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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

NQSTI
National Quantum Science and Technology Institute

COHERENT STATES DETECTION FOR LIGHT DARK MATTER SEARCHES USING MULTI-QUBIT SENSOR

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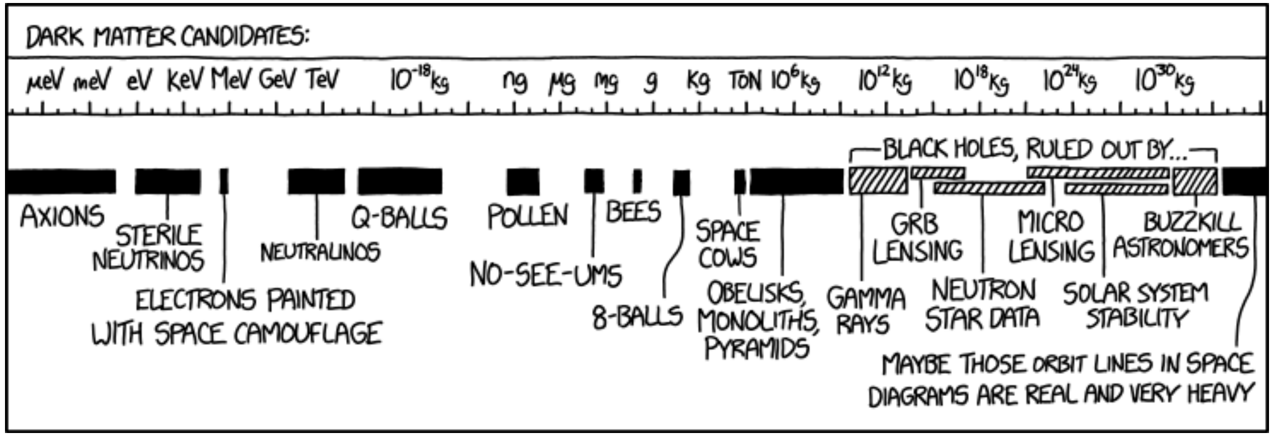
INFN – Milano-Bicocca
Bicocca Quantum Technologies (BiQuTe) Centre

DARK MATTER

"There are a lot of things we understand about the universe, but the fun is in all the things we do not."

The evidence of existence of dark matter is based on astronomical observations of its gravitational interactions.

- Velocity discrepancy in galaxy clusters (1933 - Zwicky)
- Galaxy rotation curves (1970s - Rubin and Ford)
- Gravitational lensing (1980s - present)
- Large-scale structure of the universe
- Cosmic microwave background (CMB)
- Baryon acoustic oscillations (BAO)
- Collision of galaxy clusters
- ... and so on



Credit: xkcd

QUANTUM SENSING – LIGHT DARK MATTER SEARCHES

AXION

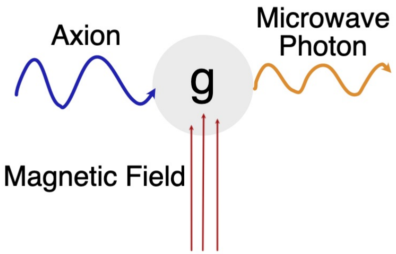
Strong CP problem:

- QCD does not conserve CP (theory);
- QCD conserves CP (experiment).

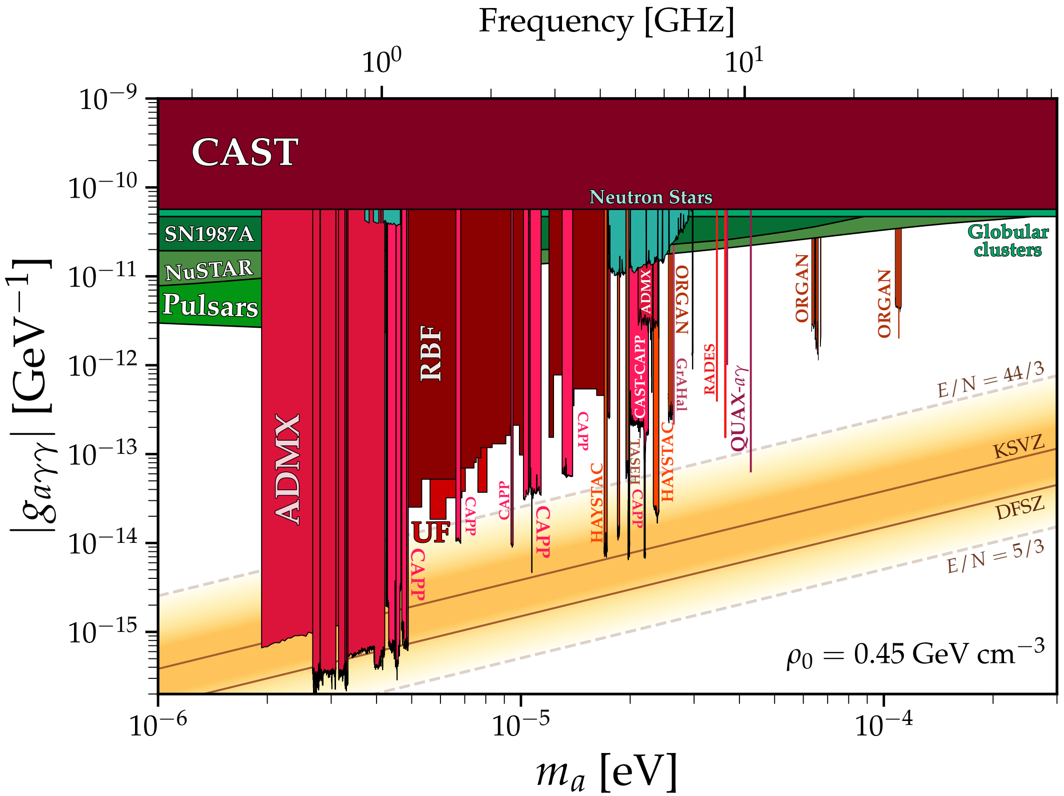
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \theta\,\frac{g^2}{32\pi^2}F^{\mu\nu}\,\tilde{F}_{\mu\nu} + \bar{\psi}\left(i\gamma^{\mu}D_{\mu} - me^{i\theta'\gamma_5}\right)\psi$$

A possible solution to conserve CP: **axion** (pseudo-Goldstone boson):

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \frac{1}{8}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$



Inverse Primakoff effect



10.5281/zenodo.3932430

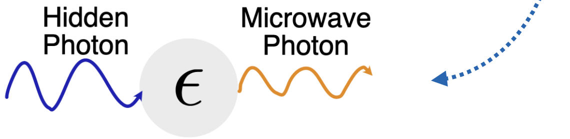
QUANTUM SENSING – LIGHT DARK MATTER SEARCHES

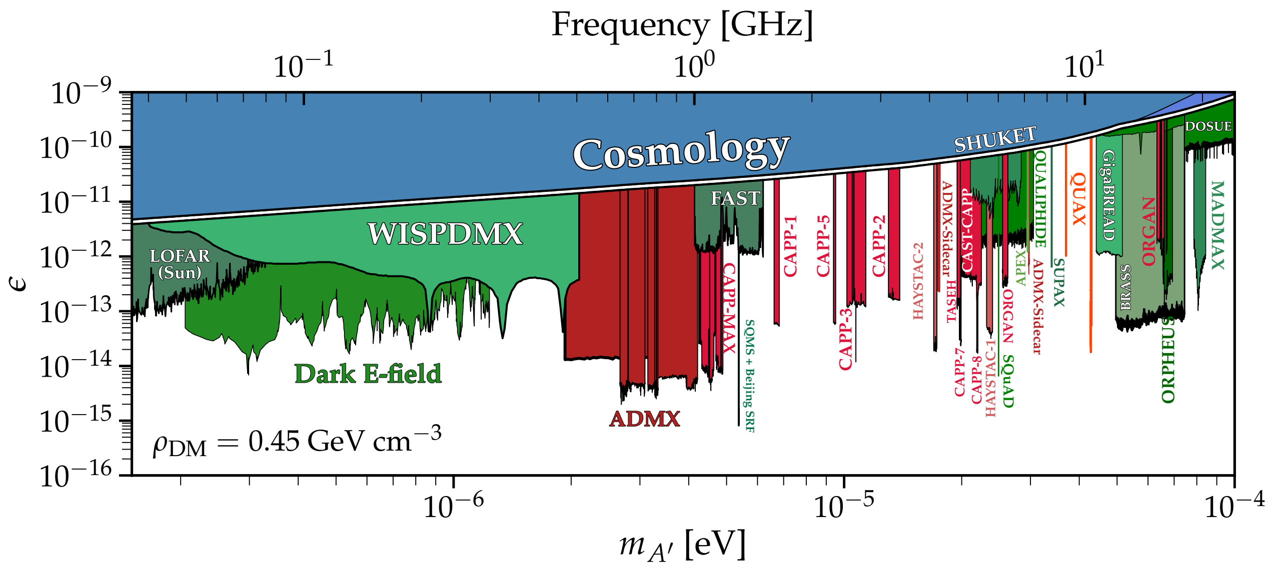
DARK PHOTON

Some anomalies in astrophysics could be explained through the interactions between the **dark matter** and **dark photons**.

- Introducing a new gauge $U(1)$ symmetry in the Standard Model
- **Kinetic mixing** with the electromagnetic field.

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}A'^{\mu}A'_{\mu} + \epsilon e A'^{\mu}J^{EM}_{\mu}$$





10.5281/zenodo.3932430

DM DETECTION USING QUBITS: DIRECT EXCITATION

Assumption: the DM candidate generates a weak coherent effective electromagnetic field.

If the field is resonant with the qubit $|g\rangle \rightarrow |e\rangle$ transition it can trigger the qubit to be in an excited state.

Qubit state $|\psi(t)\rangle = \psi_g(t)|g\rangle + e^{-i\omega_q t}\psi_e(t)|e\rangle$

Hamiltonian for an axion-induced electric field $H = \omega_q|e\rangle\langle e| + 2\eta\cos(m_a t - \alpha)\left(|e\rangle\langle g| + |g\rangle\langle e|\right)$

$$p_{eg}(\tau) \simeq 0.11\left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{m_a}{1\ \mu\mathrm{eV}}\right)^2\left(\frac{B_0}{1\ \mathrm{T}}\right)^2\left(\frac{\tau}{100\ \mu\mathrm{s}}\right)^2\kappa^2\left(\frac{C}{0.1\ \mathrm{pF}}\right)\left(\frac{d}{100\ \mu\mathrm{m}}\right)^2\left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeV/cm^3}}\right)$$

Hamiltonian for a dark photon-induced electric field $H = \omega_q|e\rangle\langle e| + 2\eta\sin m_{A'}t\left(|e\rangle\langle g| + |g\rangle\langle e|\right)$

$$p_{eg}(\tau) \simeq 0.12\kappa^2\cos\Theta\left(\frac{\epsilon}{10^{-11}}\right)^2\left(\frac{f}{1\ \mathrm{GHz}}\right)\left(\frac{\tau}{100\ \mu\mathrm{s}}\right)^2\left(\frac{C}{0.1\ \mathrm{pF}}\right)\left(\frac{d}{100\ \mu\mathrm{m}}\right)^2\left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeV/cm^3}}\right)$$

10.1103/PhysRevD.110.115021, 10.1103/PhysRevLett.131.211001

DM DETECTION USING QUBITS: QUANTUM NON-DEMOLITION MEASUREMENTS

Qubit state dependent on cavity population

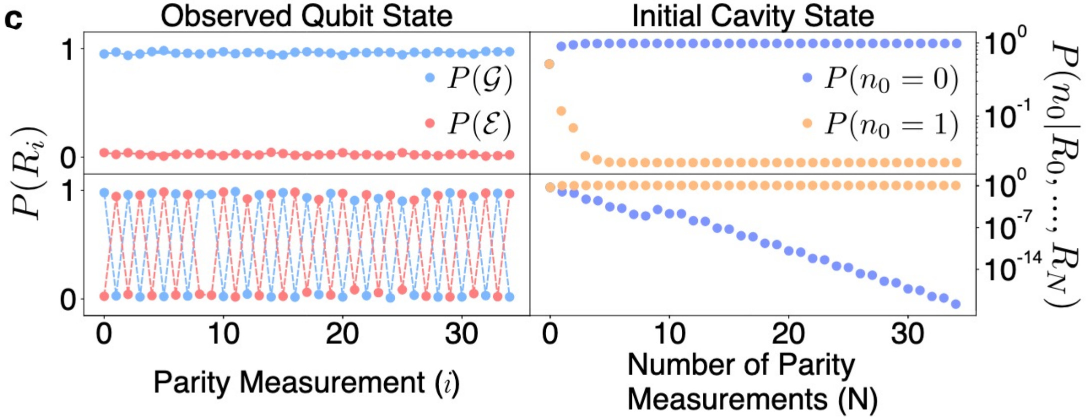
$$H = \omega_c a^\dagger a + \frac{1}{2}\left(\omega_q + \mathbf{2\chi a^\dagger a}\right)\sigma_z$$

1

$$|g\rangle \xrightarrow{Y/2} \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\phi}|e\rangle\right) \longrightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i(\phi + 2\chi a^\dagger a \Delta t)}|e\rangle\right)$$

$$\Delta t = \pi/(2\chi) \longrightarrow \Delta\phi = \boldsymbol{\pi} a^\dagger a$$

$$\xrightarrow{-Y/2} \quad |g\rangle \longleftrightarrow |e\rangle$$



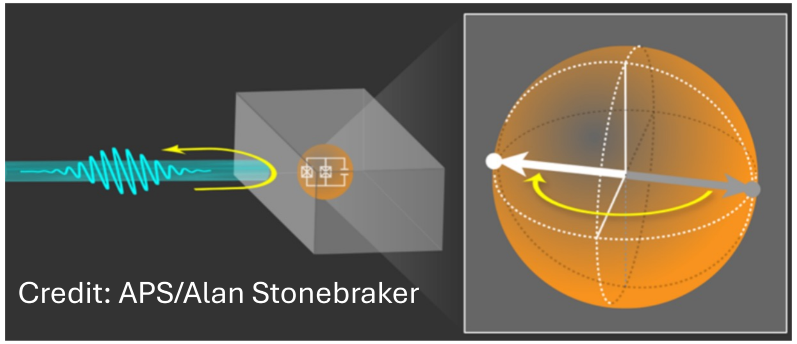
10.1103/PhysRevLett.126.141302

2

$$\kappa_{\text{ext}} = 2\chi \longrightarrow \phi = \pi$$

$$|g\rangle \xrightarrow{Y/2} \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\phi}|e\rangle\right) \xrightarrow{\gamma} \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i(\phi+\pi)}|e\rangle\right)$$

$$\longrightarrow \frac{1}{\sqrt{2}}\left(|g\rangle - e^{i\phi}|e\rangle\right) \xrightarrow{Y/2} |e\rangle$$



10.1038/s41567-018-0066-3

EXTENDING THE QUANTUM NON-DEMOLITION DETECTION SCHEME

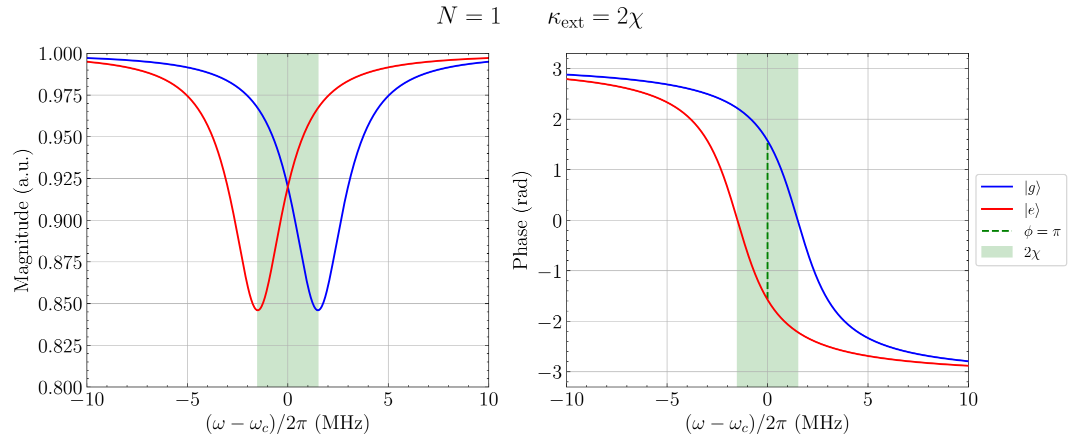
Increasing the number of qubits (N) in a photon counter device provides several advantages:

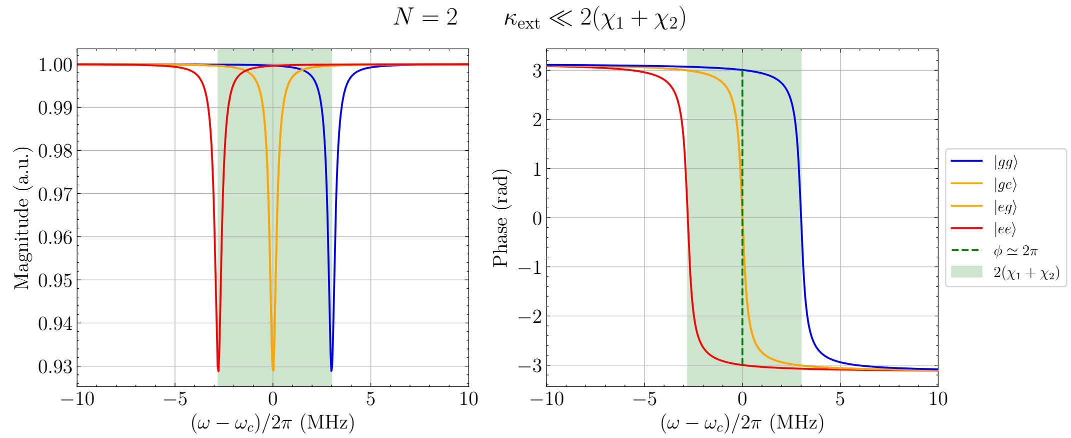
1. Reduction of readout errors

$$p_{\mathrm{err}}\left(\otimes_i^N |e\rangle_i\right) = \prod_{i=1}^{N} p_{\mathrm{err}}(|e\rangle) \qquad p_{\mathrm{err}}^{\mathrm{best}}(|e\rangle) = 0.3\%$$

2. Improved detection efficiency;
3. More effective quantum non-demolition (QND) measurement;
4. Reduced scan time in experimental searches.

$$\kappa_{\mathrm{ext}} \ll 2\sum_{i=1}^{N} \chi_i \;\cdots\rightarrow\; \text{Total phase shift } \phi = 2\pi$$





10.3390/app14041478

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SIMULATION OF MULTI-QUBIT CHIP DEVICE

Using an input-output theory we can model:

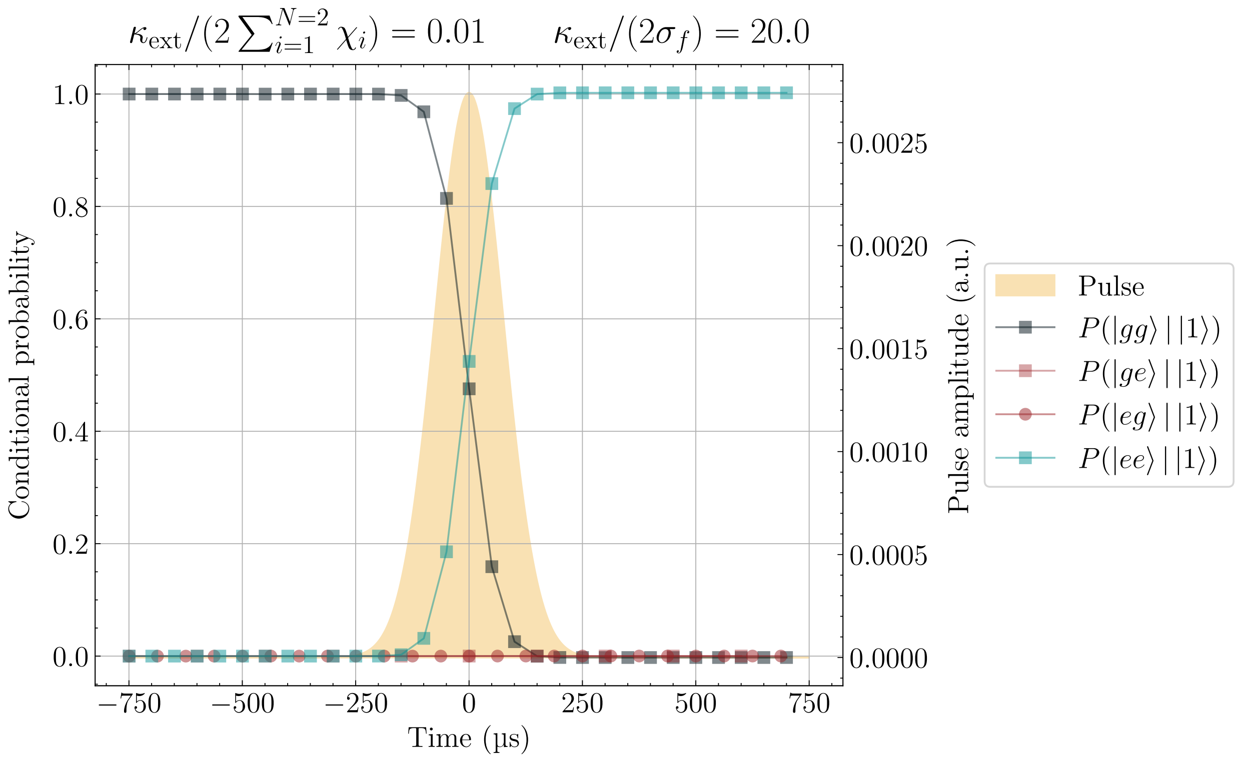
- The interaction between an input field and the cavity
- The interaction between the cavity and the qubits

From the model, it is possible to evaluate the conditional probability

$$P(|q\rangle \mid |1\rangle) = \frac{P(|q\rangle)P(|1\rangle \mid |q\rangle)}{P(|1\rangle)}$$

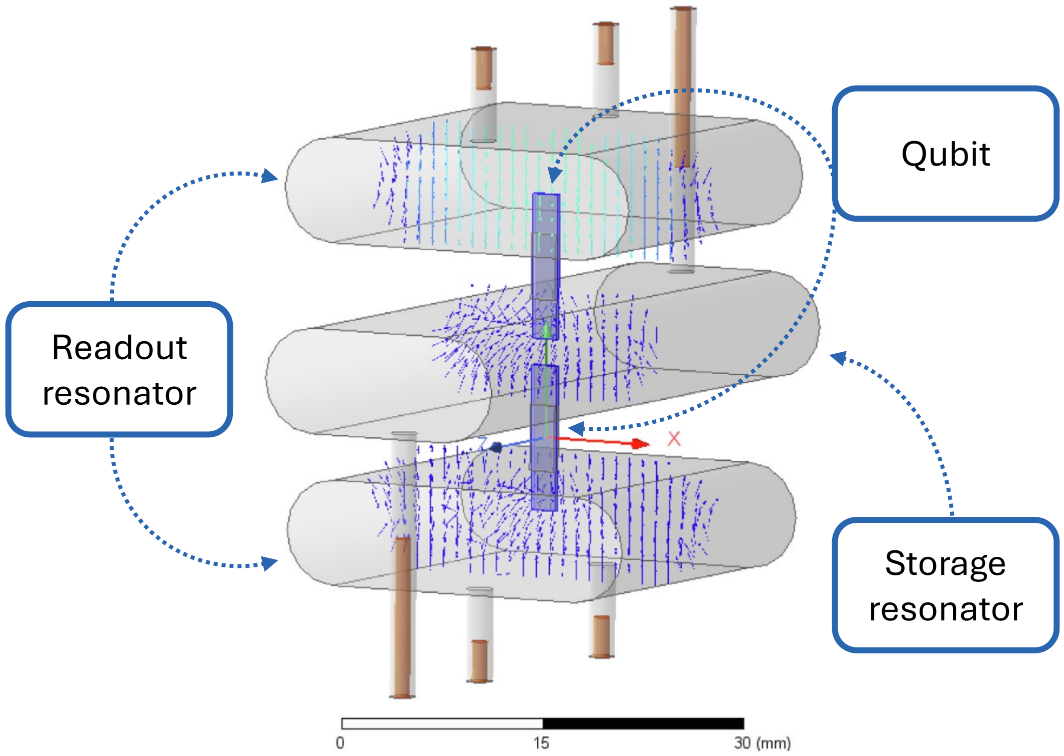
$$P(|n\rangle) = \frac{|\alpha|^{2n}}{n!} e^{-|\alpha|^2}$$

SIMULATIONS OF MULTI-QUBIT CHIP DEVICE – 2 QUBITS



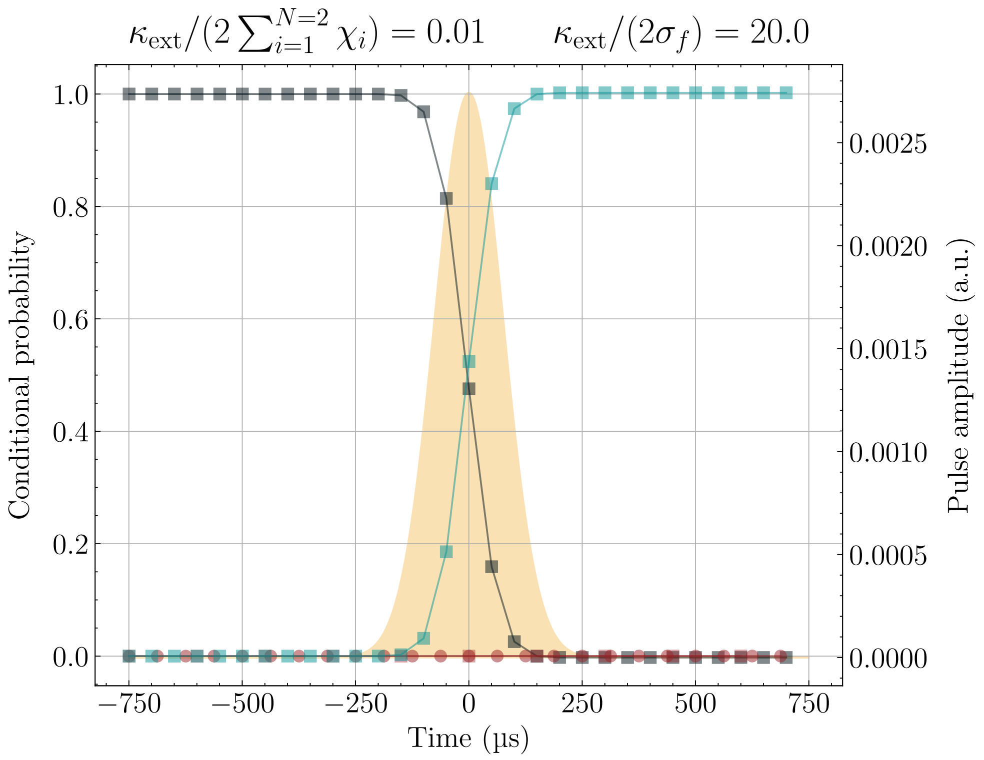
Total phase shift $\phi = 2\pi$

3D double-qubit single-photon detector

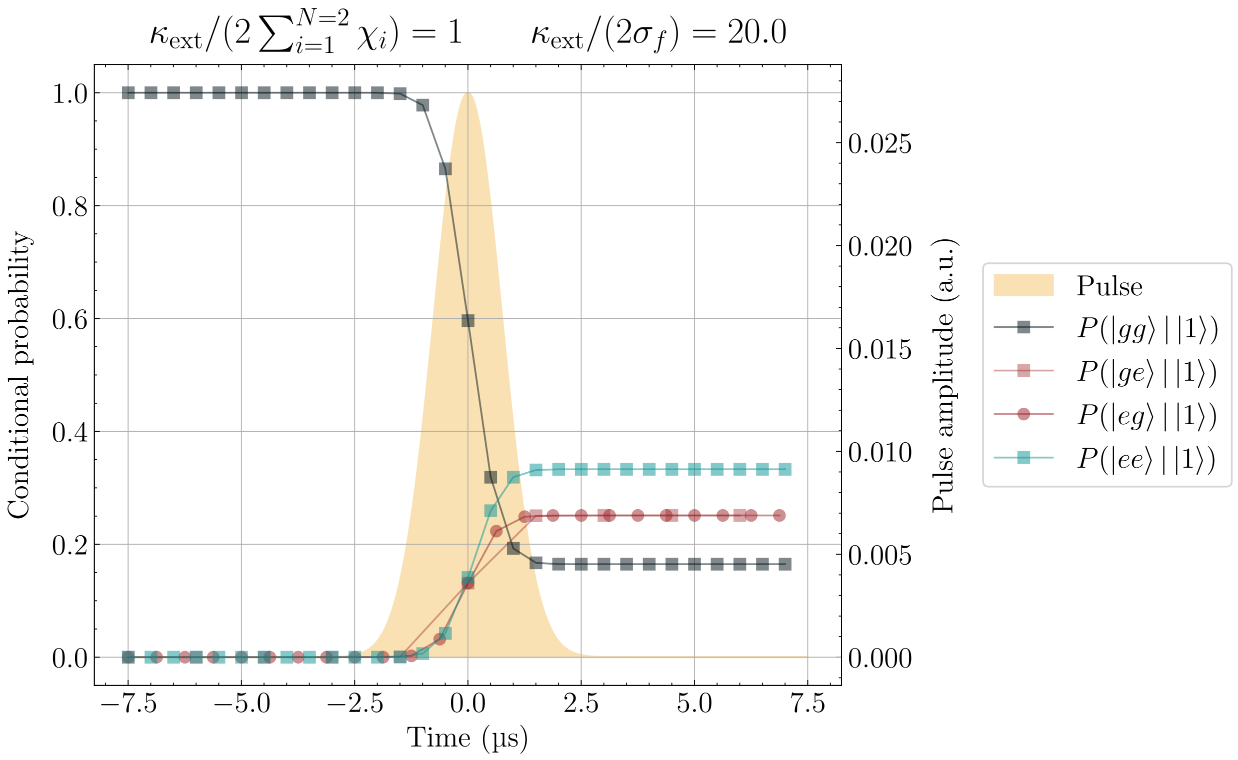


10.1016/j.nima.2024.170010

SIMULATIONS OF MULTI-QUBIT CHIP DEVICE – 2 QUBITS

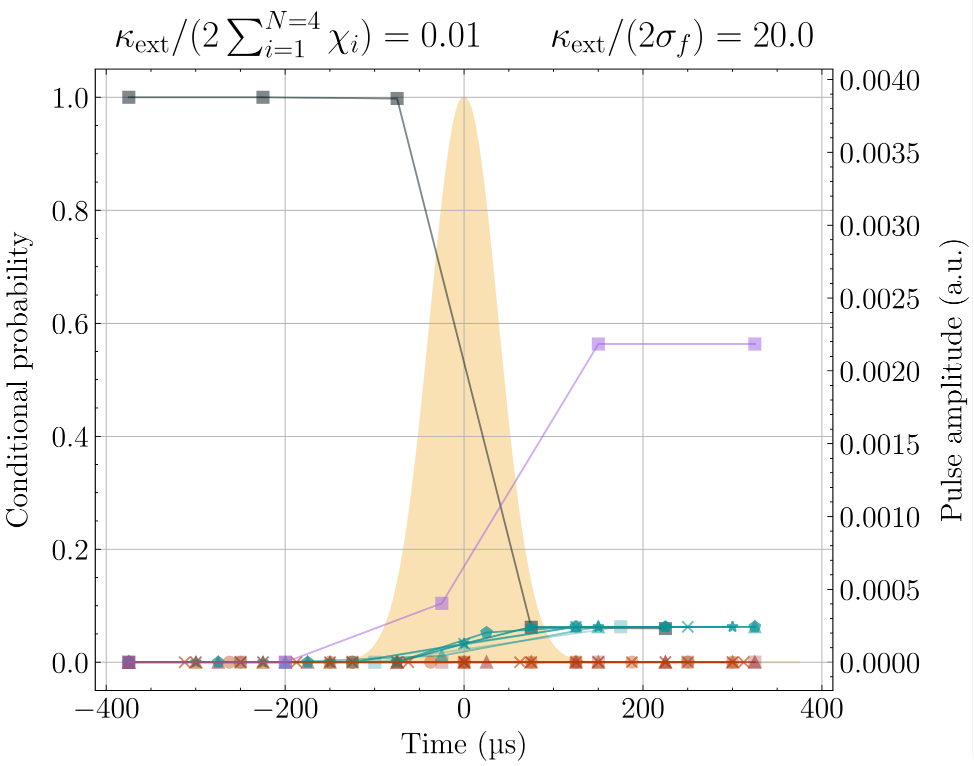


Total phase shift $\phi = 2\pi$

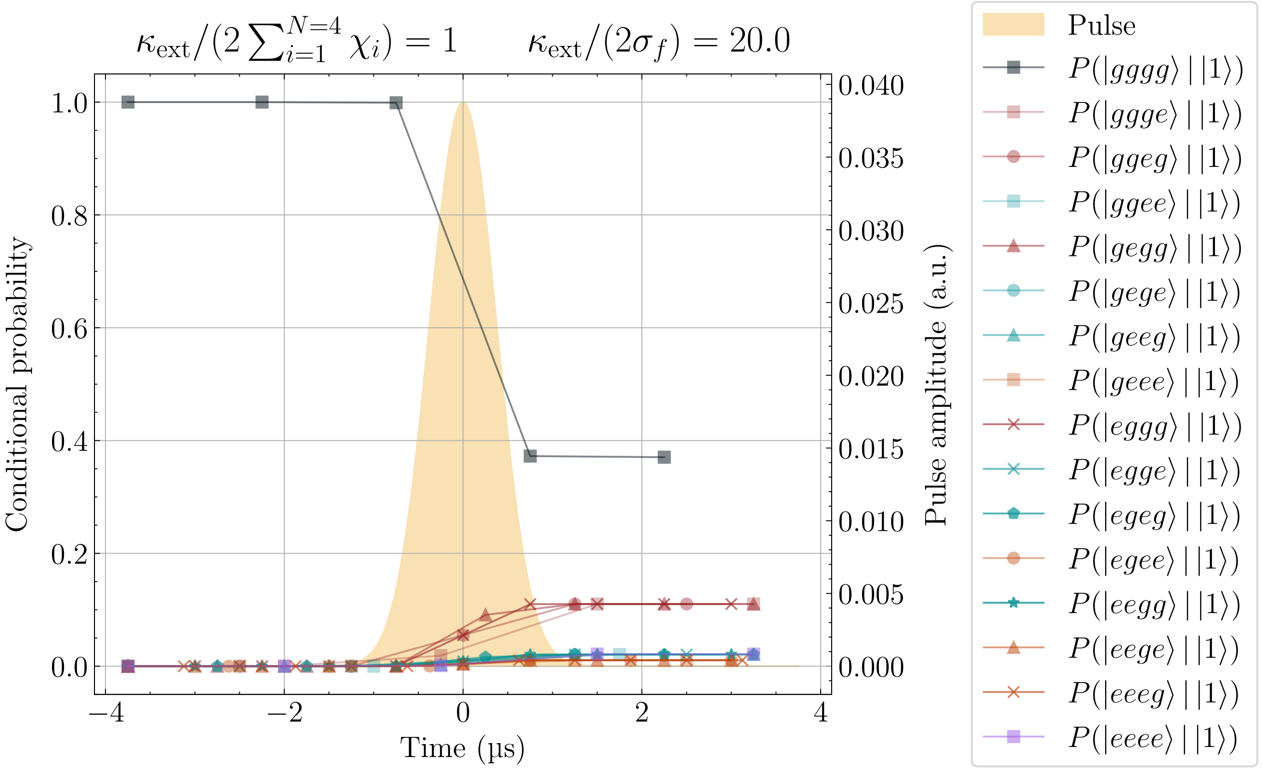


Total phase shift $\phi = \pi$

SIMULATIONS OF MULTI-QUBIT CHIP DEVICE – 4 QUBITS



Total phase shift $\phi = 2\pi$



Total phase shift $\phi = \pi$

PHASE DISTRIBUTION

Simplest case: single qubit in the absence of excitation, relaxation, and decoherence phenomena.

$$|g\rangle \xrightarrow{Y/2} \frac{|g\rangle + |e\rangle}{\sqrt{2}} \xrightarrow{\gamma} \frac{|g\rangle + e^{i\phi}|e\rangle}{\sqrt{2}} \xrightarrow{-Y/2} \frac{1}{2}\left[\left(e^{i\phi}+1\right)|g\rangle + \left(e^{i\phi}-1\right)|e\rangle\right]$$

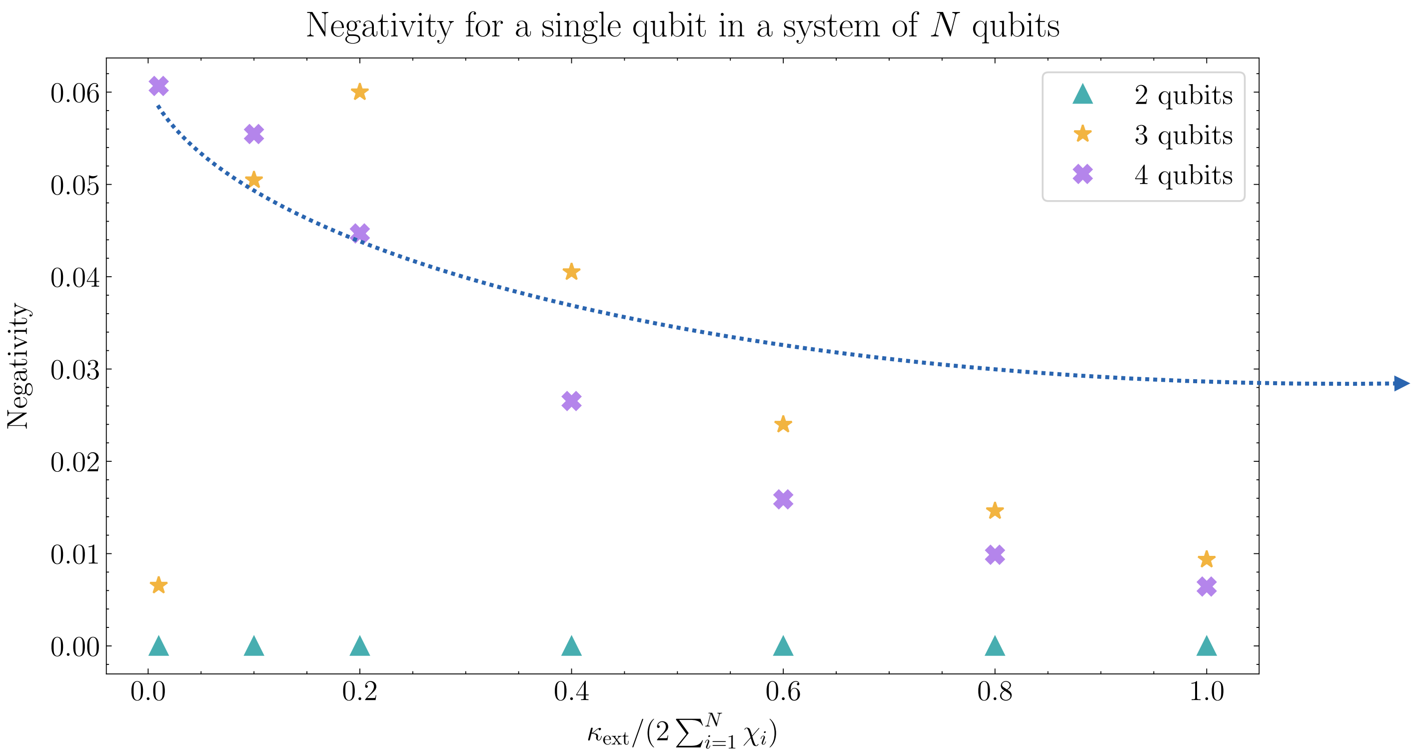
$$P(|g\rangle) = \frac{1+\cos\phi}{2} \qquad P(|e\rangle) = \frac{1-\cos\phi}{2}$$

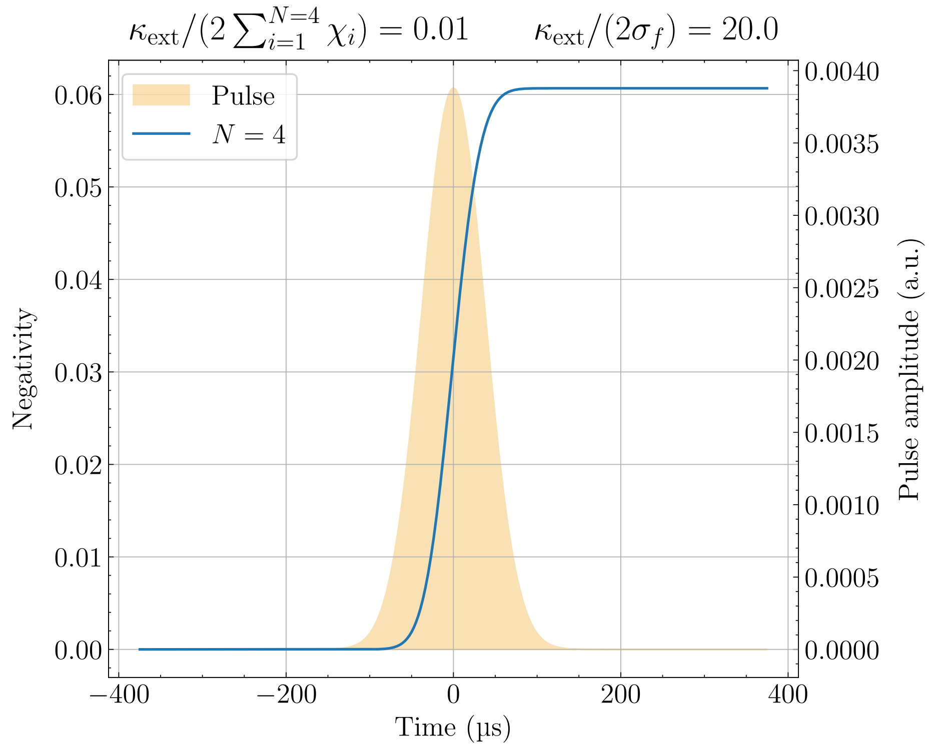
Extending to a system of independent N qubits without entanglement, in which the total phase is equally distributed $\phi_i = \phi/N$

$$P(k) = \binom{N}{k} P(|g\rangle)^k P(|e\rangle)^{N-k}$$

k is the number of qubits in the $|g\rangle$ in a system of N qubits.

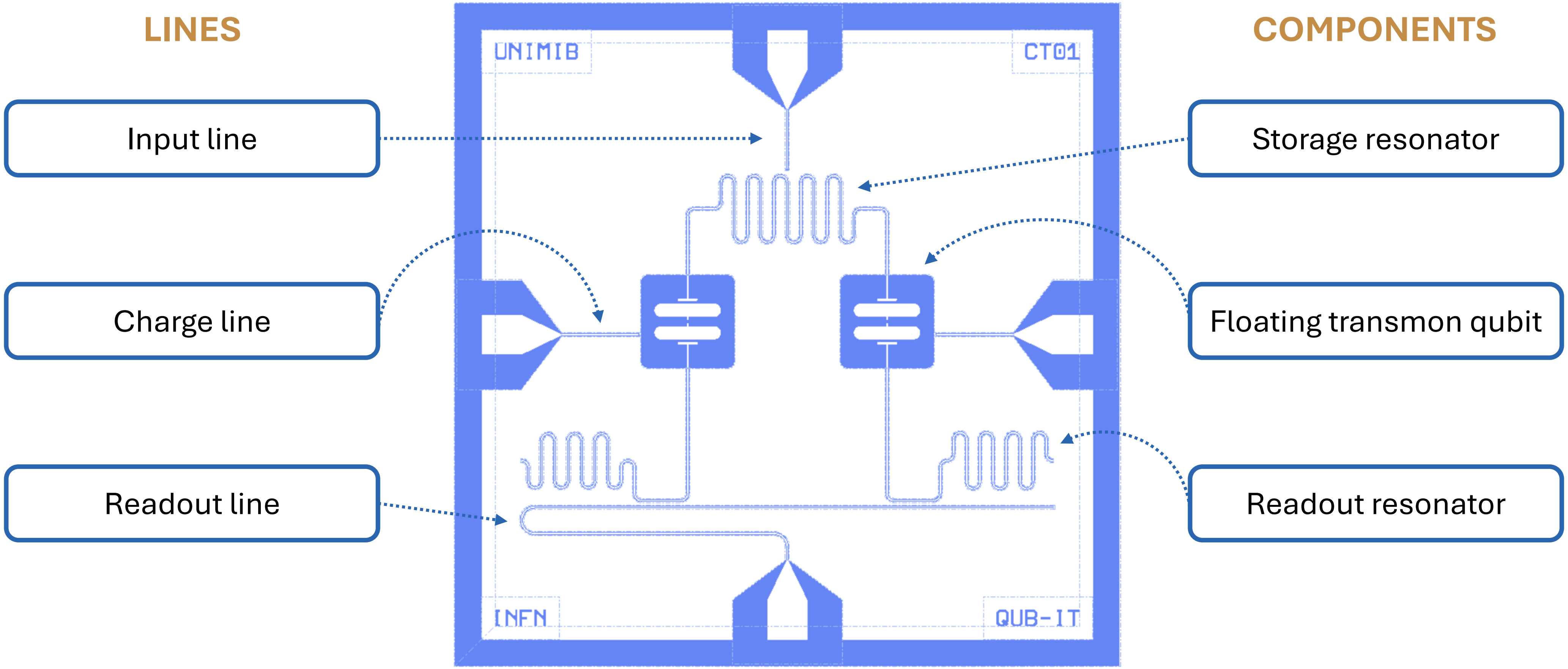
LOW-ENTANGLEMENT (?)





$\phi = 2\pi$ ← Total phase shift → $\phi = \pi$

CONCEPTUAL PLANAR CHIP DESIGN



PRELIMINARY CONCLUSIONS

- The $N = 2$ qubit model works correctly and does not introduce any entanglement effects;
- For $N \geq 3$ qubits, some low entanglement begins to emerge which:
  - Requires a more refined theoretical model for a complete description of the system's dynamics;
  - Suggests considering the use of entangled initial states, such as GHZ states, with a proper detection protocol;

$$|\mathrm{GHZ}\rangle = \frac{|g\rangle^{\otimes N} + |e\rangle^{\otimes N}}{\sqrt{2}}$$

- Further analysis is needed for cases with different χ values, particularly when dealing with non-uniform phase distributions.

NEXT-STEPS

In progress	Refine the theoretical model through the input-output theory;
Done	Design of 3D version with 2 qubits;
Planning	Design of 2D version with 2 qubits;
Not started	Fabrication of the devices;
Not started	Characterization of the devices;
Not started	Axion and dark photon measurement campaigns.

COLLABORATION

UNIMIB/INFN-MIB group

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UNIFI/INFN-FI group

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