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Recent results and future perspective in the search for Axion dark matter at LNF

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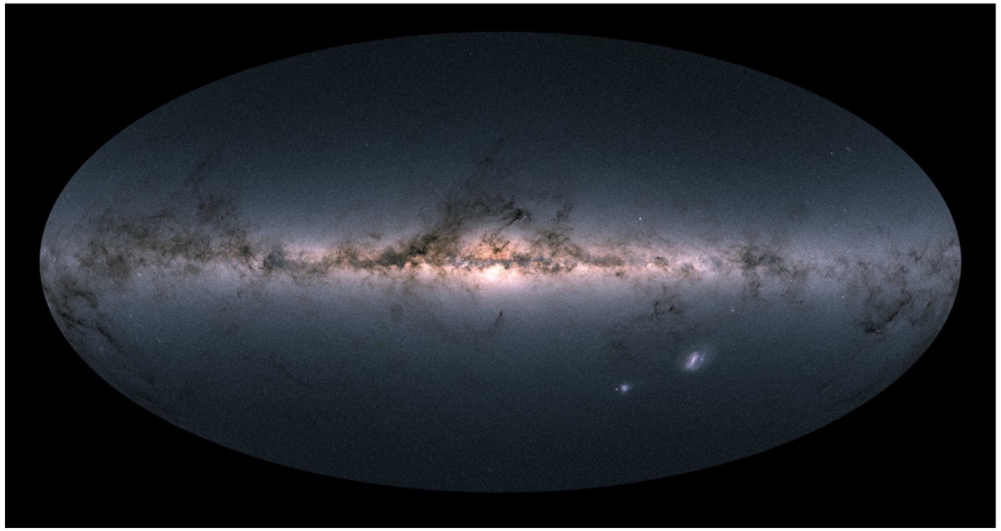
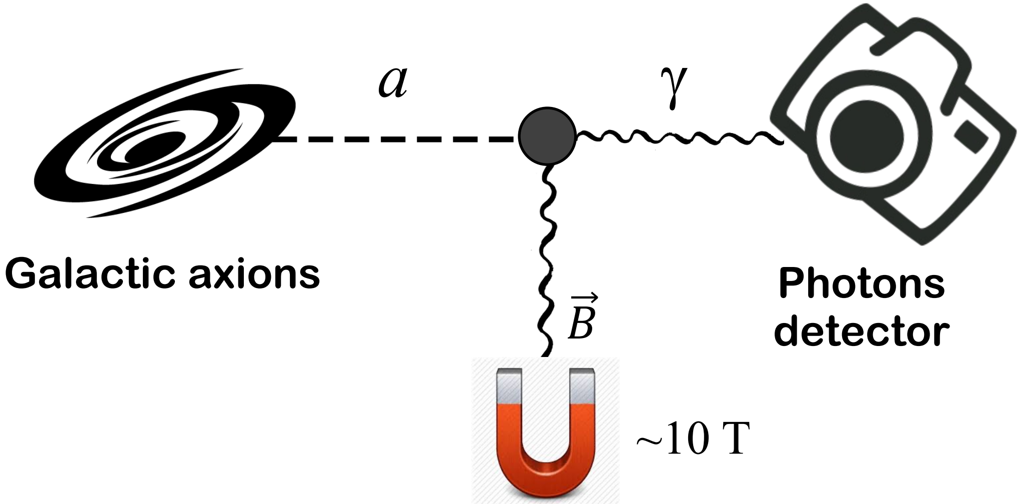
Axions as dark matter

Hypotetical particles introduced to overcome the strong CP problem

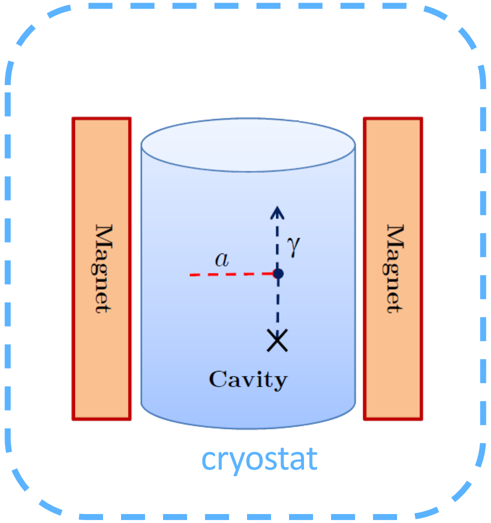
Axions properties such as charge neutrality, spin 0, small mass and negligible interaction with the ordinary matter make them an ideal candidate for dark matter

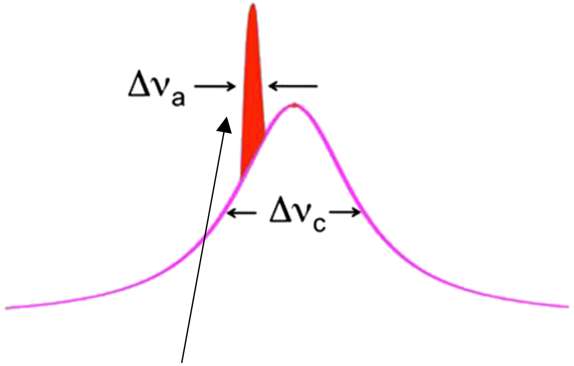




Axions as dark matter

Haloscope





Localized power excess ~10^{-23} W
@ 10 GHz

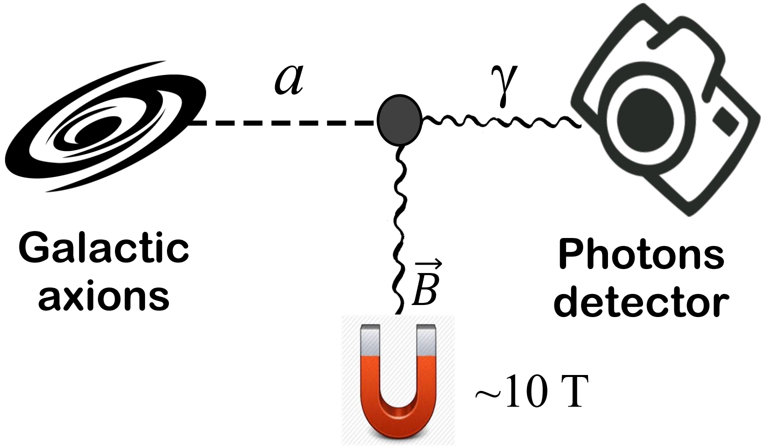
$$P_a = \left(\frac{g^2_{a\gamma\gamma}}{m_a^2}\hbar^3 c^3 \rho_a\right)\left(\frac{\beta}{1+\beta}\omega_c\frac{1}{\mu_0}B_0^2 V C_{030} Q_L\right)\left(\frac{1}{1+(2Q_L\,\Delta_\omega/\omega_c)^2}\right)$$

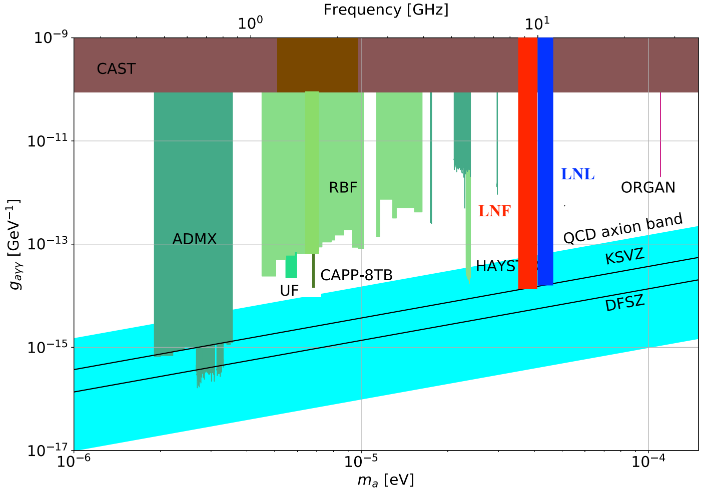
The QUAX experiment is a light DM hunt experiment

- **Classical haloscope (just like ADMX, HAYSTAC etc)**
- **Searching for QCD axions**
- **Between 8 – 10 GHz**

LNL (Legnaro)

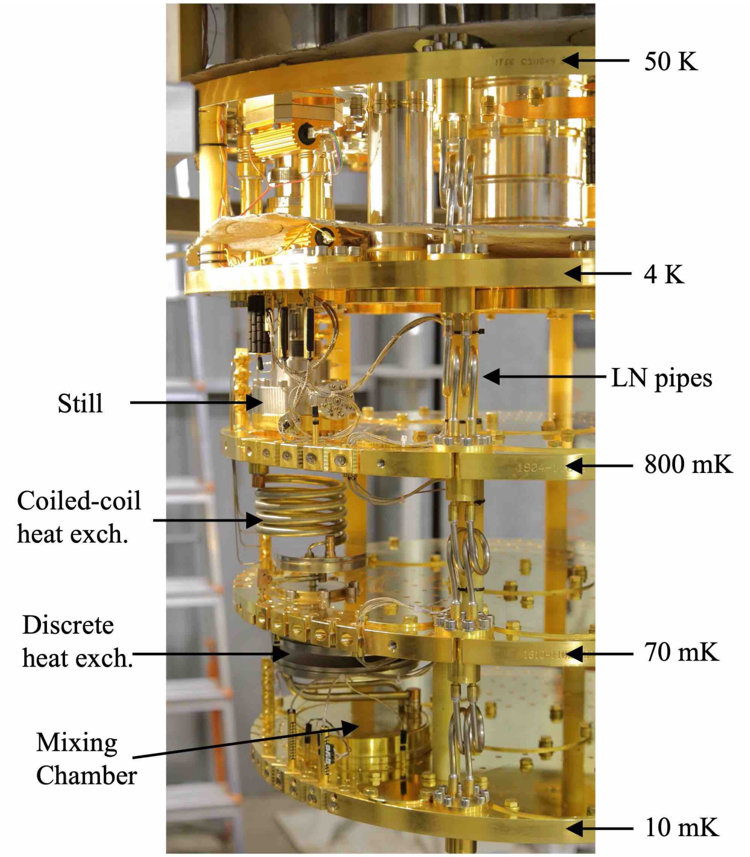
LNF (Frascati)





Courtesy of A. Rettaroli

COLD Laboratory



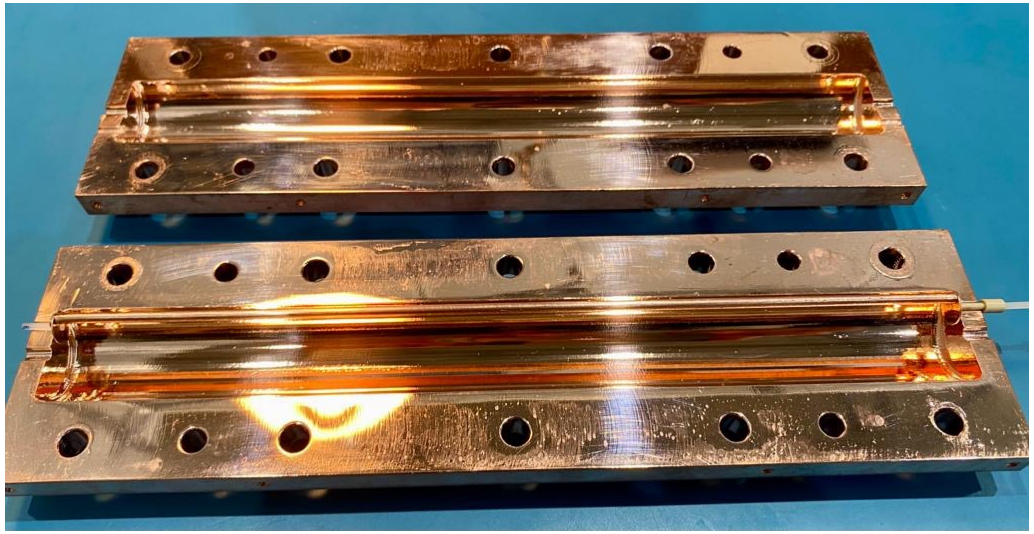
9 T magnet

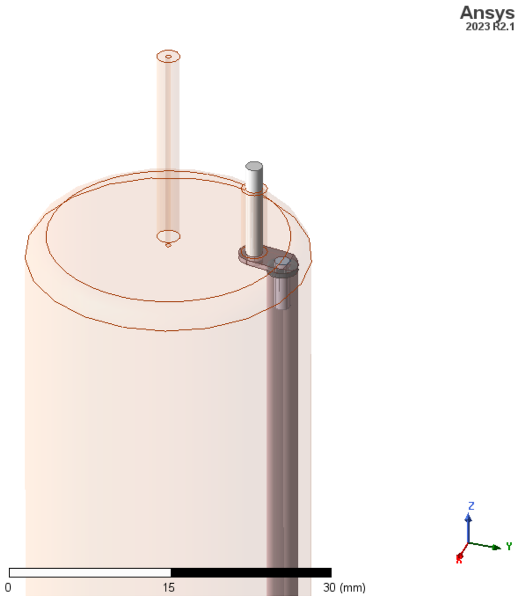
$T_{base} = 8\,mK$

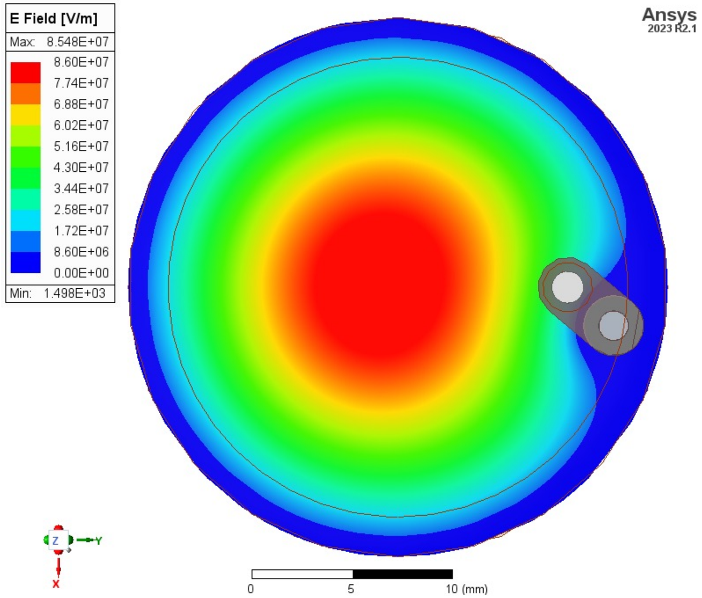
Cooling power:
$500\,\mu W$ @ $100\,mK$

Microwave cavity + tuning

HFSS simulations by Simone Tocci





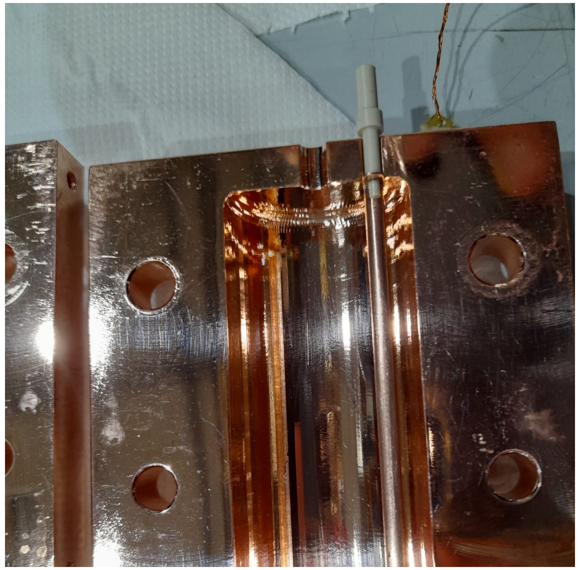


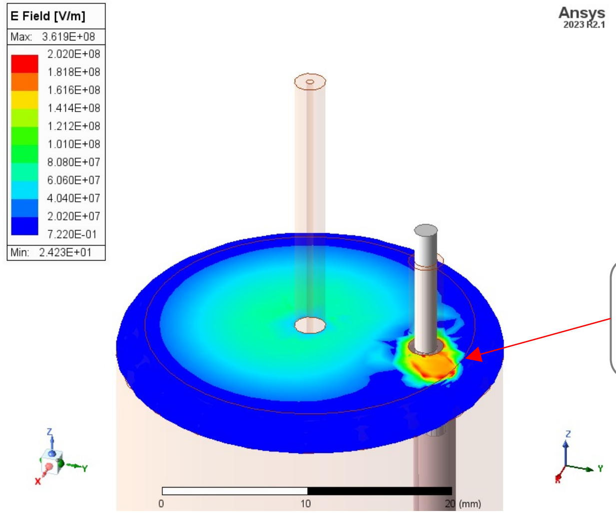
- **OFHC Copper**
- **Radius = 13.5 mm, height = 246 mm**
- **TM_{010} mode**

- **Starting frequency ($\alpha = 0°$): 8.83 GHz**
- **Tuning $\sim$300 MHz with $\Delta\alpha \sim 80°$**

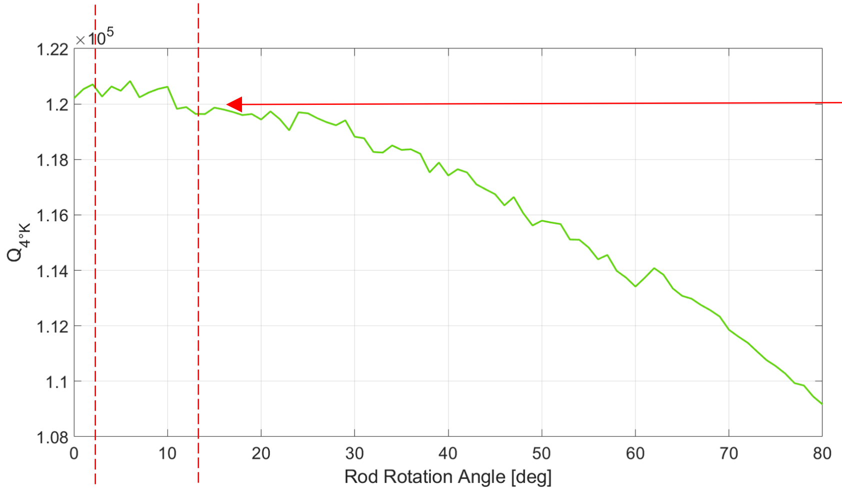
Courtesy of A. Rettaroli

Microwave cavity + tuning





Trapped field between metallic disk and cavity endcap



Expected $Q_0 \simeq 10^5$ from simulations, and measured w/out rod

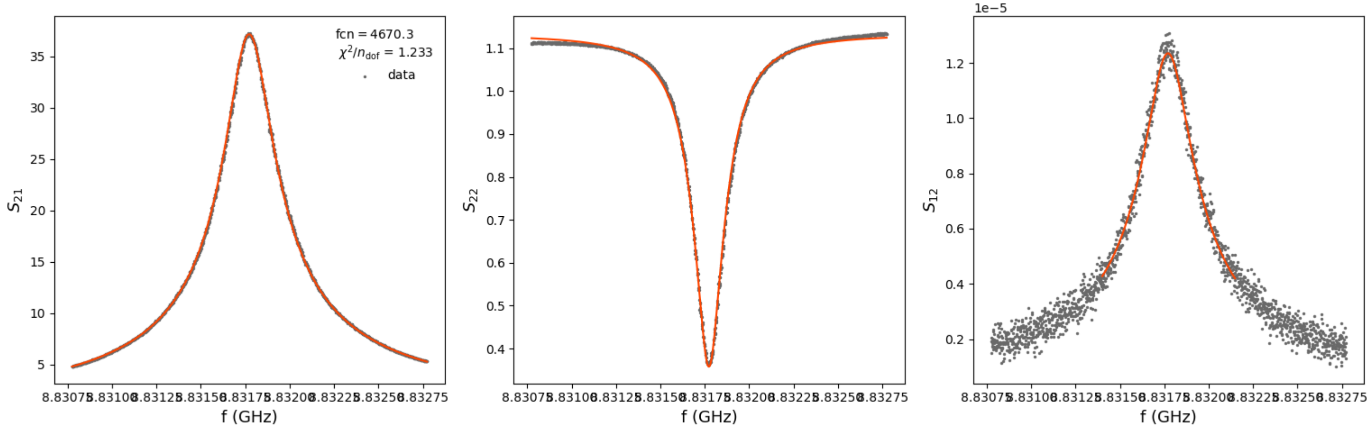
Measured $Q_0 \simeq 5{\times}10^4$ w/ rod

This is likely due to losses caused by the rod configuration and PEEK

Courtesy of A. Rettaroli

Calibration+ power spectrum

Fit procedure

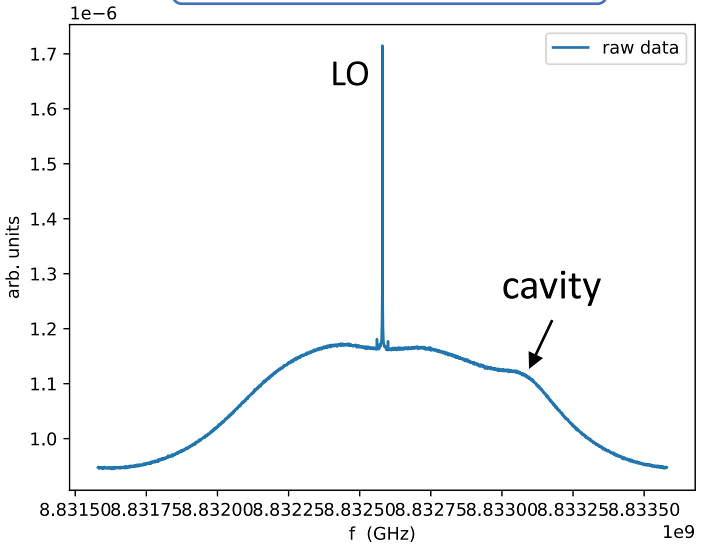


Fits by Gianluca Vidali (Master student)

From fit we extract
$\nu_c, Q_0, \beta, Gain$

- $V = 0.141\ l$
- $f_{start} = 8.83$ GHz
- $m_a = 36.5\ \mu eV$
- $Q_0 = 50000$
- β = 0.5
- C_{010} = 0.667
- $B_0 = 8$ T (B_{av}=6.5 B_0)
- $\Delta t = 3760\ s$
- $T_{cav} = 40$ mK

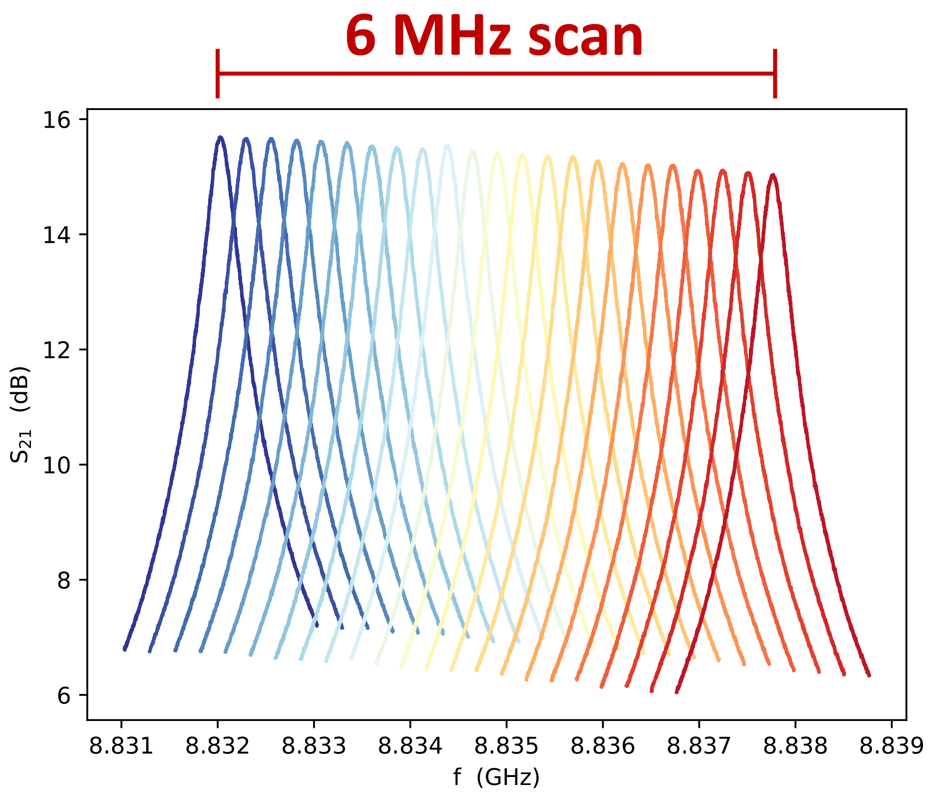
Raw power spectrum



From calibrated power spectrum
we extract the noise temp
$T_n \simeq 4.5\ K$

Courtesy of A. Rettaroli

6 MHz tuning



Performed the same procedure on each run

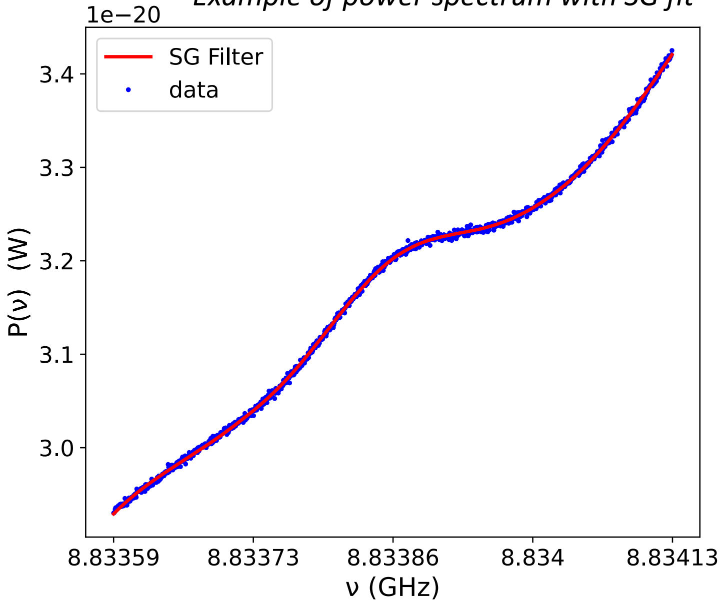
- $\boldsymbol{Q_0}$, $\boldsymbol{\beta}$ and $\boldsymbol{Gain}$ remain stable
- $\Delta m_a = \mathbf{25}\ \boldsymbol{neV}$
- Effective scan rate in this test:

220 MHz/year

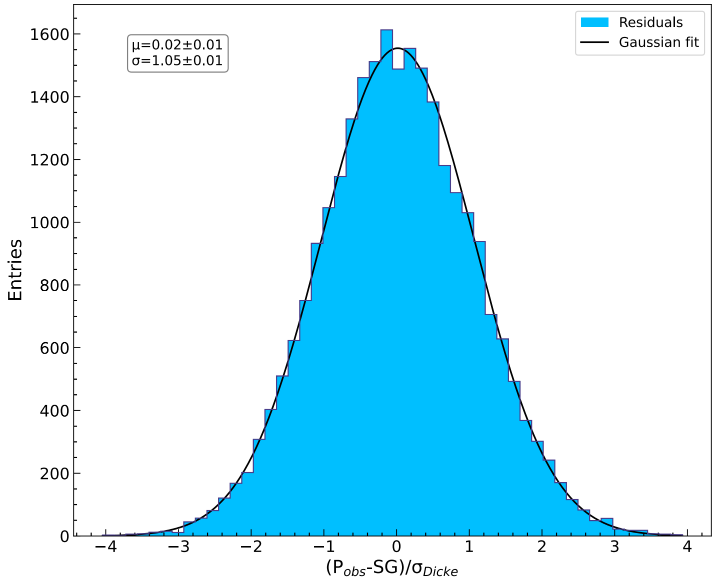
Courtesy of A. Rettaroli

Analysis

Example of power spectrum with SG fit



Cumulative normalized residuals over all scans



- Fit to power spectra with Savitzky-Golay filter to calculate residuals

- Maximum likelihood over all scans to estimate the best value $\hat{g}_{a\gamma\gamma}$

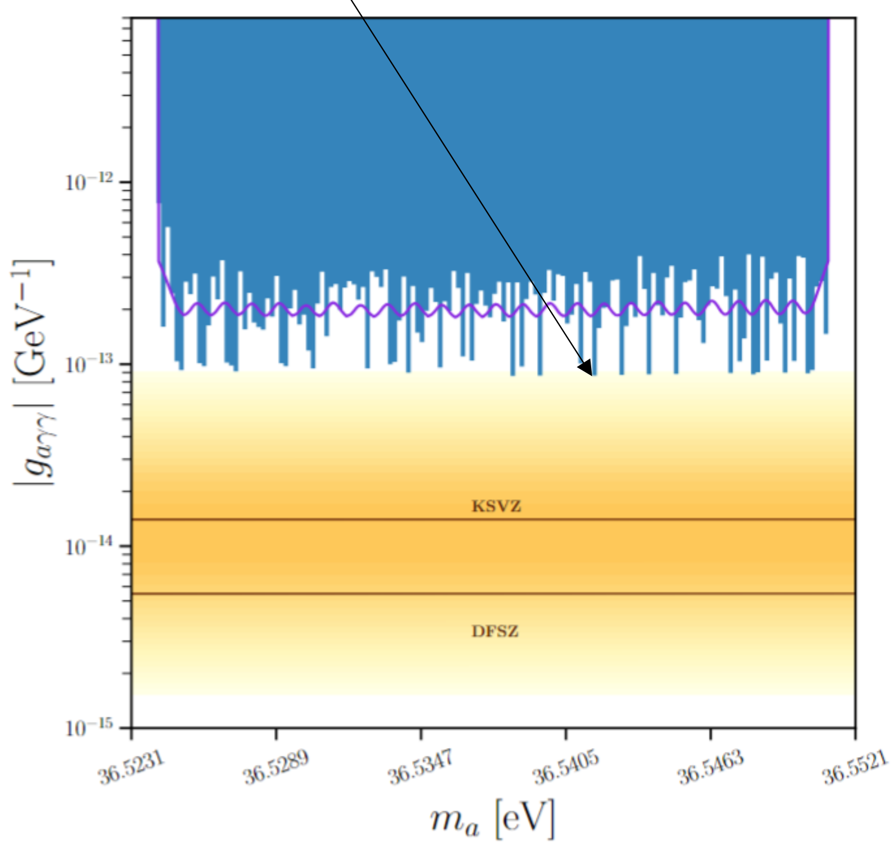
$$\chi^2 = \sum_{\alpha=1}^{N_{\text{scan}}} \sum_{i=1}^{N_{\text{bin}}} \left[\frac{R_i^{(\alpha)} - S_i^{(\alpha)}(m_a, g_{a\gamma\gamma}^2)}{\sigma_{\text{Dicke}}^{(\alpha)}} \right]^2$$

- Calculate the efficiency of the SG filter by Monte Carlo simulations with fake axion signal ($\varepsilon = 0.84$)

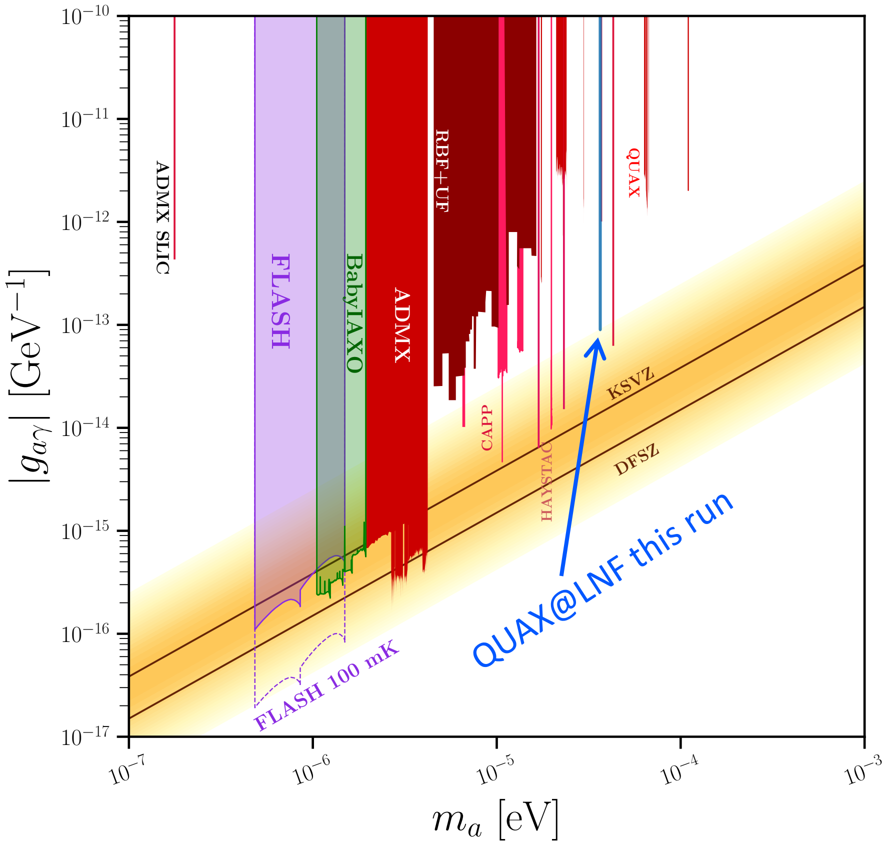
Courtesy of A. Rettaroli

Final plot $g_{a\gamma\gamma}$

Touched the QCD line



Avg value $g_{a\gamma\gamma} = 2\times10^{-13}\ GeV^{-1}$

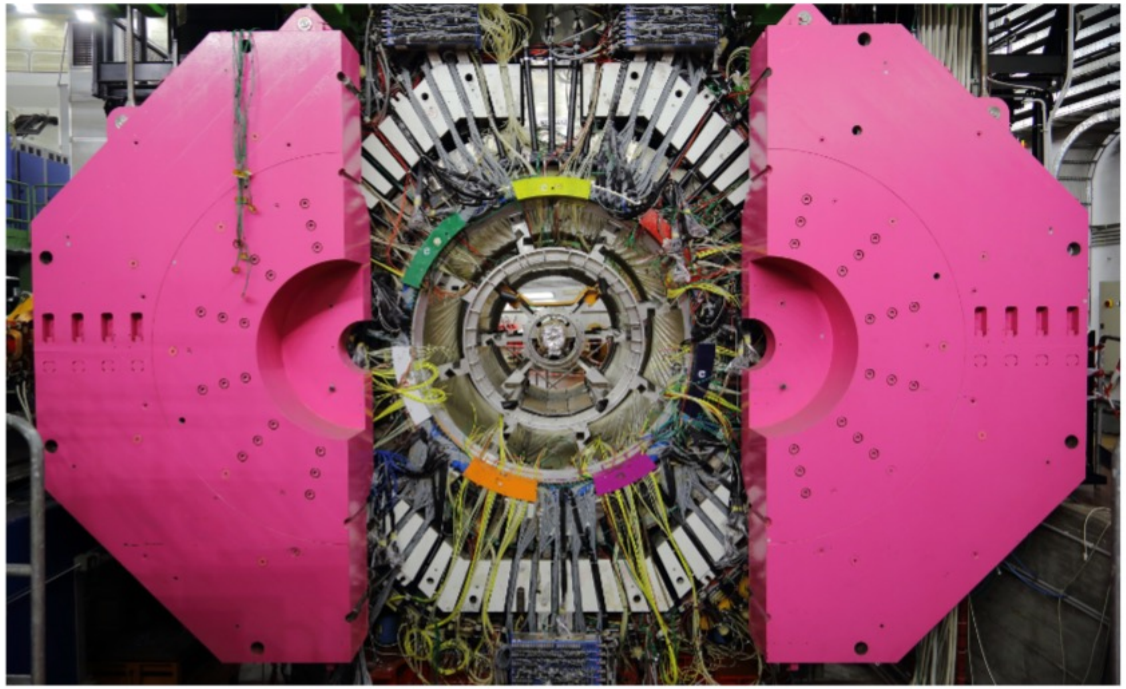


A. Rettaroli et al PRD 2024 (submitted)

Courtesy of A. Rettaroli

FLASH

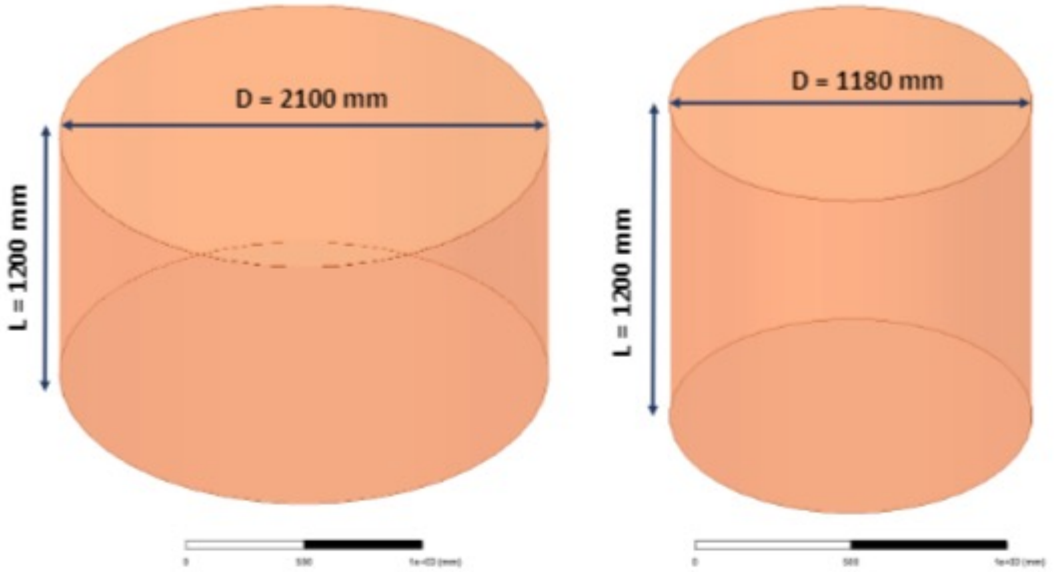
the FINUDA magnet for Light Axion SearcH



- **1.1 T superconducting magnet.**

  Succsessfully operated again after xxx years
- **240 MHz tuning (~ 1μeV of axion mass range)**
- **Low frequency region that is still unexplored (resonant cavity up to 2.5 m^3)**

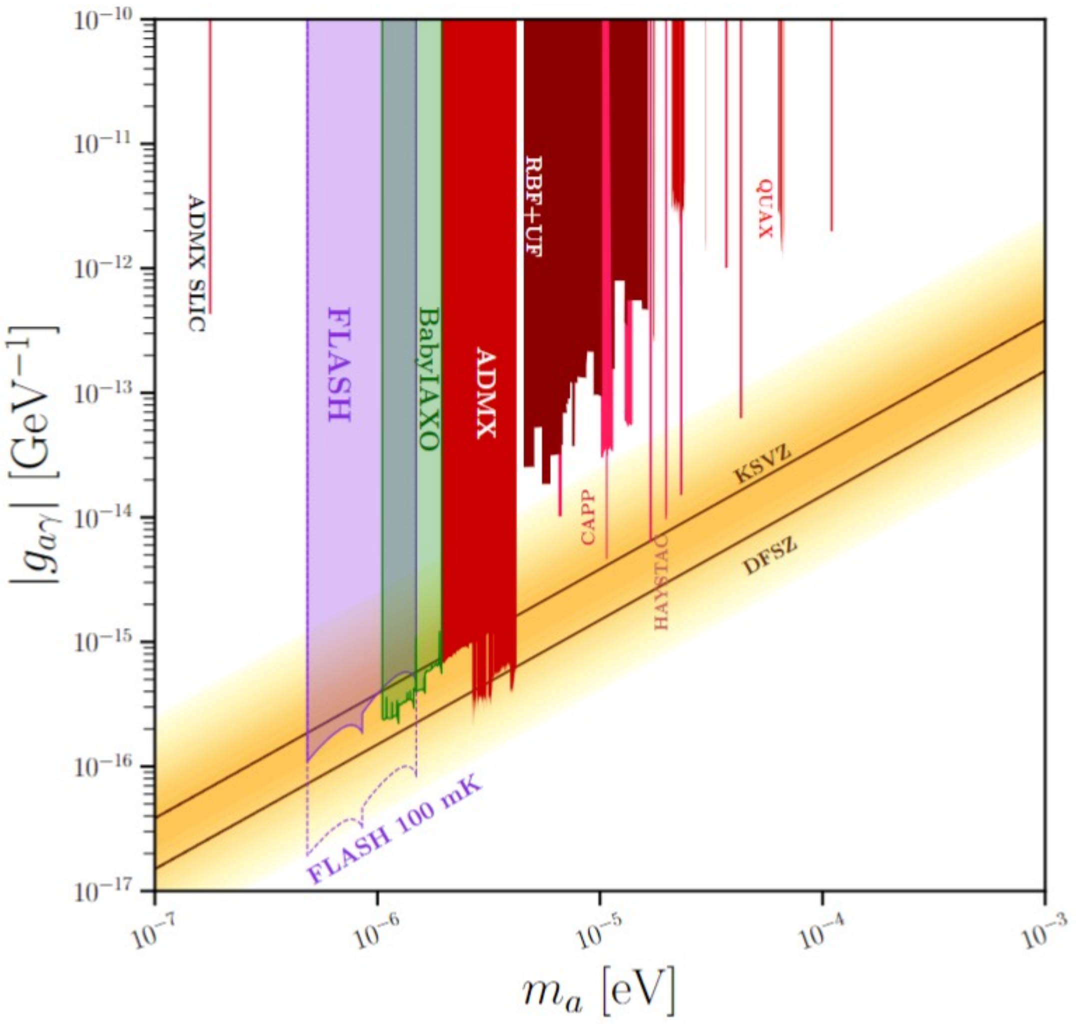
FLASH

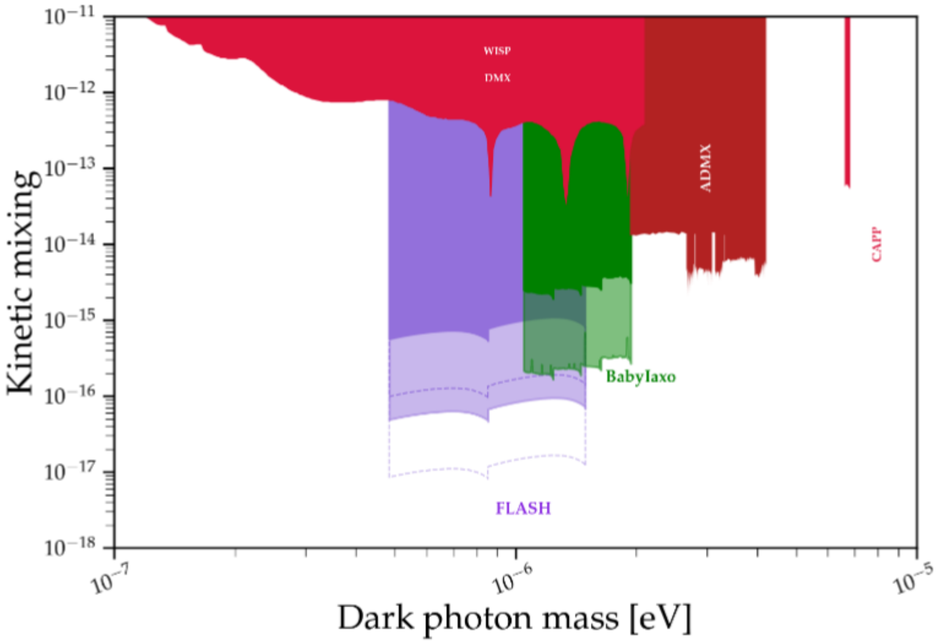


Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{KSVZ}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	1.4×10^5
C_{010}	0.53
B_{max} [T]	1.1
β	2
τ [min]	5
T_{sys} [K]	4.9
P_{sig} [W]	0.9×10^{-22}
Scan rate [Hz s^{-1}]	8
m_a [μeV]	0.49 - 1.49
$g_{a\gamma\gamma}$ 90% c.l. [GeV^{-1}]	$(1.25 - 6.06) \times 10^{-16}$

D. Alesini et al, Physics of the Dark Universe,2023

FLASH





D. Alesini et al, Physics of the Dark Universe,2023

And much more like:

- Chamaleons
- High frequency gravitational waves

Conclusions

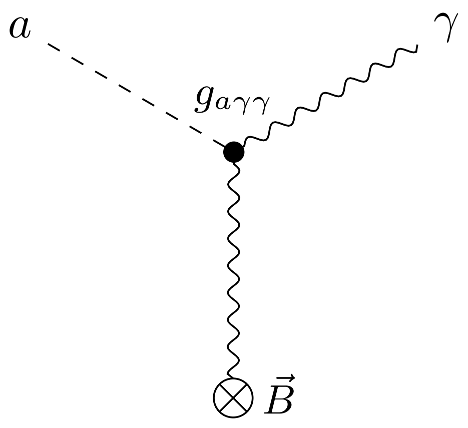
- **First QUAX@LNF run with complete haloscope**
  - **2 weeks of data taking.**
  - **9 T magnet.** Operated at 8 T.
  - **Tuning rod to scan frequencies**.
  - **~ 25 neV of axion mass scan**
- **Still much room for improvements.**
- **QUAX competitive in the panorama**.

- **Flash aims to use FINUDA magnets to operate a large haloscope**
  - **~ 1μeV of axion mass range**
  - **1.1 T magnet.** Cavity (diameter 2.1 m and 1.18 m, height 1.2 m)
- **Hunt for axion dark matter into an hardly accesible mass region**
- **Potential for discovery of new physics (chamaleons, high frequency gravitational waves)**

Thank you for your attention!

backup

Figures of merit in a haloscope



The **signal power** is very faint

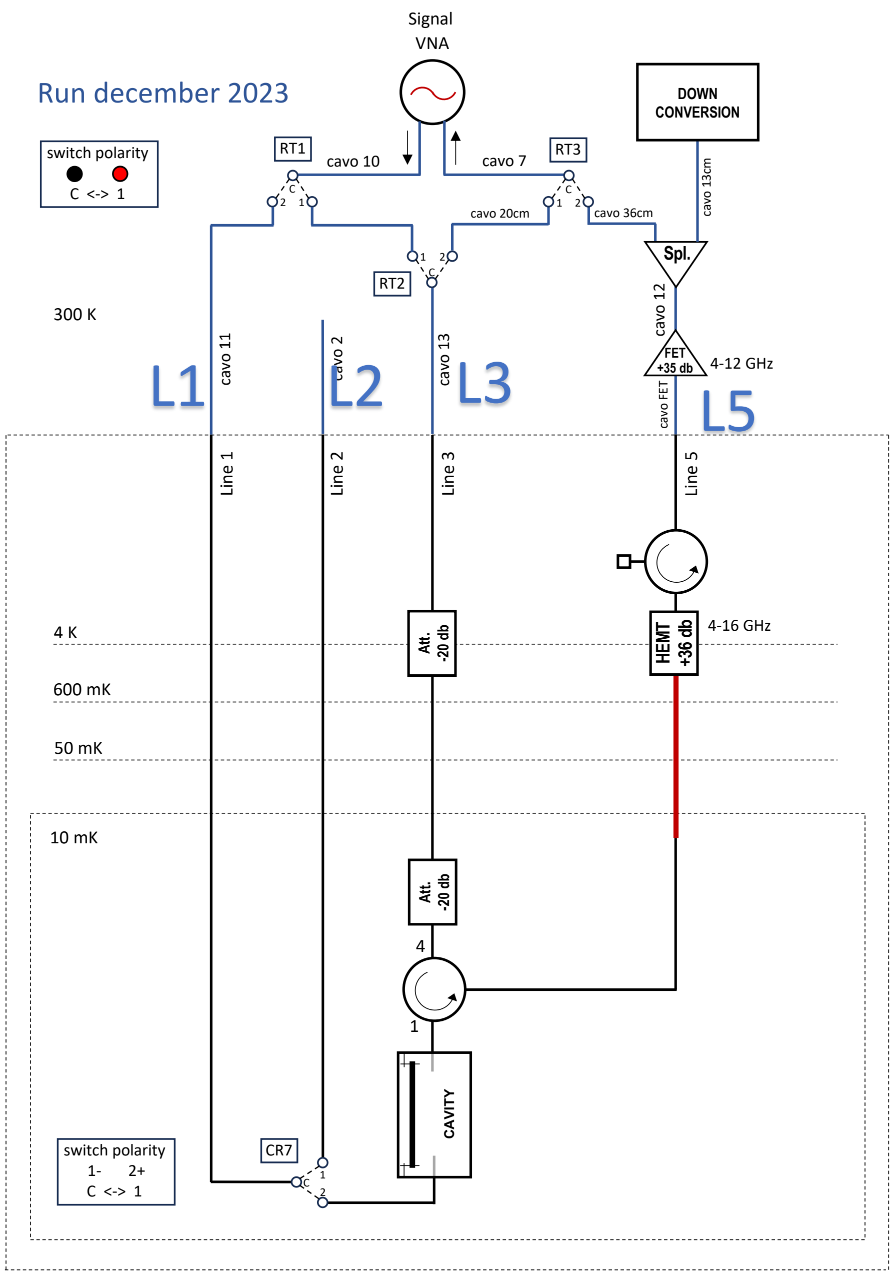
$$P_{a\gamma\gamma} \propto \left(\frac{g_{a\gamma\gamma}^2}{m_a^2}\rho_a \nu\right)\left(VB^2Q\right) \sim (10^{-22} - 10^{-23})\,\mathrm{W}$$

The **scan rate** depends critically on noise temperature

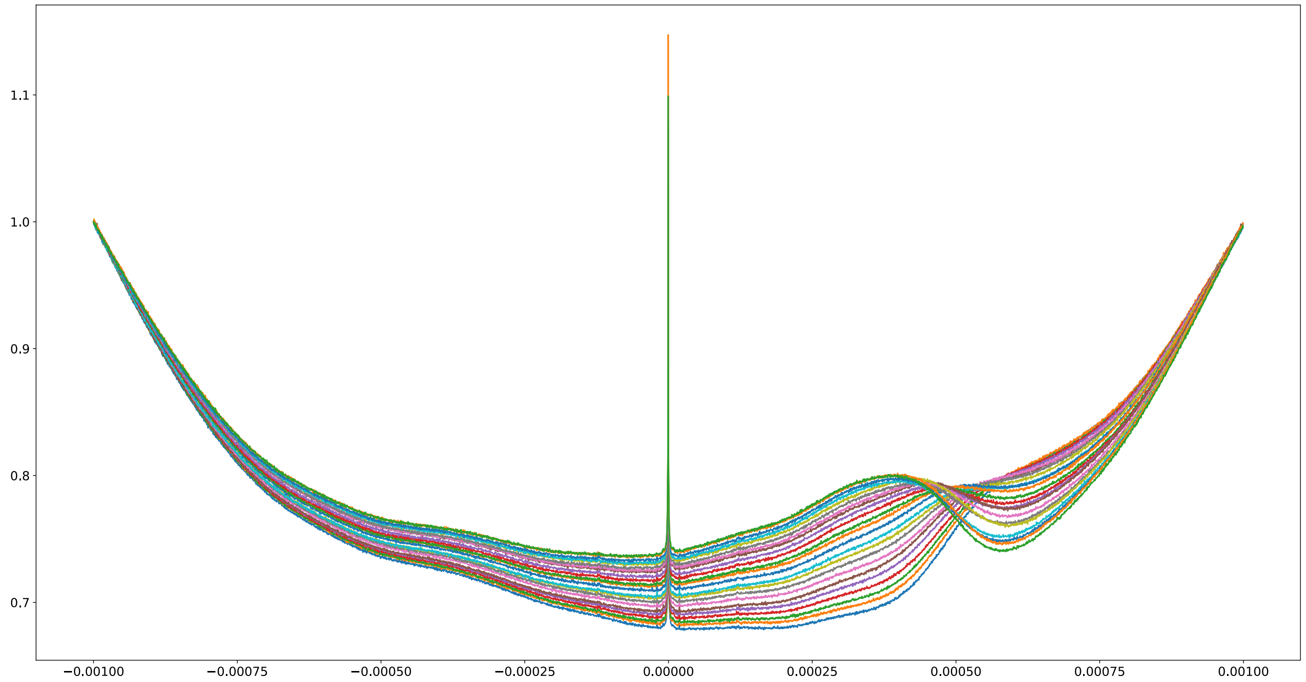
$$\frac{df}{dt} \propto \frac{B^4V^2Q_L}{T_{sys}^2}$$

$$k_BT_{sys} = h\nu\left(\frac{1}{e^{h\nu/k_BT_c}-1} + \frac{1}{2} + N_A\right)$$

$$
\begin{cases}
S_{51} = L_1 + S_{21}^{CAV}(\beta_1, \beta_2, \nu_c, Q_0) + L_5 \\
S_{13} = L_1 + S_{12}^{CAV}(\beta_1, \beta_2, \nu_c, Q_0) + L_3 \\
S_{53} = L_3 + S_{22}^{CAV}(\beta_1, \beta_2, \nu_c, Q_0) + L_5
\end{cases}
$$



All calibrated scans



Calibration of downconversion hardware