THE EUROPEAN EXPERIMENTAL LANDSCAPE OF DIRECT DETECTION OF AXION DARK MATTER

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IBS October 20th 2020

OUTLINE

- Properties of Axions
- Axion Limits
- Non DM Experiments
- Dark Matter Axion Searches in Europe
  a) Resonant Searches (haloscopes)
     I. QUAX
     II. KLASH
     III. RADES
  b) Broadband Searches
     I. DISH Antenna (BRASS)
     II. Dielectric Haloscope (MADMAX)
  c) NMR
     I. CASPEr
- Prospects for Signal Amplification (an INFN perspective)

AXIONS PROPERTIES

Created by Agarunov Oktay-Abraham
from Noun Project

Axion Mass

Interaction with gluon field $$\mathcal{L} = \left(\frac{a}{f_a} - \theta\right)\frac{\alpha_s}{8\pi} G^{\mu\nu a}\tilde{G}^{a}_{\mu\nu}$$

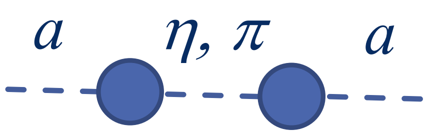
a axion field

f_a PQ breaking energy scale

G gluon field

At temperature $T=\Lambda_{QCD}$ non perturbative QCD effetcs generate an axion mass

$$m_a = 5.70(7)\left(\frac{10^{12}GeV}{f_a}\right)\mu eV \simeq \frac{m_\pi f_\pi}{f_a}$$



If $f_a \sim f_{ew} = 100\ GeV$, as in original PQ model, then $m_a \sim 100\ keV$ and $BR(K^+ \rightarrow \pi^+ a) \sim 10^{-5}$
This is ruled out by measurements $BR(K^+ \rightarrow \pi^+\ nothing) < 10^{-8}$

Asztalos et al. Ann. Rev. Nucl. Part. Sci. 56 2006

Axion Interaction with Matter

Axion interaction with matter described by an effective lagrangian

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

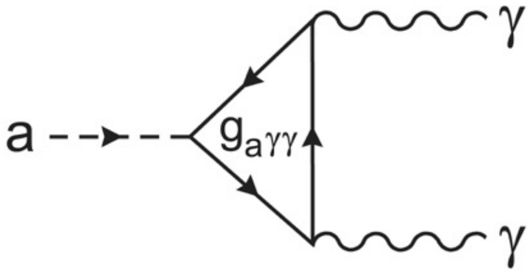
Casper Electric Experiment

Casper Wind Experiment

Quax-ae Experiment

Elioscopes
Haloscopes
LSW

Axion Lifetime



$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right)$$

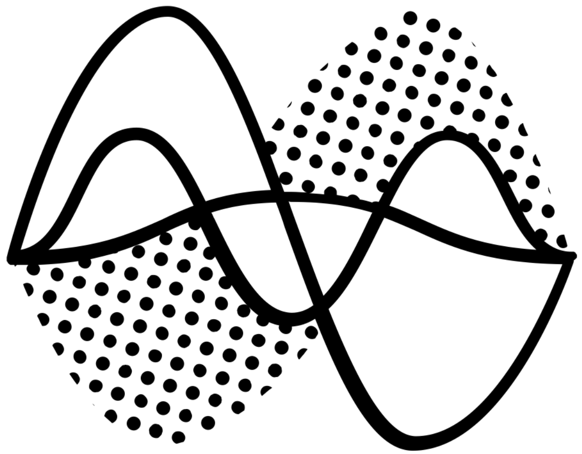
Coupling inversely proportional to PQ breaking scale

The effective coupling is model dependent:
E/N=0 KSVZ model
E/N=8/3 DSFZ model

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 1.1\times 10^{-24} s^{-1}\left(\frac{m_a}{eV}\right)^5$$

Light axion are stable particles

LIMITS ON AXIONS



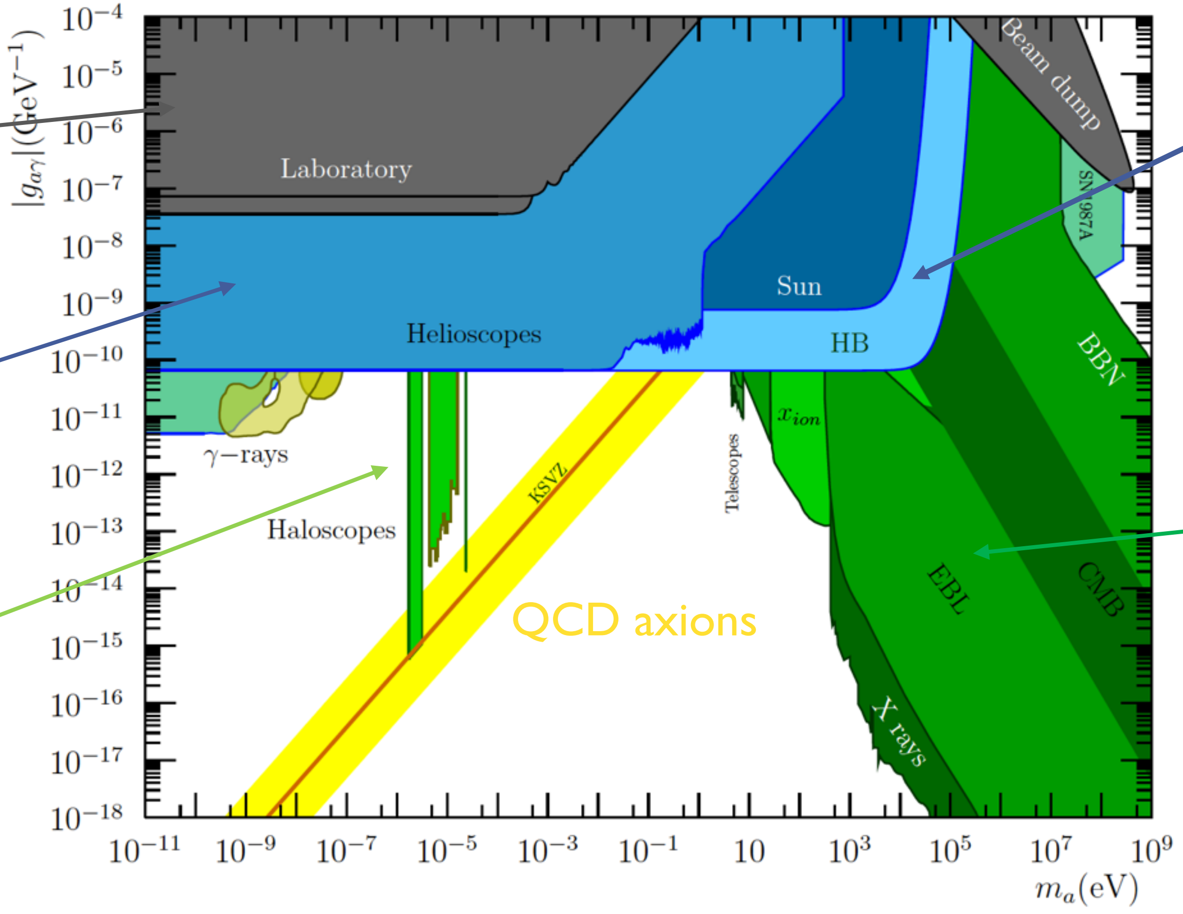
Created by Joey Hiller
from the Noun Project

Limits

Laboratory experiments

Detection of axions from the Sun (Elioscopes)

DM axion detection (Haloscopes)

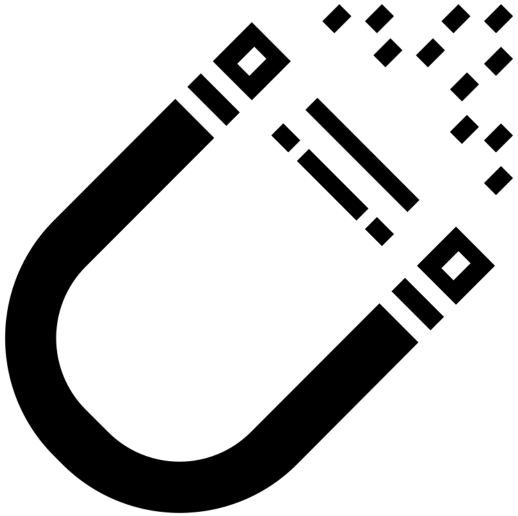


Stellar physics:
Primakoff process in stars $\gamma Ze \rightarrow a\, Ze$.
Constraints on stellar lifetime or energy-loss rates: Sun, HB.

Cosmology:
No DM $a \rightarrow \gamma\gamma$ decays seen in the visible region from galaxies with telecopes. Similar searches with X-rays and extragalactic background light (EBL) or H ionization.

Ringwald et al. PDG 2017

Irastorza Redondo arxiv:1801.08127

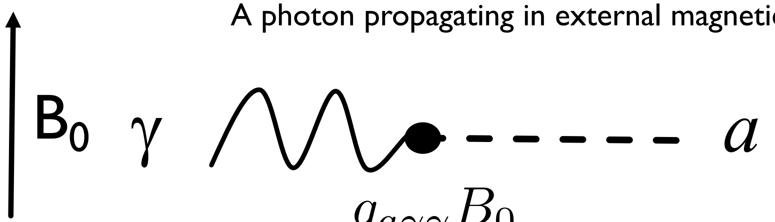


NON DARK MATTER EXPERIMENTS IN EU

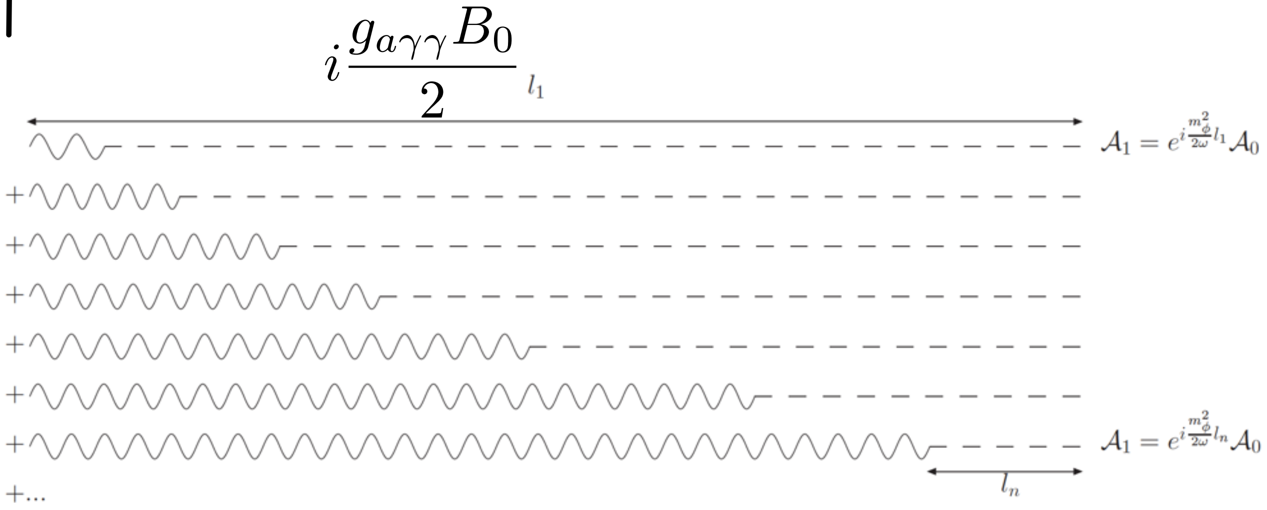
Created by mareerat jaikae

Axion Conversion in a Magnetic Field

A photon propagating in external magnetic field



$$\mathcal{L} = g_{a\gamma\gamma} a E \cdot B$$



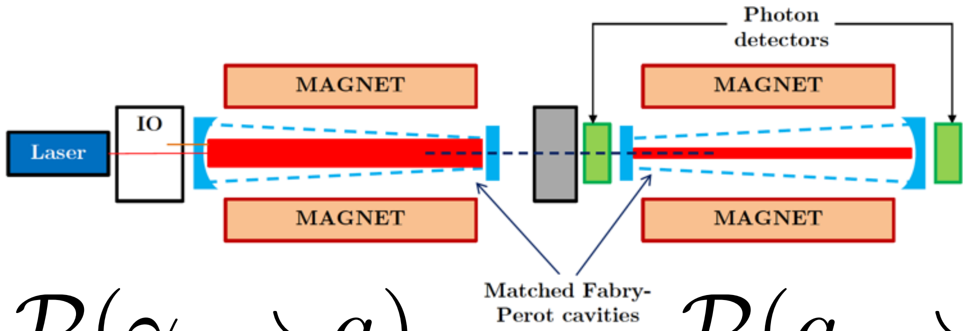
Conversion probability

$$\mathcal{P}(\gamma \to a) = |\mathcal{A}|^2 = 4\frac{g_{a\gamma\gamma}^2 B_0^2 \omega^2}{m_a^4} \sin^2\left(\frac{m_a^2 L}{4\omega}\right)$$

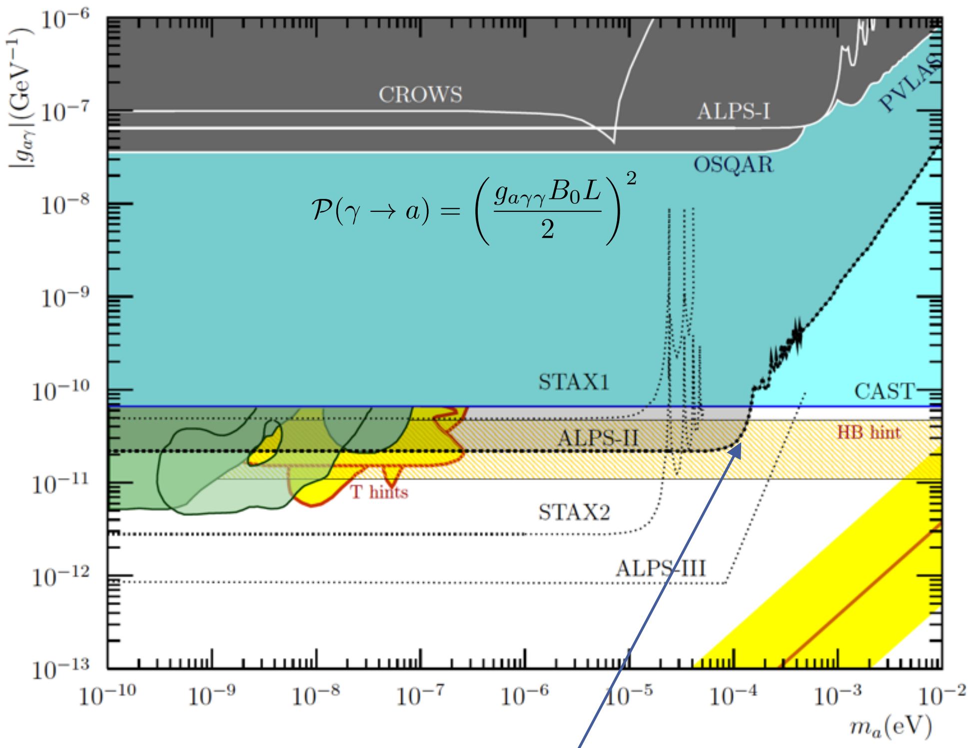
Coherence condition $m_a \ll \sqrt{\frac{4\omega}{L}}$

Redondo Ringwald arxiv:1011.3741

Light-shining-through Wall Experiments



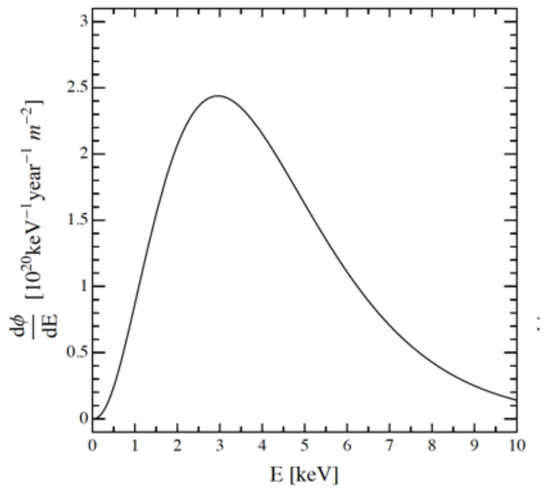
$$\mathcal{P}(\gamma \to a) \qquad \mathcal{P}(a \to \gamma)$$



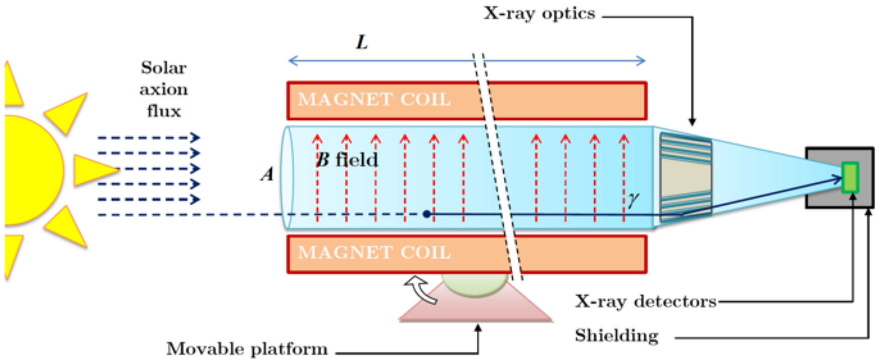
Decoherence point

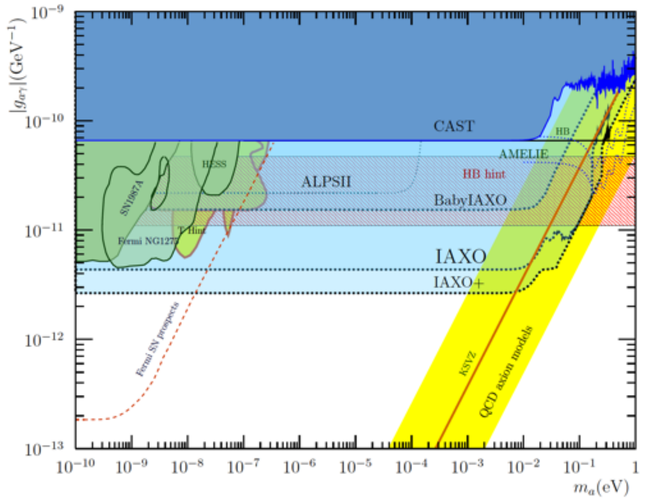
Experiment	status	B(T)	L(m)	P_{in}(W)	$G_{a\gamma\gamma}$ (GeV^{-1})
ALPS-I	done	5	4.3	4	5×10^{-8}
OSQAR	ongoing	9	14.3	18.5	3.5×10^{-8}
ALPS-II	In preparation	5	100	30	2×10^{-11}
STAX	concept	15	0.5	10^5	5×10^{-11}
JURA	concept	13	480	-	10^{-12}

Elioscopes



$$\mathcal{P}(a \to \gamma)$$





$$\mathcal{P}(a \to \gamma) = \left(\frac{g_{a\gamma\gamma} B_0 L}{2}\right)^2$$

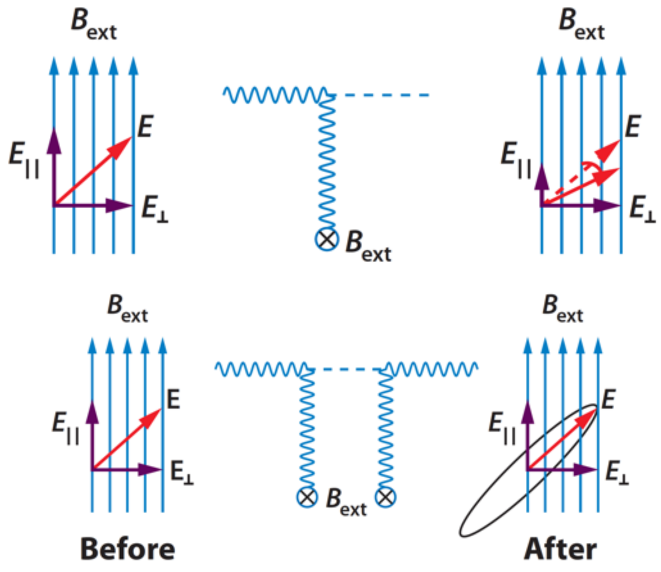
Axion produced in the core of the Sun from Primakoff conversion with typical energy few keV.

Experiment	status	B(T)	L(m)	A(cm^2)	$G_{a\gamma\gamma}$ (GeV^{-1})
CAST	ongoing	9	9.3	30	6.6×10^{-11}
IAXO	In design	2.5	22	2.3×10^{4}	4×10^{-12}
Baby Iaxo	In design	2.5	10	0.8×10^{4}	2×10^{-11}
TASTE	Concept	3.5	12	30	2×10^{-11}

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

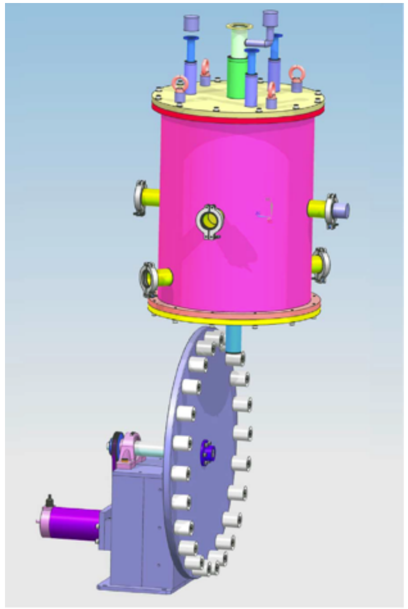
Other Searches

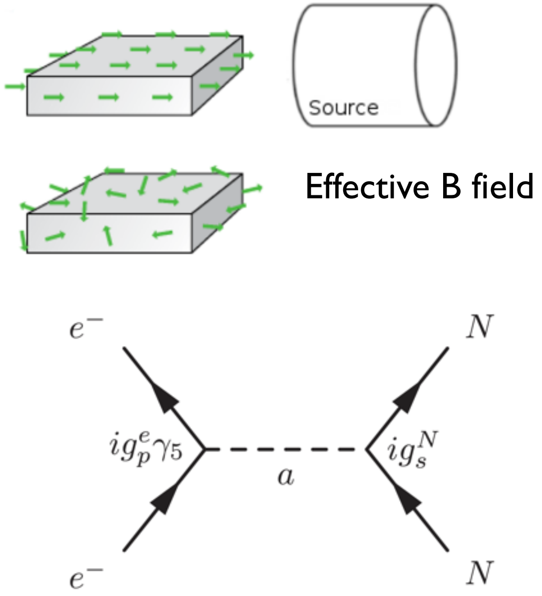
PVLAS: Polarizazion Experiment



PVLAS Experiment Eur. Phys. J. C (2016) 76:24

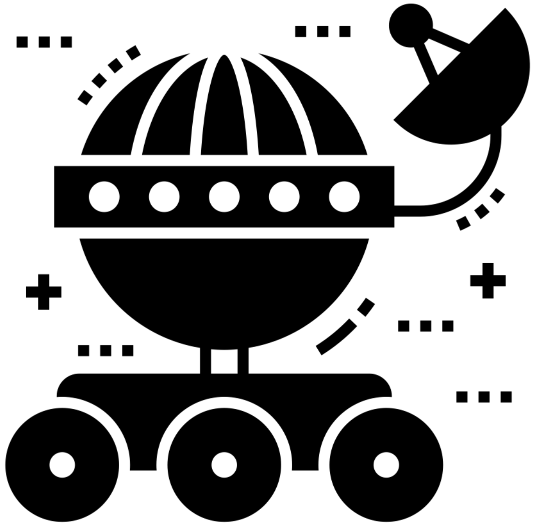
Quax-g_pg_s: 5th force experiment





NIM A842 (2017)
PLB 773 (2017)

DIRECT SEARCH OF AXION DARK MATTER IN EU



Created by ProSymbols from the Noun Project

Axion Dark Matter

Local Dark Matter density

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

Axion density

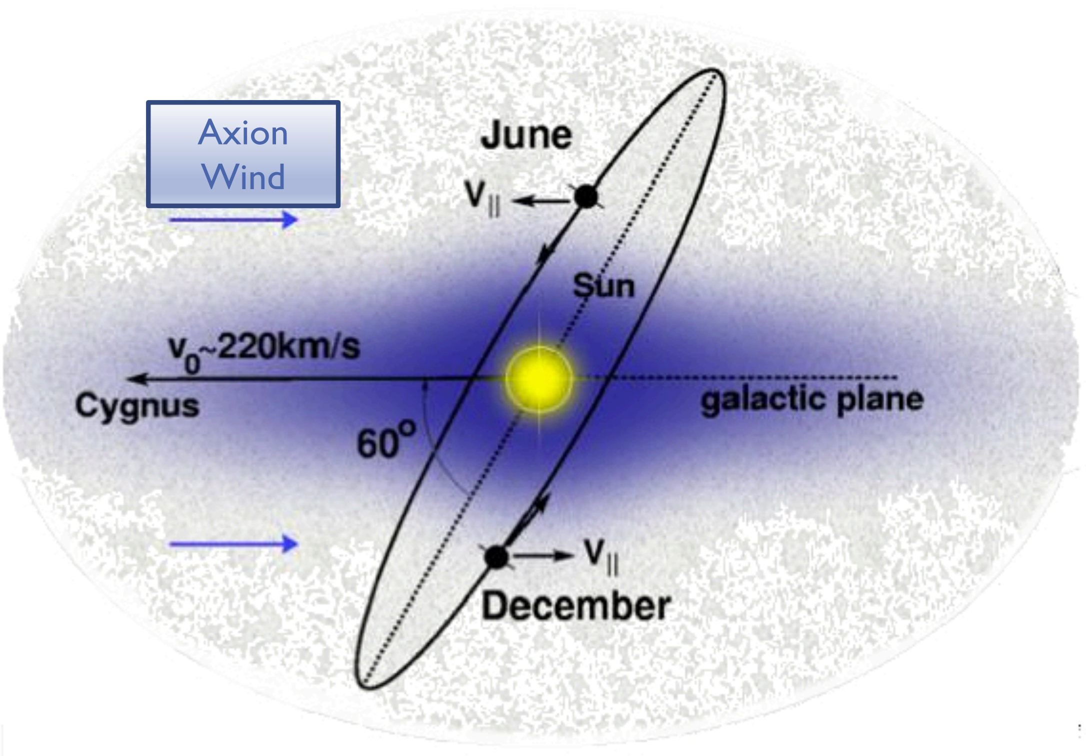
$$n_a \simeq 3 \times 10^{12} \left(\frac{100\mu eV}{m_a}\right) 1/\mathrm{cm}^3$$

Axion-Earth relative speed

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

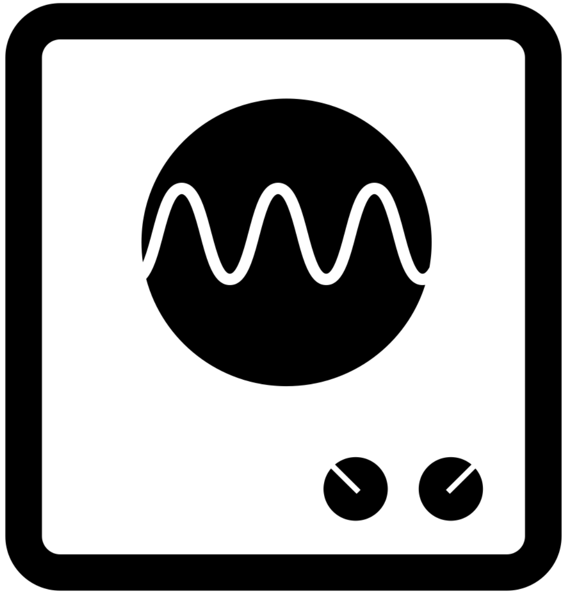
Treat axion as a classical field

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



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

RESONANT SEARCHES



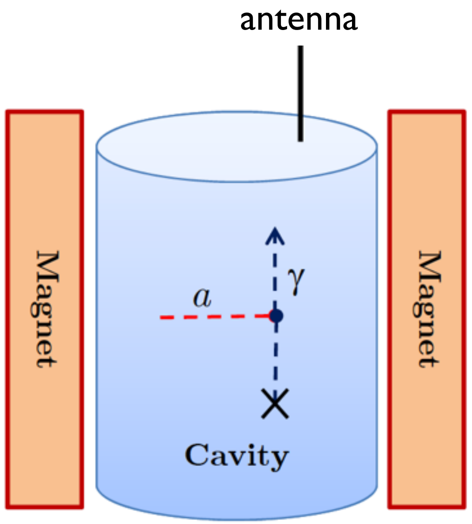
Created by James Christopher
from the Noun Project

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

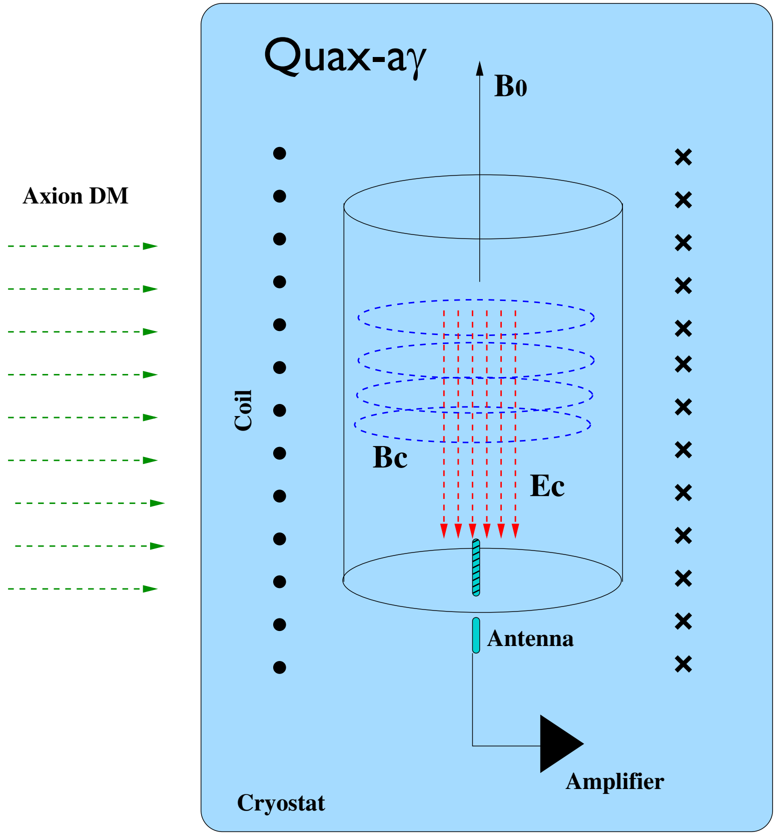
V cavity volume

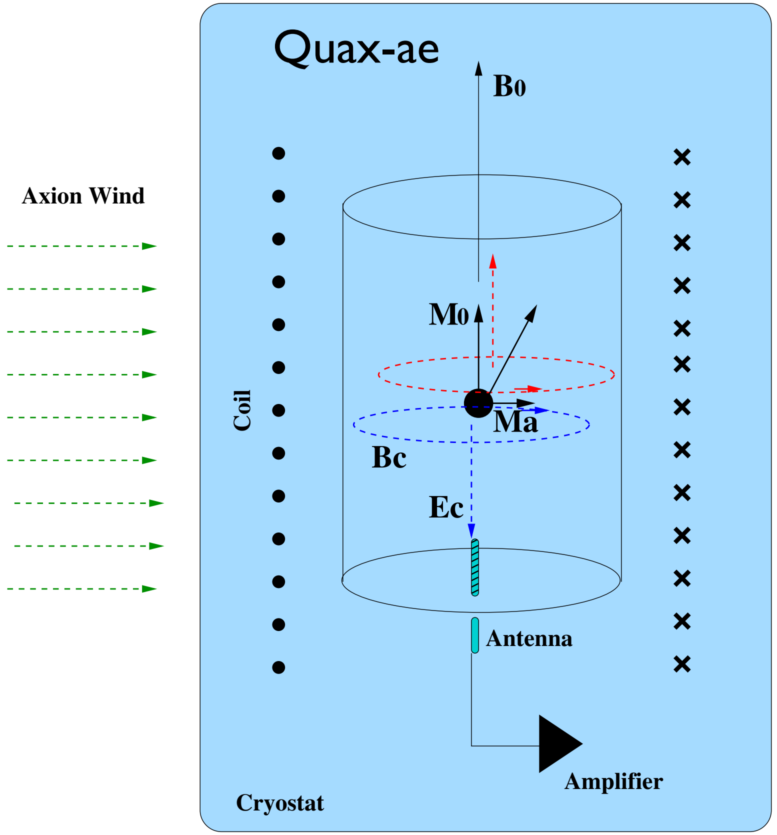
C_{mnl} mode dependent factor about 0.6 for TM010

Q_L cavity "loaded" quality factor

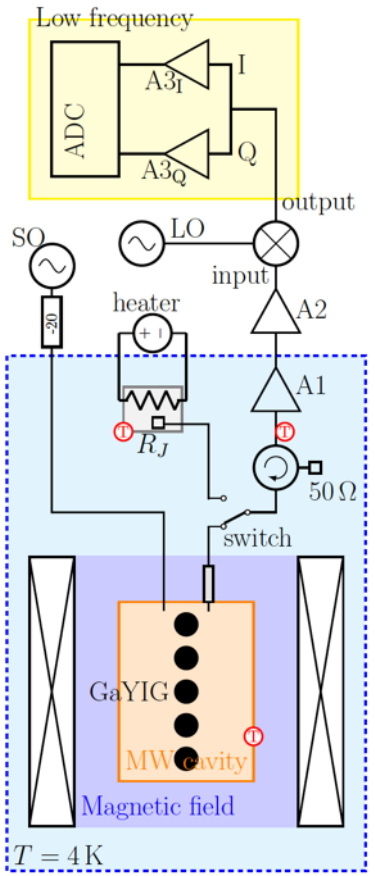
QUAX: Quest for Axions

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



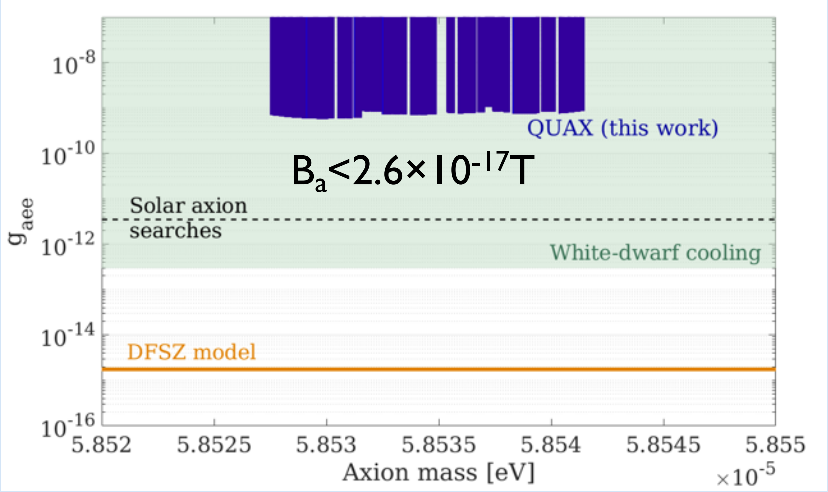


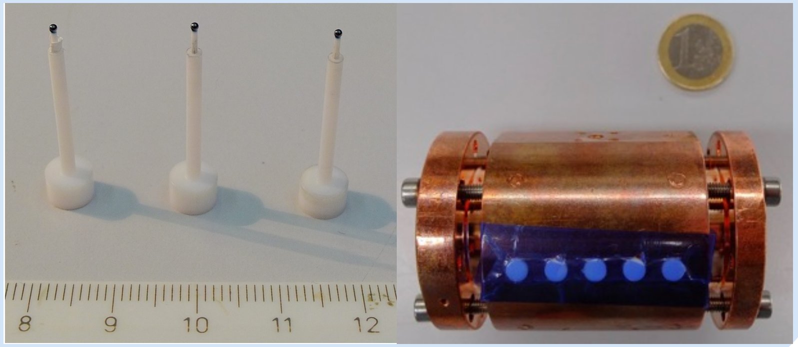
QUAX-ae Result with Ferromagnetic Axion Haloscope at m_a = 58μeV



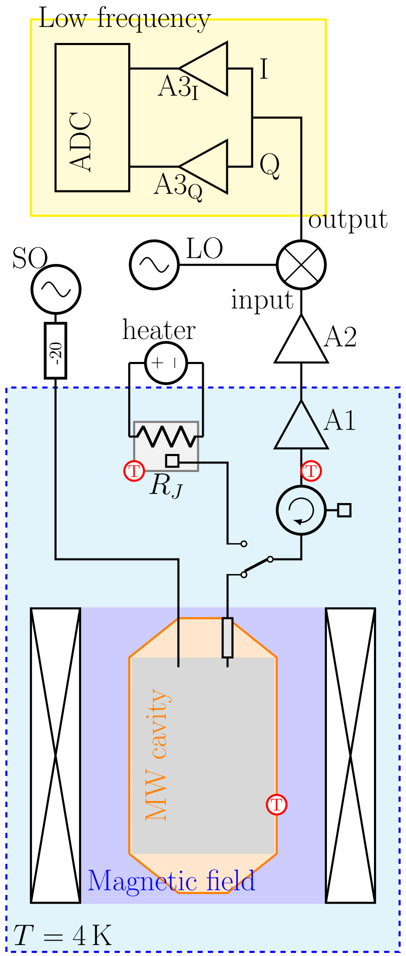
Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =1 mm)	5
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.11
Frequency [GHz]	13.98
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [K]	5.0
T amplifier [K] (HEMT)	11

EPJC (2018) 78:703

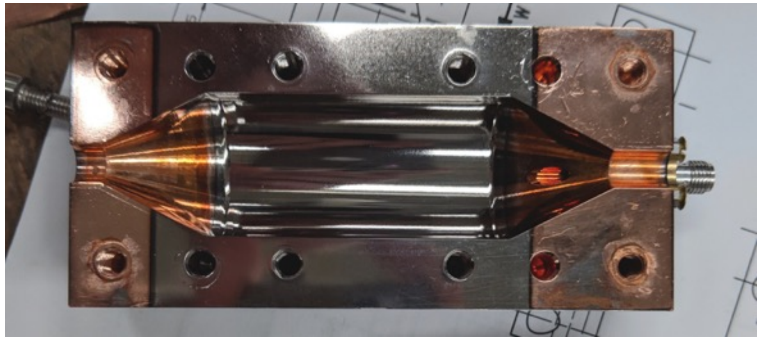




QUAX-aγ Result with Superconductive Resonant Cavity at $m_a = 37.5\ \mu eV$

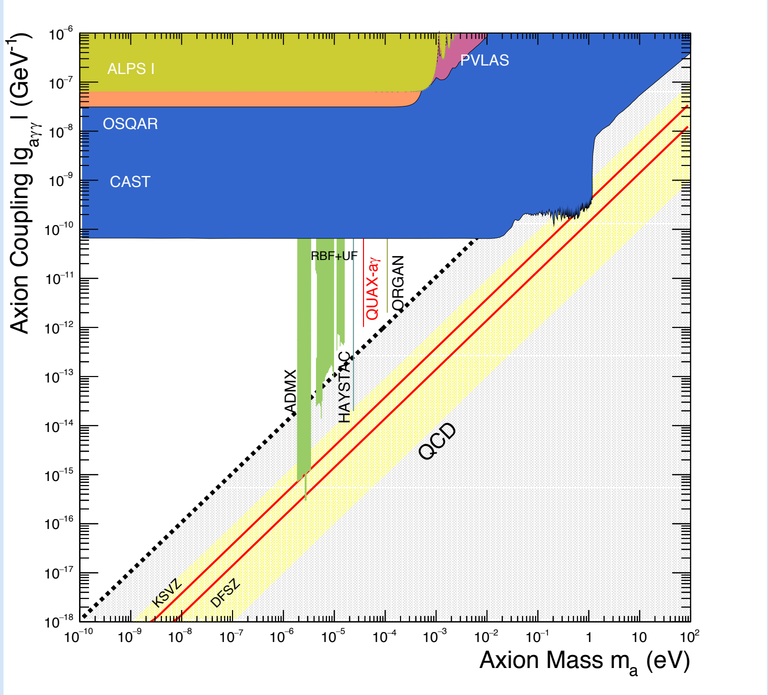


Experimental Setup	
B [T]	2
Frequency [GHz]	9
NbTi cavity Q (mode TM010)	400,000
T_{cavity} [K]	5.0
T amplifier [K] (HEMT)	11



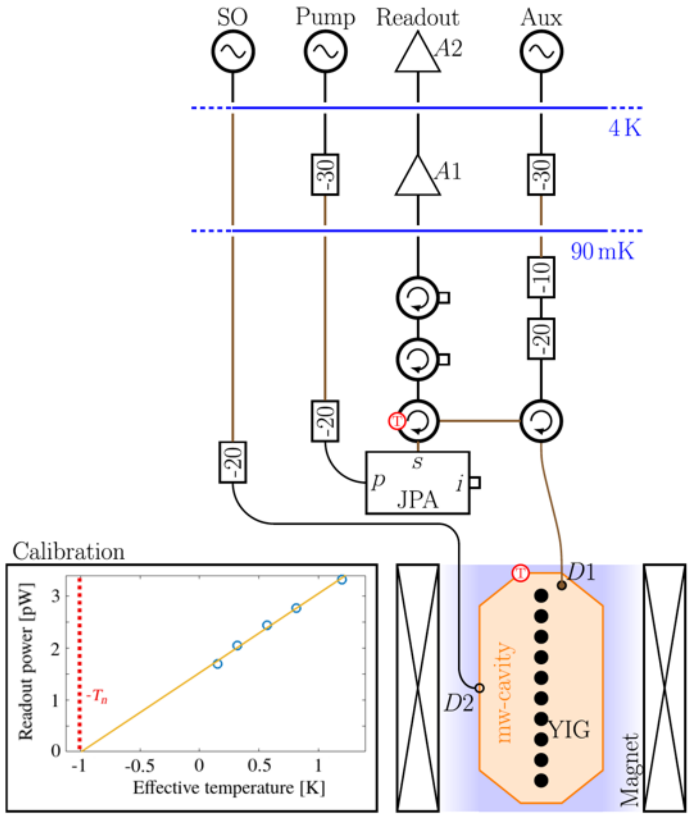
IEEE TRANS. APP. SUPERCOND. 29, 5 (2019)

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



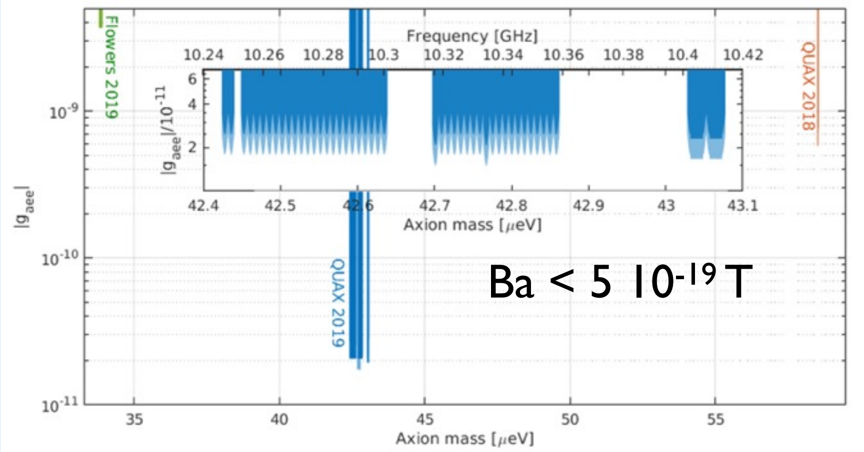
Phys. Rev. D **99**, 101101(R) (2019)

QUAX-ae Result with Quantum-Limited Ferromagnetic Haloscope

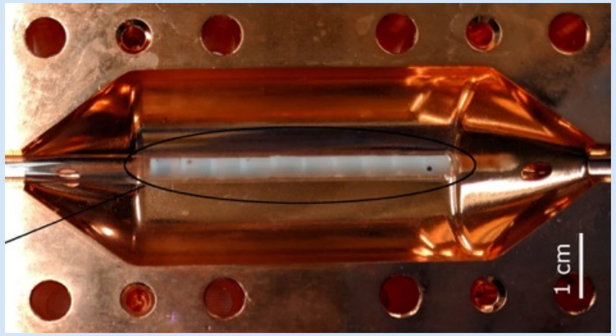


Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =2.1 mm)	10
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.1
Frequency [GHz]	10.7
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [mK]	90
T amplifier [K] (JPA)	0.5-1

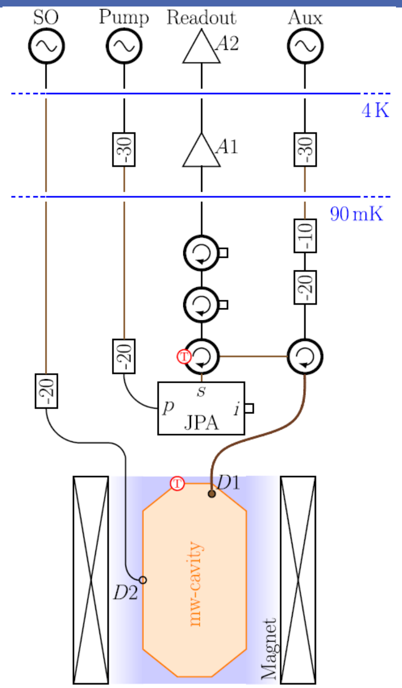
Phys. Rev. Lett. **124**, 171801 (2020)



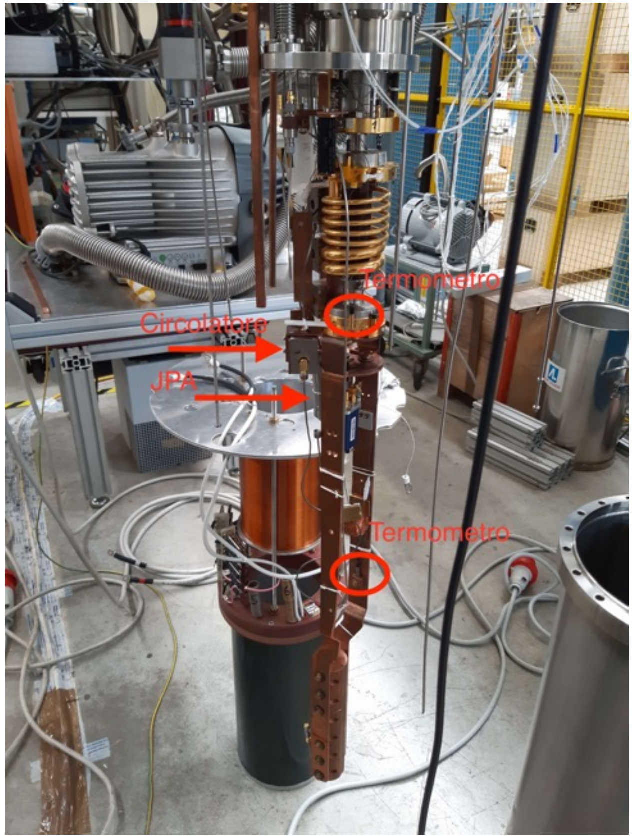
Ba < 5 10^{-19} T



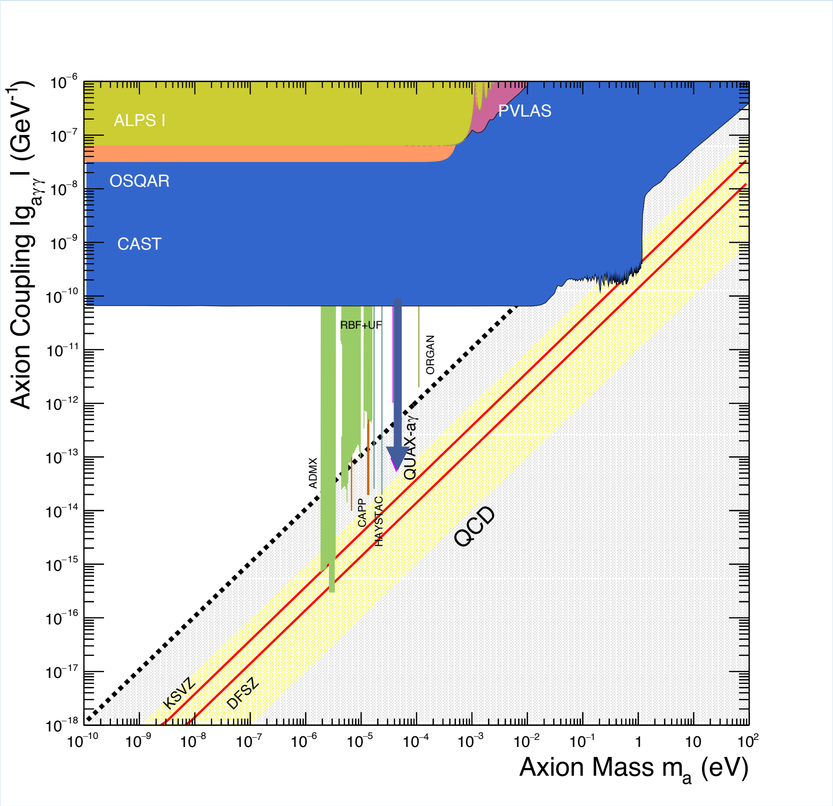
QUAX-aγ Reached the Sensitivity to QCD Axion m_a=40 μeV



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

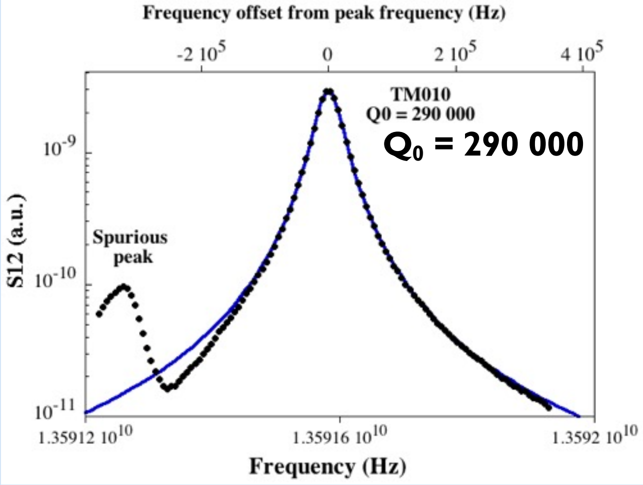


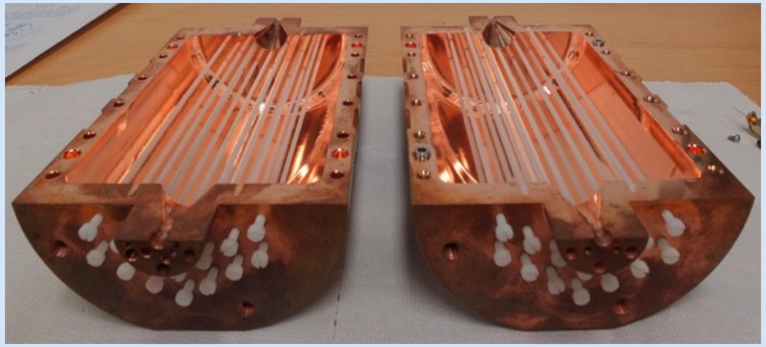
Paper in preparation



High Quality Factor Dielectric Cavities

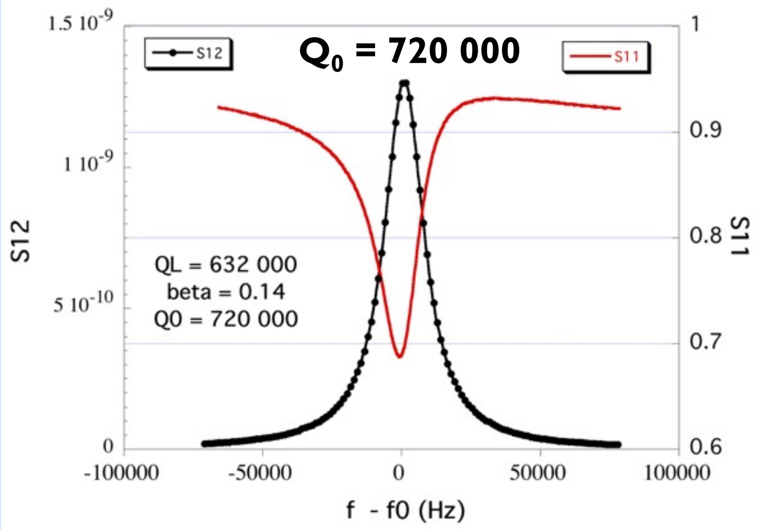
High quality factor photonic cavity





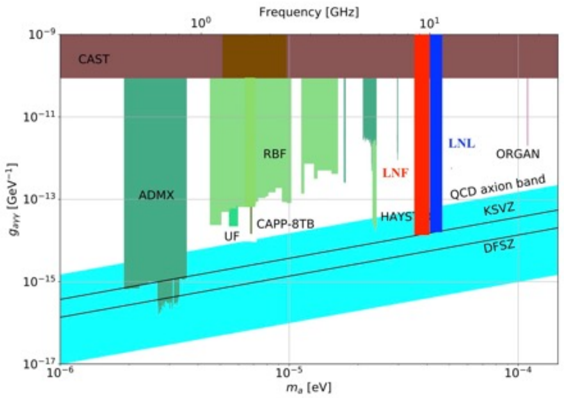
Review of Scientific Instruments 91, 094701 (2020)

High quality factor photonic resonator with hollow dielectric cylinders



10.1016/j.nima.2020.164641

QUAX 2021-2025



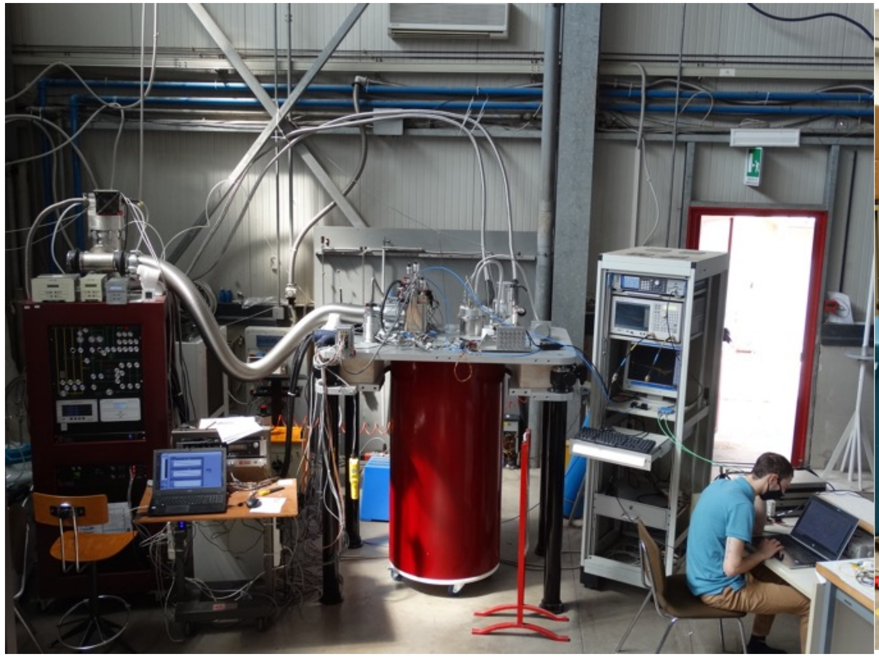
	LNF	LNL
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	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

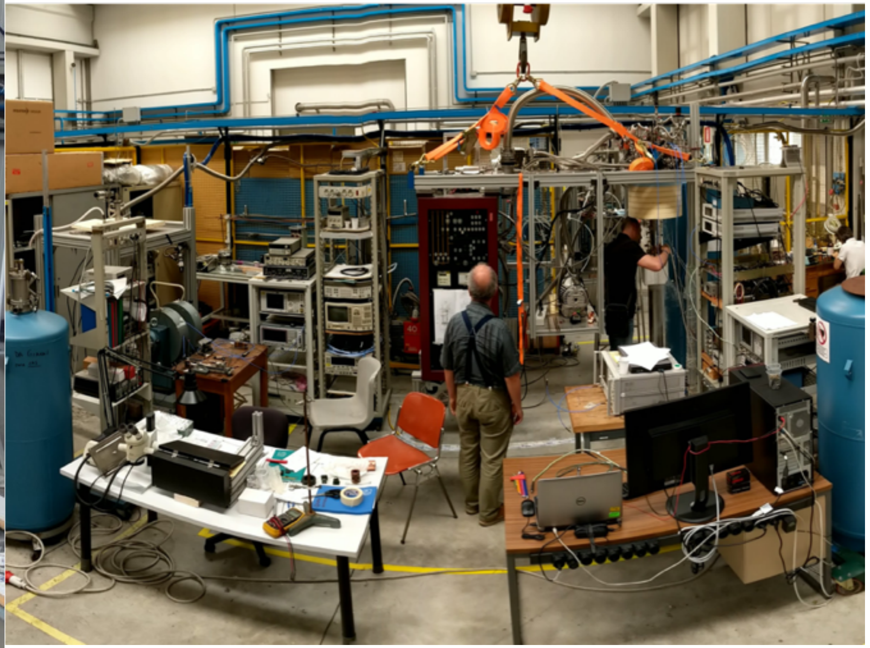
2021	2022	2023	2024	2025

Assembly of haloscopes at LNL and LNF

Data Taking

Scan in range 8.5 - 11 GHz



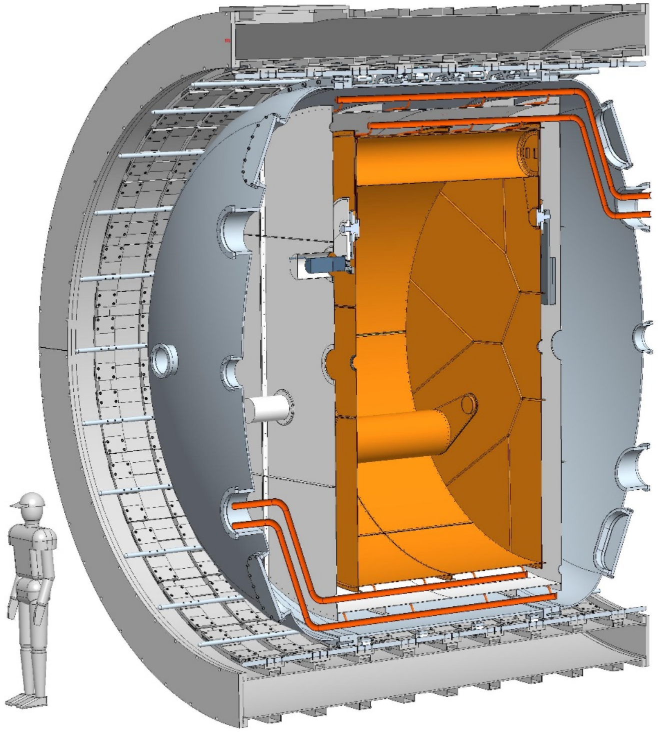


KLASH

- KLASH - KLoe magnet for Axions SearcH
- Proposal of a large Haloscope at LNF
- Search of galactic axions in the mass range 0.3-1 μeV
- Large volume RF Cavity (22 m^3)
- Moderate magnetic field (0.6 T)
- Copper rf cavity Q~600,000
- T 4.5 K

KLOE magnet

INFN
Istituto Nazionale di Fisica Nucleare



Experiment	$\omega B^2 V Q_L$ (rad $T^2 m^3/s$) ($\times 10^{15}$)
The KLASH	1
ADMX	4
HAYSTAC	0.05

KLASH CDR arxiv:1911.02427

KLASH

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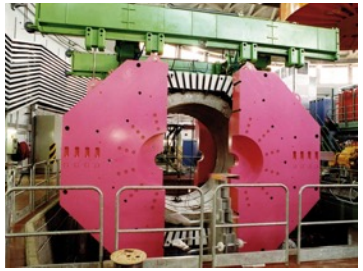
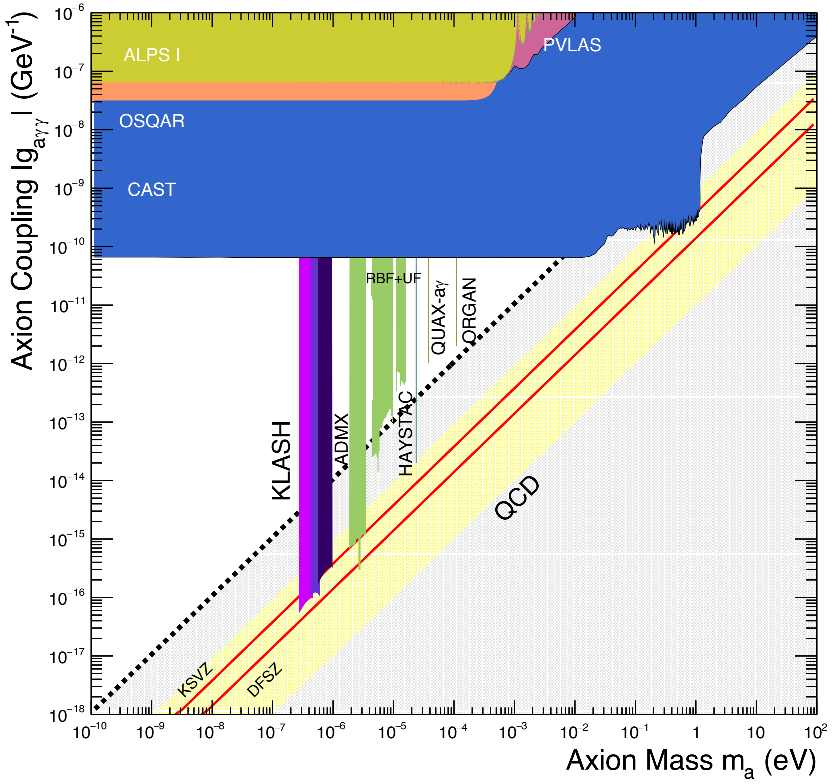


Finuda magnet



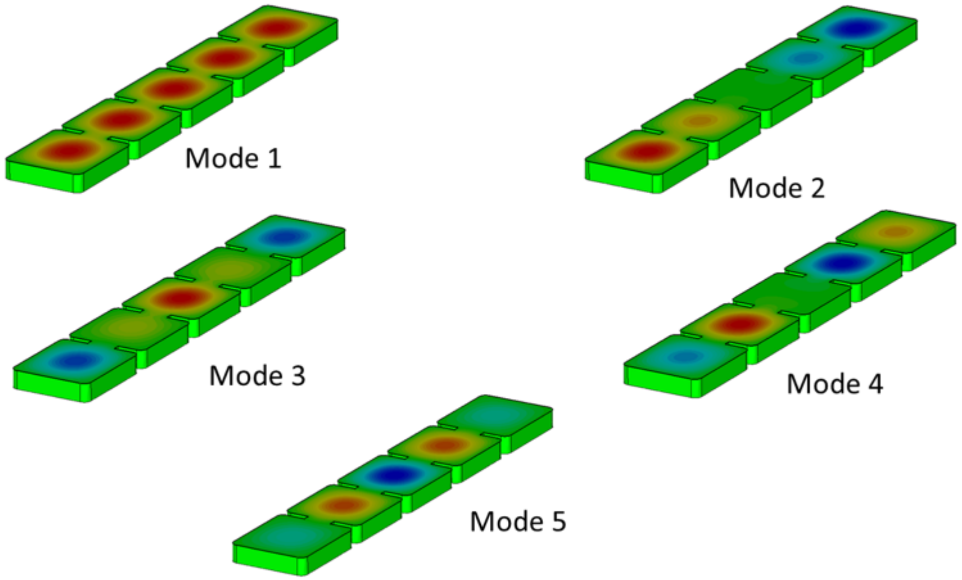
Experiment	ω $B^2 V Q_L$ (rad $T^2 m^3/s$) (×10^{15})
The KLASH	1
ADMX	4
HAYSTAC	0.05

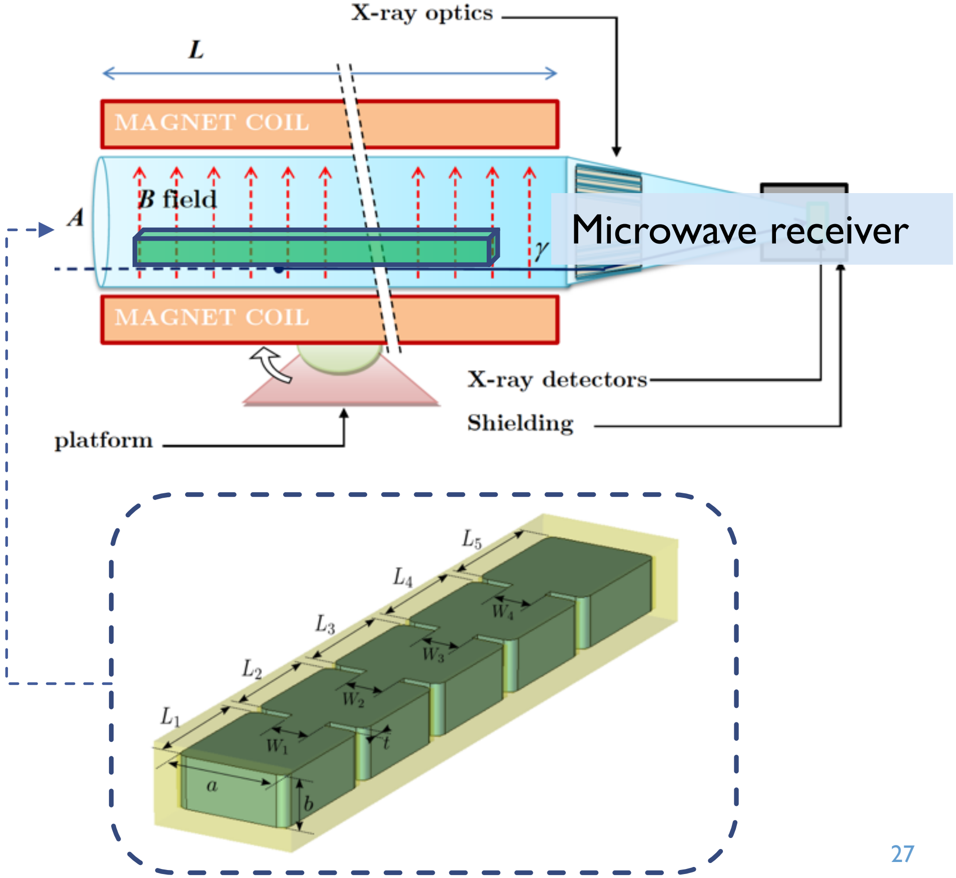
KLASH CDR arxiv:1911.02427

RADES: Relic Axion Detector Exploratory Setup

Insert resonant cavities (8.5 GHz) inside the dipole magnet of CAST experiment. In the long term take data in the (Baby) IAXO magnet.

Design cavities and couplings to maximize coupling to axion field



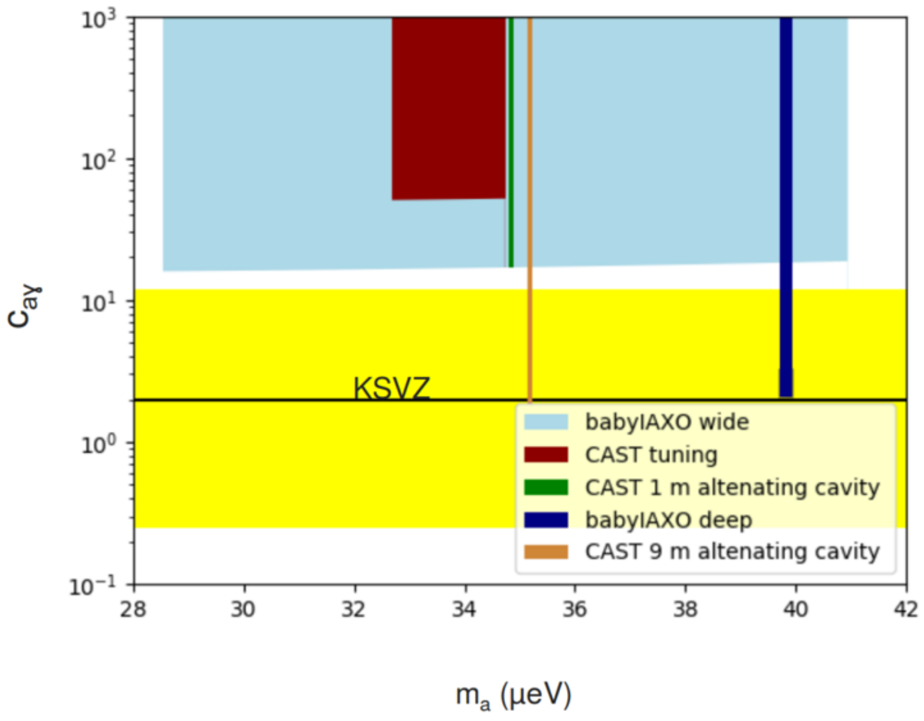


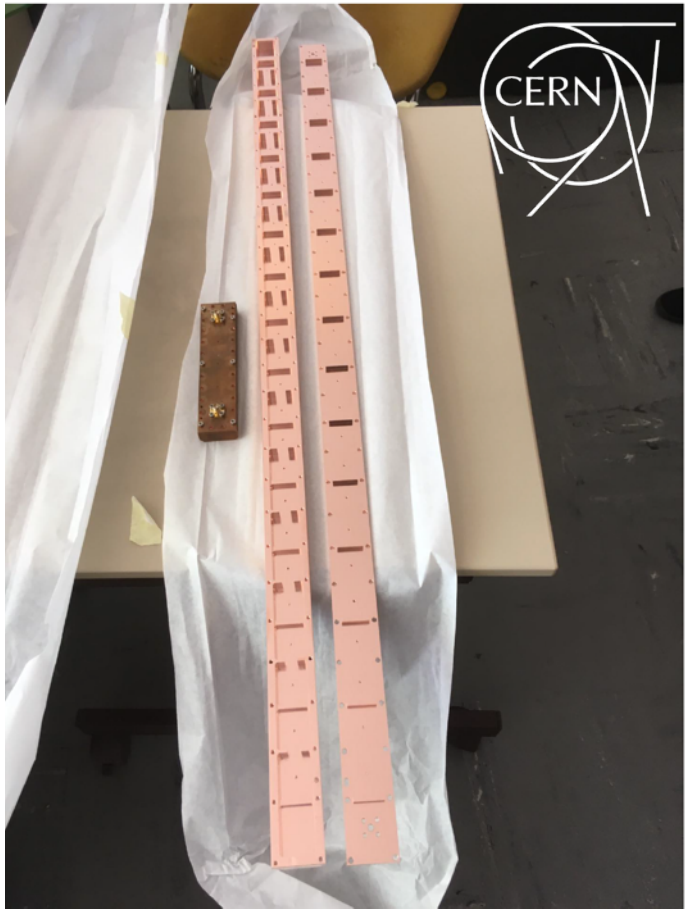
Arxiv:2002.07639

RADES: Relic Axion Detector Exploratory Setup

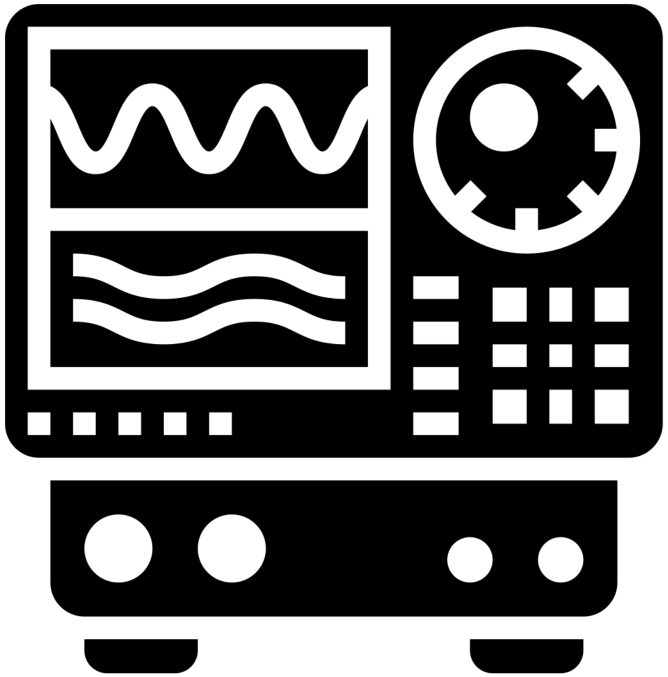
CAST 1 m 2020-2021

Baby Iaxo 2023-…





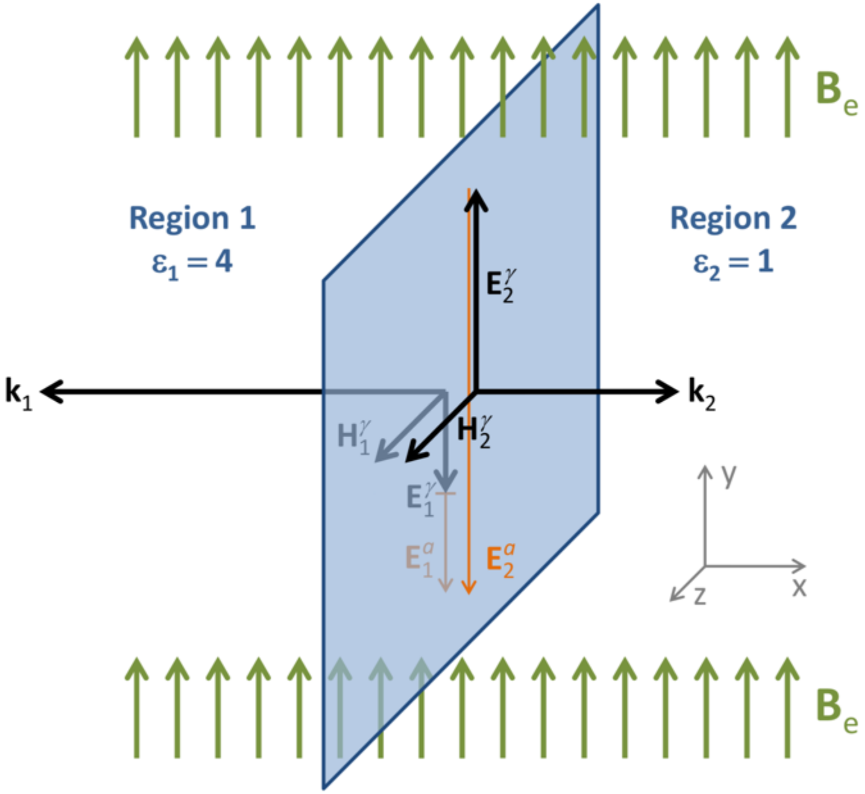
BROADBAND SEARCHES



Created by Eucalyp

Axion Induced e.m. Radiation at Interface

When an interface between different dielectric media is inside a magnetic field, the oscillating axion field acts as a source of electromagnetic waves, which emerge in both directions perpendicular to the surface.



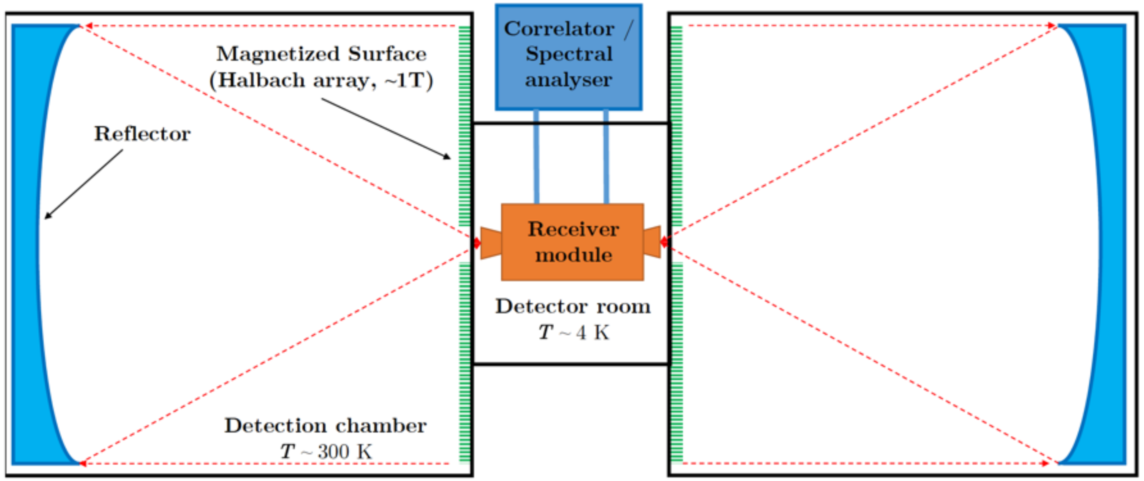
$$E_{\parallel,1} = E_{\parallel,2} \text{ Faraday}$$
$$H_{\parallel,1} = H_{\parallel,2} \text{ Ampere}$$

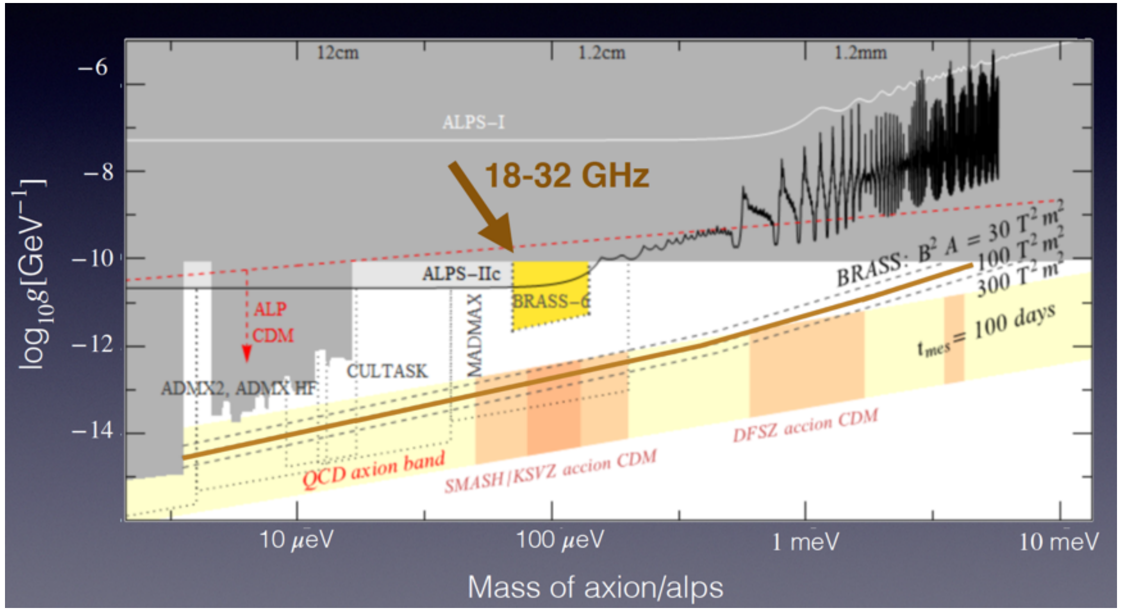
$$E = -\frac{g_{a\gamma\gamma} B_0 a}{\varepsilon}$$

arXiv:1212.2970
arXiv:1612.07057

BRASS Broadband Radiometric Axion Searches

- Broadband acquisition: 16 GHz bandwidth
- Photon flux $B^2 \times$ Disk Area
- BRASS-6: Disk diameter 2m; B=0.5T
- Experiment in the preparatory stage for data taking



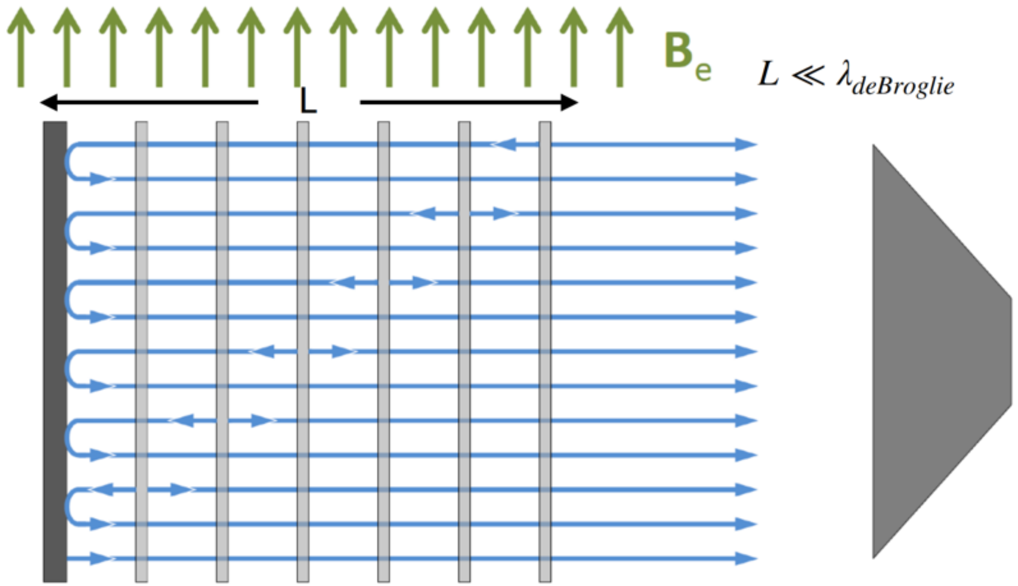


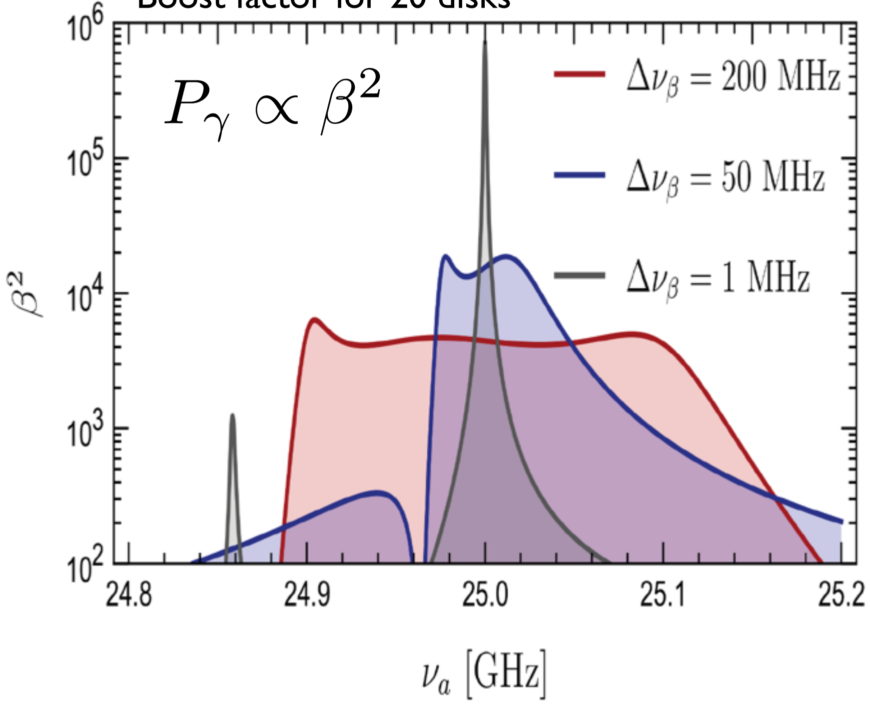
Max-Planck-Institut für Radioastronomie

UH

TUHH Technische Universität Hamburg

MADMAX Magnetized Disk and Mirror Axion eXperiment

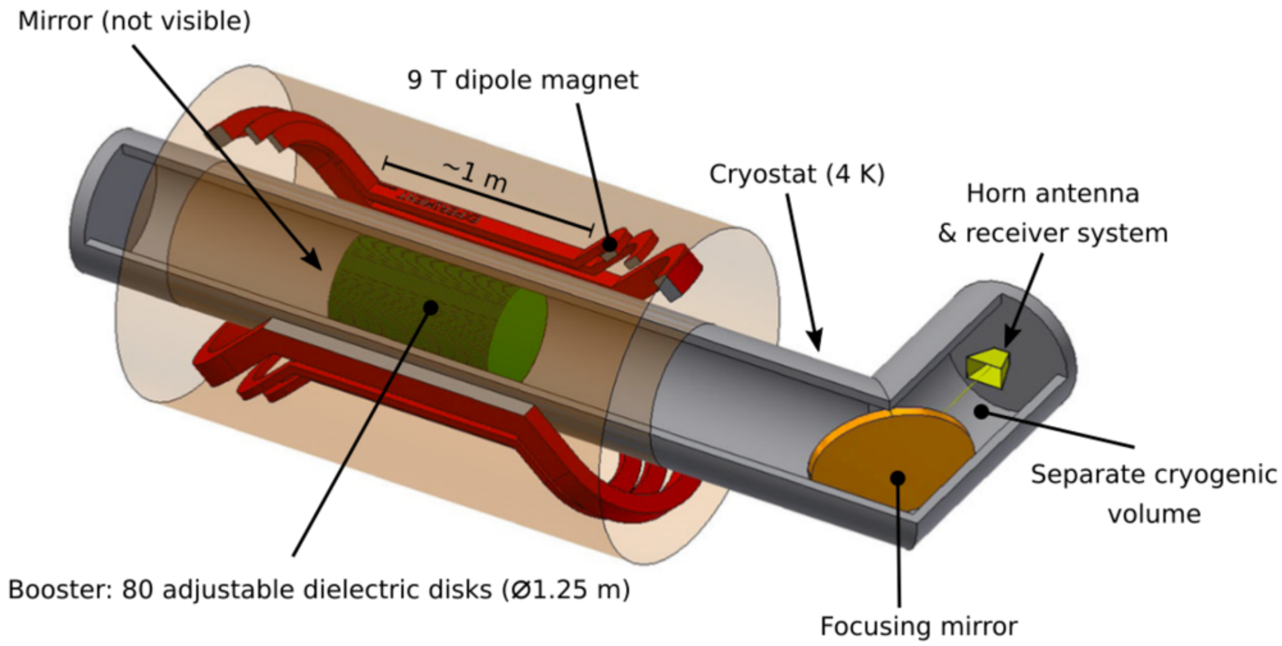


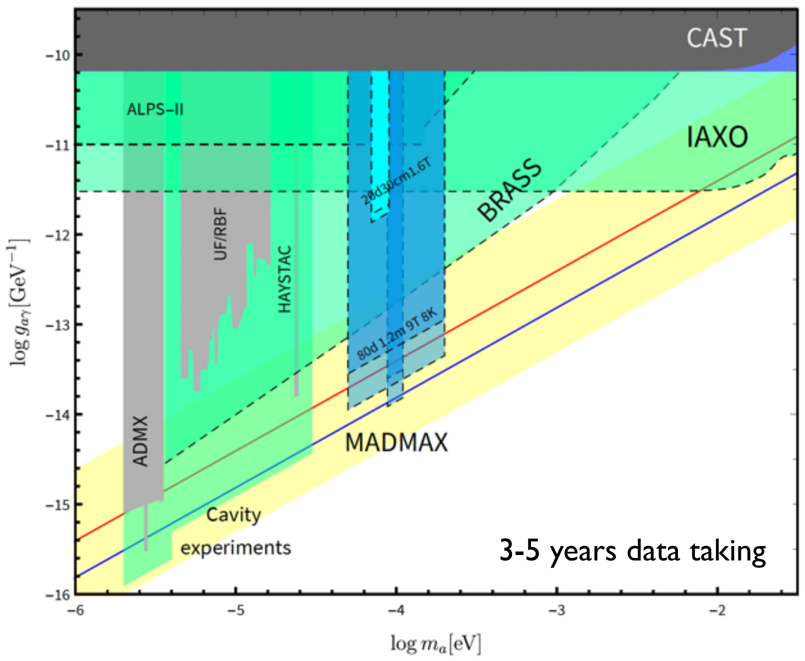


Movable dielectric disks in front of a metallic mirror exploiting constructive interference and resonant enhancements of the radiation emitted at the many interfaces.

Status Report arxiv:2003.10894
XIAOYUE LI talk at Axion Cosmology MIAPP 2020

MADMAX Magnetized Disk and Mirror Axion eXperiment

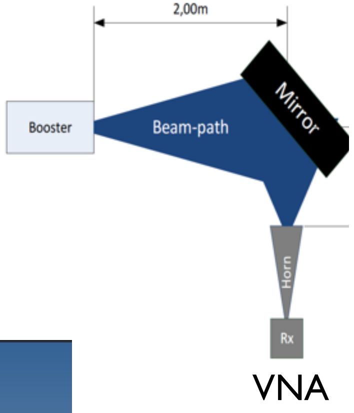


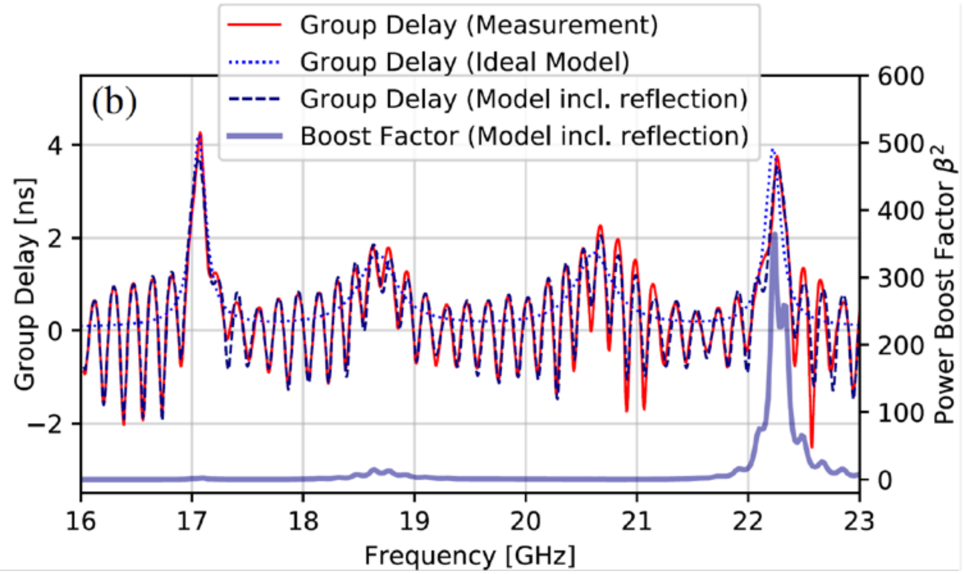


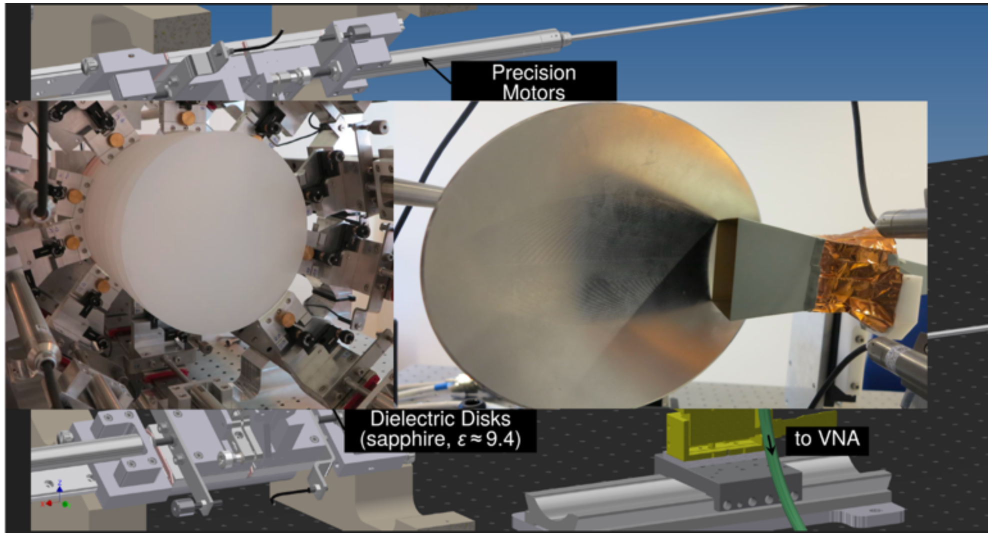
arXiv:1901.07401

MADMAX Magnetized Disk and Mirror Axion eXperiment

Proof of principle setup: 5 sapphire disks with a diameter of 20 cm mounted in front of a copper mirror. Reflections measured with a vector network analyzer (VNA).







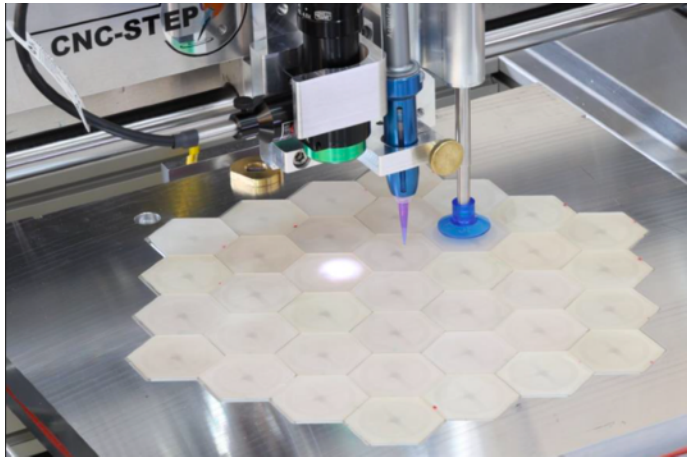
$$\tau_g = -\frac{d\phi}{d\omega}\Big|_{\omega=\omega_0} \sim \frac{Q_0}{\omega_0}$$

ϕ phase of reflected signal

MADMAX Magnetized Disk and Mirror Axion eXperiment

2020-2021

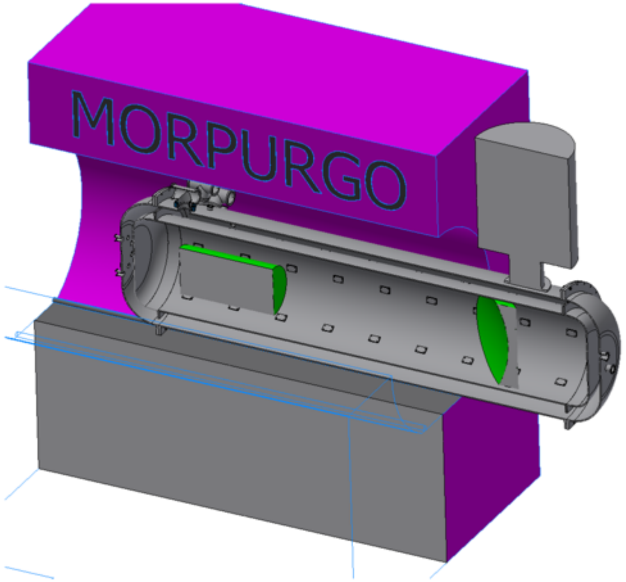
Prototype construction



Tiling of $LaAlO_3$ disk:
$\varepsilon=24$
$\tan\delta=$ few$\times 10^{-5}$

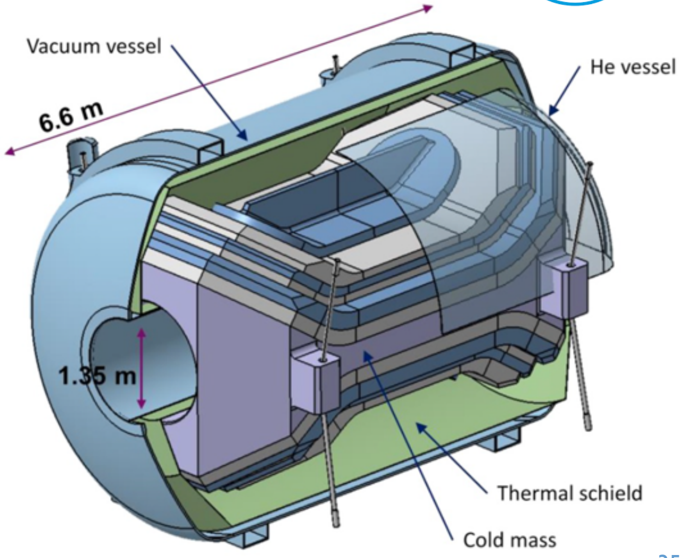
2021-2022

Madmax prototype: 20 disks of diameter 30 cm. Cryostat 750 mm diameter inside MORPURGO (1.6 T, L=1m) magnet at CERN.



2022-2035

Detector construction and Data taking at DESY.



NMR

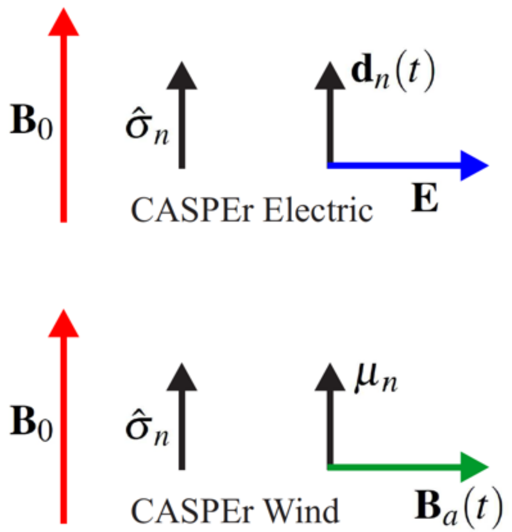
Created by Jeff Portaro
from the Noun Project

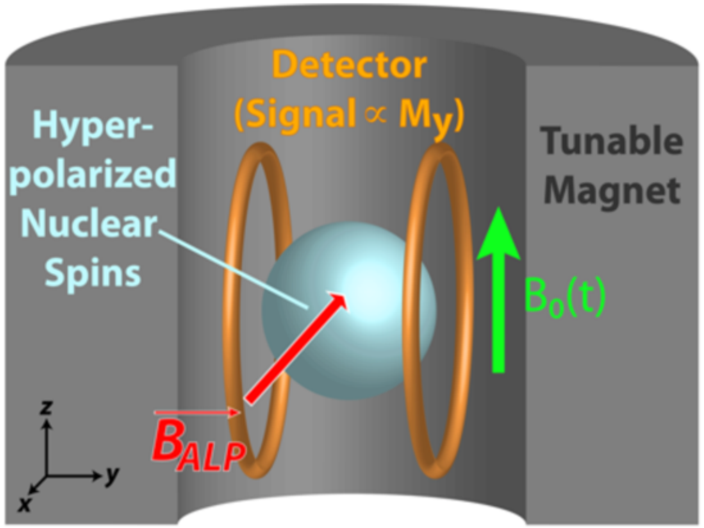
CASPEr Cosmic Axion Spin Precession Experiment

- CASPERr Electric detects axion-induced electric dipole oscillations in ferroelectric samples
- CASPEr Wind detects axion-induced oscillations of nuclear spin

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$\frac{\partial_\mu a}{f_a} \bar{f} \gamma^\mu \gamma^5 f$$





arXiv:1711.08999v

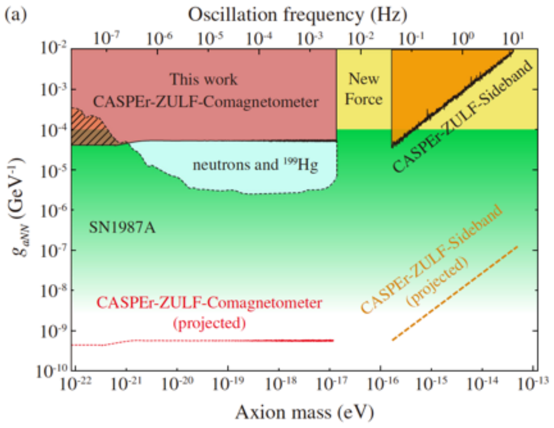
A. Wickenbrock Talk at Patras 2019 Freiburg

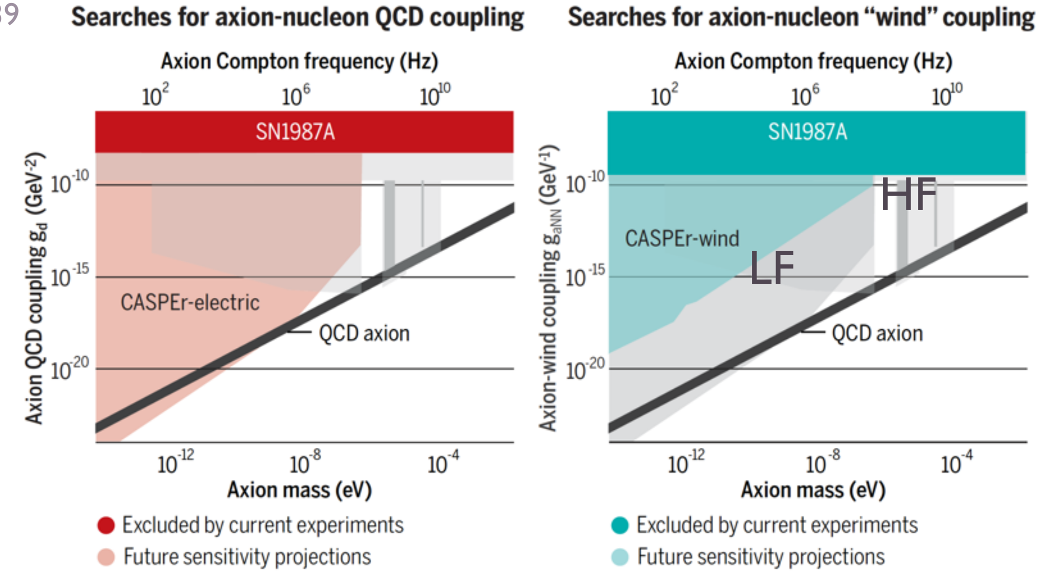
CASPEr Cosmic Axion Spin Precession Experiment

- CASPERr Electric detects axion-induced electric dipole oscillations in ferroelectric samples
- CASPEr Wind detects axion-induced oscillations of nuclear spin in liquid Xenon

Phys. Rev. Lett. **122**, 191302

Science Advances 25 Oct 2019 Vol. 5, no. 10, eaax4539





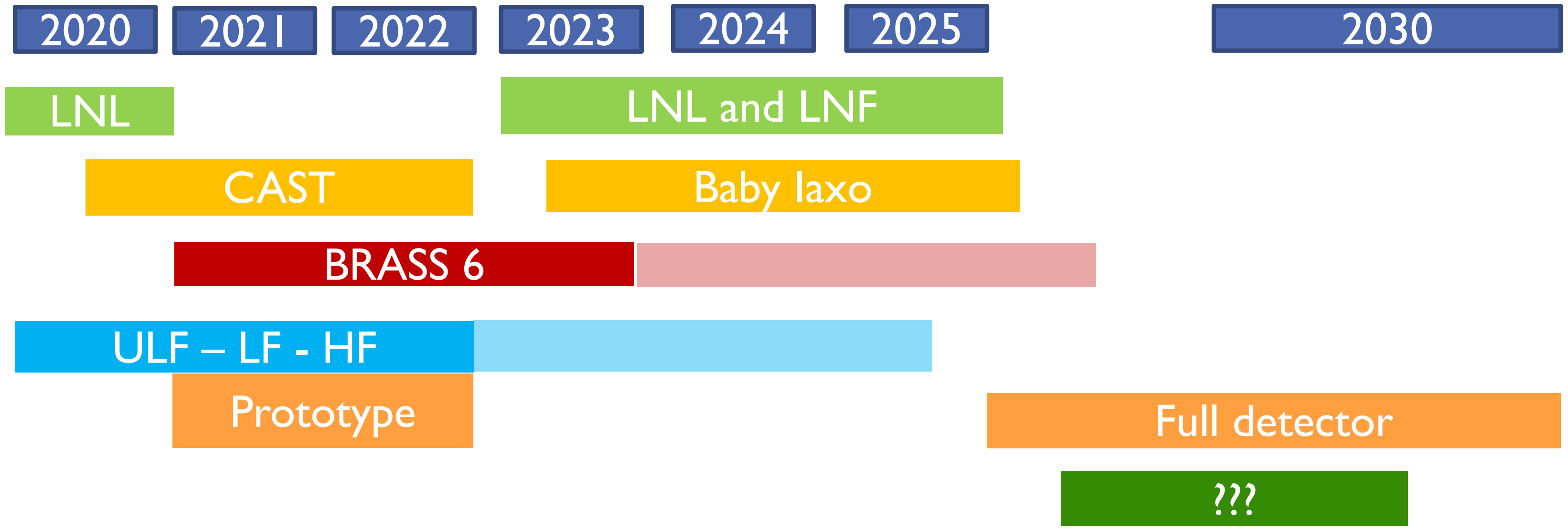
2020 - Casper-electric and Casper ZULF taking data; Casper wind Xe in preparation

arXiv:1711.08999v

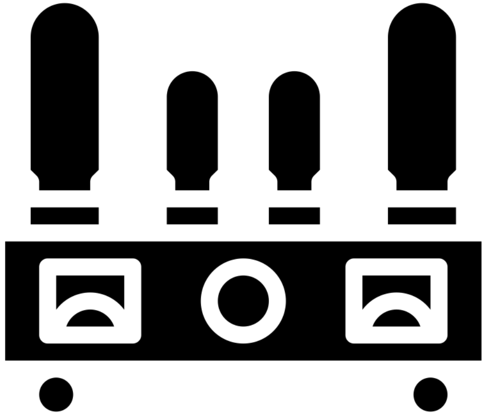
A.Wickenbrock Talk at Patras 2019 Freiburg

Tentative Timeline of EU Experiments

Experiment
QUAX 9-12 GHz
RADES 8.5 GHZ
BRASS 18 - 32 GHz
CASPER <100 MHz
MADMAX 10 - 40 GHz
KLASH 50 - 250 MHz



SIGNAL AMPLIFICATION (AN INFN PERSPECTIVE)



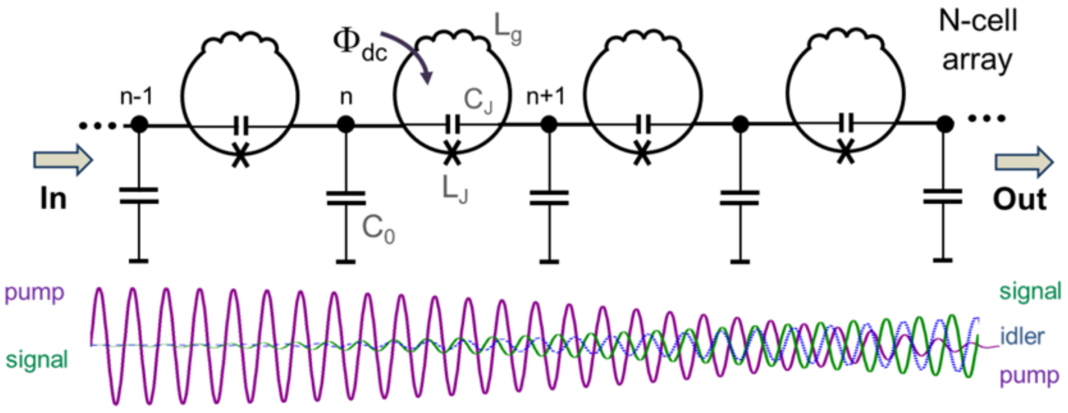
TWJPA

Travelling Wave Josephson Parametric Amplifiers amplify microwave signal over a broad range adding the minimum noise set by quantum mechanics. Two devices developed in Eu with 3-wave and 4-wave mixing:

PTB
Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

arXiv:1602.02650

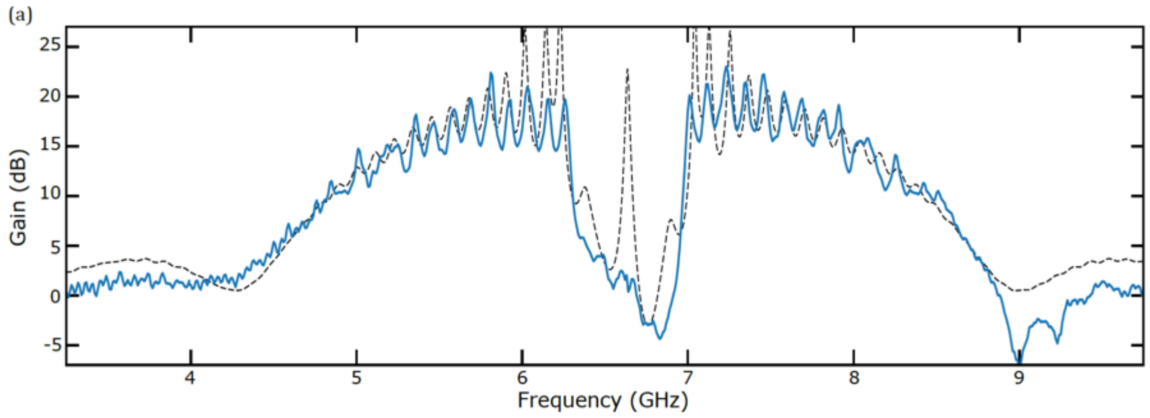
PHYS. REV. APPLIED 12, 044051 (2019)



3-wave mixing device

NÉEL institut

arXiv:1907.10158



4-wave mixing device

Recent collaboration with LNL QUAX group

DART WARS

INFN Istituto Nazionale di Fisica Nucleare

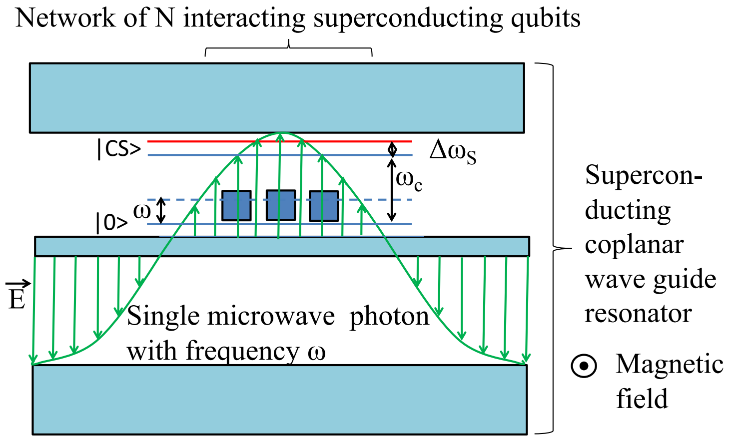
Detector Array Readout with Travelling Wave AmplifieRS project recently approved by INFN

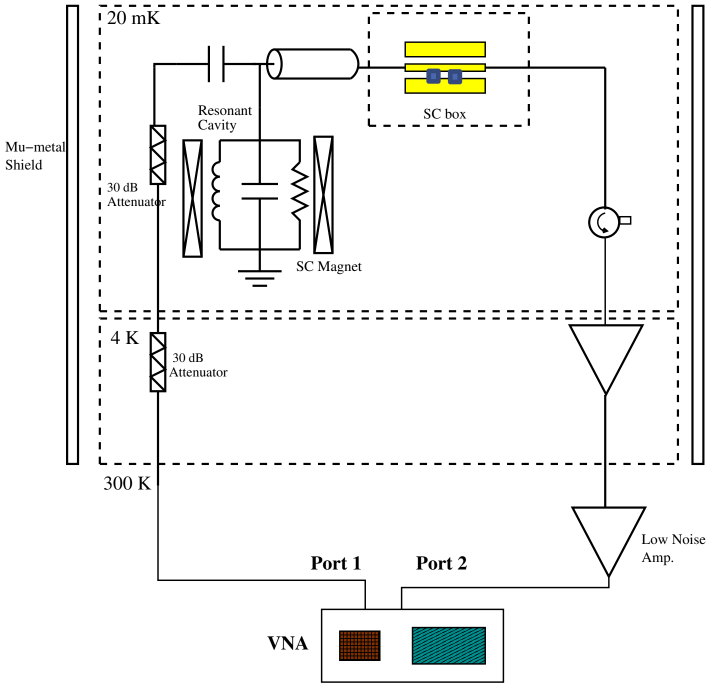
C.Federici

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)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863313. Grant amount 2 456 232.50 Euro.



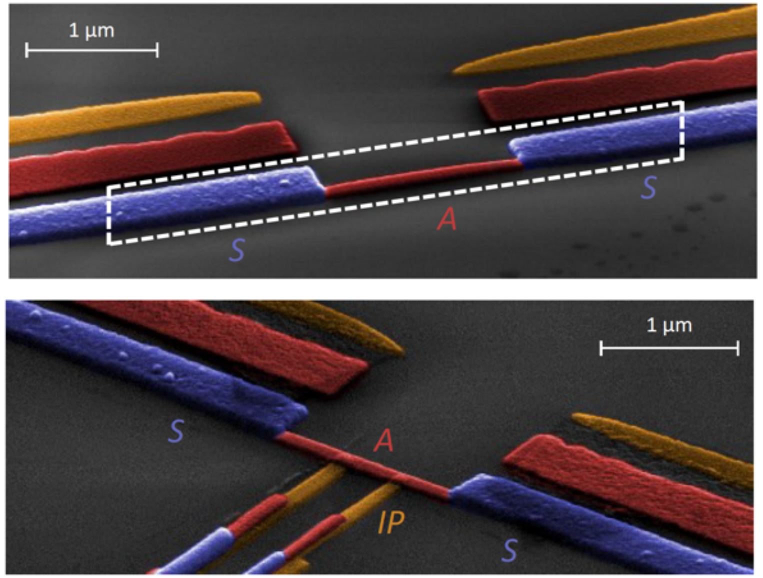


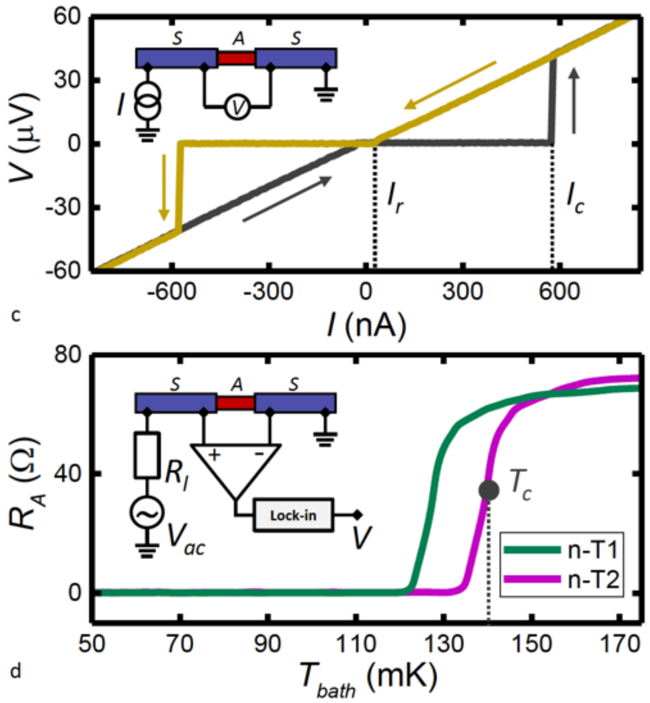
Objective: Develop a single microwave photon detector for axion search in QUAX experiment with an array of SC qubits.

https://supergalax.eu

Nanowire Tes For Single Photon Detection

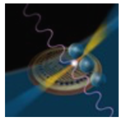
Development of a TES nanowire sensitivie to 100-200 GHz single photons





Lenght	1.5 µm
Width	100 nm
t_{Al}	10.5 nm
t_{Cu}	15 nm

C	5×10^{-20} J/K
G	5×10^{-15} W/K
σ_ν	100-200 GHz
NEP	50 zW/√Hz



INFN SIMP project

F. Paolucci et al arXiv:2007.08320

Thank you