Haloscopes

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CA21106

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Frascati, 23-24 february 2023

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

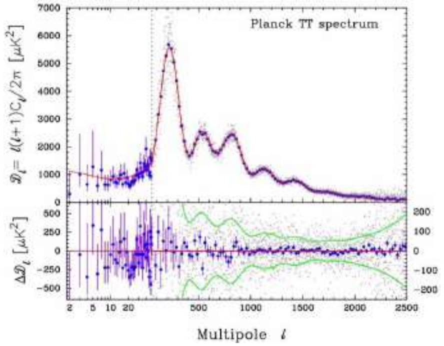
Funded by the European Union

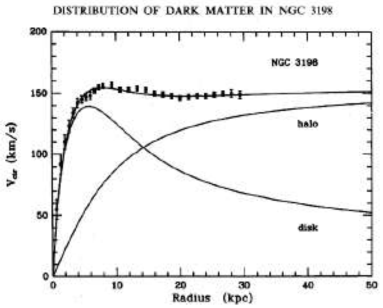
- Haloscope concept
- WISPs to be probed
- Detection scheme

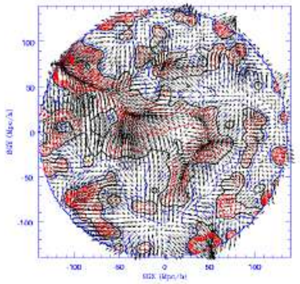
- Haloscopes of the world in detail:
  - Currently running
  - Future haloscopes (incomplete list?)

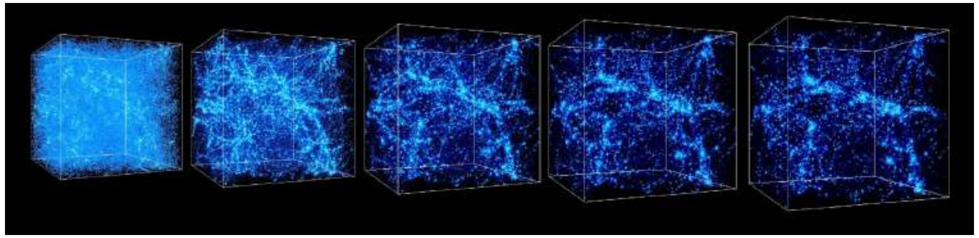
Halo- -scope : Detector of the galactic halo of Dark Matter

DM evidence from observations in different scales of the Universe



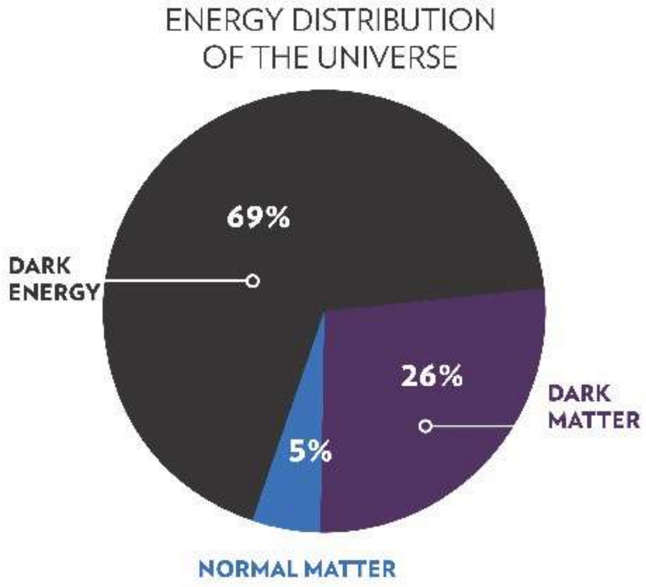






$$\Omega_{DM}h^2 \simeq 0.1186$$

(From Astron. & Astrophys. 594, A13 (2016))



Credit: NASA/CXC/K.Divon

WISPs: Weakly Interacting Slim Particles

Axions [Peccei,Quinn `77; Weinberg `78; Wilczek `78]

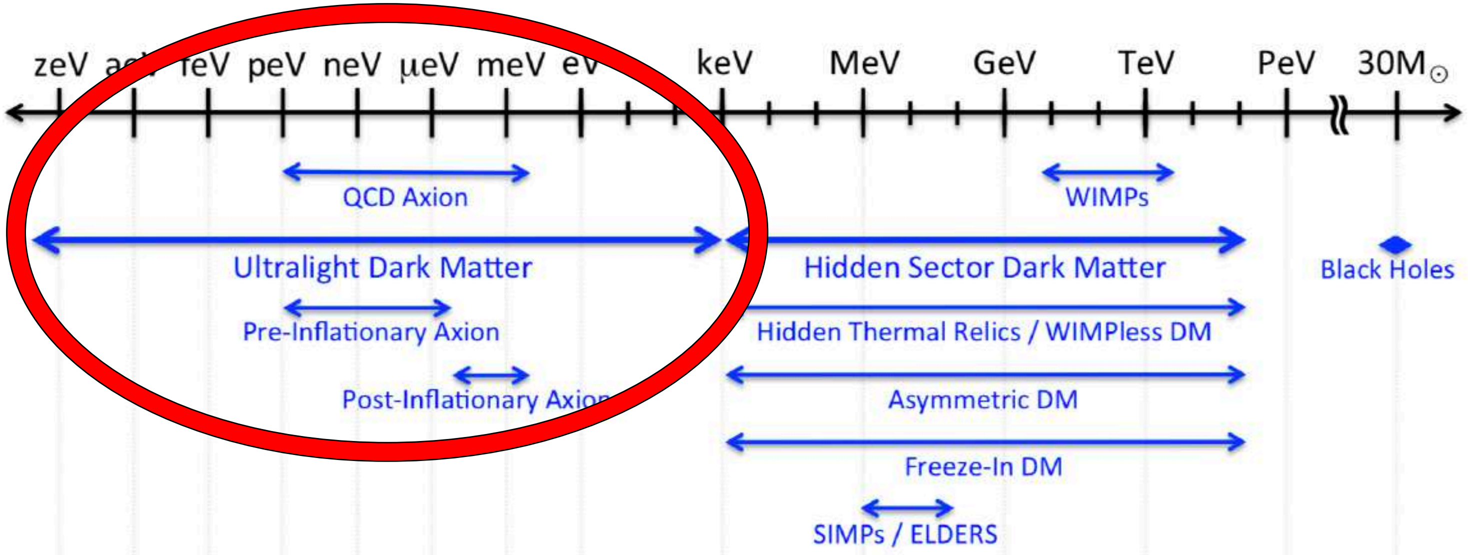
Axion-like particles [Witten `84; Arvanitaki et al. `10; Acharya et al. `10; Cicoli et al. `12; Halverson et al. `17]

Dilaton [Kaluza 1921; Klein 1926;...]

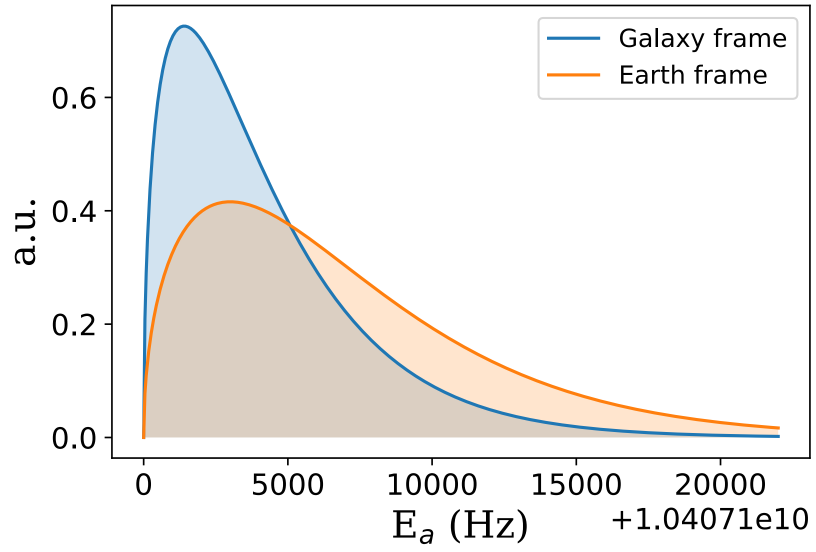
Majoron [Chikashige,Mohapatra,Peccei `81, Gelmini,Roncadelli `81]

Dark Photon [Holdom 86]

Ultralight Dark Matter Candidates are necessarily bosons



WISPs: Weakly Interacting Slim Particles



- Halo is virialized, so the energy is

$$E_{\rm dm} = mc^2 + \cancel{\frac{1}{2}mv^2}$$

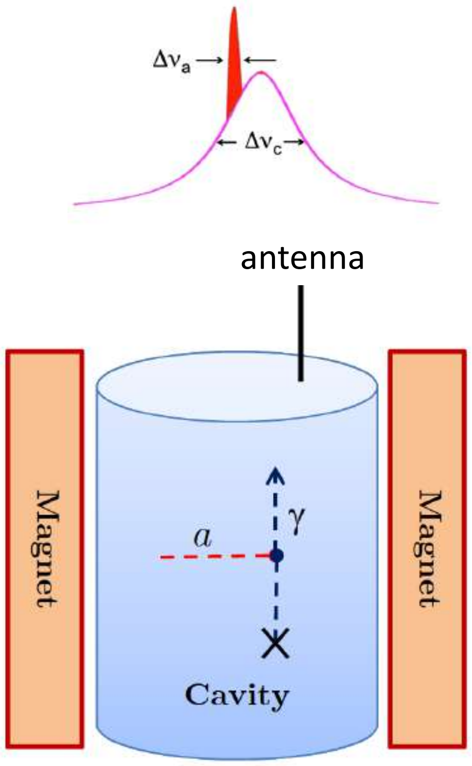
- Boost from number density

$$N_{\rm DM}\,|_{\rm dB} = 1.3\times 10^6 \left(\frac{\rm eV}{m_{\rm DM}}\right)^4 \left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3 \left(\frac{\rho_{\rm DM}}{0.4\,{\rm GeV/cm^3}}\right)$$

- Frequencies in the microwave range for masses of

$$0.4\ \mu{\rm eV} \lesssim m_{\rm dm} \lesssim 0.4\ {\rm meV}$$

Haloscope: detection concept



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

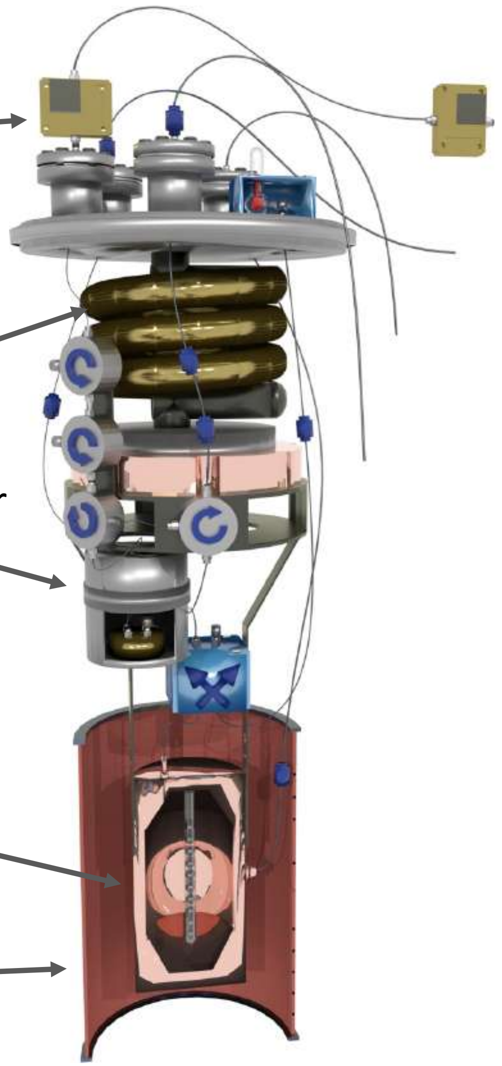
$$m_a \simeq 2\pi\nu \sim 4\,\mu\text{eV}\left(\frac{\nu}{\text{GeV}}\right)$$

Axions and ALPs: photon conversion in microwave cavity placed in a strong magnetic field

$$P_{a\gamma\gamma} \propto \left(\frac{g^2_{a\gamma\gamma}}{m_a^2}\rho_a\nu\right)\left(VB^2Q\right)$$

Hidden photons: no need of magnetic field

$$P_{\gamma'} \propto \left(\chi^2\rho_{\gamma'}m_{\gamma'}\right)\left(V\,Q\right)$$



Room Temperature Amplifiers

Dilution Refrigeretor T<100 mK

Cryogenic Amplifier (noise at SQL)

Resonant cavity

SC magnet (~10 T)

A caccia di assioni

Deutsches Elektronen-Synchrotron (DESY)
- ▲ Any Light Particle Search II (ALPS II)
- ▲ Baby IAXO
- ○ Magnetized Disc and Mirror Axion Experiment (MADMAX)

Consiglio europeo per la ricerca nucleare (CERN)
- ■ Optical Search for QED Vacuum Bifringence, Axions and Photon Regeneration (OSQAR)
- ■ CERN Axion Solar Telescope (CAST) and RADES
- ○ International Axion Observatory (IAXO)

Laboratori Nazionali di Legnaro
- ■ Polarizzazione del Vuoto con LASer (PVLAS)
- ■ QUest for AXions (QUAX)

Laboratori Nazionali del Gran Sasso
- ■ XENON1T

■ TASEH (Taiwan)

Massachusetts Institute of Technology (MIT)
- ■ A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus (ABRACADABRA)

Laboratori Nazionali di Frascati
- ■ QUest for AXions (QUAX)
- ○ KLoe magnet for Axion SearcH (~~KLASH~~) FLASH

Wright Lab - Yale University
- ■ Haloscope At Yale Sensitive To Axion CDM (HAYSTAC)

Axion search experiments in Center for Axion and Precision Physics Researches (CAPP)
- ■ CAPP Ultra-Low Temperature Axion Search in Korea (CULTASK)

Deep Underground Science and Engineering Laboratory (DUSEL)
- ■ Large Underground Xenon (LUX)

Center for Experimental Nuclear Physics and Astrophysics (CENPA)
- ■ Axion Dark Matter Experiment (ADMX)

Western Australia University
- ■ Oscillating Resonant Group AxioN (ORGAN)

■ operativo ▲ in costruzione ○ in progetto

Crediti: Maura Sandri/Media Inaf

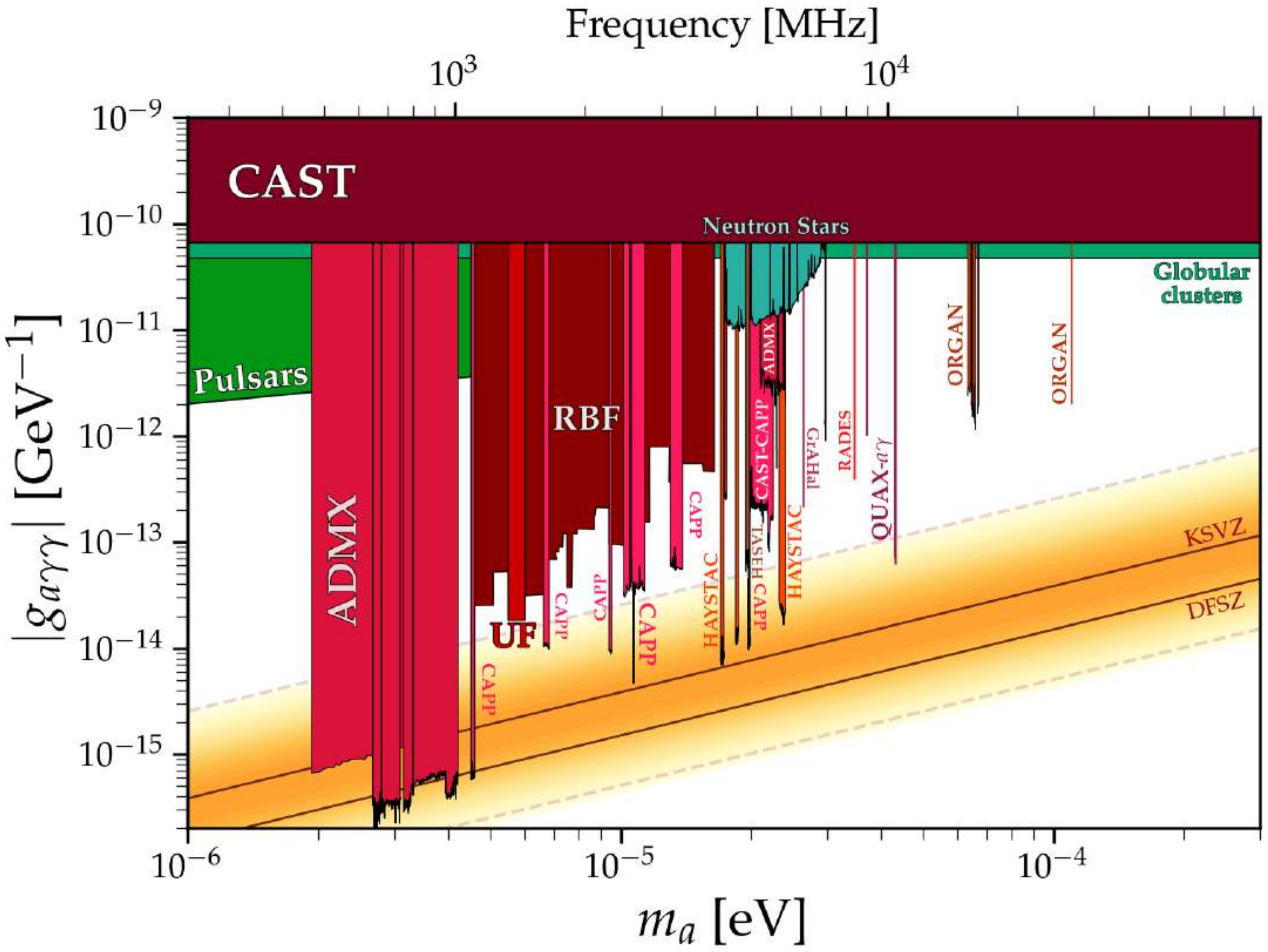
Haloscopes closeup

Currently running:

- ADMX
- CAPP
- HAYSTAC
- ORGAN
- QUAX
- RADES
- TASEH

Future haloscopes:

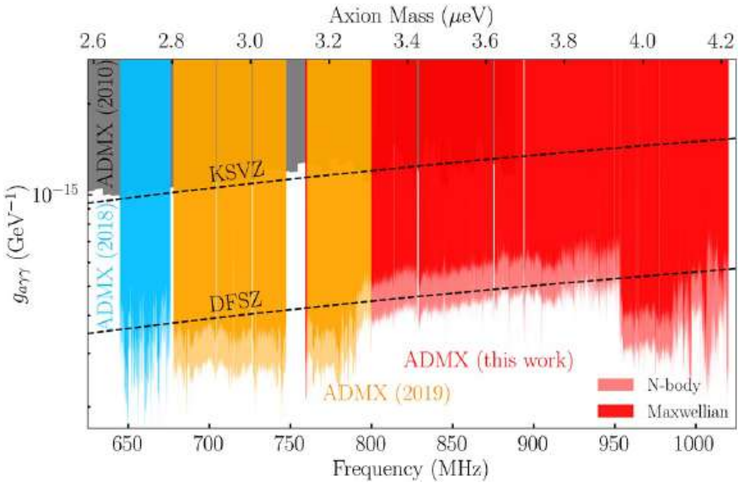
- MADMAX
- ABRACADABRA
- FLASH
- ALPHA



C. O' Hare, https://cajohare.github.io/AxionLimits/

ADMX – Axion Dark Matter Experiment

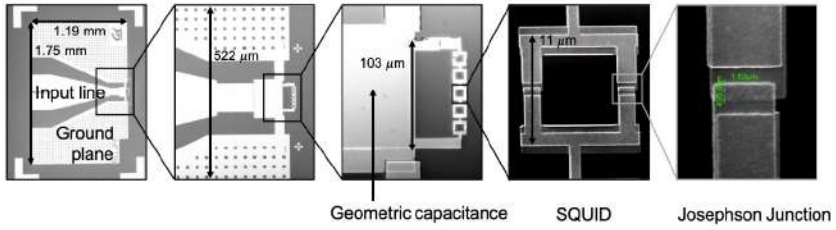
Washington University



PHYSICAL REVIEW LETTERS 127, 261803 (2021)

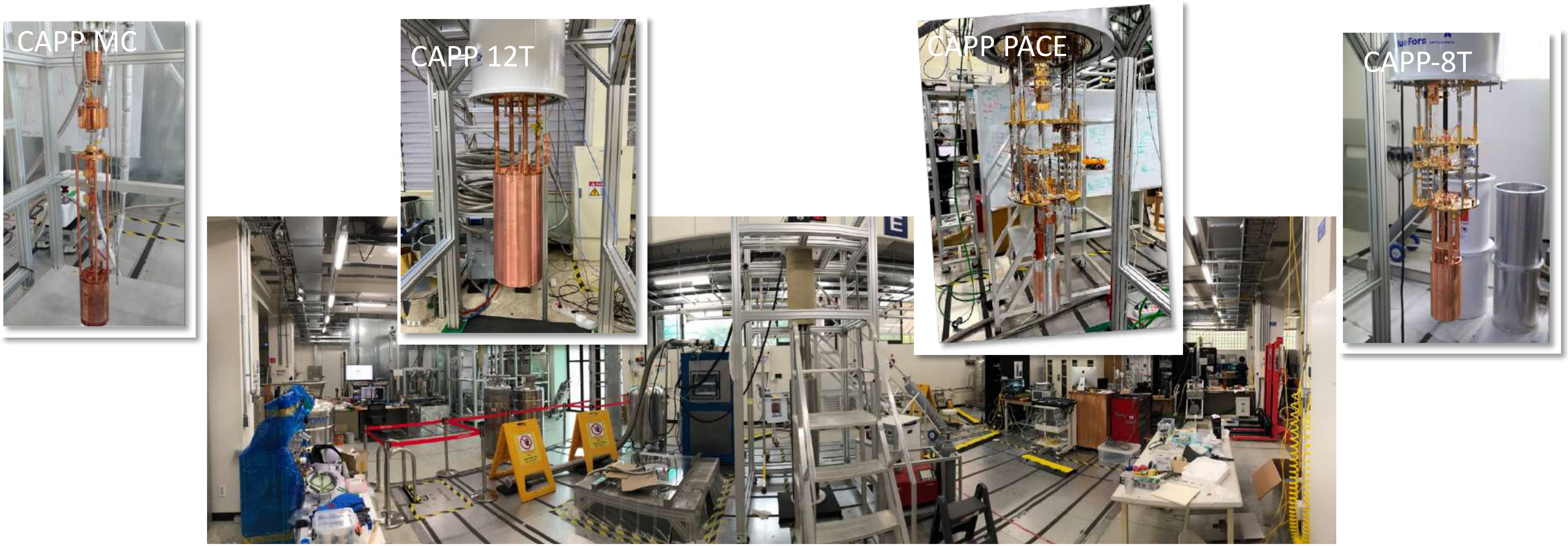
ADMX	800-1000 MHz
Volume	136 L
Q_0	200,000
B	7.5 T
T_{noise}	600 mK

Josephson parametric amplifier



IBS CAPP – Center of Axion and Precision Physics

South Korea



CAPP 12T	1.1 GHz
Volume	37 L
Q_0	90,000
B	12 T
T_{noise}	120 mK

CAPP 8T	1.6 GHz
Volume	3.47 L
Q_0	90,000
B	8 T
T_{noise}	900 mK

PACE	2.2 GHz
Volume	1.12 L
Q_0	90,000
B	7.2 T
T_{noise}	200 mK

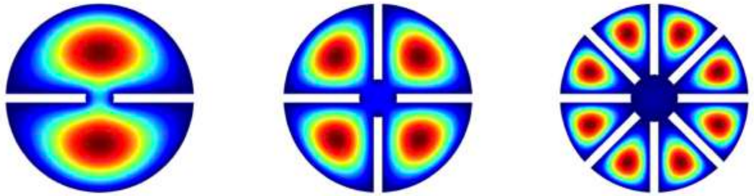
CAPP MC	3.2 GHz
Volume	0.65 L
Q_0	60,000
B	8 T
T_{noise}	3.8 K

CAPP 18T	4.79 GHz
Volume	1 L
Q_0	70,000
B	18 T
T_{noise}	500 mK

IBS CAPP – Center of Axion and Precision Physics

Committed in new technologies R&D:

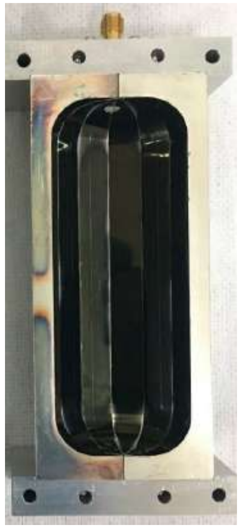
Multicell cavity



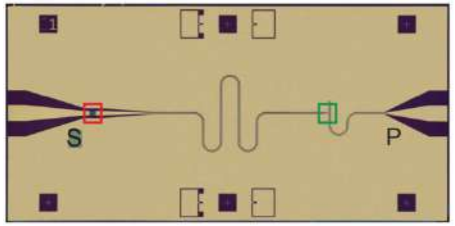
Phys. Lett. B 777 412 2018

18 T HTS magnet

$GdBa_2Cu_3O_{7-x}$ (GdBCO) tapes



SC cavity (YBCO tapes)

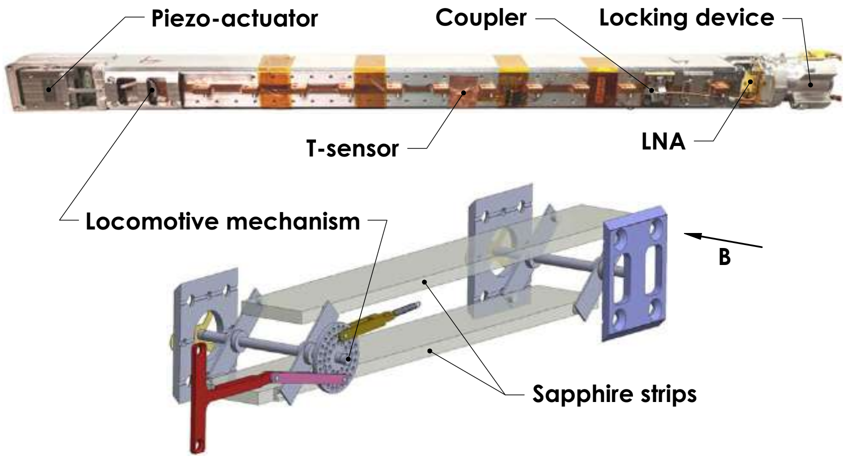


JPA

PHYSICAL REVIEW LETTERS 124, 101802 (2020)
PHYSICAL REVIEW LETTERS 125, 221302 (2020)
PHYSICAL REVIEW LETTERS 126, 191802 (2021)
PHYSICAL REVIEW LETTERS 128, 241805 (2022)
arXiv:2207.13597
PHYSICAL REVIEW D 106, 092007 (2022)

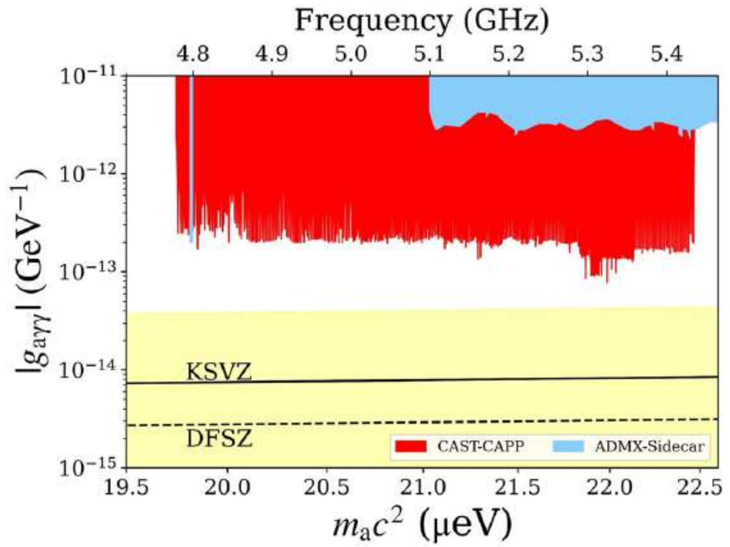
CAST-CAPP

CAST, CERN



Parameters	Explanation	Values	Uncertainty
B	Static dipole magnetic field	8.8 T	10^{-3}
V	Cavity volume	224 cm^3	0.1 cm^3
C	Form factor	0.53	10%
β	Main port coupling factor	1	0.3
Q_L	Loaded quality factor	20000	3%
T_S	System noise temperature	9 K	1 K
η	Signal attenuation coefficient	0.717	0.01

- **Array of 4 phase-matched rectangular cavities**
- **Tuning between 4.774 and 5.434 GHz**

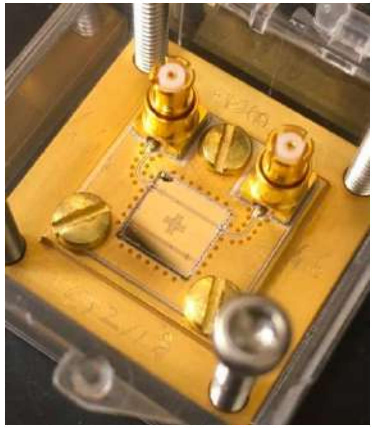


Nature Communications, (2022)13:6180

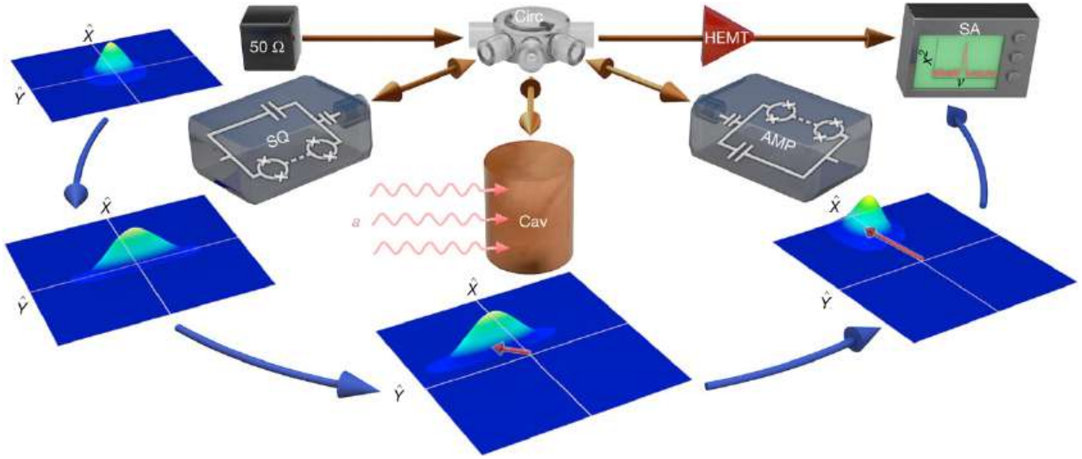
HAYSTAC – Haloscope At Yale Sensitive To Axion CDM

Yale's Wright Lab

HAYSTAC	5 GHz
Volume	1.5 L
Q_L	30,000
B	8 T
T_{noise}	120 mK



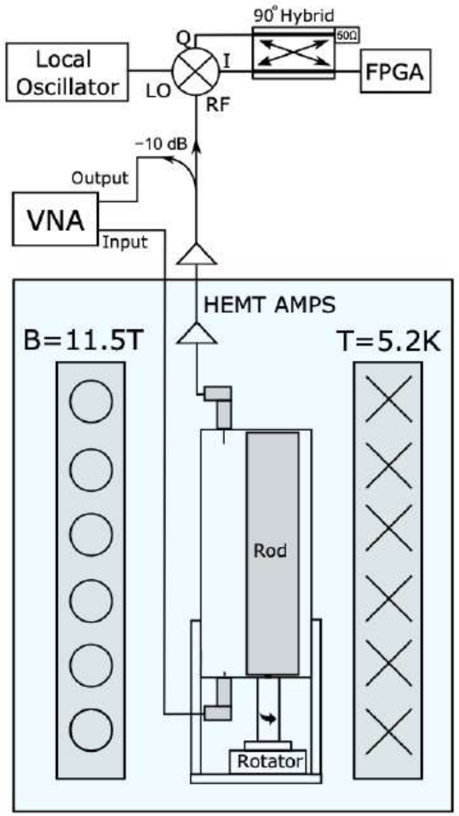
Squeezed-vacuum state receiver improves sensitivity and doubles the scan rate



Backes et al. Nature 590, 238–242 (2021)
PHYSICAL REVIEW D 97, 092001 (2018)

ORGAN – Oscillating Resonant Group AxioN

University of Western Australia

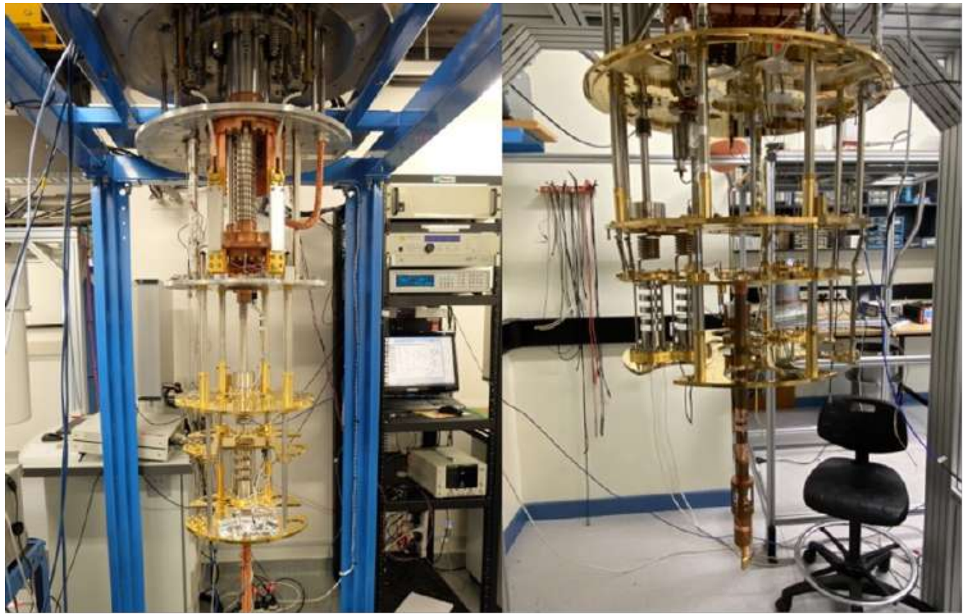


arXiv:2203.12152v1

Phase 1a completed

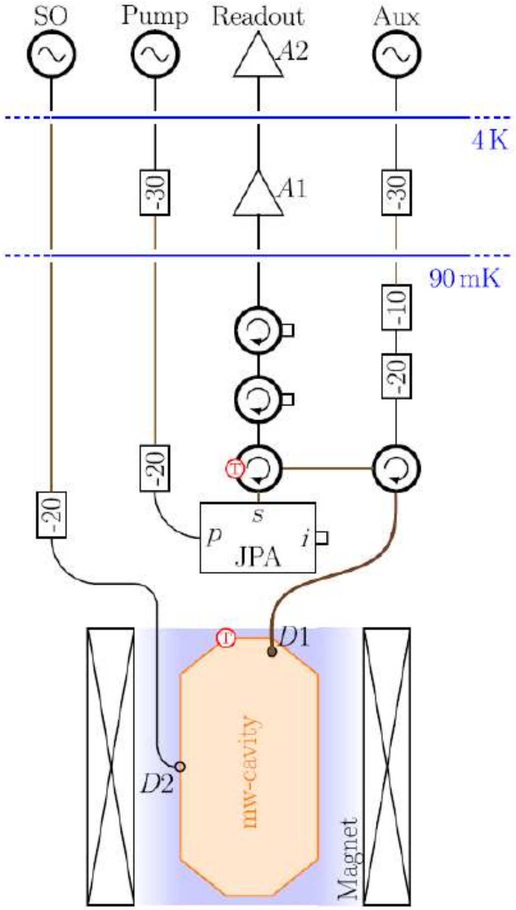
ORGAN	15 GHz
Q_L	7000
B	11.5 T
T_{noise}	5.2 K

Planned for phase 2:
From 15 to 50 GHz – quantum tech – multicavity approach – single photon counters

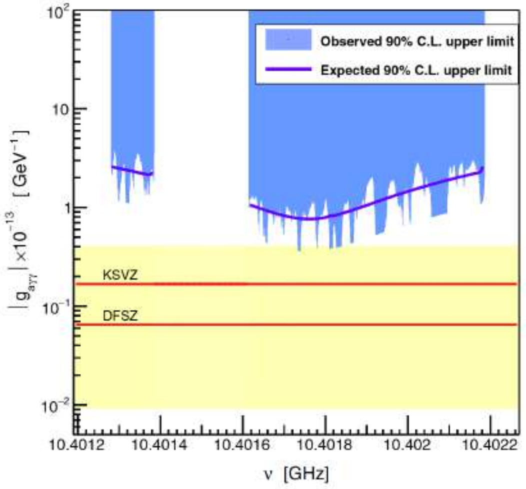


QUAX – Quest for Axions

Laboratori Nazionali di Legnaro (LNL)



QUAX	10 GHz
Volume	0.08 L
Q_0	80,000
B	8 T
T_{noise}	1 K

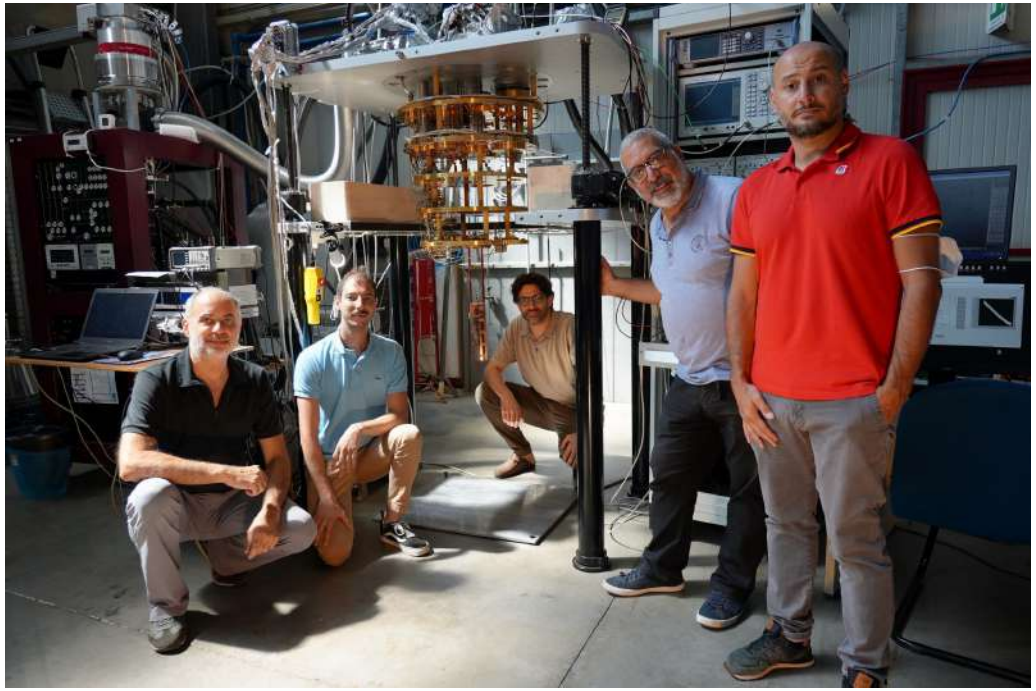


PHYS. REV. D 103, 102004 (2021)

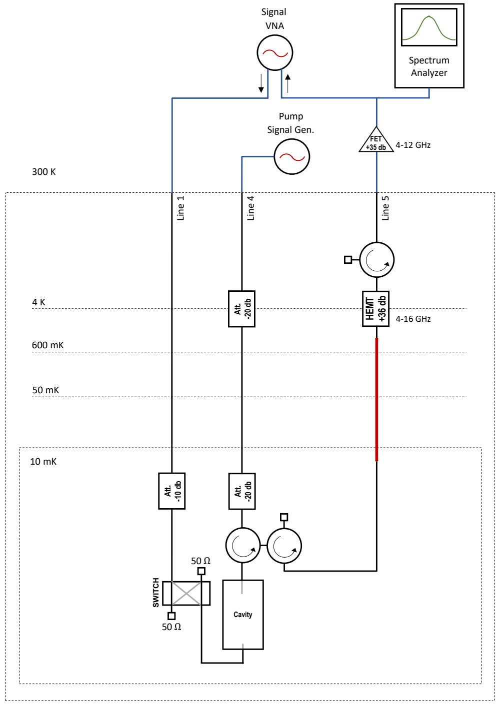
QUAX – Quest for Axions

Setting up the new haloscope at:

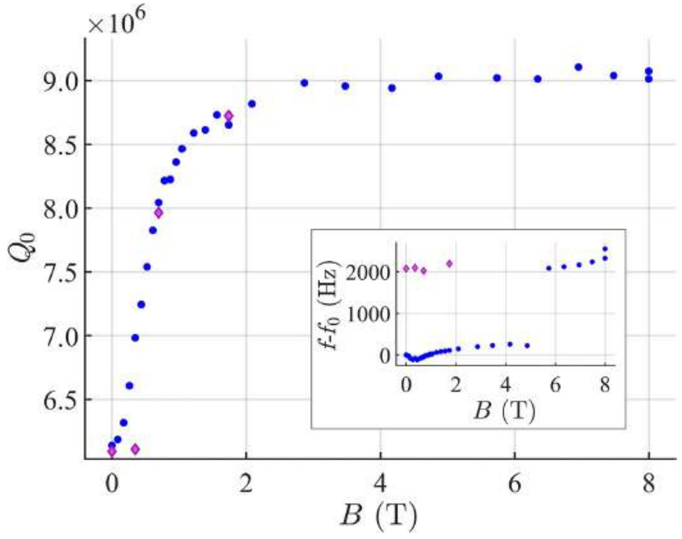
Laboratori Nazionali di Frascati (LNF)



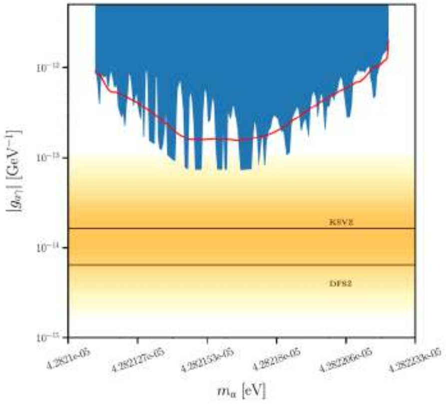
QUAX	8.5 GHz
Volume	0.14 L
Q_0	100,000
B	9 T
T_{noise}	5 K



QUAX – Dielectric and superconducting cavities



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



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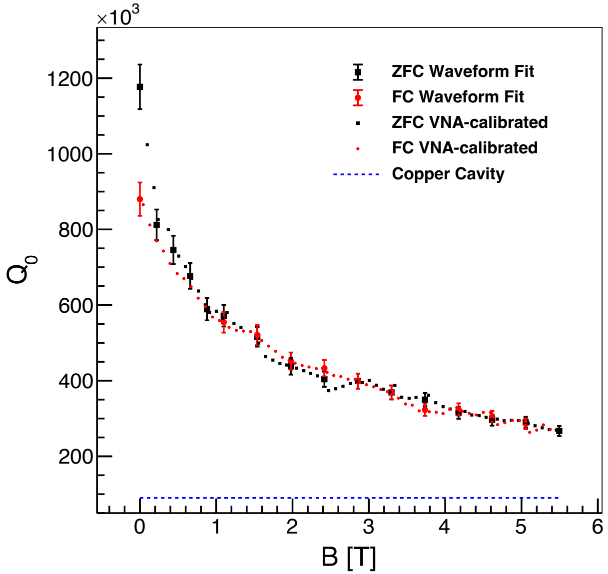
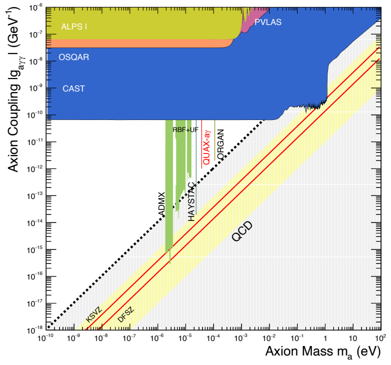
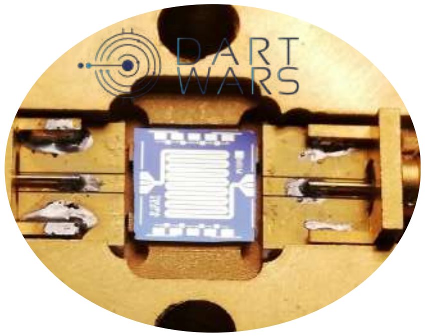




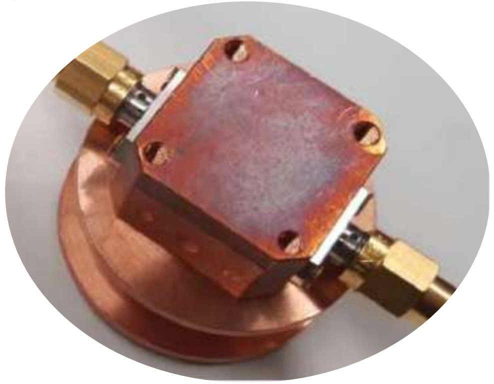
Phys. Rev. D **99**, 101101(R) (2019)

QUAX – Superconducting quantum devices

TWPA

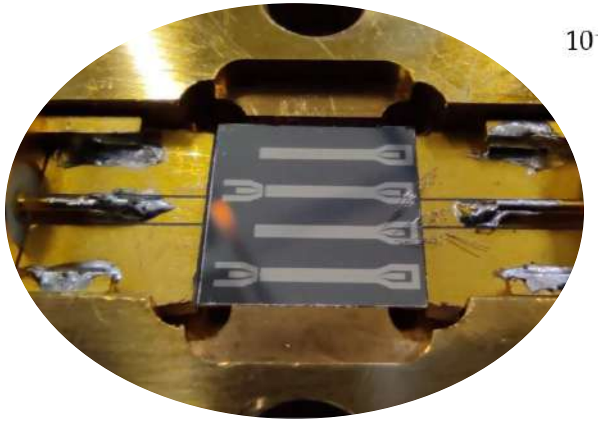


https://arxiv.org/abs/2111.01512



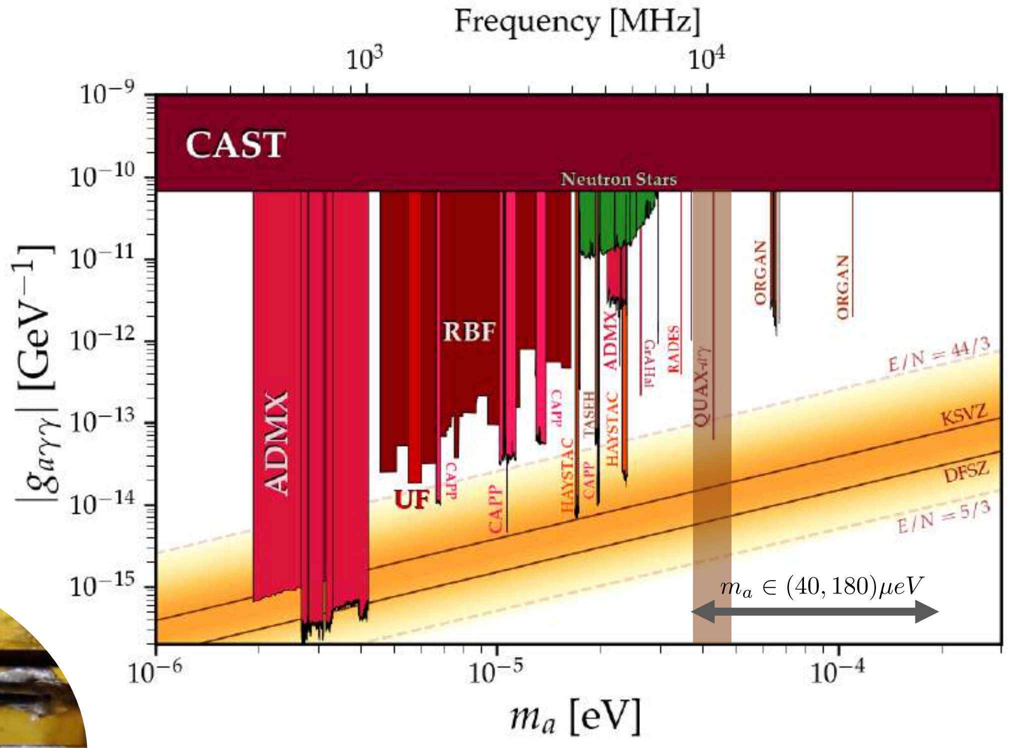
arXiv:2205.02053

JPA



JJ Single microwave photon counters

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



LNF:

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

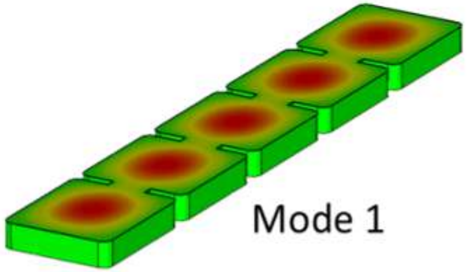
LNL:

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

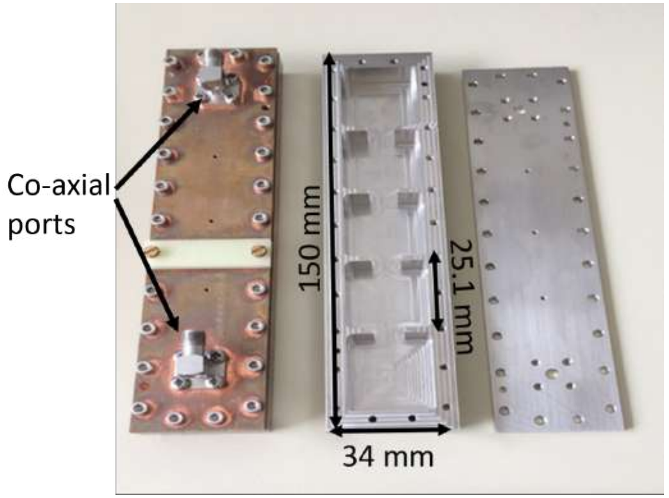
RADES – Relic Axion Dark-matter Exploratory Setup

GHz cavity put inside the CAST dipole magnet

RADES	8.4 GHz
Volume	0.03 L
Q_0	16,000
B	8.8 T
T_{noise}	1.8 K



5 sub-cavities connected by inductive irises

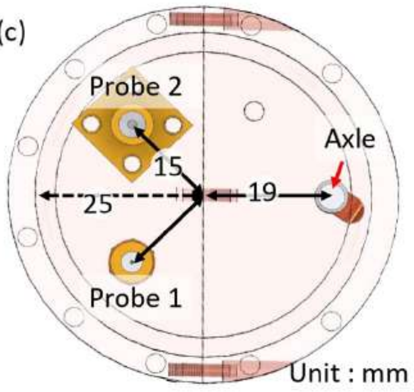


doi.org/10.1007/JHEP10(2021)075

TASEH – Taiwan Axion Search Experiment with Haloscope

National Central University, Taiwan

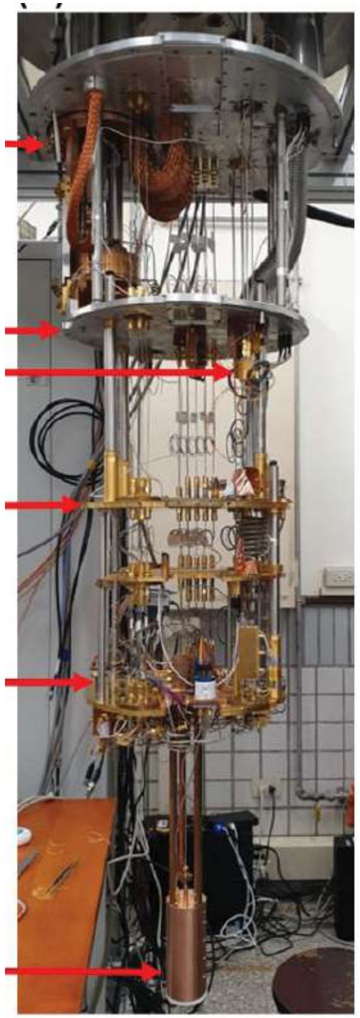
(c)

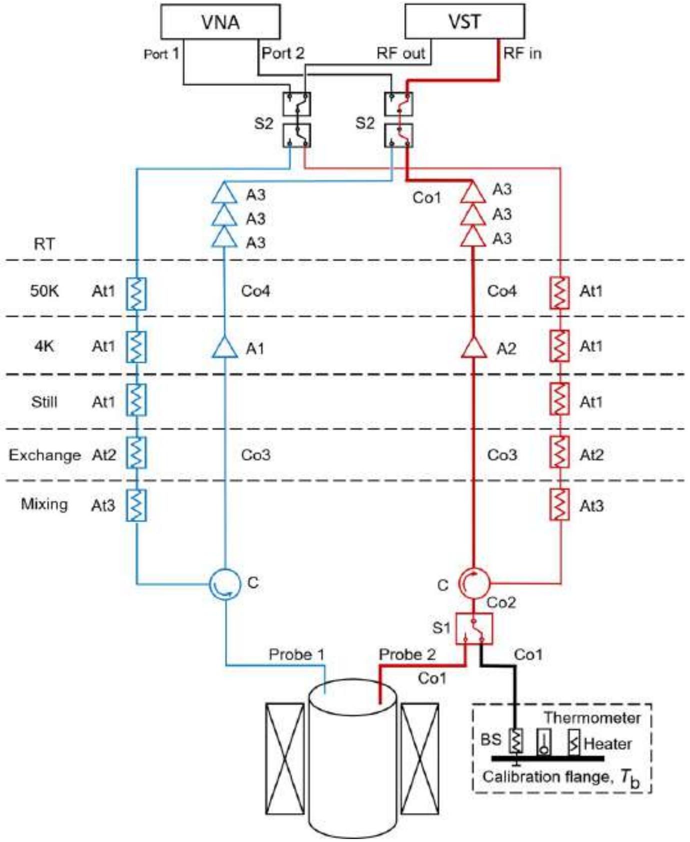


(d)

New entry!

TASEH	5 GHz
Volume	0.234 L
Q_0	60,000
B	8 T
T_{noise}	2.2 K





PHYSICAL REVIEW LETTERS 129, 111802 (2022)

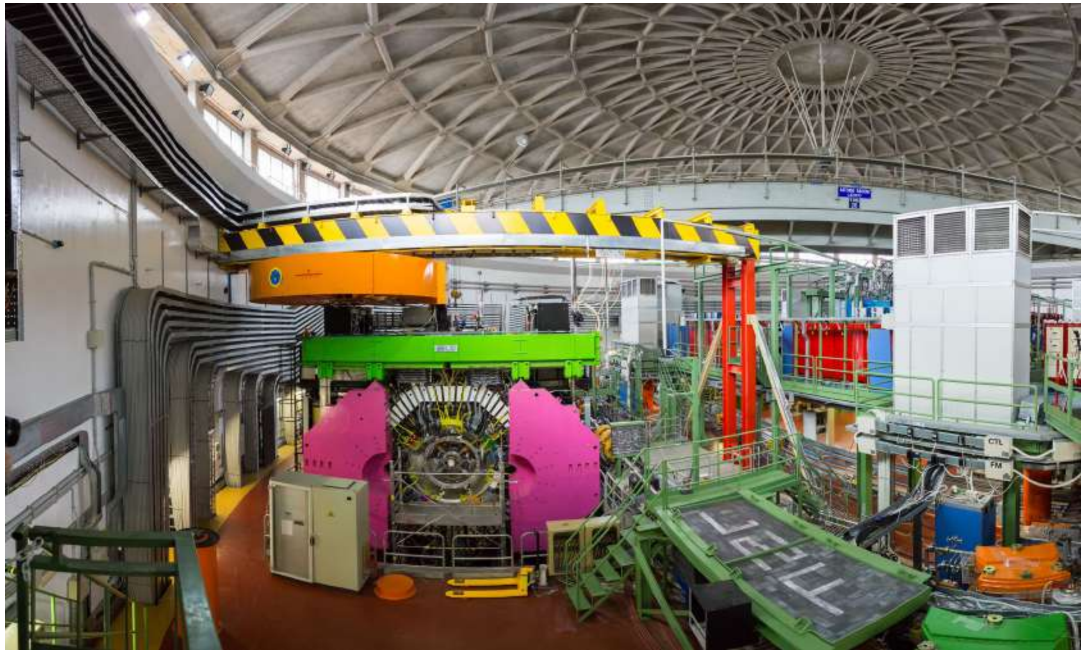
Future experiments

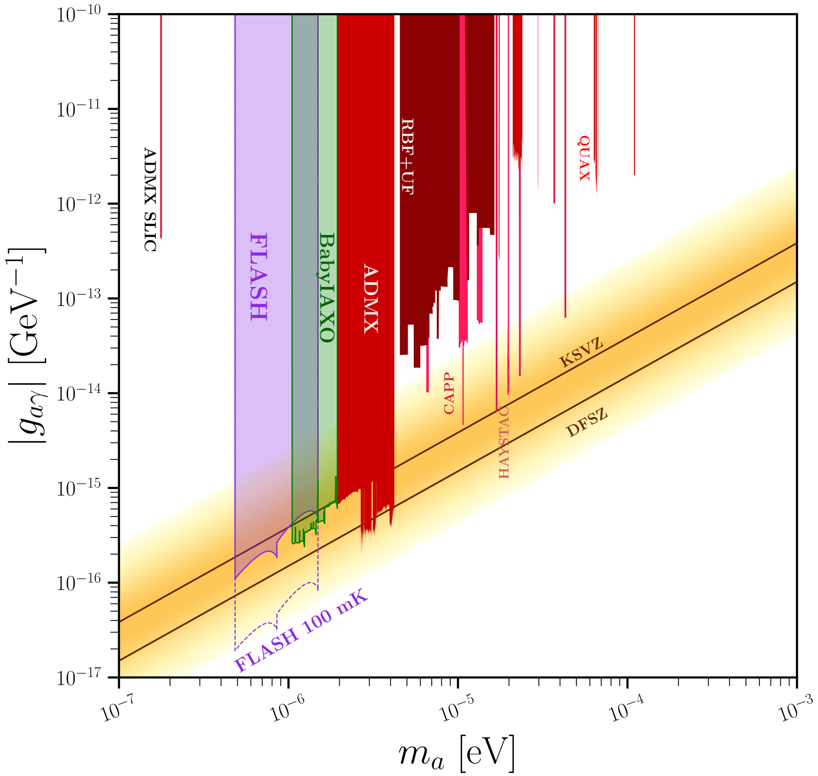
FLASH – Finuda magnet for Light Axion SearcH

Recycling of the FINUDA 1.1 T magnet
at Laboratori Nazionali di Frascati (LNF)

Tuning from 100 to 300 MHz

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati





CDR in preparation

GRAHAL – Grenoble Axion Haloscope

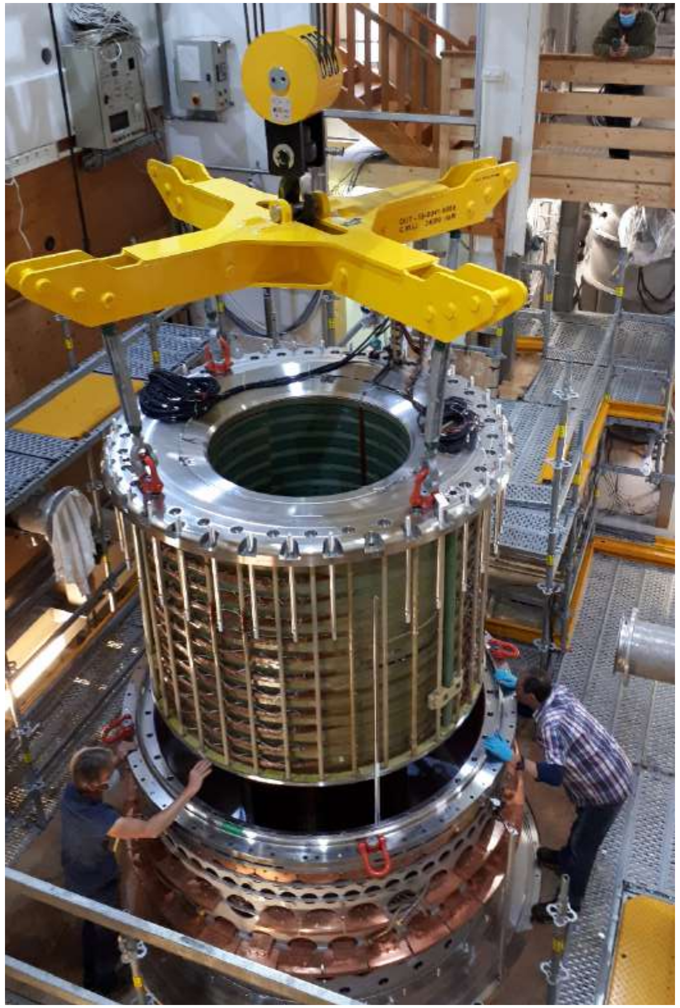
Grenoble, France

arXiv:1610.09344v1

43 T magnet, 11.5 GHz frequency

Field	Warm dia.	RF-cavity dia.	Freq. TM010	Axion mass
43 T	34 mm	20 mm	11.5 GHz	47.2 μeV

Grenoble Hybrid in the commissioning phase, operation foresees in 2024

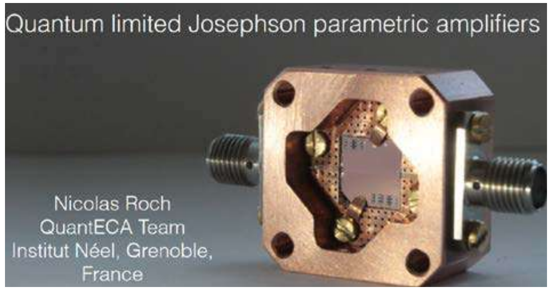


Collaboration with QUAX from INFN & University of Padova

Dielectric cavities (7-10 GHz)

Collaboration with CAPP/IBS, KAIST, Daejeon, South Korea

Thin Cu cavities (200-600 MHz)

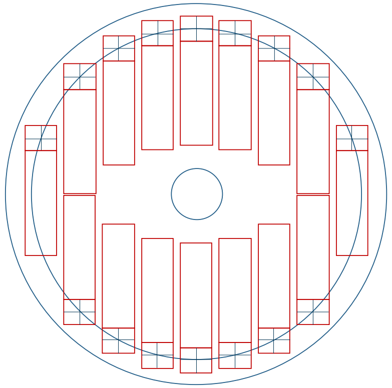


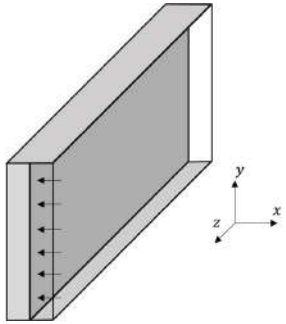
CADEx – Canfranc Axion Detection Experiment

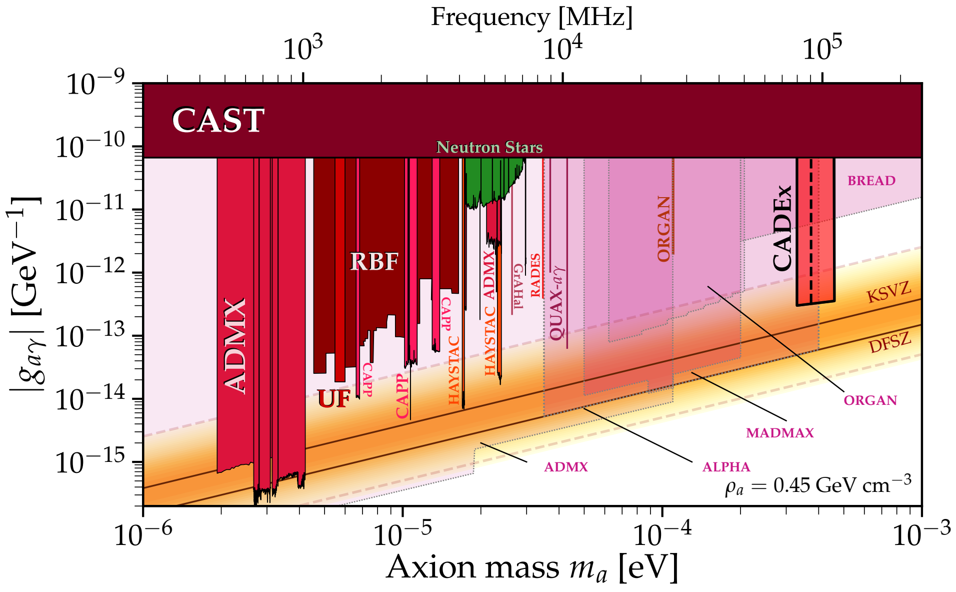
Canfranc Underground Laboratory - Spain

- **Haloscope from 80 to 110 GHz**

- Multicavity scheme with tunable rectangular cavities

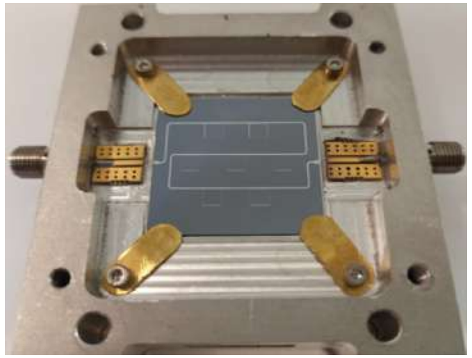






arXiv:2206.02980v1

- Kinetic Inductance Detectors



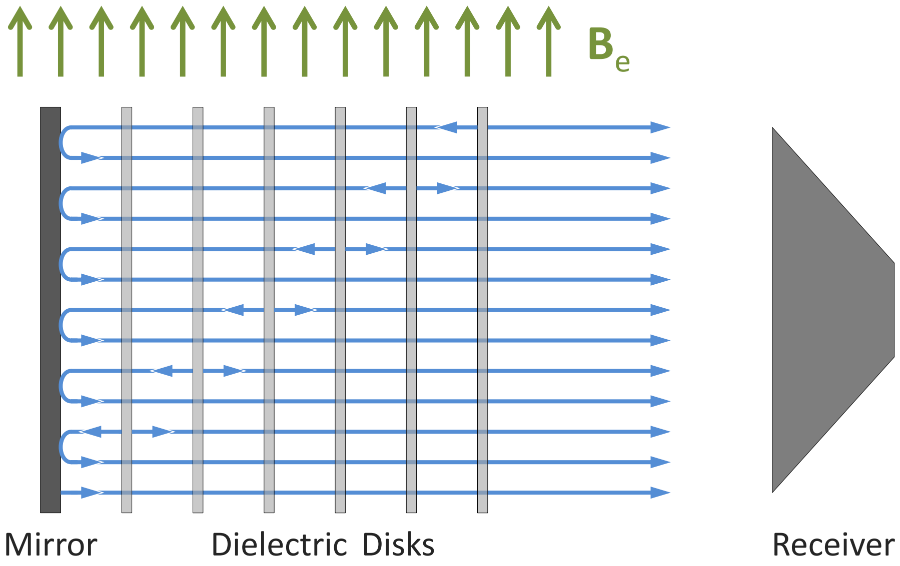
MADMAX – MAgnetized Disc and Mirror AXion experiment

DESY, Hamburg

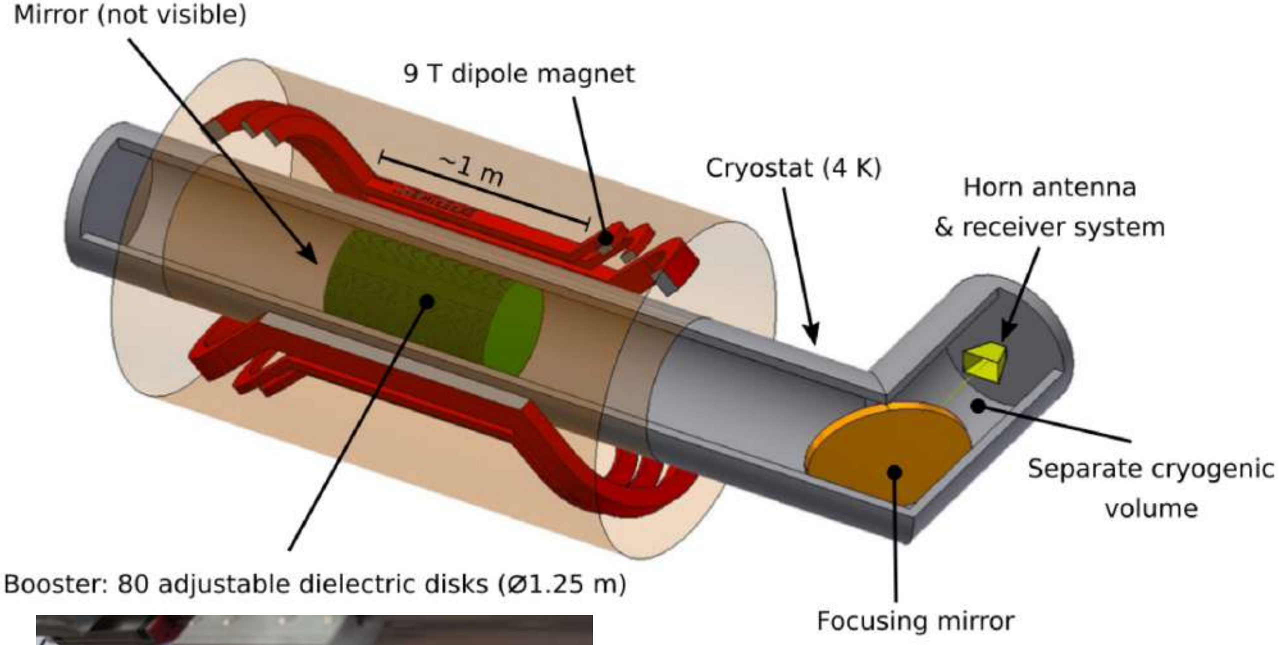
From 10 to 50 GHz

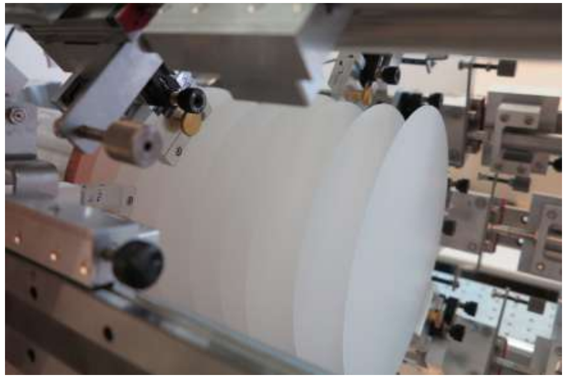
Dish antenna haloscope + dielectric boost

$$\mathbf{E}_a(t) = -g_{a\gamma}\mathbf{B}_e a(t)$$



arXiv:1901.07401





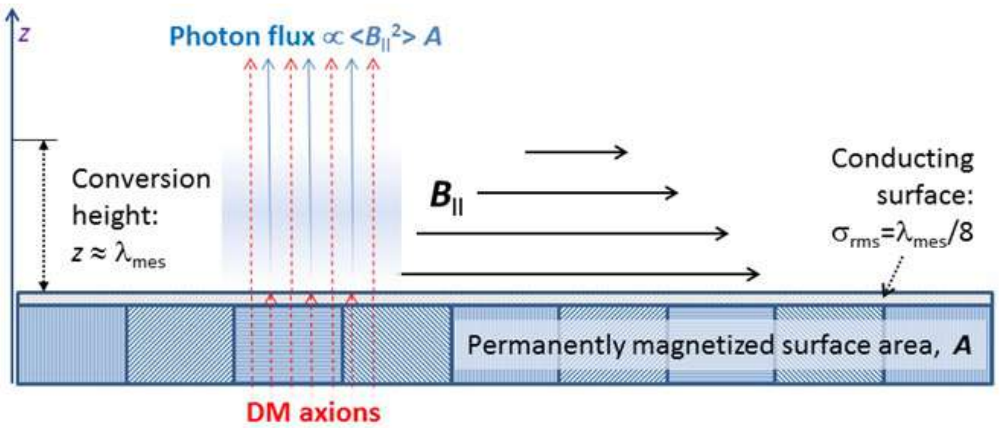
Boost factor

$$\beta^2 = \frac{P_{dh}}{P_{\rm dish}} \sim 2N_d^2$$

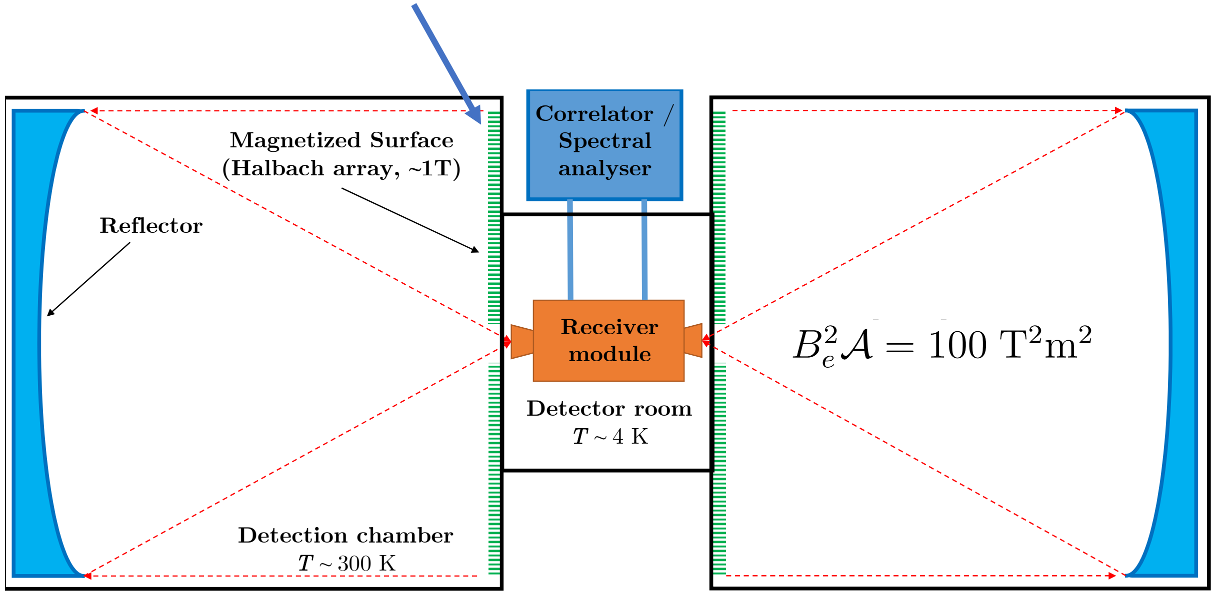
BRASS – Broadband Radiometric Axion SearcheS

University of Hamburg

A broadband (16 GHz bandwidth) dish antenna haloscope



Permanently magnetized surface for axion/ALP conversion



Correlations with multiple chambers

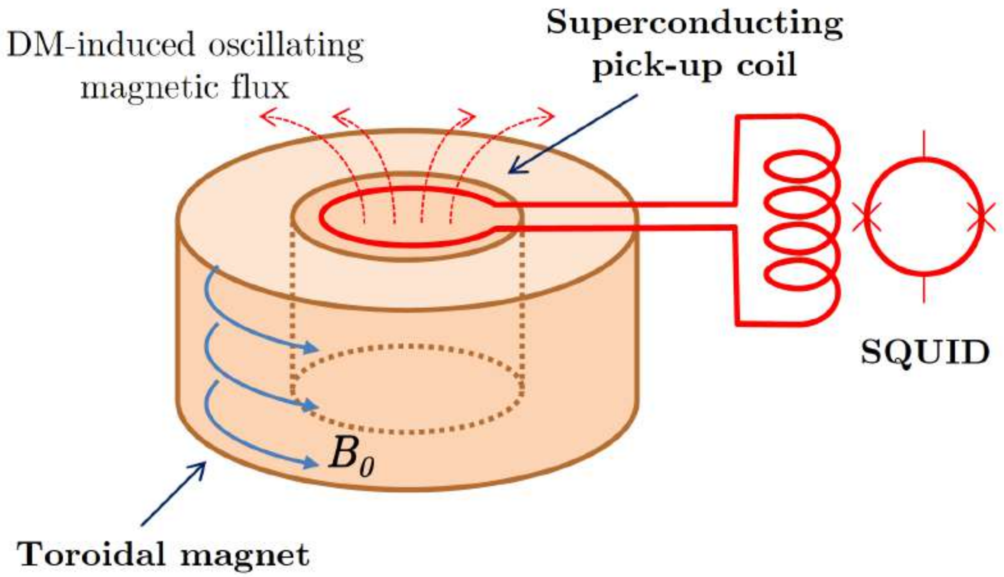
http://wwwiexp.desy.de/groups/astroparticle/brass/brassweb.htm

ABRACADABRA

A Broadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

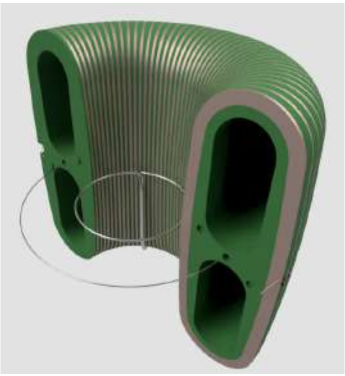
MIT

LC resonator



$$\underline{J}_a = -g\underline{B}_0\partial_t a$$

Snowmass Axion Paper arXiv:2203.14923



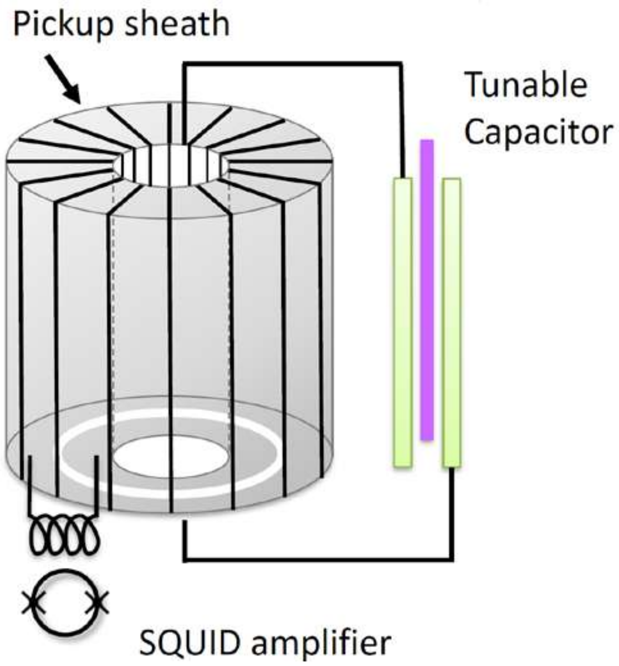
PHYSICAL REVIEW D 99, 052012 (2019)

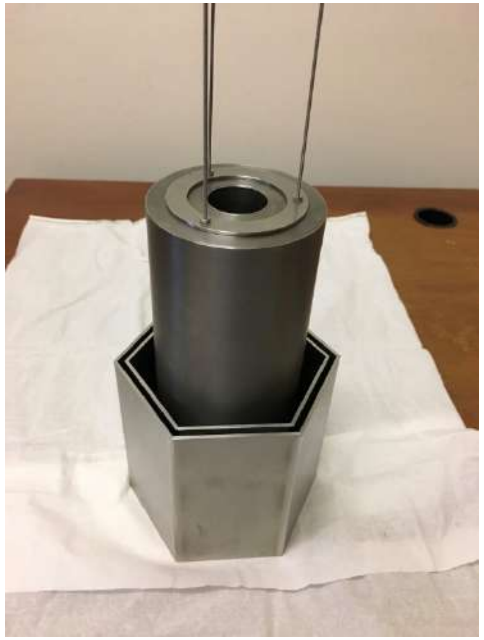
DM-radio

100 kHz – 10 MHz range

- DMRadio-50L
- DMRadio-m^3
- DMRadio-GUT

DM-radio pathfinder: http://schmidta.scripts.mit.edu/tabletop_workshop/slides/irwin.pdf

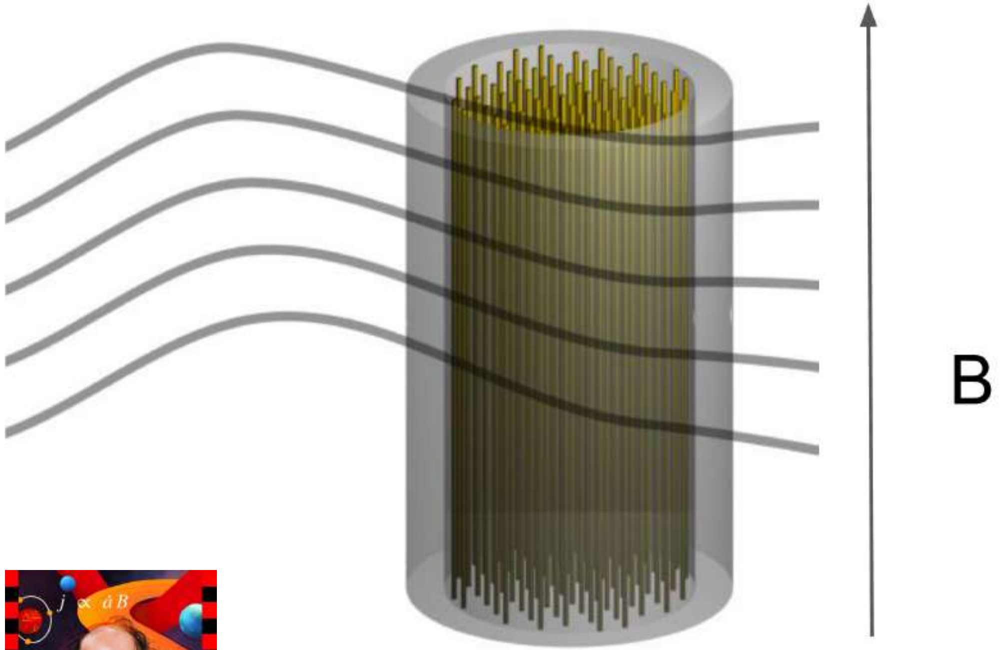


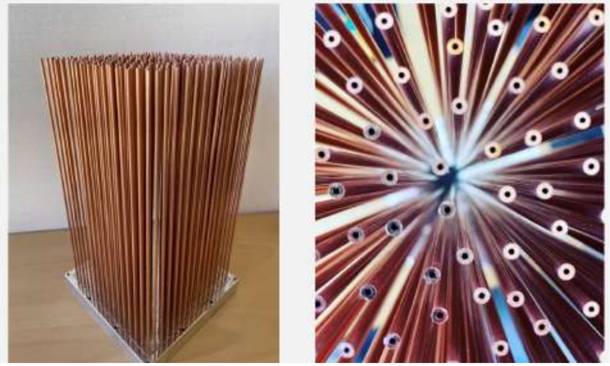


ALPHA – Axion Longitudinal Plasma HAloscope

Detection through metamaterial
From 5 to 50 GHz

$$\underline{E} = -g\underline{B}_0 a \frac{\omega_a^2 - i\omega_a\Gamma}{\omega_a^2 - \omega_p^2 - i\omega_a\Gamma}$$





Stockholm University

Oskar Klein centre

alpha

Phys. Rev. Lett. **123**, 141802 (2019)

Many others

	Type	source
SHAFT	LC (with ferromagnetic toroids)	arXiv:2003.03348v2
TOORAD	Topological antiferromagnets	arXiv:1807.08810v2
BREAD	Cylindrical dish antenna	arXiv:2111.12103v2
WISPLC	LC circuit	arXiv:2111.04541v3
ORPHEUS	Fabry-Pérot cavity	Phys. Rev. D 91, 011701(R)
ADMX-SLIC	LC circuit	Phys. Rev. Lett. 124, 241101
ADMX-Sidecar	Resonant cavity	Phys. Rev. Lett. 121, 261302
T-RAX	Rectangular waveguide	arXiv:2203.15487v2
SRF-m^3	Supercond. Radio Freq. Cavities	arXiv:2007.15656v1
DANCE	Bow-tie optical cavity	arXiv:2303.03594v1
LAMPOST	Dielectric haloscope	arXiv:1803.11455v3

Thank you!

backup

Others: BRASS, SHAFT, DM-Radio, TOORAD

GRAHAL

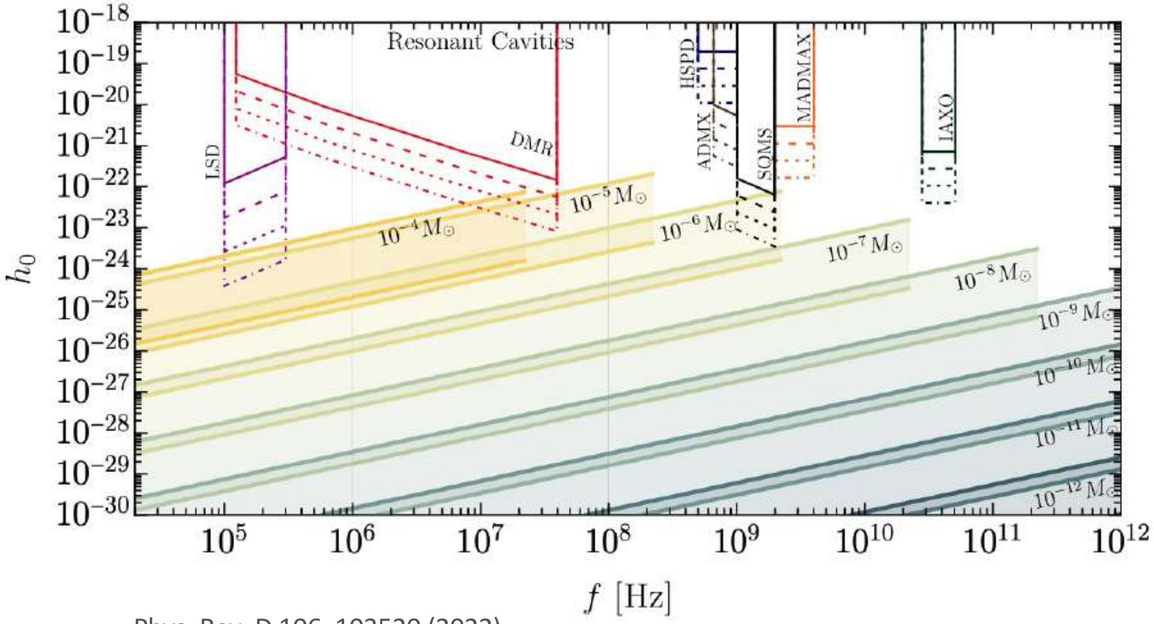
Cast-capp
Cadex
BREAD??
LAMPOST?? (fa DP)
SRF-m^3 ?? (non trovato)
WISPLC??
WISPFI?? (Laboratory exp)
ORPHEUS ??
WISPDMX ?? (fa DP)
SLIC ??

High frequency gravitational waves detection

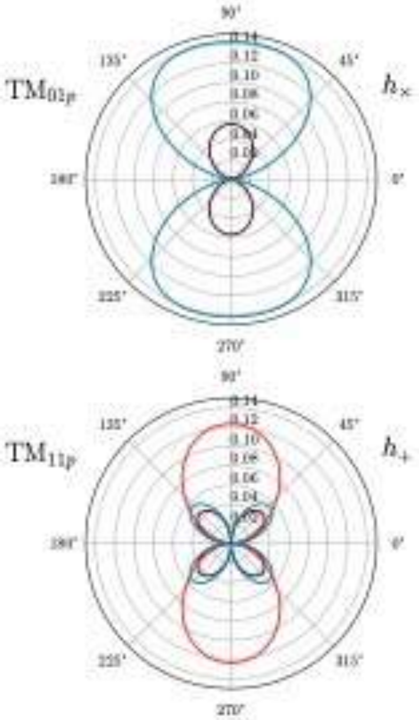
Sources: primordial black holes, stochastic background of HFGW

The haloscope is directional

Resonant modes different from TM010



Phys. Rev. D 106, 103520 (2022)



arXiv:2112.11465v1

Scan rate

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

$\beta = 2$ maximizes the scan rate