

Quantum Sensing Radiative Decays of Neutrinos and Dark Matter Particles



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2508.09139, work in collaboration with
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Plan

- Quantum Sensing
- Quantum Enhancement of the Signal Rate
- Summary

2025 KPS Fall Meeting

Regular Academic Conference of the Korean Physical Society

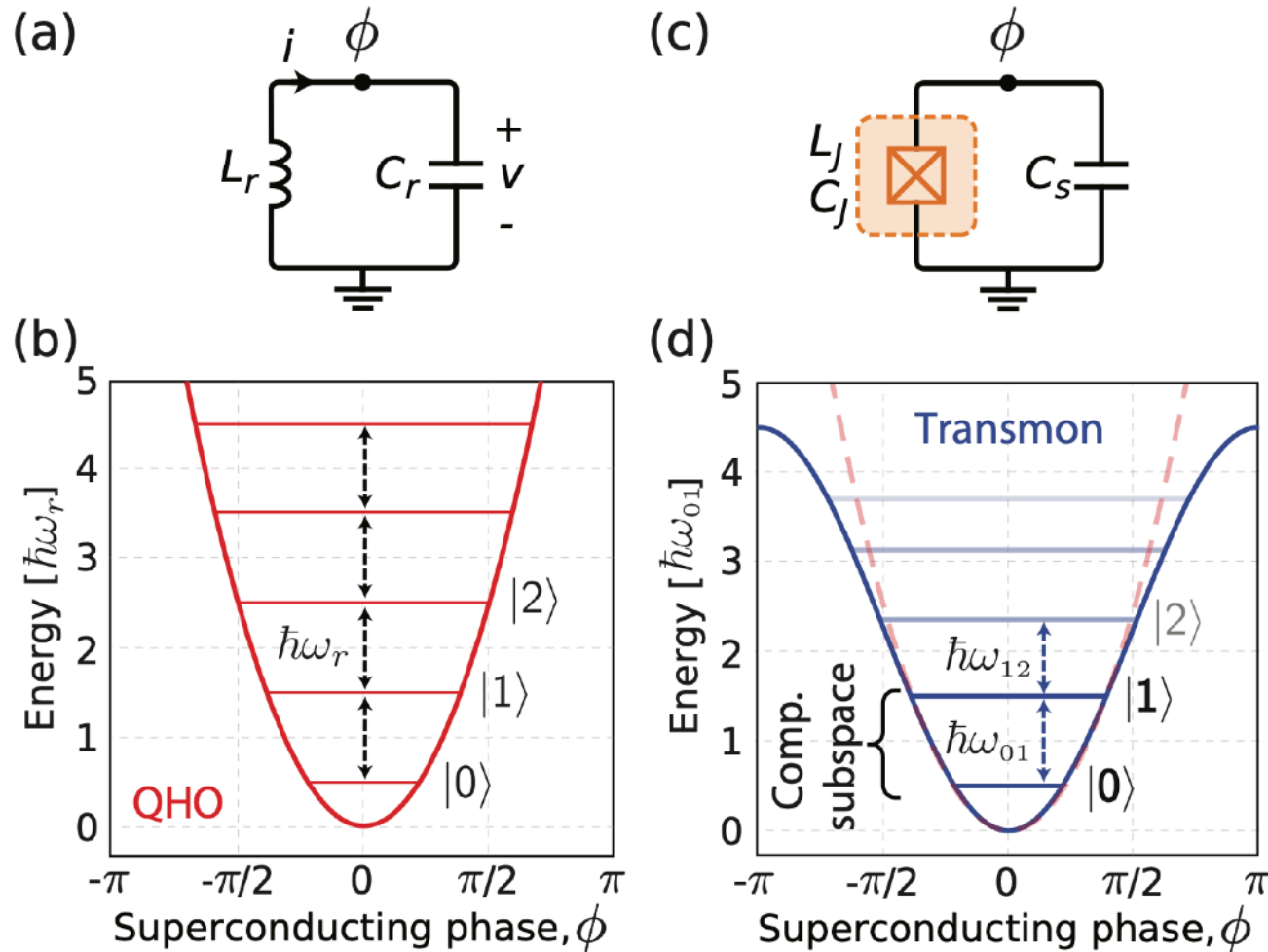


•• **October 21(Tue) ~ 25(Sat), 2025**
•• **Kimdaejung Convention Center, Gwangju**

Where quantum computers are (potentially) useful

- Quantum optimization: combinatorial problems at the LHC [2410.22417](#)
 - Finance, physics, materials discovery, science [2508.09139](#)
- Quantum devices (qubits) as sensors: detection of dark matter and neutrino decays
 - Dark matter detection, quantum magnetometry + electrometry, atomic clocks
- Quantum simulation/Hamiltonian simulation
 - Physics, chemistry
- Quantum machine learning [2510.10501](#), [2411.15315](#), [2412.21082](#), [2411.13520](#)
 - Classification, generative models, anomaly detection
- Quantum cryptography and security
 - Quantum key distribution, post-quantum cryptography
- Quantum linear algebra and numerical methods
 - HHL algorithms, eigenvalue problems
- Quantum communication and networks
 - Entanglement and violation of Bell's inequality [2407.01663](#), [2305.07075](#)
 - Teleportation, quantum internet
- Quantum sampling
 - Supremacy tasks, random circuits

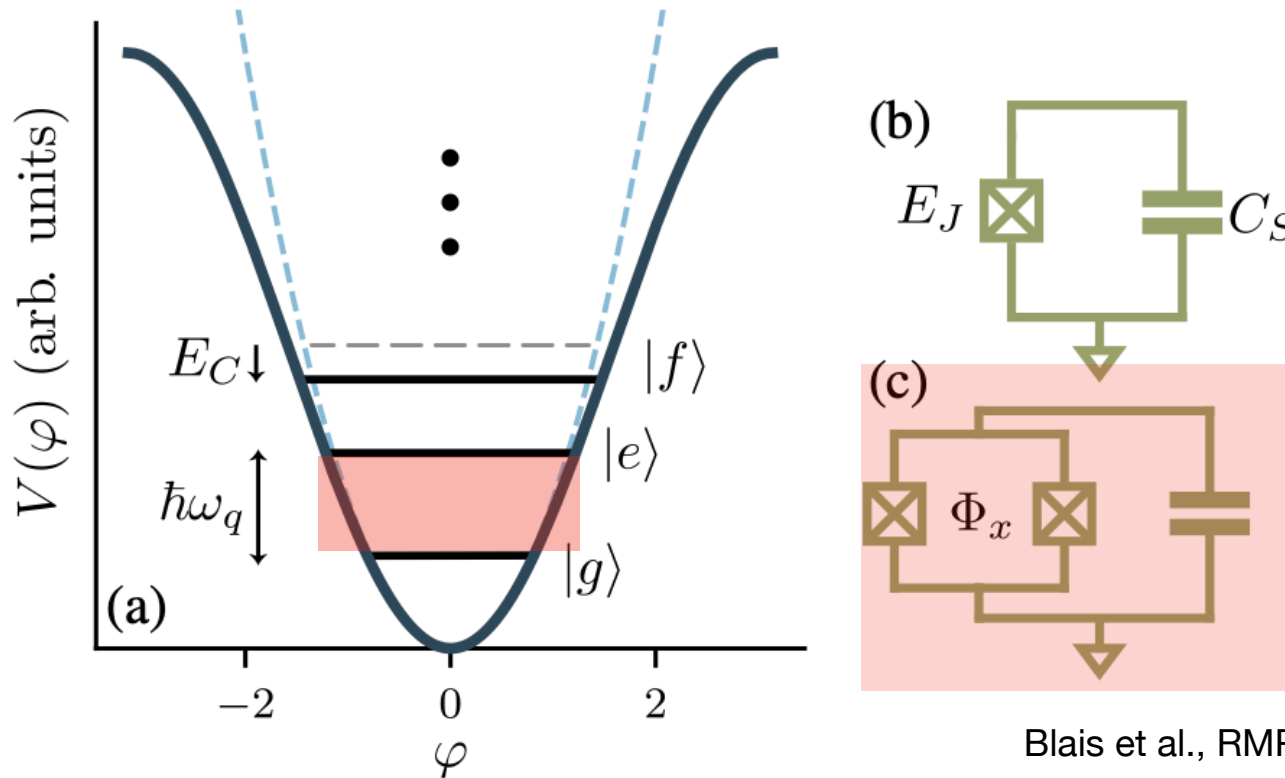
Transmon qubit = Capacitor + Josephson junction



P. Krantz et.al Applied Physics Reviews 6, 021318 (2019)

- Josephson nonlinearity breaks the harmonic spectrum, leading to discrete, unequal energy levels.
- A system of two lowest states can be considered as qubit with ω_{01} .

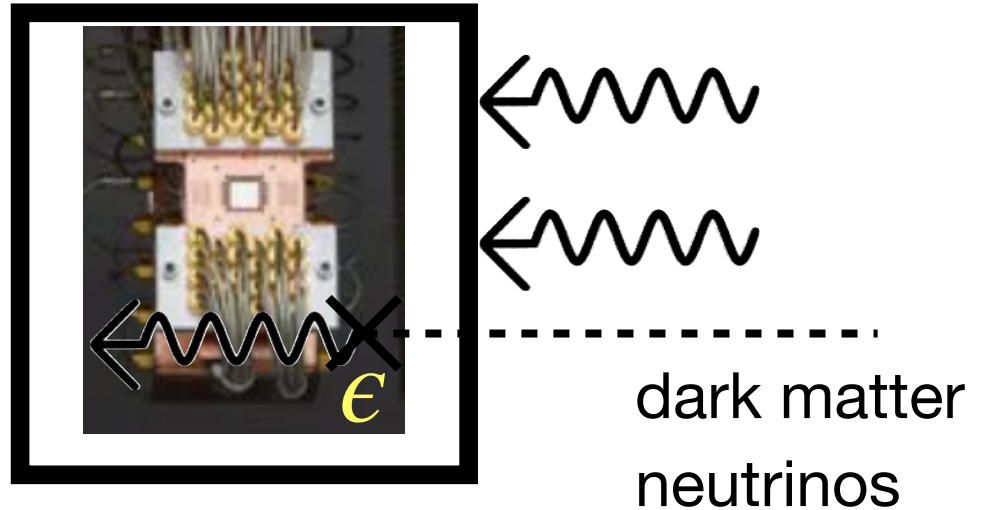
Transmon qubit = Capacitor + Josephson junction



Blais et al., RMP 93 025005 (2021)

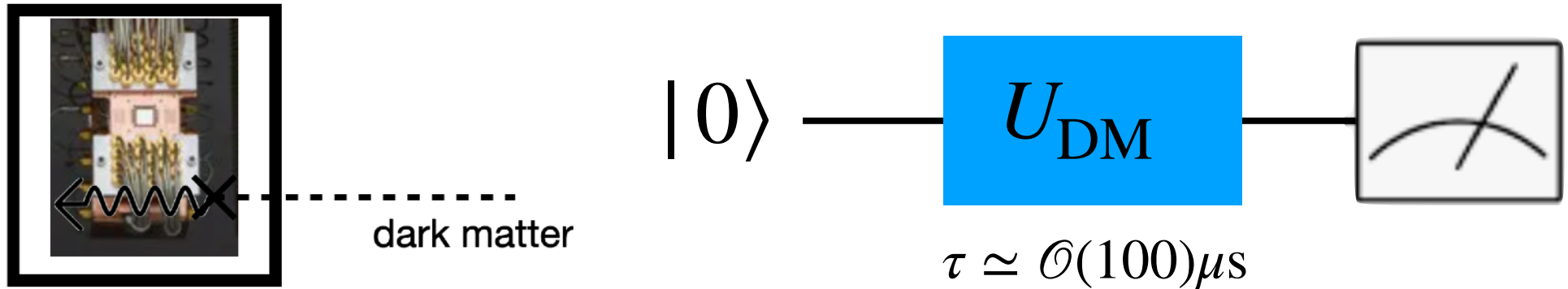
- "By using a superconducting quantum interference device (**SQUID**) rather than a single junction, the **frequency of the transmon qubit becomes flux tunable.**"
- Transmon qubits have discrete energy levels that can be controlled.
- One can scan the frequency ω_q in the (c) SQUID-based system.

$$\omega \simeq \mathcal{O}(1 - 10) \text{ GHz} \quad \lambda \simeq \mathcal{O}(3 - 30) \text{ cm}$$



- For typical device parameters, $\omega \simeq \mathcal{O}(1 - 10)\text{GHz}$ with $\lambda \simeq \mathcal{O}(3 - 30)\text{cm}$
- At refrigerator temperatures $\mathcal{O}(1 - 10)\text{mK}$, a few-GHz transition satisfies $k_B T \ll \hbar\omega$.
 - Thus thermal excitation is strongly suppressed, and the qubit stays in the ground state.
- "Dark Matter" could penetrate the shield, and induce a weak electric field that couples to qubit, $E^{(\text{ext})} = \epsilon\sqrt{2\rho_{\text{DM}}}\sin m_X t$, here ϵ is a kinetic-mixing parameter, ρ_{DM} is the local DM density.
- **If the DM-induced photons fall within this frequency band, they can resonantly excite the qubit - effectively turning dark-matter interactions into observable qubit errors.** For a de Broglie wavelength in this range, $m_{\text{DM}} \sim \mathcal{O}(4 - 40)\mu\text{eV}$

Dark Matter as an operator U_{DM}



- Signal: a weak classical field: wave-like DM, high-frequency gradational waves
- The interaction between DM and qubits, $H_{\text{DM}} = \epsilon (\cos \alpha \sigma_X + \sin \alpha \sigma_Y)$ will drive transitions from $|0\rangle$ to $|1\rangle$.
- The Goal to estimate the signal strength ϵ .

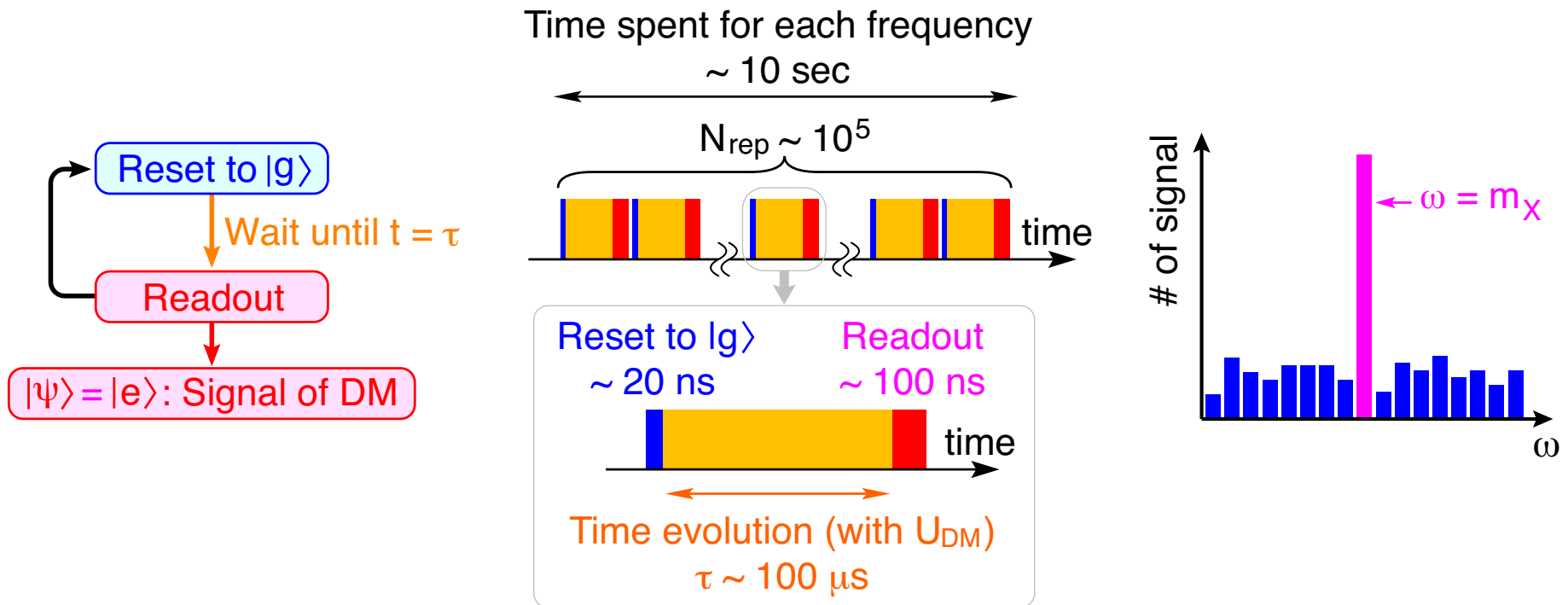
1. Evolve: System evolves from $|0\rangle$ (ground state of free Hamiltonian) under H_{DM} . For a weak signal $\epsilon t \ll 1$,

$$|\psi(0)\rangle = |0\rangle \longrightarrow |\psi(t)\rangle = U(t) |\psi(0)\rangle \approx |0\rangle - ie^{i\alpha} \epsilon t |1\rangle$$

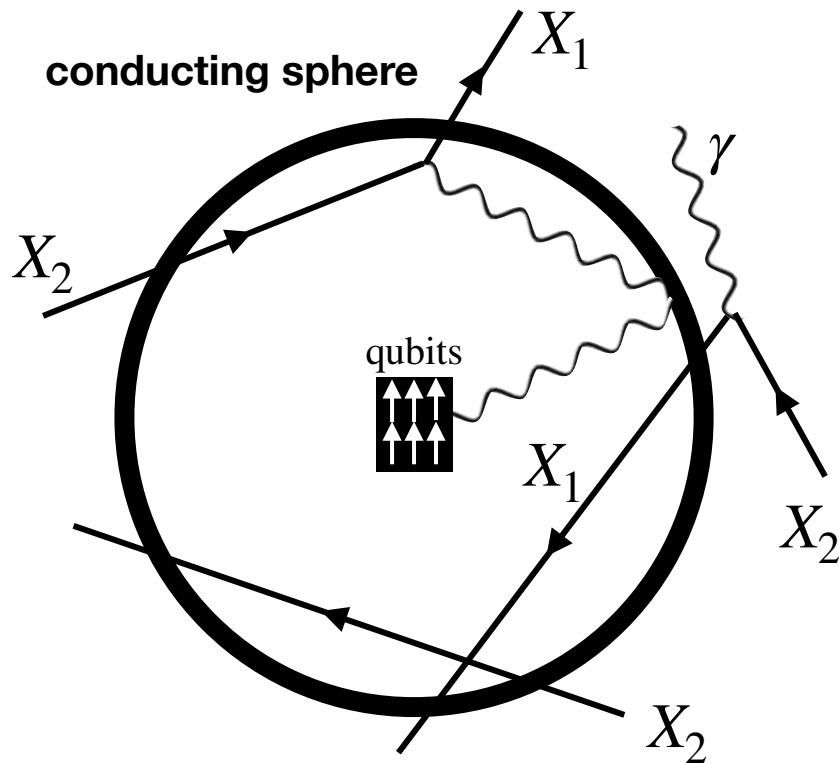
2. Measure: Project $|\psi(t)\rangle$ onto $|0\rangle$ and $|1\rangle$. Probability of finding $|1\rangle$:

$$p_1 = \left| \langle 1 | \psi(t) \rangle \right|^2 = \epsilon^2 t^2$$

Dark Matter as an operator U_{DM}



- Qubits are exposed to microwaves from dark matters over the coherence time $\mathcal{O}(100)\mu\text{s}$
- One can repeat a cycle of (Reset $\rightarrow U_{\text{DM}} \rightarrow$ Measurement) as many as $\mathcal{O}(10^5)$ during 10 seconds.
 - Time for reset qubits $\sim \mathcal{O}(10)\mu\text{s}$
 - Time for measurement $\simeq \mathcal{O}(100)\text{ns}$



- Photon from the transition process of a heavier state into a lighter state will couple to qubits.
- A conducting cavity with reflective inner walls confines photons.

- Two scenarios :

1) Heavier "dark" particle X_2 decays into lighter particle X_1 and a photon γ , with an interaction Lagrangian $\mu X_1^\mu X_2^\nu \tilde{F}^{\mu\nu}$

2) Cosmic neutrino background $C\nu B$, with transition via neutrino magnetic moment interaction, $L \ni (\mu_\nu^{ij}/2) \bar{\nu}_i \sigma^{\mu\nu} \nu_j F_{\mu\nu}$

2508.09139

(Many thanks to Prof. Kyu Jung Bae and Prof. Takeo Moroi for useful discussion.)

Radiative Decays of Neutrinos and Dark Matter Particles

- Photon from a decay process is described by a plane-wave

$$\vec{E}_{\text{eff}} = \bar{E}_{\text{eff}} \vec{n}_E \sin(E_\gamma t) \text{ with a photon energy } E_\gamma = \frac{m_{X_2}^2 - m_{X_1}^2}{2m_{X_2}}.$$

- Energy density of photons $\rho_\gamma = E_\gamma n_\gamma = \epsilon_0 \bar{E}_{\text{eff}}^2$ with $n_\gamma \propto \Gamma_{X_2} n_{X_2}$
- Interaction between a photon from decay process and qubit,

$$H_{\text{int}} = CV d\bar{E}_{(\text{eff})} \cos \Theta \sin(E_\gamma t) \equiv 2\eta \sin(E_\gamma t)(\hat{a} + \hat{a}^\dagger),$$

so that the total Hamiltonian

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

- If one tunes $\omega \simeq E_\gamma$, then with rotating-wave approximation which neglects the rapid oscillation with averaging into 0,

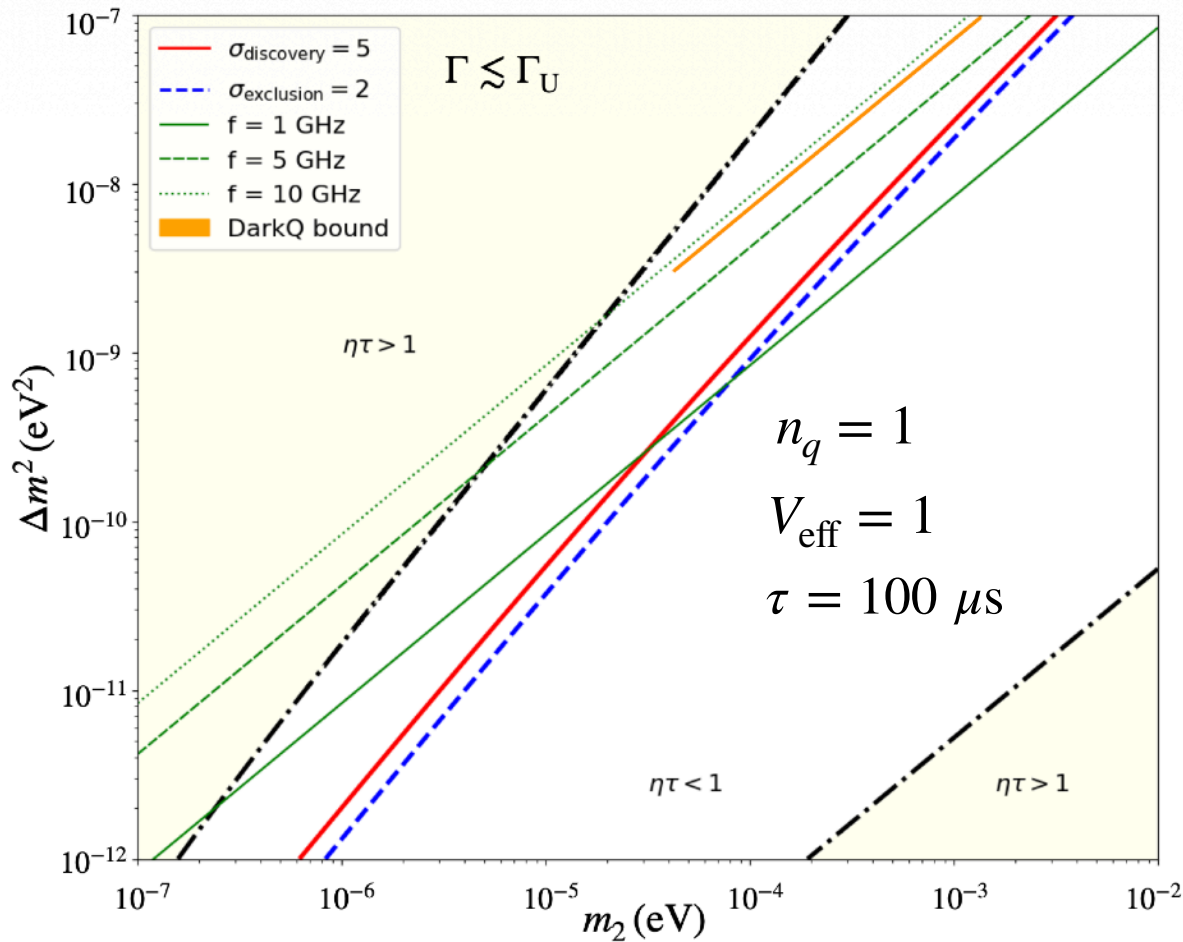
$$i \frac{d}{dt} \begin{pmatrix} \psi_g(t) \\ \psi_e(t) \end{pmatrix} \simeq \begin{pmatrix} 0 & -i\eta \\ -i\eta & 0 \end{pmatrix} \begin{pmatrix} \psi_g(t) \\ \psi_e(t) \end{pmatrix} \Rightarrow \begin{aligned} \psi_g(t) &\simeq \cos \eta t \\ \psi_e(t) &\simeq \sin \eta t \end{aligned}$$

with initial condition of $\psi_g(0) = 1$ and $\psi_e(0) = 0$

- Thus, a transition probability $p_{g \rightarrow e}(t)$ from $|g\rangle \rightarrow |e\rangle$

$$p_* \equiv p_{g \rightarrow e}(\tau) = |\psi_e(\tau)|^2 \simeq \sin^2(\eta\tau) \simeq (\eta\tau)^2 \text{ within a coherent time}$$

- Signals: $N_{\text{sig}} = p_* \times N_{\text{try}}$
- Backgrounds
 - Uniform 0.1% readout error: $10^{-3} \times N_{\text{try}}$
 - Thermal noise: $e^{-\omega/T} \times N_{\text{try}}$, where $T \sim 30$ mK



- Scanning the frequency range from **1 - 10 GHz** with a quality factor $Q = 10^6$, which sets the frequency resolution to $\delta f = f/Q$.
- This corresponds to about 2.3×10^6 resolvable frequency bins across the **1-10GHz** range
- One year continuous scan (3.15×10^7 s) yields 14s of integration time per frequency bin, corresponding to $N_{\text{try}} = \mathcal{O}(10^5)$ / bin

$$p_* = 0.069$$

$$p_* \simeq p_*^0 \times \cos^2 \Theta \left(\frac{V_{\text{eff}} \rho_{\text{DM}}}{0.45 \text{ GeV cm}^{-3}} \right) \left(\frac{\Delta m^2}{m_2^2} \right) \left(\frac{d}{100 \text{ } \mu\text{m}} \right)^2 \left(\frac{C}{0.1 \text{ pF}} \right) \left(\frac{f}{1 \text{ GHz}} \right) \left(\frac{\tau}{100 \text{ } \mu\text{s}} \right)^3$$

- Assuming a local dark matter density $\rho_{\text{DM}} = 0.45 \text{ GeV/cm}^3$ and decay rate $\Gamma \lesssim \Gamma_{\text{U}} = 2.299 \times 10^{-18} \text{ s}^{-1}$ ensuring that X_2 remains stable over the age of the universe.

Quantum Enhancement of the Signal Rate

- Suppose we have N identical sensors. What is the maximum sensitivity?

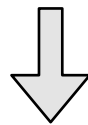
Without entanglement

$$|0\rangle \xrightarrow{\text{DM}} |0\rangle - i\epsilon\tau |1\rangle \Rightarrow p = \epsilon^2\tau^2$$

$$|0\rangle \xrightarrow{\text{DM}} |0\rangle - i\epsilon\tau |1\rangle \Rightarrow p = \epsilon^2\tau^2$$

⋮

$$|0\rangle \xrightarrow{\text{DM}} |0\rangle - i\epsilon\tau |1\rangle \Rightarrow p = \epsilon^2\tau^2$$



$$p_{\text{total}} = 1 - (1 - p)^N \approx Np = N\epsilon^2\tau^2$$

Classical

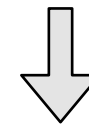
- N independent system are prepared and separately detected

With entanglement

$|\psi\rangle \equiv$ some entangled state

$$|\psi\rangle \xrightarrow{\text{DM}} |\psi\rangle + O(N\epsilon\tau) |\psi_{\perp}\rangle$$

An example of such a state is the GHZ state.



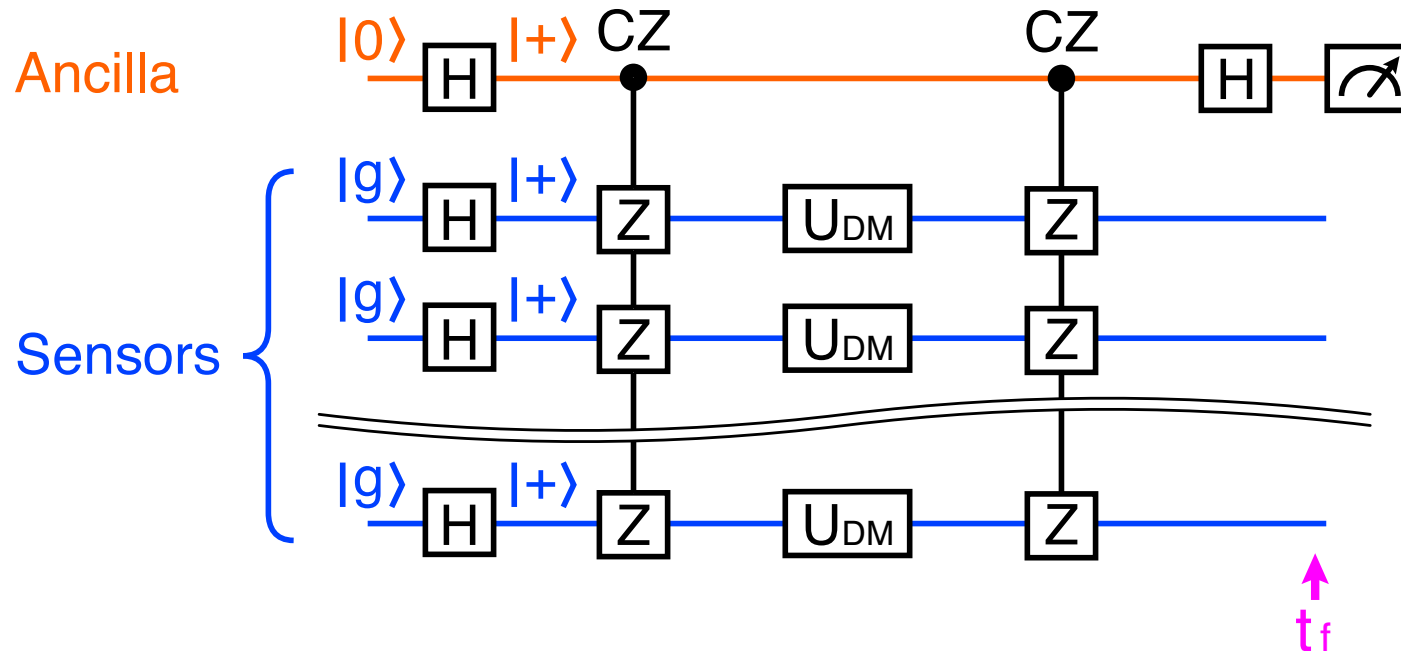
$$p \sim N^2\epsilon^2\tau^2 \quad ?$$

Quantum

- Highly correlated configurations are measured collectively with a single measurement that encompasses all the systems.

Quantum Enhancement of the Signal Rate

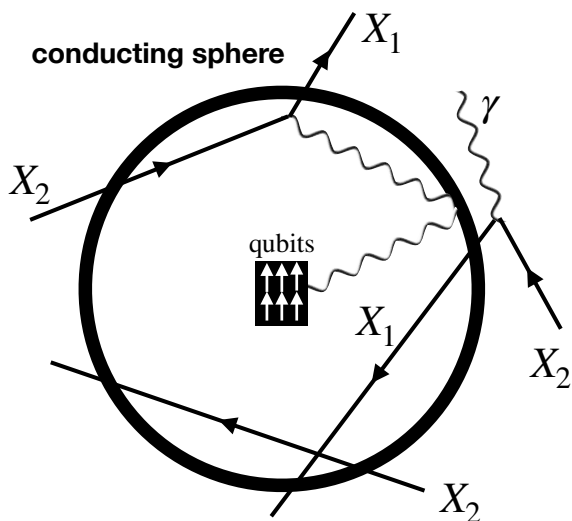
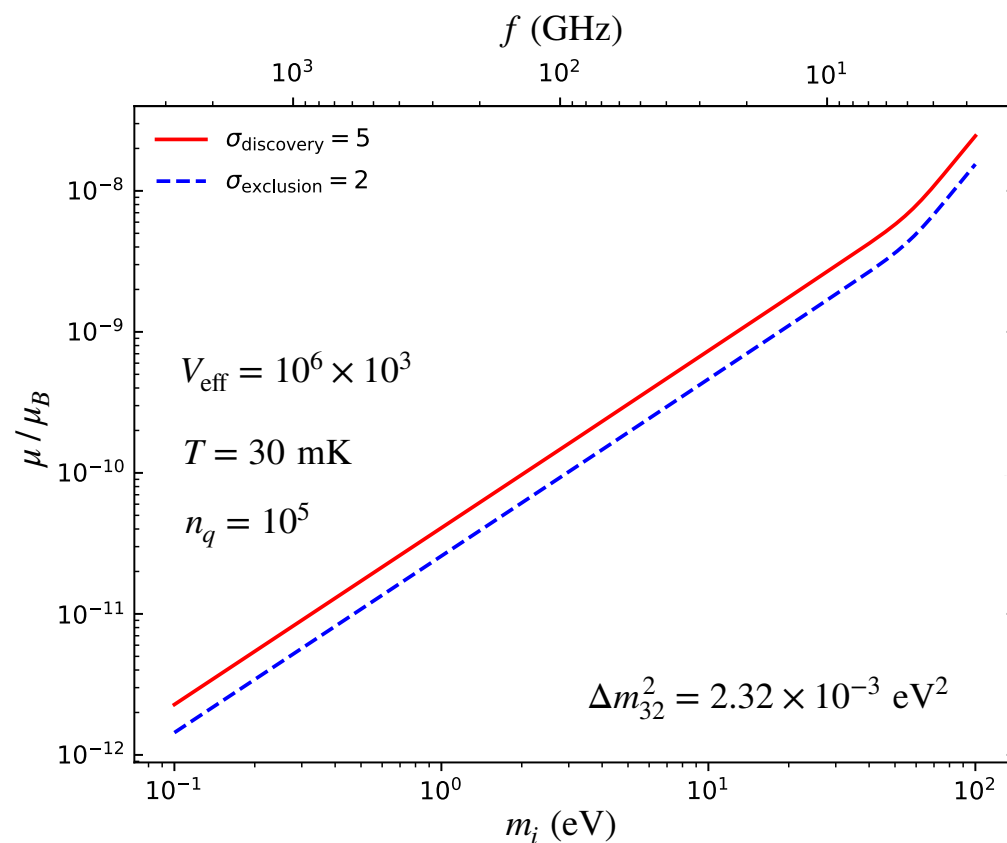
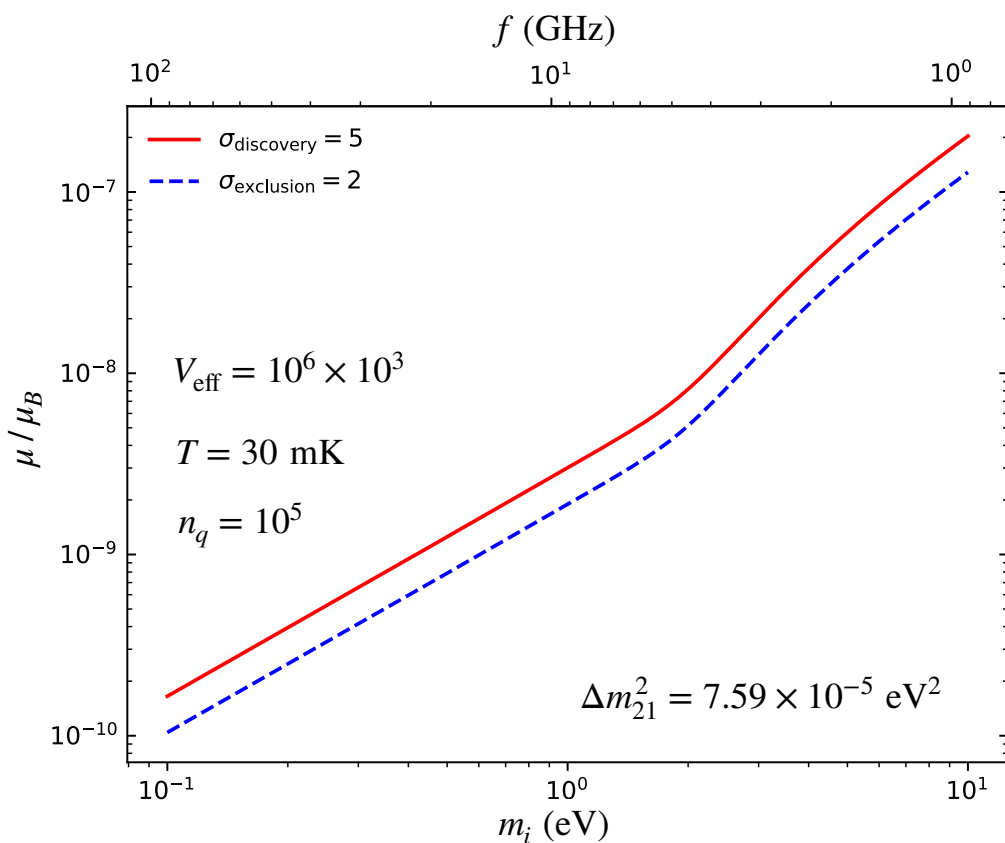
One measurement cycle for the signal enhancement



$$|\Psi(t_f)\rangle = (\cos N_q \delta |0\rangle + i \sin N_q \delta |1\rangle) \otimes |+\rangle^{\otimes N_q}$$

$\Rightarrow$ Ancilla qubit can be excited: $P_{0 \rightarrow 1} \simeq \sin^2 N_q \delta \simeq N_q^2 \delta^2$

Bounds on neutrino transition magnetic moment



Decay volume

$$n_2 \rightarrow n_2 \left(\frac{V_{\text{eff}}}{\text{cm}^3} \right)$$

$$V_{\text{eff}} = 1 \text{ m}^3 = 10^6 \text{ cm}^3$$

Entanglement

$$P_* \simeq n_q^2 (\eta \tau)^2$$

$$n_q = 10^5$$

Current reactor bounds are $\mu < 10^{-11} \mu_B$ 2508.09139

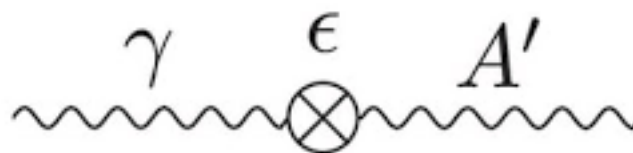
Summary

- It has been shown that quantum computing has the potential to provide a better performance than their classical counterparts in experimental and theoretical high energy physics
- Qubit-sensor may be used for look for rare decays of dark matter particles and neutrinos
- What other signals?
 - Hidden photon dark matter, axions, DM decays
 - High frequency gravitational wave detection
- What other quantum devices?
 - Transmon, trapped ion, Rydberg, what else?
 - Ge-based spin qubits
- Quantum enhancement of signal rate
 - Quantum algorithms that could enhance beyond n_q^2
- Testing on real quantum computers is being discussed.

Sources of Electric Fields

- $|g\rangle \leftrightarrow |e\rangle$ transition occurs if **DM field** generates electric field

- Hidden photon



2212.03884, transmon

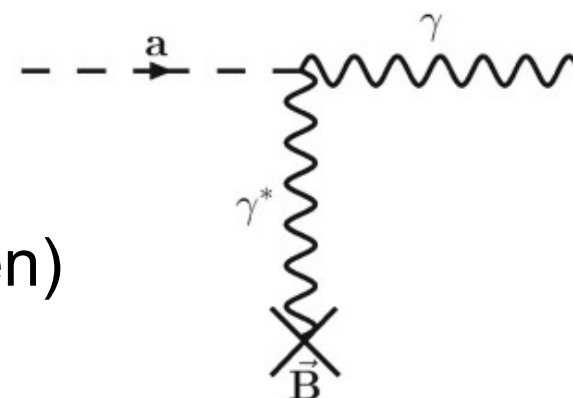
2507.12860, Rydberg atom

2507.17825, trapped ion

- Axions (if external magnetic field is given)

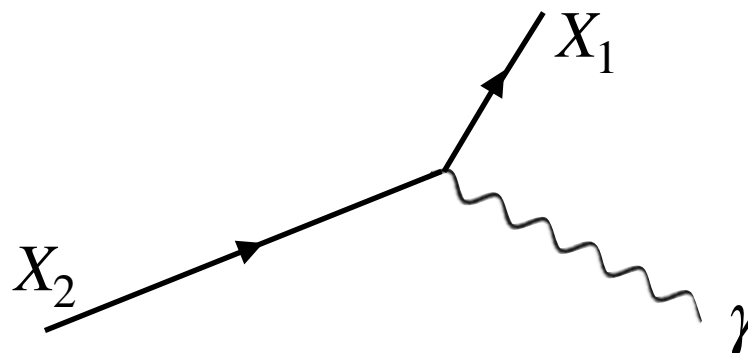
2407.19755, transmon

2507.17825, trapped ion



- DM and neutrino decays

2508.09139, transmon, trapped ion

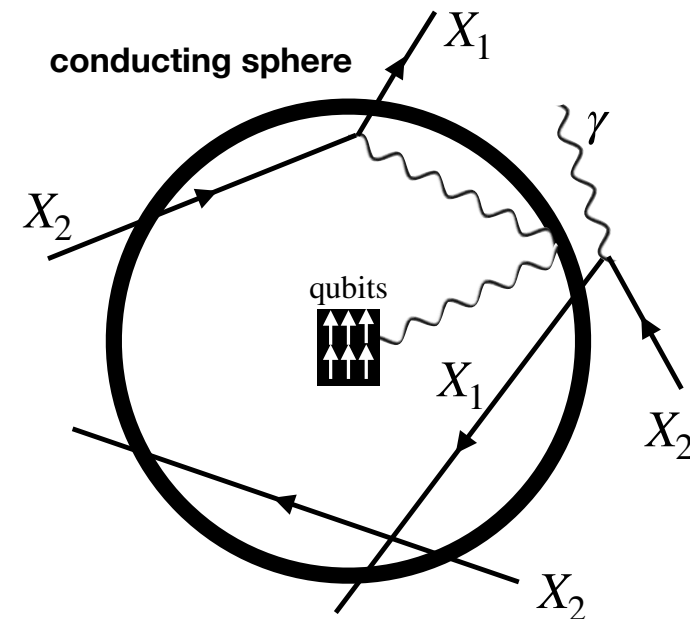


Radiative Decays of Dark Matter Particles

$$X_2 \rightarrow X_1 + \gamma \quad E_\gamma = \frac{m_2^2 - m_1^2}{2m_2} = \frac{\Delta m^2}{2m_2}$$

$$\rho_\gamma = E_\gamma n_\gamma = \Gamma \mathcal{T} n_2 \frac{\Delta m^2}{2m_2}$$

$$\vec{E}_{(\text{eff})} = \bar{E}_{(\text{eff})} \vec{n}_E \sin(E_\gamma t) \quad \bar{E}_{(\text{eff})} = \sqrt{\frac{\Gamma \mathcal{T} n_2 \Delta m^2}{2m_2 \varepsilon_0}}$$



For transmon qubits

$$\begin{aligned} \mathcal{H}_{\text{int}} &= CV d \bar{E}_{(\text{eff})} \cos \Theta \sin(E_\gamma t) \\ &= 2\eta \sin(E_\gamma t) (\hat{a} + \hat{a}^\dagger), \end{aligned}$$

$$\eta \equiv \frac{1}{2\sqrt{2}} d \sqrt{C\omega} \cos \Theta \bar{E}_{(\text{eff})}$$

For trapped ions

$$\begin{aligned} \mathcal{H}_{\text{int}} &= e \vec{E}_{(\text{eff})} \cdot \vec{x} \\ &= \sum_n \frac{e E_{(\text{eff})}^n}{\sqrt{2m_{\text{ion}} w_r^n}} \hat{a}_n^\dagger e^{-i\omega_r^n t} + h.c., \end{aligned}$$

$$\eta \equiv \frac{1}{2\sqrt{2}} \frac{e \bar{E}_{(\text{eff})}}{\sqrt{m_{\text{ion}} w_r^n}}$$

Radiative Decays of Dark Matter

$$\mathcal{H} = \omega |e\rangle\langle e| + 2\eta \sin(E_\gamma t) (|e\rangle\langle g| + |g\rangle\langle e|)$$

$$i \frac{d}{dt} \begin{pmatrix} \psi_g(t) \\ \psi_e(t) \end{pmatrix} \simeq \begin{pmatrix} 0 & -i\eta \\ -i\eta & 0 \end{pmatrix} \begin{pmatrix} \psi_g(t) \\ \psi_e(t) \end{pmatrix} \Rightarrow \begin{aligned} p_{g \rightarrow e}(t) &= |\psi_e(t)|^2 \simeq \sin^2 \eta t \\ p_* &\equiv p_{g \rightarrow e}(\tau) \simeq (\eta \tau)^2 \\ \text{Transition probability} \end{aligned}$$

$$\psi_g(t) \simeq \cos \eta t, \quad \psi_e(t) \simeq \sin \eta t.$$

- Signals: $N_{\text{sig}} = p_* \times N_{\text{try}}$, where $N_{\text{try}} = n_q \times n_{\text{rep}}$
- Backgrounds
 - Uniform 0.1% readout error: $10^{-3} \times N_{\text{try}}$
 - Thermal noise: $e^{-\omega/T} \times N_{\text{try}}$, where $T \sim 30$ mK

Dark matter decay

$$\mu X_1^\mu X_2^\nu \tilde{F}_{\mu\nu}$$

$$\Gamma(X_2 \rightarrow X_1 + \gamma) = \frac{\mu^2}{96\pi} \frac{(m_2^2 - m_1^2)^3 (m_2^2 + m_1^2)}{m_2^5 m_1^2}$$

$$\rho_{\text{DM}} \approx m_2 n_2 ,$$

$$\approx \frac{\mu^2}{48\pi} \frac{(\Delta m^2)^3}{m_2^5}, \quad \Delta m^2 \ll m_1^2 \lesssim m_2^2$$

Bound on life time

$$\Gamma \lesssim \Gamma_{\text{U}} = 2.299 \times 10^{-18} \text{ s}^{-1}$$

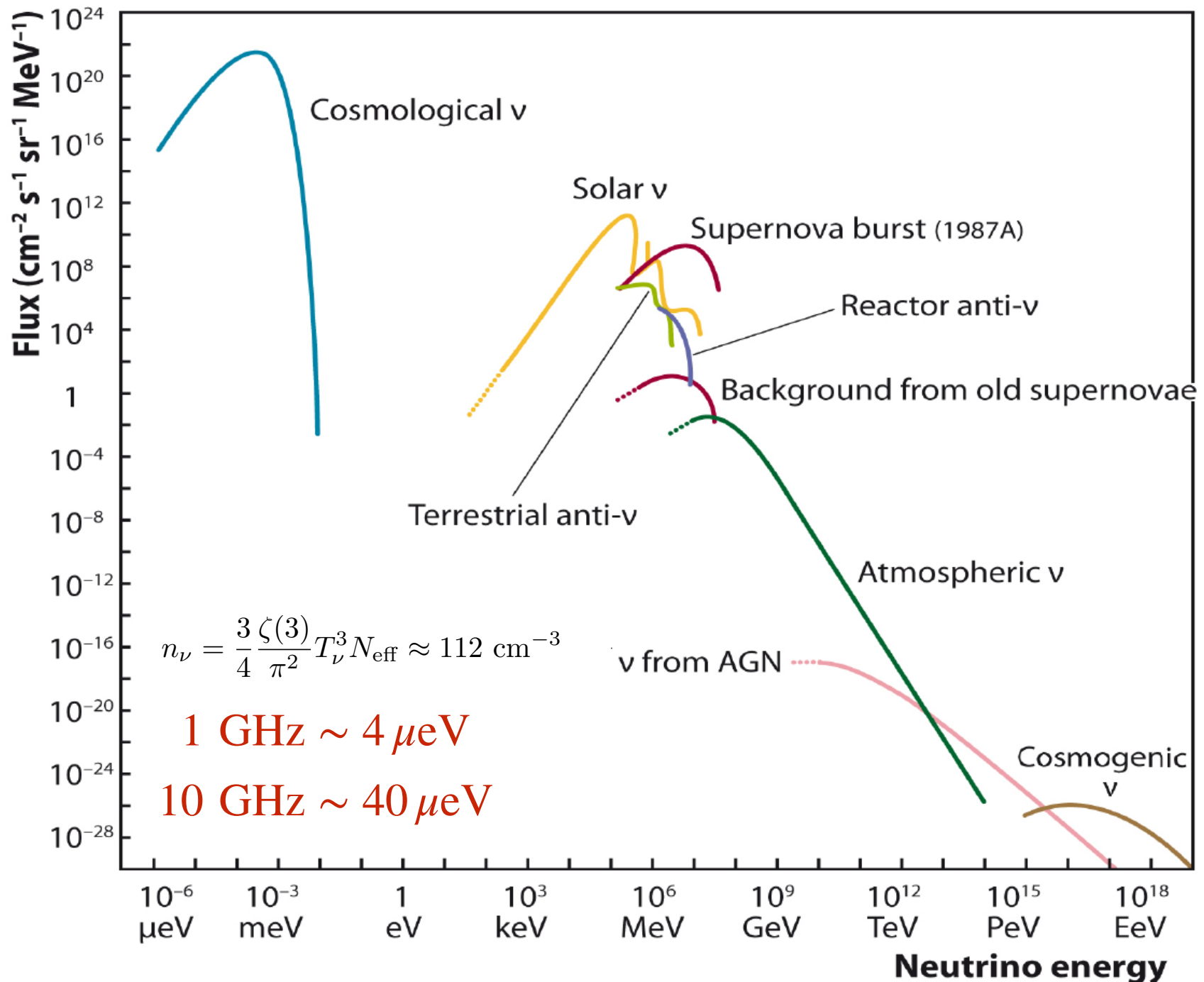
$$(\mu_{\text{max}}^{\text{Uni}})^2 \approx 48\pi m_2^2 \left(\frac{m_2}{\Delta m^2} \right)^3 \Gamma_{\text{U}}$$

$$p_* \simeq p_*^0 \times \cos^2 \Theta \left(\frac{V_{\text{eff}} \rho_{\text{DM}}}{0.45 \text{ GeV cm}^{-3}} \right) \left(\frac{\Delta m^2}{m_2^2} \right) \left(\frac{d}{100 \text{ } \mu\text{m}} \right)^2 \left(\frac{C}{0.1 \text{ pF}} \right) \left(\frac{f}{1 \text{ GHz}} \right) \left(\frac{\tau}{100 \text{ } \mu\text{s}} \right)^3$$

$$p_*^0 = 0.069.$$

$$f \simeq 1.2 \text{ GHz} \times \left(\frac{\Delta m^2}{10^{-10} \text{ eV}^2} \right) \left(\frac{10^{-5} \text{ eV}}{m_2} \right)$$

Neutrino fluxes from different sources as a function of the neutrino energy



Neutrino transition magnetic moment

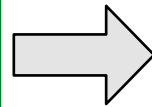
$$E_{C\nu B} \sim 10^{-6} - 10^{-4} \text{ eV}$$

$$n_\nu = \frac{3}{4} \frac{\zeta(3)}{\pi^2} T_\nu^3 N_{\text{eff}} \approx 112 \text{ cm}^{-3}$$

$$\frac{\mu_\nu^{ij}}{2} \bar{\nu}_i \sigma^{\mu\nu} \nu_j F_{\mu\nu} + h.c.$$

$$\mu_\nu = \frac{3eG_F m_\nu}{8\sqrt{2}\pi^2} \approx 3 \times 10^{-19} \mu_B \left(\frac{m_\nu}{1 \text{ eV}} \right)$$

$$\Gamma_{ij} = \Gamma(\nu_i \rightarrow \nu_j + \gamma) = \frac{\mu_{ij}}{8\pi m_i} \frac{\Delta m_{ij}^2}{2m_i}$$



$$\Delta m_{21}^2 = 7.59 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{32}^2 = 2.32 \times 10^{-3} \text{ eV}^2$$

$$m_2 \simeq \sqrt{\Delta m_{21}^2} \sim 8.6 \times 10^{-3} \text{ eV}$$

$$m_3 \simeq \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2} \sim 0.05 \text{ eV}$$

NH

$$m_1 \simeq \sqrt{|\Delta m_{32}^2 + \Delta m_{21}^2|} \sim 0.0492 \text{ eV}$$

$$m_2 \simeq \sqrt{|\Delta m_{32}^2|} \sim 0.05 \text{ eV},$$

IH

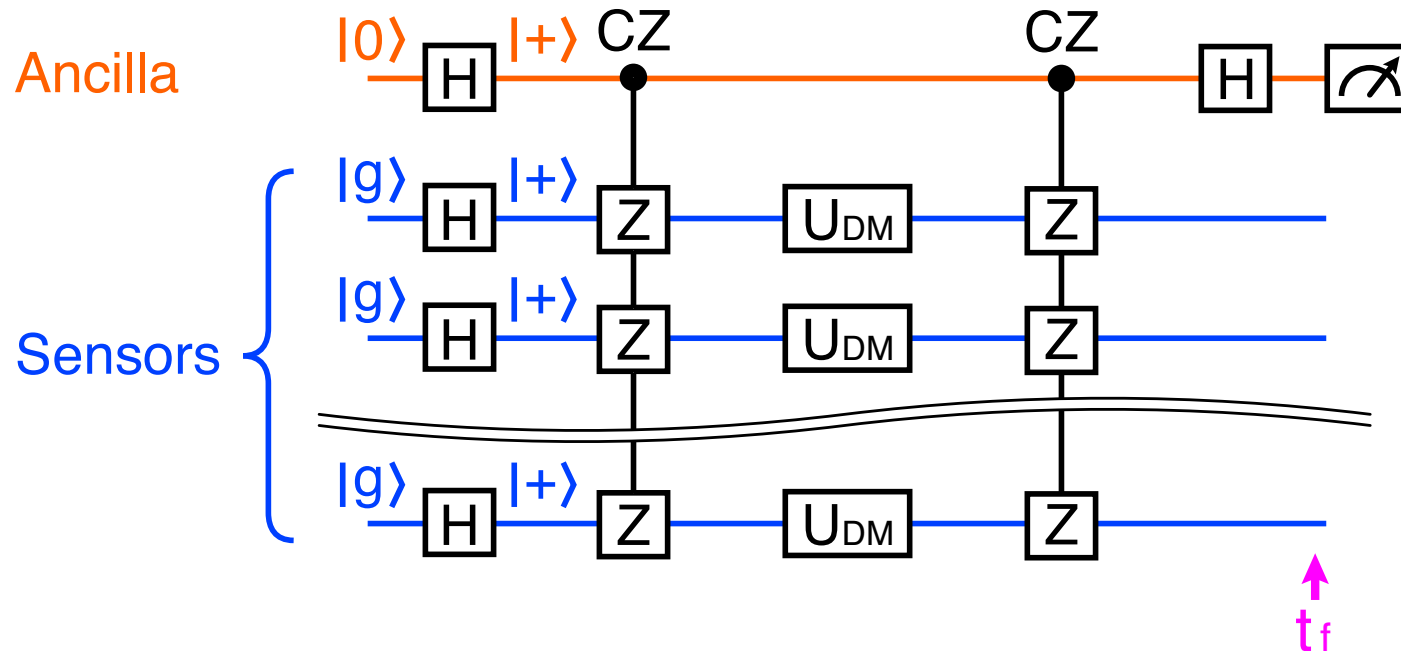
$$\bar{E}_{(\text{eff})} = \sqrt{\frac{\Gamma_{ij} \mathcal{T} V_{\text{eff}} n_\nu \Delta m_{ij}^2}{2m_i \epsilon_0}}$$

$$p_* \simeq p_*^0 \times \left(\frac{d}{100 \mu\text{m}} \right)^2 \left(\frac{C}{0.1 \text{ pF}} \right) \left(\frac{f}{1 \text{ GHz}} \right) \left(\frac{\tau}{100 \mu\text{s}} \right)^3 \left(\frac{\mu}{10^{-11} \mu_B} \right)^2 \left(\frac{\Delta m_{ij}^2}{10^{-5} \text{ eV}^2} \right)^4 \left(\frac{V_{\text{eff}} n_\nu}{112 \text{ cm}^{-3}} \right) \left(\frac{0.05 \text{ eV}}{m_i} \right)^4$$

$$p_*^0 = 2.1 \times 10^{-27} \quad f \simeq 24 \text{ GHz} \times \left(\frac{\Delta m_{ij}^2}{10^{-5} \text{ eV}^2} \right) \left(\frac{0.05 \text{ eV}}{m_i} \right)$$

Quantum Enhancement of the Signal Rate

One measurement cycle for the signal enhancement



$$|\Psi(t_f)\rangle = \left(\cos N_q \delta |0\rangle + i \sin N_q \delta |1\rangle \right) \otimes |+\rangle^{\otimes N_q}$$

$\Rightarrow$ Ancilla qubit can be excited: $P_{0 \rightarrow 1} \simeq \sin^2 N_q \delta \simeq N_q^2 \delta^2$

DarQ bounds

$$\bar{E}_{(\text{eff})} = \sqrt{\frac{\Gamma \mathcal{T} n_2 \Delta m^2}{2m_2 \epsilon_0}} \quad \rho_{\text{DM}} \approx m_2 n_2$$

$$E_\gamma = \frac{\Delta m^2}{2m_2} = \omega_{\text{res}}^{\text{DarQ}} = 36.1 \mu\text{eV}$$

$$f_{\text{res}}^{\text{DarQ}} = \frac{\omega_{\text{res}}^{\text{DarQ}}}{2\pi} = 8.74 \text{ GHz}$$

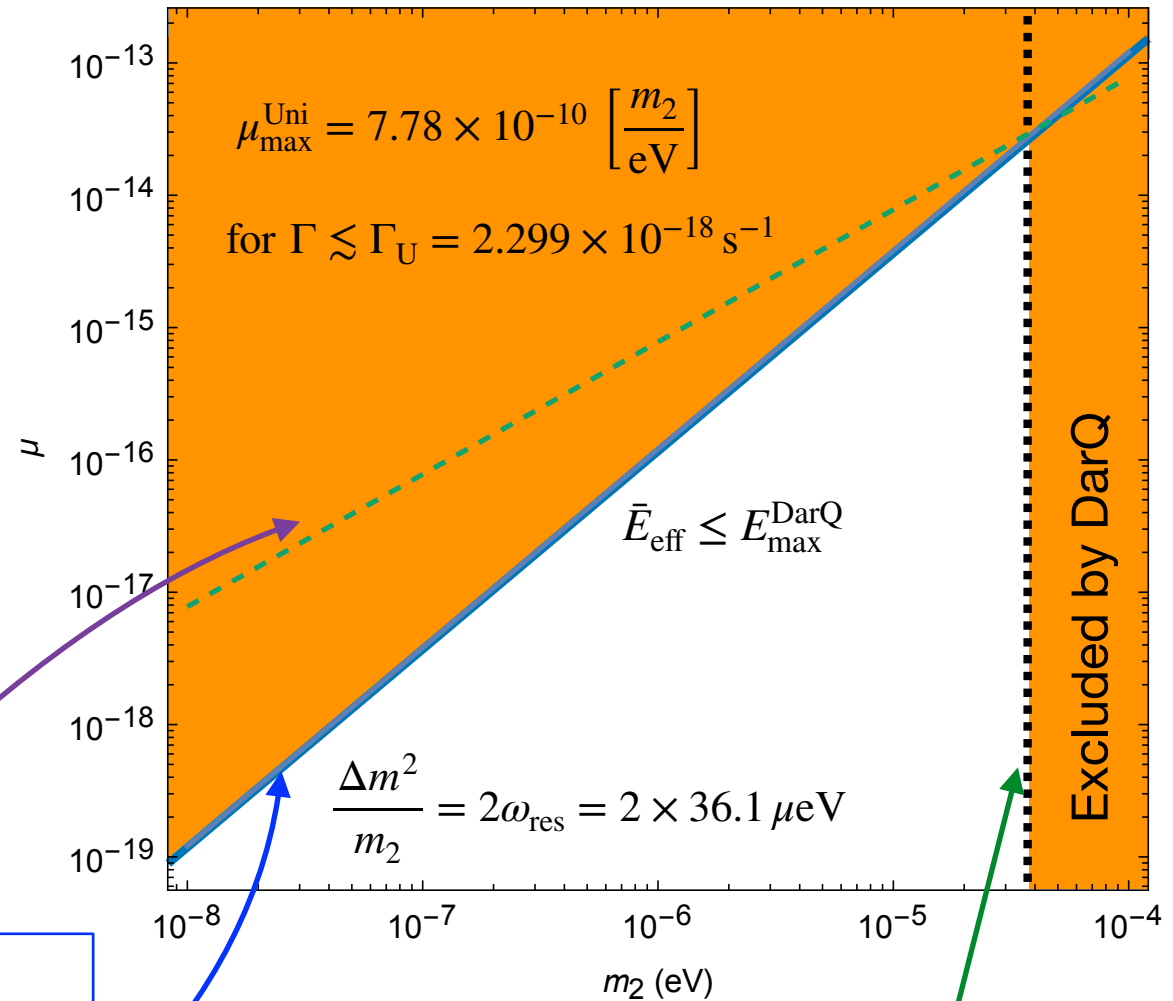
$$\Gamma \lesssim \Gamma_U = 2.299 \times 10^{-18} \text{ s}^{-1}$$

$$(\mu_{\text{max}}^{\text{Uni}})^2 \approx 48\pi m_2^2 \left(\frac{m_2}{\Delta m^2} \right)^3 \Gamma_U$$

$$\mu \leq \mu_{\text{max}}^{\text{Uni}} = 7.78 \times 10^{-10} \times \left(\frac{m_2}{\text{eV}} \right)$$

$$\Gamma(X_2 \rightarrow X_1 + \gamma) \approx \frac{\mu^2}{48\pi} \frac{(\Delta m^2)^3}{m_2^5}$$

$$\mu^2 < \frac{12\pi\epsilon^2\epsilon_0}{(\omega_{\text{res}}^{\text{DarQ}})^4 \mathcal{T}} m_2^3 = 1.46 \times 10^{-14} \times \left(\frac{m_2}{\text{eV}} \right)^3$$



$$\bar{E}_{(\text{eff})} < E_{\text{max}}^{\text{DarQ}} = \epsilon \sqrt{2\rho_{\text{DM}}}$$

$$m_2 = \frac{\Gamma \mathcal{T} \omega_{\text{res}}^{\text{DarQ}}}{2\epsilon_0 \epsilon^2} = 4.15 \times 10^{-5} \text{ eV}$$

$$E = 2.63 \times 10^{-15} \text{ eV}^2 \approx 1.35 \times 10^{-17} \text{ T} \approx 4 \times 10^{-9} \text{ V/m.}$$

Quantum devices (qubits) as sensors

Detecting Hidden Photon Dark Matter Using the Direct Excitation of Transmon Qubits

Shion Chen,¹ Hajime Fukuda,² Toshiaki Inada¹,² Takeo Moroi,^{2,3,*} Tatsumi Nitta,¹ and Thanaporn Sichanugrist²

Quantum Enhancement in Dark Matter Detection with Quantum Computation

Shion Chen,¹ Hajime Fukuda²,² Toshiaki Inada,¹ Takeo Moroi,^{2,3} Tatsumi Nitta,¹ and Thanaporn Sichanugrist^{2,*}

Eliminating Incoherent Noise: A Coherent Quantum Approach in Multi-Sensor Dark Matter Detection

Jing Shu,^{1,2,3} Bin Xu,¹ and Yuan Xu^{4,5}

Search for QCD axion dark matter with transmon qubits and quantum circuit

Shion Chen^(a), Hajime Fukuda^(b), Toshiaki Inada^(c), Takeo Moroi^(b,d),
Tatsumi Nitta^(c), Thanaporn Sichanugrist^{(b)*}

Quantum entanglement of ions for light dark matter detection

Asuka Ito^{1,2}, Ryuichiro Kitano^{2,3}, Wakutaka Nakano² and Ryoto Takai^{2,3}

Directional search for light dark matter with quantum sensors

Hajime Fukuda*

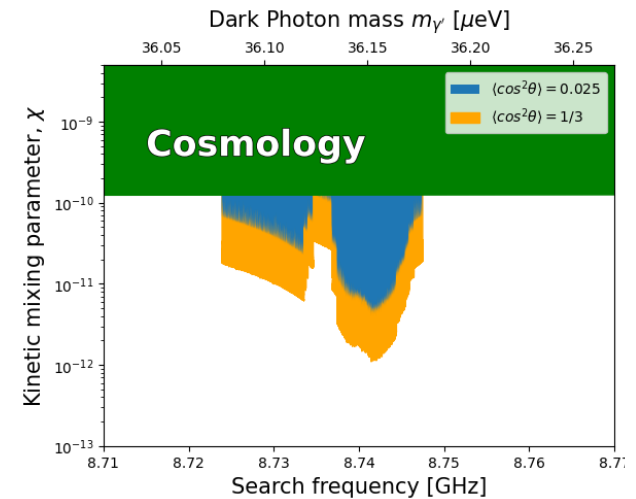
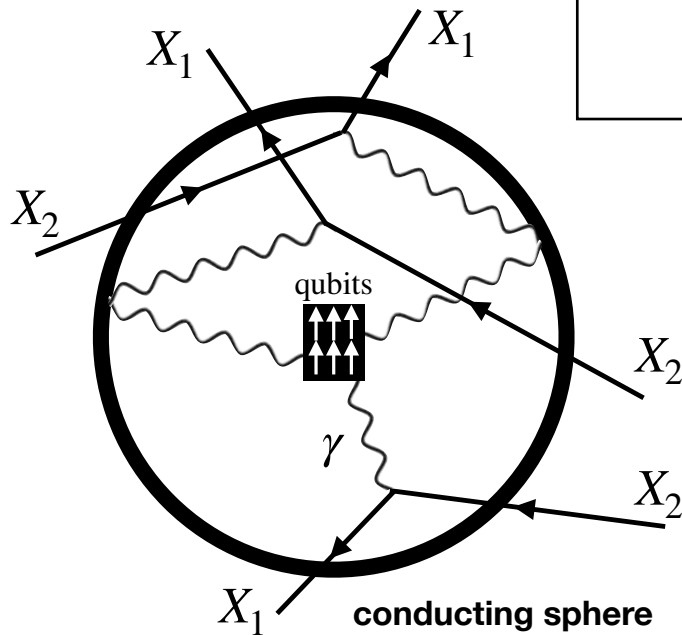
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Ultralight dark matter detection with trapped-ion interferometry

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Search for Dark Photon Dark Matter of a Mass around $36.1 \mu\text{eV}$ Using a Frequency-tunable Cavity Controlled through a Coupled Superconducting Qubit

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Quantum Sensing Radiative Decays of Neutrinos and Dark Matter Particles

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