Quantum and Classical Effects of Axion Dark Matter

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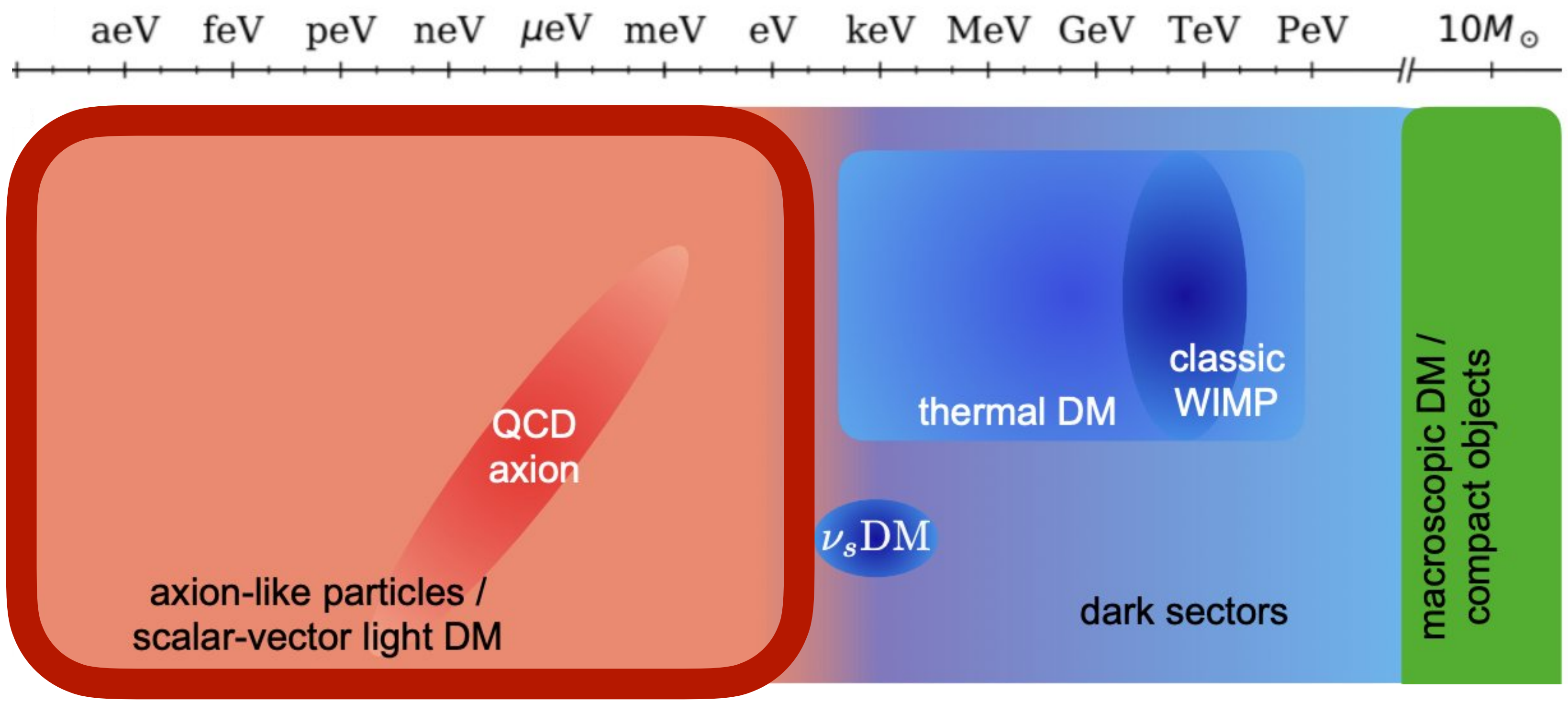
arXiv:2510.05198 (to appear in PRL), with Yunjia Bao, Dhong Yeon Cheong, Nicolas Rodd, Joey Takach, Lian-Tao Wang

Why Search for Ultralight Dark Matter?



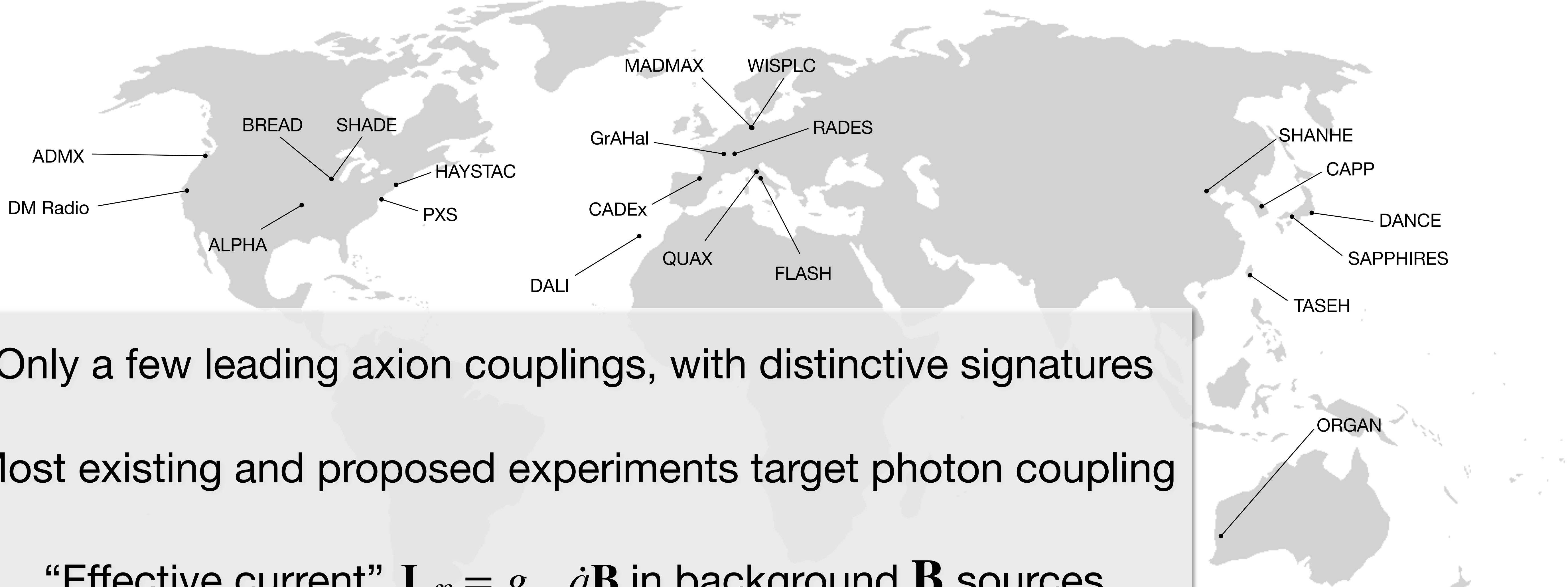
- Simply produced: gives right amount of dark matter with minimal cosmology
- Generic: required ultralight fields automatically appear in many models
- Minimal: requires introduction of only a single new field at low energies
- Low-hanging fruit: new experiments are needed, inexpensive, and very effective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

$(\partial_\mu a)\, K^\mu_{\rm EM}$	$(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N$	$(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e$	$a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu}$
axion-photon	axion-nucleon	axion-electron	axion-EDM

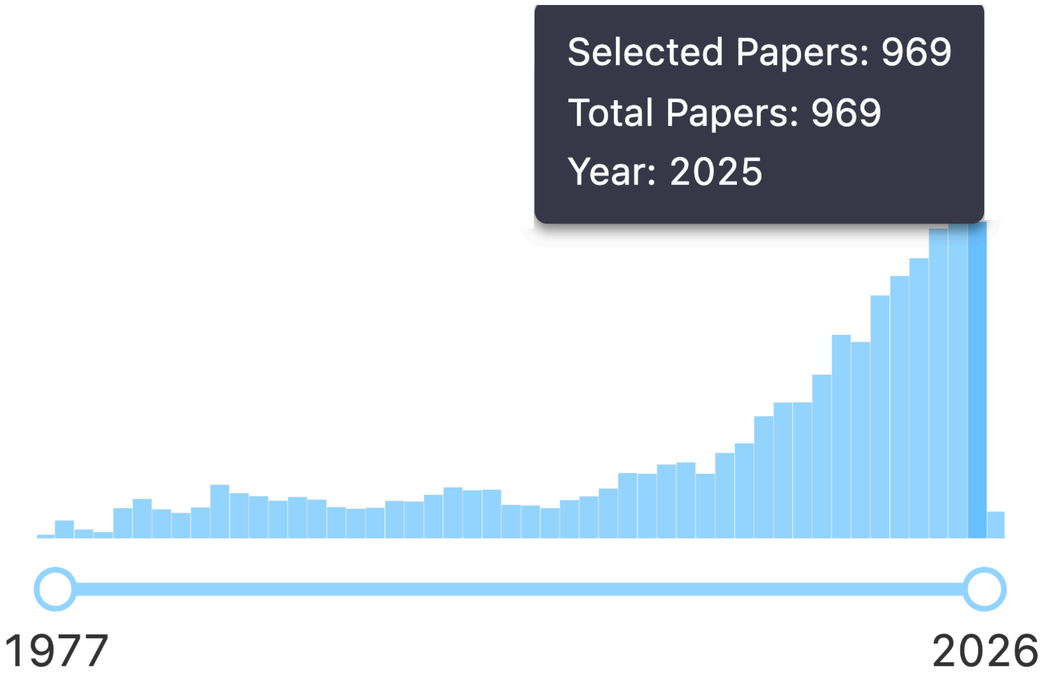


Only a few leading axion couplings, with distinctive signatures

Most existing and proposed experiments target photon coupling

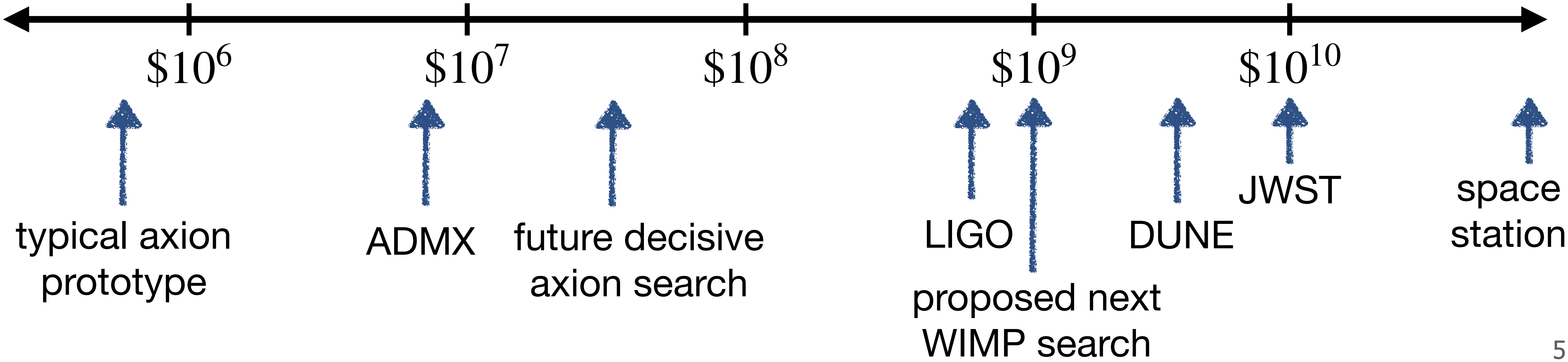
"Effective current" $\mathbf{J}_{\rm eff} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$ in background $\mathbf{B}$ sources secondary, detectable electromagnetic fields

Axion Dark Matter Searches in 2026

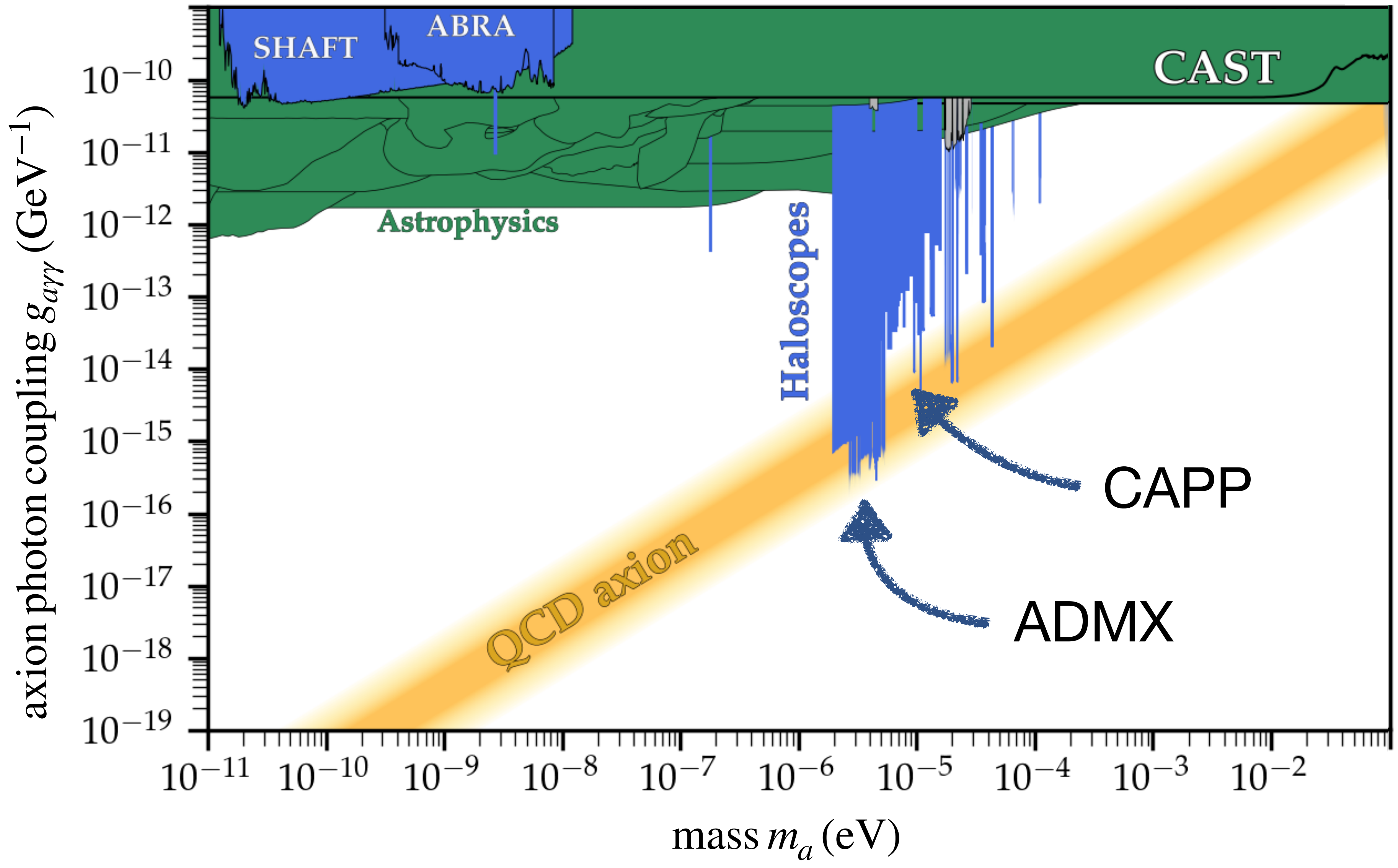


Subject of much excitement among both theorists and experimentalists, but **not** a finished subject

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

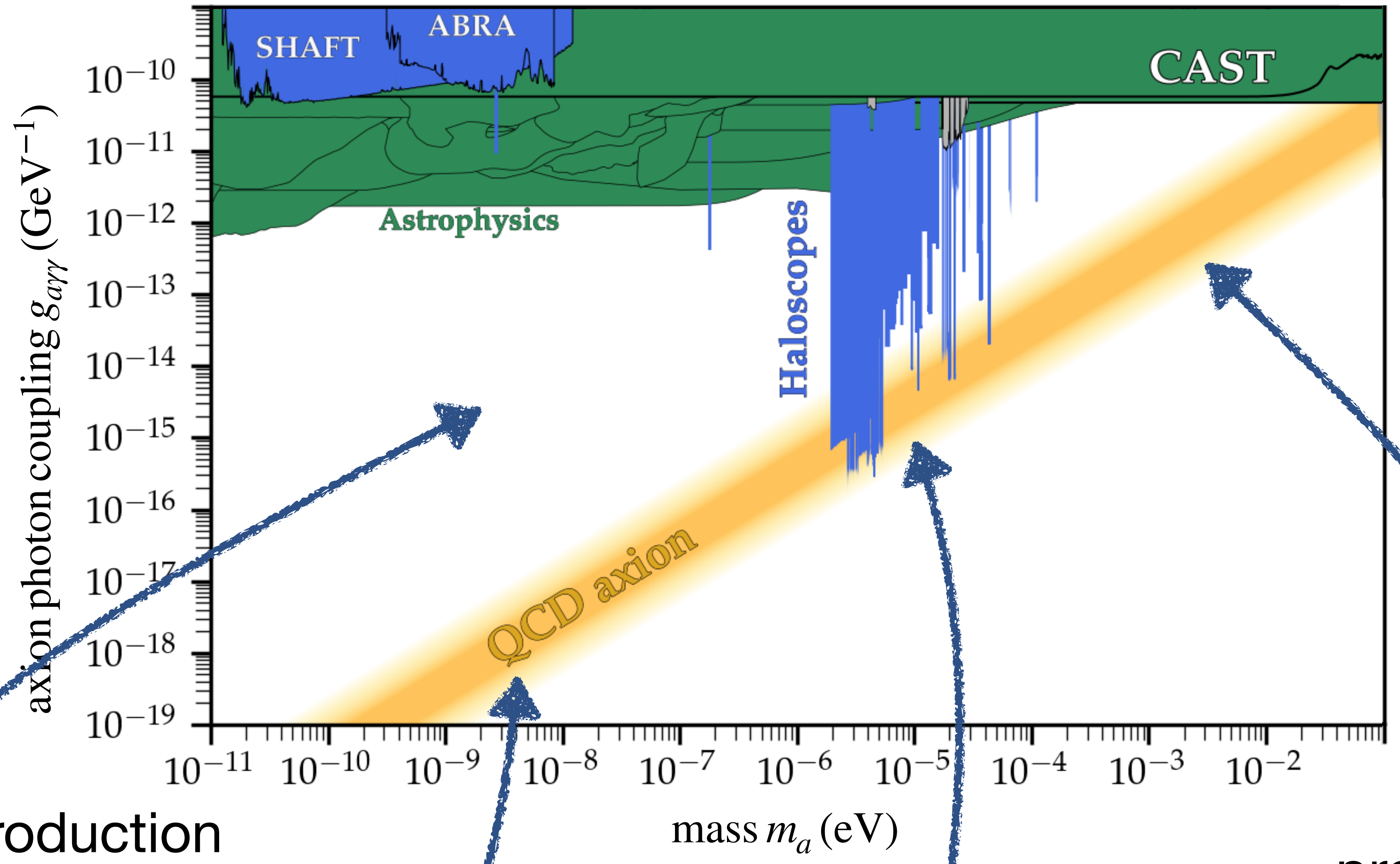


Axion Mass Benchmarks



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

Axion Mass Benchmarks



misalignment production of non-QCD axion

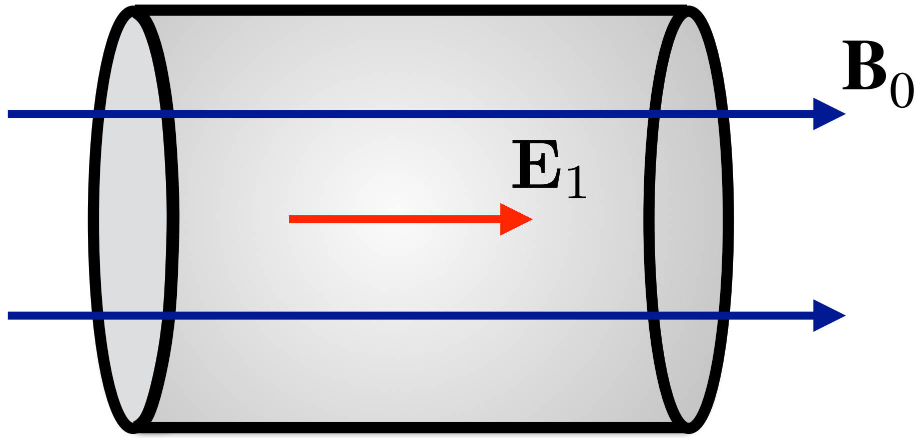
QCD axions at grand unification scale

misalignment production of QCD axion

post-inflation production of QCD axion

GHz Axions: The Cavity Haloscope

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

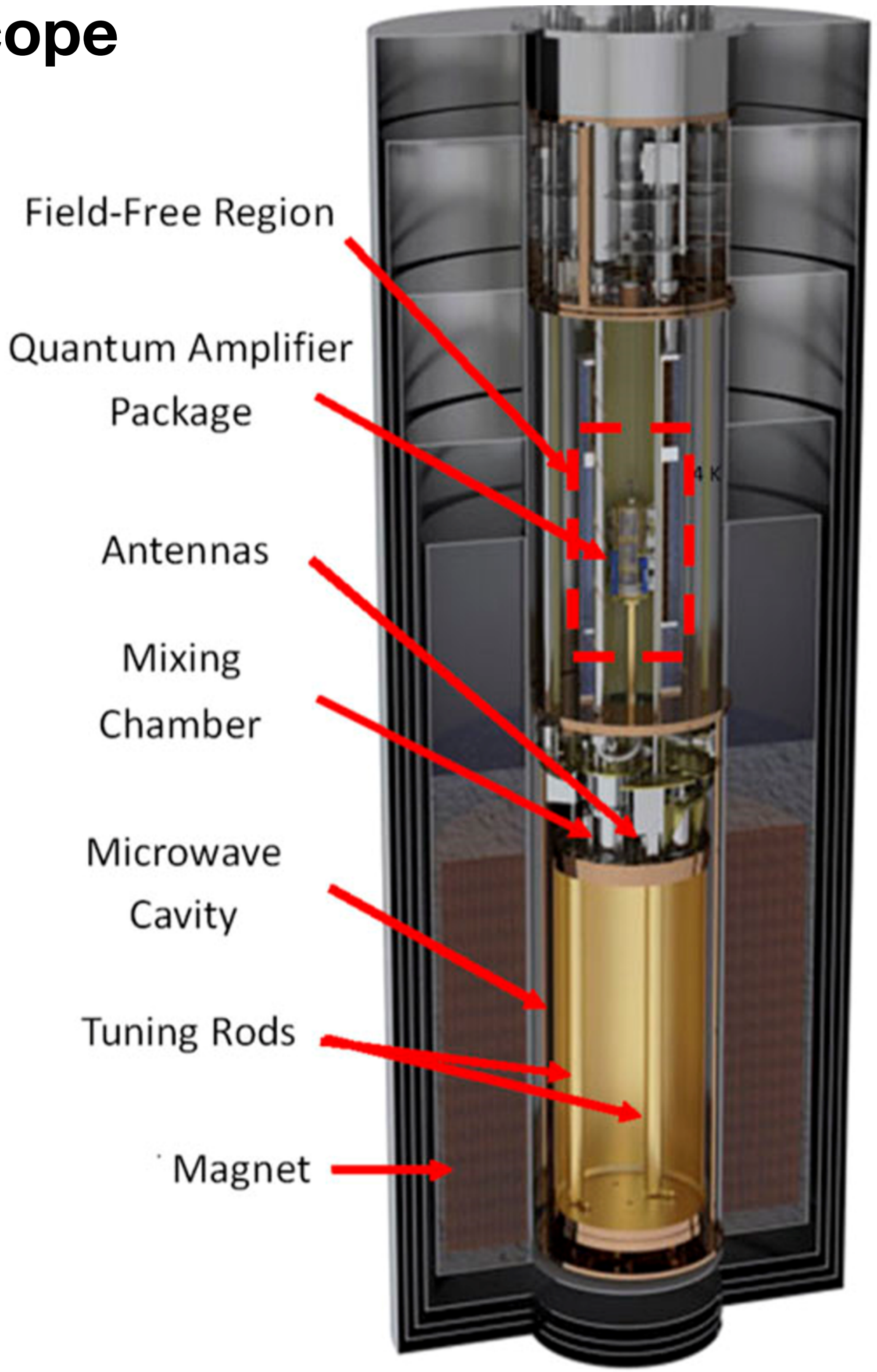


$$P_{\rm sig} \sim (g_{a\gamma\gamma}^2 \rho_{\rm DM})\,(B_0^2 V)\,(Q_1/\omega_1)$$

magnetic energy in cavity

decay time of cavity mode

Most well developed approach; will be central example of this talk, though results apply more broadly

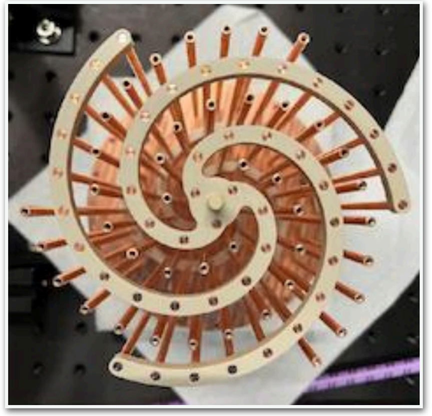


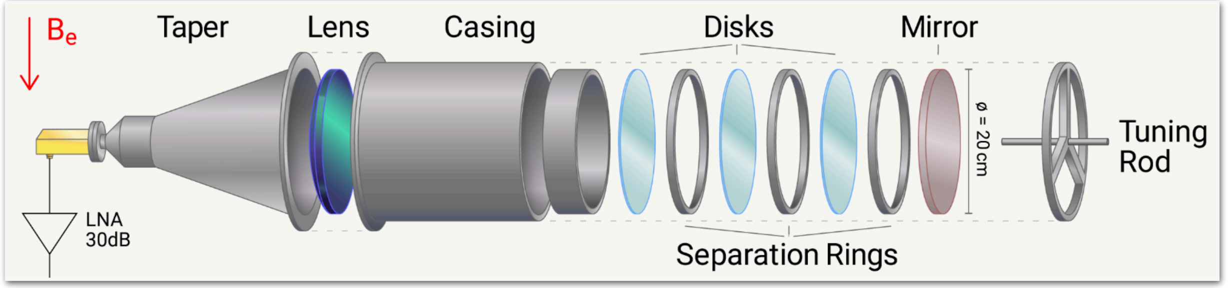
Axion Searches Above GHz

$$P_{\text{sig}} \sim (g_{a\gamma\gamma}^2 \rho_{\text{DM}})\,(B_0^2 V)\,(Q_1/\omega_1) \qquad V \propto 1/\omega_1^3 \qquad S_{\text{SQL}} \sim \hbar\omega_1$$

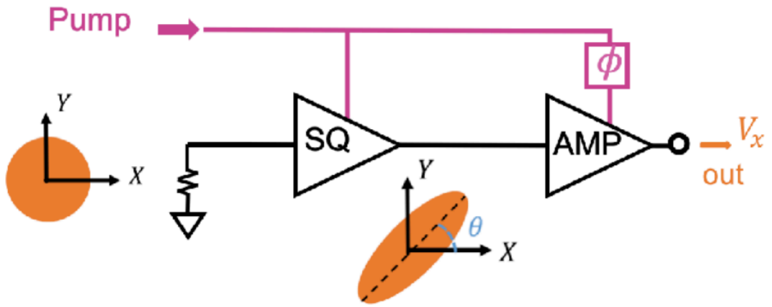
As axion mass increases, signal power decreases but SQL noise increases

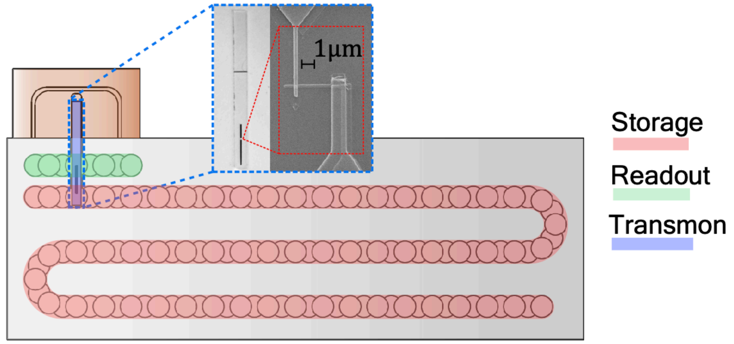
exotic design to maintain large volume





quantum measurement to evade SQL





squeezed vacuum

entangled cavities or qubits

Fock or cat states

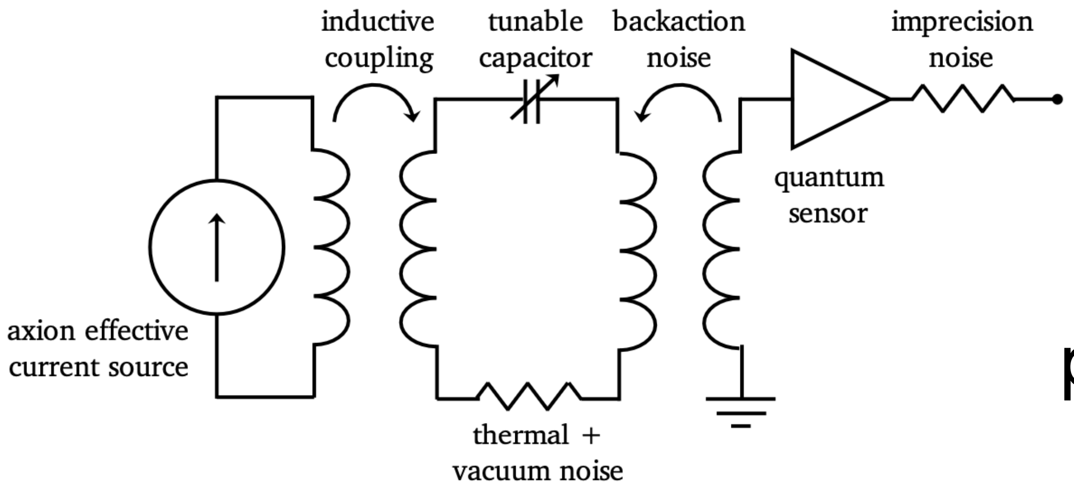
single photon detection

Naturally suited for many small-scale efforts

Potential of these approaches long recognized, technology rapidly maturing

Axion Searches Below GHz

Reasonable cavity mode can't have frequency $m_a \ll \mathrm{GHz}$, two main alternatives in play



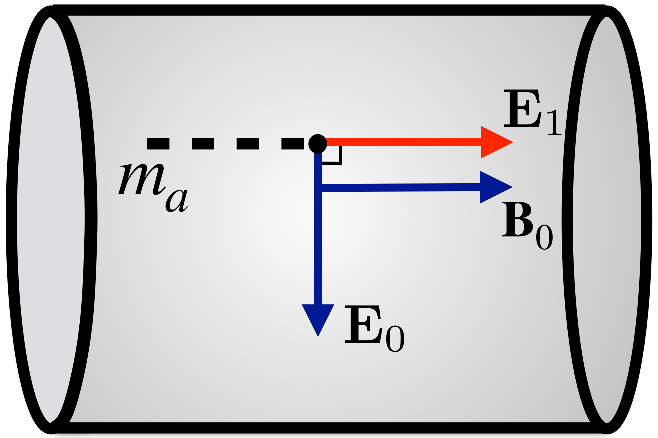
lumped element approach

use LC circuit with resonant frequency m_a

great potential precision with quantum techniques

parametrically suppressed signal power $P_{\mathrm{sig}} \propto (m_a L)^2$

Kahn, Safdi, Thaler, PRL (2016)



heterodyne SRF approach

drive a cavity mode at $\omega_0 \sim \mathrm{GHz}$

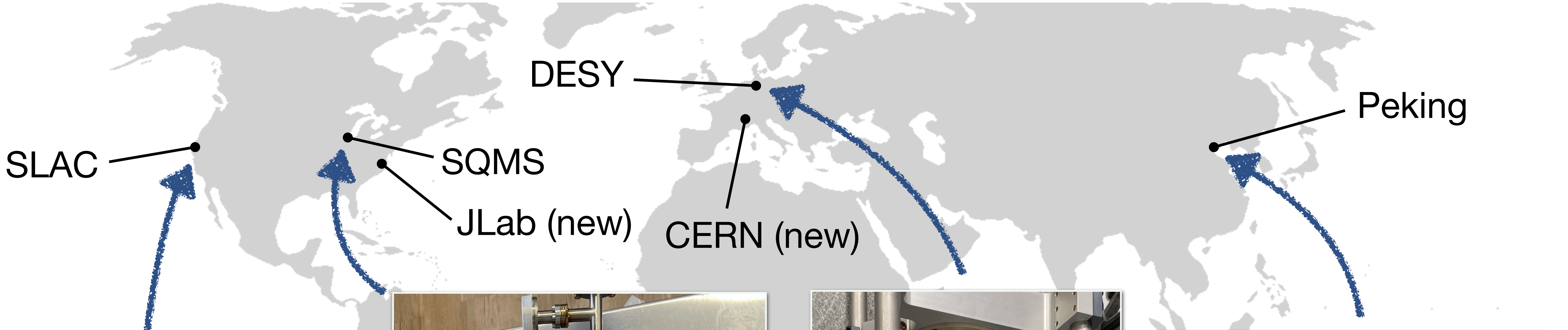
axion excites another mode at $\omega_1 = \omega_0 \pm m_a$

aided by well-developed SRF accelerator cavities

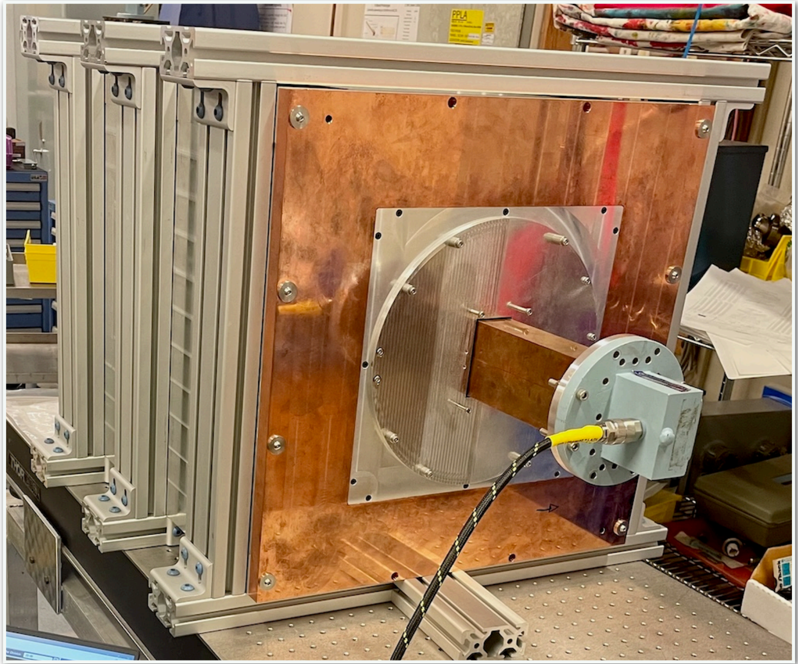
noisier, but much higher signal power, no magnet

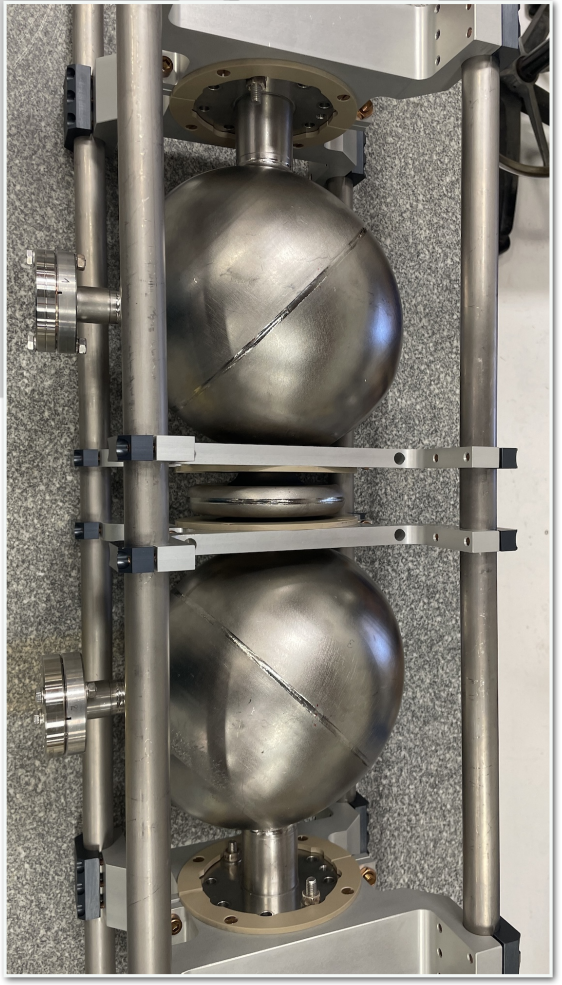
Berlin, D'Agnolo, …, KZ, JHEP (2020)
Berlin, D'Agnolo, Ellis, KZ, PRD (2021)

Global Status of the Heterodyne Approach



Li, KZ, Oriunno, et al. (2507.07173)





Why can the axion be treated as a classical field?

An increasingly pressing question, since many axion detectors will operate in a highly nonclassical regime!

Why can the axion be treated as a classical field?

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

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

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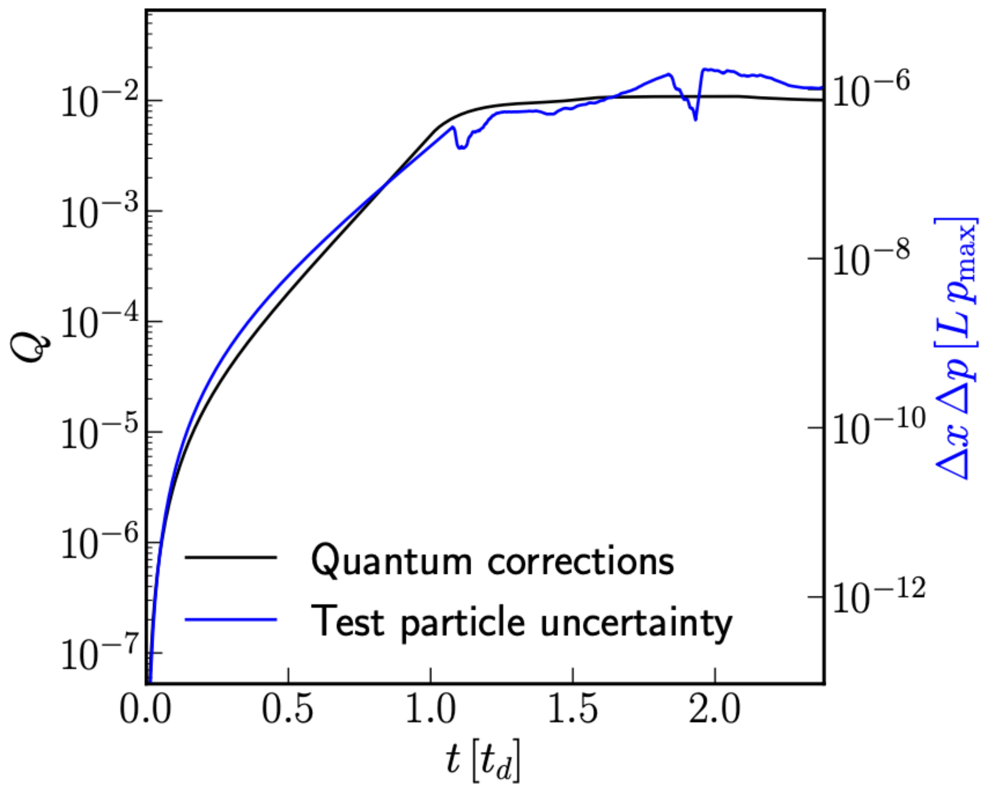
"Because misalignment produces the axion in a coherent state"

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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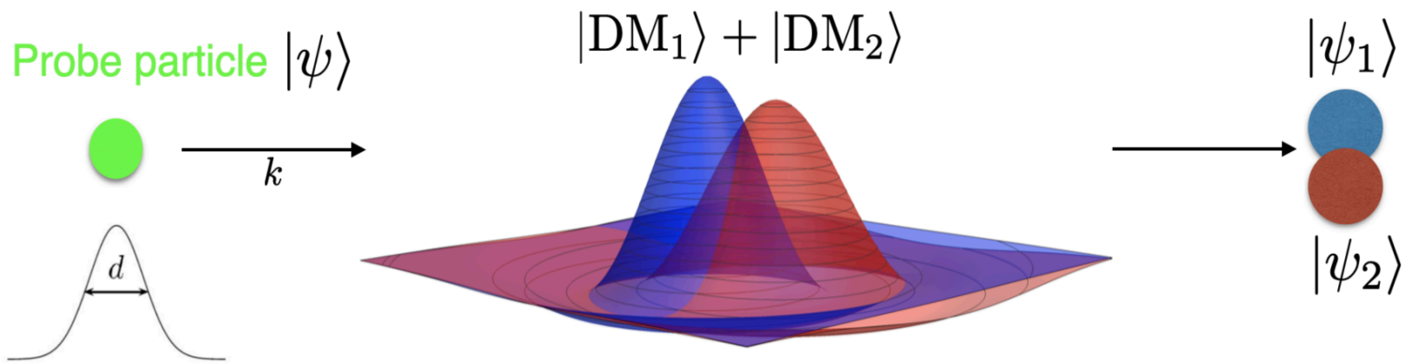
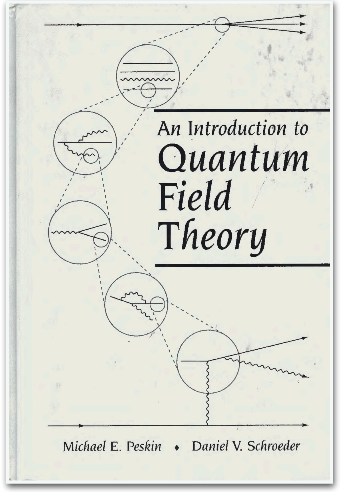
"Because intrinsically quantum states would decohere"

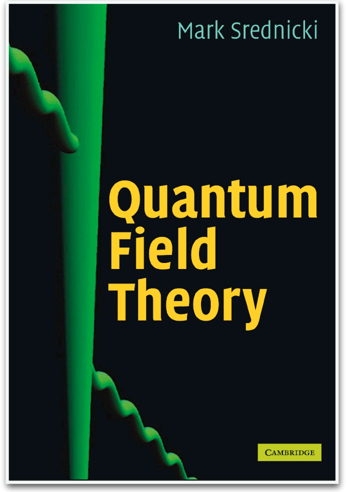


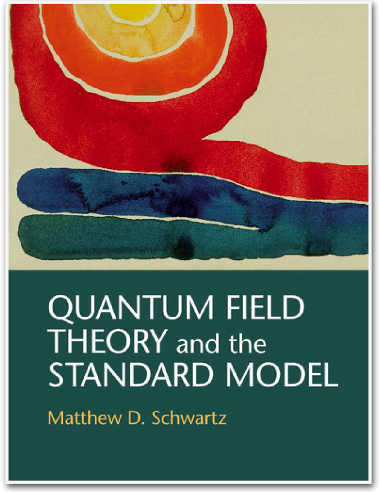
Allali and Hertzberg, PRL (2021)

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

Why think about this question?







High-energy particle physics texts avoid even mentioning the state of a quantum field!

$$\frac{|\,\text{a big deal}\rangle + |\,\text{no big deal}\rangle}{\sqrt{2}}$$

But it's genuinely unclear if the quantum state matters a little, a lot, or not at all!

Will show inherently quantum effects of the axion are suppressed by its **weak coupling**

The State of a Quantum Field

A quantum field is just an infinite collection of harmonic oscillators

Attempt #1: generalize number basis $|\psi\rangle = \sum_n c_n |n\rangle$ to $|\Psi\rangle = \sum_{n_1, n_2, \ldots} c_{n_1 n_2 \ldots} |n_1 n_2 \ldots\rangle$

Closest to QFT textbook, but far from axion DM states, classical limit unclear

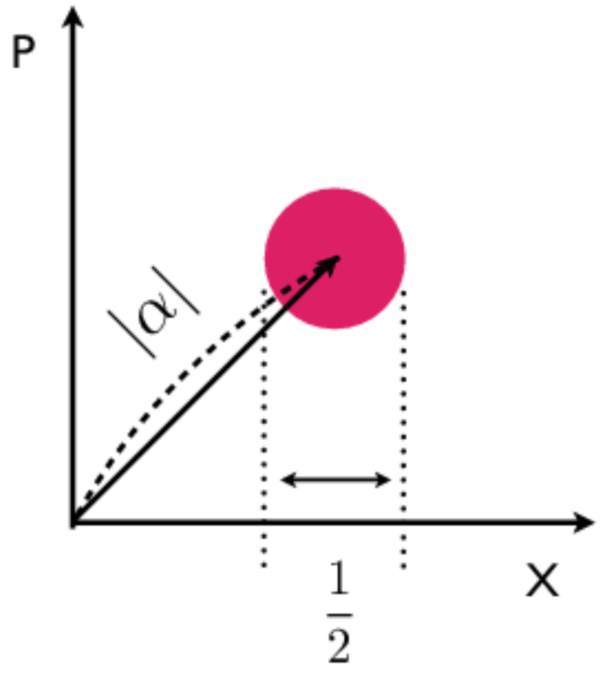
Attempt #2: generalize position basis $|\psi\rangle = \int dx\, \psi(x) |x\rangle$ to $|\Psi\rangle = \int \mathscr{D}\psi(\mathbf{x})\, \Psi[\psi(\mathbf{x})]\, |\psi(\mathbf{x})\rangle$

Hard to compute with this “Schrodinger wavefunctional”, mixed states even worse

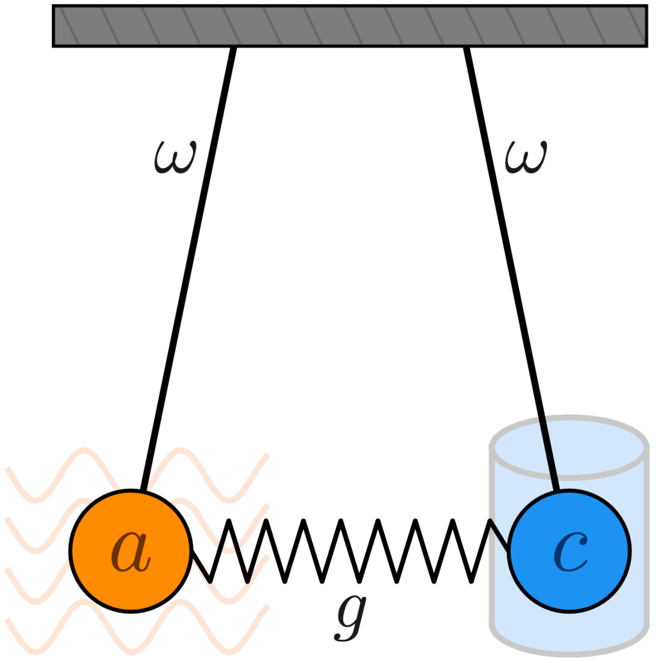
Attempt #3: generalize coherent states $|\alpha\rangle$ where $a|\alpha\rangle = \alpha|\alpha\rangle$

Glauber’s 2005 Nobel prize: this is the right approach!

Coherent States Act Classically



Coherent states have relatively well-defined values of both quadratures



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

a is a classical complex number α

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

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

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

From cavity's perspective, coherent states act like classical field values!

Defining Nonclassical States

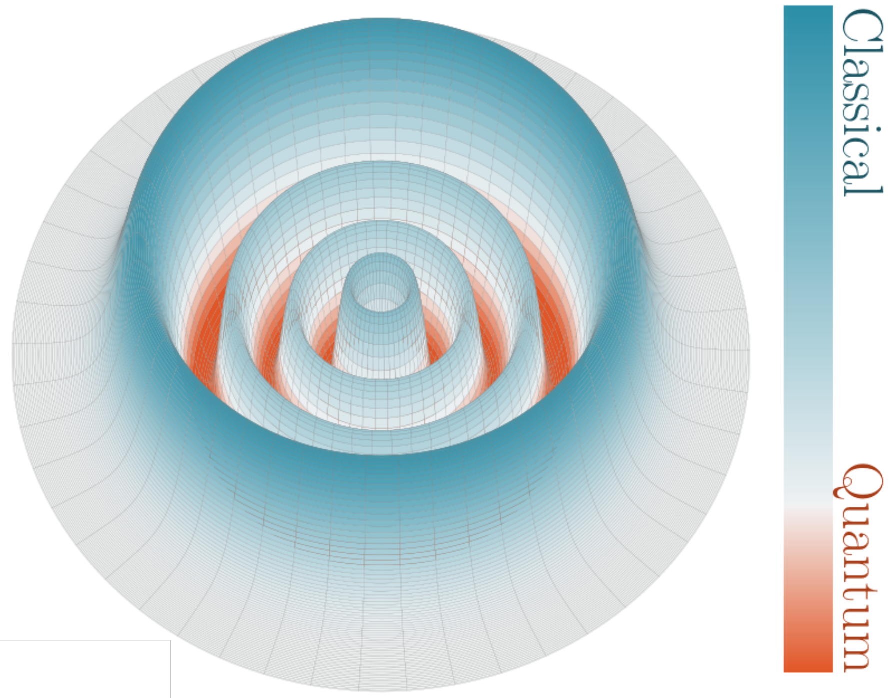
State of field with probability distribution $P(\alpha)$ of classical values is $\rho = \int d^2\alpha\, P(\alpha)\,|\alpha\rangle\langle\alpha|$

$P(\alpha) = \delta^{(2)}(\alpha - \alpha_0)$	$P(\alpha) \propto \delta(\|\alpha\| - \|\alpha_0\|)$	$P(\alpha) \propto e^{-\|\alpha\|^2/\|\alpha_0\|^2}$
coherent state	phase-averaged coherent state	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 $\rho = \int \left(\prod_i d^2\alpha_i \, |\alpha_i\rangle\langle\alpha_i| \right) P(\alpha_1, \alpha_2, \ldots)$

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

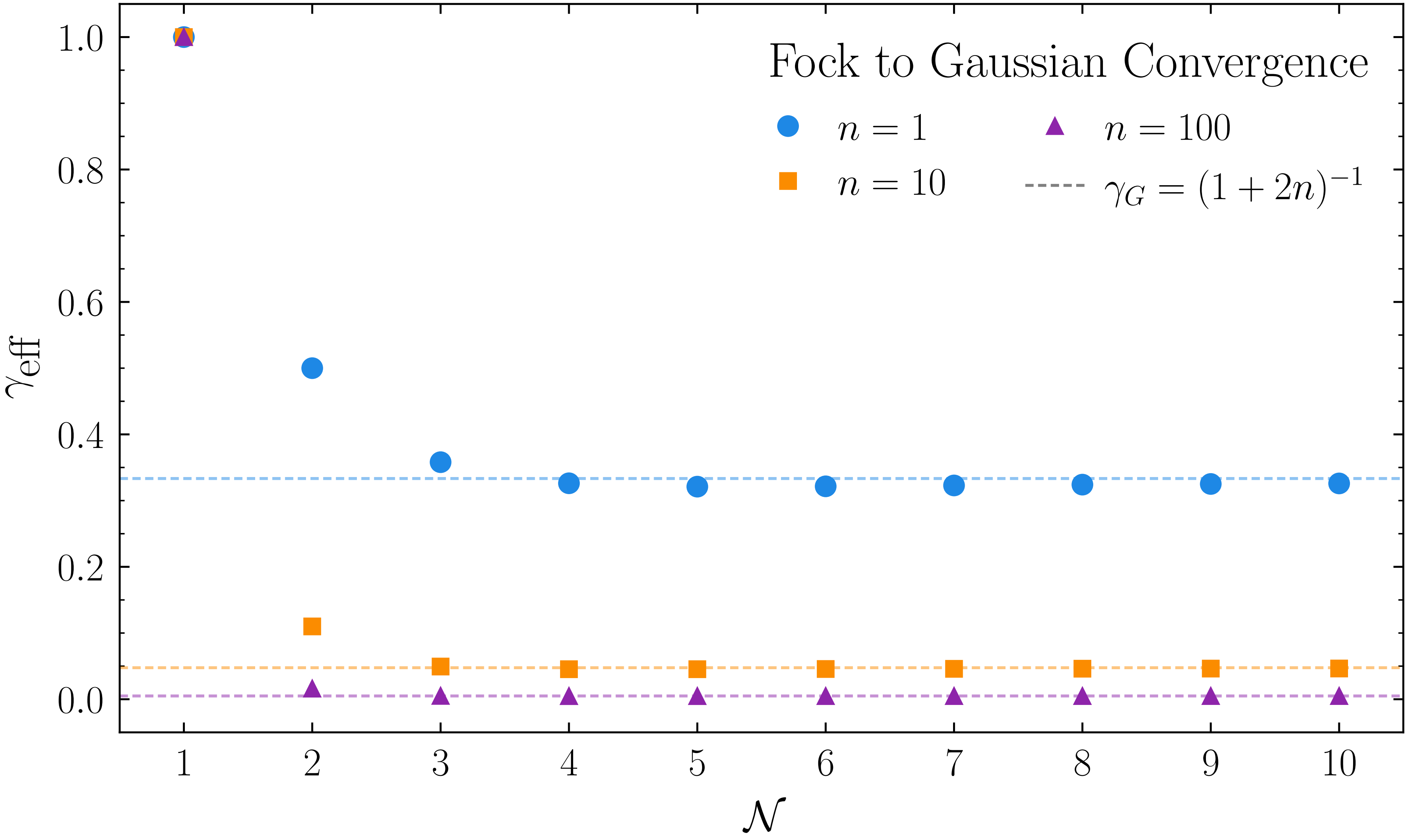
$$P_{\mathrm{eff}}(\alpha) = \int \left(\prod_i d^2\alpha_i \right) P(\alpha_1, \alpha_2, \ldots) \, \delta\Big(\alpha - \sum_i C_{\mathbf{p}} e^{-iK_p t} \alpha_i\Big)$$

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 $P_{\mathrm{eff}}(\alpha) \propto e^{-|\alpha|^2/\langle n \rangle}$

Generically makes axion behave effectively 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, theorem doesn't apply in case of mode correlations, extreme case of 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

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

scaled convolution of axion state and initial cavity state

assume initial cavity vacuum state here for simplicity

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

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

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

Example: Nonclassical Number Statistics

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

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

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

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

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

Example: Nonclassical Number Statistics

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

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

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

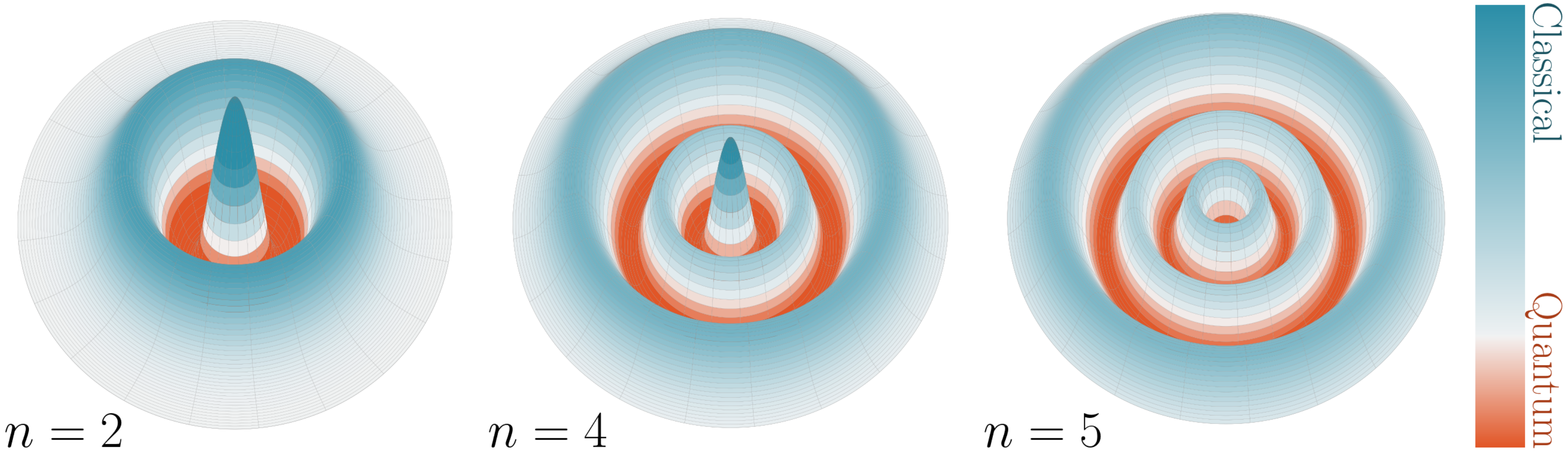
No distinctive effect for nonclassical axion states

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 $P_{\mathrm{cav}}^{f}(\alpha) = P_{\mathrm{eff}}(\alpha/\sqrt{\eta})/\eta$ 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 $T \lesssim \frac{m_a}{\log(1/\eta)} \simeq 2\,\mathrm{mK}\left(\frac{m_a}{10^{-5}\,\mathrm{eV}}\right)$

(tough but possible)

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

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

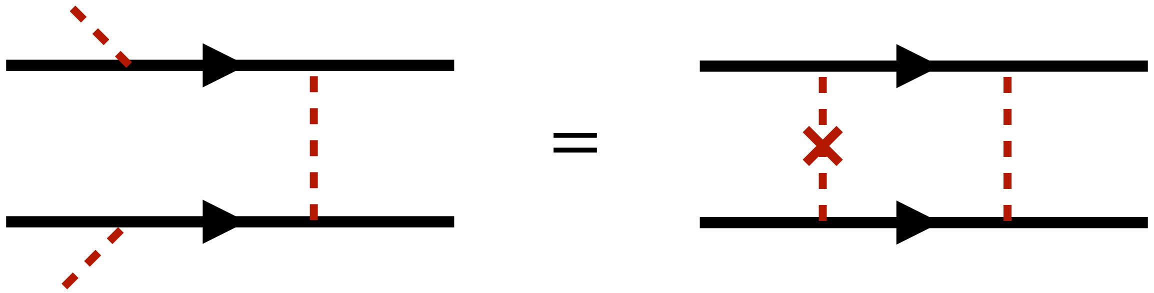
$$p' = \int d\alpha\, P_{\mathrm{cav}}^{f}(\alpha) \int d\beta\, f(\alpha - \beta) \frac{e^{-|\beta|^2/\eta}}{\pi\eta}$$

$$p - p' = \mathcal{O}(\eta)$$

difference from “nearest” classical state always suppressed by η

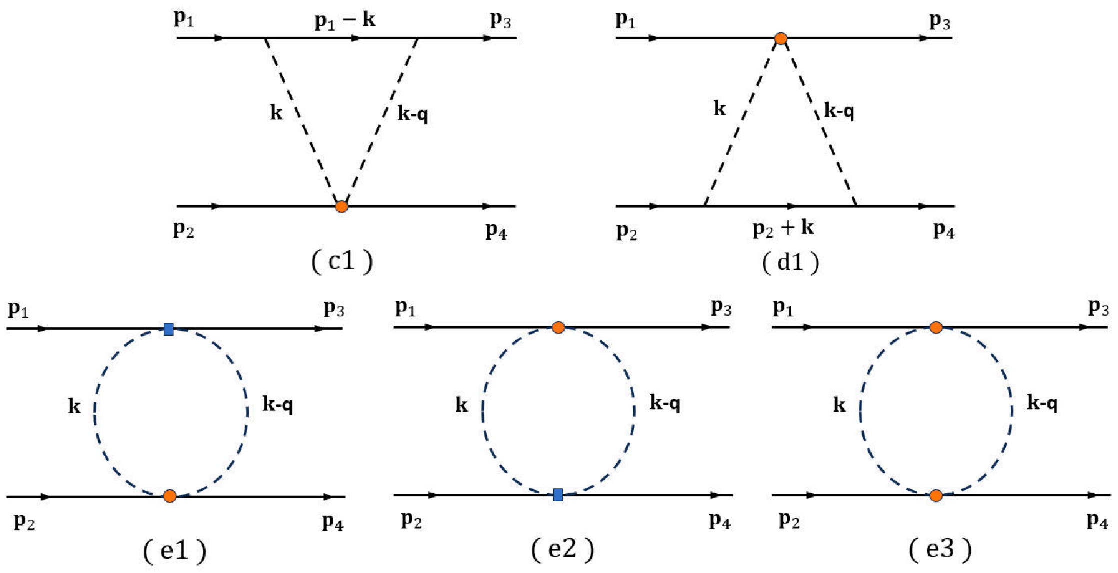
“DM Background-Induced” Forces are Classical

Tree-level coupling to two external axions is formally background-corrected loop diagram



In axion DM, axion-mediated potential can become $1/r$, spin independent

Uses quantum language, but a short classical calculation gives same result



$$(\partial^2 + m_a^2)\, a = J$$

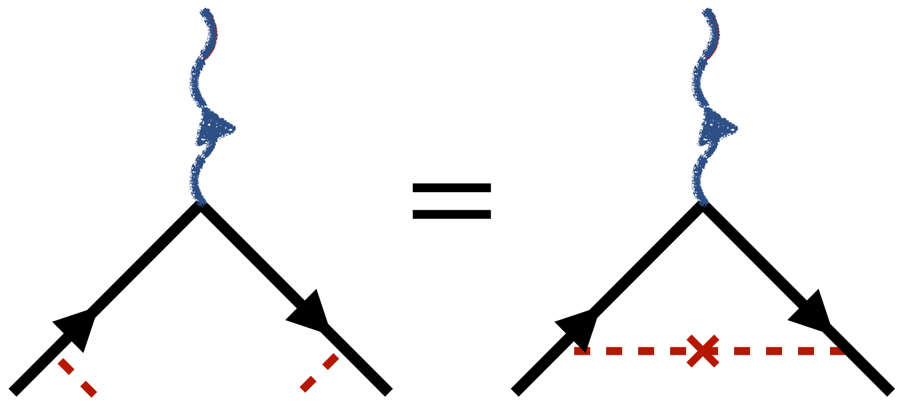
$$J(\mathbf{x}, t) = \partial_t(\mathbf{v} \cdot \hat{\mathbf{s}})\, \delta^{(3)}(\mathbf{x} - \mathbf{r}(t))\,.$$

$$\frac{d\mathbf{v}}{dt} = \frac{\mathbf{F}}{m} = \frac{g\, \ddot{a}\, \hat{\mathbf{s}}}{m}$$

Classical analogues for ultralight DM effects essentially always exist

“DM Background-Induced” $g-2$ Shifts are Classical

Claim: DM background yields very strong shifts of electron $g-2$ and EDMs



$$\Delta g_e \sim \frac{\rho_{\rm DM}}{m_{\rm DM}^2 m_e^2}\, g^2$$

2302.08746, PRL (2024)
2308.05375, JHEP (2025)
2410.10715
2412.14664
2509.12869

Described in quantum language, but again can be derived classically!

KZ, JHEP (2025)

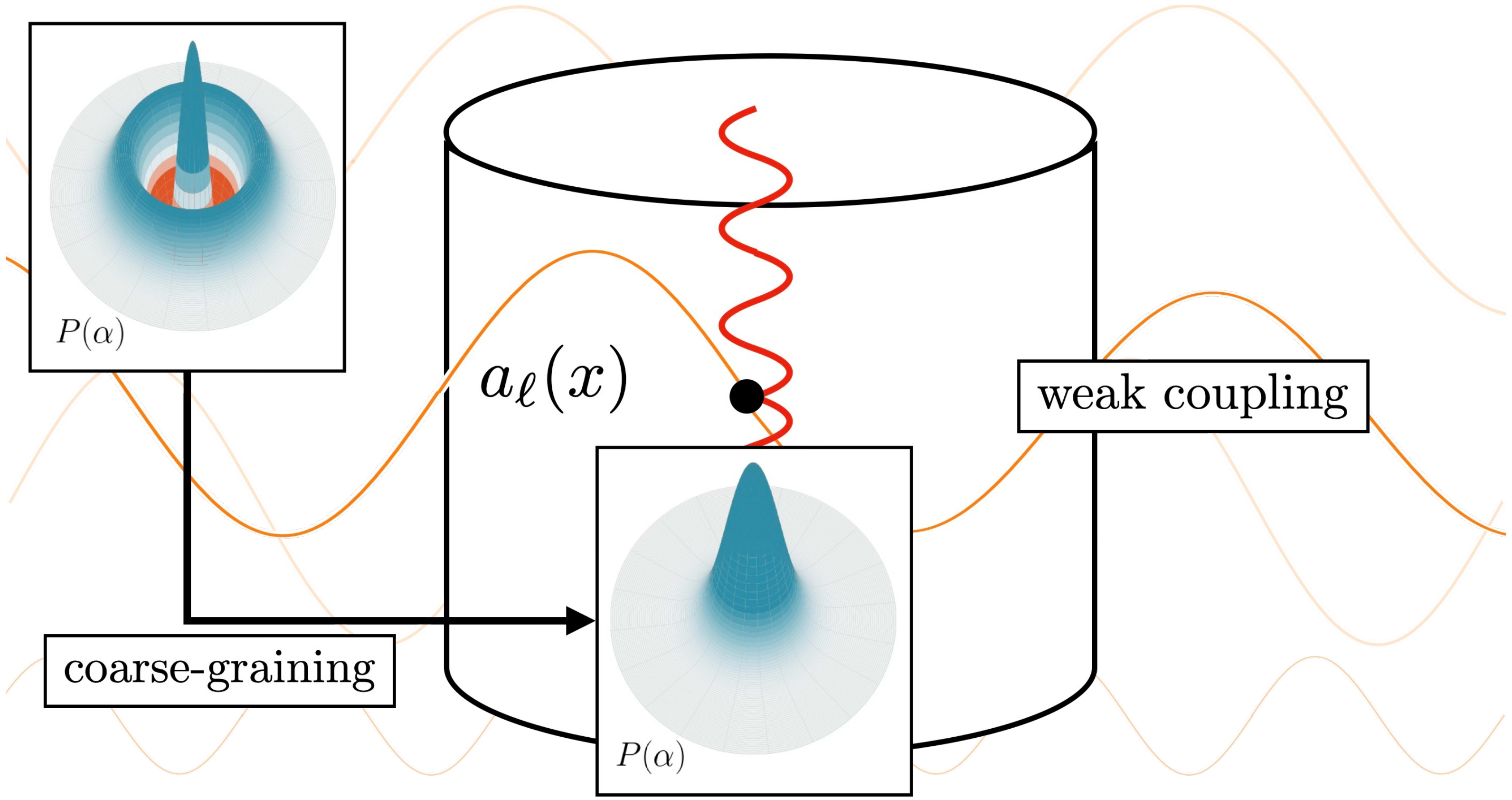
$$\frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B}) \qquad \frac{d\mathbf{S}}{dt} = \mathbf{S}\times\left(\frac{qg_e}{2m_e}\left(\mathbf{B} - \frac{\gamma}{\gamma+1}(\mathbf{v}\cdot\mathbf{B})\mathbf{v} - \mathbf{v}\times\mathbf{E}\right) + \frac{\gamma^2}{\gamma+1}\mathbf{v}\times\mathbf{a}\right).$$

Like ponderomotive force or gravitational wave memory, can be derived by carefully computing classical motion at second order

But classical derivation also reveals IR cutoff, making effect negligible in practice

Conclusion

The axion is a canonical, well-motivated dark matter candidate that can be probed effectively in near-future experiments



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

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

Same conclusion applies to other weakly coupled fields, such as gravitational waves