Quantum Sensing Radiative Decays of Neutrinos and Dark Matter Particles

K.C. Kong
University of Kansas

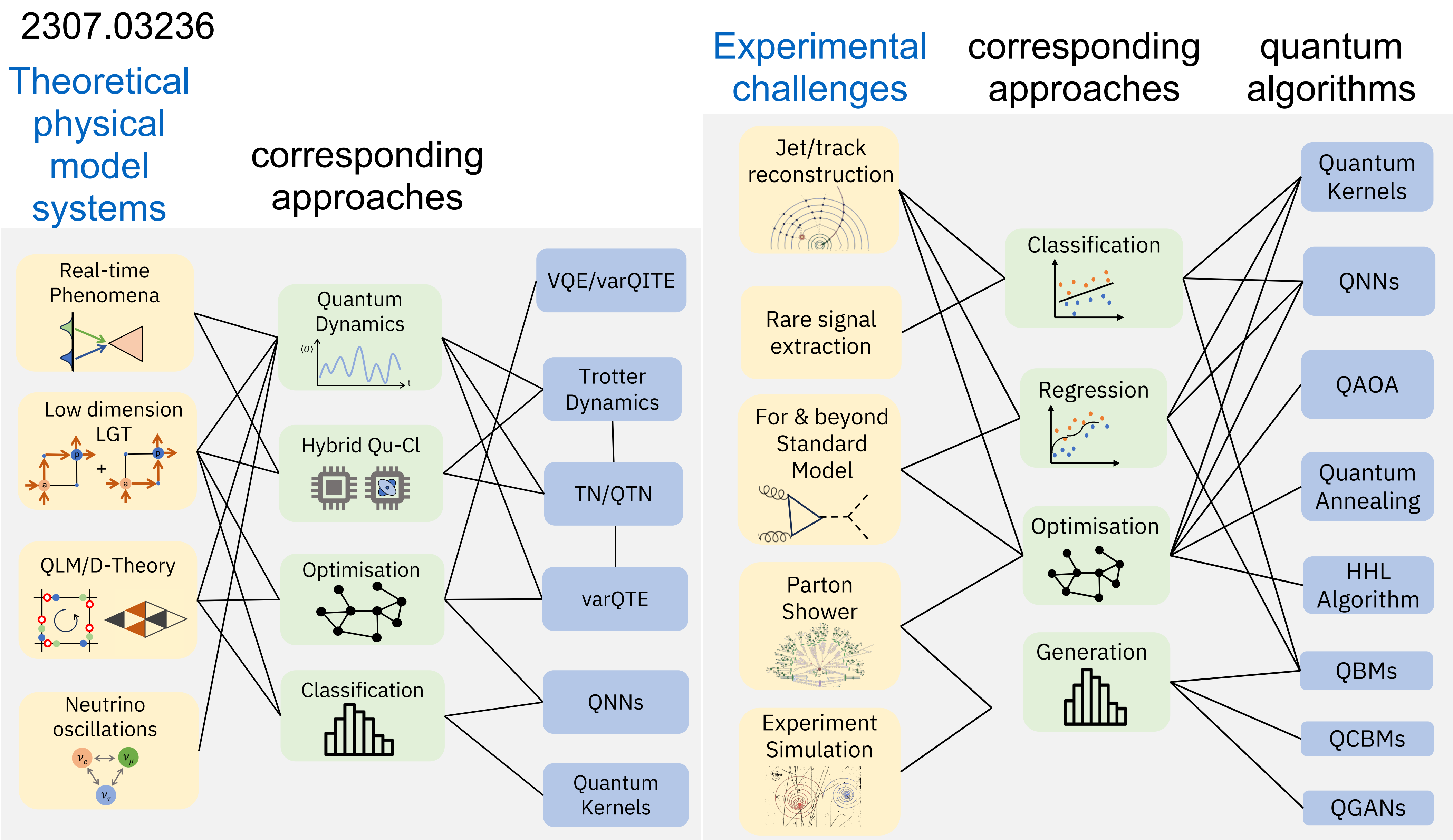
2508.09139: in collaboration with Z. Dong, D. Kim, M. Park, M. Soto Alcaraz

CPNR Workshop
Neutrinos and Physics beyond the Standard Model
Chonnam National University
October 24-27, 2025

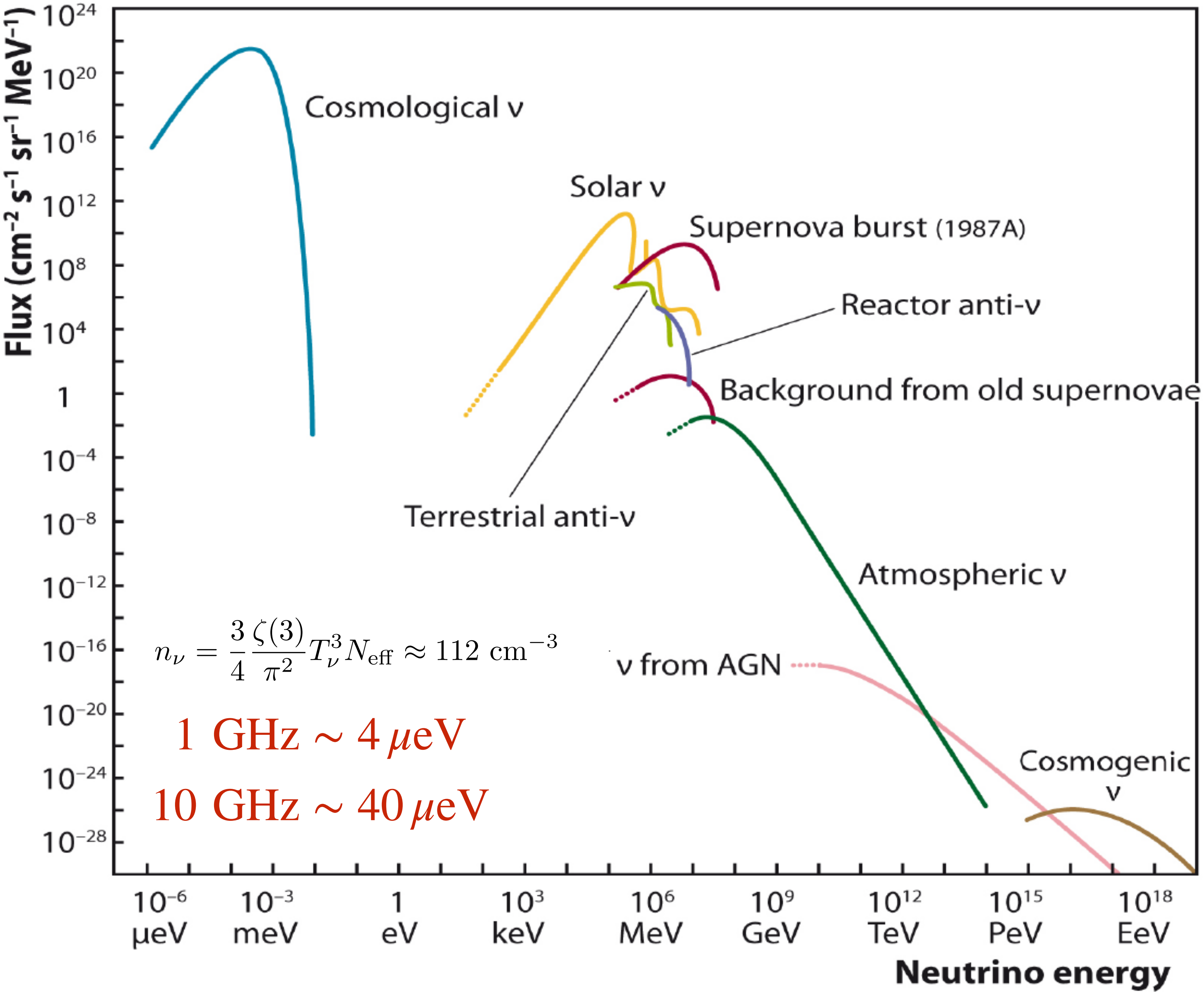
Where quantum computers are (potentially) useful

- Quantum optimization: combinatorial problems at the LHC 2410.22417
  - Finance, physics, materials discovery, science
- Quantum devices (qubits) as sensors: detection of dark matter and neutrino decays 2508.09139
  - 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, 2407.07147, 2305.07075
  - Teleportation, quantum internet
- Quantum sampling
  - Supremacy tasks, random circuits

Quantum Computing for High-Energy Physics
State of the Art and Challenges
Summary of the QC4HEP Working Group



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

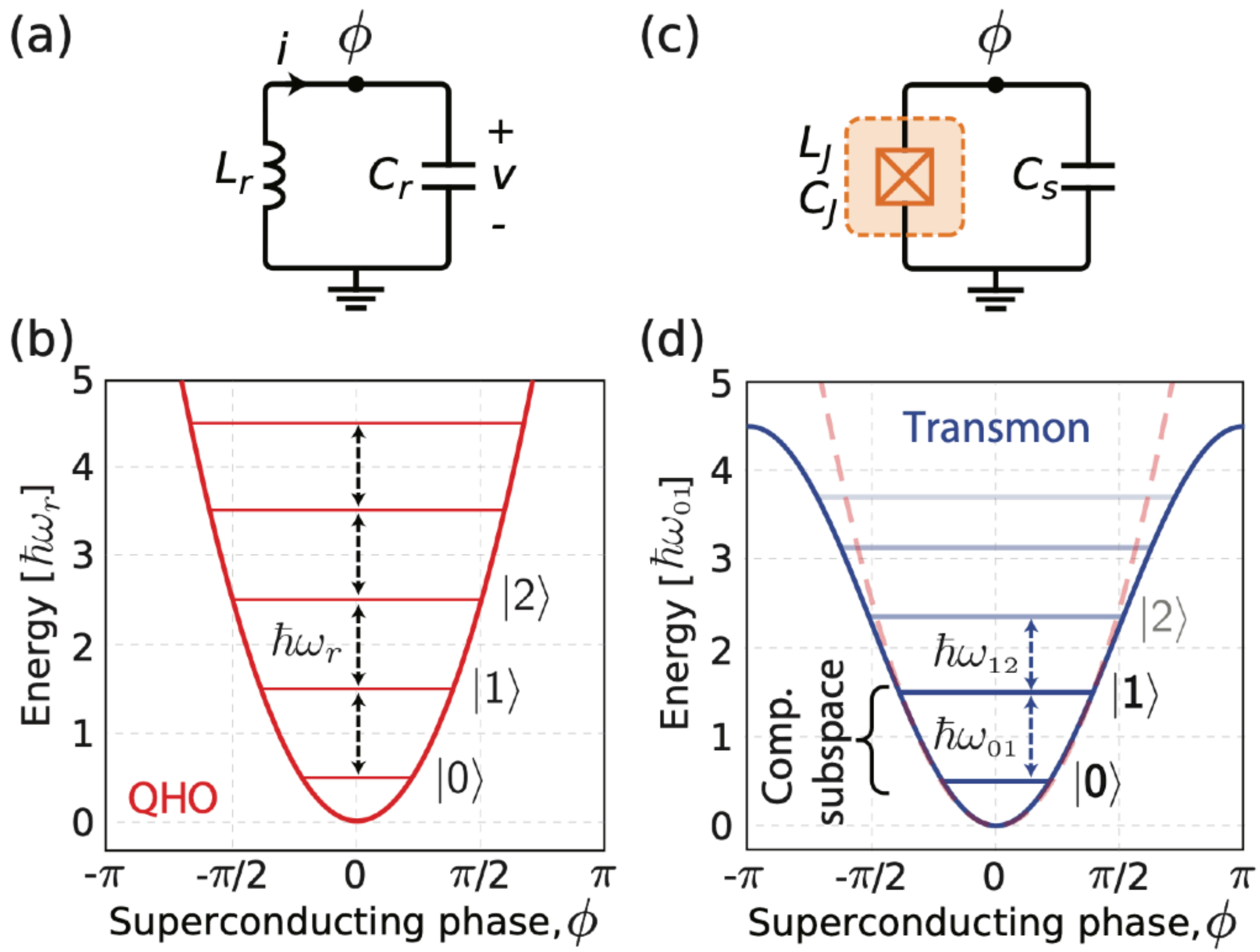


$$n_\nu = \frac{3}{4}\frac{\zeta(3)}{\pi^2} T_\nu^3 N_{\rm eff} \approx 112\ {\rm cm}^{-3}$$

$1\ {\rm GHz} \sim 4\,\mu{\rm eV}$

$10\ {\rm GHz} \sim 40\,\mu{\rm eV}$

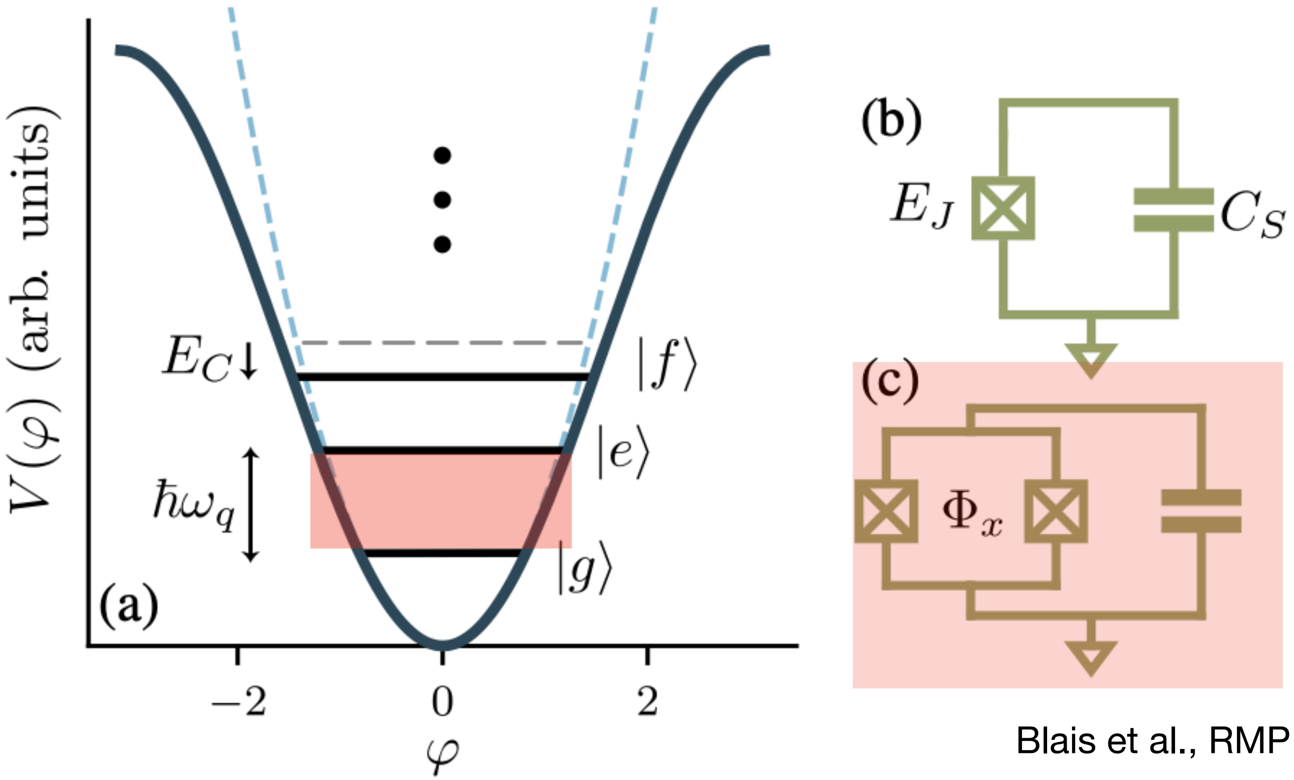
Transmon qubit = Capacitor + Josephson junction



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}.

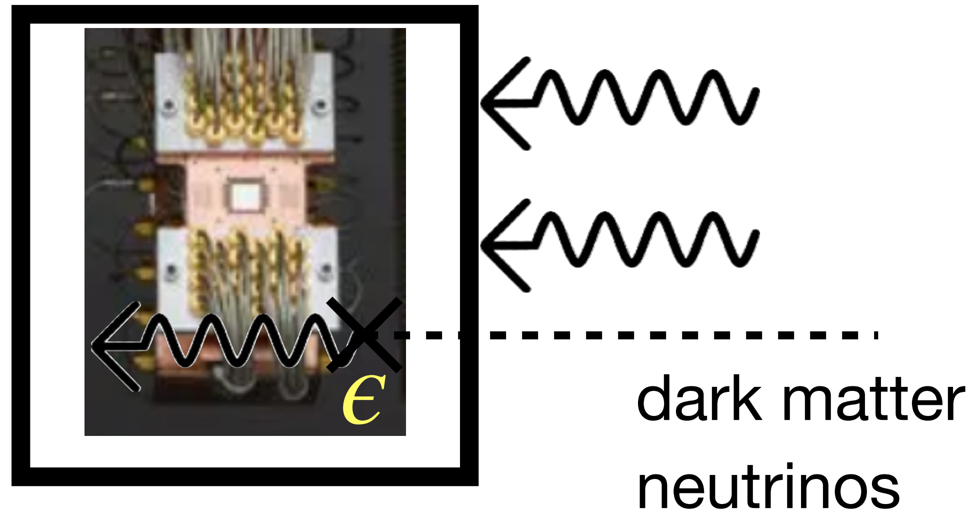
Transmon qubit = Capacitor + Josephson junction



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.

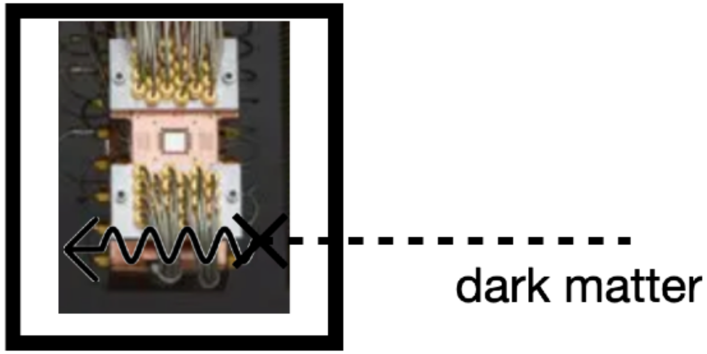
$$\omega \simeq \mathcal{O}(1-10)\,\mathrm{GHz} \qquad \lambda \simeq \mathcal{O}(3-30)\mathrm{cm}$$

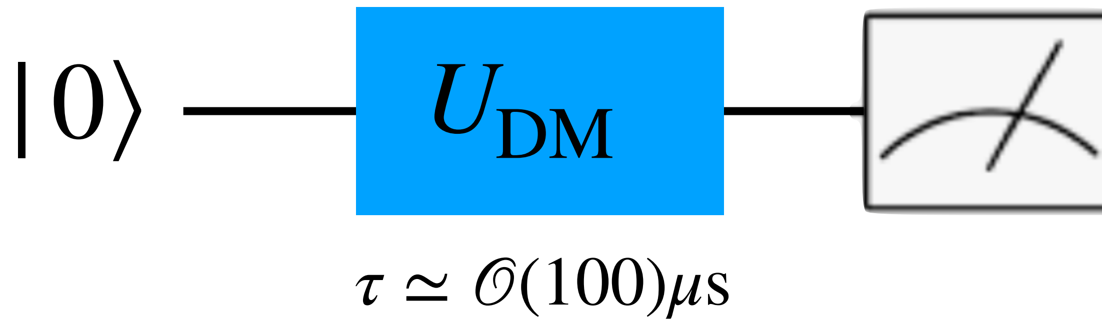


- For typical device parameters, $\omega \simeq \mathcal{O}(1-10)\mathrm{GHz}$ with $\lambda \simeq \mathcal{O}(3-30)\mathrm{cm}$
- At refrigerator temperatures $\mathcal{O}(1-10)\mathrm{mK}$, a few-GHz transition satisfies $k_B T \ll \hbar\omega$.

  - 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, $E^{(\mathrm{ext})} = \epsilon\sqrt{2\rho_{\mathrm{DM}}}\sin m_X t$, 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, $m_{DM} \sim \mathcal{O}(4-40)\mu\mathrm{eV}$

Dark Matter as an operator U_{DM}

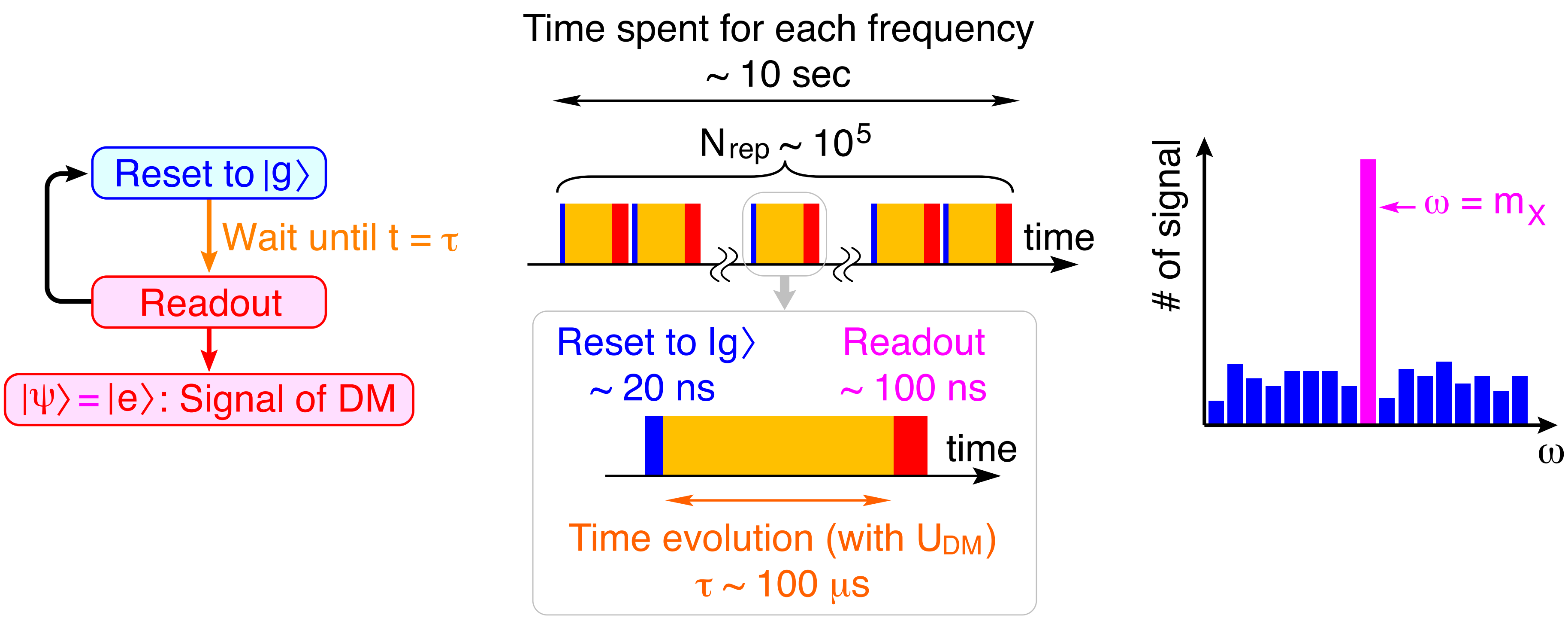




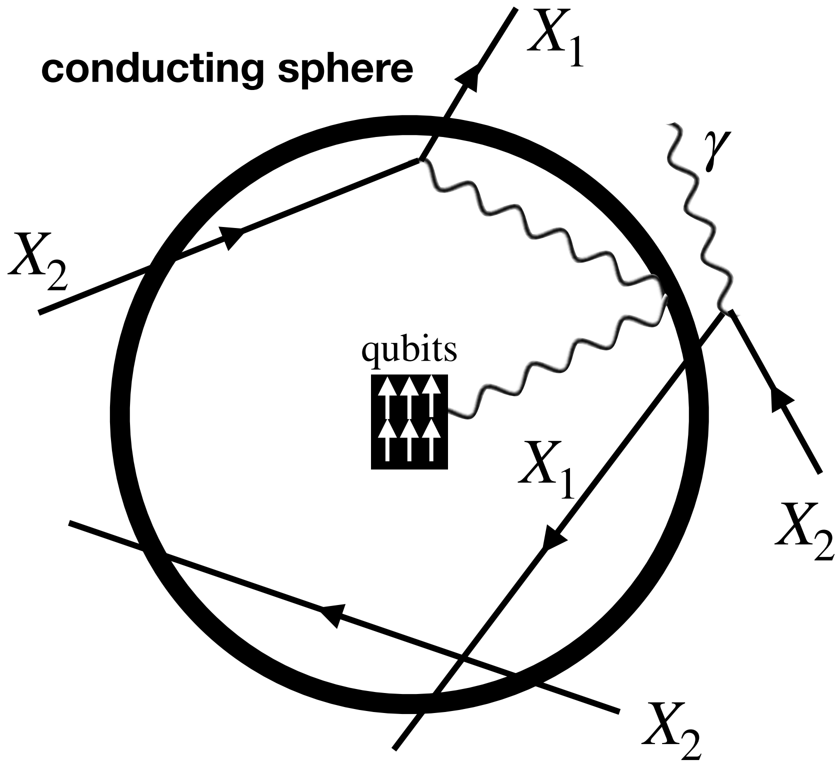
- Signal: a weak classical field: wave-like DM, high-frequency gradational waves
- The interaction between DM and qubits, $H_{DM} = \epsilon\left(\cos\alpha\,\sigma_X + \sin\alpha\,\sigma_Y\right)$ will drive transitions from $|0\rangle$ to $|1\rangle$.
- The Goal to estimate the signal strength ϵ.

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 $\mathcal{O}(100)\mu s$
- One can repeat a cycle of (Reset $\rightarrow U_{\mathrm{DM}} \rightarrow$ Measurement) as many as $\mathcal{O}(10^5)$ during 10 seconds.
  - Time for reset qubits $\sim \mathcal{O}(10)\mu s$
  - Time for measurement $\simeq \mathcal{O}(100)\mathrm{ns}$



- 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 $\mathrm{C}\nu\mathrm{B}$, 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

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

- Energy density of photons $\rho_\gamma = E_\gamma n_\gamma = \epsilon_0 \bar{E}_{\rm eff}^2$ with $n_\gamma \propto \Gamma_{X_2} n_{X_2}$

- Interaction between a photon from decay process and qubit,

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

so that the total Hamiltonian

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

2508.09139

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

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

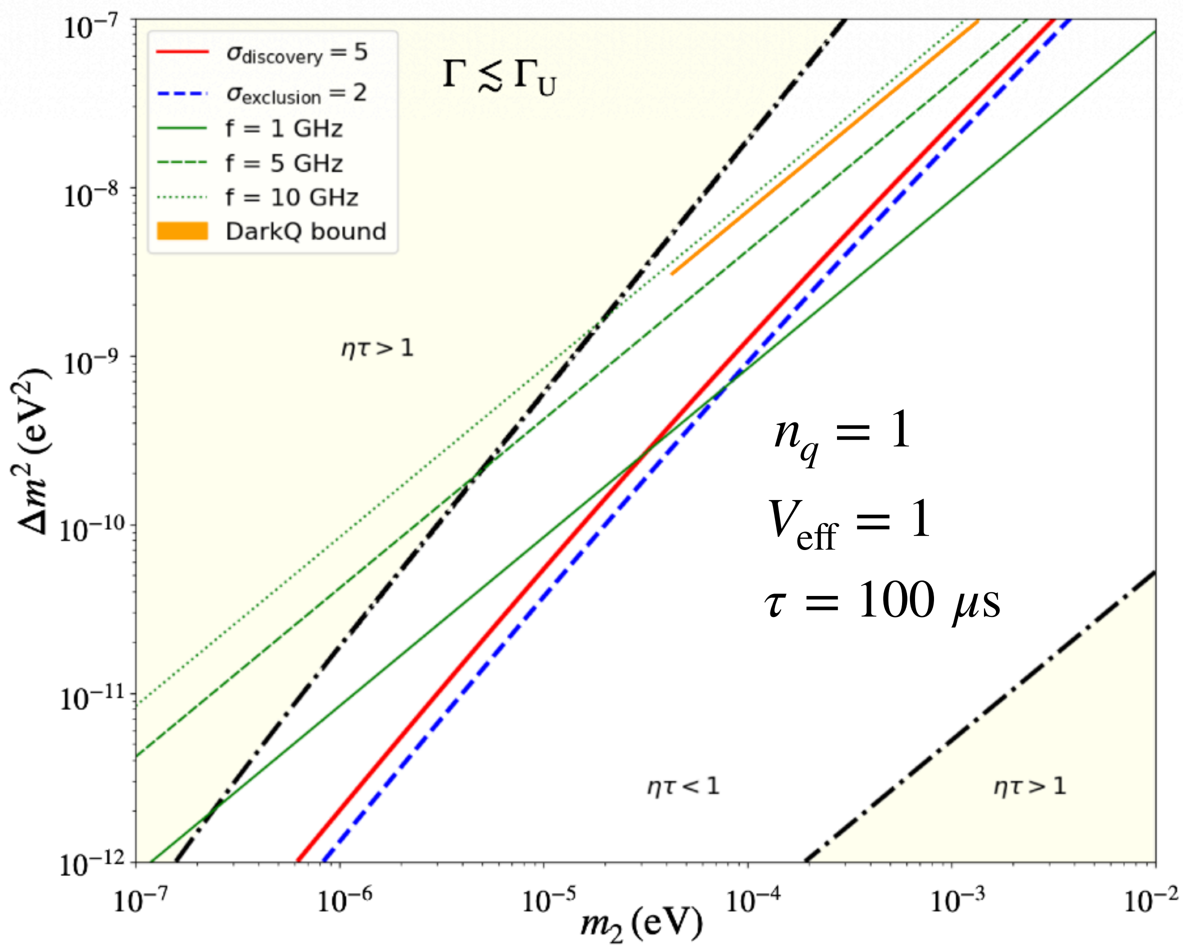
with initial condition of $\psi_g(0) = 1$ and $\psi_e(0) = 0$

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

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

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

2508.09139



- 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 (3.15×10^7s) yields 14s of integration time per frequency bin, corresponding to $N_{\rm try} = \mathcal{O}(10^5)$ / bin

$$p_* = 0.069$$

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

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

2508.09139

Quantum Enhancement of the Signal Rate

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

Without entanglement

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

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

$$\vdots$$

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

$$\Downarrow$$

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

Classical
- N independent system are prepared and separately detected

With entanglement

$$|\psi\rangle \equiv \text{some entangled state}$$

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

An example of such a state is the GHZ state.

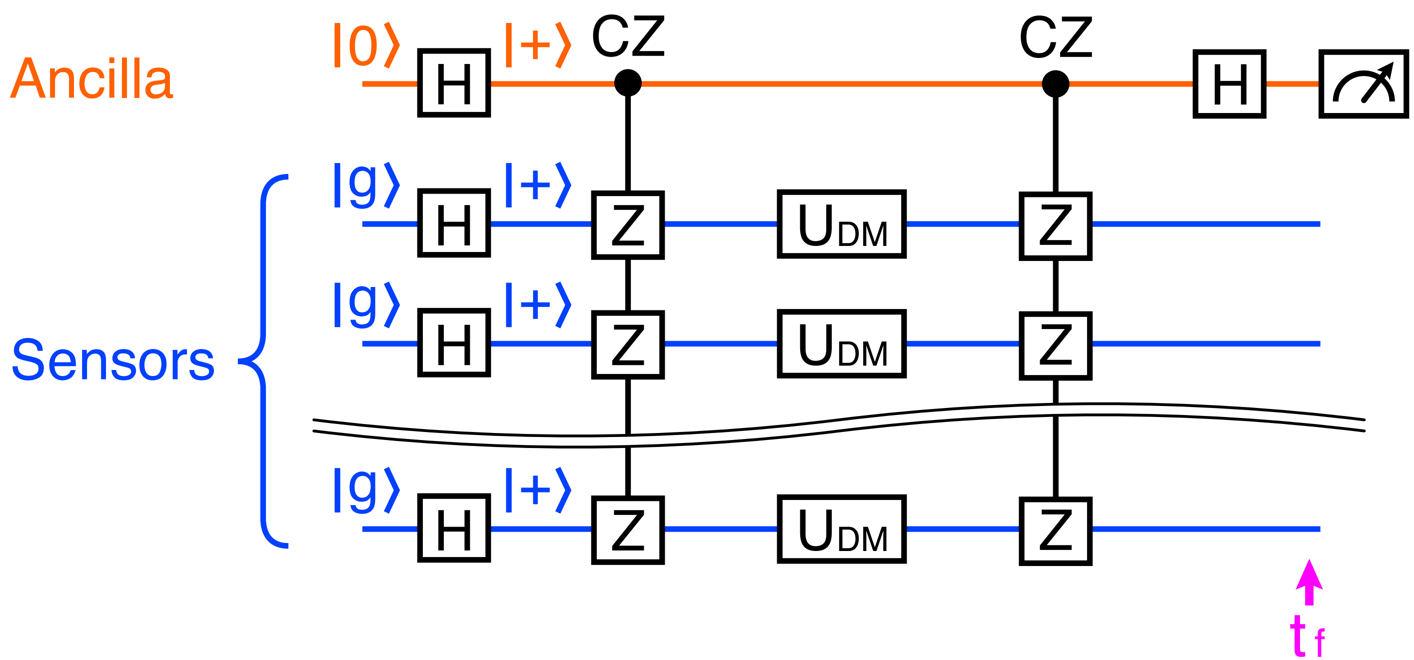
$$\Downarrow$$

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

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

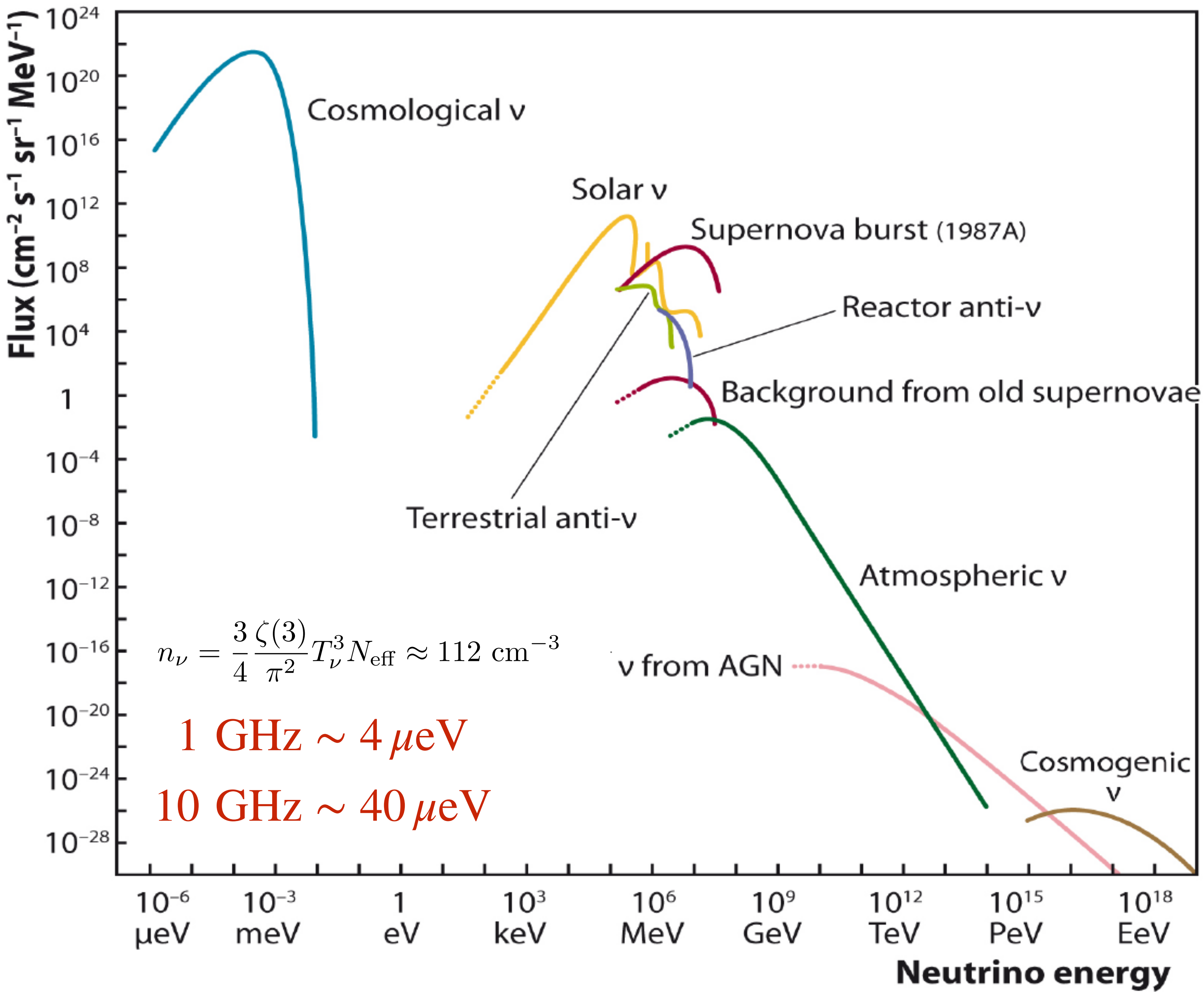


$$|\Psi(t_{\mathrm{f}})\rangle = \left(\cos\, N_{\mathrm{q}}\delta\,|0\rangle + i\sin\, N_{\mathrm{q}}\delta\,|1\rangle\right) \otimes |+\rangle^{\otimes N_{\mathrm{q}}}$$

$\Rightarrow$ Ancilla qubit can be excited: $P_{0\to 1} \simeq \sin^2 N_{\mathrm{q}}\delta \simeq N_{\mathrm{q}}^2\delta^2$

Shion Chen, Hajime Fukuda, Toshiaki Inada, Takeo Moroi, Tatsumi Nitta, Thanaporn Sichanugrist, 2024 PRL

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



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

$1\ \mathrm{GHz} \sim 4\,\mu\mathrm{eV}$

$10\ \mathrm{GHz} \sim 40\,\mu\mathrm{eV}$

Neutrino transition magnetic moment

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

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

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

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

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

$$\Delta m_{21}^2 = 7.59 \times 10^{-5} \text{ eV}^2$$
$$\Delta m_{32}^2 = 2.32 \times 10^{-3} \text{ eV}^2$$

$$m_2 \simeq \sqrt{\Delta m_{21}^2} \sim 8.6 \times 10^{-3} \text{ eV}$$
$$m_3 \simeq \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2} \sim 0.05 \text{ eV}$$

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

$$\bar{E}_{(\rm eff)} = \sqrt{\frac{\Gamma_{ij} \mathcal{T}\, V_{\rm eff}\, n_\nu \Delta m_{ij}^2}{2m_i \varepsilon_0}}$$

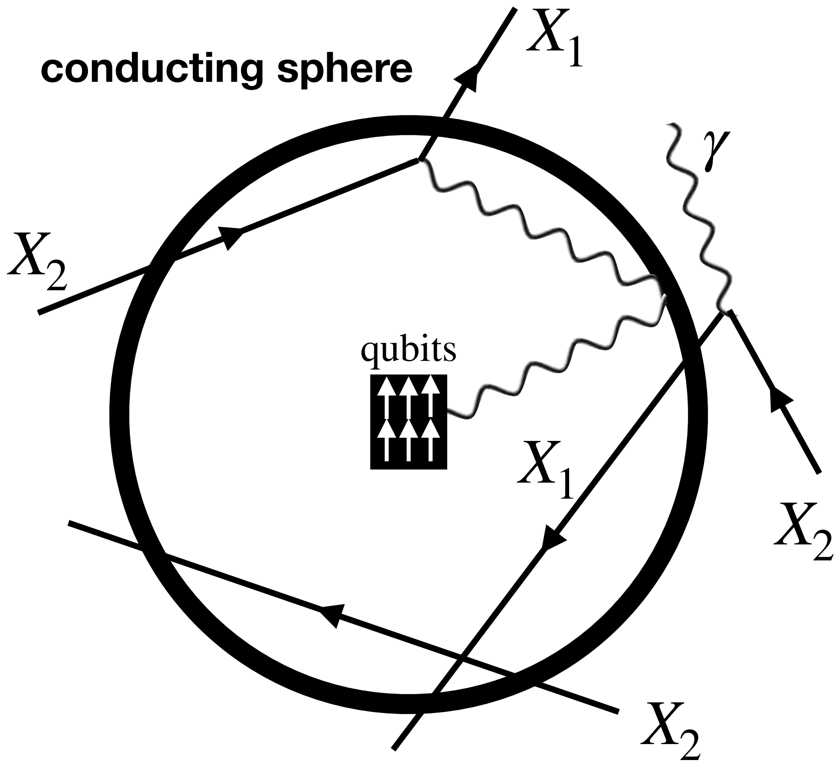
$$p_* \simeq p_*^0 \times \left(\frac{d}{100\ \mu\text{m}}\right)^2 \left(\frac{C}{0.1 \text{ pF}}\right) \left(\frac{f}{1 \text{ GHz}}\right) \left(\frac{\tau}{100\ \mu\text{s}}\right)^3 \left(\frac{\mu}{10^{-11}\ \mu_B}\right)^2 \left(\frac{\Delta m_{ij}^2}{10^{-5} \text{ eV}^2}\right)^4 \left(\frac{V_{\rm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

$$p_*^0 = 2.1 \times 10^{-27}$$

$$f \simeq 24 \text{ GHz} \times \left(\frac{\Delta m_{ij}^2}{10^{-5} \text{ eV}^2}\right) \left(\frac{0.05 \text{ eV}}{m_i}\right)$$

$$\mu_B = \frac{e\hbar}{2m_e}$$

2508.09139

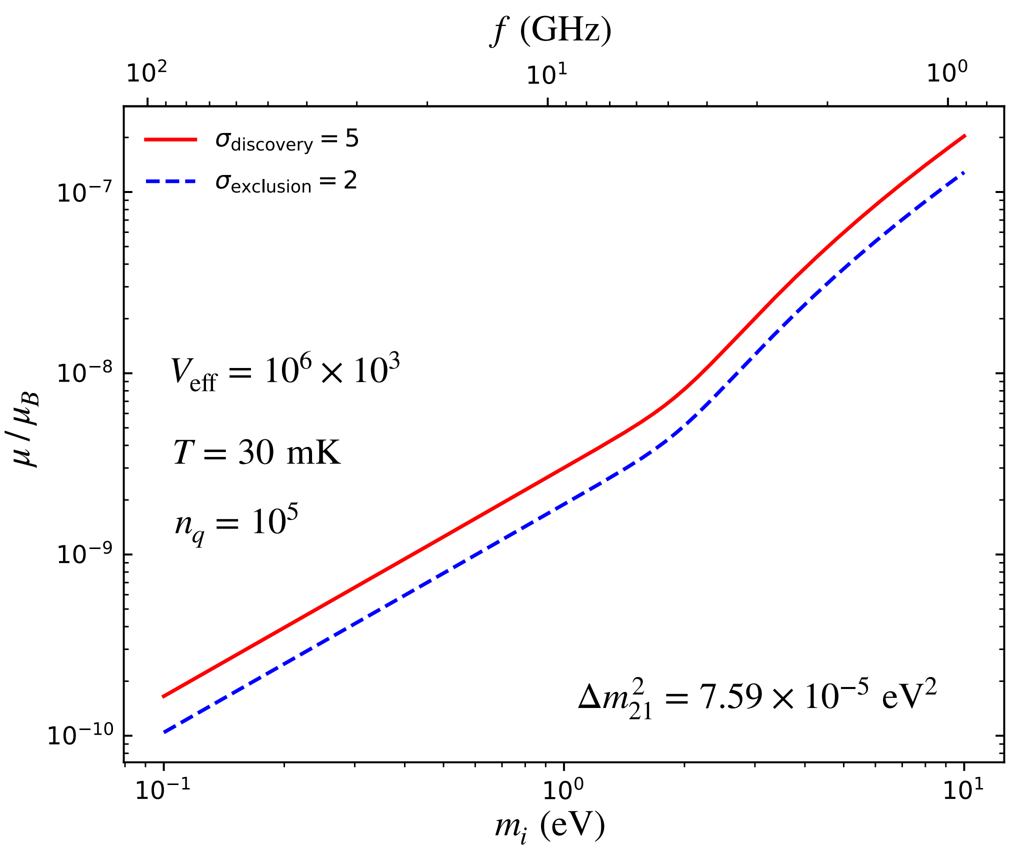


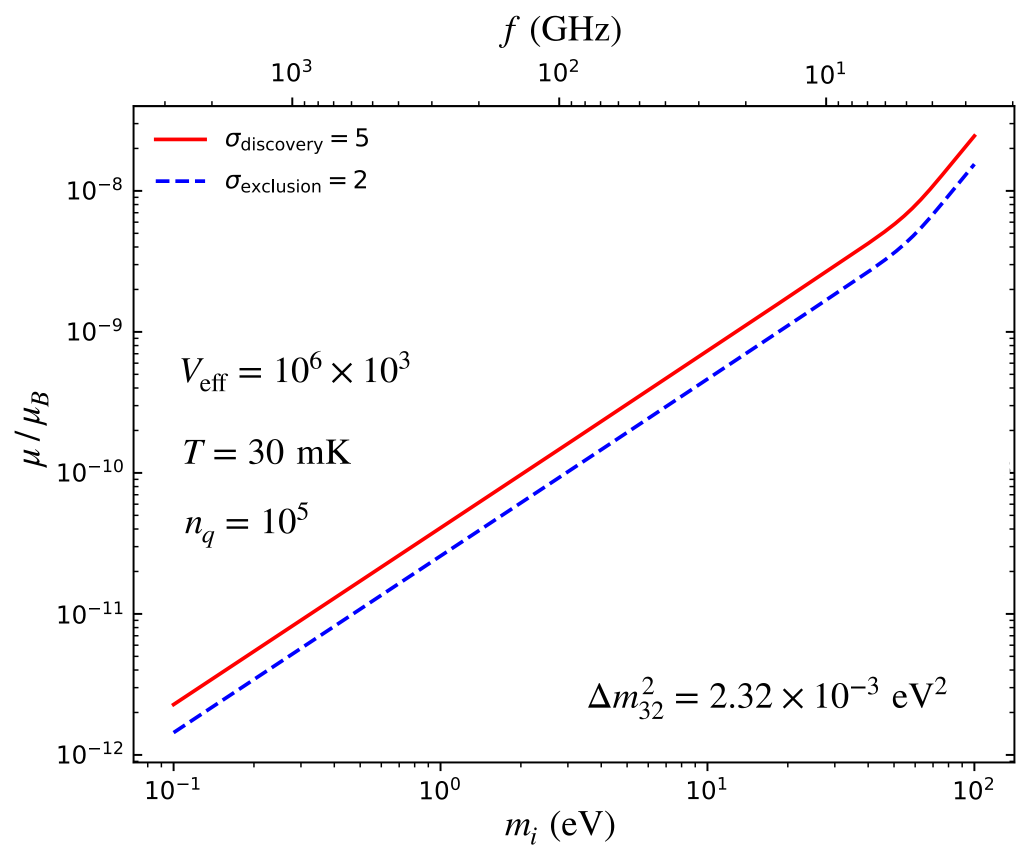
Polished aluminum and copper typically reflect 98–99% of incident radiation

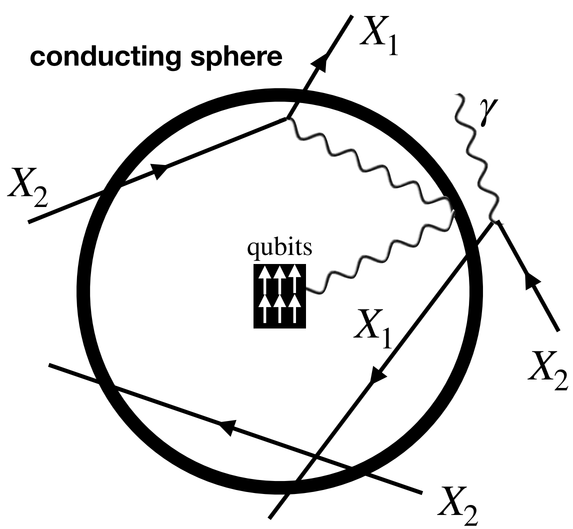
In this configuration, DM or neutrinos can freely enter the cavity, but once they decay into photons, the photons are confined. Eventually, these trapped photons will interact with the quantum device.

- This setup significantly enhances the chance of detecting a signal by effectively increasing the detection volume and thereby the expected as $n_t \to n_e \left(\frac{V_{\mathrm{eff}}}{\mathrm{cm}^3}\right) \to n_2 \times 10^6$ for $1\,\mathrm{m}^3$ cavity.

Bounds on neutrino transition magnetic moment







Decay volume

$$n_2 \to n_2 \left(\frac{V_{\rm eff}}{\rm cm^3}\right)$$

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

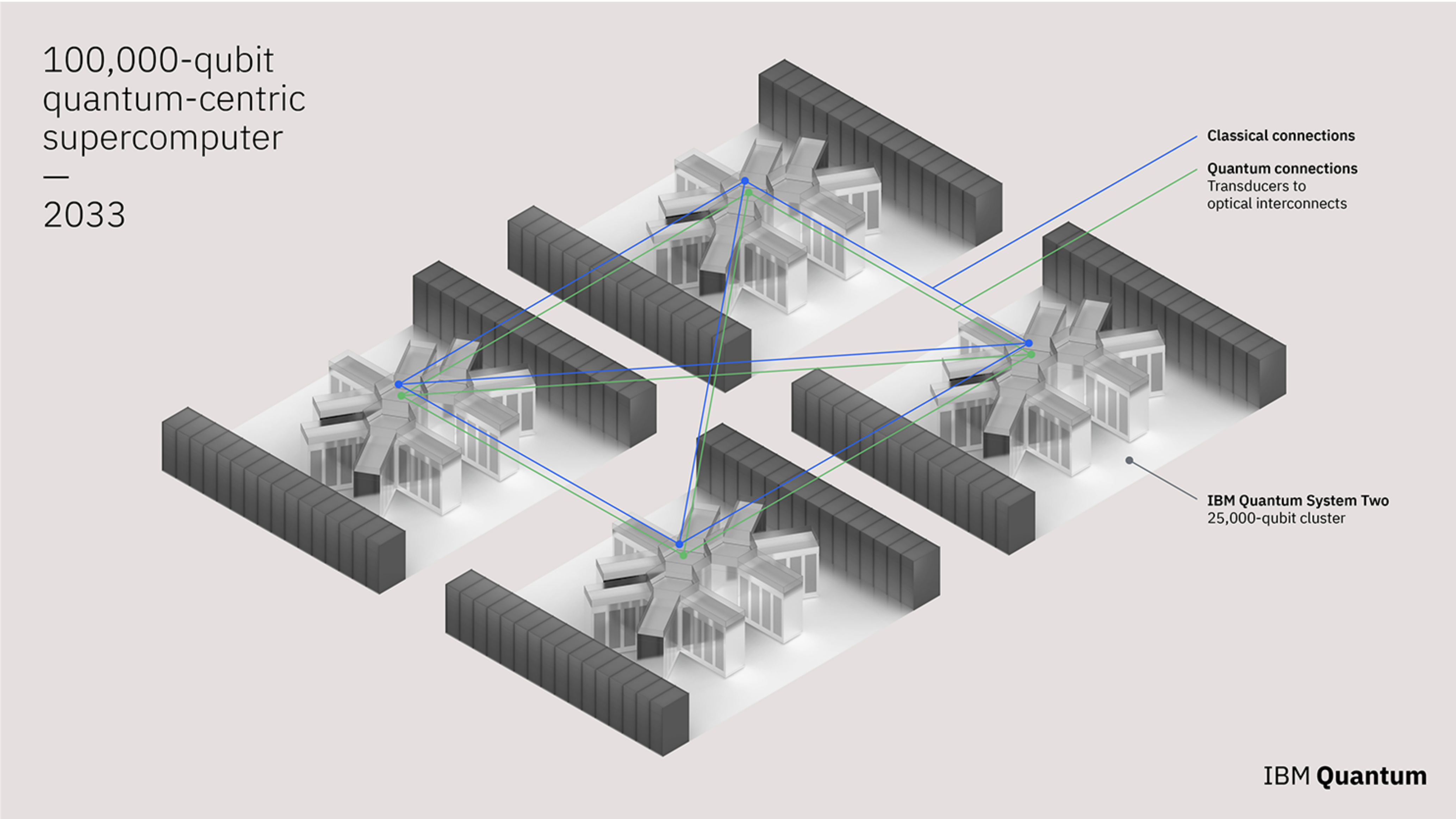
Entanglement

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

$$n_q = 10^5$$

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

Charting the course to 100,000 qubits



- All other quantum computing companies (D-wave, IonQ, Google etc) are also targeting Large-Scale, Fault-Tolerant Quantum Computers for next 10-20 years.
- The future may arrive sooner than we expect.

Quantum devices (qubits) as sensors

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

Shion Chen,[1] Hajime Fukuda,[2] Toshiaki Inada,[1] Takeo Moroi,[2,3,*] Tatsumi Nitta,[1] and Thanaporn Sichanugrist[2]

Quantum Enhancement in Dark Matter Detection with Quantum Computation

Shion Chen,[1] Hajime Fukuda,[2] Toshiaki Inada,[1] Takeo Moroi,[2,3] Tatsumi Nitta,[1] and Thanaporn Sichanugrist[2,*]

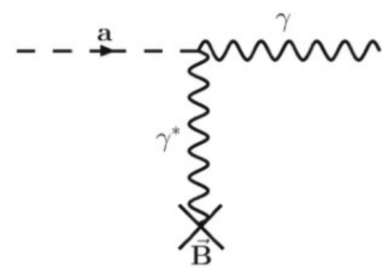
Eliminating Incoherent Noise: A Coherent Quantum Approach in Multi-Sensor Dark Matter Detection

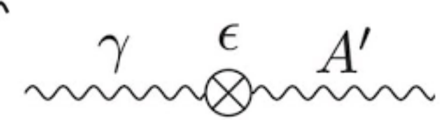
Jing Shu,[1, 2, 3] Bin Xu,[1] and Yuan Xu[4, 5]

Talk by Bin Xu on Day 3

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 Nakano[2] and Ryoto Takai[2,3]

Directional search for light dark matter with quantum sensors

Hajime Fukuda*

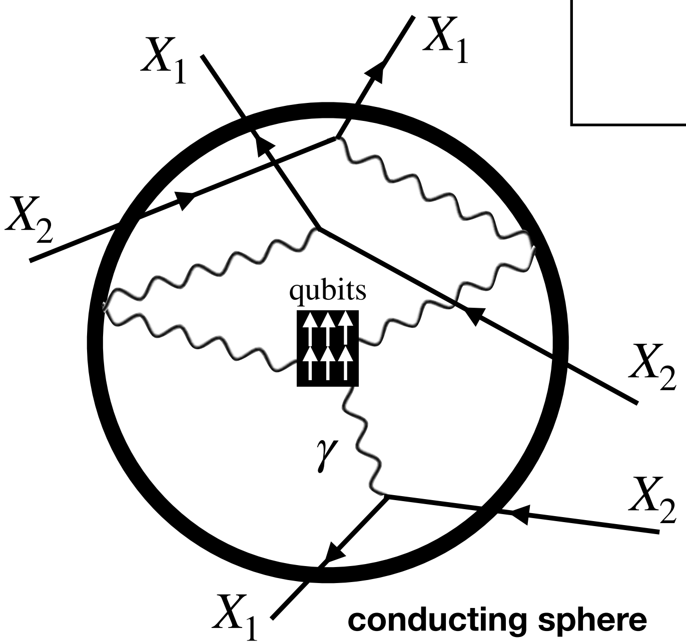
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan

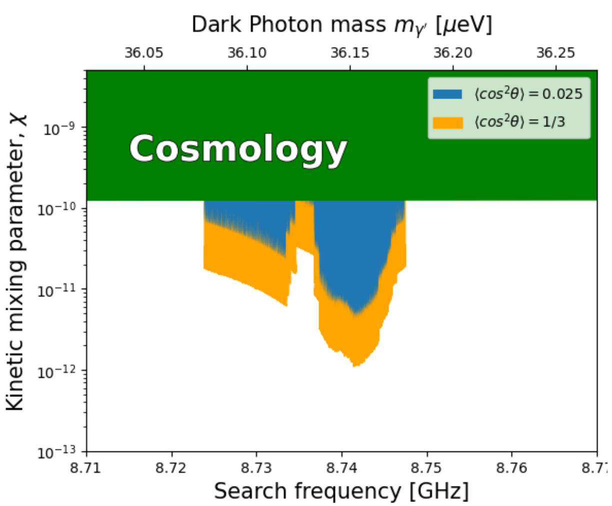
Ultralight dark matter detection with trapped-ion interferometry

Leonardo Badurina,[1] Diego Blas,[2,3] John Ellis,[4,5] and Sebastian A. R. Ellis[6]

Search for Dark Photon Dark Matter of a Mass around 36.1 μeV Using a Frequency-tunable Cavity Controlled through a Coupled Superconducting Qubit

K. Nakazono,[1,*] S. Chen,[2] H. Fukuda,[1] Y. Iiyama,[3] T. Inada,[3] T. Moroi,[1,4] T. Nitta,[4] A. Noguchi,[5,6,7] R. Sawada,[3] S. Shirai,[5,6] T. Sichanugrist,[1] K. Terashi,[3] and K. Watanabe[1]
(DarQ Collaboration)





Quantum Sensing Radiative Decays of Neutrinos and Dark Matter Particles

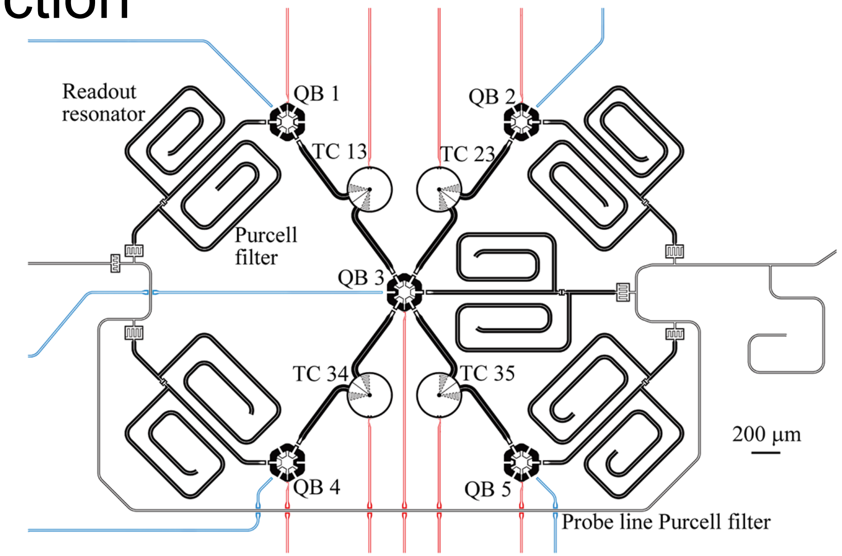
Zhongtian Dong,[1,*] Doojin Kim,[2,†] Kyoungchul Kong,[1,‡] Myeonghun Park,[3,4,5,§] and Miguel A. Soto Alcaraz[1,]

Summary

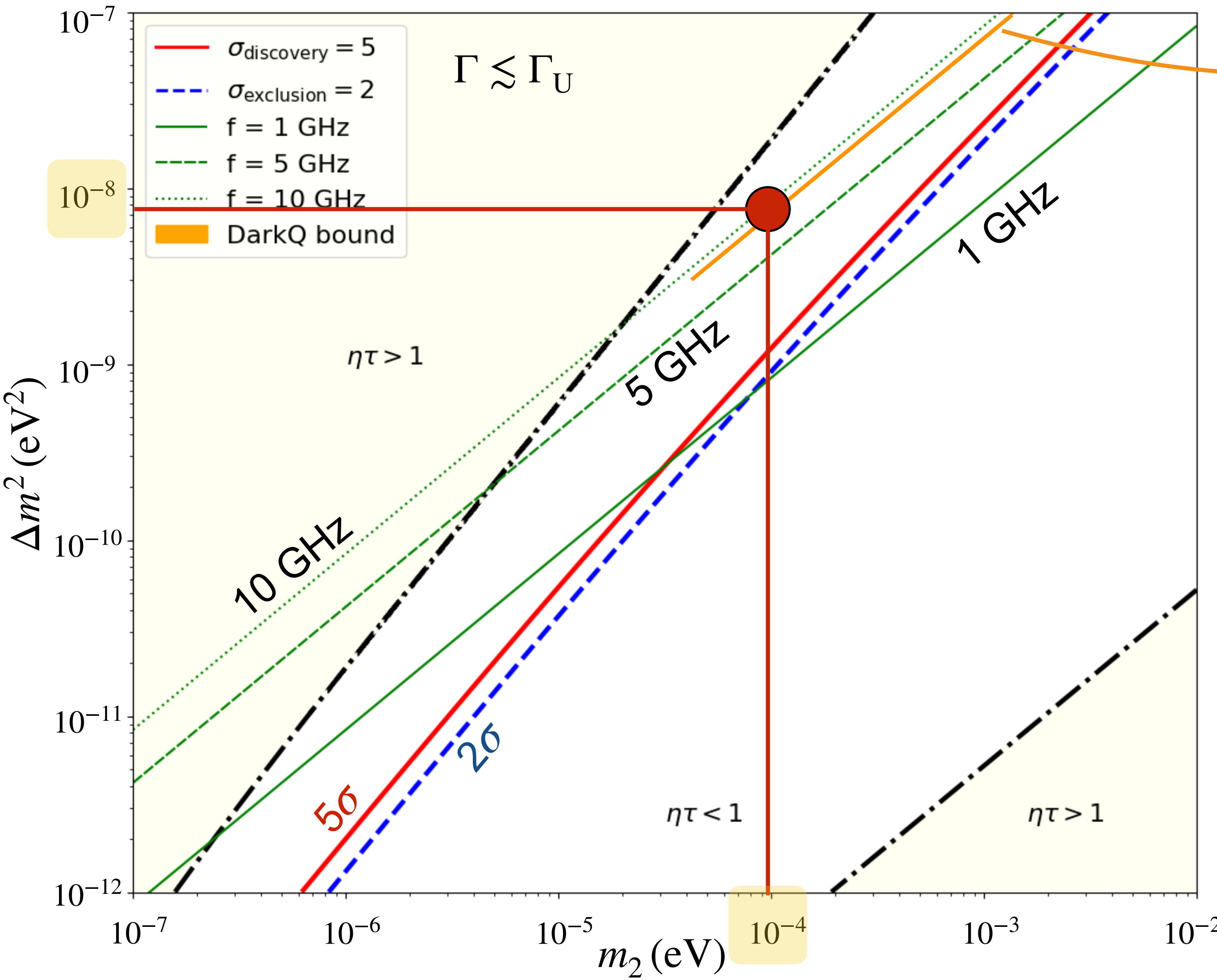
- Particle physics has long operated at the forefront of technological innovation - for example, through the development of low-temperature superconducting systems used in the LHC.
- Recently, several promising efforts have emerged to harness quantum technologies, including quantum simulation, quantum machine learning, quantum sensing, and quantum networking.
- In this talk, we showed that a gate-based quantum computer can be programmed to detect photons produced in the radiative decays of dark matter and neutrinos.
- While the proposed approach can effectively explore viable parameter spaces in two-component dark matter models, detecting cosmic neutrinos remains a significant challenge with current quantum algorithms.

Discussion

- Quantum algorithms that could enhance beyond n_q^2
- What about other quantum devices
  - Transmon, trapped ion, Rydberg, what else?
  - Ge-based spin qubits
- Testing on real quantum computers is being discussed.
  - IQM Spark 5 qubits
- Other sources of photons
  - Hidden photon dark matter, axions, DM decays
  - High frequency gravitational wave detection
  - $X_2 \longrightarrow X_1 + \gamma + \gamma$



$$X_2 \longrightarrow X_1 + \gamma + \gamma$$



DarQ

$\mu = \mu_{\max}^{\mathrm{Uni}}$

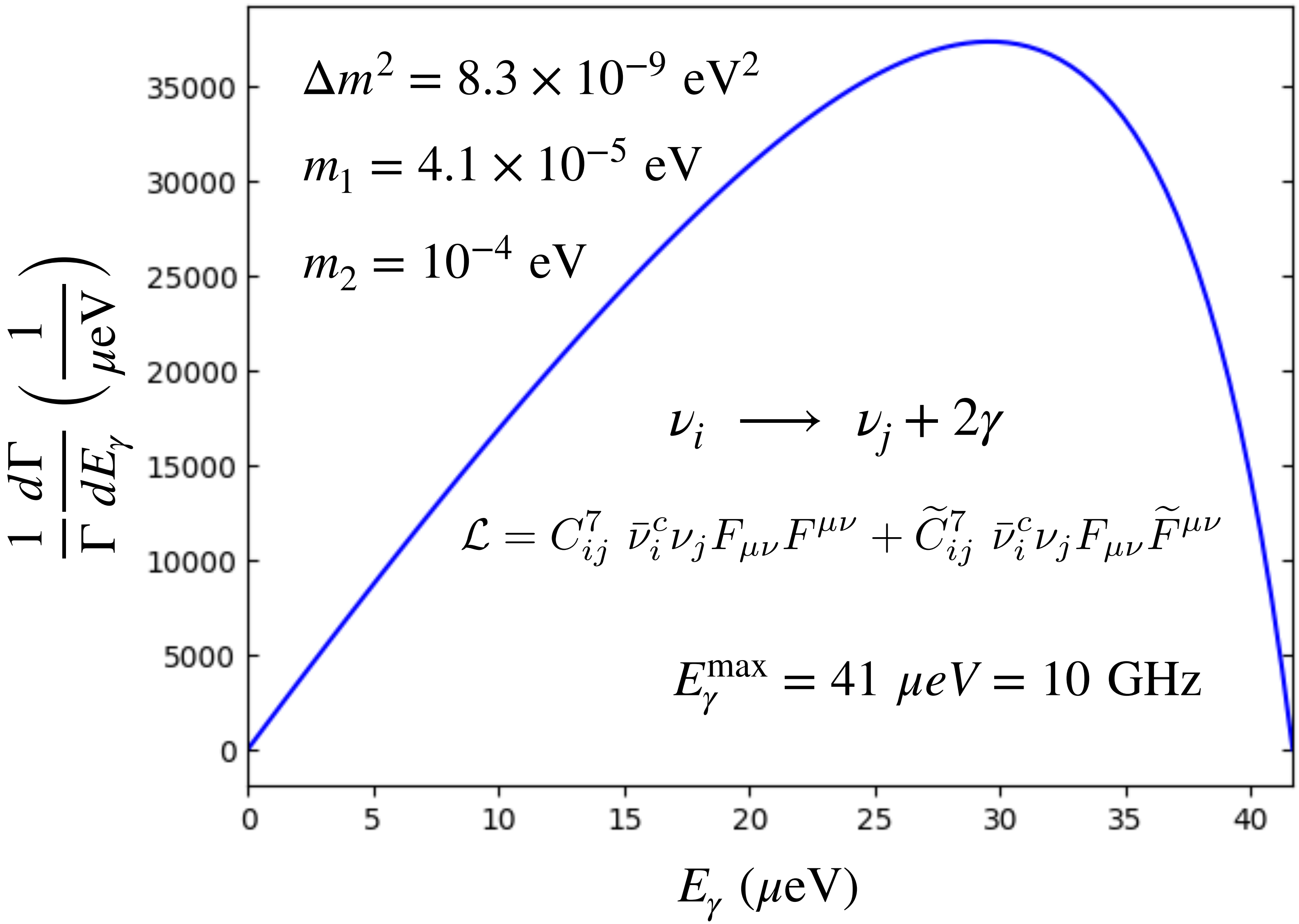
$n_q = 1$

$\tau = 100\,\mu s$

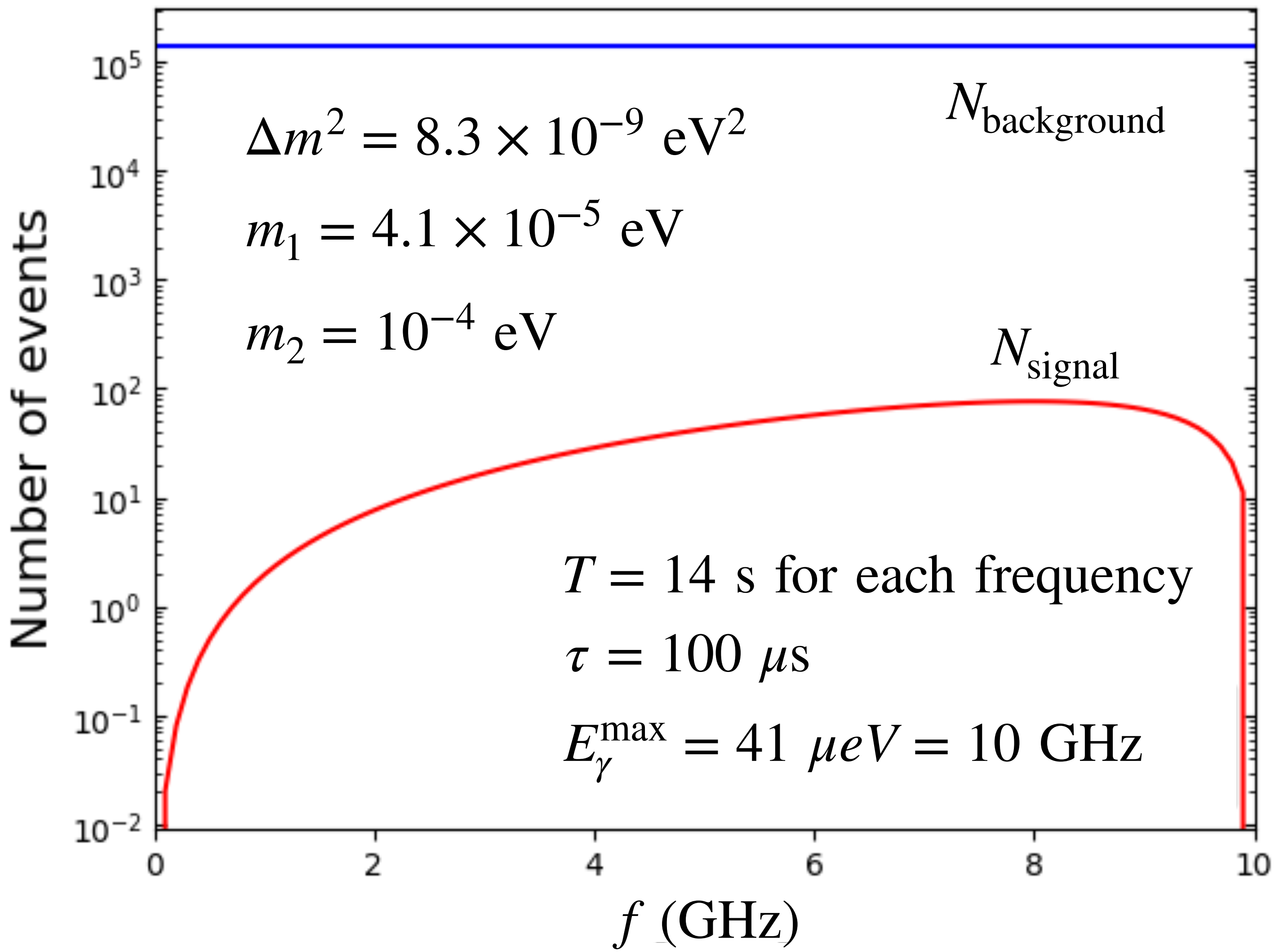
$V_{\mathrm{eff}} = 1$

14 seconds data collection for each frequency

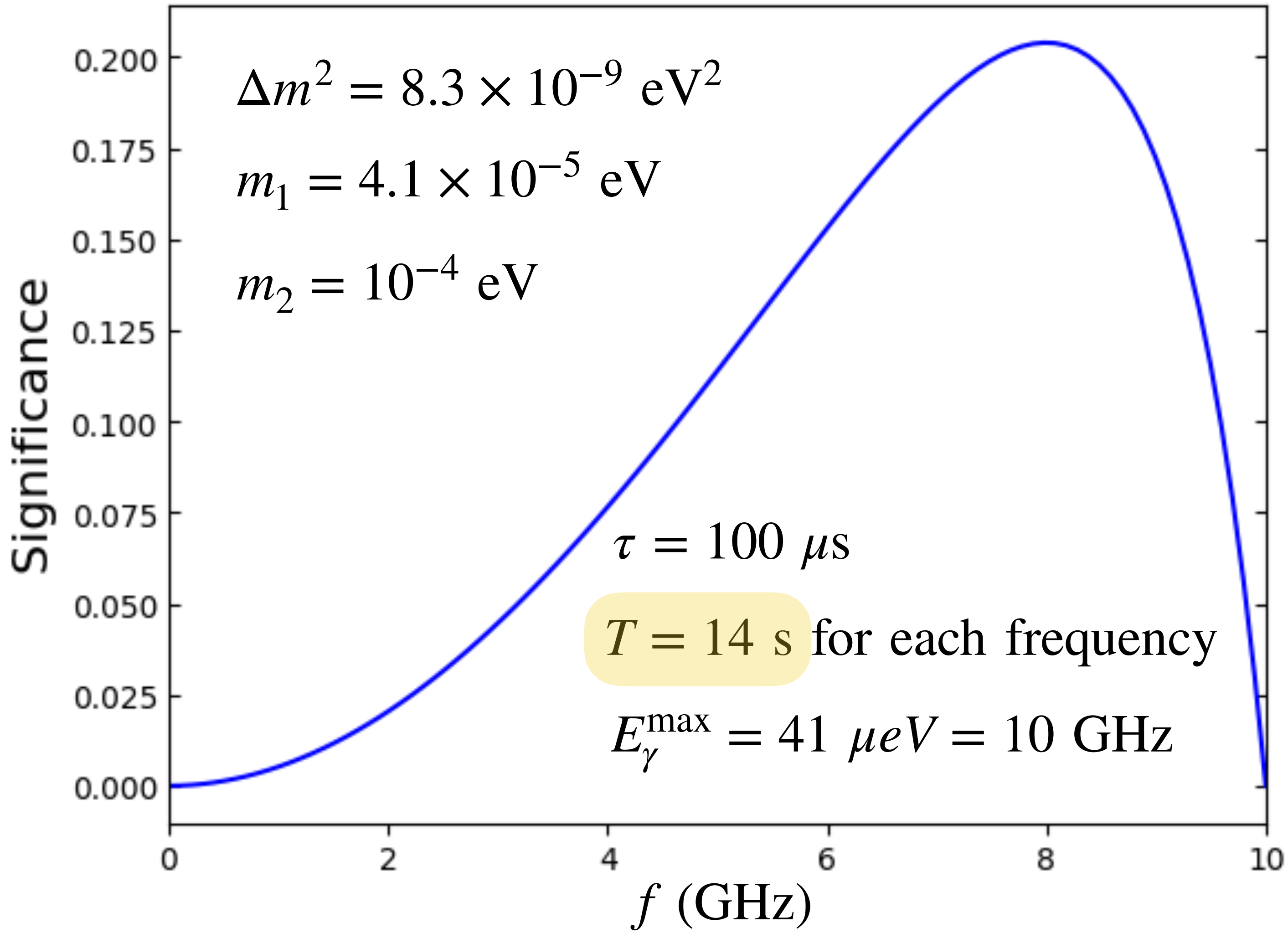
$$X_2 \longrightarrow X_1 + \gamma + \gamma$$



$$X_2 \longrightarrow X_1 + \gamma + \gamma$$



$$X_2 \longrightarrow X_1 + \gamma + \gamma$$

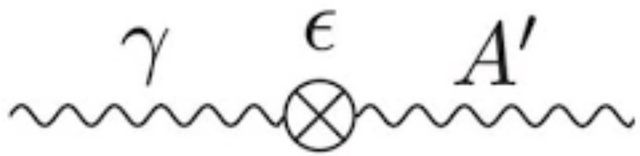


$$p_* \sim \left(\frac{\tau}{100\,\mu\text{s}}\right)^3$$

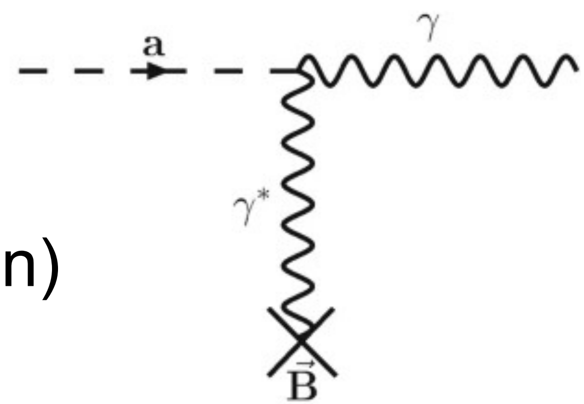
- Longer exposure will enhance the signal significance.
- Do not need to scan entire frequency range (between 1 GHz and 10 GHz).
- Signal could appear more than one place.

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

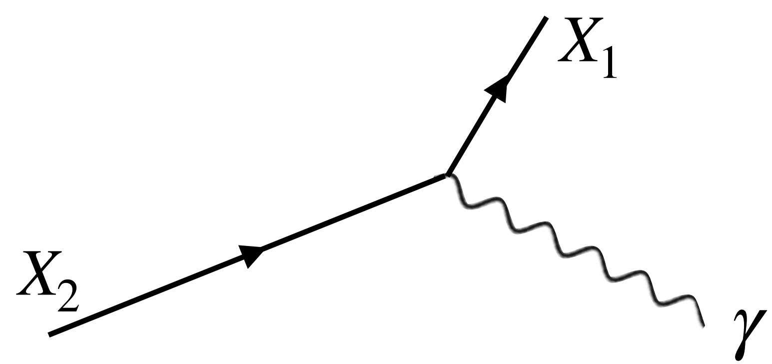


  - Axions (if external magnetic field is given)

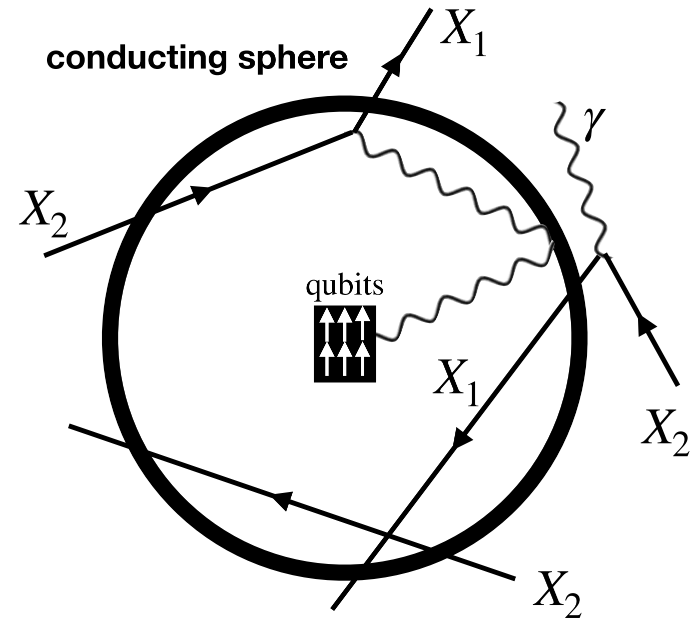
    2407.19755, transmon
    2507.17825, trapped ion

  - DM and neutrino decays

    2508.09139, transmon, trapped ion



Radiative Decays of Dark Matter Particles



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

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

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

For transmon qubits

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

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

For trapped ions

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

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

2508.09139

Radiative Decays of Dark Matter

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

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

$$p_{g\to e}(t) = |\psi_e(t)|^2 \simeq \sin^2\eta t$$

$$p_* \equiv p_{g\to e}(\tau) \simeq (\eta\tau)^2$$

Transition probability

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

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

2508.09139

Dark matter decay

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

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

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

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

Bound on life time

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

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

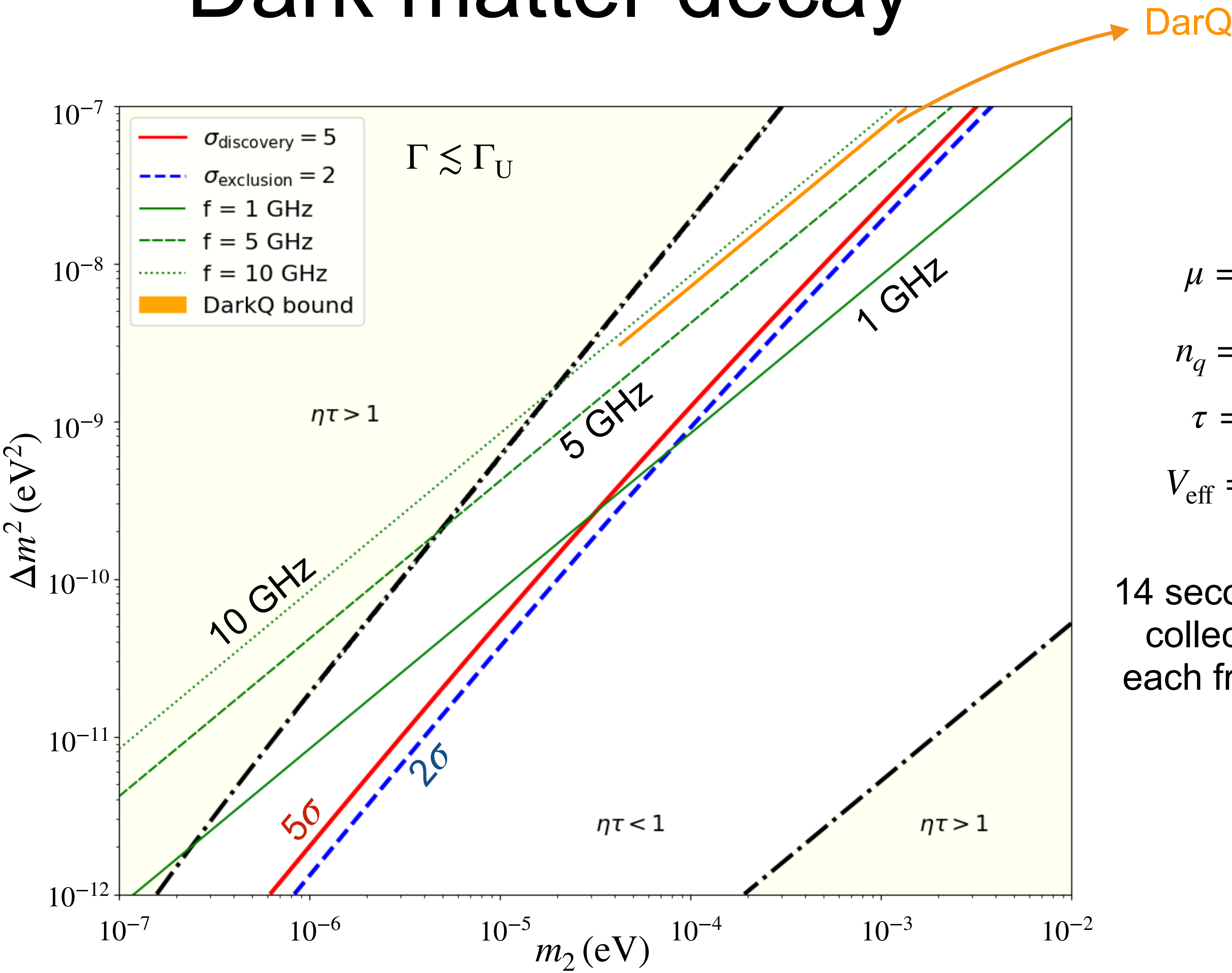
$$p_* \simeq \; p_*^0 \times \cos^2\Theta \left(\frac{V_{\mathrm{eff}} \, \rho_{\mathrm{DM}}}{0.45 \, \mathrm{GeV \, cm^{-3}}}\right) \left(\frac{\Delta m^2}{m_2^2}\right) \left(\frac{d}{100 \; \mu\mathrm{m}}\right)^2 \left(\frac{C}{0.1 \; \mathrm{pF}}\right) \left(\frac{f}{1 \; \mathrm{GHz}}\right)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

$$p_*^0 \; = \; 0.069$$

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

2508.09139

Dark matter decay



$\mu = \mu_{\max}^{\text{Uni}}$

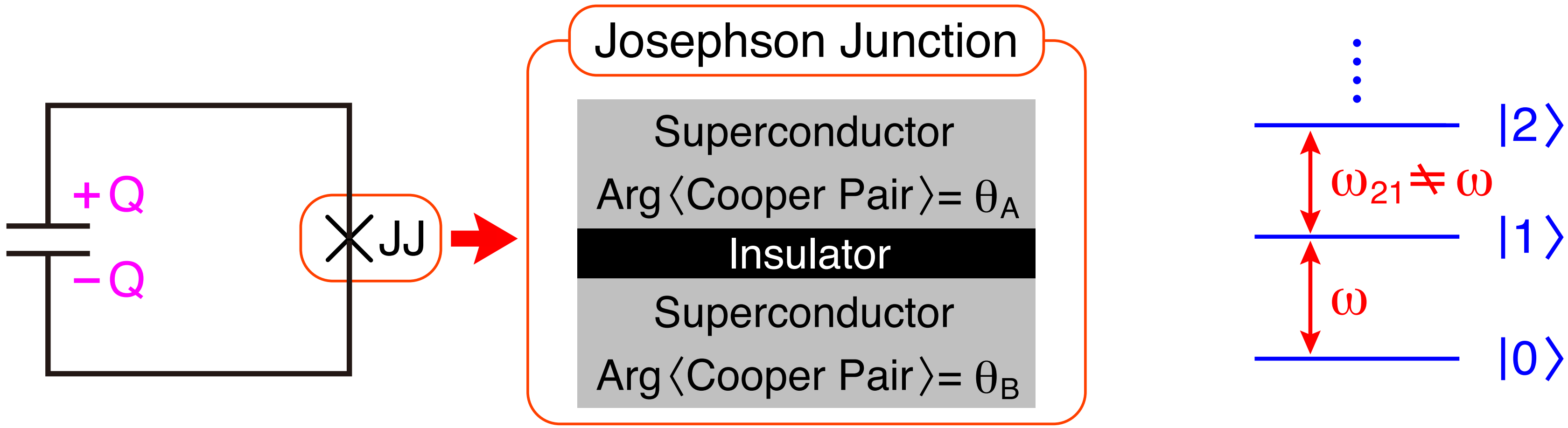
$n_q = 1$

$\tau = 100\,\mu s$

$V_{\text{eff}} = 1$

14 seconds data collection for each frequency

Transmon qubit:
Capacitor + Josephson junction (JJ)

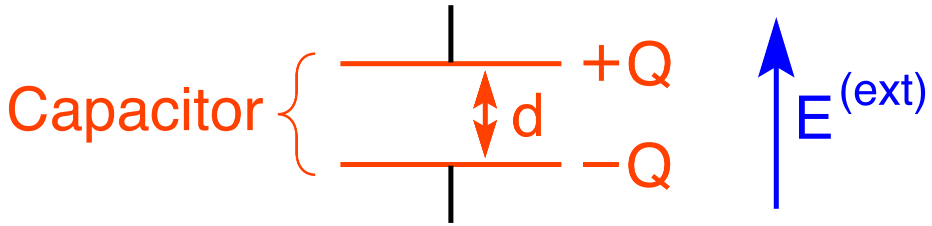


$$H_0 = \frac{1}{2C}Q^2 - J\cos\theta \simeq \frac{1}{2}\frac{C}{(2e)^2}\dot{\theta}^2 - J\cos\theta \quad \text{with } \theta = \theta_B - \theta_A$$

- Transmon qubit has discrete energy levels
  - $|0\rangle$ and $|1\rangle$ can be used as $|g\rangle$ and $|e\rangle$, respectively
  - Transmon qubits are commonly used in today's quantum computers

Transmon qubits

- Transmon qubit couples to external electric field



$$\Leftrightarrow \; H_{\text{int}} = QdE^{(\text{ext})}$$

- Charge operator in the transmon limit: $CJ \gg (2e)^2$

$$Q \simeq \frac{C}{2e}\dot{\theta} \simeq \sqrt{\frac{C\omega}{2}}\big(\,|g\rangle\langle e| + |e\rangle\langle g|\,\big)$$

- $|g\rangle \leftrightarrow |e\rangle$ transition could occur, if there is additional electric field!
  – This is not possible, since qubits are inside some cavity.

DarQ bounds

$$\bar{E}_{(\mathrm{eff})} = \sqrt{\frac{\Gamma\,\mathcal{T} n_2 \Delta m^2}{2 m_2 \varepsilon_0}} \qquad \rho_{\mathrm{DM}} \approx m_2\, n_2$$

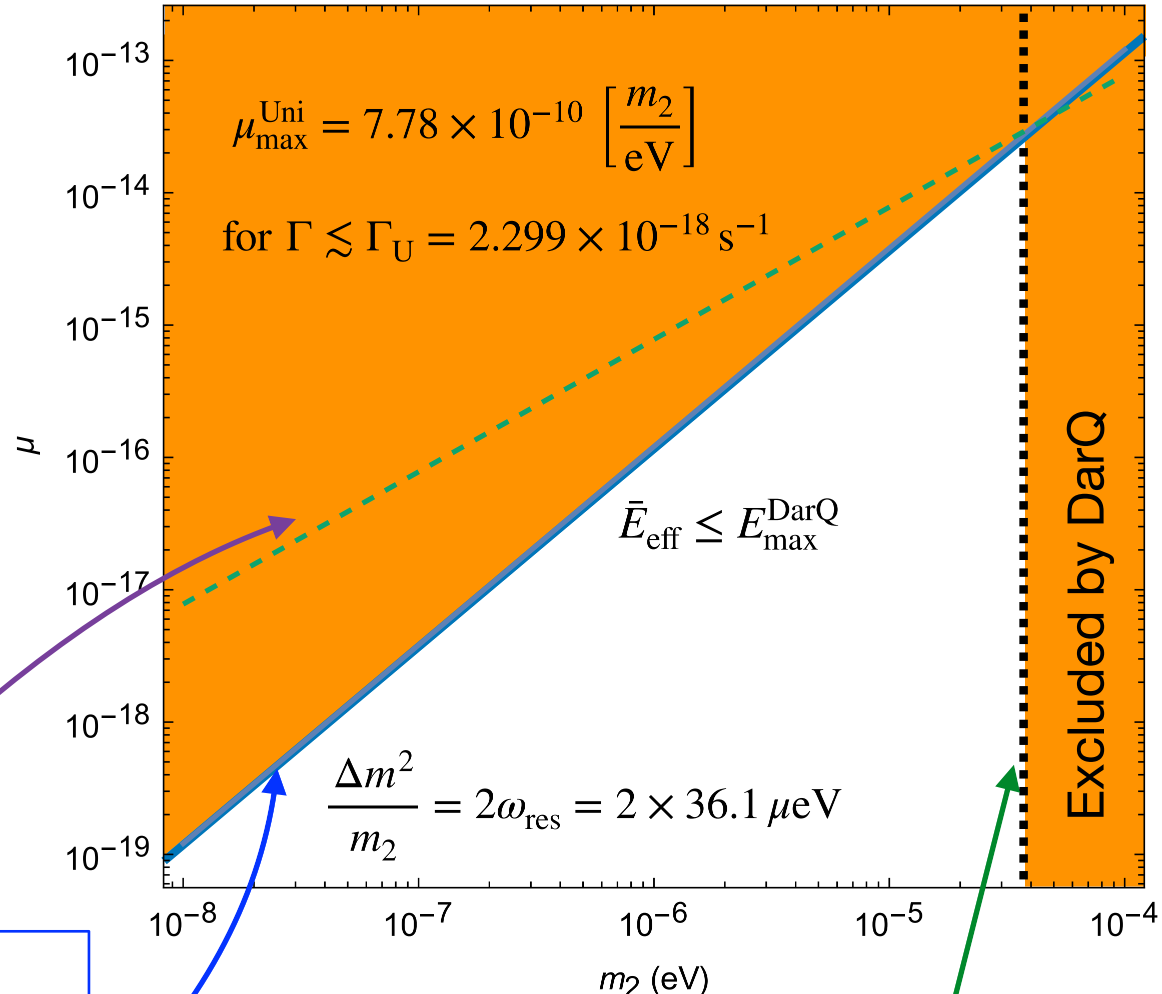
$$E_\gamma = \frac{\Delta m^2}{2m_2} = \omega_{\mathrm{res}}^{\mathrm{DarQ}} = 36.1\ \mu\mathrm{eV}$$

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

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

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

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



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

$$\mu^2 < \frac{12\pi\epsilon^2\varepsilon_0}{(\omega_{\mathrm{res}}^{\mathrm{DarQ}})^4\mathcal{T}} m_2^3 = 1.46 \times 10^{-14} \times \left(\frac{m_2}{\mathrm{eV}}\right)^3$$

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

$$m_2 = \frac{\Gamma\mathcal{T}\omega_{\mathrm{res}}^{\mathrm{DarQ}}}{2\varepsilon_0\epsilon^2} = 4.15 \times 10^{-5}\ \mathrm{eV}$$

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

2508.0913

A simplified Setup: signal-sensor interaction

- Core setup for many quantum sensing protocols in HEP (Details vary, but the essential physics is often similar)

- Sensor: A Two-Level Quantum System
  - A qubit as a simple example
  - Two states: Ground 0 and Excited 1
  - Can be a physical qubit, a cavity mode ($n = 0$, $n = 1$) etc.

- Signal: A Weak Classical Field
  - E.g., wave-like DM, high-frequency GWs
  - Drive transitions from $|0\rangle$ to $|1\rangle$
  - Interaction Hamiltonian: $H_I = \epsilon\left(\cos\alpha\,\sigma_X + \sin\alpha\,\sigma_Y\right)$
  - ϵ: Signal strength (the quantity to be estimated)
  - α: Signal phase (often stochastic/random)

- The Goal to estimate the signal strength ϵ.
  1. Evolve: System evolves from $|0\rangle$ (ground state of free Hamiltonian) under H_I. 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 $|1\rangle$: $p_1 = \left|\langle 1\,|\,\psi(t)\rangle\right|^2 = \epsilon^2 t^2$

Advantages of Quantum Sensing

- Classical sensing: typically for strong signals
- Quantum sensing: significant advantages for weak signals

- Key quantum features for sensing
  - Fundamental limits from zero-point fluctuations
  - Enhanced sensitivity through entanglement, surpassing classical limits

- Promising applications in fundamental physics, where signals are often extremely weak and changing in time with unknown frequencies.
  - Dark matter searches
  - Neutrino transition magnetic moment

Quantum Enhancement of the Signal Rate

$U_{\rm DM}$ induces pure phase rotation of its eigenstates

E.g. for $\alpha = 0$: $U_{\rm DM} \simeq \begin{pmatrix} 1 & i\delta \\ i\delta & 1 \end{pmatrix}$ with $\delta \equiv \eta\tau$

$\Rightarrow\ U_{\rm DM}|\pm\rangle = e^{\pm i\delta}|\pm\rangle$ with $|\pm\rangle \equiv \frac{1}{\sqrt{2}}\big(|g\rangle \pm |e\rangle\big)$

$\Rightarrow\ U_{\rm DM}^{\otimes N_{\rm q}}|+\rangle^{\otimes N_{\rm q}} = e^{iN_{\rm q}\delta}|+\rangle^{\otimes N_{\rm q}}$

We can design quantum operations to enhance the signal

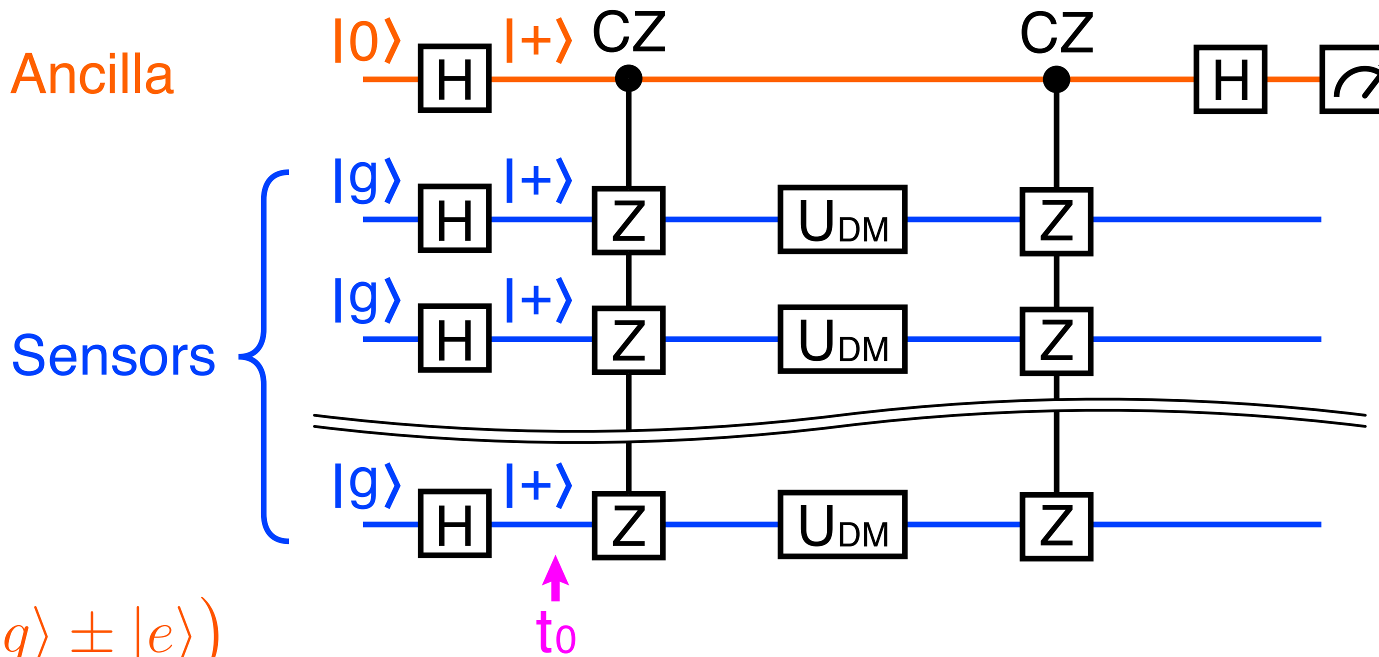
$\Rightarrow$ Quantum enhanced parameter estimation

[Giovannetti, Lloyd, Maccone ('04)]

Shion Chen, Hajime Fukuda, Toshiaki Inada, Takeo Moroi, Tatsumi Nitta, Thanaporn Sichanugrist, 2024 PRL

Quantum Enhancement of the Signal Rate

One measurement cycle for the signal enhancement

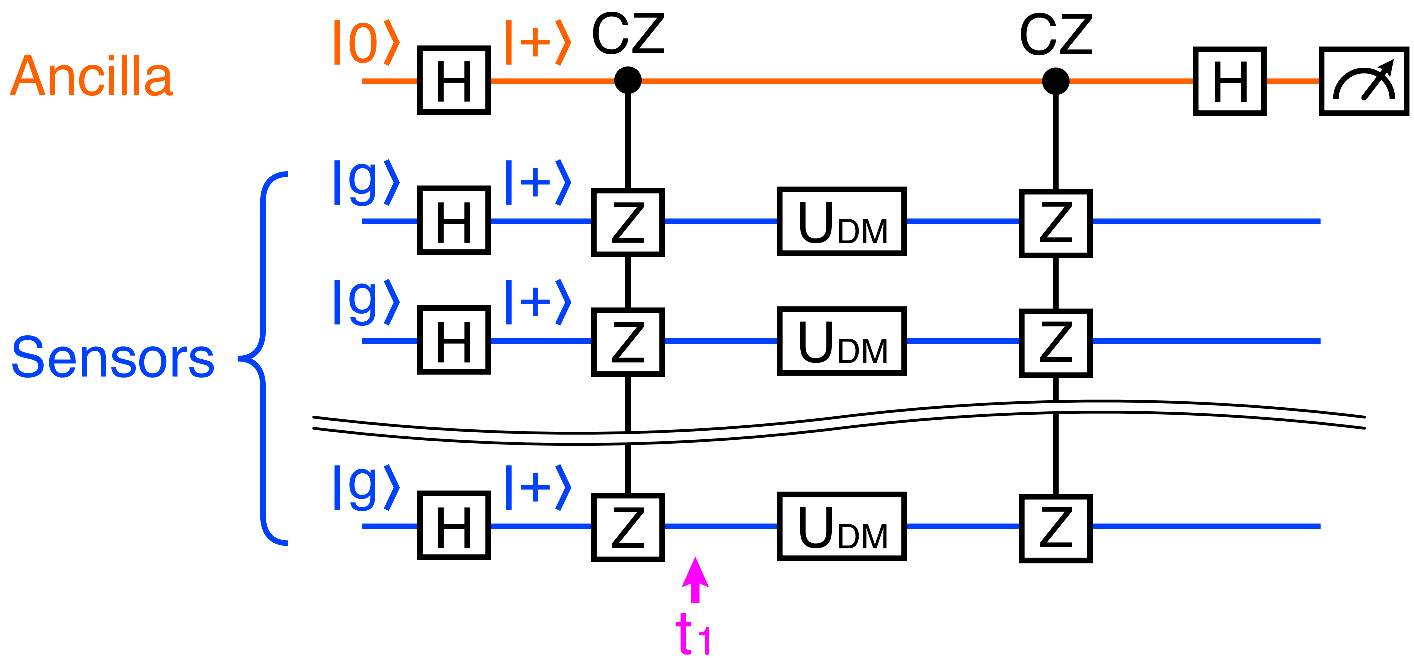


$$|\pm\rangle \equiv \frac{1}{\sqrt{2}}\big(|g\rangle \pm |e\rangle\big)$$

$$|\Psi(t_0)\rangle = |+\rangle \otimes |+\rangle^{\otimes N_q} = \frac{1}{\sqrt{2}}|0\rangle \otimes |+\rangle^{\otimes N_q} + \frac{1}{\sqrt{2}}|1\rangle \otimes |+\rangle^{\otimes N_q}$$

Shion Chen, Hajime Fukuda, Toshiaki Inada, Takeo Moroi, Tatsumi Nitta, Thanaporn Sichanugrist, 2024 PRL

One measurement cycle for the signal enhancement



$$|\Psi(t_1)\rangle = \frac{1}{\sqrt{2}}|0\rangle \otimes |+\rangle^{\otimes N_q} + \frac{1}{\sqrt{2}}|1\rangle \otimes |-\rangle^{\otimes N_q}$$

- Controlled Z gate

$$Z|\pm\rangle = \pm|\mp\rangle$$

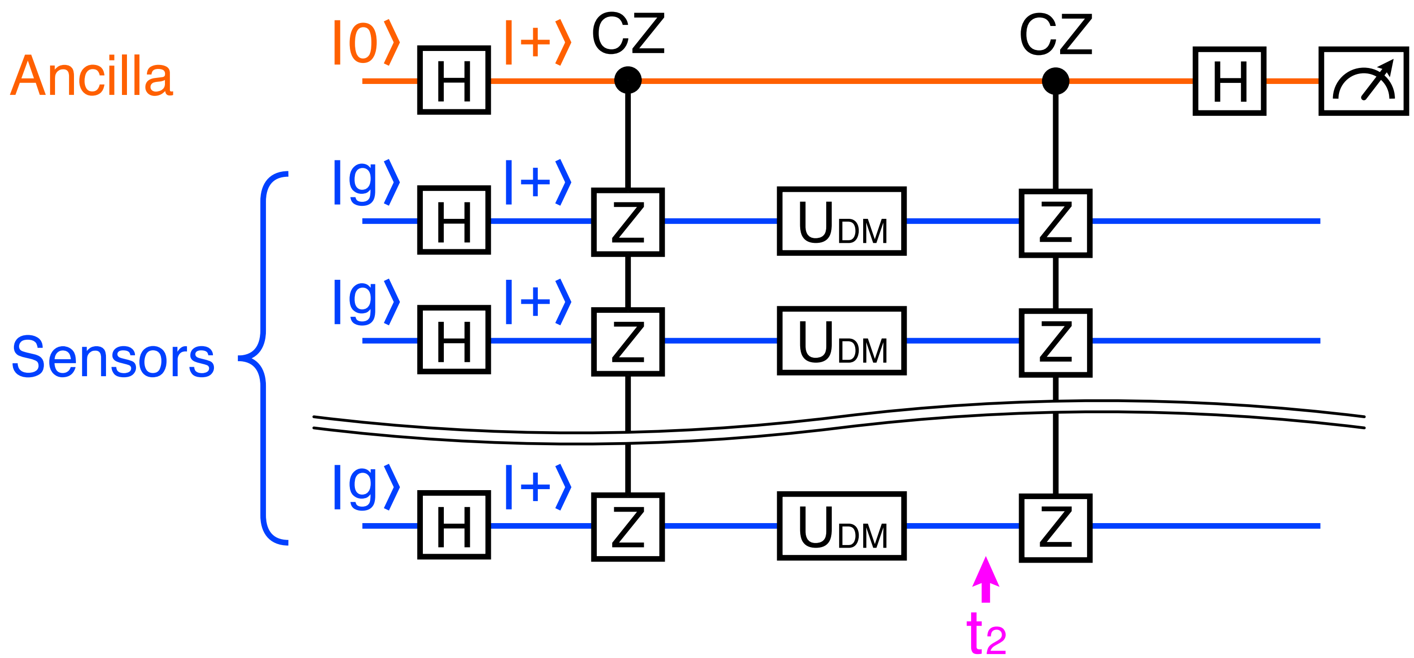
$$CZ = |0\rangle\langle 0| \otimes \mathbf{1} + |1\rangle\langle 1| \otimes Z$$

$$\Rightarrow \quad \frac{1}{\sqrt{2}}\big(|0\rangle + |1\rangle\big) \otimes |+\rangle \xrightarrow{CZ} \frac{1}{\sqrt{2}}|0\rangle \otimes |+\rangle + \frac{1}{\sqrt{2}}|1\rangle \otimes |-\rangle$$

Shion Chen, Hajime Fukuda, Toshiaki Inada, Takeo Moroi, Tatsumi Nitta, Thanaporn Sichanugrist, 2024 PRL

Quantum Enhancement of the Signal Rate

One measurement cycle for the signal enhancement

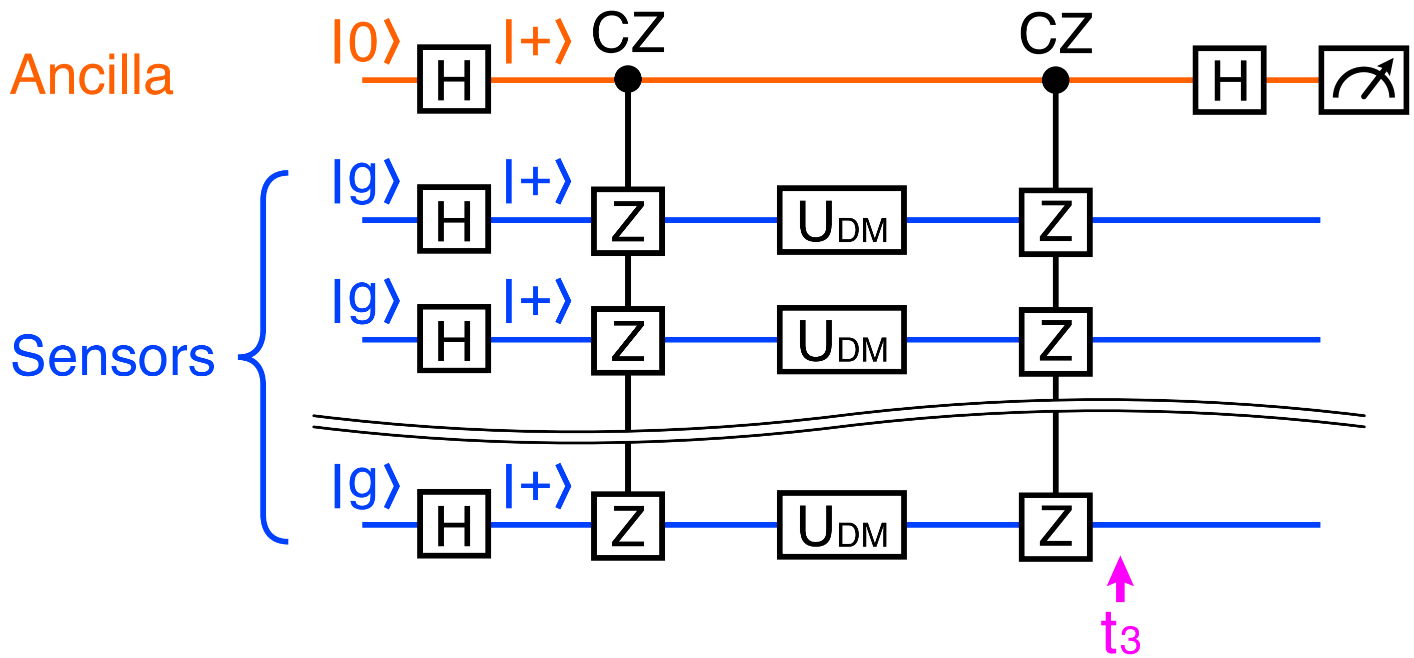


$$|\Psi(t_2)\rangle = \frac{1}{\sqrt{2}} e^{iN_{\mathrm{q}}\delta} |0\rangle \otimes |+\rangle^{\otimes N_{\mathrm{q}}} + \frac{1}{\sqrt{2}} e^{-iN_{\mathrm{q}}\delta} |1\rangle \otimes |-\rangle^{\otimes N_{\mathrm{q}}}$$

Shion Chen, Hajime Fukuda, Toshiaki Inada, Takeo Moroi, Tatsumi Nitta, Thanaporn Sichanugrist, 2024 PRL

Quantum Enhancement of the Signal Rate

One measurement cycle for the signal enhancement



$$|\Psi(t_3)\rangle = \frac{1}{\sqrt{2}}e^{iN_q\delta}|0\rangle \otimes |+\rangle^{\otimes N_q} + \frac{1}{\sqrt{2}}e^{-iN_q\delta}|1\rangle \otimes |+\rangle^{\otimes N_q}$$

$$= \left(\cos\, N_q\delta\,|+\rangle + i\,\sin\, N_q\delta\,|-\rangle\right) \otimes |+\rangle^{\otimes N_q}$$

Shion Chen, Hajime Fukuda, Toshiaki Inada, Takeo Moroi, Tatsumi Nitta, Thanaporn Sichanugrist, 2024 PRL