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Search for dark photons using direct excitations of superconducting qubits

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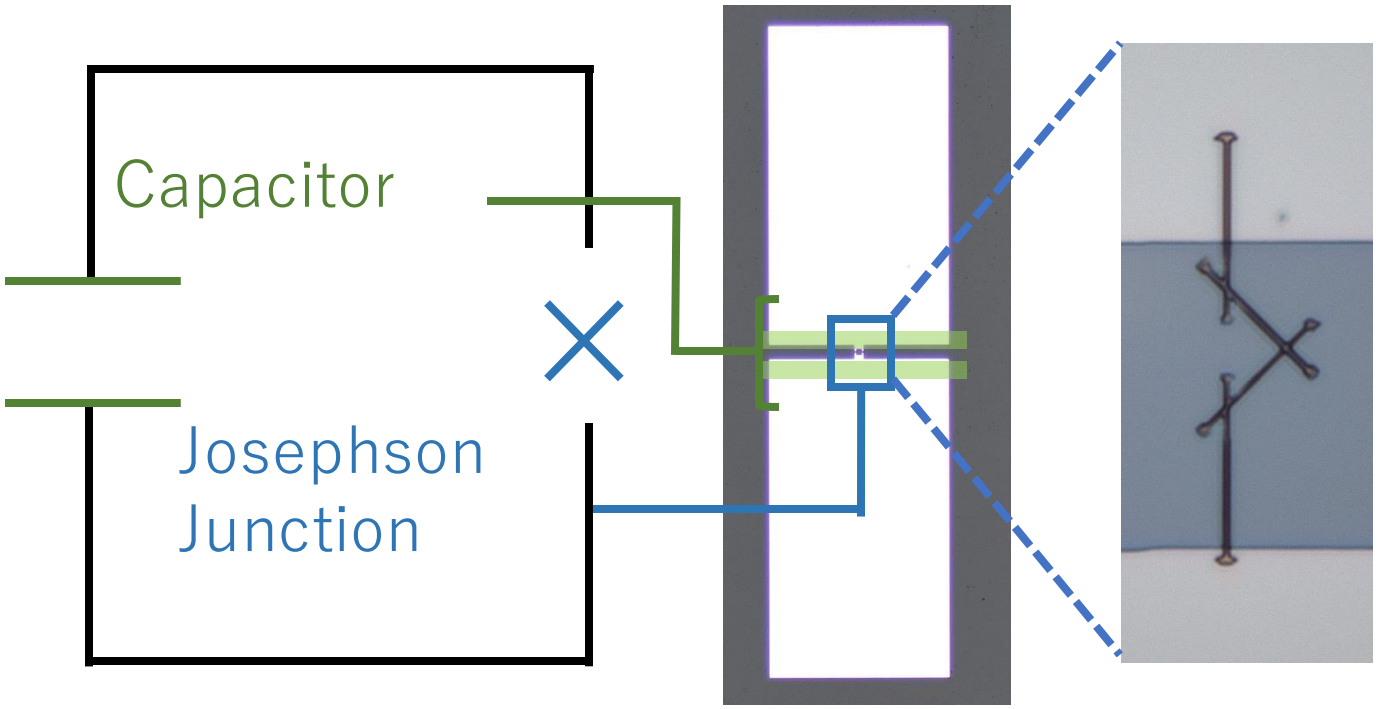
Dark photon

- Lighter mass $< \mathcal{O}(\mathrm{meV})$ ⟶ behave like a coherent wave
- Electromagnetic interaction ⟶ **freq. corresponding to DM mass**

Convert into **coherent E-field**

Superconducting qubit: transmon



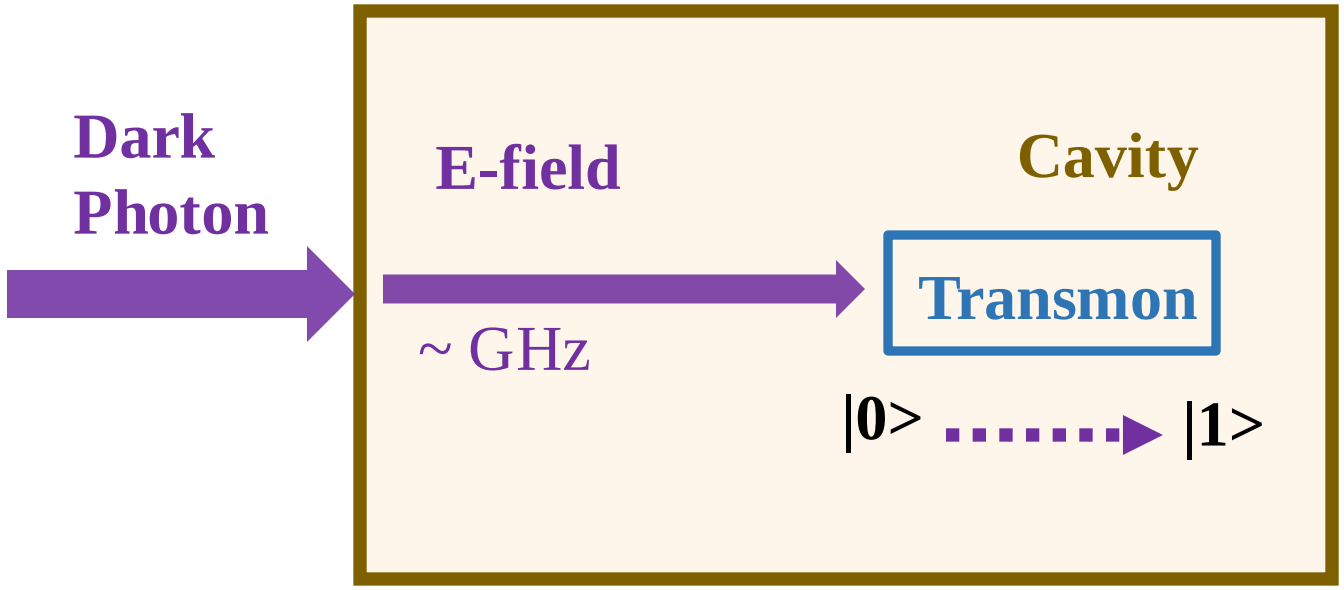
Dark photon interaction-eigenstate

$X^\mu = \tilde{X}^\mu - \epsilon A^\mu$ Ordinary photon

Dark photon mass-eigenstate kinetic mixing parameter

- Excited by **coherent E-field**
- Nonlinear LC circuit
- Josephson Junction as nonlinear inductance

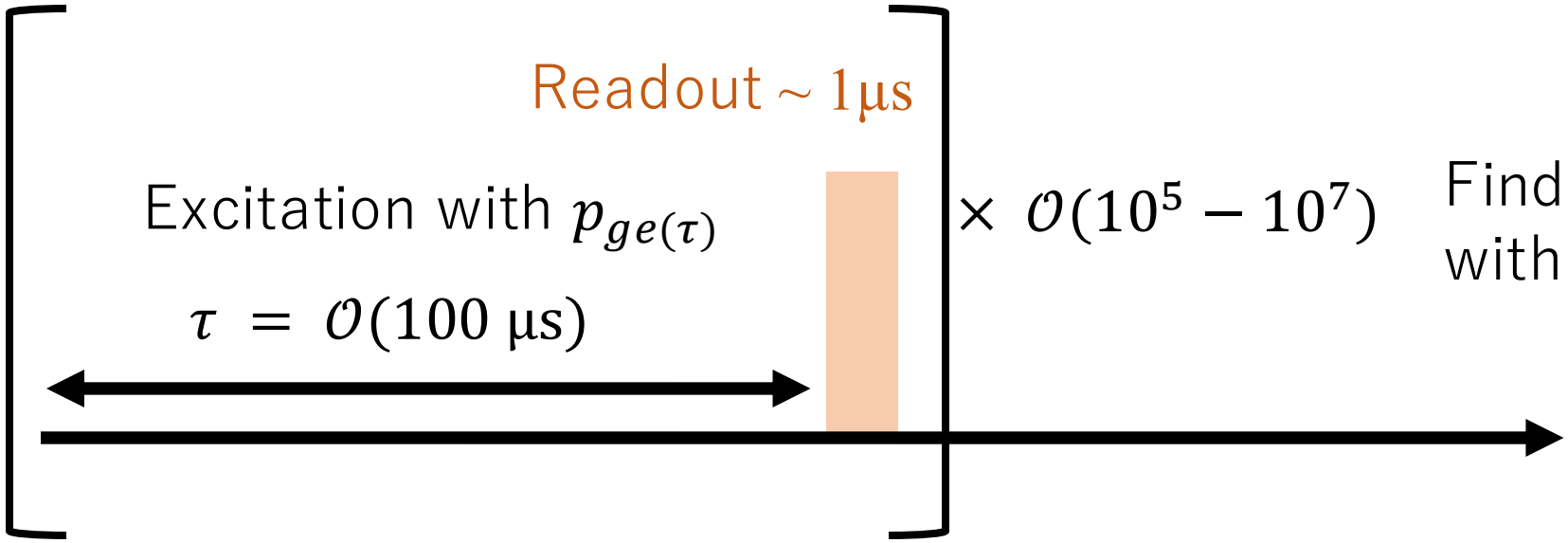
Main idea



Freq. of DM-converted E-field

⇒Excitation to |1>

Repetitive counting experiment



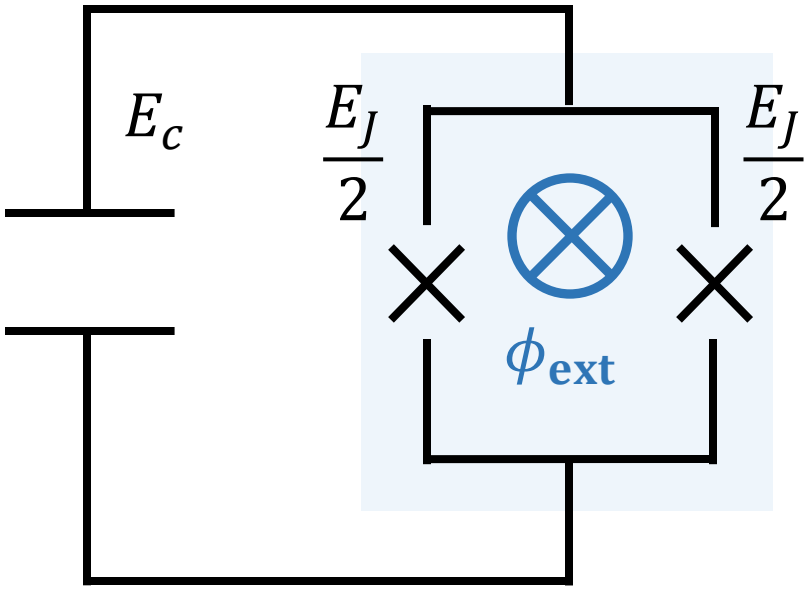
Find resonant freq.
with anomalous excitation rate

$$p_{ge} \cong 0.12 \times \kappa^2 cos^2\Theta_Z \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{f_{01}}{1\ \mathrm{GHz}}\right)\left(\frac{\tau}{100\ \mu s}\right)^2\left(\frac{C}{0.1\ \mathrm{pF}}\right)\left(\frac{d}{100\ \mu m}\right)^2 \left(\frac{\rho_{DM}}{0.45\ \mathrm{GeV/cm^3}}\right)$$

f_{01}: resonant freq. of transmon, τ: lifetime of transmon

Easy frequency tuning

- SQUID



Change resonant freq. through external magnetic flux ϕ_{ext}

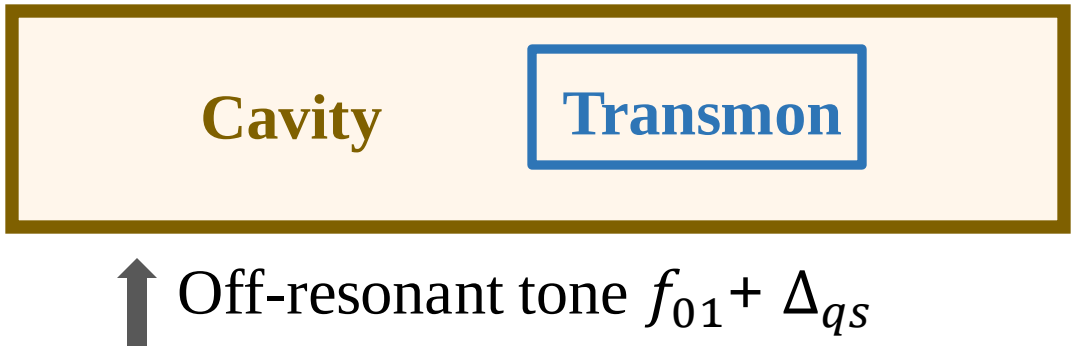
$$\phi_{\mathrm{ext}} = \varphi_{\mathrm{ext}}\,\phi_o$$

$$E_{SQUID} = E_J \cos\frac{\varphi_{\mathrm{ext}}}{2}$$

$$f_{01} \sim \sqrt{8E_{SQUID}E_C} - E_c$$

Easy frequency tuning

- **AC Stark shift**



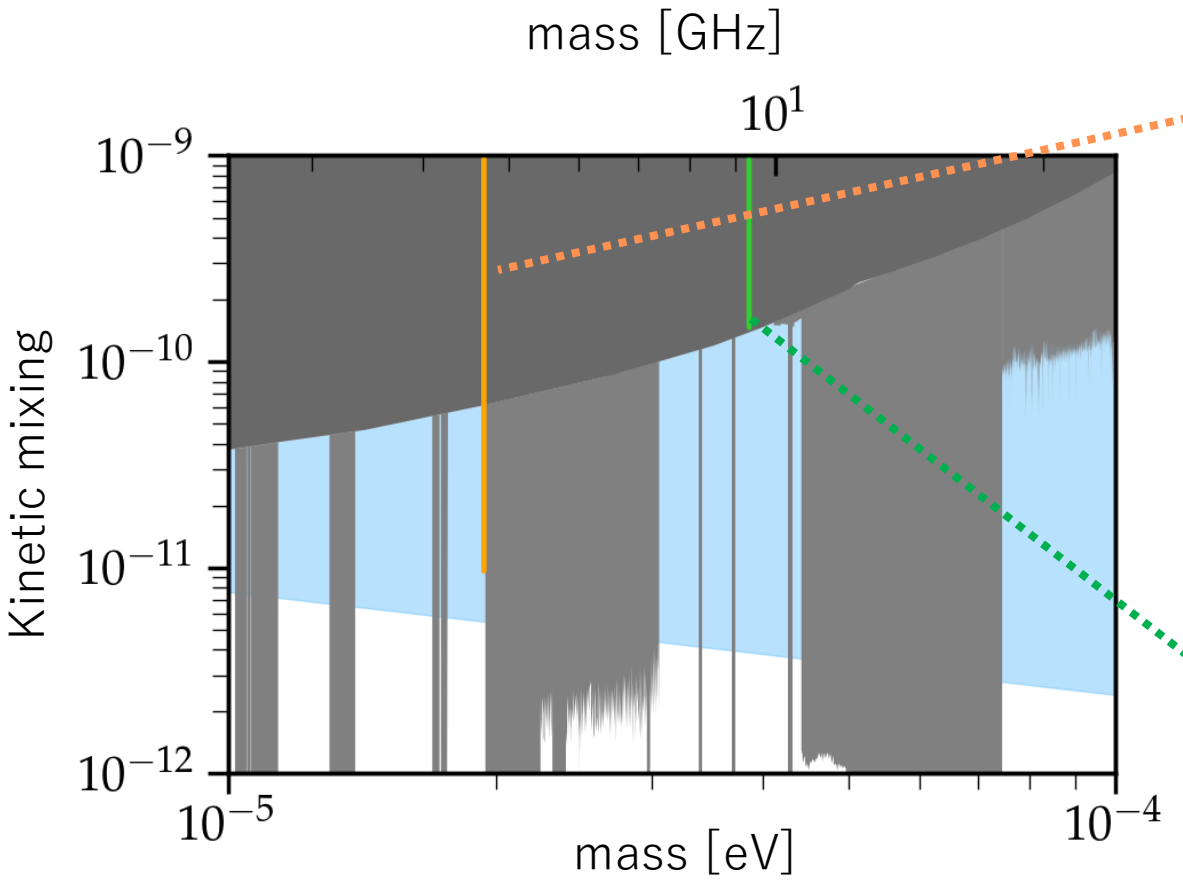
Change resonant freq. through Off-resonant tone

$$\Delta f_{01} = \frac{\delta_q \Omega_s^2}{2\Delta_{qs}(\delta_q + \Delta_{qs})}$$

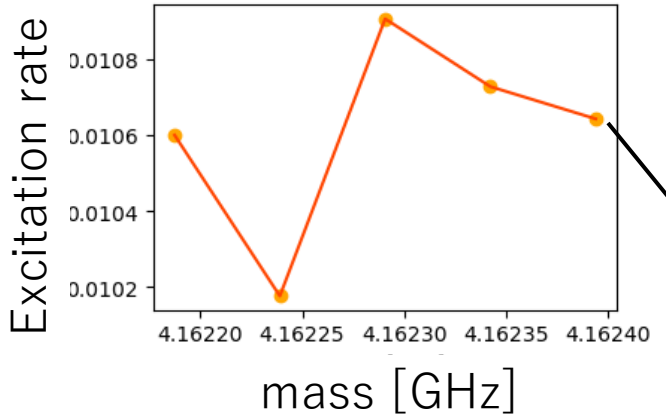
Ω_s: amplitude of off-resonant tone

δ_q: qubit anharmonicity

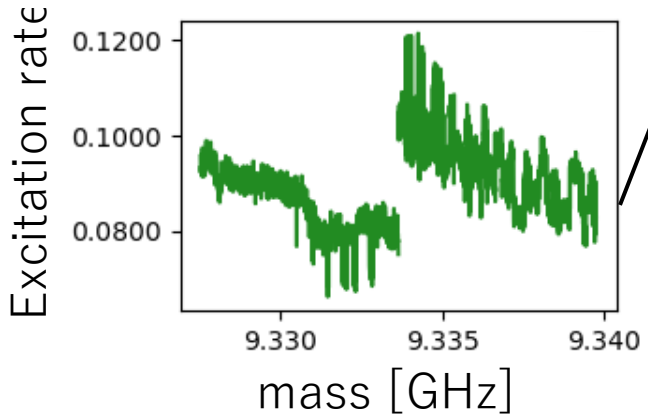
Preliminary Results



from **4.1622 to 4.1624** GHz

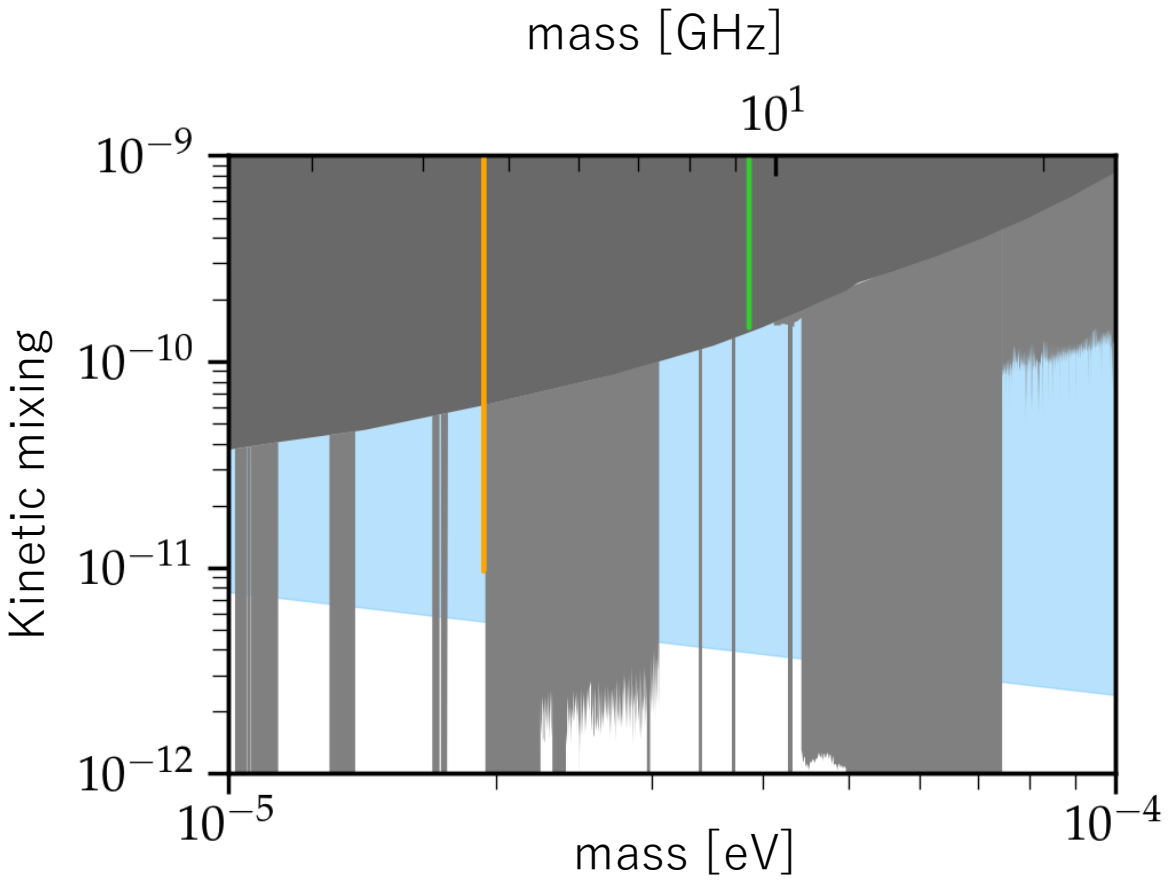


from **9.3275 to 9.3398** GHz



no peak ($> 5\sigma$) → suggest no dark photons in these freq. range

Outlook



Future exploration area by this method

-Design optimization for the search

while standard transmons are uses so far

e.g. large capacitance pads (big C)

long distance btw pads (big d)