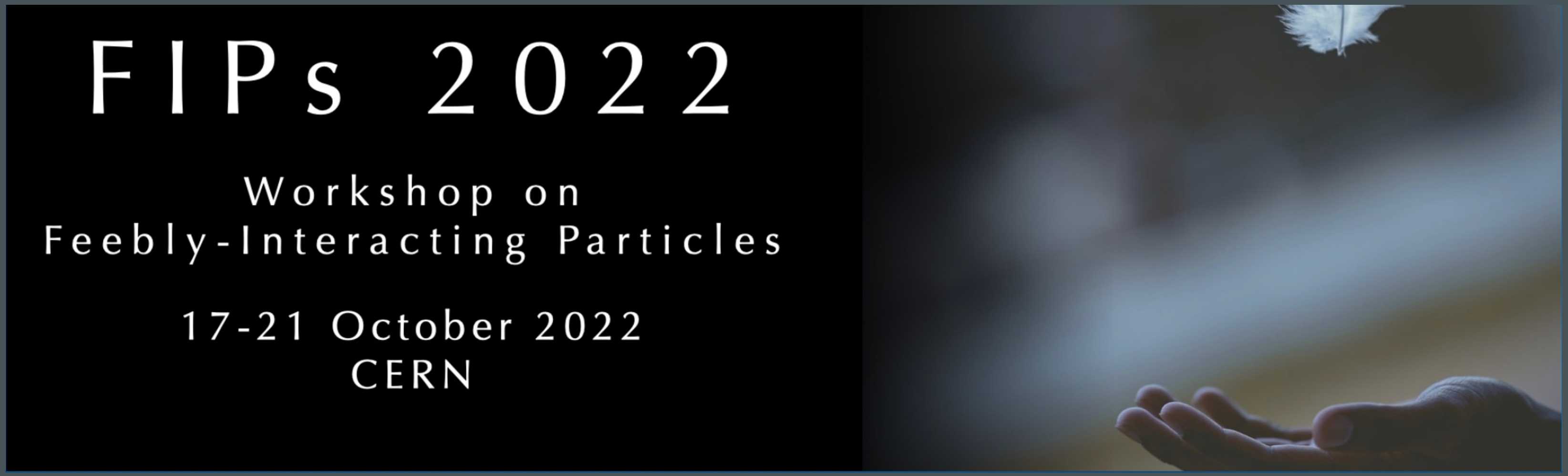
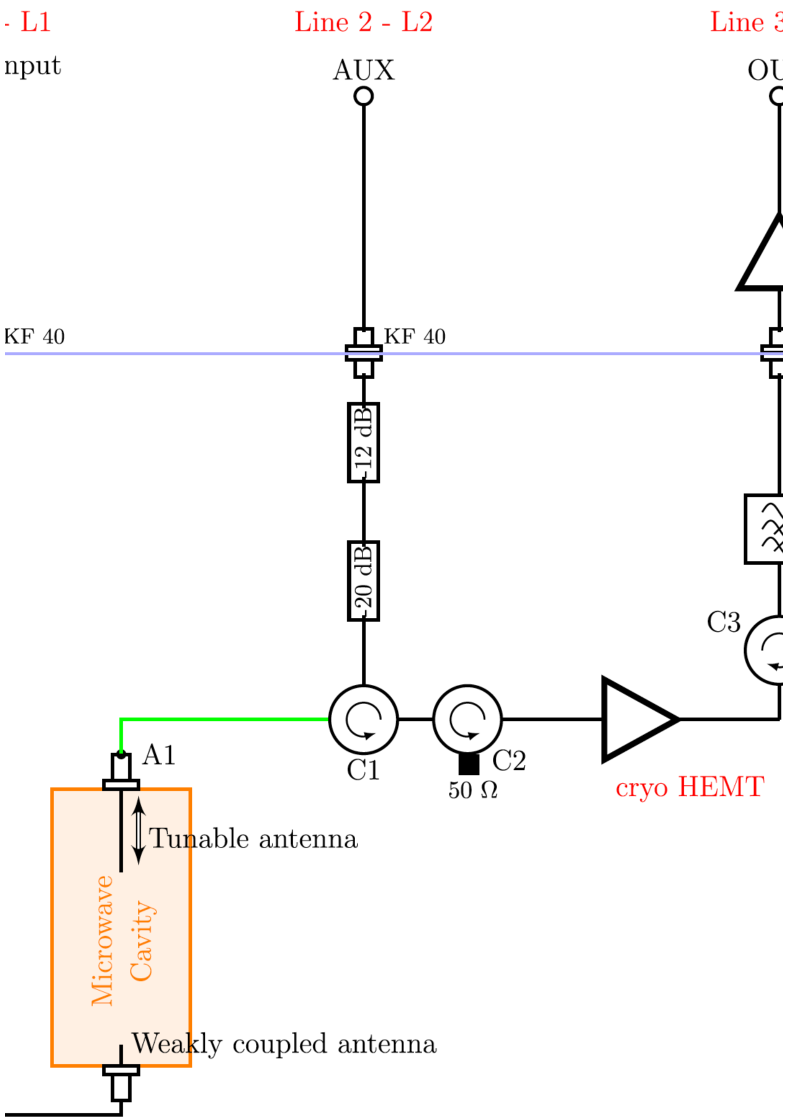
REVIEW OF AXION PROGRAM AT LNF AND LNL

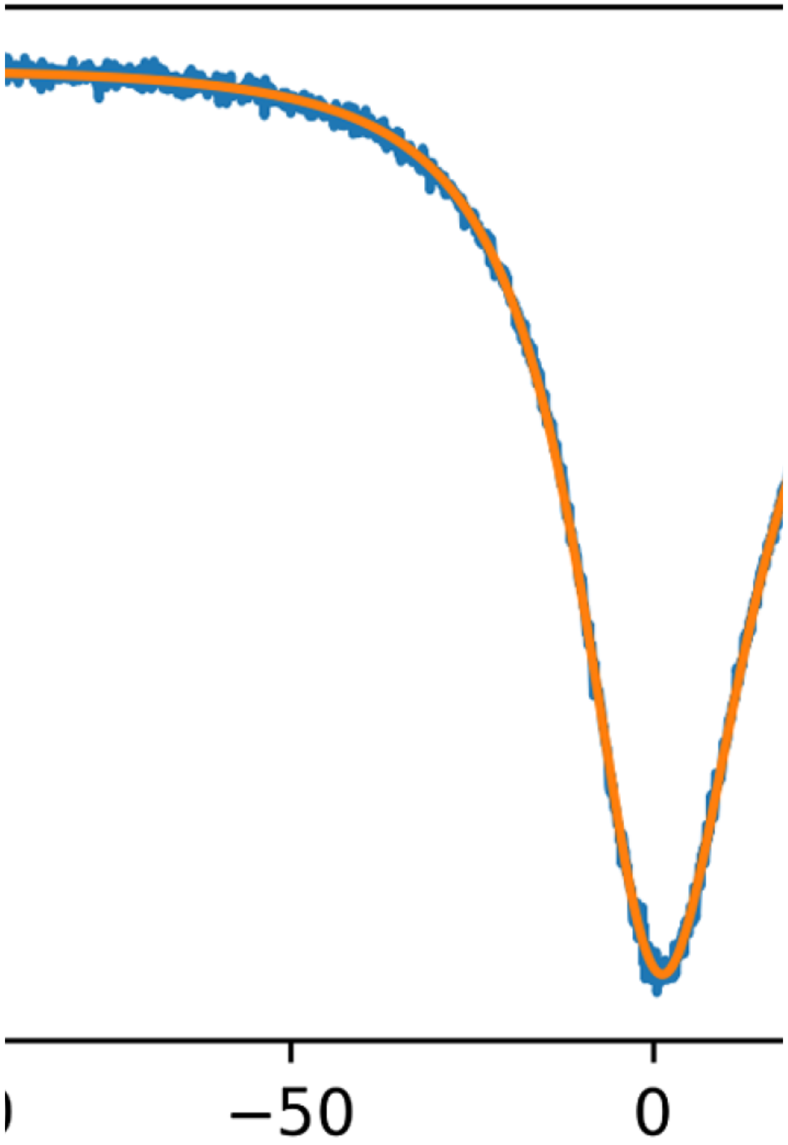
CLAUDIO GATTI - LNF-INFN - QUAX COLLABORATION



OUTLINE

- Sikivie Haloscope
- QUAX
  - Quax-ae
  - Quax-aγ
  - Quax program 2023-2025
- Signal amplification and microwave photon counters
- Search for lighter axions with FLASH
- Conclusion



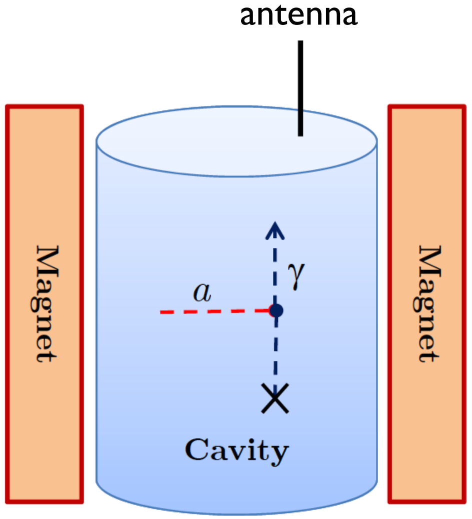


Sikivie Haloscope

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

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

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



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

β antenna coupling to cavity

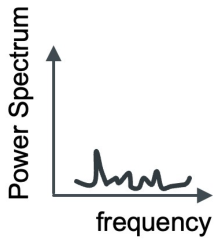
V cavity volume

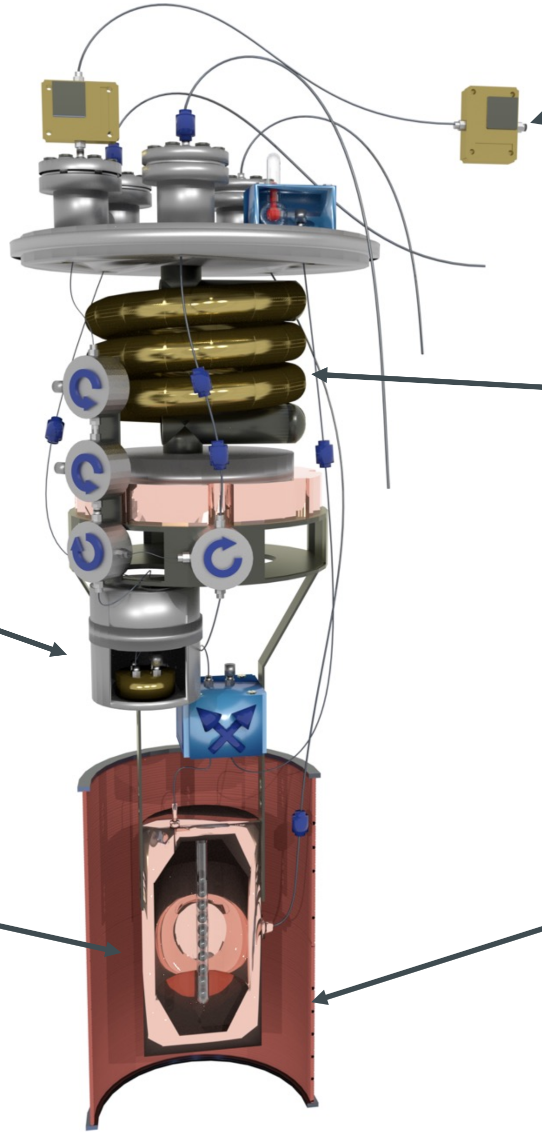
C_{mnl} mode dependent factor about 0.6 for TM010

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

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

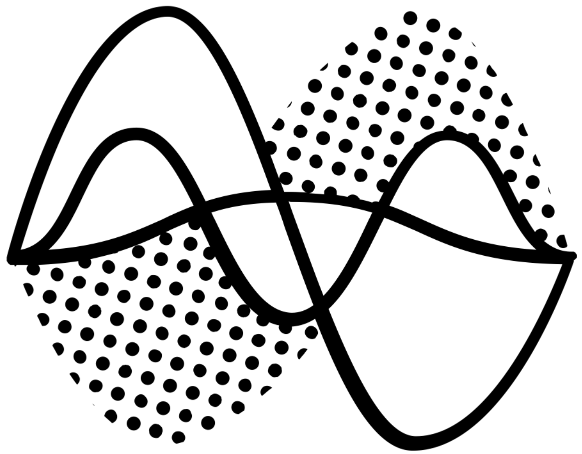
Resonant cavity

SC magnet (~10 T)

Axion signal 0.1 – 0.01 zW

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

QUAX LIMITS ON AXIONS



Created by Joey Hiller
from the Noun Project

QUAX

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

UNIVERSITY OF BIRMINGHAM

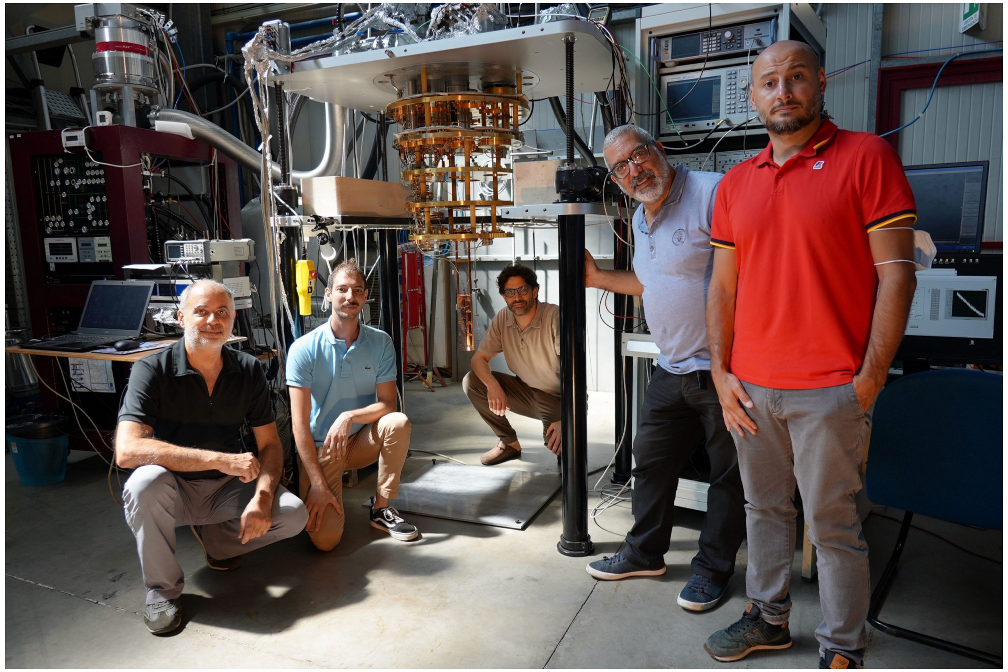
Laboratori Nazionali di Legnaro (LNL)

INFN
Istituto Nazionale di Fisica Nucleare

And new collaborations with SQMS SUPERGALAX NÉEL institut

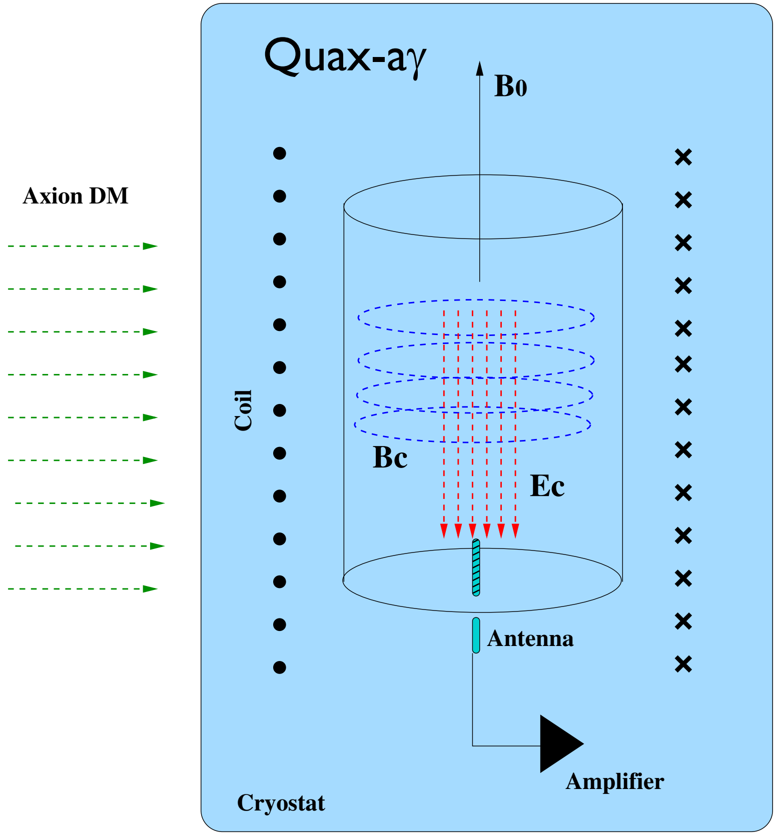
Laboratori Nazionali di Frascati (LNF)

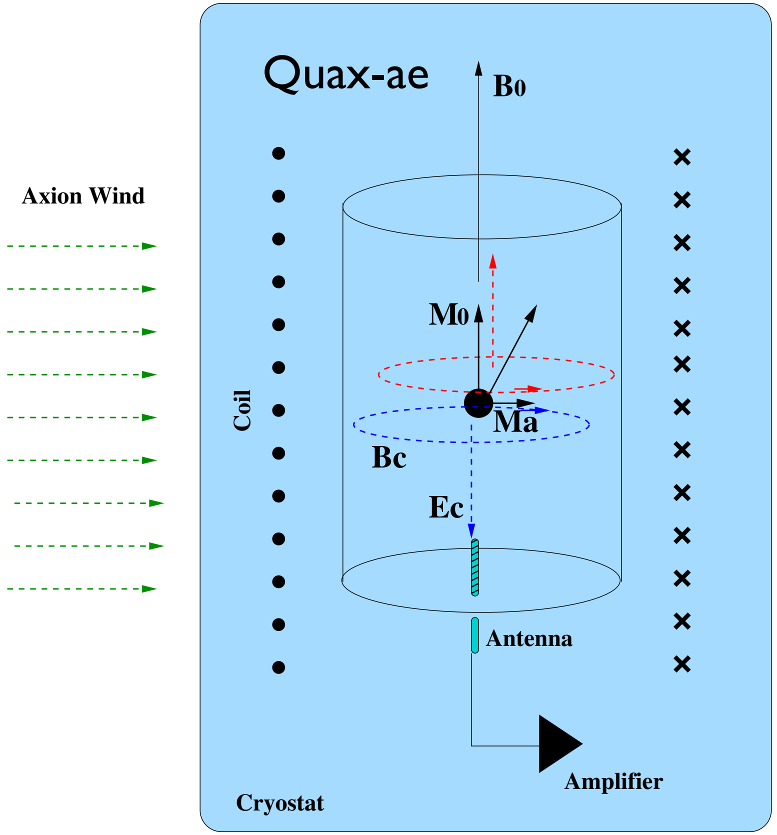
See talk by Thierry Grenet



QUAX: Quest for Axions

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

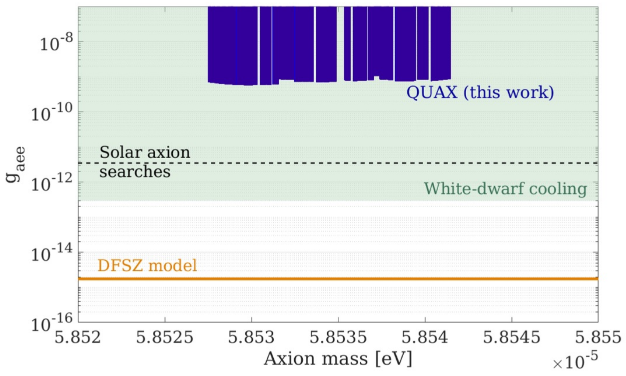




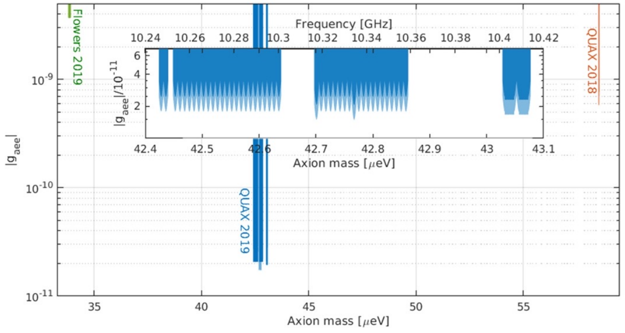
QUAX RESULTS 2018-2022

- 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).
- Search for Galactic Axions with high-Q Dielectric Cavity, Phys. Rev. D 106, 052007 (2022).

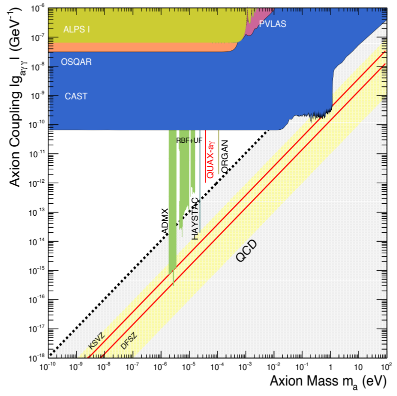
Quax-ae 2018



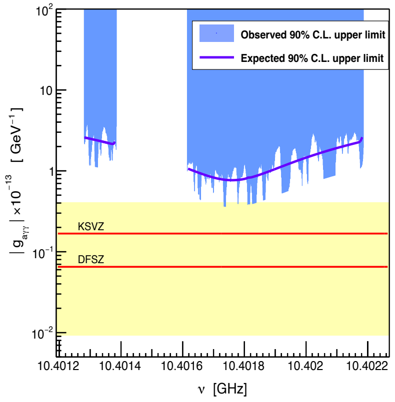
Quax-ae 2020



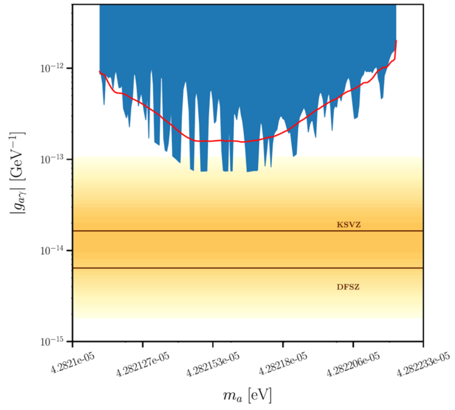
Quax-aγ 2019



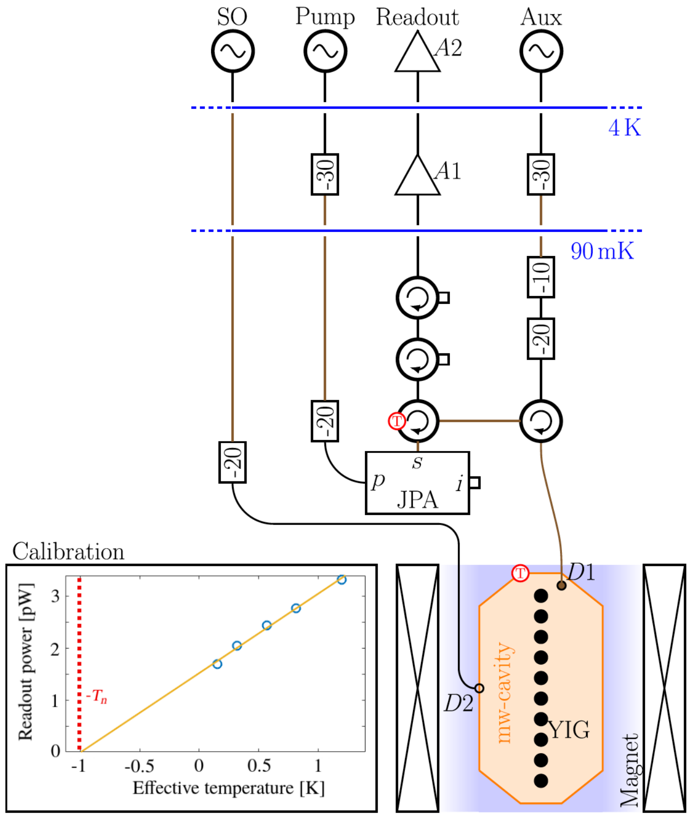
Quax-aγ 2021



Quax-aγ 2022



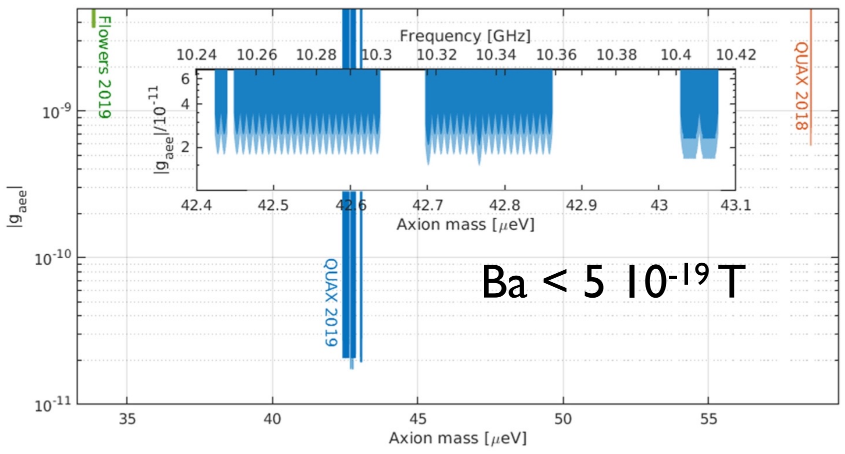
QUAX-ae Result with Quantum-Limited Ferromagnetic Haloscope

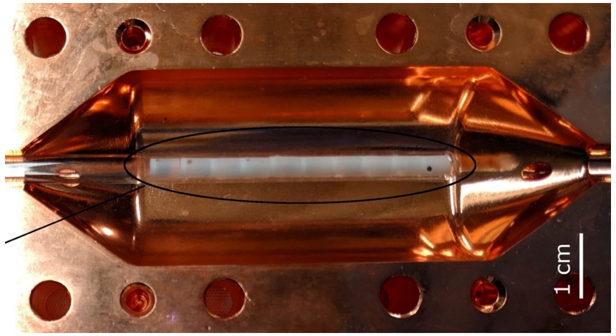


Laboratori Nazionali di Legnaro

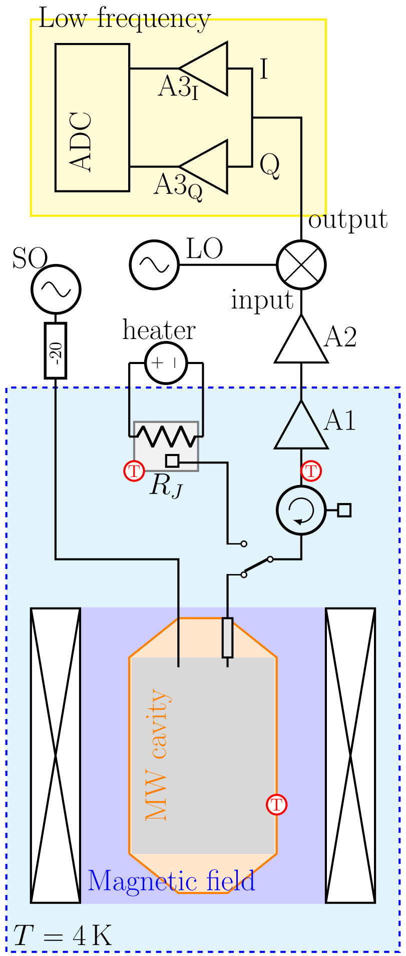
Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =2.1 mm)	10
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.1
Frequency [GHz]	10.7
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [mK]	90
T amplifier [K] (JPA)	0.5-1

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



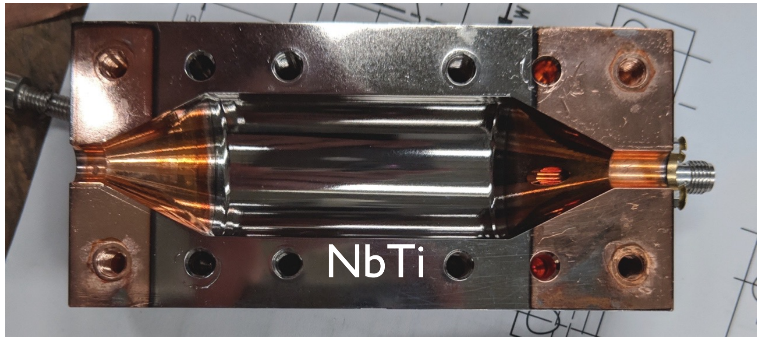


QUAX-aγ Result with Superconductive Resonant Cavity at m_a = 37.5 μeV

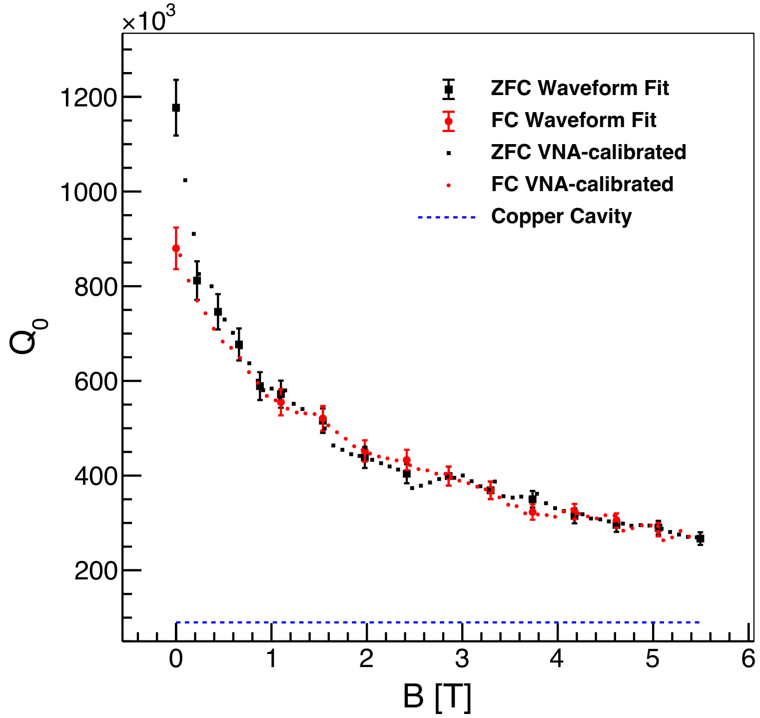


Laboratori Nazionali di Legnaro

Experimental Setup	
B [T]	2
Frequency [GHz]	9
NbTi cavity Q - TM010	400,000
Volume×C_{010} [L]	0.021
T_{cavity} [K]	5.0
T amplifier [K] (HEMT)	11

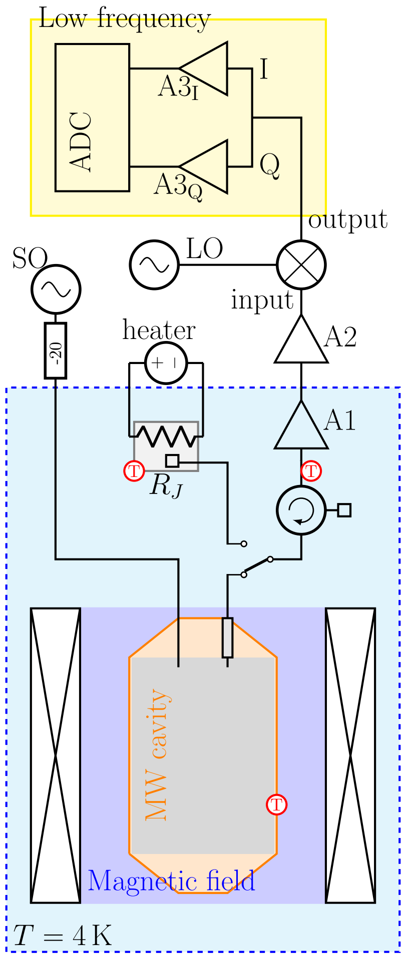


$$g_{a\gamma\gamma} < 1.03 \times 10^{-12}\ \mathrm{GeV}^{-1}$$



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

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



Laboratori Nazionali di Legnaro

Experimental Setup	
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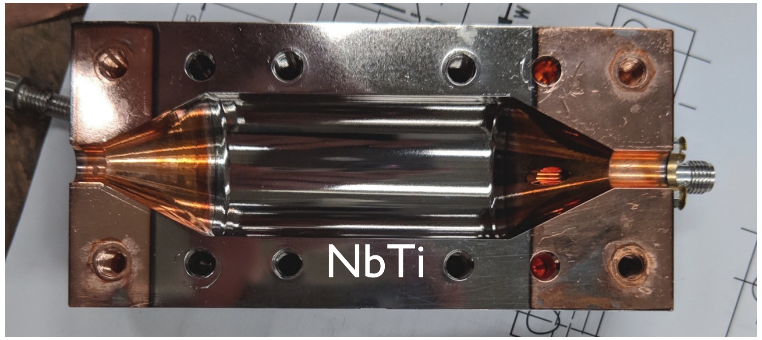
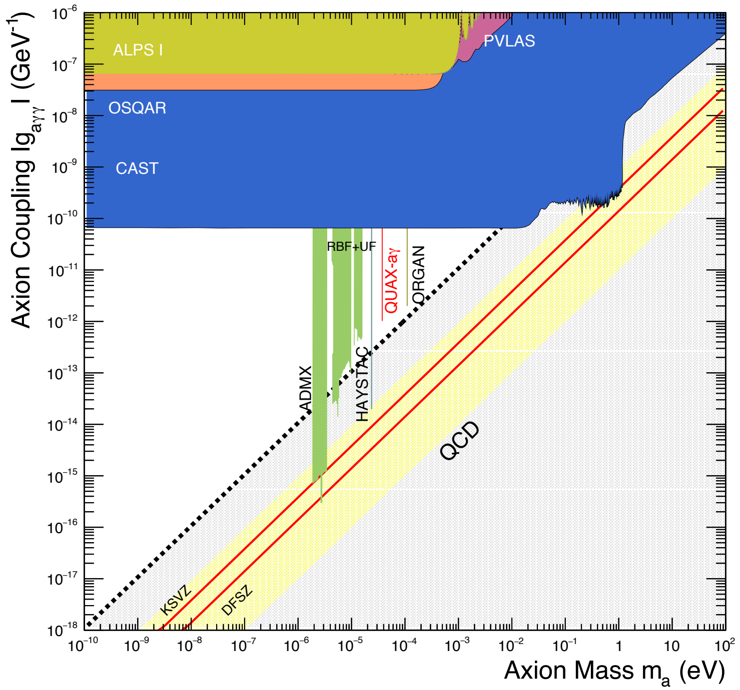
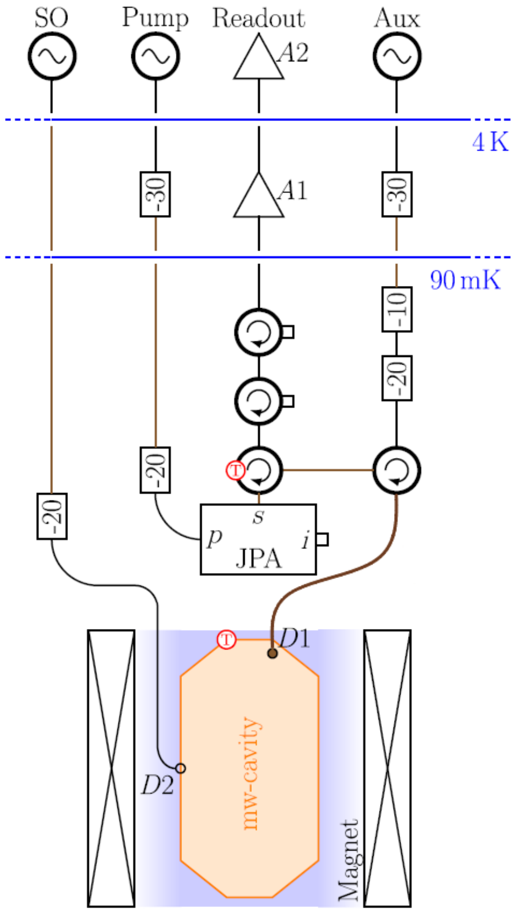


$$g_{a\gamma\gamma} < 1.03 \times 10^{-12}\,\mathrm{GeV}^{-1}$$



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

QUAX – Sensitivity to QCD Axions

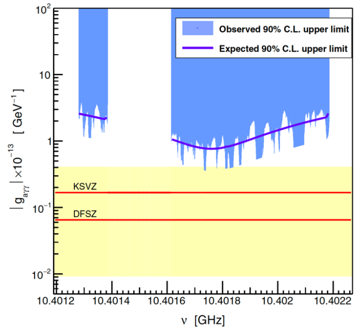


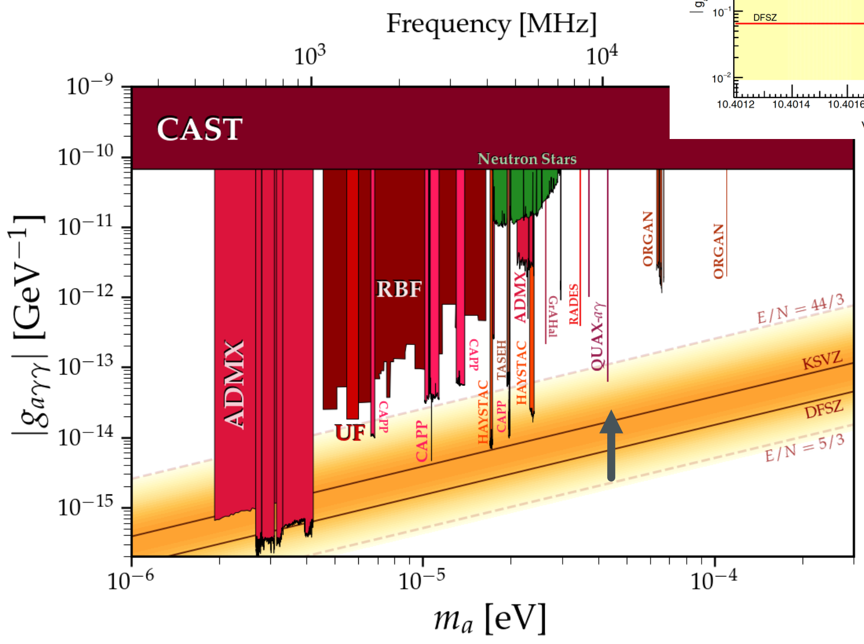
Laboratori Nazionali di Legnaro

Experimental Setup	
B [T]	8
Frequency [GHz]	10
Cu cavity Q - TM010	80,000
Volume×C_{010} [L]	0.055
T_{cavity} [mK]	90
T amplifier [K] (JPA)	1

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

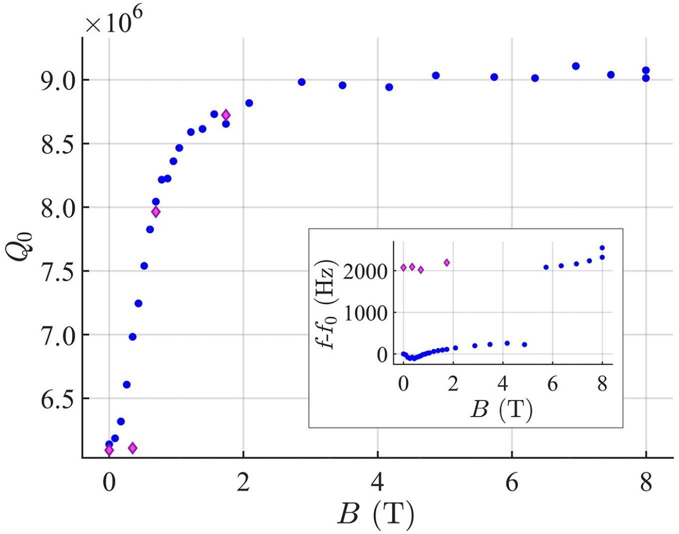
PHYS. REV. D 103, 102004 (2021)





https://cajohare.github.io/AxionLimits/docs/ap.html

QUAX-aγ Result with Dielectric Resonant Cavity

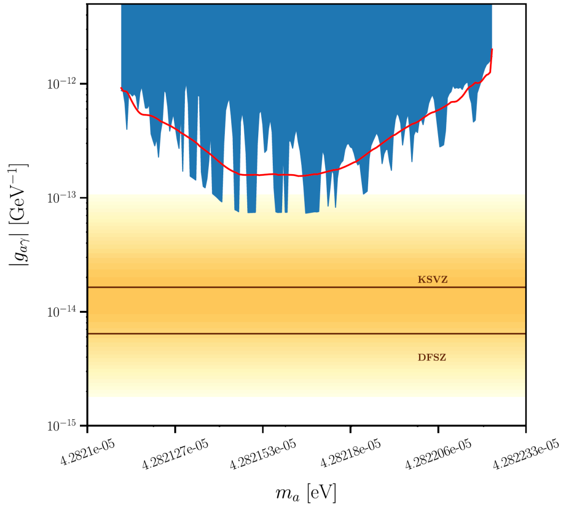


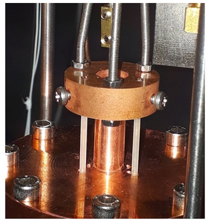
PHYSICAL REVIEW APPLIED **17,** 054013 (2022)

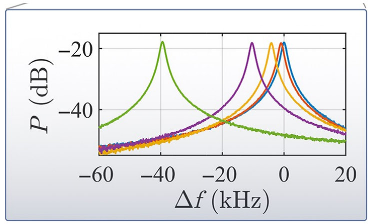
Experimental Setup	
B [T]	8
Frequency [GHz]	10
Dielectric cavity Q_L - TM030	300,000
Volume×C_{030} [L]	0.036
T_{cavity} [K]	4.5
T amplifier [K] (HEMT)	11

ν_c [GHz]	Q_L	β
10.3533667	365730	14.59
10.3533711	337630	15.91
10.3533792	315100	17.00
10.3533874	288190	18.00
10.3533955	286620	17.87
10.3534036	284810	17.66
10.3534159	283410	17.61
10.3534150	354000	13.74
10.3534250	292510	16.20
10.3534354	290290	16.42
10.3534464	285760	17.25

PHYS. REV. D 106, 052007 (2022)

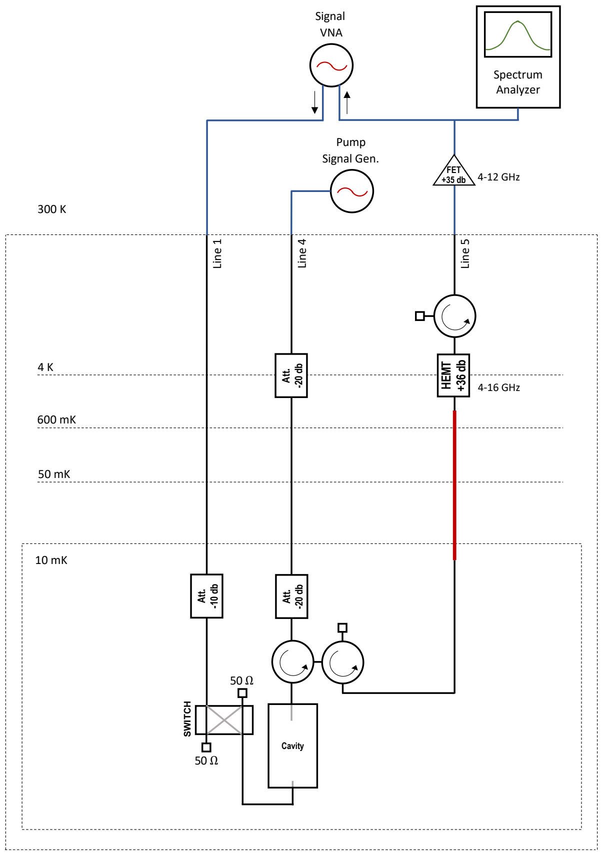




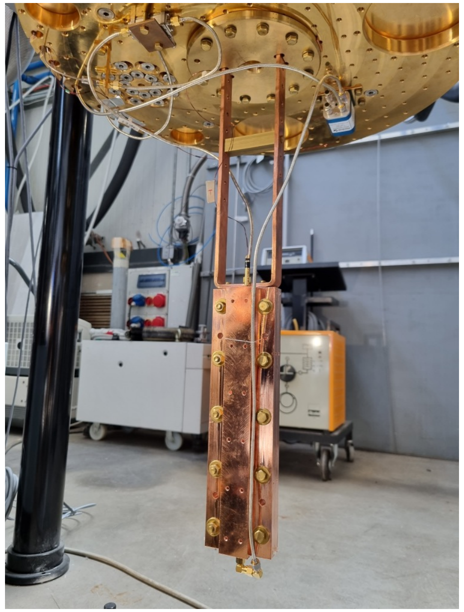


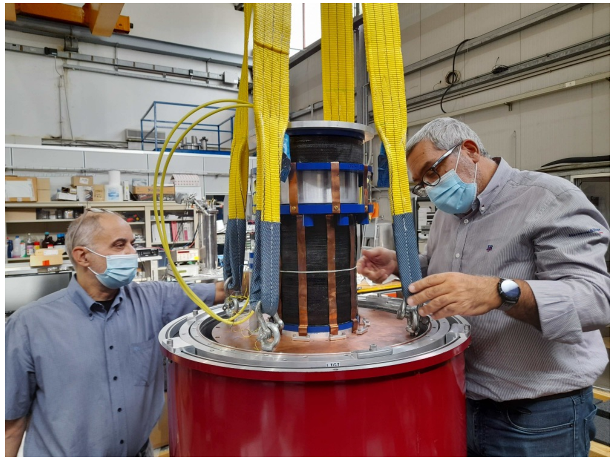
Tuning with sapphire rods

QUAX – New Haloscope at LNF



Frequency	8.5 GHz
Volume	0.14 L
Q_0	100,000
B	9 T
Tcavity	20 mK





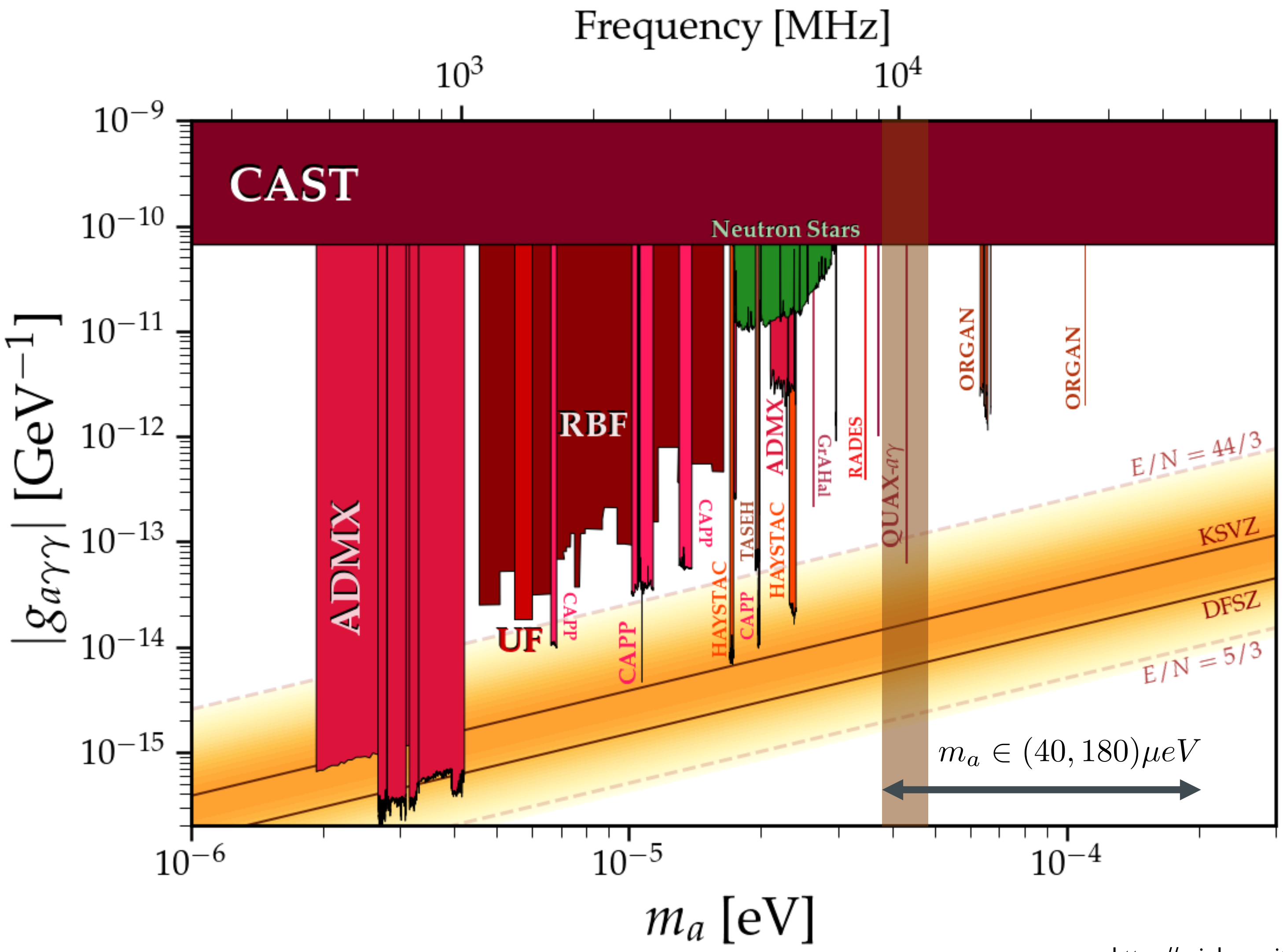
QUAX LNF&LNL 2023-2025

LNF:

- Superconducting cavity $Q_0 > 2\times10^5$
- B=9T
- Multicavity

LNL:

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

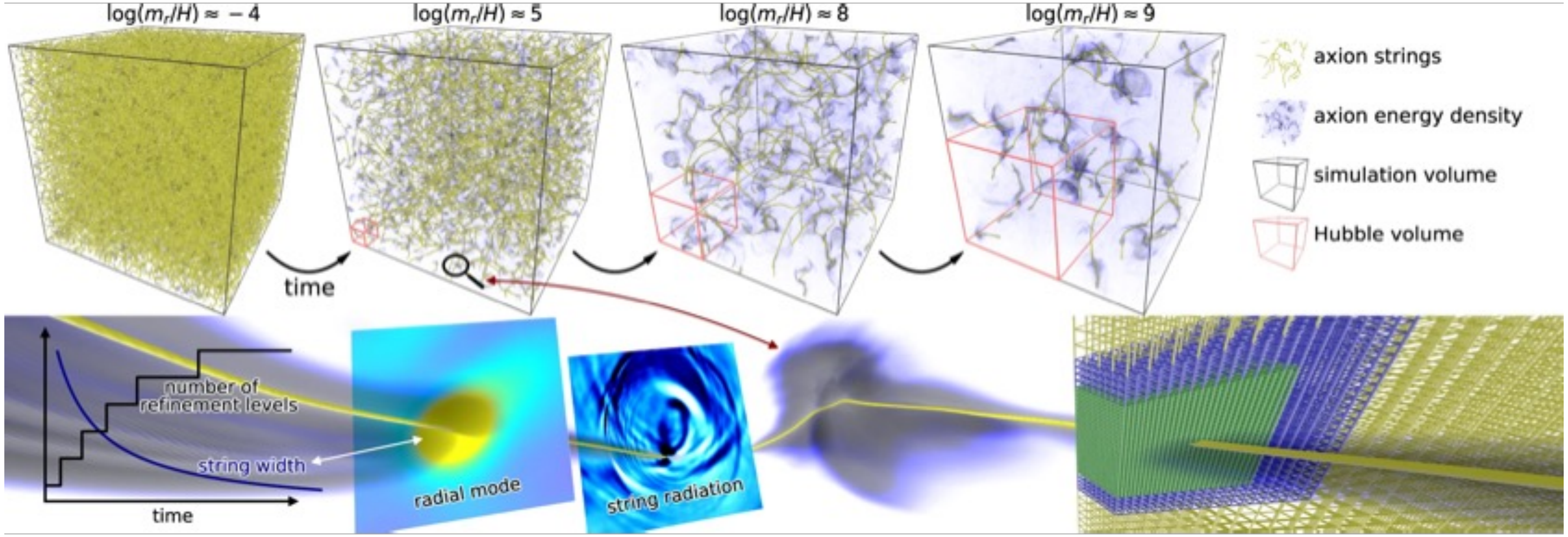


https://cajohare.github.io/AxionLimits/docs/ap.html

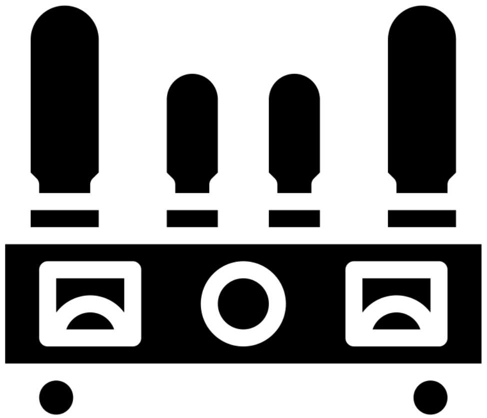
Axions DM From Axion Strings

Simulation of axion-string formation and decays in post inflationary scenarios

$$m_a \in (40, 180)\mu eV$$



Buschmann, M., Foster, J.W., Hook, A. *et al.* Dark matter from axion strings with adaptive mesh refinement. *Nat Commun* **13**, 1049 (2022).

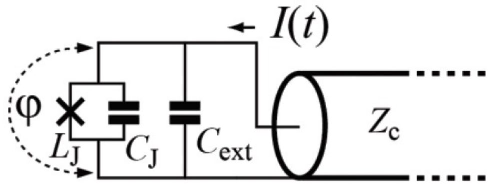


Created by Komkrit Noenp

SIGNAL AMPLIFICATION

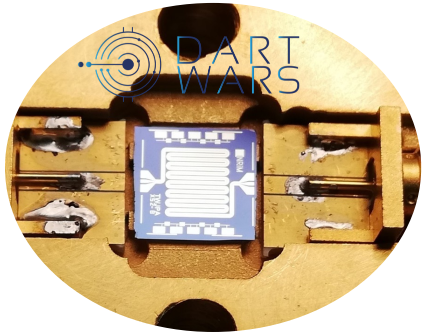
Quantum Limited Amplifiers

Josephson Parametric Amplifiers

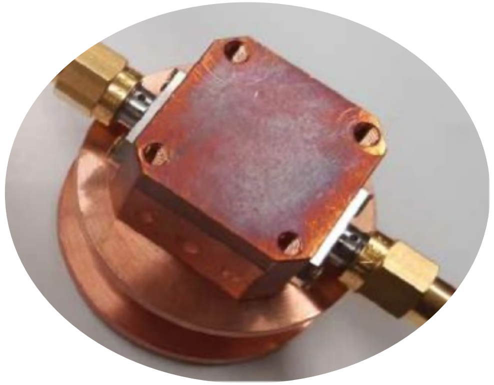


N Roch et al. PRL 108, 147701 (2012)

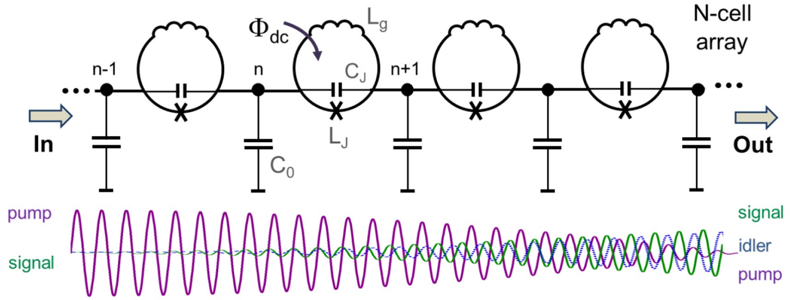
Josephson Traveling Wave Parametric Amplifiers



https://arxiv.org/abs/2111.01512

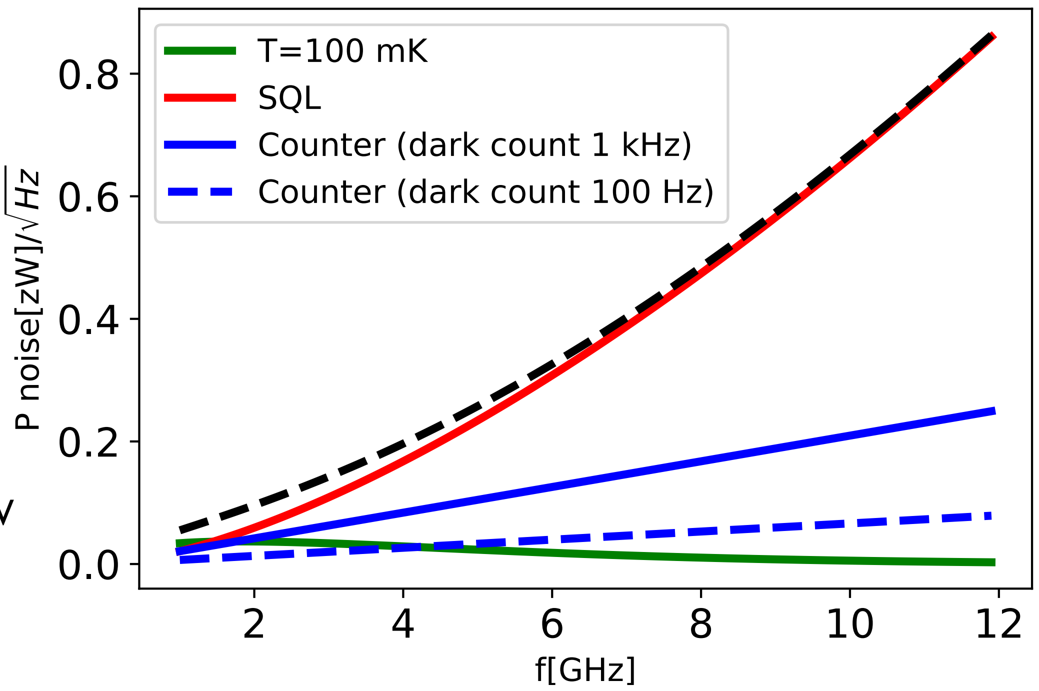


arXiv:2205.02053



Noise In Haloscopes

Axion signal 0.1 – 0.01 zW



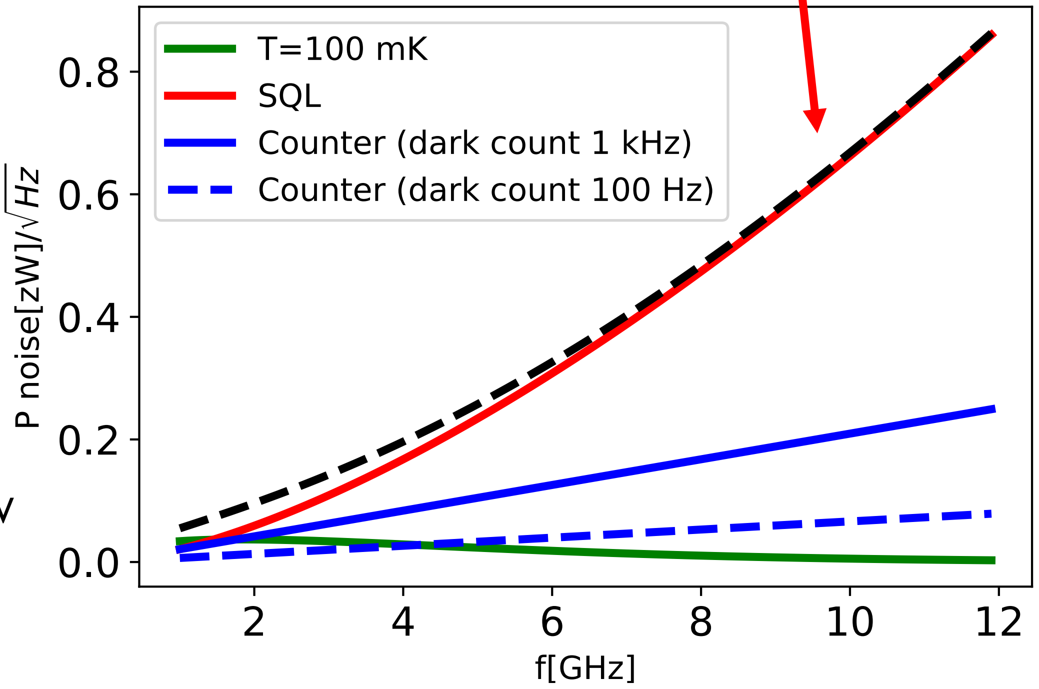
Quantum limited amplifiers

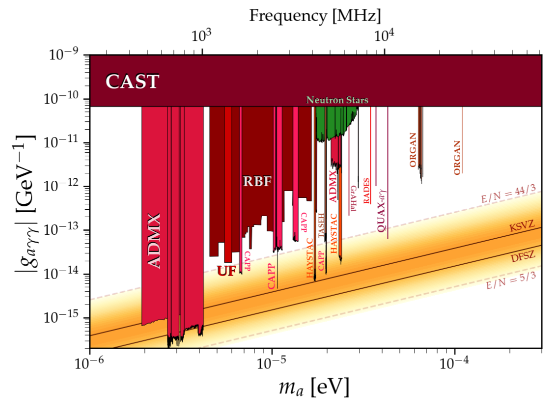
Photon counters

Thermal noise

Noise In Haloscopes

At 10 GHz, limiting factor to DFSZ-axion sensitivity





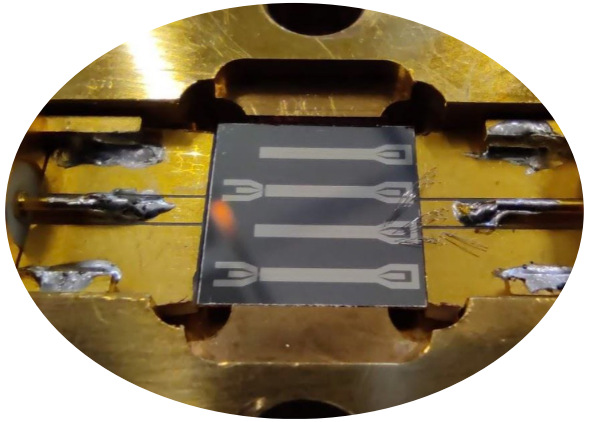
Axion signal 0.1 – 0.01 zW

Photon counters

Thermal noise

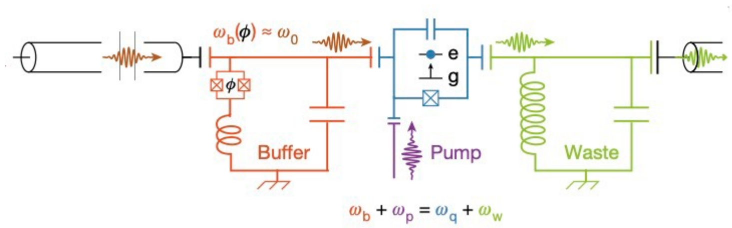
Single Microwave Photon Counters

Single Josephson Junction



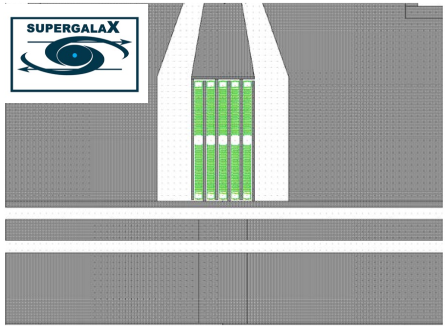
IEEE TRANS APP SUP, VOL. 32, NO. 4, JUNE 2022

Superconducting Qubits



R. Lescanne et al, Phys. Rev. X 10, 021038 (2020)

Array of Superconducting Qubits



SUPERGALAX: microwave photon detection with coherent quantum network of superconducting qubits

FET OPEN SUPERGALAX
CNR (IT, PI, exp)
INRIM (IT, exp)
INFN (IT, axion exp)
KIT (DE, exp)
Leibniz IPHT (DE, exp)
RUHR-UNIVERSITAET BOCHUM (DE theory)
LOUGHBOROUGH UNIVERSITY (UK, theory)

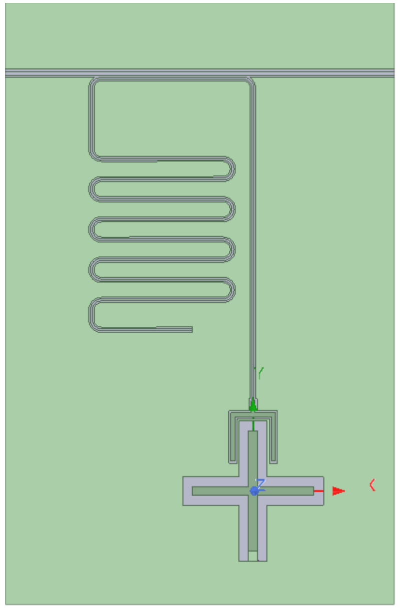
SUPERGALAX

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N. 863313

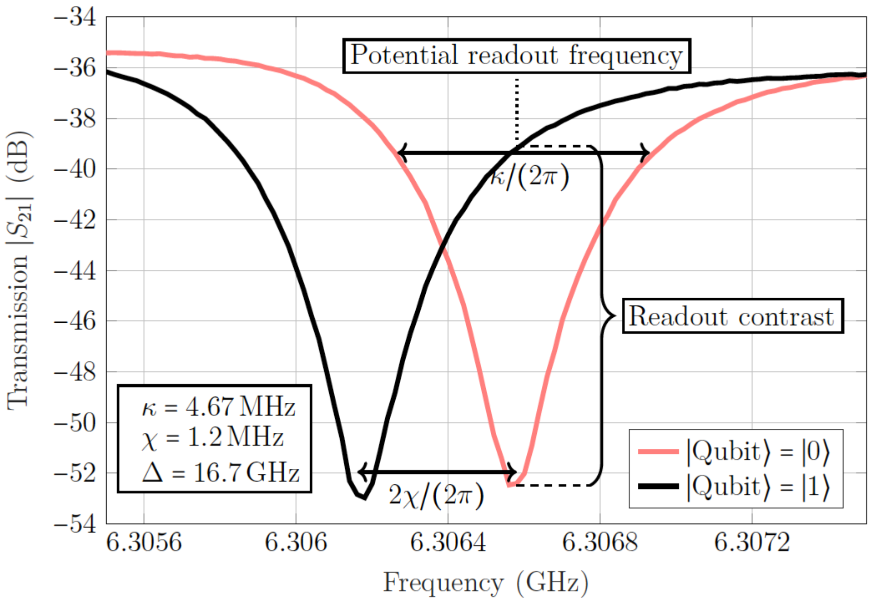
Qubit-Resonator System

A spin flip shifts the resonator resonance

$$H = \hbar \left[\omega_r' + \chi\sigma^z\right] b^\dagger b + \frac{\hbar}{2}\omega_{01}'\sigma^z$$



AC Stark Shift

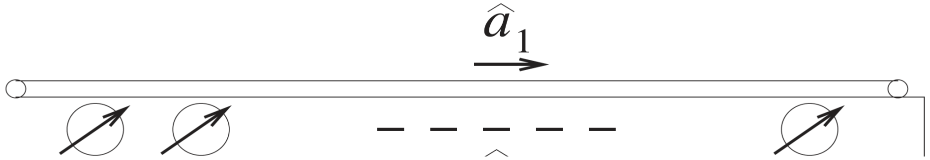


H R Nilsson Thesis, Chalmers

Heisenberg Limit In Microwave Photon Detection by Qubit Array

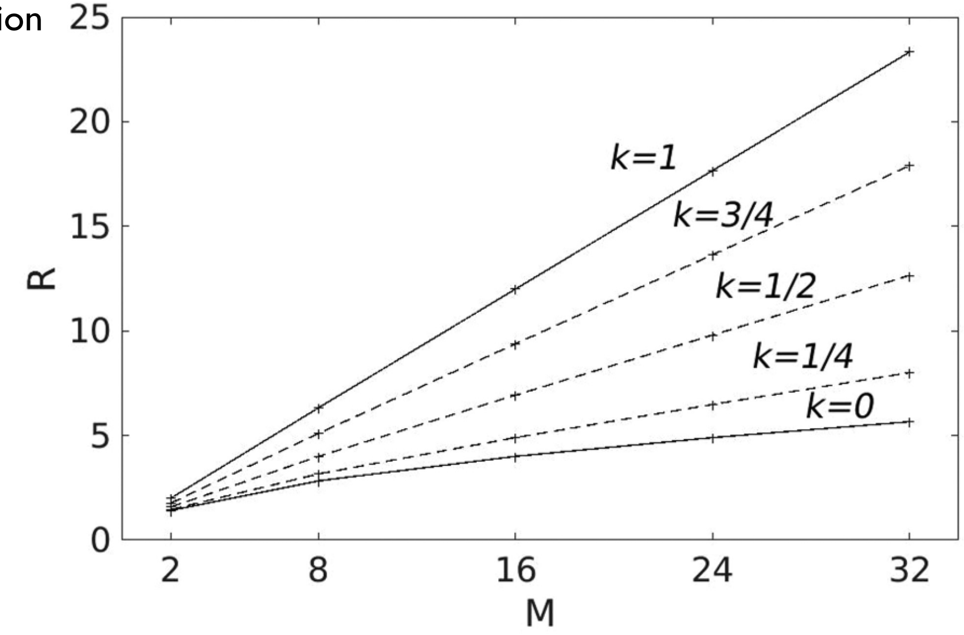
LOUGHBOROUGH UNIVERSITY

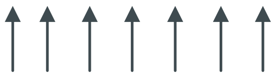
Input signal in a waveguide with M qubits



Dispersive qubit–photon interaction
Evolution in presence of noise

k=1 correlated state
k=0 uncorrelated state



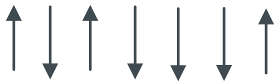


$\mathrm{SNR} \sim M$

Correlated state

Heisenberg limit

Limit of strong ferromagnetic qubit-qubit coupling, when the array represents a "giant spin".



$\mathrm{SNR} \sim \sqrt{M}$

Uncorrelated state

Standard Quantum Limit

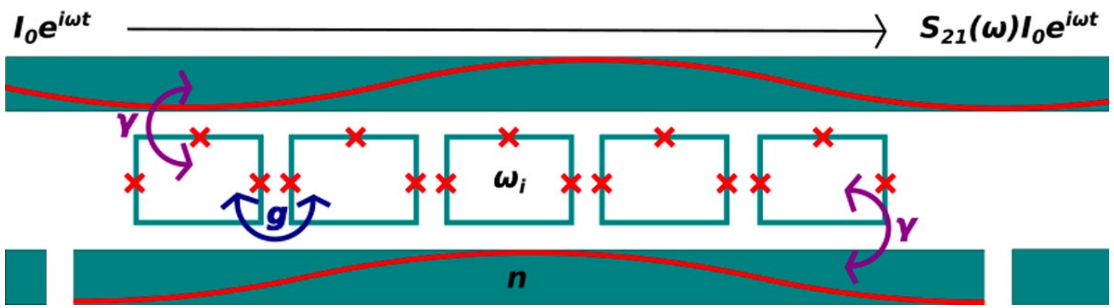
PHYSICAL REVIEW B 103, 064503 (2021)

Collective AC Stark Effect

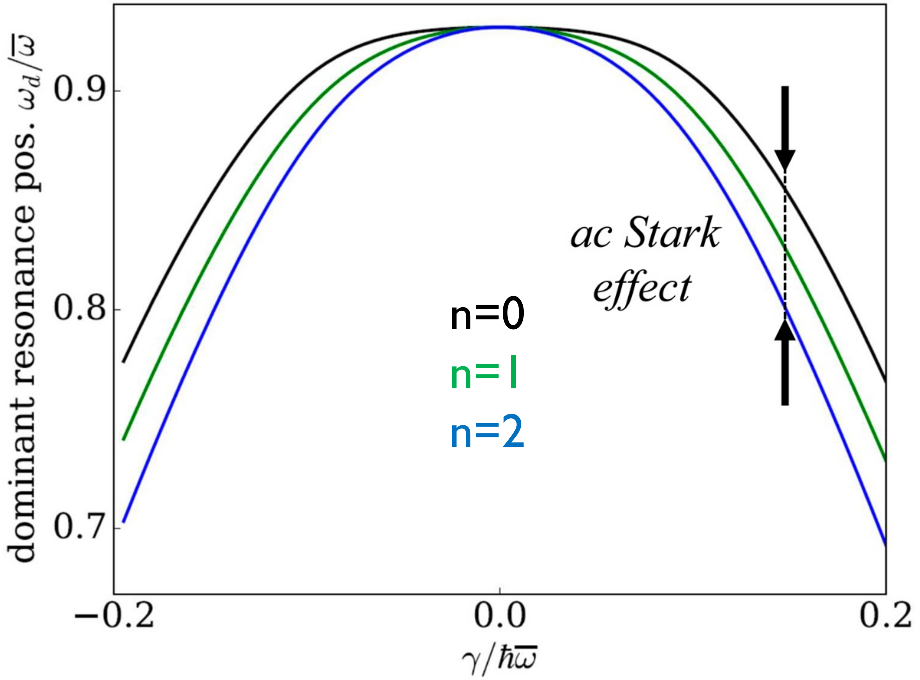
RUHR-UNIVERSITAET BOCHUM

Theoretical study of an interacting superconducting qubit array

Readout transmission line



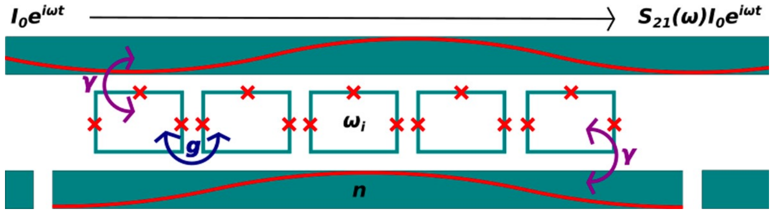
n photons



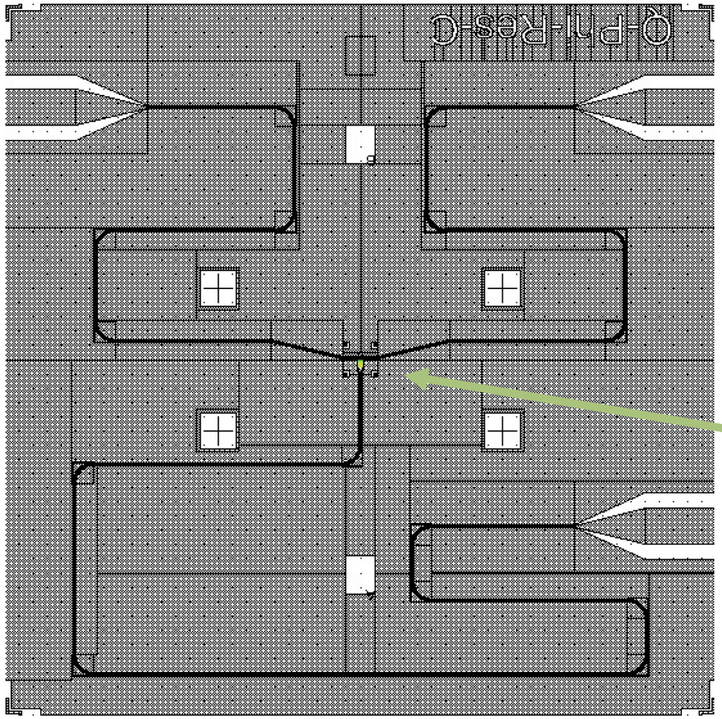
In the presence of a weak nonresonant microwave photons the positions of dominant resonances depend on the number of photons, i.e., the collective ac Stark effect.

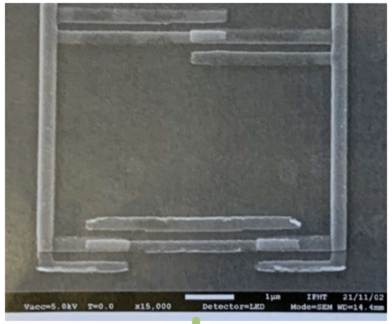
PHYSICAL REVIEW B 105, 104516 (2022)

10 Flux-Qubits Three-Ports Device

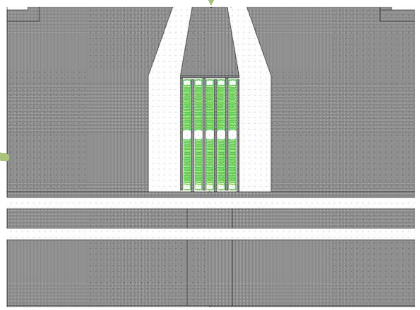


Three-ports device





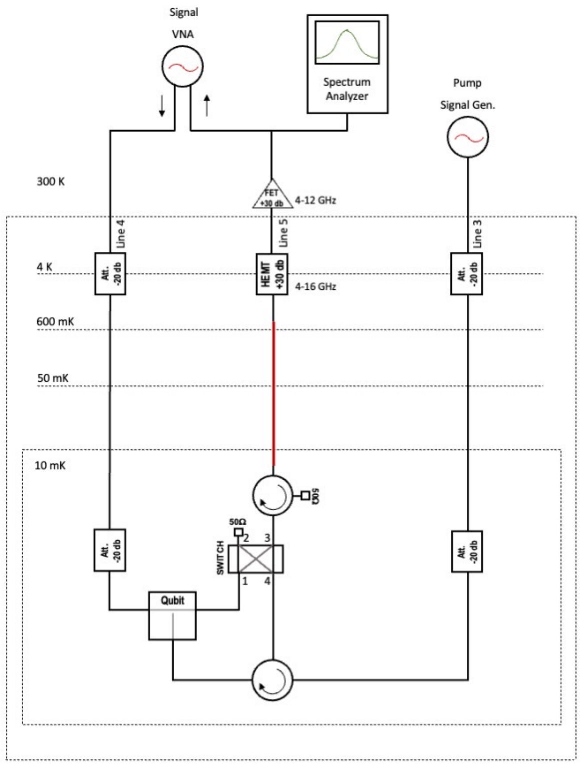
Flux qubit

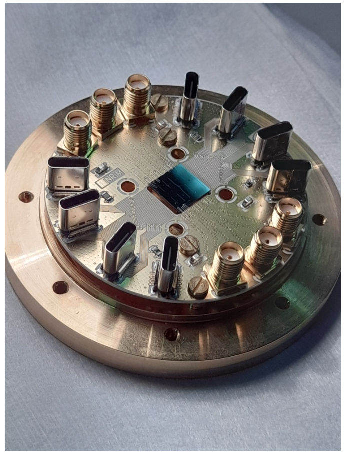


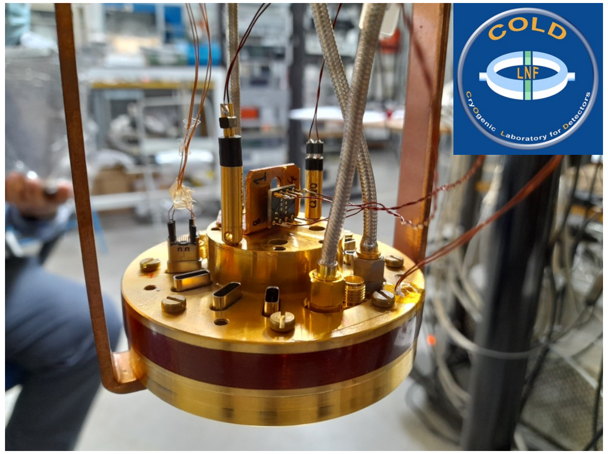
10 C-shunted flux Qubits

Three-Ports Device Characterization at LNF

INFN-LNF
CNR-SPIN

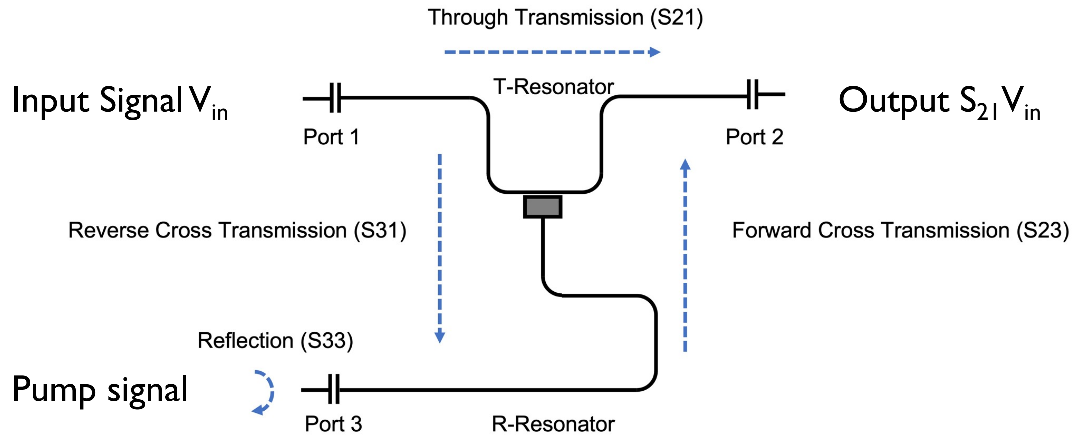


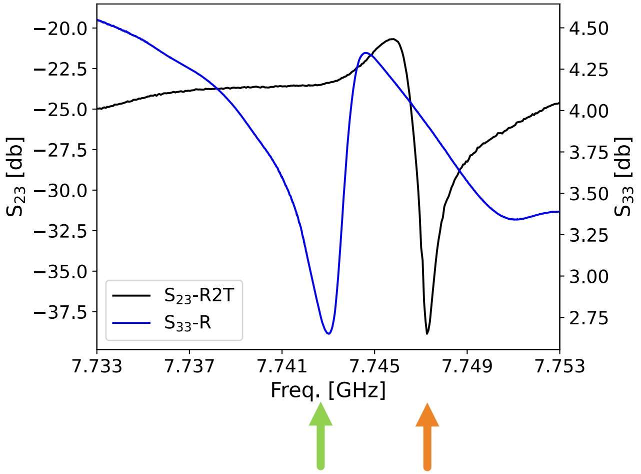




Observation of AC Stark Shift in the 3-Ports Device

SUPERGALAX
INFN-LNF
CNR-SPIN

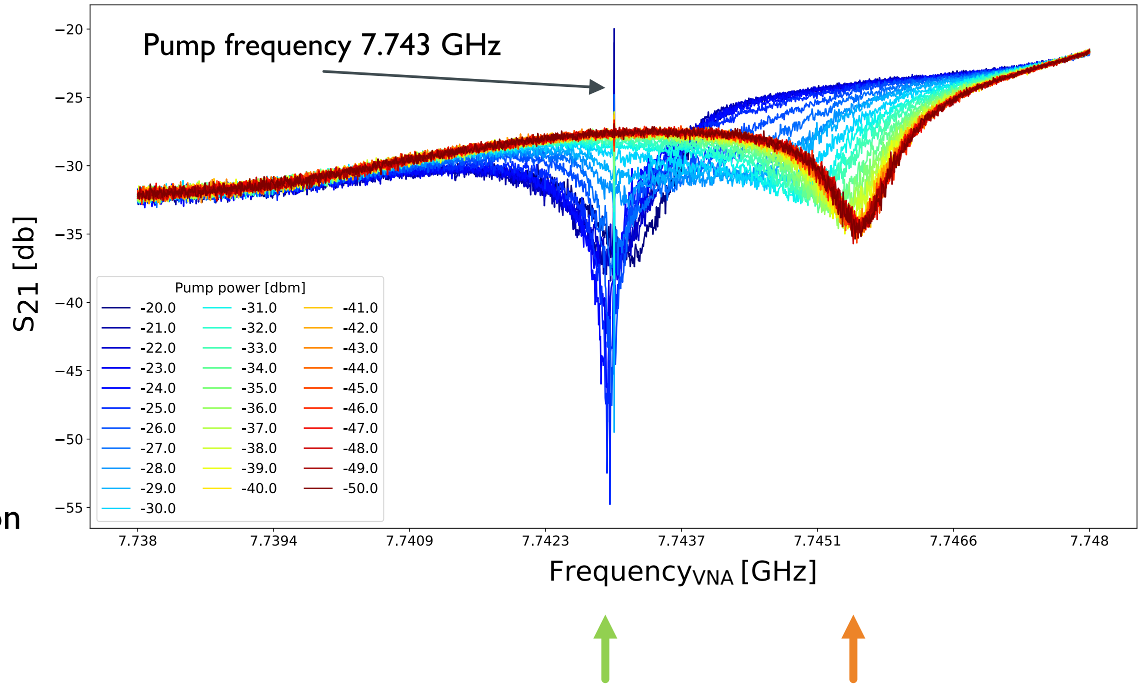




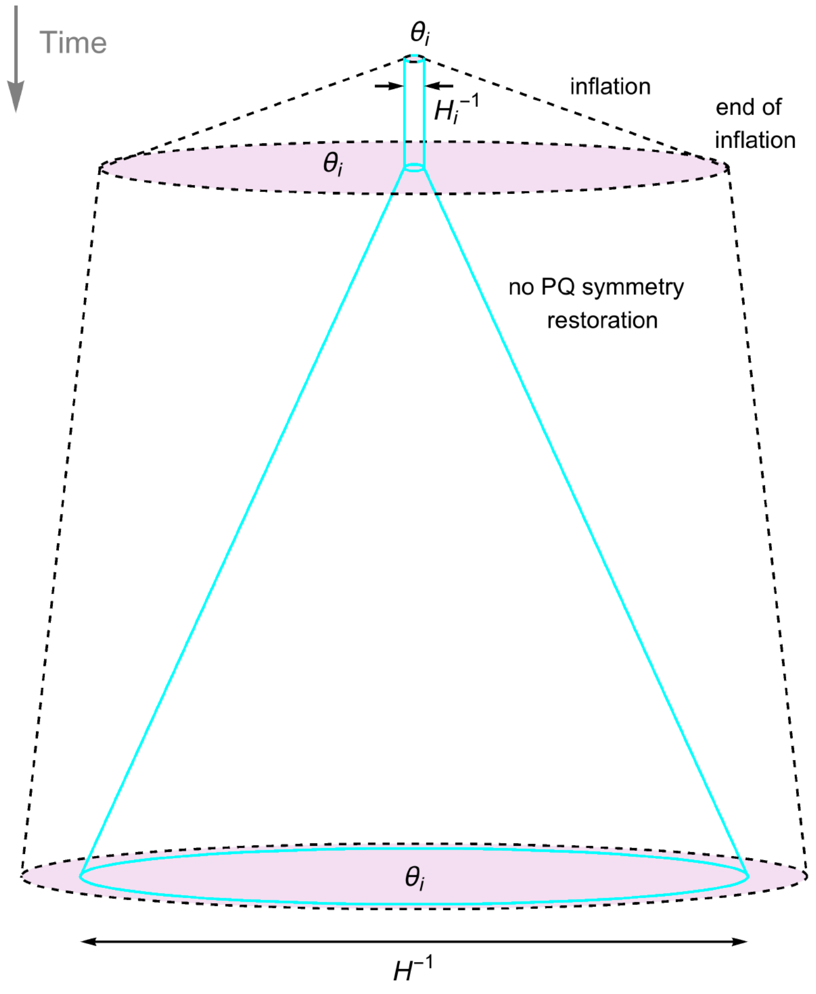
Pump signal Cross-Transmission

Pump signal reflection

Input Signal Through-Transmission



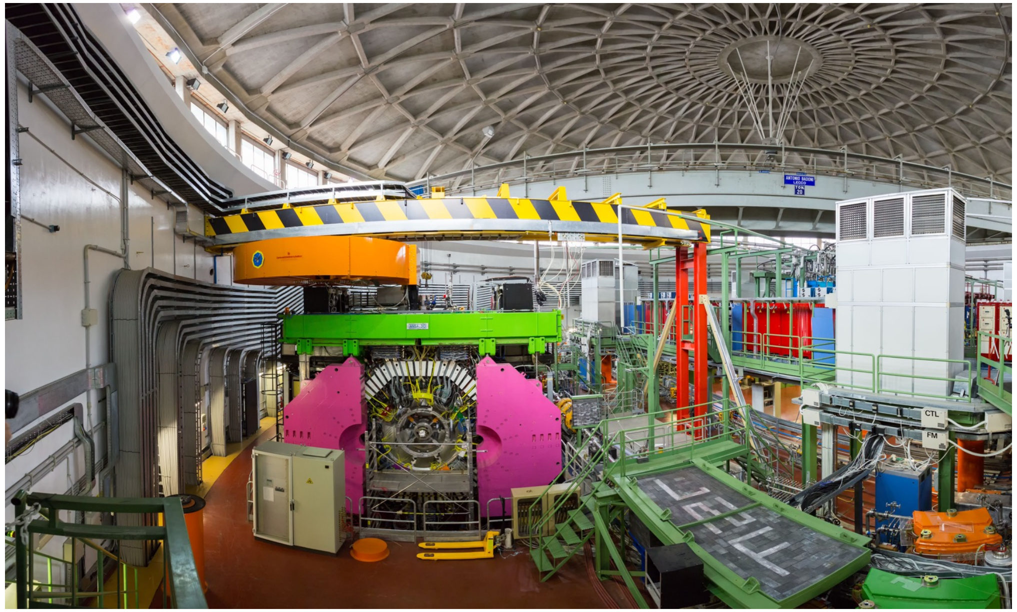
Work in progress to optimize the device for single photon detection



LIGHTER AXIONS

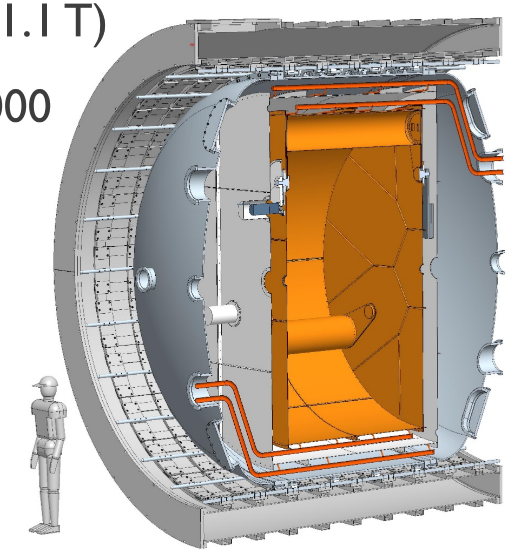
FLASH (PREVIOUSLY KLASH): Finuda Magnet for Light Axion SearcH at 100-300 MHz

Recycling of the 1.1T, 3 m diameter, magnet of FINUDA experiment for a haloscope operating at 100 to 300 MHz



Magnet test foreseen in 2023

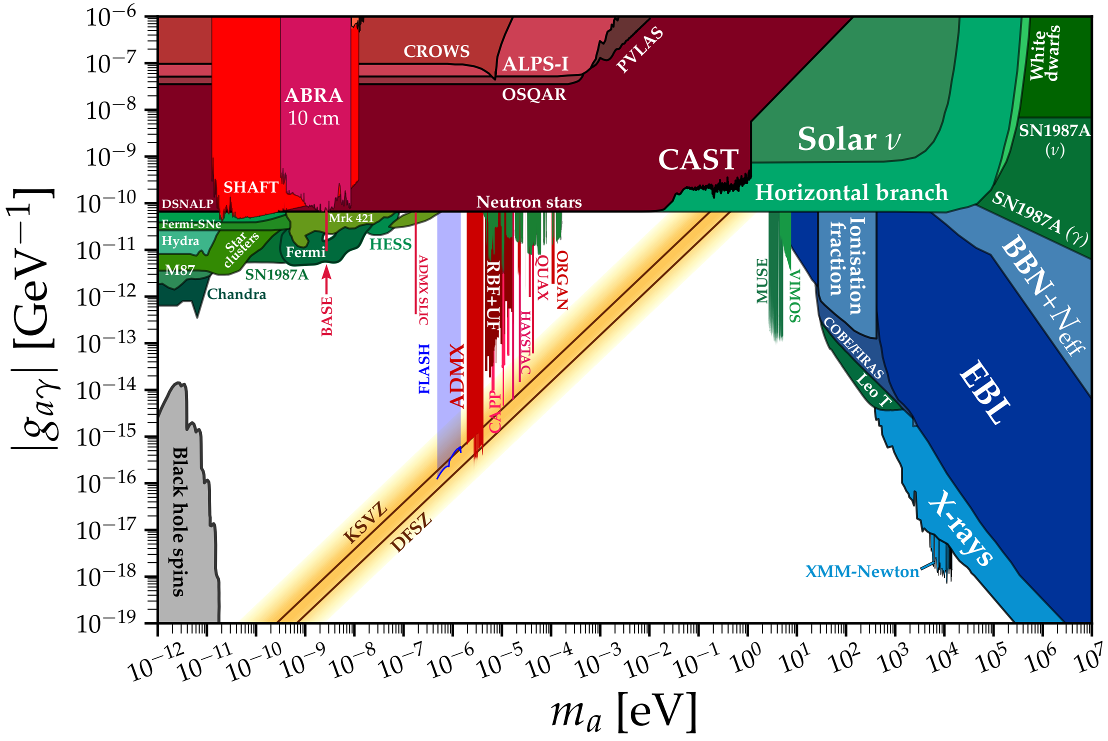
- Search of galactic axions in the mass range 0.5-1.5 μeV
- Large volume RF Cavity (4 m^3)
- Moderate magnetic field (1.1 T)
- Copper rf cavity Q~500,000
- T 4.5 K



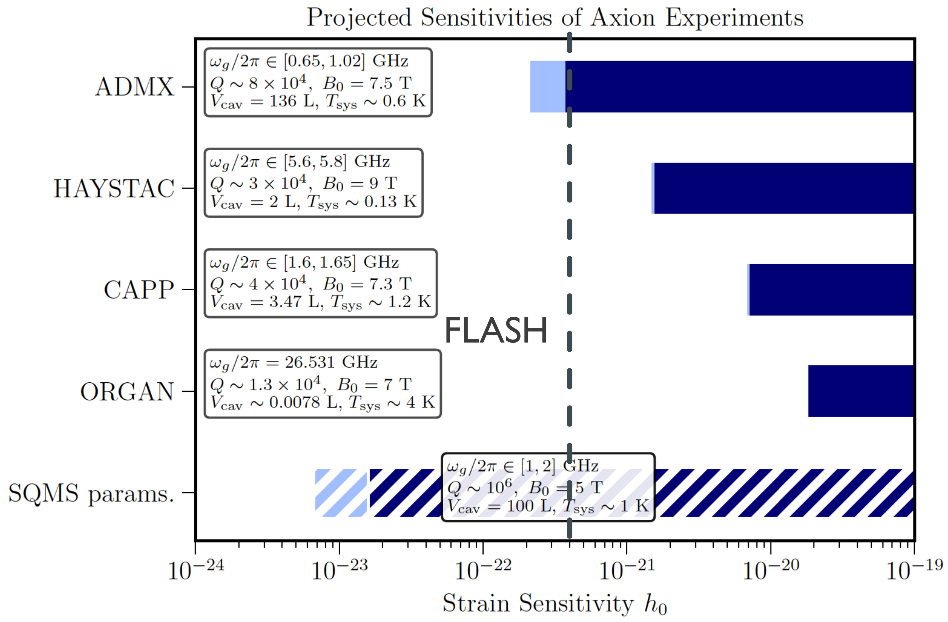
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

KLASH CDR arxiv:1911.02427

FLASH Sensitivity to QCD Axions and HFGW



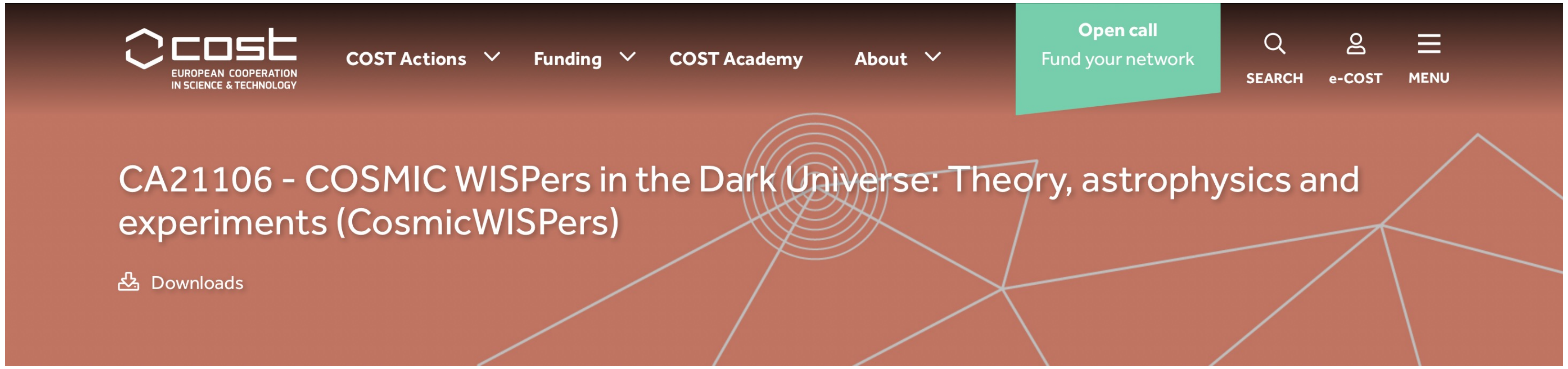
Generated with https://github.com/cajohare/AxionLimits by Ciaran O'Hare



A. Berlin et al. Phys. Rev. D 105, 116011

Conclusion

- QUAX reached the sensitivity to QCD axions in 2021
- A second Haloscope was put in operation this year at LNF
- The two Haloscopes will probe a 1 GHz wide region at 10 GHz to look for KSVZ axions (2023-2025)
- This mass region is strongly motivated in post-inflationary scenario
- Experience gained in superconducting quantum devices
- Thinking also to lighter axions with a large haloscope



COSMIC WISPERS
CA 21106

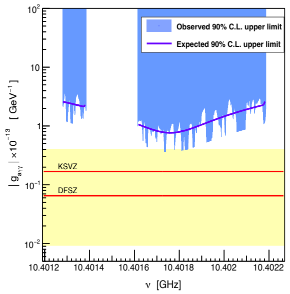
https://www.cost.eu/actions/CA21106/

COLD - Cryogenic Laboratory for Detectors

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

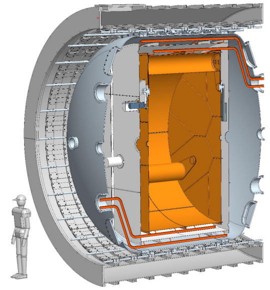
COSMIC WISPERS
CA 21106

EXPERIMENTS



QUAX – QUest for AXions

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



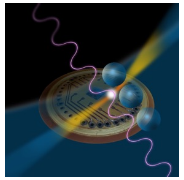
(K)FLASH

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



SIMP (Single Microwave Photon detectors)

Development of single-microwave photon detector

Qub-IT Quantum Sensing with superconducting qubits

Supergalax FET H2020 Project

SC-qubits array photon-detector for axion experiments

SQMS USA DOE Project

Superconducting Quantum Materials and Systems