RADES & DarkQuantum

Laura Seguí, on behalf of the collaboration

29/05/2025

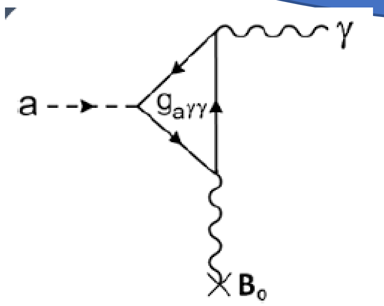
Axion as Dark matter

- Axions Proposed as a solution to the strong CP problem via the Peccei–Quinn mechanism in QCD.
- Well-motivated cold dark matter candidates:
    - very light, stable, and extremely weakly interacting.
- Produced non-thermally in the early universe
- Couple weakly to photons via the interaction term:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Axion Searches

- axion–photon coupling
- Three different detection techniques
- Depends on the sources and their expected masses



inverse Primakoff effect Phys. Rev., vol. 81, 1951, pp. 899

Axion Searches

Axions from astronomical sources (Baby IAXO from Sun)
→Helioscopes

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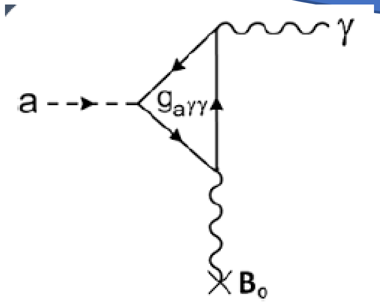
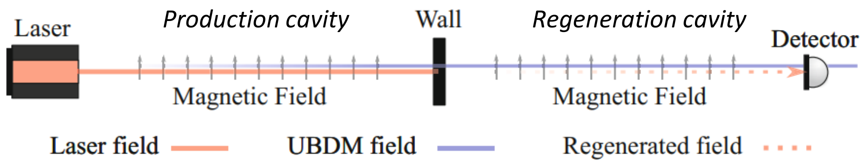


Axion Searches

Axions from astronomical sources (Baby IAXO from Sun)
→Helioscopes

Axions produced on laboratory (ALPS II)
→ Light Shining through Walls (LSW)



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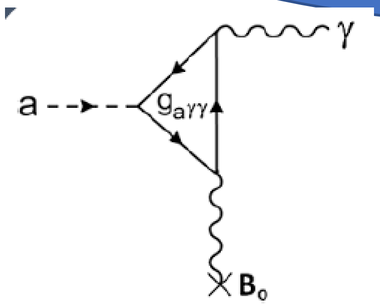

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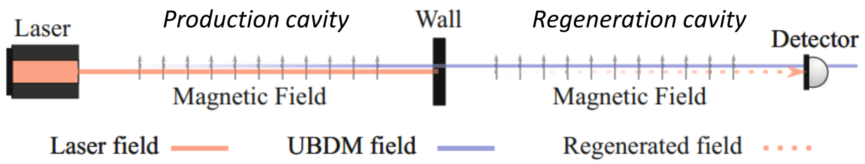

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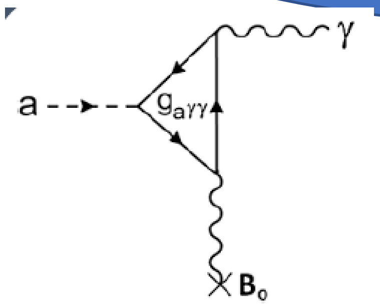
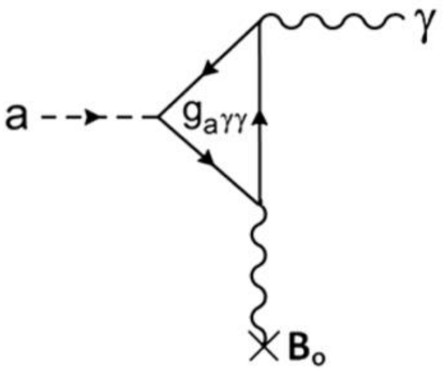


Axions in the galactic halo as dark matter
→ Haloscopes

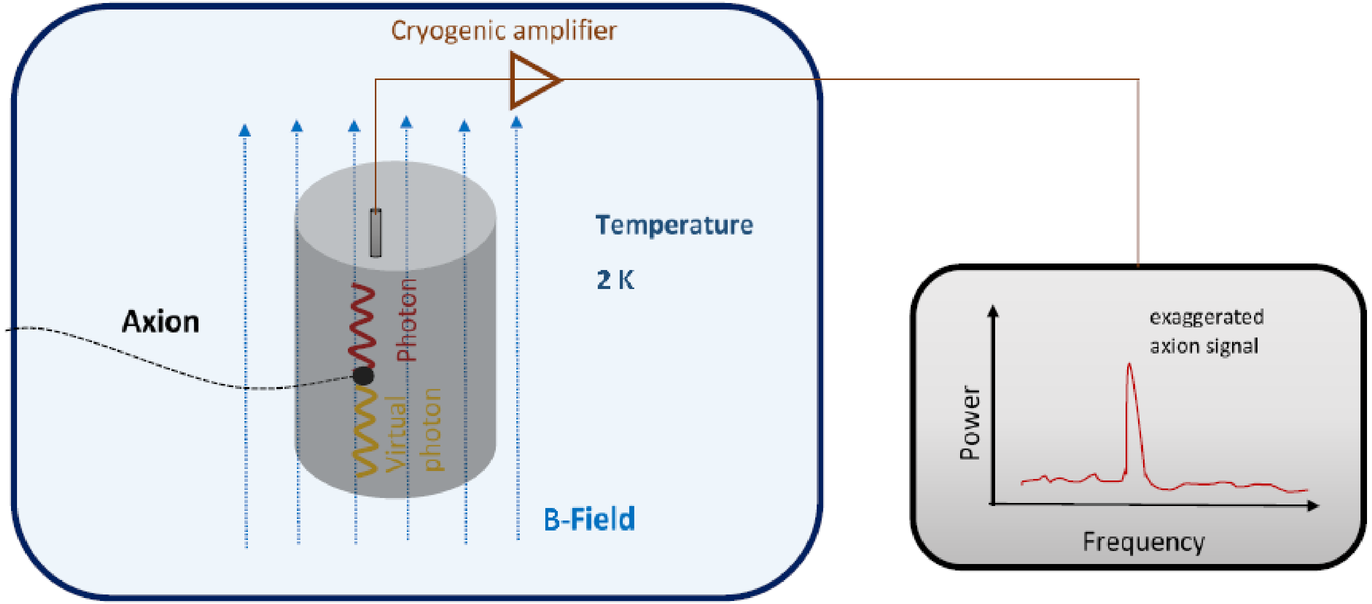
Detection of dark matter axions using microwave haloscopes: the inverse Primakoff effect

- Proposed by P. Sikivie in the mid-80s.
  - Phys. Rev. Lett., vol. 51, 1983, pp. 1415-1417
- The conversion axion to photon is described by the equation: **$m_a c^2 = h\nu$** m_a is the axion mass at rest

$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\text{sys}}^{-2} |\mathcal{G}|^4 Q$$



Inverse Primakoff effect



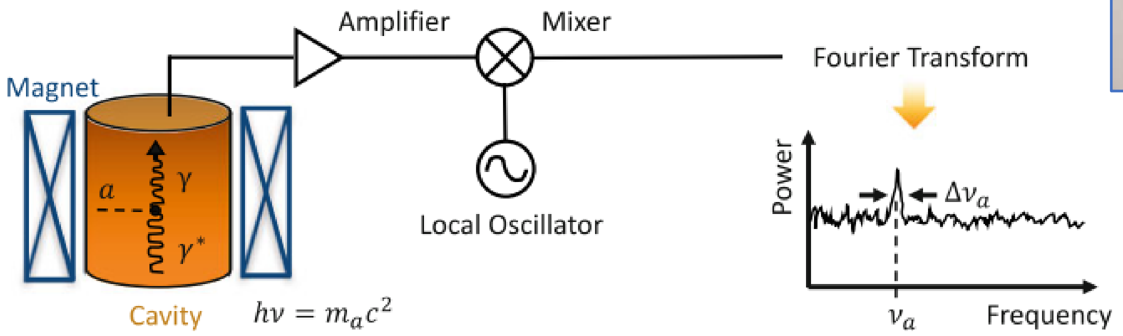
measured RF power ≈ 10^{-22} W ➡ cryogenic systems are requested !!

RADES: Relic Axion Detector Exploratory Setup

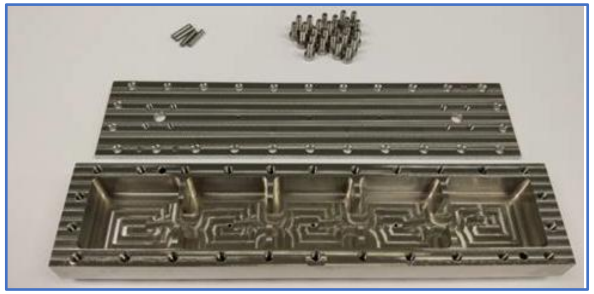
- Started ~2016 with the aim to establish an axion-haloscope (DM axions) search in the CAST magnet (handful of people), now >30 collaborators!
  - Aalto U., BSC-CNS, **CAPA**, Cartagena-UPCT, ICMAB, **IFIC**, **ITA**, KIT, Mainz U., Max Planck, ENS-Paris, TRIUMF, OAN Yebes
- Pioneered idea of multicavities (large volume cavities at high frequencies)
- First physics result with CAST in 2020
- Now moved to R&D for babyIAXO

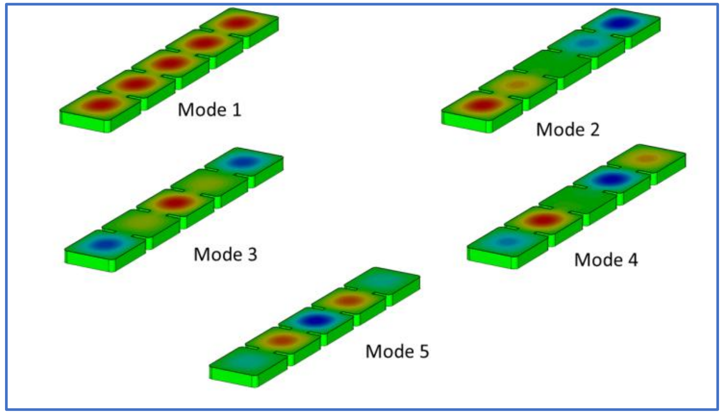
  and high-frequency

https://rades.upct.es/home.html



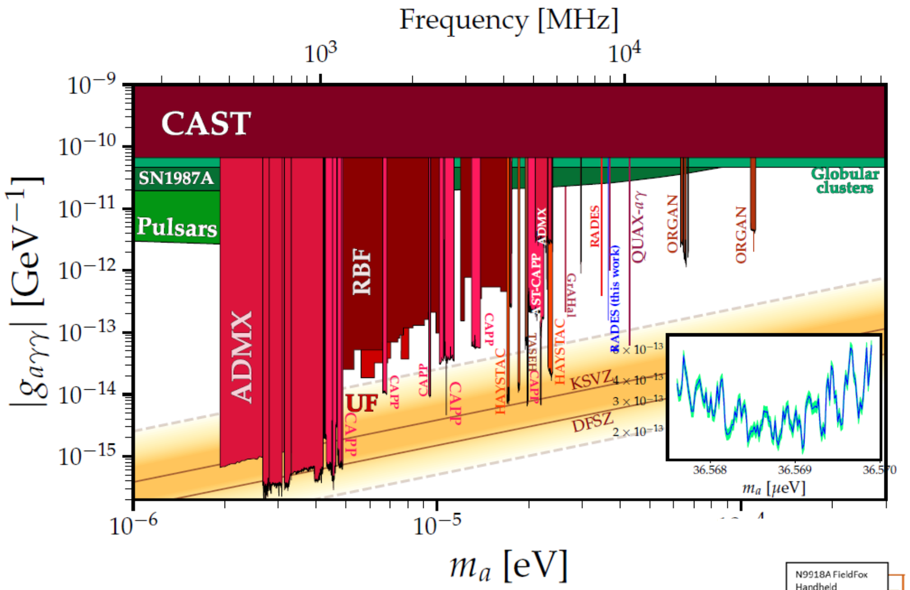
Haloscope Concept





First RADES haloscope and E-field modal patterns

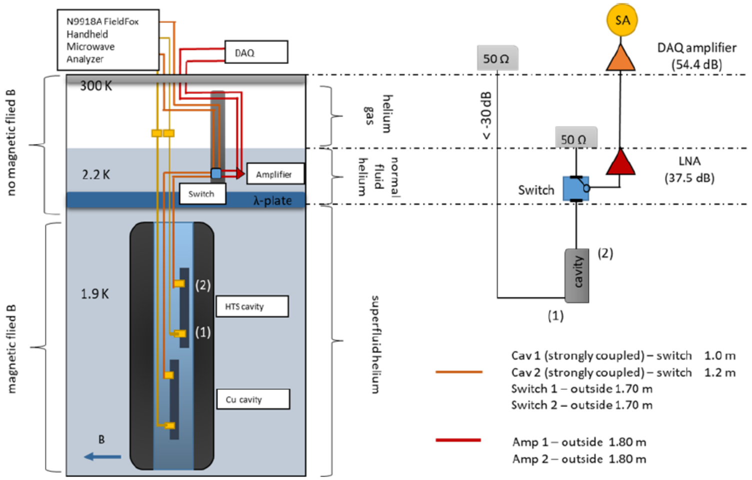
RADES Results

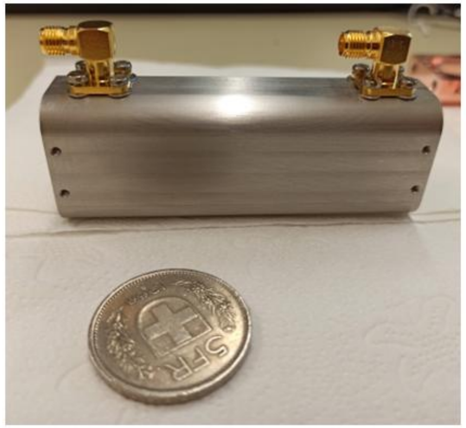


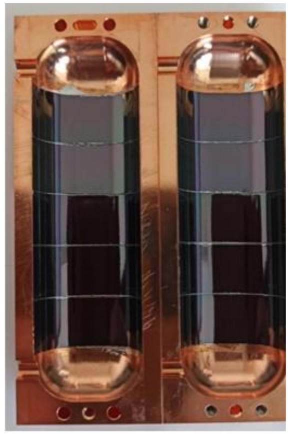
J. High Energ. Phys. **2025**, 113 (2025)

- 3 experimental campaigns: at CAST (2019) and at SM18, (CERN), 11.7 T in 2021 and 2024
- At SM18 → HTS superconductive cavities
- Limit in the coupling constant for a mass range

  36.5676 μeV < *ma* < 36.5699 μeV
- New data taking in 2024: analysis on-going



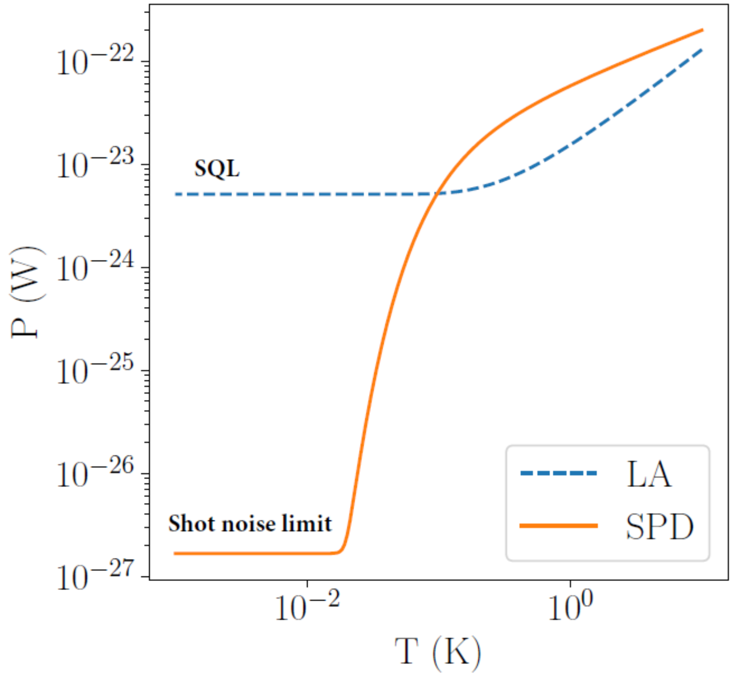


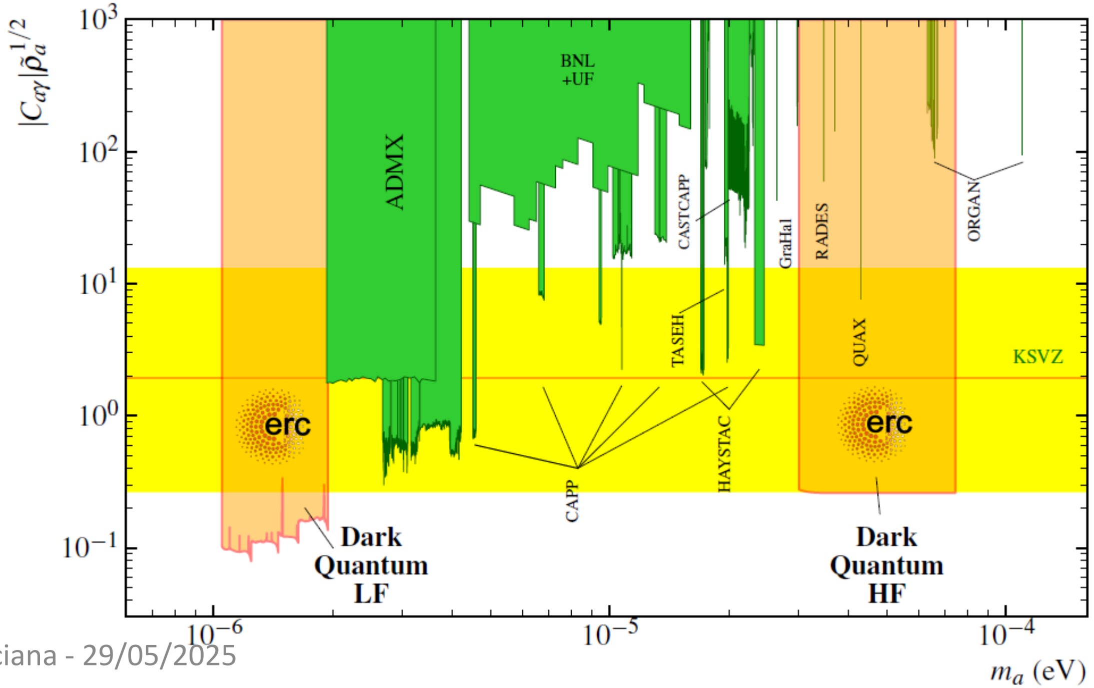


Dark Quantum

- Build two quantum-enhanced haloscopes for axion dark matter
- Dual-frequency strategy: low-frequency (200-500 MHz) and high-frequency (8-18 GHz)
- With quantum single-photon counter at high frequencies
- Developing quantum sensors to surpass the Standard Quantum Limit (SQL) : $T_{SQL} \sim hf/k_B$
- Synergy grant ERC (+ QUANTERA project QRADES)
  - Nodes: CAPA (coordinator), ENS-Paris, KIT, Aalto
  - Partners: ICMAB, UPCT, DESY, MPP

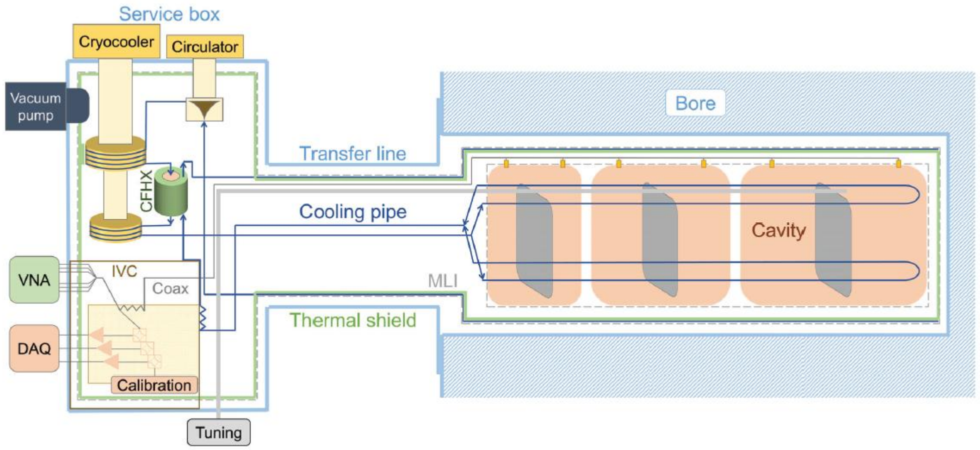
$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\rm sys}^{-2} |\mathcal{G}|^4 Q$$



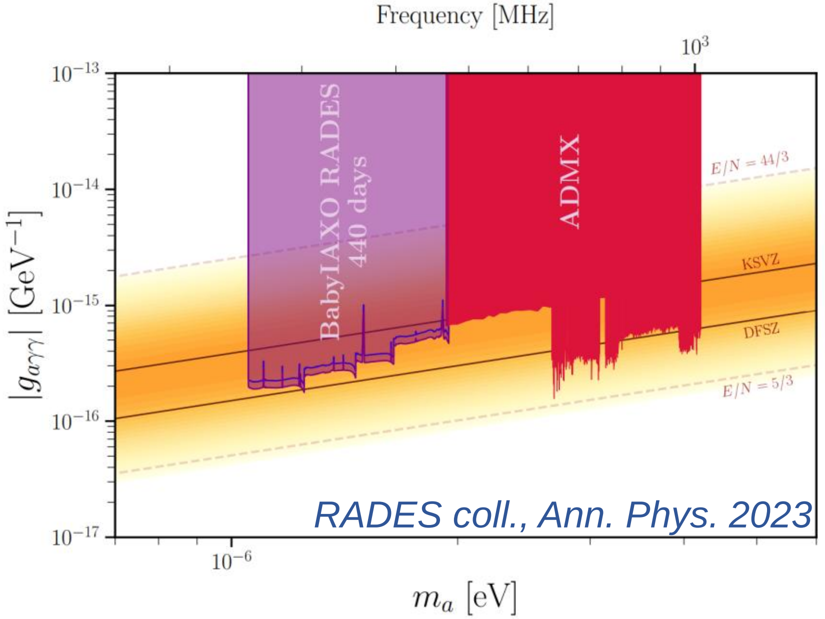


Low-frequency searches: BabyIAXO-RADES

- Large V haloscopes are technologically simpler, but expensive → huge magnet needed.
- Integration of a halosocpe in the magnetic bores of BabyIAXO
- potential sensitivity down to values corresponding to the KSVZ model, between **1-2 μeV**, after a total effective exposure of 440 days
- 4 x Cavity of 5m L x ~0.5 cm diam.



- **50cm cavity tested successfully at KIT Summer 2024**
- **Building a >1m prototype**



RADES coll., Ann. Phys. 2023

Low-frequency searches: BabyIAXO-RADES

LA5.1: Integration of the ultra-low background detection line of the axion helioscope BabyIAXO, and study of the extension of the physics case to the detection of Dark matter axions (RADES)

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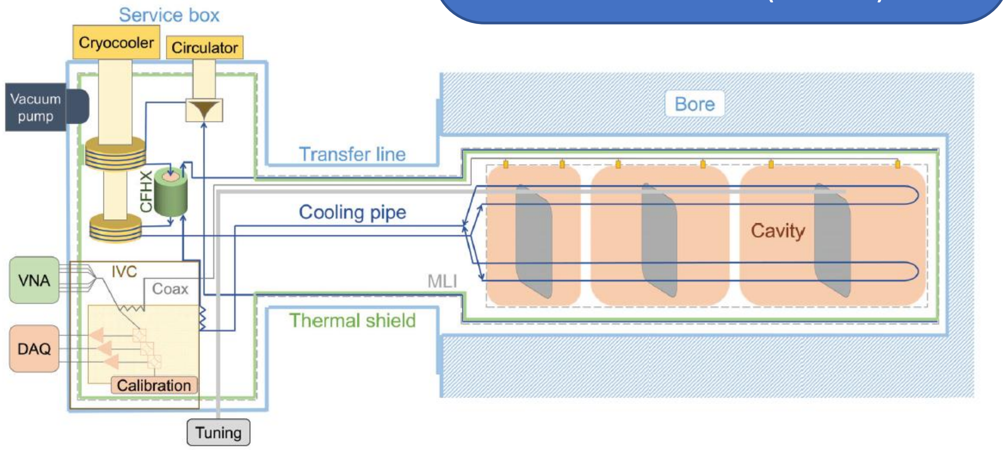

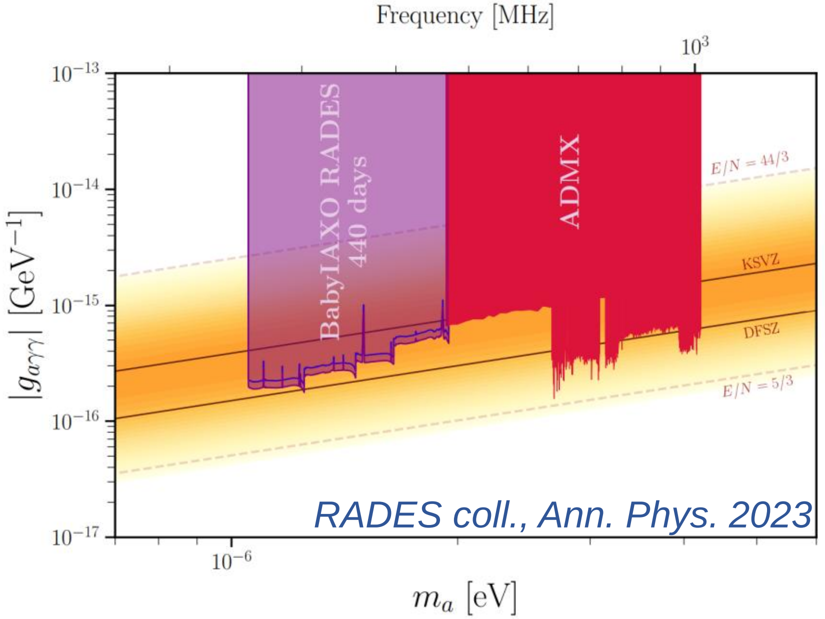

RADES coll., Ann. Phys. 2023

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H5.1.2 – Resonant Cavity prototype for BabyIAXO built and in operation

BabyIAXO-RADES: High Frequency Gravitational Waves detection

B. Gimeno talk

- The haloscopes designed for BabyIAXO might be used for High Frequency Gravitational Waves search
- PHYSICAL REVIEW D 111, 043024 (2025)

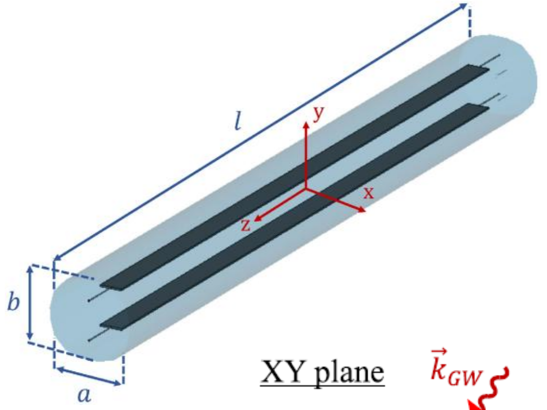


TABLE I. Dimensions and operational frequency range of the studied cavities. The thickness of both metallic plates is 1 cm.

Cavity model	a (cm)	b (cm)	l (cm)	Frequency range
Cavity 1	56	50.4	500	252.8–333.2 MHz
Cavity 2	5.5	4.9	50	2.504–3.402 GHz

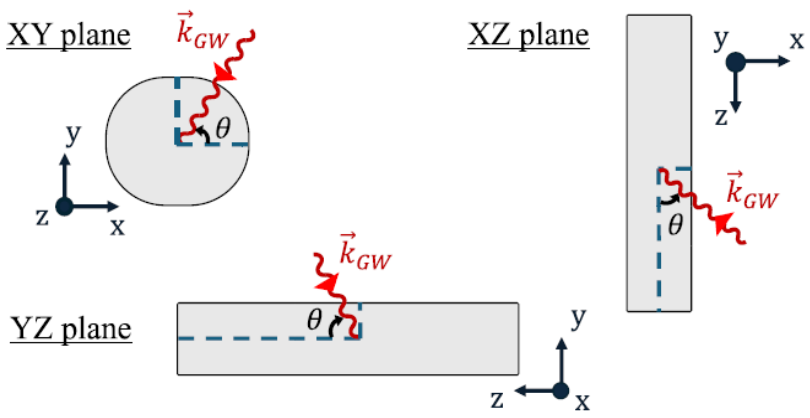


FIG. 6. Scheme of HFGWs incidence in each plane.

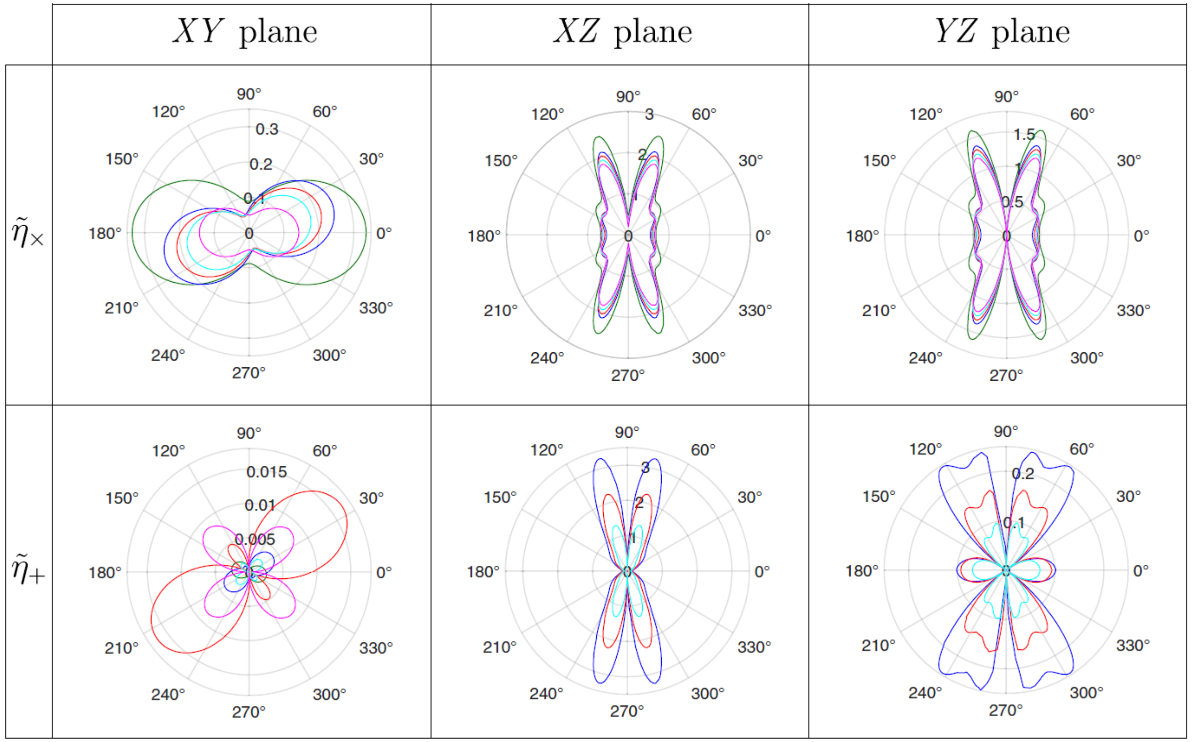
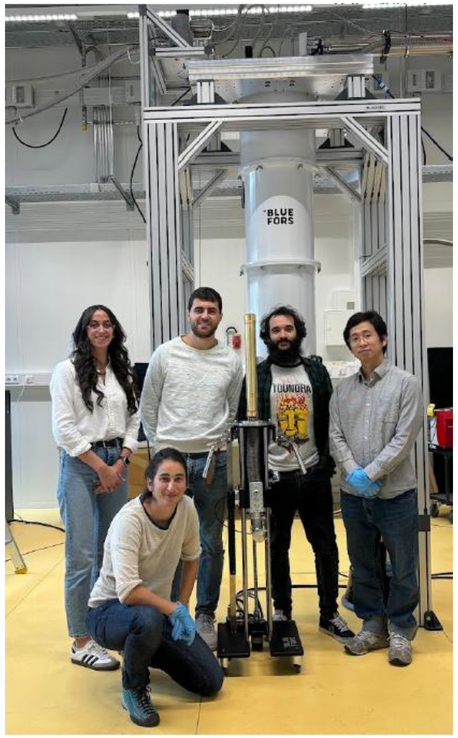


FIG. 7. Form factors for mode 1 in cavity 1 as a function of the incidence angle θ. Rows make reference to the two different polarizations of the HFGW and columns make reference to the three different planes in which the incidence of the HFGW is studied. Each plates angle (α) is illustrated with a different color: Green for $\alpha = 0°$, blue for $\alpha = 30°$, red for $\alpha = 45°$, cyan for $\alpha = 60°$, and magenta for $\alpha = 90°$. In the $\tilde{\eta}_+$ XZ plane and $\tilde{\eta}_+$ YZ plane cases $\alpha = 0°$ and $\alpha = 90°$ cannot be seen since the coupling is much lower in comparison to the rest of the angles. The same occurs for 0° in the $\tilde{\eta}_+$ XY plane case.

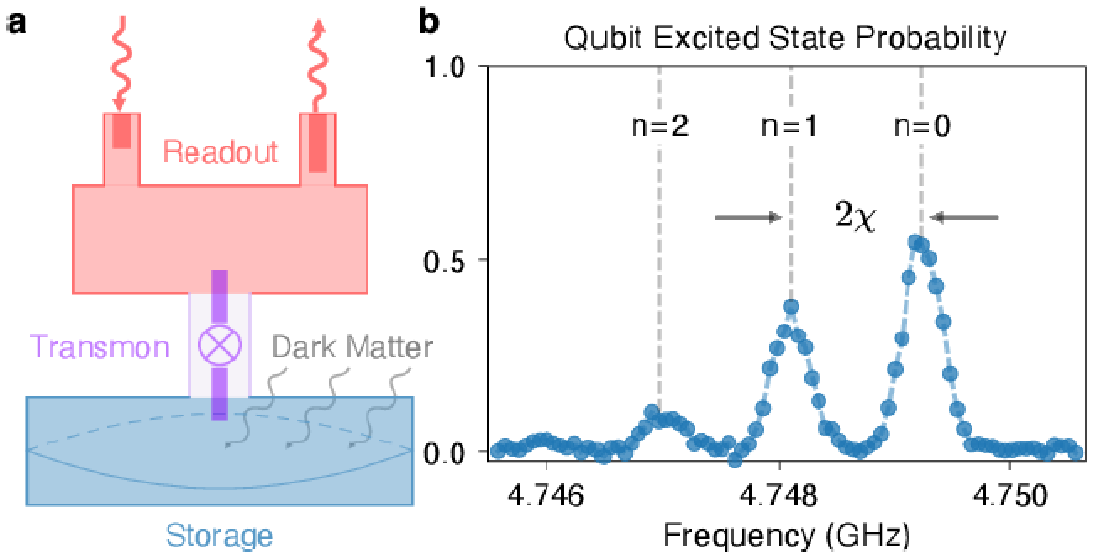
Set-up at MPP

- First RADES set-up to be tested at 10 mK soon at MPP
- Cryostat with T<7mK and B=12T installed at MPP in early November 2024
- Studies of long cavities
- Vertical cut tuning
- Frequency range 8-9 GHz
- “Standard” haloscope, no qubit sensors



High frequencies with quantum sensors

Qubit-based Single Photon Detector (SPD)

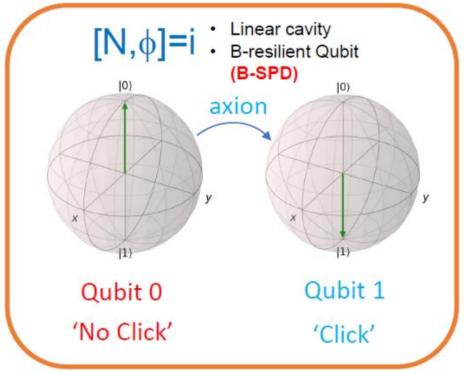


- **Dixit et al. Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126**

Presented by D. Diez last year national meeting

- Develop quantum sensors (trasnmon)
- Count individual photons (surpass the SQL limit)
- Challenge to work in magnetic fields

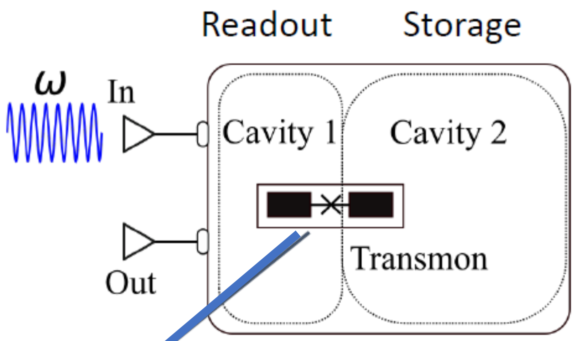
Counting photons

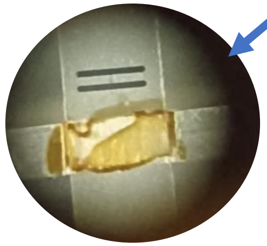


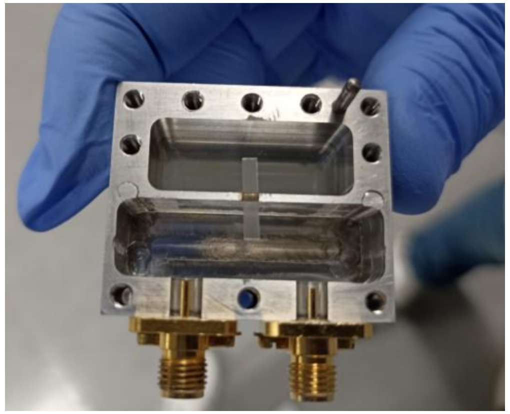
change of paradigm → Number-Phase conjugates evade the SQL

High frequencies with quantum sensors

- Data taking at Aalto University + analyzed by Zaragoza (D. Diez)







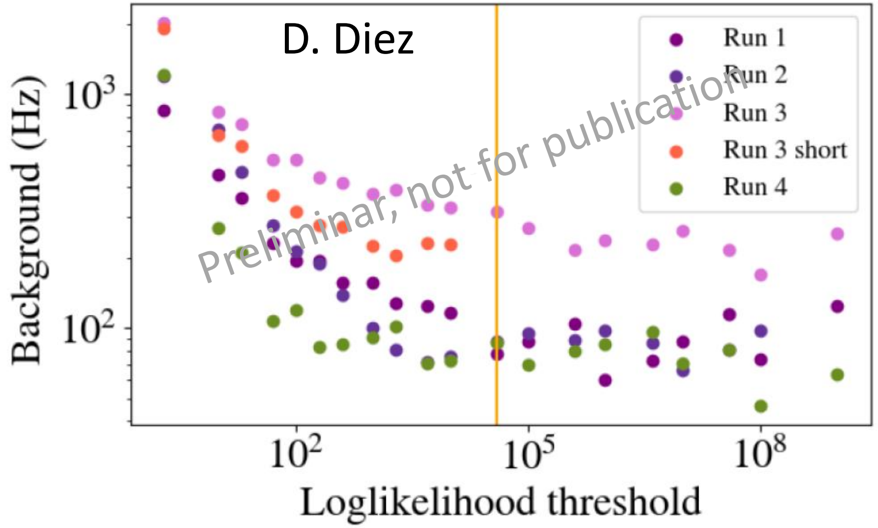


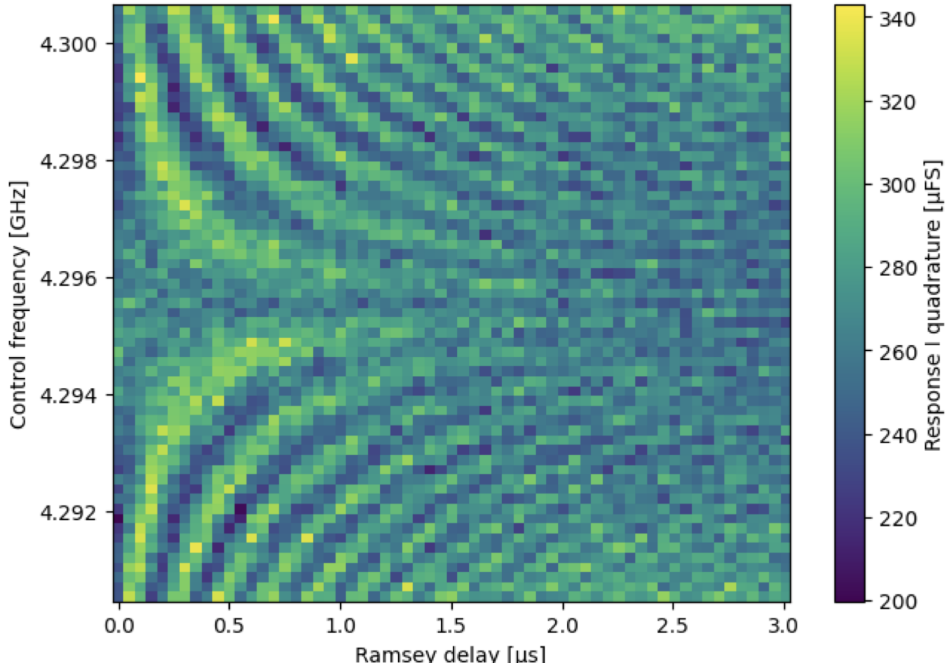
Figure 19: Background rate corrected by efficiency for each threshold value. Rate computed with 10000×0.00002 s because storage cavity $T_1^s = 20\ \mu s$. Vertical at proposed threshold $\lambda_{th} = 4 \times 10^4$.

$\lambda_{th} = 4 \times 10^4$	Bkg (Hz)	Efficiency
Run 1	77.94	0.257
Run 2	87.35	0.286
Run 3	315.96	0.317
Run 4	86.62	0.231

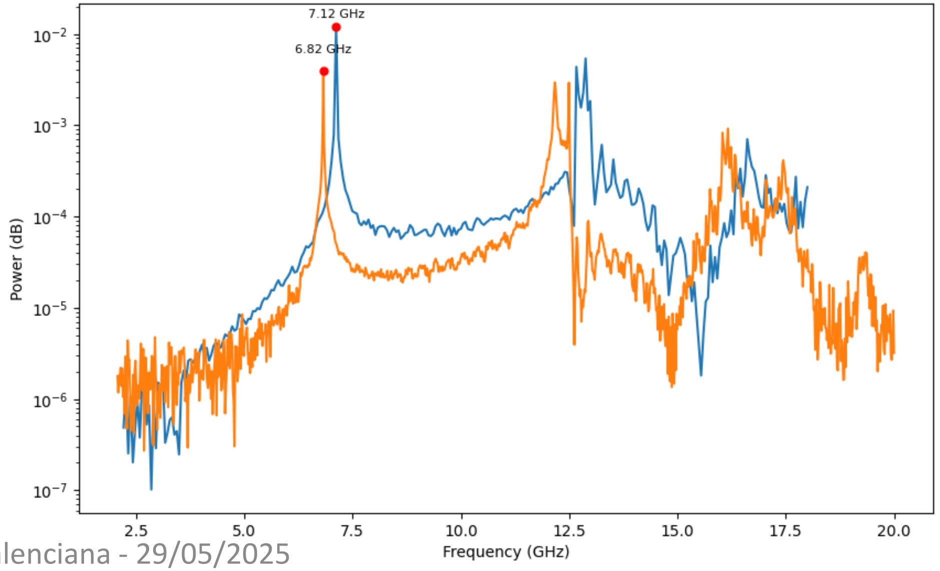
Chicago group (D. Schuster)	Bkg (Hz)	Efficiency
Searching for dark matter with a superconducting qubit	1.1	40%
A flux-tunable cavity for dark matter detection	64	15%

Set-up at CAPA

- Using refrigerator from QMAD group (INMA)
  - Tendering open for our own → expected spring 2026
- Characterization of qubit in single and double cavity
  - New cavity data taking on-going
- Defining electronic control system (with ITA)
- Preparing set-up and scripts to repeat parity measurements done at Aalto



D. Diez and Y. Gu



CONCLUSIONS

- RADES is opening new windows in the search for axion dark matter
- Now under active development for BabyIAXO
- New phase started with the DarkQuantum ERC-SyG started Oct 2024 integrating quantum technologies and sensors.
- New ideas also to explore in BabyIaxo→ HFGW
  - International observatory
- Setting up laboratories at CAPA and MPP
  - First qubits and cavities characterized at Zaragoza
- Planes complementarios very helpful to progress along these lines
  - Different milestones on-going

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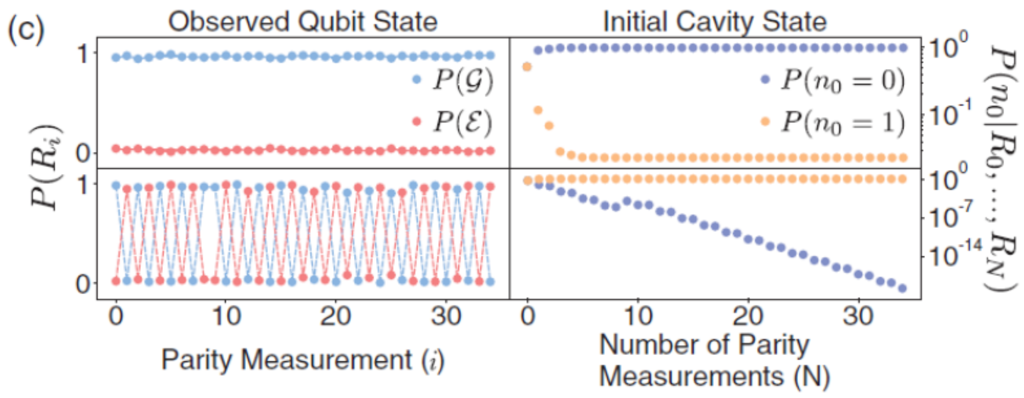
THANK YOU FOR YOUR ATTENTION

Quantum sensors for haloscopes

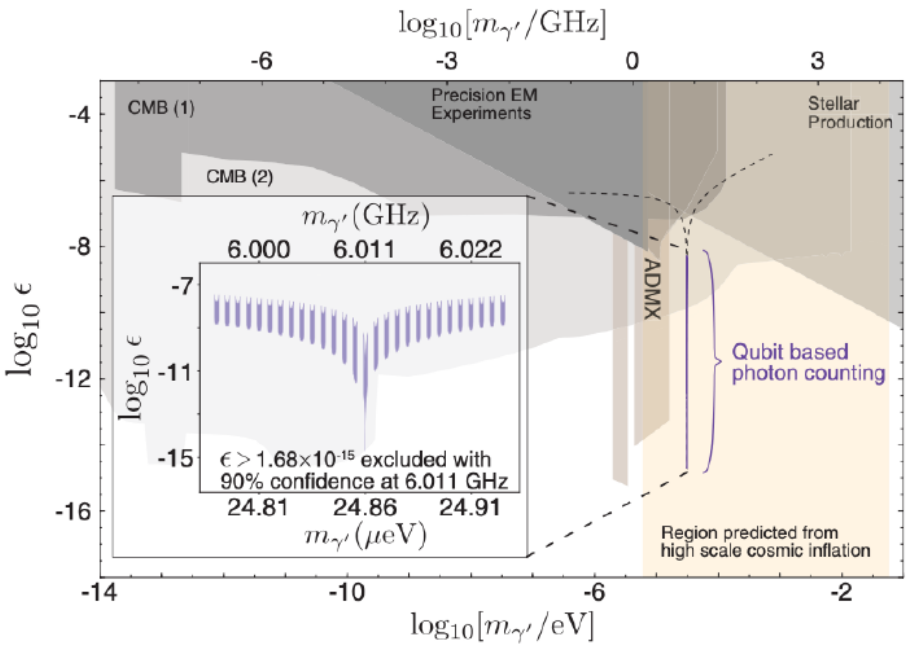
D. Diez
AstroHEP-
PPCC-2024

Independent measurement with 30 parity measurements



In total 15141 independent measurements.
9 photons detected.
846 us each measurement.
→ 12,81s with 65% duty cycle = 8,33 s

Dark photon sensitivity plot



- Dixit et al. Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126

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