RADES axion searches with quantum - enhanced haloscopes

David Díez Ibáñez

On behalf of RADES collaboration

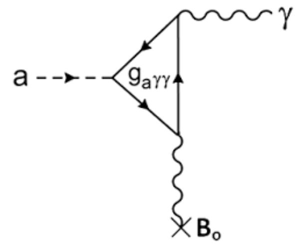
Laboratoire de Physique de l'École Normale Supérieure (LPENS)
École Supérieure de Physique et de Chimie Industrielles (ESPCI)

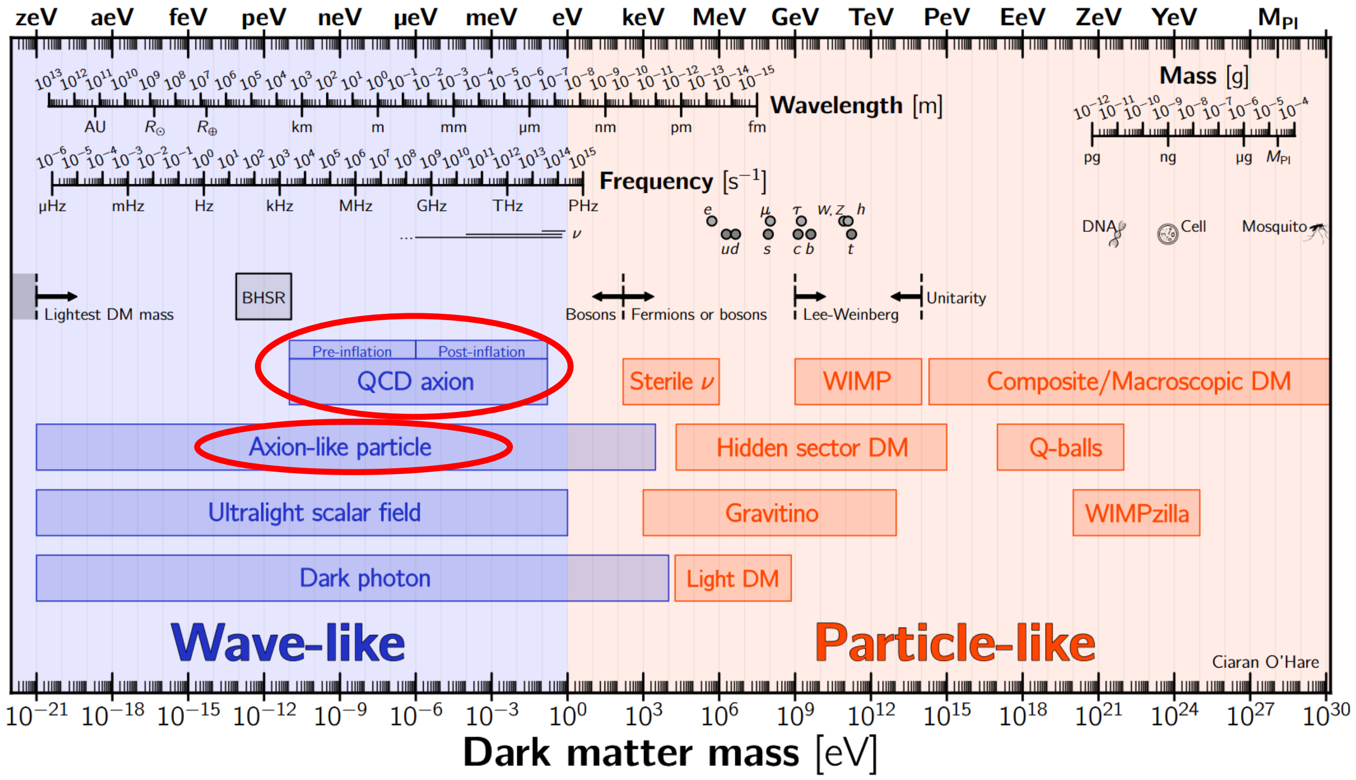
High precision experiments for light dark matter, Durham, September 2026

Axions as dark matter

- Proposed solution for strong CP problem: not observed charge and parity violations in strong interactions, as it is predicted by SM.
- Viable dark matter candidate.
- Conversion into photons via inverse Primakoff effect:

$$\mathcal{L}_{a\gamma\gamma} \propto g_{a\gamma} a \vec{E} \cdot \vec{B}_e$$

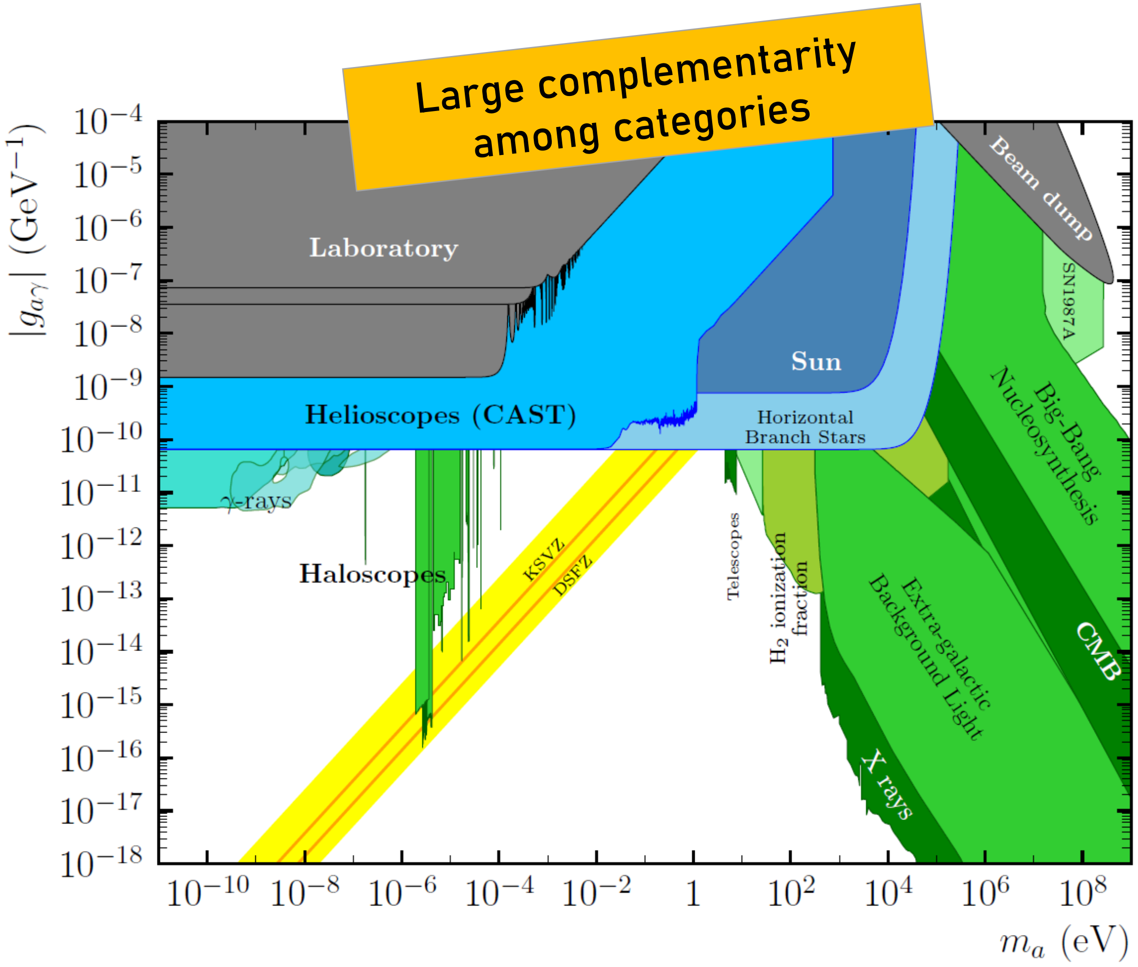




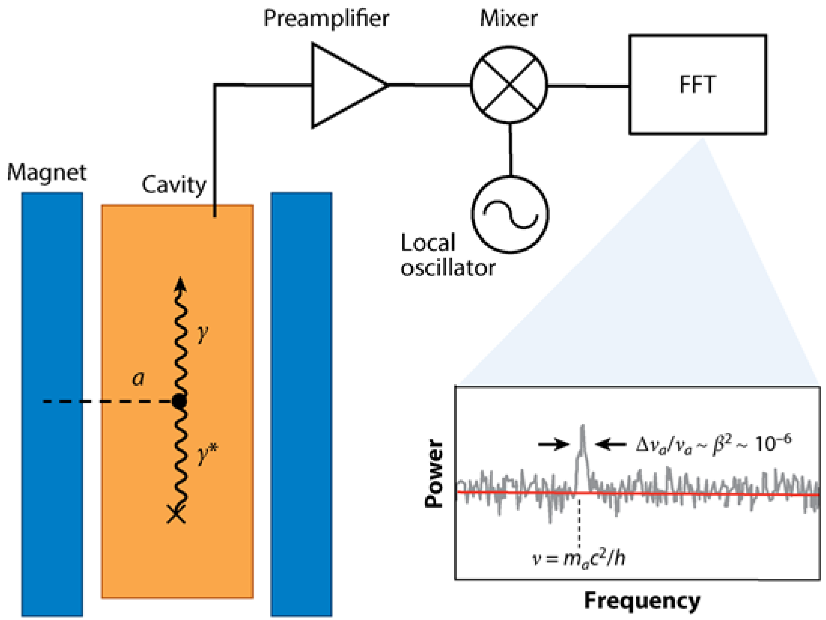
C. O'Hare

Axions as dark matter

Source	Experiments	Model & Cosmology dependency
Relic axions	ADMX, HAYSTAC, CASPEr, CAPP, MADMAX, QUAX, RADES, ORGAN, …	High
Lab axions	ALPS, OSQAR, CROWS, ARIADNE,…	Very low
Solar axions	SUMICO, CAST, (Baby)IAXO	Low



Haloscope: a resonant cavity immersed in a magnetic field for galactic dark matter axion conversion into microwave photons.



DOI:[10.1146/annurev-nucl-102014-022120](https://doi.org/10.1146/annurev-nucl-102014-022120)

ADMX collab.

Haloscope experiments → ADMX, HAYSTAC, CAPP, QUAX, MADMAX, RADES, …

Haloscopes

- **Problematic:**

higher m_a → lower V → lower sensitivity

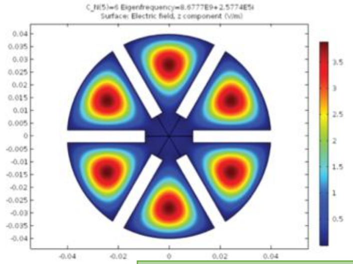
$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\mathrm{sys}}^{-2} |\mathcal{G}|^4 Q$$

- R&D to go to:
  - Higher B magnets
  - Larger instrumented volumes
  - Lower noise sensors
  - Higher Q cavities

Very active R&D in many groups!

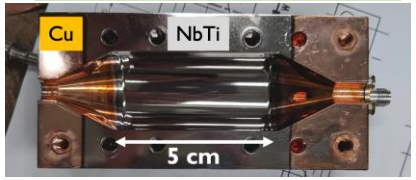
- More powerful magnets
- Multicell structures:
  - Phase-matched
  - Filter-like
  - Dielectric loading
  - Photonic bandgap
  - Dielectric layers/mirrors (dielectric haloscopes)
  - …
- SC deposited cavities
- Lowering T with cryogenics and novel sensing techniques

CAST-CAPP project
In the CAST magnet



"Pizza cavity"
at CAPP
→ 2008.10141

QUAX at LNL



RADES colaboration

The team

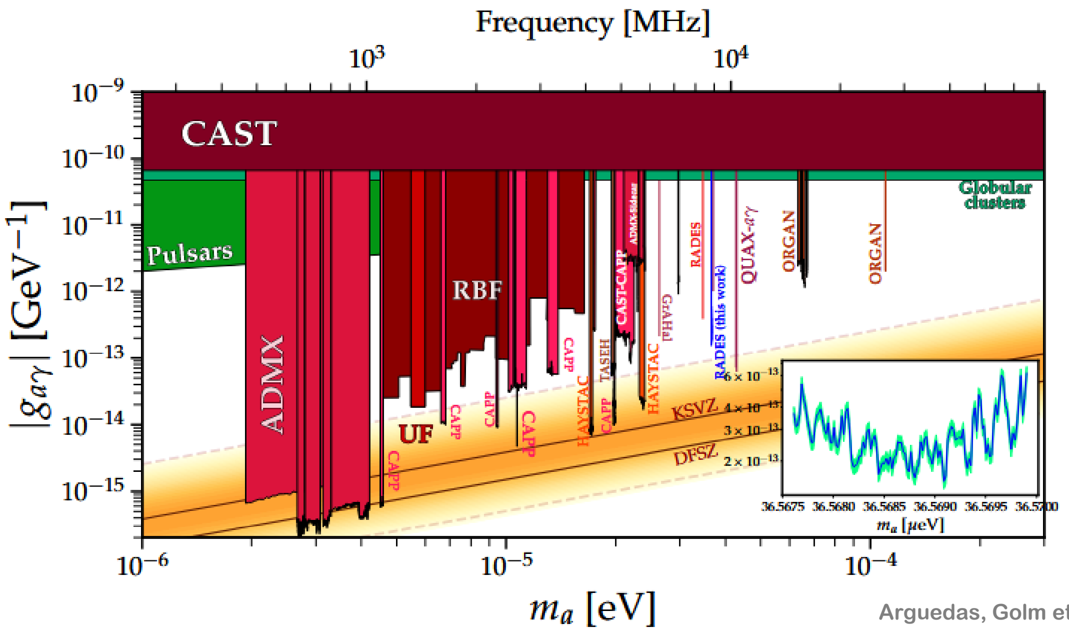
KIT, Aalto U., MPP, Zaragoza U., CERN, Barcelona U., Cartagena U., LPENS, IFIC, ICMAB, IFAE, ITA, Bonn U., DESY, …

Expertise in:
- Cryogenics
- Cavities and MW filters
- Particle physics
- Quantum devices
- Magnetic materials
- …

RADES previous projects

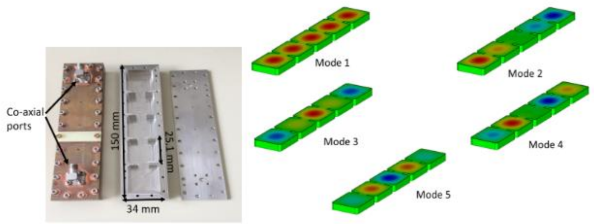
- Born at CERN in CAST helioscope.
- Exploring haloscope technologies (HTS coatings, multicavities…)
- MMP Munich setup in commissioning (dilution fridge with 12T magnet)
- Experience with several data taking campaigns (CAST, SM18)
- ERC Synergy Grant 2023: Dark Quantum (Irastorza, Kontos, Paraoanu, Wernsdorfer)

DarkQuantum
ERC Synergy Grant 2023

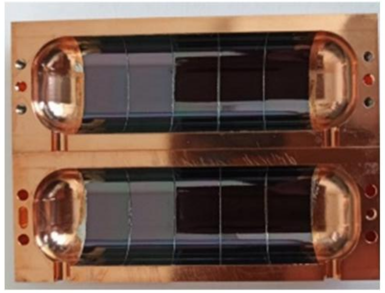


Arguedas, Golm et al. JHEP (2021)

CAST - Rades



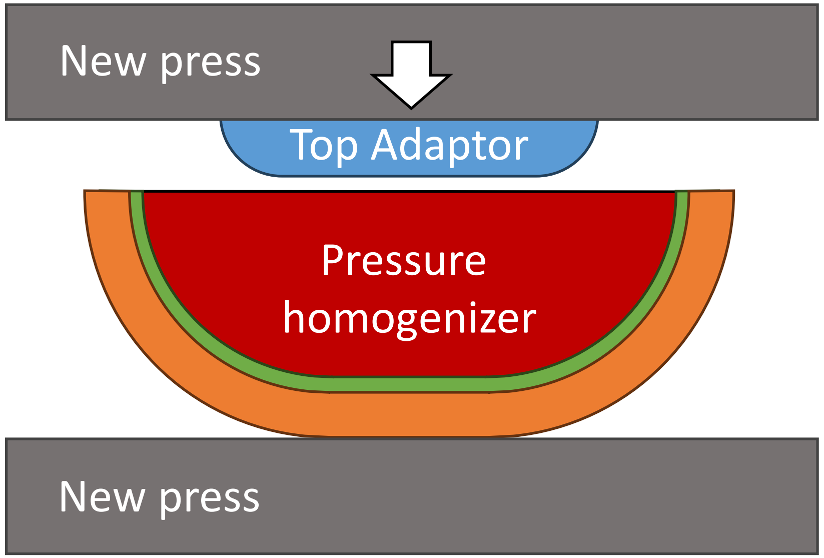
SM18 - Rades



Arguedas, Golm et al. JHEP (2025)

High temperature superconductors

- REBCO (Rare-earth barium copper oxide) tape covering the surface.
- Increase Q factor in magnetic fields.
- Challenges: cover non flat surfaces, bubbles, big cavities…



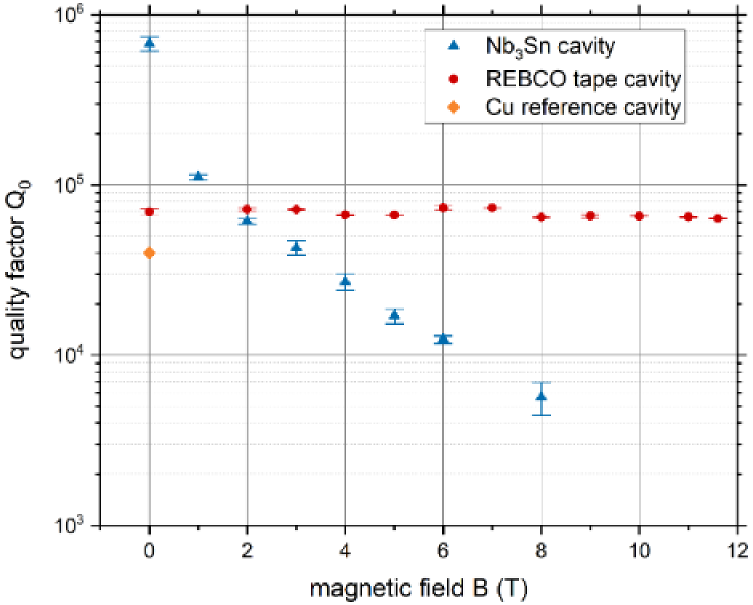
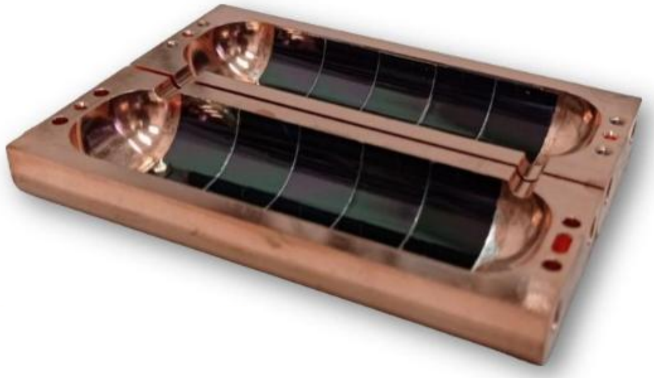


Fig. 6: Results of quality factor measurements with the cavity immersed in liquid helium. The resonance frequency of the cavities is f = (8.8 ±0.1) GHz at 4.5 K.

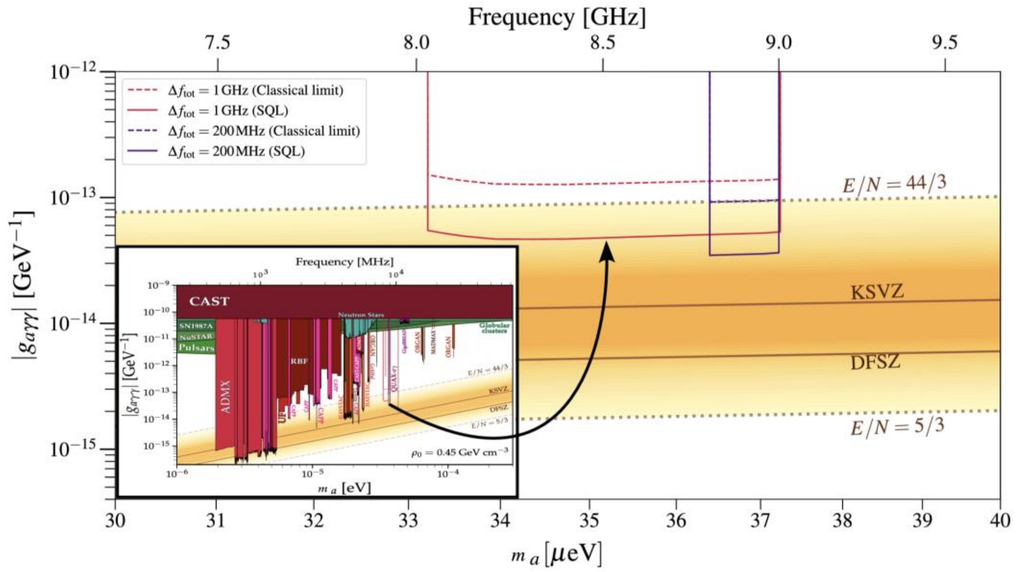
DOI: 10.1109/TASC.2022.3147741



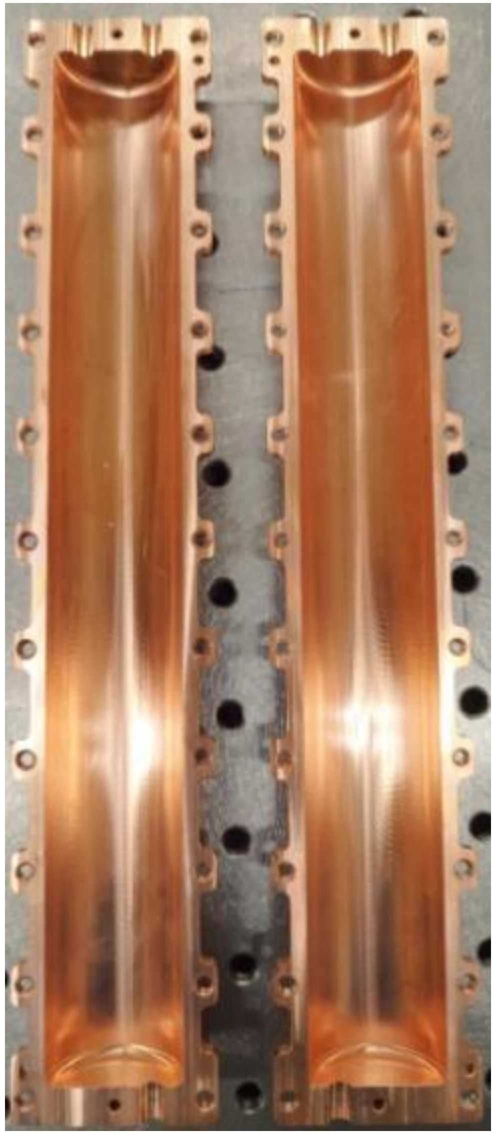
ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

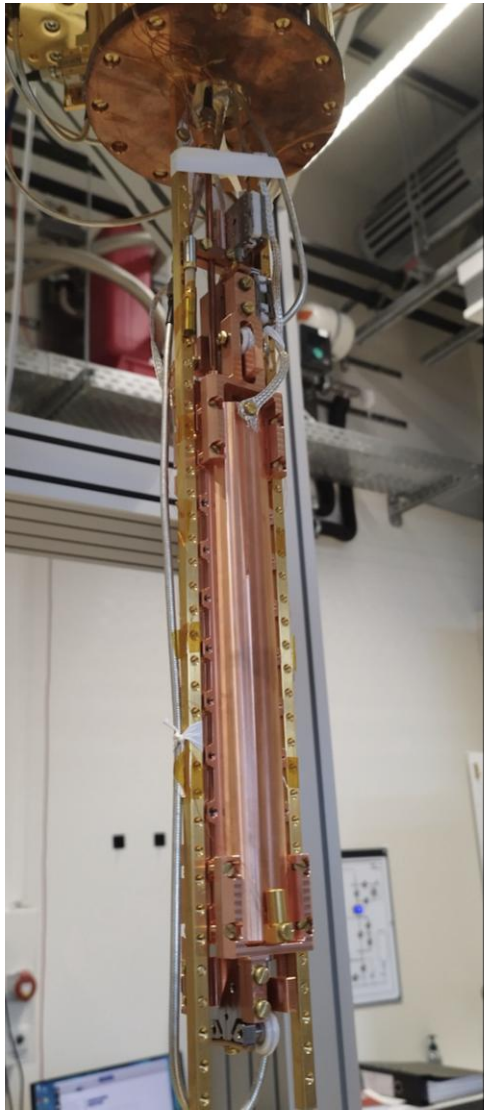
RADES haloscope at MPP Munich

- First RADES setup at ~10 mK
- Mechanical tuning via vertical cut:
  García-Barcelo et al. 2607.28883
- TWPA-based readout being implemented
- 12T solenoidal magnet



See https://doi.org/10.22323/1.474.0044

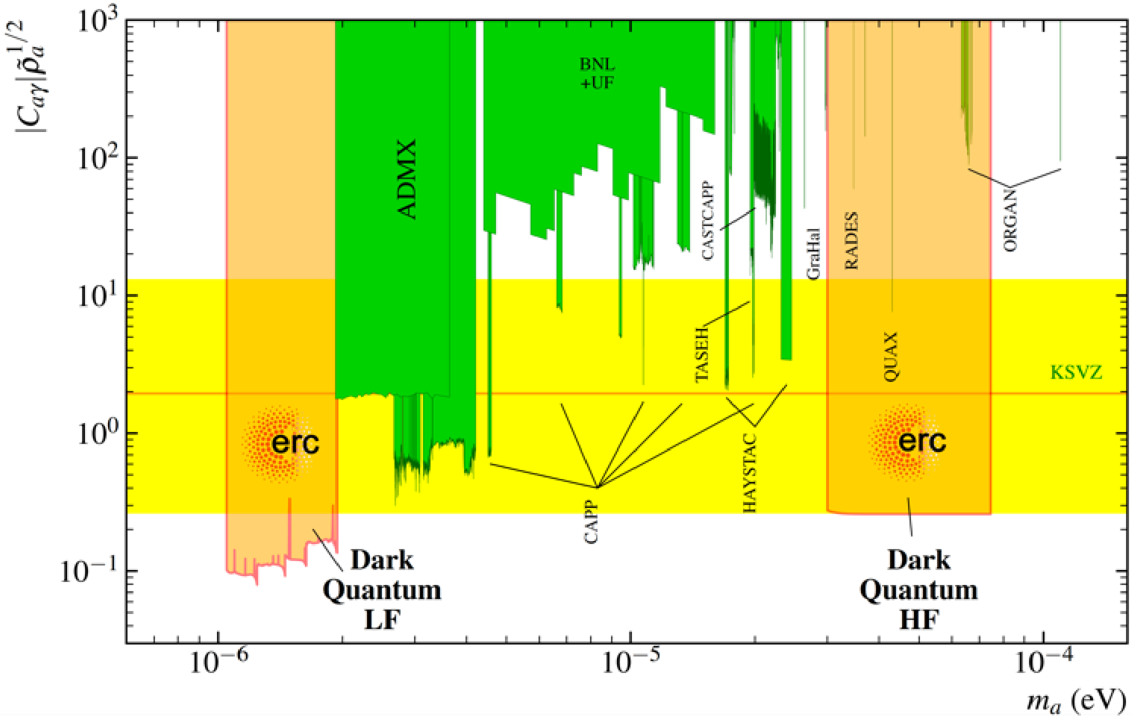




ERC Synergy grant: DarkQuantum

Enhance haloscope searches with quantum techniques.

- Low frequency range: 200-500 MHz (1-2 μeV).
  Quantum-limited linear amplifiers
- High frequency range: 8-18 GHz (30-75 μeV).
  Quantum readout to surpass Standard Quantum Limit.



PI researchers:

- Igor G. Irastorza (Unizar, Zaragoza)
- Takis Kontos (LPENS, Paris)
- Sorin Paraoanu (Aalto University, Helsinki)
- Wolfgang Wernsdorfer (KIT, Karlsruhe)

Collaborators:

- MPP (Munich)
- Universidad Politécnica de Cartagena (Region de Murcia)
- DESY (Hamburg)
- Laboratorio subterráneo de Canfranc (Huesca)
- ICMAB (Barcelona)

DQLF: RADES - BabyIAXO

Low frequency range: 200-500 MHz (1-2 μeV)

DarkQuantum enhances the readout chain of the RADES-BabyIAXO proposal

Current BabyIAXO timeline:
- **2026**: Site activation
- **2027**: *magnetless*-commissioning
- **2028**: dark photon run
- **2029**: magnet installation
- **2030+**: commissioning + axion runs

Roadmap Toward RADES-BabyIAXO experiment

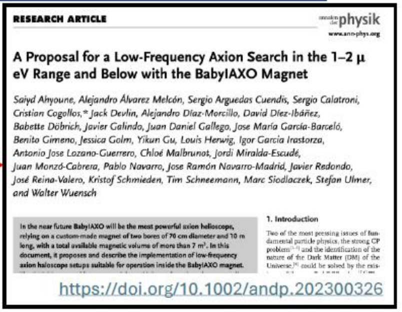
Scaling Up Detection Volume: Scaling physical cavity dimensions from the 1m prototype to 5m multi-haloscope arrays, matching BabyIAXO magnet sub-volumes.

RADES-LF @ BabyIAXO: very competitive prospects for 1-2 meV DM axion searches.

4 x 5m long cavities with tuning slabs.

DarkQuantum will push RADES-LF to SQL.

Standard axion DM paradigm could be fully tested in this range.



RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

A Proposal for a Low-Frequency Axion Search in the 1–2 μ eV Range and Below with the BabyIAXO Magnet

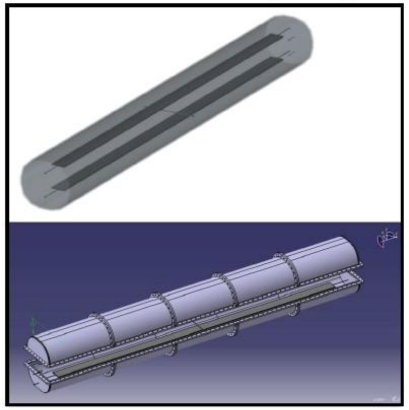
Saiyd Ahyoune, Alejandro Álvarez Melcón, Sergio Arguedas Cuendis, Sergio Calatroni, Cristian Cogollos, Jack Devlin, Alejandro Díaz-Morcillo, David Díez-Ibáñez, Babette Döbrich, Javier Galindo, Juan Daniel Gallego, Jose María García-Barceló, Benito Gimeno, Jessica Golm, Yikun Gu, Louis Herwig, Igor García Irastorza, Antonio Jose Lozano-Guerrero, Chloé Malbrunot, Jordi Miralda-Escudé, Juan Monzó-Cabrera, Pablo Navarro, Jose Ramón Navarro-Madrid, Javier Redondo, José Reina-Valero, Kristof Schmieden, Tim Schneemann, Marc Siodlaczek, Stefan Ulmer, and Walter Wuensch*

In the near future BabyIAXO will be the most powerful axion helioscope, relying on a custom-made magnet of two bores of 70 cm diameter and 10 m long, with a total available magnetic volume of more than 7 m³. In this document, it proposes and describe the implementation of low-frequency axion haloscope setups suitable for operation inside the BabyIAXO magnet.

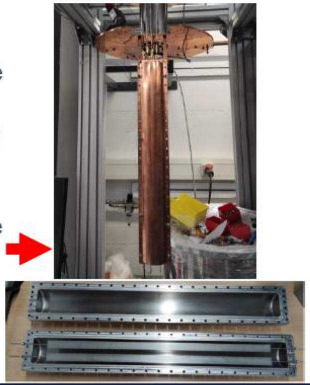
1. Introduction

Two of the most pressing issues of fundamental particle physics, the strong CP problem[1–3] and the identification of the nature of the Dark Matter (DM) of the Universe,[4] could be solved by the exis-

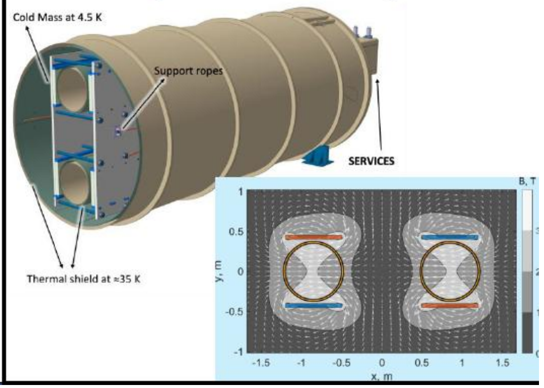
https://doi.org/10.1002/andp.202300326



- BabyIAXO: unprecedented magnetic volume to be available to axion community
- Ultra-cryogenics for unorthodox size and dimensions: challenging but possible.
- First 10x-scaled-down prototype cavity built and tested.



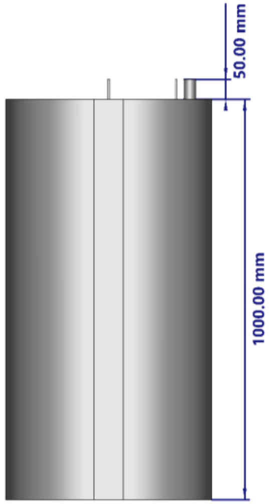
2 x 10-m long 70-cm diameter magnet bores

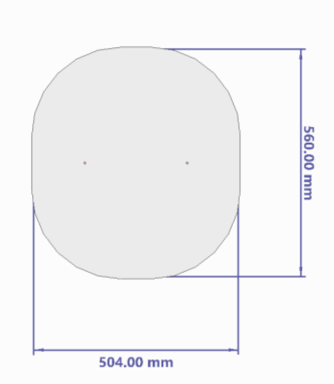


Baseline proposal:
- 4 cavities, 5m long
- Tuning slabs.
- 2 x 70cm diameter bores
- 2T magnet
- mK temperatures

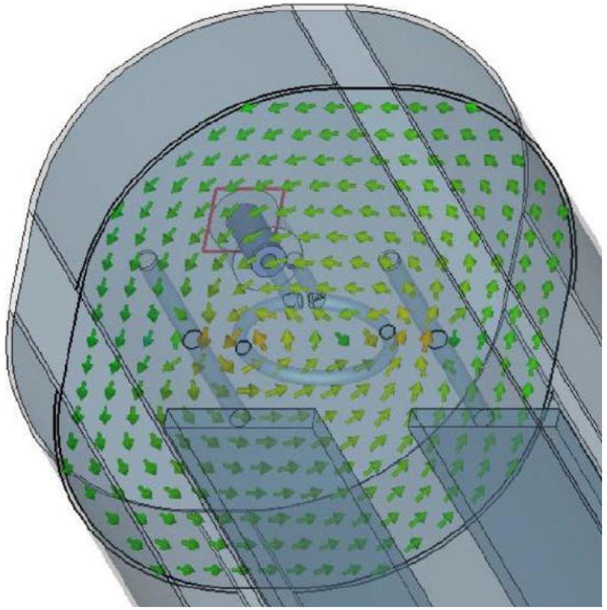
J.M. García-Barceló

1m long prototype is being developed within the RADES collaboration



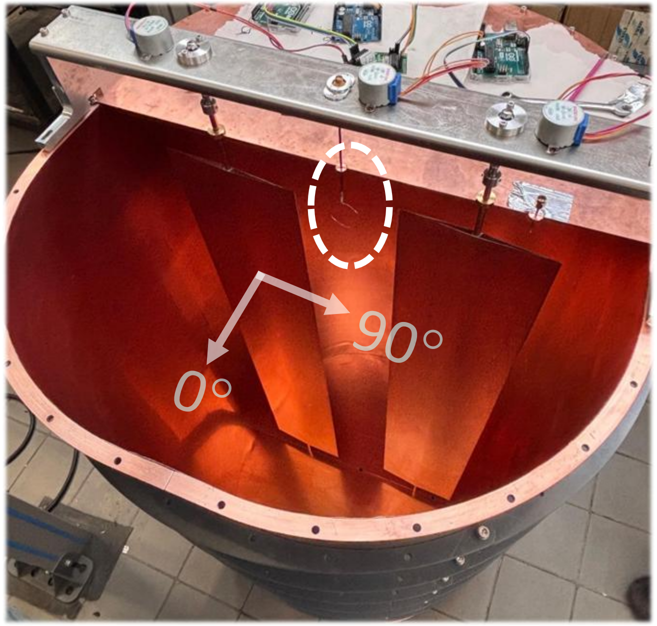


Simulations

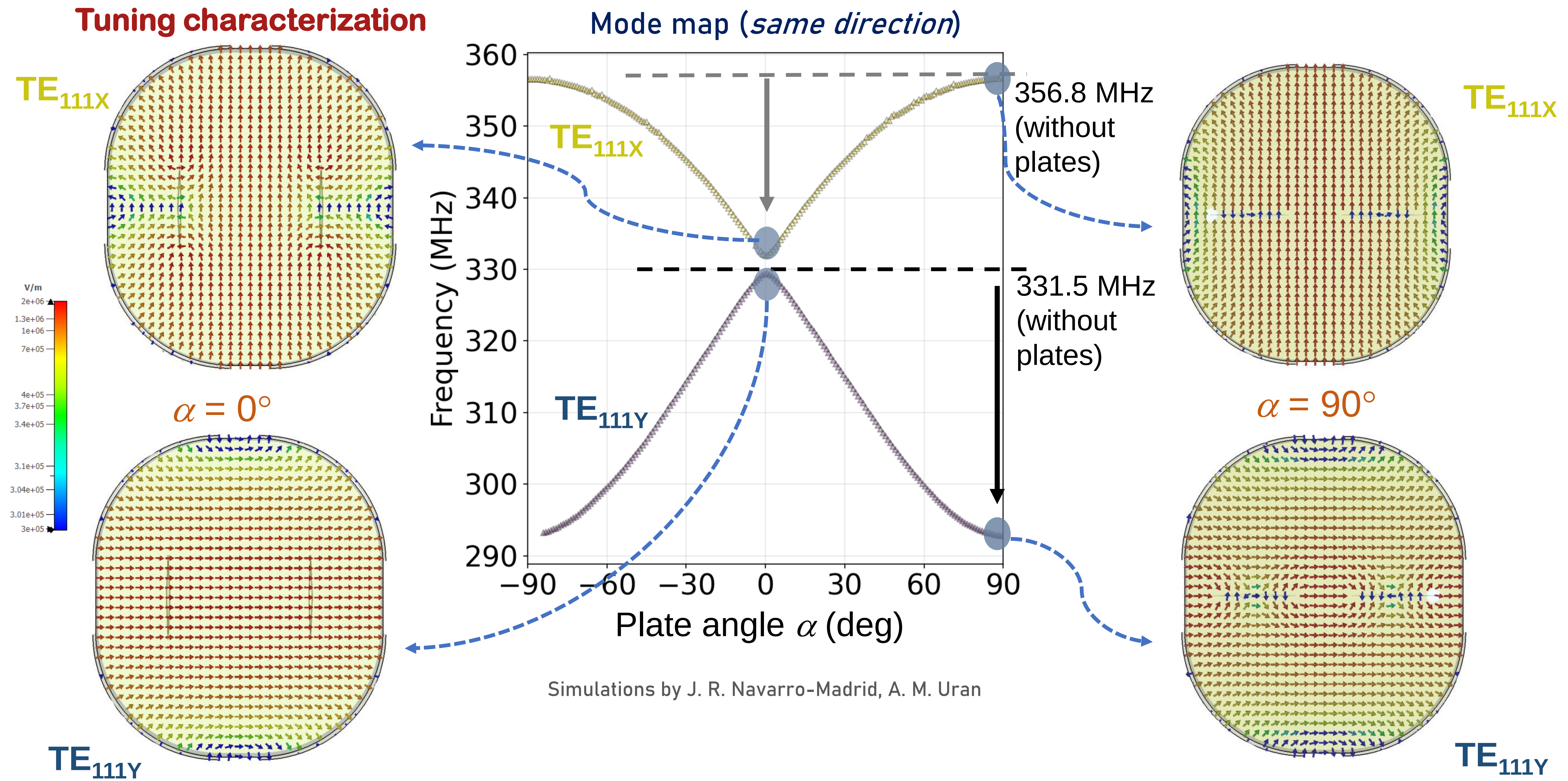


Antenna at $\phi \sim 90°$

Experimental characterization

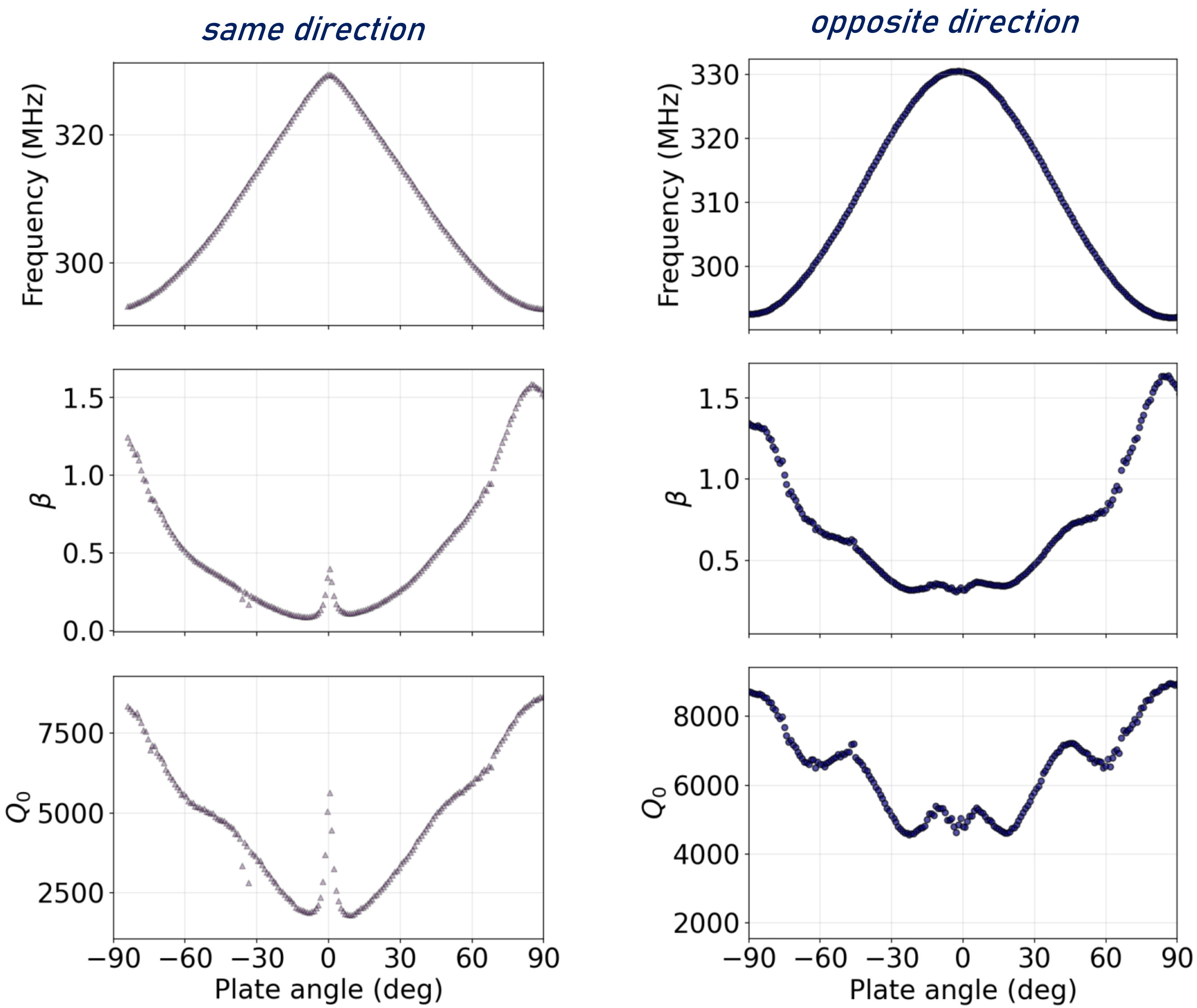


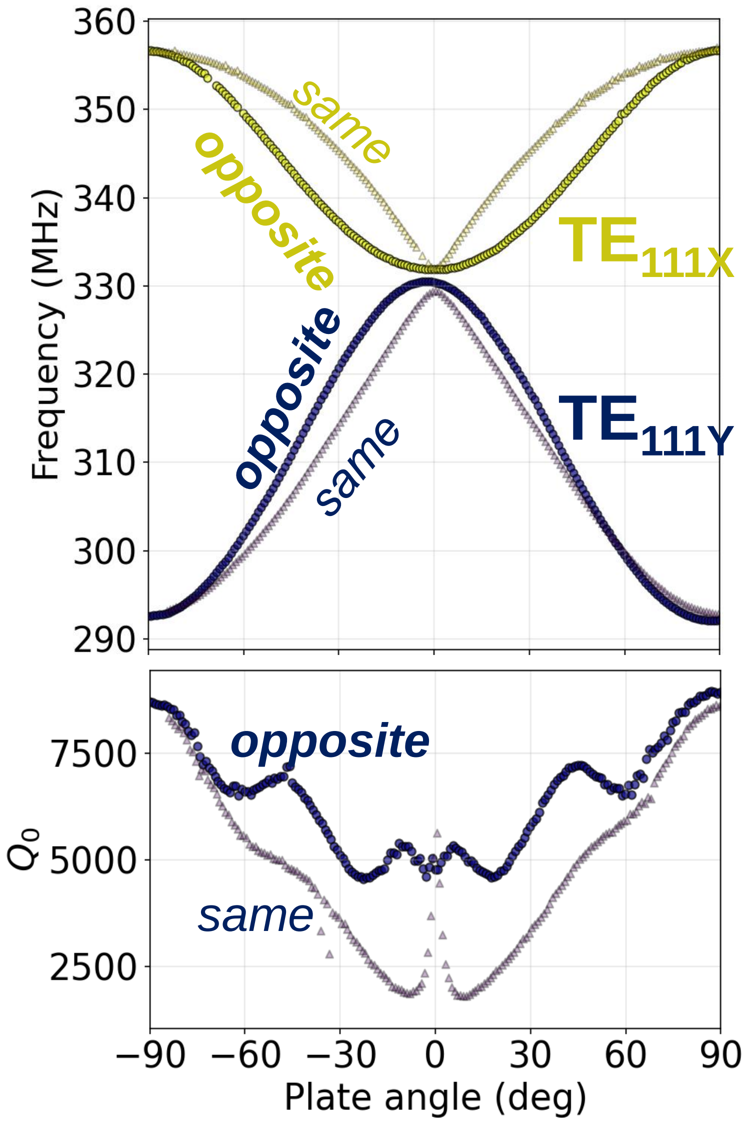
Work done at Karlsruhe Institute of Technology and Universidad Politécnica de Cartagena



Simulations by J. R. Navarro-Madrid, A. M. Uran

Experimental measurements





Characterization of 1m long prototype at KIT:

- Q factor tested (26k in simulations, 10k in measurements at RT)
- Better behaviour with opposite rotating plates
- Different materials for plates being tested
- Optimization of antenna coupling
- Full readout chain in operation

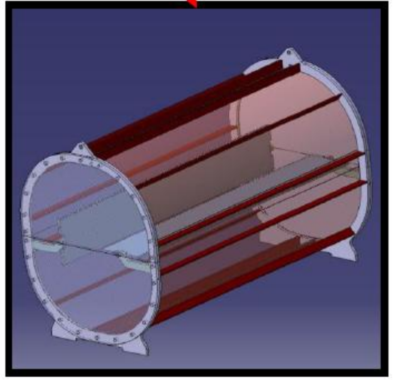
This allows to plan the first data taking campaign in a magnetic field:

M1 magnet at CERN

DQLF First-Gen Prototype

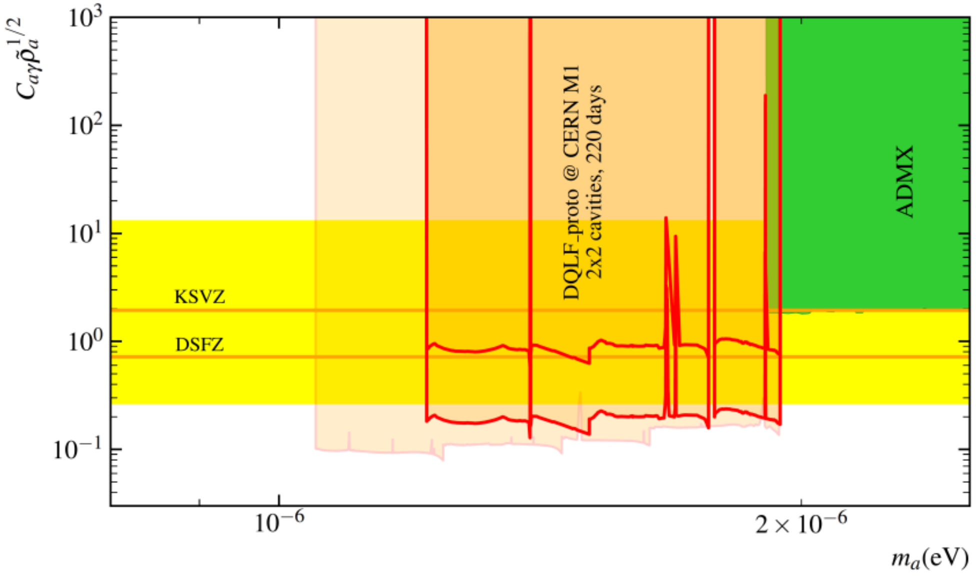
Establishing the Testbed

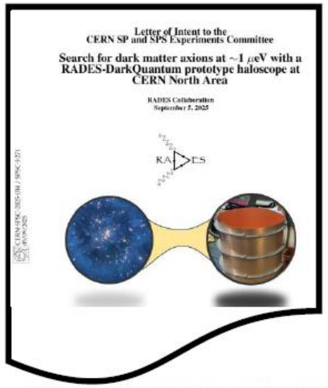
~1 Meter Resonant Cavity: Currently under construction to evaluate detection mechanics at sub-GHz frequencies. First prototype already built and tested at KIT. Second design effort ongoing at CERN.



Availability of suitable magnets at CERN North Area + Long-Shutdown-3 (LS3) a unique opportunity M1 magnet: 3T, 80-cm wide. Could already get physics from them: using M1 magnet at CERN North Area? Recent EoI to CERN SPSC submitted (sept-2025).

J.M. García-Barceló




Letter of Intent to the CERN SP and SPS Experiments Committee

Search for dark matter axions at ~1 μeV with a RADES-DarkQuantum prototype haloscope at CERN North Area

https://cds.cern.ch/record/2941908

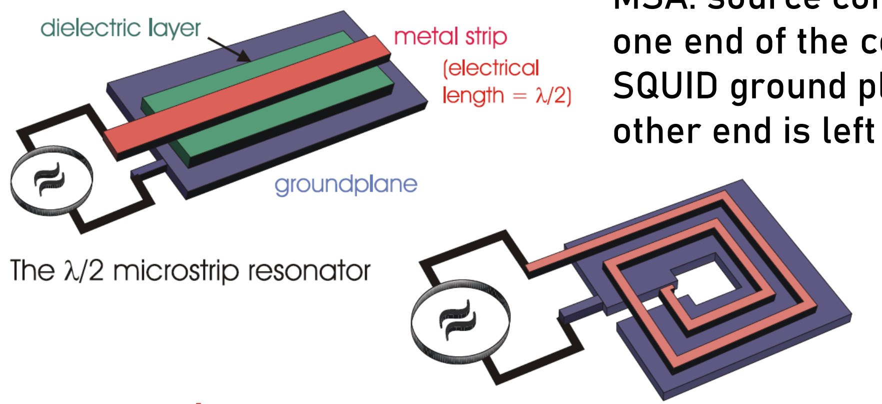
Measurements during Long Shutdown 3 in a 3T, 80cm wide magnet.

mK dilution refrigerator designed for this cavity.

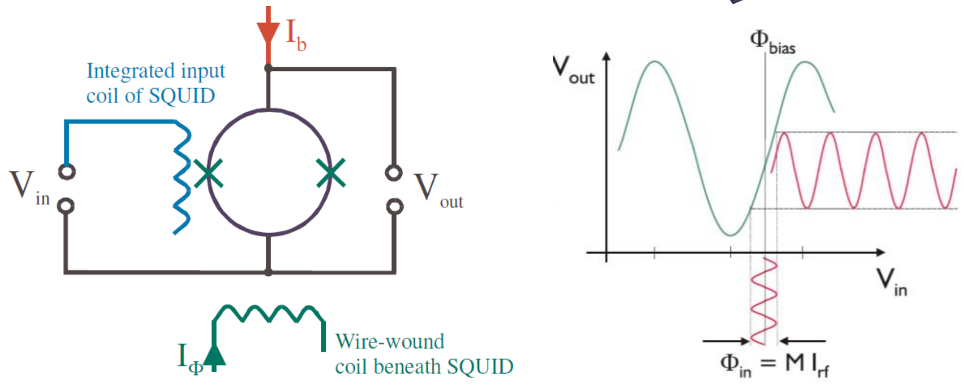
- Proposal submitted and strong support from Magnets team at CERN.
- Meaningful physics results already achievable with a 1m long cavity.

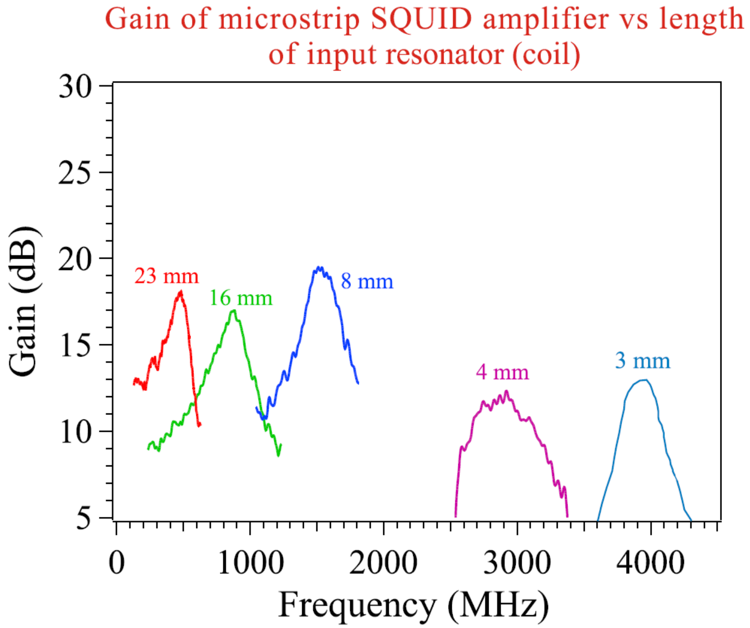
Microstrip SQUID amplifier (MSA)

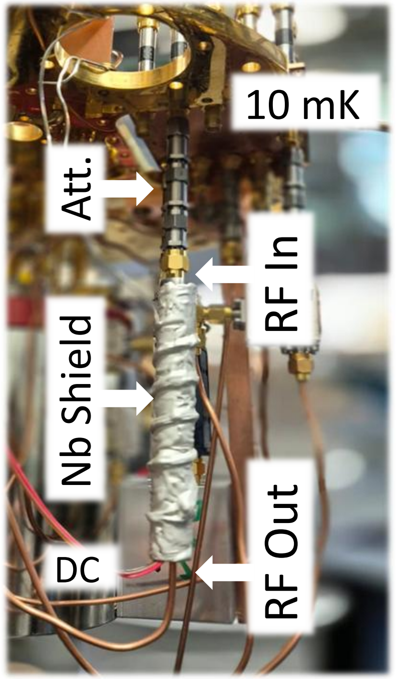
- Quantum limited readout at hundreds of MHz.
- Standard SQUIDs very low gain for these frequencies.
- Microstrip SQUIDs well suited for higher frequencies (MHz/GHz)



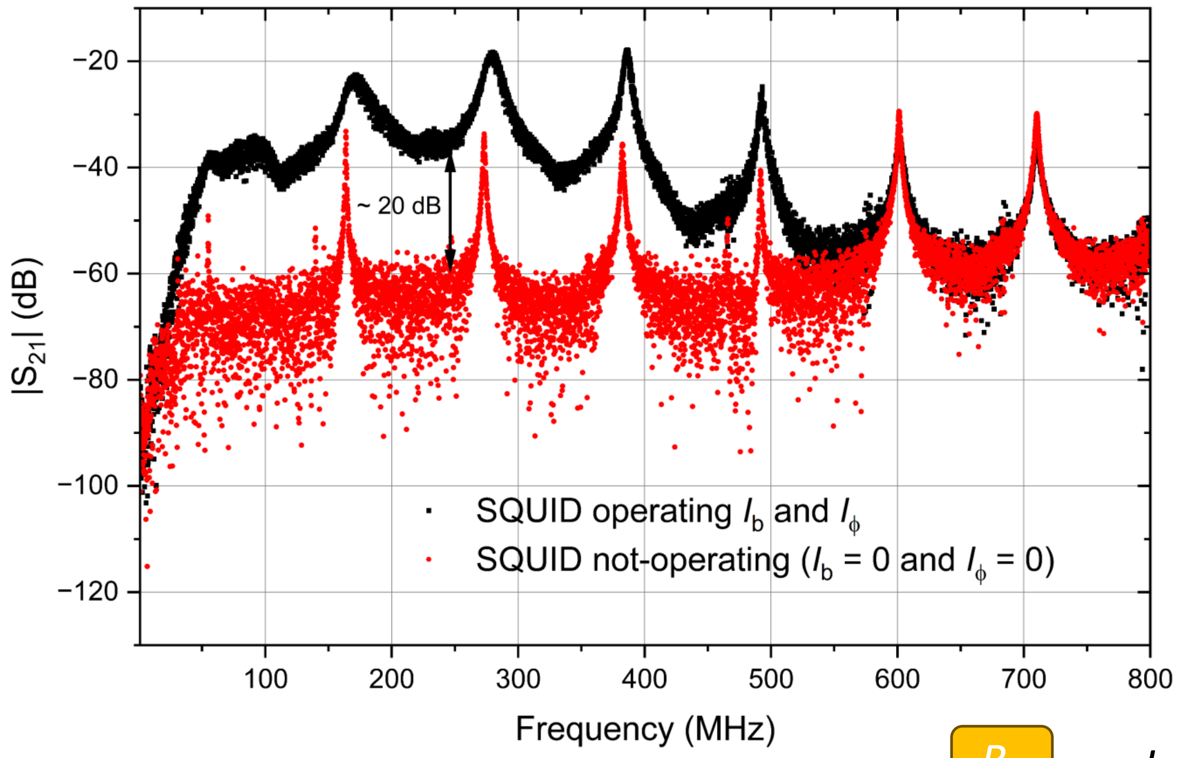
MSA: source connected to one end of the coil and SQUID ground plane, the other end is left open.







Adapted from presentation by Sean O'Kelley,
Clarke Group, University of California, Berkeley (LLNL, 2018)

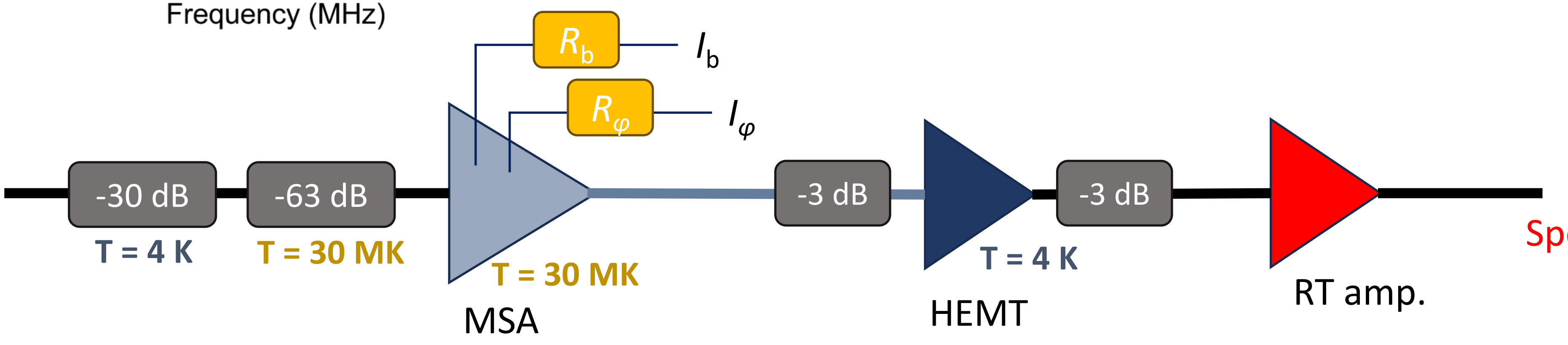


Gain measurements at 30 mK:

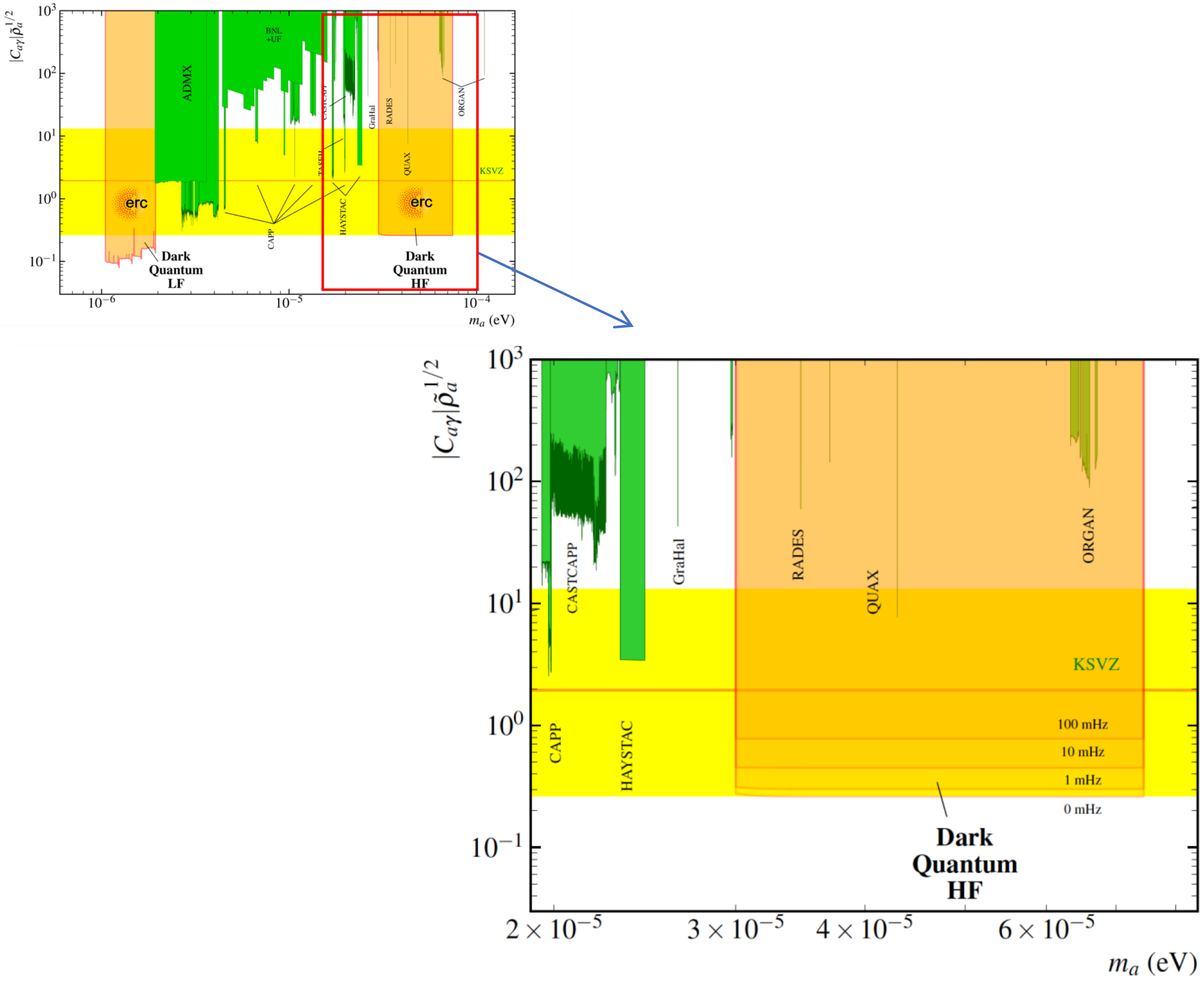
- Homogeneous gain of 20 dB (at 280-360 MHz).
- sensitive to small external field noise, flux trapping
  → needs perfect shielding & 'zero-field'.
- Noise temperature characterization ongoing
  (measured added noise <200mK, target 50mK)

VNA port1 /
Signal generator

Input between
-20dBm to -10 dBm



VNA port2 /
Spectrum analyzer

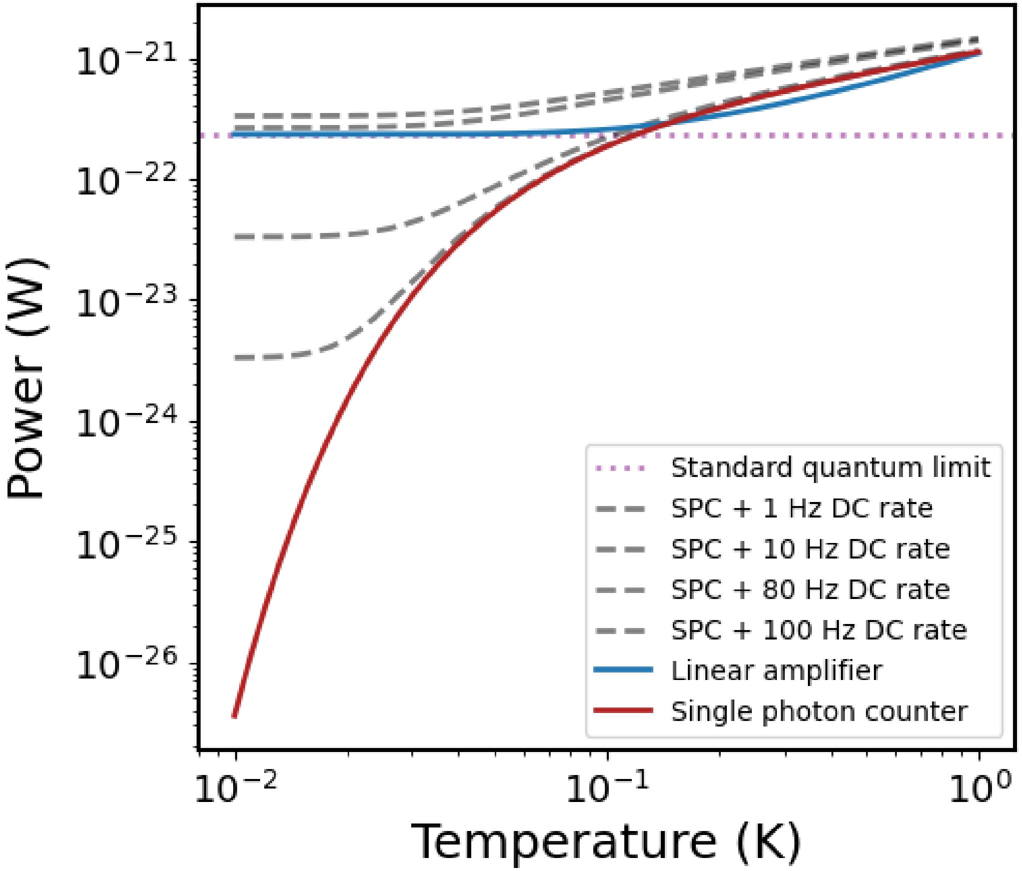


DarkQuantum
ERC Synergy Grant 2023

DarkQuantum high frequency:

- 8-18 GHz (30-75 μeV).
- Qubits as quantum sensors
- Tests in Underground Laboratory of Canfranc (LSC)
- Main challenge: Superconducting qubit in a magnetic field

Overcome standard quantum noise limit



(f=5 GHz, Q=10^6, t=1s)

Linear receiver:

$$P_{LR} = h\nu(\bar{n}+1)\sqrt{\frac{\Delta\nu}{t}}$$

Standard quantum limit:

$$P_{SQL} = h\nu\sqrt{\frac{\Delta\nu}{t}}$$

Single photon counter (SPC)

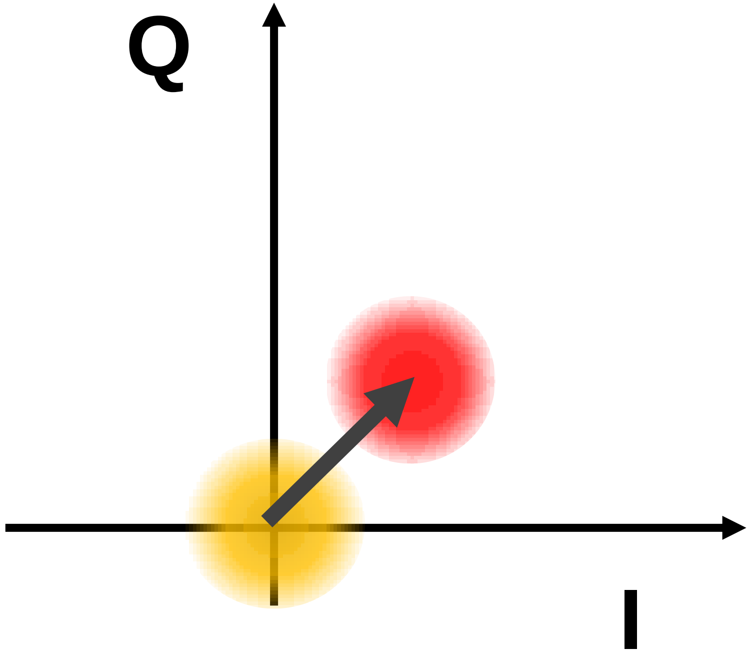
$$P_{SPC} = h\nu_a\frac{\sqrt{N}}{t} = h\nu_a\sqrt{\frac{2\pi\nu\bar{n}}{Q_c t}}$$

Lamoreaux et al. Phys. Rev. D 88, 035020 (2013)

Move from measuring IQ conjugate variables to Nϕ and measure only one of them

Measuring power

Axion conversion induces
a displacement in IQ plane

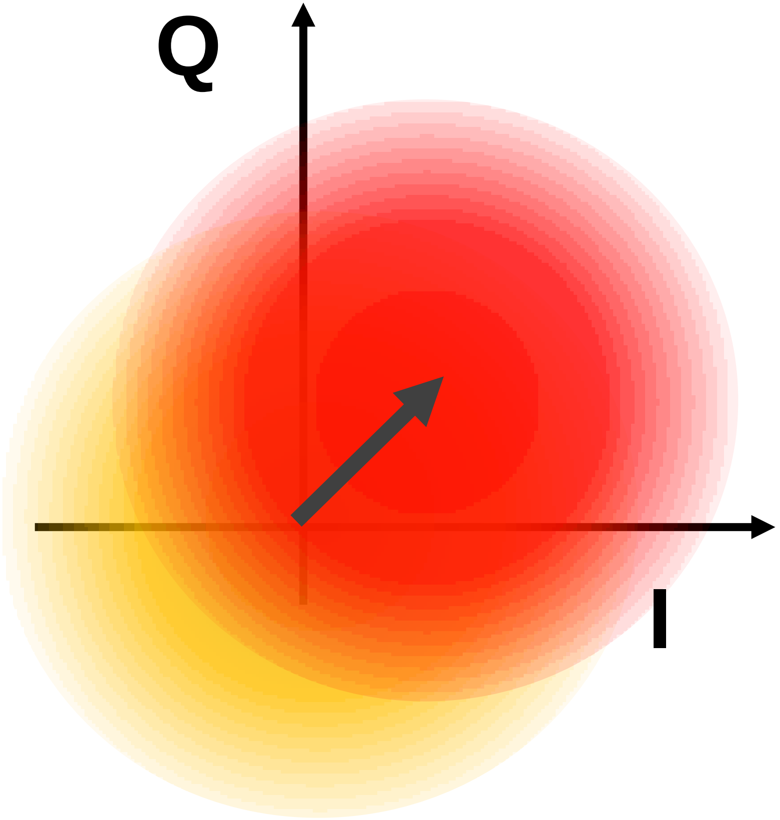


Move from measuring IQ conjugate variables to Nϕ and measure only one of them

Measuring power

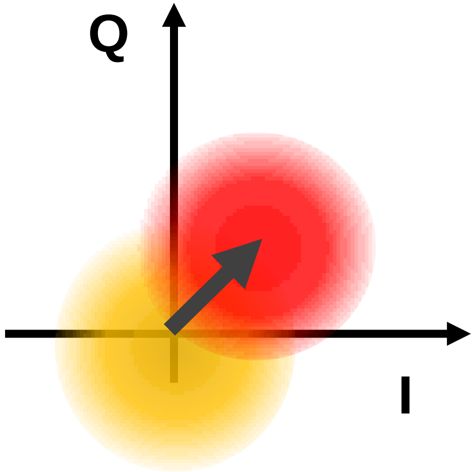
Axion conversion induces a displacement in IQ plane.

Acual displacement could be tiny compared to noise.



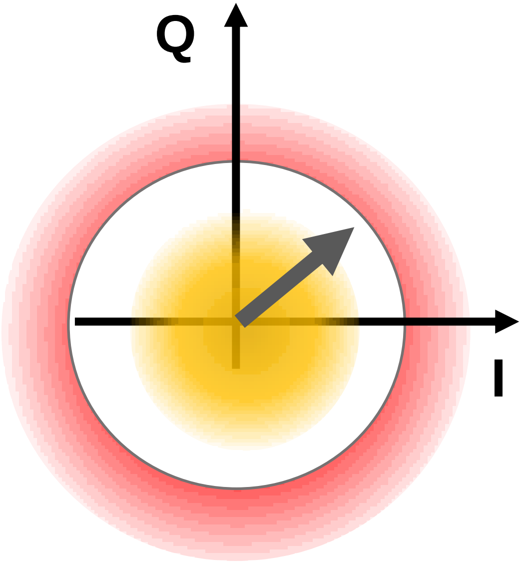
Quantum readout of an haloscope

Move from measuring IQ conjugate variables to Nϕ and measure only one of them.

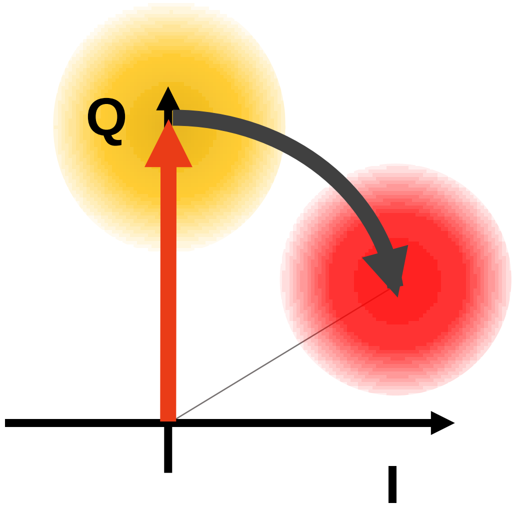


Measuring power (IQ)

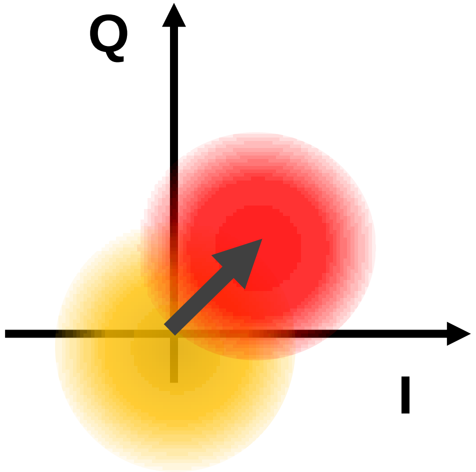
Counting photons (N)



Measuring phase (ϕ)

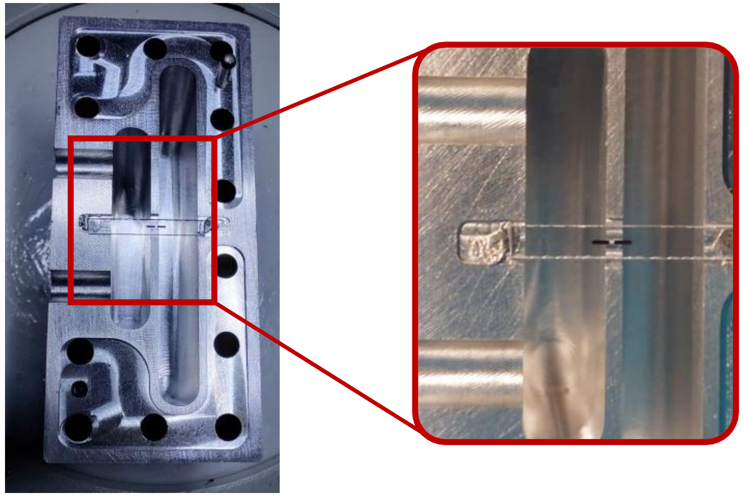


Move from measuring IQ conjugate variables to Nϕ and measure only N



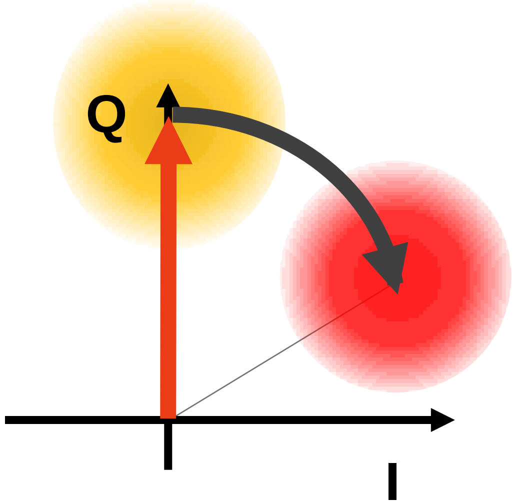
Measuring power

Counting photons



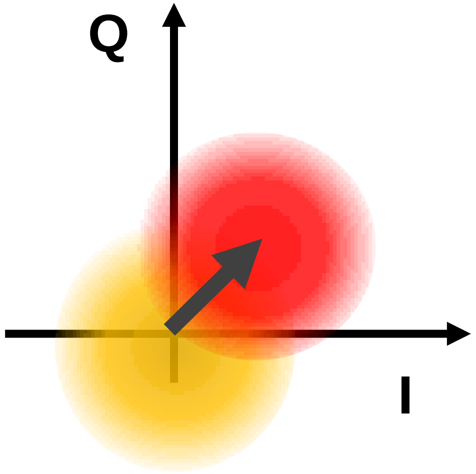
Microwave single photon counter

Measuring phase (ϕ)



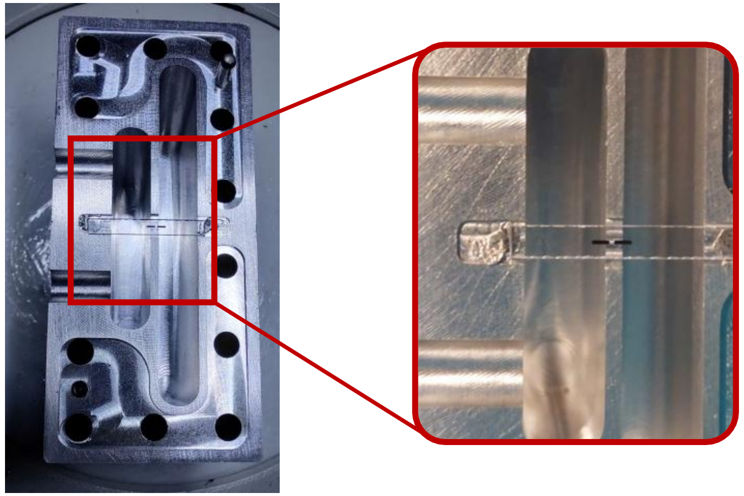
Quantum readout of an haloscope

Move from measuring IQ conjugate variables to Nϕ and measure only N



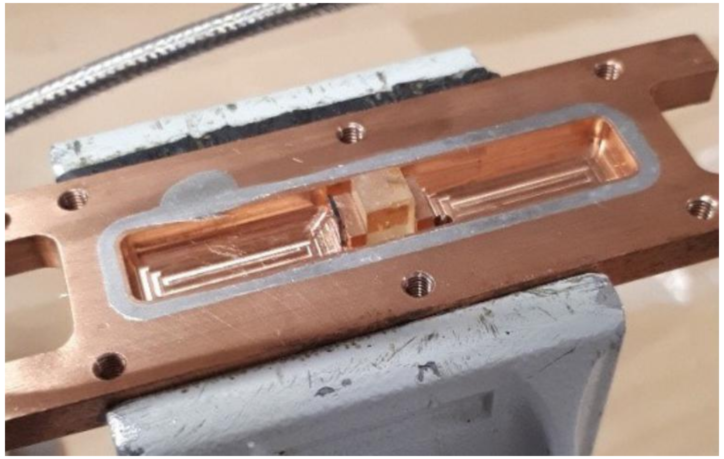
Measuring power

Counting photons



Microwave single photon counter

Measuring phase (ϕ)



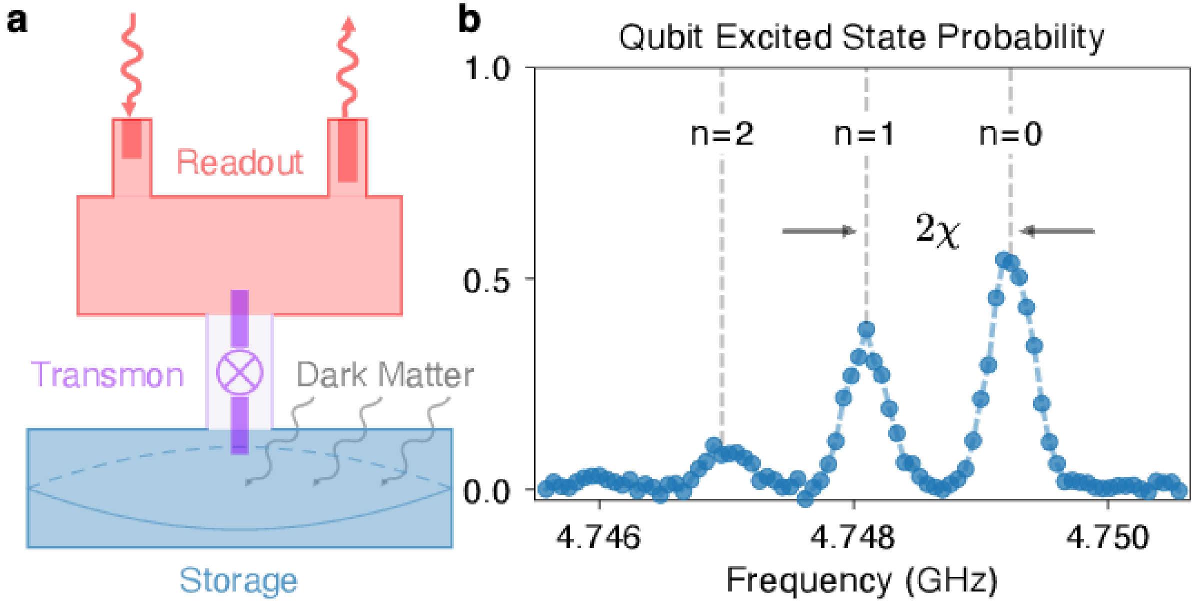
Phase resolved haloscope

Working principle

- Readout cavity: To check the state of the transmon
- Transmon: Superconducting qubit
- Storage cavity: dark matter conversion into photons

Characteristic qubit frequency changes when a photon appears in the storage cavity.

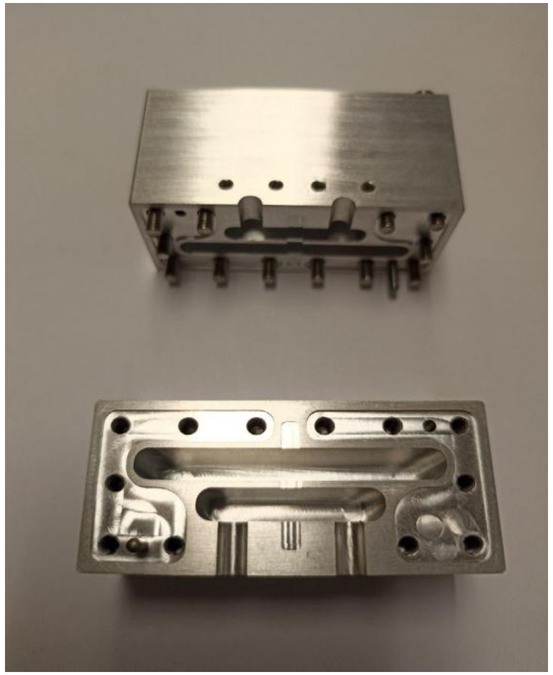
Readout sequence designed to be sensitive to storage photon presence and to reduce quantum errors through quantum non-demolition measurements.

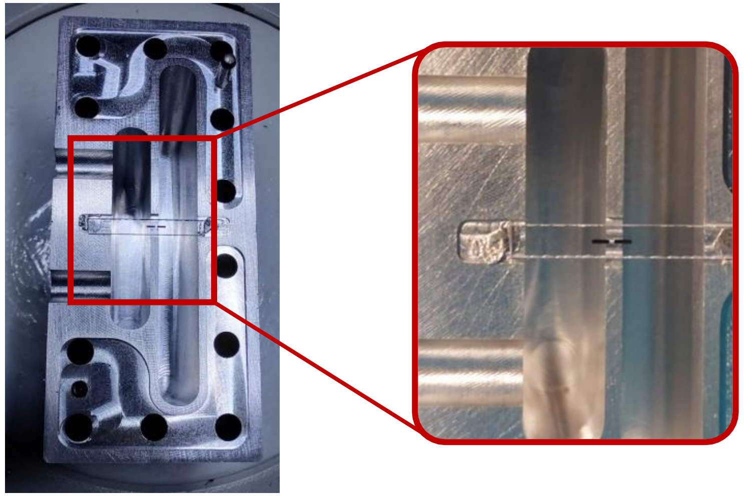


Dixit et al. Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126

Ingredients for a microwave SPC

Double cavity
(Readout + Storage)



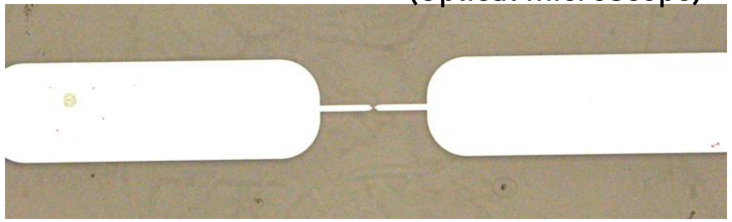


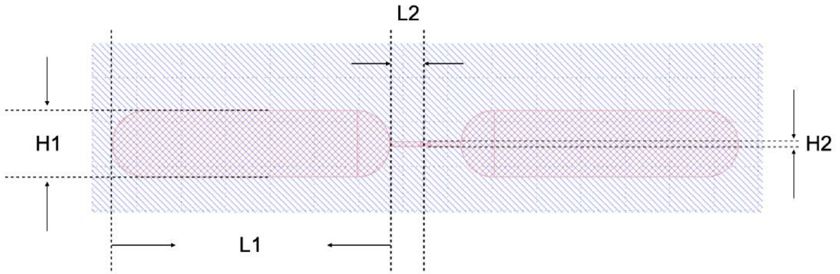
Cold!

Dilution refrigerator: 10-20 mK

Transmon

(Optical microscope)



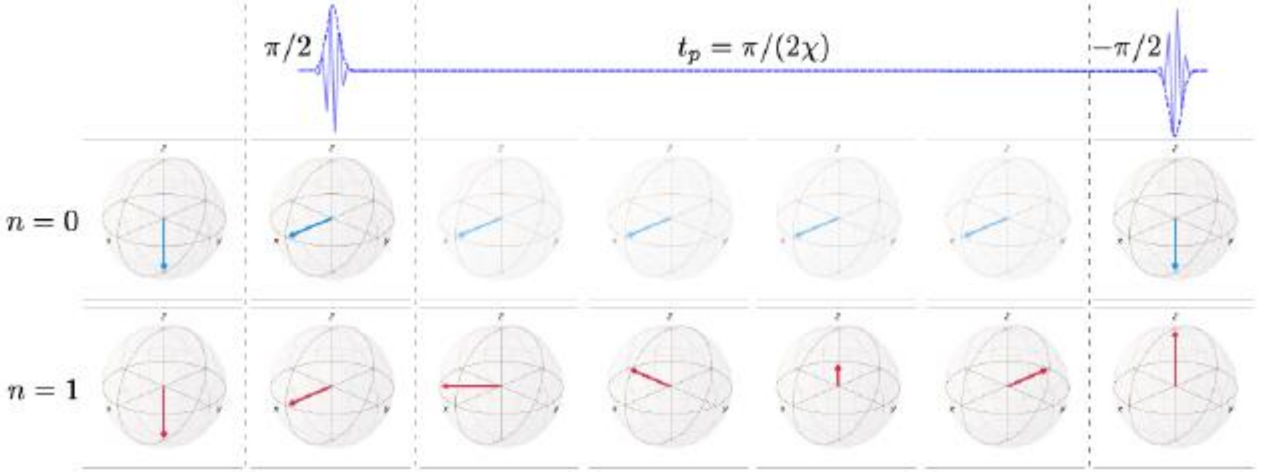


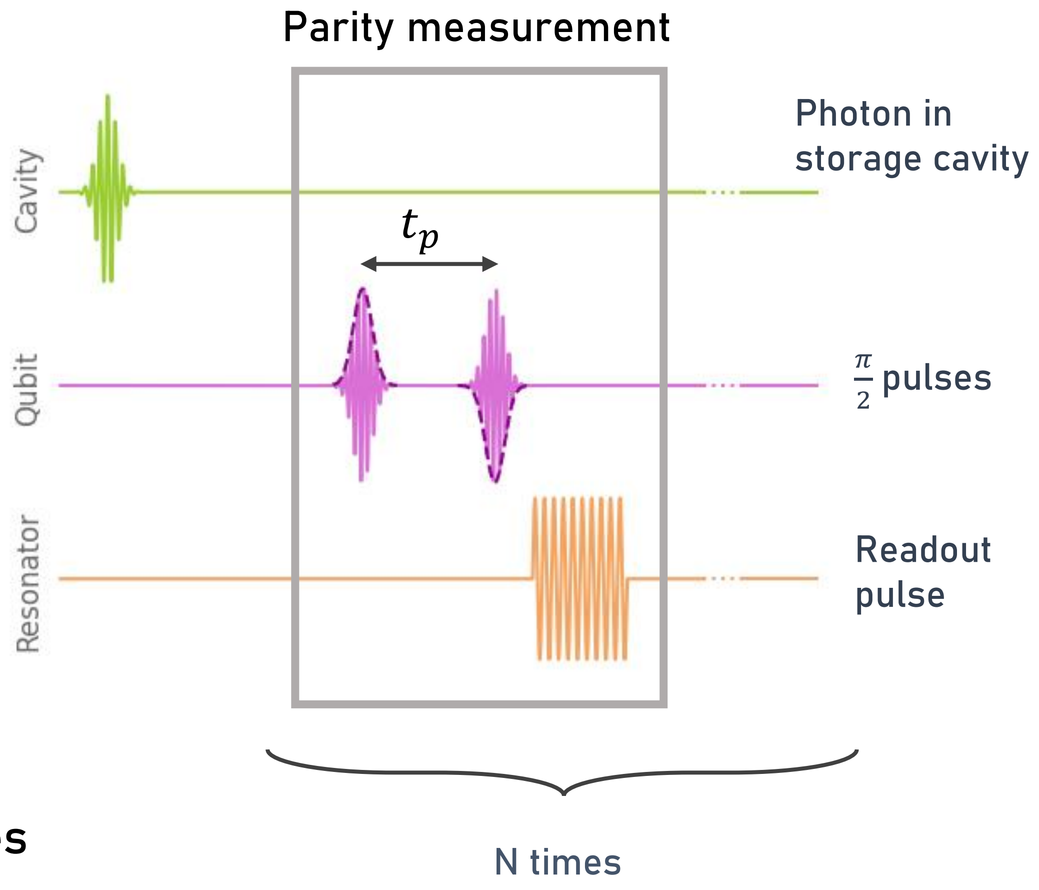
	Q1
L1 (mm)	1
H1 (mm)	0.3
L2 (mm)	0.15
H2 (mm)	0.02

Parity measurement

Interferometric measurement.

Precession of qubit state in the Bloch sphere dependent on photon content.

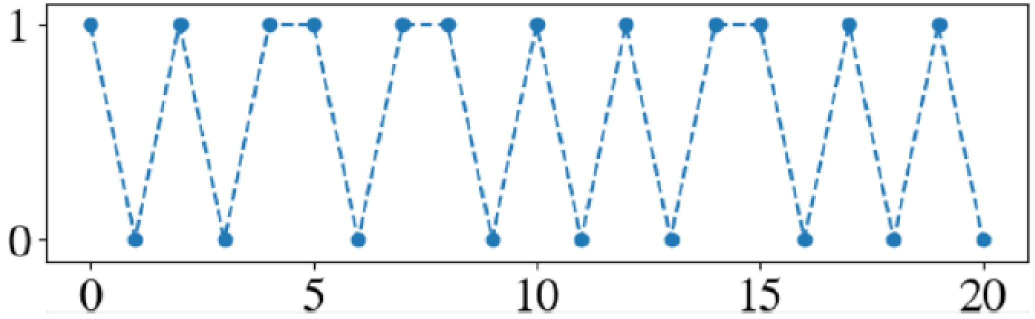




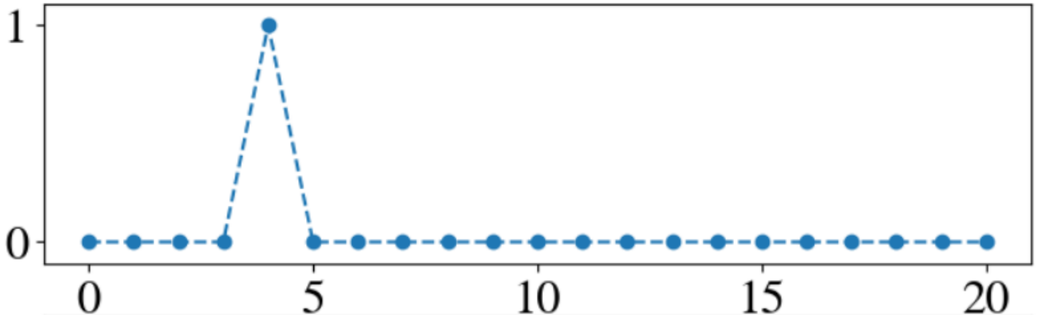
Parity sequence: ($\pi/2$ + Wait t_p + $-\pi/2$ + Readout) x N times

Parity sequence

Injecting photons



Not injecting photons



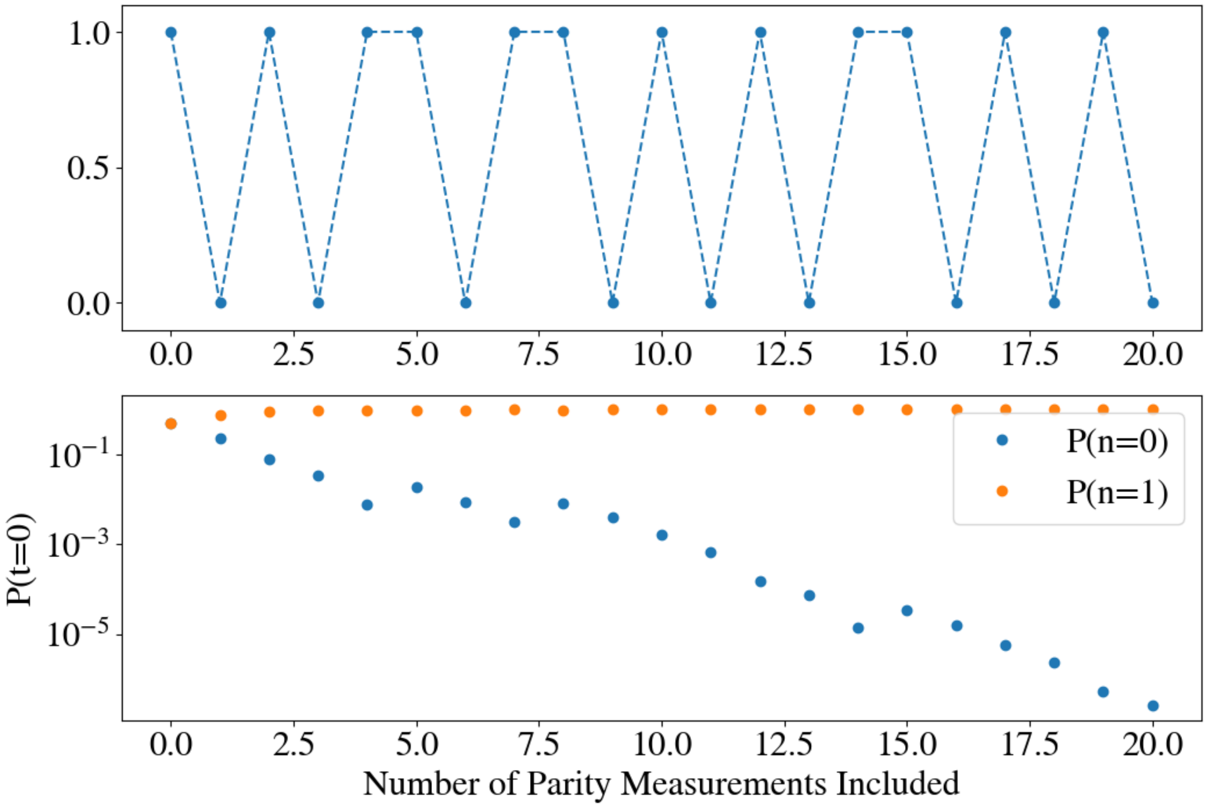
N = 21

Nth measurement

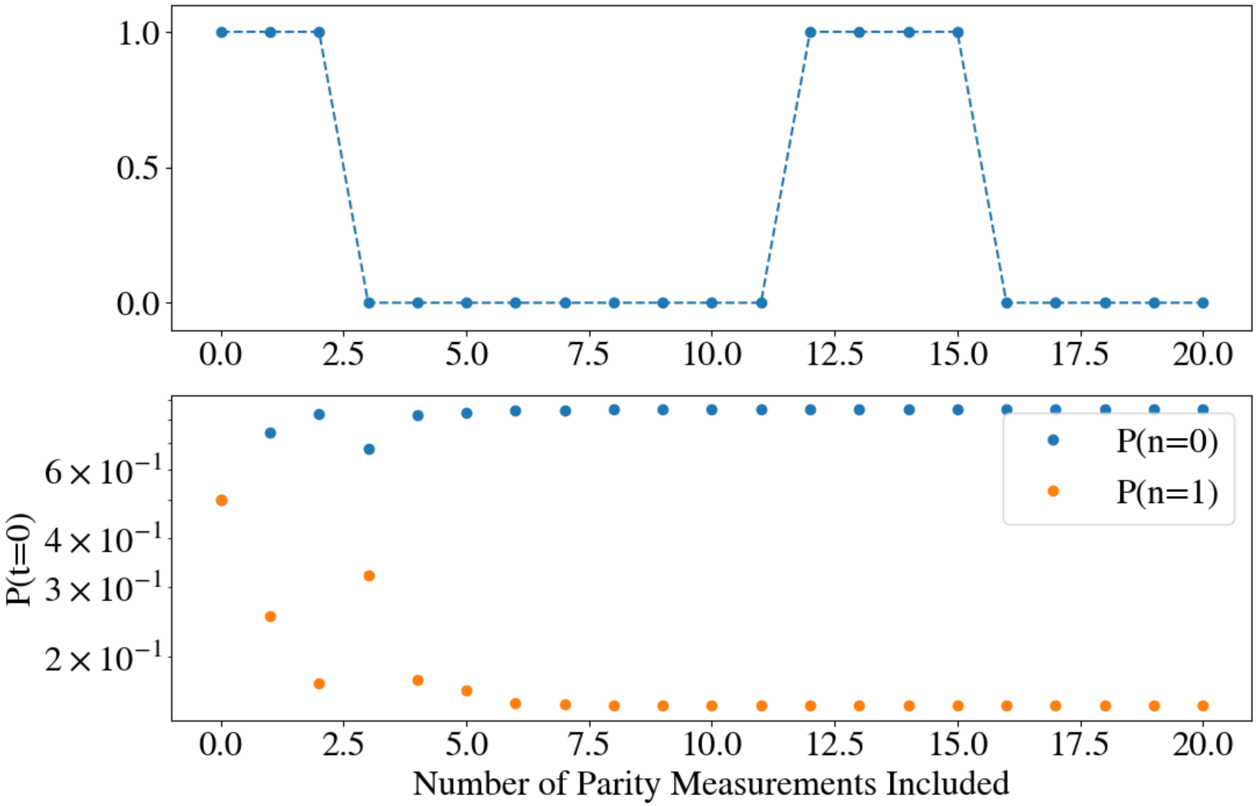
Nth measurement

Probabilities of hidden states: Hidden Markov Model

Photon in storage cavity

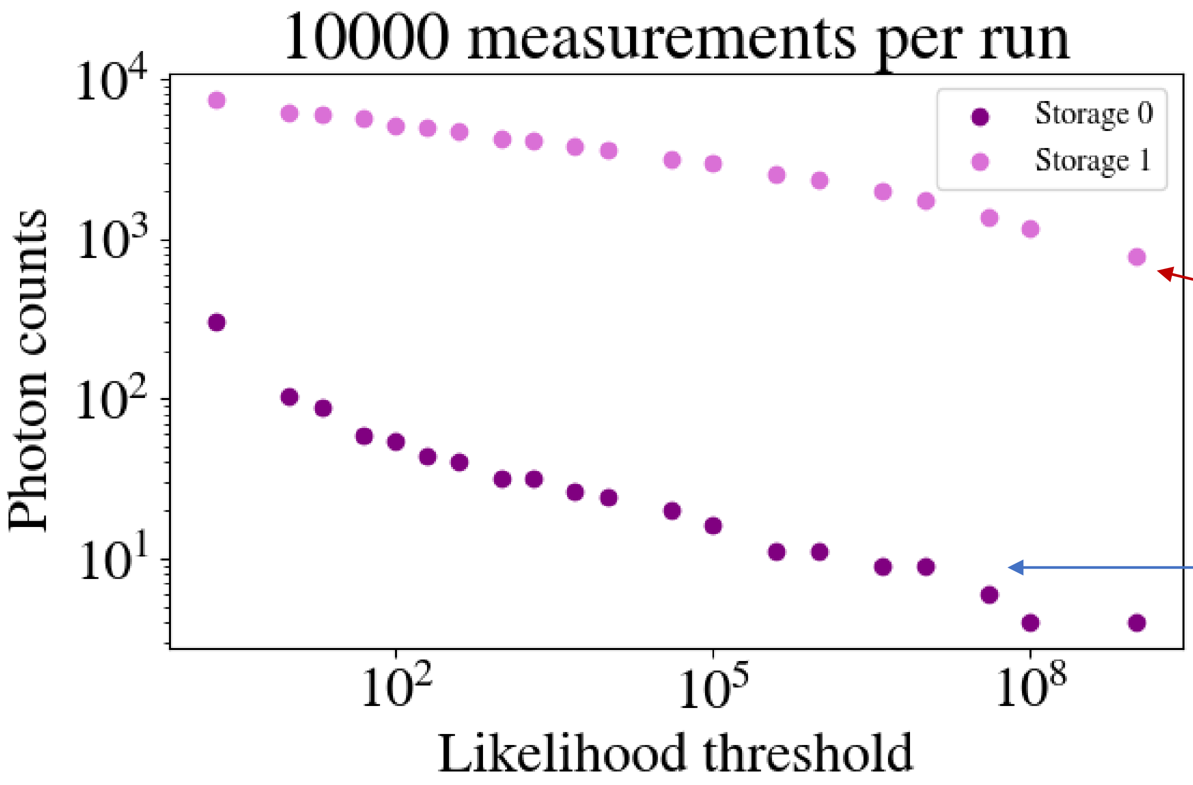


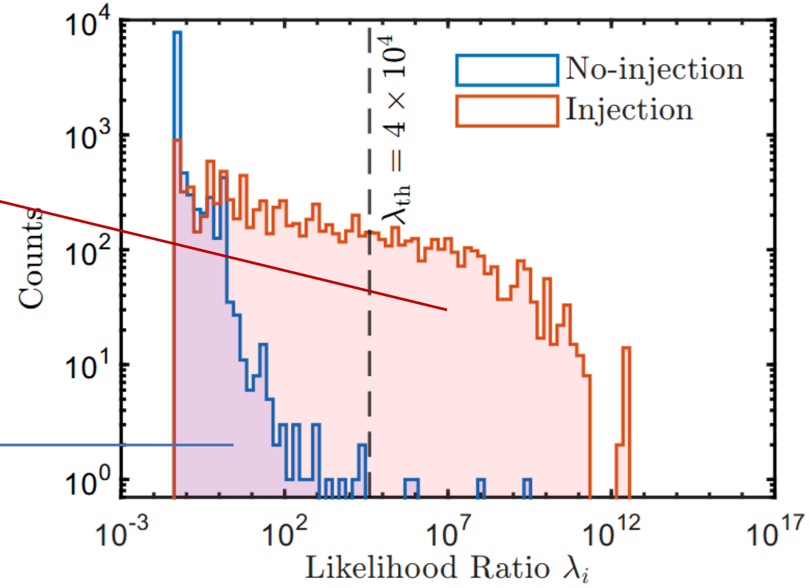
No photon in storage cavity



Distributions of likelihood test

Likelihood test: $\lambda = \dfrac{P(n_0 = 1)}{P(n_0 = 0)}$





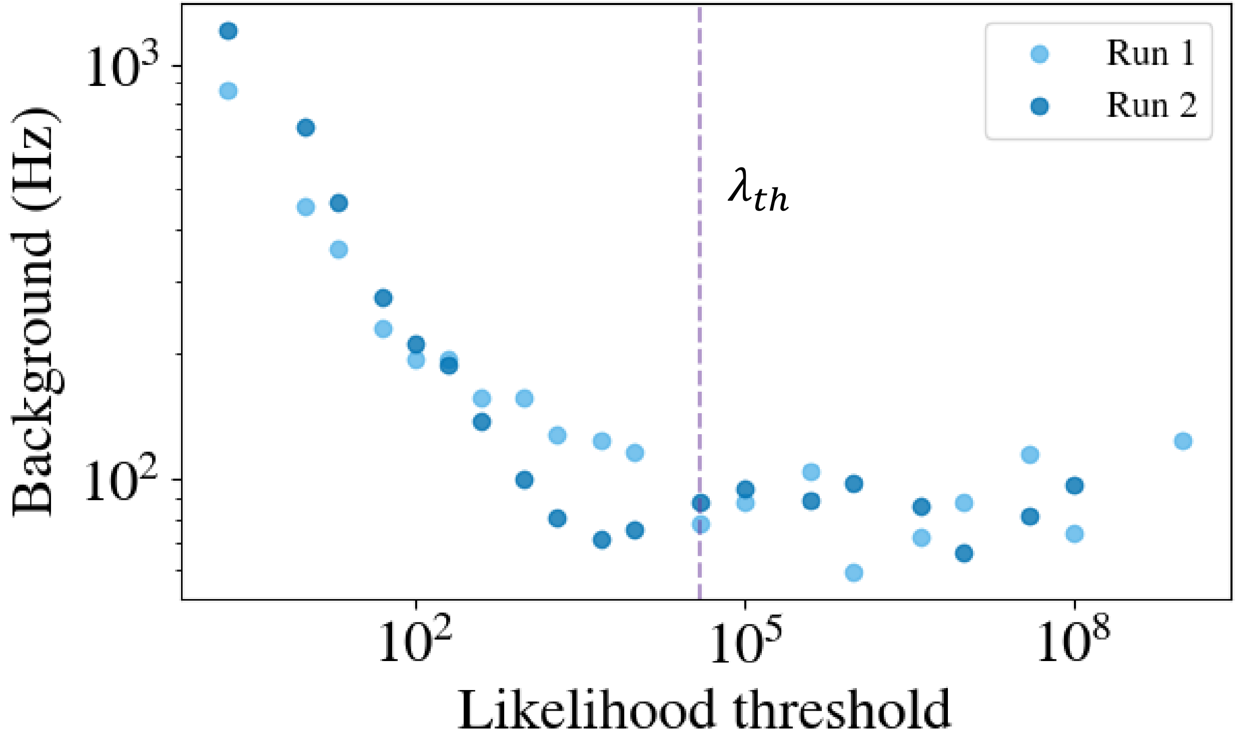
Likelihood threshold: Chosen λ value to discriminate the presence of a photon.

First RADES runs in Aalto University

	$\Pi/2$	t_p	$-\Pi/2$	Readout	Delay	t_m	Total time (N=21)
Run 1	52 ns	88 ns	52 ns	800 ns	100 ns	1092 ns	22.932 us
Run 2	52 ns	88 ns	52 ns	800 ns	100 ns	1092 ns	22.932 us

Two runs with 10000 parity sequences each.
Same parameters in both runs.

Background rate estimation

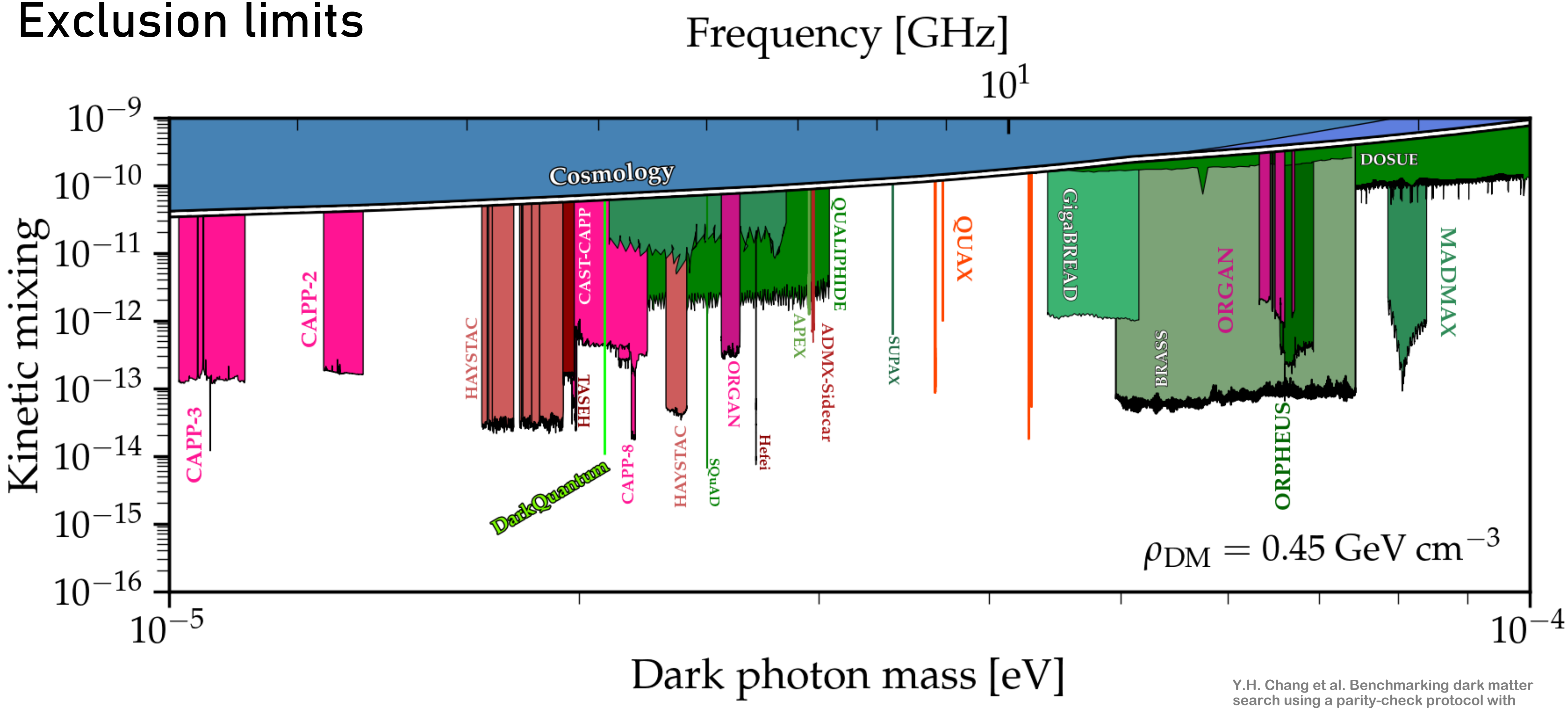


10000 measurements
$T_1^s = 20\ \mu s$
$\lambda_{th} = 4 \times 10^4$

$\lambda_{th} = 4 \times 10^4$	Background (Hz)	Efficiency	Live time (s)
Run 1	77.94	25.7%	0.2
Run 2	87.35	28.6%	0.2

* Efficiency corrected background

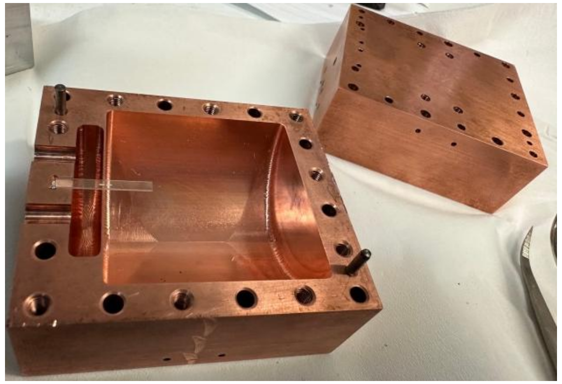
Exclusion limits



Y.H. Chang et al. Benchmarking dark matter search using a parity-check protocol with machine-learning optimized pulses, Phys. Rev. D

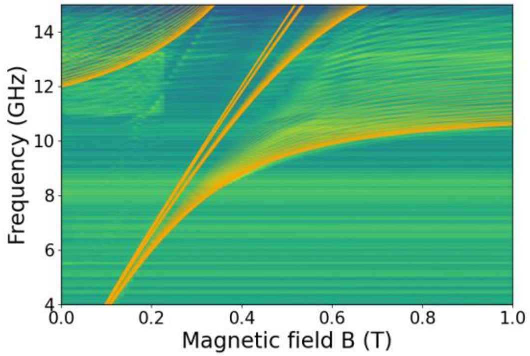
Scale up

- Increase volume for higher sensitivity
- Test mode clustering and qubit couplings



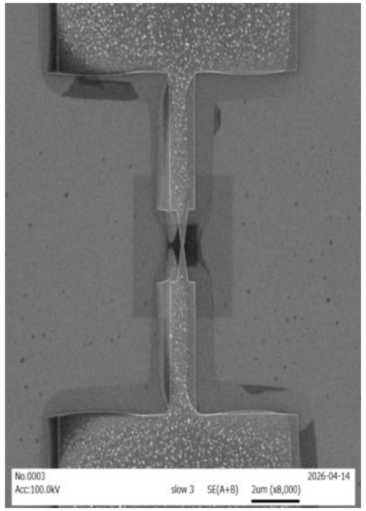
Tuning sytems

- Vertical cut tunning
- Ferromagnetic tuning (YIG)



Magnetic field

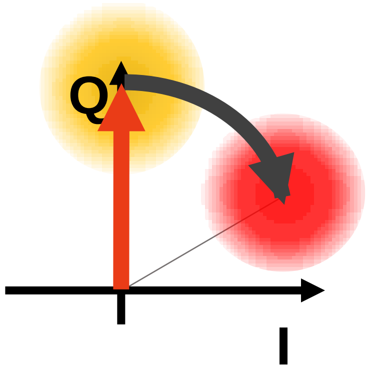
- Magnetic resilient qubits: Granular aluminium
- Shielding and counter coils

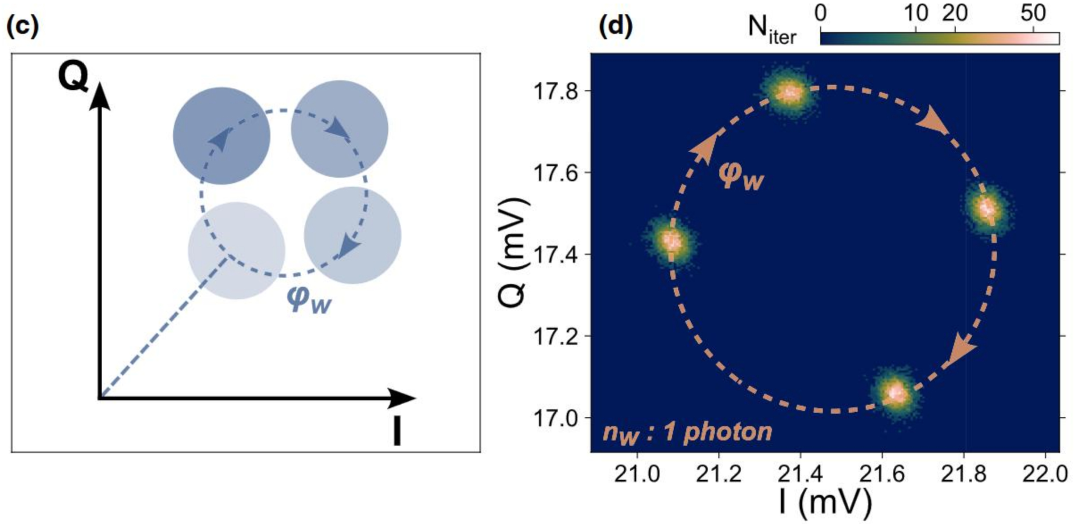


Look for a coherent signal interfering with a known reference tone.

Coherent axion signal with coherence time dependent on the linewidth:

$$\tau_a = \frac{Q_a}{f} \Rightarrow 5GHz\ axion\ \rightarrow \tau_a = \frac{10^6}{5 * 10^9 Hz} = 200\ \mu s$$





Axion phase measured with respect a coherent reference tone (â)

$$\Delta\omega_q = K\ [\ |\hat{a}|^2 + |\hat{a}_{ax}|^2 + 2|\hat{a}||\hat{a}_{ax}| \cos(\varphi_{ax})]$$

The random phase of the axion signal makes the state rotate in IQ plane due to interference pattern.

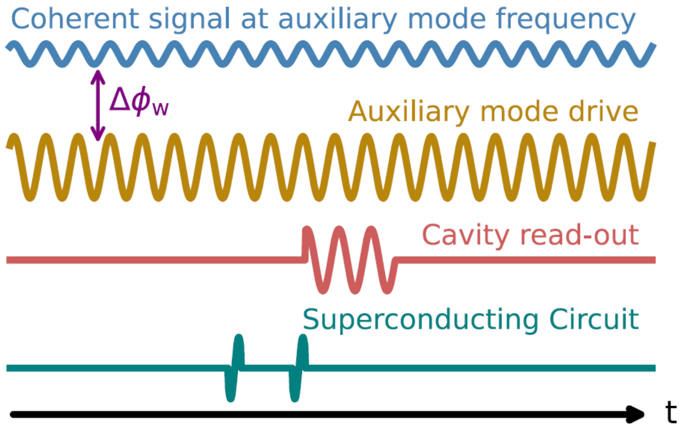
Diameter of the rotation proportional to the axion signal amplitude.

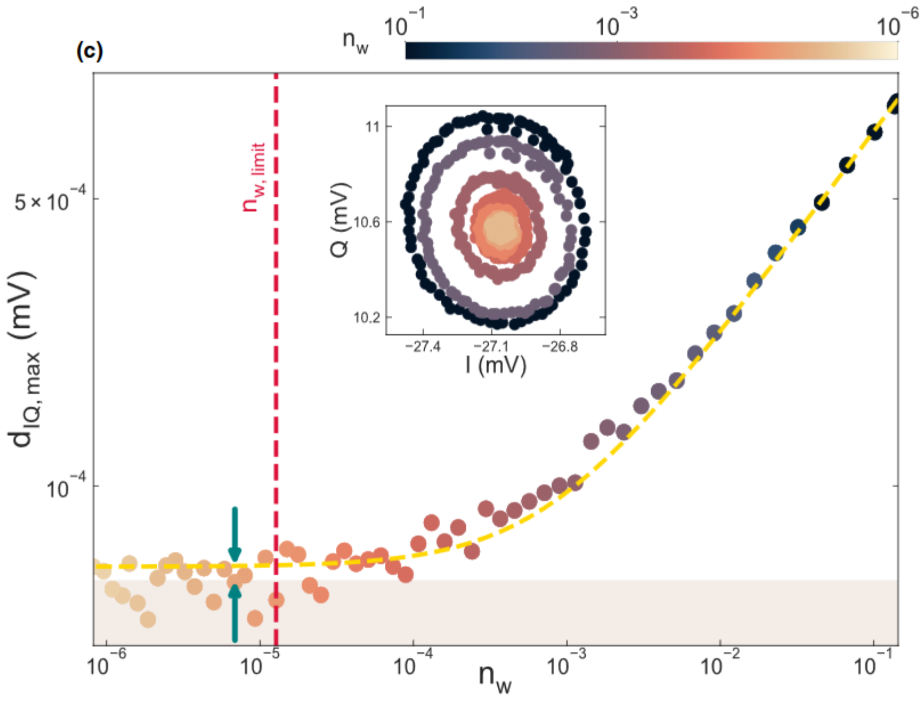
Phase resolved haloscope

Pulse sequence:

- Continous refence tone at detection mode (yellow).
- Ramsey interferometry pulses (green).
- Readout tone (red).

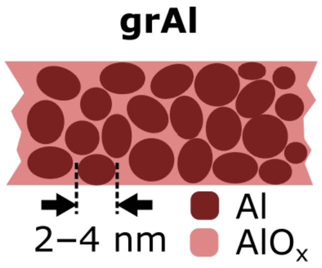
Axion weak tone injected for calibration (blue).
Amplitude and phase of the weak tone vary.





Varying pahse: circles in IQ plane
Varying amplitude: diameter of the circles
Smallest detectable signal: circles become a blob

Granular aluminium transmons

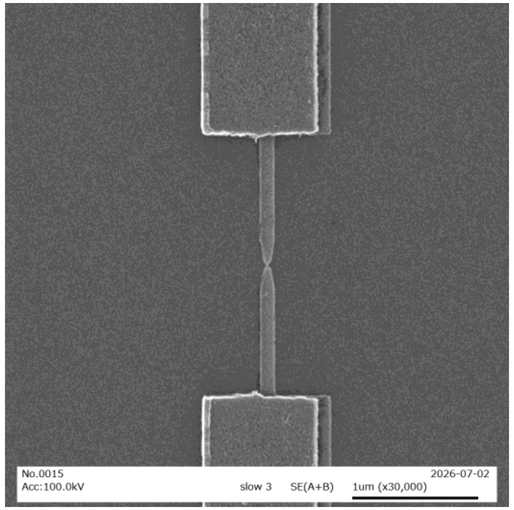


Transmon: Granular aluminium with niobium pads.
Weak anharmonicity K = 200 ± 50 kHz
This has disadvantages but helps in a high density photon environment (pump).
Works ongoing to increase anharmonicity

Al grains in a AlO matrix.

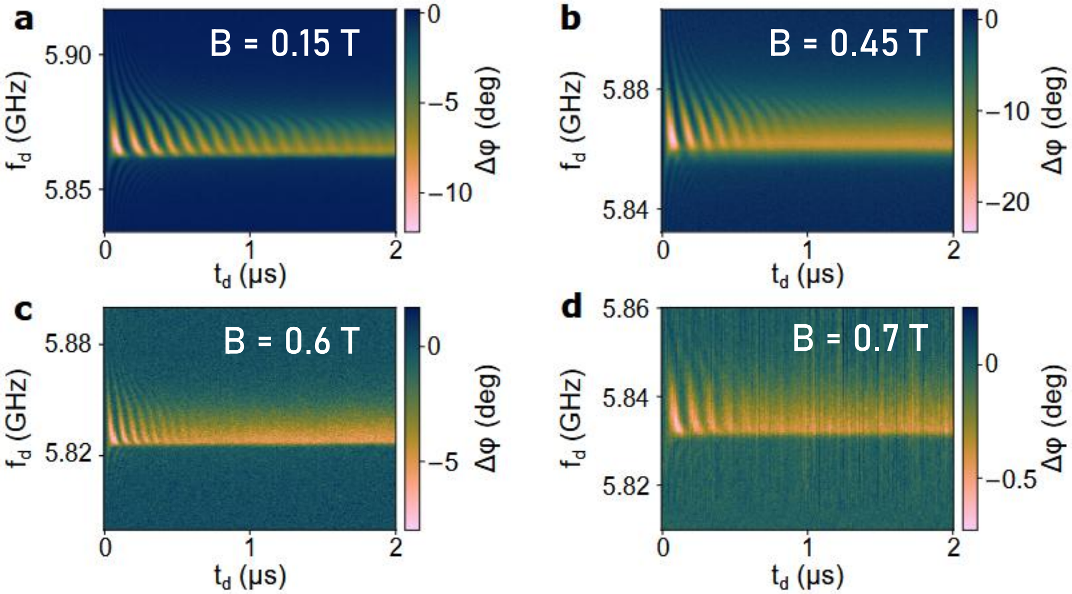
Behaves like a chain of Josephson junctions.

Superconducting circuit consisting in two pads and a point-contact union.



GrAl 25nm constriction

Rabi oscillations with in-plane B field

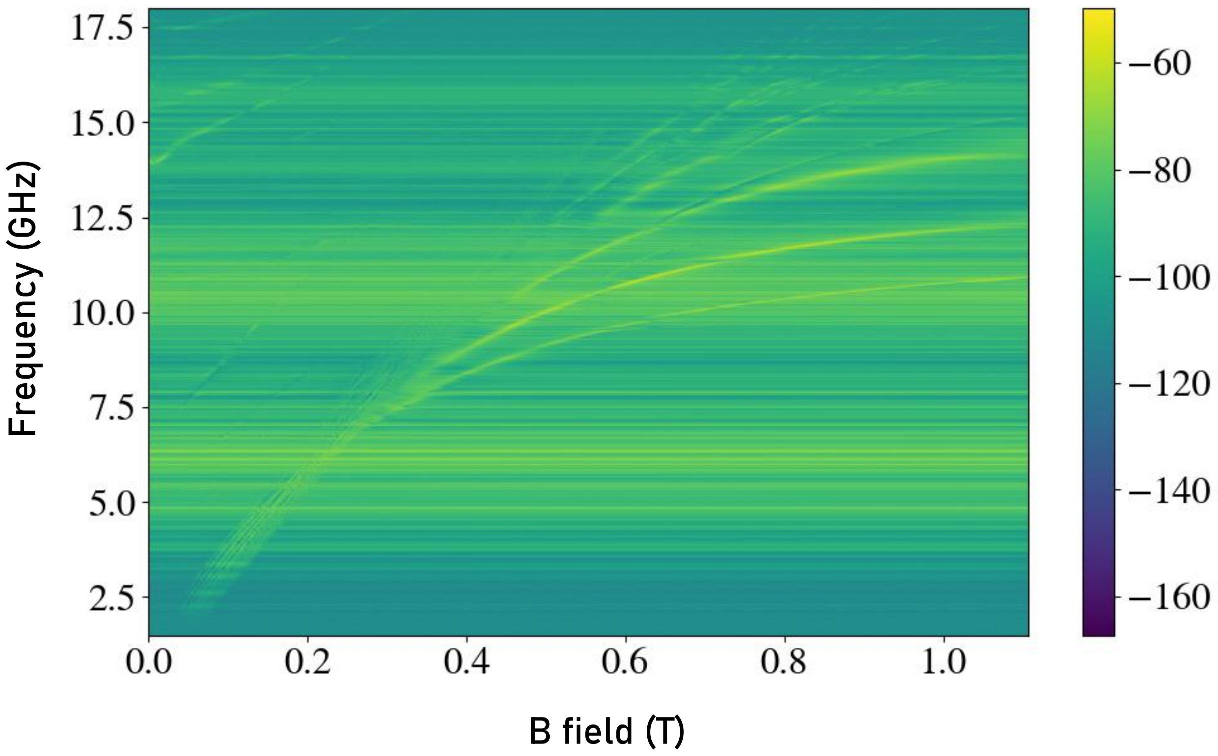


A. Théry et al. PRB 109, 06450524 (2024)
C. Fruy et al. PRA, 113 023706 (2026).

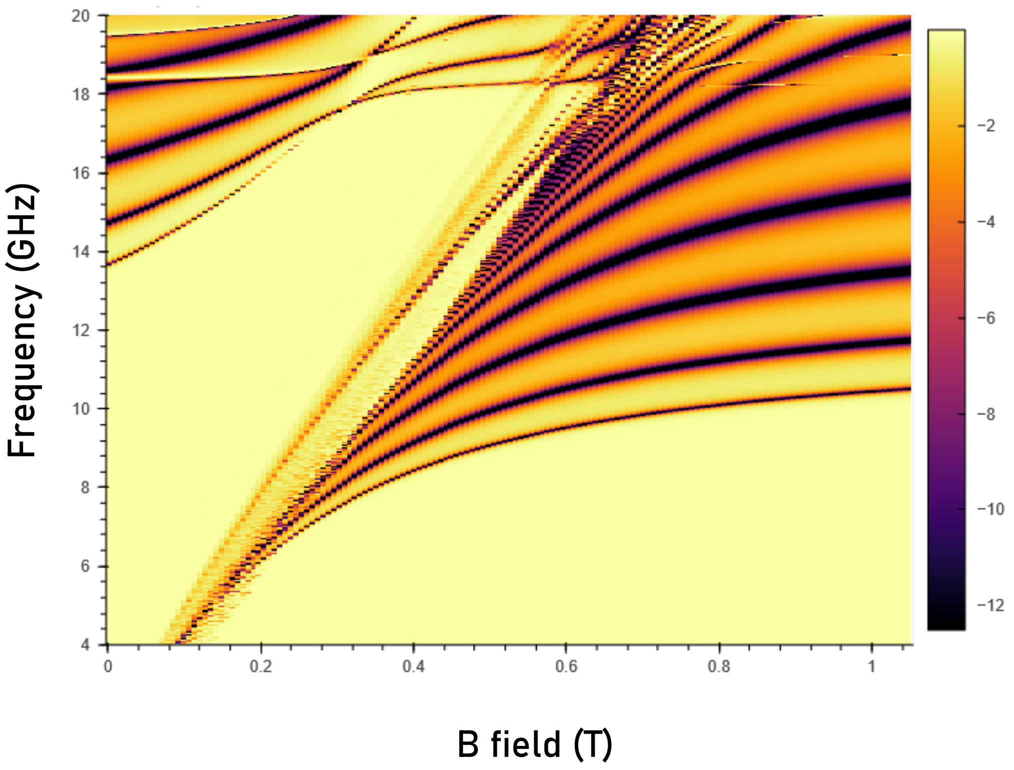
Magnetic tuning

YIG cylinder: 1 cm long, 5mm diameter
Resonant frequencies dependent on B field applied.
Ongoing work: Identification of axion mode and from factor characterization

Experimental measurement

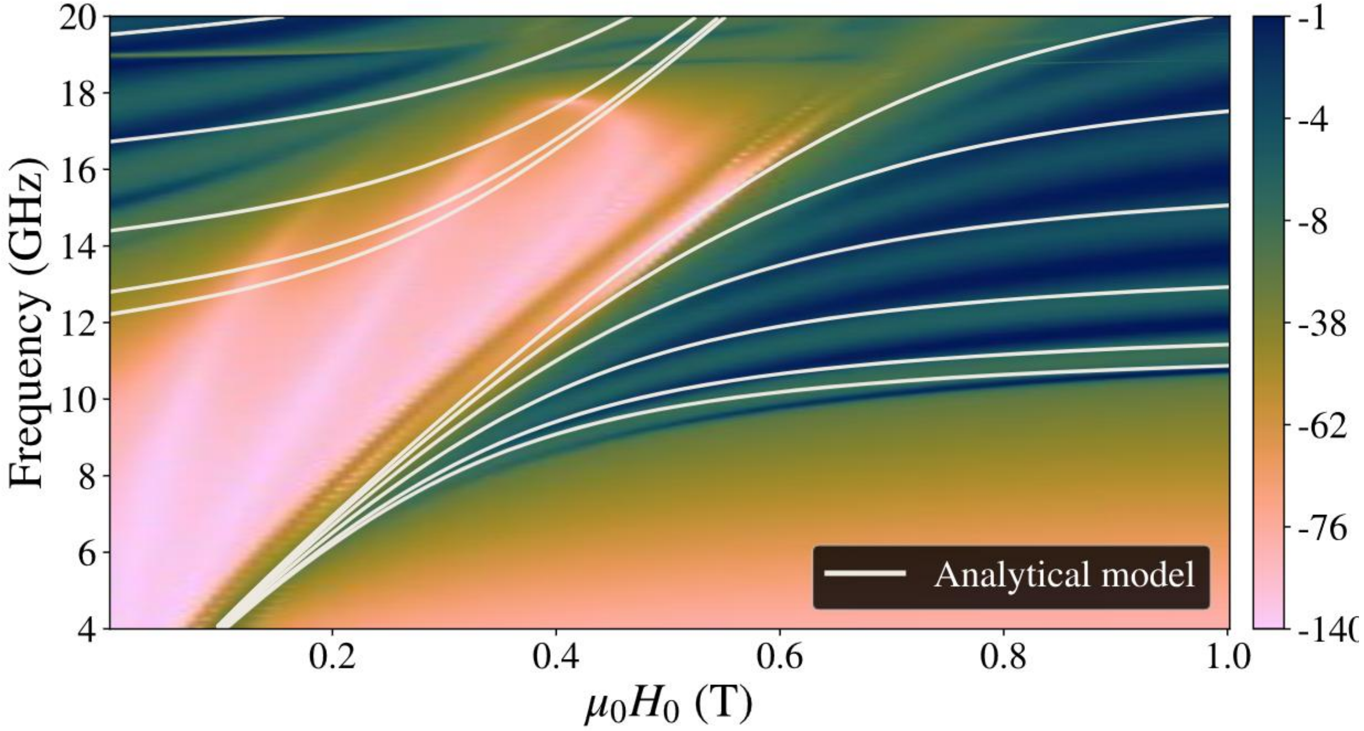


Comsol simulation

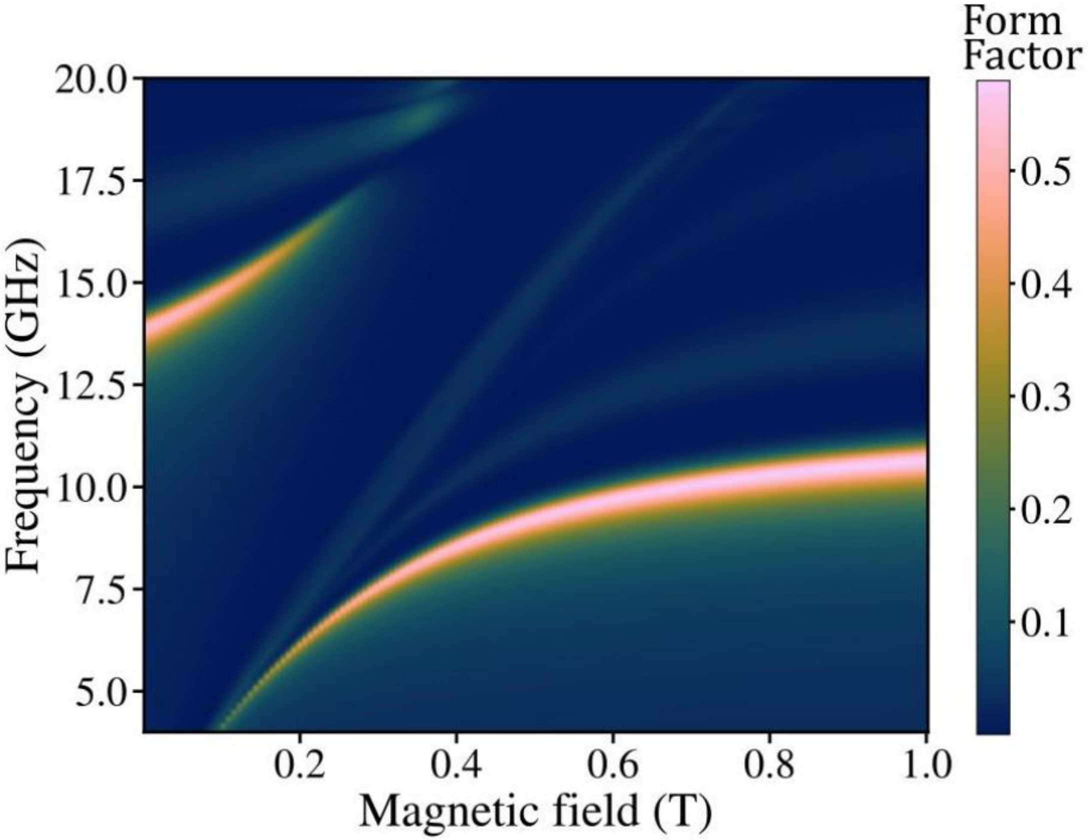


Analytical model

General trend ok, needs optimizing for details

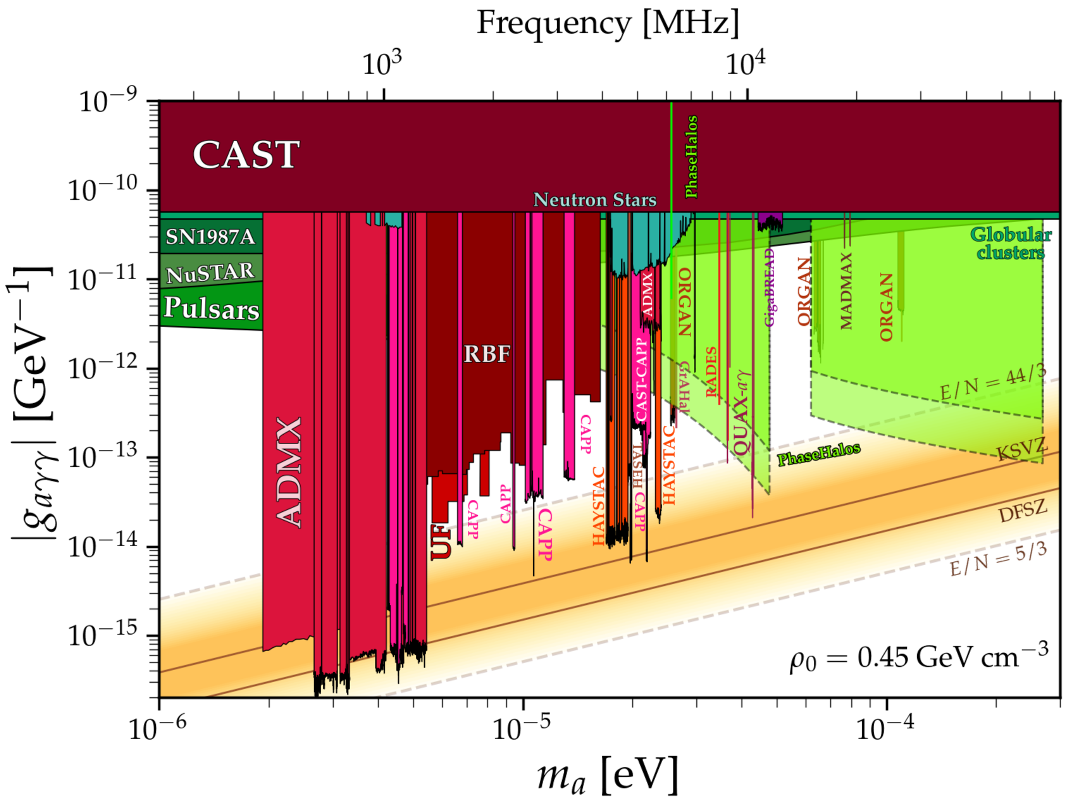


Form factor



Sensitivity prospects

If both branches of YIG resonances can be followed and assuming reachable sensitivity during data takings as in the first calibration these are the sensitivity prospects for axion searches:



For 90% C.L. → SNR = 1.28

$$SNR = \frac{P_{sig}}{\sigma_{noise}} = \frac{P_{sig}}{S_P}\sqrt{t}$$

Axion prospects:

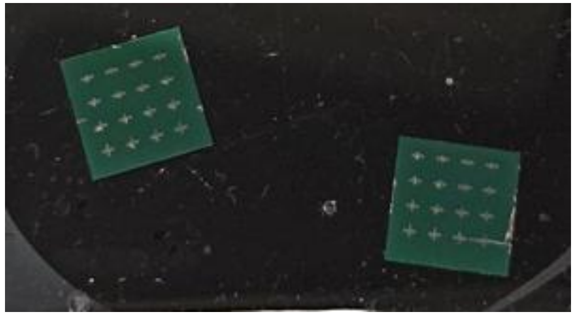
$$P_{sig} = g^2 \frac{\rho}{m_a} B^2 V G Q \frac{\beta}{1+\beta}$$

Parameter	Value
S_P	$1.2 \cdot 10^{-22(23)}\ W/\sqrt{Hz}$
Integration time (t)	10^3 s
V	$30\ cm^3$
Q	10^5
B	0-2 T
G	0.5
β	2

Next steps phase haloscope

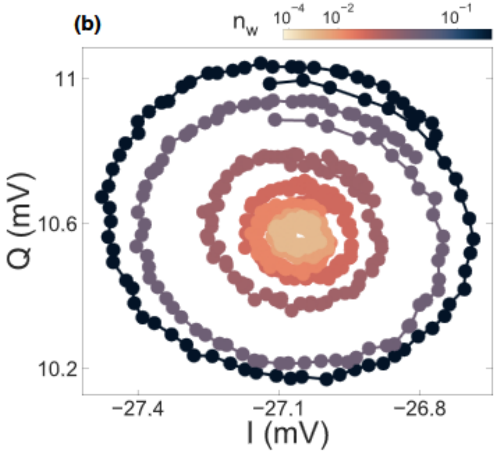
Improve GrAl circuits

- Calibrating evaporator for higher accuracy in oxygen pressure and growing rate.
- Increase anharmonicity



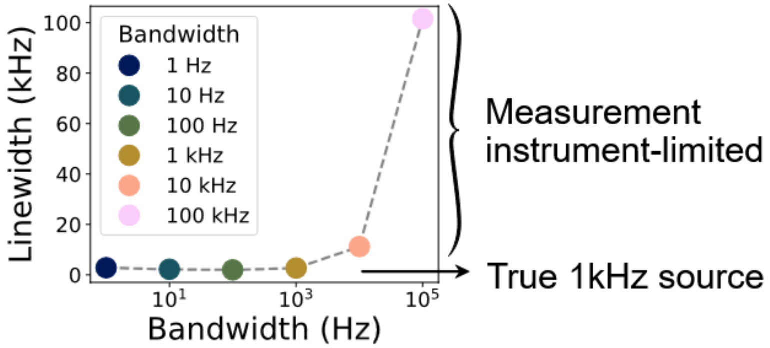
Background runs w/o B field

- Design pulse sequence for background run.
- Data managing in longer runs.
- Test different qubits with the same protocol.



Phase jamming calibration

- Develop a 1 kHz source
- Phase shifts randomly
- Mimic axion signals better than any other calibration source.



DarkQuantum roadmap

DarkQuantum-LF

- Autumn: complete working set up 1m long cavity at KIT
- Next year 2027 : Dark photons data taking.
- 2028: Several month data taking campaign at M1 magnet at CERN.
- Long term: 5m long cavities for BabyIAXO helioscope

DarkQuantum-HF

- Now: GrAl qubits to be tested in magnetic field.
- Autumn: Data taking campaign with the phase resolved haloscope.
- Autumn: Design of bigger SPC and include tuning.
- Next year 2027: Operate single photon counters in several laboratories (U. Zaragoza, MPP Munich, IFAE…)
- Next year 2027: Operate tuning system in a SPC.
- Next year 2027: REBCO tape in a SPC.

THANK YOU !!!

RADES

DarkQuantum

erc
European Research Council
Established by the European Commission

Back-up slides

Acknowledgements

The work presented in this seminar is part of the work carried out in collaborations (RADES), and funded by many agencies. But in particular I want to personally acknowledge support from:

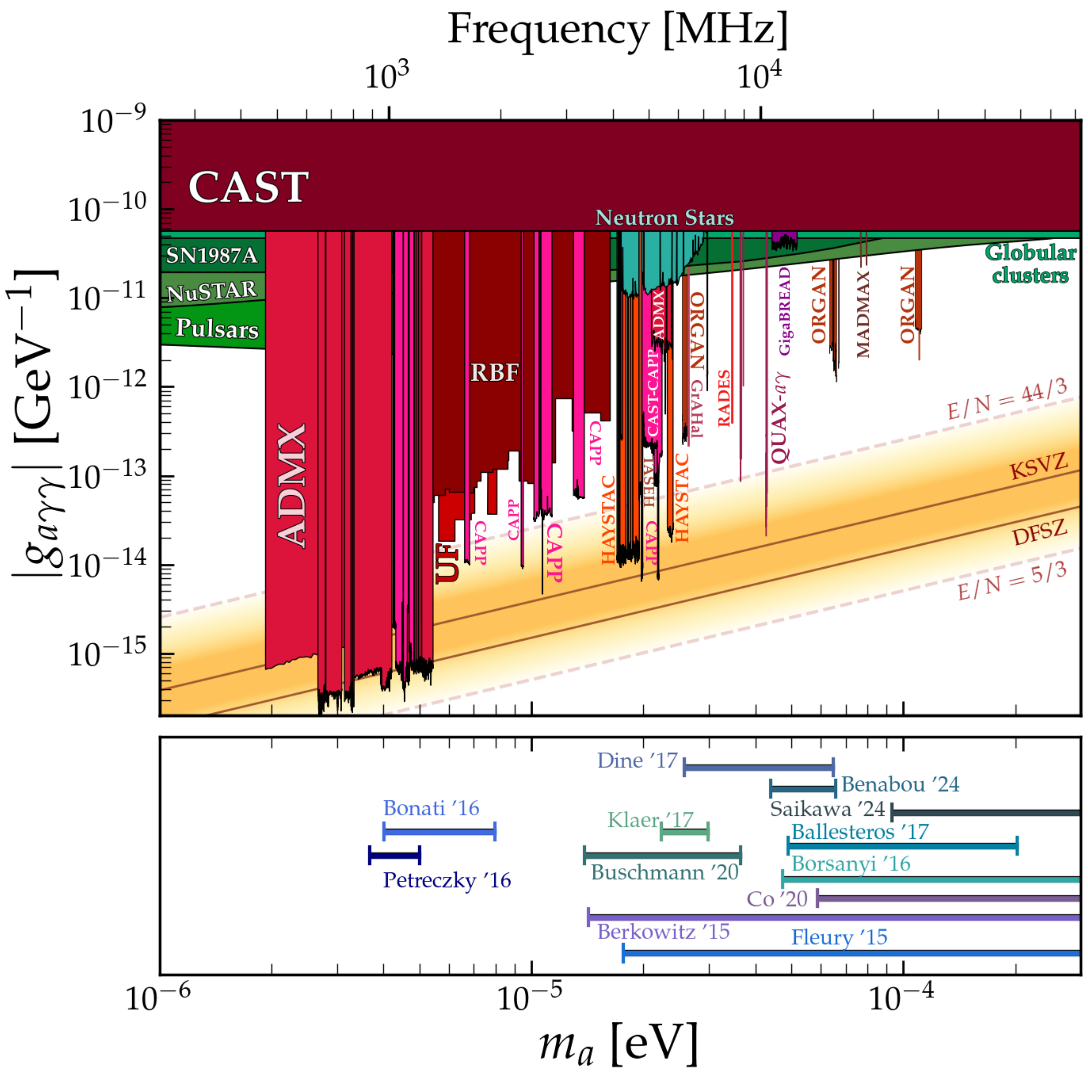
The European Union's Horizon 2020 research and innovation programme under the European Research Council (ERC) grant agreement ERC-2023-SyG 101118911 (DarkQuantum).

erc
European Research Council
Established by the European Commission

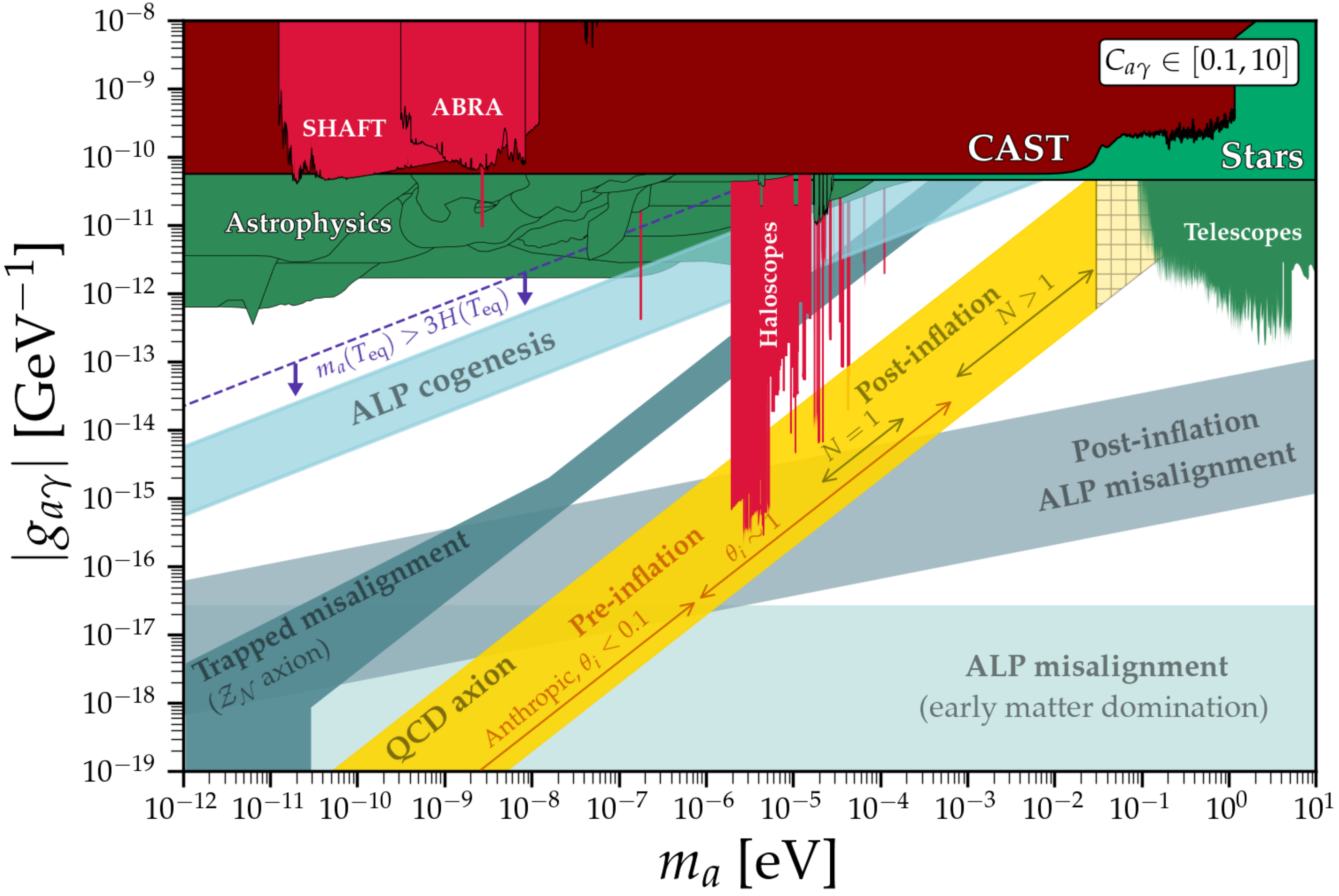
Funded by
the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

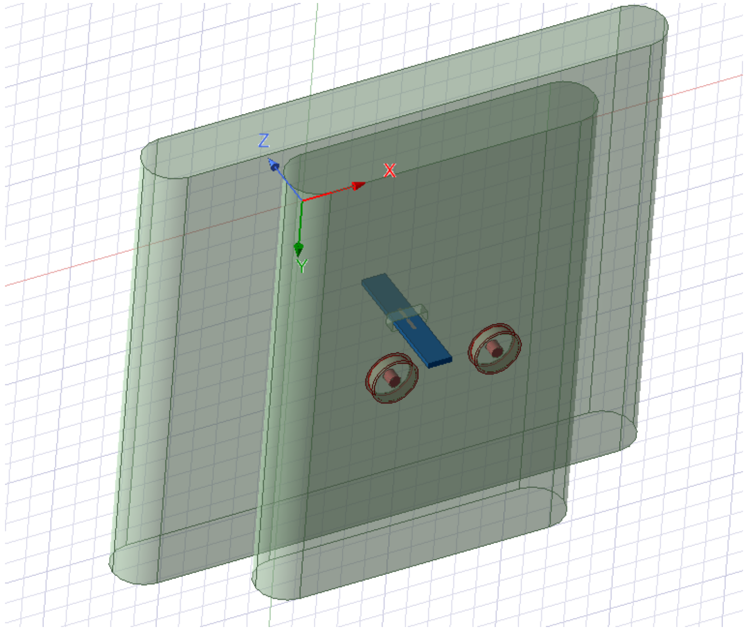
Post-inflation QCD axion predictions



Axions and ALPs predictions

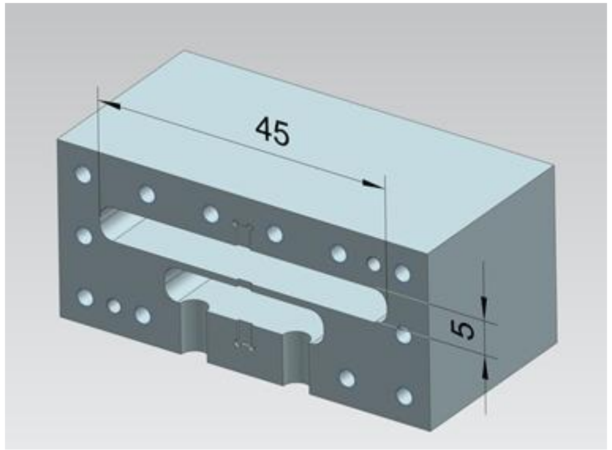


Double cavity



Frequencies

	Readout (f_r)	Storage (f_s)
Simulated	6.869 GHz	5.024 GHz
Measured	6.867 GHz	5.051 GHz



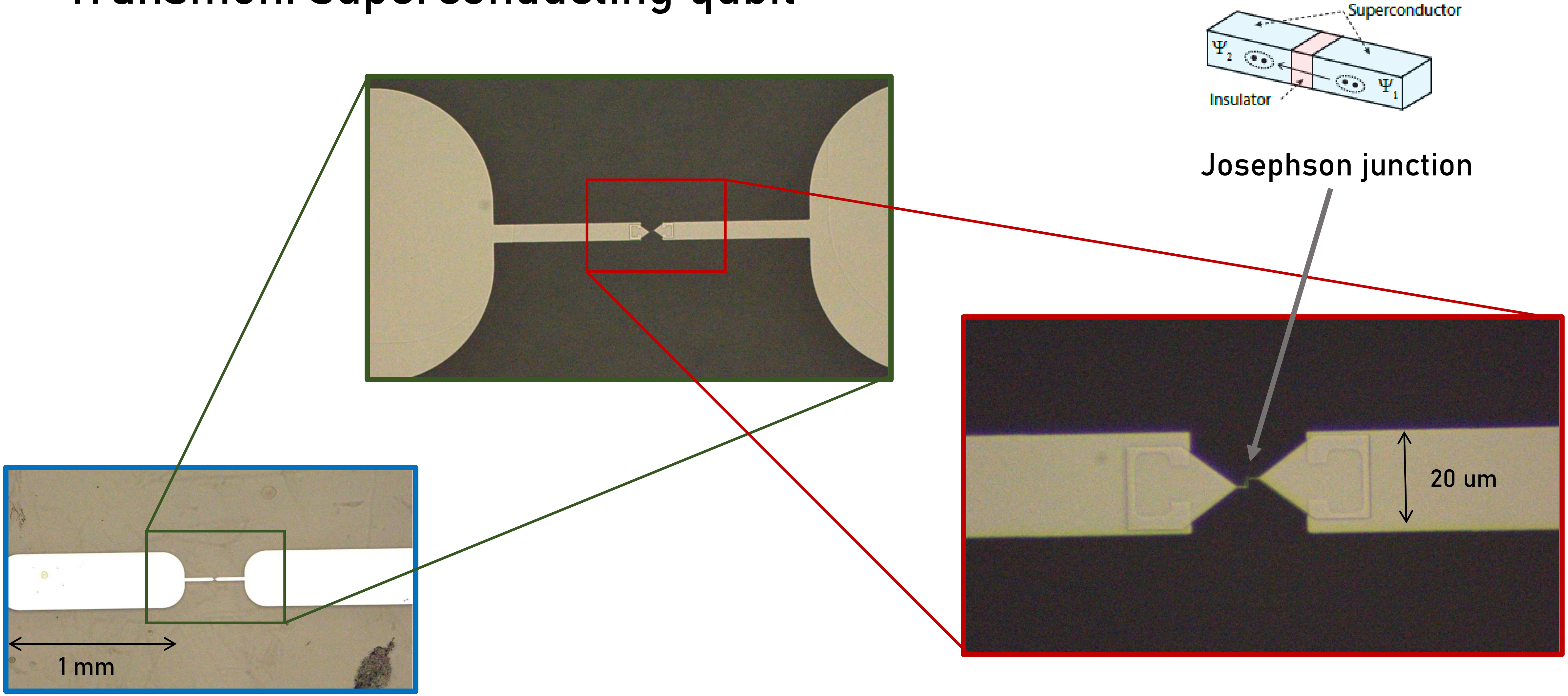
Aluminum

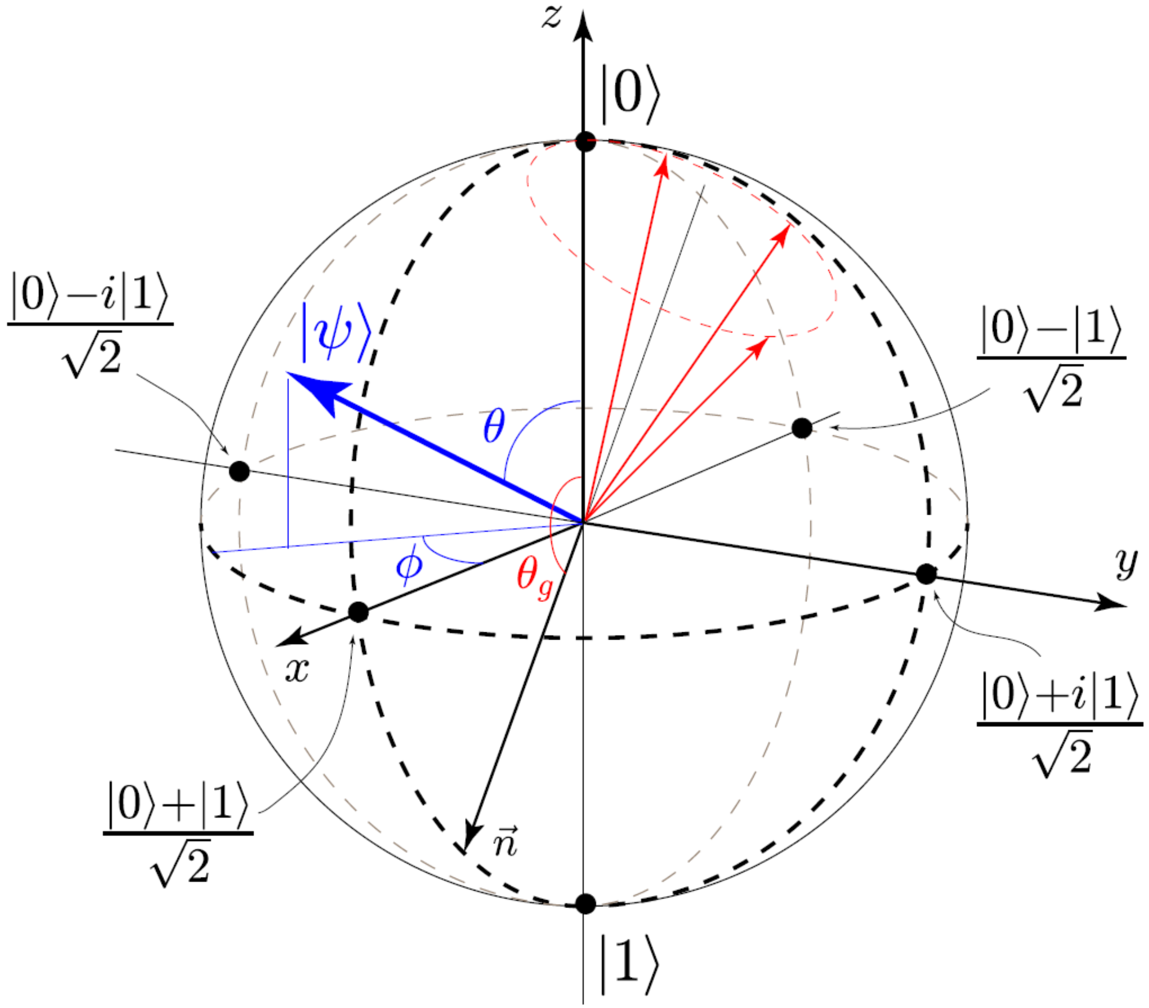
Copper

EM simulation: Ansys-HFSS
Qubit simulation: Black-box superconducting circuit quantization

S. Nigg et al. Black-box superconducting circuit quantization (2012)

Transmon: superconducting qubit




z
$|0\rangle$
$\frac{|0\rangle - i|1\rangle}{\sqrt{2}}$
$|\psi\rangle$
θ
ϕ
θ_g
$\frac{|0\rangle - |1\rangle}{\sqrt{2}}$
y
x
$\frac{|0\rangle + i|1\rangle}{\sqrt{2}}$
$\frac{|0\rangle + |1\rangle}{\sqrt{2}}$
$\vec{n}$
$|1\rangle$

Readout fidelity

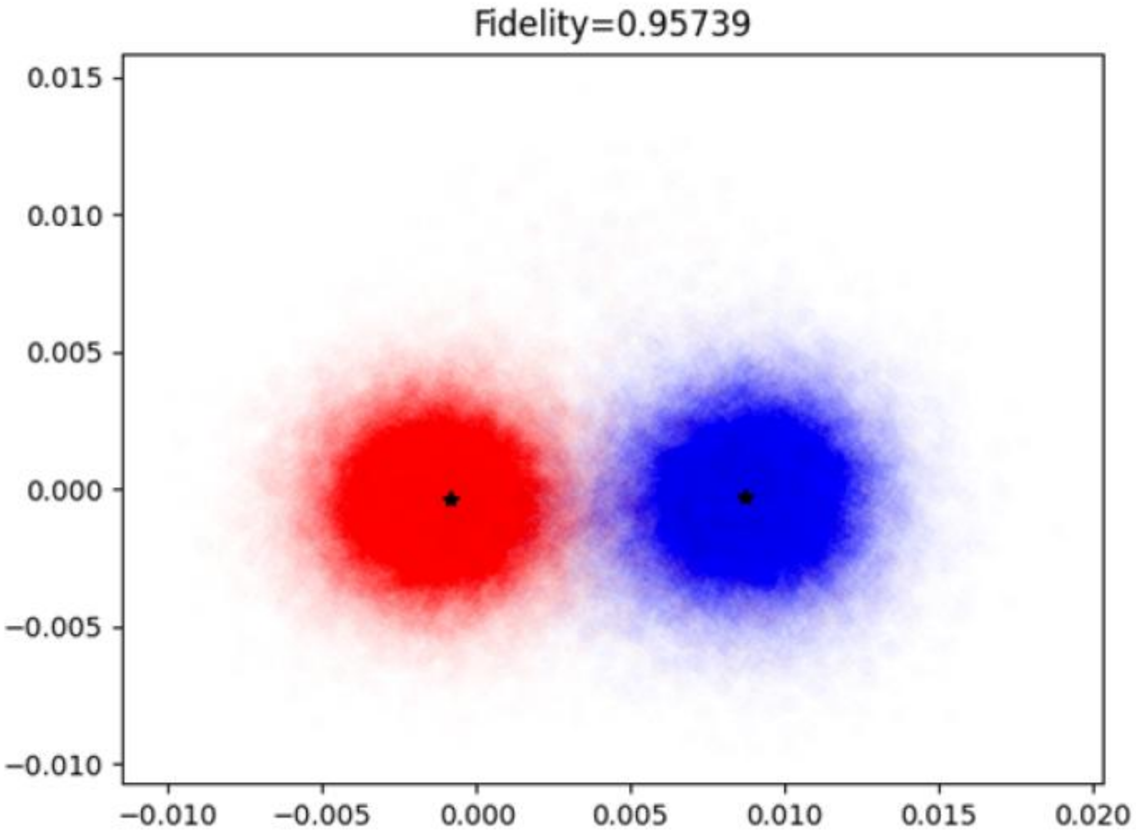


Figure 8: Readout fidelities. Blue measurements with qubit in ground state, red with qubit in first excited state.

- Prepare state
- Readout pulse
- Plot in IQ plane
- Set threshold value

Pairs of conjugate variables

[I,Q]=i

[N,ϕ]=i

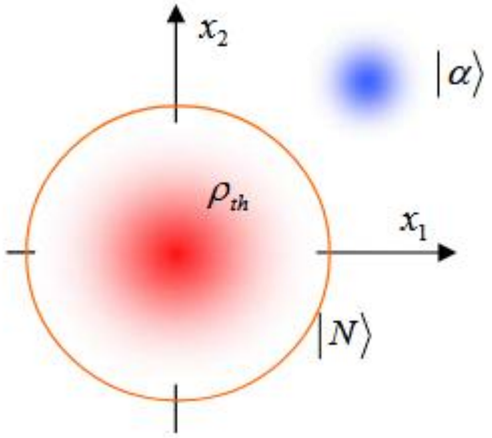
$$I = \frac{a + a^\dagger}{2}$$

$$N = a^\dagger a$$

$$Q = \frac{a - a^\dagger}{2i}$$

$$e^{i\phi} = (N+1)^{-1/2} a$$

$$N = a^\dagger a = I^2 + Q^2 - \frac{1}{2}$$



Coherent state in blue
Thermal state in red
Fock state in orange

- **Coherent state**: well-defined phase, Poissonian number distribution.
- **Fock state**: perfectly defined number → complete phase uncertainty.

Power measurement

$$P = \hbar\omega\langle a^\dagger a\rangle = \hbar\omega\langle N\rangle$$

$$\boxed{P = \hbar\omega\left(\langle I^2\rangle + \langle Q^2\rangle - \frac{1}{2}\right)}$$

Parameters of the single photon counter

Device parameter	Symbol	Value
Transmon frequency $\|g\rangle \longrightarrow \|e\rangle$	w_q	$2\pi \times 4.629$ GHz
Transmon frequency $\|e\rangle \longrightarrow \|f\rangle$	w_{ef}	$2\pi \times 4.357$ GHz
Sideband qubit-storage frequency $\|f0\rangle \longrightarrow \|g1\rangle$	w_{f0-g1}	$2\pi \times 3.935$ GHz
Transmon anharmonicity	α_q	$-2\pi \times 272$ MHz
Transmon decay time	T_1^q	16.7 μs
Transmon decoherence time	T_2^q	6.2 μs
Transmon background photon	$\bar{n}_q$	
Storage frequency	w_s	$2\pi \times 5.051$ GHz
Storage decay time	T_1^s	20 μs
Storage decoherence time	T_2^s	
Storage-Transmon Stark shift	2χ	$-2\pi \times 4.6$ MHz
Storage background photon	$\bar{n}_s$	
Readout frequency	w_r	$2\pi \times 6.867$ GHz
Readout-Transmon Stark shift	$2\chi_{qr}$	
Readout fidelity $\|g\rangle$	$F_{g\mathcal{G}}$	0.95739
Readout fidelity $\|e\rangle$	$F_{e\mathcal{E}}$	
Readout time	t_r	800 ns
Parity time	t_p	88 ns
90º rotation pulse time	$\pi/2$	52 ns
Waiting time between measurements	t_w	100/1000 ns
Time between parity sequences	t_t	1 ms

Table 3: Parameters of the single photon counter.

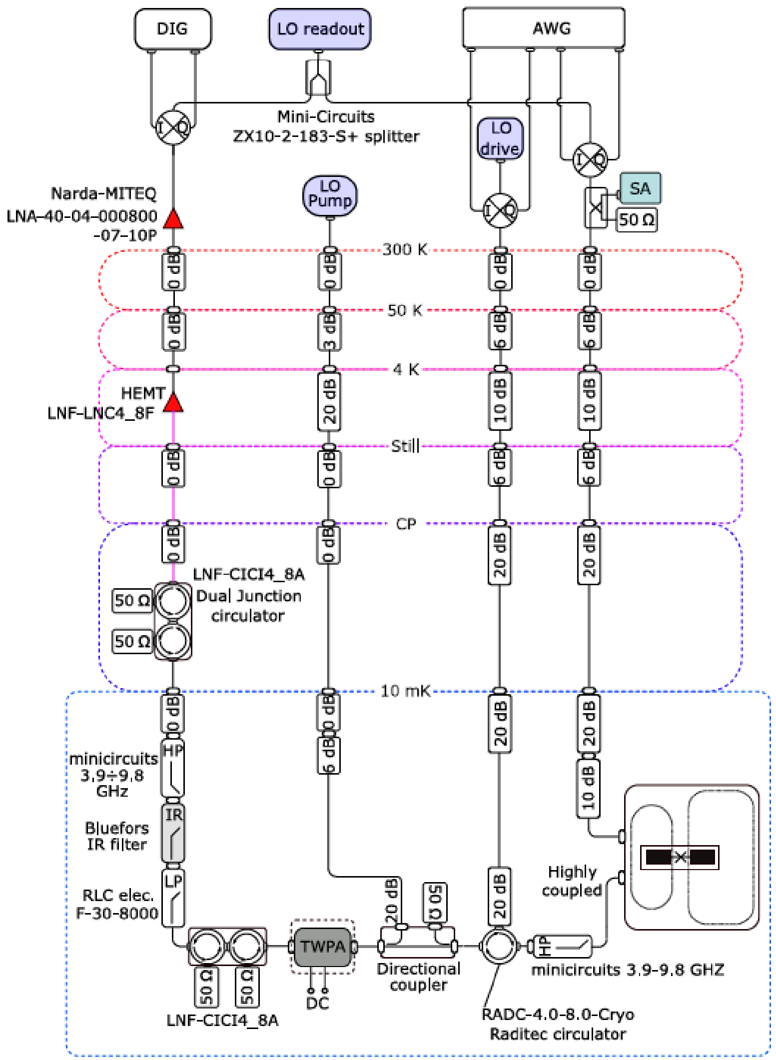
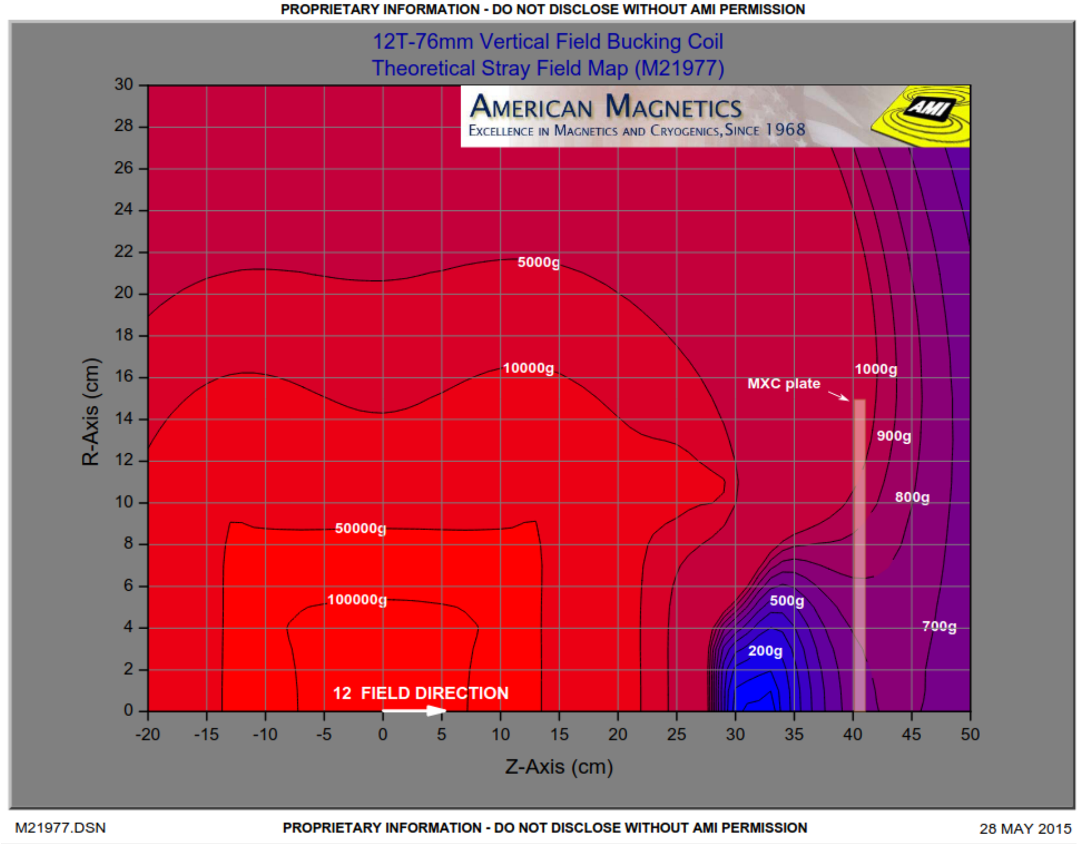
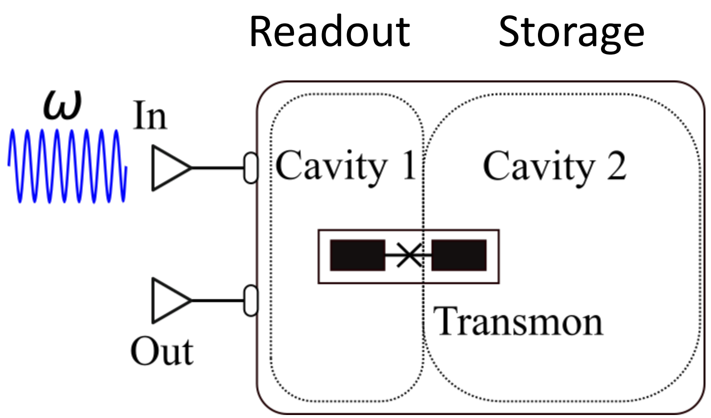


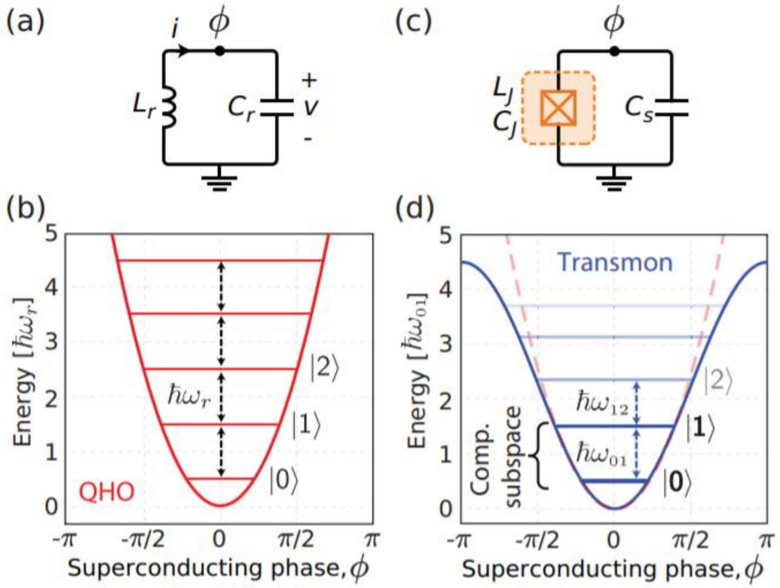
Figure 7.20: Layout of the input and output RF lines inside the cryostat during the parity measurements.

Bluefors LD dilution cryostat at MPP Munich

12 T magnet
Diameter: 7cm
Height: 40 cm



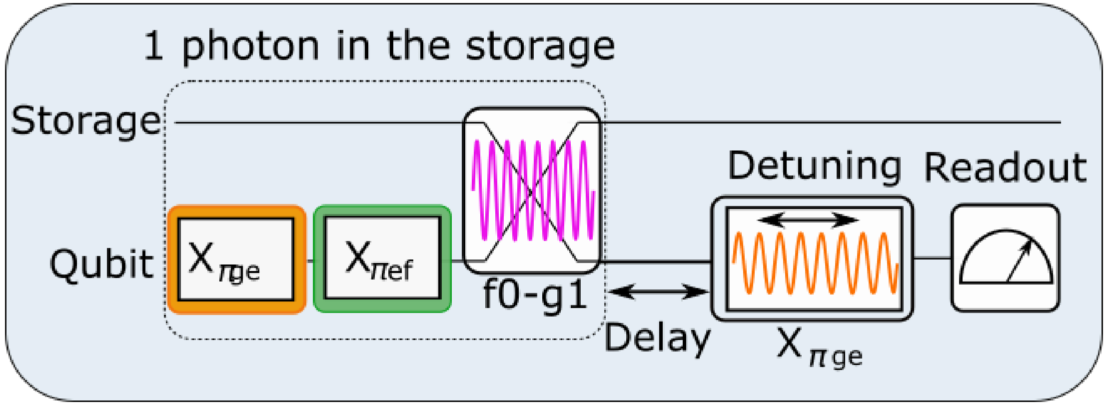


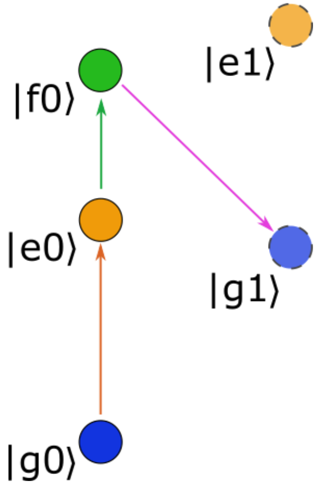


$$\hat{H}_{eff} = \underbrace{\frac{1}{2}\hbar\omega'_{01}\sigma_z}_{\text{qubit}} + \overbrace{(\underbrace{\hbar\omega'_{c1}}_{\text{cavity 1}} + \underbrace{\hbar\chi^{c1}\sigma_z)\hat{a}^{\dagger}\hat{a}}_{\text{Stark shift 1}}}^{\text{Readout}} + \overbrace{(\underbrace{\hbar\omega'_{c2}}_{\text{cavity 2}} + \underbrace{\hbar\chi^{c2}\sigma_z)\hat{b}^{\dagger}\hat{b}}_{\text{Stark shift 2}}}^{\text{Storage}}$$

$$\boxed{\chi^{c2} > \chi^{c1}}$$

Pulse sequence to inject a photon in the storage cavity

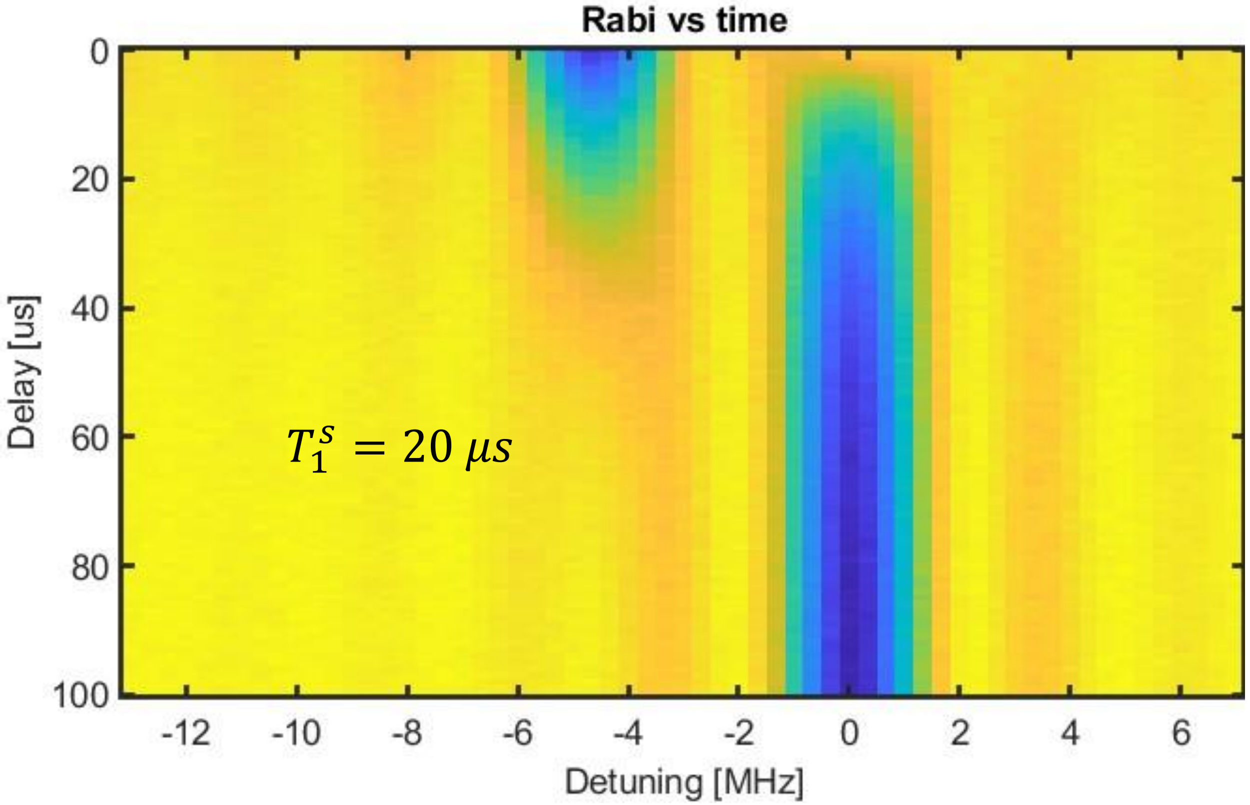




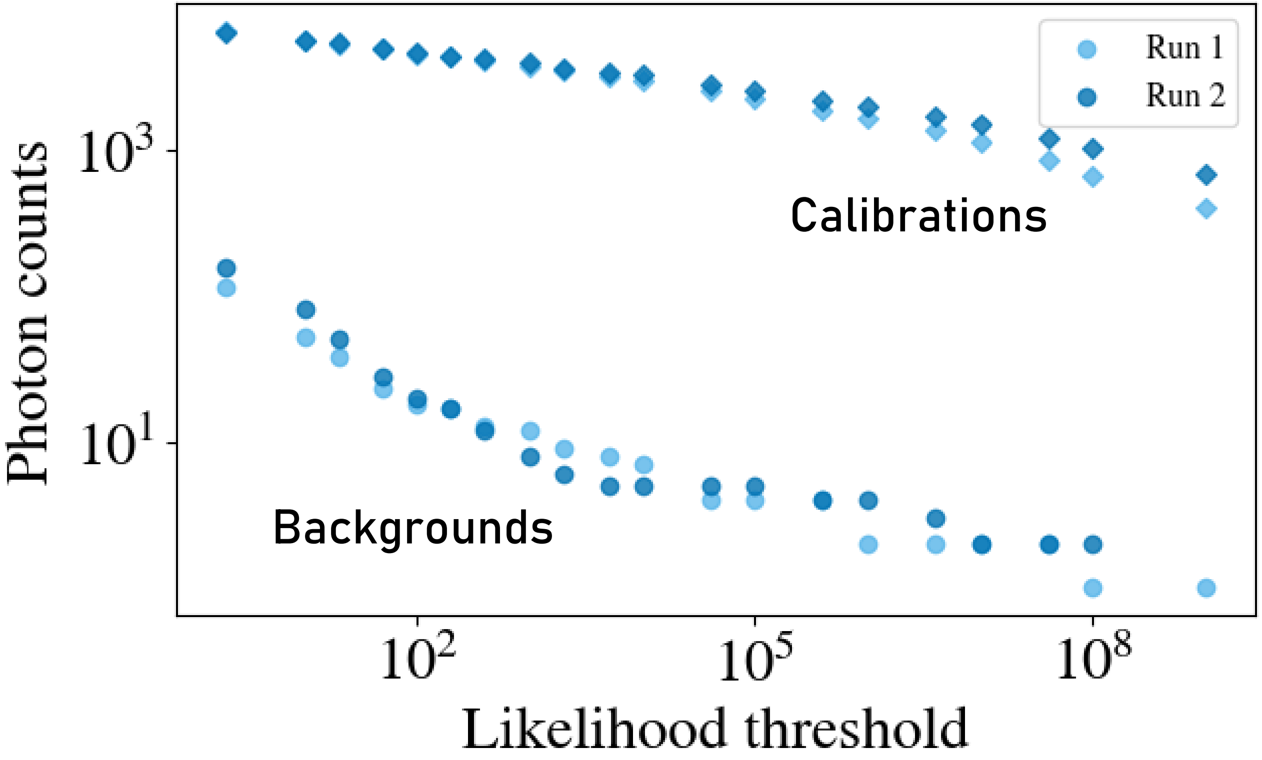
$$\omega_{ge}/_{2\pi} = 4.629 \text{ GHz}$$

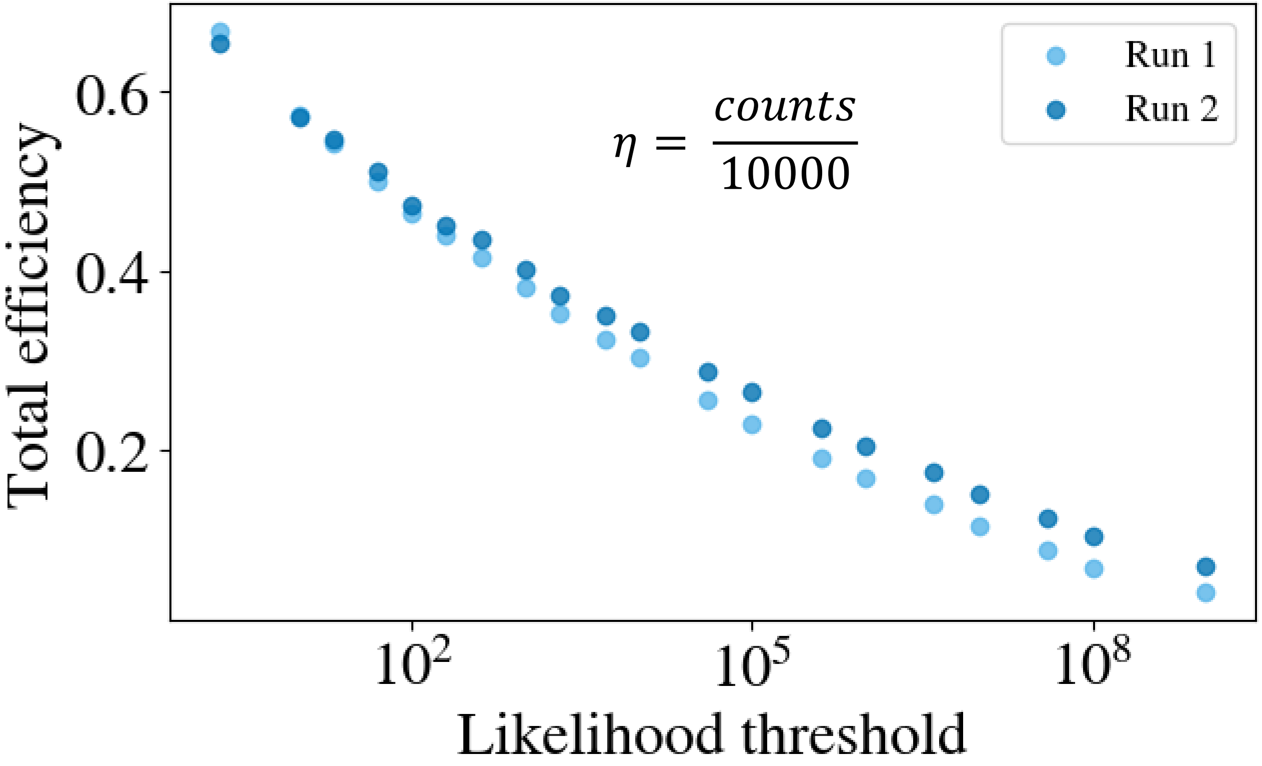
$$\omega_{ef}/_{2\pi} = 4.357 \text{ GHz}$$

$$\omega_{f0-g1}/_{2\pi} = 3.935 \text{ GHz}$$



Results: counts and efficiencies





Comparison with previous works

$\lambda_{th} = 4 \times 10^4$	Background (Hz)	Efficiency	Live time (s)
Run 1	77.94	25.7%	0.2
Run 2	87.35	28.6%	0.2

Chicago group (D. Schuster)	Background (Hz)	Efficiency	Live time (s)
Searching for dark matter with a superconducting qubit	1.1	40%	8.33
A flux-tunable cavity for dark matter detection	64	15%	135201.75 (37.5 h)

Hidden Markov Model

Bayesian method to assign probabilities to each sequence.

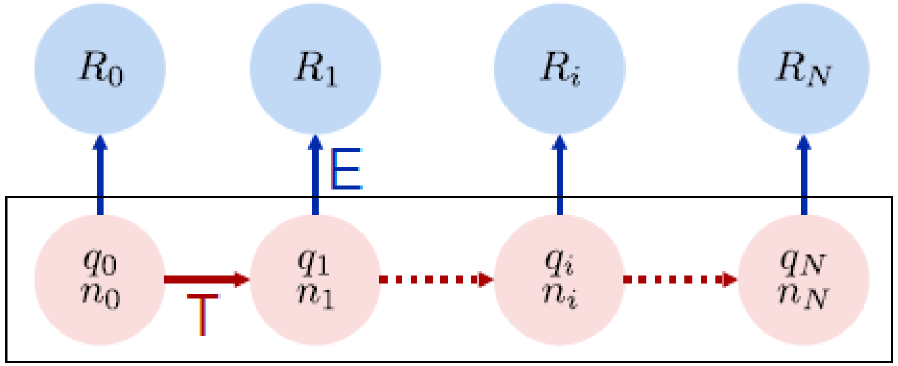
Flat prior + forward/backward method.

Transmission matrix

$$\mathbf{T} = \begin{array}{c} \begin{array}{cccc} |0g\rangle & |0e\rangle & |1g\rangle & |1e\rangle \end{array} \\ \begin{bmatrix} P_{00}P_{gg} & P_{00}P_{ge} & P_{01}P_{ge} & P_{01}P_{gg} \\ P_{00}P_{eg} & P_{00}P_{ee} & P_{01}P_{ee} & P_{01}P_{eg} \\ P_{10}P_{gg} & P_{10}P_{ge} & P_{11}P_{ge} & P_{11}P_{gg} \\ P_{10}P_{eg} & P_{10}P_{ee} & P_{11}P_{ee} & P_{11}P_{eg} \end{bmatrix} \end{array} \begin{array}{c} |0g\rangle \\ |0e\rangle \\ |1g\rangle \\ |1e\rangle \end{array}$$

Emission matrix

$$\mathbf{E} = \frac{1}{2} \begin{array}{c} \begin{array}{cc} \mathcal{G} & \mathcal{E} \end{array} \\ \begin{bmatrix} F_{g\mathcal{G}} & F_{g\mathcal{E}} \\ F_{e\mathcal{G}} & F_{e\mathcal{E}} \\ F_{g\mathcal{G}} & F_{g\mathcal{E}} \\ F_{e\mathcal{G}} & F_{e\mathcal{E}} \end{bmatrix} \end{array} \begin{array}{c} |0g\rangle \\ |0e\rangle \\ |1g\rangle \\ |1e\rangle \end{array}$$



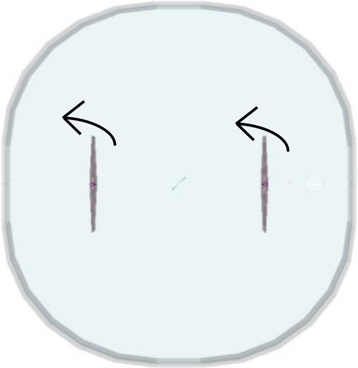
Observations
$R_i \in [\mathcal{G}, \mathcal{E}]$

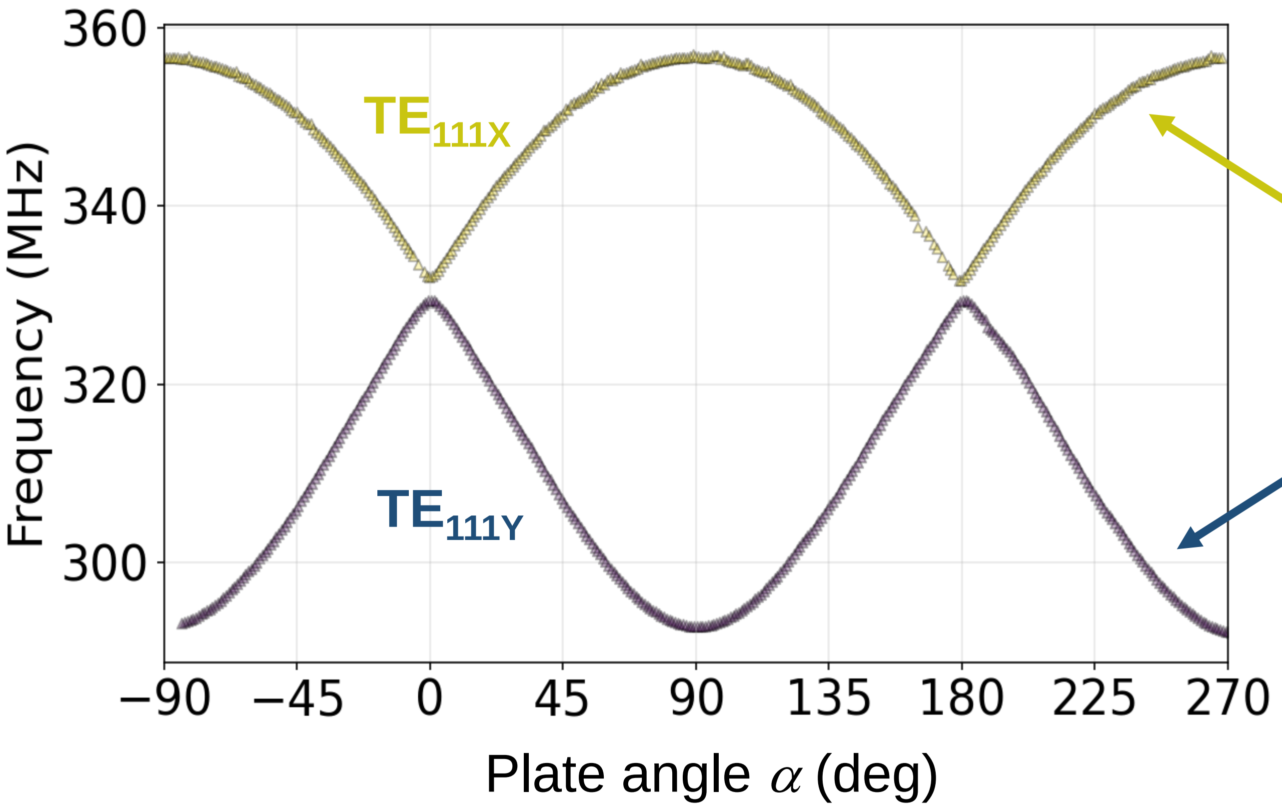
Hidden states
$q_i \in [g, e]$
$n_i \in [0, 1]$

$$\begin{cases} P_{gg} = 1 - P_{ge}, P_{ee} = 1 - P_{eg} \\ P_{ge} = \bar{n}_q \left[1 - e^{-t_m/T_1^q}\right] + 1 - e^{-t_p/T_2^q} \\ P_{eg} = 1 - e^{-t_m/T_1^q} + 1 - e^{-t_p/T_2^q} \\ P^{\phi} = 1 - e^{-t_p/T_2^q} \\ P_{00} = 1 - P_{01}, P_{11} = 1 - P_{10} \\ P_{01} = \bar{n}_s \left[1 - e^{-t_m/T_1^u}\right] \\ P_{10} = 1 - e^{-t_m/T_1^u} \end{cases}$$

Tuning characterization

Mode map simulation
(*slab same direction rotation*)



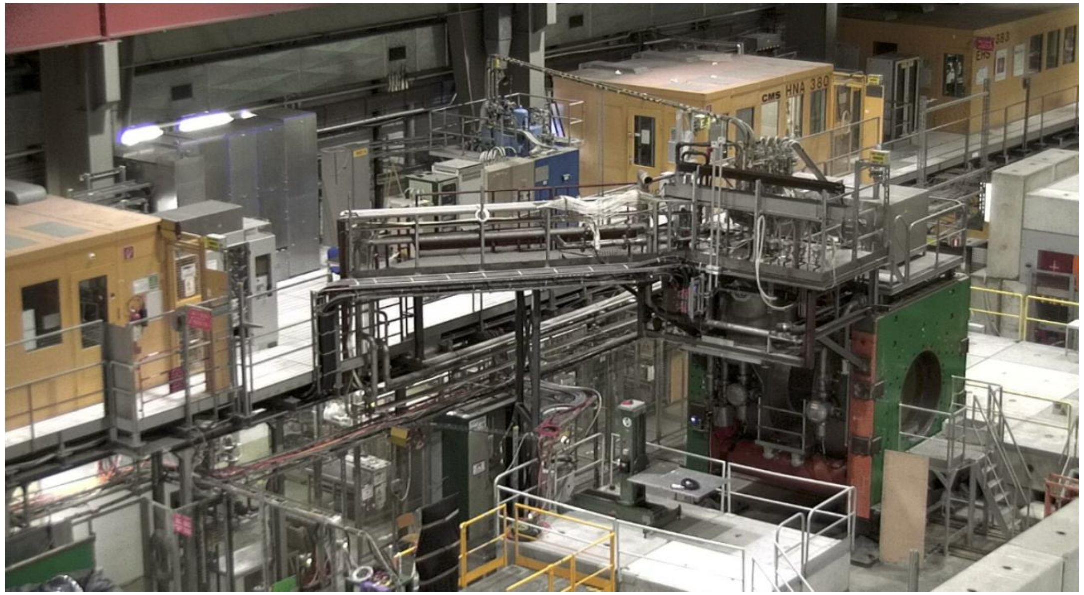


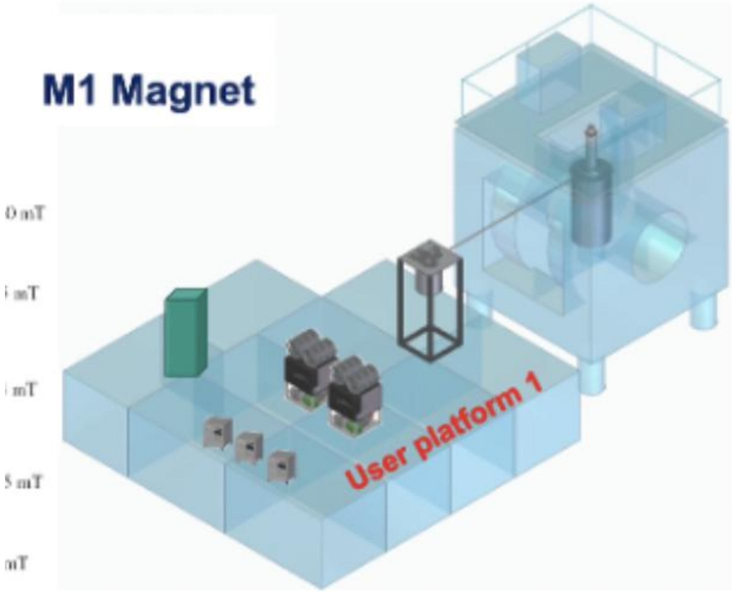
Antenna at $\varphi = 0°$

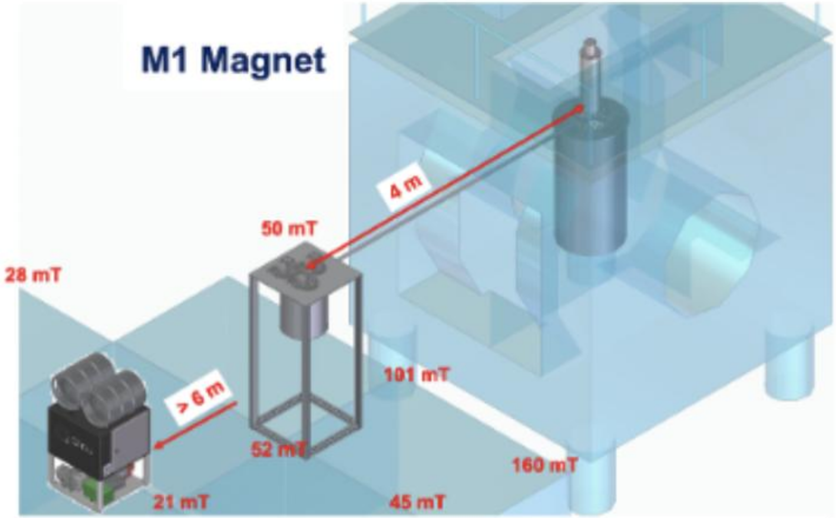
Antenna at $\varphi = 90°$

DQLF @ M1 layout

- Every component placed according to stray field Map & magnetic sensitivity.







- Will be read by quantum-limited microstrip SQUID amplifier
- SQUID gain already characterized (KIT)
- First noise figure measurements (<200 mK added noise, target 50 mK)