20th Patras Workshop on Axions, WIMPs, and WISPs

DarQ:

Search for Dark Photons Using Direct Excitations of Superconducting Qubits

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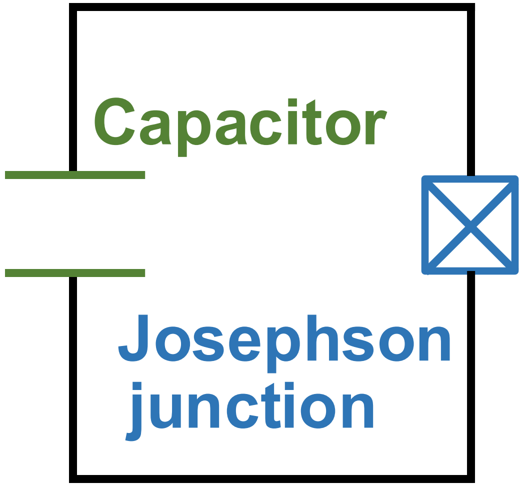
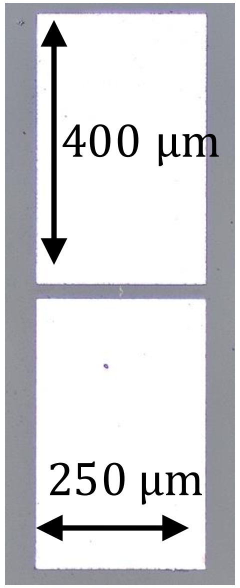
Dark Photon

- ➢ Light mass $< \mathcal{O}(\text{eV})$ → behave as a coherent wave
- ➢ Interact with ordinary photons

converted into a coherent electric field

Superconducting Qubit





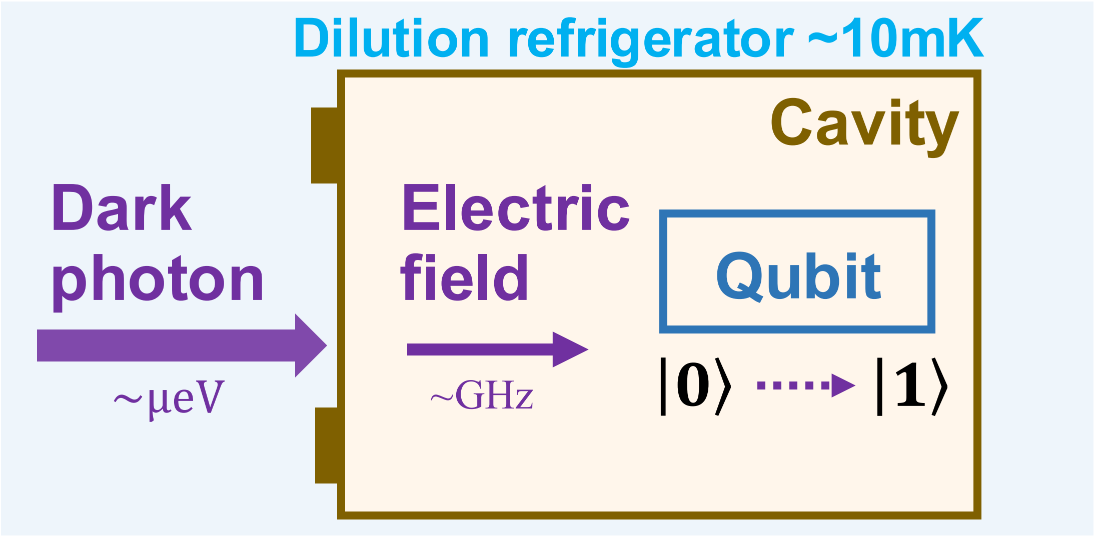
10x
microscope image

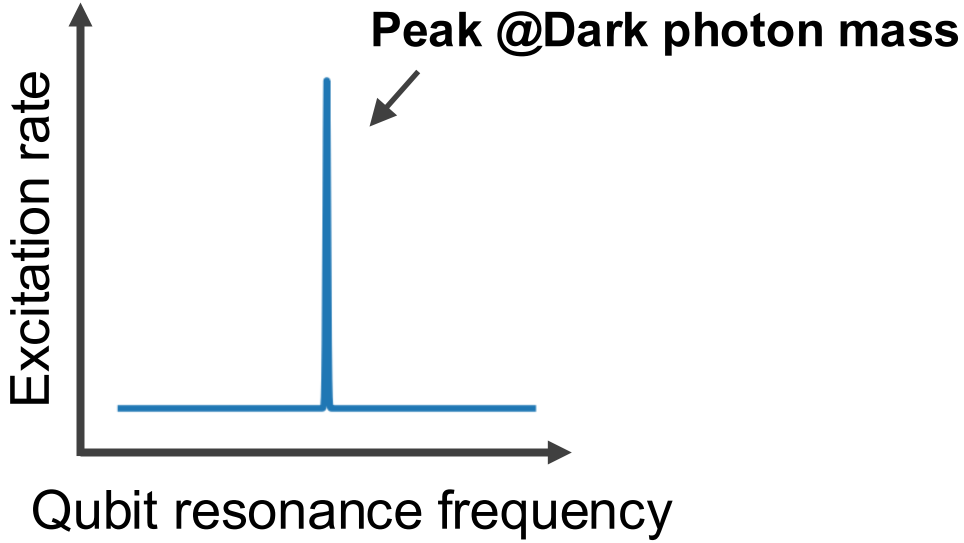
- Nonlinear LC circuit
- Large dipole moment
- **Excited by a coherent electric field**
- **Tunable** across wide frequency ranges

$\sim \mathcal{O}$ (1) GHz

Using superconducting qubits
as tunable sensors
for dark-photon-induced electric fields

Dark Photon Search using Superconducting Qubit – Basic Idea





- When a dark photon passes through the metal wall, it is converted into an electric field at the frequency corresponding to its mass.

$$f \sim \frac{mc^2}{h}$$

- The electric field frequency matches the qubit resonance frequency.
  → The qubit is excited.
- Sweep the qubit resonance frequency to find the peak of the excitation rate.

Moroi et al. PRL 131 (21), 211001 (2023)

Dark Photon Search using Superconducting Qubit – Expected Excitation Rate

When the qubit resonance frequency = the dark photon mass,
the expected excitation rate p_{ge} is

0.1 – 10%

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

κ: $\left|\frac{\text{Effective electric field}}{\text{Electric field converted from the dark photon}}\right|$

Θ: Angle between the effective electric field and the capacitance pad $\rightarrow \cos^2\Theta = \frac{1}{3}$

assume random polarization

ϵ: kinetic mixing

f_{01}: Qubit resonance frequency i.e. target mass

t : Effective search time = $\sqrt{T_1 T_{2r}}$

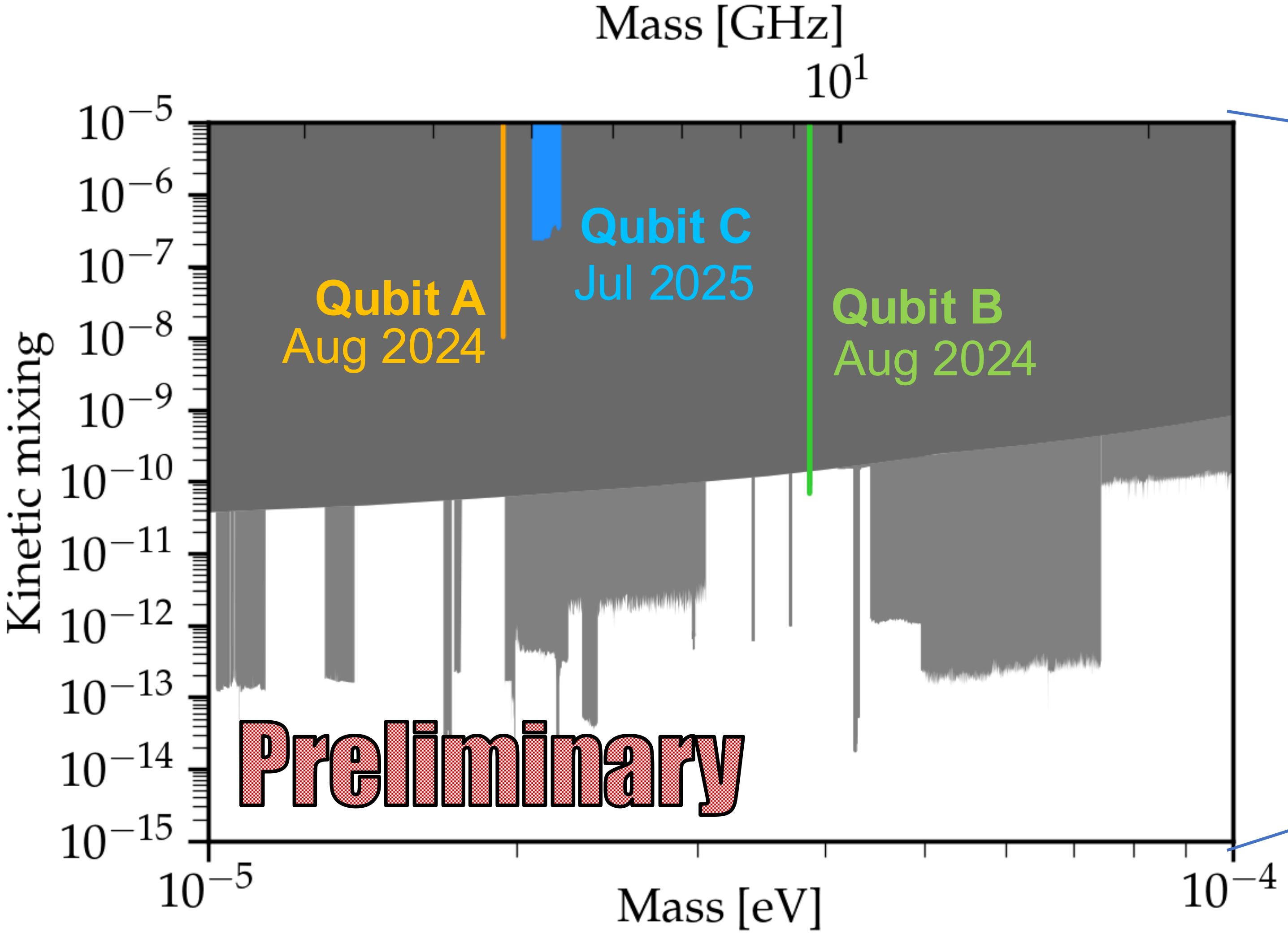
C : Qubit capacitance

d : Distance between qubit capacitance pads

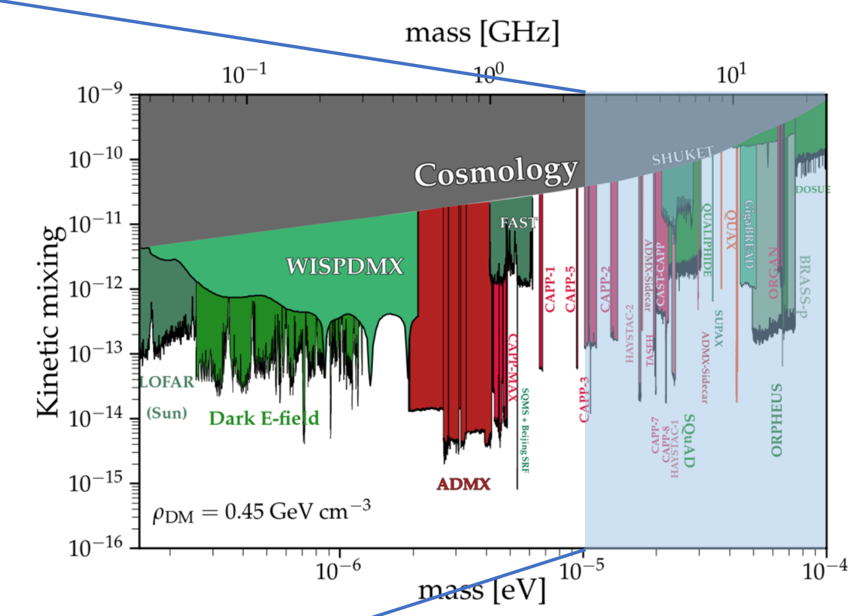
ρ_{DM}: Local energy density of dark matter ~ $0.45\ \mathrm{GeV/cm^3}$

Dark Photon Search using Superconducting Qubit – Demonstration

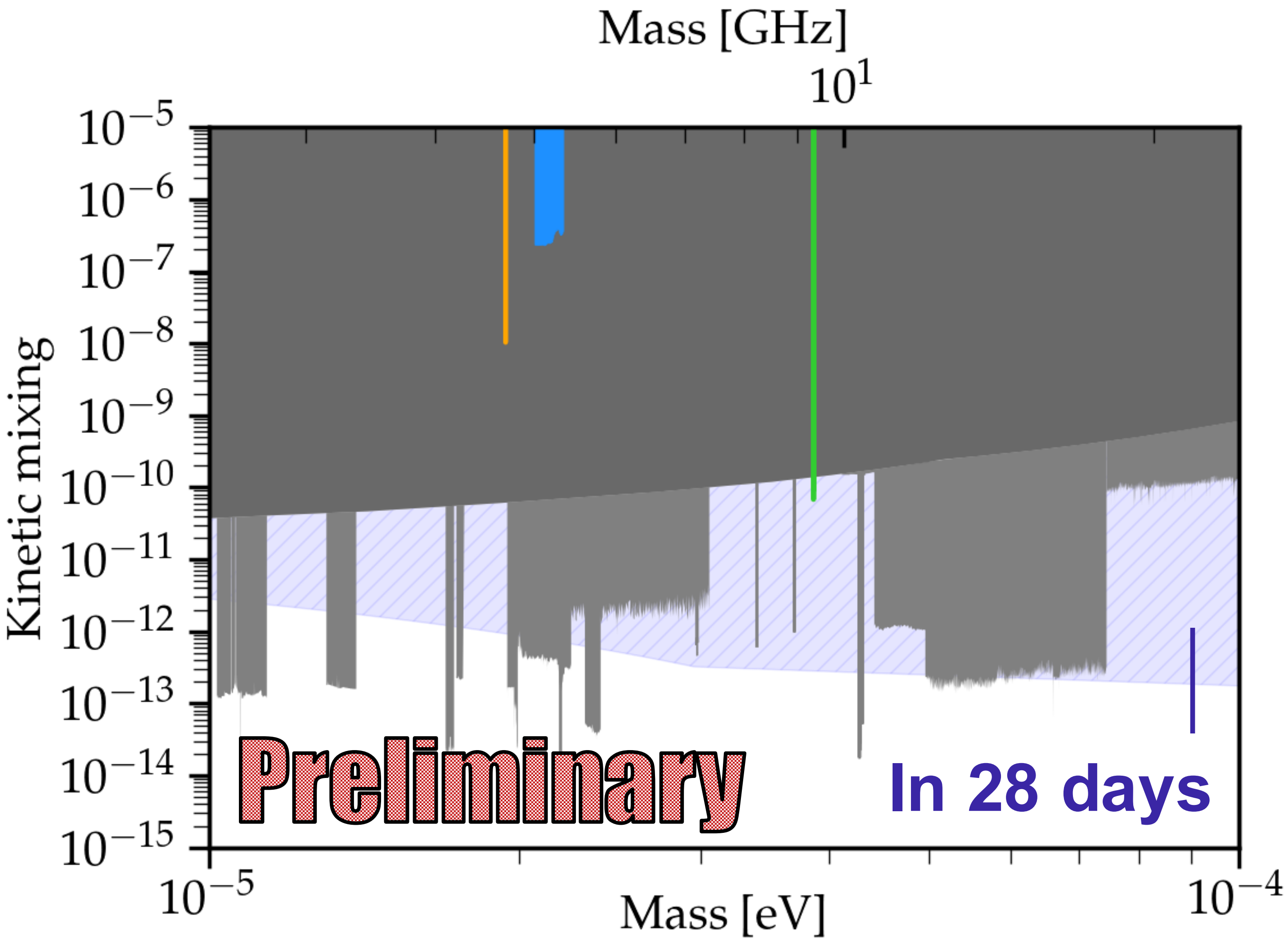
3 demonstration short runs (Qubit-A, Qubit-B and Qubit-C)



Exclusion Limit on Kinetic Mixing ϵ (90% C.L.)



Dark Photon Search using Superconducting Qubit – Future Search Region



Enabling **wide-range** search

in a **practical time**

with sensitivity
beyond the CMB limits

$T_1 = 100\ \mu s$

$T_{2r} = 10\ \mu\mathrm{s}$

$\kappa = 1$

$C = 0.1\ \mathrm{pF}$

$d = 100\ \mu\mathrm{m}$

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