Distributed quantum sensing for ultralight dark matter

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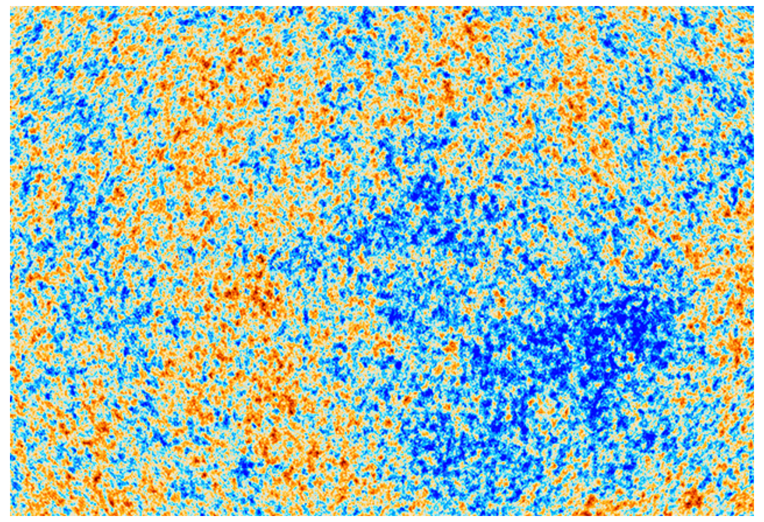
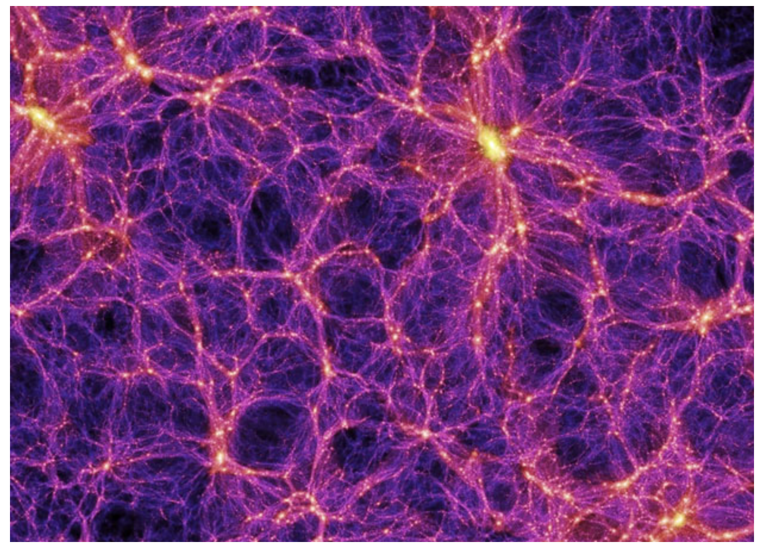
- Introduction
- Eliminating Incoherent Noise
- Quantum Metrology for Dark Matter
- Conclusion

What is dark matter?

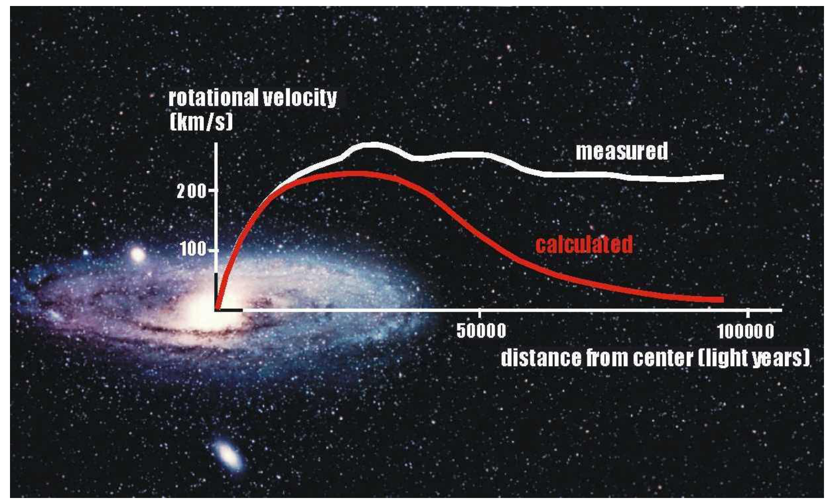
CMB



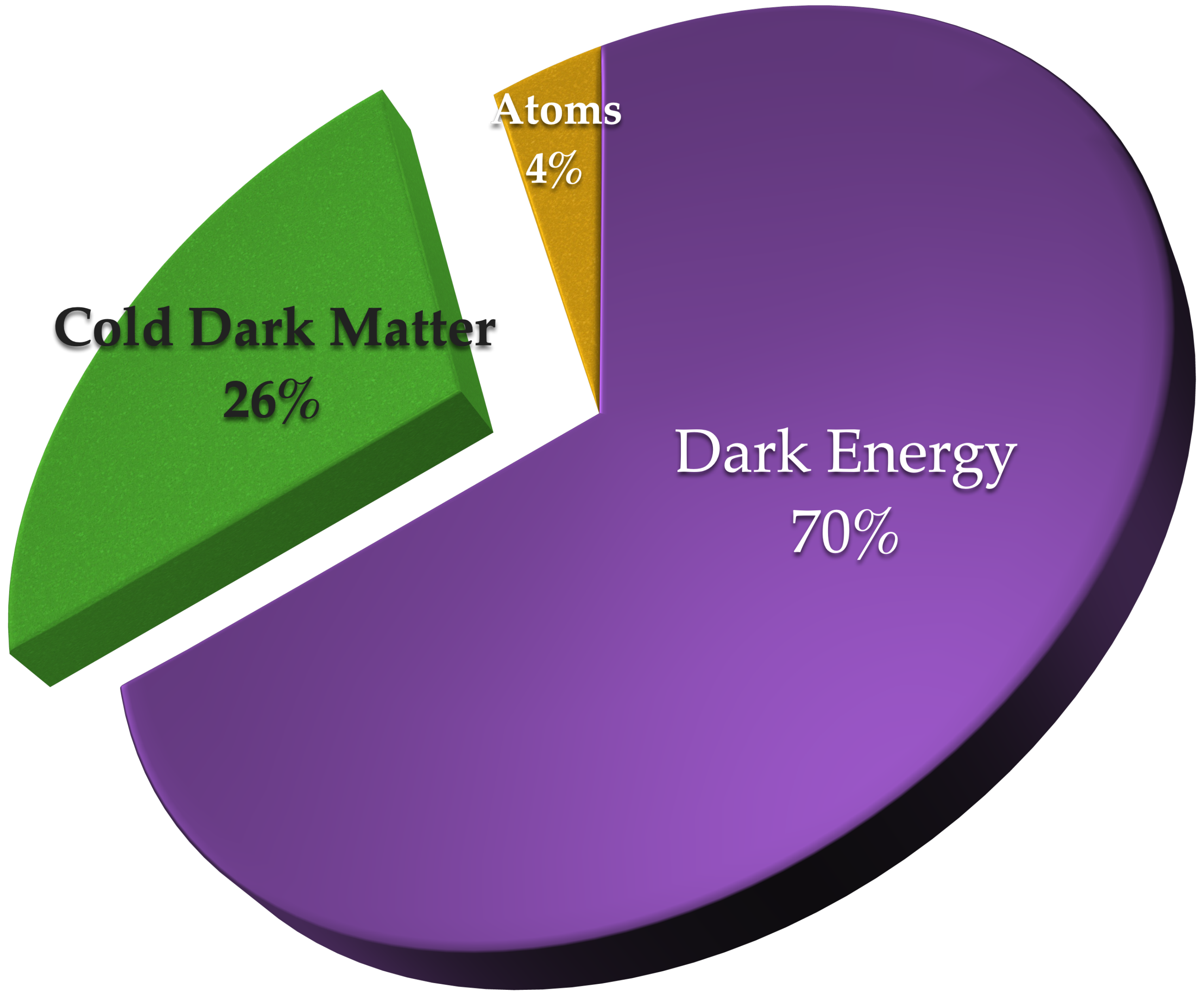
LSS

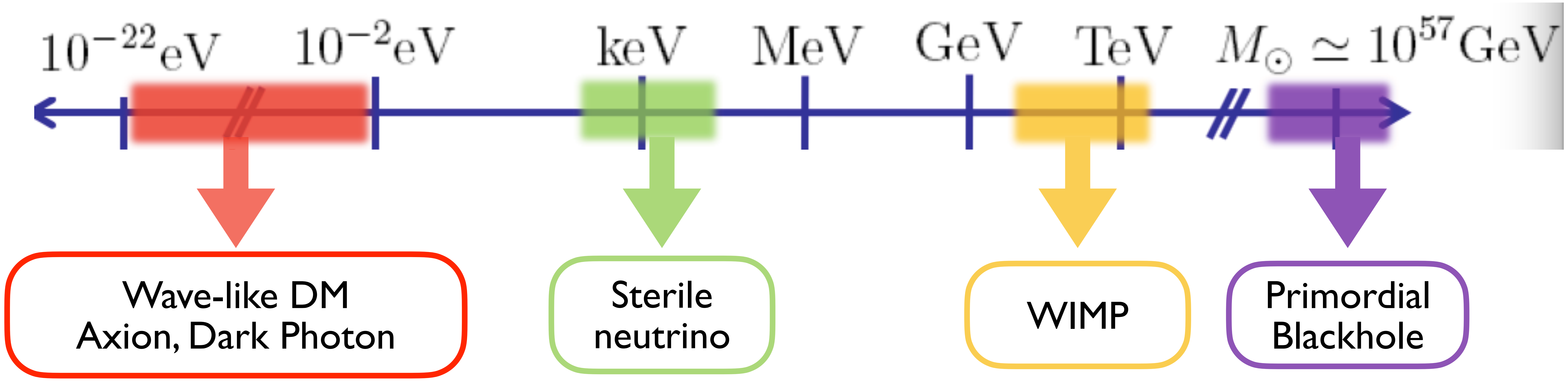


Bullet cluster



rotation curve



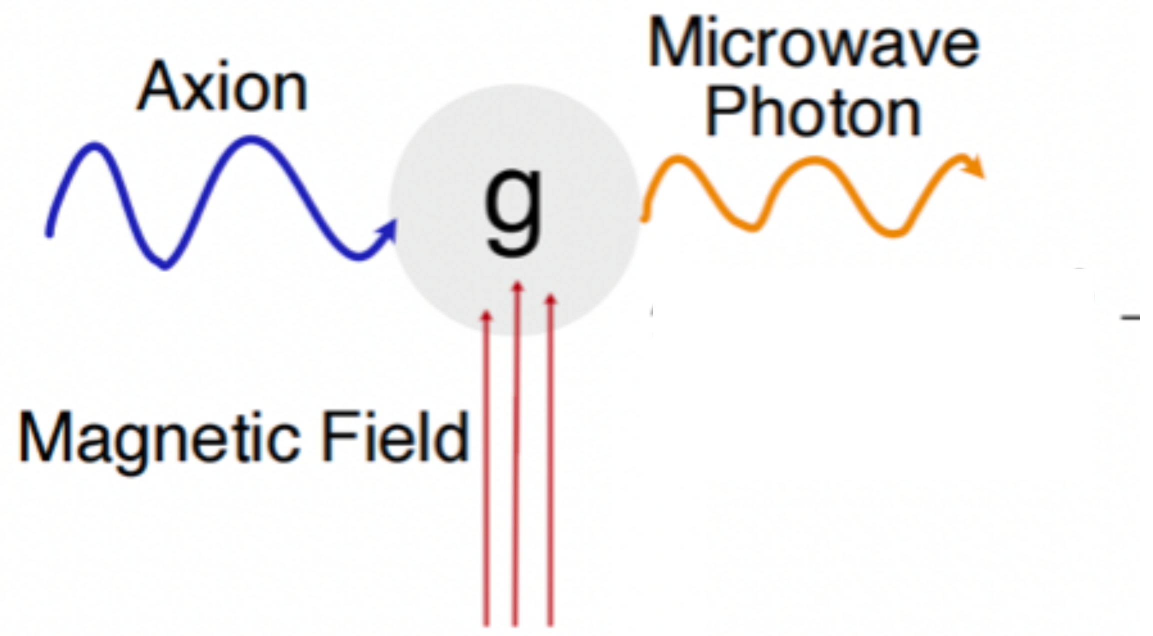


Wave-like DM candidates

- Axion (ALPs)

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

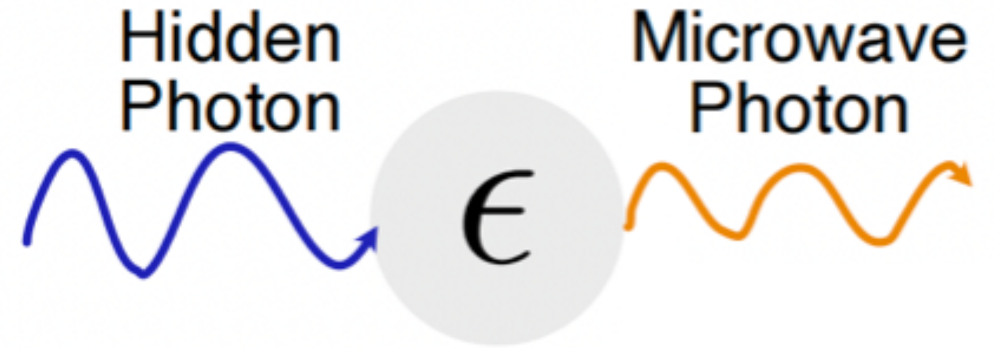
inverse primakoff effect



- Dark photon

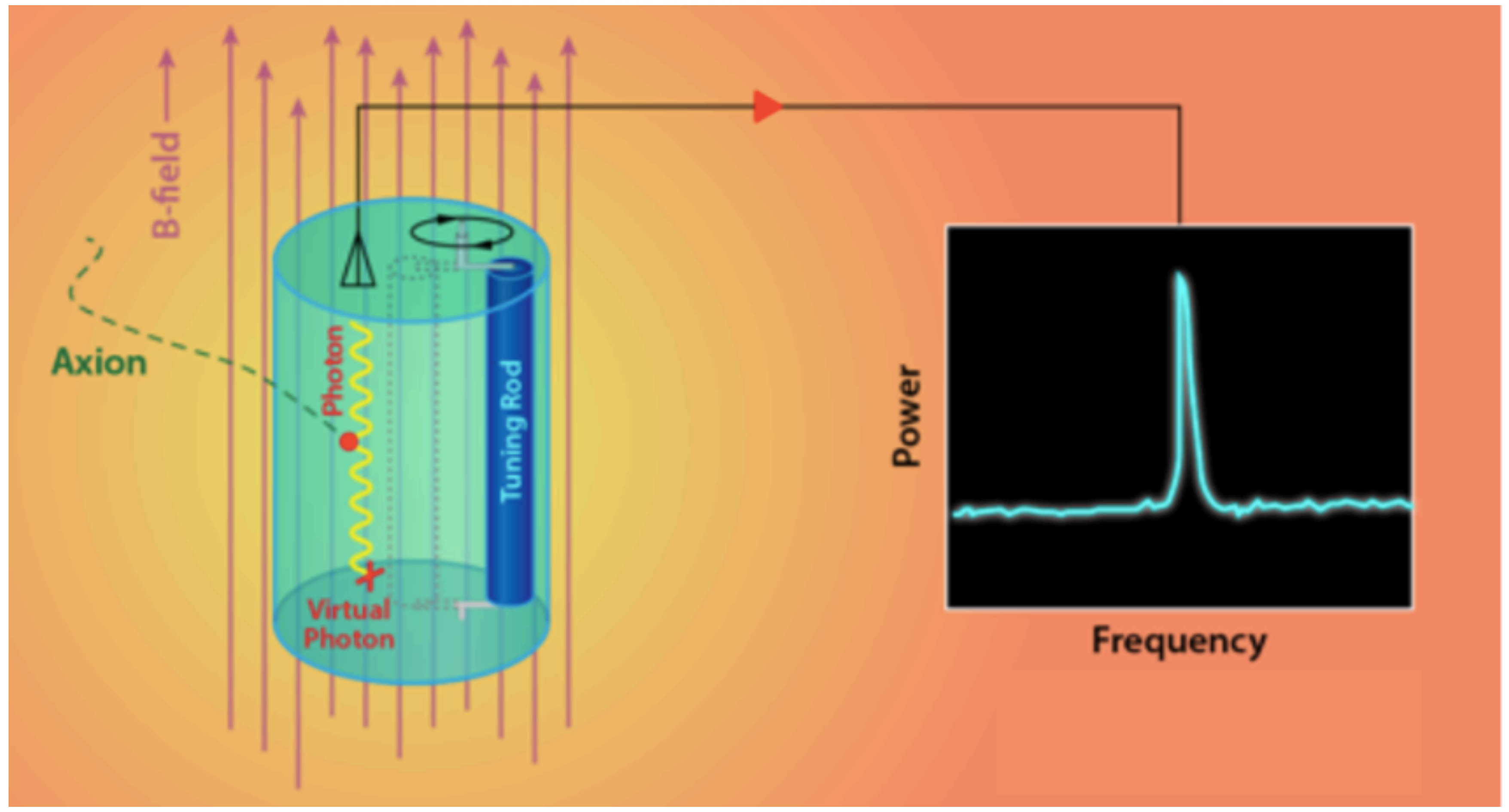
$$\mathscr{L}_{A'} \supset \epsilon m_{A'}^2 A'^{\mu} A_\mu \quad \rightarrow \quad J^{A'\,\mu}_{\text{eff}} = \epsilon m_{A'}^2 A'^{\mu}$$

kinetic mixing



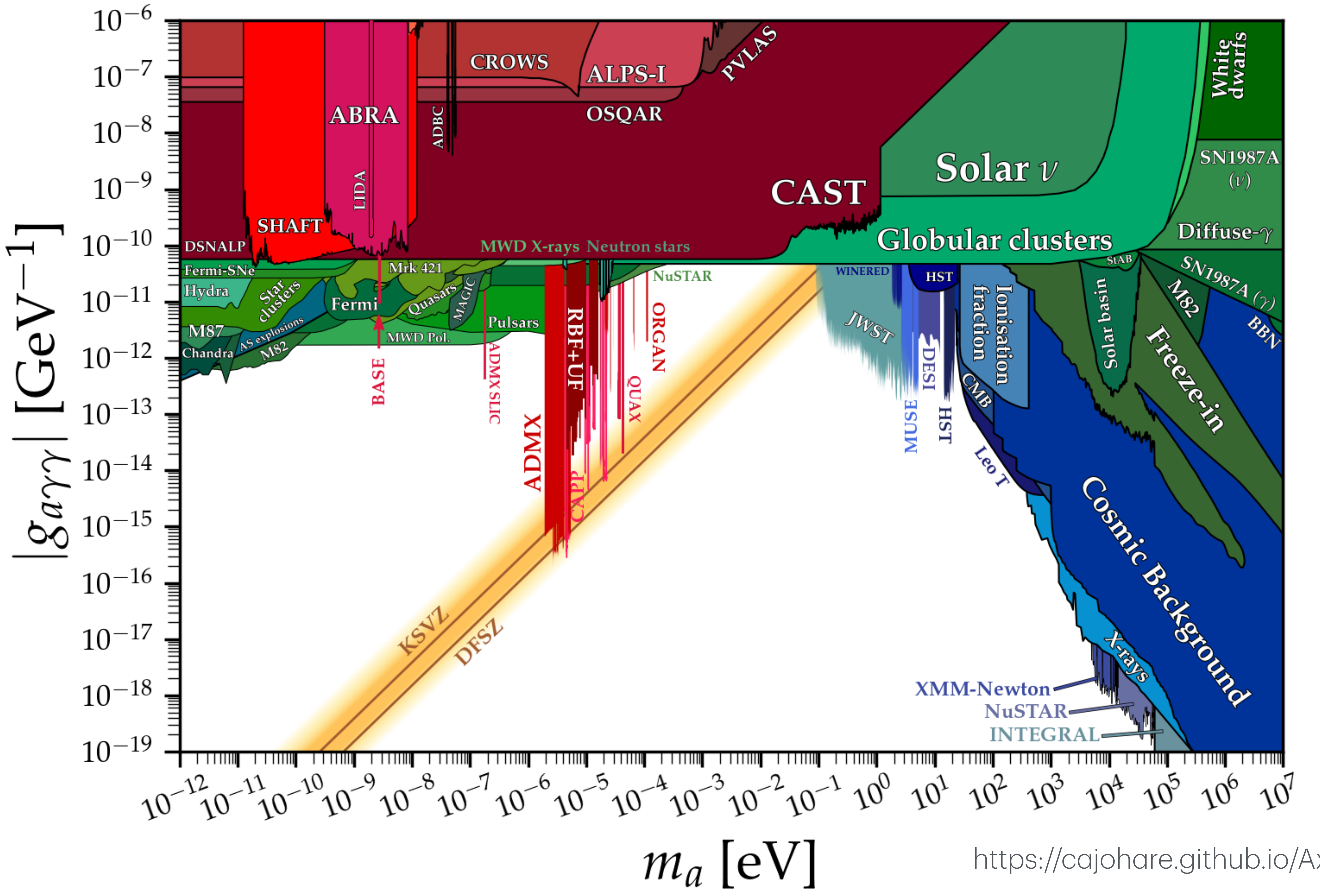
de Broglie wavelength $\lambda_d \sim \dfrac{1}{m_{DM} v_0} \sim \dfrac{10^3}{m_{DM}} \sim 100\ m$

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



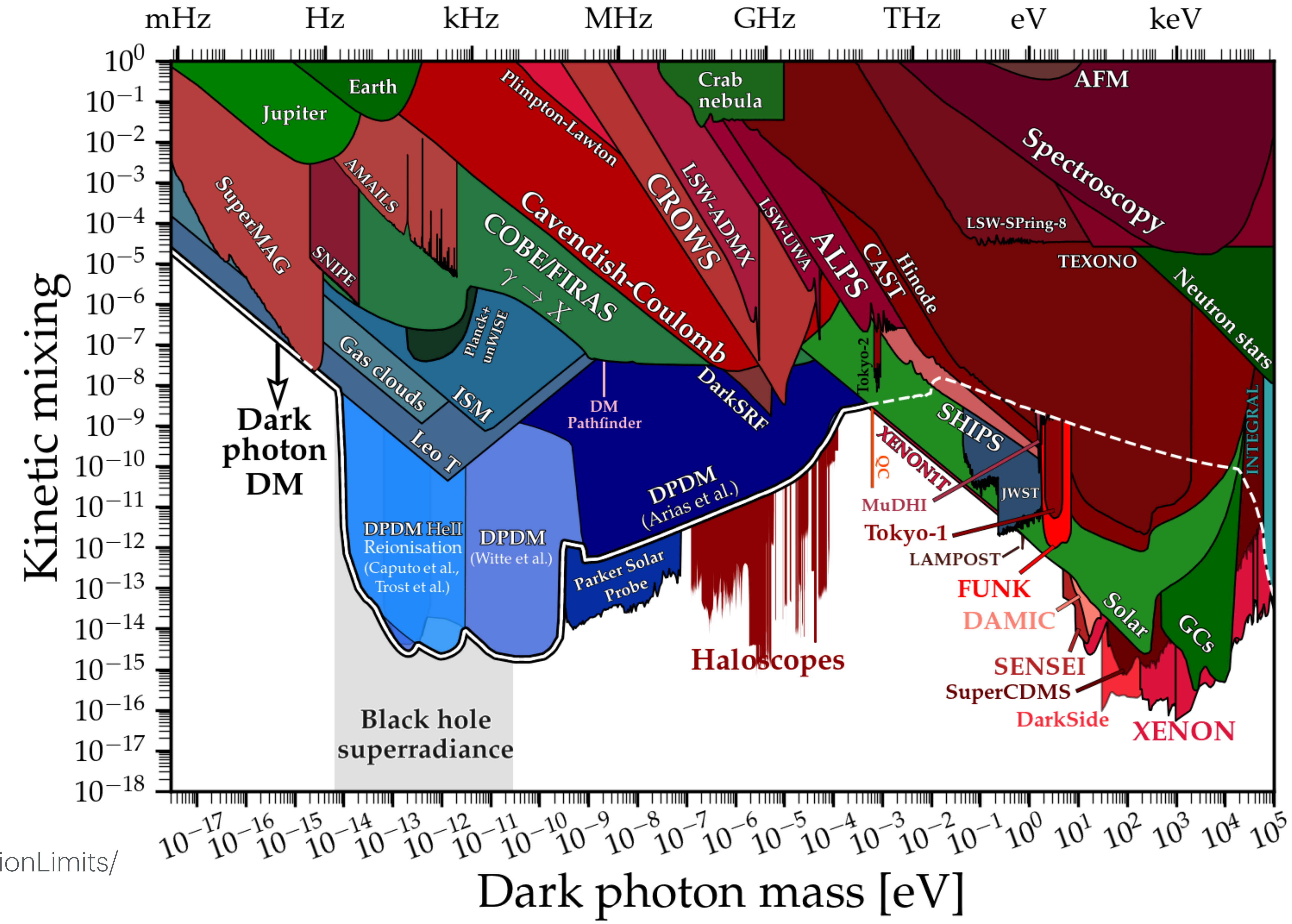
Current limits

Axion



https://cajohare.github.io/AxionLimits/

Dark Photon



With such large parameter space, scan rate is crucial!

What is a quantum sensor?

Quantum 1.0

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

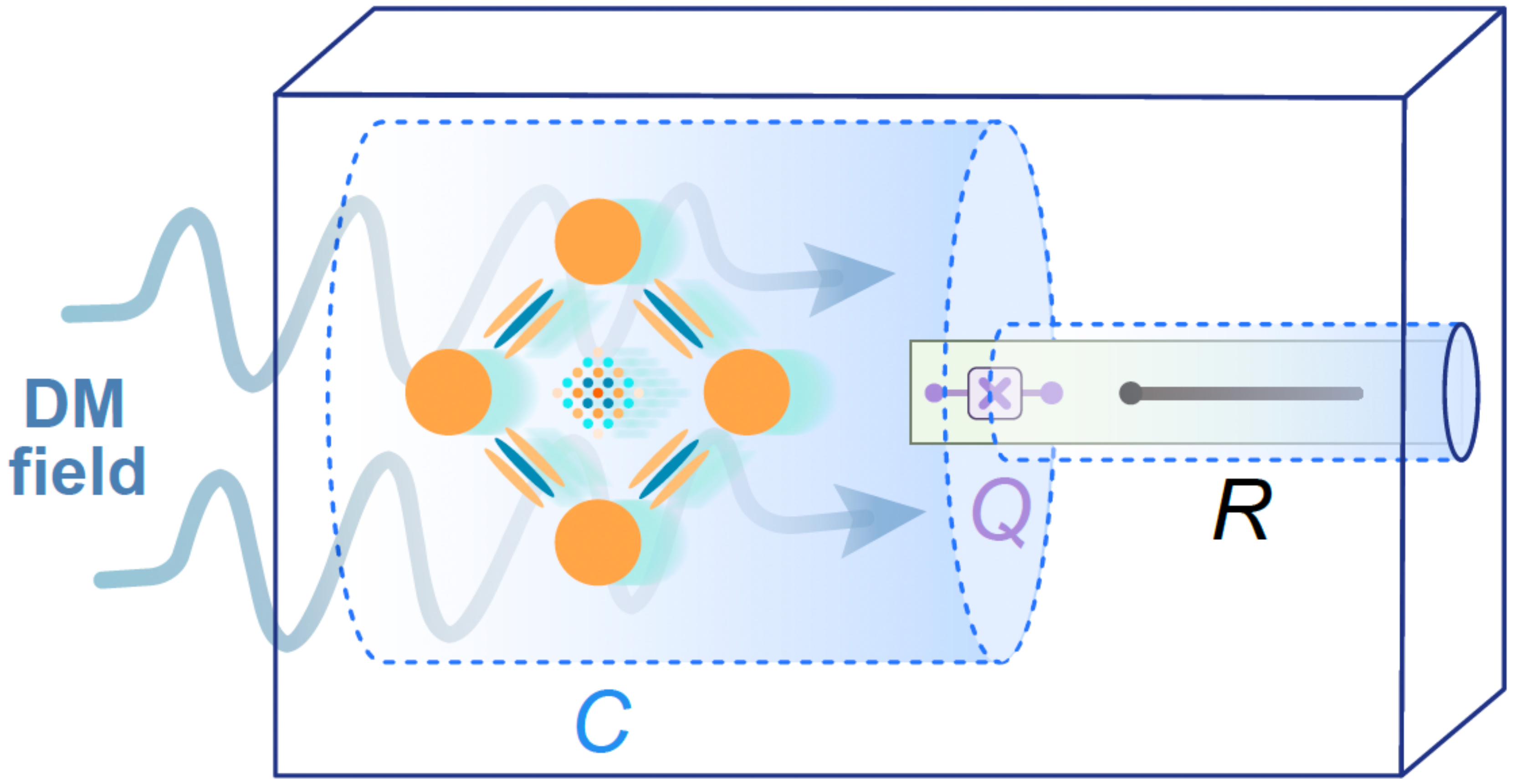
Quantum 2.0

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

  for better sensitivity or noise performance

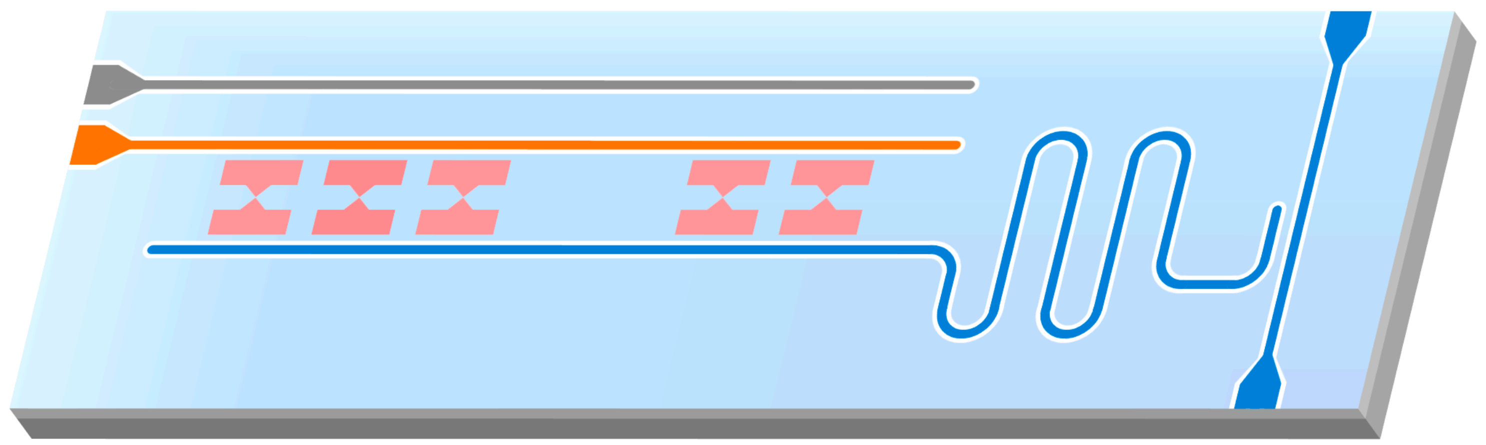
Quantum Sensor

- Detector: two-level system $\{|g_I\rangle, |e_I\rangle\}$, $H_0 = \frac{1}{2}\omega_I \sigma_z^I$
- Coupling to DM: $H_I = \eta \cos(\omega_{DM} t + \phi_{DM}) \hat{\sigma}_I^x = \eta e^{-i[(\omega_{DM}-\omega_I)t+\phi_{DM}]} \hat{\sigma}_I^+ + \text{h.c.}$
- Excitation probability: $p_I = |\langle e_I | \mathcal{T} e^{-iH\tau} | g_I \rangle|^2 \propto (\eta\tau)^2$



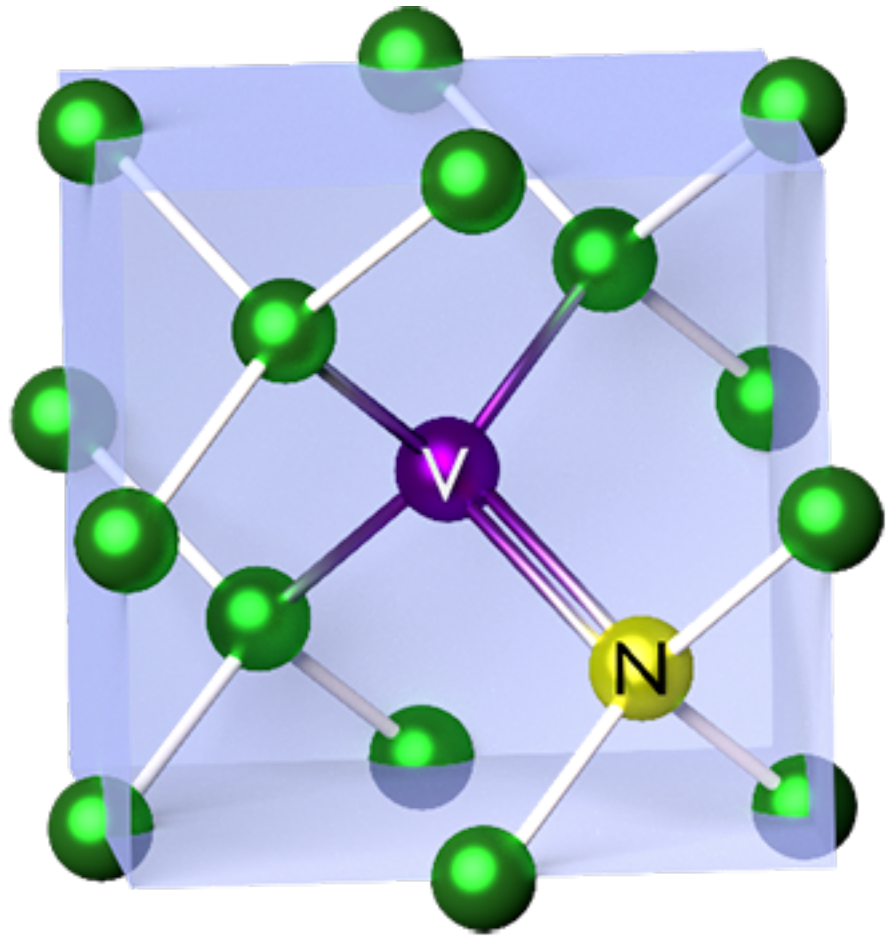
Superconducting Cavity

A. Dixit et al. PRL 126.14 (2021): 141302
A. Agrawal et al. PRL 132.14 (2024): 140801
P. Zheng, Y. Cai, **BX** et al., arXiv:2507.23538



Transmon qubits

S. Chen, et al. Physical Review Letters 131.21 (2023): 211001
S. Chen, et al. Physical Review Letters 133.2 (2024): 021801
S. Chen, et al. Physical Review D 110.11 (2024): 115021
R. Kang, et al. Phys.Rev.Lett. 135 (2025) 18, 181004



NV centers

S. Chigusa et al. JHEP 03 (2025) 083
S. Chigusa et al. *Phys.Rev.D* 111 (2025) 7, 075028

Quantum Coherence measurement

Coherent excitation due to DM, but noise uncorrected

Measuring the coherence between $|W\rangle = (|e_1 g_2\rangle + |g_1 e_2\rangle)/\sqrt{2}$

$$\rho_0 = |g_1 g_2\rangle\langle g_1 g_2| \to \bar{\rho}_\eta = \begin{array}{cc} \begin{array}{cccc} \langle e_1 e_2| & \langle g_1 e_2| & \langle e_1 g_2| & \langle g_1 g_2| \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & p_2 + n_2 & C_{12} & 0 \\ 0 & C_{12}^* & p_1 + n_1 & 0 \\ 0 & 0 & 0 & 1 - p_1 - p_2 - n_1 - n_2 \end{pmatrix} & \begin{array}{c} |e_1 e_2\rangle \\ |g_1 e_2\rangle \\ |e_1 g_2\rangle \\ |g_1 g_2\rangle \end{array} \end{array}$$

Projecting to $\Pi_{12} = |e_1 g_2\rangle\langle g_1 e_2| + |g_1 e_2\rangle\langle e_1 g_2|$:

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

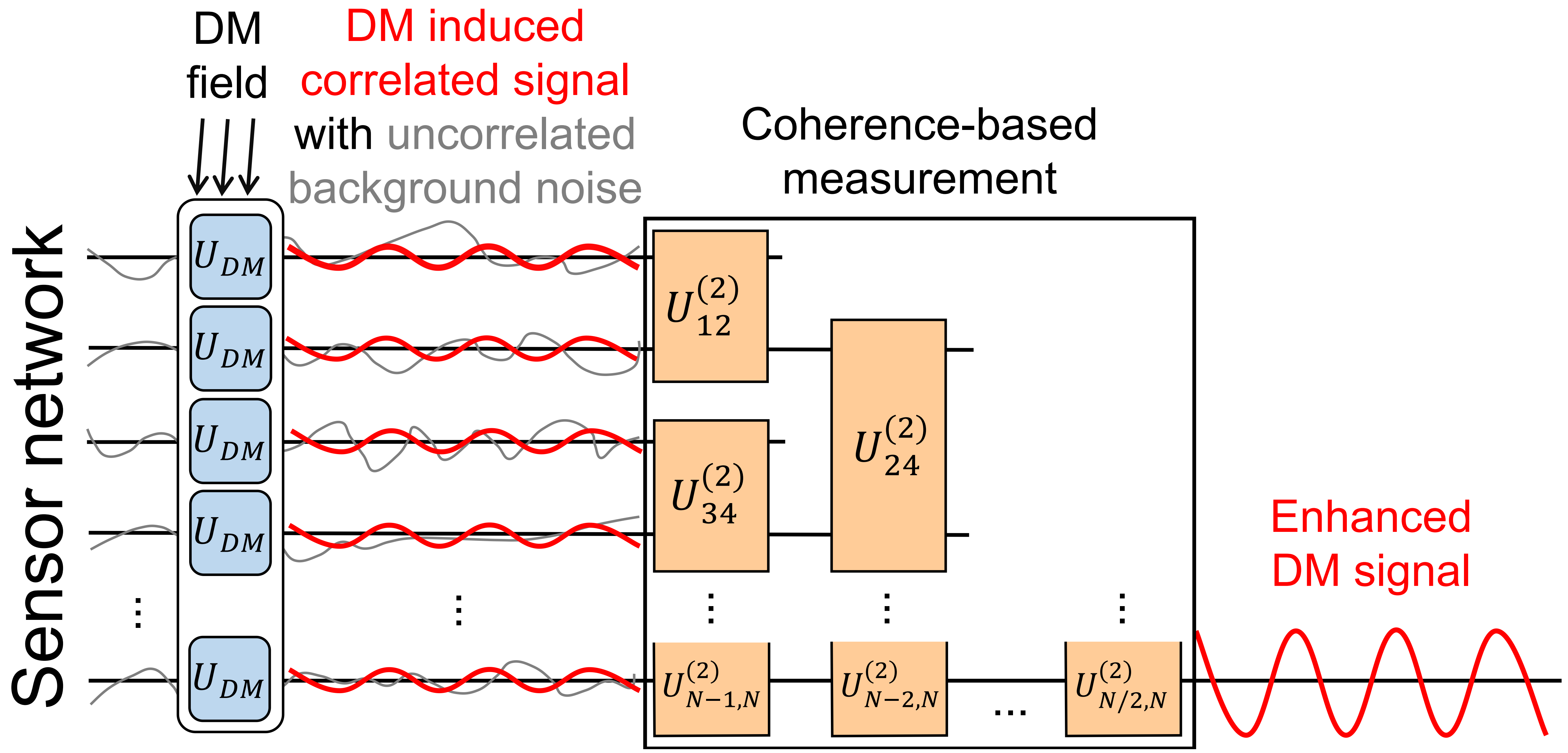
J. Shu, **BX**, and Y. Xu, arXiv:2410.22413
H. Fukuda et al, arXiv:2506.19614
S. Chen et al, arXiv: 2510.01816

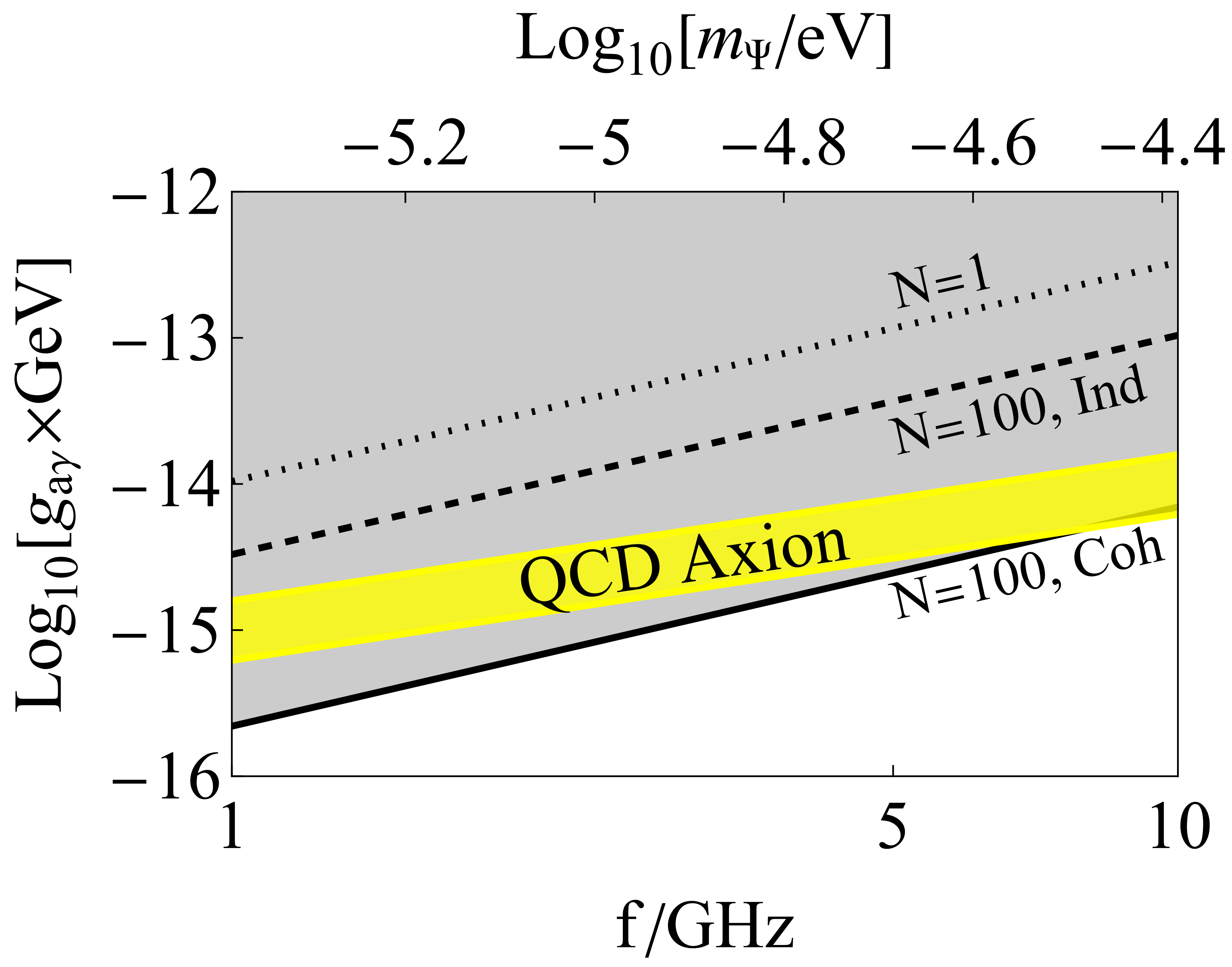
Noise free with full correlation information included!

Quantum Coherence measurement

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

Use of the W state: $|W\rangle = \frac{1}{\sqrt{N}}(|e_1 g_2 \ldots g_N\rangle + |g_1 e_2 \ldots g_N\rangle + \ldots + |g_1 g_2 \ldots e_N\rangle)$





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

Enhancement from entanglement

Single detector:

$$|g_I\rangle = \frac{|+_I\rangle + |-_I\rangle}{\sqrt{2}} \rightarrow \frac{e^{i\eta\tau}|+_I\rangle + e^{-i\eta\tau}|-_I\rangle}{\sqrt{2}} \sim |g_I\rangle + i\eta\tau|e_I\rangle, \quad p_I \simeq (\eta\tau)^2$$

where $H_I|\pm_I\rangle = \pm|\pm_I\rangle$, $|\pm_I\rangle = \dfrac{e^{\pm i\phi_I}|g_I\rangle + |e_I\rangle}{2}$

N detectors:

$$|\psi\rangle = \frac{|+_I\rangle^{\otimes N} + |-_I\rangle^{\otimes N}}{\sqrt{2}} \rightarrow \frac{e^{iN\eta\tau}|+_I\rangle + e^{-iN\eta\tau}|-_I\rangle}{\sqrt{2}} \sim |\psi\rangle + iN\eta\tau|\psi_\perp\rangle, \; p \simeq (N\eta\tau)^2$$

For GHZ states: $|\psi\rangle = \dfrac{|+_x\rangle^{\otimes N} + |-_x\rangle^{\otimes N}}{\sqrt{2}}$, $p \simeq \dfrac{1}{2}(N\eta\tau)^2$

S. Chen, et al. Physical Review Letters 133.2 (2024): 021801

Quantum Metrology for DM

Quantum estimation theory

Initial state preparation → Parameter encoding → POVM Measurement

ρ_0 $\quad$ $\overline{\rho_\eta} = \overline{U_I(t)\rho_0 U_I^\dagger(t)}\,.$ $\quad$ $p(X|\eta) = \mathrm{Tr}[\rho_\eta \Pi_X]$

The Cramer-Rao inequality: $n\mathrm{Var}(\eta) \geq F_C^{-1}(\eta) \geq F_Q^{-1}(\eta)$

Quantum Fisher information: $F_Q(\eta) = \mathrm{Tr}[\rho_\eta L_\eta^2]$ where $L_\eta \rho_\eta + \rho_\eta L_\eta = 2\,\partial_\eta \rho_\eta$

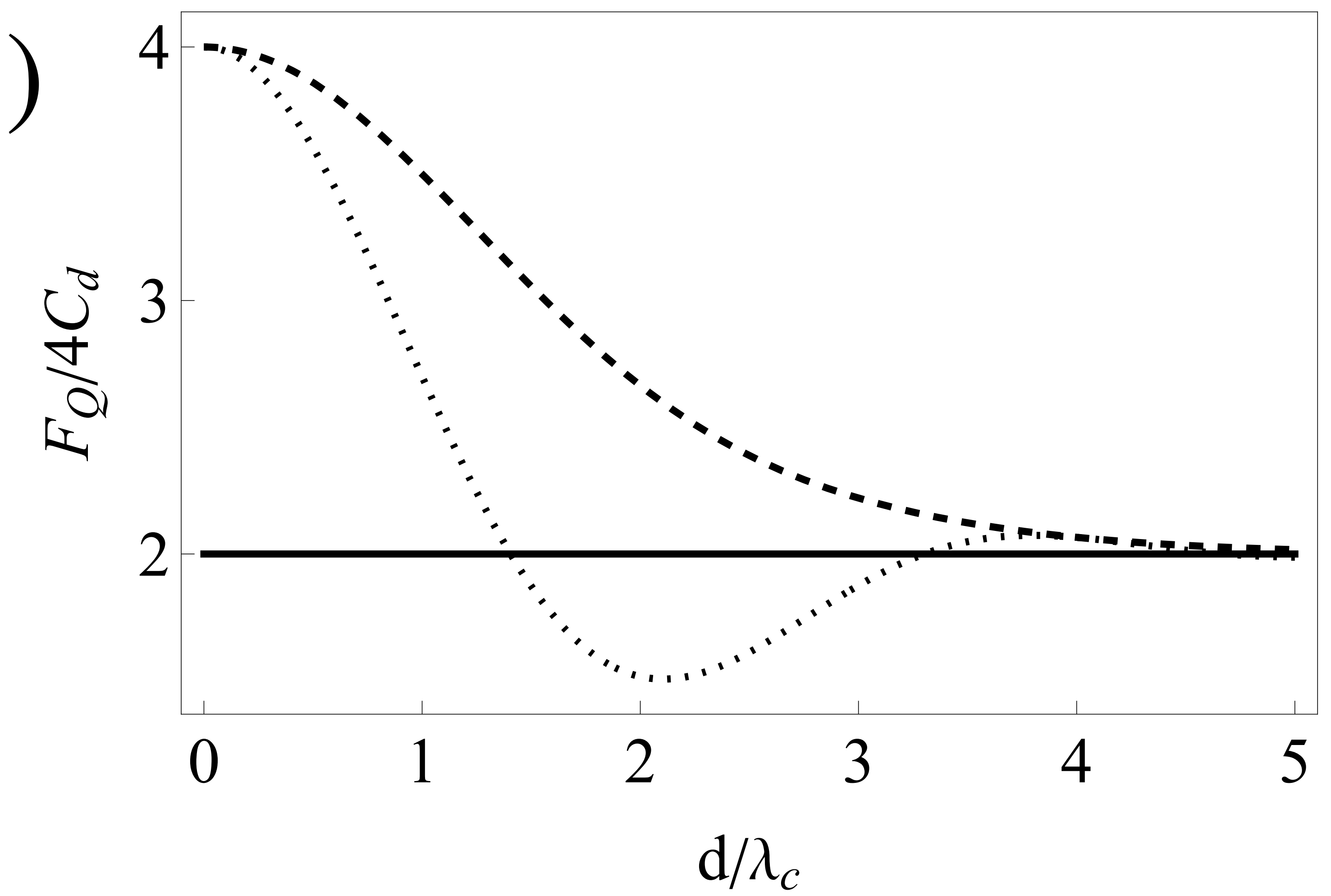
Classical Fisher information: $F_C(\eta) = \sum_X \frac{1}{p(X|\eta)} \left(\frac{\partial p(X|\eta)}{\partial \eta} \right)^2$

Quantum Metrology for DM

- For two detectors, inequalities saturated by the optimal state

$$|\psi_{\text{opt}}\rangle = \frac{1}{\sqrt{2}}\left(e^{i\phi_{12}}|e_1 g_2\rangle + |g_1 e_2\rangle\right), \text{ where } \phi_{12} = \arg(C_{12}(t, \vec{x}_{12}))$$

$$(\overline{F_Q})_{\text{max}} = 4(\underbrace{C_{11}}_{\bar{F}_{Q,1}} + \underbrace{C_{22}}_{\bar{F}_{Q,2}} + \underbrace{2|C_{12}|}_{\text{Enhancement due to entanglement}})$$



- For N identical detectors at same location, inequalities saturated by Dicke states

$$|D_j^N\rangle = \mathcal{N}\sum_{\pi}\mathscr{P}_\pi\left(|g\rangle^{\otimes(N/2+j)} \otimes |e\rangle^{\otimes(N/2-j)}\right), \text{ where } \begin{cases} j = 0 \text{ for N even} \\ j = \pm 1/2 \text{ for N odd} \end{cases}$$

$$(\overline{F_Q})_{\text{max}} = 2(N^2 + 2N - 2|j|)C$$

P. He, J. Shu, **BX**, and J. Xu, in preparation, arXiv:2512.xxxxx

Quantum Metrology for DM

Noise resilience

$F_C^{(\mathrm{Dicke})} = (1 - p_{\mathrm{AD}})^{N_d/2+m+1} N_d^2\, C_d$

$F_C^{(\mathrm{GHZ})} = \mathcal{O}(g^2),$

$F_C^{(\mathrm{ind})} = (1 - p_{\mathrm{AD}})\, 4 N_d C_d$

P. He, J. Shu, **BX**, and J. Xu, in preparation, arXiv:2510.xxxxx

Conclusion

- Detection of dark matter benefit from quantum technologies.
- **W states** can be used to eliminate incoherent noises.
- Fundamental Heisenberg limits are saturated by the **Dicke states**.
- Future direction: exploring the quantum nature of DM and GW

Thank you!

Backups

DM distribution

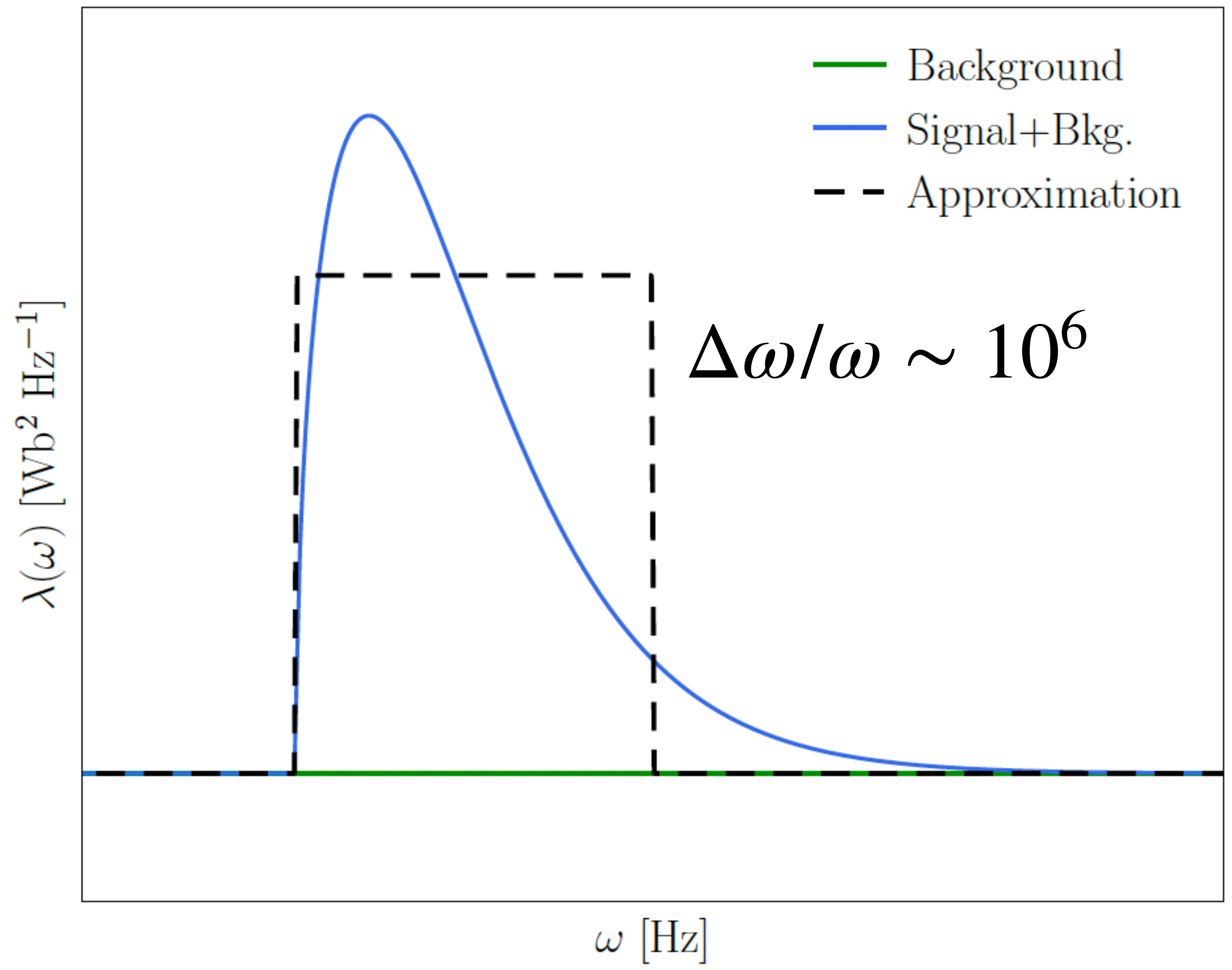
Non-relativistic limit: $\omega_j = m_{DM}(1 + v_j^2/2)$, $k_j = m_{DM} v_j$

The standard Halo model (Maxwellian distribution):

$$f_{DM}(\vec{v}) = (2\pi v_{vir}^2)^{-3/2} \exp\left[-\frac{(\vec{v}-\vec{v}_g)^2}{2v_{vir}^2}\right], \; v_{vir} \approx v_g \approx 10^{-3}$$

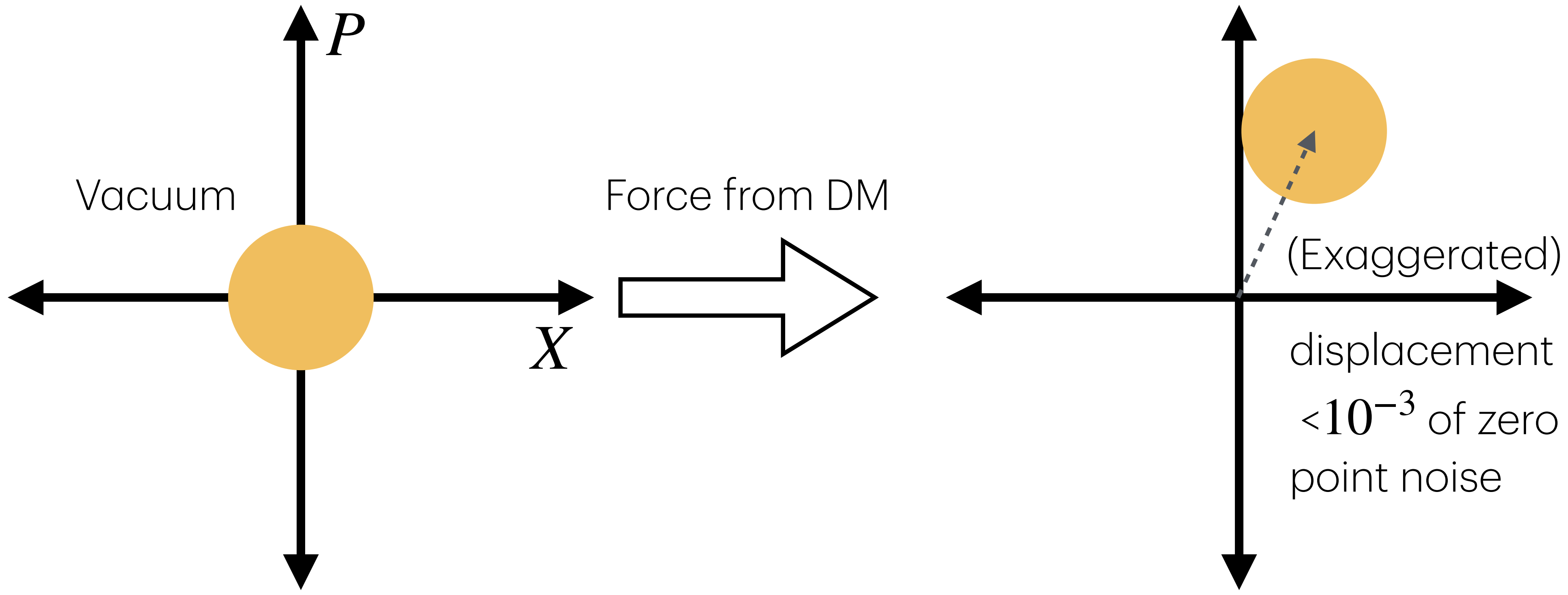
de Broglie wavelength $\lambda_d = \dfrac{1}{m_{DM} v} \approx 10^3 \dfrac{1}{m_{DM}}$

Coherence time $\tau_c \approx \dfrac{10^6}{m_{DM}}$



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



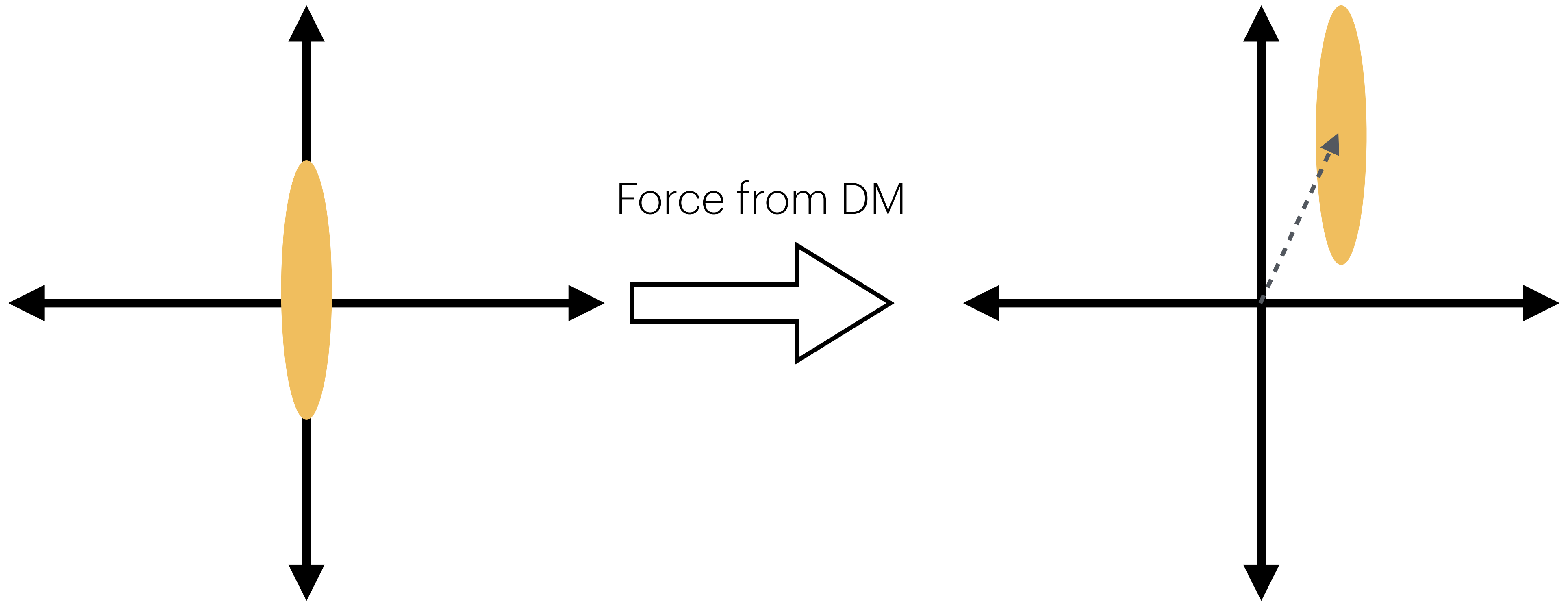
Heisenberg uncertainty principle

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

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

Beyond the SQL

- Squeezing: reduce uncertainty in one quadrature

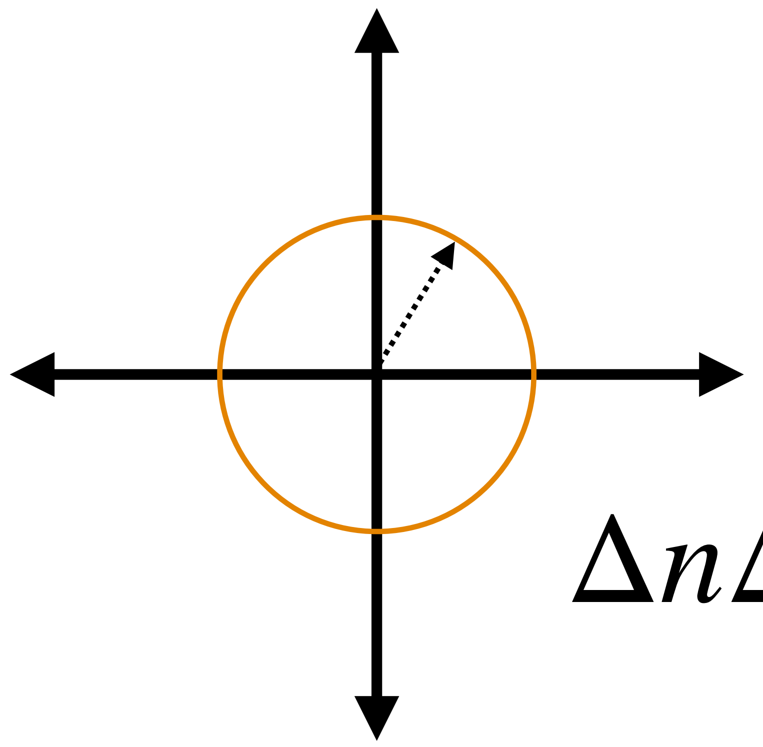


Backes et al. Nature 590.7845 (2021): 238-242

- Single Photon Counter:

  measure only displacement amplitude

  disregard phase (since it is randomized)

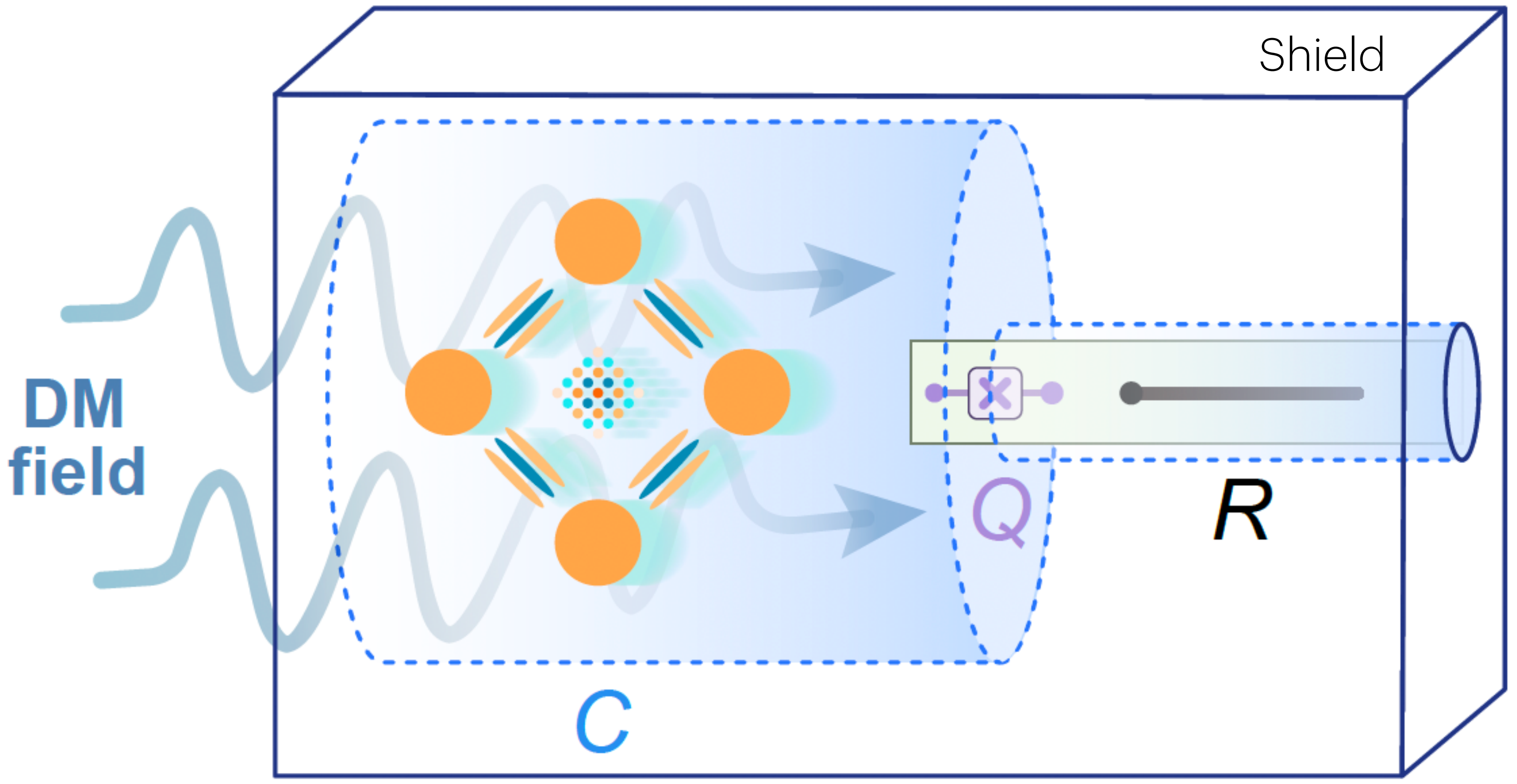


$$\Delta n \Delta \phi \geq 1$$

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

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

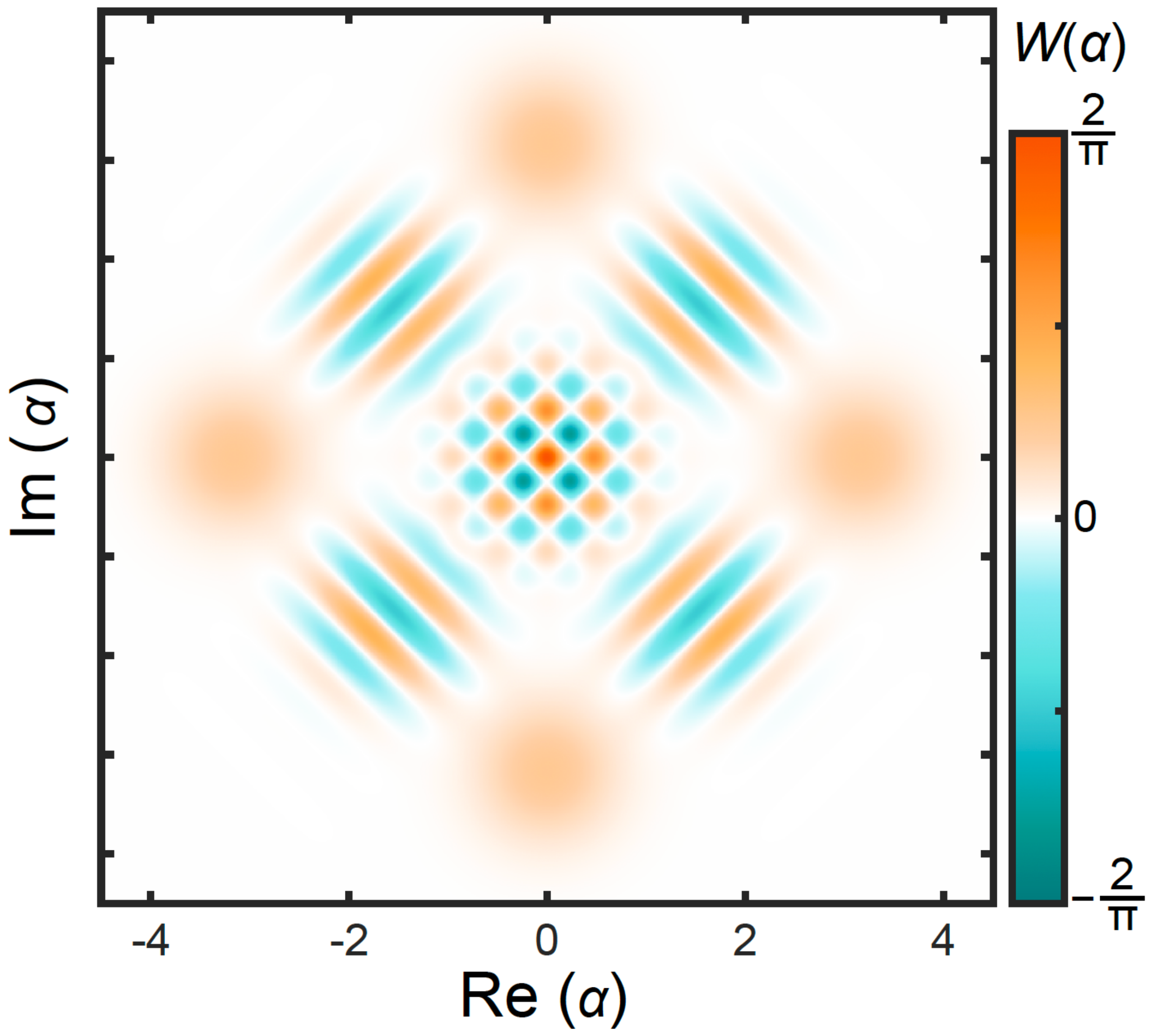
- Sensitivity limited by $\bar{n}_{th} \approx 10^{-3} \sim T_{eff} = 20$ mK

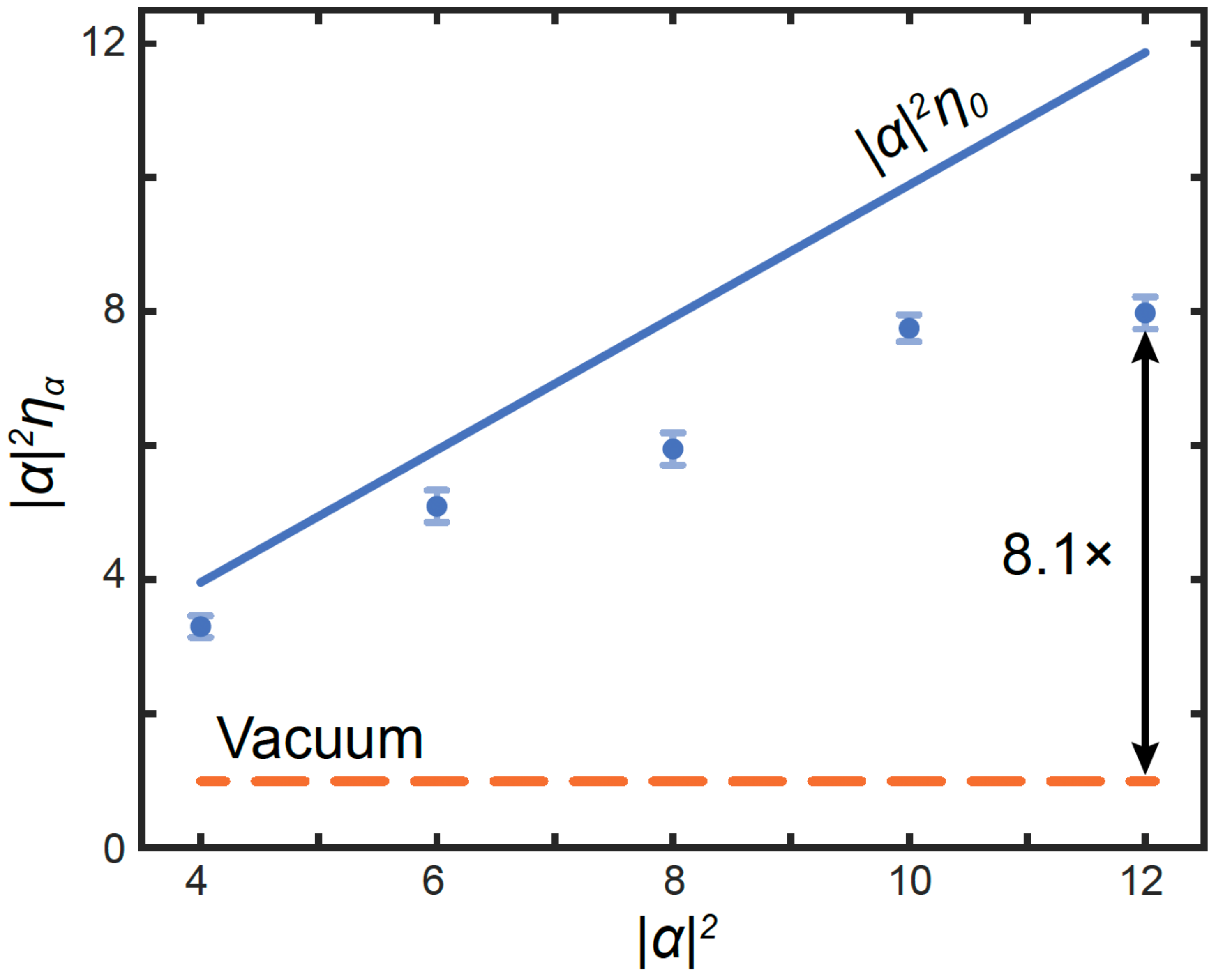
Enhancement by stimulated emission

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 $|\alpha|^2 = 12, \eta = 0.68$





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