Quantum Sensing for Invisibles

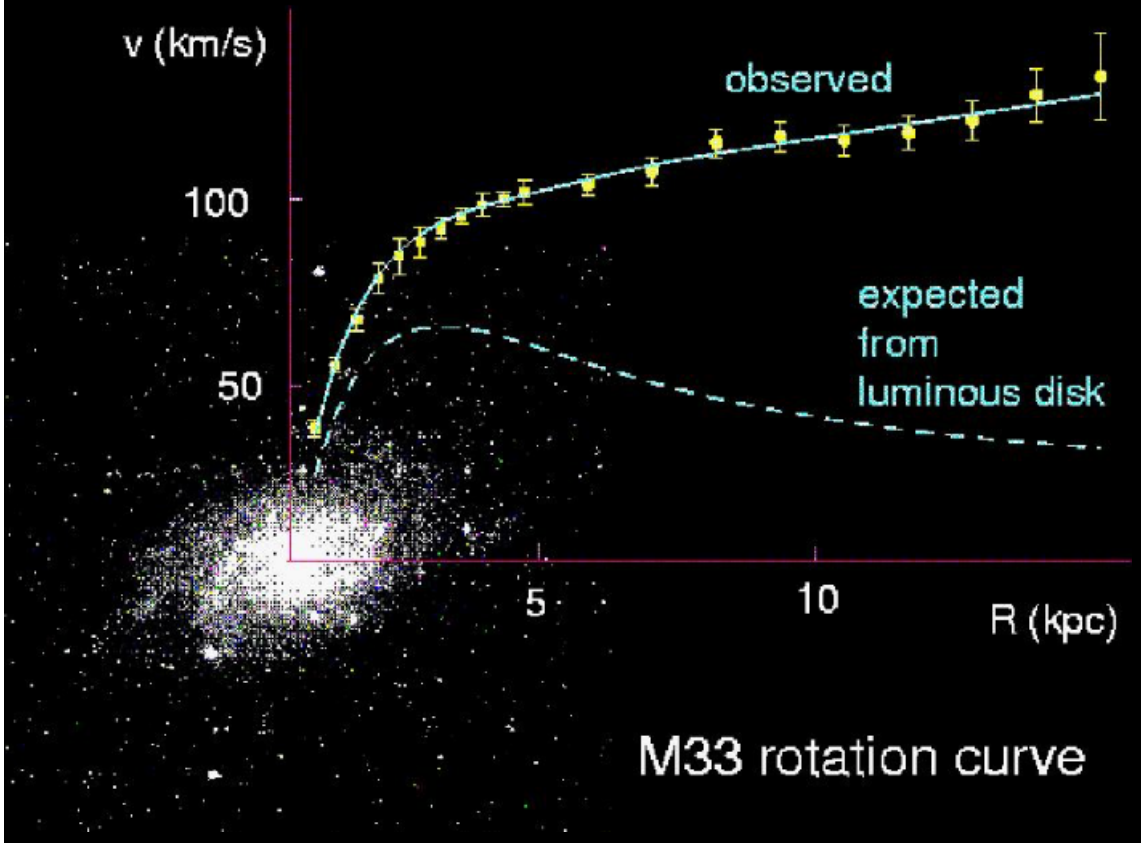
Myeonghun Park

SeoulTech

2026 CPNR Workshop

Unknown portion of the Universe

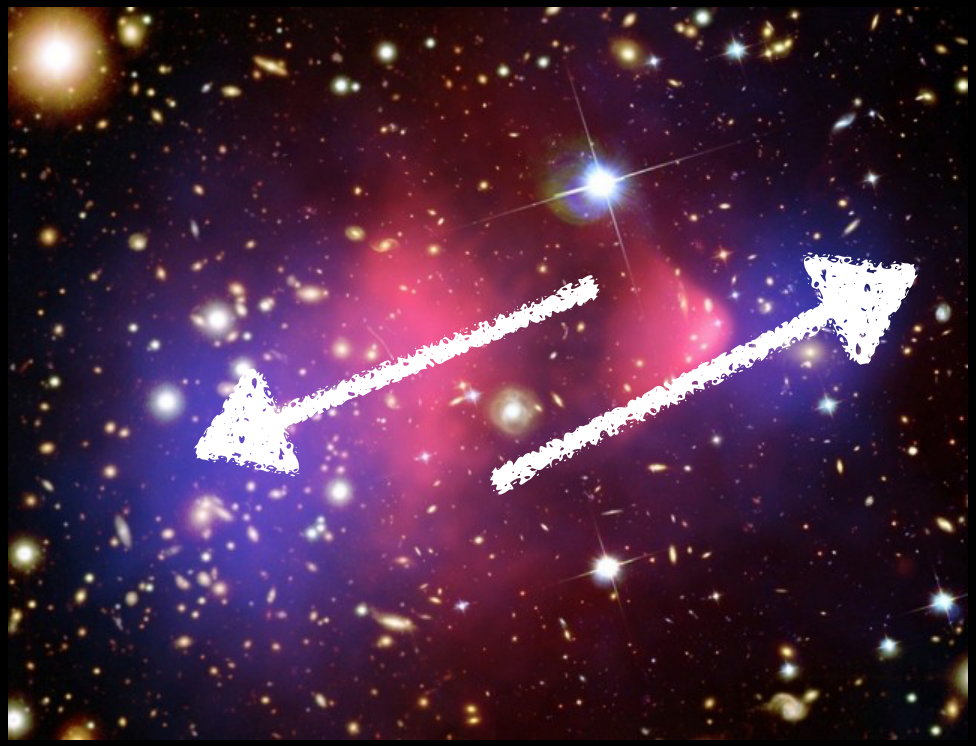
- **This rotation curve reveals an unseen source of gravity: stars move faster than visible matter alone can explain.**

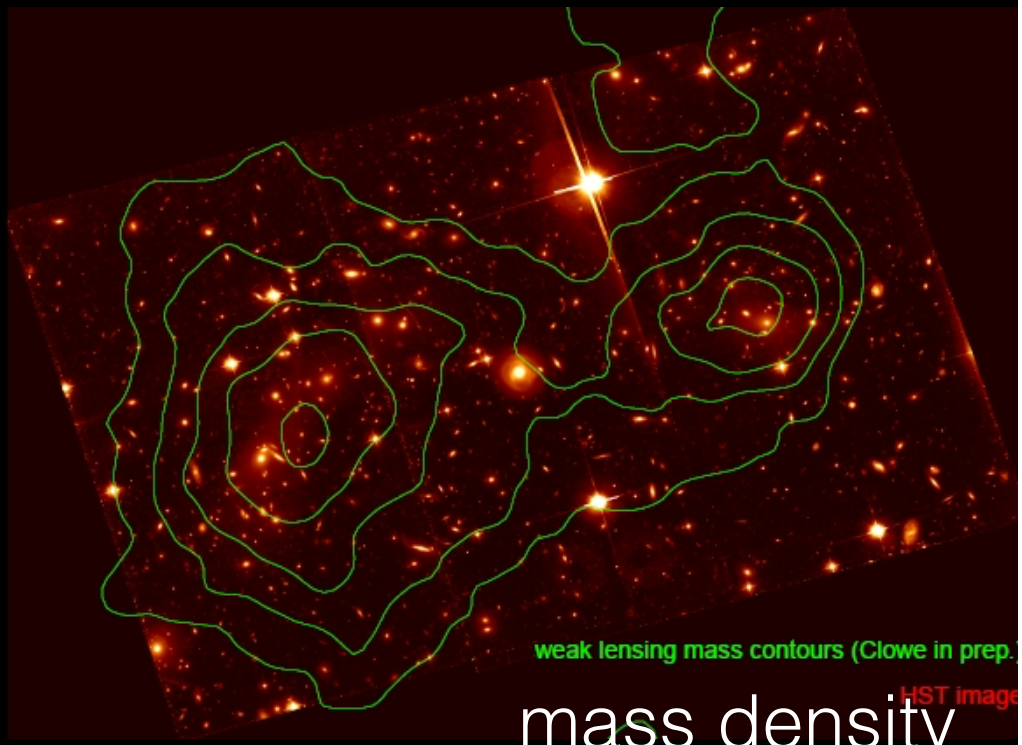


M33 rotation curve

- **Simple interpretations:**
  - **Extra, unseen matter**
  - **Modified gravity at large distances**

- When two galaxy clusters collide,





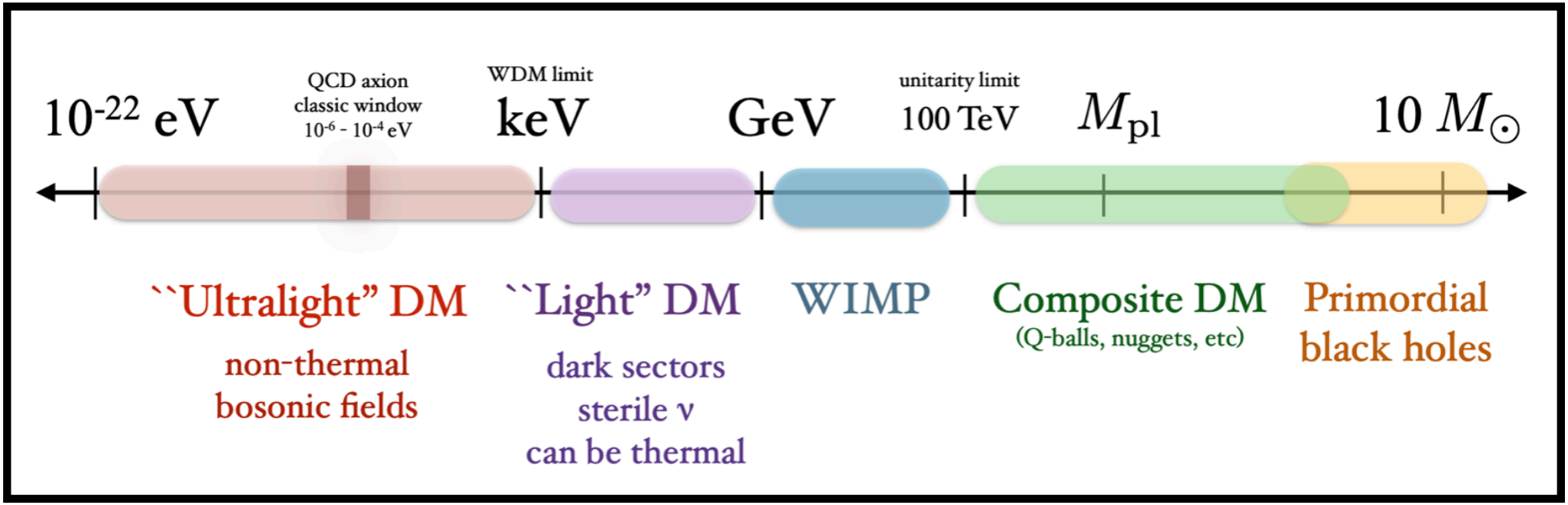
mass density

- The visible matter interacts during the collision, is slowed down, and is observed in X-rays.

- **The mass distribution inferred from gravitational lensing appears elsewhere**

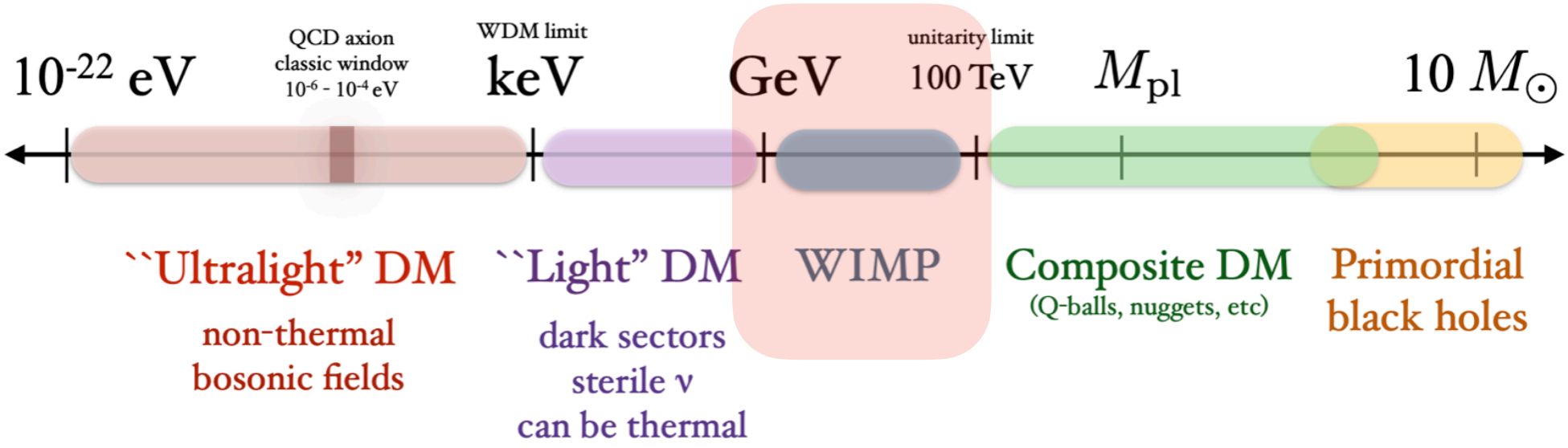
- **This makes "dark matter" the simplest explanation.**

Dark Matter



- We have no direct information about the particle properties of dark matter, including its mass scale.

Dark Matter

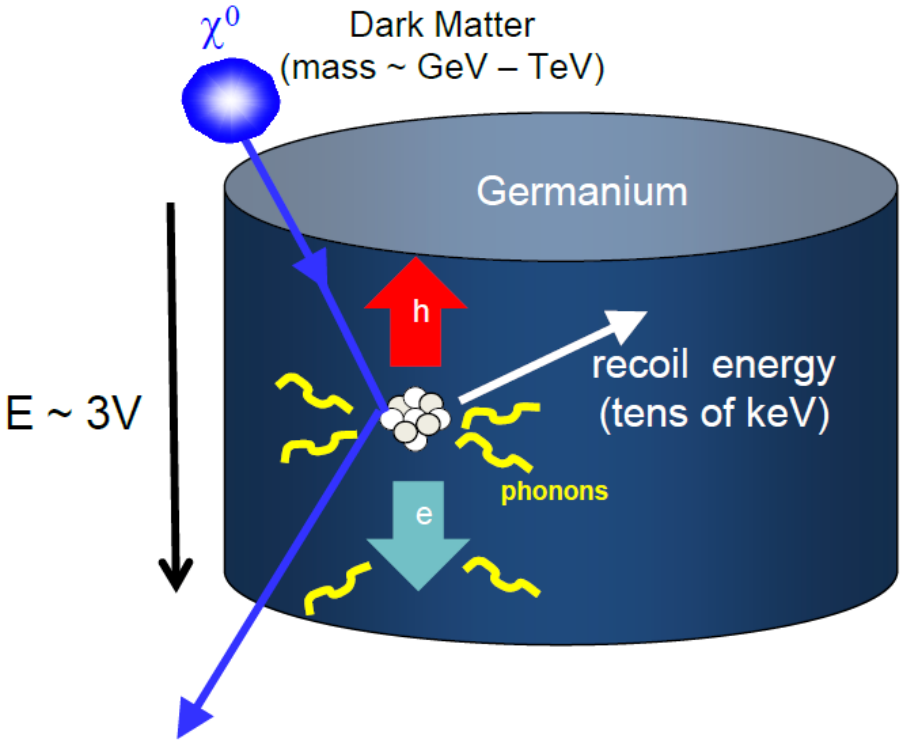


- **Motivated by theoretical arguments, much of the community has focused on dark matter searches at the GeV scale.**

WIMP Dark Matter

A Successful Interface of Particle and Nuclear Physics

- **As early as 1985, dark matter detection was formulated as a nuclear scattering problem.** (Mark W. Goodman & Edward Witten PRD 1985)



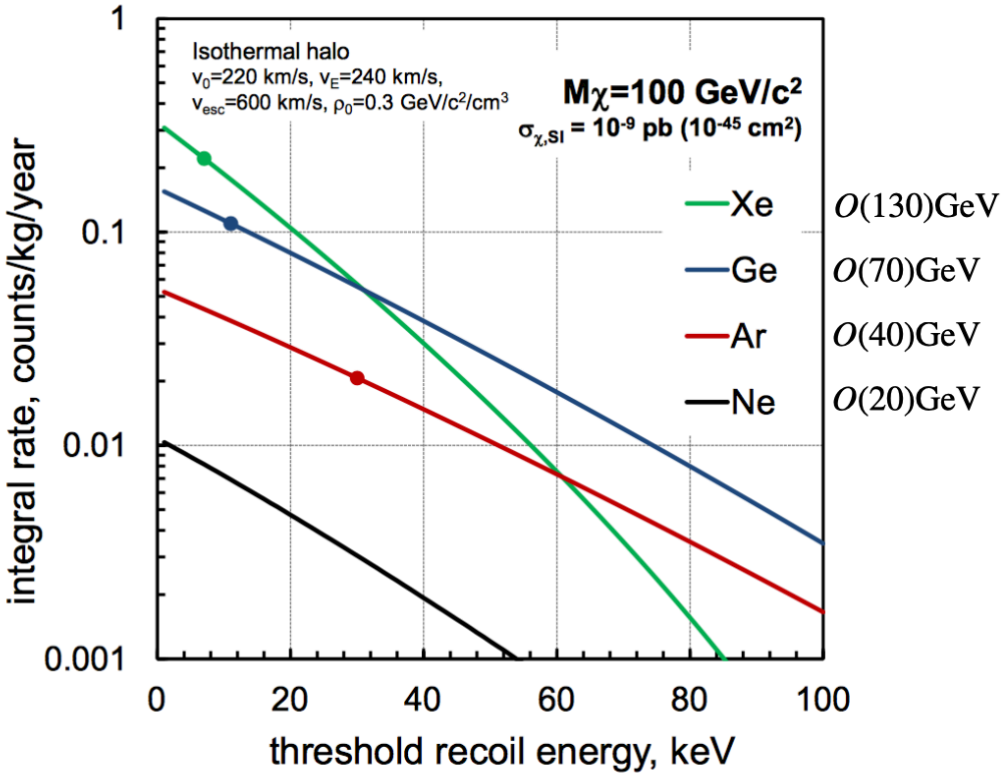
Nuclear physics enabled the experiments

- **Nuclear recoil as the detection channel**
- **Nuclear response functions and form factors**
- **Low-background detectors and rare-event techniques**

WIMP Dark Matter

A Successful Interface of Particle and Nuclear Physics

- Heavier nuclei give higher rates at low recoil thresholds, but lose sensitivity rapidly as the threshold increases.



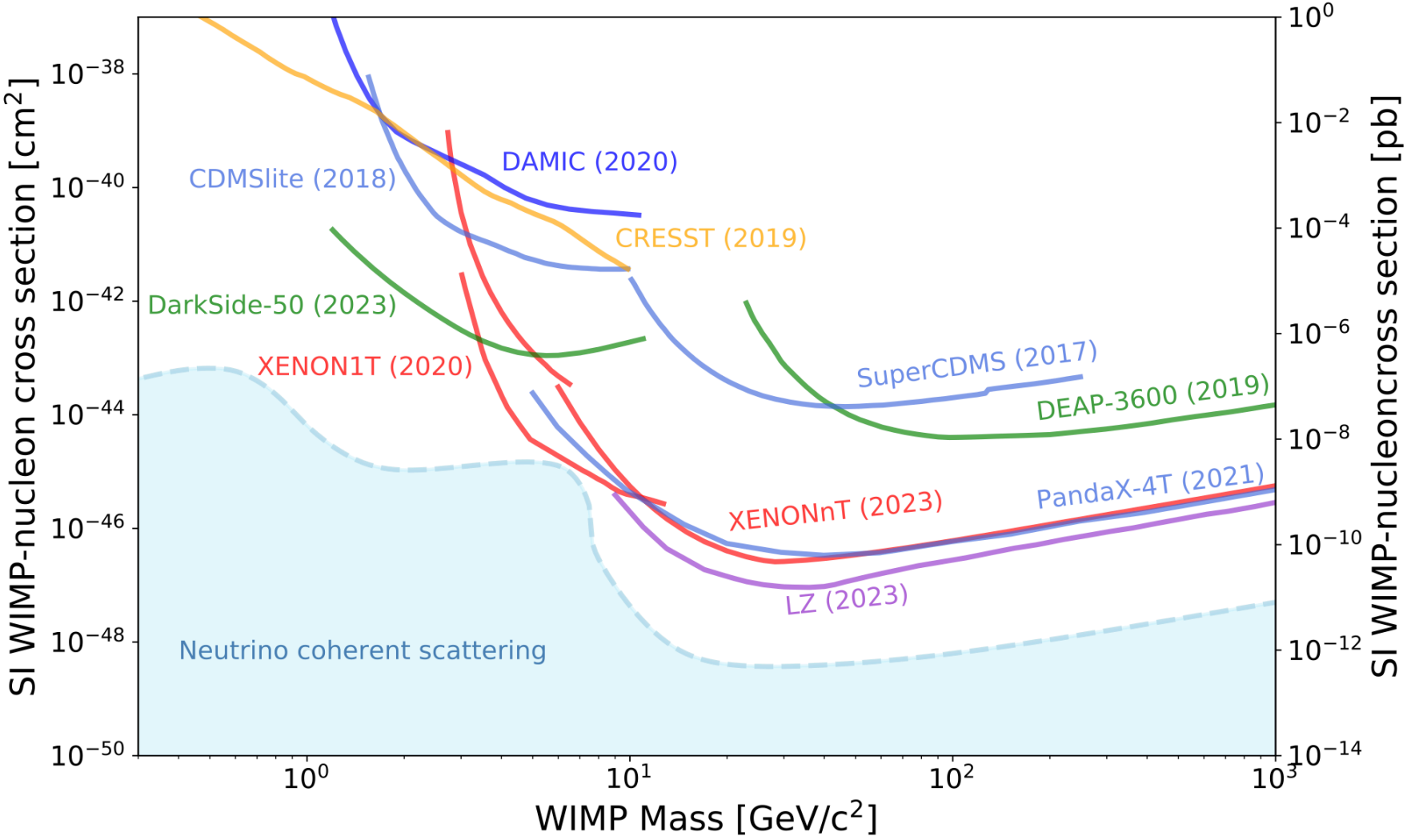
- The recoil energy is maximized when the dark matter mass is comparable to the nuclear mass.

$$< E_R >= E_0 \left(\frac{4 m_\chi m_A}{(m_\chi + m_A)^2} \right) \simeq \frac{1}{2} m_\chi v_0^2$$

sensitive @ $m_\chi \simeq m_A$

- **Nuclear kinematics naturally favors GeV-scale dark matter**

PDG (Particle Data Group) Review 2025 (containing up to 2023 results)

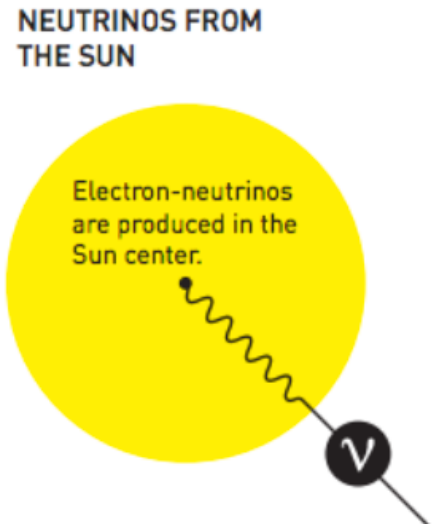


- **Nuclear scattering experiments have been successful, approaching Neutrino coherent scattering limits!**

- **Quantum sensors offer new ways to disentangle dark matter signals from neutrino backgrounds.**

Neutrino from the Sun

- Neutrino come from fusion, proton-to-helium conversion via weak interactions



$$p + p \longrightarrow {}^2H + e^+ + \nu_e \qquad (\nu_{pp})$$

$$p + {}^2H \longrightarrow {}^3He + \gamma$$

86 % (pp-I) | 14 %

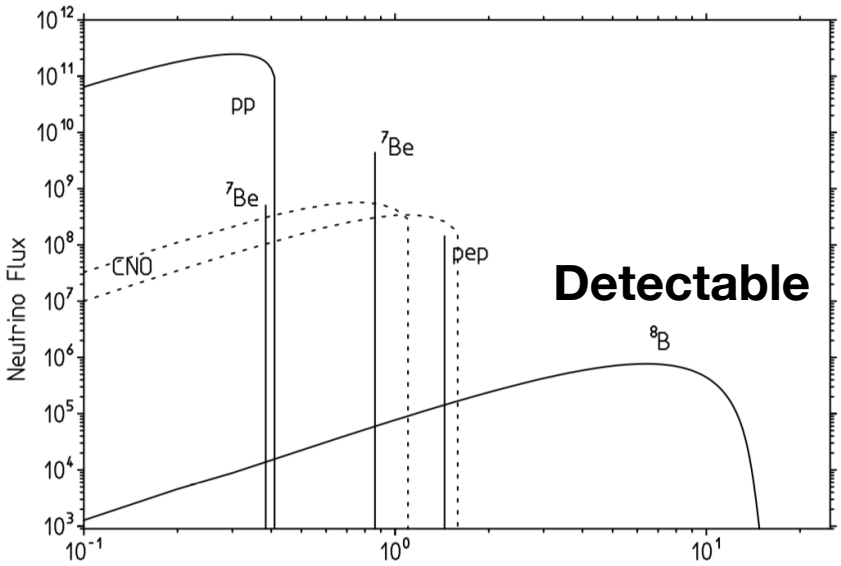
$${}^3He + {}^3He \longrightarrow {}^4He + 2p \qquad {}^3He + {}^4He \longrightarrow {}^7Be + \gamma$$

14 % (pp-II) | 0.02 % (pp-III)

$$(\nu_{Be}) \quad {}^7Be + e^- \longrightarrow {}^7Li + \nu_e \qquad {}^7Be + p \longrightarrow {}^8B + \gamma$$

$$p + {}^7Li \longrightarrow {}^4He + {}^4He \qquad {}^8B \longrightarrow {}^8Be^* + e^+ + \nu_e \qquad (\nu_B)$$

$$\hookrightarrow {}^4He + {}^4He$$



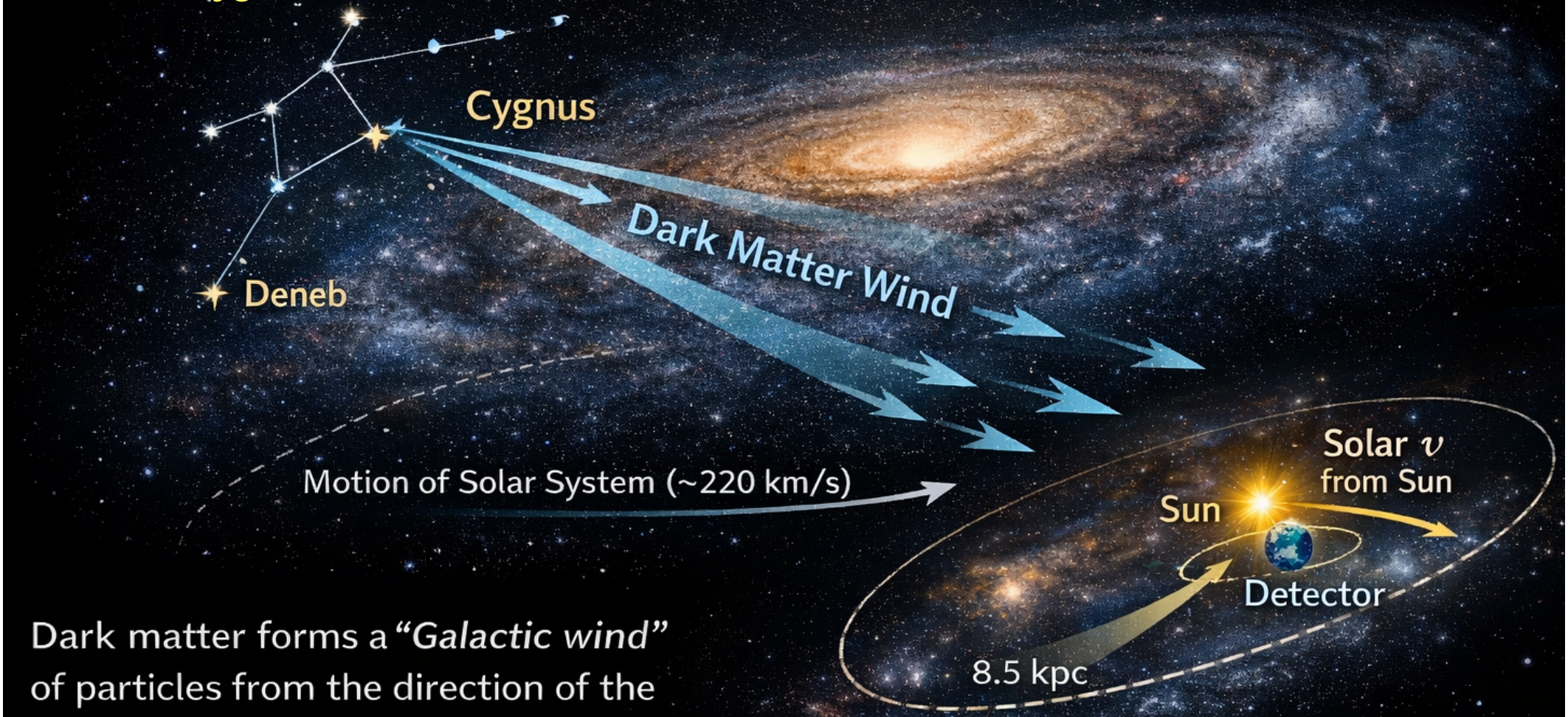
- Size of heavy nucleus, $R \simeq 1.2A^{1/3}\,\mathrm{fm}$.
  The de Broglie wave length of neutrino

$$\bar{\lambda} = \frac{\hbar c}{E_\nu} \simeq O(20)\,\mathrm{fm} \text{ for } E_\nu = O(10)\,\mathrm{MeV}$$

- **Coherent elastic scattering off the whole nucleus**.

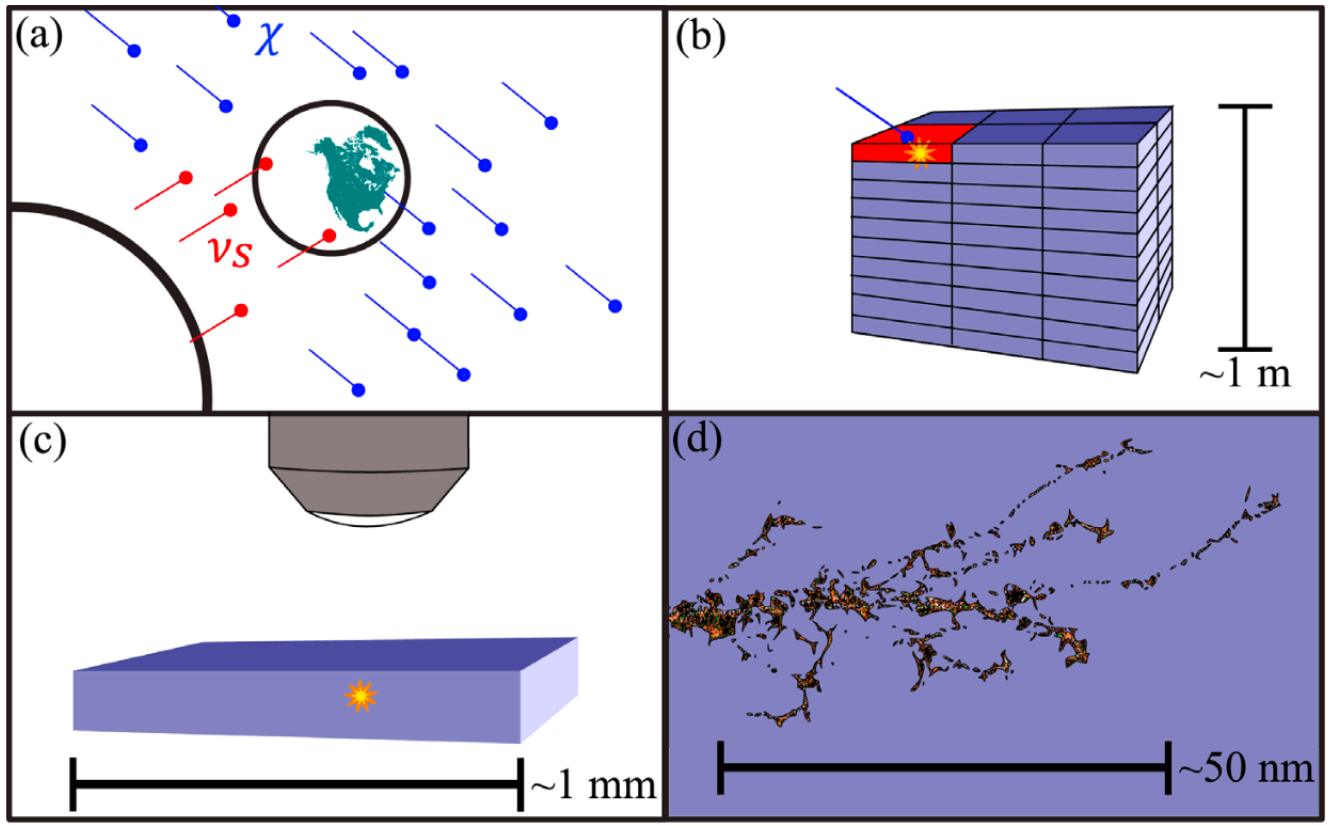
Dark Matter Wind in the Galactic Frame

The Solar System moves around the Galactic center, and its velocity points roughly toward Cygnus.

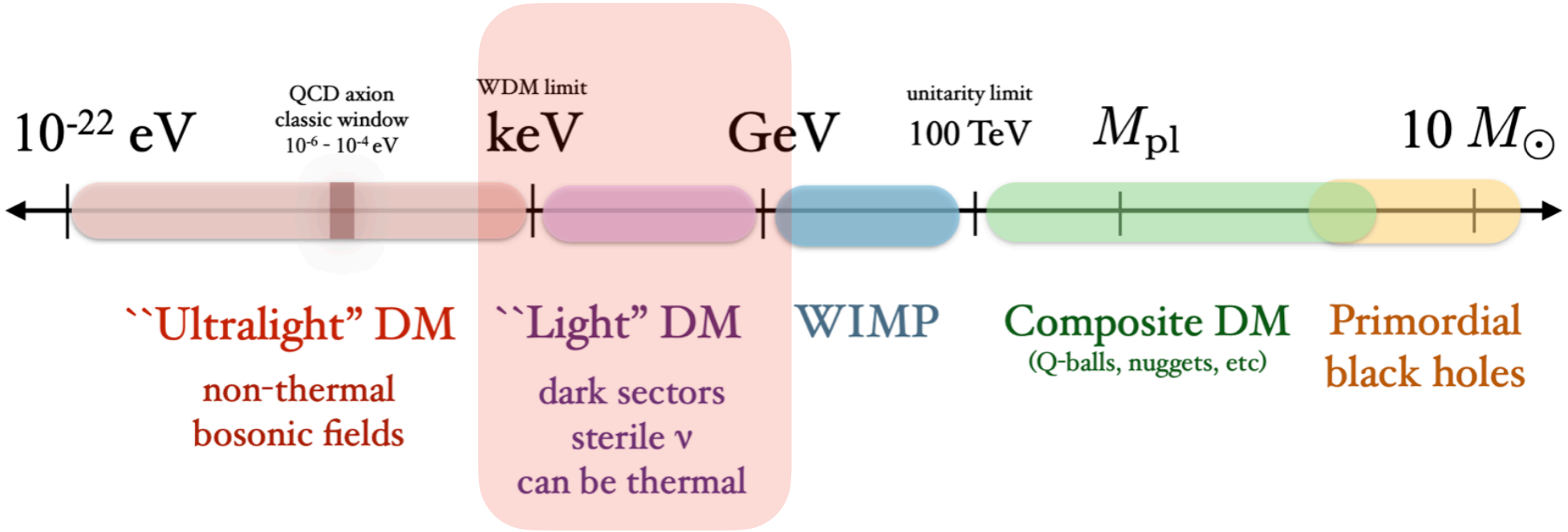


Dark matter forms a *"Galactic wind"* of particles from the direction of the Solar System's motion in the Milky Way.

Marshall et al. Quantum Science. Technol. 6. 024011 (2021)

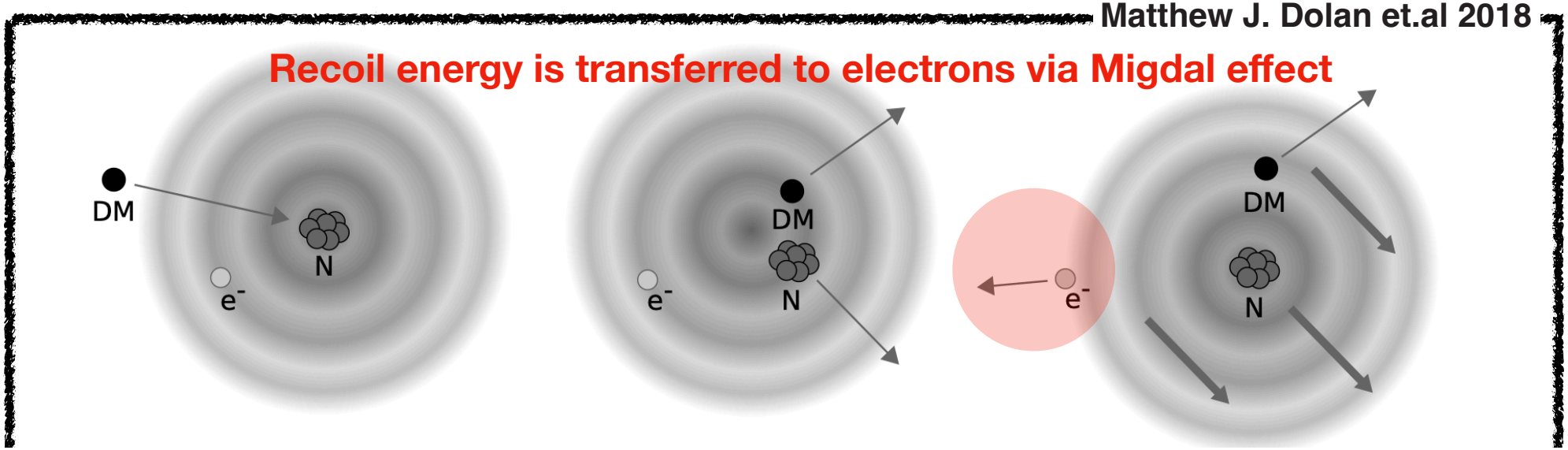


- WIMP or neutrino scatters off a carbon nucleus in diamond.
  - $O(10)\,\mathrm{MeV}$ neutrino can produce $O(10)\,\mathrm{keV}$ nuclear recoil.
    > $40\mathrm{eV}$ threshold for displacing a carbon atom in the diamond lattice.
- Subsequent atomic-scale lattice collisions create a nanoscale damage cluster that preserves the recoil direction, and hence carries information about the incoming particle direction.
- **Directional information** (e.g. via X-ray microscopy) can be used to distinguish dark matter signals from solar neutrino backgrounds.



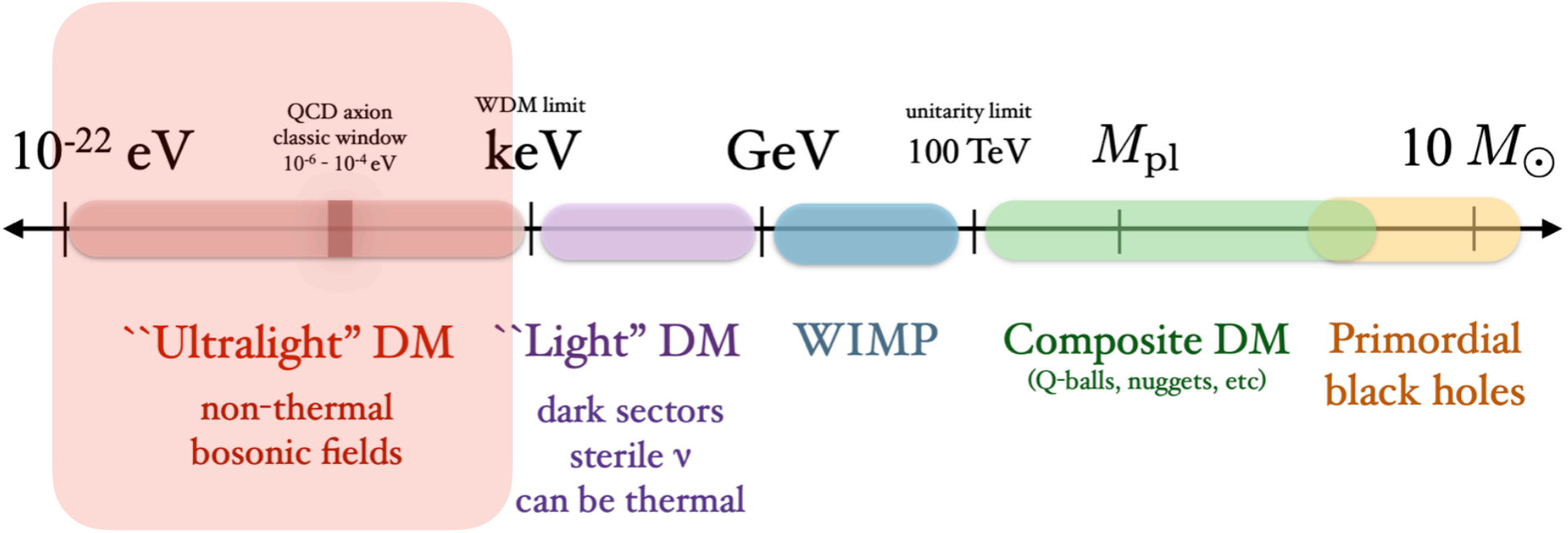
- Even when nuclear recoils are too small to detect, the sudden acceleration of the nucleus can ionize electrons (Migdal effect) producing detectable eV-scale electronic signals.

Matthew J. Dolan et.al 2018



Migdal converts a hard phonon problem into a more experimentally accessible electron problem

Quantum Devices as Sensors



- **Fermionic dark matter** is constrained by the **Pauli exclusion** principle. In small, low-velocity systems like dwarf galaxies, fermions cannot be packed densely enough to reproduce the observed dwarf galaxy halos $\rightarrow m_{DM} \geq O(\mathrm{keV})$

- **Bosonic dark matter** is not limited by Pauli exclusion.
  → Its structure is instead set by the de Broglie wavelength.

- **Bosonic dark matter has a macroscopic de Broglie wavelength**

$$\lambda_{\rm dB} = \frac{2\pi}{m_{\rm DM} v} \approx 0.4\ {\rm kpc} \left(\frac{10^{-22}{\rm eV}}{m_{\rm DM}}\right)$$

$$\simeq O(10^3)\,{\rm ly}$$

→ **comparable to the size of dwarf galaxies**

→ **structure is suppressed below this scale implying** $m_{\rm DM} \gtrsim 10^{-22}\,{\rm eV}$

- Occupation number within a de Broglie volume

$$N = \frac{\rho_{\rm DM}}{m_{\rm DM}} (\lambda_{\rm dB})^3 \approx 10^{94} \left(\frac{10^{-22}{\rm eV}}{m_{\rm DM}}\right)^4$$

- With $N \gg 1$, **dark matter behaves as a coherent classical field**, coherent over a de Broglie wavelength.

Quantum Sensing for Ultralight DM

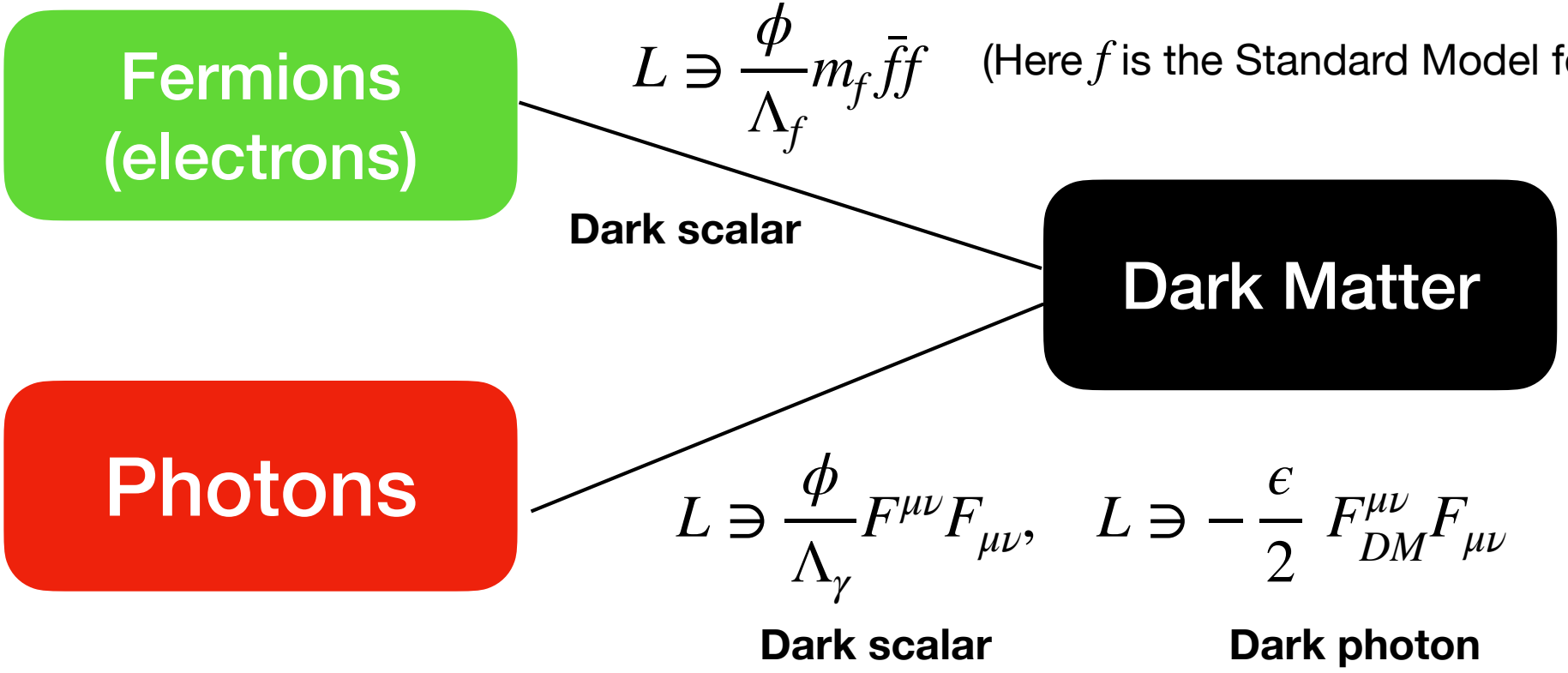
- Ultralight dark matter behaves as a coherent, oscillating classical field.

- It produces continuous, **narrow-band signal**; oscillating forces or effective EM-like signals.

  - $\phi(\vec{x},t) \simeq \phi_0 \cos(\omega t - \vec{k}\cdot\vec{x}),\ \omega = \sqrt{m_{\mathrm{DM}}^2 + k^2} \simeq m_{DM} + \frac{1}{2} m_{DM} v^2$

  - Line Width $\frac{\delta\omega}{\omega} \sim \frac{\delta\left(1/2 m_{DM} v^2\right)}{m_{DM}} \simeq v^2 \sim 10^{-6}$ (with $v \simeq 10^{-3} c$)

- Quantum sensors are optimized to resolve fractional shifts at the level of 10^{-6}



- This picture is very different from the standard nuclear-recoil paradigm.

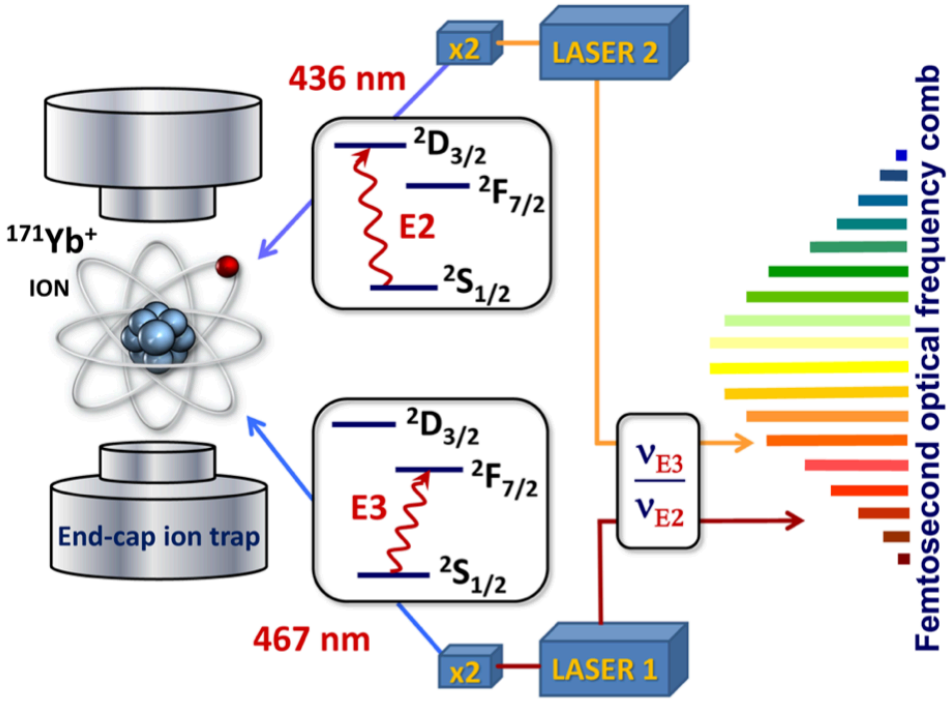
- Through these interactions, "dark matter wave" can induce oscillations of fundamental constants, such as the fine-structure constant α or fermion mass

$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}, \qquad \frac{dm_e}{m_e} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_e}$$

Atomic spectroscopy

- Ultralight dark matter induces an oscillation of α, leading to periodic shifts in atomic transition frequencies.

  → observed as oscillations in frequency ratios $R = \dfrac{\nu_{E3}}{\nu_{E2}}$



- Common-mode noise rejection:
  - Taking ratios cancels common noise (laser drift, environment)

- Enhance sensitivity to α
  - Different transitions respond differently to α, $(\nu_{Ei} \propto \alpha^{K_i})$

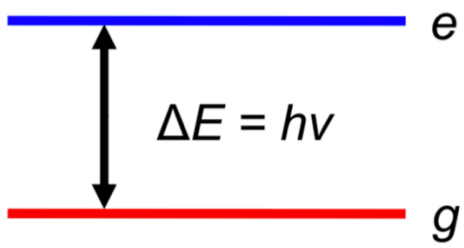
$$\frac{\dot{R}}{R} = (K_3 - K_2)\frac{\dot{\alpha}}{\alpha}$$

- **E3 involves more relativistic orbitals near the nucleus, making it much more sensitive to α than E2**

- Ytterbium ion (heavy atom → relativistic effect ↑) already set constrains on fractional variations of α at the level of 10^{-17} per year.

- Atomic clocks are sensitive only within a finite mass window.

$$\alpha(t) \simeq \alpha_0 \left(1 + \delta\alpha \cos(m_{DM} t)\right) \rightarrow \delta(\nu_1/\nu_2) \propto \cos(m_{DM} t)$$



- The bound on mass is from the experimental set-up,

  - If a dark matter is too light, $m_{DM} \ll \frac{1}{T_{\text{obs}}}$, then it looks like a constant over a time (no observation on oscillation)

  - If a dark matter is too heavy, $m_{DM} \gg \frac{1}{\tau_{\text{servo}}}$, then it would be averaged out (τ_{servo} : clock control and readout response time)

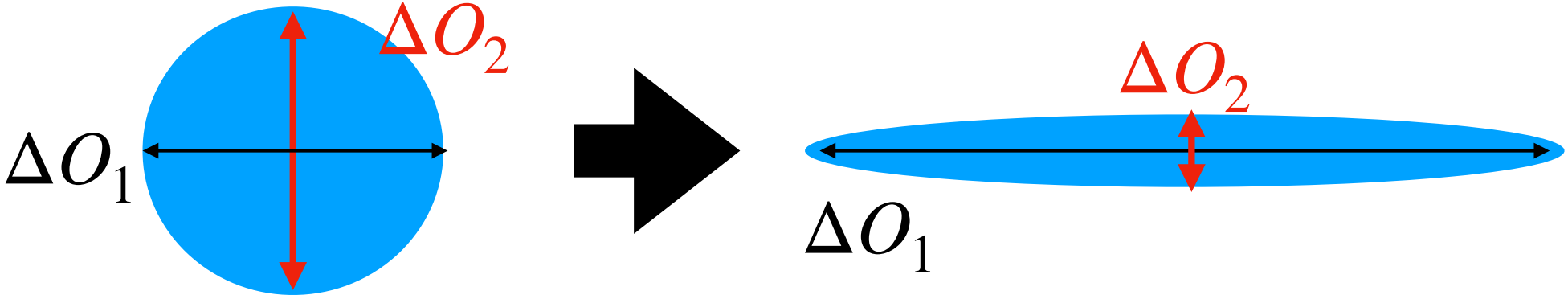
Accessible mass window: $O(10^{-23})\,\text{eV} \leq \text{m}_{\text{DM}} \leq \text{O}(10^{-16})\,\text{eV}$

- Can we detect the same oscillation using an engineered quantum system—such as a superconducting transmon qubit?

- **Engineered quantum systems can target different frequency ranges and offer tunable sensitivity.**

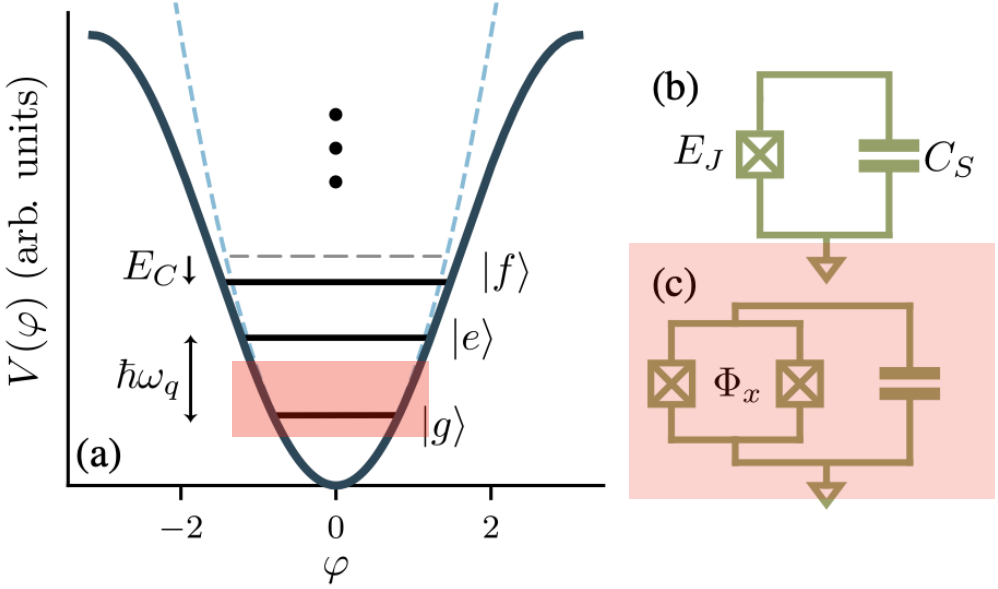
- **Quantum Sensing**: using coherent quantum control to detect extremely small signals

  - Discrete quantum state (for example, $|0\rangle$, $|1\rangle$)
  - Possibility to reset and read out
  - Coherent state manipulation possible
  - Entanglement and squeezing (in superconducting circuits) can further enhance sensitivity.



- Reduce noise in one observable at the expense of increased noise in the conjugate observable.

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.**"

- **Tunable gap** $\omega \sim 1 - 10\,\mathrm{GHz}$ → sits right on the DM line.
  Sweep ω to scan the mass

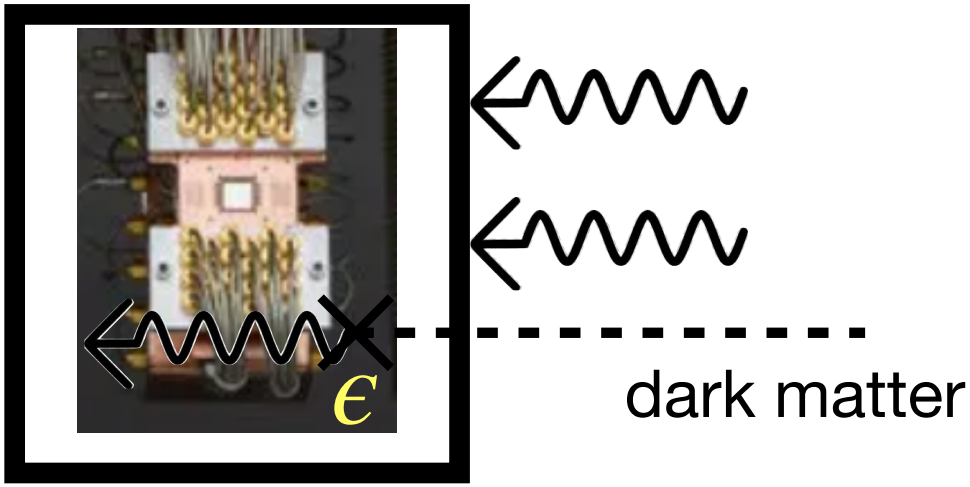
- **Strong coupling to E-fields**
  → a tiny effective field is enough to drive $|g\rangle \rightarrow |e\rangle$

- **mK operation** ($k_B T \ll \hbar\omega$) → thermal noise frozen out, quiet ground state

- Coherent control + single-shot readout → resolves the narrow ($\delta\omega/\omega \sim 10^{-6}$) line and counts rare excitations; **entanglement/squeezing** push further.

- **Dark Matter penetrates the shield, and induces an effective oscillating signal that couples to the qubit.**

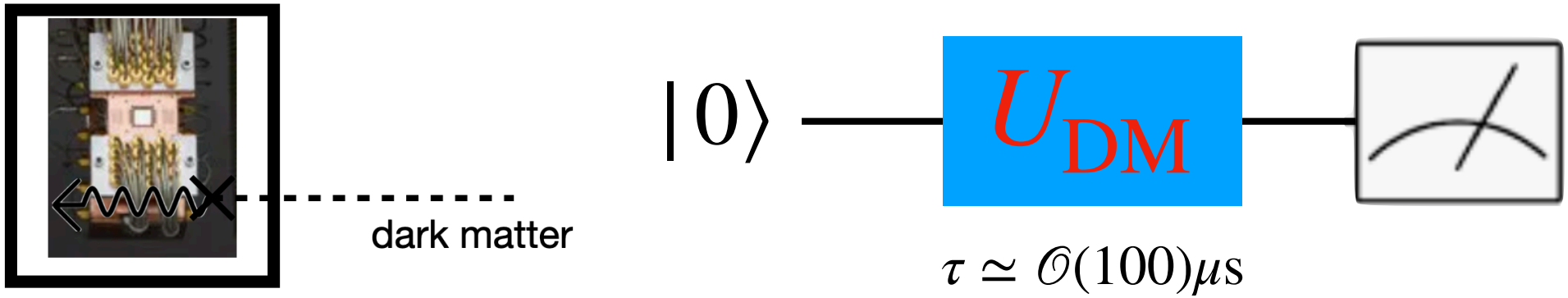




- For typical device parameters, $\omega \simeq \mathcal{O}(1-10)\mathrm{GHz}$
- At refrigerator temperatures $\mathcal{O}(1-10)\mathrm{mK}$, a few-GHz transition satisfies $k_B T \ll \hbar\omega$.
- If the DM-induced signal falls within this frequency band, it can resonantly excite the qubit - effectively turning dark matter interactions into observable qubit errors.
- **From the qubit's point of view, this is just a very weak microwave drive.**

Dark-matter-induced microwave drive as a unitary evolution U_{DM} in Quantum Computer

- Qubits are exposed to microwaves from dark matter over the coherent time $\mathcal{O}(100)\mu s$ sets the maximum interaction time.

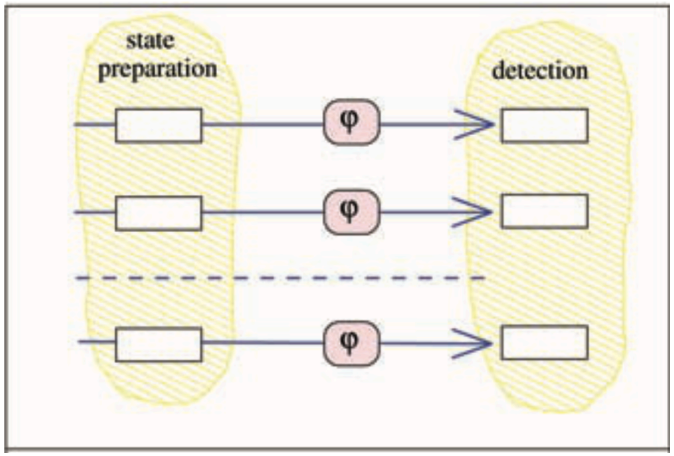


- What would be good if we use a qubit as a sensor?

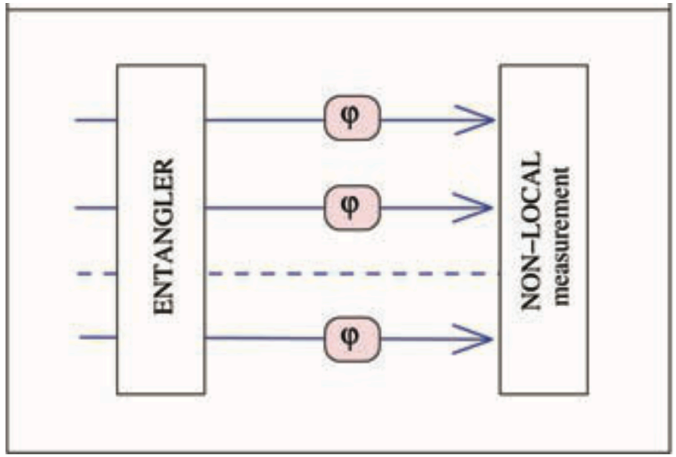
Quantum Computation Enhanced Sensing

- As the microwave from dark matter activates the qubit in a quantum circuit, we can "**program**" the circuit to **enhance a signal**

- V. Giovannetti, S. Lloyd, and L. Maccone, Science 306, 1330 (2004).



Classical
- N independent systems are prepared and separately detected



Quantum
- Highly correlated configuration and are measured collectively with a single “nonlocal” measurement that encompasses all the systems.

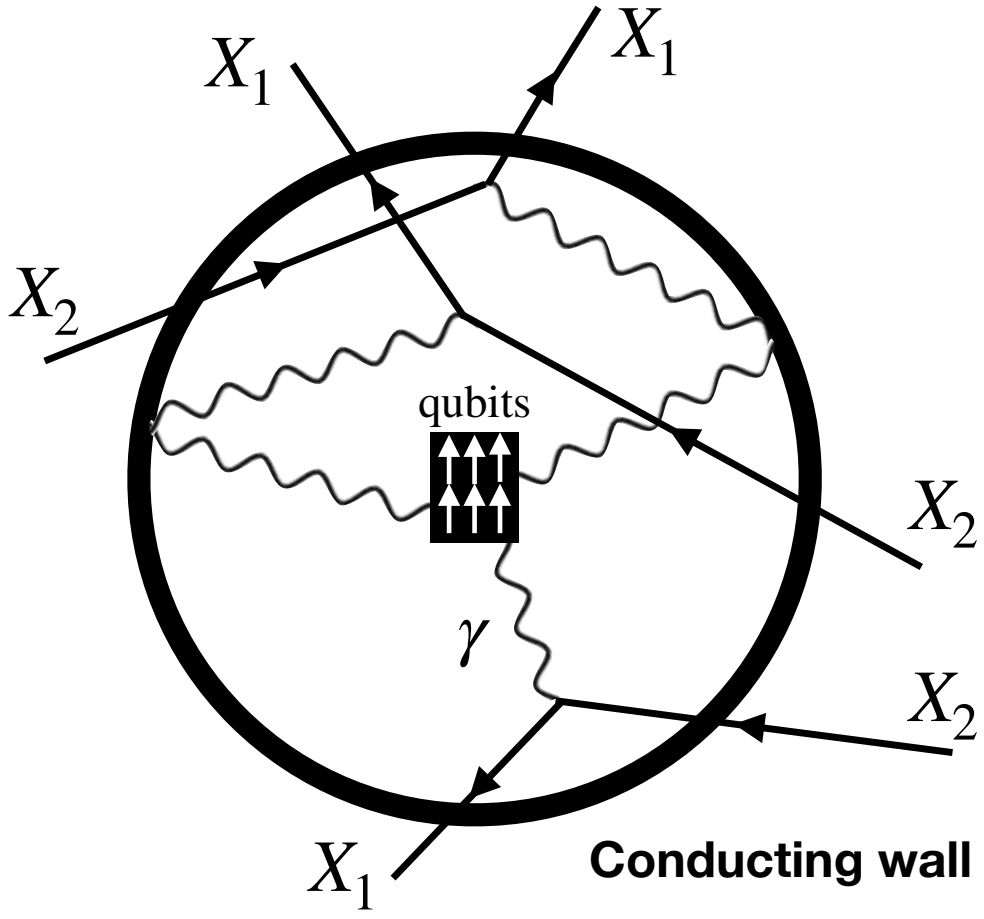
- For Dark Matter application, see: Shion Chen, Hajime Fukuda, Toshiaki Inada, Takeo Moroi, Tatsumi Nitta, and Thanaporn Sichanugrist PRL 133, 021801 (2024)

So far, the applications are for coherent signals

from Dark Matter.

Could this approach be extended to probe a rare event?

Other interesting possibilities for photon signals



- Two scenarios :

  1) Heavier "dark" particle X_2 **decays** into lighter particle X_1 and a photon

- 2) **Cosmic neutrino background** $\mathrm{C}\nu\mathrm{B}$, with **transition** via neutrino magnetic moment interaction

Radiative Decays of Neutrinos and Dark Matter Particles

- The decay photon provides near-monochromatic spectral weight at E_γ

  - Photon energy is determined by the mass differences between two unknown particles with $E_\gamma = \dfrac{m_{X_2}^2 - m_{X_1}^2}{2m_{X_2}}$

  - Energy density of photons is characterized by the decay probability of a heavier particle and its density as $\rho_\gamma = E_\gamma n_\gamma$ with $n_\gamma \propto \Gamma_{X_2} n_{X_2}$

  - The effective electric field $\bar{E}_{(\mathrm{eff})} = \sqrt{\dfrac{\Gamma T n_2 \Delta m^2}{2m_2 \varepsilon_0}}$ within $T < \tau$

  for a given decoherence time τ of a specific transmon qubit.

From Radiative Decay Photons to Qubit Dynamics

- The decay photon is not a classical coherent wave.
  One-point field expectation vanishes $\hat{E}(t)$,

$$\text{namely } \langle 1 \,|\, \hat{E}(t) \,|\, 1 \rangle = 0$$

- However, the qubit excitation probability is governed by the normally ordered two-point function, and near resonance this response can be estimated by an effective sinusoidal drive.

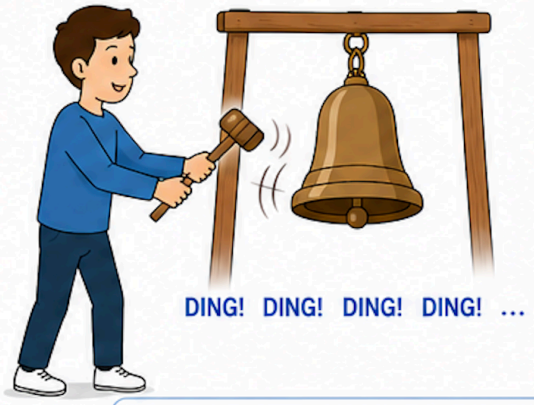
$$G^{(1)}(t_1, t_2) \equiv \left\langle \hat{E}^{(+)}(t_1)\, \hat{E}^{(-)}(t_2) \right\rangle \neq 0$$

- The probability of transition $p_{g\to e} = g^2 \int_0^T dt_1 \int_0^T dt_2 e^{-i\omega(t_1 - t_2)} G^{(1)}(t_1, t_2)$

Coherent Dark Matter Wave case

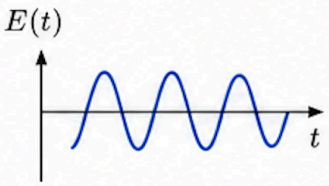
1. Coherent Classical Wave (Continuous Drive)

Keep hitting the bell continuously.

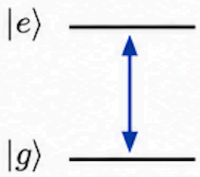


Field amplitude

$$\langle \hat{E}(t) \rangle \neq 0$$



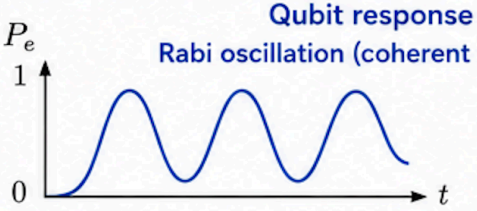
What the qubit feels



- Coherent drive in phase.
- Amplitude adds up coherently.

Qubit response

Rabi oscillation (coherent accumulation)

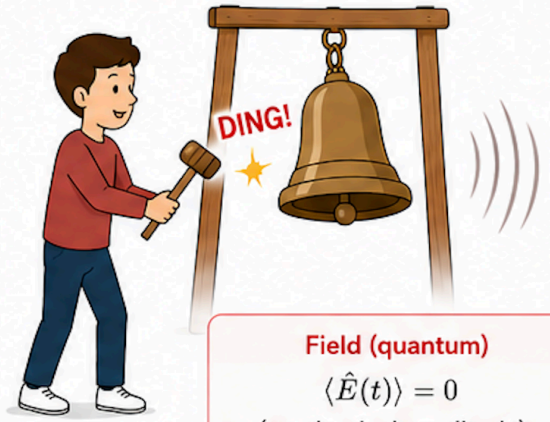


Transition probability $\propto T^2$ near resonance.

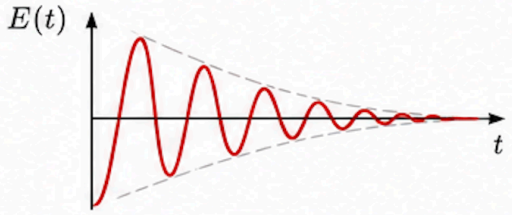
Decaying Heavier Dark Matter case

2. Single Decay Photon (Our Case)

Strike the bell once → it rings for a while.



The bell rings and gradually decays.



Field (quantum)

$$\langle \hat{E}(t) \rangle = 0$$

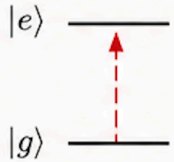
(no classical amplitude)

Two-time correlation

$$G^{(1)}(t_1, t_2) \neq 0$$

(temporal correlations exist)

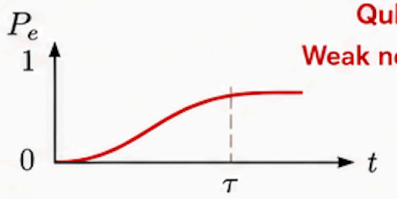
What the qubit feels



- No continuous push.
- The bell rings at frequency E_γ during the measurement (coherence) time τ.
- The qubit responds to these temporal correlations.

Qubit response

Weak near-resonant excitation



$$P_e \propto |g|^2 \, |E_{\text{eff}}|^2 \, \tau^2$$

(within qubit coherence time τ)



A decay photon is not a continuously driven wave.
It is a single excitation that rings for a finite time,
and the qubit absorbs energy from those temporal correlations.

Key Point

The qubit can absorb energy from the photon only during its coherence time τ.

Result

Near resonance ($\omega \simeq E_\gamma$):

$$P_e \propto \tau^2$$

Person: Dark Matter / Bell: Photon

- The temporal correlation of the decay photon acts as an effective resonant drive.
- If the qubit is tuned near resonance $\omega \simeq E_\gamma$, the rotating-wave approximation applies, and fast oscillating terms average to zero.

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

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

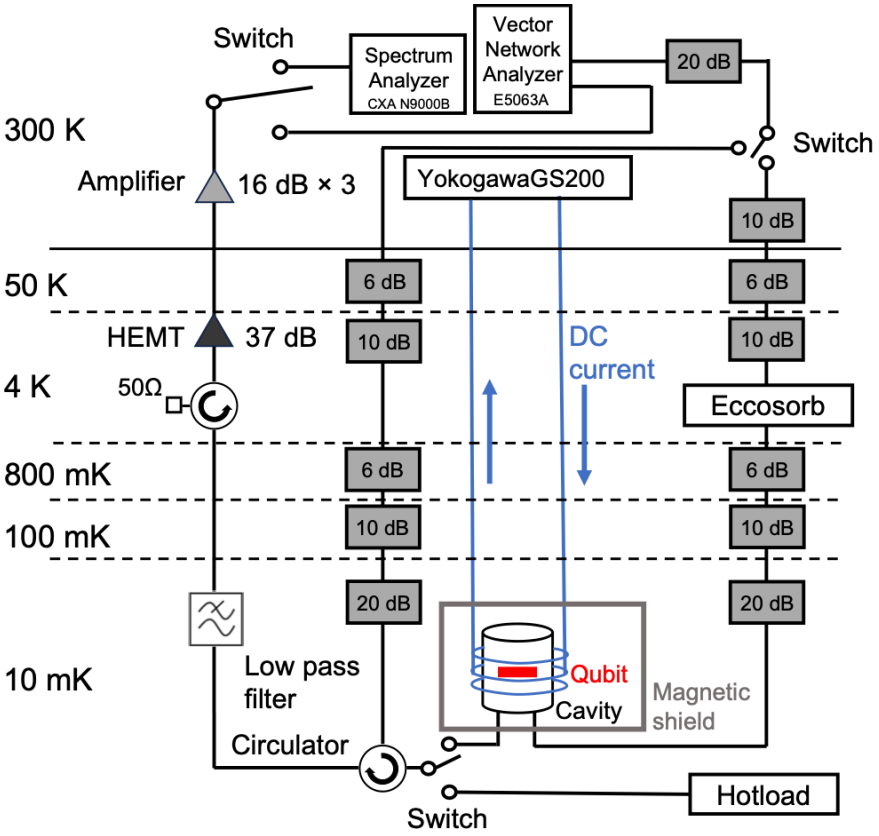
- Thus, a transition probability $p_{g\to e}(t)$ from $|g\rangle \to |e\rangle$

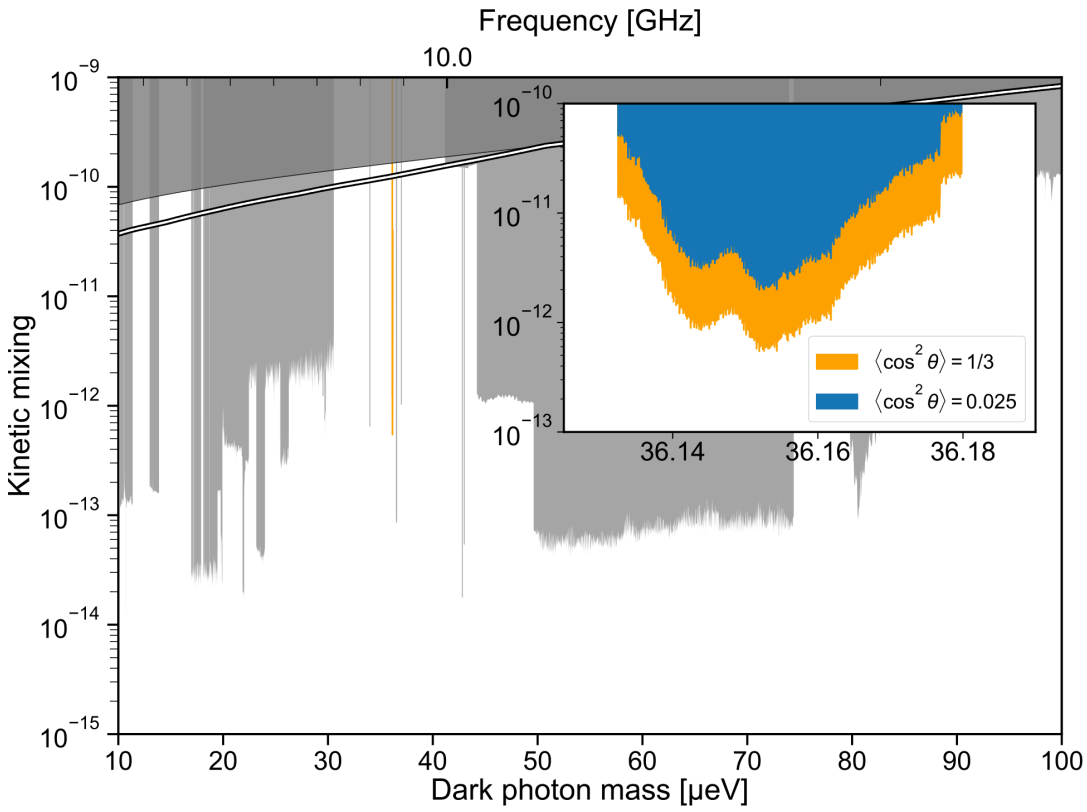
$p_* \equiv p_{g\to e}(\tau) = |\psi_e(\tau)|^2 \simeq \sin^2(\eta\tau) \simeq (\eta\tau)^2$ within a coherent time

- Signals: $N_{\text{sig}} = p_* \times N_{\text{try}}$
- 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

Recasting the DarQ experiment

Kan Nakazono et. al, arXiv:2505.15619





- Resonance frequency of cavity $f_{\rm res}^{\rm DarQ} = \dfrac{\omega_{\rm res}^{\rm DarQ}}{2\pi} = 8.74\ \text{GHz}$
- This experiment constrains both the dark photon mass and its mixing with the photon; the mixing bound can be recast as a limit on the effective electric field. $E_{\rm eff} \leq E_{\rm max}^{\rm DarQ} = 2.63 \times 10^{-15}\text{eV}^2$ through $E_{\rm eff} = \epsilon E_{\rm Dark}$

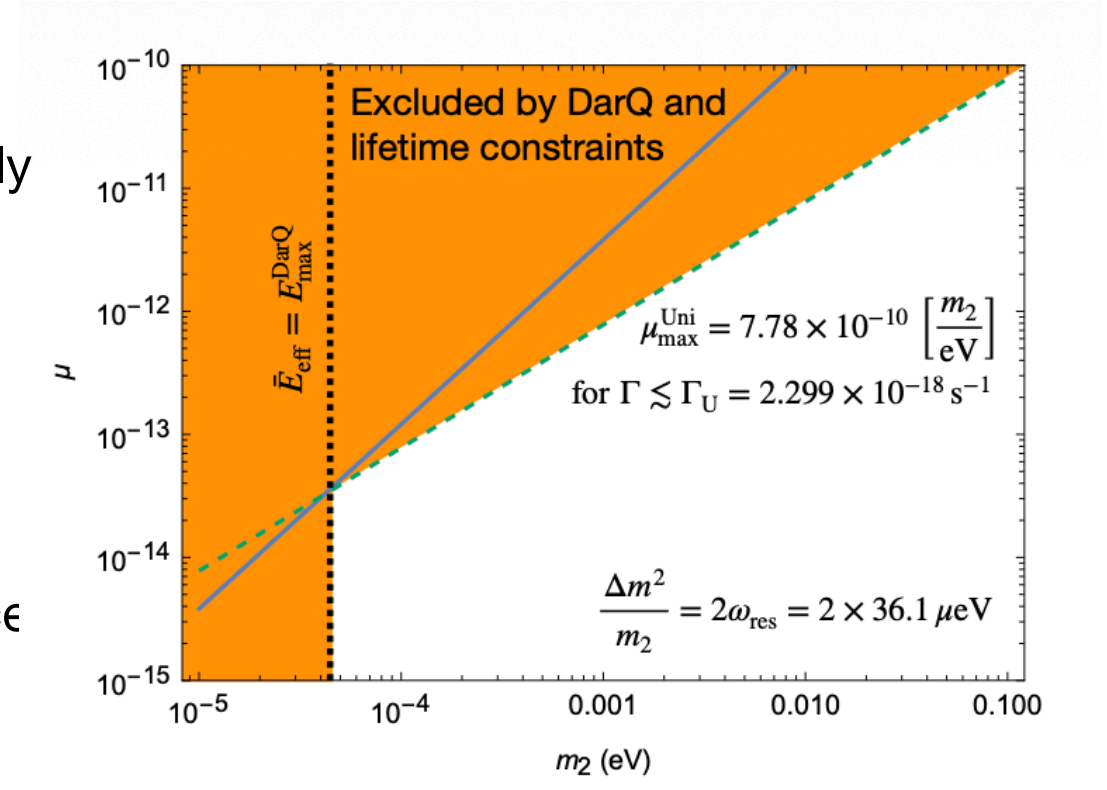
Constraints on radiative decaying dark matter

- We take a local dark matter density $\rho_{\rm DM} = 0.45\ {\rm GeV/cm^3}$ (inferred from Milky Way dynamics).
- We take a limit on decay rate of X_2 :$\Gamma \lesssim \Gamma_{\rm U} = 2.299 \times 10^{-18}\,{\rm s}^{-1}$ ensuring that X_2 remains stable over the age of the universe.
- Transition probability $p_* \propto p_*^0 \left(\frac{V_{\rm eff}\rho_{\rm DM}}{0.45\,{\rm GeV\,cm^{-3}}}\right)\left(\frac{\Delta m^2}{m_2^2}\right)\left(\frac{f}{1\ {\rm GHz}}\right)\left(\frac{\tau}{100\ \mu{\rm s}}\right)^3$

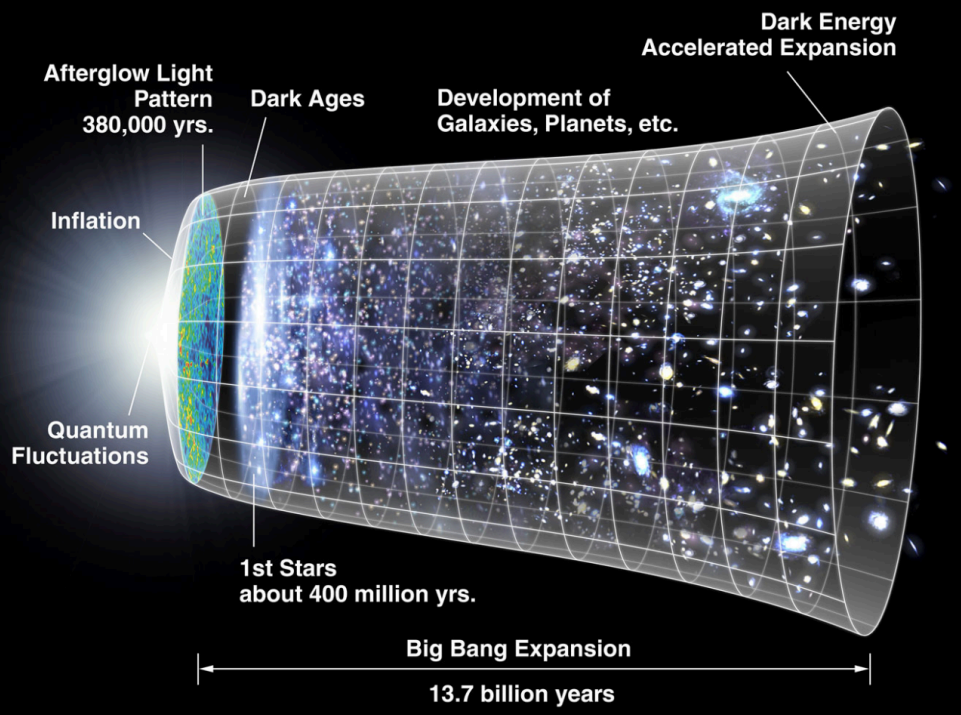
  with $p_*^0 = 0.069$.

- Decay photons must not significantly alter the observed CMB spectrum. Taking the CMB bound, $\Gamma < \Gamma_{\rm CMB} = 1.7 \times 10^{-25}{\rm s}^{-1}$, the bound on $m_2 > 3.07 \times 10^{-12}{\rm eV}$

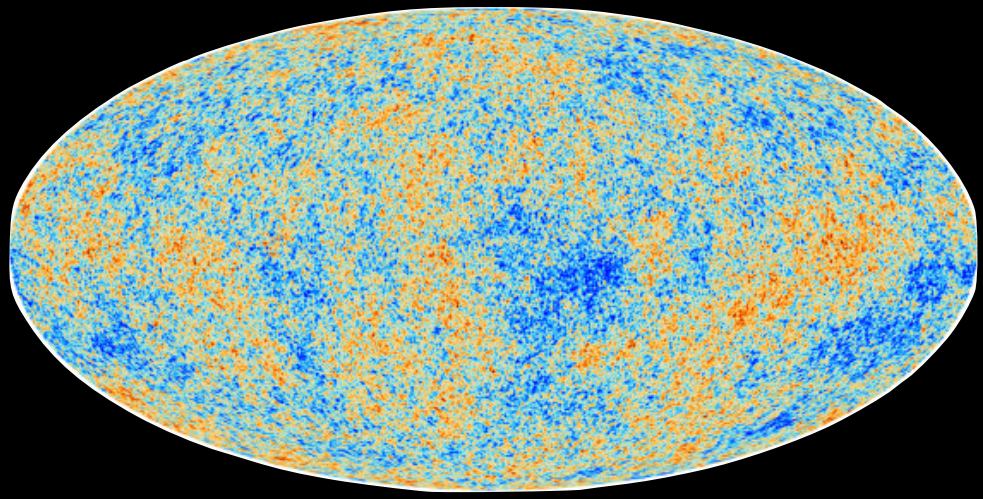
- The existing DarQ data already place strong constraints on radiatively decaying dark matter.



Cosmic Neutrino Background
A Deeper View of the Early Universe



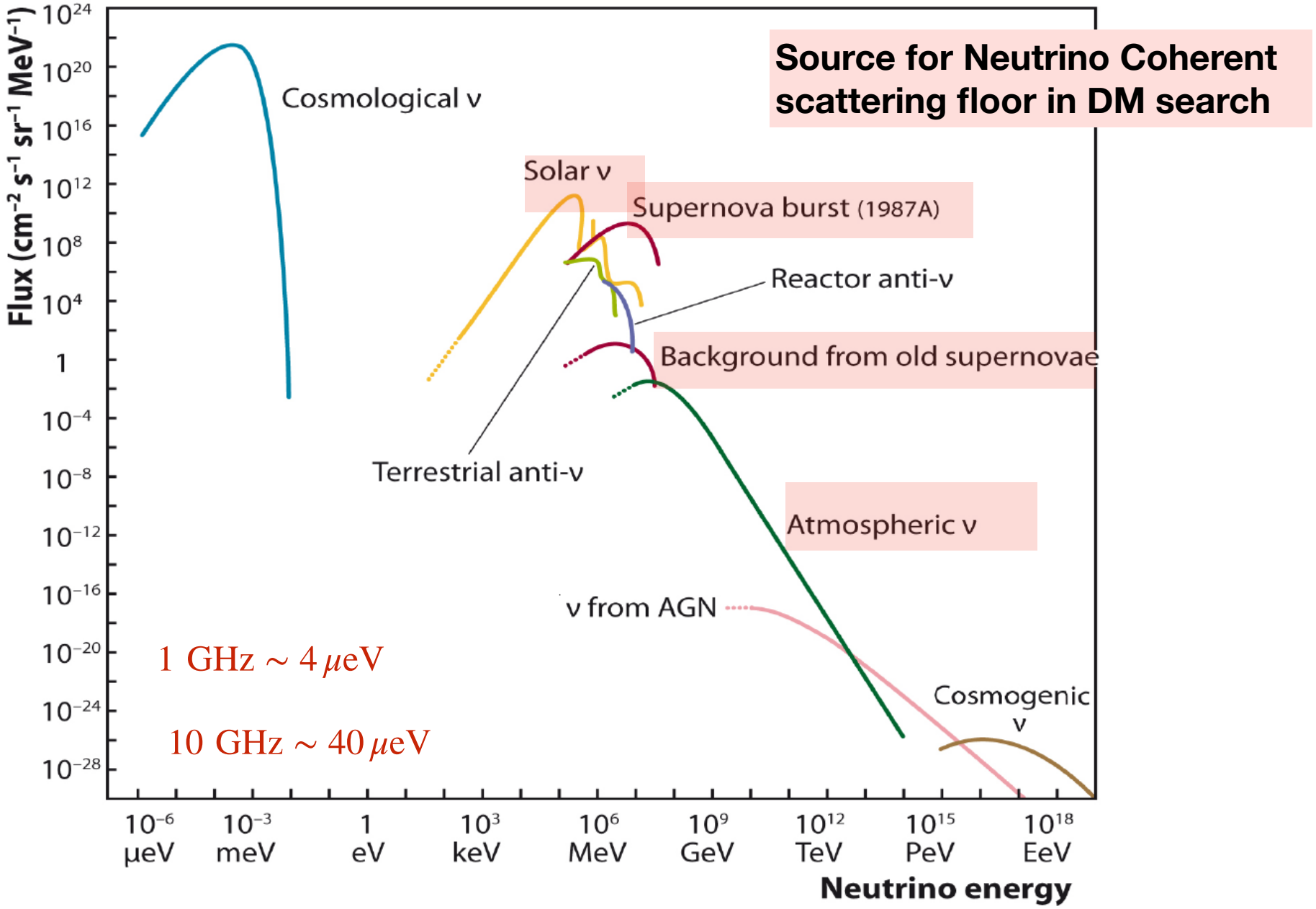
Cosmic Microwave Background (CMB)



- The Cosmic Microwave Background (CMB) probes the Universe after recombination, when electrons and protons combine to form neutral atoms (~380,000 years)

- The CvB carries information from the first seconds of the Universe—far earlier than the CMB epoch. Cosmic neutrinos decouple when weak interactions freeze out.

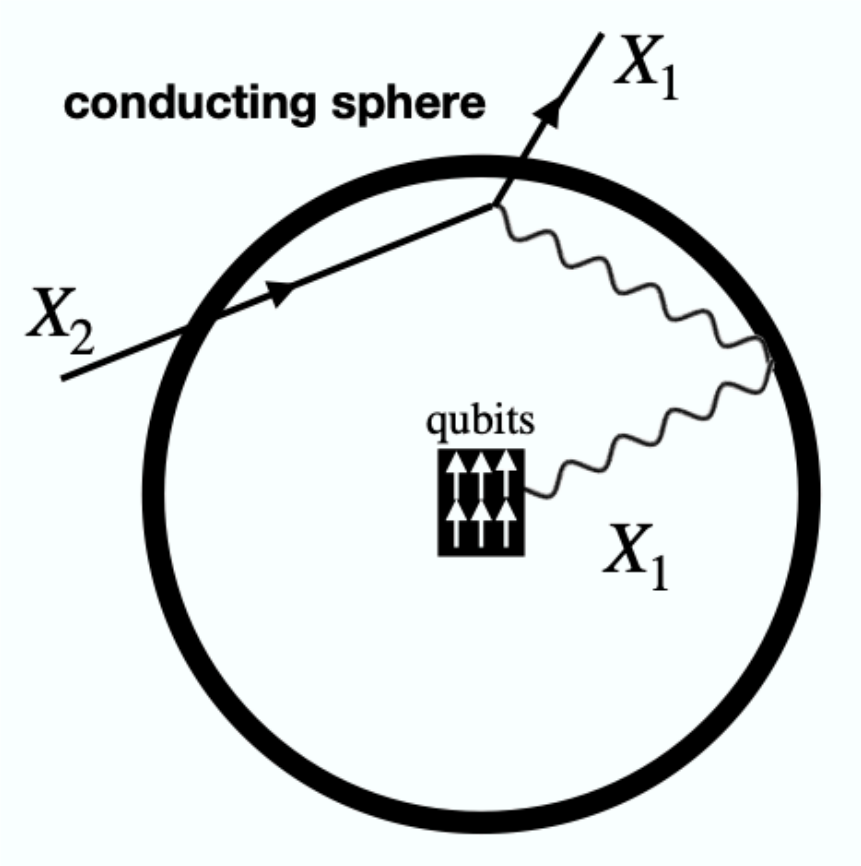
Neutrino fluxes from different sources as a function of the neutrino energy



Source for Neutrino Coherent scattering floor in DM search

- **The Cosmic Neutrino Background lies at extremely low energies, beyond the reach of conventional detection techniques.**

Other interesting possibilities for photon signals



$$L \ni \frac{\mu_\nu^{ij}}{2} \bar{\nu}_i \sigma^{\mu\nu} \nu_j F_{\mu\nu}$$

$$(i \neq j)$$

- **Cosmic neutrino background** $\mathrm{C}\nu\mathrm{B}$, with **transition** via extremely suppressed neutrino magnetic moment interactions.

Projected constraints on neutrino transition magnetic moments from the CvB

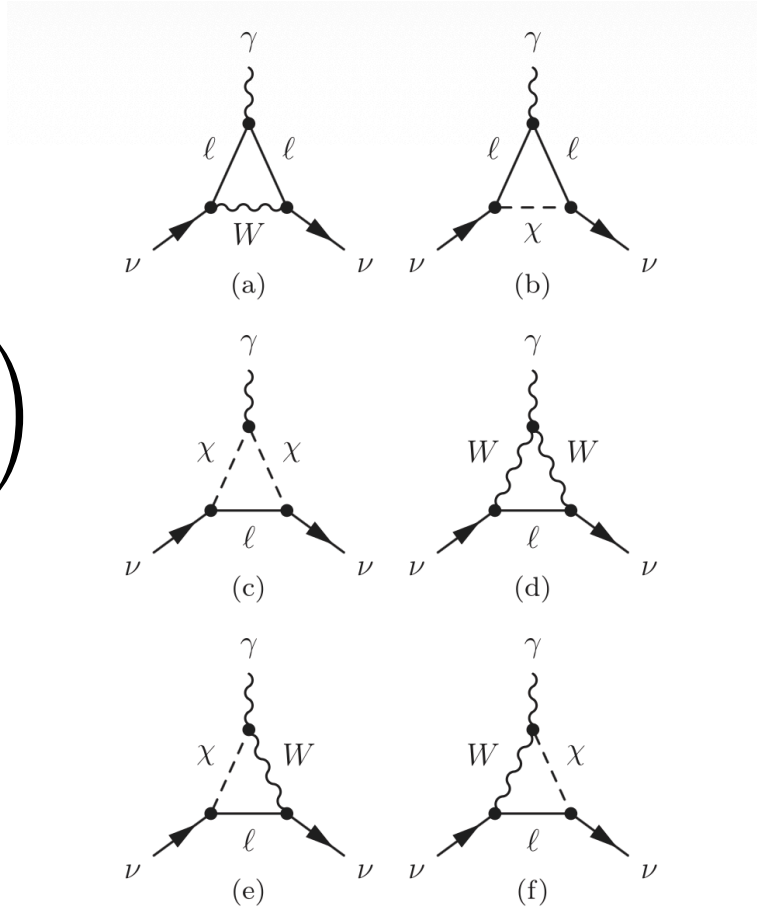
- We estimate projected constraints on the neutrino transition magnetic moment using the same framework as for radiatively decaying dark matter. The neutrino transition magnetic moment μ_ν^{ij} appears in the Lagrangian as

$$\frac{\mu_\nu^{ij}}{2}\,\bar{\nu}_i \sigma^{\mu\nu} \nu_j F_{\mu\nu},$$

- For diagonal term, only Dirac neutrino can have a non-zero value, with $\mu_\nu^{ii} \simeq O\left(10^{-19}\right)\mu_B \left(\frac{m_\nu}{1\mathrm{eV}}\right)$

- For transition (non-diagonal) moments, the magnetic moment is strongly suppressed by GIM,

$$\mu_\nu^{ij} \simeq \left(10^{-23}\right)\mu_B \left(\frac{m_\nu}{1\mathrm{eV}}\right)$$



Challenges for $C\nu B$: : Extremely Rare Decays

- Cosmic neutrinos decoupled from the primordial plasma at $T \sim \mathrm{MeV}$ and have since cooled with the expansion of the Universe, leading to a present-day density $n_\nu \sim 112\mathrm{cm}^{-3}$. (CMB photon $n_\gamma \sim 400\mathrm{cm}^{-3}$)
- Neutrino oscillation experiments determine the mass splittings
  $\Delta m^2_{21} = 7.59 \times 10^{-5}\mathrm{eV}^2$ from transition associated with the solar mass splitting
  $\Delta m^2_{32} = 2.32 \times 10^{-3}\mathrm{eV}^2$ from transition associated with the atmospheric mass splitting
- For the heaviest neutrino $m = 0.05\mathrm{eV}$ and currently experimental limit $\mu_\nu \simeq 10^{-11}\mu_B$, (corresponding roughly to the current laboratory limit from reactor and solar neutrino experiments.)
  the number density rate of photon from decaying process $\dot{n}_\gamma \simeq 10^{-18}\mathrm{m}^{-3}\mathrm{s}^{-1}$
- Even assuming the current experimental bound on the neutrino transition magnetic moment, the radiative-decay photon production rate is incredibly small.

This corresponds to roughly one photon per $1\ \mathrm{m}^3$ every 3×10^{10} years.

Challenges for $C\nu B$: Tiny Qubit Excitation Probability

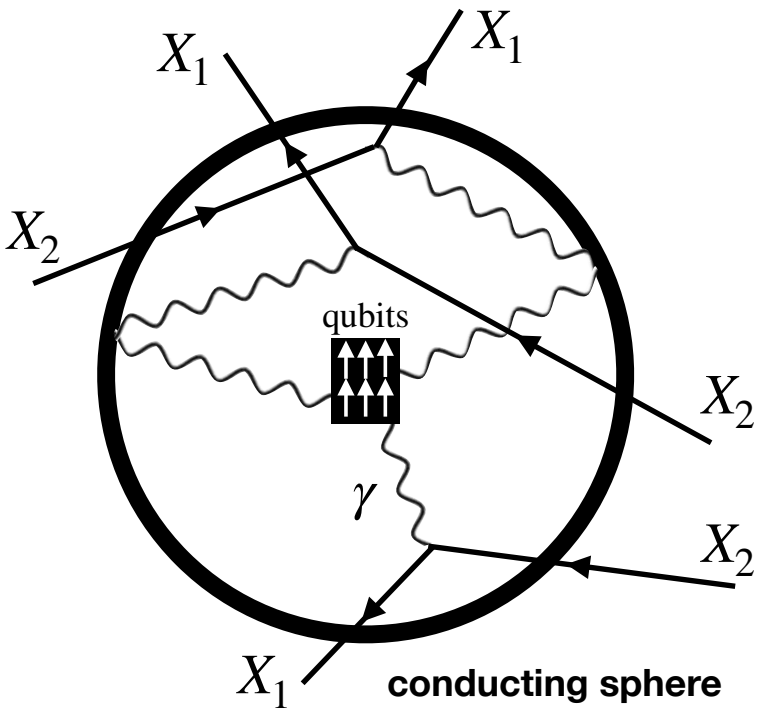
- Transition probability

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

  with $p_* = 2.1 \times 10^{-27}$, **showing that detecting the CvB requires a qualitatively different detection strategy.**

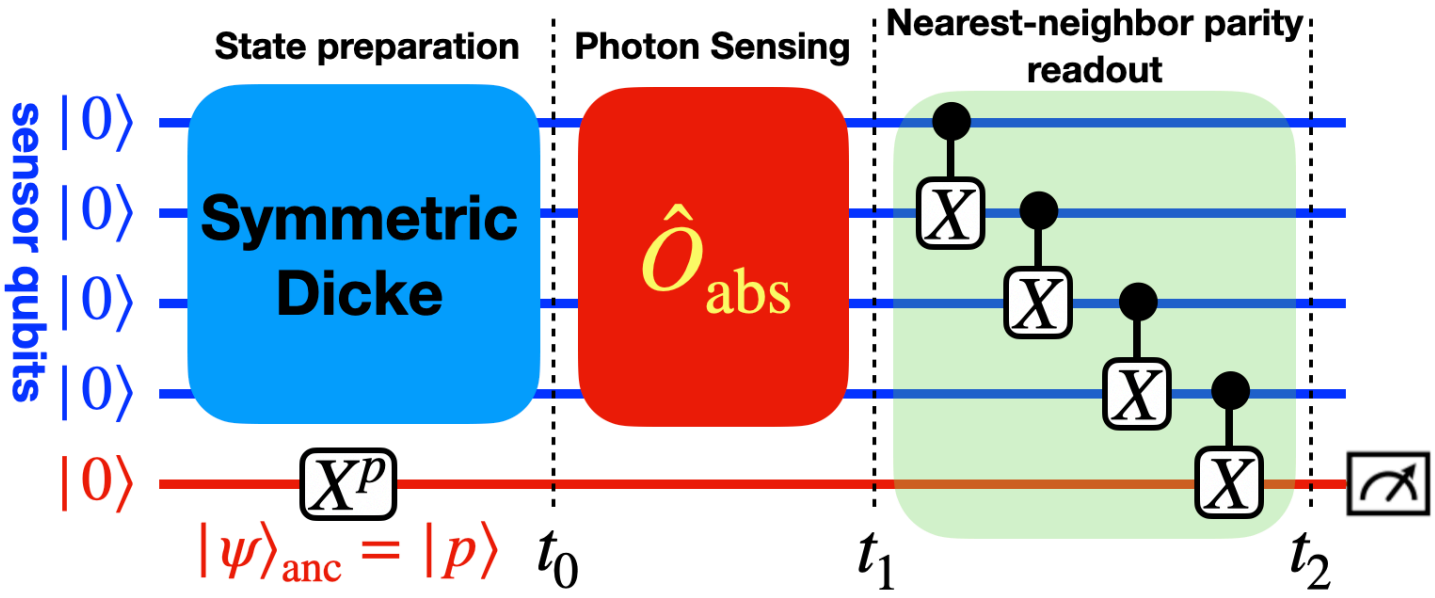
- Measuring with a single qubit is impossible.
- We need to find a way to enhance this tiny probability.

Detecting with a single qubit is impossible



- Conventional metals provide 98–99% reflectivity, while engineered high-Q cavities ($Q \sim 10^6 - 10^9$) can achieve much longer photon residence times.
- Neutrinos can freely enter the cavity, but once they generate very weak photons via suppressed interactions, the photons are confined. Eventually, these trapped photons will have an enhanced probability of interacting.

- This setup significantly enhances the chance of detecting a signal by effectively increasing the detection volume and thereby the expected as $n_2 \to n_2 \left(\frac{V_{\text{eff}}}{\text{cm}^3} \right) \to n_2 \times 10^6$ for 1m^3 cavity.
- We also utilize the quantum-enhanced parameter estimation.



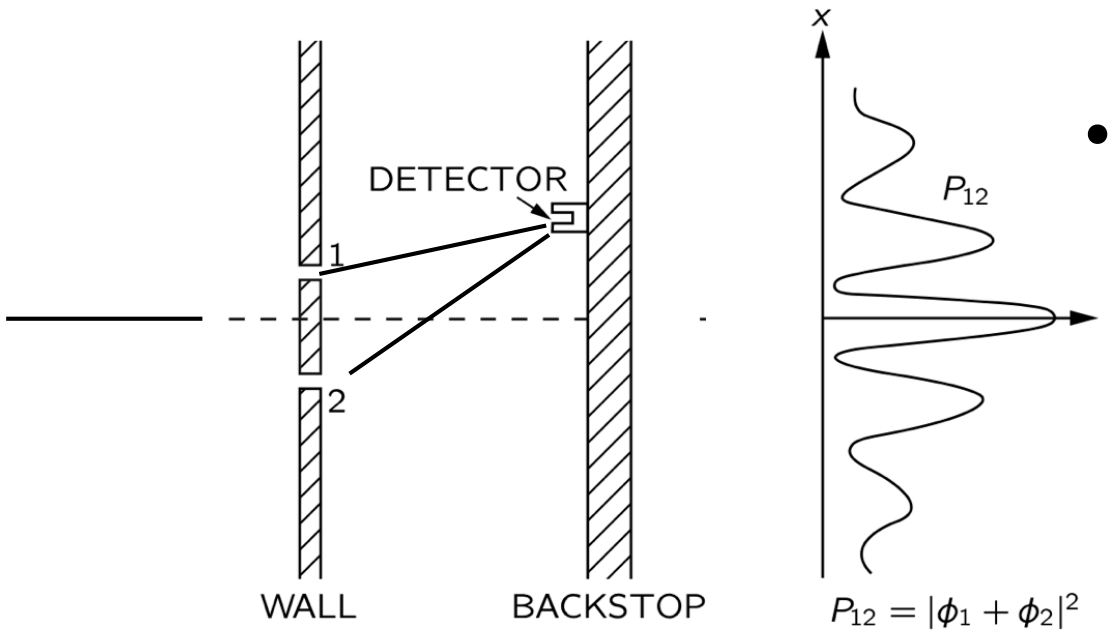
- We prepare a symmetric state $|\psi(t_0)\rangle_{\text{sensor}} = \left| J = \frac{n_q}{2}, m = 0 \right\rangle = |D_{n_q}^{(n_q/2)}\rangle$.

$$|J = 2, m = 0\rangle = \frac{1}{\sqrt{6}}\Big(|1100\rangle + |1010\rangle + |1001\rangle + |0110\rangle + |0101\rangle + |0011\rangle \Big) \text{ when } n_q = 4$$

Unlike previous coherent-Dark matter wave case which drives all sensor qubits coherently, here signal activates one of sensor qubits.

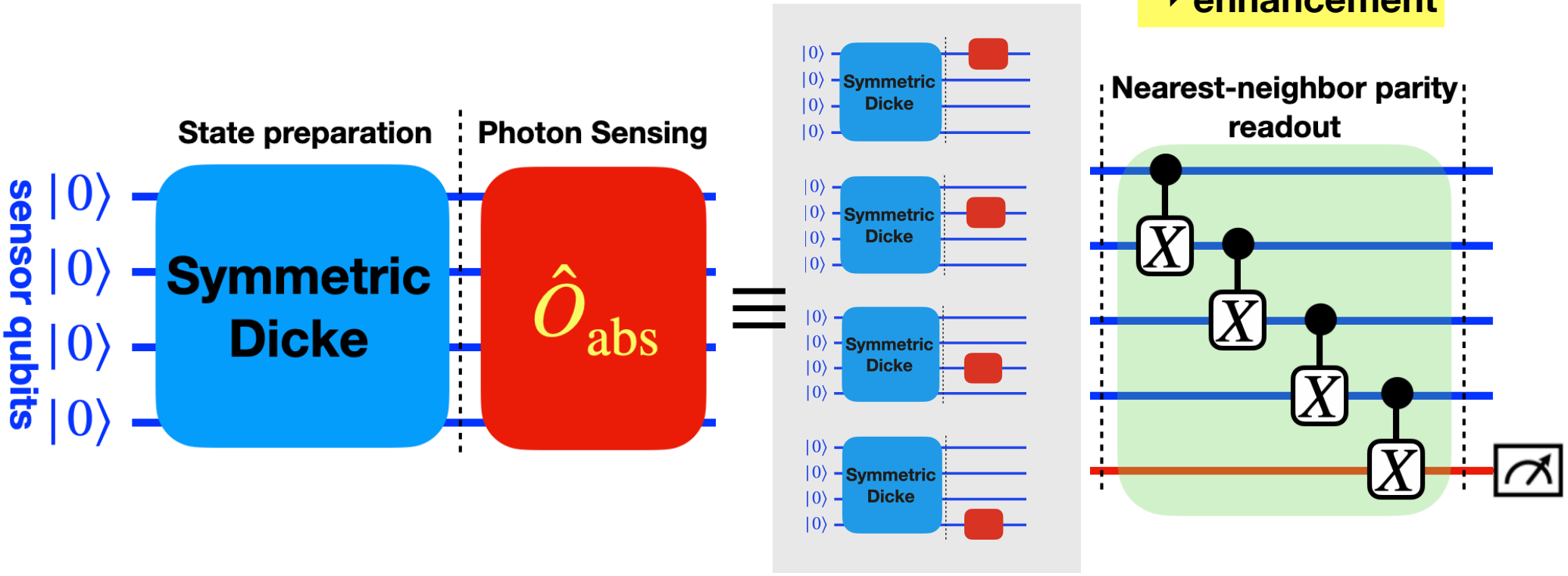
- The readout then combines all these indistinguishable possibilities into an enhanced signal.

The excitation has no which-qubit information → all possibilities interfere



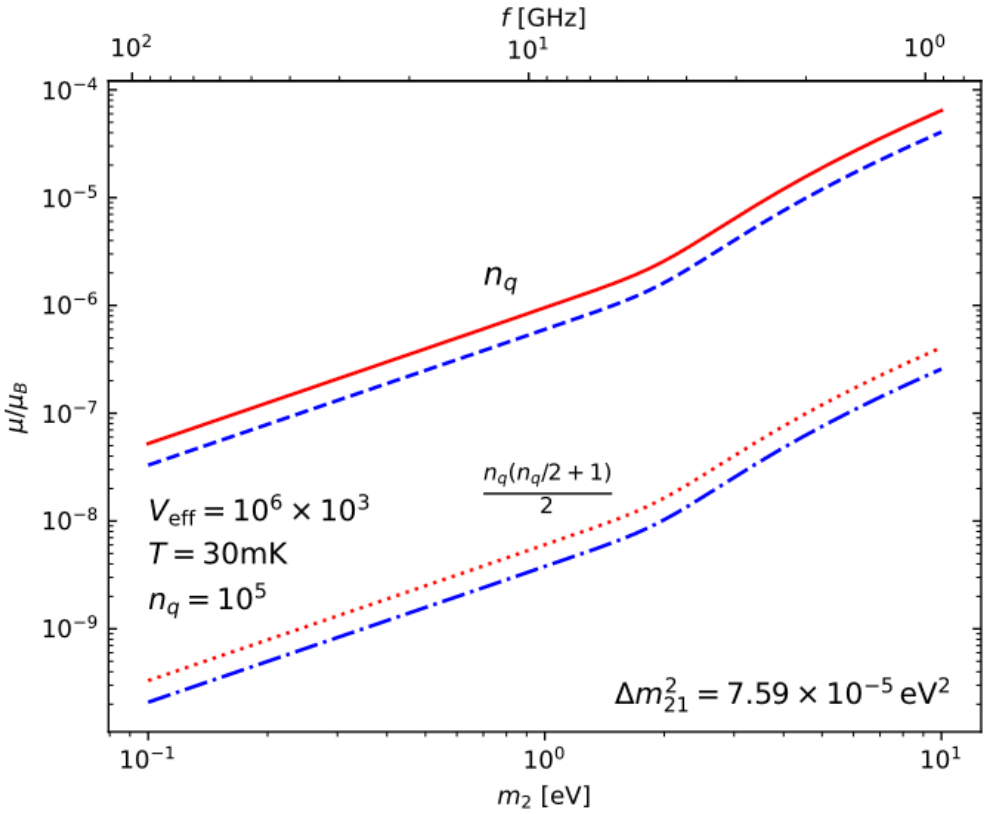
- **Just like a multi-slit experiment, signal is enhanced by constructive interference of all possible paths**

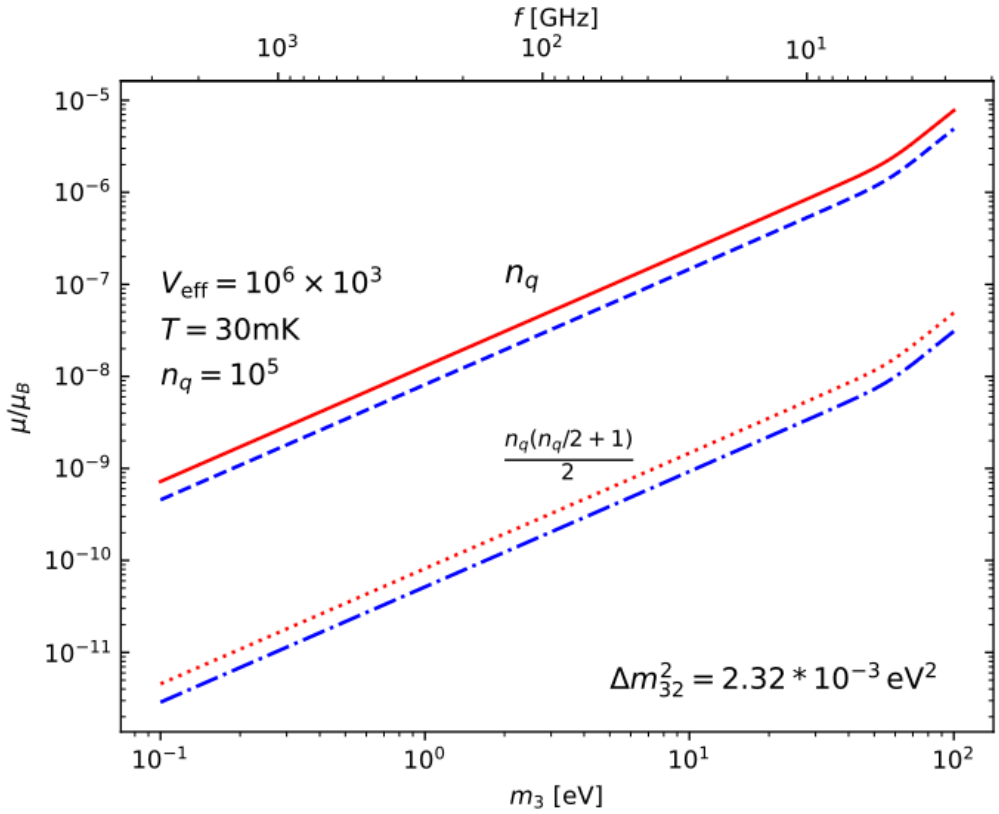
Interference → enhancement

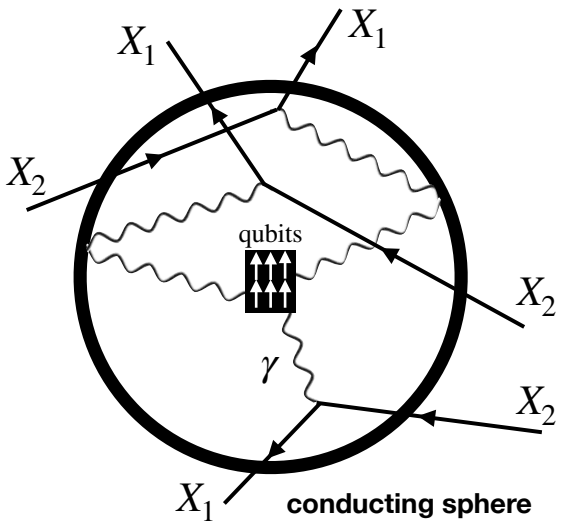


≡ **superposition of indistinguishable excitation locations**

Bounds on neutrino transition magnetic moment







Decay volume

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

Entanglement

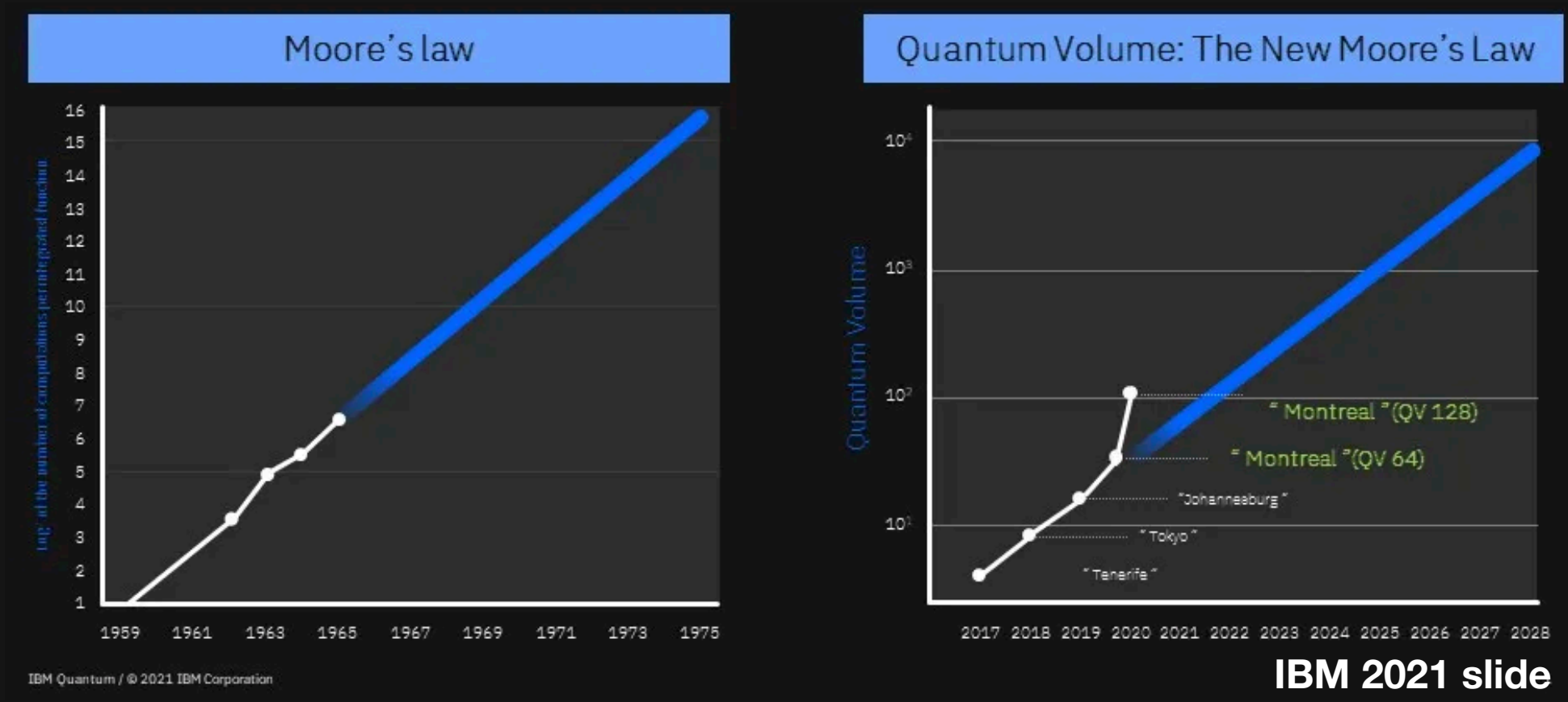
$$P_* \simeq n_q^2 \, (\eta\tau)^2$$

- Volume effect $V_{\rm eff}$ is from 1000 cavity units, each with 1m^3 volume.
- The required number of logical qubits $n_q = 10^5$

10^5 qubits?

Quantum Computing

- There is a new frontier in computing technique:



IBM 2021 slide

- A new Moore's law: Rose's law
  (A founder of D-Wave Quantum Computing)

- Conclusion -
Quantum Computational enhanced Sensing

- **QS and QI** now provide a new experimental frontier, enabling us to probe **energy scales and interaction regimes previously inaccessible** to conventional techniques.
- In this work, we showed that these tools can be applied not only to dark matter, but also to cosmic neutrinos and other feebly interacting relics.
- **Detecting the Cosmic Neutrino Background** remains extremely challenging, while providing a clear **opportunity** for quantum-enabled experiments.