

# SEARCH FOR AXION DARK MATTER

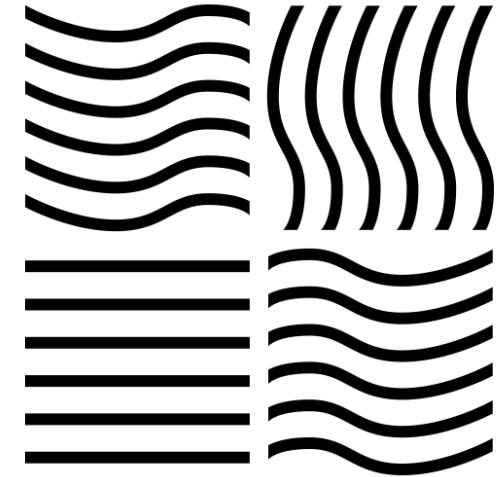
CLAUDIO GATTI, LABORATORI NAZIONALI DI FRASCATI - INFN

Vulcano Workshop 2022  
Frontier Objects in Astrophysics and Particle Physics



# OUTLINE

- Properties of Axions
- Search of Dark Matter Axions
  - a) Resonant Searches - Haloscopes
    - I. ADMX
    - II. CAPP
    - III. HAYSTAC
    - IV. QUAX
  - b) Future experiments
    - I. Large cavity Haloscope: FLASH
    - II. LC Haloscope: ABRA&DMRadio
    - III. Dielectric Haloscope - MADMAX
    - IV. Plasma Haloscope - ALPHA
- Prospects and conclusions



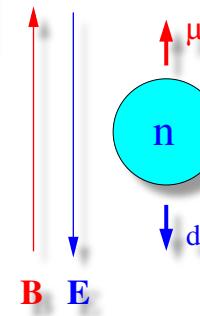
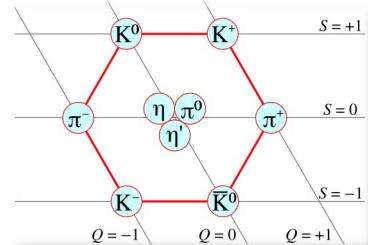
# AXION PROPERTIES

Created by Agarunov Oktay-Abraham  
from Noun Project

# Axions

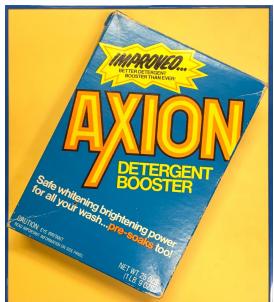
$U(1)_A$   
problem

$M_{\eta'} = 958 \text{ MeV} \gg M_\eta$   
S.Weinberg  $U(1)$  problem PRD 11 (1975)



Phys Rev Lett 82, n.5 (1999) p.904  
 $d_n < 2.9 \times 10^{-26} e \text{ cm}$   
 $\theta < 10^{-10}$

R.D.Peccei and H.R.Quinn, Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977).  
 S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).  
 F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).



Strong  
CP  
problem

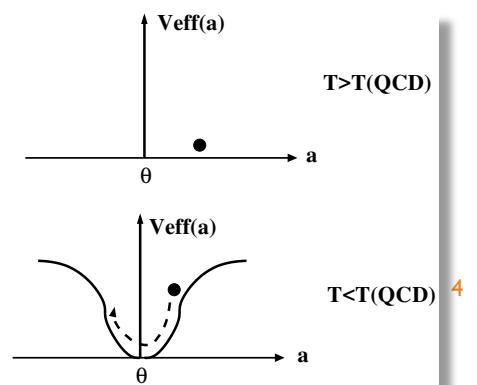
$$\mathcal{L}_{QCD}^{CP} = \theta_{QCD} \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$$

Axions

$$\mathcal{L}_{QCD}^{CP} = \left( \theta - \frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$$

Axion  
Dark  
Matter

Misalignment  
mechanism



# Axion Mass

Interaction with gluon field

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

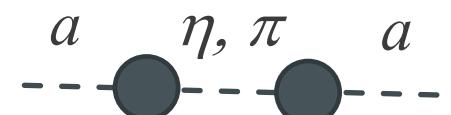
$a$  axion field

$f_a$  PQ breaking energy scale

$G$  gluon field

At temperature  $T=\Lambda_{QCD}$  non perturbative QCD effects 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  $f_a \sim f_{ew} = 100 \text{ GeV}$ , as in original PQ model, then  $m_a \sim 100 \text{ keV}$  and  $BR(K^+ \rightarrow \pi^+ a) \sim 10^{-5}$

This is ruled out by measurements  $BR(K^+ \rightarrow \pi^+ \text{ nothing}) < 10^{-8}$

# Axion Interaction with Matter

Axion interaction with matter described by an effective lagrangian

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

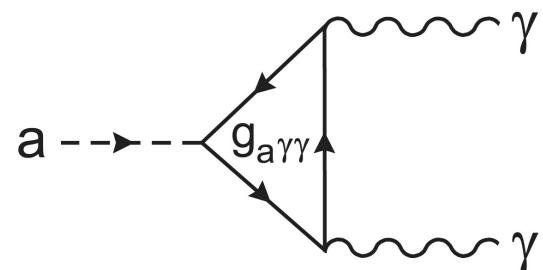
Casper Electric  
Experiment

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

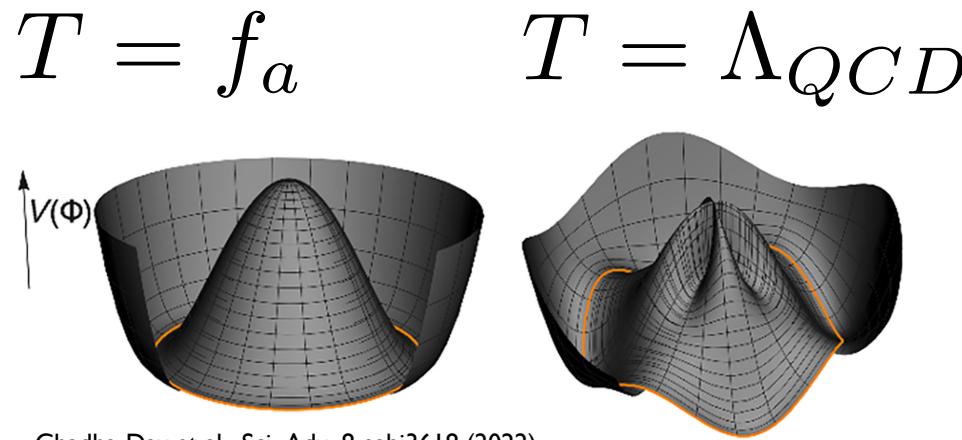
The effective coupling is  
model dependent:  
E/N=0 KSVZ model  
E/N=8/3 DSFZ model

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

Light axion are stable particles

# Axion Dark Matter Production: The Misalignment Mechanism

PQ symmetry spontaneously broken at energy scale  $f_a$



Chadha-Day et al., Sci. Adv. 8 eabj3618 (2022)

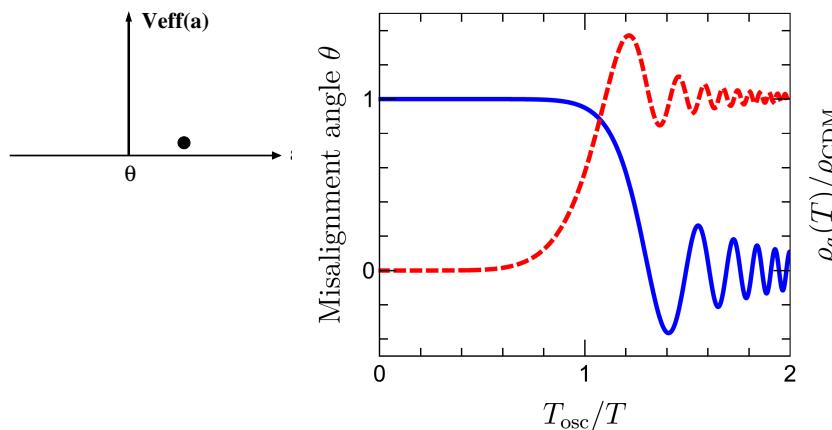
The axion corresponds to the angular direction

$$a = f_a \cdot \theta$$

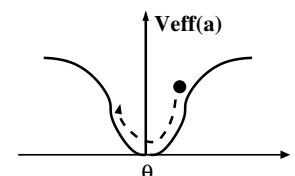
Axion DM density

$$\ddot{a} + 3H\dot{a} + m_a(t)^2 a = 0$$

Hubble friction



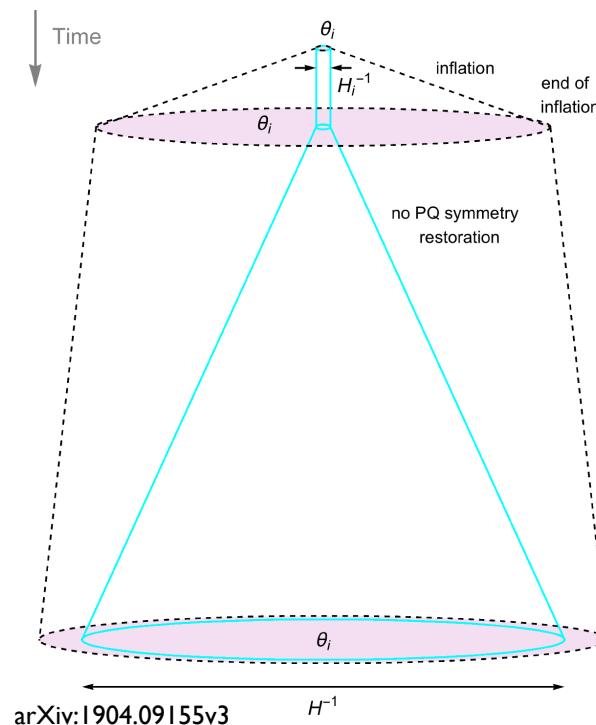
L. Di Luzio et al., Phys. Rep. 870, 1–117 (2020).



$$\rho_a \propto \frac{\theta^2}{m_a^{1 \div 1.5}}$$

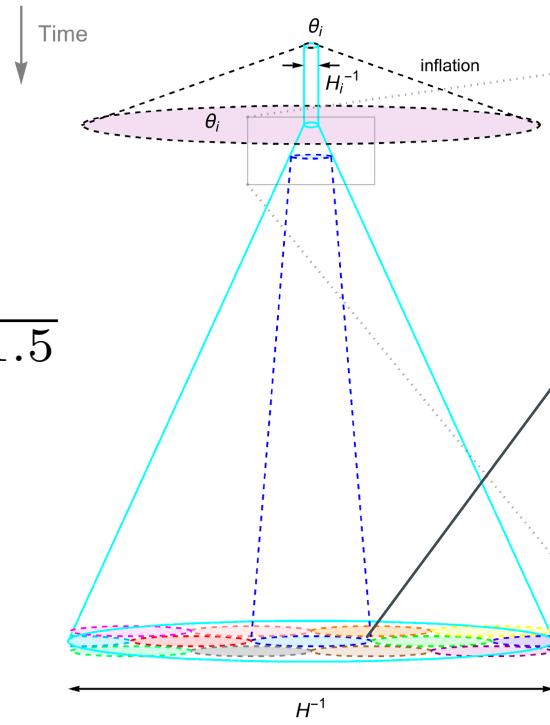
# Pre and Post Inflationary Scenarios

PQ symmetry breaks before end of inflation



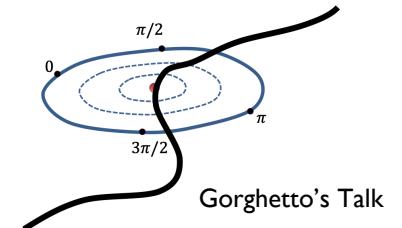
$$-\pi < \theta < \pi$$

PQ symmetry breaks after end of inflation



$$\langle \theta^2 \rangle \sim 1$$

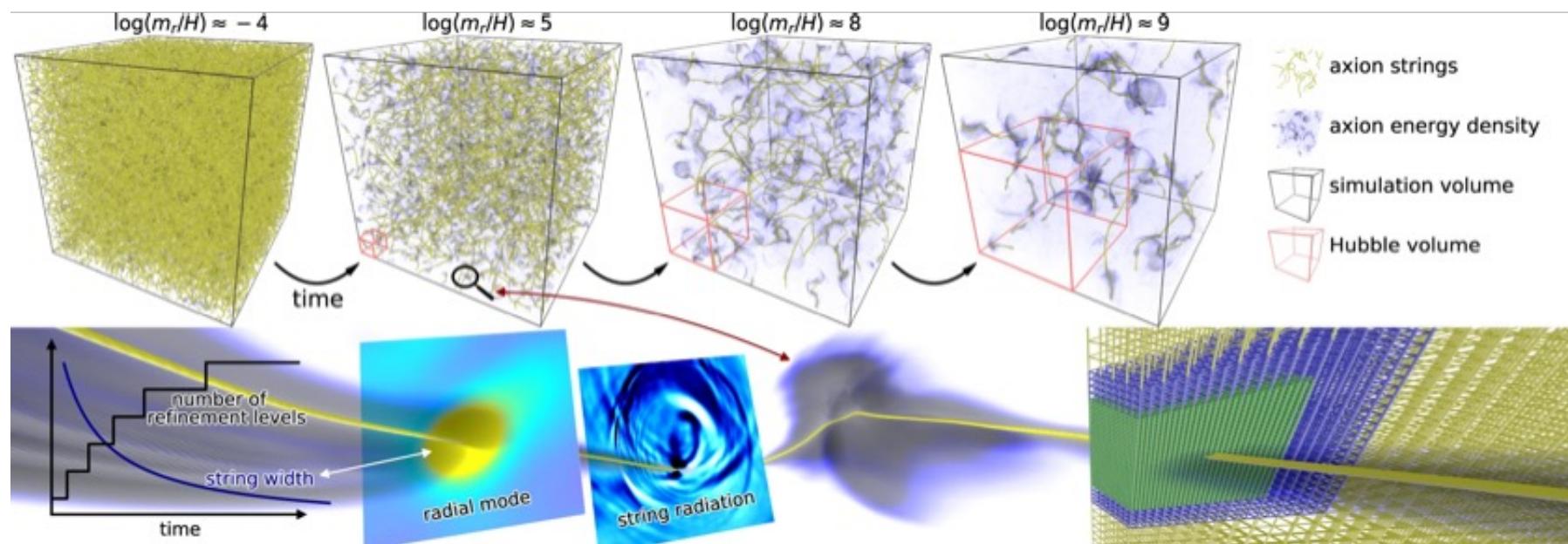
Axion String



# Axions DM From Axion Strings

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

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



Massive bosons  
(integer spin)

Ultralight  
bosons

Moduli and  
dilatons

Higgs,  $H$

Scalars  
(spin 0,  $CP$  even)

Axions and  
ALPs

QCD  
axion

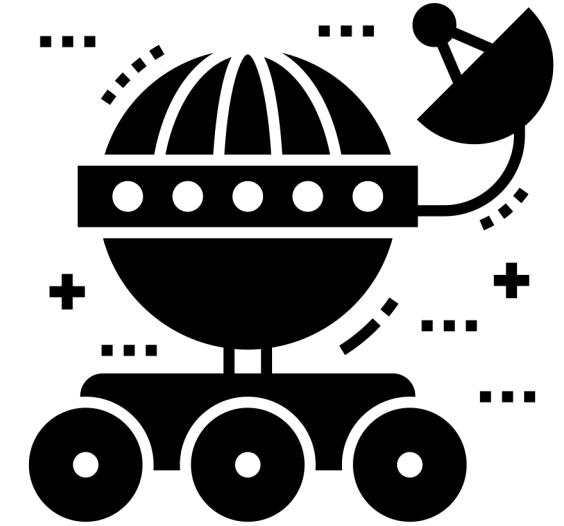
Pseudo-scalars  
(spin 0,  $CP$  odd)

Hidden photon

Vectors  
(spin 1)

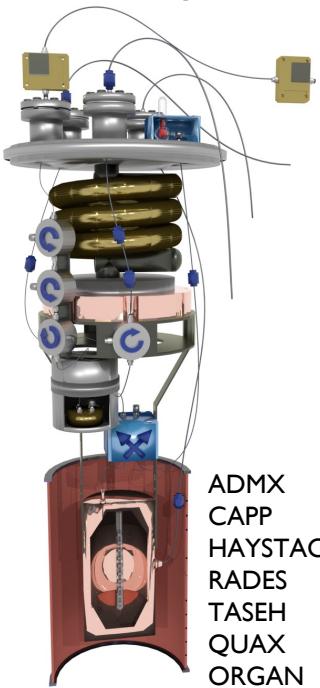
W/Z bosons

# SEARCH FOR AXION DARK MATTER

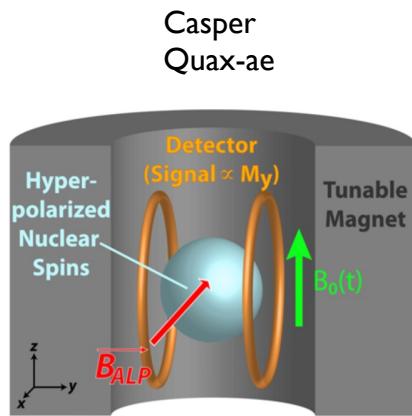


Created by ProSymbols  
from the Noun Project

## Haloscopes



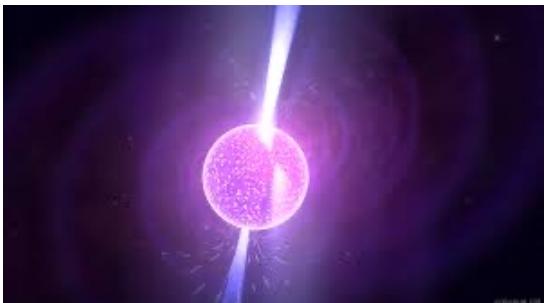
## Spin resonance



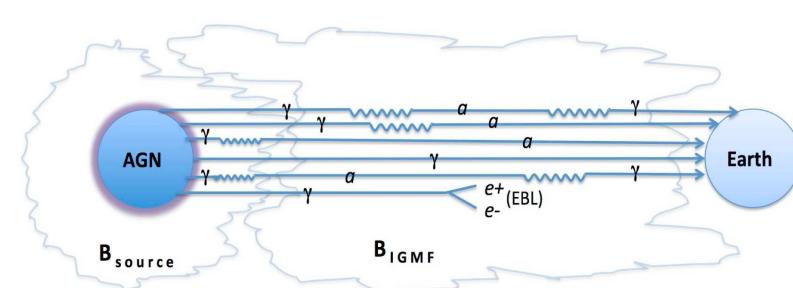
## Fifth force experiments



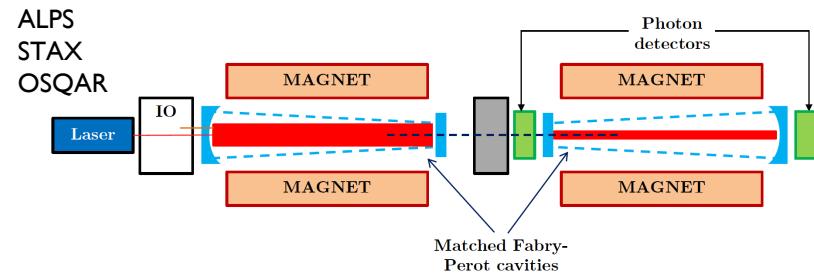
## Stars



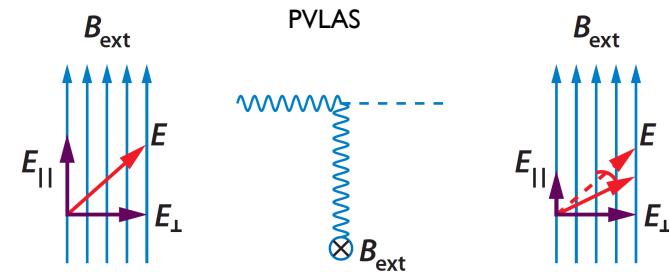
## Gamma ray transparency



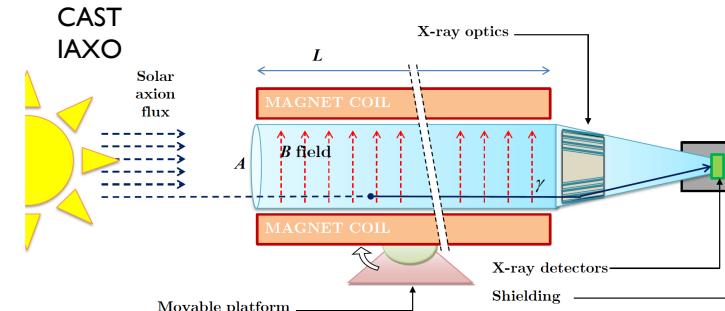
## Light shining through wall experiments



## Polarization experiments



## Helioscopes

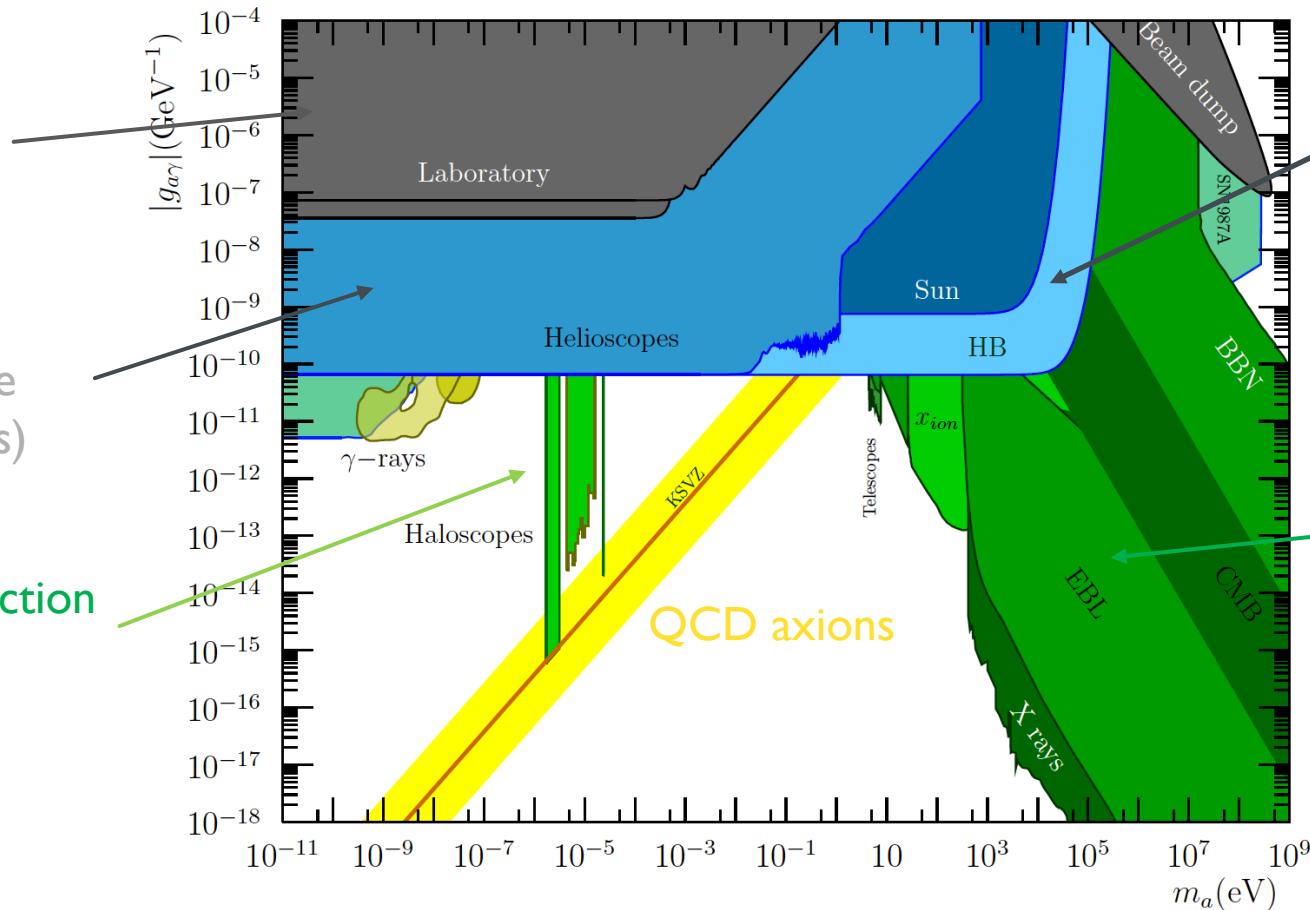


# Limits

Laboratory experiments

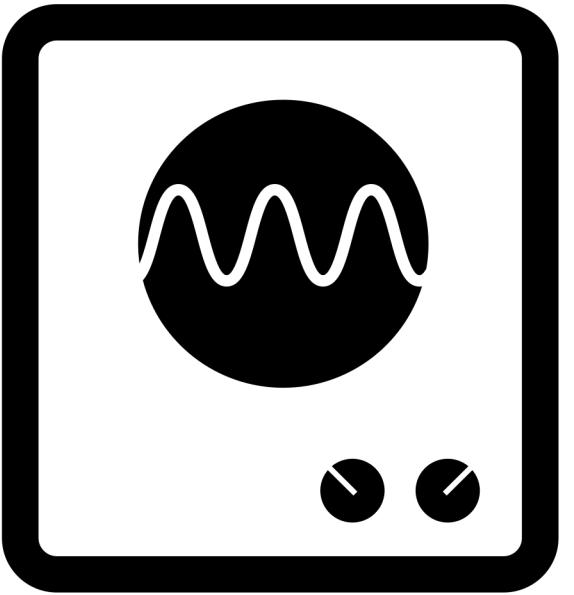
Detection of axions from the Sun (Elioscopes)

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 telescopes. Similar searches with X-rays and extragalactic background light (EBL) or H ionization.



**Created by James Christopher  
from the Noun Project**

## RESONANT SEARCHES

# Sikivie Haloscope

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

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

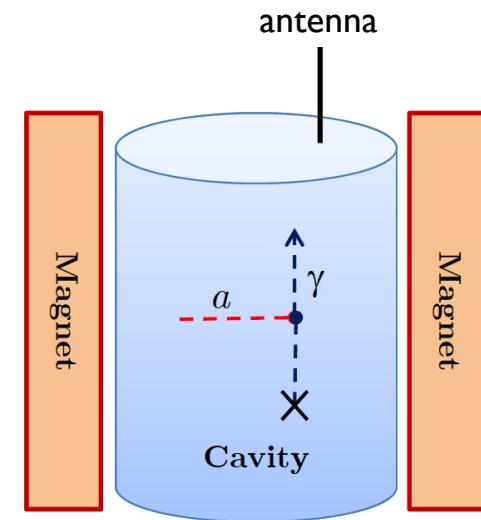
$$P_{\text{sig}} = \left( g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \times \left( \frac{\beta}{1 + \beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mnl} Q_L \right)$$

$\beta$  antenna coupling to cavity

$V$  cavity volume

$C_{mnl}$  mode dependent factor about 0.6 for TM010

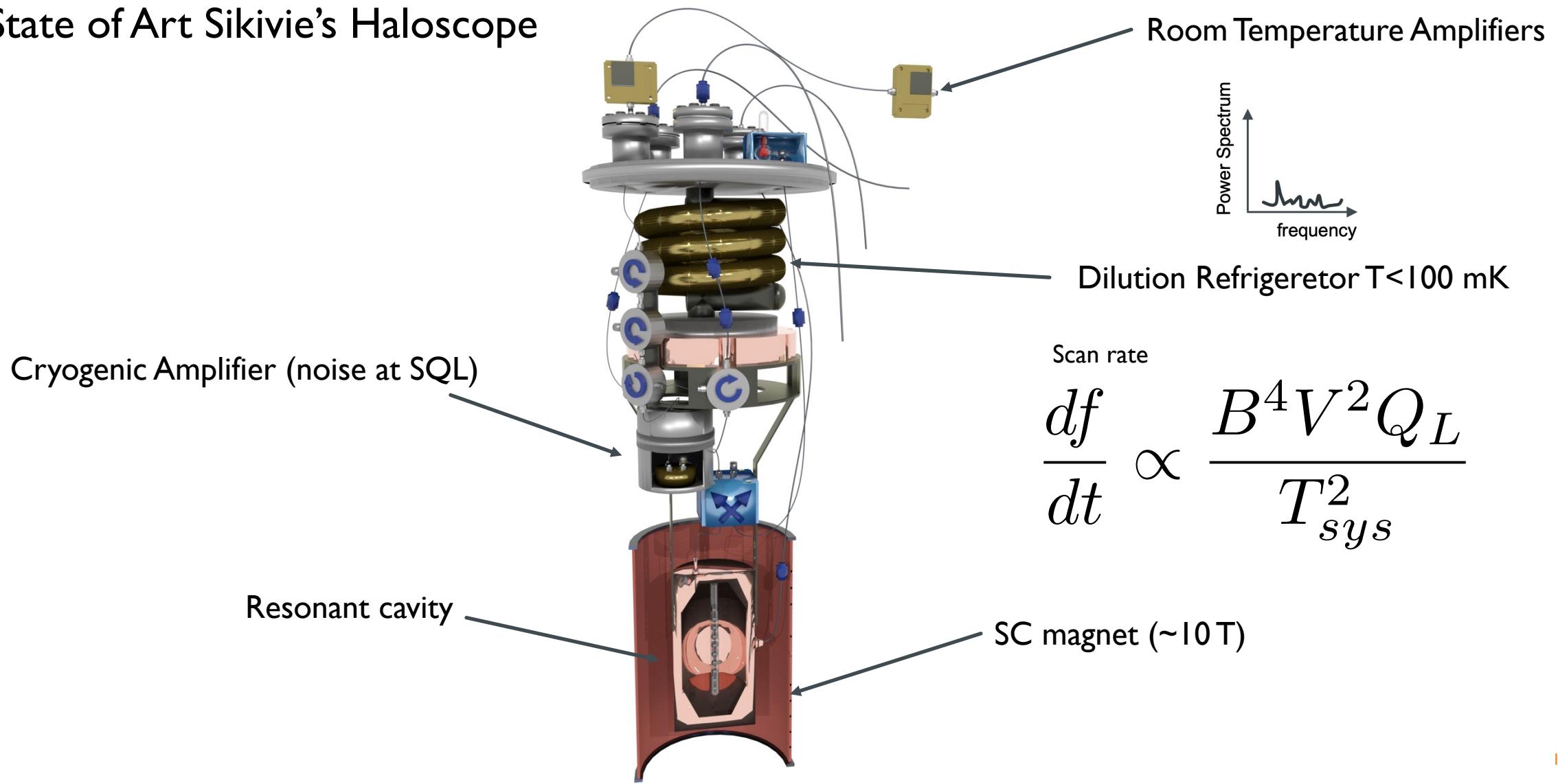
$Q_L$  cavity “loaded” quality factor



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

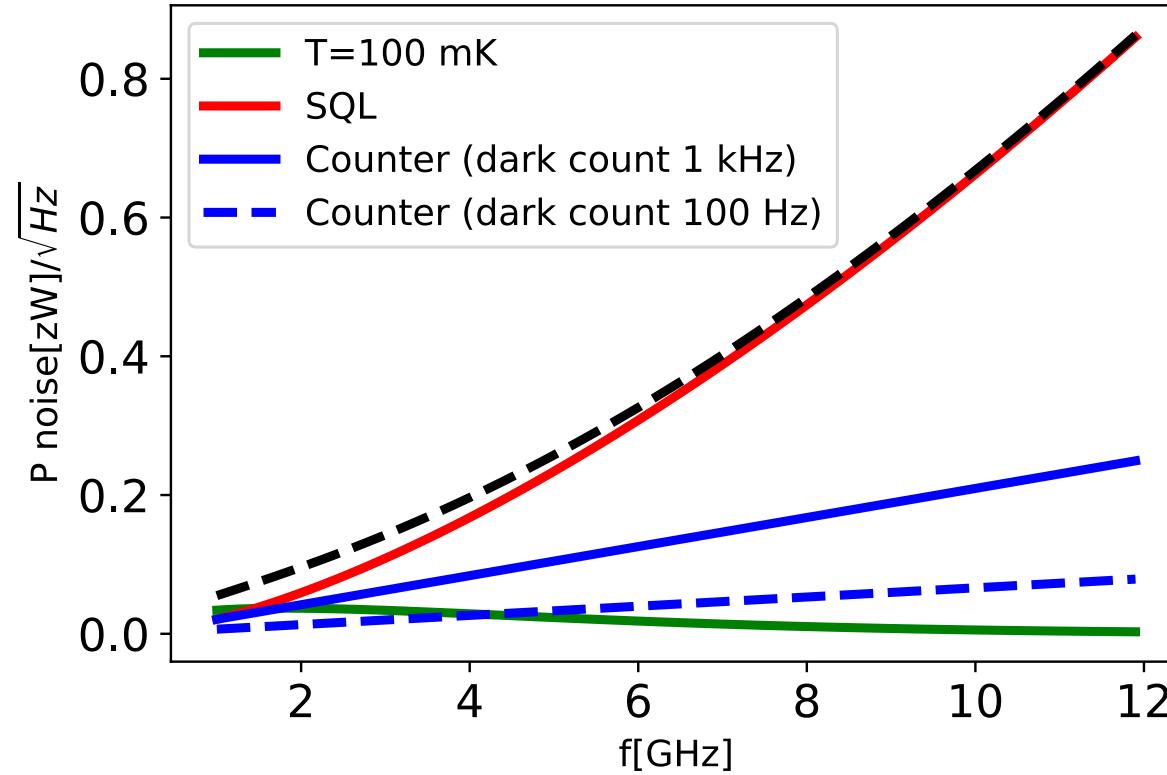
$$\hbar\omega \simeq m_a c^2$$

## State of Art Sikivie's Haloscope



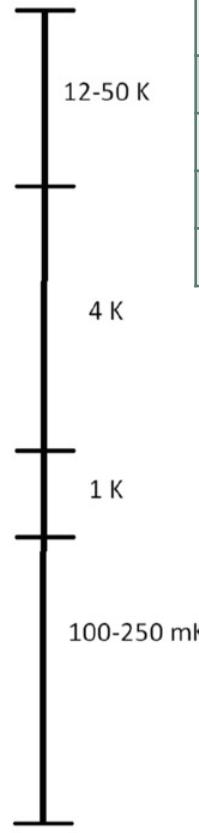
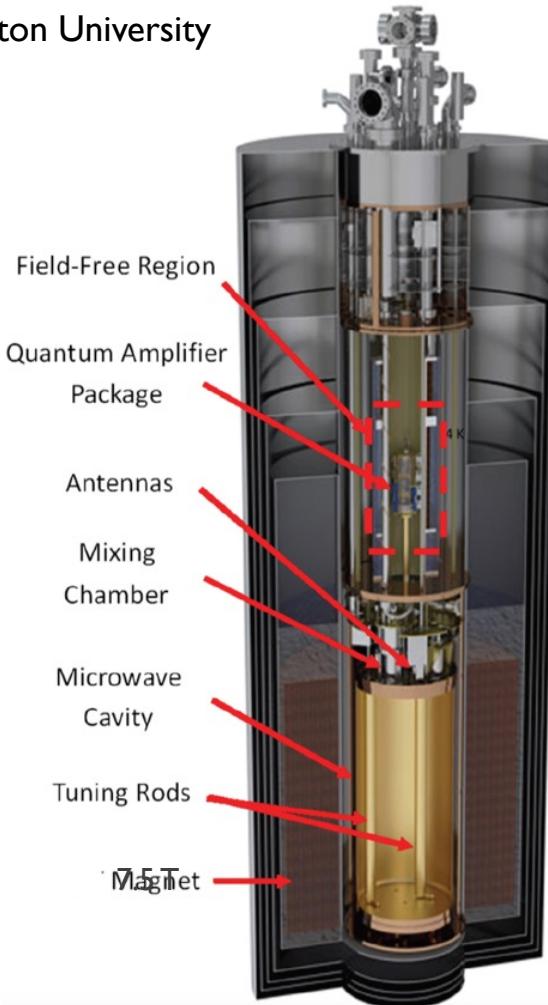
Sikivie Phys. Rev. D 32, 11 (1985)

# Noise in Haloscopes

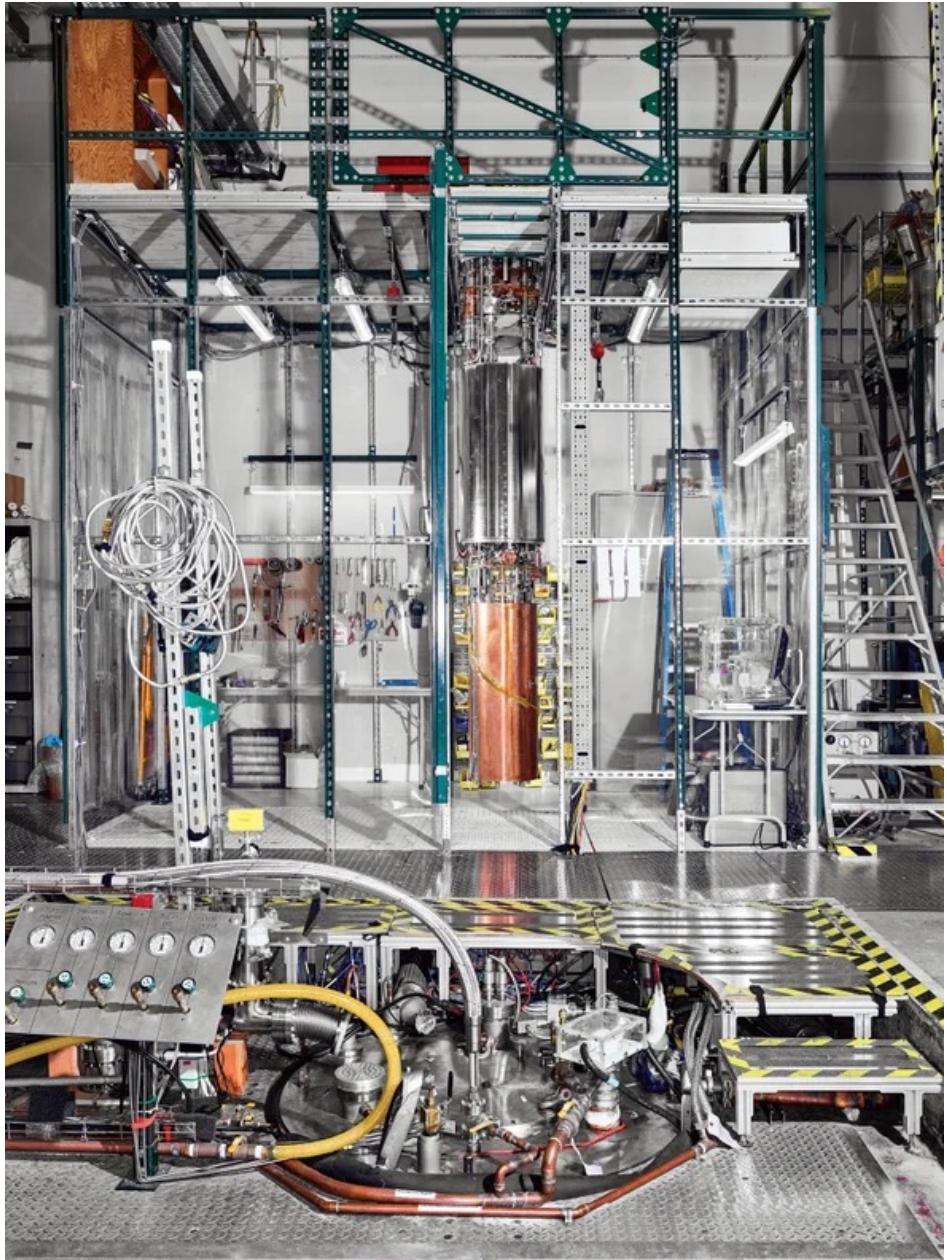


# ADMX – Axion Dark Matter Experiment

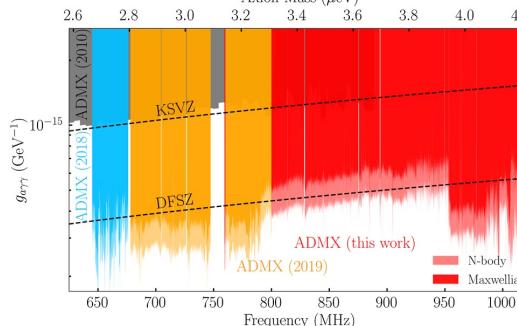
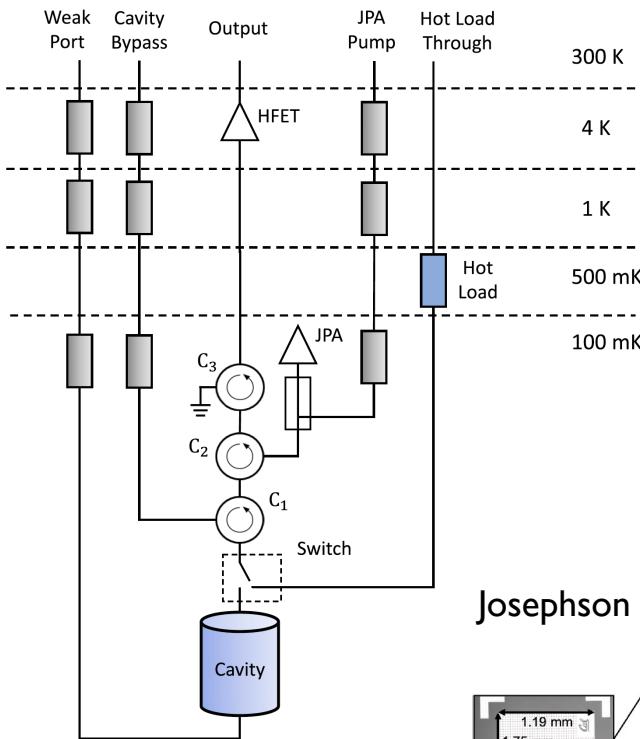
Washington University



ADMX	800 MHz
Volume	136 L
$Q_0$	200,000
B	7.5 T
$T_{\text{noise}}$	600 mK

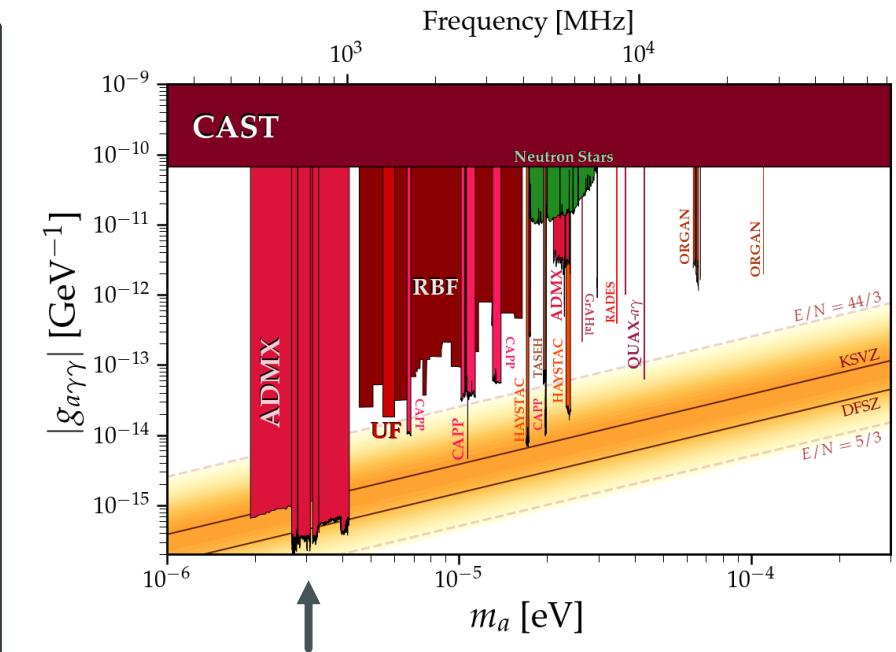
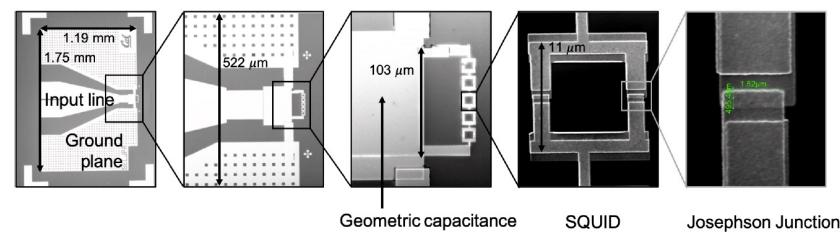


# ADMX – Axion Dark Matter Experiment



PHYSICAL REVIEW LETTERS 127, 261803 (2021)

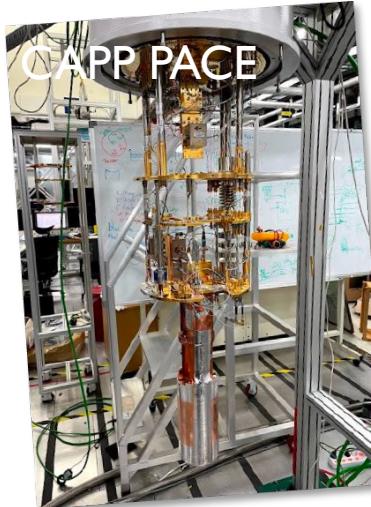
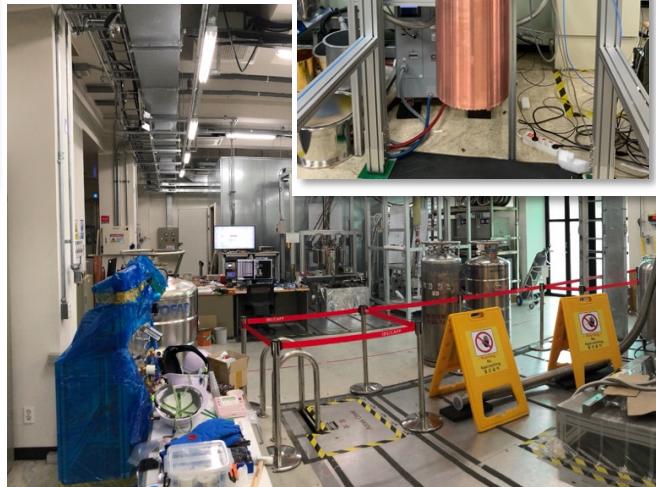
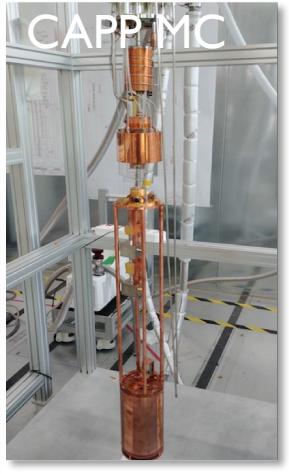
Josephson parametric amplifier



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

# IBS CAPP— Center of Axion and Precision Physics

South Korea



<b>CAPP 12T</b>	1.1 GHz
Volume	37 L
$Q_0$	90,000
B	12 T
$T_{noise}$	120 mK

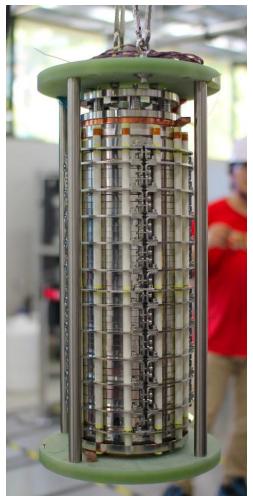
<b>CAPP 8T</b>	1.6 GHz
Volume	3.47 L
$Q_0$	90,000
B	8 T
$T_{noise}$	900 mK

<b>PACE</b>	2.2 GHz
Volume	1.12 L
$Q_0$	90,000
B	7.2 T
$T_{noise}$	200 mK

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

<b>CAPP 18T</b>	4.79 GHz
Volume	1 L
$Q_0$	70,000
B	18 T
$T_{noise}$	500 mK

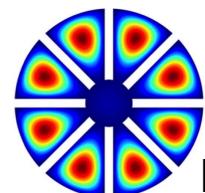
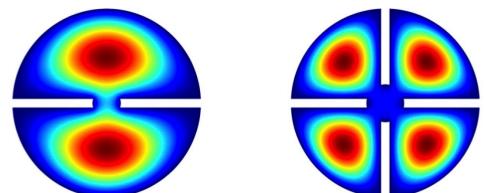
# IBS CAPP



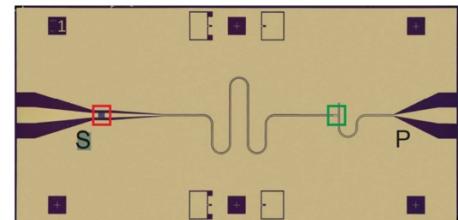
18 T HTS  
magnet



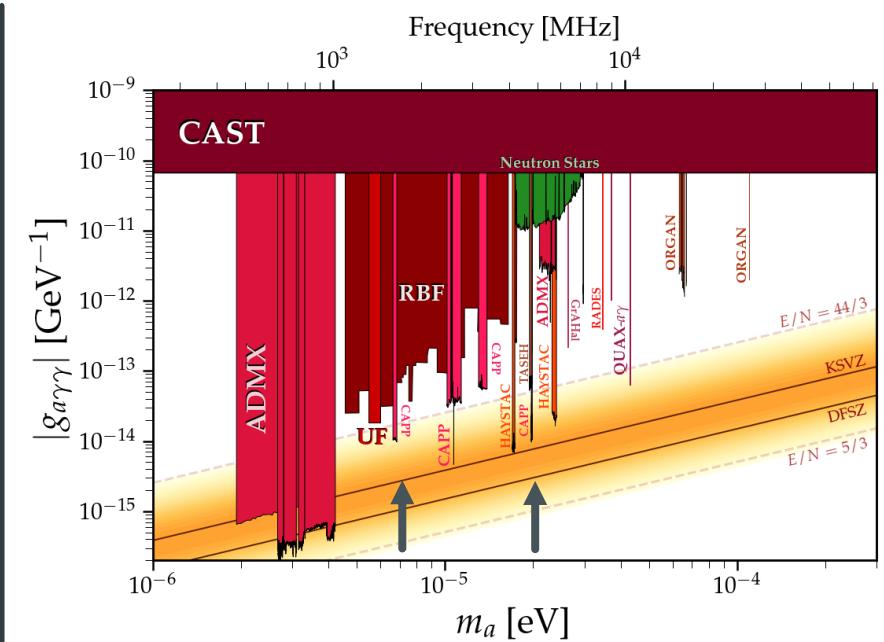
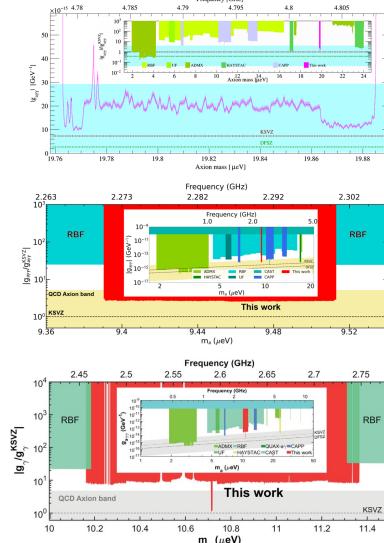
SC cavity



Multicell cavity



JPA



PHYSICAL REVIEW LETTERS 124, 101802 (2020)

PHYSICAL REVIEW LETTERS 125, 221302 (2020)

PHYSICAL REVIEW LETTERS 126, 191802 (2021)

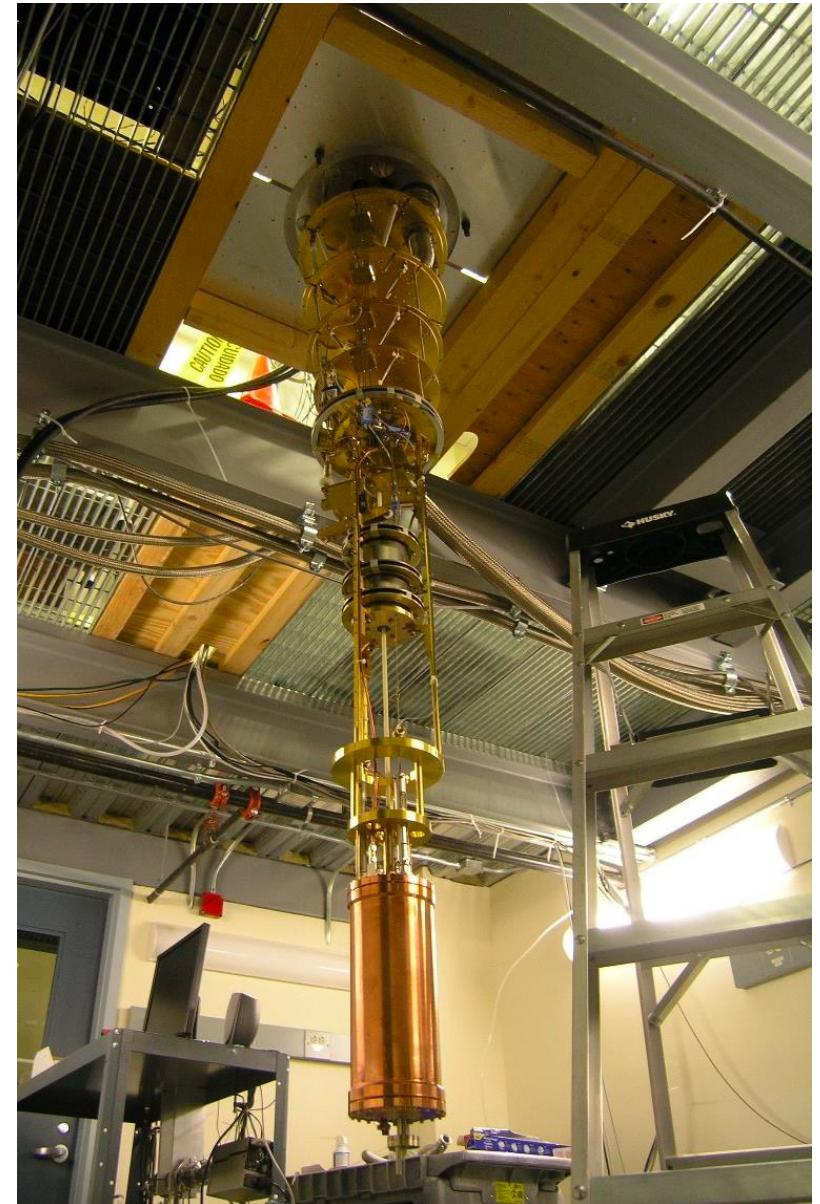
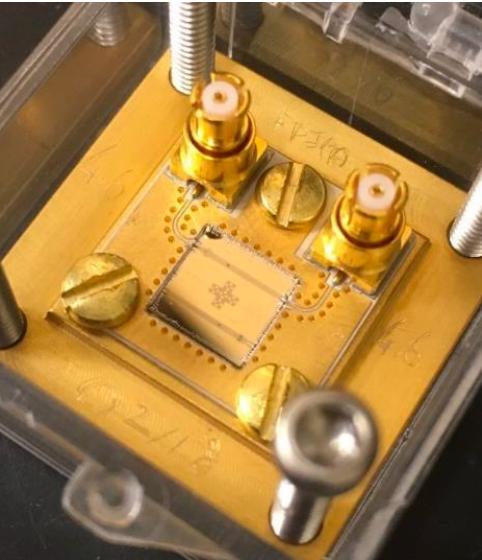
PHYSICAL REVIEW LETTERS 128, 241805 (2022)

arXiv:2207.13597

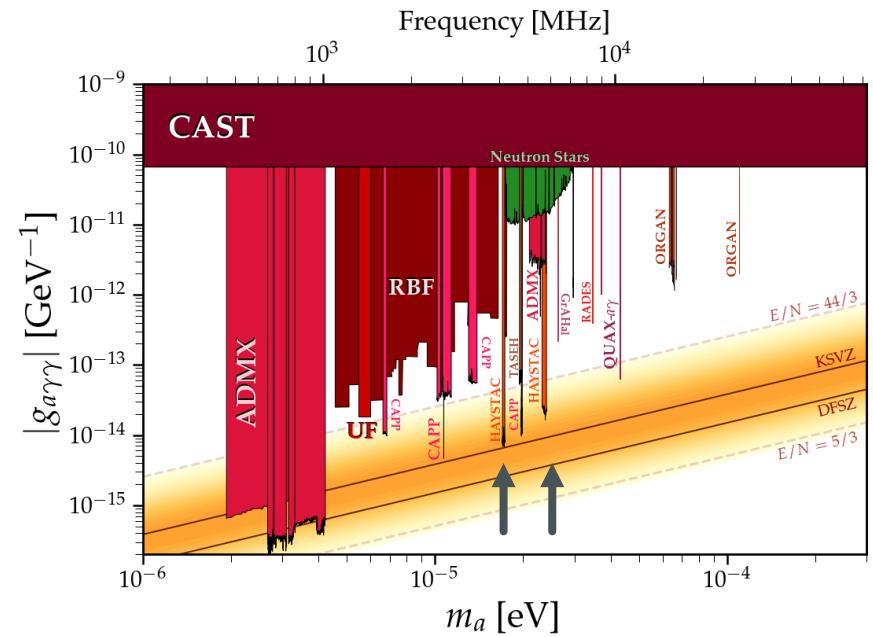
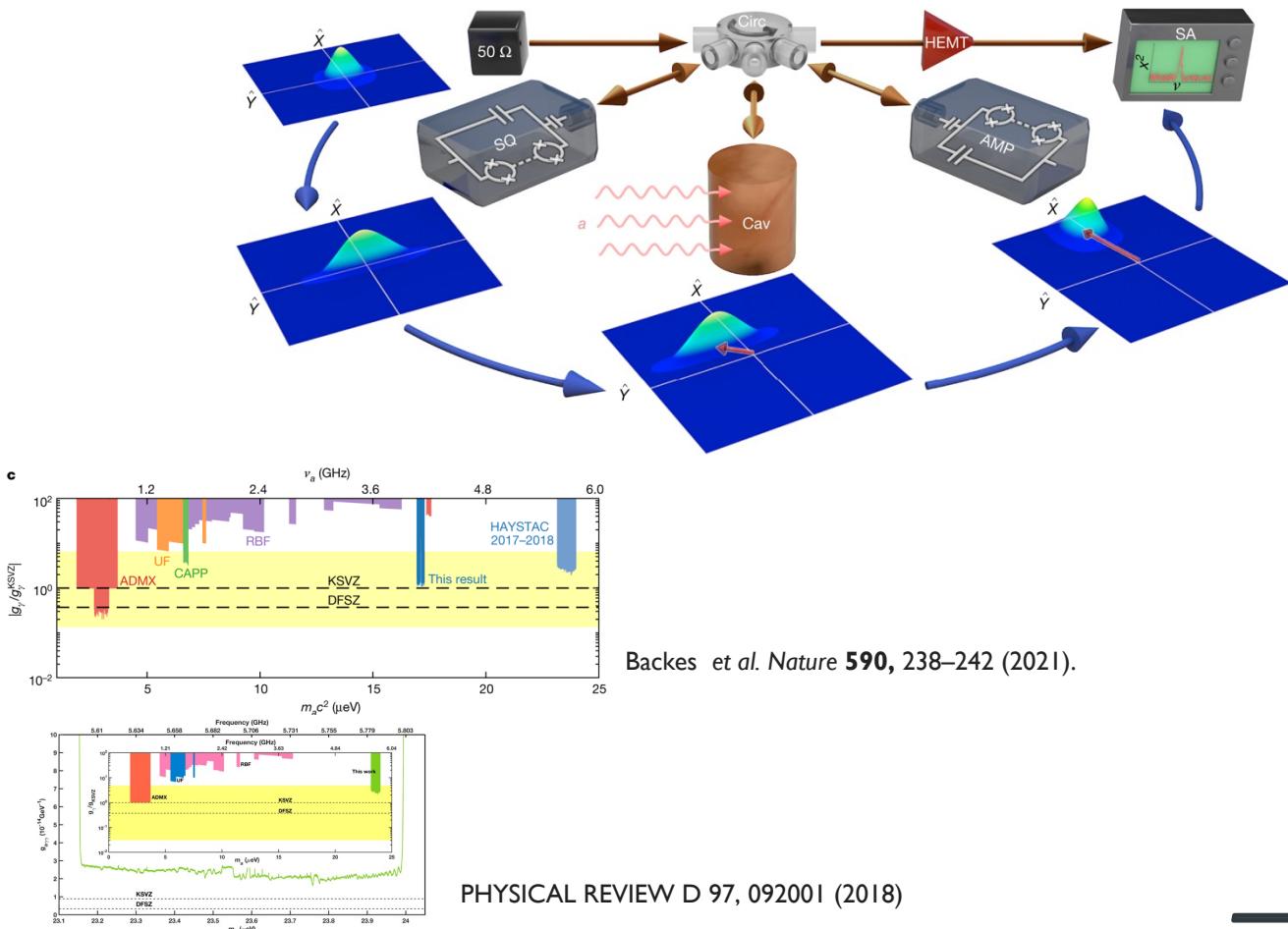
# Haystac

Yale's Wright Lab

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

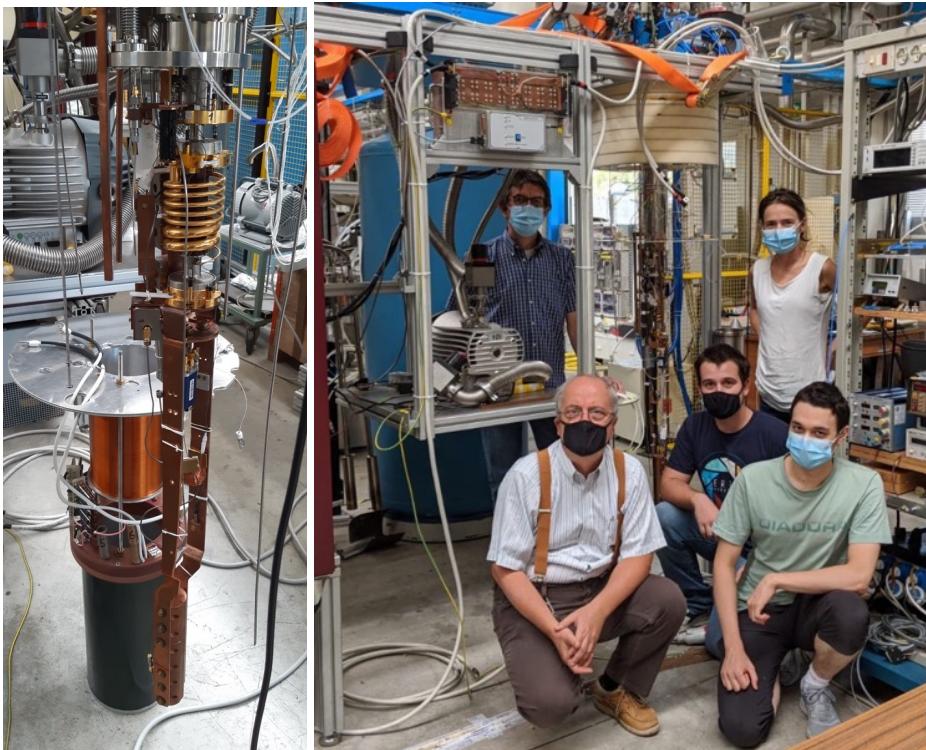


# HAYSTAC - Squeezed State Receiver



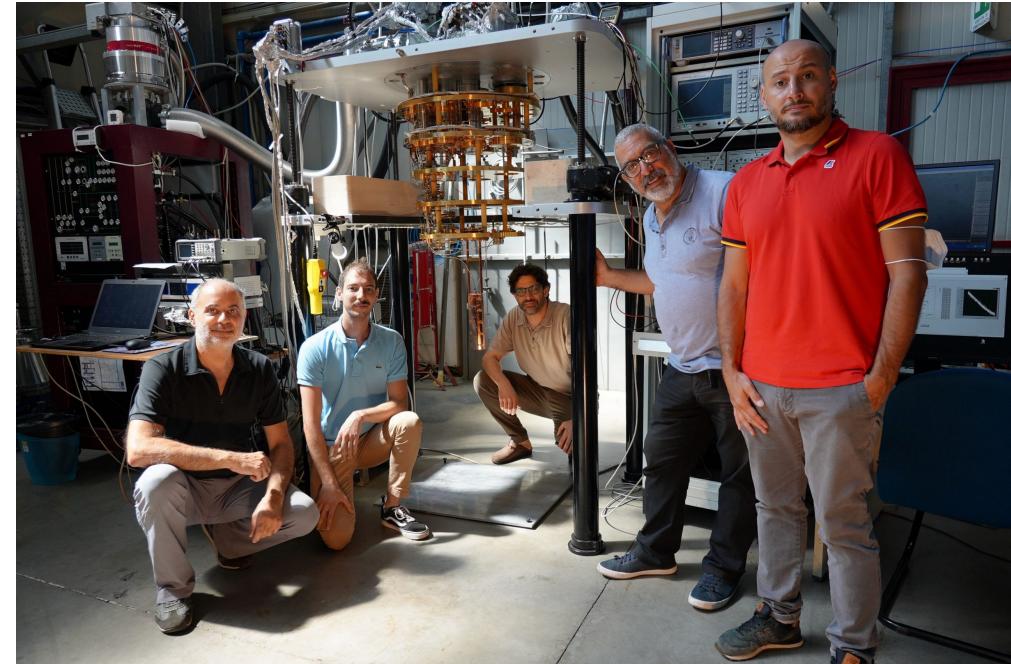
# QUAX

Laboratori Nazionali di Legnaro (LNL)

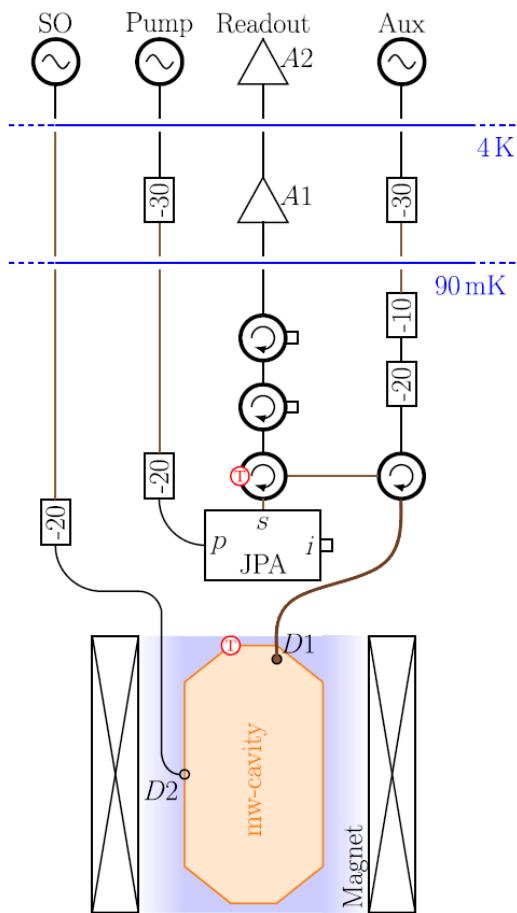


Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Frascati (LNF)

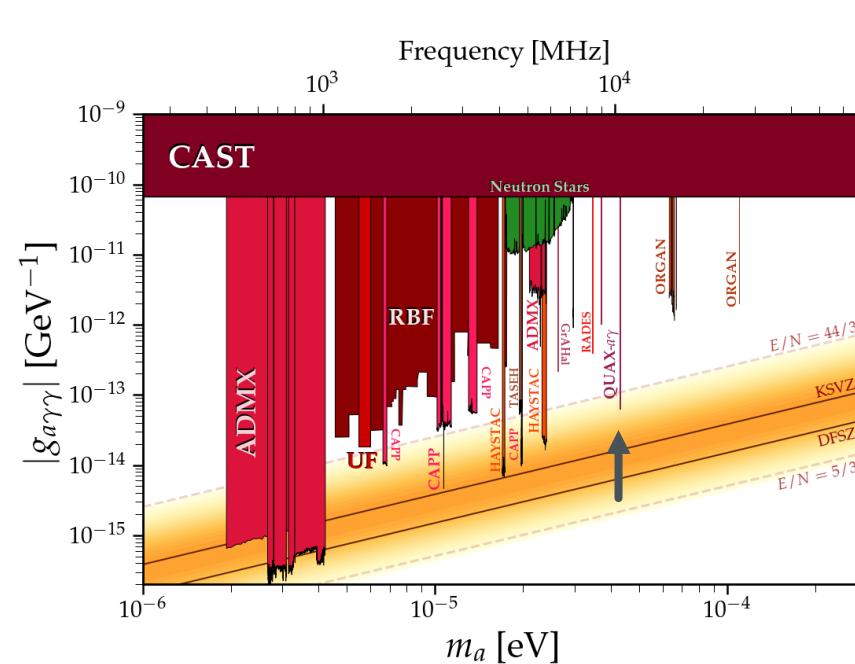


# QUAX - LNL

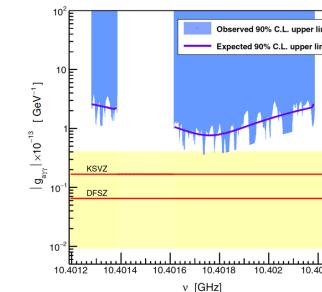


QUAX	10 GHz
Volume	0.08 L
$Q_0$	80,000
B	8 T
$T_{\text{noise}}$	1 K

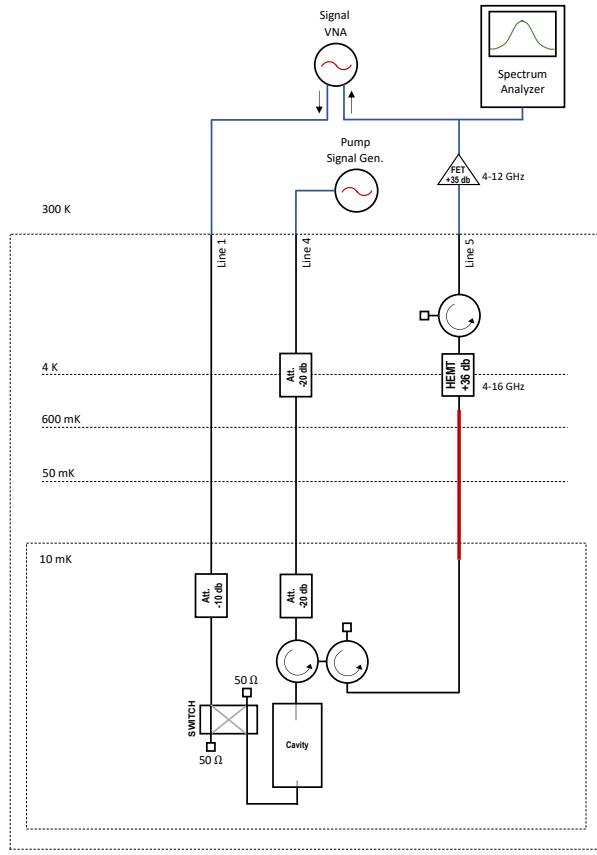
N Roch et al. PRL 108, 147701 (2012)



PHYS. REV. D 103, 102004 (2021)



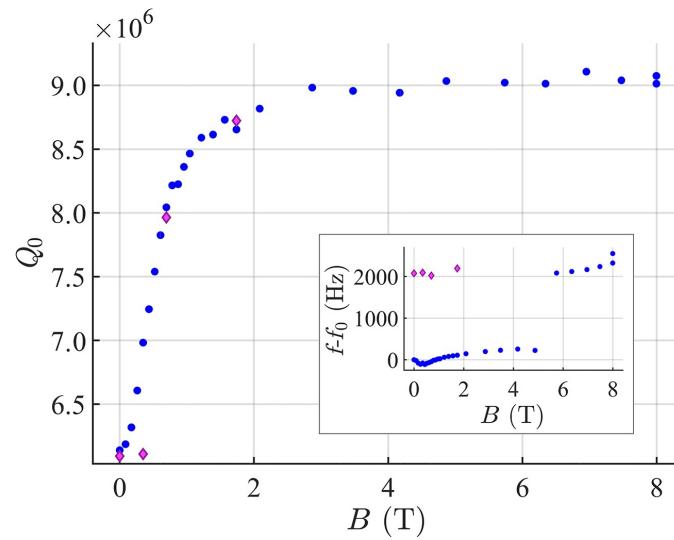
# QUAX – Setting Up a New Haloscope at LNF



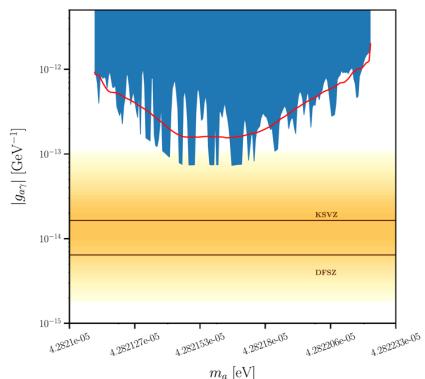
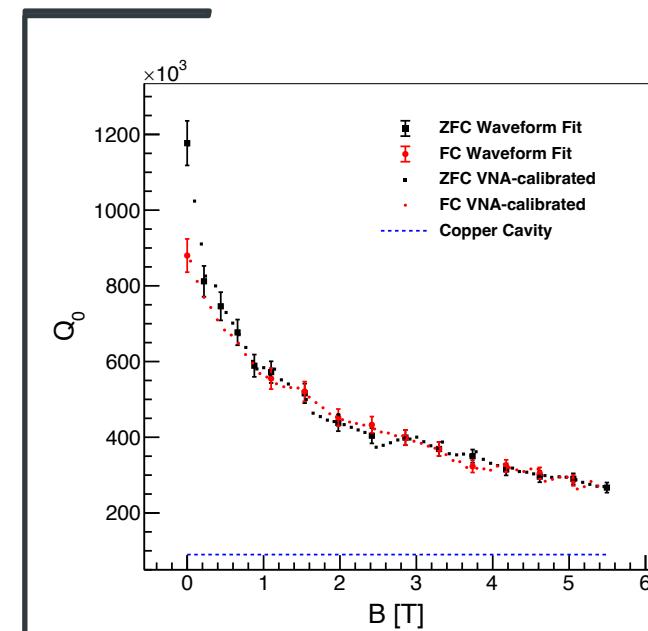
QUAX	8.5 GHz
Volume	0.14 L
$Q_0$	100,000
B	9 T
$T_{noise}$	5 K



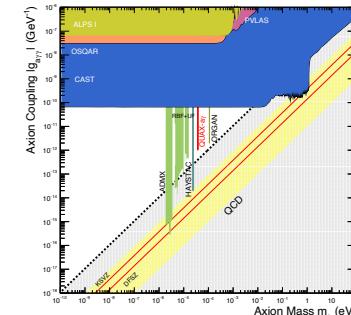
# QUAX: Dielectric and Superconducting Cavities



PHYSICAL REVIEW APPLIED 17, 054013 (2022)



PHYS. REV. D 106, 052007 (2022)

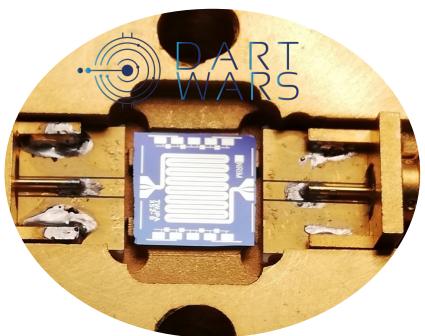


Phys. Rev. D 99, 101101(R) (2019)

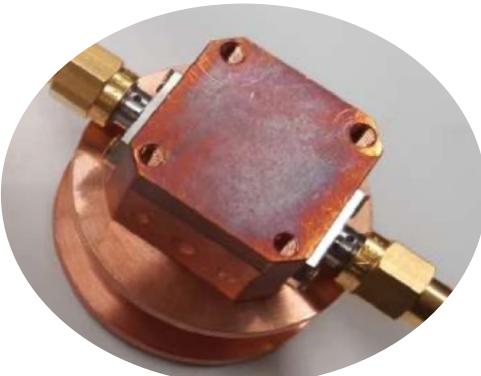


# QUAX: Superconducting Devices

TWPA



<https://arxiv.org/abs/2111.01512>

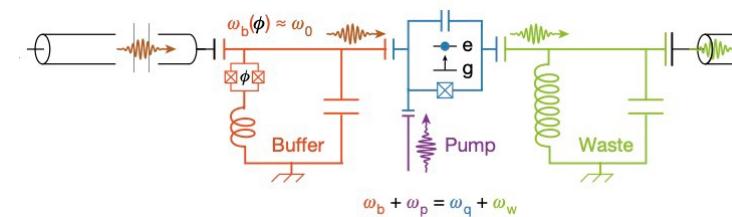


arXiv:2205.02053

JPA

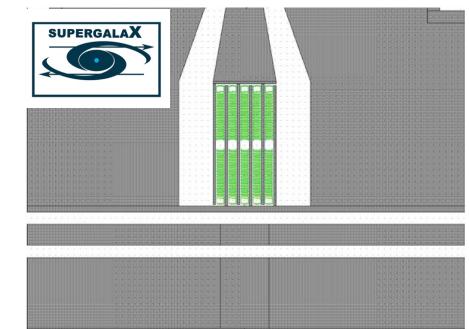
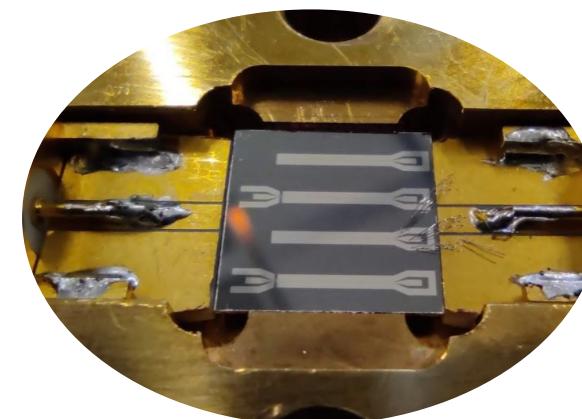


QubIT

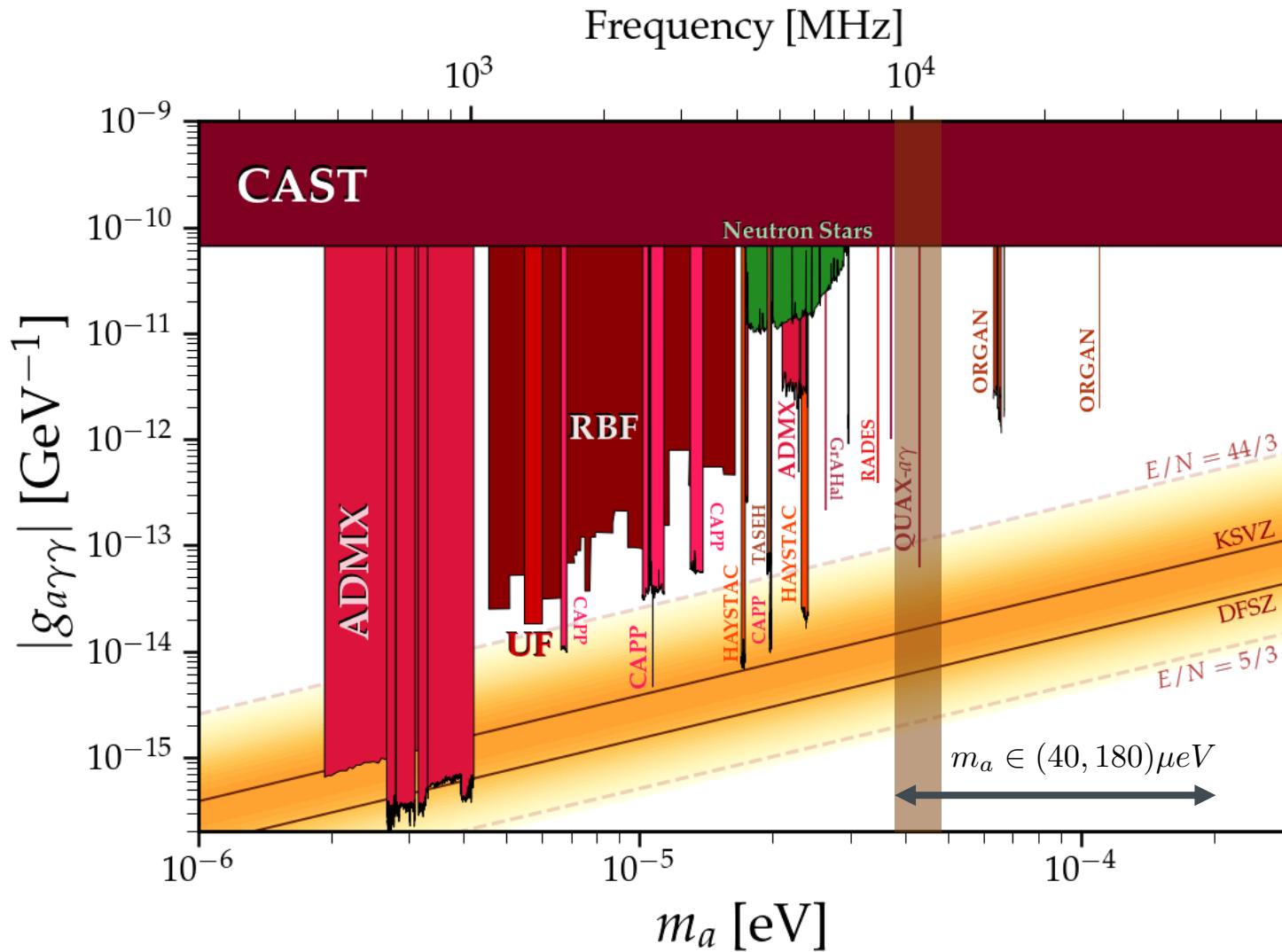


R. Lescanne et al, Phys. Rev. X 10, 021038 (2020)

Single microwave photon counters



# QUAX LNF&LNL 2023-2025

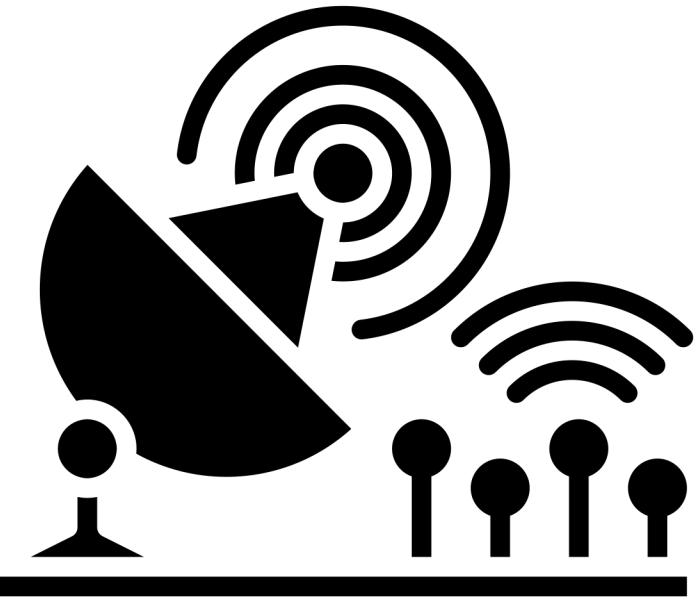


LNF:

- Superconducting cavity  $Q_0 > 2 \times 10^5$
- $B = 9\text{T}$
- Multicavity

LNL:

- Dielectric cavity  $Q_0 > 10^6$
- $B = 14\text{T}$
- Single cavity

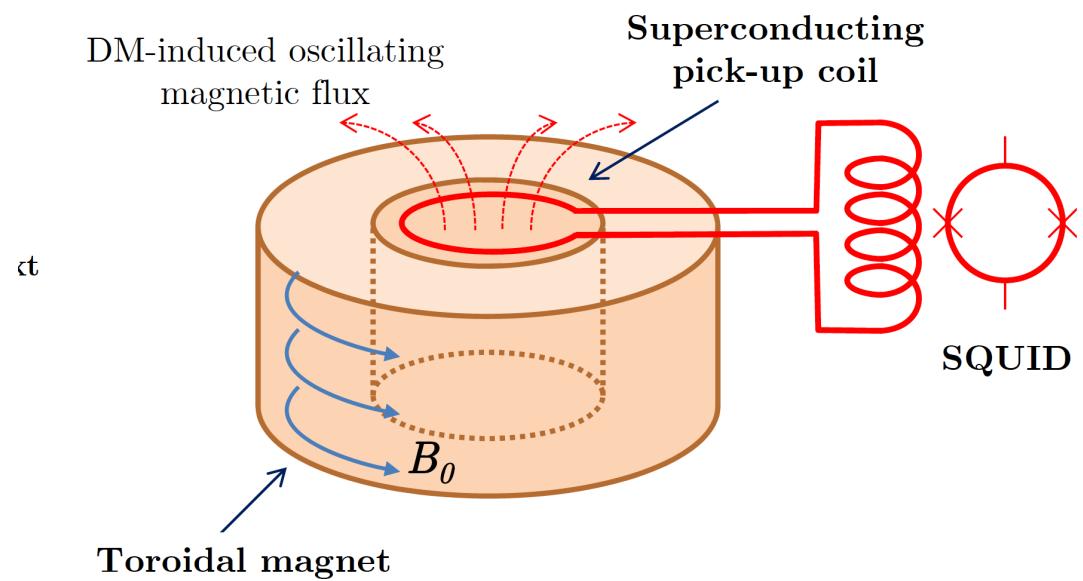


**Created by Scribble.liners  
from the Noun Project**

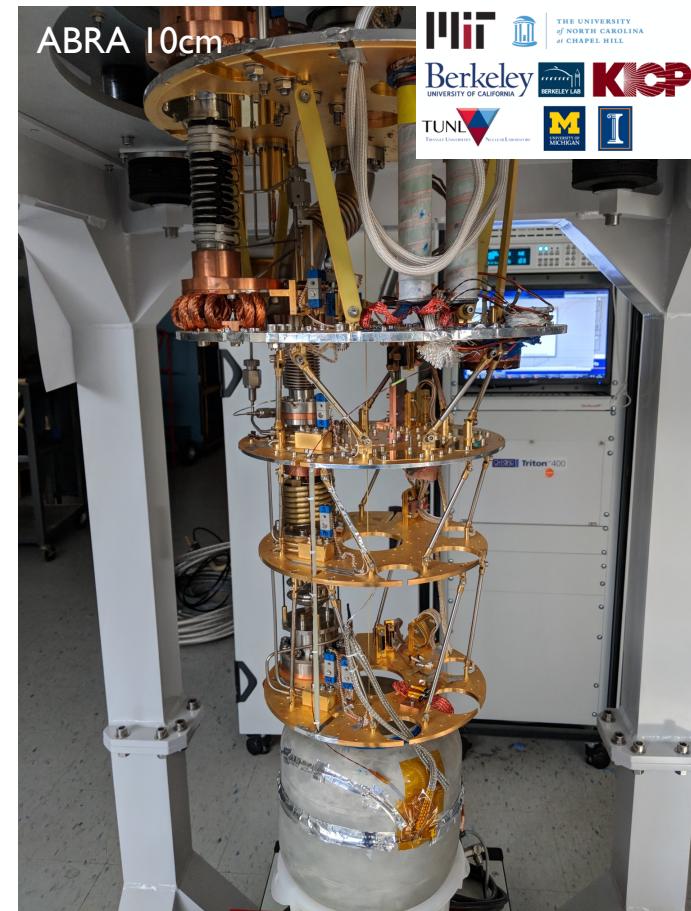
For details see P. Sikivie REVIEWS OF MODERN PHYSICS, VOLUME 93, JANUARY–MARCH 2021

## FUTURE EXPERIMENTS (AN INCOMPLETE SELECTION)

# ABRACADABRA & DM-RADIO from kHz to 100 MHz



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

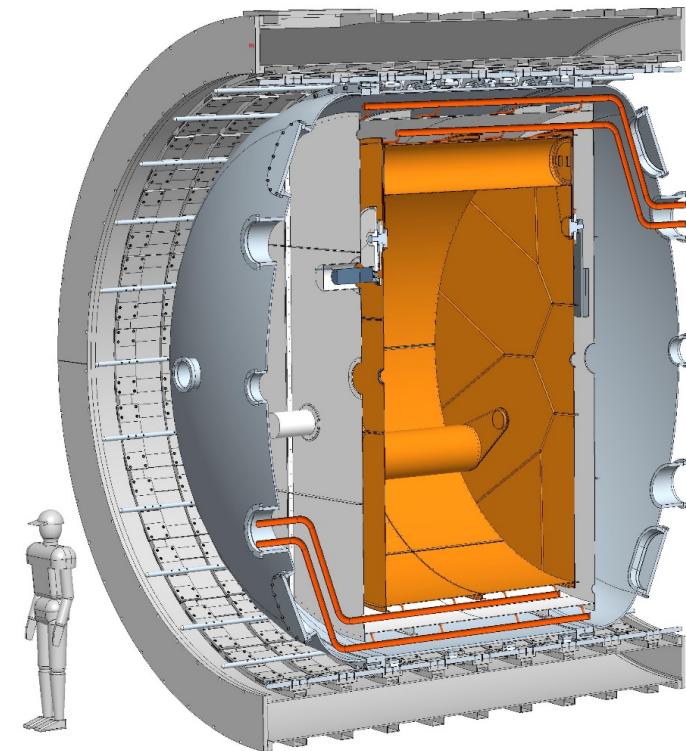


# FLASH (PREVIOUSLY KLASH): Finuda Magnet for Light Axion SearchH at 100-300 MHz

Recycling of the FINUDA I.IT magnet for a 100 MHz haloscope

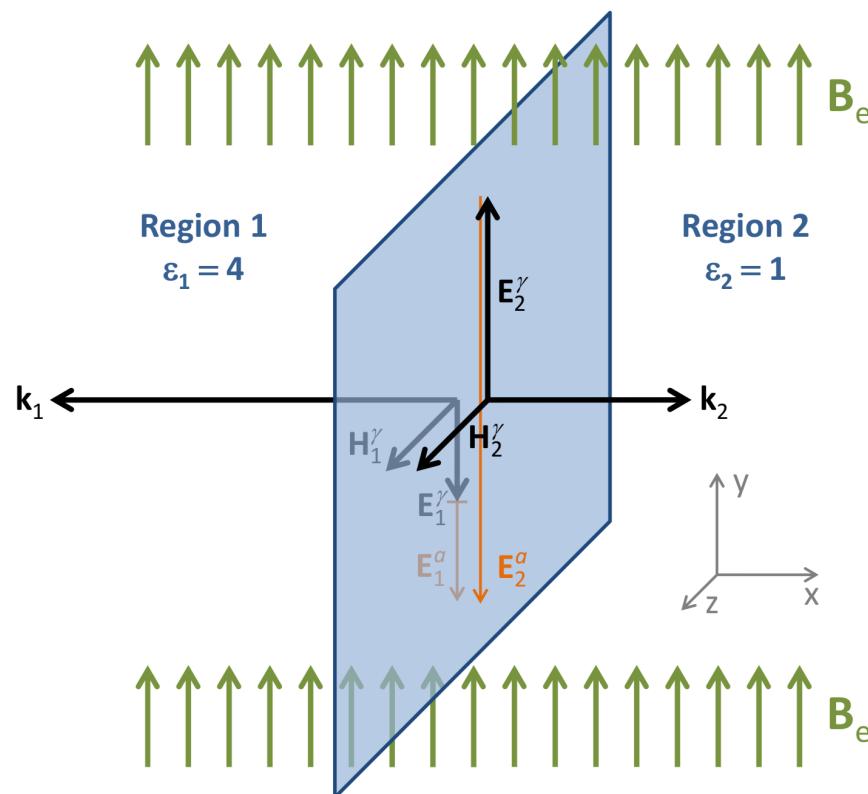


Istituto Nazionale di Fisica Nucleare  
Laboratori Nazionali di Frascati

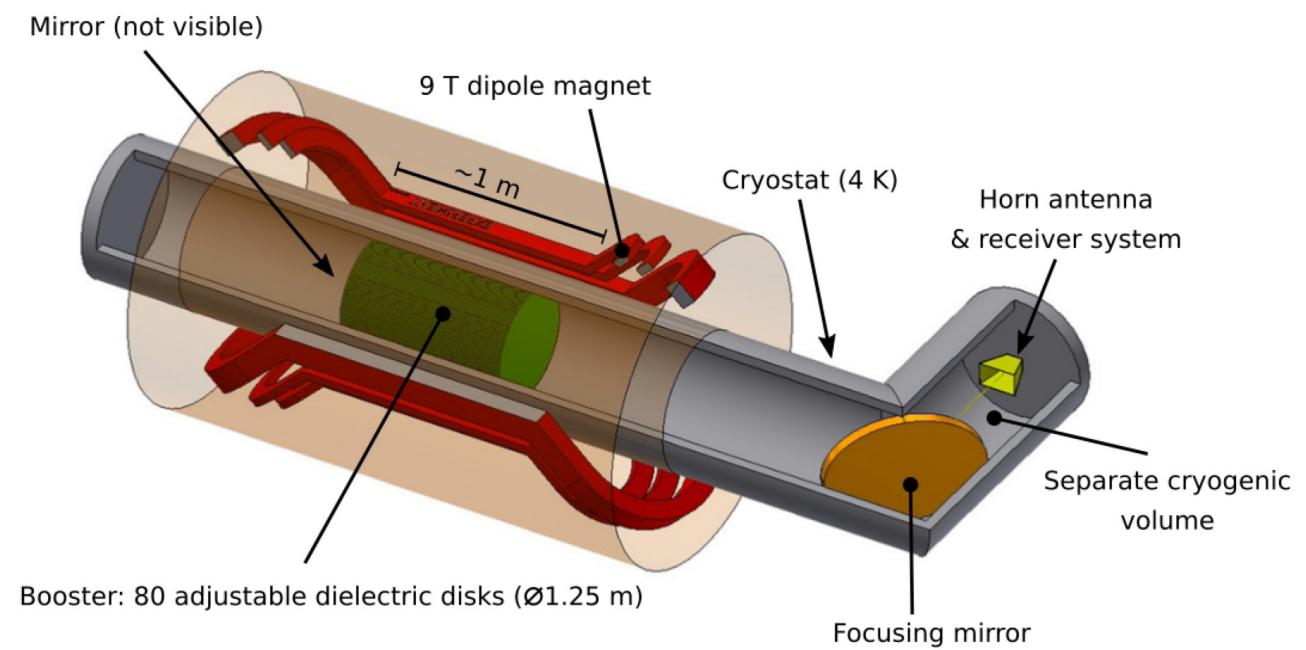


KLASH CDR arxiv:1911.02427

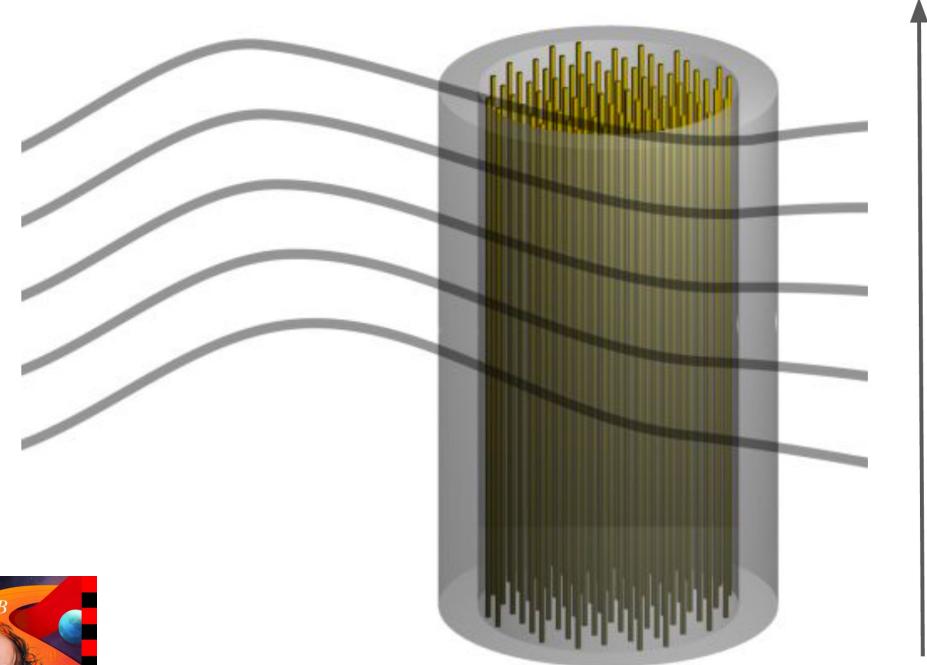
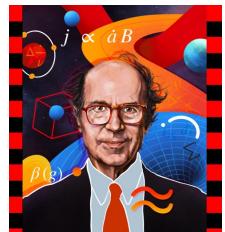
# MADMAX Magnetized Disk and Mirror Axion eXperiment at 10-50 GHz



arXiv:1901.07401



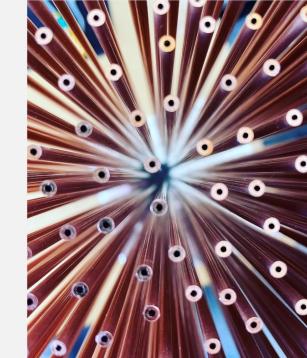
# ALPHA - Tunable Axion Plasma Haloscope at 5-50 GHz



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

$$\underline{E} = -g B_0 a \frac{\omega_a^2 - i\omega_a \Gamma}{\omega_a^2 - \omega_p^2 - i\omega_a \Gamma}$$

B

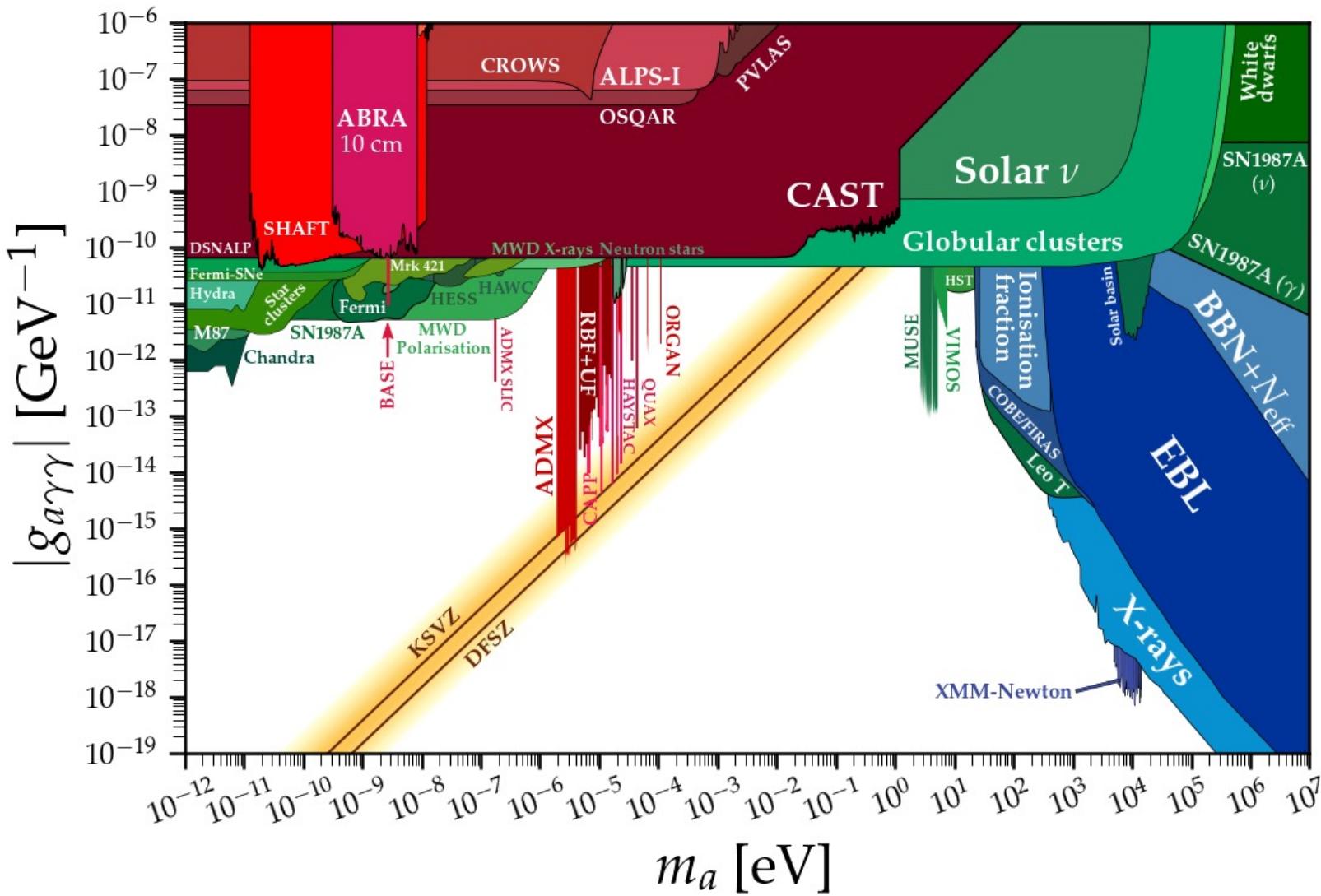


UNIVERSITET  
STOCKHOLM  
Stockholm  
University

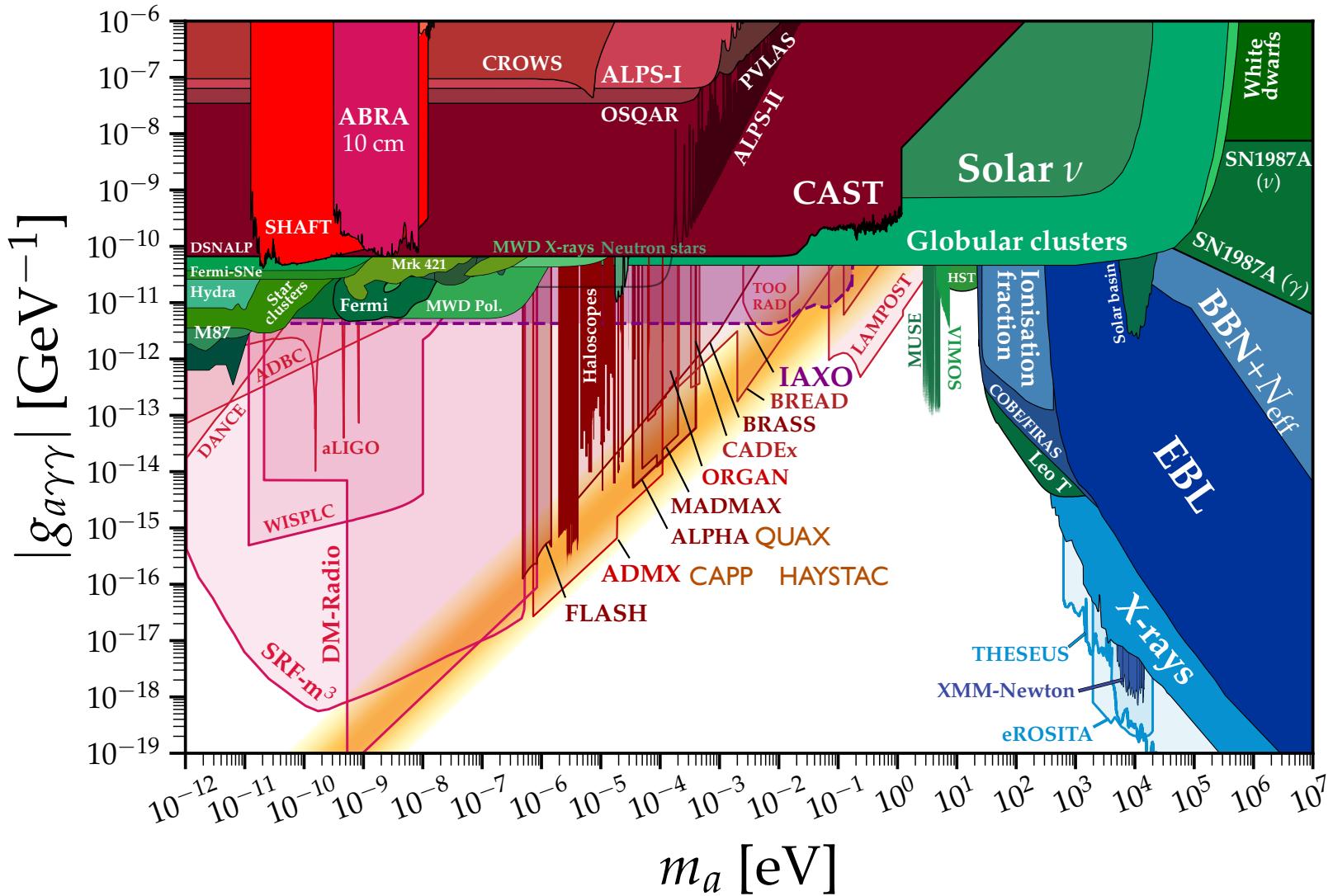
Oskar Klein  
centre

alpha

# Axion DM searches now



# Projections for axion DM searches





Thank You