RADES project

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on behalf of RADES group

University of Zaragoza

6/6/2024

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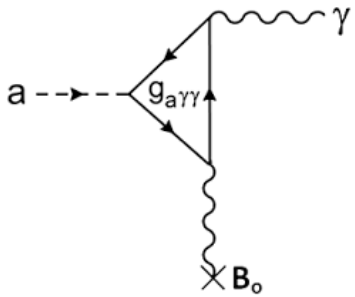
1) Axion dark matter
2) Haloscope concept
3) Rades setups
4) Future experiments
5) Quantum sensors for haloscopes

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

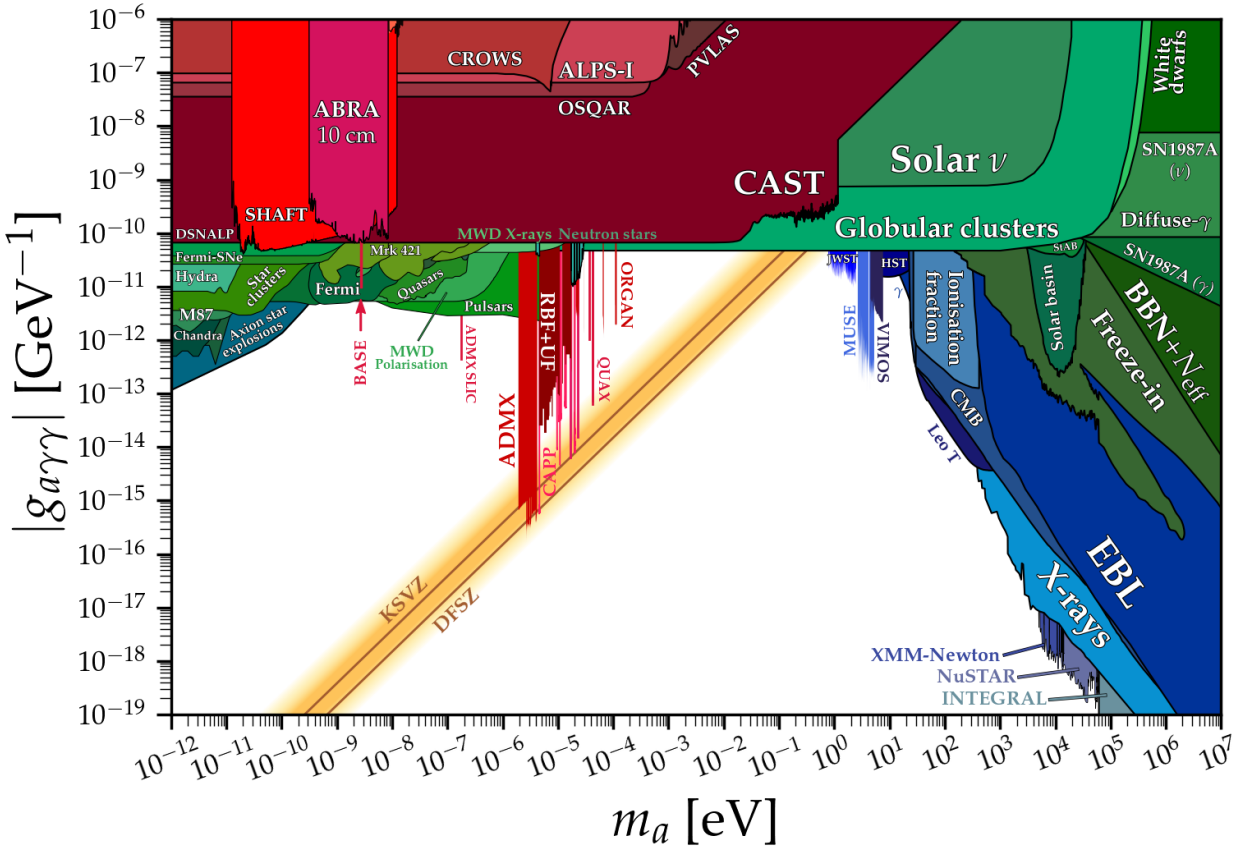


$$\mathcal{L}_{a\gamma\gamma} \propto g_{a\gamma} a \vec{E} \cdot \vec{B}_e$$

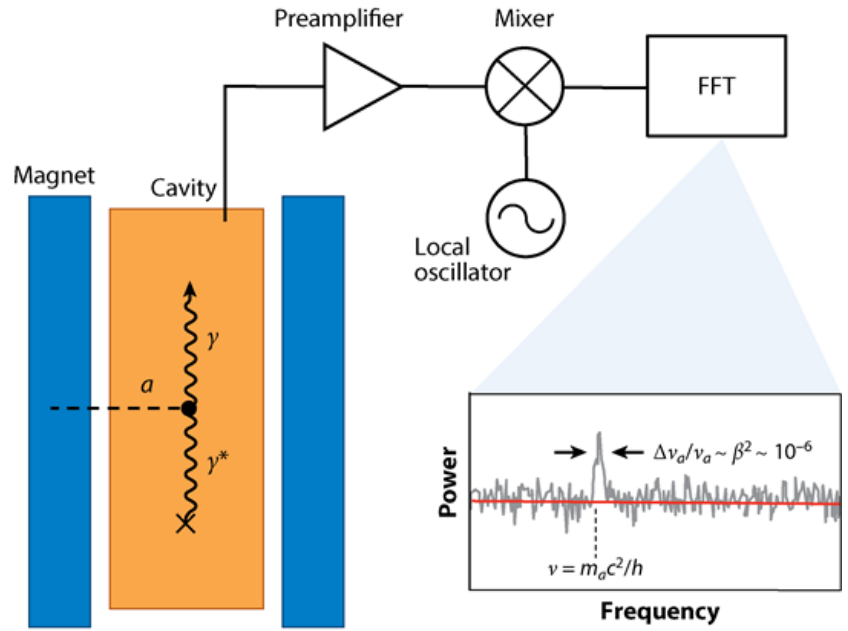
Diagram of the Primakoff effect (a-γ coupling)

Axion dark matter

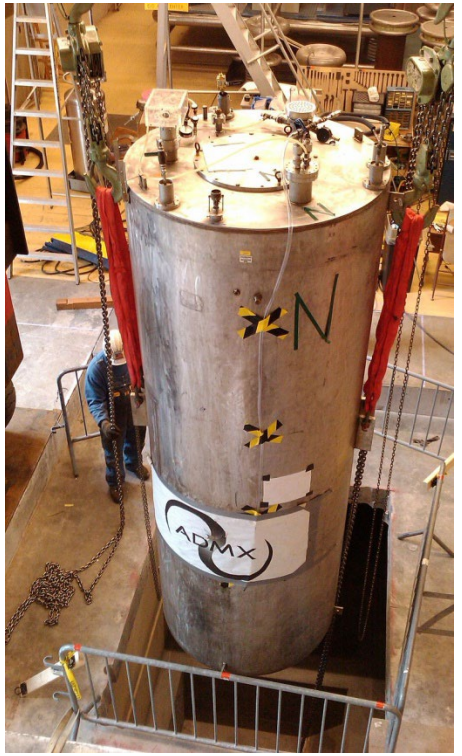
Axion's parameter space



Haloscope concept



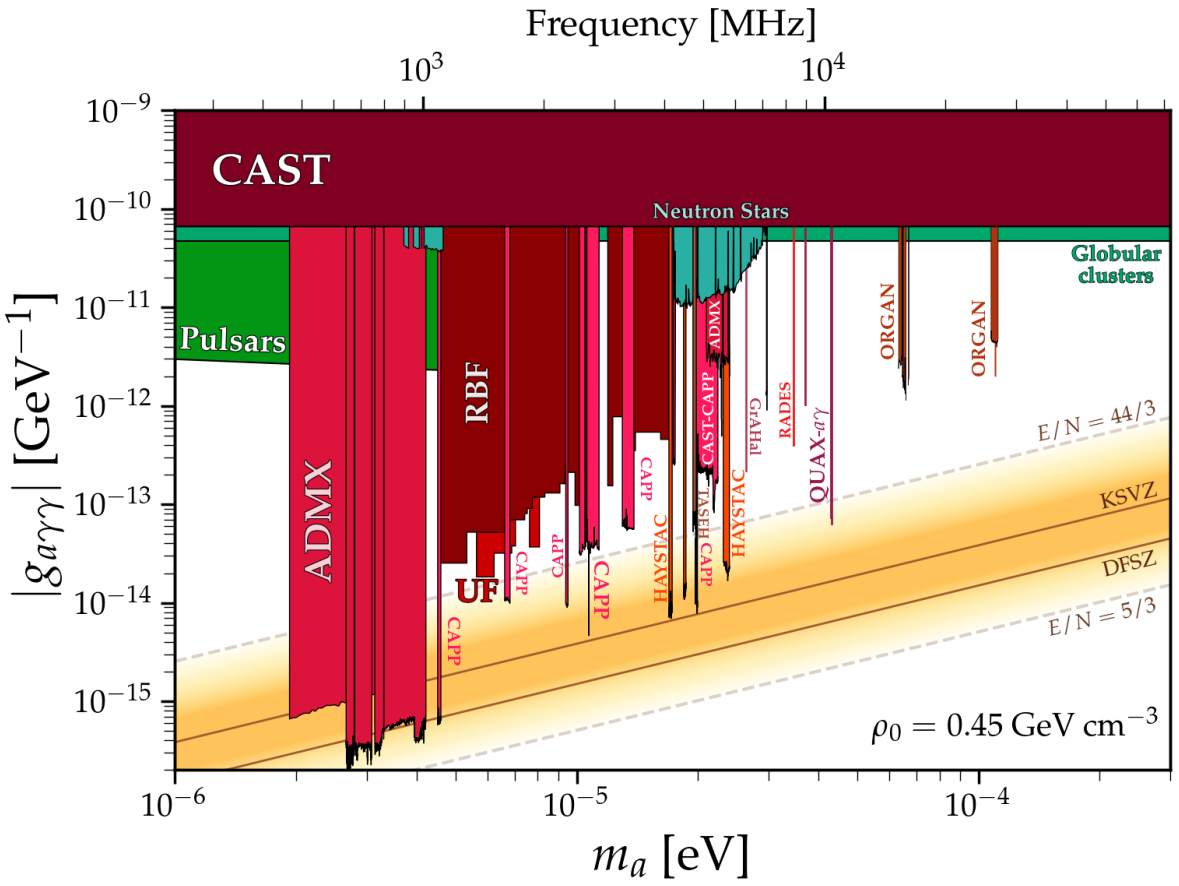
ADMX



Power:

$$P_a = g_{a\gamma}^2 \rho_{\mathrm{DM}} \frac{\beta}{1+\beta} \frac{1}{m_a} B^2 V Q_L G^2,$$

Haloscope concept



Scanning rate:

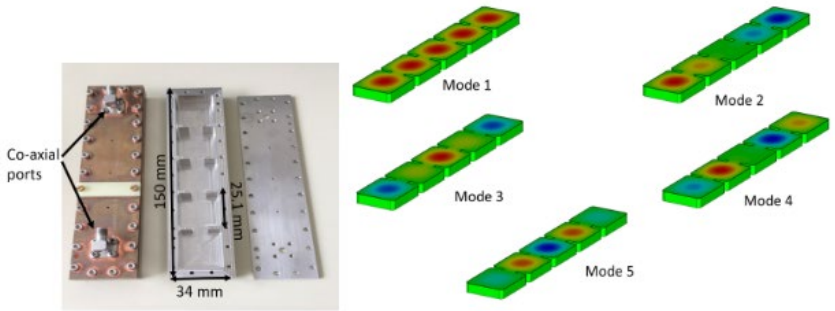
$$dt = \Delta\nu_a \left(\frac{\frac{S}{N} k_B T_{sys}}{P_d} \right)^2 = \frac{m_a}{Q_a} \left(\frac{\frac{S}{N} k_B T_{sys}}{P_d} \right)^2$$

Is used as figure of merit:

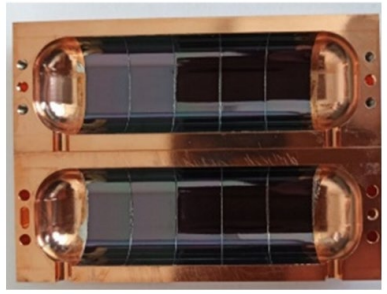
$$\frac{dm_a}{dt} = \frac{Q_a}{Q_l} \left(\frac{P_d}{\frac{S}{N} k_B T_{sys}} \right)^2 = Q_a Q_l \kappa^2 g_{a\gamma}^4 \left(\frac{\rho_a}{m_a} \right)^2 B_e^4 C^2 V^2 \left(\frac{S}{N} k_B T_{sys} \right)^{-2}$$

Rades setups

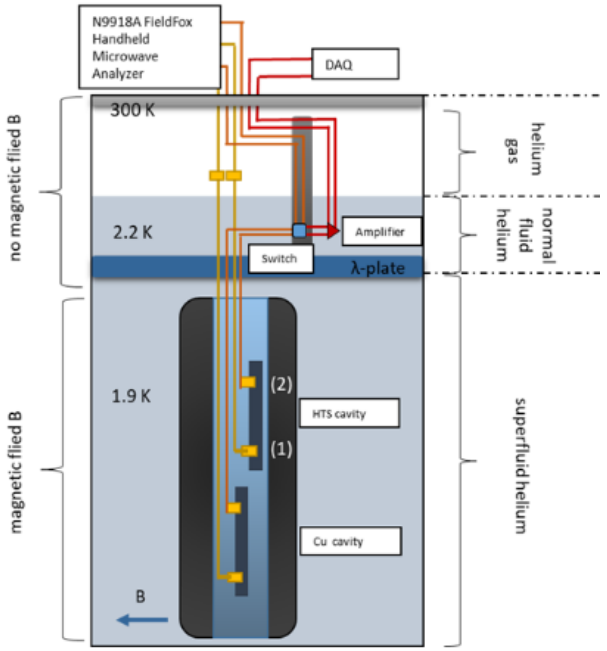
CAST - Rades

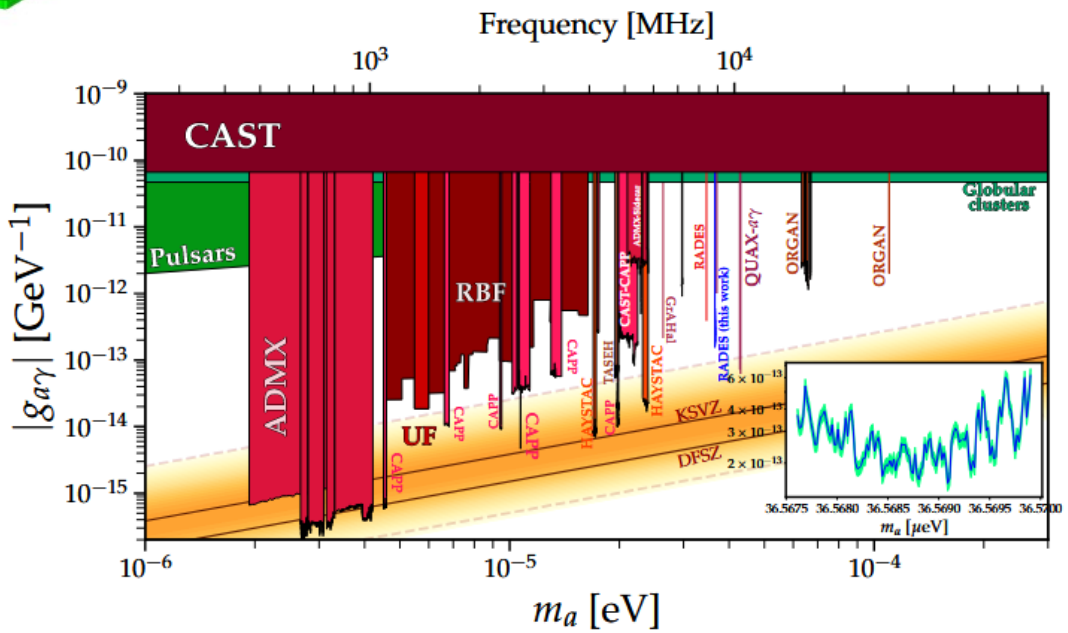


SN18 - Rades



HTS coatings
More in T. Puig's talk

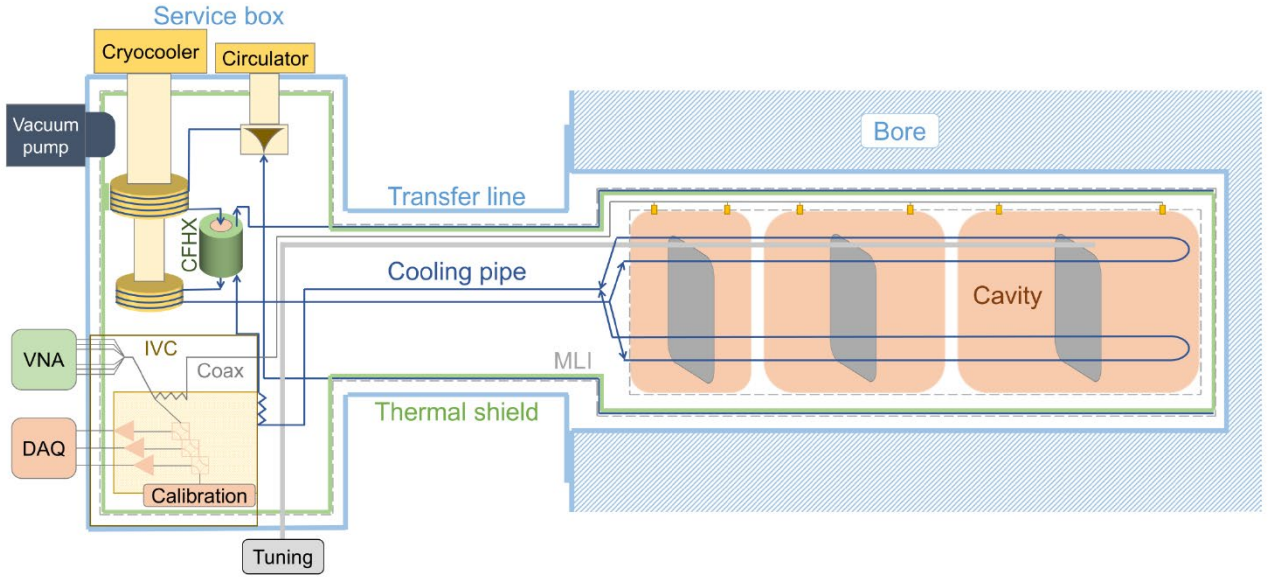




Arguedas, Golm et al. RADES axion search results with a High-Temperature Superconducting cavity in an 11.7 T magnet, https://arxiv.org/pdf/2403.07790v1

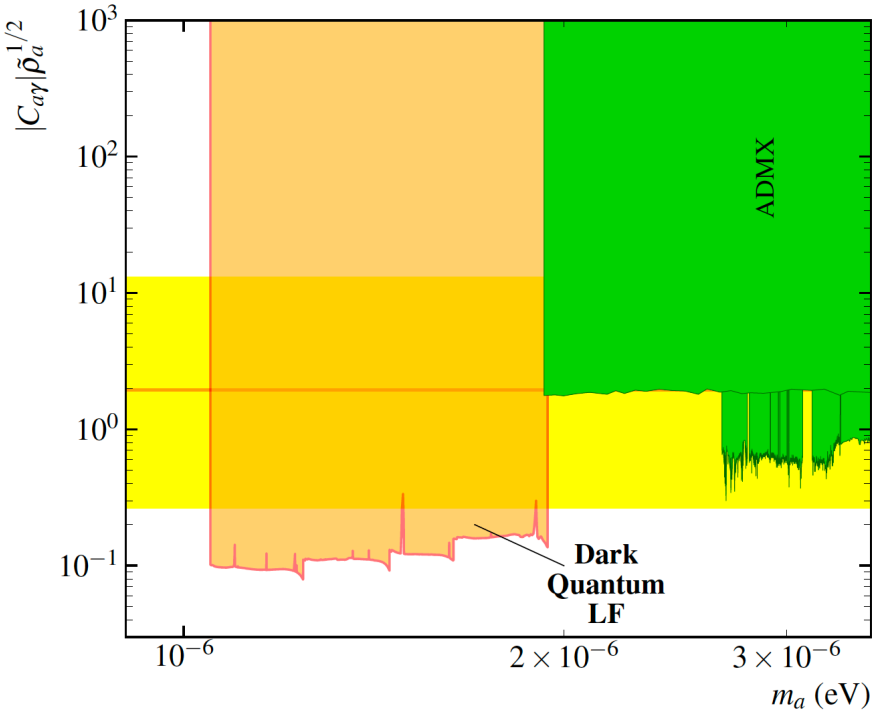
Future experiments

BabyIAXO - Rades



European Research Council
Established by the European Commission

Dark Quantum
ERC Synergy Grants 2023

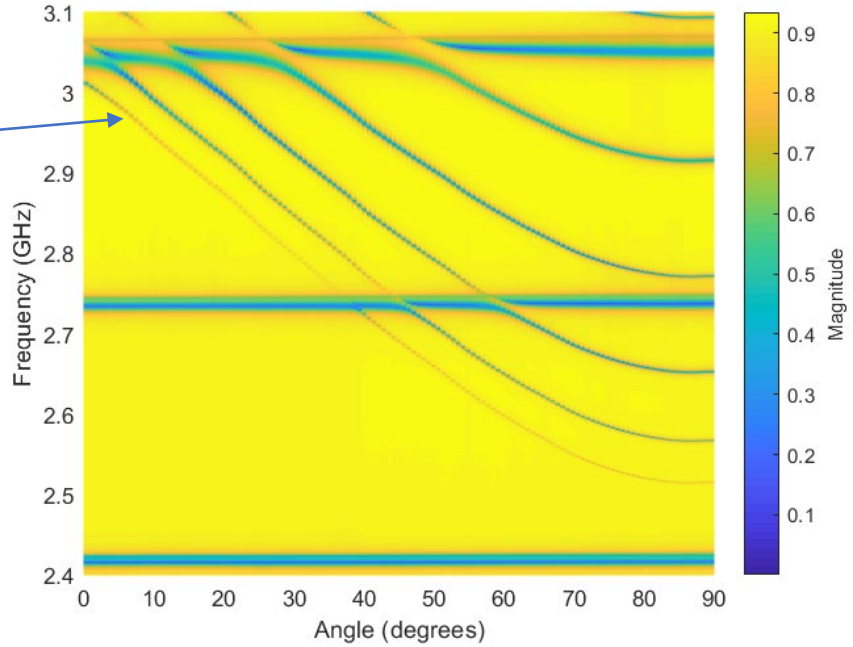


Range: 200-500 MHz (ueV)

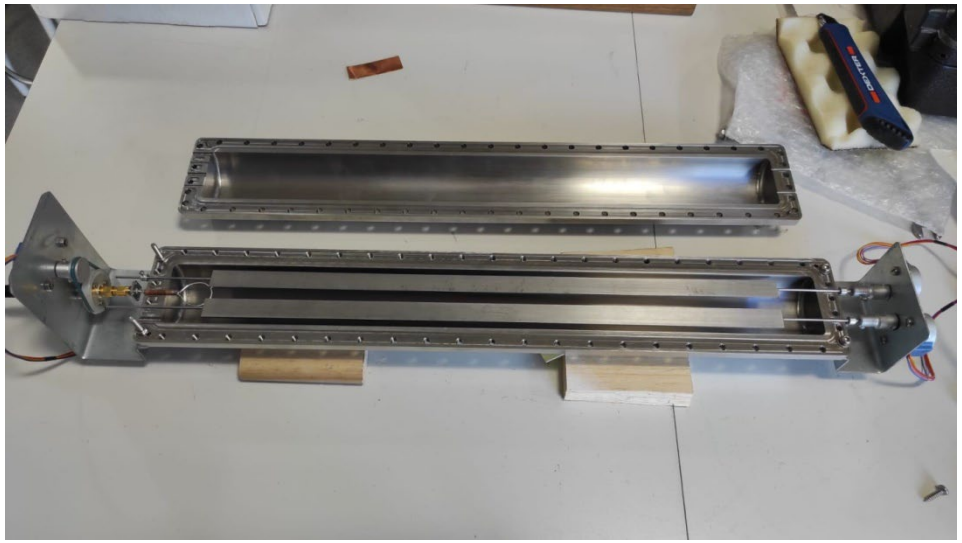
Future experiments

BabyIAXO - Rades

Axionic mode

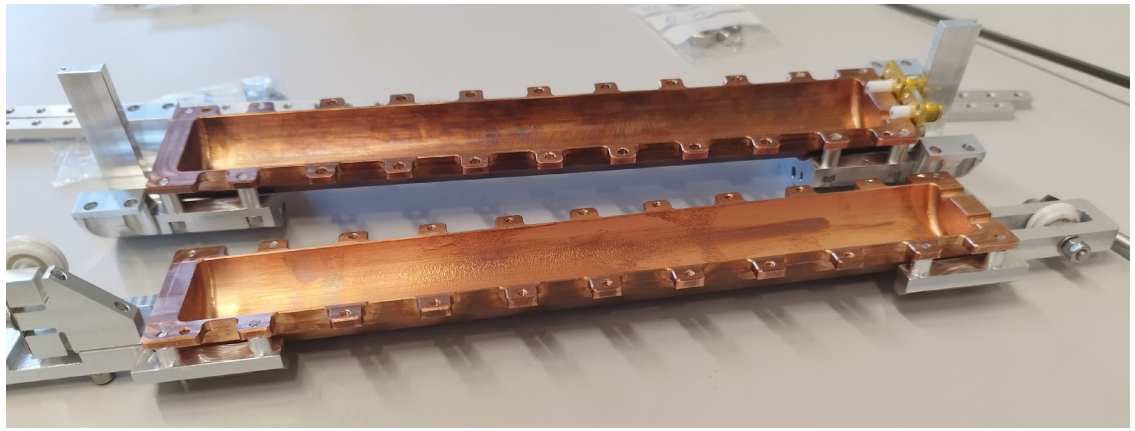


Scaled version
10 times smaller

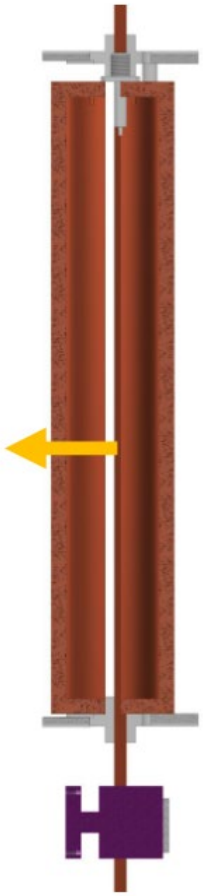


Future experiments

MPP Munch - Rades



Vertical cut tuning
Frequency range 8-9 GHz



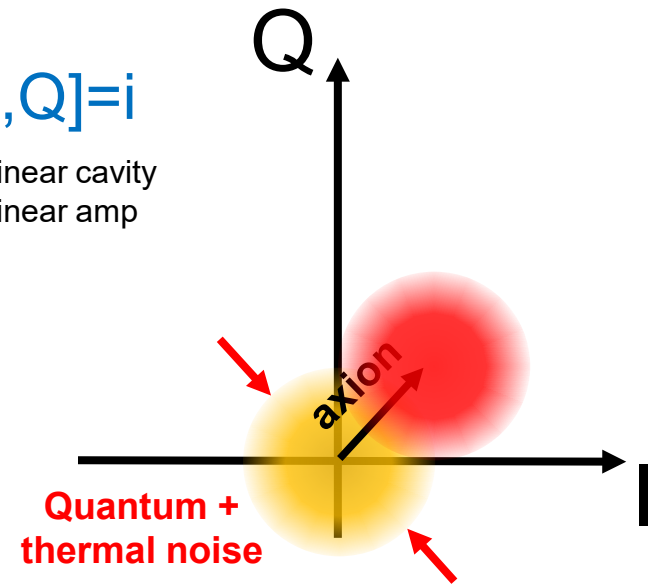
Open
5mm

Quantum sensors for haloscopes

Measuring power

$[I,Q]=i$

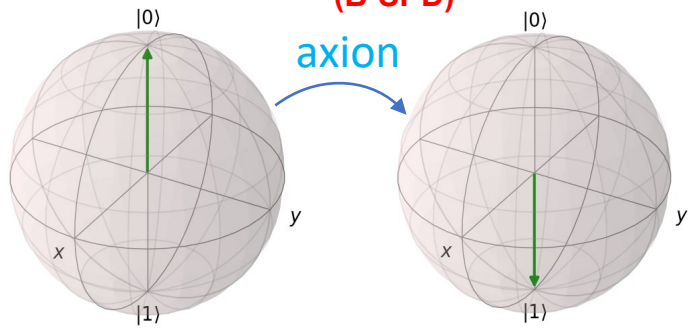
- Linear cavity
- Linear amp



Counting photons

$[N,\phi]=i$

- Linear cavity
- B-resilient Qubit **(B-SPD)**



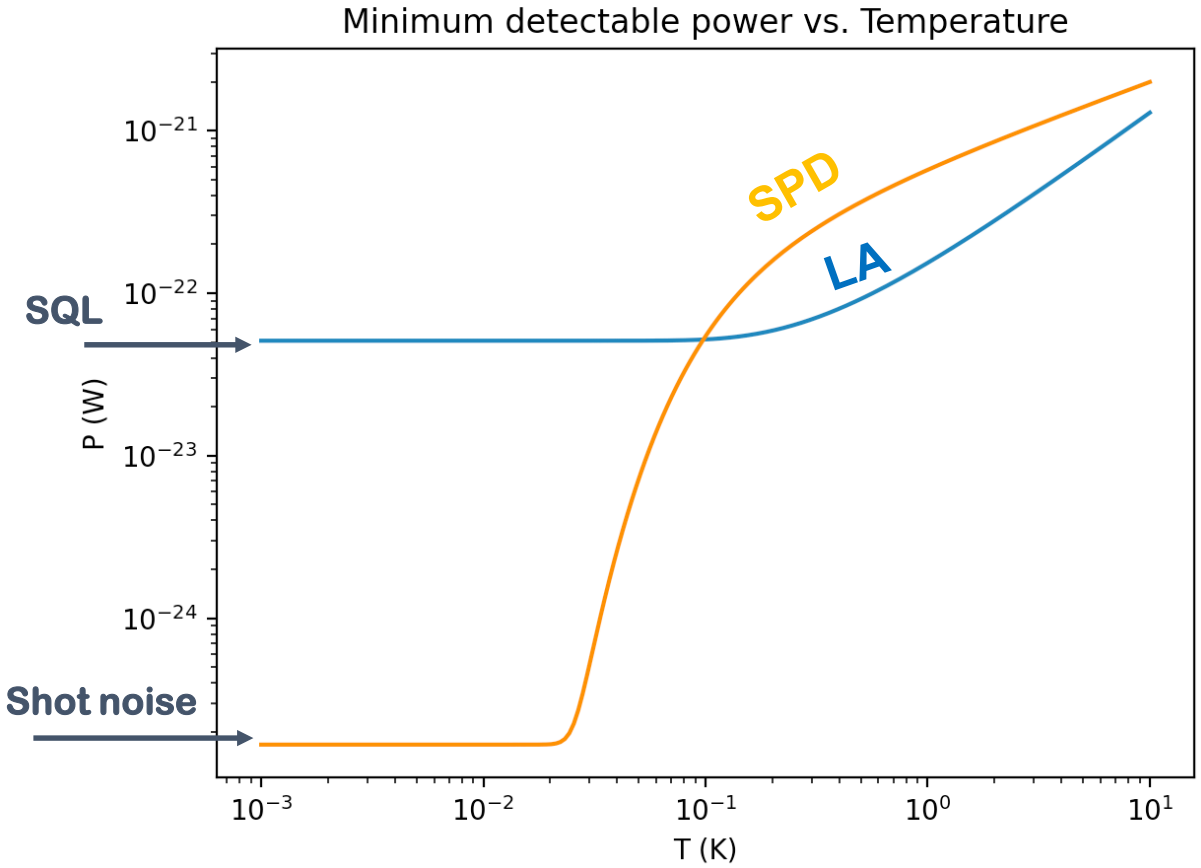
Qubit 0

'No Click'

Qubit 1

'Click'

Quantum sensors for haloscopes

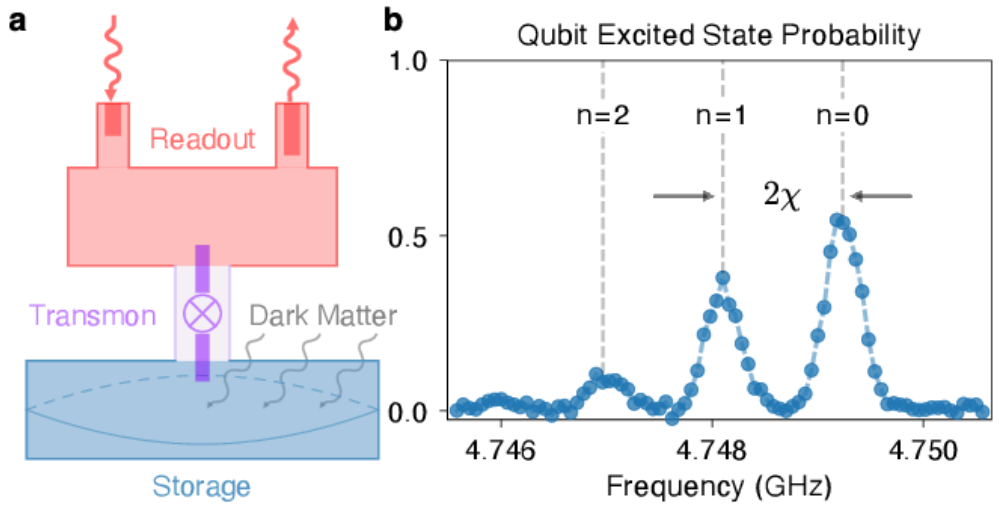


Single-photon detector (SPD)
vs Linear Amplifier (LA)

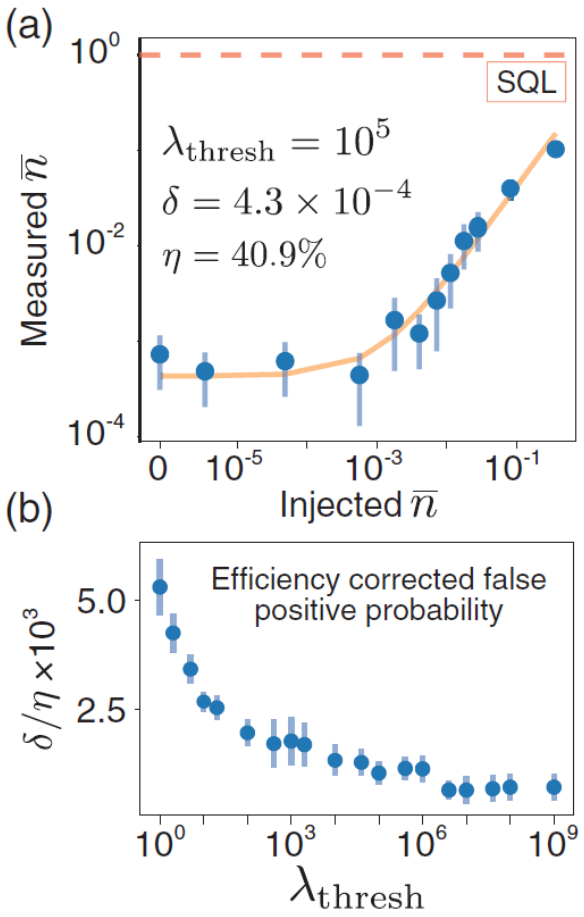
Dark count rate for
SPD: 1-100 mHz

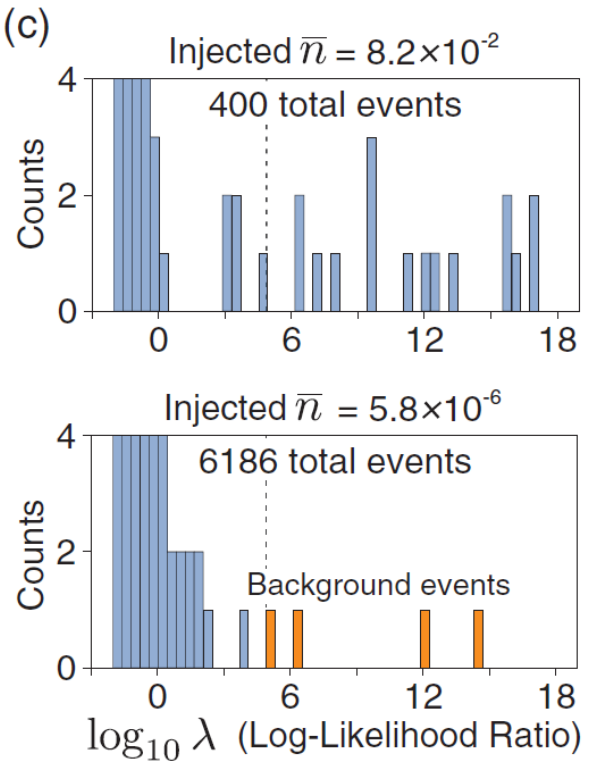
Quantum sensors for haloscopes

Qubit-based Single Photon Detector (SPD)



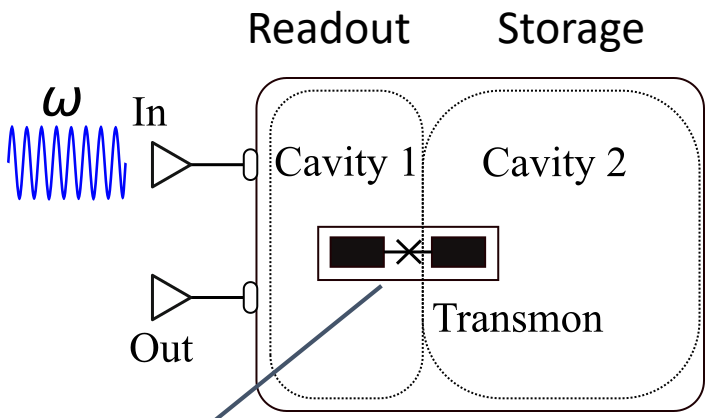
- Dixit et al. Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126

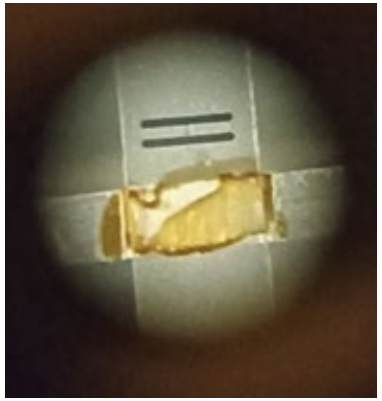




Quantum sensors for haloscopes

Experimental setup



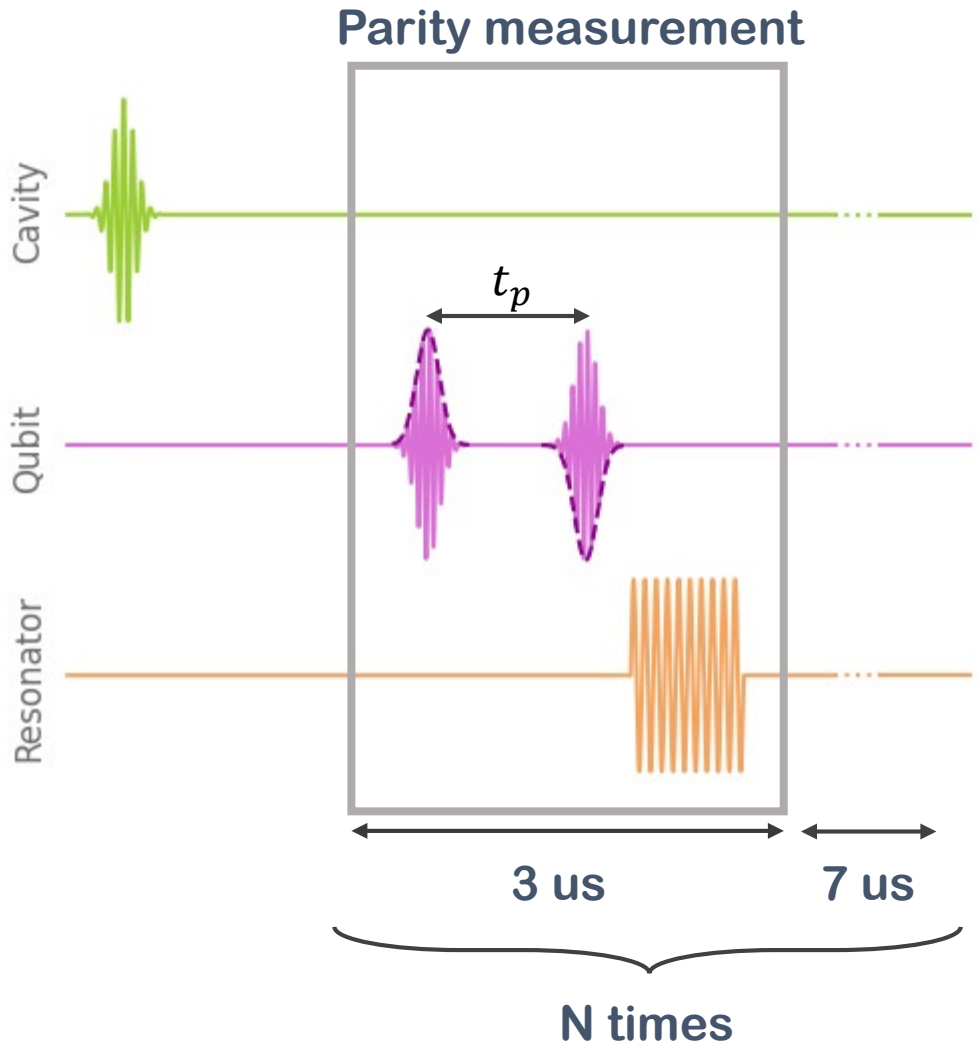


Quantum sensors for haloscopes

Dilution refrigerator

Quantum sensors for haloscopes

Measurement protocol



Photon in storage cavity (T_s)

$\frac{\pi}{2}$ pulses

Readout pulse

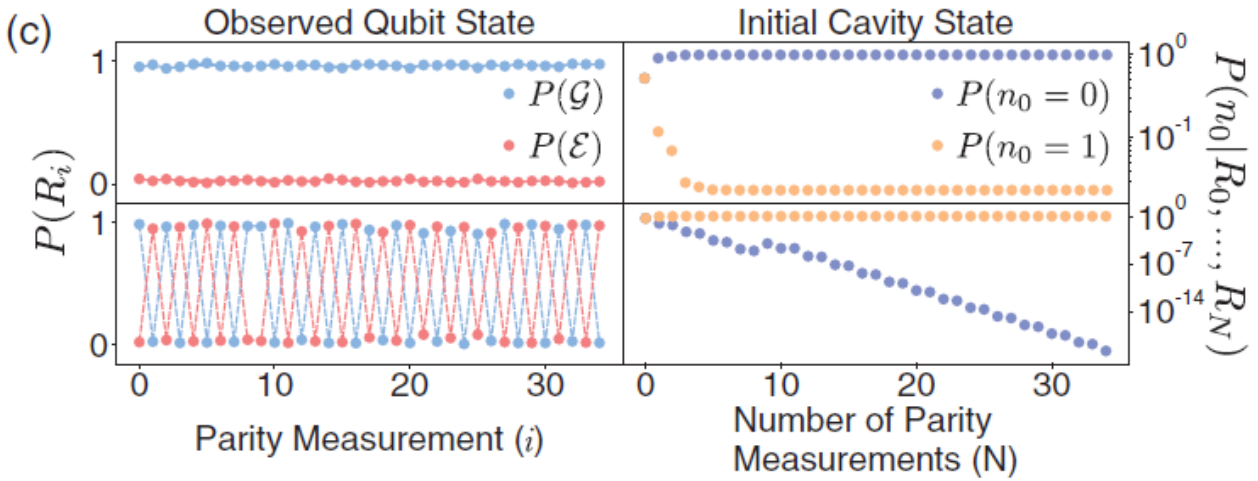
$T_s = 546\ \mu s$

$t_p = 380\ ns$

$t_m = 10\ \mu s$

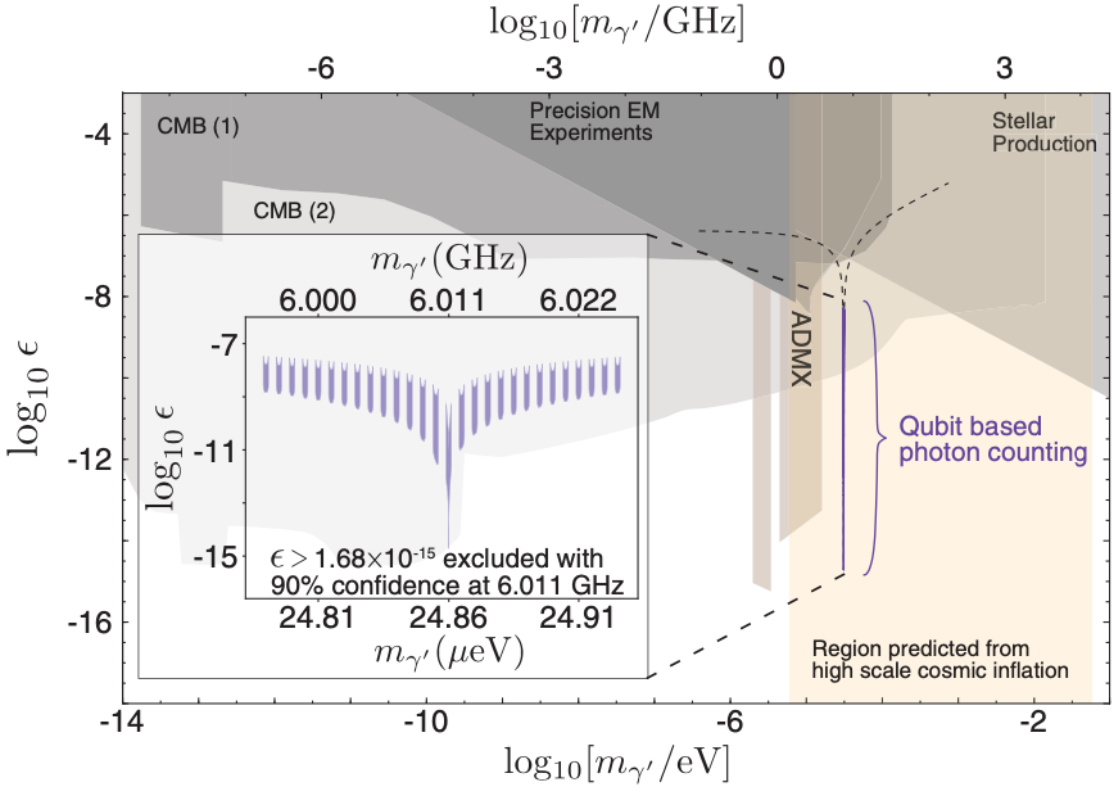
Quantum sensors for haloscopes

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

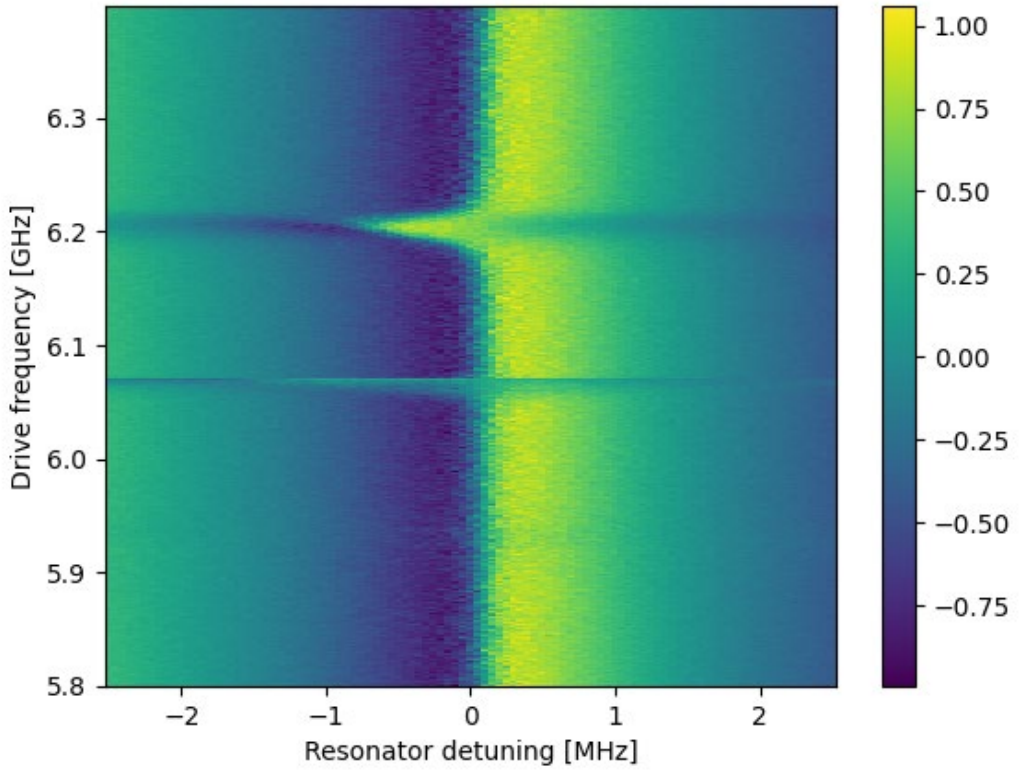


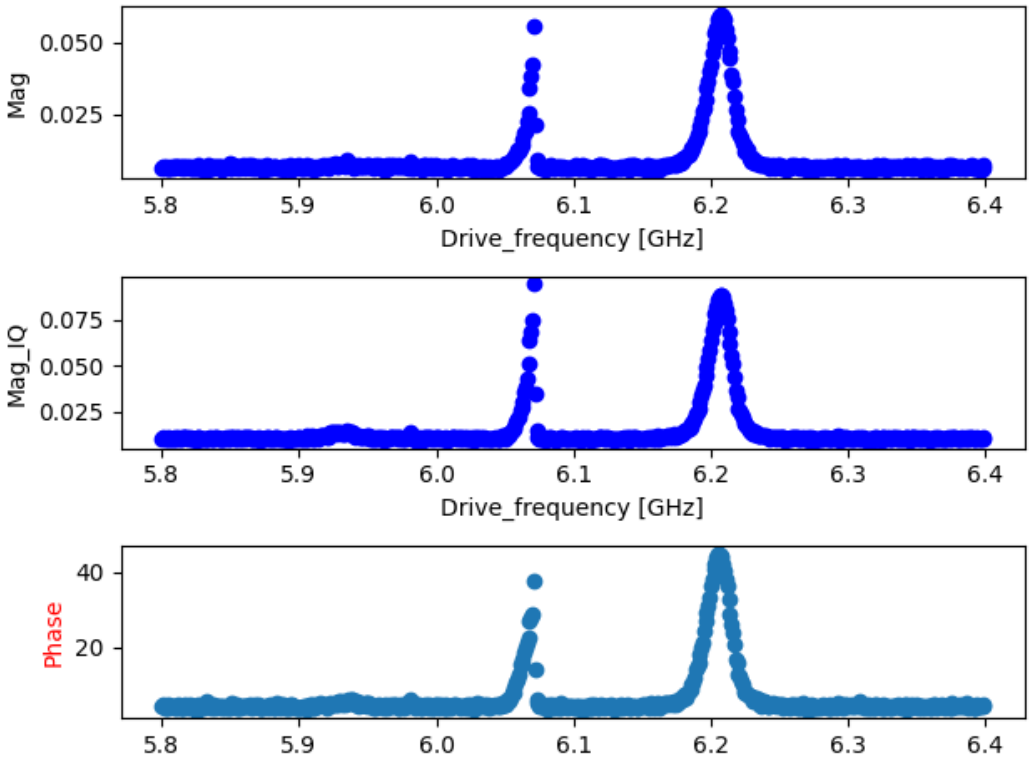
- **Dixit et al. Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126**

Thank you very much!!

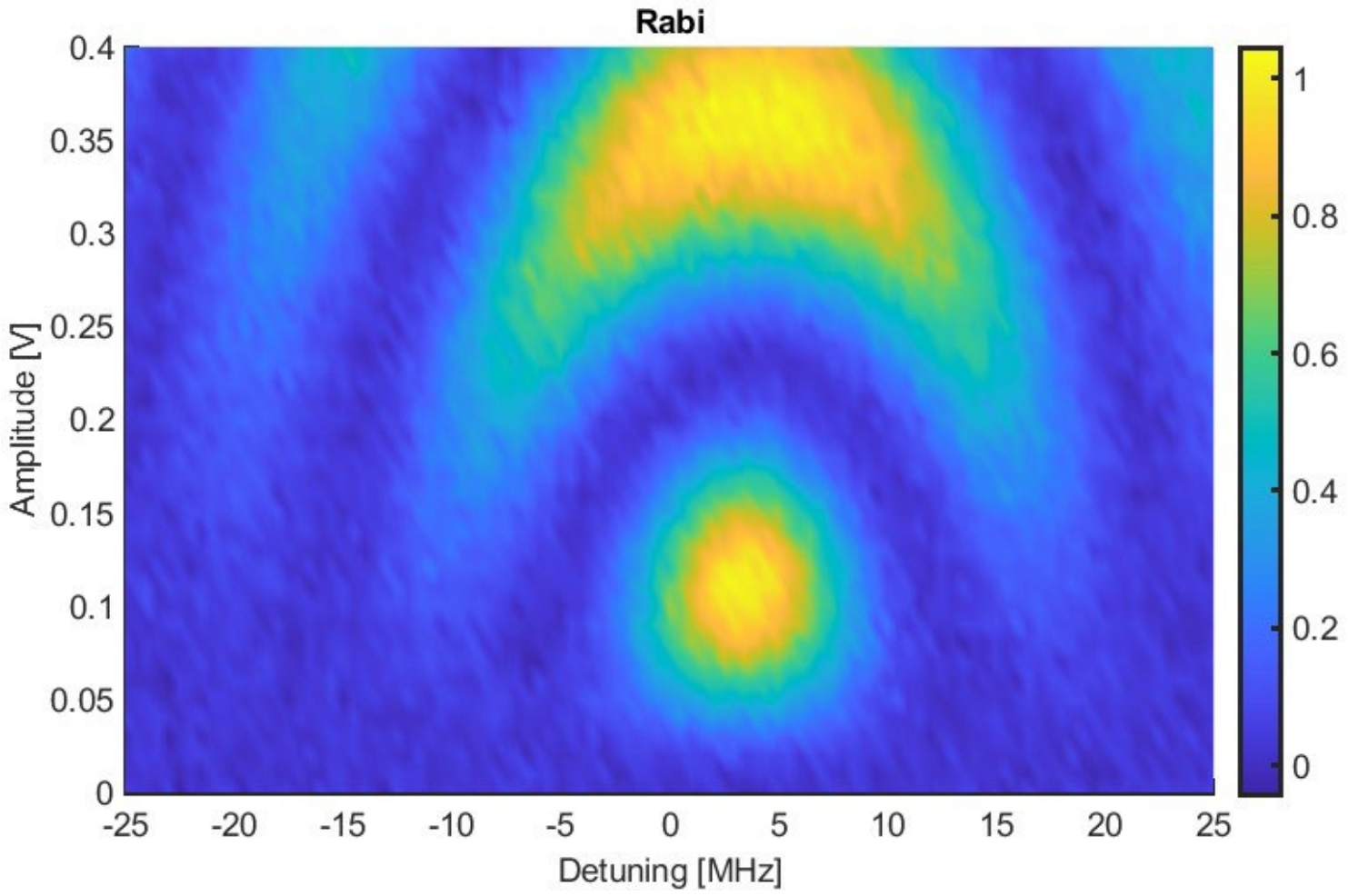
Background slides

Two tone spectroscopy

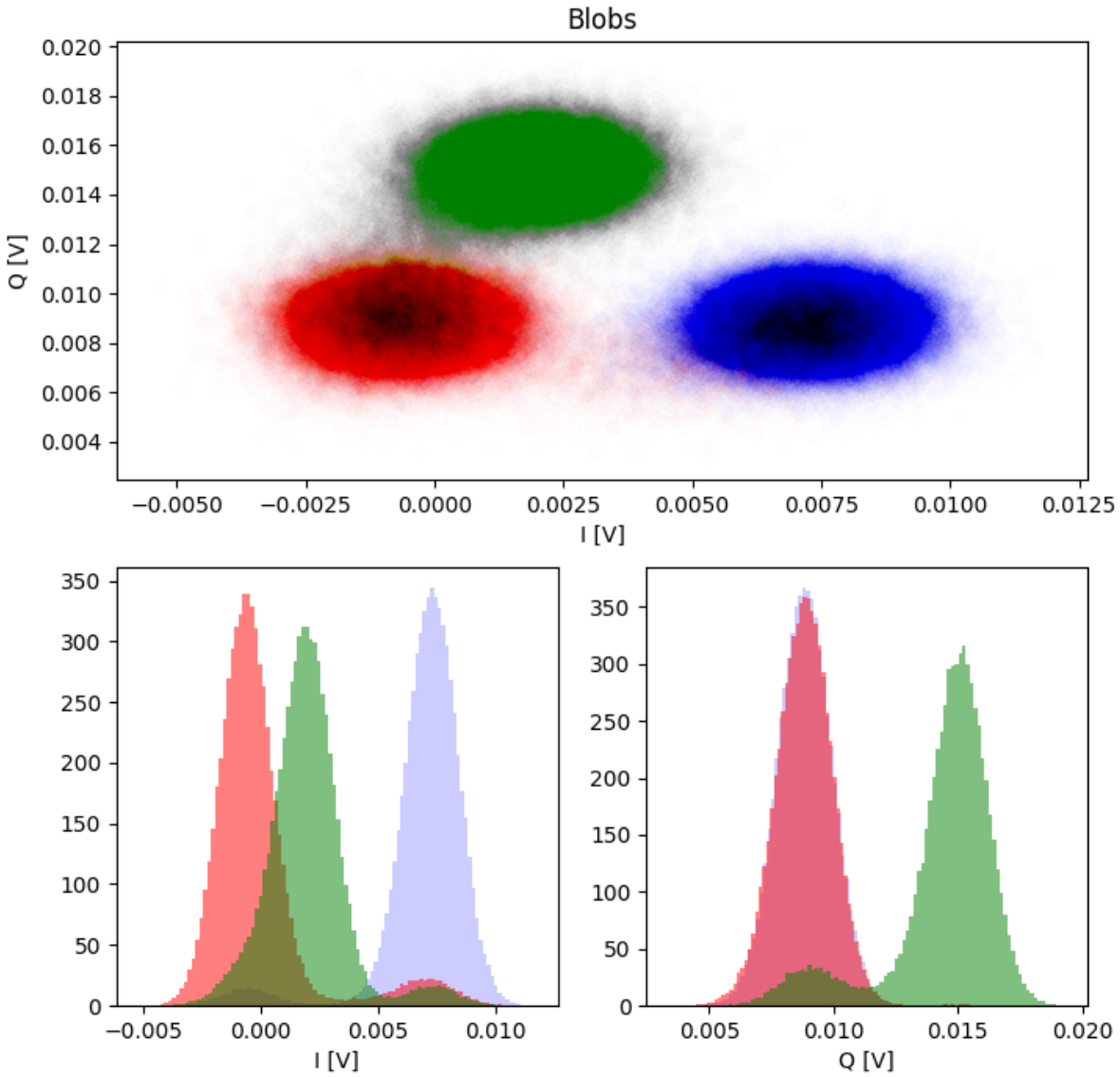


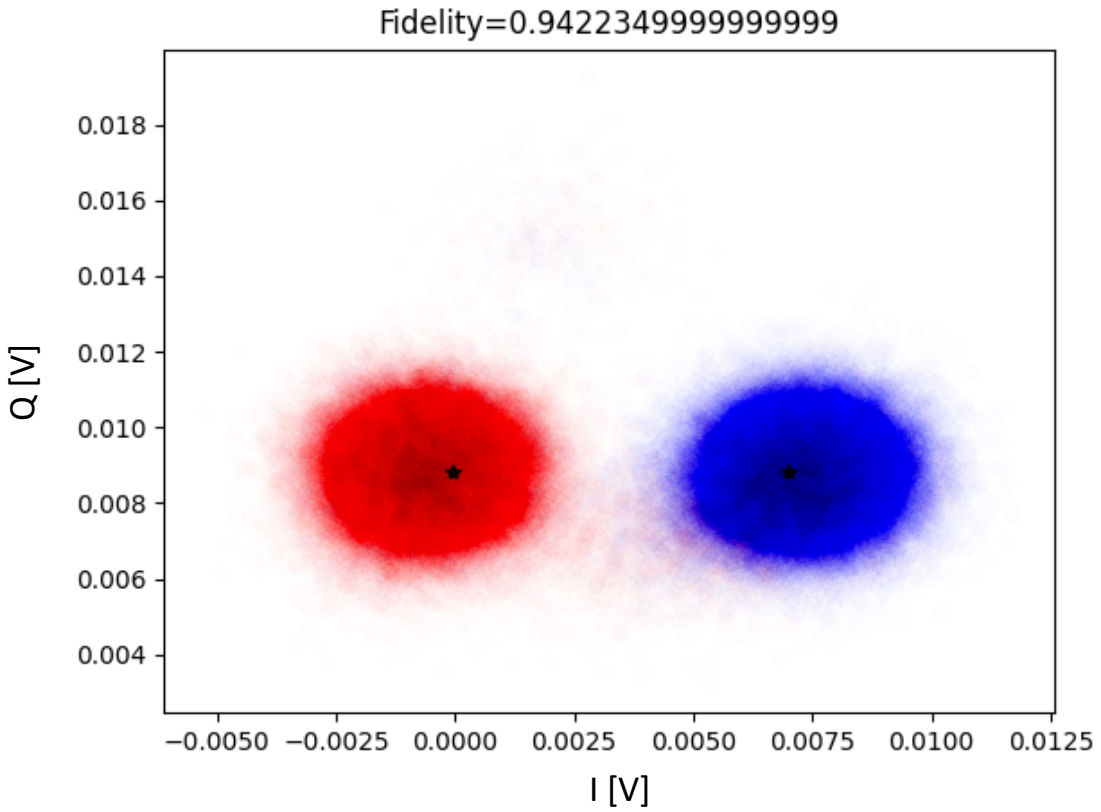


Rabi chevrons

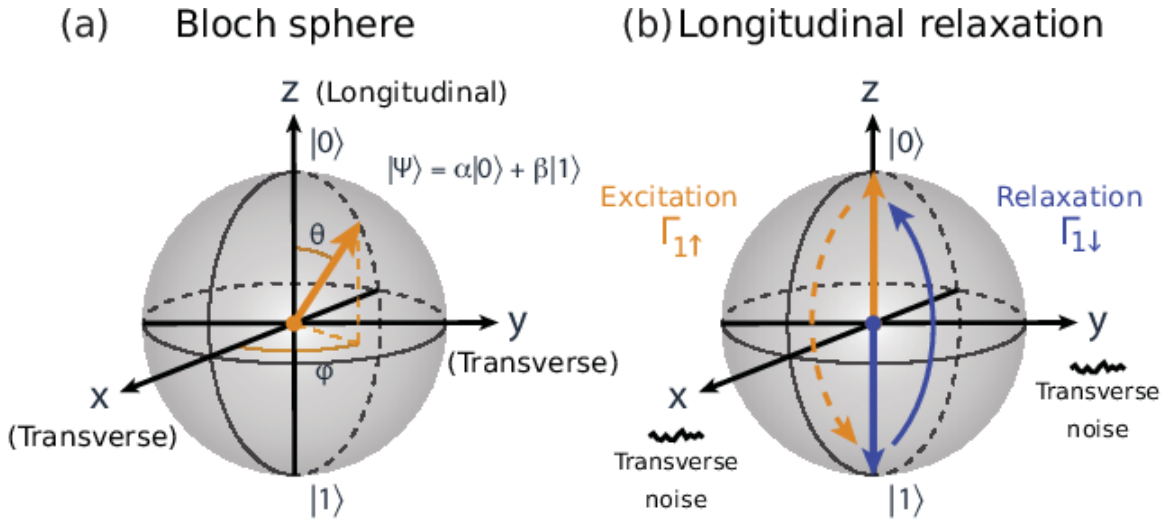


Single shot

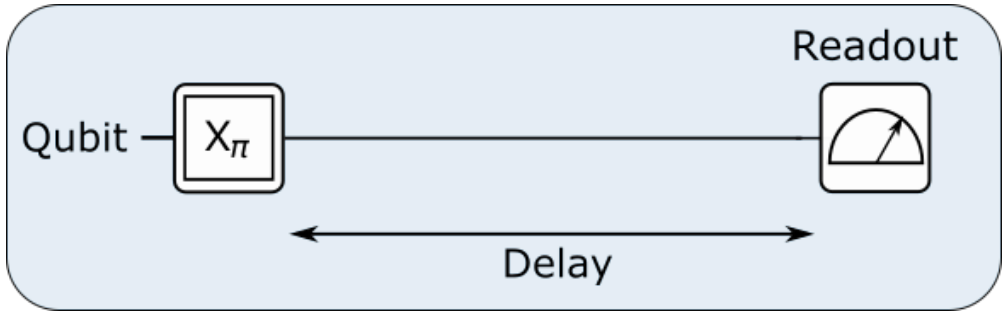




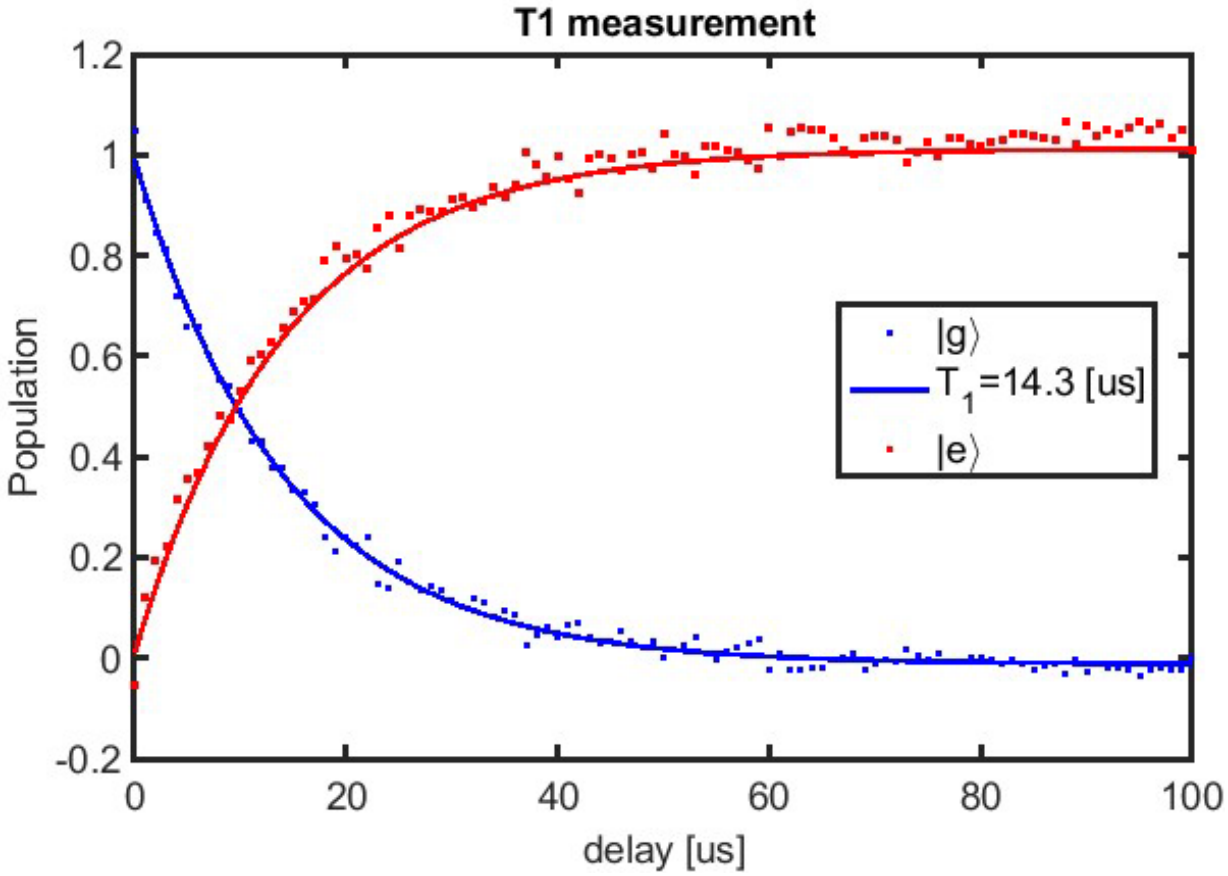
Characteristic times (Relaxation)



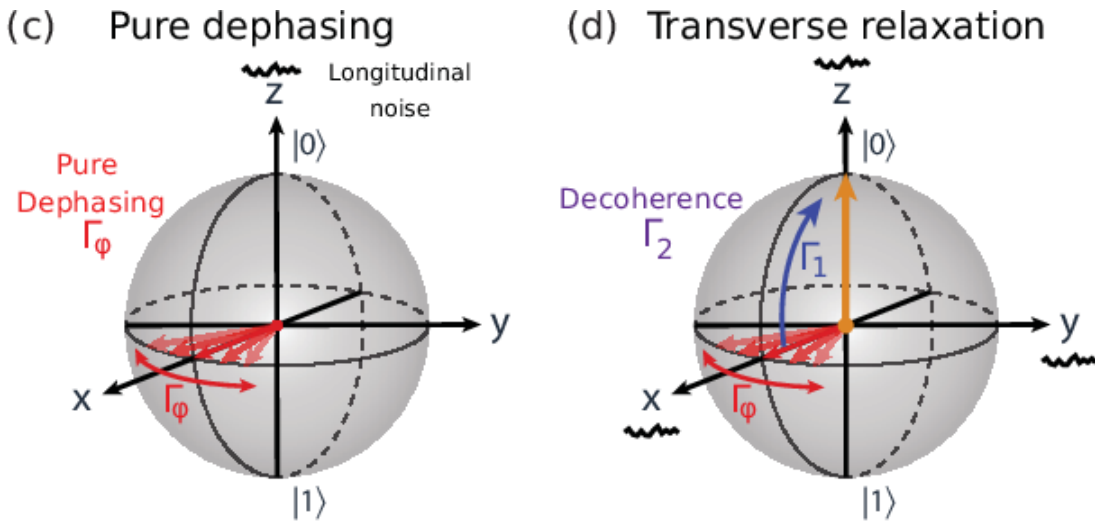
*P.Krantz, et.al., *Appl. Phys. Rev.* 6, 021318 (2019)



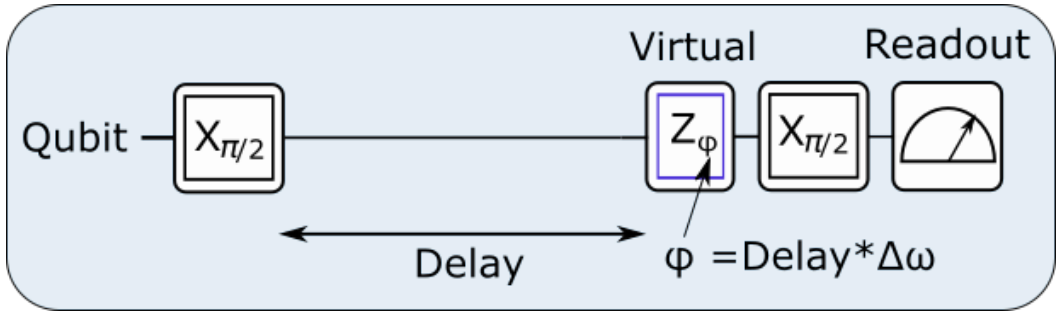
Pulse sequence



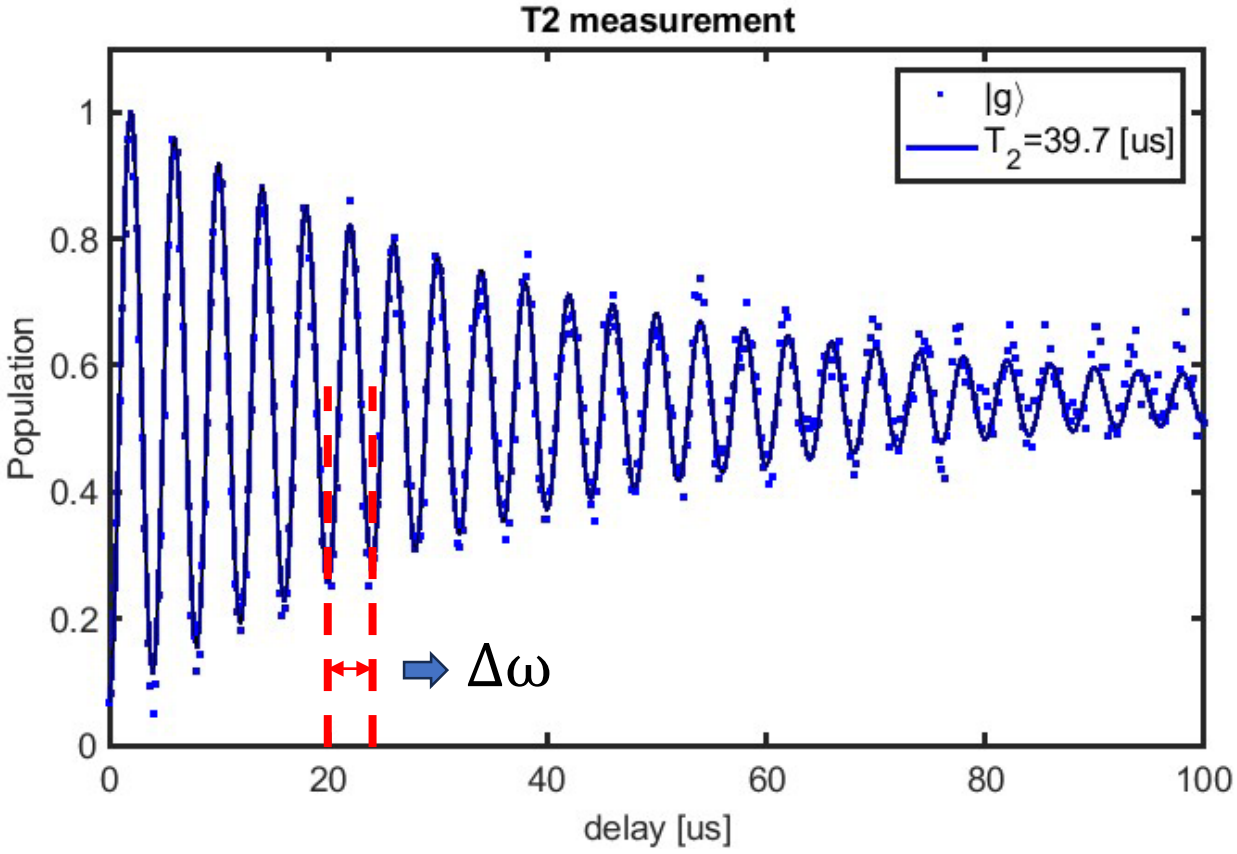
Characteristic times (decoherence)



*P.Krantz, et.al., *Appl. Phys. Rev.* 6, 021318 (2019)

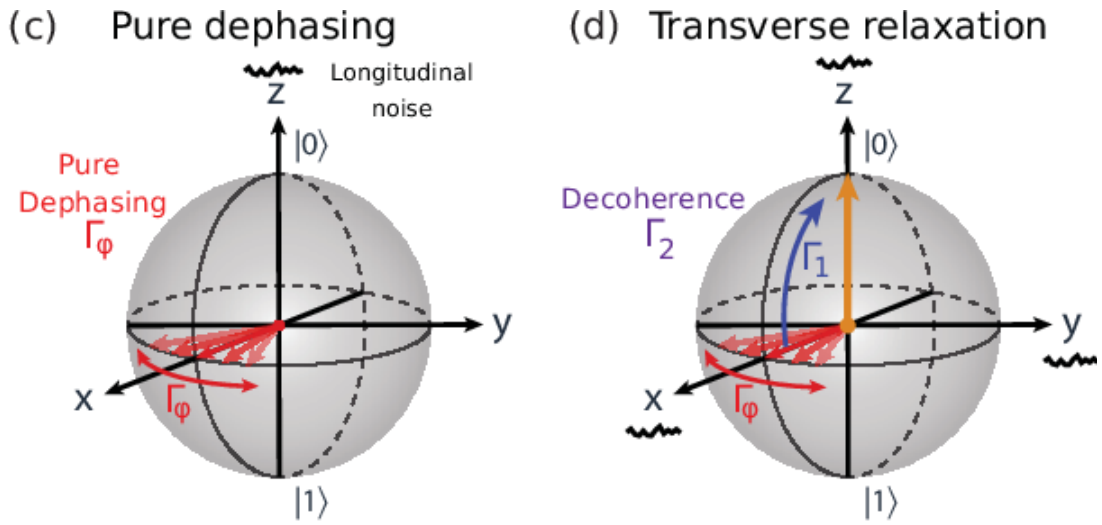


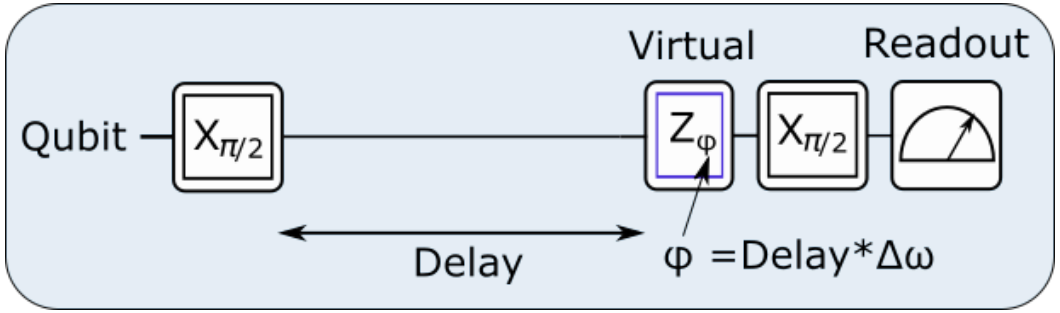
Pulse sequence



$$P = \frac{P(0)}{2}\cos(t * \Delta\omega_1 + \phi_1)\, e^{-t/T_2} + \frac{1}{2}$$

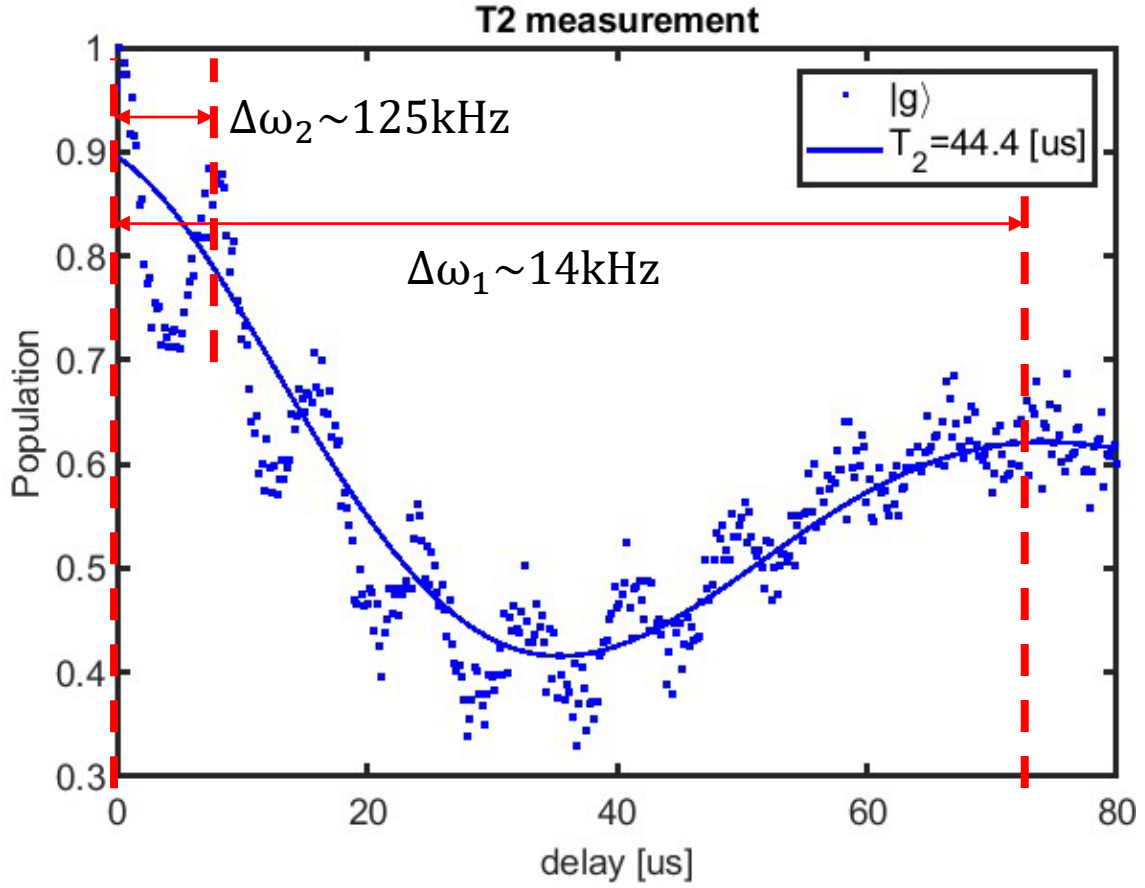
Thermal photons





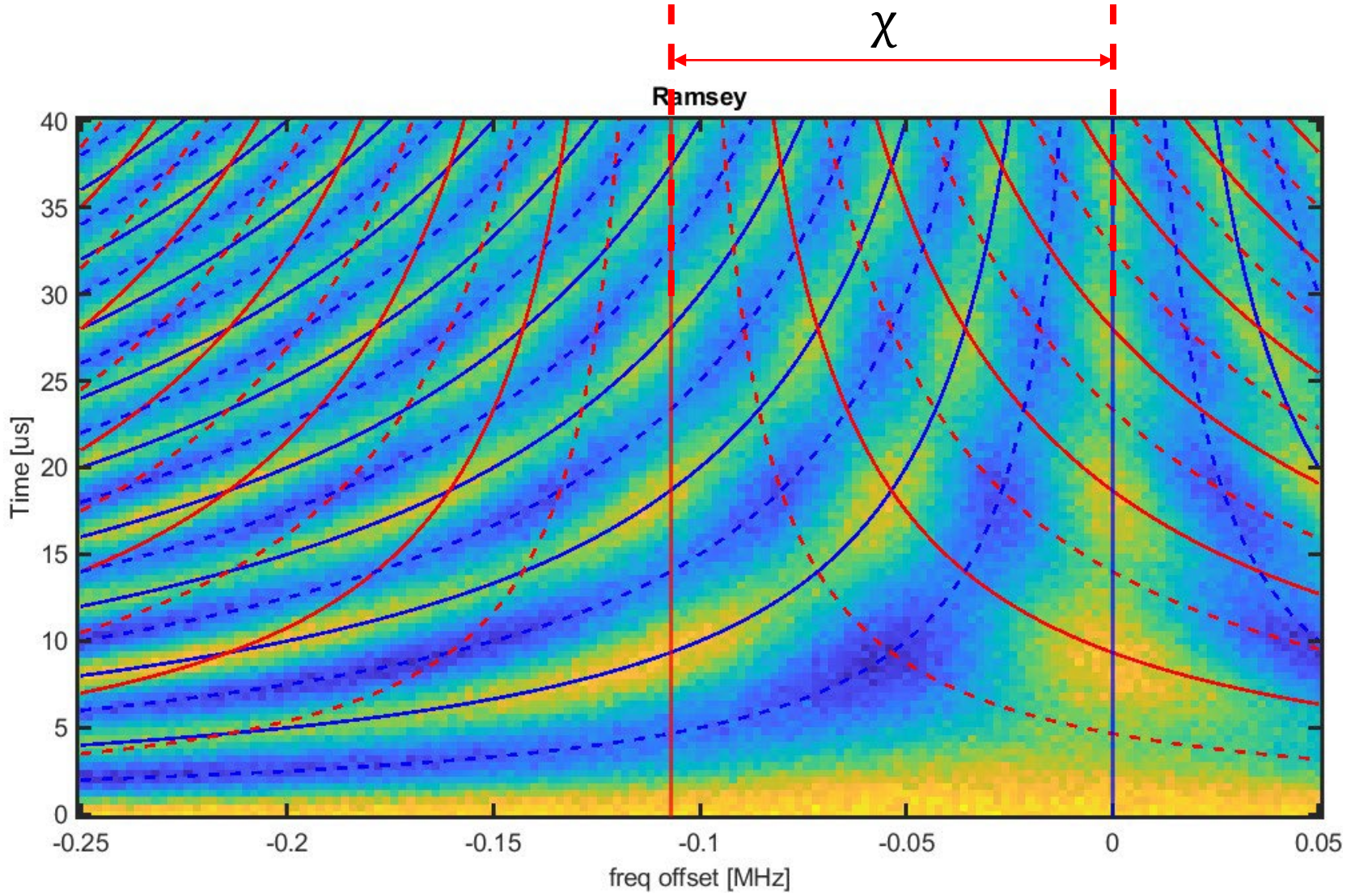
Pulse sequence

$\Delta\omega \sim 0.0\ MHz$

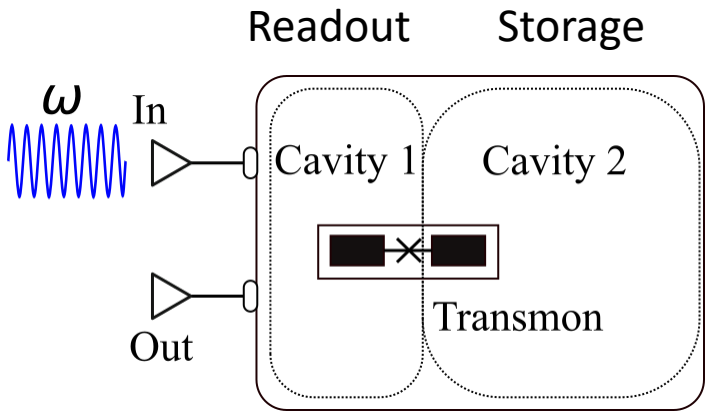


$$P = [\frac{P(0)}{2}\cos(t * \Delta\omega_1 + \phi_1) + \frac{P(1)}{2}\cos(t * \Delta\omega_1 + \phi_2)]e^{-t/T_2} + \frac{1}{2}$$

Ramsey chevrons (thermal photons in the cavity)



Measurement setup

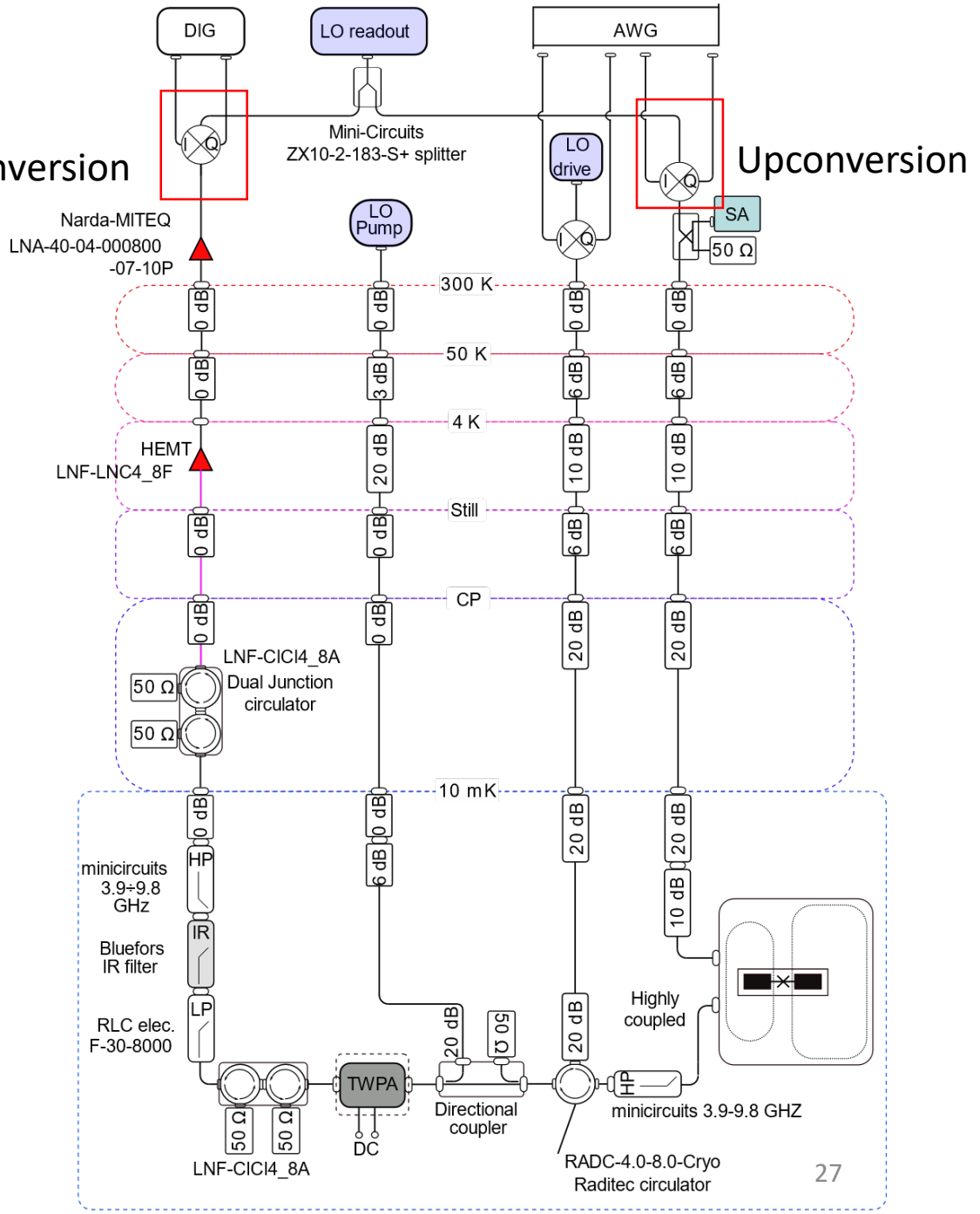


$$\hat{H}_{eff} = \frac{1}{2}\hbar\omega'_{01}\sigma_z + (\hbar\omega'_{c1} + \hbar\chi^{c1}\sigma_z)\hat{a}^\dagger\hat{a} + (\hbar\omega'_{c2} + \hbar\chi^{c2}\sigma_z)\hat{b}^\dagger\hat{b}$$

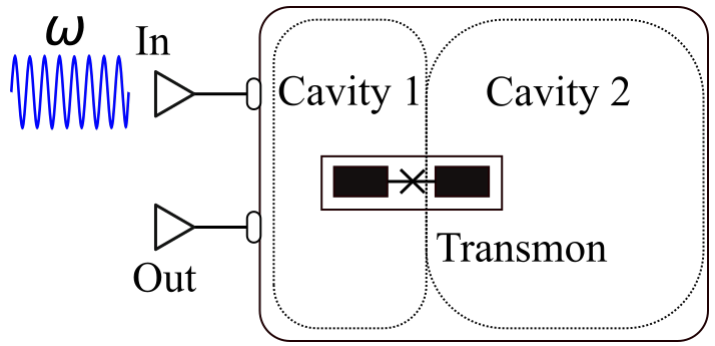
Readout: $\frac{1}{2}\hbar\omega'_{01}\sigma_z$ (qubit); $(\hbar\omega'_{c1} + \hbar\chi^{c1}\sigma_z)\hat{a}^\dagger\hat{a}$ (cavity 1, Stark shift 1)

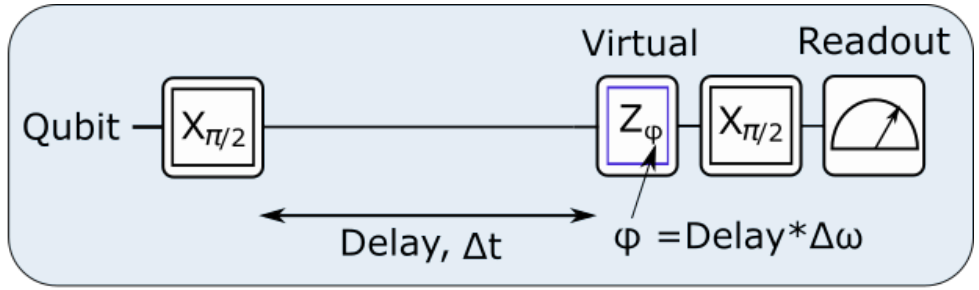
Storage: $(\hbar\omega'_{c2} + \hbar\chi^{c2}\sigma_z)\hat{b}^\dagger\hat{b}$ (cavity 2, Stark shift 2)

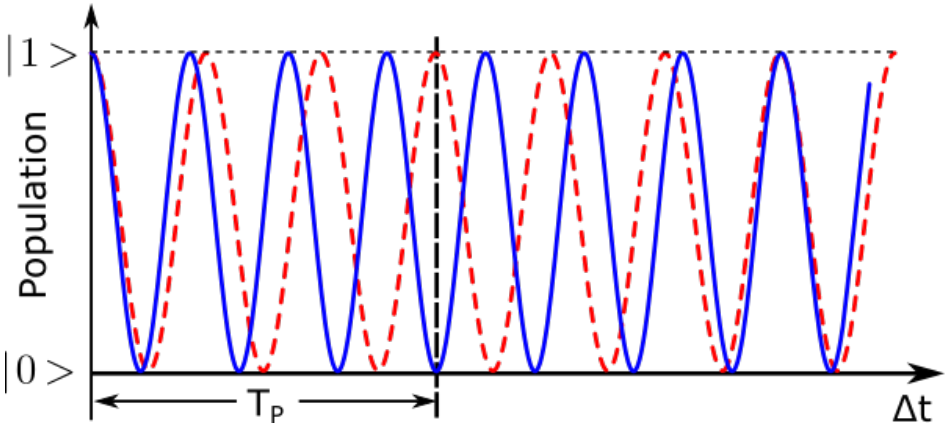
$$\chi^{c2} > \chi^{c1}$$



Detection protocol







Readout Storage

$$\hat{H}_{eff} = \frac{1}{2}\hbar\omega'_{01}\sigma_z + (\hbar\omega'_{c1} + \hbar\chi^{c1}\sigma_z)\hat{a}^\dagger\hat{a} + (\hbar\omega'_{c2} + \hbar\chi^{c2}\sigma_z)\hat{b}^\dagger\hat{b}$$

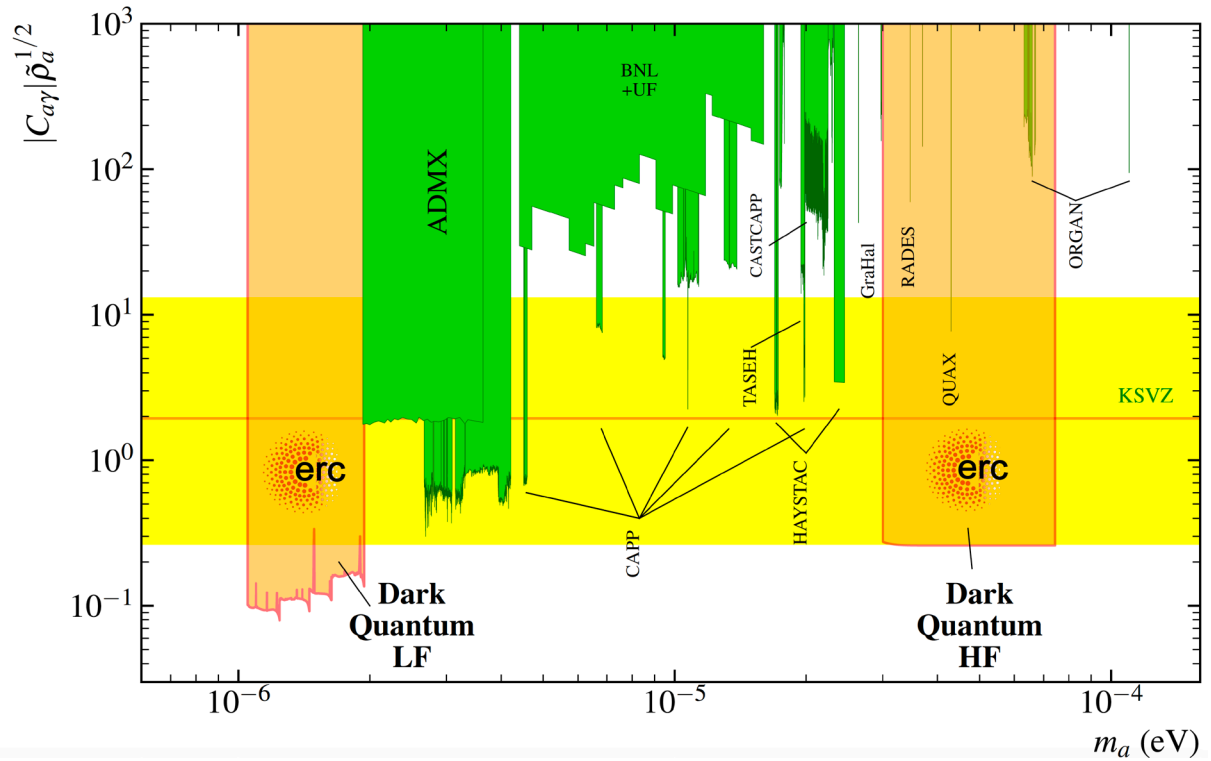
qubit cavity 1 Stark shift 1 cavity 2 Stark shift 2

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

$$\varphi = \Delta t * \Delta\omega;$$
$$\varphi = \pi;$$
$$\Delta\omega = \chi^{c2}$$

$$t_p = \frac{\pi}{\chi^{c2}}$$

ERC sensitivity bands



200-500 MHz **8-18 GHz**