

Suppressed Quantum Effects of Weakly Coupled Waves

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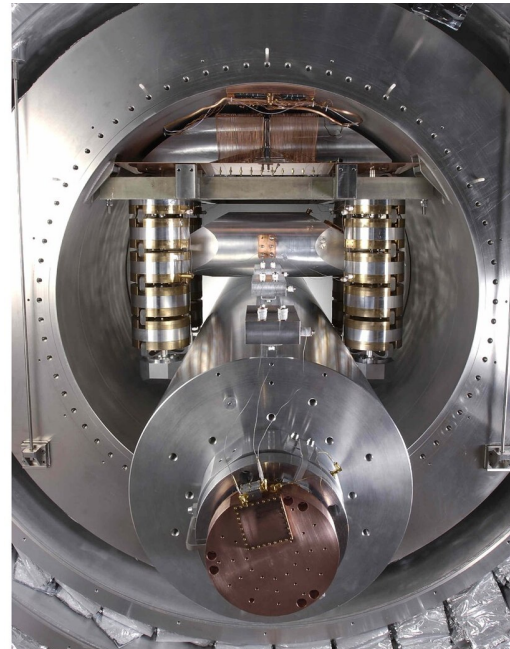
Bay Area Particle Theory Seminar — October 16, 2026

Phys. Rev. Lett. 136, 171601 (2026) and arXiv:2607.27313
with Yunjia Bao, Dhong Yeon Cheong, Nicholas Rodd, Joey Takach, Lian-Tao Wang

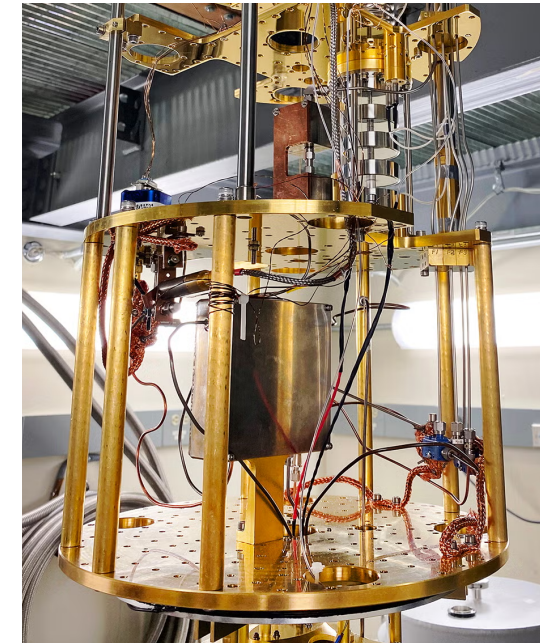
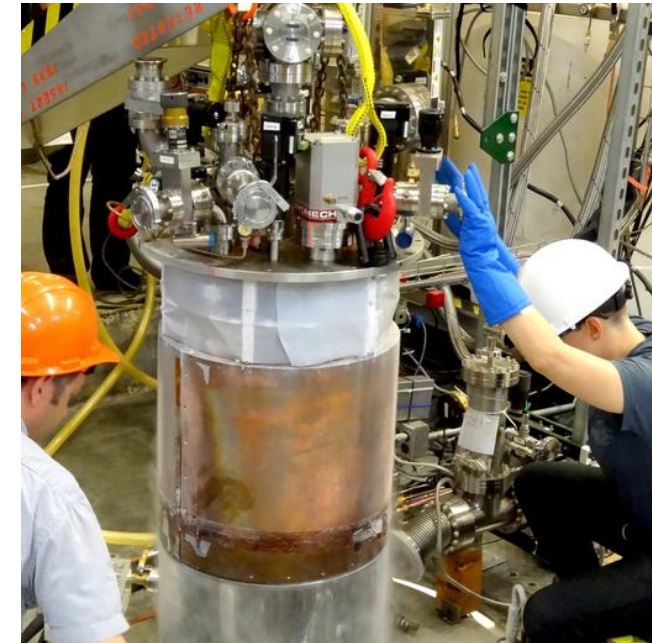
Searches for Weakly Coupled Waves

Many cutting-edge experiments search for fields with weak coupling, high occupancy

Gravitational waves: laser interferometers, Weber bars



Axion dark matter: cavity haloscopes



These detectors enhance their sensitivity by operating deep in the quantum regime

Squeezed
states

Number
measurements

Fock, “cat”, and
squeezed vacuum states

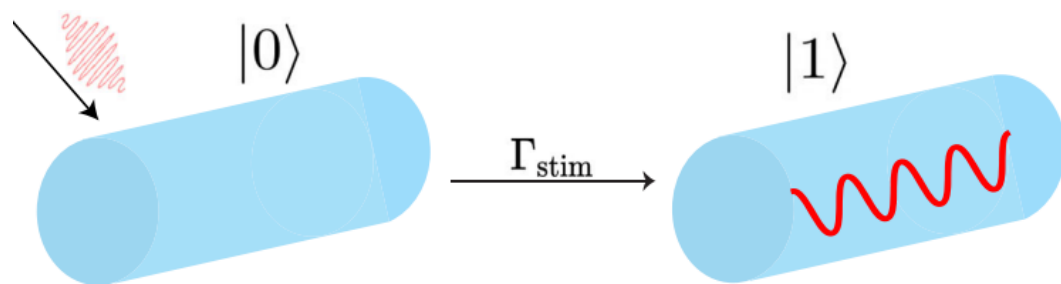
Entangled
states

Can they benefit from, or tell us about, the quantization of the field they detect?

Conflicting Conventional Wisdom

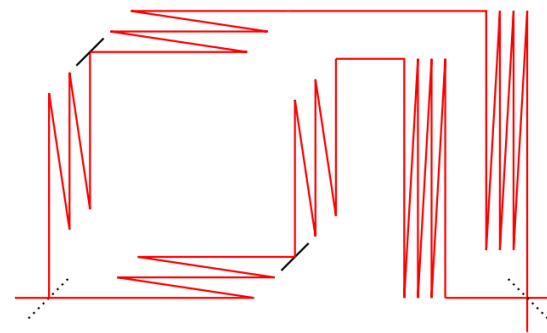
Textbook treatment describes GWs and axion DM as classical fields

But influential recent works claim quantum GW/DM effects, even probing quantum gravity!



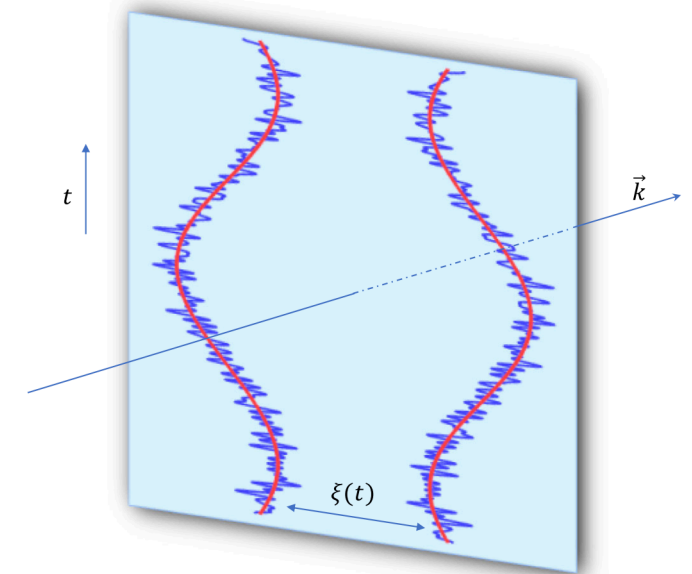
Graviton clicks

Tobar et al., Nature Commun. (2024)



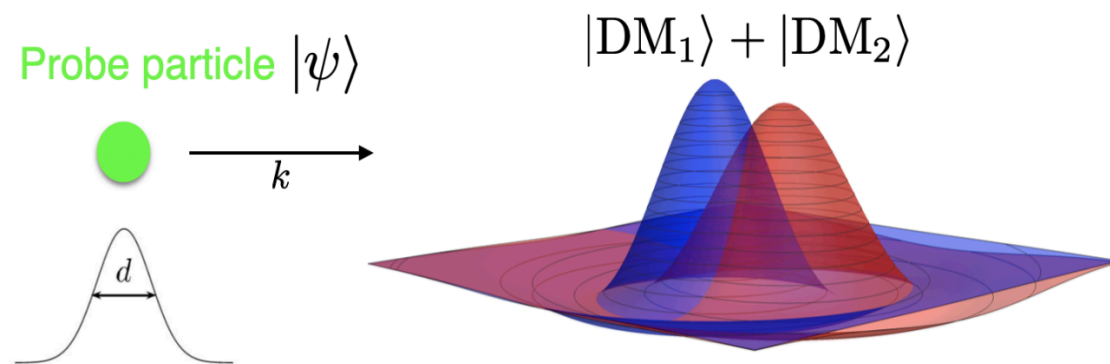
Gravitational decoherence

Schutzhold, PRL (2025)



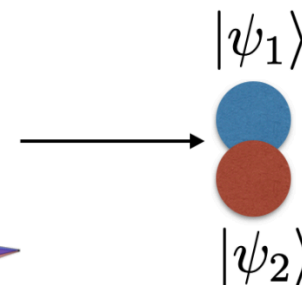
“Noise of gravitons”

Parikh, Wilczek, Zahariade, PRL (2021)



Axion cat states

Allali and Hertzberg, PRL (2021)



(+50 other recent papers with similar claims)

Defining Intrinsically Quantum Effects

Confusion arises from incompatible, incomplete definitions of “classical”/“quantum”

Quantum effects involve a quantum calculation

Must distinguish detector being quantum from the field being quantum, core insight of quantum optics

Quantum fields act like classical fields at high occupancy

Only for certain states, and claimed quantum GW/axion results all involve extremely high occupancy

Quantum effects depend on $\hbar$, vanish as $\hbar \rightarrow 0$

Depends on what you keep fixed

$$E = N\hbar\omega \rightarrow 0 \text{ as } \hbar \rightarrow 0?$$

In particle physics, only loop diagrams depend on $\hbar$
But results from quantum detectors always involve $\hbar$!

Our definition: intrinsically quantum DM/GW effects are those which cannot arise in a detector from *any* ensemble of classical fields

Outline

- **Axion DM and cavity haloscopes**

Defining the effective occupancy $N_{\text{eff}} \gg 1$ and conversion efficiency $\eta \ll 1$

GHz QCD axions and kHz GWs have $\eta \sim 10^{-20}, 10^{-30}$ with $\eta N_{\text{eff}} \sim 1$

Intrinsically quantum = negativity of the Glauber P -function

- **Suppression of intrinsically quantum effects**

Detectors see a coarse-grained effective mode, not fundamental modes

Intrinsically quantum effects are suppressed by an **extra** power of η

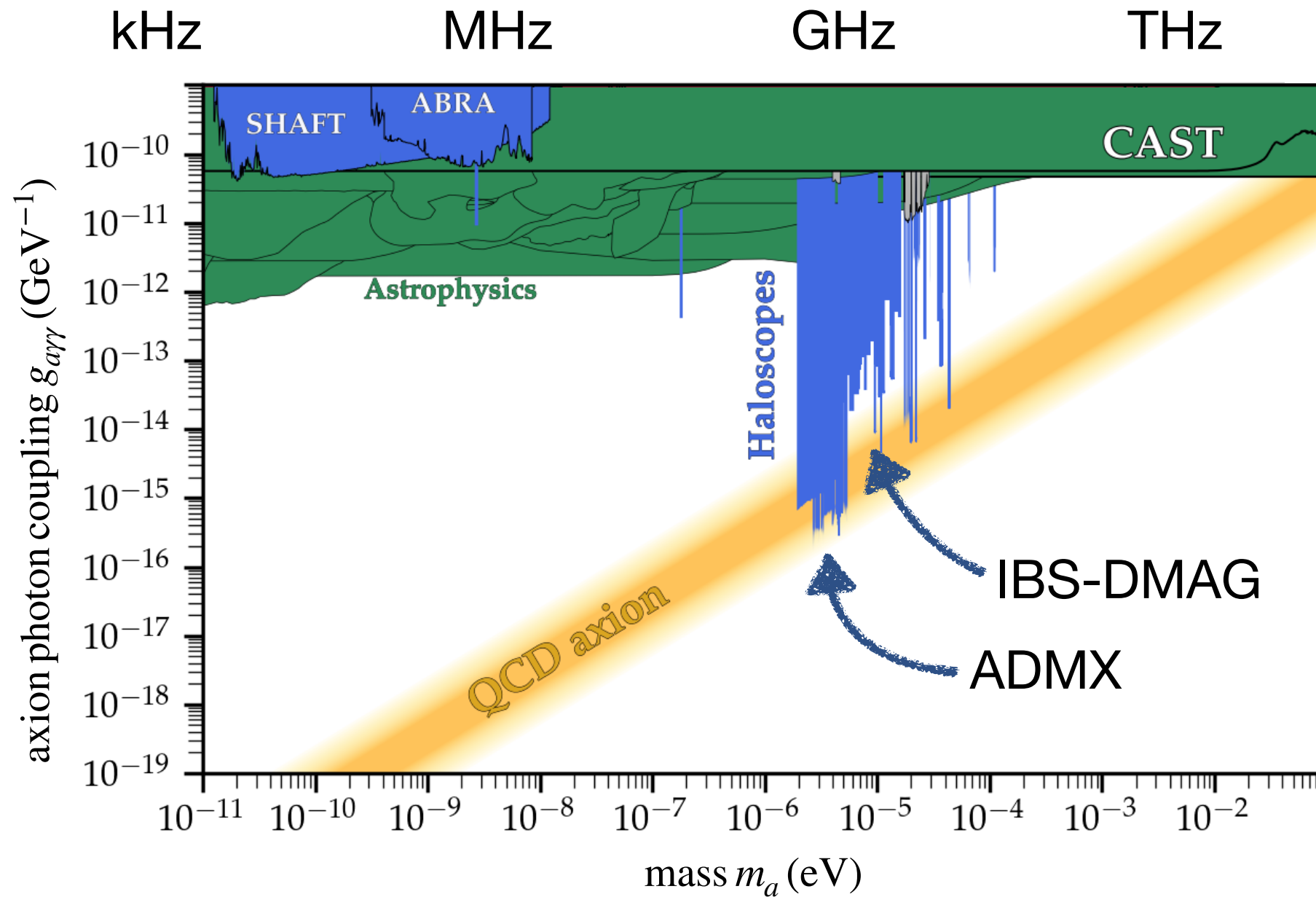
Resolving confusion in the literature

Ultralight Dark Matter Candidates

Ultralight DM is generic, viable, minimal and testable — and only a few options exist

	pseudoscalar a	scalar ϕ	vector A'_μ	axial vector V_μ
naturally light with leading coupling	✓		✓	✓
arises in high energy theories	✓✓	✓	✓	✓
can solve tuning problems	✓	?		
simply produced	✓	✓	✓?	✓?

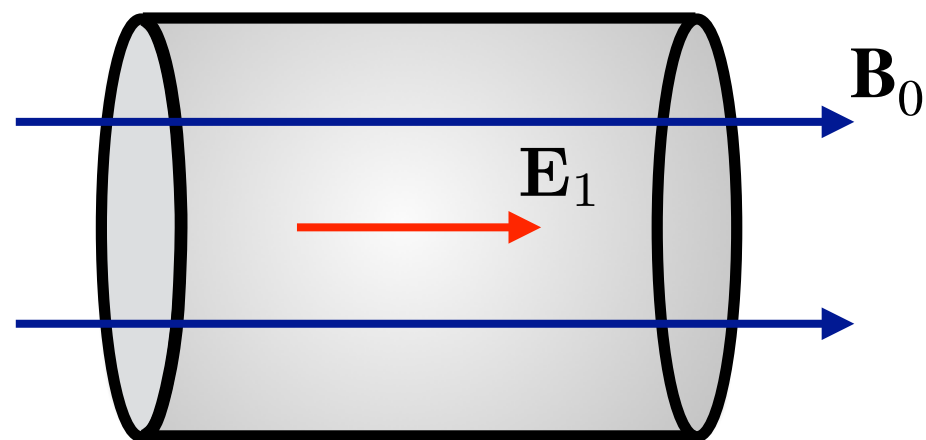
Hook, Huang, KZ,
arXiv:2609.10671



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

GHz Axions: The Cavity Haloscope

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

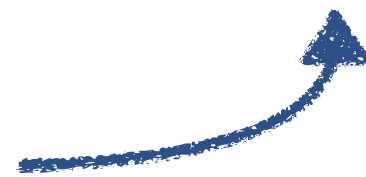


$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \dot{a} \mathbf{B}_0$$

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

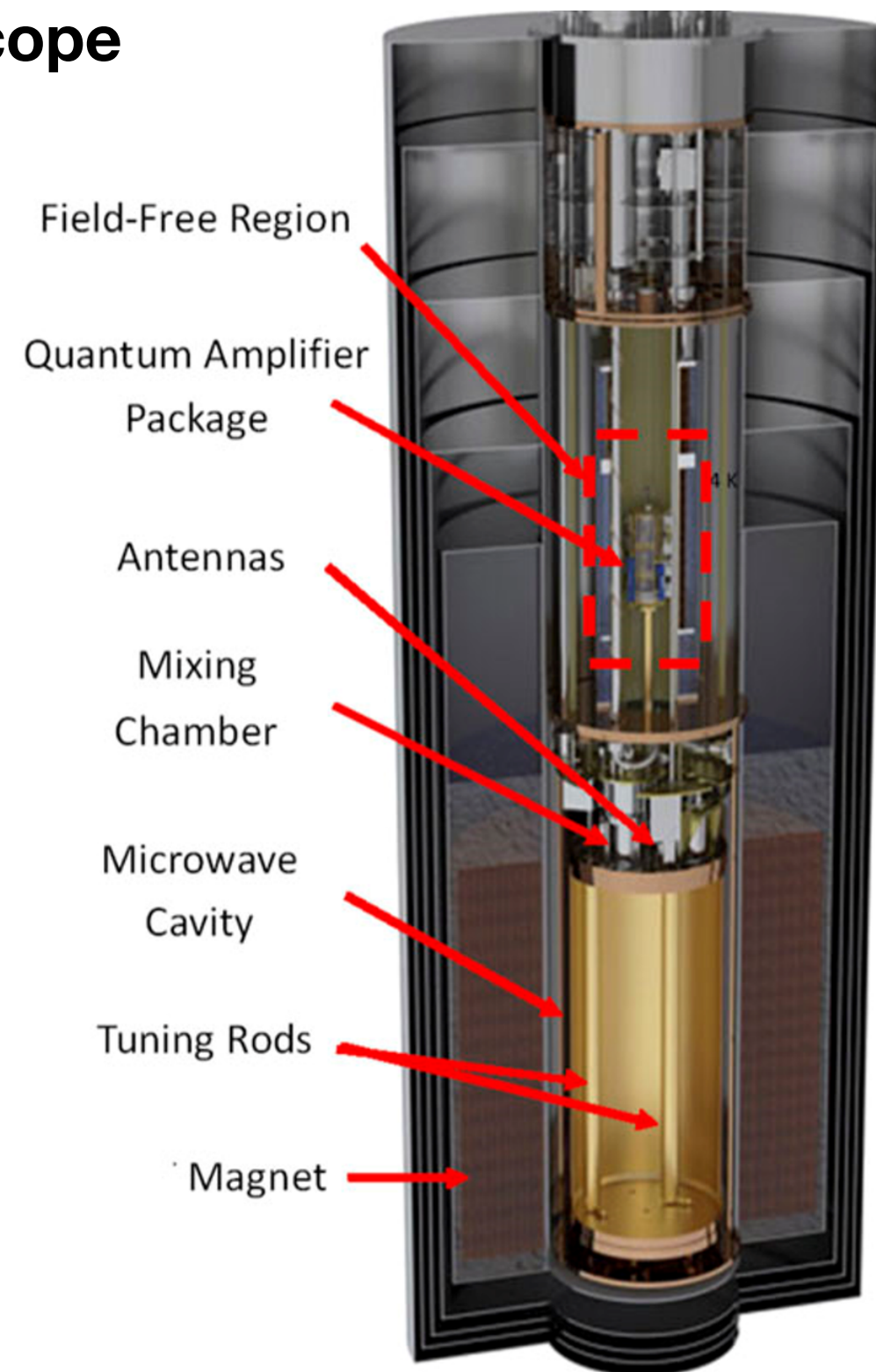
$$P_{\text{sig}} \sim (g_{a\gamma\gamma}^2 \rho_{\text{DM}}) (B_0^2 V) (Q_c / m_a)$$

decay time of cavity mode

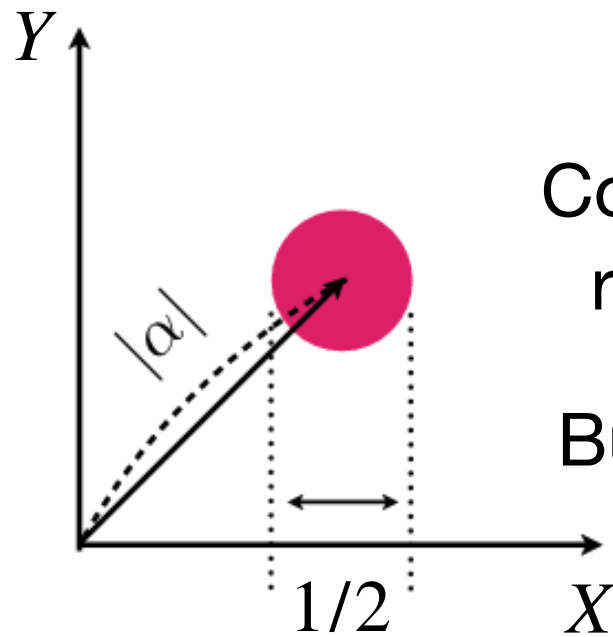


Need quantum description of axion and cavity haloscope

First question: what basis to use?

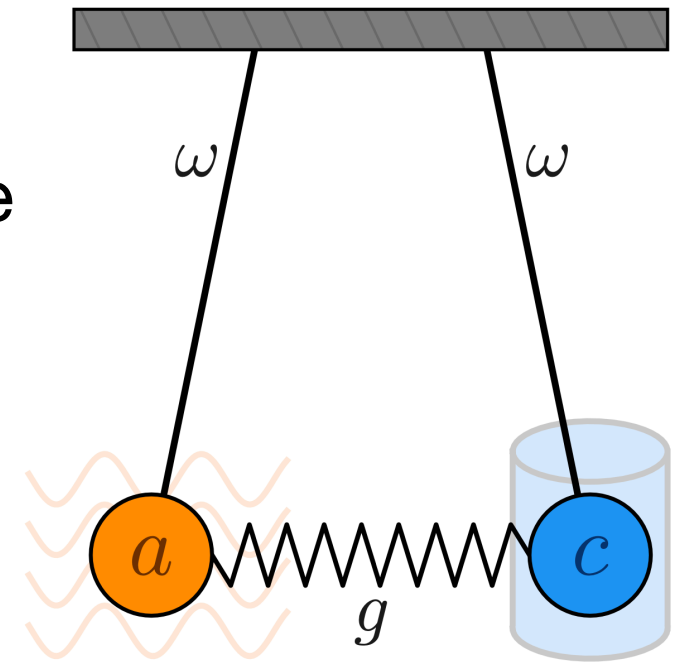


Coherent States Act Classically



Coherent states $|\alpha\rangle$ obey $a|\alpha\rangle = \alpha|\alpha\rangle$ and have relatively well-defined values of X , Y , N , and θ

But they have a much more important property!



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 $|\alpha gt\rangle$

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

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

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

Corrections to this are suppressed by $(gt)^3$, negligible for DM/GWs

Defining Nonclassical States

State of mode 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

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

thermal Gaussian state
(default assumption for DM)

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

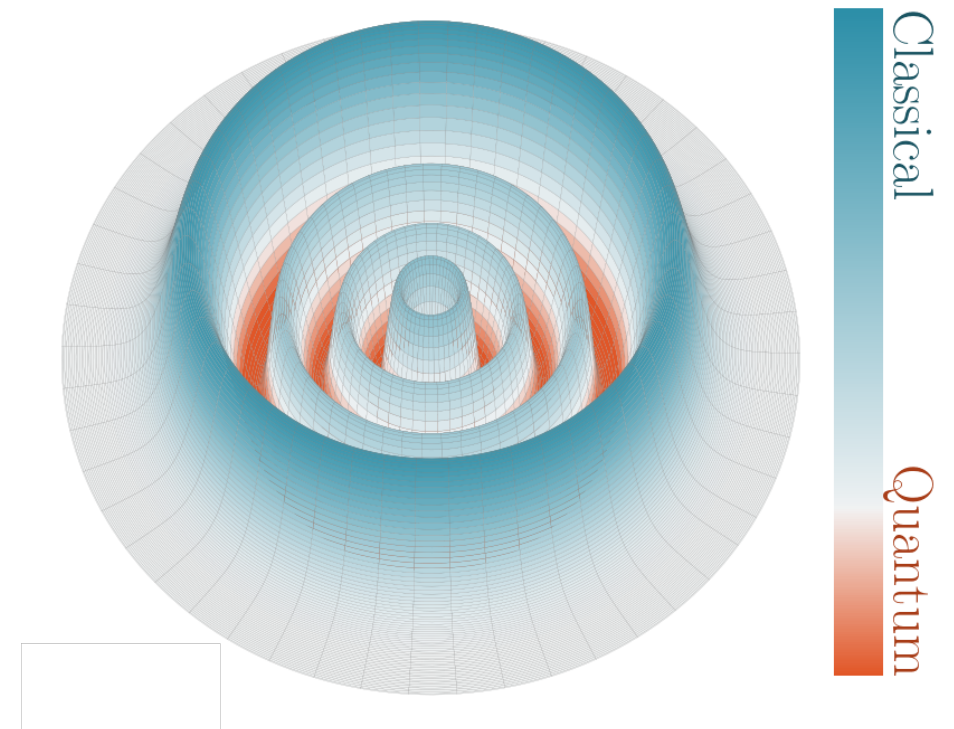
“cat” state $|\alpha\rangle + |\alpha'\rangle$

But many require $P(\alpha) < 0$, e.g. squeezed state $|\gamma\rangle$

number state $|n\rangle$

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

This remains true for arbitrarily high occupancy



Quantum Description of the Cavity Haloscope

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

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


$$\sum_{\mathbf{p}} \hat{a}_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}} + \text{h.c.} \quad \hat{c} \tilde{E}_z(\mathbf{x}) + \text{h.c.}$$

On resonance, reduces to mixing between cavity mode and an “effective” axion mode

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

Occupancy of effective mode is $N_{\text{eff}} = \langle \hat{a}_{\text{eff}}^\dagger \hat{a}_{\text{eff}} \rangle \sim \rho_{\text{DM}} V / m_a \sim 10^{19}$

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

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

Evolution of the Cavity State

Consider projectively measuring cavity after time t_m (less than DM coherence time)

$$P_{\text{cav}}^f(\alpha) \simeq \int d^2\beta \frac{P_{\text{eff}}(\beta/\sqrt{\eta})}{\eta} P_{\text{cav}}^i(\alpha - \beta) = \frac{P_{\text{eff}}(\alpha/\sqrt{\eta})}{\eta}$$

scaled convolution of axion
state and initial cavity state

if cavity begins in vacuum state

Axion-photon conversion efficiency at maximum $t_m \sim Q_c/m_a \sim 10^{-4}$ s is

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

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

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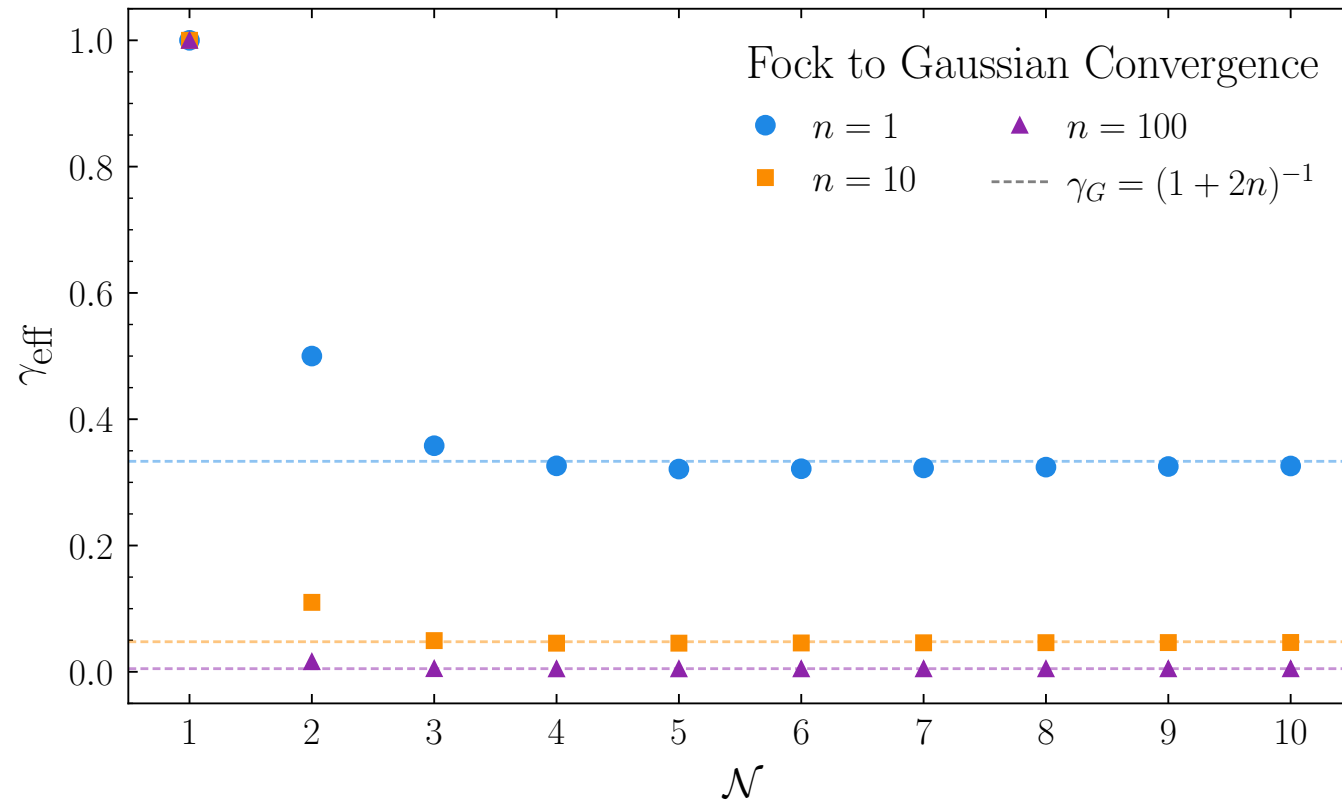
Detectors see a coarse-grained effective mode, not fundamental modes

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Resolving confusion in the literature

Quantum State of the Effective Axion Mode

If the axion's plane wave modes are independent, the central limit theorem implies the effective mode is in a Gaussian state, which is not intrinsically quantum



$$P_{\text{eff}}(\alpha) \rightarrow e^{-|\alpha|^2/\langle n \rangle} \geq 0$$

Convergence of central limit theorem rapid, even for high mode occupancy

However, can evade CLT with astrophysical sources (mode correlations, nonstationarity), Bose-Einstein condensation, or lab-sourced axions

For now, optimistically let the effective mode's state be arbitrary

Nonclassical Number Statistics

Note that $\text{var}(n) - \langle n \rangle = \int d\alpha P(\alpha) (|\alpha|^2 - \langle n \rangle)^2 \geq 0$ if $P(\alpha) \geq 0$

Thus, only nonclassical states can have Mandel $Q = (\text{var}(n)/\langle n \rangle) - 1 < 0$

DM coherent state: $Q_{\text{DM}} = 0$, Poisson number distribution

DM Gaussian state: $Q_{\text{DM}} = N_{\text{eff}}$, geometric number distribution

DM Fock state: $Q_{\text{DM}} = -1$, definite number

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

Large positive Q_{DM} is enhanced by N_{eff} and observable, but negative Q_{DM} is not

Distinguishing Number Statistics

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

Discovering the axion needs time t_m/p_1 (but does **not** show axion is quantum)

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

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

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

Quadrature Statistics

Simplest nonclassicality measure for quadrature measurements is squeezing

$$X = (a + a^\dagger)/\sqrt{2} \quad S = \text{var}(X) - 1/2$$

DM coherent state: $S_{\text{DM}} = 0$

DM Gaussian state: $S_{\text{DM}} = N_{\text{eff}}$ (all have Gaussian quadrature distribution)

DM squeezed state: $S_{\text{DM}} < 0$

Starting from an initial vacuum state, DM can induce squeezing $S_{\text{cav}} = \eta S_{\text{DM}}$

Time to distinguish coherent and Gaussian: $t_m/(\eta N_{\text{eff}})$ (reasonable)

Time to detect negative S_{cav} : t_m/η^2 (impractically long)

Similar story for higher-order generalizations of Q and S

Entanglement and Decoherence

Entangled effective modes can transmit entanglement to cavity modes

Classical correlations can be large,
but entanglement measures are not

$$E = \frac{\text{var}(X_1 - X_2) + \text{var}(Y_1 + Y_2)}{2} - 1 \geq -1$$
$$E_{\text{cav}} = \eta E_{\text{DM}} \geq -\eta$$

Axion-cavity interaction can decohere a prepared initial cavity state

Quantify by the purity loss $\delta = 1 - \text{tr}(\rho_c^2)$

$$\frac{\delta}{2\eta} = \left(\langle a^\dagger a \rangle - |\langle a \rangle|^2 + \frac{1}{2} \right) \left(\langle c^\dagger c \rangle - |\langle c \rangle|^2 + \frac{1}{2} \right) - \frac{1}{4} - (\langle (a^\dagger)^2 \rangle - \langle a^\dagger \rangle^2) (\langle c^2 \rangle - \langle c \rangle^2) + \text{c.c.}$$

Lowest for coherent DM, $\delta \sim \eta$, highest for Gaussian DM, $\delta \sim \eta N_{\text{eff}}$

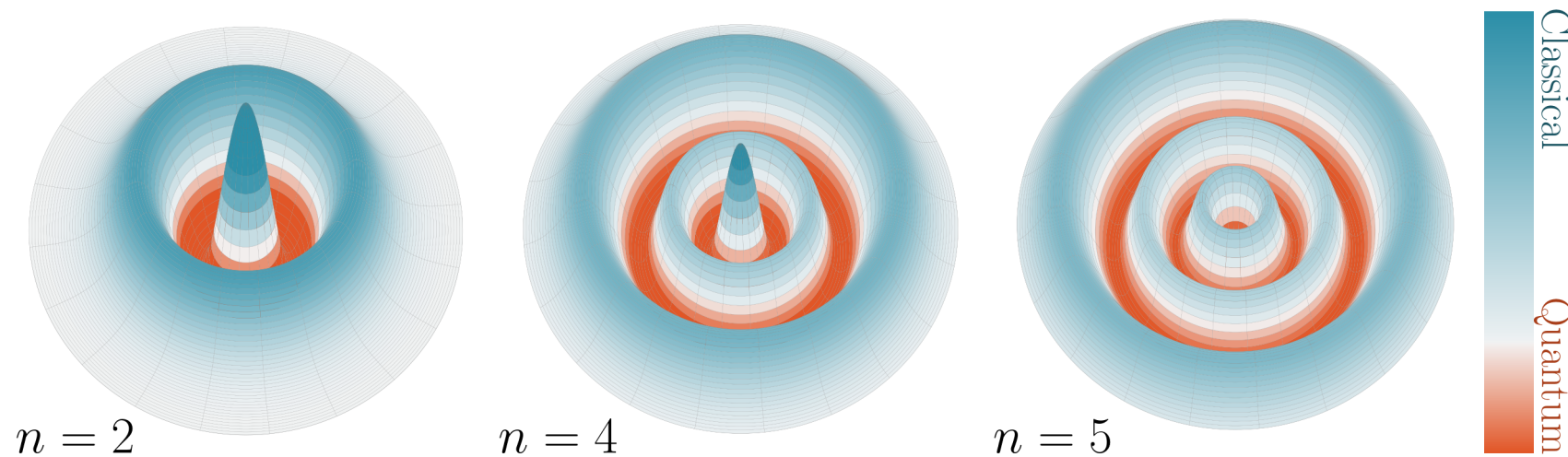
Nonclassical axion states extend the range up and down, by amount suppressed by η

A Heuristic 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



For initial vacuum state,
 $P_{\text{cav}}^f(\alpha) = P_{\text{eff}}(\alpha/\sqrt{\eta})/\eta$ oscillates on
 $\sqrt{\eta}$ scales, negativity hard to observe

Thermal fluctuations in the initial state also convolve final state with a Gaussian!

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

A Precise General Argument

For any nonclassical DM state, construct the classical state $P'_{\text{DM}}(\alpha) = Q_{\text{DM}}(\alpha) \geq 0$

Probabilities of a generic measurement outcome in both cases:

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

$$p - p' \lesssim \text{tr} |\rho^f - \rho_{\text{cl}}^f| \lesssim \eta \text{tr} |\mathcal{L}[\rho^f]| \quad \begin{array}{l} \text{difference in the probability always} \\ \text{suppressed by } \eta \end{array}$$

To cancel the suppression, the initial detector state must be nonclassical, **and** properties of the initial state must scale as $1/\eta$

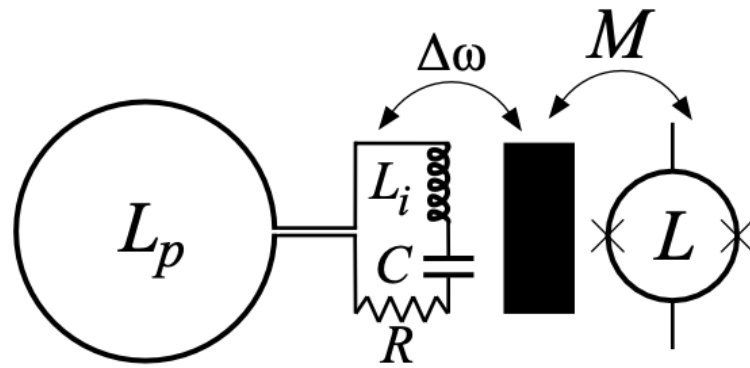
$$\text{var}(X_c) = (1 - \eta) \text{var}(X_{c,0}) + \eta \text{var}(X_a)$$

Such as squeezed vacuum with occupancy $\sim 1/\eta$, far beyond current technology

Extension to Other Detectors

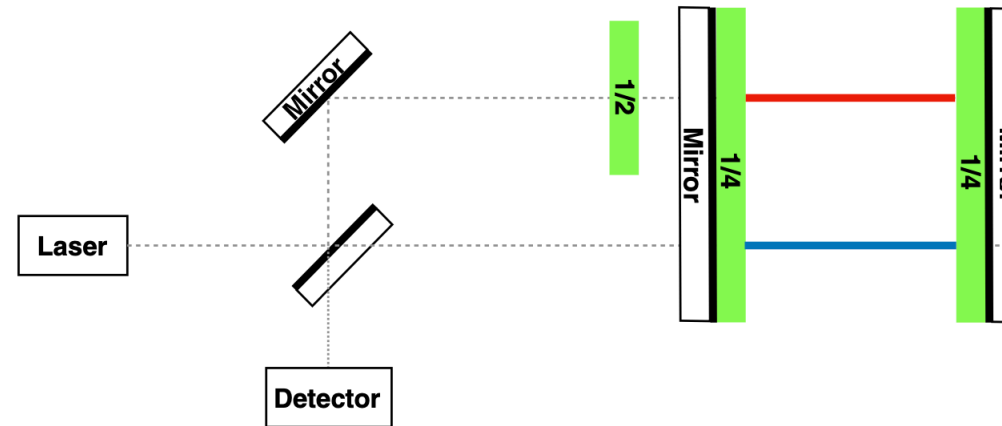
Our results apply to almost all axion DM detectors, as their interactions can be written in a linear mixing form

$$H_{\text{int}} = ig (c^\dagger a - c a^\dagger)$$



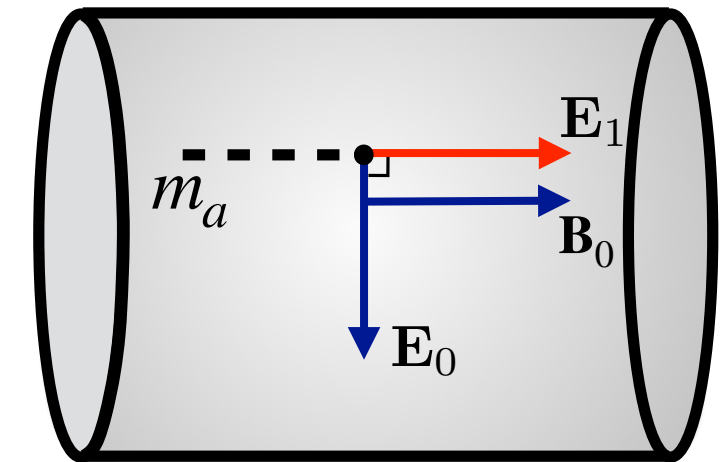
lumped element circuits

Kahn, Safdi, Thaler, PRL (2016)



axion interferometry

DeRocco and Hook, PRD (2018)



superconducting heterodyne

Berlin, D'Agnolo, Ellis, Nantista, Neilson, Schuster, Tantawi, Toro, KZ, JHEP (2020)

Also holds for many GW detectors, including LIGO

$$\eta \sim \frac{B_0^2 L^2}{M_{\text{pl}}^2} \sim 10^{-33} \left(\frac{B_0}{10 \text{ T}} \right)^2 \left(\frac{L}{10 \text{ m}} \right)^2$$

graviton-photon conversion

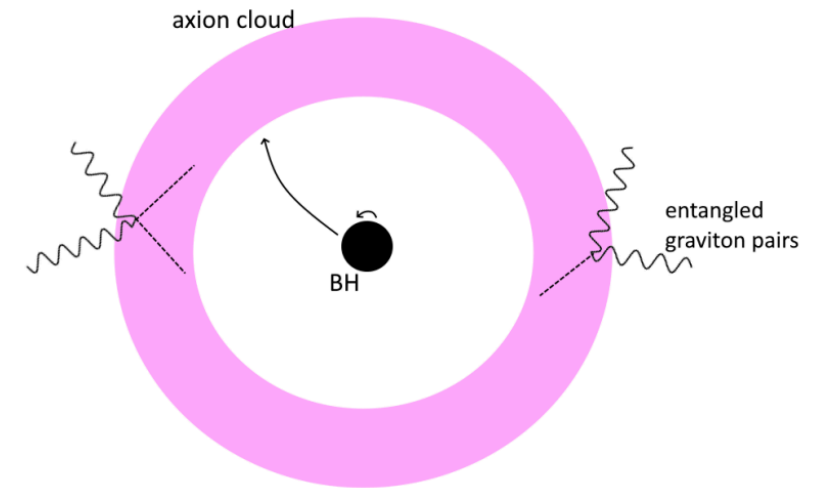
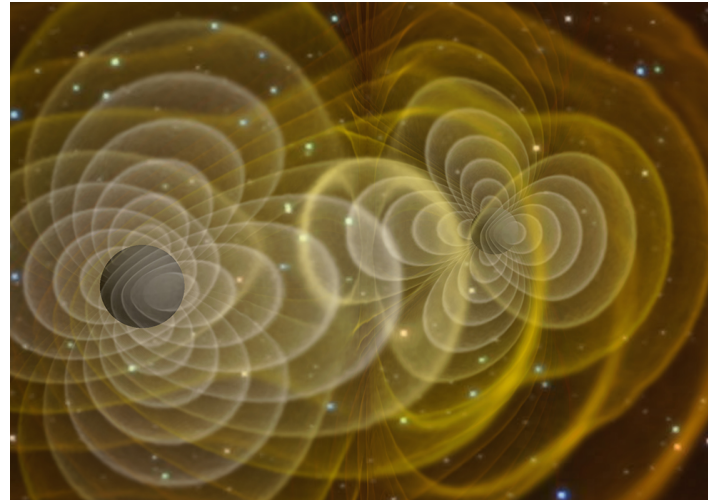
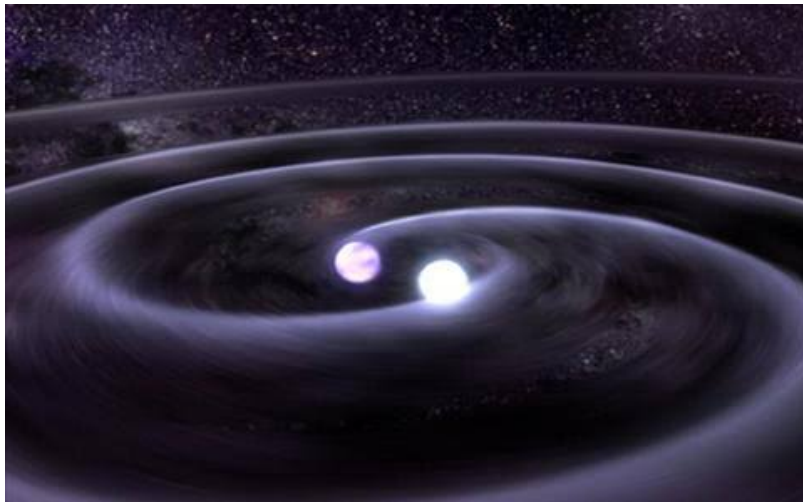
$$\eta \sim \frac{\rho Q_m v_s^5}{\omega_0^2 M_{\text{pl}}^2} \sim 10^{-32}$$

Weber bar

The Expected Graviton State

Gravitational waves are produced in a coherent state

Textbook statement; only holds for linearized gravity and a perfectly known source



Nonlinear interactions in a binary inspiral can make a weakly squeezed state

Kanno, Soda, Taniguchi, PRL (2026)

(also realized indirectly in amplitudes literature)

Britto, Gonzo, Jehu, JHEP (2022)

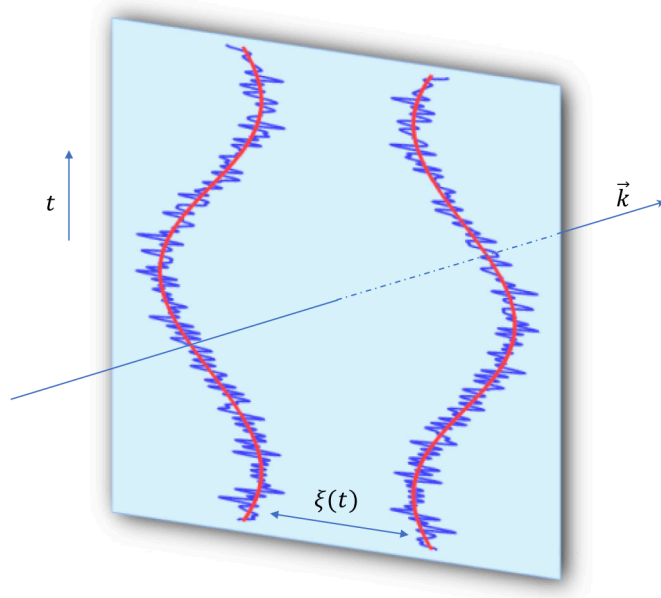
For stochastic gravitational wave background, expect Gaussian state

Superradiant axion clouds could source strongly squeezed GWs

Dorlis et al., PRL (2026)

(inflation also generates squeezed GWs)

What About Quantum Gravity Claims?

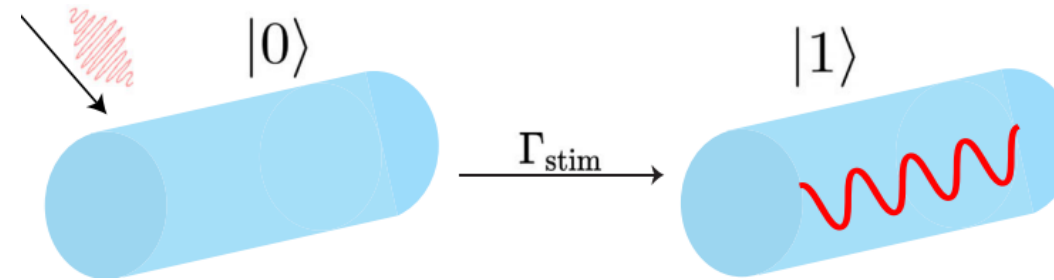


“The noise of gravitons”

Parikh, Wilczek, Zahariade, PRL (2021)

Classical GWs can have
 $\text{var}(X) \gg 1/2$

$\text{var}(X) < 1/2$ would be
 quantum, can't see

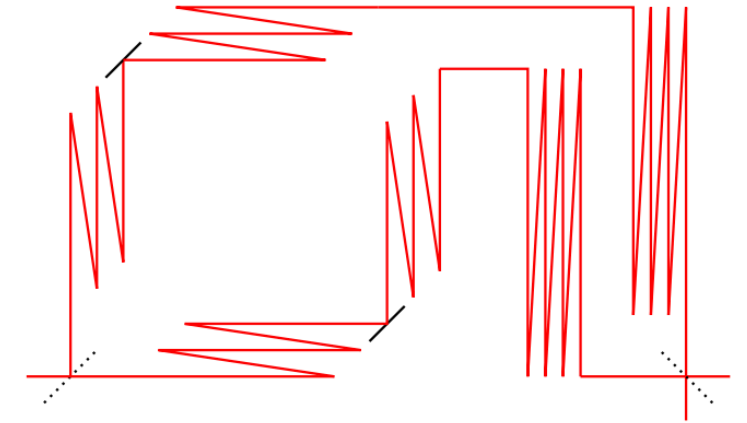


Absorption of gravitons

Tobar et al., Nature Commun. (2024)

Classical GWs can excite
 discrete energy levels

$Q < 0$ would be
 quantum, can't see



State-dependent
 decoherence

Schutzhold, PRL (2025)

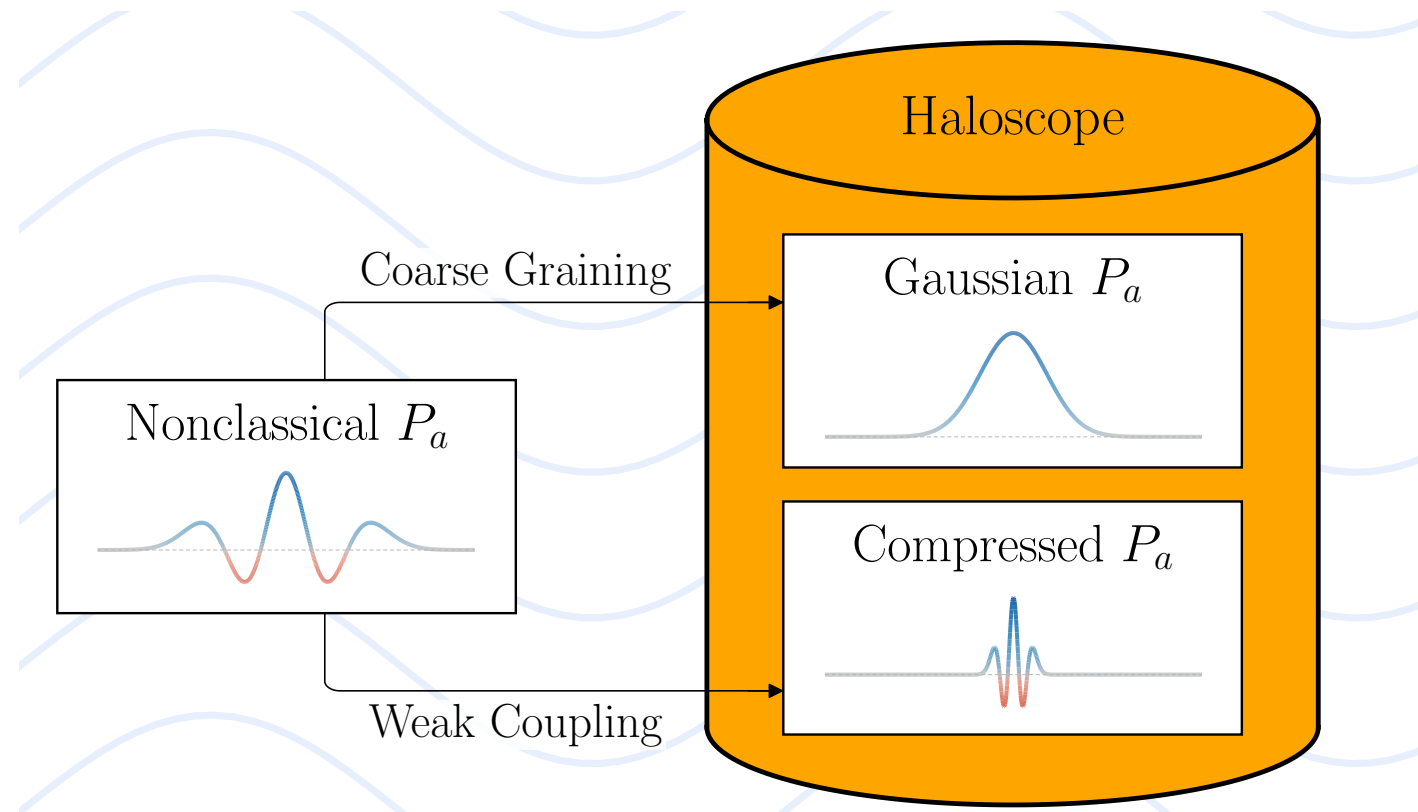
Classical GWs can yield
 low/high decoherence

Extended range would
 be quantum, can't see

Common issues: not modeling the detector, or using a formalism which obscures the GW state, making it less clear how to distinguish intrinsically quantum effects

Conclusion

Weakly coupled waves, such as axion DM and GWs, act approximately classically



Not because of high occupancy, but rather by coarse-graining and weak coupling

The classical field approximation works, and realistic DM and GW detectors cannot show the axion/gravitational field is quantized