Detecting Hidden Photon Dark Matter via the Excitation of Qubits

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Ref: Chen, Fukuda, Inada, TM, Nitta, Sichanugrist, 2212.03884

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1. Introduction

Many evidences of dark matter (DM):

Rotation curve, CMB, Bullet clusters, $\cdots$

Many candidates of DM:

- WIMPs
- Oscillating bosons
- PBH
- $\cdots$

We hope to detect DM directly

$\Rightarrow$ Need a variety of detection methods to take care of various DM candidates

Let us consider a very light (and wave-like) DM

Axion (and ALPs), Hidden photon , $\cdots$

System with very small excitation energy is needed

- Microwave cavity
- Condensed-matter excitations
- $\cdots$

Our proposal:

DM detection with "quantum bit (qubit)"

Subject today: Hidden photon DM search using qubits

$\Rightarrow$ We can probe parameter region unexplored yet!

Outline:

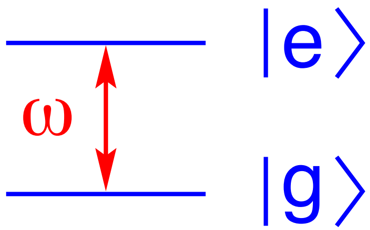
1. Introduction
2. Transmon Qubit
3. Qubit and Hidden Photon
4. Hidden Photon DM Search with Qubits
5. R&D Efforts
6. Summary

2. Transmon Qubit

Qubit:

- Two level system (consisting of $|g\rangle$ and $|e\rangle$)

$$|\Psi\rangle = \psi_g|g\rangle + \psi_e|e\rangle$$



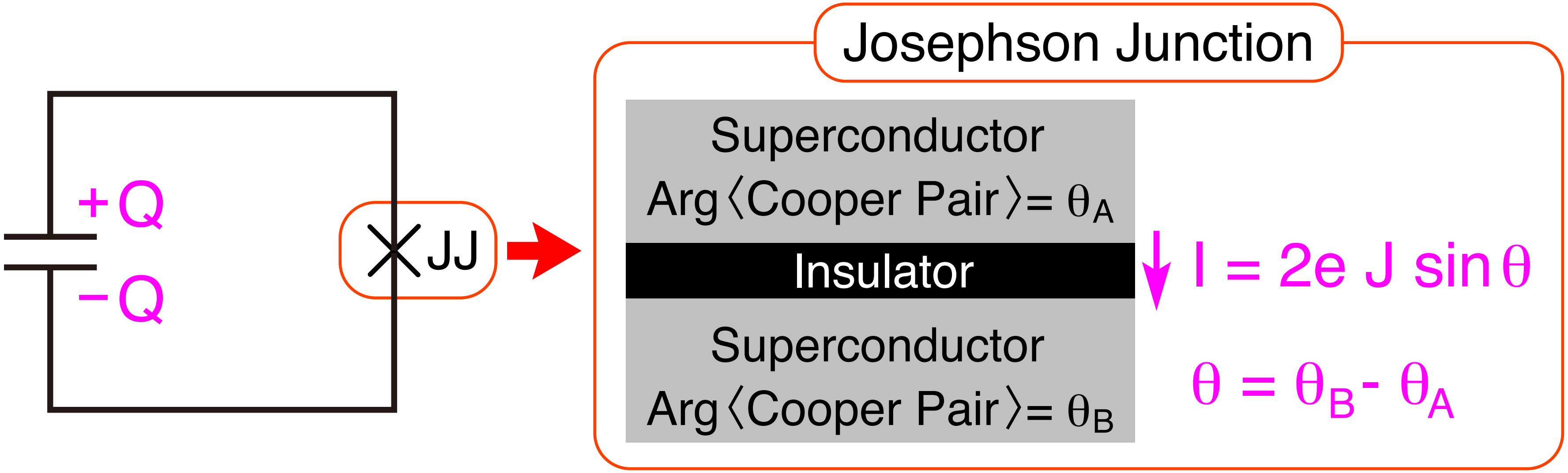
- Capacitor + Josephson junction (or SQUID) $\simeq$ Qubit
- $|g\rangle \leftrightarrow |e\rangle$ transition can be controlled by EM field

$\Rightarrow$ Application to quantum computers

$\Rightarrow$ Qubit as a quantum sensor

Qubit using Josephson junction (JJ)

- JJ: Two superconductors sandwiching an insulator



- $E_{\mathrm{JJ}} = -J\cos\theta$

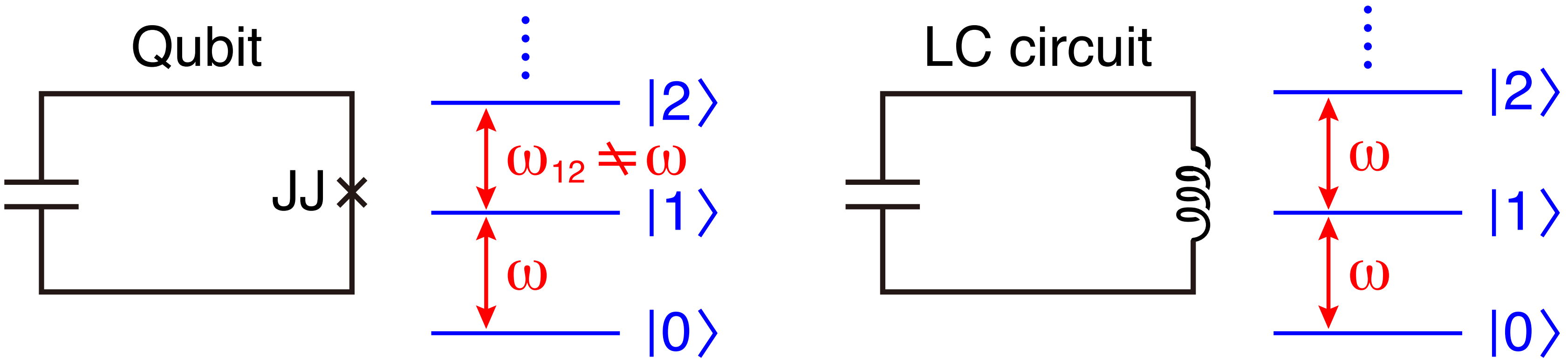
- $n = \dfrac{Q}{2e}$ is the conjugate momentum of θ $\Leftrightarrow$ $Q \simeq \dfrac{C}{2e}\dot{\theta}$

$\Rightarrow [\theta, n] = i$

Hamiltonian

$$H_0 = \frac{1}{2C}Q^2 - J\cos\theta = \frac{1}{2Z}n^2 - J\cos\theta$$

$$Z \equiv (2e)^{-2}C$$



$\Rightarrow$ Energy levels are unequally spaced

$\Rightarrow$ $|0\rangle$ and $|1\rangle$ can be used as $|g\rangle$ and $|e\rangle$

Transmon qubit: $CJ \gg (2e)^2 \quad \Rightarrow \quad \langle \theta^2 \rangle \ll 1$

[Koch et al. ('07); see also Roth, Ma & Chew (2106.11352)]

$$H_0 = \frac{1}{2Z} n^2 + \frac{1}{2} J \theta^2 + O(\theta^4)$$

$\Rightarrow$ Harmonic oscillator + small anharmonicity

We introduce annihilation and creation operators

$$\hat{a} \equiv \frac{1}{\sqrt{2\omega Z}} (n - i\omega Z \theta)$$

$$\hat{a}^\dagger \equiv \frac{1}{\sqrt{2\omega Z}} (n + i\omega Z \theta)$$

$\Rightarrow [\hat{a}, \hat{a}^\dagger] = 1$

Effective Hamiltonian (neglecting higher excited states)

$$H_0 \simeq \omega|e\rangle\langle e|$$

$$H_0|g\rangle = 0$$

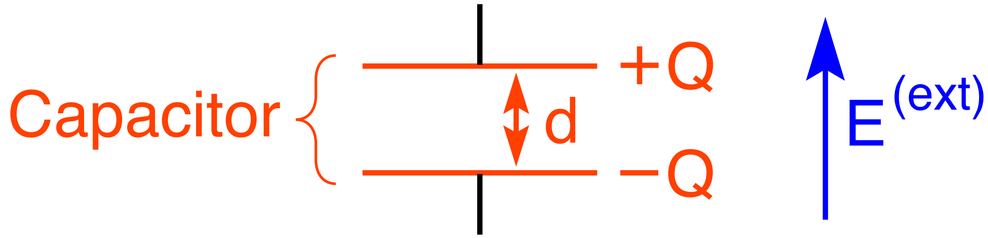
In the transmon limit:

- $|e\rangle \simeq \hat{a}^\dagger|g\rangle$
- $Q = 2en = \sqrt{\frac{C\omega}{2}}\left(\hat{a} + \hat{a}^\dagger\right)$

$$\Rightarrow\ Q \simeq \sqrt{\frac{C\omega}{2}}\left(\,|g\rangle\langle e| + |e\rangle\langle g|\,\right)$$

3. Qubit and Hidden Photon

Effect of weak external electric field



"Interaction term" in the Hamiltonian

$$H_{\rm int} = QdE^{\rm (ext)} = \sqrt{\frac{C\omega}{2}} dE^{\rm (ext)} \left(\hat{a} + \hat{a}^\dagger\right)$$

$$\Rightarrow \; H_{\rm int} \simeq \sqrt{\frac{C\omega}{2}} dE^{\rm (ext)} \Big(|g\rangle\langle e| + |e\rangle\langle g| \Big)$$

$|g\rangle \leftrightarrow |e\rangle$ transition occurs by the EM field

$\Leftrightarrow$ DM field may generate (effective) EM field

Case of hidden photon X_μ (in mass-eigenstate basis)

$$\mathcal{L} \ni -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu$$

$$+e\,\bar{\psi}_e\gamma^\mu\psi_e\,(A_\mu^{(\mathrm{EM})} + \epsilon X_\mu) + \cdots$$

Oscillating hidden photon can play the role of DM

$$\vec{X} \simeq \bar{X}\vec{n}_X \cos m_X t \quad \text{with } \rho_{\mathrm{DM}} = \frac{1}{2}m_X^2 \bar{X}^2$$

Hidden photon DM induces effective electric field

$$\vec{E}^{(X)} = -\epsilon\dot{\vec{X}} = \bar{E}^{(X)}\vec{n}_X \sin m_X t$$

$$\bar{E}^{(X)} = \epsilon m_X \bar{X} = \epsilon\sqrt{\rho_{\mathrm{DM}}}$$

Effective Hamiltonian

$$H = \omega|e\rangle\langle e| + 2\eta \sin m_X t \Big(|e\rangle\langle g| + |g\rangle\langle e| \Big)$$

$$\eta \simeq \frac{1}{2\sqrt{2}} d\bar{E}^{(X)}\sqrt{C\omega} = \frac{1}{2}\epsilon d\sqrt{C\omega\rho_{\rm DM}}$$

Evolution of the qubit

$$i\frac{d}{dt}|\Psi(t)\rangle = H|\Psi(t)\rangle$$

$$|\Psi(t)\rangle \equiv \psi_g(t)|g\rangle + e^{-i\omega t}\,\psi_e(t)|e\rangle$$

Resonance limit: $\omega = m_X$

$$i\frac{d}{dt}\begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix} \simeq \begin{pmatrix} 0 & -i\eta \\ i\eta & 0 \end{pmatrix}\begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix} + (\text{irrelevant})$$

For $t \gtrsim \tau$, coherence is lost

Coherence time: $\tau = \dfrac{2\pi Q}{\omega}$ (with Q = quality factor)

Decoherence of DM due to its velocity dispersion

$$Q_{\rm DM} = \frac{\omega}{\delta\omega} \sim v_{\rm DM}^{-2} \sim 10^6$$

Decoherence of qubit

$$Q_{\rm qubit} \sim 10^{(5-6)}$$

For our numerical analysis, we take

$$Q = 10^6$$

Solution with $|\Psi(0)\rangle = |g\rangle$

$$\psi_g(t) = \cos \eta t$$

$$\psi_e(t) = \sin \eta t \simeq \eta t \quad \textbf{(for } t \ll \eta^{-1}\textbf{)}$$

Excitation probability: $p_* \equiv p_{g \to e}(\tau) = |\psi_e(\tau)|^2$

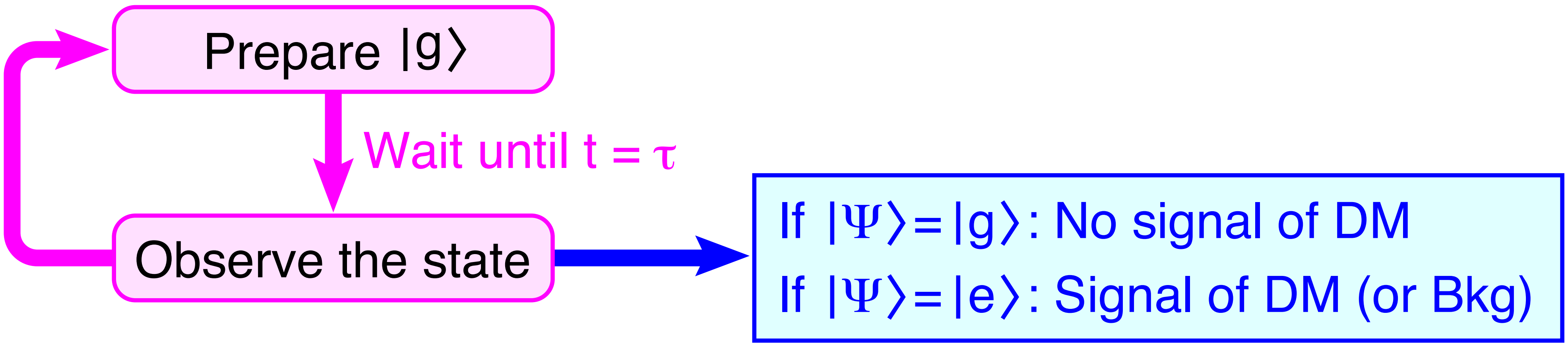
$$p_* \simeq 0.0012 \times \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{f}{1\ \mathrm{GHz}}\right) \times \left(\frac{\tau}{100\ \mu\mathrm{s}}\right)^2 \left(\frac{C}{0.1\ \mathrm{pF}}\right) \left(\frac{d}{10\ \mu\mathrm{m}}\right)^2$$

$$f \simeq 0.24\ \mathrm{GHz} \times \left(\frac{m_X}{1\ \mu\mathrm{eV}}\right)$$

4. Hidden Photon DM Search with Qubits

Search strategy

- For each ω, repeat the following process N_{rep} times



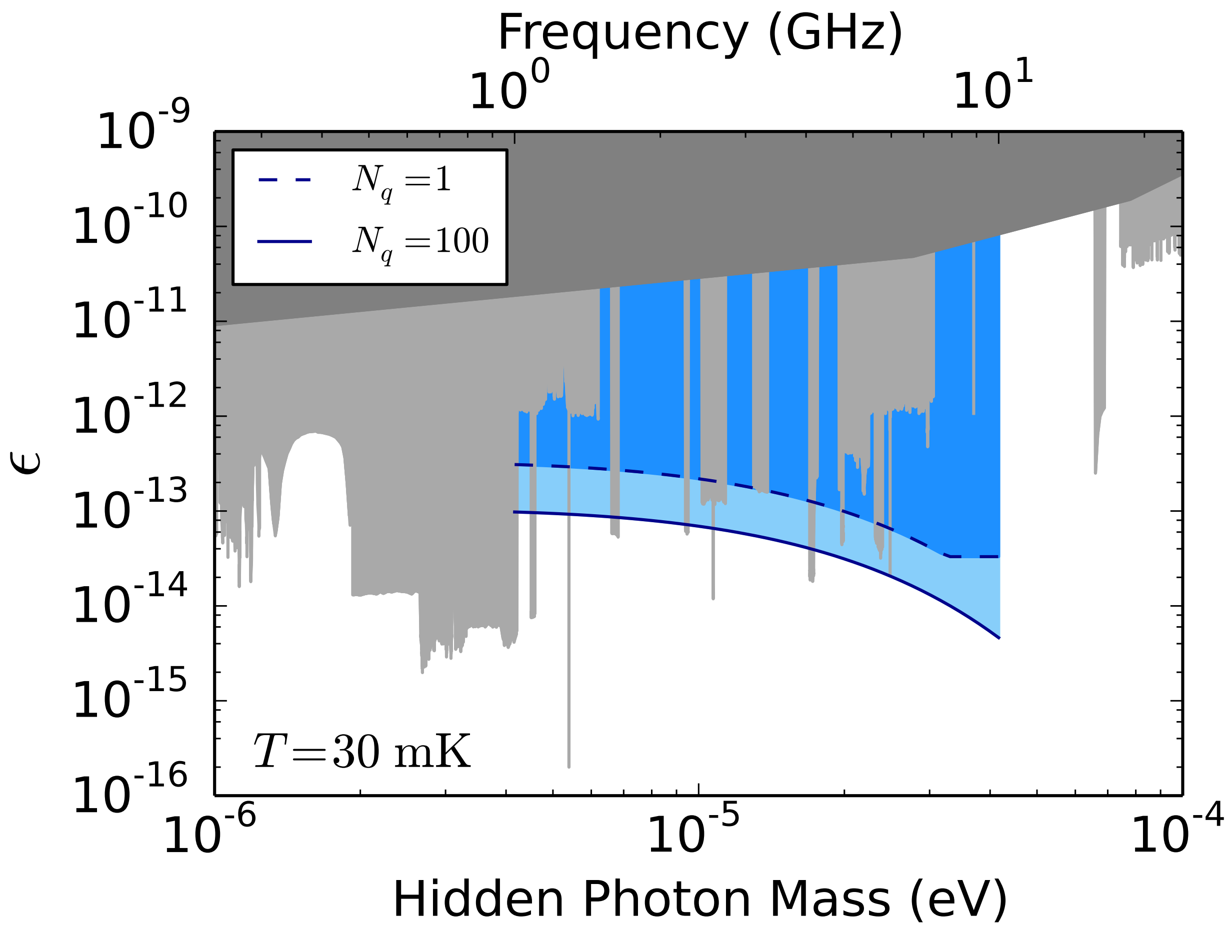
- Number of signals: $N_{\mathrm{sig}} = p_* N_{\mathrm{try}}$

  $N_{\mathrm{try}} = N_{\mathrm{qubit}} N_{\mathrm{rep}}$

- Frequency scan with the step width of $\Delta\omega = \dfrac{\omega}{Q}$

Detectability with 1 year frequency scan: $T = 30$ mK

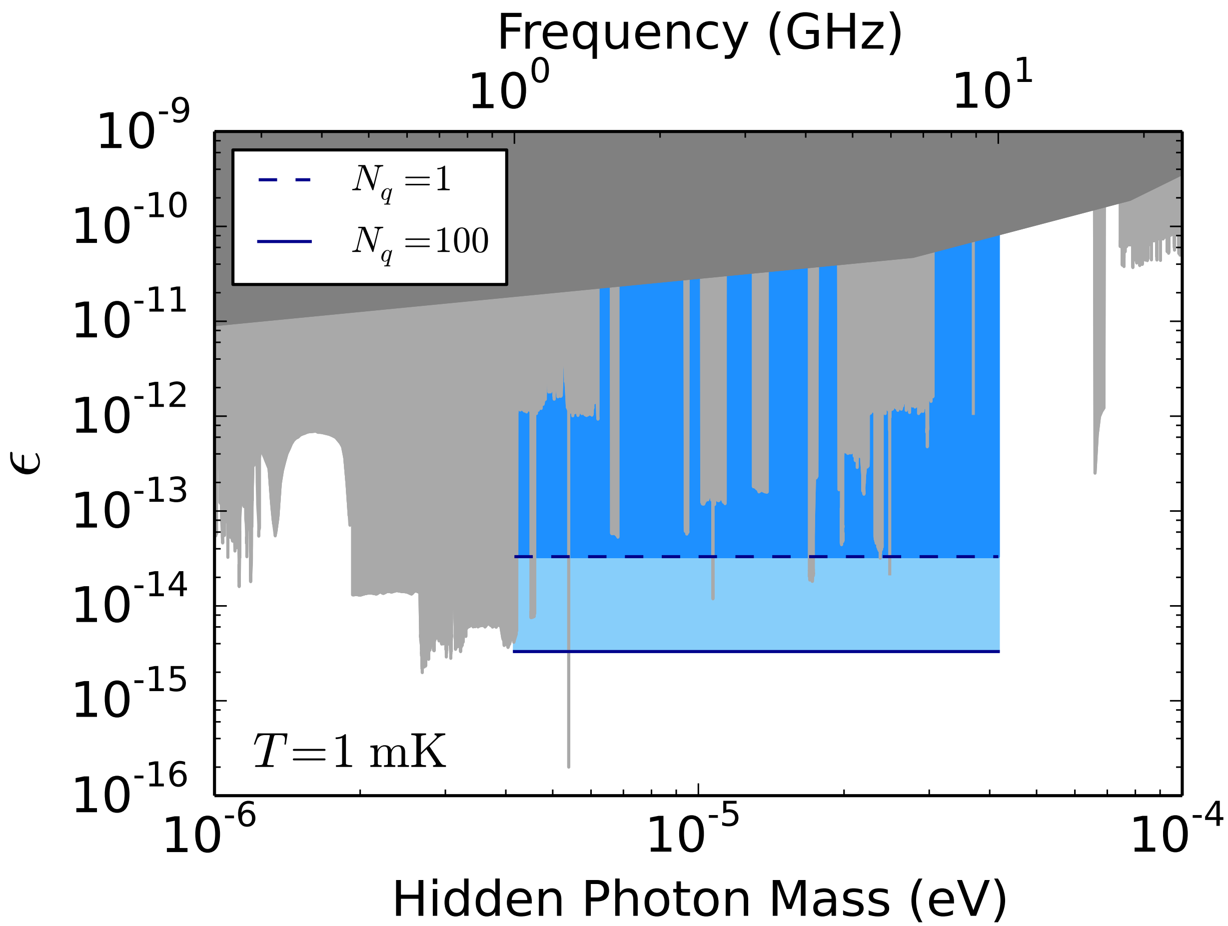
Background: thermal excitation only



- $d = 100\ \mu$m
- $C = 0.5$ pF
- $Q = 10^6$

Detectability with 1 year frequency scan: $T = 1$ mK

Background: thermal excitation only

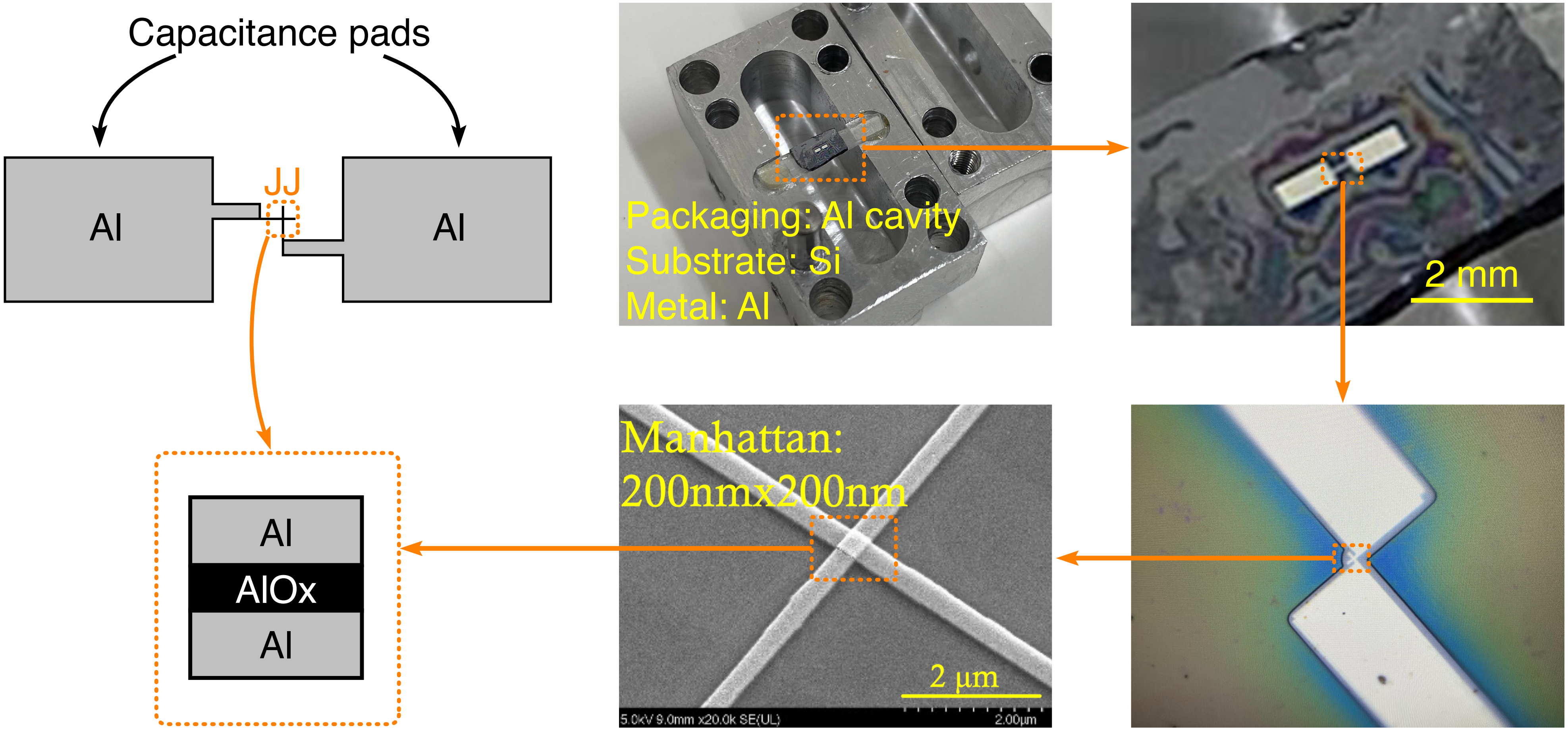


- $d = 100\ \mu\text{m}$
- $C = 0.5$ pF
- $Q = 10^6$

5. R&D Efforts at ICEPP[†]

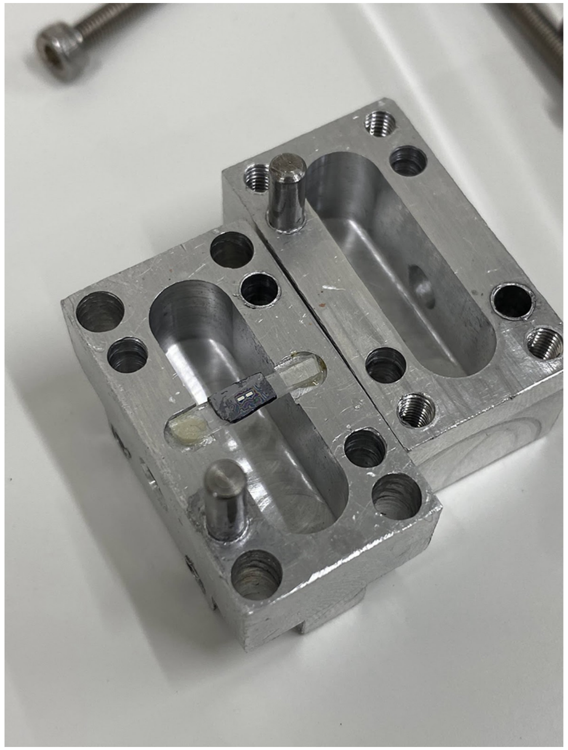
[†]ICEPP: International Center for Elementary Particle Physics, U. Tokyo

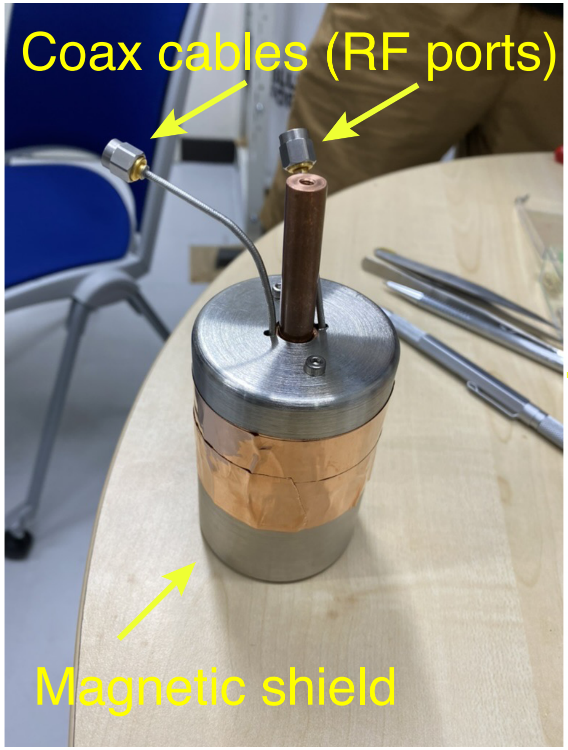
ICEPP colleagues already developed qubits (prototypes)

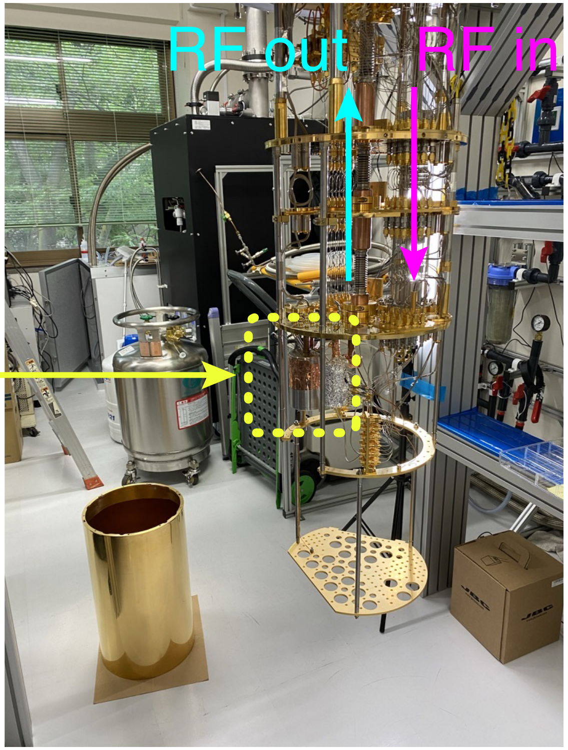


$\Rightarrow$ Rabi oscillation observed

A dilution refrigerator is available







Encapsulate

Attach to the coldest part of the fridge (~ 10 mK)

R&D for the actual DM search experiment is underway

- Development of the qubit is in progress
  - There already exist prototypes of qubits
  - A longer coherence time is desirable (currently, $\sim 10\ \mu$sec)
- A dilution refrigerator is available
- Several issues still remain, like cavity effects, backgrounds, cases of other DM candidates, etc.
- Hopefully, our first result will come out in the near future

6. Summary

DM search using qubit is an interesting possibility

- It can probe parameter regions unexplored yet (in particular, for the case of hidden photon)

- R&D efforts are underway, so stay tuned

Backup: Comments on Backgrounds

Thermal noise: qubits may be thermally excited

- Probability of thermal excitation: $e^{-\omega/T}$
- Number of background events $N_{\rm bkg} = e^{-\omega/T} N_{\rm try}$

Our (simple) criterion for DM detection

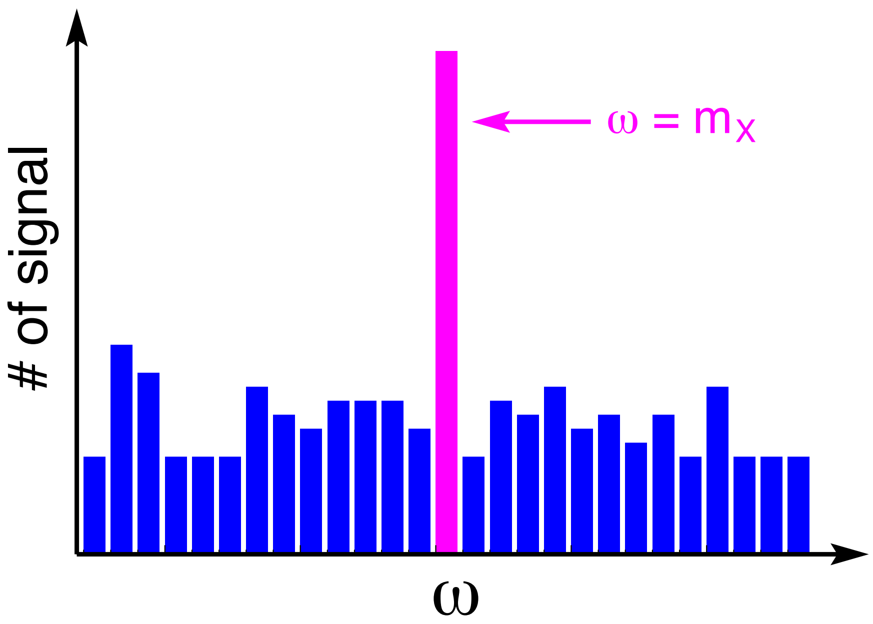
$$N_{\rm sig} > \max(3, 5\sqrt{N_{\rm bkg}})$$

Example: 1 year scan of $1 \leq f \leq 10$ GHz

- Scan time for each frequency: ~ 14 sec
- $N_{\rm rep} \sim O(10^4 - 10^5)$

Comment on the background (1)

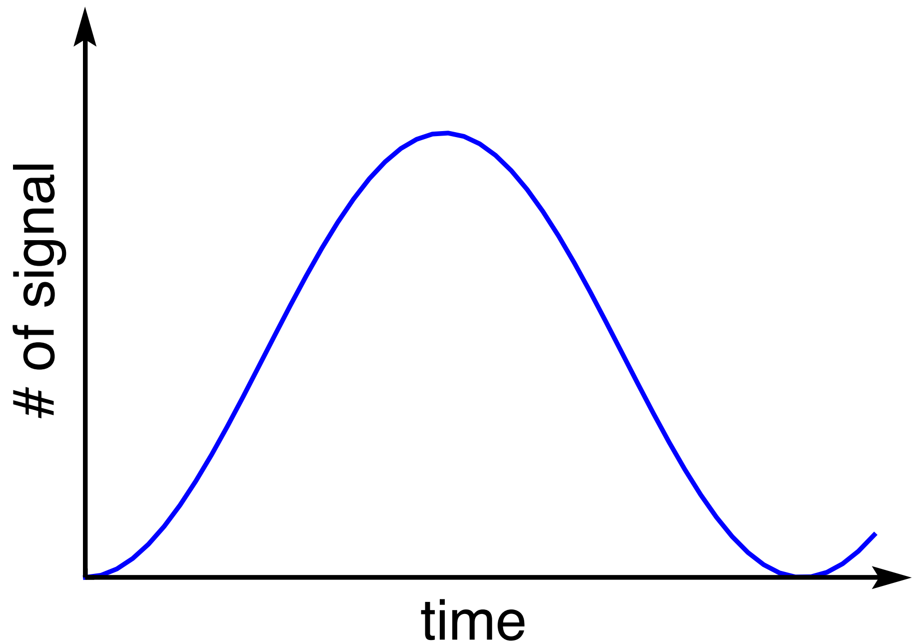
- Signal is peaked at a single frequency bin
- Bkg can be validated with the use of "sideband"



- Step width of the scan $\Delta\omega \sim \frac{\omega}{Q}$

Comment on the background (2)

- $p_{g\to e}(t) \simeq \sin^2 \eta t$
- Signal and Bkg may be distinguished by observing Rabi oscillation



Backup: Hidden Photon DM

Case of hidden photon X_μ

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

$F'_{\mu\nu}$: EM field (in gauge eigenstate)

Vector bosons in the mass eigenstates

$$A_\mu \simeq A'_\mu - \epsilon X_\mu \text{ and } X_\mu$$

Interaction with electron

$$\mathcal{L}_{\rm int} = e \bar{\psi}_e \gamma^\mu A'_\mu \psi_e = e \bar{\psi} \gamma^\mu \psi (A_\mu + \epsilon X_\mu)$$

Hidden photon as dark matter

$$\vec{X} \simeq \bar{X} \vec{n}_X \cos m_X t$$

Energy density of hidden photon DM

$$\rho_{\rm DM} = \frac{1}{2} \dot{\vec{X}}^2 + \frac{1}{2} m_X^2 \vec{X}^2 \simeq \frac{1}{2} m_X^2 \bar{X}^2$$

$$\Leftrightarrow \ \rho_{\rm DM} \sim 0.45 \ {\rm GeV/cm^3}$$

Effective electric field induced by the hidden photon

$$\vec{E}^{(X)} = -\epsilon \dot{\vec{X}} = \bar{E}^{(X)} \vec{n}_X \sin m_X t$$

$$\bar{E}^{(X)} = \epsilon m_X \bar{X} = \epsilon \sqrt{\rho_{\rm DM}}$$

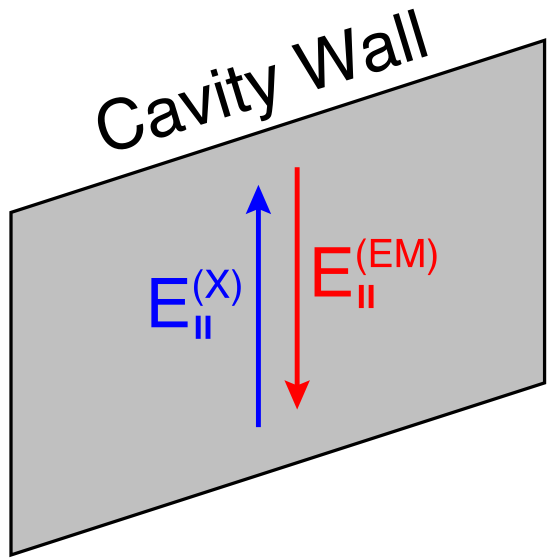
Backup: Cavity Effect

Qubits are usually set in a "microwave cavity"

$\Rightarrow$ Qubits are surrounded by metals

$\Rightarrow$ $\vec{E}_{\parallel}^{(\mathrm{eff})}$ should vanish at the cavity wall

"Effective" electric field: $\vec{E}^{(\mathrm{eff})} = \vec{E}^{(\mathrm{EM})} + \vec{E}^{(X)}$



$\Leftrightarrow$ $\vec{E}^{(\mathrm{eff})}$ induces the qubit excitation

Equations to be solved to obtain $\vec{E}^{(\mathrm{EM})}$ for given $\vec{E}^{(X)}$

- $\Box \vec{E}^{(\mathrm{EM})} = 0 \quad \text{and} \quad \vec{\nabla} \vec{E}^{(\mathrm{EM})} = 0$
- $[\vec{E}_{\parallel}^{(\mathrm{EM})} + \vec{E}_{\parallel}^{(X)}]_{\mathrm{wall}} = 0$

  $\vec{E}^{(X)}$ is unaffected by the cavity and is homogeneous

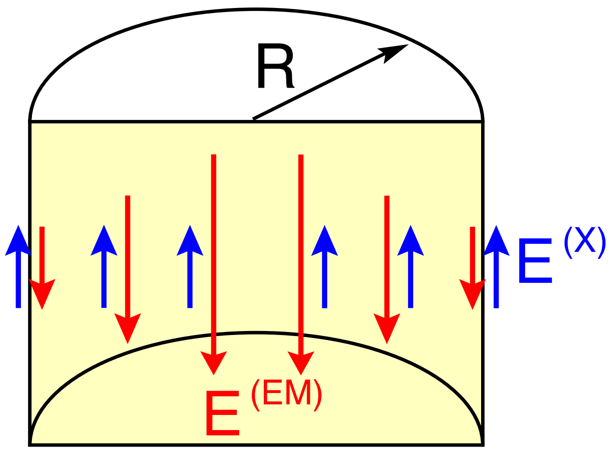
$\vec{E}^{(\mathrm{EM})}$ at the position of the qubit depends on:

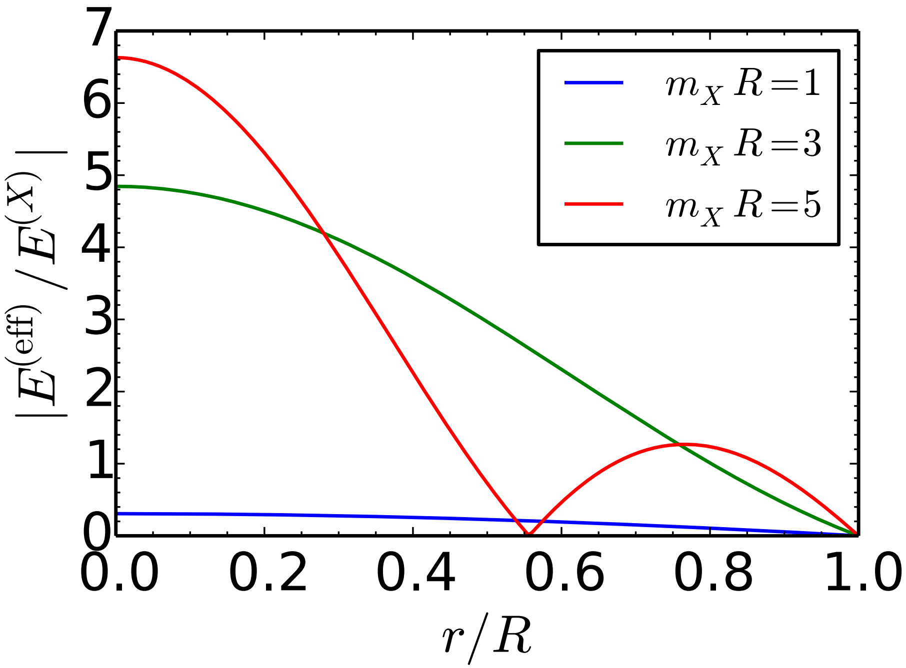
- Geometry of the cavity
- Location of the qubit

  $\Rightarrow$ No excitation, if the qubit is located on the wall

Cylinder-shaped cavity (with $\vec{E}^{(X)} //$ cylinder axis)

$$\vec{E}^{(\mathrm{EM})}(\vec{x},t) = -\frac{J_0(m_X r)}{J_0(m_X R)}\vec{E}^{(X)}(t)$$



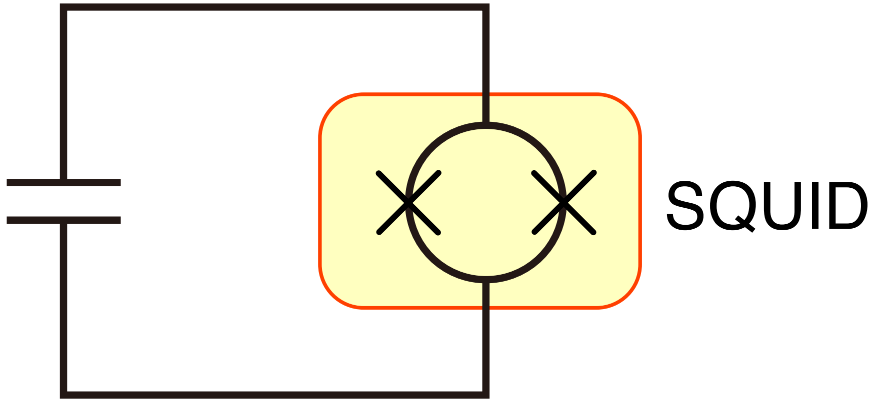


$\Rightarrow |\vec{E}^{(\mathrm{eff})}| \gtrsim |\vec{E}^{(X)}|$ is possible if $R \gtrsim m_X^{-1}$

Backup: Frequency Scan

Frequency scan

Frequency scan is possible with qubit consisting of SQUID and capacitor

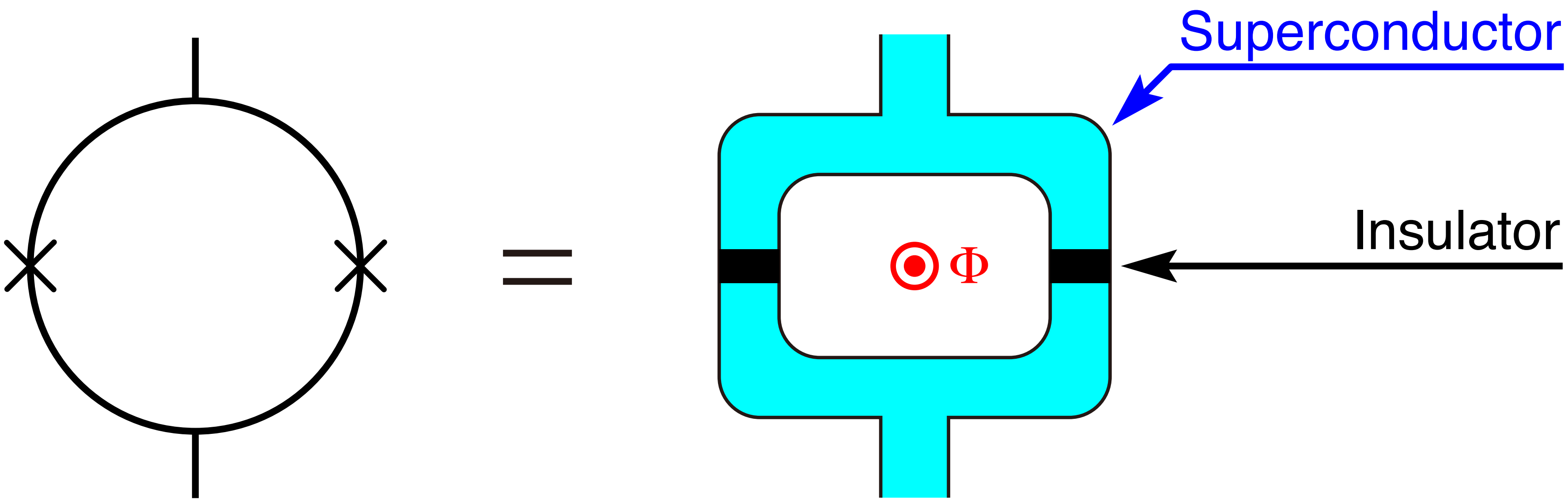


SQUID: superconducting quantum interference device

- Quantum device sensitive to magnetic flux

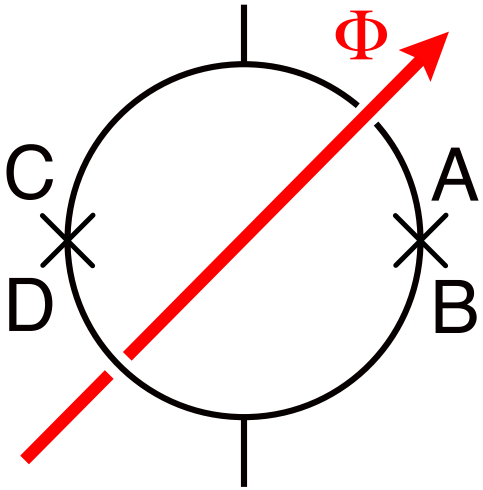
SQUID

- Loop-shaped superconductors separated by insulating layers



- We consider the case with external magnetic flux Φ going through the loop

Phases in the presence of magnetic flux



$$\theta_C - \theta_A = (2e)\int_{A\to C}\vec{A}(\vec{x})\,d\vec{x}$$

$$\theta_B - \theta_D = (2e)\int_{D\to B}\vec{A}(\vec{x})\,d\vec{x}$$

$$\theta_{BA} - \theta_{DC} = (2e)\oint \vec{A}(\vec{x})\,d\vec{x} = (2e)\,\Phi = \frac{2\pi}{\Phi_0}\Phi$$

$$\theta_{YX} = \theta_Y - \theta_X$$

$\Phi_0 = \dfrac{h}{2e}$: magnetic flux quantum

Define: $\theta \equiv (\theta_{BA} + \theta_{DC})/2$

$$H_{\rm SQUID} \simeq -J\left(\cos\theta_{BA} + \cos\theta_{DC}\right) = -2J\cos(e\Phi)\cos\theta$$

Based on the previous analysis with $J \to 2J\cos(e\Phi)$

$$\omega \simeq \sqrt{\frac{2J}{Z}\cos(e\Phi)}$$

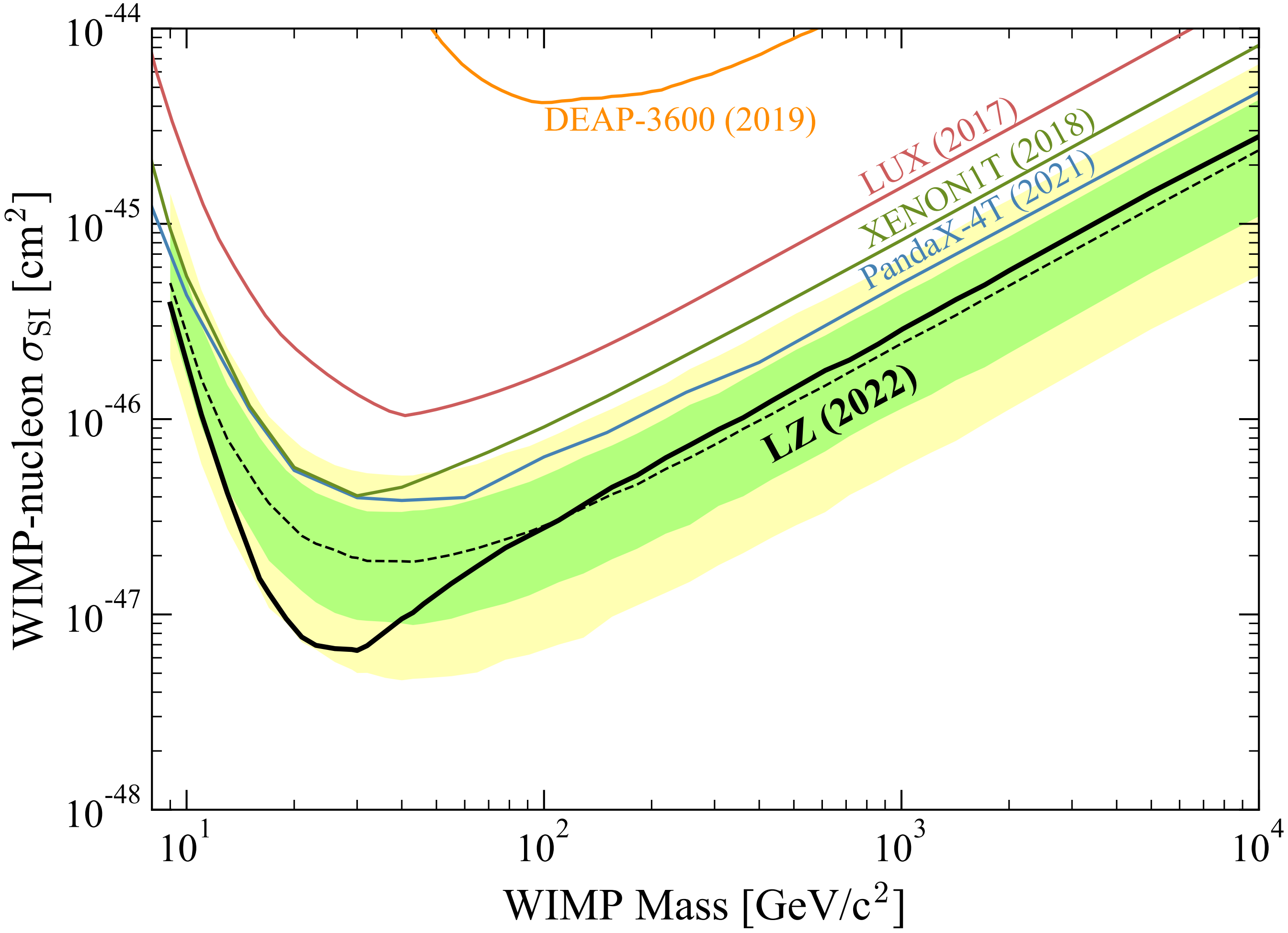
$$Z = (2e)^{-2}C$$

The excitation energy depends on Φ

$\Rightarrow$ Frequency scan is possible with varying the external magnetic field

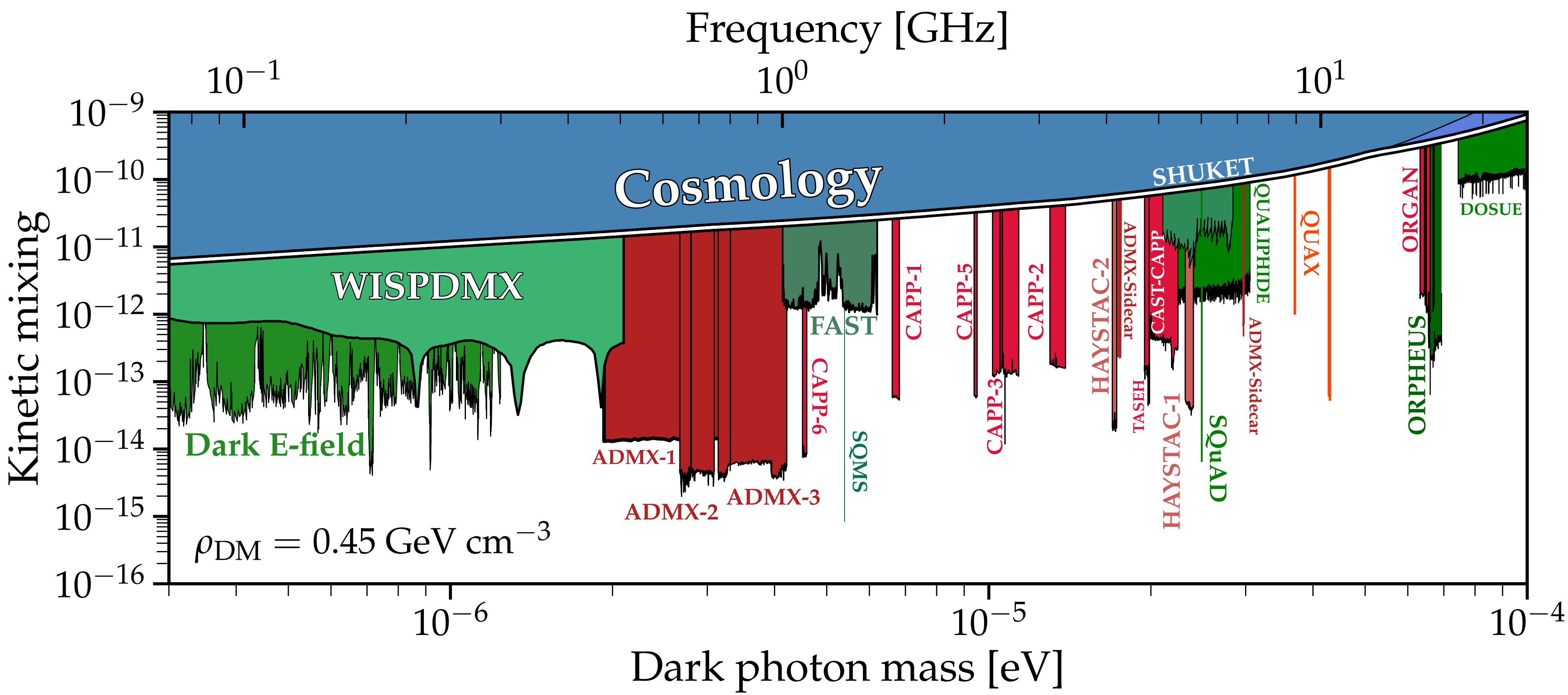
Backup: Misc

No direct evidence of WIMP DM



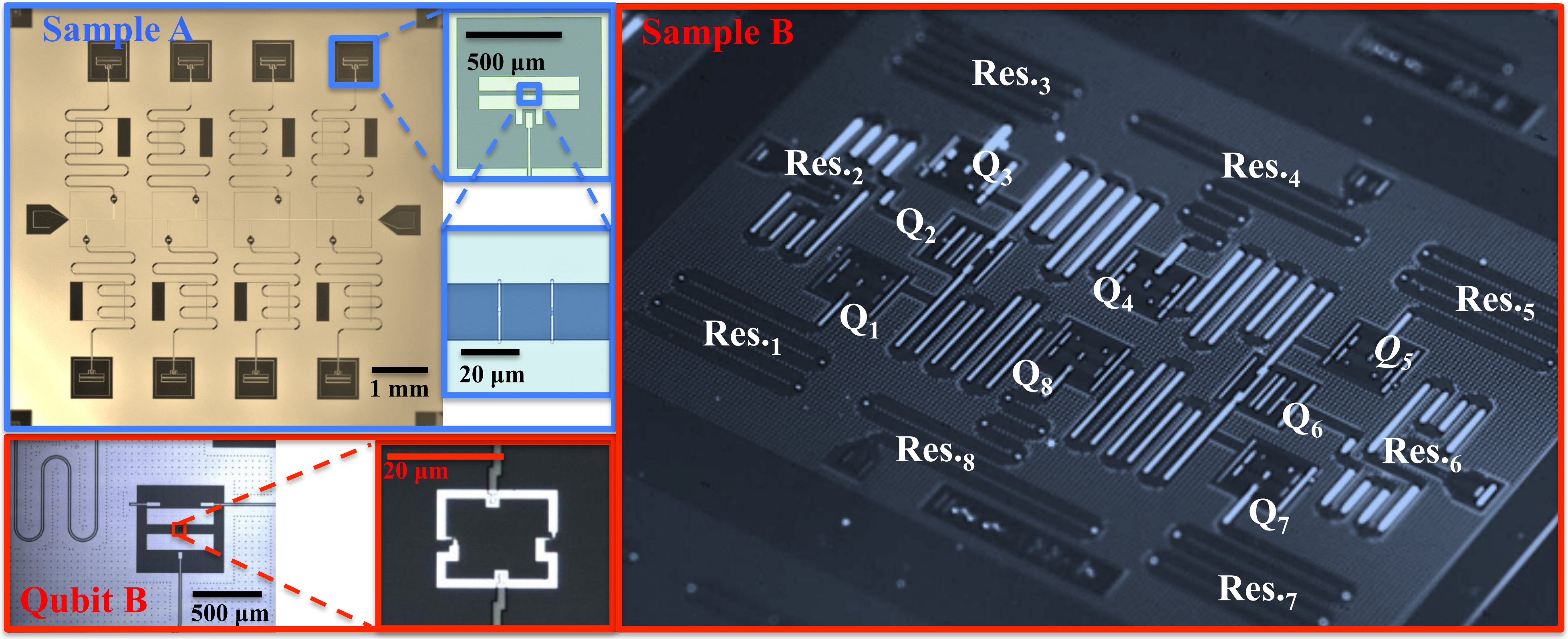
[LZ Collaboration ('22)]

Constraints on hidden photon DM



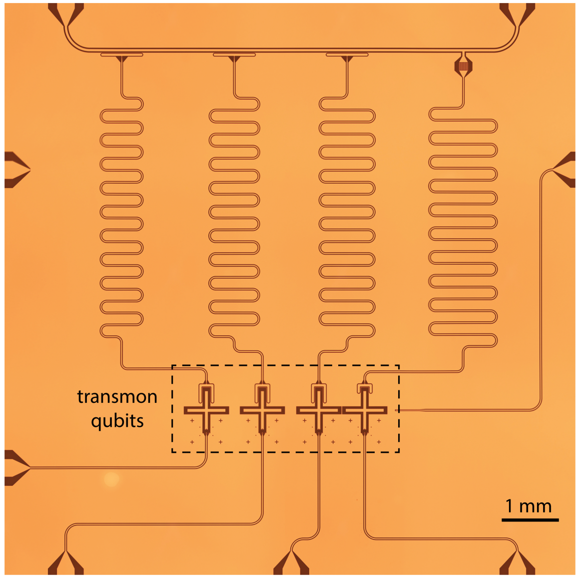
[Caputo, Millar, O'Hare & Vitagliano (2105.04565)]

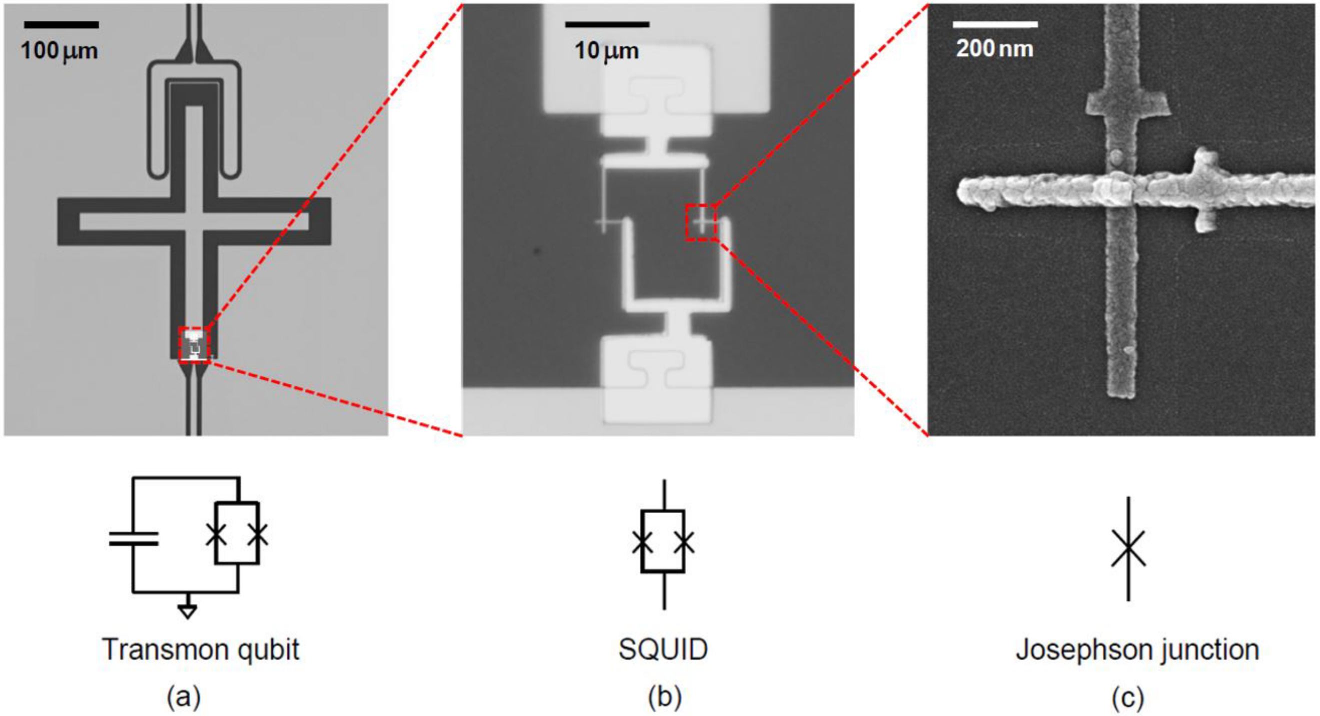
Image of a qubit fabricated on a silicon substrate



[Hutchings, Hertzberg, Liu et al. (1702.02253)]

Image of a qubit





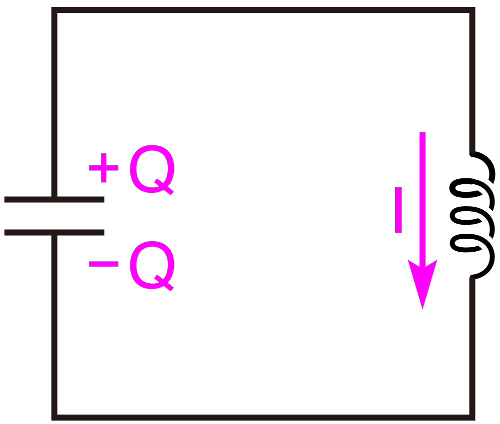
[Roth, Ma & Chew (2106.11352)]

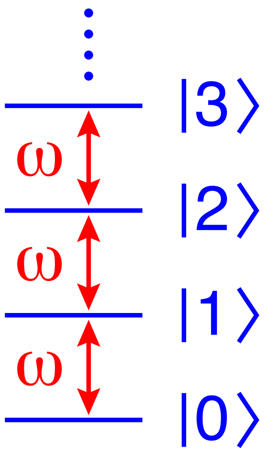
LC circuit (consisting of inductor and capacitor)

- $H = \dfrac{1}{2C}Q^2 + \dfrac{1}{2L}I^2$
- LC circuit is equivalent to a harmonic oscillator

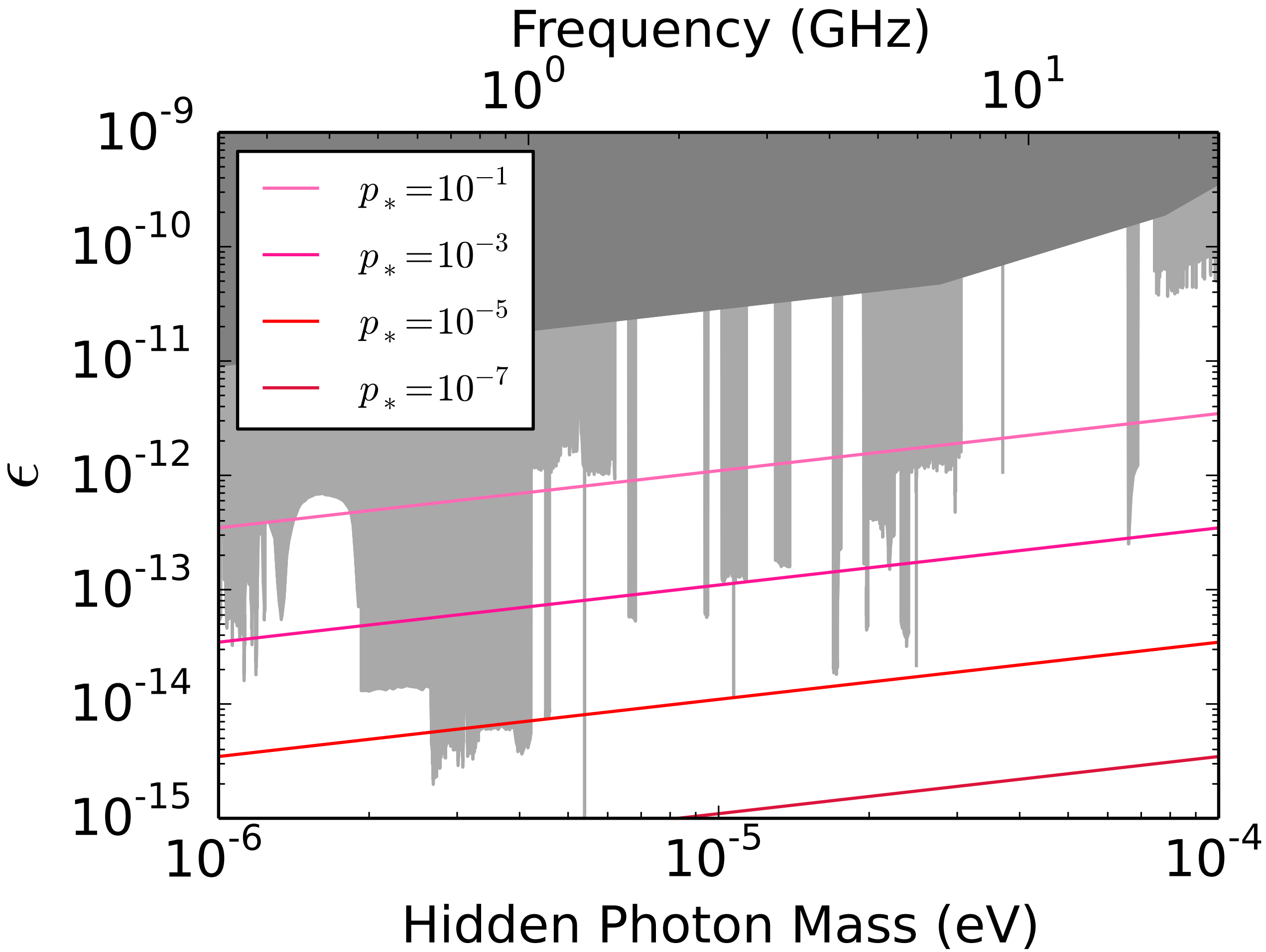
  $\Rightarrow$ The energy levels are equally spaced

  $\Rightarrow$ LC circuit is not a good candidate of qubit





$|g\rangle \to |e\rangle$ transition probability p_*



- $d = 100\ \mu\text{m}$
- $C = 0.5\ \text{pF}$
- $Q = 10^6$

$\Rightarrow$ p_* can be sizable