Just How Classical is the Axion?

The (In)Feasibility of Detecting Non-Classical Effects

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Based on: arXiv:2510.05198, with Yunjia Bao, Dhong Yeon Cheong, Nicholas Rodd, Lian-Tao Wang, Kevin Zhou

The Half-Quantum Story

The **classical** axion field couples to the **quantum** cavity haloscope

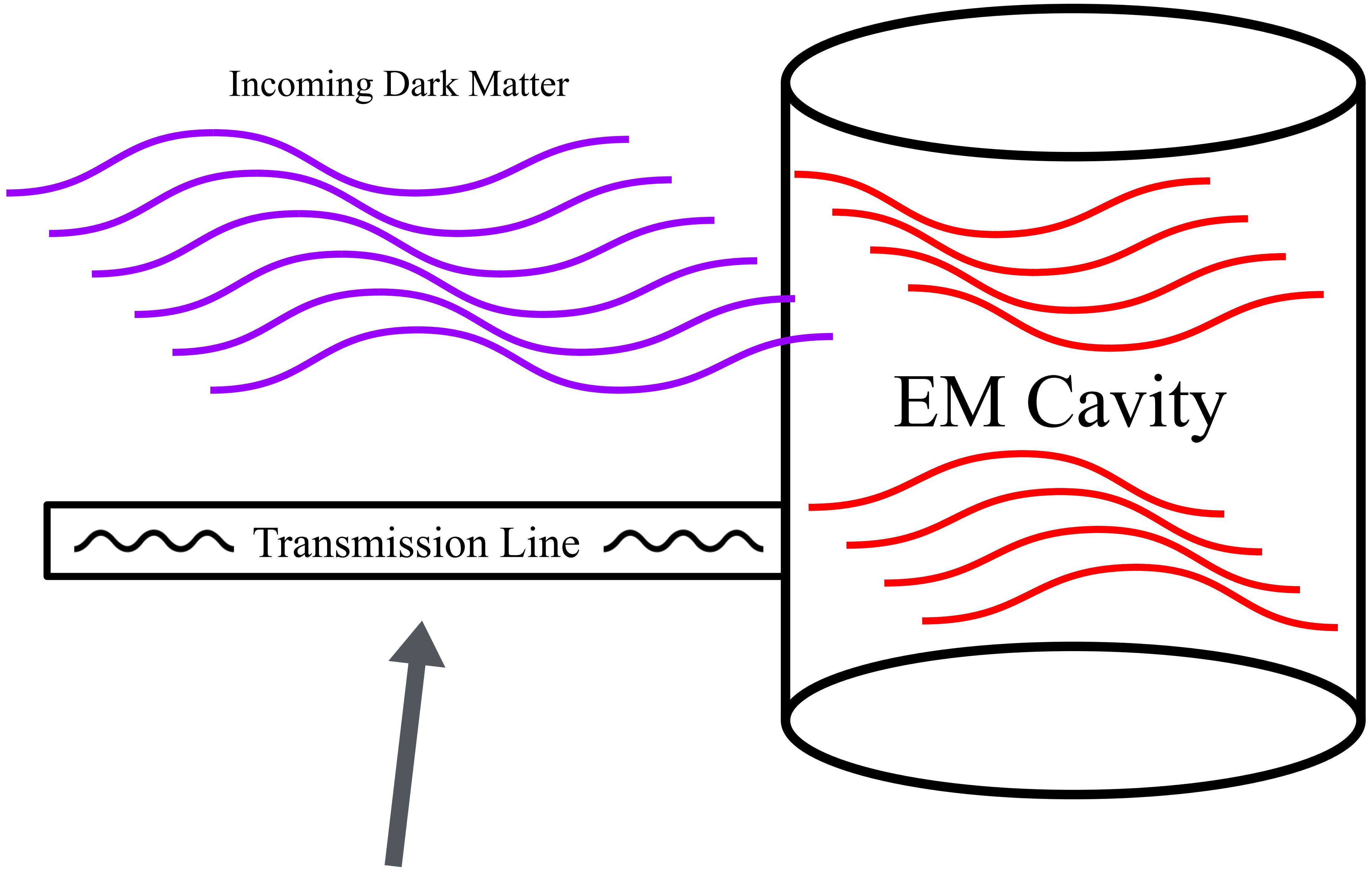
$$\phi_{cl}(\mathbf{x}, t) = \sum_{\mathbf{k}} A_{\mathbf{k}} \cos(\omega_{\mathbf{k}} t - \mathbf{k} \cdot \mathbf{x})$$

$$H_{\text{int}}(t) = g_{a\gamma\gamma} B_0 \int_V d^3\mathbf{x}\, \phi_{cl}(\mathbf{x}, t) \hat{E}_z(\mathbf{x})$$

$$= ig\alpha(t)(\hat{c} - \hat{c}^\dagger)$$

Classical Drive

Quantum Cavity



Quantum Readout —> sub SQL?

Why the Axion is(n't) Classical

Bedtime Stories for Axion Physicists

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1. "The enormous occupation number implies classicality"

$$n_{\mathrm{DM}} V_{\mathrm{dB}} \approx \frac{\rho_{\mathrm{DM}}}{m_a\,(m_a v_{\mathrm{DM}})^3} \approx \left(\frac{10\,\mathrm{eV}}{m_a}\right)^4$$

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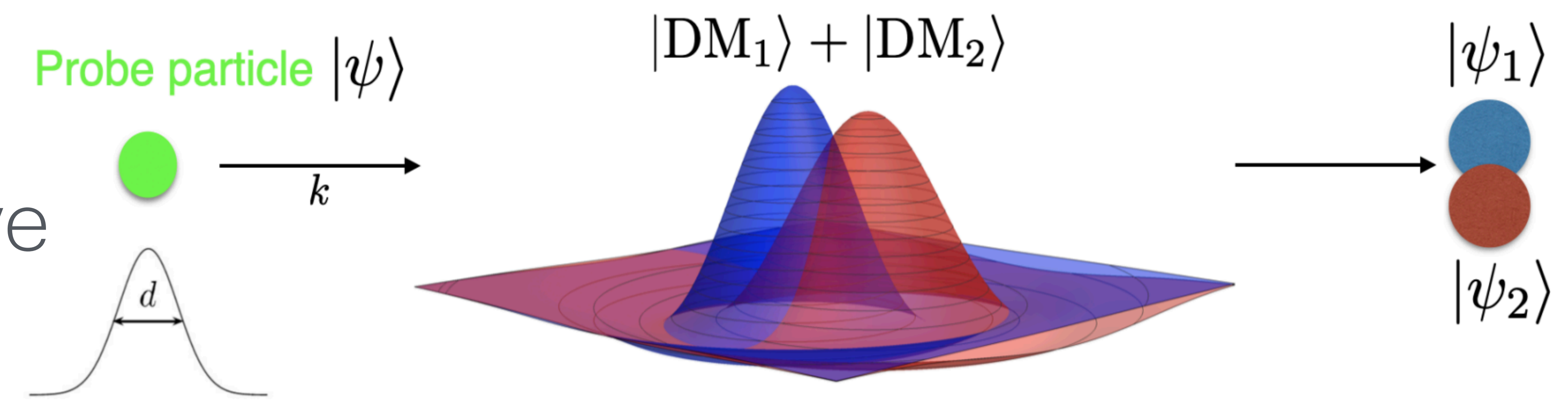
3. "Decoherence washes out non-classicality"

Spatial superpositions die, but others can survive

$$|{\rm cat}\rangle \propto |\alpha\rangle + |-\alpha\rangle$$



Allali and Hertzberg, PRL (2021)

So….. what is the axion's quantum state?

We don't know, but we can refine the question:

1. What does it mean for a general quantum state to be "non-classical"? What about for a quantum field?

2. Even if the axion does possess this "non-classicality", how does it imprint on observables we can measure?

Target: Measures of non-classicality are heavily suppressed by powers of our detector efficiency, and are effectively unobservable.

What Makes a State "Non-Classical"?

Start with states that are *the most* classical, i.e. coherent states:

$$\rho = |\alpha\rangle\langle\alpha| \quad \Longrightarrow \quad \rho(t) = |\alpha e^{-i\omega t}\rangle\langle\alpha e^{-i\omega t}|$$

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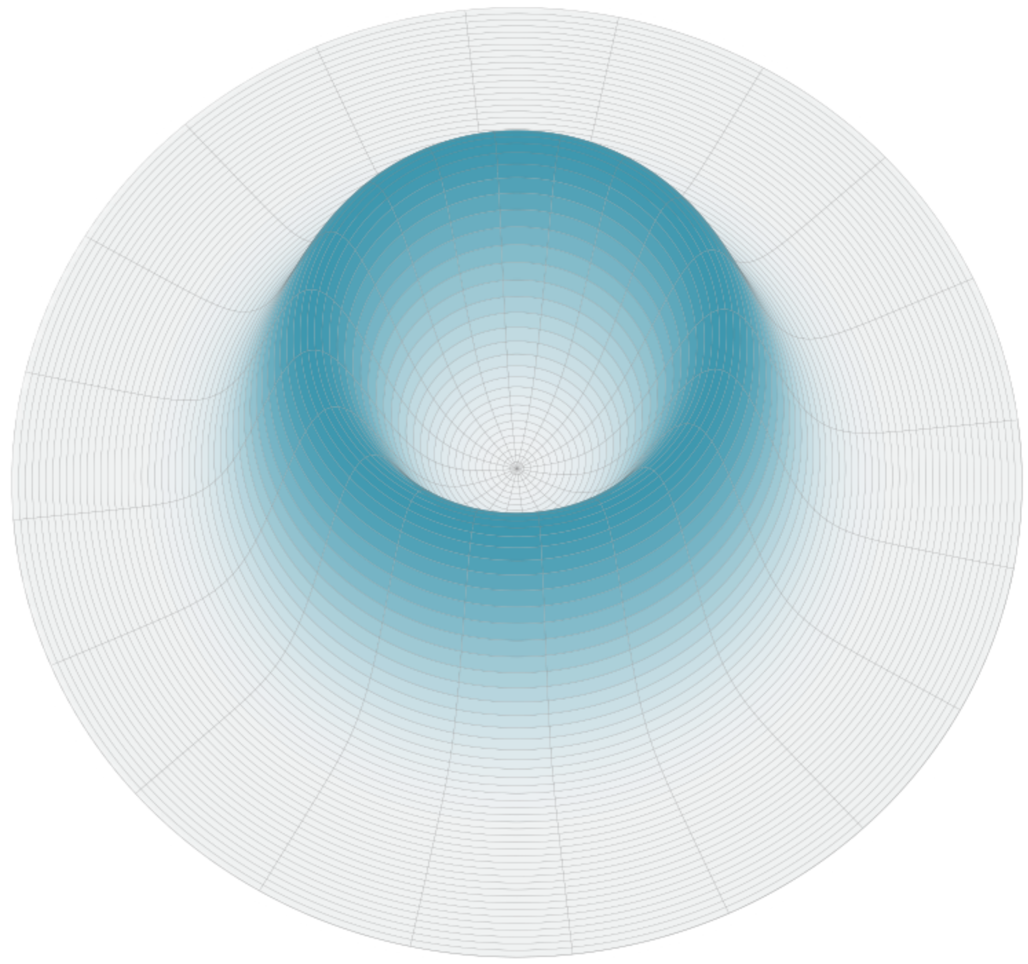

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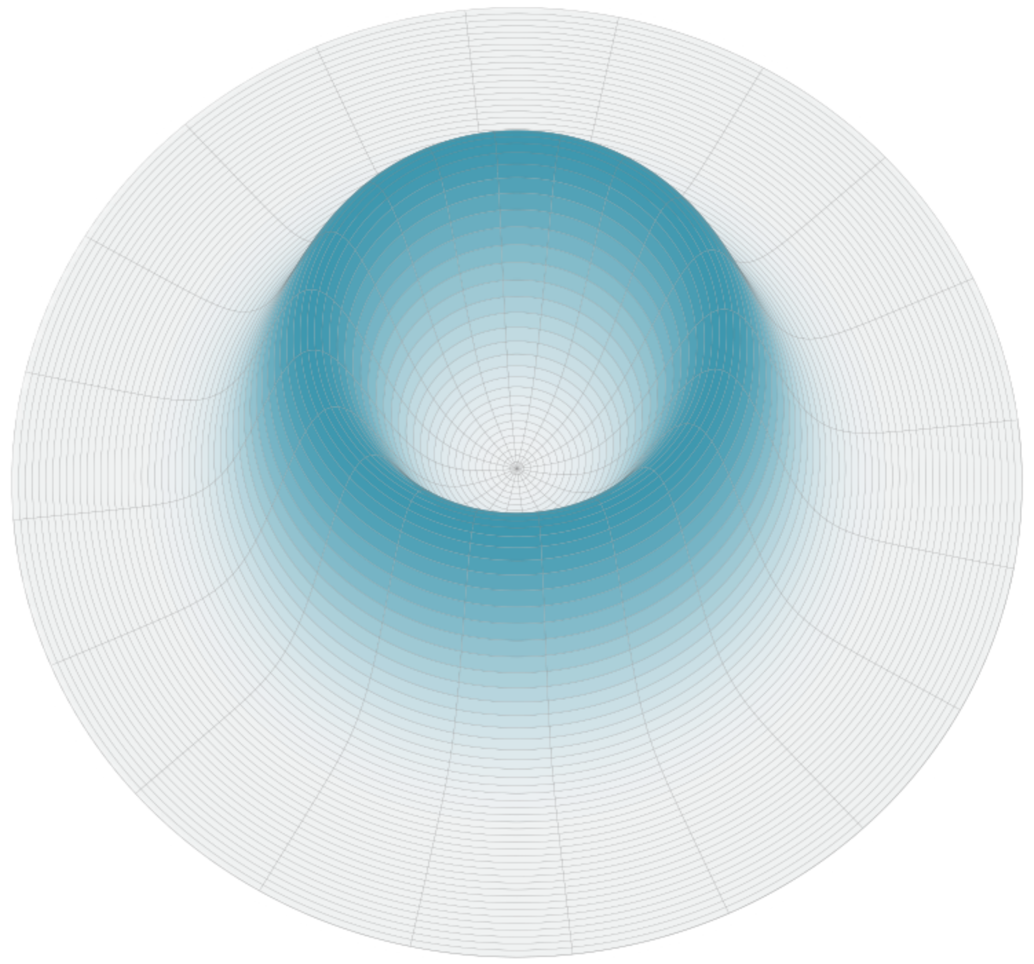

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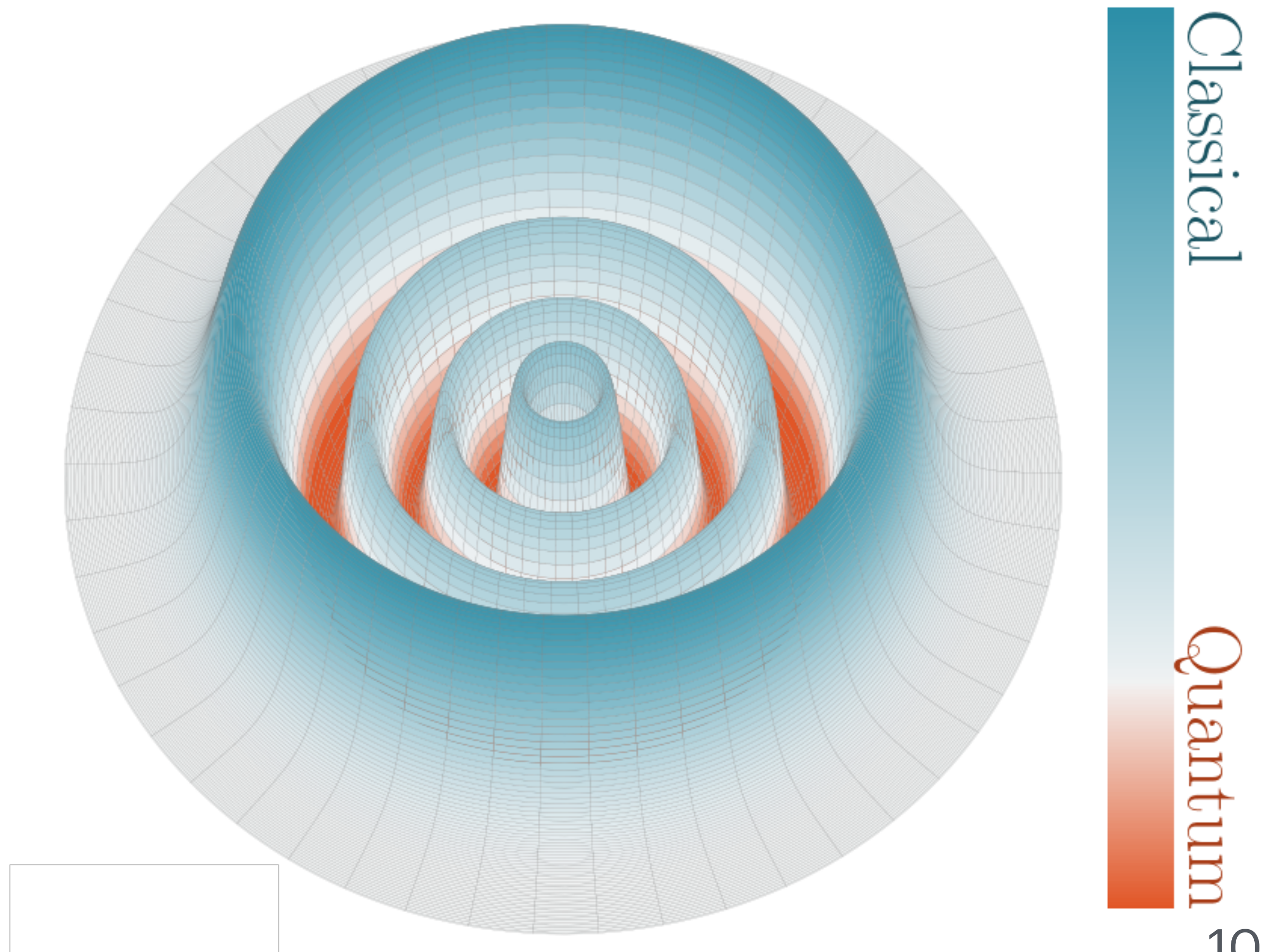

Glauber (1963): We can generalize to *all* states by letting $P(\alpha) < 0$
+ Sudarshan

Non-Classicality $\iff$ P-Function Negativity

Quantum States of Quantum Fields?

We just generalize: $\alpha \longrightarrow \boldsymbol{\alpha} = \{\alpha_{\mathbf{k}}\}$

$$\rho_{\text{DM}} = \int d^2\boldsymbol{\alpha}\, P_{\text{DM}}(\boldsymbol{\alpha})\,|\,\boldsymbol{\alpha}\rangle\langle\boldsymbol{\alpha}\,|$$

Joint quasi-probability density for each axion mode

How do we Probe P-negativity?

Unfortunately, there is no experiment that can ever fully determine an entire P-function.

So what *can* we learn about a state's P-function? → **Moments!**

Measure $\langle \hat{N} \rangle$, reconstruct: $\langle \hat{N} \rangle = \mathrm{Tr}\{\hat{a}\rho\hat{a}^\dagger\} = \int d^2\alpha\, P(\alpha)\,|\alpha|^2 = \langle\, |\alpha|^2 \rangle_P$

Measure $\langle \hat{X} \rangle$, reconstruct: $\langle \hat{X} \rangle = \frac{1}{\sqrt{2}}\left\langle \hat{a} + \hat{a}^\dagger \right\rangle = \frac{1}{\sqrt{2}}\left(\langle \alpha \rangle_P + \langle \alpha^* \rangle_P \right)$

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To probe quantumness, construct "smoking gun" statistics:

eg, Mandel Q: $$Q = \frac{1}{\langle |\alpha|^2 \rangle_P}\Big(\underbrace{\langle |\alpha|^4 \rangle_P - \langle |\alpha|^2 \rangle_P^2}_{\text{" Var}(|\alpha|^2)\text{ "}}\Big) \geq -1$$

$Q < 0 \implies$ **Non-Classical!**

The Fully Quantum Story

Same interaction: $$H_{\text{int}} = g_{a\gamma\gamma}\, B_0 \int_V d^3\mathbf{x}\, \hat{\phi}(\mathbf{x}) \hat{E}_z(\mathbf{x})$$

Quantum Axion Field: $$\hat{\phi}(\mathbf{x}) = \sum_{\mathbf{p}} \frac{1}{\sqrt{2\omega_p \mathscr{V}}} (\hat{a}_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}} + \text{h.c.})$$

Rewrite Interaction: $$H_{\text{int}} = ig(c^\dagger a_{\text{eff}} - c a_{\text{eff}}^\dagger)$$ (ignoring terms like ca , $c^\dagger a^\dagger$, RWA)

$$a_{\text{eff}} = \sum_{\mathbf{p}} C_{\mathbf{p}}\, a_{\mathbf{p}} \quad , \quad [a_{\text{eff}}, a_{\text{eff}}^\dagger] = 1$$

Cavity - DM mode form factors

The Quantum Central Limit Theorem

All cavity observables depend only on $a_{\text{eff}} = \sum_{\mathbf{p}} C_{\mathbf{p}} a_{\mathbf{p}}$

Therefore all statistics we can observe are given by an "effective P-function":

$$P_{\text{eff}}(\alpha) = \underbrace{\int d^2\boldsymbol{\alpha}\, P_{\text{DM}}(\boldsymbol{\alpha})\delta^2\Big(\alpha - \sum_{\mathbf{p}} C_{\mathbf{p}}\alpha_{\mathbf{p}}\Big)}_{\text{Convolution/Marginalization}}$$

Barring strong inter-mode correlations:

QCLT $\Longrightarrow$ $$P_{\text{eff}}(\alpha) \approx \frac{1}{\pi N_{\text{eff}}} \exp\left\{-\frac{|\alpha|^2}{N_{\text{eff}}}\right\}$$ Classical!!

Maximal Optimism - No QCLT

$H_{\text{int}} = ig(c^\dagger a_{\text{eff}} - c a_{\text{eff}}^\dagger)$ ⟶ Short evolution, then measure cavity

P-function evolution: $P_{\text{cav}}(\alpha) = \frac{1}{\eta} P_{\text{eff}}(\alpha/\sqrt{\eta})$

$$\eta = \sin^2(gt) \sim 10^{-14} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\text{GeV}^{-1}} \frac{B_0}{10\,\text{T}} \frac{Q_c}{10^6} \frac{10^{-5}\,\text{eV}}{m_a} \right)^2 \qquad (t = Q_c/m_a)$$

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All moments suppressed by increasing powers of, η eg $Q_{\text{cav}} = \eta Q_{\text{eff}} \geq -\eta$

Maximally optimistic time to measure negative Q is $$t_m/\eta^2 \sim 10^{10}\,\text{years} \left(\frac{10^{-12}\,\text{GeV}^{-1}}{g_{a\gamma\gamma}} \frac{30\,\text{T}}{B_0} \right)^4 \left(\frac{10^6}{Q_c} \frac{m_a}{10^{-6}\,\text{eV}} \right)^3$$

Conclusions

- Even if the DM state is “highly quantum”, **we will not be able to tell**
- All non-classicality contained in higher moments of the P-function, which are heavily suppressed by the detection efficiency
- It will be **indistinguishable** from a state with classical statistics $P_{\mathrm{DM}}(\boldsymbol{\alpha}) \geq 0$

Thank You!