Exploring axion dark matter with quantum sensors in the RADES collaboration

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Tenerife - Spain

Contents

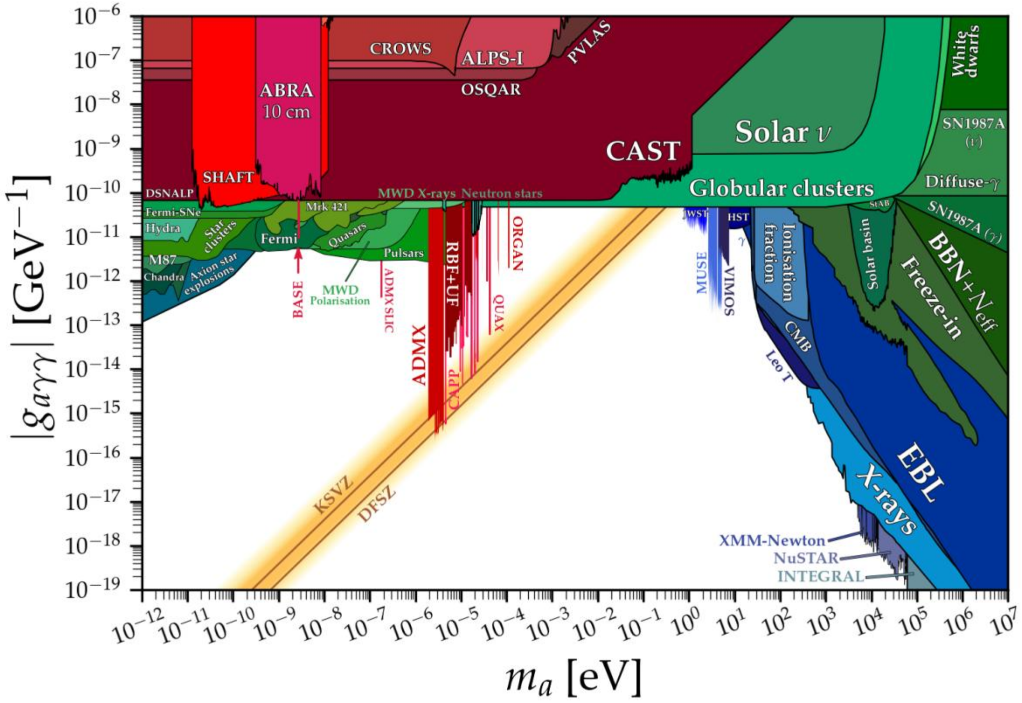
- RADES collaboration
- Single photon counter
- Parity measurement
- Background rate
- Exclusion limits for dark photons

Axion dark matter

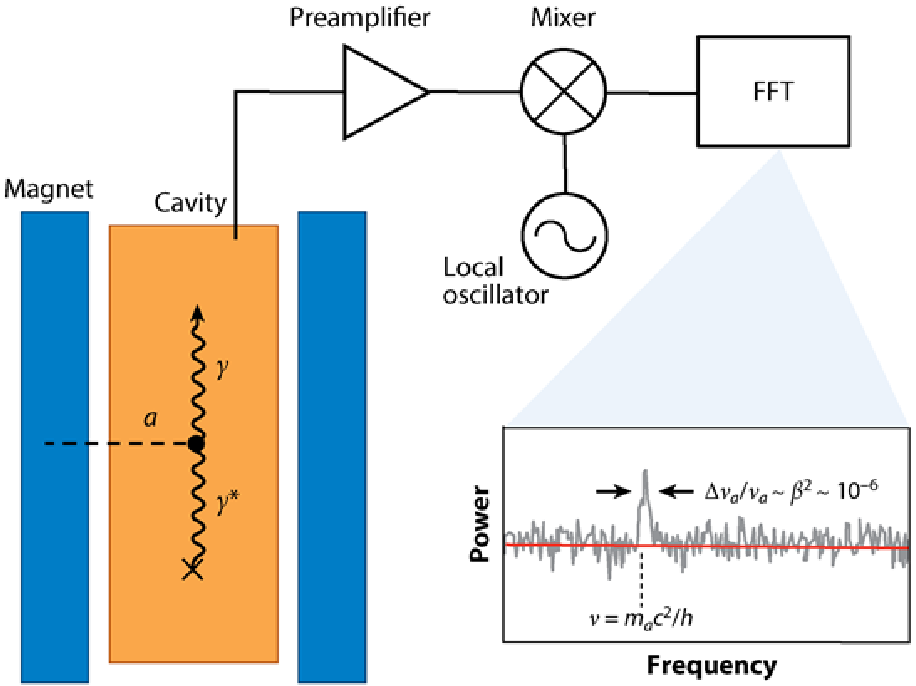
- **Axions from astronomical sources (Baby IAXO from Sun)**

- **Axions produced on lab (ALPS II)**

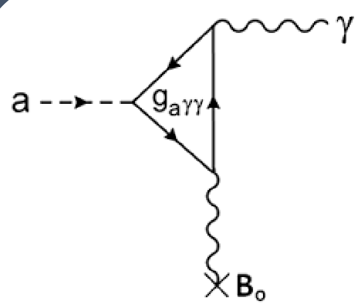
- **Axions in the galactic halo as dark matter**



Axion dark matter with haloscopes



Axion mass in the μeV range



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

Diagram of the Primakoff effect (a-γ coupling)

The team

LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE
IFIC INSTITUT DE FÍSICA CORPUSCULAR
UNI BONN
IFAE Institut de Física d'Altes Energies
Aalto University
ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
ita Instituto Tecnológico de Aragón

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

Expertise in:

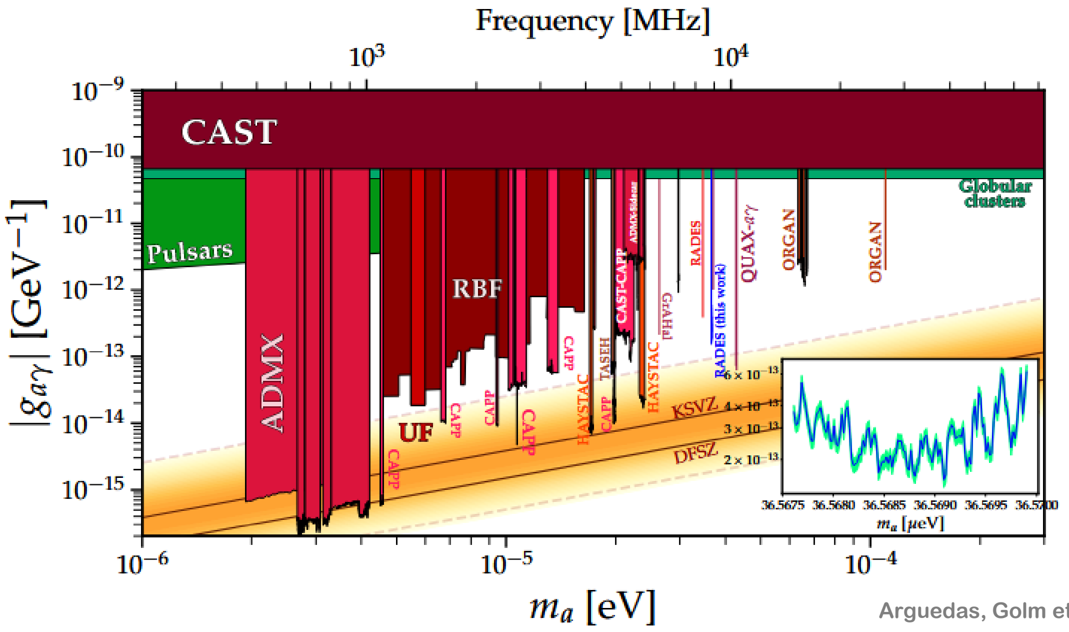
- Cryogenics
- Cavities and MW filters
- Particle physics
- Quantum devices
- Magnetic materials
- …

KIT Karlsruher Institut für Technologie
Universidad Zaragoza 1542
MAX-PLANCK-INSTITUT FÜR PHYSIK
CERN
UNIVERSITAT DE BARCELONA
Universidad Politécnica de Cartagena
DESY.

RADES projects

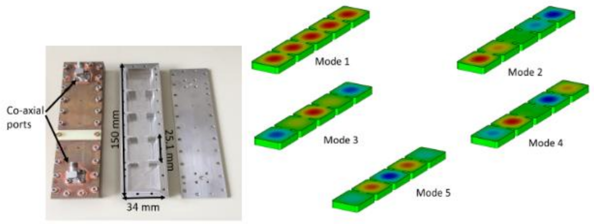
Dark Quantum
ERC Synergy Grant 2023

- Exploring haloscope technologies (HTS, multicavities…)
- Munich setup in commissioning (dilution fridge with 12T magnet)
- Experience with several data taking campaigns (CAST, SM18)
- ERC Synergy Grant 2023: Dark Quantum

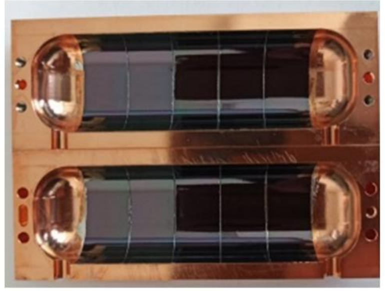


Arguedas, Golm et al. JHEP (2021)

CAST - Rades



SM18 - Rades

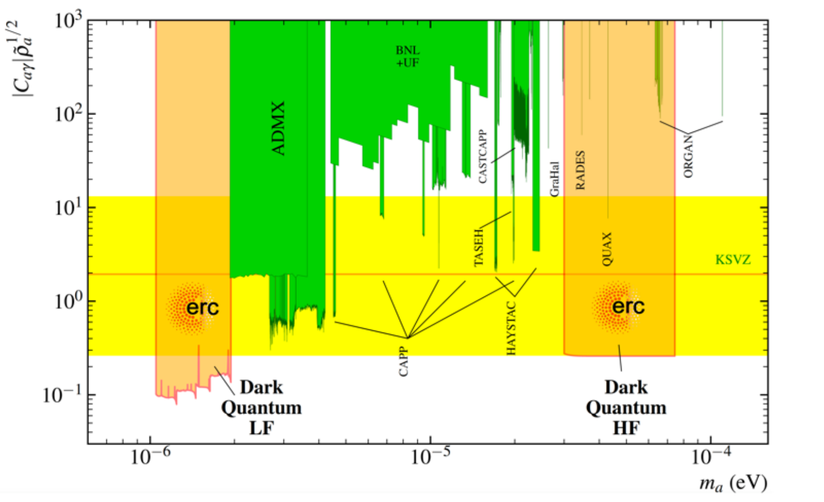


Arguedas, Golm et al. JHEP (2025)

RADES projects

Dark Quantum
ERC Synergy Grant 2023

ERC Synergy Grant 2023: Dark Quantum



Low frequency

High frequency

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

+

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

RADES projects

Dark Quantum
ERC Synergy Grant 2023

Dark Quantum low frequency:

- BabyIAXO magnet (2T, $8m^3$)
- 200-500MHz
- Four 5m long cavities
- 440 days in 2 runs (only 1 bore)
- 1m long section to be tested in a magnet

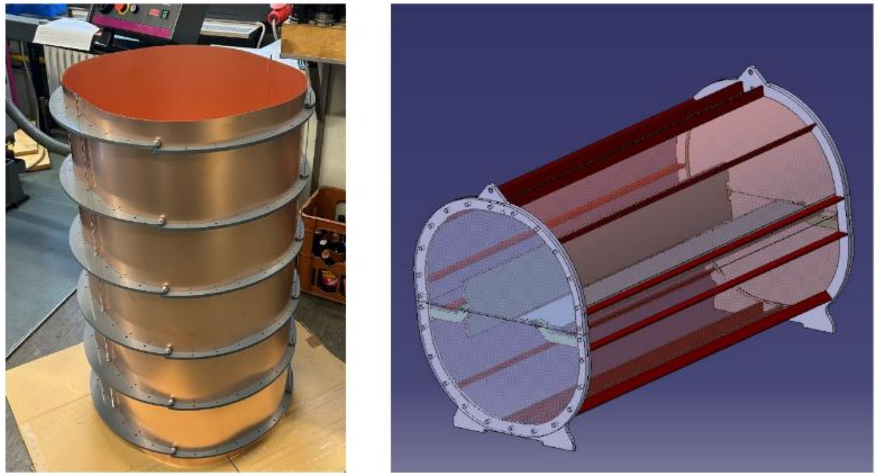
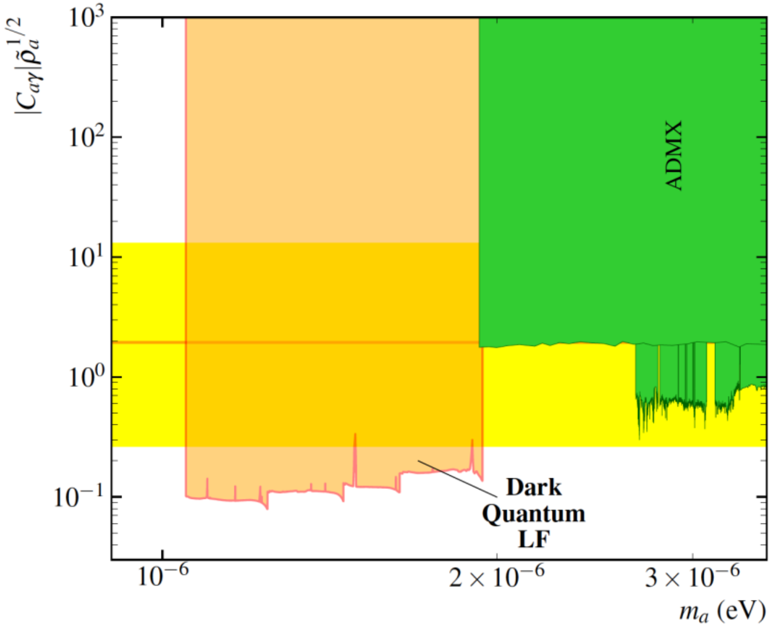


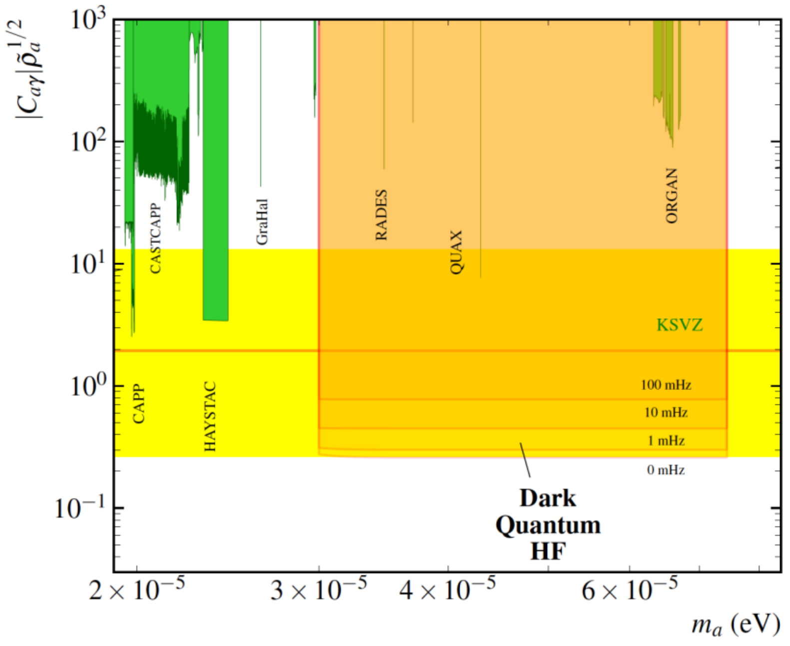
Figure 4: **Left:** Picture of the DQLF prototype cavity under construction at KIT. **Rigth:** CAD model of the design of a second version of the DQLF cavity at CERN.



Cryogenics + quantum-limited readout

RADES projects

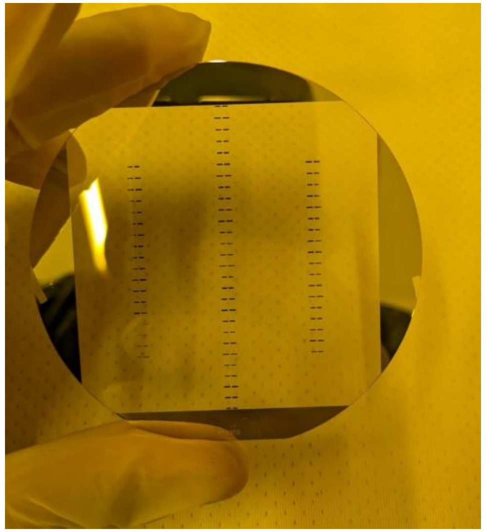
Dark Quantum
ERC Synergy Grant 2023



Single photon counter in a magnetic field

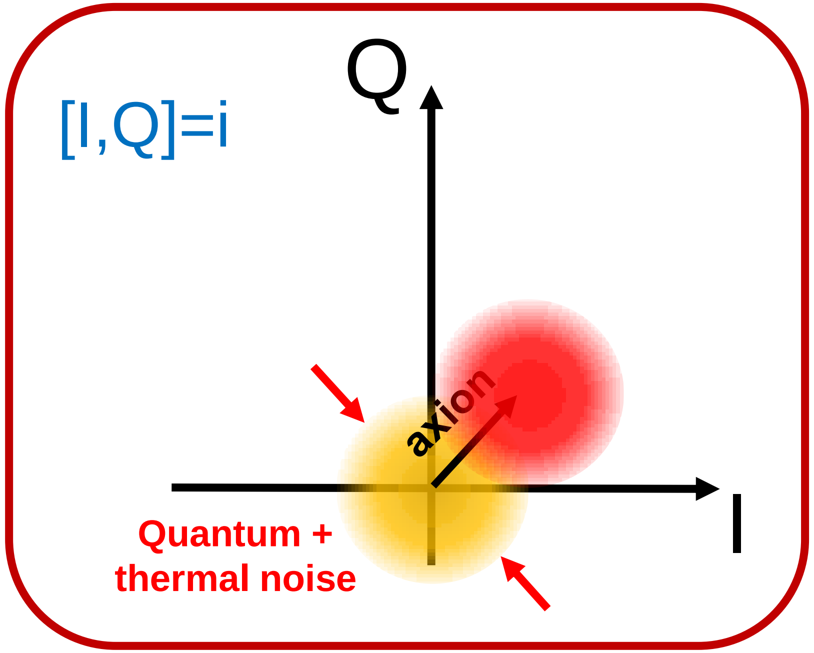
Dark Quantum high frequency:

- 8-18 GHz
- Microwave Single Photon Counter
- Qubit as quantum sensor
- Tests in Underground Laboratory of Canfranc (LSC)
- Main challenge: Superconducting qubit in a magnetic field



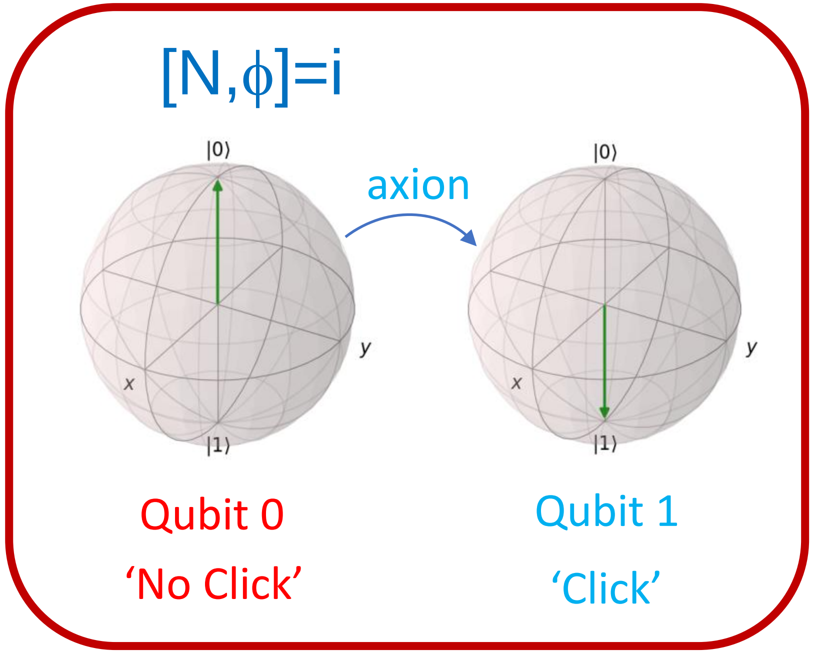
Microwave single photon counter

Measuring power



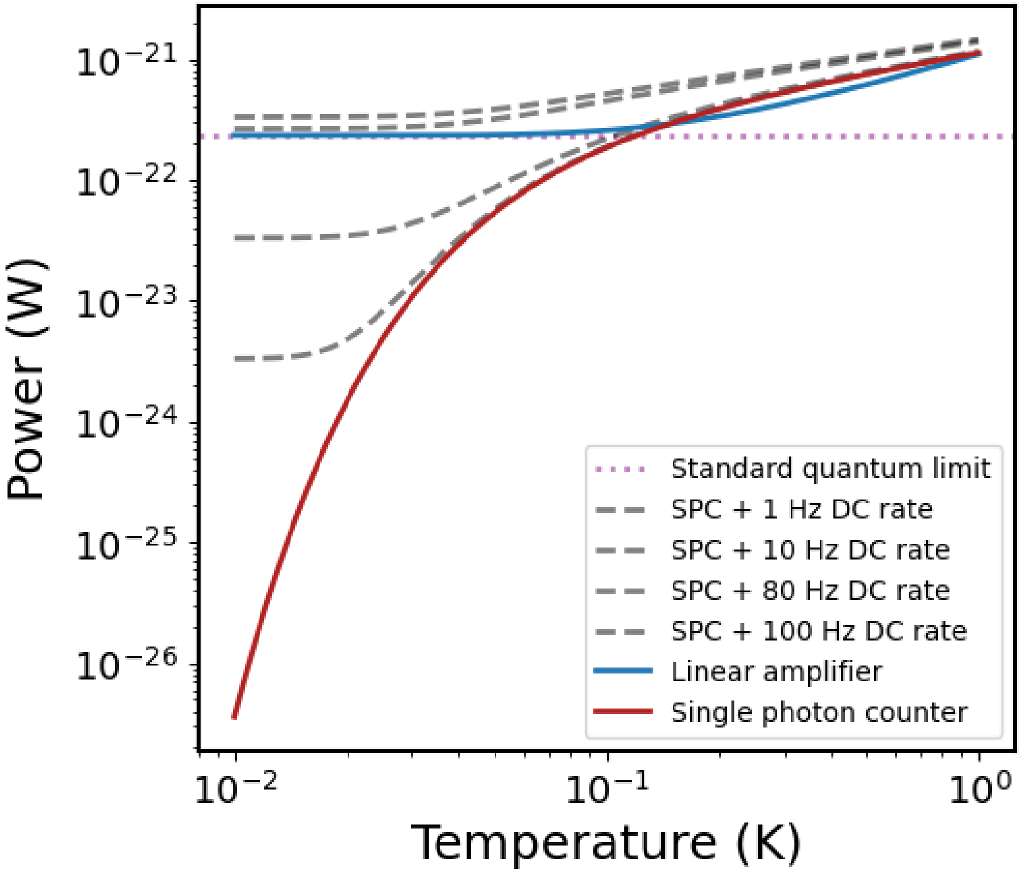
Cavity + linear amplifier

Counting photons



Cavity + qubit

Overcome standard quantum noise limit



Linear receiver:

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

Standard quantum limit:

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

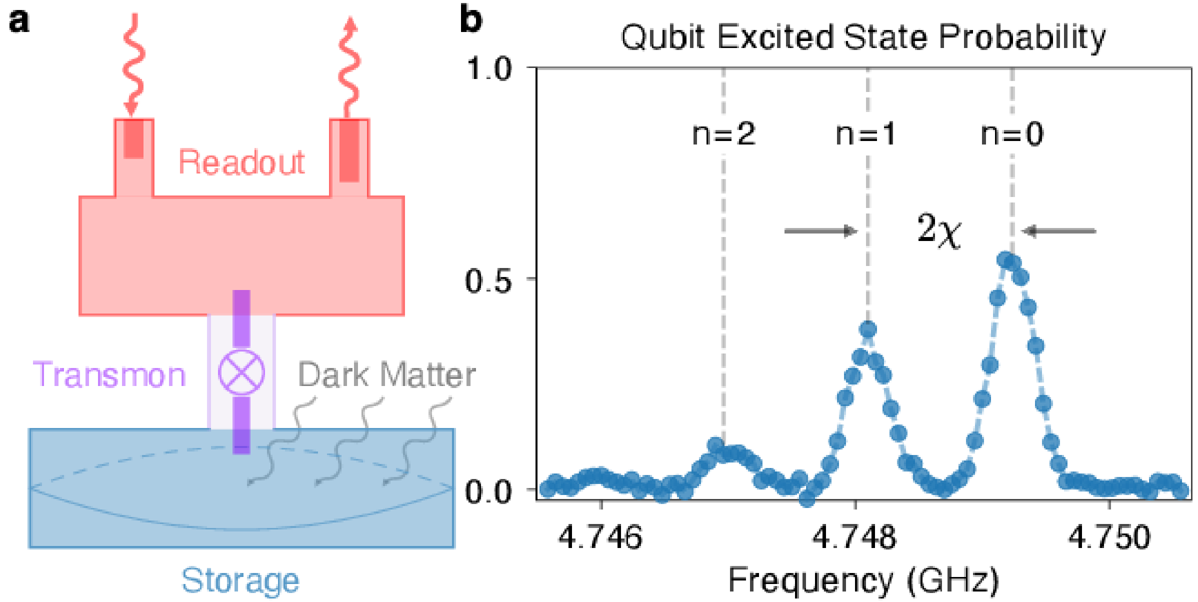
Single photon counter

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

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

Working principle

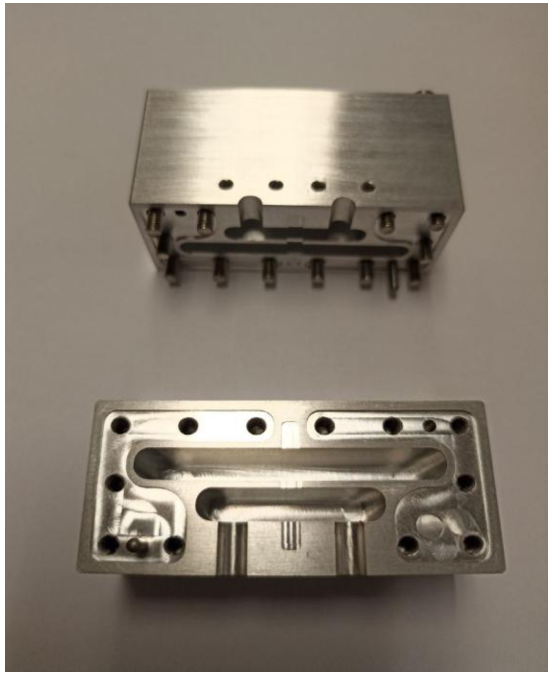
Characteristic qubit frequency changes when there is a photon in the cavity.

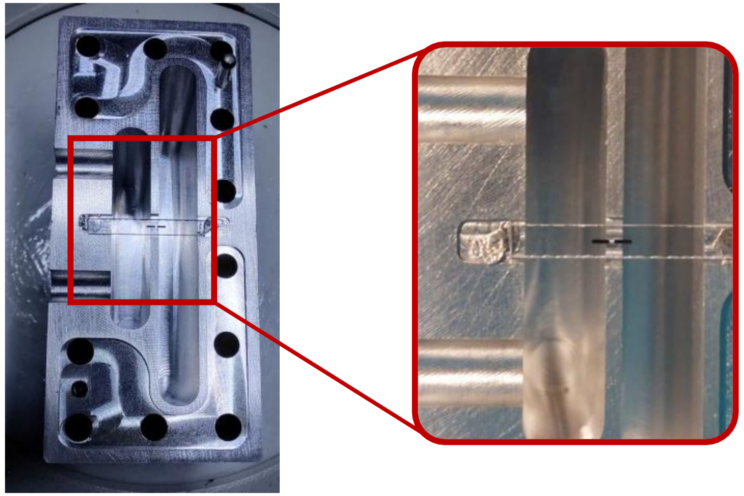


Dixit et al. Searching for dark matter with a superconducting qubit, [Phys. Rev. Lett. 126]

Ingredients for a microwave SPC

Double cavity (Readout + Storage)



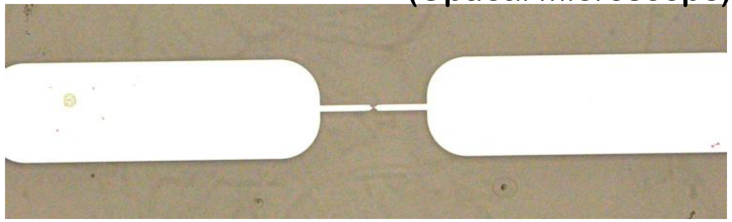


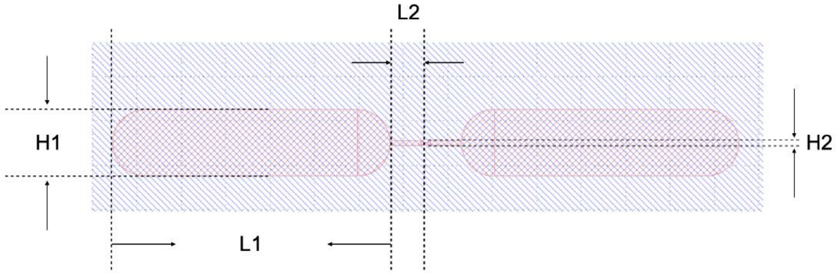
Cold!

Dilution refrigerator: 10-20 mK

Transmon

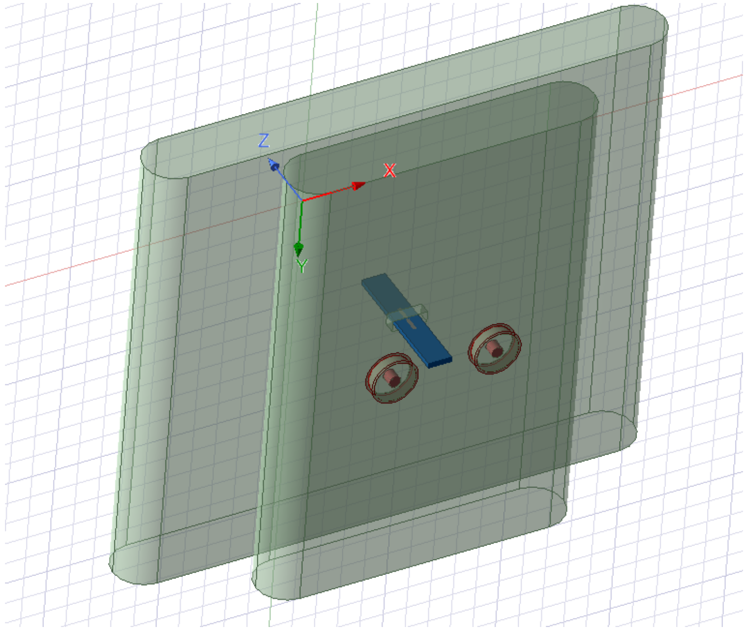
(Optical microscope)



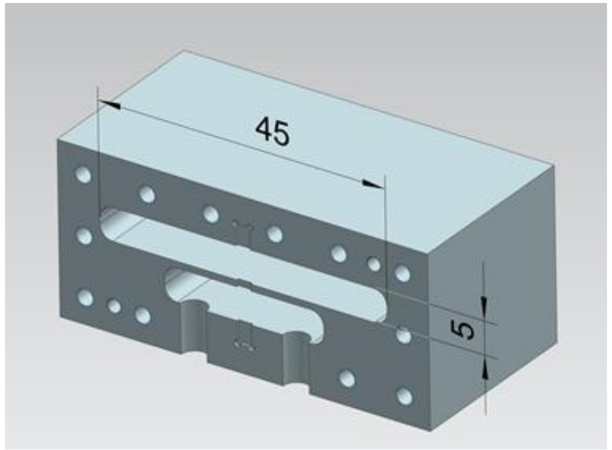


	Q1
L1 (mm)	1
H1 (mm)	0.3
L2 (mm)	0.15
H2 (mm)	0.02

Double cavity



Dimensions	X	Y	Z
Readout cavity (6.8 GHz)	26.6 mm	40 mm	5 mm
Storage cavity (5 GHz)	45 mm	40 mm	5 mm



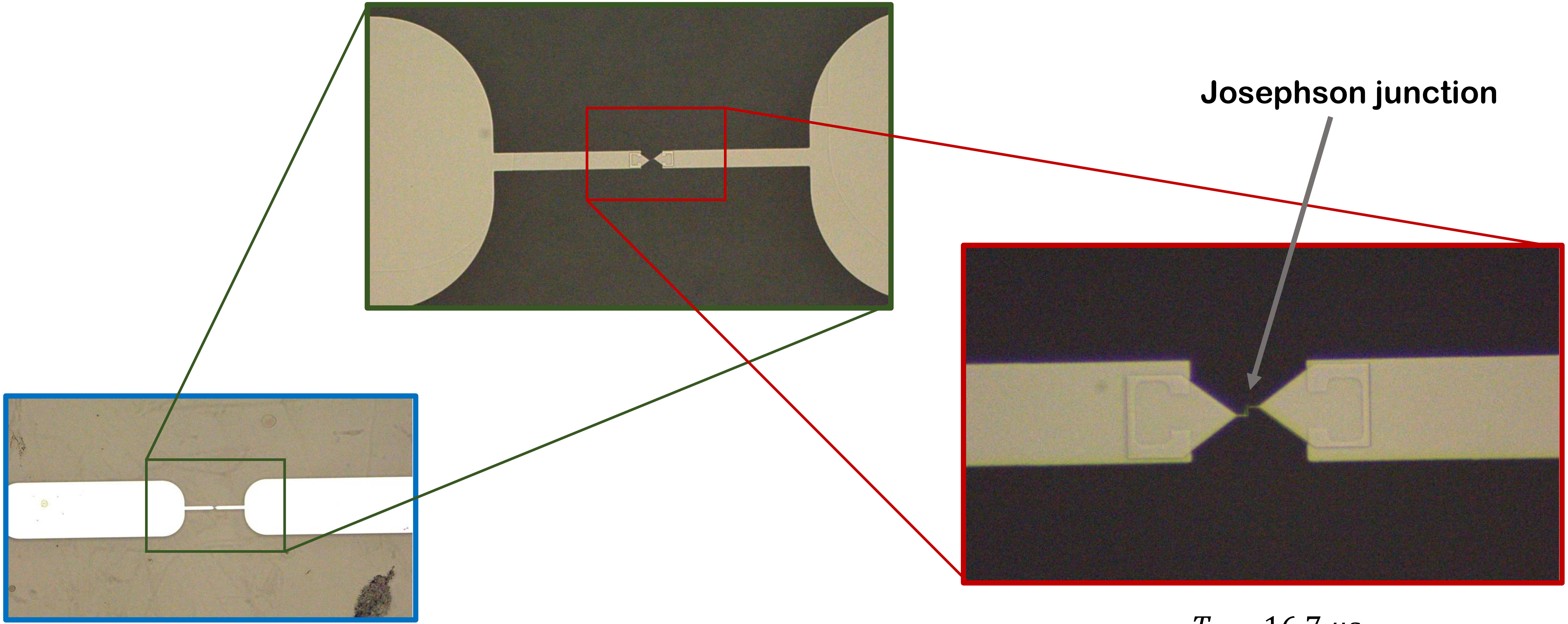
Aluminum

Copper

Frequencies

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

Transmon: superconducting qubit

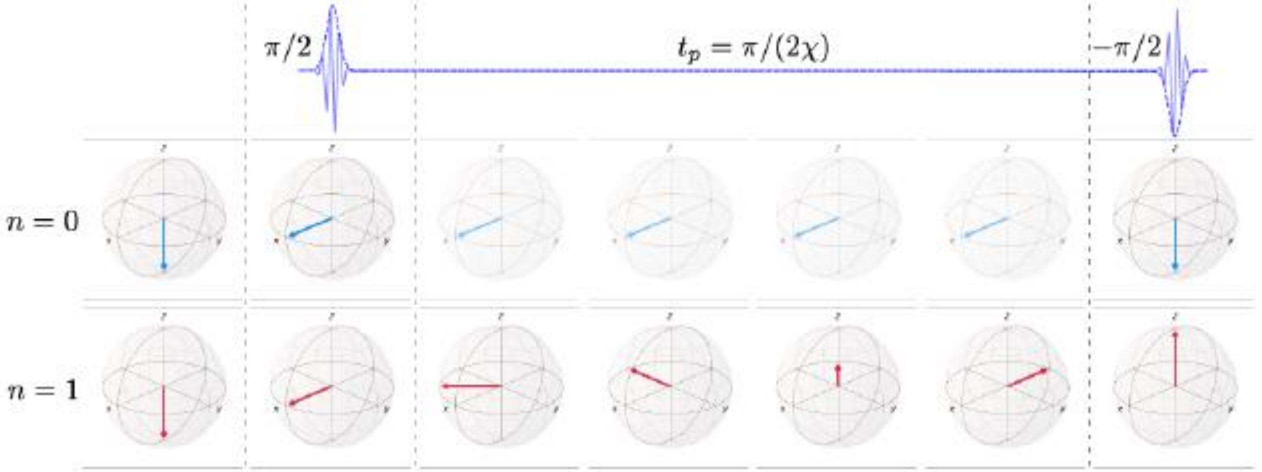


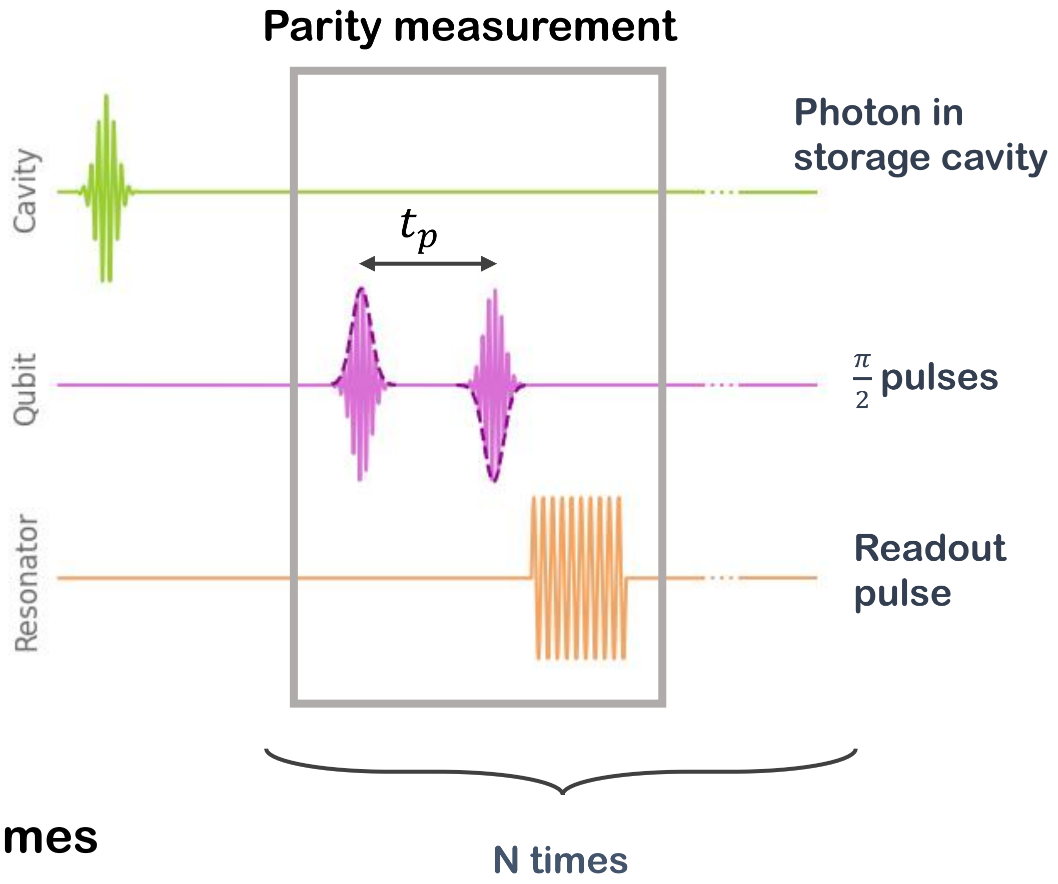
$T_1 = 16.7\ \mu s$

Parity measurement

Interferometric measurement.

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

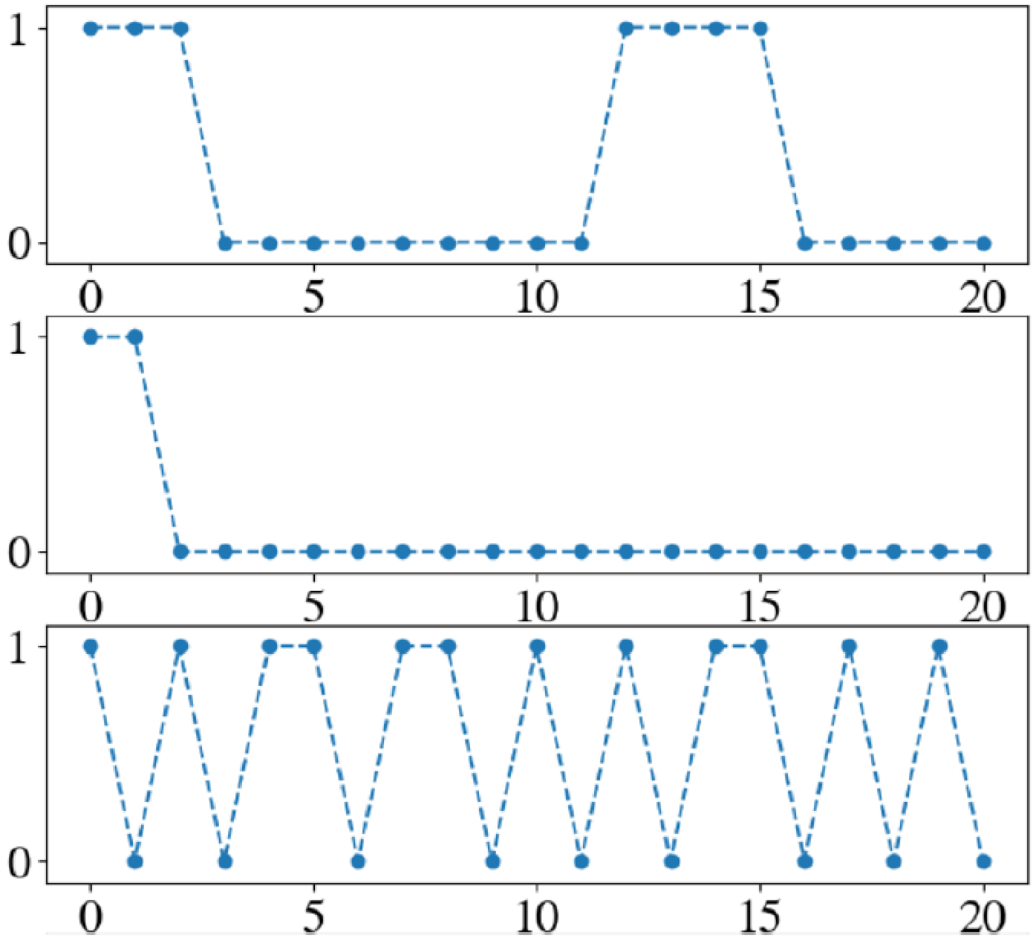




Parity sequence: ($\pi/2$ + Wait t_p + $-\pi/2$ + Readout) x N times

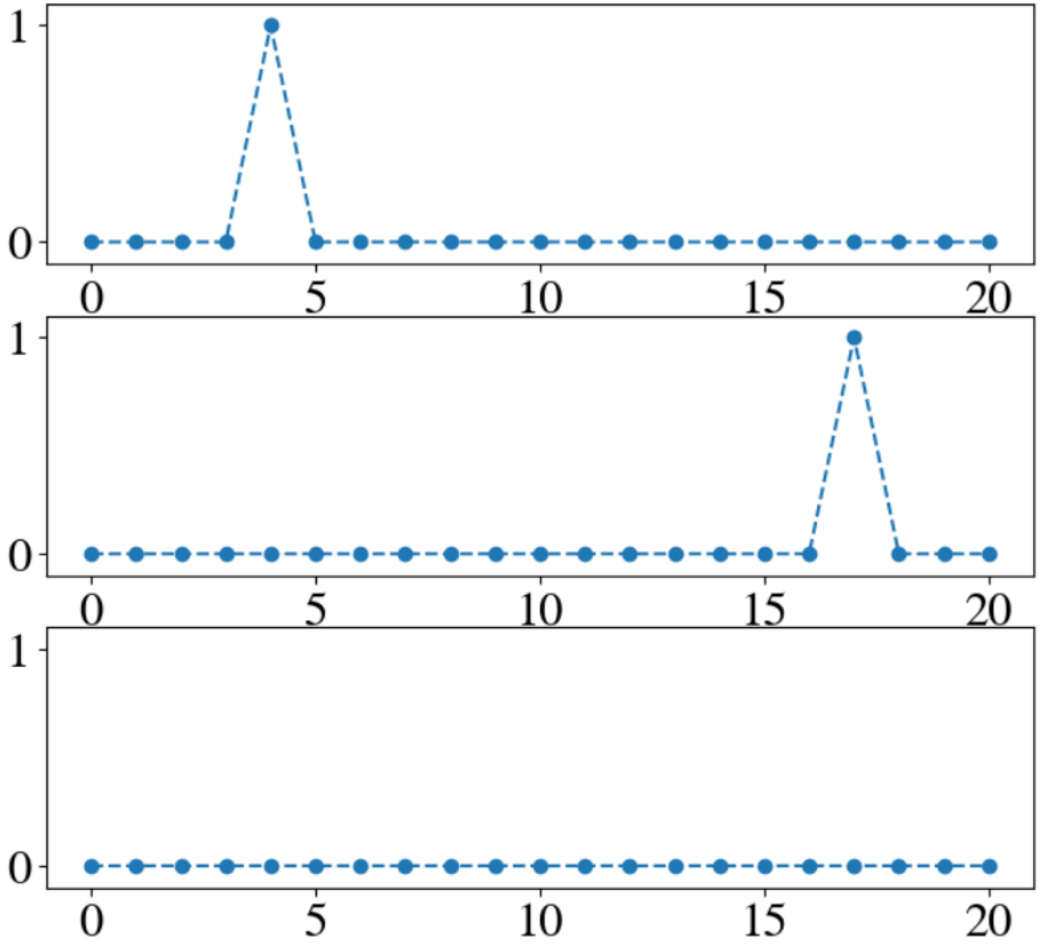
Parity sequence

Injecting photons



N = 21

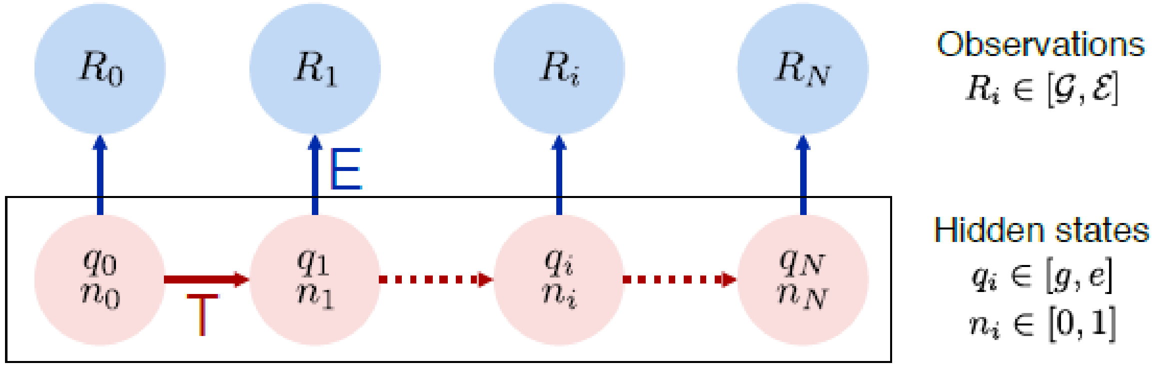
Not injecting photons



Hidden Markov Model

Bayesian method to assign probabilities to each sequence.

Flat prior + forward/backward method.



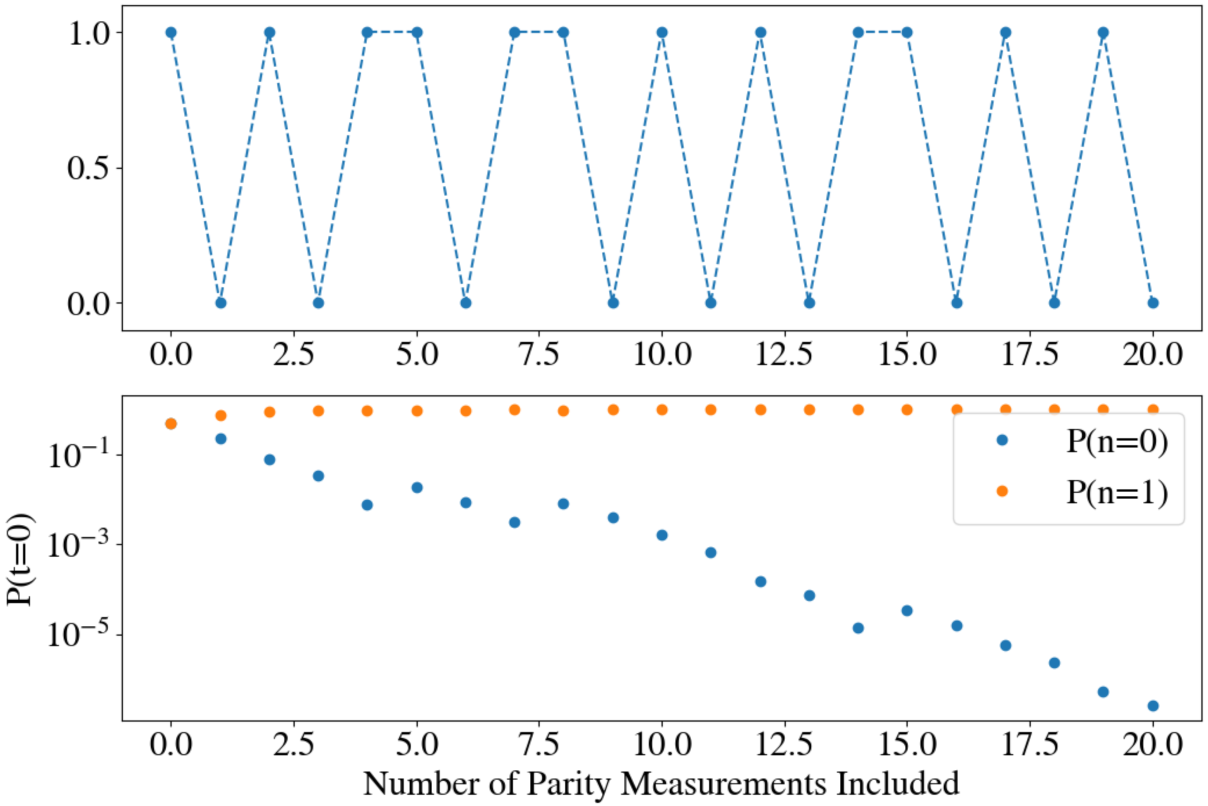
$$\mathbf{T} = \begin{array}{c} \\ \\ \end{array}\begin{array}{cc} \begin{array}{cccc} |0g\rangle & |0e\rangle & |1g\rangle & |1e\rangle \end{array} & \\ \begin{bmatrix} P_{00}P_{gg} & P_{00}P_{ge} & P_{01}P_{ge} & P_{01}P_{gg} \\ P_{00}P_{eg} & P_{00}P_{ee} & P_{01}P_{ee} & P_{01}P_{eg} \\ P_{10}P_{gg}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

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

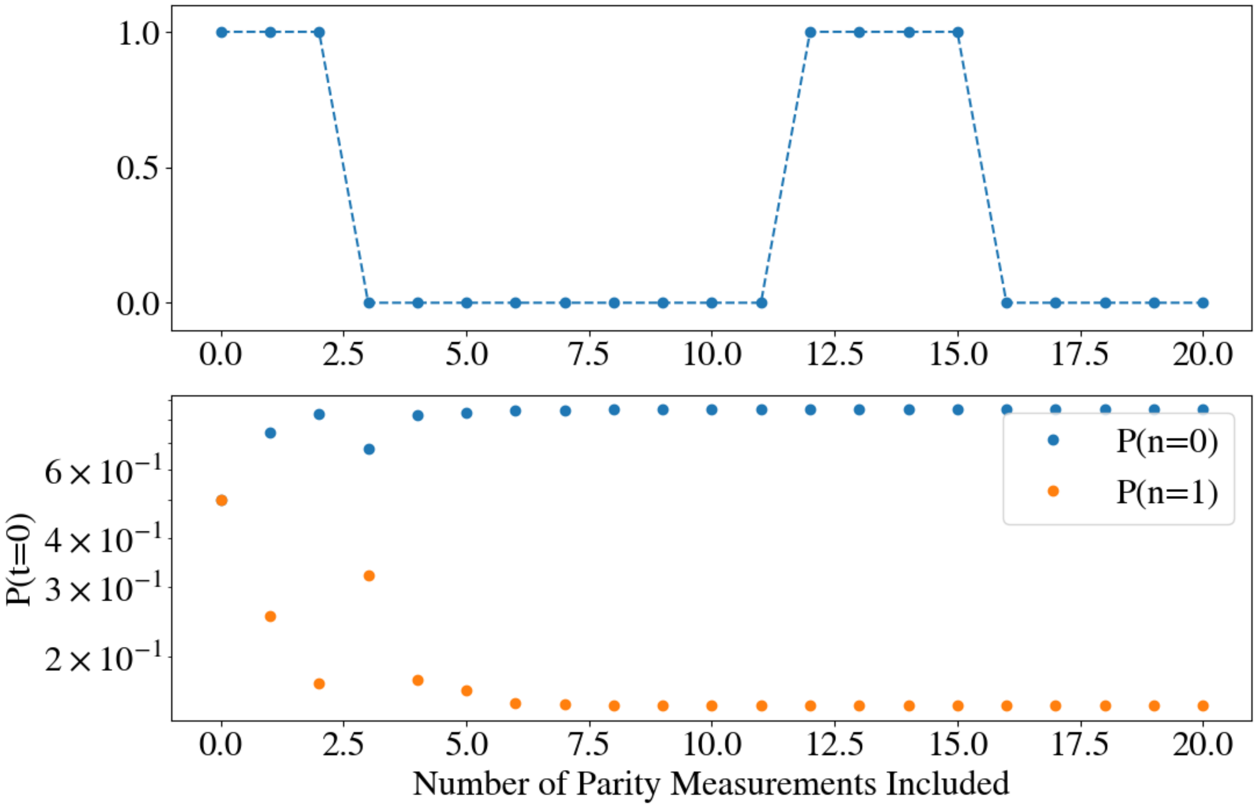
$$\begin{cases} P_{gg} = 1 - P_{ge}, P_{ee} = 1 - P_{eg} \\ P_{ge} = \bar{n}_q \left[1 - e^{-t_m/T_1^q}\right] + 1 - e^{-t_p/T_2^q} \\ P_{eg} = 1 - e^{-t_m/T_1^q} + 1 - e^{-t_p/T_2^q} \\ P^{\phi} = 1 - e^{-t_p/T_2^q} \\ P_{00} = 1 - P_{01}, P_{11} = 1 - P_{10} \\ P_{01} = \bar{n}_s \left[1 - e^{-t_m/T_1^u}\right]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

Probabilities of hidden states

Photon in storage cavity



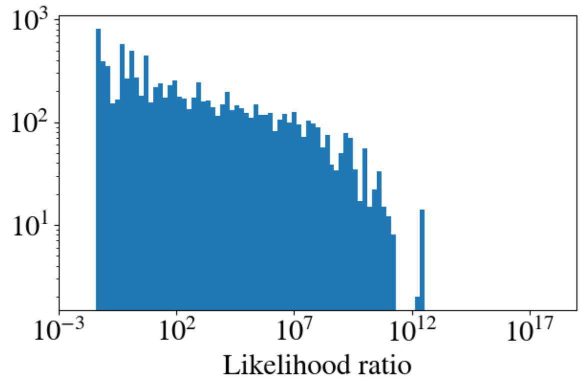
No photon in storage cavity



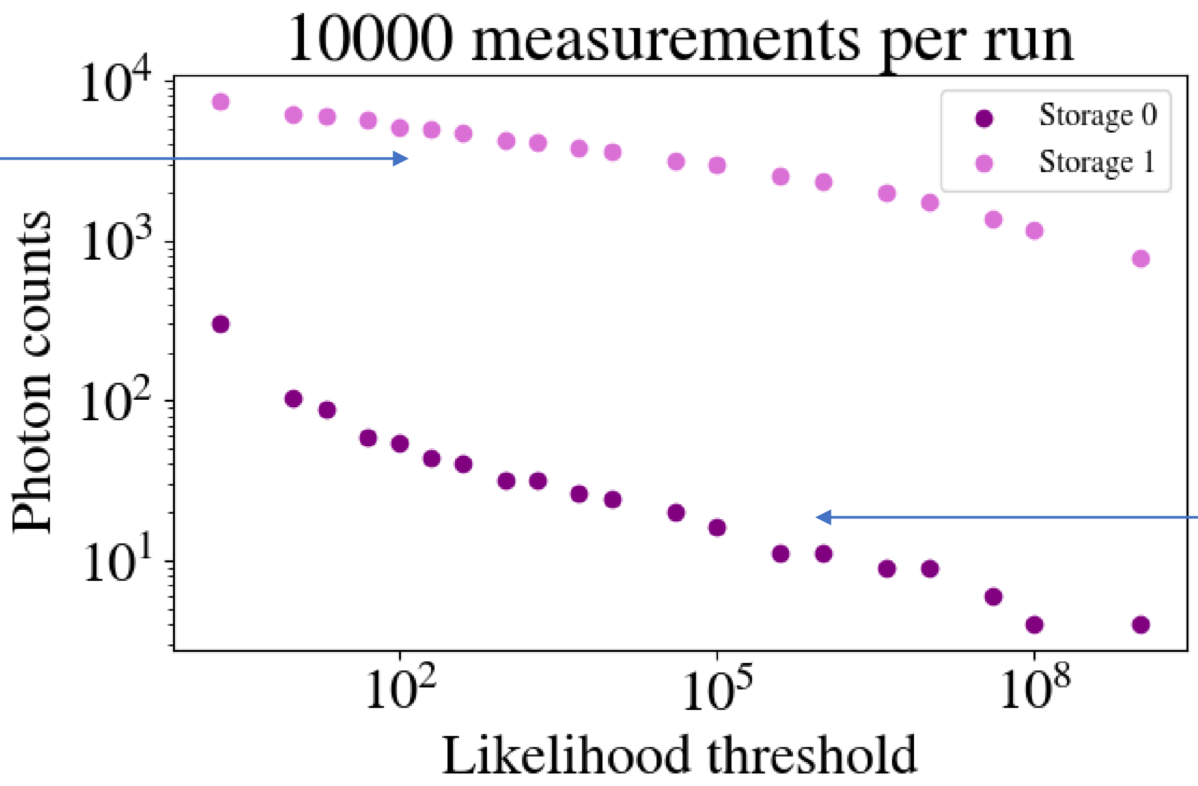
Distributions of likelihood test

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

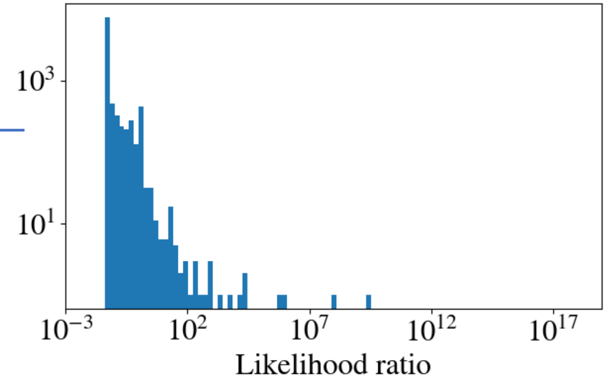
Calibrations



Injecting photons in the storage cavity



Background



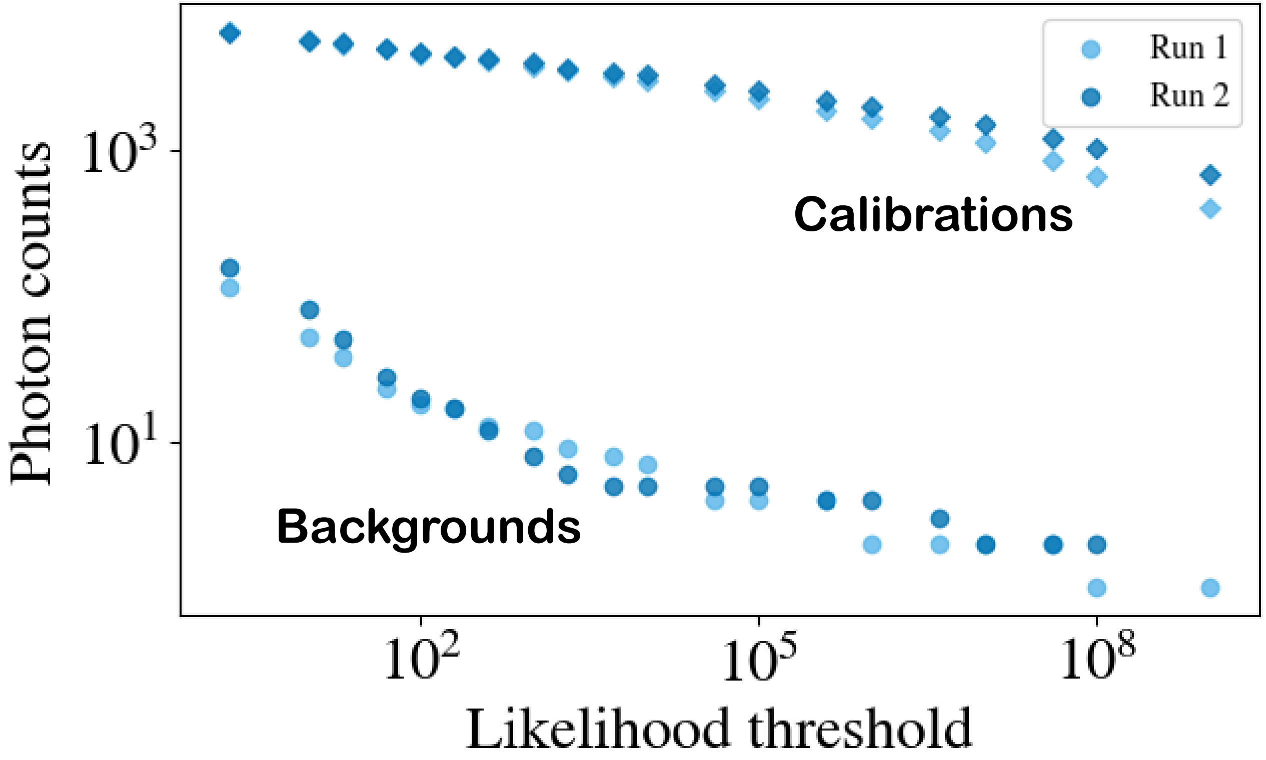
Likelihood threshold: Chosen value to discriminate the presence of a photon.

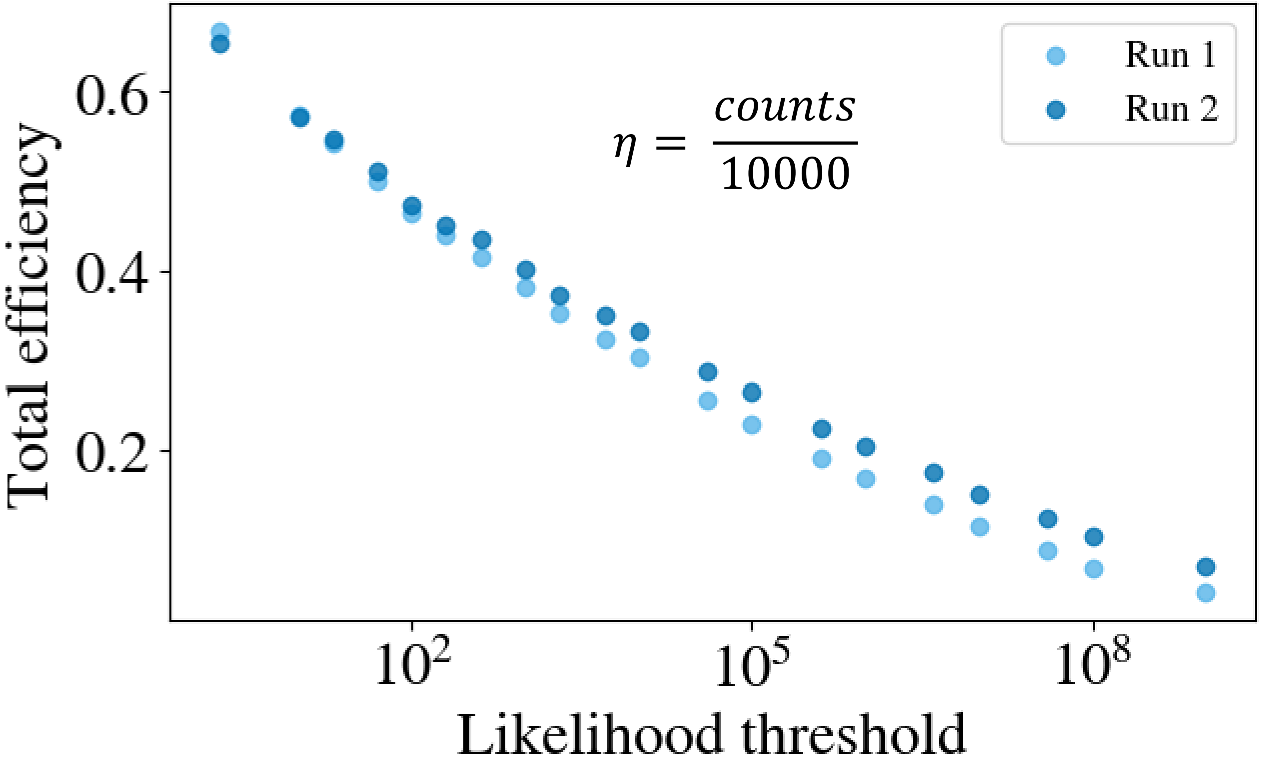
First RADES runs in Aalto University

	$\Pi/2$	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

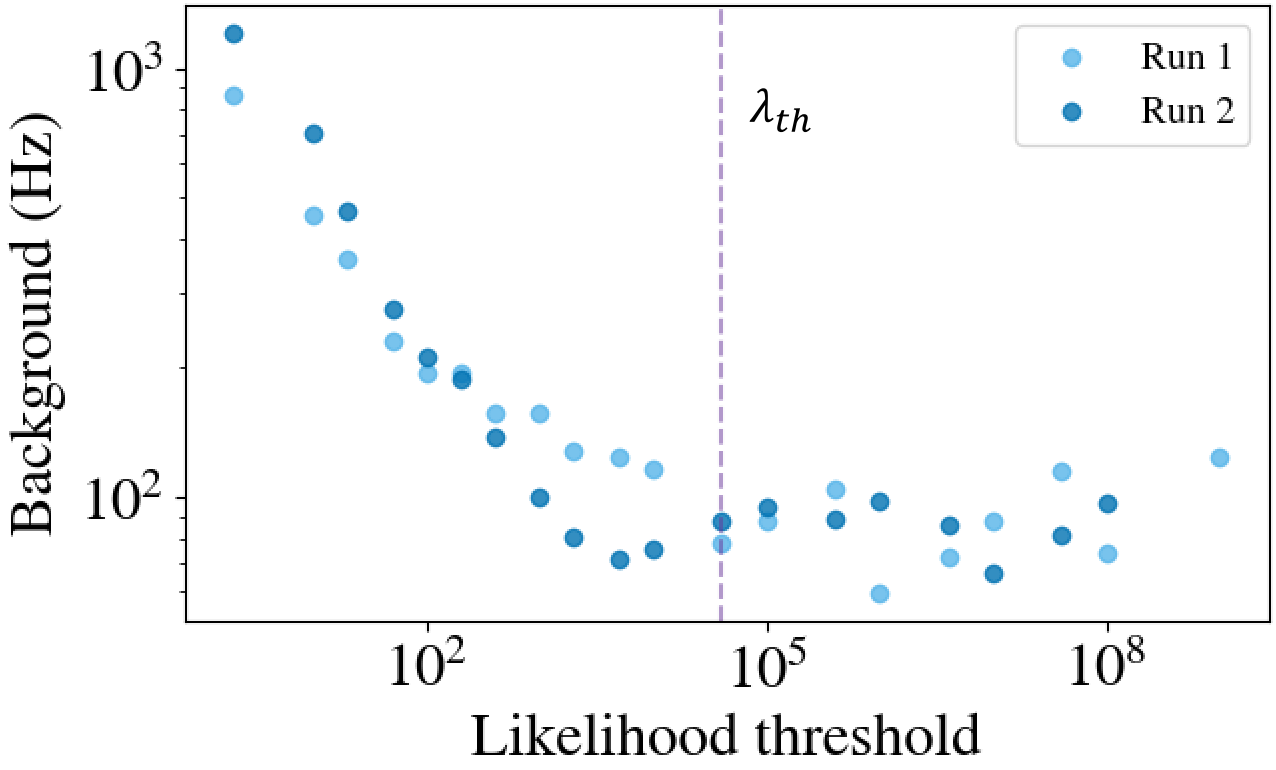
Two runs with 10000 parity sequences each.
Same parameters in both runs.

Results: counts and efficiencies





Background rate estimation



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

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)

Conclusions and future works

- RADES ongoing efforts: bigger cavities for BabyIAXO and develop a quantum sensor.
- First single photon counter successfully tested.
- Next prototype for magnetic tests.
- Transmon properties relevant but no critical.
- Room to optimize the readout protocol.
- Increase Q factor of storage cavity.

THANK YOU VERY MUCH!!

Backup

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.

Parameters of the single photon counter

Readout fidelity

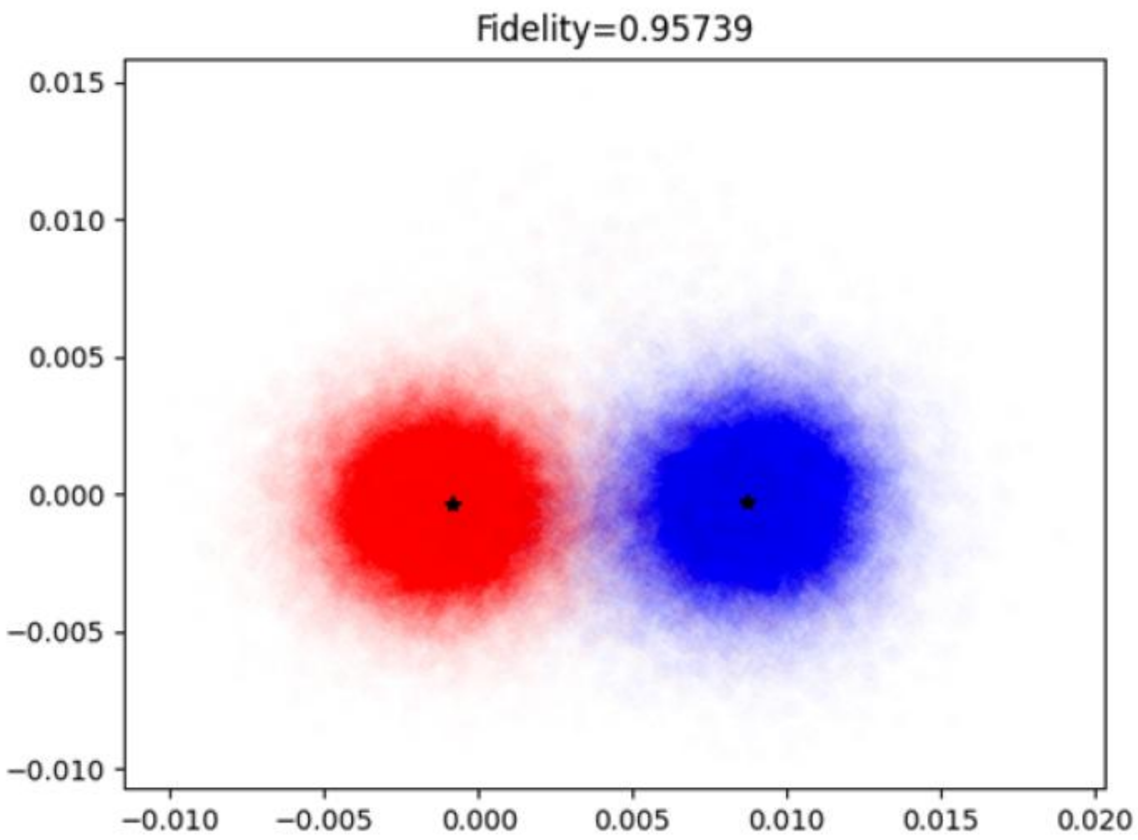


Figure 8: Readout fidelities. Blue measurements with qubit in ground state, red with qubit in first excited state.

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

Backup

Other tests with higher delay between parity measurements.
They can be too long for N=21 parity measurements, photons decay always while measuring.

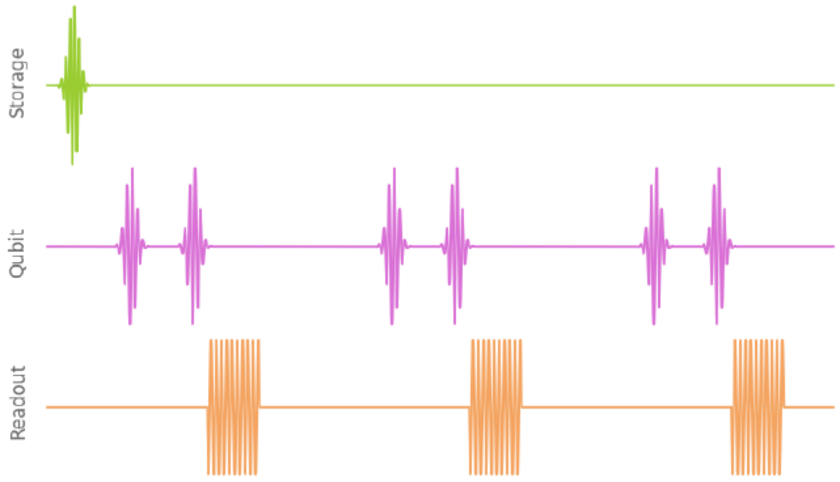


Figure 7: Parity sequence with $N = 3$.

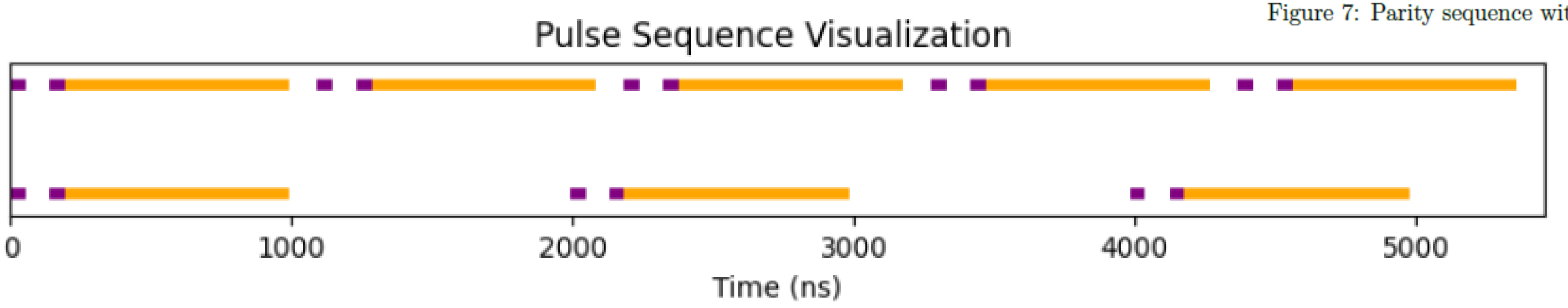
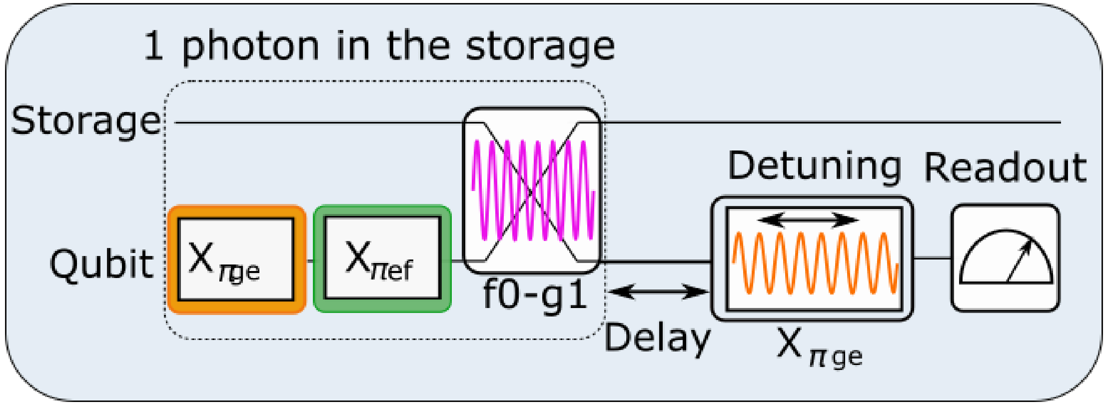
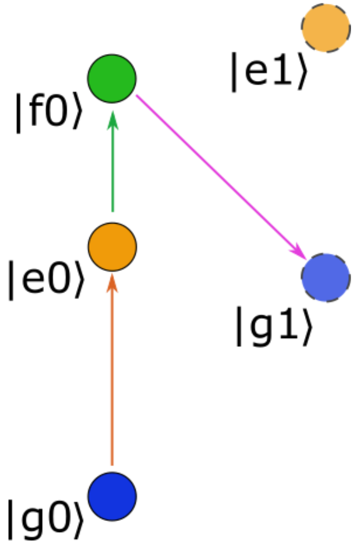


Figure 16: Different waiting times between parity measurements, 100 ns (Runs 1 and 2) and 1000 ns (Runs 3). Same $\pi/2$ (52 ns, in purple) and readout (800 ns, in yellow) pulses. Parity time delay $t_p = 88$ ns. For $N = 21$, total pulse sequence time is 22.932 μs and 41.832 μs.

Pulse sequence to inject a photon in the storage cavity

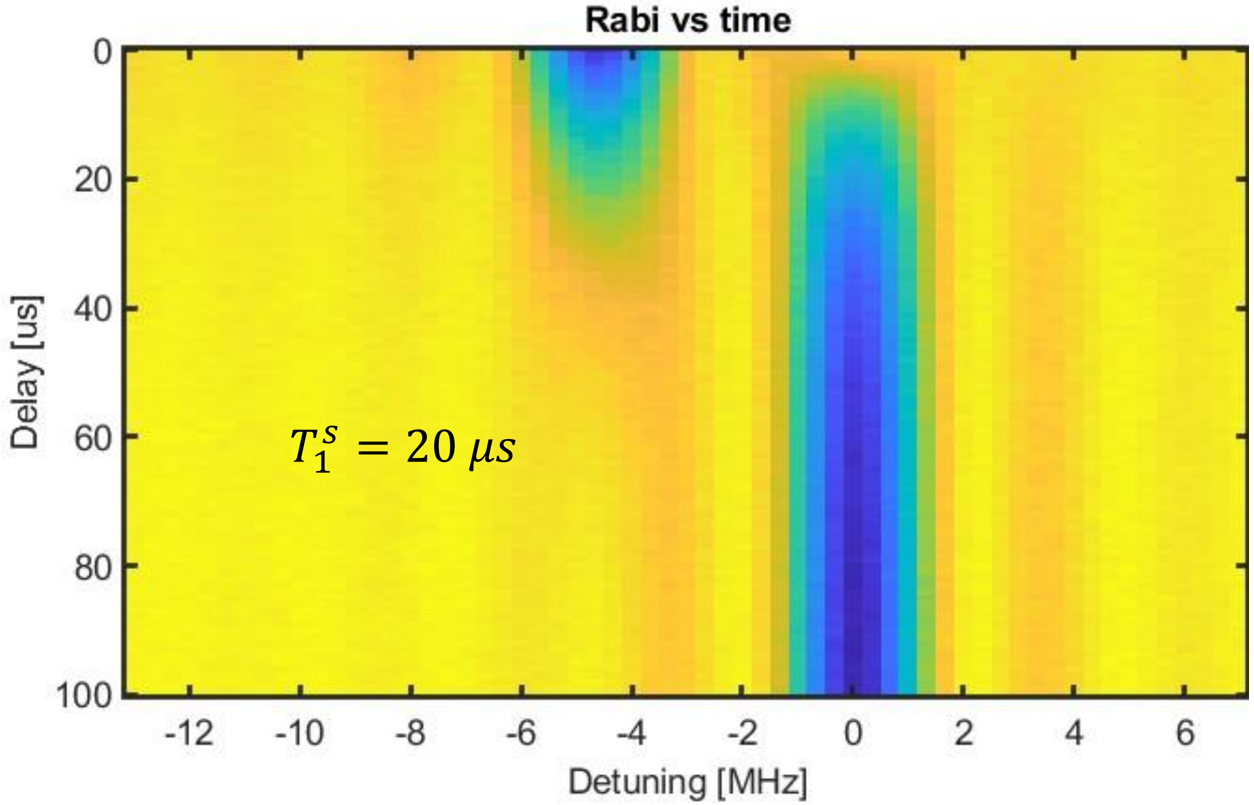




$\omega_{ge}/_{2\pi} = 4.629$ GHz

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

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



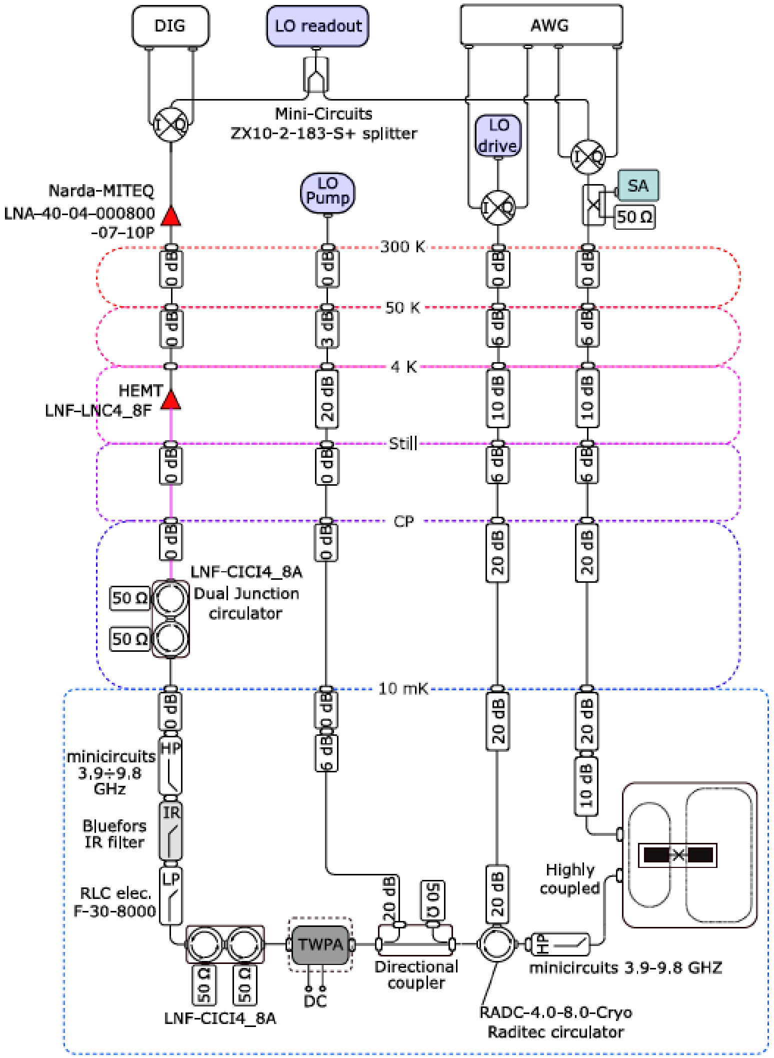
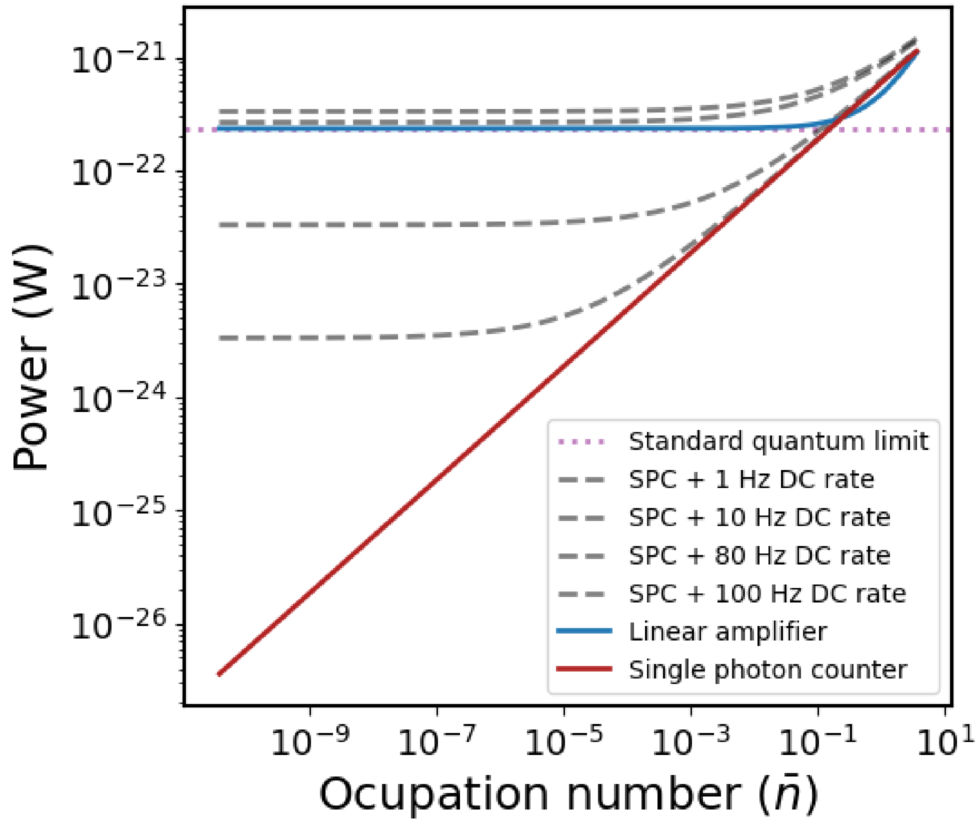
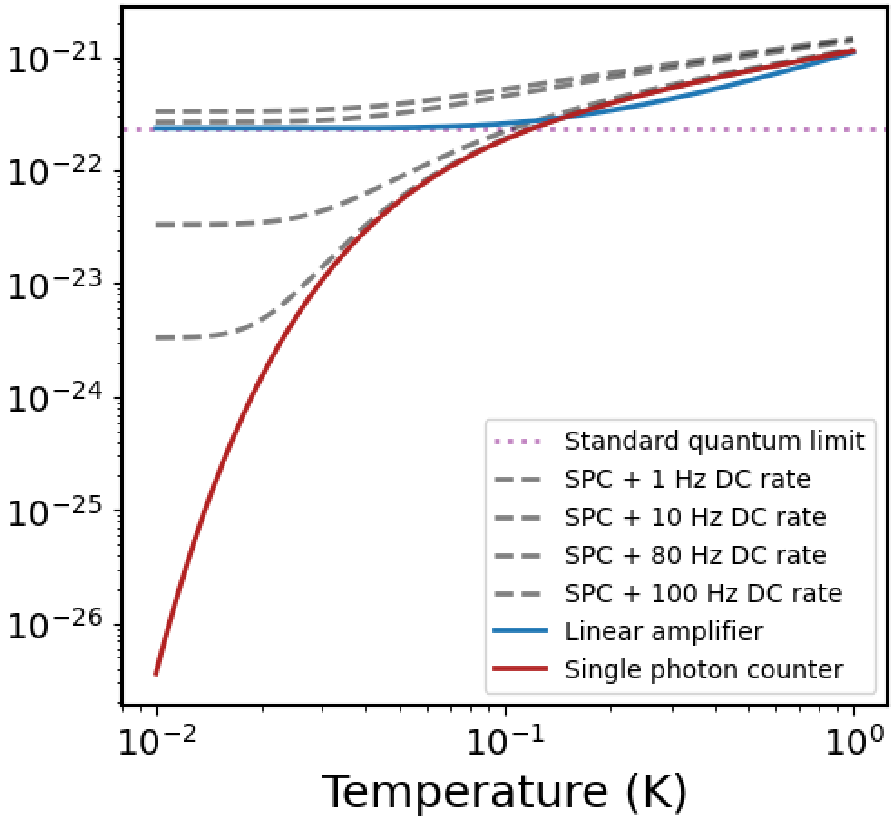


Figure 7.20: Layout of the input and output RF lines inside the cryostat during the parity measurements.

Backup





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

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

Calibrate the pulse sequence

Blue: No photon in the storage cavity.
Red: A photon in the storage cavity.

Black circle: the spot selected for parity measurements. Different behavior with respect to photon content.

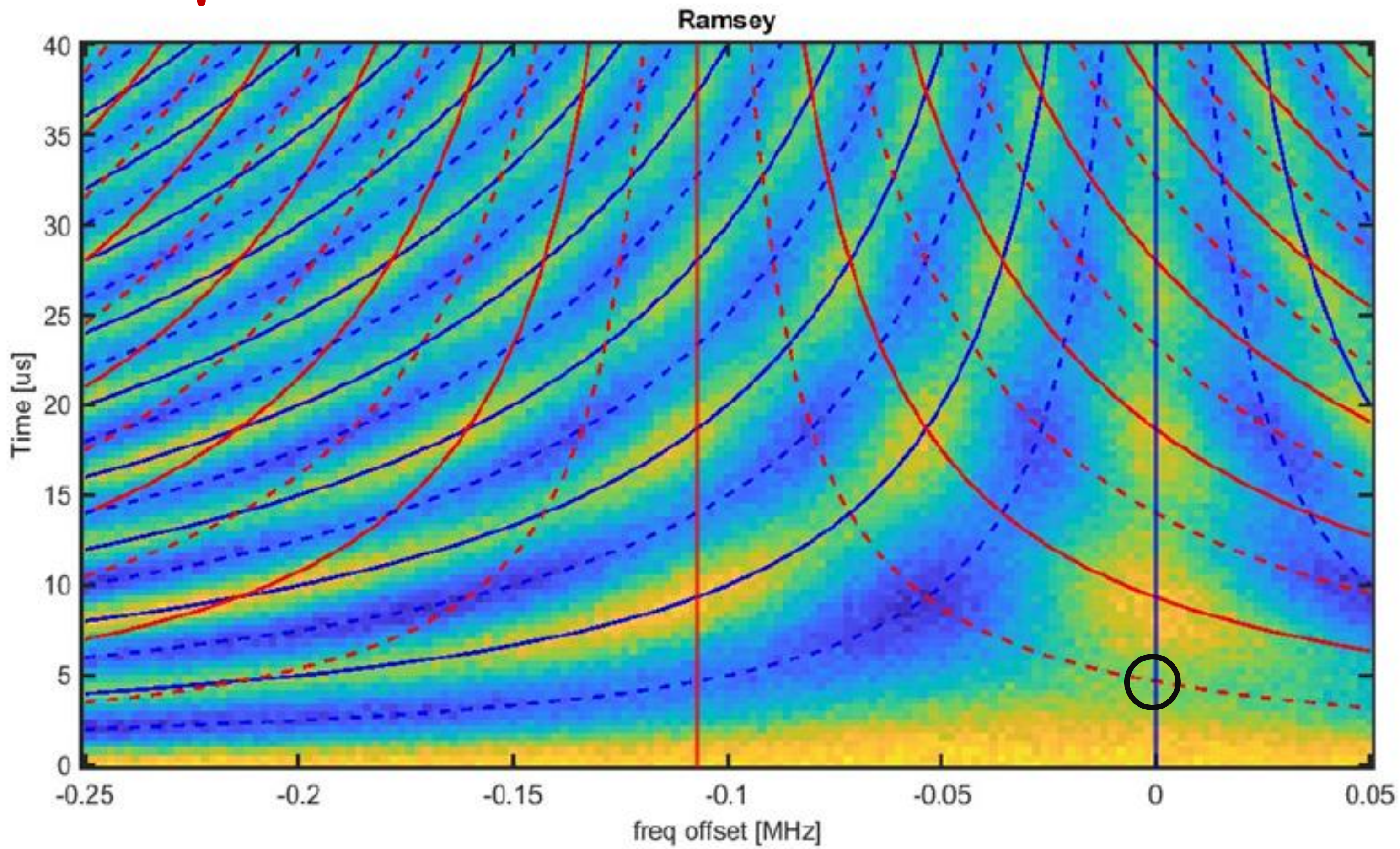
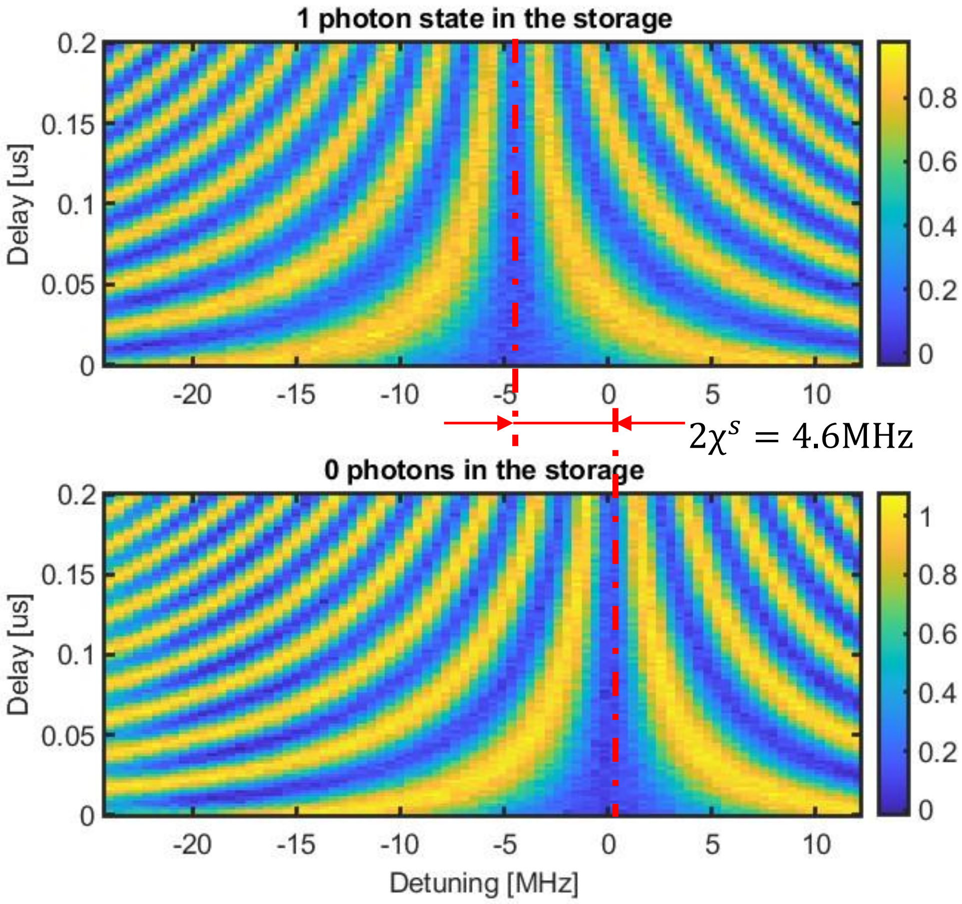
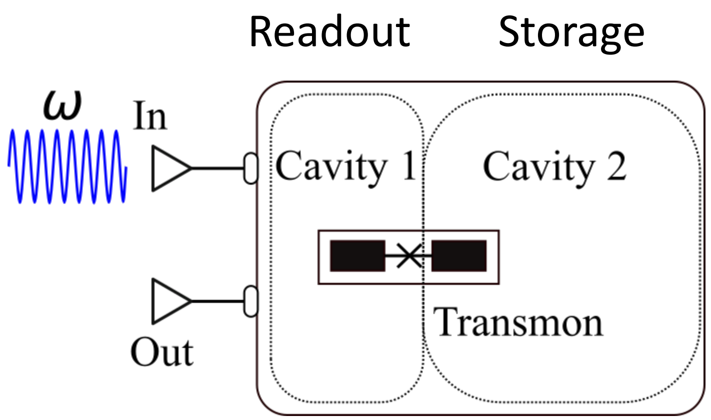
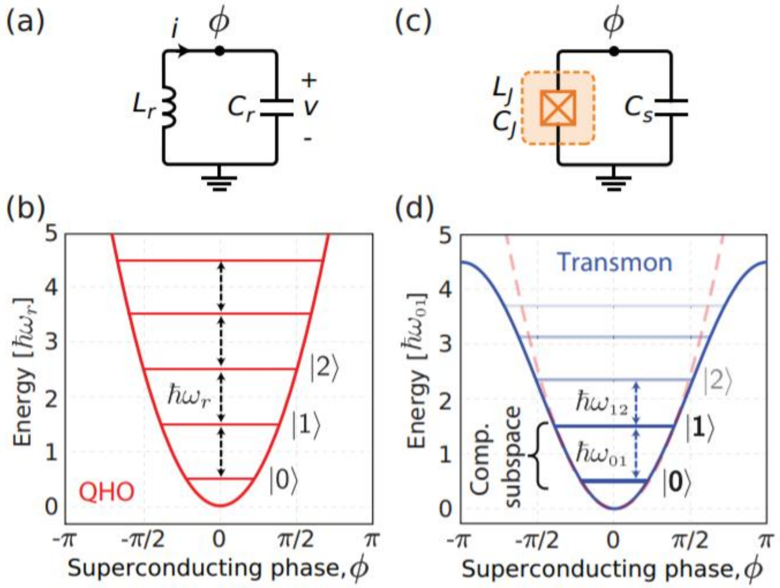


Figure 5: Ramsey measurement. Two patterns appear due to the presence of photons in the cavity, which produces a shift in frequency. Lines just to guide the eyes, not fitted.

Backup


1 photon state in the storage
0 photons in the storage
Delay [us]
Detuning [MHz]
$2\chi^s = 4.6\text{MHz}$





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

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

Backup

Parameter	Run 1 ($\rho_{DM} = 0.45$, 95% CL)	Run 2 ($\rho_{DM} = 0.45$, 95% CL)	Runs 1 + 2 ($\rho_{DM} = 0.45$, 95% CL)
f_s (GHz)	5.051	5.051	5.051
Q_s	634727 (0.6M)	634727 (0.6M)	634727 (0.6M)
N_{DM}	4	5	4 - 5
N_{meas}	10000	10000	20000
Efficiency η	0.257	0.286	0.257 - 0.286
n^{CL}	0.00358	0.00368	0.00261
ε^{CL}	$1.2217 \cdot 10^{-14}$	$1.2387 \cdot 10^{-14}$	$1.0446 \cdot 10^{-14}$

Table 7.8: Table with exclusion limits for the mixing angle of dark photons at 95% C.L. from Runs 1, 2 and the combined analysis (explained in the text) using a quantum sensor as single photon counter.