Searching for dark matter with a superconducting qubit

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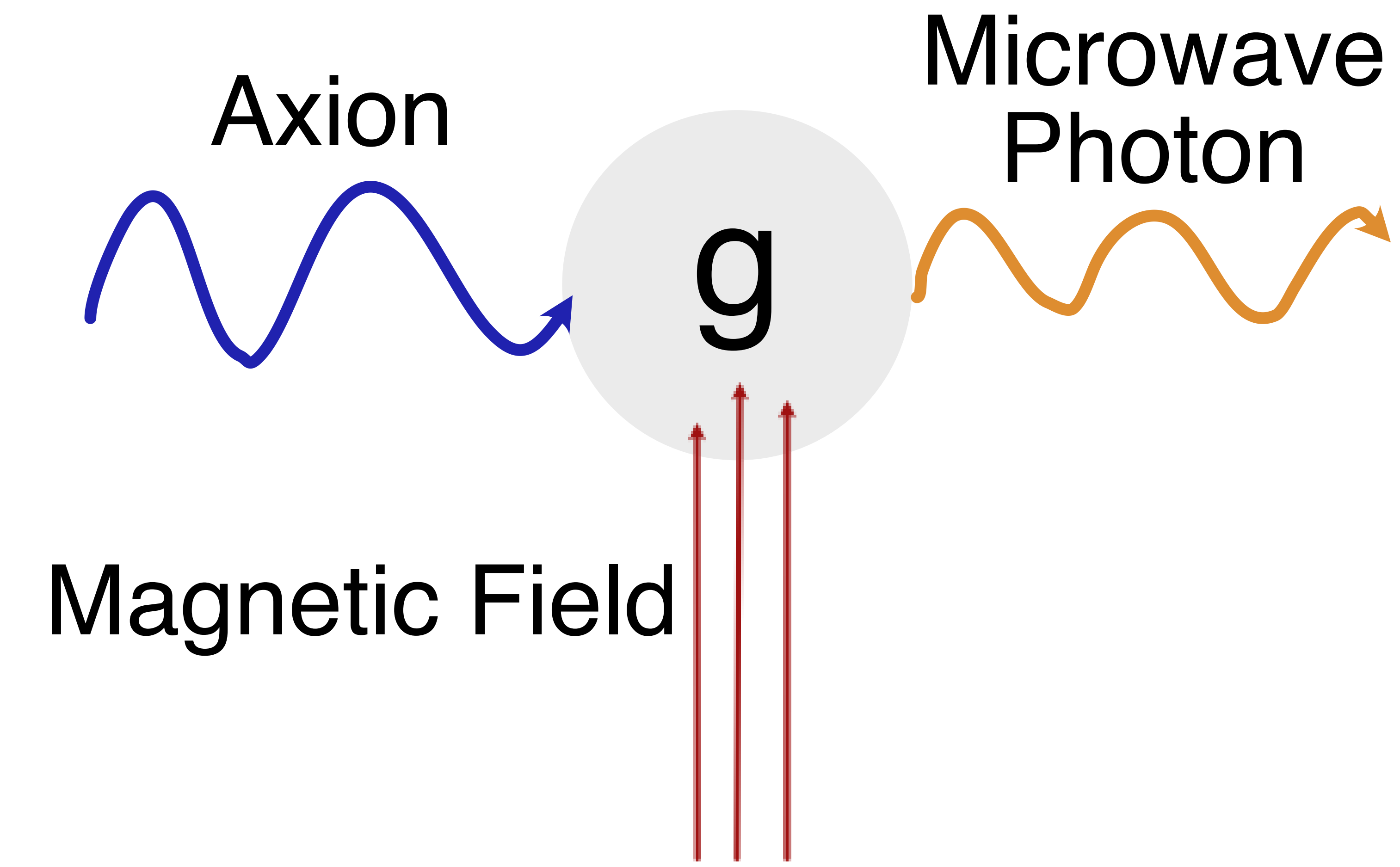
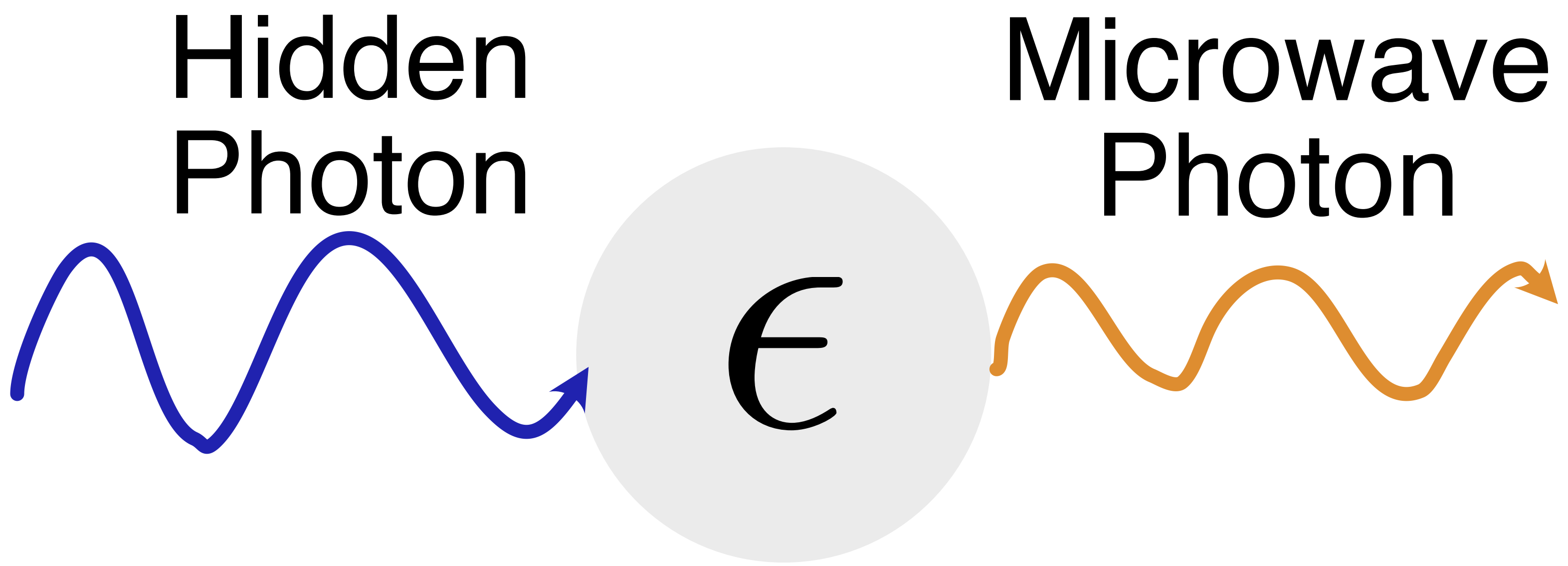
Outline of talk

- 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

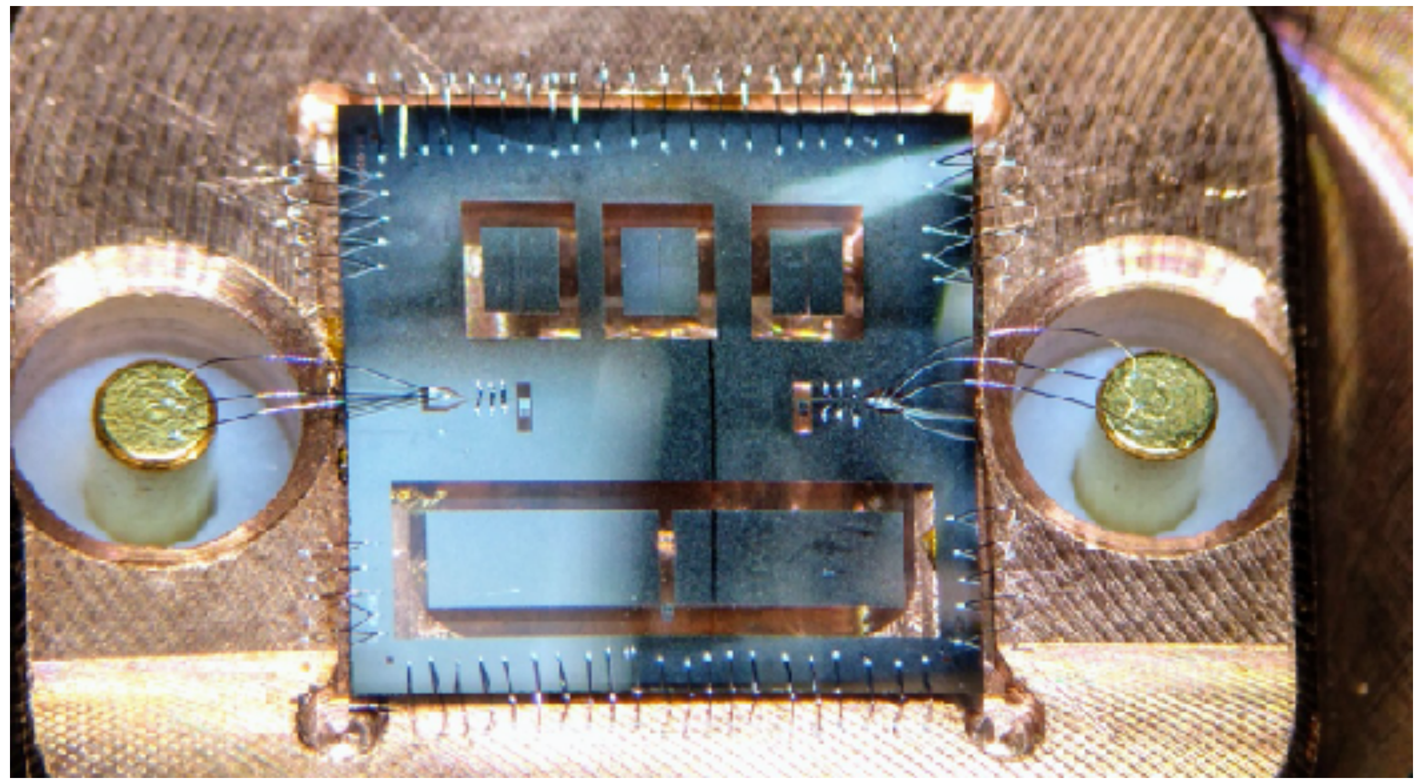
How dark matter might couple to electromagnetism



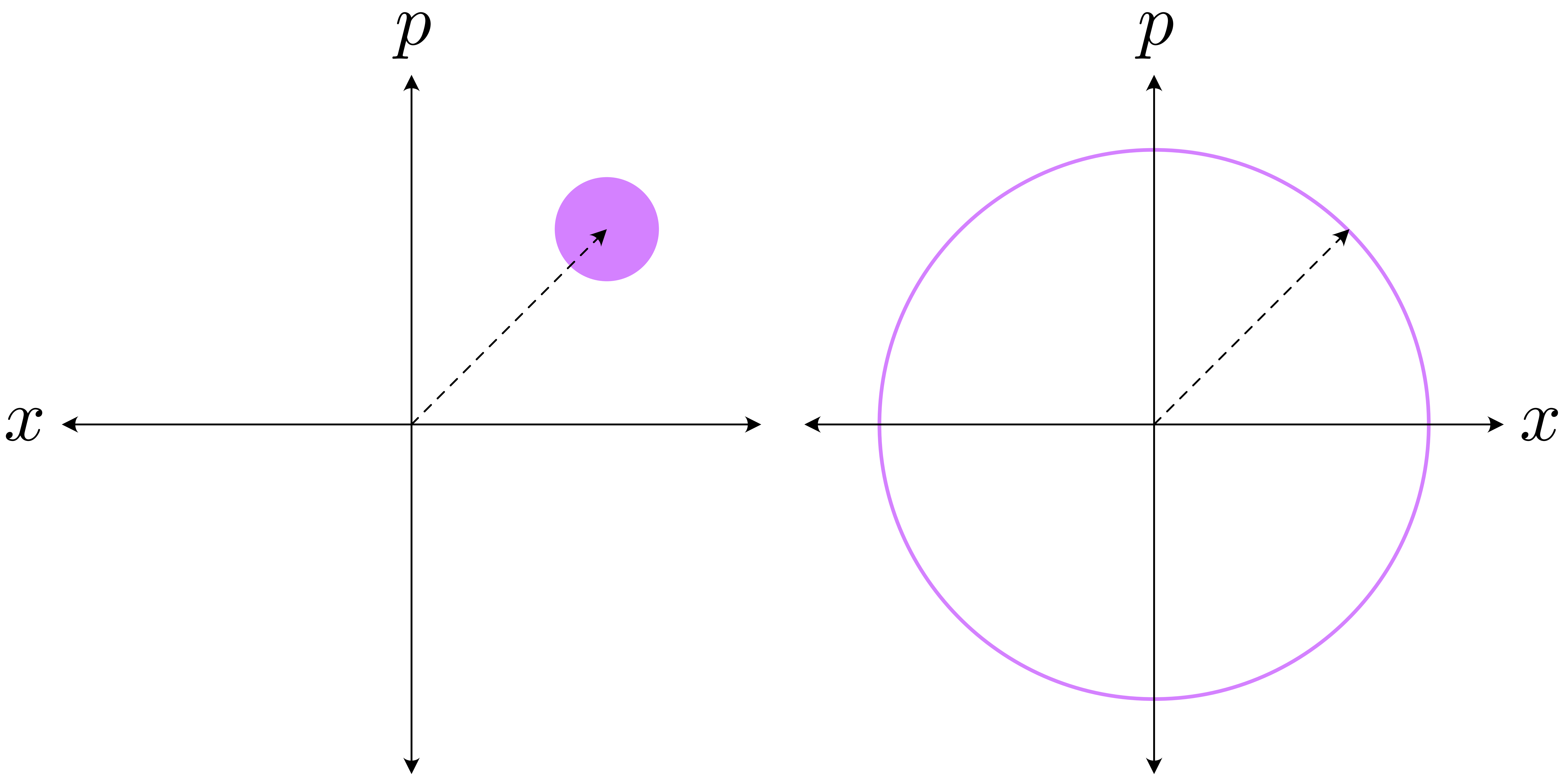


Resonant cavity to capture signal

Quantum limited amplifier for readout



Count photons to subvert quantum limit



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

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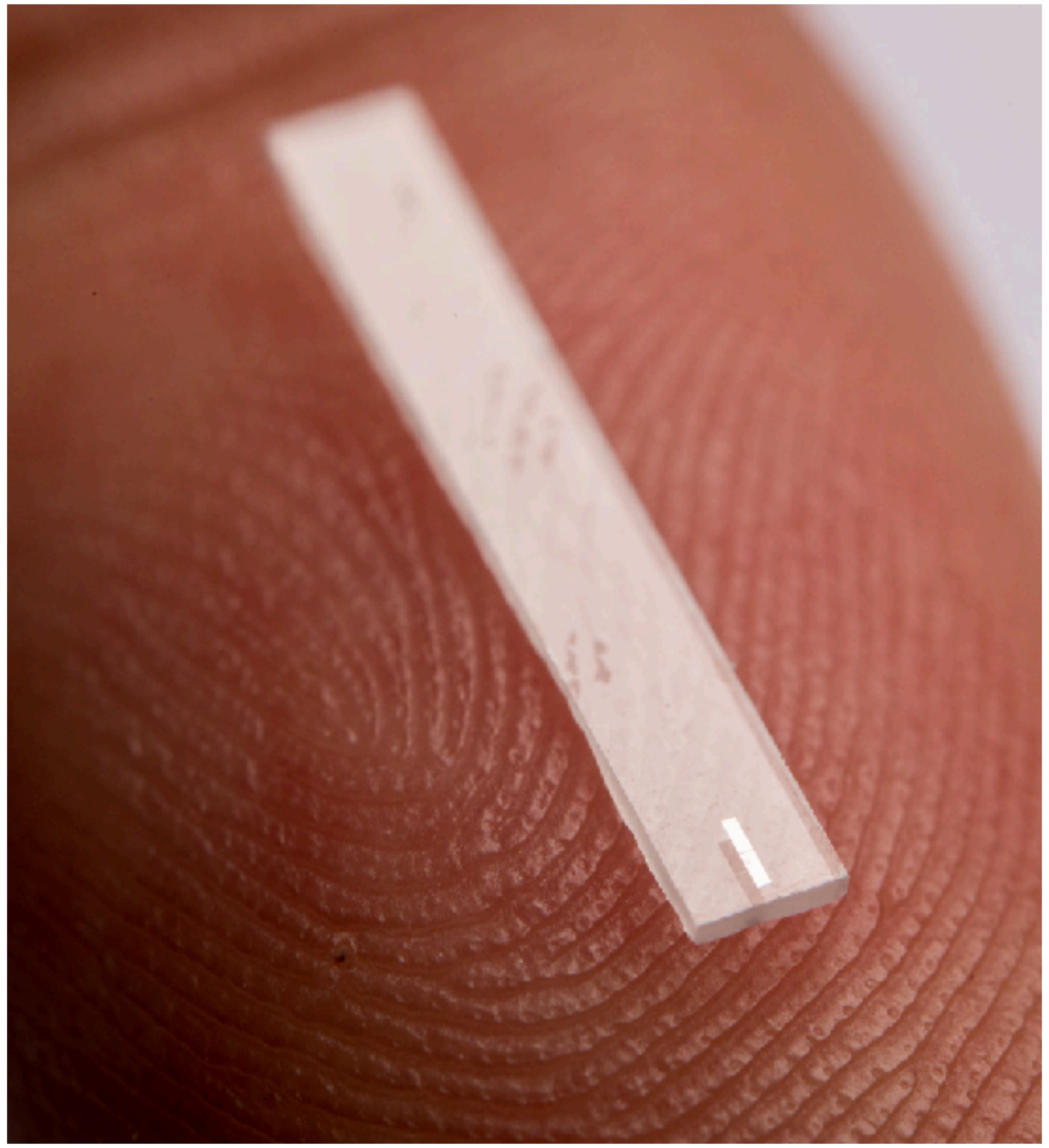
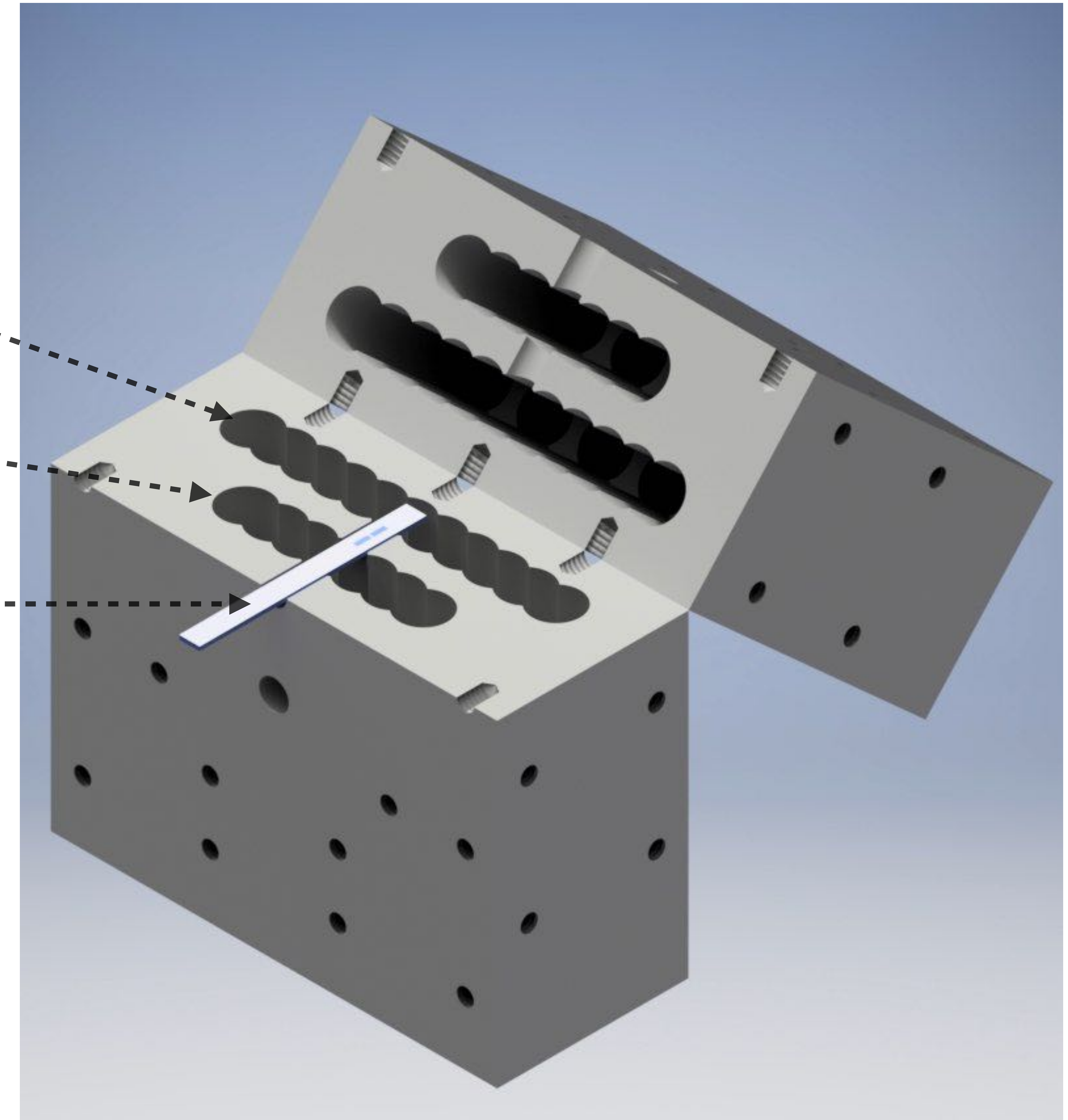


Photon counting device

Storage Cavity 6.011 GHz

Readout Cavity 8.052 GHz

Qubit on sapphire chip 4.749 GHz

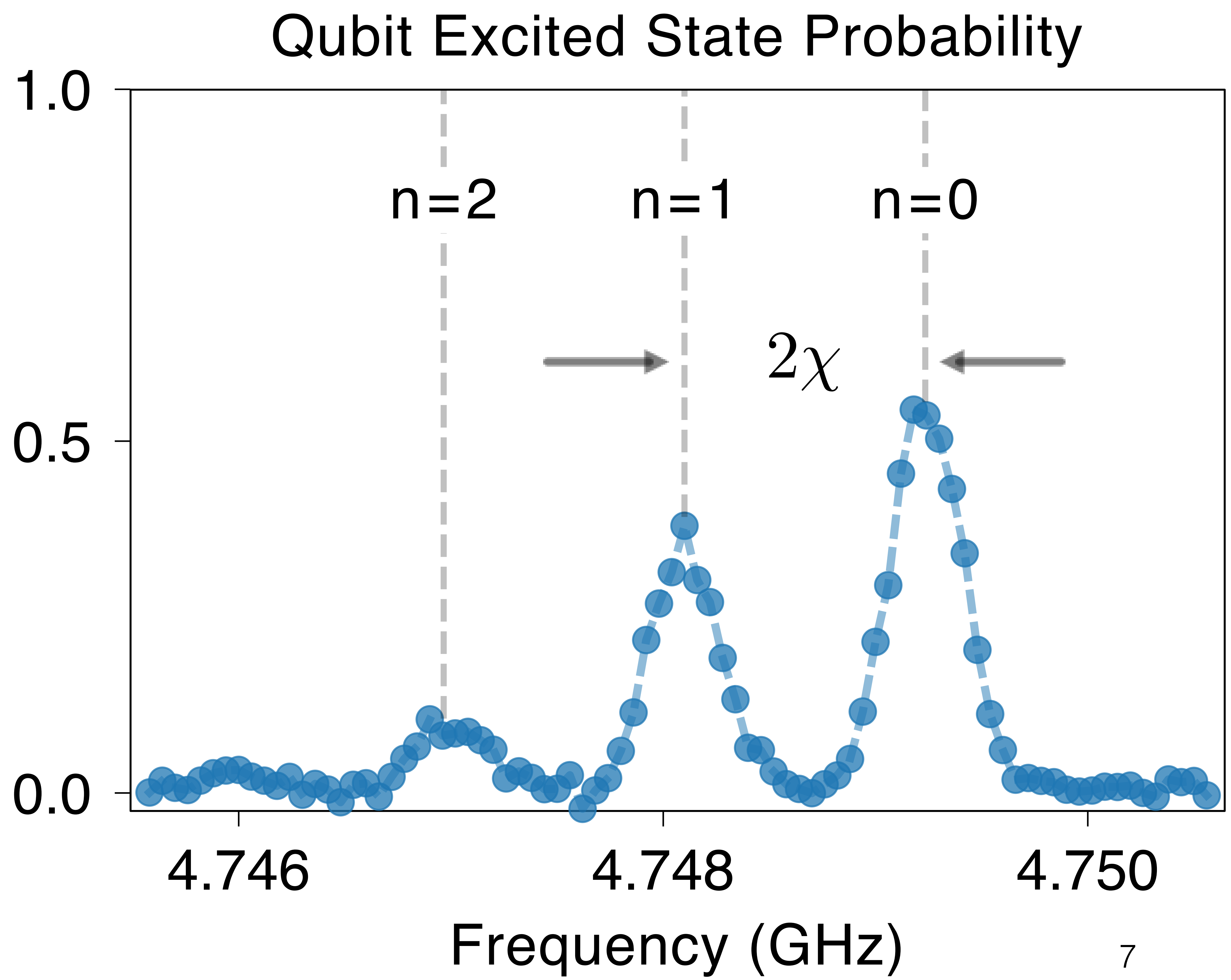


$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Operated in a dilution refrigerator @ 8mK

Cavity occupation imprinted on qubit transition frequency

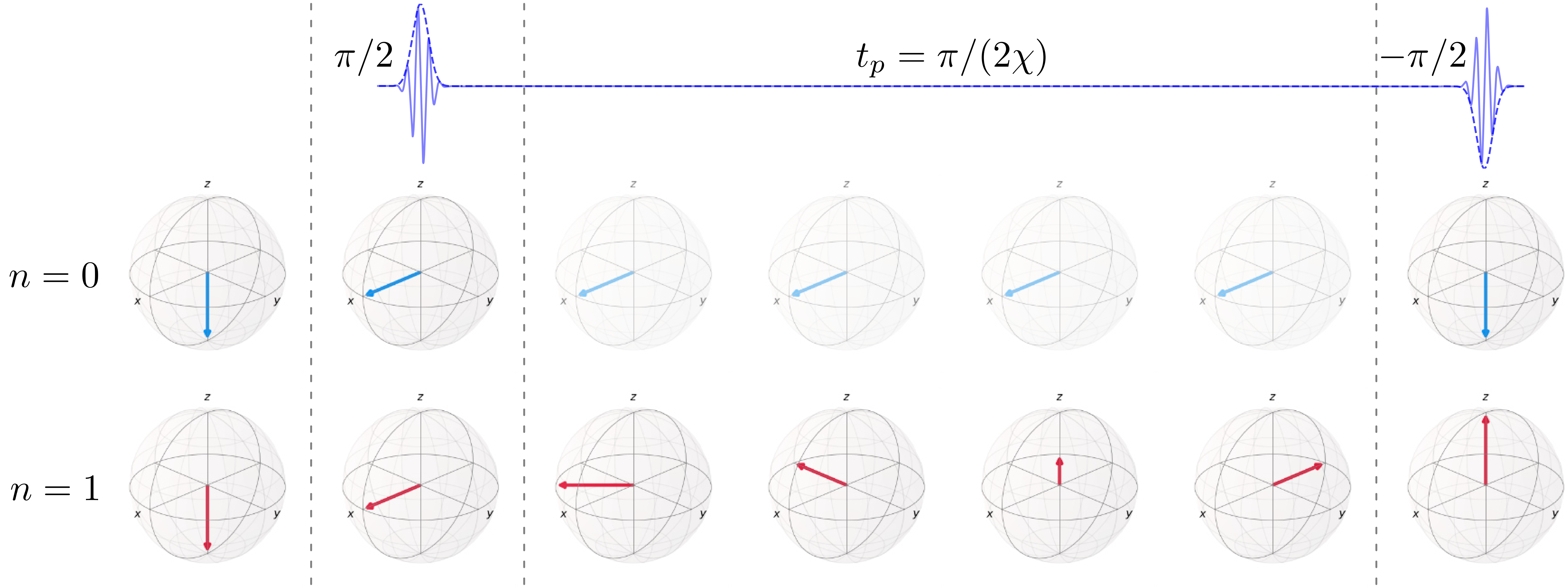
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$



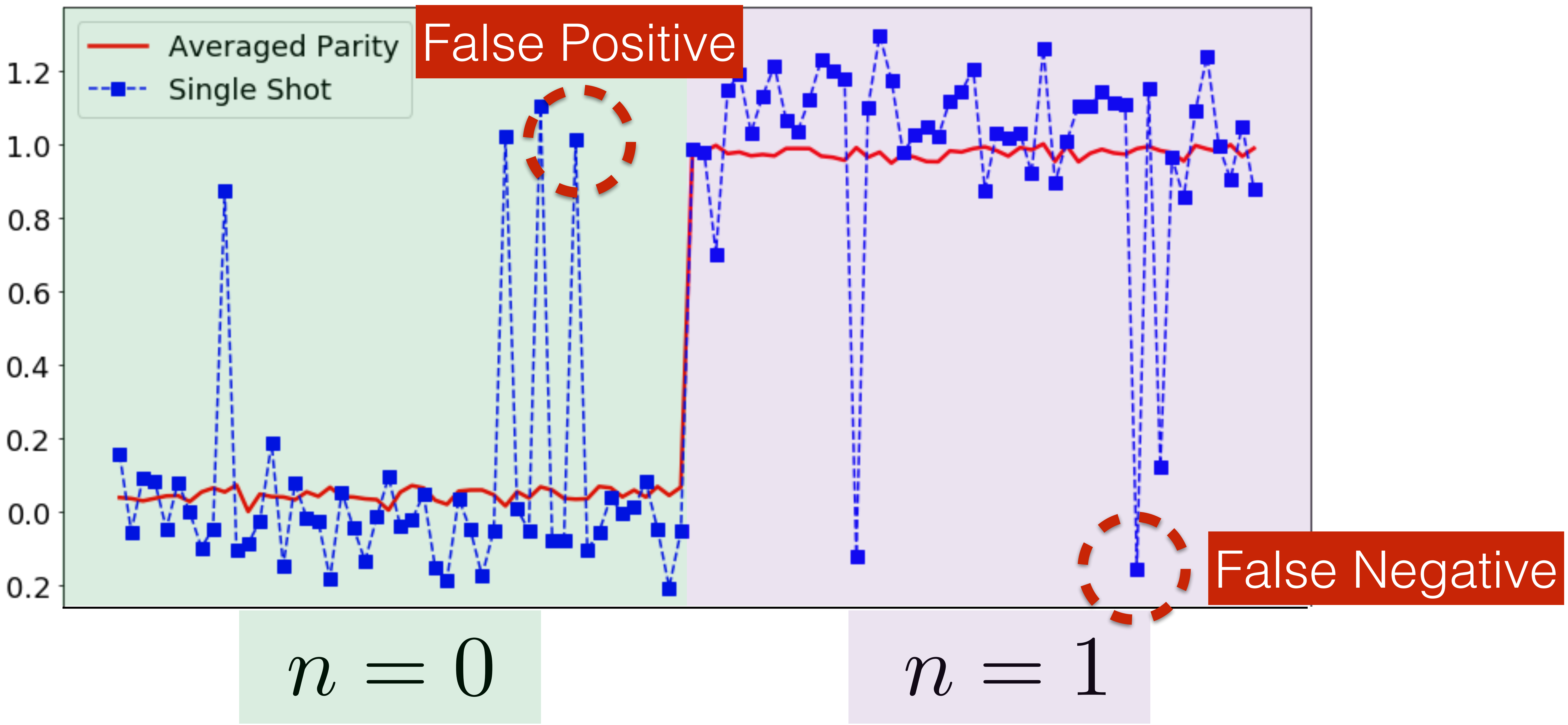
Qubit transition frequency is photon number dependent

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

Parity measurement maps cavity state onto qubit



Qubit makes too many errors



Spurious qubit excitations are dominant source of errors

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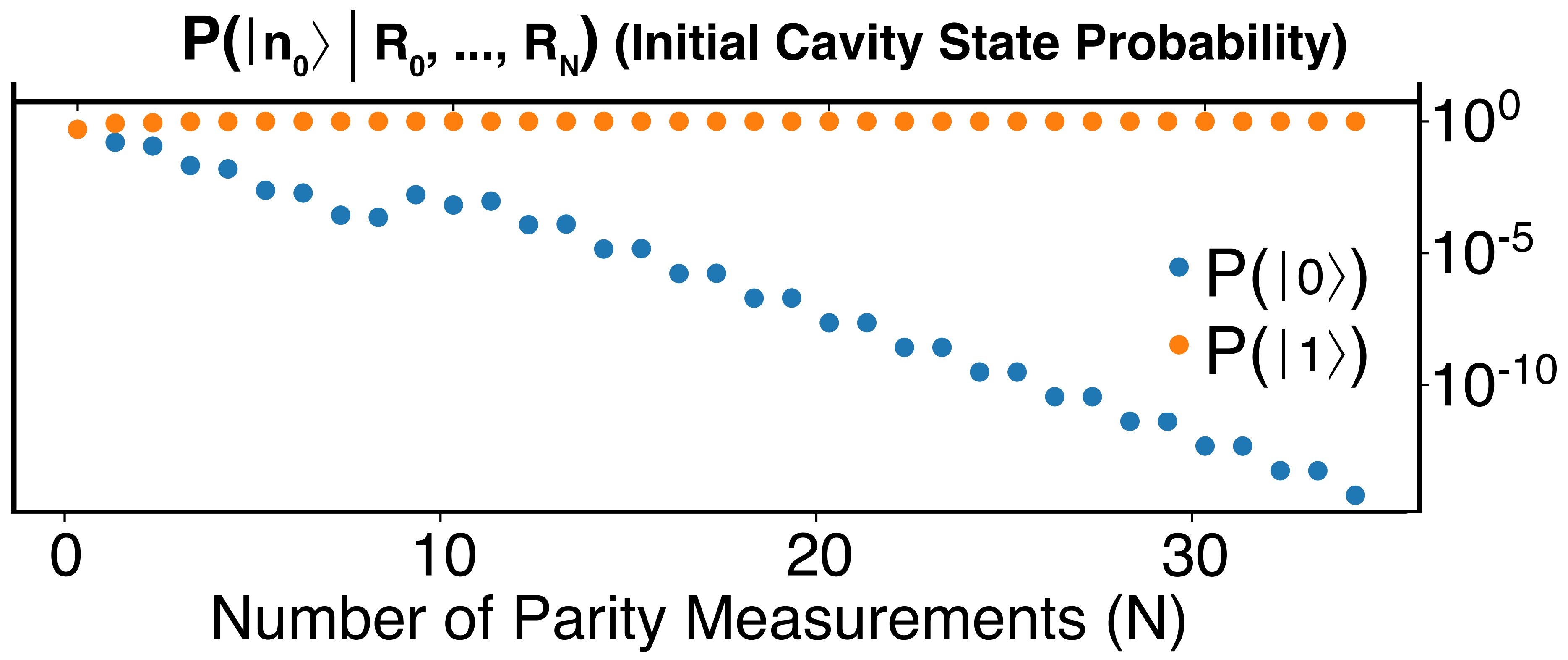
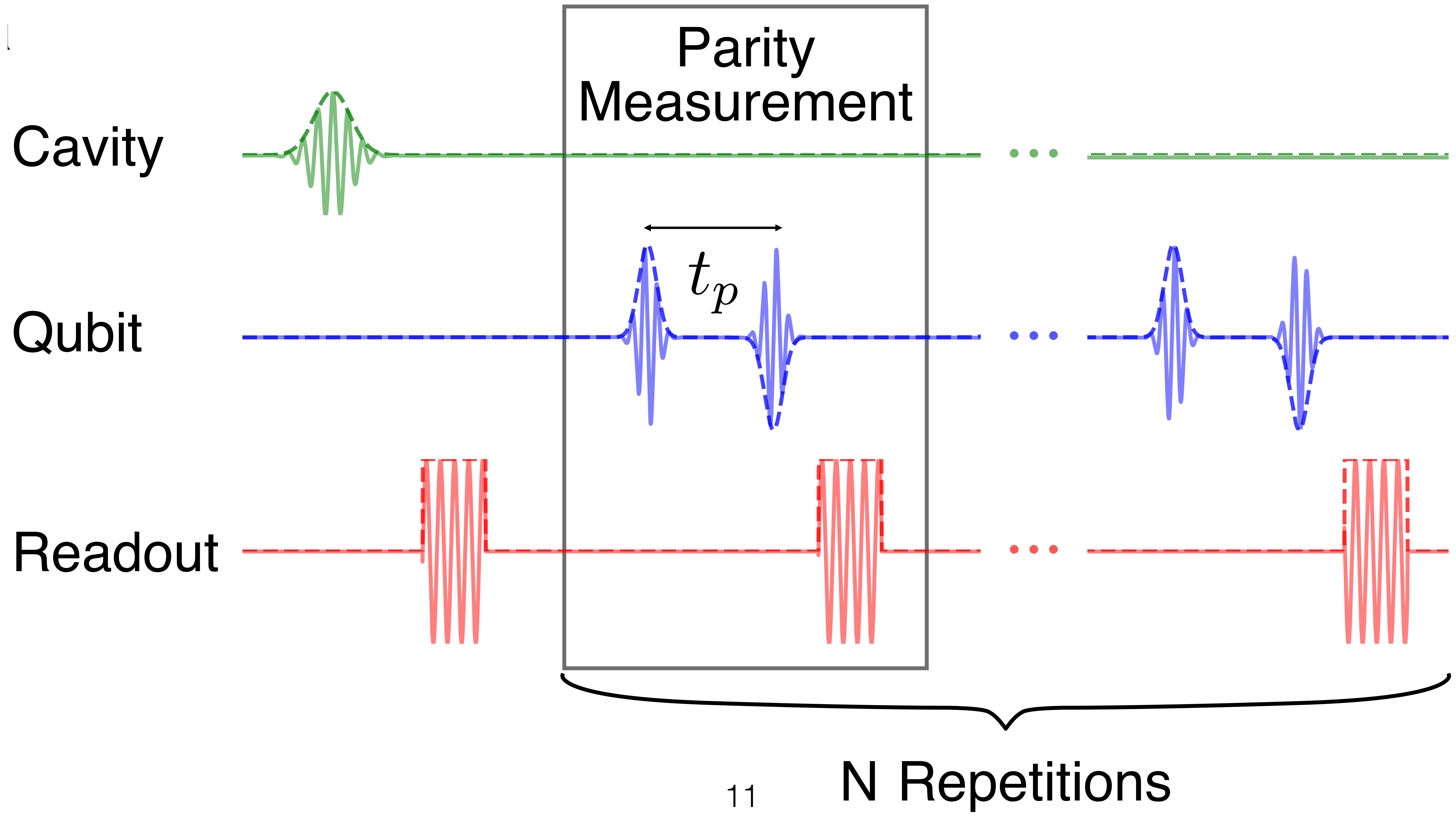


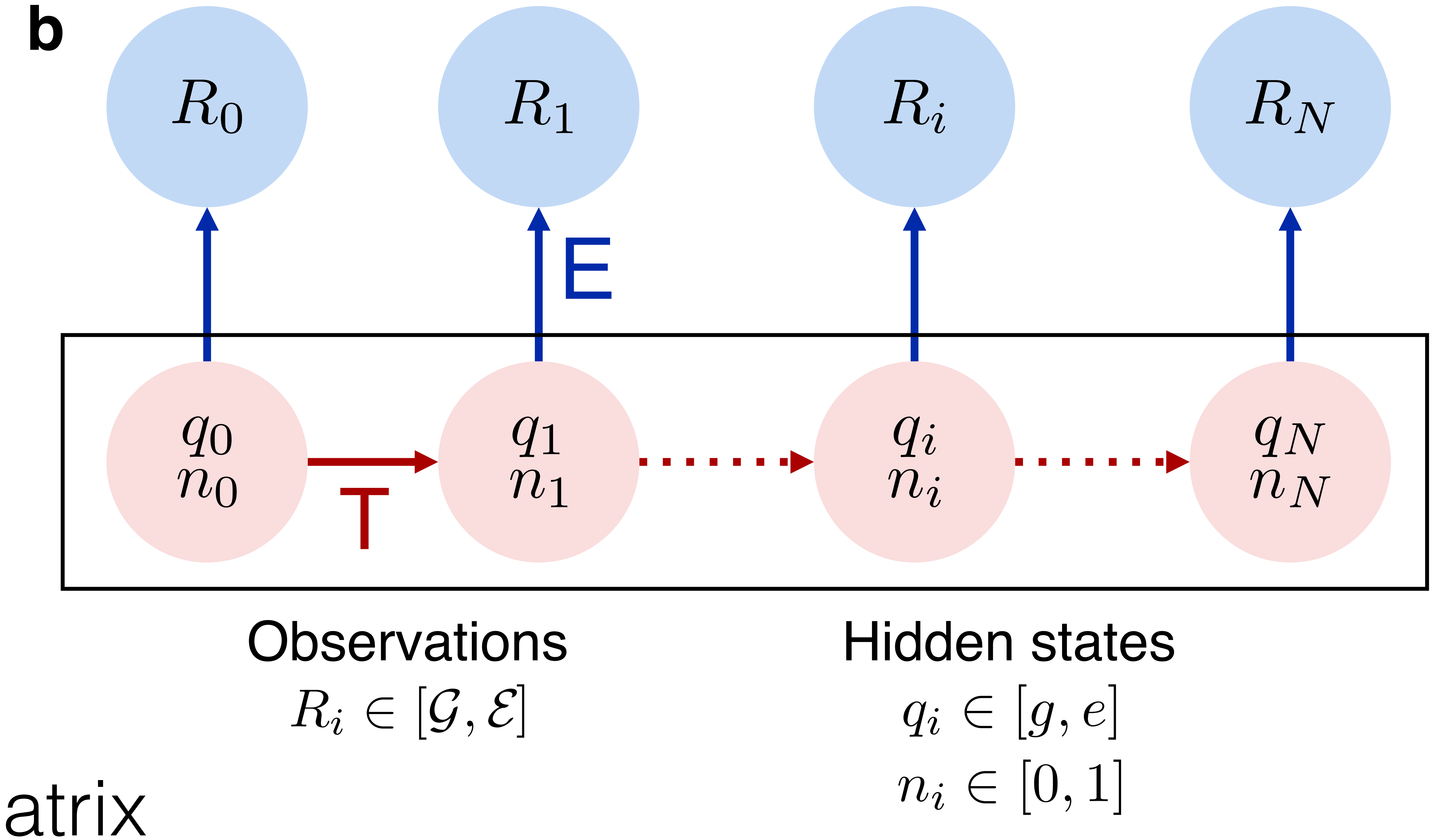
Mitigate the errors by making repeated measurements

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

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



Use hidden Markov model analysis to reconstruct cavity state



T = Transition matrix

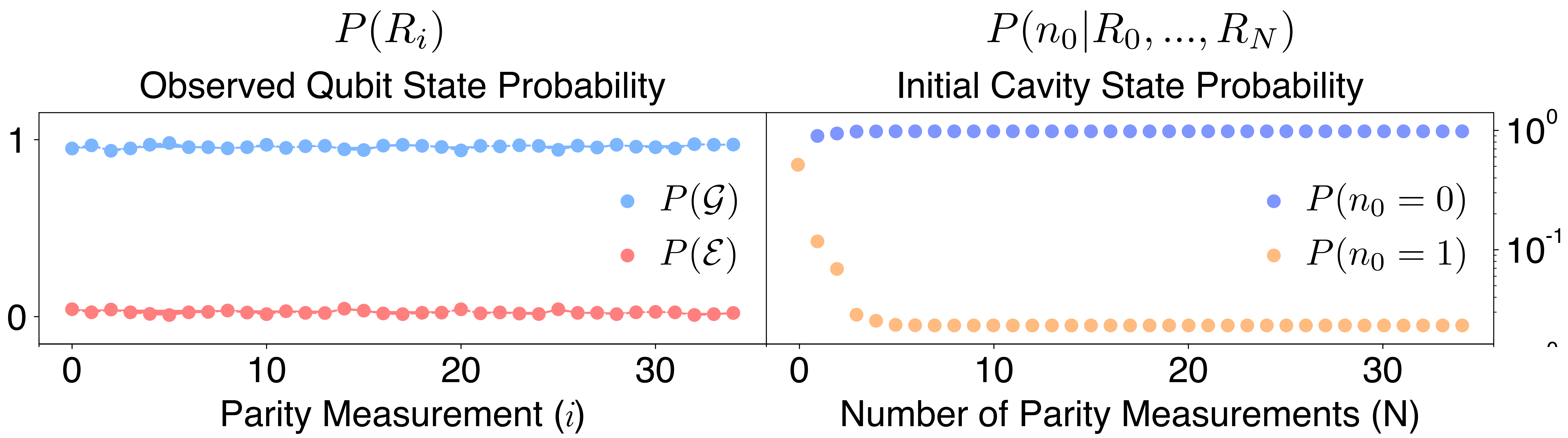
- qubit (108μs), cavity (546μs) lifetime
- qubit spurious population (0.05)
- time between experiments (10μs)
- qubit dephasing (T_2 = 61μs)
- parity time (t_p = 0.4μs)

E = Emission matrix

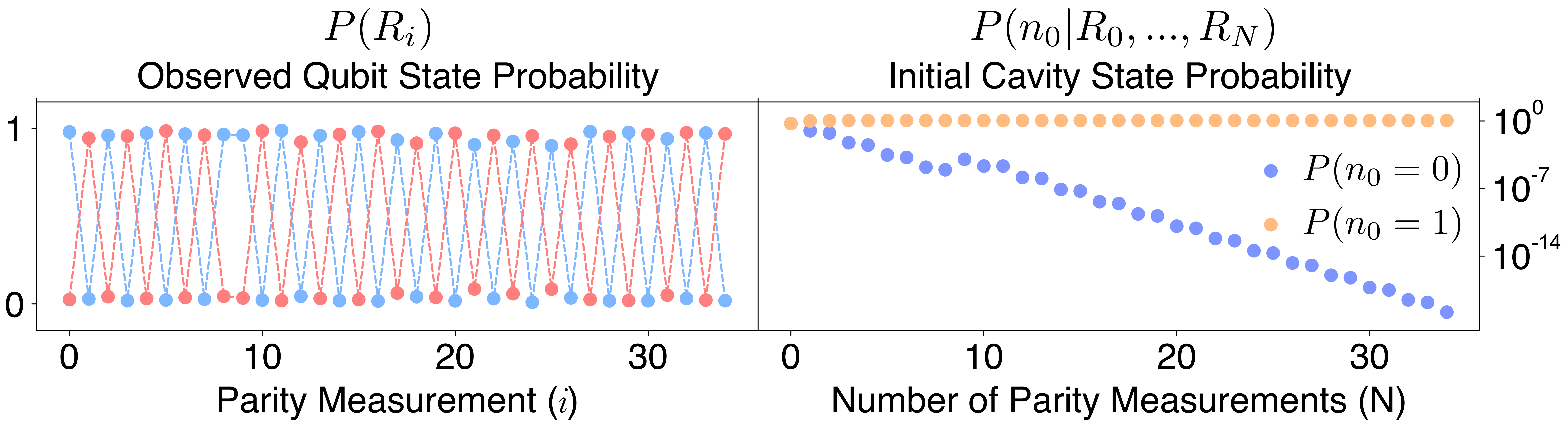
- ground and excited state readout fidelity (~0.95)

arxiv.org/pdf/1607.02529.pdf

Detector response in the presence of zero photons



Detector response in the presence of one photon



Exponential suppression of detector based false positives

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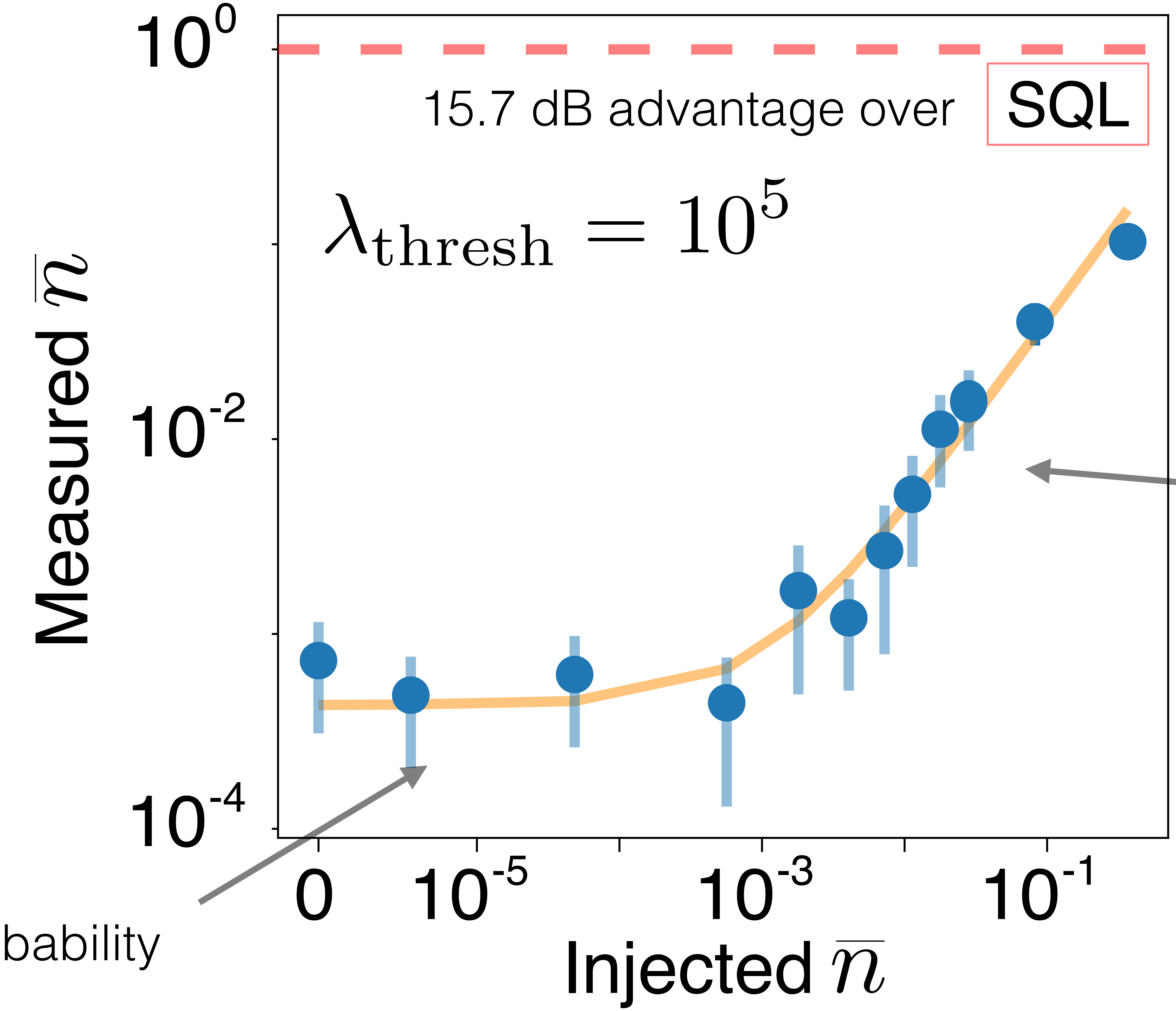
Detected photon occupation vs injected photon occupation



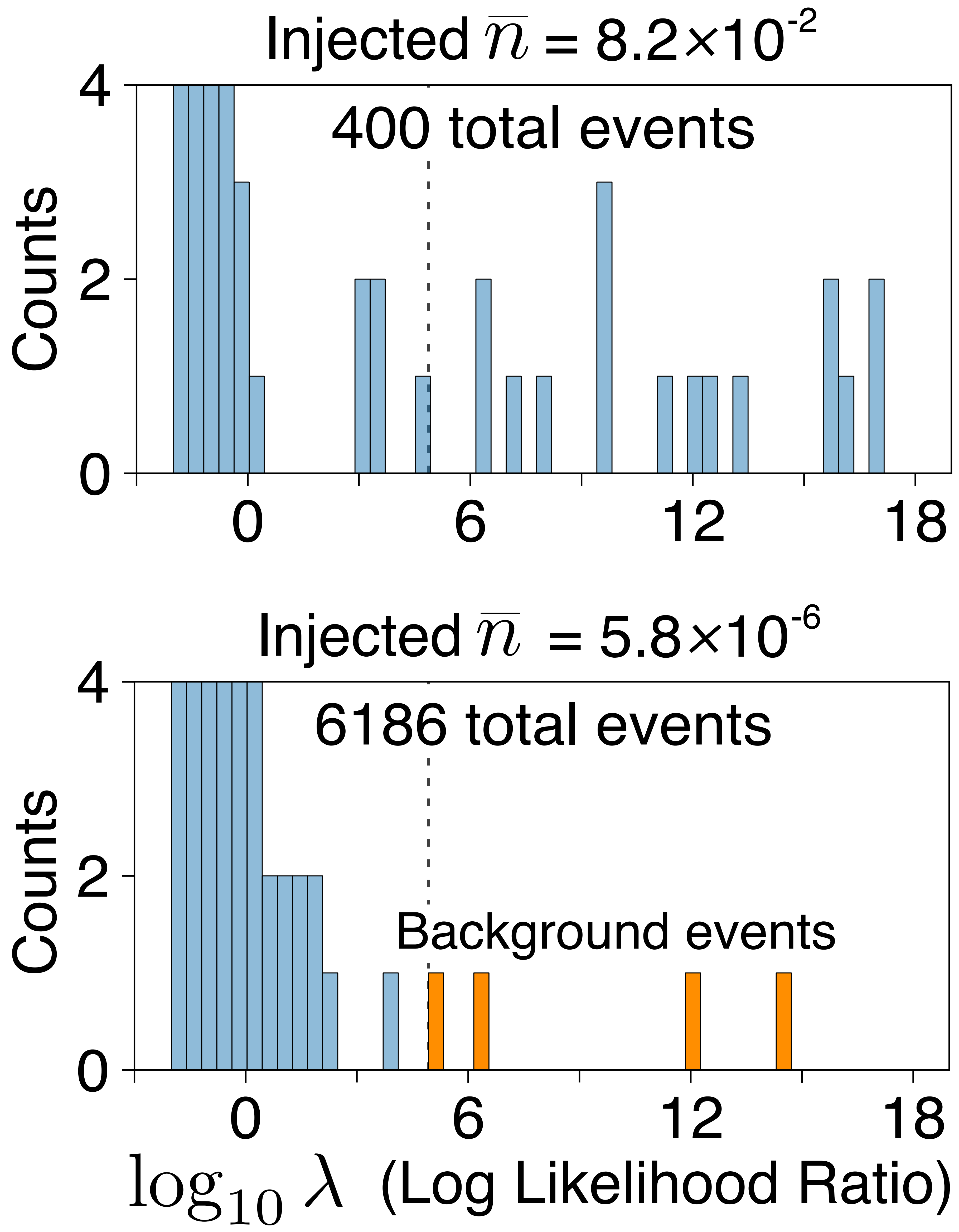
Efficiency

$\eta = 40.9\%$

False positive probability

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

Achieved sensitivity 1000 times better than quantum limit



Photons detected when none are injected

Eliminated detector errors as a source of false positives

Entered a new, background limited regime

$$\bar{n}_c = 7.3 \times 10^{-4} \ll \bar{n}_{\mathrm{SQL}} = 1$$

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

$$t > R_b / R_s^2$$

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

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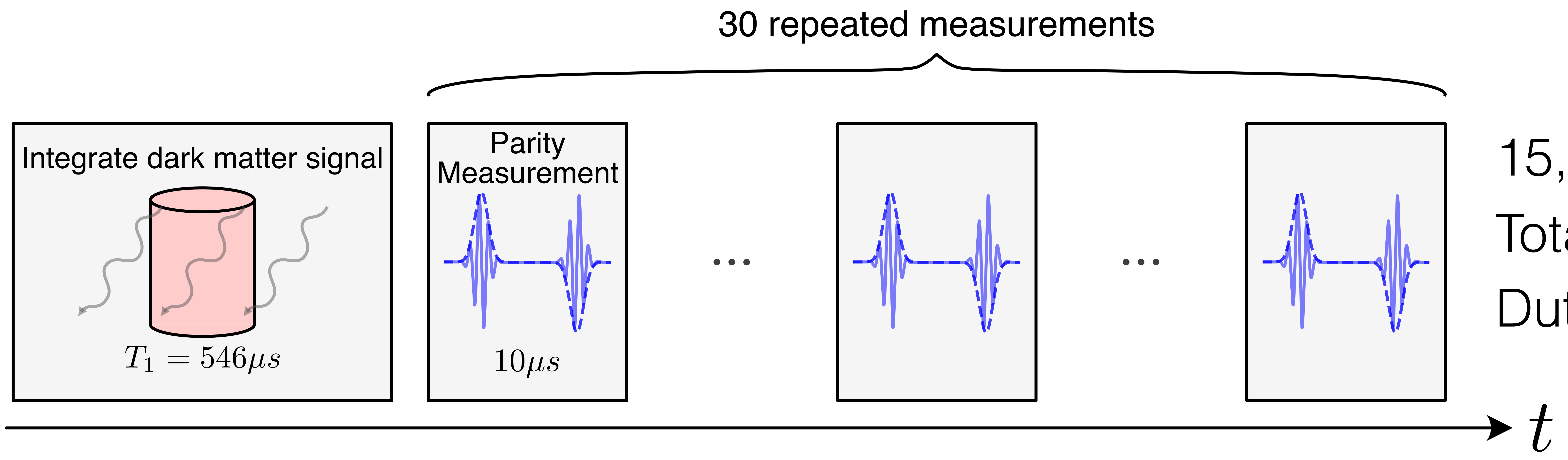
Dark matter search protocol

Signal cannot build up while measuring (quantum Zeno effect)



15,141 experiments performed

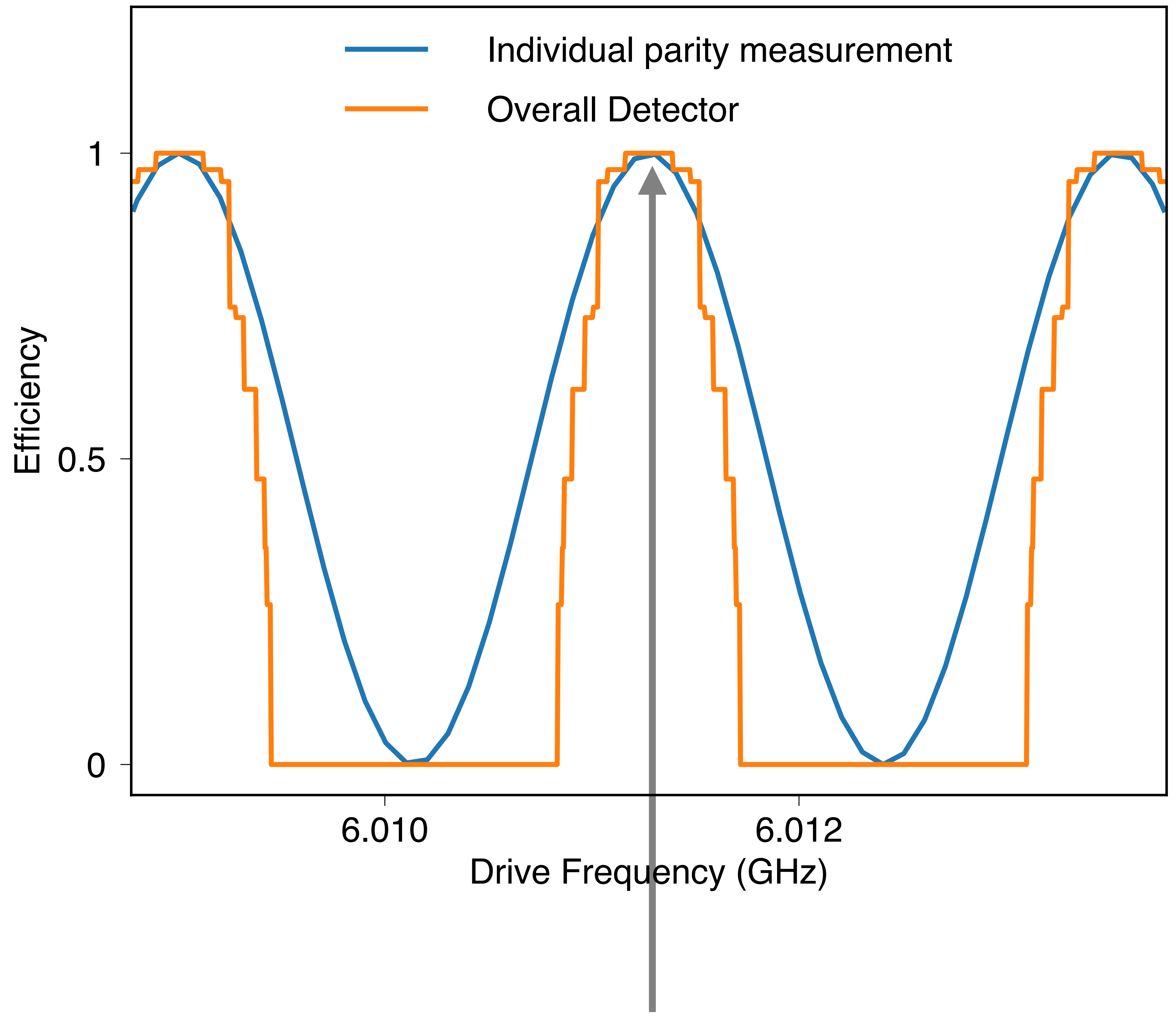
Total experiment time of 12.81 s

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

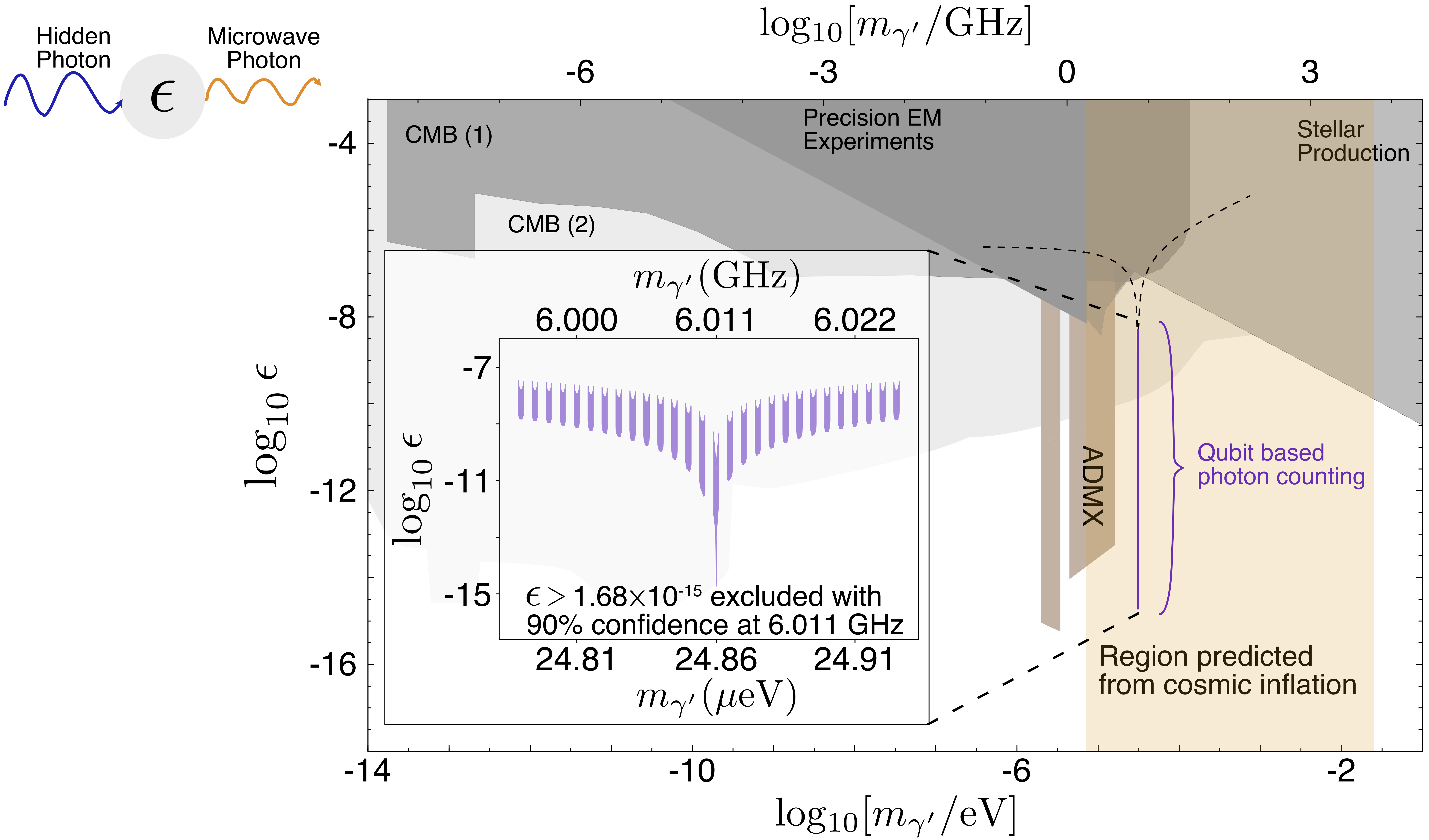


Parity procedure tuned for excitations on resonance

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



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

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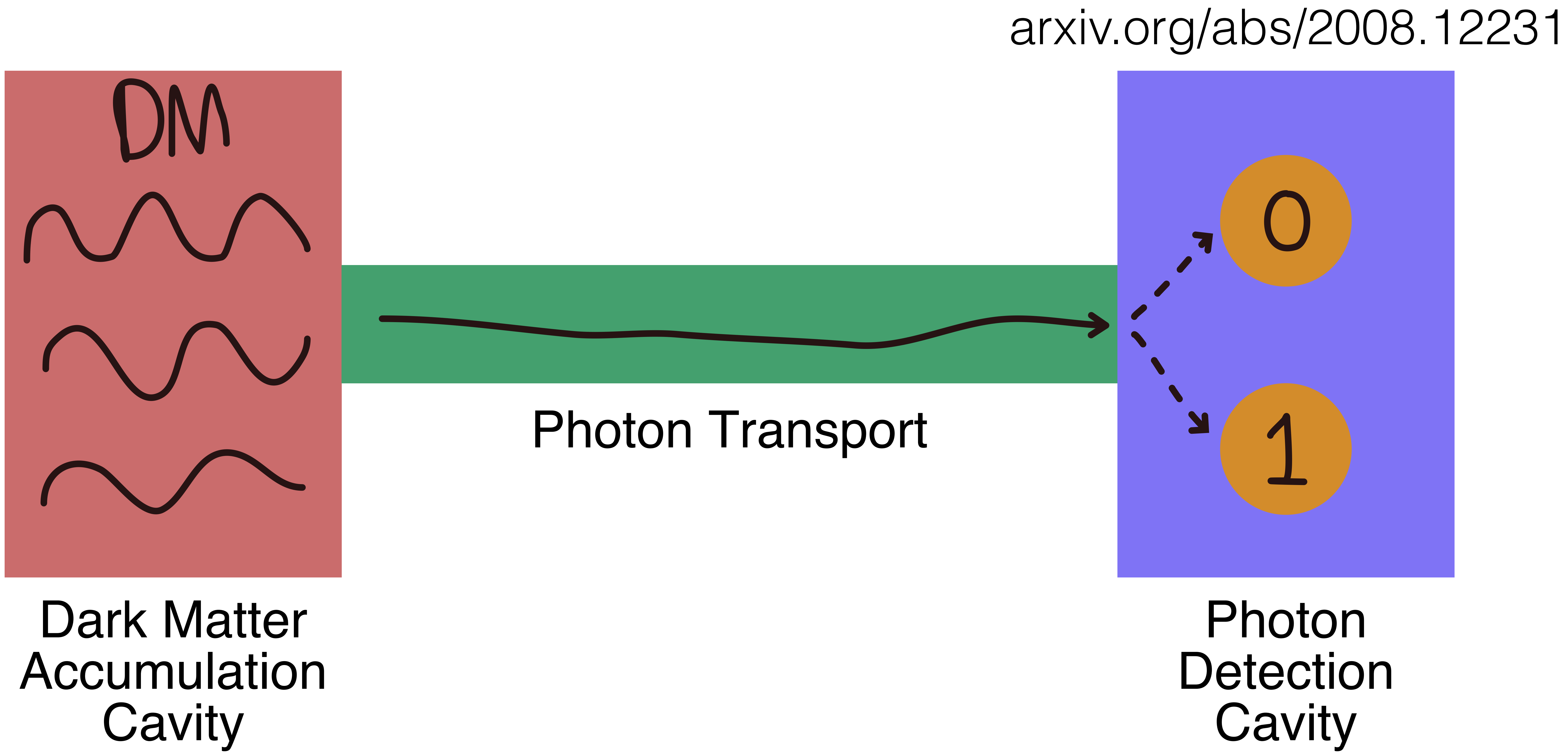
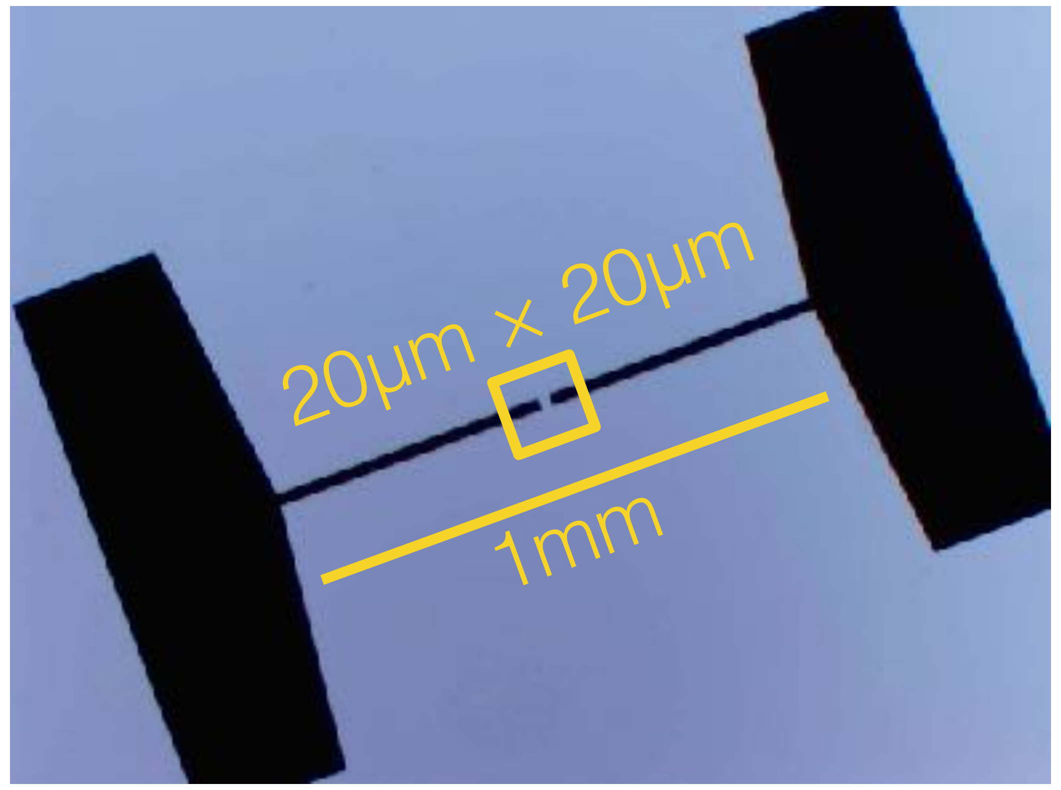
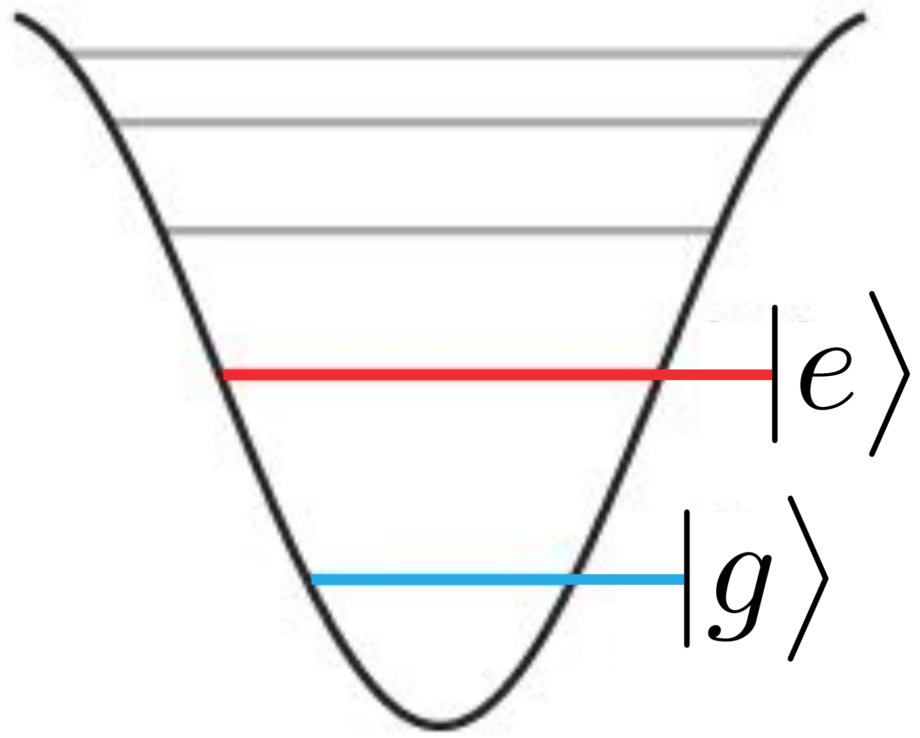
Dark matter detection strategy



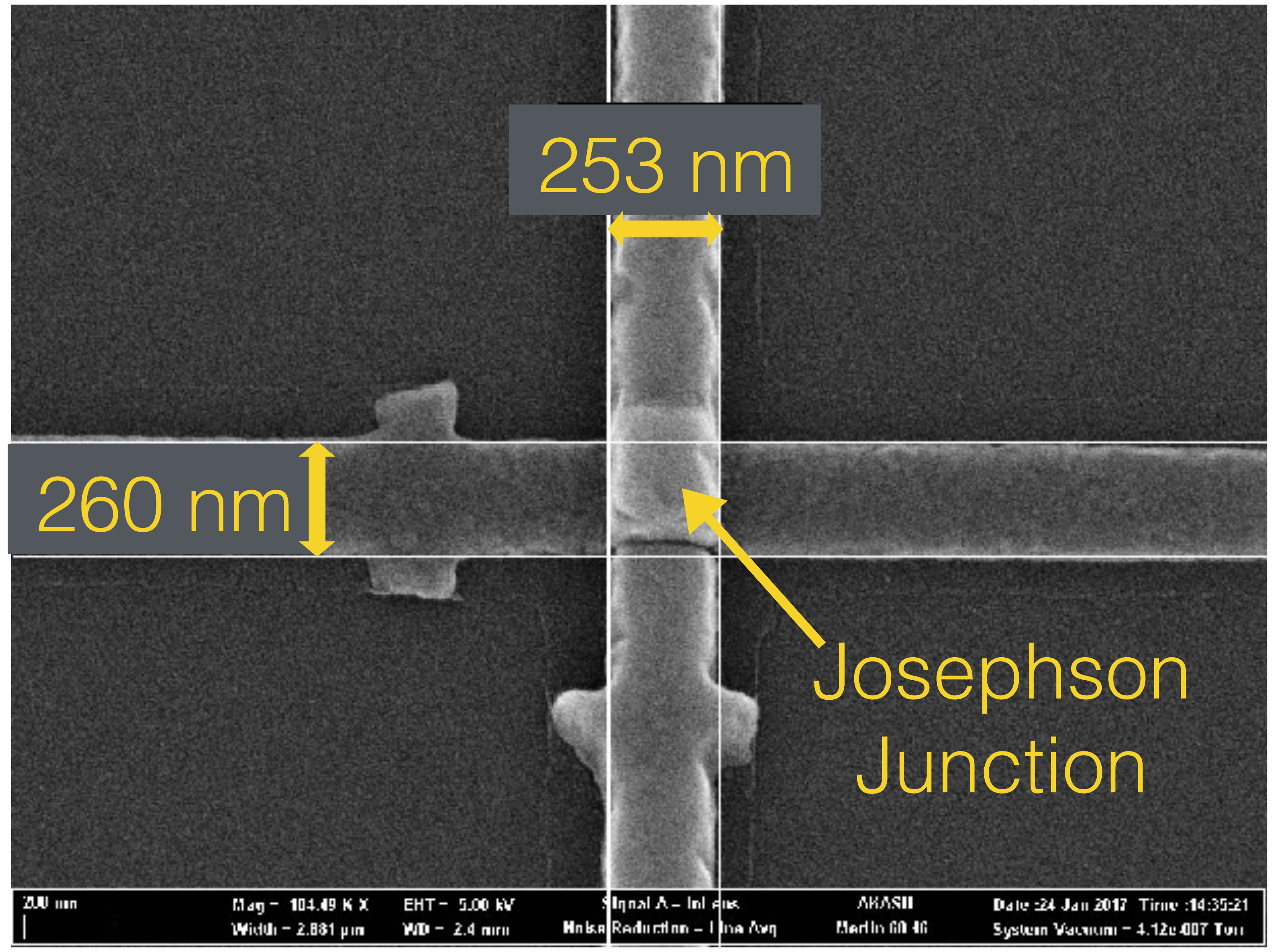
Building a superconducting qubit



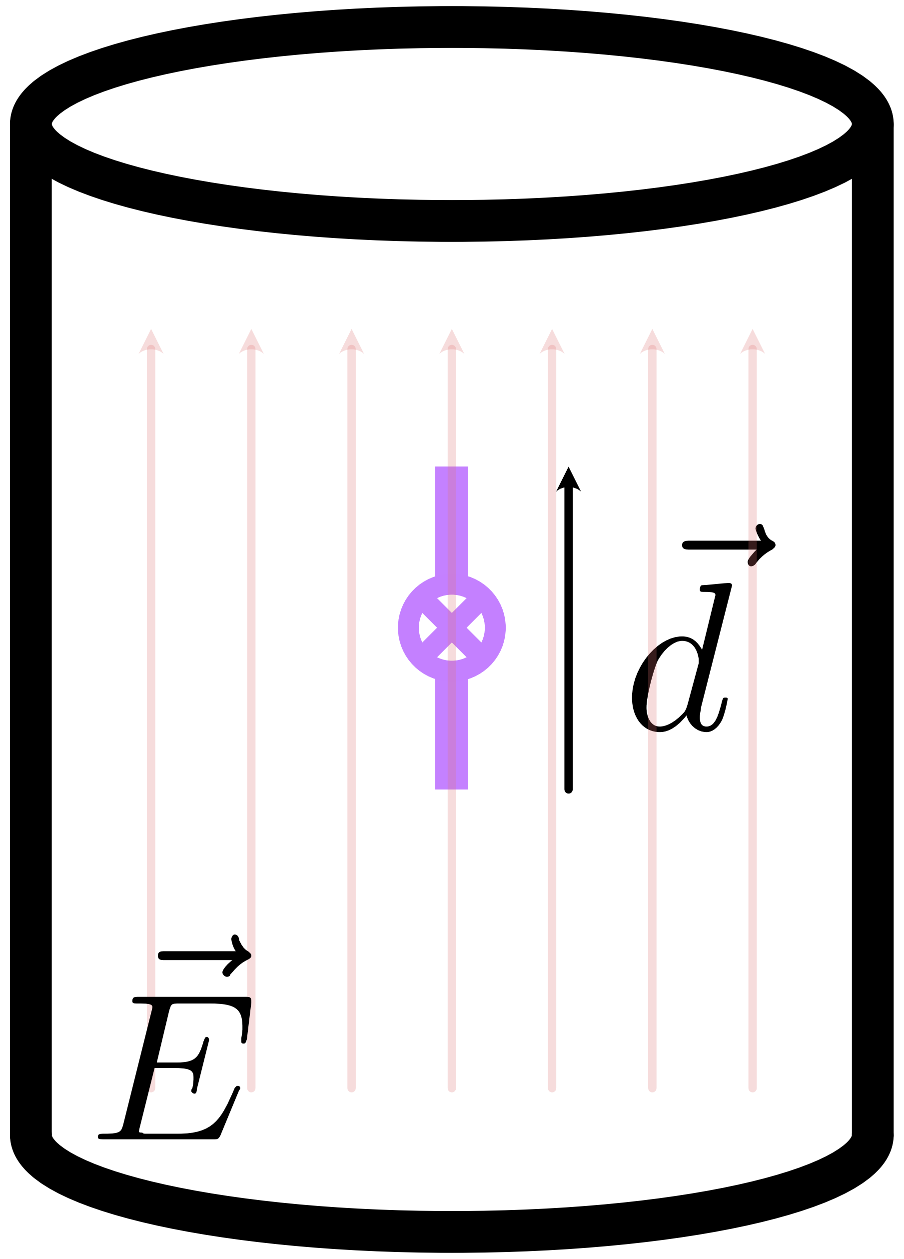
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$



Harmonic Oscillator (LC) + nonlinearity (Josephson Junction)



Engineering the qubit-cavity interaction



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

Two-level spin

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

Transmon qubit

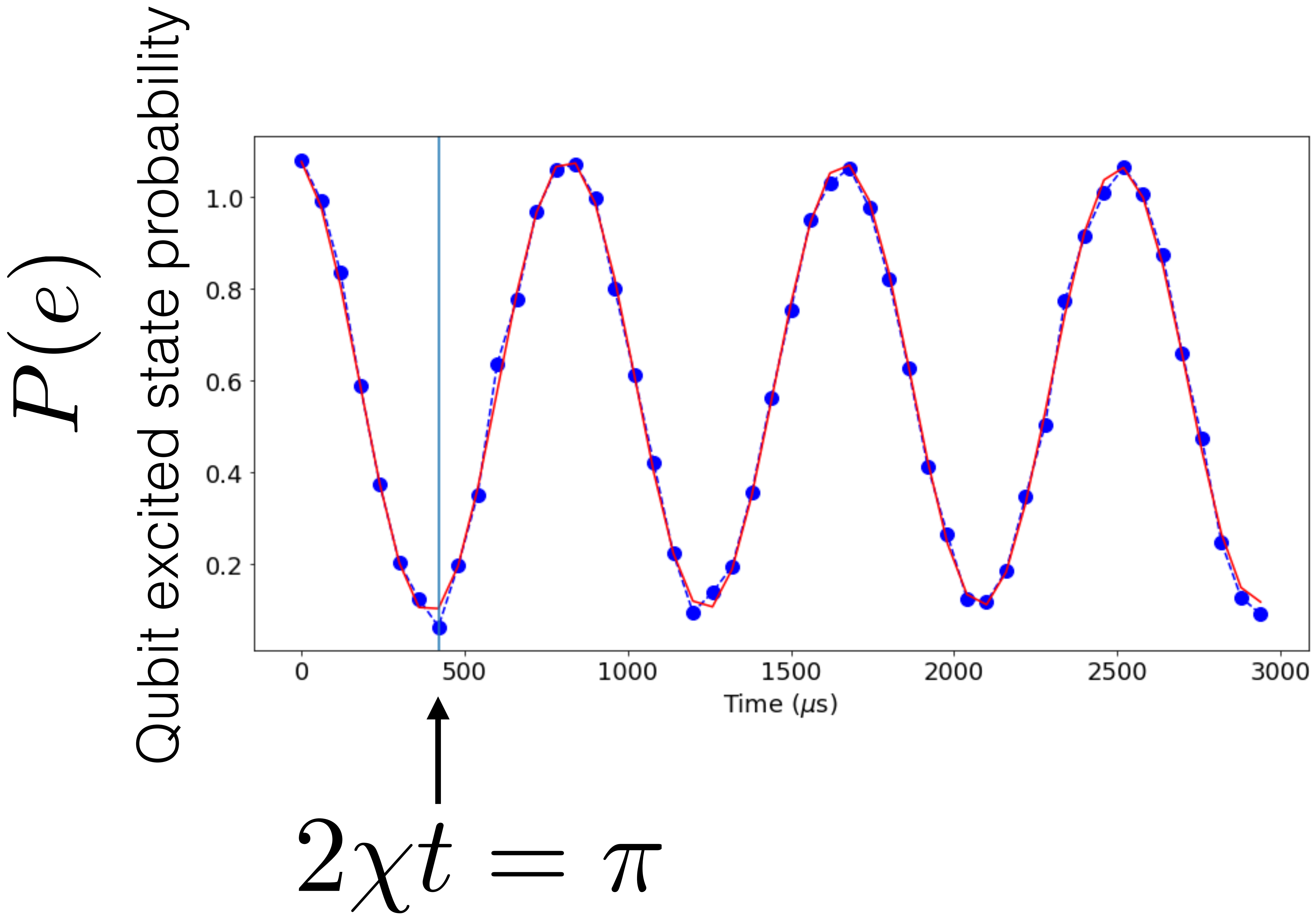
$$\chi = \frac{g^2}{\Delta(\Delta + \alpha)}\alpha$$

Δ qubit-cavity detuning

α qubit anharmonicity

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

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

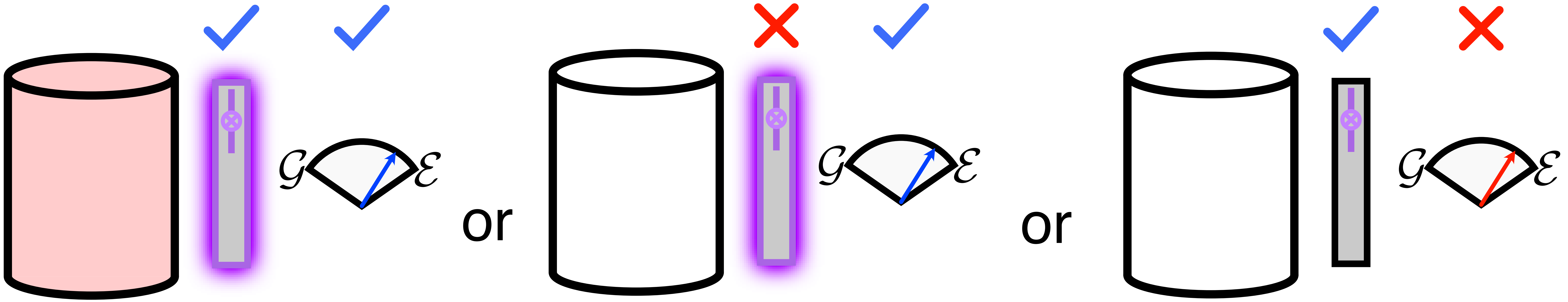
https://arxiv.org/pdf/1607.02529.pdf

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

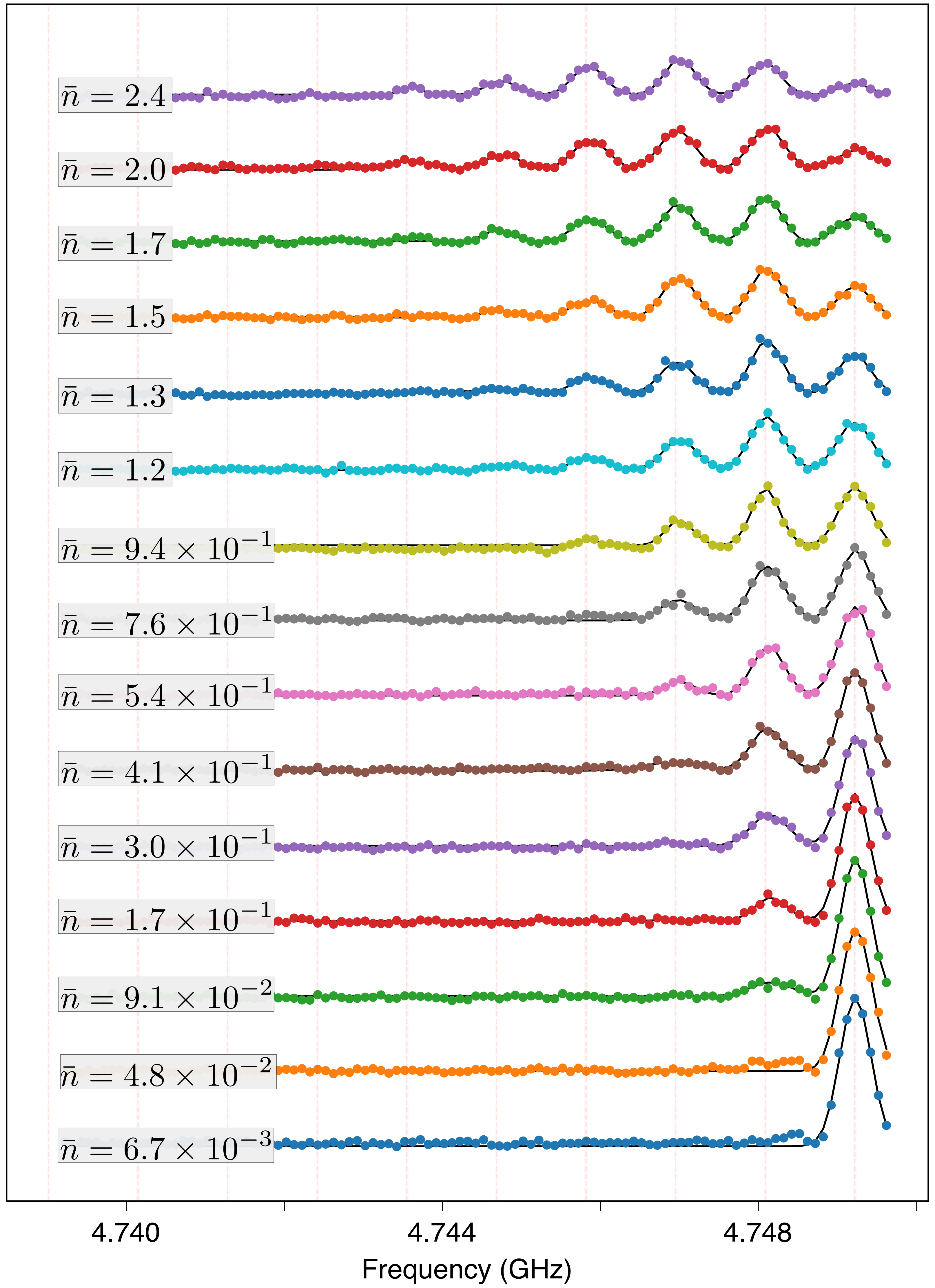
Cavity state reconstruction

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

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



Calibrate photon injection



Coherent drive of variable length and amplitude

Perform spectroscopy of qubit to infer cavity population

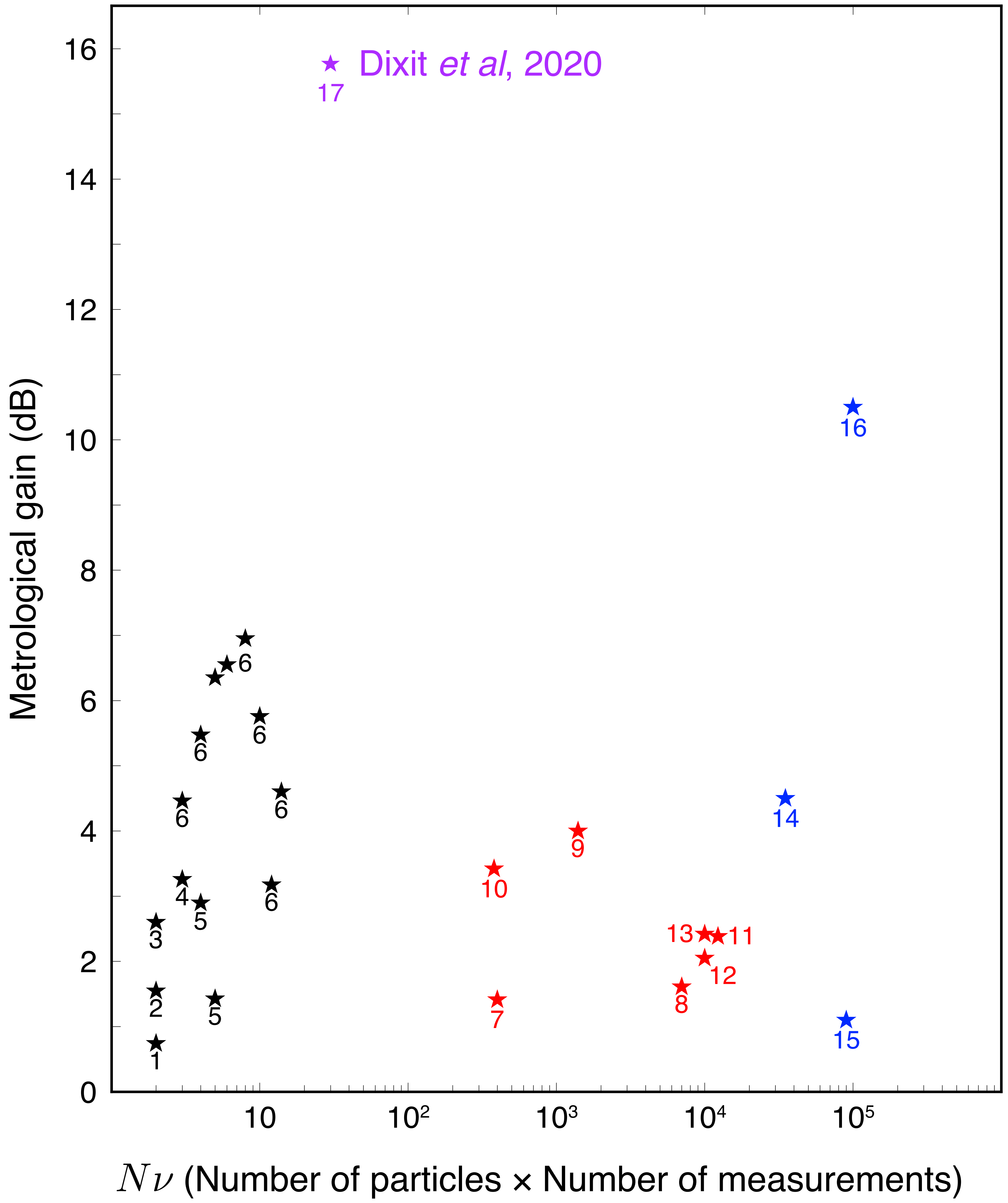
Extract photon number distribution

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

Background sources and mitigation strategies

<u>Photons coming down lines</u>

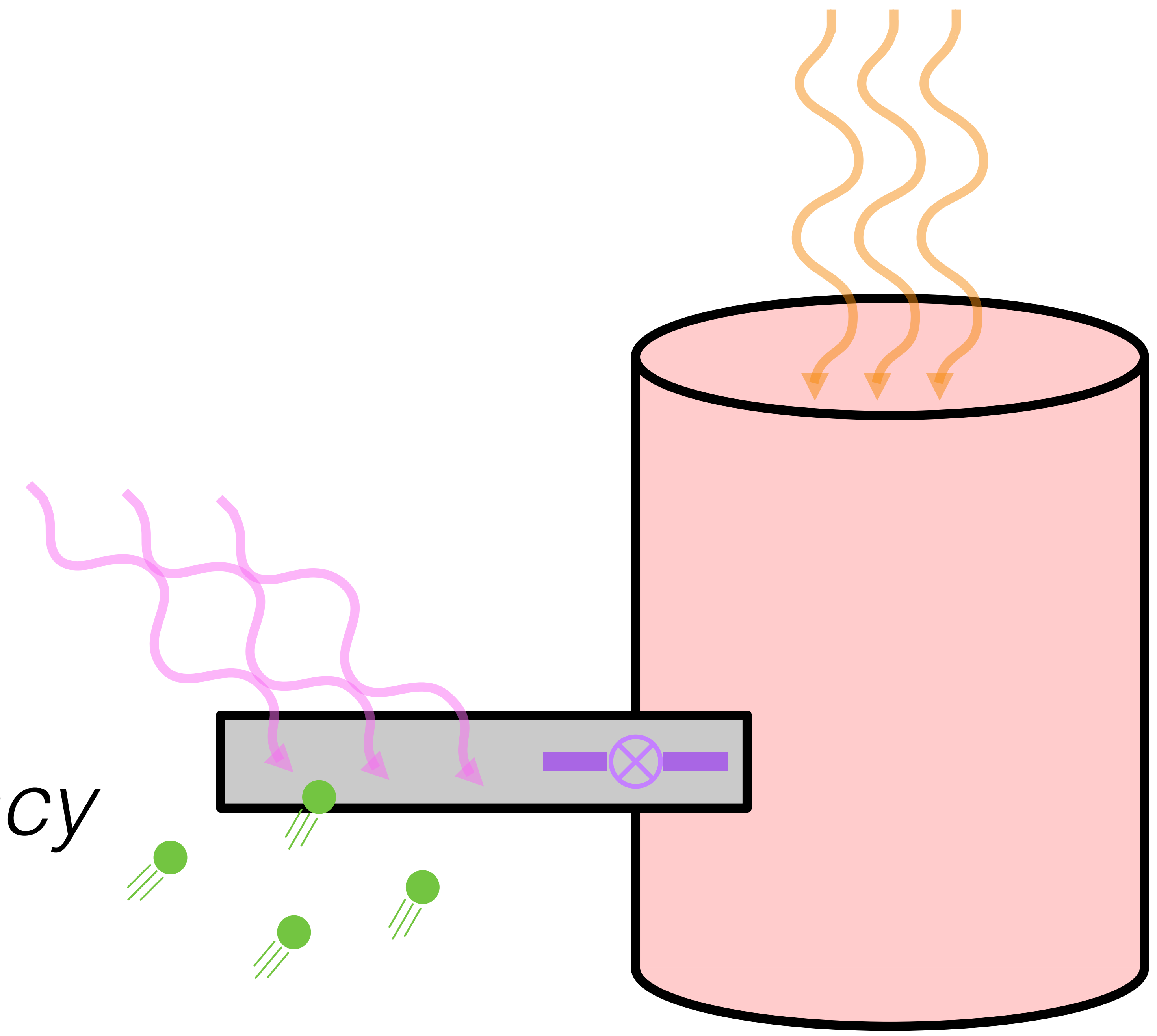
- more attenuation and filtering
- better thermalization of components

<u>Spurious qubit excitations convert to photons</u>

Sourced by terrestrial and cosmogenic radiation, high frequency photons

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

<u>TLS and maybe more</u>



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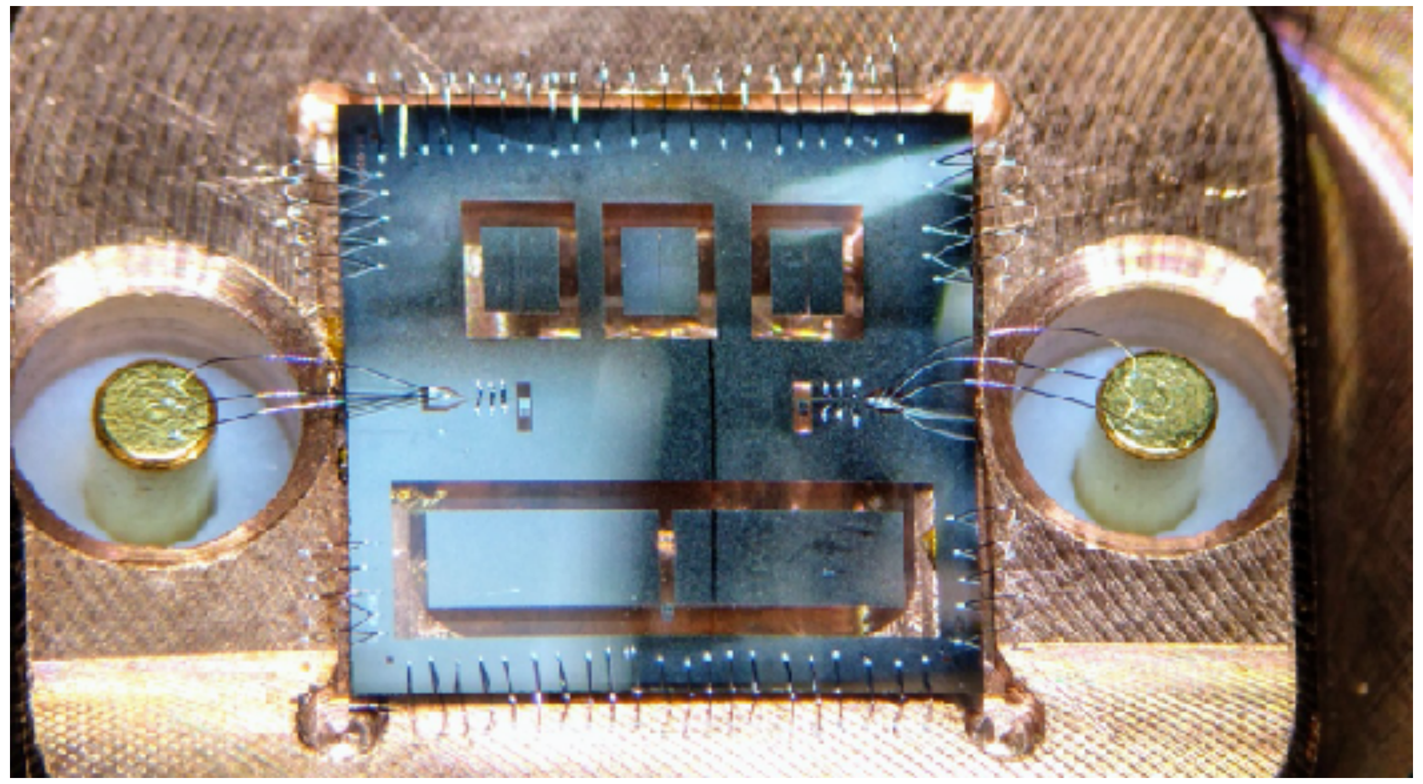
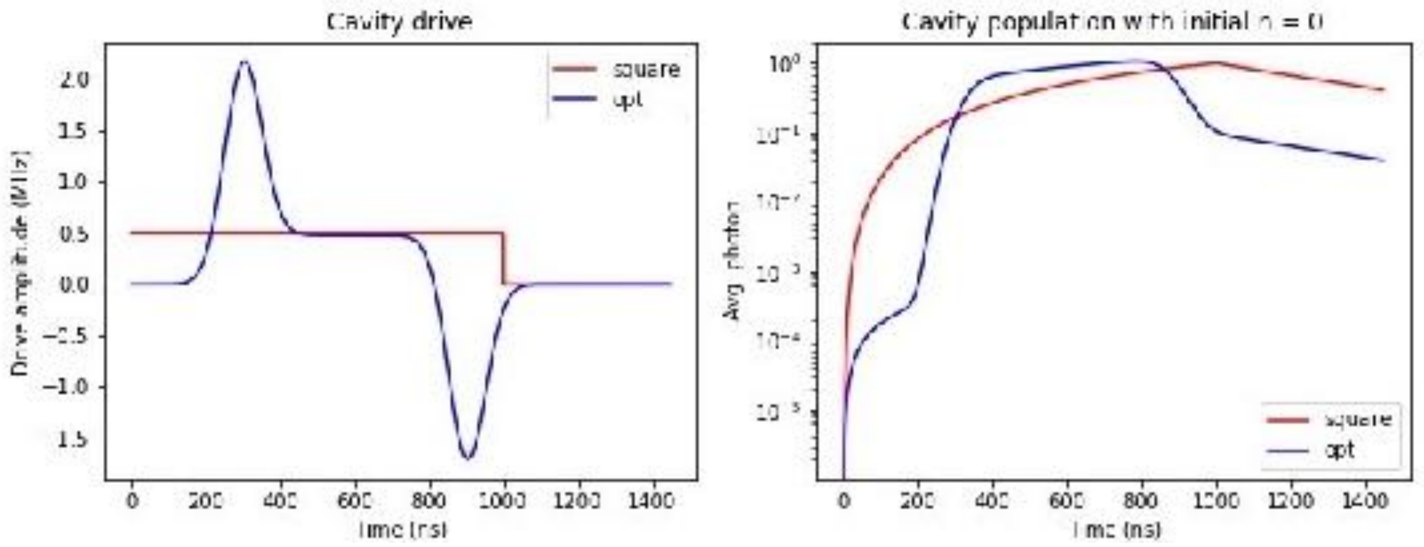
journals.aps.org/prb/abstract/10.1103/PhysRevB.94.104516
www.nature.com/articles/s41586-020-2619-8
journals.aps.org/prb/abstract/10.1103/PhysRevB.100.140503
journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.157701

Further improvements to protocol

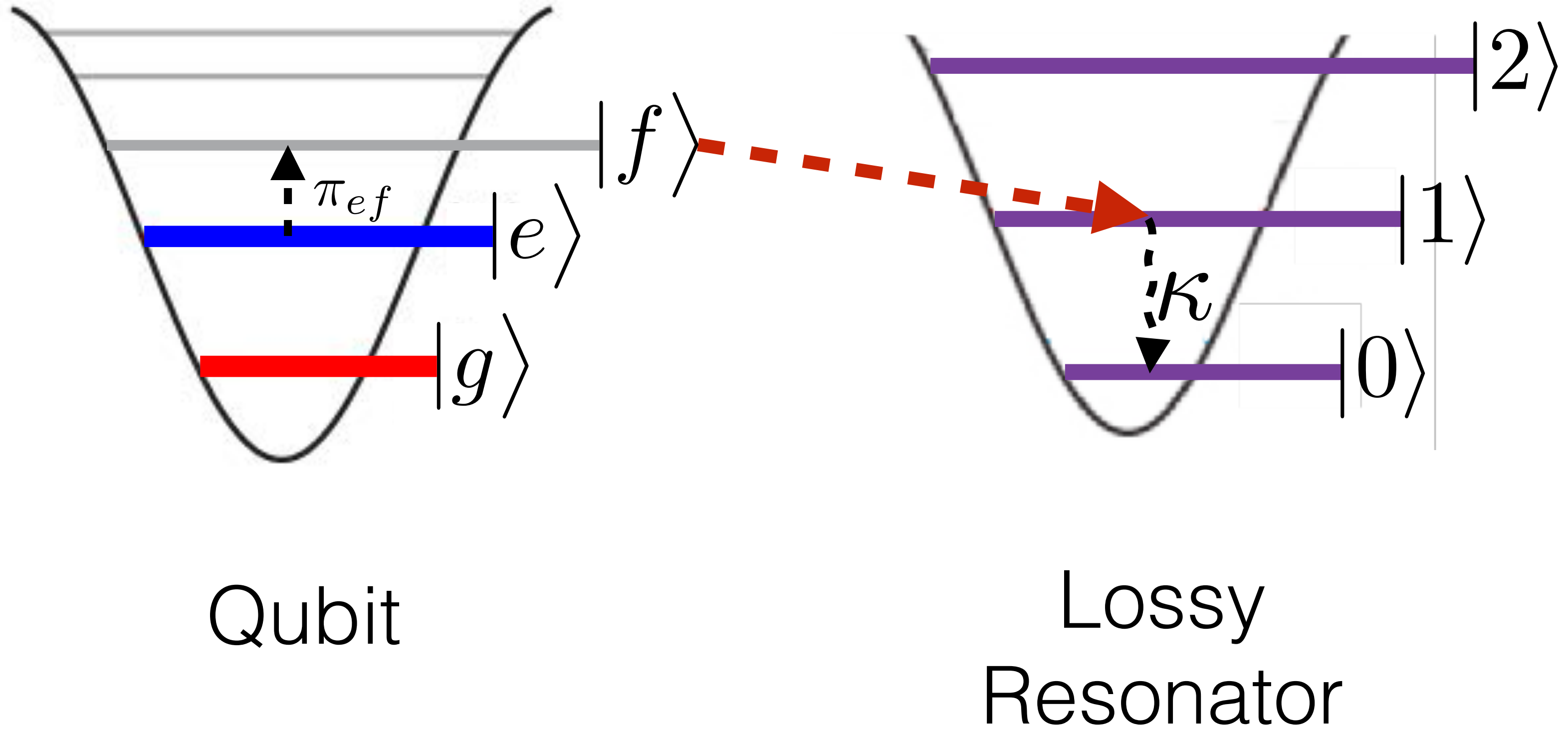
Parametric amplifier
- increases readout fidelity
- reduces readout time
- reduces readout cavity photon number



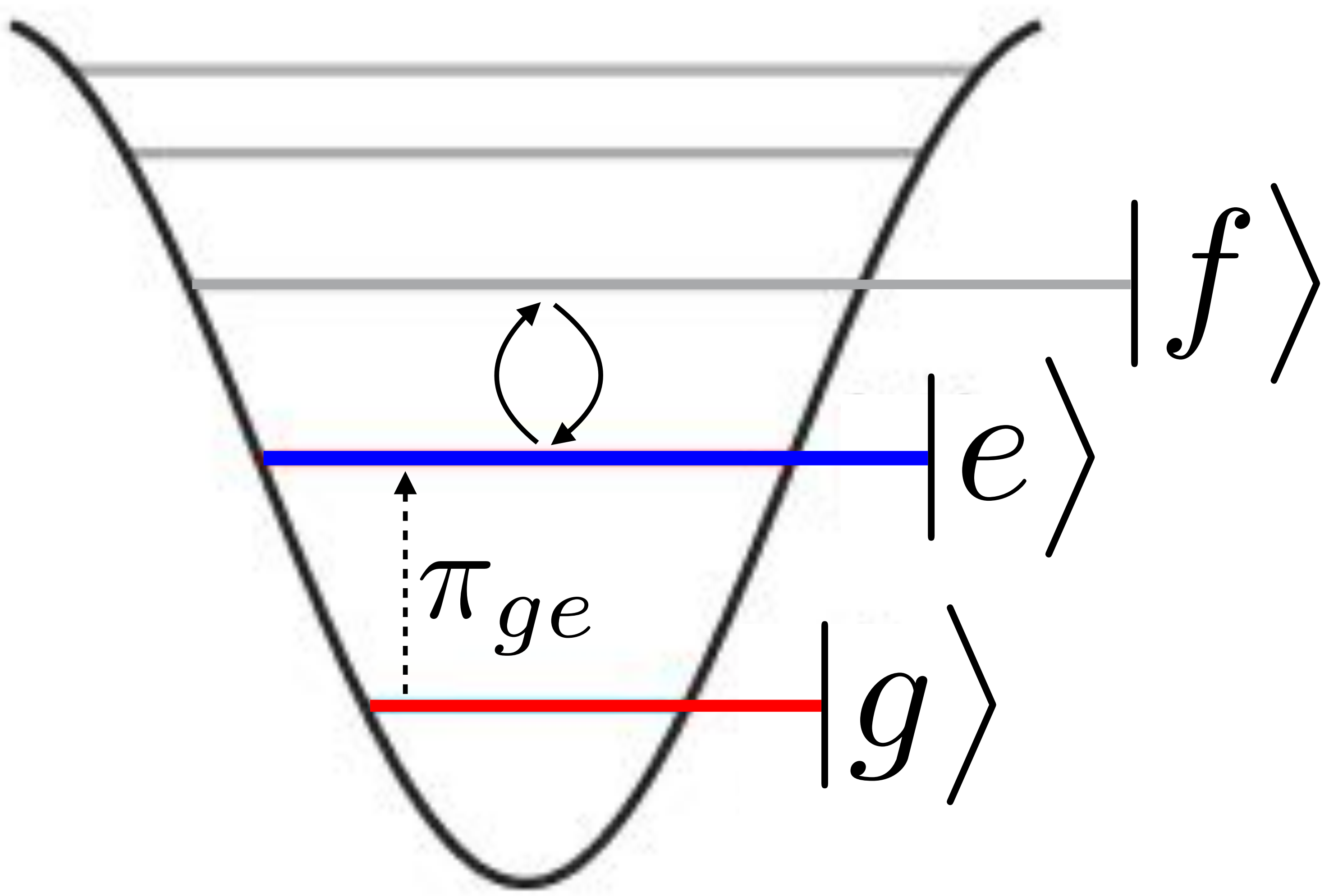
Reset readout cavity with optimized pulse shape
- readout decay is dominant time scale in expt

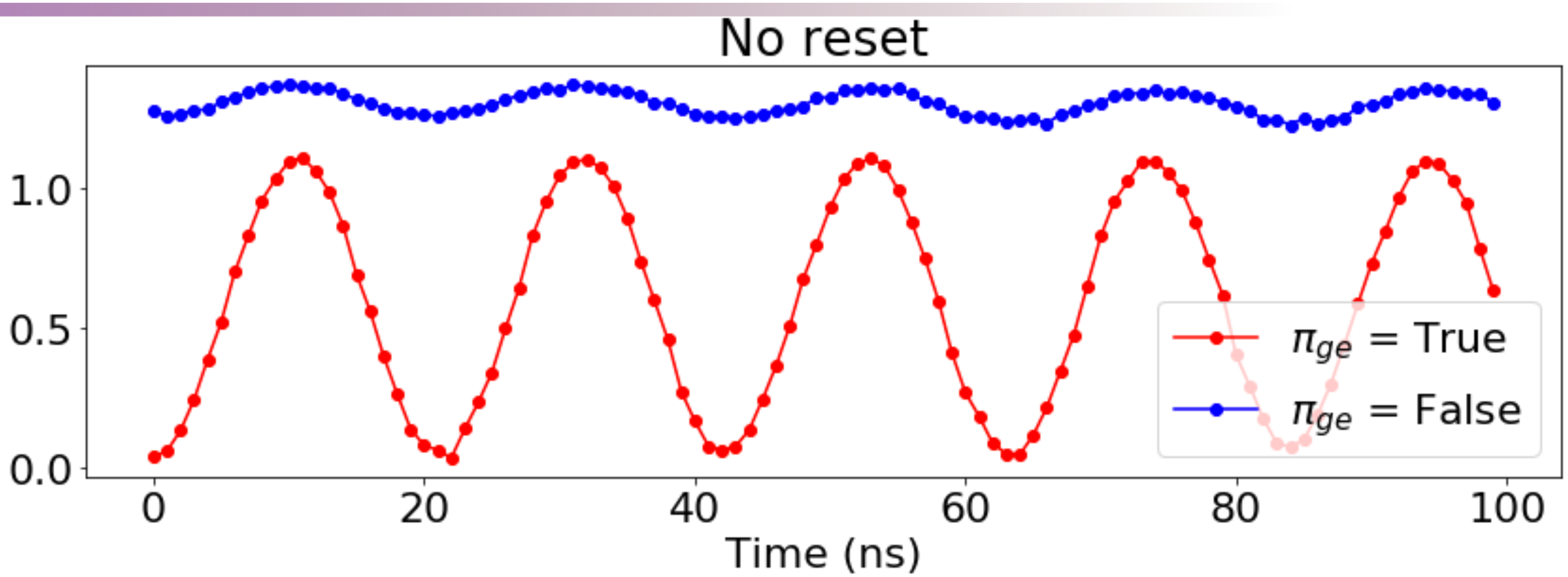


Reset qubit between measurements
- P(decay) ~ 9%
- P(heating) ~ 0.4%



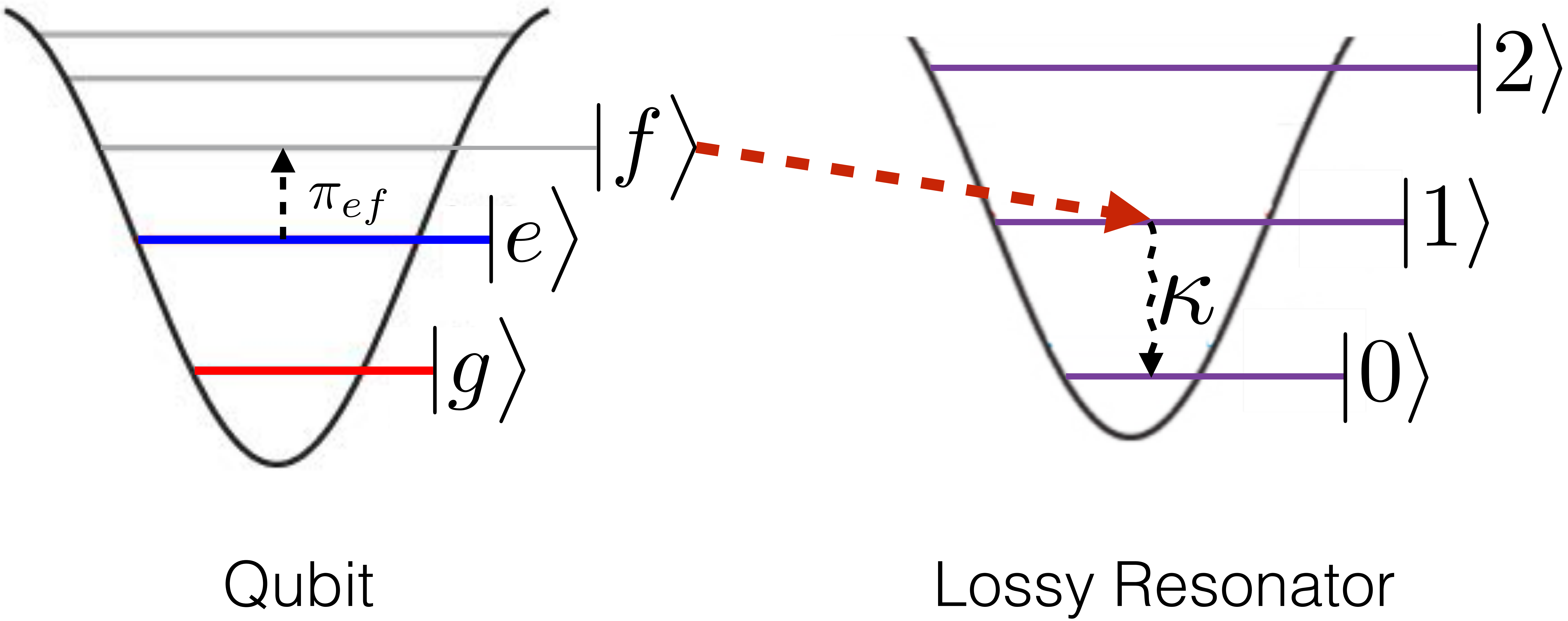
Qubit Spurious Excitations Produce Dark Counts



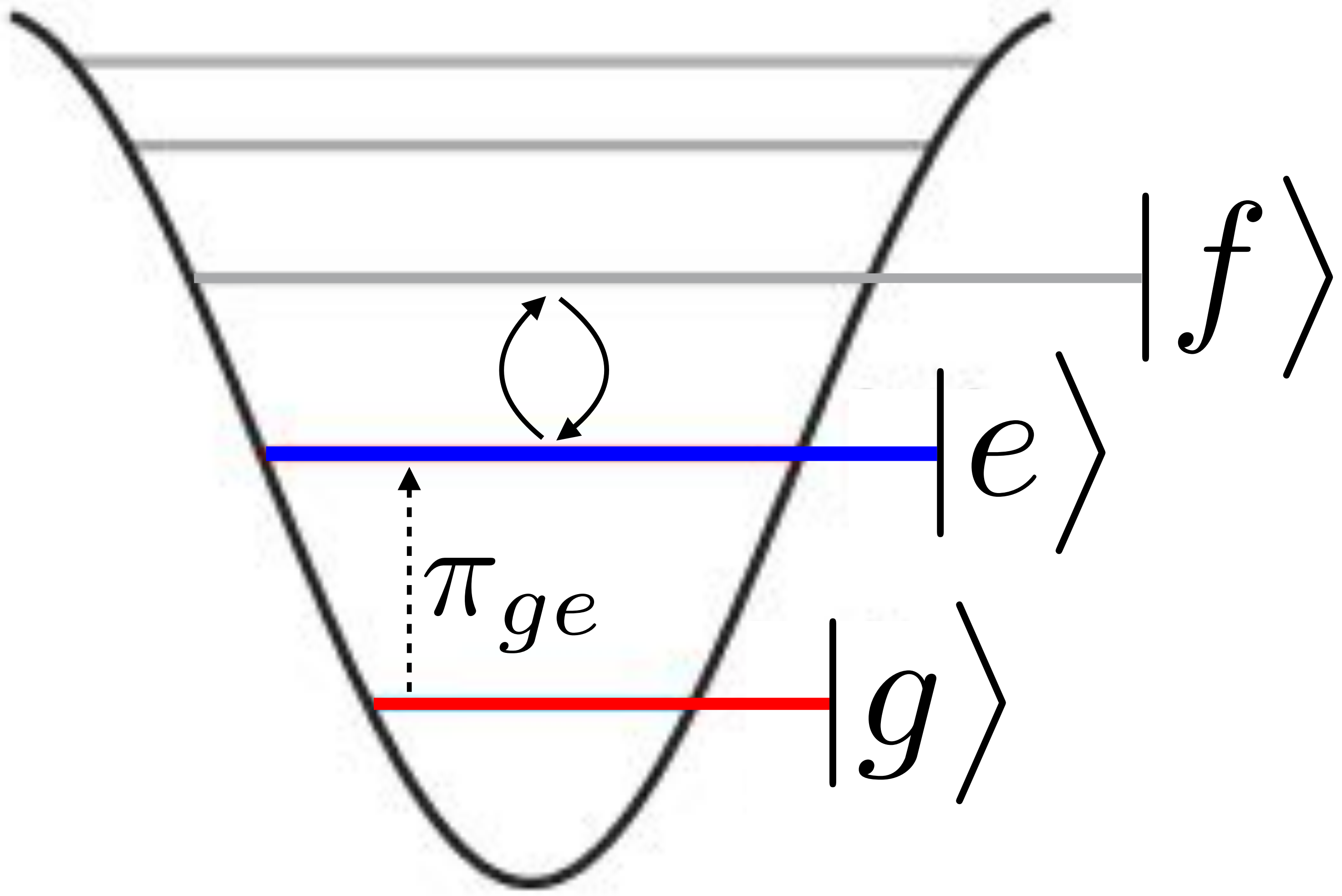


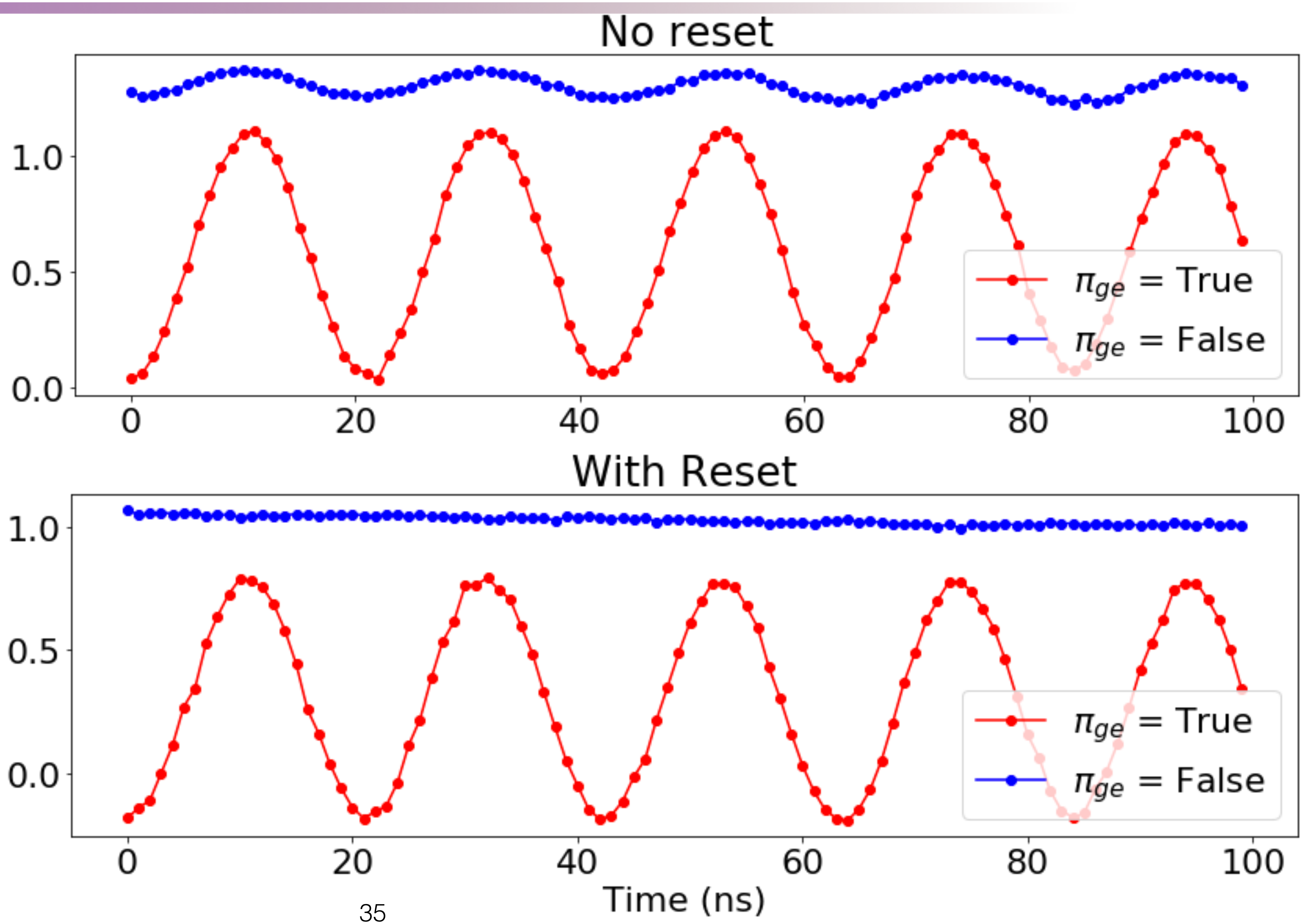
Ratio of oscillation amplitudes
=
Ratio of ground/excited state populations

Cool Qubit with Lossy Resonator Mode



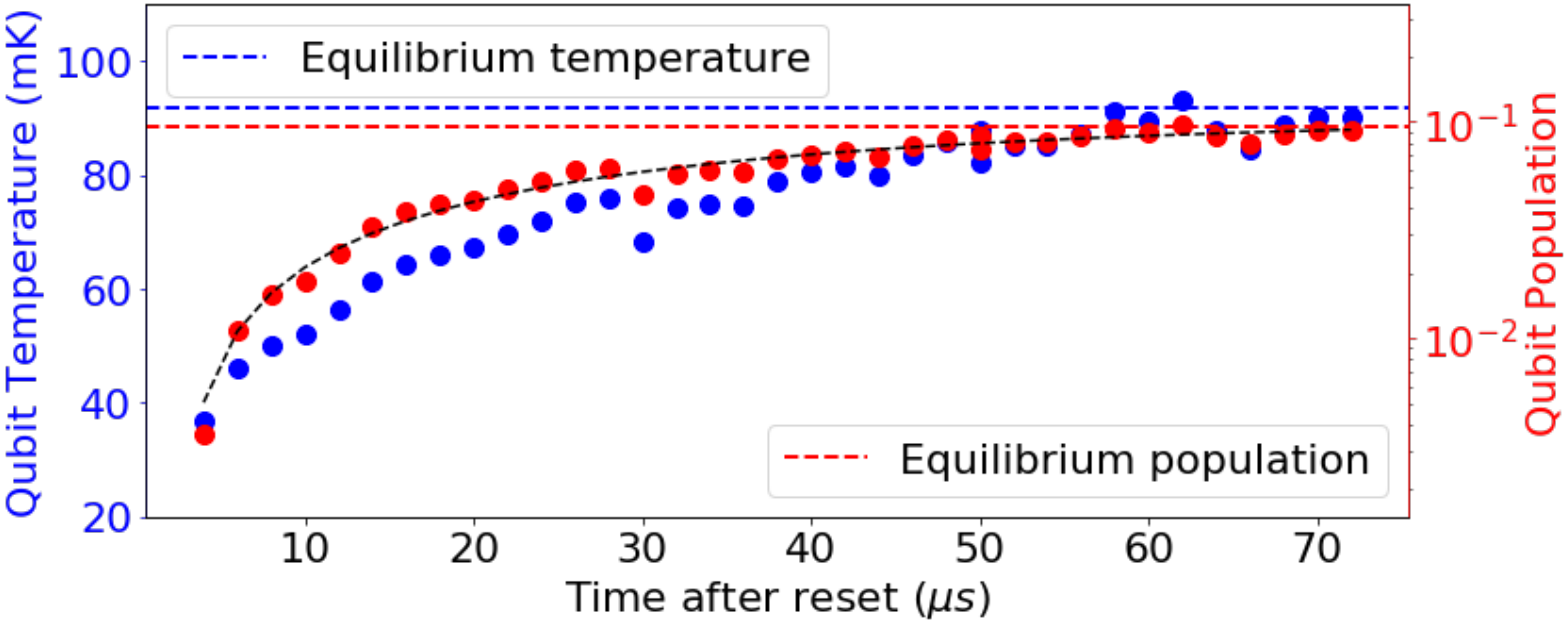
Qubit Spurious Excitations Suppressed with Cooling





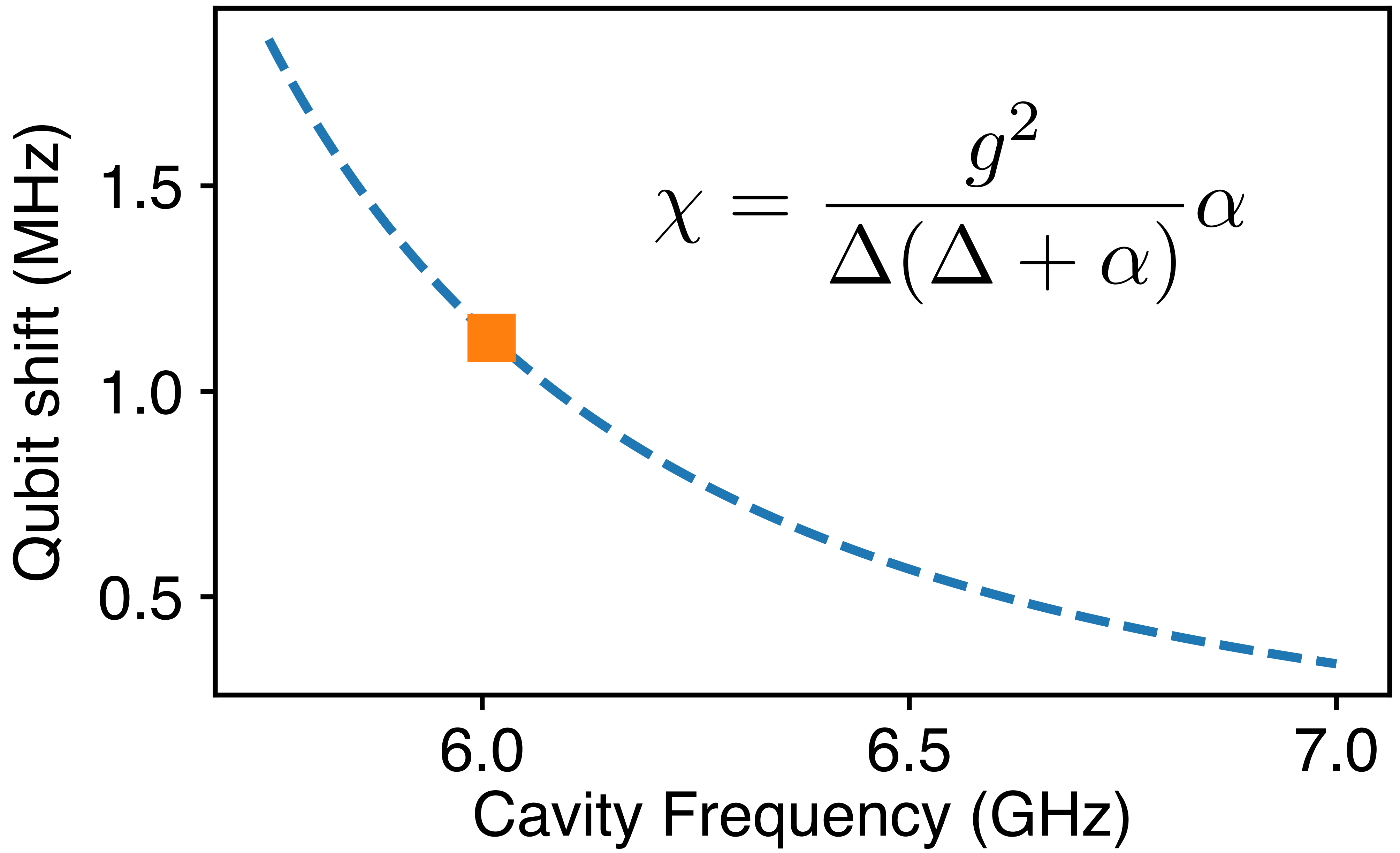
Ratio of oscillation amplitudes
=
Ratio of ground/excited state populations

Suppressing Spurious Qubit Excitations



Integration with a scanning experiment

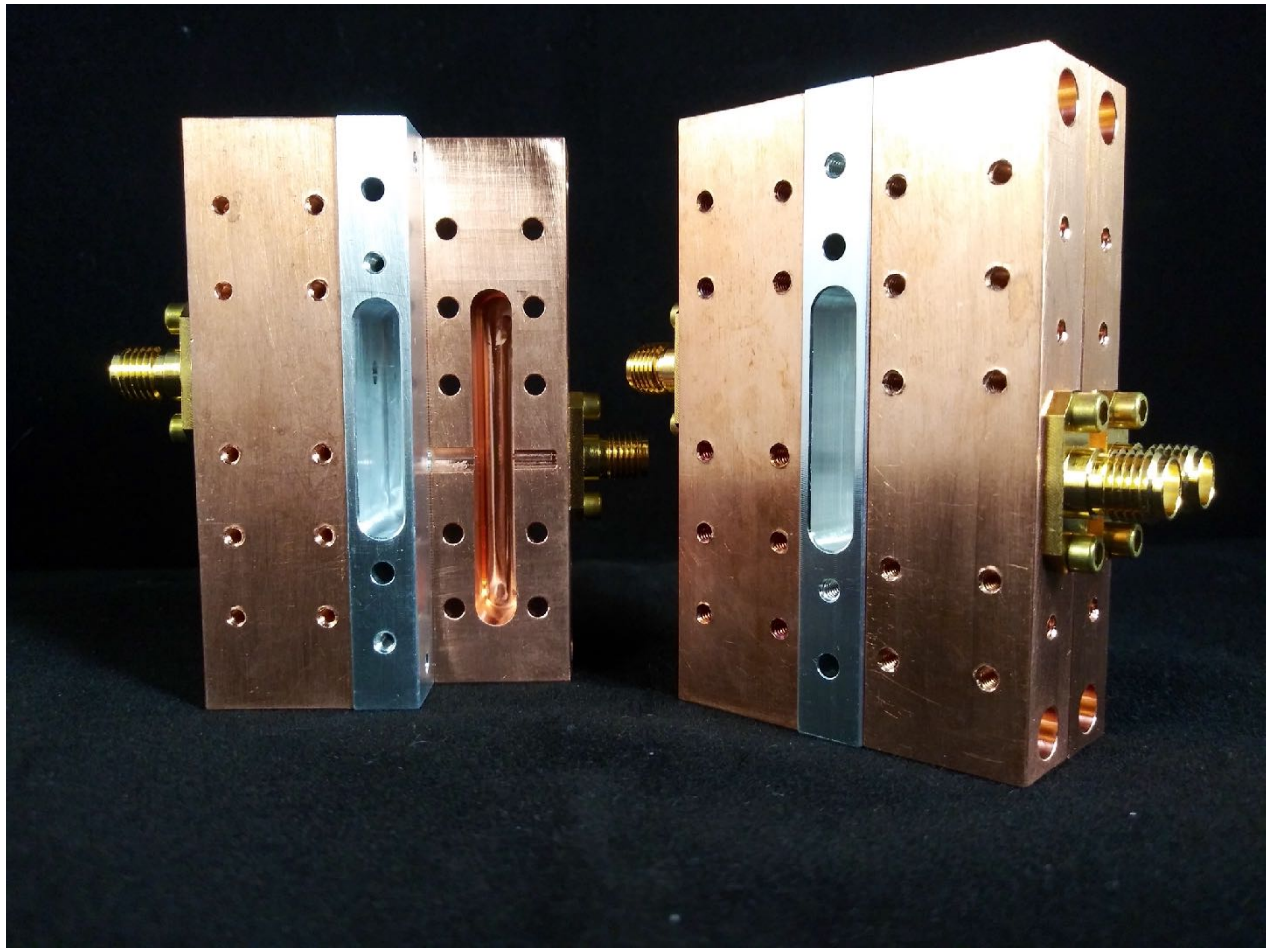
- Keep qubit fixed in frequency
- QND interaction unchanged as cavity tunes
- Calibrate photon dependent qubit shift



Further increasing sensitivity for dark matter searches

Investigate and mitigate photon backgrounds

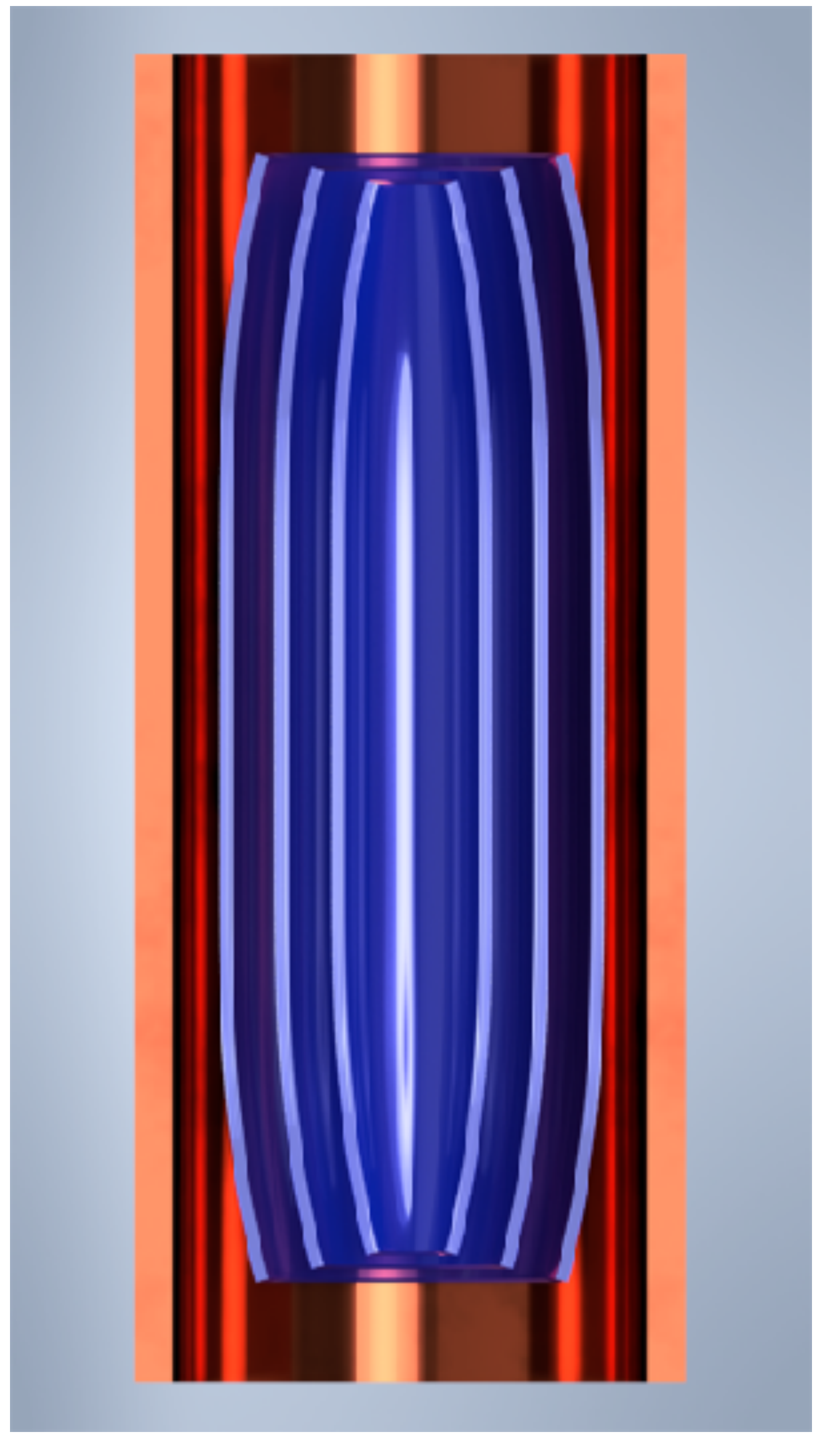
Use multiple entangled qubits for enhanced metrology



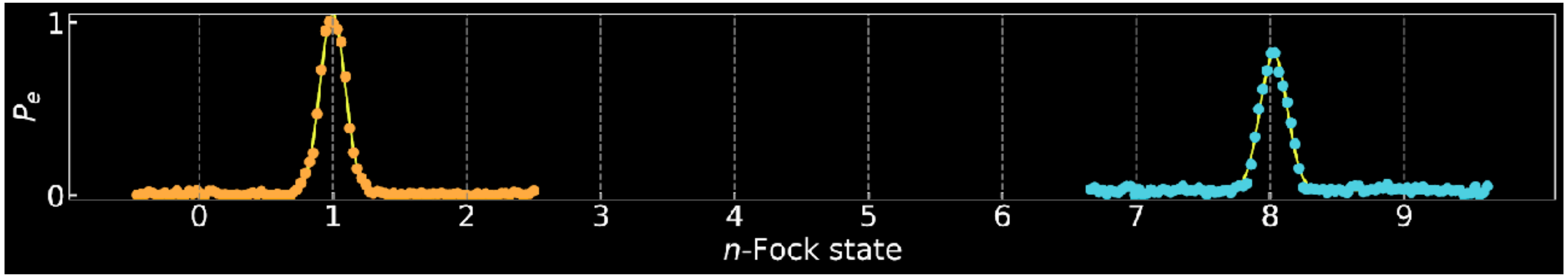
Boosting dark matter induced signal

Novel materials/designs for high Q cavities

Use nonclassical cavity states for signal enhancement



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



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