Detection of Ultraweak Forces from DM using Stimulated Emission
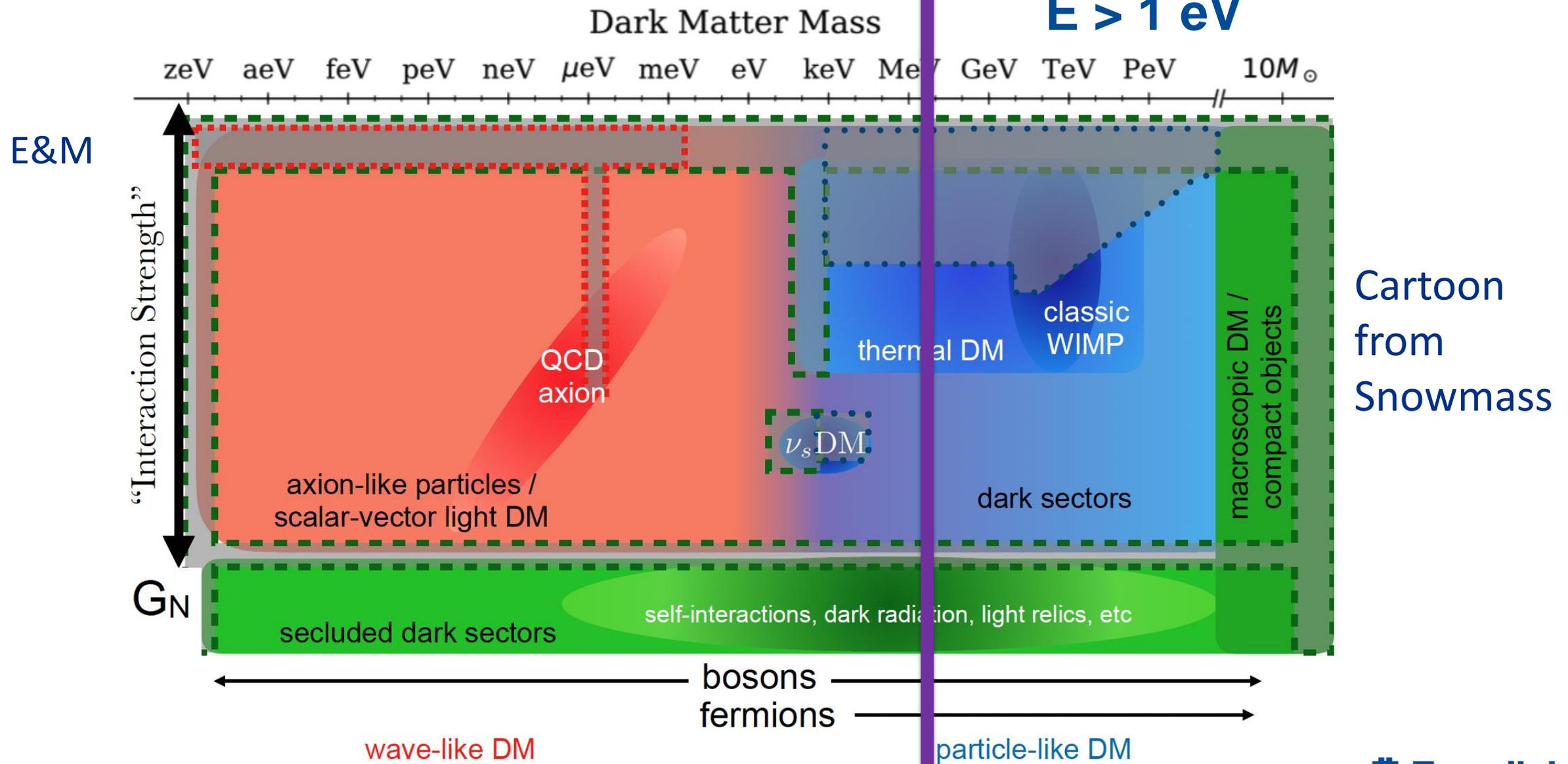
Aaron S. Chou

Fermilab
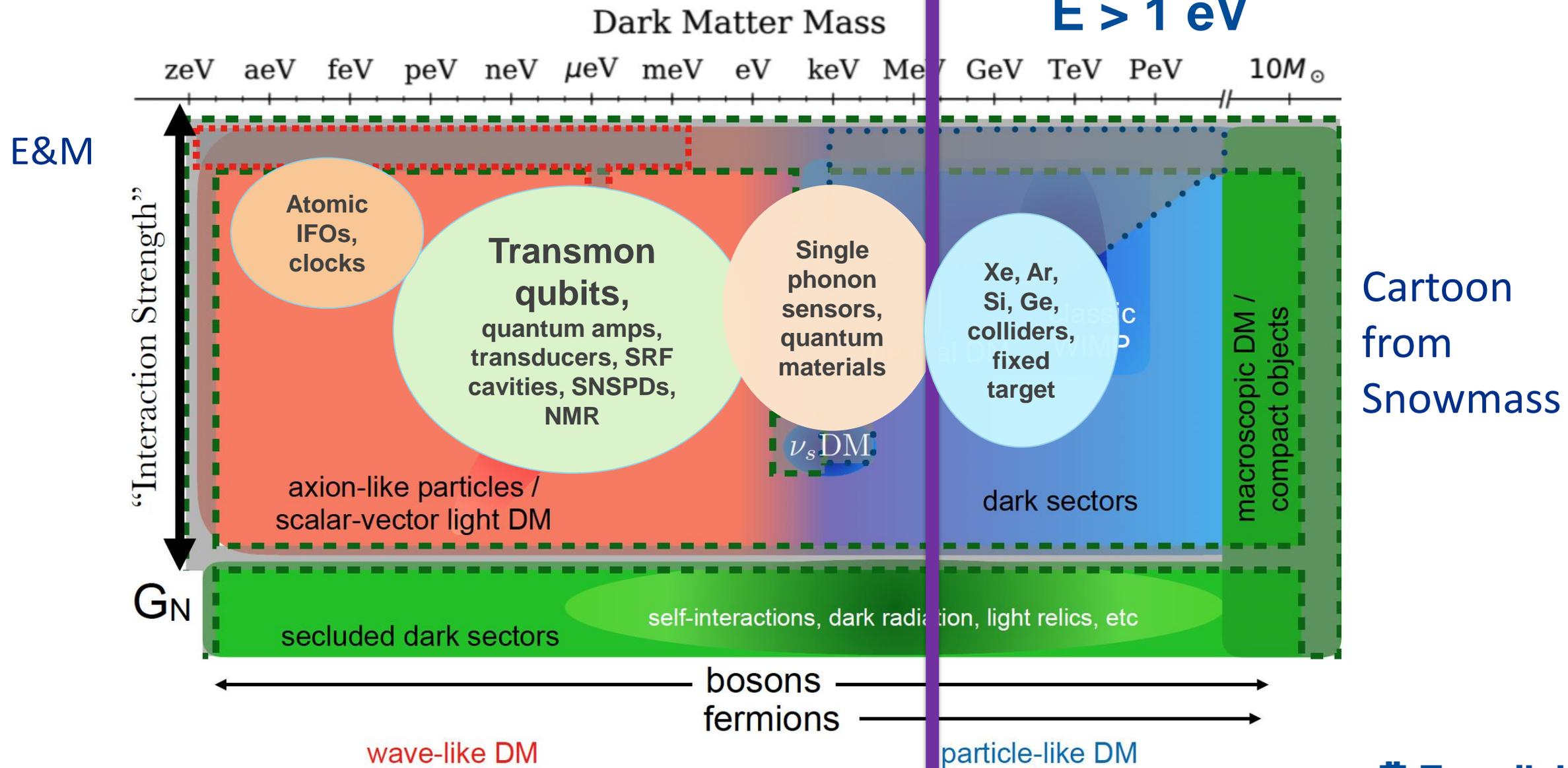
April 6, 2023

Quantum sensors: E < 1 eV ⟵ ⟶ Conventional tech: E > 1 eV

Dark Matter Mass

zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 10$M_\odot$

E&M

"Interaction Strength"

QCD axion

axion-like particles / scalar-vector light DM

thermal DM

classic WIMP

ν_sDM

dark sectors

macroscopic DM / compact objects

Cartoon from Snowmass

G_N

self-interactions, dark radiation, light relics, etc

secluded dark sectors

bosons
fermions

wave-like DM

particle-like DM

🐝 Fermilab

Quantum sensors: E < 1 eV ⬅️ ➡️ Conventional tech: E > 1 eV

Dark Matter Mass

zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 10M⊙

E&M

"Interaction Strength"

Atomic IFOs, clocks

Transmon qubits, quantum amps, transducers, SRF cavities, SNSPDs, NMR

Single phonon sensors, quantum materials

Xe, Ar, Si, Ge, colliders, fixed target

macroscopic DM / compact objects

Cartoon from Snowmass

axion-like particles / scalar-vector light DM

ν_s DM

dark sectors

G_N

secluded dark sectors

self-interactions, dark radiation, light relics, etc

bosons
fermions

wave-like DM

particle-like DM

🟰 Fermilab

Hybrid Town Hall on Quantum Sensors for HEP

April 27 afternoon

Abstract submission is open for 2-slide presentations on new ideas,

i.e. not previously discussed at Snowmass or other past community meetings, and not already fundable by some existing program

https://indico.fnal.gov/event/59102/

Quantum Sensors for HEP

Apr 27 – 29, 2023
Yale University
US/Eastern timezone

Enter your search term 🔍

Overview
Call for Abstracts
Timetable
Book of Abstracts
Registration
Participant List

The goal of this workshop is to explore the most promising directions for applying quantum sensing technologies to DOE-OHEP science targets, with a focus on sensors that could be deployed in future DOE-funded experiments. While we will provide an overview of existing DOE-OHEP quantum sensing programs for context, the workshop's main emphasis will be on novel ideas that can form the foundation of new DOE-OHEP quantum sensing programs or possibly to significantly enhance current programs. The goal is to pinpoint areas where DOE-OHEP can have a unique impact, leveraging its people, technological capabilities, and facilities. We are particularly interested in identifying new research directions not currently covered by existing funding sources and which could benefit the DOE-OHEP mission.

The in-person workshop is open to invited participants and we will have a hybrid town hall to capture ideas from the broader community. Travel and other local information can be found on the event page here: https://campuspress.yale.edu/quantisedhep23/.

🕐 **Starts** Apr 27, 2023, 9:00 AM
Ends Apr 29, 2023, 1:00 PM
US/Eastern

📍 Yale University
Yale Quantum Institute / Wright Laboratory
17 Hillhouse Ave., 4th floor
New Haven, CT 06511
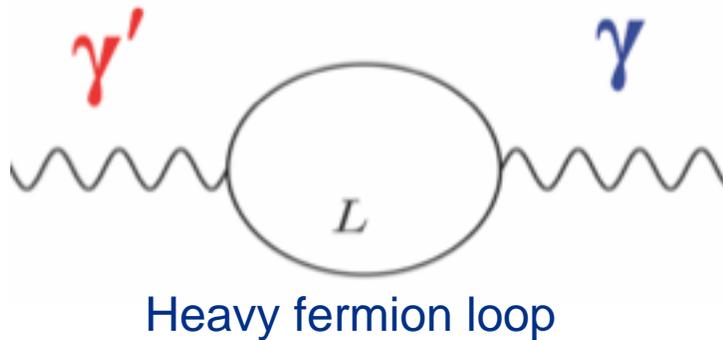Go to map

👤 Aaron Chou
Kathryn Zurek
Kent Irwin
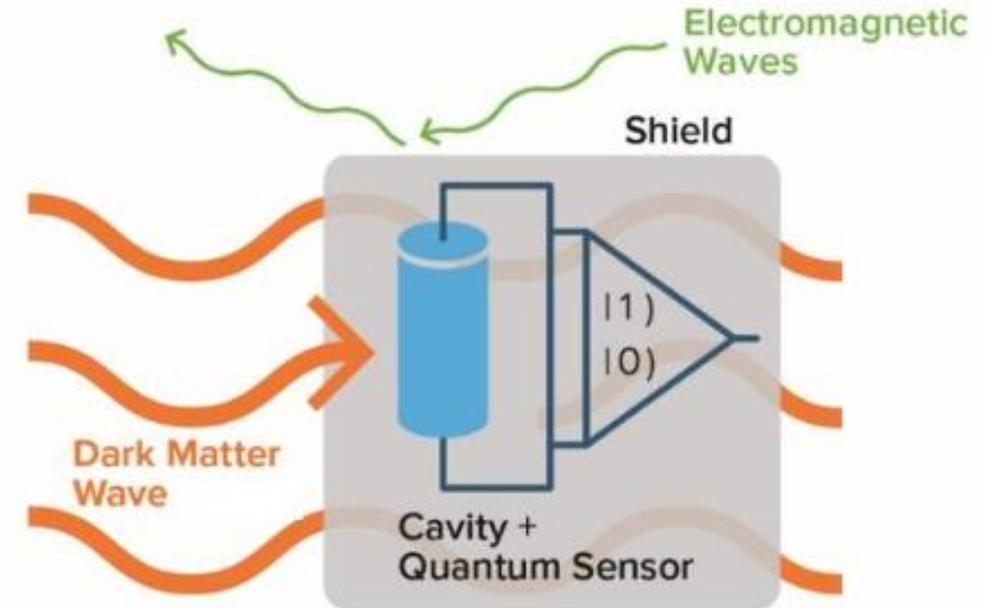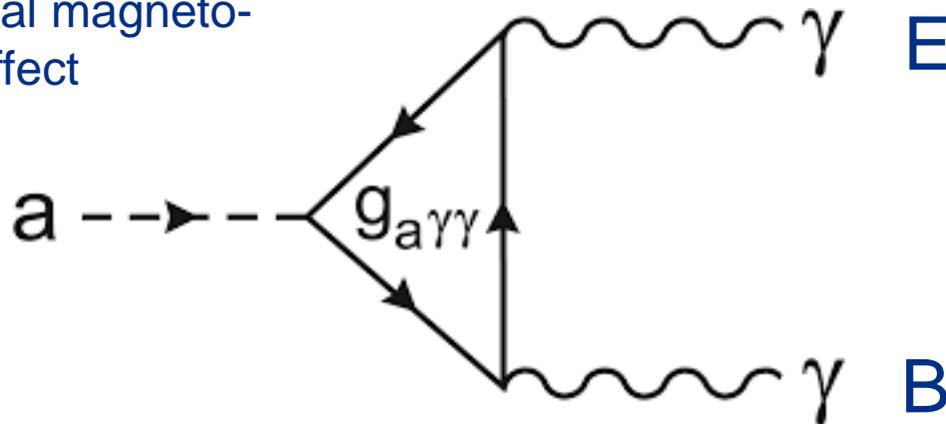Reina Maruyama

📎 There are no materials yet.   ✎

🔷 **Fermilab**

Bosonic DM waves: dark photons, spin-0 particles like the QCD axion

Flavor mixing

γ' γ

Heavy fermion loop

Topological magneto-electric effect

a ---►--- $g_{a\gamma\gamma}$ γ E

γ B

Electromagnetic Waves

Shield

$|1\rangle$

$|0\rangle$

Dark Matter Wave

Cavity + Quantum Sensor

Forces from classical dark matter waves can deliver energy/momentum in the form of single photons that mysteriously appear in your well-shielded apparatus.

🐾 Fermilab

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 and one only gets the transfer of an occasional single quantum of energy.

Sine waves are described by phasors

$y(t)$
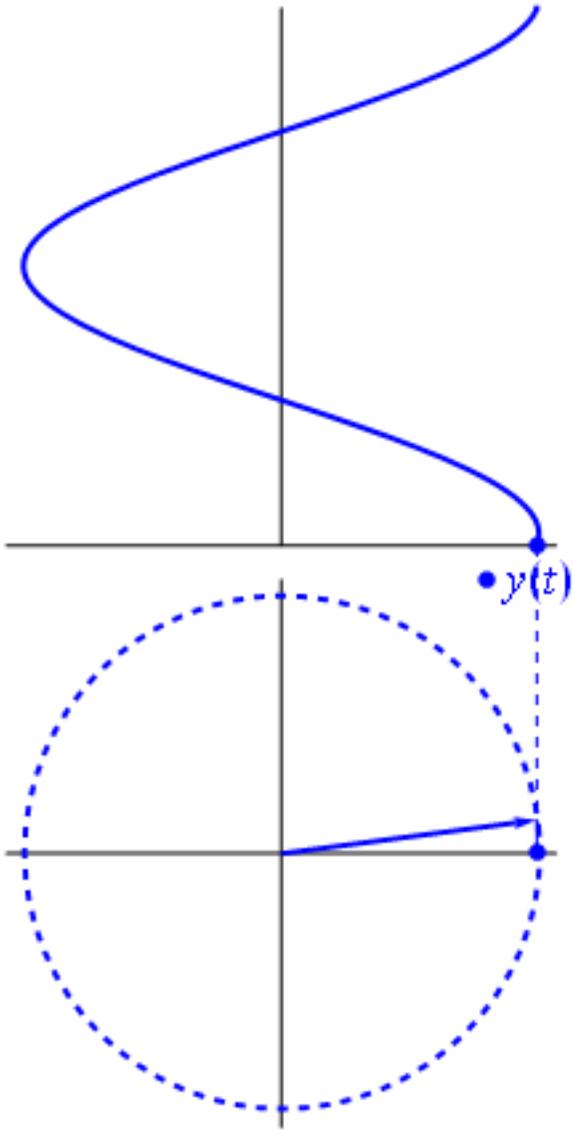
Quantum mechanics:
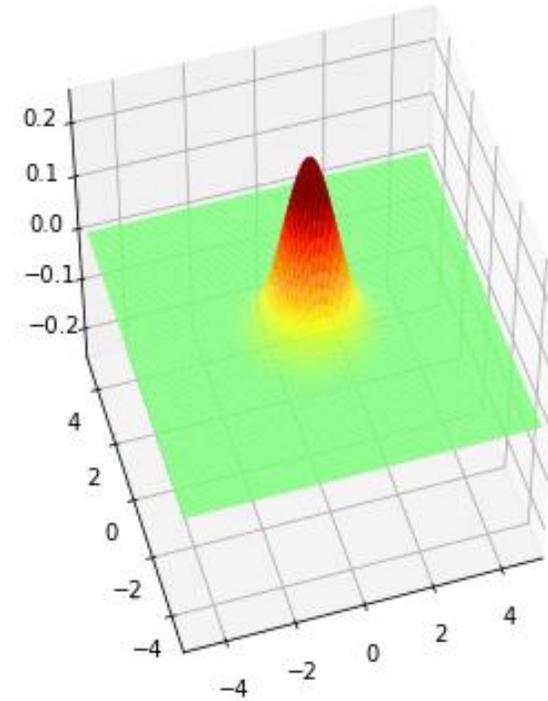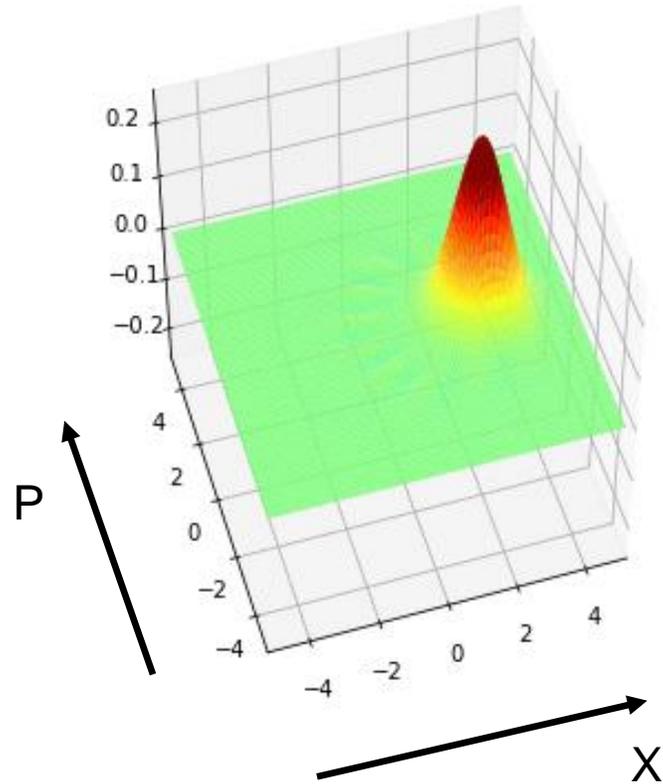Endpoint of phasor in X, P phase space has uncertainty principle

$$\Delta X \times \Delta P \geq \tfrac{1}{2}.$$

In polar coordinates this becomes:

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

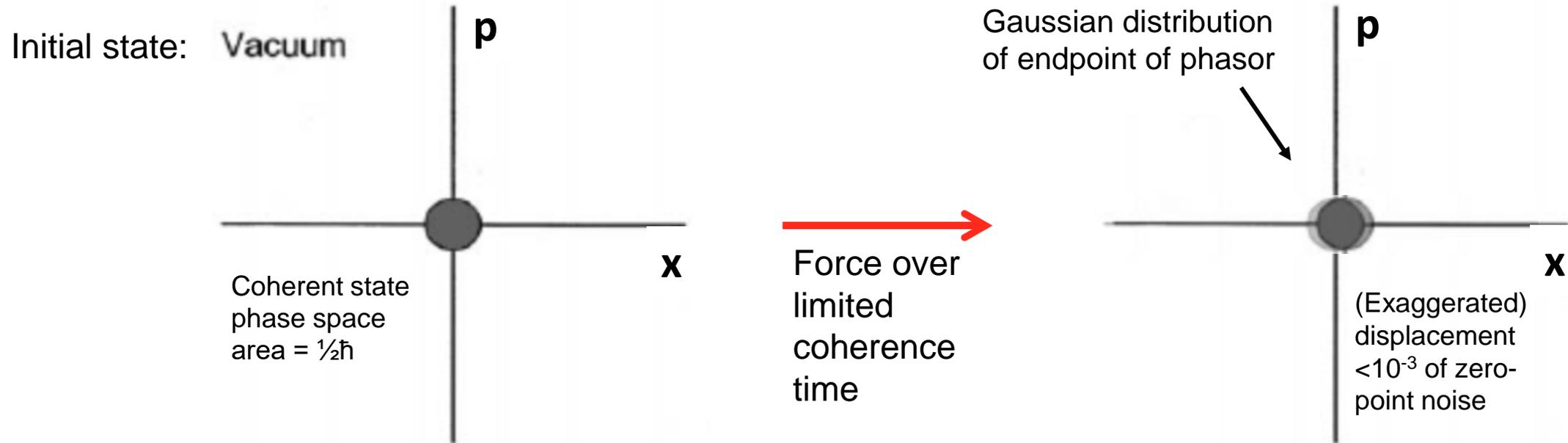# Classical pendulum system: $|\alpha = 3\rangle \otimes |\alpha = 0\rangle$

Time evolution of Wigner distributions in X-P "phasor" space.
Each gaussian blob of phase space area satisfies $\Delta X \cdot \Delta P = \frac{1}{2}$

P

X

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

Big Problem: Signal/Noise Ratio

Initial state: Vacuum

p

x

Coherent state
phase space
area = ½ℏ

Force over
limited
coherence
time

Gaussian distribution
of endpoint of phasor

p

x

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

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 $\Delta N \times \Delta \varphi \geq \frac{1}{2}$.

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

To reduce readout noise, use photon counting to project displacements into the Fock basis, i.e. number eigenstates

Previously we measured *both amplitude and phase*, but this is dumb since the dark matter phase is random and not interesting. Useless information obtained at high cost!

Blue rings give the probe resolution
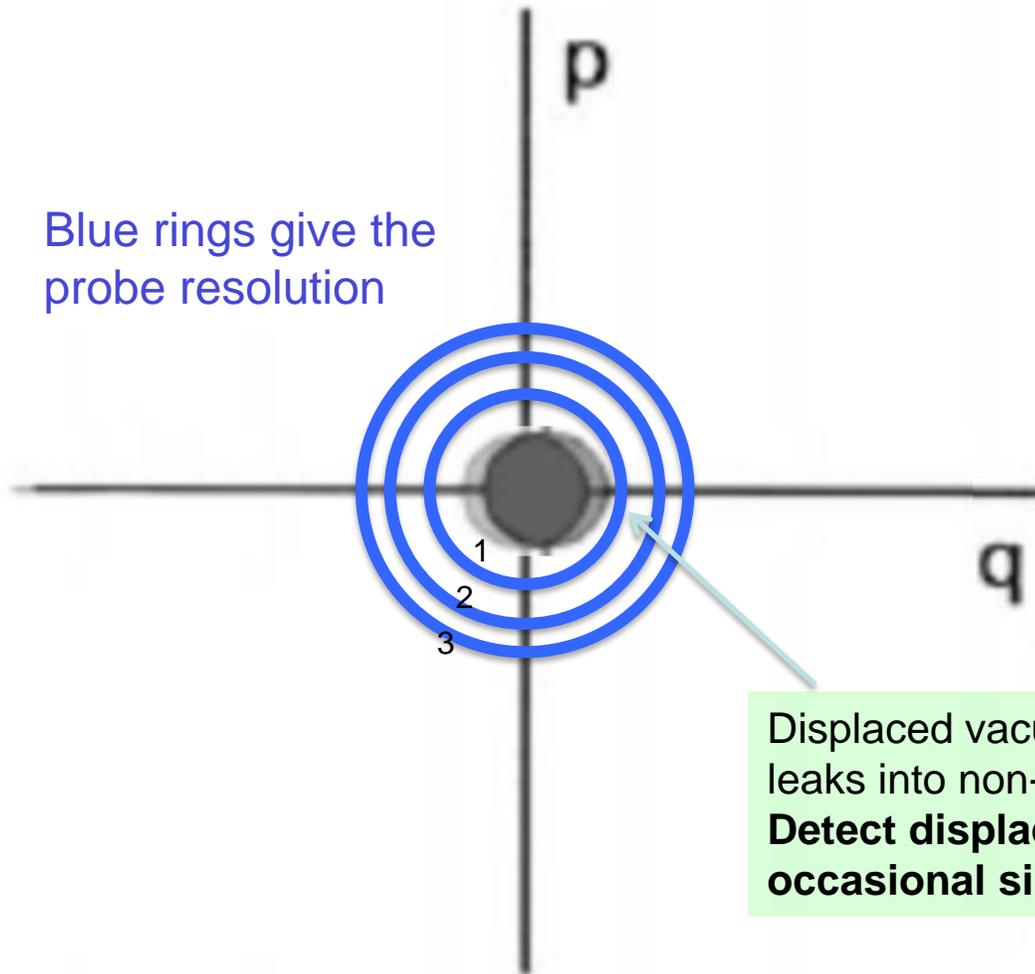
Instead, measure only displacement amplitude
→ no zero-point noise since we are not simultaneously measuring non-commuting observables
→ **Measurement noise, e.g. from dark counts can be arbitrarily low**

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

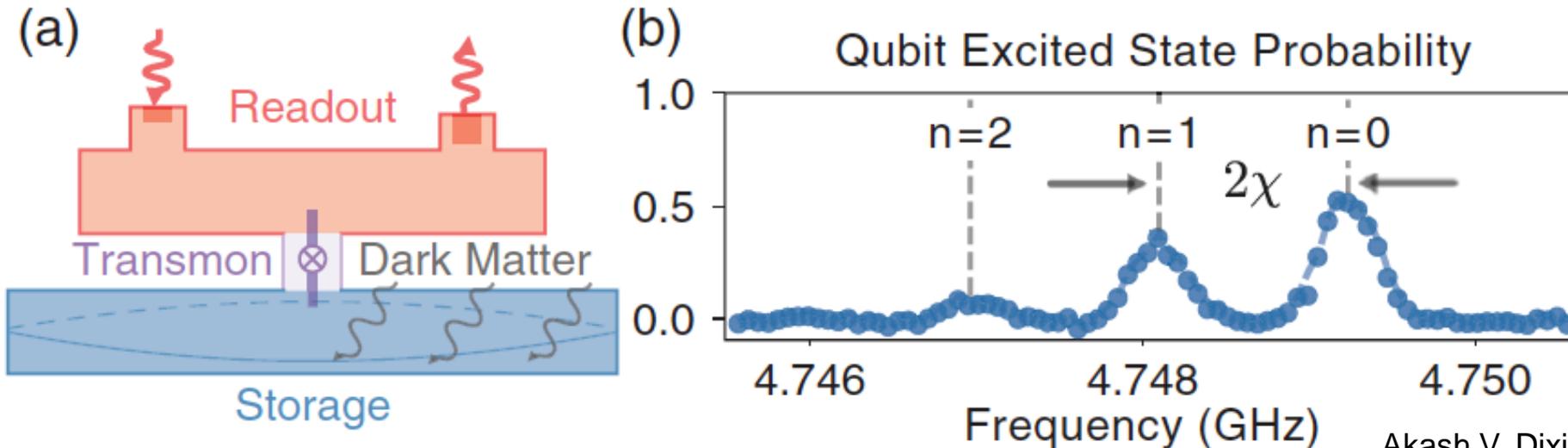# Transmon qubit in 6 GHz aluminum cavity
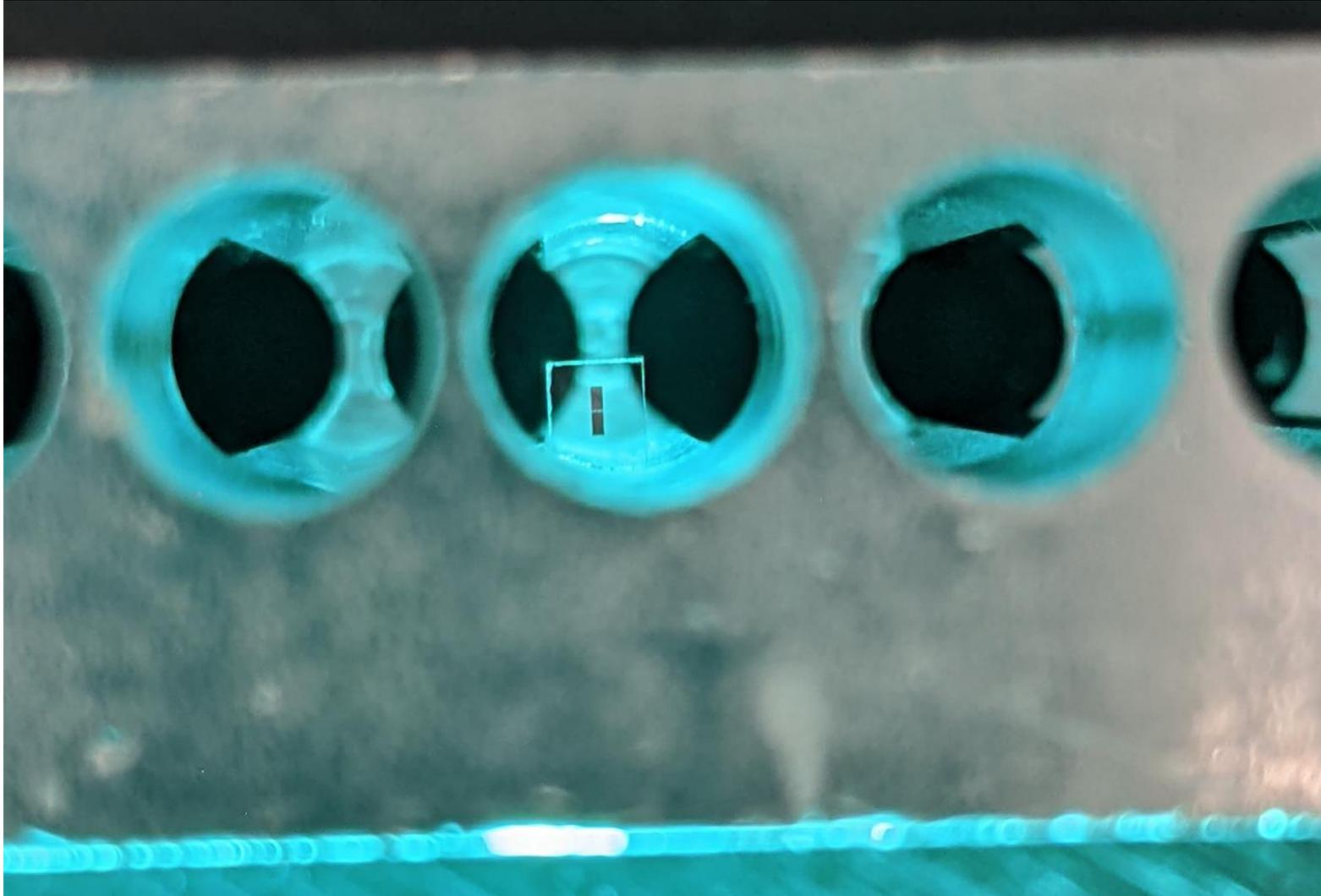
Cavity = quantum RAM

Qubit = nonlinear LC oscillator

Dark matter waves scatter on walls of cavity, depositing occasional single photons whose electric field drives the qubit nonlinear. → Measure AC Stark shift of the qubit's frequency.

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

Example: Measure qubit $|g\rangle \rightarrow |e\rangle$ transition frequencies after mimicking the DM signal by weakly driving the primary cavity mode into a coherent state with $\langle n\rangle = 1$

(a)

Readout

Transmon ⊗ Dark Matter

Storage

(b) Qubit Excited State Probability

n=2   n=1   n=0

2χ

Frequency (GHz)

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

The measured qubit response 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 via this "quantum non-demolition" measurement.
- Repeat many times for high fidelity single photon detection.
- **Demonstrated reduction in noise levels to 40x below the Standard Quantum Limit**

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.

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

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: $\Delta N \times \Delta \varphi \geq \frac{1}{2}$
→ **responds equally well to pushes at any time.**

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

… and force × velocity still works:

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

N=1 Fock state

Idea from Konrad Lehnert
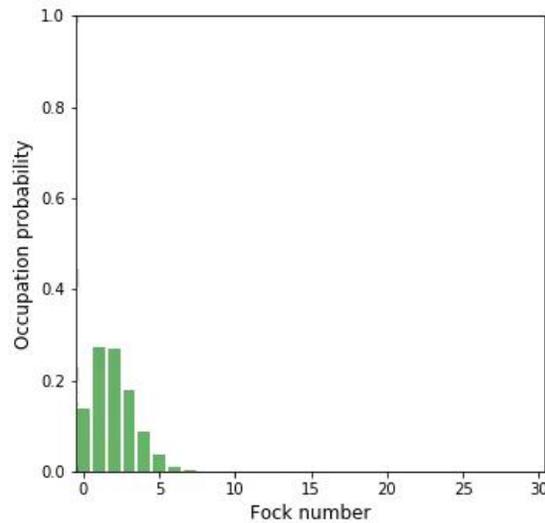(JILA/U.Colorado)
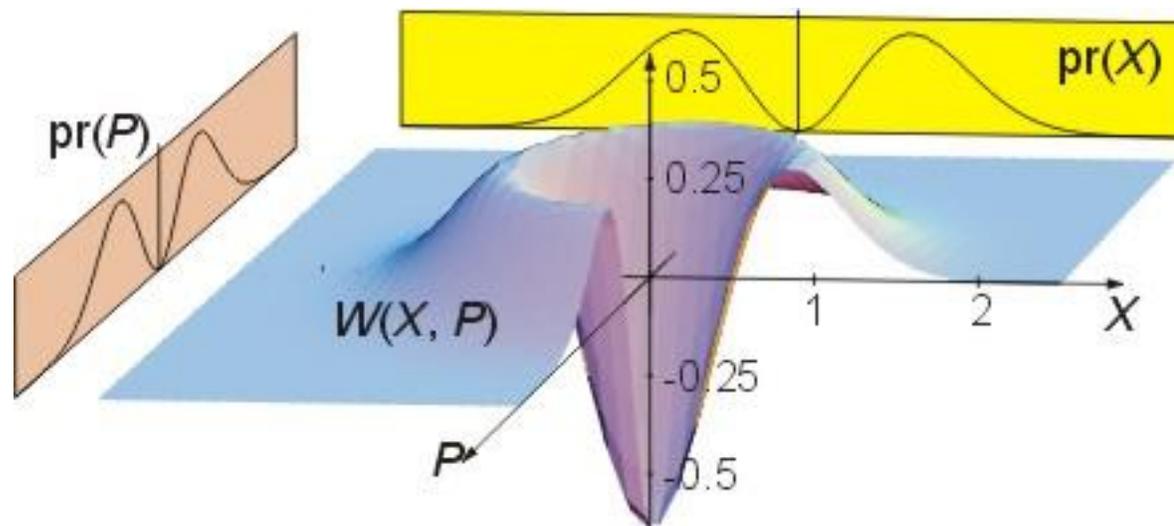
Mixing between a coherent state and a Fock state

The dark matter wave is a sine wave described by a Glauber coherent state
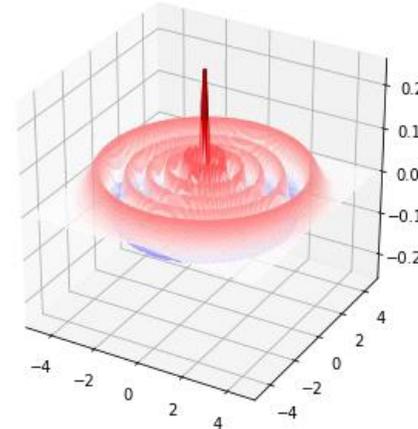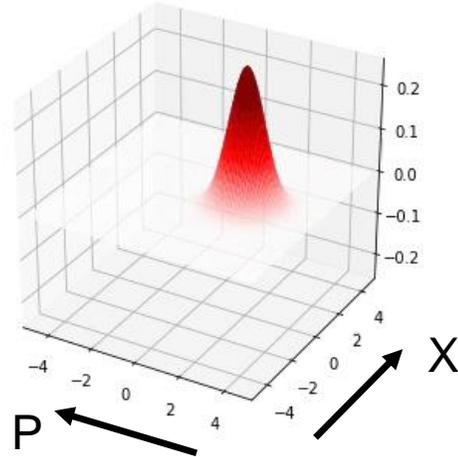
The cavity photon mode has been prepared as a N=10 Fock state, highly sensitive to environmental disturbances
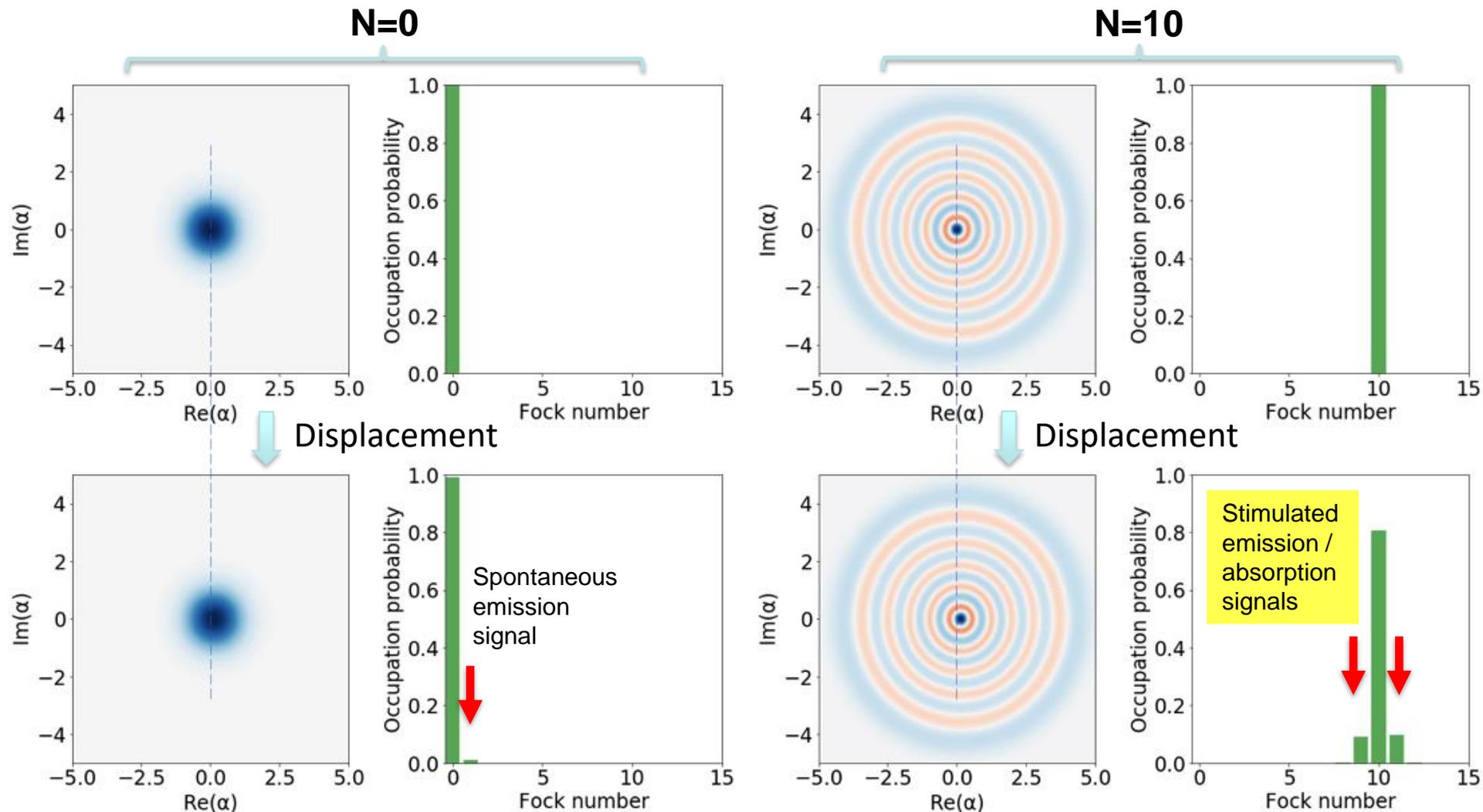
QuTiP simulation
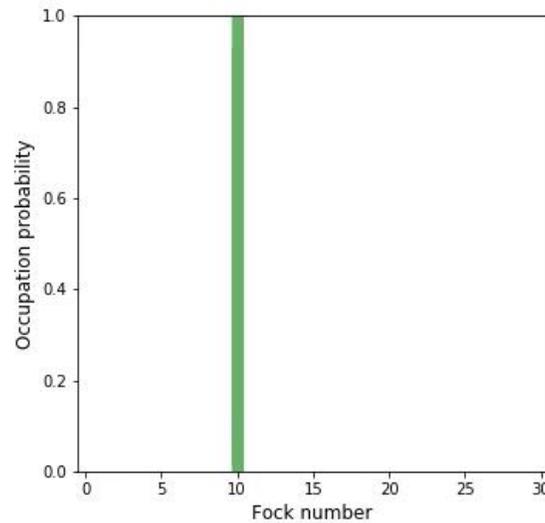
The two oscillators swap states! This can be understood by decomposing the Fock state into a linear superposition of coherent states (which form an overcomplete basis for the phase space).

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

$$D(\alpha)|n\rangle \approx (1 + \alpha a^\dagger + \alpha^* a)|n\rangle = |n\rangle + \alpha\sqrt{n+1}\,|n+1\rangle + \alpha^*\sqrt{n}\,|n-1\rangle$$
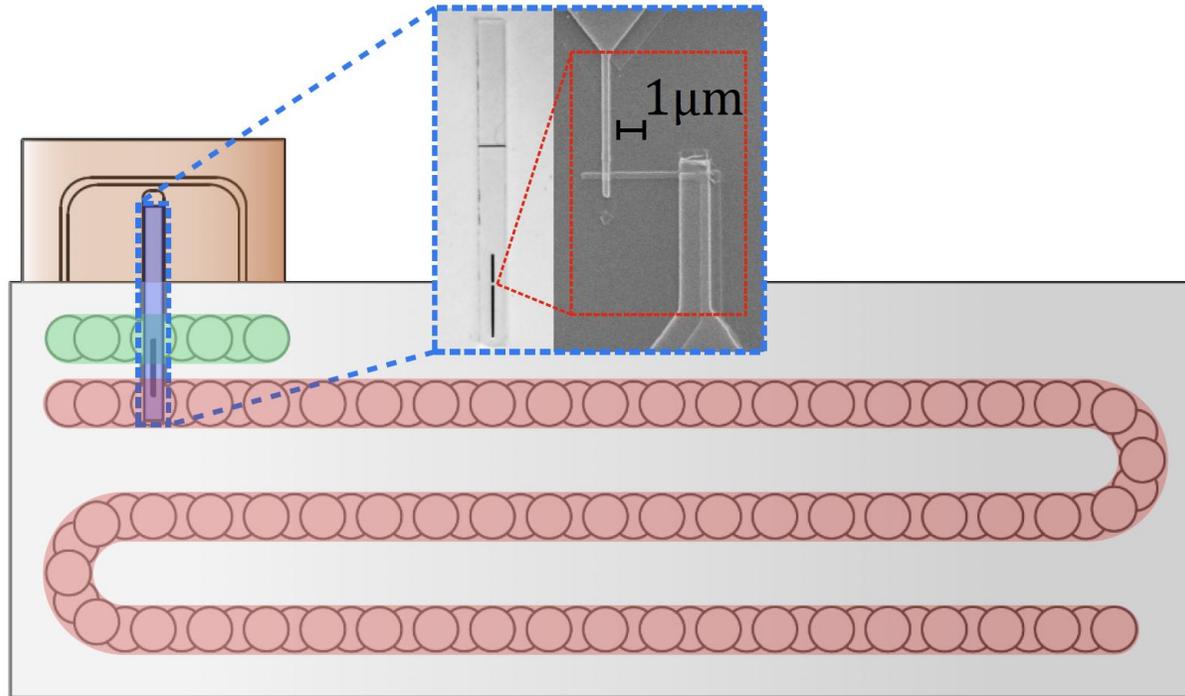
N=0 **N=10**

Displacement Displacement

Spontaneous emission signal

Stimulated emission / absorption signals

QuTiP simulation

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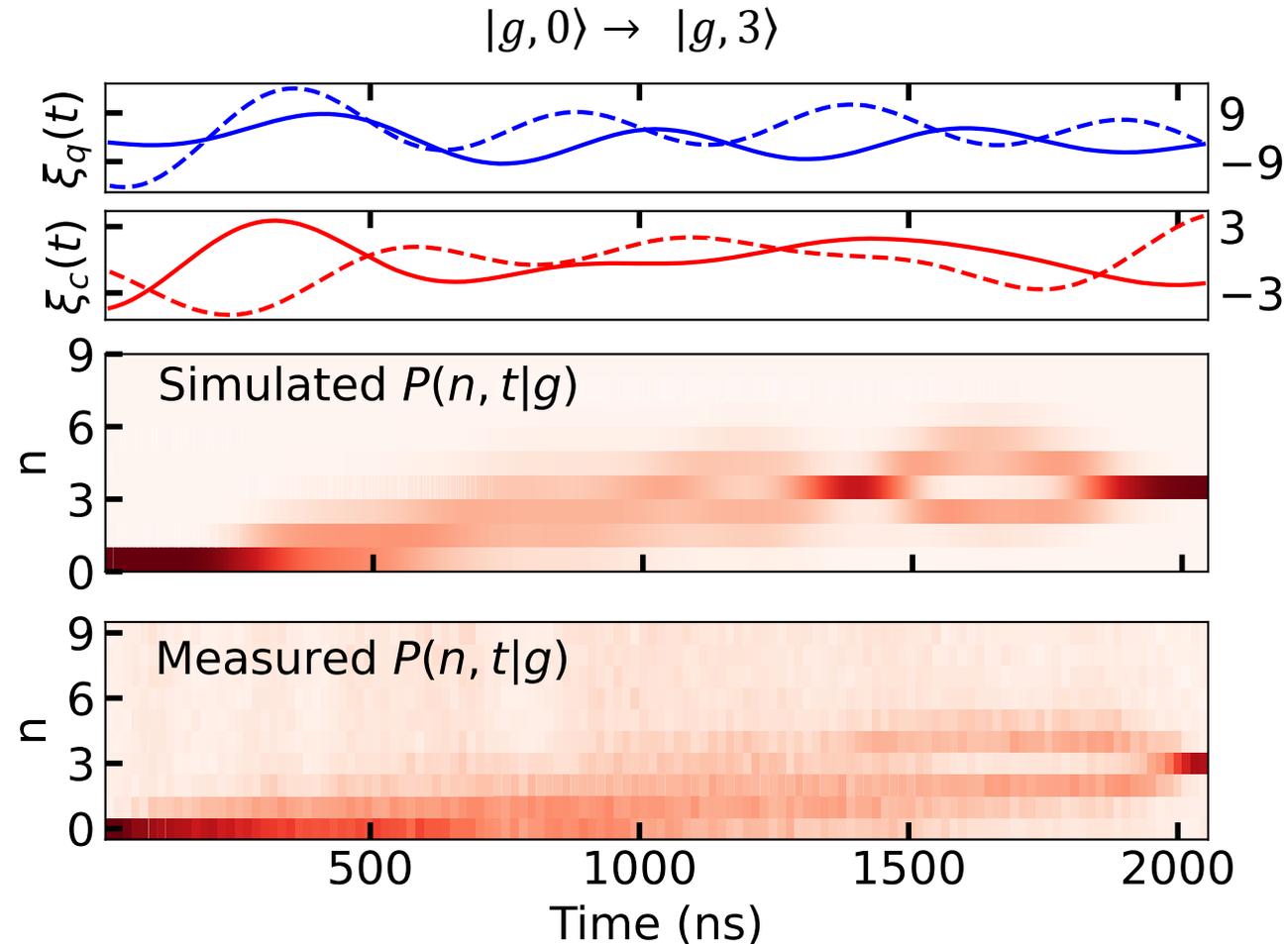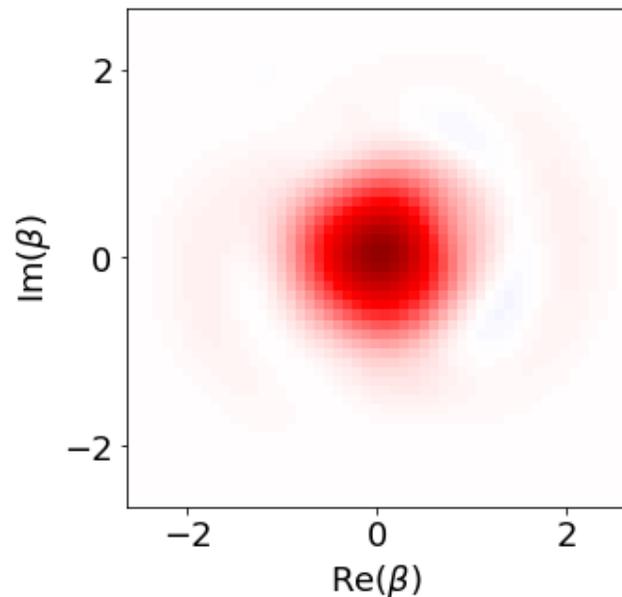
Qubit-cavity system

Storage   6.011 GHz

Readout   8.052 GHz

Transmon   4.749 GHz

$$\widehat{\mathcal{H}} = \omega_c \, a^\dagger a \; + \; \omega_q \frac{\sigma_z}{2} + \chi \, a^\dagger a \frac{\sigma_z}{2}$$

Aaron S. Chou, IQ/PACC axion workshop, 4/6/2023

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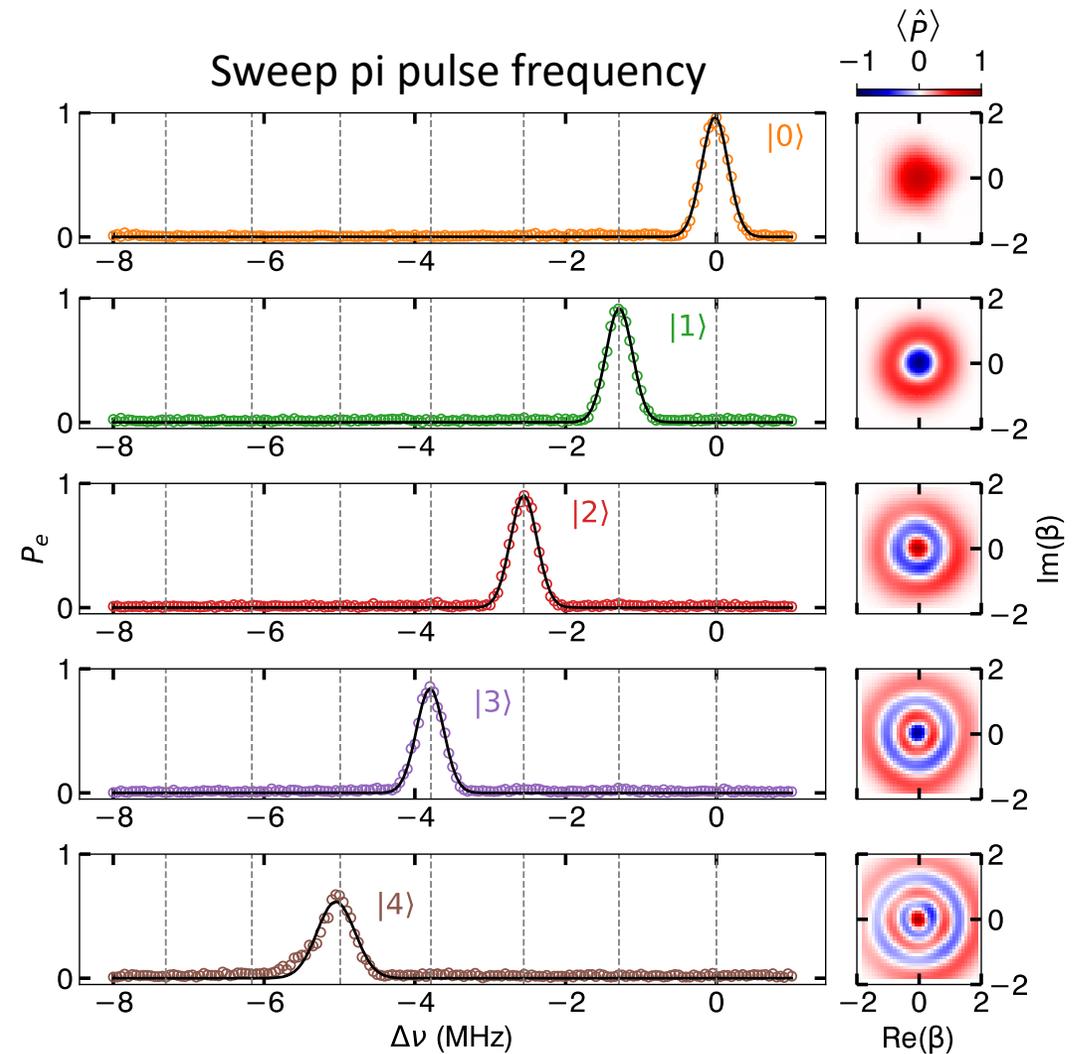
$$\hat{\mathcal{H}} = \left(\omega_c + \chi \frac{\sigma_z}{2}\right) a^\dagger a + \omega_q \frac{\sigma_z}{2}$$

$|g, 0\rangle \rightarrow |g, 3\rangle$

Slide/data from Ankur Agrawal

Verifying the state preparation

Method 1: Qubit spectroscopy with a number resolved π pulse

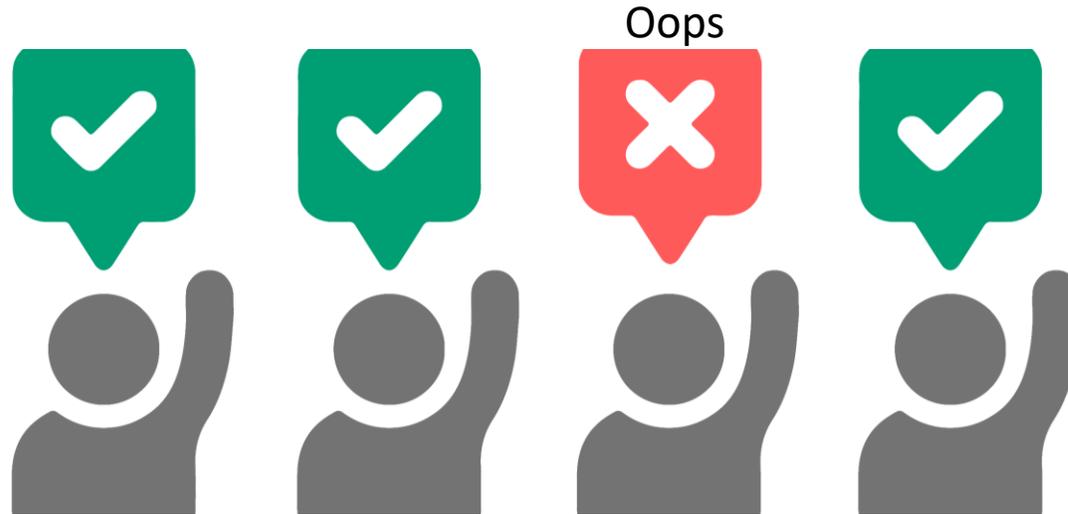Method 2: Wigner tomography to reconstruct the density matrix

Slide/data from Ankur Agrawal

Repeated measurements to mitigate errors

$$\widehat{\mathcal{H}} = \omega_c\, a^\dagger a \;+\; \omega_q \frac{\sigma_z}{2} + \chi\, a^\dagger a\, \frac{\sigma_z}{2}$$

1st pi pulse if successfully flips the qubit, collapses cavity wavefunction into definite $|n\rangle$
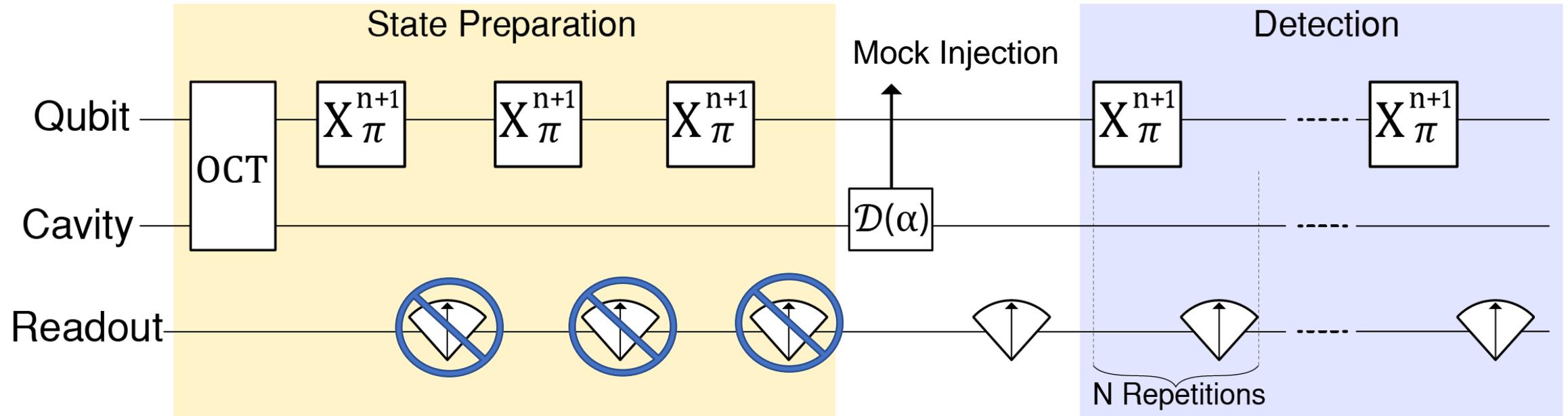
Subsequent pi pulses to measure n are **quantum non-demolition** since [H,n]=0

Oops

AV Dixit, AA et al.
PRL 126, 141302, 2021

Ask the qubit same question multiple times to boost the confidence and assign a probability for tagging the photon
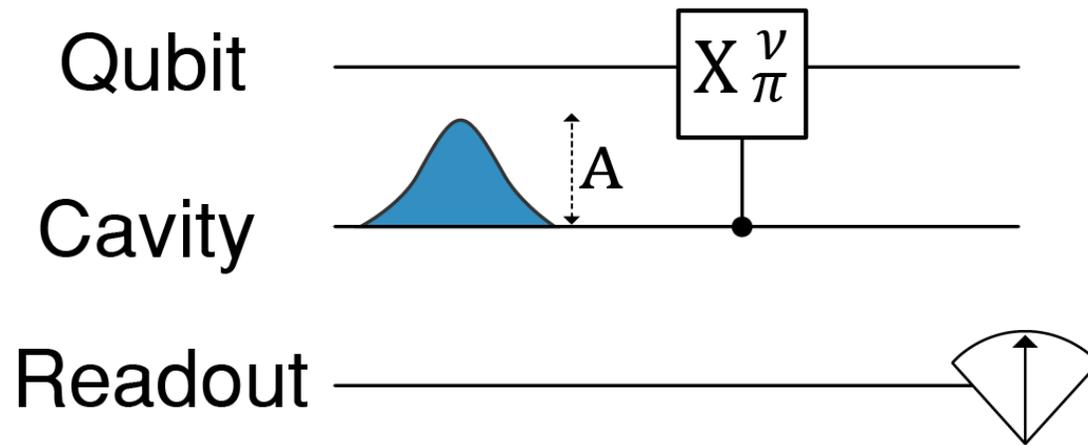
Stimulated emission protocol

Ensures false positive probability from accidentally prepping $|n+1\rangle$; < 3%, comparable to measured cavity occupation probability
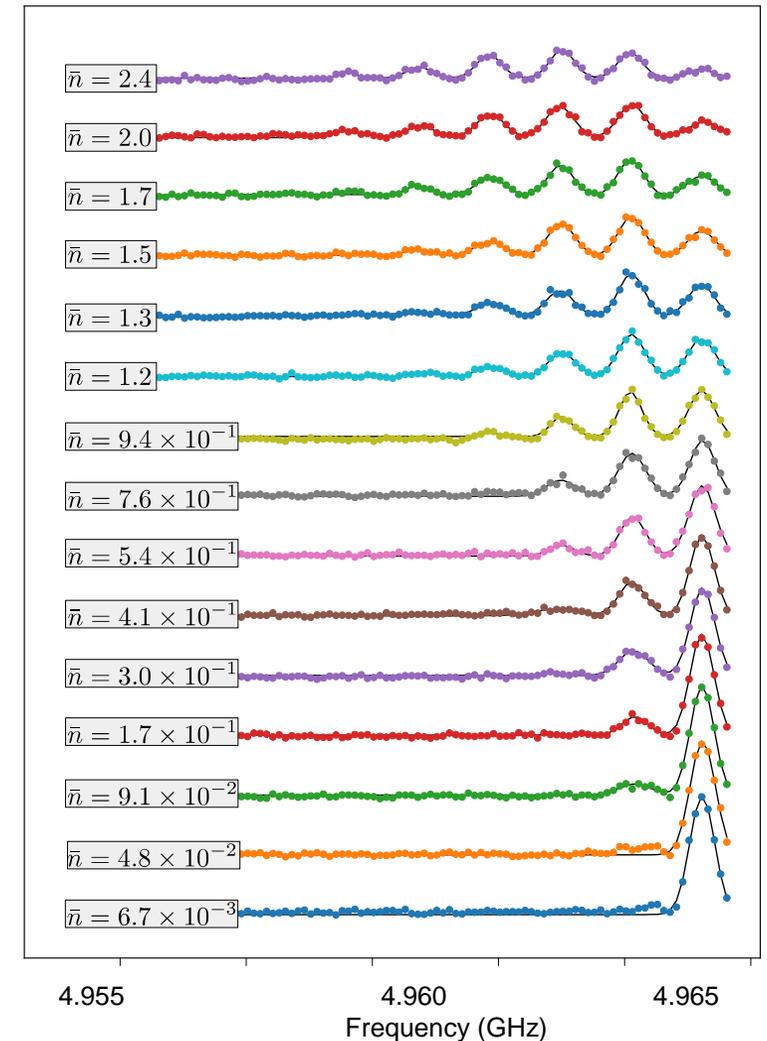
Hidden Markov model analyzes probability of observed sequence of yes's and no's from repeated pi pulses.

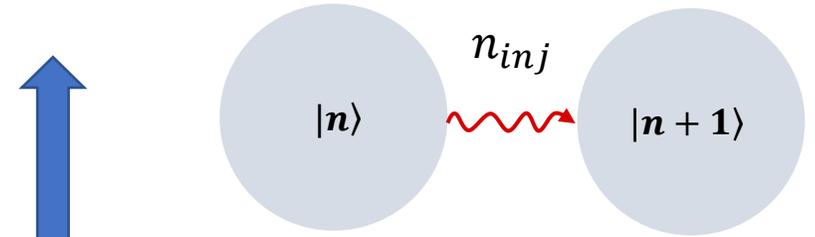# Absolutely calibrated photon injection

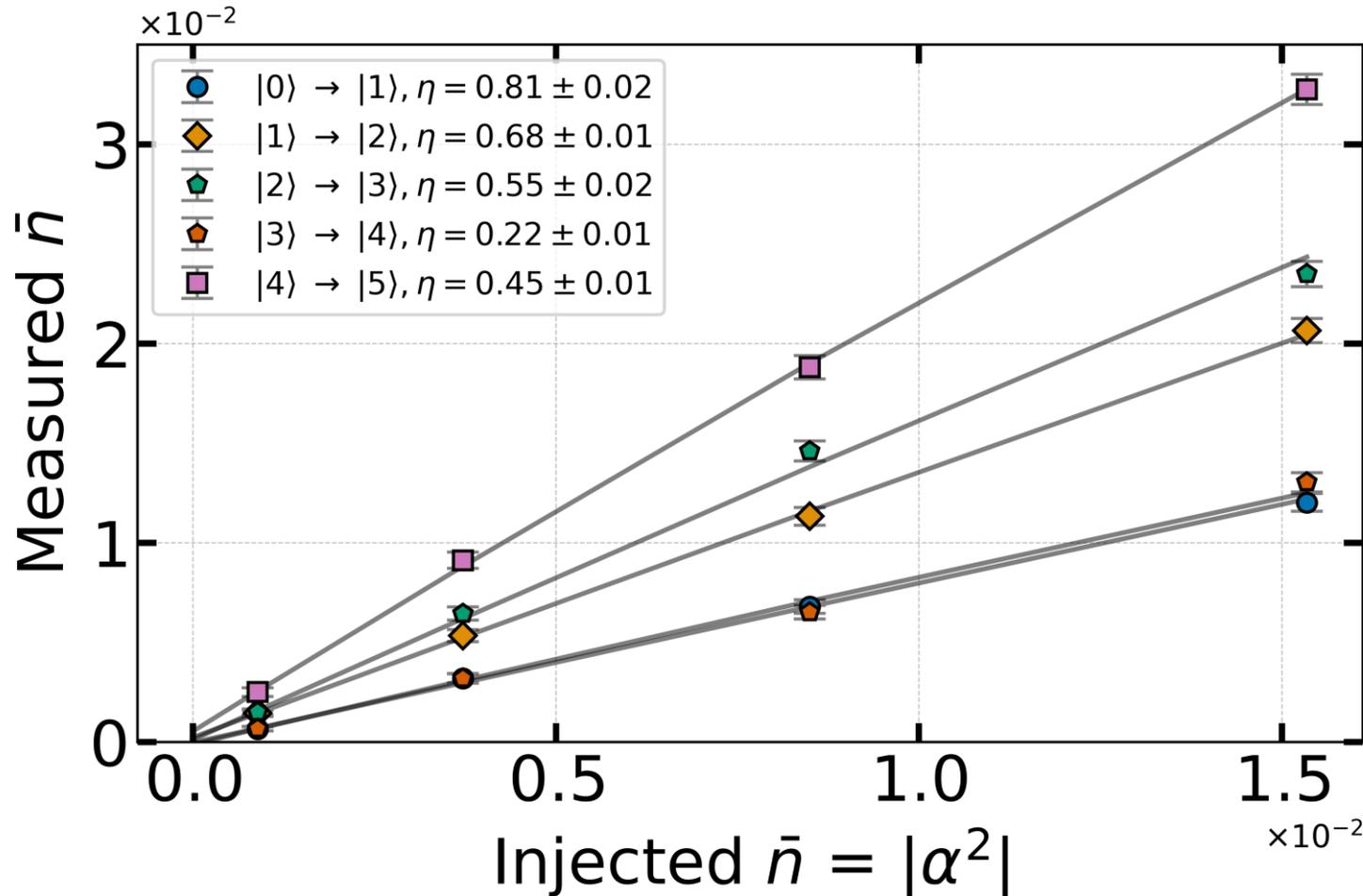Inject sine wave in Gaussian envelope.

Measure resulting Poisson distribution of cavity occupation number

Slide/data from Ankur Agrawal,
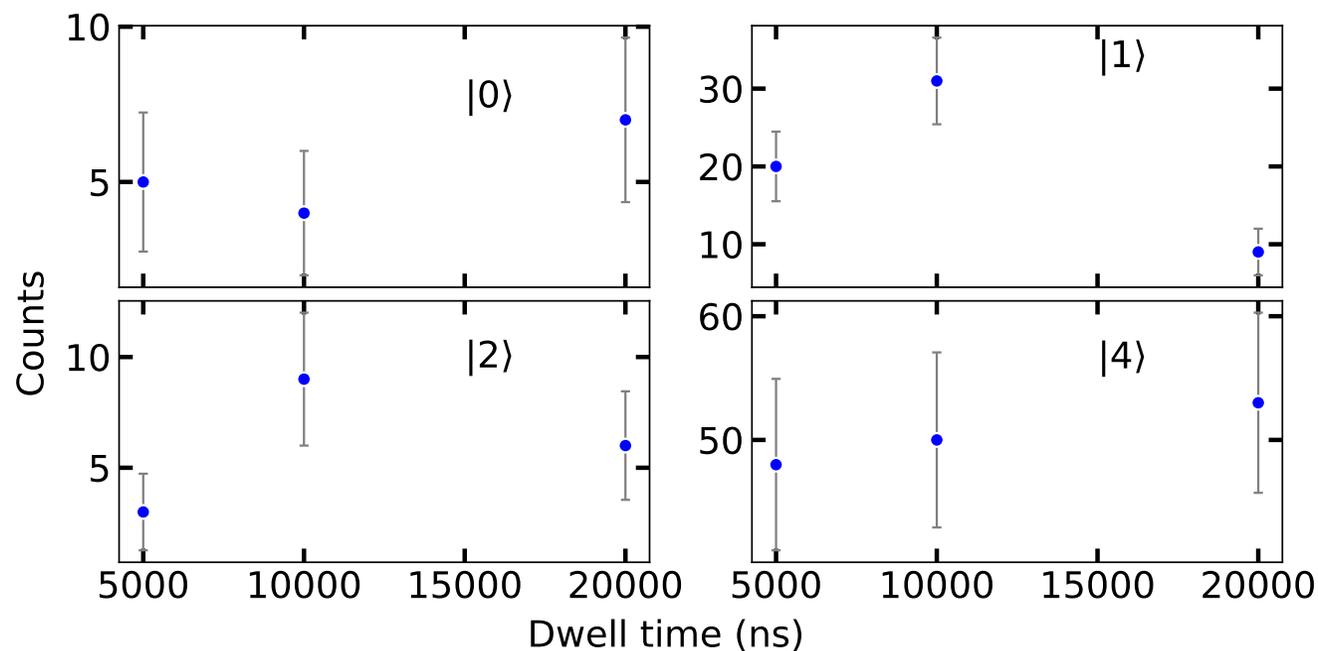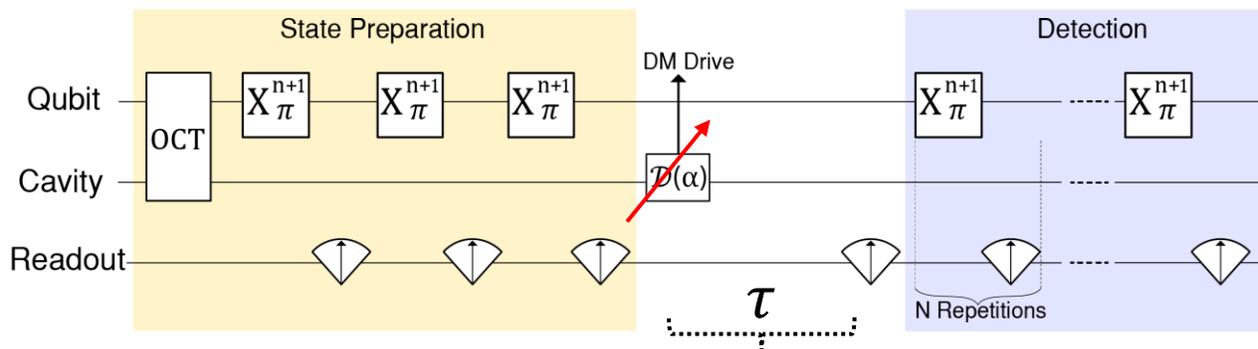Preprint in prep.

Signature of enhancement

This is the first demonstration so far showing signal enhancement with $|n\rangle = |4\rangle$ Fock state

Less than a factor of (n+1) due to measurement inefficiencies, e.g. photon decays during measurement, QND has small demolition probability, etc. HMM optimized for small background rate $n_{bkgd} < 1\%$

Backgrounds

$$N_{meas} \propto a_0(n+1)\tau + b_0 + c_n$$

Could be dark matter?

Coherent

Incoherent

State prep.

$$\varepsilon \propto \sqrt{\frac{a_0}{m_{\gamma'}}}$$

~ 20000 trials for each point. $\tau \sim 10$ us, $\tau_{DM} \sim 100$ us, $\tau_{cav} \sim 1$ms

Slide/data from Ankur Agrawal, Preprint in prep.

Hidden photon search

$m_{\gamma'}$ (GHz)

5.9646   5.9651   5.9656

$\log_{10} \epsilon$

-1

-5

-9

-13

Fock state preparation

Preliminary

Stimulated emission

24.6675   24.6696   24.6717

$m_{\gamma'}$ (μeV)
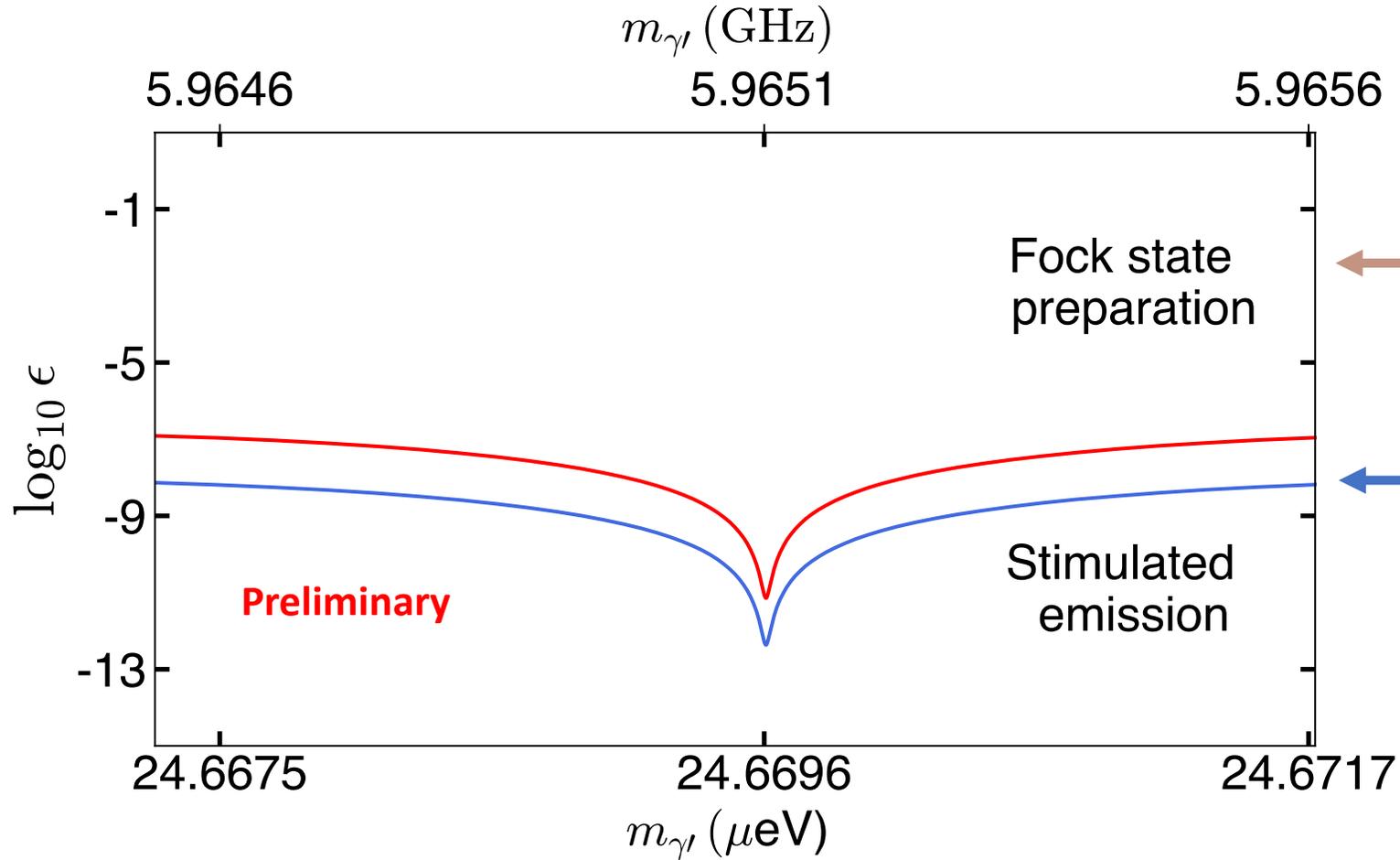
Dark matter drive is always on. If too large, this would have screwed up the Fock state prep.

Conservative limit set by assuming all background counts are dark matter

Agrawal et. al.
(Preprint on arxiv soon)

Slide/data from Ankur Agrawal,
Preprint in prep.

Hidden photon search

Slide/data from Ankur Agrawal,
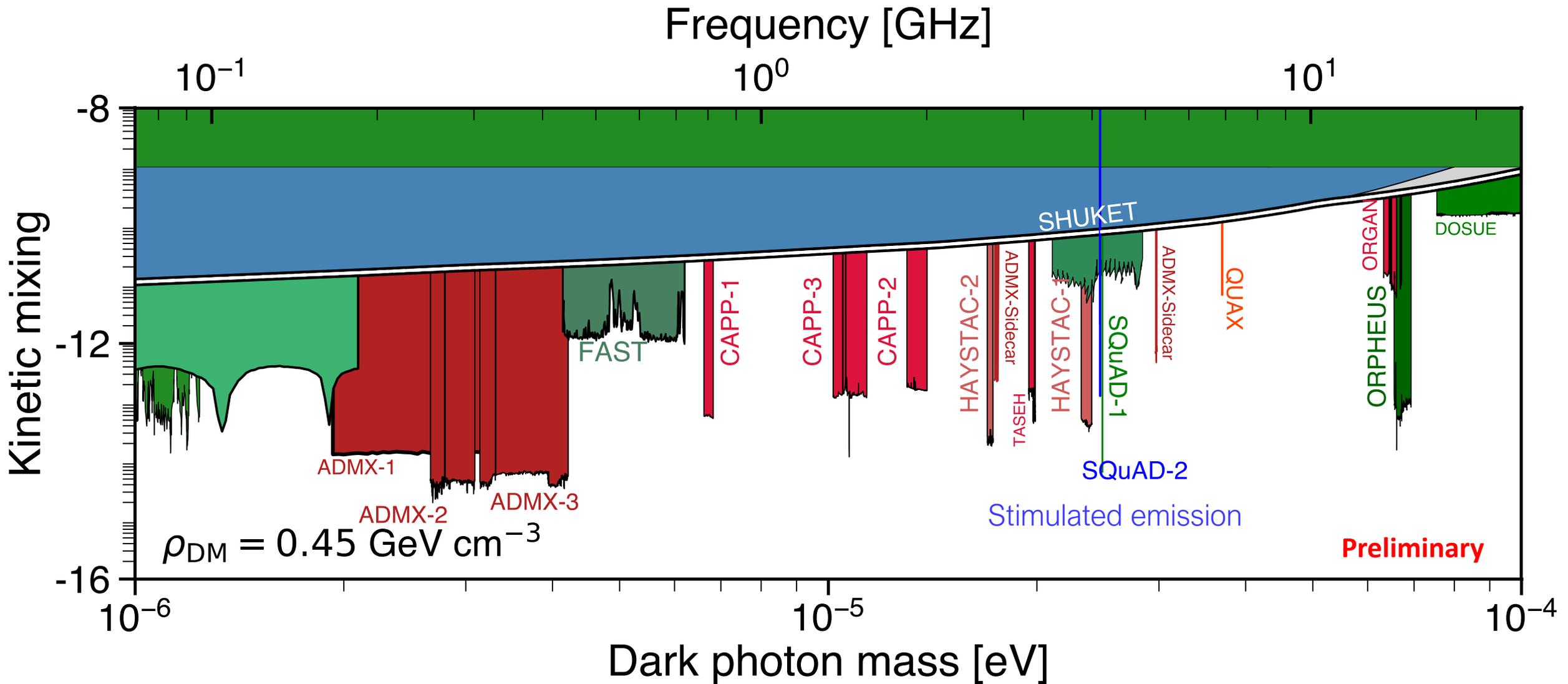Preprint in prep.

Aaron S. Chou, IQ/PACC axion workshop,
4/6/2023

To make compatible with large B fields for axions

Tuner   Storage   Readout   Transmon
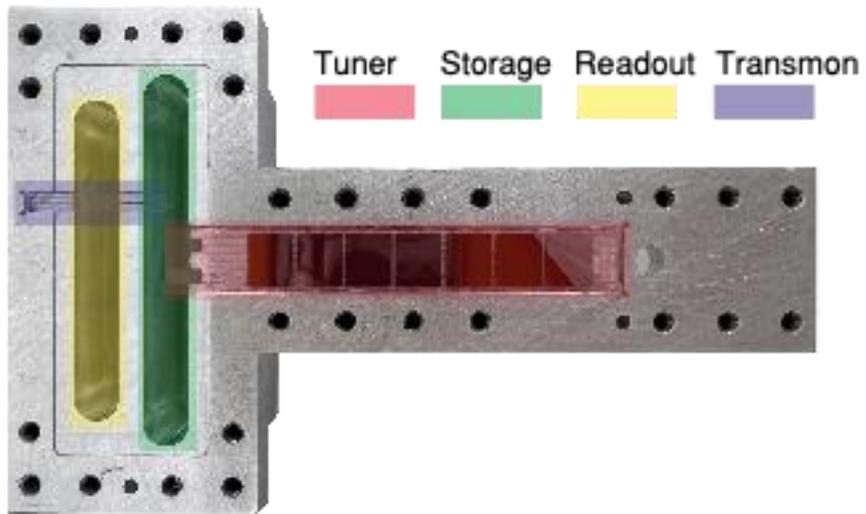
Tunable photon counter

Tuning rod
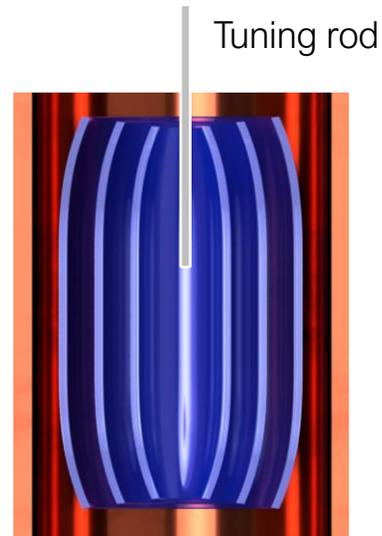
Tunable photonic cavity

Magnetic shielding

Tuner   Storage   Readout   Transmon

$\vec{B}$
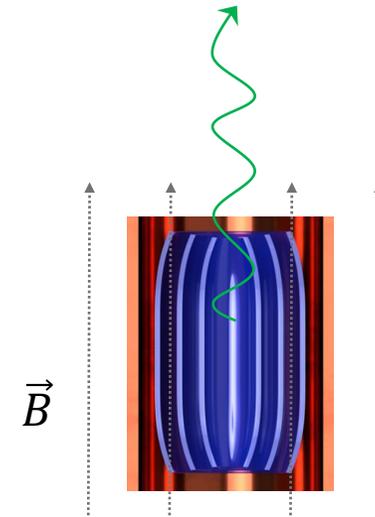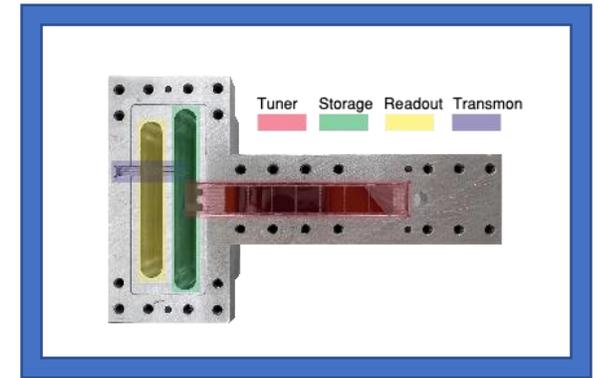
State swap

Summary

- SNR for resonant detectors plummets at higher frequencies as cavity volume shrinks and SQL noise increases

- Photon counting measurements have no Heisenburg uncertainty limit and can achieve 10^{-2} SQL.
  - Increases scan speed by $(SNR)^2 = 10^4$.

- Signal can be boosted using stimulated emission with Fock states
  - Potentially increase scan speed by factor (n+1)
  - Demonstrated in hidden photon search

- TBD: transport of Fock state via state swap for axion search, demonstration of improvement in scan speed

Paper coming soon!

Stimulated emission of signal photons from dark matter waves

Ankur Agrawal,[1,2,3,*] Akash V. Dixit,[1,2,3,†] Tanay Roy,[1,2,‡] Srivatsan Chakram,[1,2,4,§]
Kevin He,[1,2] Ravi K. Naik,[5] David I. Schuster,[1,2,6,7] and Aaron Chou[8]

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[3] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois 60637, USA*
[4] *Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA*
[5] *Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[6] *Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, USA*
[7] *Department of Applied Physics, Stanford University, Stanford, California 94305, USA*
[8] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

Backup slides

Axion mass = harmonic oscillator frequency

V(a)

a

$\overline{\Theta}=0$

Axion

Λ_{QCD}^4

VEV $f_a > 10^9$ GeV

$m_a = \Lambda_{QCD}^2 / f_a < 10^{-3}$ eV
Single parameter model for axions

31
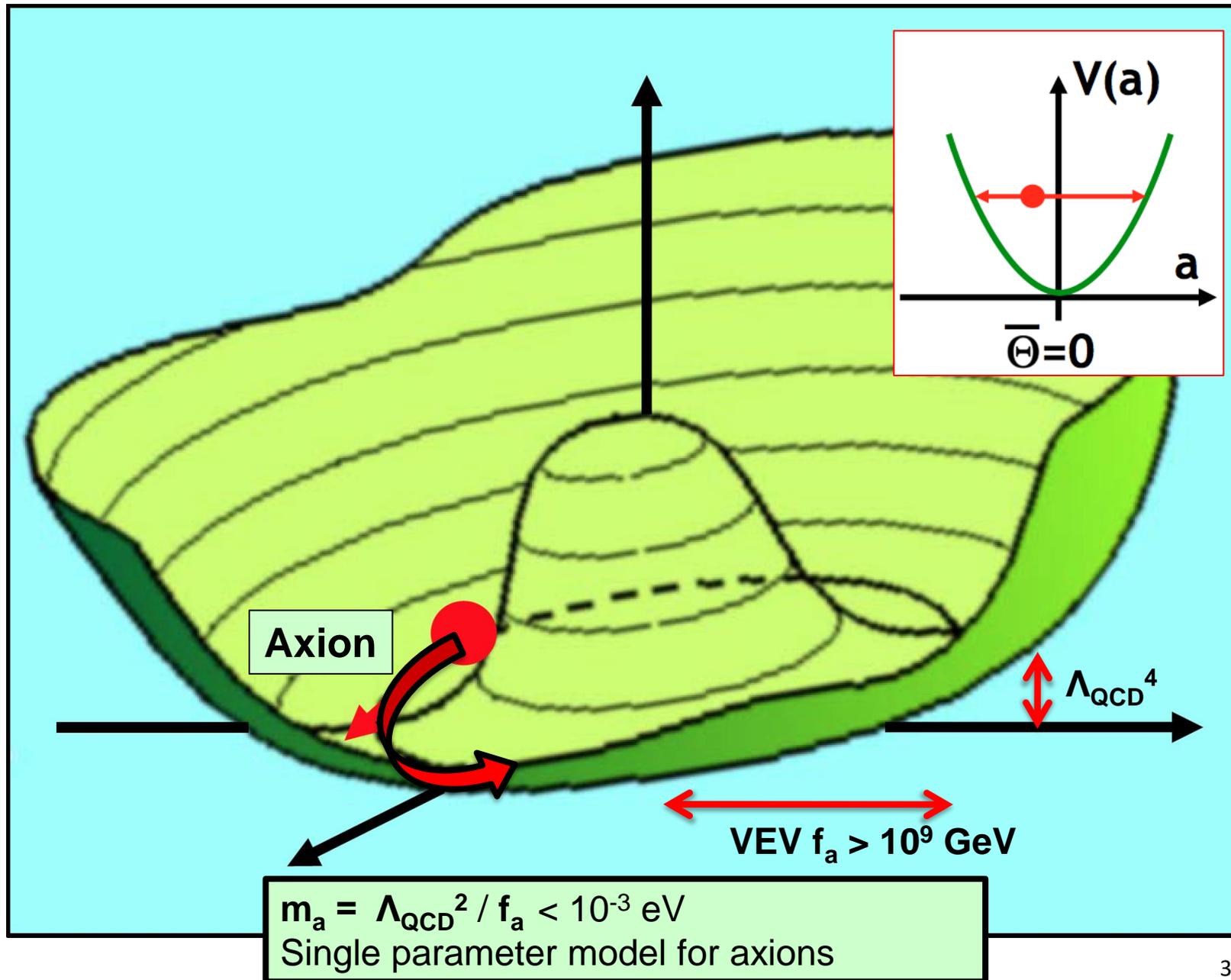
Hmmm… quantum computing platforms look just like dark matter searches:

DOE-OHEP Basic Research
Needs white paper, 2018
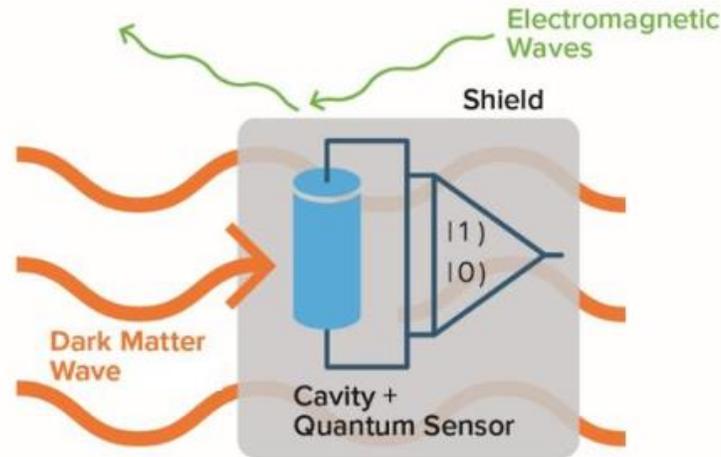
Sensitive single-quantum devices are operated in a cryostat and/or vacuum system and well-shielded from external disturbances (heat, light, sound) in order to maximize their coherence time.

Impossible to shield from the dark matter – the DM interacts so weakly that it flies right through the walls.

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.

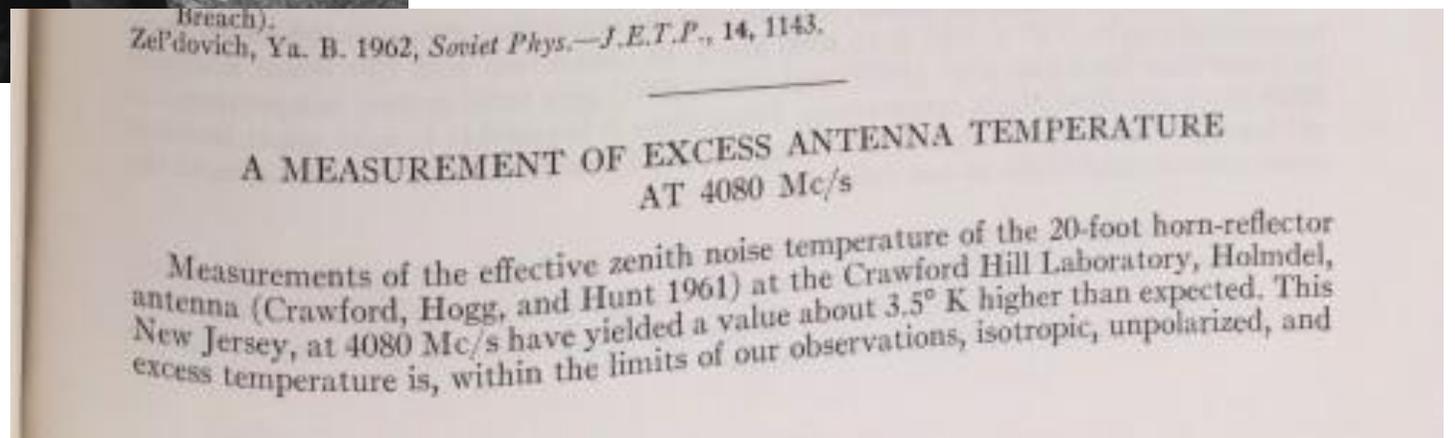# Mystery noise in your experimental apparatus is not necessarily mundane

Penzias and Wilson, 1965:
After chasing away nesting birds with a shotgun, discovered the cosmic microwave background

– They had no idea that this was first evidence for the big bang theory
– Nobel Prize, 1978

N.B. Discovery of color photography would have to wait until the 1970's.

Breach).
ZeI'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, 14, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Need 10^5 seconds to completely convert the axion wave into a photon wave. But only have 10^{-4} s of cavity time…

"Real world values"
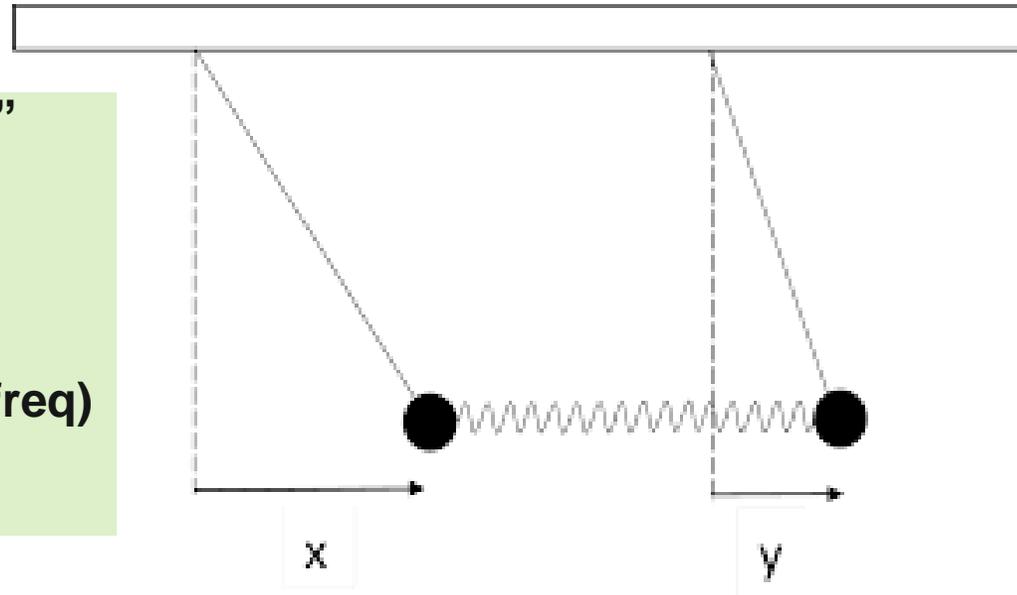
$|\alpha\rangle = 10^{11}$

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

$\frac{2g}{2\pi} = 10^{-5}$ Hz (beat freq)

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

Axion = classical wave

$$\theta(t) = \sqrt{\frac{2\rho_a}{\Lambda_{QCD}^4}} \, e^{im_a t}$$

$$H_I = igB\sqrt{\omega V} \left(\theta(t)a^\dagger - \theta(t)^* a\right)$$

Beat frequency **(derive this!)**

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

DFSZ Signal, 7T, 1λ³

Solves nEDM problem

ADMX Sensitivity

Standard Quantum Limit Noise

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

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)

Photon rate dN/dt [s⁻¹]

Photon frequency [GHz]
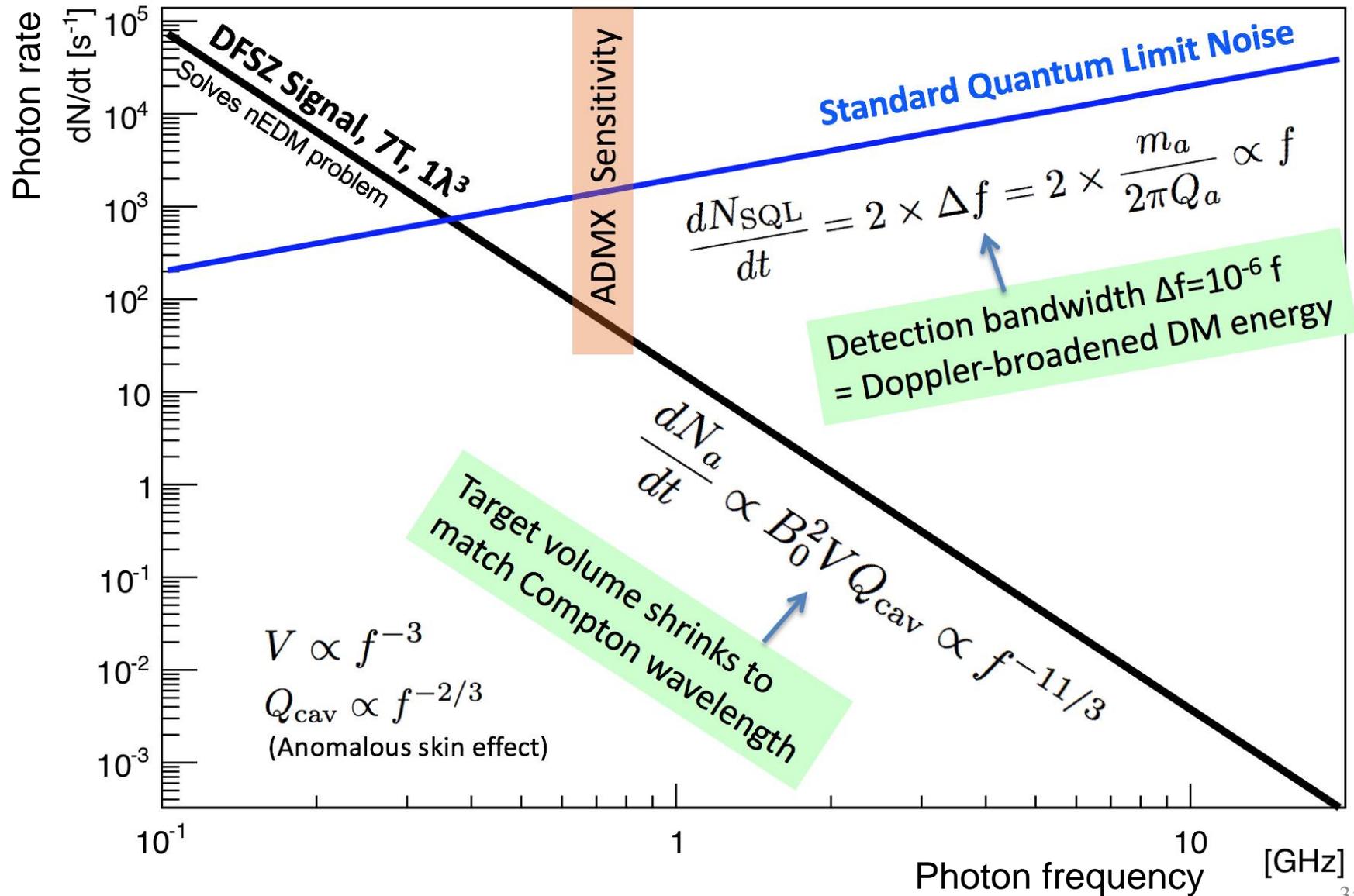
The Glauber displacement operator and coherent states

$$p = i\frac{d}{dx}$$

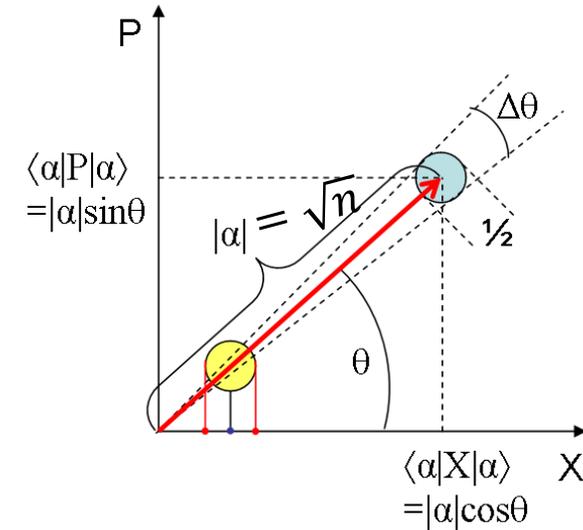Generates translations in position

$$x = i\frac{d}{dp}$$

Generates translations in momentum

$$a^\dagger = x + ip$$
$$a = x - ip$$

Generate translations in an arbitrary direction in x-p phase space

Exponentiate differential operator to get finite translation α in complex plane:

$$\hat{D}(\alpha) = \exp\left(\alpha\hat{a}^\dagger - \alpha^*\hat{a}\right)$$

Phasor of amplitude α is generated as: $D(\alpha)\,|0\rangle = |\alpha\rangle$ Classical sine wave

This is an eigenstate of the annihilation operator: $a\,|\alpha\rangle = \alpha\,|\alpha\rangle$ Prove this!