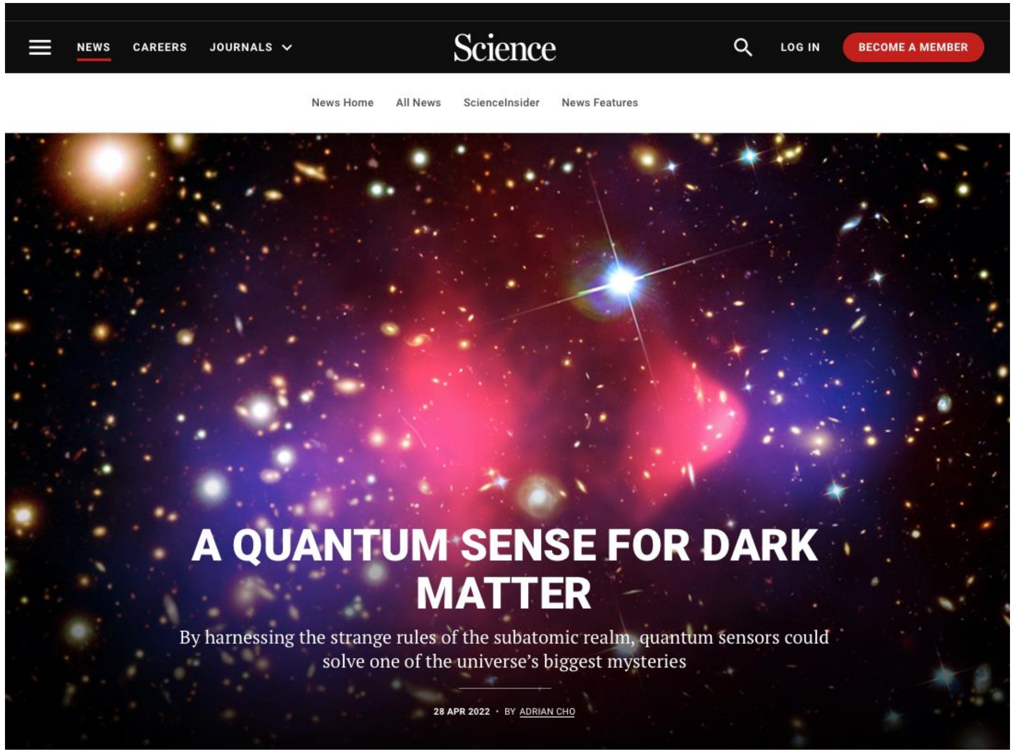
Quantum Sensor Needs for Dark Matter Axion Searches



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A QUANTUM SENSE FOR DARK MATTER

By harnessing the strange rules of the subatomic realm, quantum sensors could solve one of the universe's biggest mysteries

28 APR 2022 · BY ADRIAN CHO

Science, April 28, 2022

Karl van Bibber is a professor of nuclear engineering and associate dean for research of the College of Engineering at the University of California, Berkeley. **Konrad Lehnert** is a professor of physics and JILA Fellow at the University of Colorado, Boulder, and the National Institute of Science and Technology. **Aaron Chou** is a senior scientist at the Fermi National Accelerator Laboratory in Batavia, Illinois.

Putting the squeeze ON AXIONS

Karl van Bibber, Konrad Lehnert, and Aaron Chou

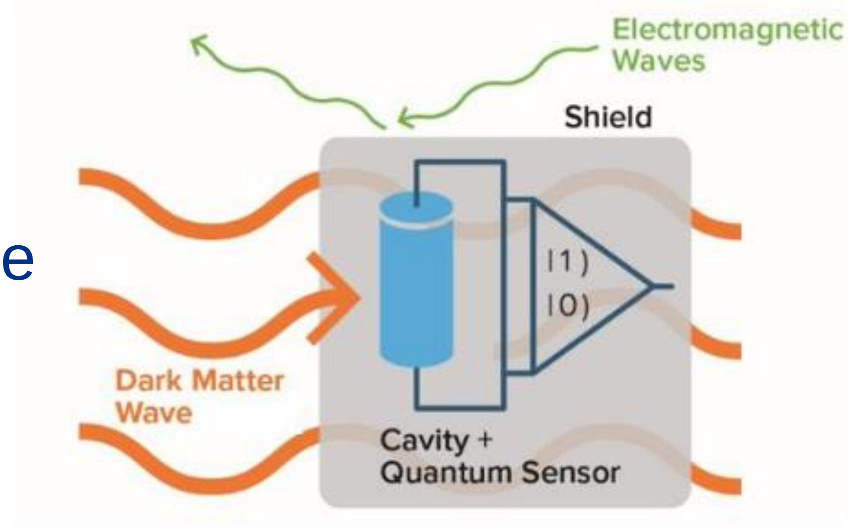
Microwave cavity experiments make a quantum leap in the search for the dark matter of the universe.

Physics Today, June 2019

Aaron S. Chou
Fermilab
March 22, 2024

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

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

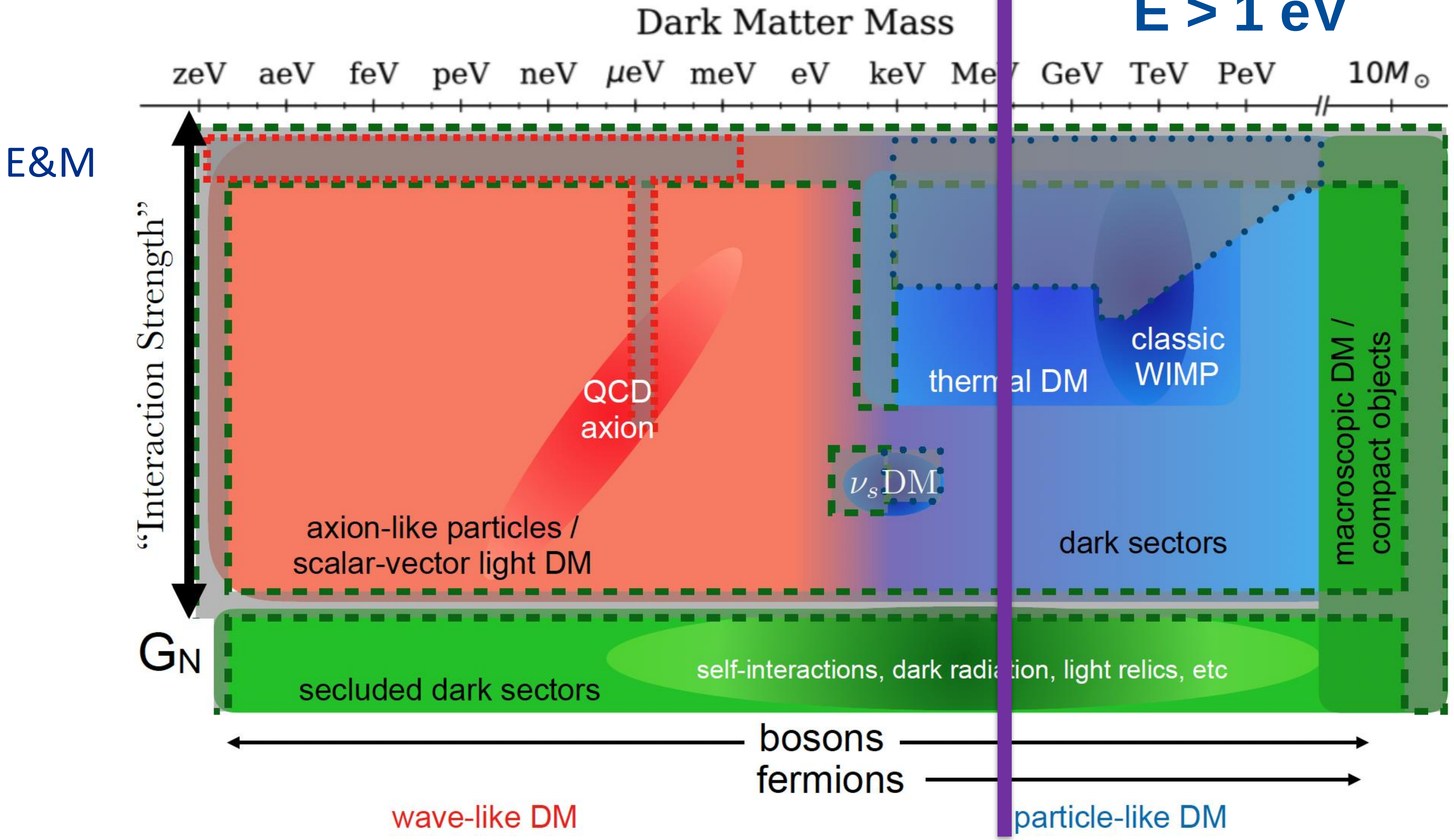


Sensitive single-quantum devices are operated in a cryostat and/or vacuum system and well-shielded from external disturbances (heat, light, sound) in order to maximize their coherence time.

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.

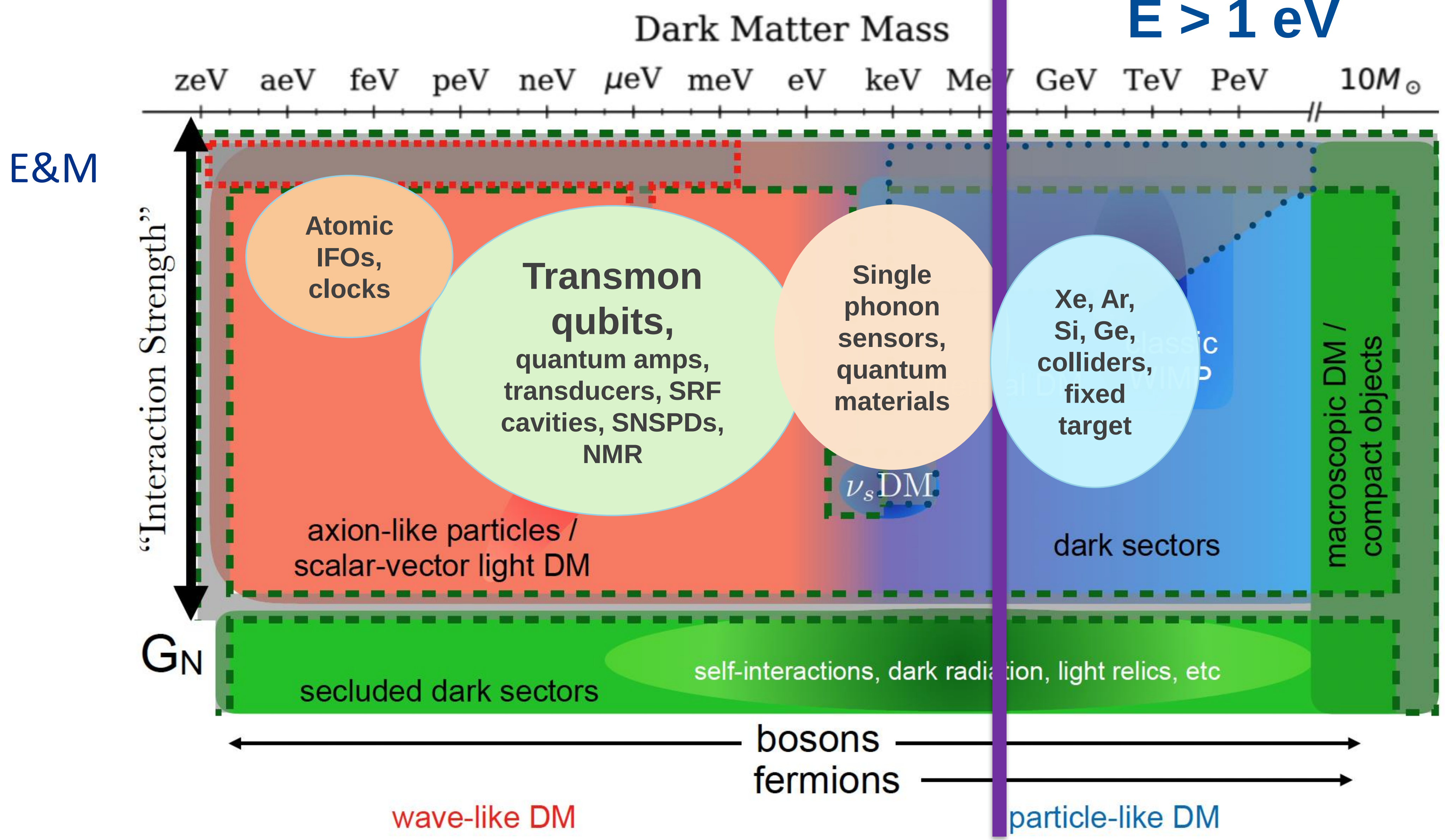
Quantum sensors: $E < 1$ eV ⟵ ⟶ Current HEP tech: $E > 1$ eV



Cartoon from Snowmass

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

E&M



Atomic IFOs, clocks

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

Single phonon sensors, quantum materials

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

Cartoon from Snowmass

The Sikivie Haloscope technique (1983)
Classical axion wave drives RF cavity mode

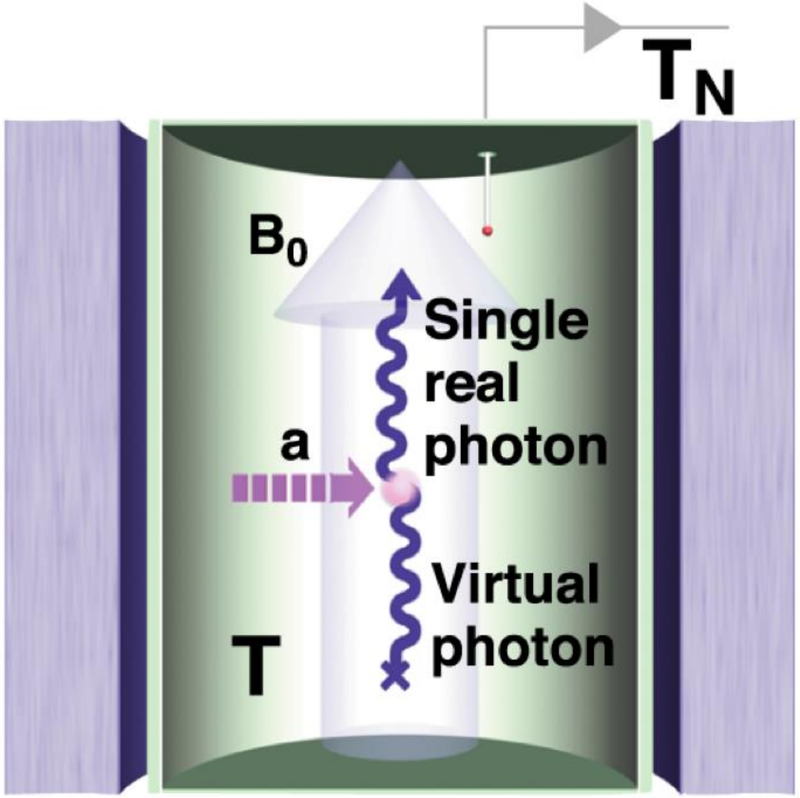
- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

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

which drives E&M via Faraday's law:

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

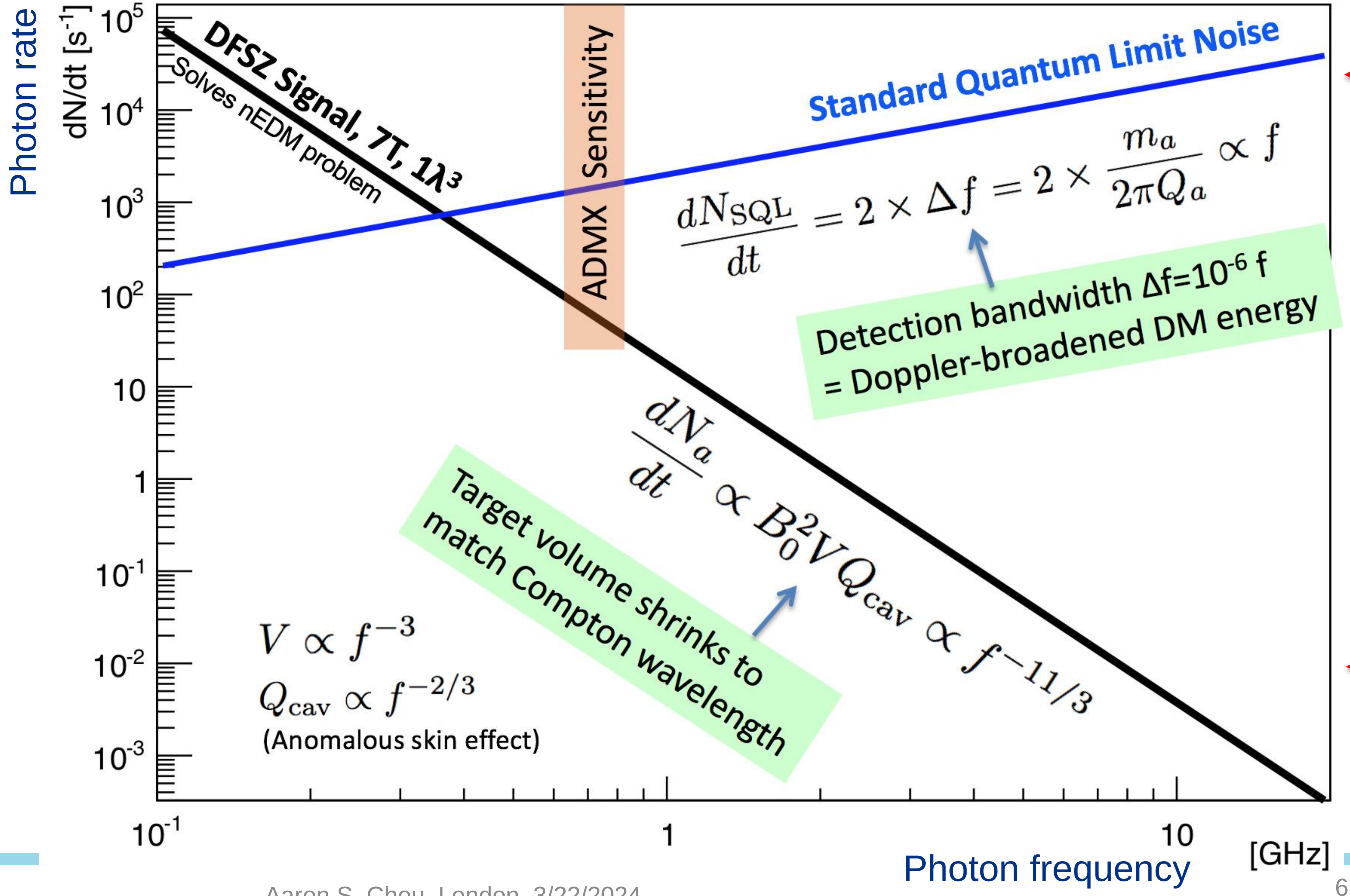
- In the presence of matched cavity boundary conditions to absorb momentum (cavity size ≈ $1/m_a$), the exotic source current excites standing-wave RF photons.
- The gravitational potential well acts as a low pass filter on the dark matter kinetic energy → Signal linewidth $f/Q = f/10^6$
- Axion mass is unknown – **must do radio scan over large frequency range by tuning the resonant cavity 10^6 times per octave**



A spatially-uniform cavity mode can **optimally** extract power from the potential energy of interaction:

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

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



Effective DCR = 10^4/s

Need DCR < 10^{-2}/s

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

Increase signal?

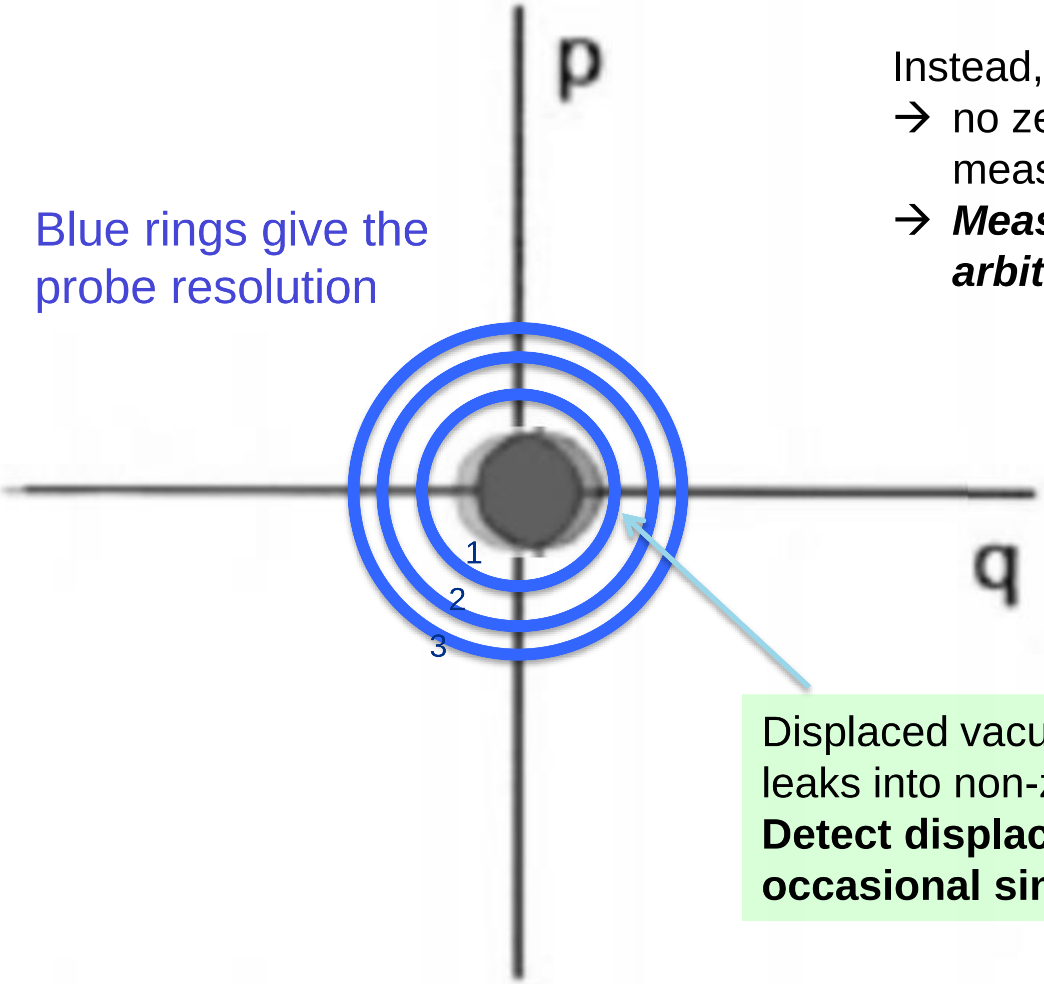
We do need more magnets, but these are expensive and have long lead time.

Reduce noise?

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

To reduce readout noise below SQL, 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 dark matter phase is randomized every coherence time. 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.

SC qubits as single photon detectors. No quantum noise!

Fermilab/Chicago/Stanford

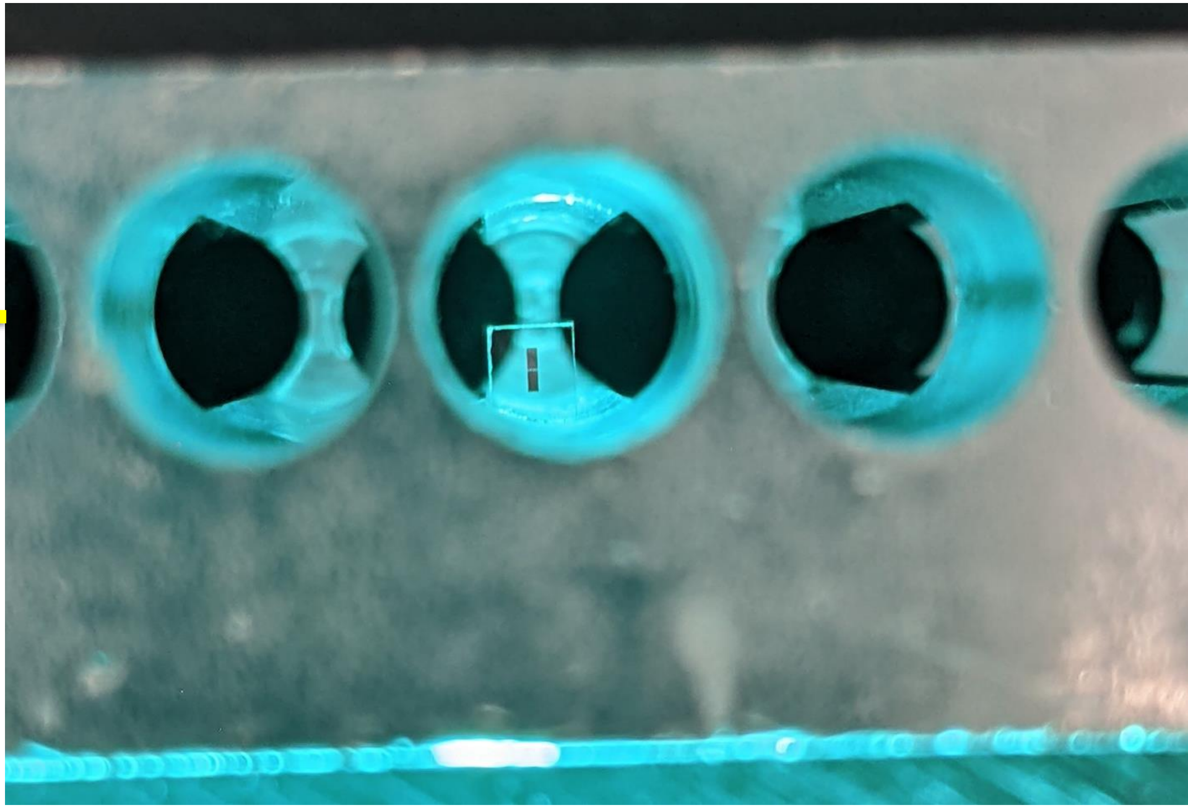
Nested sapphire cavity compatible with high B field needed for axion search: Q>10^6,
¼-wave layers reflect photon waves back to center

(based on design from INFN/QUAX)

SQuAD
(Superconducting Qubits for Axion Darkmatter)

Installed in 10 mK dilution refrigerator and 14T solenoid magnet at Fermilab

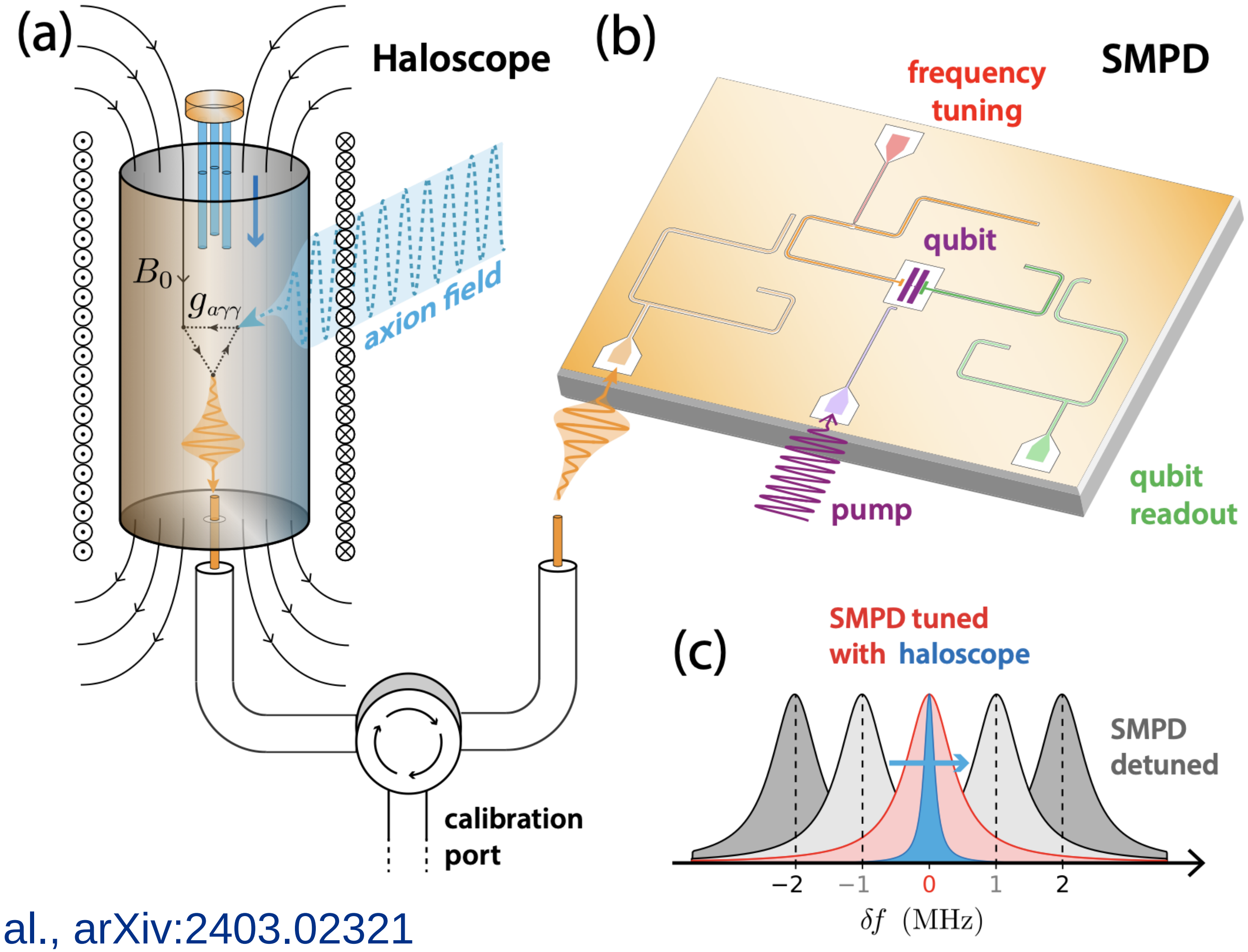
Quantum readout electronics in remote, magnetically-shielded region



Transmon qubit performs quantum non-demolition single photon counting with noise **36x lower than zero-point noise, 1300x speed-up.**
Achieved 1 Hz DCR.

A.V. Dixit et al., *Phys.Rev.Lett.* 126 (2021)

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.

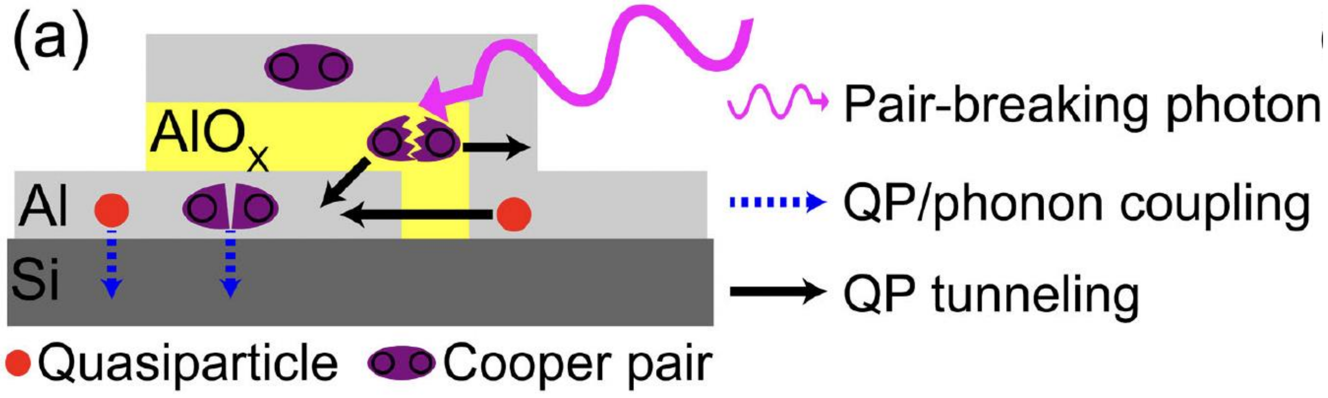
Technical complications:

- Remote buffer resonator must be co-tuned with SQUID to match the frequency of the axion cavity.
- Large **dark count rate ~100/s** from poor thermalization of rf lines, spontaneous heating of the qubit state, but better than SQL!

C. Braggio et al., arXiv:2403.02321 (SQMS)

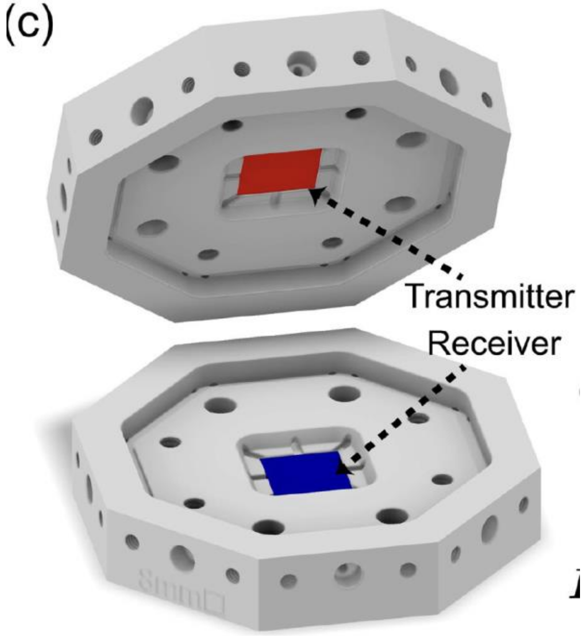
False positives g→e from direct absorption of above-gap photons

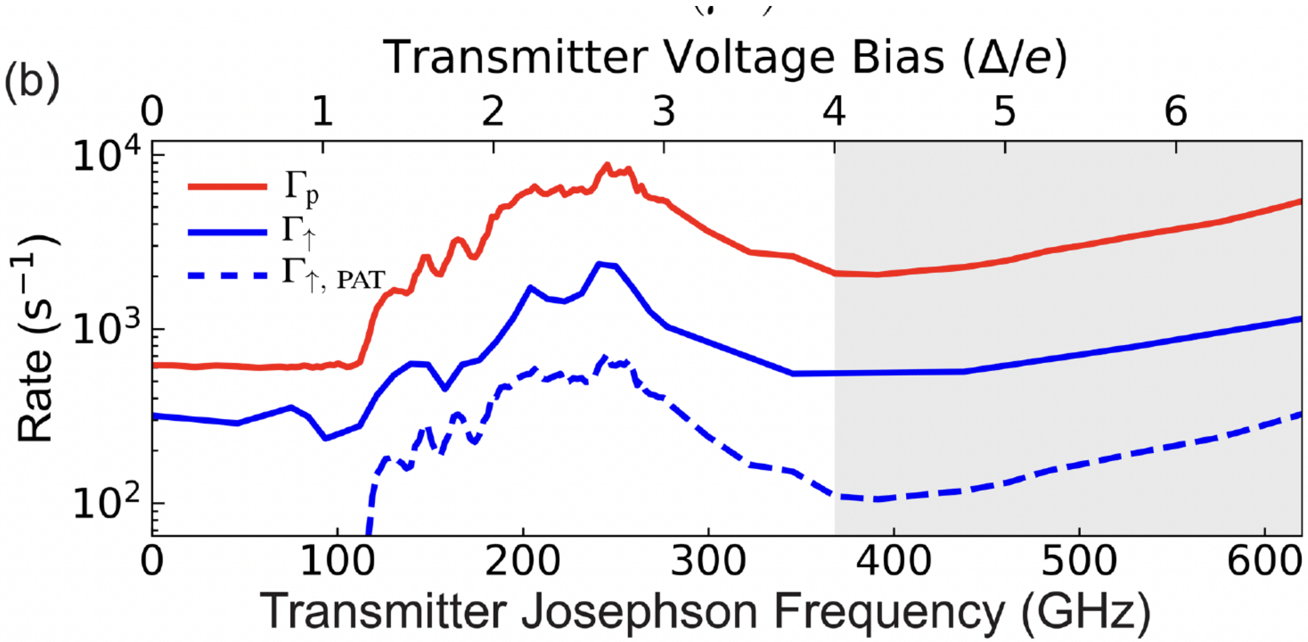
Robert McDermott's experiment
PRL 132, 017001 (2024)



Qubit excitation rate is nearly 100% correlated with charge parity switching rate caused by photon absorption!

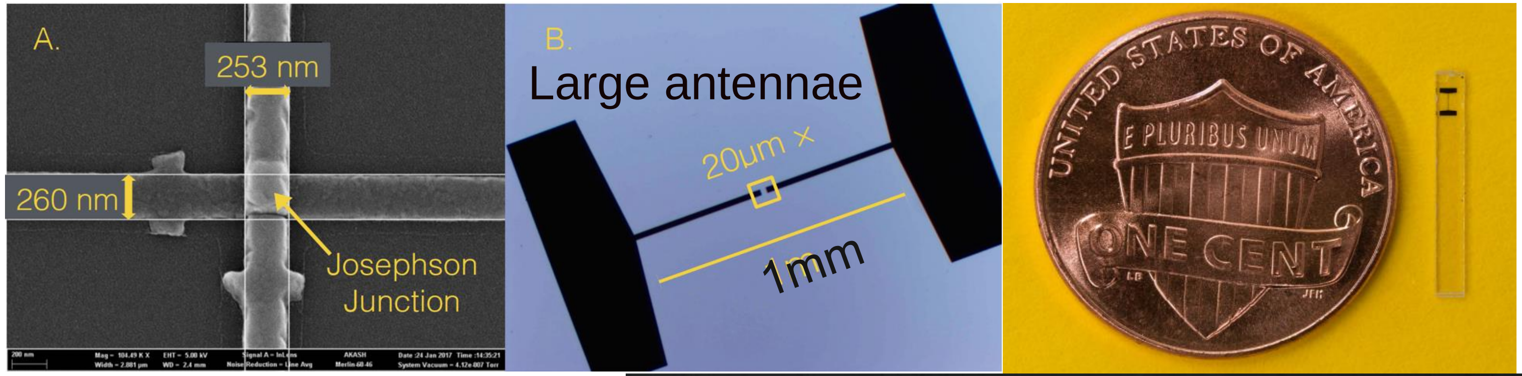
Apply dipole radiation from AC Josephson effect





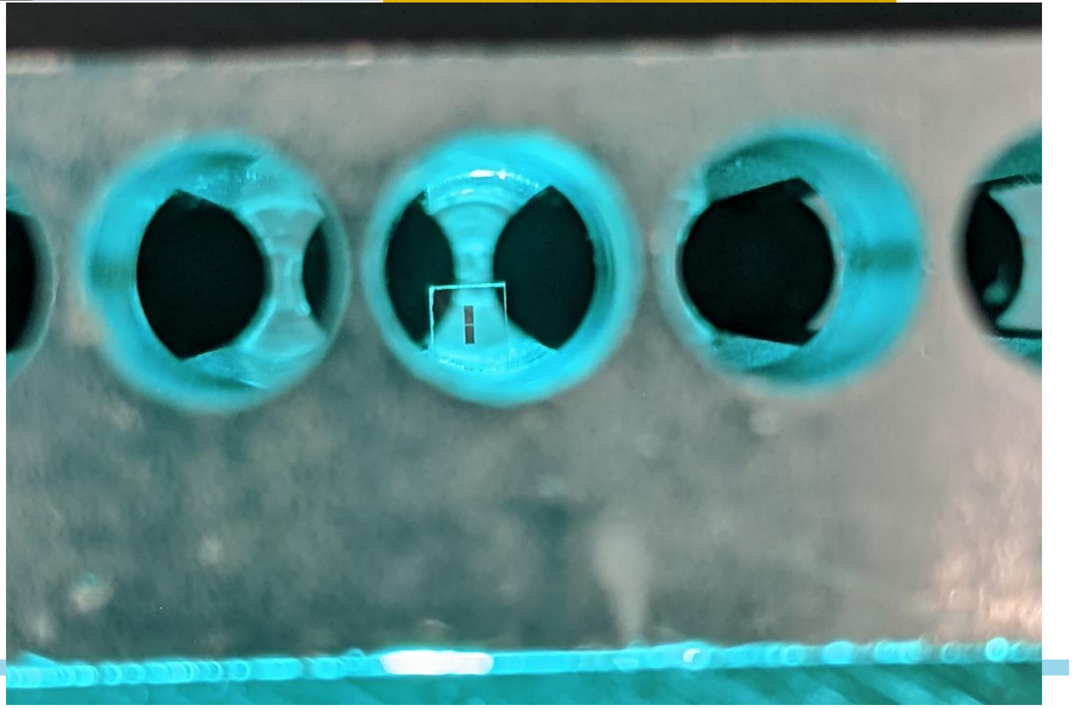
To avoid spontaneous qubit heating background, instead do quantum non-demolition measurements of the cavity photon

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



The electric field of individual photons drives a tunneling current and exercises the nonlinear inductance of the Josephson junction.

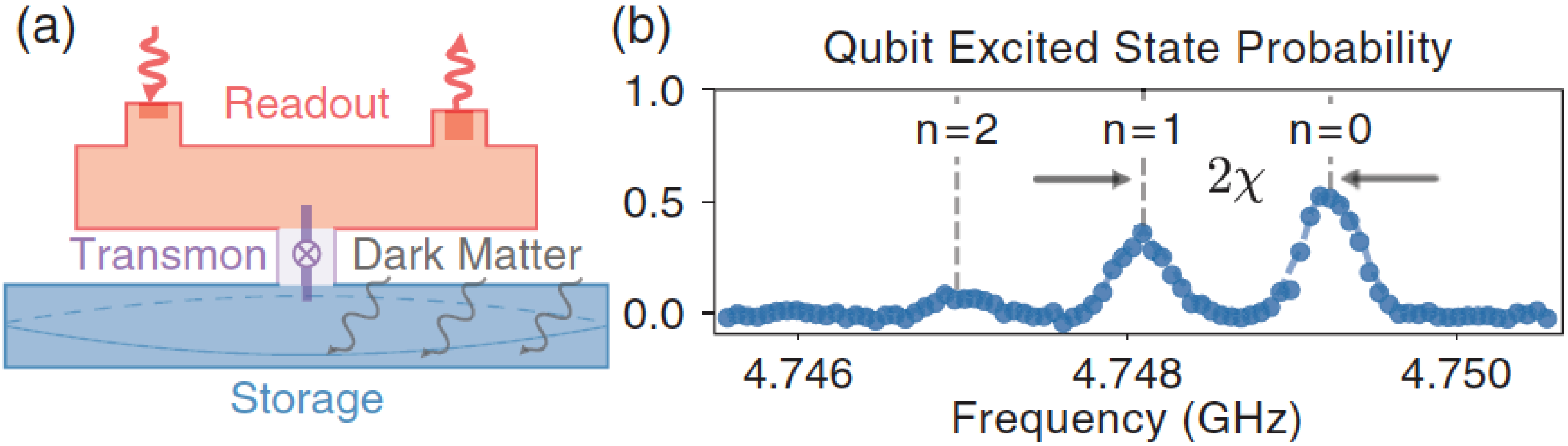
Photon number is transduced into frequency shifts of the $|g\rangle \rightarrow |e\rangle$ transition of this nonlinear LC oscillator.



Transmon qubit in pan flute cavity (photo credit: Akash Dixit)

Qubit Stark shift provides single microwave photon resolution:

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



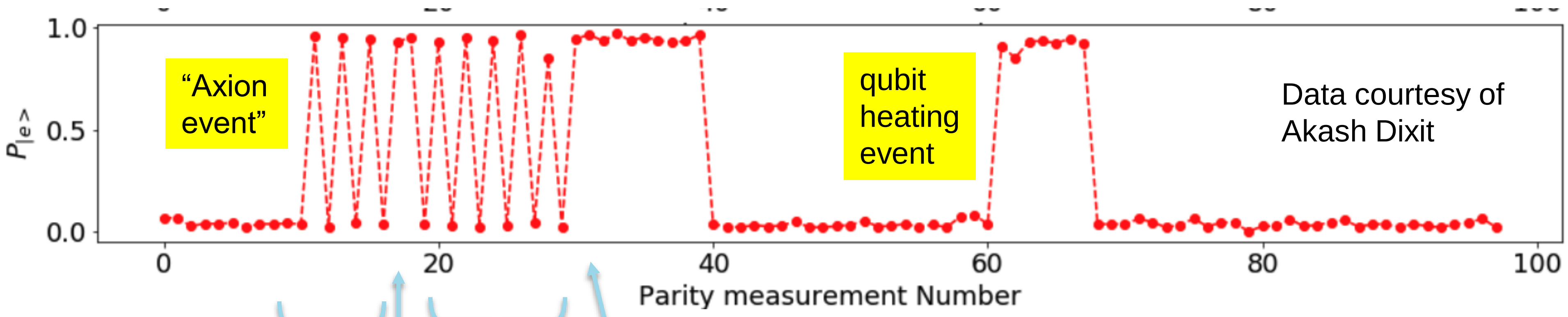
Non-destructively count photons by measuring the qubit's quantized frequency shift.

e.g. Measure spectral response by applying pi-pulse to the qubit at the postulated shifted frequency to see if it absorbs the photon.

A.V. Dixit et al., *Phys.Rev.Lett.* 126 (2021)

Repeated quantum non-demolition measurements ensure high fidelity tagging of single photon events, rejects qubit heating backgrounds

Signature of a single signal photon is many sequential successful qubit “spin-flips” from $|g\rangle \leftrightarrow |e\rangle$ when probing at the postulated shifted frequency



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.

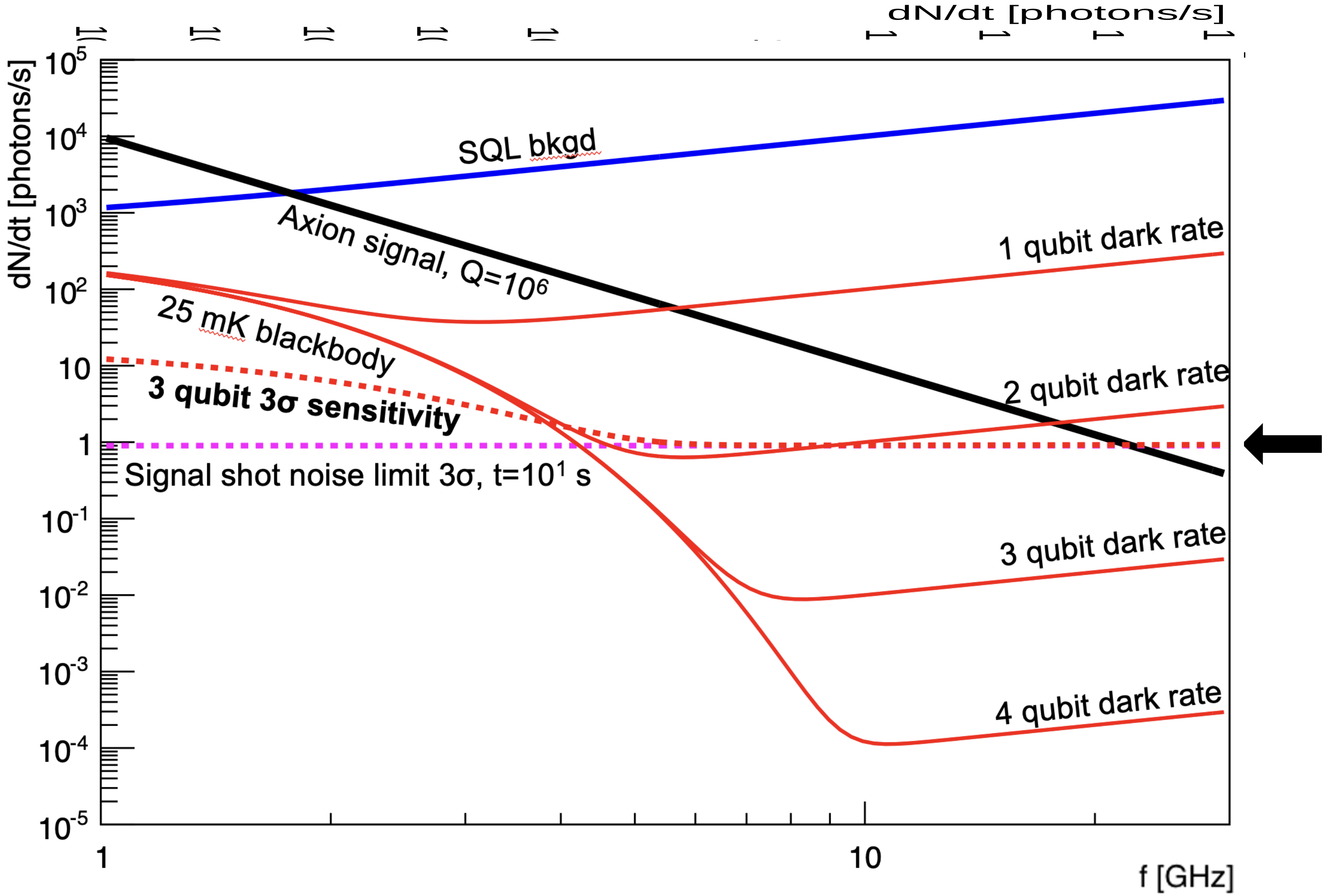
Achieved dark count rate = **1 photon/s.** Need to further reduce this to achieve background-free axion experiments.

Signal rate sensitivity is determined by the integration time budget:

if $Q=10^6$ then have maximum t=10 s at each tuning to get 1 octave in mass, i.e. using 10^6 tunings in 1 year

Assume that quantum sensors will continue to improve until experiments with higher Q cavities are **no longer background-limited.**

Demonstrated qubit DCR=1 Hz is already *nearly* good enough for background-free operation in 10 s integration budget.



For t = 10 s, the minimum observable signal rate is R_s=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 limited at higher frequencies: Need larger B^2V or stimulated emission to go above 20 GHz.

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: $\Delta N \times \Delta\varphi \geq ½$

→ **responds equally well to pushes at any time.**

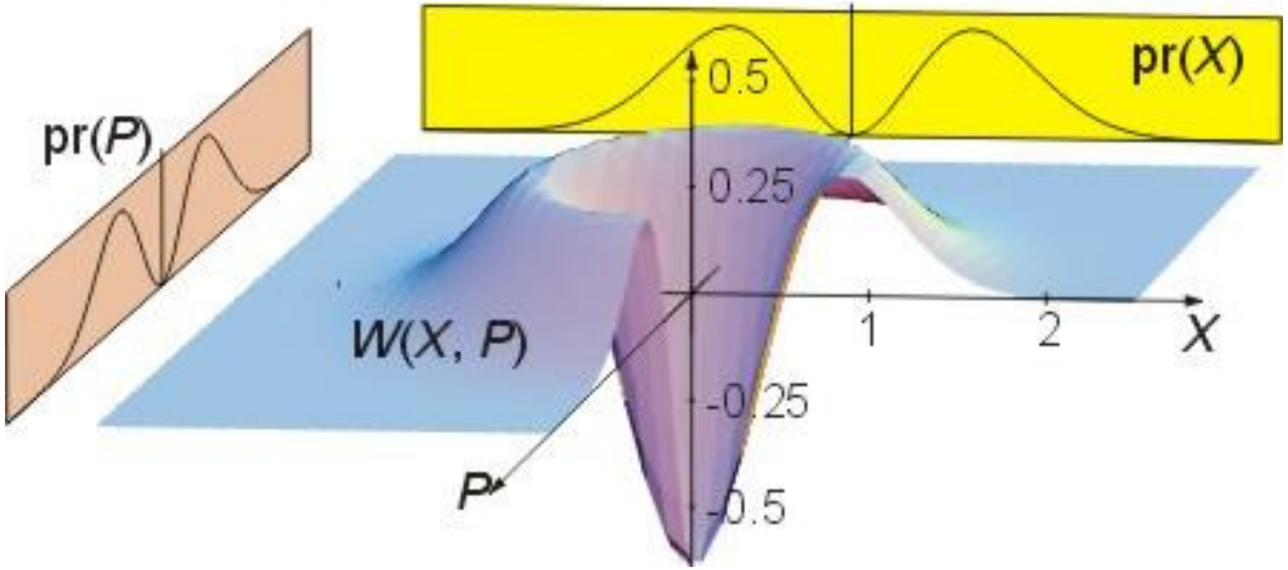
It also has definite occupation number N

→ **no Poisson noise!**

… and force × velocity still works:

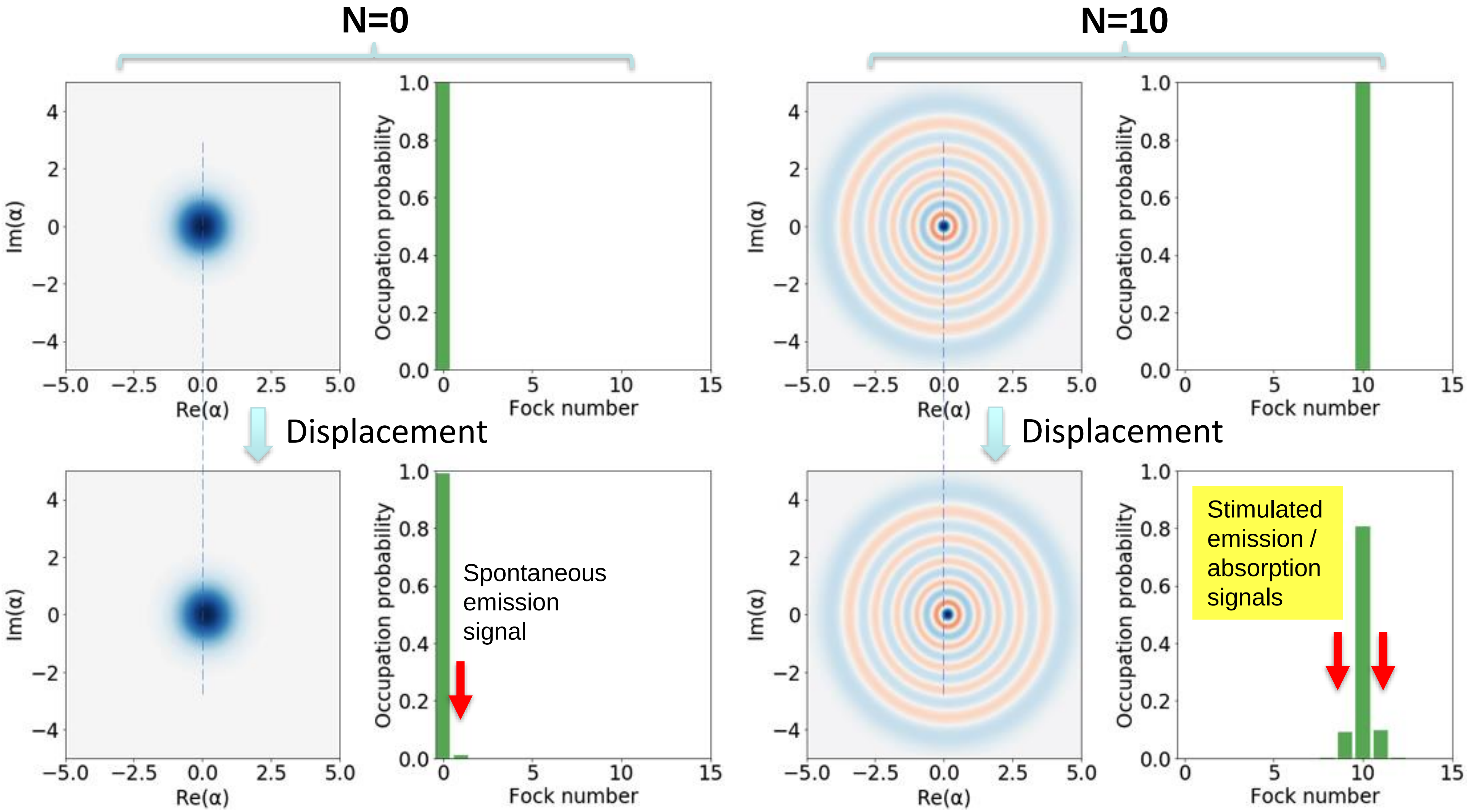
$$H_I = g(a^\dagger b + a b^\dagger) \rightarrow \langle \alpha, N+1 | H_I | \alpha, N \rangle = g\alpha\sqrt{N+1}$$

N=1 Fock state



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

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



Spontaneous emission signal

Stimulated emission / absorption signals

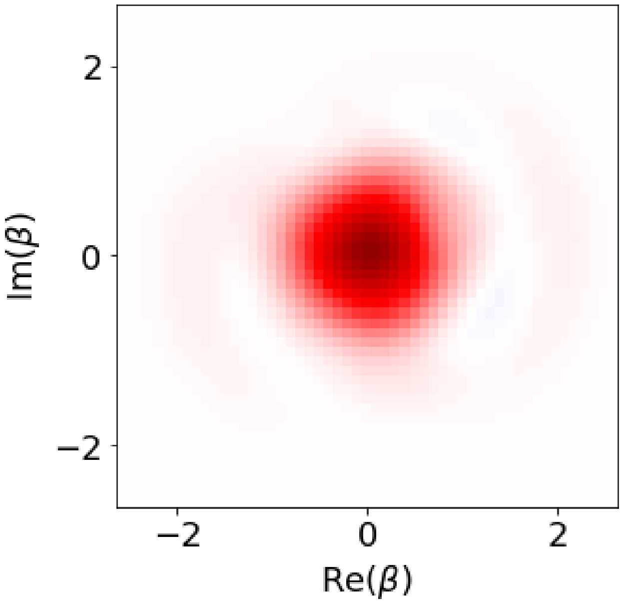
QuTiP simulation

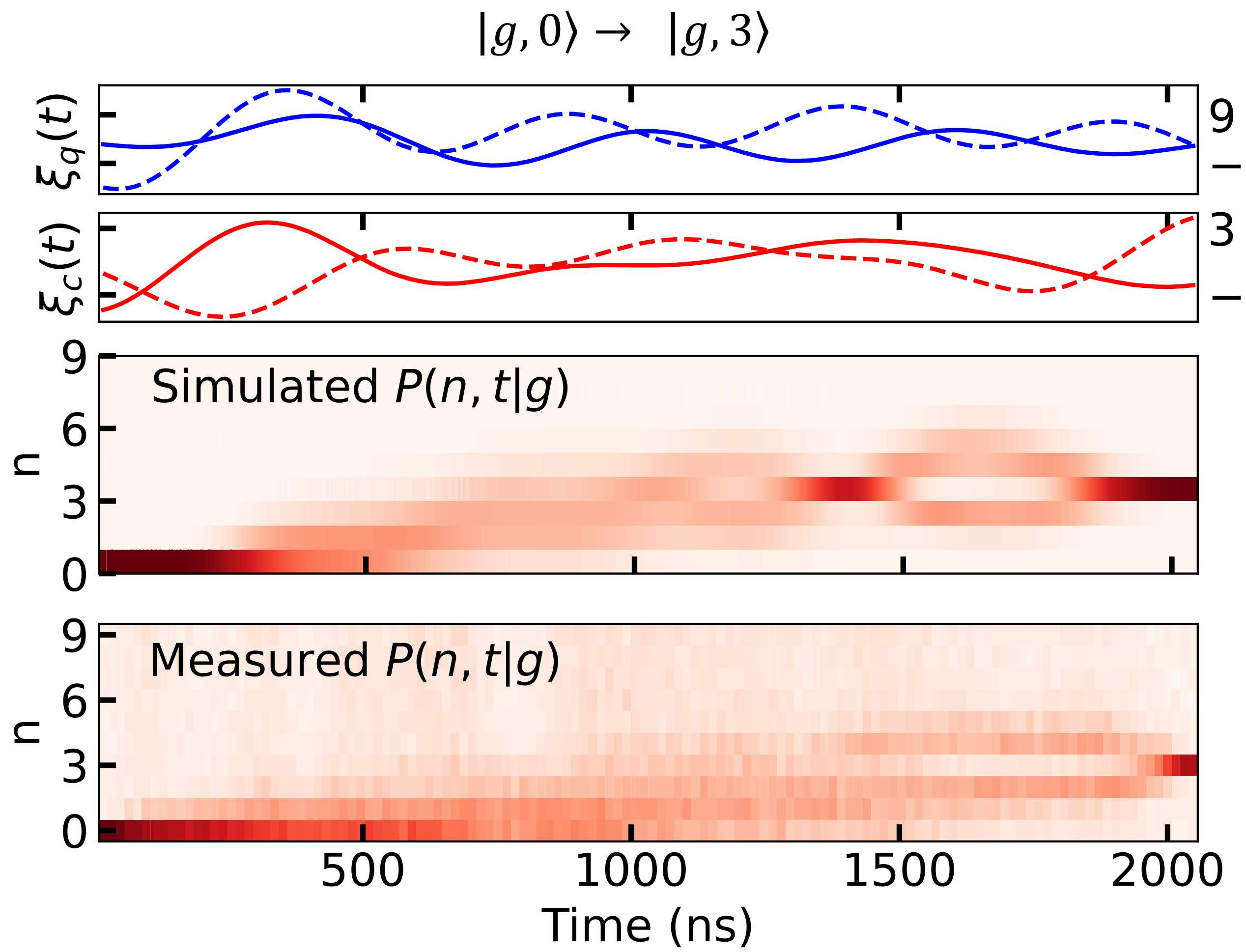
$$\boxed{\left|\langle n+1|\hat{D}(\alpha)|n\rangle\right|^2 \sim \alpha^2(n+1)}$$

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”

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



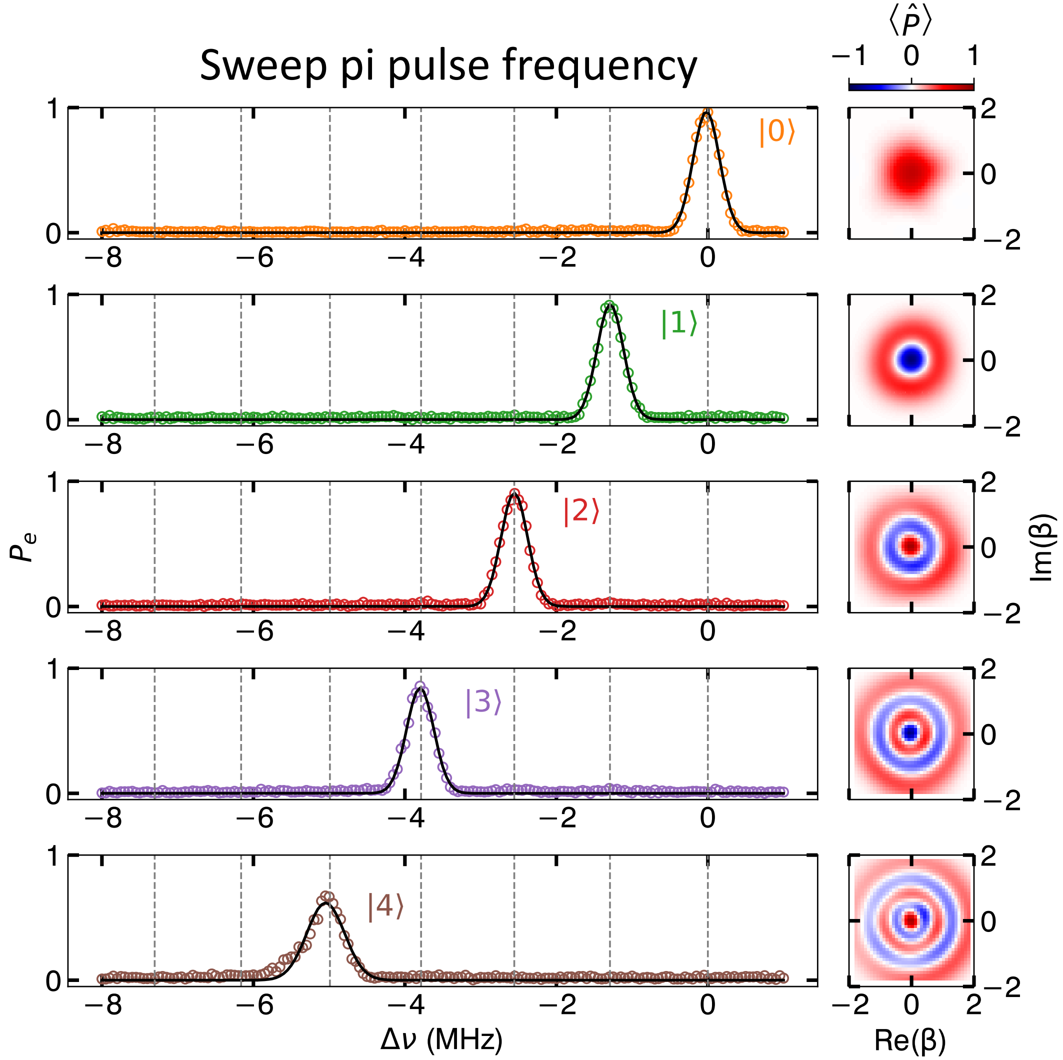


Slide/data from Ankur Agrawal

Verifying the state preparation

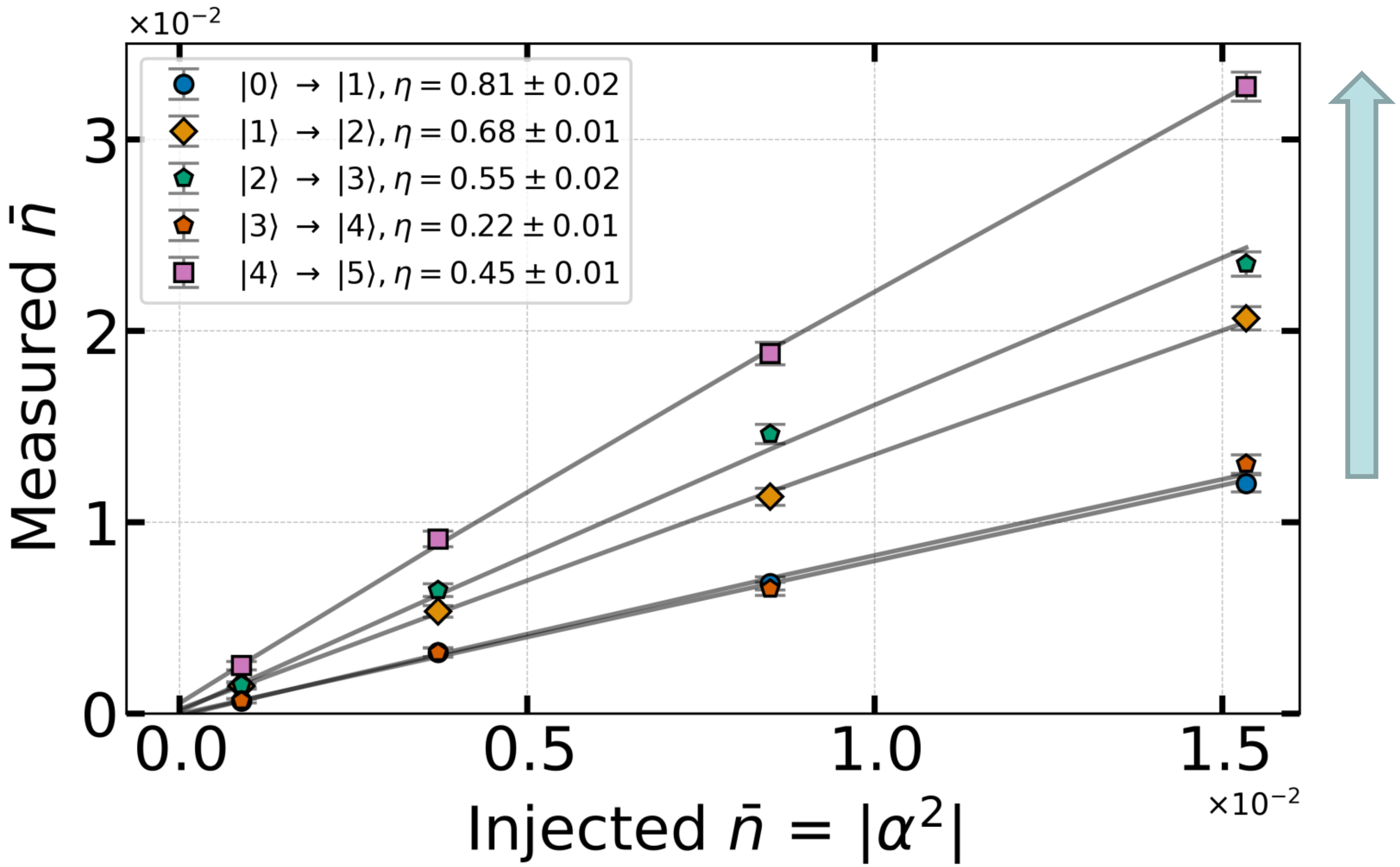
Method 1: Qubit spectroscopy with a number resolved π pulse

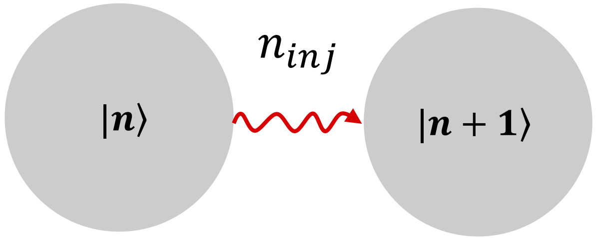
Method 2: Wigner tomography to reconstruct the density matrix



Slide/data from Ankur Agrawal

At fixed drive strength, stimulated emission creates a larger response





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

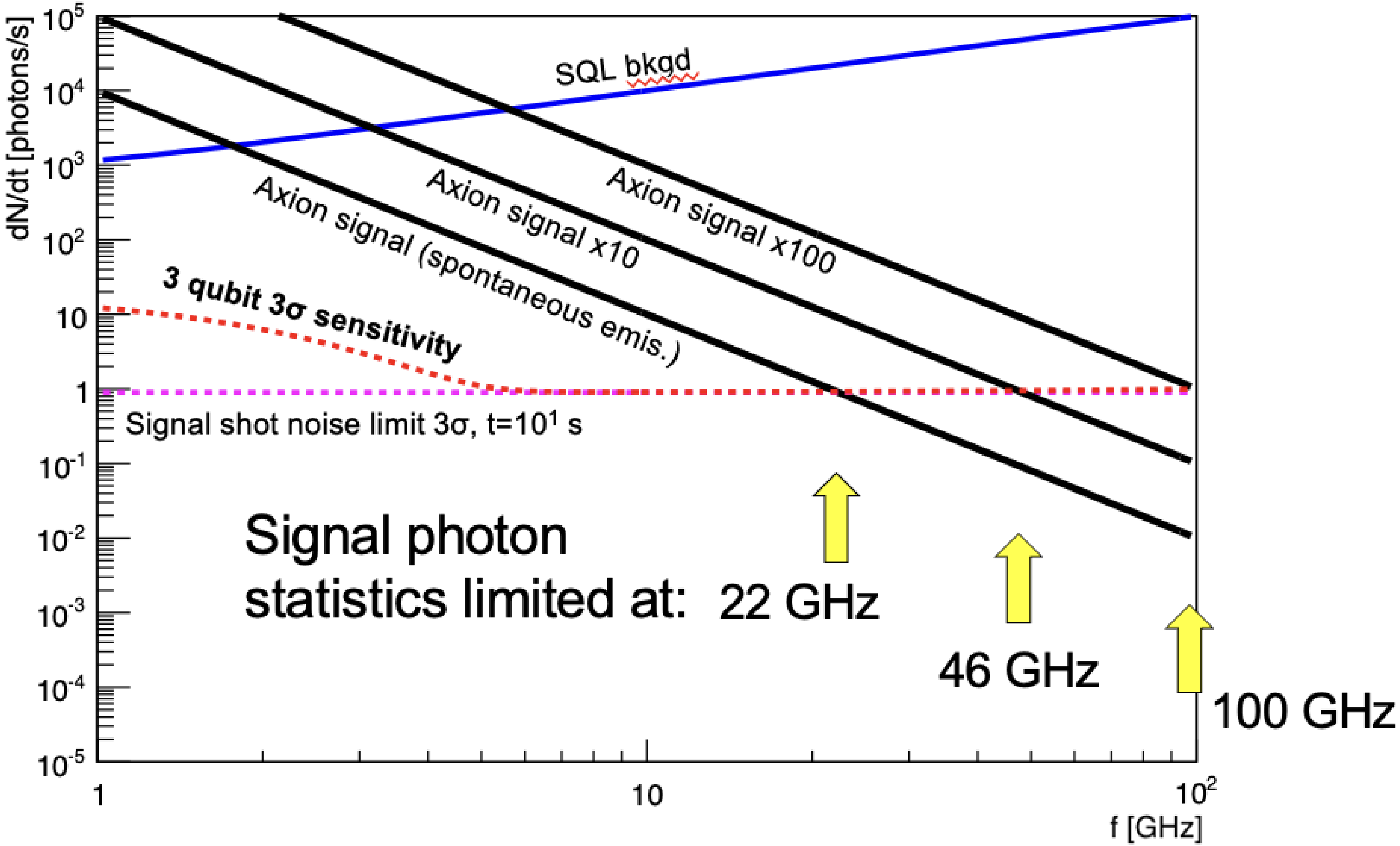
Less than a factor of (n+1) due to measurement inefficiencies.

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

Ankur Agrawal et al., 2305.03700

Using $Q=10^8$ cavities (SC or sapphire), stimulated emission could boost axion signal by factors up to n=100. Trades $Q=10^8 \rightarrow Q/n=10^6$ for large n

Not only increases SNR at lower masses, but also extends range to higher masses!

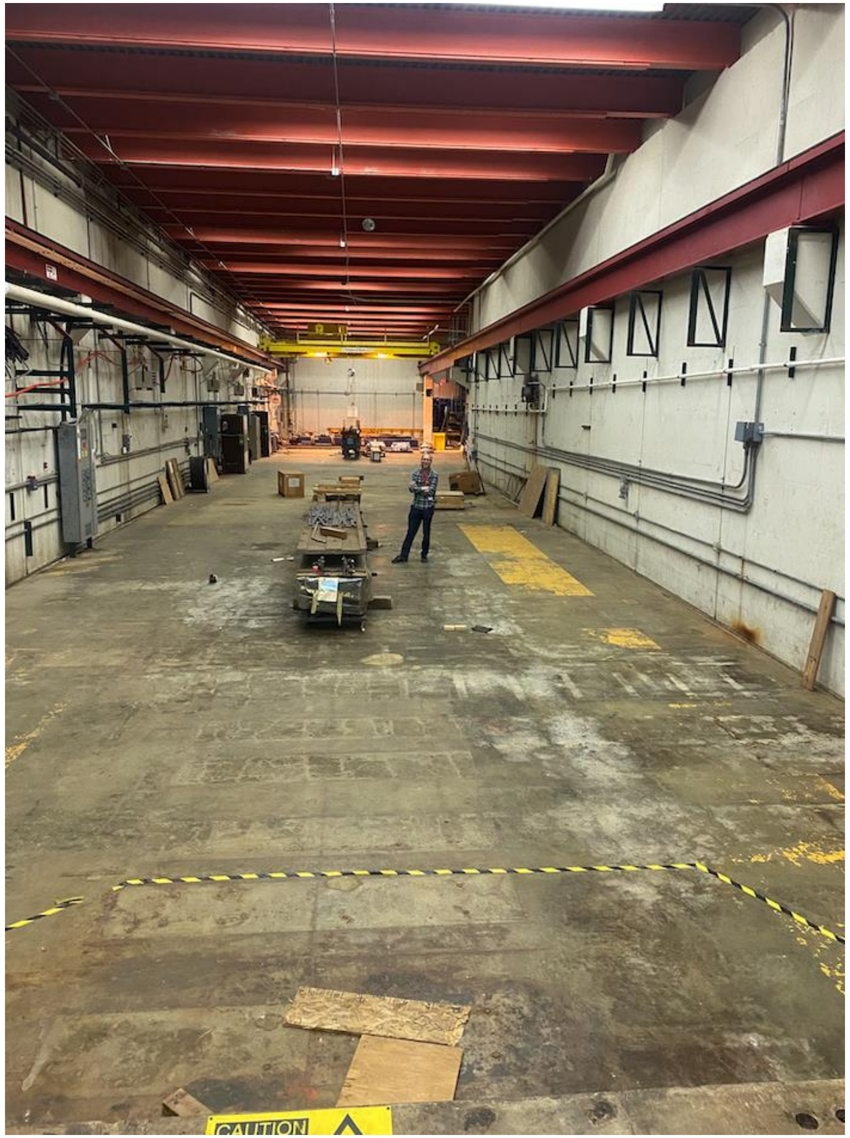


Al qubits limited f<30 GHz → **Need higher frequency qubits made of higher Tc superconductor like NbN.**
Bonus: maybe can operate these in situ in 9 T magnetic field due to higher Hc.

Quantum tricks like squeezing, stimulated emission will give a little boost to SNR, but eventually, we still need to buy/obtain big magnets **to avoid being signal-limited**!

First step: Dark Wave Lab @FNAL

First 9.4 T, warm bore MRI magnet ~$7M to be moved to Fermilab this year for ADMX-EFR. Can host other experiments.



PW8 building can house 2 magnets

Fermilab Dark Wave Lab Workshop

Apr 15 – 16, 2024
Fermilab
US/Central timezone

In this workshop, we will discuss plans for creating a shared facility for axion search experiments at Fermilab.

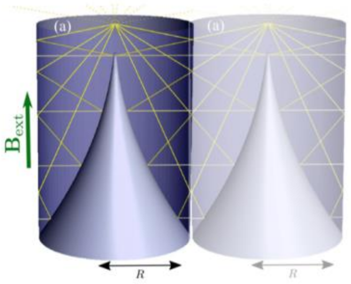
Goals:

- Identify experiments and collaborations that could benefit from common magnet and cryogenic infrastructure.
- Begin to gather requirements for desired lab features and equipment.
- Explore options for early use of the 9.4 Tesla x 800 mm bore solenoid being installed for the ADMX-EFR project. The magnet is expected to be available beginning in 2025, with full ADMX-EFR operations not anticipated before 2028.
- Discuss longer-term options for higher field and larger volume magnets.

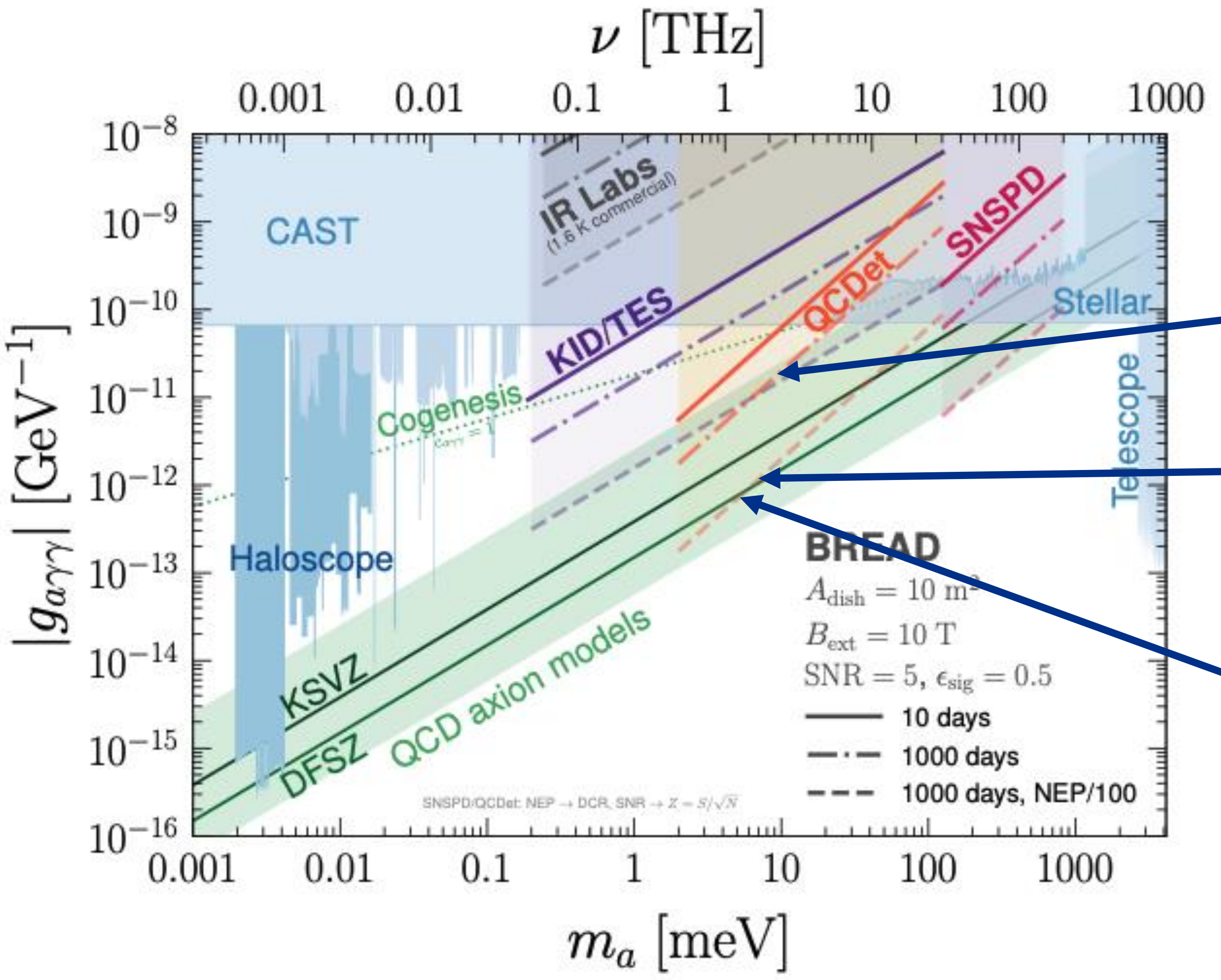
Backup slides

Cannot reject QP backgrounds in detectors that rely on Cooper pair-breaking!

BREAD experiment: Need to reduce best qubit SPD dark count rates by factor 10^4 !!!



photon-axion coupling



Dark Count Rates:

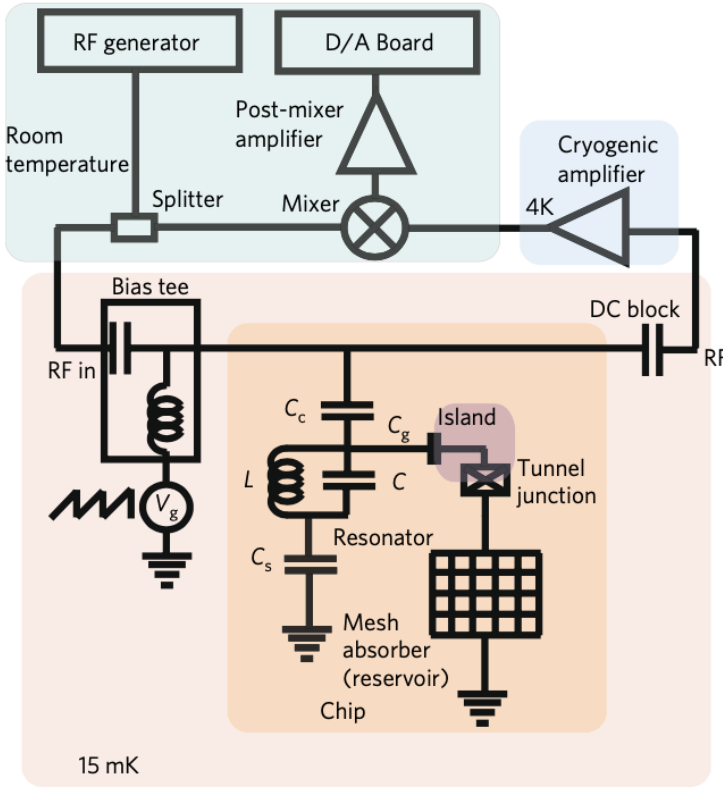
DCR=1 Hz
10^8 counts in t=10^8 s

DCR=10^{-4} Hz **(!)**
10^4 counts in t=10^8 s

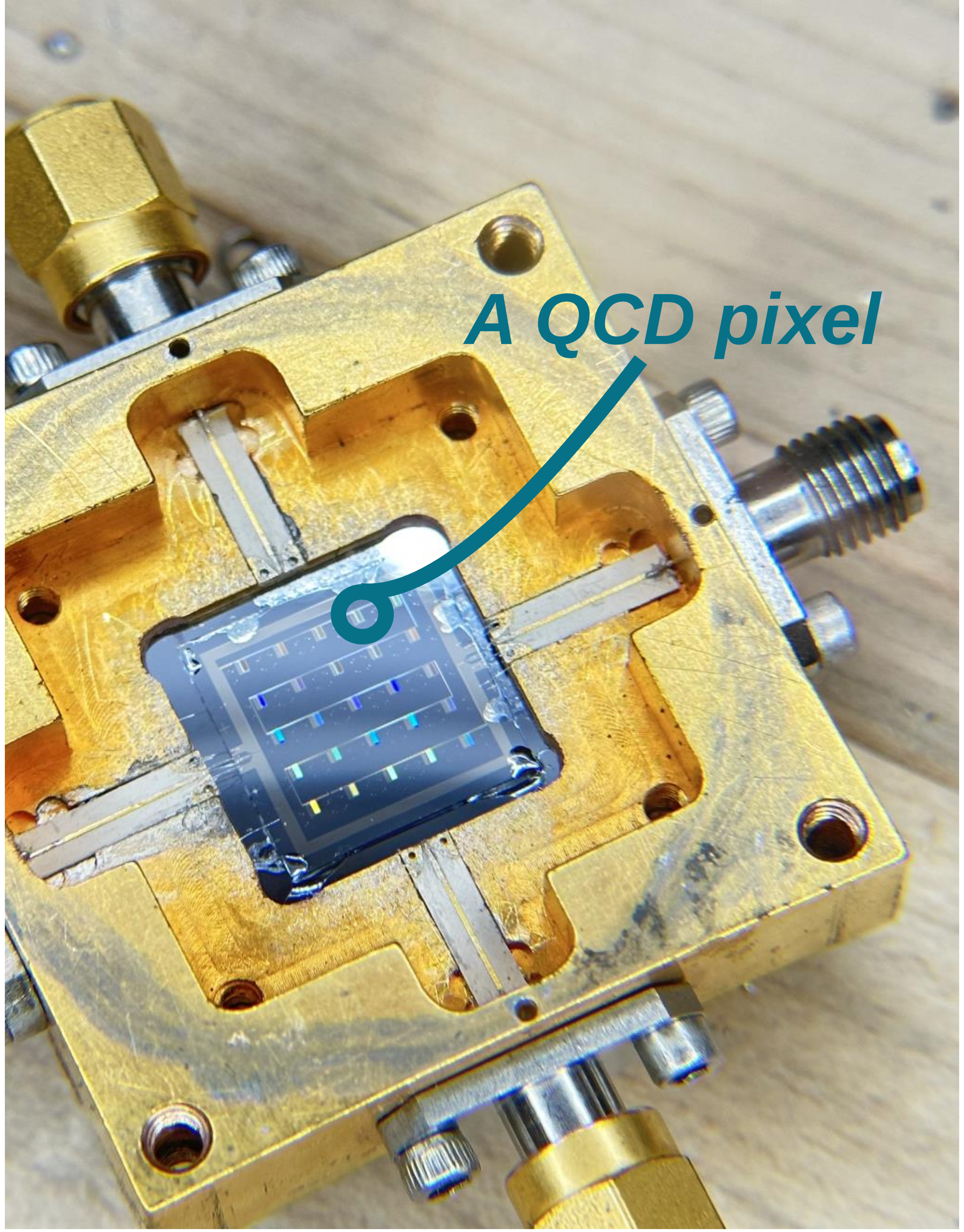
Signal rate
R_s ~ 10^{-6} Hz
100 counts in t=10^8 s
R_s limit ~ sqrt(R_b / t)

Quantum Capacitance Detector based on charge-parity switching in charge qubit.

Detect QPs from broken Cooper pairs after absorption of single THz photon.



Lowest noise-equivalent power of any THz sensor, DCR = 1 Hz



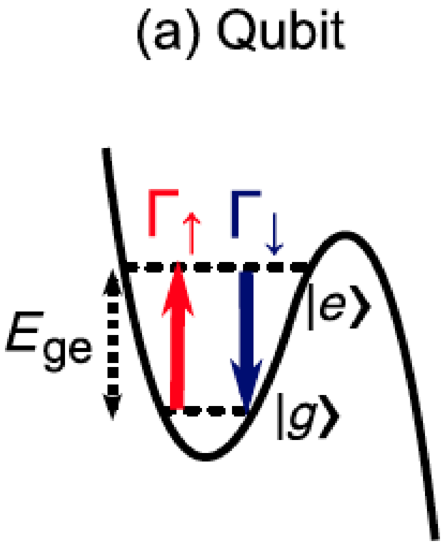
P. Echternach, A. Beyer, and C. Bradford (2021)
https://doi.org/10.1117/1.JATIS.7.1.011003

Echternach, P. M., et al. *Nature Astronomy* 2.1 (2018): 90-97.

Backgrounds for single photon / phonon detectors

Unwanted electron-like quasiparticles from broken Cooper pairs are a direct background for qubit-based photon/phonon detectors. They scramble the information stored these single quantum Cooper pair oscillators.

Potential energy diagram for qubit



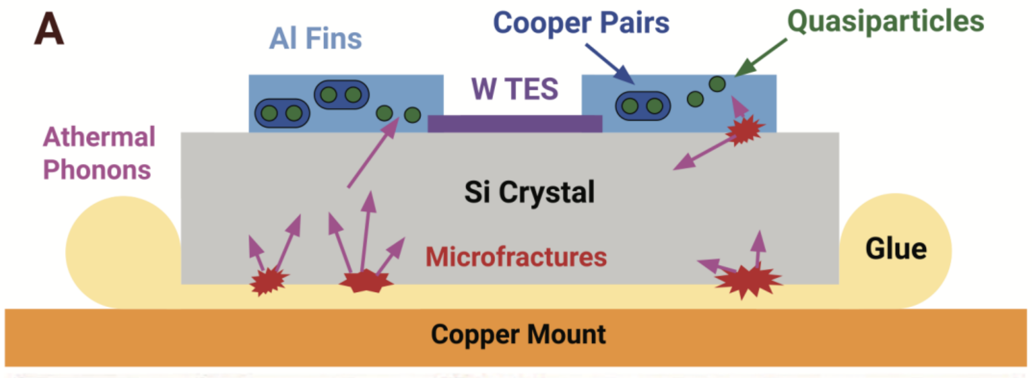
J. Wenner, et al., PRL 110, 150502 (2013)

No fair playing Dodgeball when kid is stuck in the swing!

A quasiparticle tunneling through the Josephson junction transfers energy/momentum from/to the qubit oscillator. This changes the qubit's state and creates a false positive detection.

Qubits are also great phonon sensors:

Acoustic noise from substrate microfracture events are currently far worse than ionizing radiation!

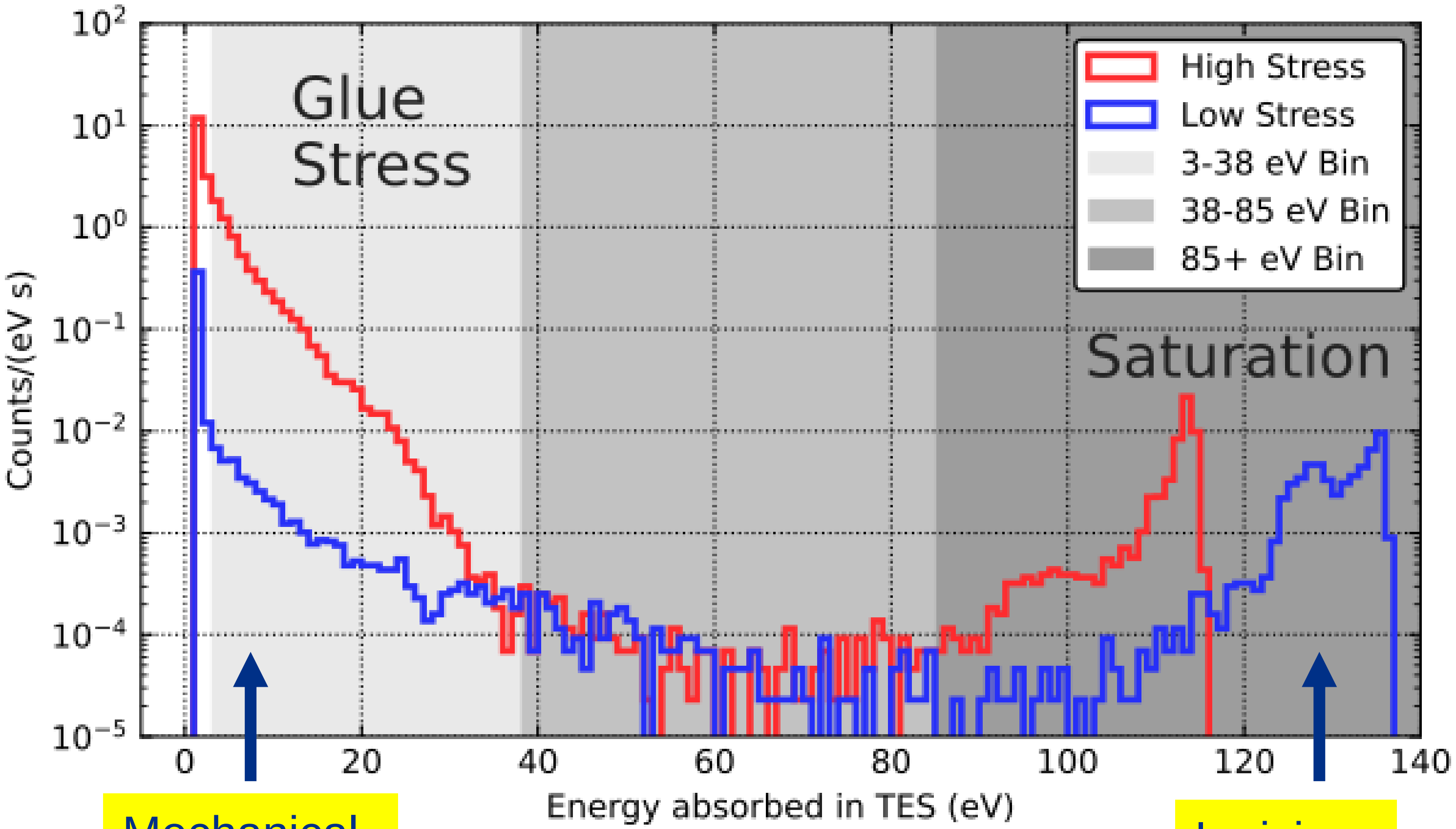


R. Anthony-Petersen… M. Pyle, et al.,
arxiv:2208.02790

Measure spectrum using tiny, cold, low heat capacity TES sensors developed for the SuperCDMS dark matter search.

Next-generation microcalorimeters will reduce thresholds to milli-eV, provide first look at sub-eV spectrum.

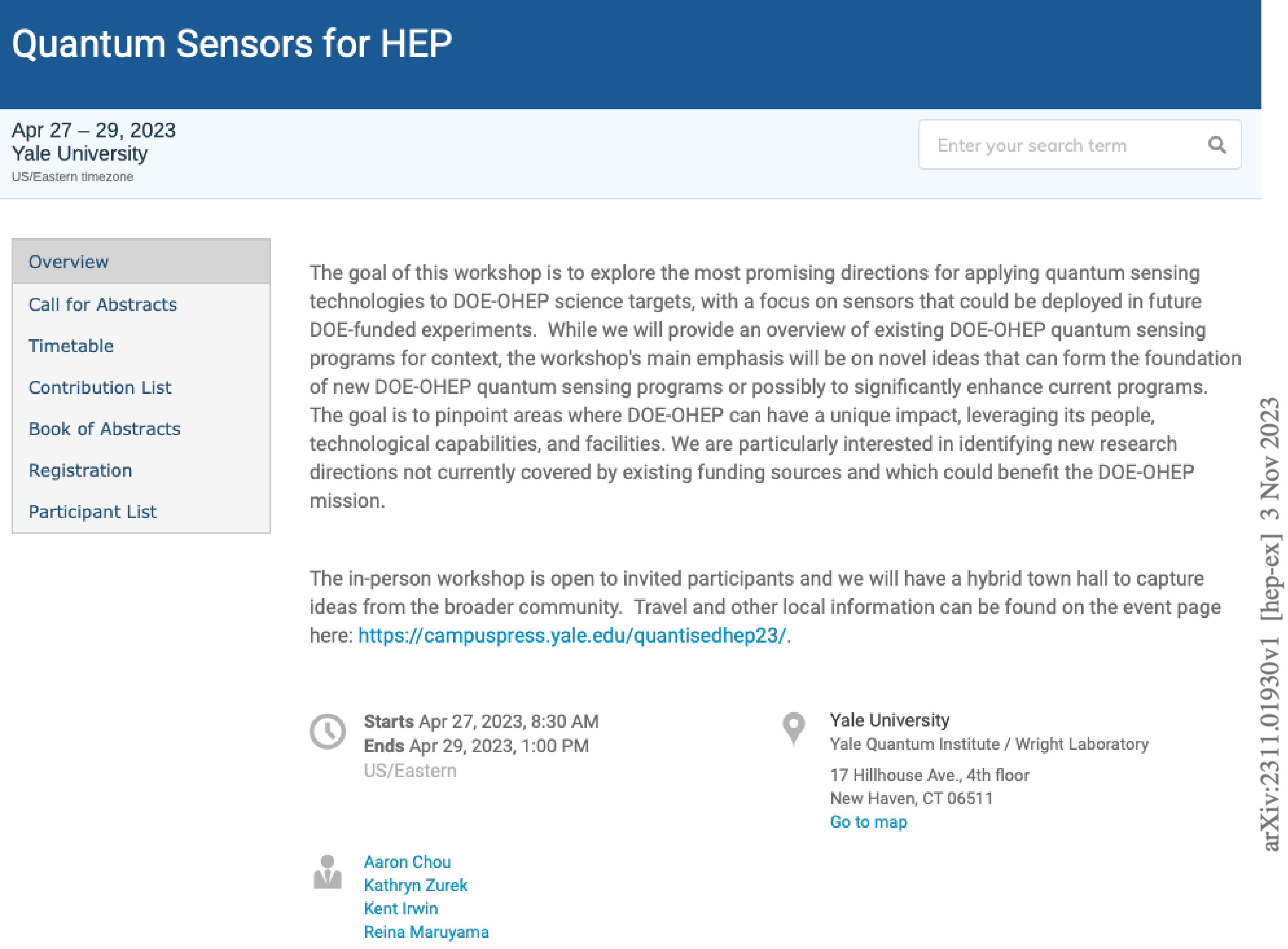
Mitigating these low energy disturbances will be critical to achieving low dark count rates in low threshold single photon/phonon detectors.



Mechanical noise

Ionizing radiation

Workshop to define strategy for the US HEP quantum sensors program



Quantum Sensors for HEP

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

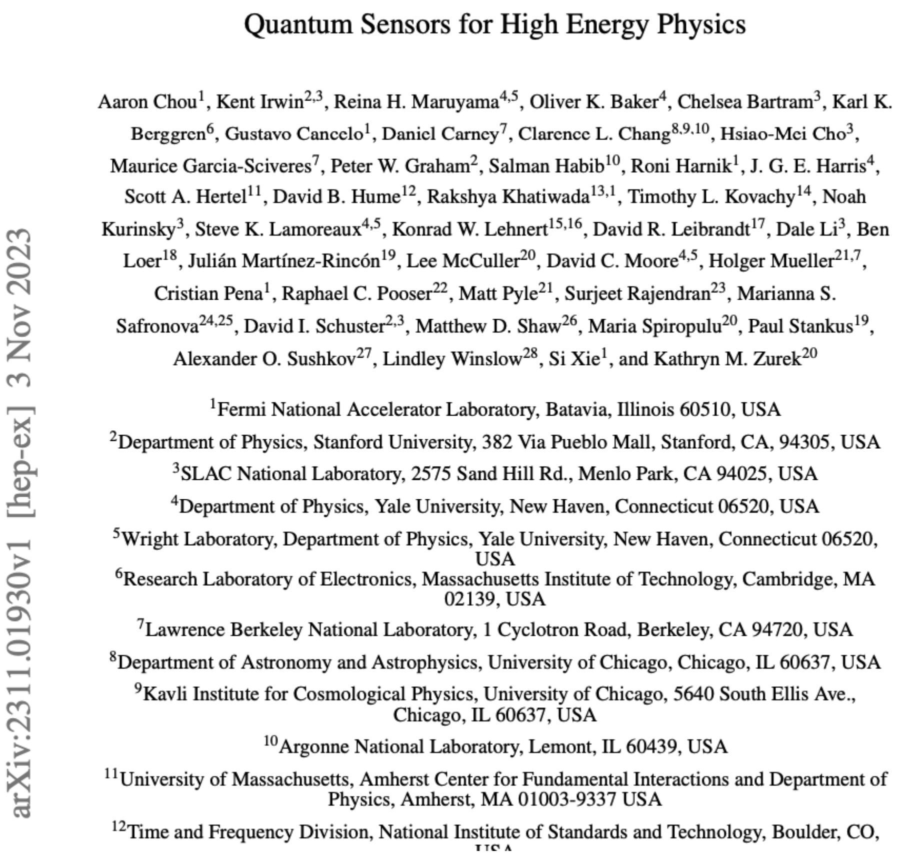
The goal of this workshop is to explore the most promising directions for applying quantum sensing technologies to DOE-OHEP science targets, with a focus on sensors that could be deployed in future DOE-funded experiments. While we will provide an overview of existing DOE-OHEP quantum sensing programs 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, 8:30 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



Quantum Sensors for High Energy Physics

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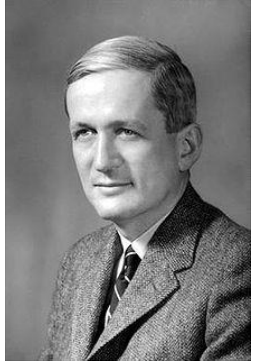
QCD axion motivated by the Strong-CP Problem:

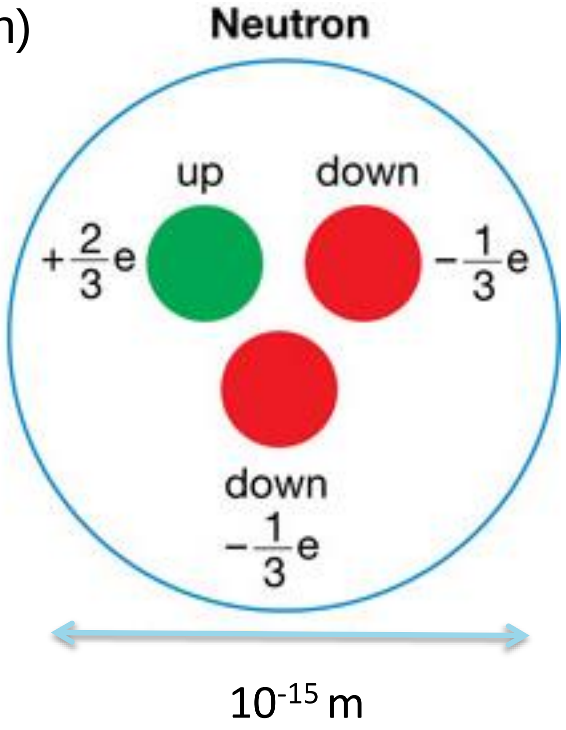
Why is the neutron electric dipole moment so small?

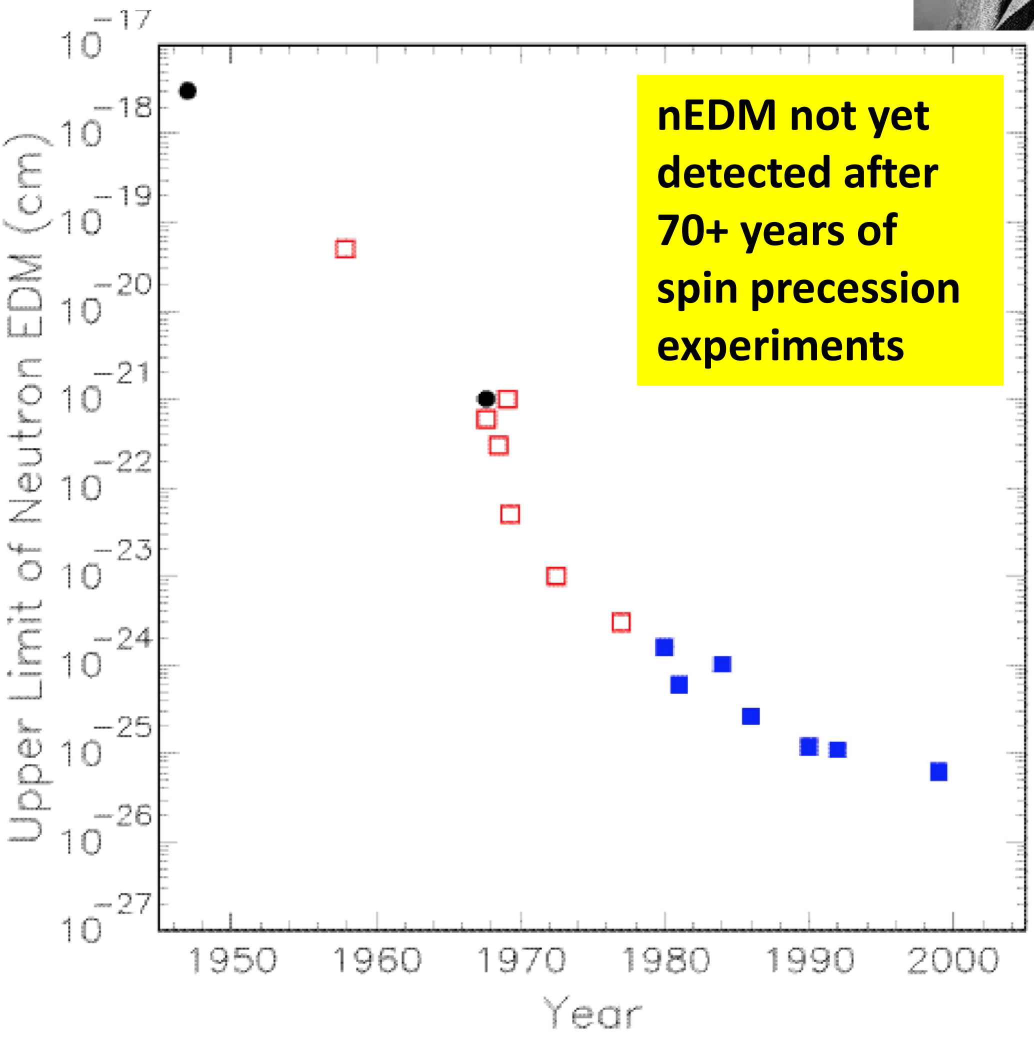


Norman Ramsey
Nobel Prize 1989

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

Violates both:
P (spatial inversion)
CP (time reversal)



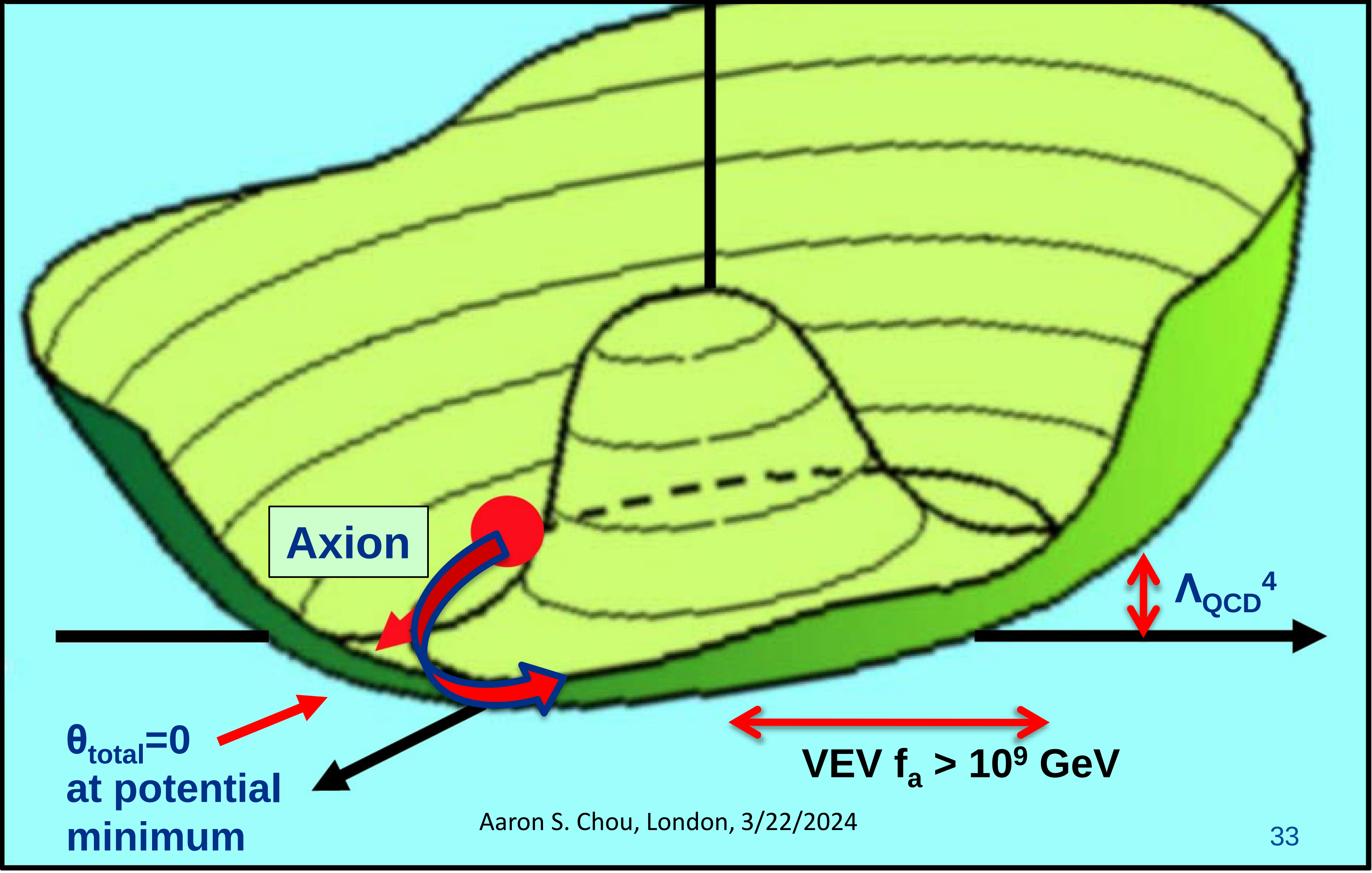


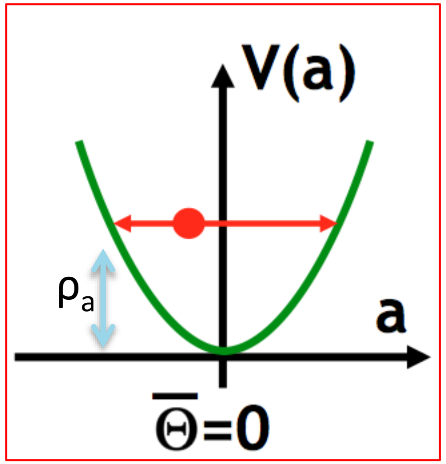
nEDM not yet detected after 70+ years of spin precession experiments

Need CP-violating phase angle θ to create charge asymmetry. But QCD theory contains this!

Natural cosmological potential energy function would cause a putative dynamical axion field A to zero out the CP-violating angle θ_{total}

$$V(A) = -f_a^2 A^2 + \frac{\lambda}{4!}A^4 + \left(\frac{g^2}{32\pi^2}\arg(A) - \frac{\alpha_s}{8\pi}\left(q_{QCD} + q_{quark}\right)\right)\langle G\tilde{G}\rangle$$





Cosmological feedback loop zeroes out $\langle\theta_{CP}\rangle$ to explain the vanishing of the neutron EDM

QCD phase transition creates residual oscillations of the QCD θ angle about its CP-conserving minimum:

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

Local axion density

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

DM oscillations partially undo the Peccei-Quinn mechanism by enabling the coherent field to climb out of the potential minimum. **Signal strength suppressed by Λ_{QCD}, not by f_a.**

Phenomenology based on a classically oscillating CP-violating angle which:

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