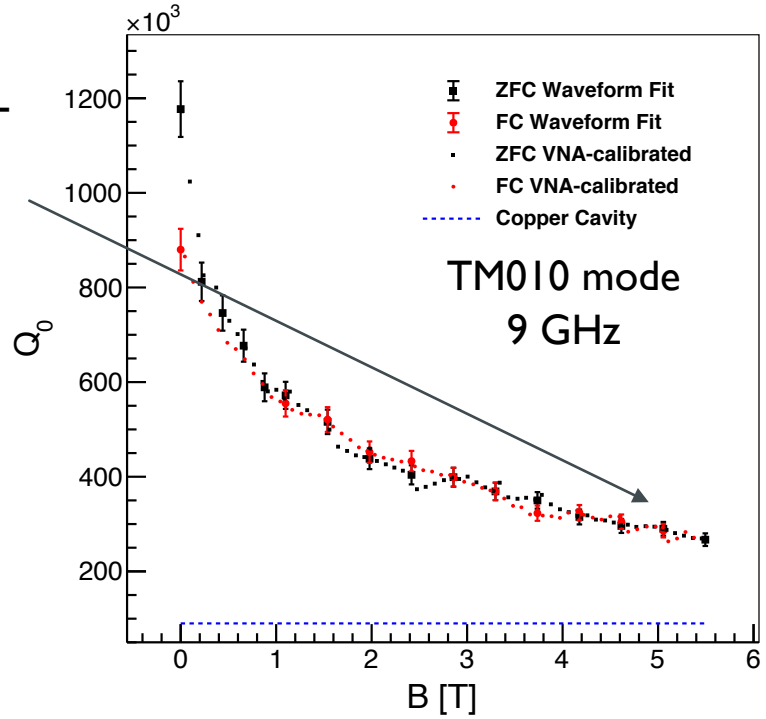


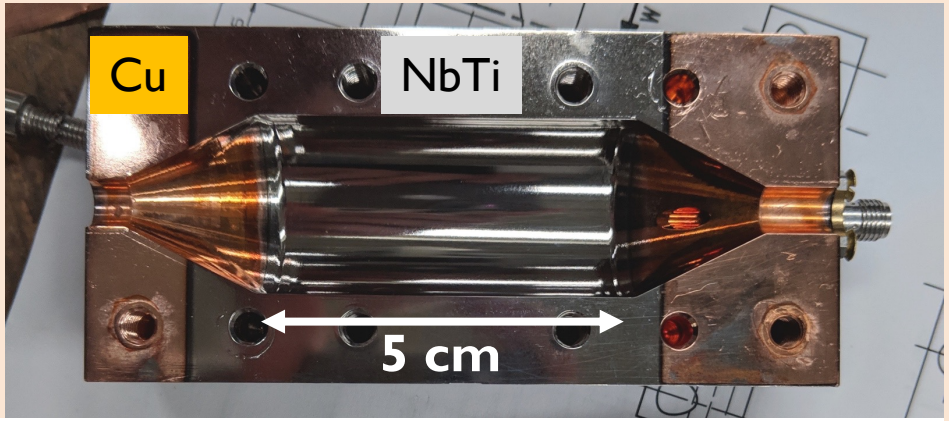
EPJC (2018) 78:703

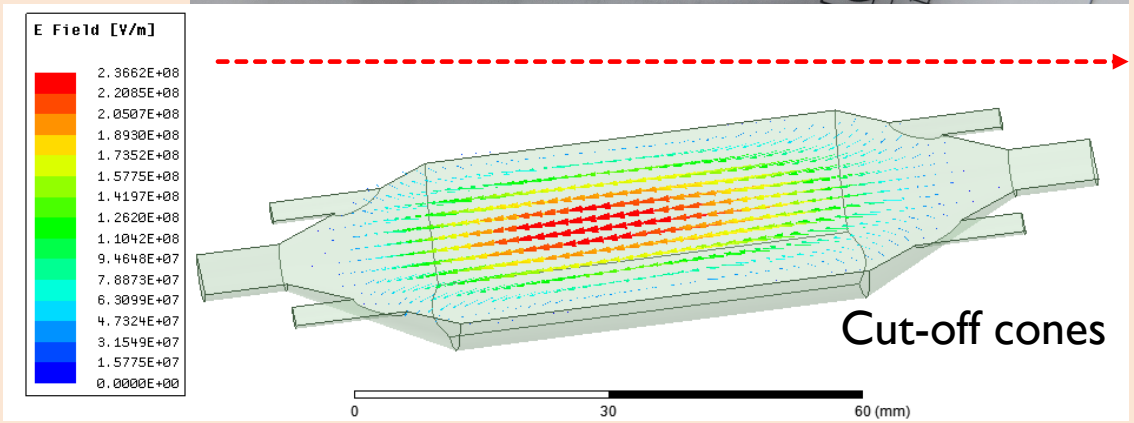
Improving Q of Resonant Cavity with Superconducting NbTi

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

Q_0=3×10^5 at 5 T
gain a factor 3.3
wrt (simulated)
Cu cavity

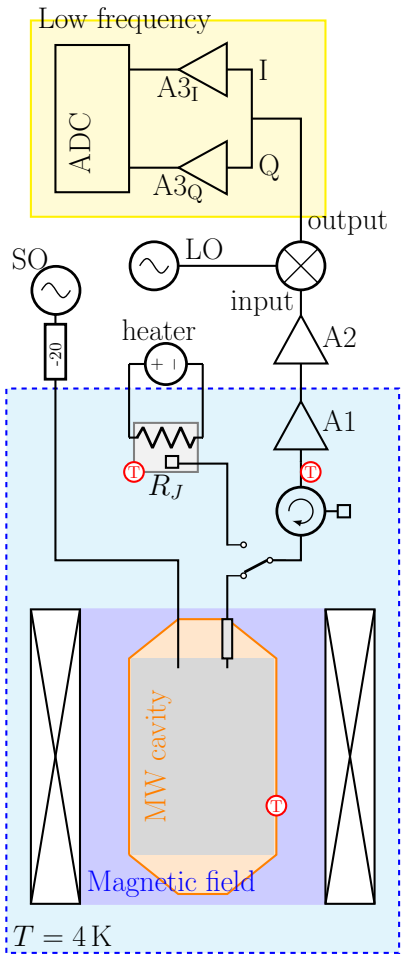




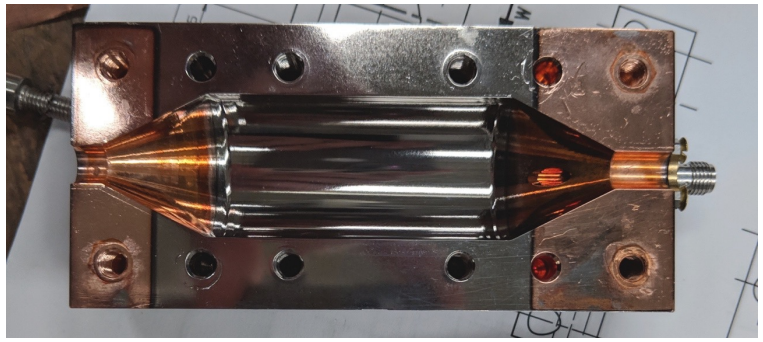


IEEE TRANS. APP. SUPERCOND. 29, 5 (2019)

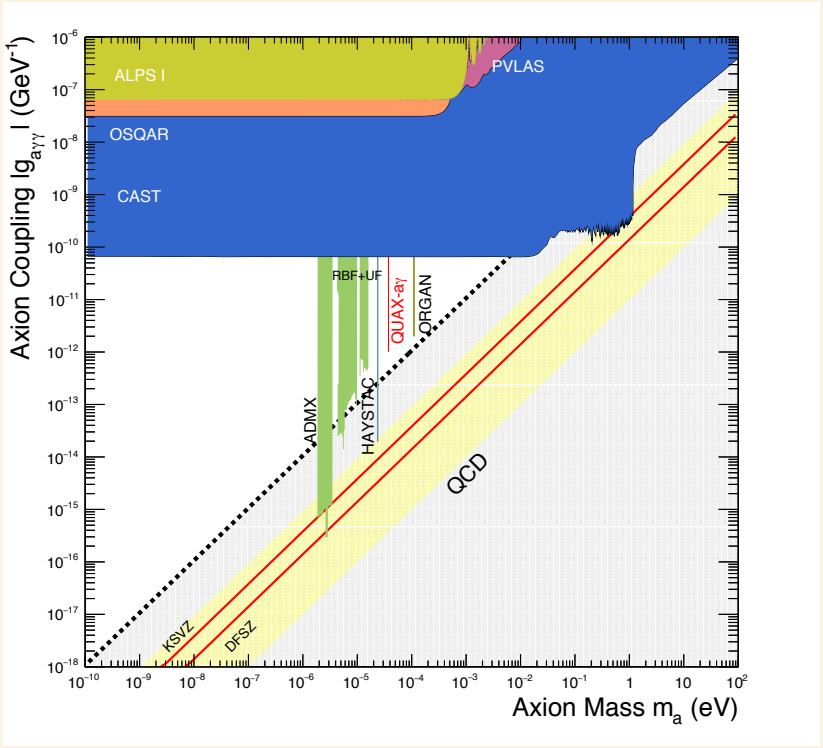
QUAX-aγ Result with Superconductive Resonant Cavity at m_a = 37.5 μeV



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

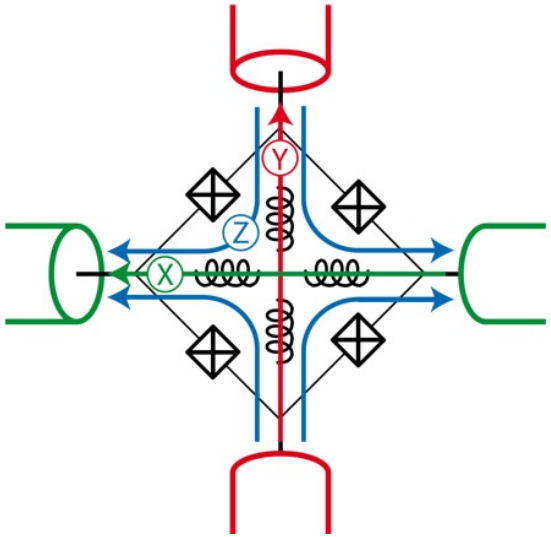


$$g_{a\gamma\gamma} < 1.03 \times 10^{-12}\,\mathrm{GeV}^{-1}$$

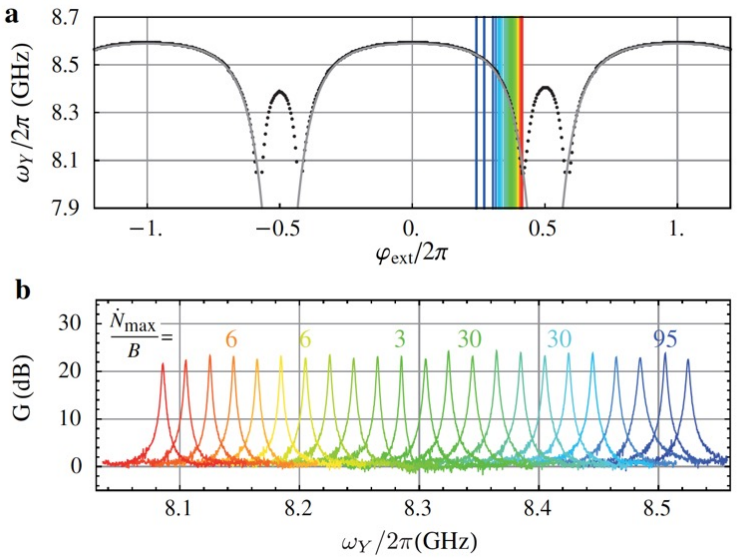


Phys. Rev. D **99**, 101101(R) (2019)

Reducing Noise with Quantum Amplifier: Ring JPA

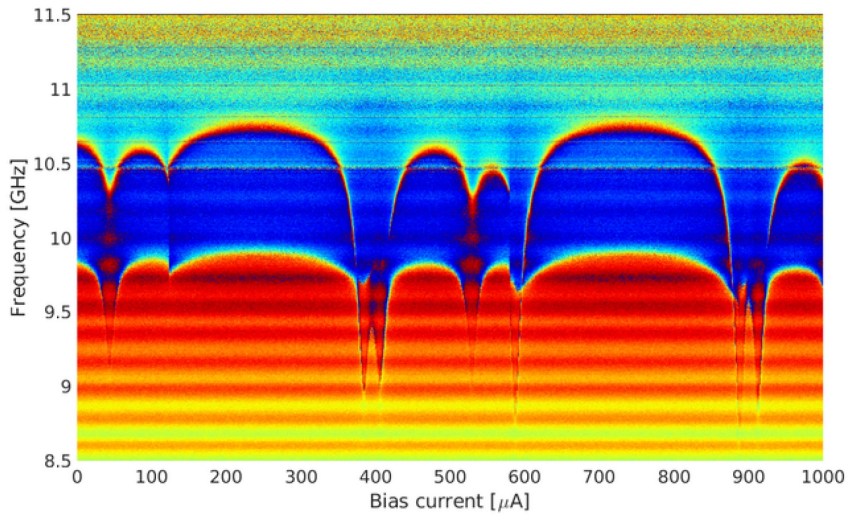


N Roch et al. PRL 108, 147701 (2012)



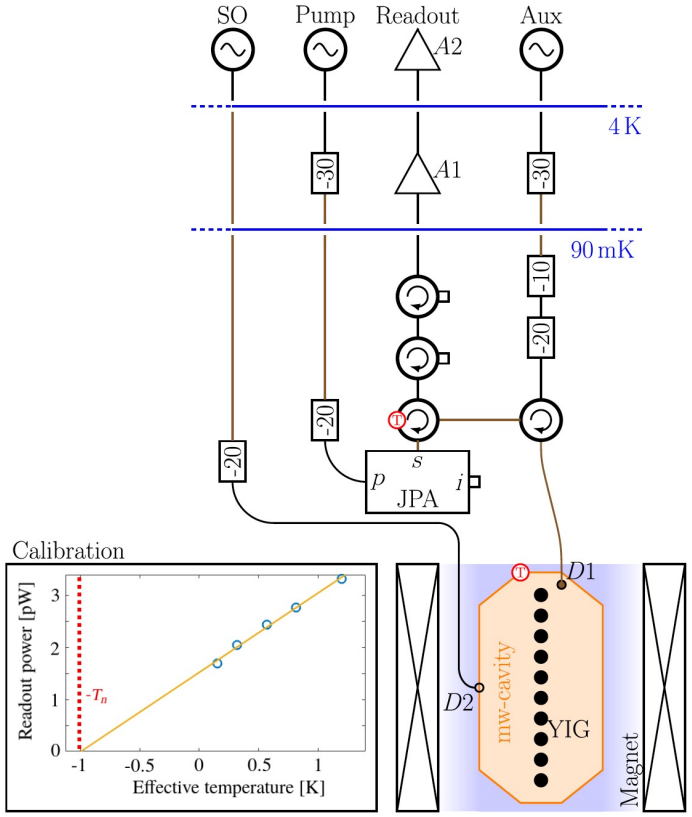
T_{noise}	0.5-1 hν
mixing	3 wave
Gain	21 dB
BW	10 MHz
Tunability	0.5 GHz

Measurement in Quax haloscope



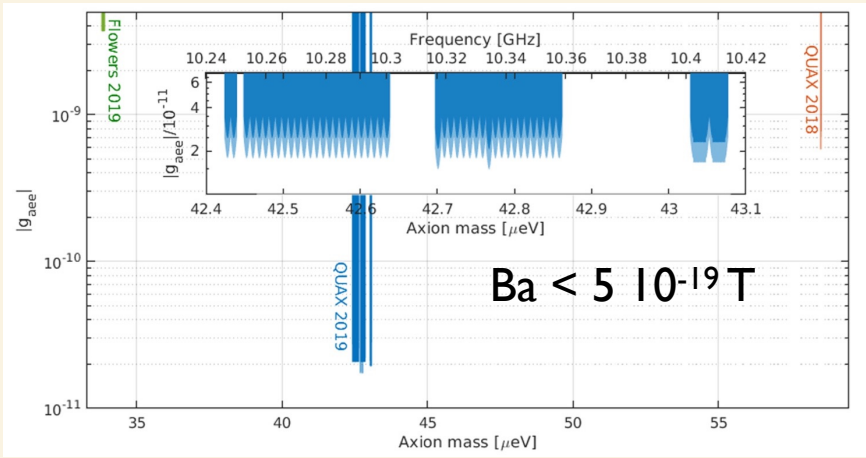


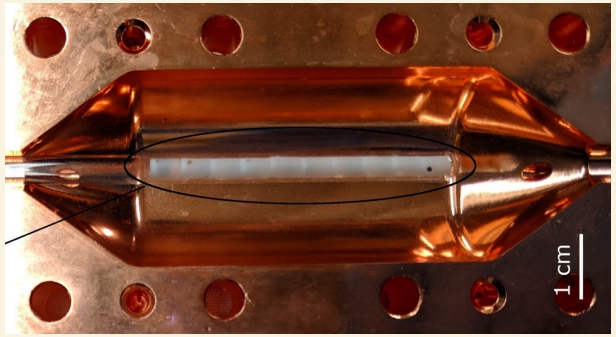
QUAX-ae Result with Quantum-Limited Ferromagnetic Haloscope



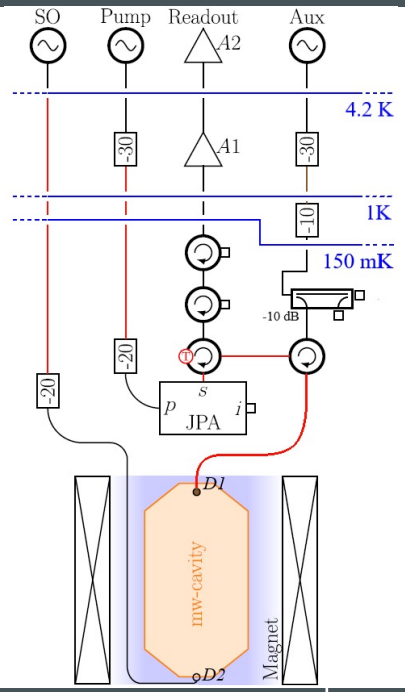
Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =2.1 mm)	10
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.1
Frequency [GHz]	10.7
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [mK]	90
T amplifier [K] (JPA)	0.5-1

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





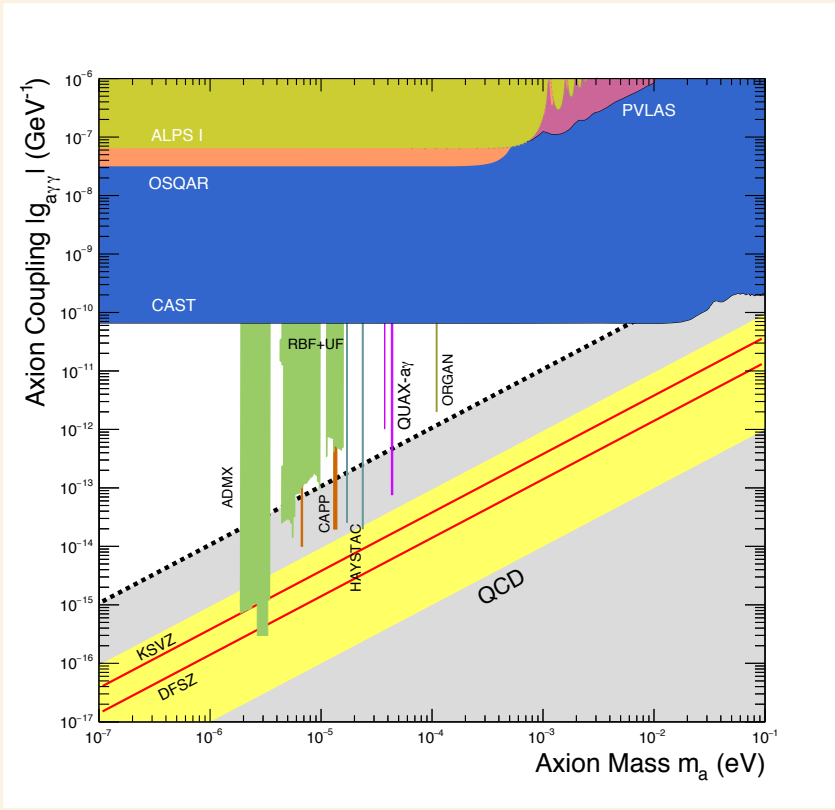
QUAX-aγ Reached the Sensitivity to QCD Axion m_a=43 μeV



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

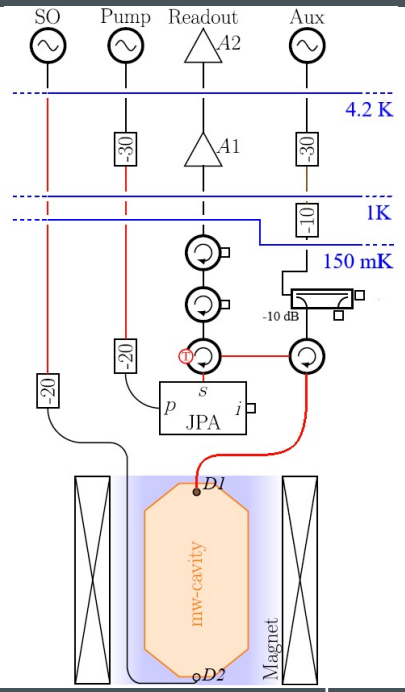


$$g_{a\gamma\gamma} < 0.766 \times 10^{-13}\ \mathrm{GeV}^{-1}$$



Phys. Rev. D 103, 102004 (2021)

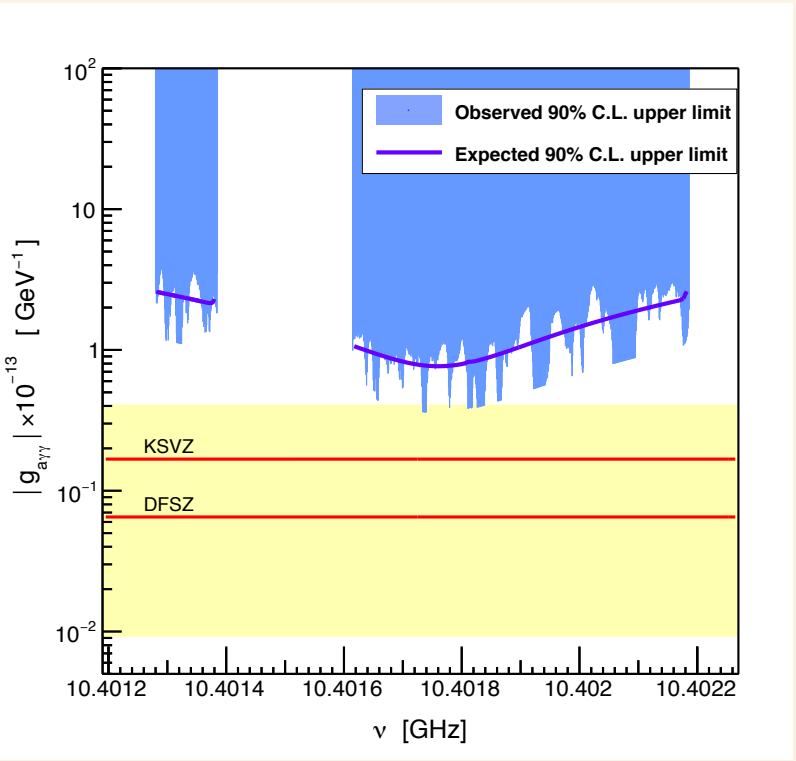
QUAX-aγ Reached the Sensitivity to QCD Axion m_a=43 μeV



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



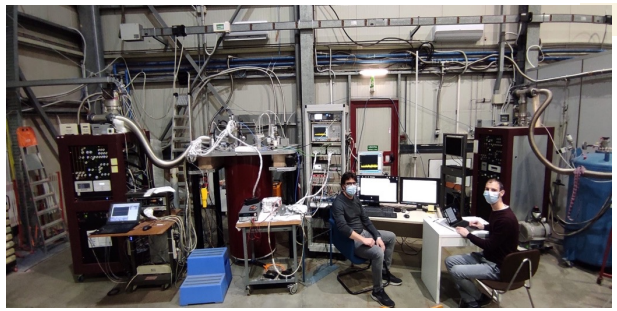
$$g_{a\gamma\gamma} < 0.766 \times 10^{-13}\ \mathrm{GeV}^{-1}$$



Phys. Rev. D 103, 102004 (2021)

QUAX 2021-2025

2021	2022	2023	2024	2025



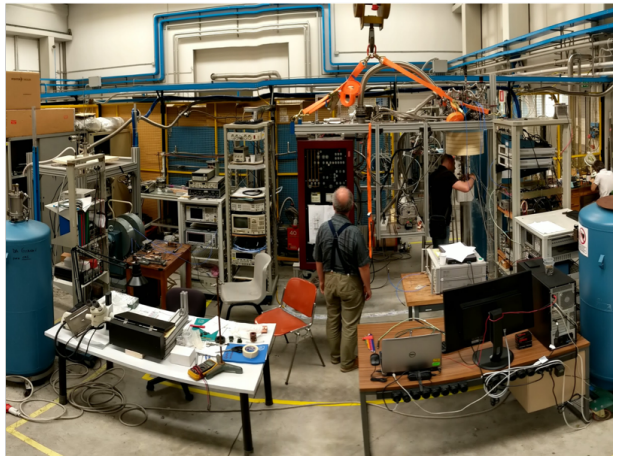
Assembly of haloscopes at LNL and LNF

Data Taking

Scan in range 8.5 - 11 GHz

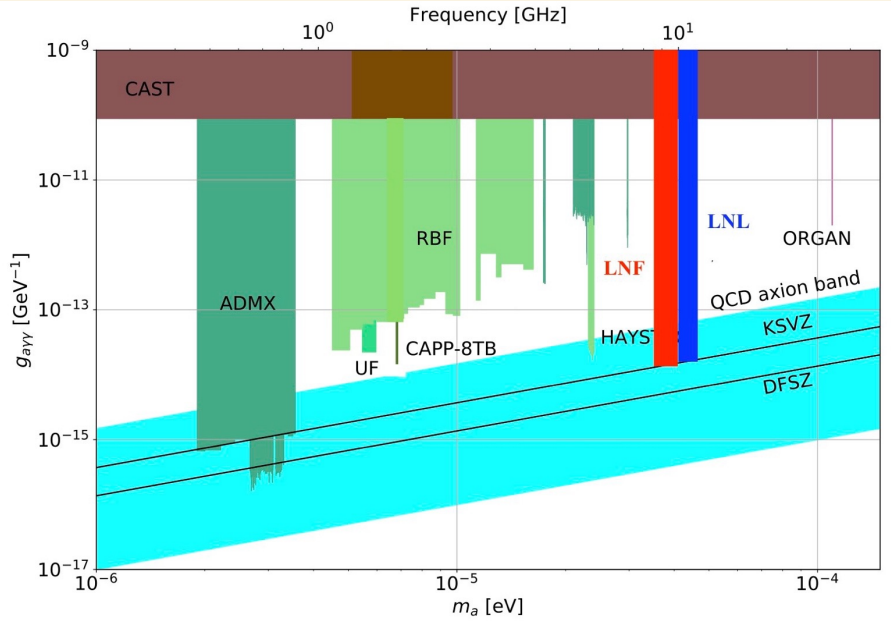
LNF:

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



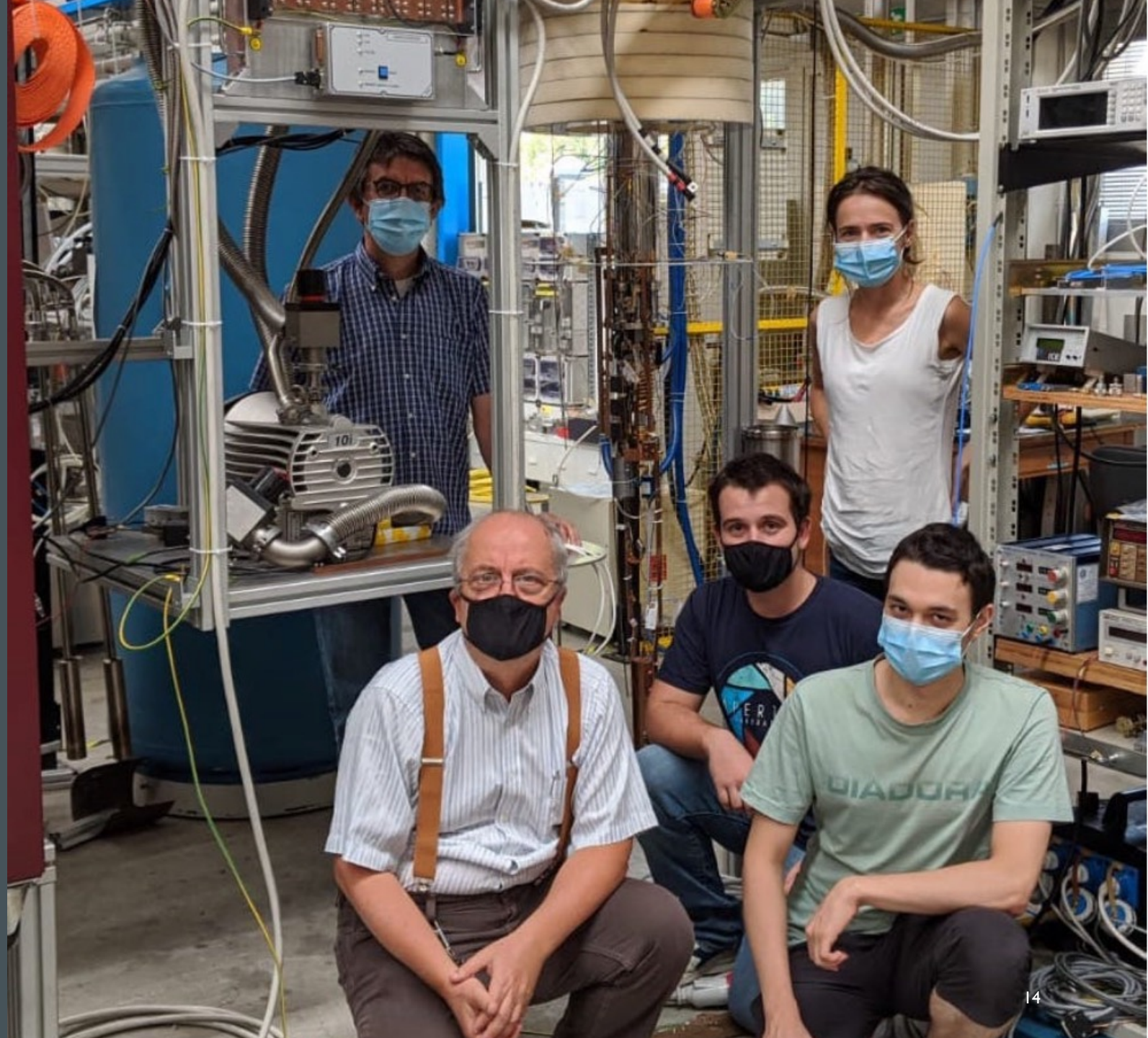
LNL:

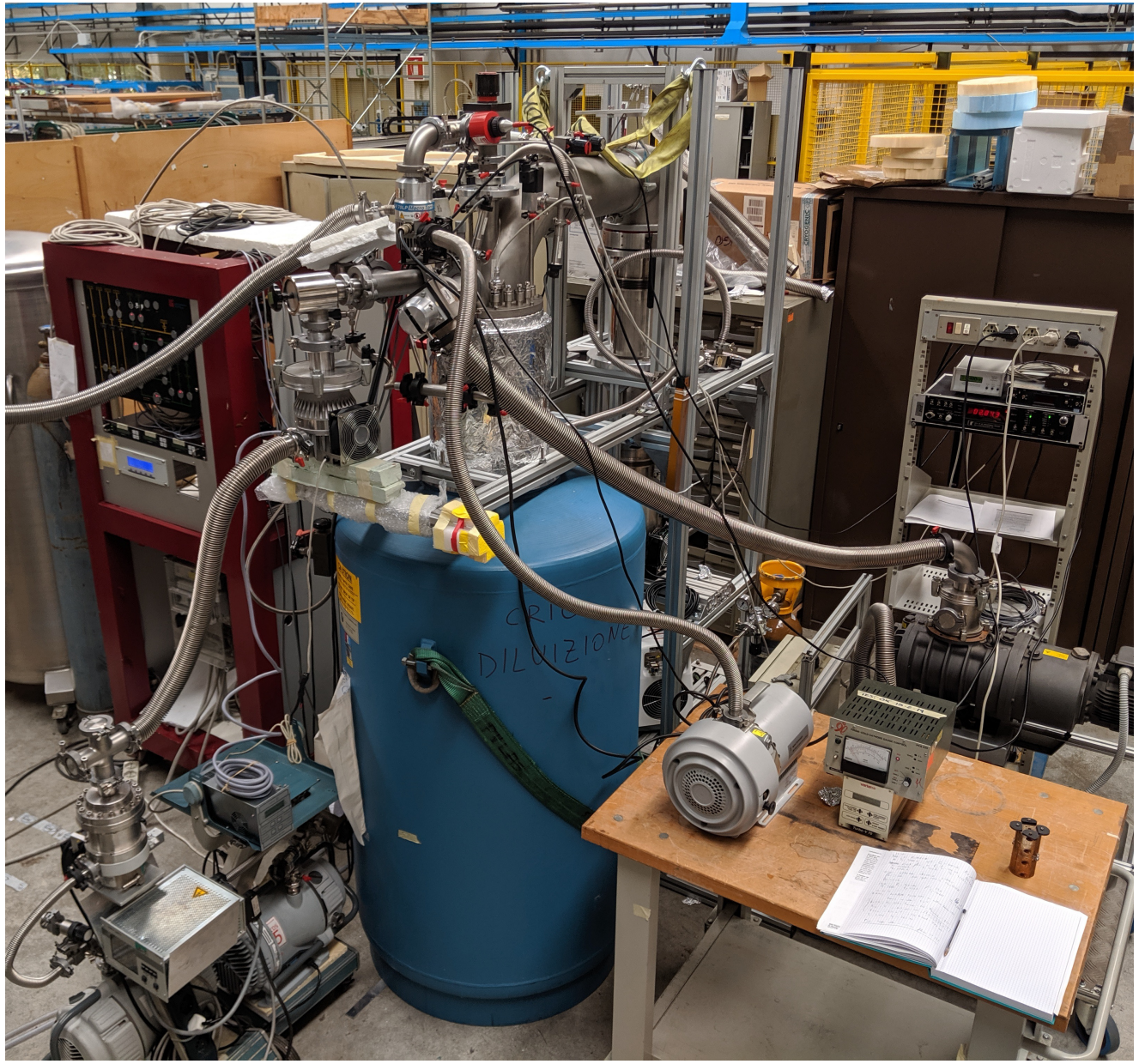
- Dielectric cavity $Q_0 > 10^6$
- B=14 T
- Single cavity



LNL HALOSCOPE

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





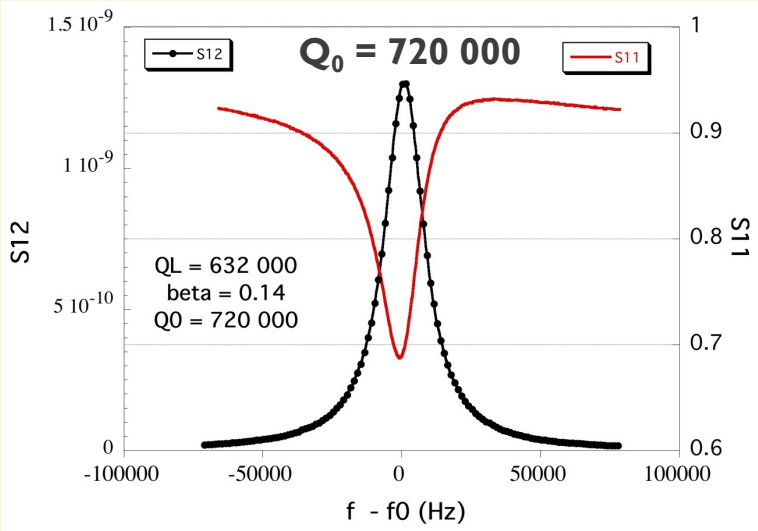
LNL LABORATORY

Auriga refurbished dilution refrigerator

- 3 mWatt @100 mK
- T_{base}=70 mK

High Quality Factor Dielectric Cavity

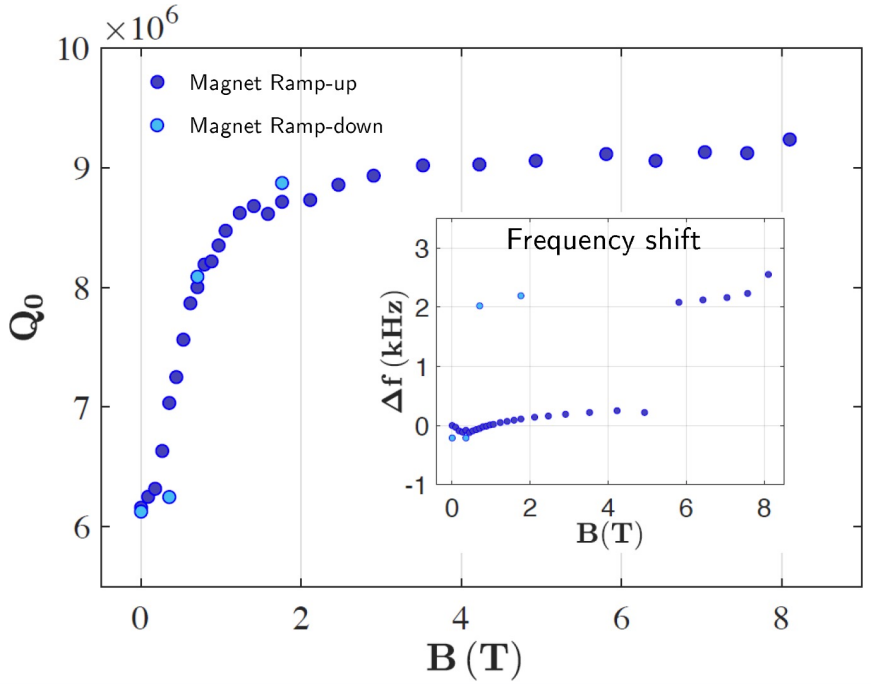
High quality factor photonic resonator with hollow dielectric cylinders



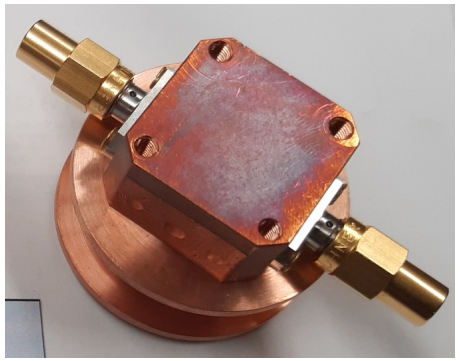


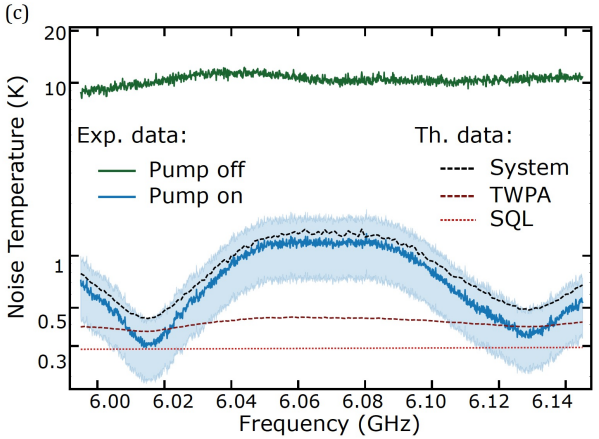
10.1016/j.nima.2020.164641

New longer cavity of 50 cm height tested in 8T magnetic field at 4 K with Q_0=9 ×10⁶!



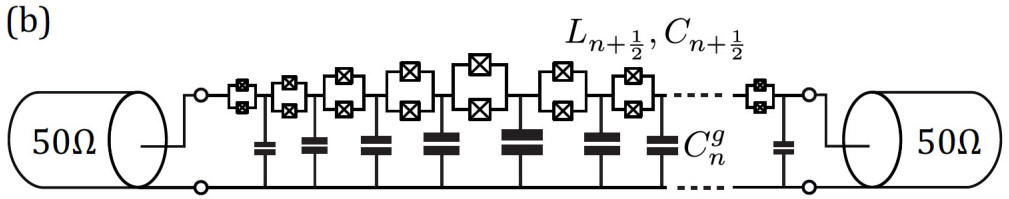
Traveling Wave JPA





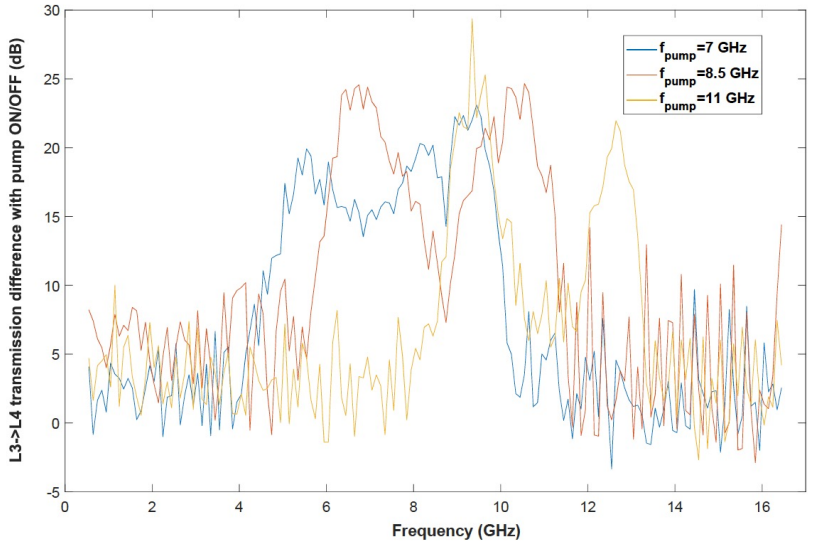
Planat et al. Phys. Rev. X 10, 021021 (2020)

4-wave mixing device



Preliminary test at LNL:

- 20 db gain
- Few GHz bandwith



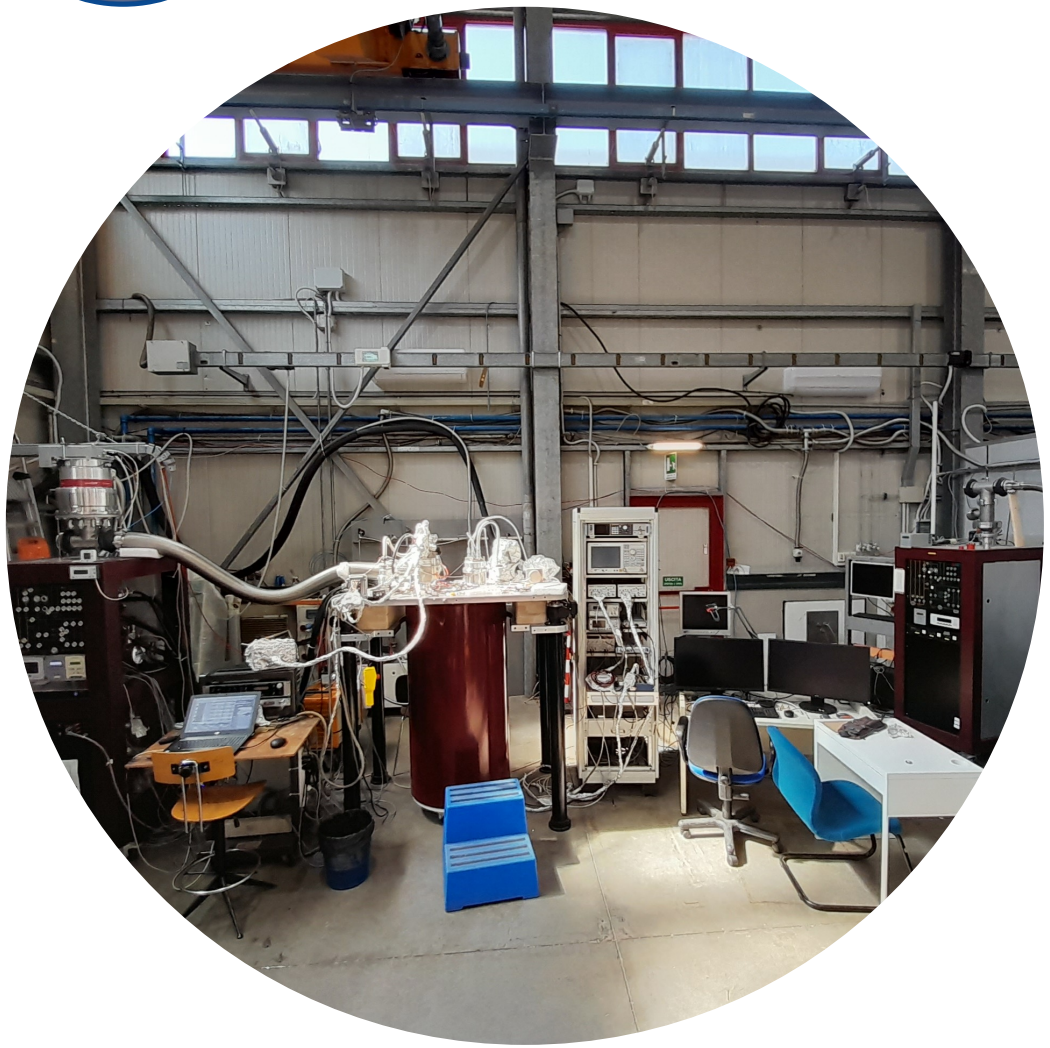
LNF HALOSCOPE

- Superconducting cavity $Q_0 > 3 \times 10^5$
- B=9T
- Multicavity

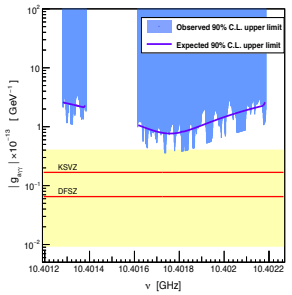


COLD - Cryogenic Laboratory for Detectors

- Axion Experiments
- Superconducting Quantum Devices
- Superconducting Cavities
- Magnetic Measurements

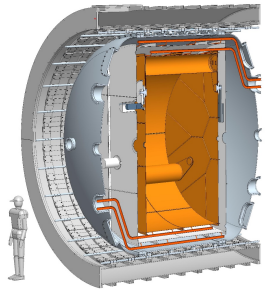


EXPERIMENTS



QUAX – QUest for AXions

Search for galactic axions with Sikivie's Haloscopes at 10 GHz (Ongoing sxperiments at LNL and LNF).



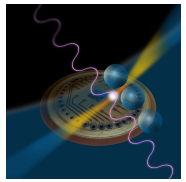
(K)FLASH

Search for galactic axions with a Sikivie's Haloscope at 100 MHz (Design Study).

Superconducting Devices

DART WARS (Detector Array Readout with Travelling Wave AmplifieRS)

Development of wide band quantum amplifiers for multi-channel detector readout (Ongoing).



SIMP (Single Microwave Photon detectors)

Development of single-microwave photon detector (Ends 2021)

Qub-IT Quantum Sensing with superconducting qubits (Starts 2022).

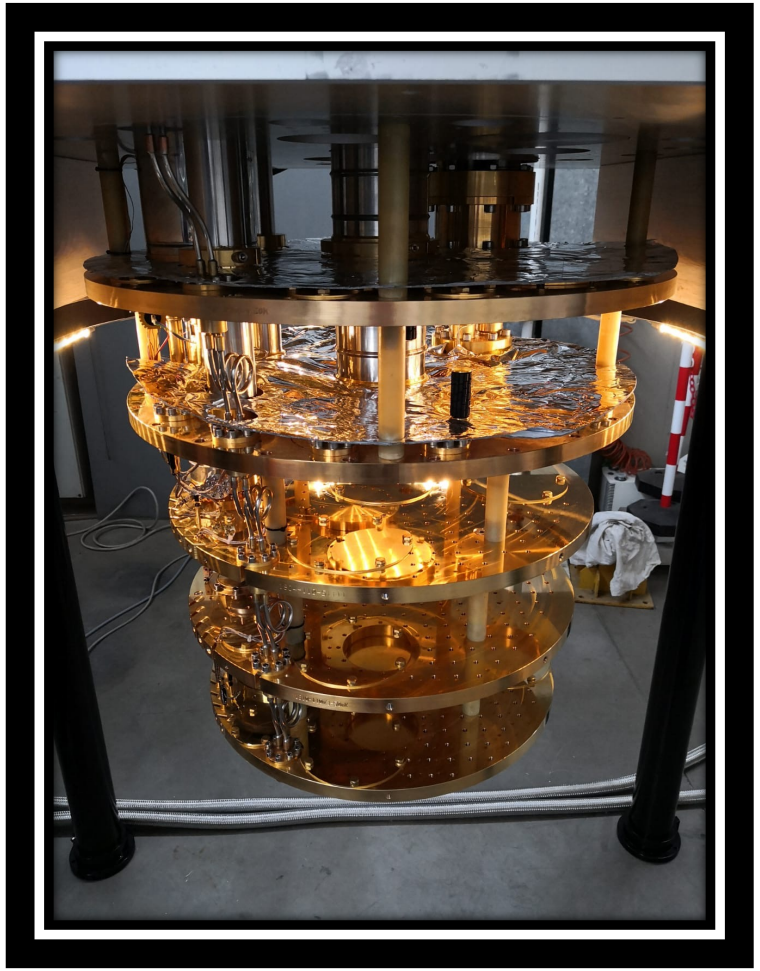
Supergalax FET H2020 Project

SC-qubits array photon-detector for axion experiments

SQMS USA DOE Project

Superconducting Quantum Materials and Systems

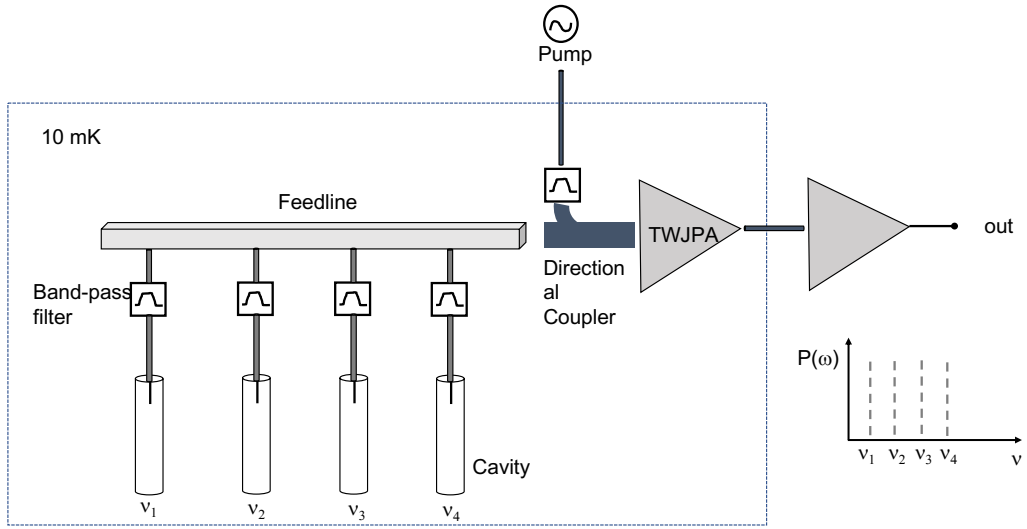
QUAX HALOSCOPE AT LNF



Operate at 10 mK inside LNF dilution refrigerator to reduce thermal noise.

Probe KSVZ axions in 1 GHz band at 9 GHz

- Multi cavity for fast scanning rate
- Wide band TWJPA quantum amplifier
- Superconducting cavities





9 T magnet for axion conversion



First 8.5 GHz cavity for LNF pilot run

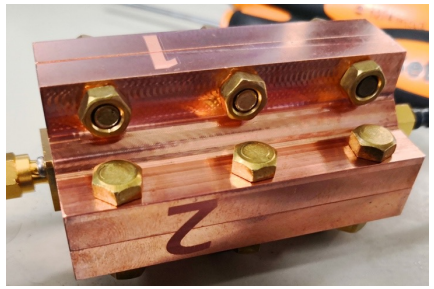
Superconducting Cavities

- NbTi

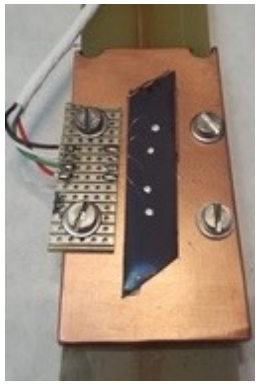
Sputtering of longer cavity and test in dilution refrigerator with 9T magnetic field.

- YBCO Tapes

R&D ongoing in collaboration with ENEA Frascati and University of Camerino



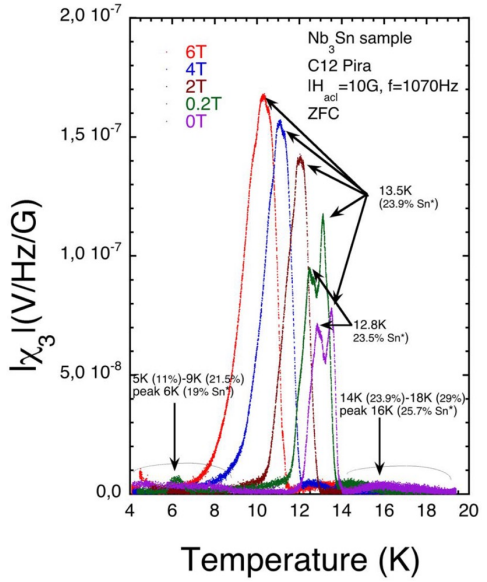




- Nb3Sn

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



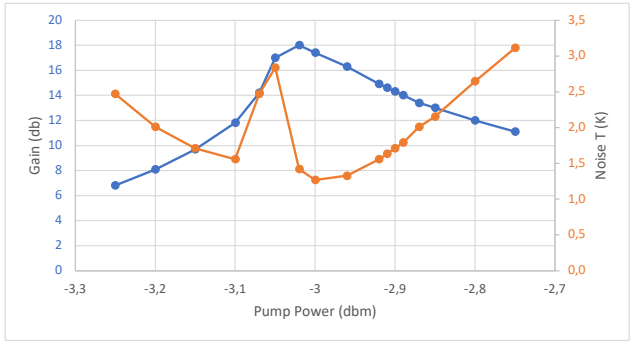


b. Promising results of Q factor calculation from vortex dynamics simulation for a 9 GHz cavity in multi Tesla field (M.Checchin)

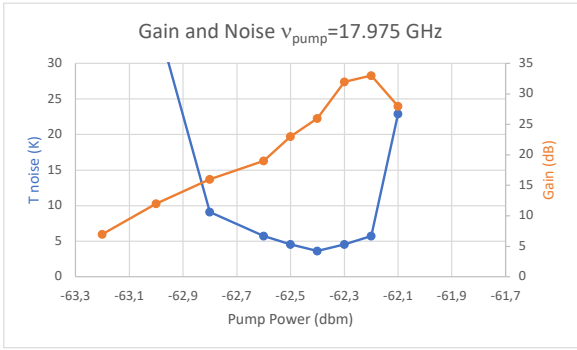
PHYSICAL REVIEW APPLIED 14, 044018 (2020)

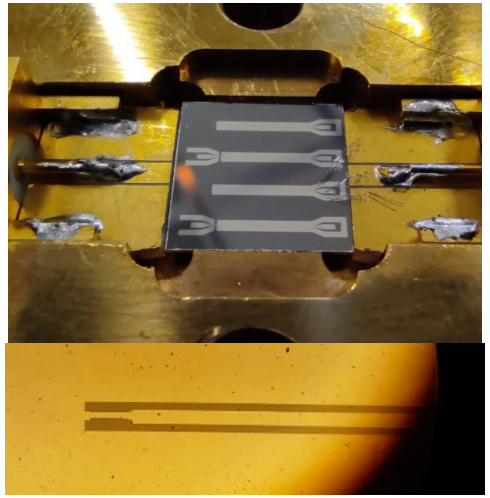
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

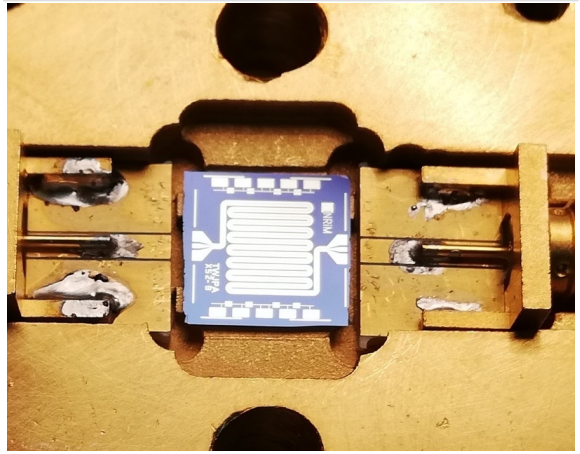
SUPERCONDUCTING QUANTUM DEVICES

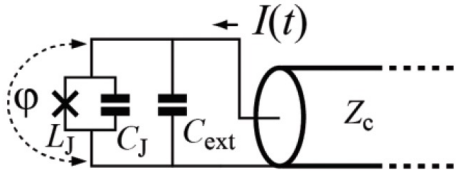






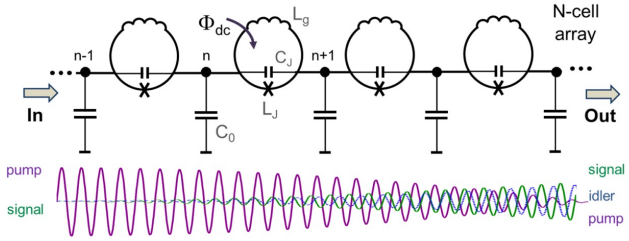






First LNF results of a JJ coupled to a transmission line operated as a Josephson parametric amplifier and as a microwave photon detector (CNR-IFN)

Characterization at LNF and IBS-Capp of first production of TWJPA of INRiM.



SUPERGALAX

FET OPEN SUPERGALAX
CNR (IT, PI, exp)
INRIM (IT, exp)
INFN (IT, axion exp)
KIT (DE, exp)
Leibniz IPHT (DE, exp)
RUB (DE theory)
LU (UK, theory)

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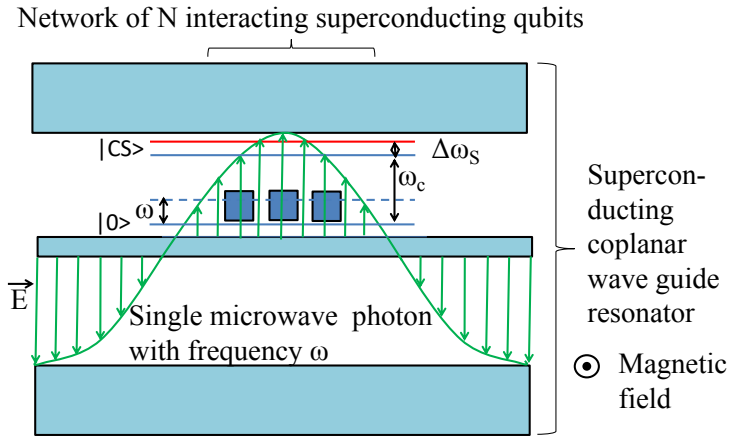
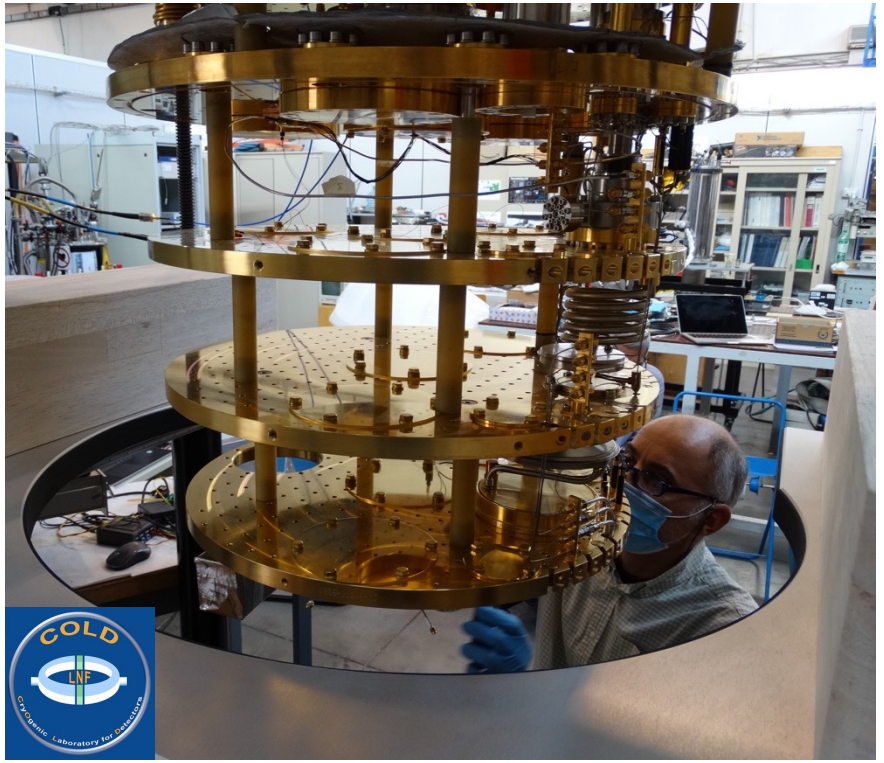


Develop a single microwave photon detector for axion search in QUAX experiment with an array of SC qubits.

https://supergalax.eu



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

