# Dark matter search with qubits

Hajime Fukuda (U. Tokyo)

In collaboration with

Chen, Inada, Moroi, Nitta, Sichanugrist

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# Outline

- Introduction
  - I'll review the physics of "transmon" qubits
- DM detection with one qubit
  - arXiv:2212.03884
  - We propose to use a transmon qubit as a dark matter detector
  - Our target is dark photon DM, $m \sim \mathrm{GHz} \sim \mu\mathrm{eV}$
- DM detection with quantum circuits
  - arXiv:2311.10413
  - We construct a quantum circuit to enhance the DM signal. With $N$ qubits, the signal is proportional to $N^2$

# Introduction

# Quantum Computation and Qubits

- The fundamental piece of the quantum computation is qubit, a two-level quantum system, $|0\rangle$ and $|1\rangle$
- By the recent development of the quantum technology, many-qubit systems gradually become available
  - Currently, the system is noisy, but hopefully future development will make more cleaner quantum systems available.

# Types of Qubits

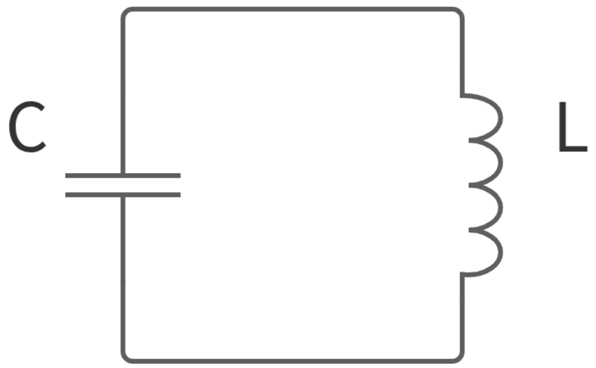
- Currently, there are several types of qubits available
  - Single photon
  - NMR
  - Ion trap
  - **Transmon qubit (superconducting qubit)**
  - …
- We focus on the transmon qubit

# An example: Harmonic Oscillator

- What is the *easiest* quantum system? It's a harmonic oscillator.
- Suppose to use a harmonic oscillator as a qubit:

$$|0\rangle = |0\rangle, |1\rangle = a^{\dagger}|0\rangle$$

- The simple example of a harmonic oscillator → LC circuit

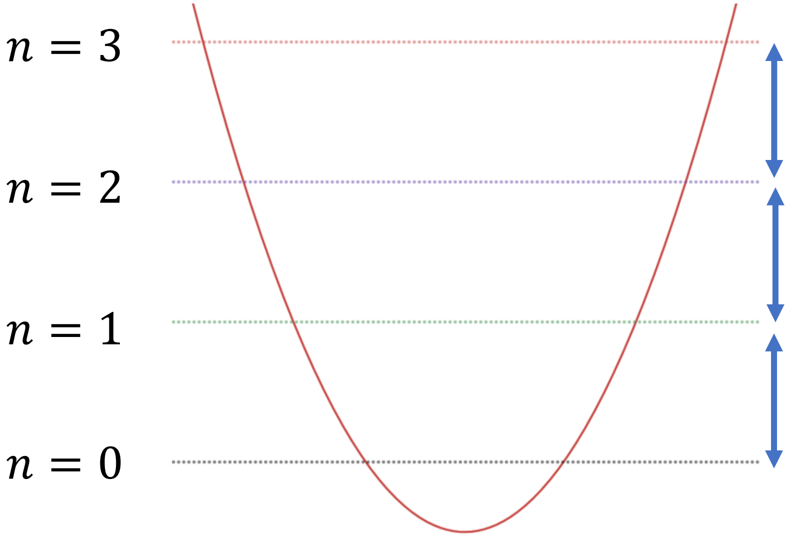



$$H = \frac{1}{2}CV^2 + \frac{1}{2}LI^2 = \frac{1}{2}CL^2\dot{I}^2 + \frac{1}{2}\,LI^2$$

We may indeed quantize the system, obtaining a quantum harmonic oscillator

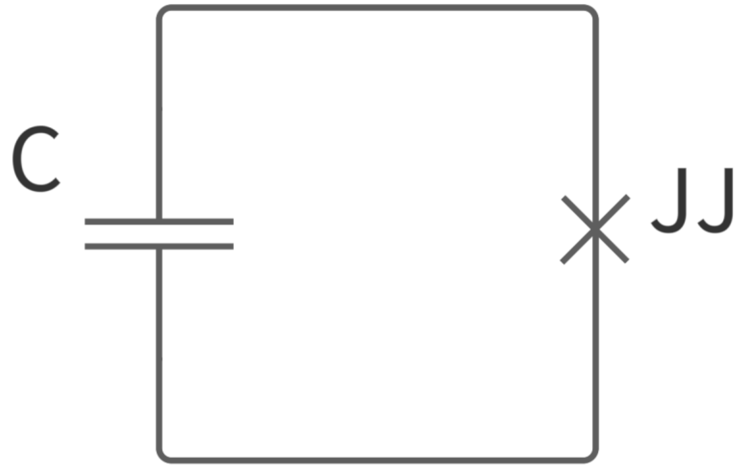
# Harmonic Oscillator cannot be Qubit

- It is NOT a two-level system!
  - Any $|n\rangle \equiv \frac{1}{\sqrt{n!}}\left(a^\dagger\right)^n|0\rangle$ is the eigenstate of the Hamiltonian
  - We cannot isolate $|g\rangle$ and $|e\rangle$




All energy differences are the same and we cannot excite only $|1\rangle$ from $|0\rangle$; then $|2\rangle$ would be excited from $|1\rangle$

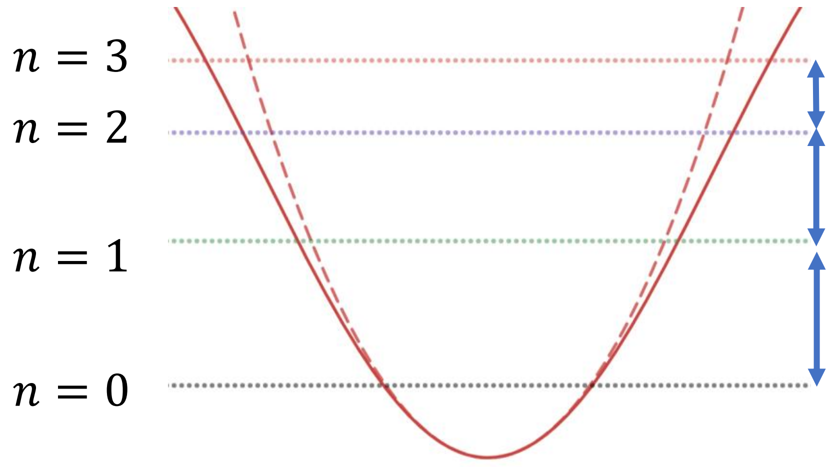
# Transmon Qubit




- We introduce a “non-linearity”
  - Replacing $L$ with a Josephson junction

$$H = \frac{1}{2}CV^2 - J_0 \cos\theta$$
$$= \frac{1}{8e^2}C\dot{\theta}^2 + J_0\left[\frac{1}{2}\theta^2 - \mathcal{O}(\theta^4)\right] + \text{const.}$$

We can replace JJ with a SQUID to effectively tune $J_0$




All energy differences are different;
we can use $|1\rangle$ and $|0\rangle$ as a two-level system

# Dark matter detection with one qubit

# Dark Photon Dark Matter

- In this study, we assume the dark photon dark matter with a kinetic mixing with the SM photon

$$\mathcal{L} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2} m_X^2 X^2 - \frac{\epsilon}{2} X_{\mu\nu} F^{\mu\nu} + \mathcal{L}_{\mathrm{SM}}$$

- After solving the kinetic mixing, $X_\mu$ couples with the SM current

$$\Delta\mathcal{L} = e\left(A_\mu + \epsilon X_\mu\right) J_{\mathrm{SM}}^{\mu}$$

- The DM background looks like “$X$ electric field”

$$\left\langle \vec{X} \right\rangle \simeq \bar{X} \vec{n}(t) \cos m_X t \, , \rho_{DM} \simeq \frac{1}{2} m_X^2 \bar{X}^2, E_X \sim \dot{X}$$

# Interaction b/w Qubit and Dark Photon

- The question is, “how does an electric field excite the transmon”?

$$
\begin{aligned}
\Delta H &= CVEd \\
&\simeq CVd\epsilon m_X \bar{X}(\vec{n}_X \cdot \vec{e}) \sin m_X t \\
&\equiv 2\eta\, \sigma_X \sin m_X t
\end{aligned}
$$

- Qubits are in a cavity and the dark photon electric field “shakes” the cavity wall. It induces additional electric field.

# Evolution of Qubit

- Roughly, the Hamiltonian of the qubit is

$$H = H_0 + \Delta H,$$
$$H_0 = \frac{1}{2}\omega\sigma_z,$$
$$\Delta H = 2\eta\sigma_X \sin m_X t$$

- We move to the interaction picture;

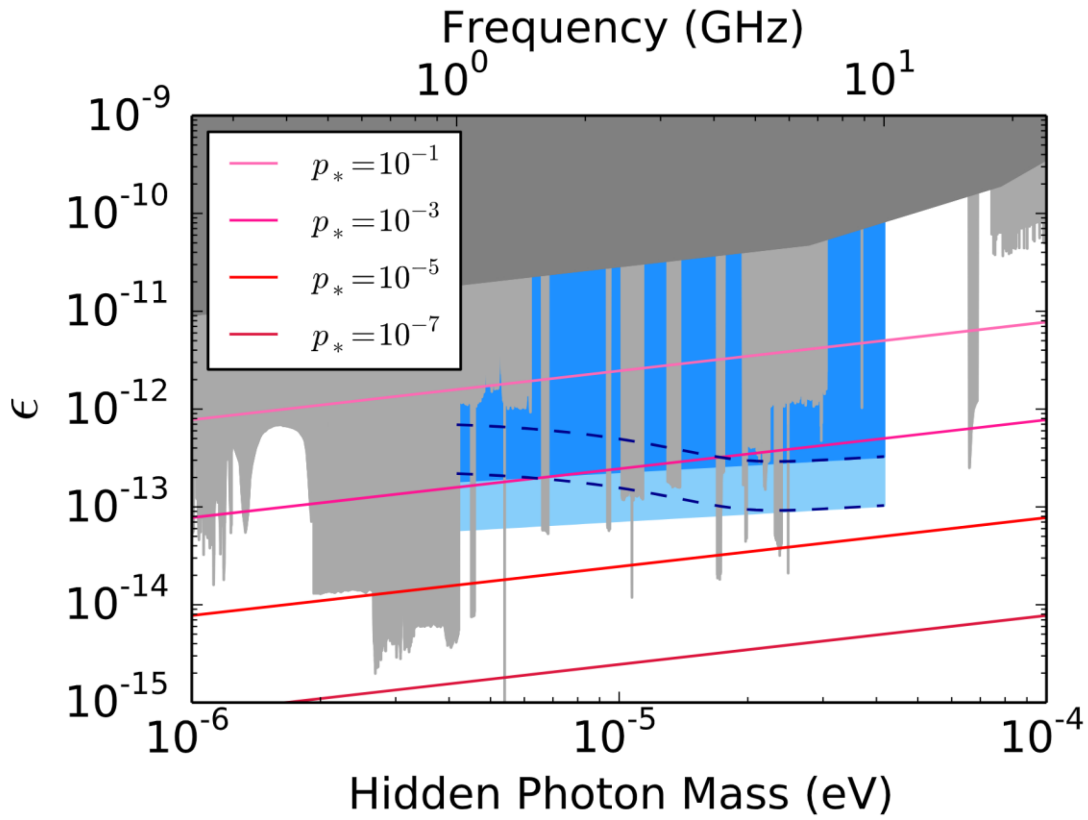
$$H_I = e_0^{iHt}\Delta H e_0^{-iHt} \simeq \eta\sigma_X \cos(m_X - \omega)t \sim \eta\sigma_X$$

- With $\sigma_X$, a qubit oscillates $|0\rangle$ and $|1\rangle$. We prepare $|0\rangle$ and measure $|1\rangle$ to see if the dark photon exists.

$$|\psi(t)\rangle \simeq |0\rangle + \eta t|1\rangle, p = |\langle 1|\psi\rangle|^2 = \eta^2 t^2$$

In reality, the DM phase is unknown;
$$\Delta H \sim 2\eta\sigma_X \sin(m_X t + \alpha)$$
Then,
$$\sigma_X \to \sigma_X \cos\alpha + \sigma_Y \sin\alpha$$
in $H_I$

# Expectation for 1-year measurement




- We assume
  - Coherent time $2\pi Q/\omega$, $Q \sim 10^6$
  - 0.1% readout error
  - "thermal noise" for 1 or 30 mK
- Blue: 1 qubit
- Light-blue: 100 qubits
- Tunability of the frequency is one of the greatest advantages of the qubit

HF Chen, Inada, Moroi, Nitta, Sichanugrist arXiv:2212.03884

# DM detection with quantum circuits

# Quantum Enhancement

- In the previous estimation, we assume to use up to 100 qubits independently.
- Is it possible to enhance the signal quantum-mechanically?
  - Yes, if we prepare an entangled initial state

$$H_I = \eta\sigma_X \Rightarrow H_I\,|\pm\rangle = \pm\eta|\pm\rangle$$
$$\Rightarrow H_I^{\otimes N}|\pm\rangle^{\otimes N} = \pm N\eta|\pm\rangle^{\otimes N}$$

  - Therefore,

$$e^{i(\sum H_{Ii})t}\left(|+\rangle^{\otimes N} + |-\rangle^{\otimes N}\right) = e^{iN\eta t}|+\rangle^{\otimes N} + e^{-iN\eta t}|-\rangle^{\otimes N}$$
$$\simeq \left(|+\rangle^{\otimes N} + |-\rangle^{\otimes N}\right)$$
$$+2iN\eta t\left(|+\rangle^{\otimes N} - |-\rangle^{\otimes N}\right)$$

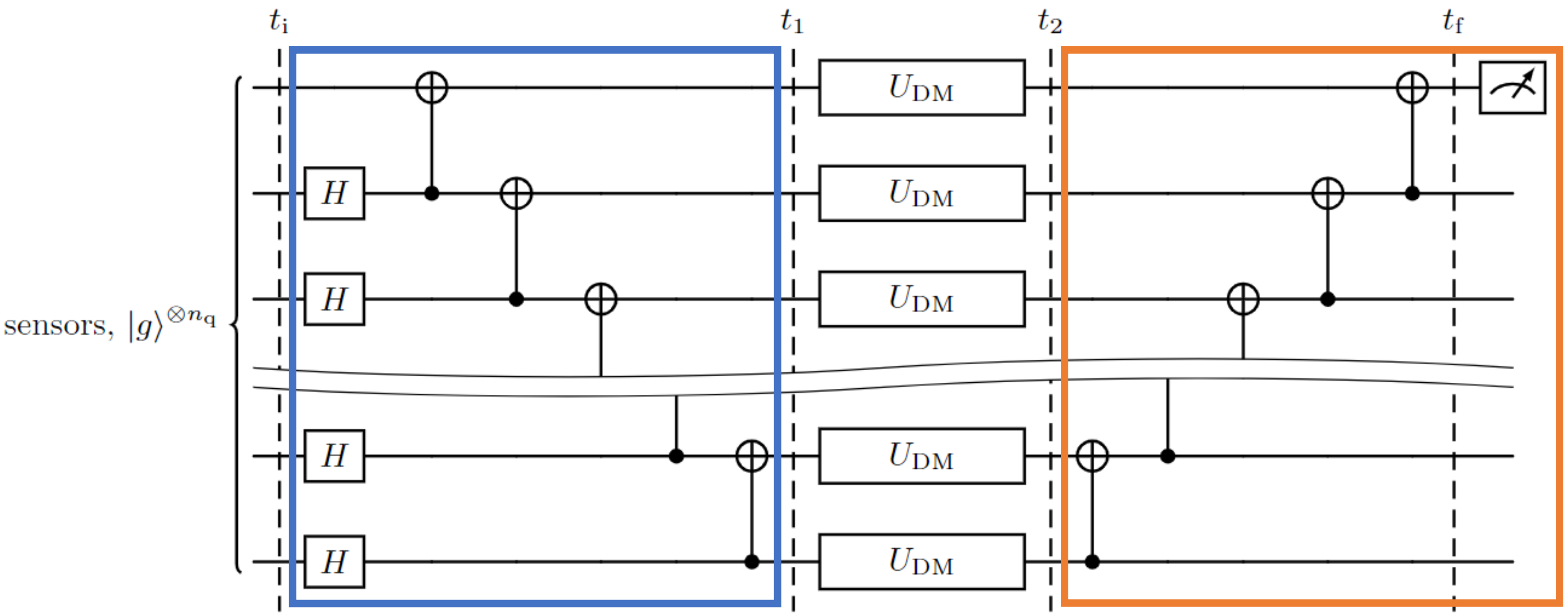
Compared to one qubit:

$$p \sim \eta^2 t^2 \Rightarrow Np \sim O(N)$$

$$\Rightarrow p \sim N^2\eta^2 t^2 \sim \mathcal{O}\left(N^2\right)\ !!$$

# Quantum Circuit

- We need to prepare $|+\rangle^{\otimes N} + |-\rangle^{\otimes N}$ (GHZ state) and measure it by $|+\rangle^{\otimes N} - |-\rangle^{\otimes N}$. This can be done by

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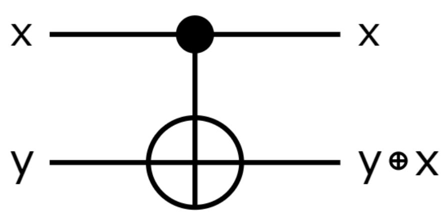


| input | | output | |
|---|---|---|---|
| x | y | x | y+x |
| $\|0\rangle$ | $\|0\rangle$ | $\|0\rangle$ | $\|0\rangle$ |
| $\|0\rangle$ | $\|1\rangle$ | $\|0\rangle$ | $\|1\rangle$ |
| $\|1\rangle$ | $\|0\rangle$ | $\|1\rangle$ | $\|1\rangle$ |
| $\|1\rangle$ | $\|1\rangle$ | $\|1\rangle$ | $\|0\rangle$ |

From Wikipedia

# Noise of the System

- Actually, the use of GHZ state is a bit subtle due to the quantum noise

Huelga et al., 1997

  - Roughly speaking, the GHZ state is an entangled state with $N$ qubits and $N$ times more fragile to quantum noises
  - In terms of the coherent time or Q-value, it is $N$ times less
- The excitation probability is $p \sim \eta^2 N^2 \tau^2$. If $\tau \to \tau/N$, the sensitivity is the same as $N = 1$
- Several ways to evade this:
  - If the qubit coherent time is $> N$ times larger than the DM coherent time, $\tau = \tau_{DM}$ and constant in $N$
  - If the noise is some special type, we may evade this by QEC

# Summary

# Summary

- We proposed to use transmon qubits as a dark matter detector
- It could constrain unexplored regions of the dark photon dark matter parameter regions
- The use of entangled initial states may improve the sensitivity
  - The evaluation of quantum noises are non-trivial, but we can show even with large noises the entangled states may have an advantage