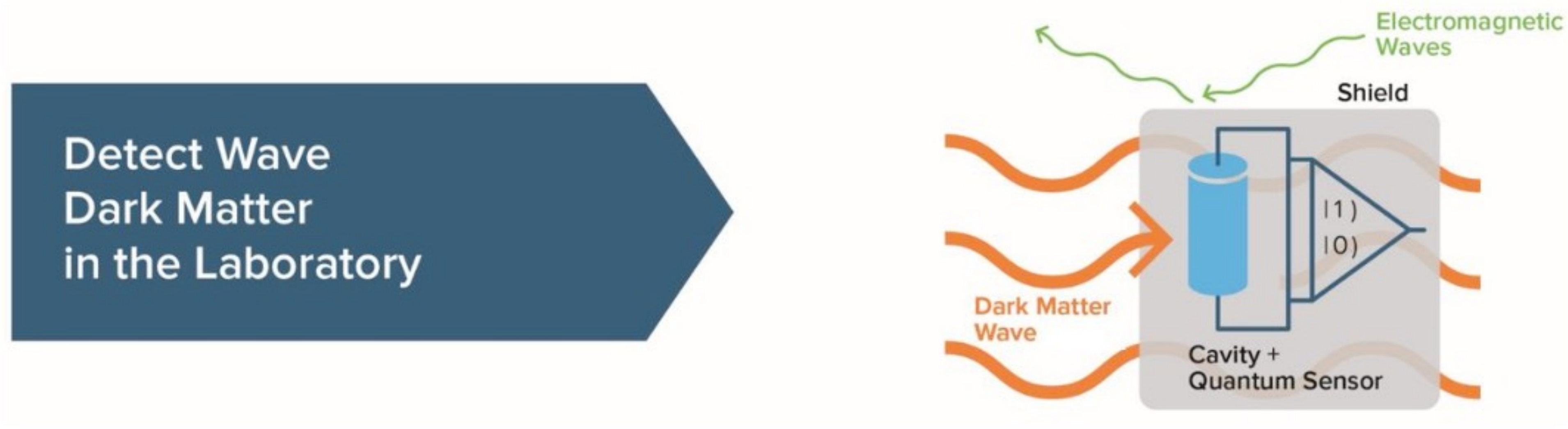
Detecting ultraweak forces (e.g. from dark matter) with quantum sensing technologies

Aaron S. Chou (Fermilab)

Physics Frontiers with Quantum Science and Technology workshop
University of Tokyo, March 9, 2022

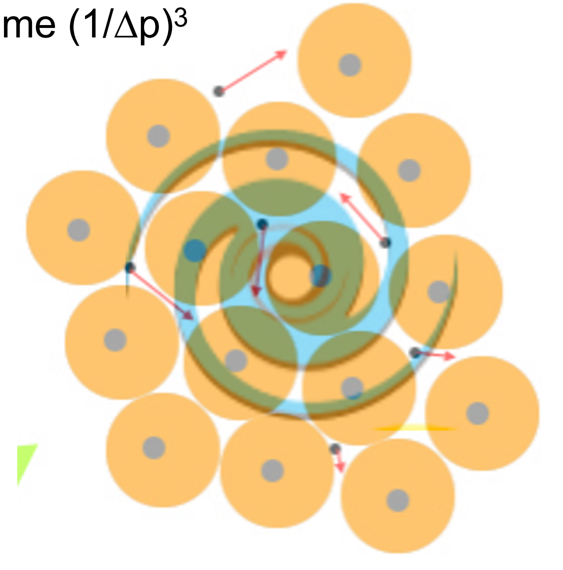


Detect Wave
Dark Matter
in the Laboratory

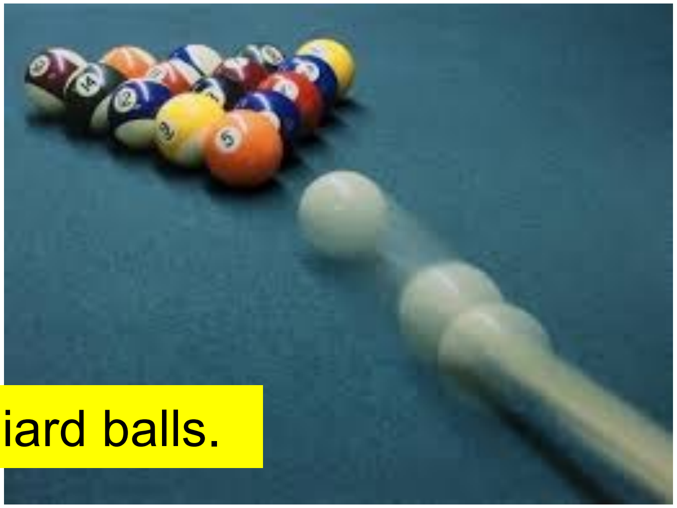
Low mass dark matter generically takes the form of classical bosonic sine waves

For **mass < 70 eV**, Fermion degeneracy pressure would cause dark matter clumps to swell up to be larger than the size of the smallest dwarf galaxies. (Randall, Scholtz, Unwin 2017)

Fermions: 1 DM particle per mode volume $(1/\Delta p)^3$



→ If lower mass, dark matter must be coherent bosonic sine waves with **macroscopic mode occupation number >>1**



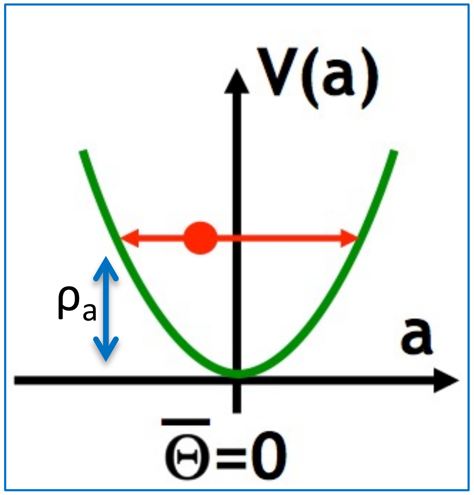
Not billiard balls.

For example, axion dark matter = waves of oscillating $\boldsymbol{\theta}_{\mathbf{CP}}$

Locally coherent oscillation of the QCD $\boldsymbol{\theta}$ angle about its CP-conserving minimum:

$$\theta(x,t) = \theta_{\max} e^{i(kx - m_a t)}$$

where $$\theta_{\max} = \sqrt{\frac{2\rho_a}{\Lambda_{\mathrm{QCD}}^4}} \approx 3.7 \times 10^{-19}\mathrm{radians}$$

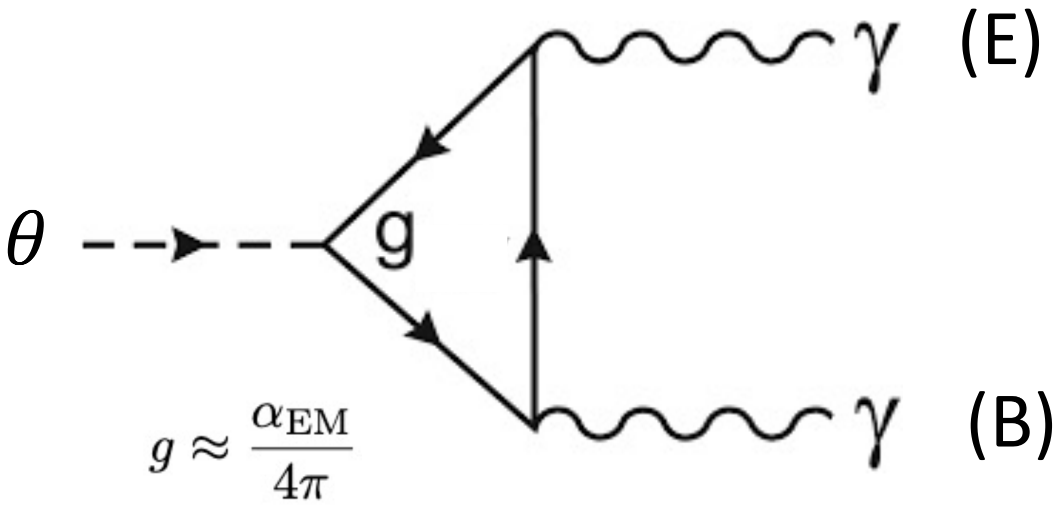


DM oscillations partially undo the Peccei-Quinn mechanism by enabling the coherent field condensate to climb out of the potential minimum.

Topological magneto-electric effect:

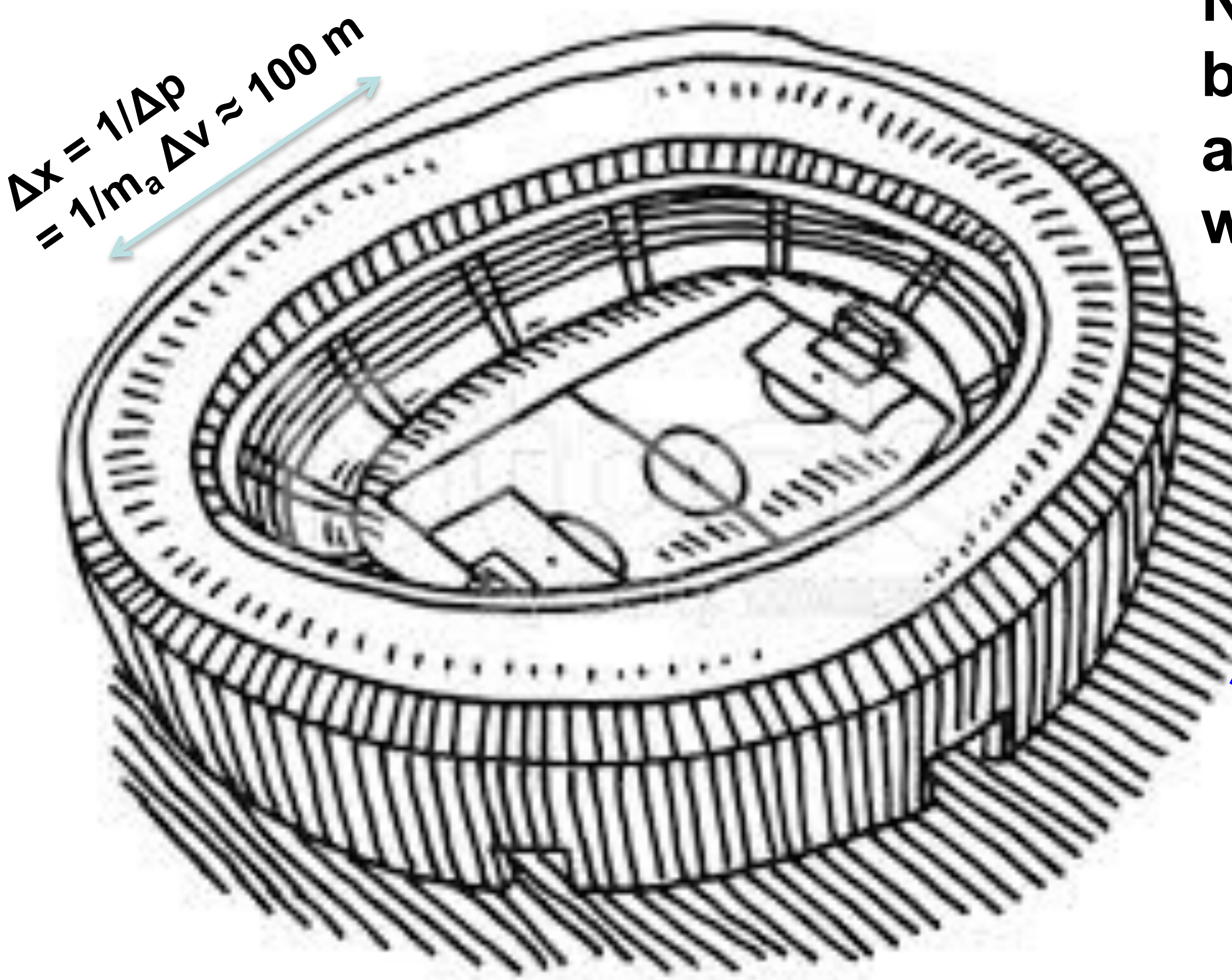
Classically oscillating angle $\boldsymbol{\theta}$:

- **Rotates B-fields into E-fields**
- Creates AC nucleon EDMs
- Creates AC torques on fermion spins

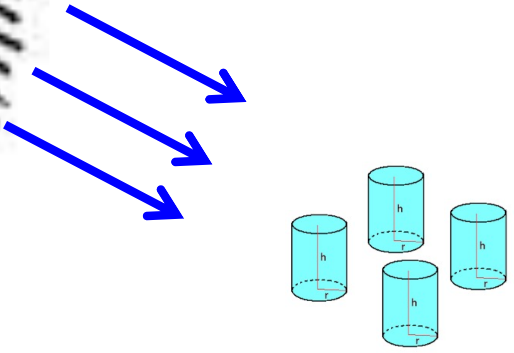


e.g. 10^{-5} eV = GHz dark matter

Non-relativistic bosonic DM is like a slow CW laser with $f=m_a/2\pi$



$v \approx \Delta v \approx 300$ km/s (galactic escape velocity)



Football stadium-sized regions of coherently oscillating **classical sine waves** slowly drifting through detectors. Mean DM occupation number **$N>10^{22}$ per mode.**

Accumulate oscillatory signals in various kinds of laboratory oscillators which are weakly coupled to the DM wave

The Dark Matter Haloscope: Classical axion wave drives RF cavity mode

Pierre Sikivie, Phys.Rev.Lett. 51, 1415 (1983)

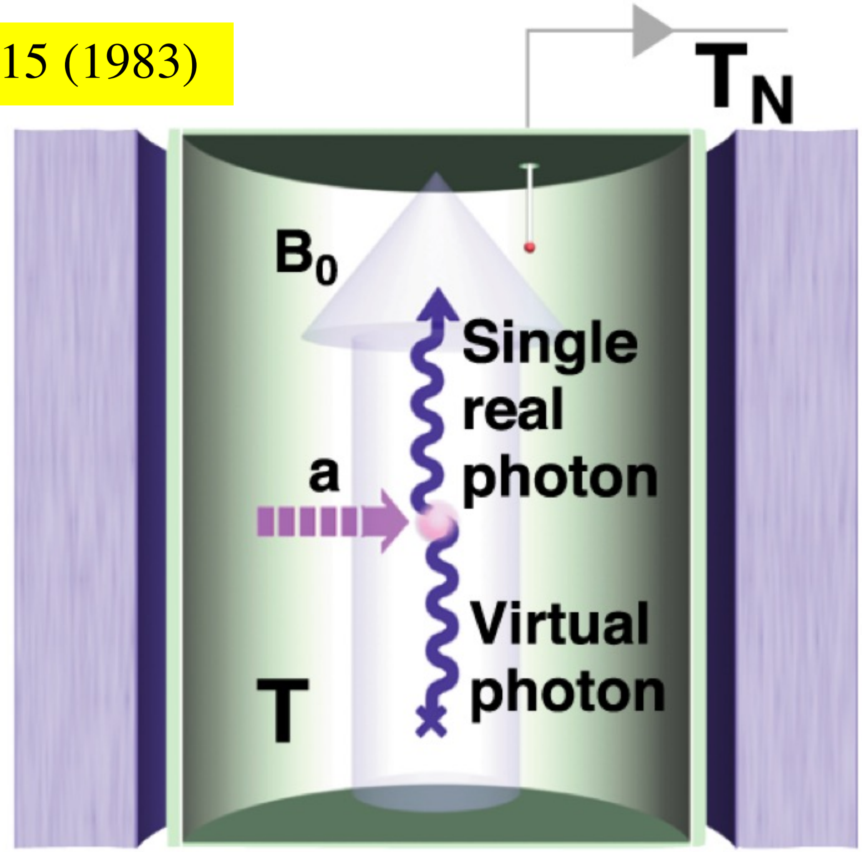
- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

$$\vec{J}_a(t) = -g\theta\vec{B}_0 m_a e^{im_a t}$$

which drives E&M via Faraday's law:

$$\vec{\nabla} \times \vec{H}_r - \frac{d\vec{D}_r}{dt} = \vec{J}_a$$

- Periodic cavity boundary conditions extend the coherent interaction time **(cavity size ≈ $1/m_a$)** → the exotic current excites standing-wave RF fields.



A spatially-uniform cavity mode can **optimally** extract power from the dark matter wave

$$P_a(t) = \int \vec{J}_a(t) \cdot \vec{E}_r(t)\, dV$$

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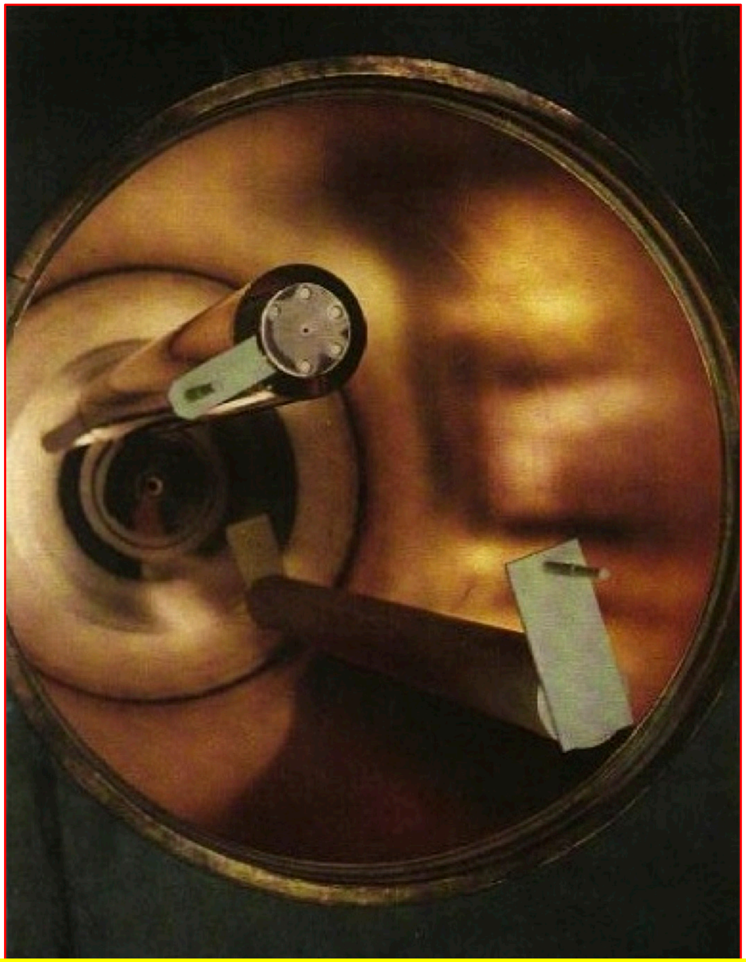
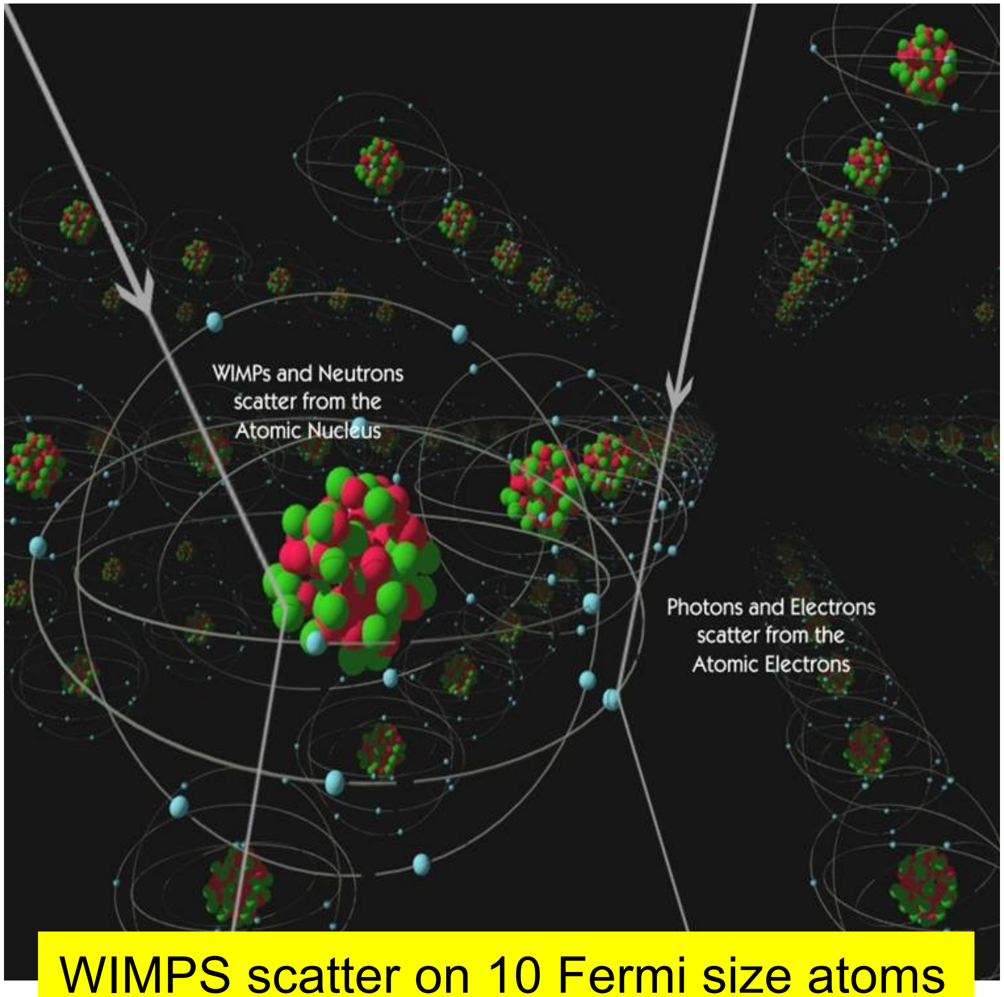
Axions vs WIMPs:

Resonant scattering if size of scattering target = 1/(momentum transfer)

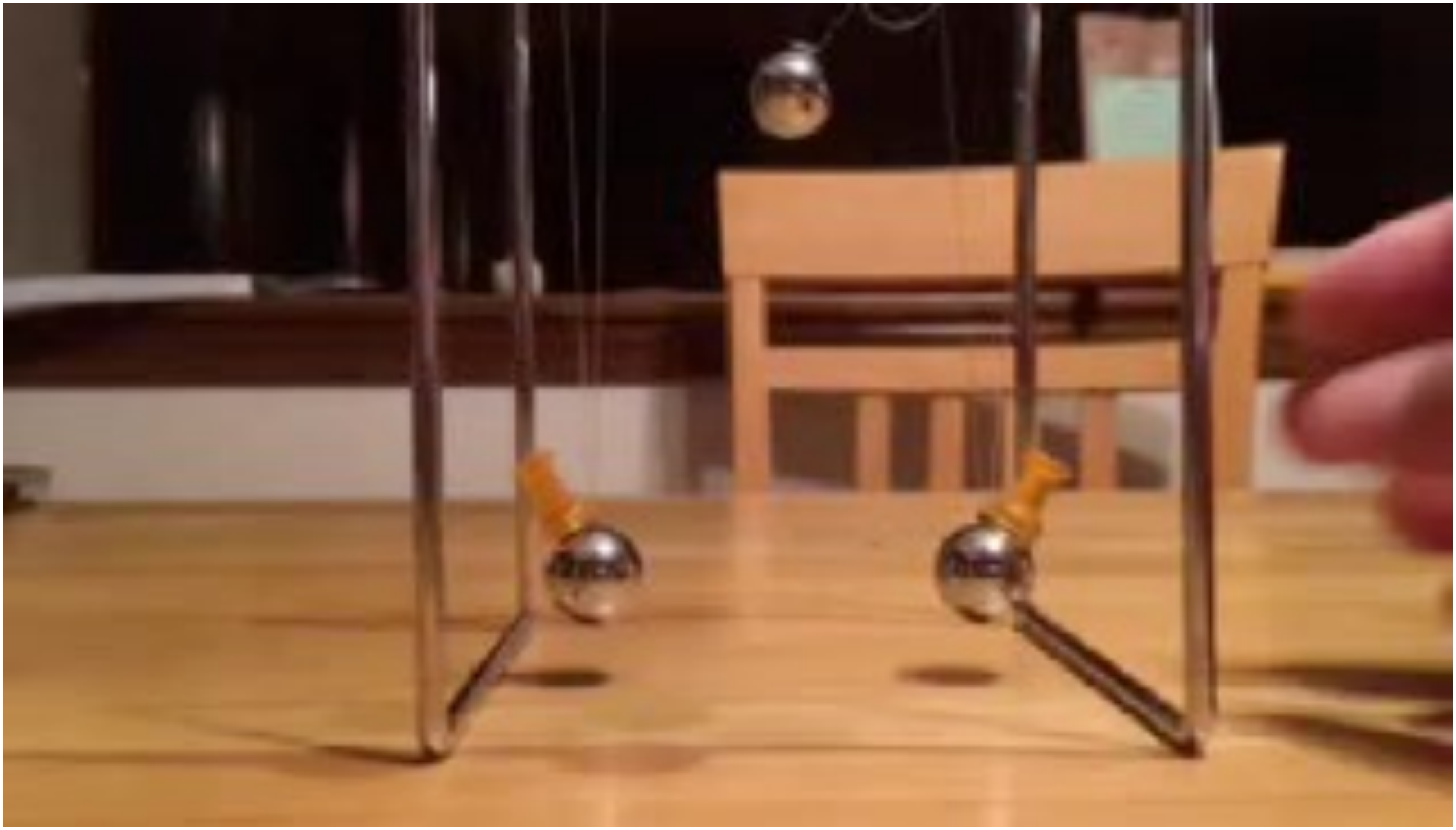


4 μeV mass axions scatter on 50cm size microwave cavities



WIMPS scatter on 10 Fermi size atoms

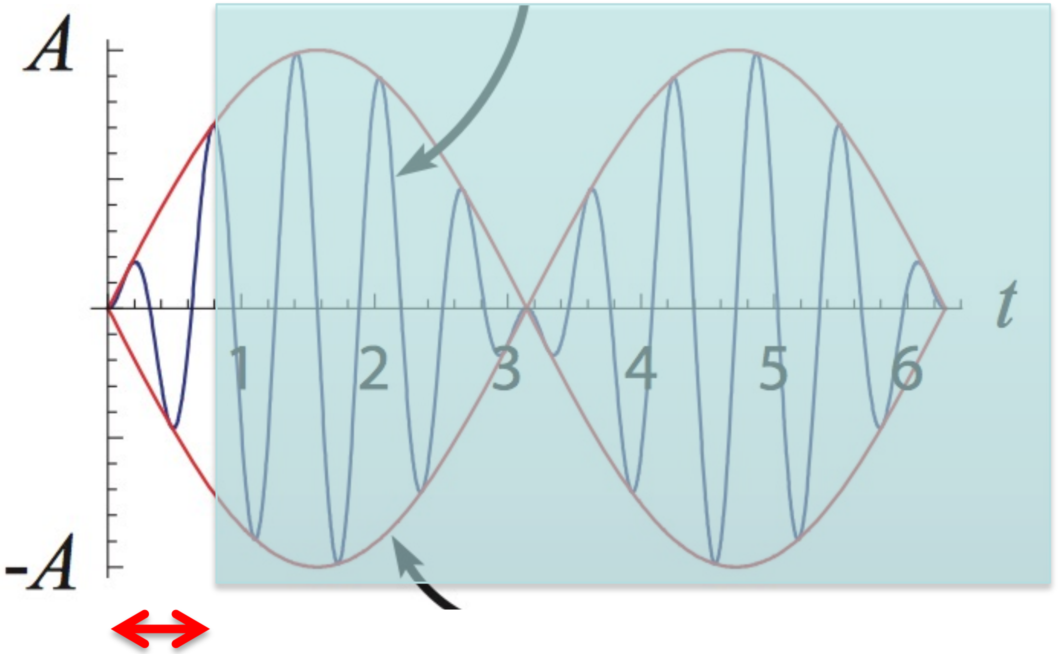
Energy transfer between axion and photon



Weak coupling -- takes many swings to fully transfer the wave amplitude.

In real life, Q = number of useful swings is limited by coherence time.

Only a small amplitude displacement of the photon field can be accumulated over the cavity or axion coherence time



$t_{cav} = 1/df_{cav} = Q_{cav}/f$

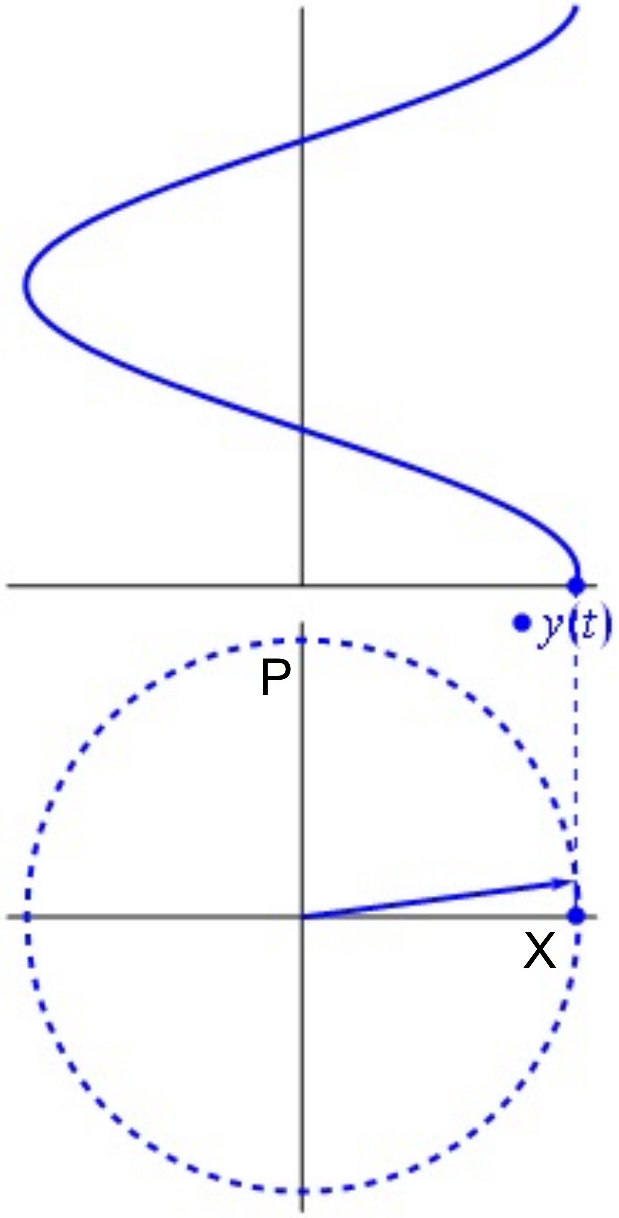
Just like neutrino mixing:

Beat period =
1/(Interaction Energy)

>> cavity coherence time

The signal will be tiny!

A classical sine wave is described by a rotating phasor:



The energy oscillates between potential energy and kinetic energy, as parameterized by the **position X** and **momentum P**.

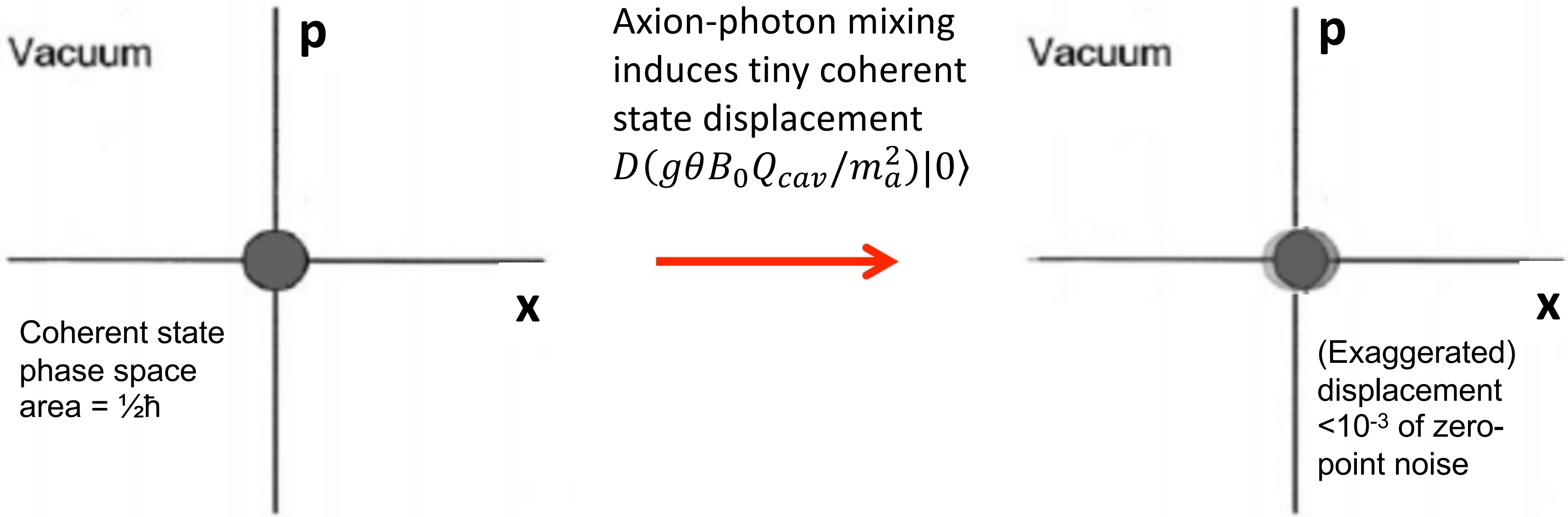
$$H = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2$$

$$= \hbar\omega(a^\dagger a + 1/2)$$

For photons, “X” and “P” are the cosine and sine quadratures of the electric field oscillation.

2nd quantization: [X,P]=i even for internal field quadratures (since these can drive mechanical oscillators.)

Due to limited coherence time << mixing period, the axion wave displaces the cavity vacuum state by an amount much smaller than the zero-point vacuum noise



Coherent state phase space area = ½ħ

Axion-photon mixing induces tiny coherent state displacement $D(g\theta B_0 Q_{cav}/m_a^2)|0\rangle$

(Exaggerated) displacement $<10^{-3}$ of zero-point noise

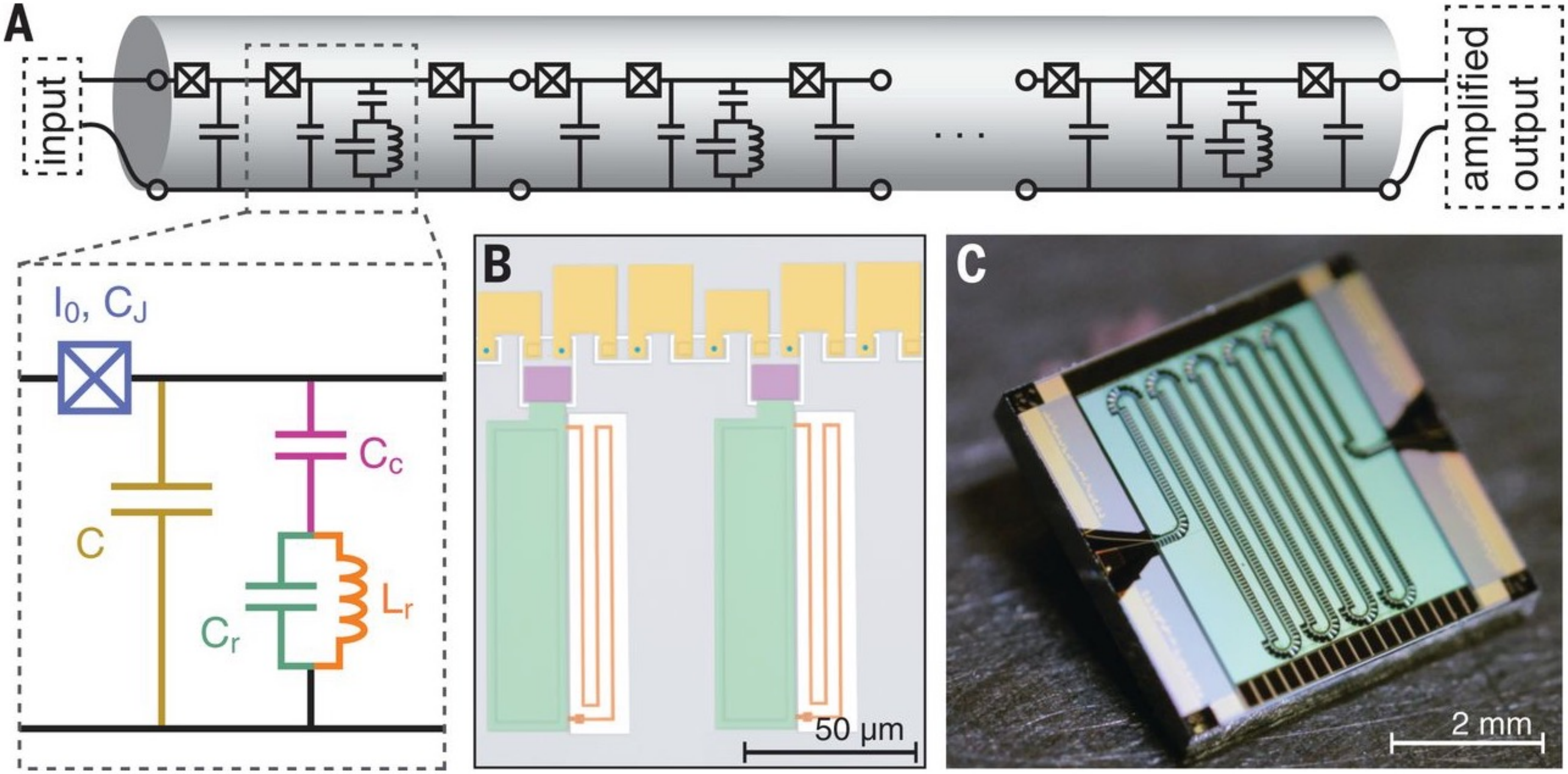
Standard quantum limit: As T→0, even the best phase-preserving amplifiers have an irreducible zero-point noise floor of +/-1 photon/mode (Carlton Caves, 1982)

Simultaneous measurement of non-commuting observables N and φ incurs the Heisenberg uncertainty principle $\Delta N \times \Delta\varphi \geq ½$. The blob is effectively the probe resolution.

Need millions of power spectrum measurements to average away the zero-point noise.

Amplifiers = scattering process via nonlinear 4-*wave mixing*

Ex. Josephson Traveling Wave Parametric Amplifier uses Josephson waveguide with >2000 aluminum Josephson junctions as the nonlinear inductive elements



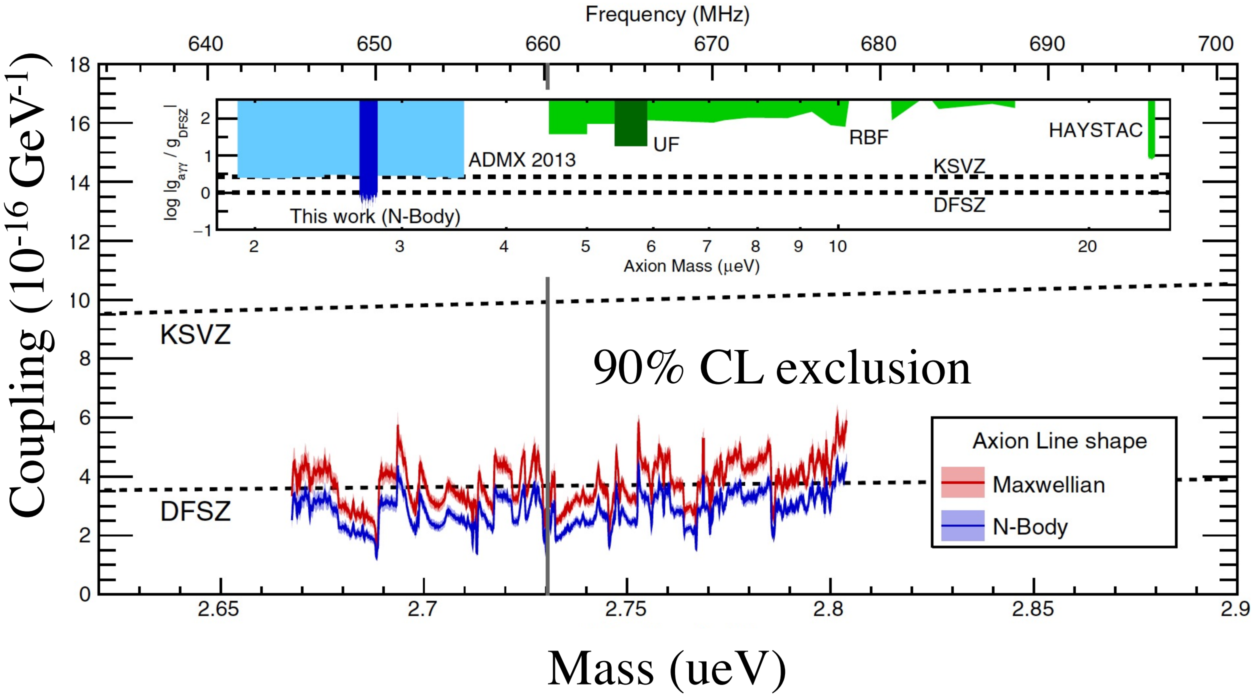
Macklin, et.al Science (2015)

2017: 30-year axion R&D program culminates in first sensitivity to DFSZ axions

PRL 120, 151301 (2018)

ADMX at U.Washington,
FNAL = DOE lead lab

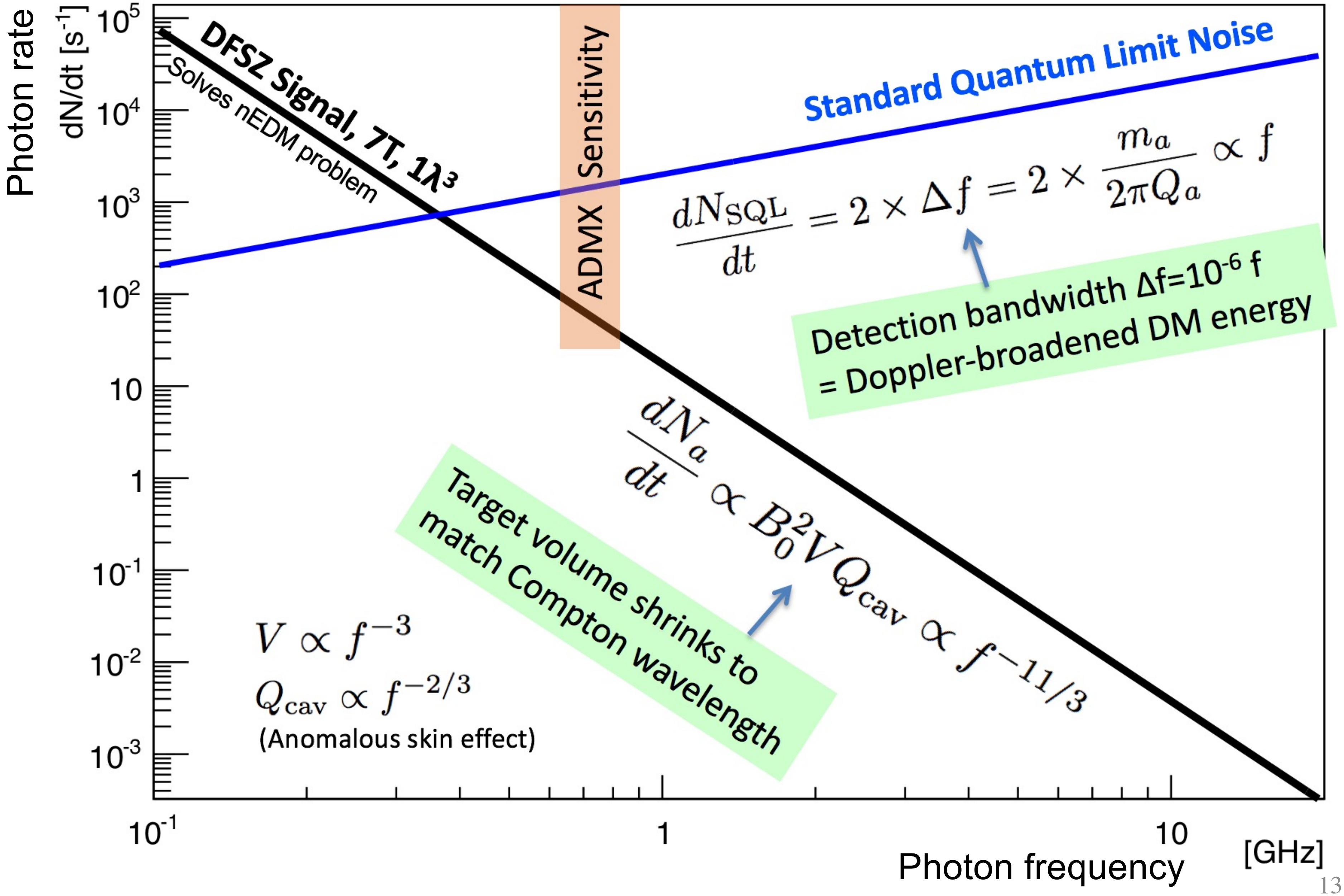
Operate an ultrasensitive radio in a cold, RF-shielded box to tune in to the axion broadcast.



Look for "spontaneous" emission from local axion dark matter into the empty cavity mode.

Signal power level = 10^{-23} W
Need 15 minutes integration per radio tuning to beat thermal noise power at 500 mK.

The predicted axion DM signal/noise ratio plummets as the axion mass increases → SQL readout is not scalable.



$$\frac{dN_{\mathrm{SQL}}}{dt} = 2 \times \Delta f = 2 \times \frac{m_a}{2\pi Q_a} \propto f$$

Detection bandwidth Δf=10^{-6} f
= Doppler-broadened DM energy

$$\frac{dN_a}{dt} \propto B_0^2 V Q_{\mathrm{cav}} \propto f^{-11/3}$$

Target volume shrinks to match Compton wavelength

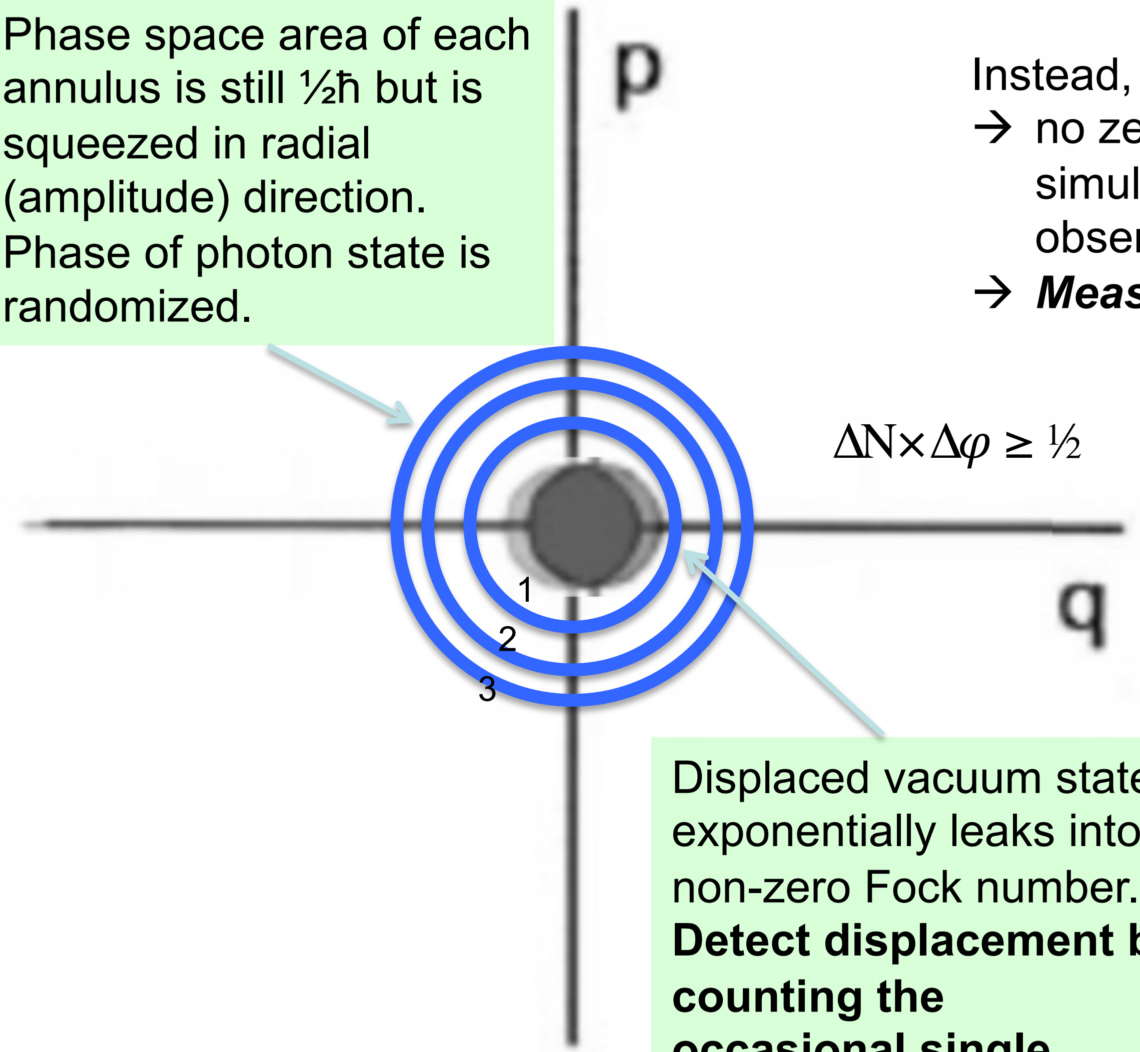
$$V \propto f^{-3}$$

$$Q_{\mathrm{cav}} \propto f^{-2/3}$$

(Anomalous skin effect)

To further reduce readout noise, use photon counting to measure displacement using the Fock basis, i.e. number eigenstates

Previously we measured *both amplitude and phase*, but this is dumb since the axion phase is randomized every coherence time. Useless information obtained at high cost!



Phase space area of each annulus is still ½ħ but is squeezed in radial (amplitude) direction. Phase of photon state is randomized.

Instead, measure only displacement amplitude

→ no zero-point noise since we are not simultaneously measuring non-commuting observables

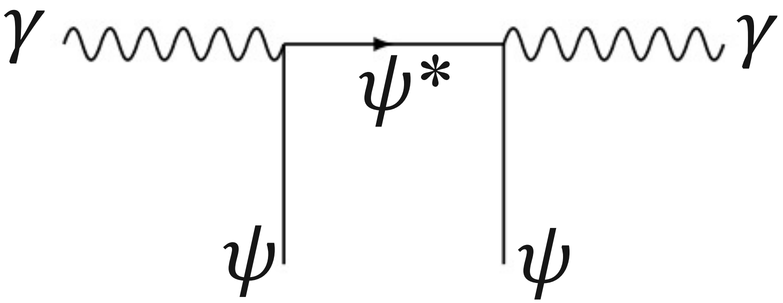
→ ***Measurement noise can be arbitrarily low***

$$\Delta N \times \Delta\varphi \geq \tfrac{1}{2}$$

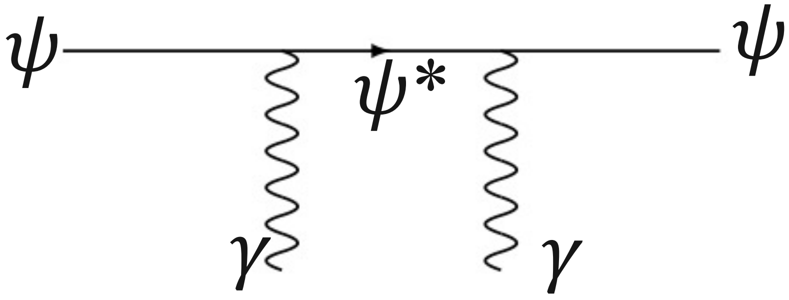
Displaced vacuum state exponentially leaks into non-zero Fock number. **Detect displacement by counting the occasional single photon.**

Quantum non-demolition “off-shell” sensors transduce photon occupation numbers into atomic frequency shifts

Index of refraction diagrams:



Photons slow down
when passing through
a dielectric medium



Atomic clocks slow down
when interacting with a bath
of background photons

The photon occupation number of the cavity mode is encoded as a frequency shift of the probe atom. (Similar to neutrino “matter effects.”)

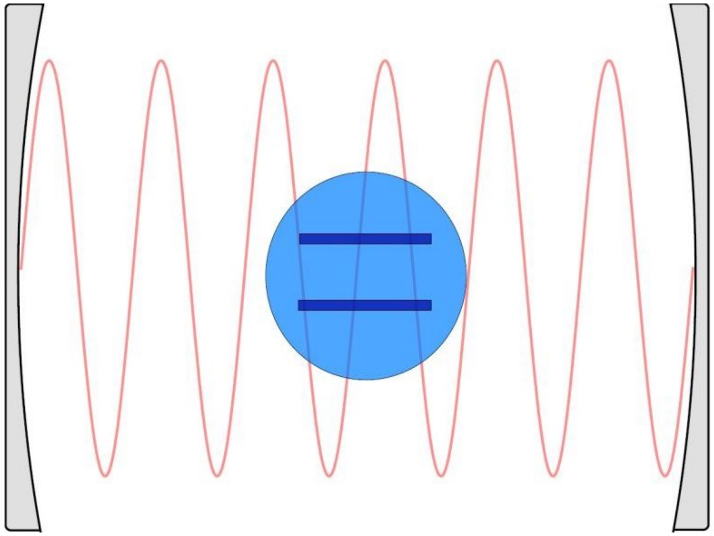
Being far off-resonance of ψ^* results in **no net absorption** of photons.

Quantum non-demolition: indirectly measure the same photon many times (via atom’s frequency shift) to achieve higher measurement fidelity.

Serge Haroche 2012 Nobel prize

Cavity QED:
Use 2-level atom to measure cavity photon population

Linear cavity
Bosonic oscillator,
Number operator = $a^\dagger a$



2-level "atom"
Fermionic oscillator,
Number operator = σ_z

The 1st order non-linearity in (number operator)^2 in the undiagonalized Hamiltonian is:

$$H \approx \hbar\omega_\mathrm{r}\left(a^\dagger a + 1/2\right) + \frac{\hbar}{2}\underbrace{\left(\omega_\mathrm{a} + \boxed{\frac{2g^2}{\Delta}a^\dagger a} + \frac{g^2}{\Delta}\right)}\sigma_\mathrm{z}$$

$$g \approx \vec{d}\cdot\vec{E}_0 \approx d\sqrt{\omega/V}$$

$\Delta = \omega_r - \omega_a$

The atom frequency depends on the cavity resonator's occupation number!
Quantized frequency shift of $2\chi = 2g^2/\Delta$ per photon in the cavity mode.
This product of number operators commutes with H and allows QND measurement.

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Use artificial atoms made of superconducting "transmon" qubits to nondestructively sense photons

A.S. Chou, Dave Schuster, Akash Dixit, Ankur Agrawal, …

$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega'_a + 2\chi a^\dagger a)\sigma_z$$

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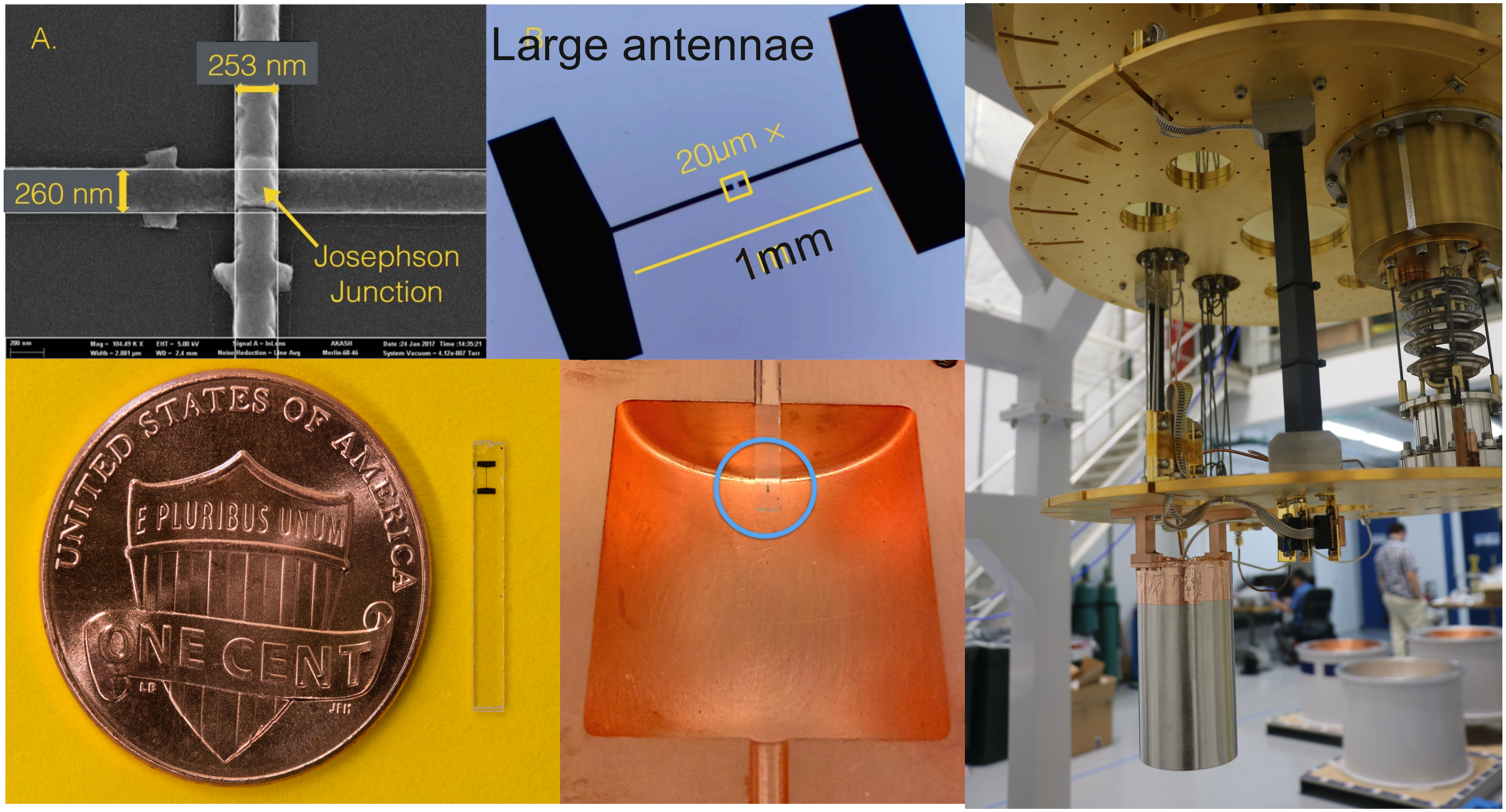
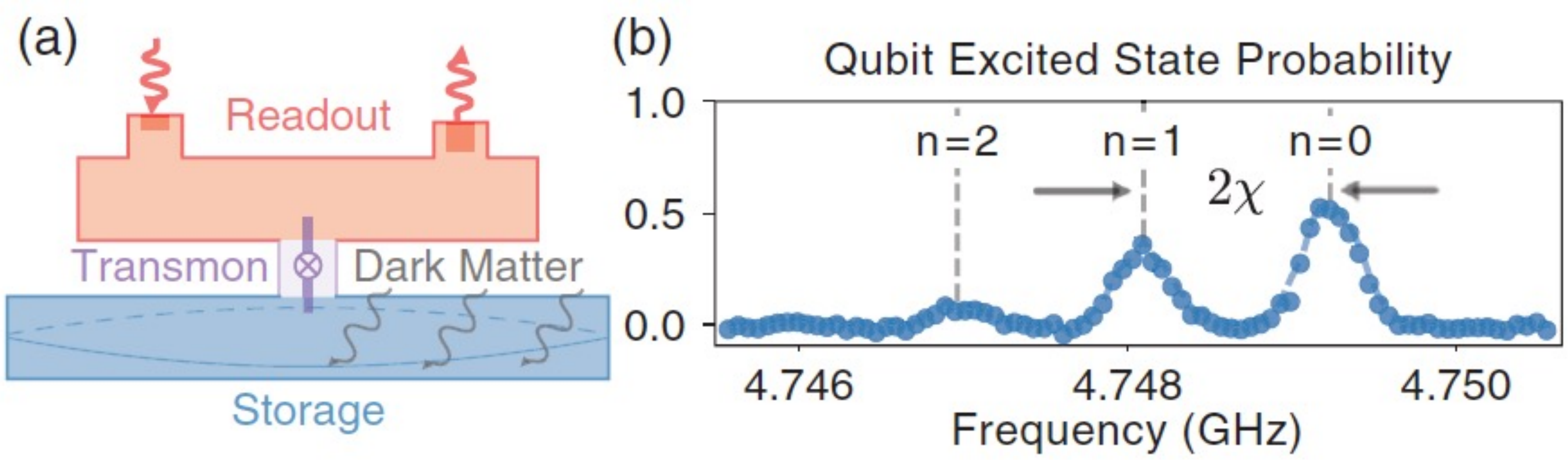


The electric field of individual photons exercises the nonlinear inductance of the Josephson junction. **Photon number is transduced into frequency shifts of the $|g\rangle \rightarrow |e\rangle$ transition.** Same as Lamb shift, but for finite photon number.

Single photon resolution:

Measure qubit $|g\rangle \rightarrow |e\rangle$ transition frequencies after weakly driving the primary cavity mode into a Glauber coherent state with <n>=1



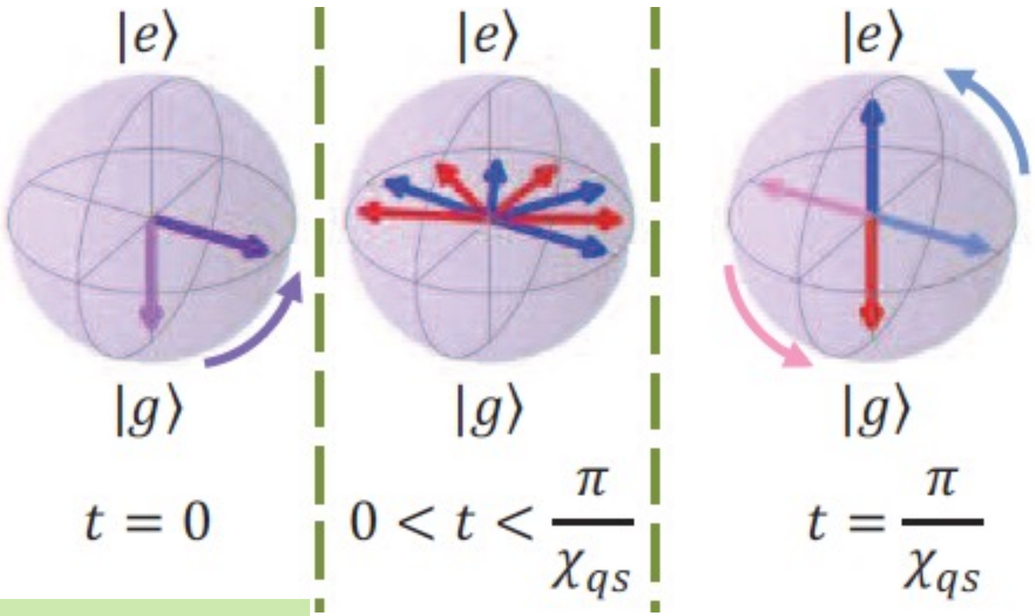
The measured qubit spectrum exhibits a distribution of resonances which are in 1-1 correspondence with the Poisson distribution of the cavity's coherent state.

Non-destructively count photons by measuring the qubit's quantized frequency shift.

If signal ϵ [0,1], perform Ramsey interferometry with the oscillating qubit “clock” to measure cavity photon number even/odd parity

Just like asking in an oscillation experiment, do the neutrinos see “matter effects” or not?
If there is a photon, the clock runs slower. If no photon, the clock runs faster.

Bloch sphere:
Map qubit states
to spin ±1/2



Prepare initial clock state with $\pi/2$ pulse to give $|g\rangle + |e\rangle$ state

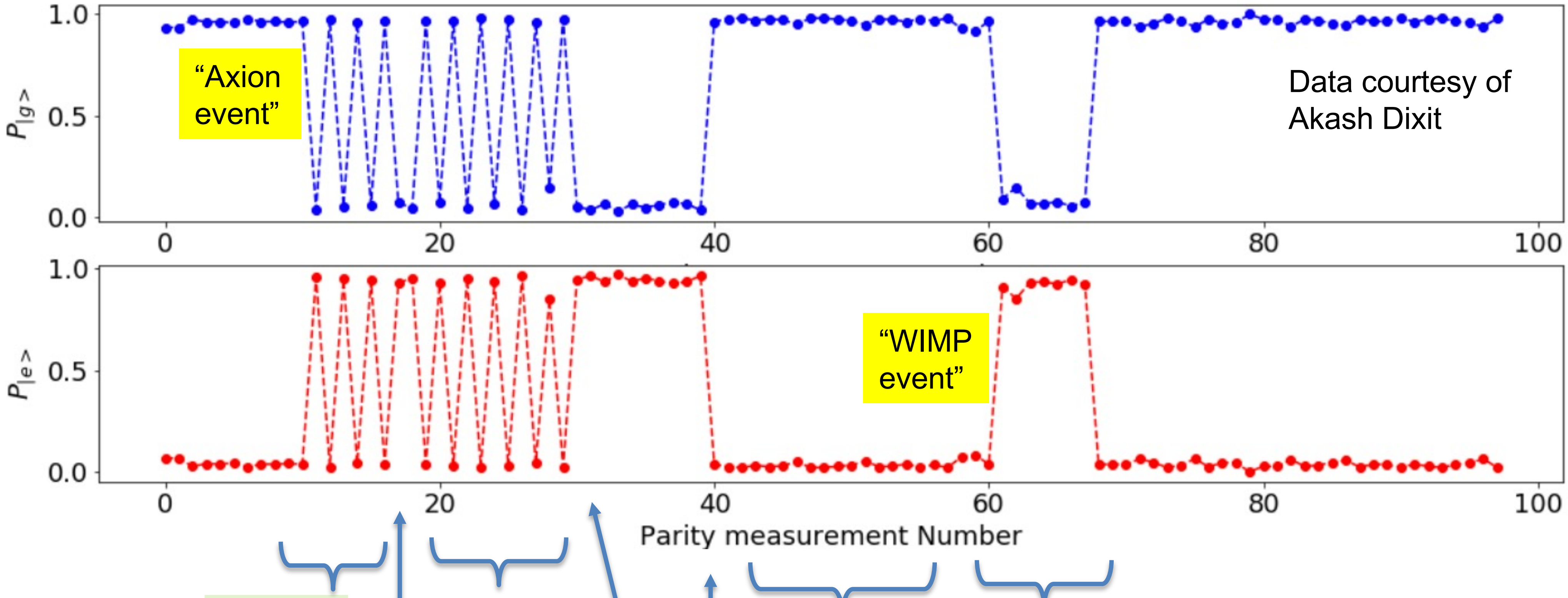
Evolve system to accumulate π phase difference over Stark period

Analyze with final $\pi/2$ pulse to map:
Even N → $|g\rangle$
Odd N → $|e\rangle$

The qubit’s “spin” flips only if a cavity photon is present.

Measure final qubit state $|g\rangle$ *or* $|e\rangle$ via freq. shift of an auxiliary cavity mode.

Signature of a single signal photon is many sequential successful qubit “spin-flips” from $|g\rangle \leftrightarrow |e\rangle$



“Axion event”

“WIMP event”

Data courtesy of Akash Dixit

Single photon injected, repeated successful qubit spin flips

Failed spin-flip = readout error

More successful readouts

Photon decays, qubit stuck in $|e\rangle$ state

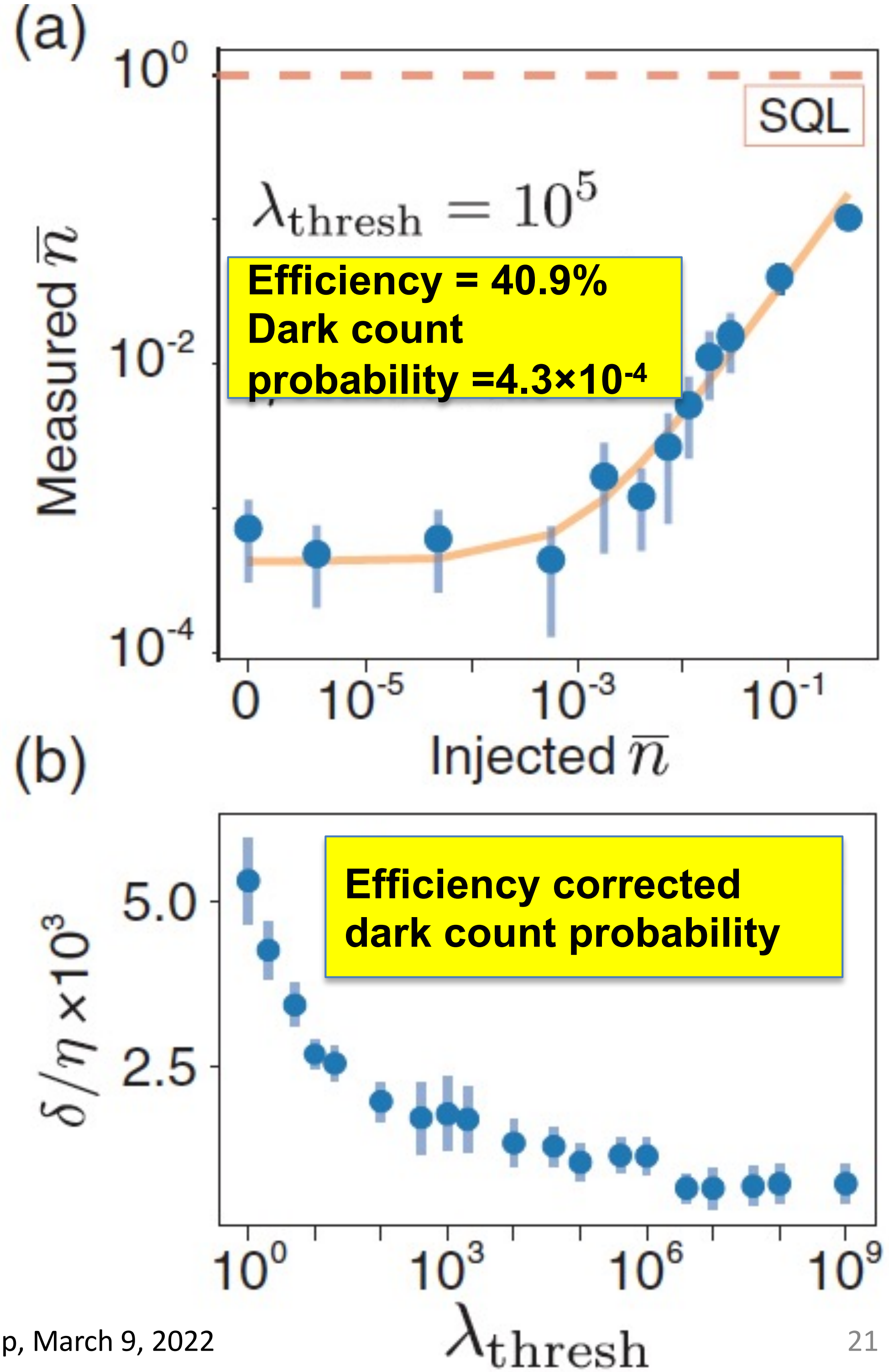
Qubit decays

Many failed spin-flips indicate that no photon is present.

Qubit spontaneously excited and then decays. Does not mimic photon event since subsequent spin-flip attempts fail.

Trigger on photons by placing threshold λ on MCMC probability ratio Prob(γ)/Prob(no γ) for observed spin-flip sequence

Akash V. Dixit, et.al, Phys.Rev.Lett. 126, 141302 (2021)



Efficiency = 40.9%
Dark count probability =4.3×10^{-4}

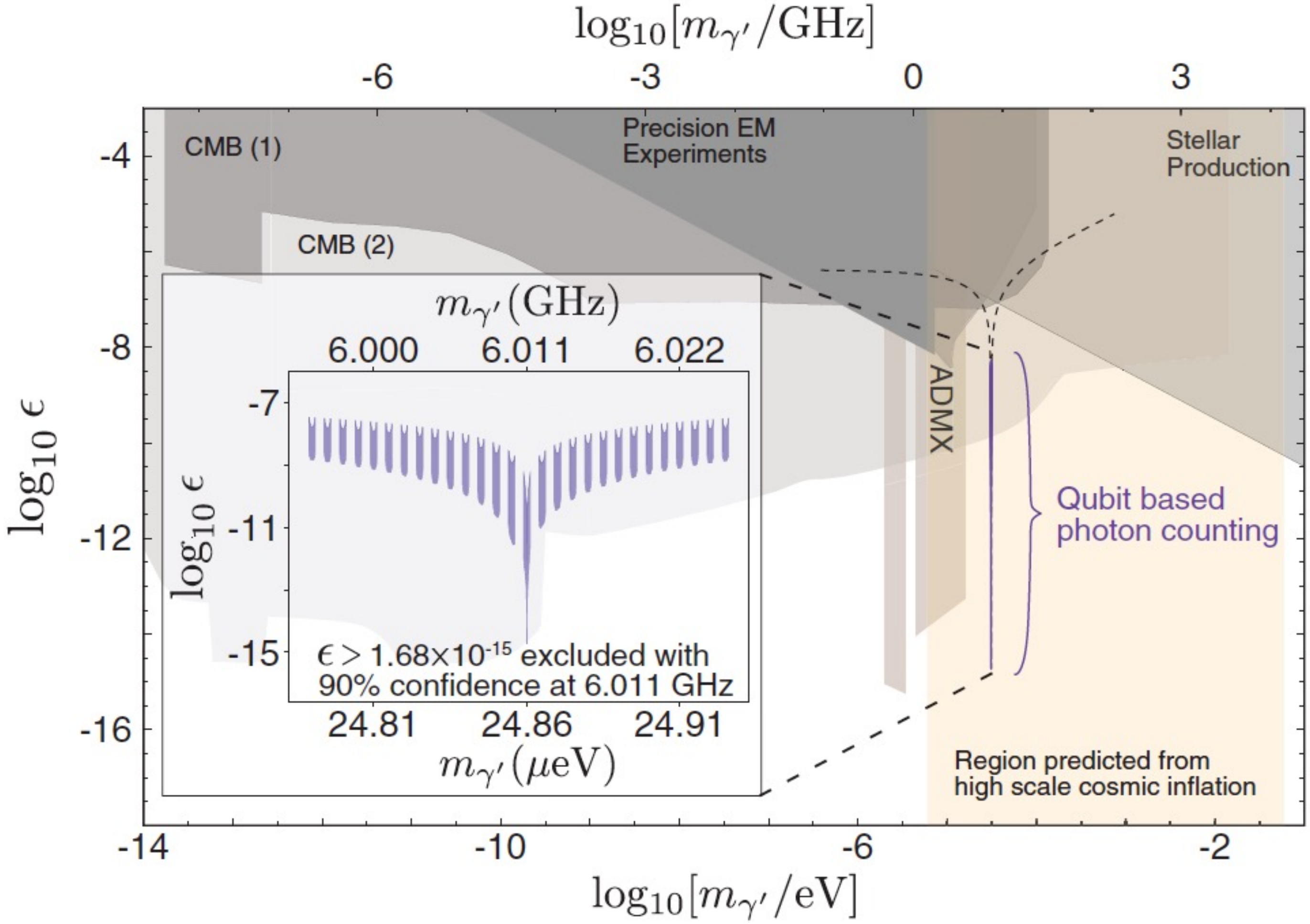
Efficiency corrected dark count probability

Background = **10^{-3} photons** per measurement (from leakage?)

Compare to amplifier readout which gives +/- **1 photon** of zero-point variance per measurement.

Noise equivalent of 15.7 dB of squeezing!

Single frequency dark photon sensitivity:



Akash V. Dixit, et.al, Phys.Rev.Lett. 126, 141302 (2021)

15,141 measurements over **12.81 s** run time with superconducting Al cavity.

Quantum Zeno effect: continuously watched system does not evolve.
Cadence: 546 μs signal accumulation + 300 μs measurement = 65% duty cycle