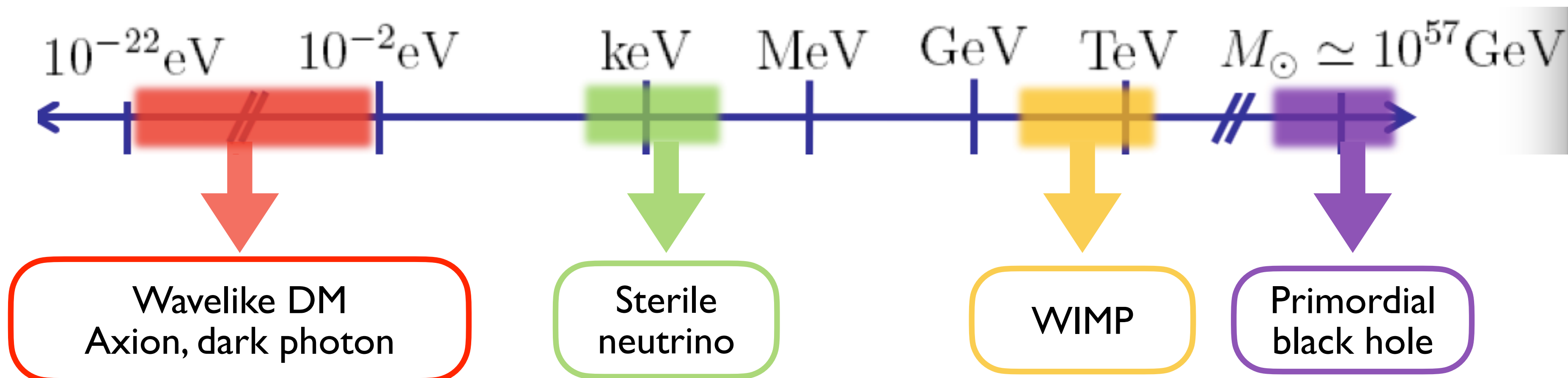
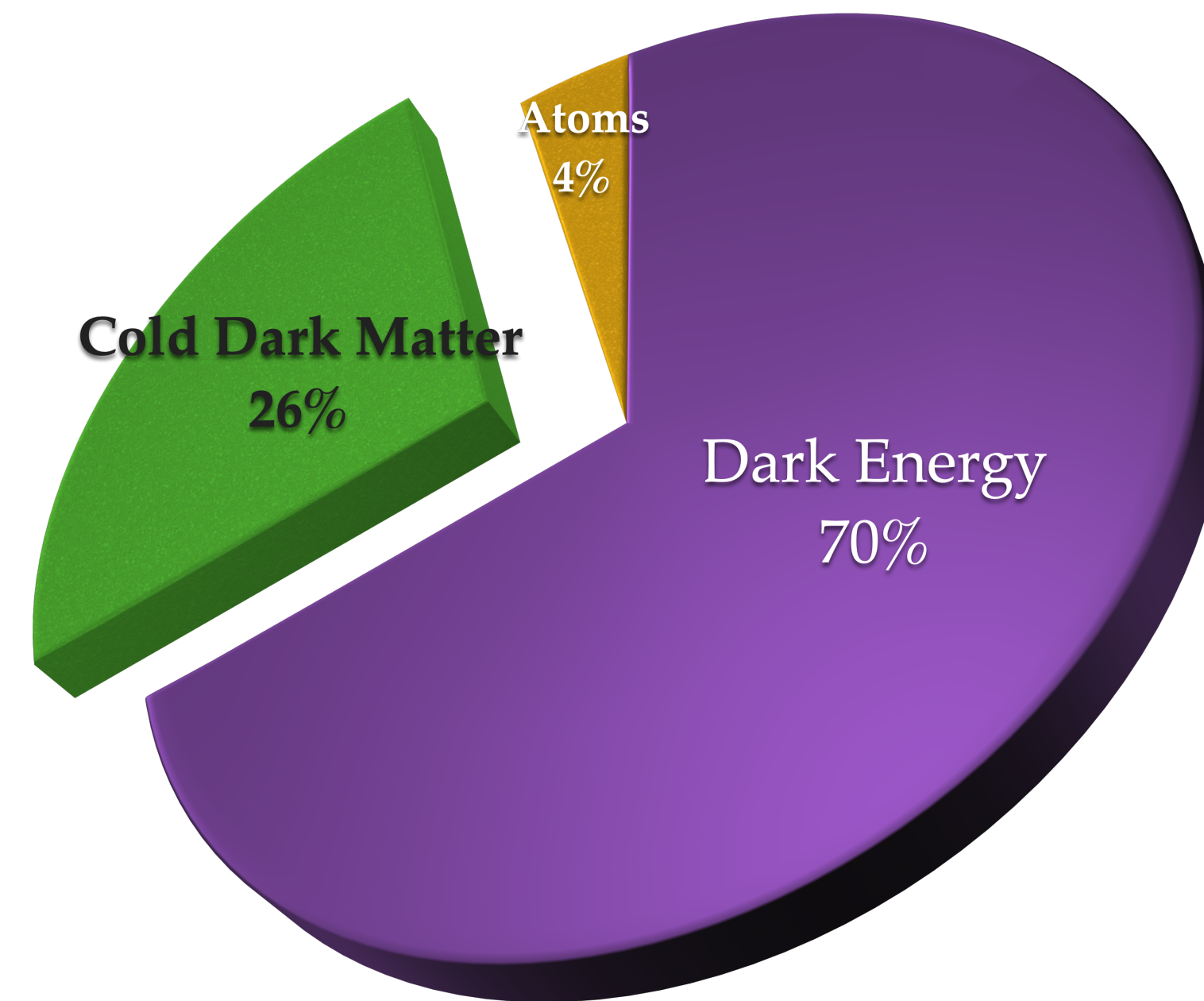
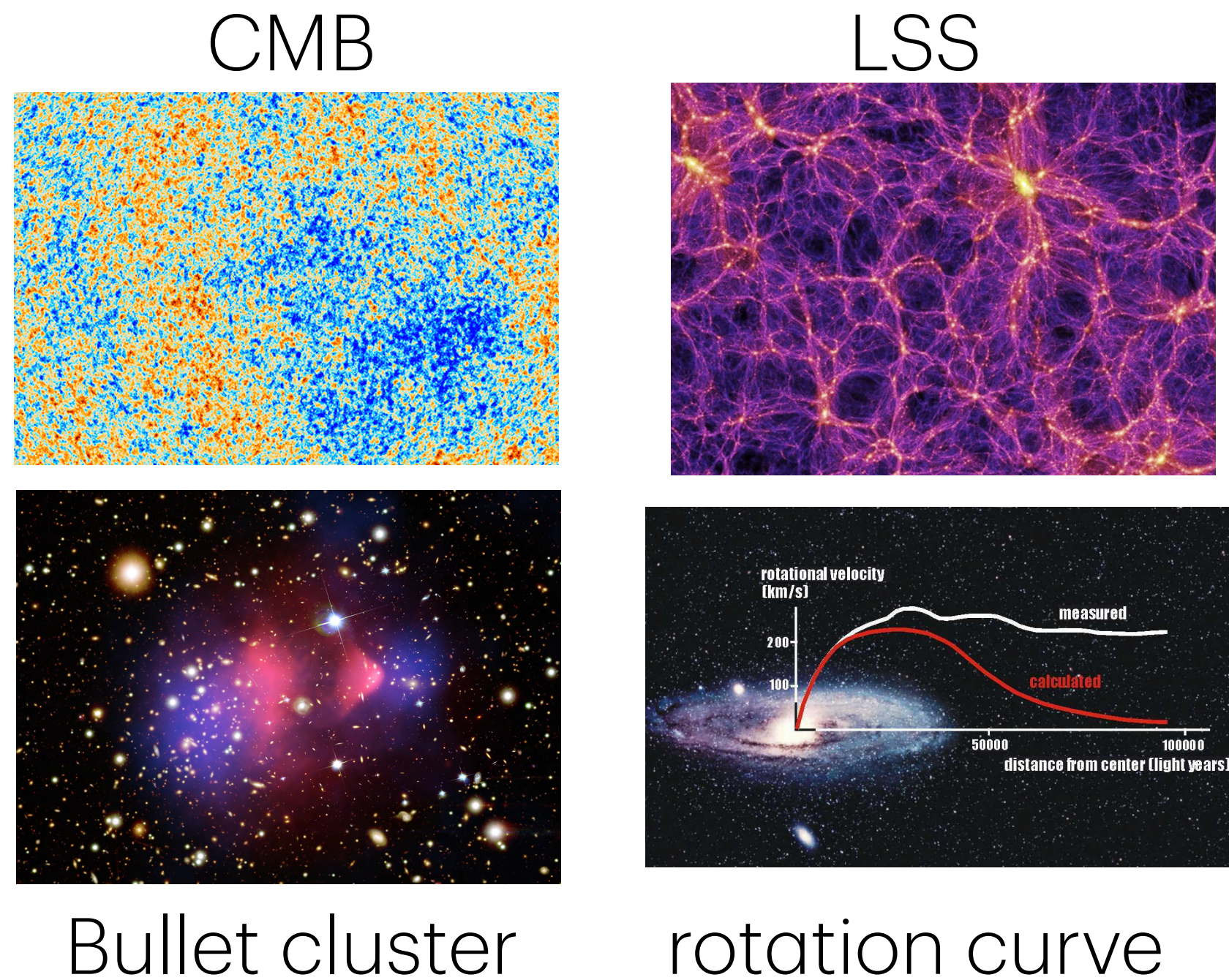


Quantum metrology for wavelike dark matter

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Dark matter spans an enormous range of possible masses



Wavelike DM candidates

- Axions and ALPs: $\mathcal{L}_a \supset \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

- Dark photon: $\mathcal{L}_{A'} \supset \epsilon m_{A'}^2 A'^{\mu} A_{\mu}$

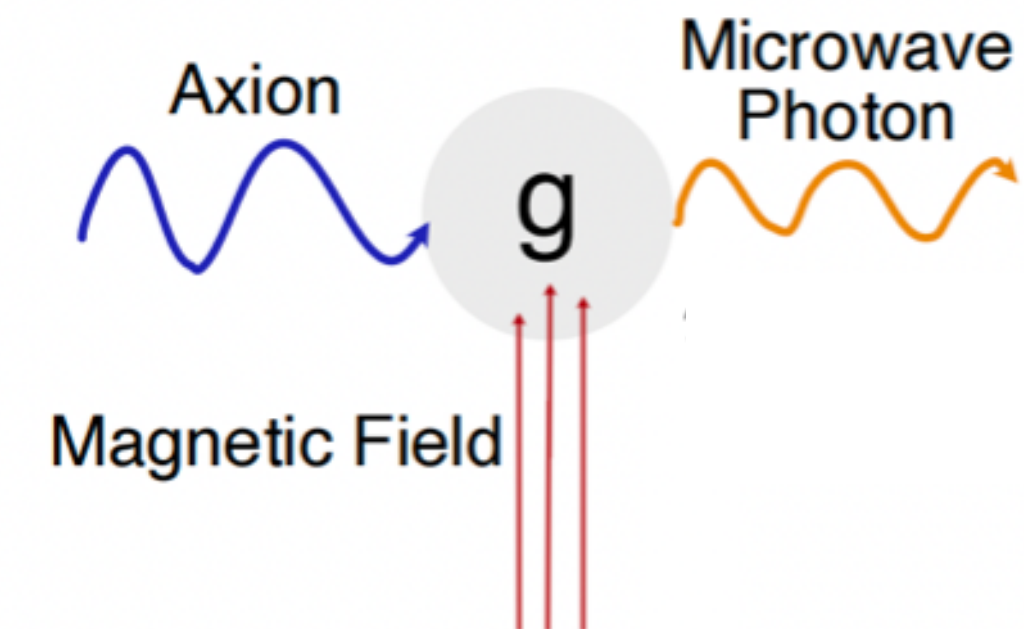
- For $m_{DM} \sim \text{GHz}$:

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

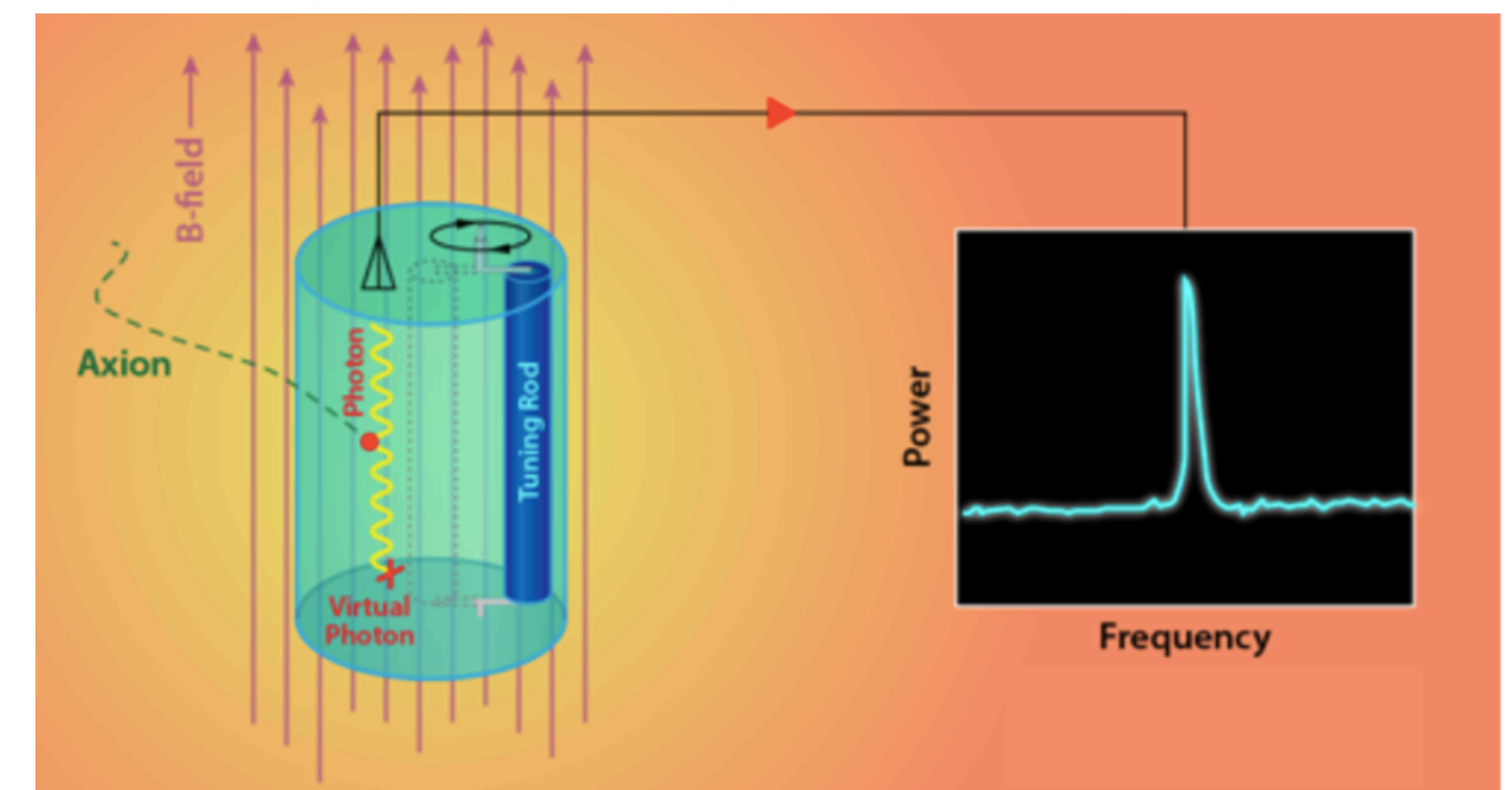
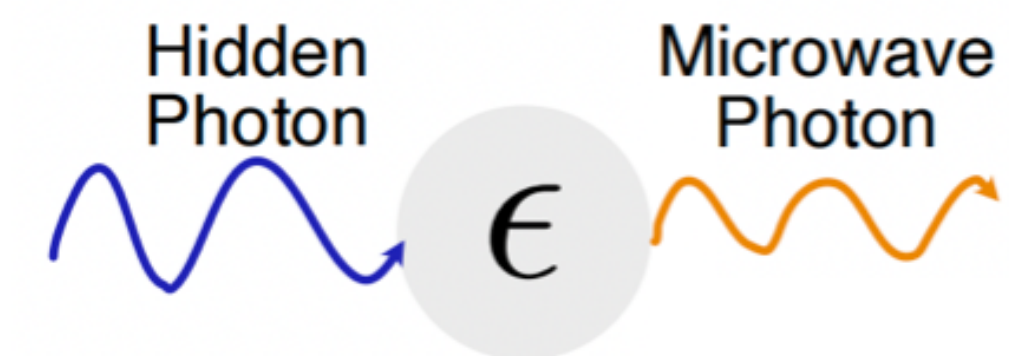
Coherence time $\tau_c \sim \frac{1}{m_{DM} \bar{v} v_0} \sim \frac{10^6}{m_{DM}} \sim 100 \mu s$

This macroscopic coherence enables distributed sensing.

inverse Primakoff effect

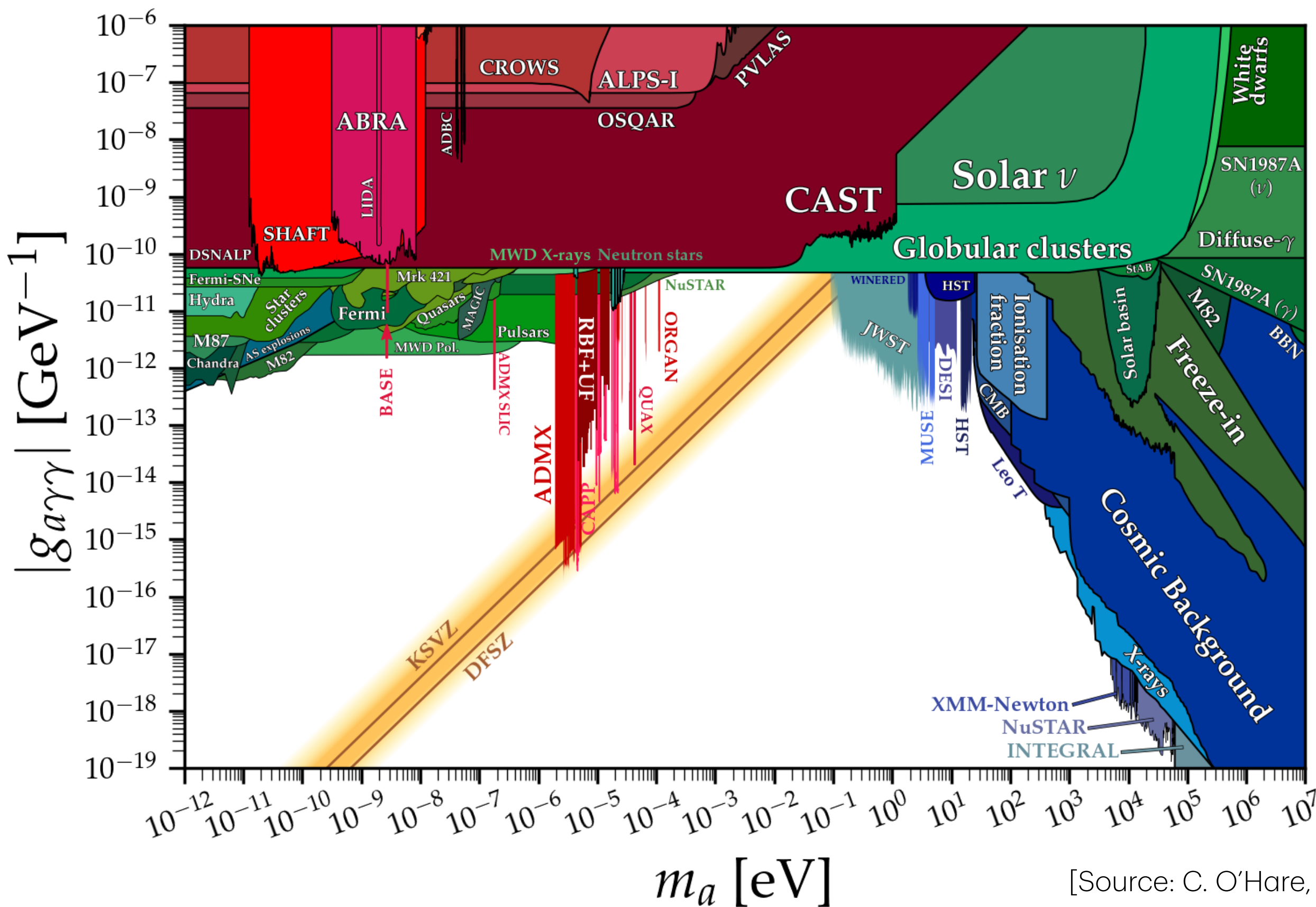


kinetic mixing

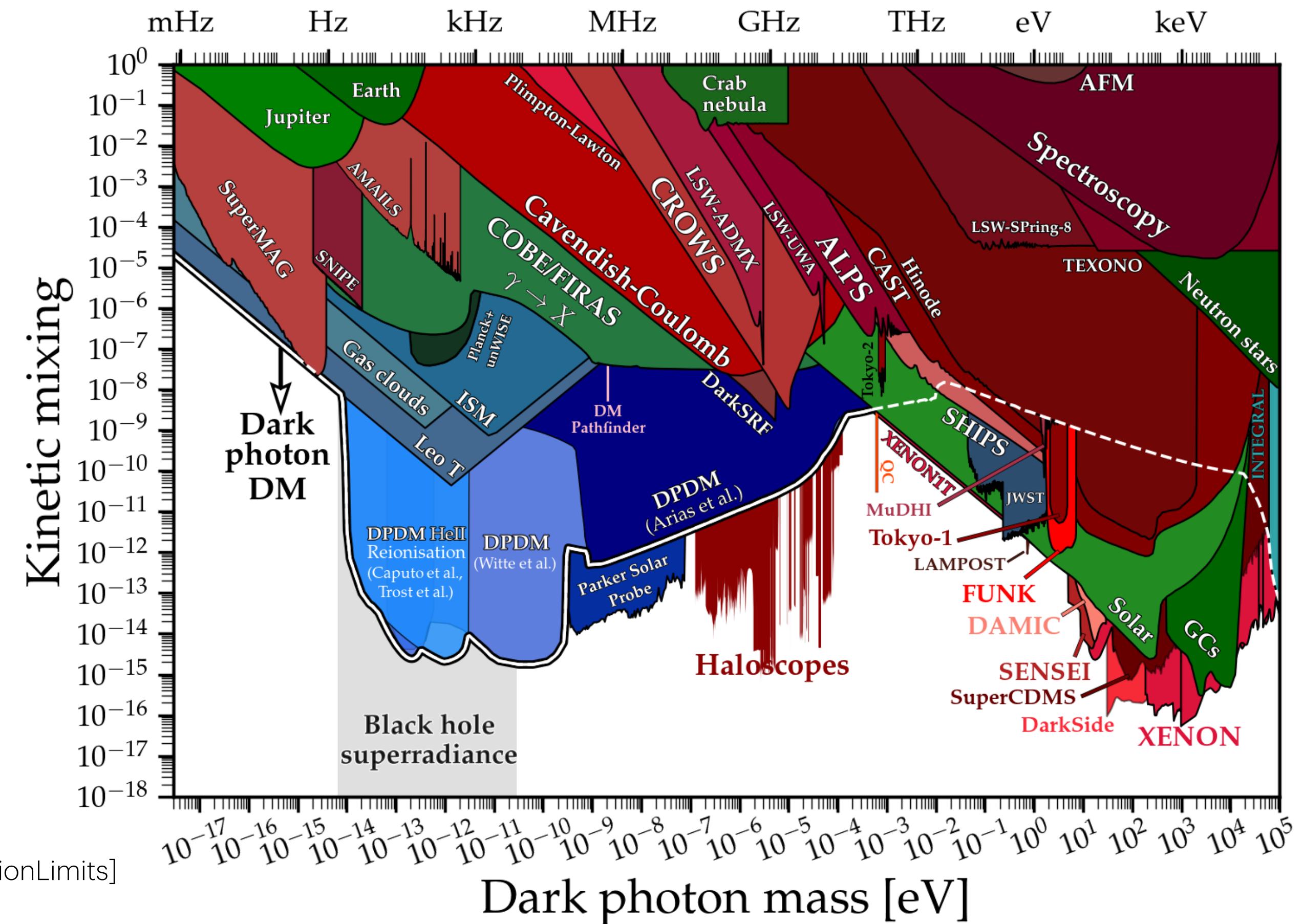


A vast parameter space

Axion



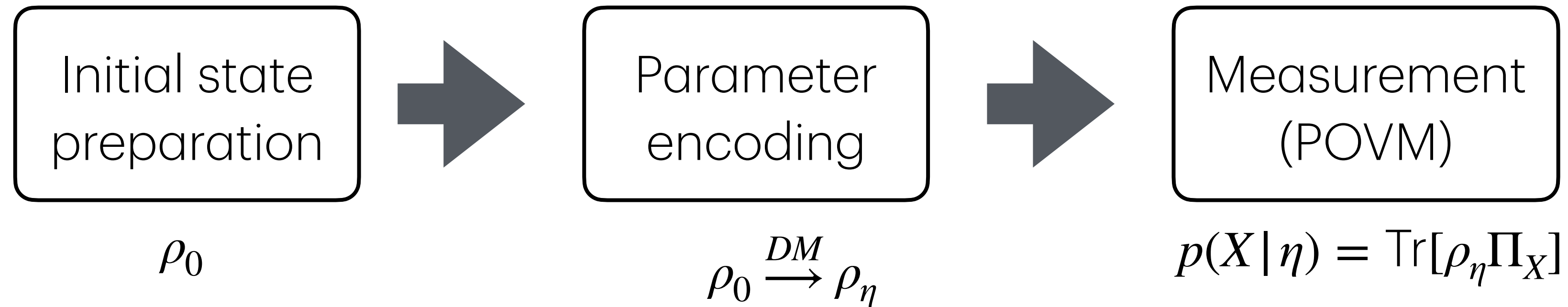
Dark photon



Scanning this vast parameter space calls for faster search strategies.

Quantum estimation theory

Quantum metrology provides three knobs



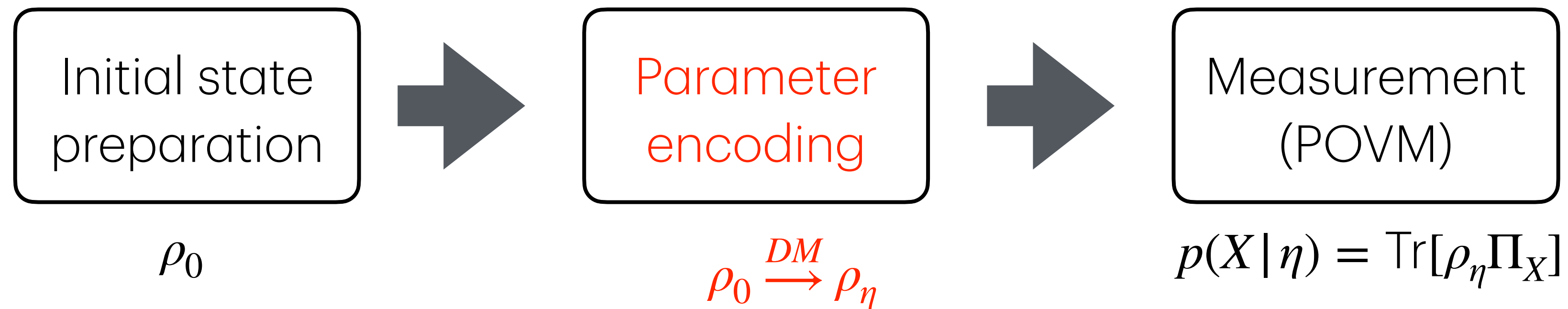
The Cramér–Rao inequality: $\text{Var}(\eta) \geq \frac{1}{N_{meas} F_C(\eta)} \geq \frac{1}{N_{meas} F_Q(\eta)}$

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

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

Quantum estimation theory

Quantum metrology provides three knobs



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Wavelike DM as a quantum state

Model the DM background as a real scalar field

$$\hat{\phi}(t, \mathbf{x}) = \sum_{\mathbf{k}} \frac{1}{\sqrt{2\omega_{\mathbf{k}}V}} \left(\hat{a}_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}t + i\mathbf{k}\cdot\mathbf{x}} + \hat{a}_{\mathbf{k}}^{\dagger} e^{i\omega_{\mathbf{k}}t - i\mathbf{k}\cdot\mathbf{x}} \right)$$

whose density matrix is a Gaussian ensemble of coherent states

[Cheong, Rodd, Wang, PRD(2025)]

$$\hat{\rho}_{\phi} = \int d\{\alpha\} P(\{\alpha\}) |\{\alpha\}\rangle \langle \{\alpha\}|, \quad |\{\alpha\}\rangle = \prod_{\mathbf{k}} |\alpha_{\mathbf{k}}\rangle, \quad P(\{\alpha\}) = \prod_{\mathbf{k}} \frac{1}{\pi N_{\mathbf{k}}} \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N_{\mathbf{k}}}\right)$$

This implies

$$\langle \hat{a}_{\mathbf{k}} \rangle = 0, \quad \langle \hat{a}_{\mathbf{k}}^{\dagger} \hat{a}_{\mathbf{k}'} \rangle = N_{\mathbf{k}} \delta_{\mathbf{k}\mathbf{k}'}, \quad \sum_{\mathbf{k}} N_{\mathbf{k}} \simeq \frac{\rho_{\text{DM}}}{m_{\phi}} V$$

For [unsqueezed](#) states, the anomalous correlator vanishes $\langle \hat{a}_{\mathbf{k}} \hat{a}_{\mathbf{k}'} \rangle = 0$

DM as a quantum channel on the detector

A two-level detector: $H_0 = \omega_0 \hat{\sigma}_z / 2$

Coupling to the DM field: $H_{\text{int}} = g \hat{\phi}(t) \hat{\sigma}_x$

Expanding the evolution operator in a Dyson series: $\hat{U}_I(T) = \mathbb{I} + \hat{U}^{(1)} + \hat{U}^{(2)} + \dots$

$$\hat{U}^{(1)} = -i \int_0^T dt \hat{H}_I(t), \quad \hat{U}^{(2)} = - \int_0^T dt_1 \int_0^{t_1} dt_2 \hat{H}_I(t_1) \hat{H}_I(t_2)$$

Tracing out the DM field gives the reduced detector response:

$$\Delta \hat{\rho}_d = \hat{\rho}_d(T) - \hat{\rho}_{d,0} = \hat{\rho}_d^{(1,1)} + \hat{\rho}_d^{(2,0)} + \hat{\rho}_d^{(0,2)} + \mathcal{O}(g^4),$$

$$\text{with } \hat{\rho}_d^{(i,j)} = \text{Tr}_\phi \left[\hat{U}^{(i)} \hat{\rho}(0) \hat{U}^{(j)\dagger} \right]$$

DM as a quantum channel on the detector

Short-time limit

Within the coherence time $T < \min\{\tau_d, \tau_\phi\}$:

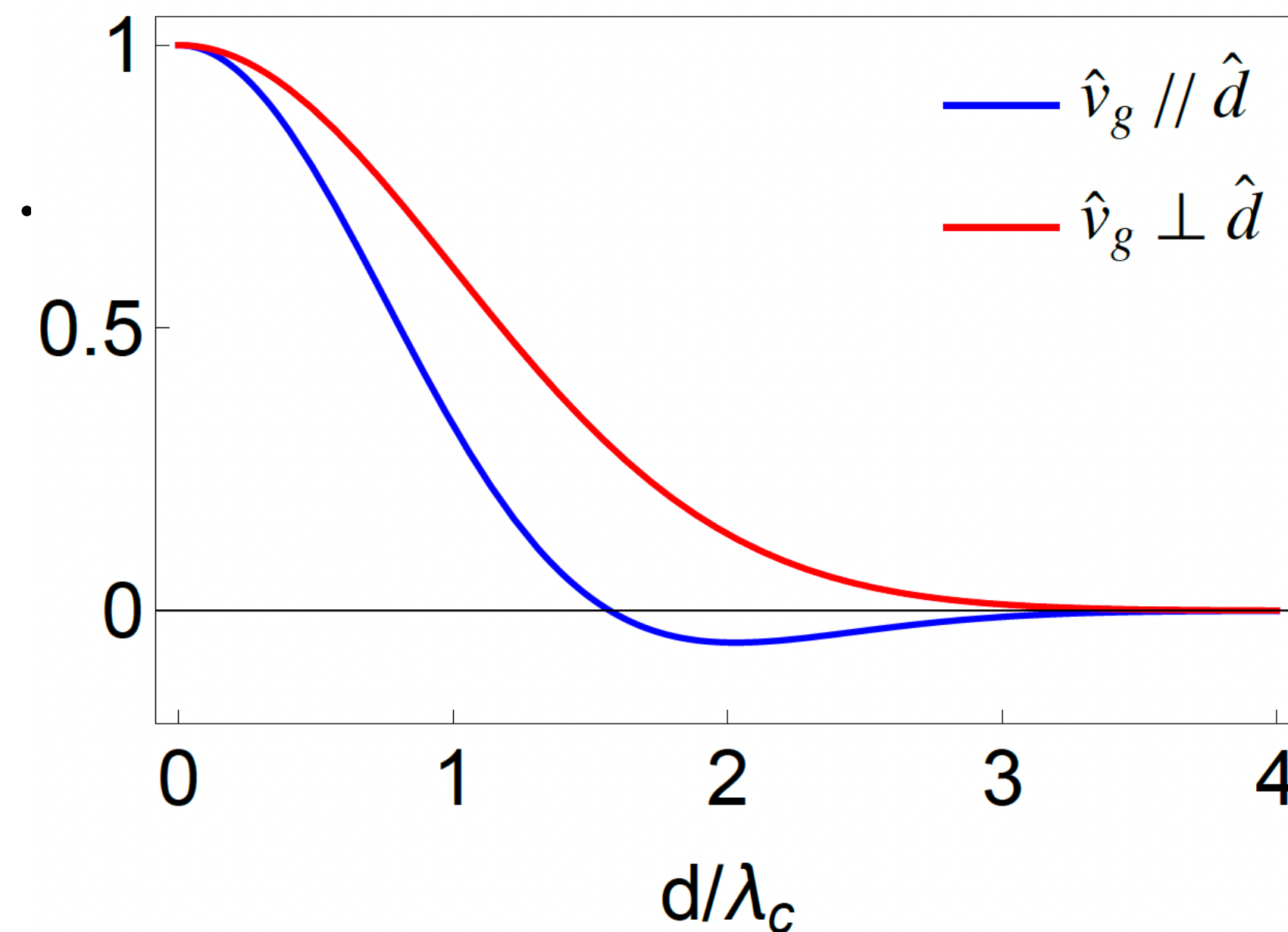
$$\Delta\hat{\rho}_d = \frac{\rho_{\text{DM}}}{2} g^2 T^2 \left(\hat{\sigma}_+ \hat{\rho}_{d,0} \hat{\sigma}_- + \hat{\sigma}_- \hat{\rho}_{d,0} \hat{\sigma}_+ - \hat{\rho}_{d,0} \right)$$

For multiple detectors:

$$\Delta\hat{\rho}_d = \frac{\rho_{\text{DM}}}{2} g^2 T^2 \sum_{i,j=1}^N C_{ij} \left[\hat{\sigma}_+^{(i)} \hat{\rho}_{d,0} \hat{\sigma}_-^{(j)} - \frac{1}{2} \left\{ \hat{\sigma}_-^{(j)} \hat{\sigma}_+^{(i)}, \hat{\rho}_{d,0} \right\} \right] + \text{h.c.}$$

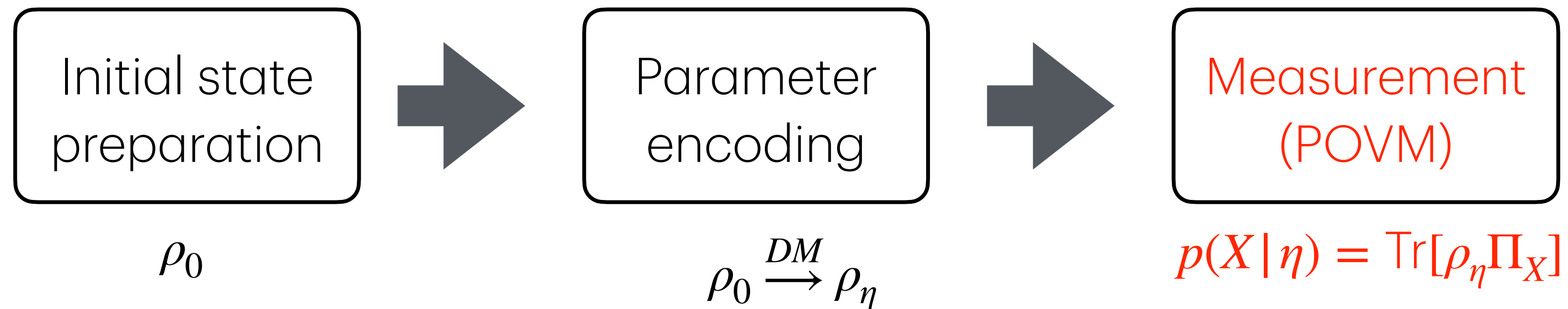
The spatial coherence matrix is

$$C_{ij} := \int d^3v f(\mathbf{v}) e^{im_\phi \mathbf{v} \cdot (\mathbf{x}_i - \mathbf{x}_j)}, \quad C_{ii} = 1, \quad C_{ji} = C_{ij}^*$$



Quantum estimation theory

Quantum metrology provides three knobs



The Cramér–Rao inequality: $\text{Var}(\eta) \geq \frac{1}{N_{meas} F_C(\eta)} \geq \frac{1}{N_{meas} F_Q(\eta)}$

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

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

Quantum coherence measurement

Direct excitation measurements cannot distinguish DM from thermal noise.

$$\rho_0 = |g_1 g_2\rangle\langle g_1 g_2| \rightarrow \rho_\eta = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & p_2 + n_2 & C_{12} & 0 \\ 0 & C_{12}^* & p_1 + n_1 & 0 \\ 0 & 0 & 0 & 1 - p_1 - p_2 - n_1 - n_2 \end{pmatrix} \begin{matrix} |e_1 e_2\rangle \\ |g_1 e_2\rangle \\ |e_1 g_2\rangle \\ |g_1 g_2\rangle \end{matrix}$$

p : DM-induced excitation probability; n : thermal excitation probability

Measuring the coherence operator $\Pi_{12} = |e_1 g_2\rangle\langle g_1 e_2| + |g_1 e_2\rangle\langle e_1 g_2|$:

[Shu, **BX**, Xu, arXiv:2410.22413]
[H. Fukuda et al., PRL(2025)]
[S. Chen et al., PRD(2026)]

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

Insensitive to uncorrelated thermal noise while retaining the full spatial-correlation signal.

The optimal measurement

Treat the unknown thermal excitation rate $\boldsymbol{n}$ as a nuisance parameter.

(Classical) Fisher information matrix $F = \begin{pmatrix} F_{gg} & F_{gn} \\ F_{ng} & F_{nn} \end{pmatrix}$

Marginalized information for g : $F_{gg}^{\text{marg}} = \frac{1}{(F^{-1})_{gg}}$

In the computational basis, $\det F \approx 0$

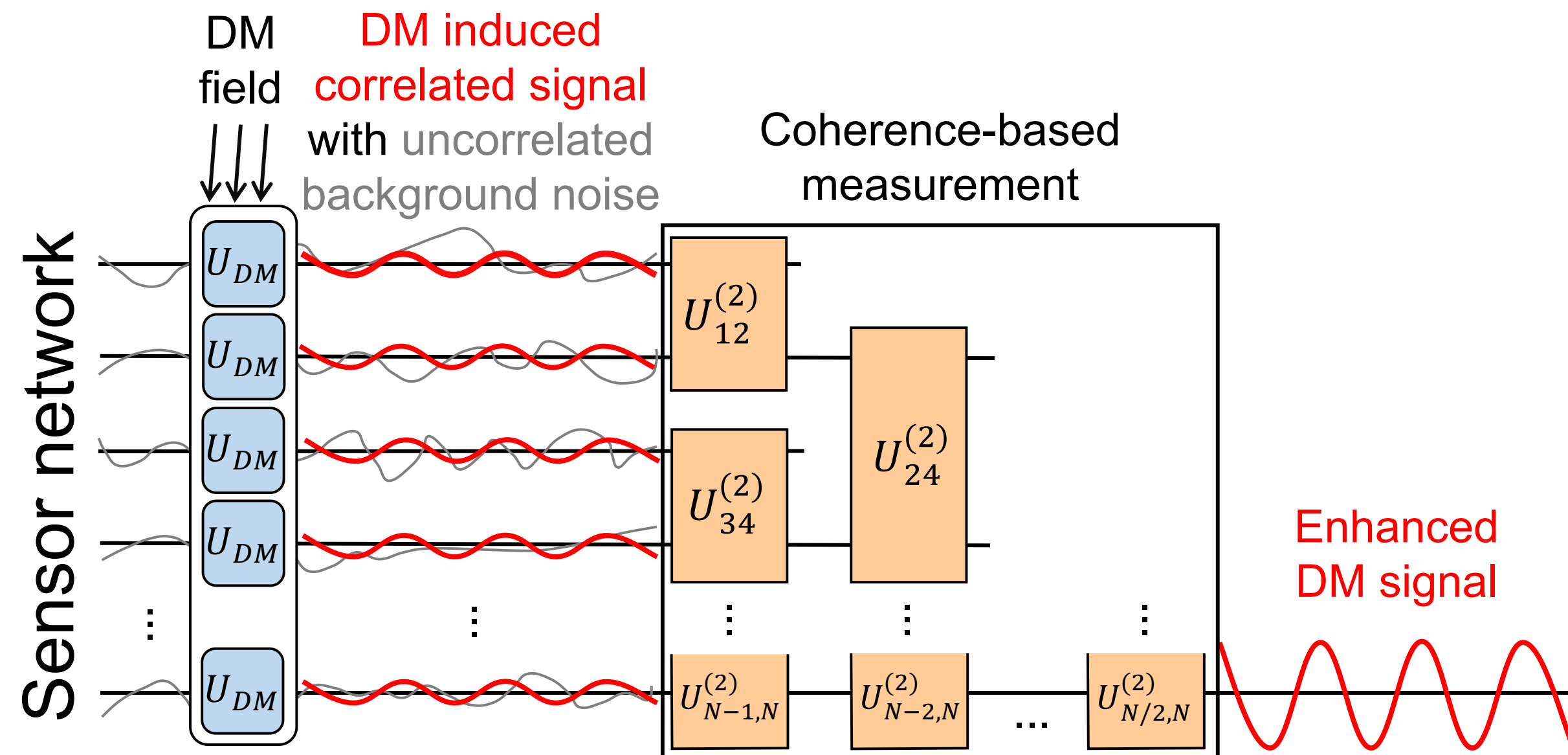
In the optimal measurement basis, $F_{gn} \ll F_{gg}$

Quantum sensor network

For N sensors, $\mathcal{O}(N^2)$ pairwise coherence channels can produce an N^2 -scaling signal.

A W state accesses all pairwise coherences:

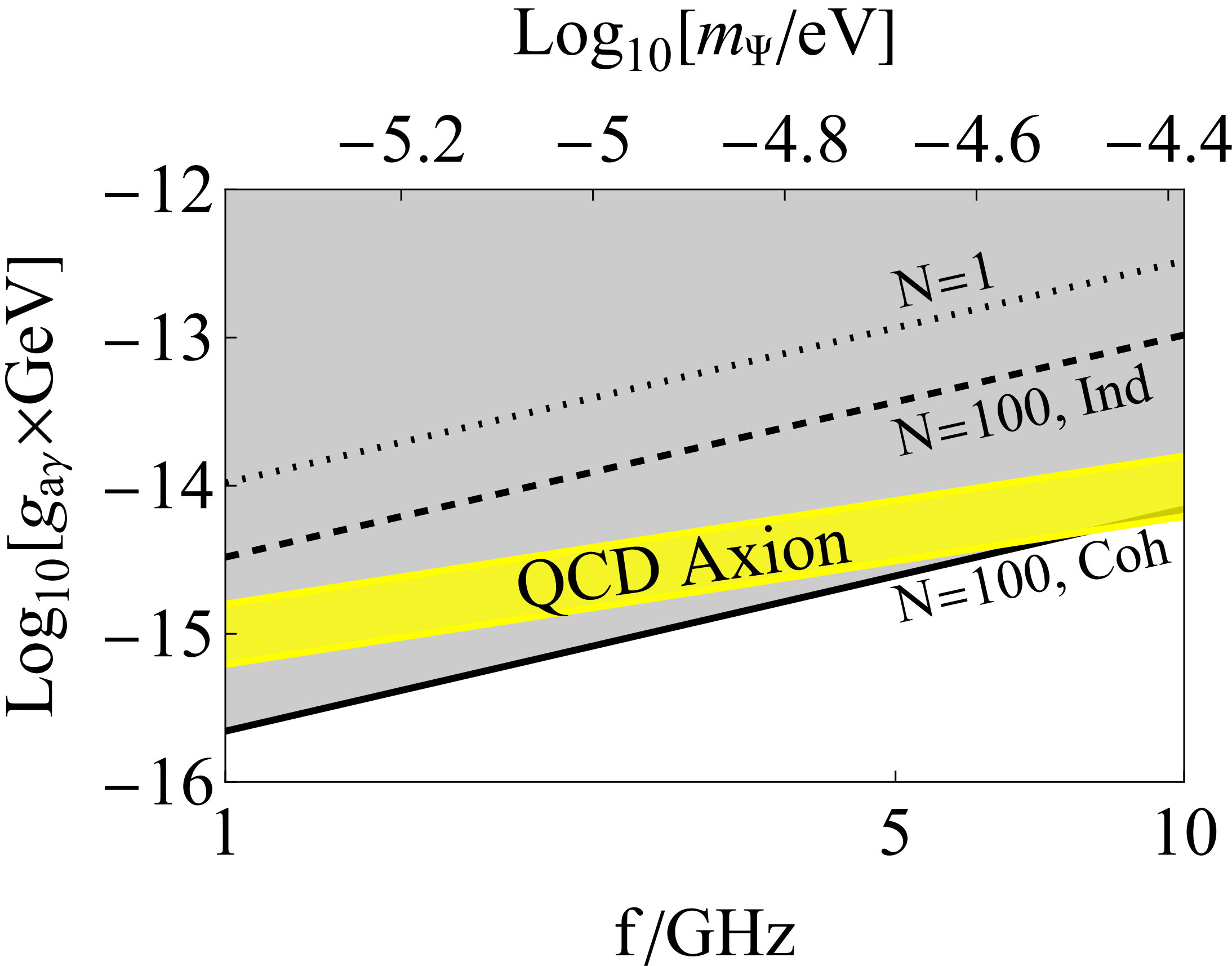
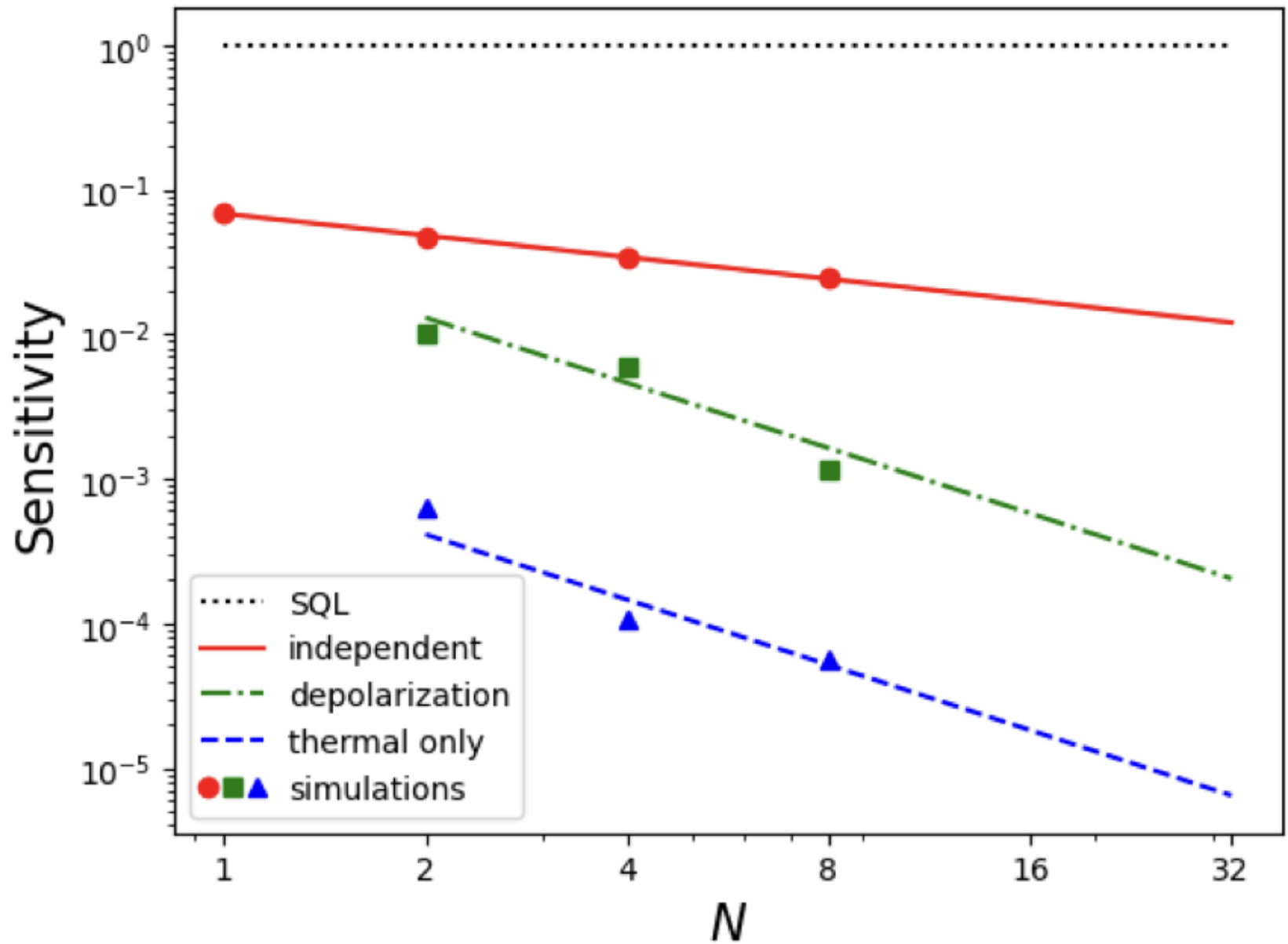
$$|W\rangle = \frac{1}{\sqrt{N}}(|e_1g_2\dots g_N\rangle + |g_1e_2\dots g_N\rangle + \dots + |g_1g_2\dots e_N\rangle)$$



Sensitivity estimation

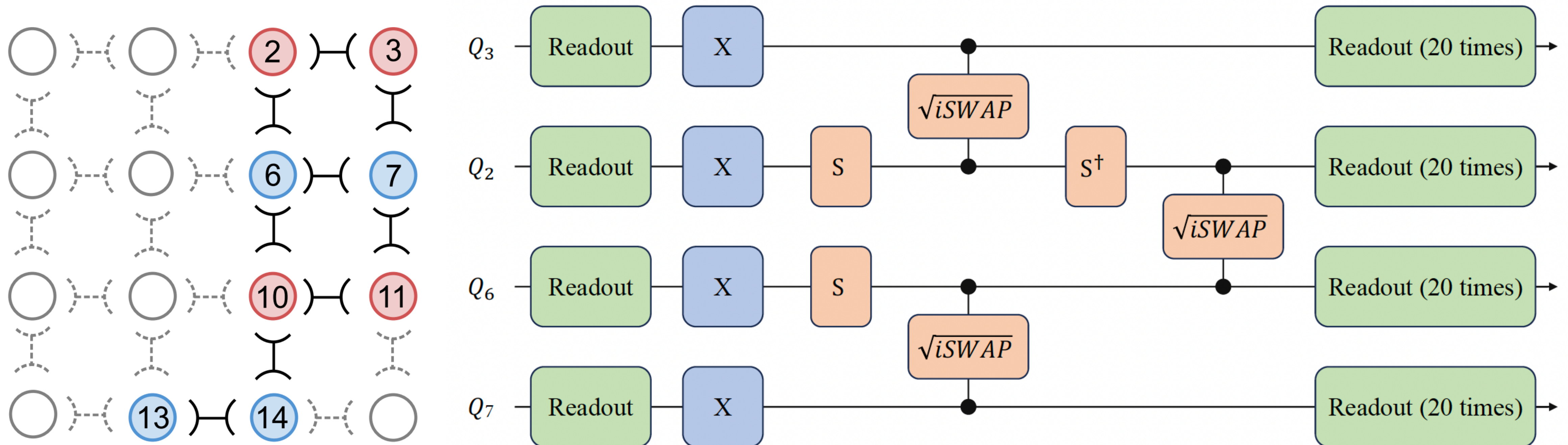
The coherence advantage can survive realistic gate errors.

Sensor type	$\bar{n}_{r0}$	Two-qubit gate infidelity $\bar{\mathcal{F}}$
Cavity	10^{-3} [46]	10^{-4} [47]
Transmon	10^{-3} [48, 49]	10^{-3} [50, 51]
Ions	10^{-2} [52]	10^{-3} [53, 54]



Testing on a 16-qubit processor

Preliminary results reach $\epsilon < 10^{-10}$ at a resonant frequency $m_{A'} = 4.3$ GHz



[He, Shu, **BX** et al., work in progress]

Squeezed dark matter

$$\rho_\eta = \begin{pmatrix} 0 & 0 & 0 & M_{12} \\ 0 & p_2 + n_2 & C_{12} & 0 \\ 0 & C_{12}^* & p_1 + n_1 & 0 \\ M_{12}^* & 0 & 0 & 1 - p_1 - p_2 - n_1 - n_2 \end{pmatrix} \begin{matrix} |e_1 e_2\rangle \\ |g_1 e_2\rangle \\ |e_1 g_2\rangle \\ |g_1 g_2\rangle \end{matrix}$$

Measuring the anomalous-coherence operator $\Pi_{12} = |e_1 e_2\rangle\langle g_1 g_2| + |g_1 g_2\rangle\langle e_1 e_2|$:

$$Tr[\rho_\eta \Pi_{12}] = 2Re[M_{12}] \propto \sum_{\mathbf{k}} \langle \hat{a}_{\mathbf{k}} \hat{a}_{-\mathbf{k}} \rangle$$

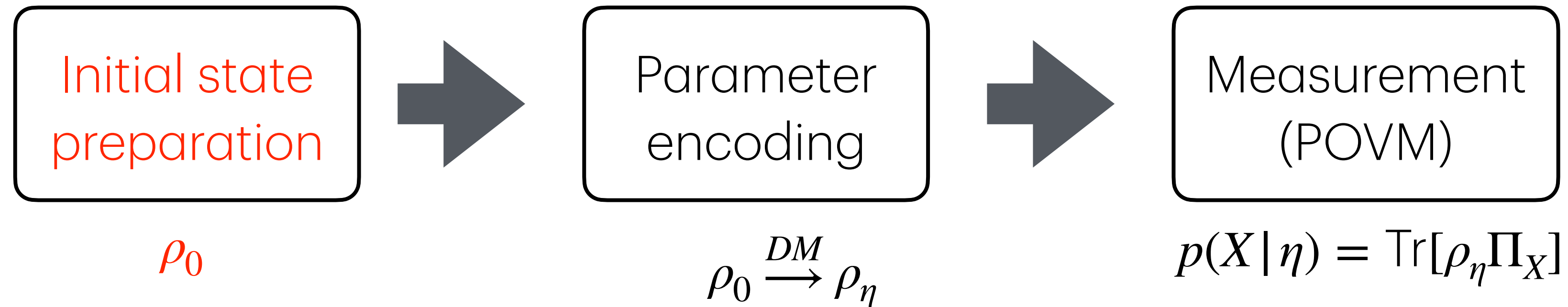
[Dong, He, Shu, **BX**, work in progress]

This observable measures how strongly the DM field is **squeezed**.

Moreover, when $|M_{12}| > p + n$, the two detectors become **entangled**.

Quantum estimation theory

Quantum metrology provides three knobs



The Cramér–Rao inequality: $\text{Var}(\eta) \geq \frac{1}{N_{meas} F_C(\eta)} \geq \frac{1}{N_{meas} F_Q(\eta)}$

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

Optimal Entangled Probe

Recall that $\Delta\hat{\rho}_d = \frac{\rho_{\text{DM}}}{2} g^2 T^2 \sum_{i,j=1}^N C_{ij} \left[\hat{\sigma}_+^{(i)} \hat{\rho}_{d,0} \hat{\sigma}_-^{(j)} - \frac{1}{2} \{ \hat{\sigma}_-^{(j)} \hat{\sigma}_+^{(i)}, \hat{\rho}_{d,0} \} \right] + \text{h.c.}$

Diagonalize the coherence matrix as

$$C_{ij} = \sum_{\alpha} c_{\alpha} u_{\alpha i} u_{\alpha j}^* \text{ with } c_{\alpha} \geq 0$$

Define the jumping operators

$$\hat{B}_{\alpha,+} = \sum_i u_{\alpha i} \hat{\sigma}_+^{(i)}, \quad \hat{B}_{\alpha,-} = \hat{B}_{\alpha,+}^{\dagger}$$

Optimal Entangled Probe

Recall that $\Delta\hat{\rho}_d = \frac{\rho_{\text{DM}}}{2} g^2 T^2 \sum_{i,j=1}^N C_{ij} \left[\hat{\sigma}_+^{(i)} \hat{\rho}_{d,0} \hat{\sigma}_-^{(j)} - \frac{1}{2} \{ \hat{\sigma}_-^{(j)} \hat{\sigma}_+^{(i)}, \hat{\rho}_{d,0} \} \right] + \text{h.c.}$

Define the number-conserving sensitivity operator

$$\hat{K} = \sum_{\alpha} c_{\alpha} \left(\hat{B}_{\alpha,-} \hat{B}_{\alpha,+} + \hat{B}_{\alpha,+} \hat{B}_{\alpha,-} \right) = N\mathbb{I} + 2 \sum_{i,j} C_{ij} \hat{\sigma}_+^{(i)} \hat{\sigma}_-^{(j)}$$

The QFI is given by:

$$F_g[\hat{\rho}_g] = \langle \hat{K} \rangle - 2 \sum_{\alpha} c_{\alpha} | \langle \hat{B}_{\alpha,+} \rangle |^2 \leq \lambda_{\text{max}}(\hat{K})$$

The optimal probe is the top eigenstate of the geometry-dependent operator $\hat{K}$.

Co-located detectors

For a perfectly coherent, common-phase array, $C_{ij} = 1$ and

$$\hat{K} = \hat{J}_- \hat{J}_+ + \hat{J}_+ \hat{J}_- = 2 \left(\hat{\mathbf{J}}^2 - \hat{J}_z^2 \right), \text{ where } \hat{J}_+ = \sum_{i=1}^N \hat{\sigma}_+^{(i)}, \hat{J}_- = \sum_{i=1}^N \hat{\sigma}_-^{(i)}$$

On a Dicke state $|J, m\rangle$, this operator has eigenvalue $K(J, m) = 2 [J(J+1) - m^2]$

The largest eigenvalue is attained by the half-excited Dicke state with $J = N/2, m = 0$:

$$|D_{N/2}^N\rangle = \mathcal{N} \sum_{\pi} \mathcal{P}_{\pi} \left(|g\rangle^{\otimes(N/2)} \otimes |e\rangle^{\otimes(N/2)} \right) \quad [\text{He, Shu, **BX**, and Xu, arXiv:2512.14821}]$$

yielding $F_g^{\text{Dicke}} \propto 2N(N+2)$

Geometry-adapted optimal states

For distributed sensors, the optimal probe

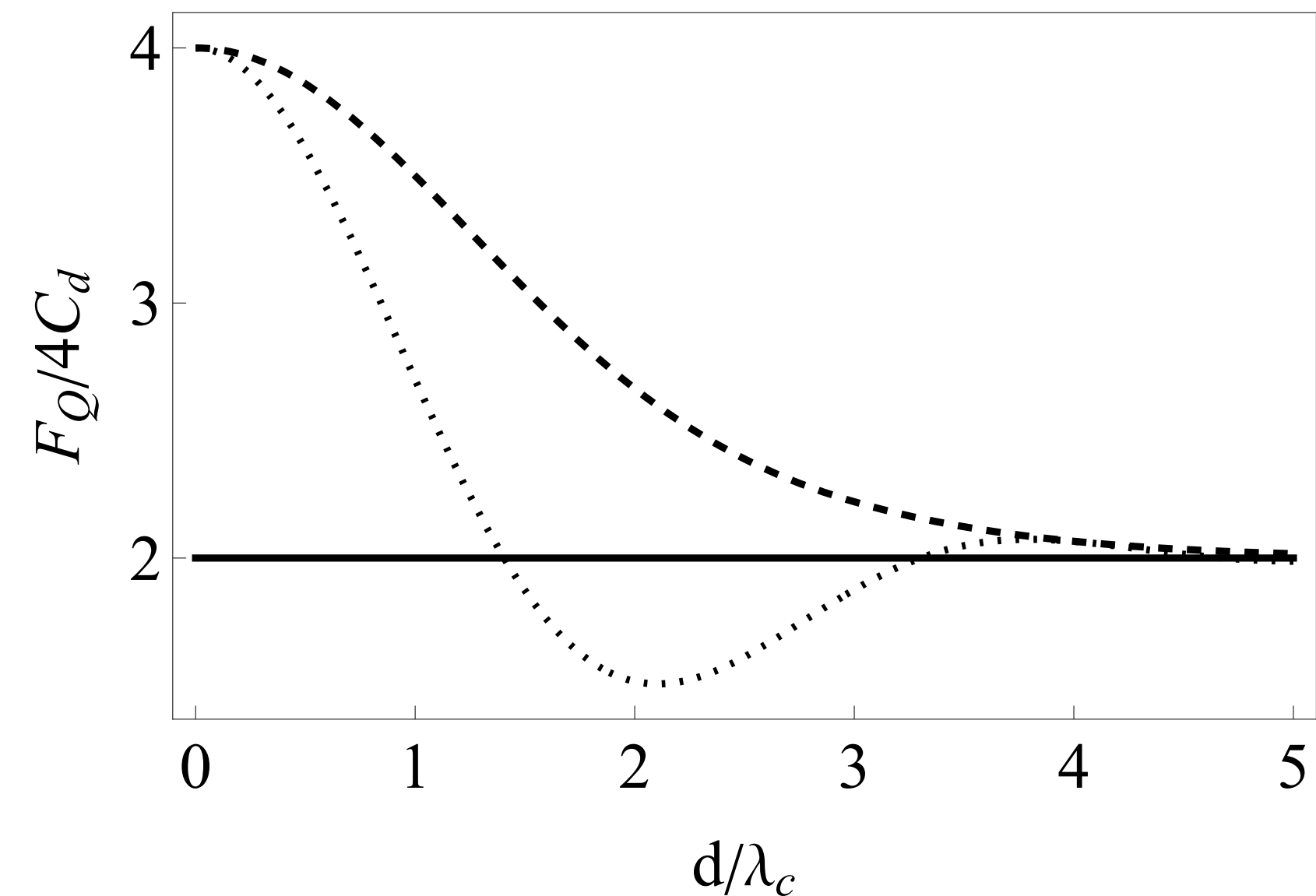
$$|\psi_{\text{opt}}\rangle = \sum_{|S|=k_*} a_S |S\rangle$$

has a fixed excitation number k_* but nonuniform amplitudes a_S .

- For two detectors, the optimal state is

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

$$F_g^{\text{opt}} = 4(C_{11} + C_{22} + 2|C_{12}|)$$



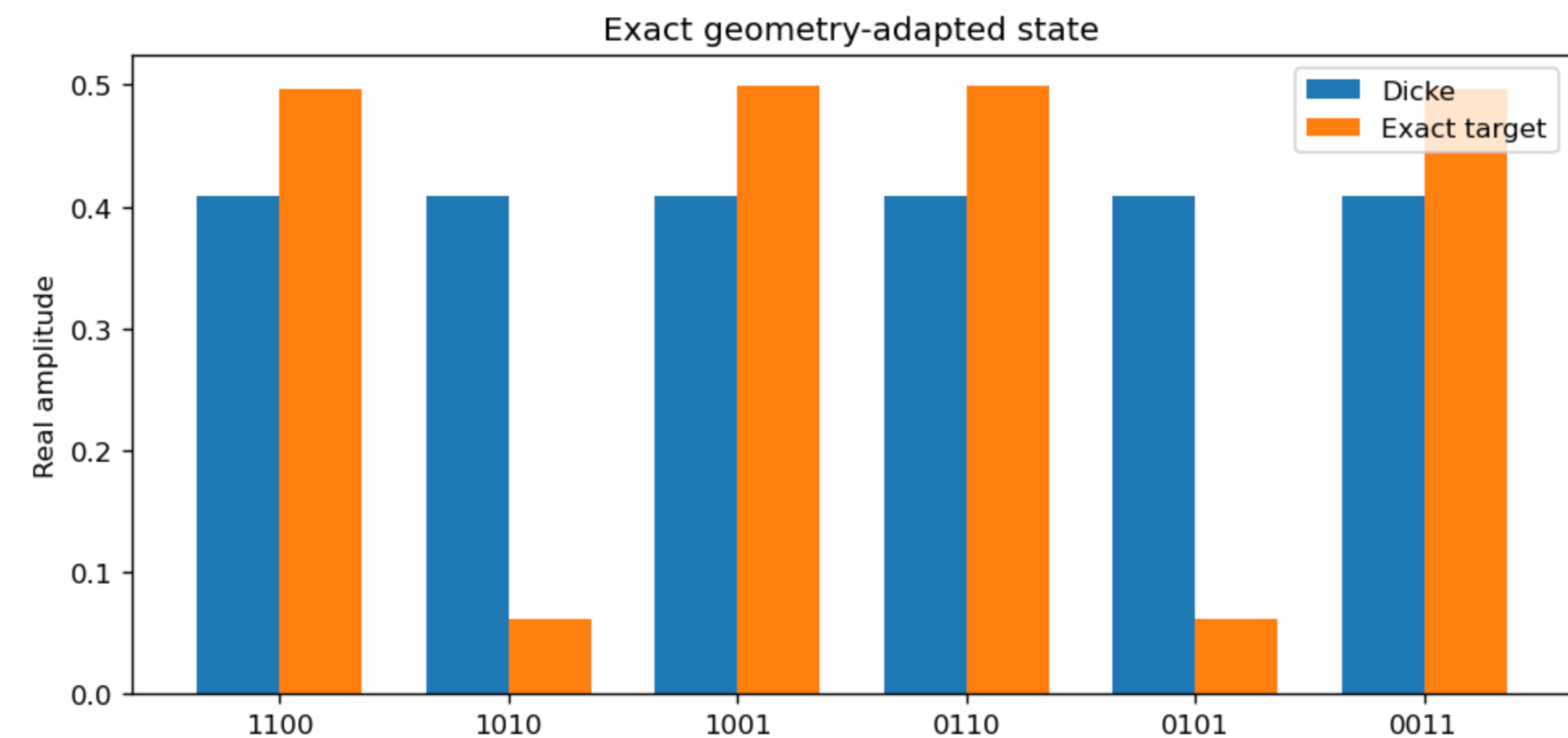
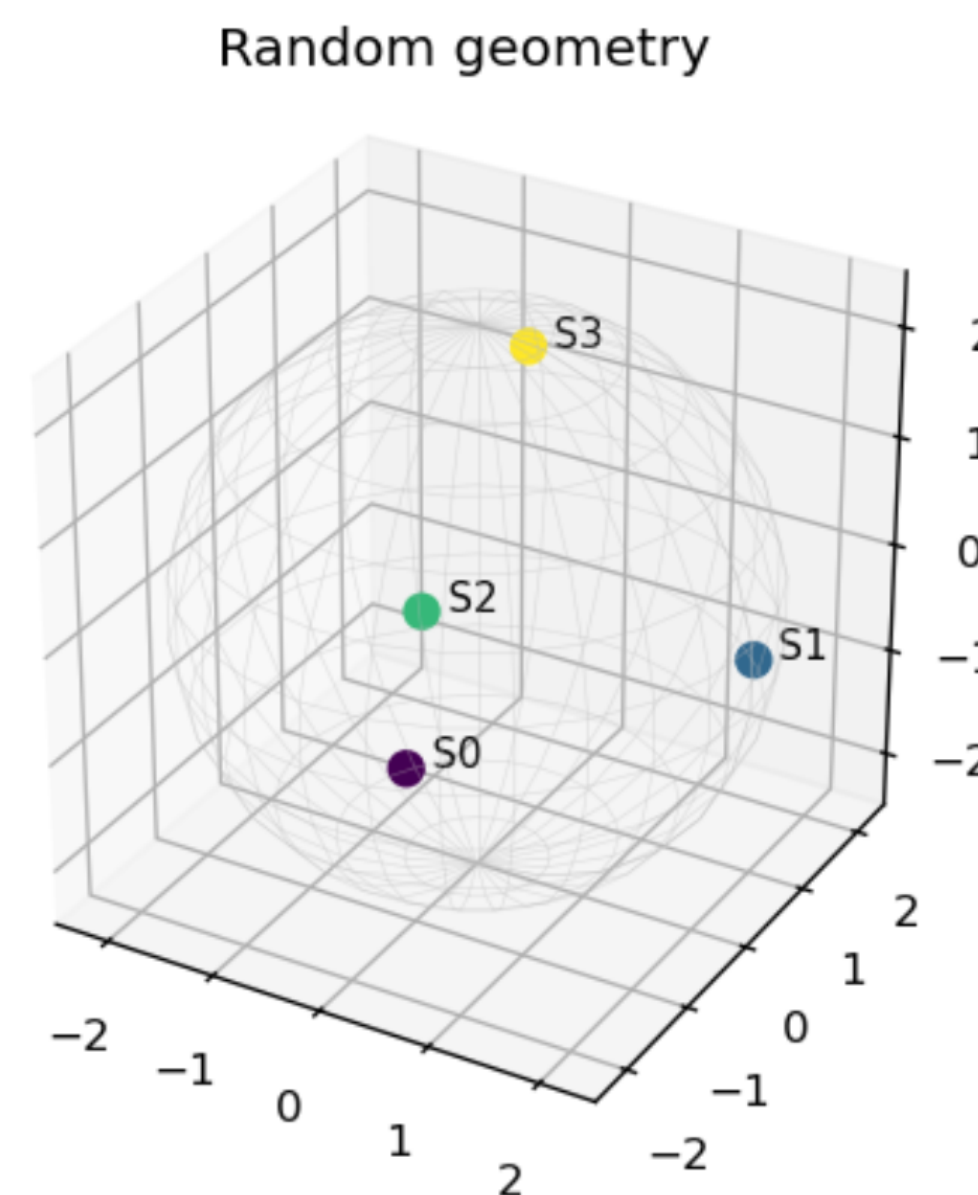
Geometry-adapted optimal states

A half-filled Dicke-like state has $\binom{N}{N/2}$ different amplitudes.

Classical diagonalization and exact state synthesis require resources that grow exponentially.

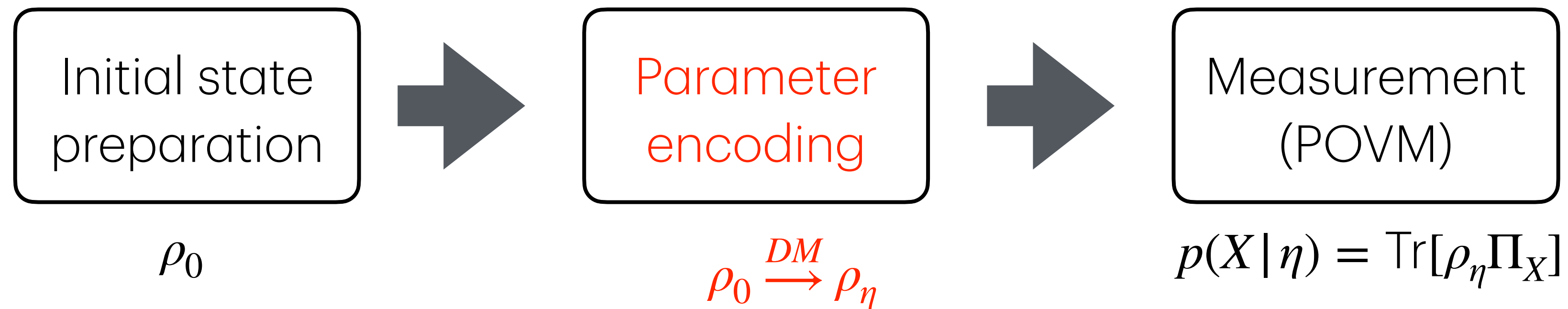
We approximately prepare the optimal probe with a [variational](#) circuit $|\psi(\boldsymbol{\theta})\rangle = U_{\text{var}}(\boldsymbol{\theta})|D_k^N\rangle$

Loss function: $E(\boldsymbol{\theta}) = -\langle \hat{K} \rangle$



Quantum estimation theory

Quantum metrology provides three knobs

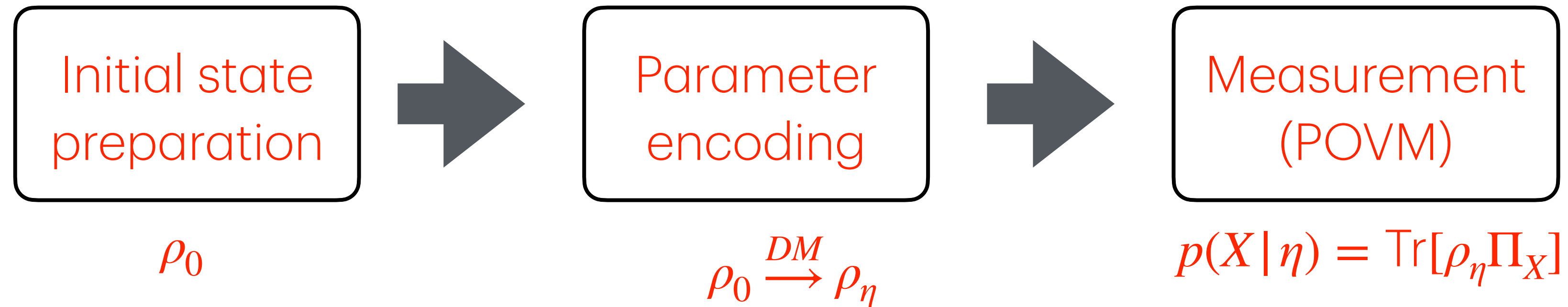


The parameter-encoding step can also be engineered:

- Quantum error correction (see Fukuda's talk)
- Dynamical Decoupling
- Optimal quantum control

Quantum estimation theory

Quantum metrology provides three knobs



A cavity experiment combines all three metrological knobs.



Photon counting device

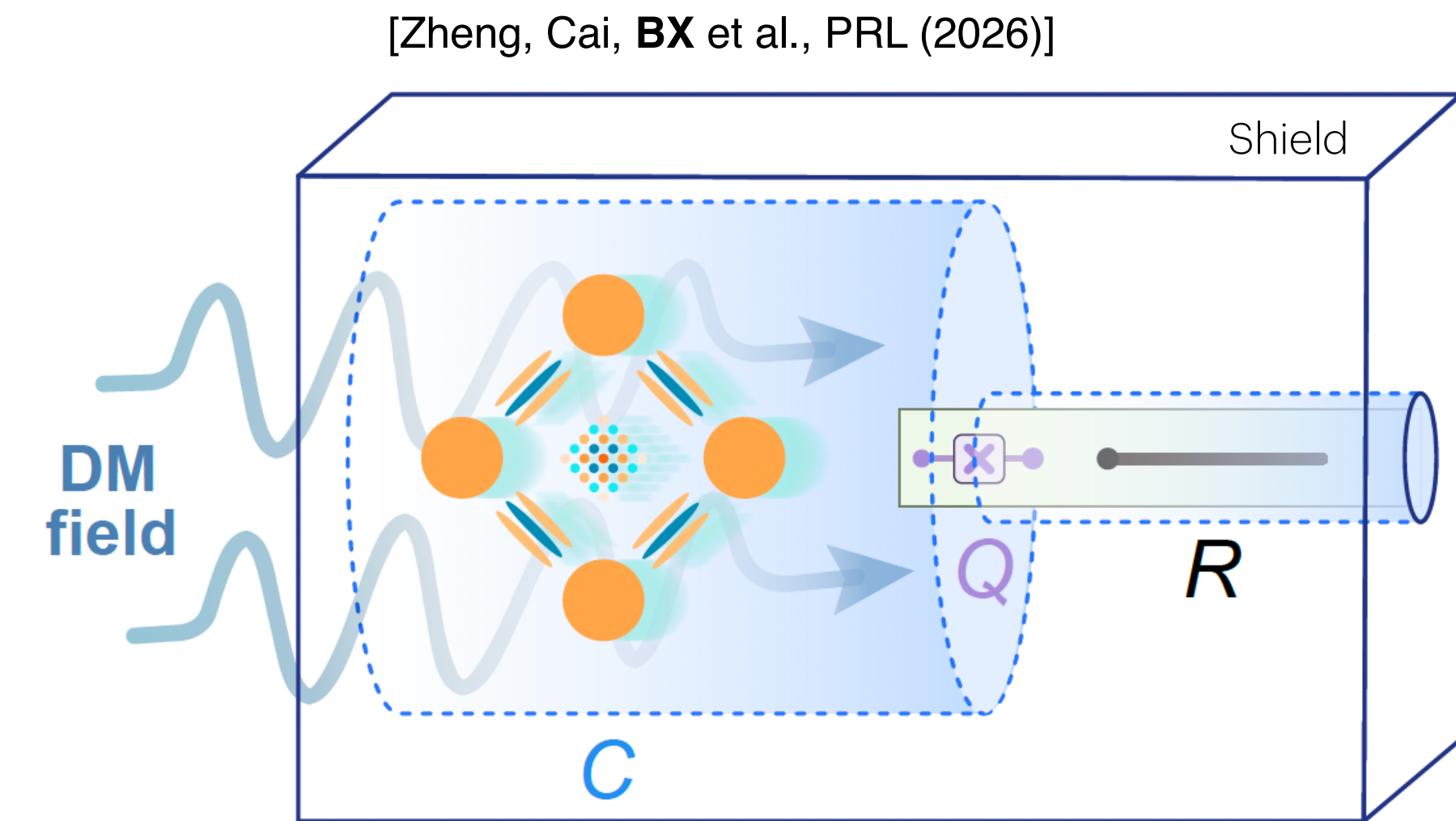
- The DM field acts as a displacement operator:

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

- Cavity QED Hamiltonian:

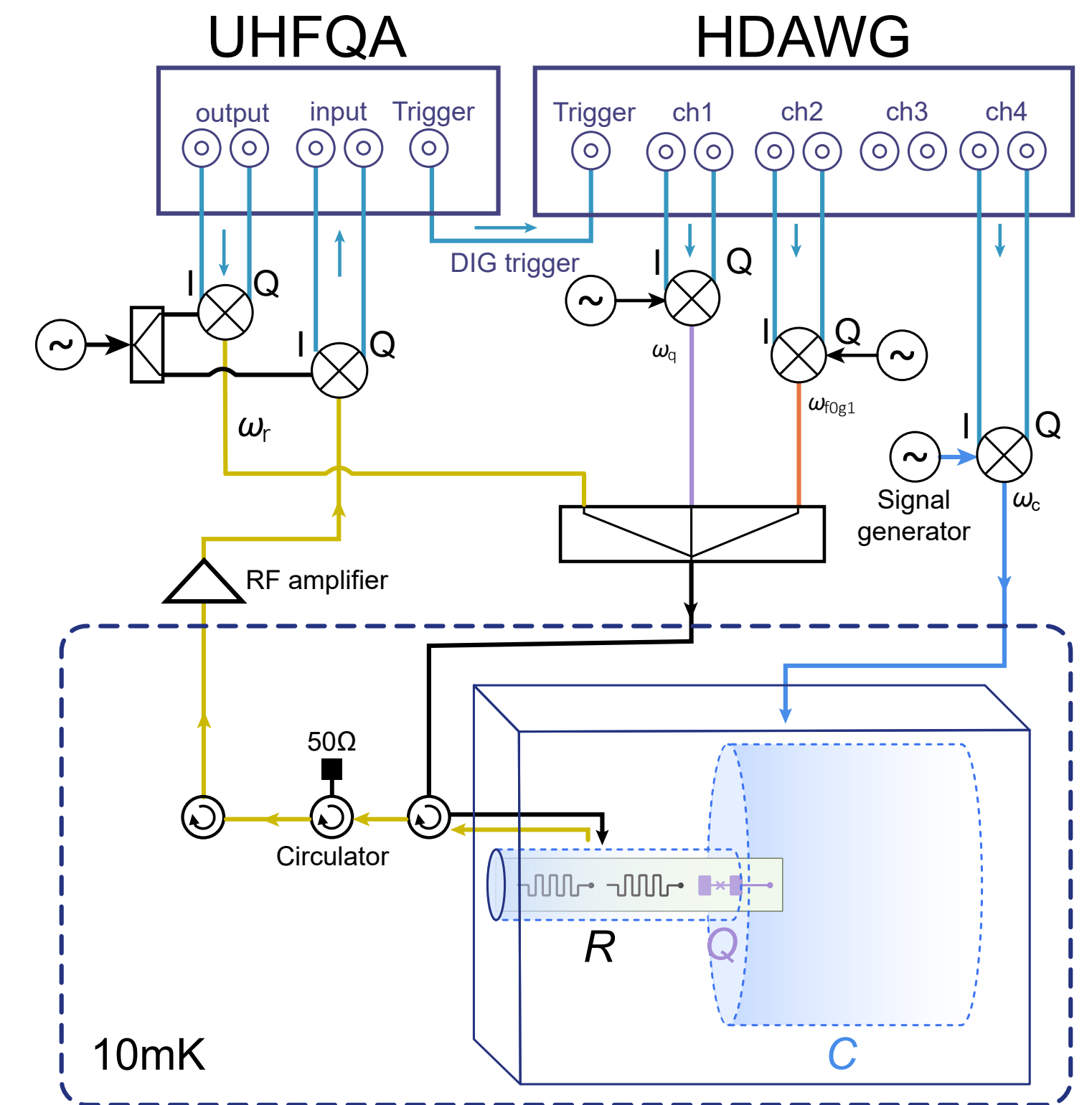
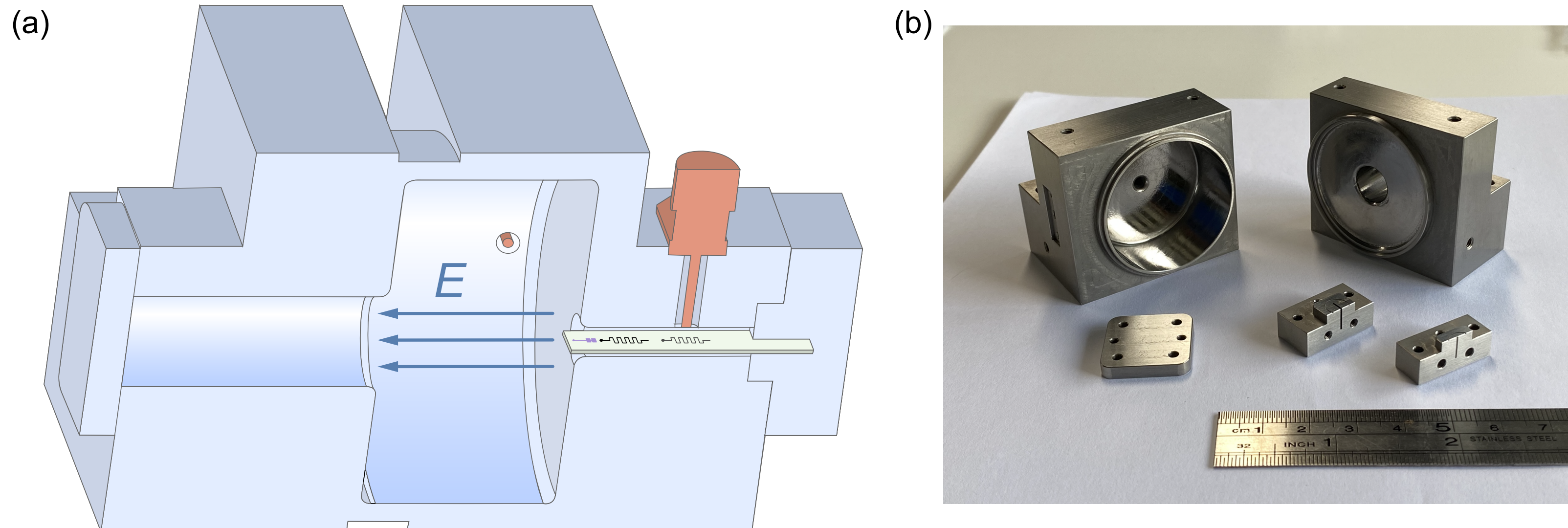
$$H_{CQ} = \underbrace{\omega_c a^\dagger a}_{\text{linear cavity}} + \underbrace{\frac{1}{2} \omega_q \sigma_z}_{\text{two-level "atom"}} + \underbrace{\chi a^\dagger a \sigma_z}_{\text{dispersive coupling}} = \omega_c a^\dagger a + \underbrace{\left(\frac{1}{2} \omega_q + \chi a^\dagger a \right)}_{\text{photon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

- A dispersively coupled qubit enables quantum nondemolition photon-number readout.
- The sensitivity is limited by the residual thermal occupation $\bar{n}_{th} \sim 10^{-3}$



Experimental setup

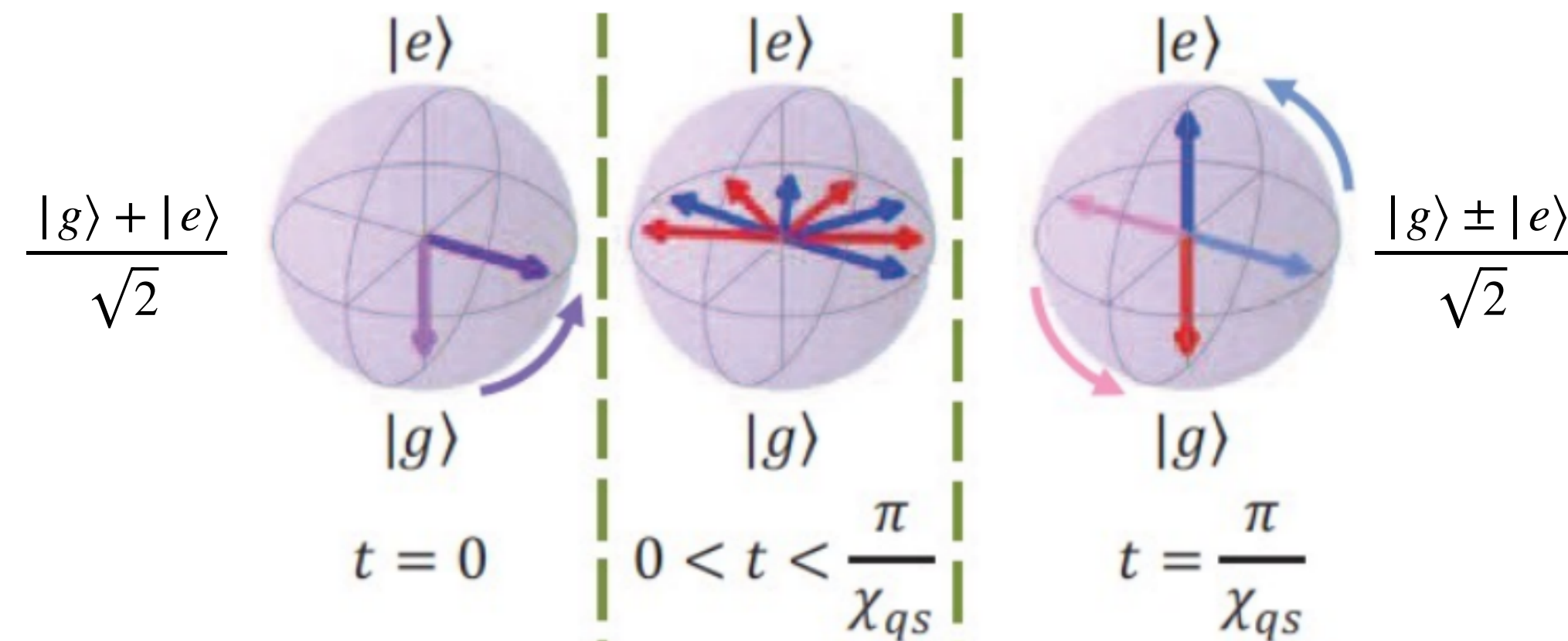
- We built a high- Q superconducting niobium cavity.
- $T_1 = 4.6$ ms, $Q \sim 10^8$



DPDM search with the vacuum state

- Ramsey interferometry

$$H_{int} = 2\chi a^\dagger a \frac{\sigma_z}{2}$$

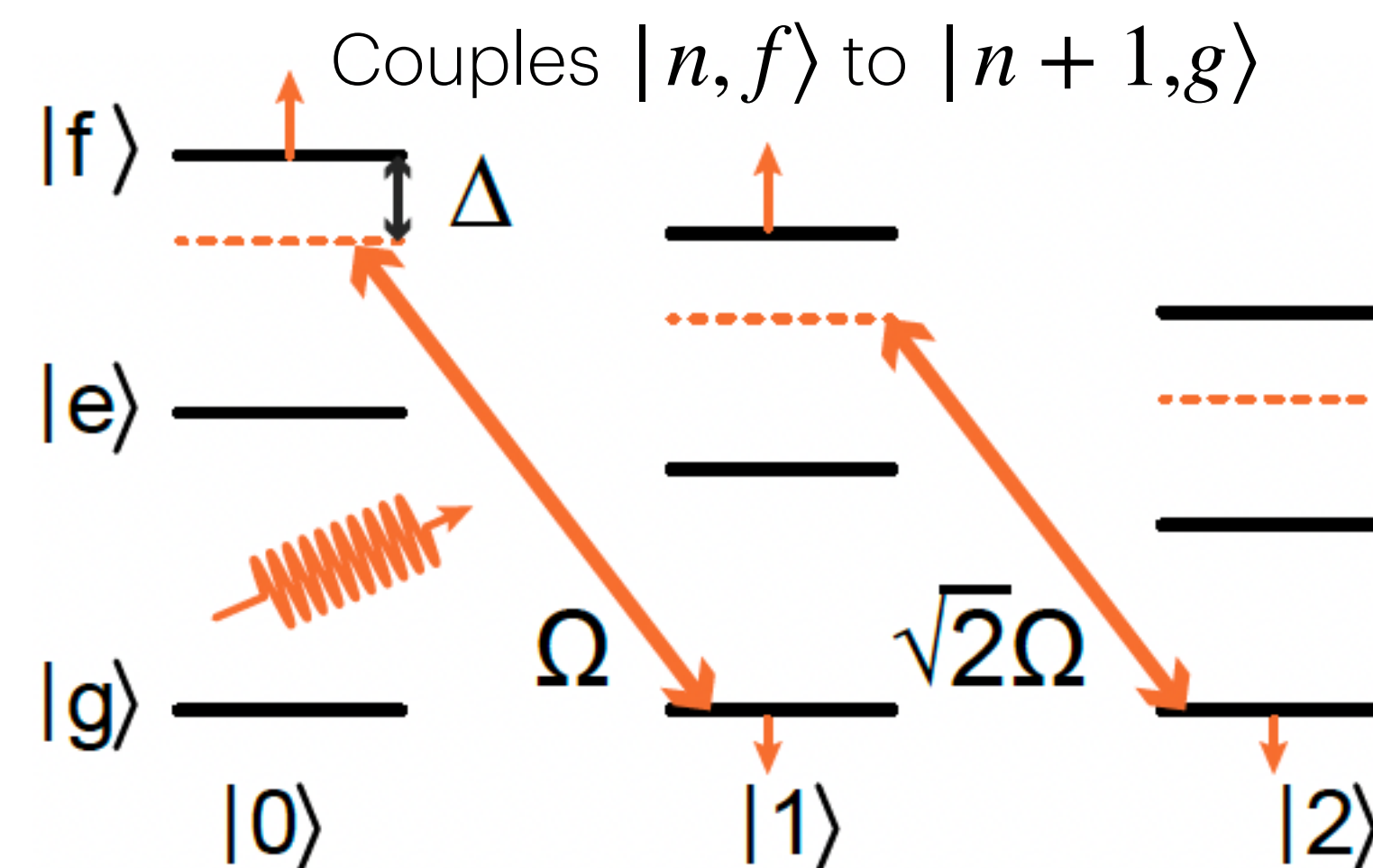


$$e^{-iH_{int}t}(|g\rangle + |e\rangle)/\sqrt{2} = (e^{i\frac{n}{2}\chi t}|g\rangle + e^{-i\frac{n}{2}\chi t}|e\rangle)/\sqrt{2}$$

- Sideband tuning: $H_d = \frac{\Omega}{2} a^\dagger |g\rangle \langle f| e^{i\Delta t} + \text{h.c.}$

$$H_{\text{eff}} \sim \frac{\Omega^2}{4\Delta} a^\dagger a |g\rangle \langle g|$$

provides an O(100) kHz scan range.



DPDM search using cat states

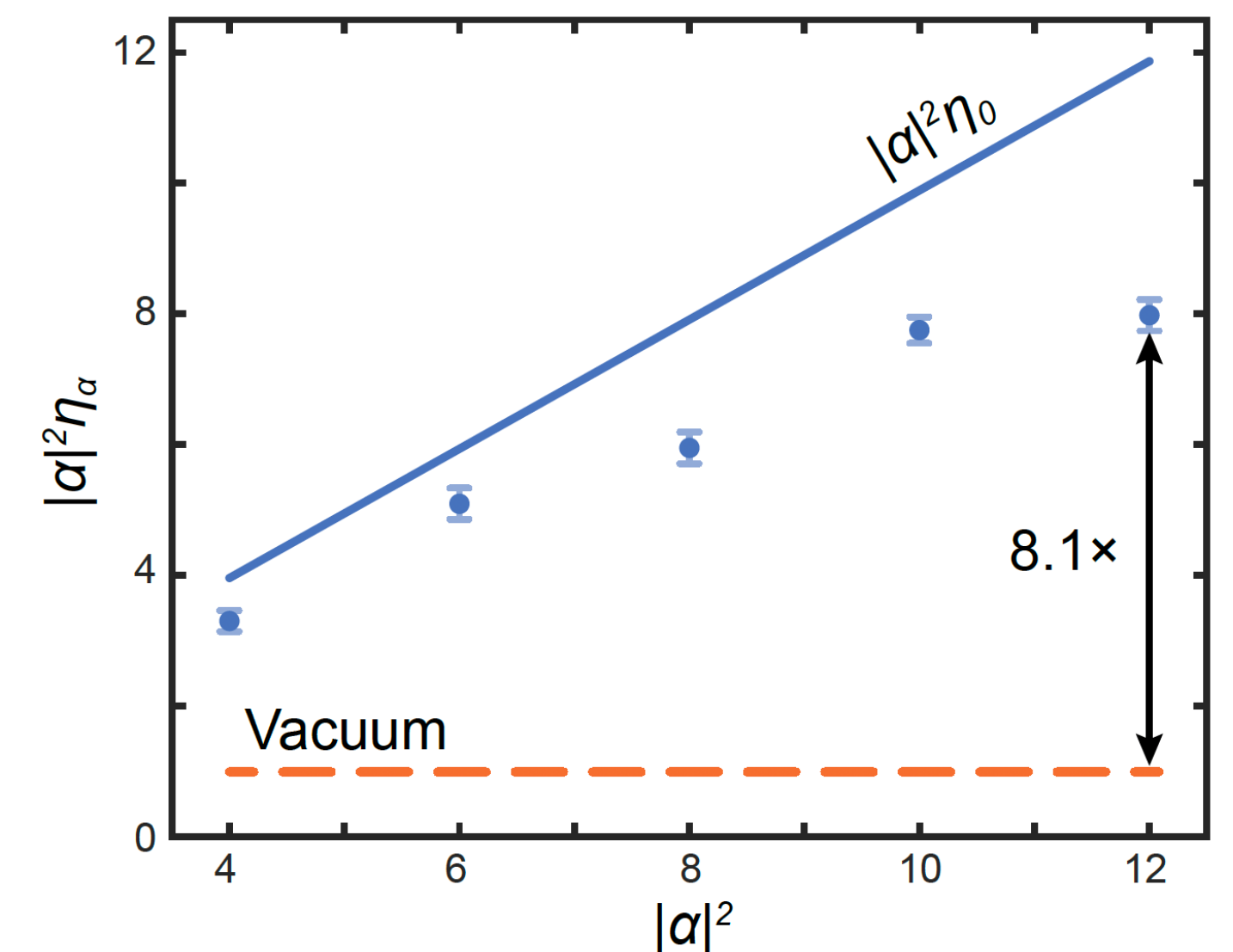
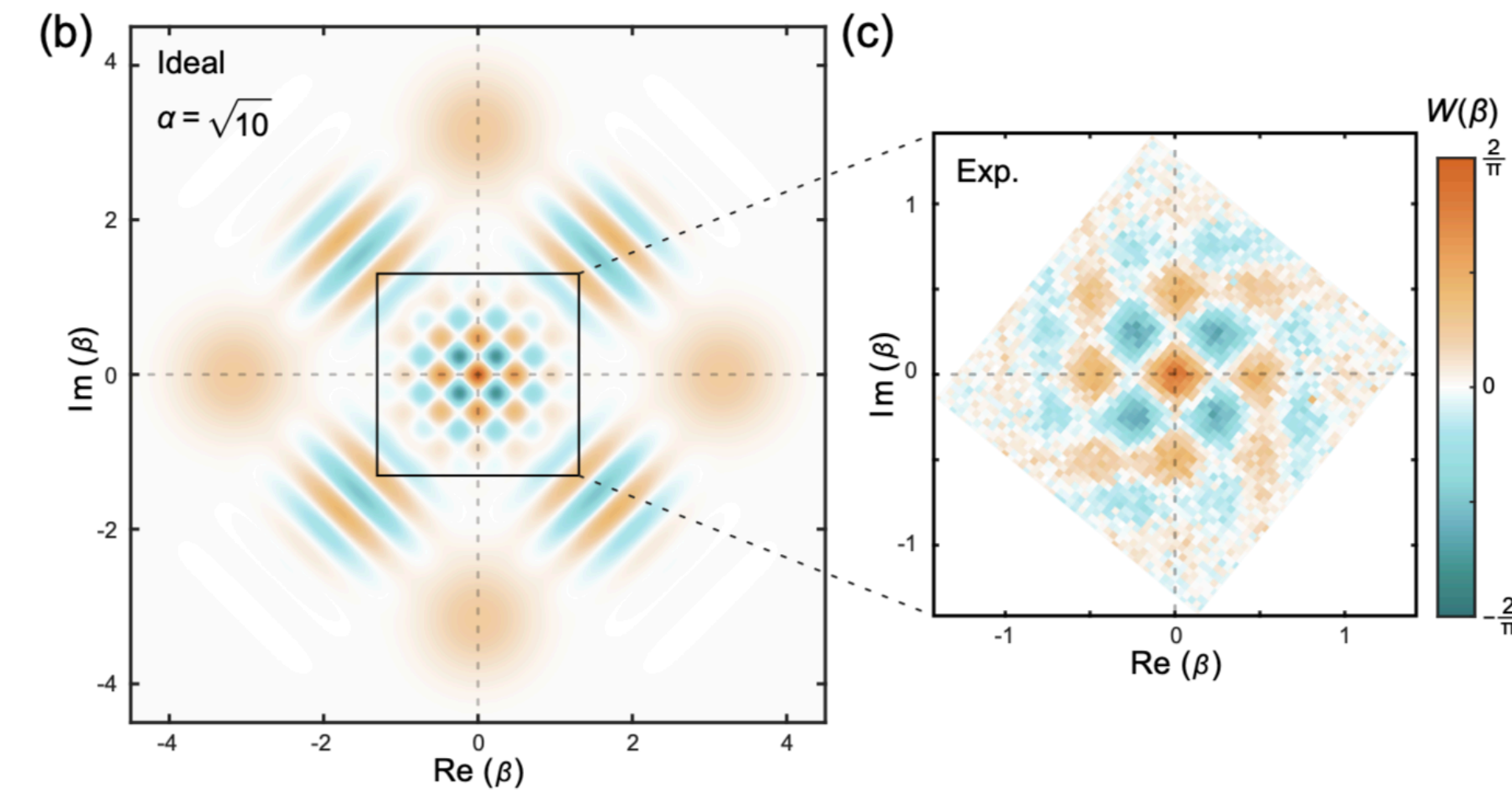
- We use a four-component cat state (compass state)
- Prepare: $|\phi_0(\alpha)\rangle \propto |\alpha\rangle + |-\alpha\rangle + |i\alpha\rangle + |-i\alpha\rangle$
- DM-induced displacements populate $|\phi_1(\alpha)\rangle$

while the dominant backgrounds populate $|\phi_3(\alpha)\rangle$

- DM displacement $\left| \langle \phi_1 | \hat{D}(\beta) | \phi_0 \rangle \right|^2 \approx |\alpha|^2 |\beta|^2$

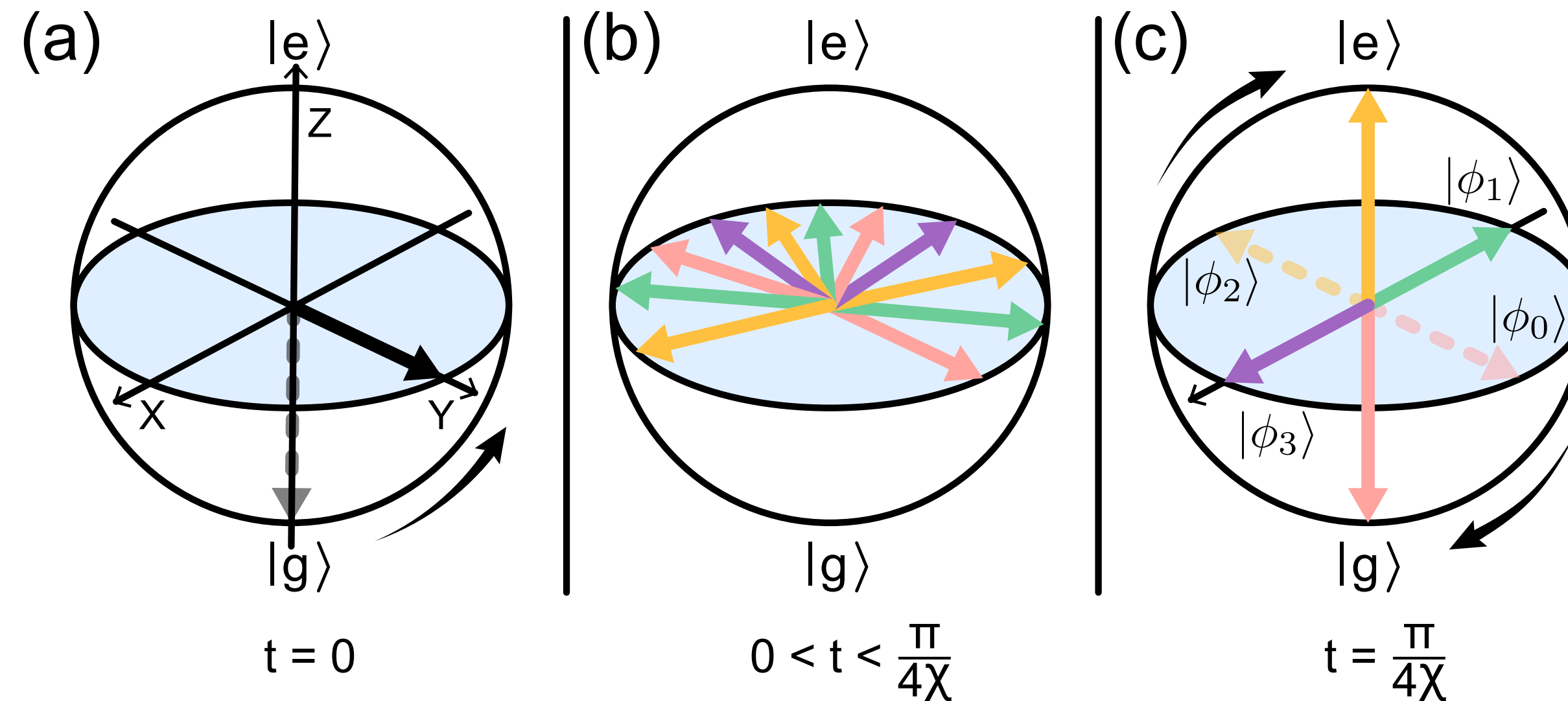
- For $|\alpha|^2 = 12$ and an overall efficiency $\eta = 0.68$,

we obtain an $8.1 \times$ scan-rate enhancement.



Ramsey Interferometry for compass states

- Compass-state readout uses fourfold parity in a Ramsey sequence.



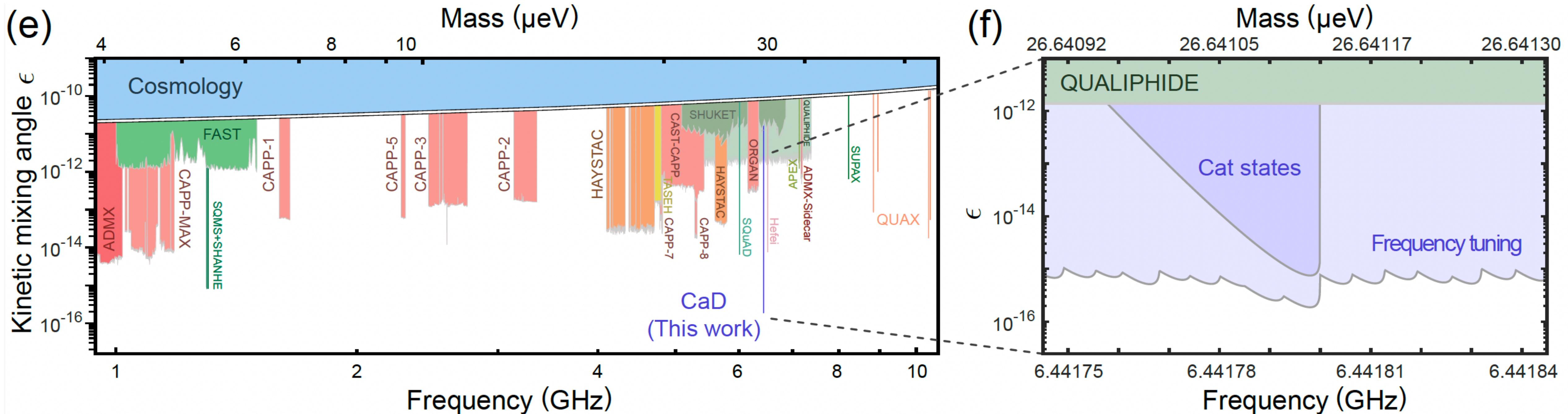
- First, a twofold-parity operation creates: $|\alpha\rangle \otimes |g\rangle \rightarrow |\phi_+\rangle \otimes |g\rangle + |\phi_-\rangle \otimes |e\rangle$
- A subsequent fourfold-parity operation resolves the four compass components:

$$|\phi_+\rangle \otimes |g\rangle \rightarrow |\phi_0\rangle \otimes |g\rangle + |\phi_2\rangle \otimes |e\rangle$$

$$|\phi_-\rangle \otimes |e\rangle \rightarrow |\phi_1\rangle \otimes |e\rangle + |\phi_3\rangle \otimes |g\rangle$$

DPDM search results

- We reach sensitivity to kinetic mixing at the level of $\epsilon \sim 10^{-16}$ near 6.44 GHz



[Zheng, Cai, **BX** et al., PRL (2026)]

Take-home messages

- Wavelike DM acts as a spatially correlated quantum channel.
- Coherence-selective measurements reject uncorrelated noise.
- Geometry-adapted entangled probes can approach the quantum limit.
- Nonclassical cavity states already enhance experimental scan rates.
- Ultimately, distributed sensors may probe the quantum state of DM itself.

Thank you!