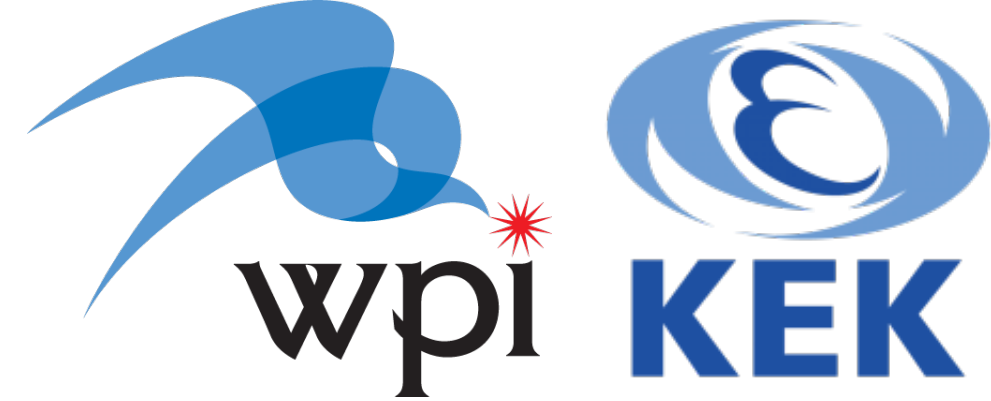




International Center for
Quantum-field Measurement Systems for
Studies of the Universe and Particles
WPI research center at KEK



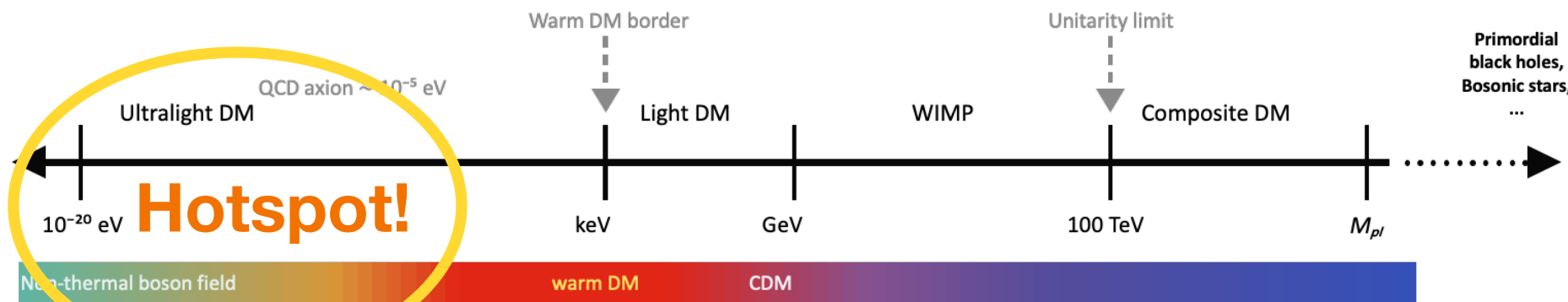
Enhanced Dark Matter Quantum Sensing via Squeezing-amplified Geometric Phase

Xiaolin Ma and Jie Sheng

arXiv: 2603.23599

(KEK/QUP)

Dark Matter at μeV Matters



- Ultralight bosonic dark matter is well motivated: axions and dark photons are prime WISP candidates.
- The μeV axion(dark photon) dark matter with various production mechanisms.

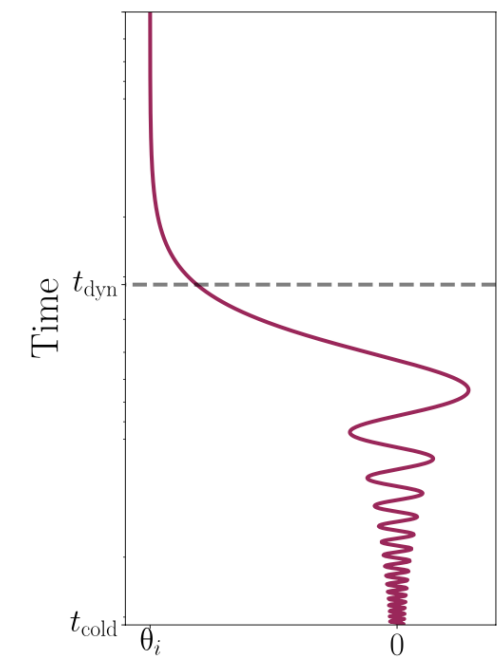
$$\theta_a \sim \mathcal{O}(1) \quad m_a \simeq 5.7 \mu\text{eV} \times \left(\frac{10^{12} \text{ GeV}}{f_a} \right) \quad \text{Axion}$$

$$m_{A'} \simeq 6 \mu\text{eV} \left(\frac{10^{14} \text{ GeV}}{H_I} \right)^4 \cdot \text{Dark photon}$$

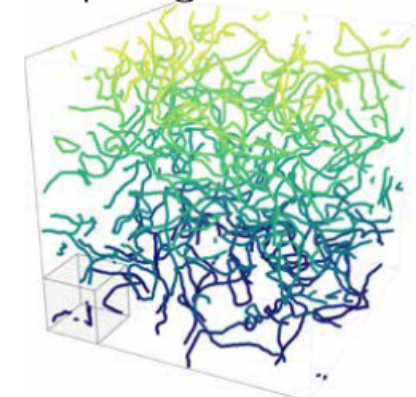
Graham, 1504.02102

SI 2026

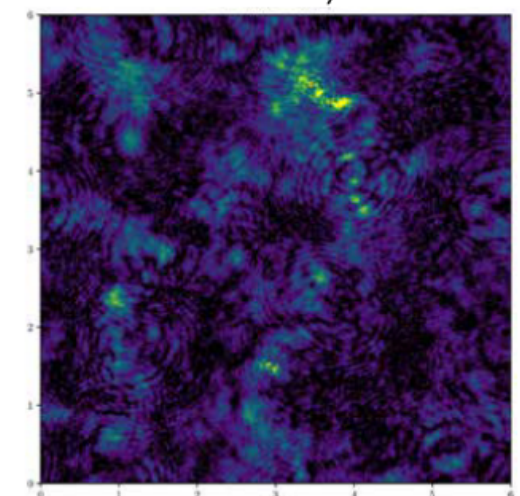
Xiaolin Ma



Topological defects



Nonlinear dynamics



Chadha-Day, Sci.Adv. 8 (2022) 8

August 9th

Cavity Searches For μeV DM

Axion and Dark photon naturally interact with Standard model photon:

$$\epsilon F_{\mu\nu} F'^{\mu\nu}$$

(Kinetic mixing with photon)

$$g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

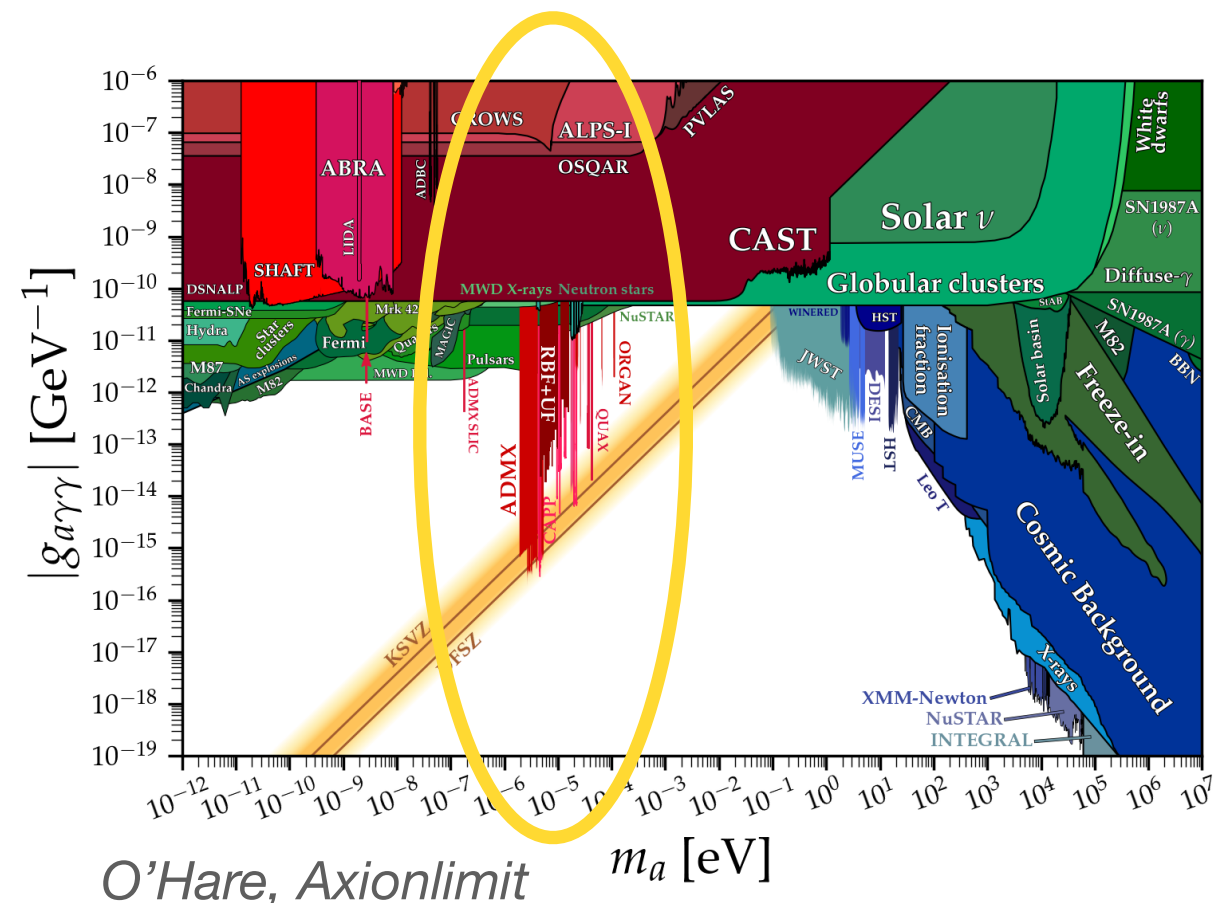
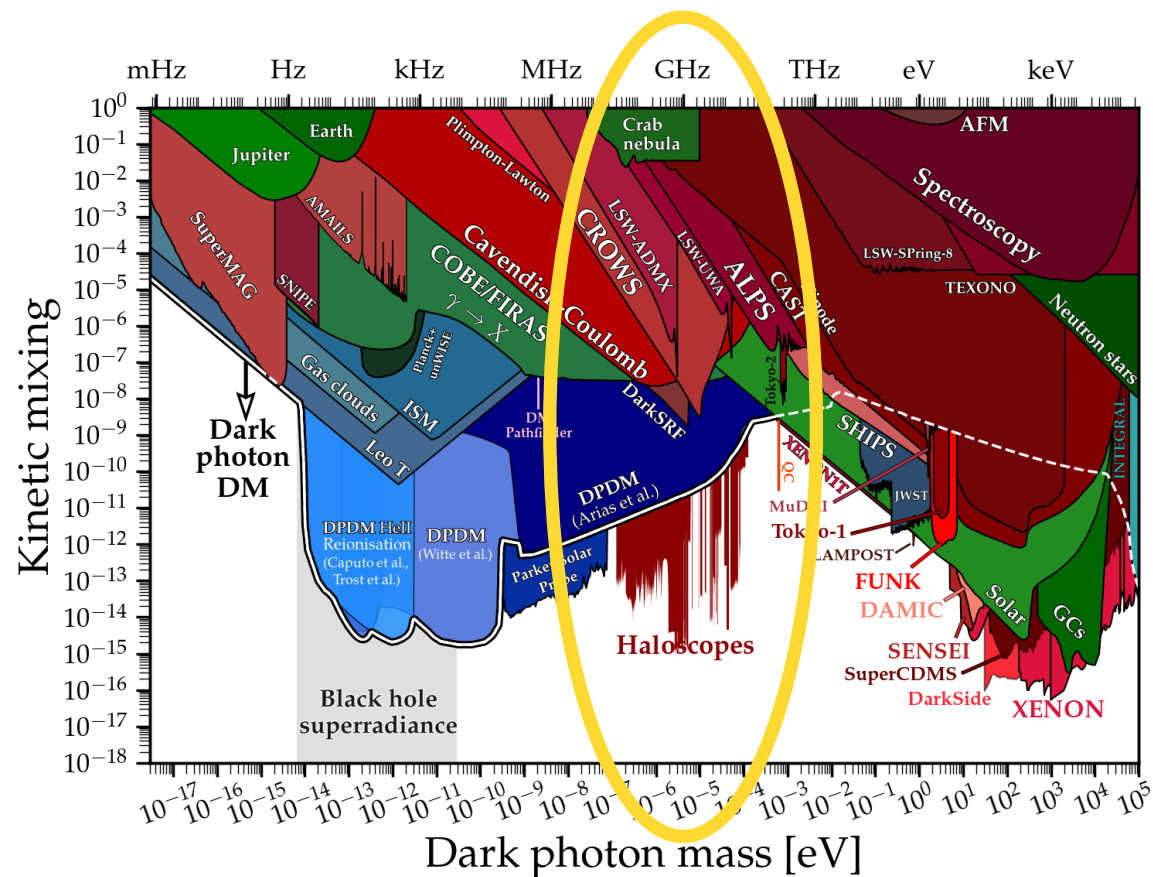
(Peccei–Quinn current EM anomaly)

$$\nabla \times (\nabla \times \mathbf{E}) + \partial_t^2 \mathbf{E} = -\partial_t \mathbf{j}_{\text{eff}}$$

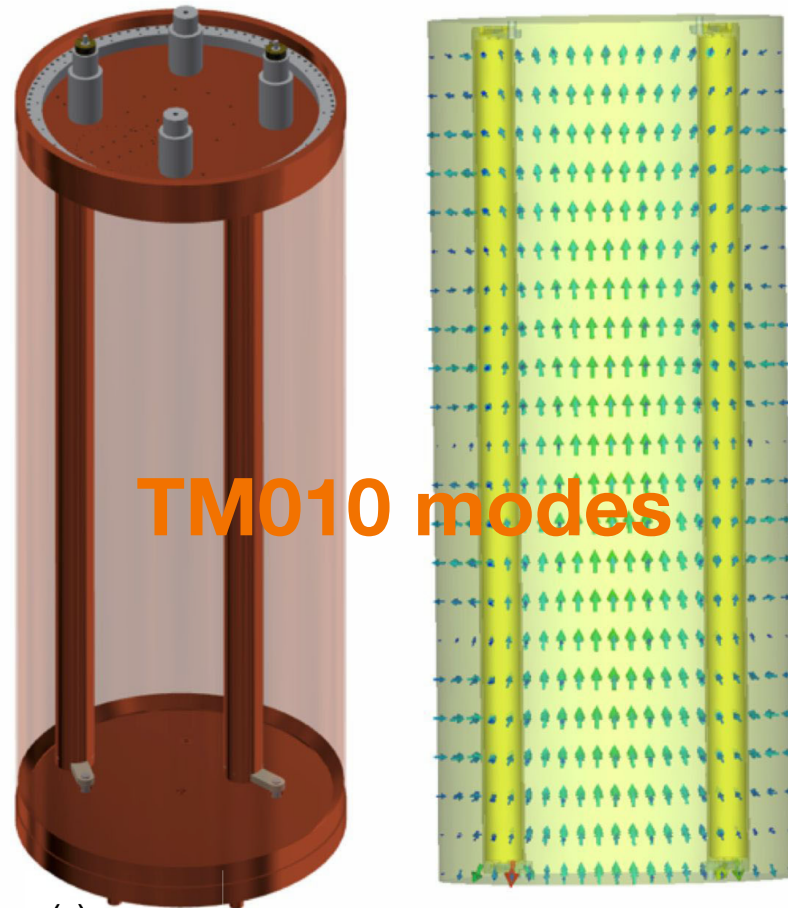
DM induced effective current

$$\mathbf{J}_{\text{eff}}(A') = \epsilon m_{A'}^2 \mathbf{A}'$$

$$\mathbf{J}_{\text{eff}}(a) = g_{a\gamma\gamma} \mathbf{B}_0 \dot{a}$$

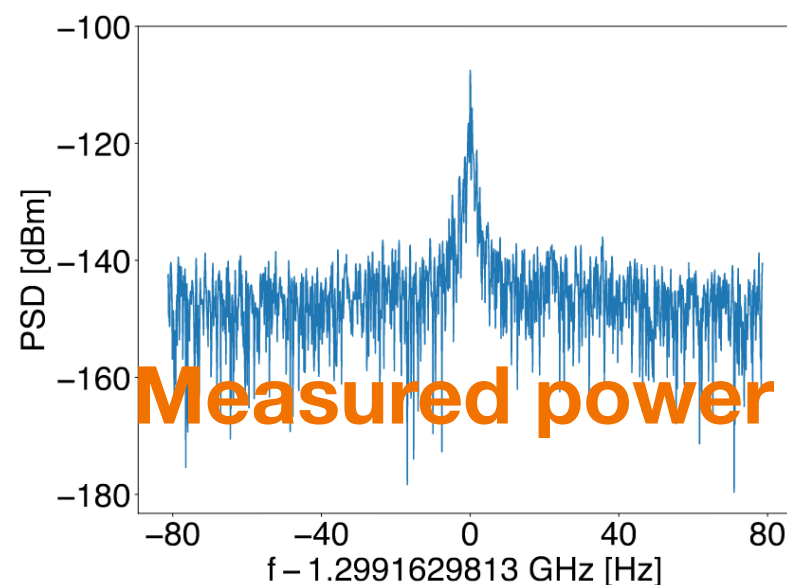


Cavity Searches For High-frequency DM



TM010 modes

Source: ADMX



Measured power

$$\mathbf{E}(\mathbf{x}, t) = \sum_c e_c(t) \mathbf{E}_c(\mathbf{x})$$

Modes decomposition

$$\left(\partial_t^2 + \frac{\omega_c}{Q_c} \partial_t + \omega_c^2 \right) e_c(t) = - \frac{\int_{V_{\text{Cav}}} d^3\mathbf{x} \mathbf{E}_c^*(\mathbf{x}) \cdot \partial_t \mathbf{j}_{\text{eff}}}{\int_{V_{\text{Cav}}} d^3\mathbf{x} |\mathbf{E}_c(\mathbf{x})|^2}$$

EOM for DM current driving cavity modes

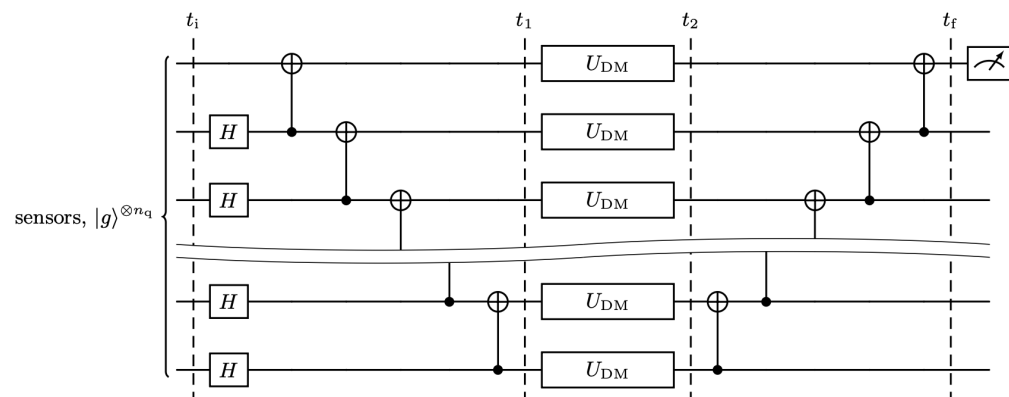
$$\epsilon \approx 10^{-16} \left(\frac{10^{10}}{Q_0} \right)^{\frac{1}{4}} \left(\frac{4 \text{ L}}{V} \right)^{\frac{1}{2}} \left(\frac{0.5}{C} \right)^{\frac{1}{2}} \left(\frac{100 \text{ s}}{t_{\text{int}}} \right)^{\frac{1}{4}} \left(\frac{1.3 \text{ GHz}}{f_0} \right)^{\frac{1}{4}} \left(\frac{T_{\text{amp}}}{3 \text{ K}} \right)^{\frac{1}{2}}$$

SHANHE Collaboration, *Phys.Rev.Lett.* 133 (2024) 2, 021005

Into the realm of quantum sensing

Quantum resources $\rightarrow$ quantum Fisher information

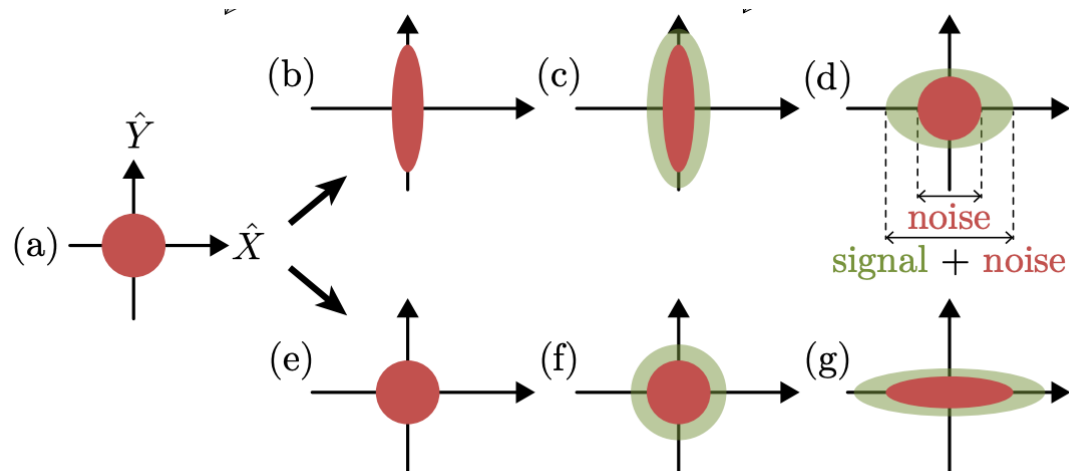
{Entanglement, squeezing, multi-levels etc} $\rightarrow$ better parameter sensitivity



Entanglement

- Entanglement of the qubits achieved the Heisenberg sensitivity scaling of the sensors.

Chen et al, PRL.133.021801

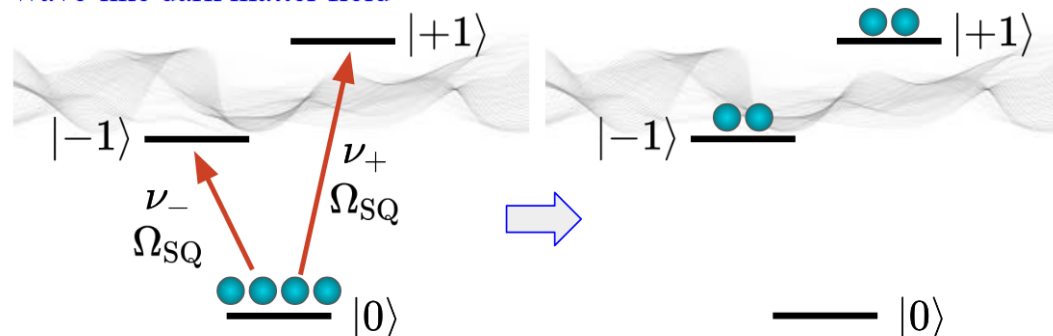


Squeezing

- Injecting squeezed vacuum in cavity greatly enhances peak SNR and the scanning rate.

Malnou et al, PRX.9.021023

Wave-like dark matter field



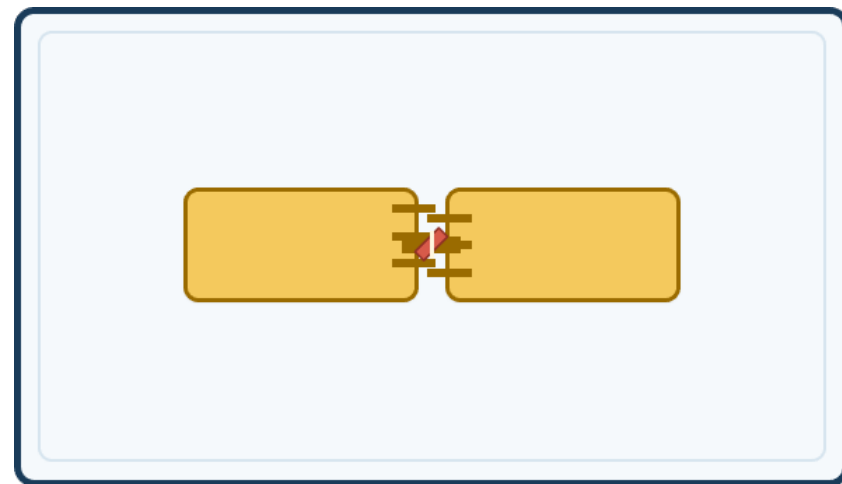
Multi-level

- Utilize the multi-level system with larger Hilbert space spectrum to increase the quantum Fisher information.

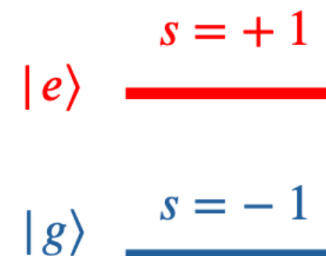
Ma et al, PRA Lett 113 (2026)

Dispersive Qubit-Cavity Sensing of Dark Matter

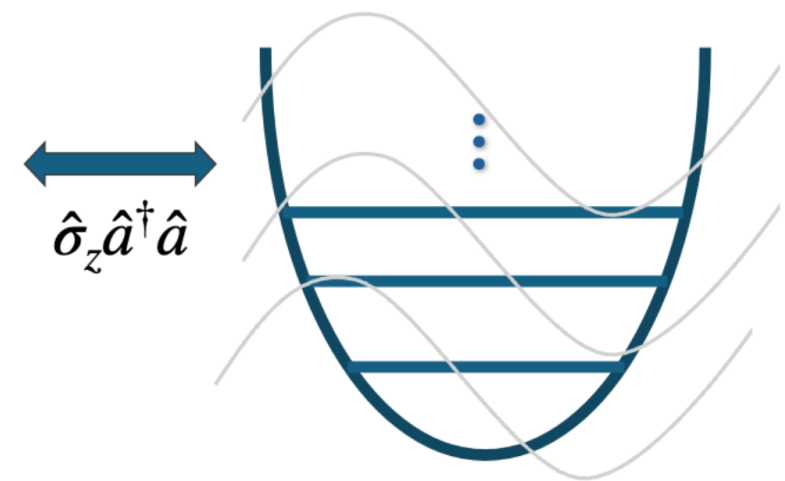
Going quantum!



Transmon



Cavity



DM Background

Dispersive coupling

$$\frac{H}{\hbar} = \omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q}{2} \hat{\sigma}_z + \frac{\chi}{2} \hat{a}^\dagger \hat{a} \hat{\sigma}_z + i \left(A e^{-i(\omega_d t + \phi_1)} \hat{a}^\dagger - A e^{i(\omega_d t + \phi_1)} \hat{a} \right).$$

Cavity Modes

(TM010 mode considered)

Qubit

DM drive (After RWA)

A: DM signal amplitude

$$\delta\omega_q = \langle a^\dagger a \rangle \chi / 2$$

Qubit-Oscillator Platform for QND& freq tuning

$$\frac{H}{\hbar} = \underbrace{\omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q}{2} \hat{\sigma}_z}_{H_0} + \frac{\chi}{2} \hat{a}^\dagger \hat{a} \hat{\sigma}_z + i \left(A e^{-i(\omega_d t + \phi_1)} \hat{a}^\dagger - A e^{i(\omega_d t + \phi_1)} \hat{a} \right).$$

$$U(t_f, t_i) = e^{i\Phi_G(s)} \hat{R}(\Omega_s \tau) \hat{D}(\delta_s).$$

DM amplitude&phases

- DM as effective current -> a tiny coherent drive into the cavity mode-> mode excitation.
- $\hat{D}(\alpha) |0\rangle \simeq |0\rangle + \alpha |1\rangle, \quad P_1 \approx |\alpha|^2$
- Experiments with a high-Q cavity plus dispersively coupled transmon can prepare, control, and read out the cavity state.
Pan Zheng et. al. [2507.23538](#)
- Ideal platform: high-fidelity qubit readout, strong bosonic control, and long cavity coherence.

The displacement and squeezing operations

$$\Delta X_1 = \Delta X_2 = 1/2$$

Laser pulse

Coherent state $\Delta X_1 \Delta X_2 = 1/4$

$$\hat{a} |\alpha\rangle = \alpha |\alpha\rangle$$

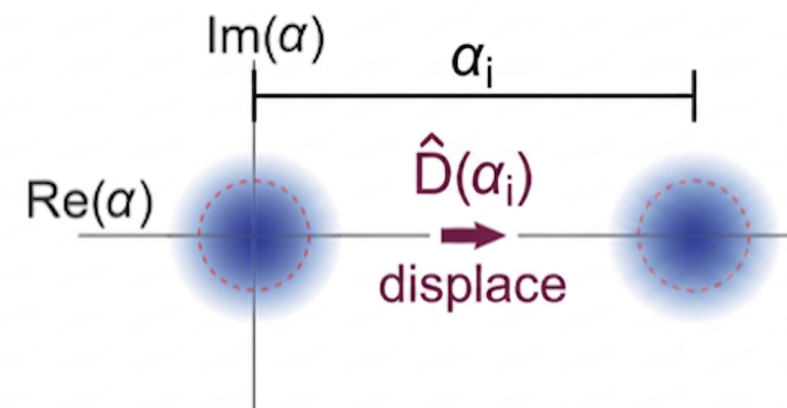
$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

$$\Delta X_1 = e^{-r}/2$$

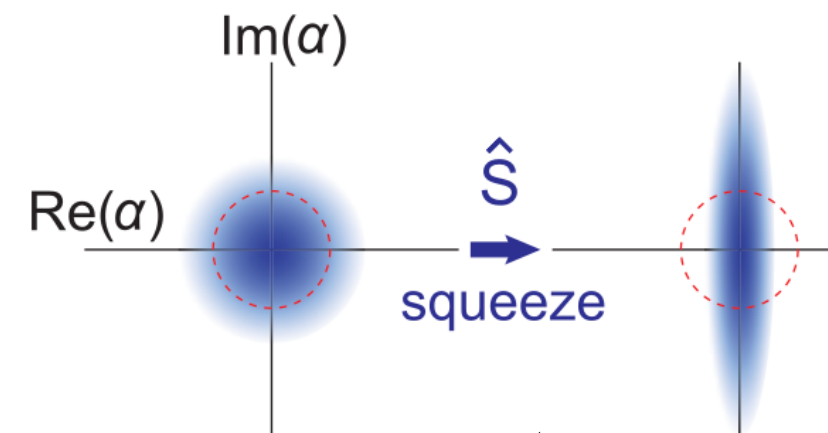
$$\Delta X_2 = e^r/2$$

Beyond standard quantum limit

Strong pump field at twice the resonance frequency



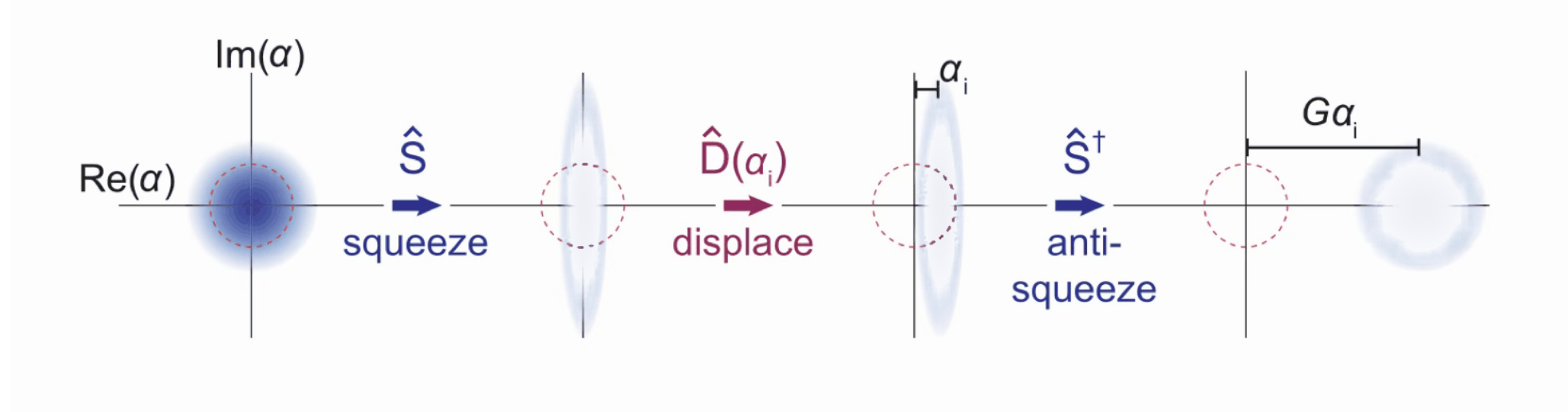
$$\hat{D}(\alpha) = \exp(\alpha \hat{a}^\dagger - \alpha^* \hat{a})$$



$$\hat{S}(\xi) = \exp\left(\frac{1}{2}\xi^* \hat{a}^2 - \frac{1}{2}\xi (\hat{a}^\dagger)^2\right)$$

$$\xi = r e^{i\theta}$$

Quantum Resource: Reversible Squeezing Amplifies Small Displacements

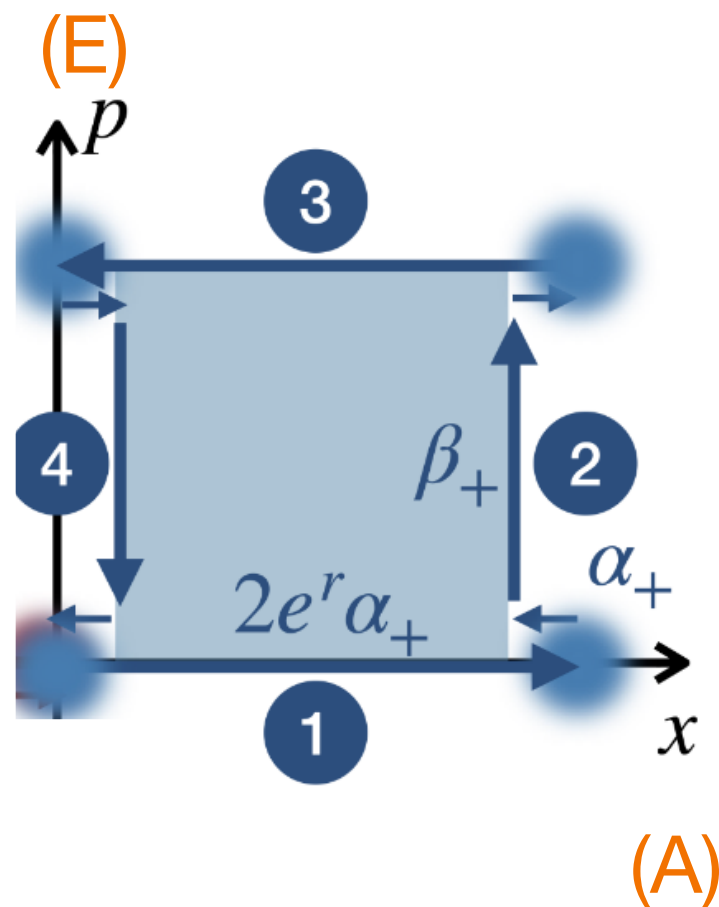


$$\hat{D}(\alpha_f) = \hat{S}^\dagger(\xi) \hat{D}(\alpha_i) \hat{S}(\xi), \quad G = e^r$$

- Tiny displacement can be amplified by sandwiching it between squeezing and anti-squeezing operation. *Burd et. al. Science.aaw2884*
- For a displacement aligned with the squeezed quadrature, the amplification gain is exponential in the squeezing strength.
- The first key intuition for our protocol.

Applicable to any harmonic oscillator! (Faster reversible squeezing)

Geometric Readout for preserving the squeezing effect



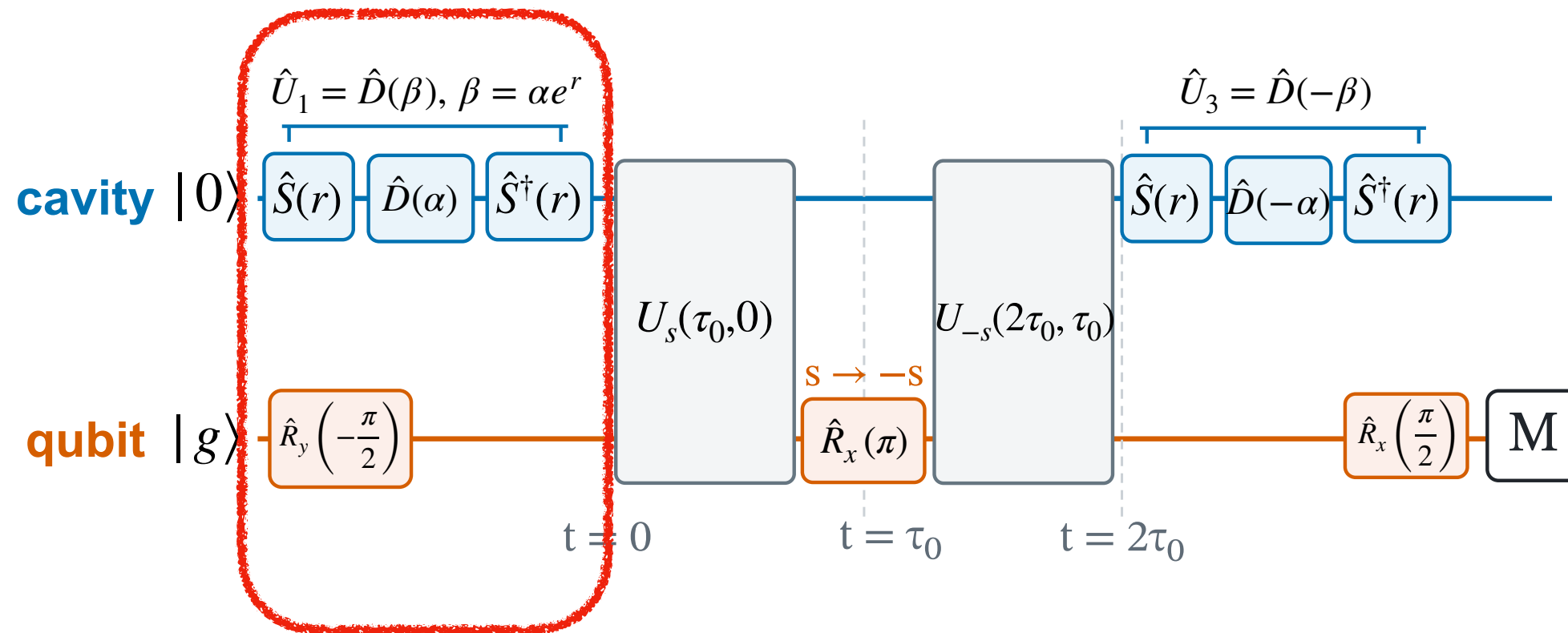
- Subtlety: squeezing enlarges bosonic displacements, but the SNR not necessarily gain. *Suri, 2511.21983*
- Steer the oscillator phase trajectory around a loop: Signal->geometric phase.
- Conceptual bridge: “bigger displacement” to “bigger phase”.
- The second key intuition for our protocol

$$D(a)D(b) = e^{i\text{Im}(a^*b)} D(a+b) \neq D(b)D(a)$$

$$\text{Area} = \text{Im} \int_{\alpha(0)}^{\alpha(T)} \alpha^* d\alpha$$

Geometric Protocol Designed for DM sensing

Preparation and squeezed displacement

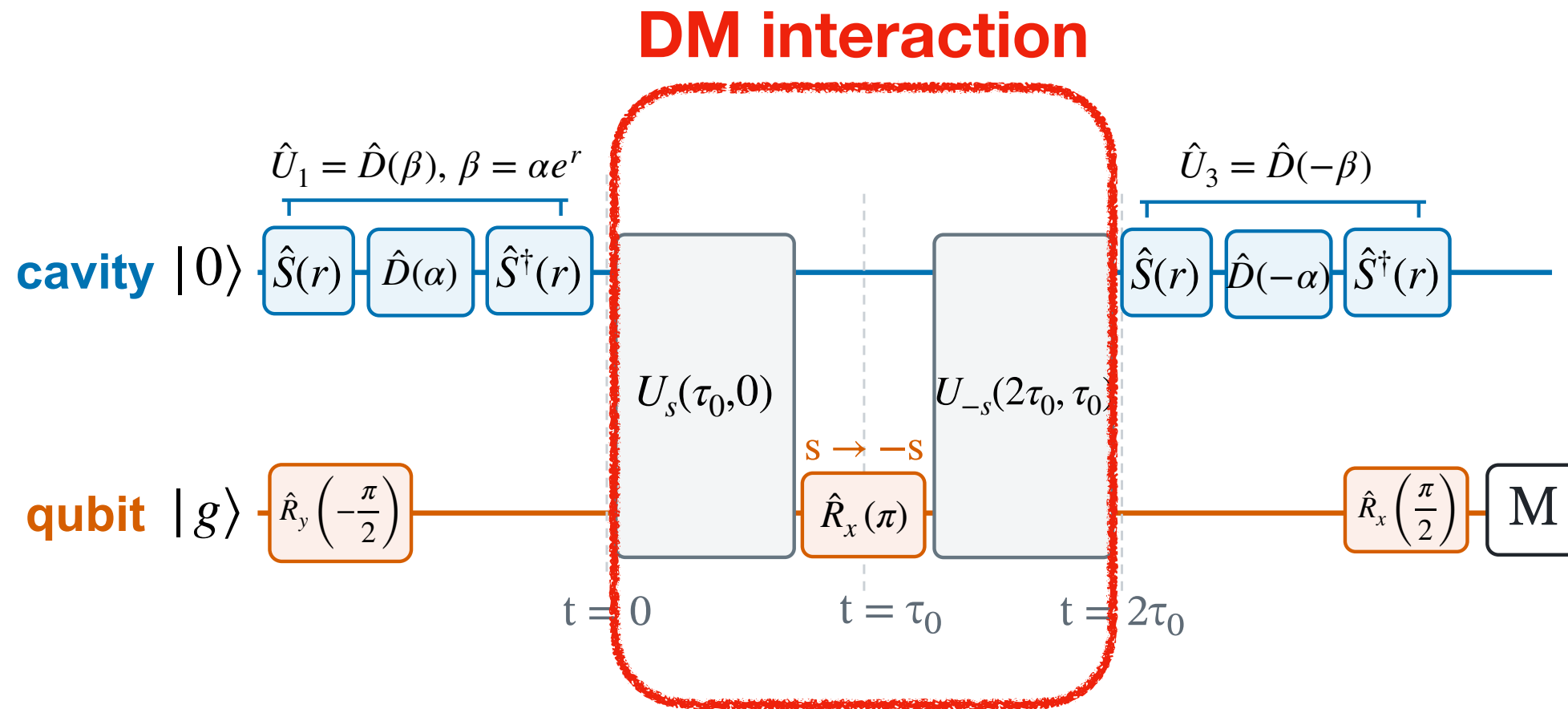


- Block 1: Prepare superposition of qubit, apply a large squeezed displacement on cavity, $U_1 = \hat{S}^\dagger(r)\hat{D}(\alpha)\hat{S}(r) = \hat{D}(\beta)$, $\beta = \alpha e^r$.

Start from $1/\sqrt{2}(|e\rangle + |g\rangle) \otimes |0\rangle$

Qubit Cavity
(Relative phase!)

Geometric Protocol Designed for DM sensing



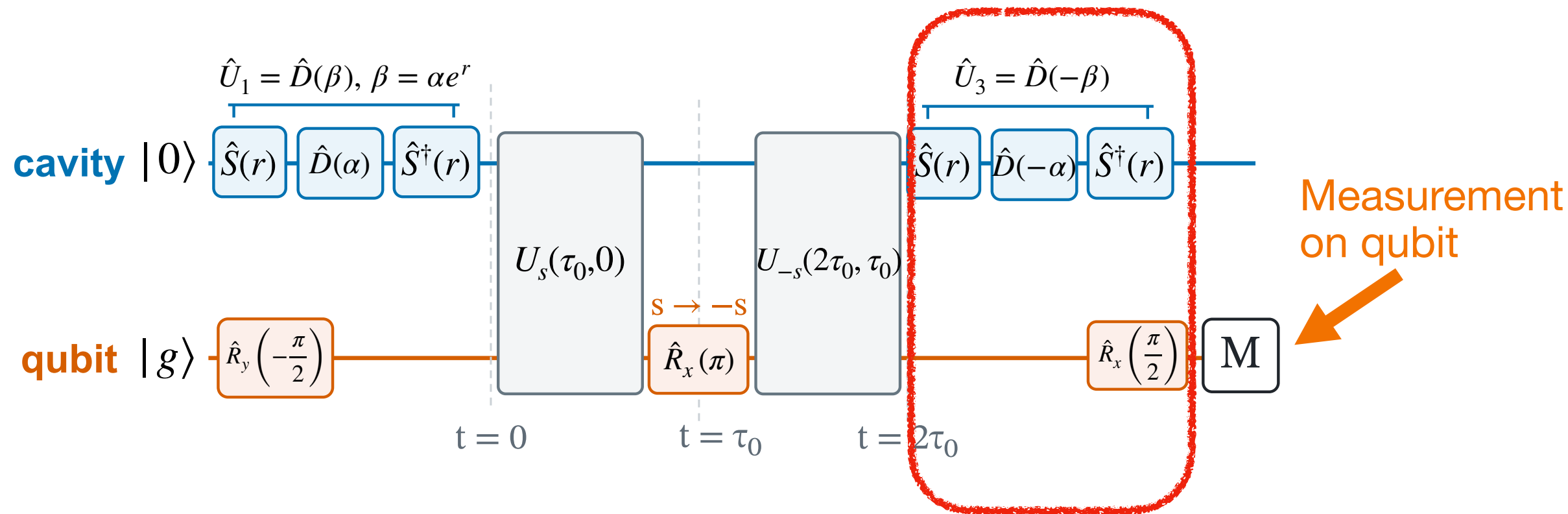
- Block 2: system evolve for $2\tau_0$ under the DM drive, with a qubit π -pulse at τ_0 to implement spin echo.

$$2\tau_0 \lesssim T_2$$

(necessary to cancel the spin dynamical phase)

Geometric Protocol Designed for DM sensing

Reverse squeezed displacement



- Block 3: apply the opposite squeezed displacement, $U_3 = \hat{D}^\dagger(\beta)$, to close the effective loop in phase space.
- $U_{\text{tot}} = U_3 U_2 U_1 = \hat{D}(\Sigma) e^{is\delta\Phi/2}$

The Signal Becomes an Enhanced Geometric Phase of qubit

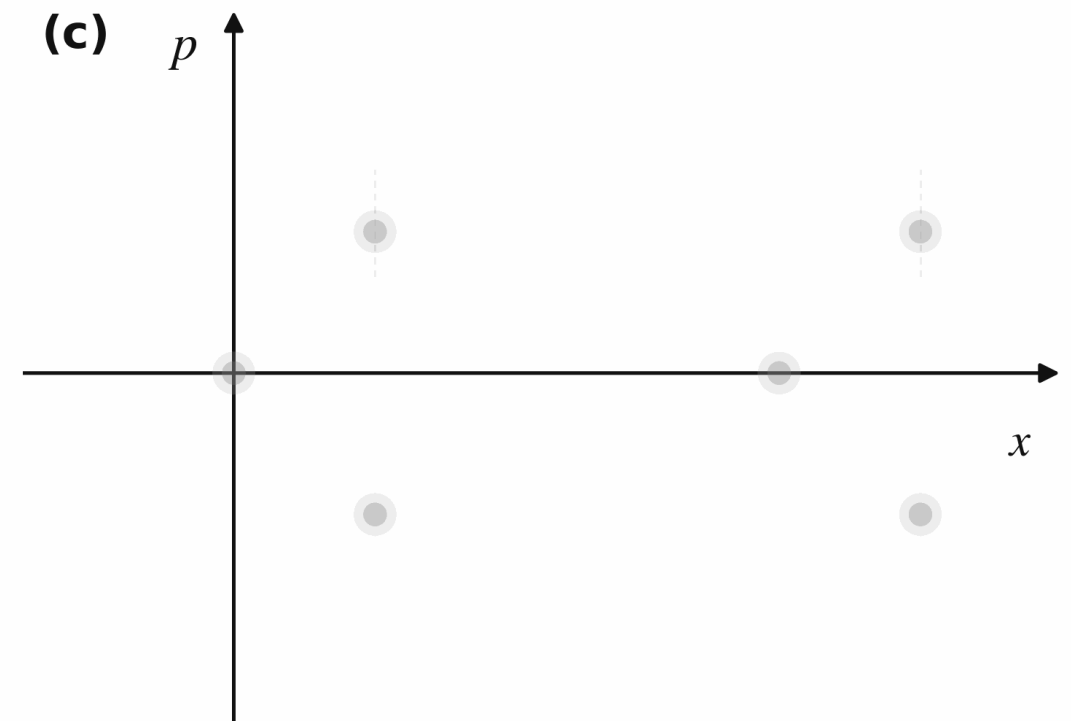
- After the loop, the residual cavity displacement is still tiny, but the qubit picks up a large relative phase (Open-path geometric phase)
- The gain comes from noncommutativity of displacement operations and the squeezed pump amplitude $\beta = \alpha e^r$.

$$\begin{aligned} & \frac{1}{\sqrt{2}}(|e\rangle + |g\rangle) \otimes |0\rangle \\ & \rightarrow \frac{1}{\sqrt{2}}(e^{i\delta\Phi/2}|e\rangle + e^{-i\delta\Phi/2}|g\rangle) \otimes |0\rangle \end{aligned}$$

+ small corrections

$$\delta\Phi \propto A\beta\chi\tau_0^2 \text{sinc}\left(\frac{(\Delta + \chi/2)\tau_0}{2}\right) \text{sinc}\left(\frac{(\Delta - \chi/2)\tau_0}{2}\right)$$

Cavity phase space with qubit spin branches (up/down)



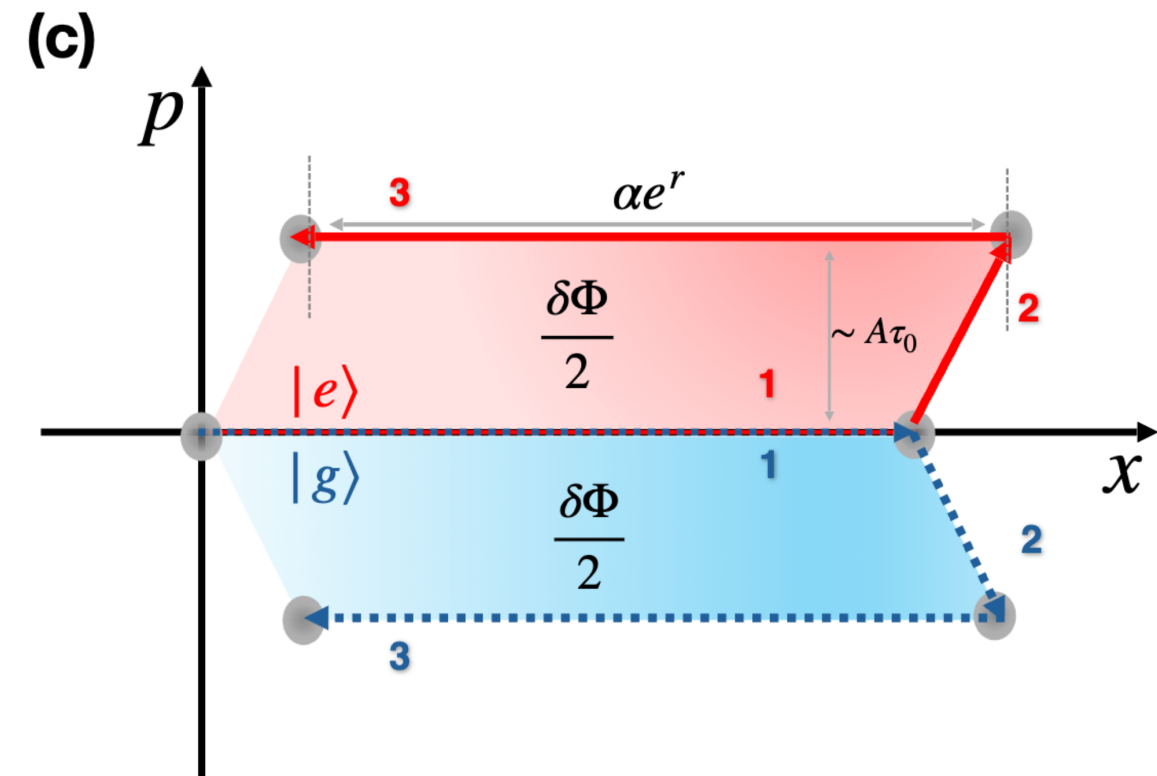
$$\Delta \equiv \omega_C - \omega_D$$

Detune

The Signal Becomes an Enhanced Geometric Phase

$$1/\sqrt{2}(e^{i\delta\Phi/2}|e\rangle + e^{-i\delta\Phi/2}|g\rangle) \otimes |0\rangle$$

- Ramsey readout turns this phase directly into an experimentally accessible qubit signal. (Expected non-vanishing variance)
- Noise effect to be discussed later.



$$\delta\Phi \propto A\beta\chi\tau_0^2 \text{sinc}\left(\frac{(\Delta + \chi/2)\tau_0}{2}\right) \text{sinc}\left(\frac{(\Delta - \chi/2)\tau_0}{2}\right)$$

$$\Delta \equiv \omega_C - \omega_D$$

Detune

QFI Enhancement and Spectral Profile

- Geometric protocol boosts the QFI by a factor set by

$$\beta^2 = (\alpha e^r)^2 \sim (3 \times 5.6)^2$$

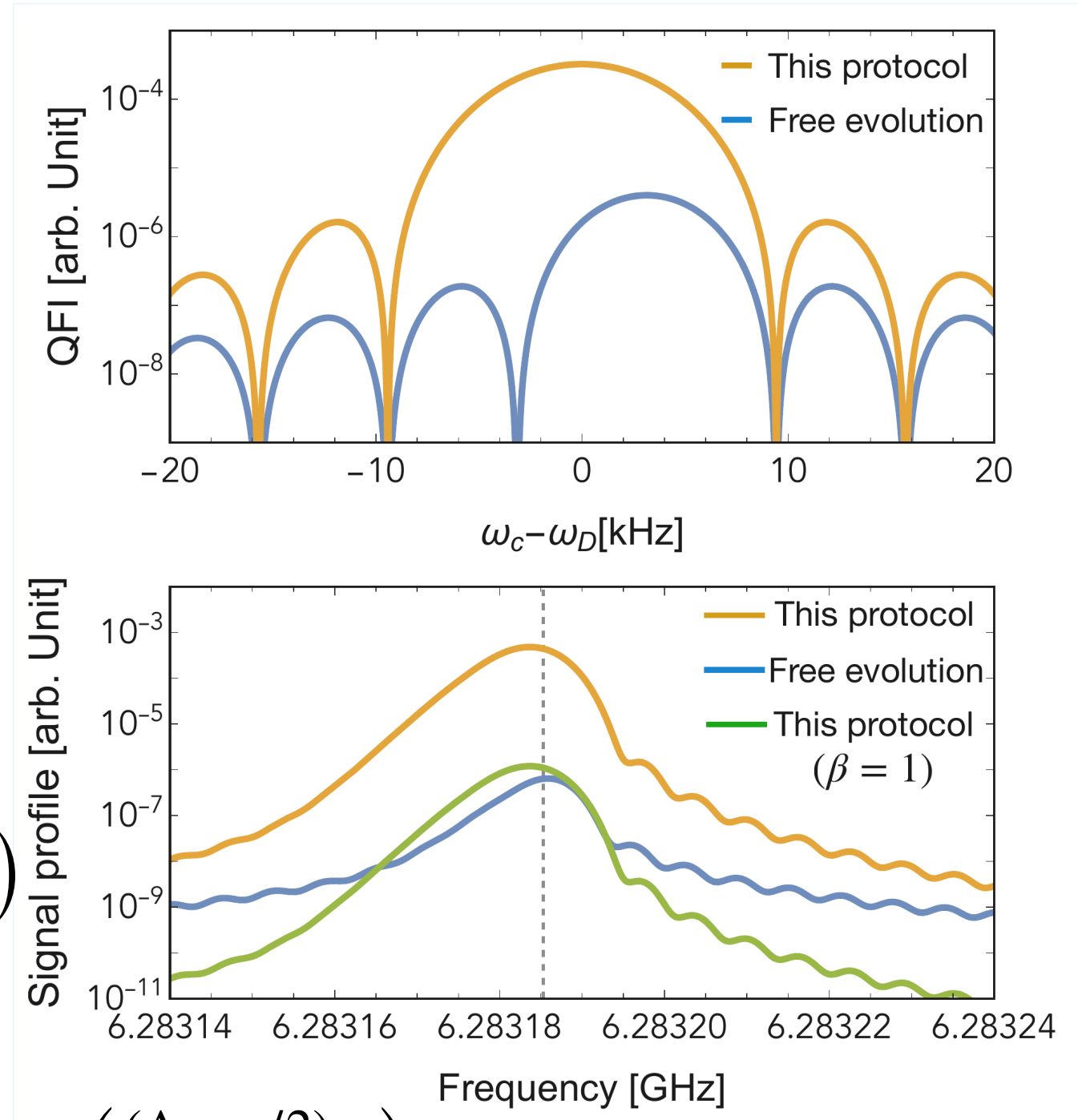
Compatible with current experiments

- After convolution with the DM linewidth, the signal develops a characteristic double-sinc spectral profile with optimal choice $\chi\tau_0 = \pi$.

$$\mathcal{F}_{Q,\text{free}}(A) \simeq 16\tau_0^2 \text{sinc}^2(\Omega_{\text{eff},s}\tau_0)$$

$$\hat{U} = e^{-iA\hat{H}}$$

$$\mathcal{F}_{Q,\text{geo}}^{\text{optimal}}(A) \approx \frac{1}{2}(\beta\chi\tau_0^2)^2 \text{sinc}^2\left(\frac{(\Delta + \chi/2)\tau_0}{2}\right) \text{sinc}^2\left(\frac{(\Delta - \chi/2)\tau_0}{2}\right)$$



New Scaling behavior from this protocol

$$P_{\text{DM}} = \int d\omega f_{\text{DM}}(\omega) \frac{1}{2} (\alpha e^r \chi \tau_0^2)^2 \text{sinc}^2 \left(\frac{(\Delta + \chi/2)\tau_0}{2} \right) \text{sinc}^2 \left(\frac{(\Delta - \chi/2)\tau_0}{2} \right). \quad \text{GHz DM as an example}$$

DM: random walk beyond
coherent time

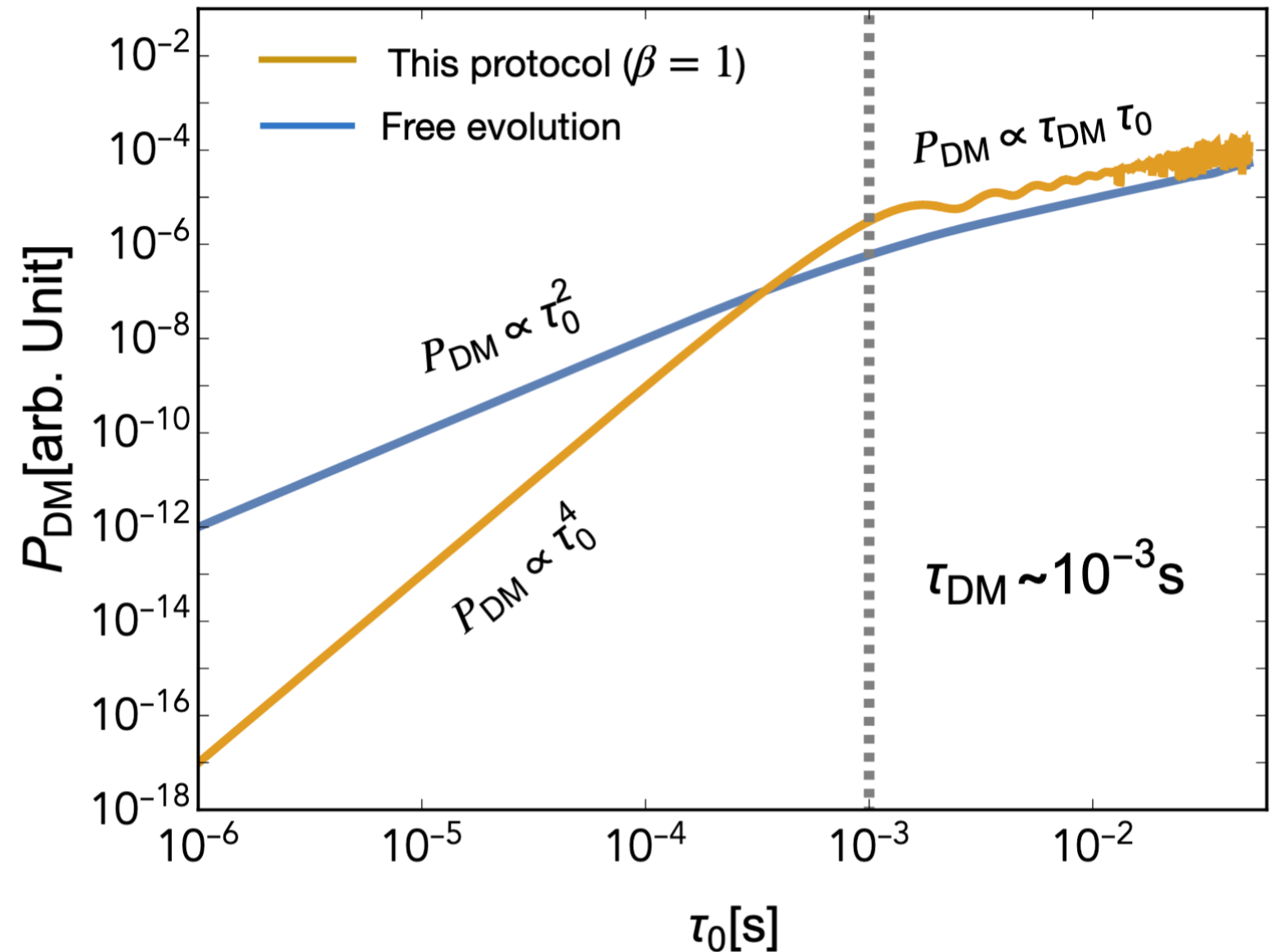
$$\frac{\sin^2(x\tau_0/2)}{(x/2)^2} \rightarrow 2\pi\tau_0\delta(x)$$

Standard:

$$P_{\text{DM}} \propto \begin{cases} \tau_0^2, & \tau_0 < \tau_{\text{DM}}, \\ \tau_{\text{DM}}\tau_0, & \tau_0 \geq \tau_{\text{DM}}. \end{cases}$$

New scaling behavior

$$P_{\text{DM}} \propto \begin{cases} \chi^2\tau_0^4, & \tau_0 < \tau_{\text{DM}}, \\ \tau_{\text{DM}}\tau_0, & \tau_0 \geq \tau_{\text{DM}}. \end{cases}$$



$$\tau_0 \sim \tau_{\text{DM}} \sim \text{ms}$$

No free lunch: Faster decoherence and the Optimal Operating Point

$$\dot{\rho}(t) = -i \left[\frac{\chi}{2} \hat{a}^\dagger \hat{a} \hat{\sigma}_z, \rho(t) \right] + \kappa(\bar{n}_{\text{th}} + 1) \mathcal{D}[\hat{a}] \rho + \kappa \bar{n}_{\text{th}} \mathcal{D}[\hat{a}^\dagger] \rho + \Gamma_1 \mathcal{D}[\sigma_-] \rho + \frac{\Gamma_\phi}{2} \mathcal{D}[\sigma_z] \rho,$$

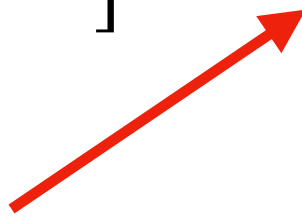
Qubit dephasing



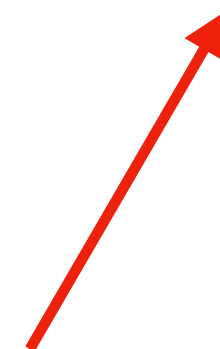
Spontaneous qubit flip



Cavity photon loss



Cavity photon excitation



Total System

System

Environment

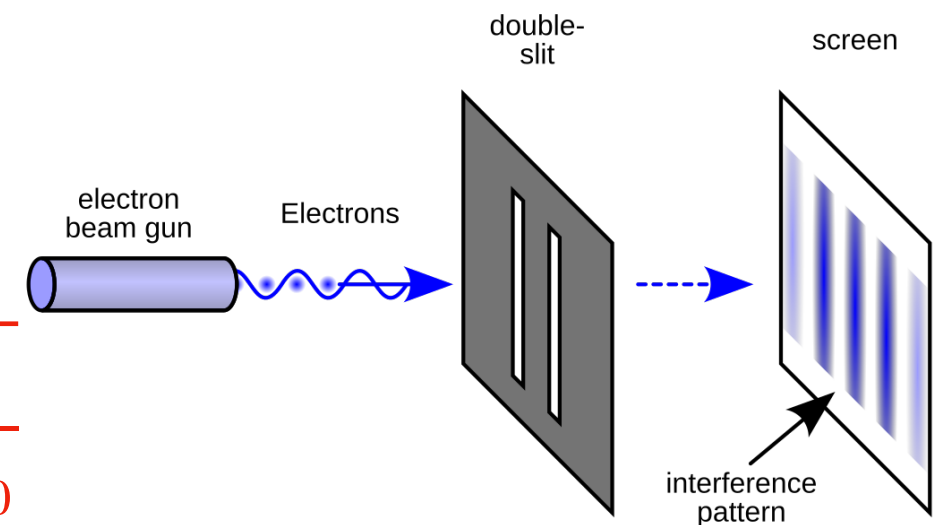
Lindblad equation for open quantum systems

$$\dot{\rho}(t) = -i \left[\frac{\chi}{2} \hat{a}^\dagger \hat{a} \hat{\sigma}_z, \rho(t) \right] + \kappa(\bar{n}_{\text{th}} + 1) \mathcal{D}[\hat{a}] \rho + \kappa \bar{n}_{\text{th}} \mathcal{D}[\hat{a}^\dagger] \rho + \Gamma_1 \mathcal{D}[\sigma_-] \rho + \frac{\Gamma_\phi}{2} \mathcal{D}[\sigma_z] \rho,$$

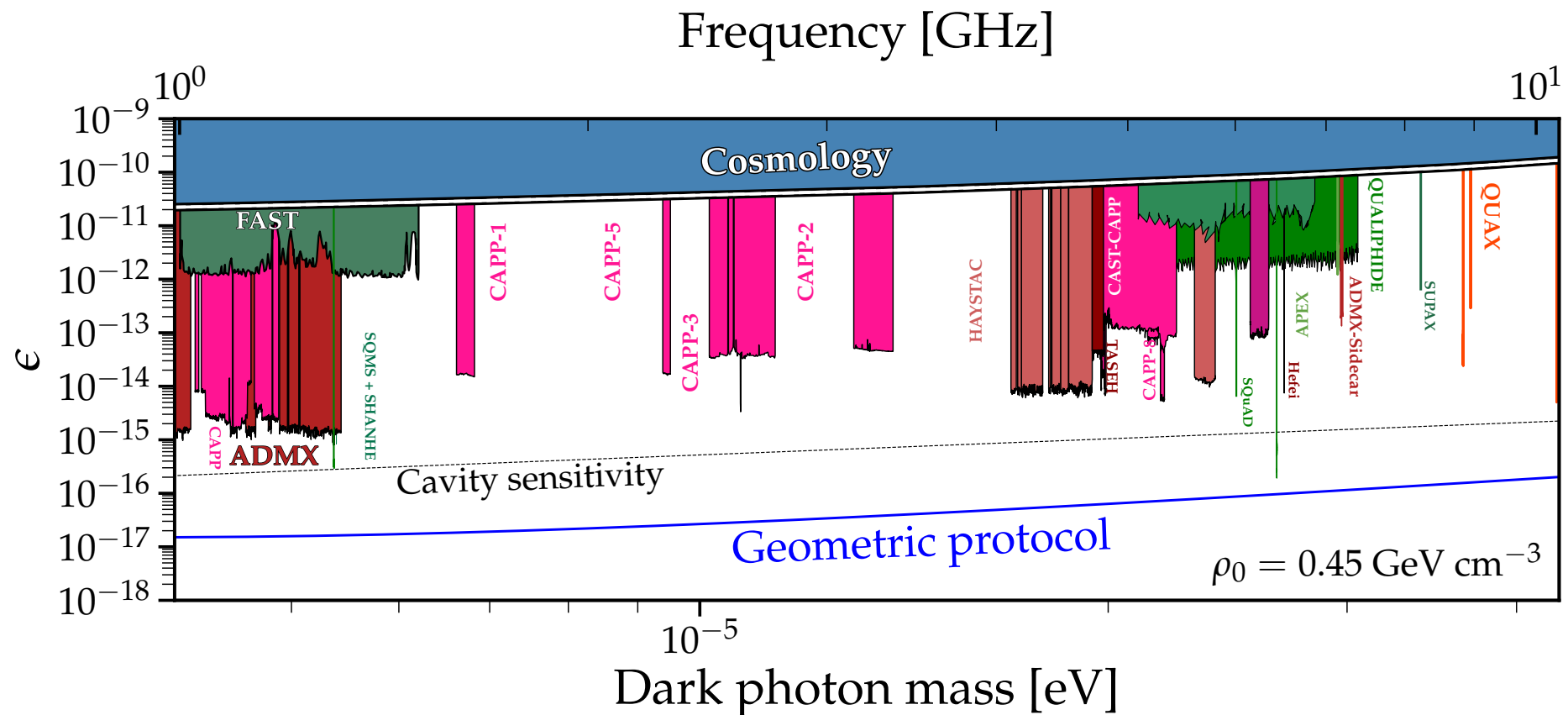
- The same enlarged phase-space separation that amplifies the signal also makes the protocol more sensitive to cavity loss and which-path dephasing.
- The signal therefore carries a competition between geometric gain and decoherence suppression.
- This tradeoff defines an optimal β for a given cavity lifetime and protocol time.

$$\eta = \exp \left[-2\tau_0 / T_{2,\text{echo}}^{(0)} - \Lambda_\kappa \right],$$

$$\Lambda_\kappa = \kappa(1 + 2\bar{n}_{\text{th}}) |\beta|^2 \tau_0 \left(1 - \frac{\sin(\chi\tau_0)}{\chi\tau_0} \right), \quad \beta_{\text{opt}} = \sqrt{\frac{T_1^c}{2\tau_0}}$$



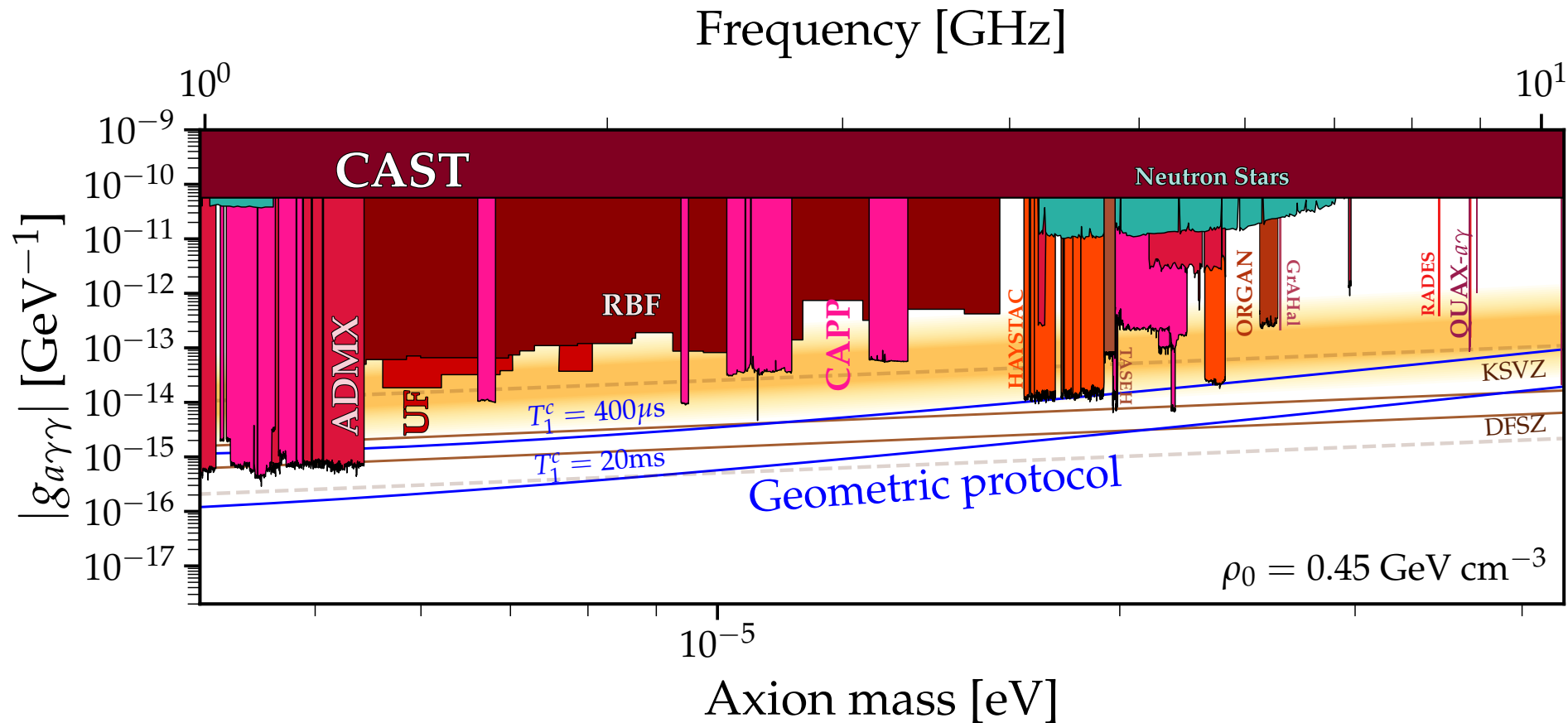
Projected Dark-Photon Reach



- Repeated Ramsey interferometry of the qubit readout, sensitivity derived from Asimov data analysis, $\mathcal{S}_k \propto 8\eta^2(\beta\tau_0)^2 |A|^2 / \pi^2$
- For benchmark parameters $T_1^c \sim 300\text{ms}$, $T_{2,\text{echo}}^{(0)} \sim 1\text{ ms}$, $t_{\text{obs}} = 60\text{s}$ per frequency bin, the reach improves substantially over cavity benchmarks.
- The projected improvement is up to one order of magnitude.

Consider only spin projection noise

Projected Axion Reach



- For axions, the same framework applies once the cavity is driven through the axion-photon coupling in a strong magnetic field.
- The quality factor decreases a lot in strong magnetic field, but the protocol still yields meaningful projected improvements.
Strong magnetic environment caveat; taken with a grain of salt.
- Outlook: extend to multi-cavity architectures, more general control sequences, and other qubit-boson sensing platforms.



Summary

- μeV dark matter is well motivated, with cavity being the one of the most powerful detector in this region.
- Using squeezed displacement as the quantum sensing resource we propose a possible detection protocol utilizing the ultrahigh Q factor of modern cavities.
- With squeezing enhanced operations, the new protocol could have a potential to improve the sensitivity of the DM, but the experiment realization is highly challenging.

Thanks !



Backup

- Open geometric phase

$$\gamma_{\text{geo}}^{\text{open}} = \arg \langle \psi(0) | \psi(T) \rangle + i \int_0^T \langle \psi(t) | \dot{\psi}(t) \rangle dt .$$

For coherent state:

$$\gamma_{\text{geo}}^{\text{open}} = \text{Im} [\alpha^*(0) \alpha(T)] - \text{Im} \int_{\alpha(0)}^{\alpha(T)} \alpha^* d\alpha$$

Area