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, $\cdots$

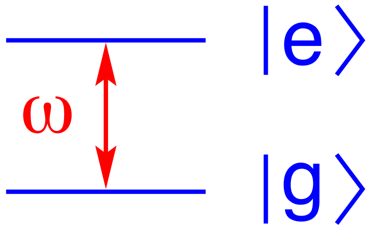
We hope to detect DM directly

$\Rightarrow$ We should consider various detection methods to take care of a variety of DM candidates

$\Rightarrow$ Today, I propose a new possibility to detect light DMs (like hidden photon, axion, $\cdots$)

Our proposal:

DM search with quantum bit (qubit)



Qubit: Two-level quantum system

- Qubit technology is developing rapidly (particularly, for quantum computation)
- Qubit can be used as a very good quantum sensor

Subject today

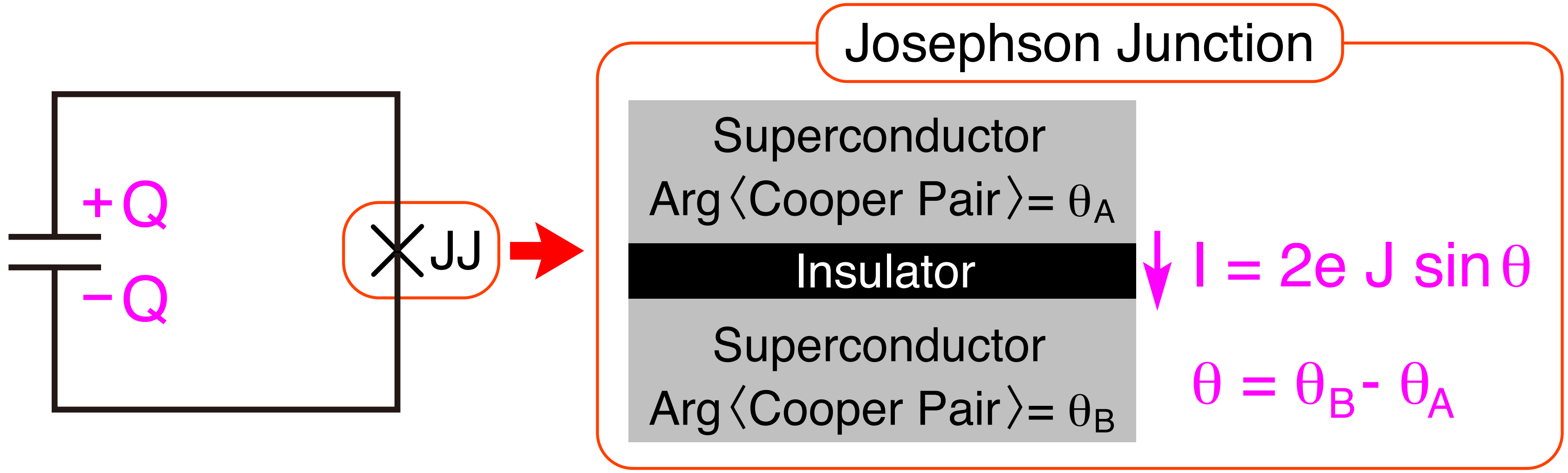
- DM search with qubits (assuming hidden photon DM)
- We can probe parameter region unexplored yet!

Outline:

1. Introduction
2. Hidden Photon DM Search with Qubits
3. R&D Efforts
4. Summary

2. Hidden Photon DM Search with Qubits

Capacitor + Josephson junction (JJ) $\simeq$ Qubit



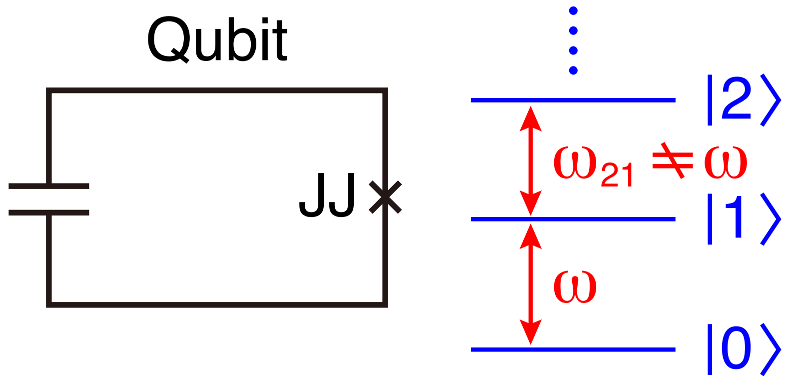
- θ plays the role of canonical variable of this system
- $E_{\mathrm{JJ}} = -J \cos\theta$
- $n = \dfrac{Q}{2e}$ is the conjugate momentum of θ

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

Hamiltonian

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

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



⇒ Energy levels are unequally spaced

⇒ $|0\rangle$ and $|1\rangle$ can be used as $|g\rangle$ and $|e\rangle$, respectively

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

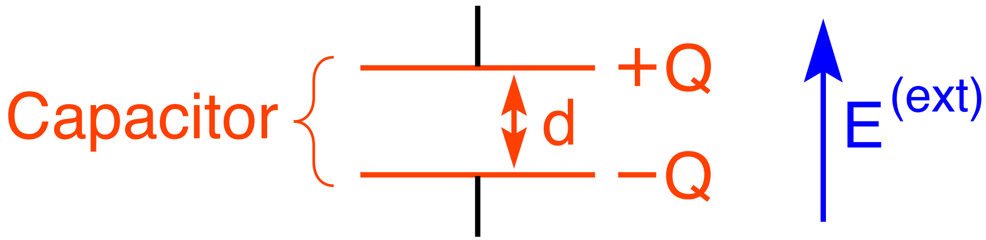
Annihilation & creation operators, satisfying $[\hat{a}, \hat{a}^\dagger] = 1$

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

$$\Rightarrow |e\rangle \simeq \hat{a}^\dagger |g\rangle$$

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

We consider DMs coupled to the electric charge



$$\Leftrightarrow \quad H_{\rm int} = QdE^{(\rm ext)}$$

Hidden photon DM induces effective electric field

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

$$\vec{E}^{(X)} = -\epsilon\dot{\vec{X}} = \bar{E}^{(X)}\vec{n}_X \sin m_X t \quad \textbf{with} \quad \bar{E}^{(X)} = \epsilon\sqrt{2\rho_{\rm DM}}$$

Oscillation of hidden photon DM excites the qubit

$\Rightarrow$ We may use the qubit as a DM detector

Effective Hamiltonian

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

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

Schrödinger equation:

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

$$|\Psi(t)\rangle \equiv \psi_g(t)|g\rangle + \psi_e(t)|e\rangle$$

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

$$P_{eg} \simeq \begin{cases} \eta^2 t^2 & : \omega = m_X \text{ (on-resonance)} \\ \sim \eta^2 (\omega - m_X)^{-2} & : \omega \neq m_X \end{cases}$$

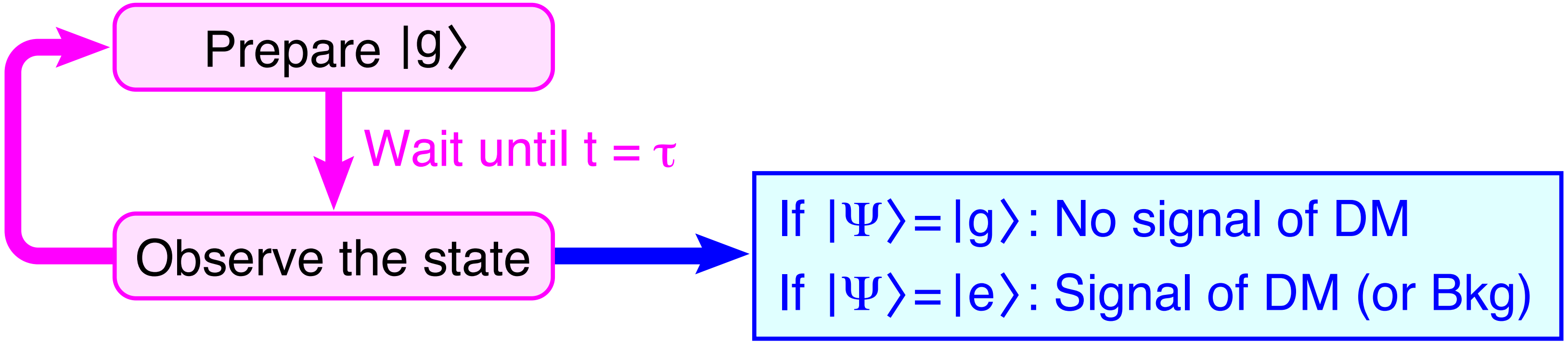
Excitation probability for $\omega = m_X$:

$$p_* \simeq 0.3 \times \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{m_X}{10\ \mu\text{eV}}\right) \times \left(\frac{\tau}{100\ \mu\text{s}}\right)^2 \left(\frac{C}{0.1\ \text{pF}}\right) \left(\frac{d}{100\ \mu\text{m}}\right)^2$$

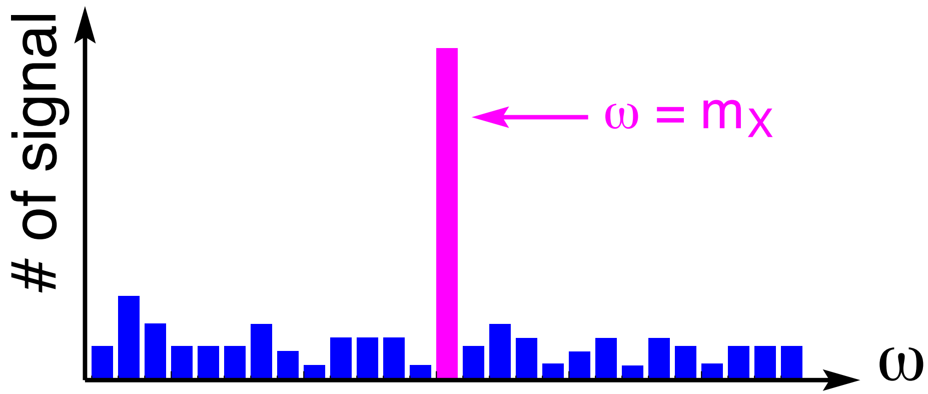
$\tau \equiv \frac{2\pi Q}{\omega}$: coherence time (with Q = quality factor)

Search strategy

For each ω, repeat the following process many times

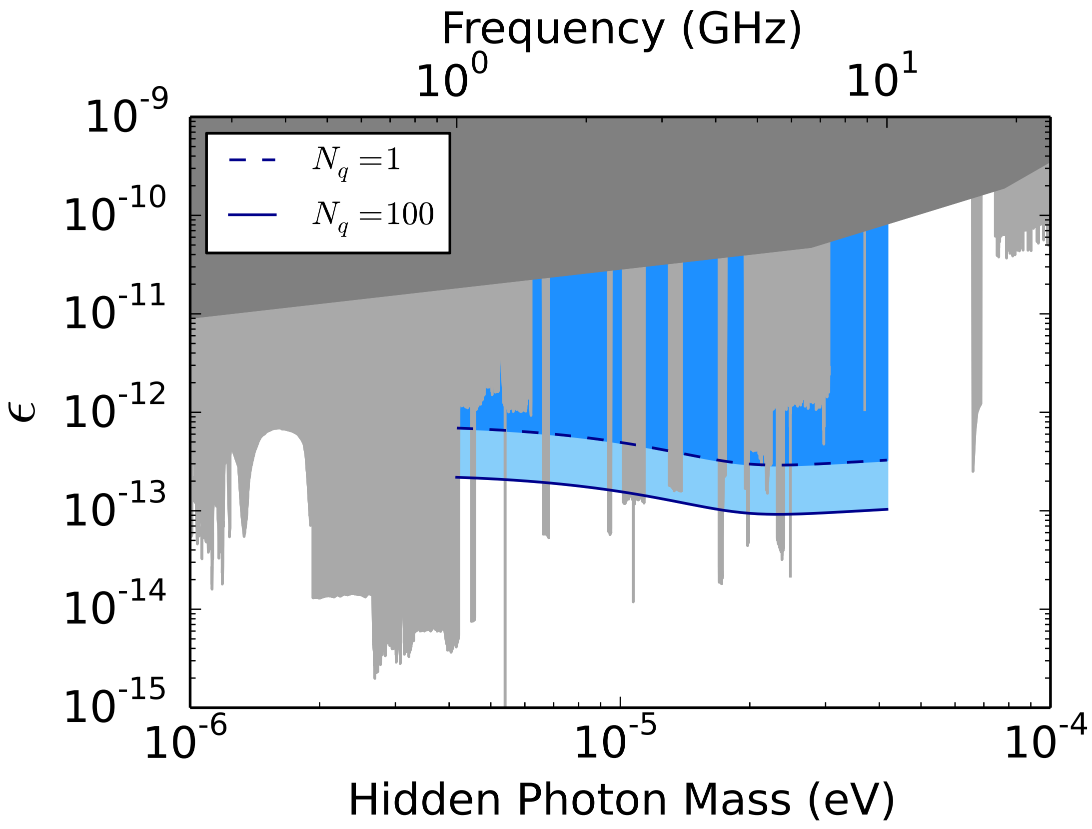


DM search with frequency scan



Discovery reach: $T = 30$ mK

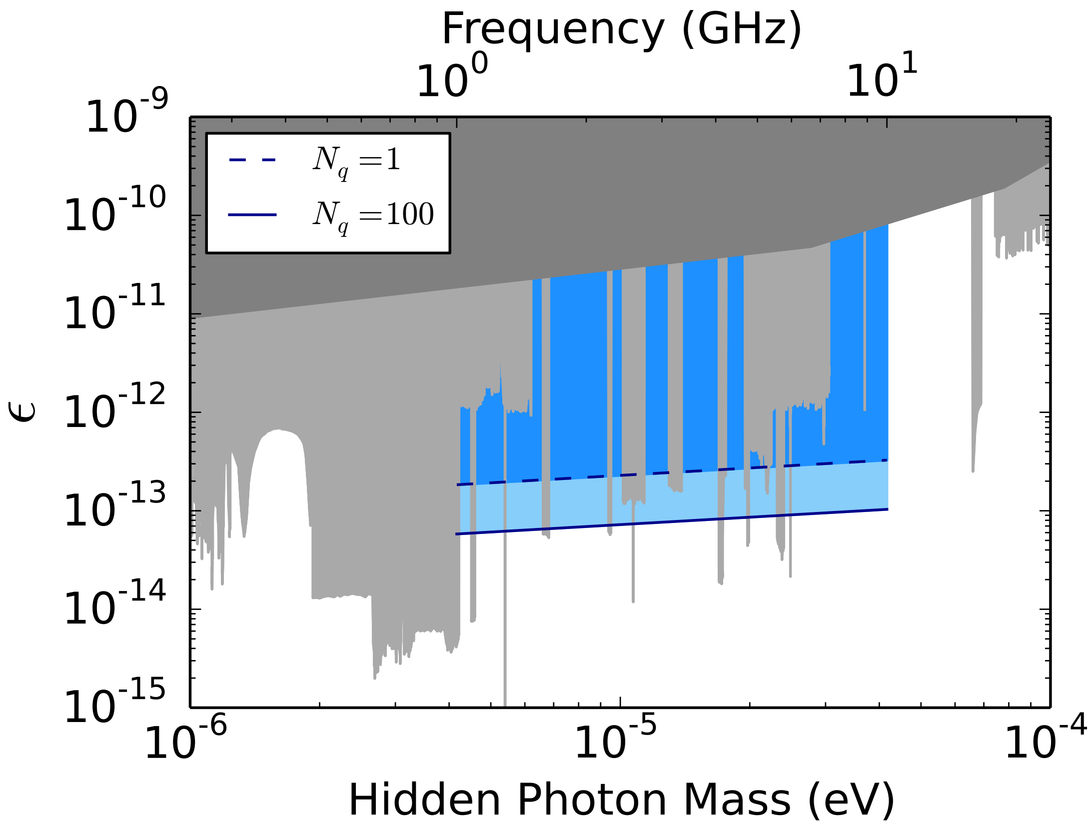
- 1 year frequency scan ($1 \leq f \leq 10$ GHz)
- Bkg: thermal excitation + readout error (0.1 %)



- $d = 100\ \mu$m
- $C = 0.1$ pF
- $\mathcal{Q} = 10^6$

Discovery reach: $T = 1$ mK

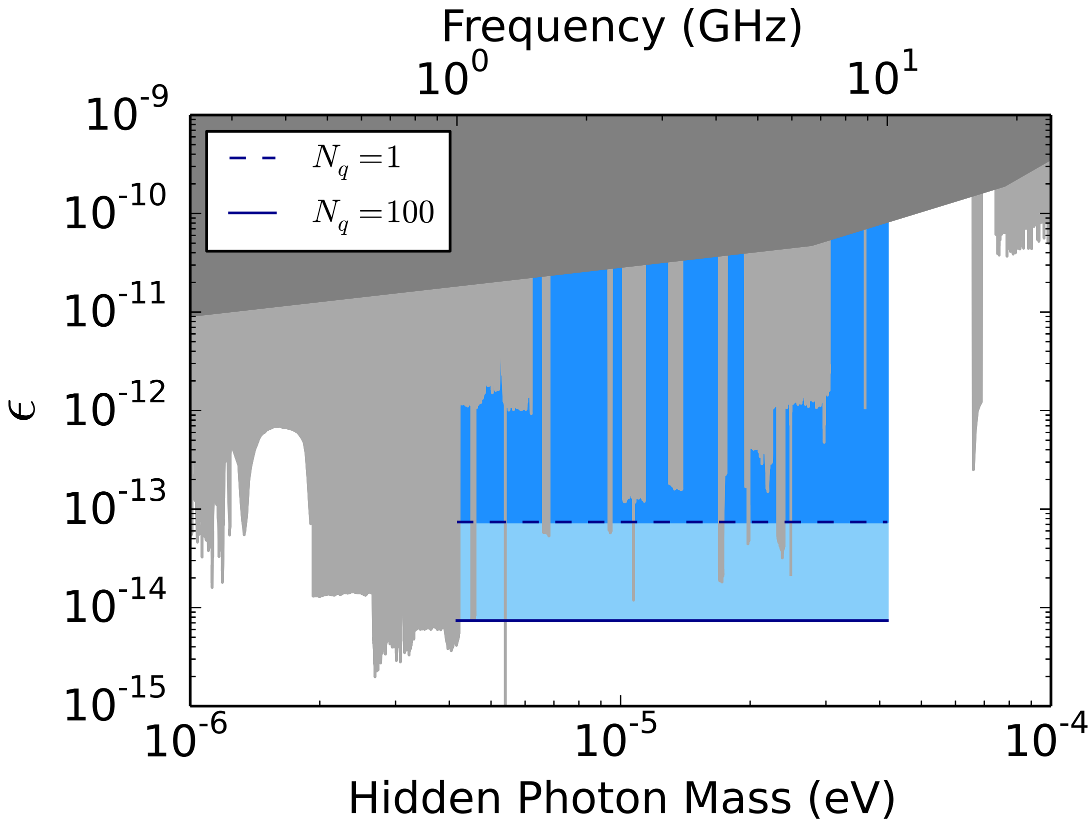
- 1 year frequency scan ($1 \leq f \leq 10$ GHz)
- Bkg: thermal excitation + readout error (0.1 %)



- $d = 100\ \mu$m
- $C = 0.1$ pF
- $\mathcal{Q} = 10^6$

Discovery reach: $T = 1$ mK

- 1 year frequency scan ($1 \leq f \leq 10$ GHz)
- Background: thermal excitation only

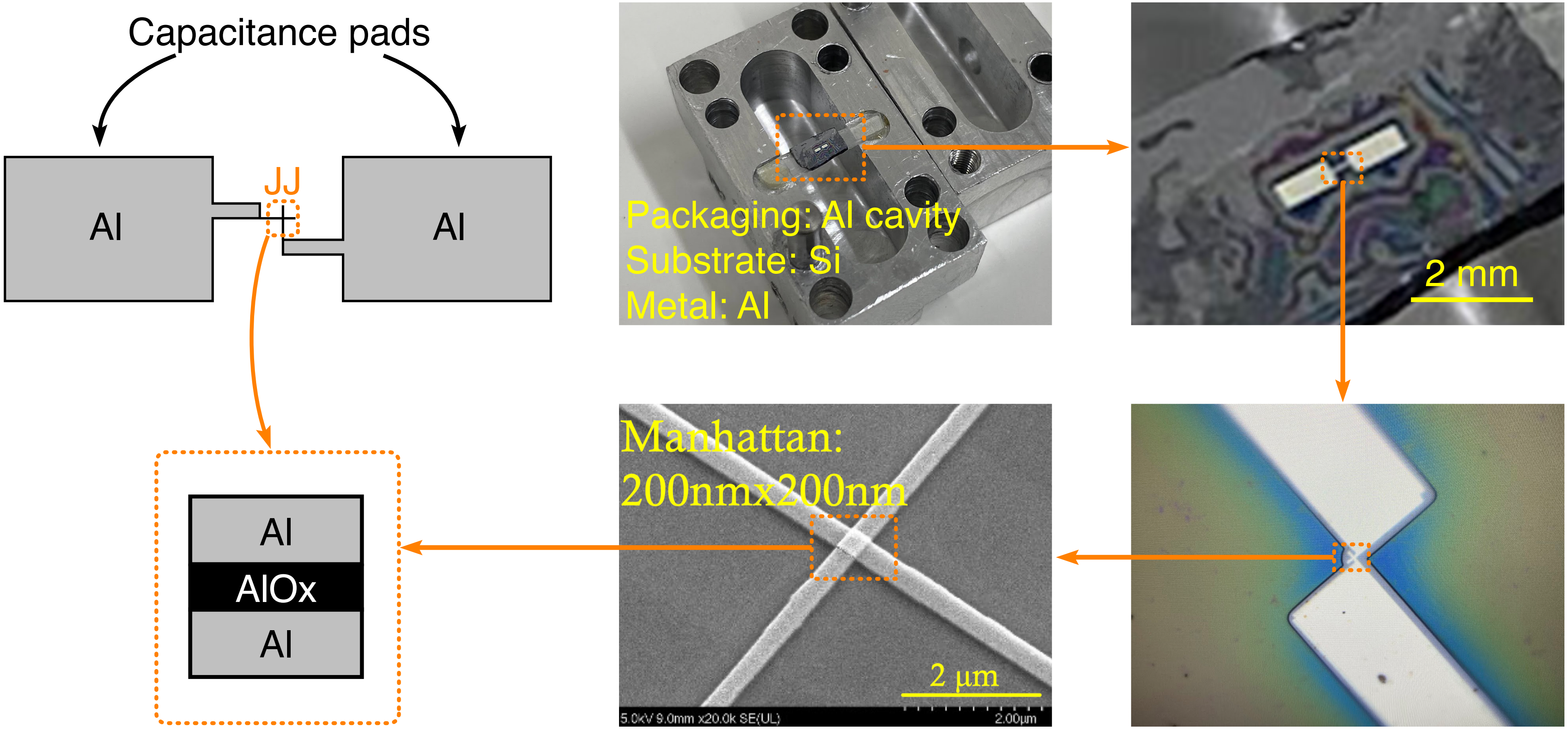


- $d = 100\ \mu$m
- $C = 0.1$ pF
- $Q = 10^6$

4. R&D Efforts at ICEPP[†]

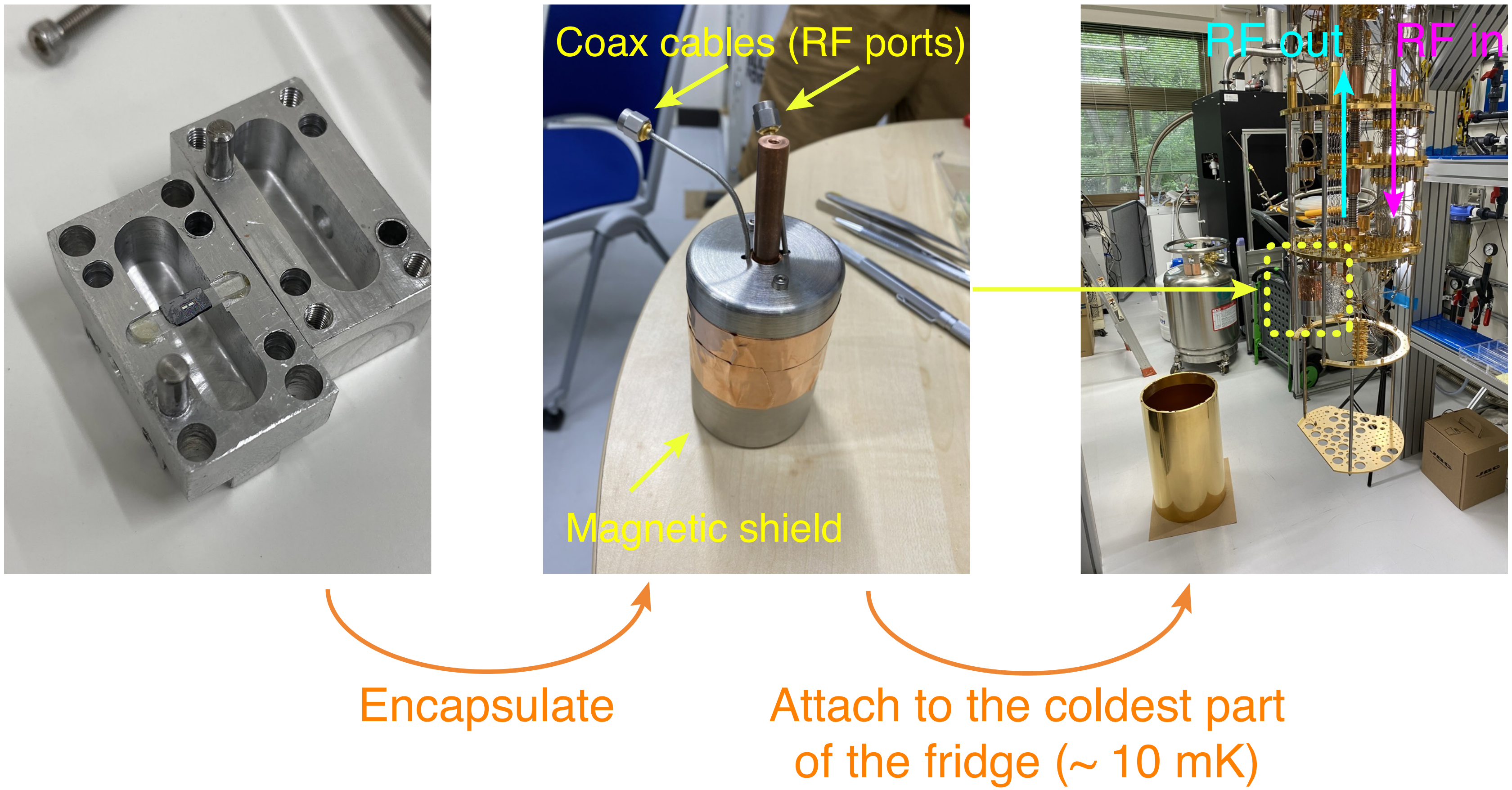
[†]ICEPP: International Center for Elementary Particle Physics, U. Tokyo

ICEPP colleagues already developed qubits (prototypes)



$\Rightarrow$ Rabi oscillation observed

A dilution refrigerator is available



⇒ R&D efforts are underway

⇒ Hopefully, our first result will come out soon

4. Summary

DM search using qubit is an interesting possibility

- It can probe parameter region unexplored yet (in particular, for the case of hidden photon)
- Significant enhancement of the reach is expected if we use the cavity effect
- Progresses in quantum technologies can be also useful for DM detection
- R&D efforts are underway, so stay tuned

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: Transmon Limit

Hamiltonian

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

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

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

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

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

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

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

In the transmon limit, anharmonicity is small:

$$\Rightarrow \; |e\rangle \simeq \hat{a}^\dagger |g\rangle$$

$$\Rightarrow \; \omega_{21} \simeq \left(1 - \frac{1}{8}\frac{2e}{\sqrt{CJ}}\right)\omega$$

Charge operator in the transmon limit

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

Interaction Hamiltonian

$$H_{\mathrm{int}} = Q\,dE^{(\mathrm{ext})} \simeq \sqrt{\frac{C\omega}{2}}\,dE^{(\mathrm{ext})}\big(\,|g\rangle\langle e| + |e\rangle\langle g|\,\big)$$

Backup: Schrd̈inger Equation

Effective Hamiltonian

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

η: Small parameter

Schrödinger equation:

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

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

$$\Rightarrow\ i\frac{d}{dt}\begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix} = 2\eta \sin m_X t \begin{pmatrix} 0 & e^{-i\omega t} \\ e^{i\omega t} & 0 \end{pmatrix}\begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix}$$

Solution with $|\Psi(0)\rangle = |g\rangle$ (for $|\omega \pm m_X|^{-1} \ll t \ll \eta^{-1}$)

$$\psi_g(t) \simeq 1 + O(\eta^2)$$

$$\psi_e(t) \simeq \eta \left(\frac{e^{i(\omega - m_X)t} - 1}{i(\omega - m_X)} - \frac{e^{i(\omega + m_X)t} - 1}{i(\omega + m_X)} \right)$$

Resonance limit: $\omega \to m_X$

$\Rightarrow$ $\psi_e(t) \to \eta t +$ (non-growing)

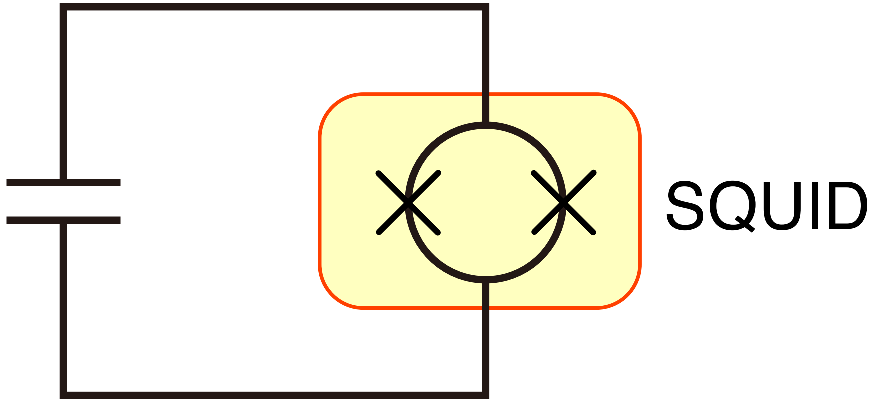
$|g\rangle \to |e\rangle$ transition rate (for $t \ll \eta^{-1}$)

$$P_{eg} = |\psi_e(t)|^2 \simeq \begin{cases} \sim \eta^2 (\omega - m_X)^{-2} & : \omega \neq m_X \\ \eta^2 t^2 & : \omega = m_X \end{cases}$$

Backup: Frequency Scan

Frequency scan

Frequency scan is possible with qubit consisting of SQUID and capacitor

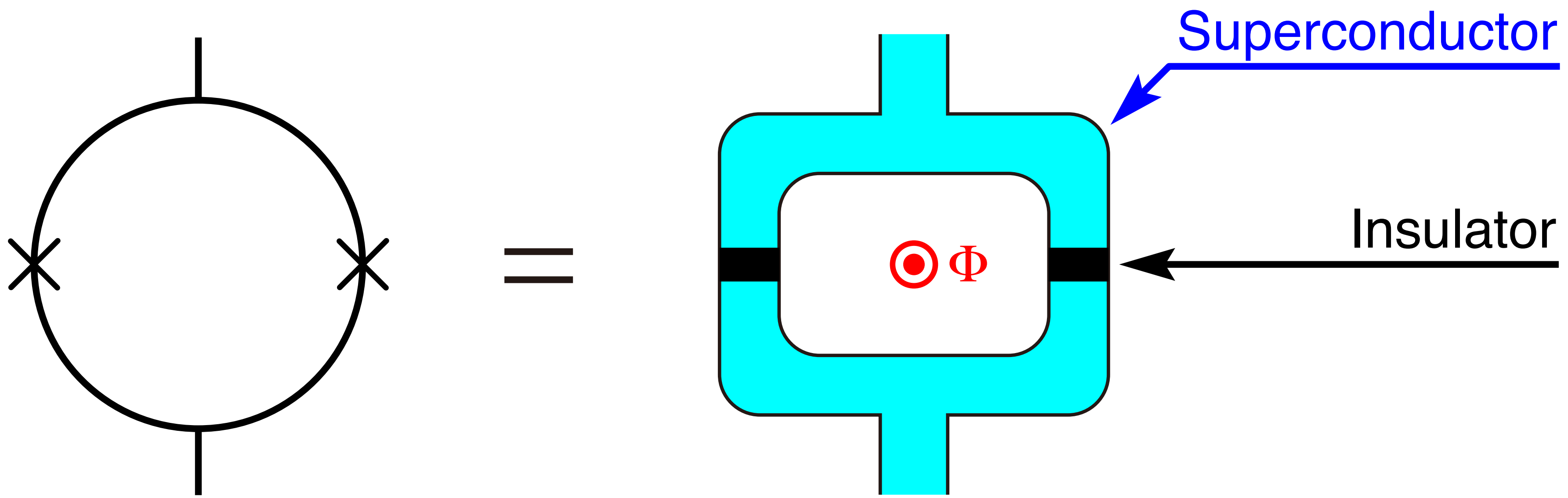


SQUID: superconducting quantum interference device

- Quantum device sensitive to magnetic flux

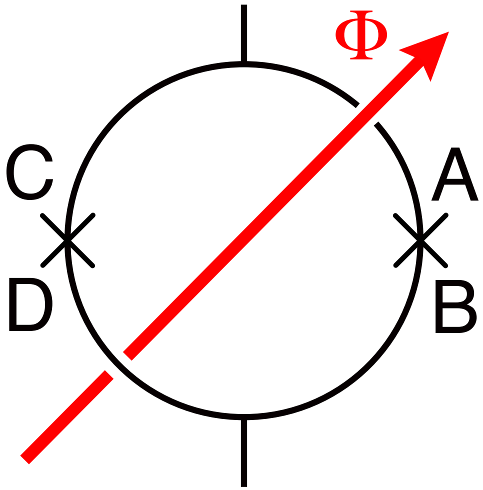
SQUID

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

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

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: Comments on Backgrounds

Backgrounds (dark counts)

- Thermal excitation
- Readout error

Our (simple) criterion for DM detection

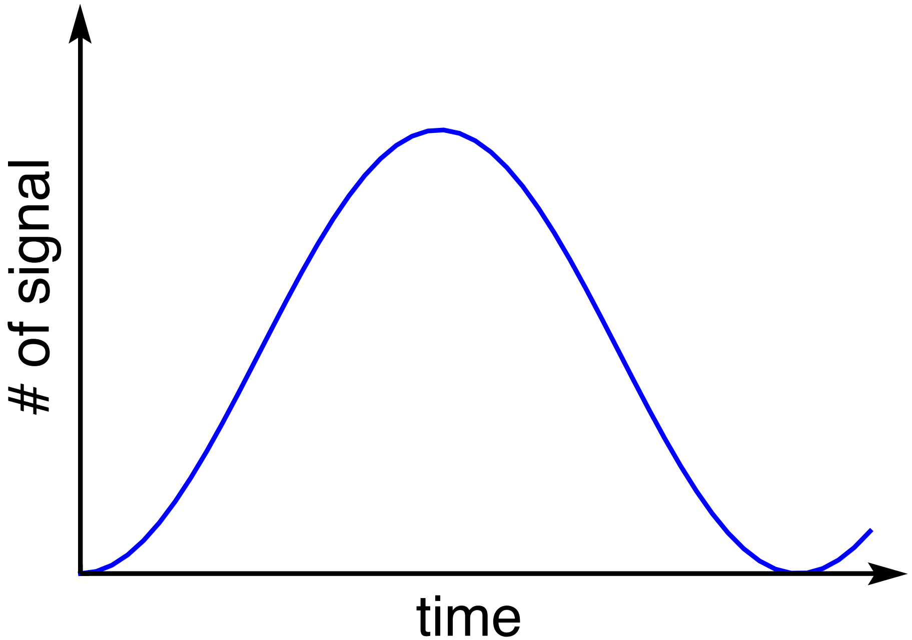
$$N_{\rm sig} > \max(3, 5\sqrt{N_{\rm bkg}})$$

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

- Scan time for each frequency: ~ 14 sec (for $Q = 10^6$)
- $N_{\rm rep} \sim O(10^4 - 10^5)$

Comment on the background

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



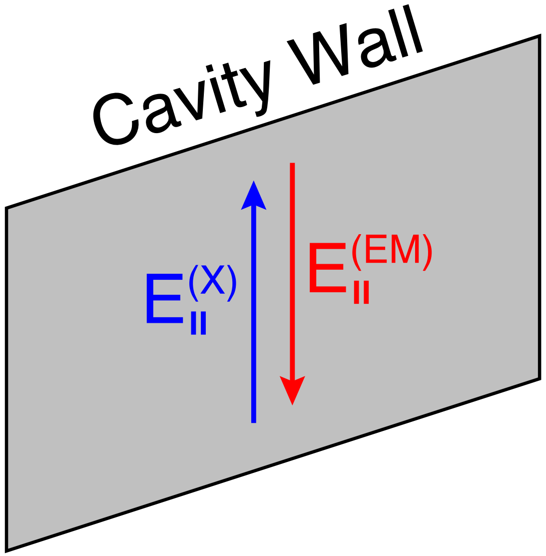
Backup: Cavity Effect

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

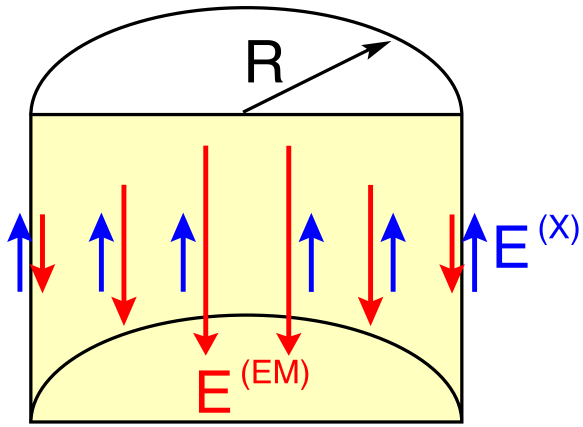
$\vec{E}^{(\mathrm{EM})}$ at the position of the qubit depends on:

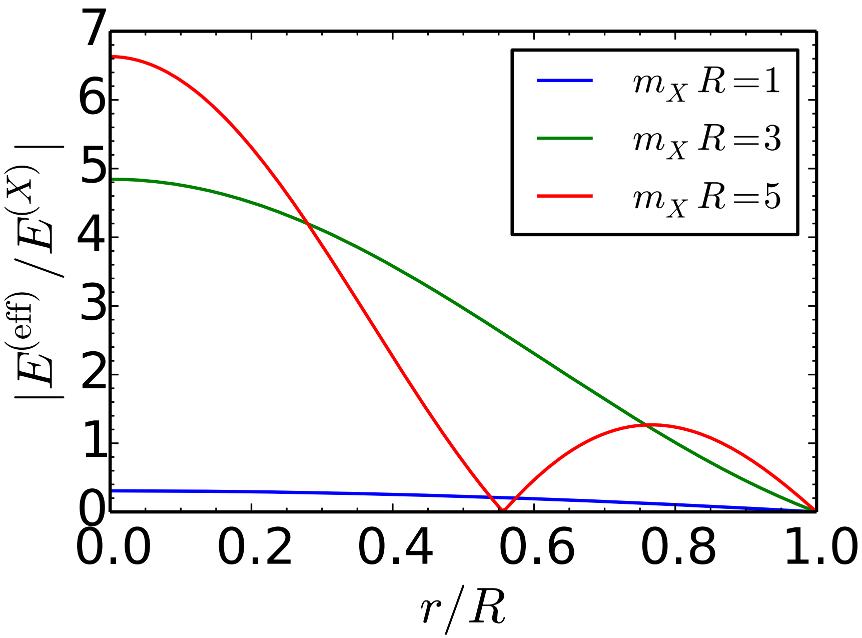
- Geometry of the cavity
- Location of the qubit

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

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

$$\vec{E}^{(\mathrm{eff})} \equiv \vec{E}^{(\mathrm{EM})} + \vec{E}^{(X)} = \left[1 - \frac{J_0(m_X r)}{J_0(m_X R)}\right] \vec{E}^{(X)}$$



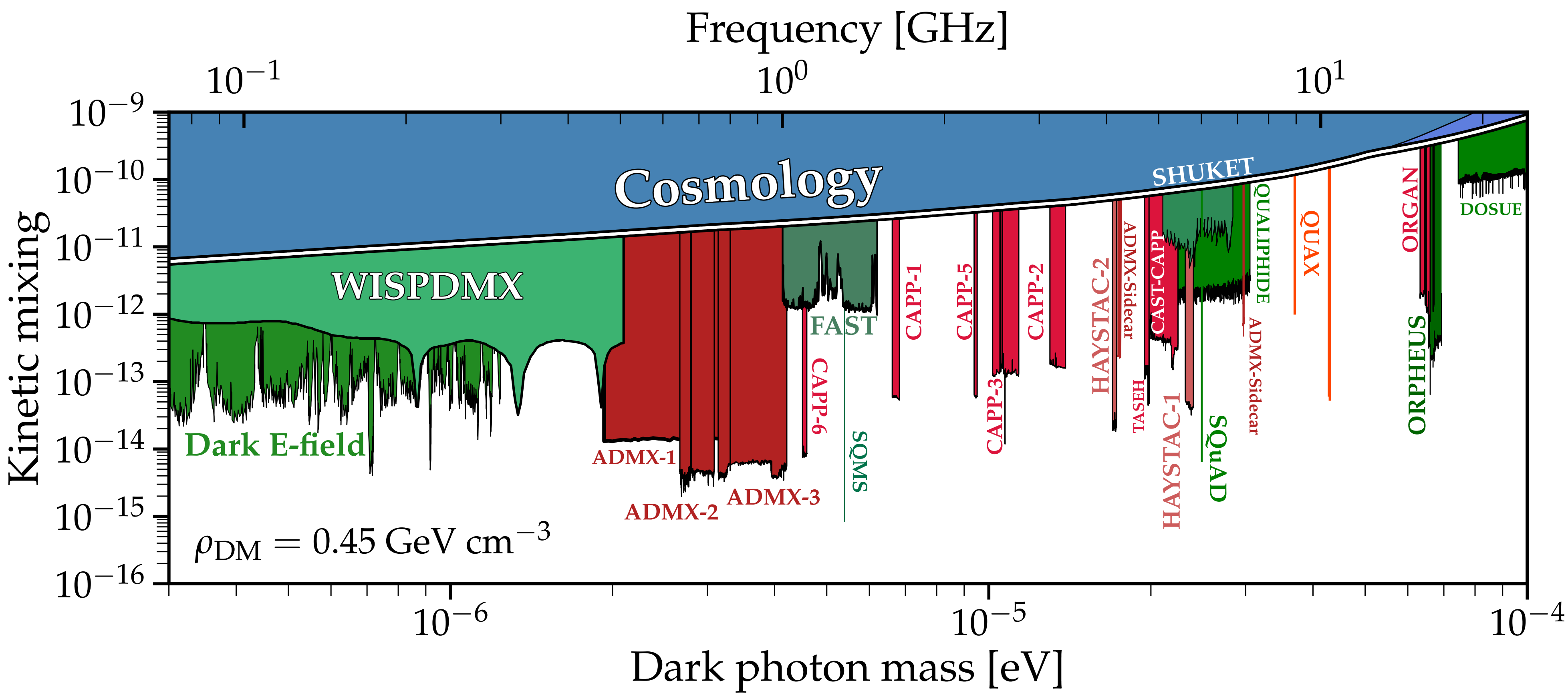


$\Rightarrow$ $|\vec{E}^{(\mathrm{eff})}| \gtrsim |\vec{E}^{(X)}|$ is possible if $R \gtrsim m_X^{-1}$

$\Leftrightarrow$ Sensitivity we have seen before: $|\vec{E}^{(\mathrm{eff})}| = |\vec{E}^{(X)}|$

Backup: Misc.

Constraints on hidden photon DM



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

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

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

Decoherence of DM due to its velocity dispersion

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

Decoherence of qubit

$$\mathcal{Q}_{\rm qubit} \sim 10^{(5-6)}$$

For our numerical analysis, we take

$$\mathcal{Q} = 10^6$$