Quantum Enhanced Sensing of Wave-like Dark Matter

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- Introduction
- Single-Photon Counter Search
- Eliminating Incoherent Noise
- Conclusion

What is a quantum sensor?

Quantum 1.0

- Detecting a single quantum of something (classically)
- Using quantum mechanics to sense small (classical) things

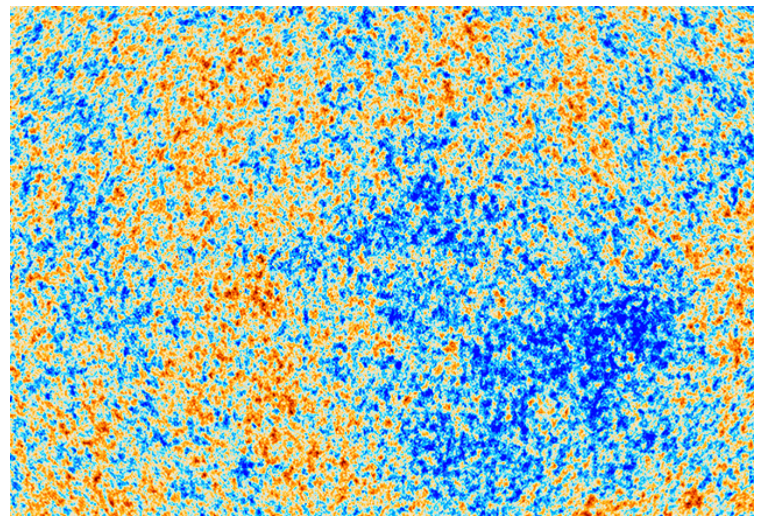
Quantum 2.0

- Both at once
- Making use of quantum squeezing, non-demolition, entanglement…

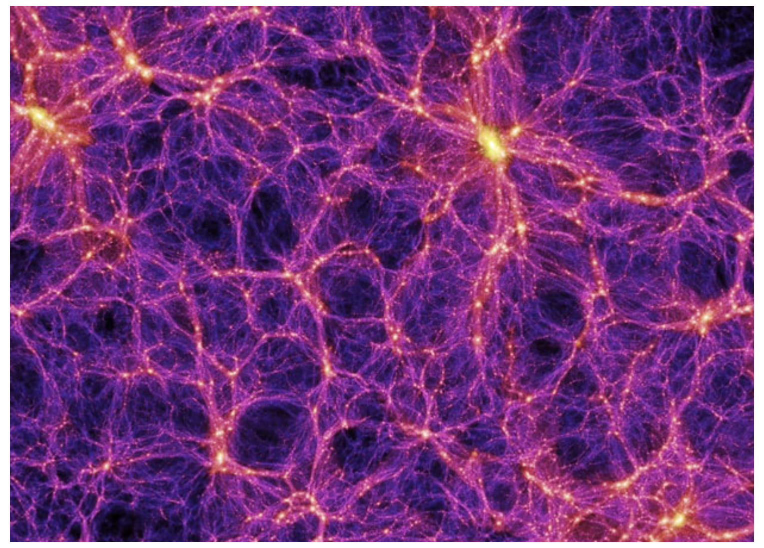
  for better sensitivity or noise performance

Why quantum sensors (for dark matter)

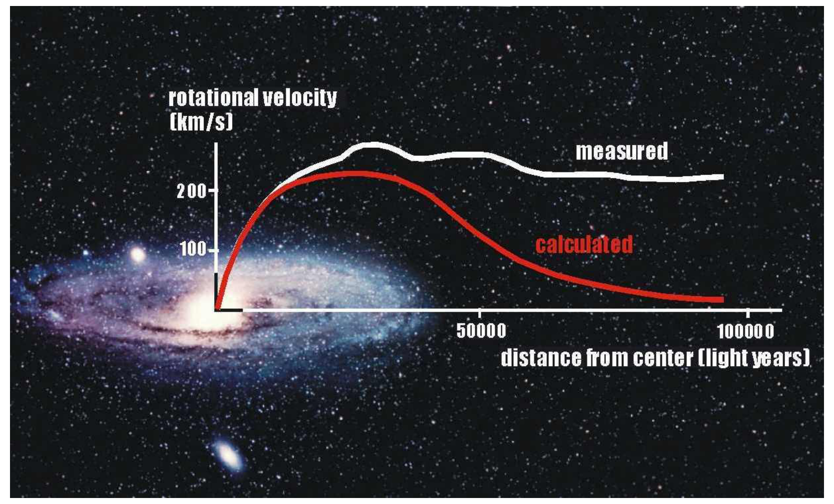
CMB



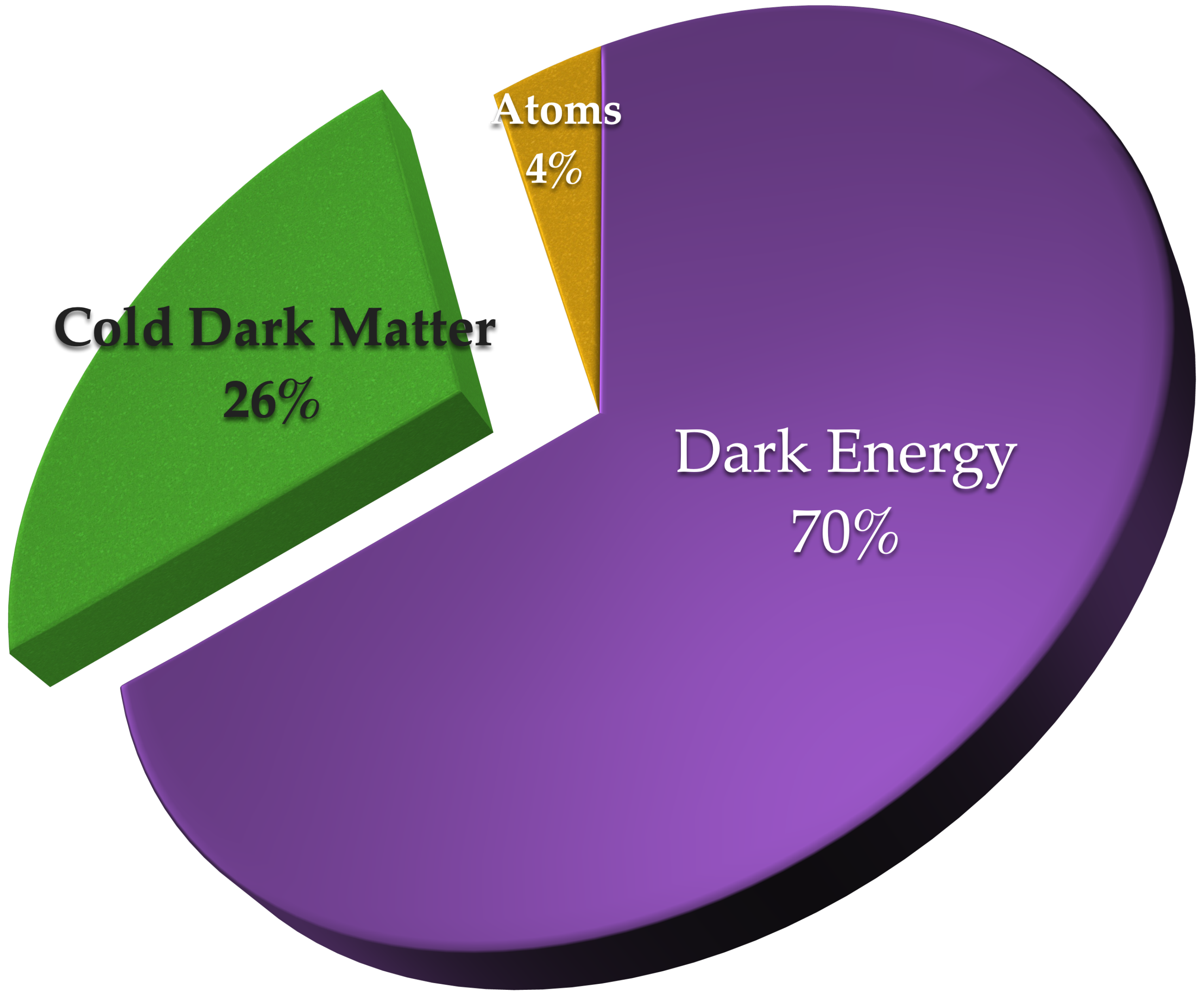
LSS

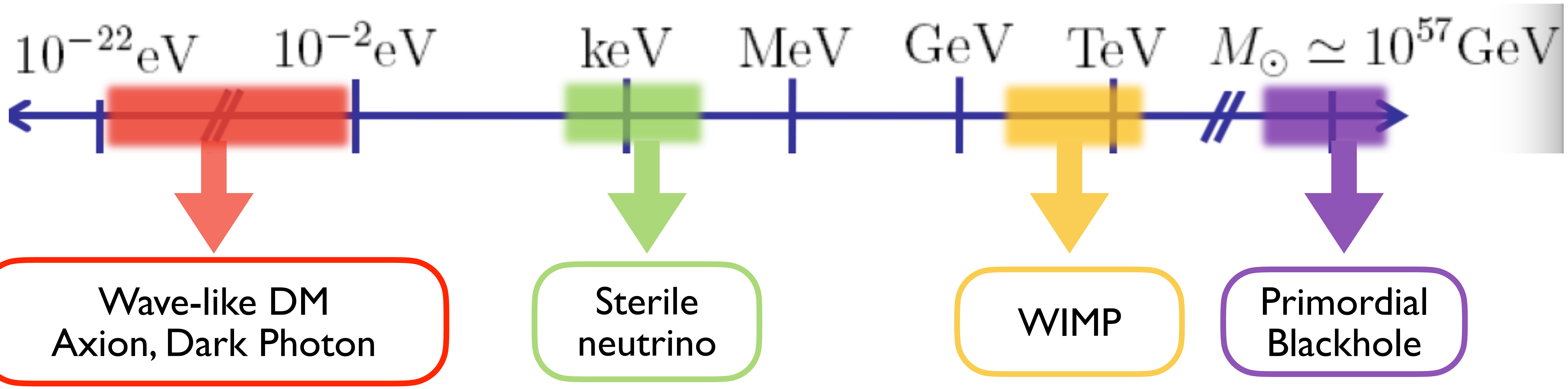


Bullet cluster



rotation curve





Wave-like DM candidates

- Axion (ALPs)

$$\mathscr{L}_a \supset \frac{1}{4} g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \rightarrow \quad J^{a\,\mu}_{\text{eff}} = -\, g_{a\gamma}\tilde{F}^{\mu\nu}\partial_\nu a$$

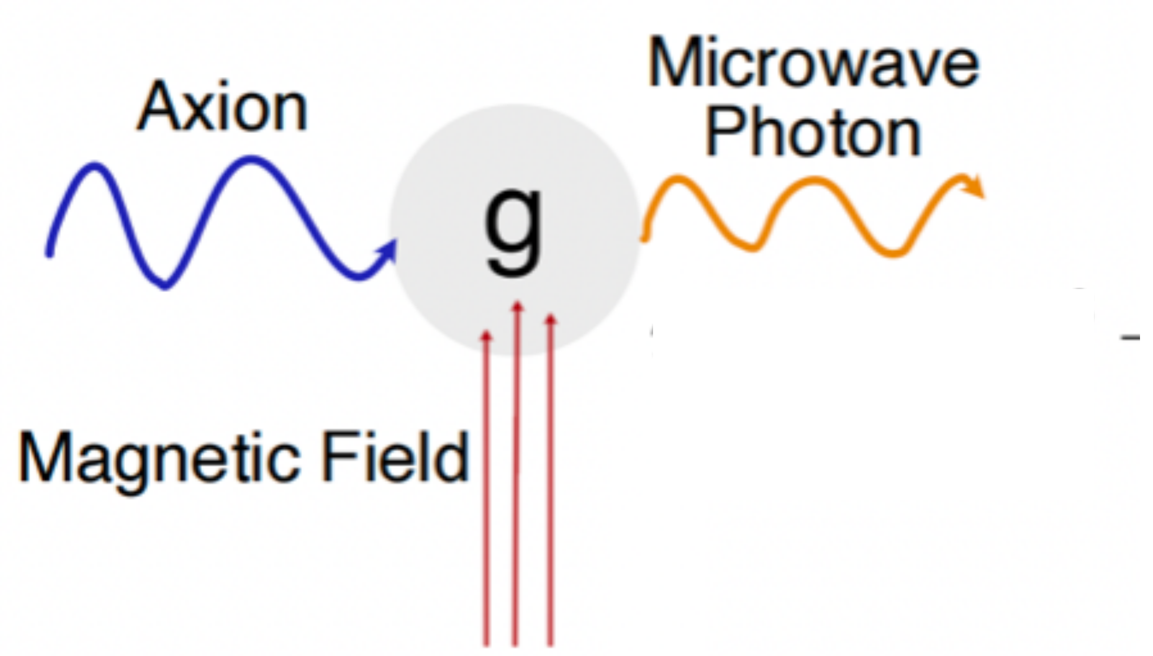
- Dark photon

$$\mathscr{L}_{A'} \supset \epsilon m_{A'}^2 A'^{\mu} A_\mu \quad \rightarrow \quad J^{A'\mu}_{\text{eff}} = \epsilon m_{A'}^2 A'^{\mu}$$

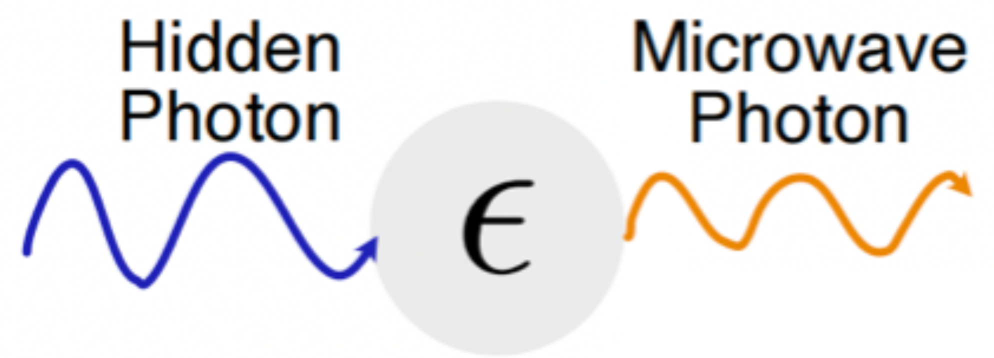
de Broglie wavelength $\lambda_d \sim \dfrac{1}{m_{DM} v_0} \sim \dfrac{10^3}{m_{DM}} \sim 100\ m$

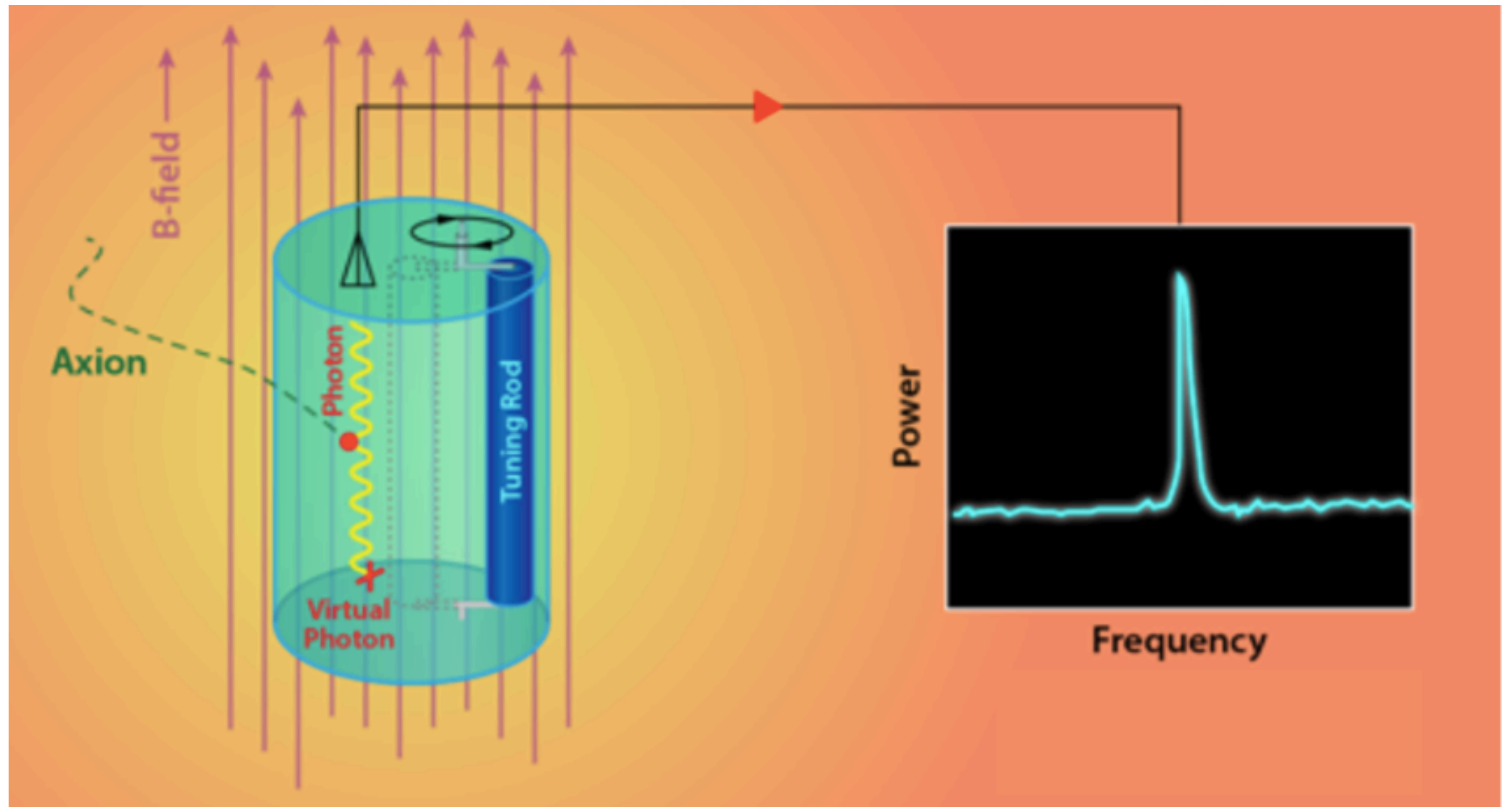
Coherence time $\tau_c \sim \dfrac{1}{m_{DM} \bar{v} v_0} \sim \dfrac{10^6}{m_{DM}} \sim 100\ \mu s$

inverse primakoff effect



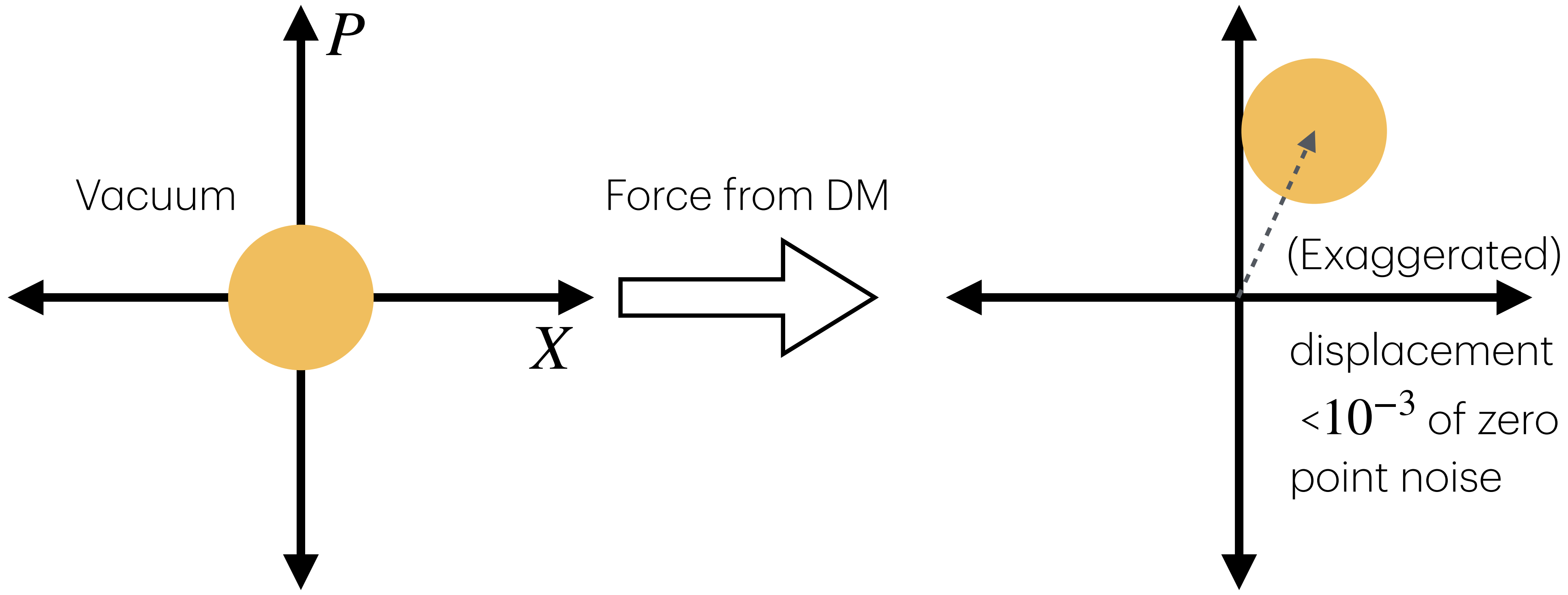
kinetic mixing





Standard quantum limit (SQL)

- Due to the limited coherence time << than the mixing period, the DM wave displaces the cavity vacuum state by an amount much smaller than the zero-point fluctuations



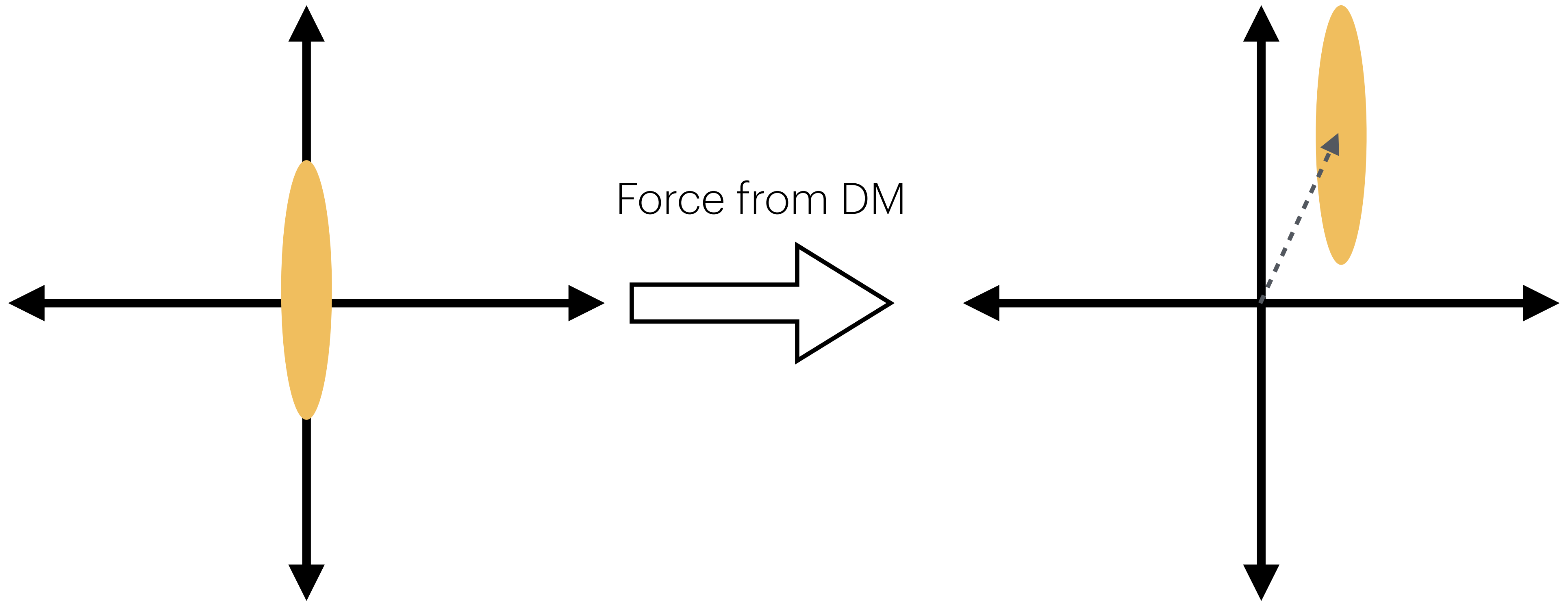
Heisenberg uncertainty principle

$$\Delta X \Delta P \geq 1/4$$

$$\bar{n}_{\mathrm{SQL}} = 1$$

Beyond the SQL

- Squeezing: reduce uncertainty in one quadrature

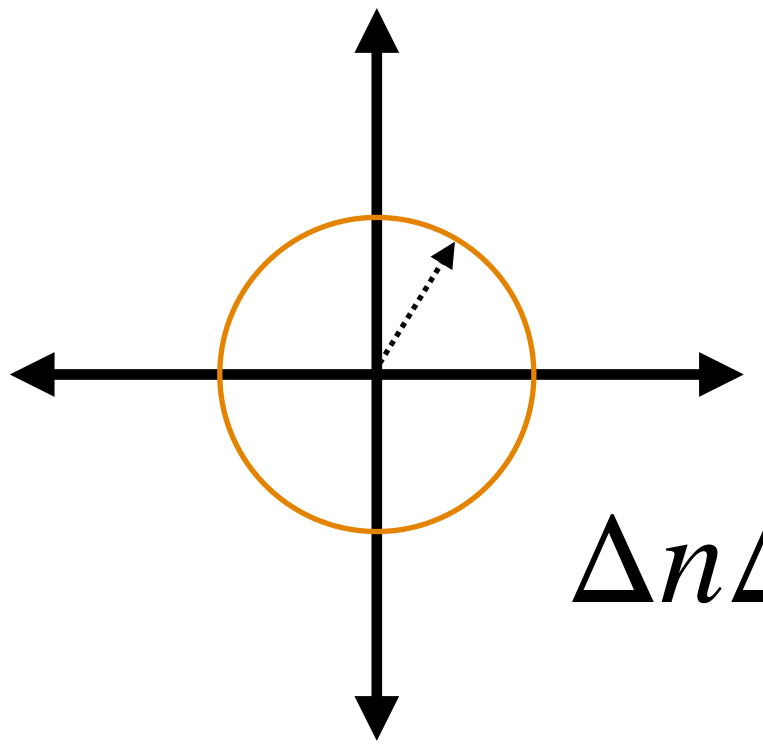


Backes et al. Nature 590.7845 (2021): 238-242

- Single Photon Counter:

  measure only displacement amplitude

  disregard phase (since it is randomized)



$$\Delta n \Delta \phi \geq 1$$

A. Dixit et al. PRL 126.14 (2021): 141302

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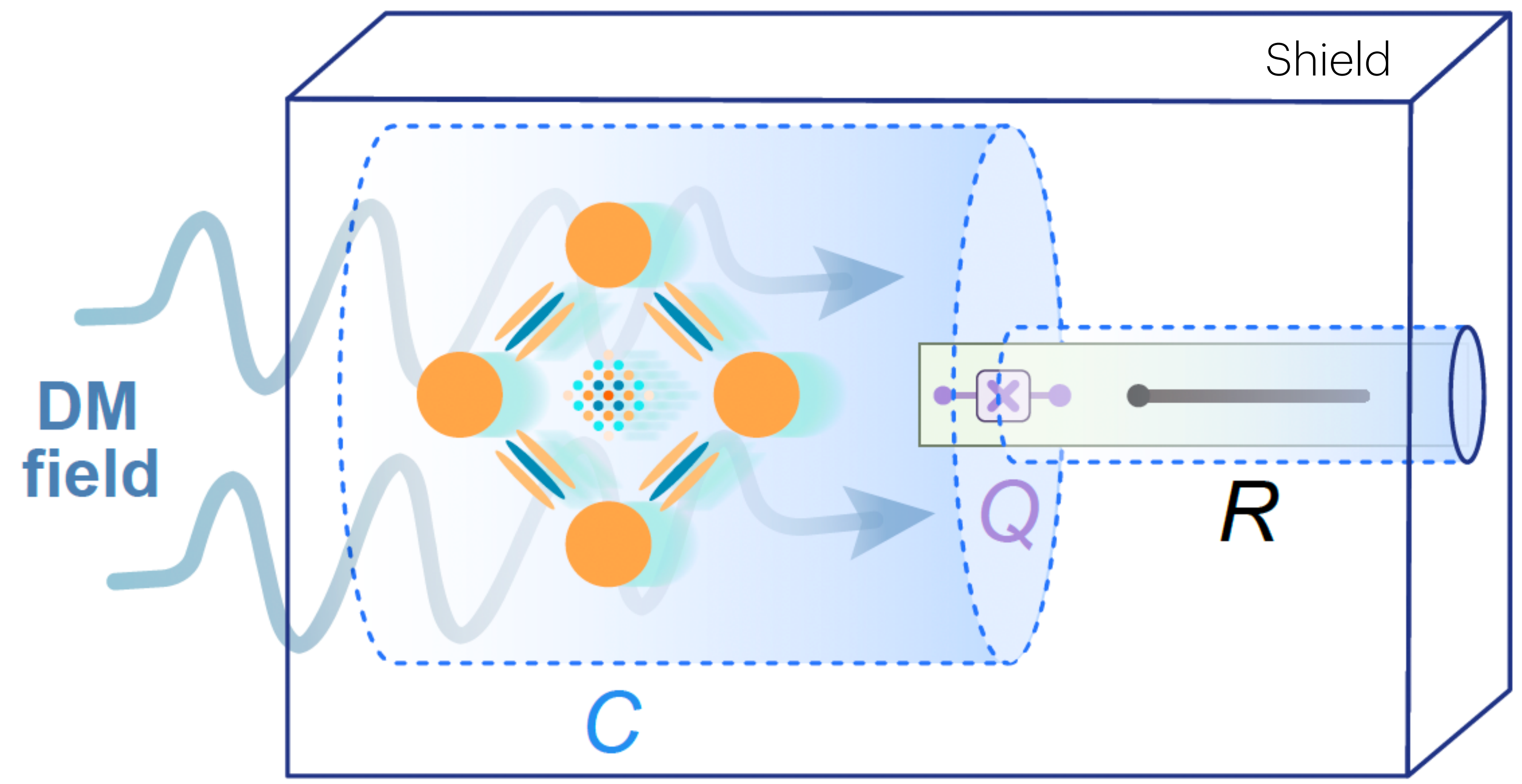
Photon counting device

P. Zheng, Y. Cai, **BX** et al., arXiv:2507.23538



- DM act as a displacement operator:

$$e^{-iH_{DM}t} \equiv \hat{D}(\beta) = e^{\beta a^\dagger - \beta^* a}, \text{ where } |\beta| = \sqrt{\rho_{DM} m_{DM} V_{eff}} \epsilon \tau$$

- Cavity QED:

$$H_{CQ} = \underbrace{\omega_c a^\dagger a}_{\text{linear cavity}} + \underbrace{\frac{1}{2}\omega_q \sigma_z}_{\text{two-level “atom”}} + \underbrace{\chi a^\dagger a \sigma_z}_{\text{dispersive coupling}} = \omega_c a^\dagger a + \underbrace{\left(\frac{1}{2}\omega_q + \chi a^\dagger a\right)}_{\text{photon number-dependent frequency}} \sigma_z$$

where $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$

- quantum non demolition readout

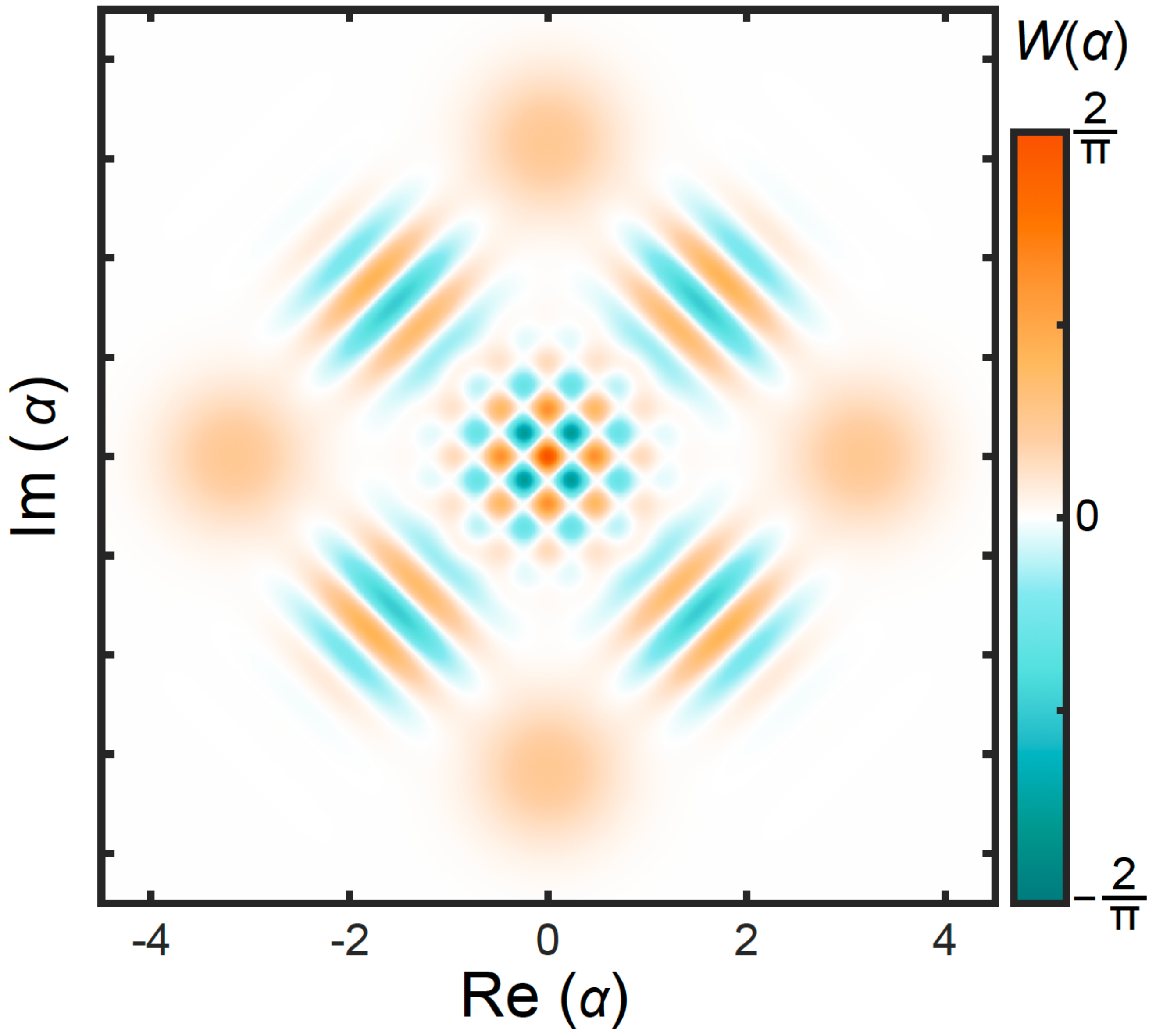
- Sensitivity limited by $\bar{n}_{th} \approx 10^{-3} \sim T_{eff} = 20$ mK

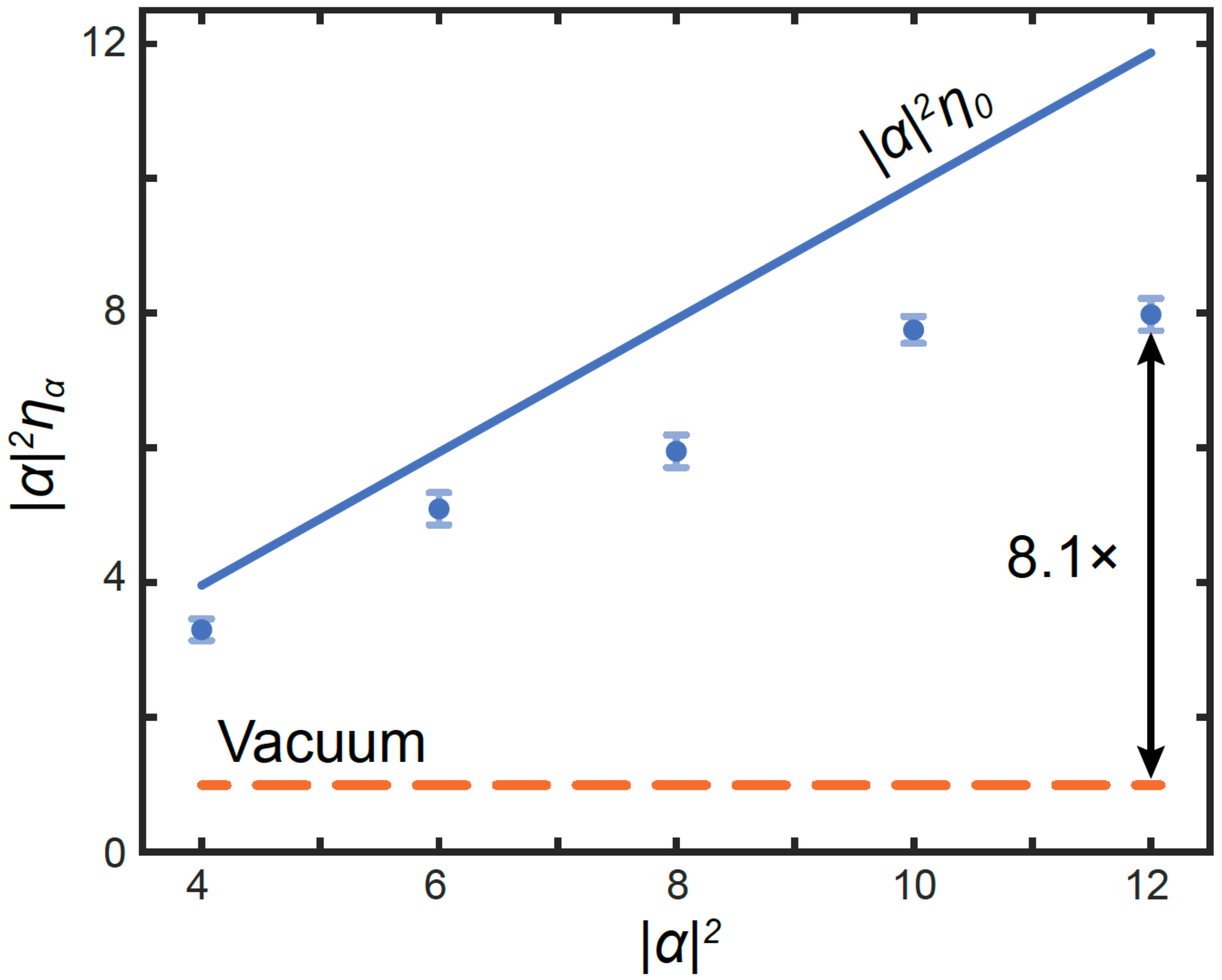
Enhancement by stimulated emission

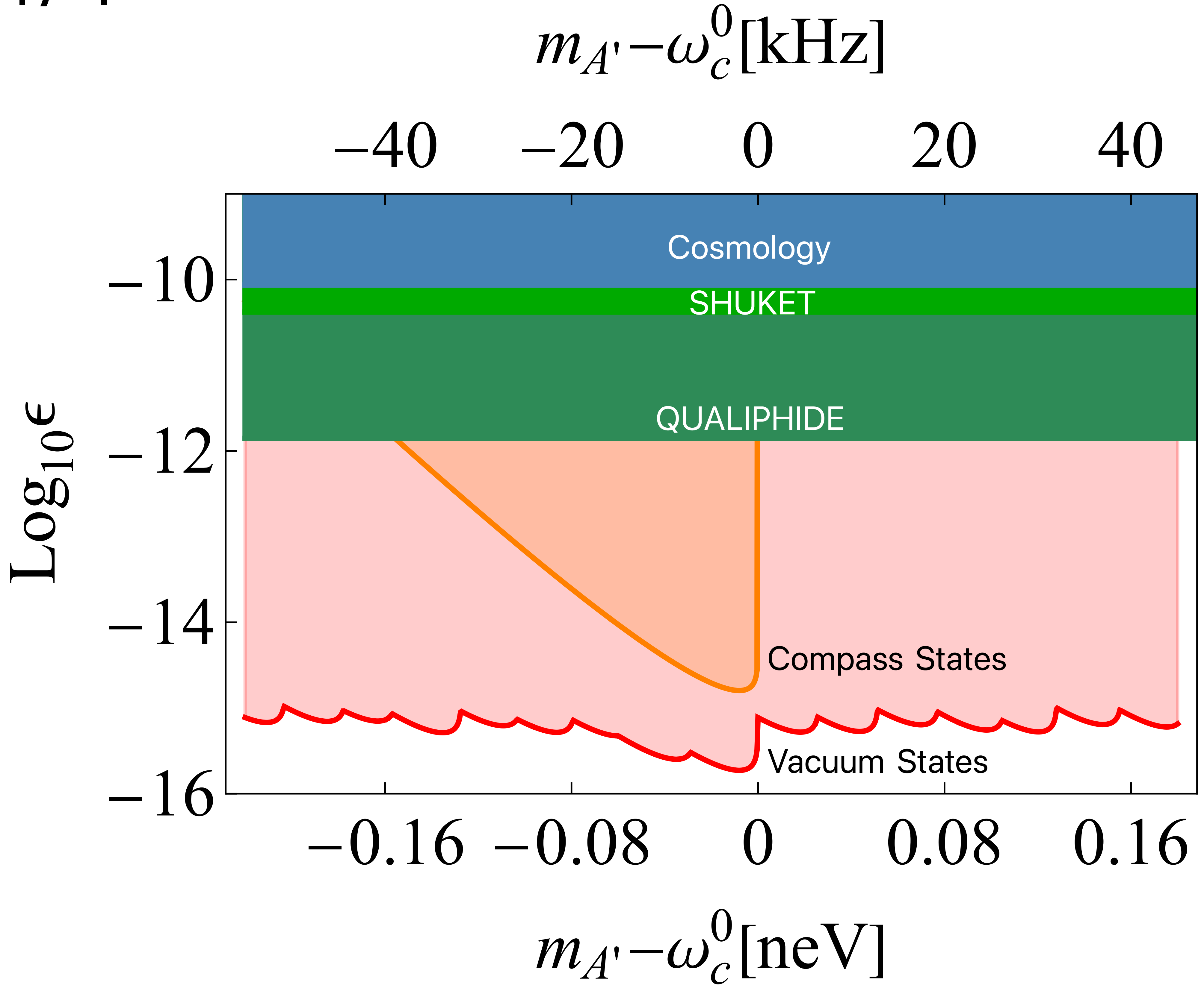
For vacuum initial state: $\left|\langle 1|\hat{D}(\beta)|0\rangle\right|^2 \approx |\beta|^2$

For Schrödinger's cat states: $\left|\langle \phi_1|\hat{D}(\beta)|\phi_0\rangle\right|^2 \approx |\alpha|^2|\beta|^2$

We obtain an 8.1-fold speed up for $|\alpha|^2 = 12, \eta = 0.68$







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Quantum Coherence measurement

Coherent excitation due to DM, but noise uncorrected

Measuring the coherence between $|W\rangle = (|e_1g_2\rangle + |g_1e_2\rangle)/\sqrt{2}$

$$\rho_0 = |g_1g_2\rangle\langle g_1g_2| \to \bar{\rho}_\eta = \begin{array}{cc} \begin{array}{cccc} \langle e_1e_2| & \langle g_1e_2| & \langle e_1g_2| & \langle g_1g_2| \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & p_2+n_2 & C_{12} & 0 \\ 0 & C_{12}^* & p_1+n_1 & 0 \\ 0 & 0 & 0 & 1-p_1-p_2-n_1-n_2 \end{pmatrix} & \begin{array}{c} |e_1e_2\rangle \\ |g_1e_2\rangle \\ |e_1g_2\rangle \\ |g_1g_2\rangle \end{array} \end{array}$$

Projecting to $\Pi_{12} = |e_1g_2\rangle\langle g_1e_2| + |g_1e_2\rangle\langle e_1g_2|$:

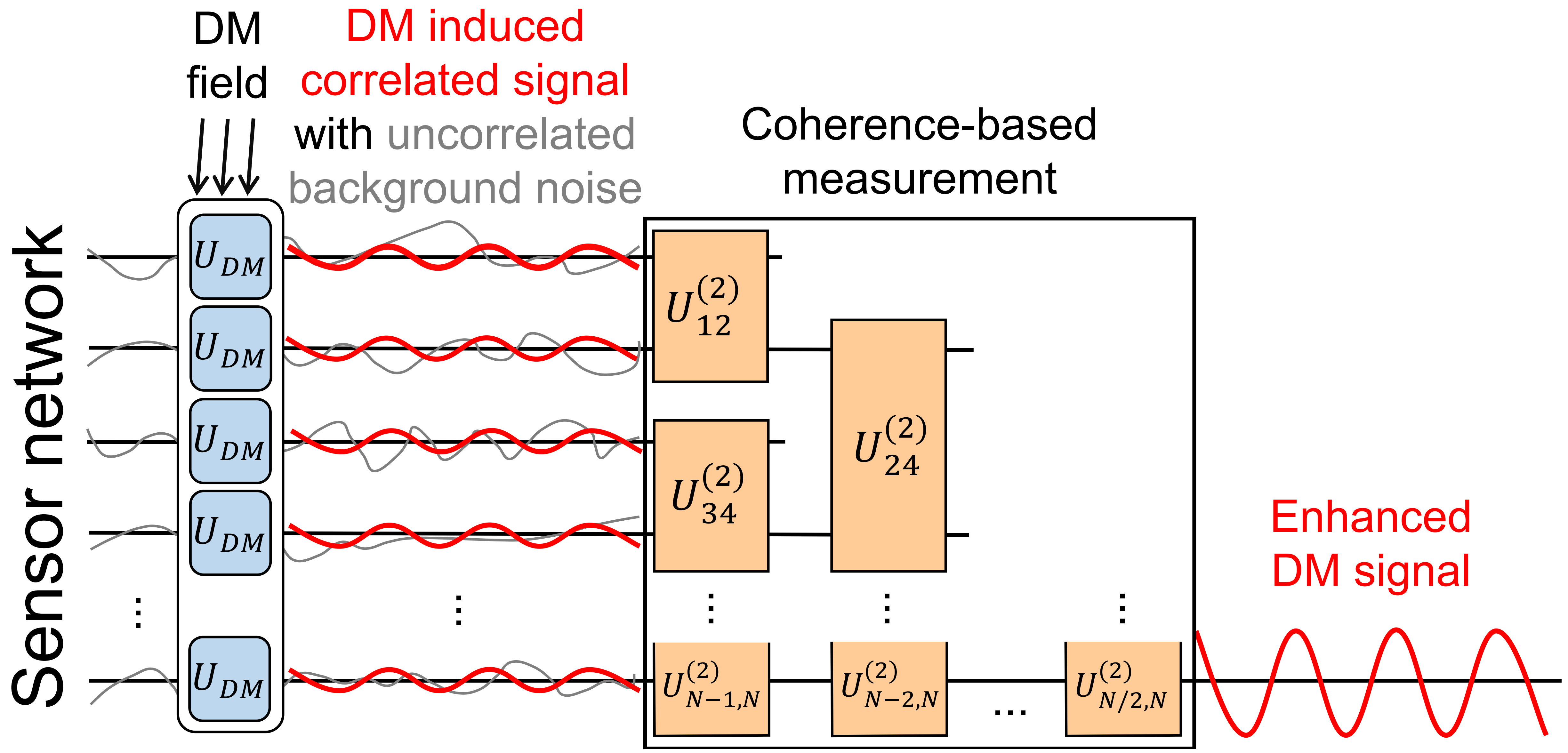
$$Tr[\rho_\tau \Pi_{12}] = 2Re[C_{12}(\tau, \vec{x}_{12})] \propto \langle \phi(\vec{x}_1)\phi(\vec{x}_2)\rangle$$

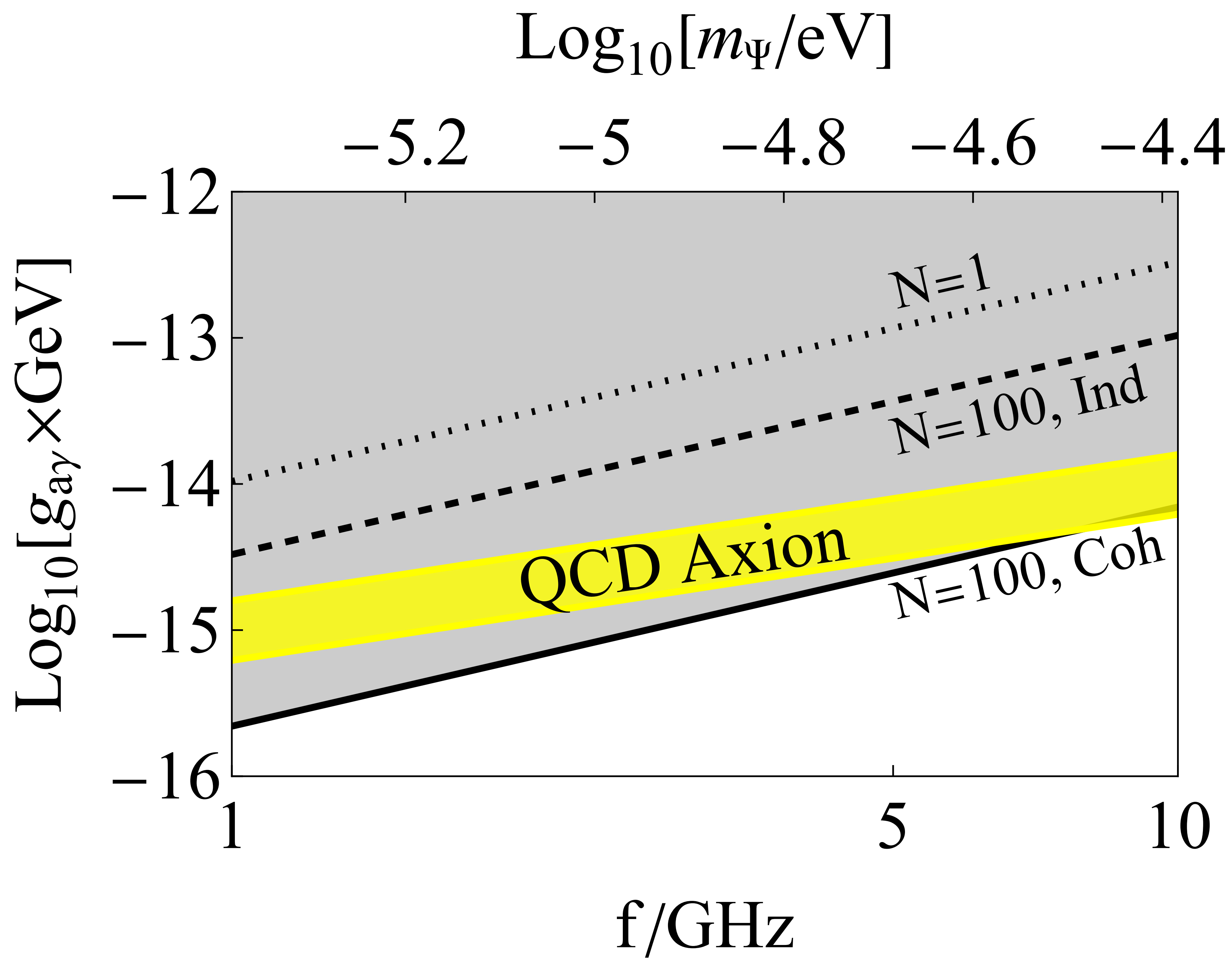
Noise free with full correlation information included!

Quantum Coherence measurement

For N quantum sensors, there are $O(N^2)$ coherence channels: signal N^2 enhanced

Use of the W state: $|W\rangle = \frac{1}{\sqrt{N}}(|e_1g_2\ldots g_N\rangle + |g_1e_2\ldots g_N\rangle + \ldots + |g_1g_2\ldots e_N\rangle)$





J. Shu, **BX**, and Y. Xu, arXiv:2410.22413

Conclusion

- Detection of dark matter benefit from quantum technologies.
- Surpass SQL via single-photon detection.
- Enhance scan rate using non-classical (cat) states.
- Suppress incoherent noise via entangled (W) states.
- Outlook: probing the quantum nature of DM and GWs.

Thank you!