Quantum Sensors for High Energy Physics

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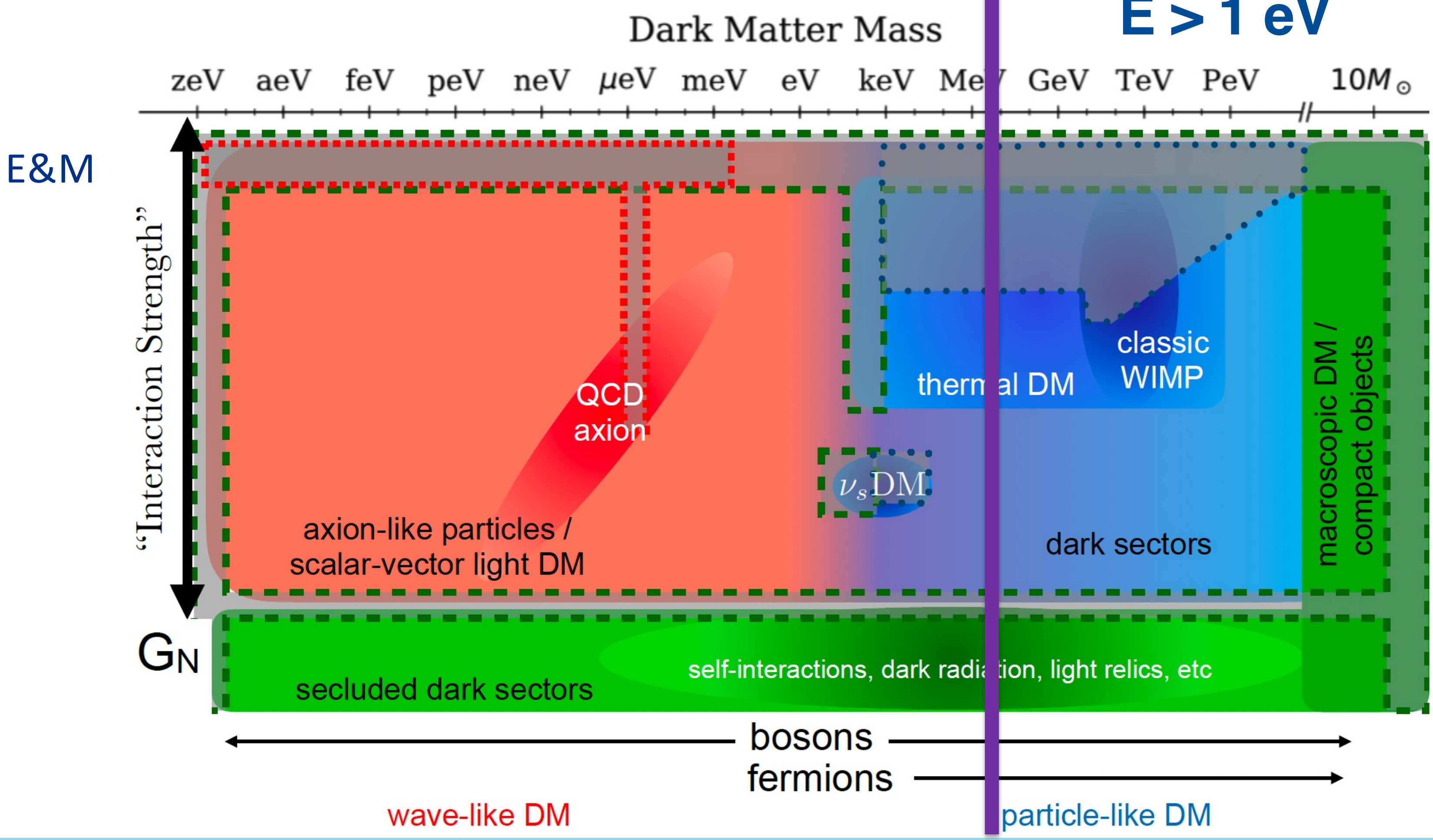
Fermilab
September 27, 2024

1. Beat the Standard Quantum Limit by photon counting!
2. Speed up time using stimulated emission!

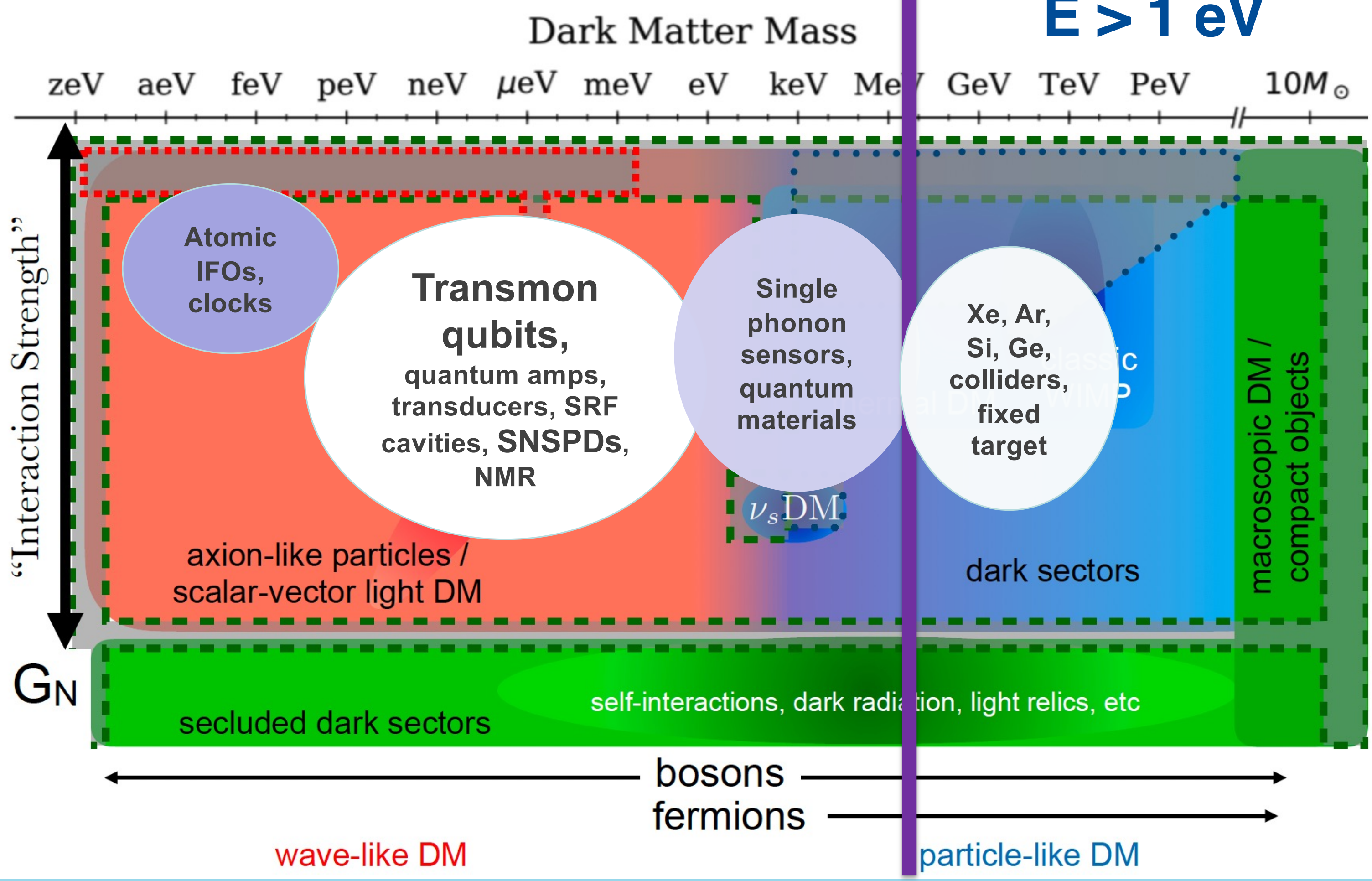
Quantum sensors: E < 1 eV ⟵ ⟶ Current HEP tech: E > 1 eV



Cartoon from Snowmass

Quantum sensors: E < 1 eV ⟵ ⟶ Current HEP tech: E > 1 eV

E&M

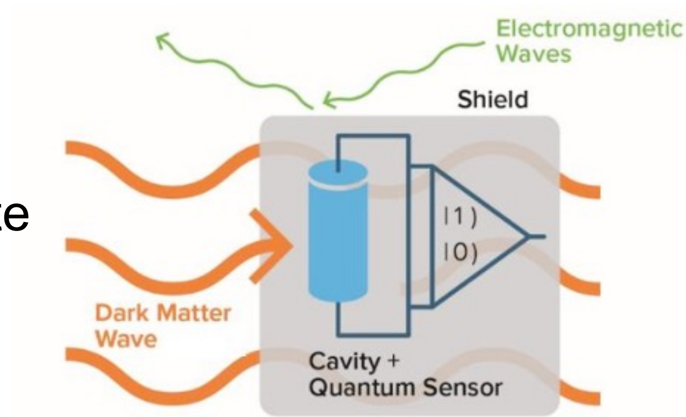


Cartoon from Snowmass

Fermilab

Hmmm… quantum computing platforms look just like dark matter searches:

DOE-OHEP Basic Research Needs white paper, 2018
(R. Harnik cartoon)



Sensitive single-quantum devices (10^{-4} eV excitation energy) are operated in a cryostat and/or vacuum system and well-shielded from external disturbances (heat, light, sound) in order to maximize their coherence time.

Impossible to shield from the dark matter
→ Google's catastrophic events wipe out all info on their multi-qubit processor

If your quantum computer crashes, it could be due to dark matter!
… but as consolation, you'll get a Nobel prize anyway for the discovery.

Example 1:
Using superconducting qubits for single microwave photon counting

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

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

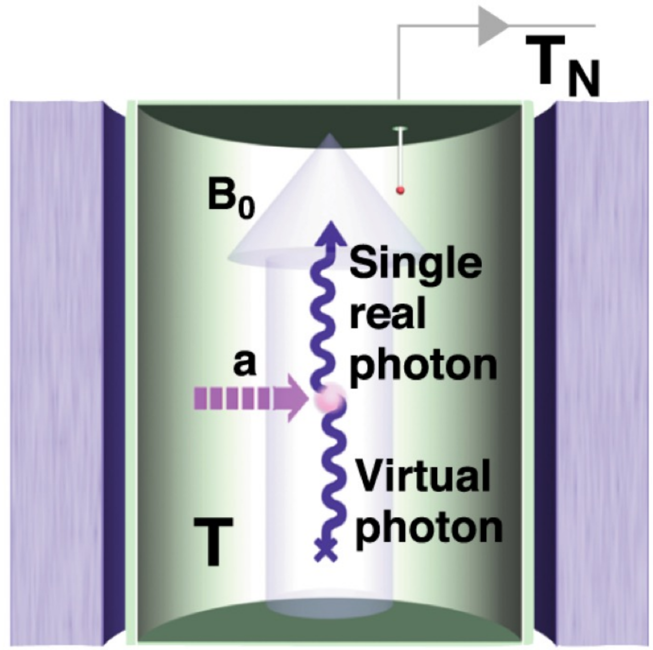
which drives E&M via Faraday's law:

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

- 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 galactic gravitational potential well acts as a low pass filter on the dark matter kinetic energy
  - Use narrowband cavity matched to signal linewidth $f/Q = f/10^6$

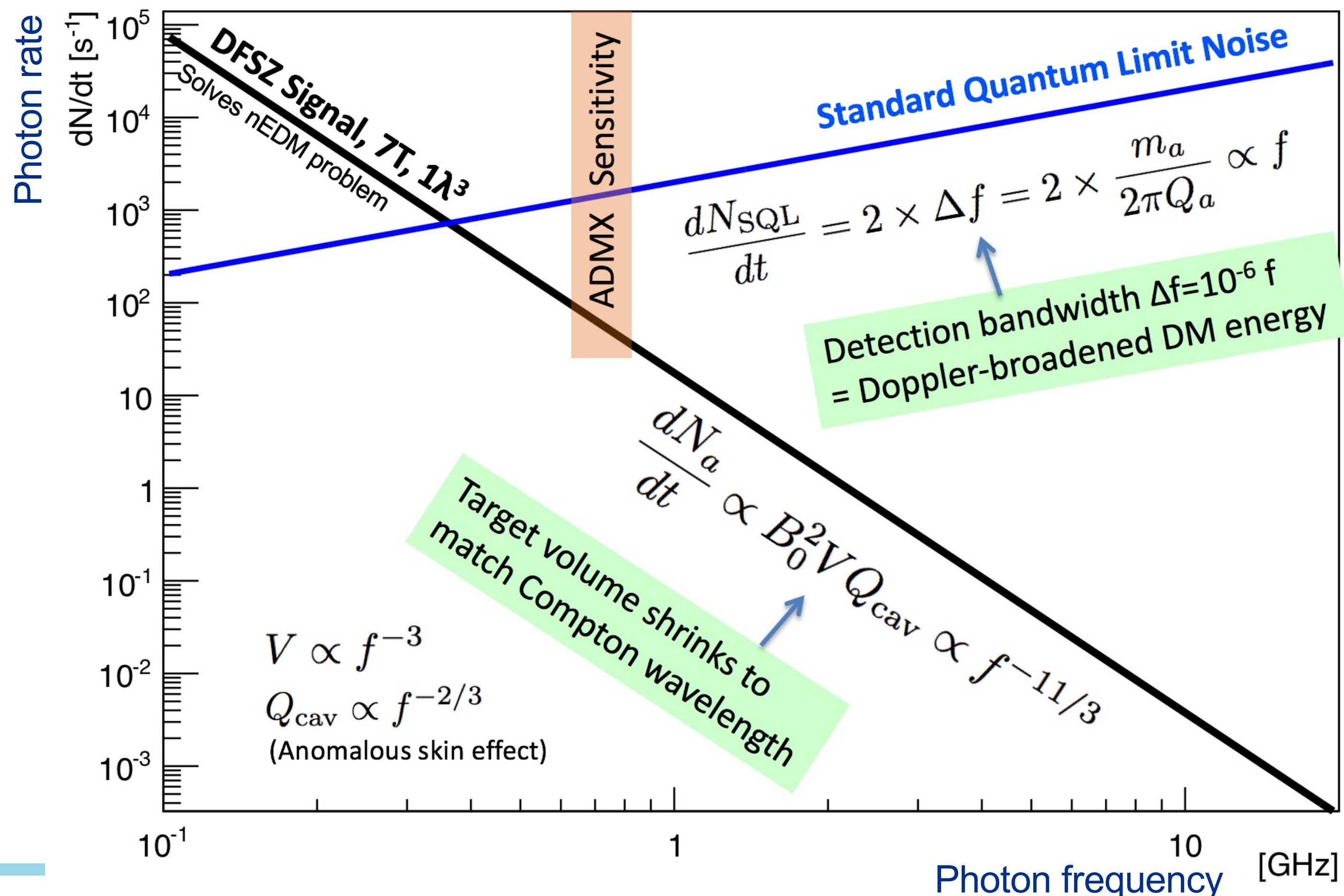
- Axion mass is unknown – **must do radio scan over large frequency range by tuning the narrowband cavity 10^6 times per octave in mass**



Power = Force times velocity

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

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



Effective DCR = 10^4/s

SQL equivalent to DCR = 1 photon per resolved mode = 1 × Δf

Need DCR < 10^{-2}/s

Poisson noise ∝ sqrt(DCR)

Need much larger signal/noise ratio in many searches for new physics.

Increase signal?

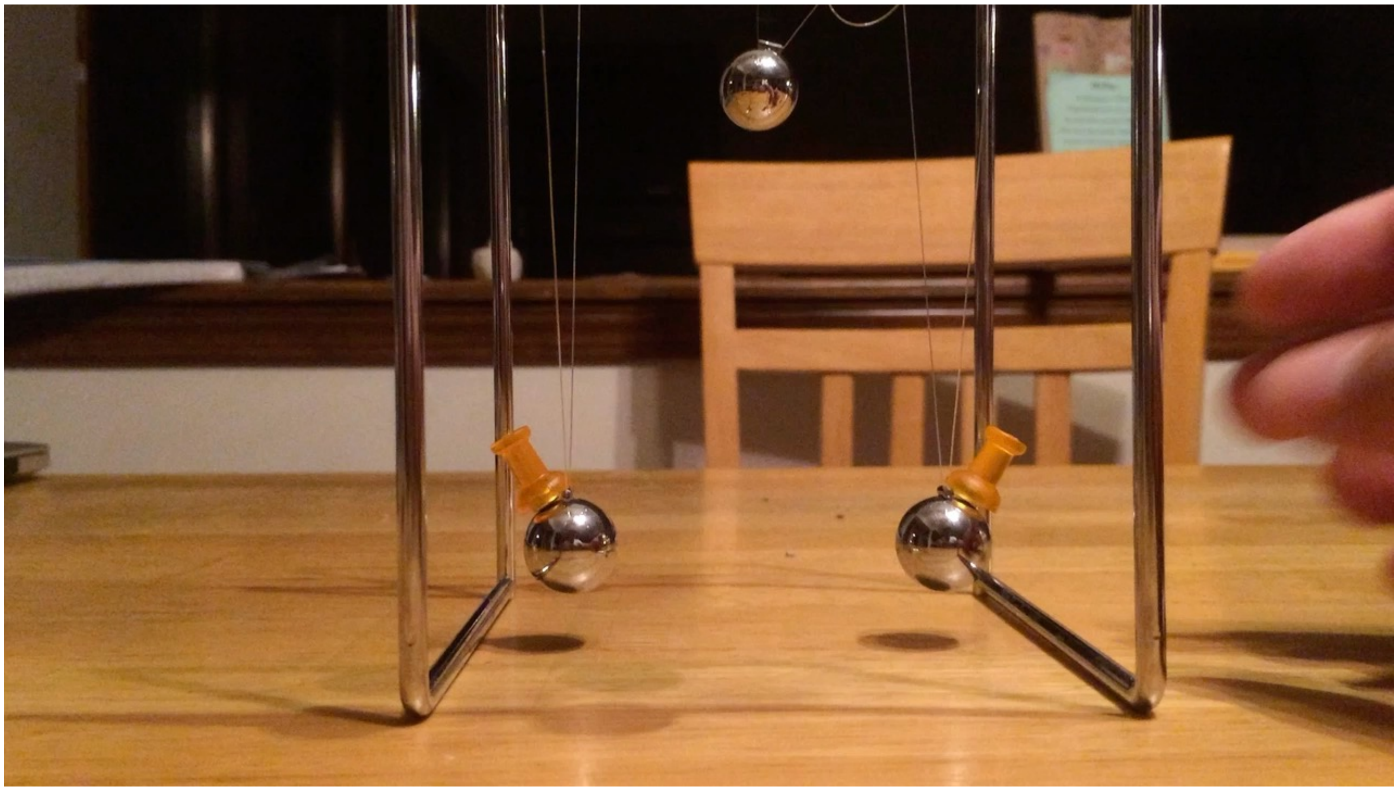
We do need more magnets, but these are expensive and have long lead time.

Reduce noise?

Many quantum tricks are possible, but must be tailored to the application.

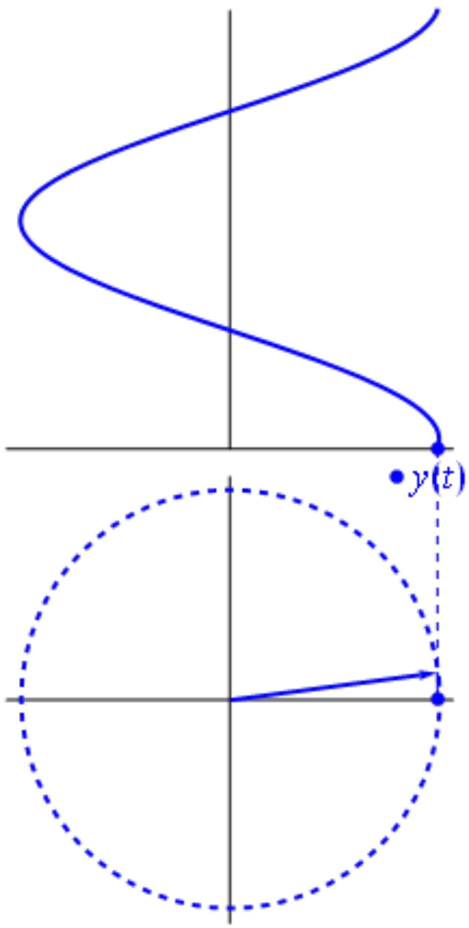
Energy transfer between two coupled oscillators

Laboratory oscillator



Dark matter wave or Grav. wave

Weak coupling -- takes many swings to fully transfer the wave amplitude.
In real life, the number of swings is limited by coherence time and one only gets the transfer of an occasional single quantum of energy.



Quantum mechanics:
Endpoint of phasor in X, P phase space has uncertainty principle

$\Delta X \times \Delta P \geq 1/2.$

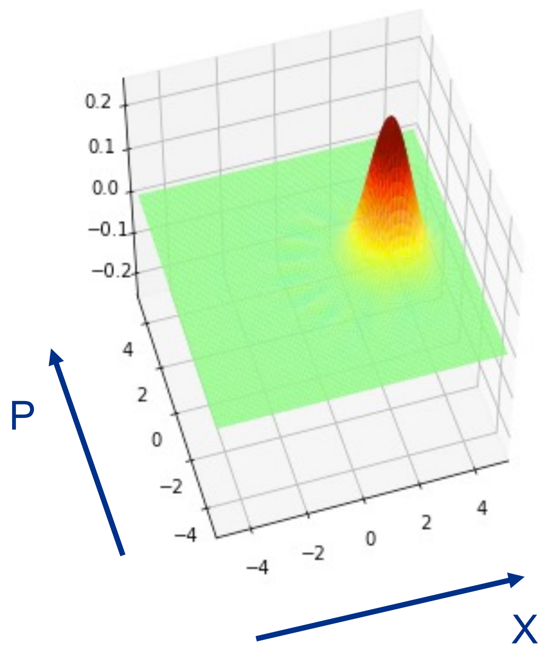
In polar coordinates this becomes:

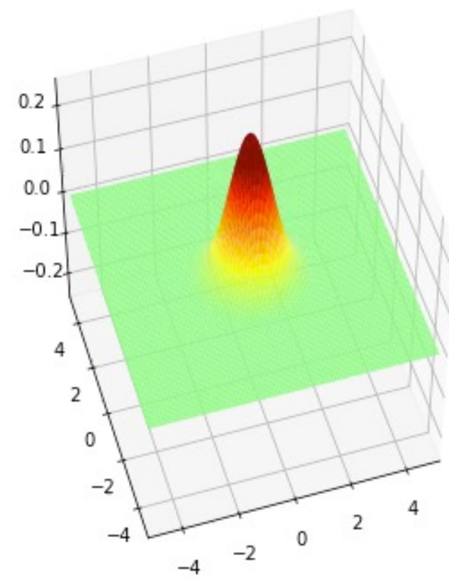
$\Delta N \times \Delta \varphi \geq 1/2.$

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

Wigner distributions: Each gaussian blob of phase space area satisfies $\Delta X \cdot \Delta P = \frac{1}{2}$

This is all the information nature has – cannot obtain more when simultaneously measuring X and P (or N and ϕ) by amplifying the signal sine wave → SQL.



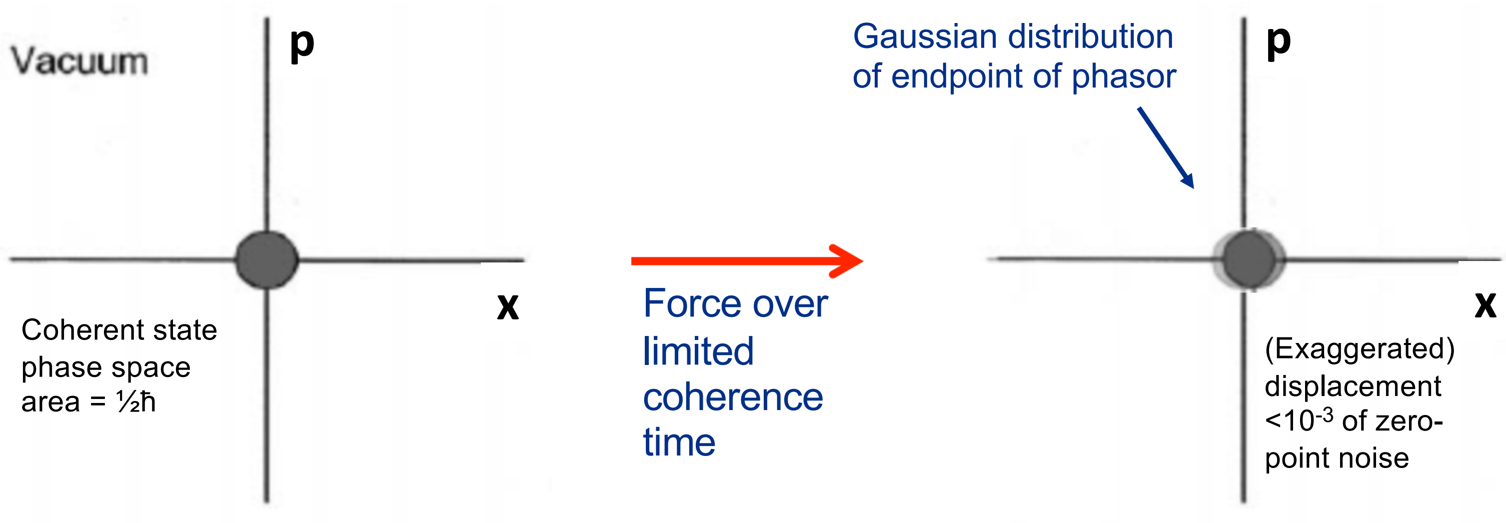


Simulated with QuTIP

Given enough time, the two pendula swap their coherent states.
Real experiments are limited by coherence time so only get the occasional single quantum of signal

A tiny problem: Signal/Noise Ratio is tiny due to finite coherence time

Initial state:



The Gaussian blob is also effectively the probe resolution when using a linear amplifier to resolve the tiny signal sine wave. Simultaneous measurement of non-commuting observables N and φ incurs the Heisenberg uncertainty principle $\Delta N \times \Delta\varphi \geq ½$.

Axion experiments need millions of standard-quantum-limit measurements to average away the zero-point noise to resolve the tiny displacement signal.

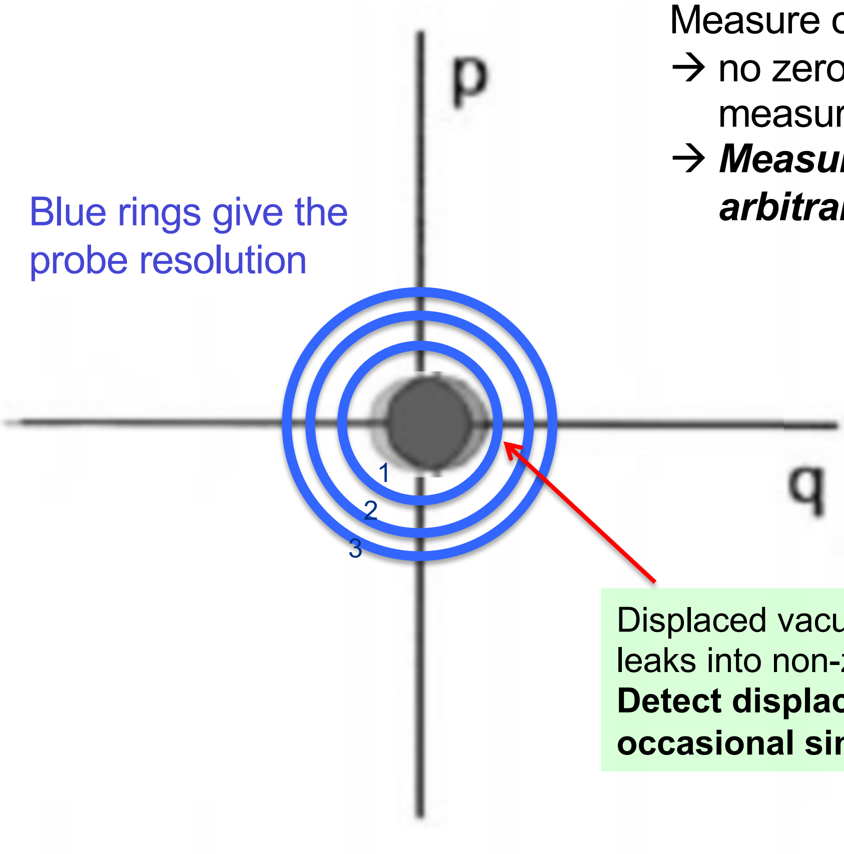
To reduce readout noise below SQL, use photon counting to measure displacement using the Fock basis, i.e. number eigenstates

Measure only displacement amplitude and not phase

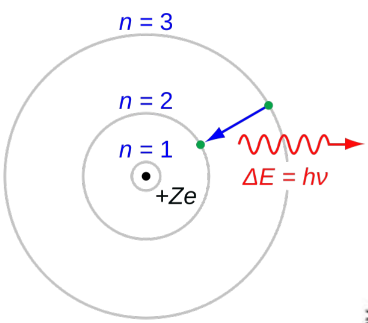
→ no zero-point noise since we are not simultaneously measuring non-commuting observables

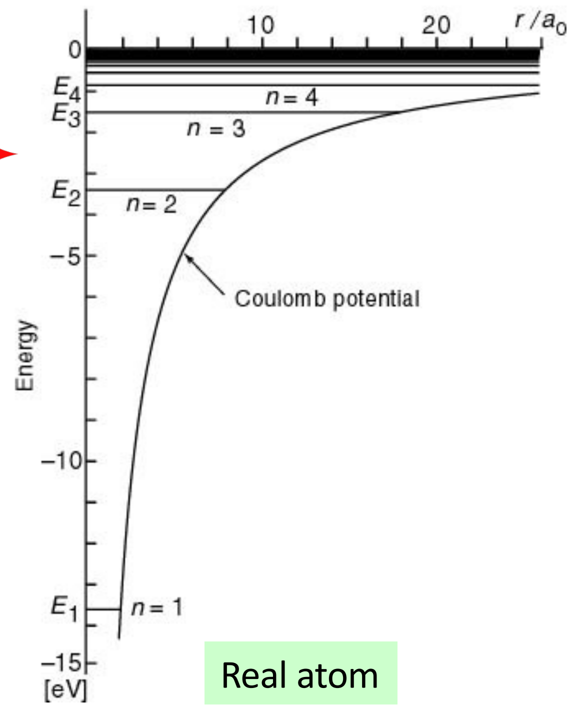
→ ***Measurement noise, e.g. from dark counts can be arbitrarily low***

Blue rings give the probe resolution

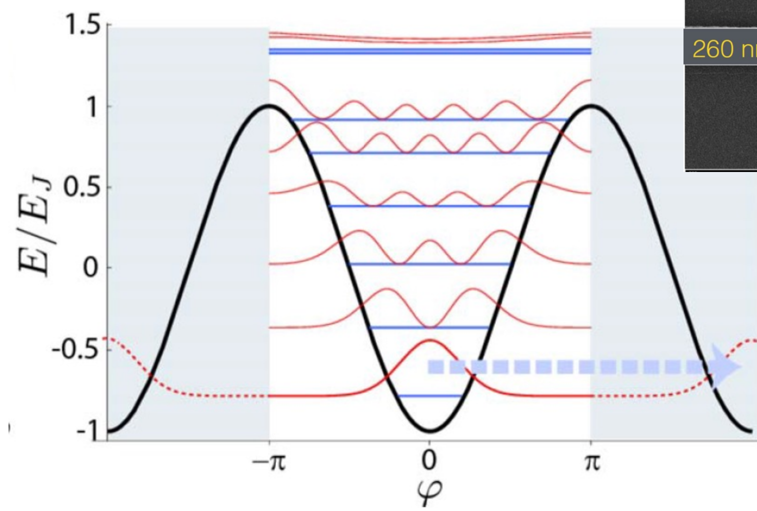


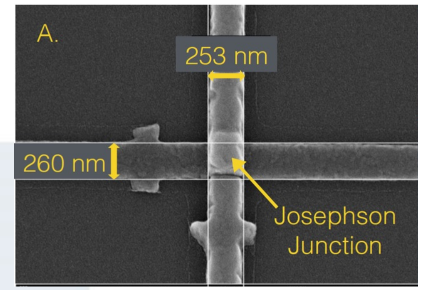
Displaced vacuum state exponentially leaks into non-zero Fock number.
Detect displacement by counting the occasional single photon.





Real atom





Artificial atom (Josephson junction oscillator)

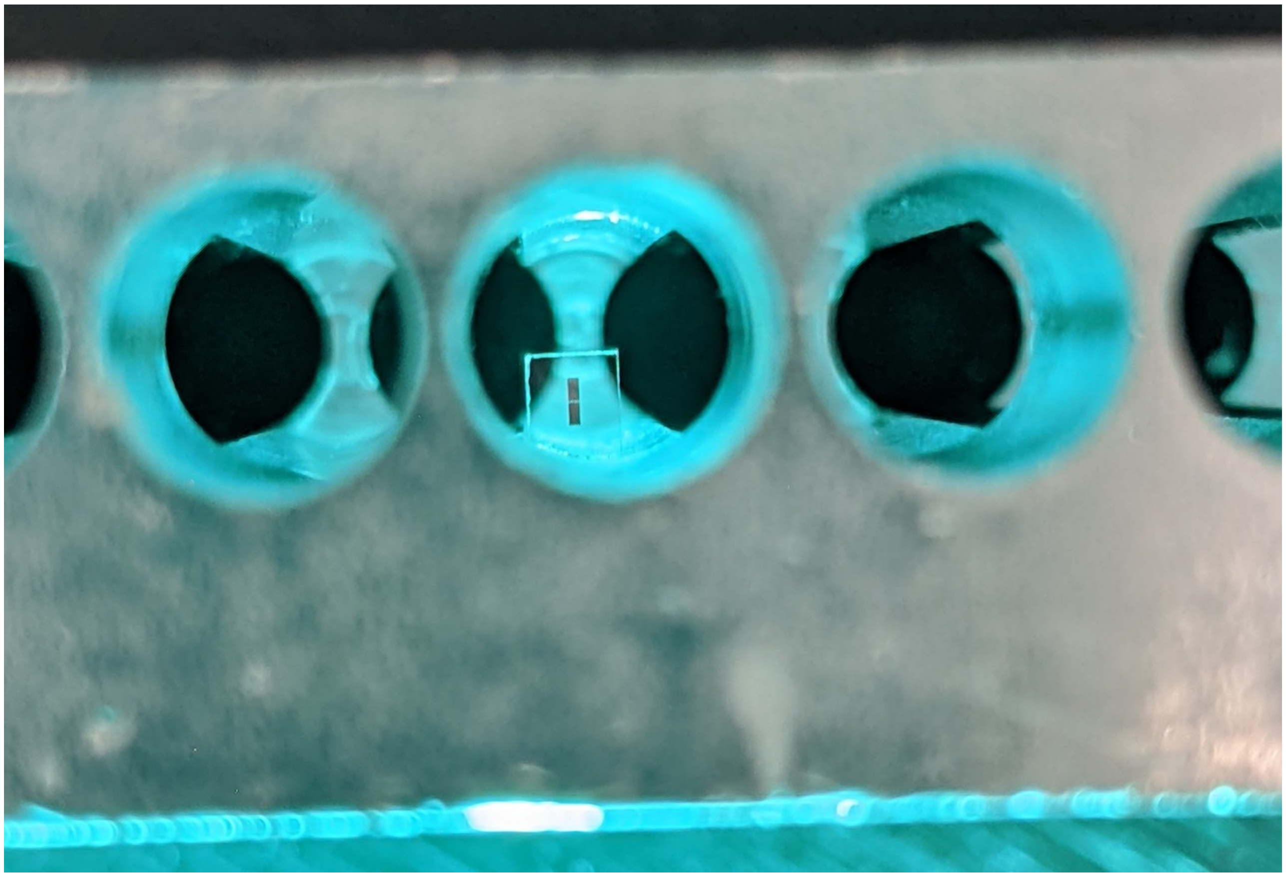
Both have non-degenerate energy level spacings due to the nonlinear potentials, and thus act as 2-level systems useful for quantum computing.

Jostling of the nonlinear oscillator due to background electromagnetic fields gives “atomic” frequency shifts

→ Lamb shift from zero-point fluctuations

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

Transmon qubit in 6 GHz aluminum cavity



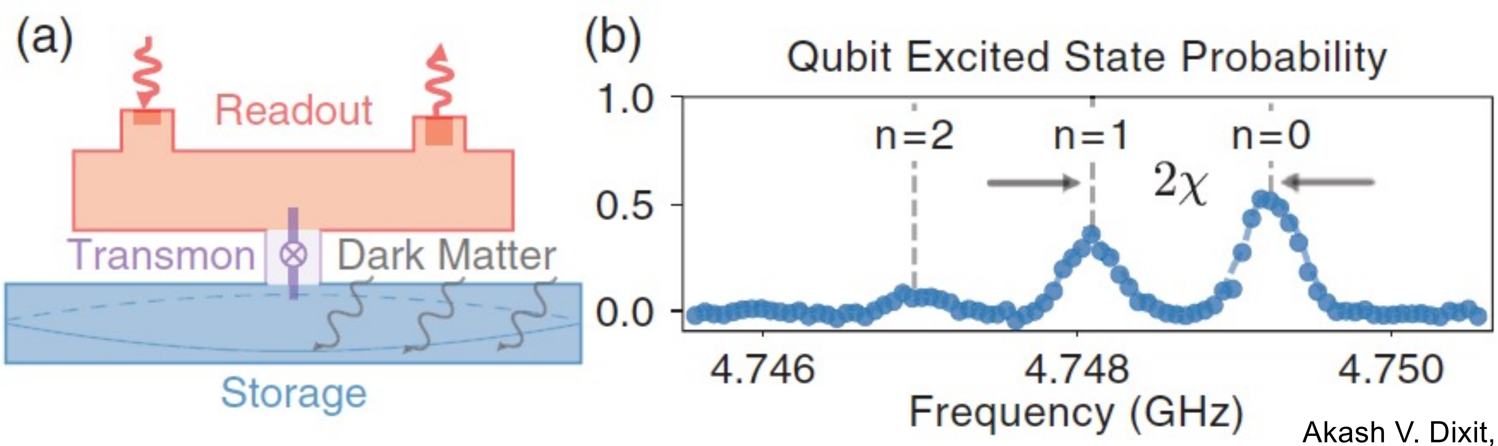
Panflute microwave cavity = QRAM storing information as single photon

Akash V. Dixit,
PhD 2021

Dark matter interaction causes a single quantum of information to mysteriously appear in your QRAM that was not part of your quantum computation

Detect single photons via the AC Stark shift of the qubit:

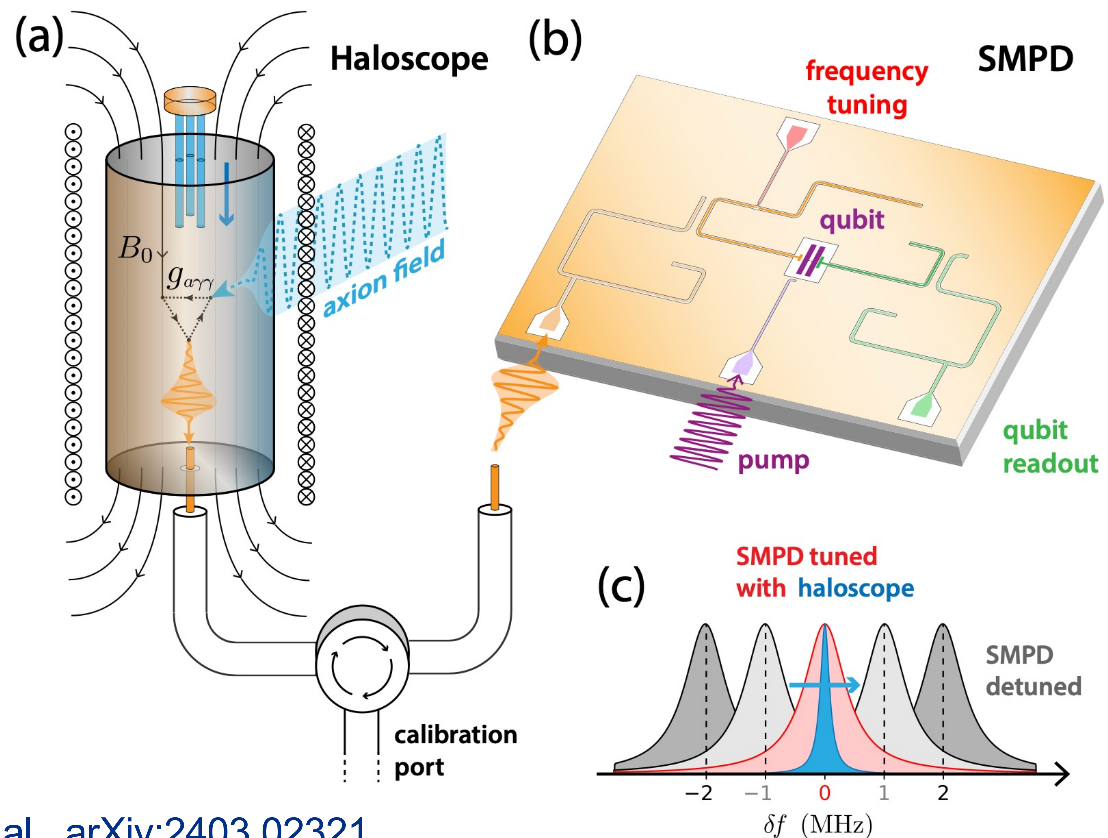
Example: Measure qubit $|g\rangle \rightarrow |e\rangle$ transition frequencies while driving the cavity to mimic the dark matter signal.



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

- Quantized frequency shifts occur because the electric field of the photons induces an oscillating Cooper pair current and drives the qubit into nonlinearity. (cf. matter effects in neutrino oscillations)
- The measured qubit excitation spectrum exhibits a distribution of resonances which are in 1-1 correspondence with the Poisson distribution of the "coherent state" of cavity photons.
- Measure the dressed qubit Hamiltonian averaged over many photon oscillation cycles
  - No information is gained on the photon phase and so there is no SQL noise!
  - **Demonstrated factor of 1300 reduction in DCR, equivalent to -36 dB of squeezing below SQL**

Patrice Bertet's remote single microwave photon receiver deployed in axion search



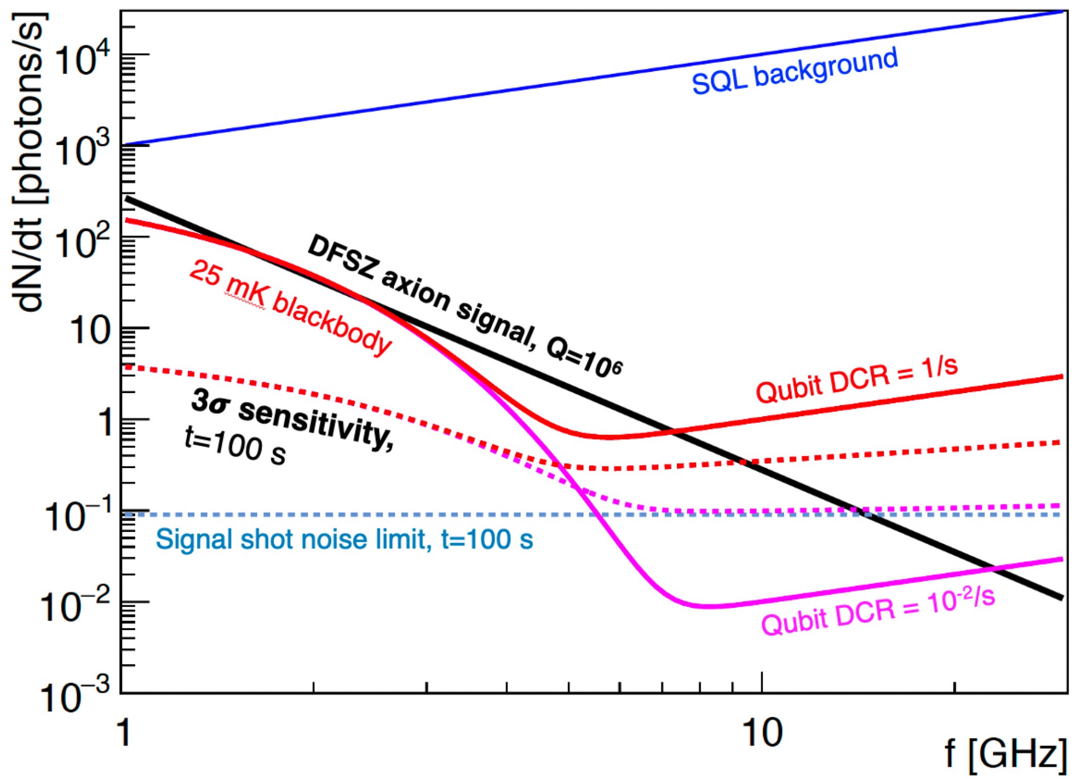
Photon is detected via a controlled-X gate, exciting the qubit **g→e** only when a signal photon is present,

e.g. perform operations at the shifted qubit frequency corresponding to exactly 1 photon.

C. Braggio et al., arXiv:2403.02321

Signal rate sensitivity is then determined by the integration time budget:

If budgeted t=100 s at each tuning, can do 10^5 tunings in 1 year. 1 octave in mass is 10^6 tunings, so do 10 concurrent experiments to cover the full octave.



For t = 100 s, the minimum observable signal rate is $R_s \gtrsim 0.1$ Hz

(Signal shot noise limit, need to count 9 ± 3 photons for 3σ sensitivity)

Once DCR is sufficiently low, cavity experiments are still **signal statistics limited at higher frequencies**

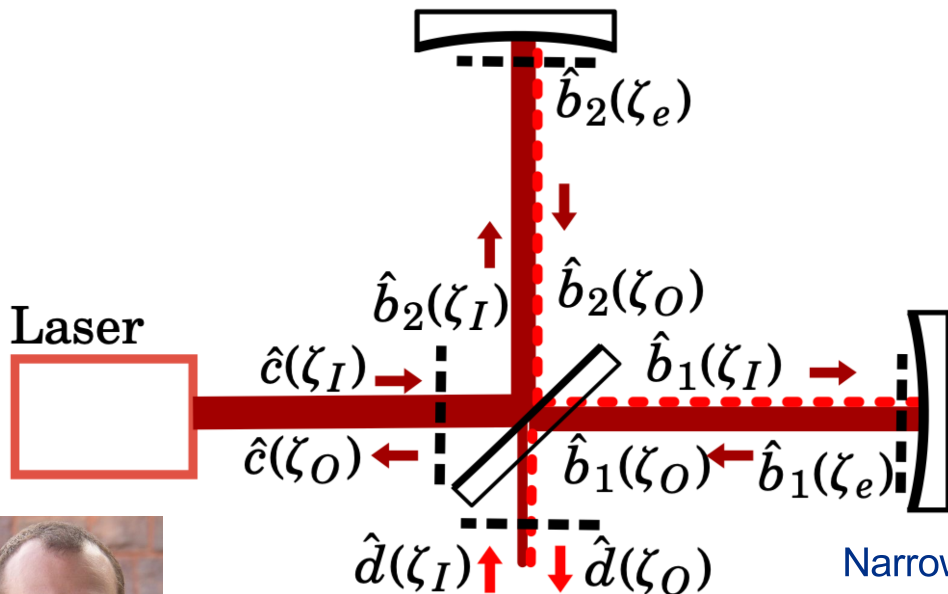
Example 2:
Using ultra low dark count rate (DCR) single photon detectors in gravitational wave laser interferometers

GQuEST: Single photon counting readout for gravitational wave interferometers

Fermilab, Caltech, JPL

Weak GW signals imprinted on MHz sidebands of 280 THz carrier wave.

- Standard readout is to use the carrier wave to parametrically amplify the weak GW signal by mixing on a square-law detector → incurs SQL
- Instead, band-pass filter the sideband to reject carrier, and count photons.

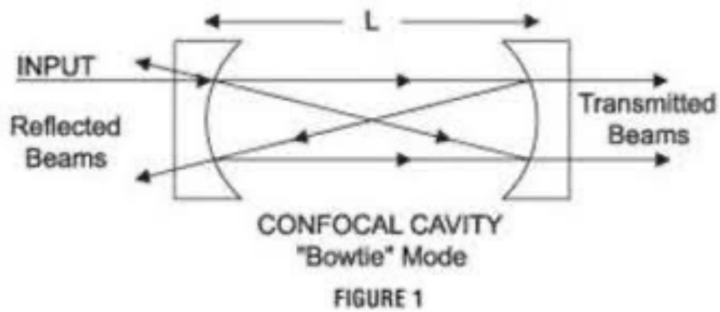


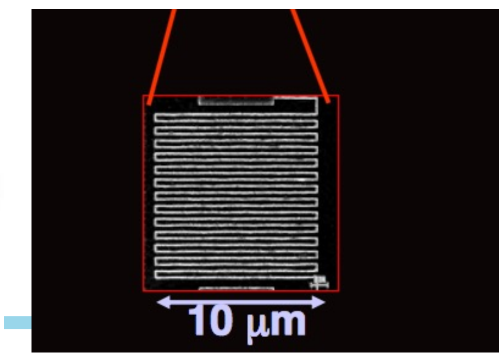
Superconducting nanowire single photon detector, DCR = 10^{-5} photon/s, vs SQL = 10^{5} photon/s.

→50 dB noise reduction!

Lee McCuller, arXiv:2211.04016

Narrowband filter cavity defines the mode linewidth





Topic 2:
Speeding up time for low event rate experiments using stimulated emission

More stupid qubit tricks:
Increase signal rate by stimulated emission of photons from DM waves

Start the photon wave swinging so it can more easily accept energy from the DM.

Power = $\overrightarrow{Force} \cdot \overrightarrow{velocity}$

Good!

Waiting…

Oops, wrong phase

Phase offset determines the direction of energy flow.

Wait ... but we don't know the instantaneous phase of the DM wave!

What happens if we initialize the probe to a Fock state instead of a Gaussian blob?

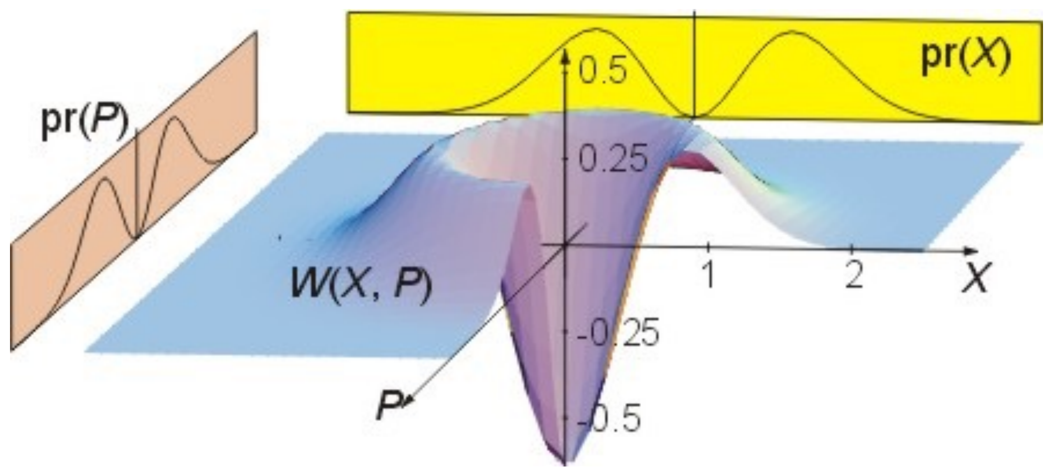
A Fock state is a superposition of an oscillator in all possible phases of its sinusoidal motion: $\Delta N \times \Delta\varphi \geq ½$
→ **responds equally well to pushes at any time.**

It also has definite occupation number N
→ **no Poisson noise!**

… and force × velocity still works:

$$H_I = g(a^\dagger b + a b^\dagger) \rightarrow \langle \alpha, N+1 | H_I | \alpha, N \rangle = g\alpha\sqrt{N+1}$$

N=1 Fock state



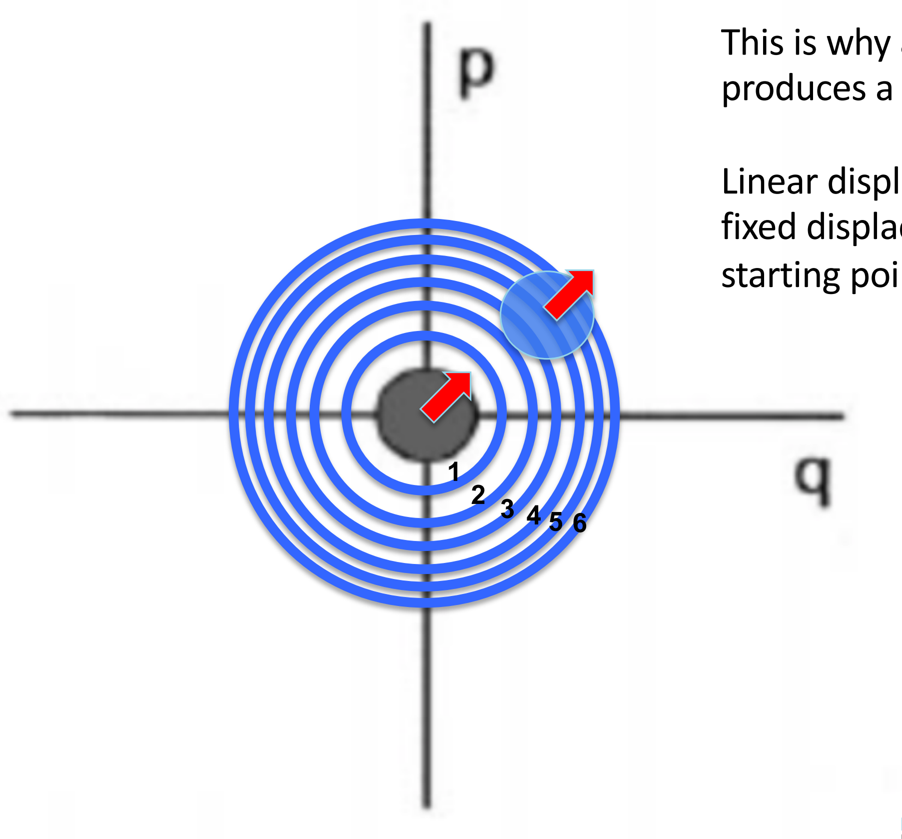
Fock state expressed in coherent state basis

$$|N\rangle = \frac{1}{2\pi\sqrt{P_m(N)}} \int_0^{2\pi} d\phi \; e^{-iN\phi} \left|\sqrt{m} e^{i\phi}\right\rangle$$

$$P_m(N) = e^{-m} m^N / N!$$

Annuli corresponding to integer occupation number become more closely spaced for larger n

$$\langle n \rangle = \langle \hat{a}^{\dagger} \hat{a} \rangle = |\alpha|^2$$



This is why a coherent state (a displaced Gaussian blob) produces a Poisson distribution.

Linear displacement already encodes the fact that for a fixed displacement D(α), more annuli are traversed if the starting point is already at finite radius β

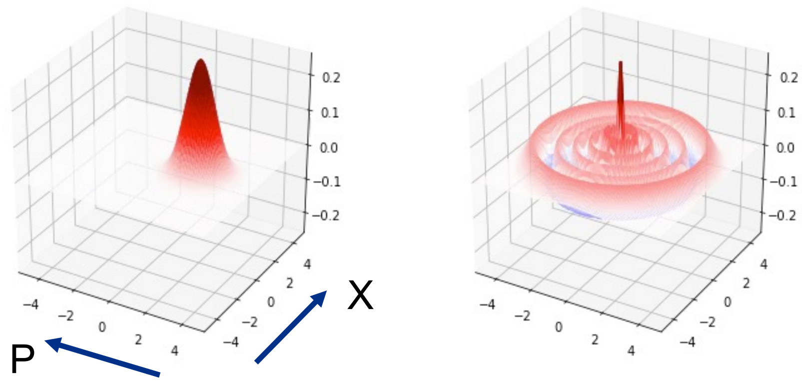
Power = Force x velocity is also already encoded in the operator normalizations:

$$a\,|n\rangle = \sqrt{n}\,|n-1\rangle$$

$$a^{\dagger}\,|n\rangle = \sqrt{n+1}\,|n+1\rangle.$$

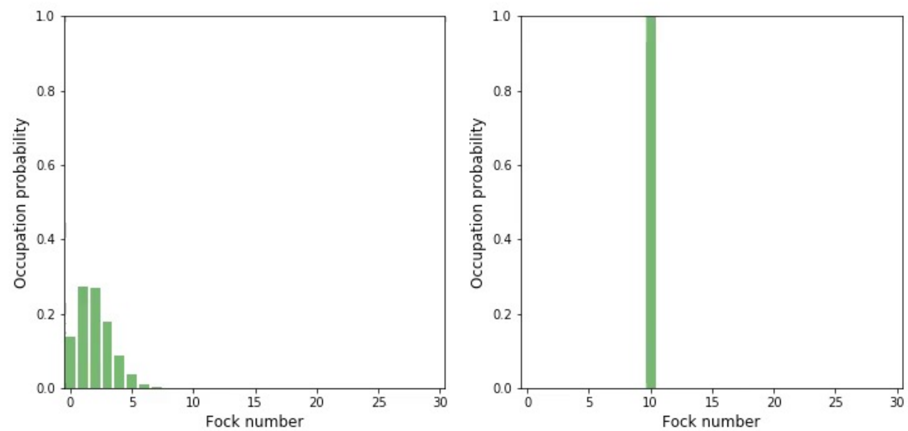
where velocity is proportional to wave amplitude

The dark matter wave is a sine wave described by a Glauber coherent state



The cavity photon mode has been prepared as a N=10 Fock state, highly sensitive to environmental disturbances

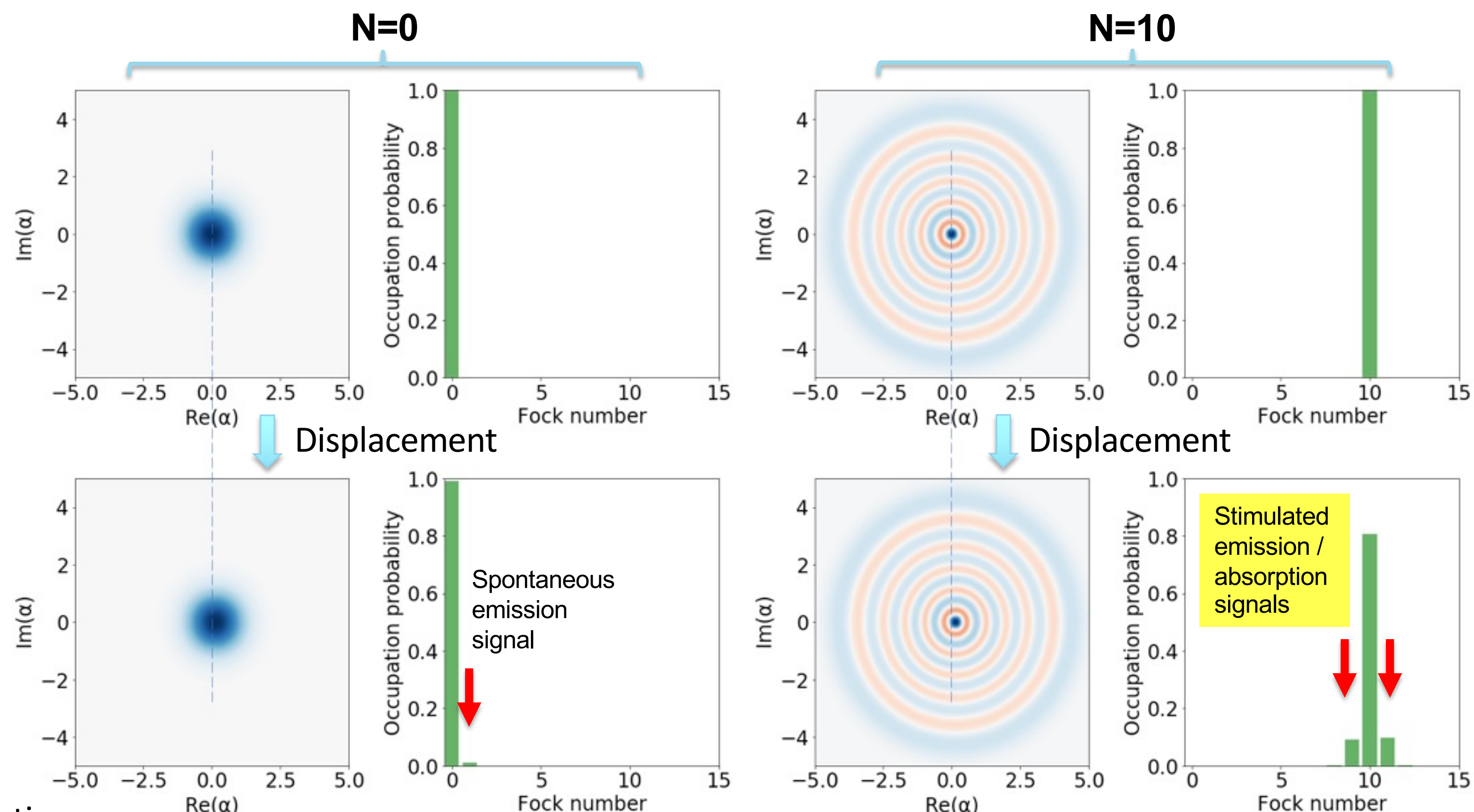
QuTiP simulation



The two oscillators swap states! This can be understood by decomposing the Fock state into a linear superposition of coherent states (which form an overcomplete basis for the phase space).

For small amplitudes α, the transfer of quanta from DM to photons is enhanced by a factor (n+1)

$$D(\alpha)\,|n\rangle \approx (1 + \alpha a^\dagger + \alpha^* a)\,|n\rangle = |n\rangle + \alpha\sqrt{n+1}\,|n+1\rangle + \alpha^*\sqrt{n}\,|n-1\rangle$$



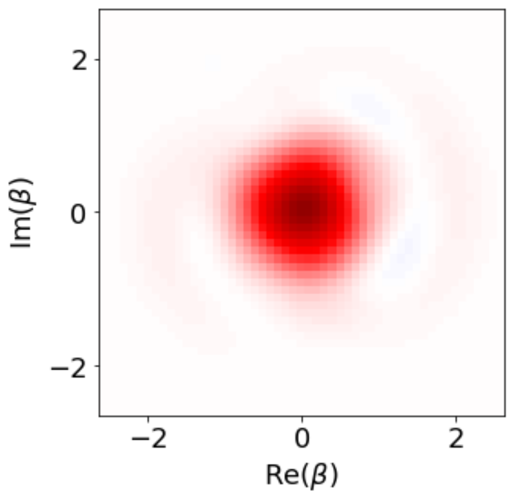
QuTiP simulation

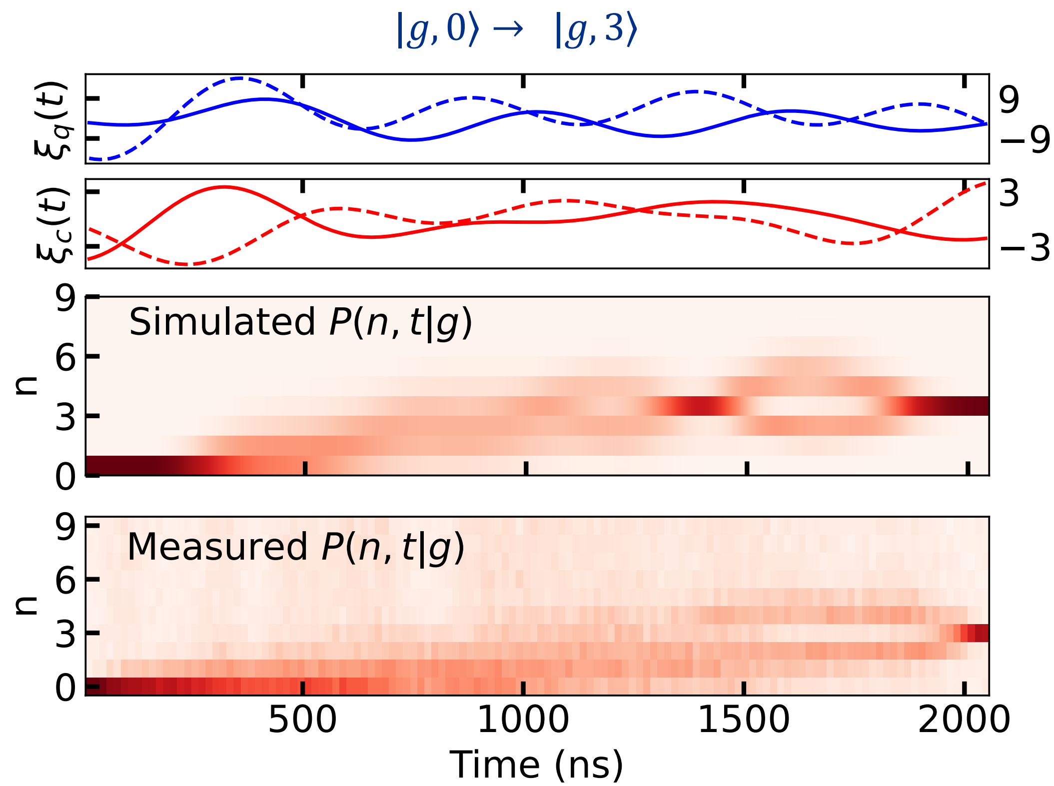
$$\left|\langle n+1|\hat{D}(\alpha)|n\rangle\right|^2 \sim \alpha^2(n+1)$$

Creating Fock states in a (non)linear system

"Optimal control" sequence of drives at both the qubit and cavity frequencies, determined by "gradient ascent pulse engineering"

$$\hat{\mathcal{H}} = \left(\omega_c + \chi\frac{\sigma_z}{2}\right)a^\dagger a + \omega_q\frac{\sigma_z}{2}$$

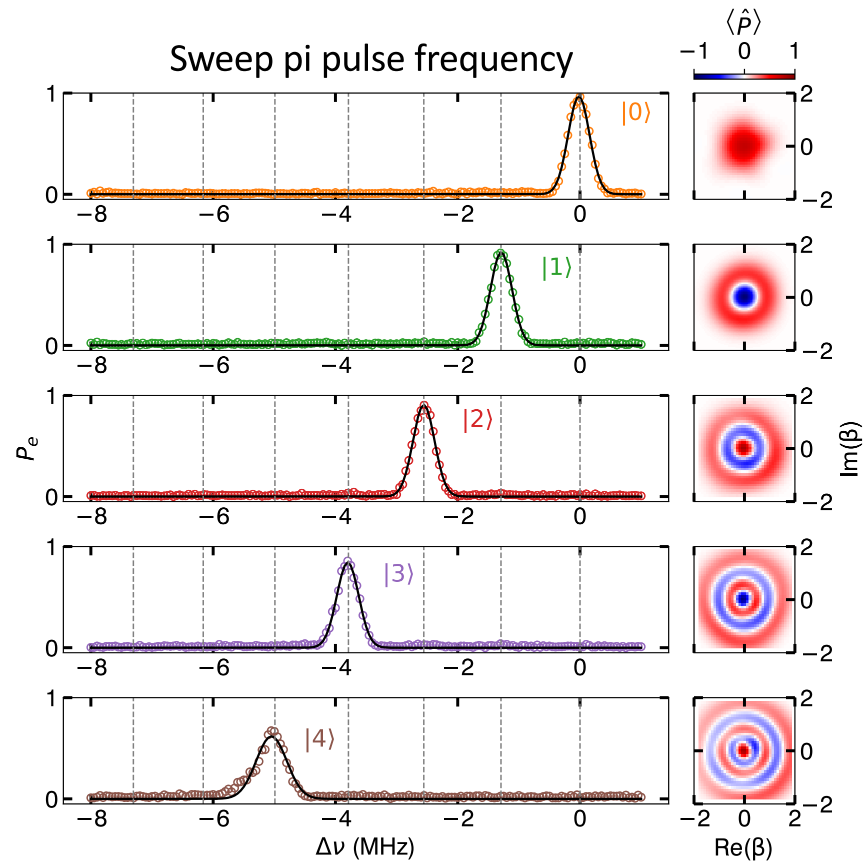




Verifying the state preparation

Method 1: Qubit spectroscopy with a number resolved π pulse

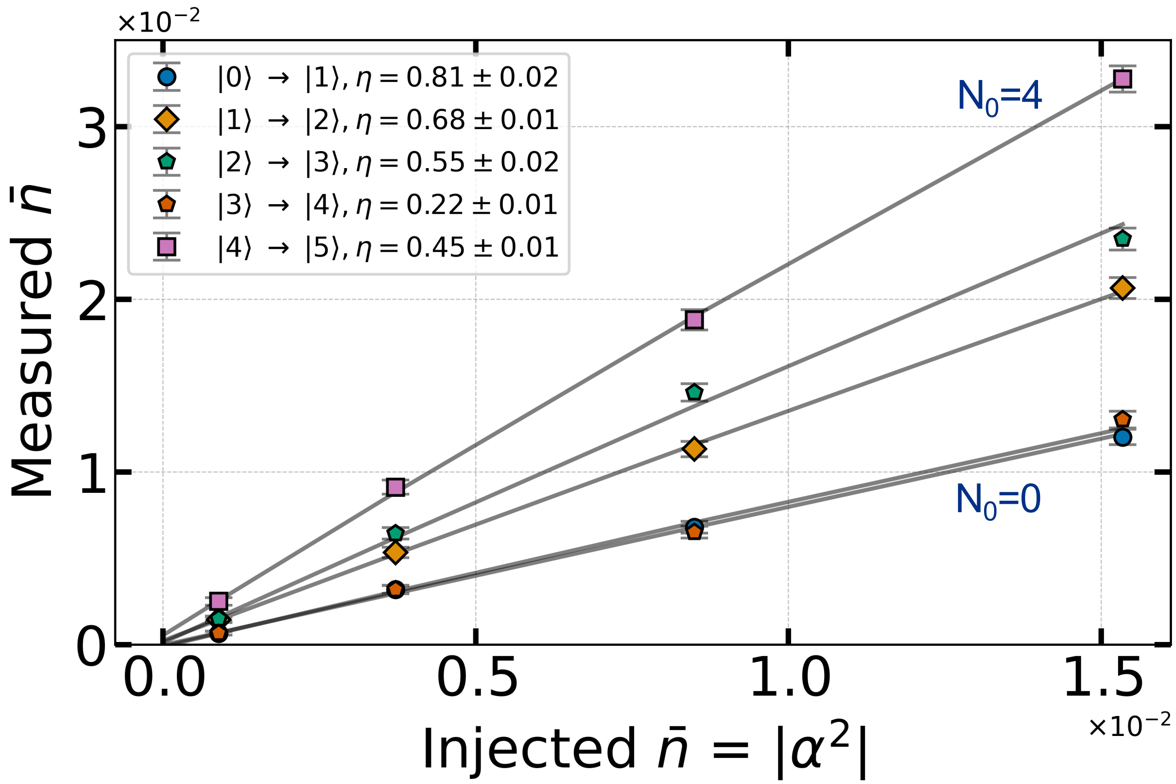
Method 2: Wigner tomography to reconstruct the density matrix



Slide/data from Ankur Agrawal

At fixed drive strength, stimulated emission creates a larger response

Count fraction of events with final state $|N+1\rangle$ to determine enhanced photon delivery rate



Observed
Rate ×3
for same drive
strength !!!

Ankur Agrawal
PhD 2022

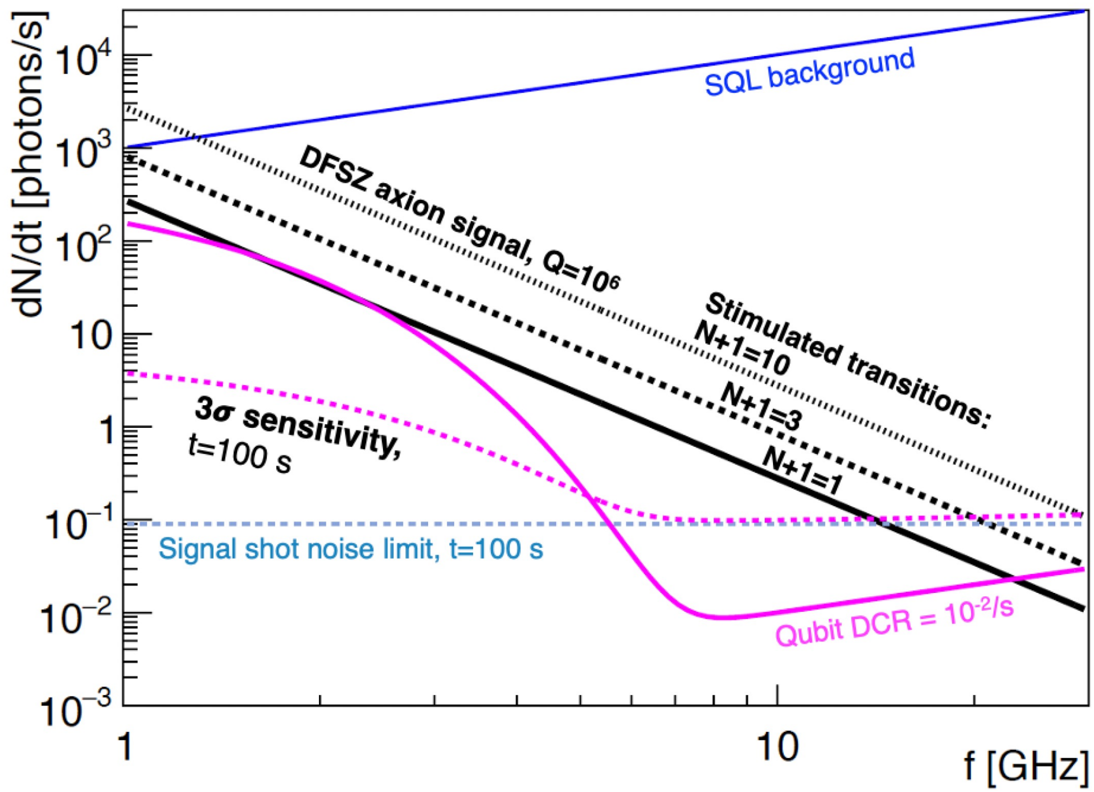
Enhancement less than a factor of (N+1) due to measurement inefficiencies.

Dark matter scan rate df/dt ∝ (N+1)
→ Factor of 3 improvement

Ankur Agrawal et al., PRL 132, 140801 (2024)

Using Q=10^7 cavities (SC or sapphire), stimulated emission could boost axion signal by factors up to N+1=10. Trades Q=10^7 → Q/N=10^6

Time is sped up for all processes including losses. Quantum resource = long (excess) coherence times.

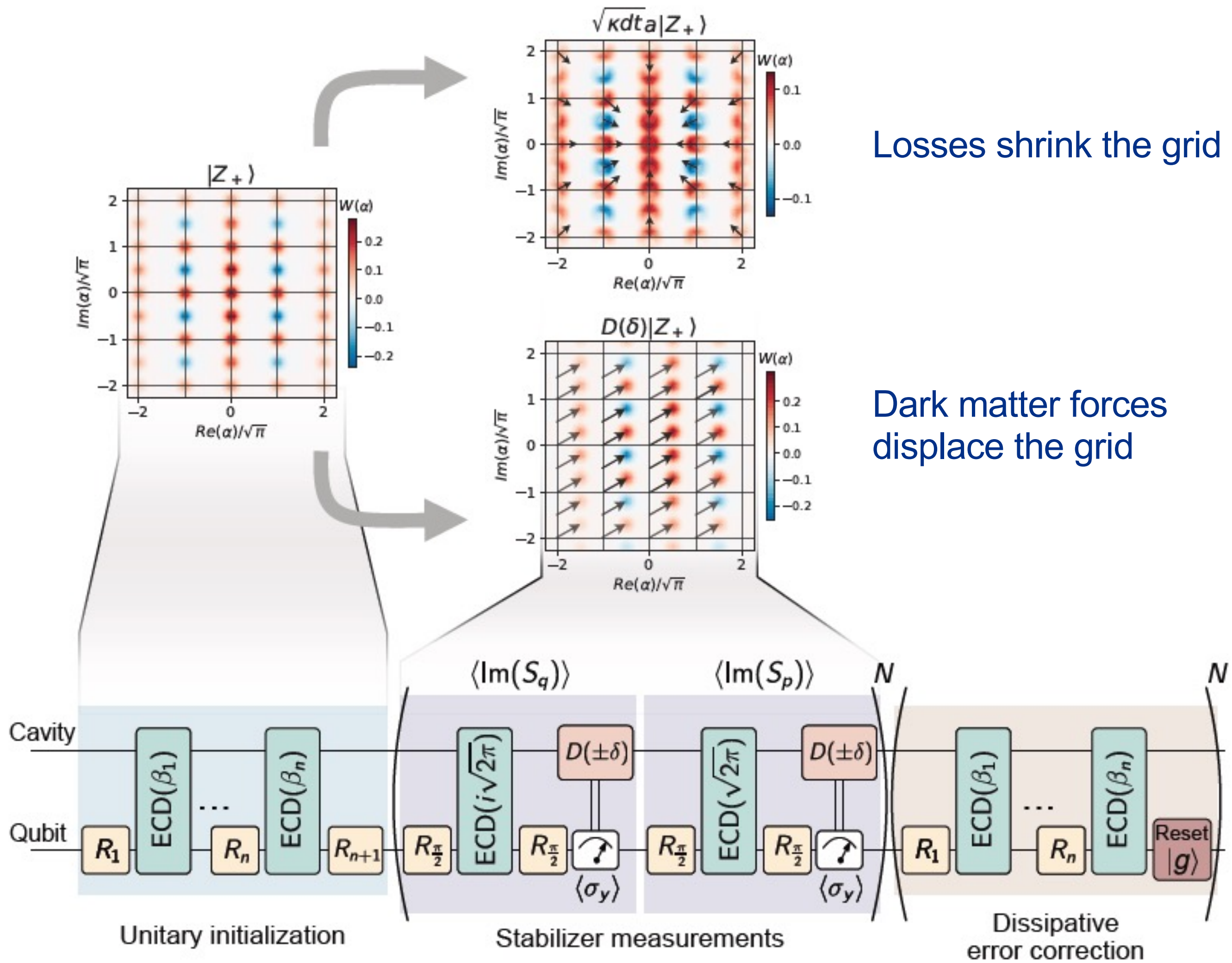


Higher signal rate increases sensitivity range to higher masses!

Enhance SNR with Gottesman-Kitaev-Preskill grid states

(recently used for break-even quantum error correction)

Numerical simulations indicate that for unknown reasons, these are better than Fock states and squeezed states for extracting quantum Fisher information.
J. Gardner et al., 2404.13867



Losses shrink the grid

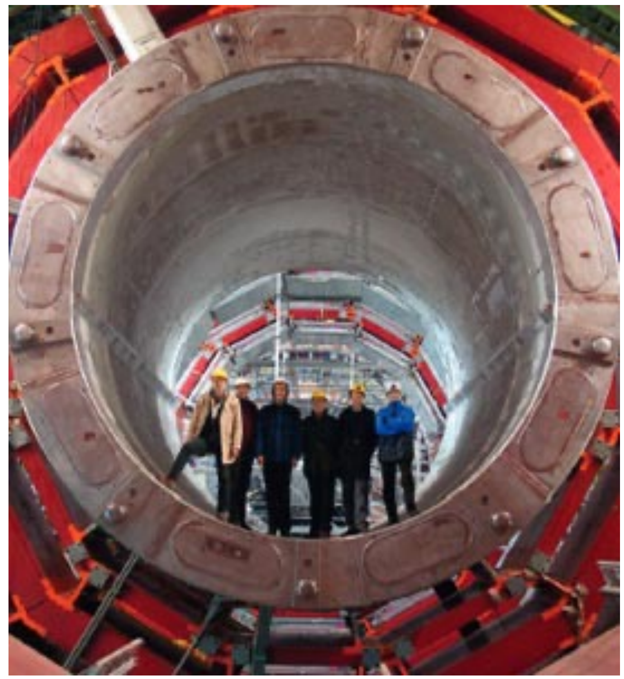
Dark matter forces displace the grid

figure from Andrei Vrajitorea (NYU)

Quantum sensors/tricks can do a great deal to improve SNR, but ultimately, we also have to bring the hammer – larger magnets!

ADMX EFR magnet now at Fermilab, 4th largest research MRI magnet ever built

~ USD$15M



CMS magnet
~USD$250M