Title: Searching for Dark Matter with Superconducting Qubits - Akash Dixit

Speakers: Akash Dixit

Series: Particle Physics

Date: February 12, 2021 - 1:00 PM

URL: http://pirsa.org/21020018

Abstract: Detection mechanisms for low mass bosonic dark matter candidates, such the axion or hidden photon, leverage potential interactions with electromagnetic fields, whereby the dark matter (of unknown mass) on rare occasion converts into a single photon. Current dark matter searches operating at microwave frequencies use a resonant cavity to coherently accumulate the field sourced by the dark matter and a near standard quantum limited (SQL) linear amplifier to read out the cavity signal. To further increase sensitivity to the dark matter signal, sub-SQL detection techniques are required. Here we report the development of a novel microwave photon counting technique and a new exclusion limit on hidden photon dark matter. We operate a superconducting qubit to make repeated quantum non-demolition measurements of cavity photons and apply a hidden Markov model analysis to reduce the noise to 15.7 dB below the quantum limit, with overall detector performance limited by a residual background of real photons. With the present device, we perform a hidden photon search and constrain the kinetic mixing angle to â‰¤ 1.68Ã—10âˆ'15 in a band around 6.011 GHz (24.86 Î¼eV) with an integration time of 8.33 s. This demonstrated noise reduction technique enables future dark matter searches to be sped up by a factor of 1300. By coupling a qubit to an arbitrary quantum sensor, more general sub-SQL metrology is possible with the techniques presented in this work.

Searching for dark matter with a superconducting qubit

Akash V. Dixit

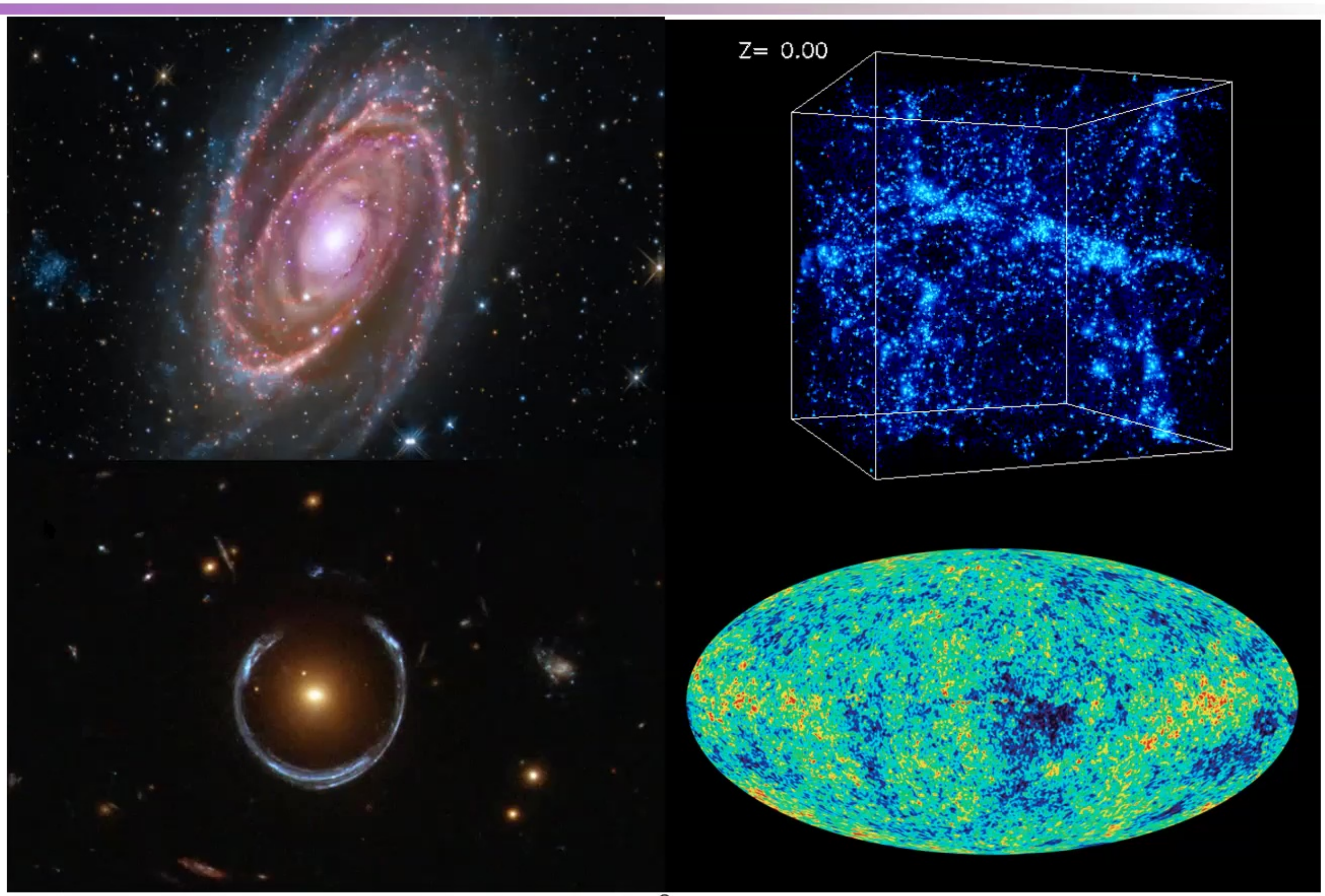
Srivatsan Chakram, Kevin He, Ravi K. Naik, Ankur Agrawal, Aaron Chou, David I. Schuster

University of Chicago
avdixit@uchicago.edu

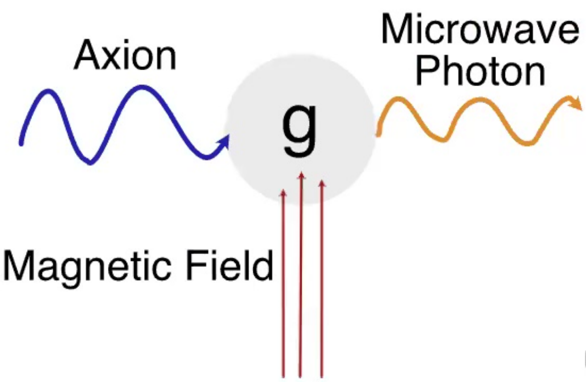
Outline of talk

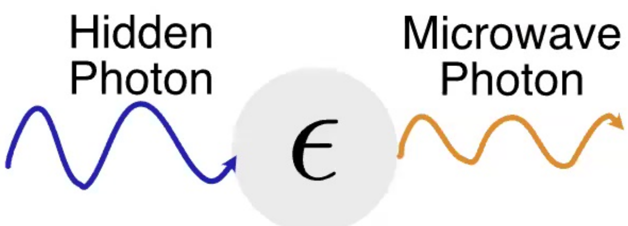
- Coupling to low mass bosonic dark matter
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search

What's the deal with dark matter



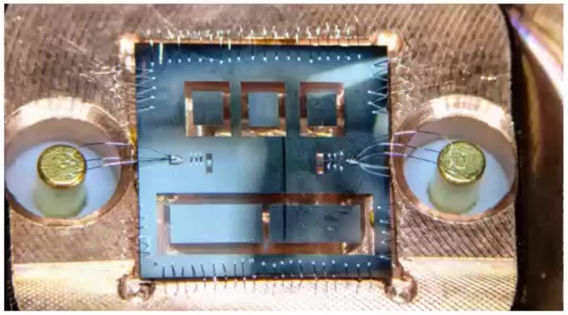
How dark matter might couple to electromagnetism





Resonant cavity to capture signal

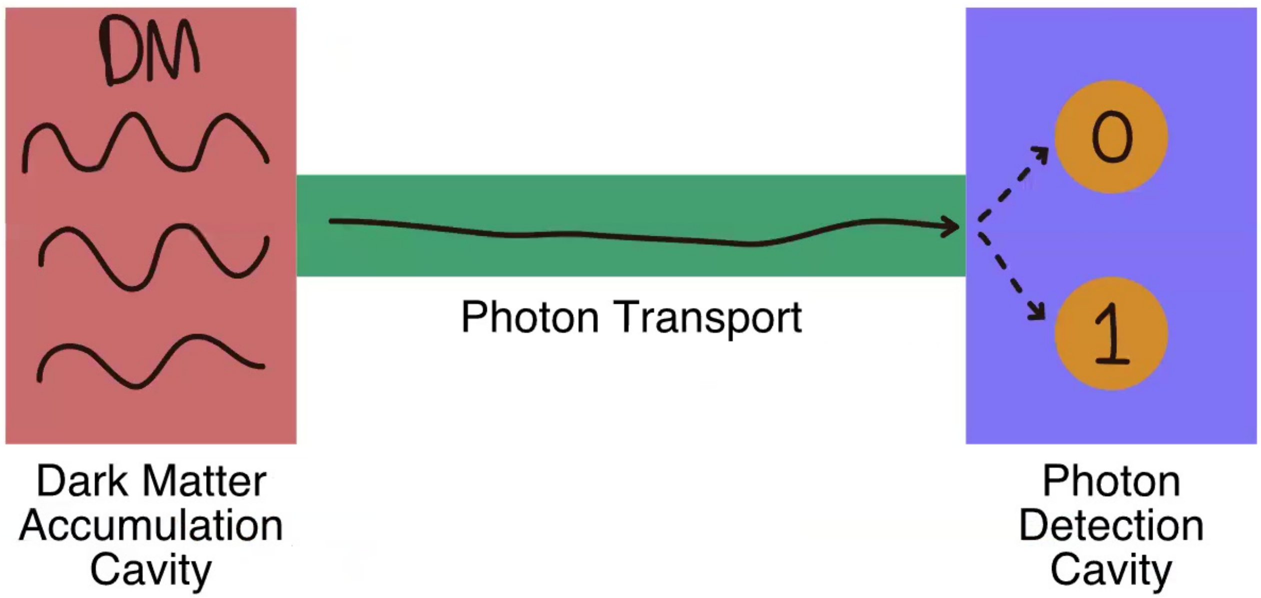
Quantum limited amplifier for readout



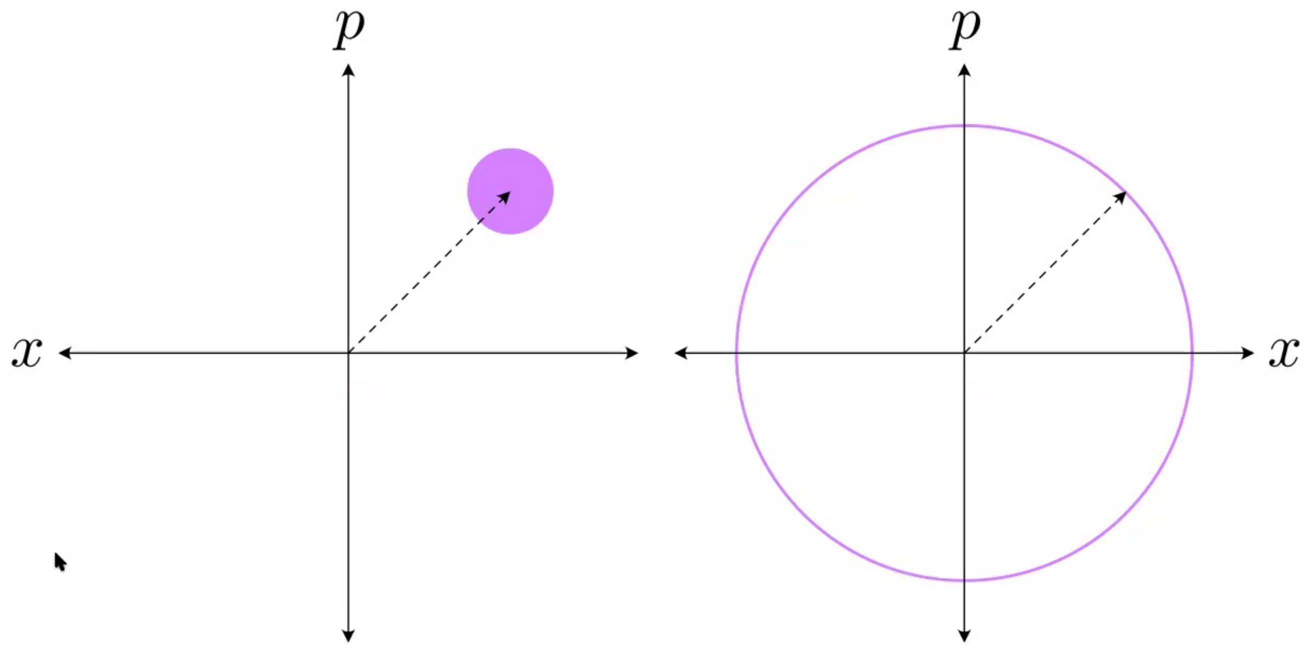
4

Dark matter detection strategy

arxiv:2008.12231



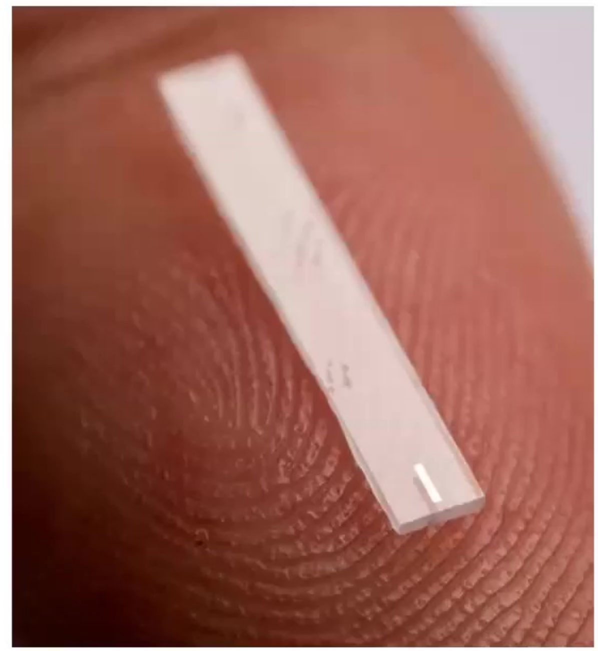
Count photons to subvert quantum limit



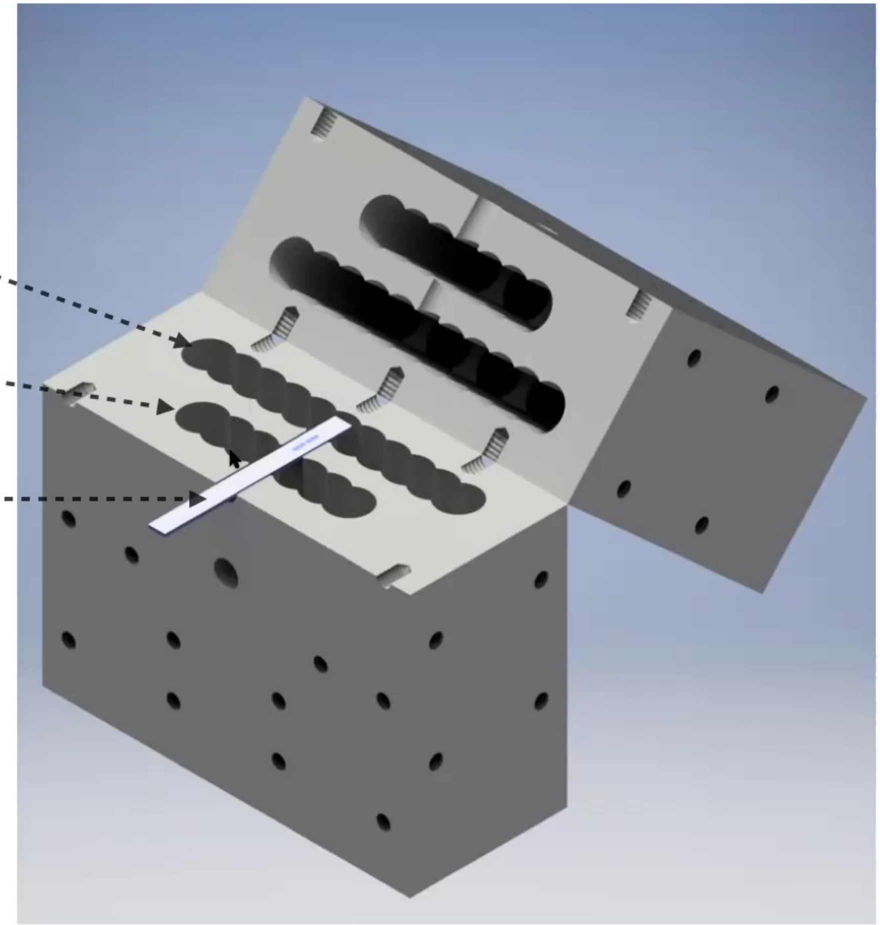
Circumvent quantum limit by counting photons. Phase space area is preserved.

Outline of talk

- Setup for detecting low mass dark matter
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search



Photon counting device



Storage Cavity 6.011 GHz

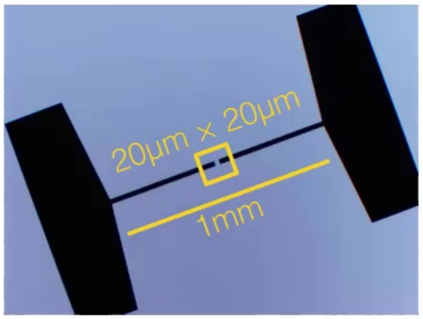
Readout Cavity 8.052 GHz

Qubit on sapphire chip 4.749 GHz

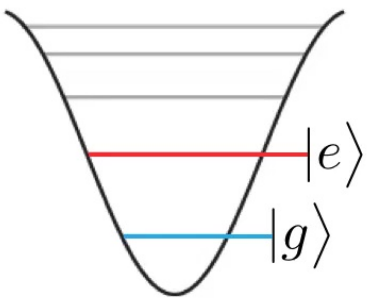
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Operated in a dilution refrigerator @ 8mK

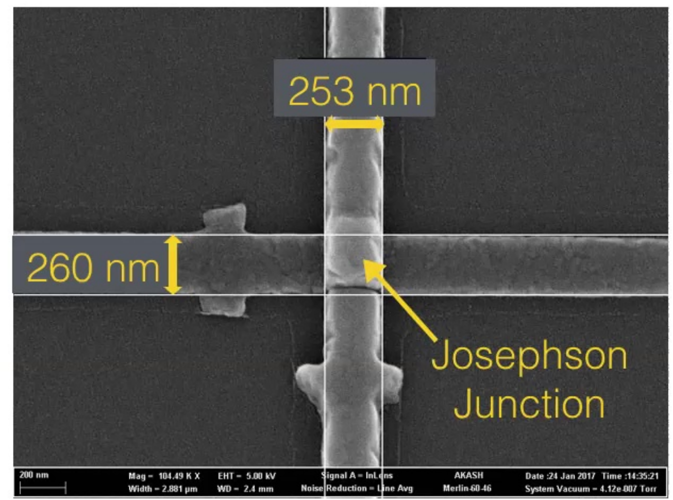
Building a superconducting qubit



$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

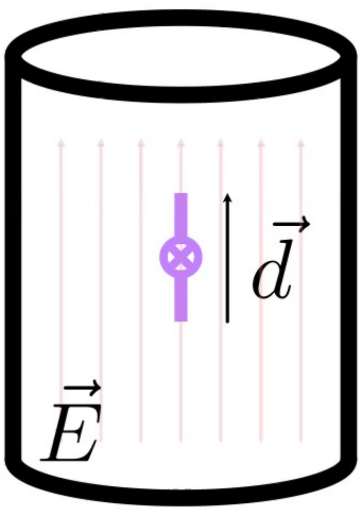


Harmonic Oscillator (LC) +
nonlinearity (Josephson Junction)



9

Engineering the qubit-cavity interaction



$$\mathcal{H}_{int} = \vec{d} \cdot \vec{E}$$
$$= g(\sigma_+ + \sigma_-)(a + a^\dagger)$$
$$\sim 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Two-level spin

$$\chi = \frac{g^2}{\Delta}$$

Transmon qubit

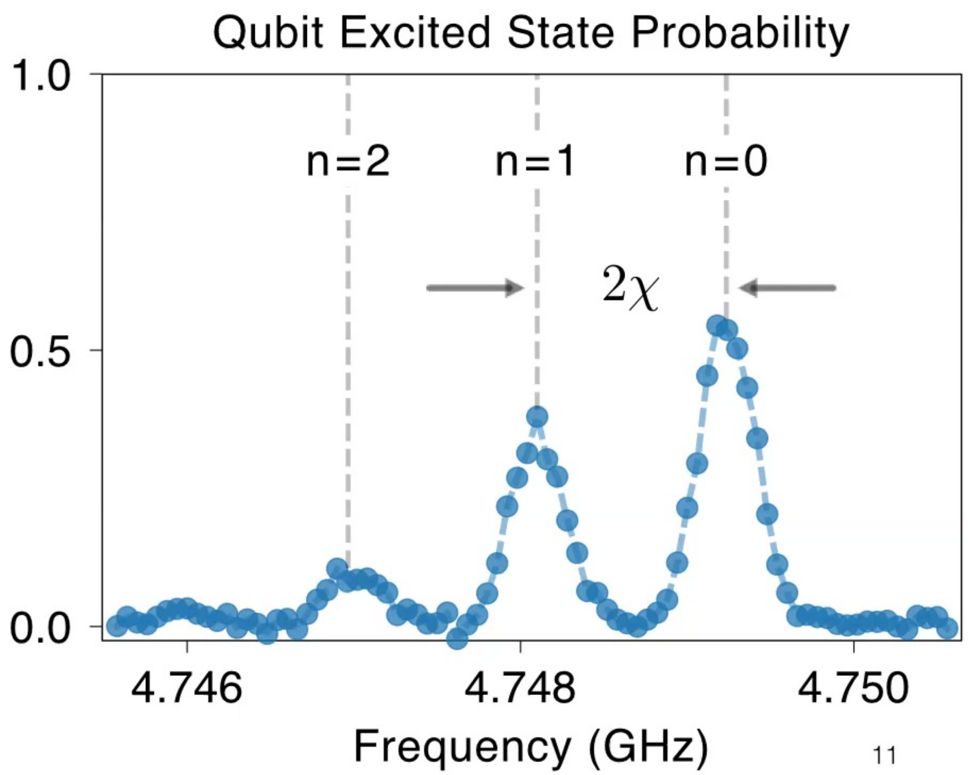
$$\chi = \frac{g^2}{\Delta(\Delta + \alpha)}\alpha$$

Δ qubit-cavity detuning

α qubit anharmonicity

Cavity occupation imprinted on qubit transition frequency

$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

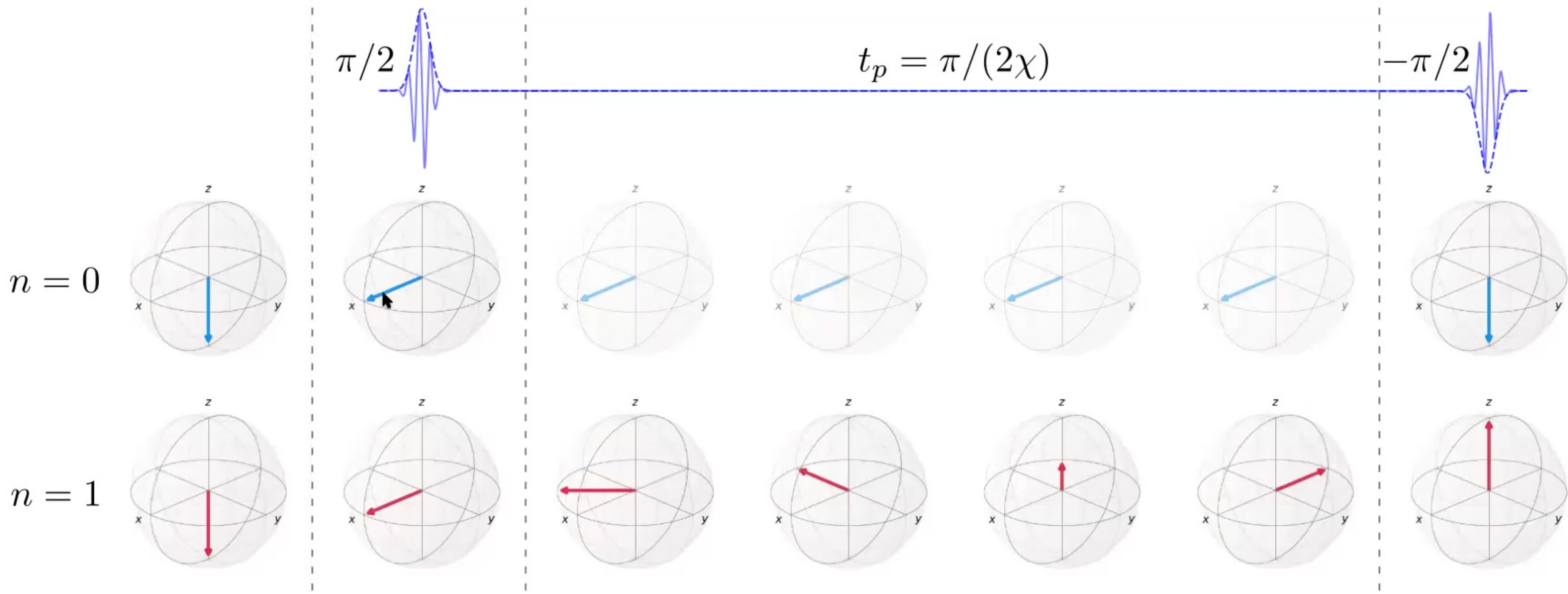


11

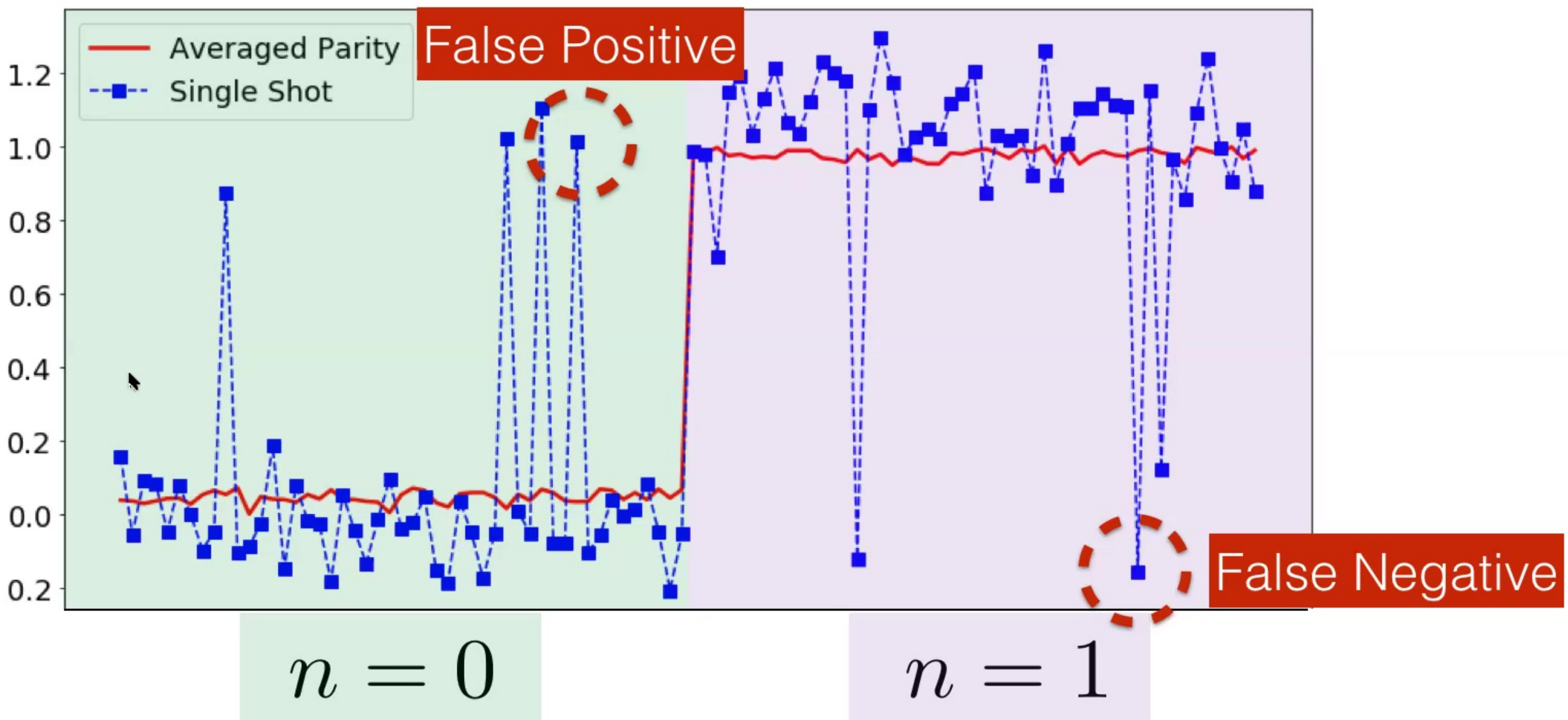
Qubit transition frequency is photon number dependent

Perform Ramsey type measurement on qubit frequency to infer cavity photon number

Parity measurement maps cavity state onto qubit

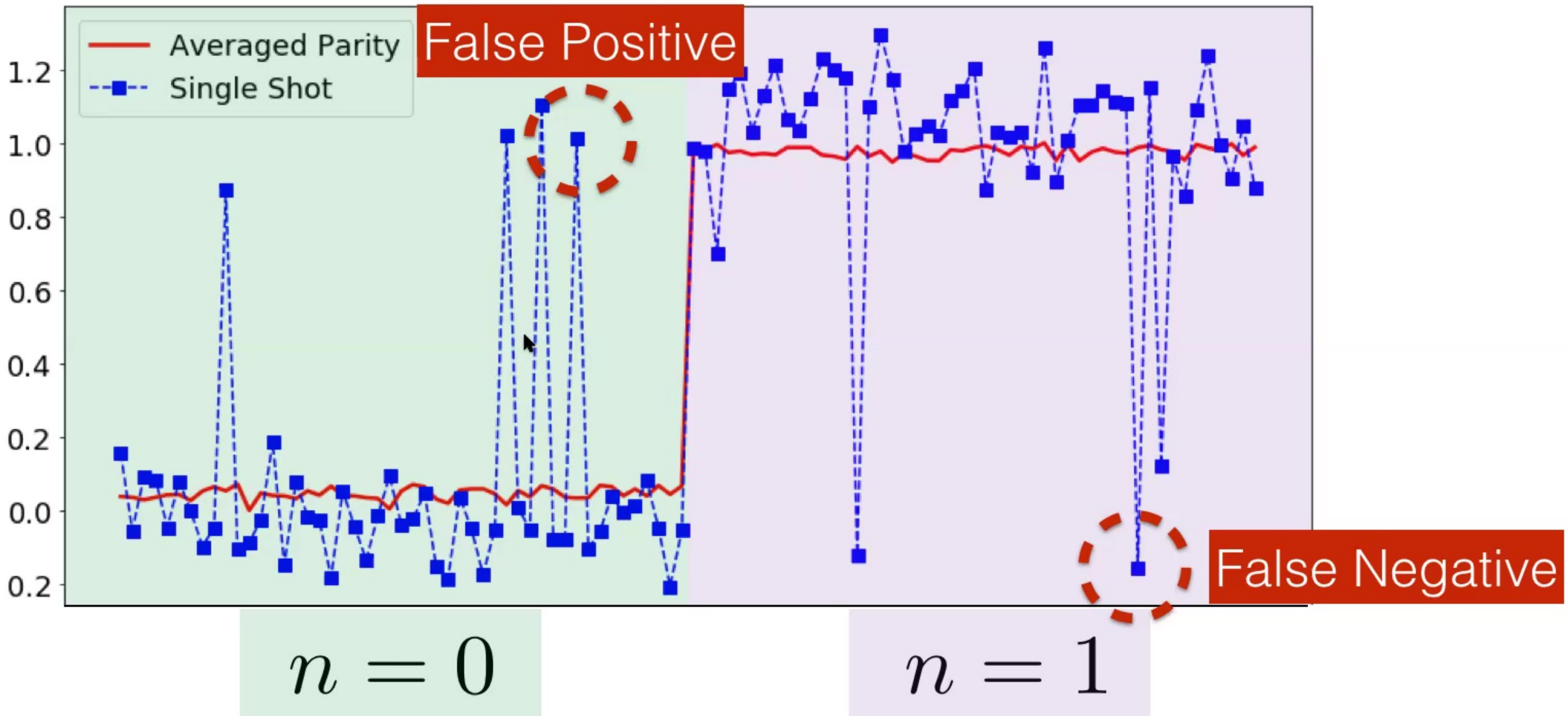


Qubit makes too many errors



Spurious qubit excitations are dominant source of errors

Qubit makes too many errors

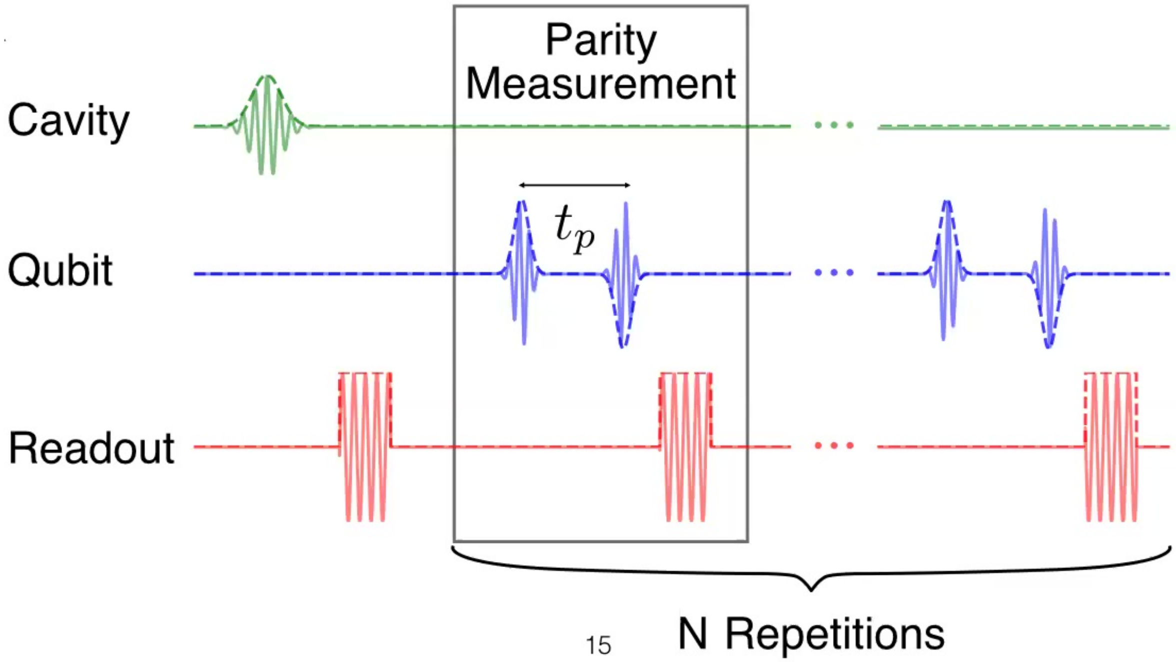


Spurious qubit excitations are dominant source of errors

Mitigate errors by making repeated measurements

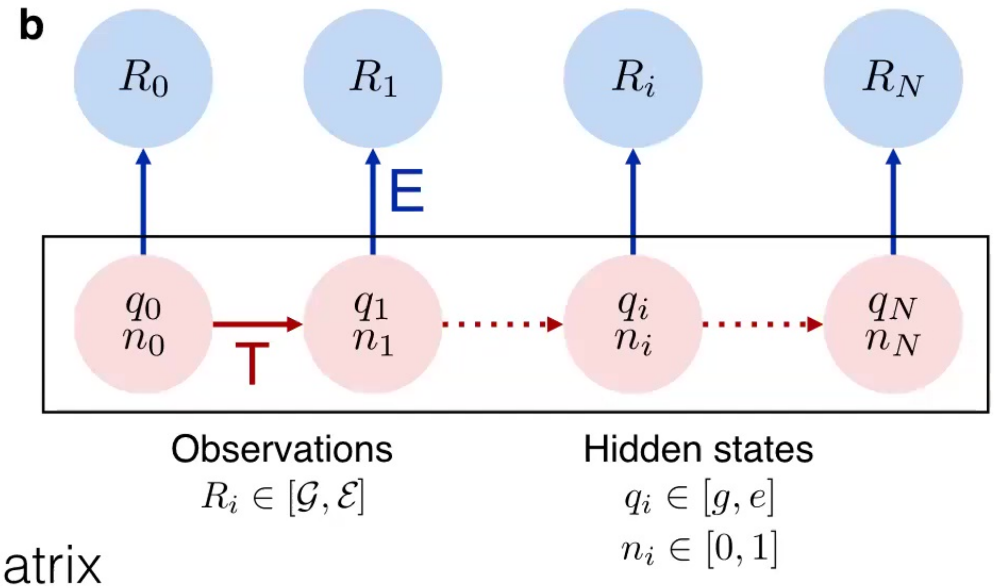
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Qubit-Cavity interaction is QND, make multiple measurements of the same photon



15

Use hidden Markov model to describe cavity and qubit evolution



T = Transition matrix

- qubit ($108\mu s$), cavity ($546\mu s$) lifetime
- qubit spurious population (0.05)
- time between experiments ($10\mu s$)
- qubit dephasing ($T_2 = 61\mu s$)
- parity time ($t_p = 0.4\mu s$)

E = Emission matrix

- ground and excited state readout fidelity (~0.95)

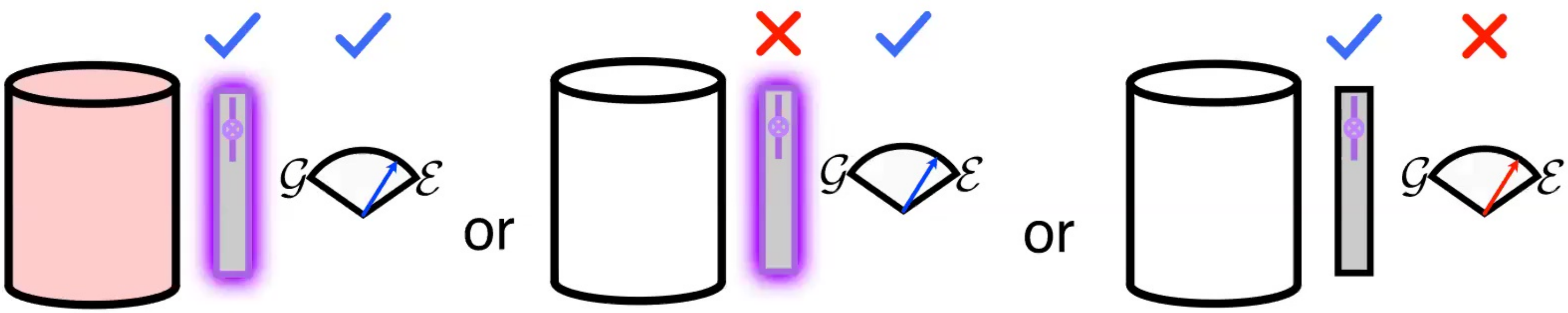
16

arxiv:1607.02529

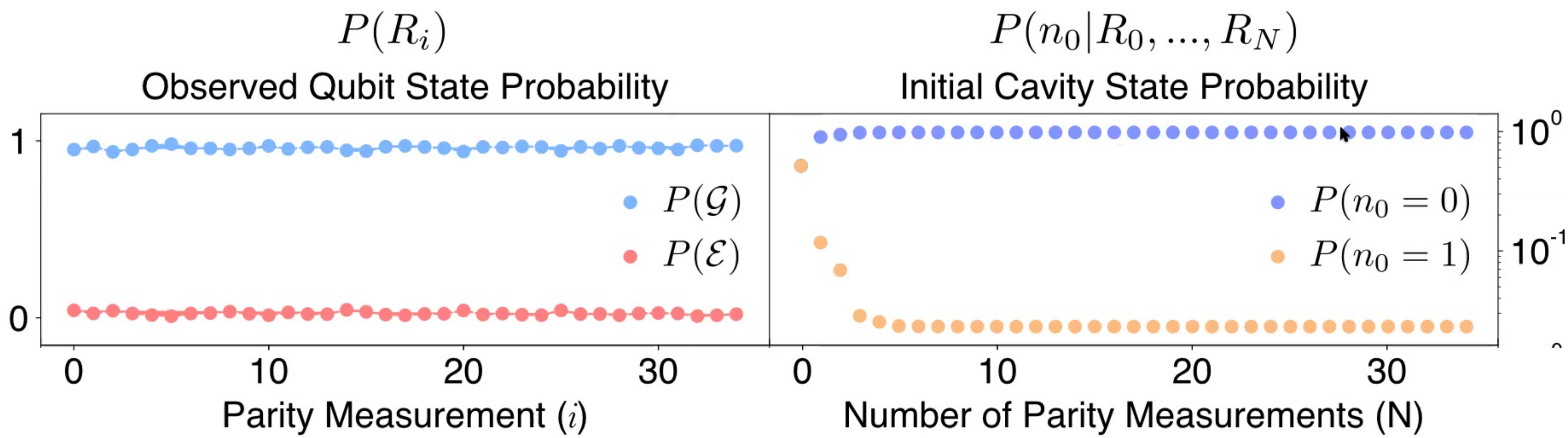
Reconstruction cavity state

$$P(n_0) = \sum_{s_0 \in [(n_0,g),(n_0,e)]} \sum_{s_1} \cdots \sum_{s_N} E_{s_0,R_0} T_{s_0,s_1} E_{s_1,R_1} \ldots T_{s_{N-1},s_N} E_{s_N,R_N}$$

Observed readout sequence: $\mathcal{G} \rightarrow \mathcal{E}$

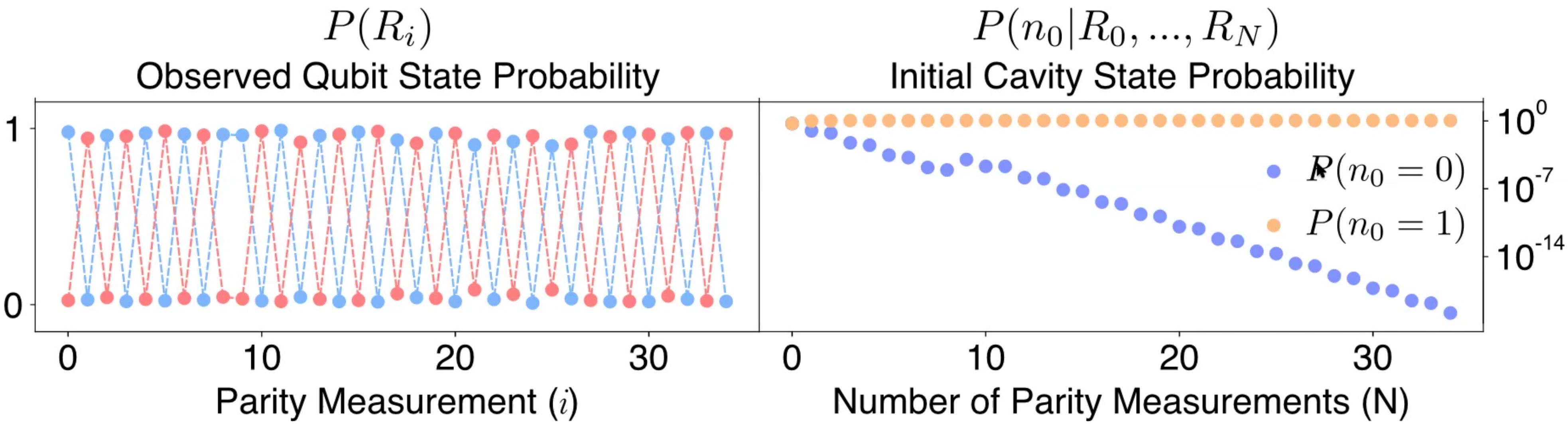


Detector response in the presence of zero photons



18

Detector response in the presence of one photon

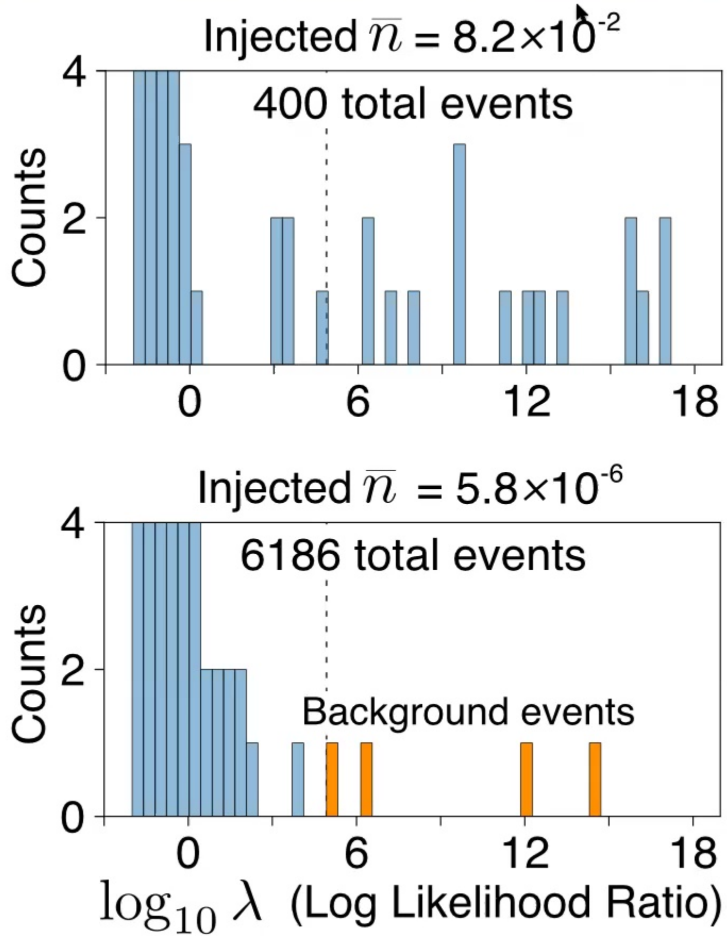


Exponential suppression of detector based false positives

Outline of talk

- Setup for detecting low mass dark matter
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search

False positives are background events



Photons detected when none are injected

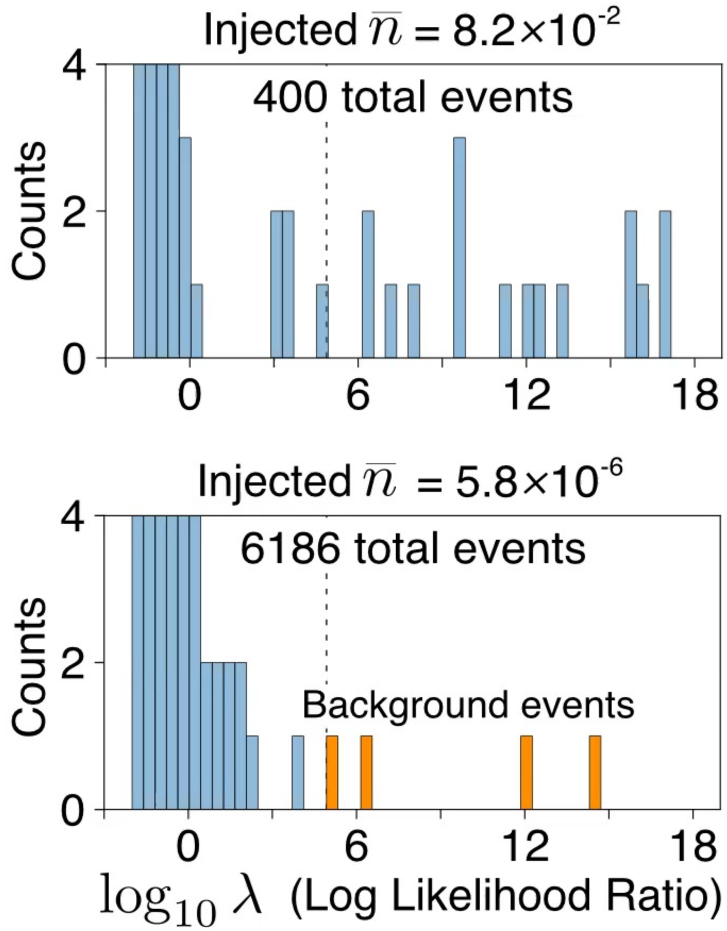
Eliminated detector errors as a source of false positives

Entered a new, background limited regime

$$\bar{n}_c = 7.3 \times 10^{-4}$$

22

False positives are background events



Photons detected when none are injected

Eliminated detector errors as a source of false positives

Entered a new, background limited regime

$$\bar{n}_c = 7.3 \times 10^{-4}$$

22

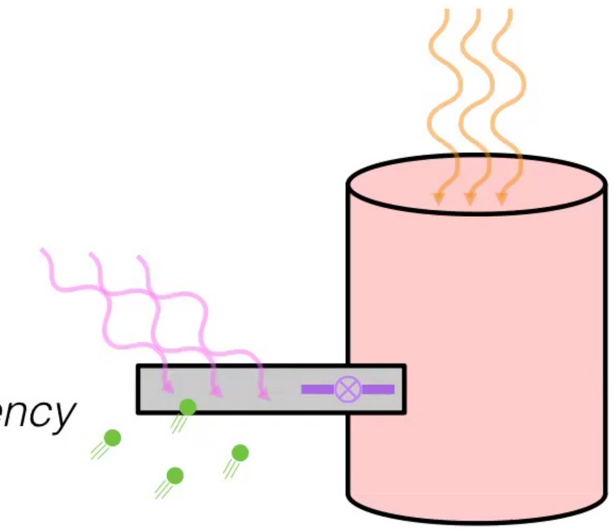
Experiment is 1000 times faster with a qubit

$$R_s t > \sqrt{R_b t}$$

$$t > \frac{R_b}{R_s^2}$$

1300 X lower background rate than SQL ⇒ 1300 X less integration time required

Background sources and mitigation strategies



Photons coming down lines

- more attenuation and filtering
- better thermalization of components

Spurious qubit excitations convert to photons
Sourced by terrestrial and cosmogenic radiation, high frequency photons

- gap engineering
- quasiparticle trapping
- new materials (Ta, Nb, TiN)

TLS and maybe more

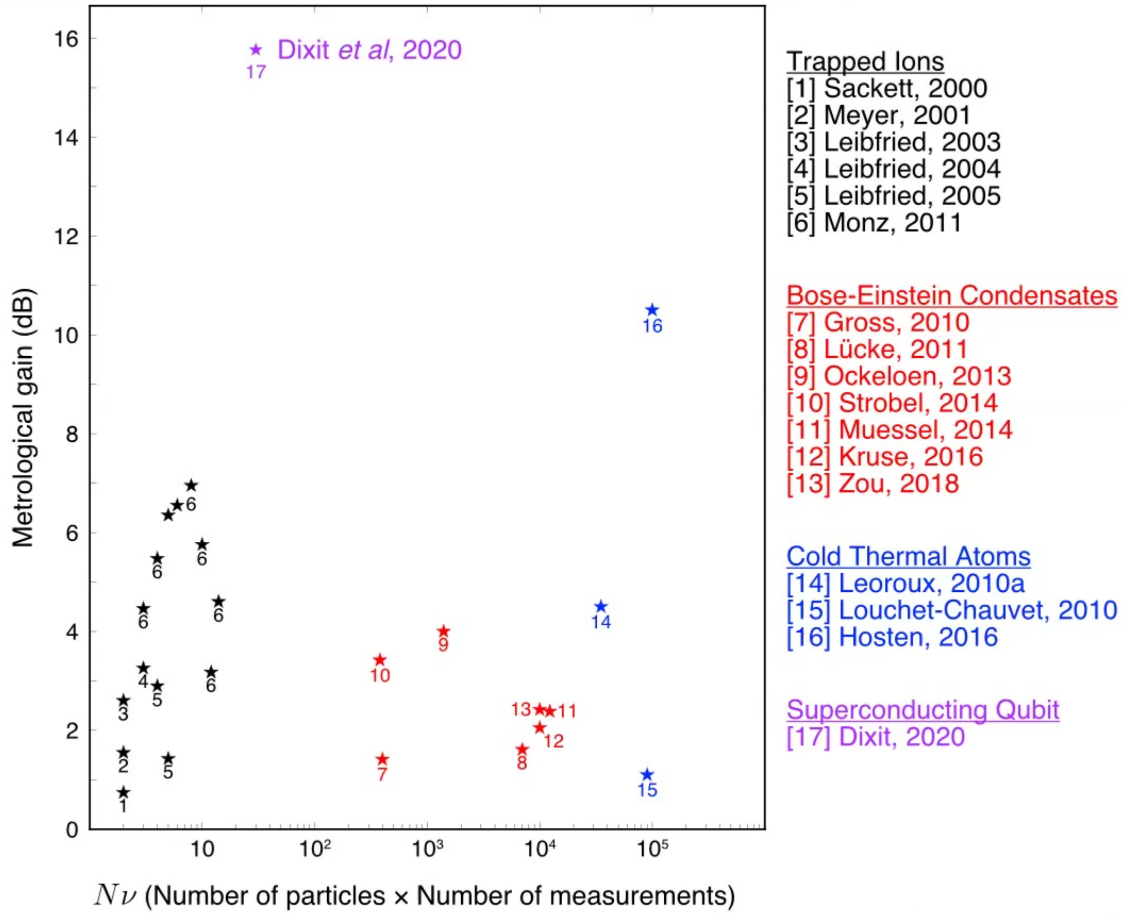
J.of App. Phys. 121, 224501 (2017)
Phys. Rev. Applied 11, 014031
Phys. Rev. B 94, 104516
Nature 584, 551–556(2020)
Phys. Rev. B 100, 140503(R)
Phys. Rev. Lett. 121, 157701

Qubit based counting can achieve the most sensitive sub-SQL metrology

Ultra sensitive metrological measurement

Assuming mixing with qubit is dominant, and P(heating) = 10^{-3}, can achieve > 25 dB

Corresponds to $>10^5$ improvement in scan time

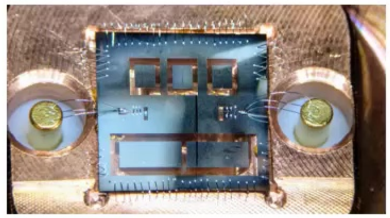


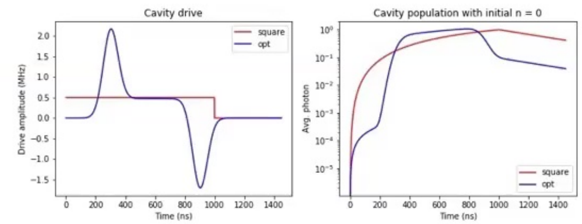
25

Rev. Mod. Phys. 90, 035005

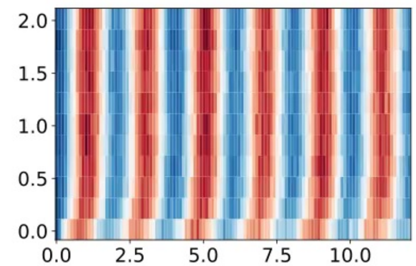
Further improvements to protocol

Parametric amplifier
- increases readout fidelity
- reduces readout time
- reduces readout cavity photon number



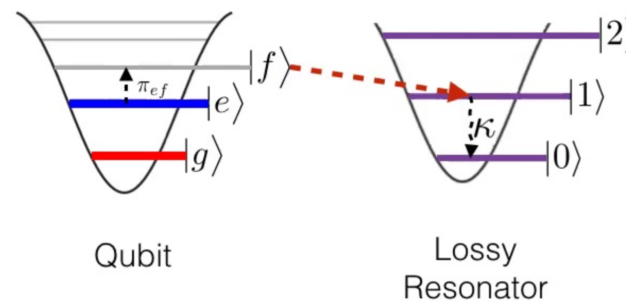


Reset readout cavity with optimized pulse shape
- readout decay is dominant time scale in expt



Meas. time
$10\mu s \rightarrow 1\mu s$

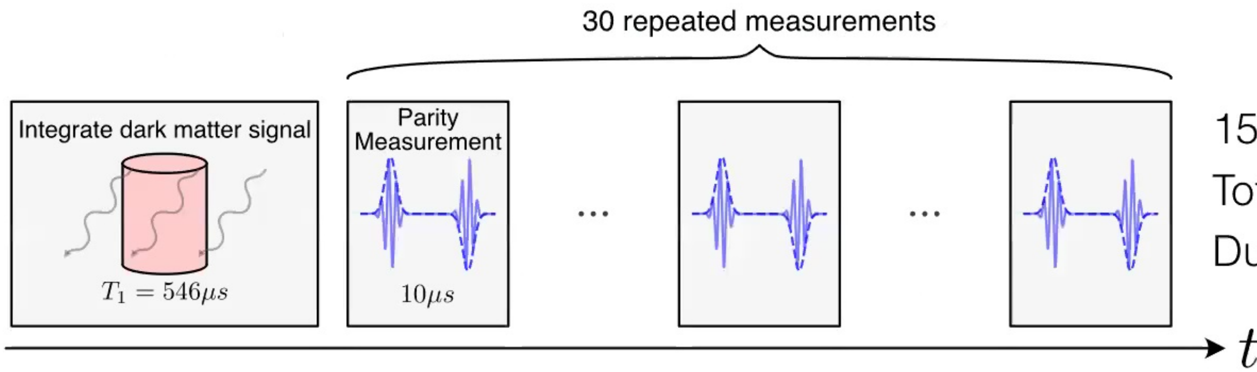
Reset qubit between measurements
- $P(\text{decay} \,|\, E) \sim 9\,\%$
- $P(\text{heating} \,|\, G) \sim 0.4\,\%$



26

Dark matter search protocol

Signal cannot build up while measuring (quantum Zeno effect)

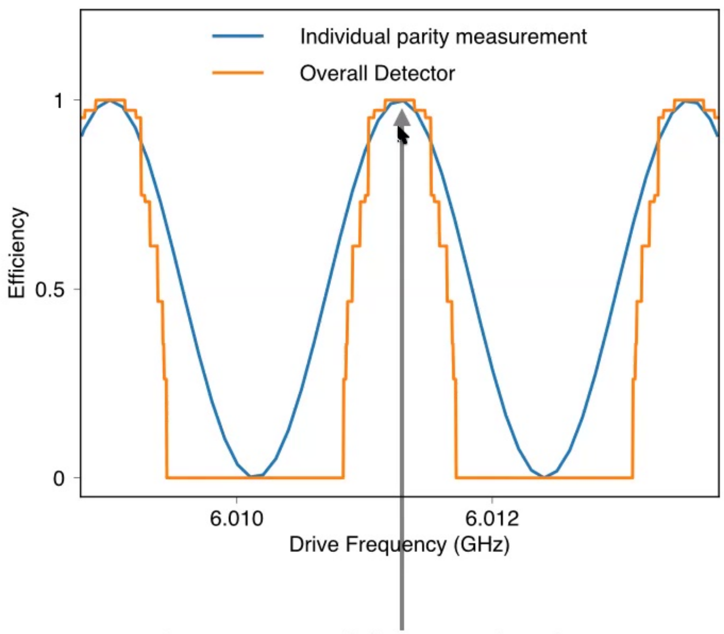


15,141 experiments performed
Total experiment time of 12.81 s
Duty cycle of 65% (8.33 s of integration)

Count 9 photons

What hidden photon mixing angle parameter space is excluded by this observation?

Detector is sensitive to off resonant and large amplitude signals

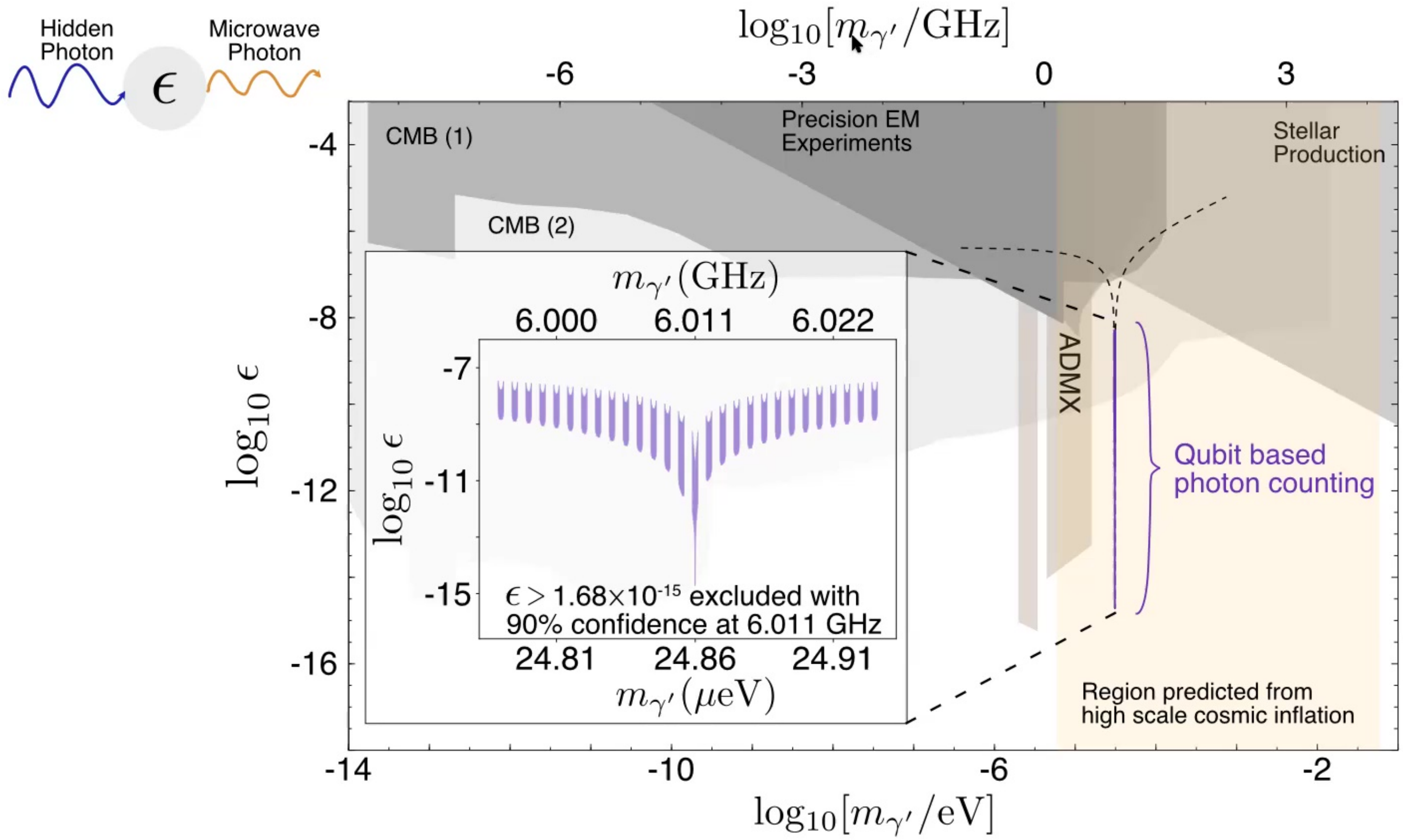


Parity procedure tuned for excitations on resonance

With parity procedure, qubit can sense:

- Off resonant photons filtered through cavity
- Large amplitude signals, with significant odd number contributions
- Limited by bandwidth of pulses

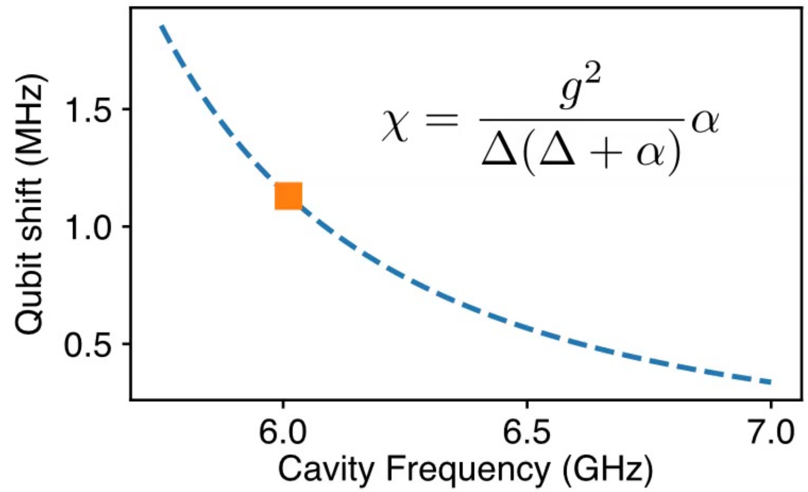
Constraining the Hidden Photon Dark Matter



Phys. Rev. D 93, 103520

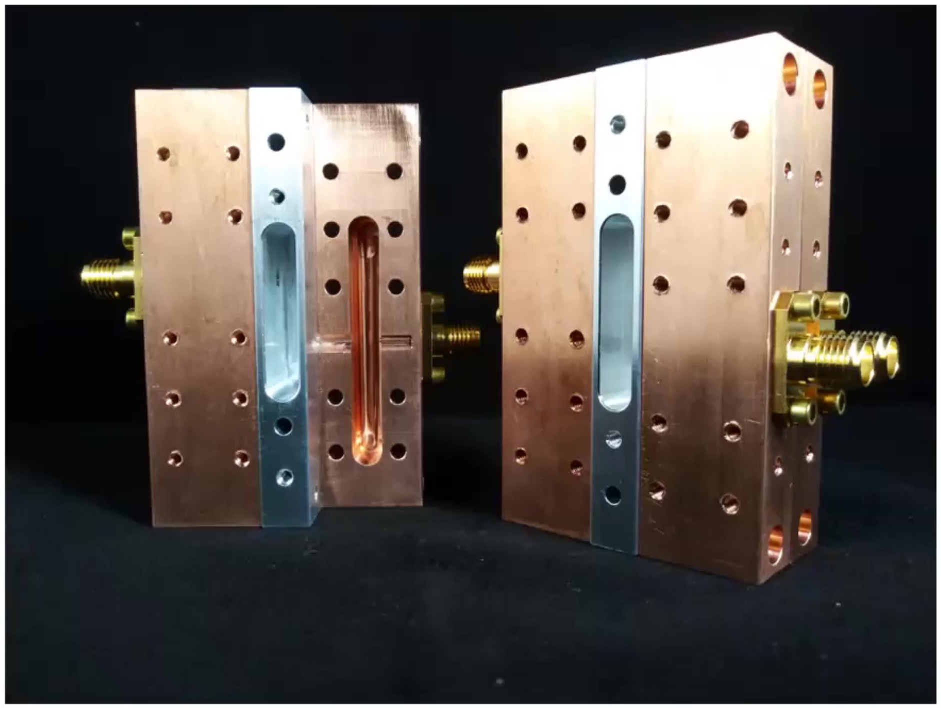
Integration with a scanning experiment

- Keep qubit fixed in frequency
- QND interaction unchanged as cavity tunes
- Calibrate photon dependent qubit shift



Further increasing sensitivity for dark matter searches

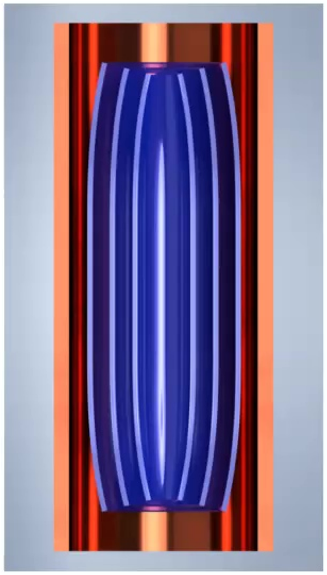
Use multiple entangled qubits for enhanced metrology



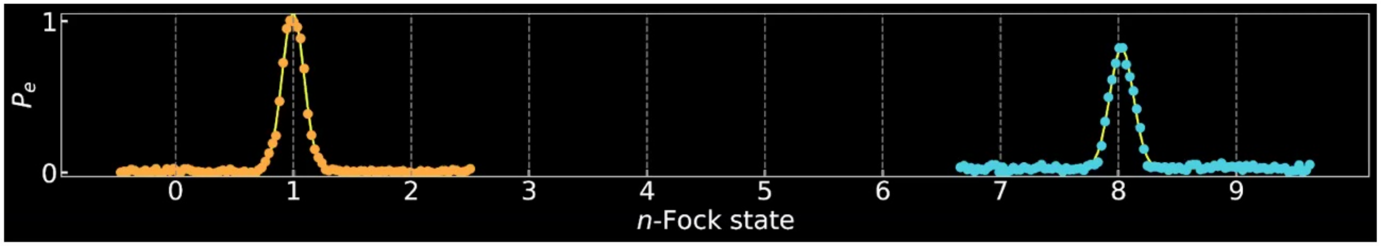
Boosting dark matter induced signal

Novel materials/designs for high Q cavities

Use nonclassical cavity states for signal enhancement



$$| < n+1|\mathcal{D}_\alpha|n > |^2 \sim n\alpha^2$$



arxiv.org/abs/2004.02754
nature.com/articles/s41467-019-10576-4

Conclusions

- Employed quantum information techniques/devices for dark matter cosmology
- Achieved 15.7 dB metrological gain, ~1300 X speed up of dark matter searches
- Unprecedented sensitivity to hidden photon dark matter
- Manuscript: arxiv.org/abs/2008.12231

Army Research Office
the David & Lucile Packard Foundation
Heising-Simons Foundation
schuster.lab
The University of Chicago
Fermilab
U.S. Department of Energy Office of Science
Pritzker Nanofabrication Facility