# Sikivie and Ferrimagnetic Haloscopes

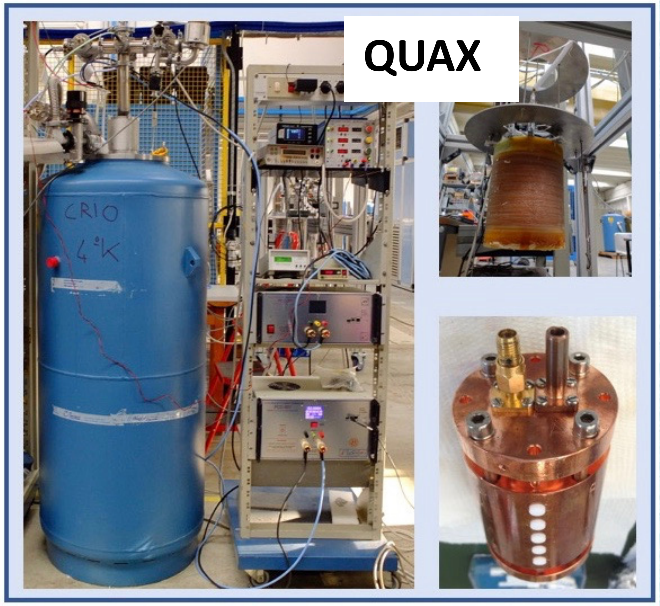
- Search for dark matter axion or axion like particles with resonant cavities

- Search for dark matter with hybrid YIG – cavity systems

Giuseppe Ruoso – Lab. Naz. Legnaro

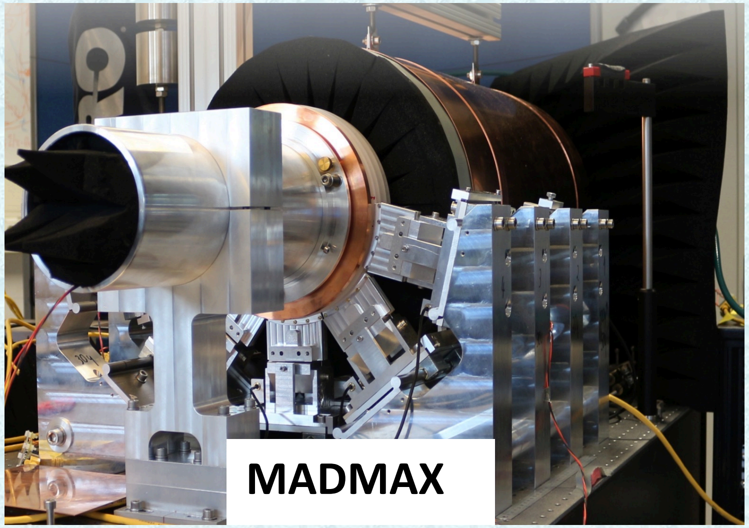
# Haloscopes – Galactic axions

## Magnetic haloscopes



## Dielectric haloscopes



# The “standard” axion

- The axion is a **light pseudoscalar boson**, its properties can be derived using current algebra techniques
- The axion is the light cousin of the $\pi^0$ :

$$m_a f_a \approx m_\pi f_\pi$$

***$m_p$* = 135 MeV – pion mass**
***$f_p$* = 93 MeV – pion decay constant**

- The most recent calculation using lattice QCD

$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

G.Grilli di Cortona et al J. High Energy Phys. 01 (2016) 034

- **Axion couplings** with ordinary matter depends on the model implementing the PQ simmetry

- Extensions of the standard model including the PQ symmetry need **extra degrees of freedom:**
  1. new scalars or fermions
  2. new quarks

# Axion Models

## 1. PQWW (Peccei, Quinn, Weinberg, Wilczeck)

R.Peccei,H.R.Quinn, PRL38(1977)1440
R.Peccei,H.R.Quinn, PRD16(1977)1791
S.Weinberg, PRL40(1978)223
F.Wilczek, PRL40(1978)279

- Introduces in the SM 2 extra Higgs doublets
- $f_a$ is at the electroweak scale $v_{weak}$(250 GeV)

**$m_a \approx$ 100 keV** → **RULED OUT BY ACCELERATOR EXPERIMENTS**

## "Invisible" axion models (classes)

### Dine-Fischler-Srednicki-Zhitnitskii (DFSZ)

M.Dine,W.Fischler,M.Srednicki,Phys.Lett.104B(1981)199
A.R.Zhitnitsky,Sov.J.Nucl.Phys.31(1980)260

- 2 extra Higgs doublets
- New complex scalar

### Kim-Shifman-Vainstein-Zakharov(KSVZ)

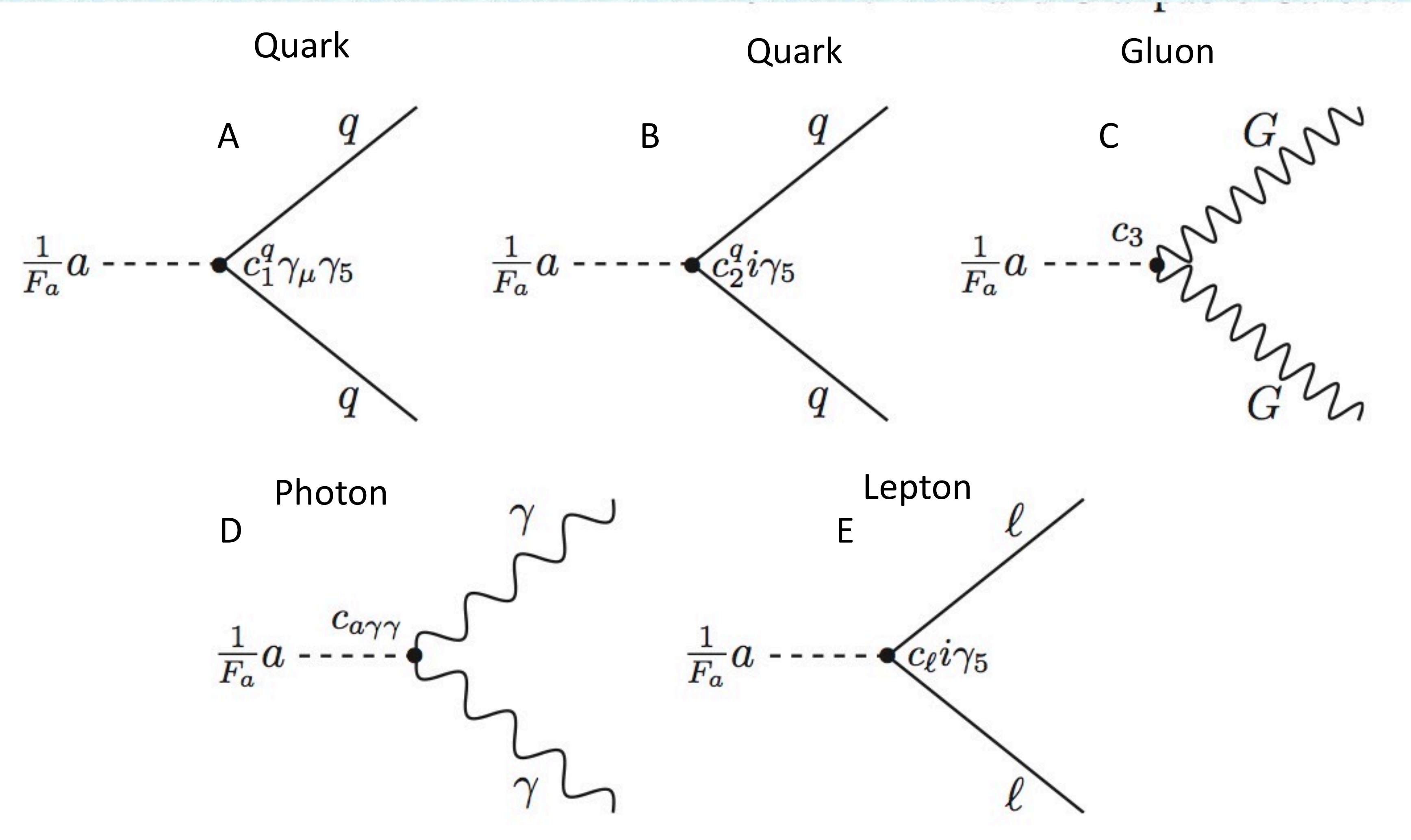
J.E.Kim,PRL43(1979)103
M.A.Shifman,A.I.Vainshtein,V.I.Zakharov,NPB166(1980)493

- New extra heavy quark
- New complex scalar

- For this models no prescription for $f_a$, hence
  - **low mass ($m_a$ < eV)** and **very weak couplings** for **$f_a$ >>** $v_{weak}$
- The strength of the axion interaction depends on the assignment of the $U_{PQ}(1)$ charge to quarks and leptons (model dependent)
- **Models list not exhaustive**, axions can be embedded in SUSY or GUT

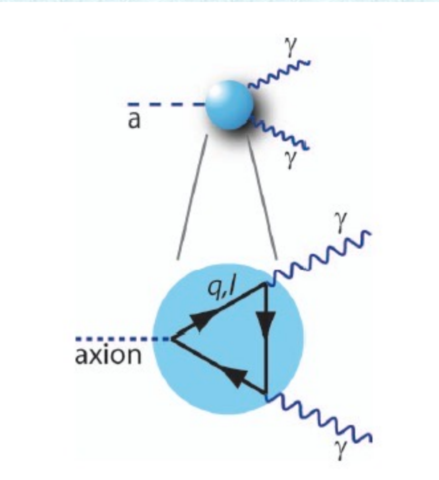
# Axion interactions

- Several interactions are possible



# Axion interactions 2

- Axion interactions are model dependent, normally small differences between models




**Axion photon photon**

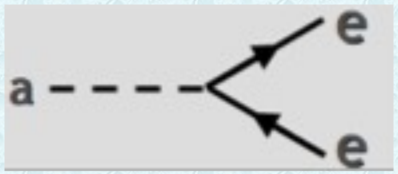
$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

$$g_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi}\frac{m_a}{m_\pi f_\pi}$$

**$g_\gamma$ = 0.36 (DFSZ)**

**$g_\gamma$ = - 0.97 (KSVZ)**

**Axion electron electron**




$$L_{aee} = -g_e \bar{e} i\gamma_5 e a$$

$$g_e \approx \frac{m_a m_e}{m_\pi f_\pi} = 4.07\times 10^{-11} m_a$$ **(DFSZ)**

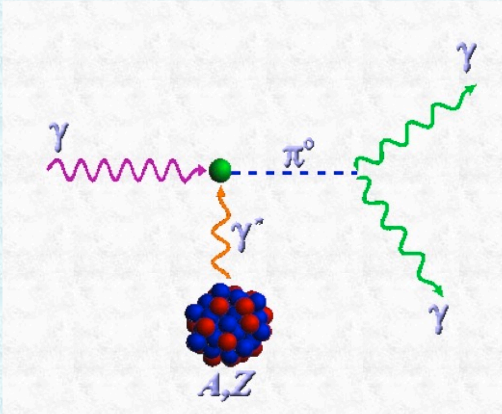
**$g_e$ ~ 0 (Strongly suppressed) (KSVZ)**

All couplings are extremely weak!

# Can we detect axions?

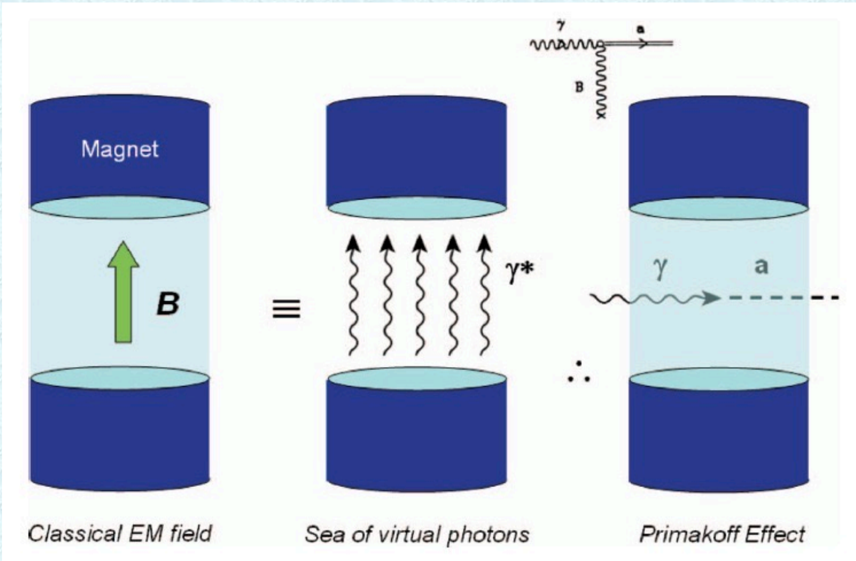
- Searching for axion extremely challenging
- Exploit coherence effect over macroscopic distance/long times
- Most promising approach: use axion-photon-photon vertex

**Primakoff effect:**
scattering from an electromagnetic field (virtual photon)




In the presence of an **external field** (magnetic or electric) the **axion and the photon mix** and give rise to **oscillation/conversion**

Higher magnetic field are easily obtainable than electric fields




G. Carosi et al, Contemp. Phys. 49, 281 (2008)

# Axion Like Particles (ALPs)

- An ALP is a particle having **interactions similar to the axion**, whose origin is expected to be similar, but with **different relation**, respect to the axion, between coupling constants and mass → **in general UNRELATED**
- For example, string theory predicts a large spectrum of ALPs, pseudo Nambu Goldstone boson of a symmetry spontaneously broken at very high energy
- For example, in the case of the photon coupling

$$L_{ALP} = \frac{1}{2}\partial^{\mu}a\,\partial_{\mu}a - \frac{1}{2}m_{ALP}^{2}a^{2} - g_{a\gamma\gamma}\vec{E}\cdot\vec{B}a$$

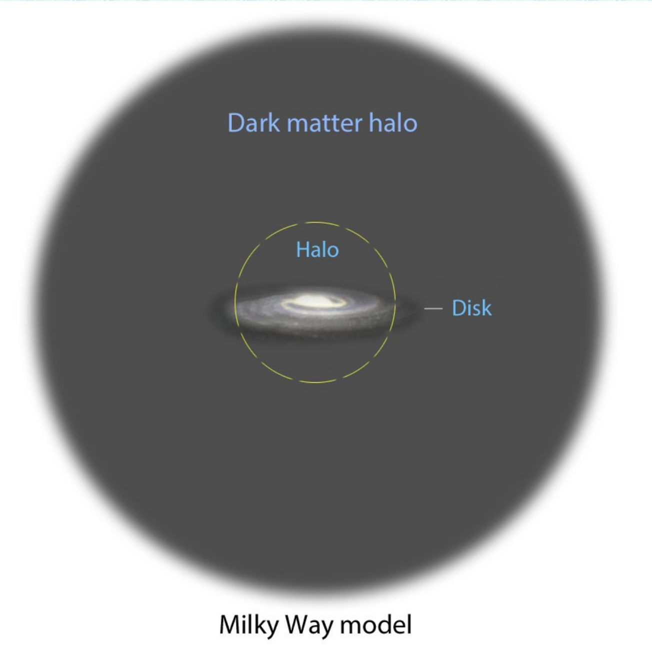
**With $g_{a\gamma\gamma}$ a free parameter to be determined experimentally**

- **Experimental searches are mainly directed to ALPs**, in order to relax the coupling parameter. Experiments looking for the ALPs are, in principle, sensitive also to the axions.

- We will often be using the word axion in a generic way including ALPs, explicitly saying **QCD axion for that ALPs that solves the strong CP problem**

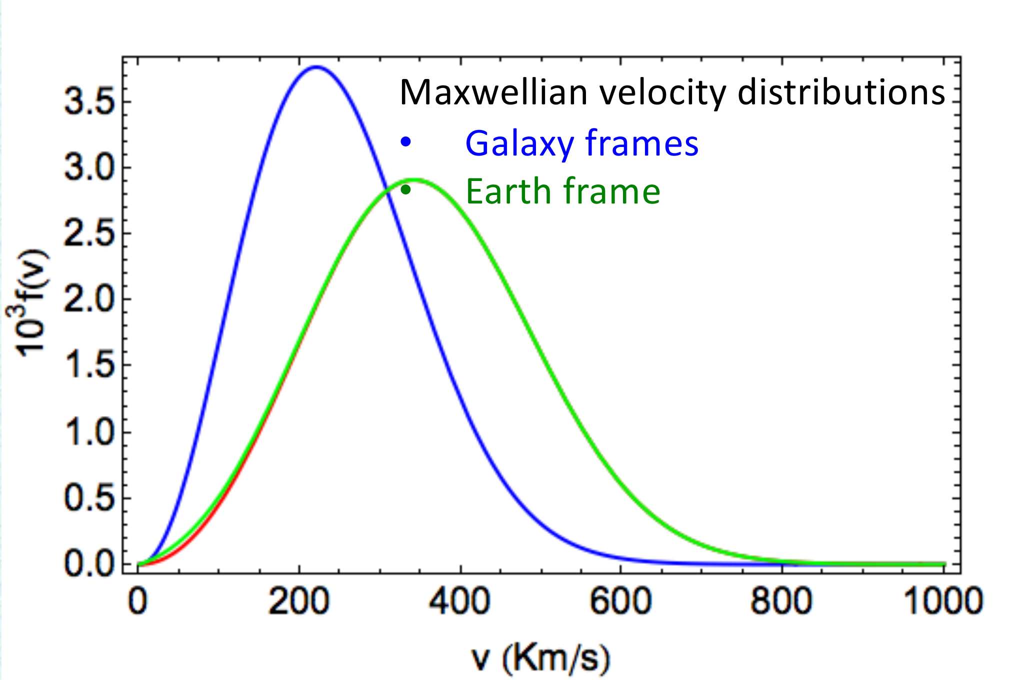
# Standard Halo Model for $\rho_{DM}$ and $f(v_a)$

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




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

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




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

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

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

# 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**

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

- 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**

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

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

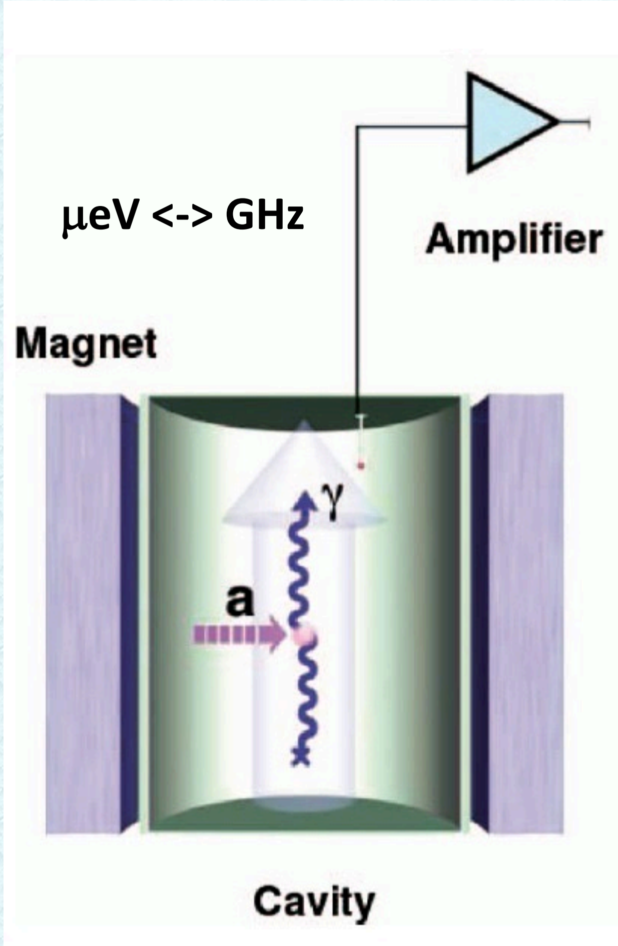
# Haloscopes – Galactic axions – Sikivie Type

- 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

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

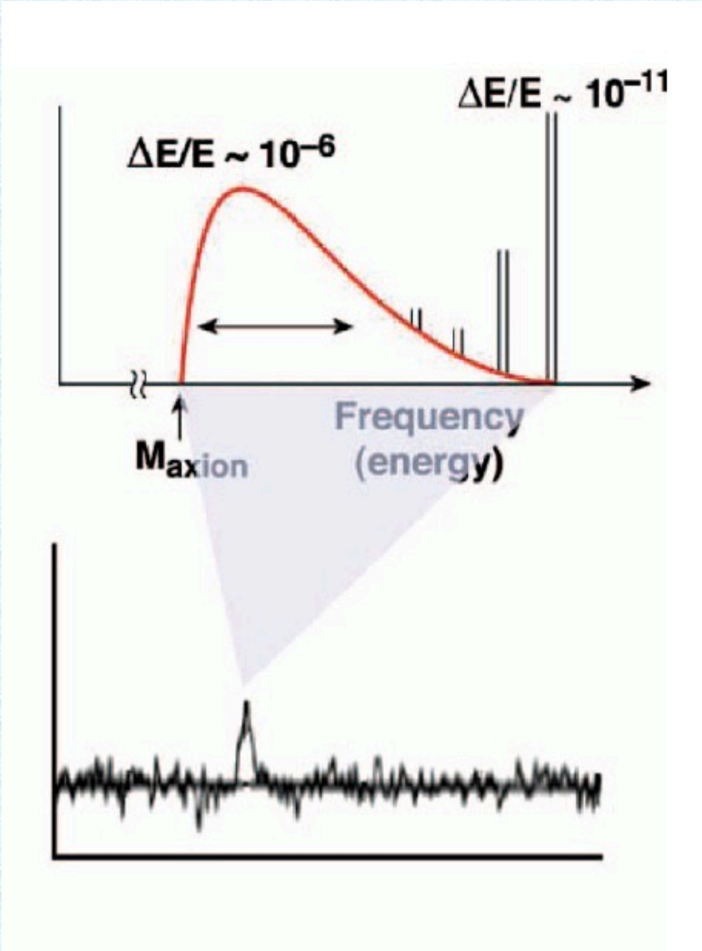
  - Possible **very sharp component due to non-thermalised** axion falling in and out of the Milky Way

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

  - **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 $Q_c$ ($Q_c << Q_a$)     $Q_L = Q_c/(1+\beta)$

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

- 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

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

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 *$t_m$***

$$\text{SNR} = \frac{P_{\text{axion}}}{k_B T_{\text{sys}}}\sqrt{\frac{t_m}{B_a}}$$

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

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

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

# Haloscopes – Galactic axions

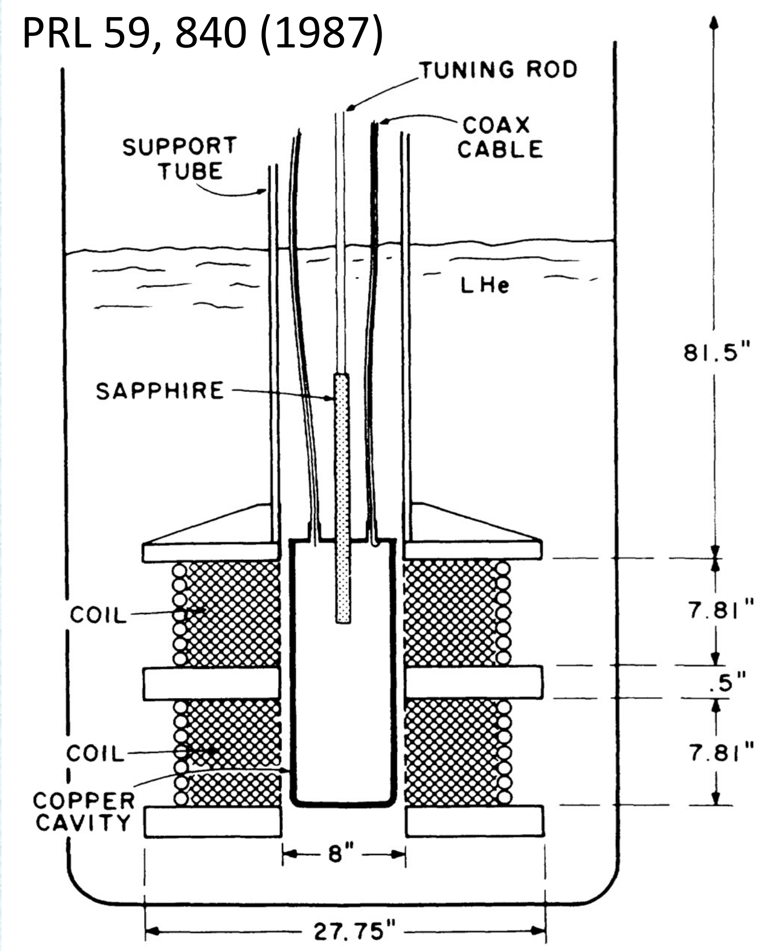
- Resonant detection of DM axions in a magnetic field. One measurement explores **only sharp cavity linewidth**. **Scanning** is necessary.

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)



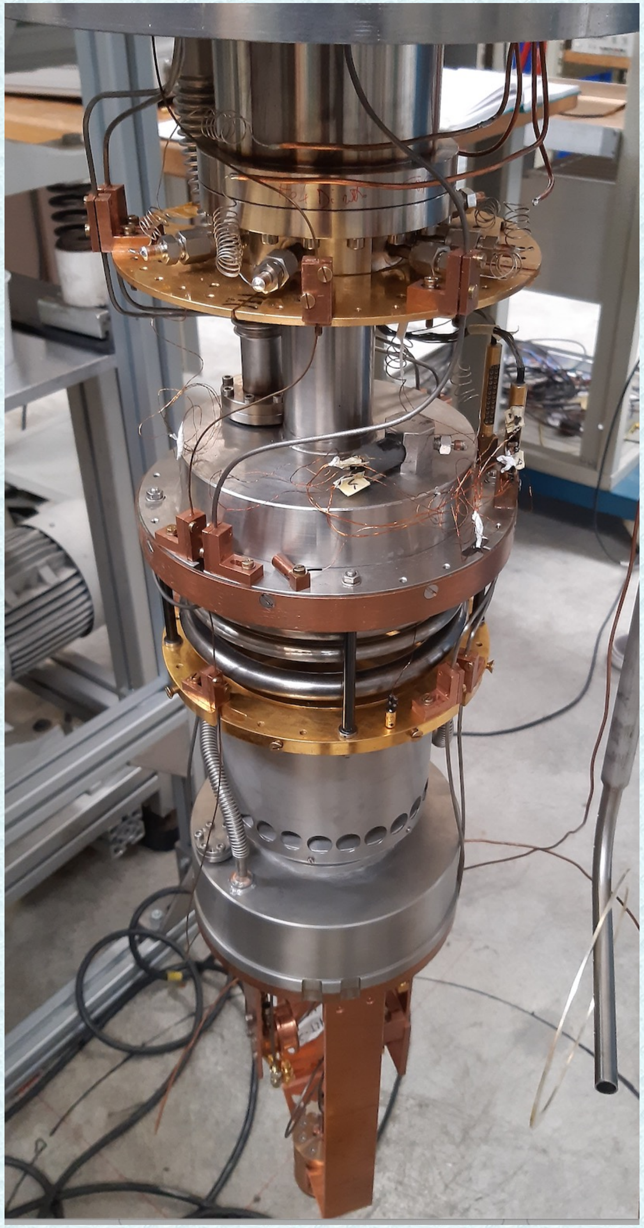

Schematic diagram of the RBF apparatus (1987)

- 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

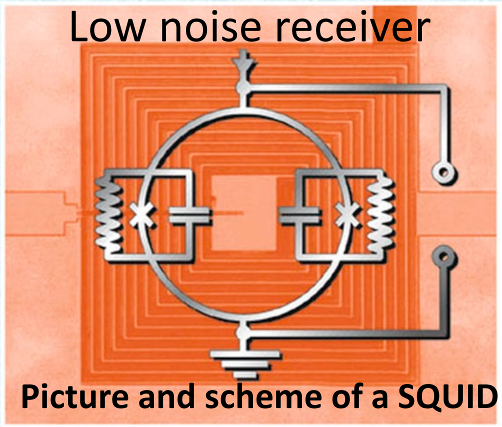
Quality Factor Qc

Form factor $C_{mnl}$

Volume V

Resonance frequency f

Tuning



Low noise receiver

Picture and scheme of a SQUID

Noise temperature $T_n$

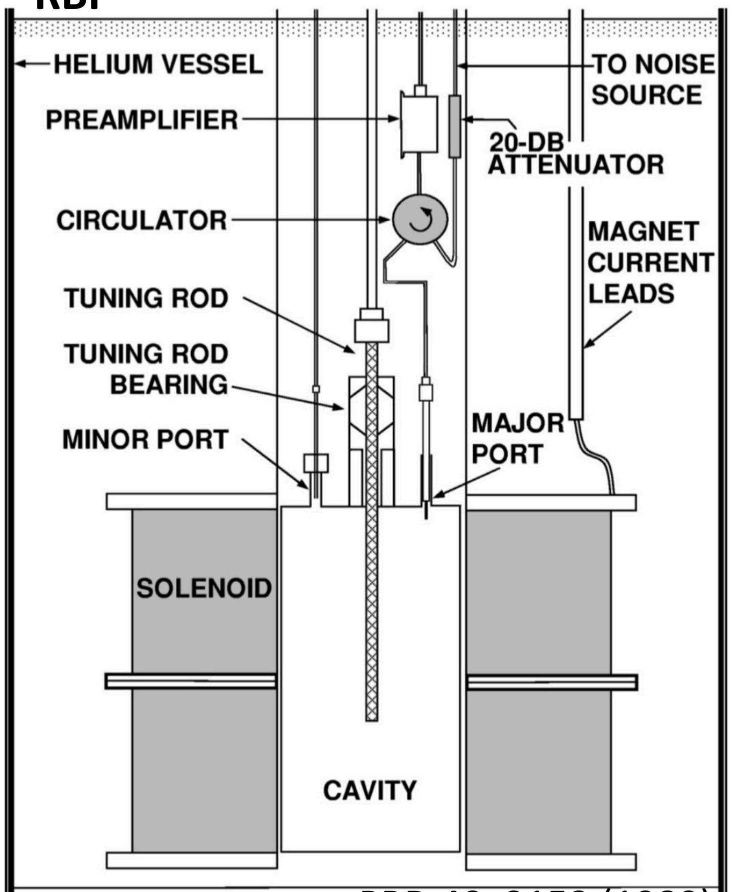
Magnetic source

Magnetic energy $B^2$ V

# Haloscope detectors - precursors

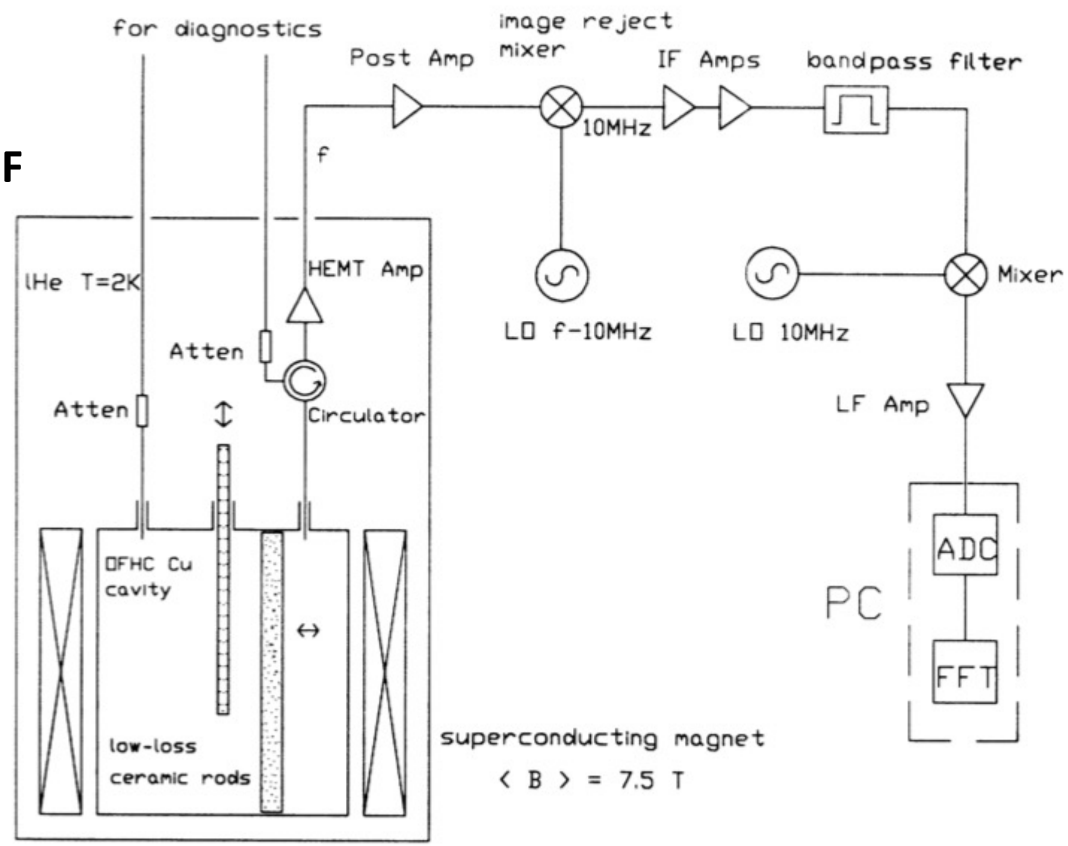
- **Pilot experiments in Brookhaven (RBF) (1988) and University of Florida (UF) (1990)**
- **Provided basic structure for even today's most sensitive experiments**

**RBF**



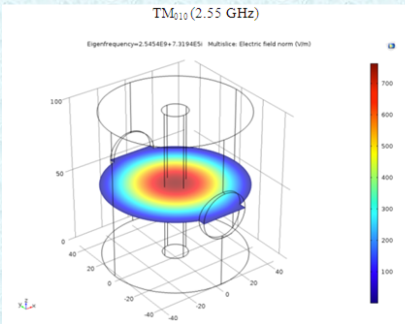

PRD 40, 3153 (1989)

**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



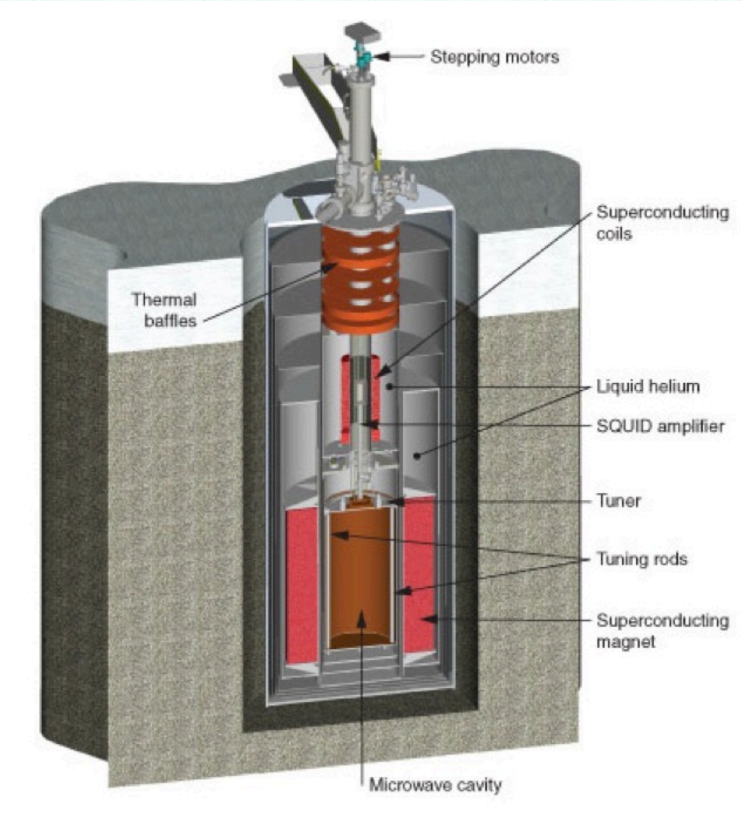

HEMT amplifier, $T_n$ 3-6 K

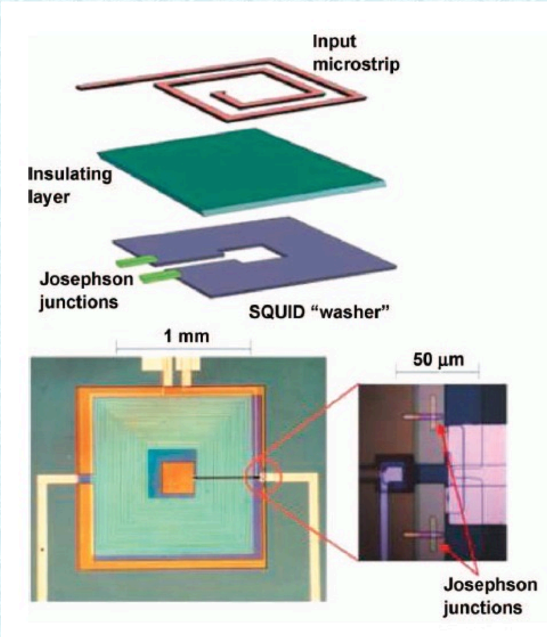
# Haloscope detectors – 1st gen - ADMX

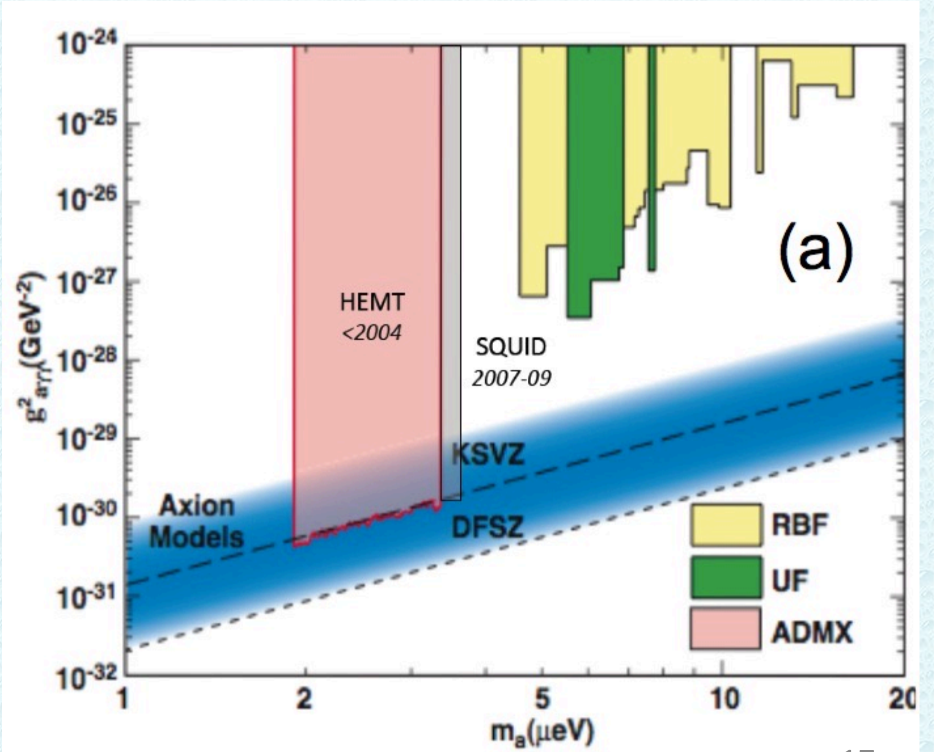
**ADMX – Axion Dark Matter eXperiment – phase I**

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)**

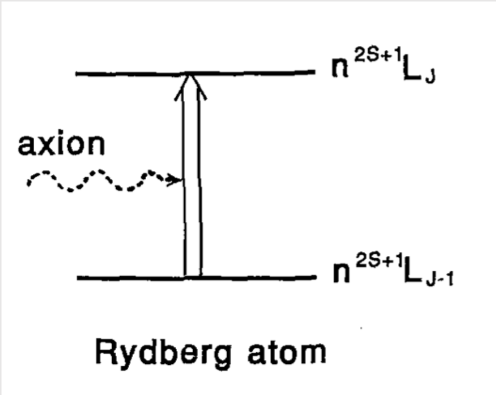
# Haloscope detectors – precursors - CARRACK

Different ideas already from the beginning:
**Rydberg atoms**

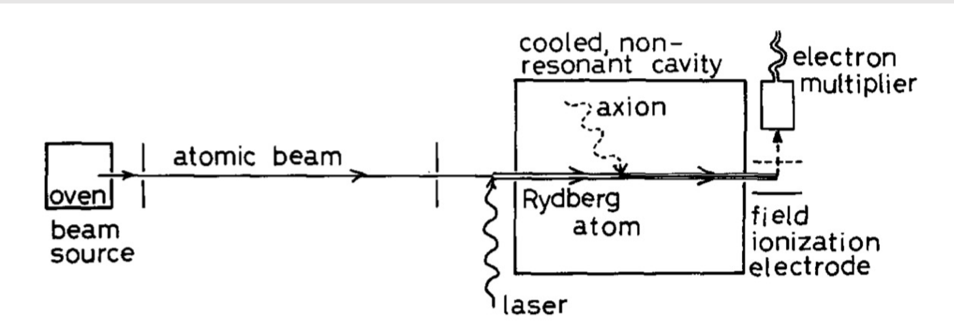
**1. Rydberg atoms as direct axion DM detectors**

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

f ~ GHz Range

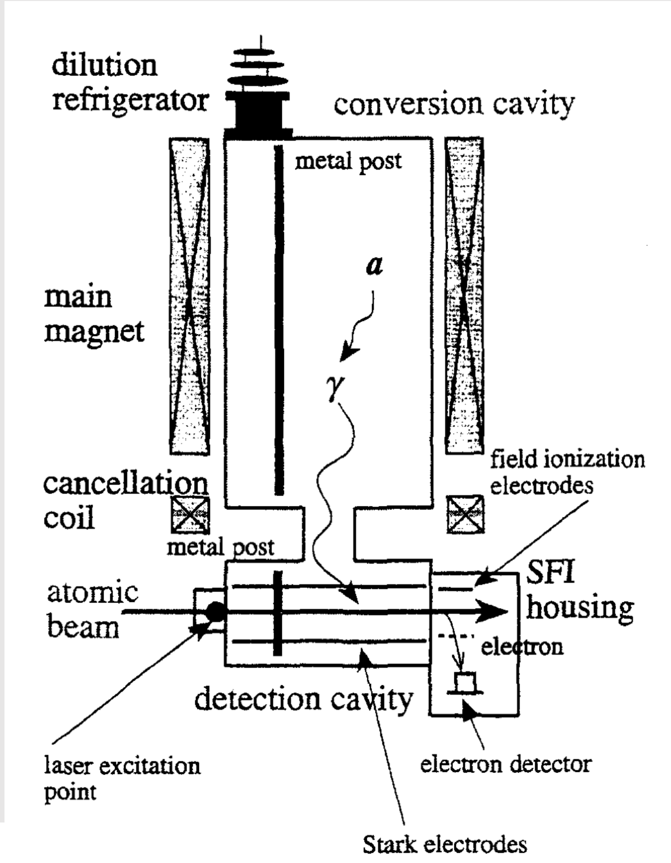


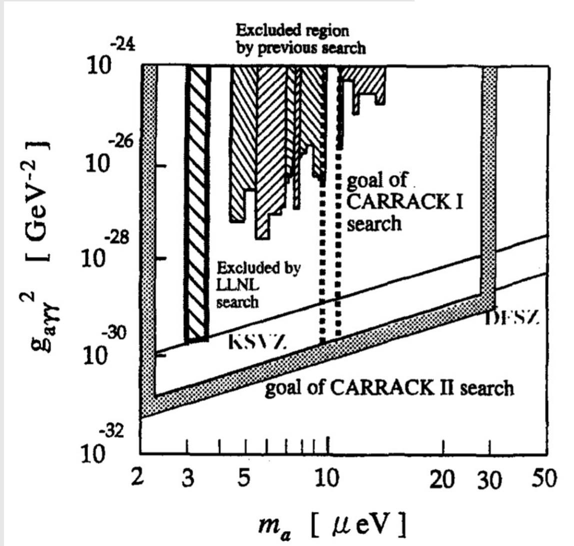

Use alkaline atomic beam in an inhibited cavity regime




PLB 263, 523 (1991)

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



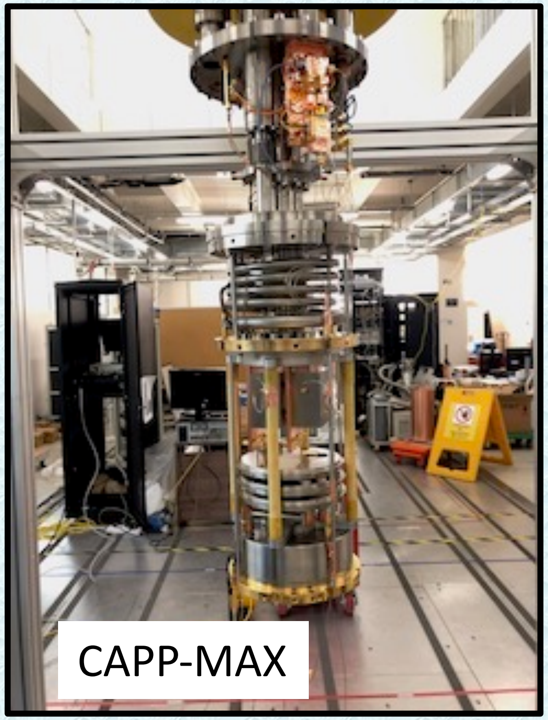



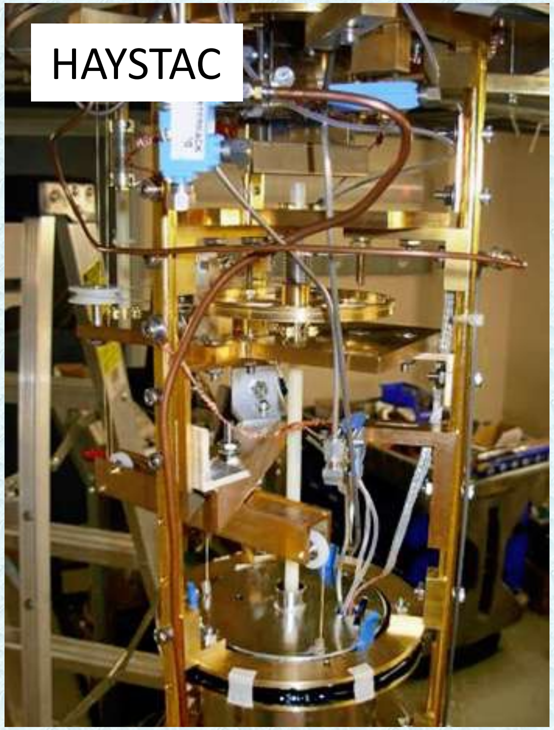

NPB (PS) 72, 164 (1999)

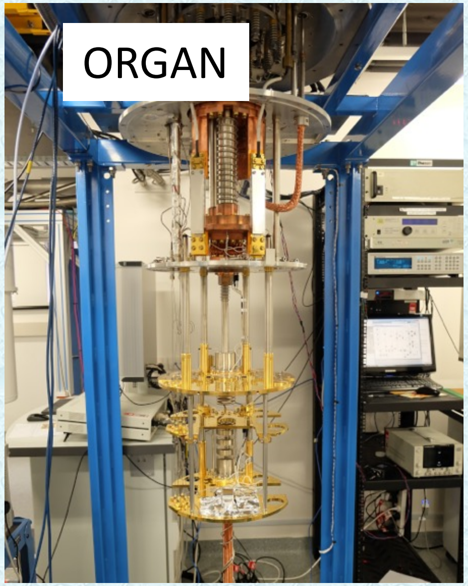
# Haloscope detectors – current situation

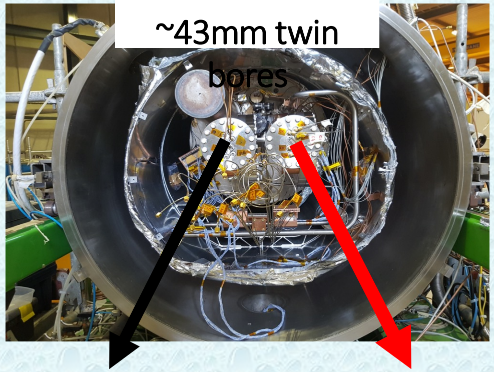
- Within the last 10 years ADMX has evolved and a large number of new apparata based on Sikivie's scheme came into play



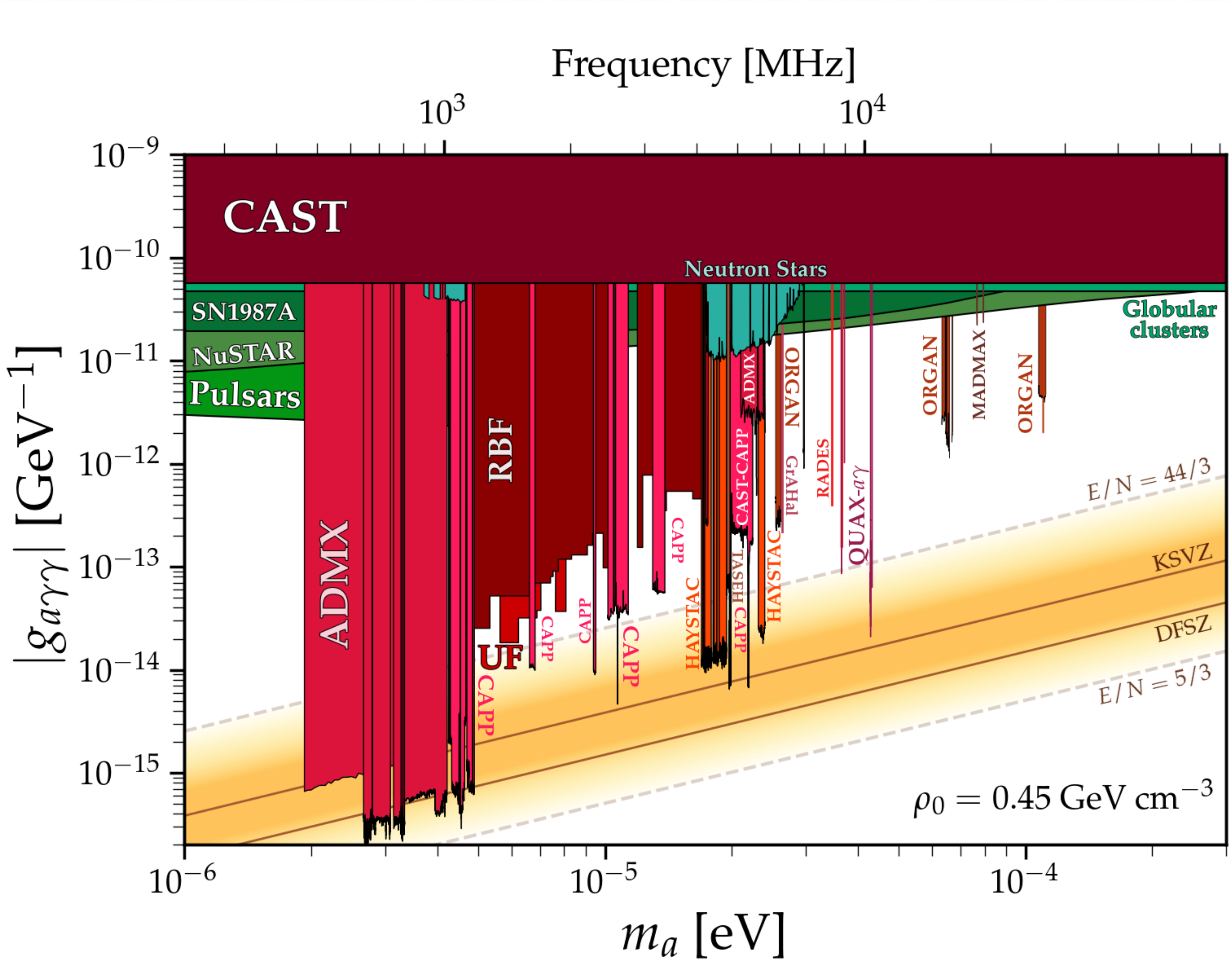


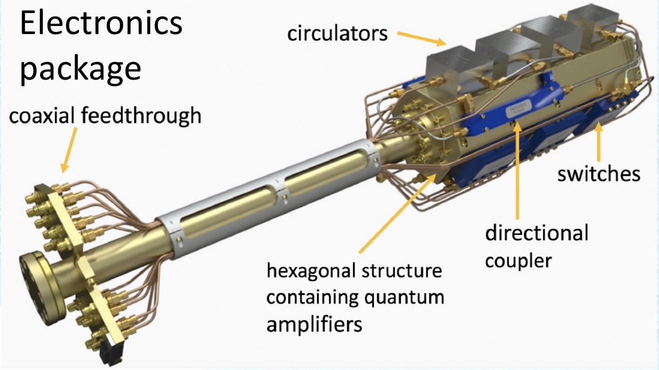
# Current limits – Sikivie's haloscopes

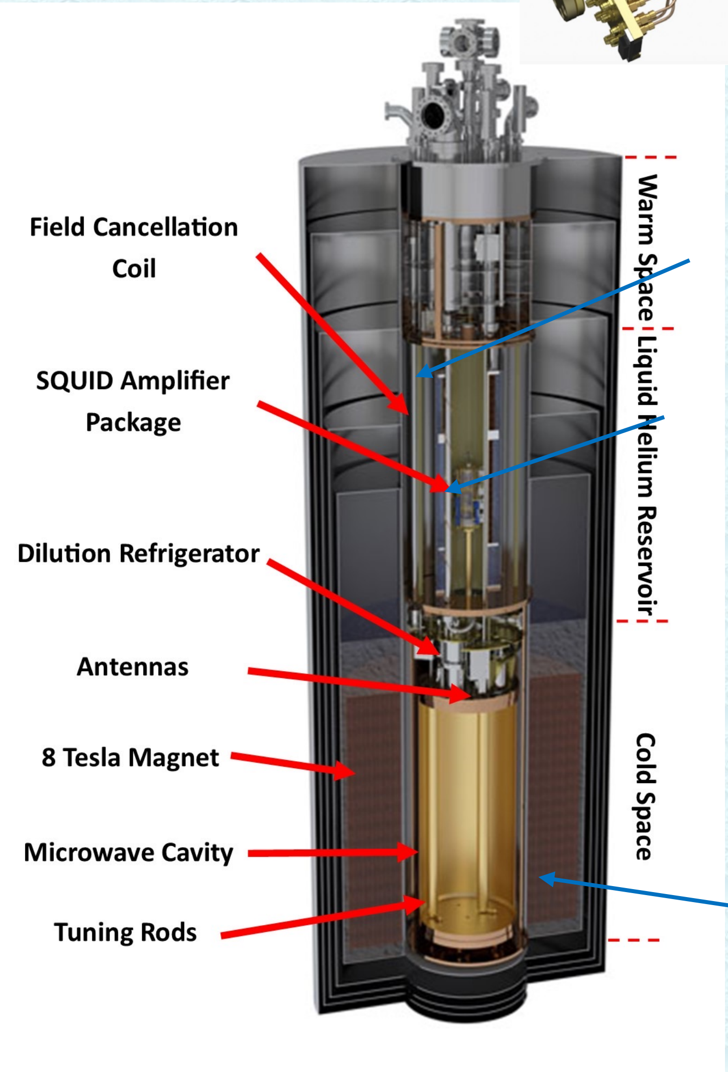



**AxionLimits** by **cajohare**.

# ADMX – Axion Dark Matter EXperiment

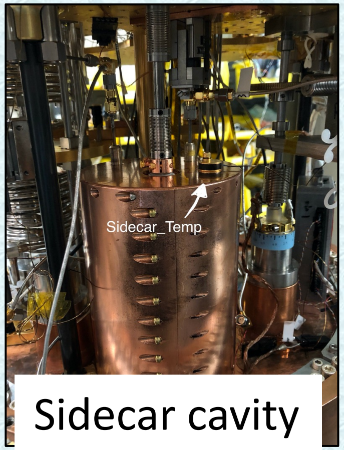
University of Washington



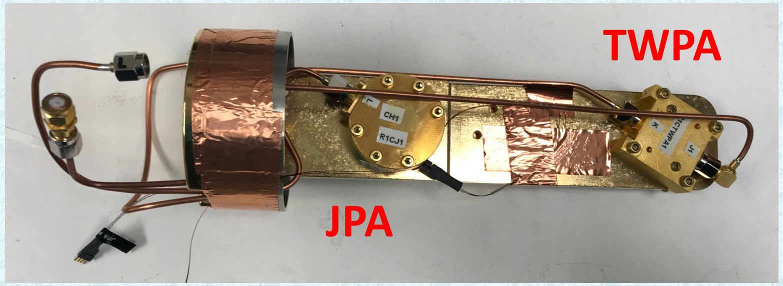




ADMX has evolved in time with the implementation of several improvements:

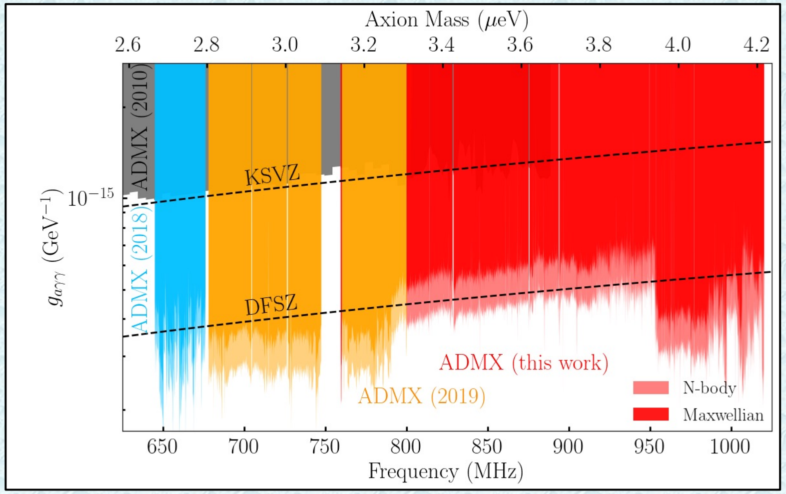
- Dilution refrigerator with lower base temperature : cavity @ 150 mK
- SQUID, JPA and TWPA amplifiers
- Multimode searches

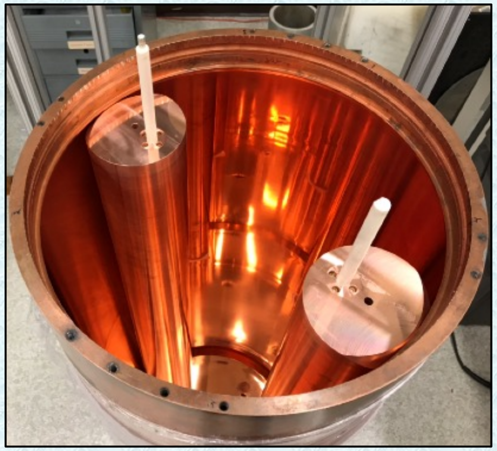



Sidecar cavity




First haloscope to reach DFSZ axion model sensitivity



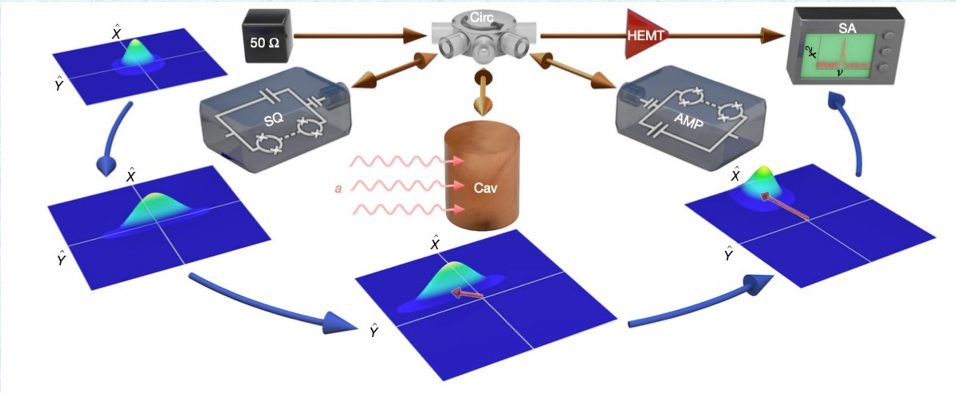



Main cavity

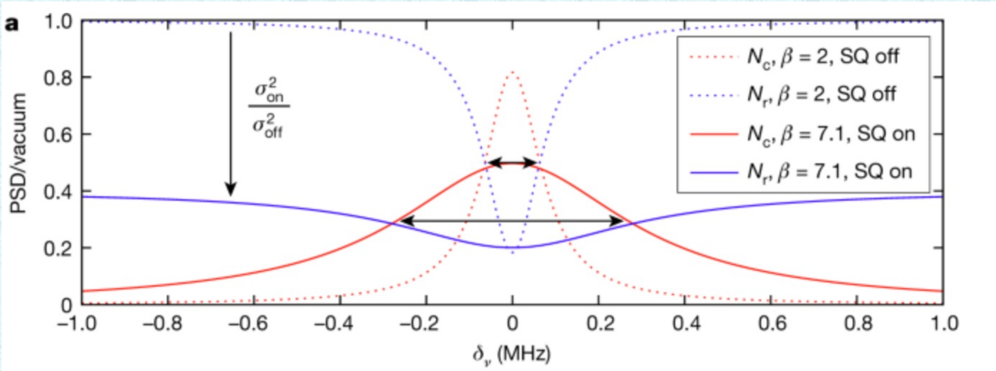
Phys. Rev. Lett. **127**, 261803 (2021)

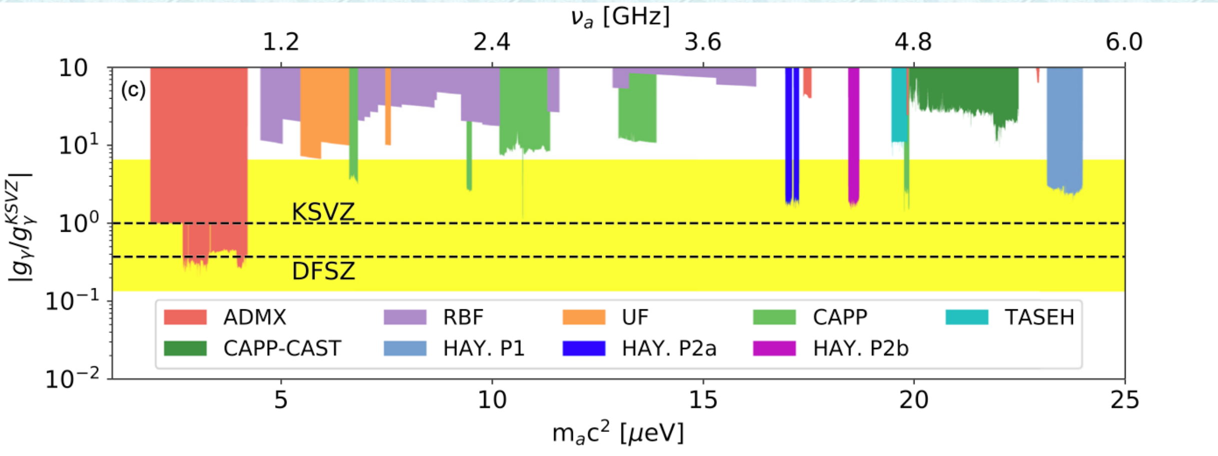
# HAYSTAC – Haloscope at Yale Sensitive To Axion CDM

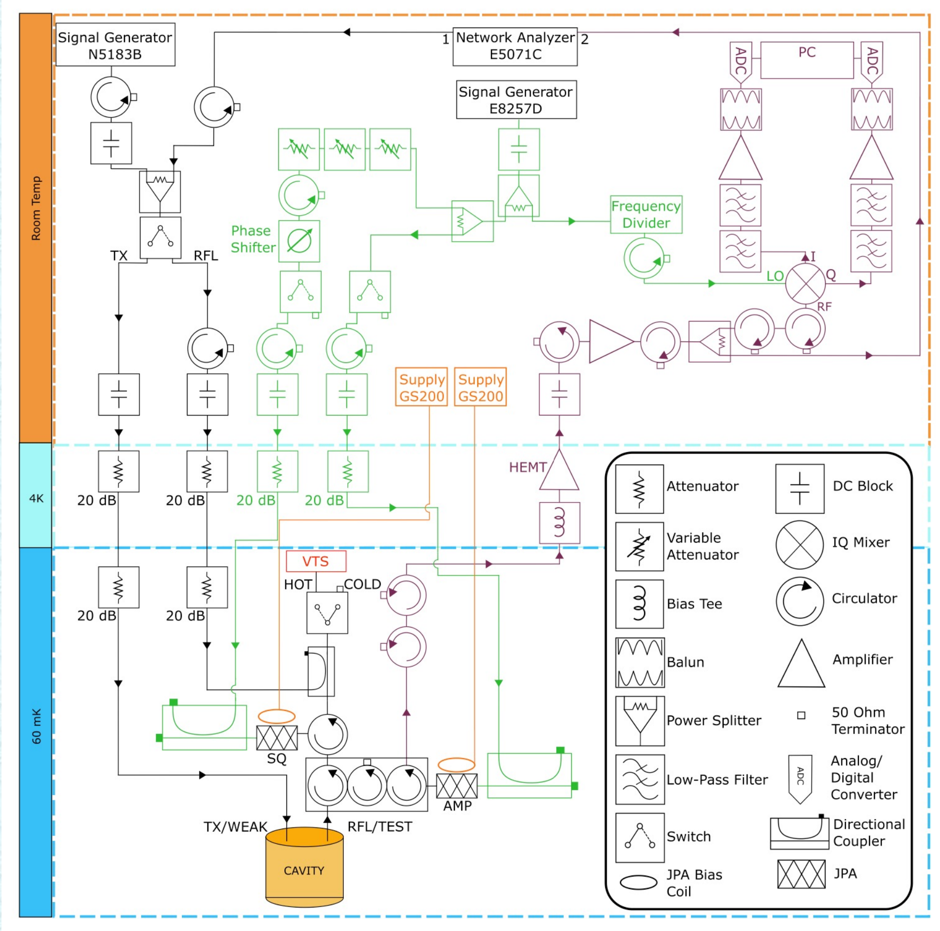
- Designed to search for dark matter axions with masses above 10 μeV
- First haloscope to use a Josephson Parametric Amplifier
- First haloscope to employ a Squeezed-state receiver (SSR)




Scan rate enhancement 1.9 over quantum limit




**Jewell et al. PRD 107, 072007 (2023)**

# IBS-CAPP Institute of Basic Science

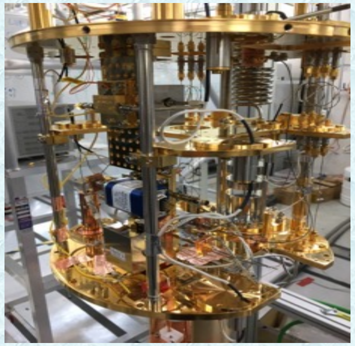
- IBS – CAPP was established in Korea with the aim of building a laboratory equipped with top infrastructure for cavity haloscope searches with enhanced sensitivities over a broader range in the microwave region.

- **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

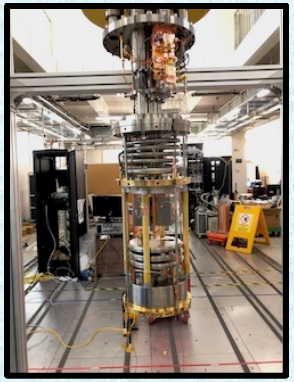
**Cryogenics** (<40mK)

Dilution Refrigerators



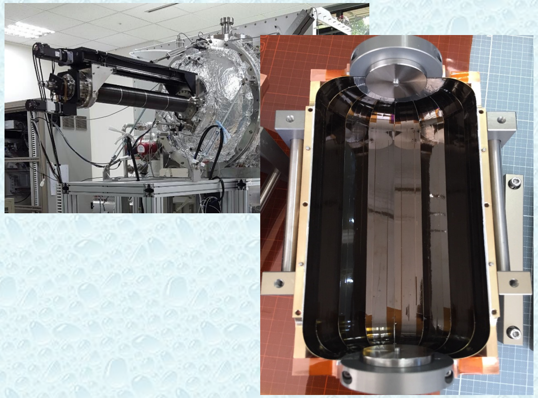
**High Field & Big bore Magnet**

12T LTS Big Bore SC Magnet



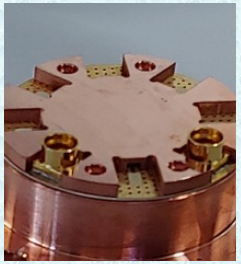
**High Q Tunable Cavity**

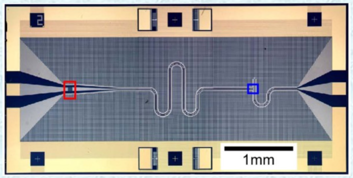
Superconducting tapes



**Quantum Amplifier**

SQUID and/or JPA ($T_N$ ~ SQL)





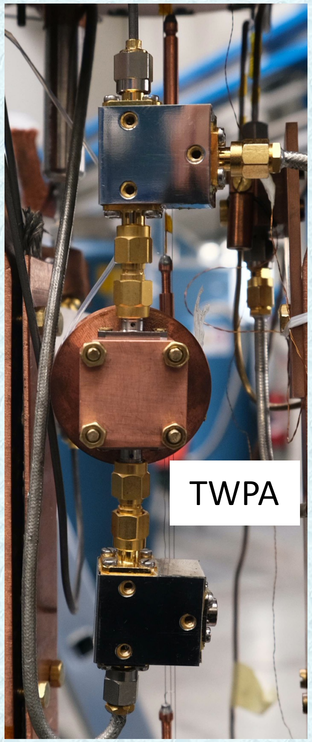
# Axion experiments at CAPP

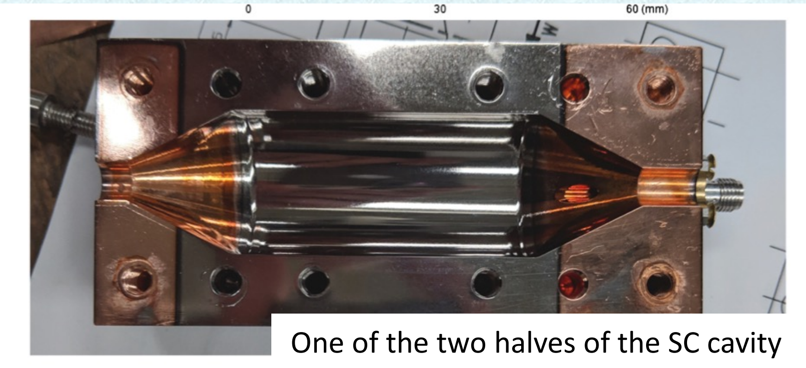
| | CAPP-PACE | CAPP-8TB | CAPP-HF | CAPP-PACE-JPA | CAPP-PACE-JPA-6cell | CAPP-8TB-JPA-8cell | CAPP-PACE-JPA-SC | CAPP-MAX | CAPP-AQN-SC | CAPP-HeT-SC | CAPP-12T-HF-3cell |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 2018 | 2019 | 2019 | 2020 | 2021 | 2021 | 2021 | 2021 | 2023 | 2023 | 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 |
| $\Delta m_a$ [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 8 - 11 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

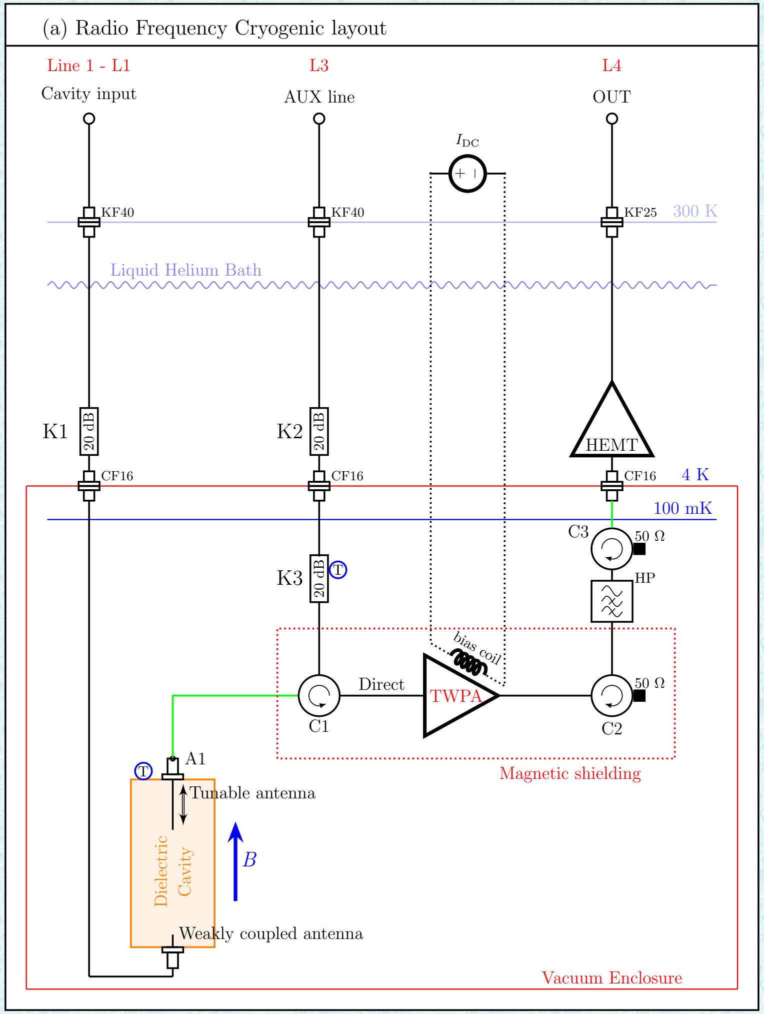


One of the two halves of the SC cavity

Achieved Tsys = 1.1 K @ 10.5 GHz
Reached QCD axion models sensitivity

Layout with novel calibration scheme





- Rettaroli et al. PRD110, 022008 (2024)
- Di Vora et al. PRD 108, 062005 (2023)
- Alesini et al. PRD 106,052007 (2022)
- Alesini et al. PRD 103, 102004 (2021)
- Alesini et al. PRD 99, 101101 (2019)

# QUAX – LNF and LNL

## LNF

8-9.5 GHz Band

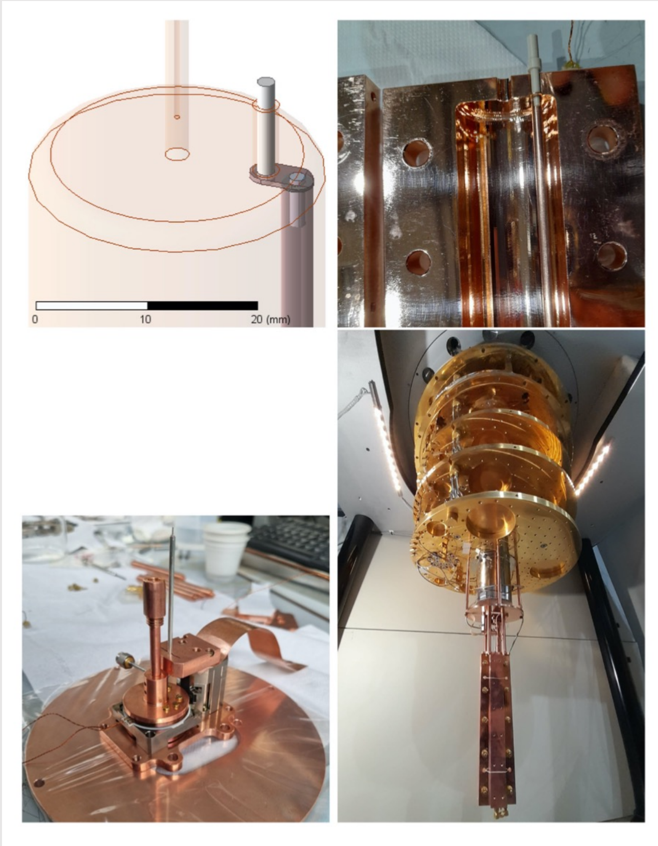
JPA

9 T field

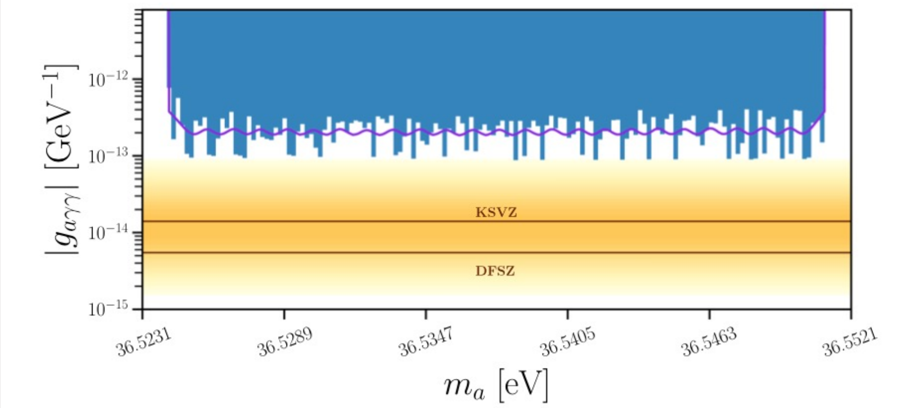
Copper cavity

Rod tuning

Dilution unit




- Rettaroli et al. PRD110, 022008 (2024)




## LNL

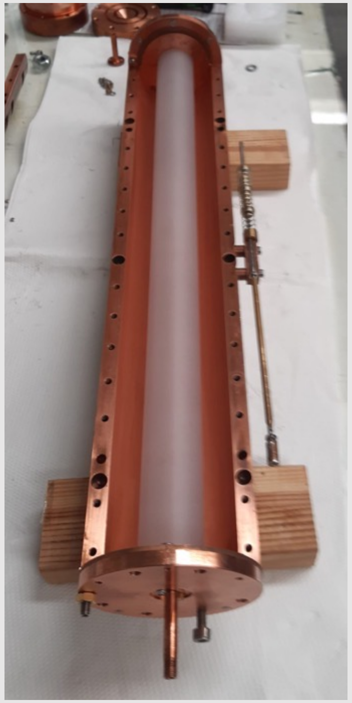
10 – 11 GHz band

TWPA

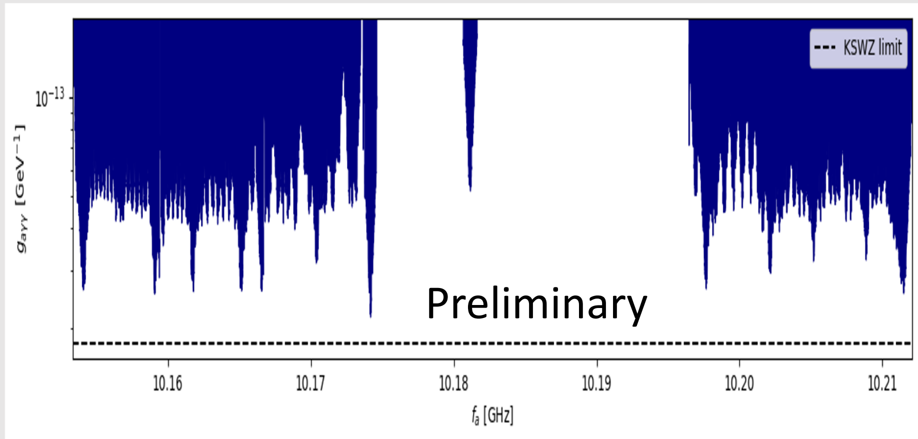
8 T field

Dielectrically loaded copper cavity

Wet dilution unit



Clamshell tuning



# Others running

Taiwan Axion Search Experiment with Haloscope

**TASEH**

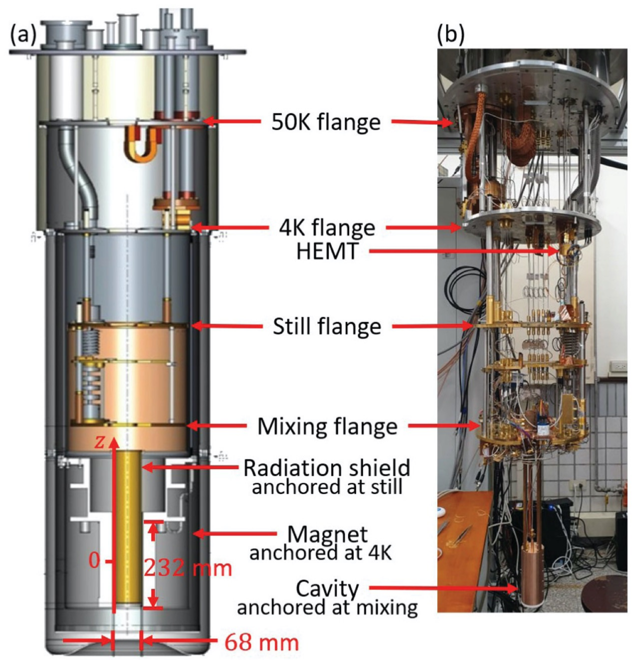
PRD 106, 052002 (2022)
PRL 129, 111802 (2022)

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:

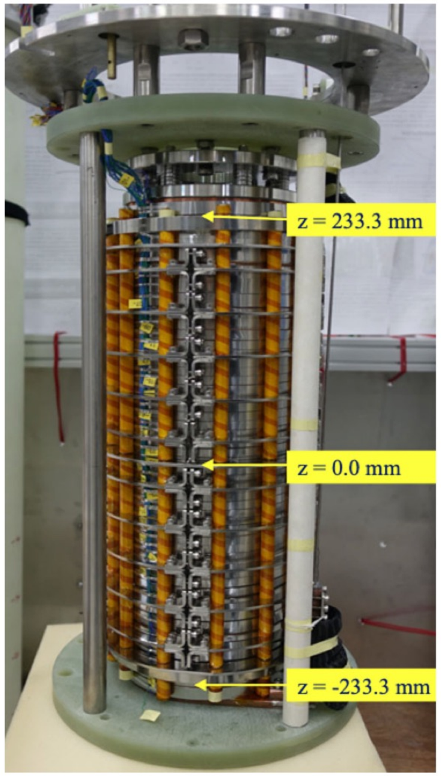
- New dilution unit for lower temperature
- Magnet upgrade 9 T and larger volume
- Use of a JPA
- New conical tunable cavity (see next)

**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



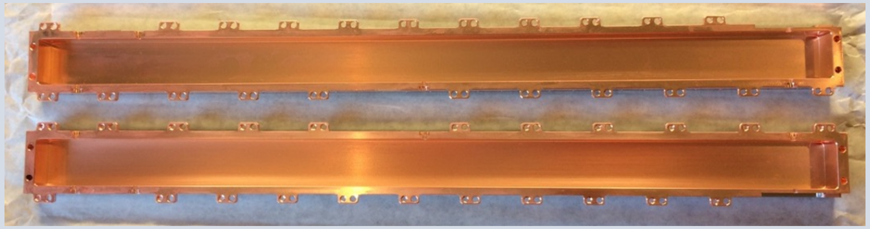
# Others running II

## CAST – CAPP

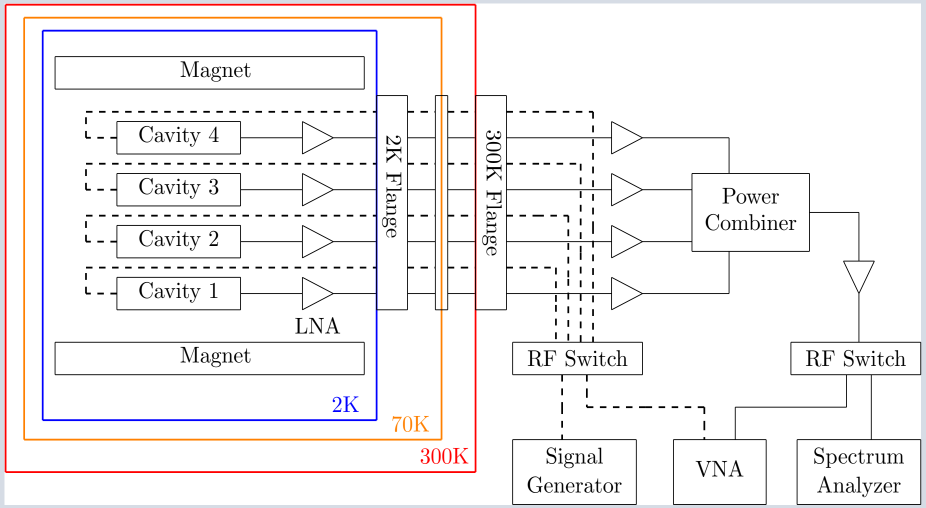
NatComm 13, 6180(2022)

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: $SNR_N = N \cdot SNR_{single}$

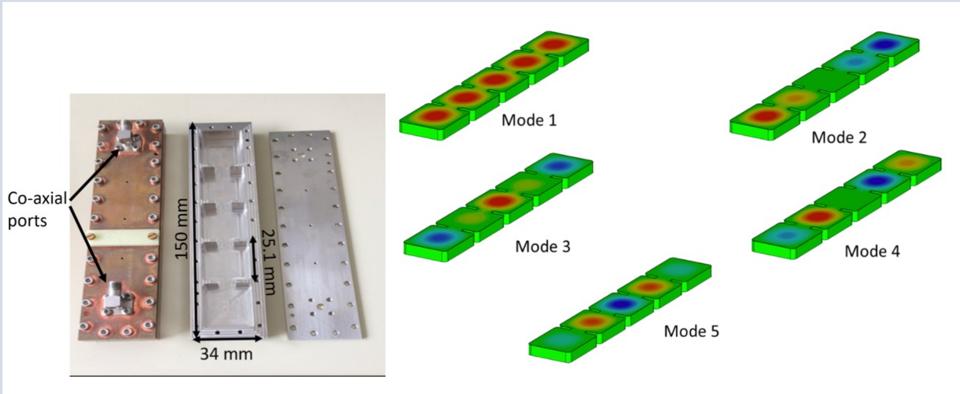
- Frequency range: ~4.8 – 5.4 GHz (660 MHz)
- Axion mass range: ~19.7 – 22.4 μeV

## CAST – RADES

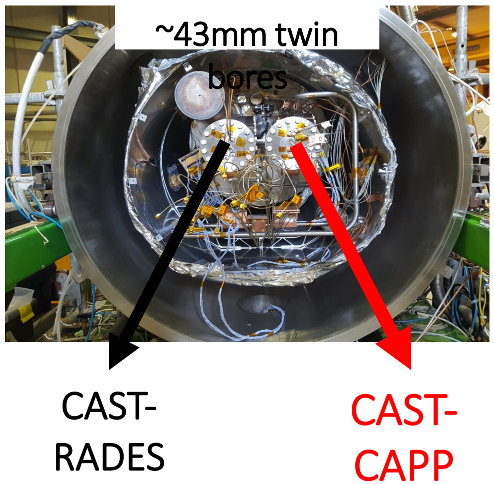
JHEP10(2021)075

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.



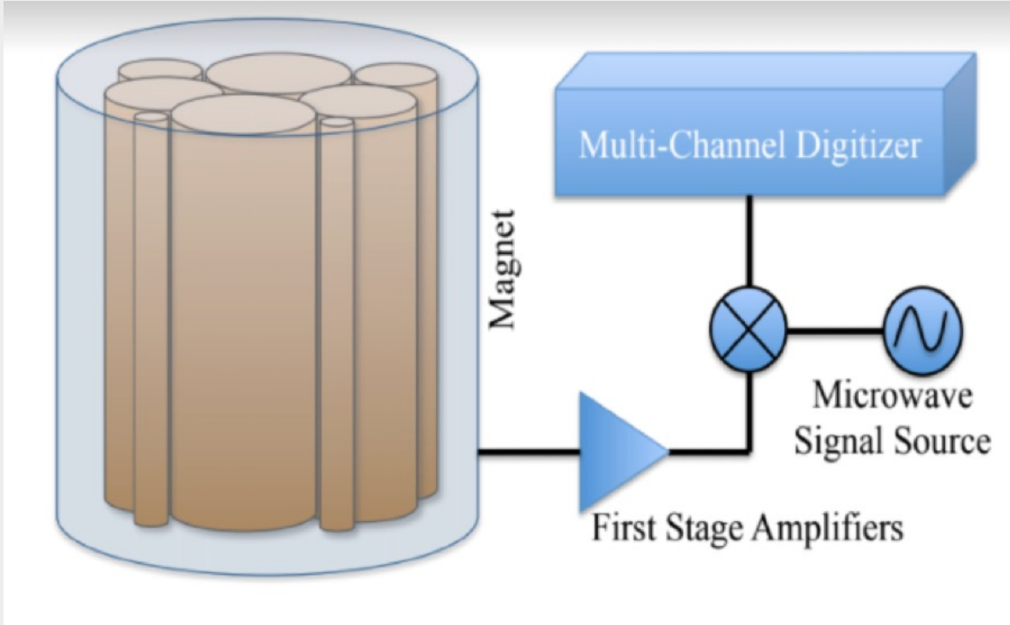

$Q_L$ ~ 11000 @ Frequency 8.384 GHz (34.67 eV)



# 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

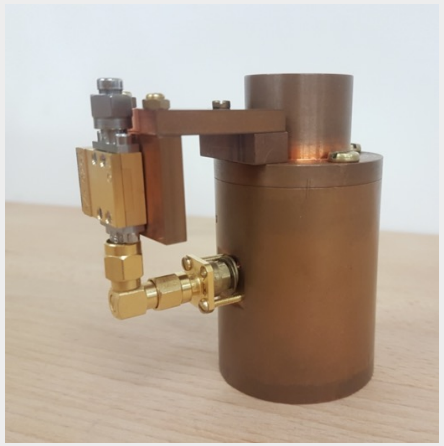
Pilot experiment with a 14 T magnet
And 6.4 GHz cavity



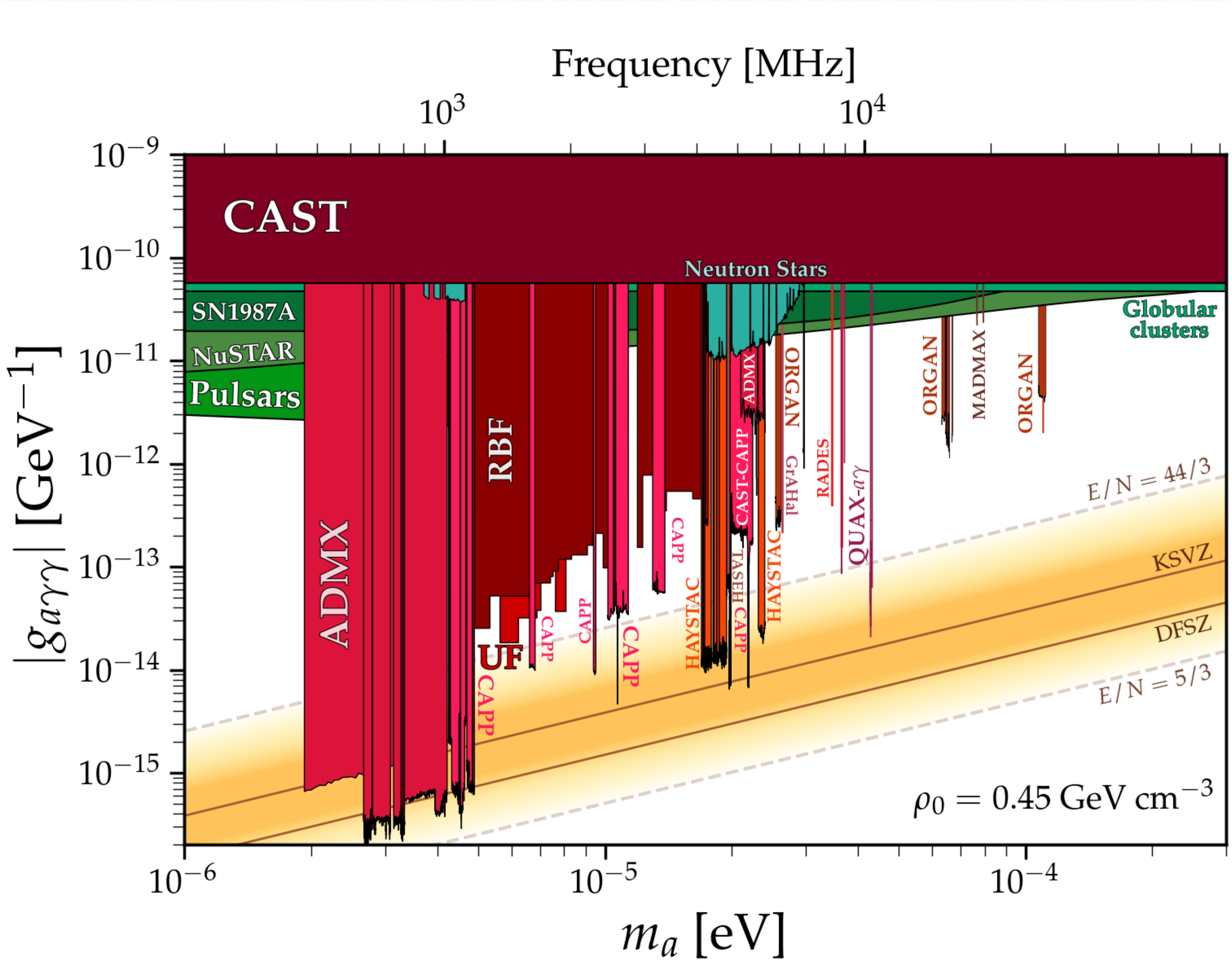

The **ORGAN** experiment (situated in Perth, Australia) is a microwave cavity axion haloscope that aims to search the mass range of 50–200 $\mu$**eV using a multi-cavity design.**

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?

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

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)

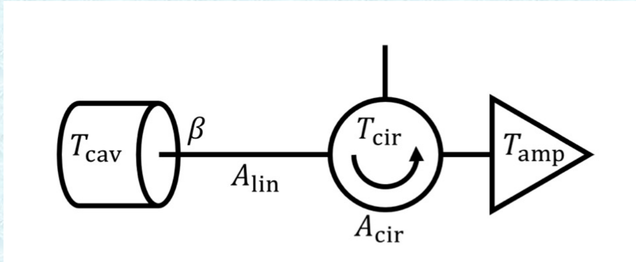
Resonant cavity volume V, mode form factor $C_{mnl}$, coupling $\beta$ and Q factor

**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)

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

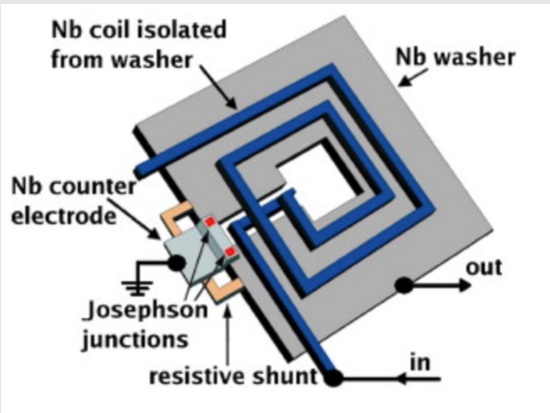



Total System Noise Level = cavity temperature + detector noise temperature

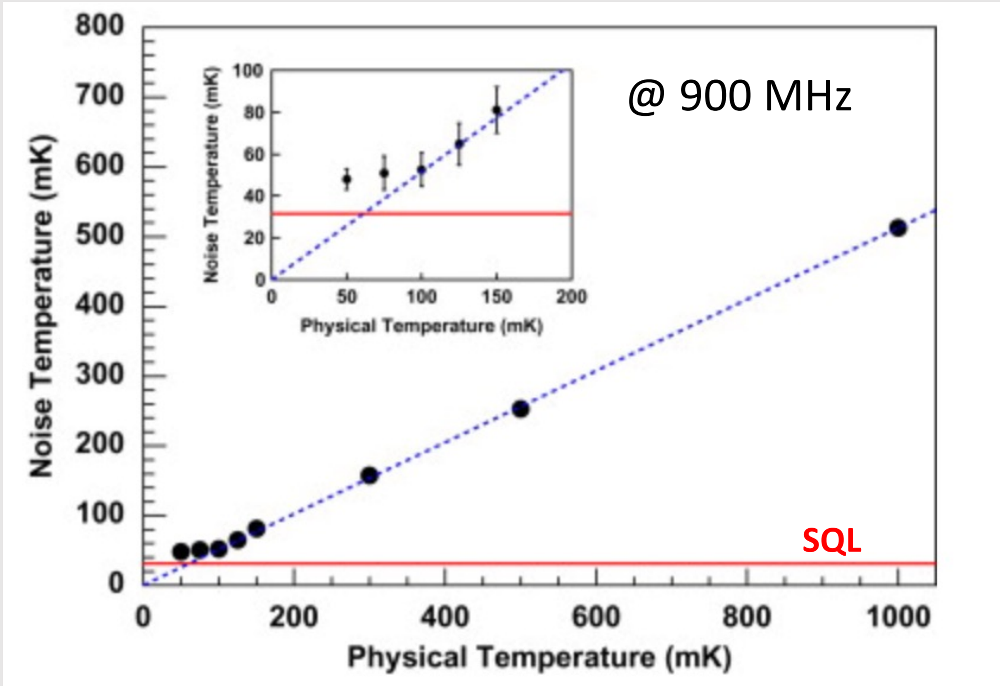
- **Irreducible noise** $k_B T_{SQL} = h\nu$ , dominant noise above 2 GHz @ 100 mK

**Low frequency**

Microstrip SQUID amplifier (ADMX) almost reached SQL




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



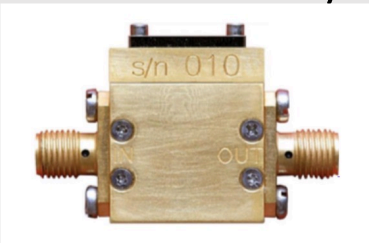

Performances drops for frequencies above a few GHz

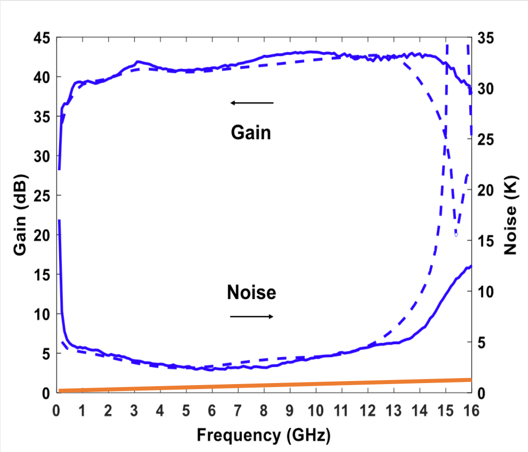
https://doi.org/10.1016/j.nima.2011.07.019

# 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

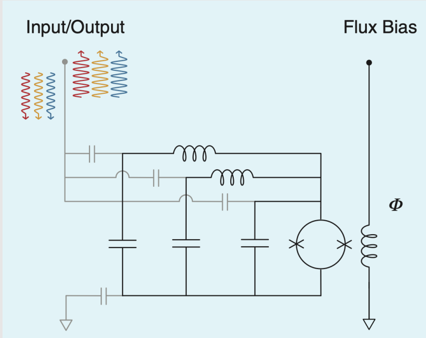
**HEMT** - high electron mobility transistor



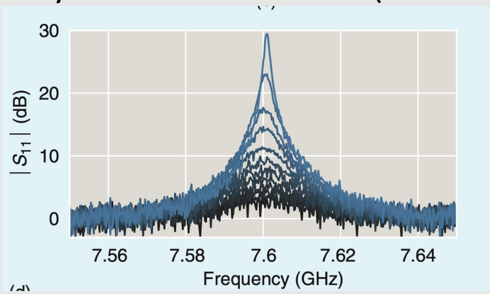




Cannot be used in ultra cryogenic environment due to power dissipation

**JPA** – Josephson Parametric Amplifier

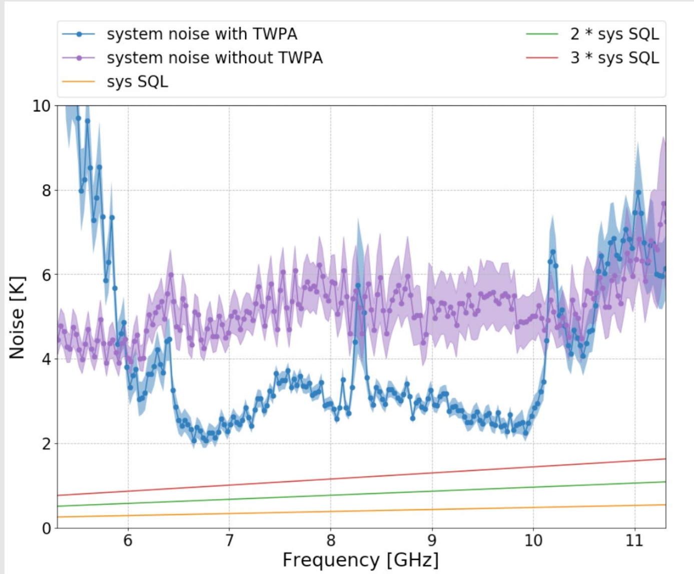



- Non linear drive of combination of Josephson Junctions
- Nominally **noiseless** parametric amplifiers → @ 1-2 SQL
- Very Limited bandwidth (10 MHz)




**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

# The road to the future: microwave cavities

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

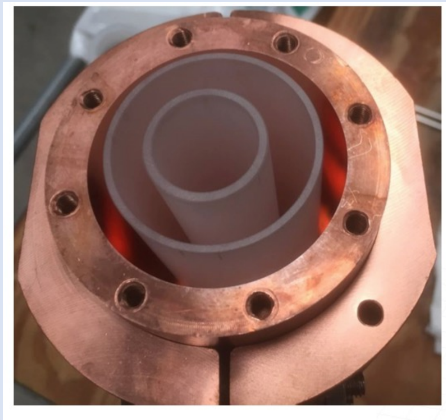
+ Tuning

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

*Snowmass 2021 White Paper Axion Dark Matter*

**Situation on 2021**


**QUAX dielectric cavity**



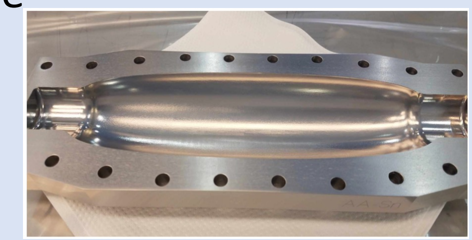
- Two nested sapphire cylinders configuration
- Q > 9x10^6 in a 8T field @ 10.4 GHz


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

(Patras workshop 2021)

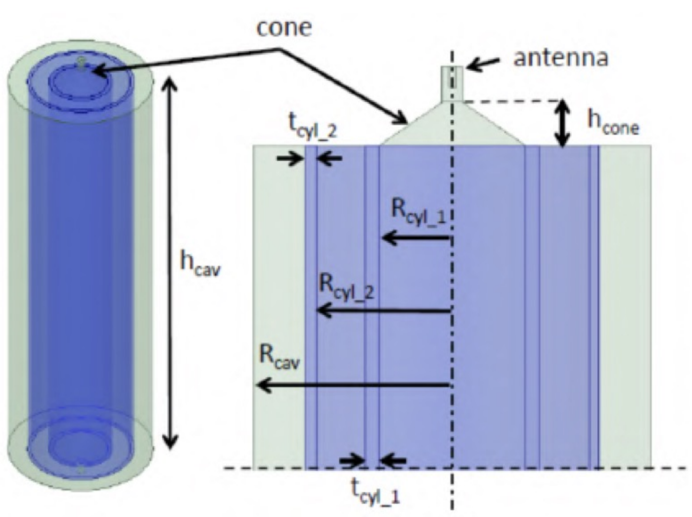
**Fermilab (SQMS) - QUAX** arXiv 2201.10733

- 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**




| | |
|---|---|
| $R_{cav}$ | 28.55 |
| $R_{cyl\_1}$ | 10.88 |
| $R_{cyl\_2}$ | 20.90 |
| $t_{cyl\_1}$ | 2.35 |
| $t_{cyl\_2}$ | 1.94 |
| $h_{cone}$ | 6.00 |
| $h_{cav}$ | 420 |

- **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

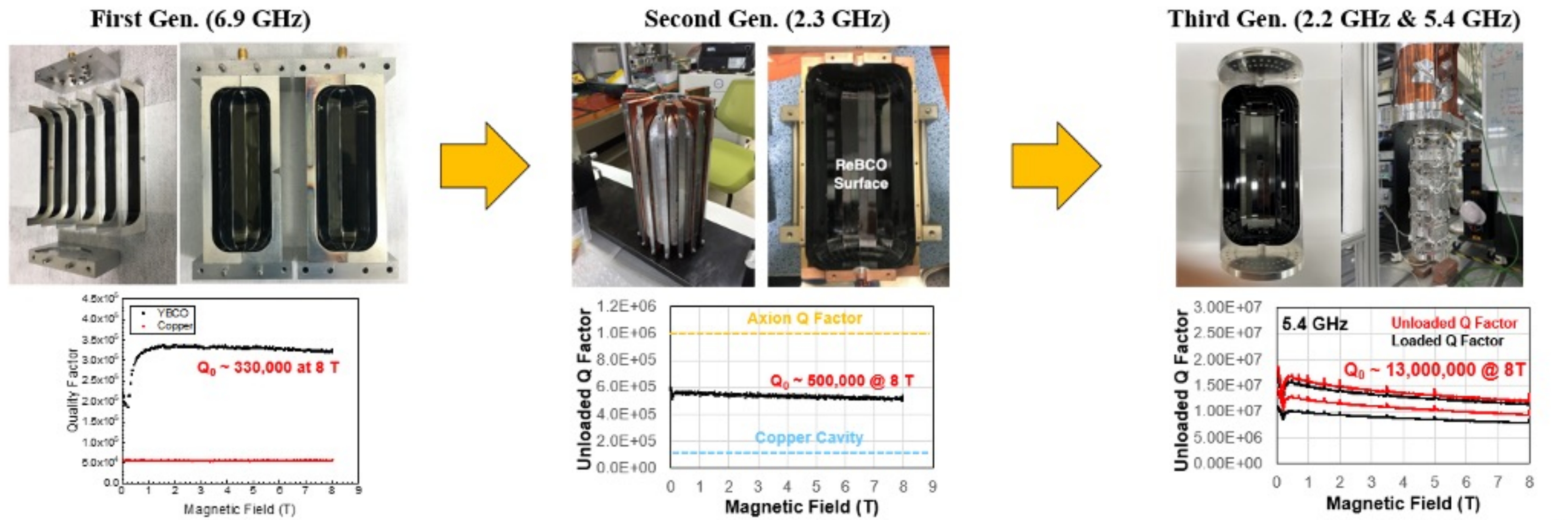
Q value @ 4 K

| Cavity | $\nu_{cav}$ | 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 (~ $10^6$)

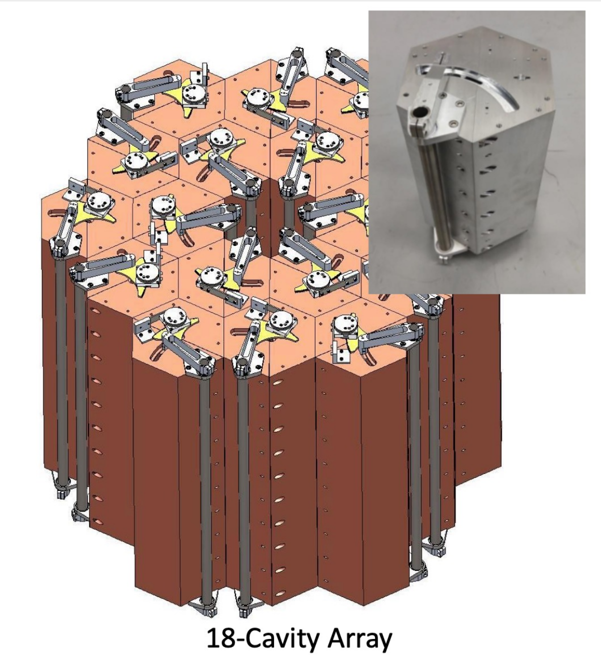
# Cavities developments - new geometries

**Find ways to increase volume at high frequency while keeping tuning**

For right cylindrical cavity, main mode volume

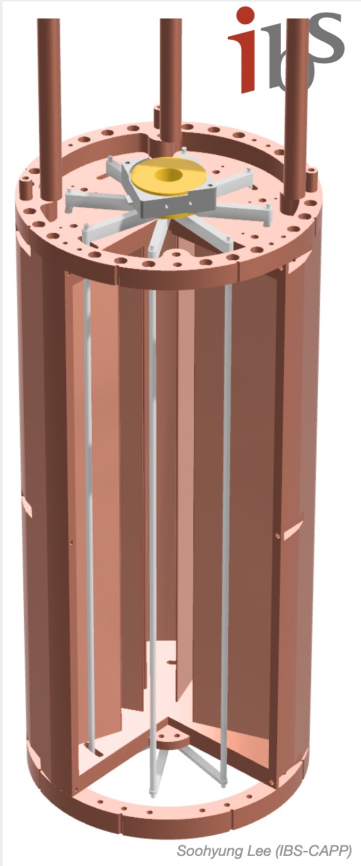
V ~ 1/d^2 ~ 1/f^2

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

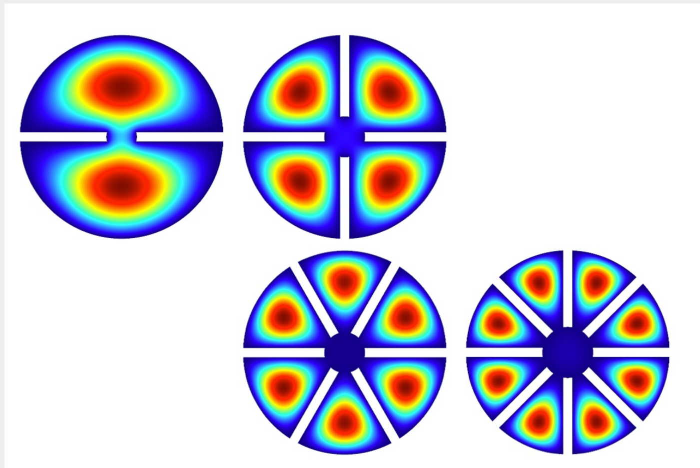



80 liters
Avg C ~ 0.4
Q ~ 90 000

**Multiple cell cavity at CAPP**

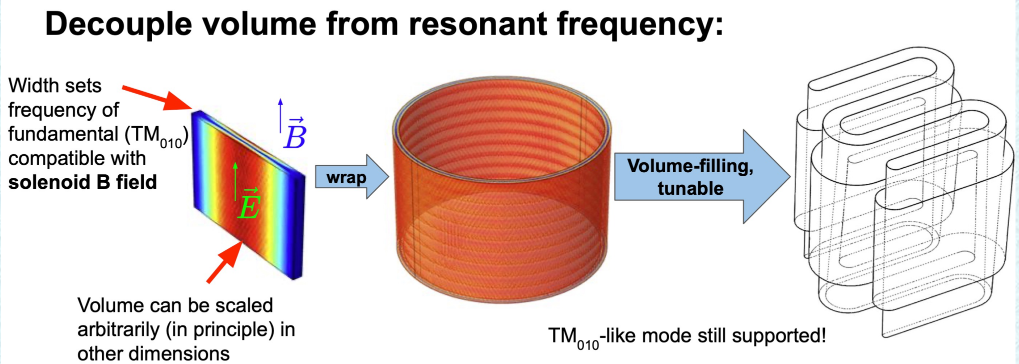



- Resonant frequency increases with the cell multiplicity.
- Same frequency tuning mechanism as multiple cavity system can be employed.
- A single RF antenna extracts the signal out of the cavity.



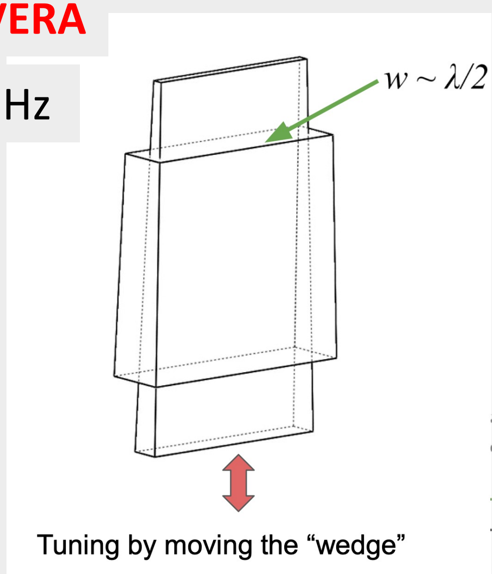
Frequency up to 8 GHz

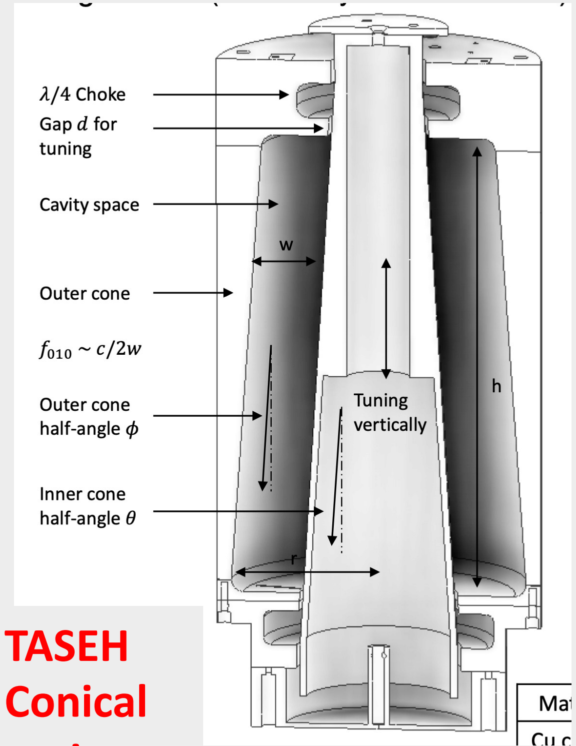
# Cavities developments – new geometries




## ADMX VERA

f > 4 GHz



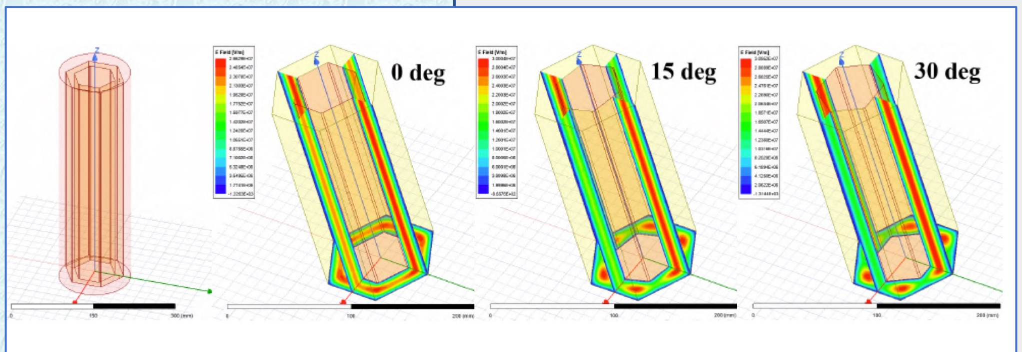

## TASEH Conical cavity

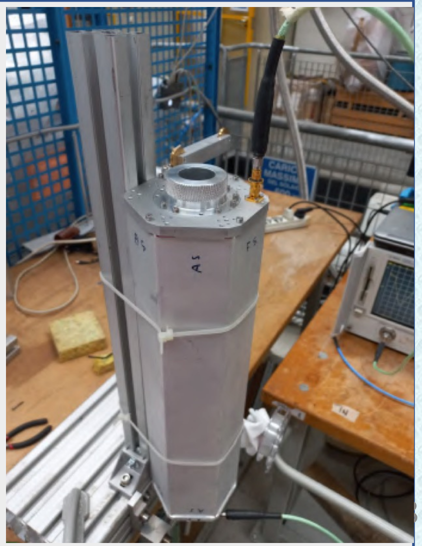
E field pattern

**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

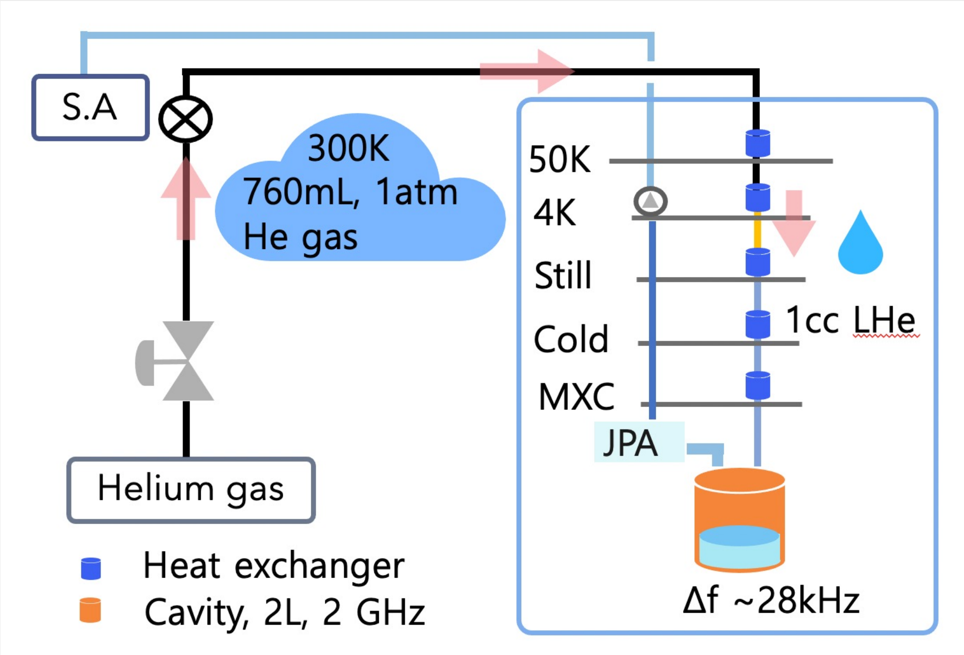
## CAPP Superfluid Helium Tuning

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

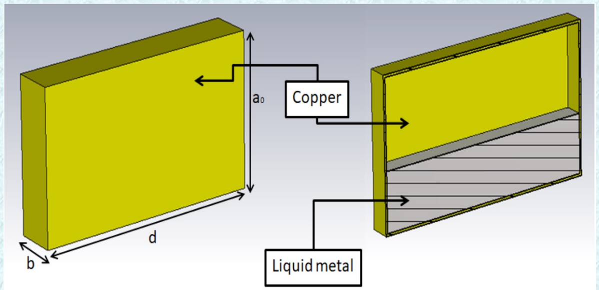
**Superfluid Helium** ($\epsilon_r \approx 1.057$) tuning

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

***~3 % frequency shift***

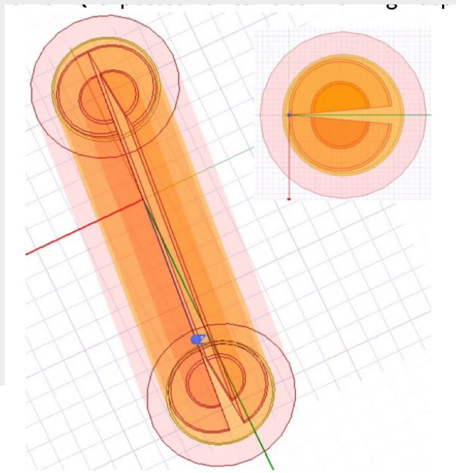


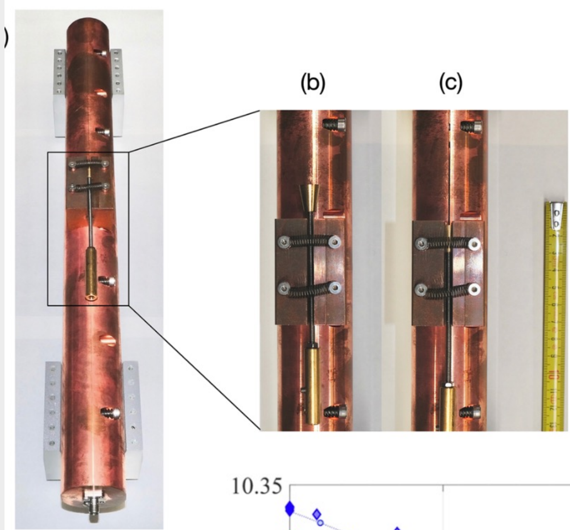

arXiv:1804.03443v1
QUAX
Liquid Metal Tuning of a resonator



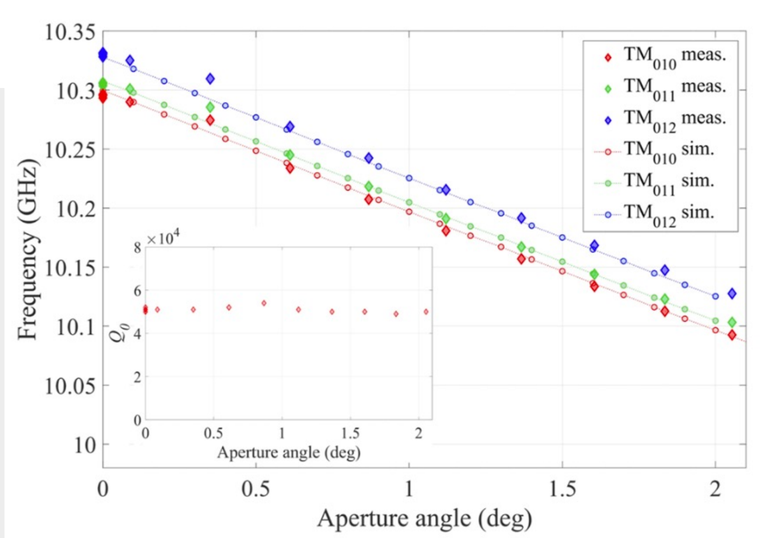

## QUAX Clamshell cavity

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





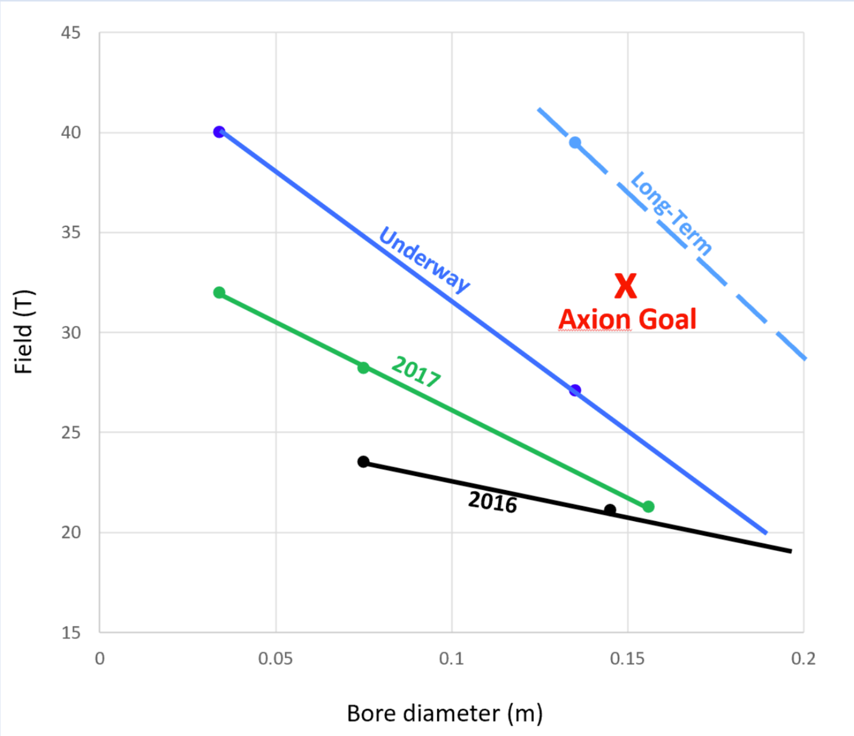

- Lack of mode crossings
- Tuning linear with aperture



# 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

LNCMI

Several lower field option will also be available

**GraHal Project**

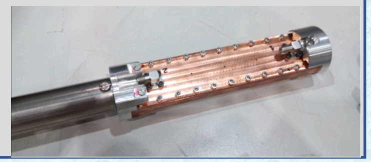
arXiv:2110.14406

# Dark matter haloscopes – what's going on

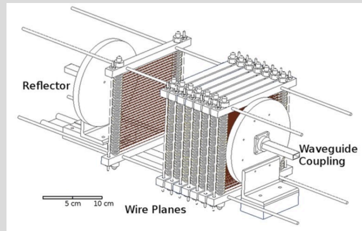
- Several other activities are starting or being proposed in the very recent time
- It is a field which is expanding very rapidly

CULTASK
CAPP

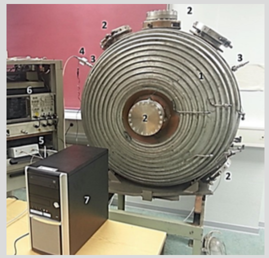
RADES / CAPP – cavities inside CAST



ORPHEUS

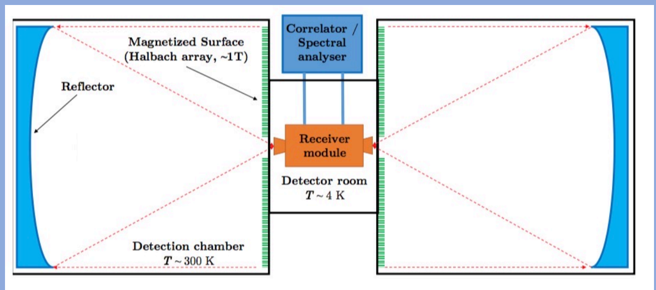



WISPDMX @DESY

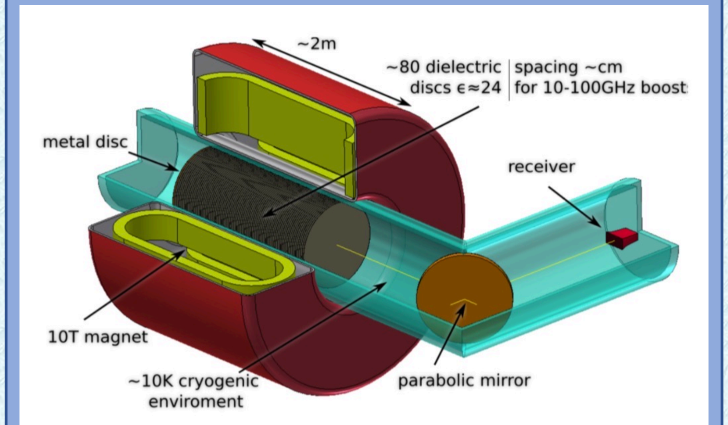


**Standard Sikivie's detectors**

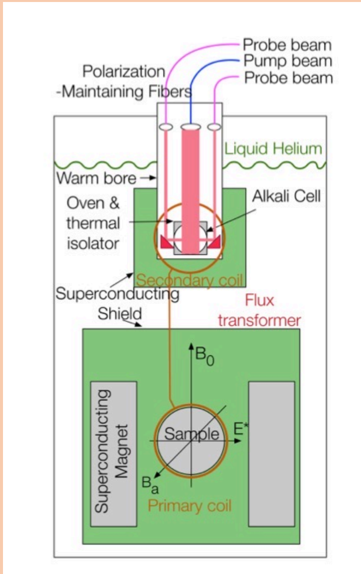
**BRASS – dish antenna**



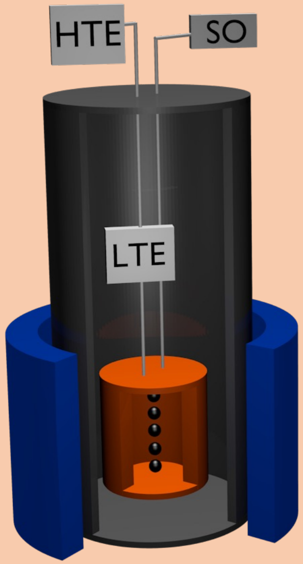

**MADMAX - Dielectric haloscope**



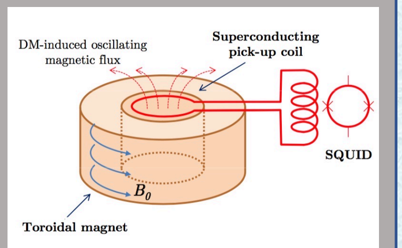

**CASPER wind – NMR**
**Axion - nucleon**



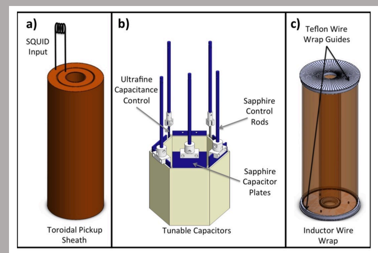

**QUAX – EPR**
**Axion - electron**




ABRACADABRA



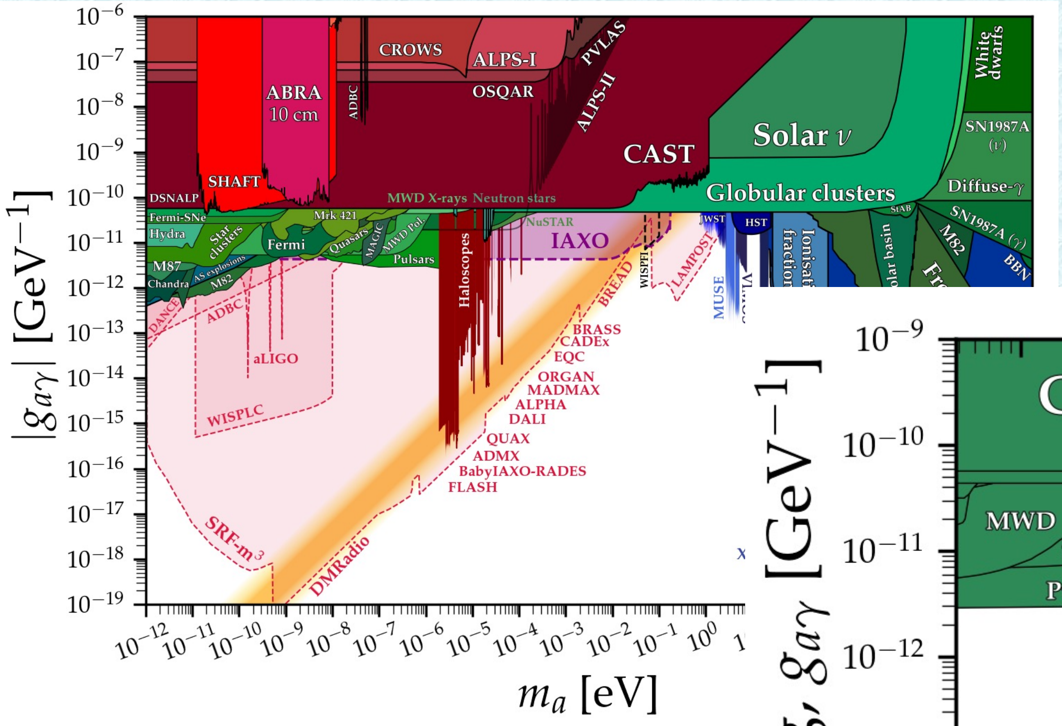

DM Radio



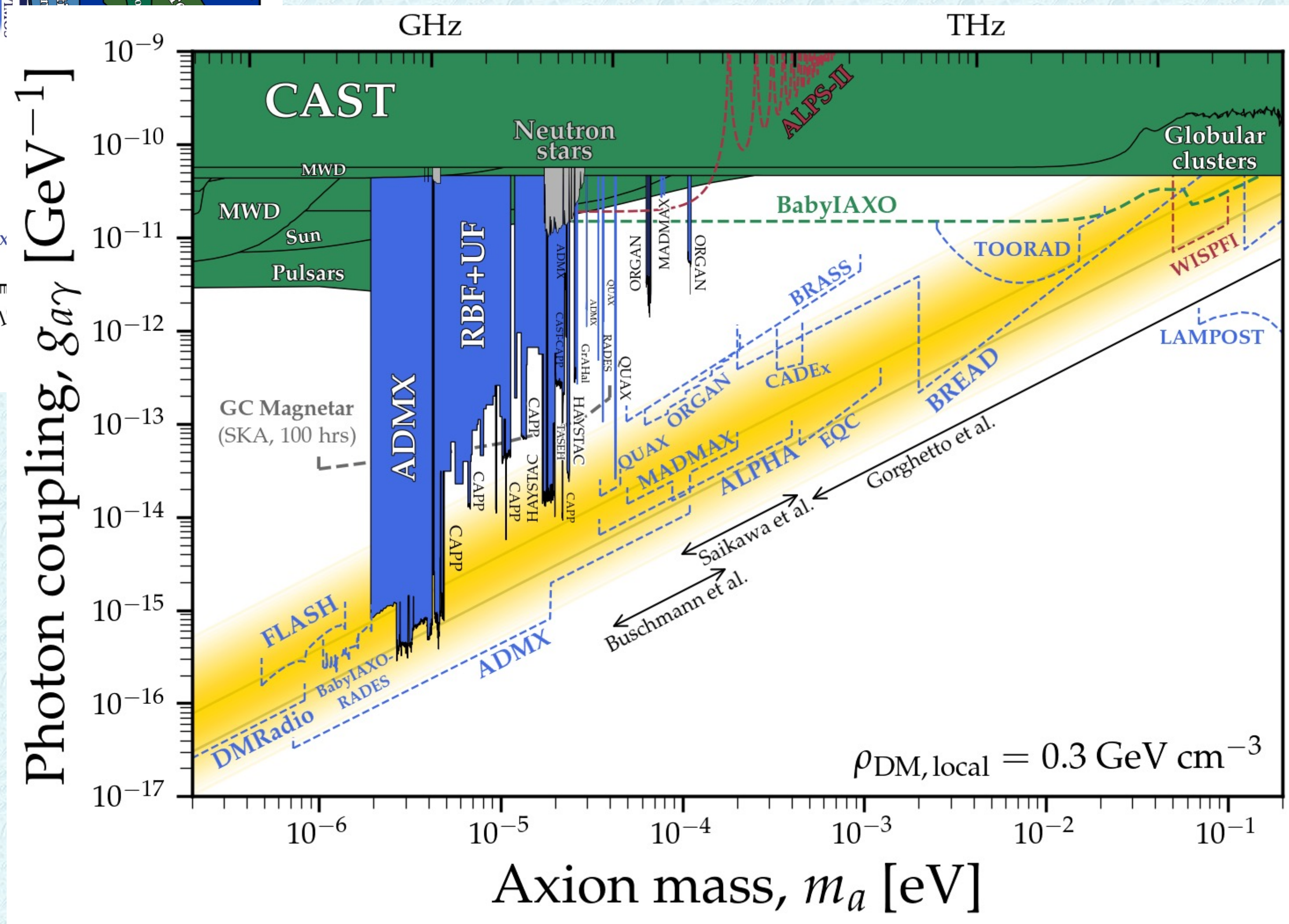

**LC circuit**

**ONLY A SELECTION!!!!!**

# Photon coupling – what next




**FLASH** – Italian based proposal to use FINUDA 1.1 T magnet




$$g_{a\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} = 2.0 \times 10^{-16} C_{a\gamma} \frac{m_a}{\mu\text{eV}} \text{GeV}^{-1}$$

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

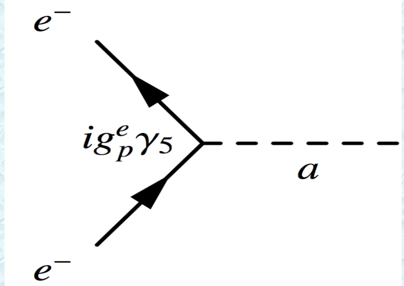
# Interaction of DFSZ axion and electron spin

- The interaction of the axion with a spin ½ particle

$$\mathcal{L}_{a,\mathrm{matter}} = f_a^{-1} g_{aij} \overline{\psi}_i \gamma^\mu \gamma^5 \psi_j \, \partial_\mu a \qquad g_p \cong \frac{m_e}{3 f_a} \cos^2 \beta \qquad g_p \approx 3 \times 10^{-11} \left( \frac{m_a}{1\, eV} \right)$$

- **DFSZ axion** model coupling with non relativistic (v/c << 1 ) electron equation of motion reduces to

$$i\hbar \frac{\partial \varphi}{\partial t} = \left[ -\frac{\hbar^2}{2m} \nabla^2 - \frac{g_p \hbar}{2m} \boldsymbol{\sigma} \cdot \boldsymbol{\nabla} a \right] \varphi$$



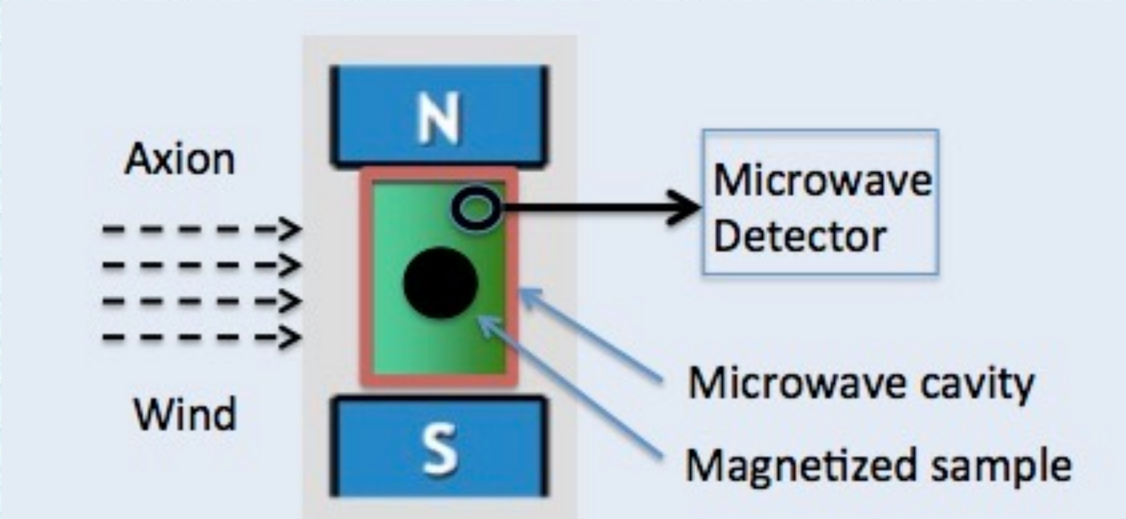

The interaction term has the form of a **spin - magnetic field interaction** with $\vec{\nabla} a$ playing the role of an **oscillating effective magnetic field**

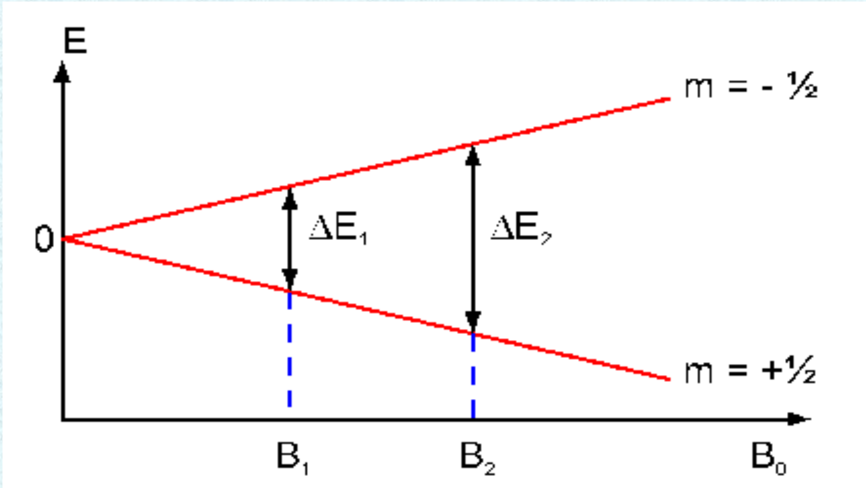
$$\mathrm{H}_{\mathrm{int}} = -2 \mu_B \vec{\sigma} \cdot \left[ \frac{g_p}{2e} \vec{\nabla} a \right] \qquad \mathrm{B}_a = \frac{g_p}{2e} \vec{\nabla} a$$

-- **Frequency** of the effective magnetic field proportional to **axion energy**
-- **Amplitude** of the effective magnetic field proportional to **axion density**

# The QUAX proposal: sensing the axion wind

- **Due to the motion of the solar system** in the galaxy, the axion DM cloud acts as an **effective RF magnetic field on electron spin**
- This field excites **magnetic transition in a magnetized sample** (Larmor frequency) and produces a detectable signal
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**




Idea comes from **several old works**:


- L.M. Krauss, J. Moody, F. Wilczeck, D.E. Morris, "Spin coupled axion detections", HUTP-85/A006 (1985)
- R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B 226, 357 (1989)
- F. Caspers, Y. Semertzidis, "Ferri-magnetic resonance, magnetostatic waves and open resonators for axion detection", Workshop on Cosmic Axions, World Scientific Pub. Co., Singapore, p. 173 (1990)
- A.I. Kakhizde, I. V. Kolokolov, Sov. Phys. JETP 72 598 (1991)

# The axion effective magnetic field

- R. Barbieri et al., *Searching for galactic axions through magnetized media: The QUAX proposal* Phys. Dark Univ. **15,** 135 - 141 (2017)

**The effective magnetic field associated with the axion wind**

$$B_a = \frac{g_p}{2e}\left(\frac{n_a h}{m_a c}\right)^{1/2} m_a \mathrm{v}_E$$

$n_a$ – axion density
$\mathrm{v}_E$ – Earth velocity

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

$$\frac{\omega_a}{2\pi} = 48 \left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \quad \mathrm{GHz},$$

$$\tau_{\nabla a} \simeq 0.68\,\tau_a = 17 \left(\frac{200\,\mu\mathrm{eV}}{m_a}\right)\left(\frac{Q_a}{1.9 \times 10^6}\right) \quad \mu\mathrm{s};$$

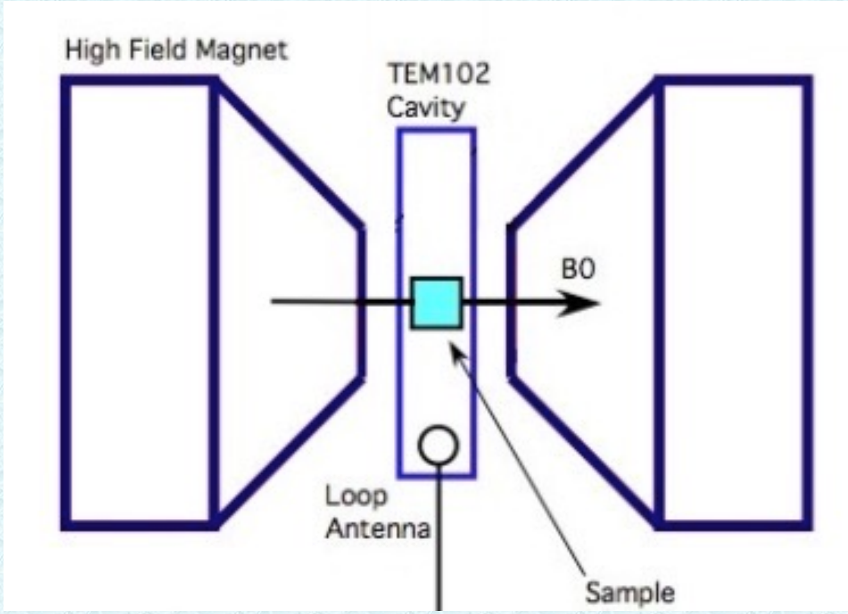
**Coherence time**

$$\lambda_{\nabla a} \simeq 0.74\,\lambda_a = 5.1 \left(\frac{200\,\mu\mathrm{eV}}{m_a}\right) \quad \mathrm{m},$$

**Correlation length**

# Detection strategy: Electron Spin Resonance

**Electron spin resonance (ESR)** arises when energy levels of a quantized system of electronic moments are **Zeeman split** (the **magnetic system** is placed in a uniform magnetic field $B_0$) and the system absorbs (emits) EM radiation (in the microwave range) at the **Larmor frequency** $\nu_L$ of the **ferromagnetic resonance**.

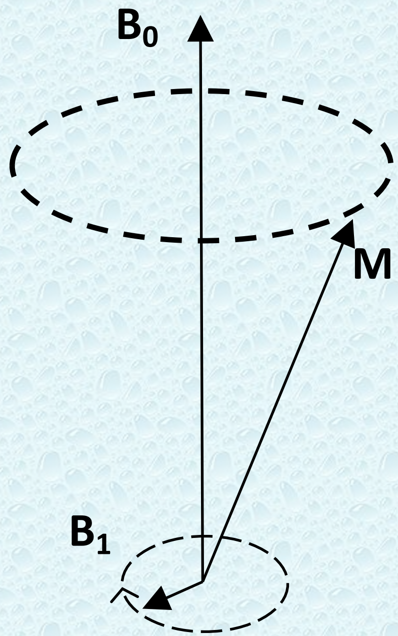



$$B = \begin{pmatrix} B_1 \cos(\omega t) \\ B_1 \sin(\omega t) \\ B_0 \end{pmatrix}$$

$$\nu_L = \gamma B_0$$

$\gamma$ = 28 GHz / T

**1.7 T -> $\nu_L$ = 48 GHz**

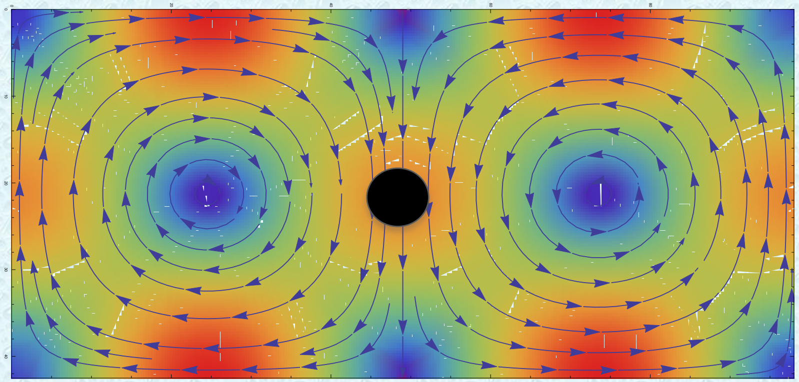



An experimental geometry with **crossed field** is needed:

- **$B_0$** along the z direction, defines the Larmor resonance
- **RF field $B_1$** in the x-y plane to excite the EPR transition

This system is described by a set of **coupled non-linear equations** due to **Bloch**.
They describe the evolution of the magnetization vector ***M***

TEM102 Resonant Cavity
$B_0$ along z axis (normal to the figure)



# The Bloch equations

The evolution of the electron spin **(spin precession)** under the influence of external fields is described by a set of coupled non-linear equations due to Bloch, modified to take into account radiation damping (Magnetizing field $\mathbf{B_0}$ along z-axis, driving rf field $\mathbf{B_1}$ in the x-y plane)

$$\frac{dM_x}{dt} = \gamma(\mathbf{M}\times\mathbf{B})_x - \frac{M_x}{\tau_2} - \frac{M_x M_z}{M_0\tau_r}$$

$$\frac{dM_y}{dt} = \gamma(\mathbf{M}\times\mathbf{B})_y - \frac{M_y}{\tau_2} - \frac{M_y M_z}{M_0\tau_r}$$

$$\frac{dM_z}{dt} = \gamma(\mathbf{M}\times\mathbf{B})_z - \frac{M_0 - M_z}{\tau_1} - \frac{M_x^2 + M_y^2}{M_0\tau_r}$$

- **Spin-lattice relaxation** time $\tau_1$: establish energetic equilibrium of $M_z$.
- **Spin-spin relaxation** time $\tau_2 < \tau_1$: $H_1$ forces $M_x$ $M_y$ to rotate and $\tau_2$ sets equilibrium
- **Radiation damping** $\tau_r$: describes interaction with environment

At low temperature T < 1 K

**$\tau_1 \sim 10^{-6}$ to 10 s**

**$\tau_2 \sim 10^{-9}$ to 0.1 s**

**depends on spin density**

**M** is the magnetization density ($M \propto n_0$)

For example, in a paramagnet

$$\mathrm{M} = n_0\mu_B \tanh[\mu_B B_0/k_B T]$$

$n_0$ – spin density

$\mu_B$ – Bohr magneton

$T$ – sample temperature

# Axion mediated rf emission

The axion wind can mimic the transverse rf magnetic field $\mathbf{B_1}$ inducing a **variable magnetization component** in the magnetic sample in the x-y plane

$$M_a(t) = \gamma \mu_B B_a n_S \tau_{\min} \cos(\omega_a t),$$

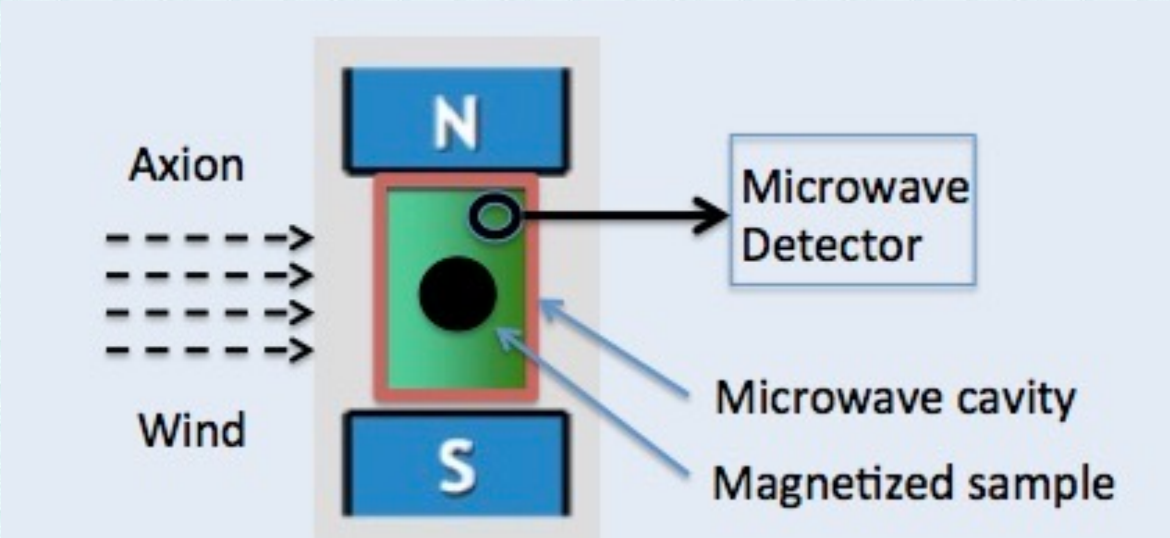
On resonance

$\tau_{min}$ **is the shortest coherence time** among:

- **axion wind** coherence $\tau_{\nabla a}$
- magnetic material **relaxation time** $\boldsymbol{\tau_2}$
- **radiation damping** $\boldsymbol{\tau_r}$

$n_s$ – material spin density

$\mu_B$ – Bohr magneton




A **volume $V_s$ of magnetized material** will absorb energy from the axion wind at a rate

$$P_{\text{in}} = \mu_0 \mathbf{H} \cdot \frac{d\mathbf{M}}{dt} = B_a \frac{dM_a}{dt} V_s = \gamma \mu_B n_S \omega_a B_a^2 \tau_{\min} V_s$$

that will be **re-emitted as electromagnetic radiation** and possibly detected

# Radiation damping

Radiation damping describes two additional **loss mechanisms in magnetized sample at the Larmor frequency $\nu_L$:**

1) the interaction of the magnetized sample with **the driving circuit**

$$\tau_R \approx (2\pi\xi\gamma M_0 Q)^{-1}$$

2) the **emission of radiation** (magnetic dipole)

$$\tau_R \approx \frac{\lambda_L^3}{\gamma \mu_0 M_0 V}$$

**ξ -> filling factor**: geometrical coupling between driving circuit and magnetized sample
**Q -> quality factor:** accounting for dissipations of rf coils of driving circuit (or rf cavity)
**$\lambda_L$ -> rf wavelength** ($c/\nu_L$)
**V -> sample volume**
**$M_0$ -> static magnetization (**proportional to the spin density $n_s$**)**

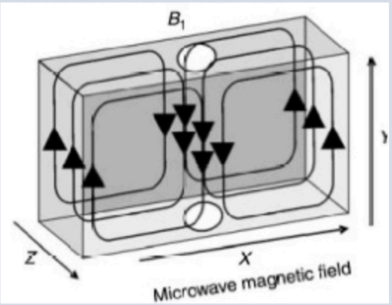
For frequencies **above 10 GHz** and large magnetization $M_0$, the only relevant radiation damping is the **emission of em radiation**.

In free space $\tau_r << ( \tau_2, \tau_{\nabla a})$ thus limiting the expected signal!

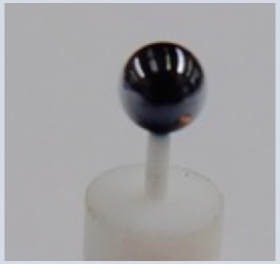
# Coupling to microwave cavity

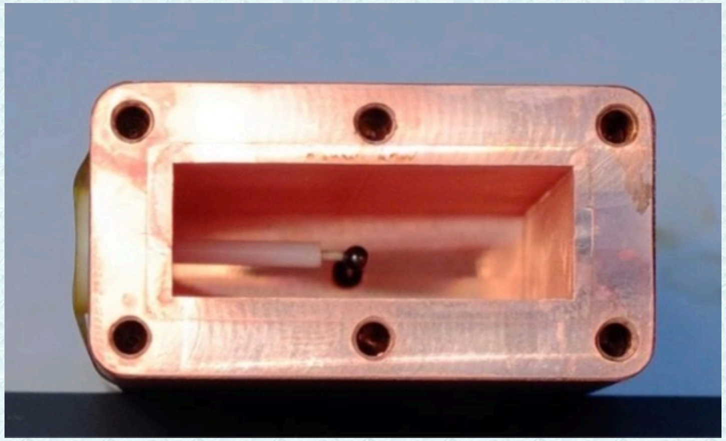
- To avoid radiation damping we place the **magnetized material inside a microwave cavity**

**Resonant cavity**
**$\omega_c, \tau_c, V_c$**

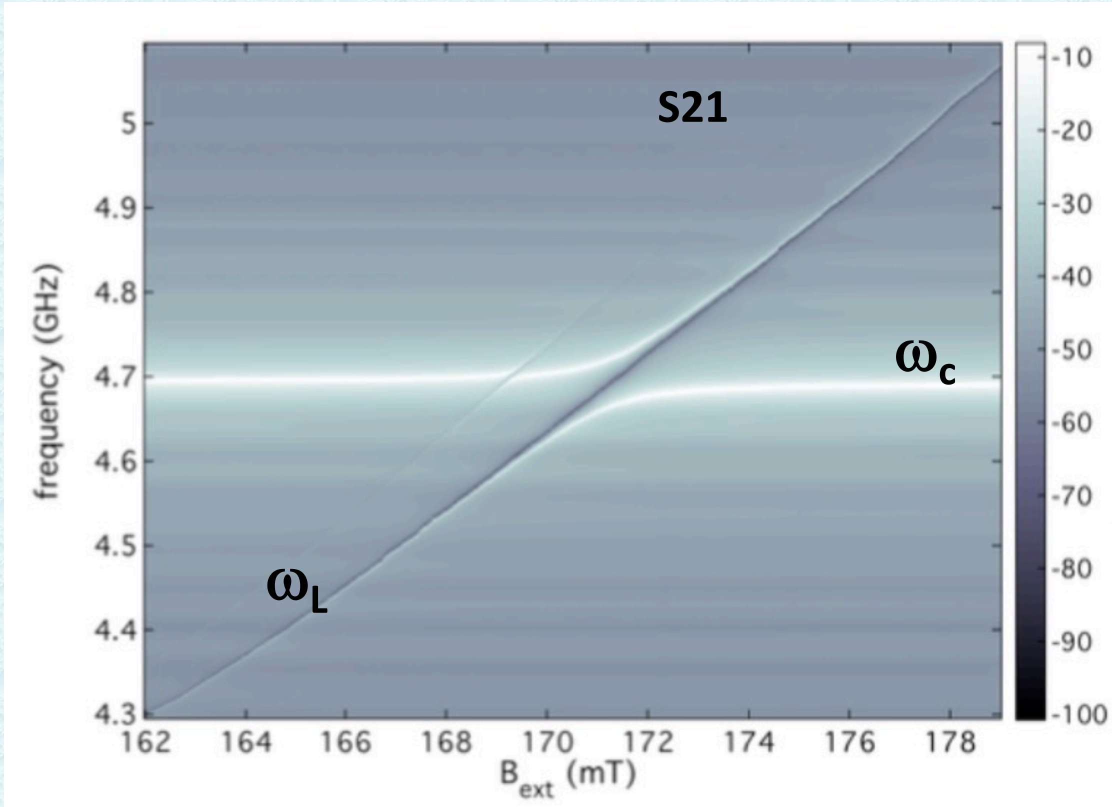



**YIG sphere (Ferrimagnet)**
**$\omega_L = \gamma B_0 \;, \tau_2, V_s$**





- When the spin resonance (Kittel mode) equals cavity resonance the **system hybridizes**



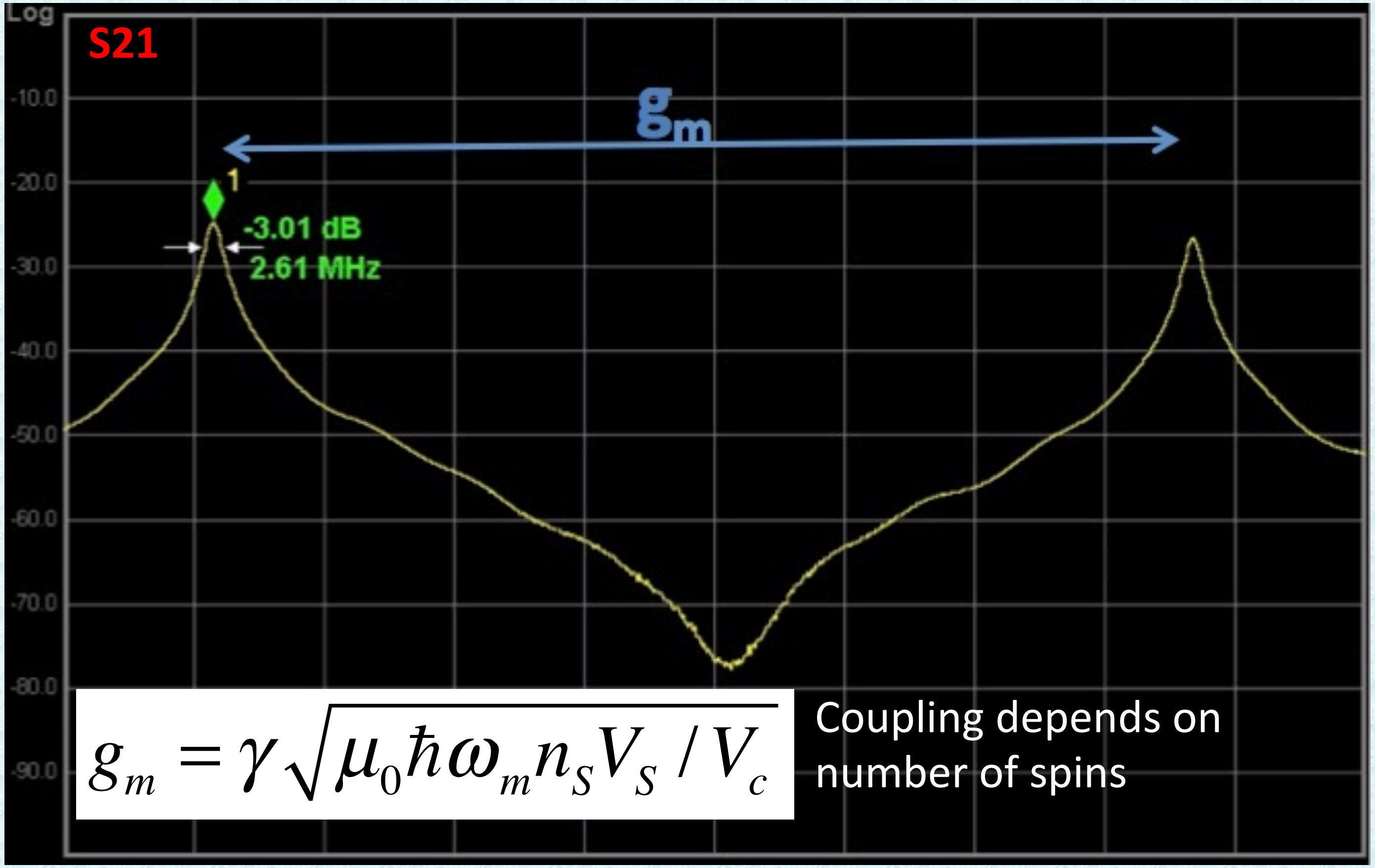
# Strong coupling regime

**Strong coupling regime**: two separate resonances

$$\omega_{\pm} + \frac{i}{2\tau_{\pm}} = \omega_L \pm \frac{1}{2}\left[\frac{4}{\tau_c}\left(\frac{1}{\tau_2}+\frac{1}{\tau_r}\right)-\left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)\right]^{1/2} + \frac{i}{2}\left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)$$

**Radiation damping effects eliminated**

**Width is the average between cavity and material relaxation time**




$$g_m = \gamma\sqrt{\mu_0 \hbar \omega_m n_S V_S / V_c}$$

Coupling depends on number of spins

Line width ←→ relaxation time ←→ Q factor

$$\Delta\omega = 2\pi\Delta\nu = \frac{1}{\tau}$$

$$Q = \frac{\Delta\omega}{\omega} = \frac{\Delta\nu}{\nu}$$

# Expected signal

Expected signal with relevant experimental parameters

**Working @ $m_a$ = 200 μeV**

**With magnetizing field**
**$B_0$ = 1.7 T => 48 GHz**

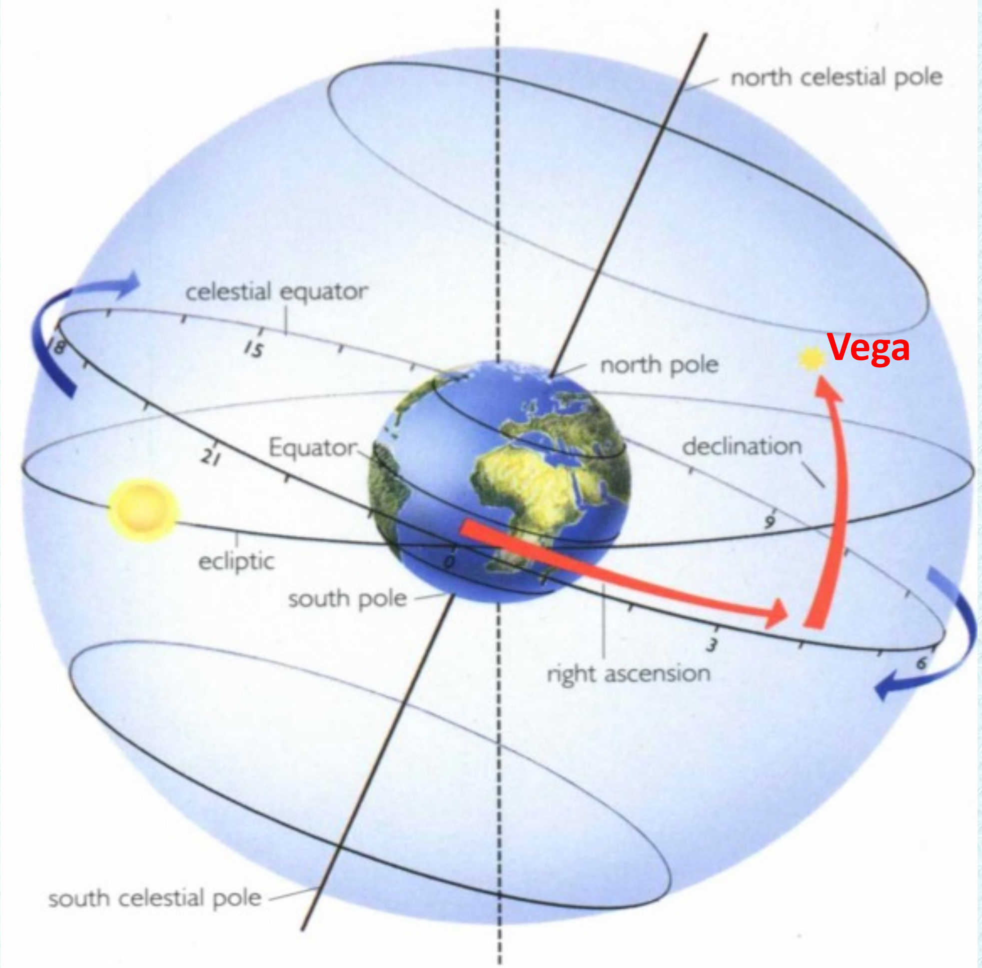
$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\,\mu\text{eV}}\right)^3 \left(\frac{V_s}{100\text{ cm}^3}\right) \left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3}\right) \left(\frac{\tau_{\min}}{2\,\mu\text{s}}\right) \text{W}$$

Such low power level out of reach of linear amplifiers → **Single photon microwave detection**

The corresponding **signal photon rate**

$$R_a = \frac{P_{\text{out}}}{\hbar\omega_a} = \mathbf{1.2 \times 10^{-3}}\,\text{Hz}$$

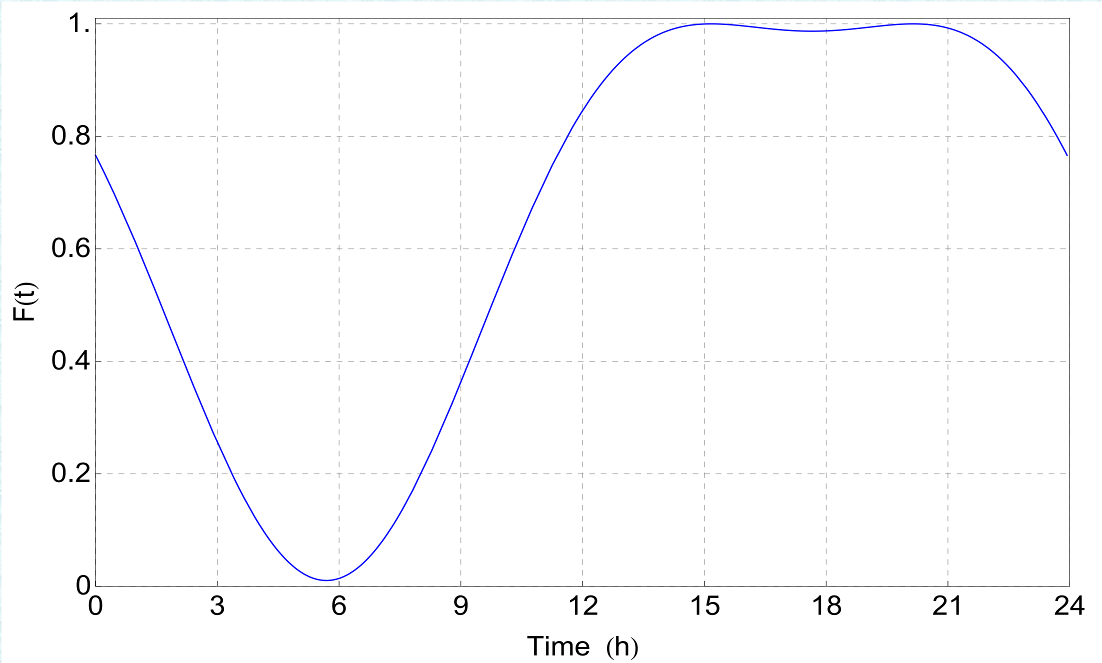
# A plus: directionality




Due to Earth rotation, the direction of the static magnetic field $\mathbf{B_0}$ changes with respect to the direction of the axion wind (Vega in Cygnus)

e.g. QUAX located @Legnaro (PD)
$\mathbf{B}_0$ in the local horizontal plane and oriented N-S (the local meridian)

QUAX Pattern




Strong modulation (up to 100%)!
Not due to seasonal or Earth rotation Doppler effect (few %) but to relative direction change of axion gradient and magnetic field

# Backgrounds

- In the **absence of technical noises**, **thermal photons** are the only **background with rate $R_t$**

$$\mathrm{SNR} = \frac{R_a}{\sqrt{R_a + R_t}}\sqrt{\eta t_m}$$

$t_m$ = 4 hours
SNR = 3

Working temperature
**T < 116 mK**

$t_m$ – measurement time
η – detector efficiency

**With a useful bandwidth of about 150 kHz**

**One has to demonstrate that this is the only relevant noise and that the idea is correct and scalable to the requested size and parameters**

# Experimental challenges

- **Magnetic material**
  - Spin density 2 x $10^{28}$ / $m^3$
  - Ferromagnetic linewidth (=1 / 2 $\pi$ $\tau_2$) of about 150 kHz ($t_2$ ~ $\mu$s)
  - Total volume about 100 $cm^3$
- **Microwave cavity**
  - Q factor of the order of $10^6$
  - To be operated in a static magnetic field
  - Must house a 100 $cm^3$ magnetic sample (use replicas?)
- **Magnetizing field**
  - Up to 2 T magnetic source
  - High uniformity and high stability – at the ppm level
- **Microwave receiver**
  - Single photon counter
- **Complete apparatus**
  - Working temperature around 100 mK
  - Noise budget limited to thermal background
  - Frequency tunability

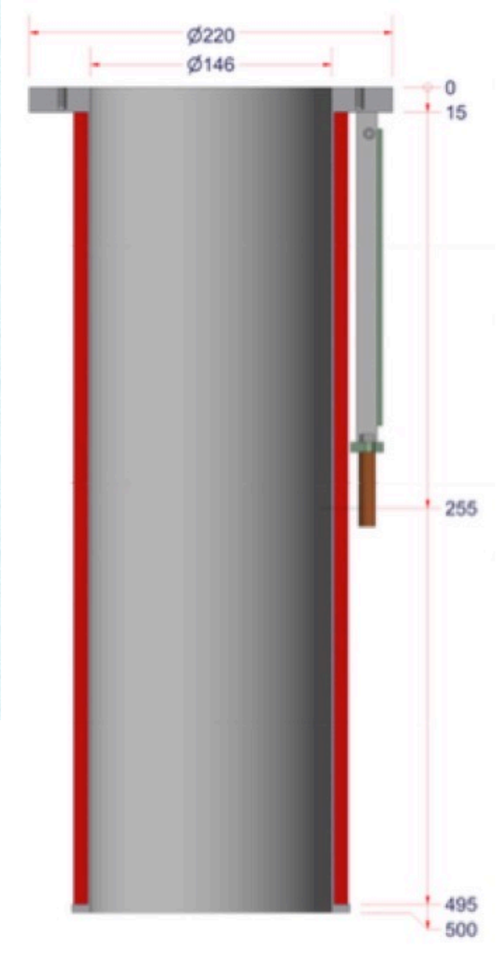
# Static Magnetic field: the source magnet

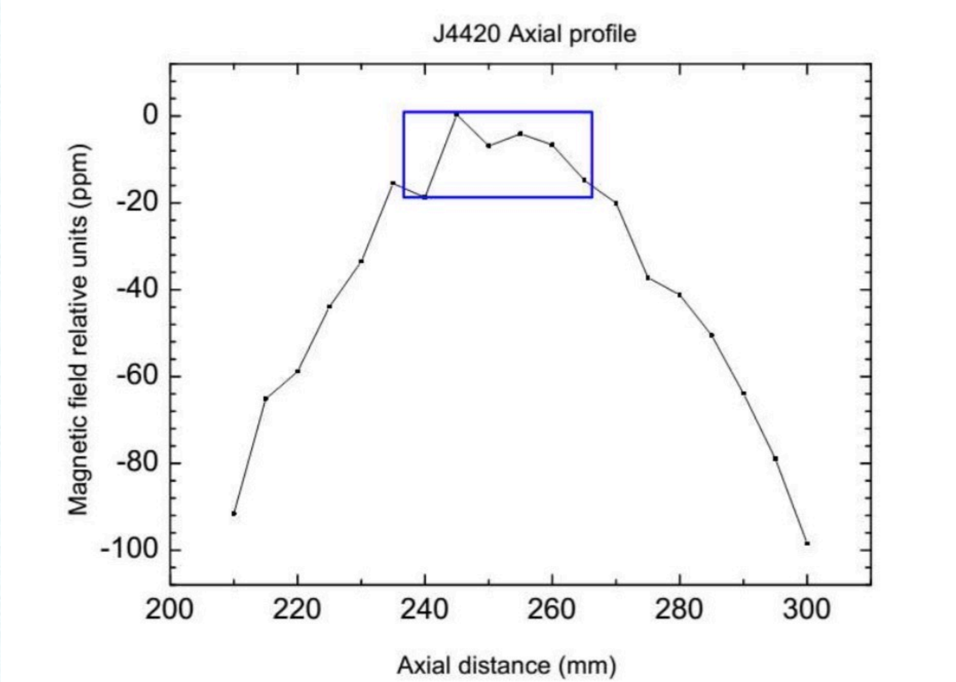
In our experiment we need an homogeneity at the **ppm level** to **avoid inhomogeneous line broadening** of the Larmor resonance **over the sample volume**.

Our solution: increase ratio length / radius

Homogeneity depends on cost

**20 ppm over 1 cm** solution from private company



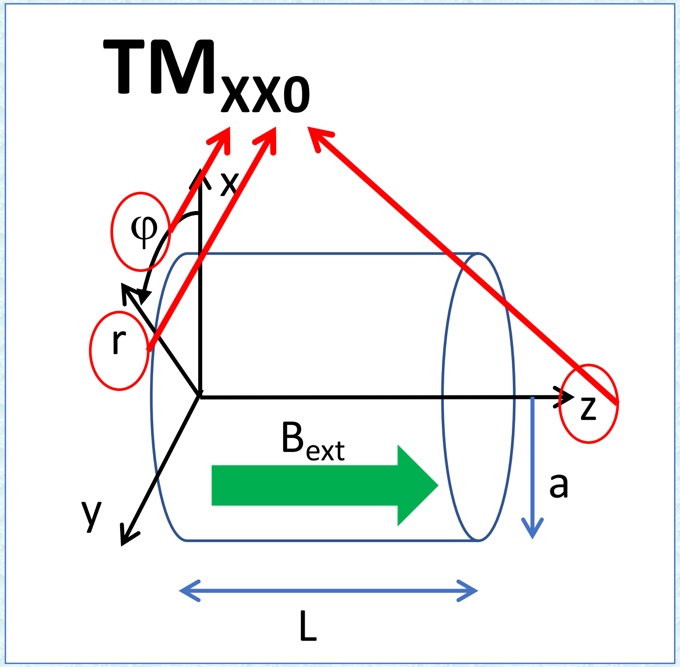

NbTi Superconducting coil

The current magnet can work up to 4 T

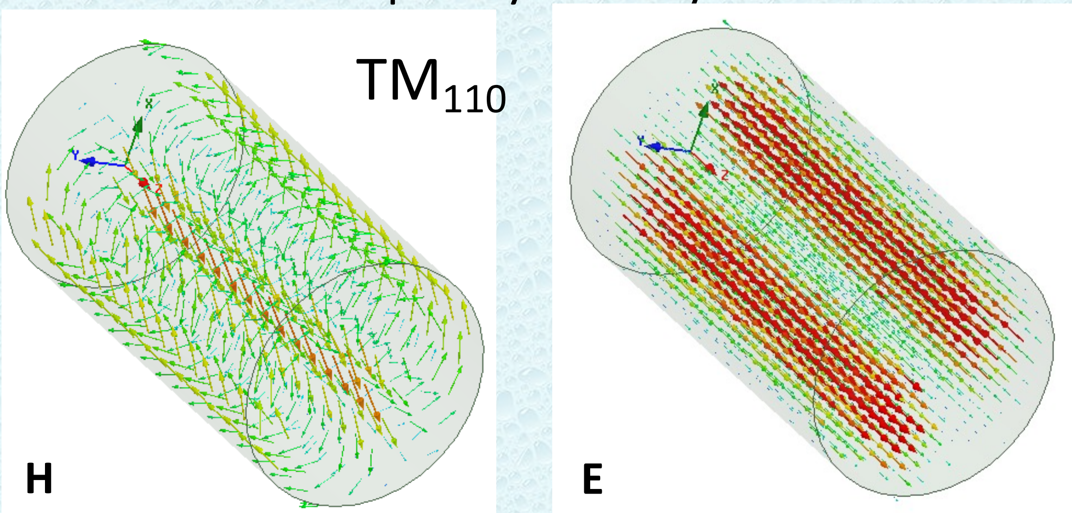
Magnetic field 1 T for 25 A

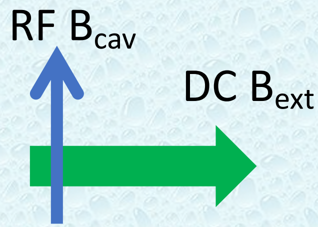
# Microwave cavity: geometry

Basic geometry: **cylindrical cavity** working in the **$TM_{XX0}$ mode**




- Simple design
- RF field uniform along the longitudinal coordinate
- Resonance frequency fixed by the radius of the cell




To increase the volume of the cavity (for YIG or other material insertion) we have to increase the **cavity length.** This does not change the resonance frequency.

This **increases the number of nearest modes** (hybridization can couple different modes?)

Cylindrical geometry produces mode degeneracy for the chosen mode

Solved by employing structure cuts

# Magnetic material

- We have tested several materials:

- **BDPA, $K_3CrO_8$** and other paramagnets
- **Lithium ferrite** (Ferrimagnet, spin density 4 $10^{28}$ /$m^3$)

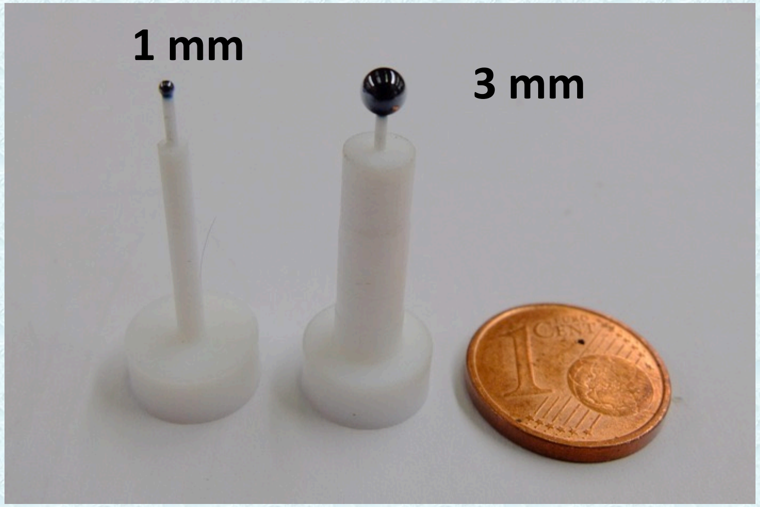
**OUR CHOICE**

- Spin density 2 x $10^{28}$ / $m^3$
- Ferromagnetic linewidth ($=1/2\pi\tau_2$) of about 150 kHz ($\tau_2 \sim \mu s$)
- Total volume about 100 $cm^3$

**YIG – Yttrium Iron Garnet** is a ferrimagnetic synthetic garnet with chemical composition $\mathbf{Y_3Fe_5O_{12}}$,
It was developed for rf applications (rf filters, synthesizers) for its sharp FMR resonance

Its **ferromagnetic linewidth** depends on temperature, **sample purity** and **geometry** (highly polished spheres to avoid demagnetization effects)

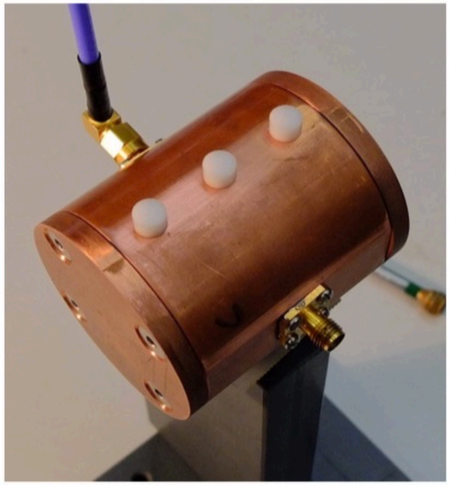
| **YIG** (room Temperature parameters) | |
|---|---|
| Spin density | 2.1 x $10^{28}$ [1/$m^3$] |
| M0 | 1.4 $10^5$ A/m |
| $\tau_1 = \tau_2$ | 0.15 $\mu s$ |
| Linewidth | ~ 1 MHz |
| Commercial Sizes | Spheres < 3 mm diameter |

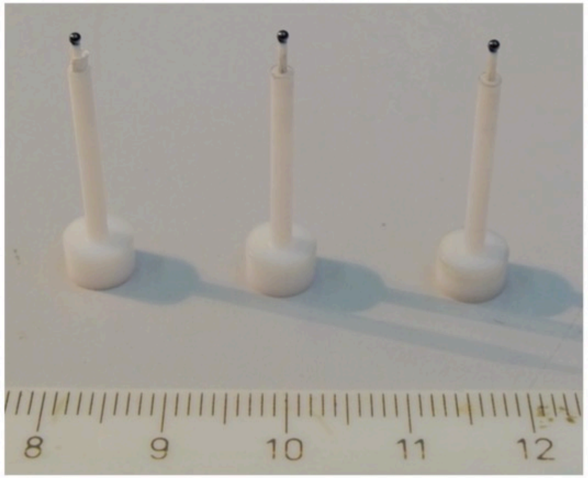


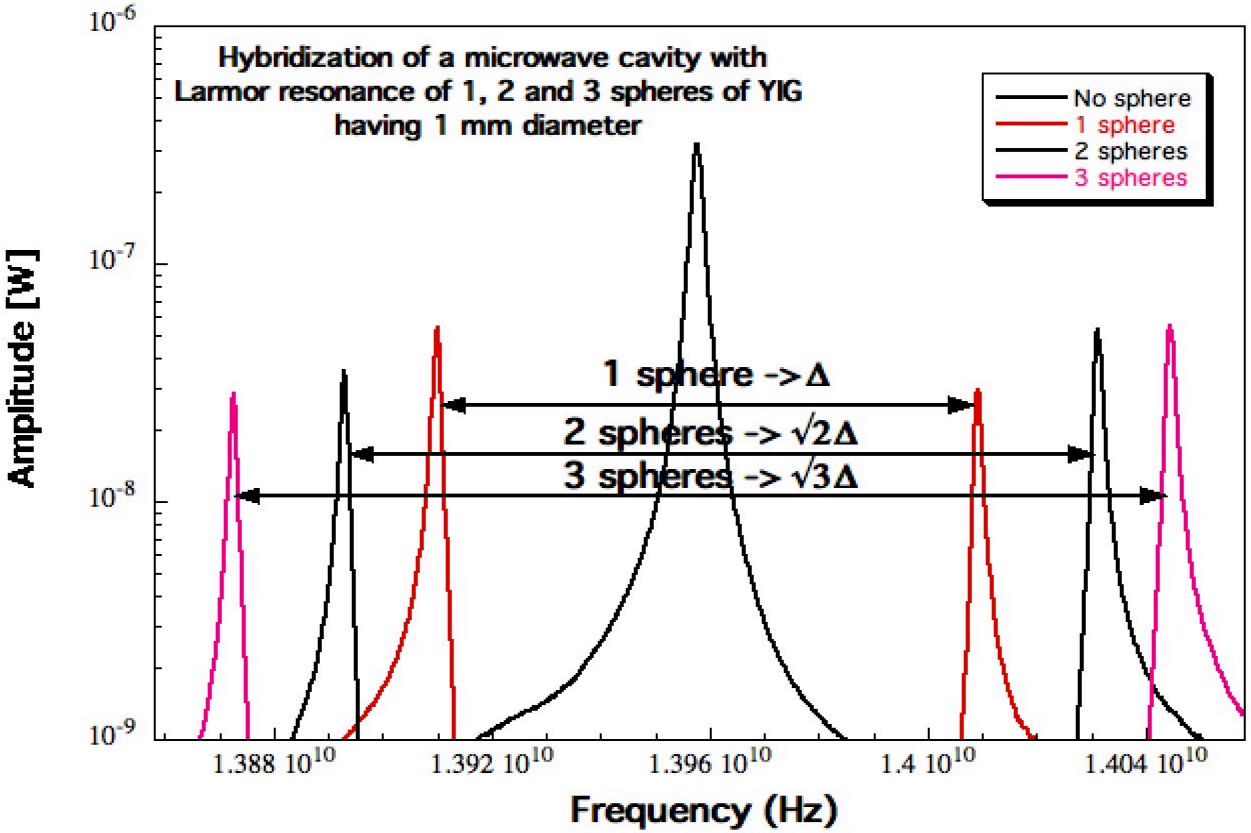
# Magnetic material: volume issue

**A possible idea to have enough volume is to have several YIG spheres**

**Test with 3 identical spheres in a cavity**






**The wavelength** for this frequency is **21.4 mm**, the YIG spheres are placed in the middle and 8 mm from the end faces, so the **separation between the outermost spheres is 34 mm**. The cavity is placed inside a homogeneous static magnetic field parallel to the cavity main axis.

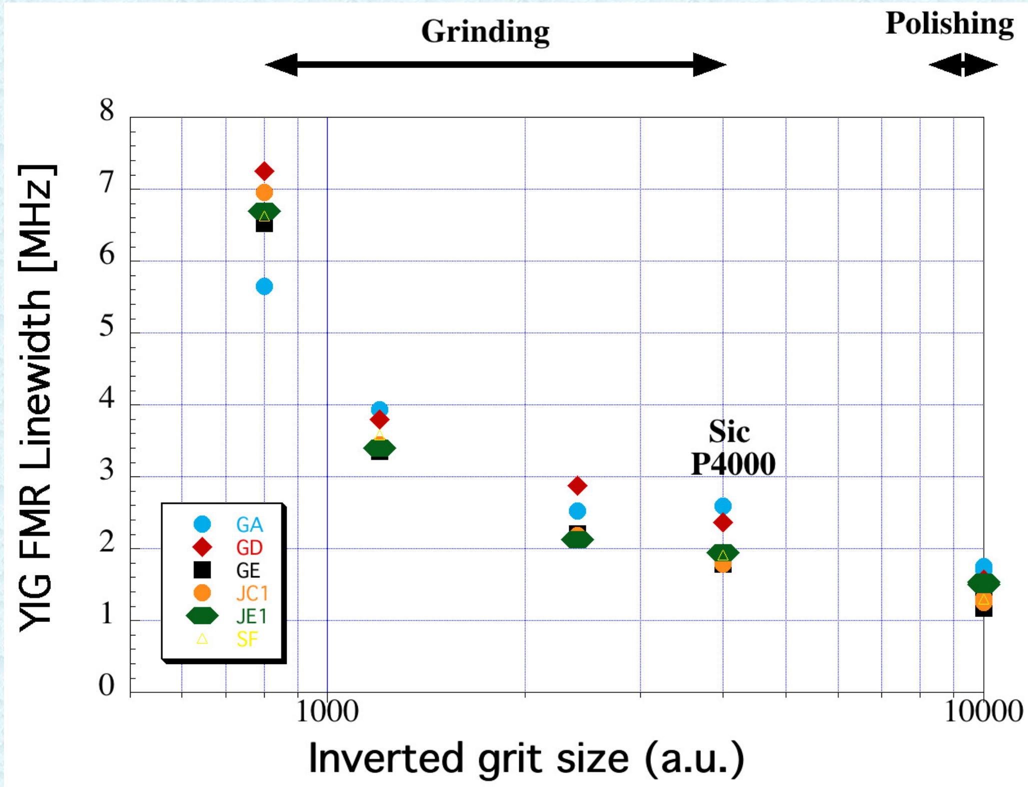
- **No effect on the linewidth**
- **All the spins behaves coherently**

# YIG Spheres Production In House

- Linewidth temperature dependence removed when using high purity samples
  - rare earth content below **1 ppm**
- **Extremely long delivery time w/out guaranteed results**

We have successfully developed a **production procedure for high quality YIG sphere**:

- High purity **YIG single crystals of $cm^3$ size** from several manufacturers
- Large crystal **cut into cubes** of 2.5 mm sides
- **Grinding into 2 mm diameter spheres** using SiC abrasive paper of different grit size
- **Polishing** with Alumina based suspension

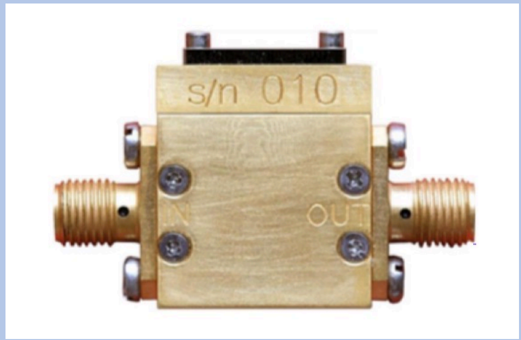



Grinding machine for 6 spheres

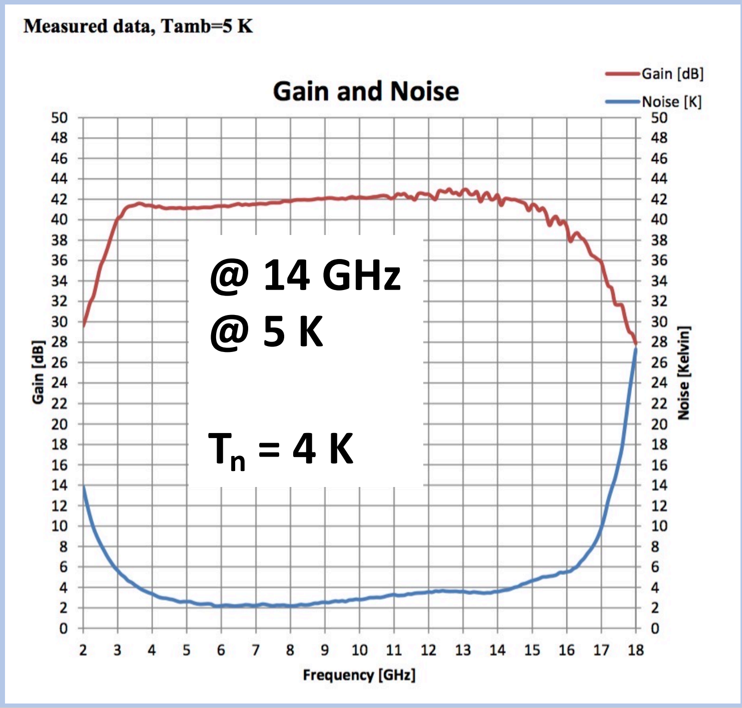
# Microwave receiver

- The request for the final apparatus is to use a **microwave quantum counter**. Worldwide researches are under way in this direction outside our collaboration. We hope we can profit of this, in the meantime we are investigating the various possibilities.

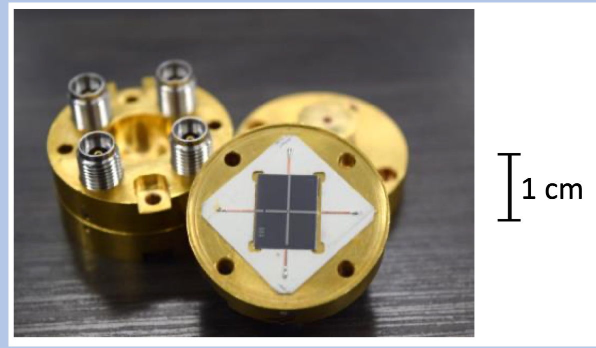
**HEMT**
**High Electron**
**Mobility**
**Transistor**




**Wide bandwidth**

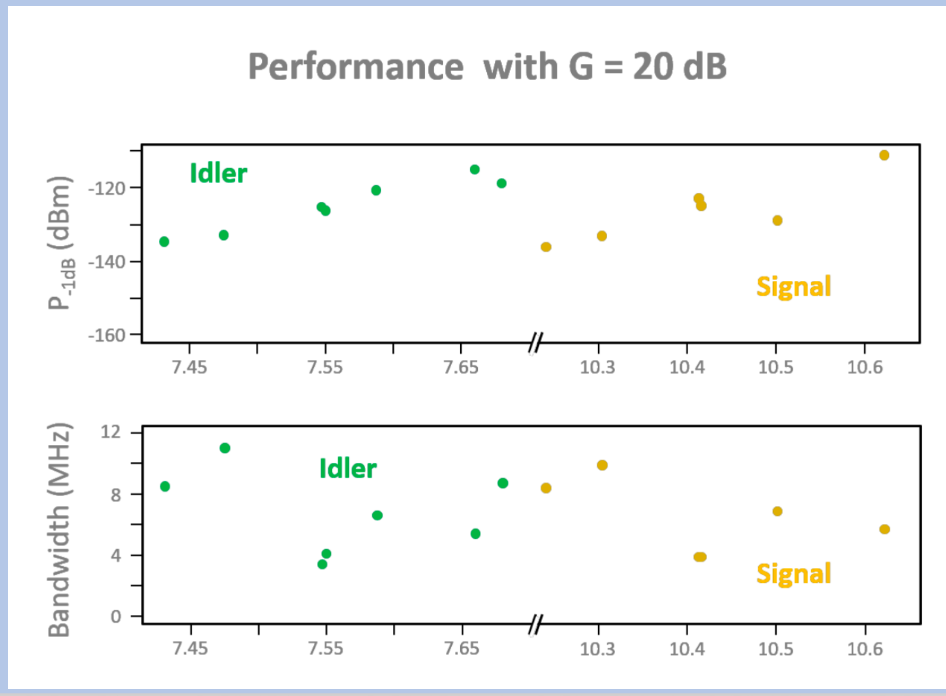



**Josephson**
**Parametric**
**Converter**



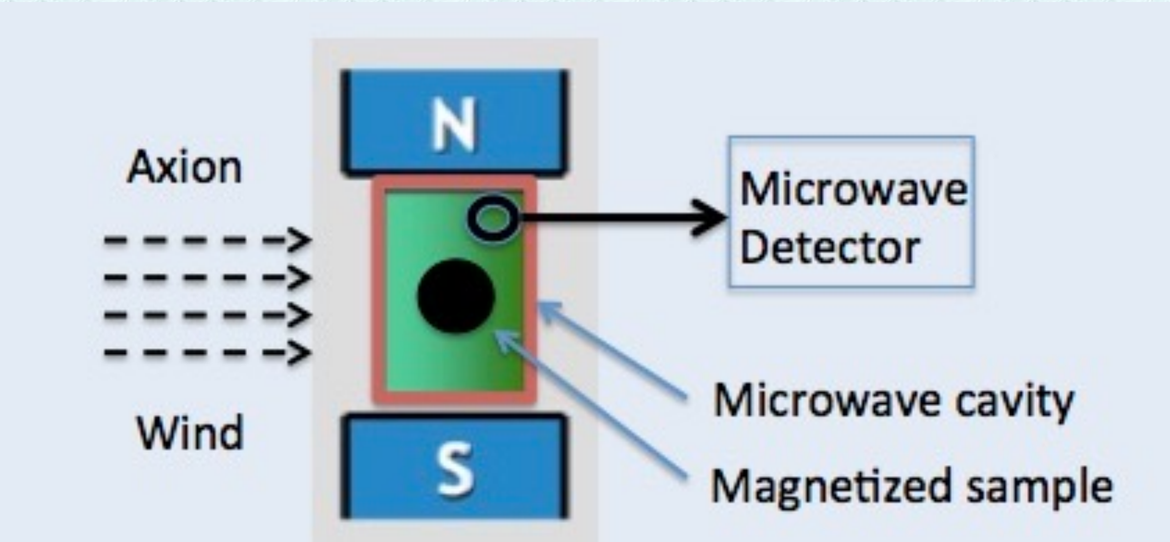

**Quantum**
**Limited**
**$T_n$ = 0.5 K**

**Resonant system**



# 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

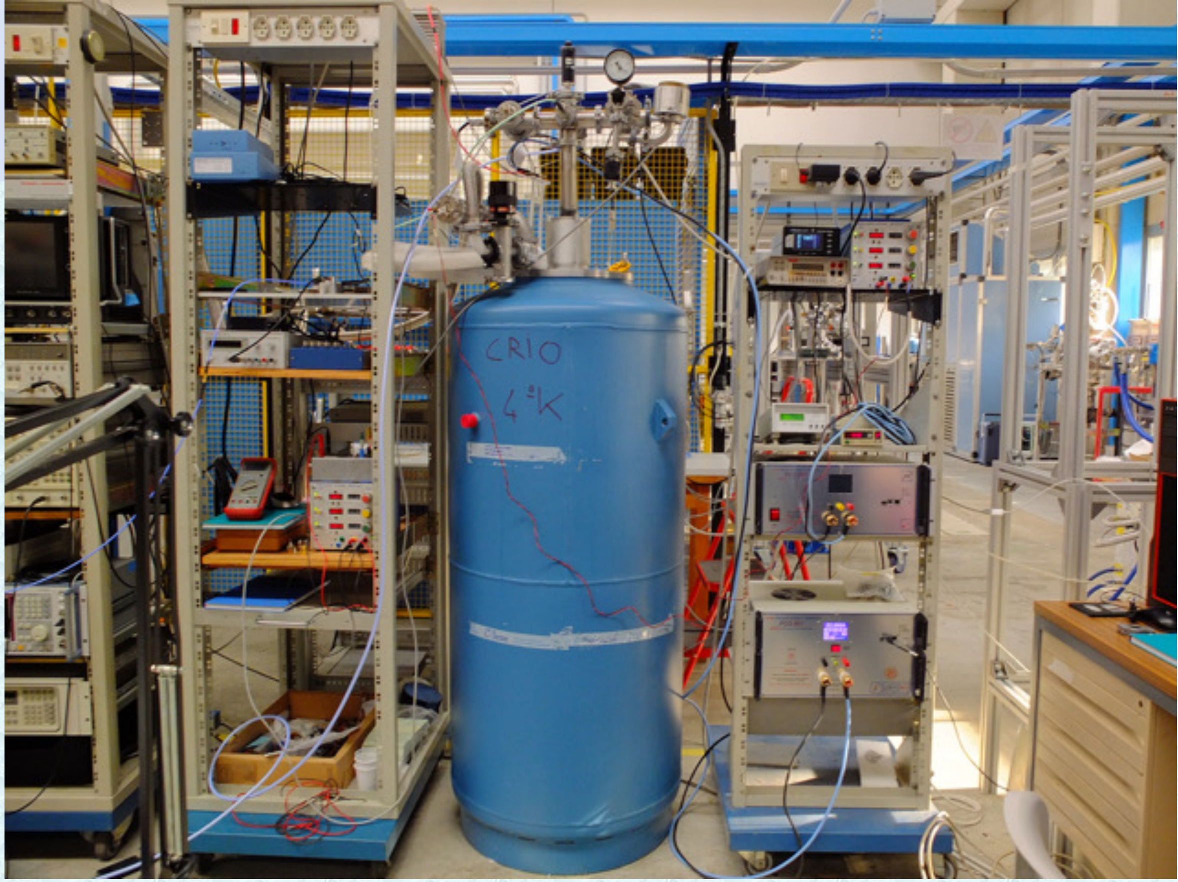
Expected RF power

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

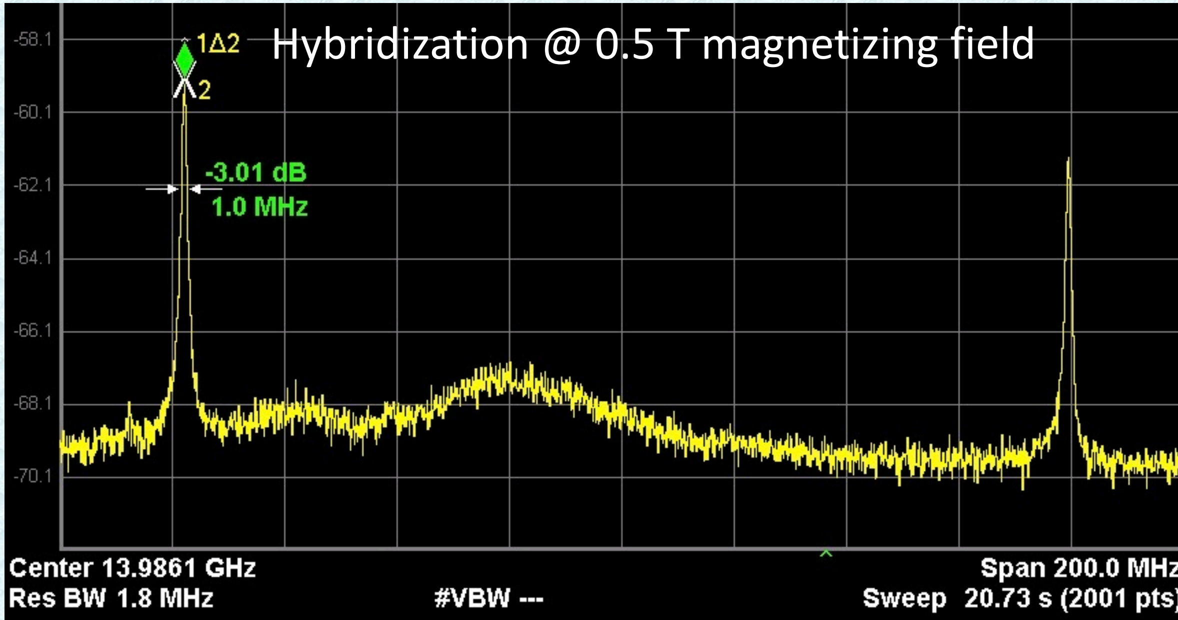
Large **volume *V*** material; high **spin density $\boldsymbol{n}_s$**; long **coherence time $\boldsymbol{t}_{\mathbf{min}}$**

# QUAX 1st prototype set-up

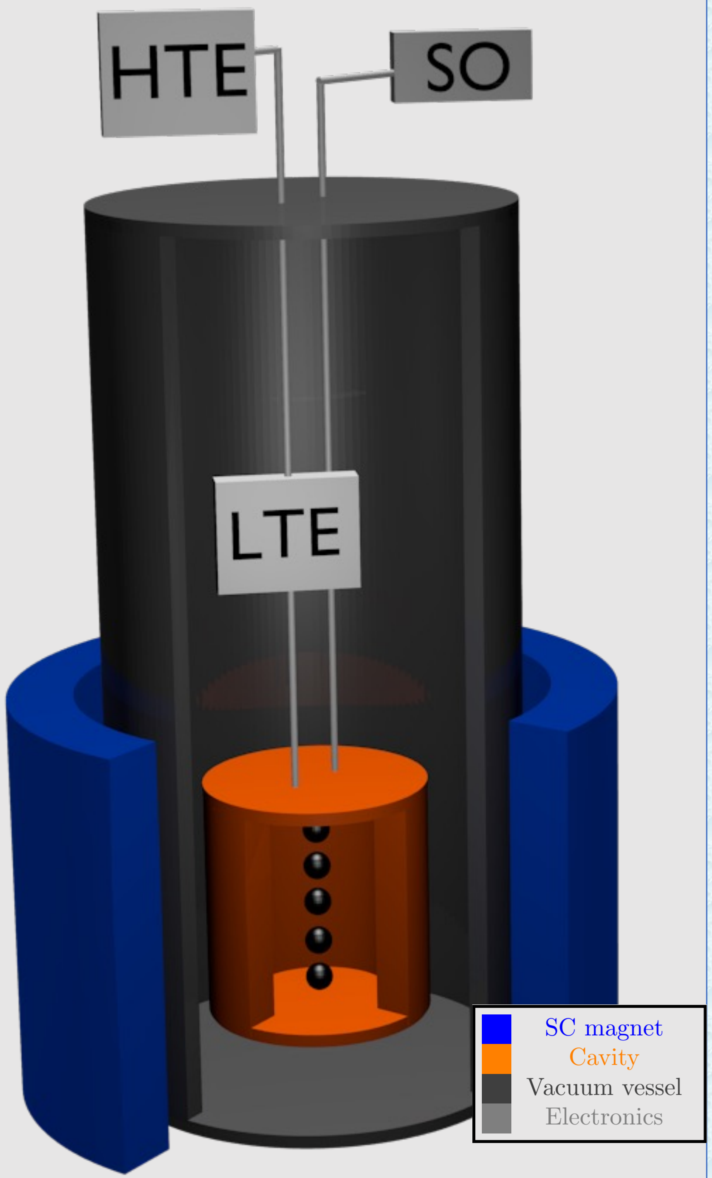
- Cylindrical copper cavity $\nu_c = 14$ GHz (26 mm diameter, 50 mm length)
- 5 commercial spheres of GaYIG – 1 mm diameter – spin density $2.1 \times 10^{28}$ 1/m$^3$ (measured from coupling/mode separation)
- HEMT amplifier – system noise temperature 9K
- LHe operation (4 K)
- High-precision and stability current generator (up to 20 A ± 0.3 mA)
- Highly uniform magnetic field (tens of ppm) with superconducting magnet (0.5 T field with 12.5 A)
- Fast ADC for data taking (2 Ms/s) – 16 bit




System transmission spectrum



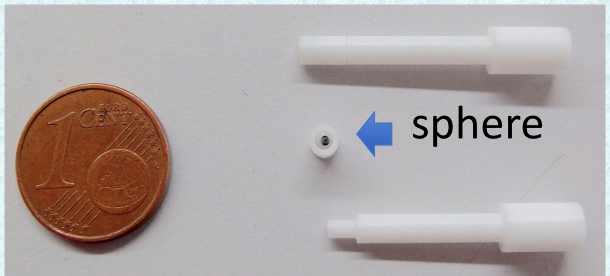
# First prototype of QUAX - 2018




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

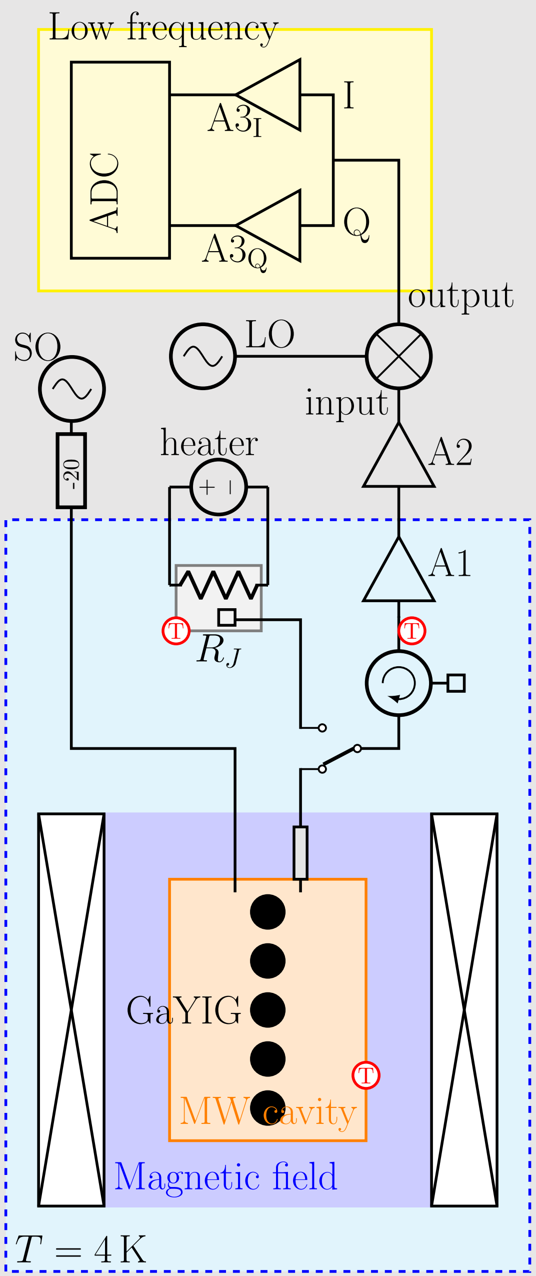
Resonant cavity with 5 GaYIG spheres inside

GaYIG holders




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

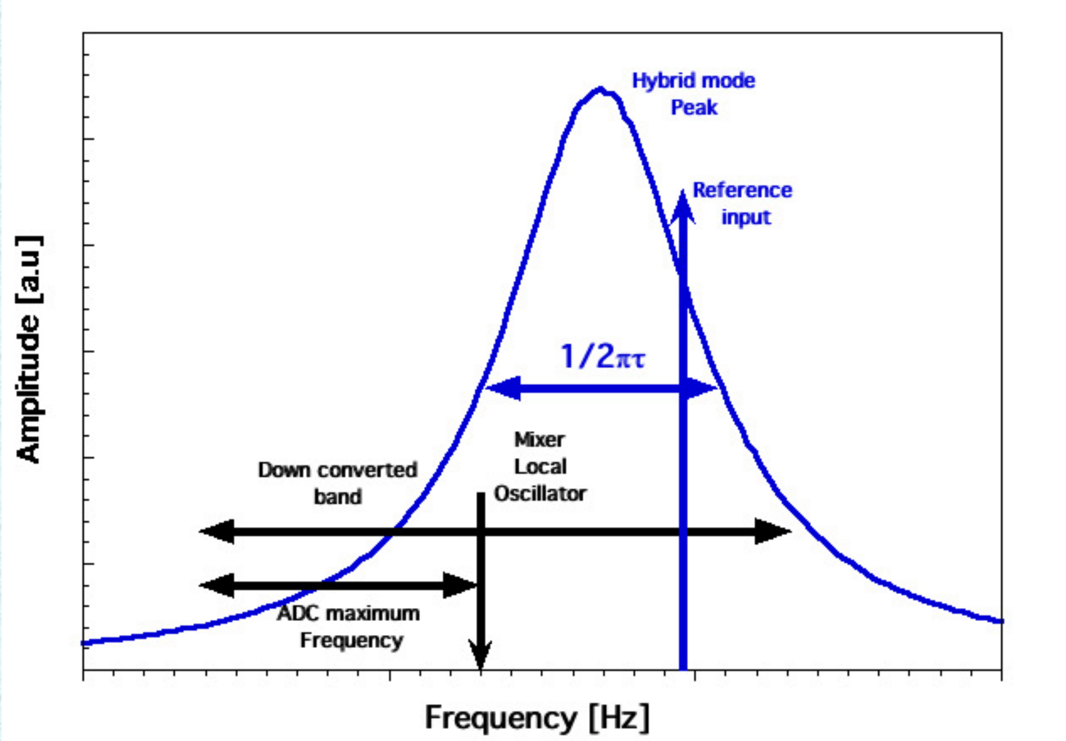
Detection chain



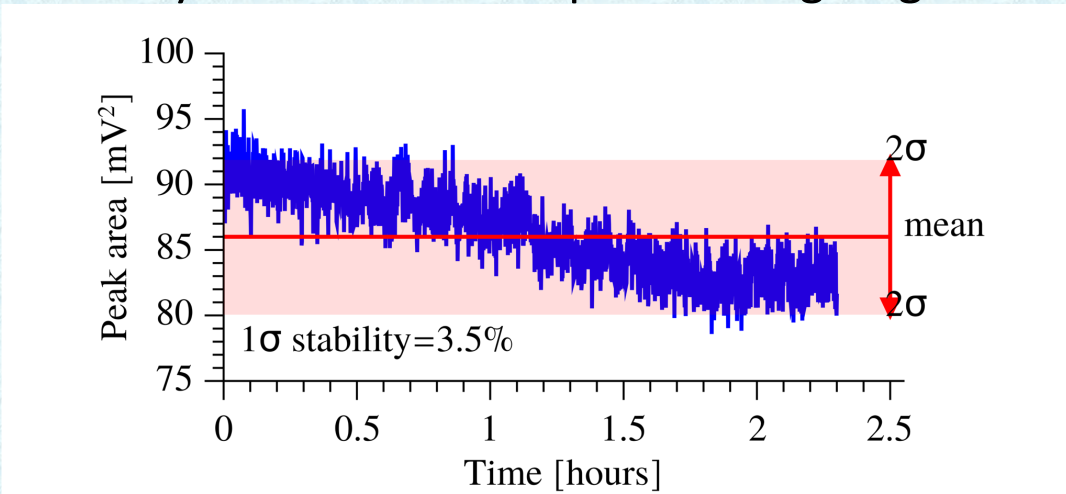
# First protype: measurements

- Several 2-3 hours runs performed in 'axion search mode'
- System **noise temperature $T_n$** and **gain G** measured for each run
- Hybrid cavity transmission measured to obtain mode resonance frequency $f_{h+}$ and characteristic time $\tau_{h+}$
- Reference signal input inserted @ about $f_h$
- Down converted data (I and Q channel), with mixer frequency set to $f_h - 0.5$ MHz, acquired with fast ADC
- Data record 5 s long stored for off line analysis

Signal down conversion scheme

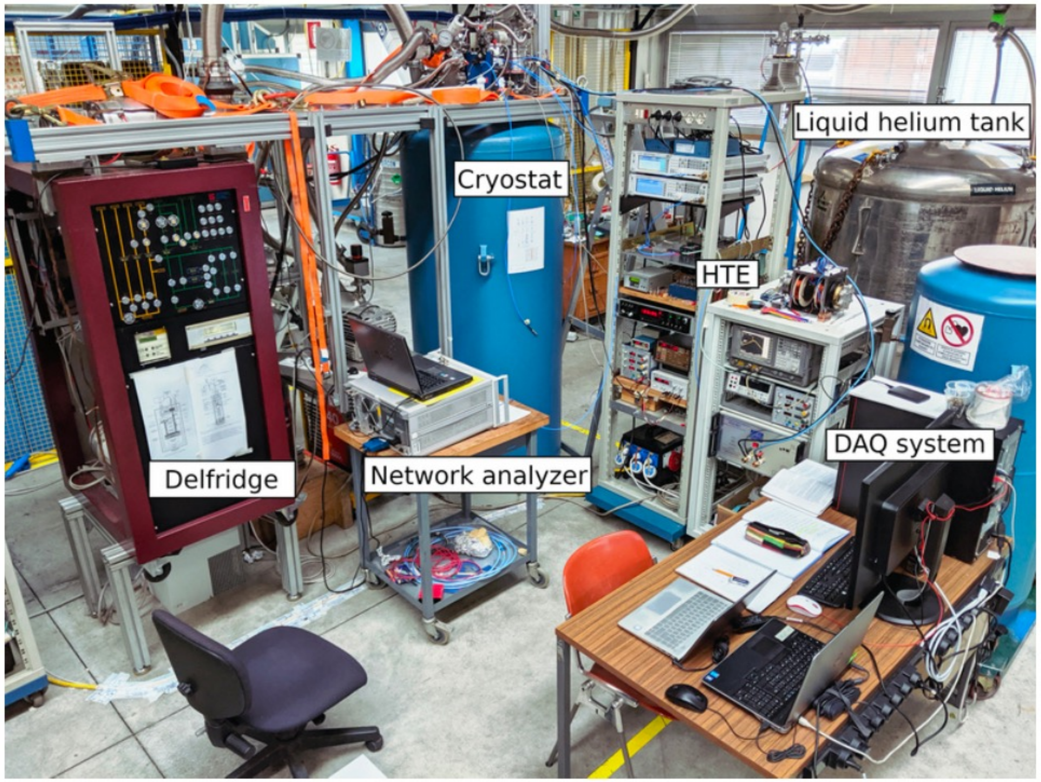


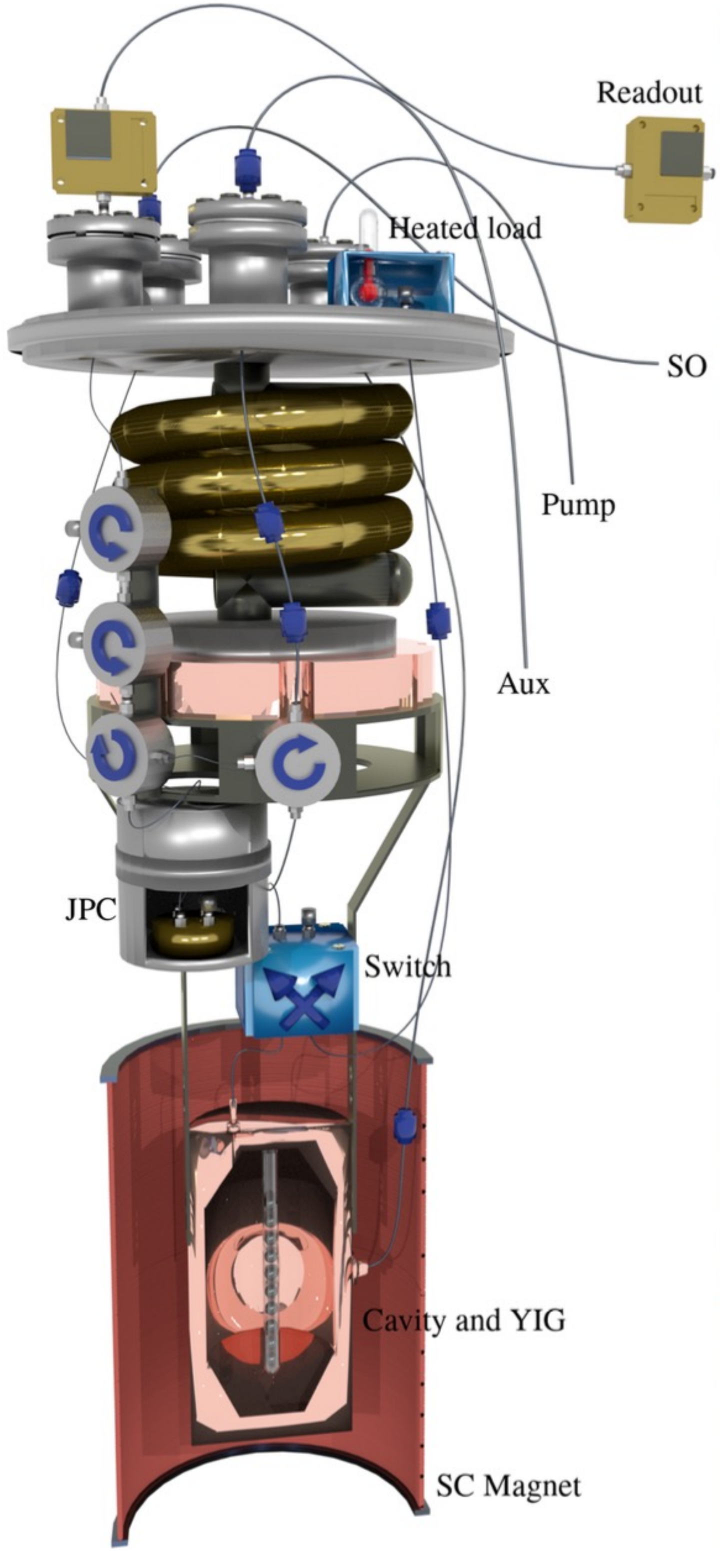

Stability of the reference peak during single run



# Ferrimagnetic QUAX 2020

- **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



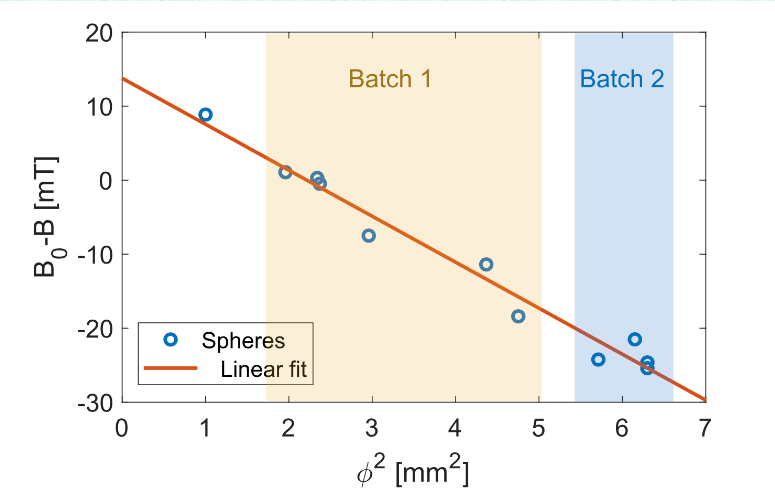

# Multi sphere system

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

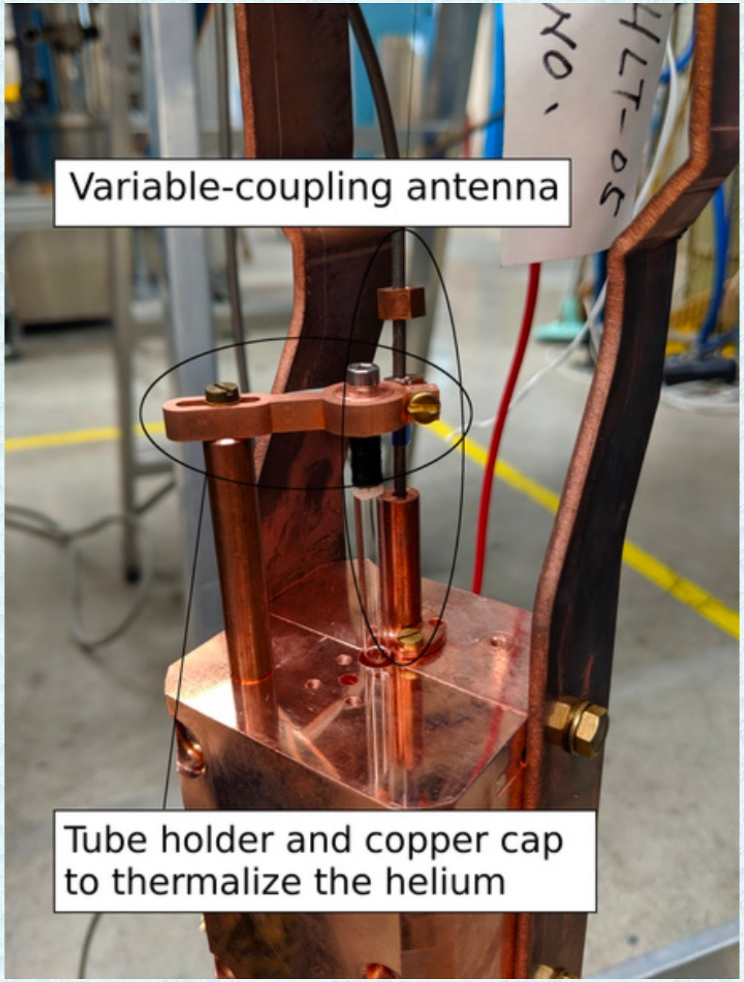
YIG spheres were produced with diameter ~ 2.1 mm, maximum value to avoid non linear effects with rf coupling

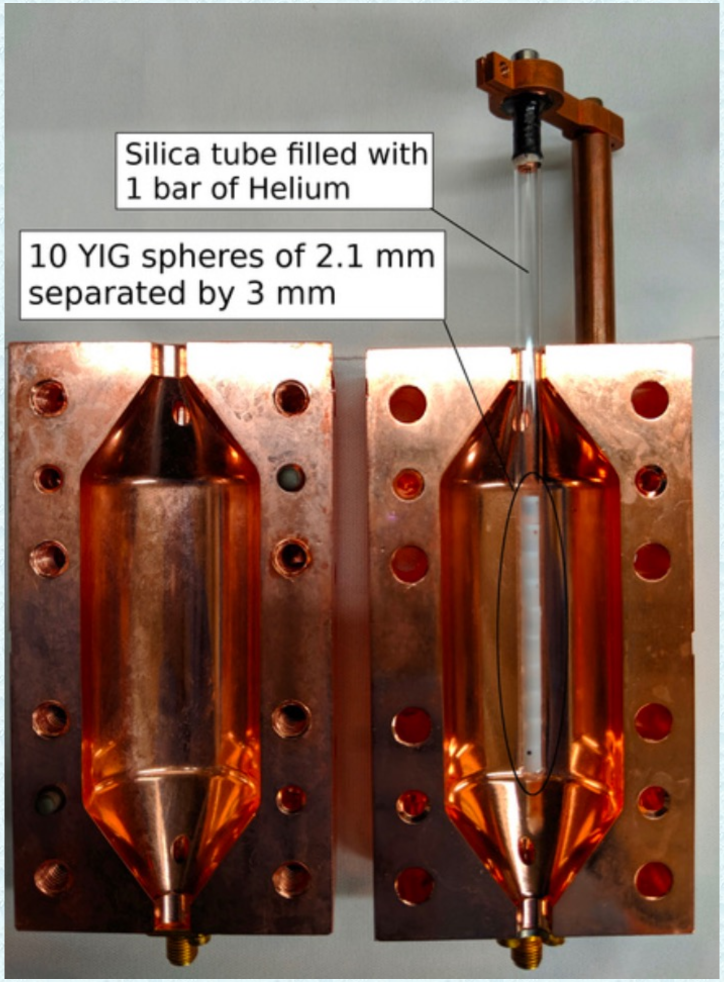
Ten good spheres were selected out of about 20

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




Magnetizing field for a given frequency vs sphere diameter

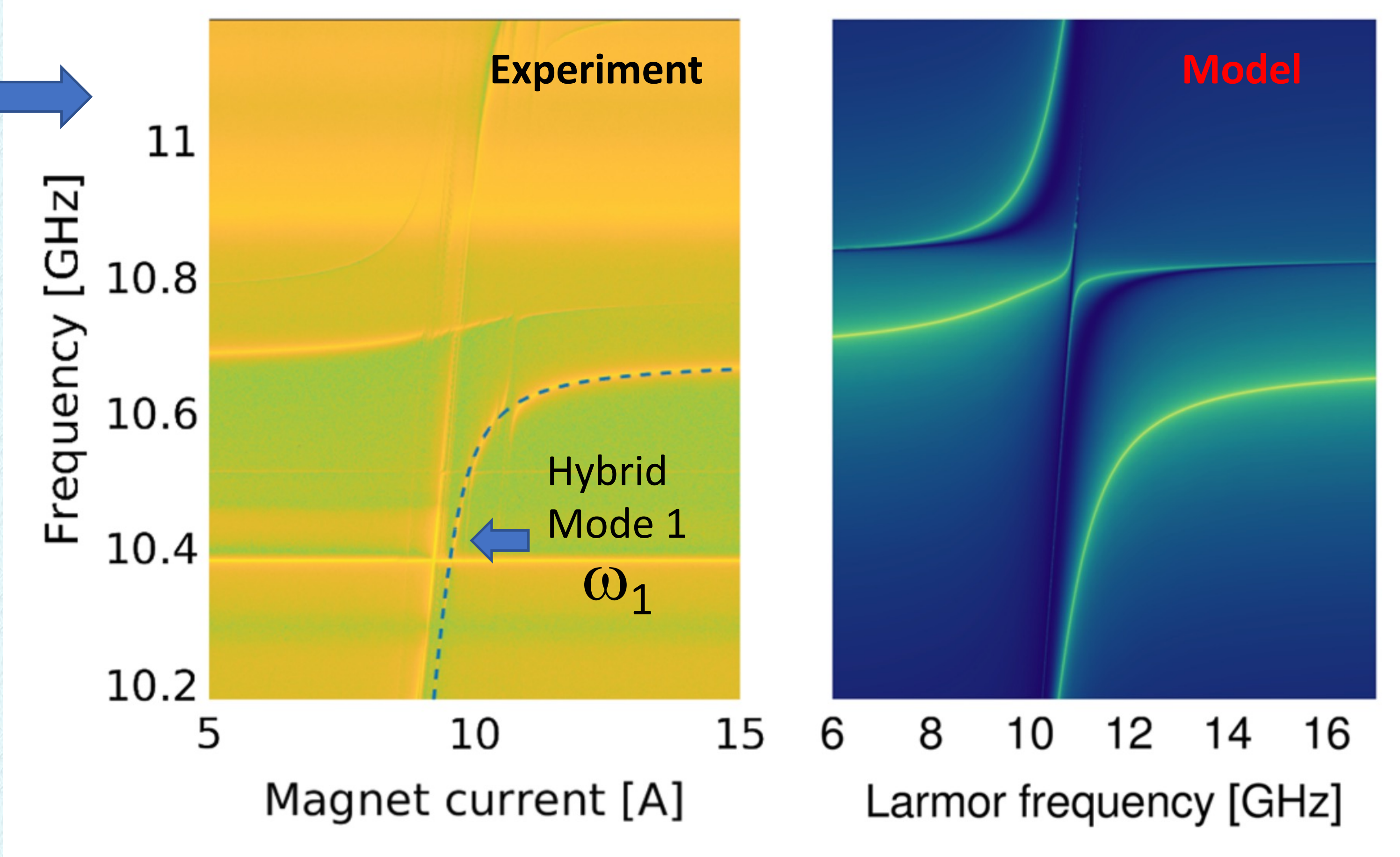



All the sphere must couple coherently to the cavity resonance

# Modelling the system - tuning

Resulting hybrid system (HS) has been studied by collecting a magnetic field $\mathbf{B_0}$ vs frequency transmission plot




Normal two oscillators description unsuitable due to large coupling, different spheres and nearby cavity modes

A model employing **two cavity modes** and **two magnetic modes** appropriately describes the system

**Linewidths**, **frequencies**, and **couplings** of the modes from fit.

**Measured number of spin = 1.0 $10^{21}$**

**10 x single sphere -> coherence**

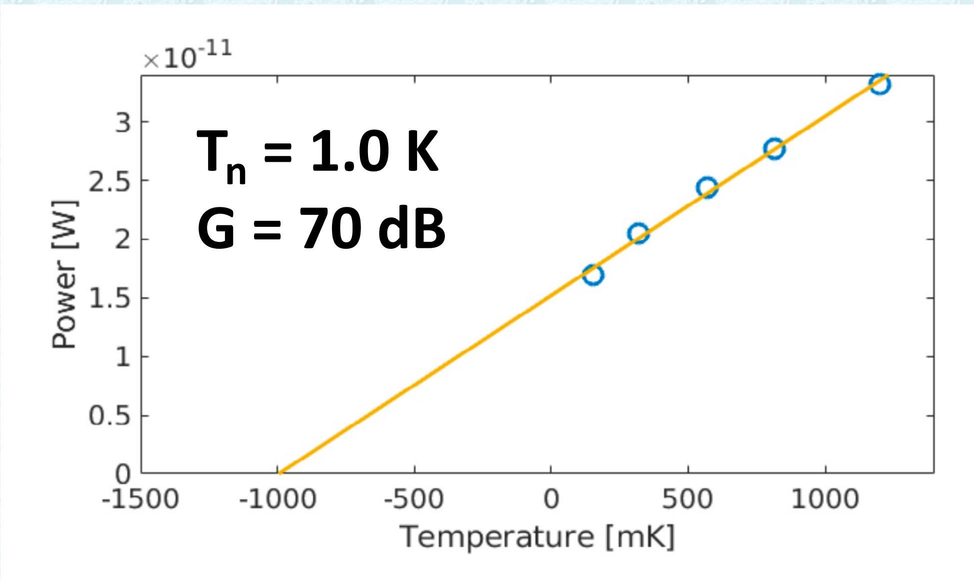
**Material relax time = 84 ns**

**Tuning**

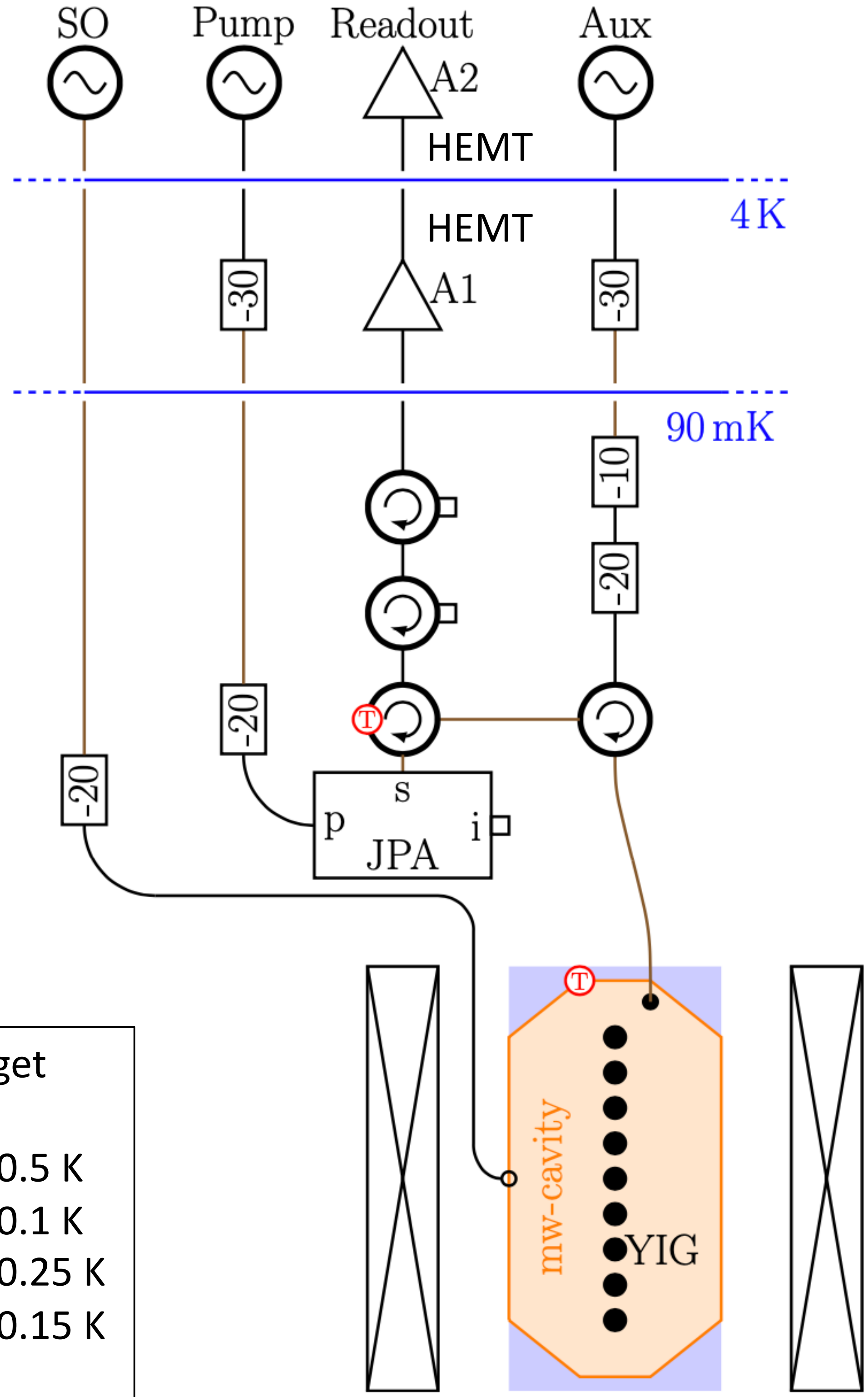
- Hybrid mode $\omega_1$ is not altered by other modes → use it to search for axion-induced signals
- For a fixed $\mathbf{B_0}$ the linewidth of the hybrid mode is the haloscope sensitive band
- By changing $\mathbf{B_0}$, we can perform a frequency scan along the dashed line, compatible with first stage amplifier specs

# Detection chain

- four rf lines used to characterize, calibrate, and operate the haloscope
- One variable coupling antenna collects signal from HS
- **Josephson Parametric Converter** as First stage amplifier
- Aux line for calibration purposes
- Transmissivity of all lines is measured
- **Direct measurement of system noise temperature $T_n$ and gain G**




| Noise budget | |
|---|---|
| JPA | 0.5 K |
| Thermal | 0.1 K |
| HEMT | 0.25 K |
| ? | 0.15 K |



# Josephson Parametric Converter

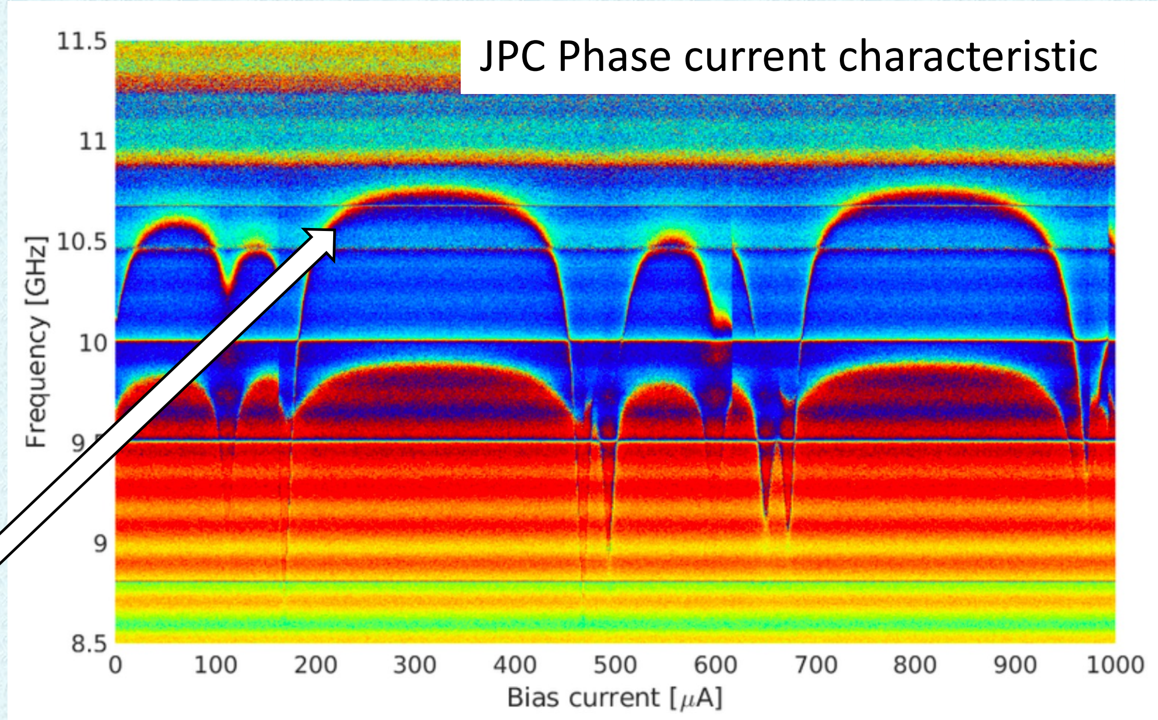
Commercial device

Parametric amplfication is obtained in the so called non degenerate 3 wave mixing

A pump tone at about 18 GHz amplifies signal at about 10.5 GHz and 7.5 GHz

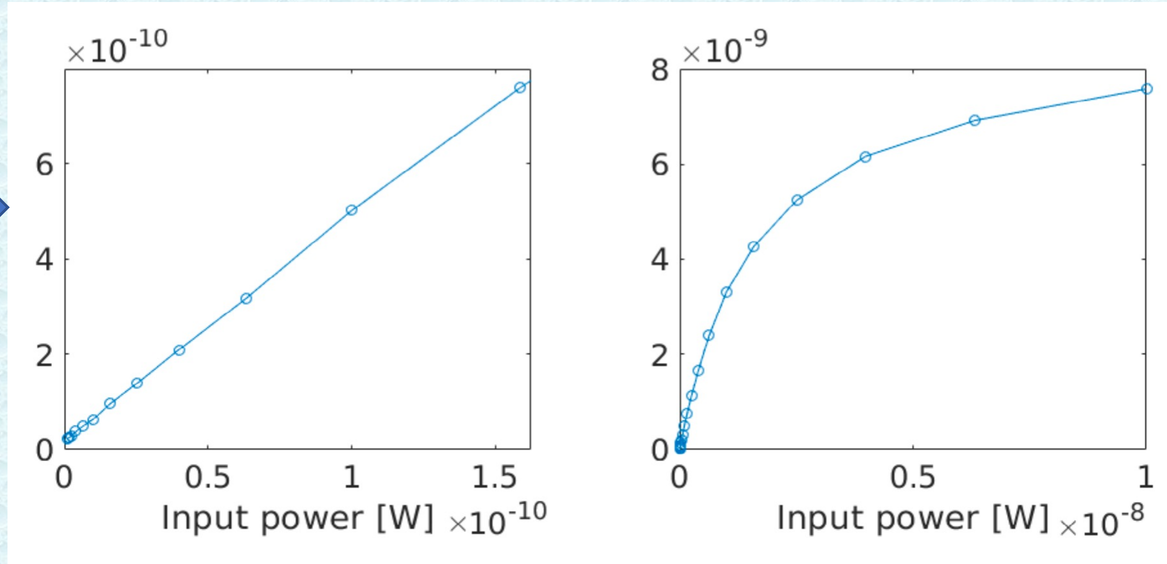
Gain 20 dB over a 10 MHz band

Tuning is done using a bias current on a coil to select correct **phase lobe**




**Magnetic shielding necessary**

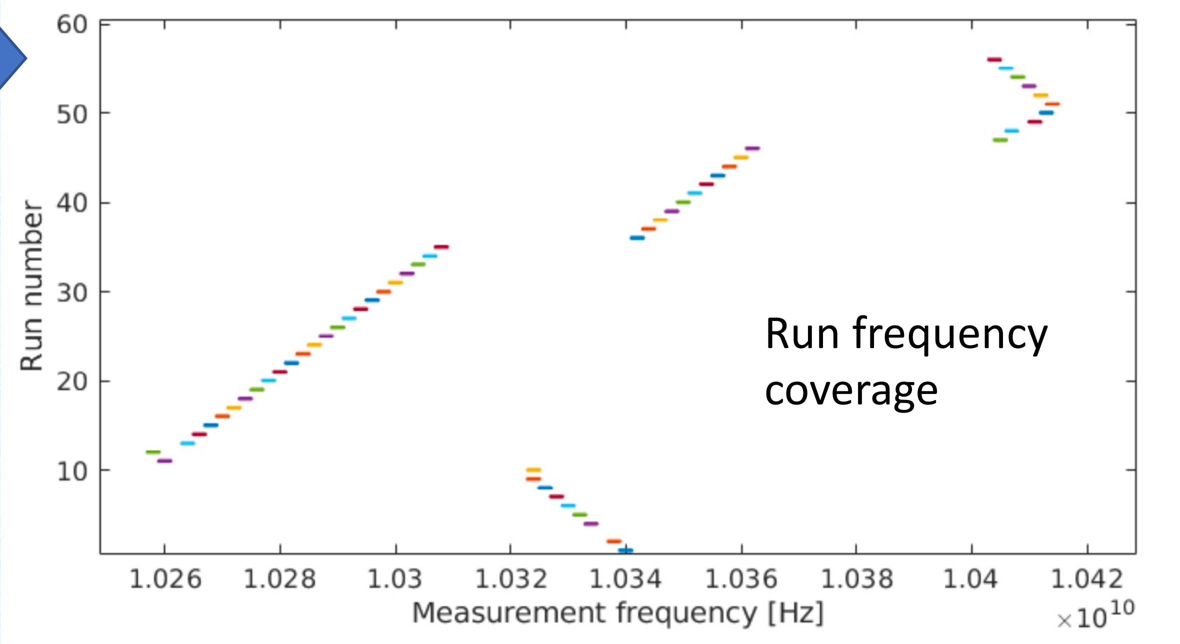
**Tested linearity  and saturation**

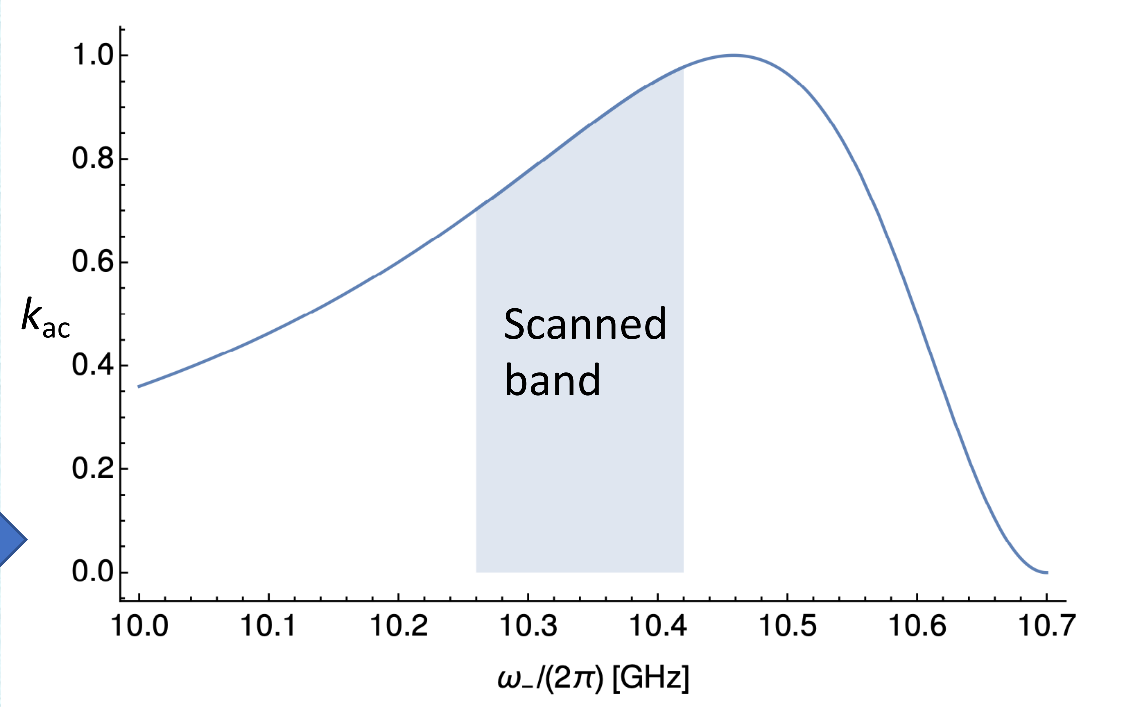



Due to low level saturation not very easy to measure noise temperature ->> added AUX line in set-up

# Axion search

- **56 runs** at fixed $\mathbf{B_0}$ - about 1 h duration
- Total run time 74 h
- For every run **measure system transmission** to:
    - set ω1 by controlling $\mathbf{B_0}$
    - critically couple the antenna
    - measure the mode linewidth
- The Readout (amplified) signal down converted with a heterodyne
- ADC sampled over a 2 MHz band and stored
- Stability of the measurement tested by injecting a signal with large SNR and monitoring its amplitude
- Extremely good field stability due to home made current generator
- **Efficiency loss** due to tuning is moderate and can be obtained by the model

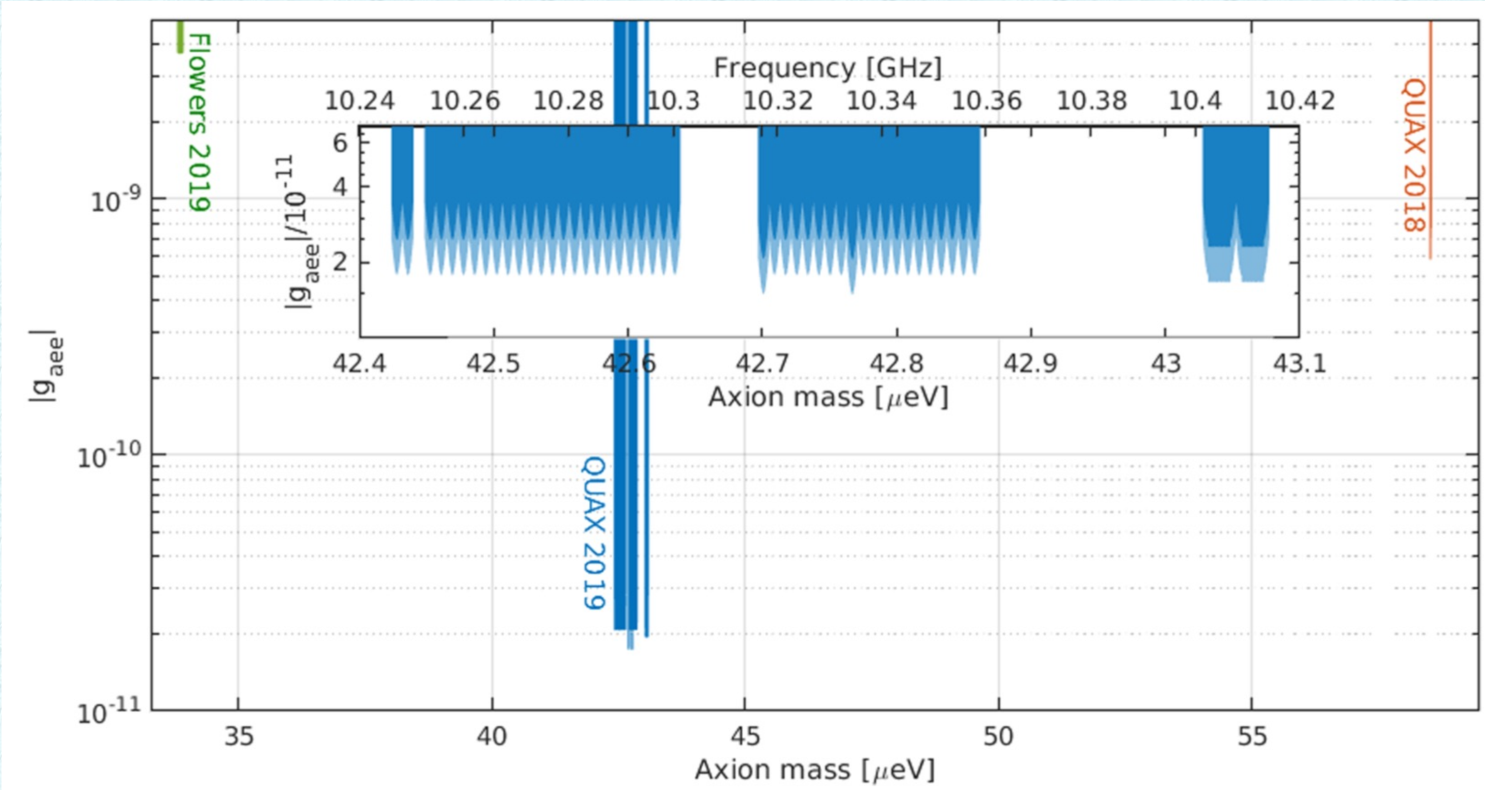


# Results

- FFT the data with a 100 Hz resolution bandwidth to identify and remove biased bins and disturbances
- Rebin the FFTs with a resolution bandwidth **RBW ≃ 5 kHz** to look for axion signal
- Look for fluctuations from thermal spectrum
- **The measured fluctuations $\sigma_P$ compatible with the estimated noise in every run**
- **Assuming DM is 100% made by ALPs ->> 95% CL plot**

$$g_{aee} < \frac{e}{\pi m_a v_a}\sqrt{\frac{k_{ac} \times 2\sigma_P}{2\mu_B \gamma_e n_a N_s \tau_s}}$$

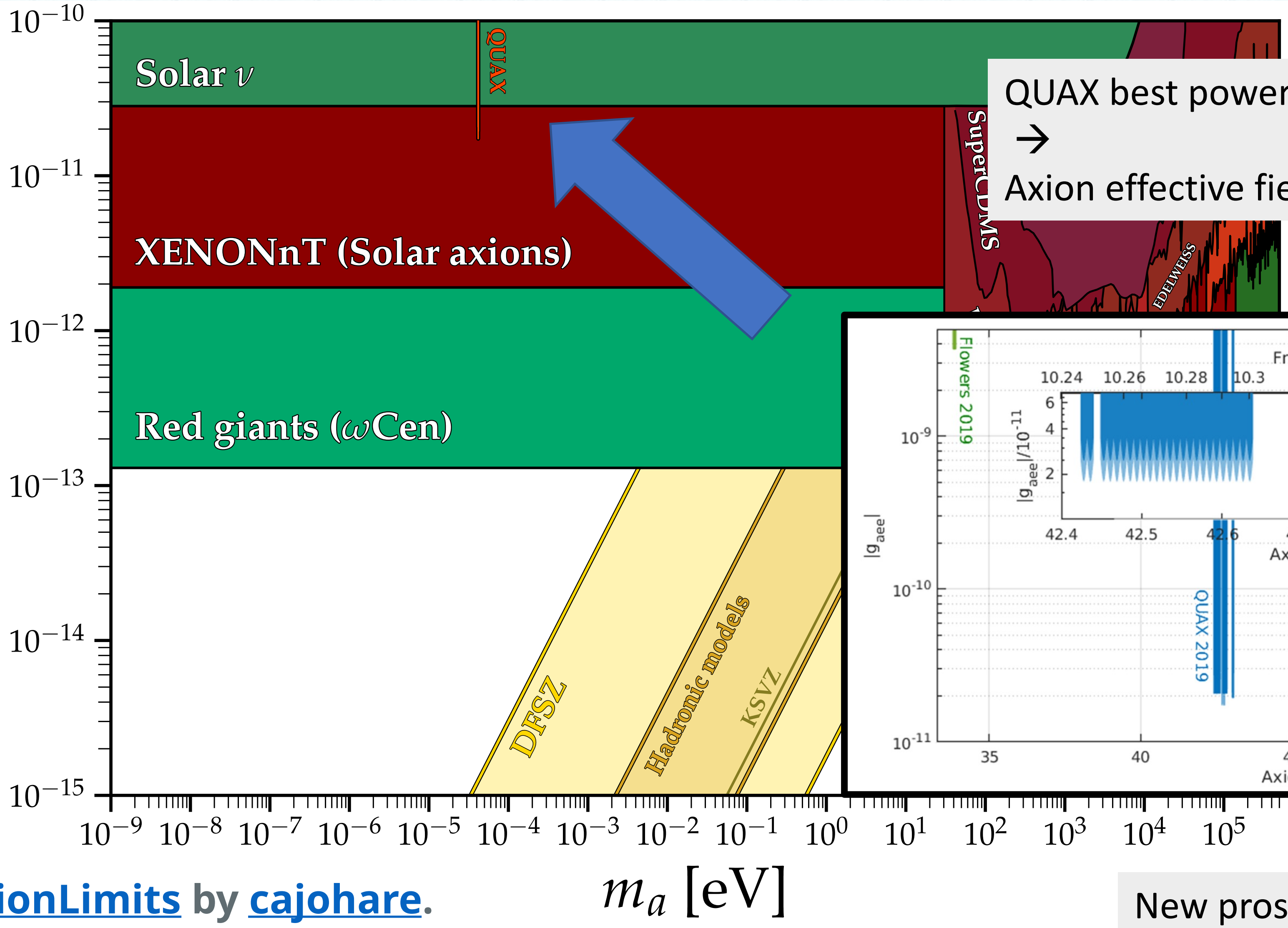



PRL **124**, 171801 (2020)

For the longest run (9 h)

best power sensitivity **$\sigma_P$ = 5.1 $10^{-24}$ W** → Axion effective field **$B_a$ = 5.5 $10^{-19}$ T**

# Axion electron coupling

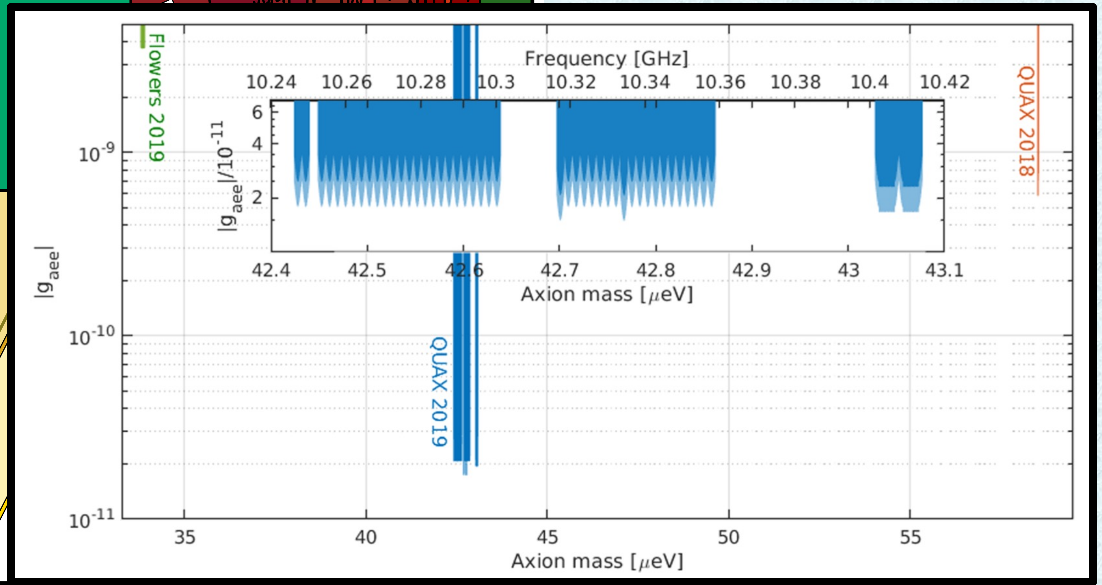



[AxionLimits](#) by [cajohare](#).

QUAX best power sensitivity **$\sigma_P$ = 5.1 $10^{-24}$ W**

→

Axion effective field **$B_a$ = 5.5 $10^{-19}$ T**




PRL **124**, 171801 (2020)

New prospects:
Increase number of spheres
Single photon counter detector

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

# Perspectives

- Larger number of spheres
  - Reach about 50 – 100 spheres in one cavity

- Quantum counter
  - Started a collaboration with experimental group in Paris to implement a quantum counter on QUAX setup

- Increase $\tau_2$ or find other magnetic material

For YIG →

- Current limits on linewidth not known
- Intrinsic linewidth well below 1 MHz

YIG → $Y_3Fe_5O_{12}$

VOLUME 70, NUMBER 10 PHYSICAL REVIEW LETTERS 8 MARCH 1993

**Dissipation by Nuclear Spins in Macroscopic Magnetization Tunneling**

Anupam Garg
*Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208*

**Possibility**: effect due to the presence of Fe57 (1/2-), about 2% of isotopic abundance

kept small by having a small value of $\mu$. [This might be achieved, e.g., if the magnetic ion was Fe. The natural abundance of $^{57}$Fe is 2.25%, effectively reducing $N$ in Eq. (17) by a factor of 50.]

**Cure**: produce a YIG sample containing enriched isotopes (0+) of Fe

# Thank you