Using Superconducting Qubits for Dark Matter Detection

Akash V. Dixit

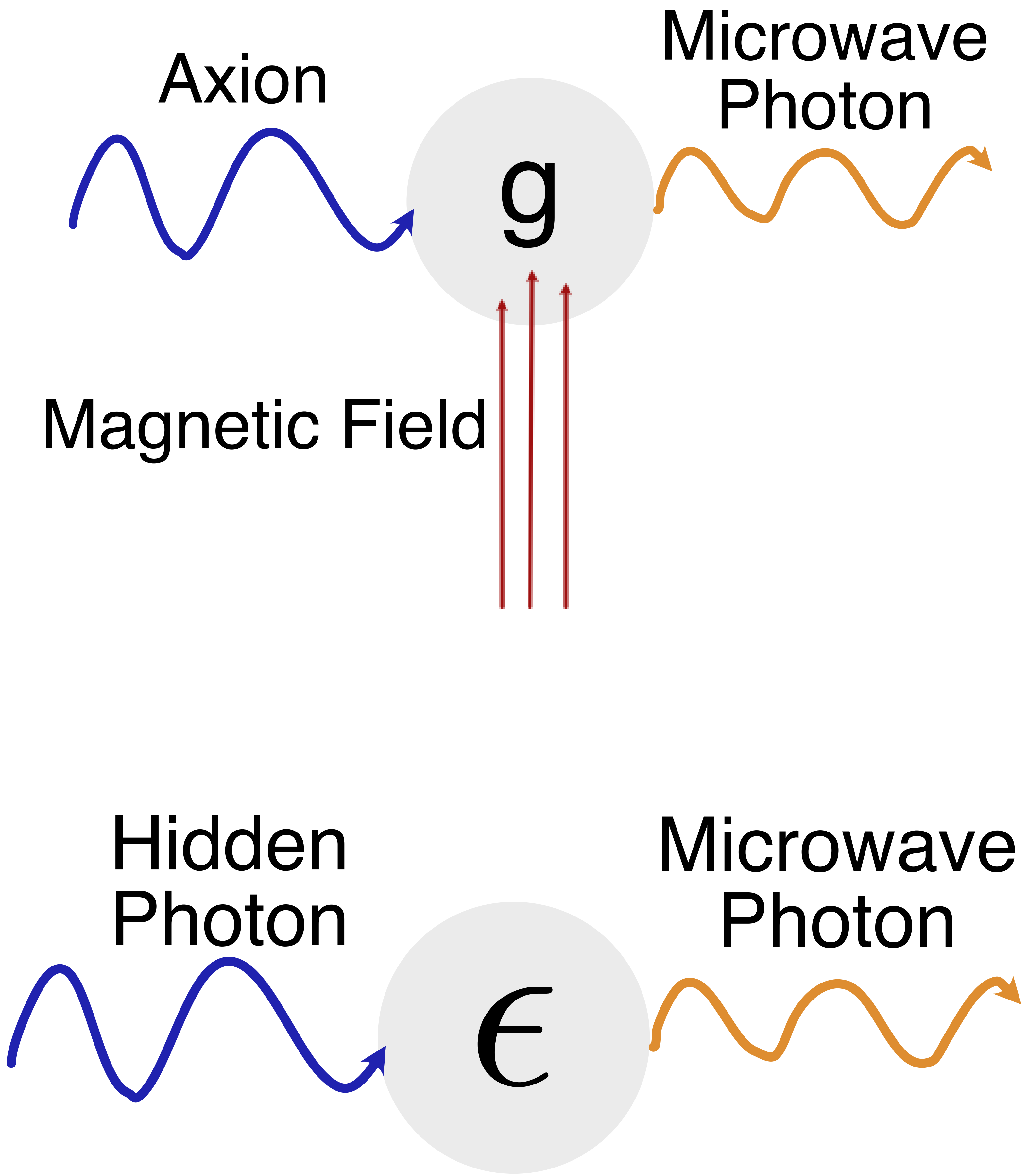
Srivatsan Chakram, Kevin He, Ravi K. Naik, Ankur Agrawal, Aaron Chou, David I. Schuster

University of Chicago
avdixit@uchicago.edu

Outline of talk

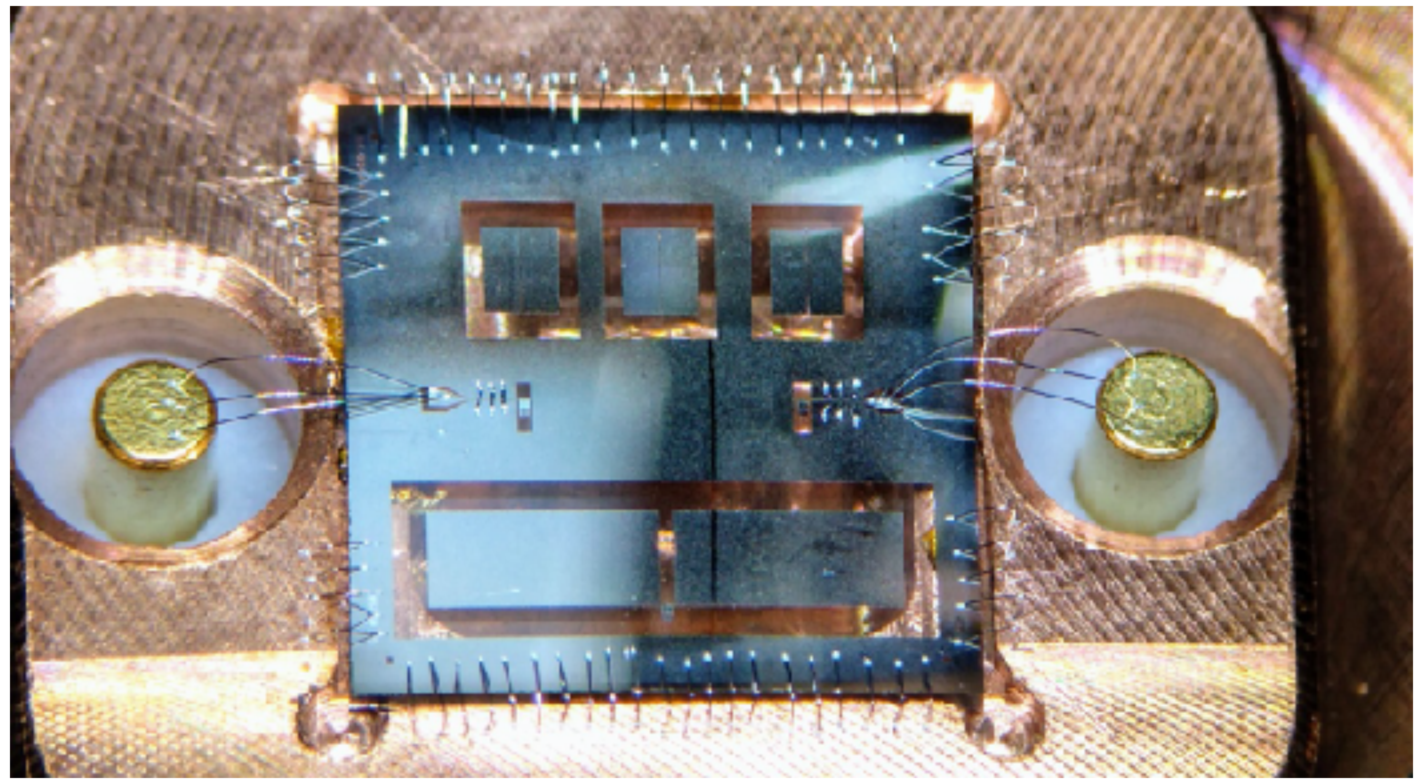
- Dark matter could couple to electromagnetism to produce photons
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search

How dark matter might couple to electromagnetism



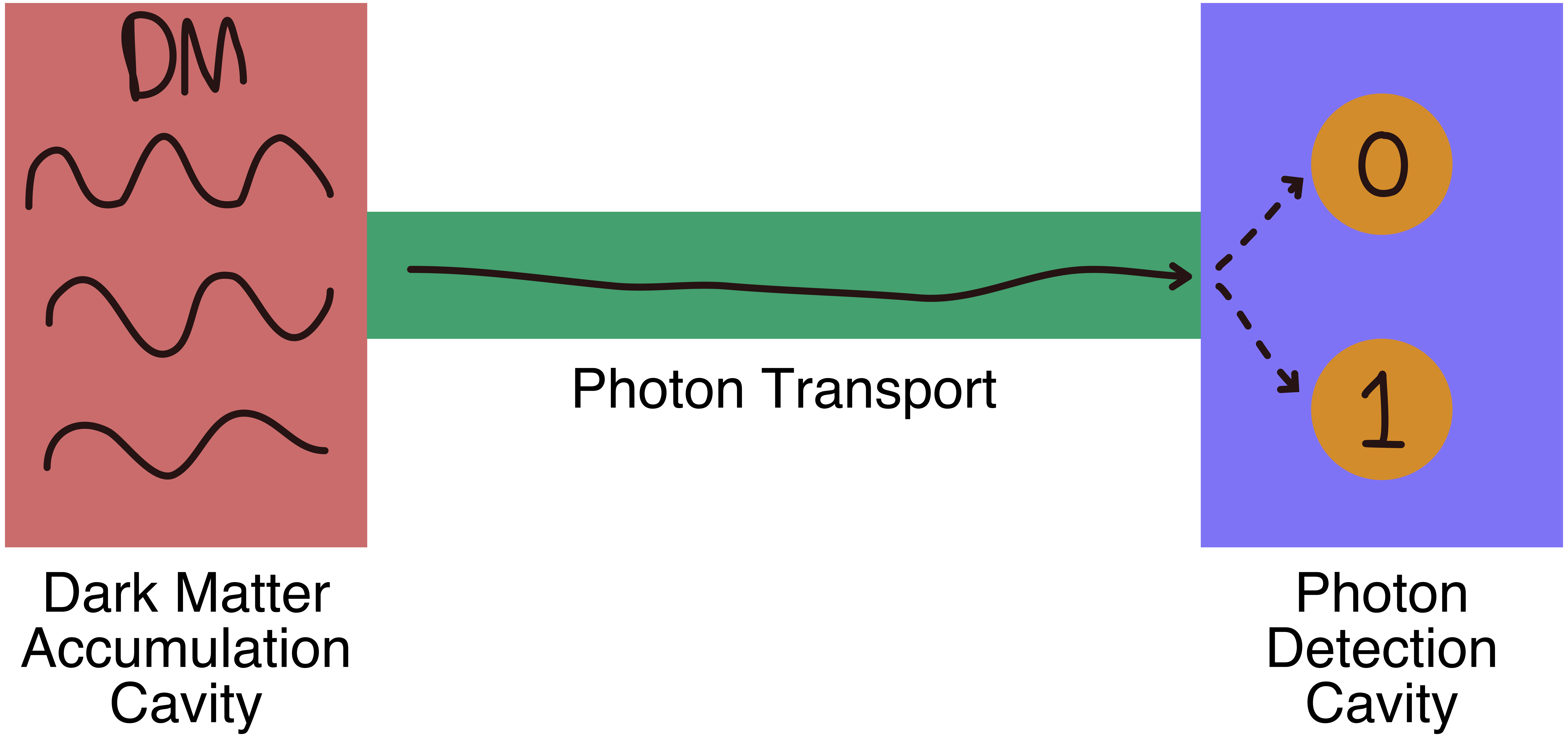
Resonant cavity to capture signal

Quantum limited amplifier for readout

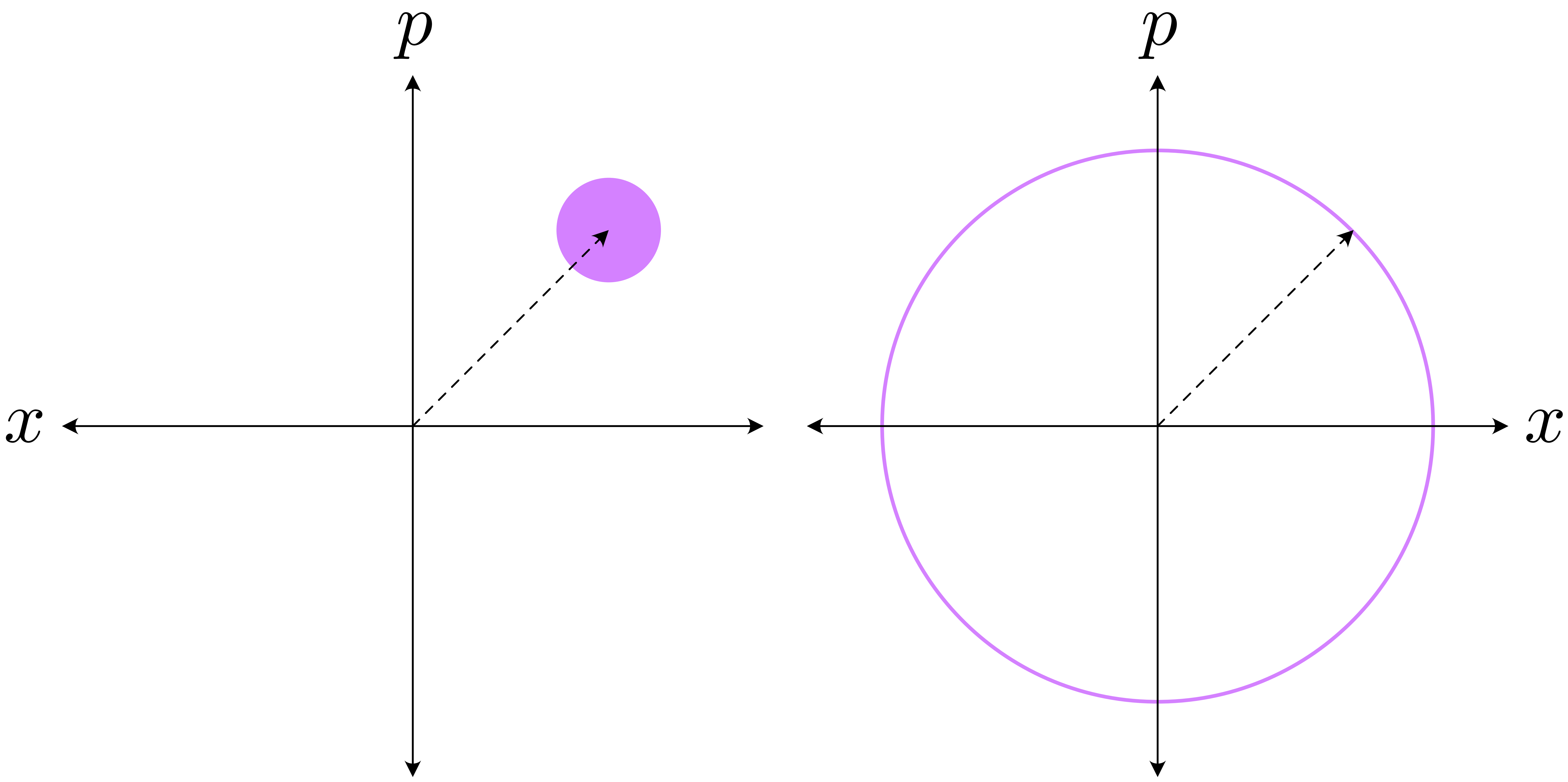


Dark matter detection strategy

arxiv.org/abs/2008.12231



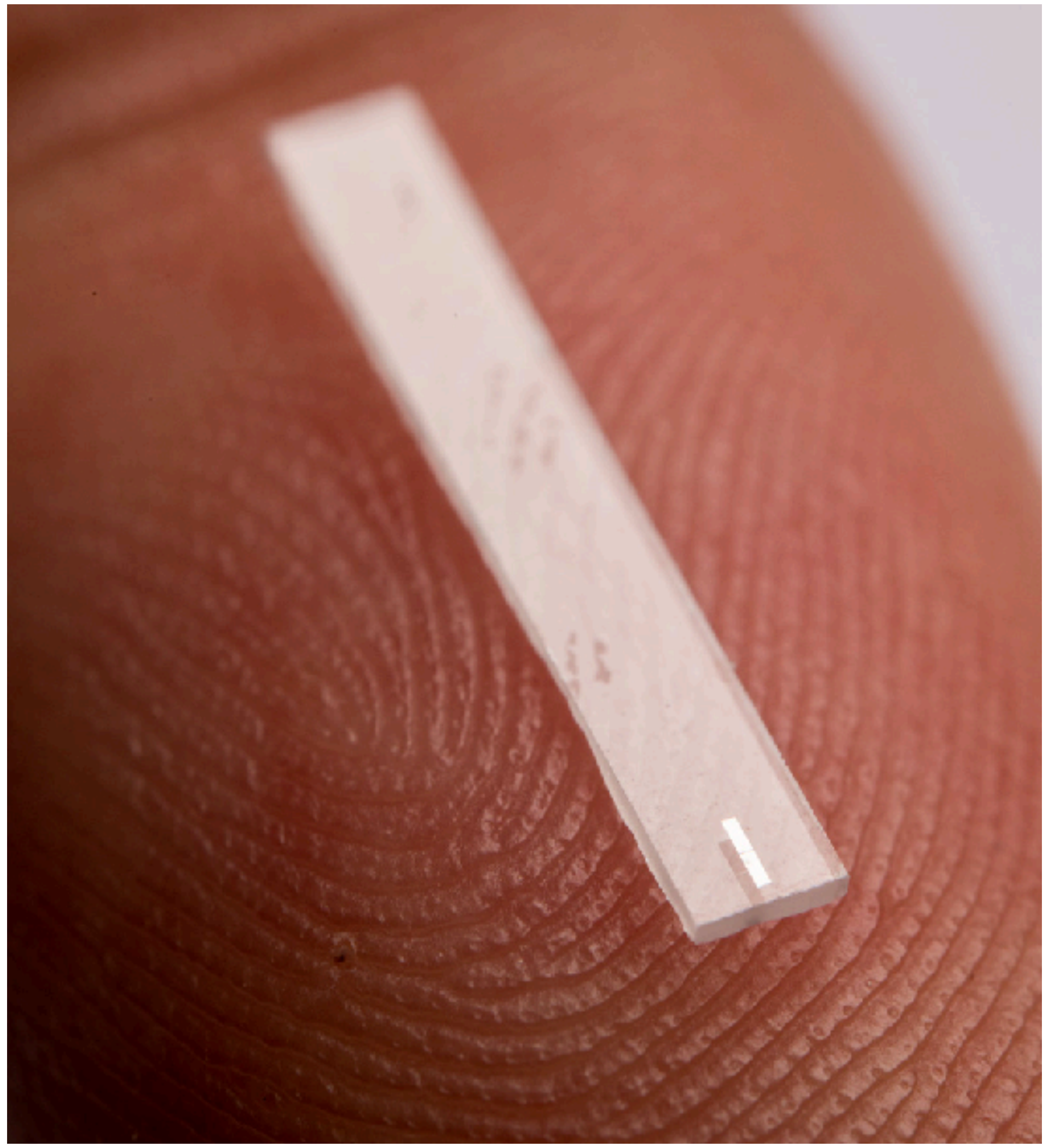
Count photons to subvert quantum limit



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

Outline of talk

- Dark matter could couple to electromagnetism to produce photons
- 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

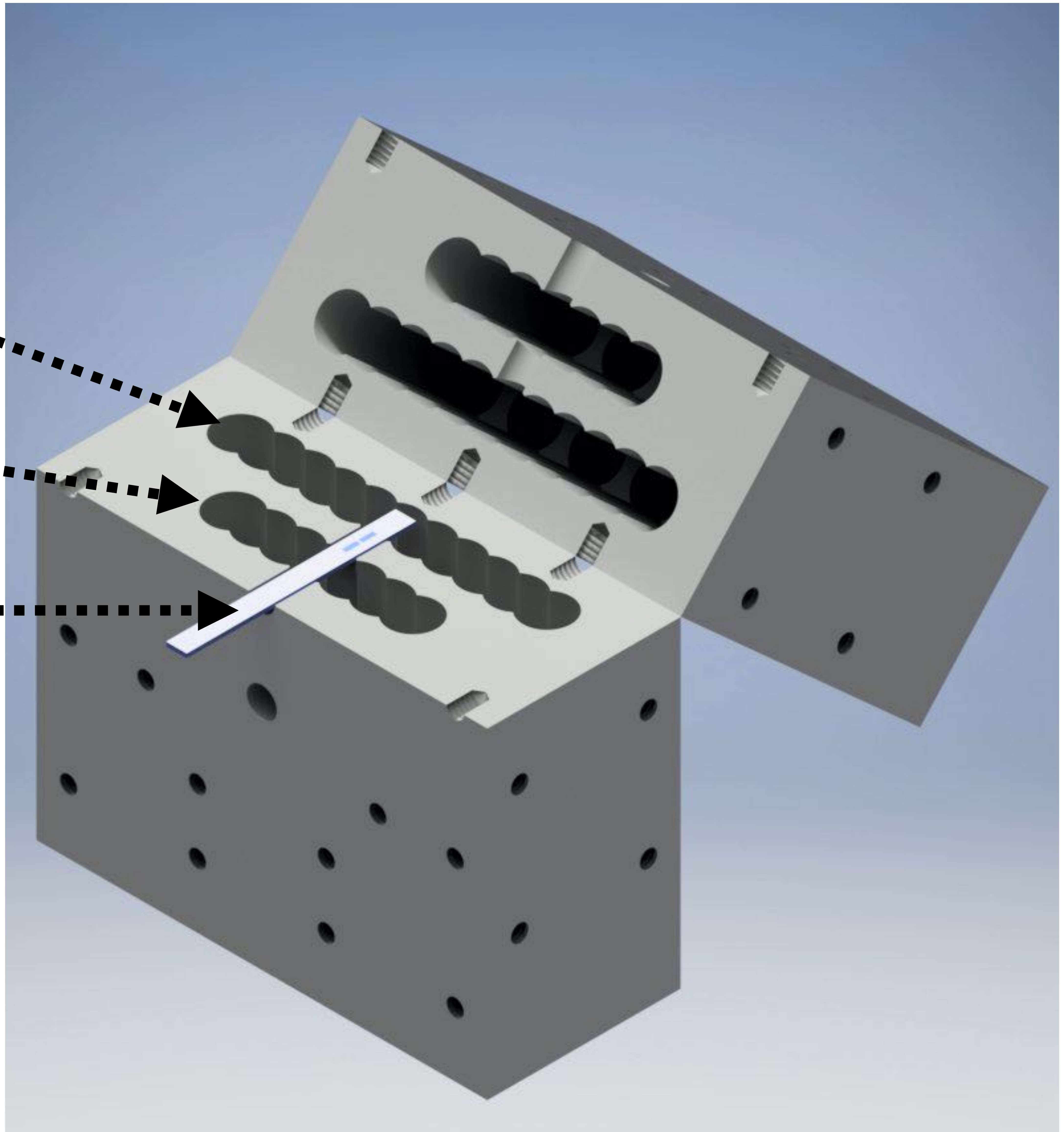


Photon counting device

Storage Cavity 6.011 GHz

Readout Cavity 8.052 GHz

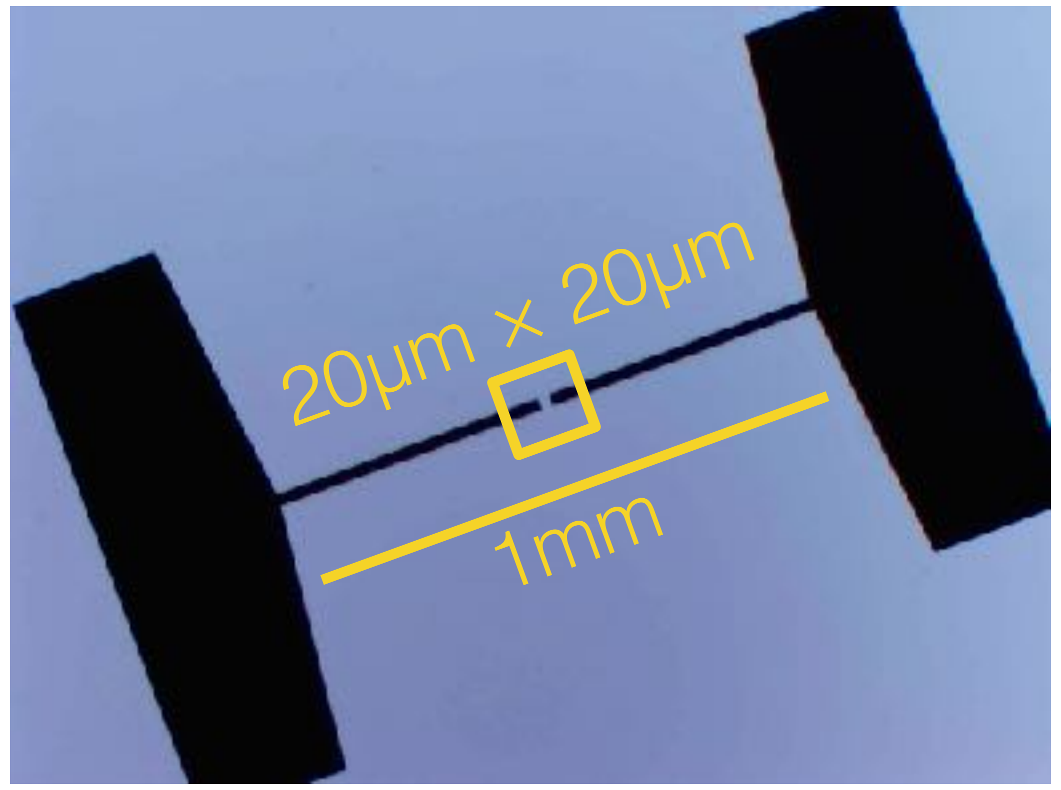
Sapphire Chip w/ Qubit 4.749 GHz



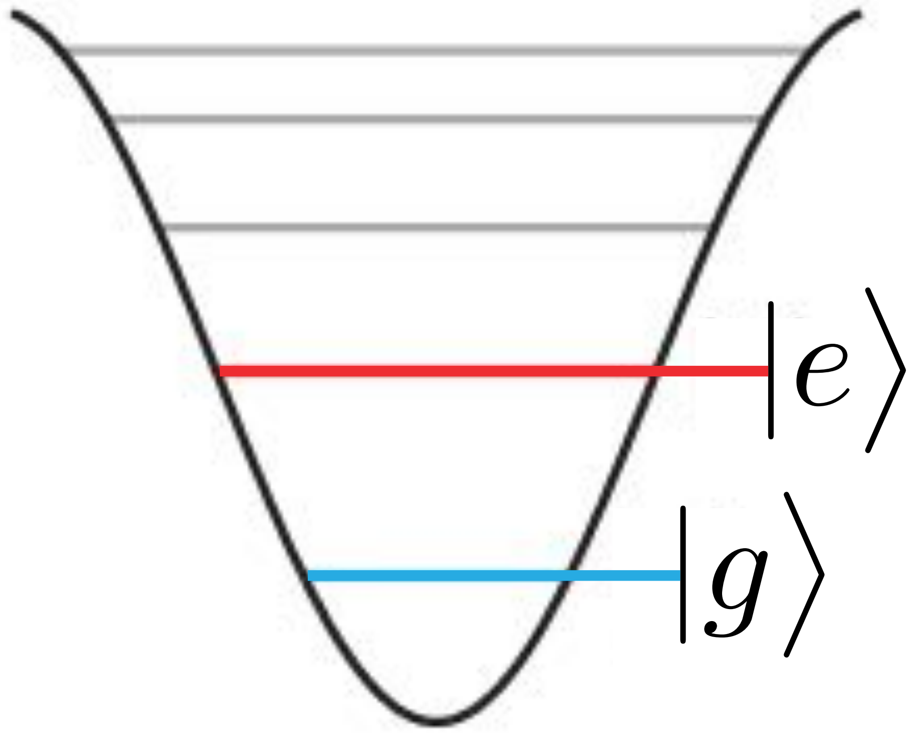
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Operated in a dilution refrigerator @ 8mK

Building a superconducting qubit

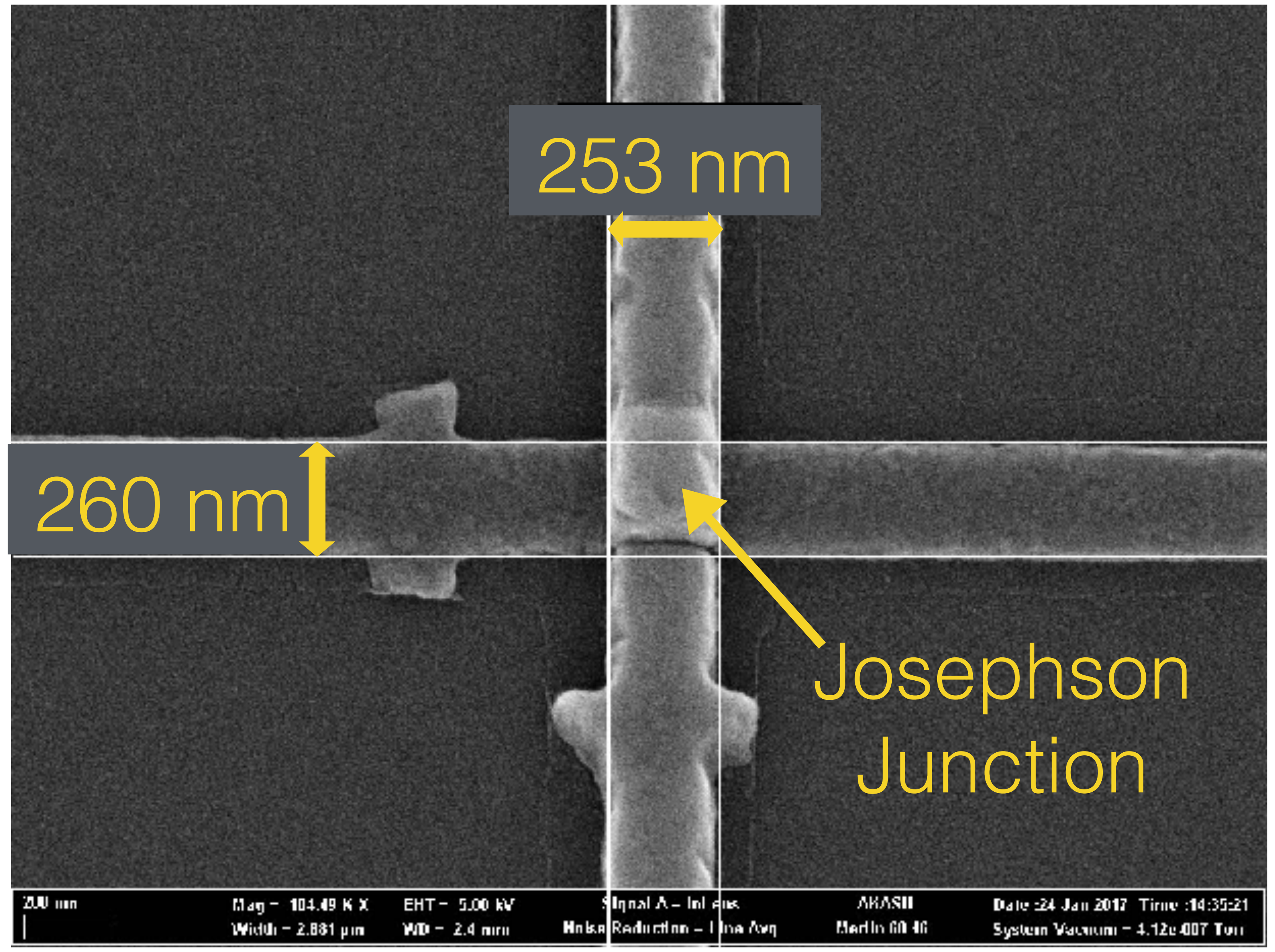


$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$



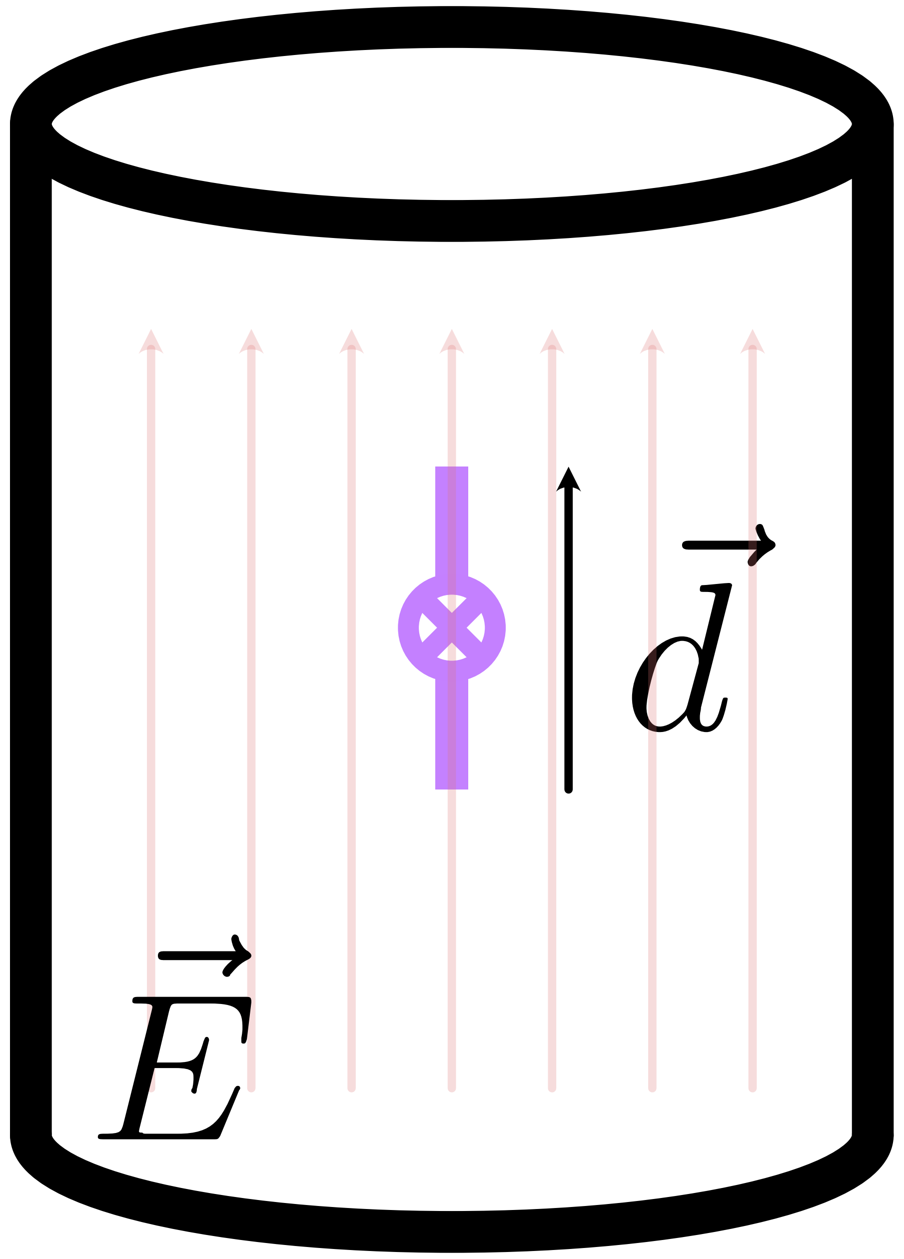
$$\omega_q = E_1 - E_0$$

Harmonic Oscillator (LC) + nonlinearity (Josephson Junction)



Customize transition frequency and dipole moment

Engineering the qubit-cavity interaction



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

Two-level spin

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

Transmon qubit

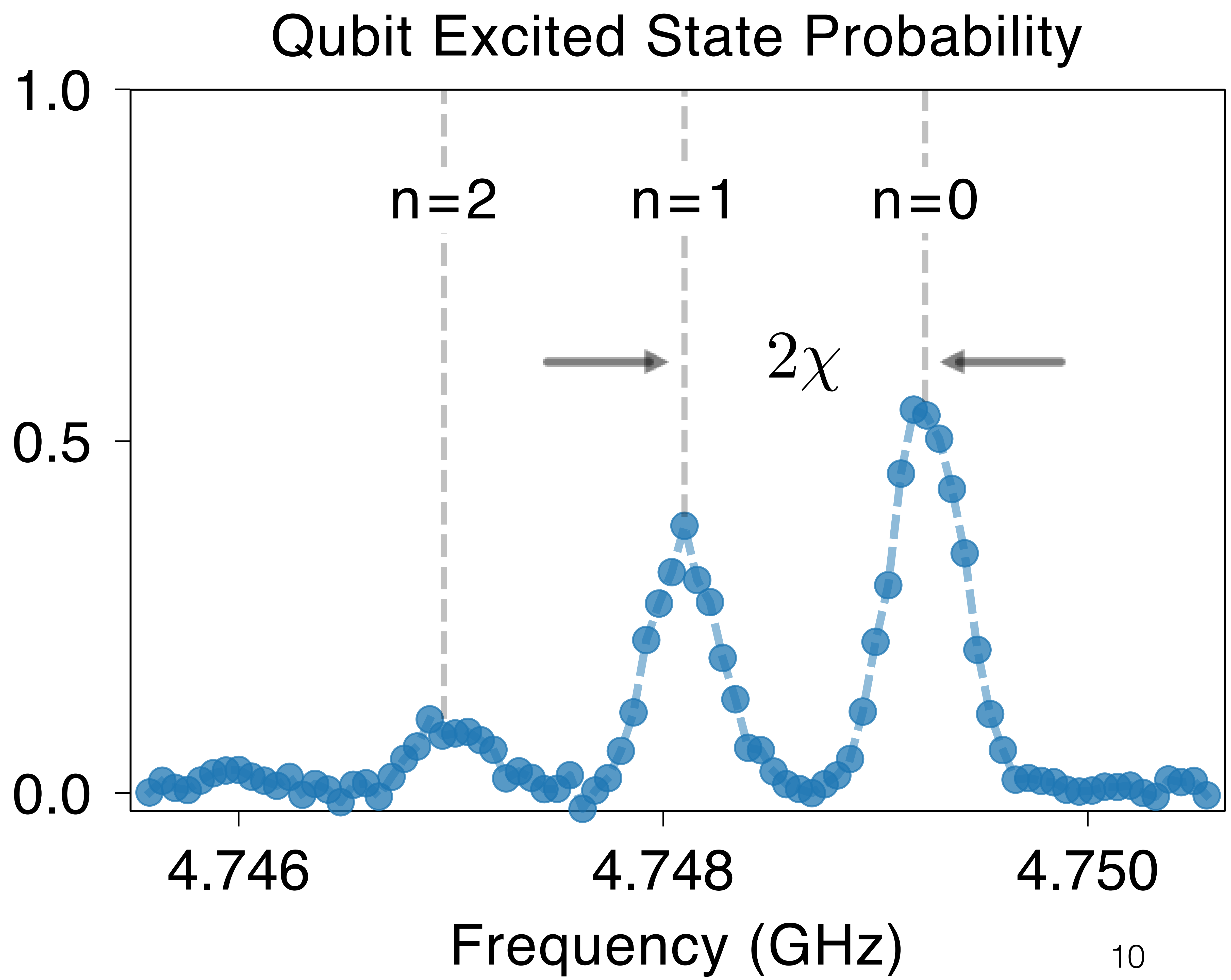
$$\chi = \frac{g^2}{(\Delta + \alpha)^2}\alpha$$

Δ qubit-cavity detuning

α qubit anharmonicity

Cavity occupation imprinted on qubit transition frequency

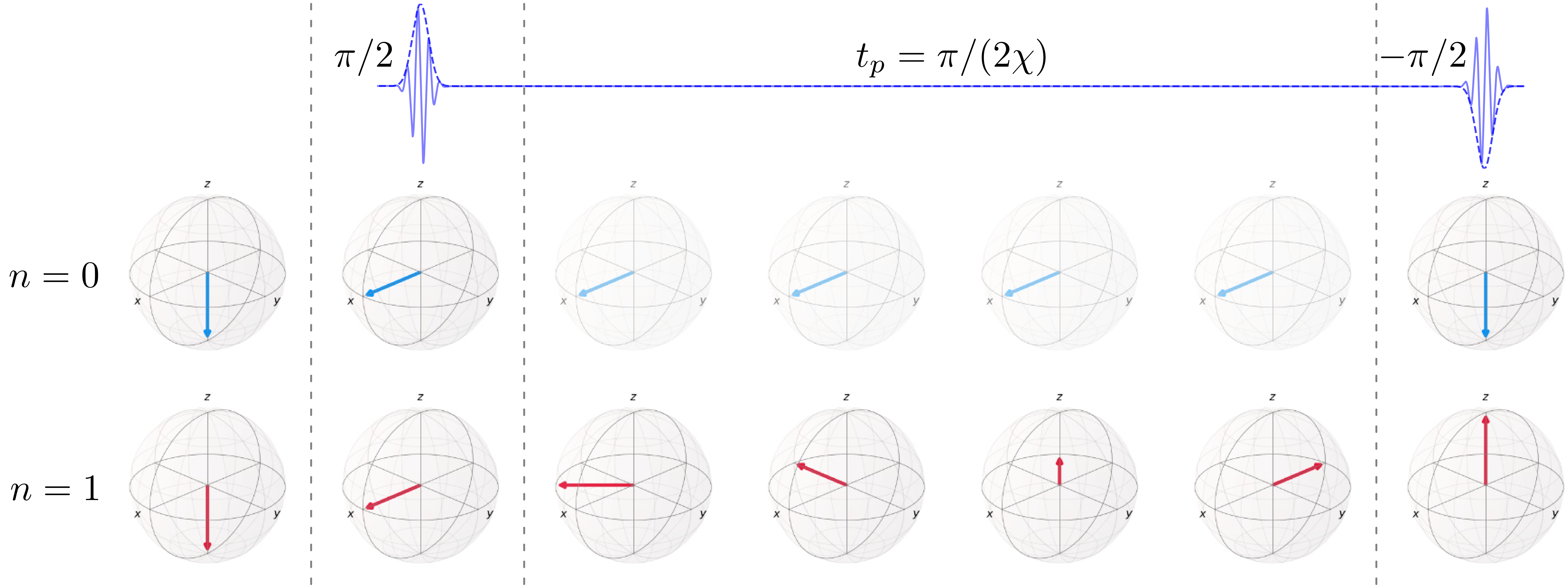
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$



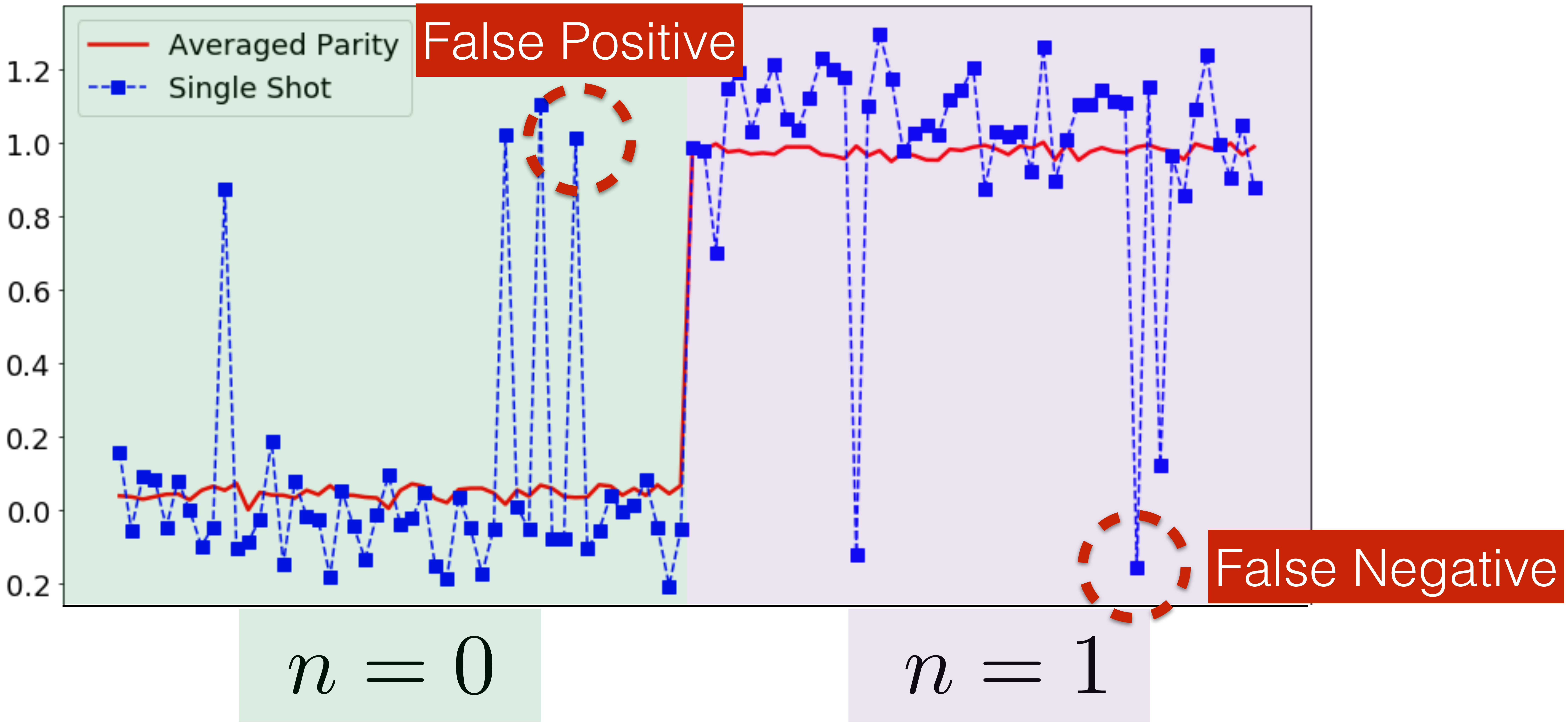
Qubit transition frequency is photon number dependent

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

Parity measurement maps cavity state onto qubit



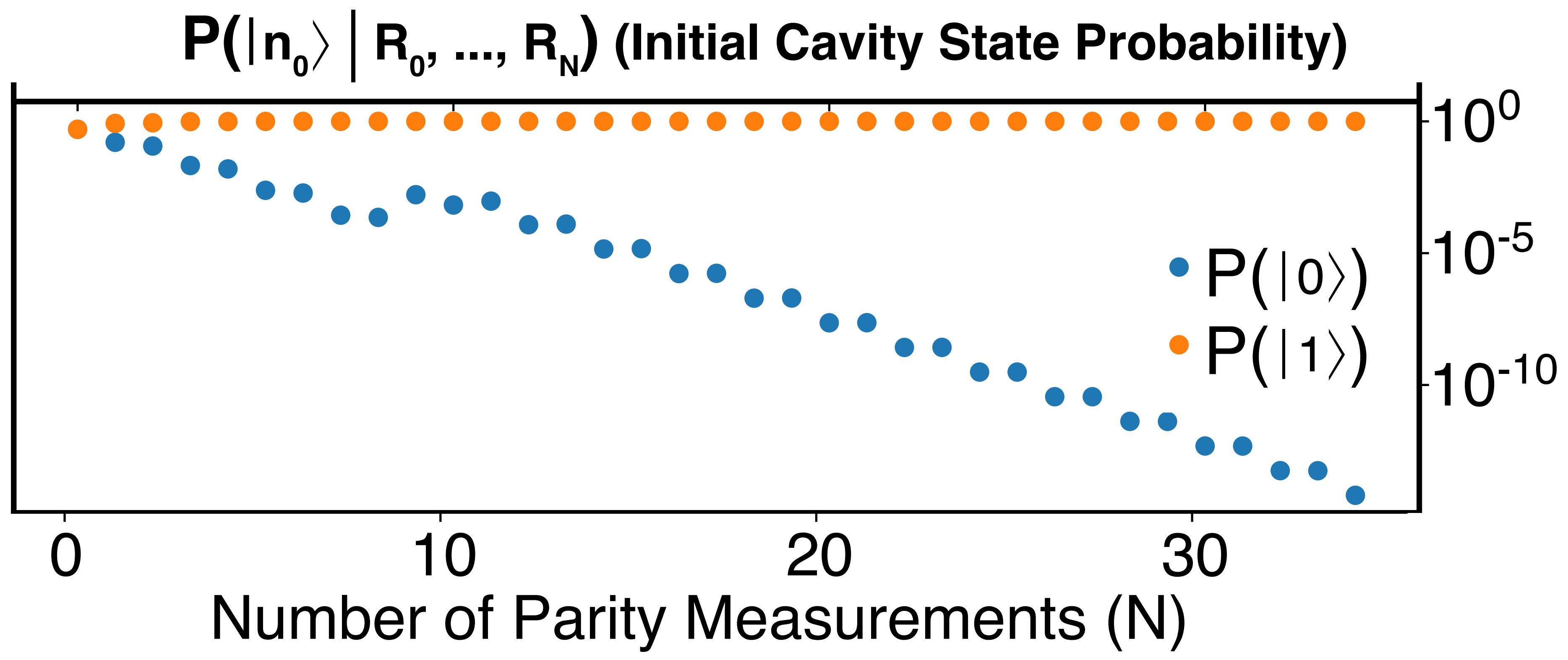
Counting cavity photons



Spurious qubit excitations are dominant source of errors

Outline of talk

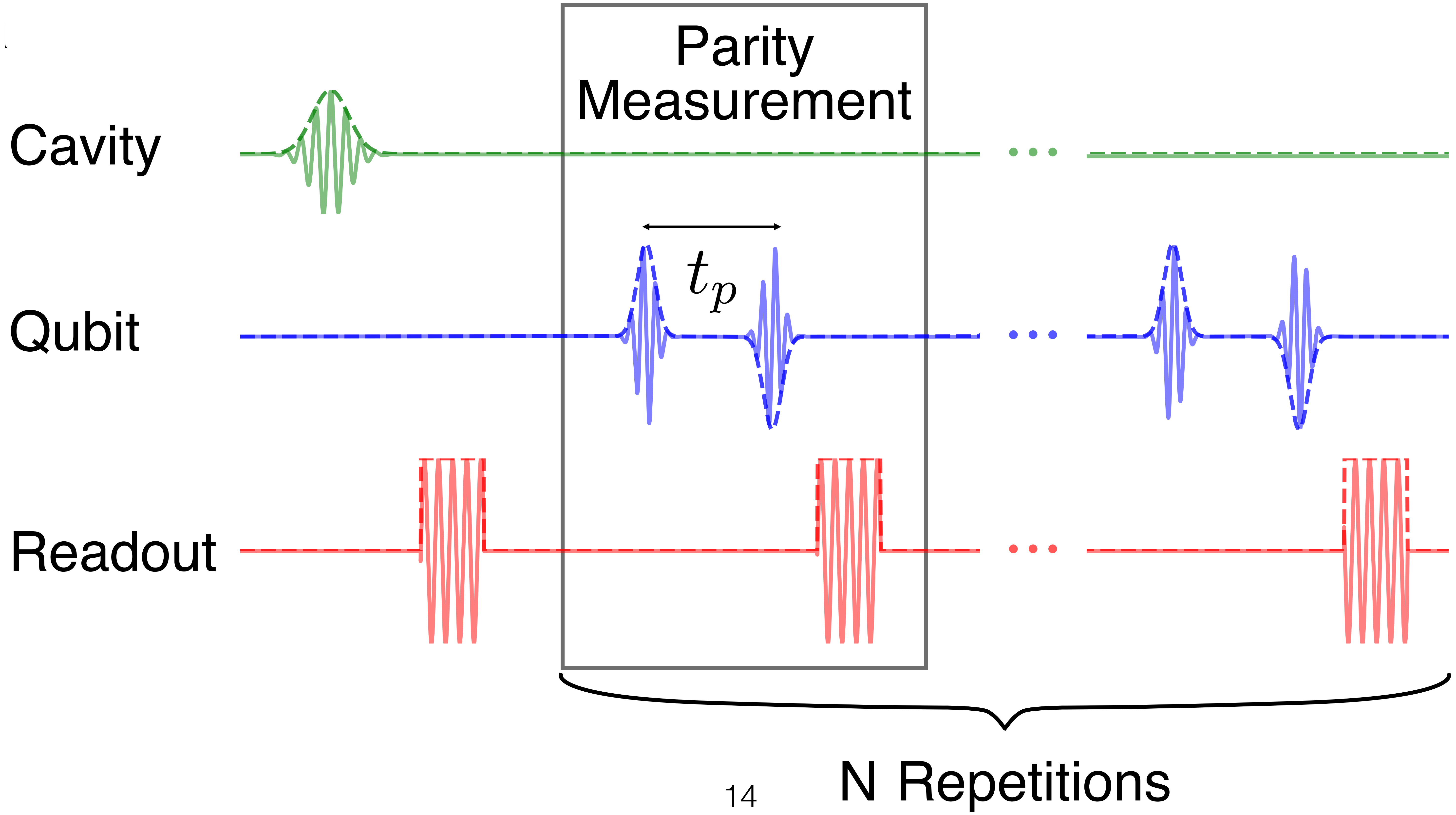
- Dark matter could couple to electromagnetism to produce photons
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search



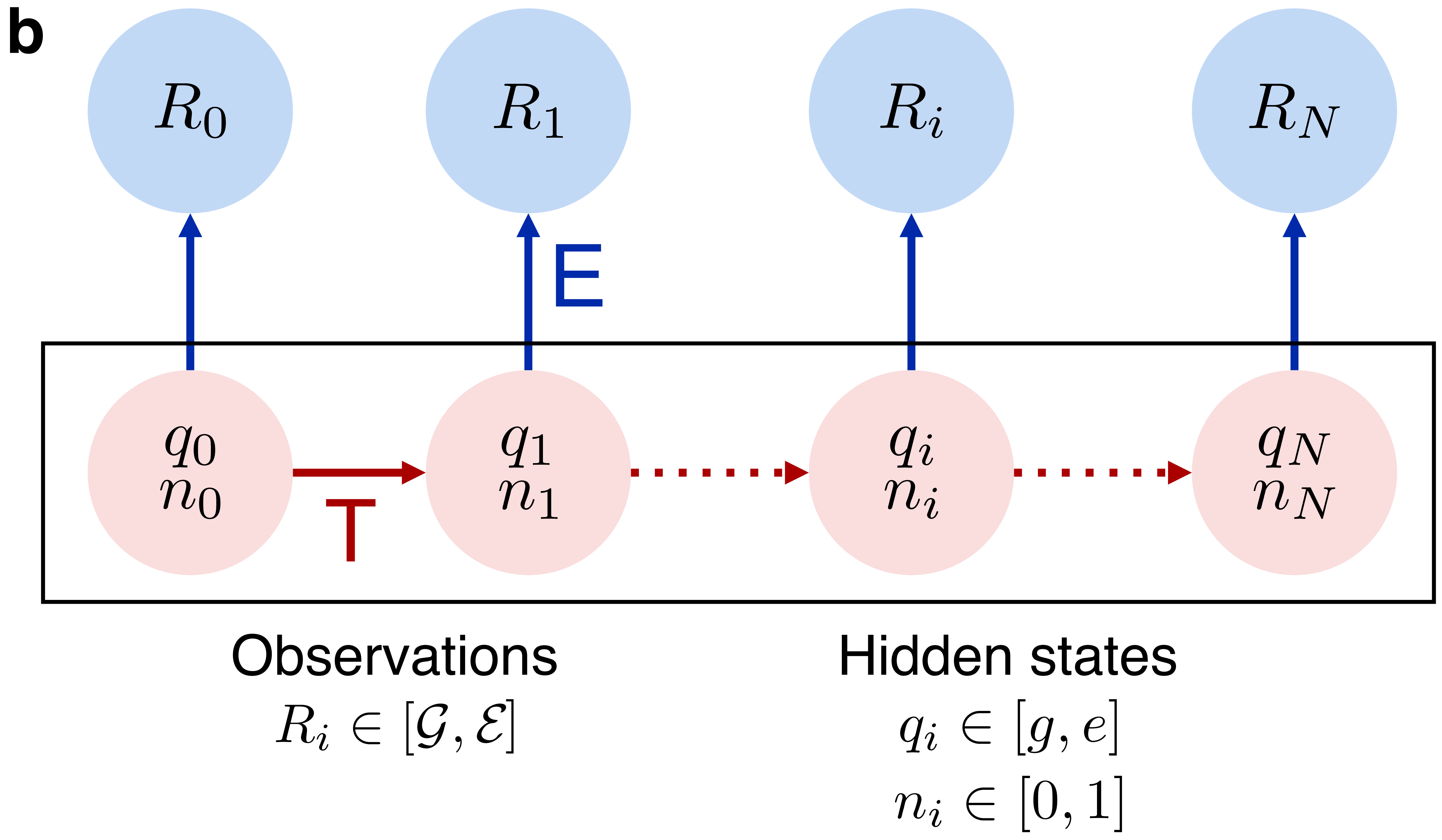
Mitigate the errors by making repeated measurements

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

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



Use hidden Markov model to describe cavity and qubit evolution



T = Transition matrix

- qubit (108μs), cavity (546μs) lifetime
- qubit spurious population (0.05)
- qubit dephasing (T_2 = 61μs)
- time between experiments (10μs)

E = Emission matrix

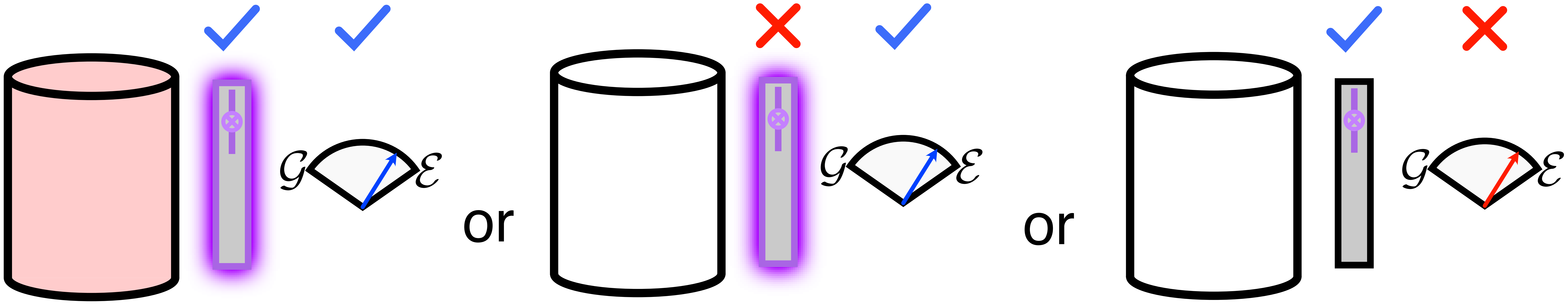
- ground and excited state readout fidelity (0.95)

arxiv.org/pdf/1607.02529.pdf

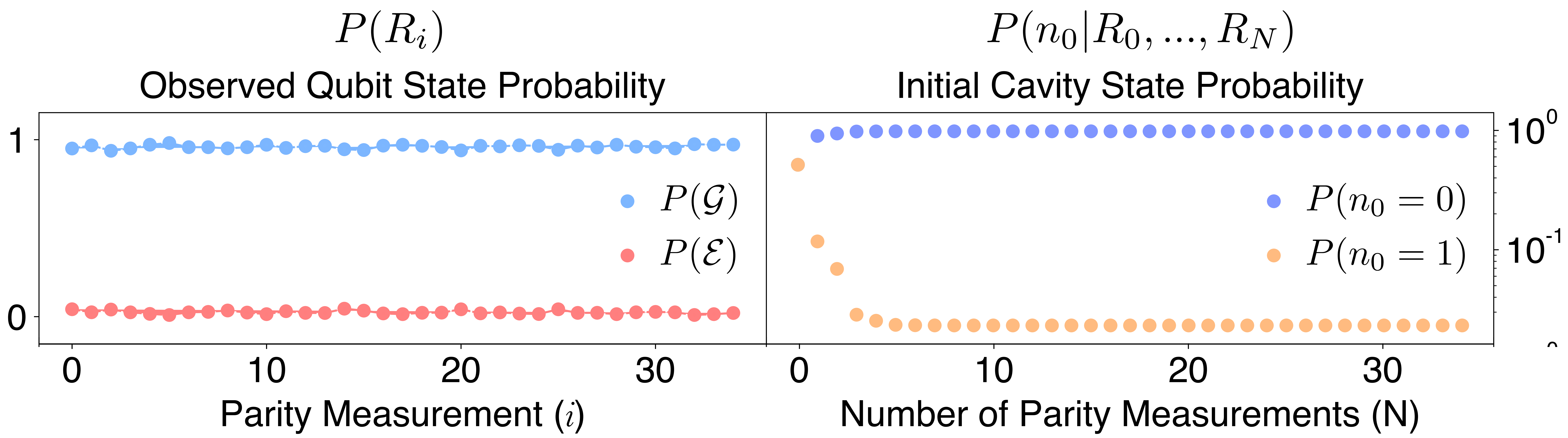
Cavity state reconstruction

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

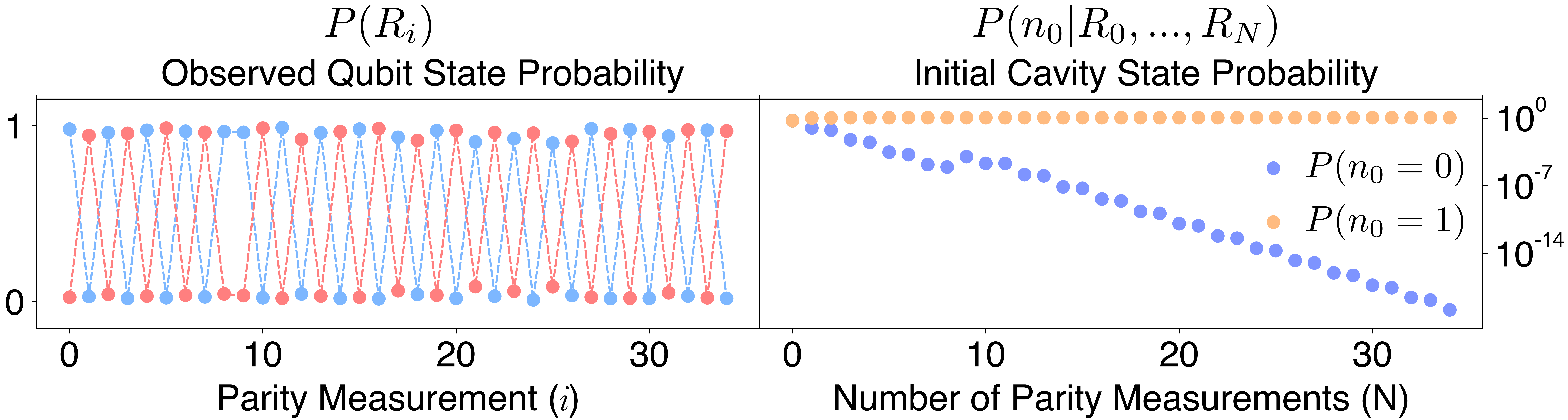
Observed readout sequence: $\mathcal{G} \rightarrow \mathcal{E}$



Detector response in the presence of zero photons



Detector response in the presence of one photon

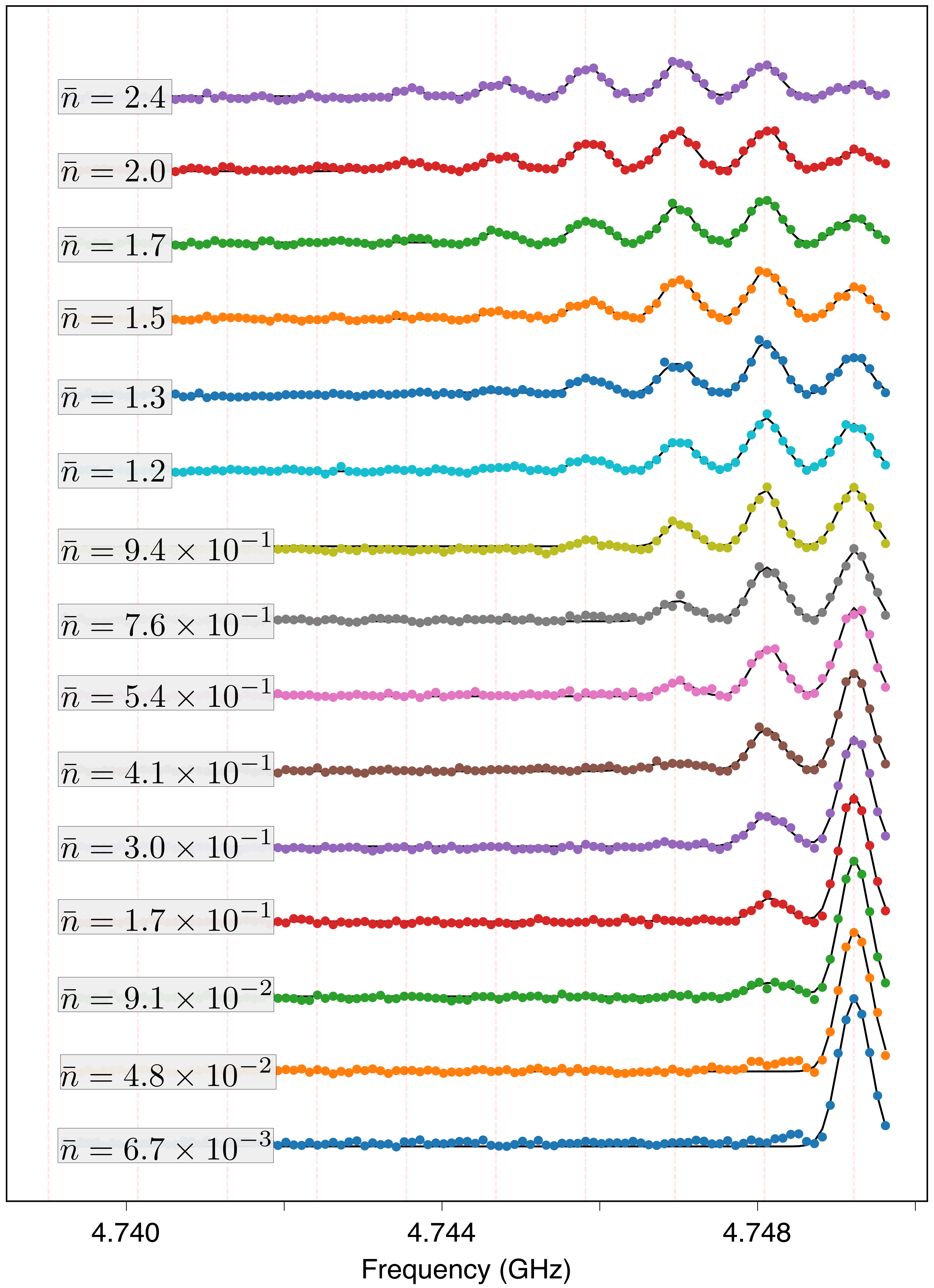


Exponential suppression of detector based false positives

Outline of talk

- Dark matter could couple to electromagnetism to produce photons
- 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

Calibrate photon injection

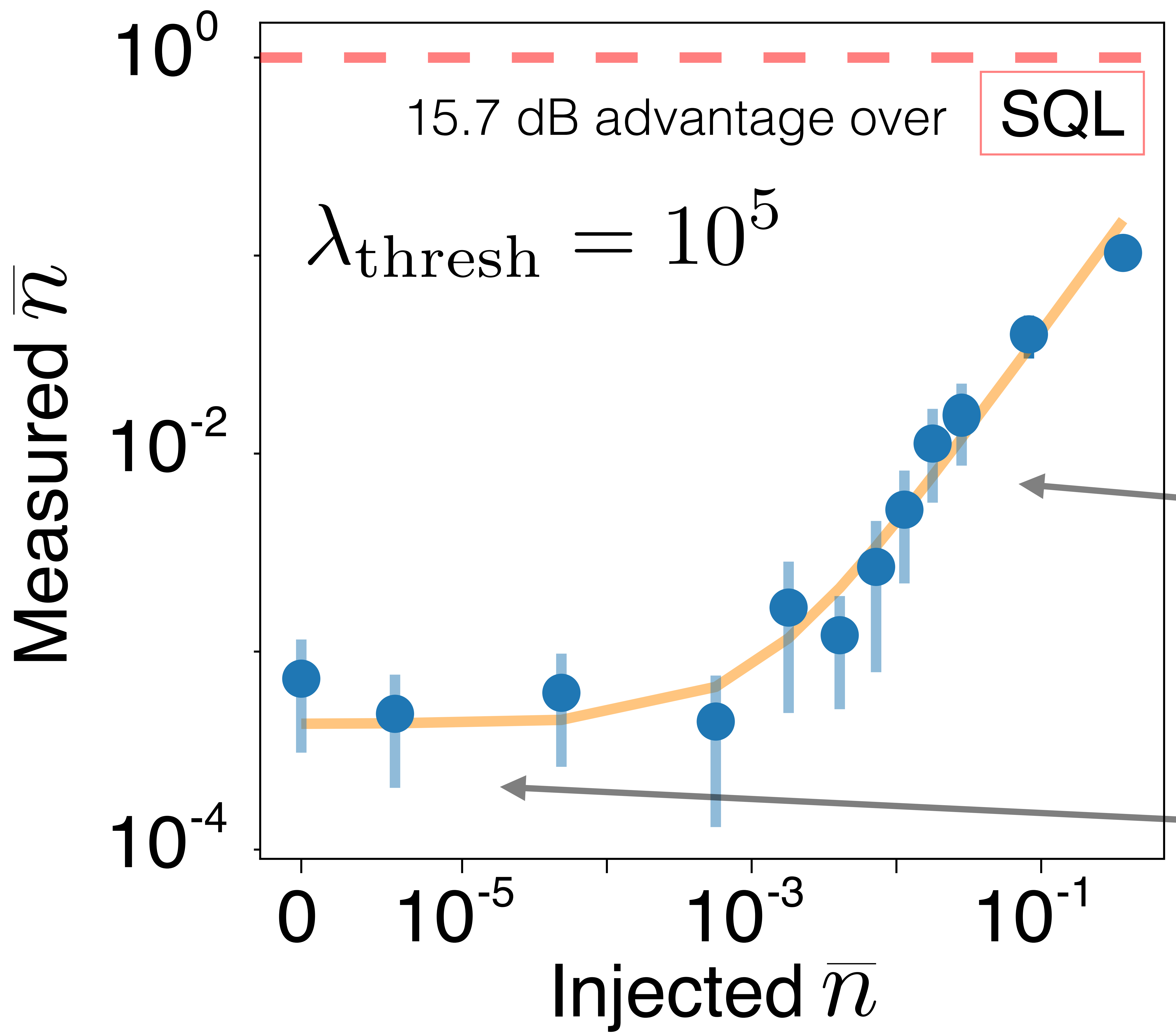


Coherent drive of variable length and amplitude

Perform spectroscopy of qubit to infer cavity population

Extract photon number distribution

Detected photon occupation vs injected photon occupation



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

~1300 X lower background rate than SQL
= 1300 X less integration time required

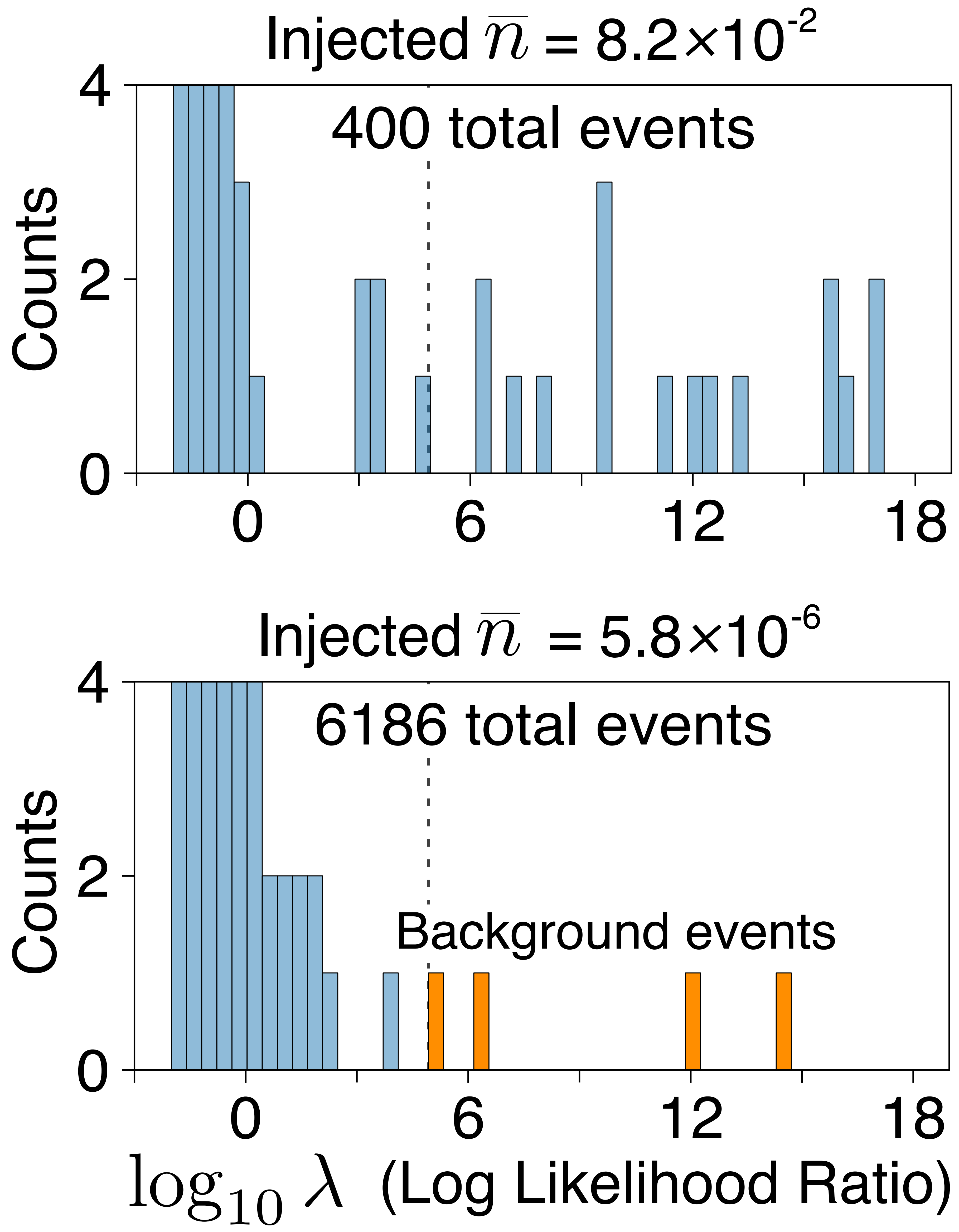
Efficiency

$\eta = 40.9\%$

False positive probability

$\delta = 4.3 \times 10^{-4}$

False positives are background events

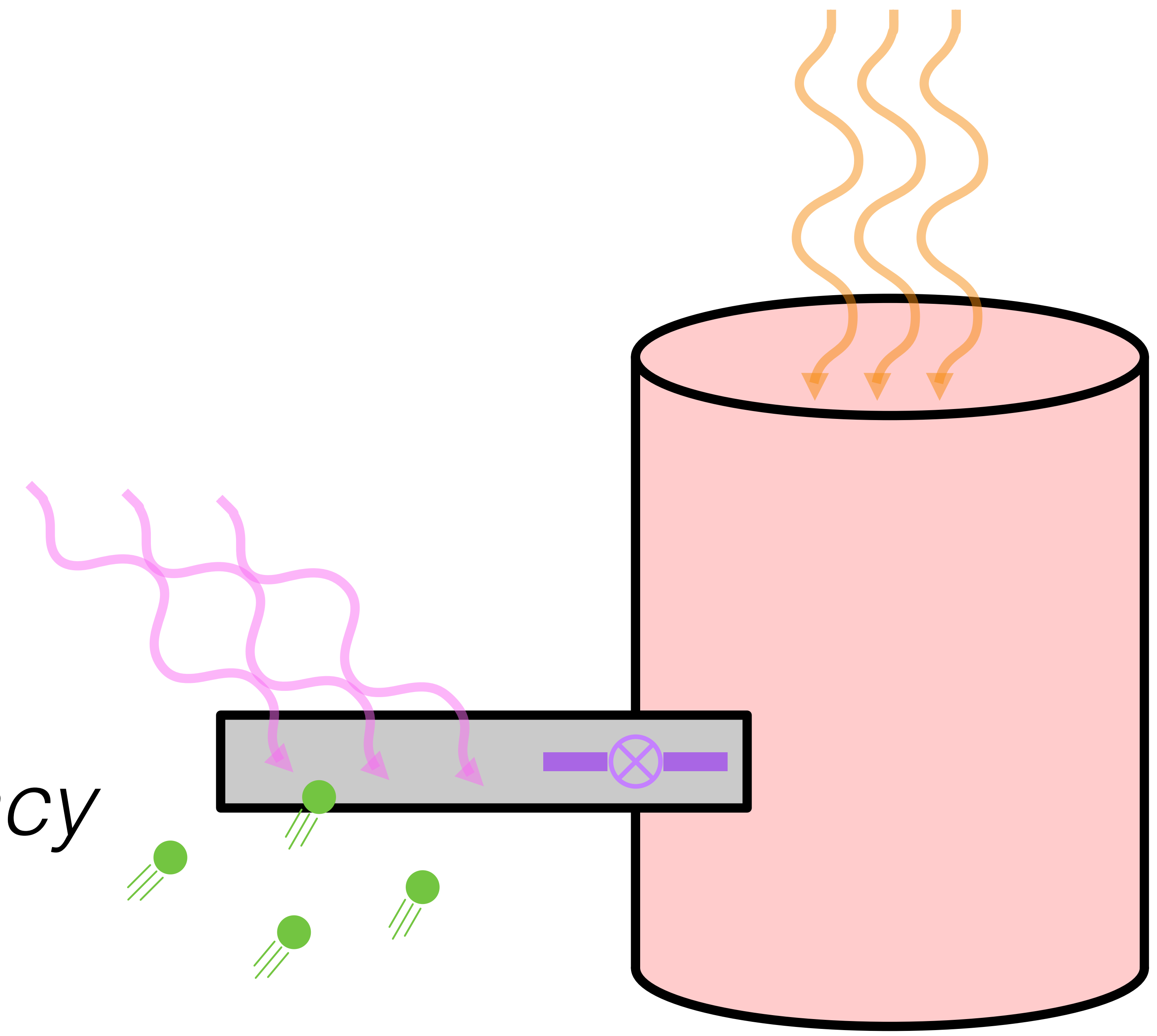


Photons detected when none are injected

Eliminated detector errors as a source of false positives

Entered a new, background limited regime

Background sources and mitigation strategies



Photons coming down lines

- more attenuation and filtering
- better thermalization of components

Spurious qubit excitations convert to photons

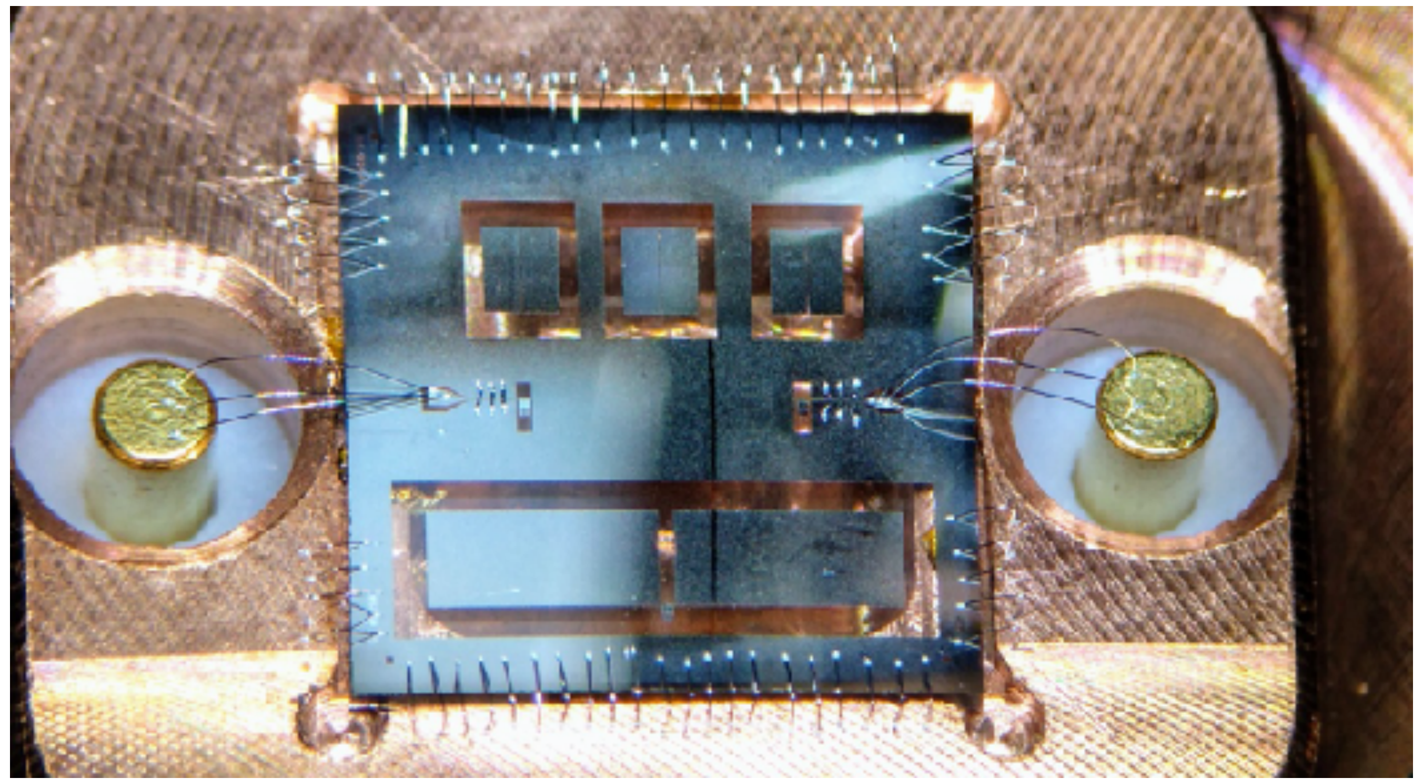
Sourced by terrestrial and cosmogenic radiation, high frequency photons

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

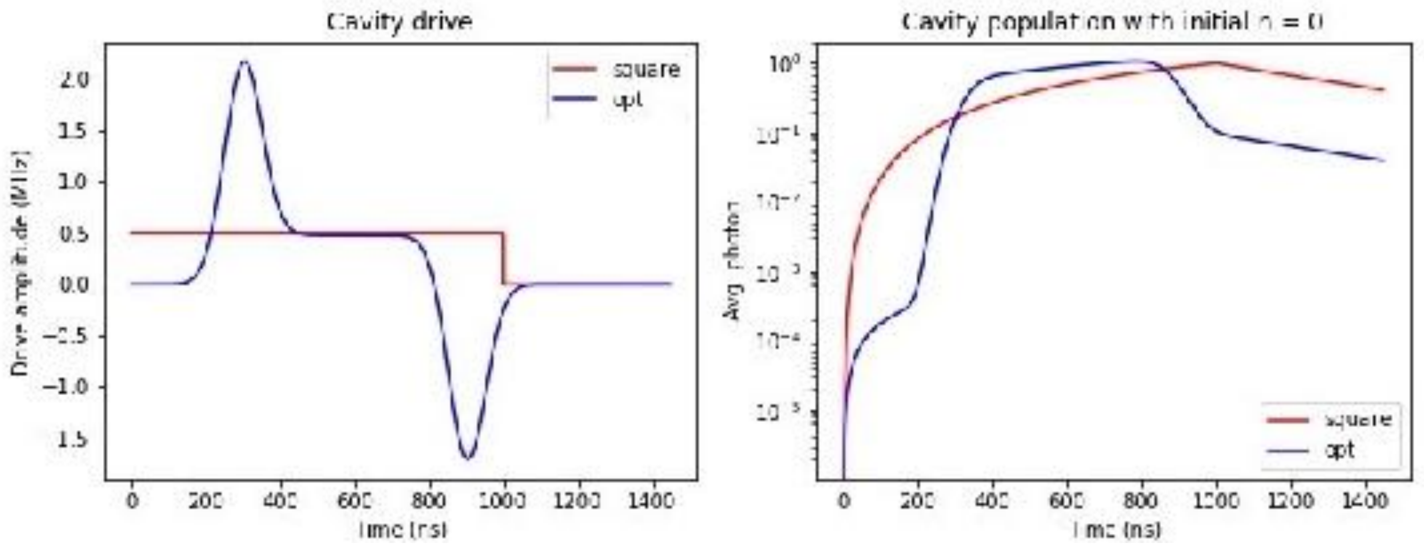
TLS and maybe more

aip.scitation.org/doi/10.1063/1.4984894
journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.11.014031
journals.aps.org/prb/abstract/10.1103/PhysRevB.94.104516
www.nature.com/articles/s41586-020-2619-8
journals.aps.org/prb/abstract/10.1103/PhysRevB.100.140503
journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.157701

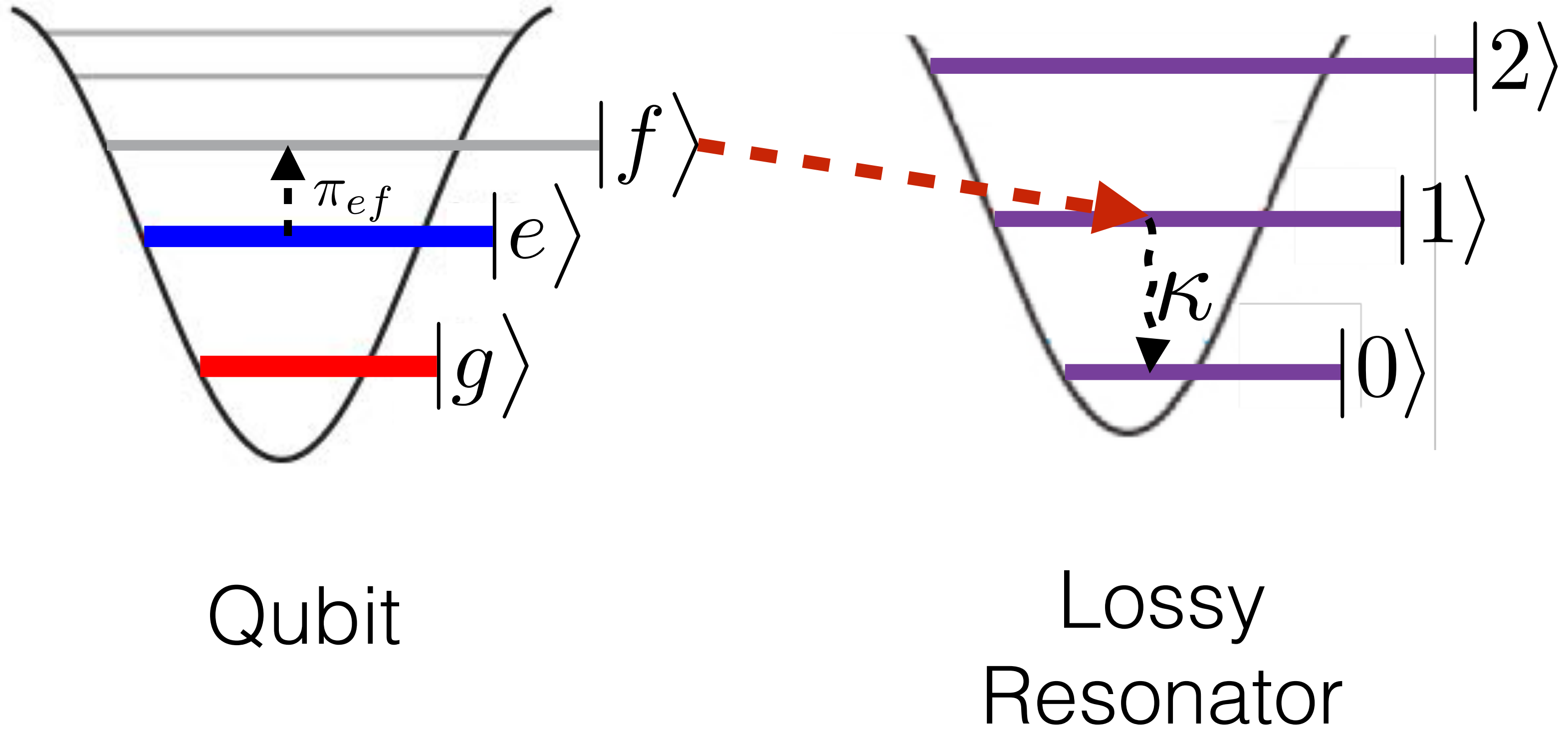
Further improvements to protocol



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



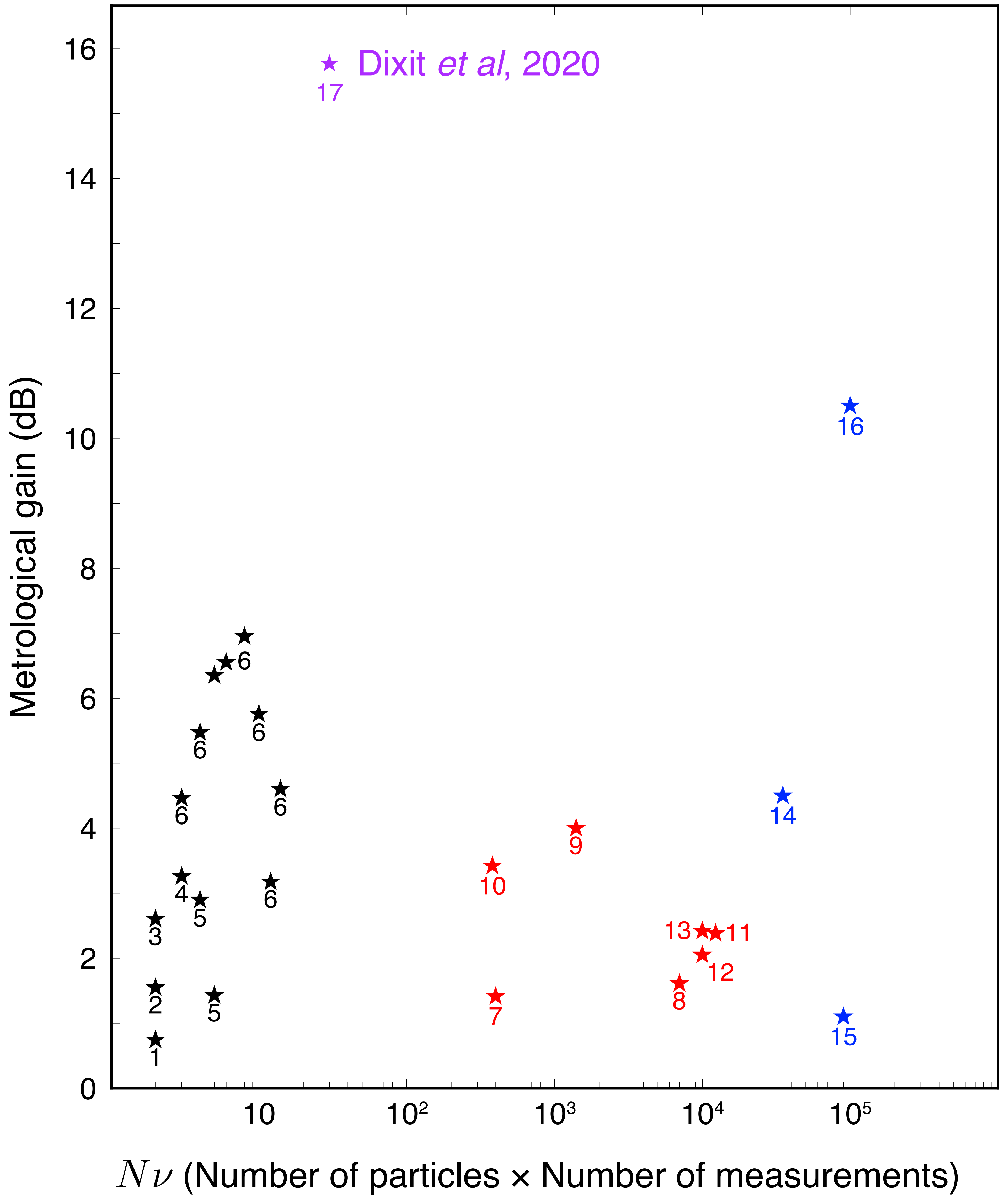
Reset qubit between measurements
- P(decay) ~ 9%
- P(heating) ~ 0.4%

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



Trapped Ions
[1] Sackett, 2000
[2] Meyer, 2001
[3] Leibfried, 2003
[4] Leibfried, 2004
[5] Leibfried, 2005
[6] Monz, 2011

Bose-Einstein Condensates
[7] Gross, 2010
[8] Lücke, 2011
[9] Ockeloen, 2013
[10] Strobel, 2014
[11] Muessel, 2014
[12] Kruse, 2016
[13] Zou, 2018

Cold Thermal Atoms
[14] Leoroux, 2010a
[15] Louchet-Chauvet, 2010
[16] Hosten, 2016

Superconducting Qubit
[17] Dixit, 2020

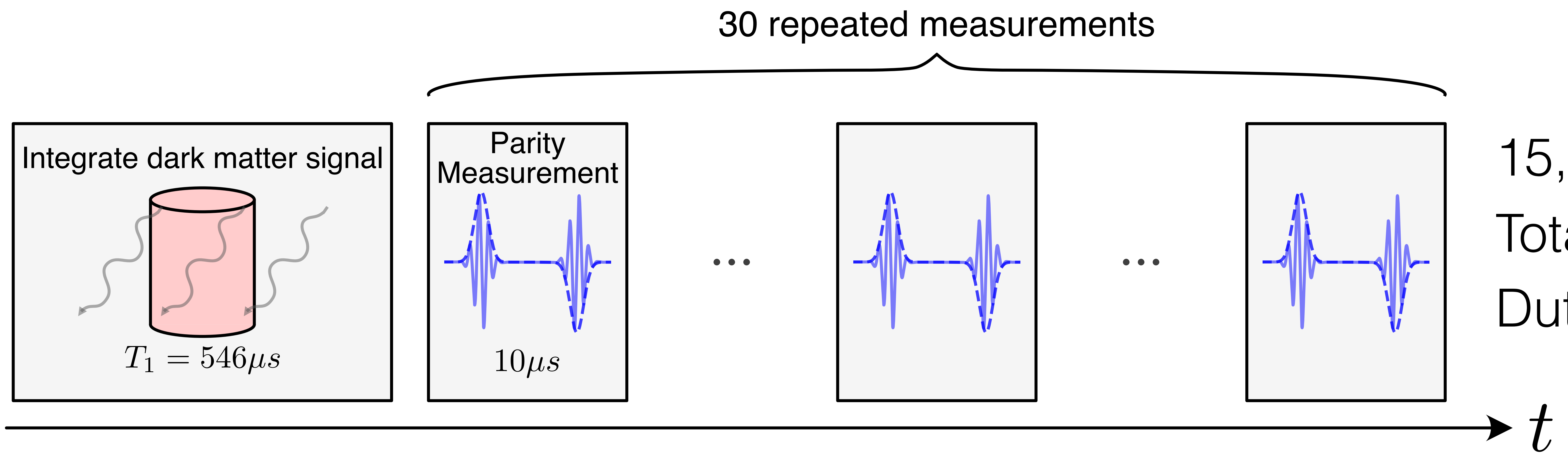
journals.aps.org/rmp/abstract/10.1103/RevModPhys.90.035005

Outline of talk

- Dark matter could couple to electromagnetism to produce photons
- 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

Dark matter search protocol

Signal cannot build up while measuring (quantum Zeno effect)



15,141 experiments performed

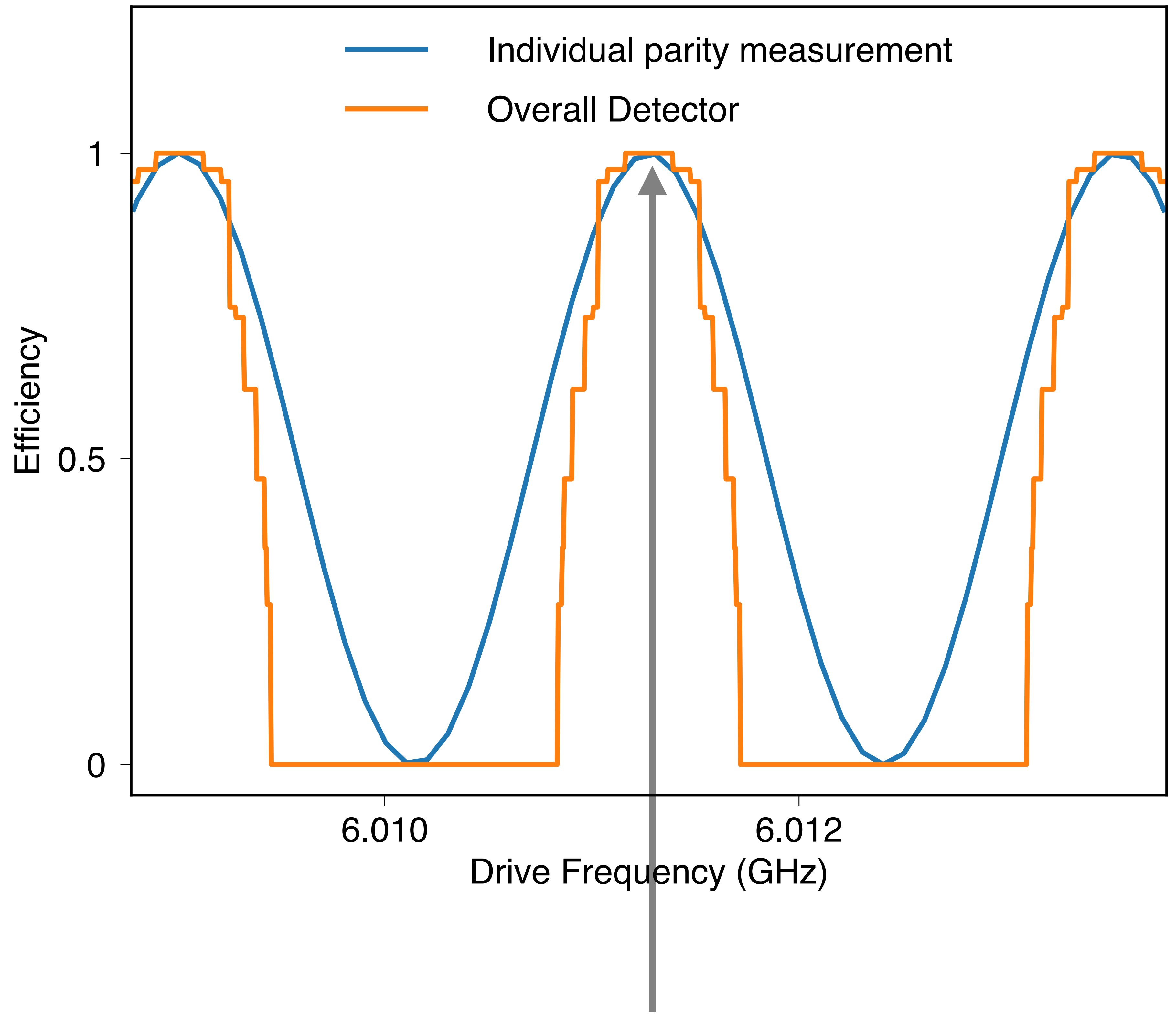
Total experiment time of 12.81 s

Duty cycle of 65% (8.33 s of integration)

Counted 22 photons

Dark matter candidate that could produce 29 or more photons excluded at the 90% confidence level

Detector is sensitive to off resonant and large amplitude signals



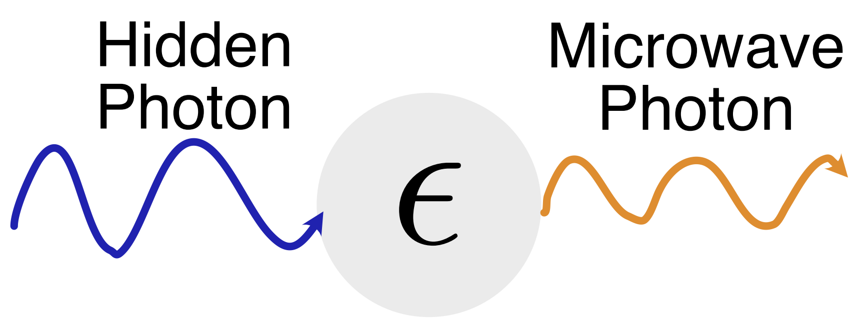
With parity procedure, qubit can sense:

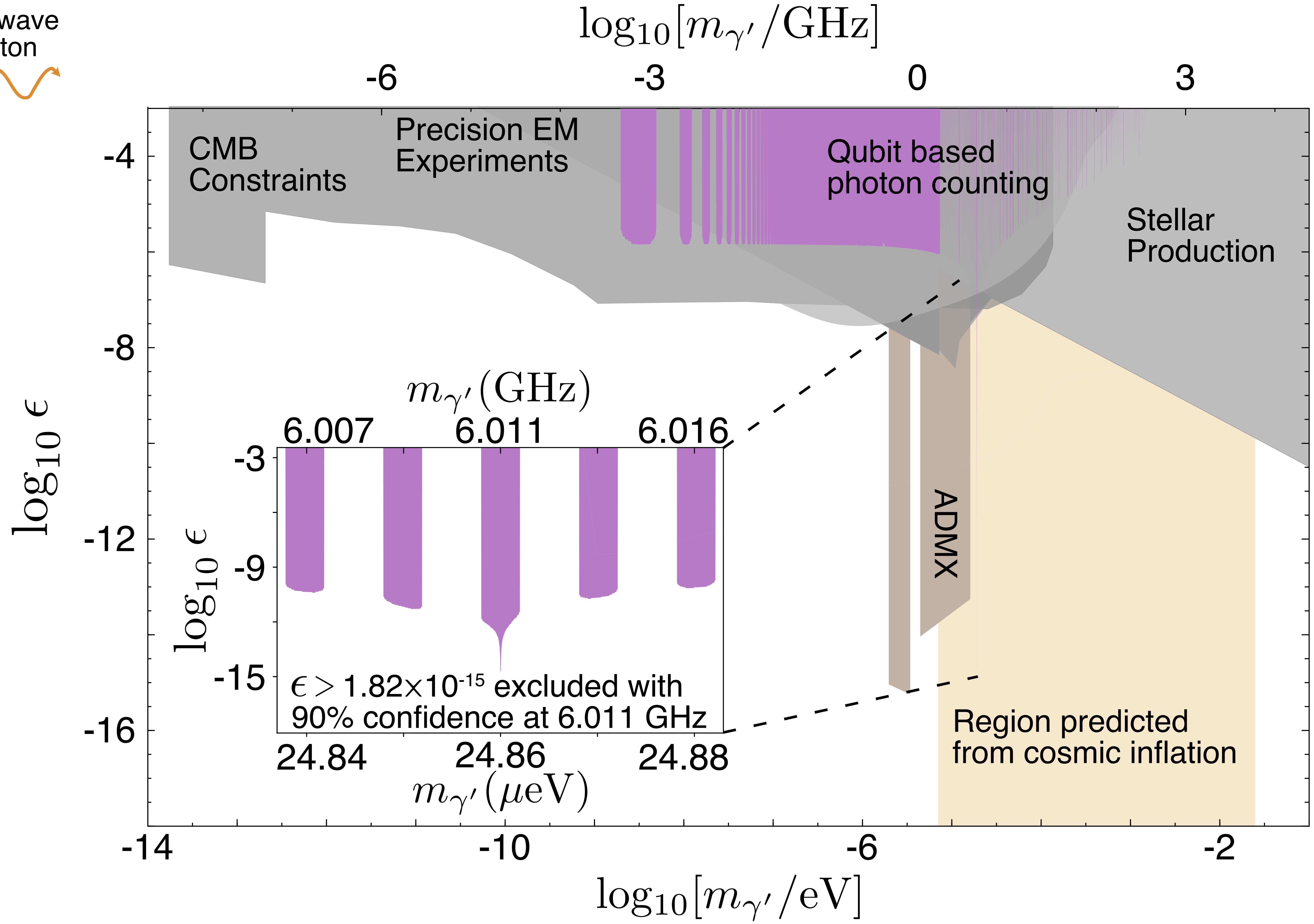
- Off resonant photons filtered through cavity

- Large amplitude signals, with significant odd number contributions

Parity procedure tuned for excitations on resonance

Constraining the Hidden Photon Dark Matter

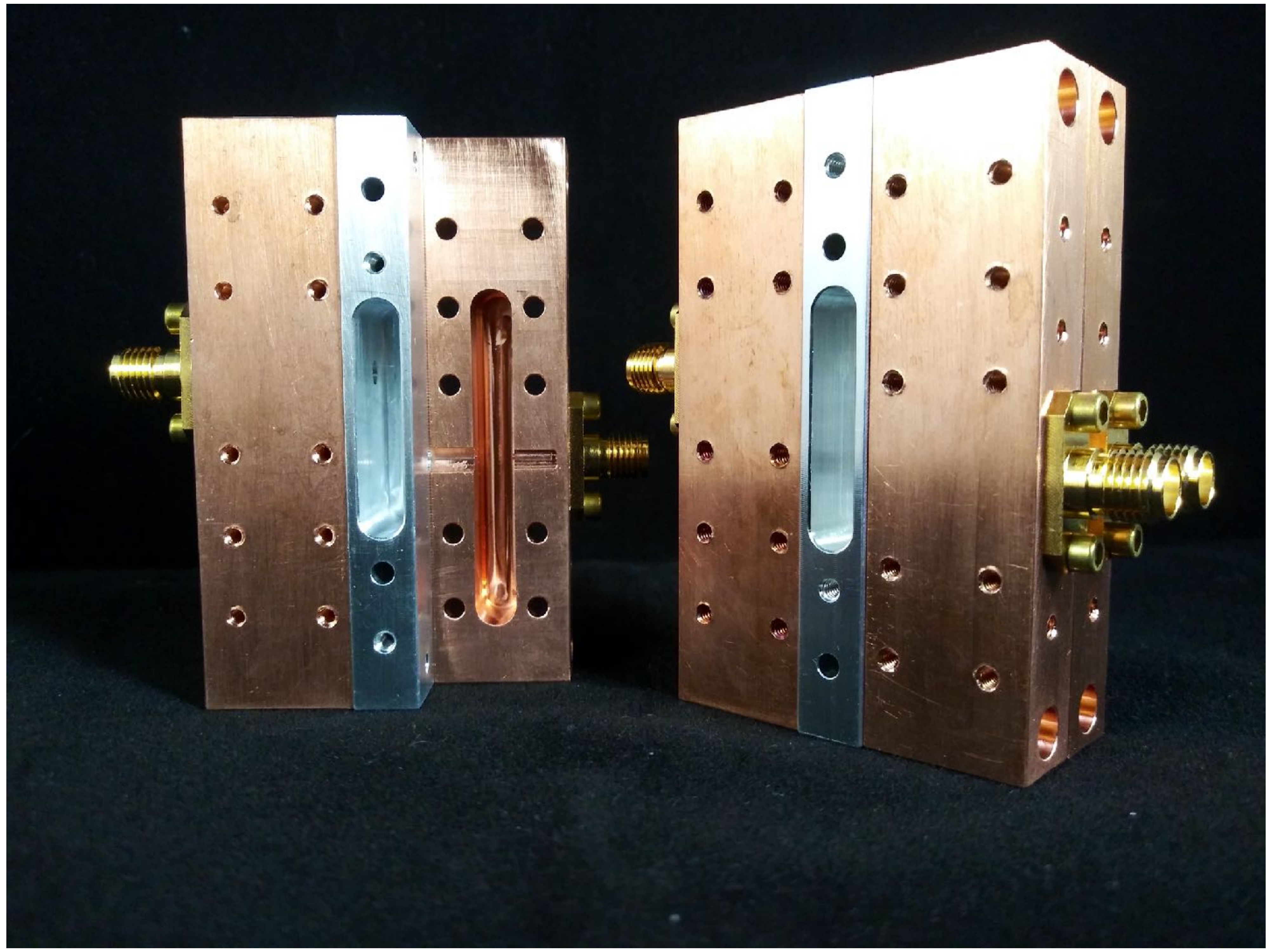




Further increasing sensitivity for dark matter searches

Investigate and mitigate photon backgrounds

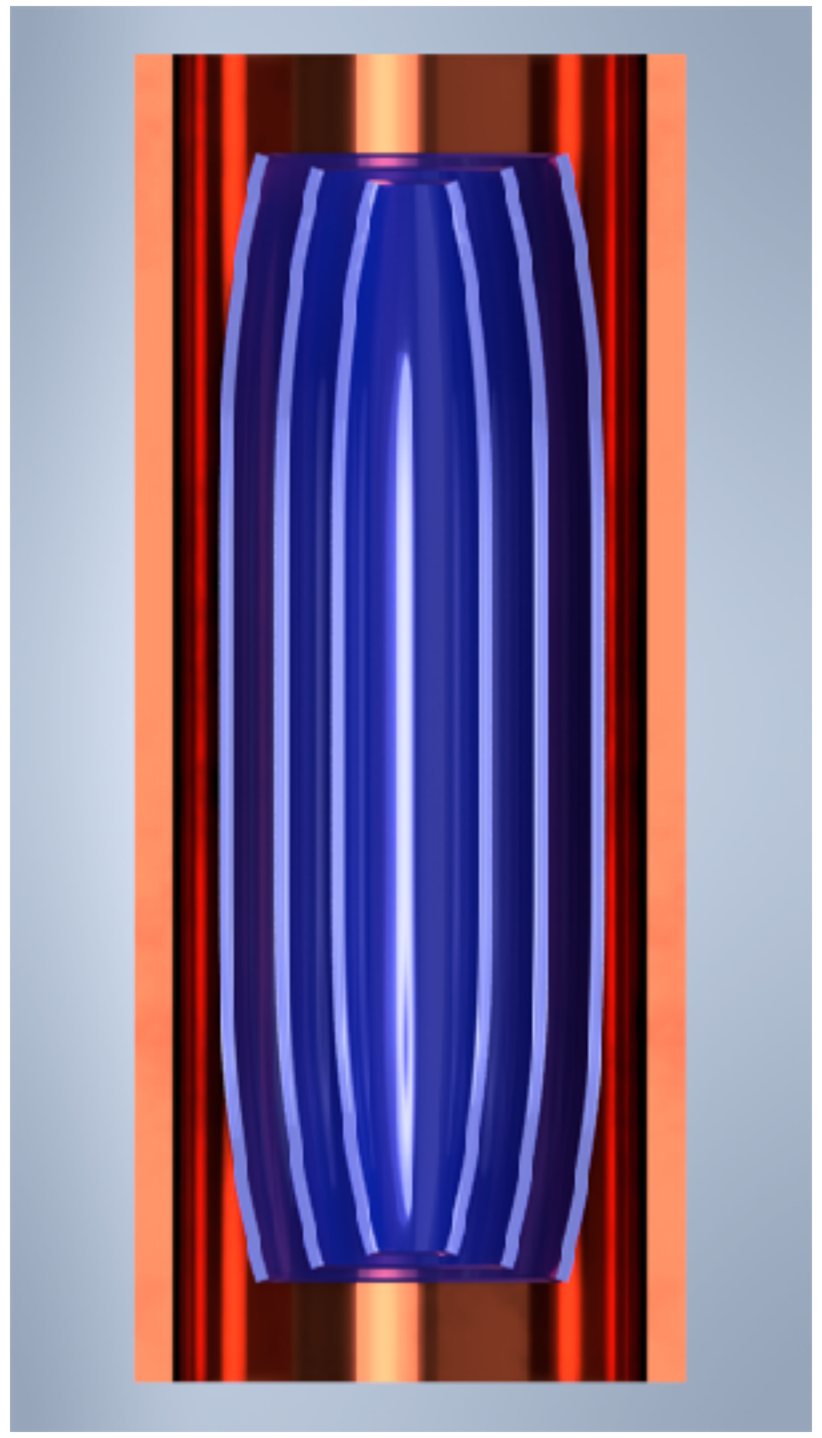
Use multiple entangled qubits for enhanced metrology

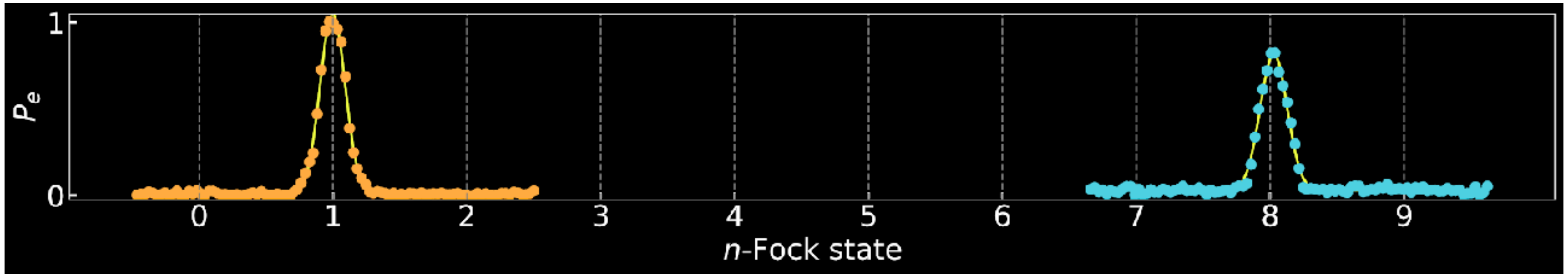


Boosting dark matter induced signal

Novel materials/designs for high Q cavities

Use nonclassical cavity states for signal enhancement





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

U.S. DEPARTMENT OF ENERGY | Office of Science

Pritzker Nanofabrication Facility

Army Research Office

the David & Lucile Packard Foundation

Heising-Simons Foundation

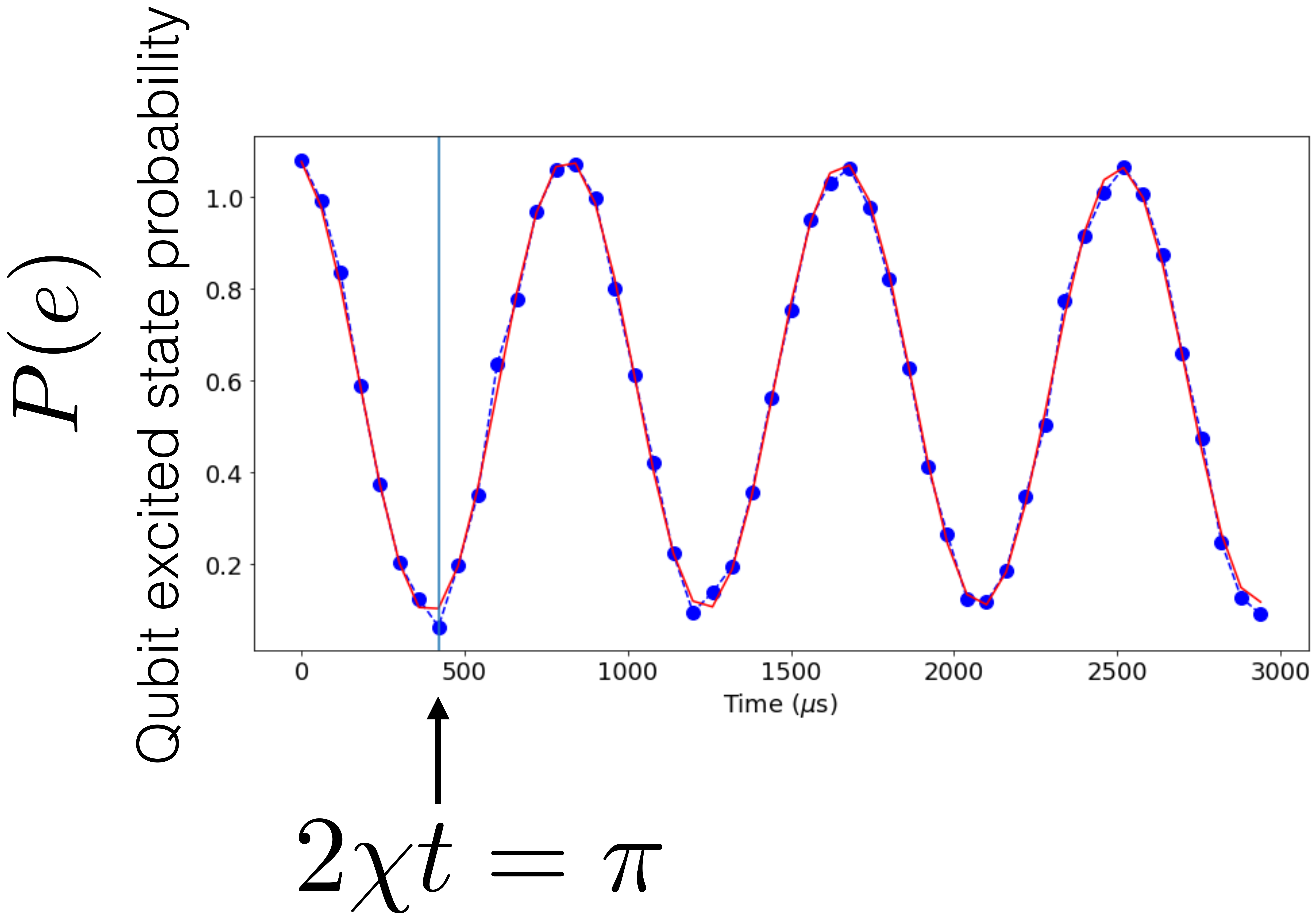
schuster.lab

The University of Chicago

Fermilab

Number Parity Measurement to Determine Cavity Photon Number

1. Place Qubit in superposition state
2. Qubit superposition precesses at 2χ in the presence of cavity photon
3. Wait (460ns) for state to rotate halfway around the plane
4. Project state onto z-axis



Forward Backward Algorithm

Forward-Backward algorithm allows us to determine the hidden state probability

$$P(n_i|R_0, R_1, ..., R_i, ..., R_n) \propto P(n_i|R_0, R_1, ..., R_i) \times P(R_{i+1}, ..., R_n|n_i)$$

Forward

$$P(n_i|R_0, R_1, ..., R_i) \propto \sum_{n_{i-1}} E(n_i, R_i) T(n_{i-1}, n_i) P(n_{i-1}|R_0, R_1, ..., R_{i-1})$$

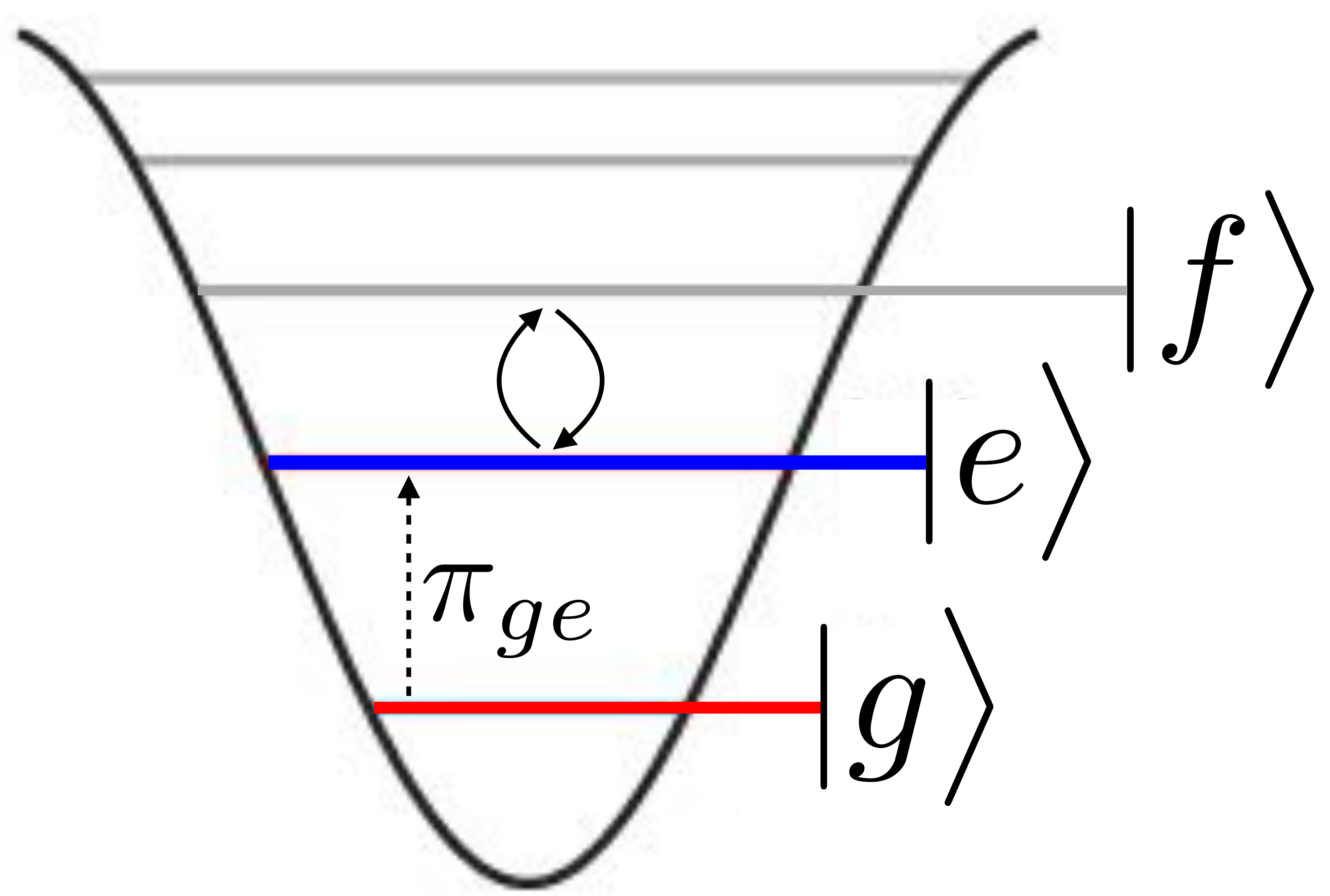
Backward

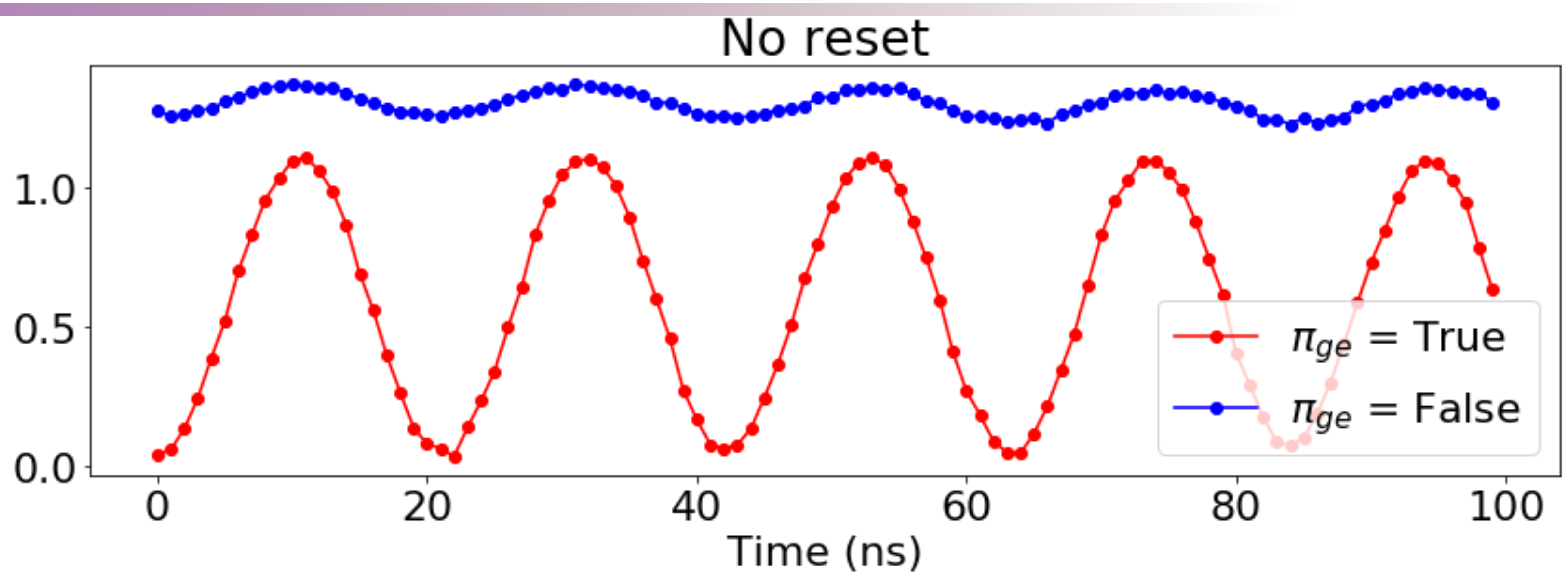
$$P(R_{i+1}, ..., R_n|n_i) \propto \sum_{n_{i+1}} P(R_{i+2}, ..., R_n|n_{i+1}) E(n_{i+1}, R_{i+1}) T(n_i, n_{i+1})$$

https://arxiv.org/pdf/1607.02529.pdf

https://web.stanford.edu/~jurafsky/slp3/A.pdf

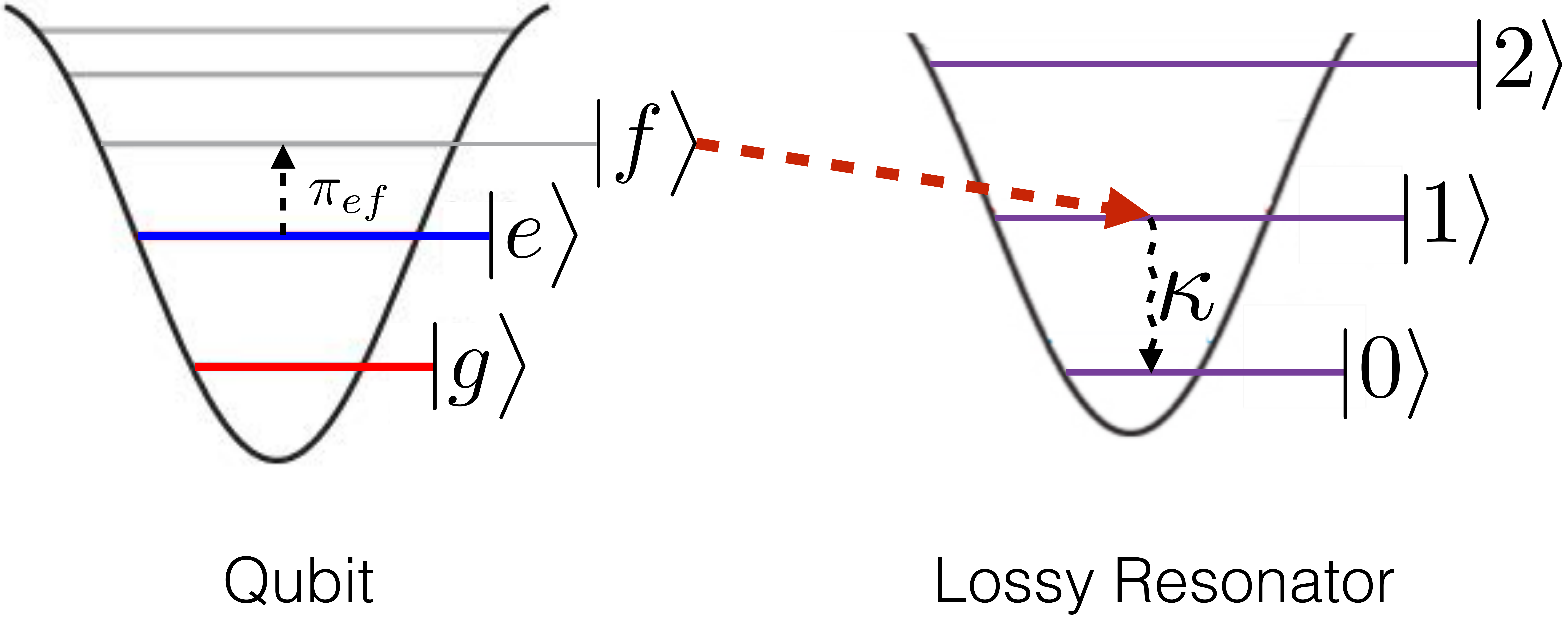
Qubit Spurious Excitations Produce Dark Counts



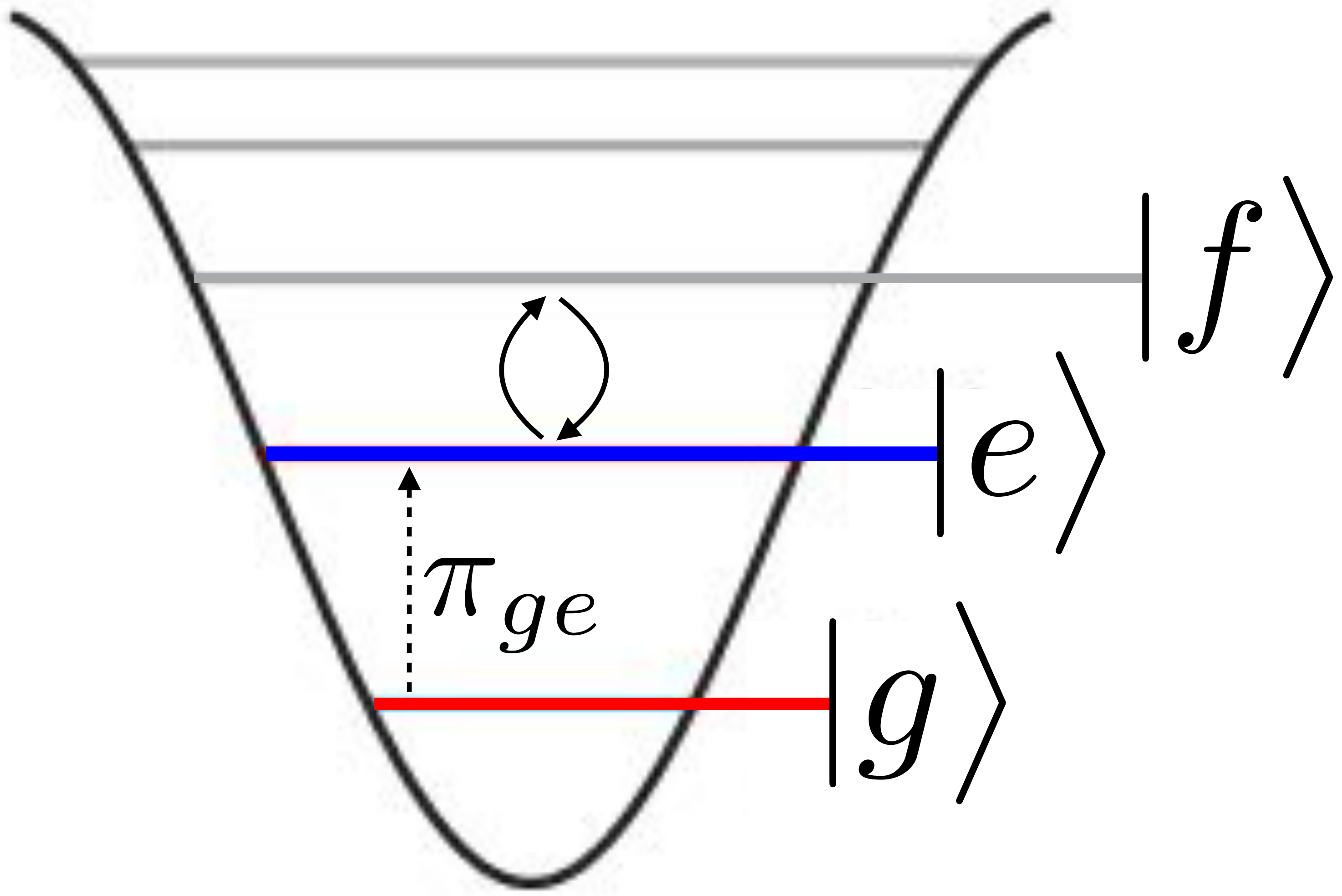


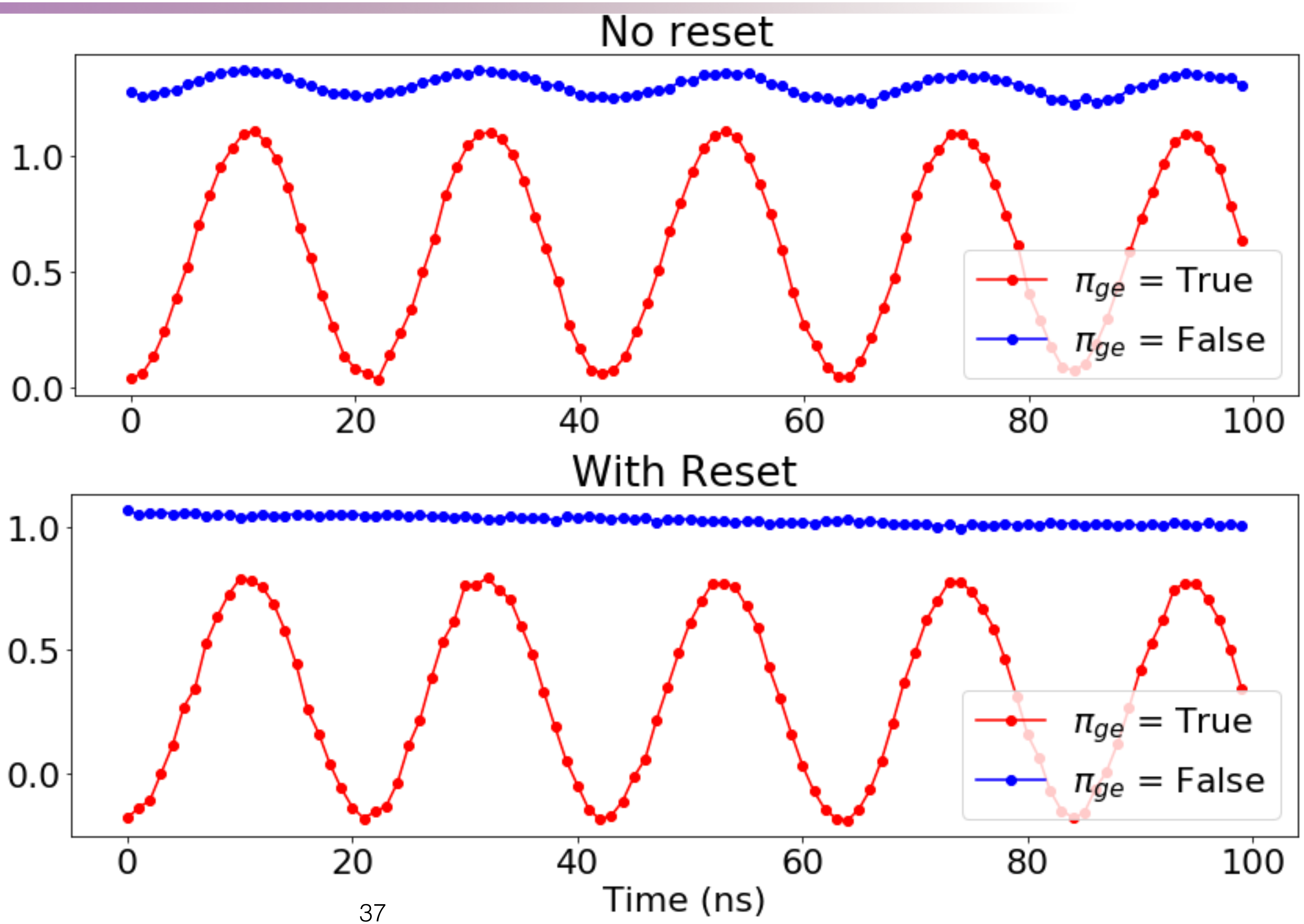
Ratio of oscillation amplitudes
=
Ratio of ground/excited state populations

Cool Qubit with Lossy Resonator Mode



Qubit Spurious Excitations Suppressed with Cooling





Ratio of oscillation amplitudes

=

Ratio of ground/excited state populations

Suppressing Spurious Qubit Excitations