Axion experiments – part II

A *partial* overview of the experimental searches for axions and axion like particles

Lecce, September 14th, 2023

COST «Cosmic Wispers» Training School

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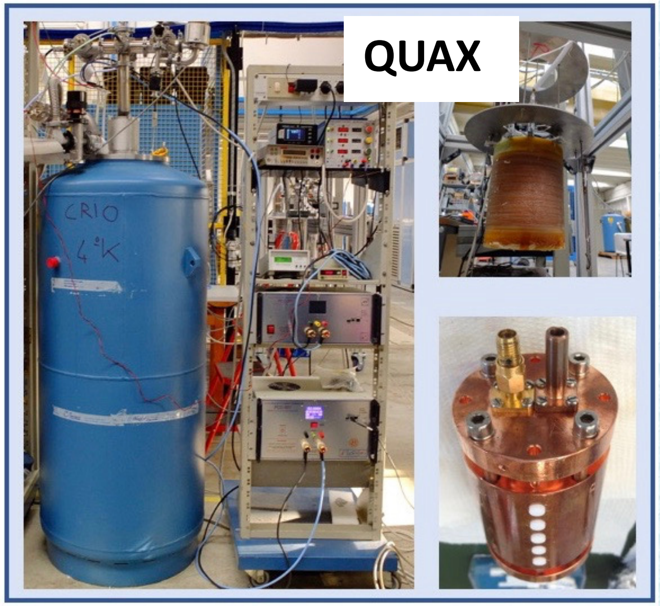
Laboratori Nazionali di Legnaro

Part II

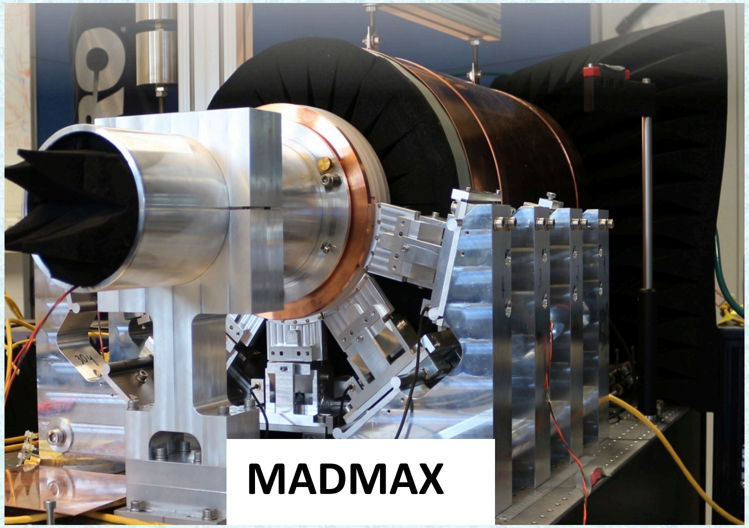
- Axion dark matter direct searches

[C] Haloscopes – Galactic axions

Magnetic haloscopes

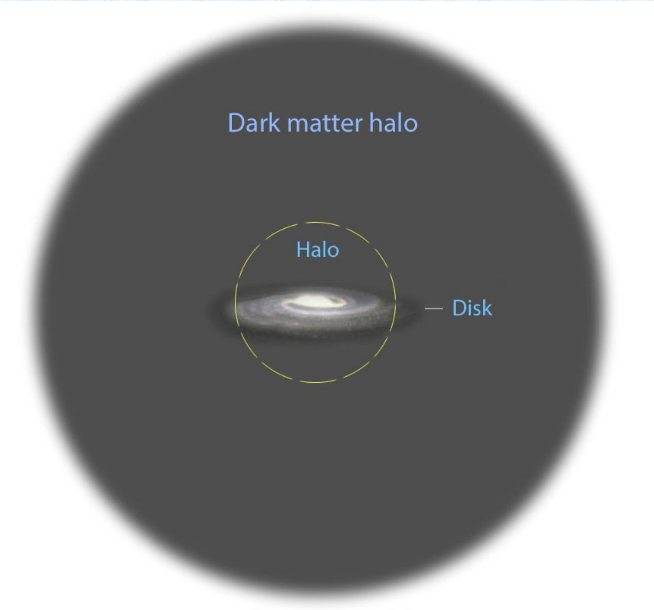


Dielectric haloscopes

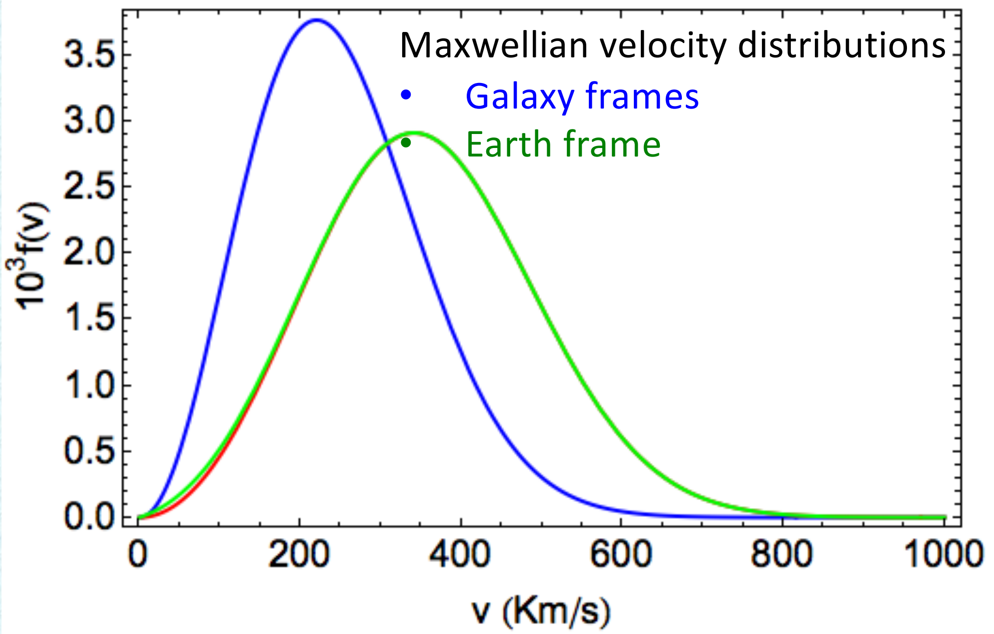


Standard Halo Model for ρ_{DM} and $f(v_a)$

Standard Halo Model: Isothermal, isotropic Maxwell-Boltzmann Distribution of DM assuming ρ_{DM} =0.3 – 0.45 Gev/cm^3



Milky Way model



$$f(v) = 4\pi \left(\frac{\beta}{\pi}\right)^{3/2} v^2 \exp(-\beta v^2)$$

Observed axion velocity $\mathbf{v}_a$=$\mathbf{v}$-$\mathbf{v}_E$, where the Earth velocity $\mathbf{v}_E$= $\mathbf{v}_{sun}$+$\mathbf{v}_{orb}$

$$f(v_a) = 2\left(\frac{\beta}{\pi}\right)^{1/2} \frac{v_a}{v_E} \exp(-\beta v_a^2 - \beta v_E^2) \sinh(2\beta v_E v_a)$$
$$\simeq 2\left(\frac{\beta}{\pi}\right)^{1/2} \frac{v_a}{v_E} \exp(-\beta(v_a - v_E)^2)$$

M. S. Turner, Periodic signatures for the detection of cosmic axions, Phys. Rev. D 42, 3572 (1990).

Axions in the galactic halo

- In order to explain galaxy rotation curves, a **halo of dark matter** is hypothesized
- Accepted value for local dark matter **density**

$$\rho_{DM} \approx 0.3 - 0.45 \ \text{GeV/cm}^3$$

- Cold dark matter component is **thermalized** and has a Maxwellian velocity distribution, with a dispersion $\sigma_v \approx 270$ km/s
- There might be a non-thermalized component with sharper velocity distribution

- **Axion can be a dominant component of the galactic DM halo**
- Its **occupation number** is large

$$n_a \approx 3\times10^{14}\left(\frac{10^{-6}\ eV}{m_a}\right) \quad \text{axions/cm}^3$$

- It can be treated as a classical oscillating field with frequency given by the axion mass

$$\frac{\omega_a}{2\,\pi} = 2.4\left(\frac{10^{-6}\ eV}{m_a}\right) \quad \text{GHz}$$

- It has **coherence length** and **time**

$$\lambda = 1400\left(\frac{10^{-6}\ eV}{m_a}\right)\ \text{m}$$

$$t = 5\left(\frac{10^{-6}\ eV}{m_a}\right)\ \text{ms}$$

[C] Haloscopes – Galactic axions – Sikivie Type

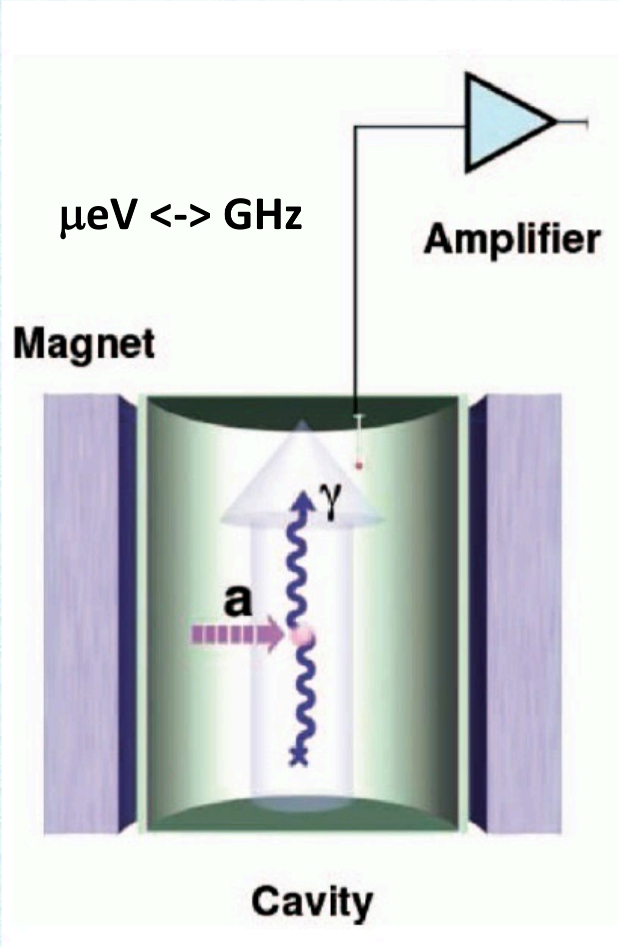
- Search for axions as cold dark matter constituent
- Original proposal by P. Sikivie (1983)
- **DM particles converted into photons inside a magnetic field (Primakoff effect), sensitivity to $g_{a\gamma\gamma}$**

  - **The mass** of the DM particle determines **the frequency of the photons** to be detected. For axions we are in the **microwave range**.

$$h\nu = E_a = m_a c^2 \left(1 + \frac{1}{2}\beta_a^2\right) = m_a c^2 (1 + O(10^{-6}))$$

$\beta_a \sim 10^{-3}$ axion velocity

  - **Use a microwave cavity** to enhance signal. Cavity must be tuned to axion mass. Being this unknown, **tuning is necessary**: very time consuming experiment!



Haloscopes – Galactic axions

- Search for axions as cold dark matter constituent
- Original proposal by P. Sikivie (1983)
- **DM particles converted into photons inside a magnetic field (Primakoff)**
    - Expected signal a **nearly monochromatic line**. Broadened by the **thermal distribution** of DM in the Milky Way

$$\frac{\Delta E}{E} \approx 10^{-6} = 1/Q_a$$

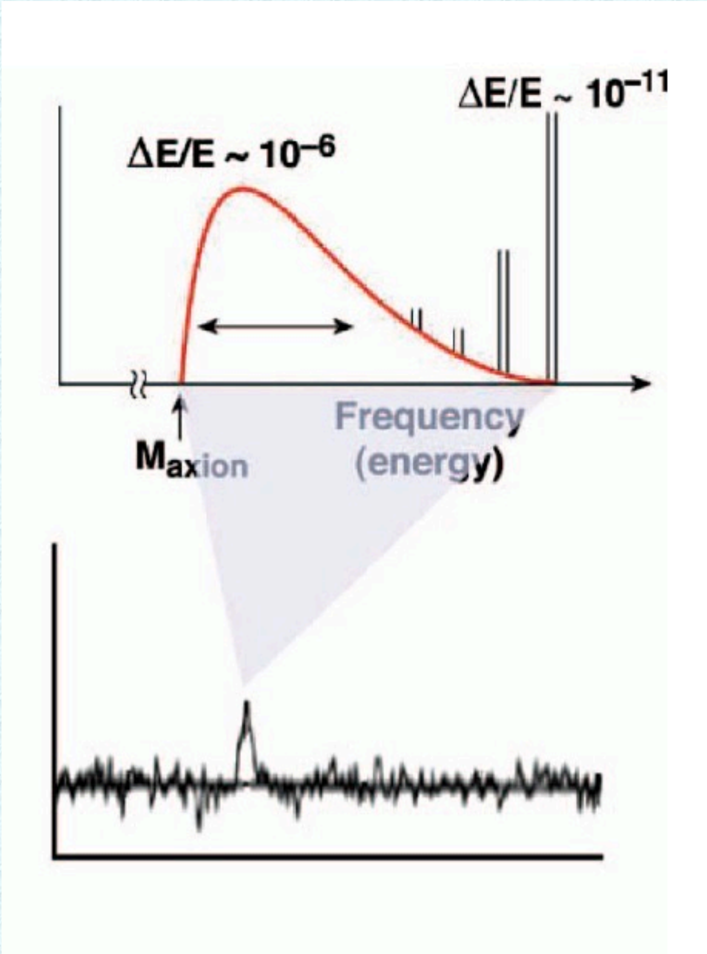
    - Possible **very sharp component due to non-thermalised** axion falling in and out of the Milky Way

$$\frac{\Delta E}{E} \approx 10^{-11}$$

    - **Power** proportional to the number density and the square of the axion-photon coupling

$$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right).$$

    - Typical powers to be measured below 10^{-23} W



Sensitivity

- When the frequency of the axion induced photon matches the frequency of the **cavity eigenmode**, the conversion power is **resonantly enhanced** via cavity Q_c $(Q_c << Q_a)$ $Q_L=Q_c/(1+\beta)$

$$P_{\rm axion} = 1.1\times10^{-23}\,{\rm W}\left(\frac{g_\gamma}{1.92}\right)^2\left(\frac{\rho_a}{0.45\,{\rm GeV/cm^3}}\right)\left(\frac{\nu_a}{1\,{\rm GHz}}\right)\left(\frac{B_0}{10\,{\rm T}}\right)^2\left(\frac{V}{1\,{\rm liter}}\right)\left(\frac{C_{mnl}}{0.69}\right)\left(\frac{Q_L}{10^5}\right)\frac{\beta}{(1+\beta)}$$

- The **power is picked up by an antenna** with coupling β and read by an amplifier. Extremely low power levels are detected by sensitive amplifiers
- In the absence of a signal, the output of a receiver is noise measured on a **bandwidth B_a** corresponding to the axion linewidth

$$P_{\rm noise} = Gk_B(T_{\rm cav}+T_{\rm ampl})B_a = Gk_BT_{\rm sys}B_a$$

Cavity noise + amplifier noise

T_{ampl} = amplifier noise temperature
G – gain ; k_B – Boltzmann constant
T_{sys} = total system noise temperature

- The **SNR** can be calculated with **Dicke's radiometer equation** for a **measurement time t_m**

$$\mathrm{SNR} = \frac{P_{\rm axion}}{k_BT_{\rm sys}}\sqrt{\frac{t_m}{B_a}}$$

- Since all the frequencies within a cavity bandwidth can be scanned simultaneously, we can calculate a **scanning rate** as

$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2}\frac{P^2_{\rm axion}}{k_B^2T^2_{\rm sys}}\frac{Q_a}{Q_L}$$

Major R&D efforts are made to **increase B_0^2 V C Q_c** and **minimizing T_{sys}**

Haloscopes – Galactic axions

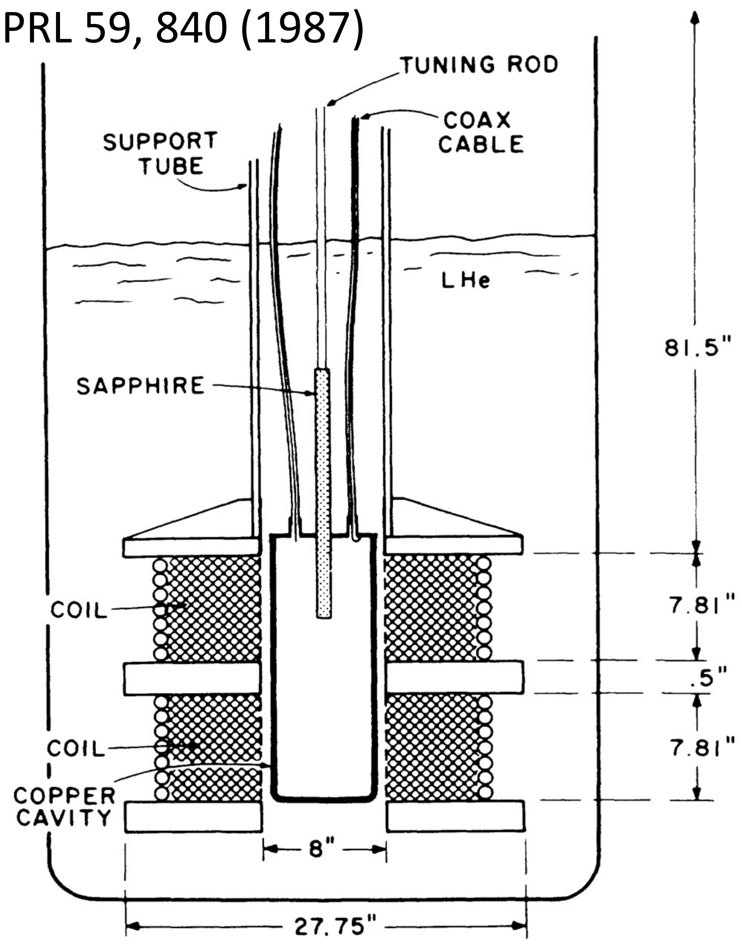
- Resonant detection of DM axions in a magnetic field. One measurement explores **only sharp cavity linewidth**.
  Scanning is necessary.

Figure of merit for scanning (mass or frequency)

$$\frac{\Delta f}{\Delta t} \propto V^2 B^4 C^2 T_{sys}^{-2} \; Q$$

- **High Q** microwave cavity operating inside a **strong magnetic field B**
- **Large volume *V*** cavity at **high rf frequency *f***
- **Low noise T_{sys}** radio frequency receiver
- Use cavity modes with **large form factor *C***

PRL 59, 840 (1987)



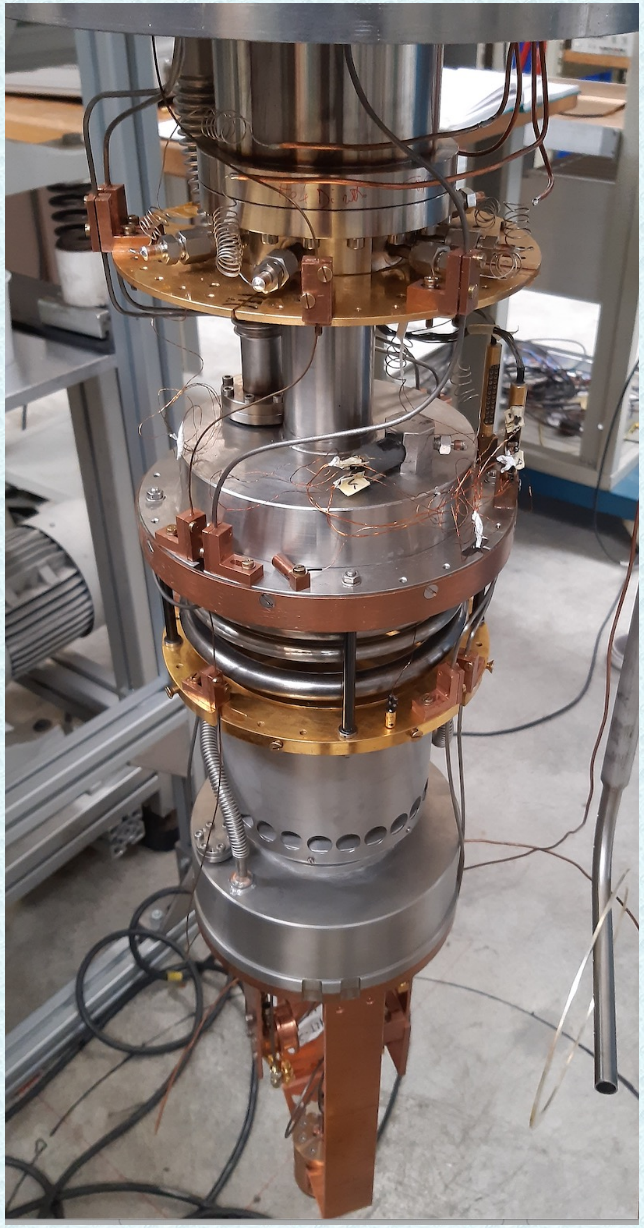
Schematic diagram of the RBF apparatus (1987)

- Scanning to high mass – high frequency very difficult due to reduced cavity volumes
- Scanning to low mass – low frequency implies large cavities and thus very big magnets

! All current limits assumes axion/ALPs saturate the local DM density

Main components of cavity haloscopes

Refrigeration system



Base temperature T

Microwave cavity

Quality Factor Qc
Form factor C_{mnl}
Volume V
Resonance frequency f
Tuning

Low noise receiver

Picture and scheme of a SQUID

Noise temperature T_n

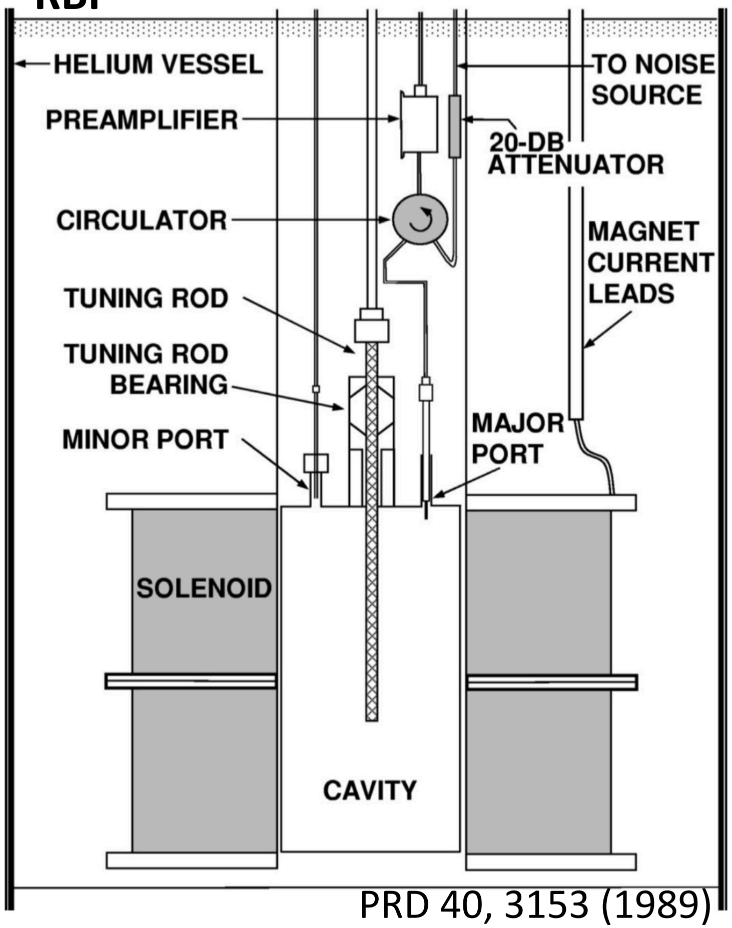
Magnetic source

Magnetic energy B^2 V

Haloscope detectors - precursors

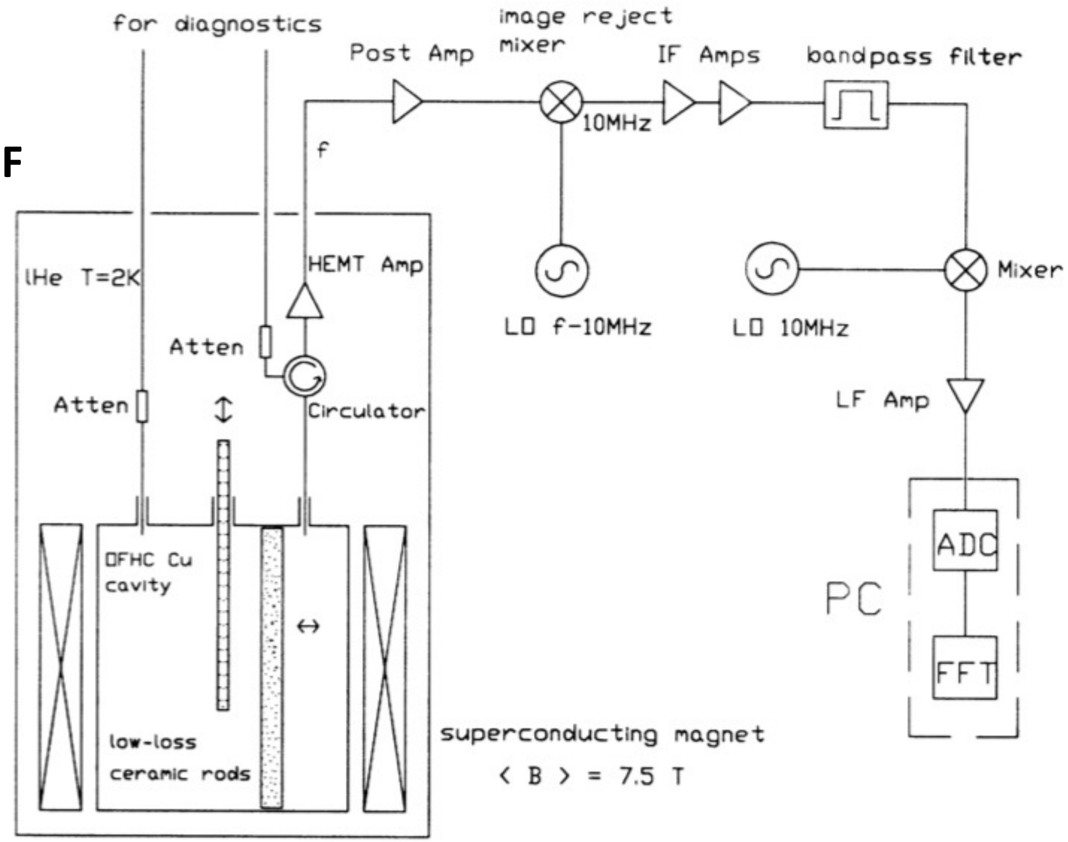
- **Pilot experiments in Brookhaven (RBF) (1988) and University of Florida (UF) (1990)**
- **Provided basic structure for even today's most sensitive experiments**

RBF



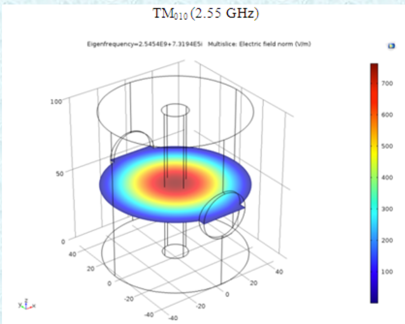
PRD 40, 3153 (1989)

UF



PRD 42, 1297 (1990)

7 cavities, Brms 7.5 T phi 20 cm, L 40 cm
Copper cavity TM010 with Q_L up to 70000
Cavity tuning with sapphire rods
7 GaAs FET amplifier, T_n 10-20 K



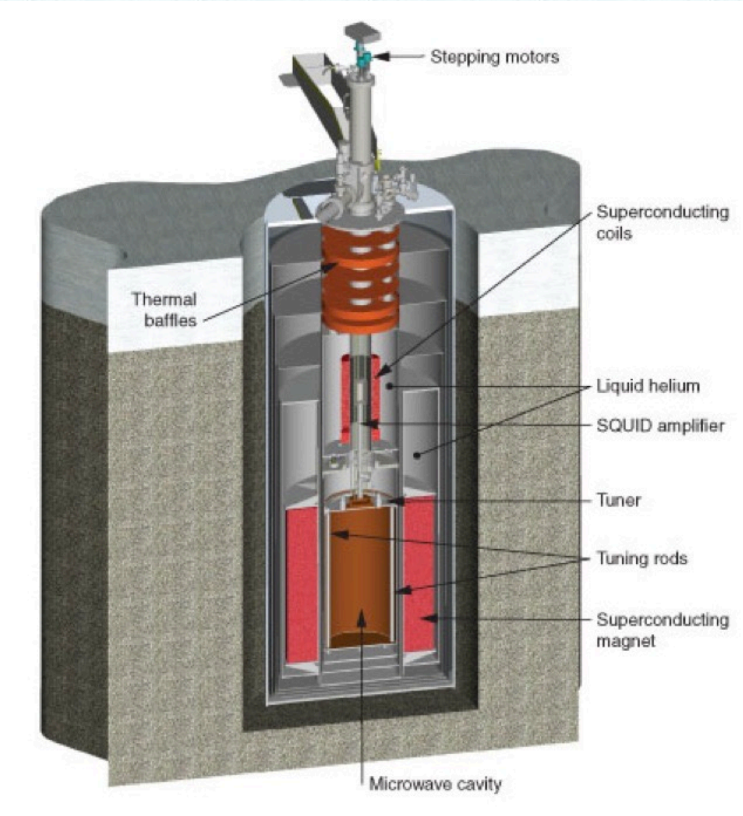
HEMT amplifier, T_n 3-6 K

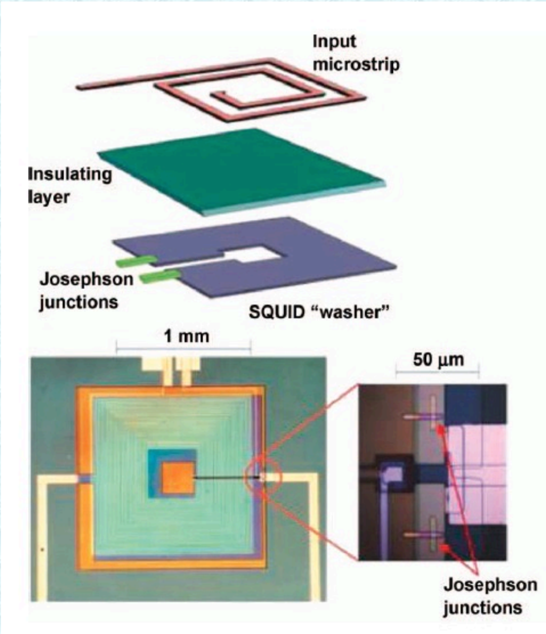
Haloscope detectors – 1st gen - ADMX

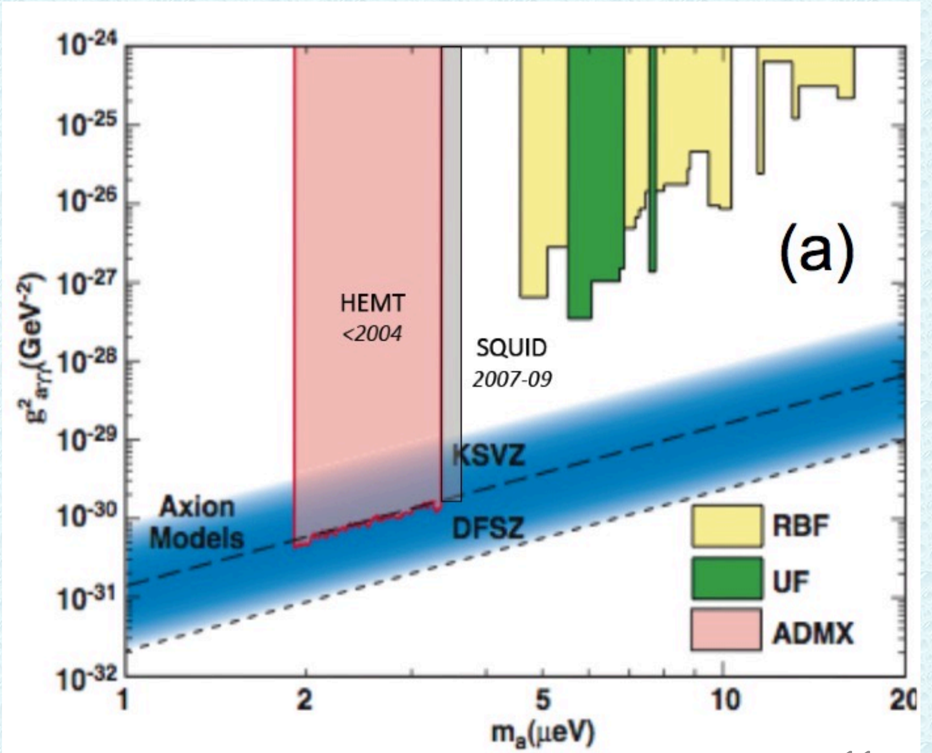
ADMX – Axion Dark Matter eXperiment – phase I

Collaboration started in 1990 to explore new ways forward:

- SC quantum interference device (SQUID) receiver
- Large size copper cavity inside 8.5 T magnet
- Running temperatures around 1.5 K
- System noise temperature at few K
- Cavity tuning with rods







- **Reached QCD axion model (KSVZ)**

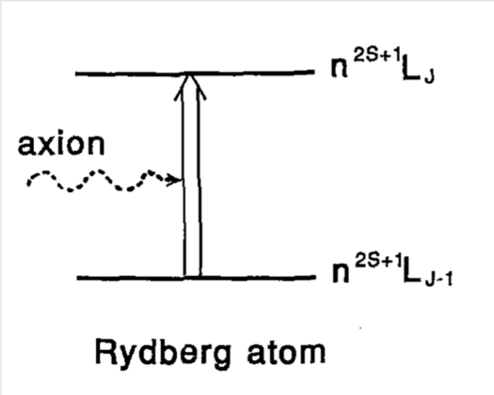
Haloscope detectors – precursors - CARRACK

Different ideas already from the beginning:
Rydberg atoms

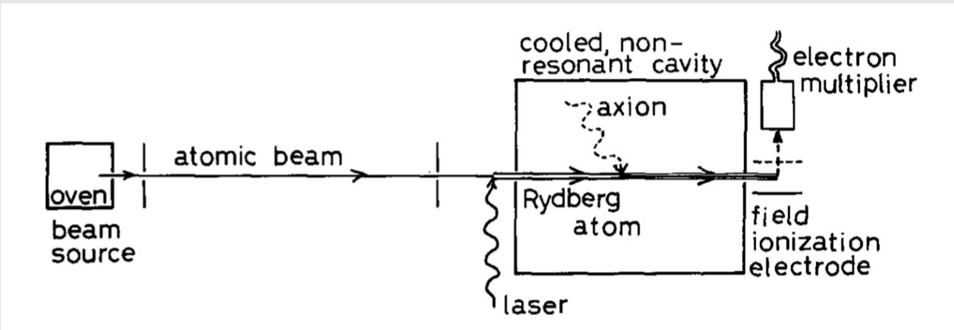
1. Rydberg atoms as direct axion DM detectors

Exploit the **axion-electron coupling** to excite Rydberg transitions

f ~ GHz Range

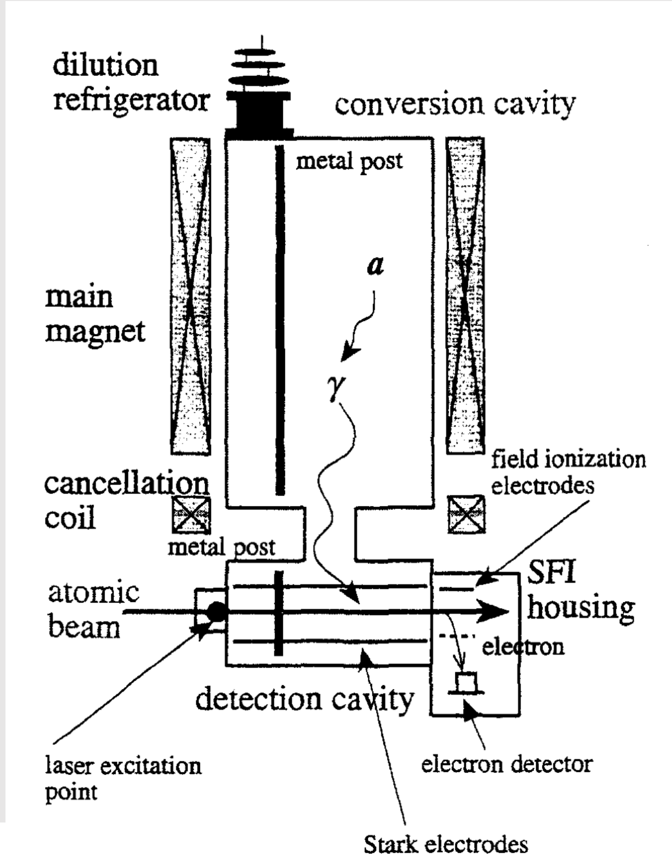


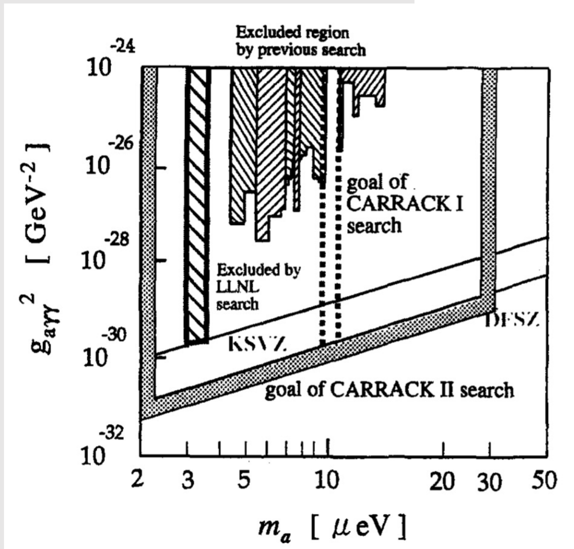
Use alkaline atomic beam in an inhibited cavity regime



PLB 263, 523 (1991)

2. Rydberg atoms as photon detectors in a Sikivie's type scheme

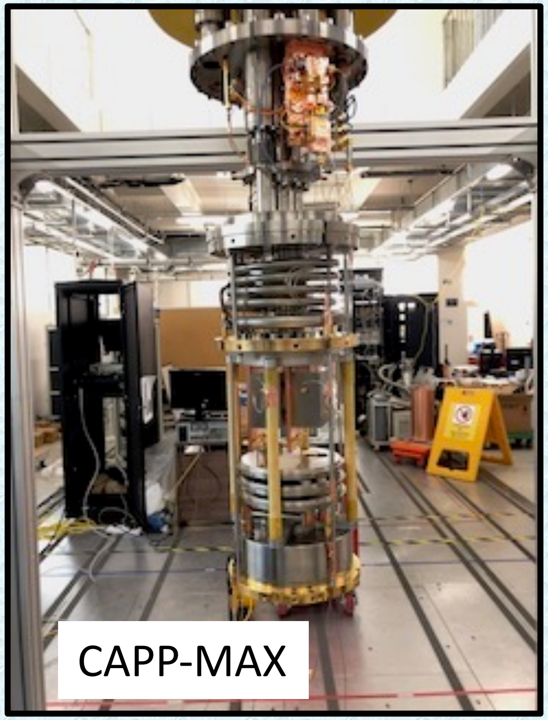


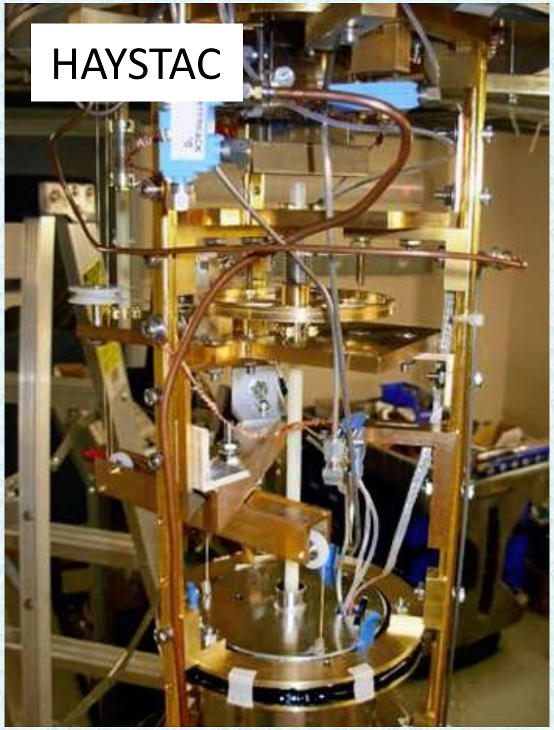


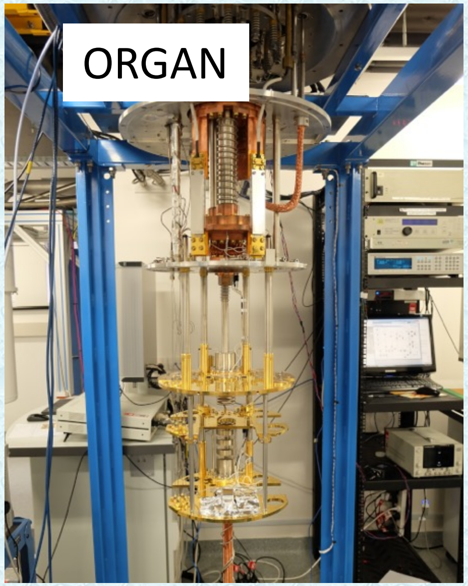
NPB (PS) 72, 164 (1999)

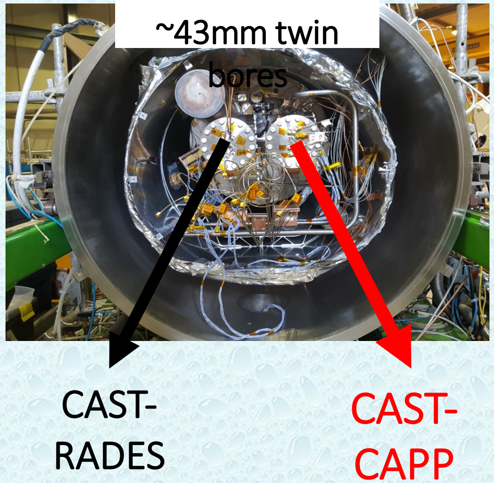
Haloscope detectors – current situation

- Within the last 10 years ADMX has evolved and a large number of new apparata based on Sikivie's scheme came into play

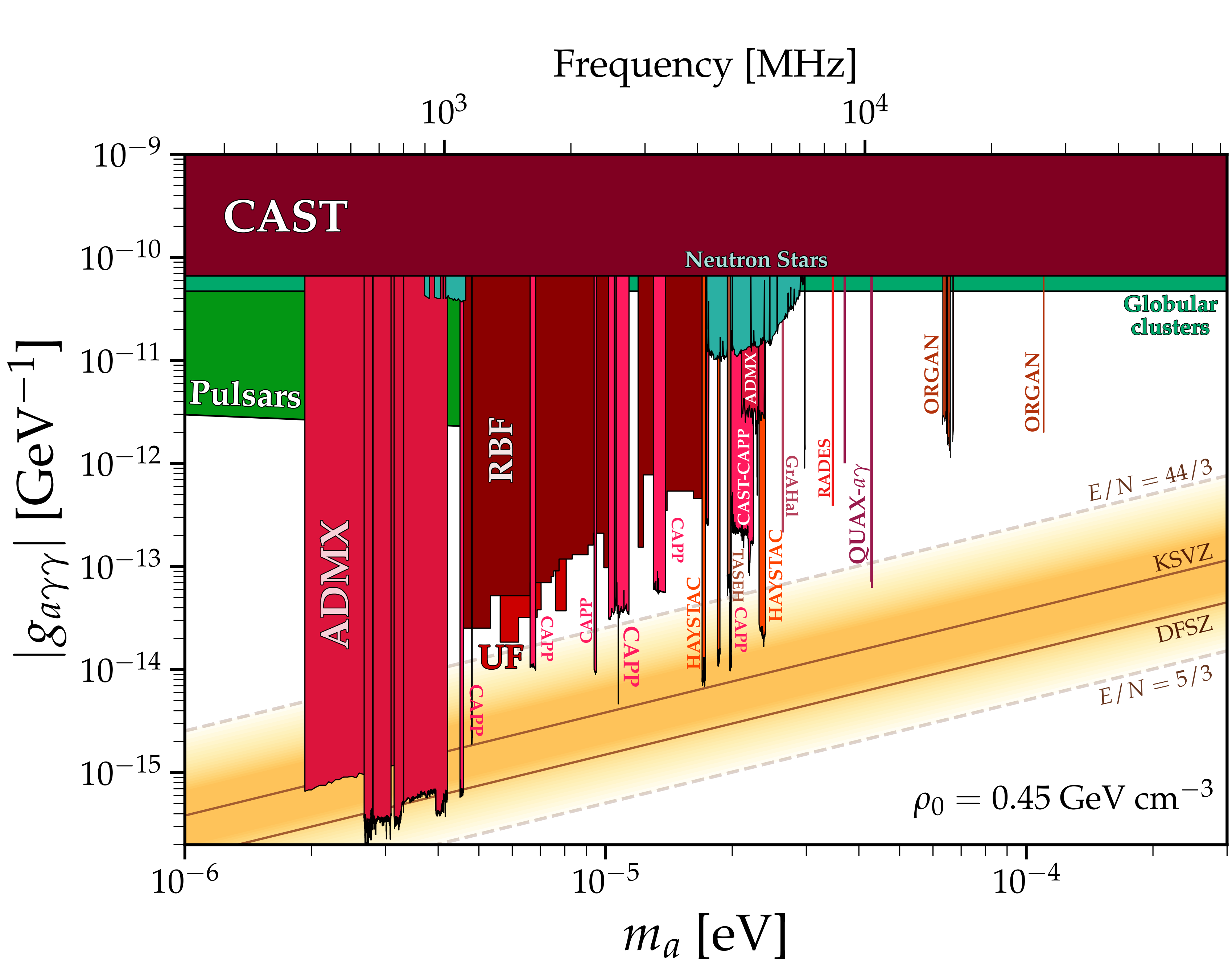








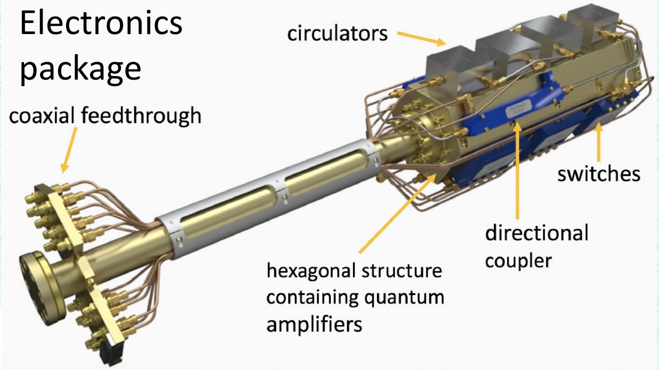
Current limits – Sikivie's haloscopes



AxionLimits by **cajohare**.

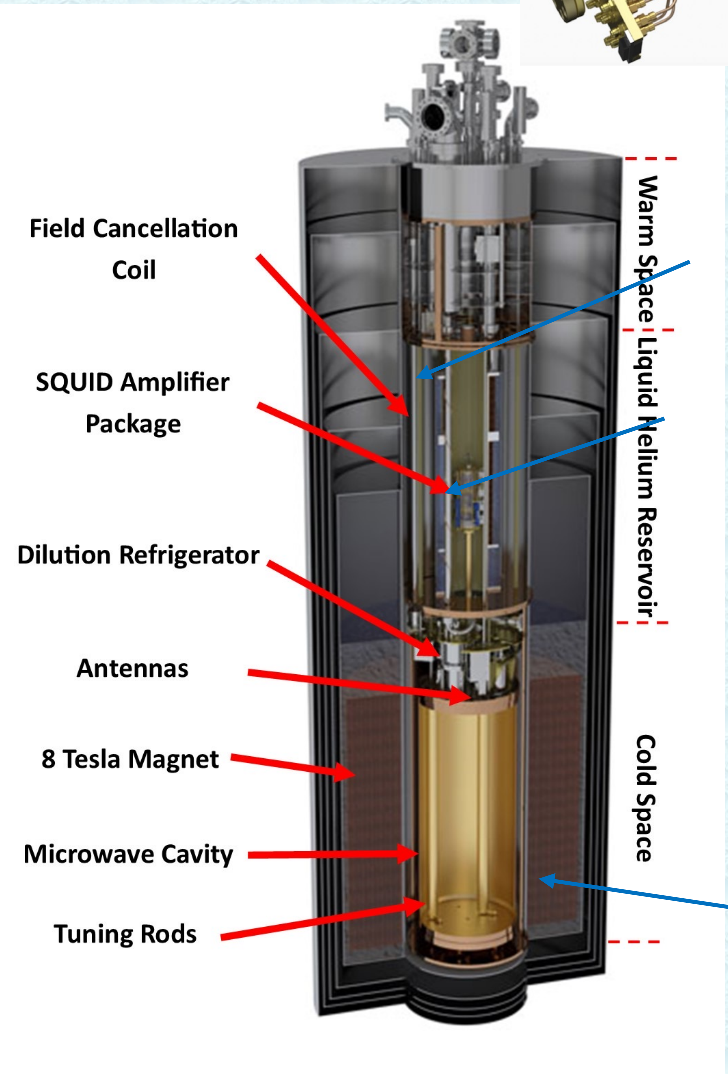
ADMX – Axion Dark Matter EXperiment

University of Washington

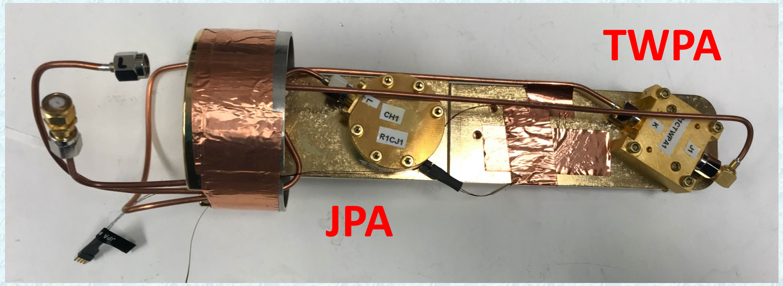


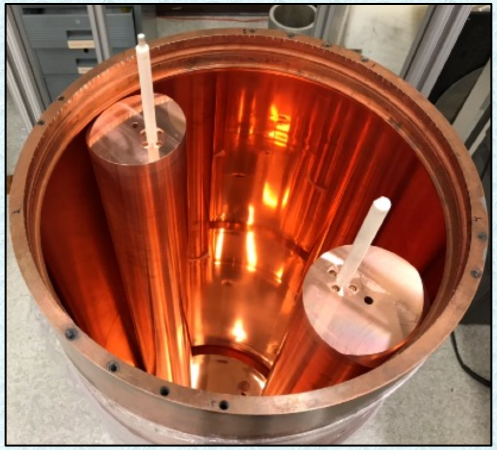
ADMX has evolved in time with the implementation of several improvements:

- Dilution refrigerator with lower base temperature : cavity @ 150 mK
- SQUID, JPA and TWPA amplifiers
- Multimode searches

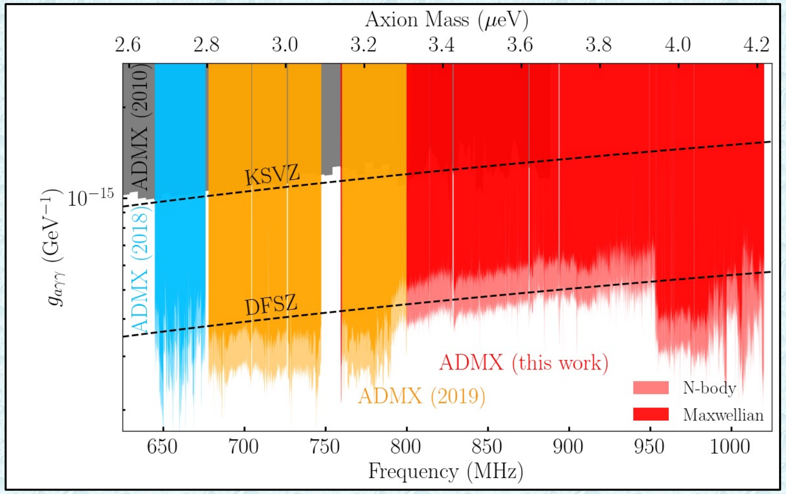


Sidecar cavity




Main cavity

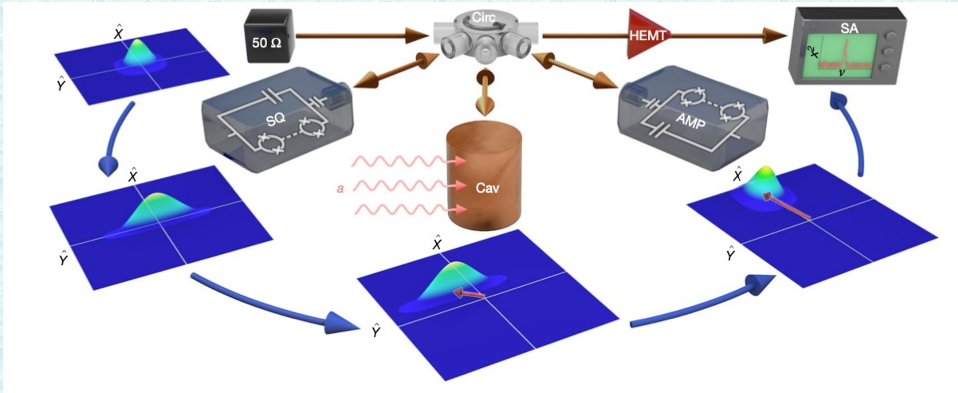
First haloscope to reach DFSZ axion model sensitivity



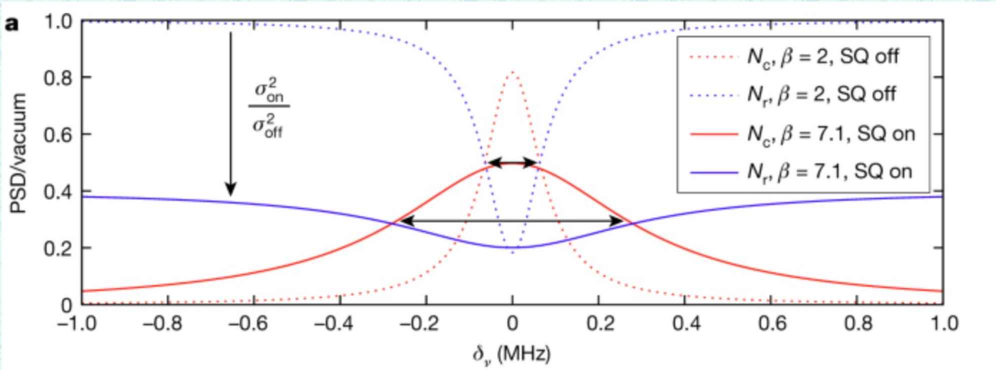
Phys. Rev. Lett. **127**, 261803 (2021)

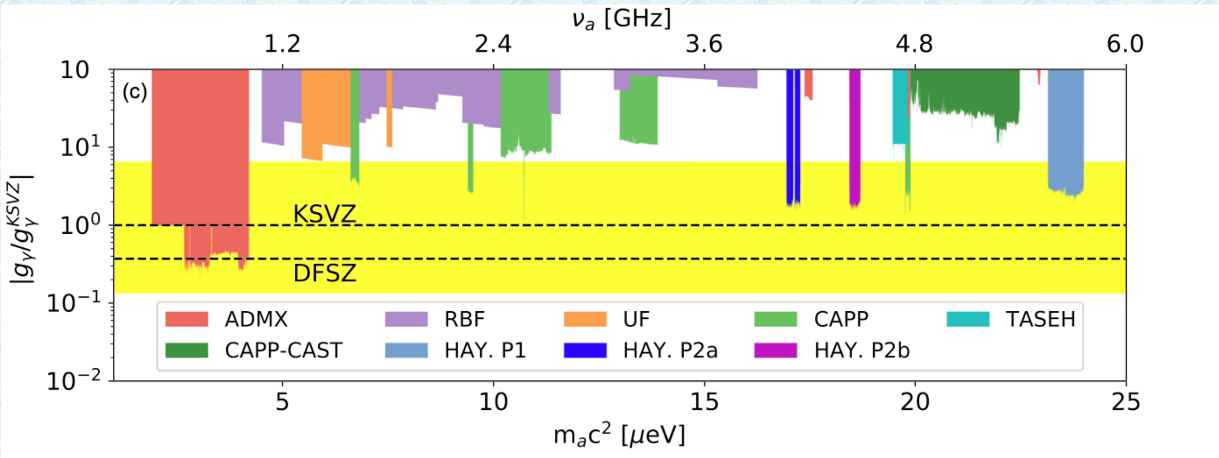
HAYSTAC – Haloscope at Yale Sensitive To Axion CDM

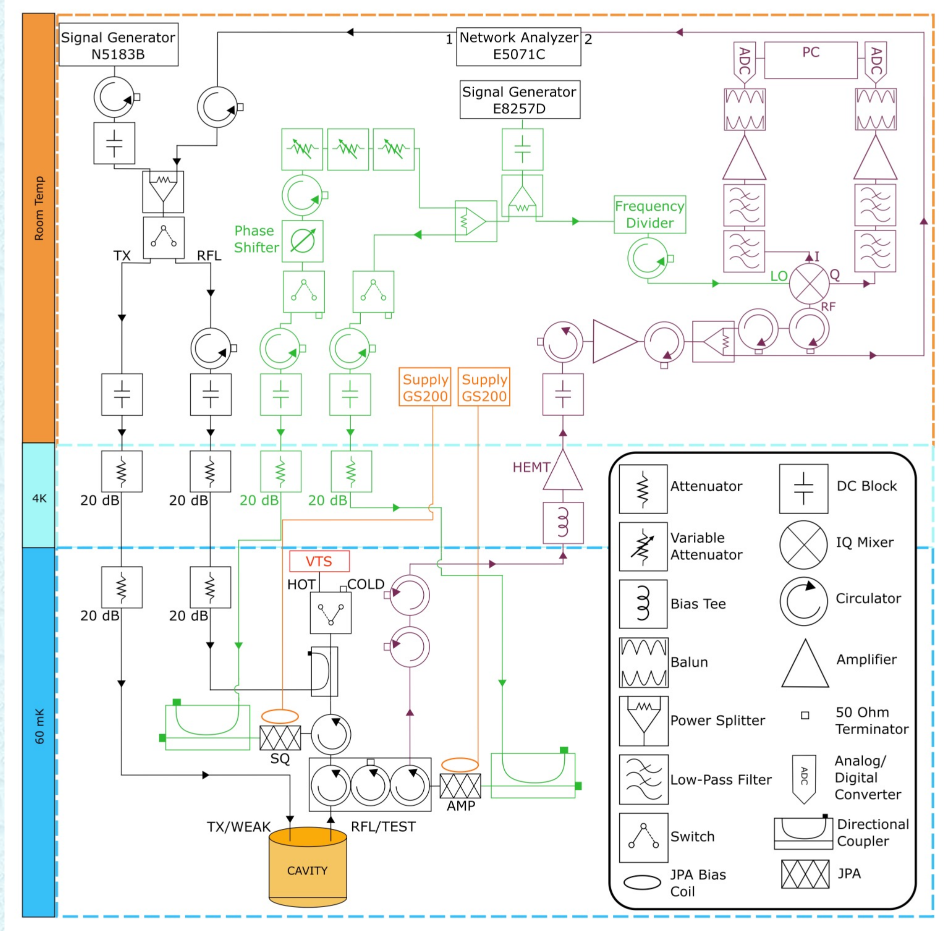
- Designed to search for dark matter axions with masses above 10 μeV
- First haloscope to use a Josephson Parametric Amplifier
- First haloscope to employ a Squeezed-state receiver (SSR)



Scan rate enhancement 1.9 over quantum limit







Jewell et al. PRD 107, 072007 (2023)

IBS-CAPP Institute of Basic Science

- IBS – CAPP was established in Korea with the aim of building a laboratory equipped with top infrastructure for cavity haloscope searches with enhanced sensitivities over a broader range in the microwave region.

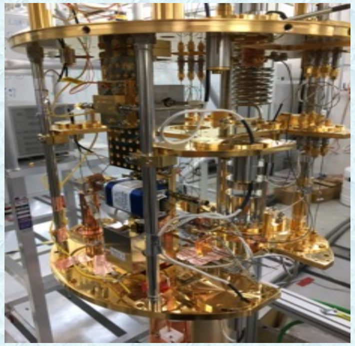
Institute for Basic Science
ibs
CAPP
Center for Axion and Precision Physics Research

- **High Temperature Magnets** based on ReBCo tape
- **High field and large volume** Low Temperature magnet
- Powerful **dilution refrigerators** to achieve ultralow temperature
- Design and construction of **large-effective-volume high-frequency high-Q** microwave resonator
- Use of very low noise Josephson Parametric Amplifiers working at different frequencies

Several running experiments

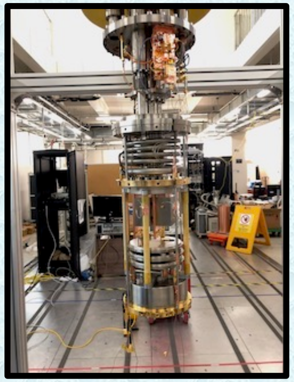
Cryogenics (<40mK)

Dilution Refrigerators



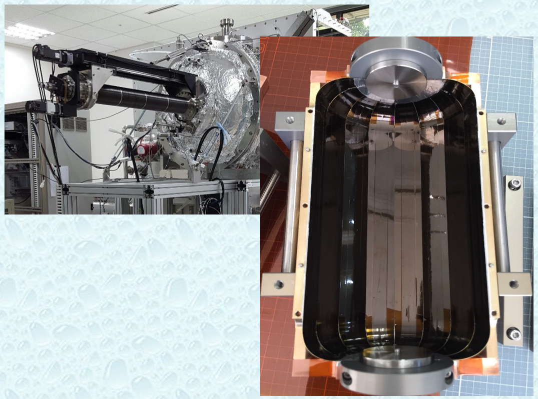
High Field & Big bore Magnet

12T LTS Big Bore SC Magnet



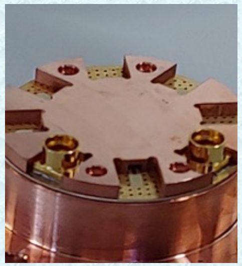
High Q Tunable Cavity

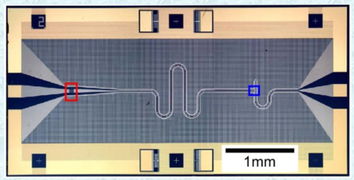
Superconducting tapes



Quantum Amplifier

SQUID and/or JPA (T_N ~ SQL)





Axion experiments at CAPP

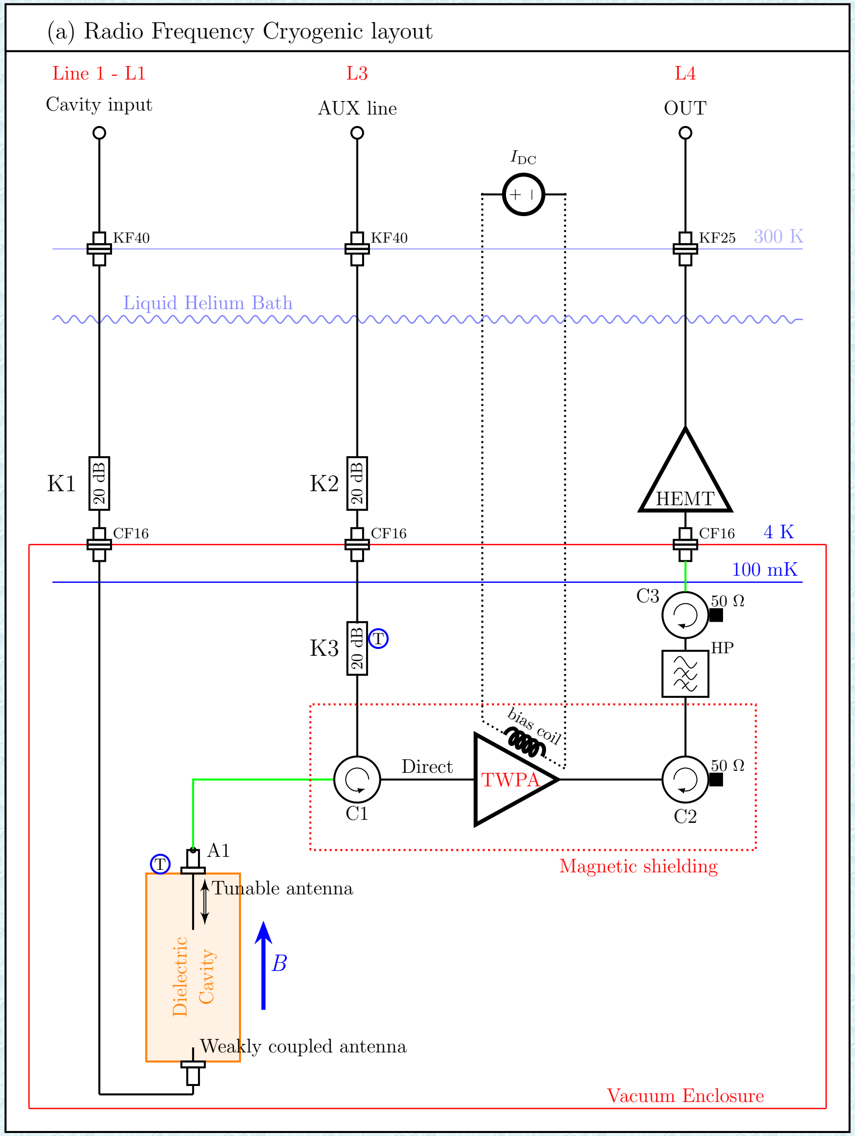
	CAPP-PACE	CAPP-8TB	CAPP-HF	CAPP-PACE-JPA	CAPP-PACE-JPA-6cell	CAPP-8TB-JPA-8cell	CAPP-PACE-JPA-SC	CAPP-MAX	CAPP-AQN-SC	CAPP-HeT-SC	CAPP-12T-HF-3cell
Year	2018	2019	2019	2020	2021	2021	2021	2021	2023	2023	2023
Magnet [T]	8	8	9	8	8	8	8	12	8	8	12
m_a [GHz]	~2.5	~1.6	~4.0	~2.3	~5.6	~5.8	~2.3	1.0 ~ 2.0	~2.3	~5.4	~5.3
Δm_a [MHz]	250	200	250	30	80	>100	30	20 ~ 300	-	> 50	~30
Sensitivity	10*KSVZ +KSVZ	4*KSVZ	10*KSVZ	2*KSVZ	3*KSVZ	KSVZ	KSVZ	DFSZ	DFSZ	KSVZ	KSVZ
T_{phy} [K]	< 0.05	< 0.05	~2	~0.05	~0.05	~0.03	~0.04	~30 mK	60 mK	30 mK	30 mK
T_{sys} [K, mK]	~1 K (HEMT)	~1 K (HEMT)	~2 K (HEMT)	~200 mK	<300 mK	<300 mK	<200 mK	<300 mK	~200 mK	~400 mK	~400 mK
Comments	R&D machine: First physics run (coldest axion data)	First result published by CAPP	First multi-cell cavity result	First run with JPA	First run with JPA+6-cell	First run with JPA+8-cell	First run with JPA+SC	CAPP's main axion detector with JPA	Axion Quark Nugget + SC cavity (Q~1.6M)	First run with He tuning + SC cavity (Q~10M)	3-cell with 12T mag + JPA SC cavity (future)
Publication	Published in PRL	Published in PRL	Published in PRL	Published in PRL	--	Will publish	Will publish	Published in PRL			

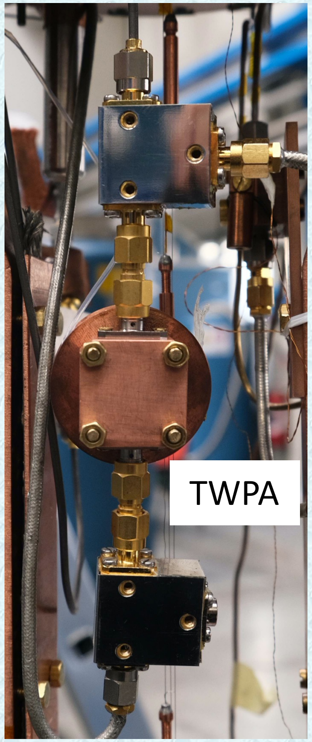
QUAX – QUaerere AXion – QUest for AXion

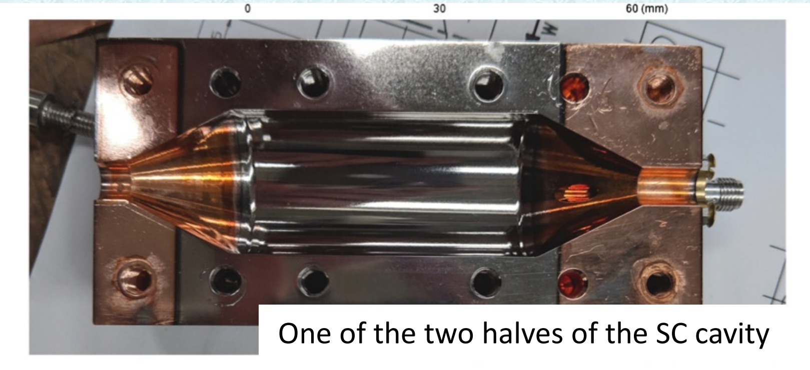
Experiment designed to look for dark matter axion in the 10 GHz region

- First apparatus to use a superconducting cavity in a strong magnetic field   Q0 = 4.5 10^5 @ 2 T
- Operation of a quantum limited JPA at high frequency
- Operation of a near quantum limited TWPA at high frequency
- Use of hybrid cavity design (copper-sapphire) to get high Q and large volume
- First haloscope employing a cavity with Qc > Qa

Layout with novel calibration scheme







One of the two halves of the SC cavity

Achieved Tsys = 2.1 K @ 10.5 GHz
Reached QCD axion models sensitivity

See description in the tutorial this afternoon

Others running

TASEH

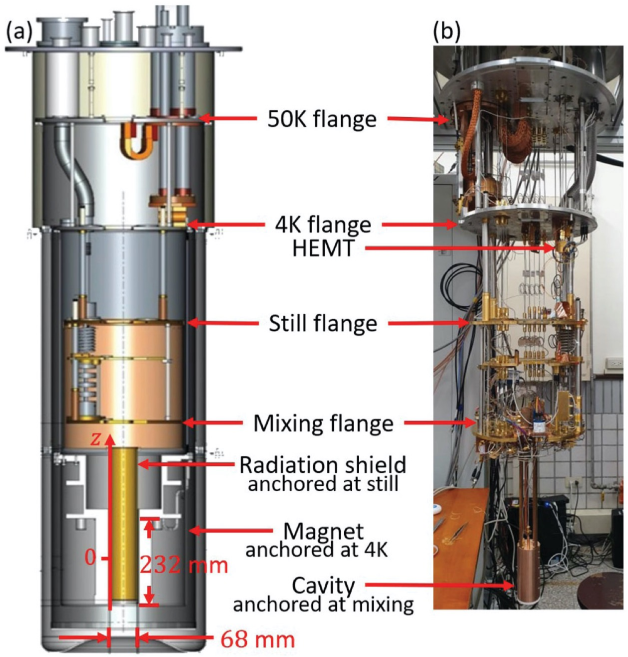
PRD 106, 052002 (2022)
PRL 129, 111802 (2022)

Range (4.70750 – 4.79815) GHz

- OFHC copper, split cavity
- Volume *V*: ~ 0.234 L
- *Q*0: ~ 62000
- C010 ~ 0.62

- B = 8 T
- Tsys 2.1 – 2.4 K

- Reach ~ 10 times KSVZ sensitivity over a 100 MHz window



Next steps:

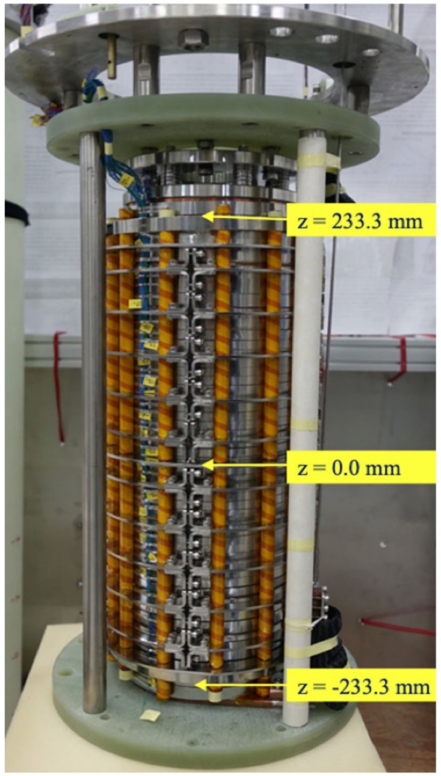
- New dilution unit for lower temperature
- Magnet upgrade 9 T and larger volume
- Use of a JPA
- New conical tunable cavity (see next)

CAPP18T

PRL 128, 241805 (2022)
PRD 106, 092007 (2022)
PRL 131, 081801 (2023)

Range (4.7789 – 4.8094) GHz

- **Strongest magnet for haloscope 18 T**
- JPC amplifier
- Tsys 0.62 K
- Reach KSVZ sensitivity over a 40 MHz window



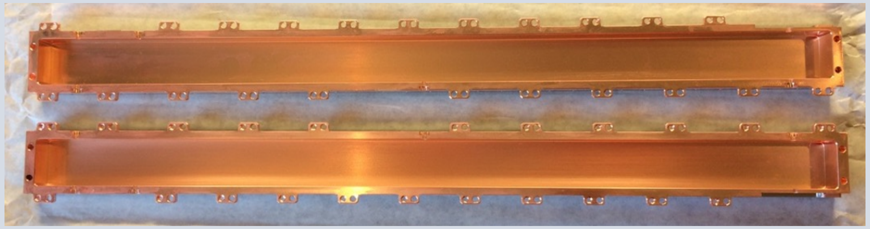
Others running II

CAST – CAPP

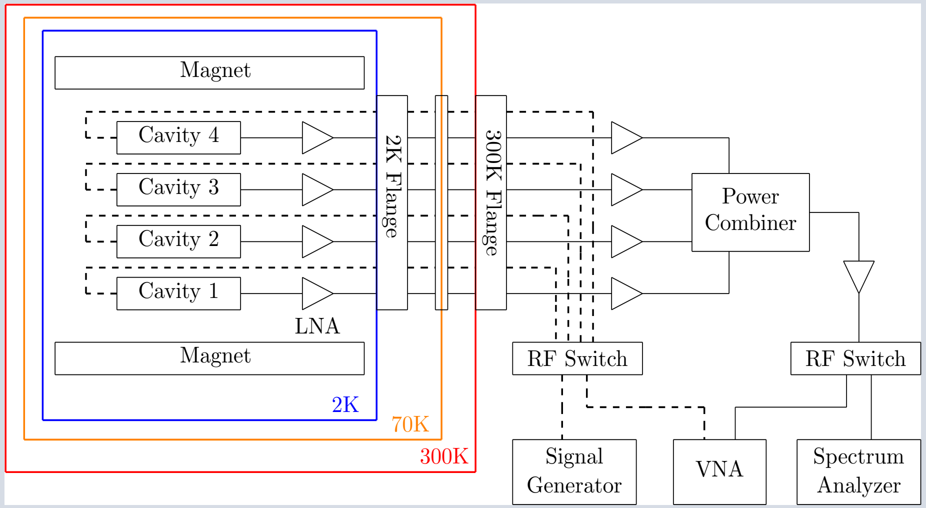
NatComm 13, 6180(2022)

Use of the LHC – CAST magnet as an haloscope

4 identical stainless steel tunable cavities



Increase the sensitivity via ***coherent* combination** of the power outputs of 4 frequency-matched cavities *after* individual signal amplification.



- No phase-matching: $SNR_N = \sqrt{N} \cdot SNR_{single}$
- With phase-matching: $SNR_N = N \cdot SNR_{single}$

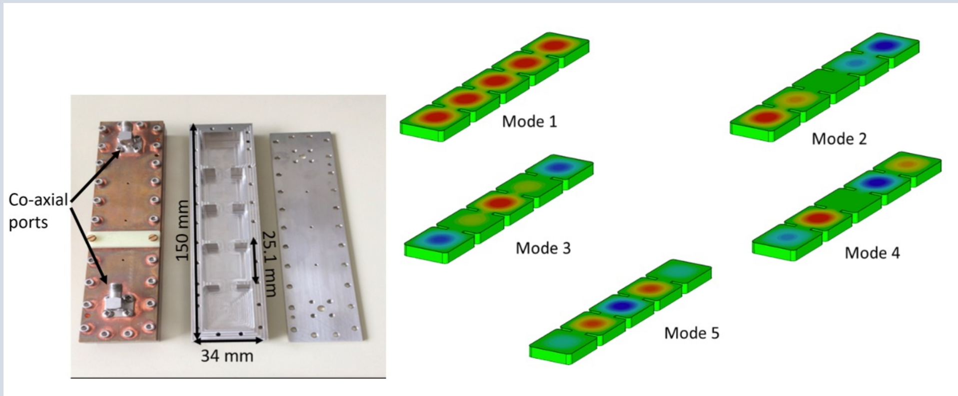
- Frequency range: ~4.8 – 5.4 GHz (660 MHz)
- Axion mass range: ~19.7 – 22.4 μeV

CAST – RADES

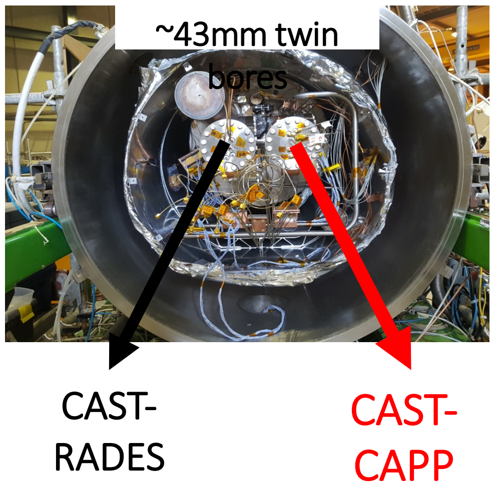
JHEP10(2021)075

Use of the LHC – CAST magnet as an haloscope

A radio frequency cavity consisting of 5 sub-cavities coupled by inductive irises took physics data inside the CAST dipole magnet for the first time using this filter-like haloscope geometry.



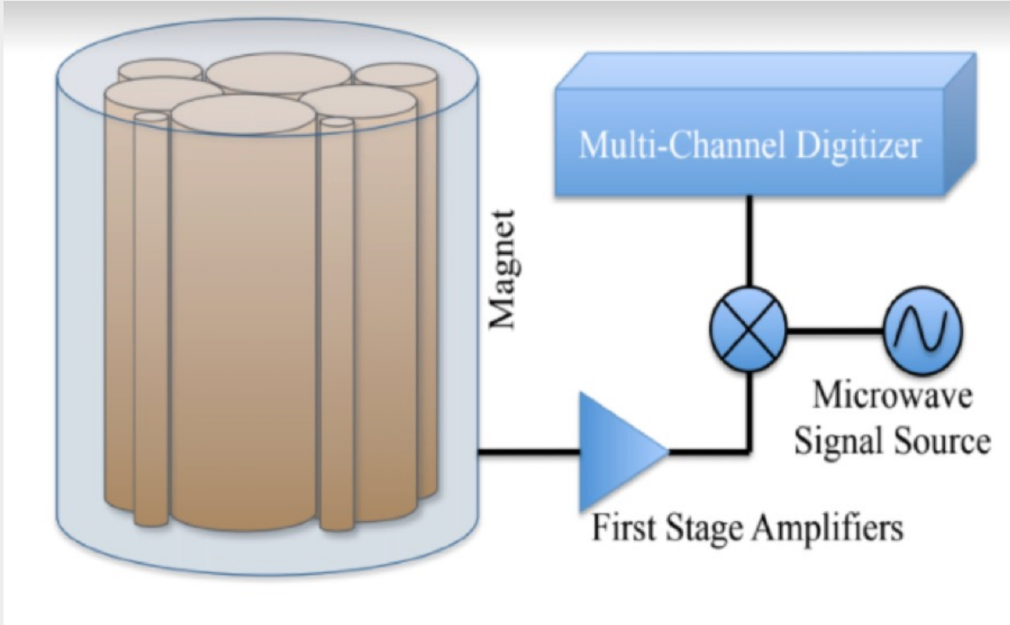
Q_L ~ 11000 @ Frequency 8.384 GHz (34.67 eV)



Others running III

The Grenoble Axion Haloscope project (**GrAHal**) aims at developing a haloscope platform in Grenoble (France), able to run detectors of different sizes and designs for the search of galactic axions and ALPs at the best sensitivity in the 0.3 – 30 GHz frequency range

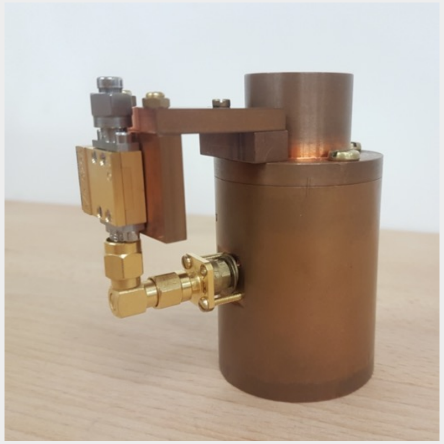
Pilot experiment with a 14 T magnet
And 6.4 GHz cavity



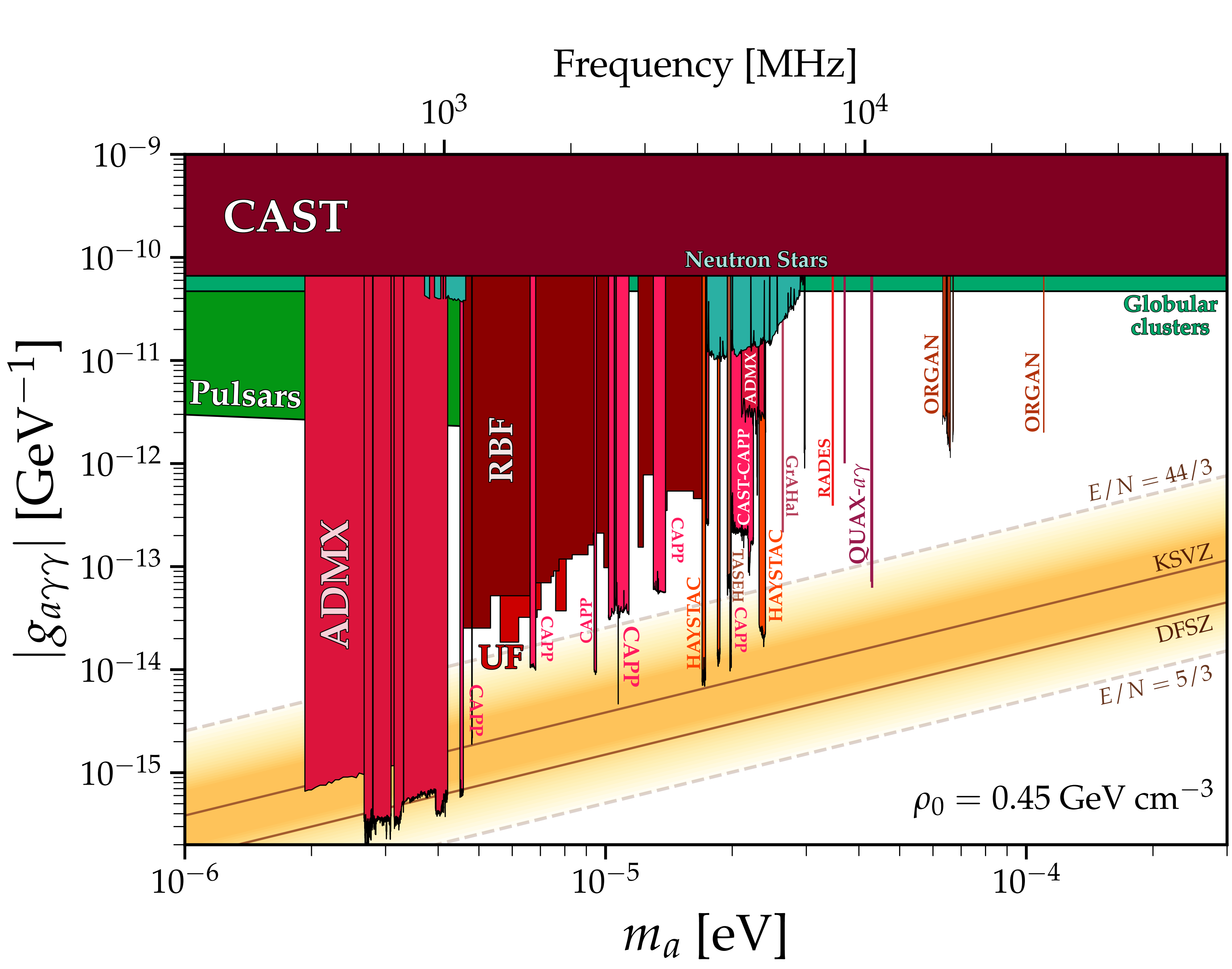
The **ORGAN** experiment (situated in Perth, Australia) is a microwave cavity axion haloscope that aims to search the mass range of 50–200 μeV **using a multi-cavity design.**

Pathfinder meas
@ 26.5 GHz

@ 15.3 – 16.2 GHz



Current limits – Sikivie's haloscopes



AxionLimits by **cajohare**.

Cavity Haloscopes: what next?

- **Haloscopes** seems to be CURRENTLY the most promising detectors to search for QCD axion dark matter – bandwidth limited – scanning required
- BEWARE: limits always assume axion as the dominant (100%) DM component

- **How fast can we scan** with a resonant detector?

$$\frac{df}{dt} = \frac{1}{SNR^2}\frac{g_{a\gamma\gamma}^4\rho_a^2}{m_a^2}\frac{B_0^4}{k_B^2T_{sys}^2}\frac{\beta^2C_{mnl}^2V^2}{(1+\beta)^2}\frac{Q_cQ_a^2}{(Q_c+Q_a)}$$

SNR - target signal to noise ratio

Dark matter axion parameters – independent of detector

Magnetic field B_0 and system noise temperature T_{sys} (related to apparatus environment)

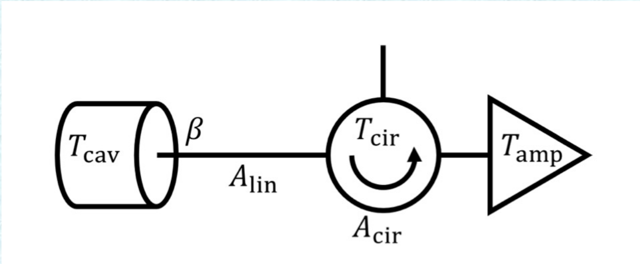
Resonant cavity volume V, mode form factor C_{mnl}, coupling β and Q factor

Optimization of values of technical parameters will be strongly dependent on the frequency range where the detector is operated

The road to the future: detectors

- **Frequency scan** inversely proportional to square of detection noise level
- Linear amplifiers limited to the Standard Quantum Limit (SQL)

$$k_B T_N = h\nu \left(\frac{1}{e^{h\nu / k_B T} - 1} + \frac{1}{2} \right) + k_B T_A .$$

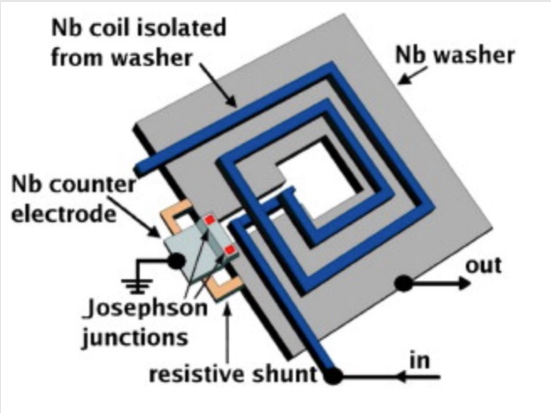


Total System Noise Level = cavity temperature + detector noise temperature

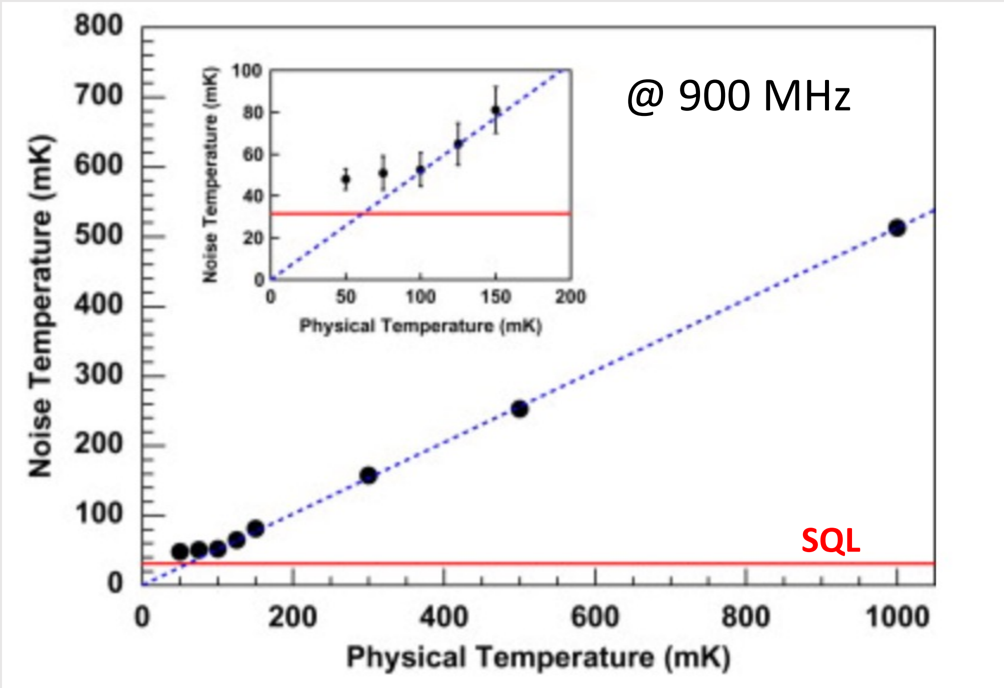
- **Irreducible noise** $k_B T_{SQL} = h\nu$, dominant noise above 2 GHz @ 100 mK

Low frequency

Microstrip SQUID amplifier (ADMX) almost reached SQL



Nucl. Instrum. Methods Phys. Res. A 656, 39 (2011).



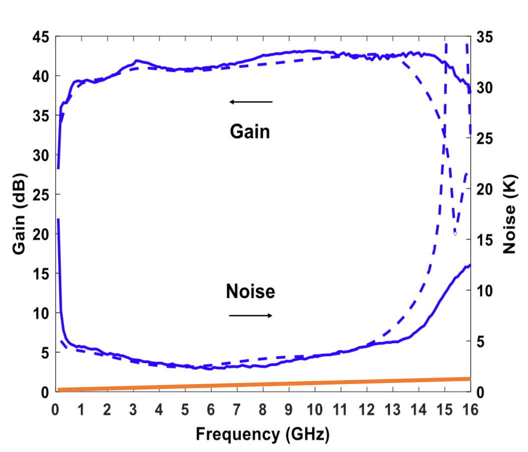
Performances drops for frequencies above a few GHz

https://doi.org/10.1016/j.nima.2011.07.019

The road to the future: detectors (high frequency)

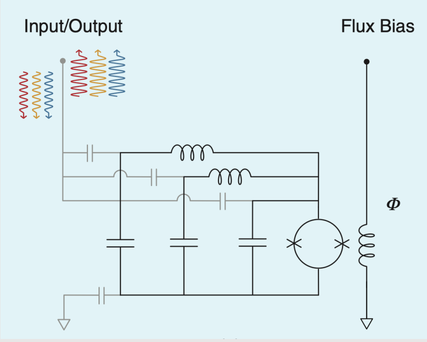
- For **frequencies above a few GHz**, it is much difficult to reach the limit of a linear amplifier

HEMT - high electron mobility transistor

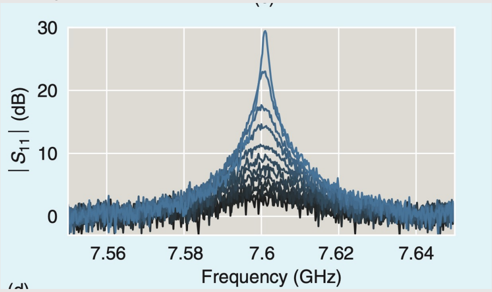


Cannot be used in ultra cryogenic environment due to power dissipation

JPA – Josephson Parametric Amplifier

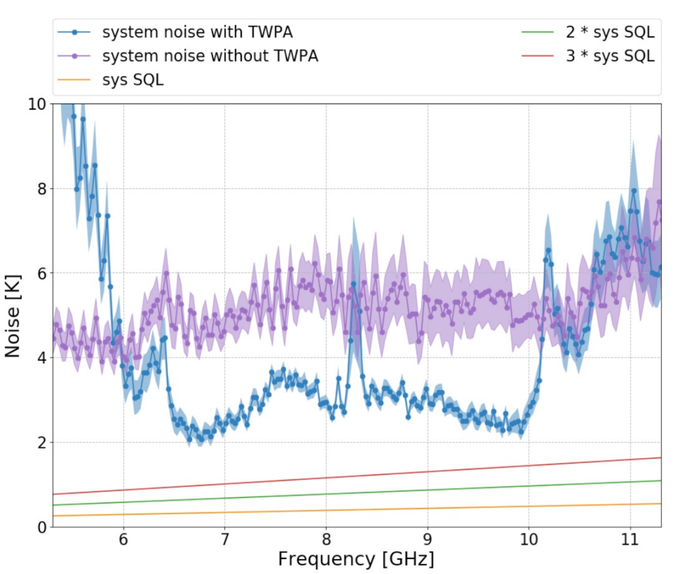


- Non linear drive of combination of Josephson Junctions
- Nominally **noiseless** parametric amplifiers → @ 1-2 SQL
- Very Limited bandwidth (10 MHz)



JTWPA – Josephson Travelling Wave Parametric Amplifier

- Transmission lines comprised of series connected junctions
- Can operate over a wide bandwidth (GHz)
- Still @ a development level



Other options : **Squeezing** → Increase the measurement bandwidth

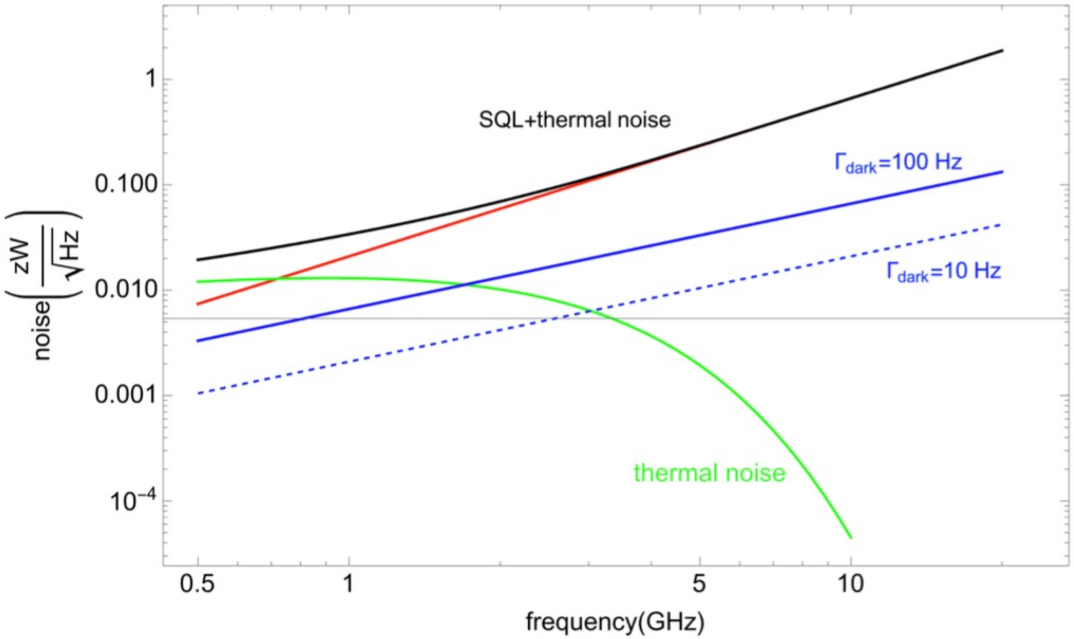
Single photon counter → Lots of R&D on the way

Single photon counting

Why do we need Single Microwave Photon Detectors (SMPD) in haloscope search?

Using quantum-limited **linear amplifiers** (Josephson parametric amplifiers) the **noise set by quantum mechanics** exceeds the **signal** in the high frequency range, whereas **photon counting** has no intrinsic limitations

	ν_c [GHz]	Q_0	B T	V [liter]	$P_{a\gamma\gamma}$ [10^{-24} W]	Γ_{sig} [Hz]
QUAX$_{a\gamma}$	10.48	1×10^6	14 T	1.15	439 (KSWZ) 60 (DFSZ)	63 8.7
Pilot exp.	7.3	1×10^6	2 T	0.11	0.8 (KSWZ) 0.11 (DFSZ)	0.16 0.02



axion linewidth $= \Delta\nu_a$

$P_n^{\rm SQL} = h\nu_a\sqrt{\Delta\nu_a}$

$P_n^{\rm th} = h\nu_a\bar{n}\sqrt{\Delta\nu_a}$, with $\bar{n} = \frac{1}{e^{h\nu/kT}-1}$, T=50 mK

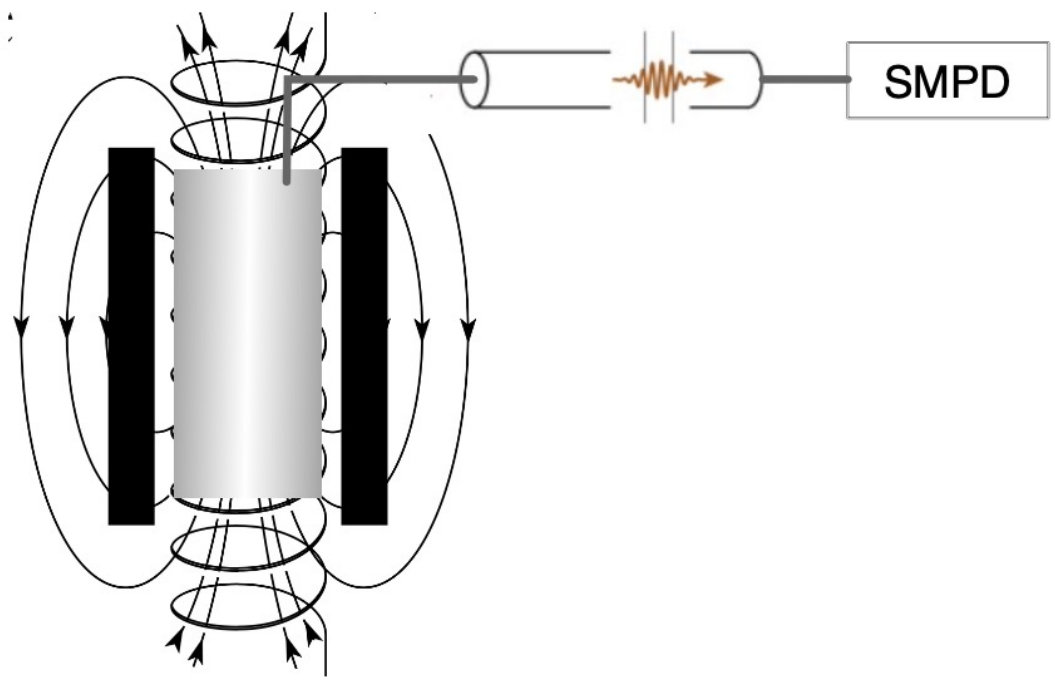
$P_n^{\rm SMPD} = h\nu_a\sqrt{\Gamma_{\rm dark}}$

- Detection of individual microwave photons is a challenging task because of their **low energy** e.g. $h\nu = 2.1 \times 10^{-5}$ eV for ν = 5 GHz

Single photon counting

Requirements for axion dark matter search:

- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate $\Gamma < 100$ Hz
- $\gtrsim$ 40−50% efficiency
- large “dynamic” bandwidth ~ cavity tunability



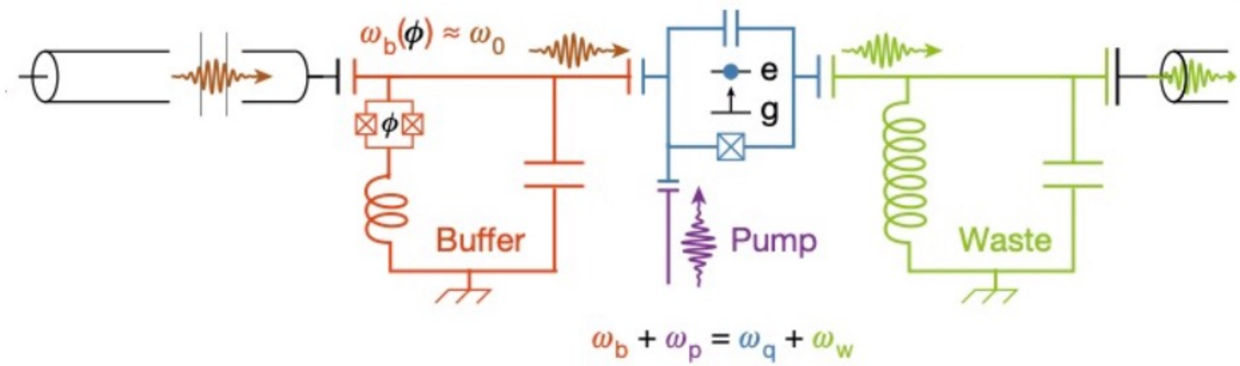
detection of *itinerant photons*
applicable to axion searches (multi-Tesla fields)

Single microwave photon counter (SMPD)

Most advanced schemes for the detection of **itinerant photons**

Details in the tutorial this afternoon

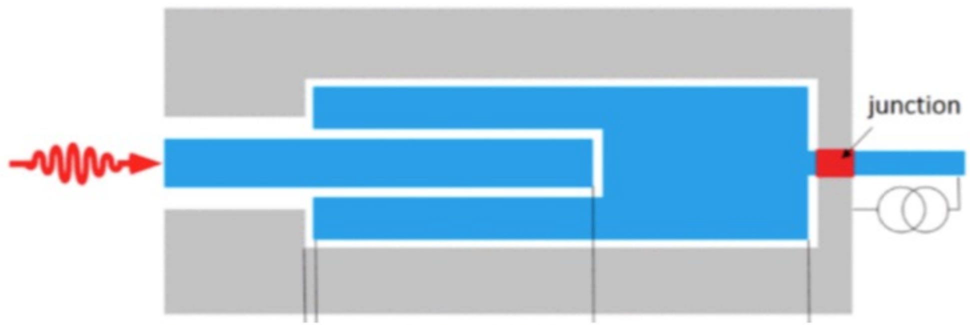
- "**artificial atoms**" introduced in circuit QED, their transition frequencies lie in the ~GHz range



E. Albertinale *et al*, Nature **600**, 434–438 (2021)

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

- single **current-biased Josephson junction (JJ)**

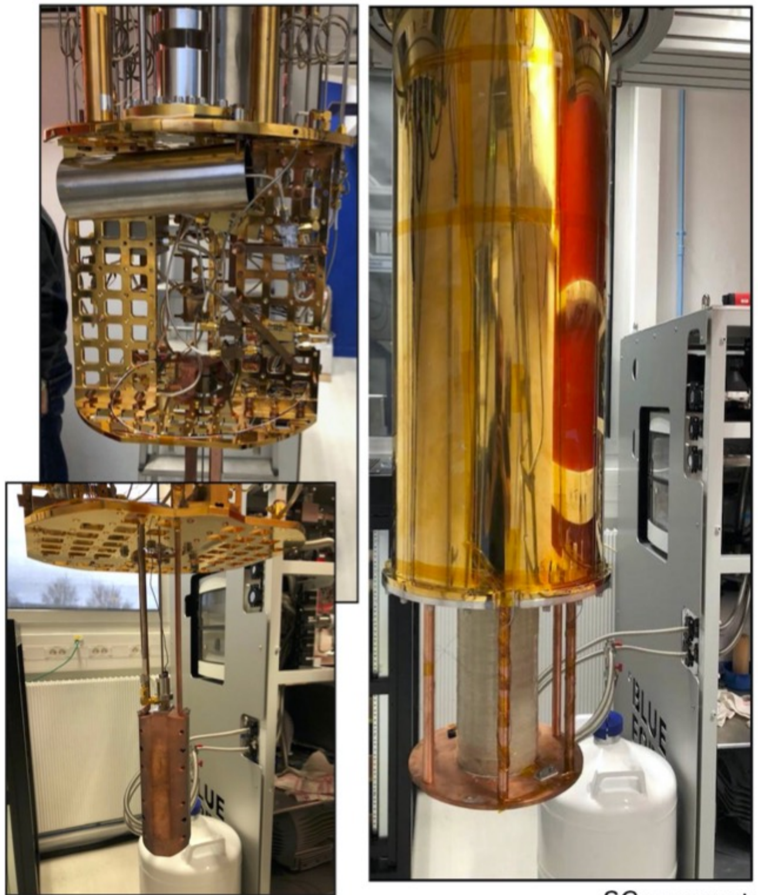


npj Quantum Information **8**, 61 (2022)

IEEE Tras. Appl. Supercond. **33**, 1-9 (2023)

SMPD Haloscopes

Pilot experiment conducted @ Quantronics lab in Saclay (Paris)
SMPD @ 7 GHz, 2 T Magnetic field
Hybrid cavity with small tuning
Manuscript in preparation



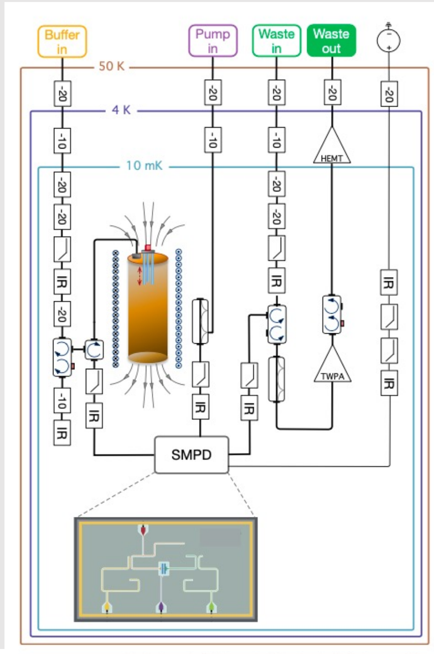
SMPD (top) and cavity

SC magnet

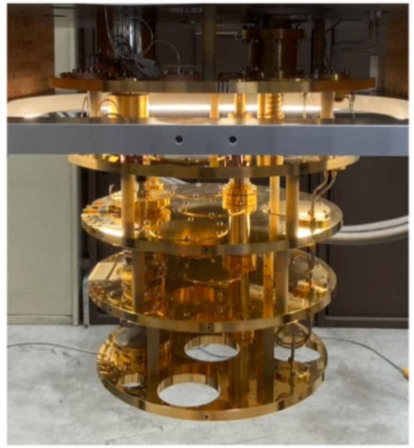
A copy of the Saclay device will be installed in Padova for an haloscope with:

- Larger tuning (200 MHz)
- Higher Magnetic field (6 T)

We are looking for students!!



building a SMPD-HALOSCOPE IN PADOVA

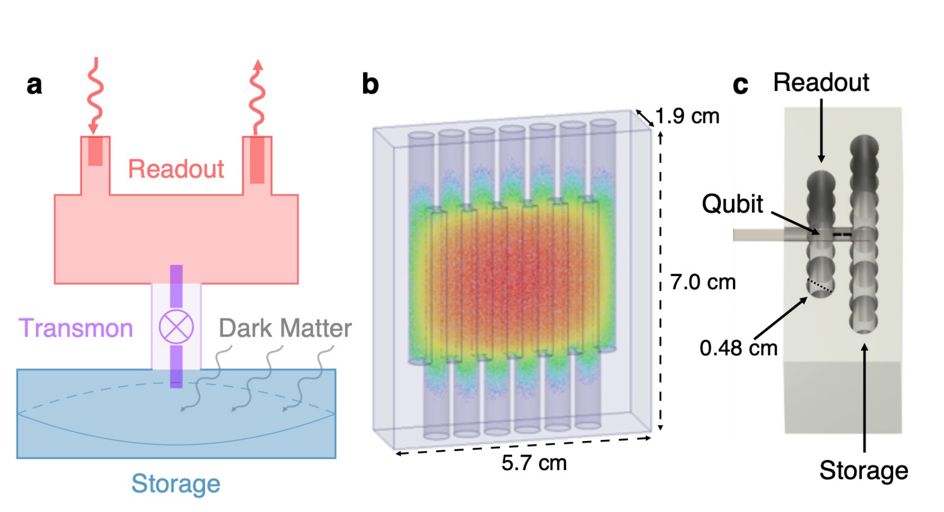


INFN
Istituto Nazionale di Fisica Nucleare

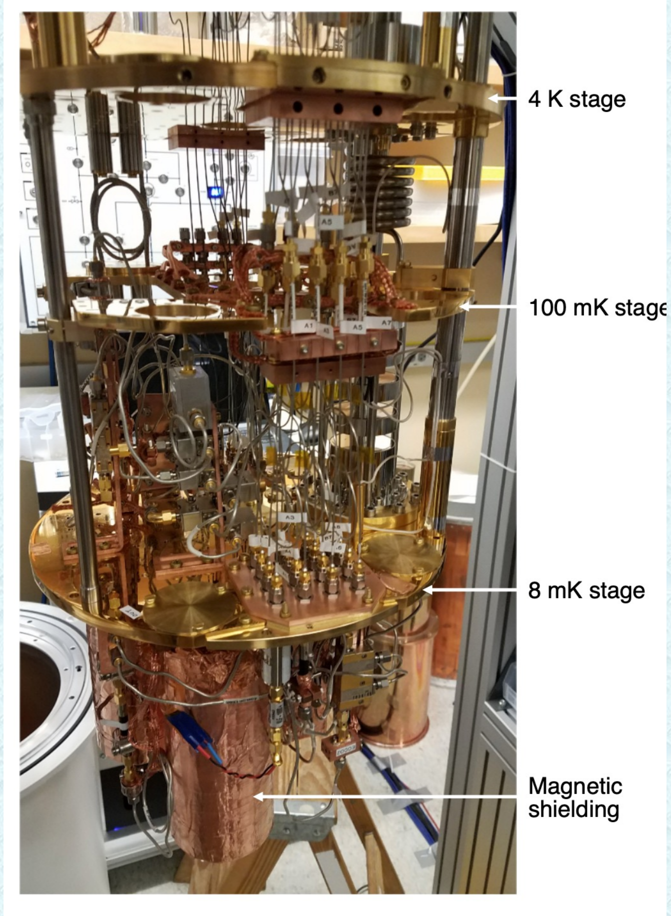
SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Dark photon haloscopes – quantum sensing

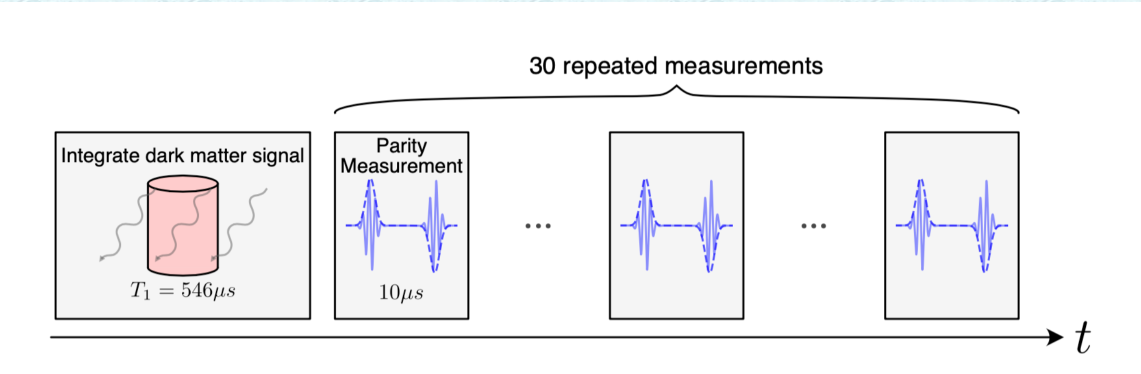
A transmon qubit coupled to a microwave cavity has been used to search for dark photons - A. Dixit et al. Phys. Rev. Lett. **126**, 141302 (2021)



Storage Cavity 6.011 GHz
Readout Cavity 8.052 GHz
Qubit 4.749 GHz



- A superconducting qubit bridges the storage and readout cavities.
- The storage is used to hold the dark matter generated photon
- The readout is used to measure the state of the qubit.
- Dedicated **dark matter search protocol** to look for qubit state changes induced by the presence of a photon in the cavity



Sensitivity improved by factor 37 over SQL
1300 x faster scanning rate

No tuning
No magnetic field
Axion searches needs more development

The road to the future: microwave cavities

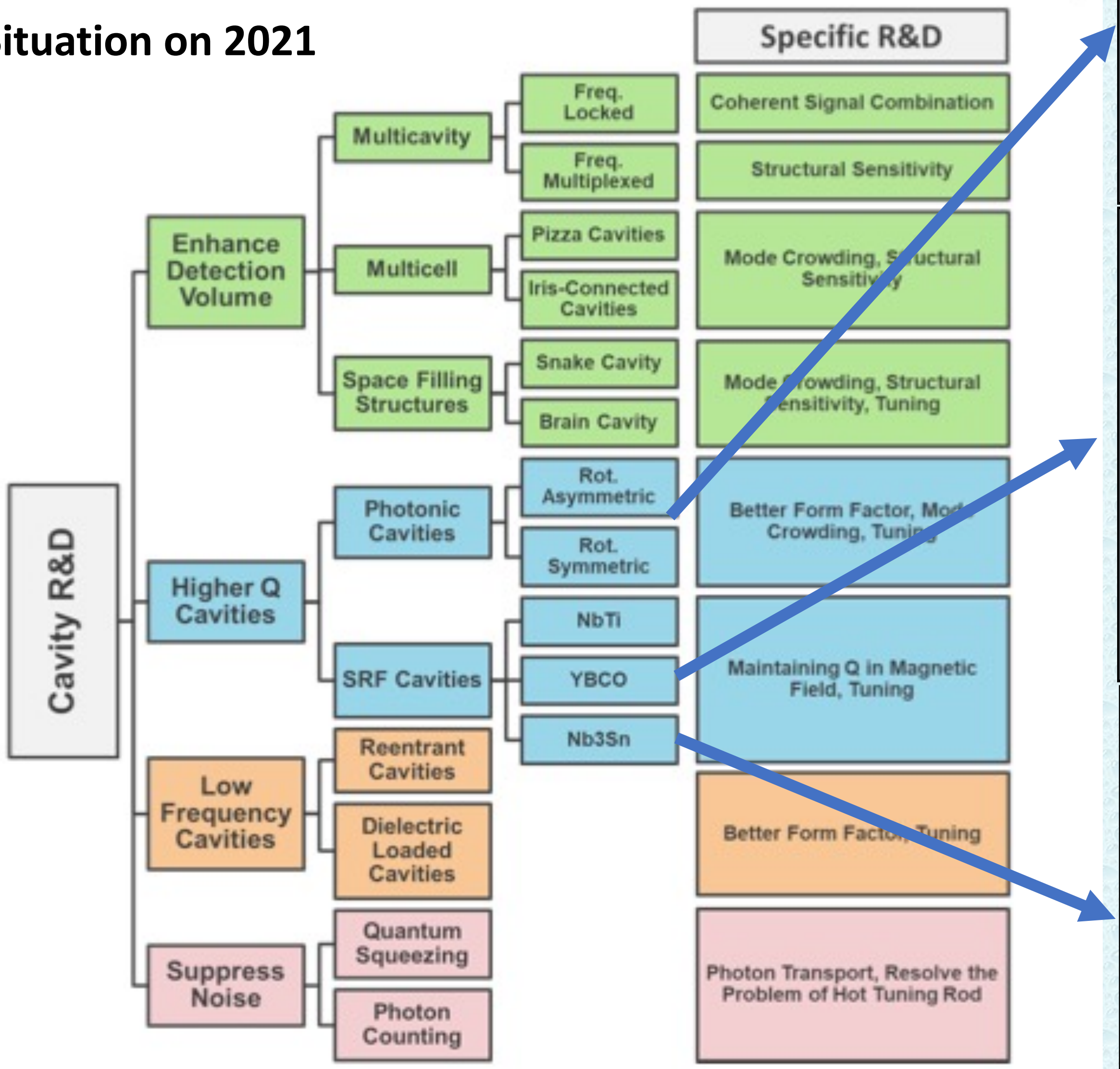
Figure of merit
$F = C^2_{mnl} V^2 Q_0$

+ Tuning

$$C_{mnl} = \frac{\left|\int_V \mathbf{E}_{\mathbf{mnl}} \cdot \mathbf{B}\, d^3x\right|^2}{\int_V |\mathbf{B}|^2 d^3x \int_V \varepsilon |\mathbf{E}_{\mathbf{mnl}}|^2 d^3x},$$

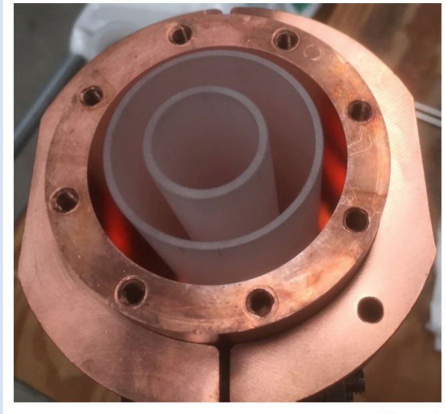
Snowmass 2021 White Paper Axion Dark Matter

Situation on 2021



QUAX dielectric cavity

- Two nested sapphire cylinders configuration
- Q > 9x10^6 in a 8T field @ 10.4 GHz

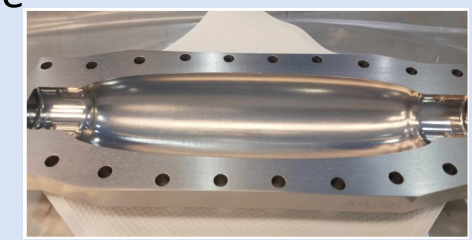


- **CAPP** biaxially textured YBa2Cu3O7−x cavity
- Q ~ 500 000 @ 8T field @ 2.3 GHz

(Patras workshop 2021)

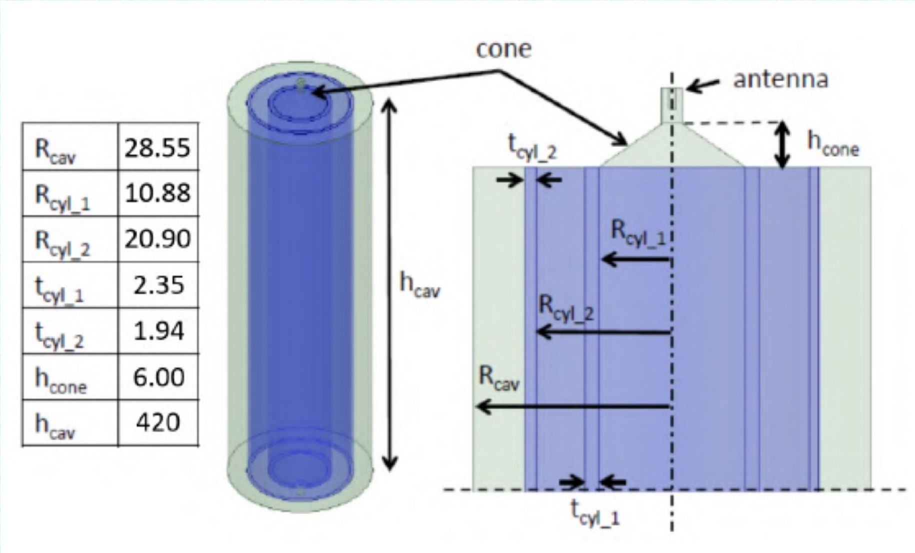
Fermilab (SQMS) - QUAX arXiv 2201.10733

- SC cavity with optimized geometry and choice of fabrication technique
- Q ~ 500 000 @ 6T field @ 3.9 GHz



Cavities developments – larger Q

QUAX double shell dielectric cavity



- **dielectric materials** properly placed inside traditional cylindrical resonant cavities, operated in TM modes of higher order

PHYS. REV. APPLIED **17,** 054013 (2022)

- Exploit TM030 mode
- High Q-factor due to field confinement by dielectric shells
- Q0 = 9.3 million in a 8 T magnetic field
- Small cavity tuning (few MHz) with sapphire rods

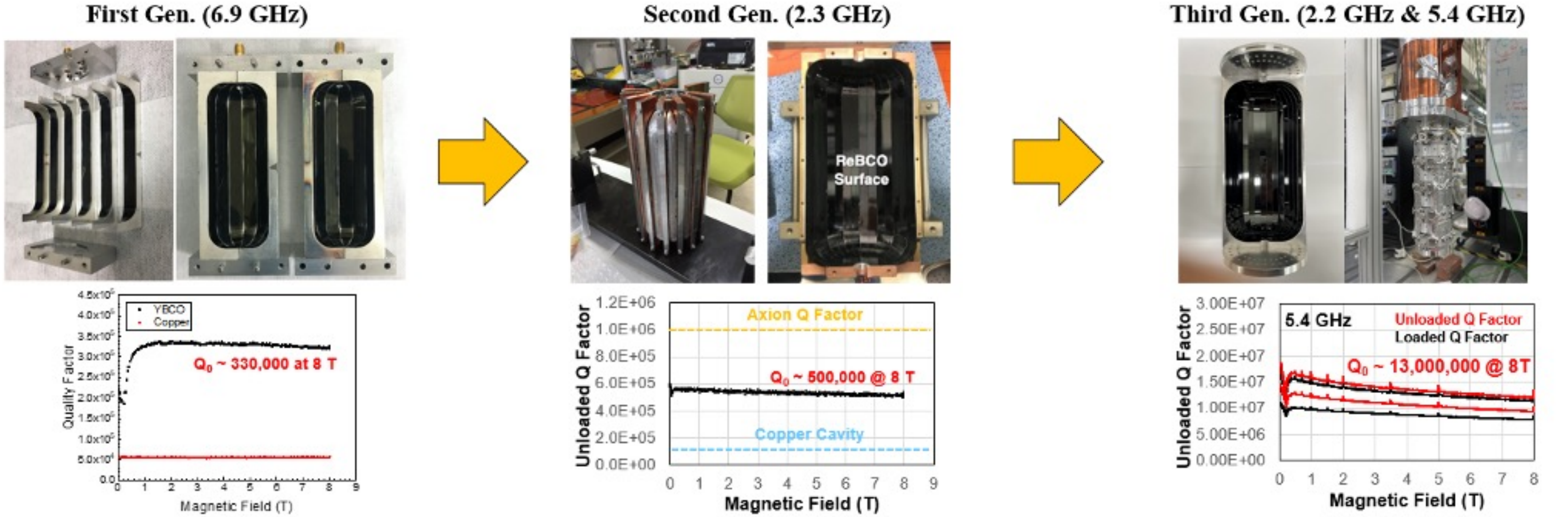
Q value @ 4 K

Cavity	ν_{cav}	V	C_{nml}	$V_{eff}=C\cdot V$	Q_0
QUAX 2020	10.4 GHz	80 cm^3	0.69	55.6 cm^3	76000
QUAX 2022	10.35 GHz	1056 cm^3	0.033	34.7 cm^3	$9.1\cdot10^6$

Cavities developments – larger Q

CAPP High Temperature Superconductor cavities

- A polygon-shaped cavity design with biaxially textured ReBCO superconducting tapes covering the entire inner wall.
- Using a 12-sided polygon cavity, substantially improved *Q* factors
- No considerable degradation in the presence of magnetic fields up to 8 T



Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T
					330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	0.2	5.4	13,000,000 @ 8 T
	EuBCO + APC	Hastelloy	1.5	2.3	4,500,000 @ 7 T
	EuBCO + APC	Hastelloy	36	~ 1	?

From Woohyun Chung talk @ Patras 2023

HTS cavity can reach 10 times larger than axion quality factor (~ 10^6)

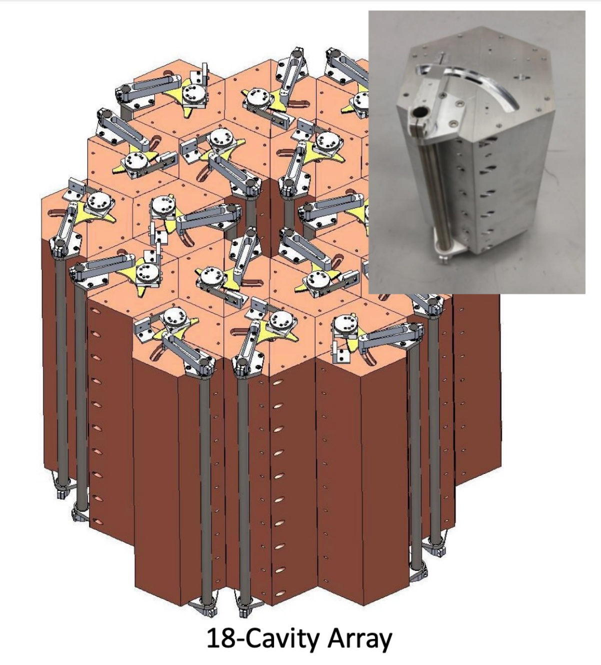
Cavities developments - new geometries

Find ways to increase volume at high frequency while keeping tuning

For right cylindrical cavity, main mode volume

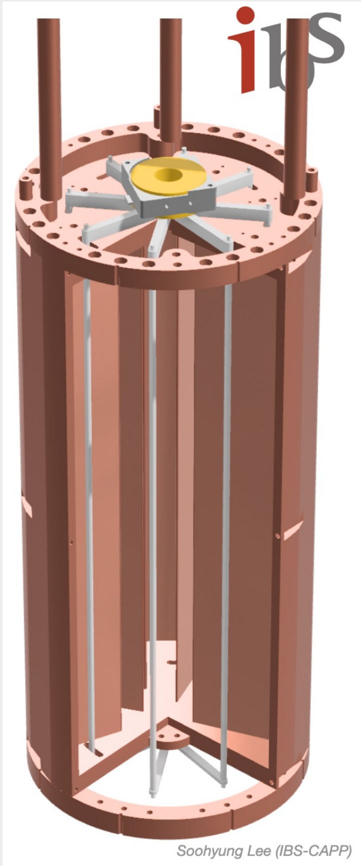
$V \sim 1/d^2 \sim 1/f^2$

ADMX Extended frequency range (2-4GHz): cavity array

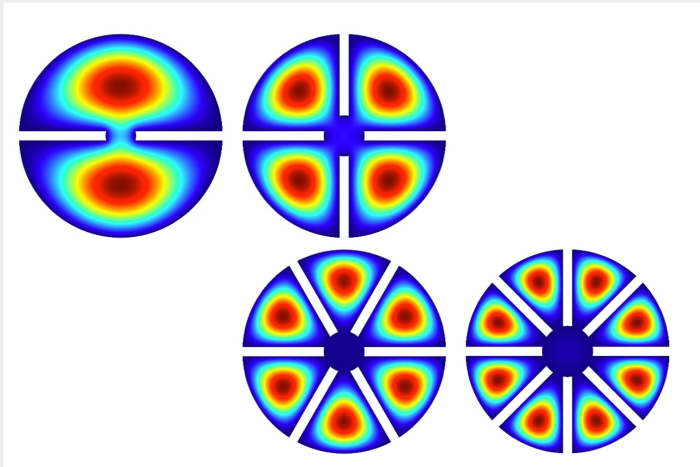


80 liters
Avg C ~ 0.4
Q ~ 90 000

Multiple cell cavity at CAPP

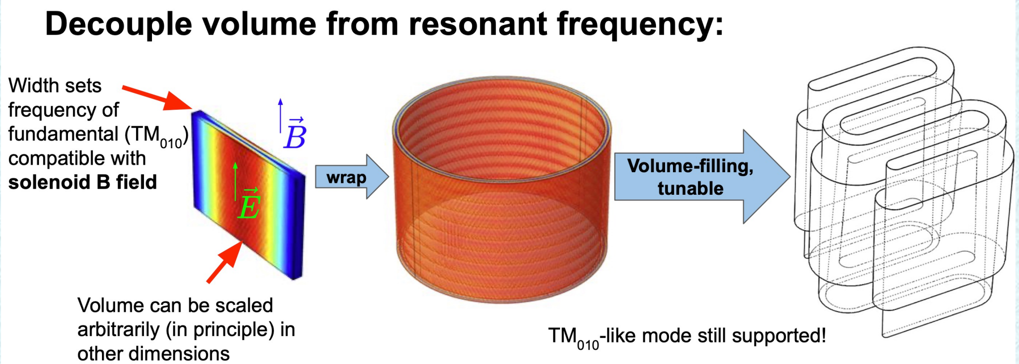


- Resonant frequency increases with the cell multiplicity.
- Same frequency tuning mechanism as multiple cavity system can be employed.
- A single RF antenna extracts the signal out of the cavity.



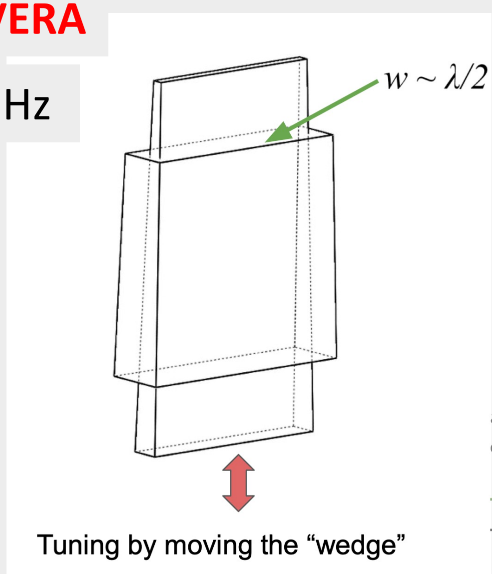
Frequency up to 8 GHz

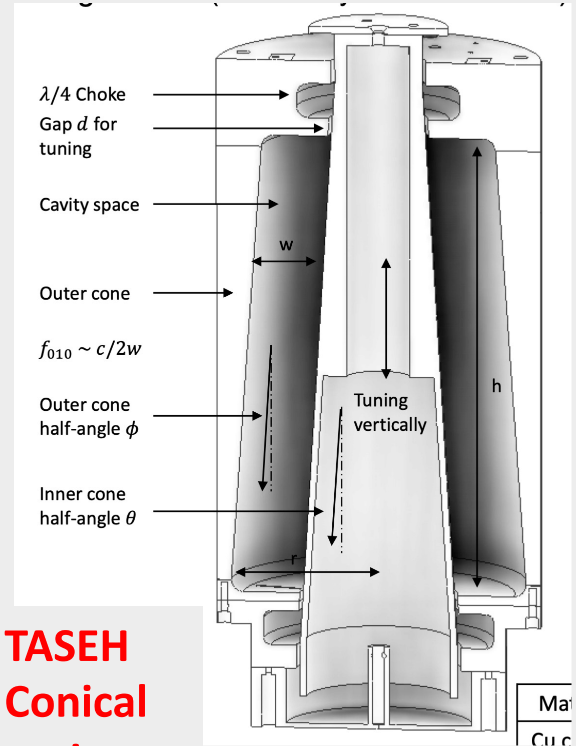
Cavities developments – new geometries



ADMX VERA

f > 4 GHz





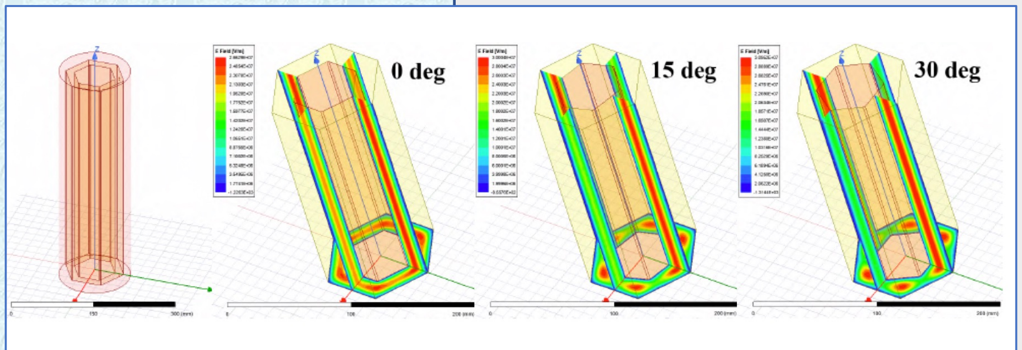
TASEH Conical cavity

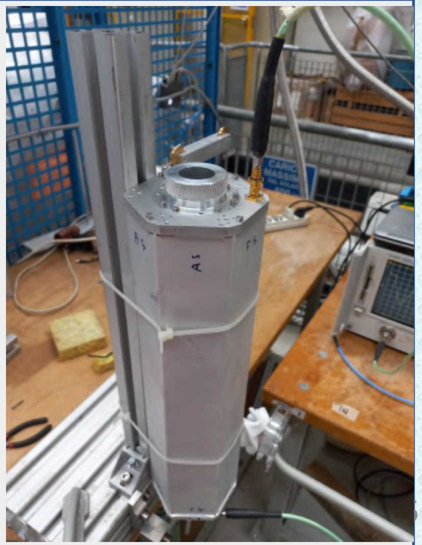
E field pattern

f ~ 5 GHz

QUAX Polygonal cavity

f ~ 10 GHz





Major issues for all:

- Surface quality
- Alignment
- Spurious modes
- All degrade Cmnl
- Q factor?

Cavities developments – tuning

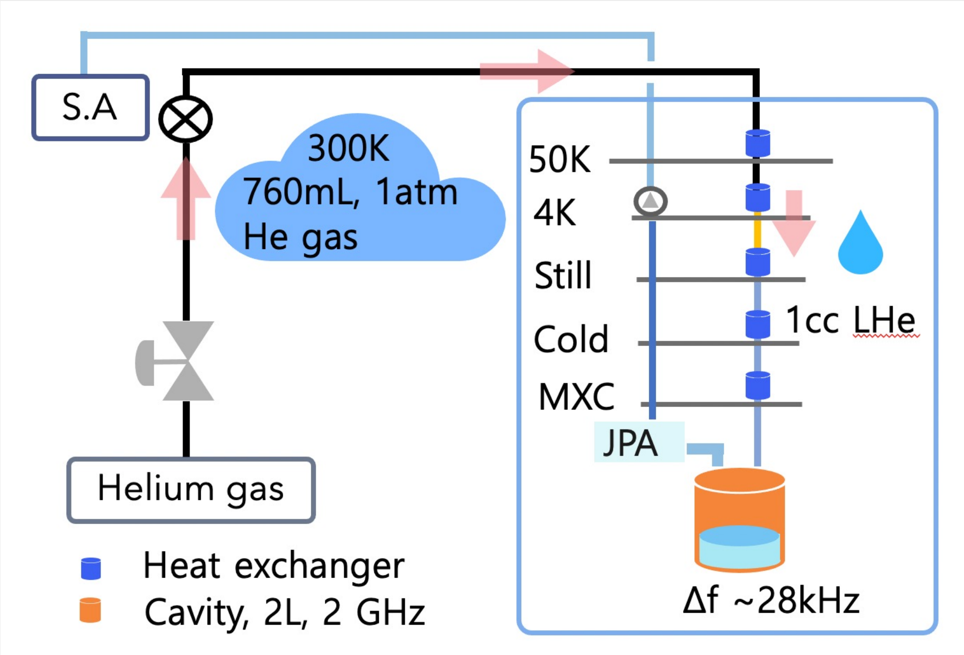
CAPP Superfluid Helium Tuning

- Fill SC cavities with He
- He Level set the frequency change

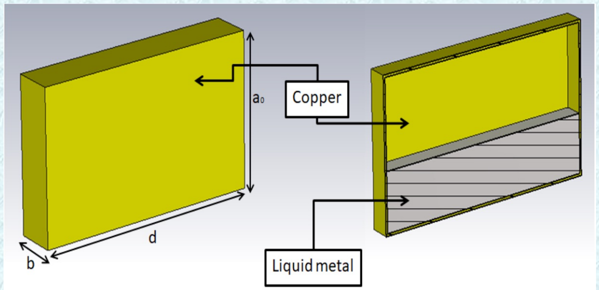
Superfluid Helium ($\epsilon_r \approx 1.057$) tuning

- $f_{TM010} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \frac{2.405}{R}$
- $\frac{f_{empty} - f_{LHe}}{f_{LHe}} = \sqrt{\epsilon_{LHe}} - 1 \approx 0.028,$

~3 % frequency shift

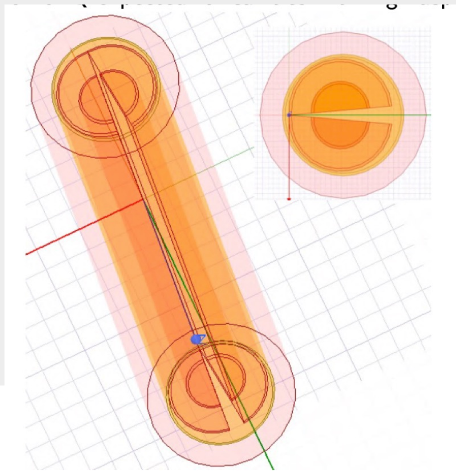


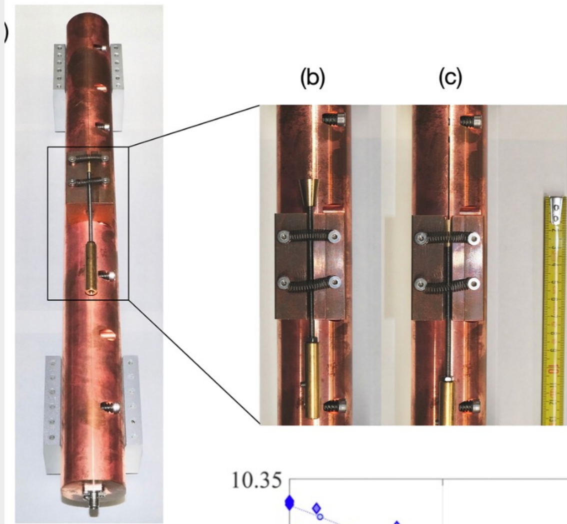
arXiv:1804.03443v1
QUAX
Liquid Metal Tuning of a resonator



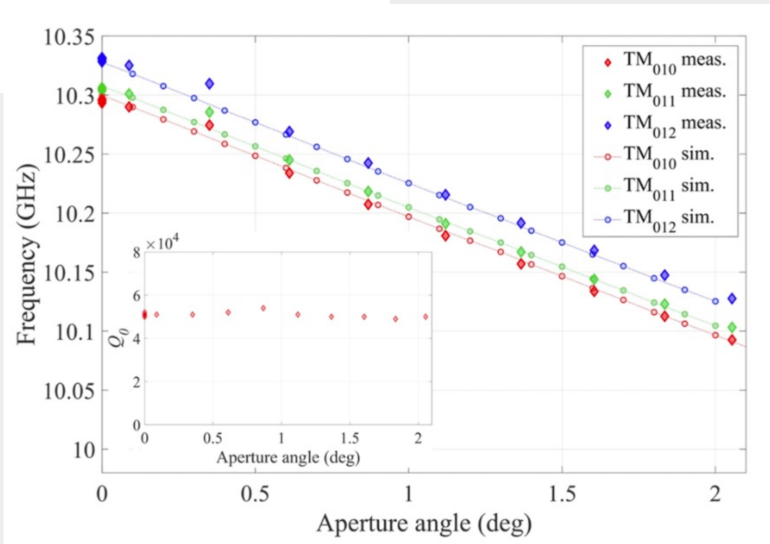
QUAX Clamshell cavity

- Simple way to tune right circular cavities
- Effective radius can be modified by separating the two halves of a clamshell





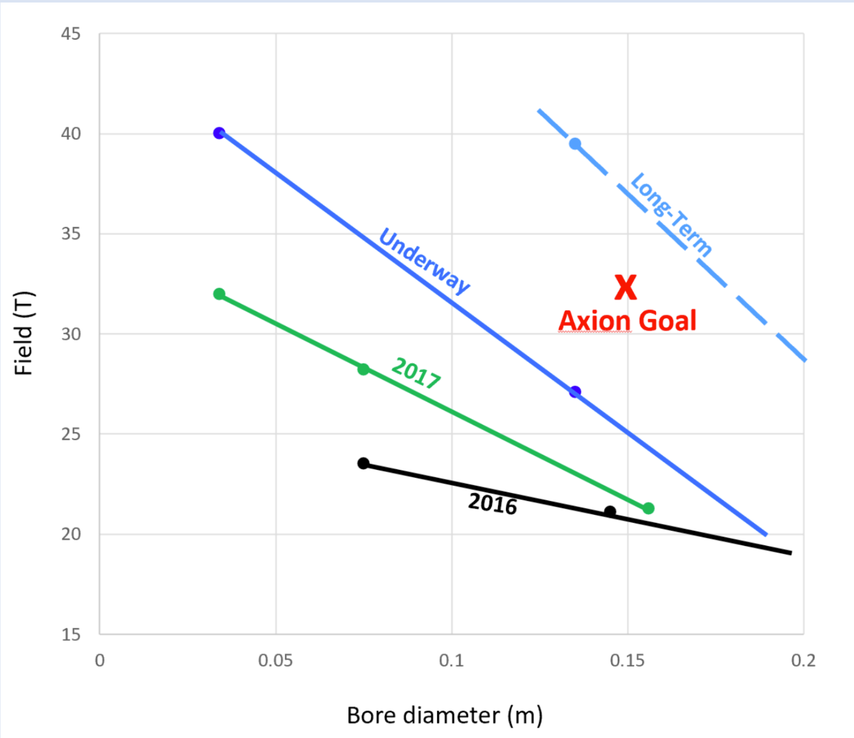
- Lack of mode crossings
- Tuning linear with aperture



The road to the future: magnets

- For haloscope a dedicated **magnet R&D program** for higher strength (up to 45+ Tesla) and optimized magnet designs is needed to maximize B^2 V
- Up to now standard superconducting magnets provided field up to about 12-14 T
- Hybrid magnets are foreseen to be used in next generation haloscopes

In the **US the National High Magnetic Field Laboratory (MagLab)** has been developing higher field REBCO (Rare Earth barium copper oxide) inserts with current designs reaching a maximum field of 45 T



From Snowmass 2021 Axion Dark Matter White Paper

In **Grenoble** a combination of resistive polyhelix and Bitter coils inserted within a large bore superconducting one, a maximum field of at least **43 T** will be produced in a 34 mm diameter aperture with 24 MW of electrical power

Several lower field option will also be available

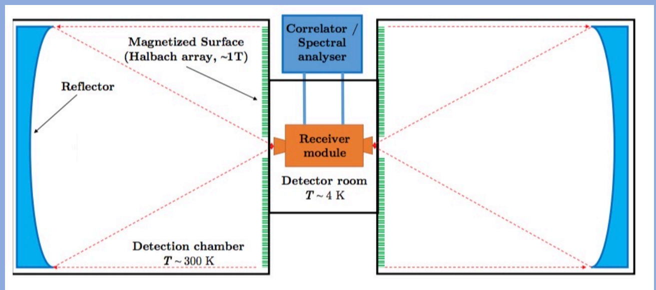
GraHal Project

arXiv:2110.14406

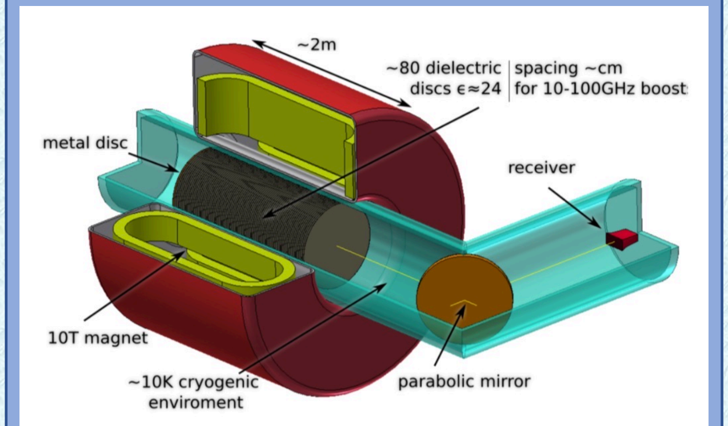
Dark matter haloscopes – what's going on

- Several other activities are starting or being proposed in the very recent time
- It is a field which is expanding very rapidly

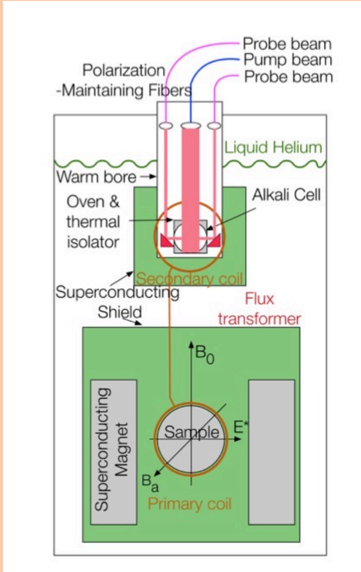
BRASS – dish antenna



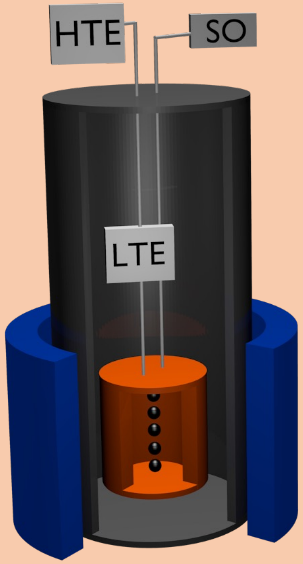
MADMAX - Dielectric haloscope



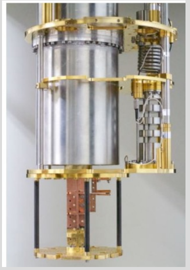
CASPER wind – NMR
Axion - nucleon



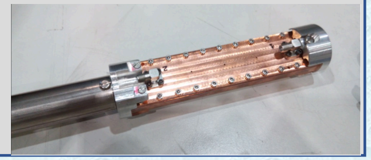
QUAX – EPR
Axion - electron



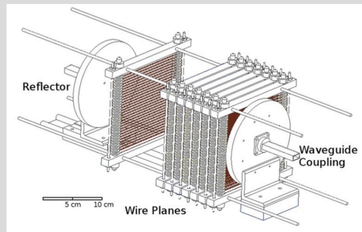
CULTASK
CAPP



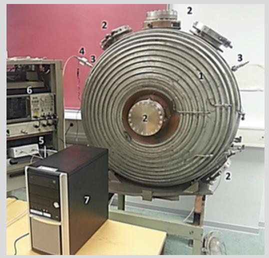
RADES / CAPP – cavities inside CAST



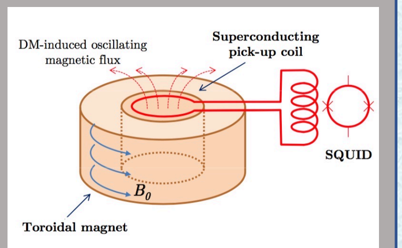
ORPHEUS



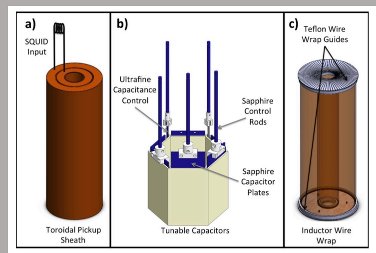
WISPDMX @DESY



ABRACADABRA



DM Radio



LC circuit

Standard Sikivie's detectors

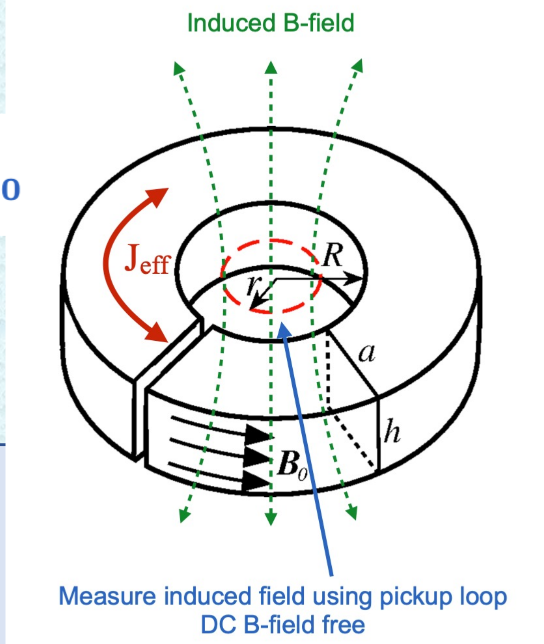
ONLY A SELECTION!!!!!

Update: Dark Matter Haloscopes – Lumped elements

- A new way to look for dark matter axion of **very low mass : $m_a \ll 1\ \mu$eV**
- Measure axion induced electric current in a strong magnetic field

$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}}\cos(m_a t)\mathbf{B_0}$$

- **Toroidal** magnet configuration
- **Broadband** and resonant detection of induced ac magnetic field

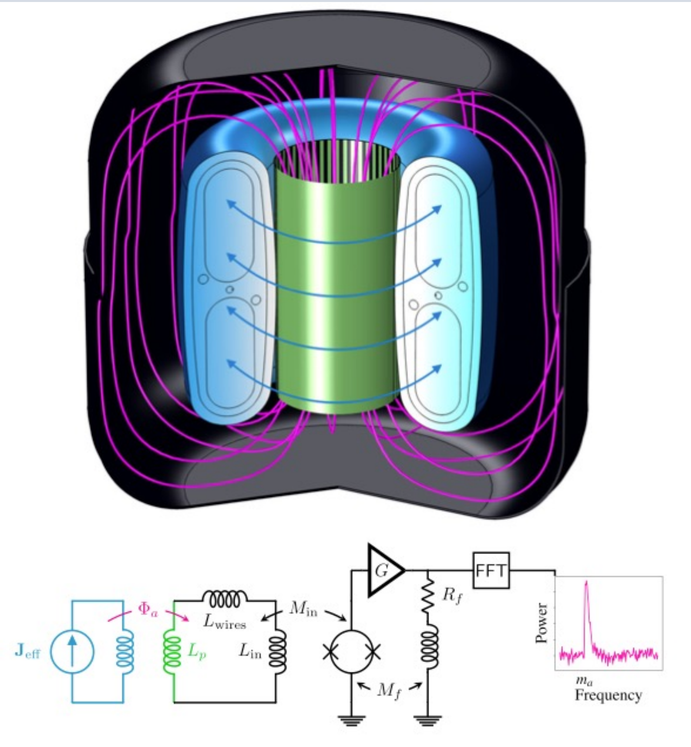


ABRACADABRA (PRL 127, 081801 (2021))

12 cm x 12 cm 1 T toroid

SQUID detection

m_a range 0.41–8.27 neV (50 kHz – 2 MHz)



See also **DM-RADIO**

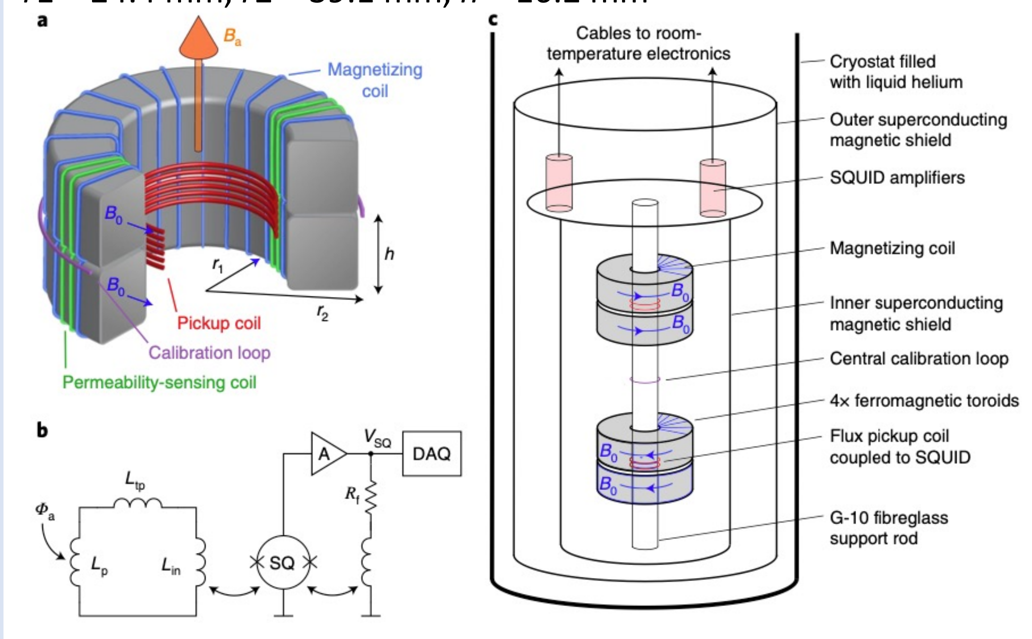
SHAFT *Nature Physics 17 (2021) 79*

1.5 T toroid with FeNi alloy core

SQUID detection @ s = 150 aT/√Hz

m_a range 0.012 –12 neV (3 kHz – 2.9 MHz)

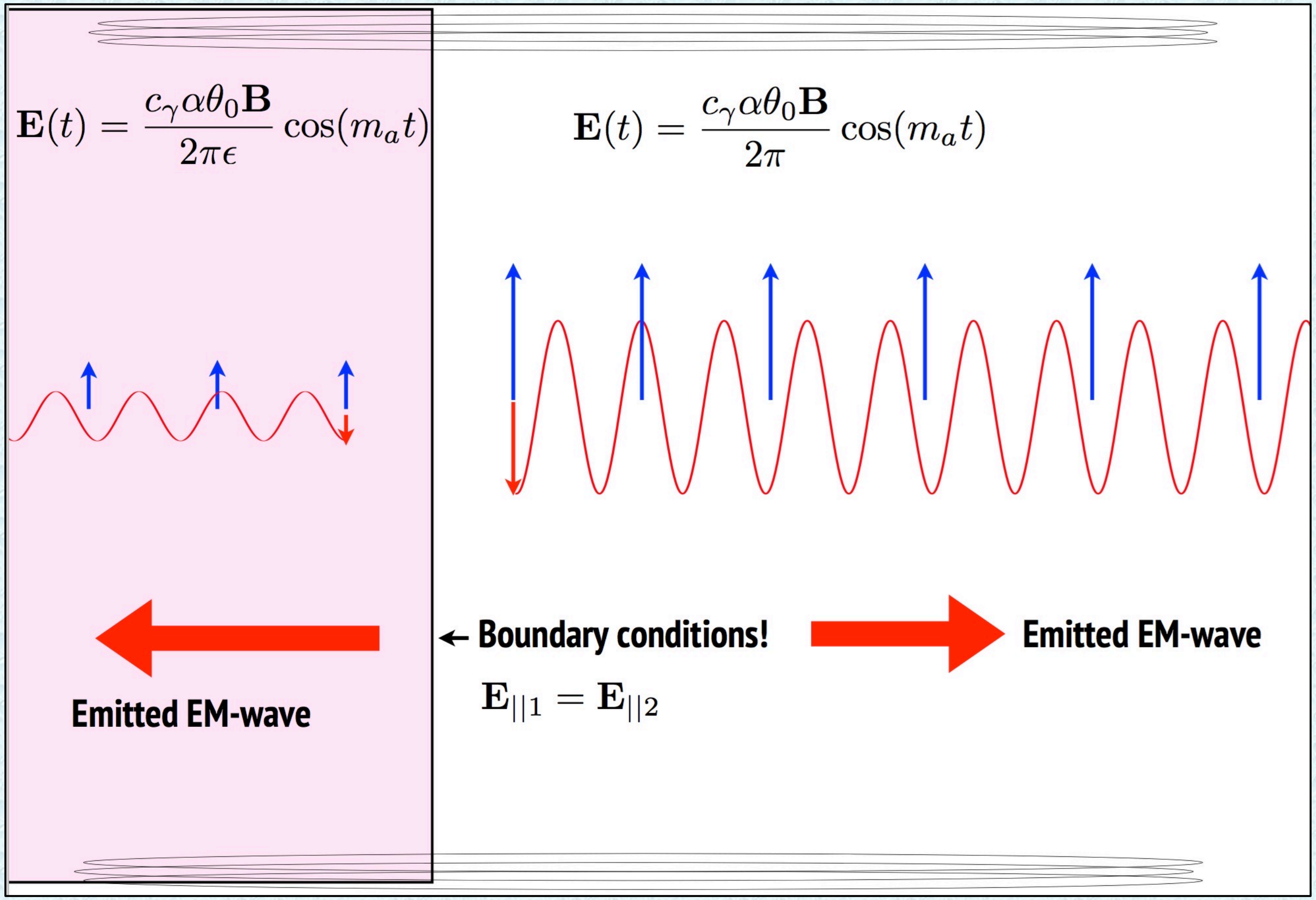
*r*1 = 24.4 mm, *r*2 = 39.1 mm, *h* = 16.2 mm



Other techniques for DM detection: dish antenna

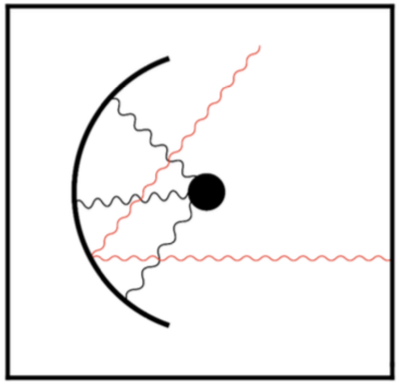
Axion-Induced Electromagnetic Radiation from Reflecting/Refractive Surface in Magnetic Field

- Very hard to reach high masses (tens of μeV) with resonant cavities
- New techniques exploits alps induced effects in a magnetized boundary



- A dielectric/conductive interface **immersed in** a static homogeneous **magnetic field** will **radiate EM-wave** at the frequency corresponding to the mass of the ALP dark matter surrounding it

- Wide band system



"Dish Antenna" Horns, Jaeckel, Lindner, Lobanov, Redondo & Ringwald, 2012

Emtted power $P \propto AB^2 f^{-2}$

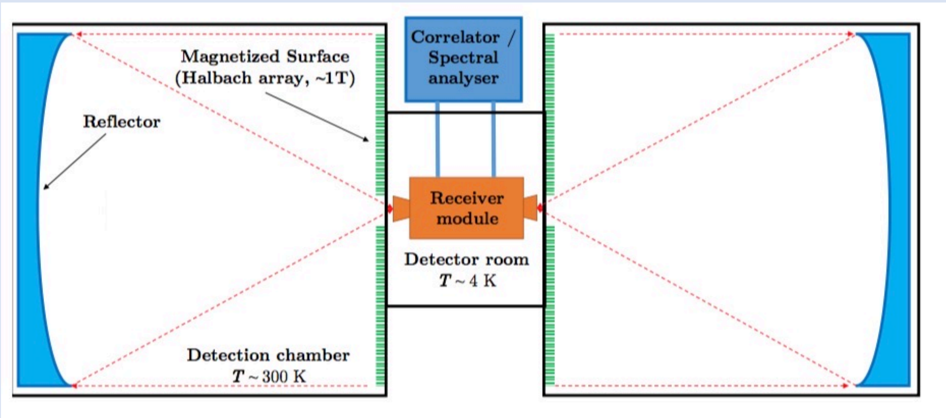
Large area A, Strong Fields B

Other techniques: proposals

Conductive mirror

BRASS experiment (Hamburg)

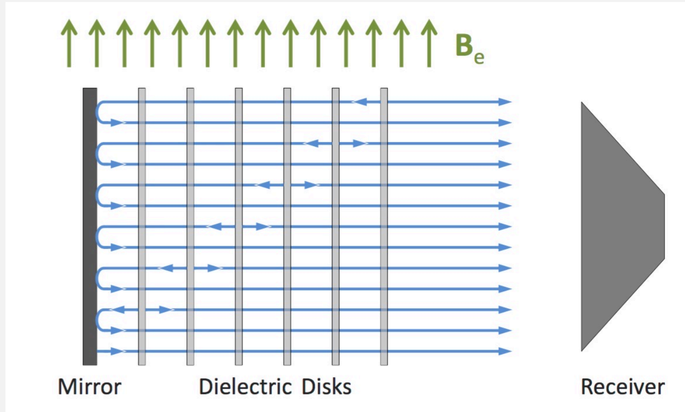
- Large surface mirror; 8 m radius
- Halbach array of permanent magnets
- Rejection of background thanks to spherical shape

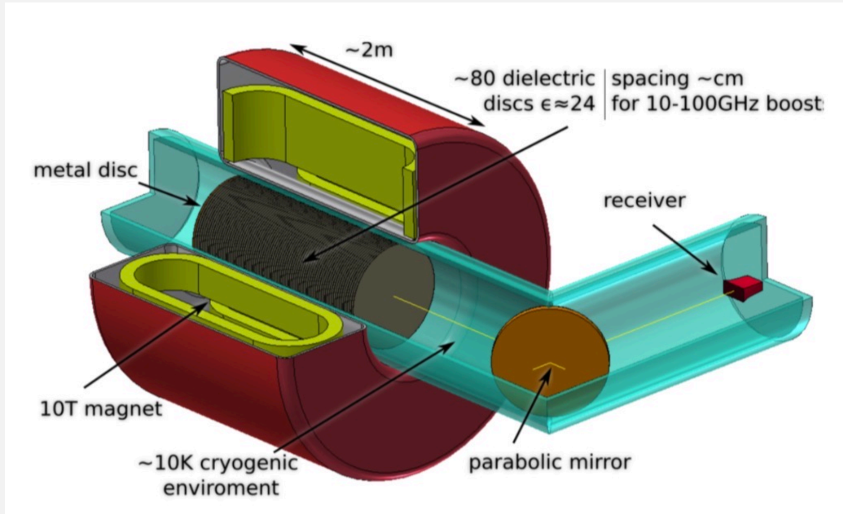


Stacked dielectric mirrors

MADMAX experiment (Germany)

- Stacked structure of dielectric plates
- Interference between each emission boost sensitivity





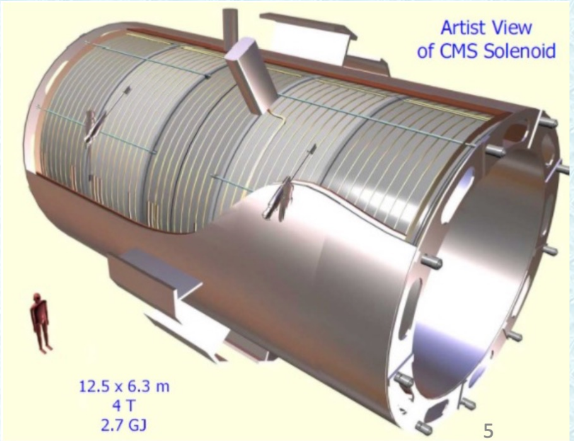
- 80 dielectric discs with 60 cm diameter (1 m^2) each
- 10 T magnetic field
- Large epsilon material to increase boost factor
- Tuning mechanism (interference is not broadband)

More details in the tutorial this afternoon

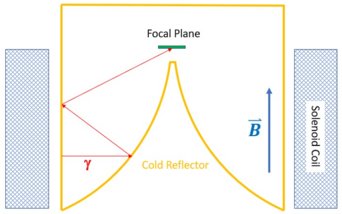
Large volume dish antenna

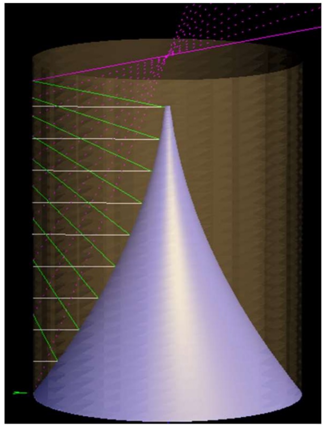
Broadband Reflector Experiment for Axion Detection (BREAD) - PRL **128**, 131801 (2022)

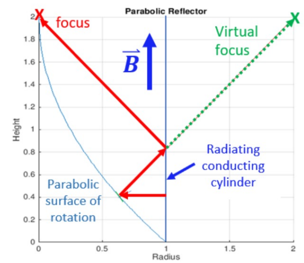
Find solution for large solenoids



"Coaxial Dish": Optical Concentrator for Solenoid Magnets







- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections.

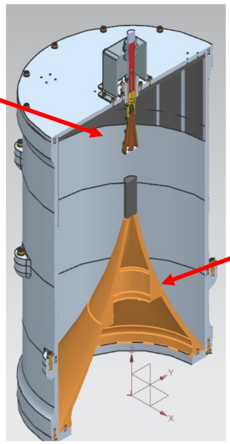
Proof of Concept Experiments: GigaBREAD and InfraBREAD

GigaBREAD: 10-20 GHz experiment with HEMT amplifier

InfraBREAD: 300 THz experiment (~1 micron) with Superconducting Nanowire Detectors (SNSPDs)

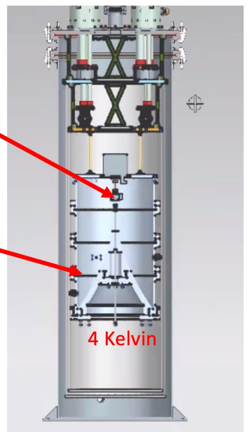
Horn Antenna with Axial position adjustment

Room temperature

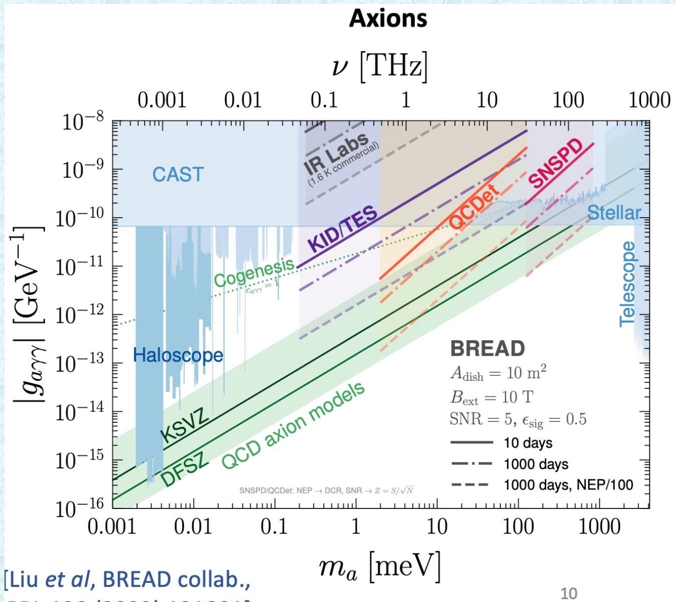


400 mm diameter Coaxial Dish

SNSPD @ 800 mK



With state of the art sensors QCD axion sensitivity



[Liu *et al*, BREAD collab., PRL 128 (2022) 131801]

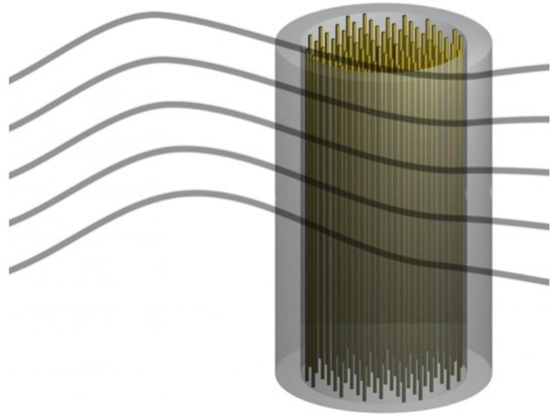
The road to the future: high frequency (>20 GHz)

Plasma haloscopes use a wire metamaterial to create a tuneable artificial plasma frequency, decoupling the wavelength of light from the Compton wavelength and allowing for much stronger signals.

Plasma haloscope: project ALPHA

- **Meta material composed by a dense array of parallel wires** electrically connected to top and bottom walls.
- **Large conversion volume** in a magnetic field even for high frequency
- Recent experimental work on seems to confirm feasibility

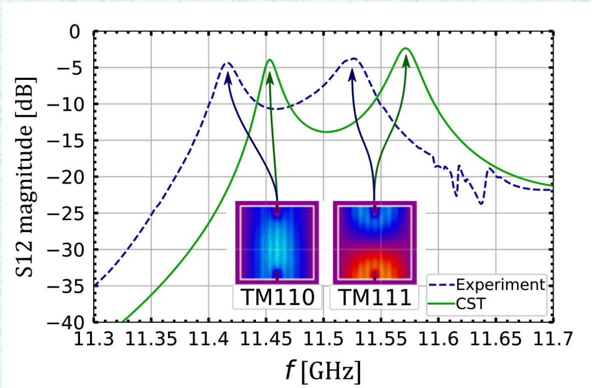
- *Resonance w/ plasma frequency*



$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{s^2 \log(s/d)}$$

ω_p depends on s & d

- *s: inter space*
- *d: wire radius*



Phys. Rev. D **107**, 055013 (2023)

ALPHA PHASE I

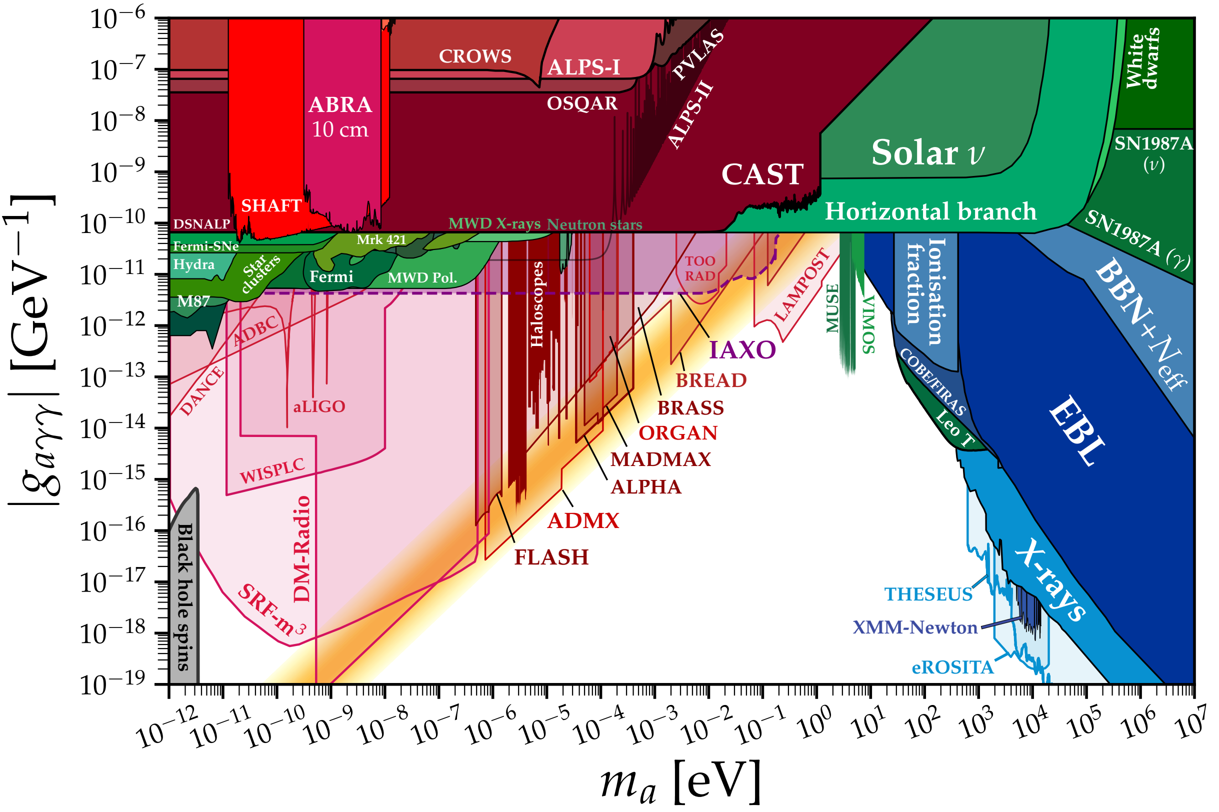
- 2 years run
- $(5 \div 40)$ GHz
- HEMT amplifiers
- Single scan (see [8])

ALPHA PHASE II

- 2 years run
- $(5 \div 45)$ GHz
- Quantum limited
- Single scan (see [8])

$(Q \sim 10^4,\ B \sim 10\,\mathrm{T},\ V \approx 0.3\,\mathrm{m}^3)$

Photon coupling – what next

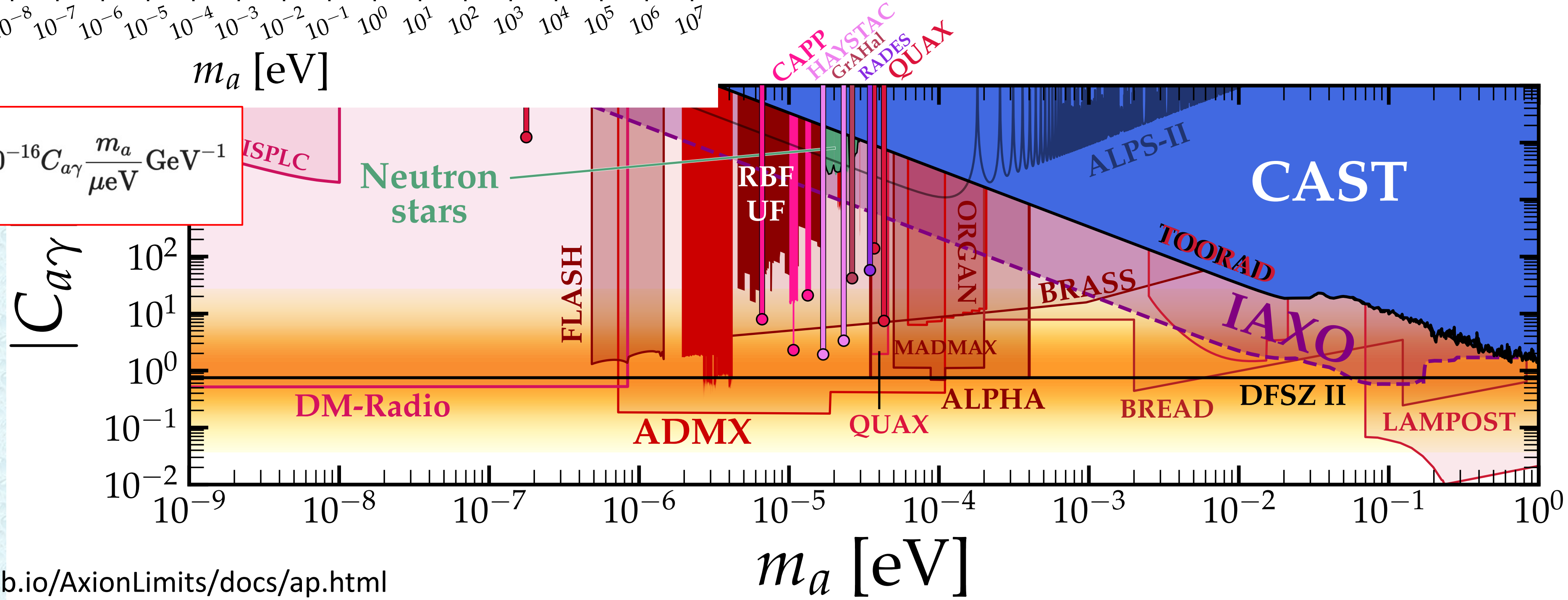


FLASH – Italian based proposal to use FINUDA 1.1 T magnet

TOORAD – International collaboration planning to use metamaterials - topological insulators allowing axion quasiparticles @ THz

- Preliminary material study in CSN5 – project TERAPOL

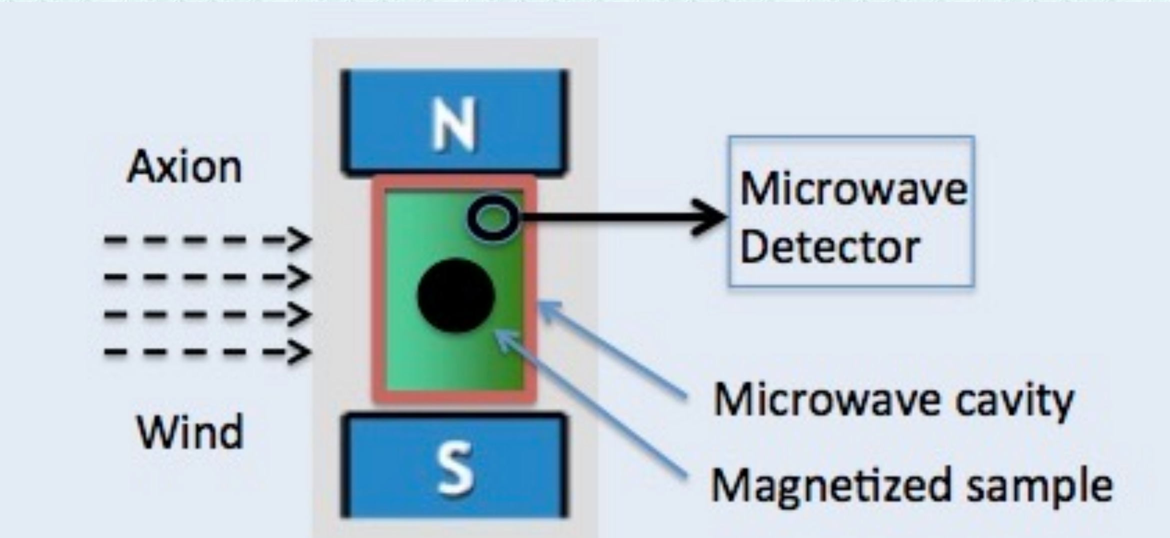
$$g_{a\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} = 2.0\times10^{-16} C_{a\gamma}\frac{m_a}{\mu\text{eV}}\,\text{GeV}^{-1}$$



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

Electron Paramagnetic Resonance: the QUAX proposal

- A new proposal tries to exploit the axion electron coupling $\boldsymbol{g}_{\mathbf{aee}}$
- Due to the motion of the solar system in the galaxy, the axion DM cloud acts as an **effective magnetic field on electron spin $\boldsymbol{g}_{\mathbf{aee}}$**
- The **ferromagnetic transition in a magnetized sample** can be excited and thus **emits microwave photons**



Effective magnetic field

$$B_a = 2.0 \cdot 10^{-22} \left(\frac{m_a}{200\,\mu\text{eV}} \right) \text{ T,}$$

$$B_a \equiv \frac{g_p}{2e} \nabla a$$

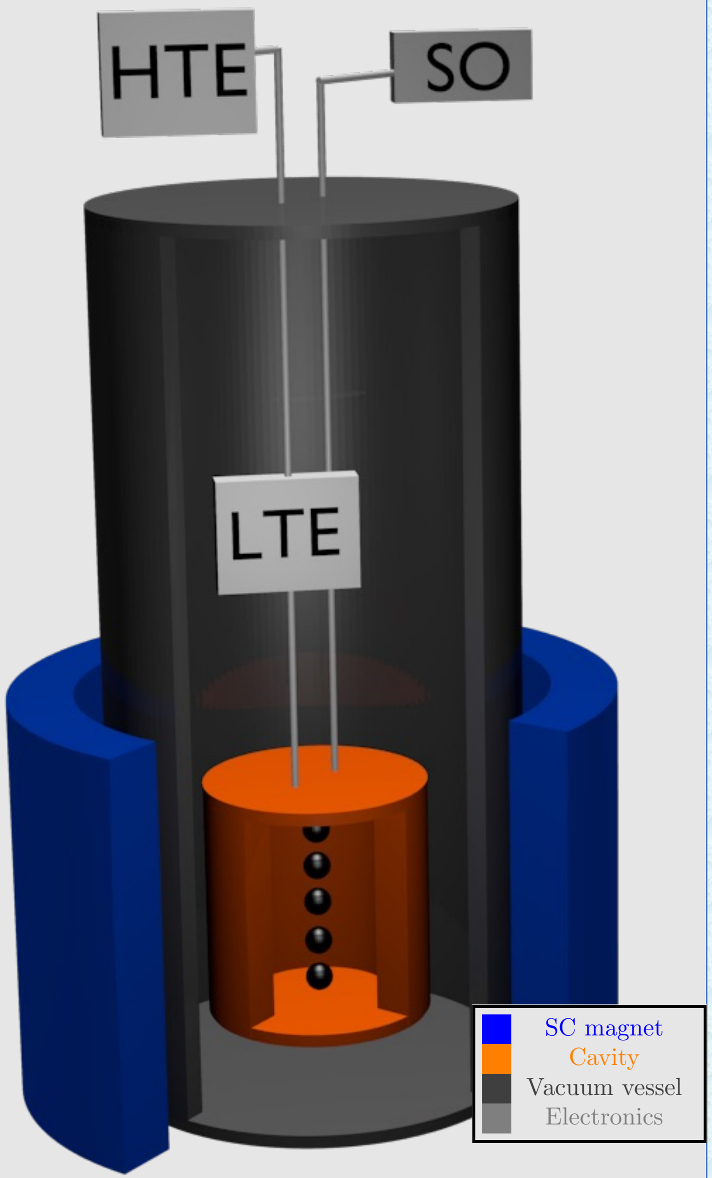
directionality

Expected RF power

$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\,\mu\text{eV}} \right)^3 \left(\frac{V_s}{100\text{ cm}^3} \right) \left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3} \right) \left(\frac{\tau_{\text{min}}}{2\,\mu\text{s}} \right) \text{W}$$

Large **volume *V*** material; high **spin density $\boldsymbol{n}_s$**; long **coherence time $\boldsymbol{t}_{\mathbf{min}}$**

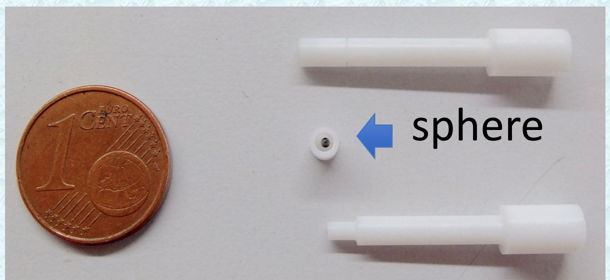
First prototype of QUAX - 2018



HTE – high temp electronics
LTE – low temp electronics
SO – source generator

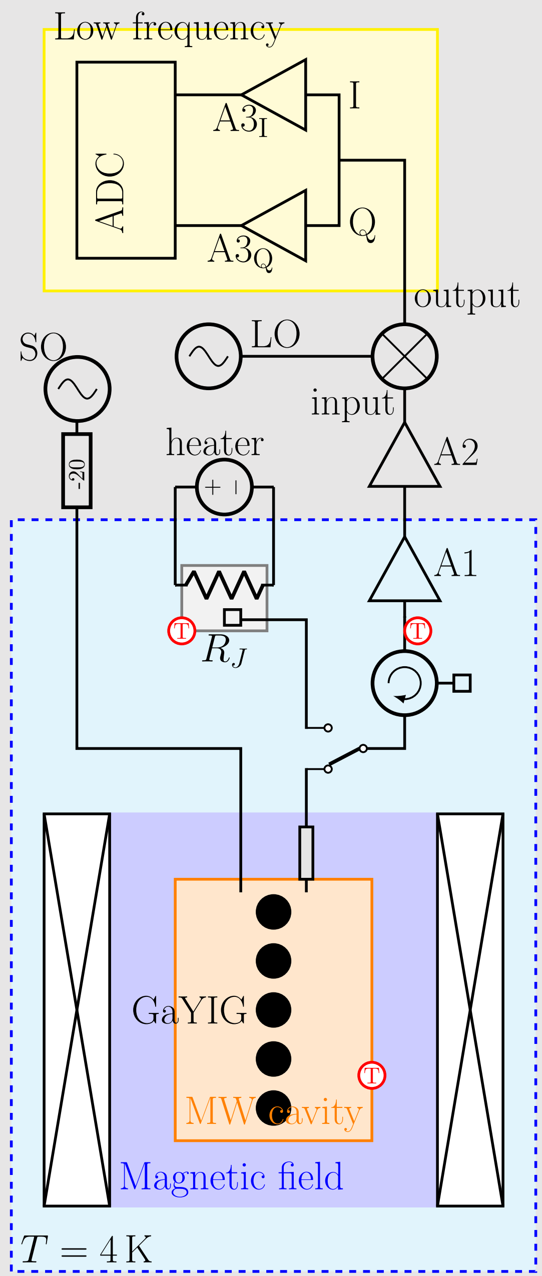
Resonant cavity with 5 GaYIG spheres inside

GaYIG holders



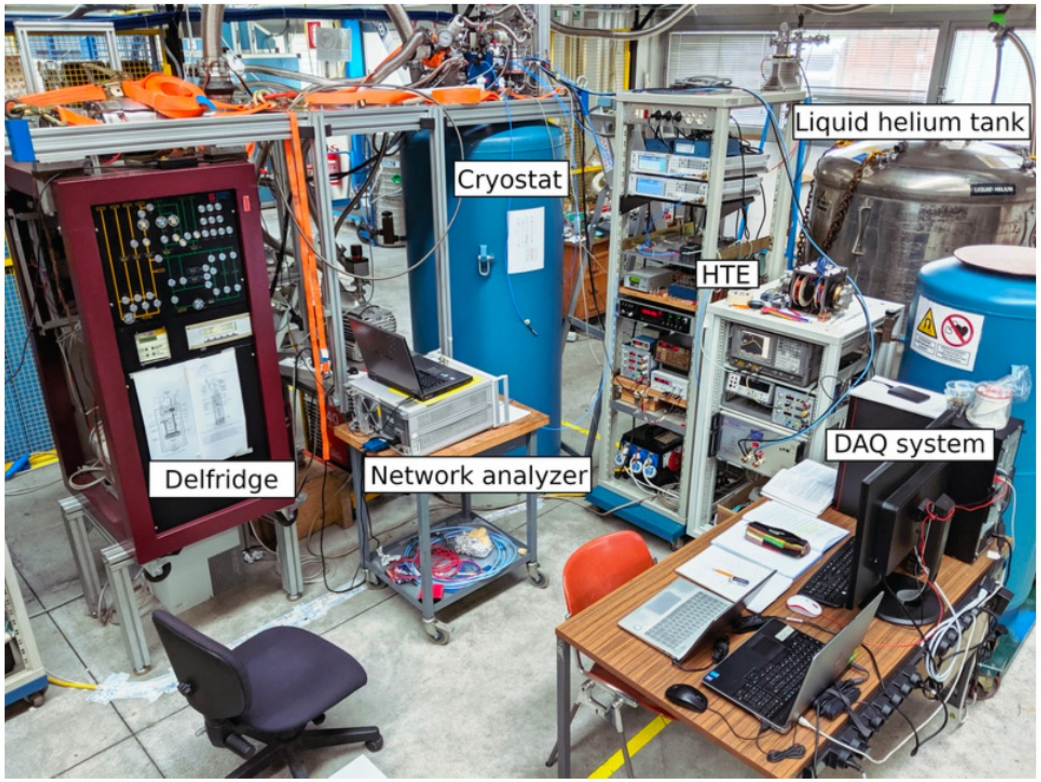
Spheres are free to rotate for correct alignment (easy axis || B)

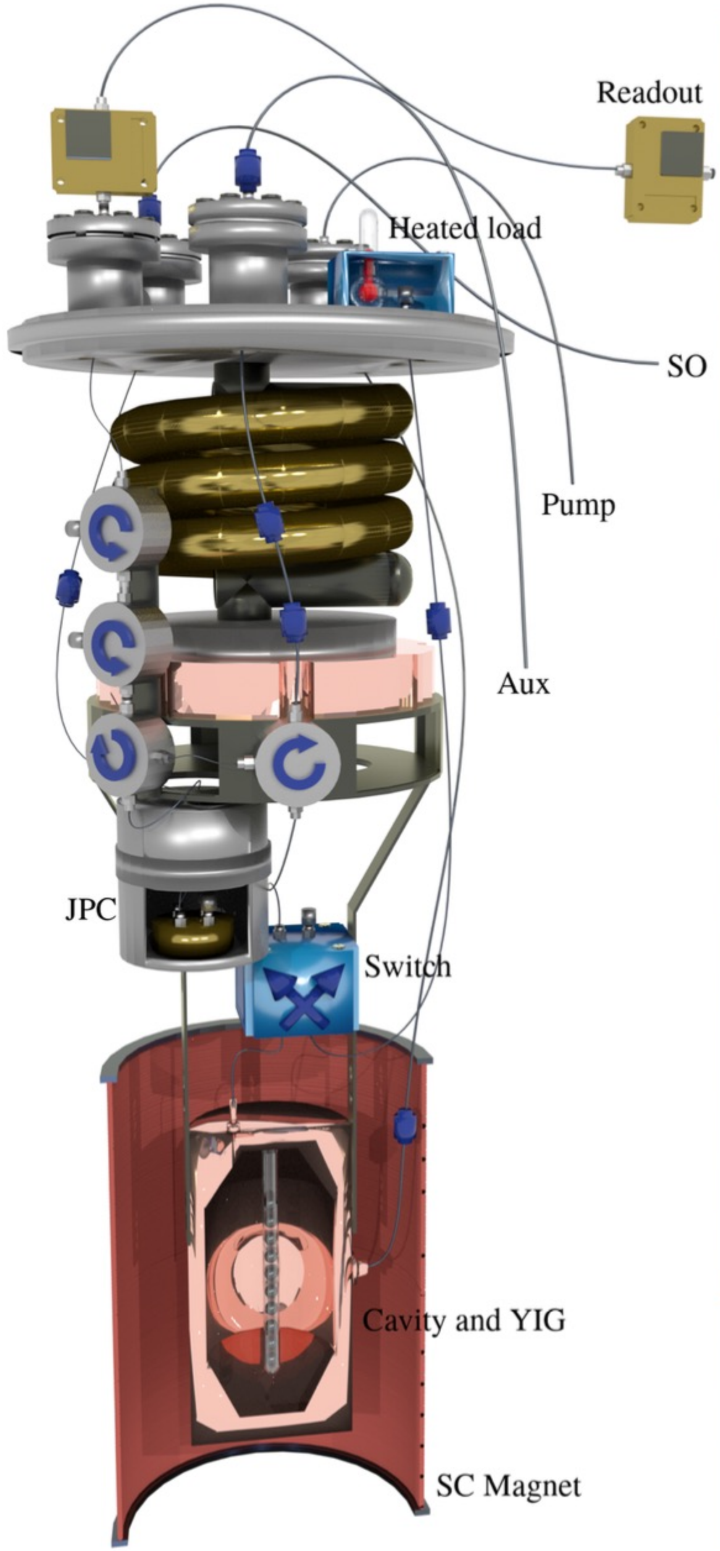
Detection chain



2nd prototype of QUAX

- **Increase signal**
  10 YIG sphere 2.1 mm diameter
- **Reduce noise**
  Quantum limited amplifier (JPC)
  Dilution refrigerator (100 mK)
- **Scan axion mass range**
  Magnetic field tuning





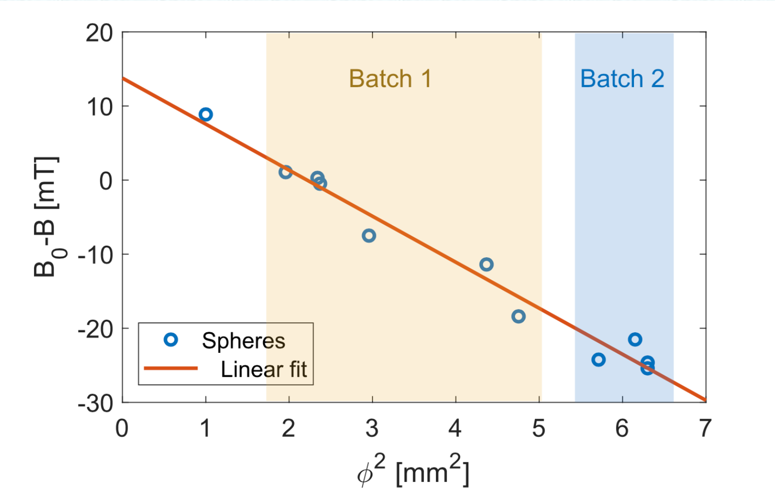
QUAX - Multi sphere system

A new cavity with resonance frequency of 10.7 GHz was realize to match the JPC amplifier working frequency

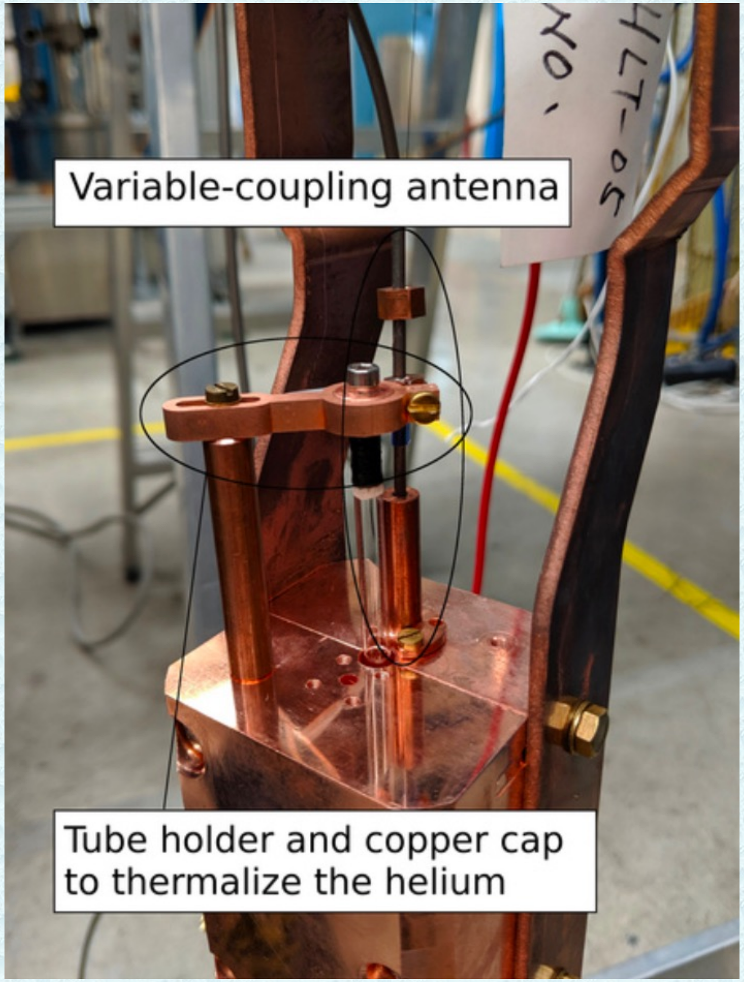
YIG spheres were produced with diameter ~ 2.1 mm, maximum value to avoid non linear effects with rf coupling

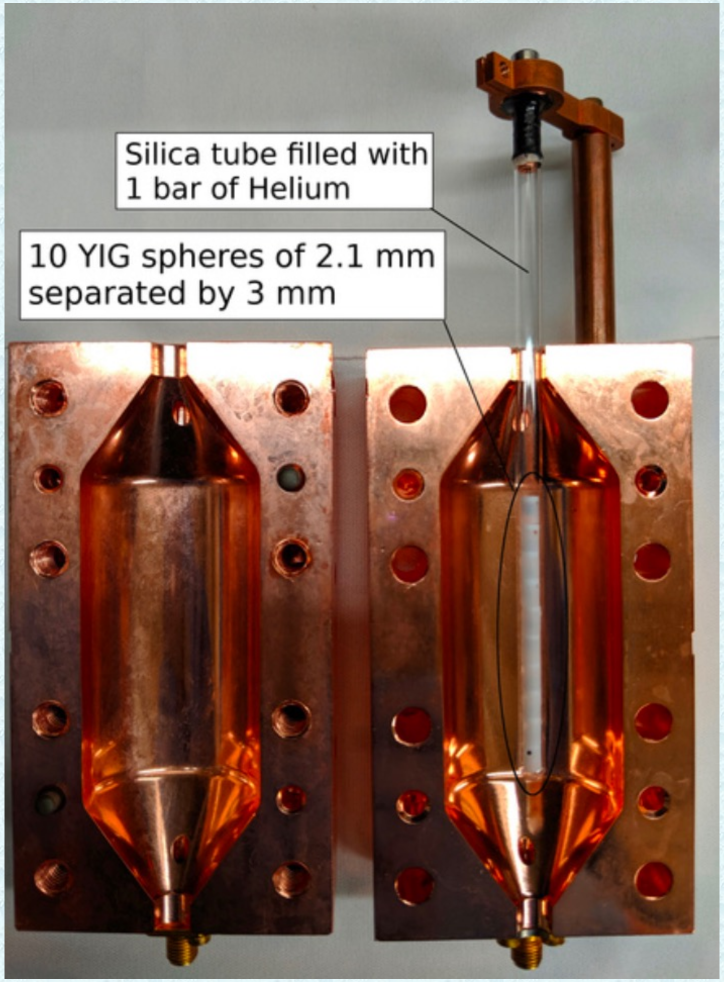
Ten good spheres were selected out of about 20

- Best linewidth
- Same Larmor frequency for a given external static field



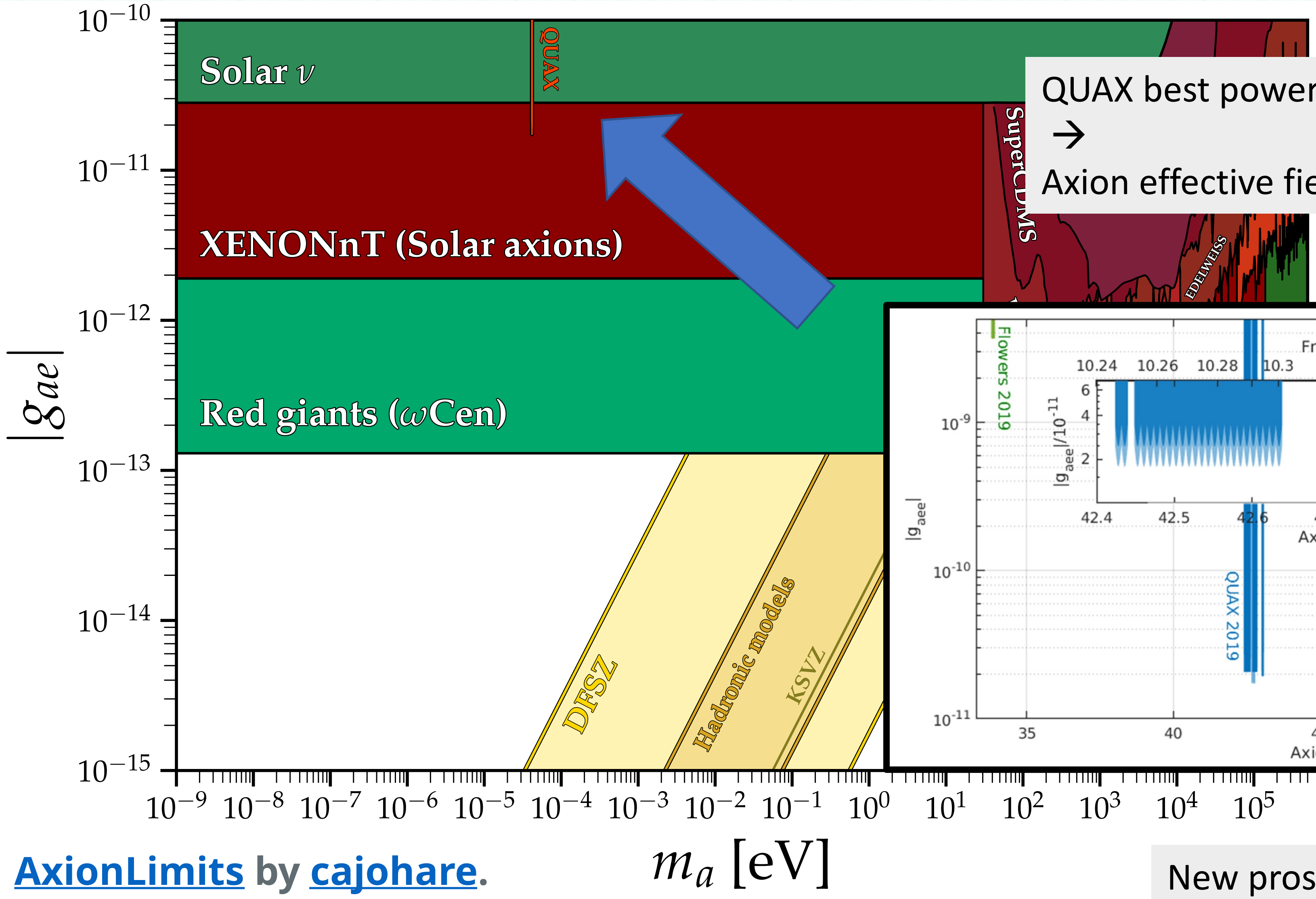
Magnetizing field for a given frequency vs sphere diameter



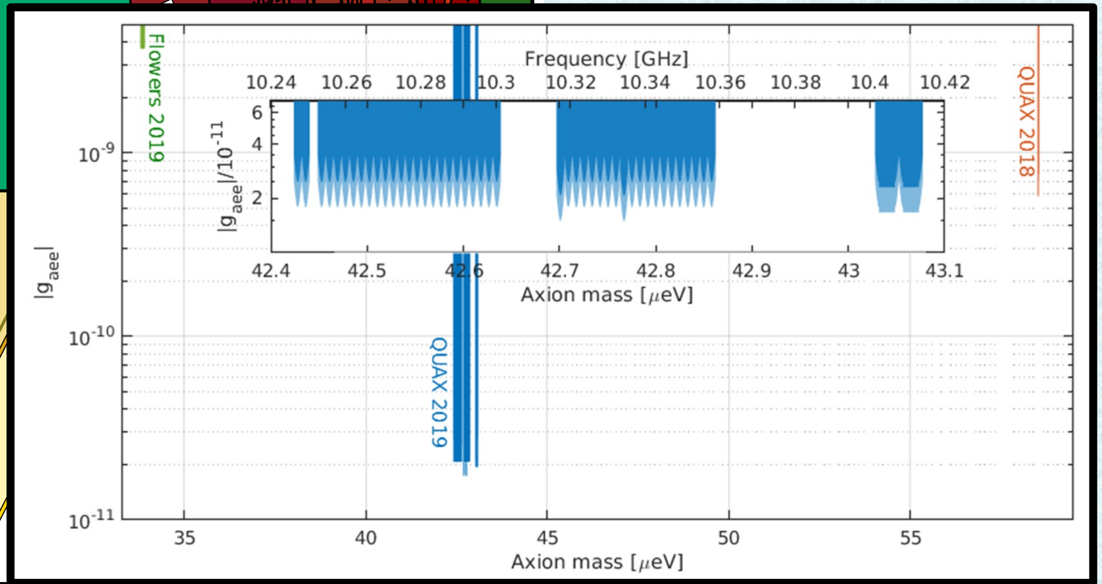


All the sphere must couple coherently to the cavity resonance

Axion electron coupling



QUAX best power sensitivity σ_P = **5.1 10^{-24} W**
→
Axion effective field **B$_a$ = 5.5 10^{-19} T**



PRL **124**, 171801 (2020)

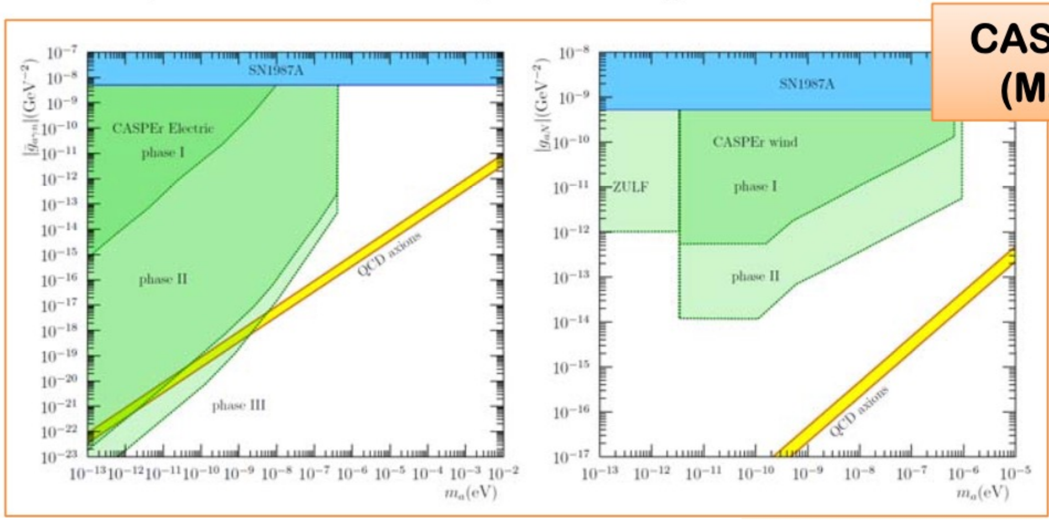
AxionLimits by **cajohare**.

New prospects:
Increase number of spheres
Single photon counter detector

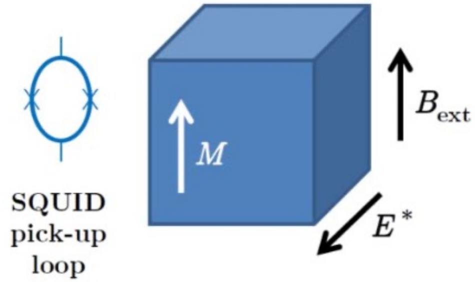
Probing a different coupling gives prospects for model discrimination in the event of discovery

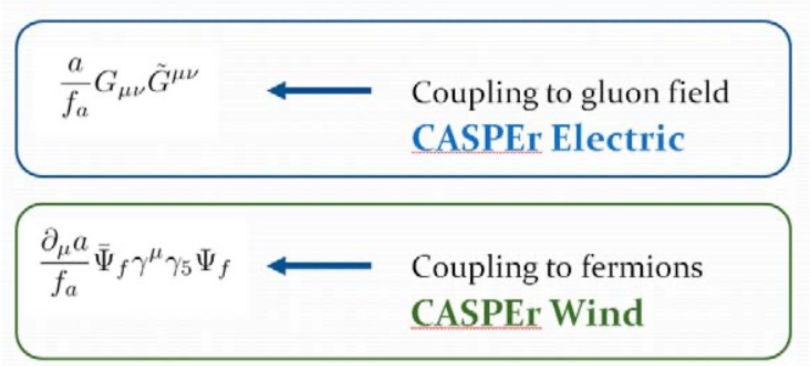
NMR Casper

- **DM-induced spin precession → it can be detected with very sensitive NMR techniques**
- **Directly sensitive to the gluon term (also to fermionic couplings)**
- **Maybe important at very low m_a**



CASPEr experiment (Mainz-Berkeley)

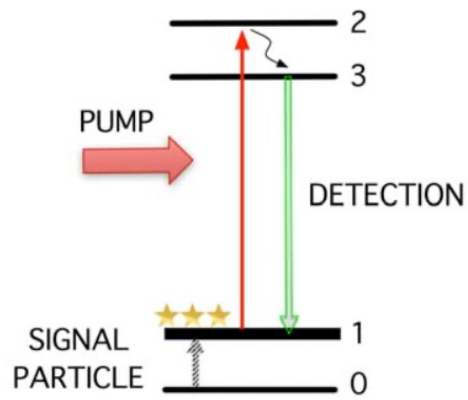




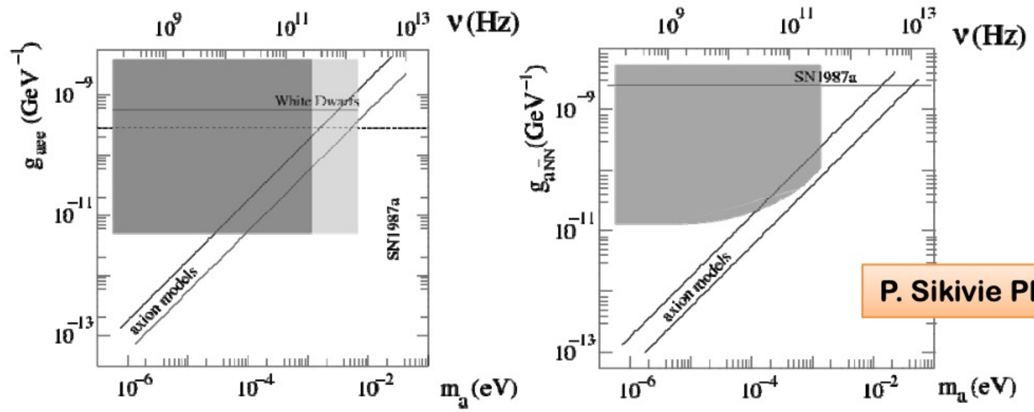
Phys. Rev. X 4, 021030 (2014)

Dark matter induced atomic transitions

- DM can induce atomic excitations equal to m_a.
- Sensitive to axion-electron and axion-nucleon coupling
- Zeeman effect → create atomic transitions tunable to m_a
- Detection of excitation via pump laser
- AXIOMA → recent project aiming at an implementaiton



Relevant sensitivity for $m_a \sim 10^{-4}$ eV seems possible for kg-sized samples

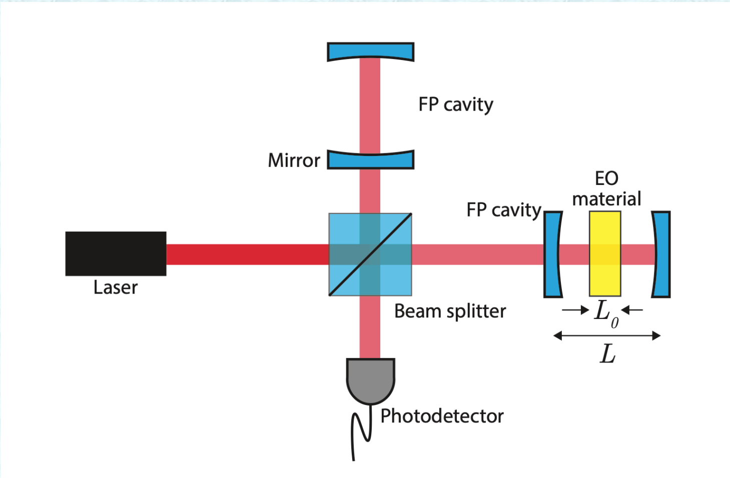


P. Sikivie PRL 113(14)

Other ideas – Optical devices

arXiv:2306.02168
Galactic Axion Laser Interferometer Leveraging Electro-Optics: GALILEO

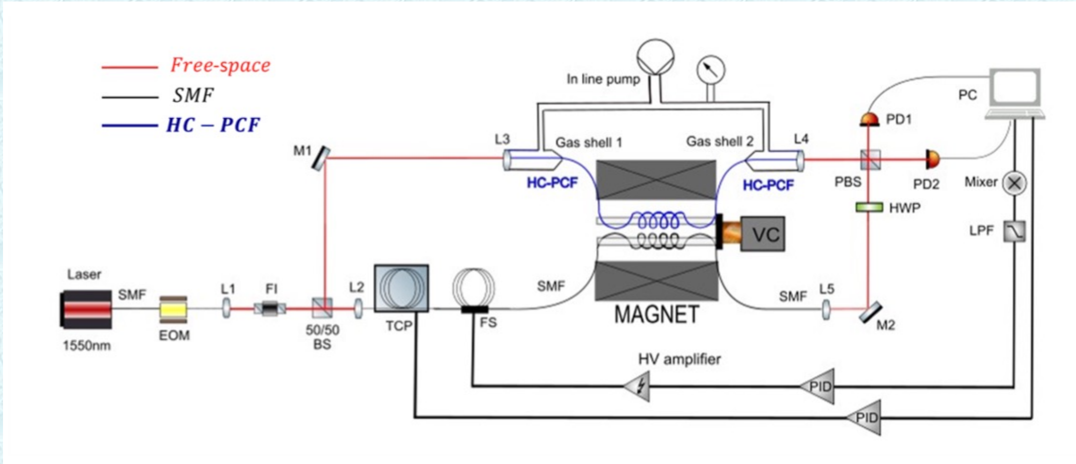
electro-optical material's refractive index modified by the presence of a coherently oscillating dark matter background

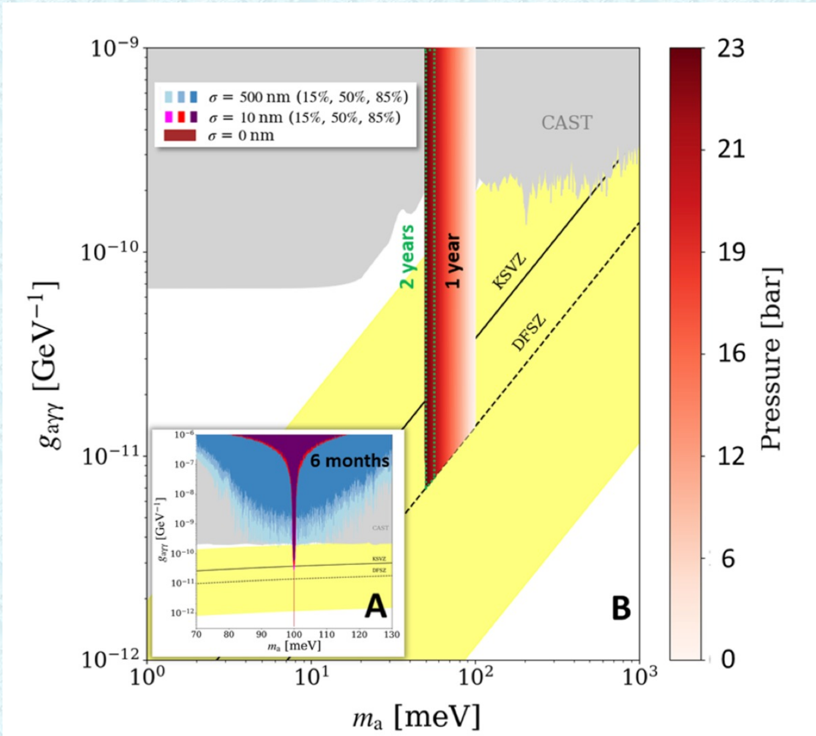


$$\mathrm{SNR} \simeq \left(\frac{L_0 N \mathcal{F}}{6.7\,\mathrm{mm}\times 1.5\times 10^5}\right)\left(\frac{\lambda}{1064\,\mathrm{nm}}\right)^{-1/2}\left(\frac{P_{\mathrm{in}}}{5\,\mathrm{W}}\right)^{1/2}\left(\frac{T}{\mathrm{s}}\right)^{1/4}\times\begin{cases}20\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)\left(\frac{B}{10\,\mathrm{T}}\right)\left(\frac{m_{\mathrm{DM}}}{100\,\mu\mathrm{eV}}\right)^{-5/4}\\ 120\left(\frac{\kappa}{10^{-11}}\right)\left(\frac{m_{\mathrm{DM}}}{100\,\mu\mathrm{eV}}\right)^{-1/4}\end{cases}$$

WISP Searches on a Fiber Interferometer under a Strong Magnetic Field: WISPFI

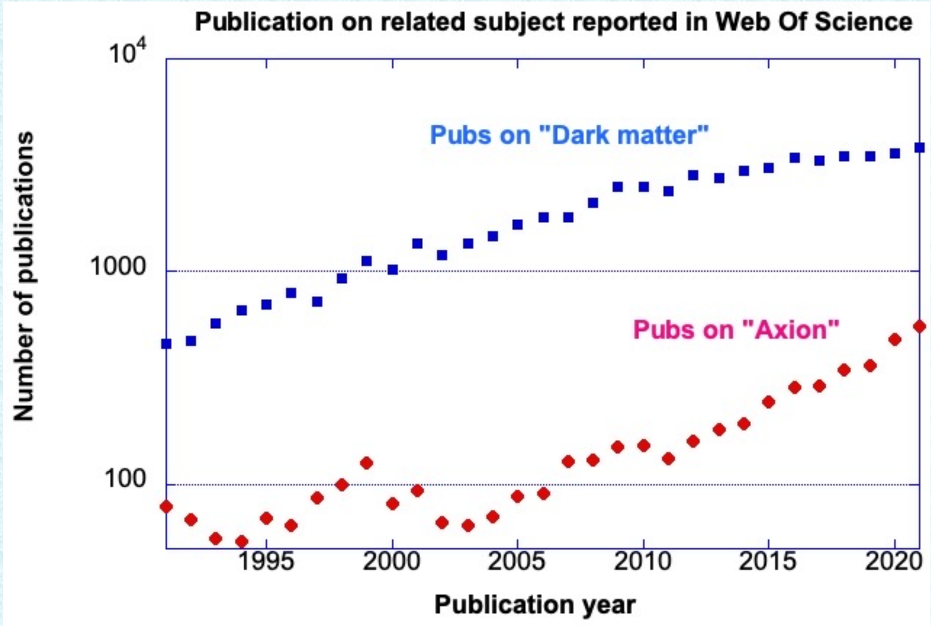
arXiv:2305.12969

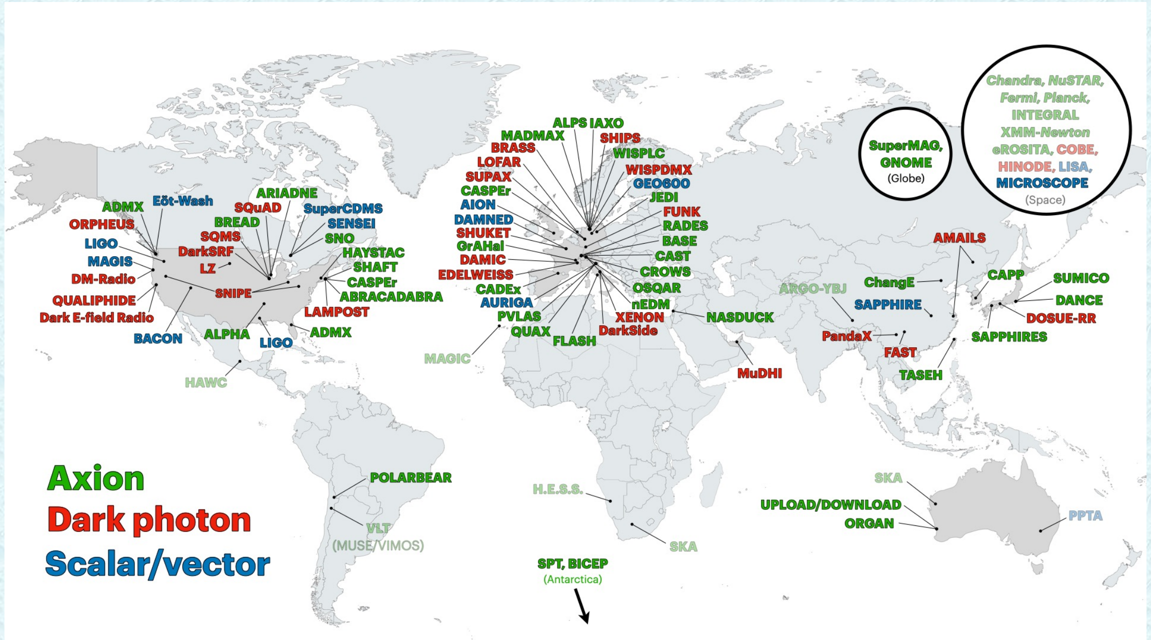




Summarizing the axion

- The research on axion is showing an **increasing interest in the physics community**
- **Different detection schemes** have been developed to probe **different mass ranges – different couplings (useful to obtain axion DM fractional density)**
- The **haloscope experiments have entered a very exciting phase**, reaching the theoretically interesting territory to test the **favoured axion models** (QCD axion)
- We are still in a pioneering era with **several small scale experiments** running and being proposed





https://cajohare.github.io/AxionLimits/

Thank you