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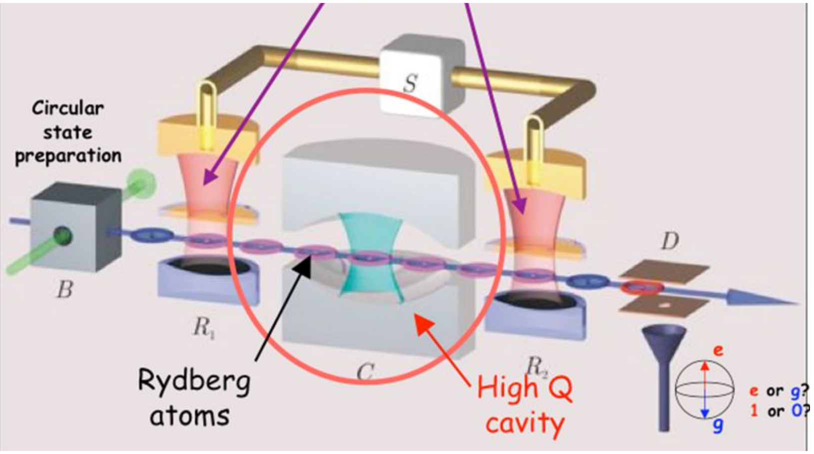
$\Psi_{\mathbf{kitty}} = \frac{1}{\sqrt{2}}\Psi_{\mathbf{alive}} + \frac{1}{\sqrt{2}}\Psi_{\mathbf{dead}}$

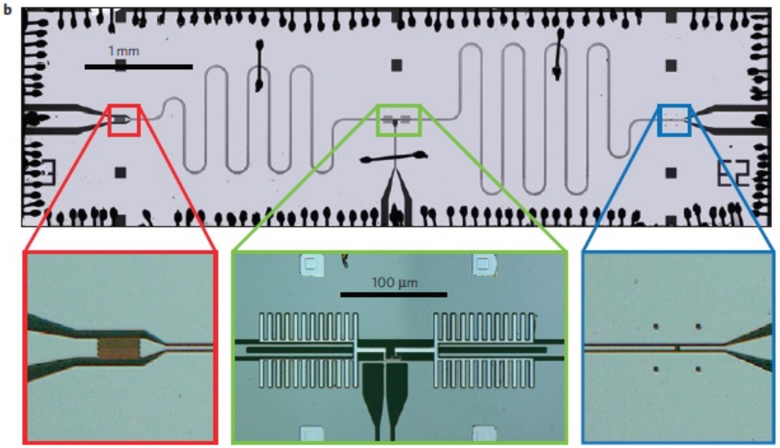
Quantum Metrology Techniques for Dark Matter Axion Detection

Aaron S. Chou (FNAL)

KITP New Probes of Physics Beyond the Standard Model

April 12, 2018





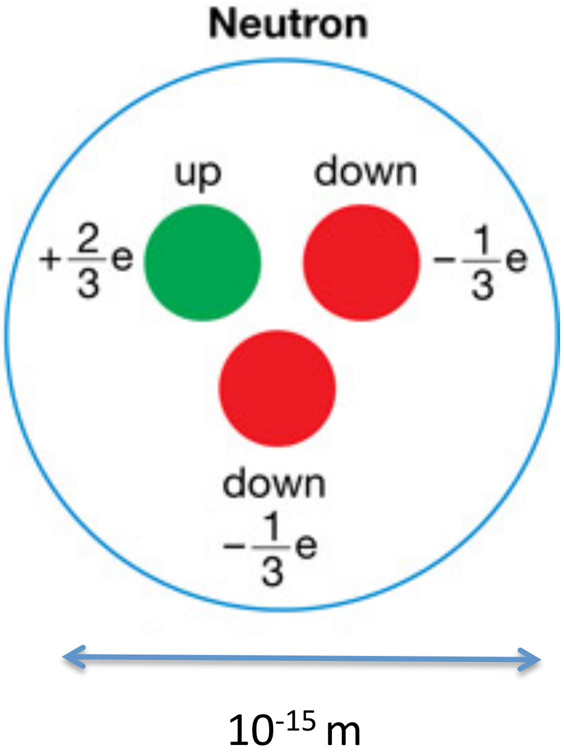
Topics (30 minutes each)

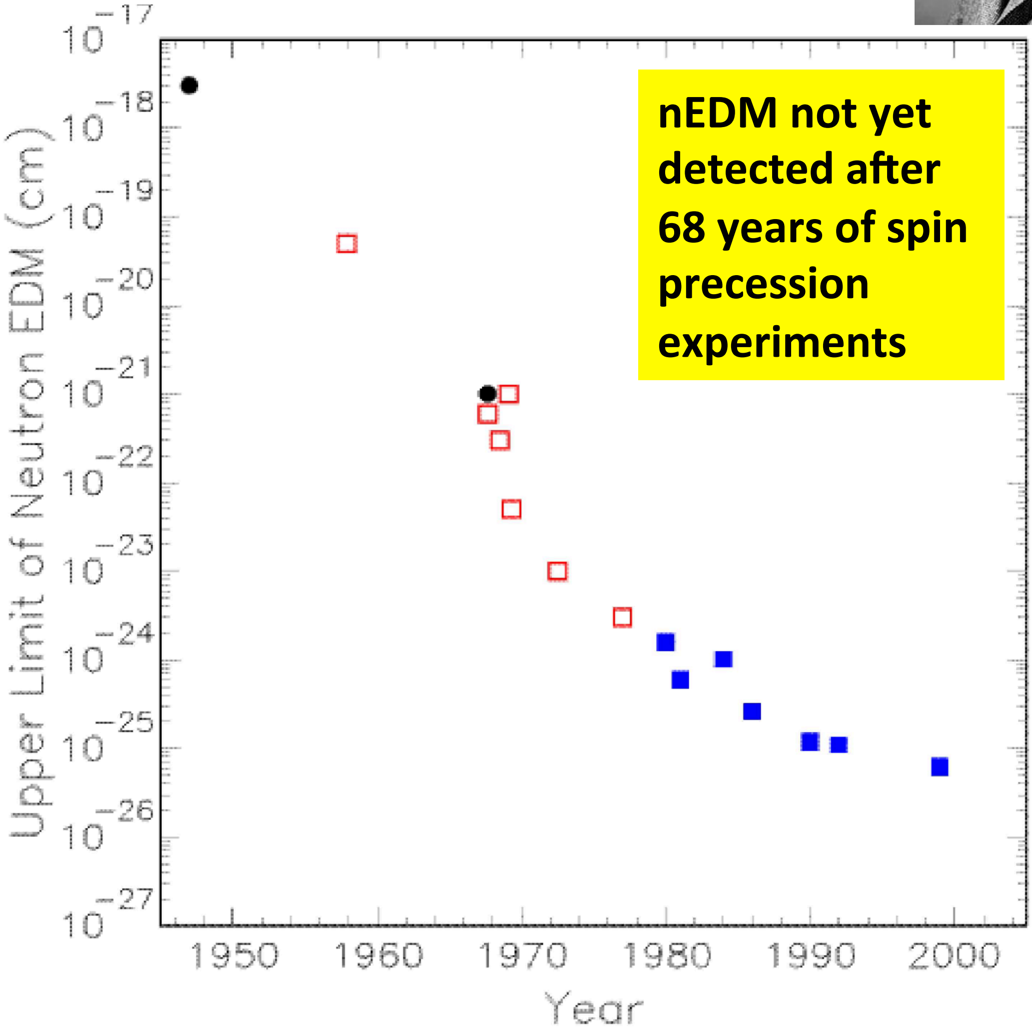
- Axion detection with “conventional” quantum-limited signal amplifiers – **new ADMX results**
- Quantum non-demolition detection to evade noise from measurement back-action
- Stimulated emission from bosonic dark matter into photons
- High-Q cavities to accumulate random walk signals

The Strong-CP Problem: Why is the neutron electric dipole moment so small?

Norman Ramsey
Nobel Prize 1989

Naive estimate gives
nEDM ≈ 10^{-16} e-cm

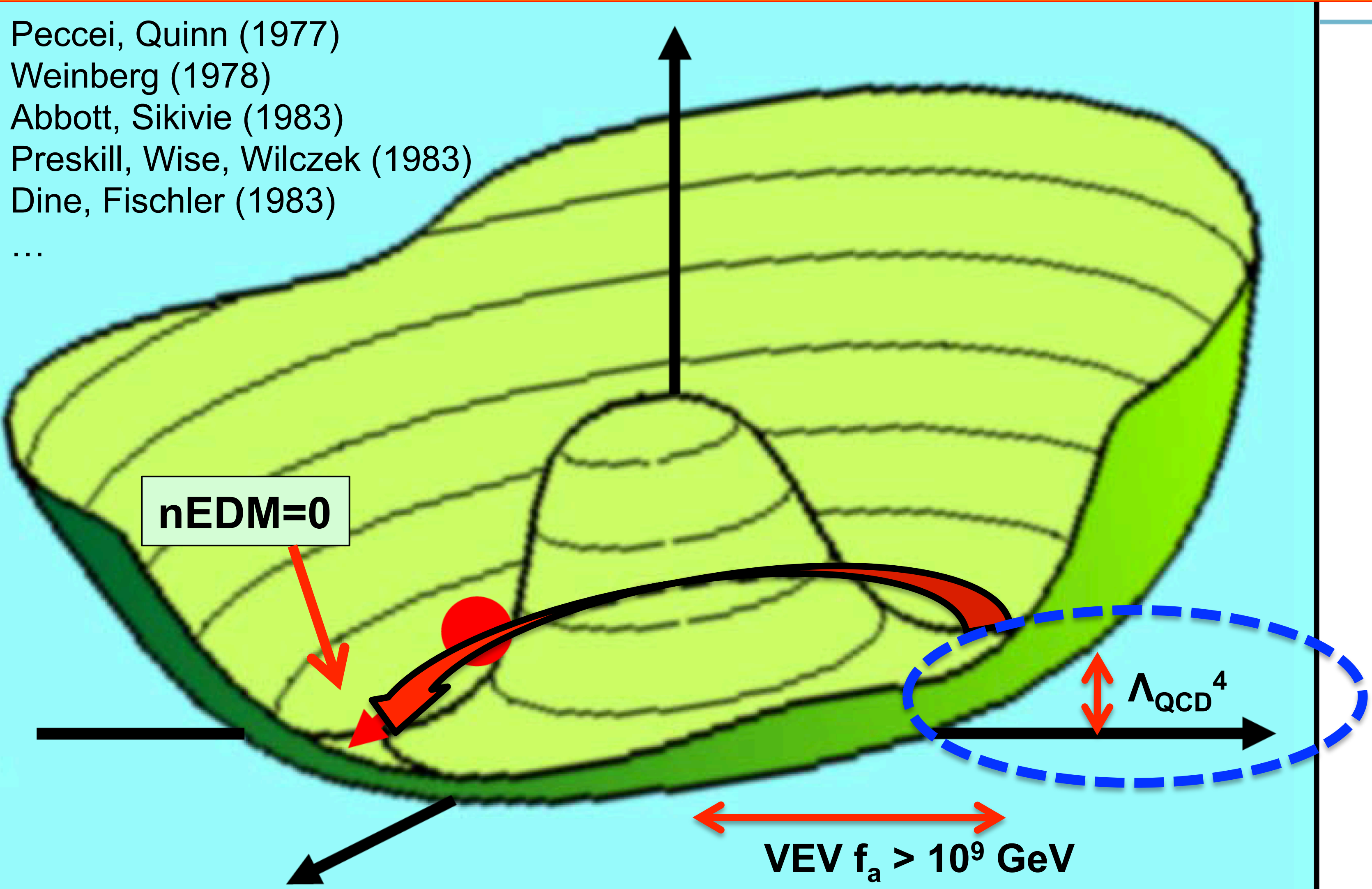




nEDM not yet detected after 68 years of spin precession experiments

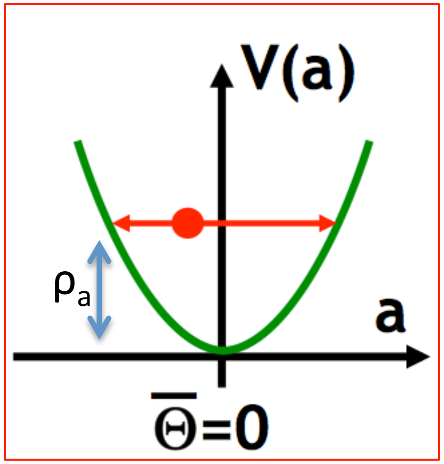
Axion model: Cosmological feedback loop zeroes out the nEDM. Initial potential energy is released as wave-like dark matter.

Peccei, Quinn (1977)
Weinberg (1978)
Abbott, Sikivie (1983)
Preskill, Wise, Wilczek (1983)
Dine, Fischler (1983)
…



Low mass $m_a = \Lambda_{QCD}^2 / f_a < 10^{-2}$ eV.
Single parameter model for axions.

Axion dark matter = waves of oscillating θ_{CP}



Locally coherent oscillation of the QCD θ angle about its CP-conserving minimum:

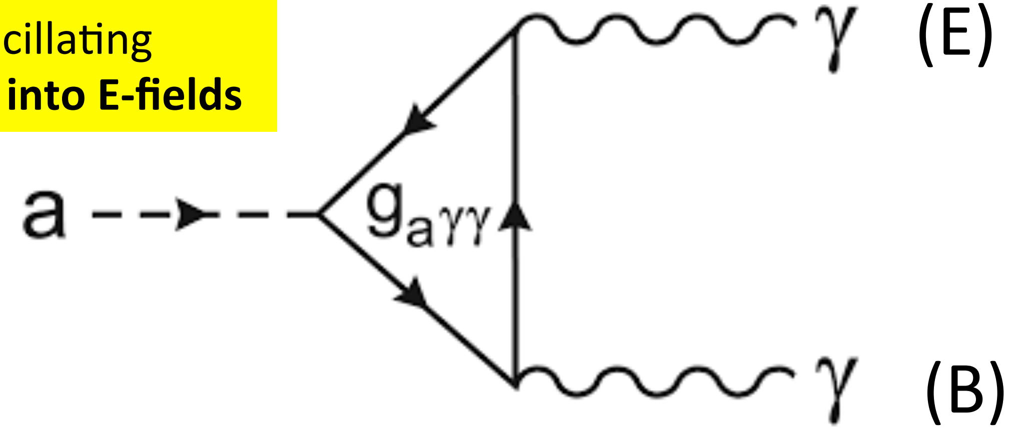
$$\theta(x,t) = \theta_{\max} e^{i(kx - m_a t)}$$

where

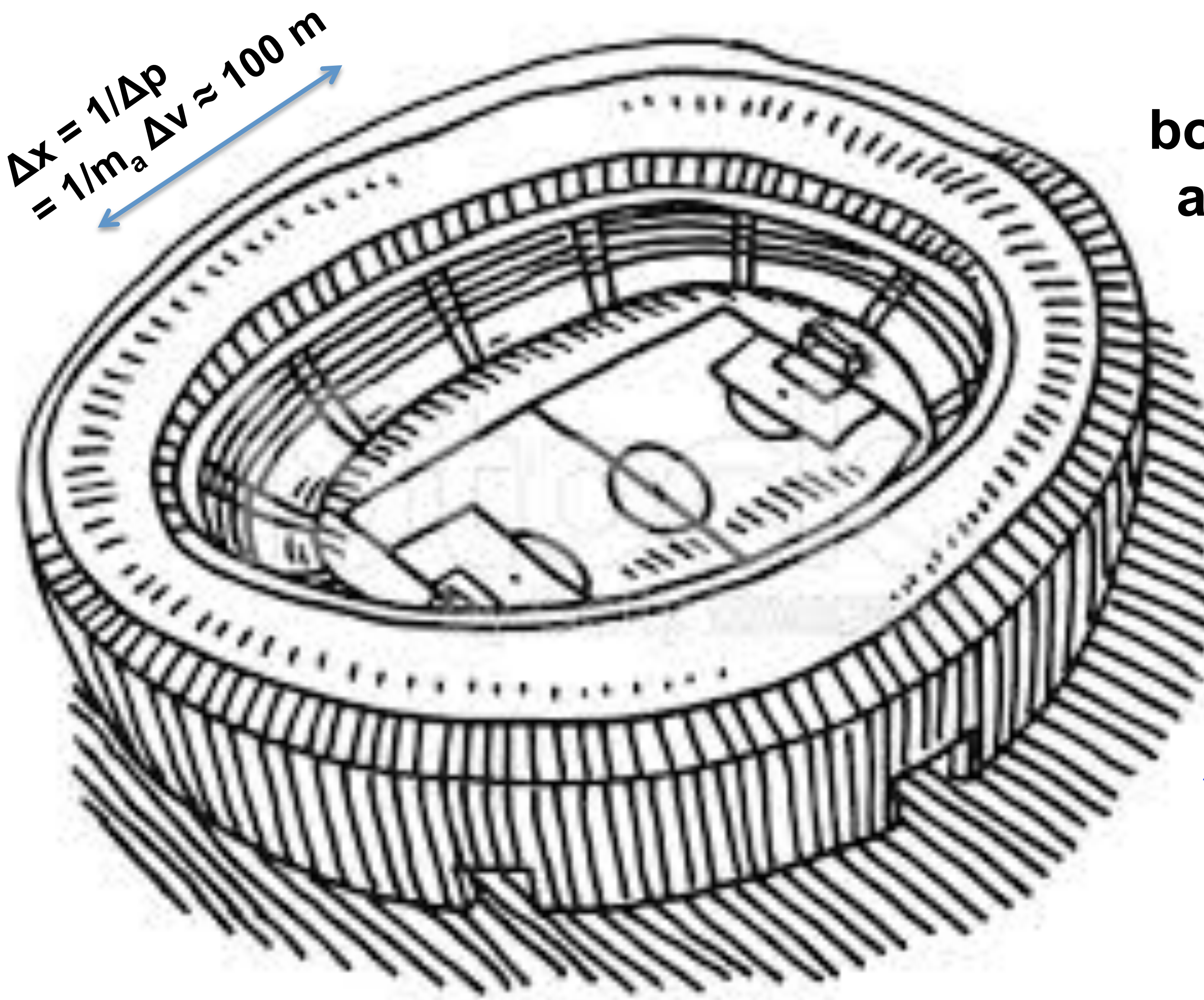
$$\theta_{\max} = \sqrt{\frac{2\rho_a}{\Lambda^4_{\mathrm{QCD}}}} \approx 3.7 \times 10^{-19} \mathrm{radians}$$

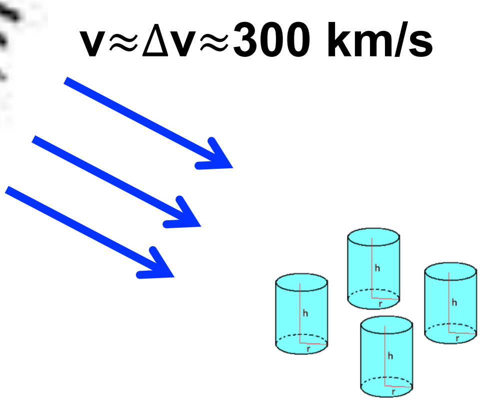
DM oscillations partially undo the Peccei-Quinn mechanism by enabling the coherent field to climb out of the potential minimum.

Phenomenology based on a classically oscillating CP-violating angle which **rotates B-fields into E-fields**



Low mass bosonic DM is like a slow CW laser with f=$m_a/2\pi$





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

→ **$\Delta f \sim m_a/10^6$ ~kHz linewidth**

→ Phase coherent signals over 10^{-3} s.

The Sikivie Haloscope technique (1983)

Classical axion wave drives RF cavity mode

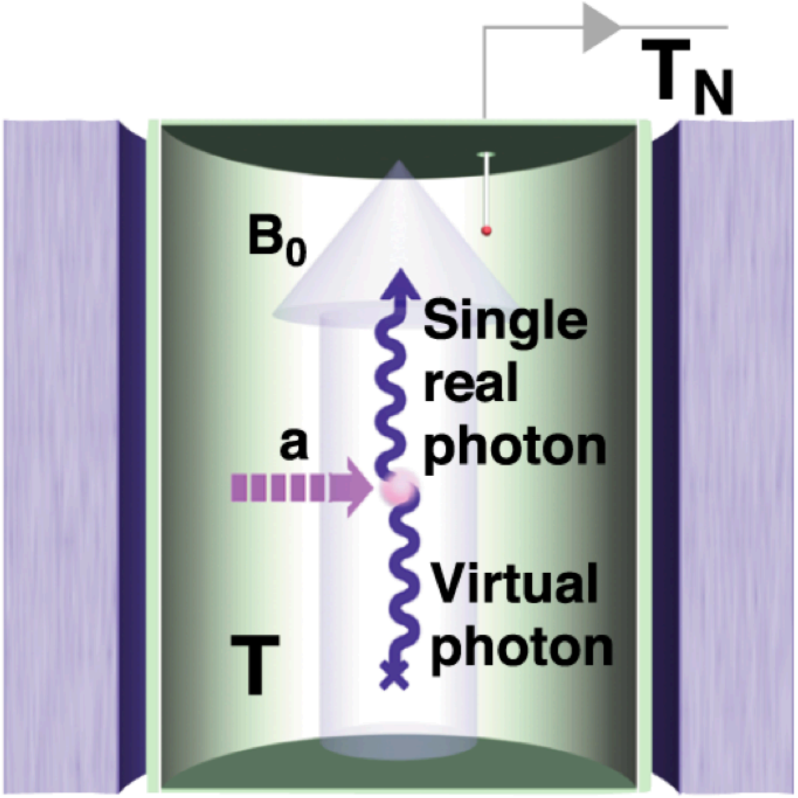
- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

$$\vec{J}_a(t) = -\frac{g\alpha}{\pi}\left(\frac{\sqrt{2\rho_a}}{\Lambda^2_{\mathrm{QCD}}}\right)\vec{B}_0 m_a e^{im_a t}$$

which drives E&M via Faraday's law:

$$\vec{\nabla}\times\vec{B}_r - \frac{d\vec{E}_r}{dt} = \vec{J}_a$$

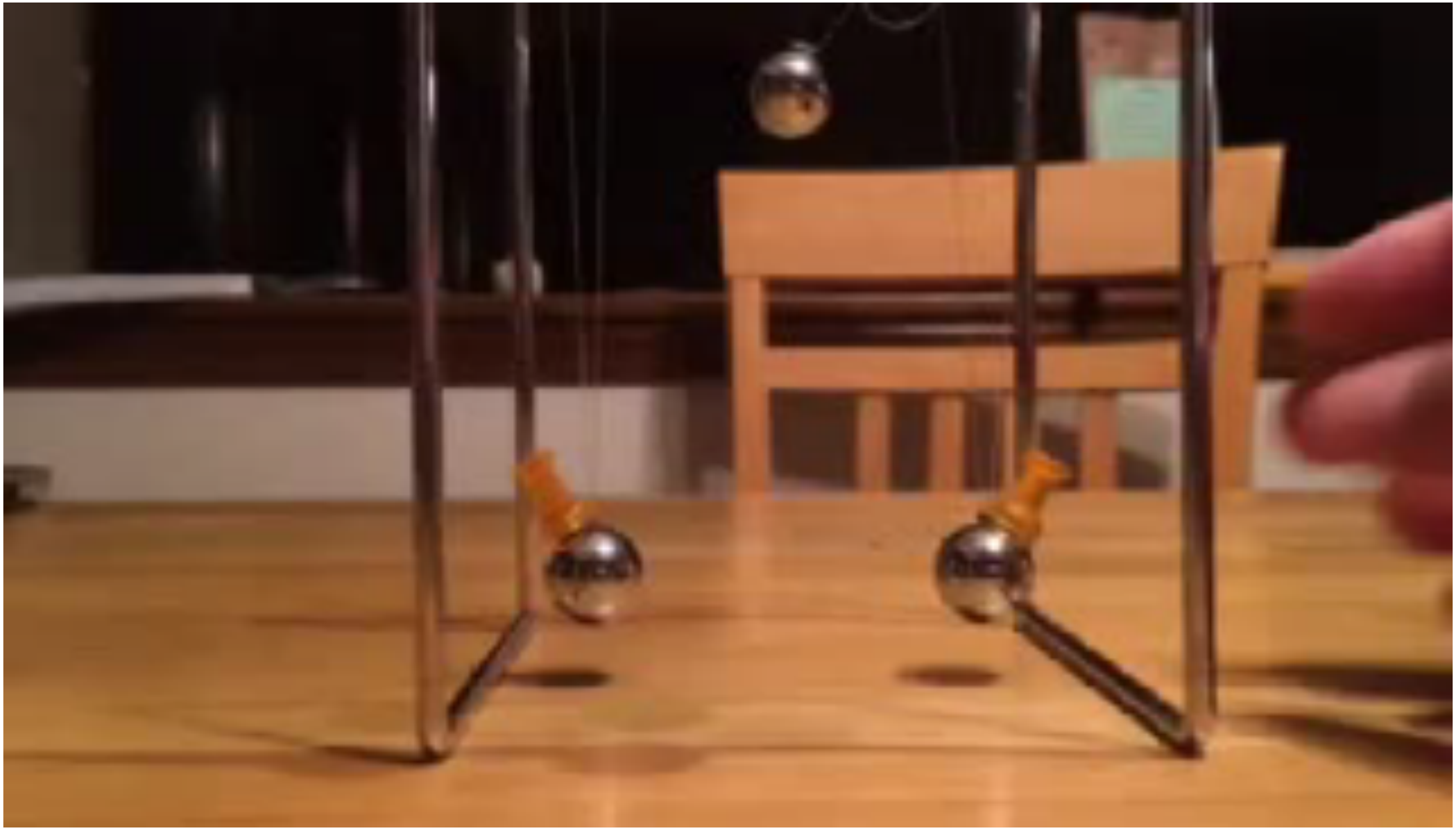
- In the presence of matched cavity boundary conditions to absorb momentum (cavity size ≈ $1/m_a$), the exotic source current excites standing-wave RF photons.



The Haloscope **optimally** extracts power from the potential energy of interaction:

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

Energy transfer between two coupled oscillators

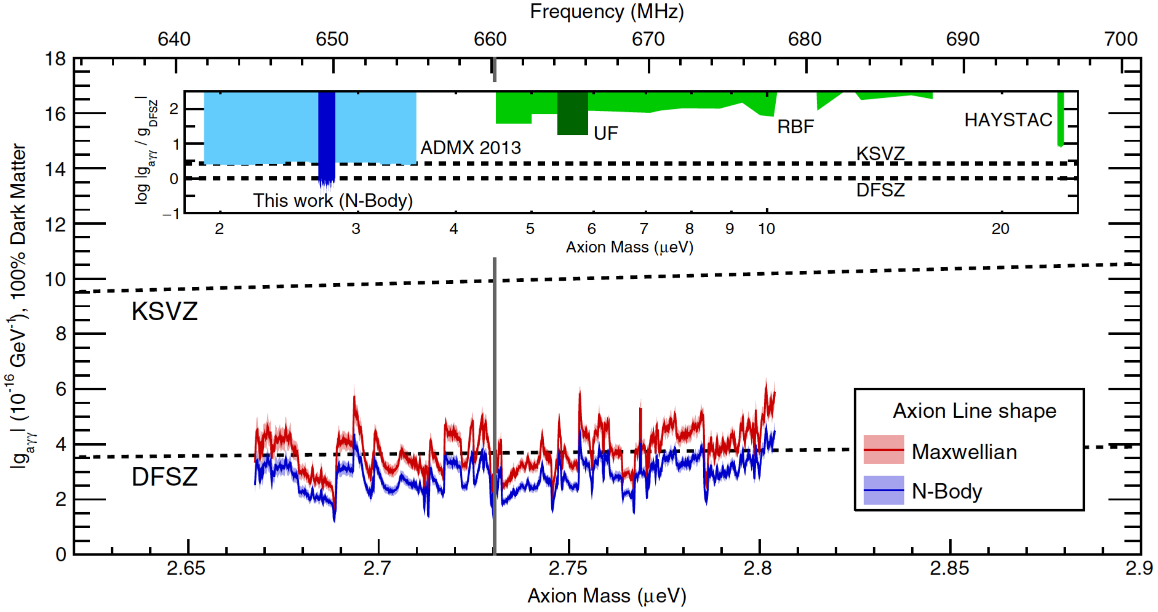


Weak coupling -- takes many swings to fully transfer the wave amplitude.
In real life, the number of swings is limited by coherence time.
Narrowband cavity response → iterative scan through frequency space.

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

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.

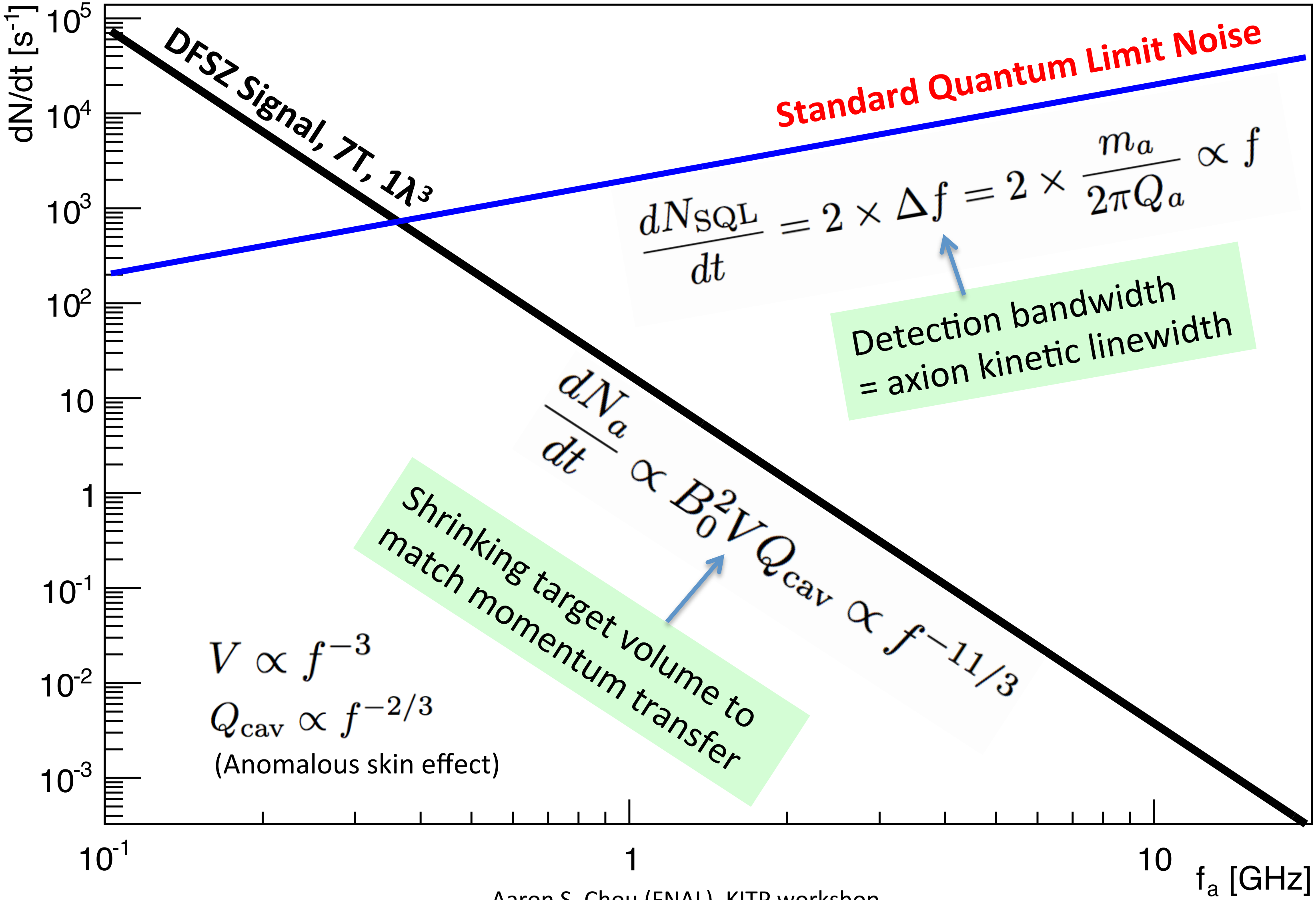


Hot off the presses: PRL 120, 151301 (2018)

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 frequency bin to beat thermal noise power at 500 mK.

Axion signal/noise ratio plummets at higher mass, i.e. the region compatible with observable CMB B-modes



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

Detection bandwidth = axion kinetic linewidth

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

Shrinking target volume to match momentum transfer

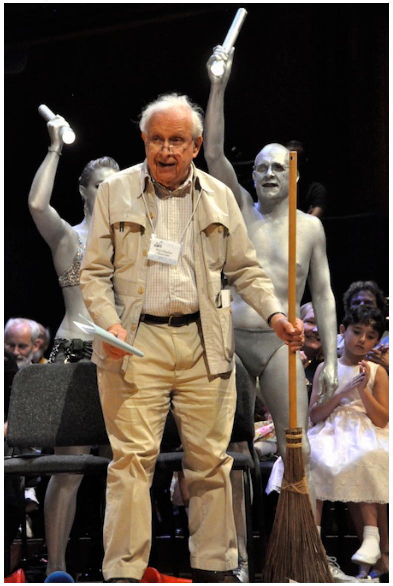
$$V \propto f^{-3}$$

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

(Anomalous skin effect)

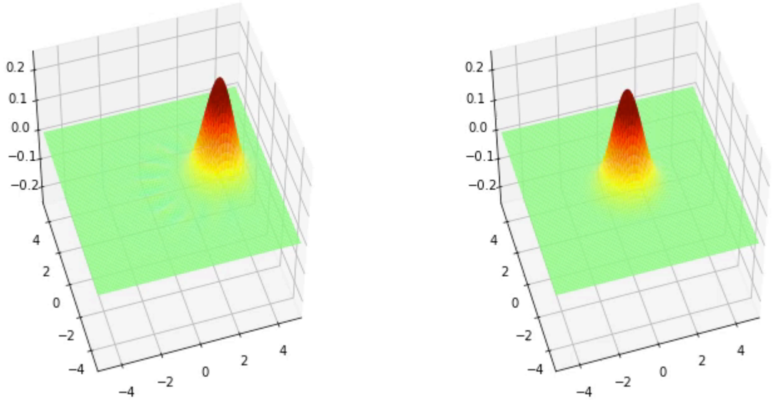
10 GHz = 40 μeV

Quantum non-demolition measurements of field amplitude (photon number)



Classically-driven quantum harmonic oscillator

Roy Glauber
Nobel Prize 2005,
“Keeper of the
Broom”



Phasor space evolution of coupled oscillators

$$\boxed{U_{\mathrm{I}}(t) = \exp\left[(f_0 a^\dagger - f_0^* a)t\right]}$$

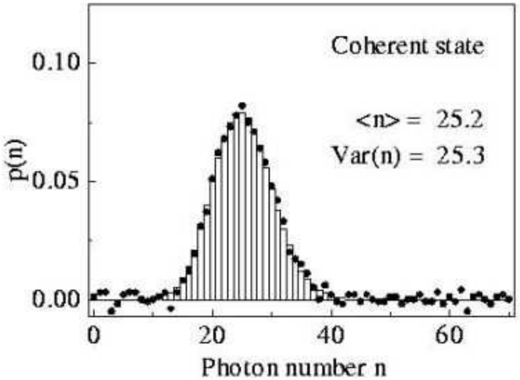
f_0 = classical sine wave drive

$$|\psi(t)\rangle_{\mathrm{I}} = \exp[(f_0 a^\dagger - f_0^* a)t]|0\rangle = e^{-|f_0|^2 t^2/2} e^{f_0 a^\dagger t}|0\rangle$$

$=D(f_0\, t)|0\rangle$ **Glauber displacement operator**

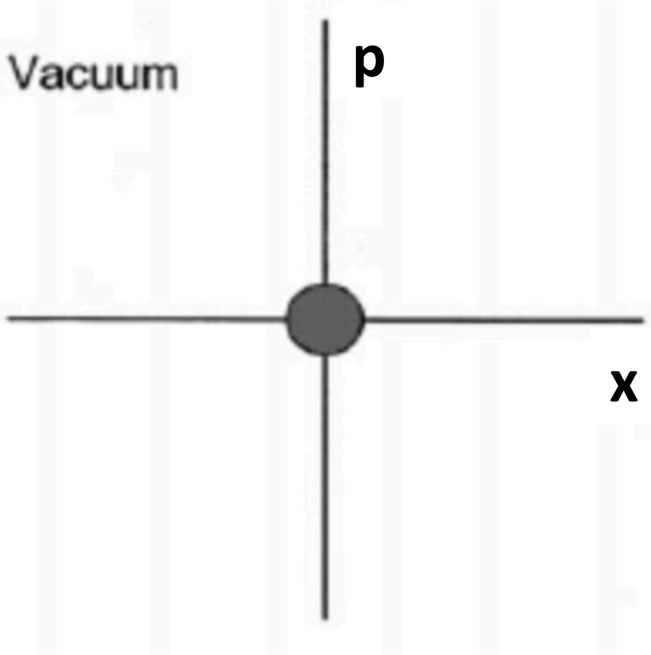
$\equiv|\alpha=f_0\, t\rangle$ **Glauber coherent state:** quantum description of a classical sine wave, eigenstate of the annihilation operator:

$a|\alpha\rangle=\alpha|\alpha\rangle$



The coherent state is a pure state with a Poisson distribution in the Fock basis.

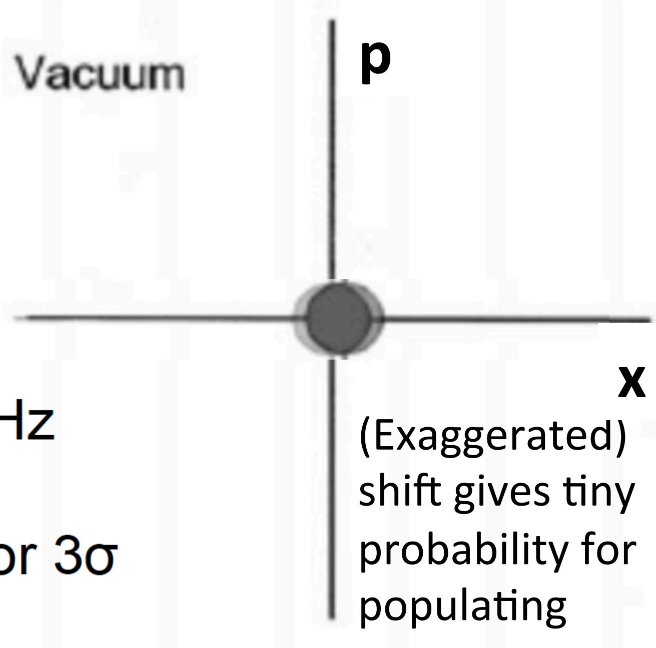
The axion wave displaces the cavity vacuum state by an amount much smaller than the zero-point vacuum noise



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

Axion-photon mixing induces tiny coherent state displacement

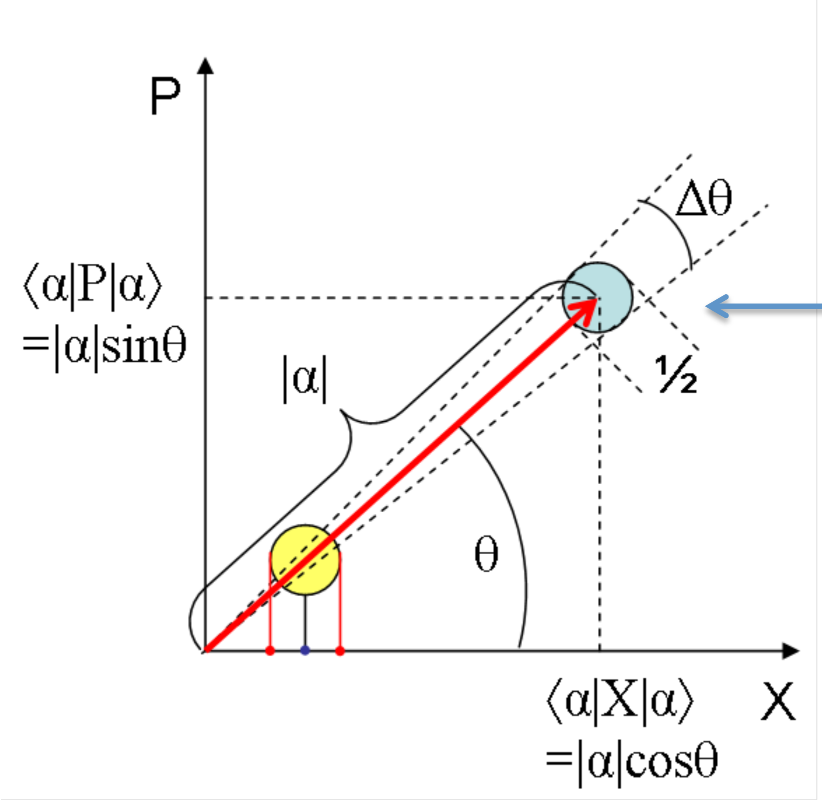
0.01% shift @ 2 GHz
(20 kHz BW)
Avg >900M FFTs for 3σ



(Exaggerated) shift gives tiny probability for populating N=1 state

Cannot easily see the tiny shift above the zero-point noise of the vacuum…

Quantum-limited amplifiers (kT→0) suffer from zero-point readout noise – the Standard Quantum Limit (SQL)



½ ħ= quantum of phase space area.
Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.
(Caves, 1982)

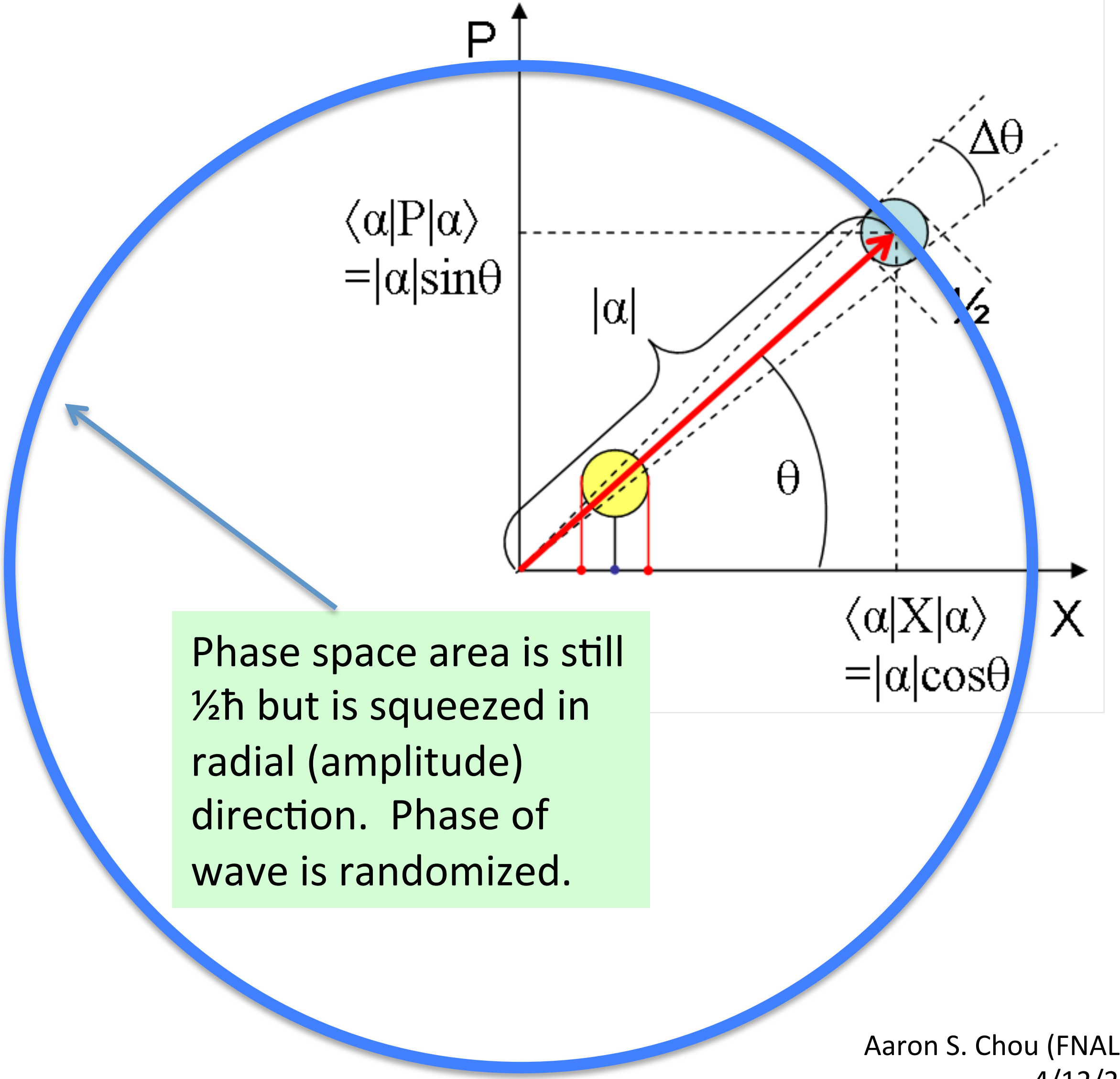
Thermal noise = kT of energy per resolved mode
→ **Quantum noise = 1 photon per resolved mode in the T=0 limit.**

Noise photon rate exceeds signal rate in high frequency dark matter axion searches. Need new sensor technology….

Aaron S. Chou (FNAL), KITP workshop, 4/12/2018

Quantum non-demolition (QND) single photon detectors can do much better than SQL amplifiers

Number operator commutes with the Hamiltonian→ all backreaction is put into the unobserved phase – which we don't care about...



Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.

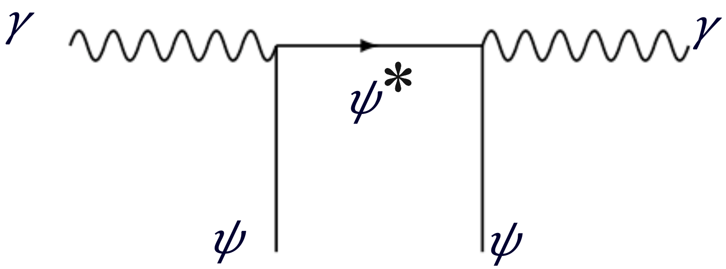
Avoid the zero-point noise by making measurements in the Fock basis instead of the coherent state basis.

Demonstrated with Rydberg atoms, (Serge Haroche Nobel Prize 2012)

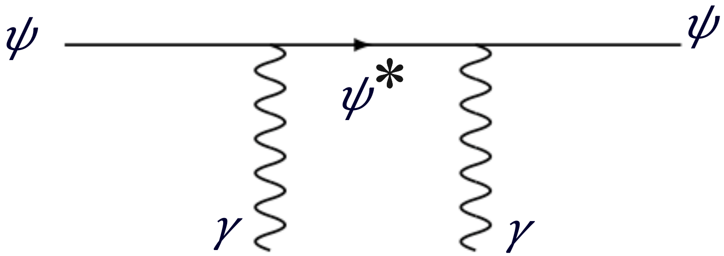
Implementation using solid state artificial atom qubits, D.Schuster et.al, 2007

Proposed for axion search: Lamoreaux, Lehnert, et.al, 2013, Zheng, Lehnert, et.al, 2016

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



Photon 2-point function measures the density of background fermions.



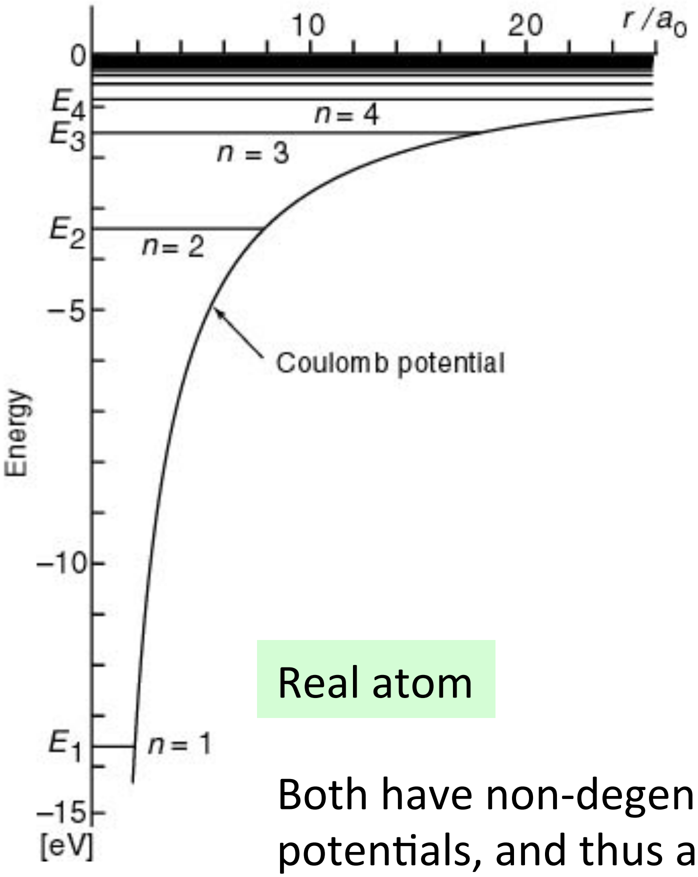
Fermion 2-point function measures the density of background photons

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

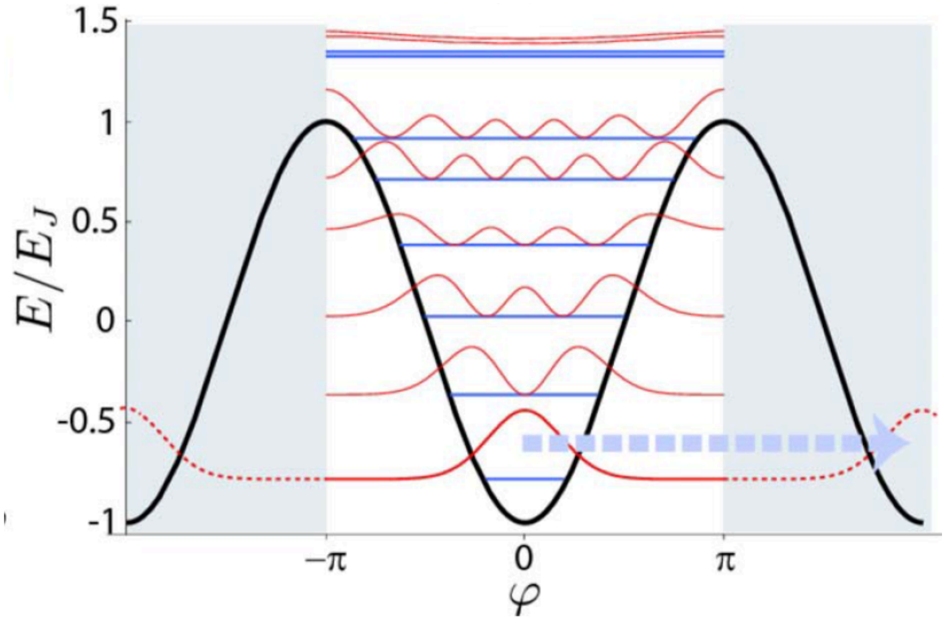
Purely a refractive effect -- the background particle occupation number is encoded as a frequency shift of the probe atom.

Potential energy of interaction is averaged over many mixing cycles
→ no measurement of phase, only occupation number

Any anharmonic oscillator exhibits 2-level system behavior and acts as a fermionic artificial atom



Real atom



Artificial atom (Josephson junction oscillator)

Both have non-degenerate energy level spacings due to the nonlinear potentials, and thus act as fermionic 2-level systems.

Jostling of the nonlinear oscillator due to electric fields from background electromagnetic modes gives atomic frequency shifts

→ Lamb shift from zero-point fluctuations

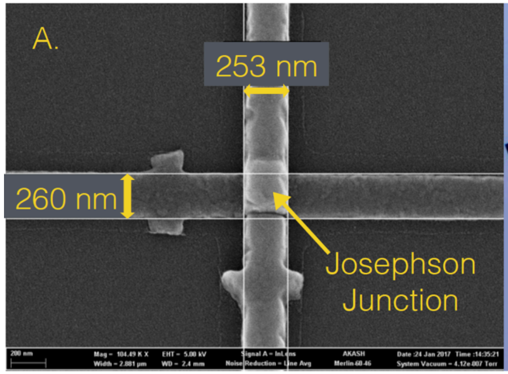
→ **quantized AC Stark shift from finite background photon occupation number**

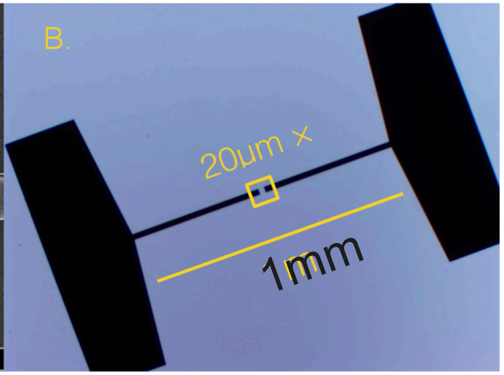
3D "Transmon" qubit-based quantum non-demolition single microwave photon detectors

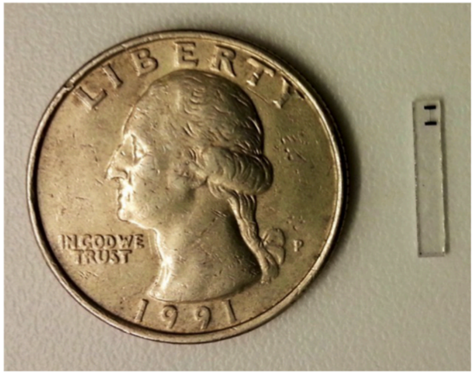
A.S. Chou, David Schuster (UC) + 3 Chicago graduate students

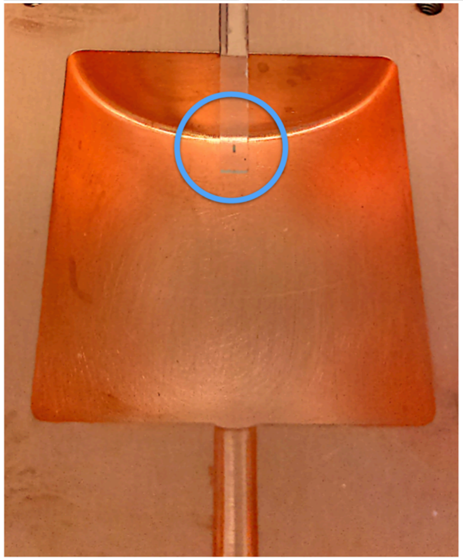
Funded by

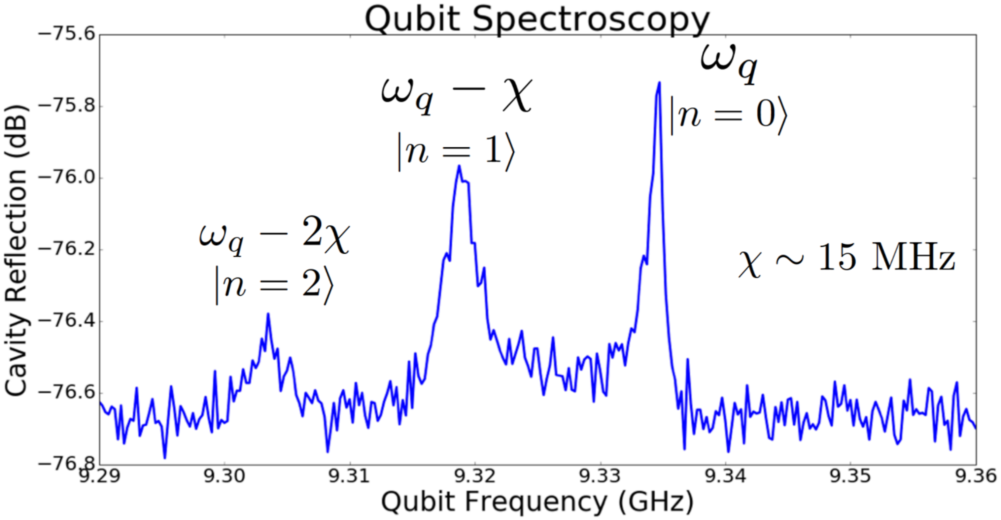
HEISING-SIMONS FOUNDATION





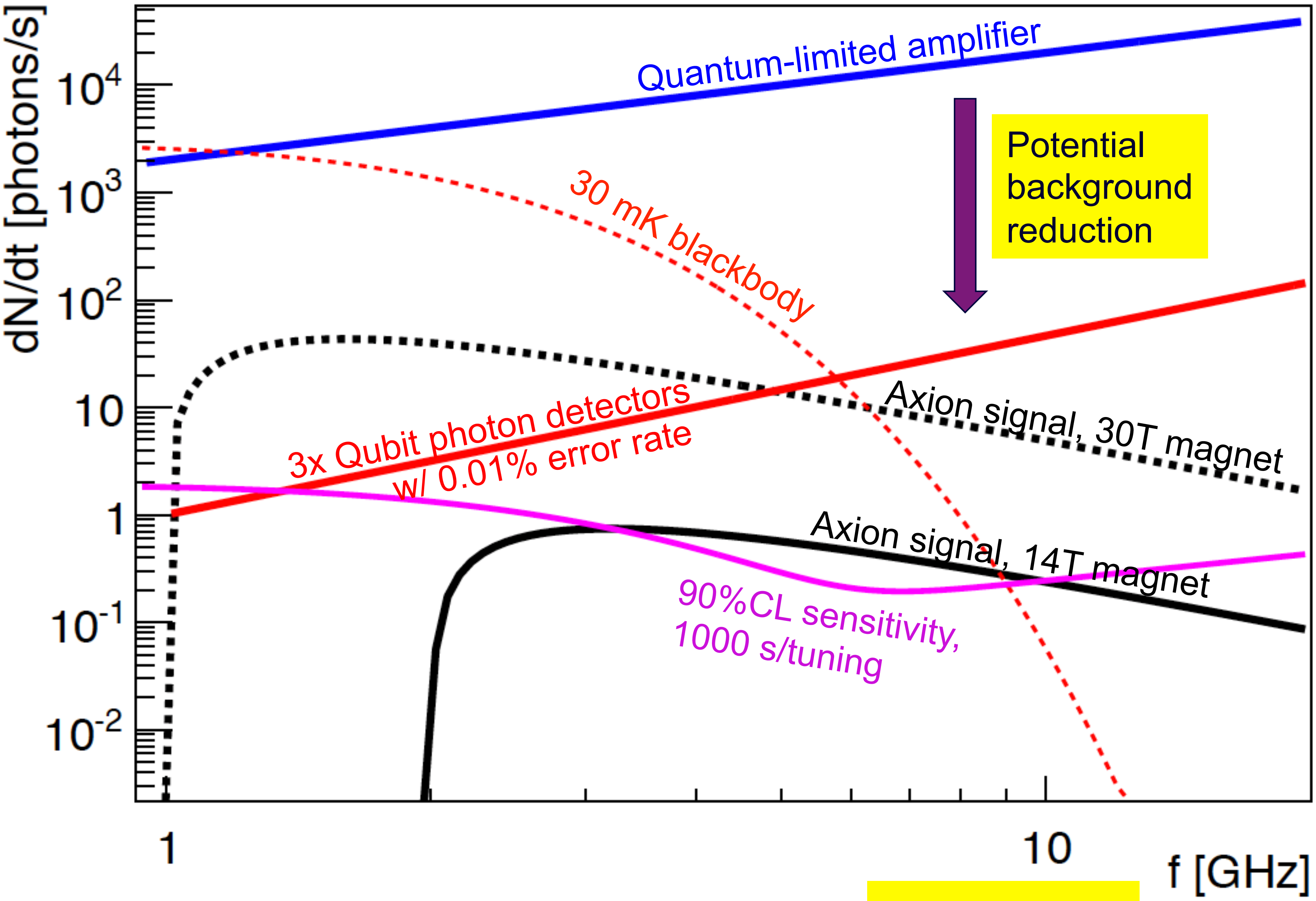






Photon-amplitude-to-qubit-frequency transduction enabled by the nonlinearity of the 2-level system

Qubit sensors may be the **enabling technology** for higher mass dark matter axion searches



Potential background reduction

10 GHz = 40 μeV

Stimulated emission of bosonic dark matter into photons

Axion haloscopes are classically-driven quantum harmonic oscillators

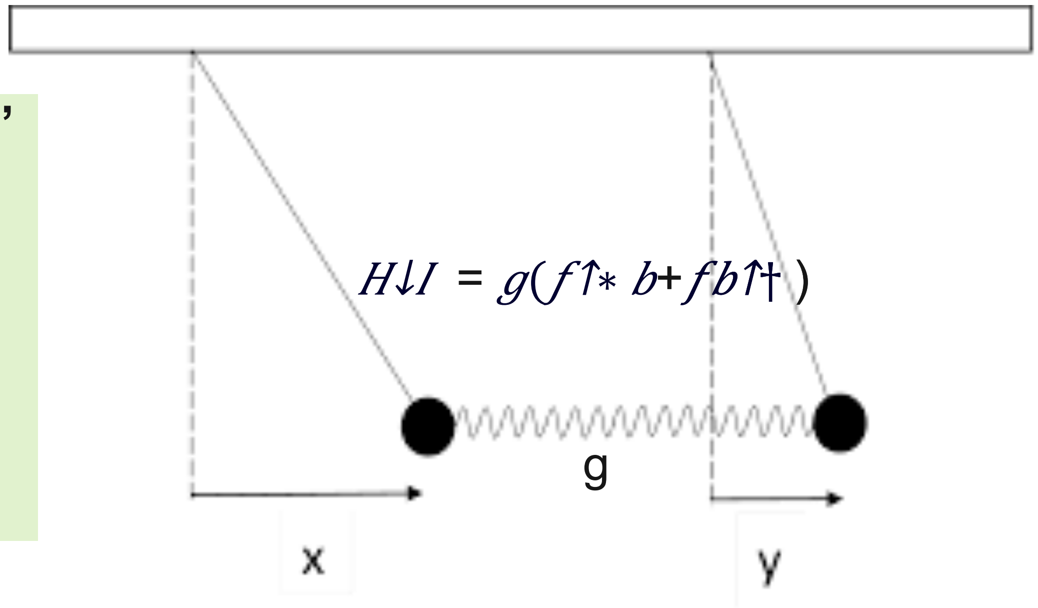
“Real world values”

$|\alpha\rangle = 10^{11}$

$\omega/2\pi = 10^{10}$ Hz

$2g/2\pi = 10^{-5}$ Hz

$t_{coherence} = 10^{-4}$ s



$$H_I = g(f^* b + f b^\dagger)$$

$f(\omega_1)$=classical sine wave.

Look for resonant transfer of power at $\omega 1 = \omega 2$ due to 2-mode mixing at frequency = 2g

Can we get enhanced Power = (Force × velocity) if we start the detection pendulum swinging with some initial velocity?

Pushing the swing at the wrong phase

Good!

Waiting…

Oops

Power = $Force \cdot velocity$

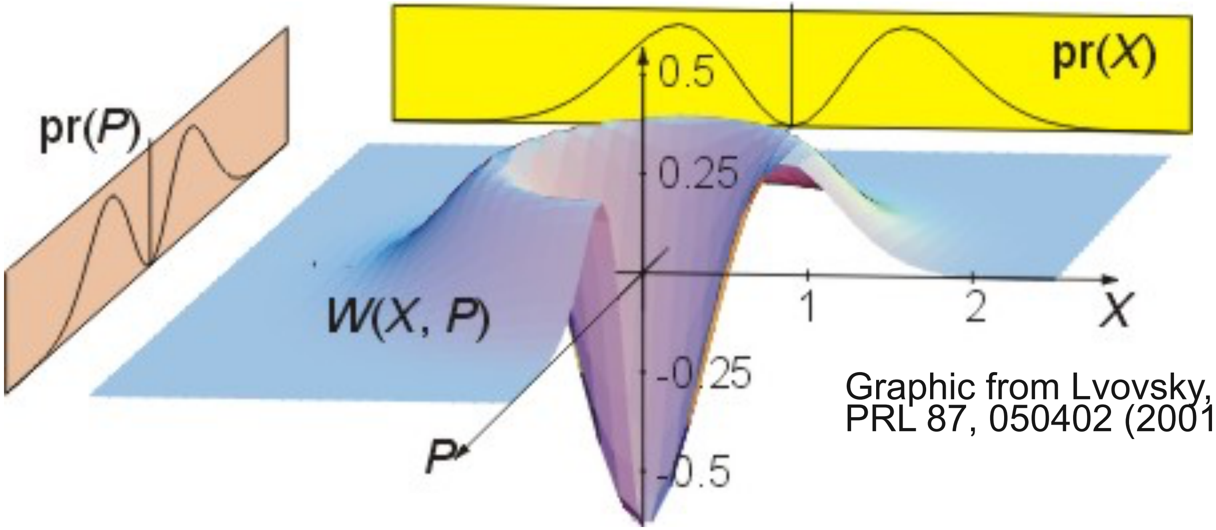
Sign of phase offset determines the direction of energy flow.

But the axion wave is a coherent state of unknown phase which changes every millisecond… How do we prepare the cavity oscillator???

Solution: Prepare the cavity in a Fock state which has definite photon number but maximally indeterminate phase

Schrodinger's cat state of the cavity mode in a symmetric superposition of all possible oscillation phases. Just like the vacuum state, this Fock state will respond equally well to any arbitrary phase of the axion wave…and it has no Poisson noise!

N=1 Fock state

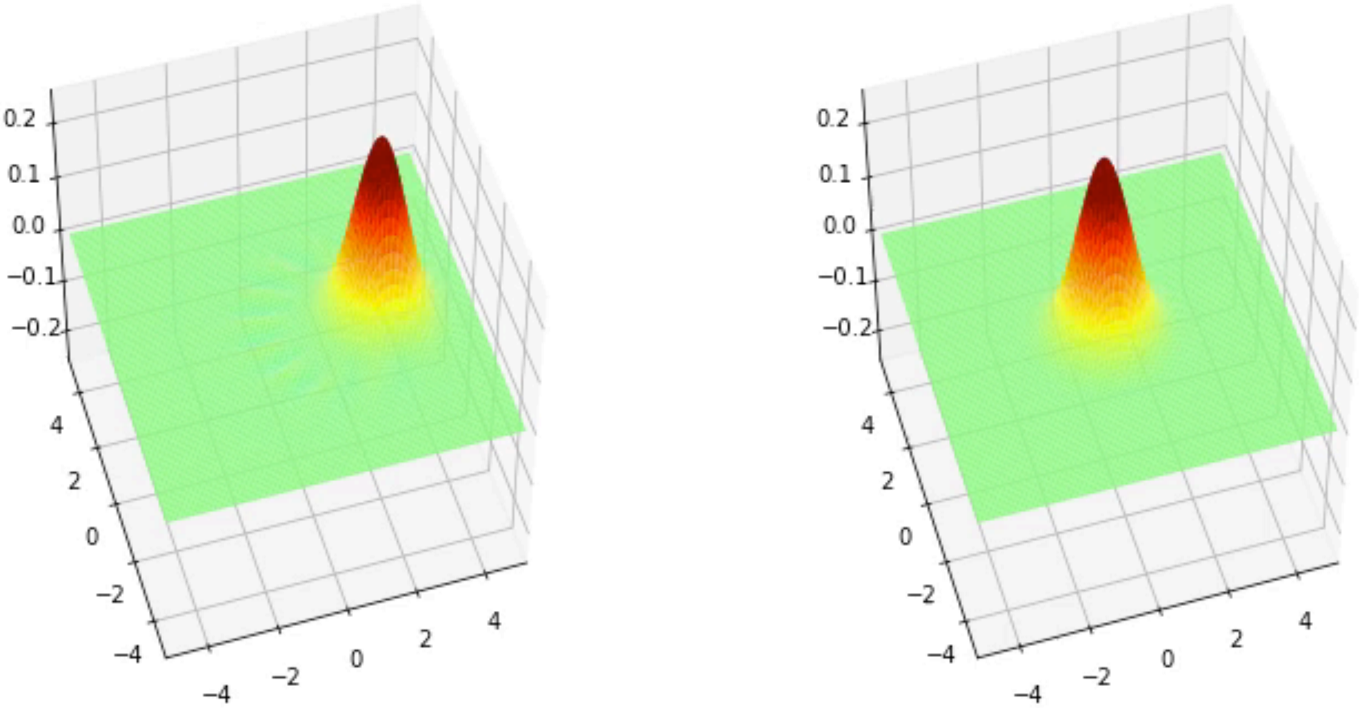


Graphic from Lvovsky, et.al, PRL 87, 050402 (2001)

Think of the phase space distribution as standing waves inside a 2-dimensional potential well. **Wigner distributions are Laguerre-Gauss functions.**

Classical pendulum system: $|\alpha{=}3\rangle \otimes |\alpha{=}0\rangle$

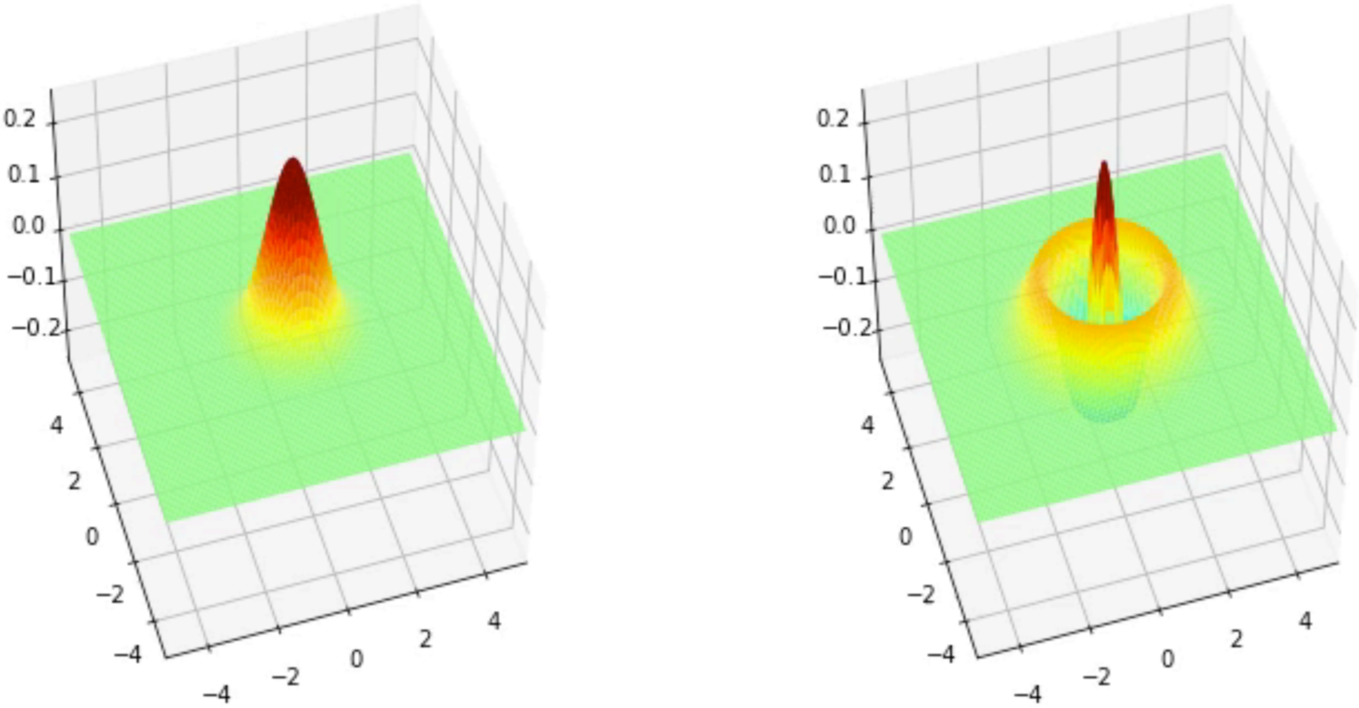
Time evolution of Wigner distributions in X-P "phasor" space



The two pendula swap their coherent states.

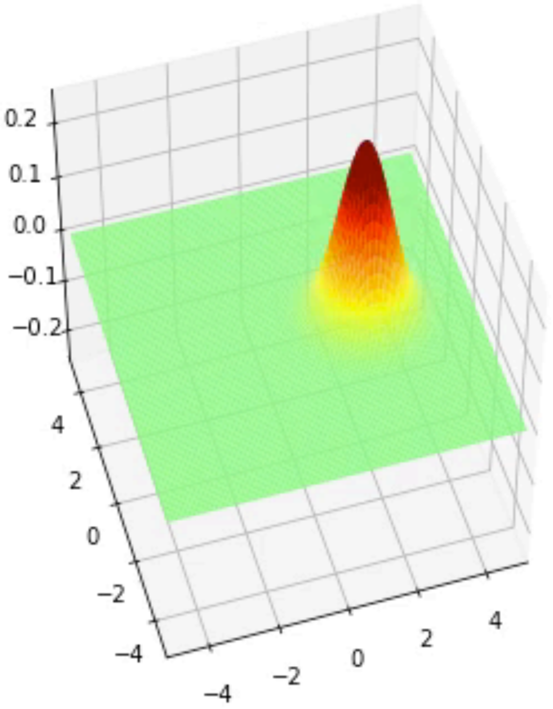
Simulated with QuTIP

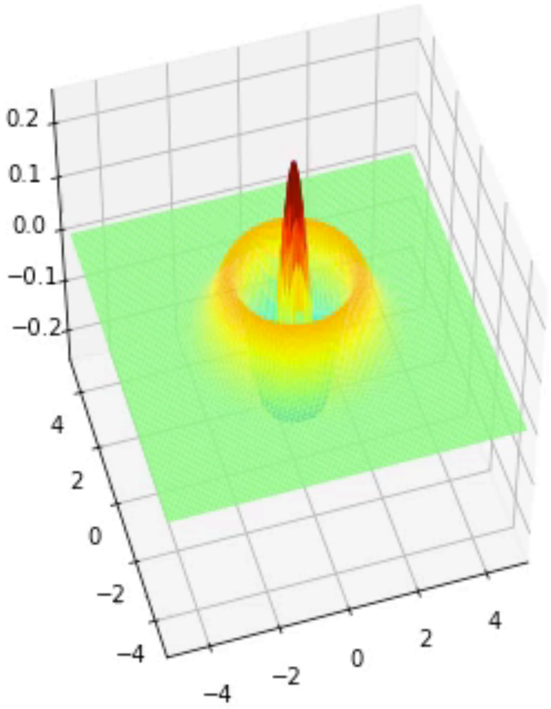
$|\alpha=0\rangle\otimes|N=2\rangle$



Vacuum and Fock states swap places

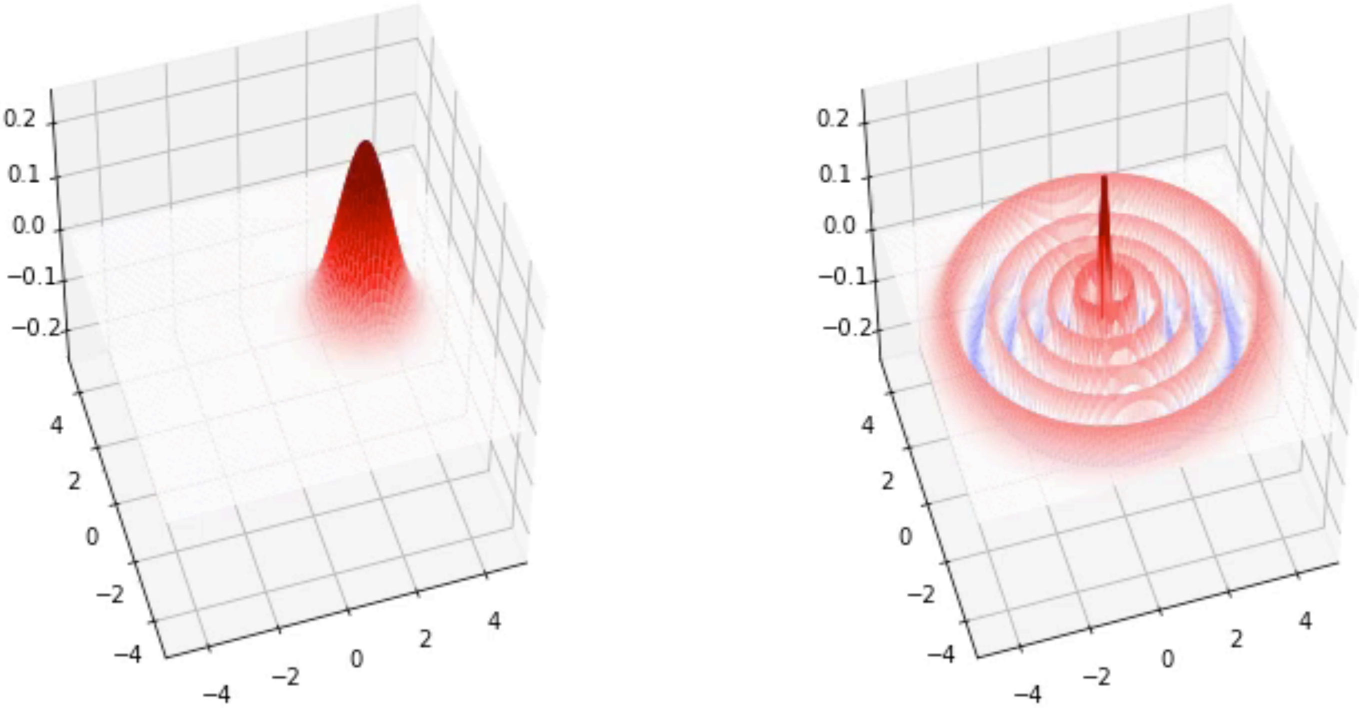
$|\alpha=\sqrt{2}\rangle\otimes|N=2\rangle$



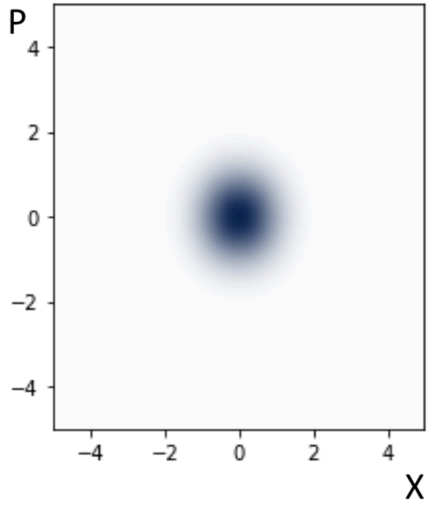


Coherent and Fock states swap places

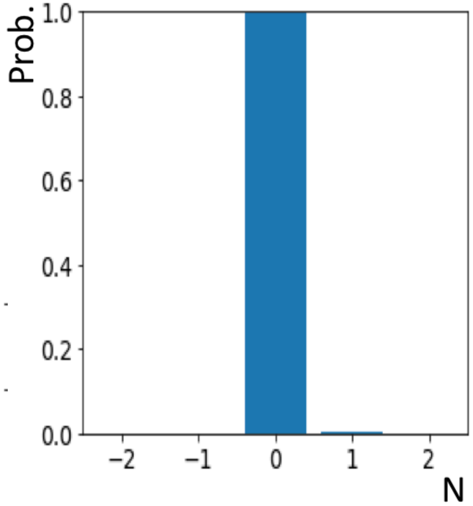
$|\alpha=\sqrt{2}\rangle\otimes|N=10\rangle$



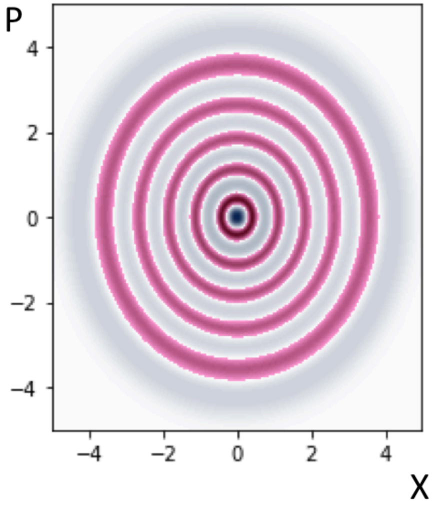
Spontaneous vs Stimulated Emission



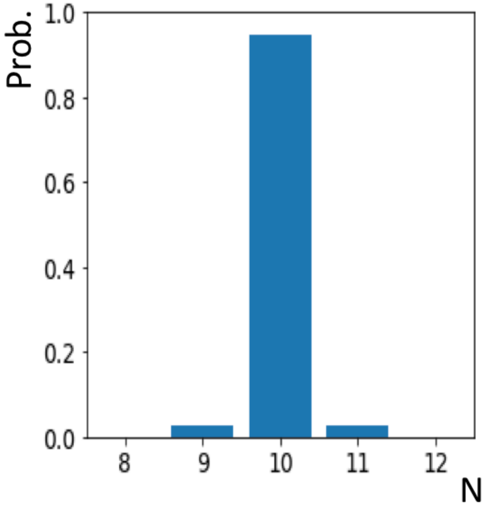
Cavity prepared in vacuum state N=0. Interaction with axions displaces this from the origin.



Spontaneous emission gives small population of N=1 state



Cavity prepared in N=10 Fock state. Displacement due to axions moves some components to smaller radius and some components to larger radius, corresponding to stimulated absorption and stimulated emission, respectively

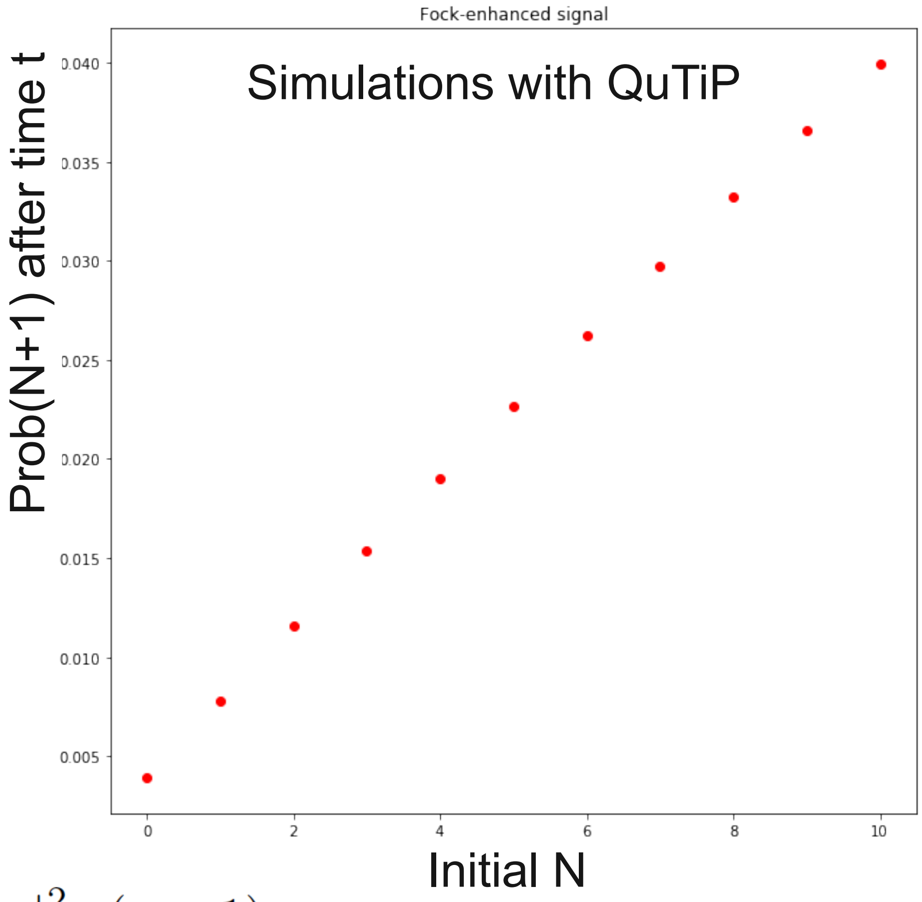


Factor of 10 in transition rates gives much larger signal in the N=11 state

Again, use qubit QND photon counting to measure the final state Fock number.

Fock enhancement in linear regime of two-state mixing

Start with coherent state $|\alpha = 1\rangle$ and Fock state $|N\rangle$ with same frequency ω and weak cross-coupling g $\ll \omega$. (wc = 1.0*2pi , g =0.001*2pi)
Evolve system for time t such that **2gt** $\ll$ **1** and look at occupation of state $|N+1\rangle$.



Simulations with QuTiP

Enhancement by factor N is evident

→Achieves Heisenberg limit of maximal squeezing!

At order $\alpha\uparrow 2$:

$$|\langle n+1|D(\alpha)|n\rangle|^2 = |\alpha|^2 \cdot (n+1)$$

Cavity Fock-state preparation gives stimulated emission/absorption between axion and cavity modes

Interaction Hamiltonian for direct product of 2 bosonic modes:

$$H_I = g(a^\dagger b + a b^\dagger)$$

Start with axion coherent state displacement α and cavity photon Fock number N:

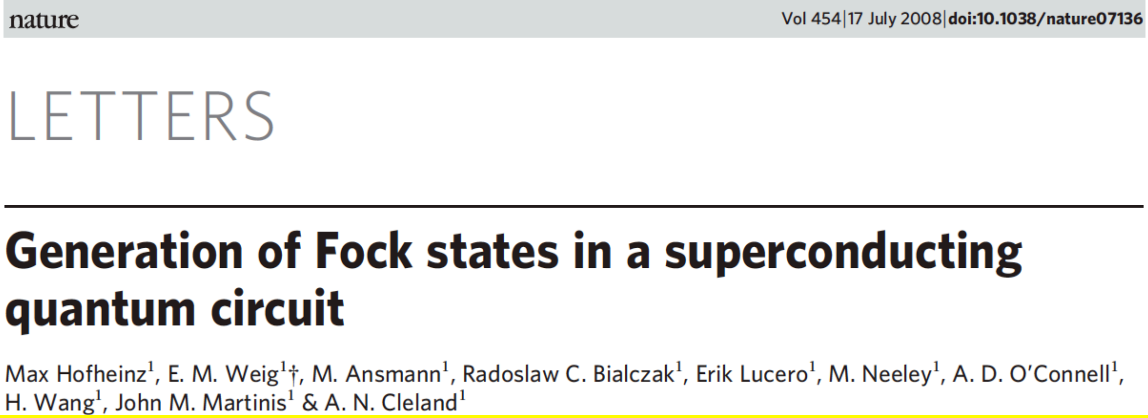
$$\langle \alpha, N+1 | H_I | \alpha, N \rangle = g\alpha\sqrt{N+1}$$

Matrix element is enhanced by factor $\sqrt{N+1}$,

Signal rate in linear mixing regime is enhanced by factor $N+1$

Faster exchange of quanta to/from axion wave via stimulated emission/absorption.

- **Laser: stimulated emission rapidly erases a population inversion in a lasing medium to reach a Boltzmann equilibrium between atom and photon states**
- **Axion cavity: stimulated absorption/emission more rapidly smears out the initial "delta function" Fock state of the cavity.**
  - Also need higher Q cavity resonator since Q → Q/N

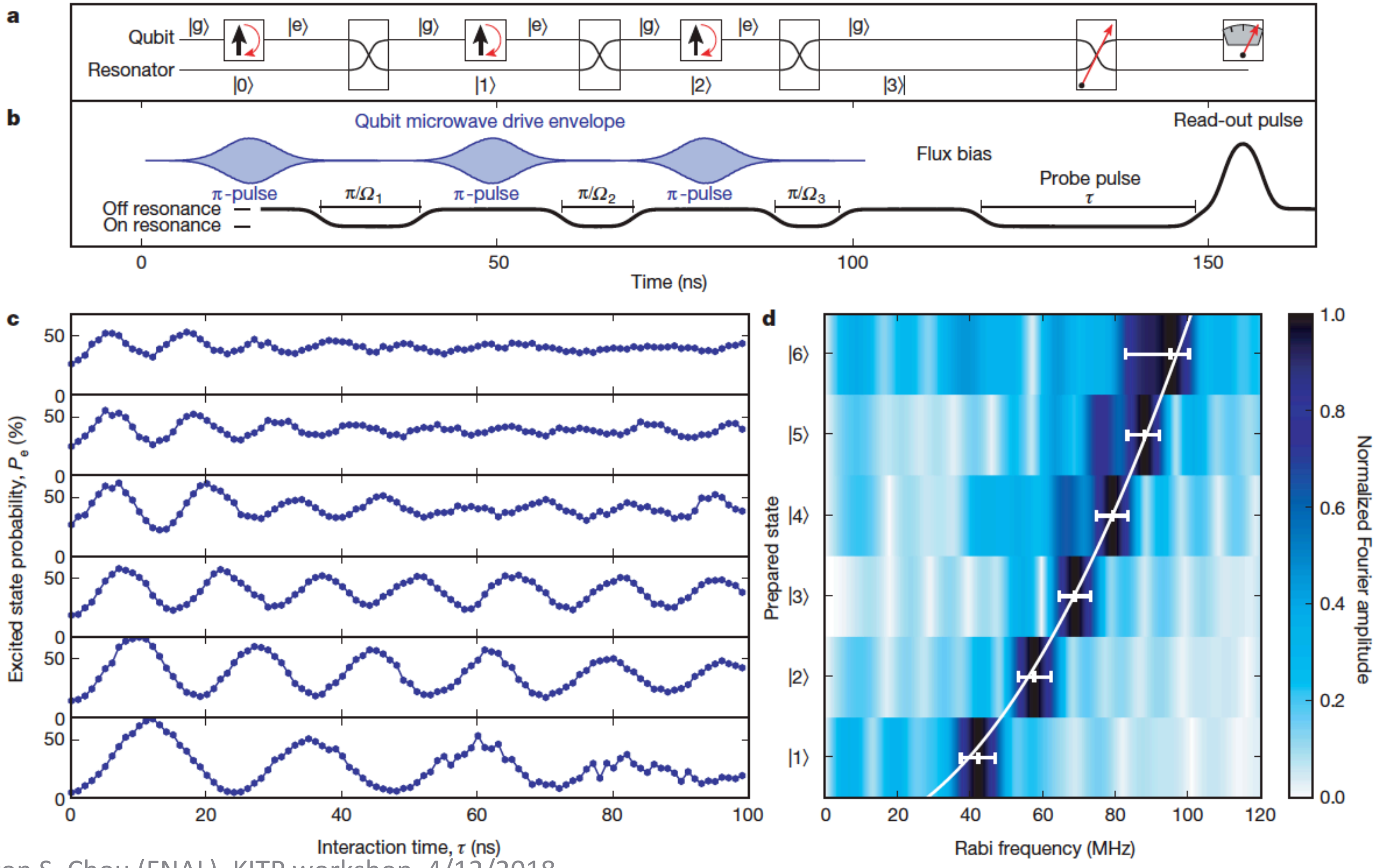

nature Vol 454|17 July 2008|doi:10.1038/nature07136

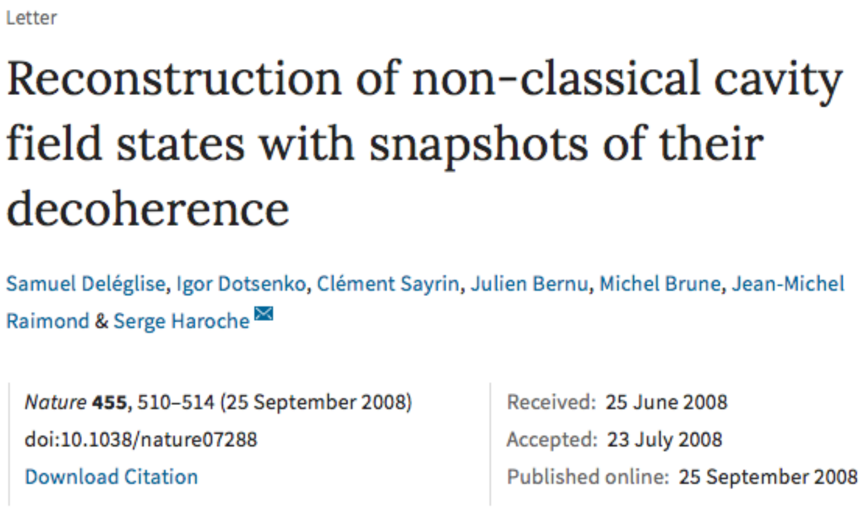
LETTERS

Generation of Fock states in a superconducting quantum circuit

Max Hofheinz[1], E. M. Weig[1]†, M. Ansmann[1], Radoslaw C. Bialczak[1], Erik Lucero[1], M. Neeley[1], A. D. O'Connell[1],
H. Wang[1], John M. Martinis[1] & A. N. Cleland[1]

Loading one quantum at a time using swept-frequency qubits as buckets





Letter

Reconstruction of non-classical cavity field states with snapshots of their decoherence

Samuel Deléglise, Igor Dotsenko, Clément Sayrin, Julien Bernu, Michel Brune, Jean-Michel Raimond & Serge Haroche

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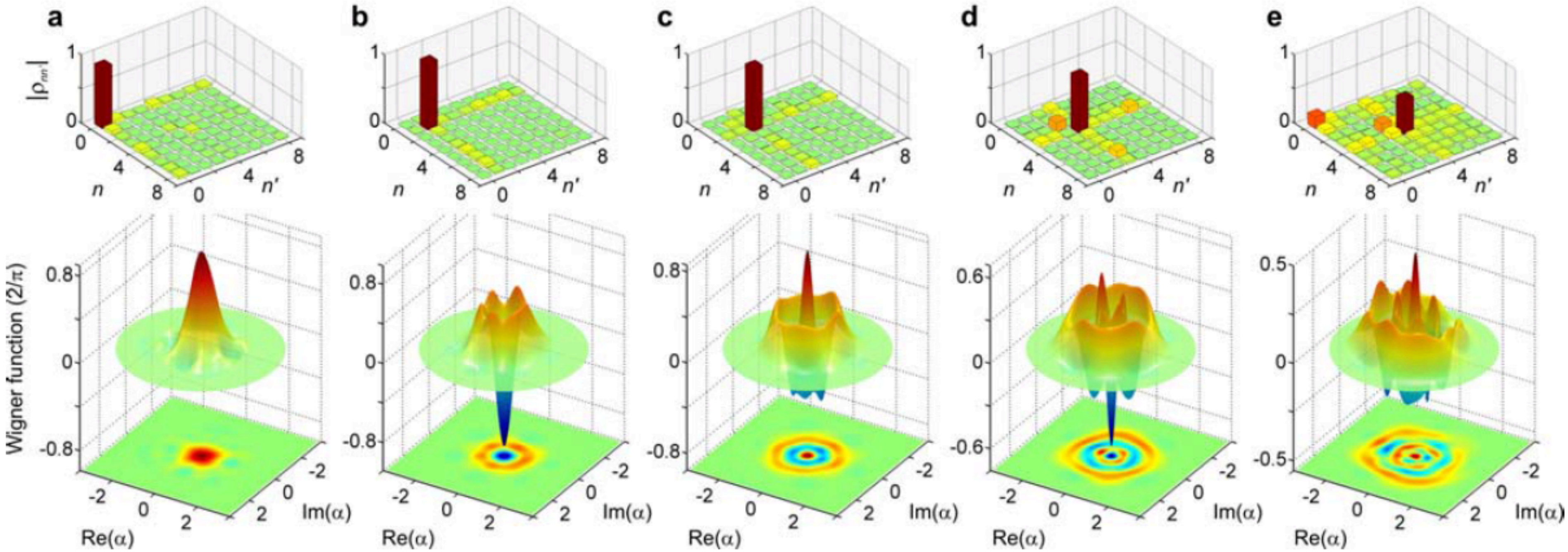
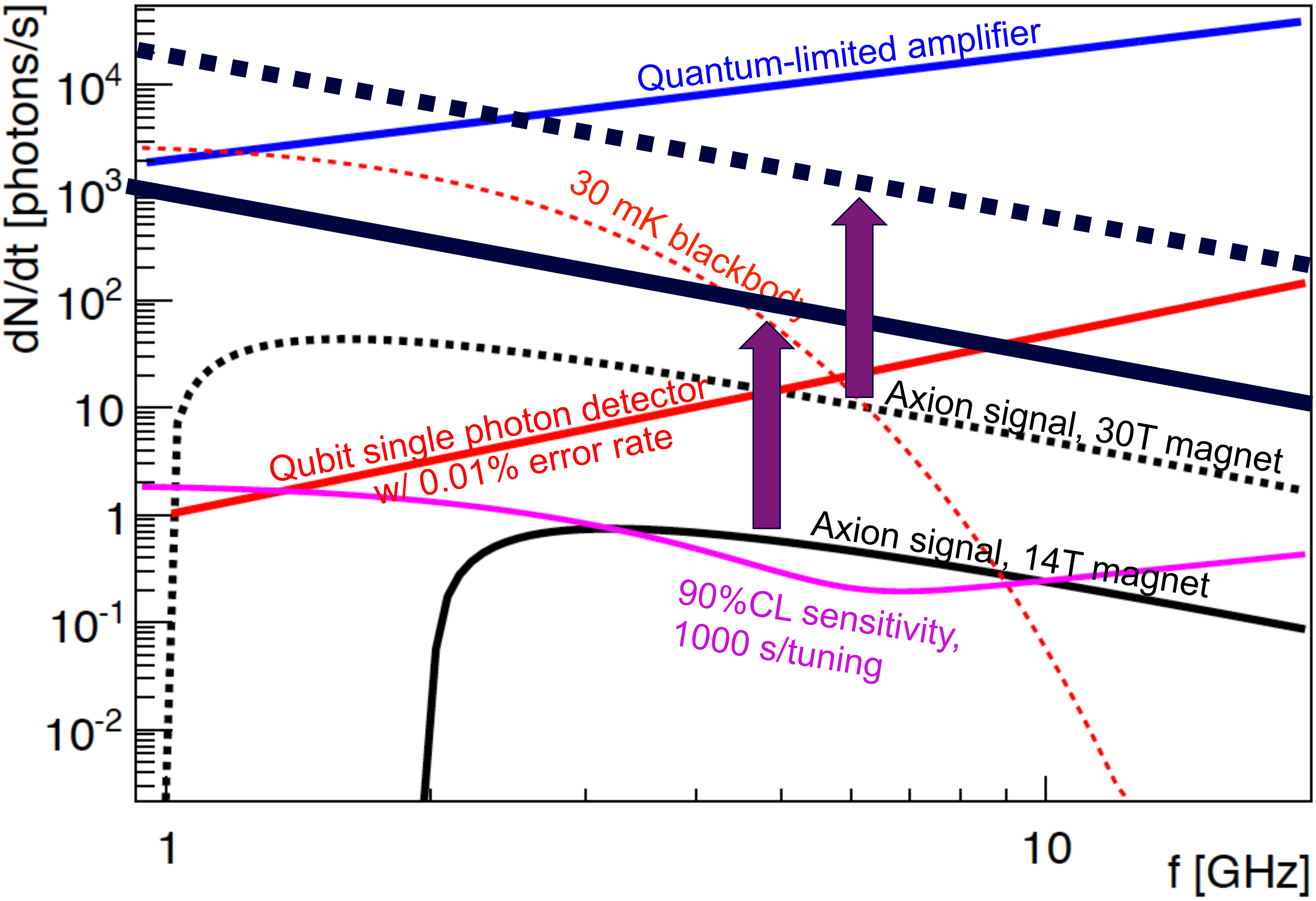
Preparation of Fock state via postselection

Density matrices after QND projection of coherent states into Fock states



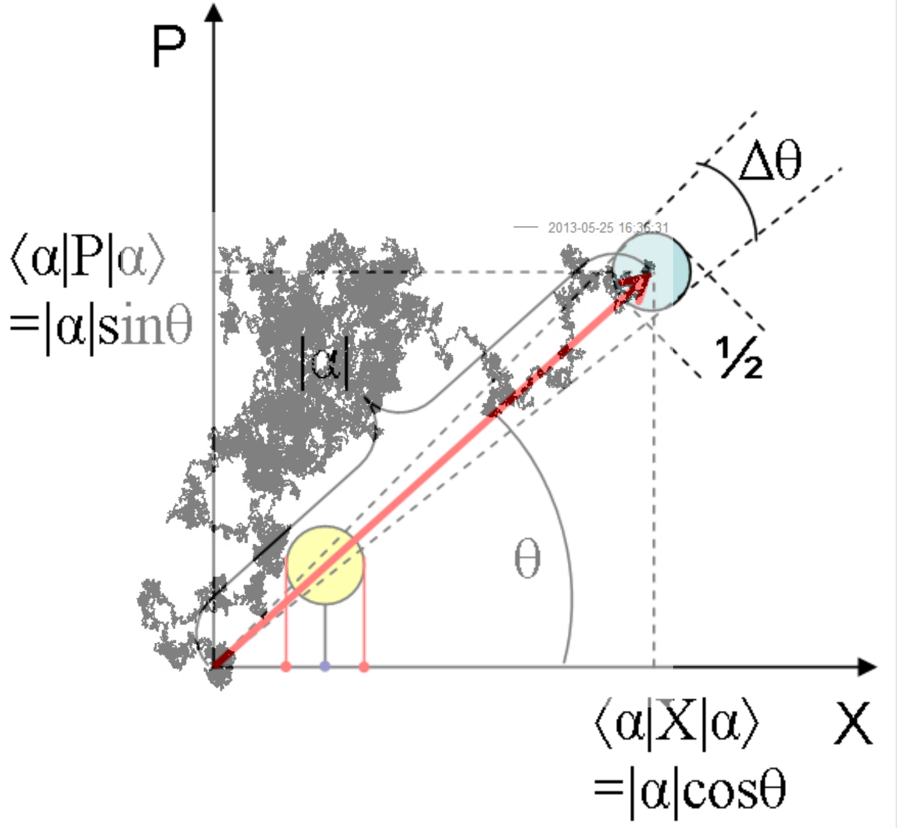
Measured Wigner functions using homodyne tomography.

If high-Q resonators compatible with B-field can be used → sensitivity to frequencies up to 100 GHz



High-Q cavities to accumulate random walk signals

Accumulating random phase dark matter signal as a random walk in high-Q cavities($Q_c>10^{10}$ for SRF)



Integrating over each dark matter coherence time Q_a/m_a gives a tiny displacement $\Delta\alpha$ of the initial vacuum state in some **random direction** depending on the instantaneous random phase of the axion field.

These displacements accumulate as a 2-dim random walk over $N_{steps}= Q_c/Q_a =10^4$ steps.

The net displacement is $\sqrt{N_{steps}}\,\Delta\alpha$.

This gives a net signal of $N_{steps}\,\Delta\alpha^2$ per cavity lifetime while keeping the noise constant with a

Accumulate signal in the cavity and reduce the readout cadence:

SNR → SNR×N_{steps}

Improved sensitivity to the kinetic mixing angle or to the axion-photon coupling

Displacement operators:

$$\hat{D}(\alpha)\hat{D}(\beta) = e^{(\alpha\beta^*-\alpha^*\beta)/2}\hat{D}(\alpha+\beta)$$

$$\rightarrow \prod_i D(\Delta\alpha_i) = D(\underbrace{\textstyle\sum_i \Delta\alpha_i}_{\sqrt{N_{steps}}\,\Delta\alpha})\, e^{i(phase)}$$

See also Chaudhuri, et.al arXiv:1803.01627

Outlook

- The axion model simultaneously explains both the vanishing neutron EDM and the dark matter
- The conventional haloscope technique for detecting axion DM relies on using amplifiers with quantum-limited noise to see the spontaneous emission of axions into photons.
  - Cannot scale to higher masses due to plummeting Signal/Noise ratio
- **Techniques which only measure amplitude (such as QND photon counting) can evade the standard quantum limit noise and thus enable higher mass searches**
- **Large signal rate enhancement factors are possible by preparing the cavity in a Fock state and using stimulated transitions and/or by using high Q cavities and accumulating a random walk signal to reduce the readout cadence.**

Orders of magnitude improvement in sensitivity to ultraweak couplings is possible by employing the quantum metrologist's toolbox.

New Consortium: Quantum Metrology for Dark Matter Axion Detection

- Aaron Chou (FNAL), David Schuster(Chicago): Qubit QND sensors
- Konrad Lehnert(Colorado/JILA): Stimulated emission, photon transport
- Reina Maruyama (Yale): Rydberg atom single photon detection
- You?