

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

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Quantum computers are DM detectors

E-field from the DM is Qubit drive pulse



Excitation rate after τ:

Moroi et al. PRL 131, 211001 (2023)

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

Out detector



Qubit:

IEM Kawasaki

Median 1.200e-2



as of 16th Sep 2024

127
Qubits
3.2%
EPLG
29K
CLOPS

Status:	• Online
QPU region:	us-east
Total pending jobs:	1222 jobs
Processor type 🛈:	Eagle r3
Version:	2.1.37
Basis gates:	ECR, ID, RZ, SX, X
Your instance usage:	157 jobs

Median ECR error:	7.134e-3
Median SX error:	2.449e-4
Median readout error:	1.130e-2
Median T1:	197.19 us
Median T2:	140.62 us



Connection:

Median 7.649e-3

127-bit Eagle processor





Jobs

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~	V OPEN EDITORS 9 unsaved	DM_IBMQ > 🛢	ultibit_launch.ipynb > 🍨 #qprop = backend_properties.qubits[0]	
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, o	multibit_launch.ipynb DM_IBMQ			
63	analyze_multibit_delay.ipynb DM_I	def si	<pre>mit(delay, shots=100000, ncircuits=600, session=None, batch=None):</pre>	
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	floquet_calib.ipynb			
	🖴 memo.key			
	multibit_floquet_launch.ipynb		-qc.measure(qr, cr1)	
٦,	multibit_launch.ipynb		# Visualize the circuit	
	multibit.ipynb		<pre>qc.draw('mpl')</pre>	
9	pi_pulse_on_floquet_calib.ipynb			
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6	() qiskit-ibm_kawasaki.json		reuite[0] drau([m]])	
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	() qiskit-ibm.json		_compiled = transpile(circuits, backend, initial_layout = list(range(nq)), optimization_level=0, schedul	ing_method='asap')
	() qiskit-ibm1.json			
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3)	> qc-workbook-lecturenotes		if batch:	
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Submit a script like this

5min queue, 1min run time







o Nothing (very) suspicious found

o Limit setting is nearly impossible

IBM doesn't publish qubit design, packaging etc..

- o Need a dedicated reverse engineering
- Assuming a typical transmon and loose packaging for now (likely optimistic).
- Sensitivity limited by the uncertainty on the RO error
- Width not considered yet
 But probably have some width in sensitivity due to the off-resonant Rabi oscillation response.



Outlook - Axion

Unlikely to happen at this point. Only if the quantum industry ends.



Towards deeper sensitivity: Multi-bit interference

Sichanugrist et al. PRL 133 (2), 021801



Towards wide-band: ac Stark shift

Adding one more CW tone at $\omega = \alpha_{drive}$ Rabi oscillation is driven by DM when $\omega_{DM} = \omega_q \pm \alpha_{drive'}$ $\langle X(t) \rangle = \cos\left(\frac{\alpha_{DM}}{2}t\right)$ $\langle Y(t) \rangle = \pm \sin\left(\frac{\alpha_{DM}}{2}t\right) \cos(\alpha_{drive}t \pm \phi_{DM})$ $\langle Z(t) \rangle = \pm \sin\left(\frac{\alpha_{DM}}{2}t\right) \sin(\alpha_{drive}t \pm \phi_{DM})$

 \checkmark

Upper limit on the DM drive strength (in the unit of Rabi freq.)



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First Result @Fixed frequency



Selection on aubits used

- a T₁>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 D Chip package effect not considered yet
- The DM-induced E-field is likely suppressed by the chip package (K<<1).
- Width not considered yet. May have O(IMHz) sensitivity width from qubit's off-resonant response
- Systematic dominant Better understanding on noise can still boost a lot

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):

 $H(t) = -\frac{\omega_{\rm r}}{2}\sigma_{\rm Z} + \left[\alpha_{\rm drive}\cos\omega_{\rm q}t\right]\sigma_{\rm X} + \left[\alpha_{\rm DM}\cos(\omega_{\rm DM}t + \phi_{\rm DM})\right]\sigma_{\rm X}$ $H_{\rm DM}(t)$ $H_{r}(t)$

- Floquet theory: "For H(t + T) = H(t), there exist solutions $e^{-ic_n t} |\psi_n(t)\rangle$ where $|\psi_n(t+T)\rangle = |\psi_n(t)\rangle^*$
- e_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 gubitais resonant at $w_q \pm \alpha_{drive}$ ("AC Stark shift" of the gubit)
- |0_F) and |1_F) have ×~2.5 enhanced coherence times ("spin locking")

Sichanugrist et al. Why just delay? → Gate operation PRL 133 (2), 021801 +A Ulani 0'mi oded" state to be measured $|\Psi(t_l)\rangle = |\cos(u_l t)|_{\beta}$ + $i\sin(u_l \delta)|_{\delta} |_{\beta} |_{\beta} |_{\beta} |_{\gamma}$ - 11 Um fraction of $||_{\mathcal{C}}$) readout ~ $n^2\delta^2$ + Cau + 0 +22 Um GHZ stat $|\Psi(t_2)\rangle = \frac{1}{\sqrt{2}} \left(e^{in_q \delta} |+\rangle^{\otimes n_q} + e^{-in_q \delta} |-\rangle^{\otimes n_q} \right)$ $|\Psi(t_1)\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle^{\otimes n_{\eta}} + |-\rangle^{\otimes n_{\eta}}\right)$ Entanglement enables "summation" of the phase acquired in each bit. o Signal rate $\propto n_0^2$ instead of n_0 Technical requirements: o Qubit frequencies need to be aligned o Per-bit T1>O(ms) and QEC → Reasonable in FTQC era?

IBM

178

-73

e.g. <u>n</u>₄=3

Delay 1

preparation DM evolution Measurement

Example of a

single bit experiment

75 300 115 150 175 Delay T [un]

on Mass (eV)

- 1

State

 $p = \sin^2(q)$

25 50

Towards deeper sensitivity: ng2-enhancement

 $T_{\rm delay} < T_1$

DM search via qubit dynamics

- When $\omega_{\rm DM} = \omega_q \pm \alpha_{
 m driver}$ qubit-frame Pauli expectation values evolve as $\langle X(t) \rangle = \cos \left(\frac{a_{DM}}{2} t \right)$
- $\langle Y(t) \rangle = \pm \sin\left(\frac{\alpha_{\rm DM}}{2}t\right) \cos(\alpha_{\rm drive}t \pm \phi_{\rm DM})$
- $\langle Z(t) \rangle = \pm \sin \left(\frac{\alpha_{\text{DM}}}{2} t \right) \sin(\alpha_{\text{drive}} t \pm \phi_{\text{DM}})$
- → 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 $a_{\rm drive}{\sim}20 {\rm MHz}$

and artificial a_{DM}~1MHz on an IBM device





