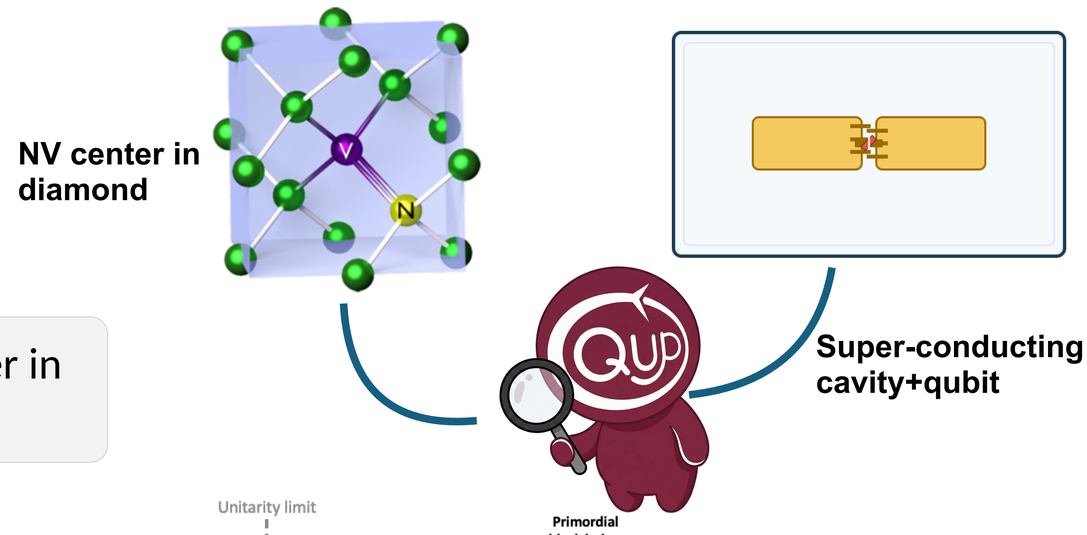
International Center for
Quantum-field Measurement Systems for
Studies of the Universe and Particles
WPI research center at KEK

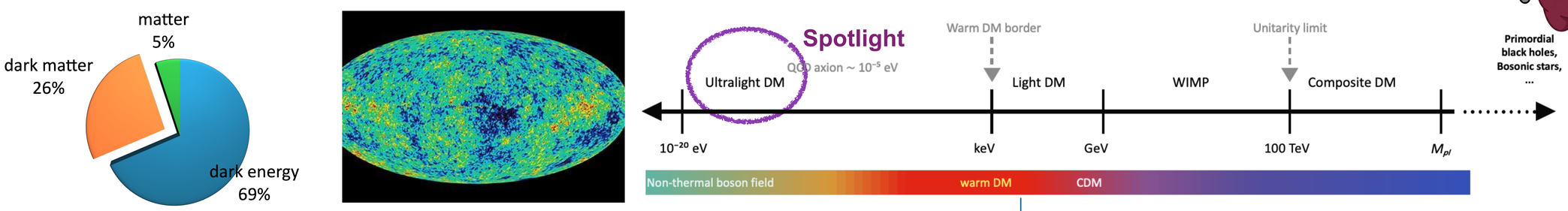
Multi-level as a quantum resource for quantum sensing of the dark matter

Beyond qubits: Multilevel quantum sensing for dark matter (Phys.Rev.A Lett. 113 (2026) 6, L060802)
Xiaolin Ma[1], Volodymyr Takhistov[1,2,3,4], Norikazu Mizuochi[5], and Ernst David Herbschleb[1]
Enhanced Dark Matter Quantum Sensing via Geometric Phase (arXiv:2603.23599)
Xiaolin Ma[1], and Jie Sheng[4]

1. International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP), KEK
2. Theory Center, Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK)
3. Graduate University for Advanced Studies (SOKENDAI)
4. Kavli Institute for the Physics and Mathematics of the Universe (WPI), Chiba
5. Institute for Chemical Research, Kyoto University, Gokasho, Uji-city, Kyoto

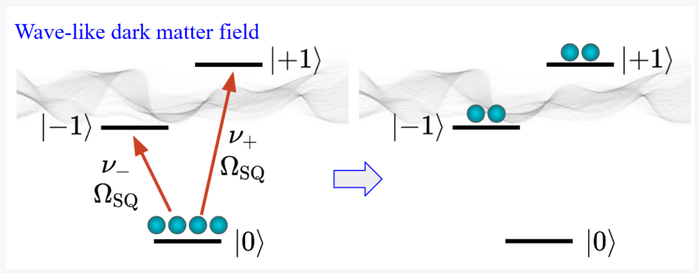


Tabletop experiments, particularly **quantum sensors**, lie at the precision frontier in searches for extremely weak signals from **wave-like dark matter**



- Dark matter: unknown matter that accounts for approximately 26% energy density of the Universe.
- Variety of well-motivated theories (**Axion**, Dark photon etc) predict very light dark matter ($m \ll \mathrm{eV}$).
- Weak, wave-like dark matter signals require unconventional detection methods, such as NV (nitrogen-vacancy) center in diamond magnetometry for effective magnetic fields induced by axion dark matter, and superconducting qubit of dark photon dark matter.

Qutrit system in NV center in diamond



NV center spin Hamiltonian

$$H = 2\pi D S_{e,z}^2 + \gamma_e B_0 S_{e,z} + \gamma_e \vec{B} \cdot \vec{S}_e,$$

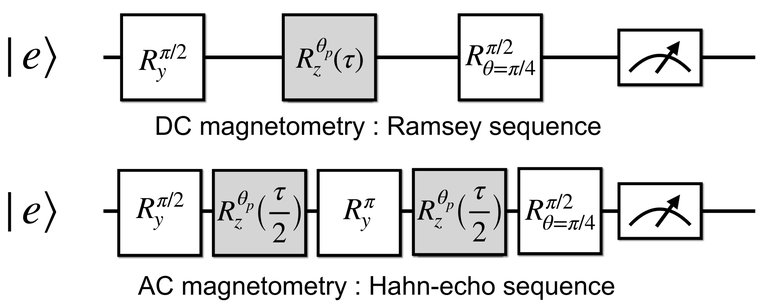
Axion dark matter-electron interaction induces effective magnetic field $\vec{B}_{\mathrm{eff}}$

$$H_{\mathrm{eff}} = \frac{g_{aee}}{m_e} \vec{\nabla} a \cdot \vec{S}_e = \gamma_e \vec{B}_{\mathrm{eff}} \cdot \vec{S}_e .$$

D: zero field splitting, $\vec{S}_e$ electron spin, B_0 bias field, γ_e electron gyromagnetic ratio

- Many quantum systems possess multiple energy levels, conventional quantum sensing often uses **only two as qubit.**
- The NV center is a spin-1, 3-level system—a **qutrit**. We show NV qutrits can be used for sensitive DM detection.

Specially designed the protocol for qutrit Ramsey (Direct Current signal) or Hahn-echo (Alternating Current signal) sensing.



Non-resonance!

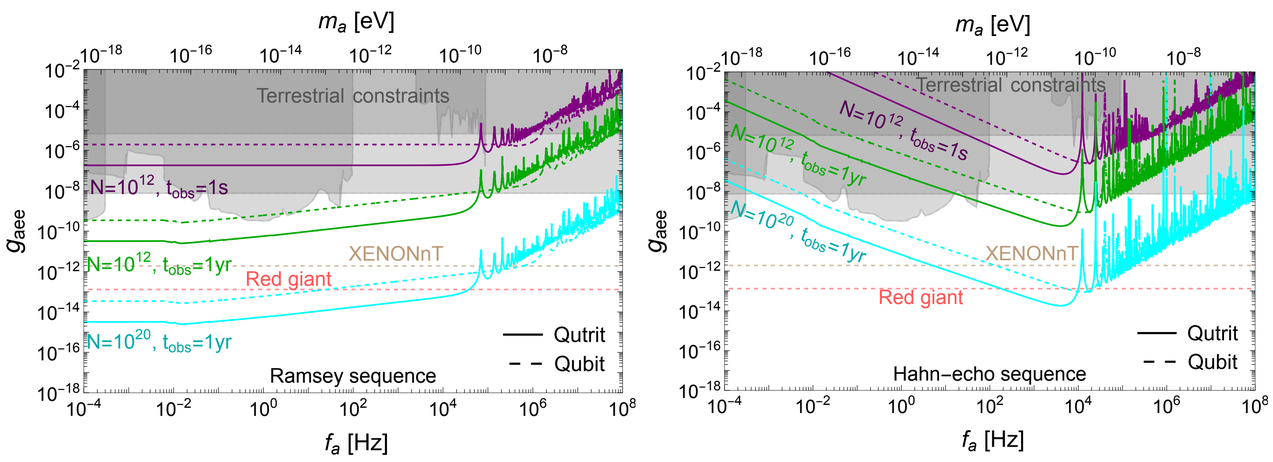
- Qutrits could be implemented using the balanced double drive to excite the $|+\rangle$ and $|-\rangle$ states simultaneously.

The qutrit sensing protocol suppresses common-mode shifts thus extending the dephasing time.

$$\Delta B_{\mathrm{min}} \simeq \frac{e^{\tau/T_2^*}}{\gamma_e \sqrt{N \tau t_{\mathrm{obs}}}\,|\Delta m|} \Rightarrow g_{aee}^{-1} \propto |\Delta m| \sqrt{N\tau}\,.$$

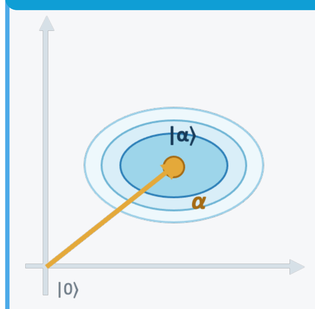
Multi-level gain

T_2^*: qutrit dephasing time, τ: sequence time, t_{obs} :total observation time, Δm: magnetic quantum number difference, N: number of NV centers.



Projected axion-electron dark matter coupling sensitivity: Qutrit vs Qubit

Large displacement in qubit-oscillator system



Large coherent state within Multi-level cavity system

Qubit $|e\rangle$ $s=+1$ — $|g\rangle$ $s=-1$

$\hat{\sigma}_z \hat{a}^\dagger \hat{a}$

Cavity

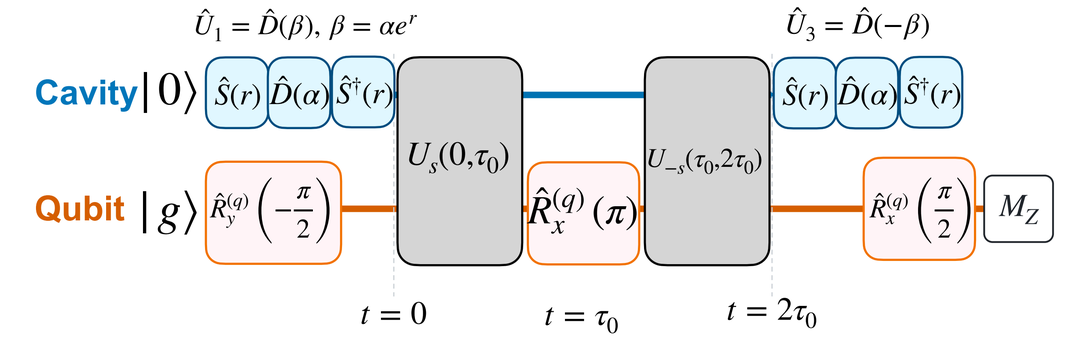
DM

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle .$$

Dispersively coupled cavity-qubit Hamiltonian

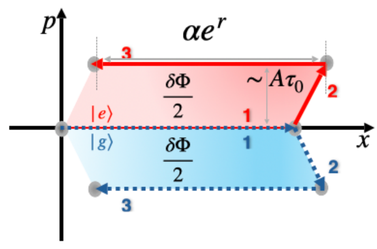
$$H_I(t) \equiv H_0 + V(t) = \frac{\chi}{2} \hat{\sigma}_z \hat{a}^\dagger \hat{a} + \left[A \hat{a}^\dagger e^{i(\Delta t - \phi_1)} + \mathrm{h.c.} \right].$$

χ: dispersive couping strength , $\hat{a}$ cavity mode operator, A dark photon field, $\hat{\sigma}_z$ qubit operator



Effective operation $U_{\mathrm{tot}} = U_3 U_2 U_1 = \hat{D}(\Sigma) e^{is\delta\Phi/2}$.

Transforms the squeezed displacement into geometric phase.

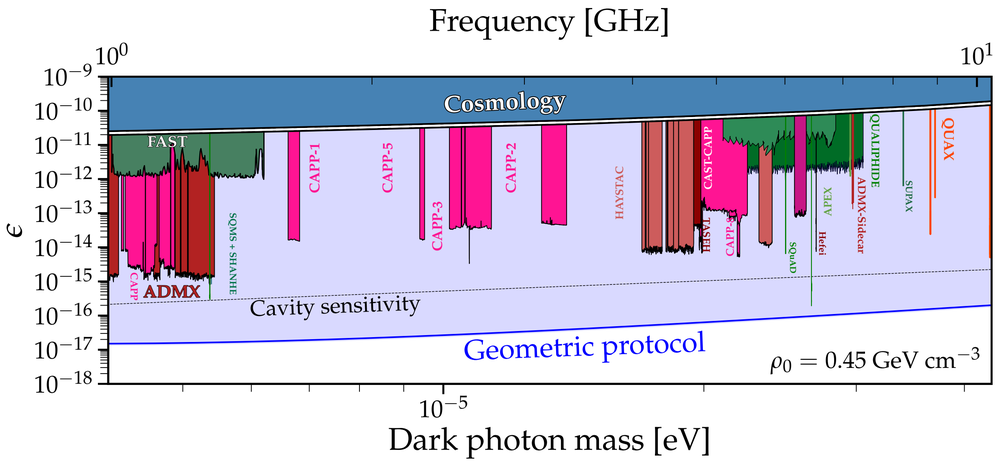


$$\delta\Phi = A\beta\chi\tau_0^2 \sin(\Delta\tau_0 - \phi_1)\mathrm{sinc}\left(\frac{(\Delta+\chi/2)\tau_0}{2}\right)\mathrm{sinc}\left(\frac{(\Delta-\chi/2)\tau_0}{2}\right).$$

Geometric phase boosted from Multi-level gain

Effects of the noise

$$\frac{1}{T_{2,\mathrm{eff}}} \simeq \underbrace{\frac{1}{T_{2,\mathrm{echo}}^{(0)}}}_{\text{Intrinsic Qubit Decay}} + \underbrace{\kappa|\beta|^2\left(1-\frac{\sin(\chi\tau_0)}{\chi\tau_0}\right)}_{\text{Cavity Vacuum Dephasing}} + \underbrace{2\bar{n}_{\mathrm{th}}\kappa|\beta|^2\left(1-\frac{\sin(\chi\tau_0)}{\chi\tau_0}\right)}_{\text{Cavity Thermal Dephasing}} .$$



Projected dark photon sensitivity with geometric phase protocol

Conclusions

- We developed novel complementary tabletop quantum sensing approaches to search for ultralight dark matter and spin-dependent fifth forces.
- Multilevel NV sensing enhances spin-phase accumulation and suppresses common-mode noise, while polarized Casimir platforms provide a differential probe of spin-dependent forces with modulation to reduce magnetic backgrounds.
- Multilevel sensing extends tabletop sensitivity to weakly coupled ultralight dark matter, improving performance without increasing the number of sensors.

References

1. X. Ma, V. Takhistov, N. Mizuochi and E. D. Herbschleb, *Beyond Qubits: Multilevel Quantum Sensing for Dark Matter*, Phys.Rev.A Lett. 113 (2026) 6, L060802.
2. S. Chigusa, M. Hazumi, E. D. Herbschleb, N. Mizuochi,and K. Nakayama, *Light dark matter search with nitrogen-vacancy centers in diamonds*, JHEP 03, 083(2025).
3. N. Suri, Z. Wang et al, *Quantum Sensing using Geometrical Phase in Qubit-Oscillator Systems,* arXiv:2511.21983.

Contact: xlmphy@post.kek.jp, KEK/QUP