Suppressed Quantum Effects of Weakly Coupled Waves

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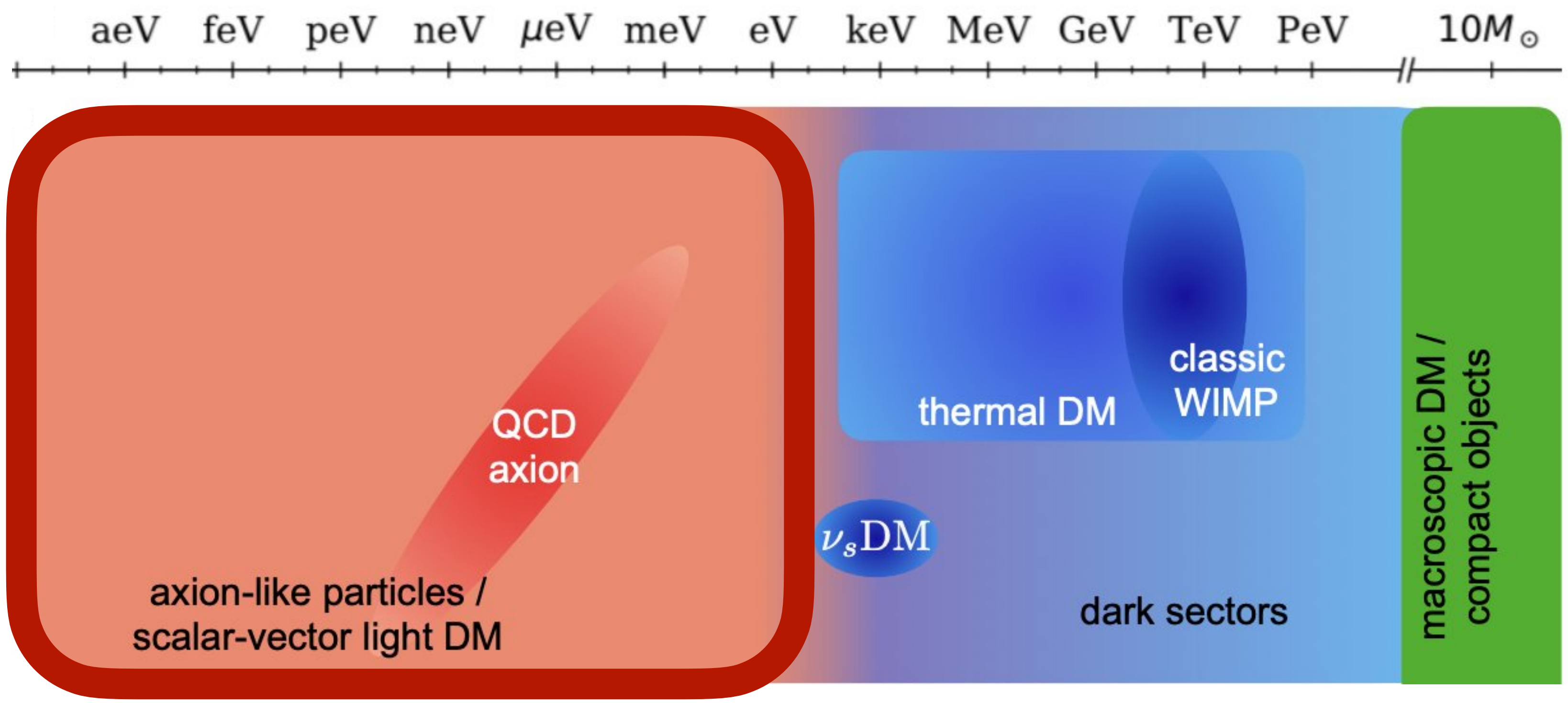
with Yunjia Bao, Dhong Yeon Cheong, Nicolas Rodd, Joey Takach, Lian-Tao Wang

Why Search for Ultralight Dark Matter?



- Simply produced: gives right amount of dark matter with minimal cosmology
- Generic: required ultralight fields automatically appear in many models
- Minimal: requires introduction of only a single new field at low energies
- Low-hanging fruit: new experiments are needed, inexpensive, and very effective
- Bounded: only a few interactions are natural and leading in effective field theory

Ultralight Dark Matter Candidates

In field theory, only a few candidates are possible!

	pseudoscalar a	scalar ϕ	vector A'_μ	tensor $h'_{\mu\nu}$
naturally light with leading coupling	✓		✓	✓?
arises in high energy theories	✓✓	✓	✓	
can solve tuning problems	✓	?		
simply produced	✓	✓	✓?	?

$$\boxed{(\partial_\mu a)\, K^\mu_{\mathrm{EM}}}$$

axion-photon

$$(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N$$

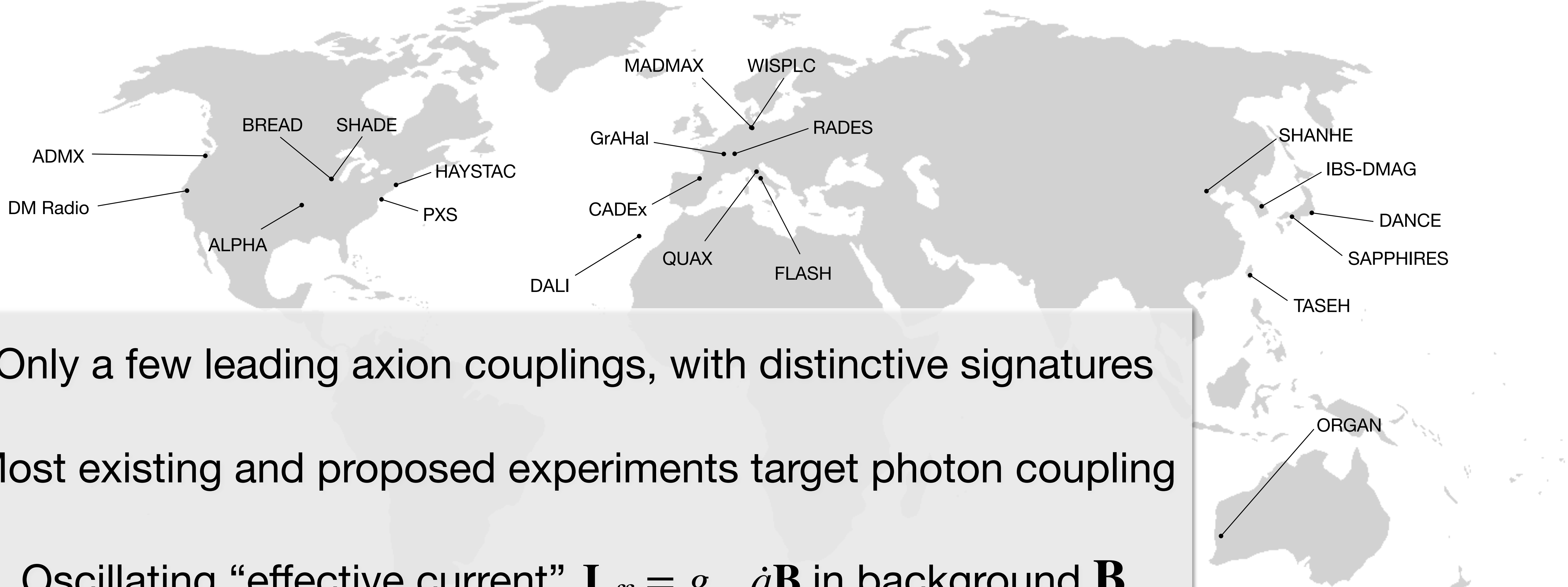
axion-nucleon

$$(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e$$

axion-electron

$$a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu}$$

axion-EDM

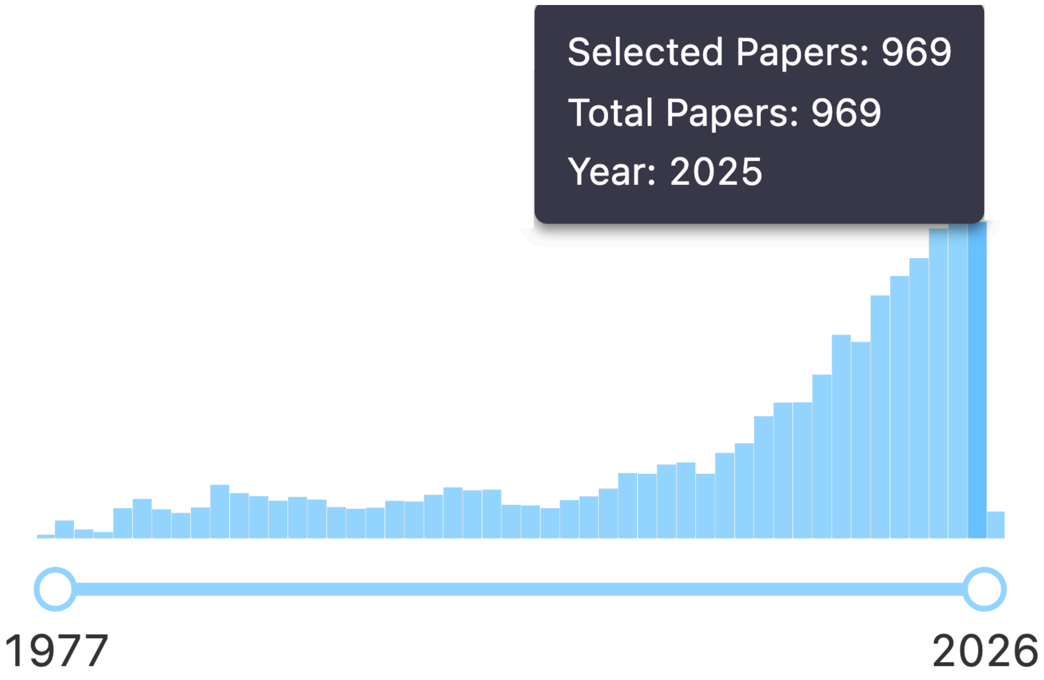


Only a few leading axion couplings, with distinctive signatures

Most existing and proposed experiments target photon coupling

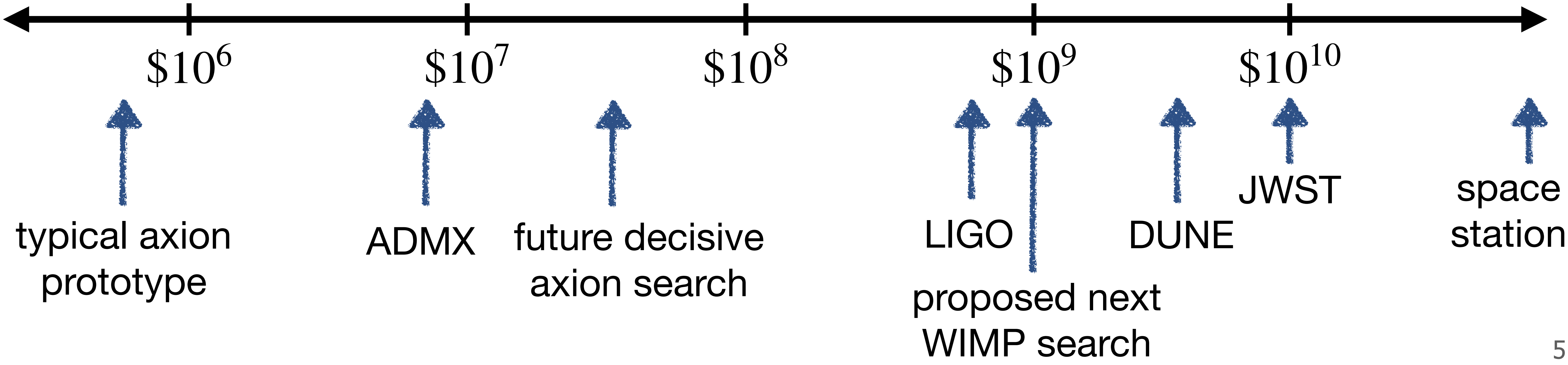
Oscillating "effective current" $\mathbf{J}_{\mathrm{eff}} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$ in background $\mathbf{B}$ sources secondary, detectable electromagnetic fields

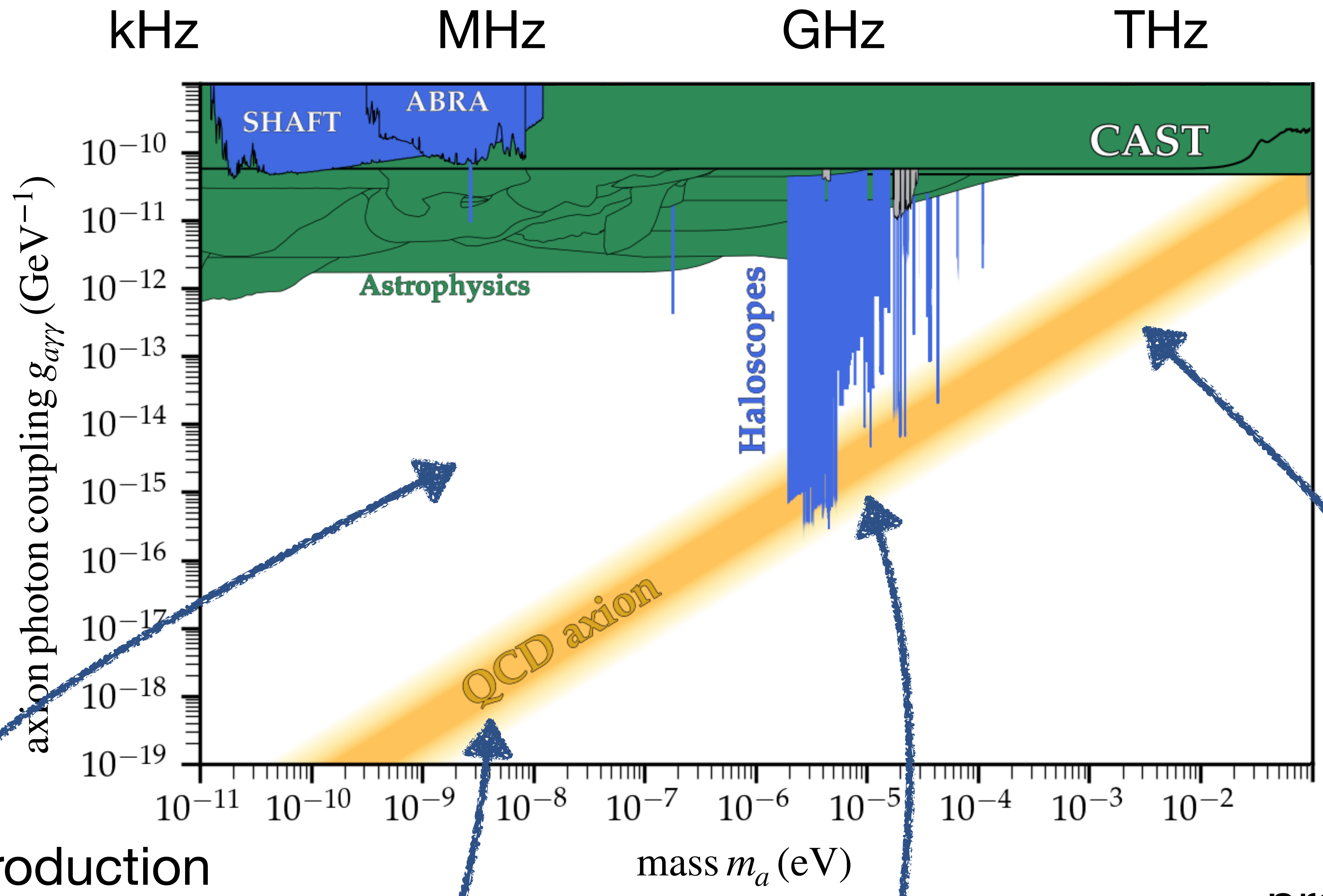
Axion Dark Matter Searches in 2026



Subject of much excitement among both theorists and experimentalists, but **not** a finished subject

Like gravitational wave detection in 1970s: some confusion over foundations, some small prototypes, new methods still being discovered, yet to scale up



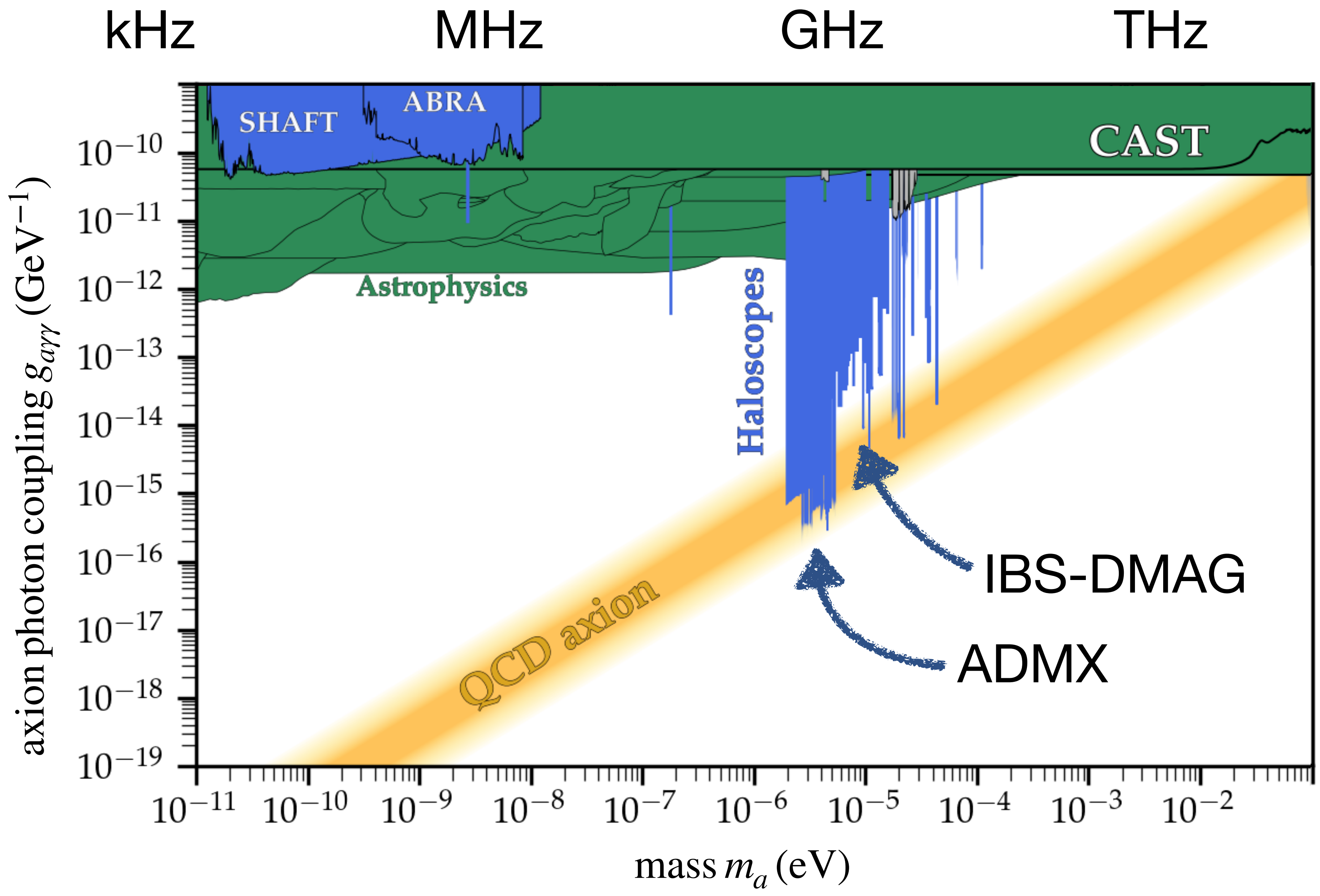


misalignment production of non-QCD axion

post-inflation production of QCD axion

QCD axions at grand unification scale

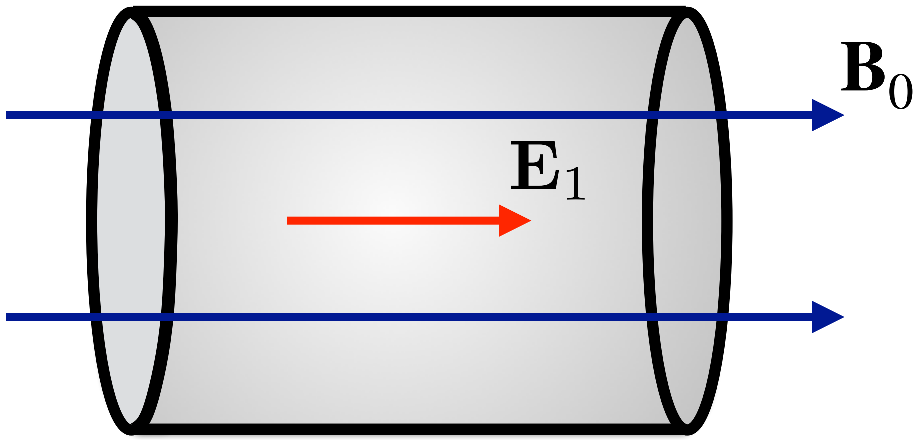
misalignment production of QCD axion



Only the axion-photon coupling has been probed significantly, and only around $f \sim \mathrm{GHz}$, largely by two experiments using the same method

GHz Axions: The Cavity Haloscope

In background $\mathbf{B}_0$, axion drives cavity mode with profile $\mathbf{E}_1$



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

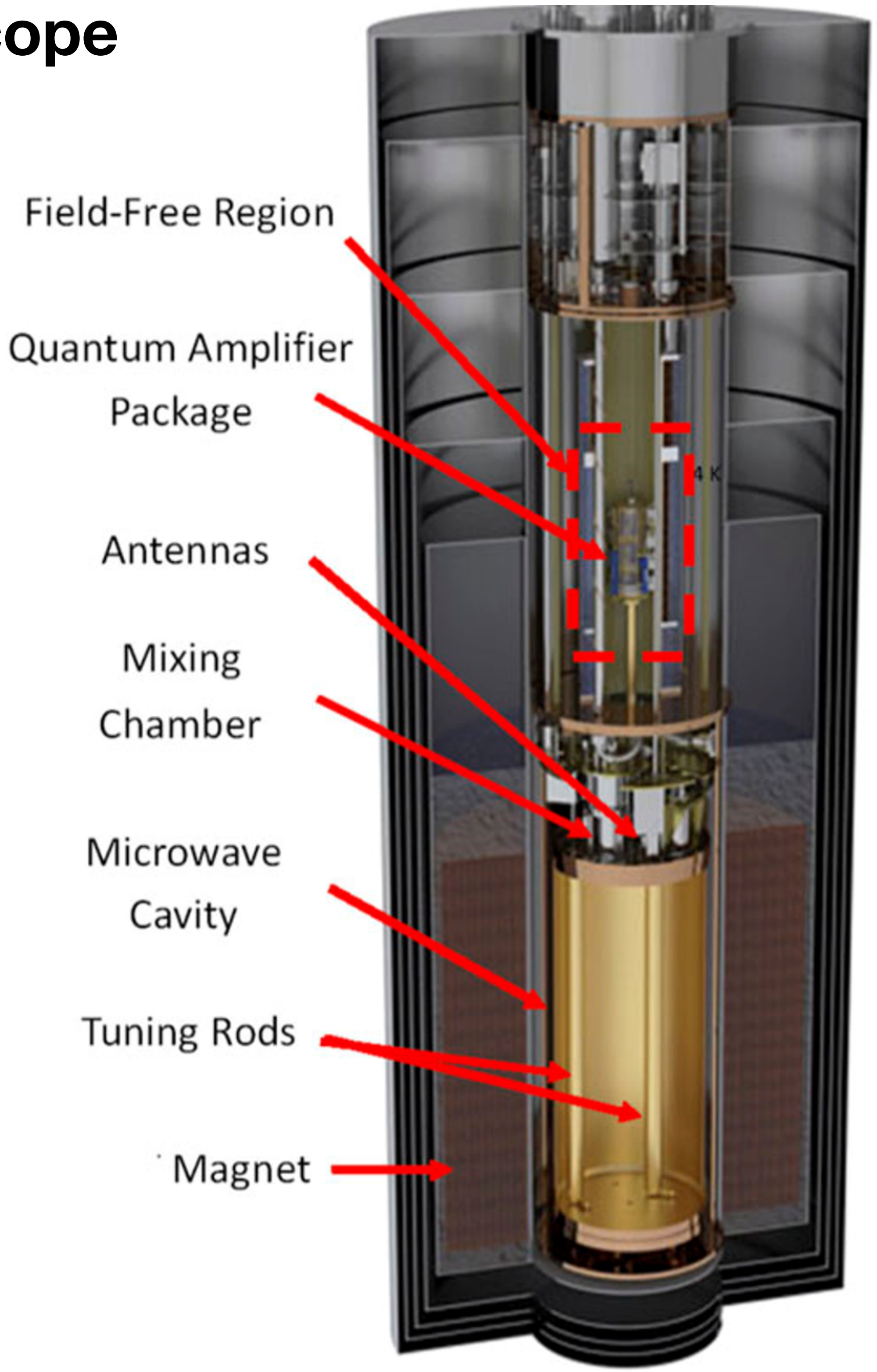
$$\dot{a}(t) = \sqrt{\rho_{\text{DM}}}\,\cos(m_a t)$$

$$P_{\text{sig}} \sim (g_{a\gamma\gamma}^2 \rho_{\text{DM}})\,(B_0^2 V)\,(Q_1/\omega_1)$$

magnetic energy in cavity

decay time of cavity mode $\omega_1 \simeq m_a$

Cavity haloscopes now operate in the quantum regime, will be central example of this talk



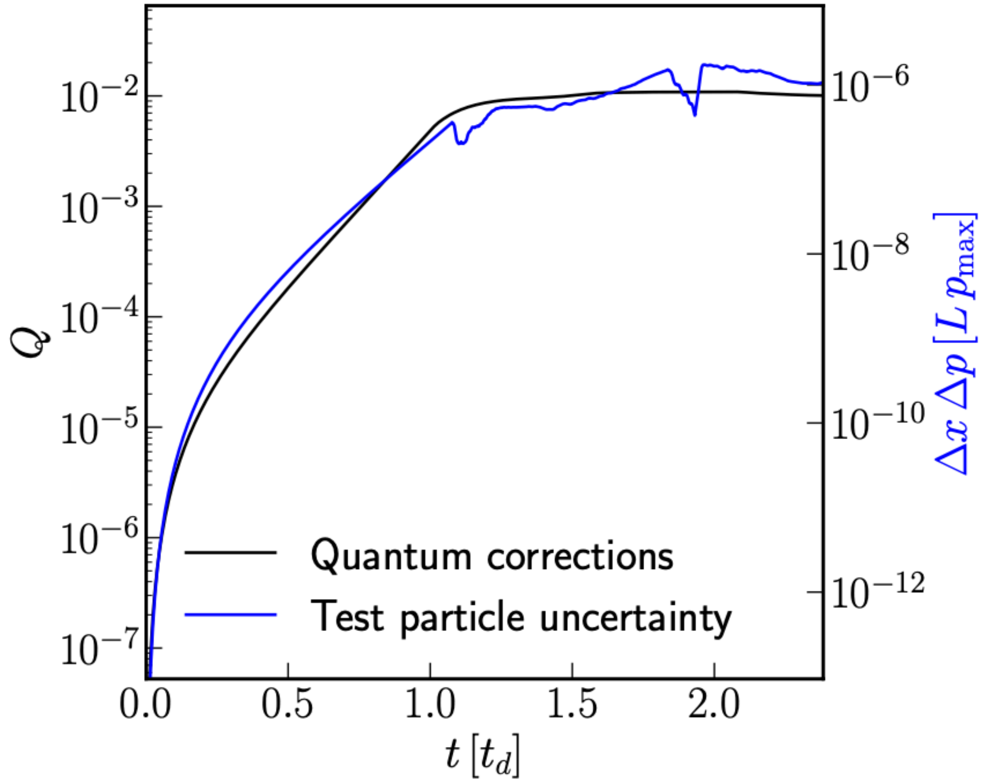
Why can the axion be treated as a classical field?

“Because the average mode occupancy $N \sim \dfrac{\rho_{\mathrm{DM}}}{m_a (m_a v_{\mathrm{DM}})^3} \sim \left(\dfrac{10\,\mathrm{eV}}{m_a}\right)^4$ is high”

Most states, even with large N, are intrinsically quantum!

“Because misalignment produces the axion in a coherent state”

Foundational works confused “coherent oscillation” with “coherent state”!



Misalignment doesn’t actually make coherent state, and inflation squeezes the state

In gravitational collapse, deviations from coherent state grow exponentially

Eberhardt et al., PRD (2024)

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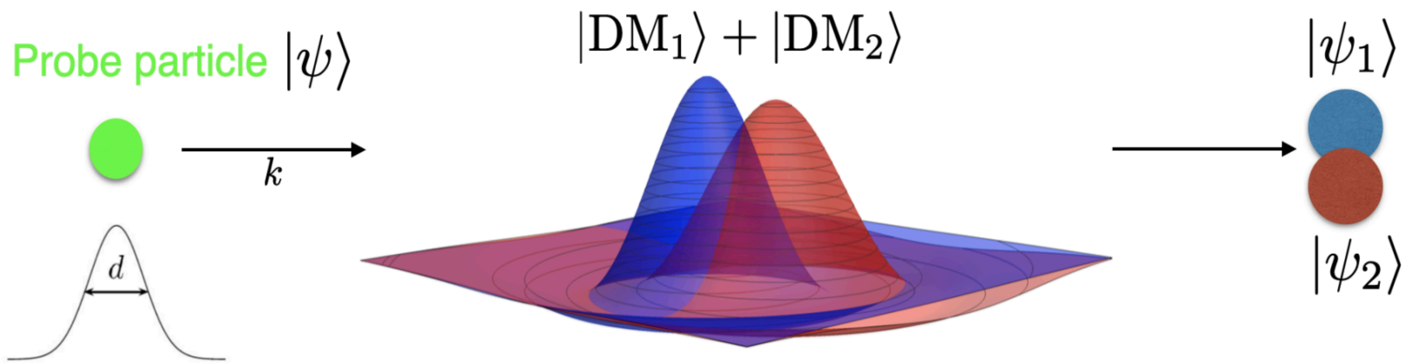
"Because the average mode occupancy $N \sim \dfrac{\rho_{\rm DM}}{m_a\,(m_a v_{\rm DM})^3} \sim \left(\dfrac{10\,{\rm eV}}{m_a}\right)^4$ is high" F-

Most states, even with large N, are intrinsically quantum!

"Because misalignment produces the axion in a coherent state" D

Foundational works confused "coherent oscillation" with "coherent state"!

"Because intrinsically quantum states would decohere" C



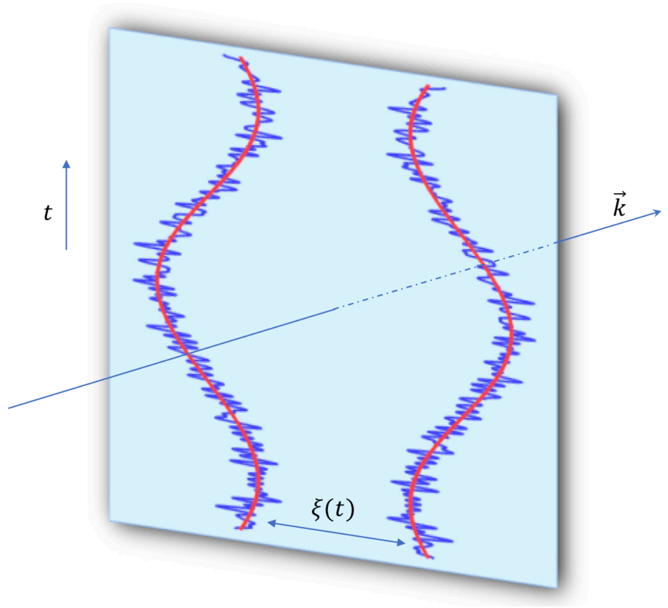
Allali and Hertzberg, PRL (2021)

Superposition of $|\alpha\rangle$ and $|-\alpha\rangle$ has negligible gravitational decoherence (same Newtonian potential)

Could intrinsically quantum effects significantly affect measurements?

Equivalently, can these experiments show the axion field is quantized?

In the gravitational wave literature, many papers say yes!

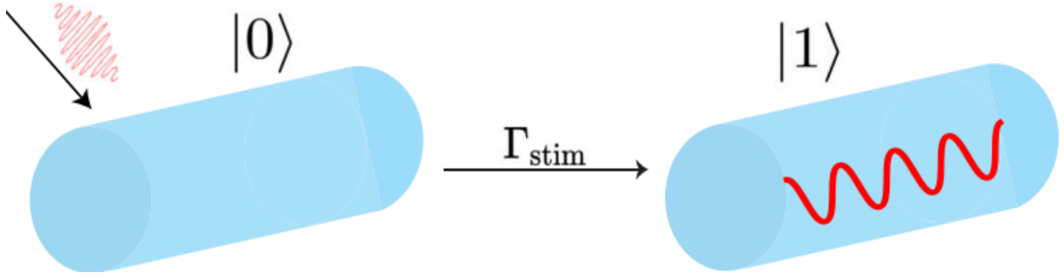


“The noise of gravitons”

Parikh, Wilczek, Zahariade, PRL (2021)

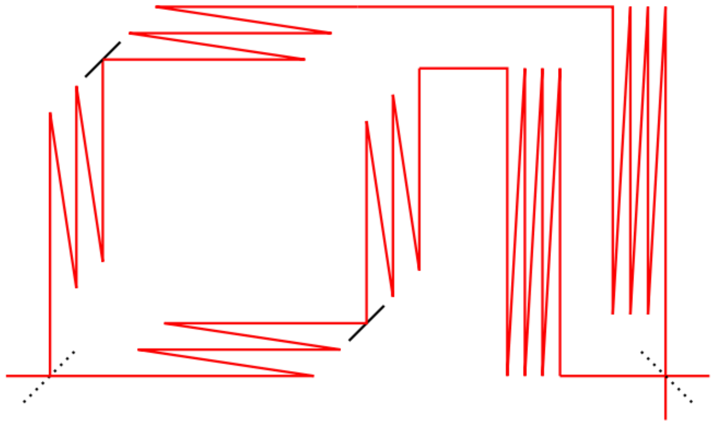
Deviations from coherent state

Manikandan and Wilczek, PRA (2024)



Absorption of gravitons

Tobar et al., Nature Commun. (2024)



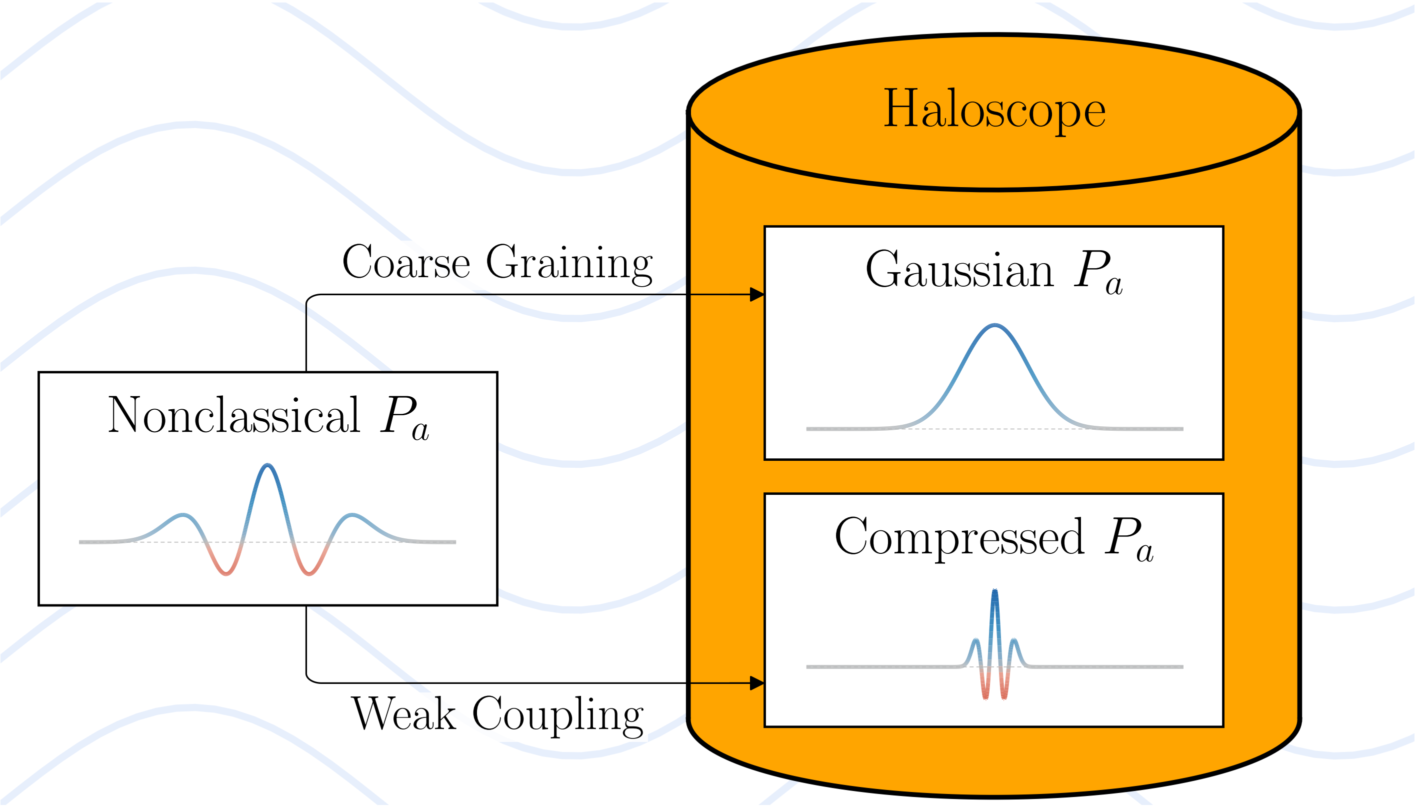
State-dependent decoherence

Schutzhold, PRL (2025)

(+100 other papers making similar claims)

But axion DM and GWs are both weakly coupled waves, answer should be same

Two Obstructions to Observing Intrinsically Quantum Effects



Experiments measure coarse-grained "effective" modes, not fundamental modes

Size of intrinsically quantum effects always suppressed by **extra** powers of the coupling

In a typical haloscope:

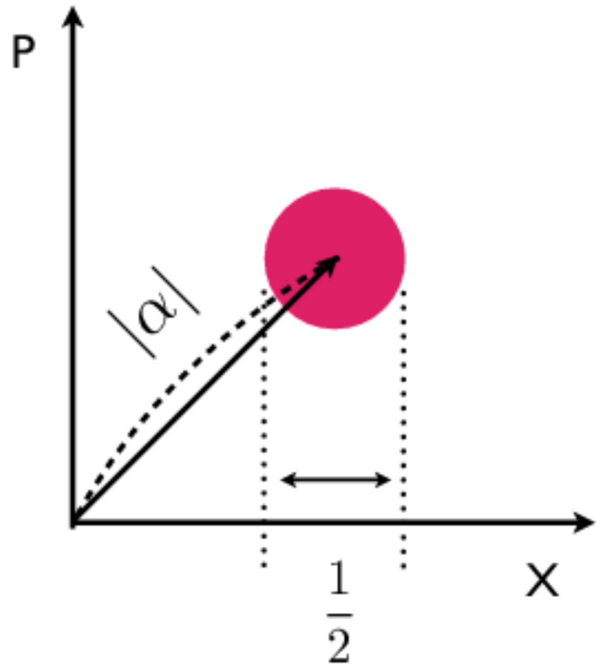
Effective mode occupancy $N_{\mathrm{eff}} \sim \rho_{\mathrm{DM}} V / m_{\mathrm{DM}} \sim 10^{19}$

Axion-photon conversion efficiency $\eta \sim (g_{a\gamma\gamma} B_0 Q_c / m_{\mathrm{DM}})^2 \sim 10^{-21}$

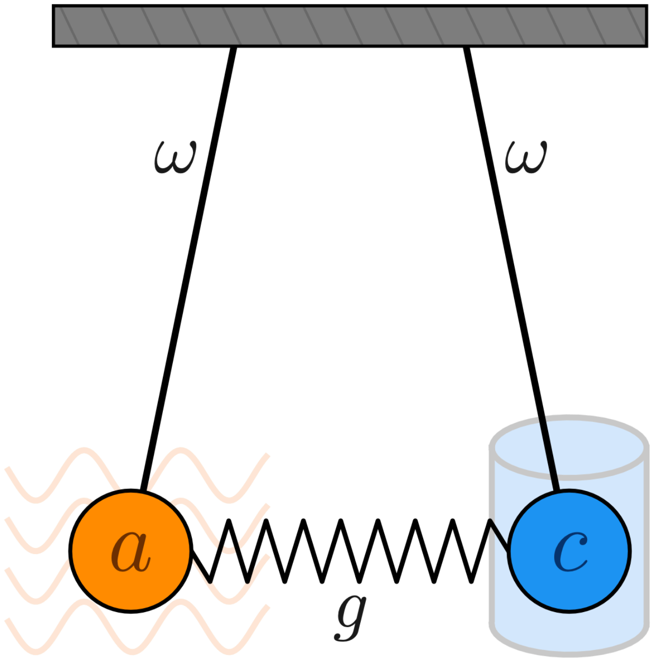
Classical effects (e.g. signal power) scale as powers of ηN_{eff}

Intrinsically quantum effects are penalized by η, but **not** enhanced by N_{eff}

Coherent States Act Classically



Coherent states $|\alpha\rangle$ obey $a|\alpha\rangle = \alpha|\alpha\rangle$ and have relatively well-defined values of both quadratures



Axion mode and cavity mode like coupled harmonic oscillators $H_{\text{int}} = ig\,(c^\dagger a - c\,a^\dagger)$

a is a classical complex number α

cavity state $|0\rangle$ evolves to coherent state $|\alpha g t\rangle$

quantum mode $\hat{a}$ is in coherent state $|\alpha\rangle$

joint state $|0\rangle|\alpha\rangle$ evolves to joint coherent state $|\alpha\sin(gt)\rangle|\alpha\cos(gt)\rangle$

At leading order, coherent states act on cavity like classical field values!

Defining Nonclassical States

State of field with probability distribution $P(\alpha)$ of classical values is $\rho = \int d^2\alpha\, P(\alpha)\,|\alpha\rangle\langle\alpha|$

$P(\alpha) = \delta^{(2)}(\alpha - \alpha_0)$

coherent state

$P(\alpha) \propto \delta(|\alpha| - |\alpha_0|)$

phase-averaged coherent state

$P(\alpha) \propto e^{-|\alpha|^2/|\alpha_0|^2}$

Gaussian state

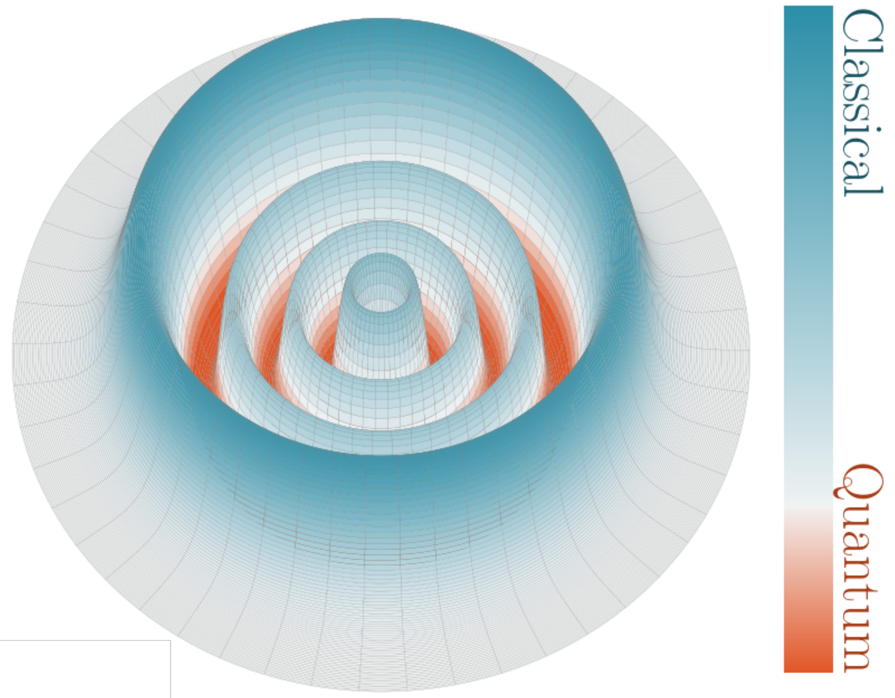
Glauber's key insight: every state corresponds to a essentially unique $P(\alpha)$!

But many require $P(\alpha) < 0$, e.g.

"cat" state $|\alpha\rangle + |\alpha'\rangle$

squeezed state $|\gamma\rangle$

number state $|n\rangle$



These "intrinsically quantum" states give measurement statistics that classical ensembles can't

Quantum Description of the Cavity Haloscope

Consider coupling a cavity mode to the axion's many plane wave modes

$$H_{\text{int}} = g_{a\gamma\gamma} B_0 \int_V d^3\mathbf{x}\, \hat{\phi}(\mathbf{x}) \hat{E}_z(\mathbf{x}) \qquad \hat{E}_z(\mathbf{x}) \supset i\hat{c}\tilde{E}_z(\mathbf{x}) + \text{h.c.} \qquad \hat{\phi}(\mathbf{x}) \sim \sum_{\mathbf{p}} \hat{a}_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}} + \text{h.c.}$$

On resonance in interaction picture, reduces to a rotation between cavity mode and one "effective" axion mode

$$H_{\text{int}}(t) \simeq ig\,(\hat{c}^\dagger \hat{a}_{\text{eff}}(t) - \hat{c}\,\hat{a}^\dagger_{\text{eff}}(t))$$

Identity of this effective mode varies over the axion coherence time

$$\hat{a}_{\text{eff}}(t) = \sum_{\mathbf{p}} C_{\mathbf{p}}\, e^{-i(p^2/2m_a)t}\, \hat{a}_{\mathbf{p}}$$

Occupancy of effective mode is "mean number of axions in cavity"

$$N_{\text{eff}} = \langle \hat{a}^\dagger_{\text{eff}} \hat{a}_{\text{eff}} \rangle \sim \rho_{\text{DM}} V/m_a \sim 10^{19}$$

Effective coupling $g \sim g_{a\gamma\gamma} B_0$ implies axion-photon conversion efficiency $\eta = \sin^2(gt) \approx g^2 t^2$

Quantum State of the Effective Axion Mode

Full state of axion field has joint P-function $\rho = \int \Big(\prod_i d^2\alpha_i \, |\alpha_i\rangle\langle\alpha_i| \Big) P(\alpha_1, \alpha_2, \ldots)$

P-function of the effective mode found by tracing out all other modes

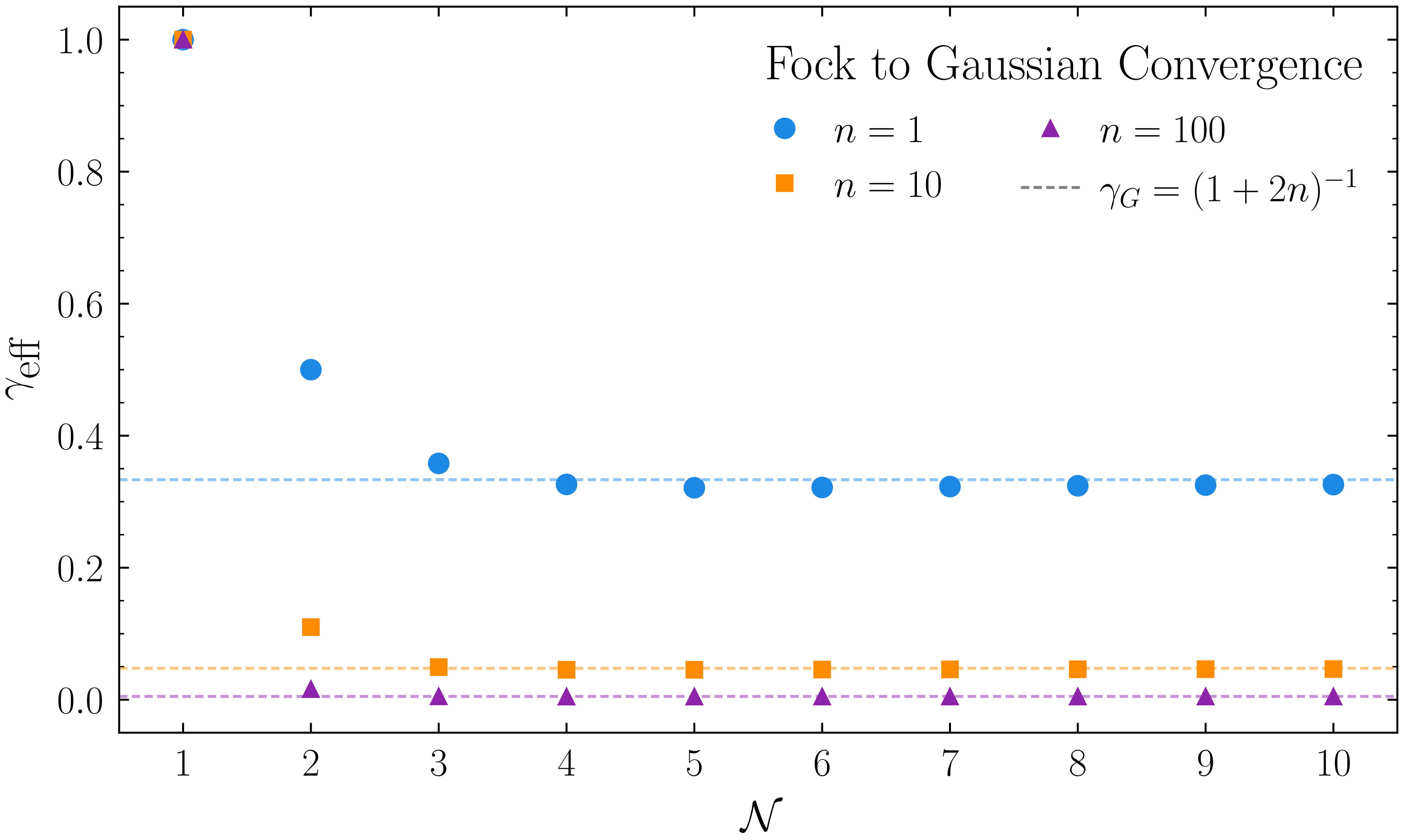
$$P_{\text{eff}}(\alpha) = \int \Big(\prod_i d^2\alpha_i \Big) P(\alpha_1, \alpha_2, \ldots)\, \delta\Big(\alpha - \sum_i C_{\mathbf{p}} e^{-iK_p t} \alpha_i\Big)$$

If the plane wave modes are independent, $P(\alpha_1, \alpha_2, \ldots) = \prod_i P_i(\alpha_i)$

By central limit theorem, this convolution yields Gaussian state $P_{\text{eff}}(\alpha) \propto e^{-|\alpha|^2/\langle n\rangle}$

Makes axion behave like a classical Gaussian random field,
regardless of state of the fundamental plane wave modes

Quantum Central Limit Theorem



Convergence of central limit theorem rapid, independent of mode occupancy

However, can evade theorem with mode correlations, nonstationary axions, Bose-Einstein condensation, or laboratory-sourced axions

Evolution of the Cavity State

For simplicity, projectively measure cavity after short time t_m, where $K_p t_m \lesssim 1$

Straightforward to compute the time evolution in general

$$P^f_{\rm cav}(\alpha) \simeq \int d^2\beta \, \frac{P_{\rm eff}(\beta/\sqrt{\eta})}{\eta} \, P^i_{\rm cav}(\alpha - \beta) = \frac{P_{\rm eff}(\alpha/\sqrt{\eta})}{\eta}$$

scaled convolution of axion state and initial cavity state

assume initial cavity vacuum state here for simplicity

Conversion efficiency at maximum $t_m \sim Q_c/m_a \sim 10^{-4}\,\mathrm{s}$

$$\eta \simeq g^2 t_m^2 \sim 10^{-21} \left(\frac{g_{a\gamma\gamma}}{10^{-15}\,\mathrm{GeV}^{-1}} \frac{B_0}{10\,\mathrm{T}} \frac{Q_c}{10^5} \frac{10^{-5}\,\mathrm{eV}}{m_a} \right)^2$$

Any negativity in $P_{\rm eff}$ directly imprinted on cavity state, but scaled by small η

Nonclassical Number Statistics

Cavity number distribution $p_n = \int d\alpha\, P_{\rm eff}(\alpha)\, |\langle n | \sqrt{\eta}\, \alpha \rangle|^2 = \sum_{k=n}^{\infty} \binom{k}{n} p_k^{\rm DM} \eta^n (1-\eta)^{k-n}$

Simplest criterion: only nonclassical states have Mandel $Q = (\mathrm{var}(n)/\langle n \rangle) - 1 < 0$

$$p_n^{\rm DM} \text{ is} \begin{cases} \text{Poisson} \\ \text{geometric} \\ \text{definite value} \end{cases} \quad \text{and} \quad Q_{\rm DM} = \begin{cases} 0 & \text{DM coherent state} \\ N_{\rm eff} & \text{DM Gaussian state} \\ -1 & \text{DM Fock state} \end{cases}$$

But the value of Q imprinted in the cavity state is suppressed, $Q_{\rm cav} = \eta Q_{\rm DM} \geq -\eta$

Intuitively, because converting axions to photons itself
imprints approximately Poisson fluctuations

Distinguishing Number Statistics

Consider edge of sensitivity, $p_2 \ll p_1 \ll p_0 \approx 1$, mean signal photons $\eta N_{\text{eff}} \simeq p_1 \sim 10^{-2}$

Time to discover axion at this coupling: t_m/p_1 (reasonable time by definition)

Infer Mandel Q through its effect on $p_2 \simeq \begin{cases} p_1^2/2 & \text{DM coherent state} \\ p_1^2 & \text{DM Gaussian state} \\ p_1(p_1-\eta)/2 & \text{DM Fock state} \end{cases}$

Time to distinguish coherent and Gaussian: t_m/p_1^2 (reasonable for post-discovery)

Time to see negative Q: $t_m/\eta^2 \sim 10^{30}\,\text{years} \left(\dfrac{10^{-15}\,\text{GeV}^{-1}}{g_{a\gamma\gamma}} \dfrac{10\,\text{T}}{B_0} \right)^4 \left(\dfrac{10^5}{Q_c} \dfrac{m_a}{10^{-5}\,\text{eV}} \right)^3$

Suppression of Other Nonclassical Signatures

Simplest nonclassicality measure for quadrature measurements is squeezing

$$X = (a + a^\dagger)/\sqrt{2}$$

$$S = \mathrm{var}(X) - 1/2$$

$$S_{\mathrm{cav}} = \eta S_{\mathrm{DM}} \geq -\eta/2$$

Higher-order generalizations of Q and S suppressed by more powers of η

Entangled effective modes can transmit entanglement to cavity modes

Simplest entanglement measure involves quadrature correlations

$$E = \frac{\mathrm{var}(X_1 - X_2) + \mathrm{var}(Y_1 + Y_2)}{2} - 1$$

$$E_{\mathrm{cav}} = \eta E_{\mathrm{DM}} \geq -\eta$$

Axion-cavity interaction can decohere a general initial cavity state

Decoherence rates minimized for coherent DM, maximized for Gaussian DM

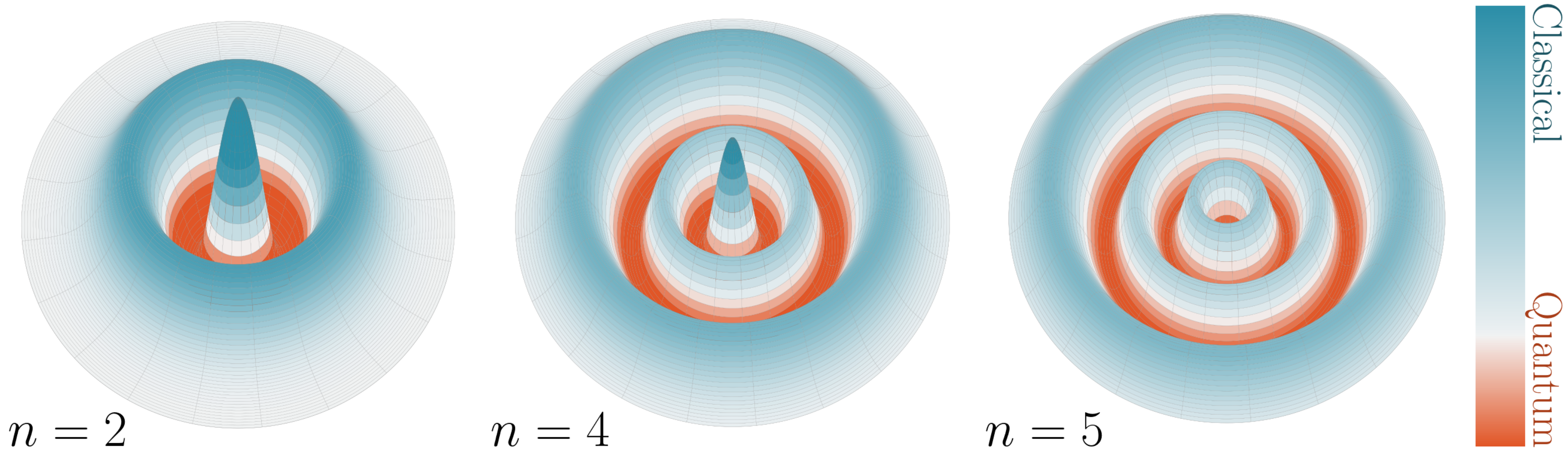
No distinctive effect for nonclassical axion states

A General Geometric Argument

The probability $Q(\alpha)$ to be in a coherent state $|\,\alpha\rangle$ can't be negative:

$$Q(\alpha) = \langle \alpha\,|\,\rho\,|\,\alpha \rangle = \int d\beta\, P(\beta)\,|\,\langle \beta\,|\,\alpha\rangle\,|^2 = \int d\beta\, P(\beta)\, e^{-|\alpha-\beta|^2} \geq 0$$

Thus, **any** negative P-function must effectively oscillate on $\mathcal{O}(1)$ scales



Then $P^f_{\text{cav}}(\alpha) = P_{\text{eff}}(\alpha/\sqrt{\eta})/\eta$ oscillates on $\mathcal{O}(\sqrt{\eta})$ scales, making negativity hard to observe

Consequences of the Geometric Argument

Initial cavity state is actually thermal, but this also convolves final state by a Gaussian

This will already remove negativity unless $T \lesssim \dfrac{m_a}{\log(1/\eta)} \simeq 2\,\mathrm{mK}\left(\dfrac{m_a}{10^{-5}\,\mathrm{eV}}\right)$

(tough but possible)

The probability of a generic measurement outcome is $p = \int d\alpha\, P^f_{\mathrm{cav}}(\alpha) f(\alpha)$

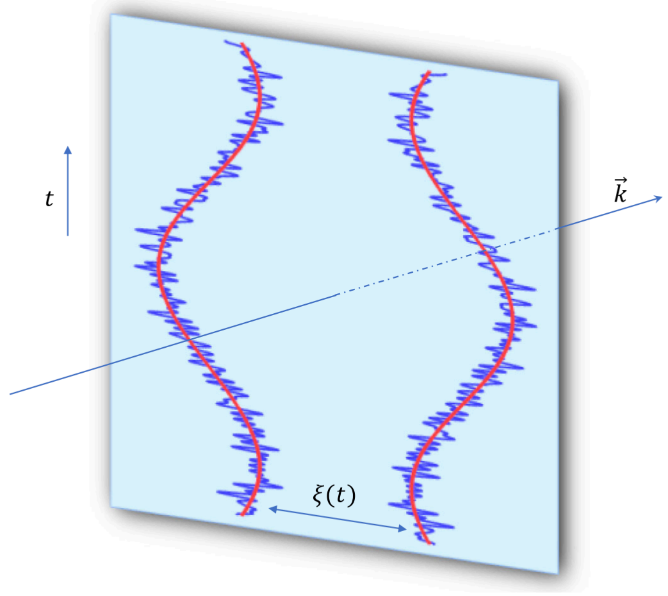
For an alternative DM state with $P'_{\mathrm{DM}}(\alpha) = Q_{\mathrm{DM}}(\alpha) \geq 0$, probability of same outcome is

$$p' = \int d\alpha\, P^f_{\mathrm{cav}}(\alpha) \int d\beta\, f(\alpha - \beta) \frac{e^{-|\beta|^2/\eta}}{\pi\eta}$$

$$p - p' \lesssim \mathrm{tr}\,|\rho^f - \rho^f_{\mathrm{cl}}| \propto \eta$$

difference from “nearest” classical state always suppressed by η

What About Quantum Gravity Claims?



“The noise of gravitons”

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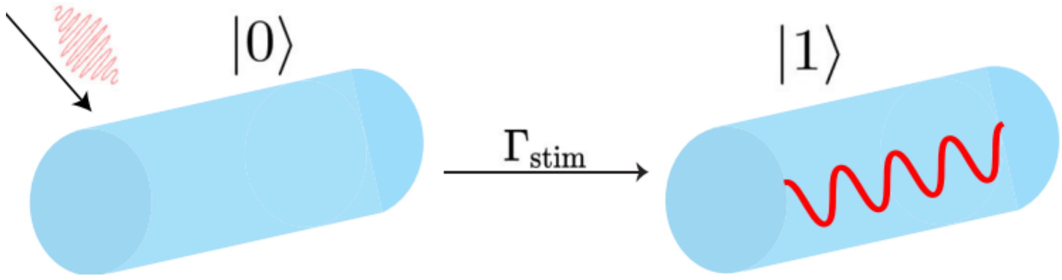

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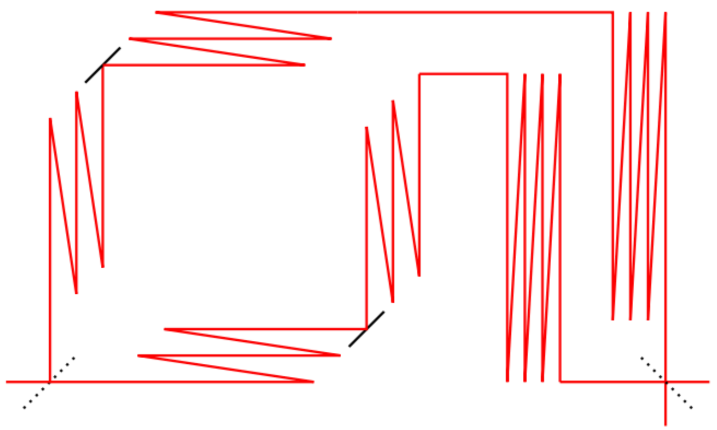


State-dependent decoherence

Schutzhold, PRL (2025)

Considers $\mathrm{var}(X) \gg 1/2$, which is classical

$\mathrm{var}(X) < 1/2$ would be quantum, but can’t be measured

Classical GWs also excite discrete energy levels

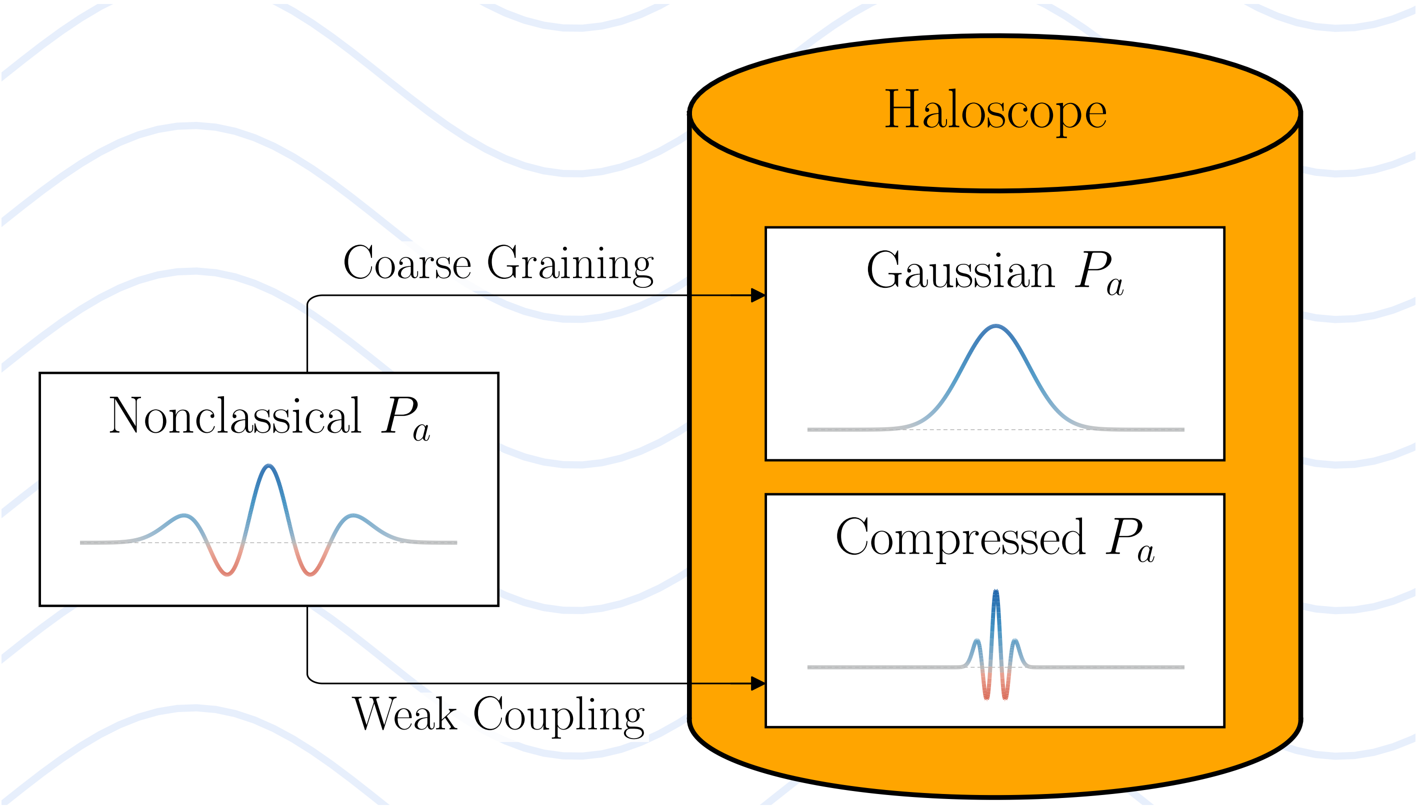
$Q < 0$ would be quantum, but can’t be measured

Classical states can yield both low or high decoherence

Other works drop the η suppression, or consider quantity that isn’t intrinsically quantum, or compare only to a coherent state rather than a general classical ensemble

Conclusion

The axion state could well be nonclassical, but it **appears** classical



Due to detector coarse-graining and weak coupling, not high occupancy

All observable signals in axion DM and GW detectors can be described classically, and these detectors cannot show the axion/gravitational field is quantized