

Searching for dark matter with a superconducting qubit



Akash V. Dixit

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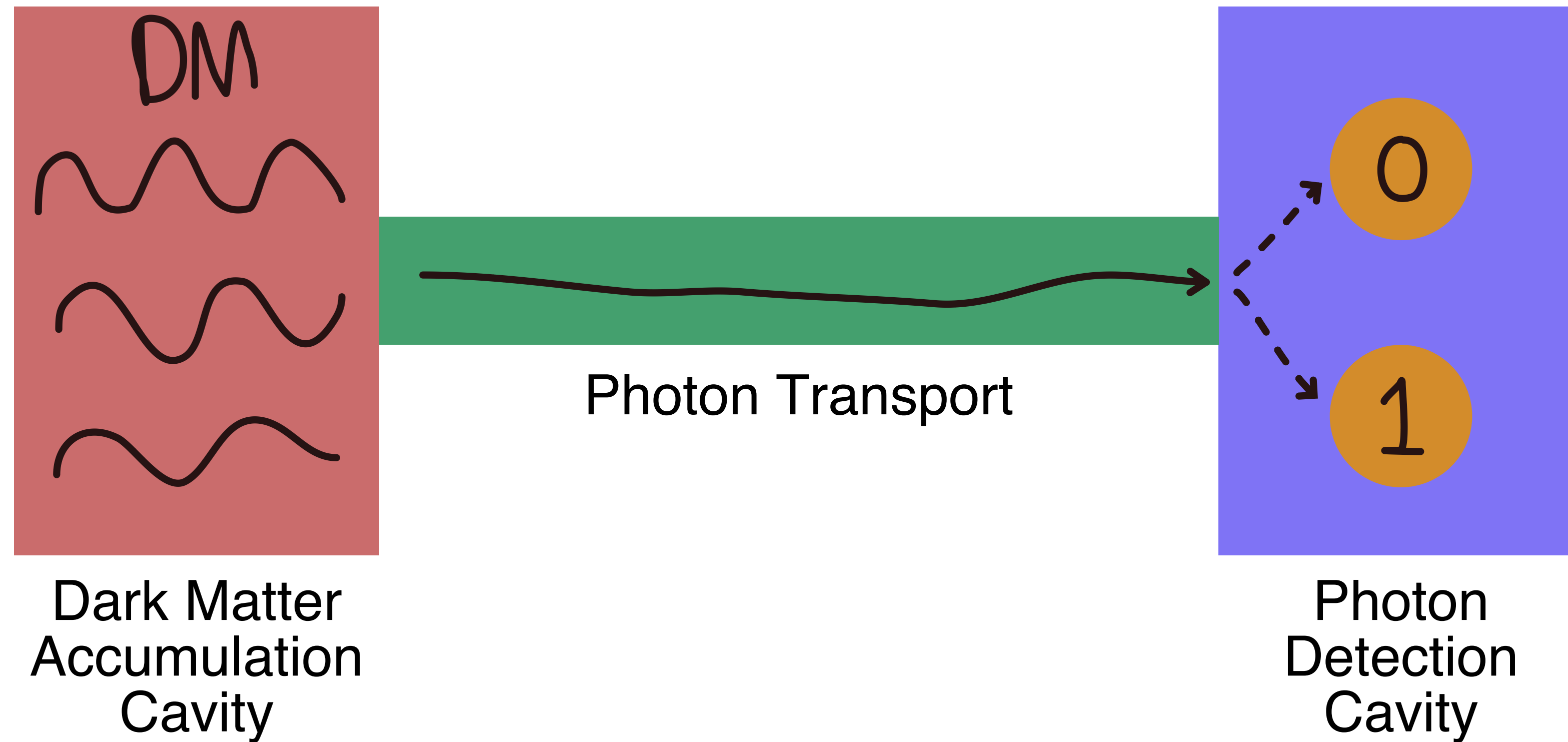
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Outline of talk

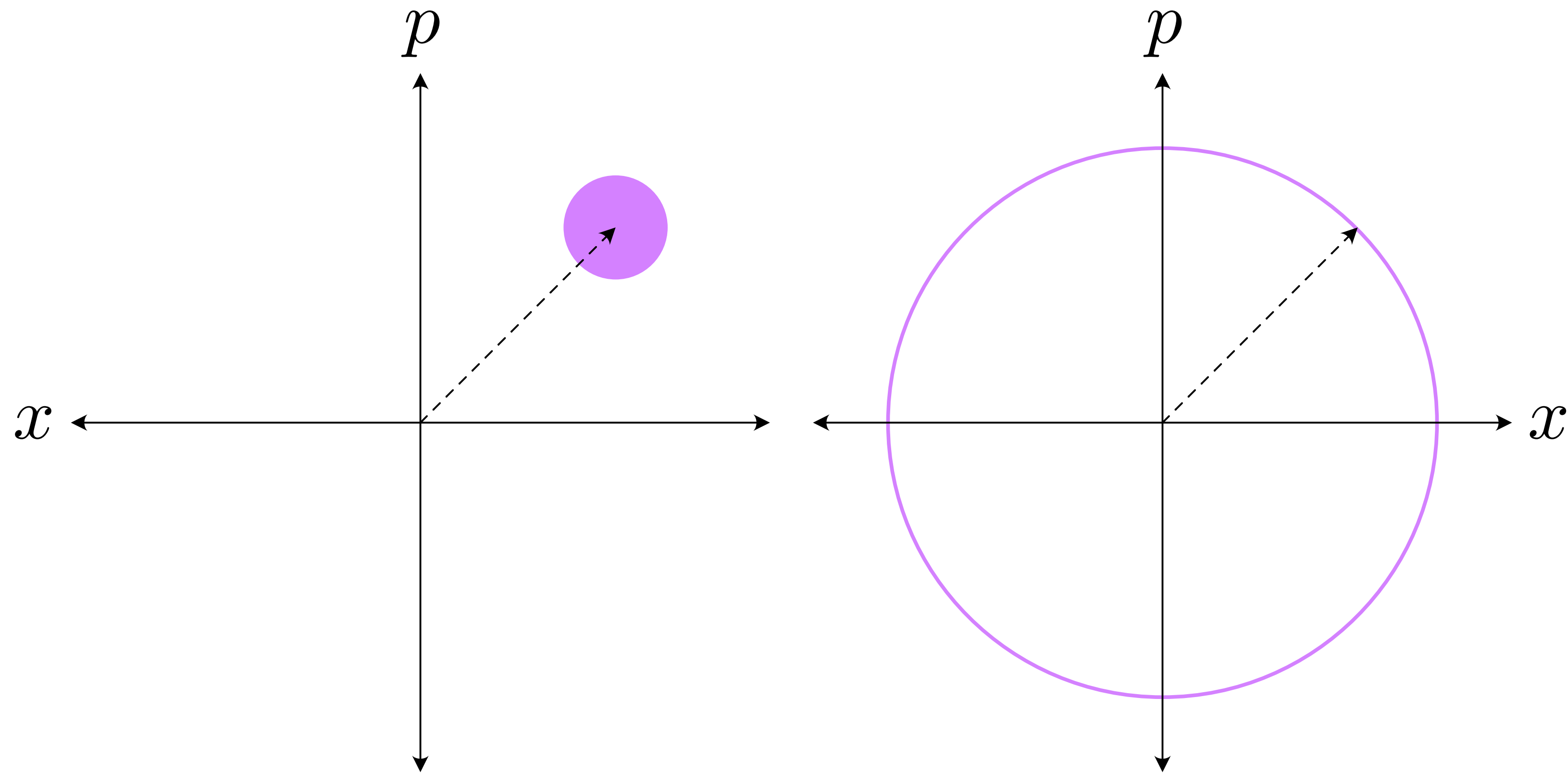
- Setup for detecting low mass dark matter
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search

Dark matter detection strategy

arxiv.org/abs/2008.12231



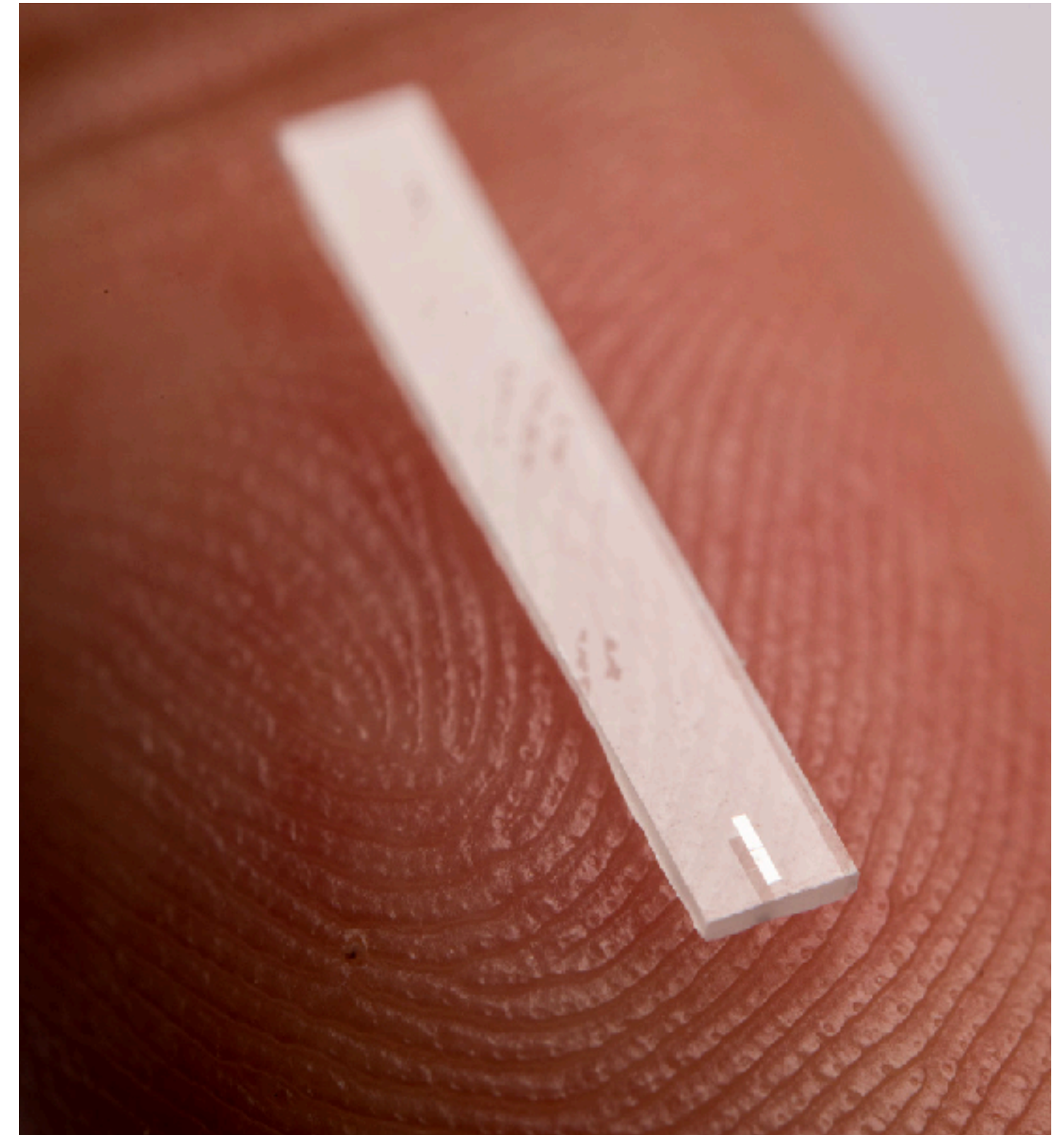
Count photons to subvert quantum limit



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

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Photon counting device

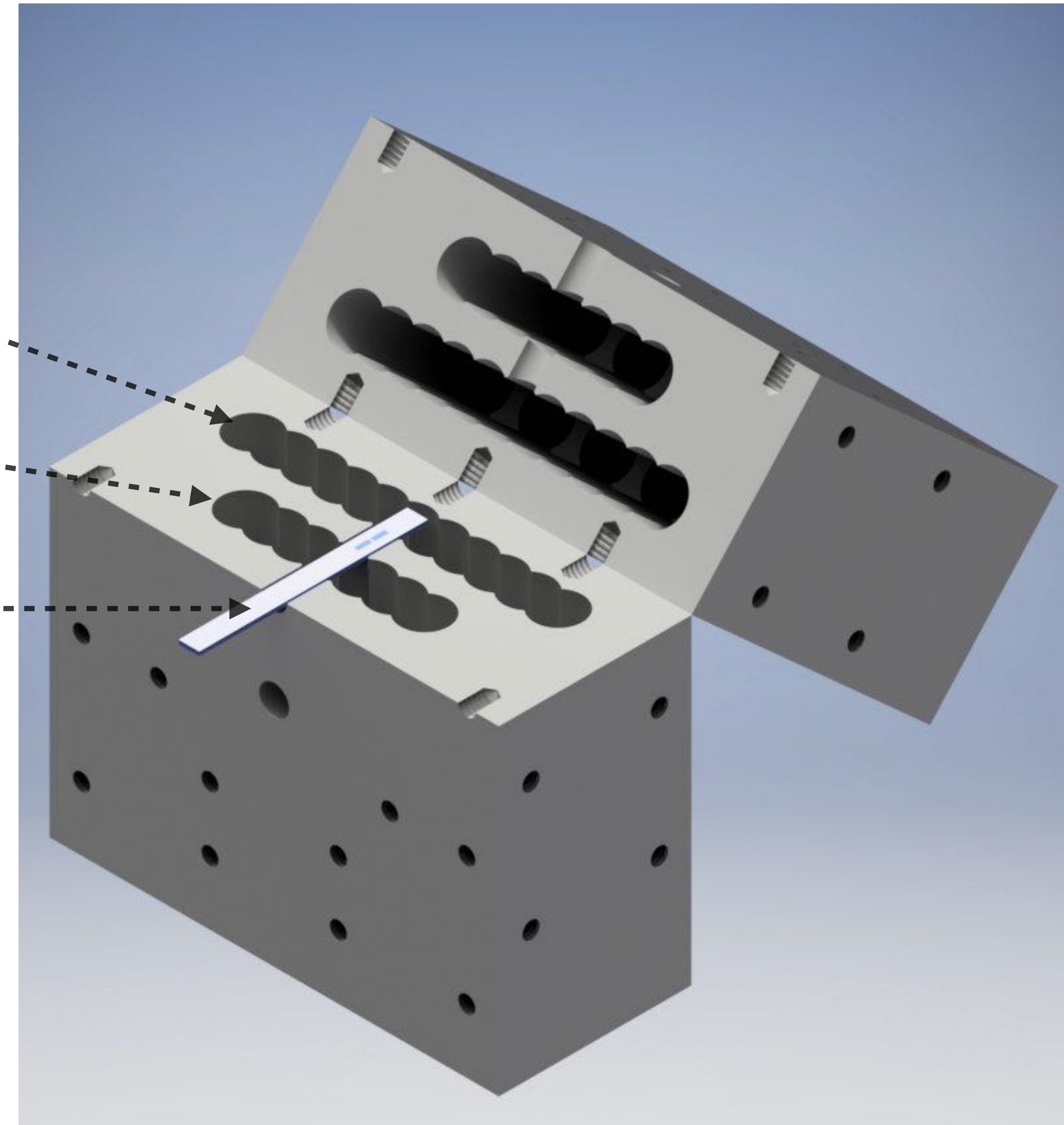
Storage Cavity 6.011 GHz

Readout Cavity 8.052 GHz

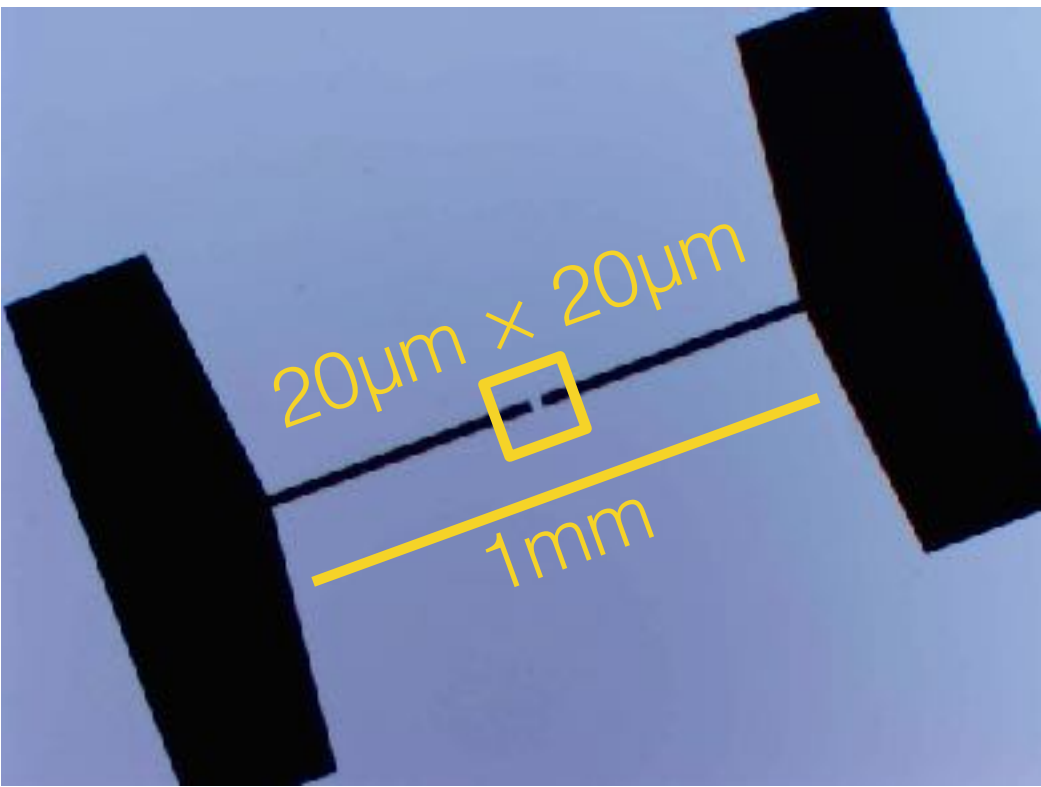
**Qubit on
sapphire chip** 4.749 GHz

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

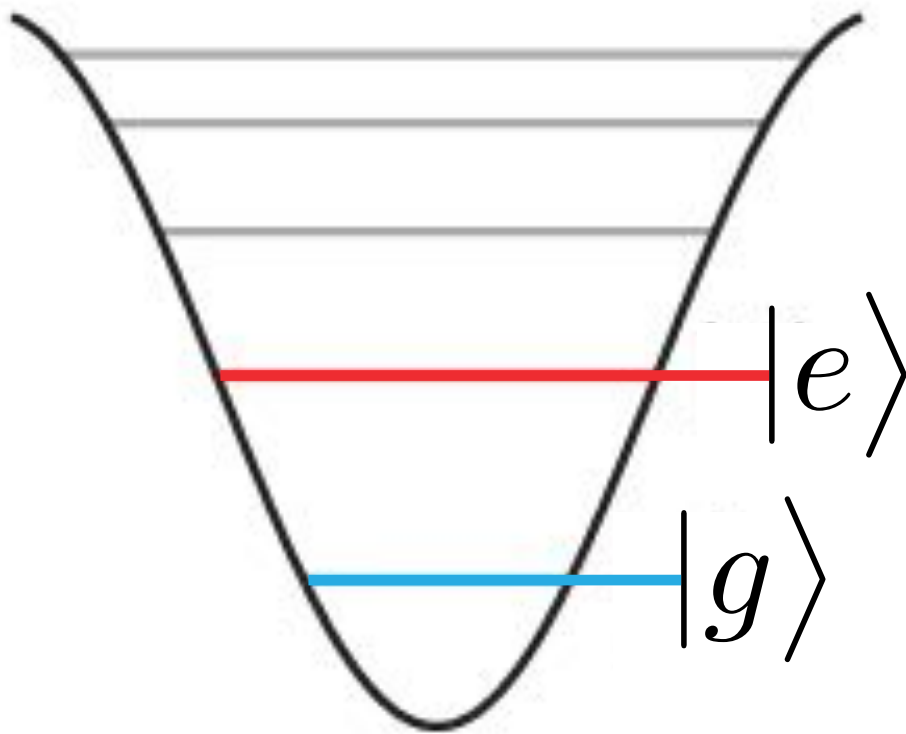
Operated in a dilution refrigerator @ 8mK



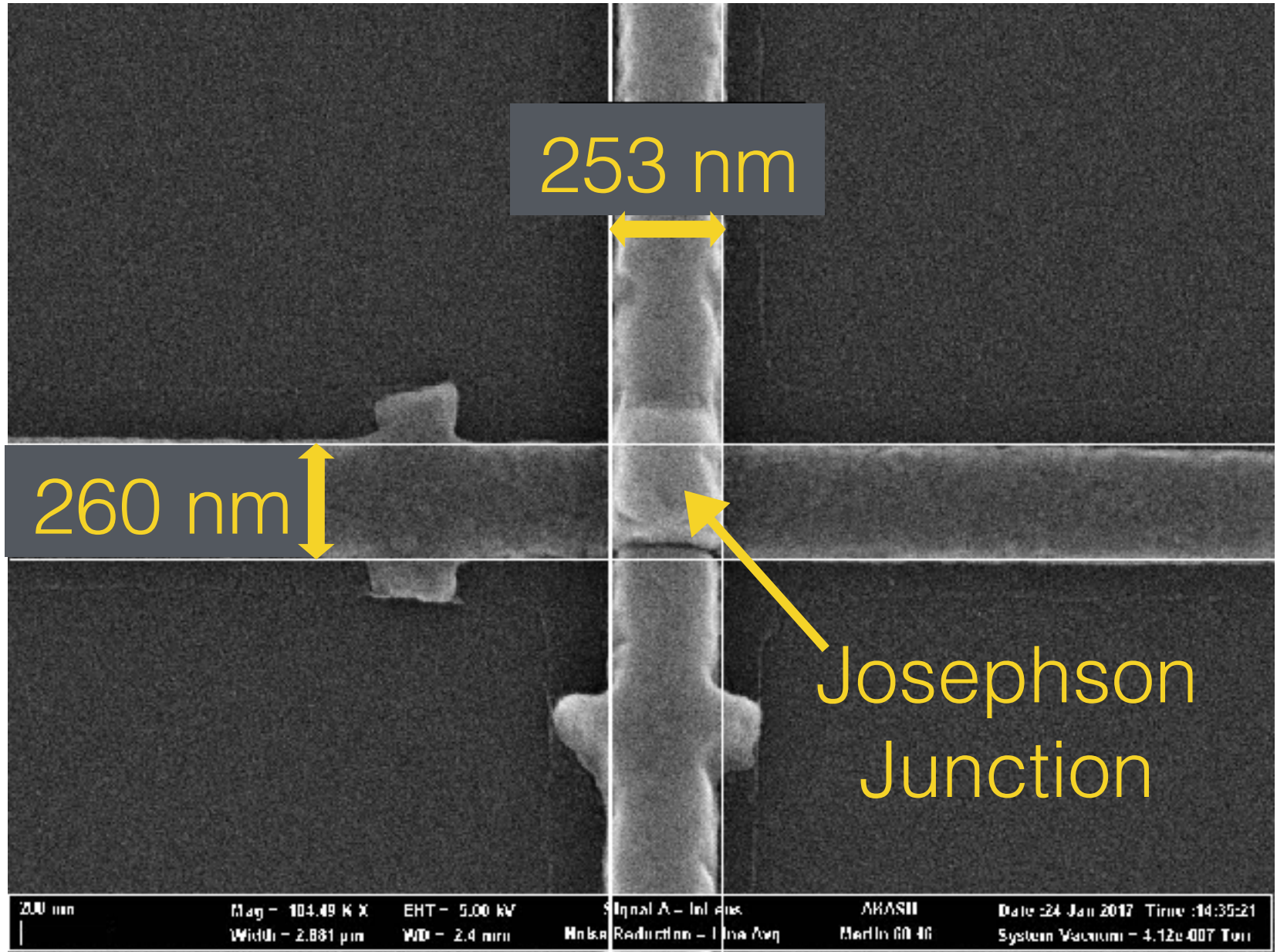
Building a superconducting qubit



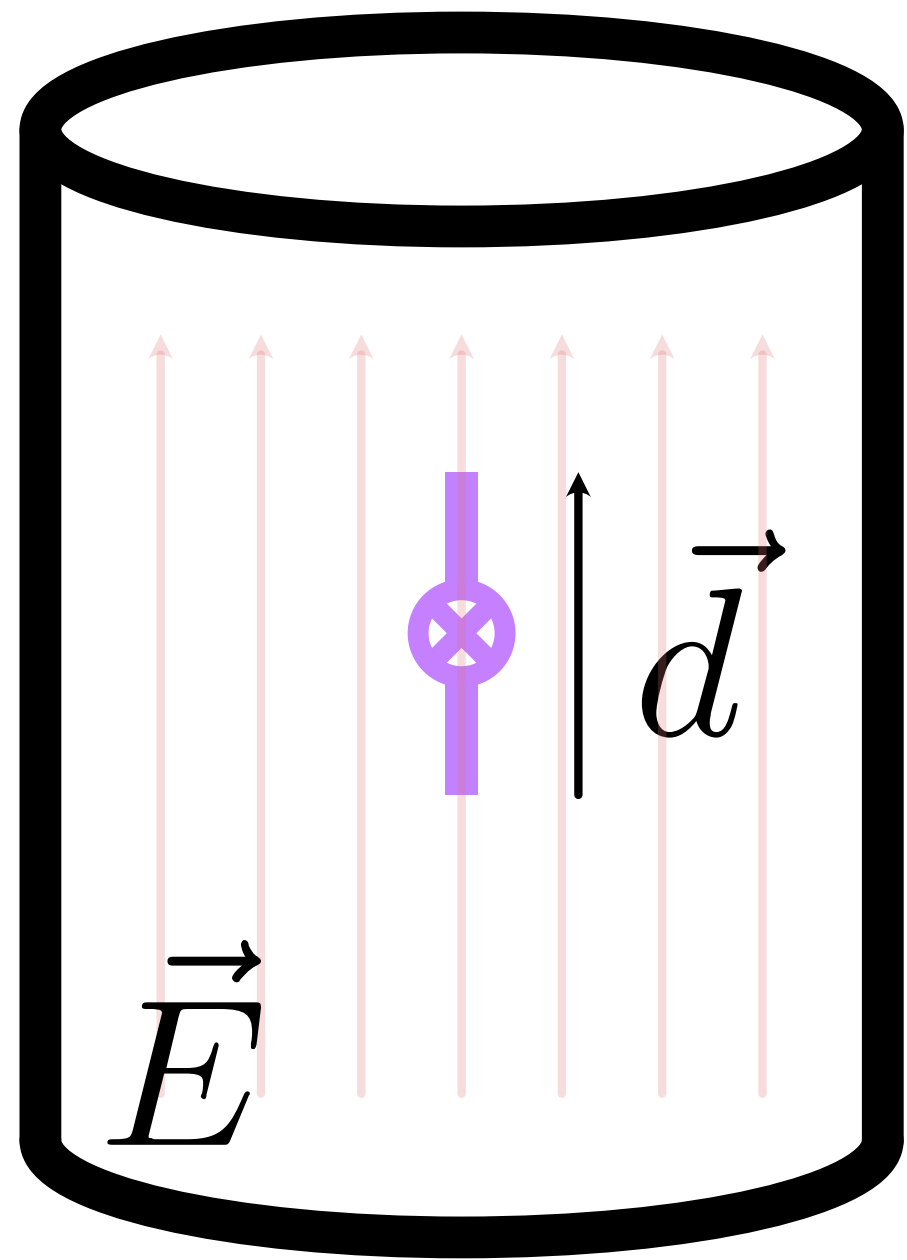
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2} \omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2} \sigma_z$$



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

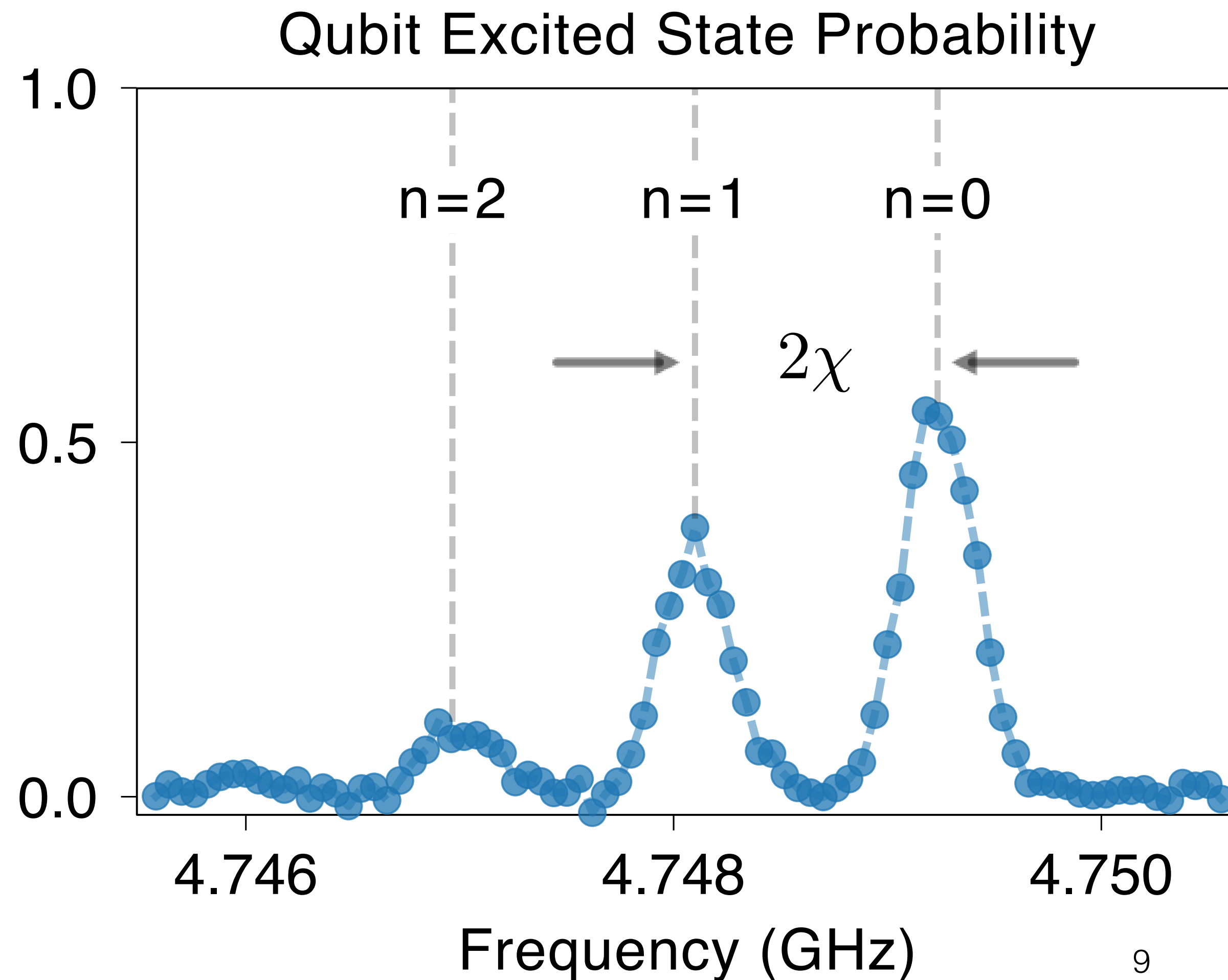
$$\chi = \frac{g^2}{\Delta(\Delta + \alpha)}\alpha$$

Δ qubit-cavity detuning

α qubit anharmonicity

Cavity occupation imprinted on qubit transition frequency

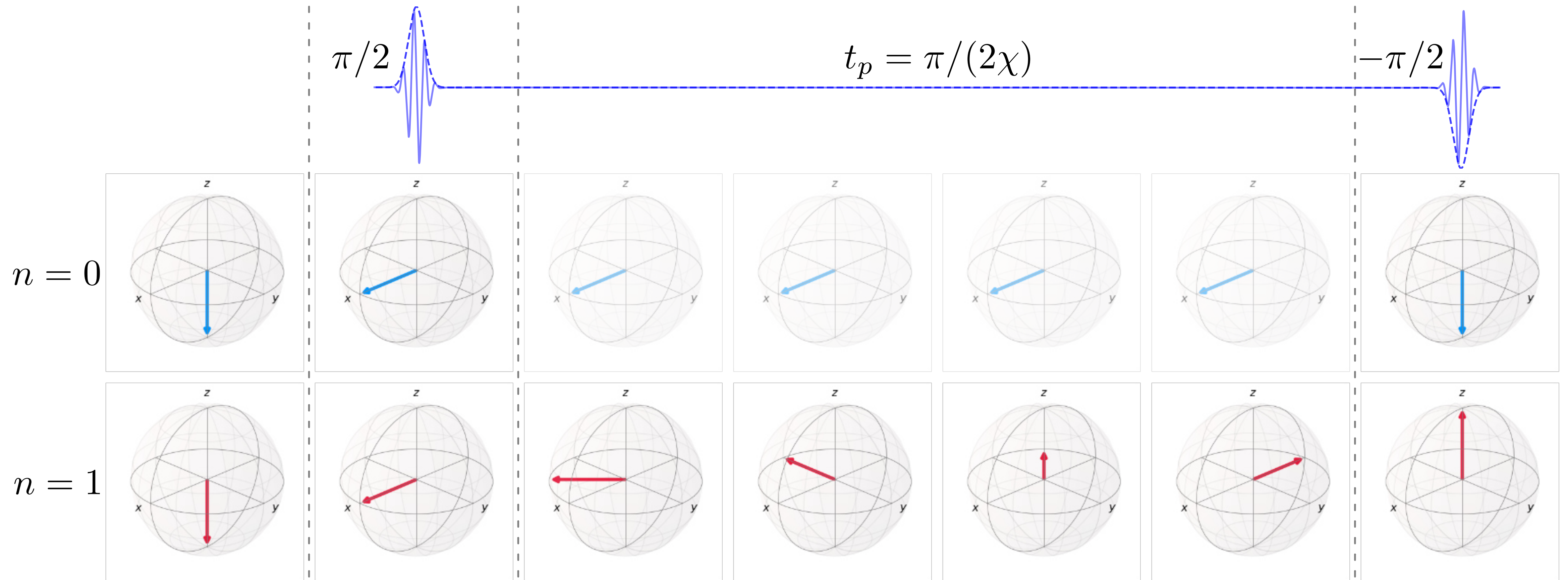
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2} (\omega_q + 2\chi a^\dagger a) \sigma_z$$



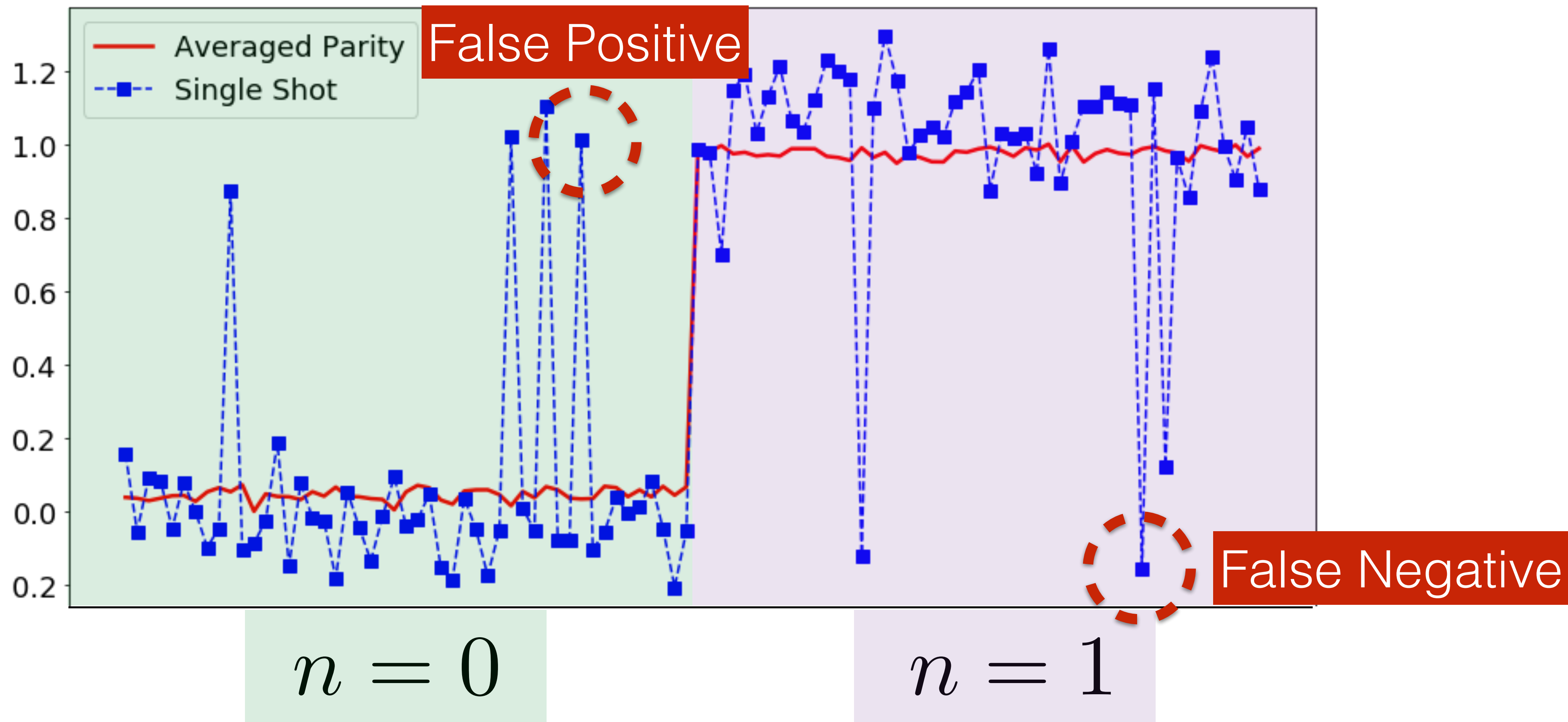
Qubit transition frequency is photon number dependent

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

Parity measurement maps cavity state onto qubit



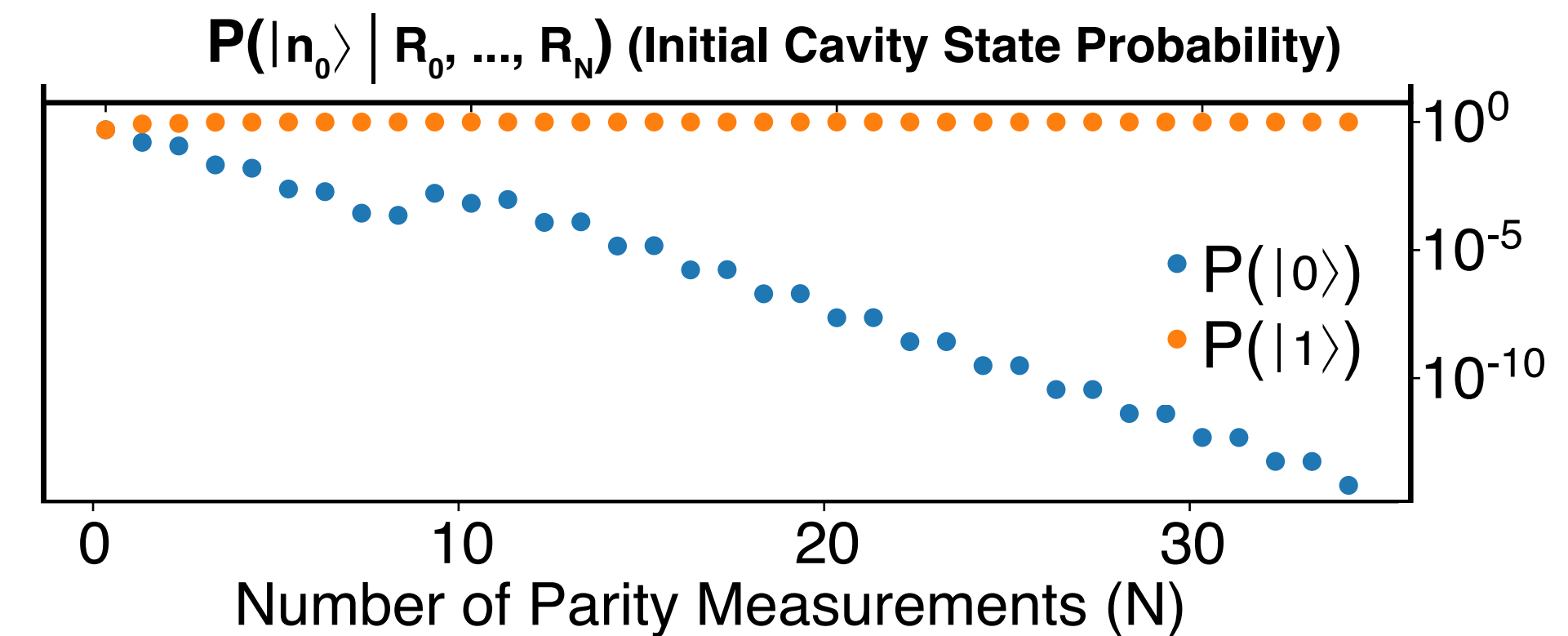
Qubit make too many errors



Spurious qubit excitations are dominant source of errors

Outline of talk

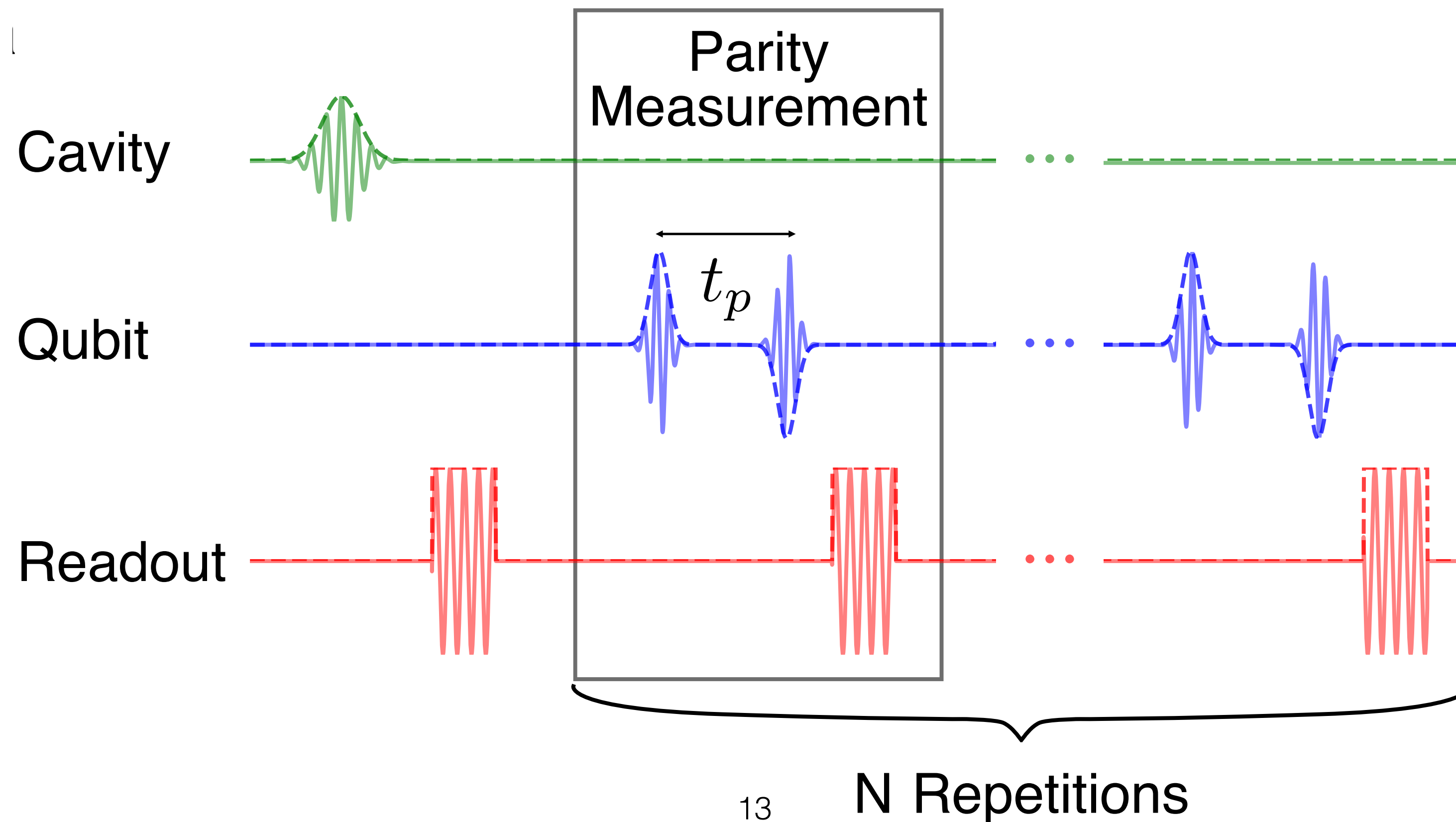
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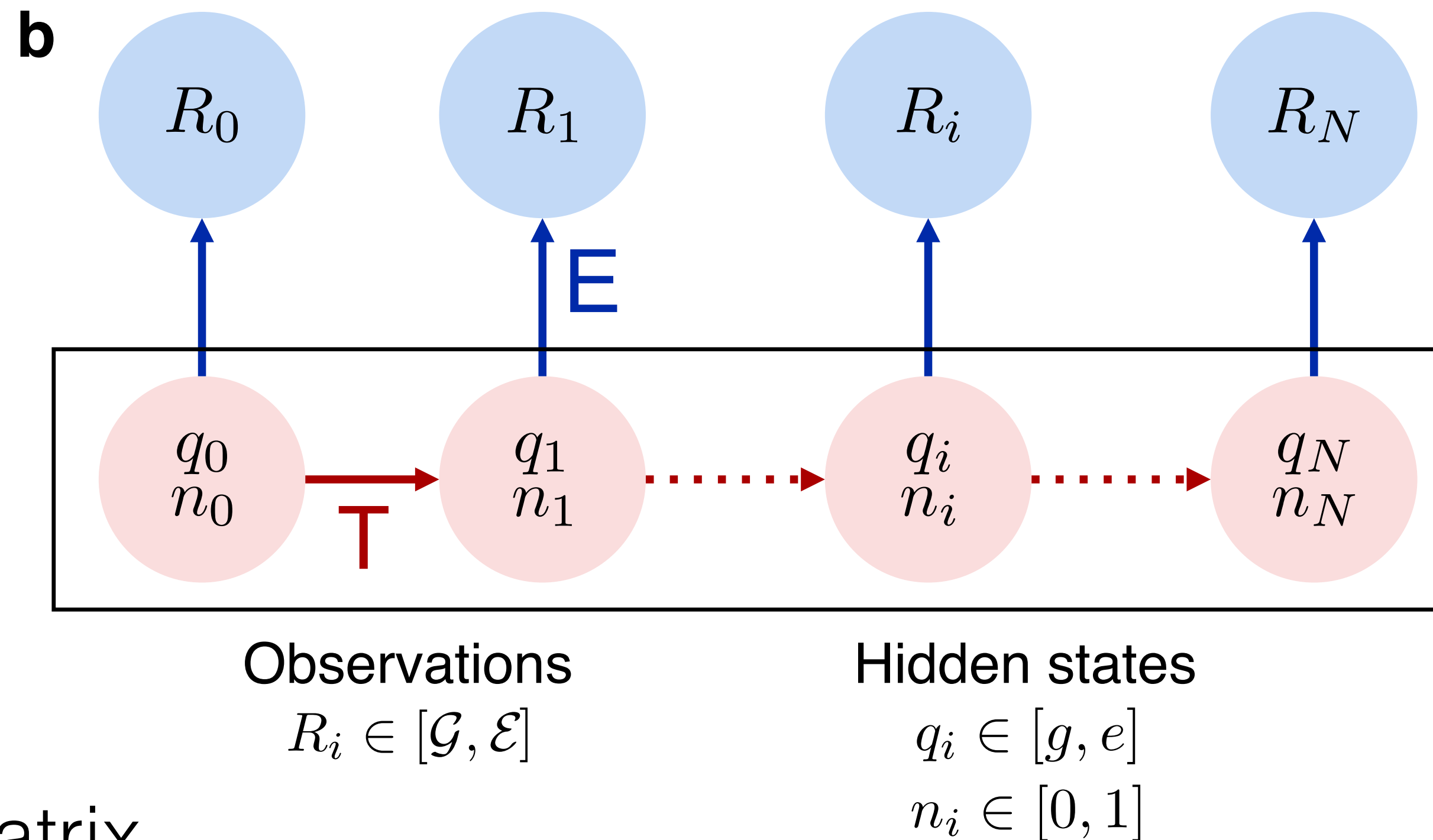
Mitigate the errors by making repeated measurements

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

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



Use hidden Markov model 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 ($t_p = 0.4\mu s$)

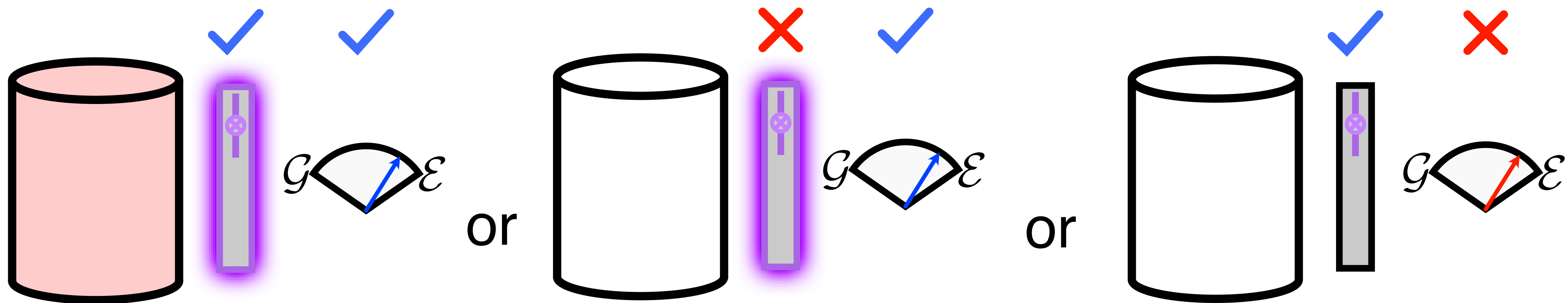
E = Emission matrix

- ground and excited state readout fidelity (~ 0.95)

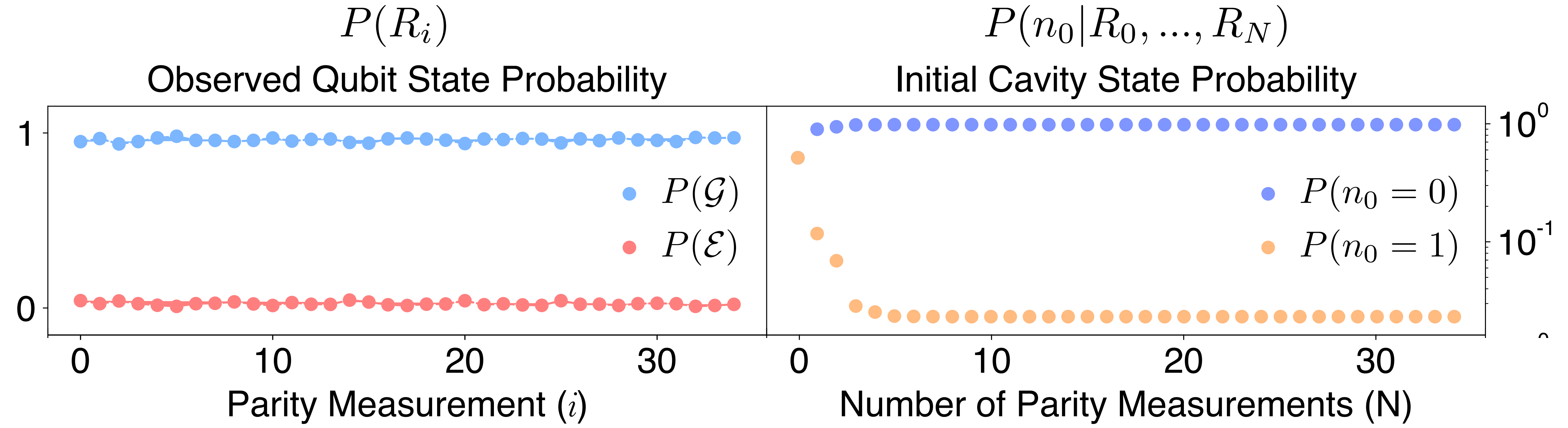
Cavity state reconstruction

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

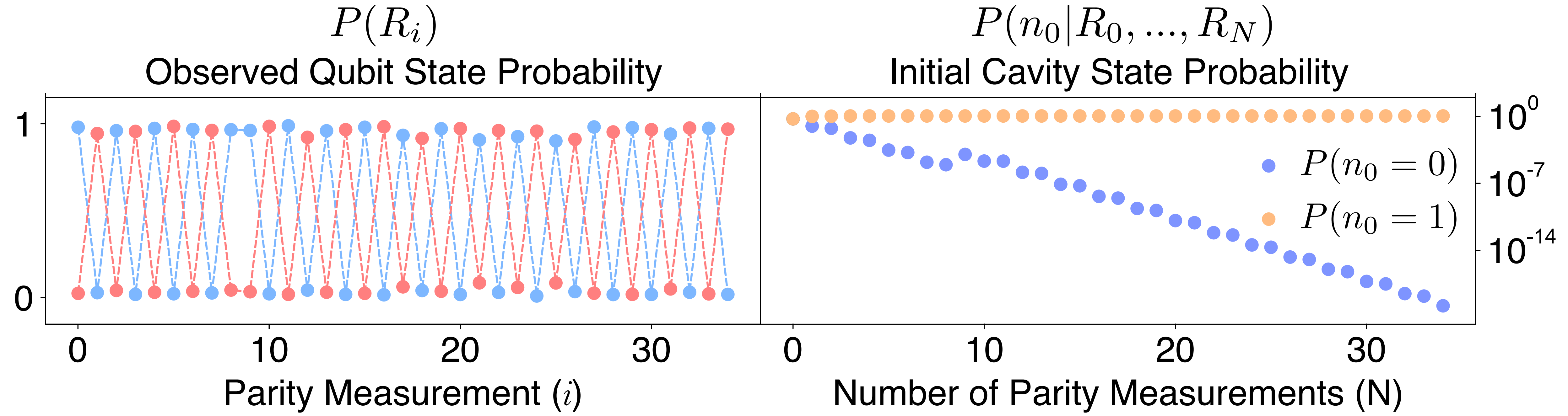
Observed readout sequence: $\mathcal{G} \rightarrow \mathcal{E}$



Detector response in the presence of zero photons



Detector response in the presence of one photon

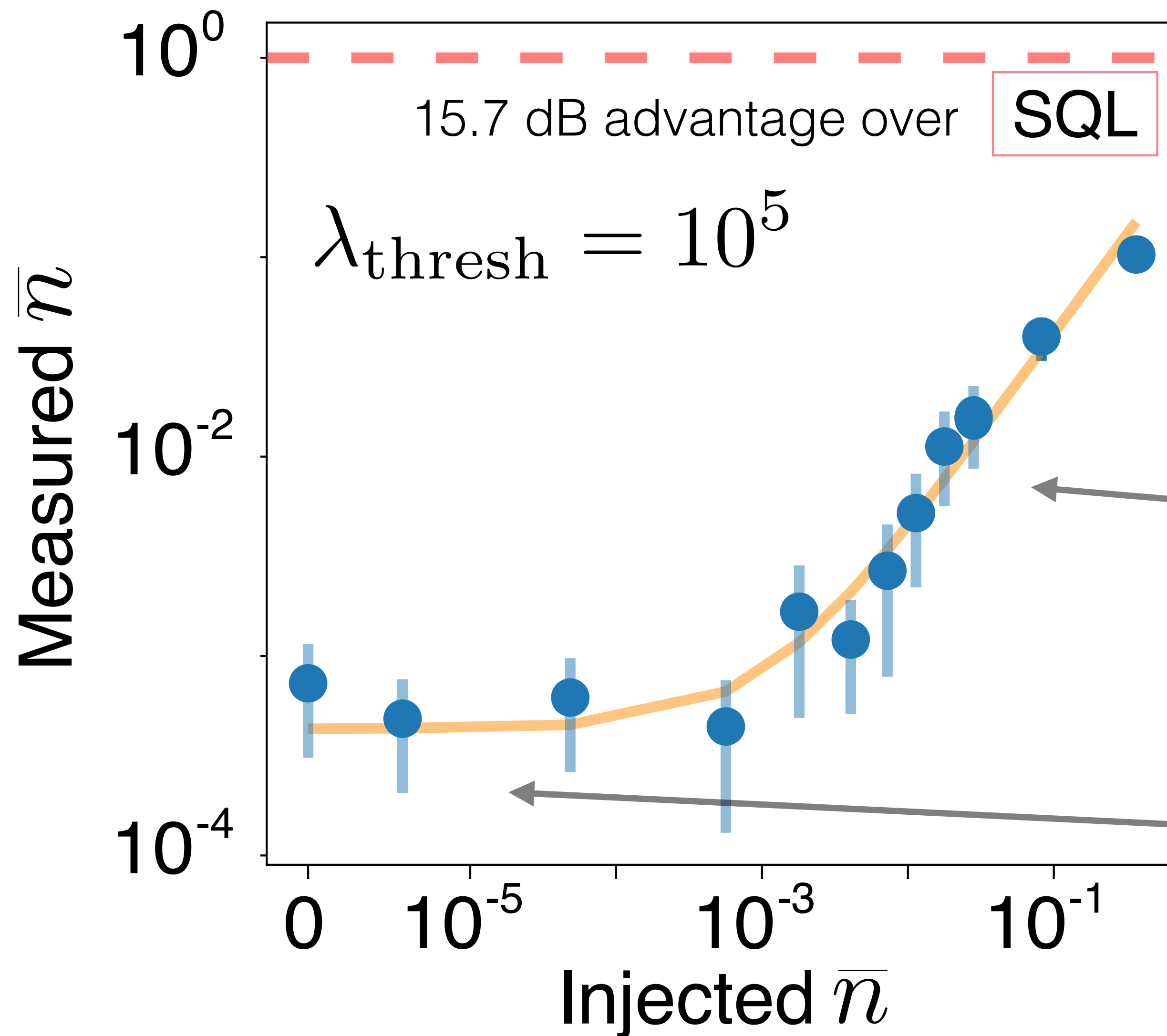


Exponential suppression of detector based false positives

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Detected photon occupation vs injected photon occupation



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

$$t > R_b / R_s^2$$

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

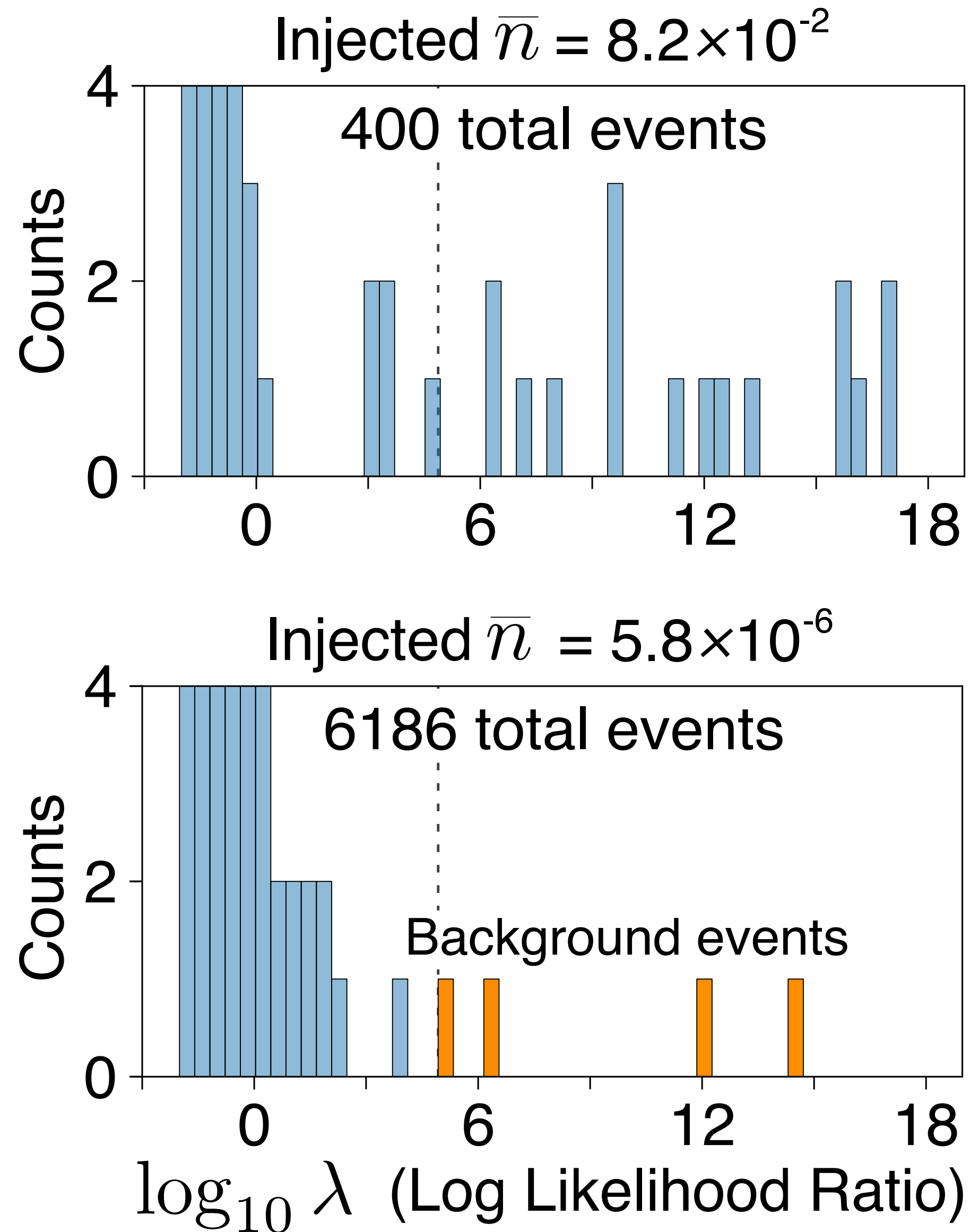
Efficiency

$$\eta = 40.9\%$$

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

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

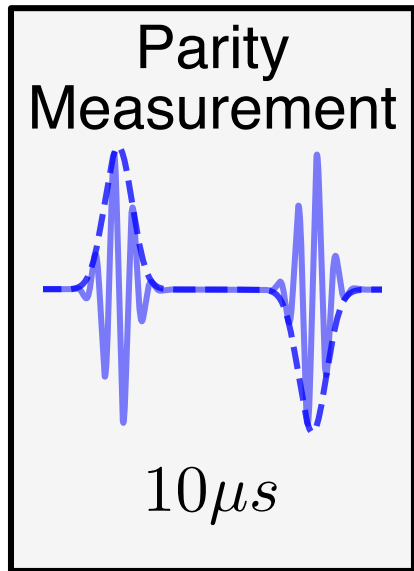
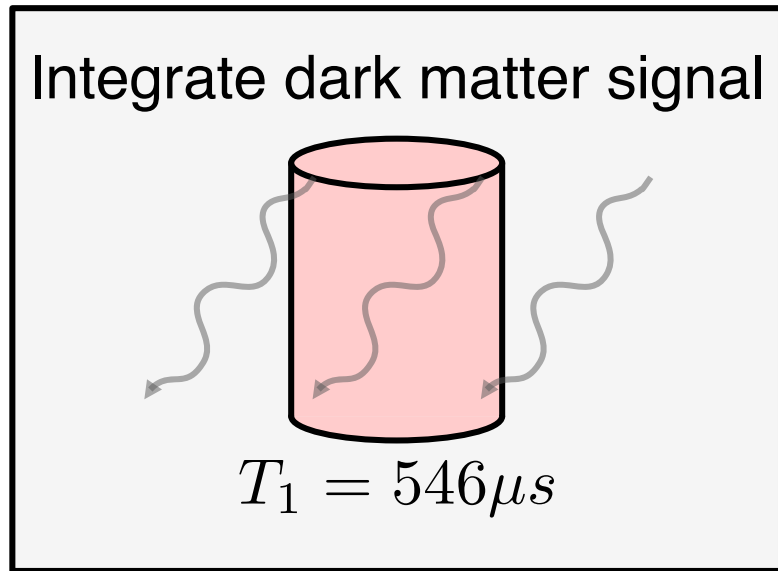
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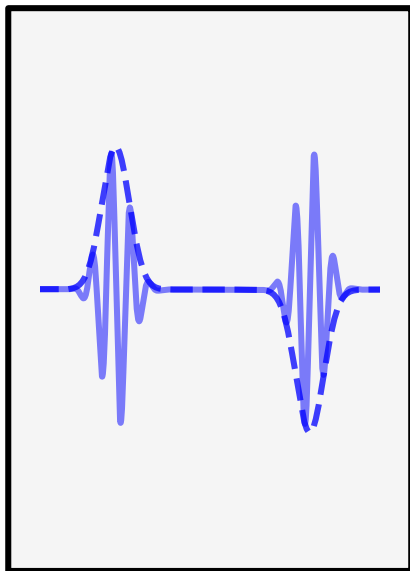
Dark matter search protocol

Signal cannot build up while measuring (quantum Zeno effect)

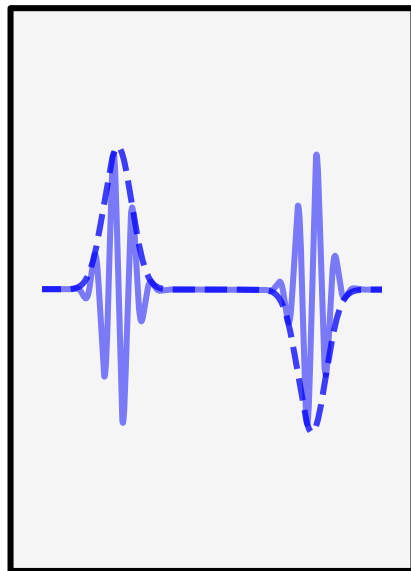
30 repeated measurements



...



...



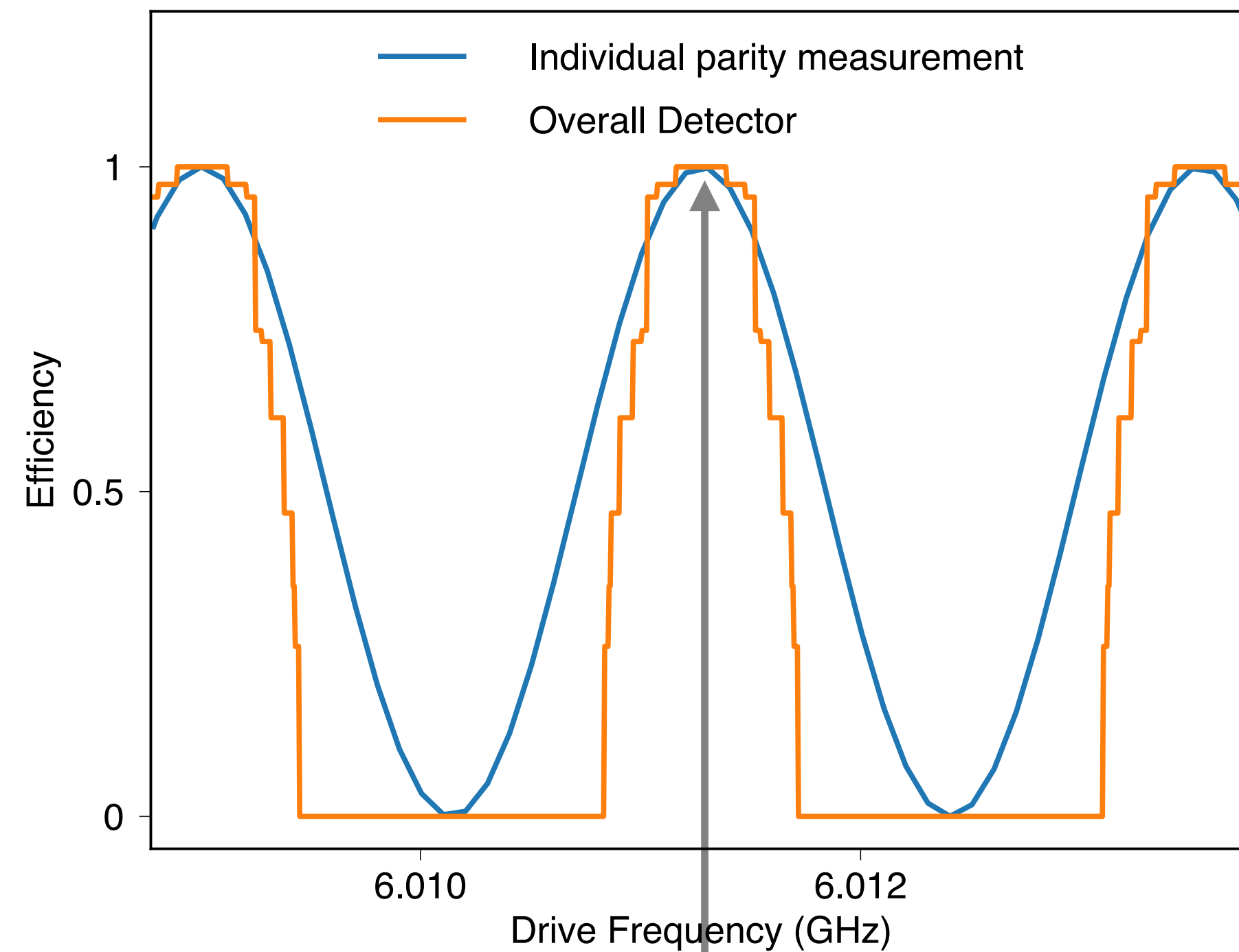
15,141 experiments performed
Total experiment time of 12.81 s
Duty cycle of 65% (8.33 s of integration)

t

Count 9 photons

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

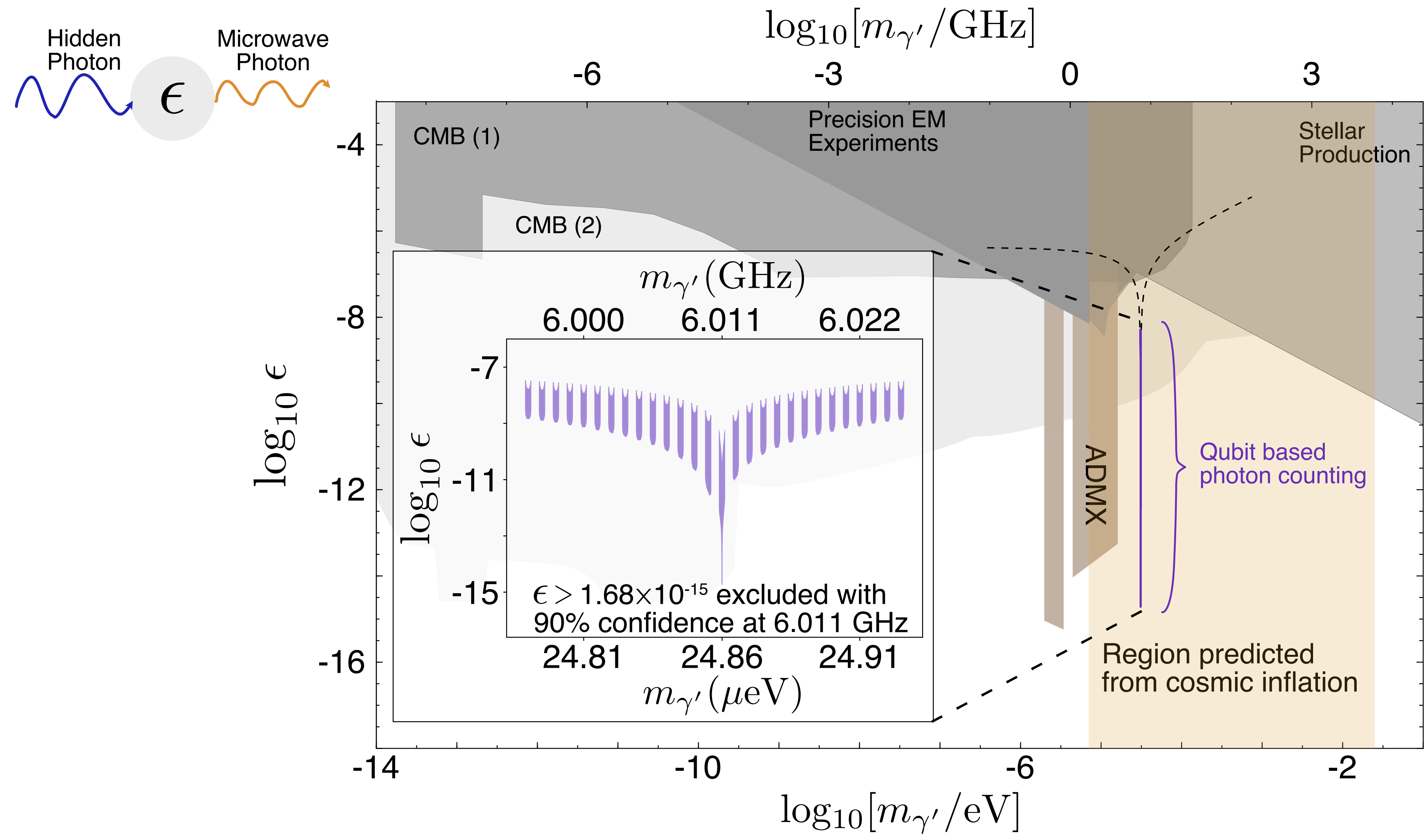
Detector is sensitive to off resonant and large amplitude signals



Parity procedure tuned for excitations on resonance

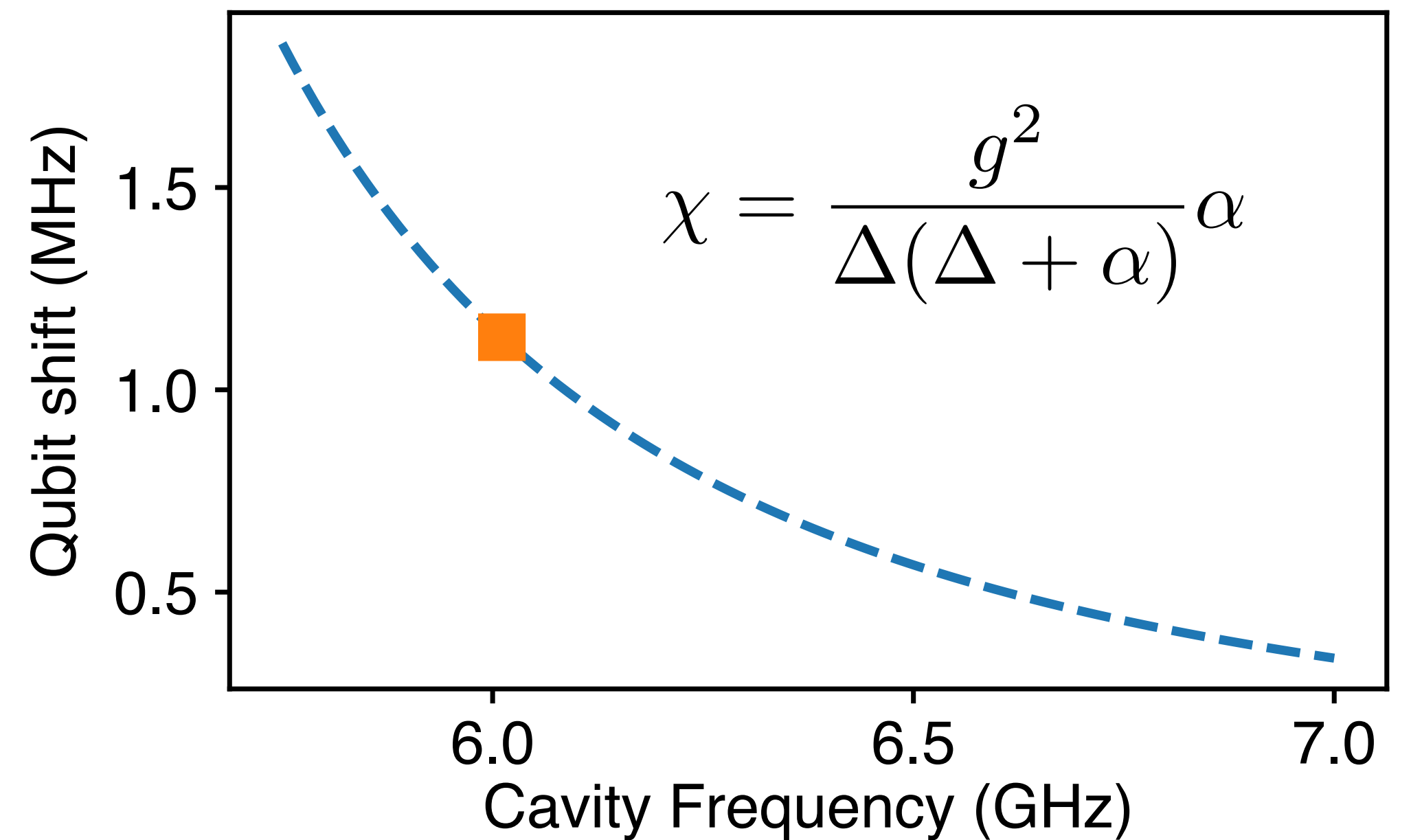
- With parity procedure, qubit can sense:
- Off resonant photons filtered through cavity
 - Large amplitude signals, with significant odd number contributions
 - Limited by bandwidth of pulses

Constraining the Hidden Photon Dark Matter



Integration with a scanning experiment

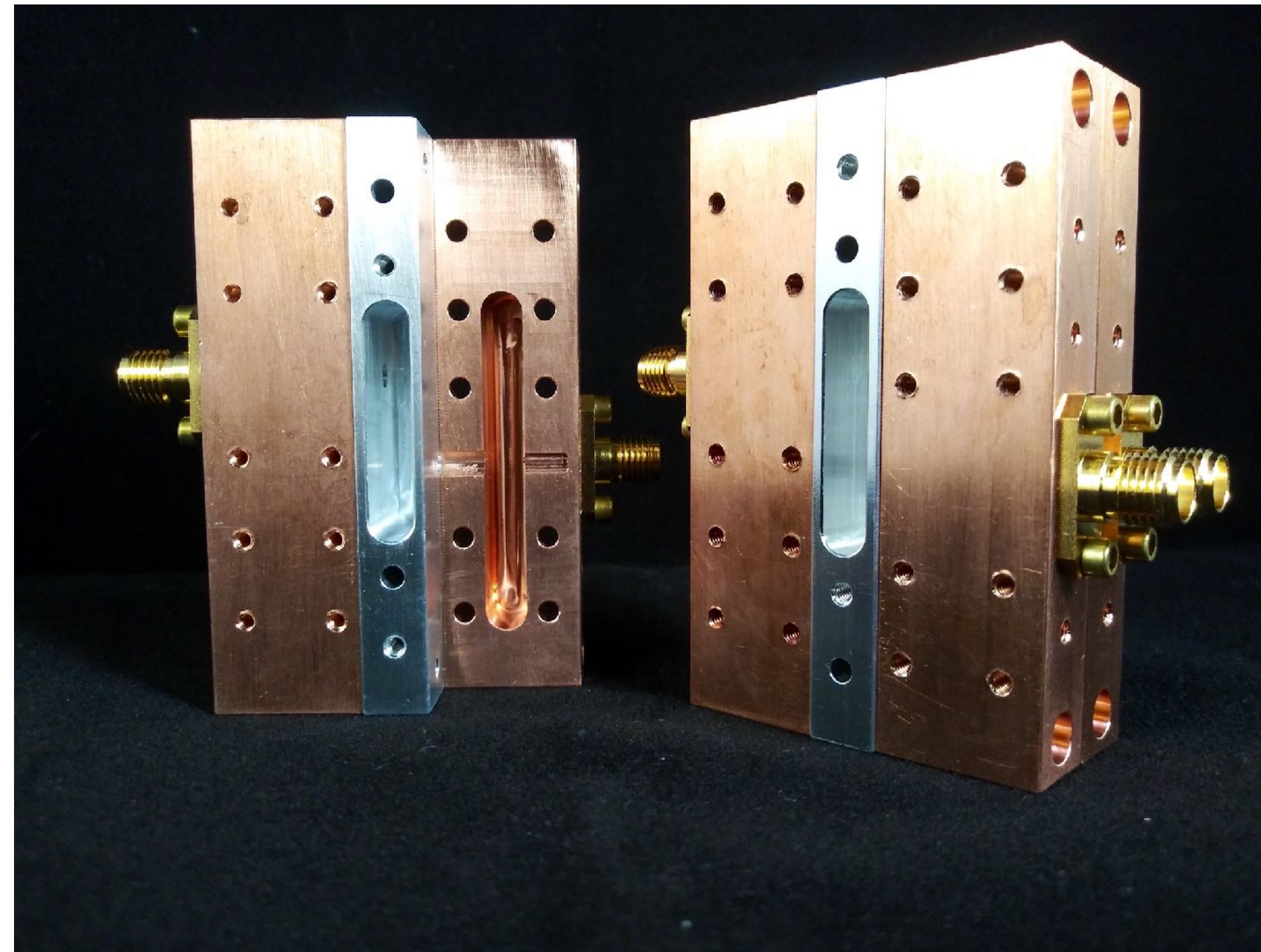
- Keep qubit fixed in frequency
- QND interaction unchanged as cavity tunes
- Calibrate photon dependent qubit shift



Further increasing sensitivity for dark matter searches

Investigate and mitigate photon backgrounds

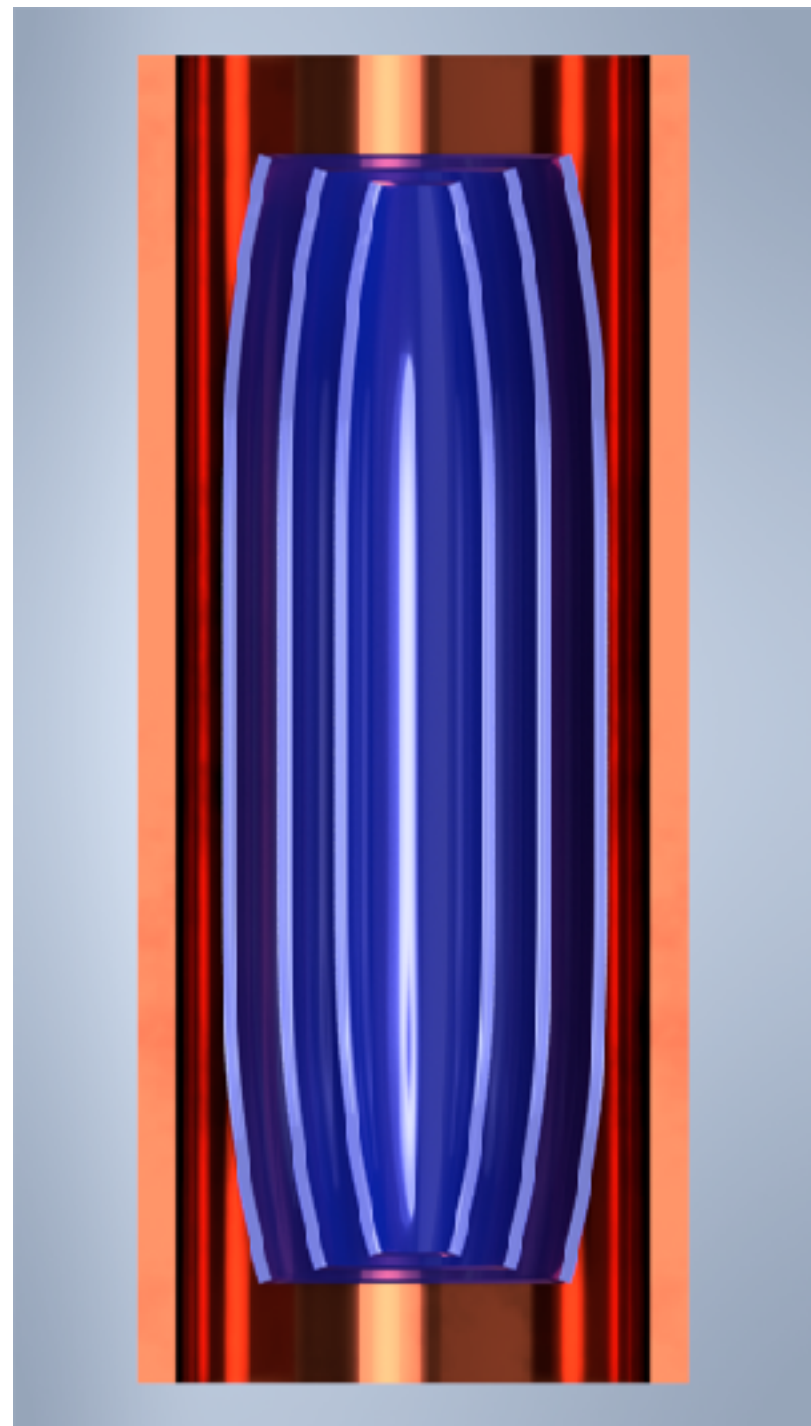
Use multiple entangled qubits for enhanced metrology



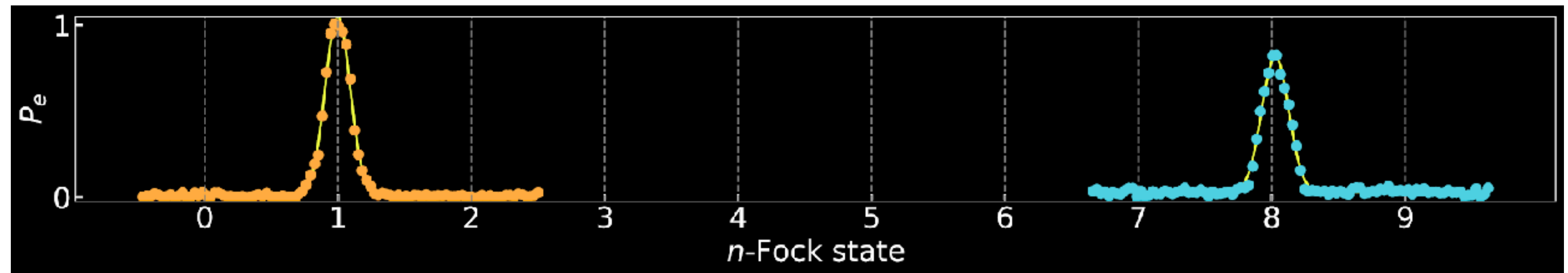
Boosting dark matter induced signal

Novel materials/designs for high Q cavities

Use nonclassical cavity states for signal enhancement



$$| \langle n + 1 | \mathcal{D}_\alpha | n \rangle |^2 \sim n \alpha^2$$



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

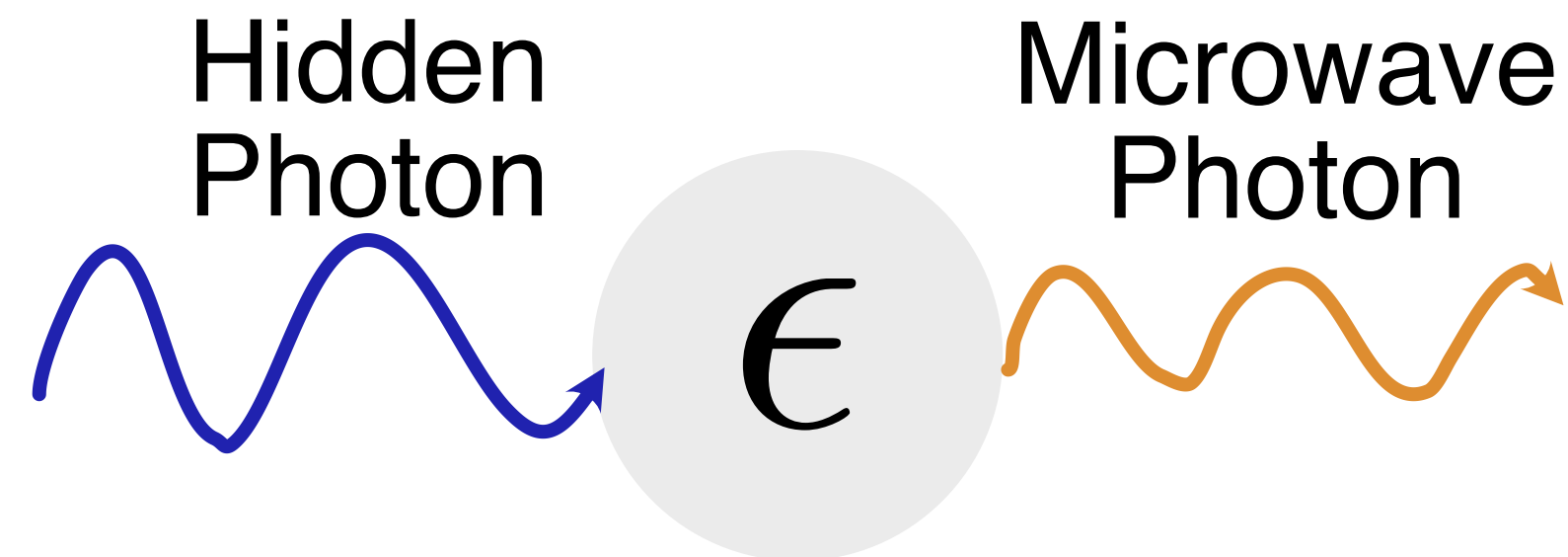
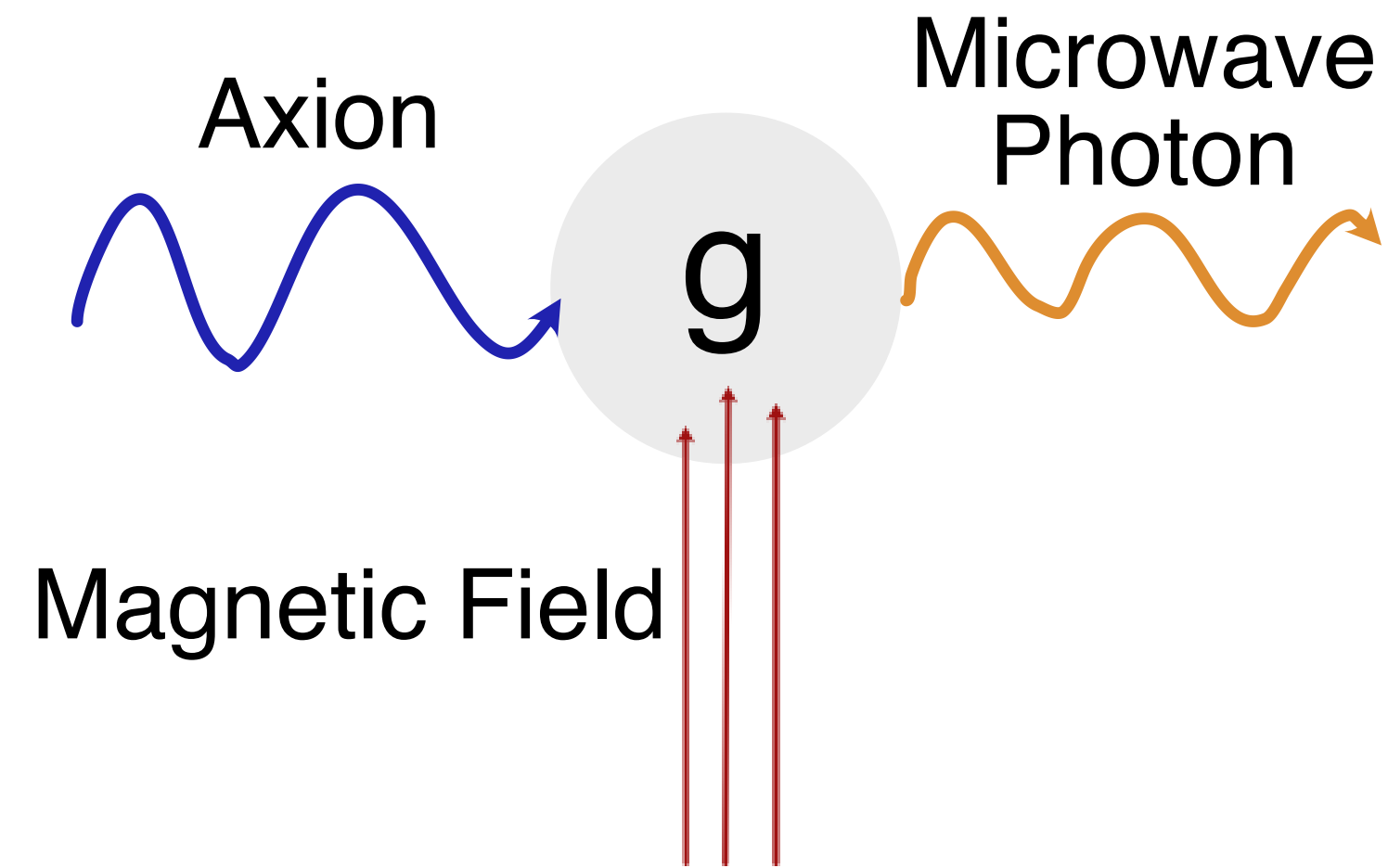


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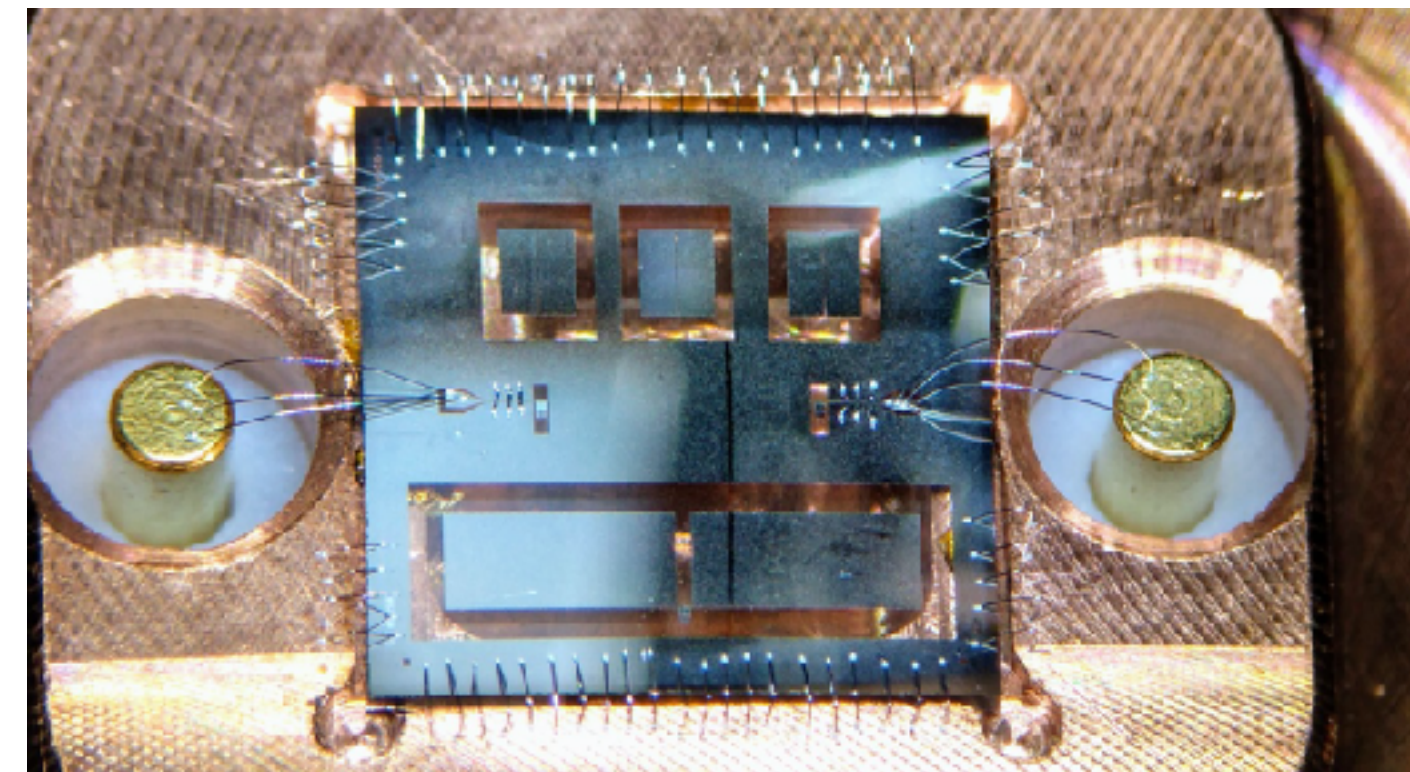
How dark matter might couple to electromagnetism



Resonant cavity to capture signal



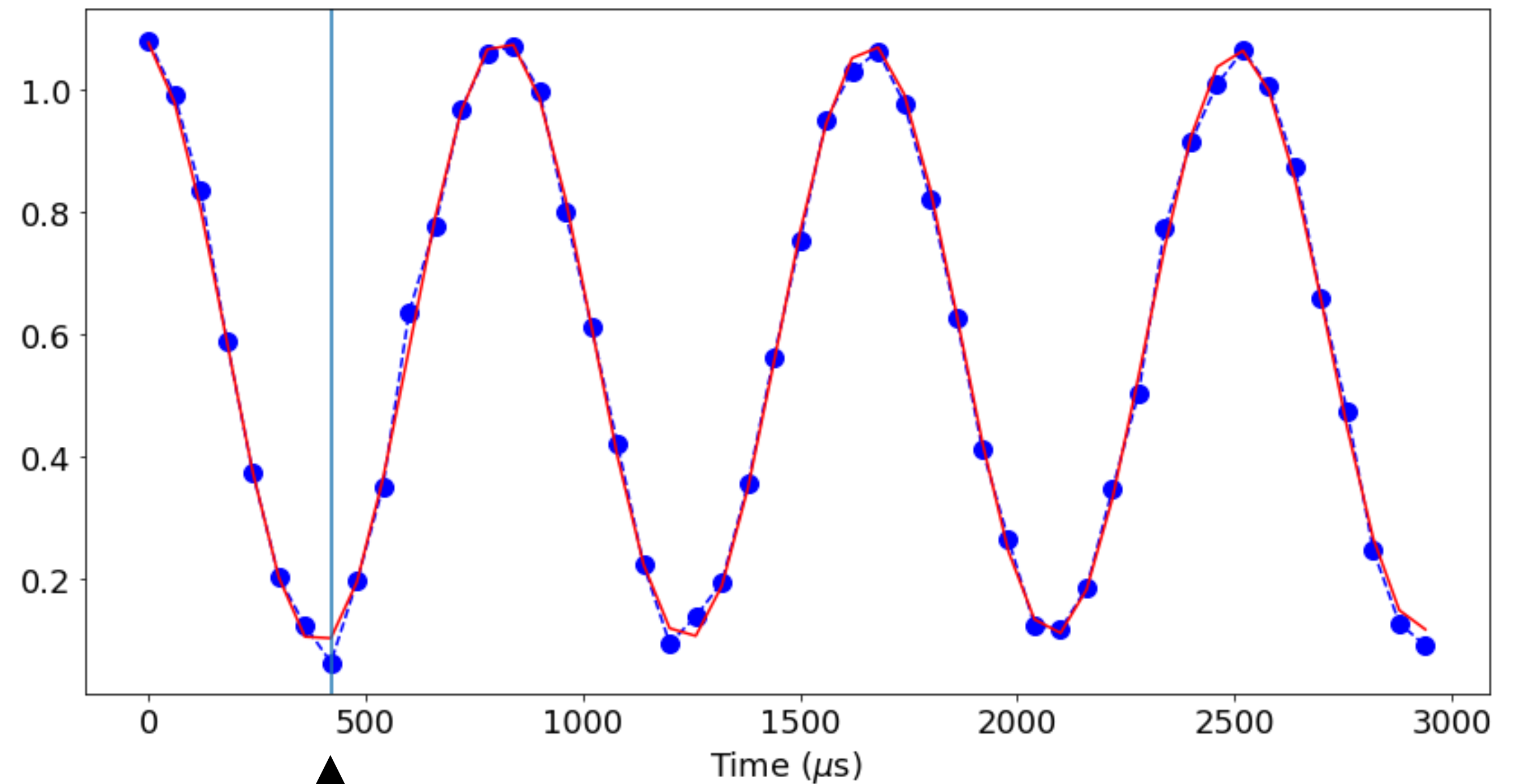
Quantum limited amplifier for readout



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

$P(e)$
Qubit excited state probability



Forward Backward Algorithm

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

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

Forward

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

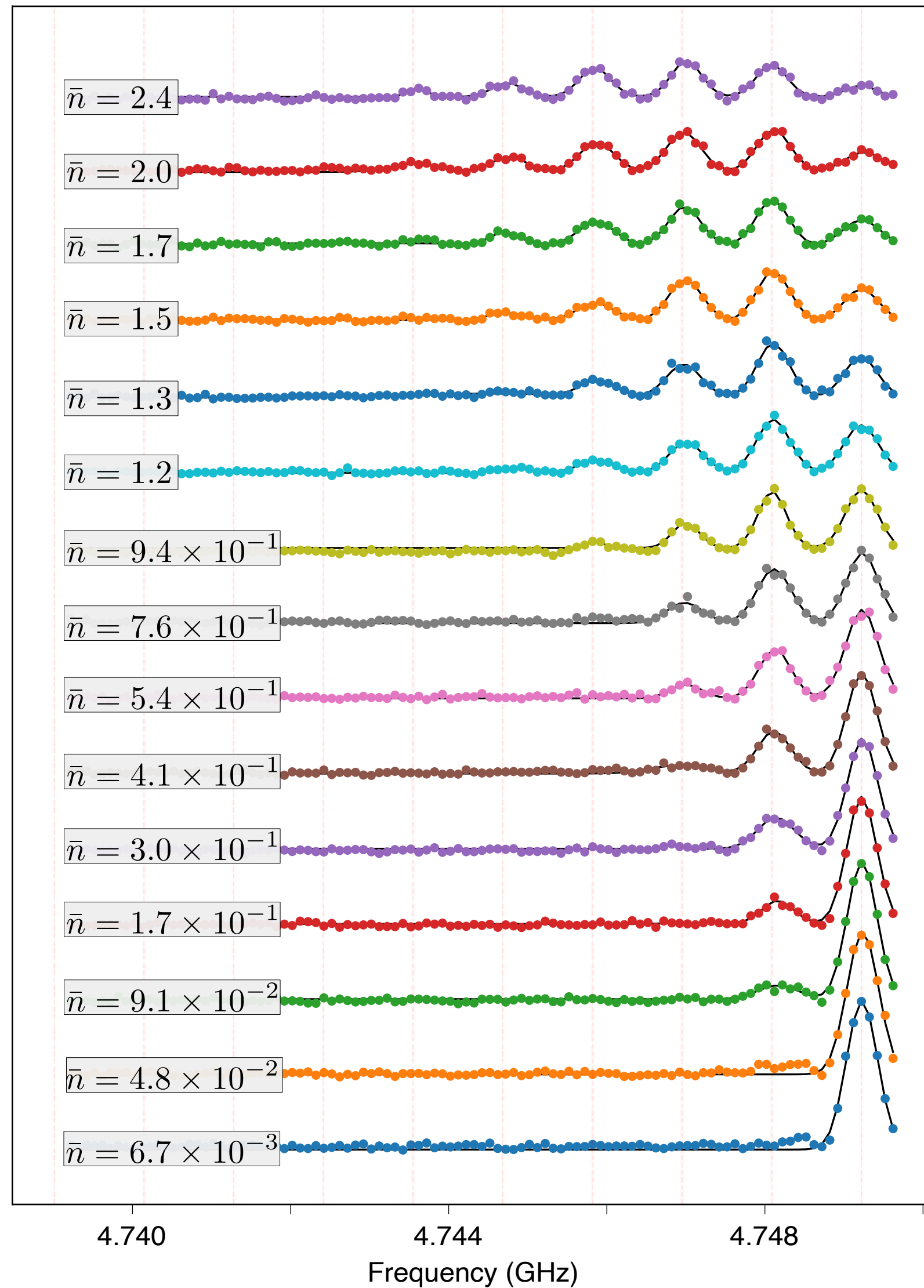
Backward

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

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

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

Calibrate photon injection



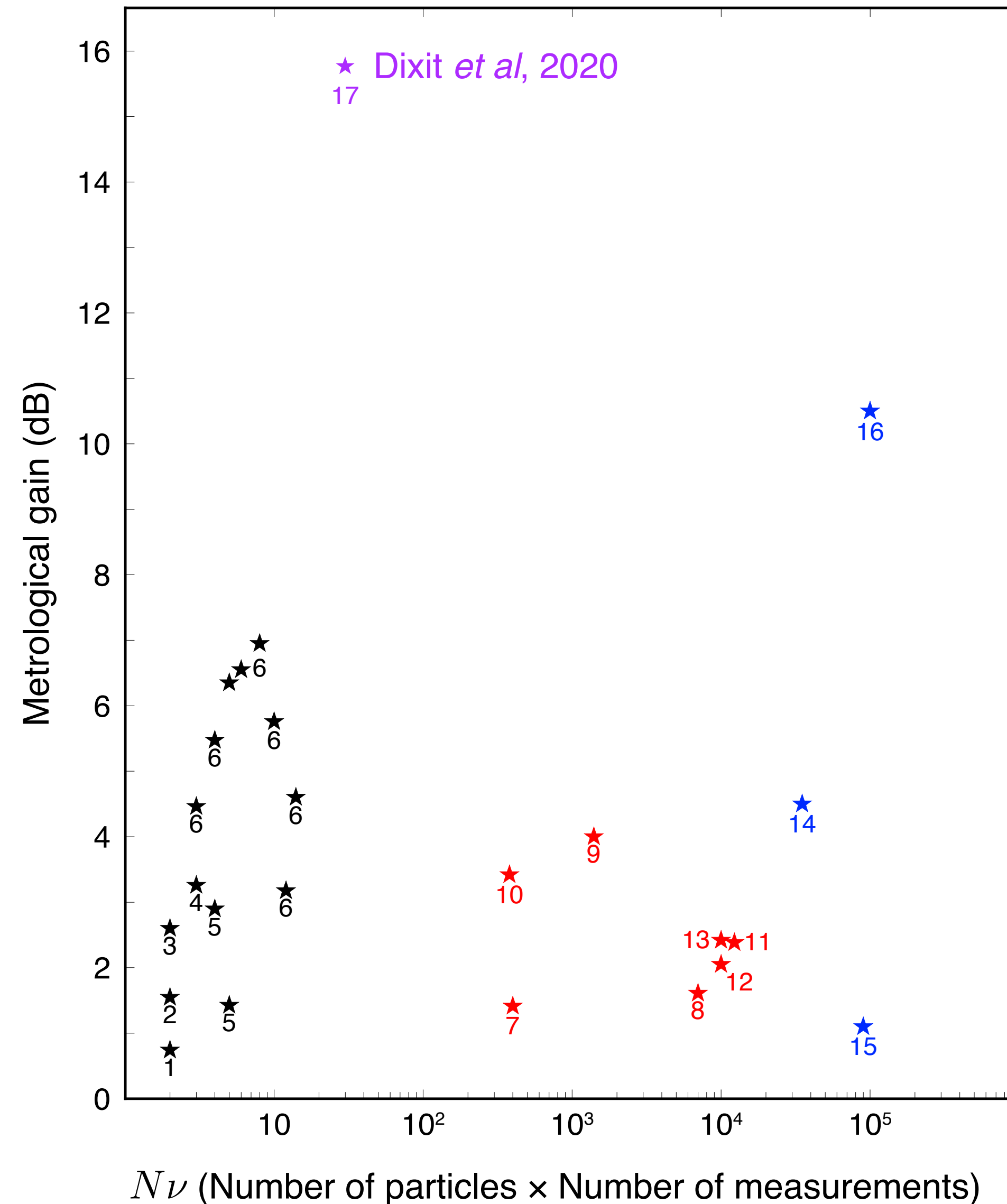
Coherent drive of variable length and amplitude

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 $P(\text{heating}) = 10^{-3}$, 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

Background sources and mitigation strategies

Photons coming down lines

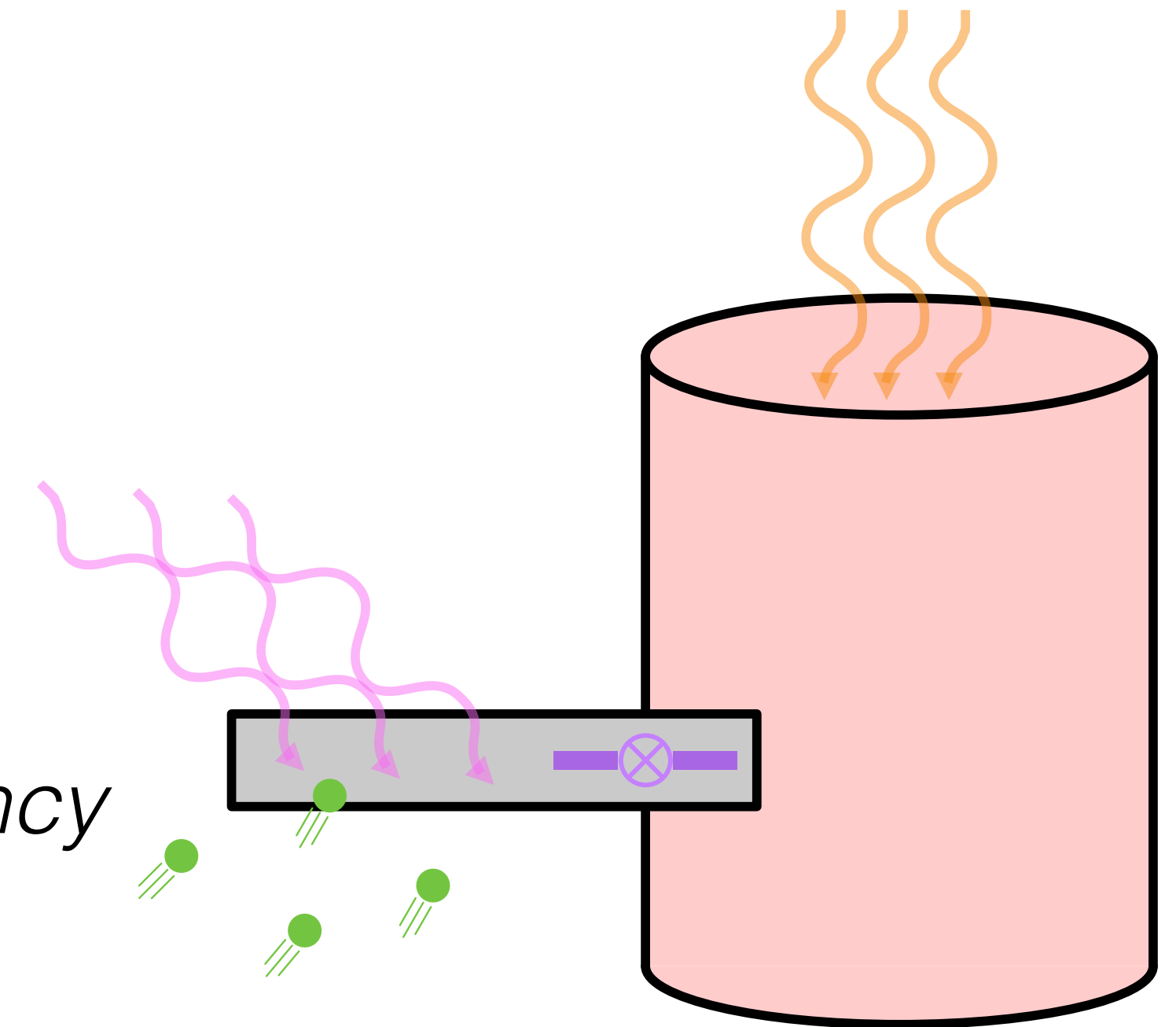
- more attenuation and filtering
- better thermalization of components

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

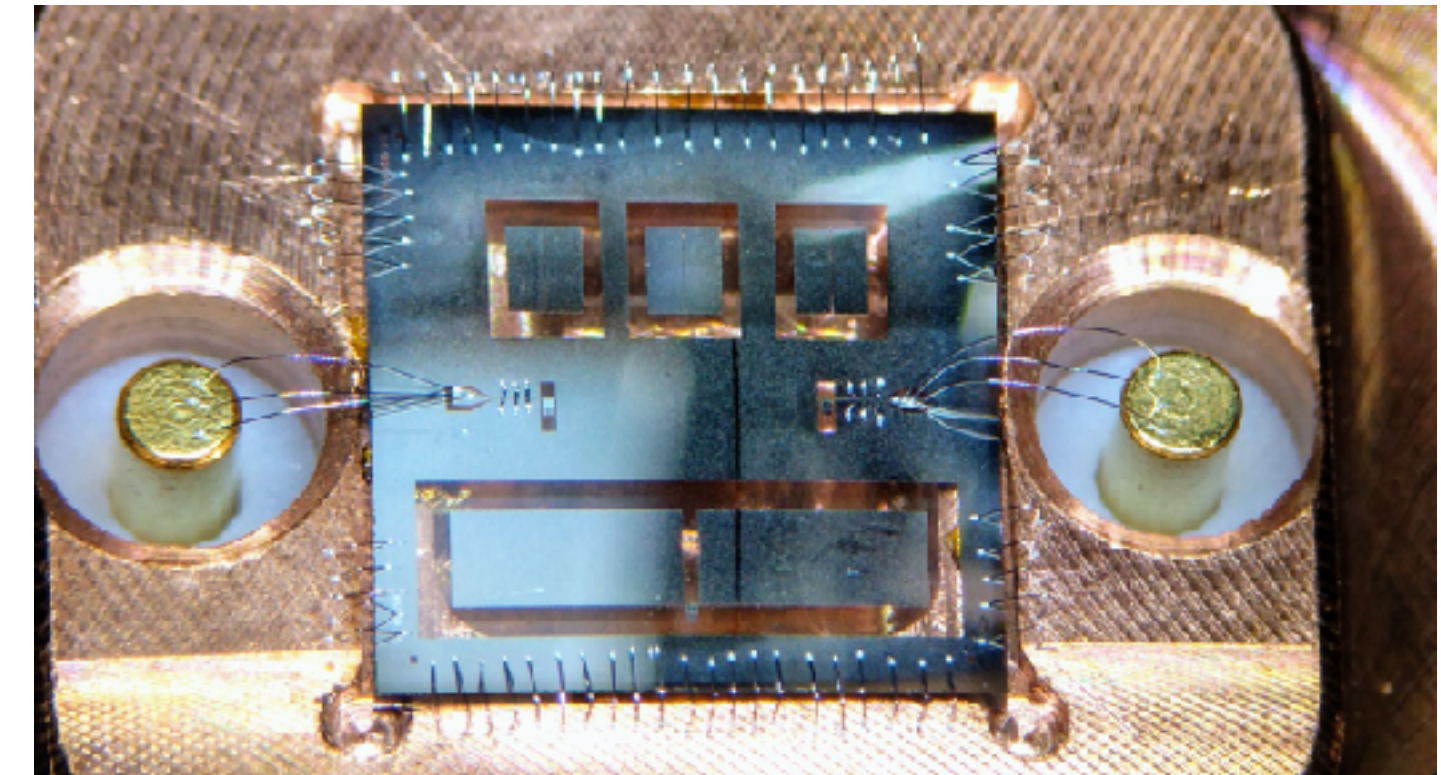


aip.scitation.org/doi/10.1063/1.4984894
journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.11.014031
journals.aps.org/prb/abstract/10.1103/PhysRevB.94.104516
www.nature.com/articles/s41586-020-2619-8
journals.aps.org/prb/abstract/10.1103/PhysRevB.100.140503
journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.157701

Further improvements to protocol

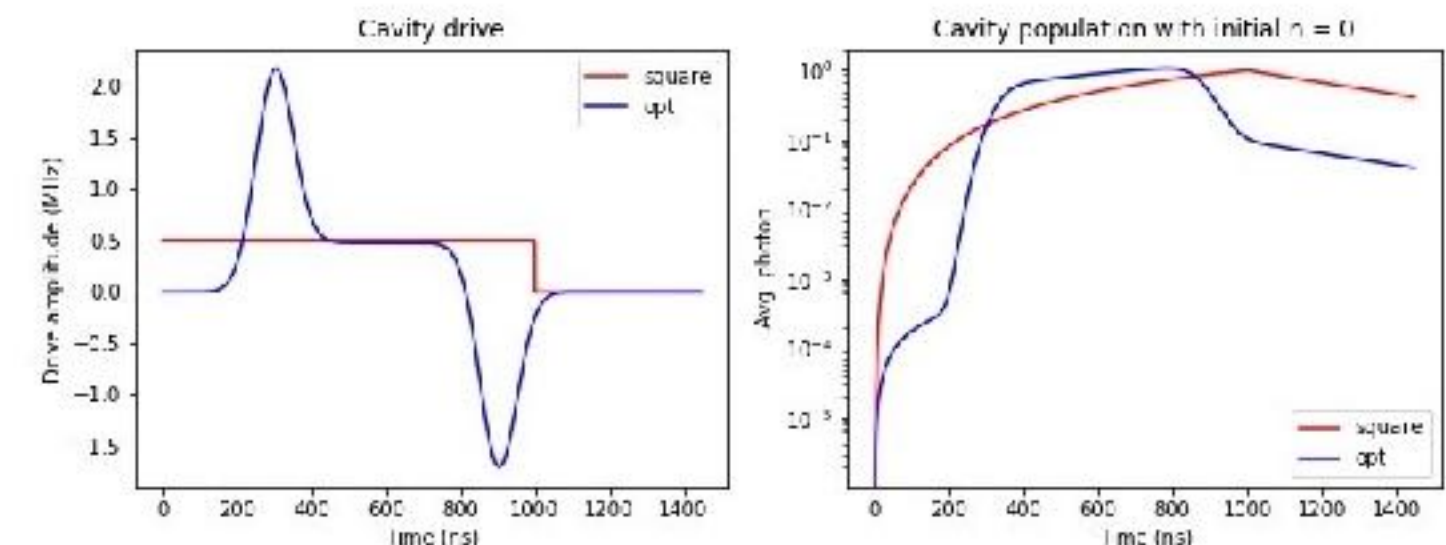
Parametric amplifier

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



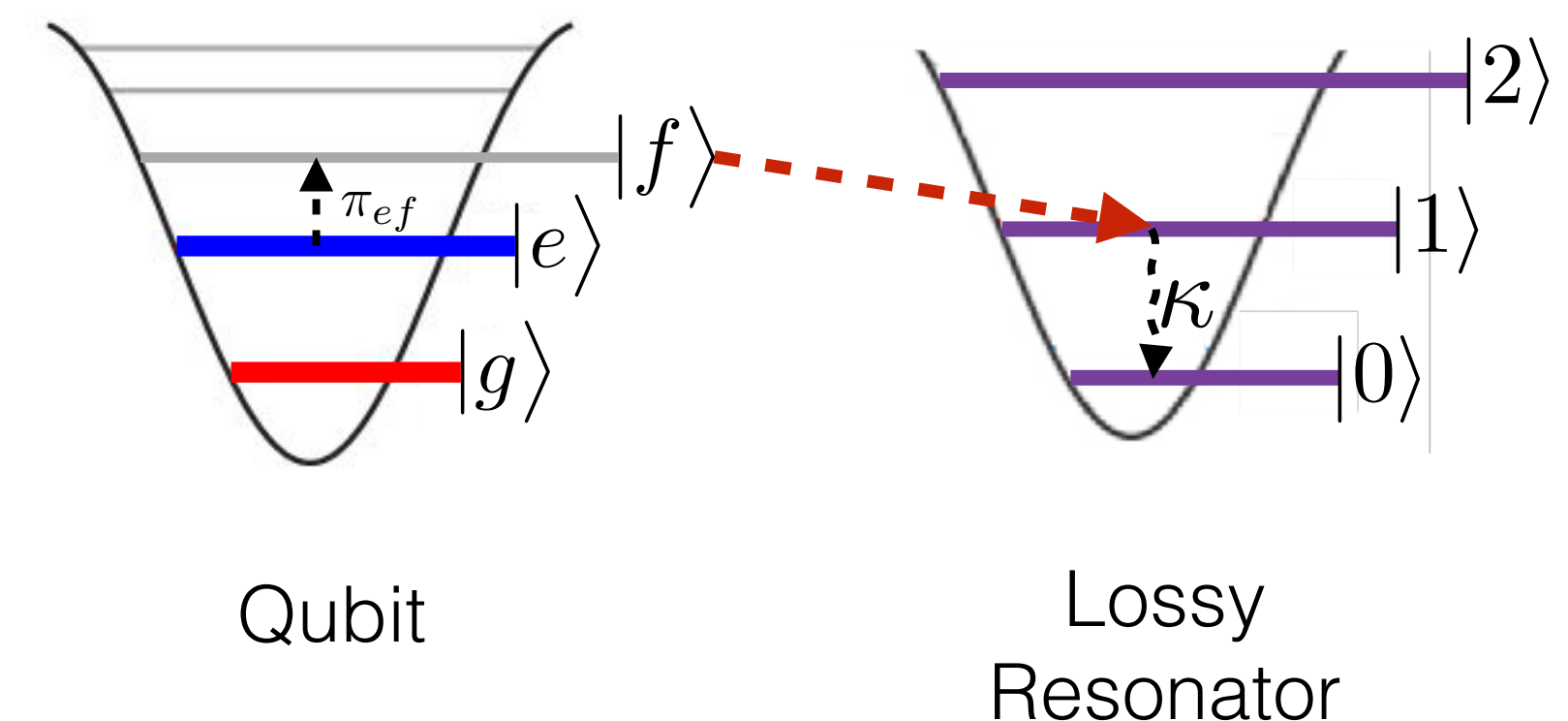
Reset readout cavity with optimized pulse shape

- readout decay is dominant time scale in expt

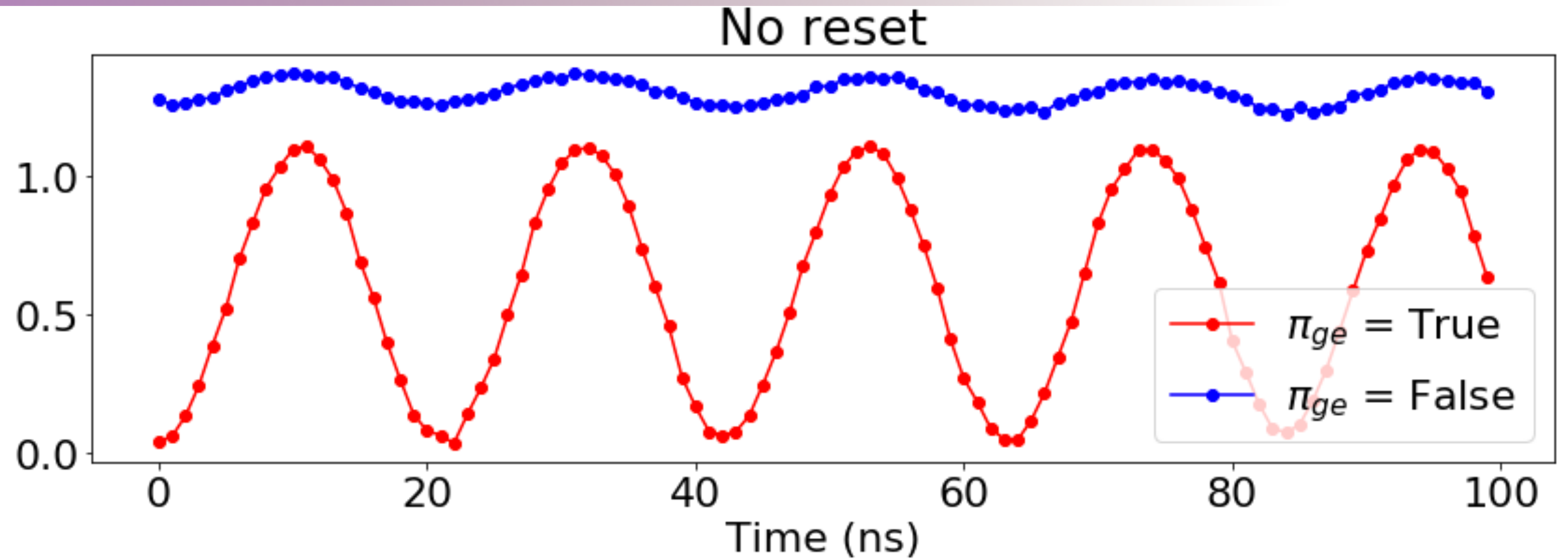
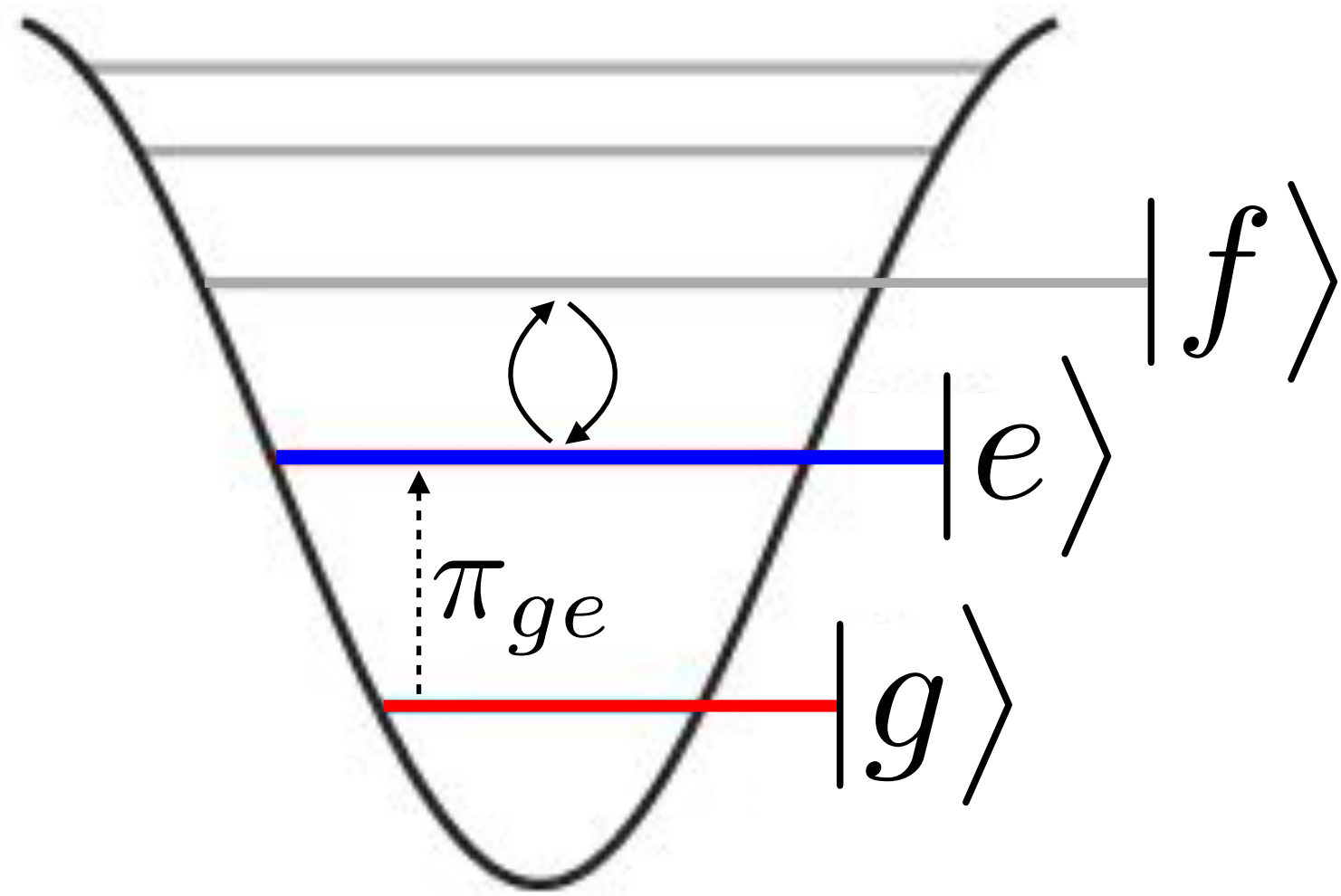


Reset qubit between measurements

- $P(\text{decay}) \sim 9\%$
- $P(\text{heating}) \sim 0.4\%$



Qubit Spurious Excitations Produce Dark Counts

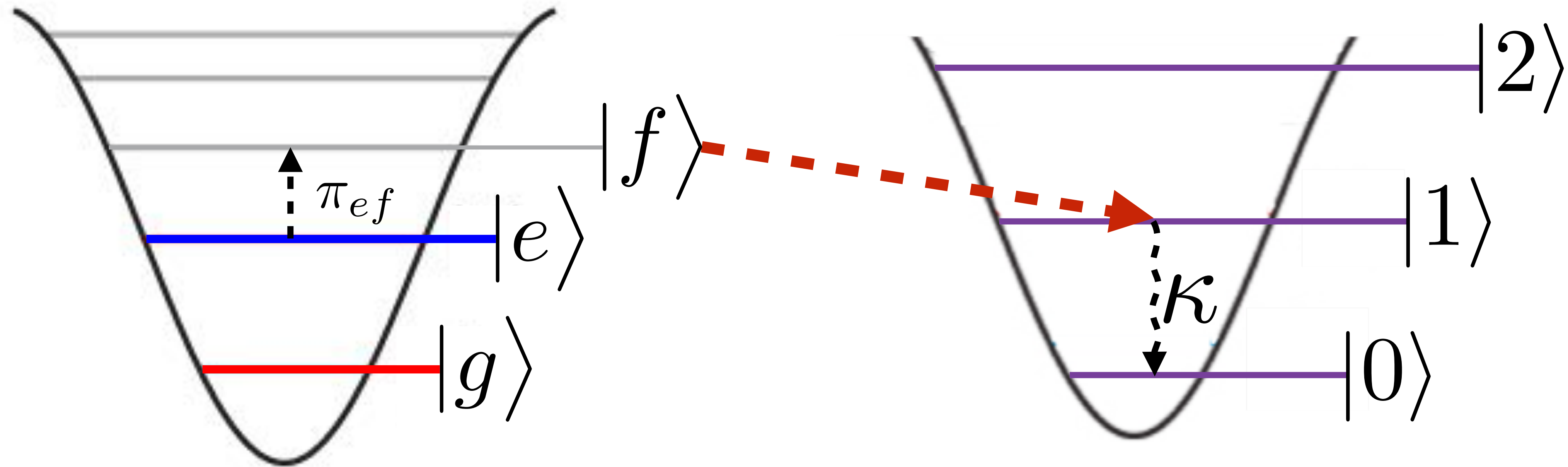


Ratio of oscillation
amplitudes

=

Ratio of ground/excited
state populations

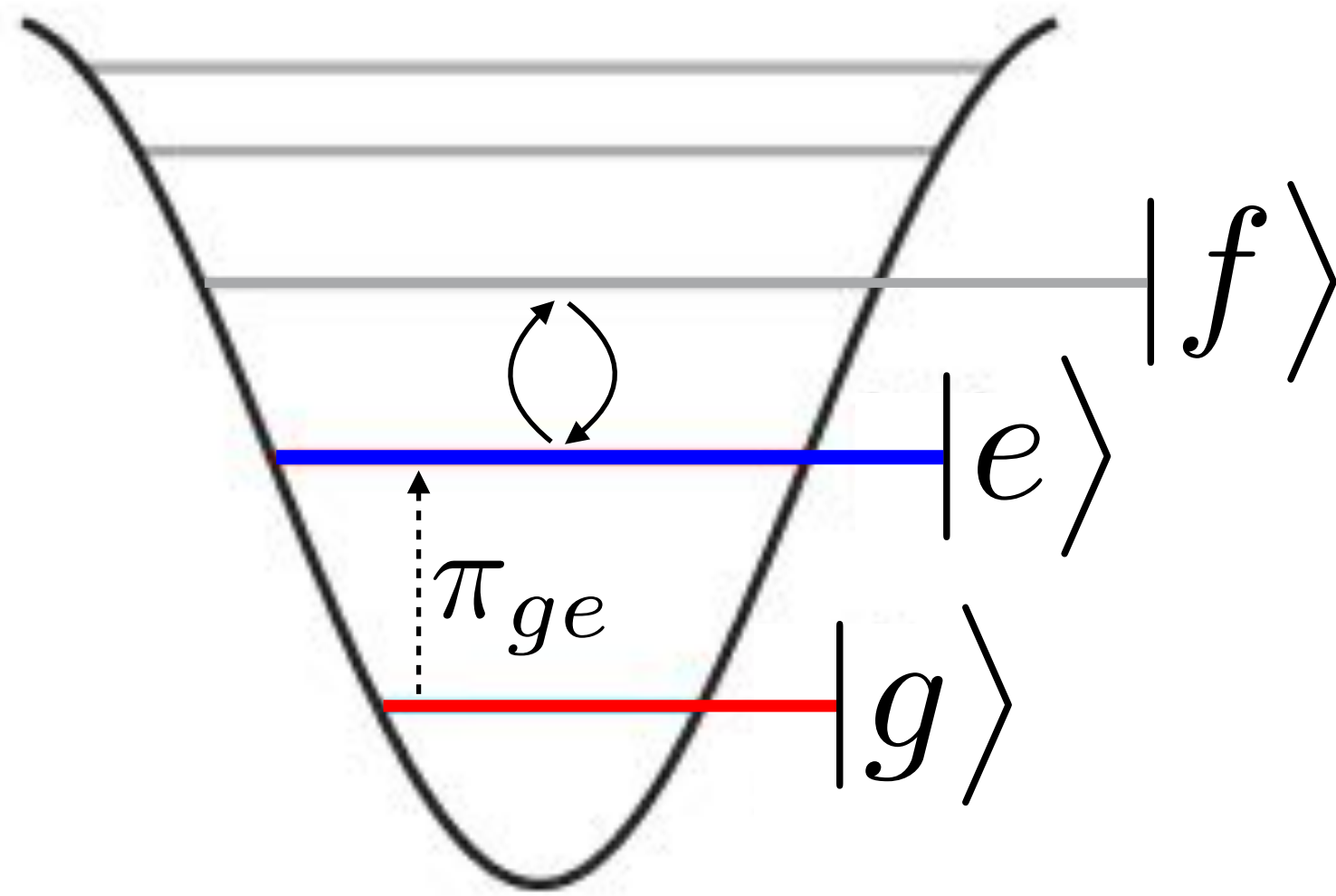
Cool Qubit with Lossy Resonator Mode



Qubit

Lossy Resonator

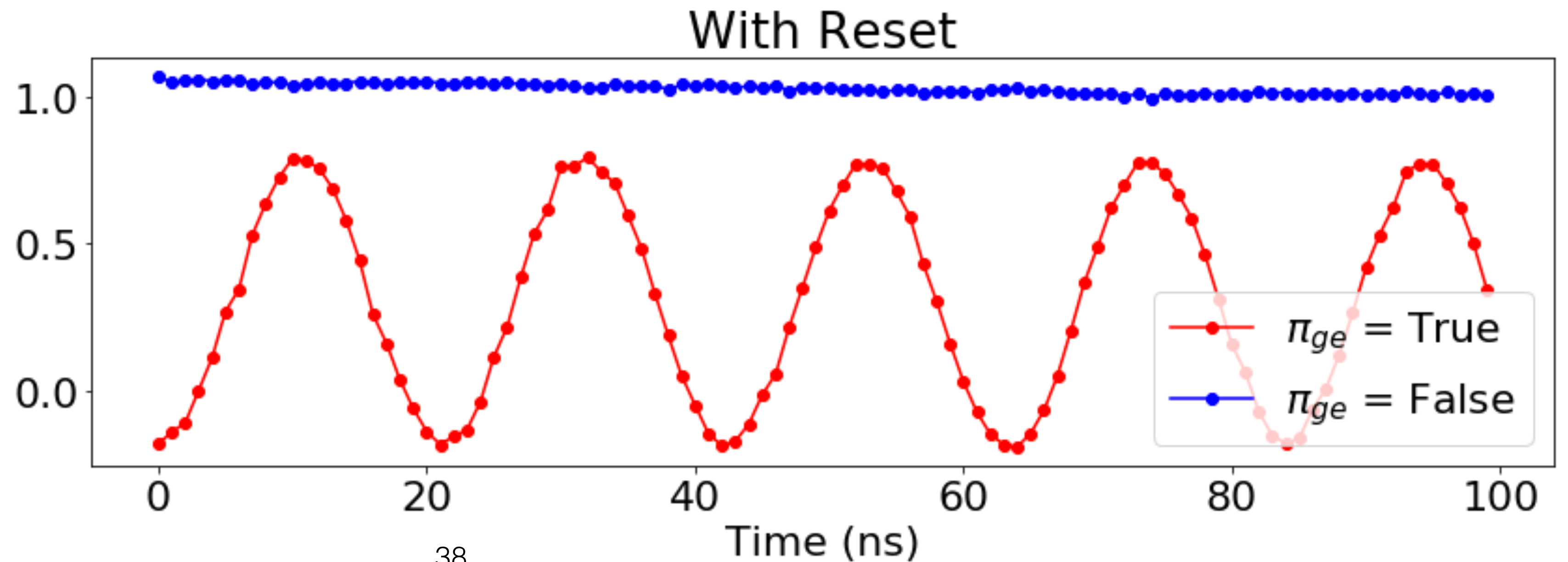
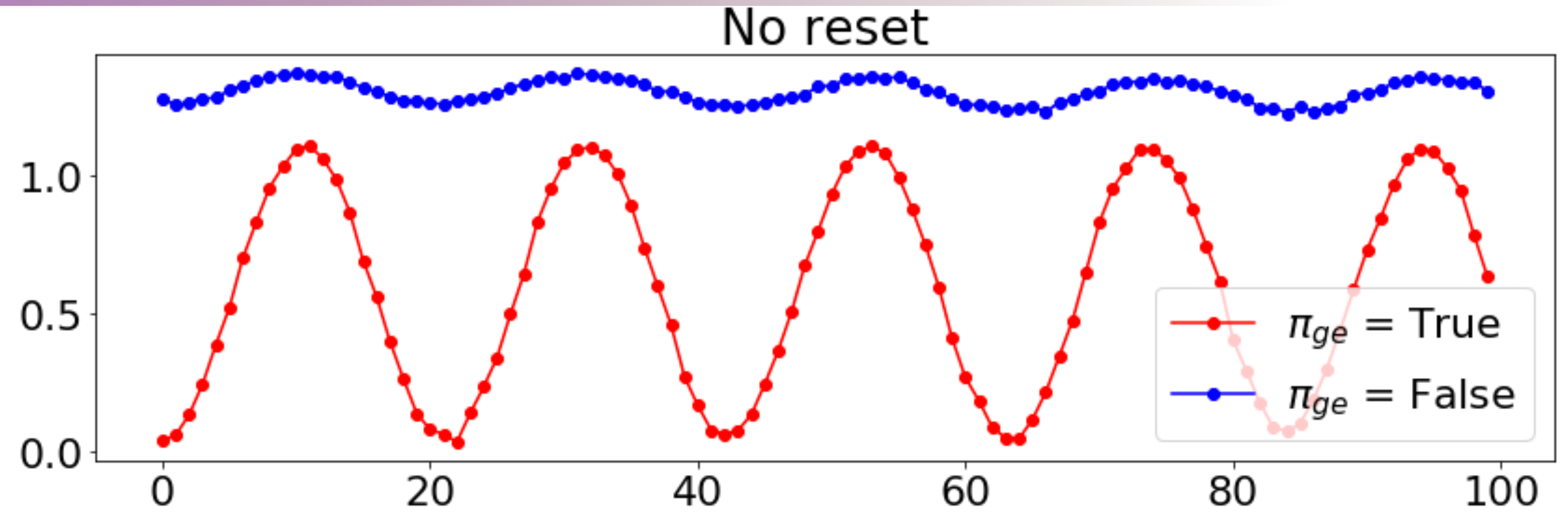
Qubit Spurious Excitations Suppressed with Cooling



Ratio of oscillation
amplitudes

=

Ratio of ground/excited
state populations



Suppressing Spurious Qubit Excitations

