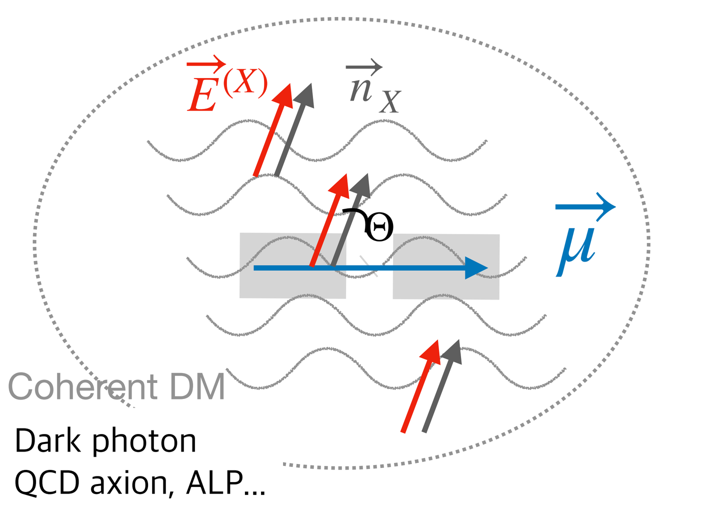
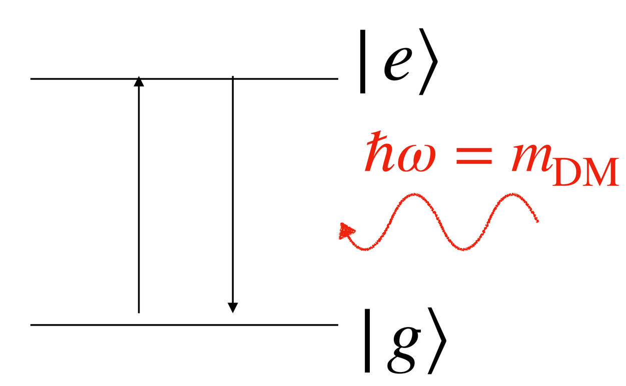
Search for dark photon dark matter using large-scale superconducting quantum computers as detectors

Shion Chen (Kyoto University), Yutaro Iiyama (UTokyo ICEPP)

Quantum computer as DM detector

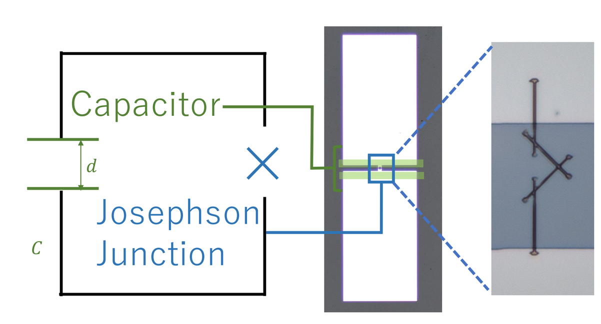
Coherent E-field from DM = **Qubit drive pulse**



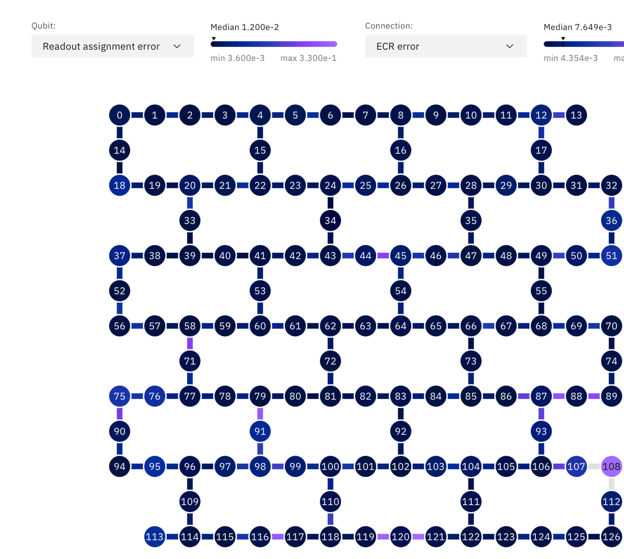


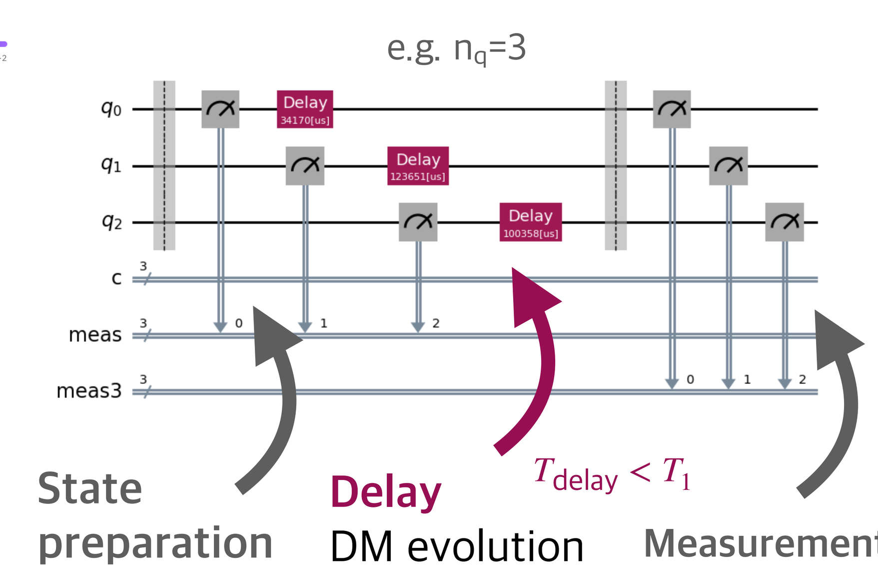
Excitation rate after τ: Moroi et al. PRL 131 (21), 211001

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



Experiment in an actual QC



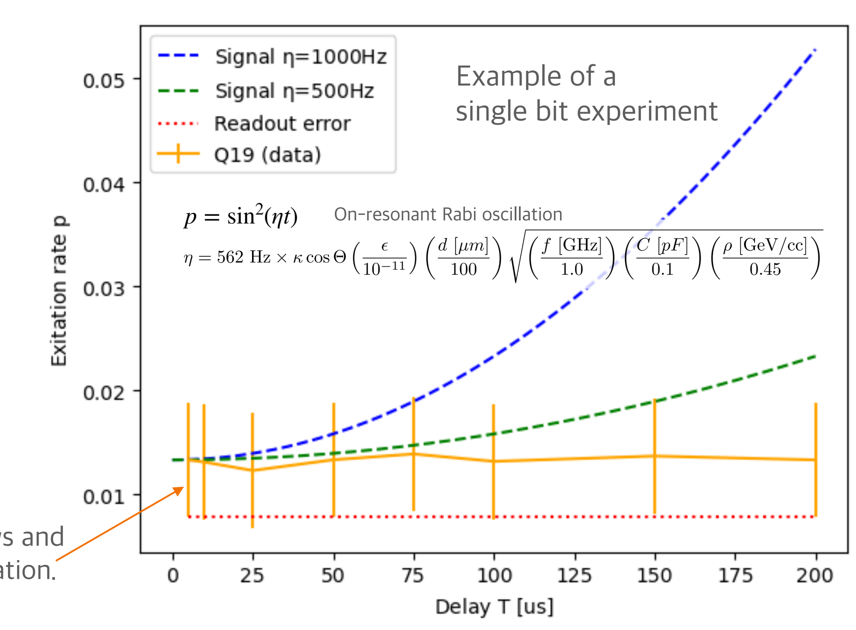


IBM Kawasaki 127 bit

- T_1 average: 202μs
- Ave. readout error: 1.1%
- 10^5 sampling per bit Completed in ~60s

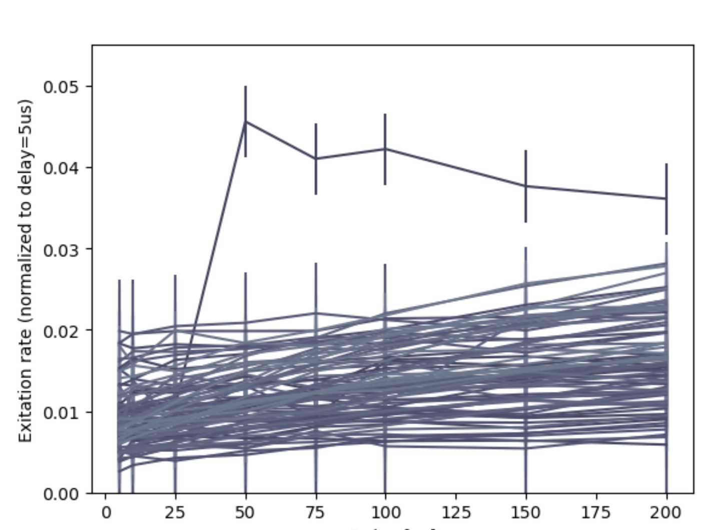
Signal: $|e\rangle$ **fraction**

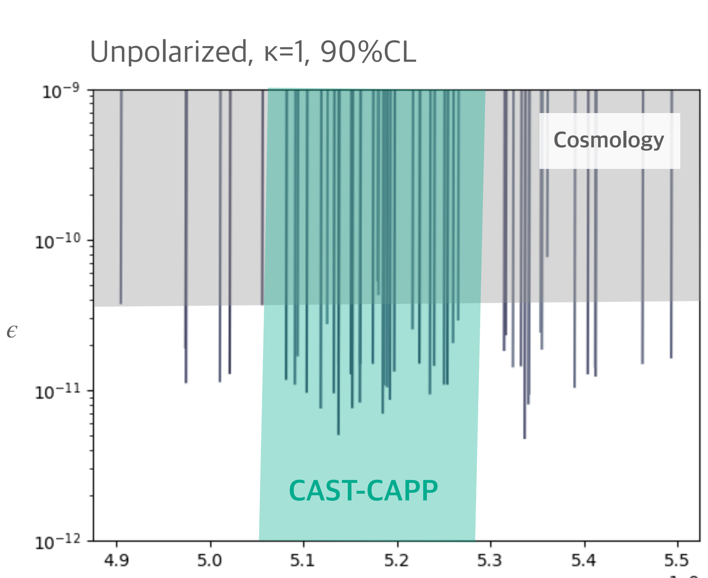
- Proportional to the delay



Error bar in the data includes stat.+syst.
Syst. error: Diff. btw. the excitation rate w/ T=5μs and the readout error reported by calibration.
Likely too conservative!

First Result @Fixed frequency





Selection on qubits used:

- T_1>100μs
- Readout error <2%, $p(T=5\mu s)$ / Readout error < 2 → **52 bits selected**

No anomalous increase in the excitation rate observed.

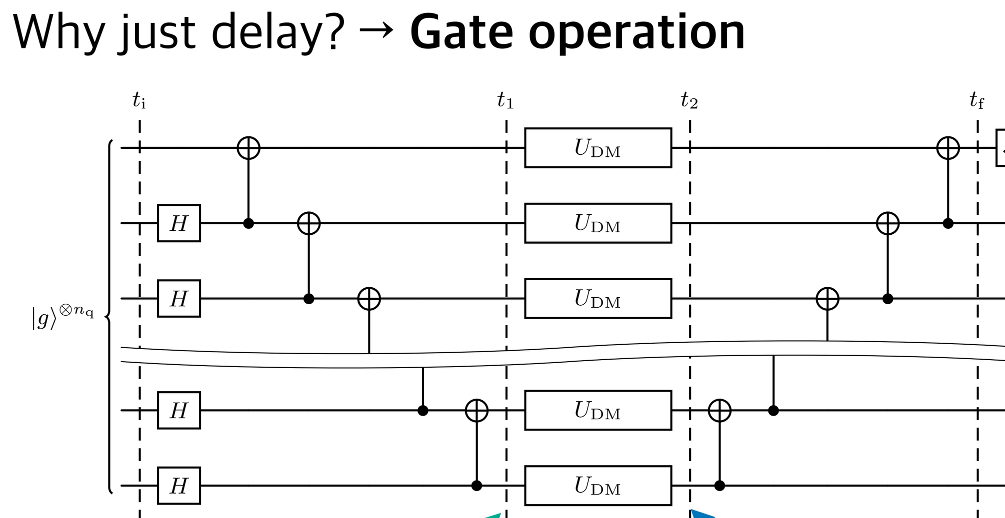
Tentative limit & Outlook

- Transmon design/parameter assumed: Quoted from the pheno paper
- Chip package effect not considered yet
  The DM-induced E-field is likely suppressed by the chip package (κ<<1).
- Width not considered yet.
  May have O(1MHz) sensitivity width from qubit's off-resonant response
- Systematic dominant Better understanding on noise can still boost a lot

Towards deeper sensitivity: n_q^2-enhancement

Why just delay? → **Gate operation**

Sichanugrist et al. PRL 133 (2), 021801

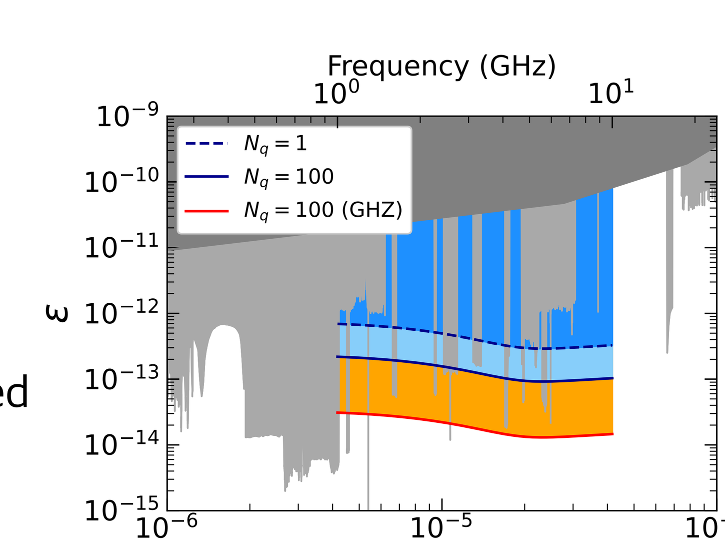


$|\Psi(t_1)\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle^{\otimes n_q} + |-\rangle^{\otimes n_q}\right)$

$|\Psi(t_2)\rangle = \frac{1}{\sqrt{2}}\left(e^{in_q\delta}|+\rangle^{\otimes n_q} + e^{-in_q\delta}|-\rangle^{\otimes n_q}\right)$

$|\Psi(t_f)\rangle = [\cos(n_q\delta)|g\rangle + i\sin(n_q\delta)|e\rangle] \otimes |+\rangle^{\otimes(n_q-1)}$

- Entanglement enables "summation" of the phase acquired in each bit.
- Signal rate ∝ n_q^2 instead of n_q
- Technical requirements:
  - Qubit frequencies need to be aligned
  - Per-bit T_1>O(ms) and QEC → Reasonable in FTQC era?



Towards a wide-band search

1. SQUID-based tuning → See Karin Watanabe's poster
2. Use of Floquet qubit resonance

"Floquet qubit"

Hamiltonian of a qubit driven at two frequencies (one on resonance):

$$H(t) = \underbrace{-\frac{\omega_q}{2}\sigma_Z + \left[\alpha_{drive}\cos\omega_q t\right]\sigma_X}_{H_F(t)} + \underbrace{\left[\alpha_{DM}\cos(\omega_{DM}t + \phi_{DM})\right]\sigma_X}_{H_{DM}(t)}$$

- Floquet theory: "For $H(t+T) = H(t)$, there exist solutions $e^{-i\epsilon_n t}|\psi_n(t)\rangle$ where $|\psi_n(t+T)\rangle = |\psi_n(t)\rangle$"
  - ϵ_n: quasienergies
  - Apply to $H_F(t)$ → Periodic solutions = Floquet qubit is approximately $|0_F\rangle = |+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and $|1_F\rangle = |-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$ with quasienergies $\pm\alpha_{drive}$
- This Floquet qubitais resonant at $\omega_q \pm \alpha_{drive}$ ("AC Stark shift" of the qubit)
- $|0_F\rangle$ and $|1_F\rangle$ have ×~2.5 enhanced coherence times ("spin locking")

DM search via qubit dynamics

When $\omega_{DM} = \omega_q \pm \alpha_{drive}$, qubit-frame Pauli expectation values evolve as

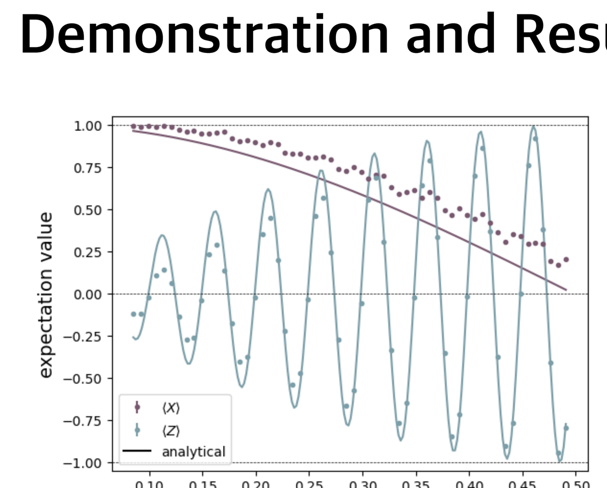
$\langle X(t)\rangle = \cos\left(\frac{\alpha_{DM}}{2}t\right)$

$\langle Y(t)\rangle = \pm\sin\left(\frac{\alpha_{DM}}{2}t\right)\cos(\alpha_{drive}t \pm \phi_{DM})$

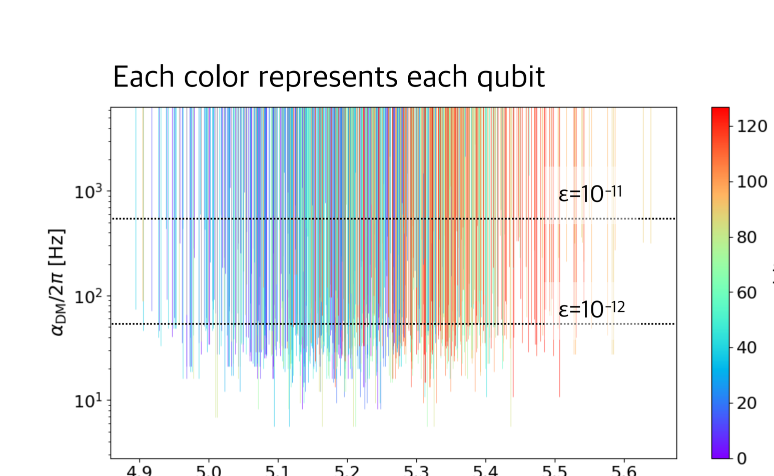
$\langle Z(t)\rangle = \pm\sin\left(\frac{\alpha_{DM}}{2}t\right)\sin(\alpha_{drive}t \pm \phi_{DM})$

→ Probe DM frequency by scanning α_{drive} and observing $\langle X\rangle, \langle Y\rangle, \langle Z\rangle$

Demonstration and Results



$\langle X\rangle$ and $\langle Z\rangle$ with α_{drive}~20MHz and artificial α_{DM}~1MHz on an IBM device



Preliminary observed limits (90% CL) on α_{DM}

※ Upper limit of <562Hz reads ε<10⁻¹¹ with assuming a starndard transmon design, κ=1, and no systematics assigned.