Enhancing Axion Searches with Quantum Coincidence in Superconducting Qubits

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INFN - LNF

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Incontri di Fisica delle Alte Energie
Cagliari, 9-11 Aprile 2025

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

Qub-IT

COLD LNF CryOgenic Laboratory for Detectors

PRIN IRONMOON (2022BPJL2L)

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

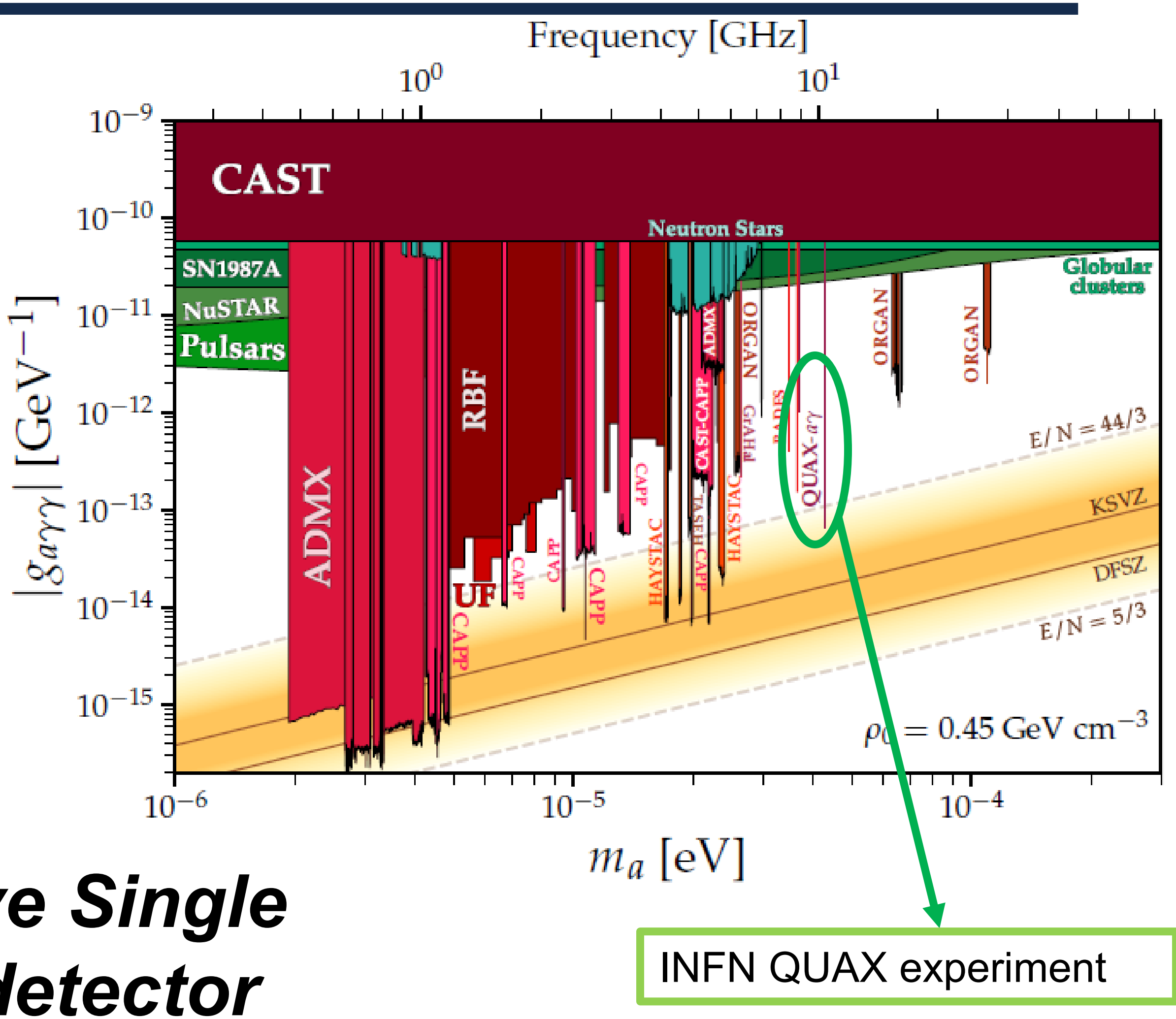
ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

NQSTI National Quantum Science and Technology Institute

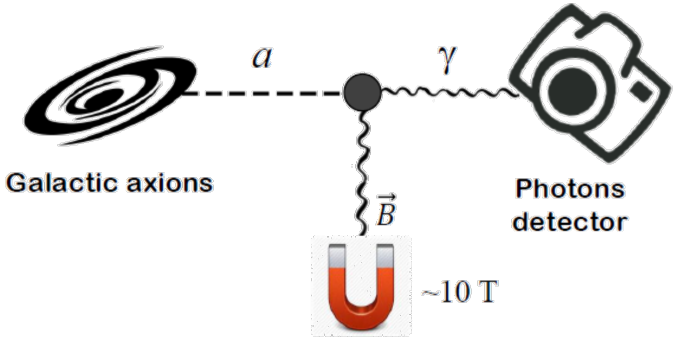
Axions as dark matter

- Dark Matter:
  - ~85% of universe.
  - Axions are a leading candidate.

- Axions:
  - **Strong CP problem**:
    QCD does not conserve CP (theory);
    QCD conserves CP (experiment).



Inverse Primakoff effect: Axion is converted into a photon in presence of a strong magnetic field

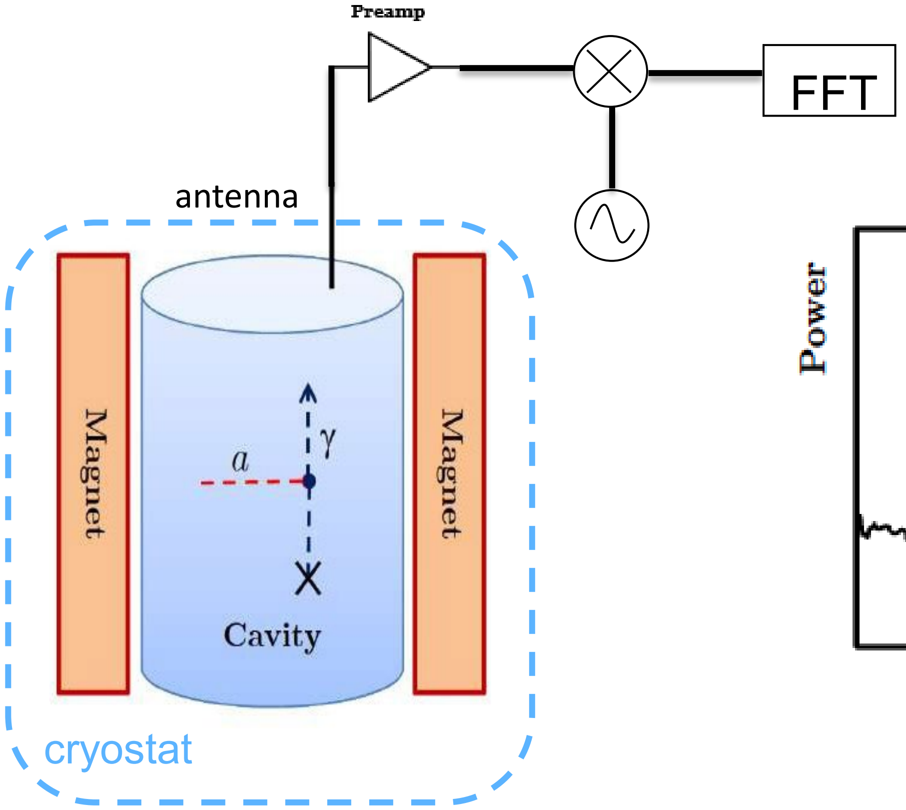


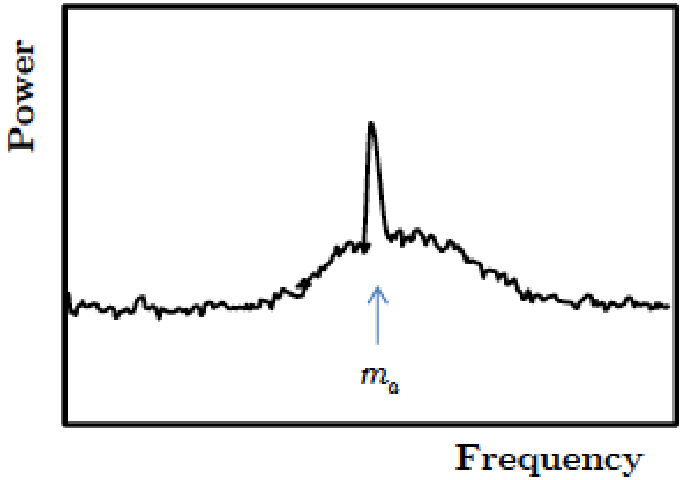
Microwave Single photon detector required

10.5281/zenodo.3932430

Haloscope scheme

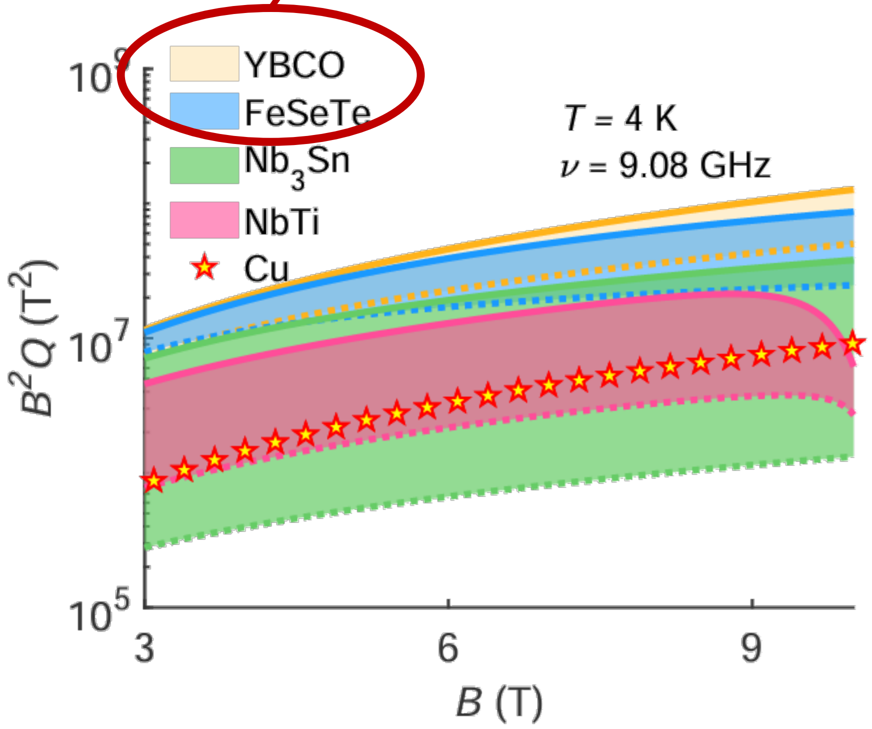
$$P_{a\rightarrow\gamma_{ph}} \propto \left(B^2VQ\right)\left(g^2_{a\gamma_{ph}}\rho_a\nu\right)$$





$$10^{-23} < P_{a\rightarrow\gamma_{ph}}/(W) < 10^{-22}$$

Currently being investigated



Sikivie Phys. Rev. D 32,11 (1985)

doi.org/10.3390/instruments6010001

Cavity-QED with transmon qubit

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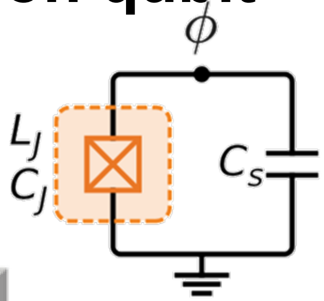
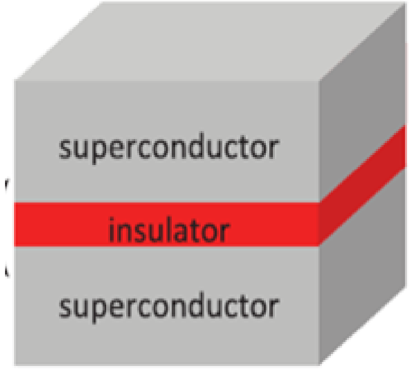
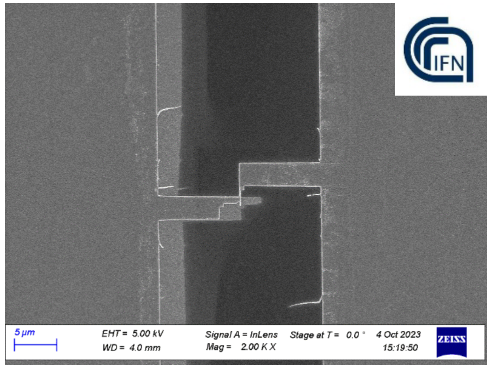
Transmon qubit



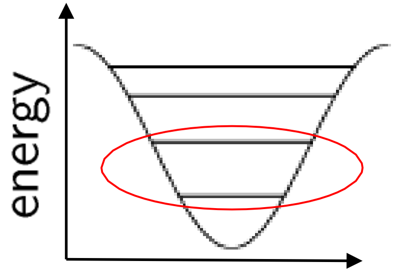
Josephson junction (JJ)



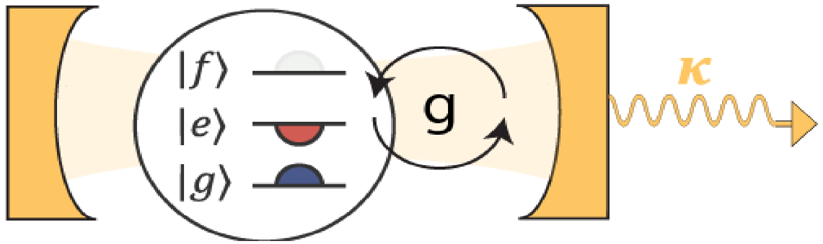


Josephson Junction (JJ):

- 2 superconducting materials separated by an insulator
- Non-linear inductor
- Anharmoic resonator



Cavity QED with Superconducting Circuits

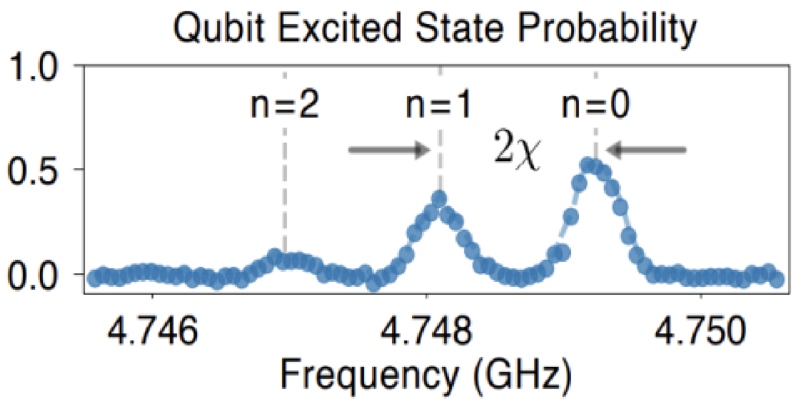


$$H = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

$$\chi = \chi_{01} - \frac{\chi_{12}}{2}$$

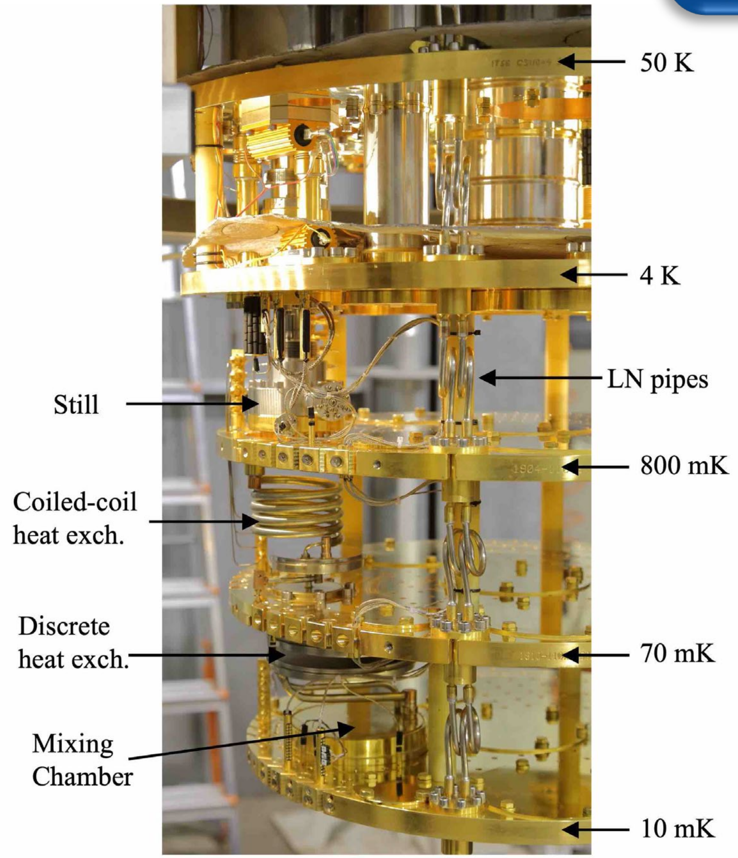
$$\chi_{ij} = \frac{g_{ij}^2}{\Delta_{ij}}$$

$\Delta_{01}=\omega_c-\omega_q$ $\omega_q=\omega_{01}$



A. Blais, et al. , *PRA* **69**, 062320 (2004)
A. Wallraff et al., *Nature (London)* **431**, 162 (2004)
Dixit et al., Phys. Rev. Lett. **126**, 141302

Qubit inside 3D cavity



LEIDEN CRYOGENICS

$$T_{base} = 8\, mK$$

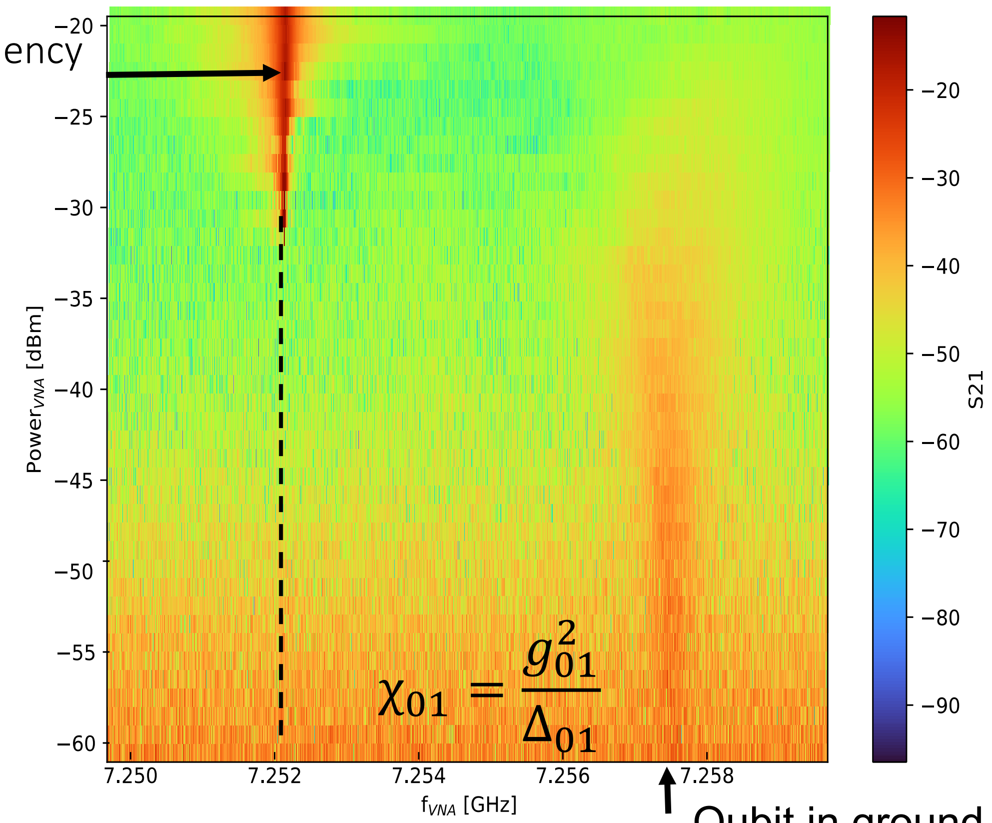
Cooling power:

$$500\, \mu W \ \ @ \ \ 100\, mK$$

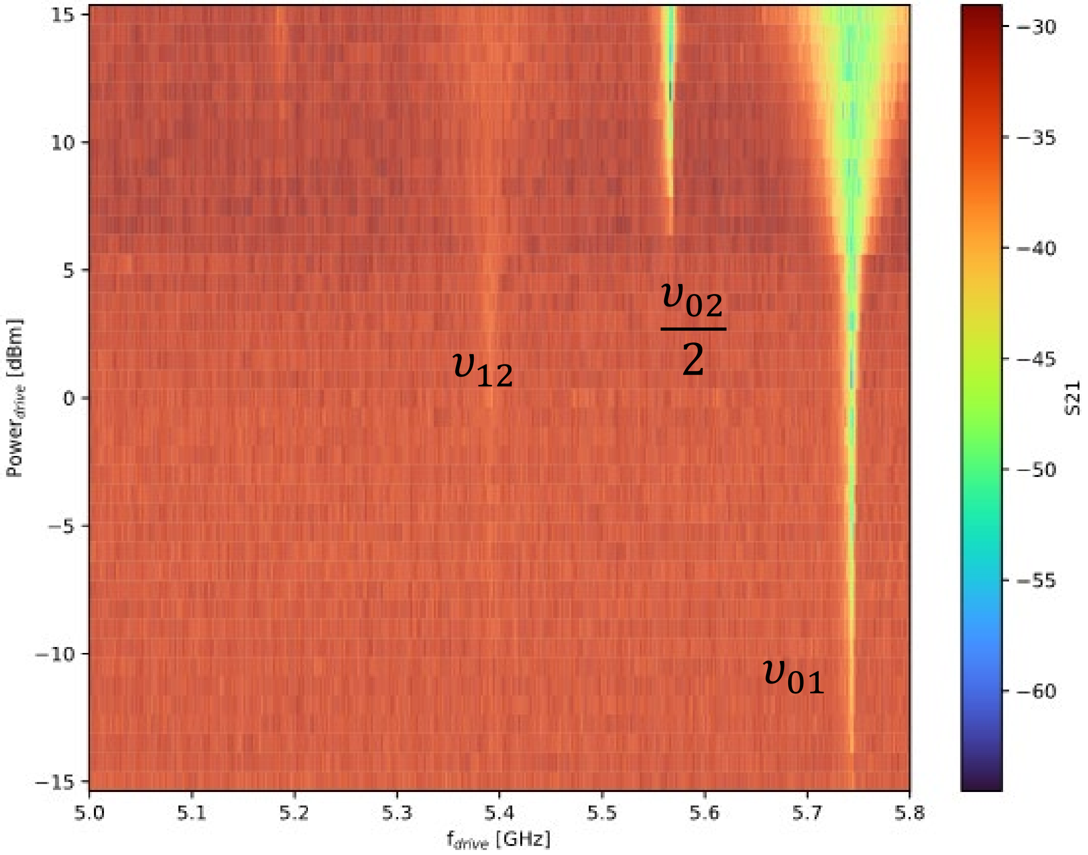
Al Qubit fabricated at IFN CNR;
Pure Al cavity fabricated at LNL – INFN;

Qubit in 3D cavity : cavity and qubit spectroscopy

Bare cavity frequency
ν_r= 7.252 GHz



Qubit in ground state



$$\chi_{01} = \frac{g_{01}^2}{\Delta_{01}} = -\mathbf{5.24}\ \boldsymbol{MHz}$$

$$\upsilon_{01} - \upsilon_{12} = 2\pi\alpha$$

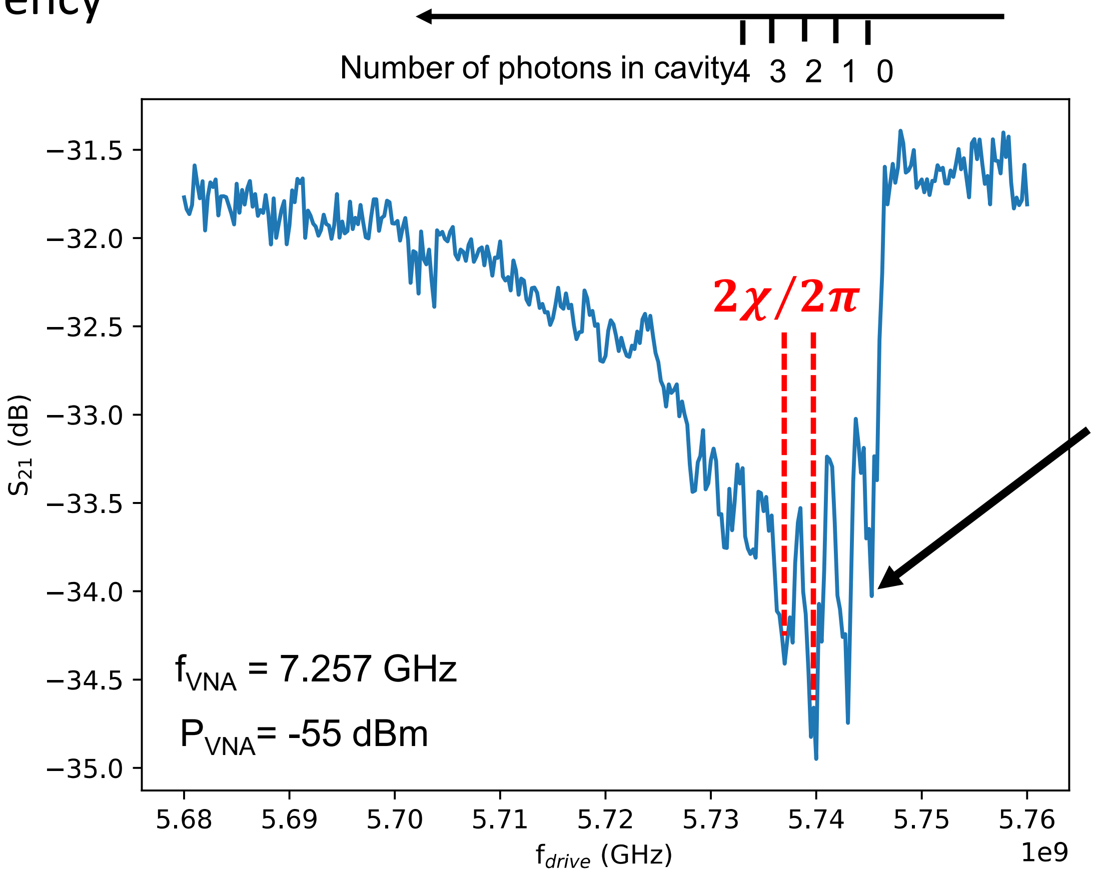
α = **353** ***MHz***

Qubit in 3D cavity : resolving photon number

With a two tone measurement,
we measure the qubit frequency

The deep position depends on the number of photons (P_{VNA}) in the cavity

The qubit frequency depends on the number of photons in the cavity



$$\frac{\chi}{2\pi} = -\mathbf{1.2}\ \boldsymbol{MHz}$$

$$\frac{\omega_{|0\rangle}}{2\pi} = \frac{1}{2\pi}(\omega_{01} + \chi_{01}) = \mathbf{5.7452}\boldsymbol{GHz}$$

$$\frac{\omega_{01}}{2\pi} = \nu_{01} = \mathbf{5.739}\ \boldsymbol{GHz}$$

Qubit in 3D cavity : measured data vs simulated

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$$\frac{\chi_{01}}{2\pi} = -5.24 \pm 0.1\ MHz$$

$$\frac{\chi}{2\pi} = -1.2 \pm 0.08\ MHz$$

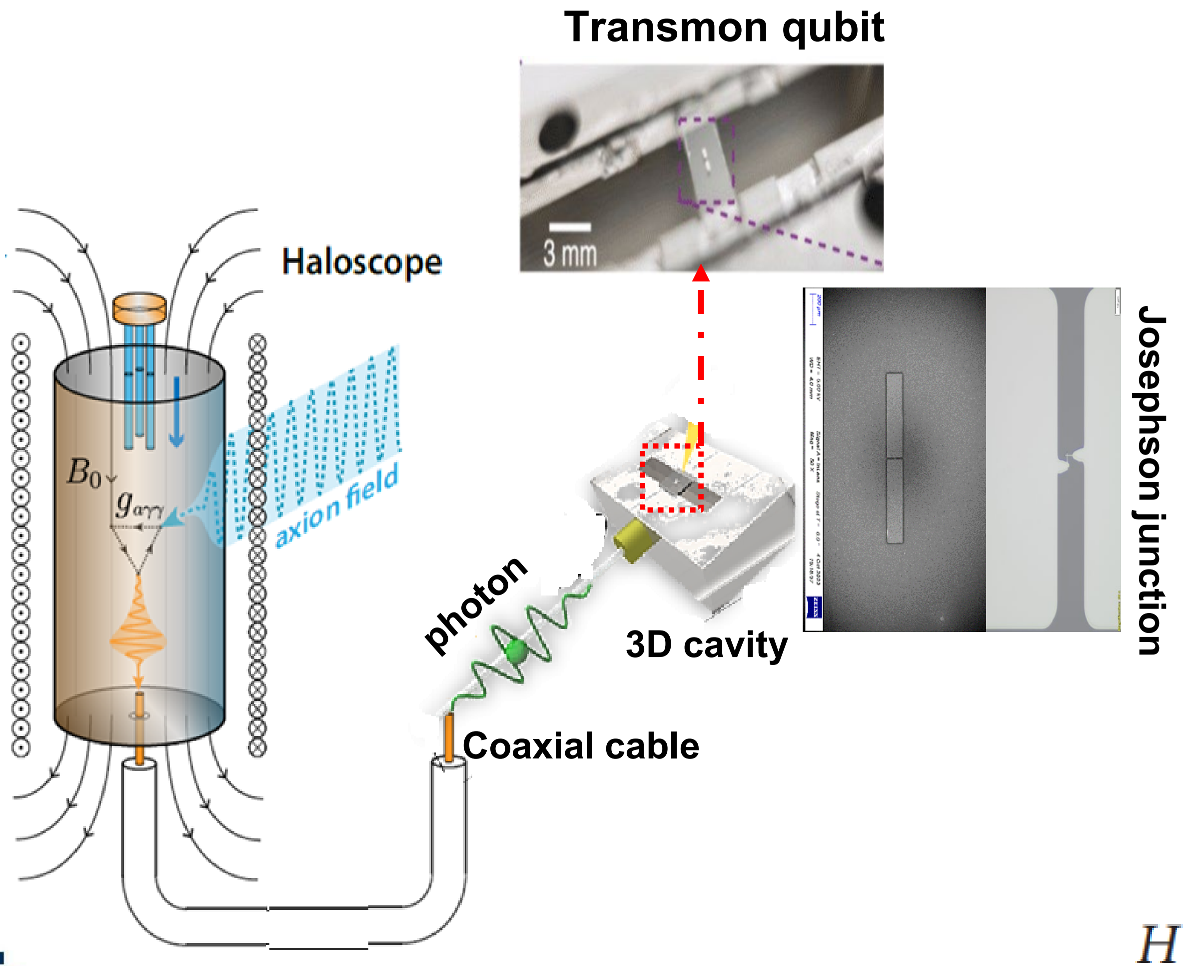
$$\frac{\Delta_{01}}{2\pi} = \omega_q - \omega_r = -1510\ GHz$$

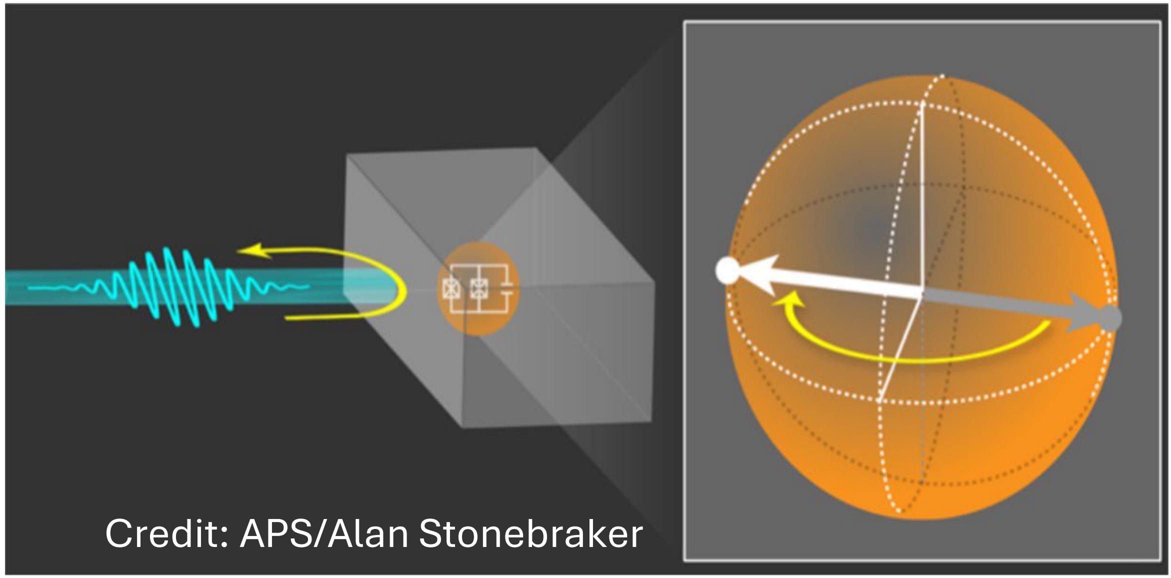
$$\frac{g_{01}}{2\pi} \cong 90\ MHz$$

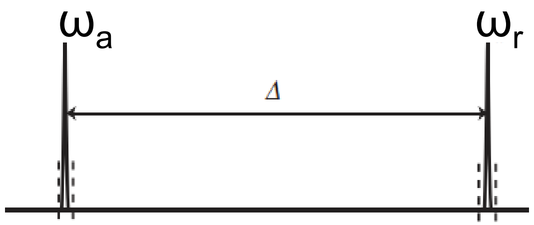
Parameters	Measured $\left(\frac{1}{2\pi}\ MHz\right)$	Simulated $\left(\frac{1}{2\pi}\ MHz\right)$	Error $e = \|(s - m)/s\|$
Qubit frequency ω_q	5740	5739.04	0.0167%
bare cavity frequenc	7252	7436	2.40%
Anharmonicity α	353	359	1.67%
Capacity C	54.87 fF	53.94 fF	1.73%
Detuning Δ	1510	1696.96	11.01%
Dispersive shift χ	1.2	1.405	14.29%
Coupling strength g	90 $(from\ \chi_{01})$	94.33	4.59%

Experimental data validated the simulations values within a few percent

Transmon-based haloscope: QND measurements



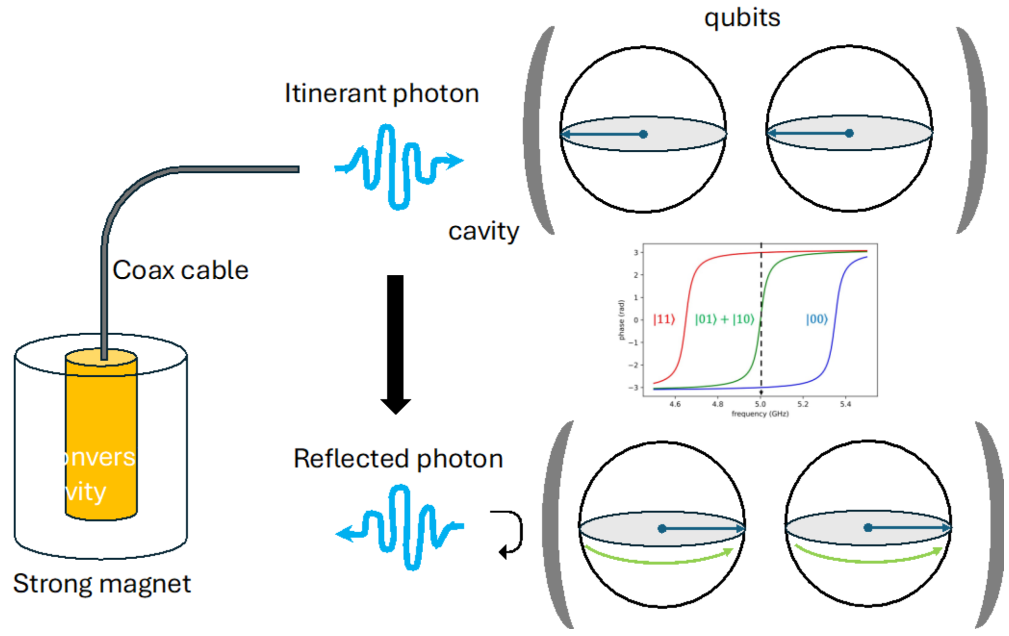




$$H = \hbar\omega_r\left(a^\dagger a + 1/2\right) + \hbar\omega_a\sigma_z/2 + \hbar\chi\left(a^\dagger a + 1/2\right)\sigma_z$$

Kono, S. *et al. Nature Phys* **14**, 546–549 (2018)

Two qubits photon sensor



1. Reduction of readout errors

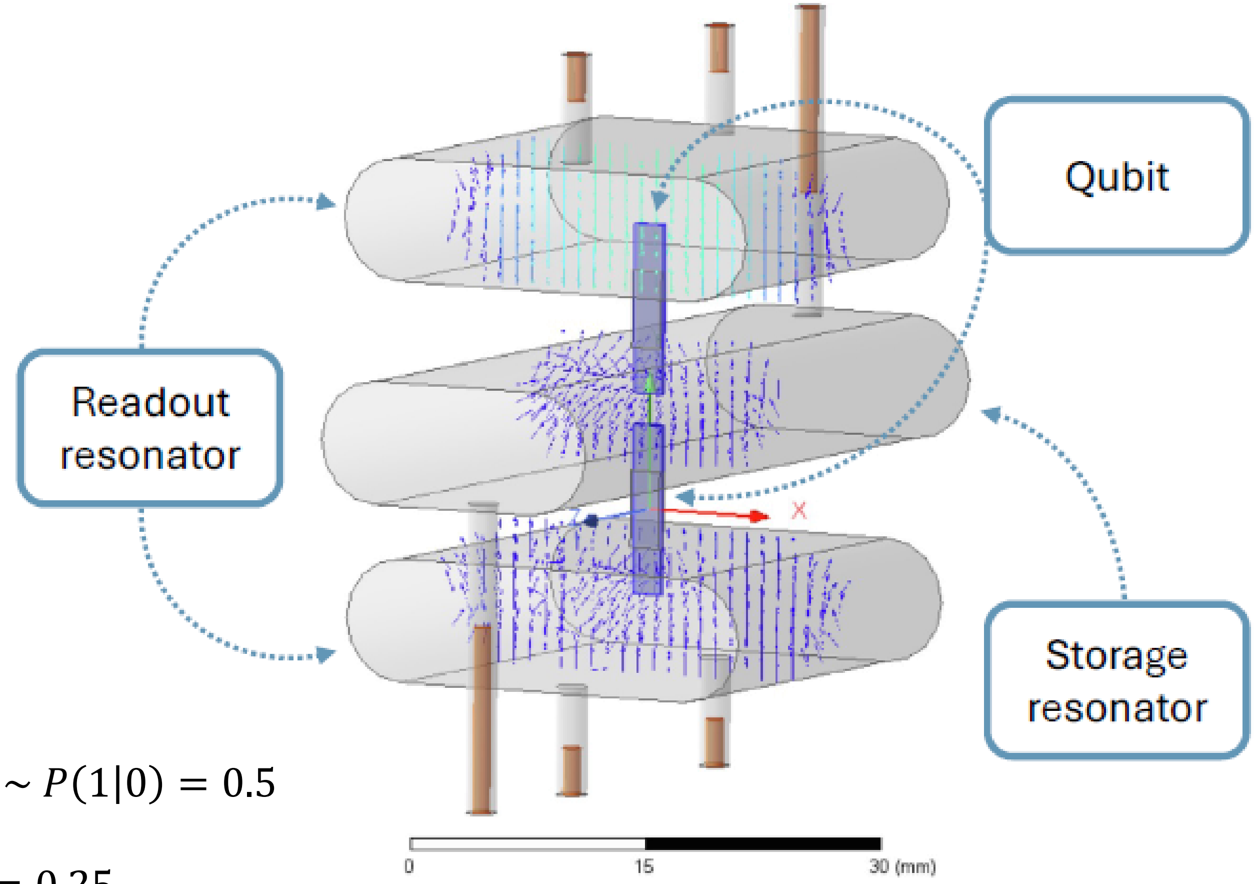
$$p_{err}(\otimes_i^N |e\rangle_i) = \prod_{i=1}^{N} p_{err}(|e\rangle)$$

1_qubit:

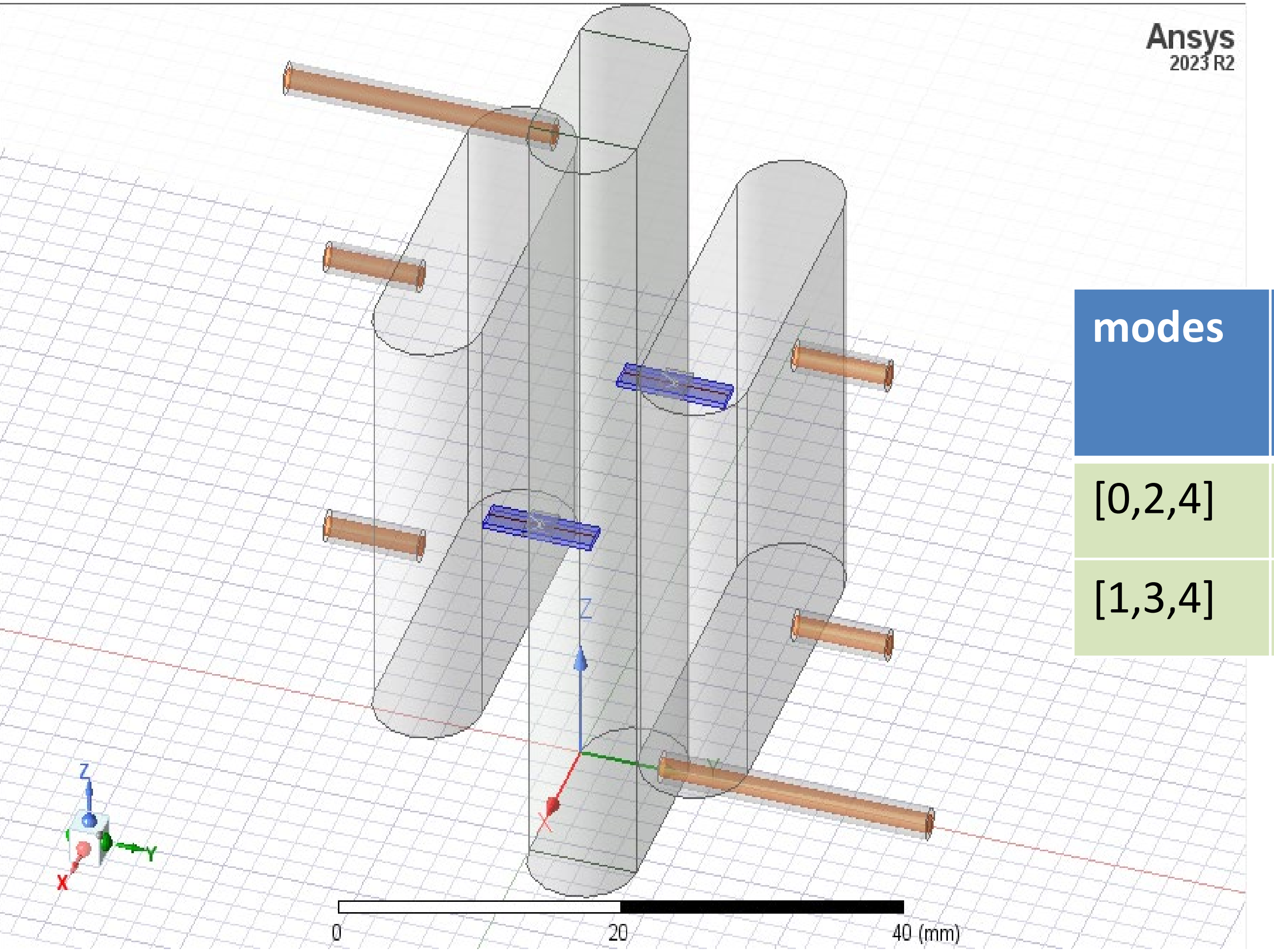
Rate_dark_counts $\sim P(1|0) = 0.5$

2_qubit $\sim P(1|0)^2 = 0.25$

2. Improved detection efficiency;
3. More effective quantum non-demolition (QND) measurement;



Two qubits photon sensor: preliminary simulation



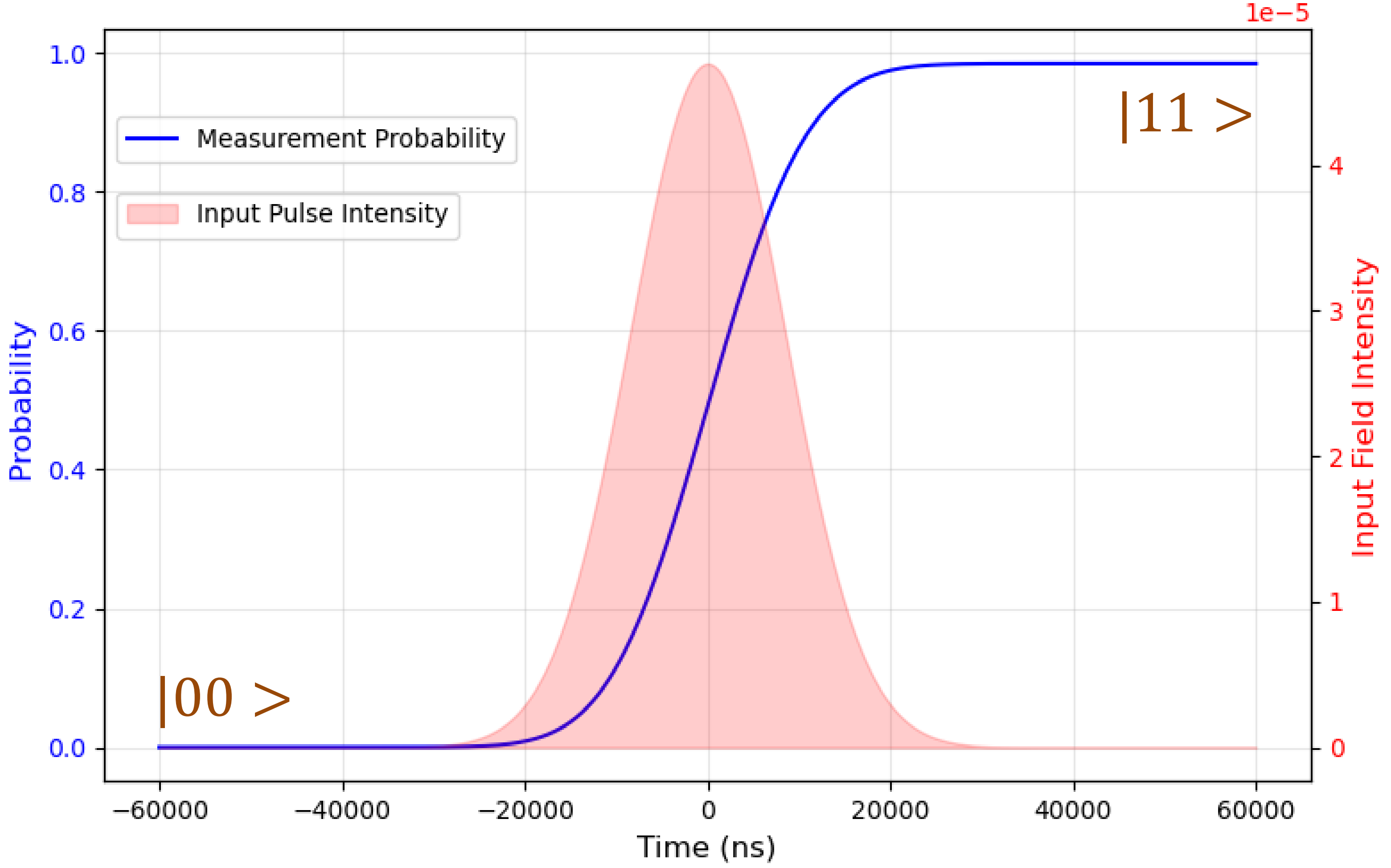
Both qubits are detuned and separated from each other by a distance dz

$$L_{j1} = 11\,nH$$
$$L_{j2} = 9\,nH$$

modes	fq [GHz]	g01 1° [MHz]	g01 2° [MHz]	α [MHz]	χ 1° [MHz]	χ 2° [MHz]
[0,2,4]	4.61	52.33	57.82	119.97	0.87	0.79
[1,3,4]	5.01	53.50	56.91	104.11	1.01	0.84

$Modes\ 0\ \&\ 1:\ Qubits\ 1\ \&\ 2$
$Modes\ 2\ \&\ 3:\ Readout\ cavities\ 1\ \&\ 2$
$Mode\ 4:\ storage\ cavity$

Two qubits photon sensor : Efficiency



Parameters from QUAX experiments

- Cavity
  - Frequency: $\frac{\omega_c}{2\pi} = 8.83\ GHz$
  - Quality factor: $Q_L = 32540$
- Input coherent pulse
  - Frequency: $\frac{\omega_{ph}}{2\pi} = 8.83\ GHz$
  - $\sigma_{FWHM} = 20\mu s$
  - $\sigma_\omega = \frac{2\sqrt{2\log 2}}{\sigma\_FWHM}$
  - Coherent state: $\alpha = \sqrt{0.1}$

Two qubits photon sensor

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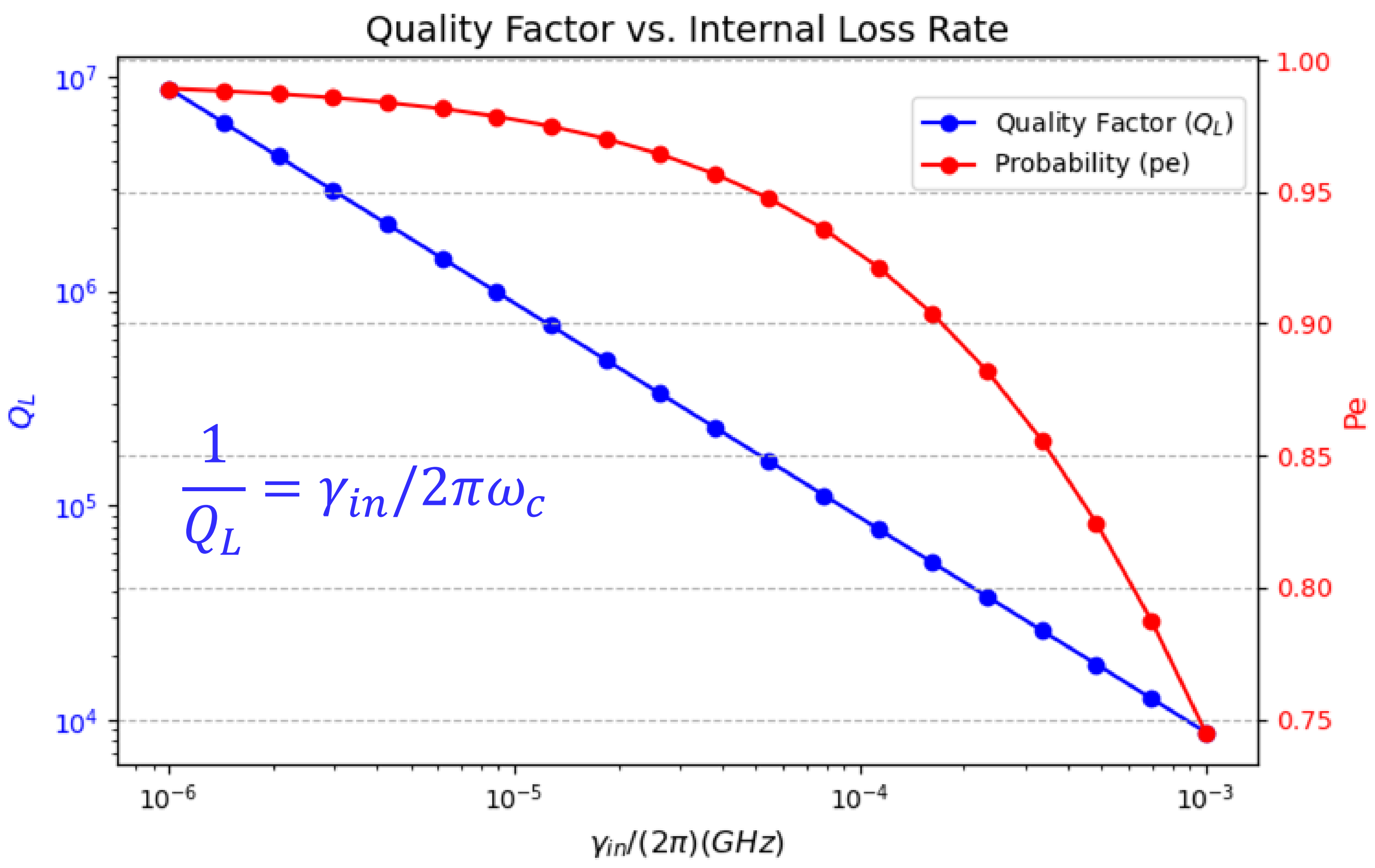

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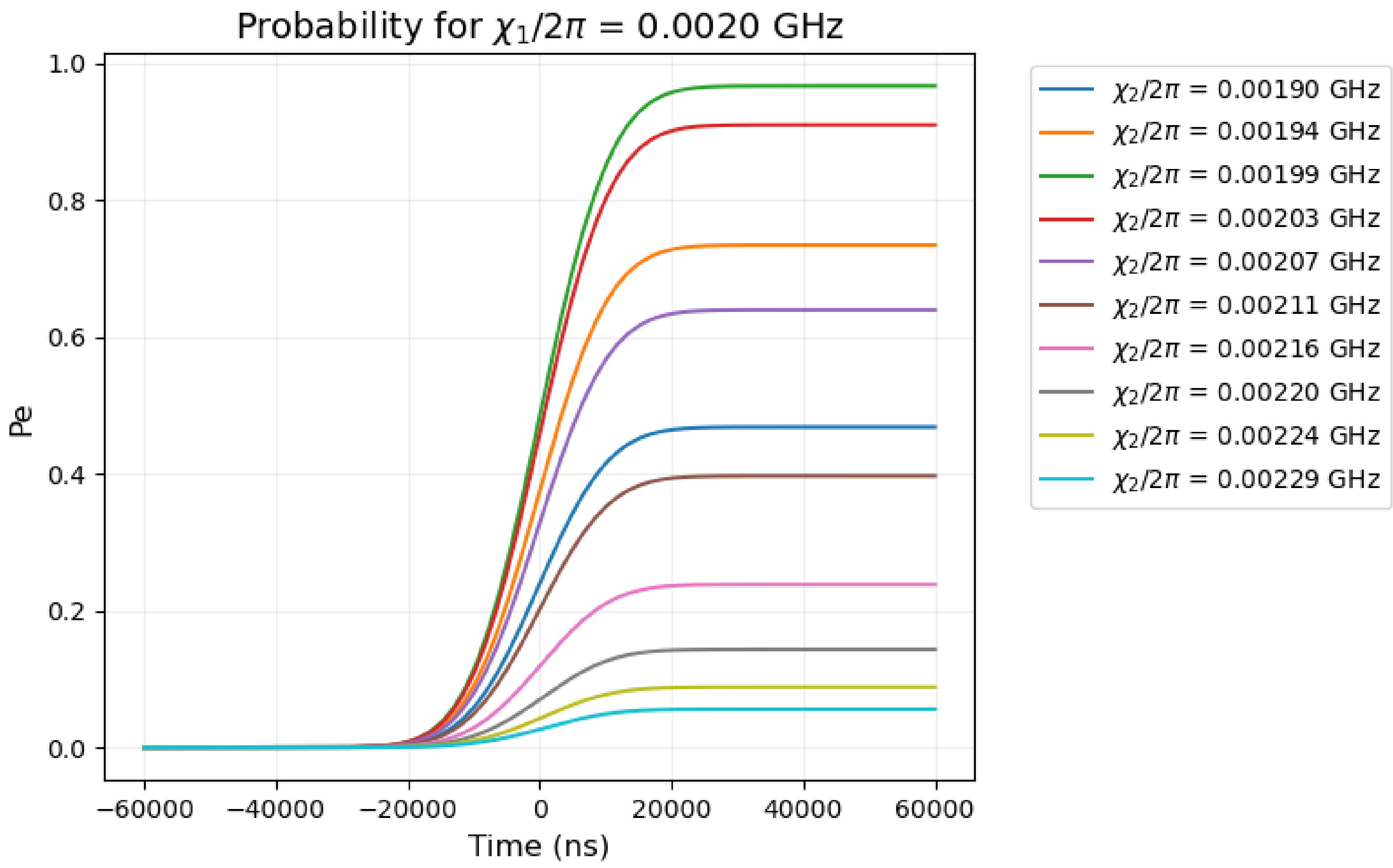
Two qubits photon sensor

$Efficiency\ P_e\ \ with\ \chi_1 \neq \chi_2$



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Conclusion

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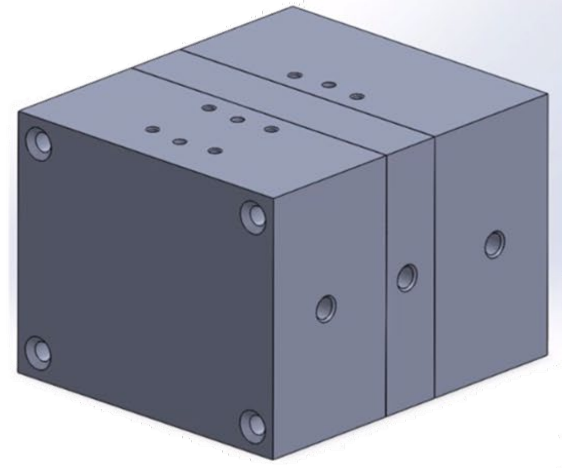
- ✓ We characterized the transmon using spectroscopic techniques and measured all the main parameters of Hamiltonian; qubit frequency, dispersive shift, qubit capacitance, anharmonicity etc.
- ✓ We designed the device for two qubits photon sensor
- ✓ The technique will benefit the search for any dark matter candidate because, when invisible particles convert into photons, they can be detected. And this could be a great add-up for the INFN QUAX experiment

Optimization of the two qubits device is in progress

Fabrication

Characterization of the device

Axion measurement campaigns



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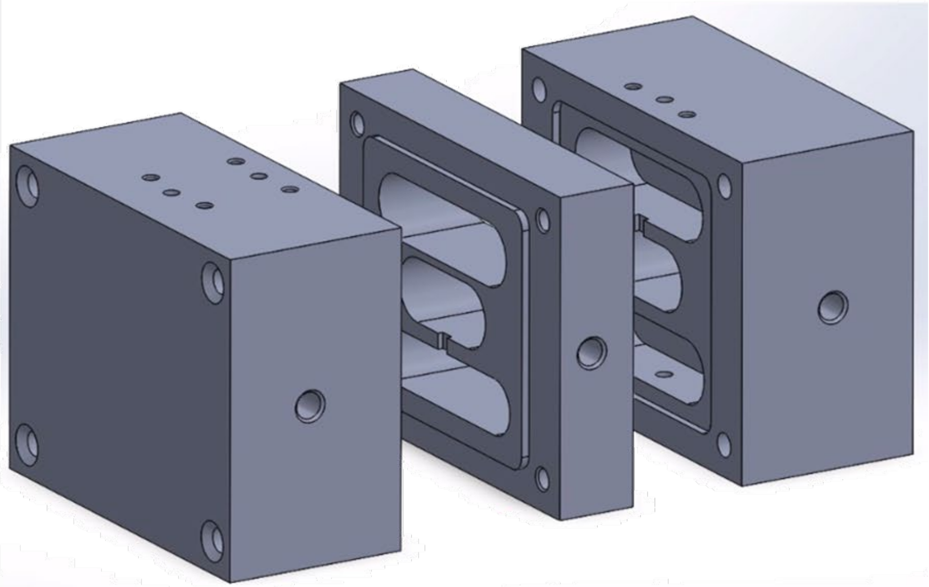

Collaboration

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CryOgenic Laboratory for Detectors:

- Axion Dark Matter Experiments
- Quantum Sensing with Superconducting Devices
- Type II and HTC Superconducting Cavities

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Laboratori Nazionali di Legnaro

CNR IFN
Istituto di Fotonica e Nanotecnologie

TII Technology Innovation Institute

Università degli Studi Firenze

BIQUTE

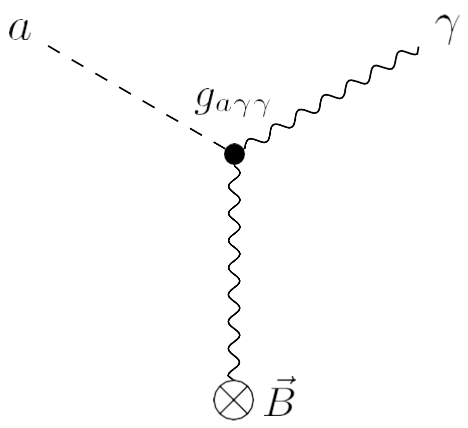
Università degli Studi di Milano Bicocca

Roma Tre Università degli Studi


Grazie per la vostra attenzione

Backup slides

Figures of merit in a haloscope



The **signal power** is very faint

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

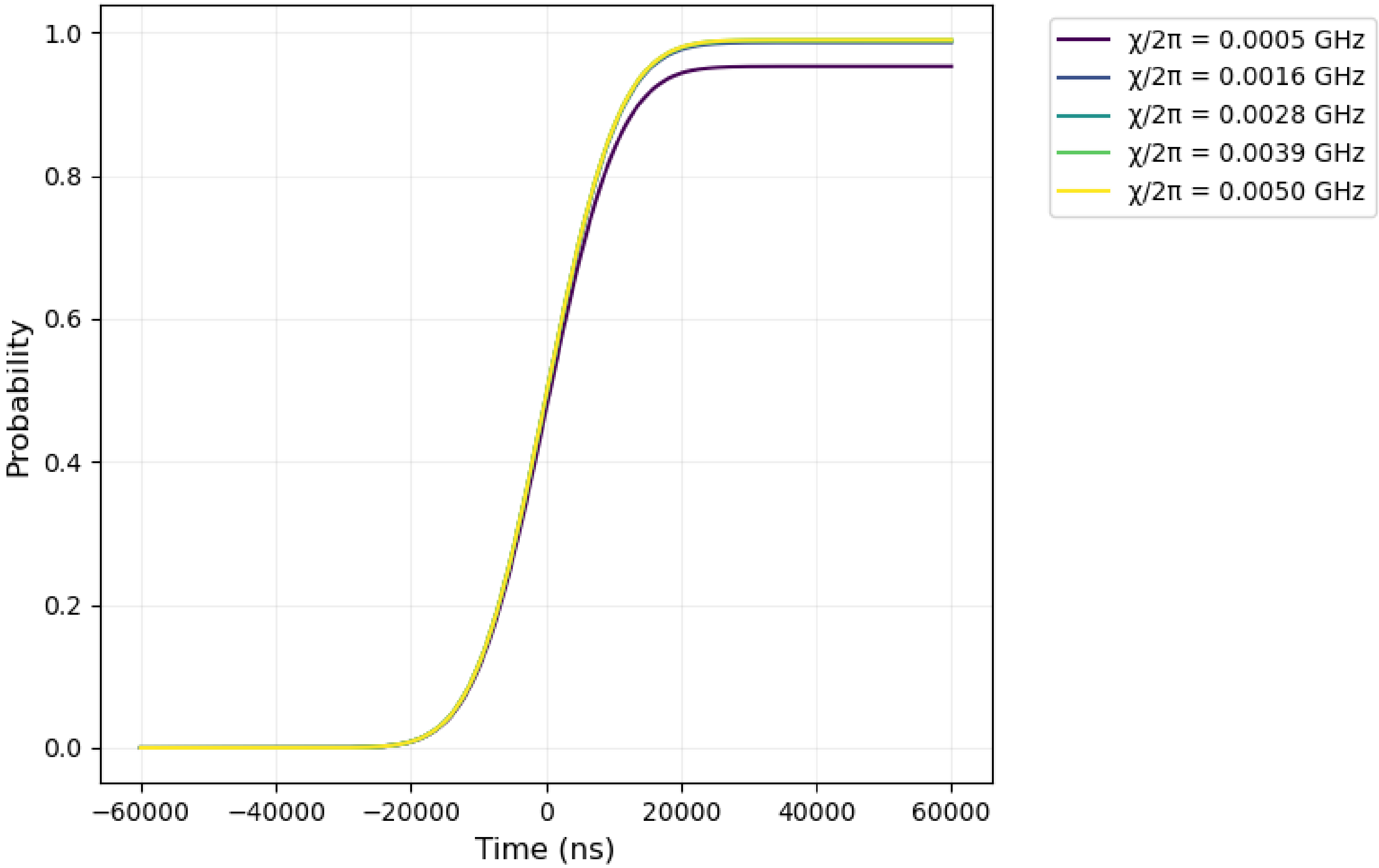
The **scan rate** depends critically on noise temperature

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

$$k_B T_{sys} = \hbar\omega \left(\frac{1}{e^{\hbar\omega / k_B T_c} - 1} + \frac{1}{2} + N_A \right)$$

Two qubits photon sensor

$Efficiency\ P_e\ \ with\ \chi_1 = \chi_2$



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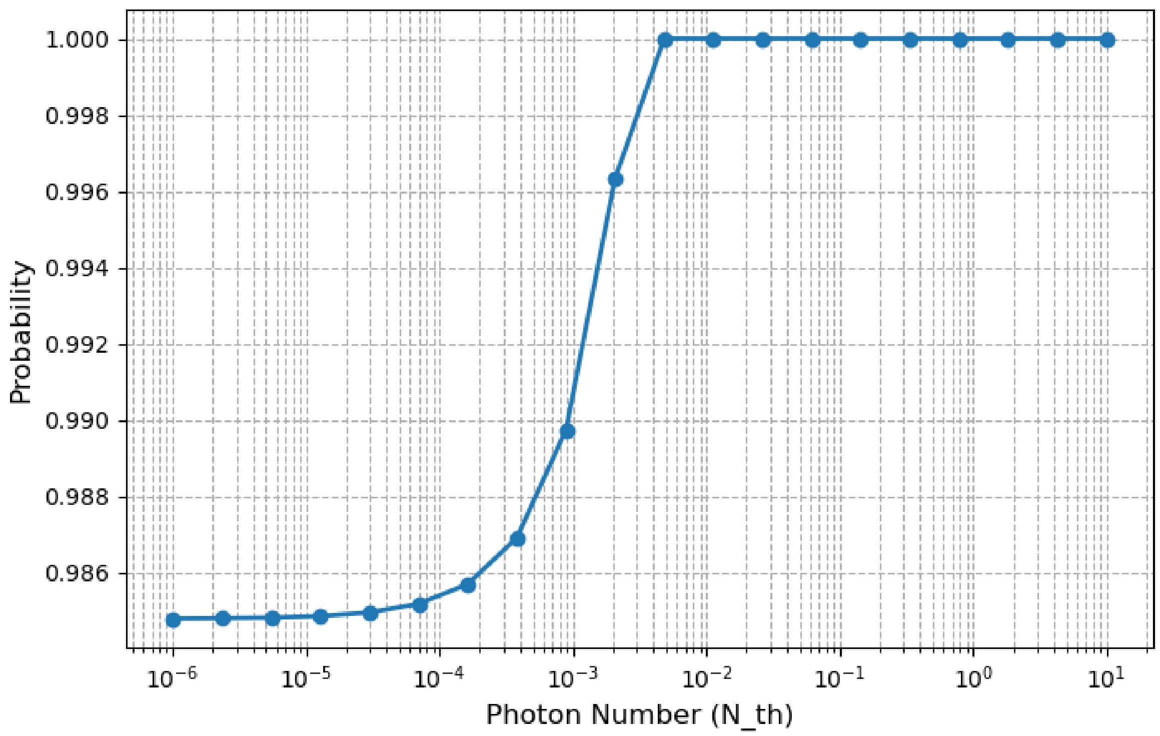
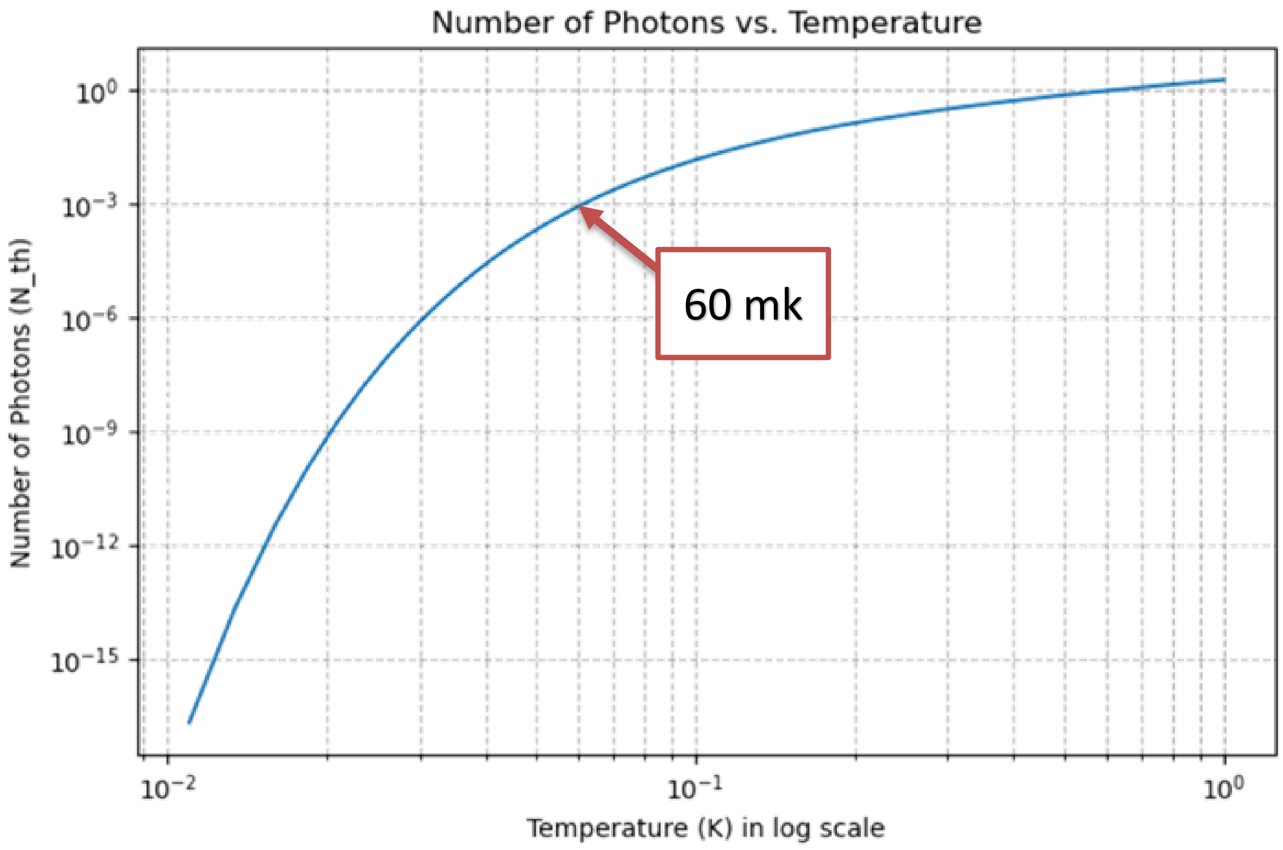
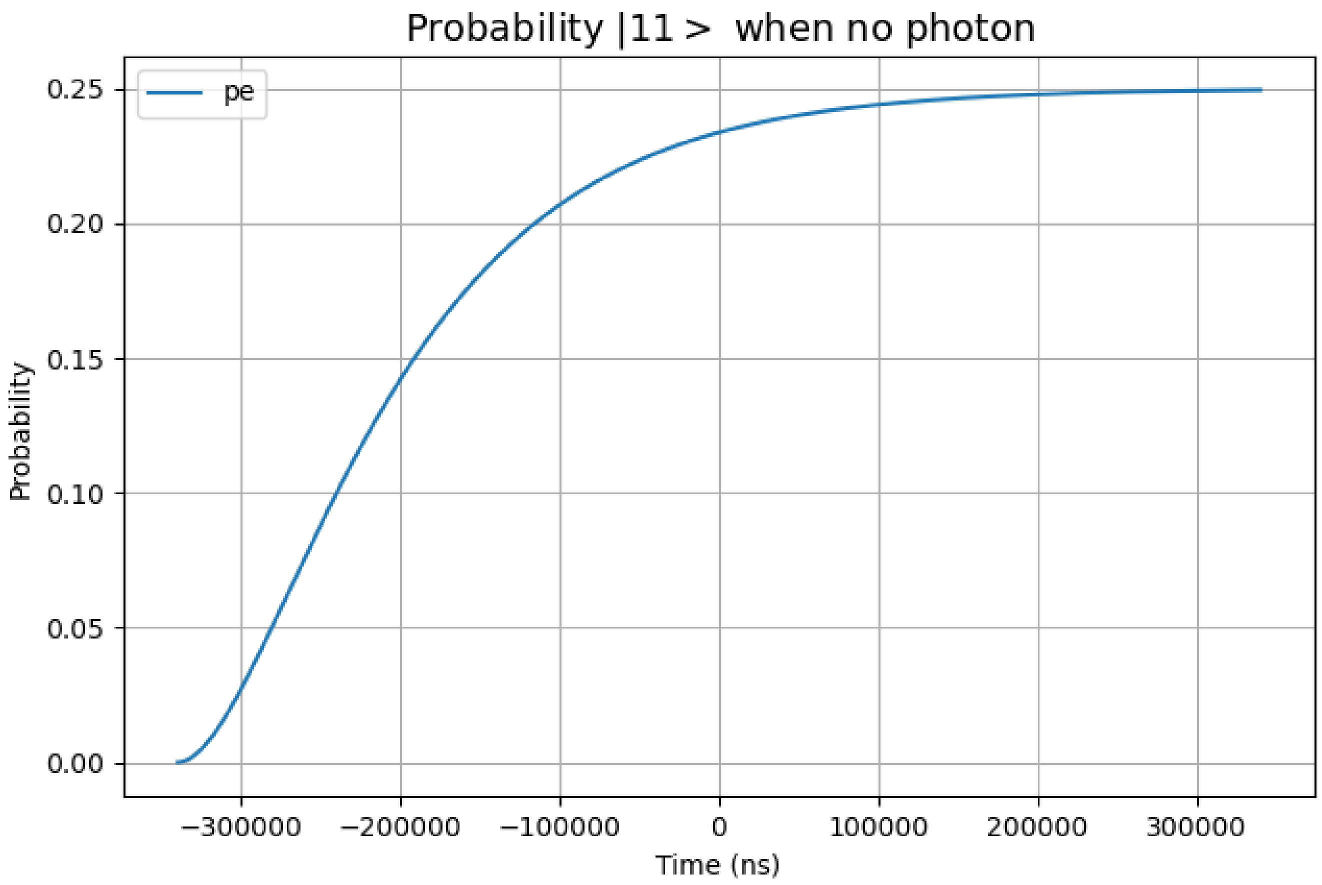
  - $\sigma_{FWHM} = 20000\ ns\ (20\mu s)$
  - $\sigma_\omega = \frac{2\sqrt{2\log 2}}{\sigma\_FWHM}$
  - Coherent state: $\alpha = \sqrt{0.1}$

Two qubits photon sensor $P_e = f(N_{th})$





Two qubits photon sensor : No photon



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  - Coherent state: $\alpha = \sqrt{0.1}$