# Searching for dark matter with superconducting qubits


Akash V. Dixit

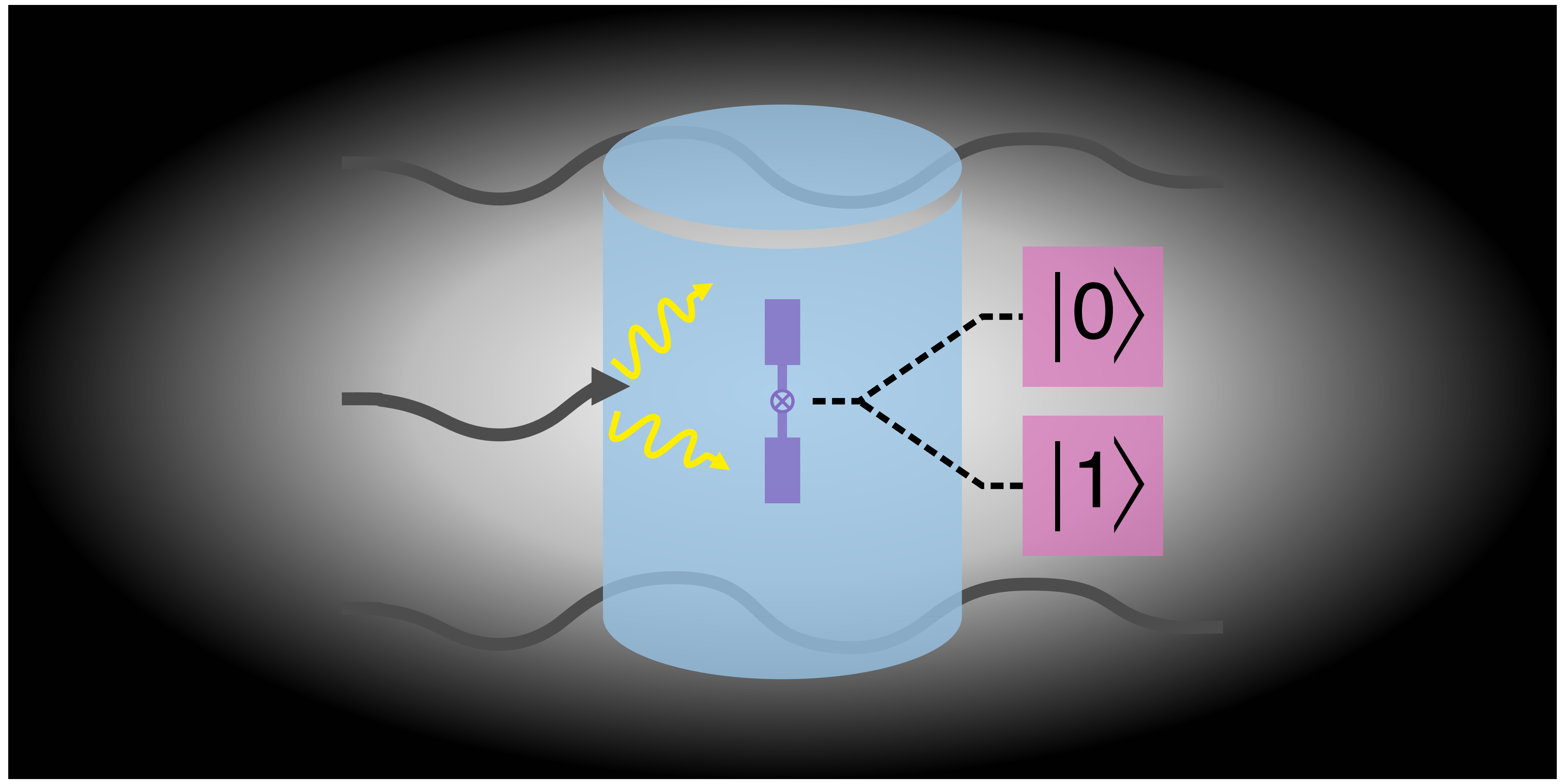
Srivatsan Chakram, Kevin He, Ankur Agrawal, Aaron Chou, David Schuster

University of Chicago

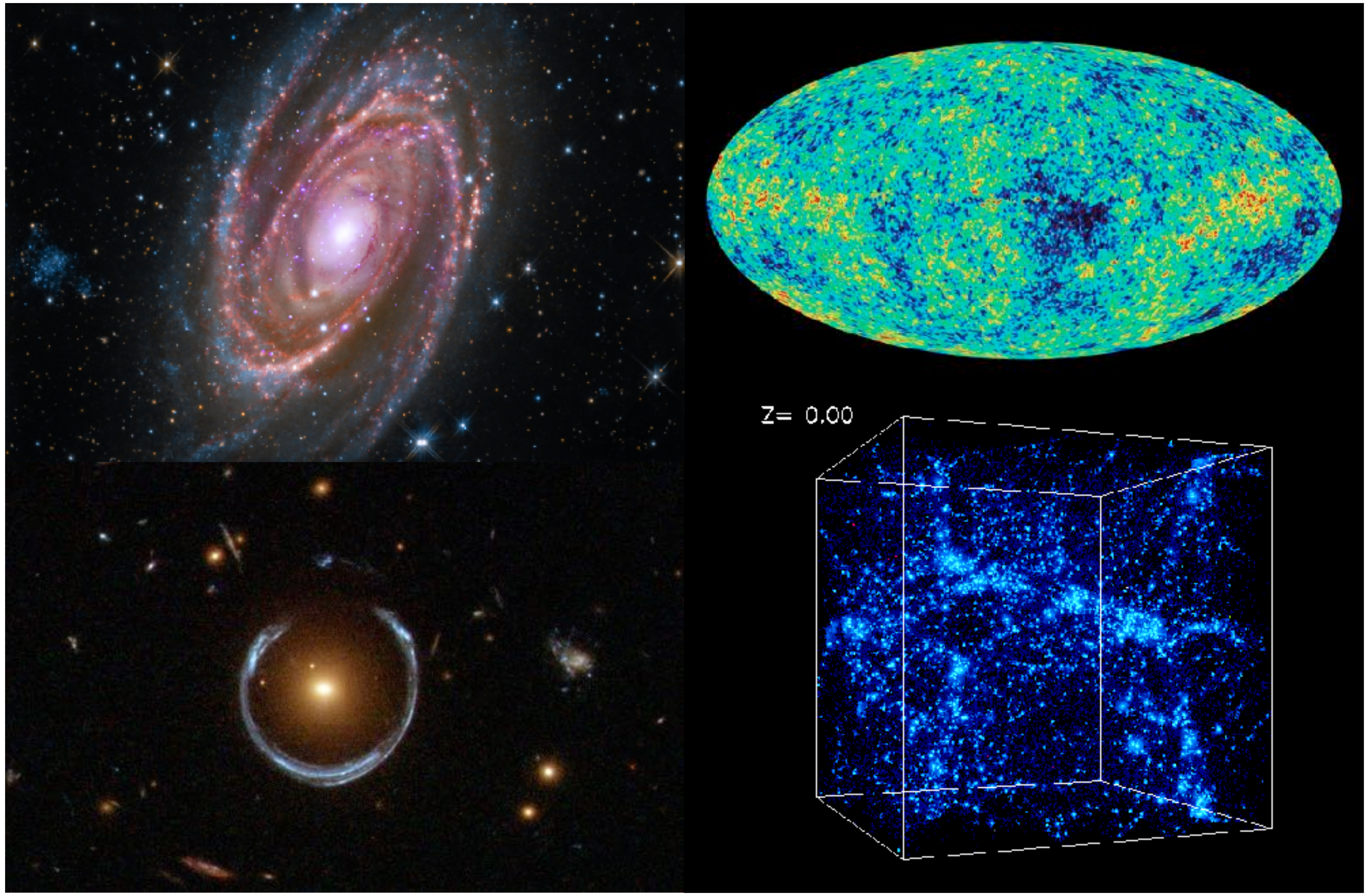
avdixit@uchicago.edu

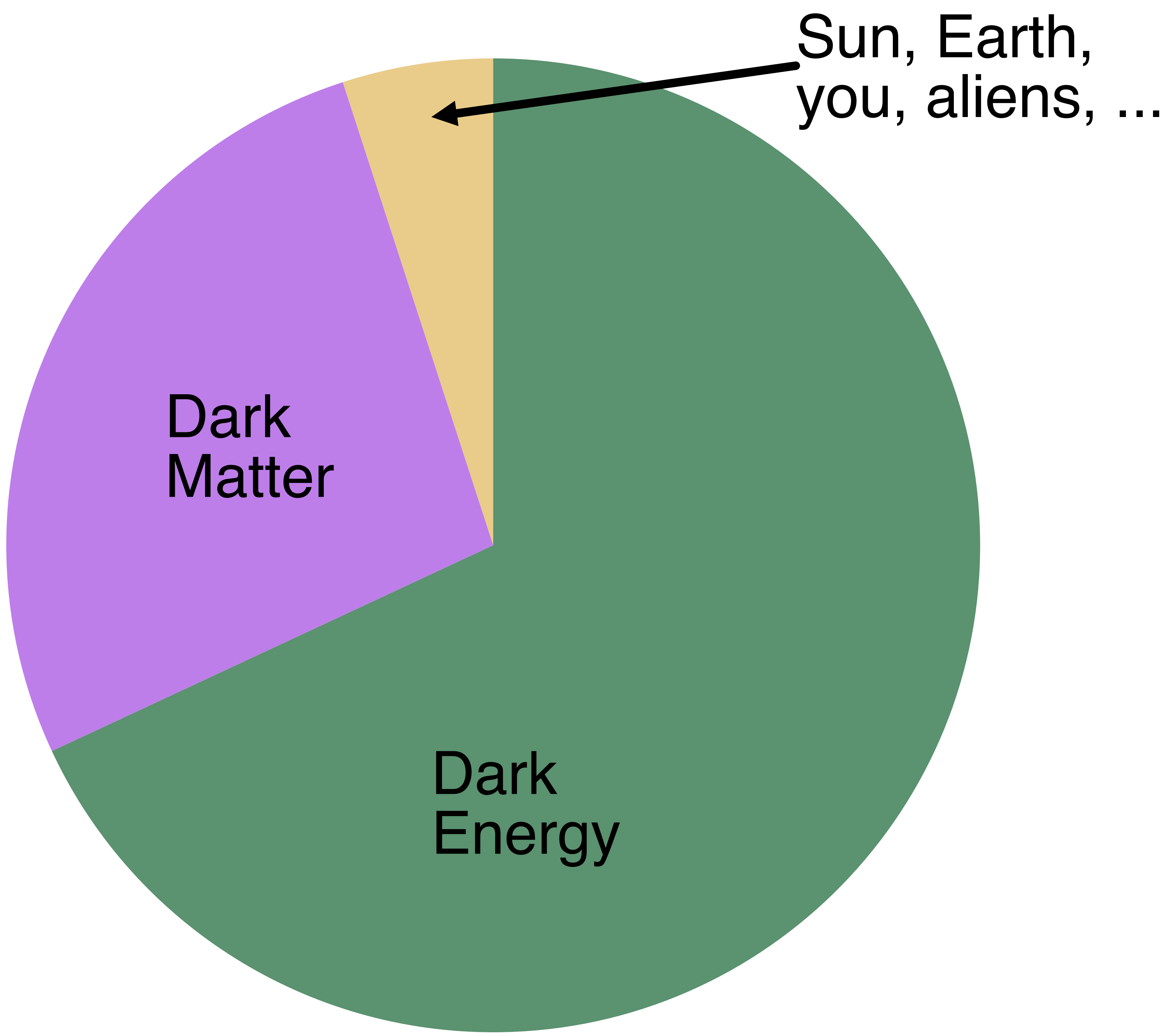
# Outline of talk

- Dark matter and detection mechanisms
- 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
- Improvements and future experiments

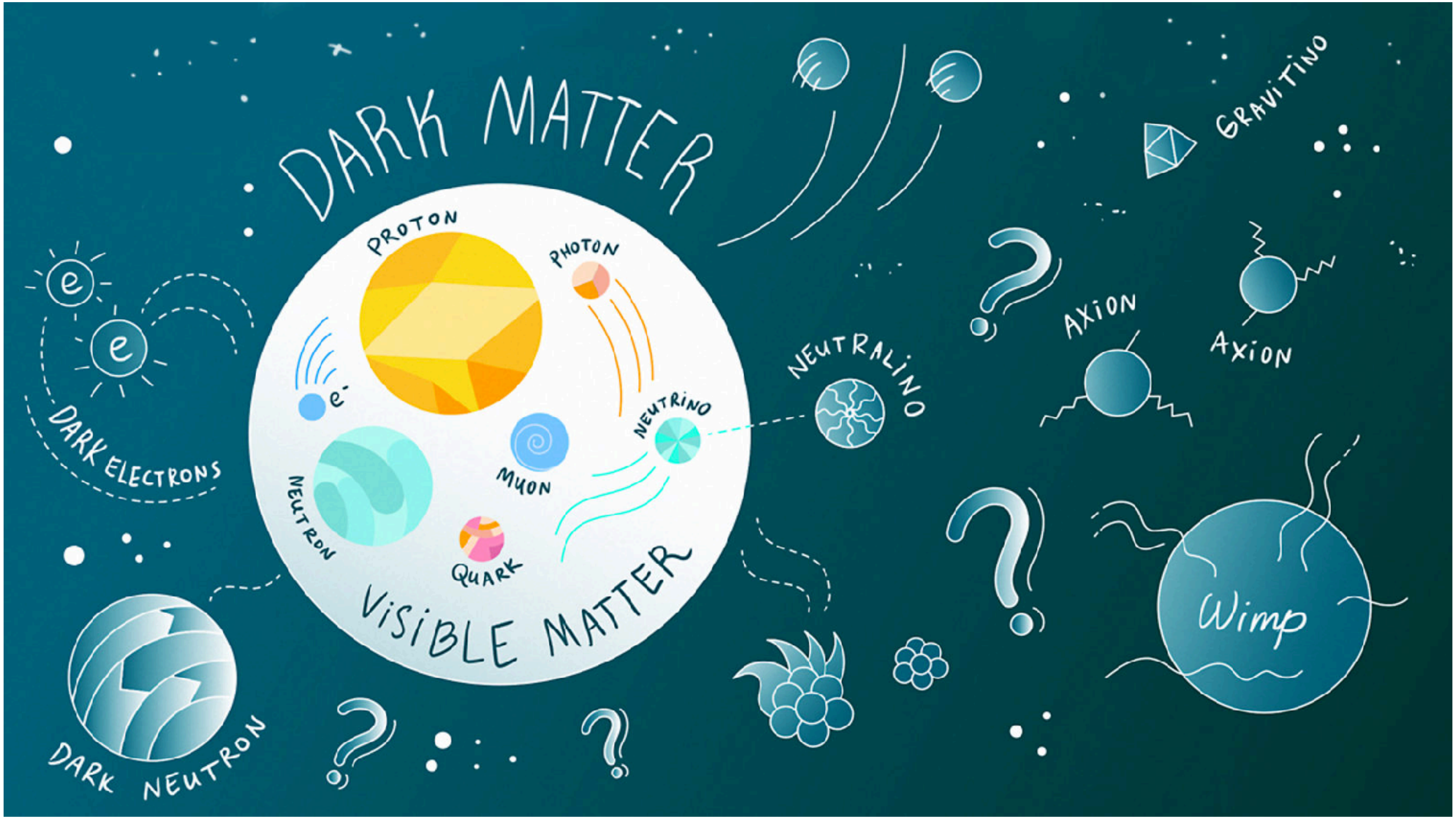


# What's the deal with dark matter



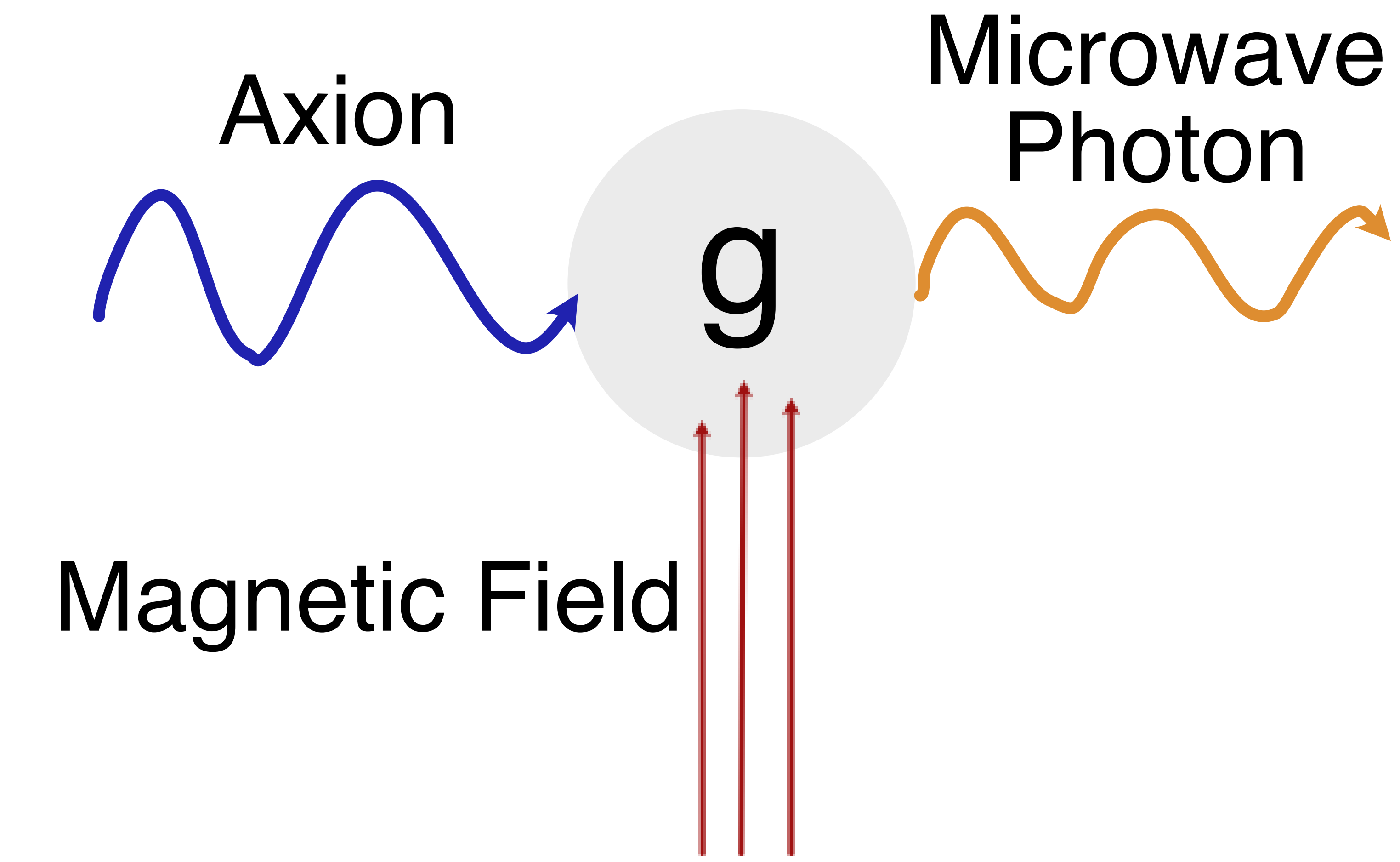



# Lots of ideas for what dark matter is

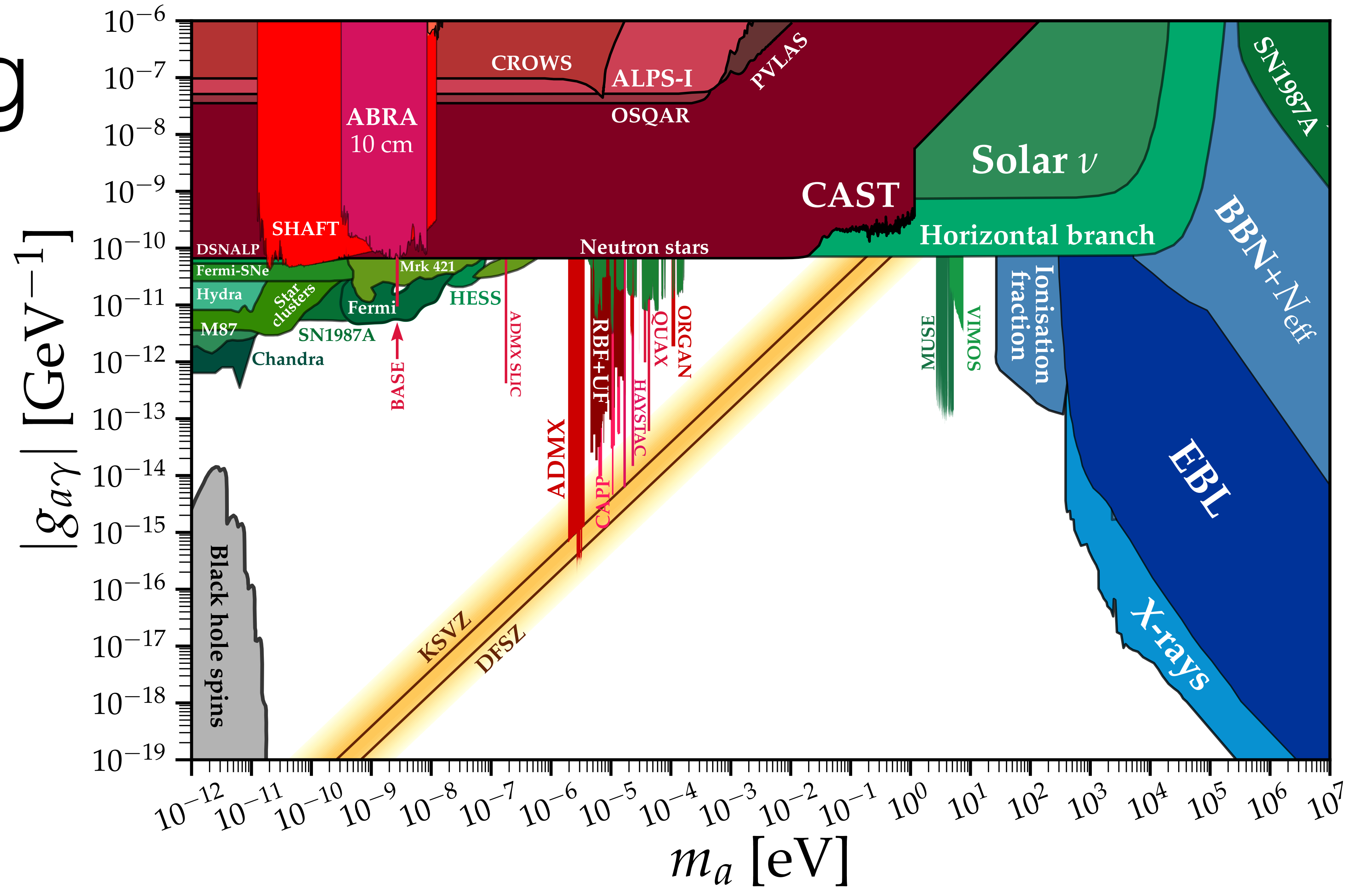


# Light dark matter

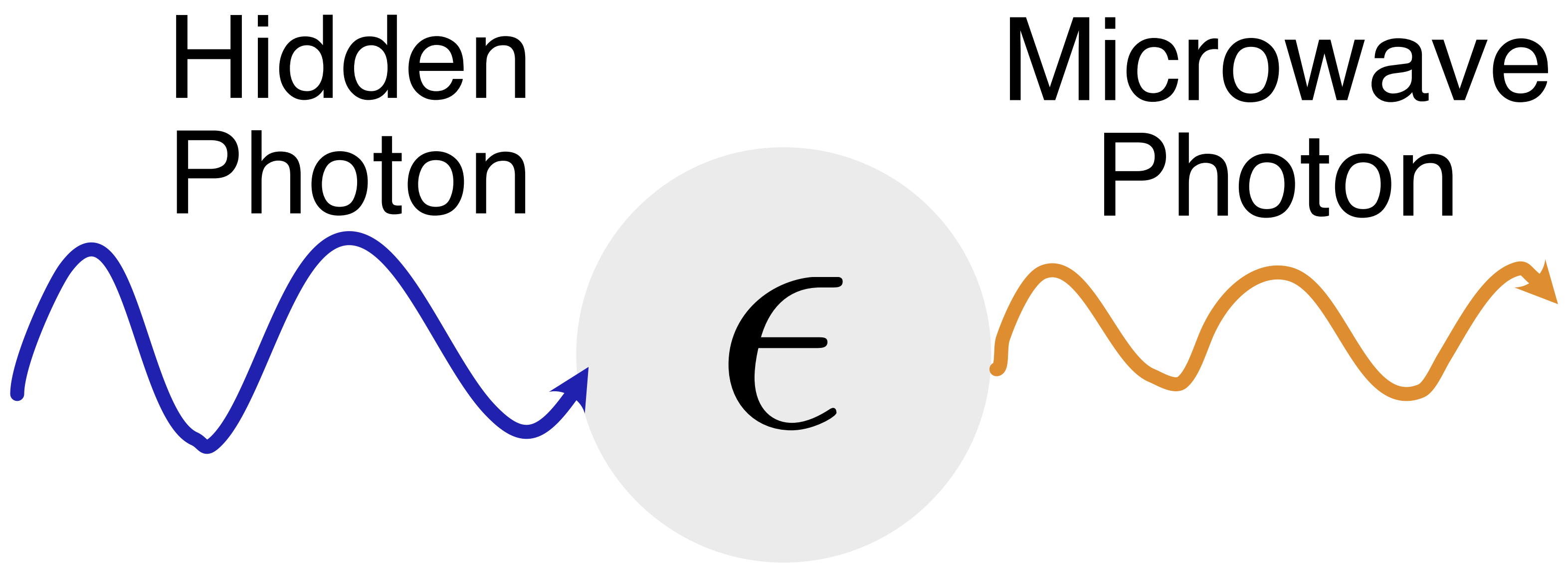
## Axion - Photon coupling



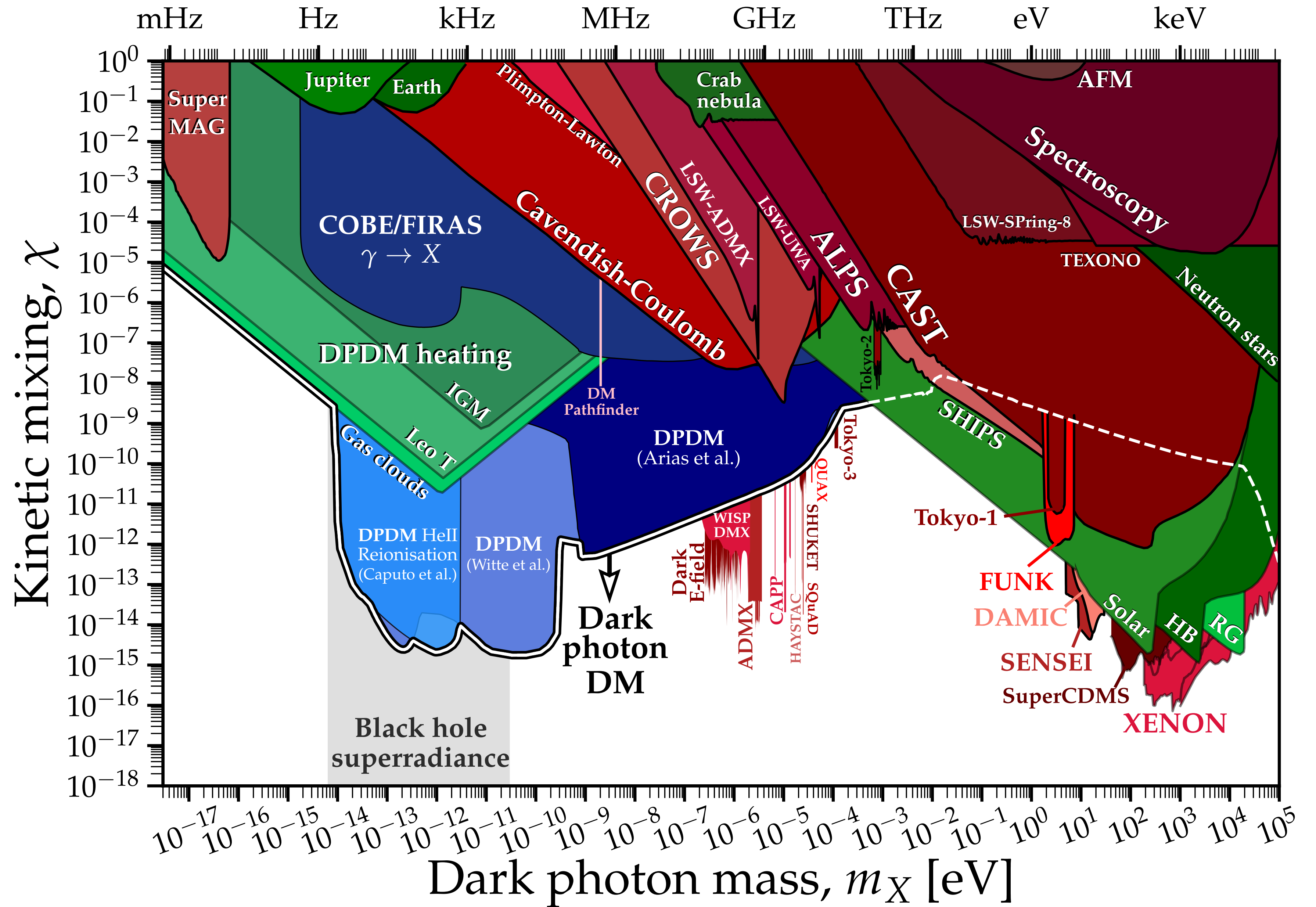

Peccei, Quinn PRL **38** (25): 1440–1443
Preskill, Wise, Wilczek, PRL 120B, 127
Abbott, Sikivie, PRL 120B, 133
Dine, Fischler PRL 120B, 137



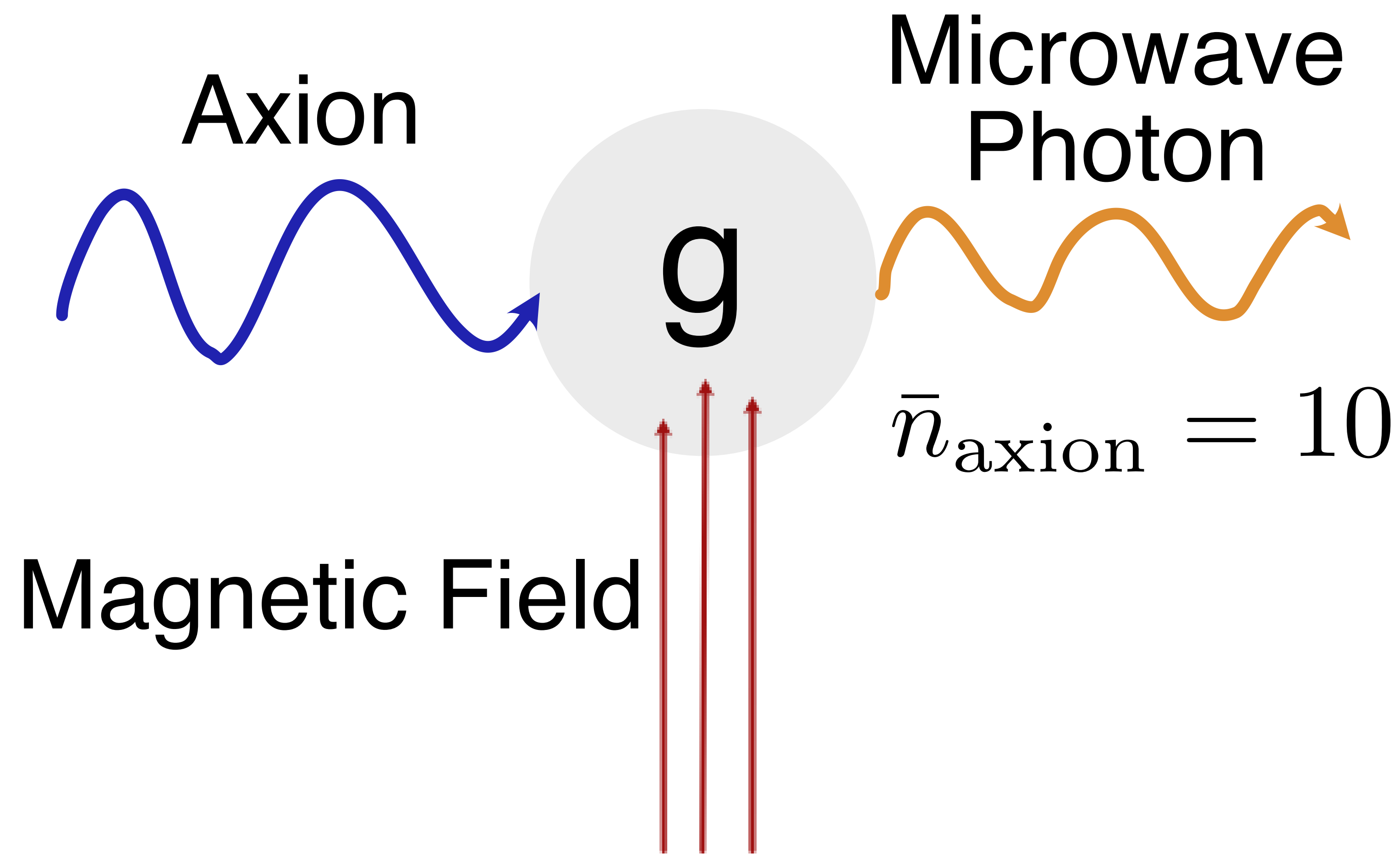

## Hidden photon - Photon mixing



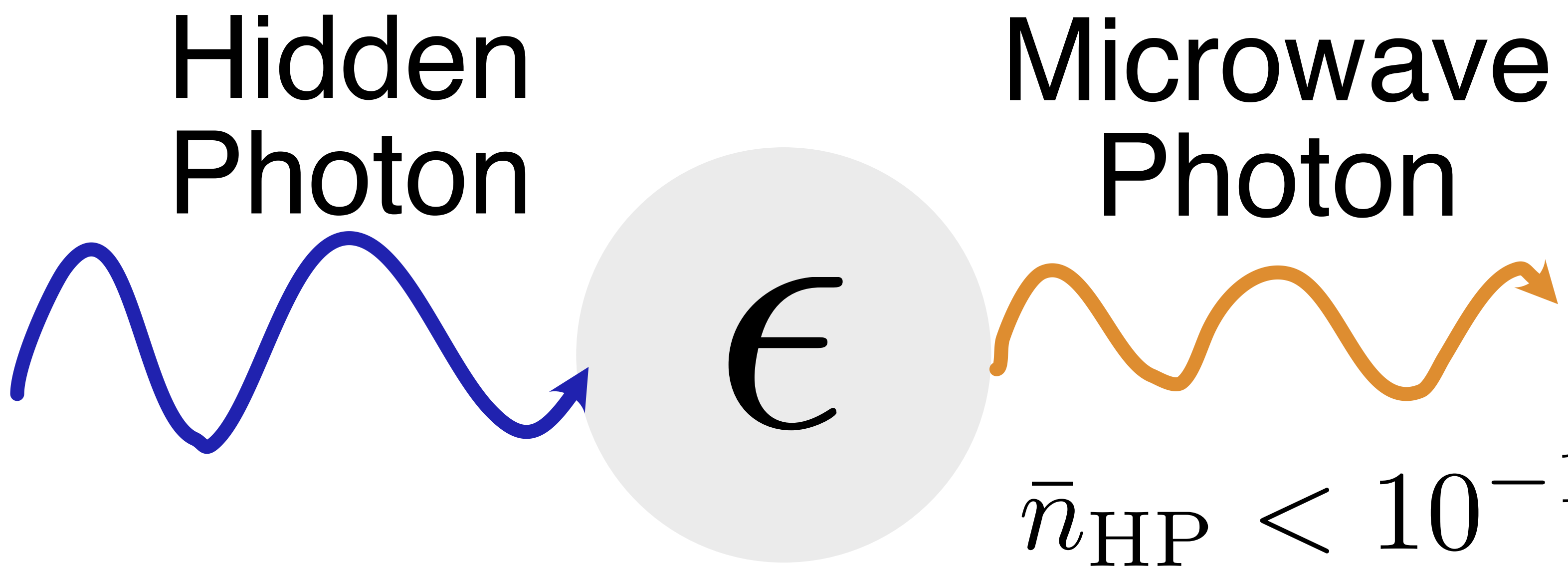

Arias et. al. J. Cosmol. Astropart. Phys. 06 013
Graham, Mardon, Rajendran, PRD 93, 103520



# How dark matter might couple to electromagnetism

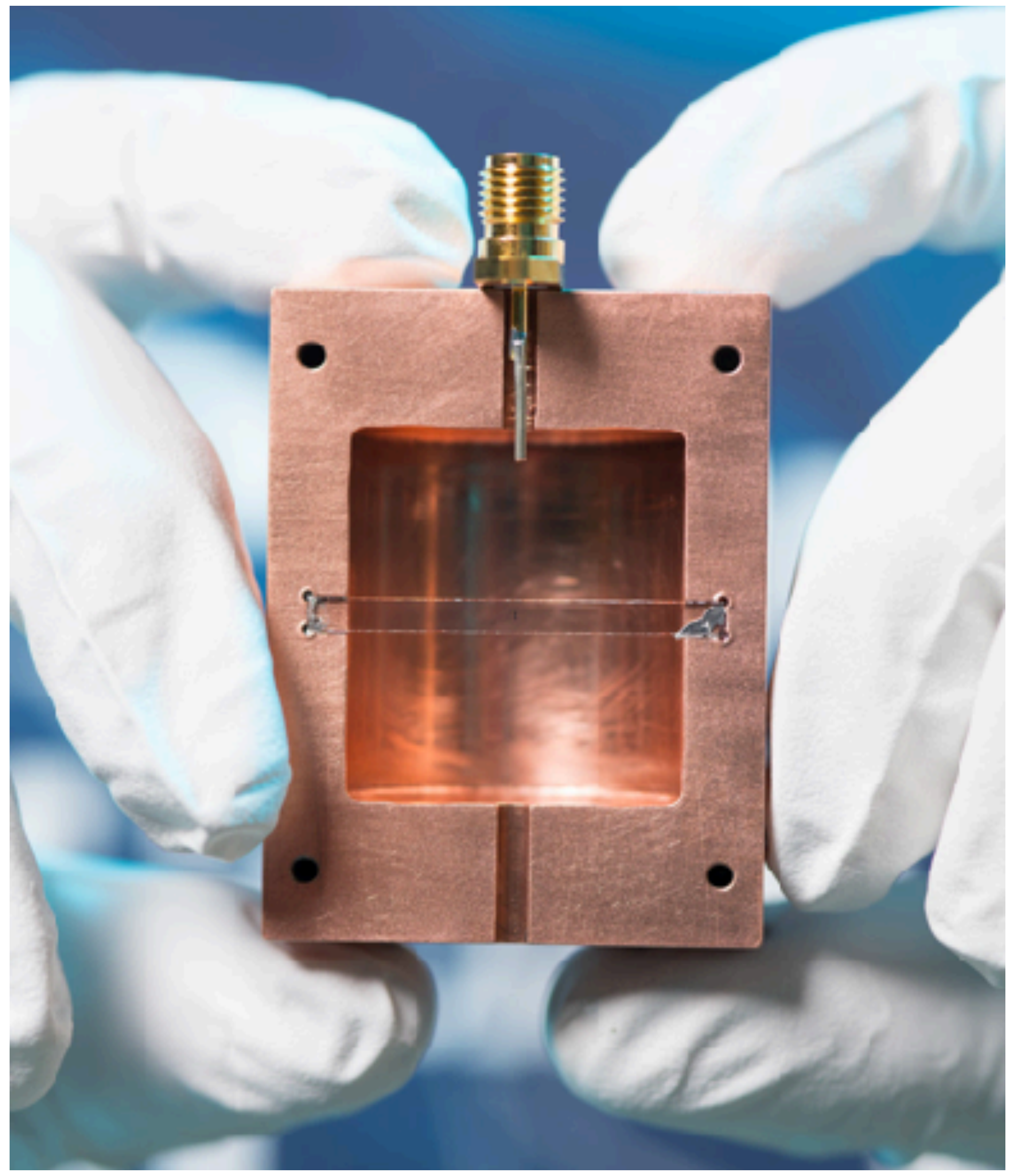



$\bar{n}_{\mathrm{axion}} = 10^{-8} - 10^{-5}$




$\bar{n}_{\mathrm{HP}} < 10^{-1}$

Resonant microwave cavity to capture signal

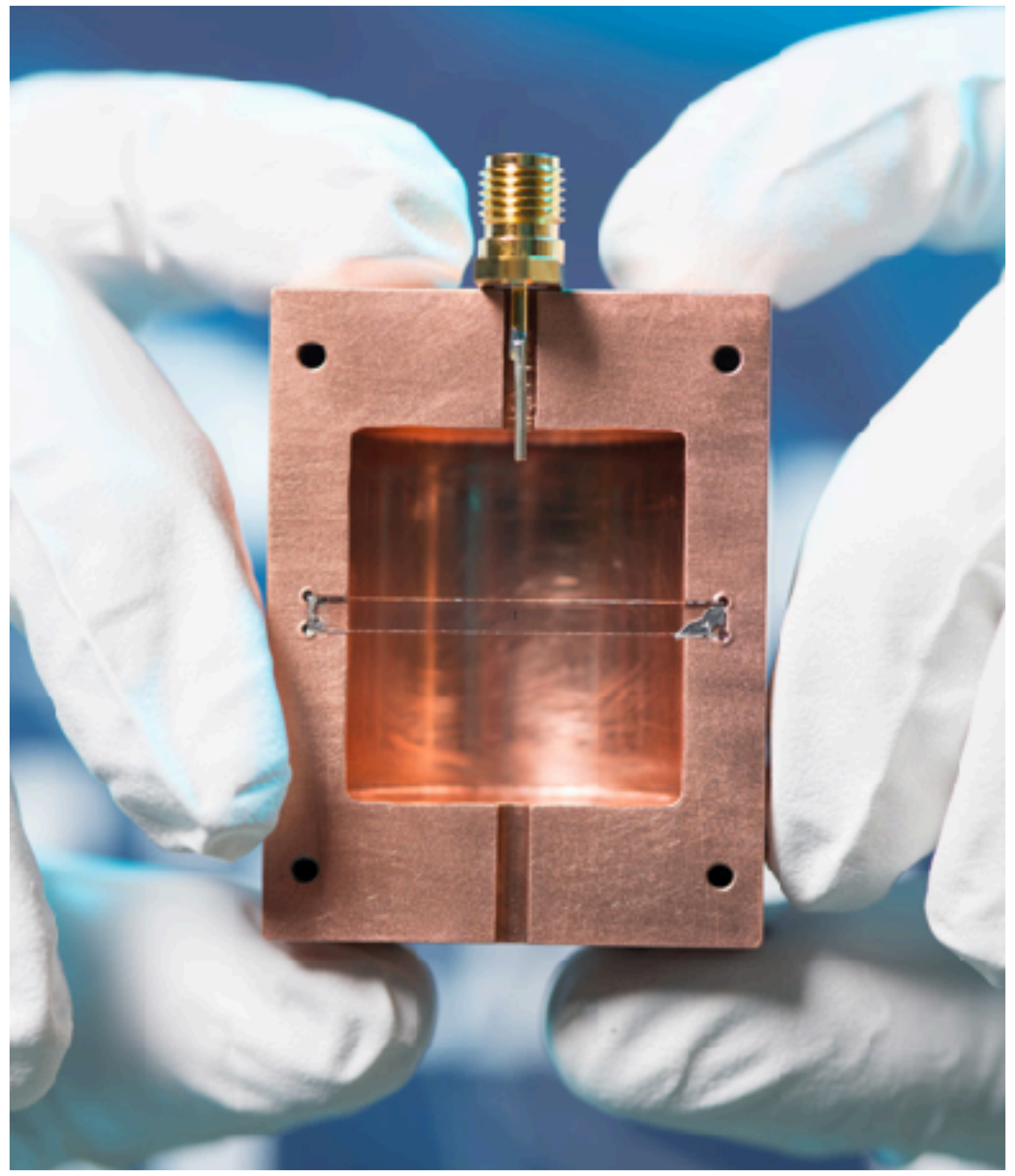


Sikivie, PRL 51, 1415 (1983).

# Dark matter signal scales poorly with frequency

$$\bar{n}_{\rm DM} \sim V \sim \lambda^3 \sim \frac{1}{f^3}$$

Signal scales with volume of cavity



Current searches are probing mass ranges $O(1\mu eV)$

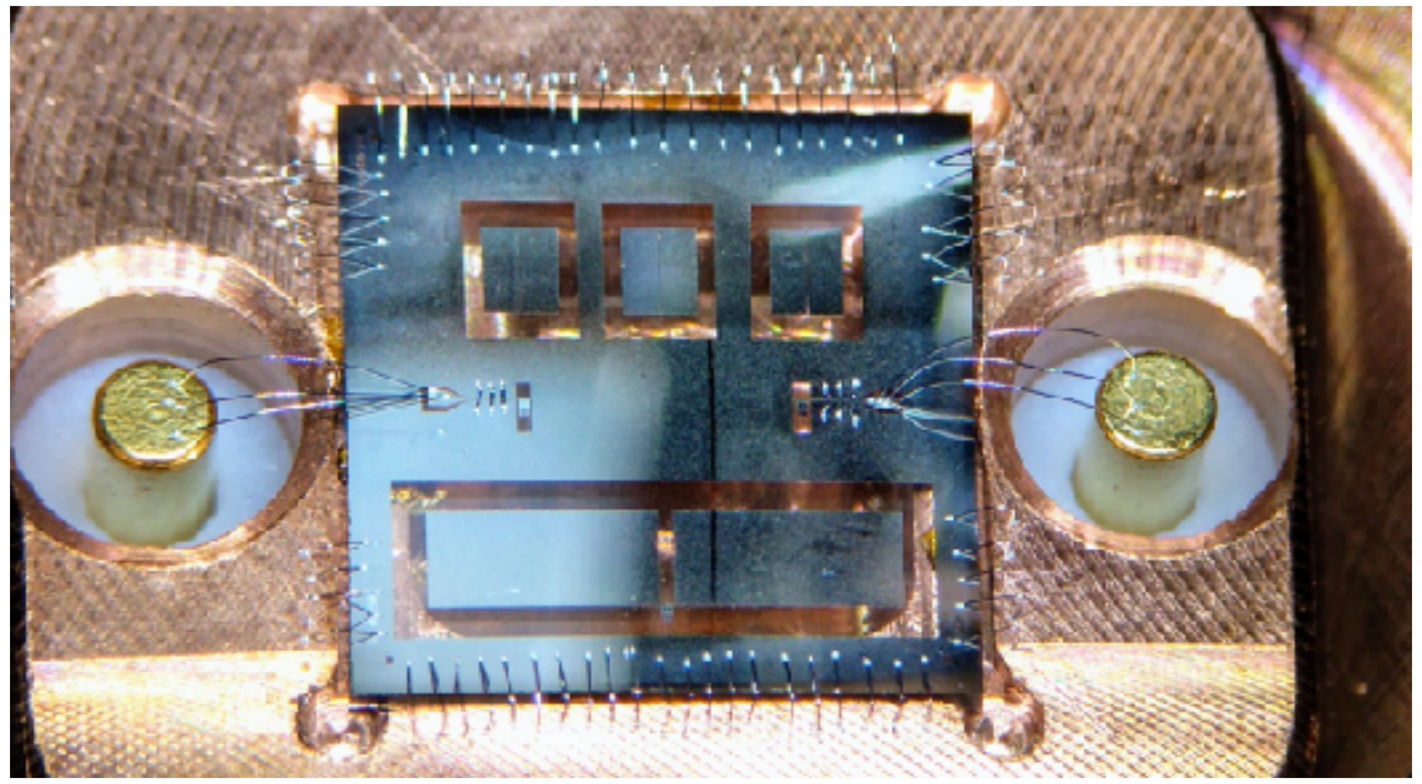
$V \sim 1/(2\mu eV)^3 = 1/(500\text{MHz})^3$

To probe higher mass ranges $O(10\mu eV)$

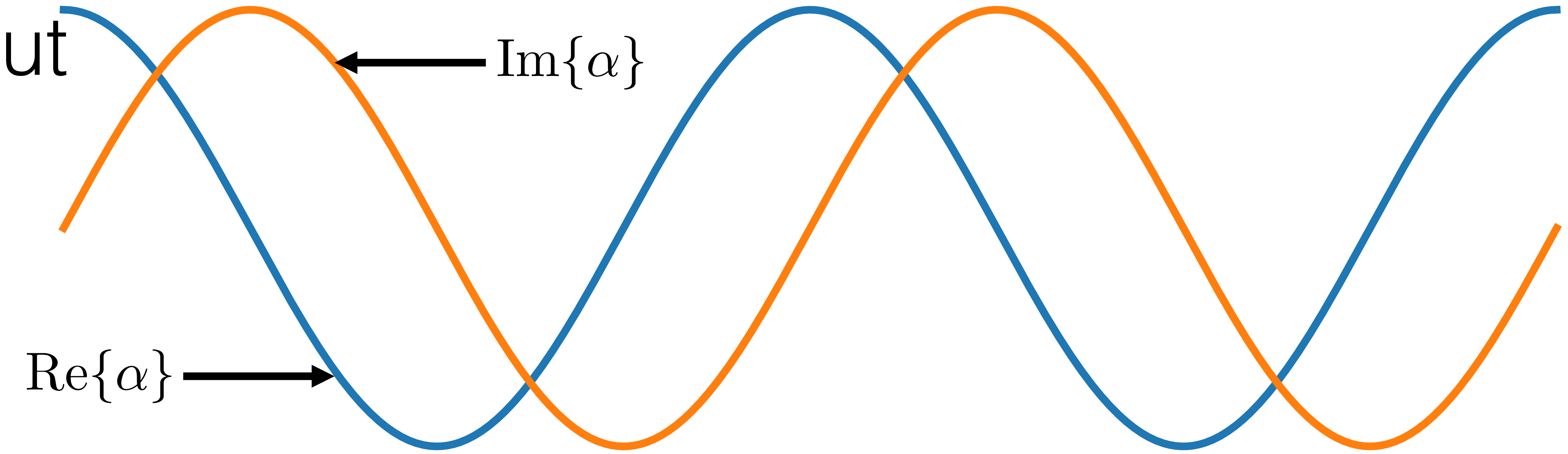
$V \sim 1/(20\mu eV)^3 = 1/(5\text{GHz})^3$

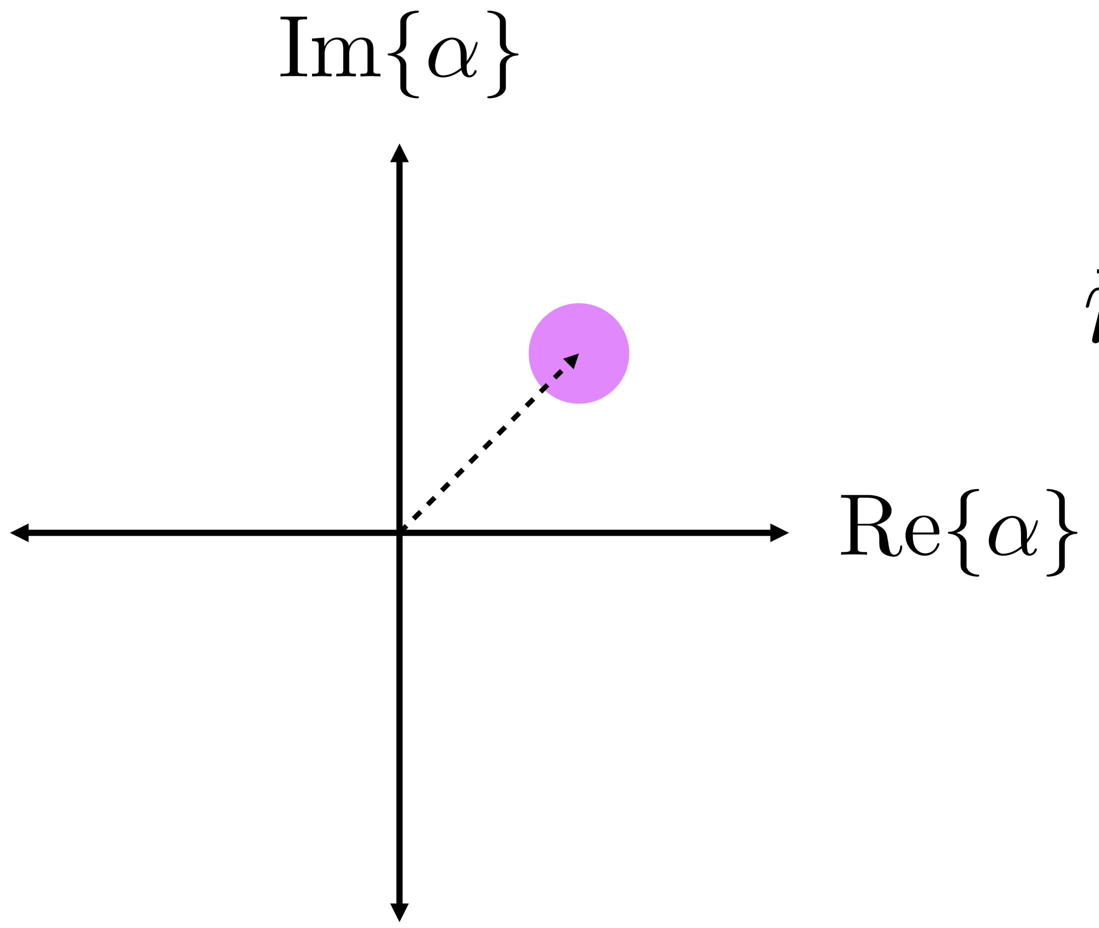
# Linear amplification noise overwhelms signal

Quantum limited amplifier for readout



Can't measure both components of field with arbitrary accuracy, Heisenberg uncertainty principle



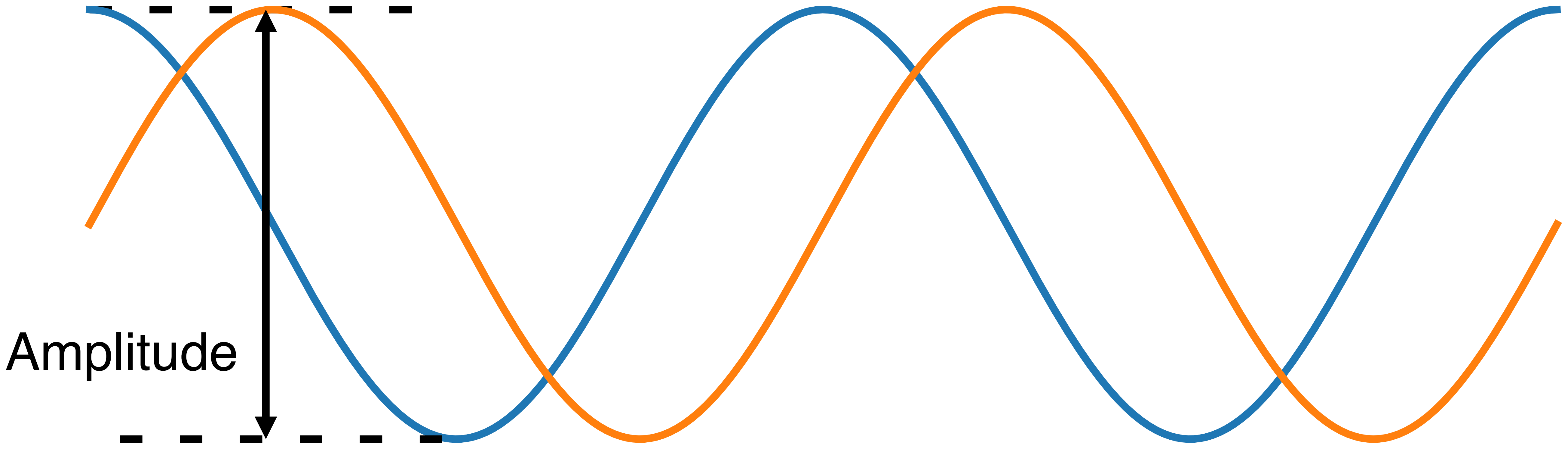

$$\bar{n}_{\mathrm{SQL}} = 1$$

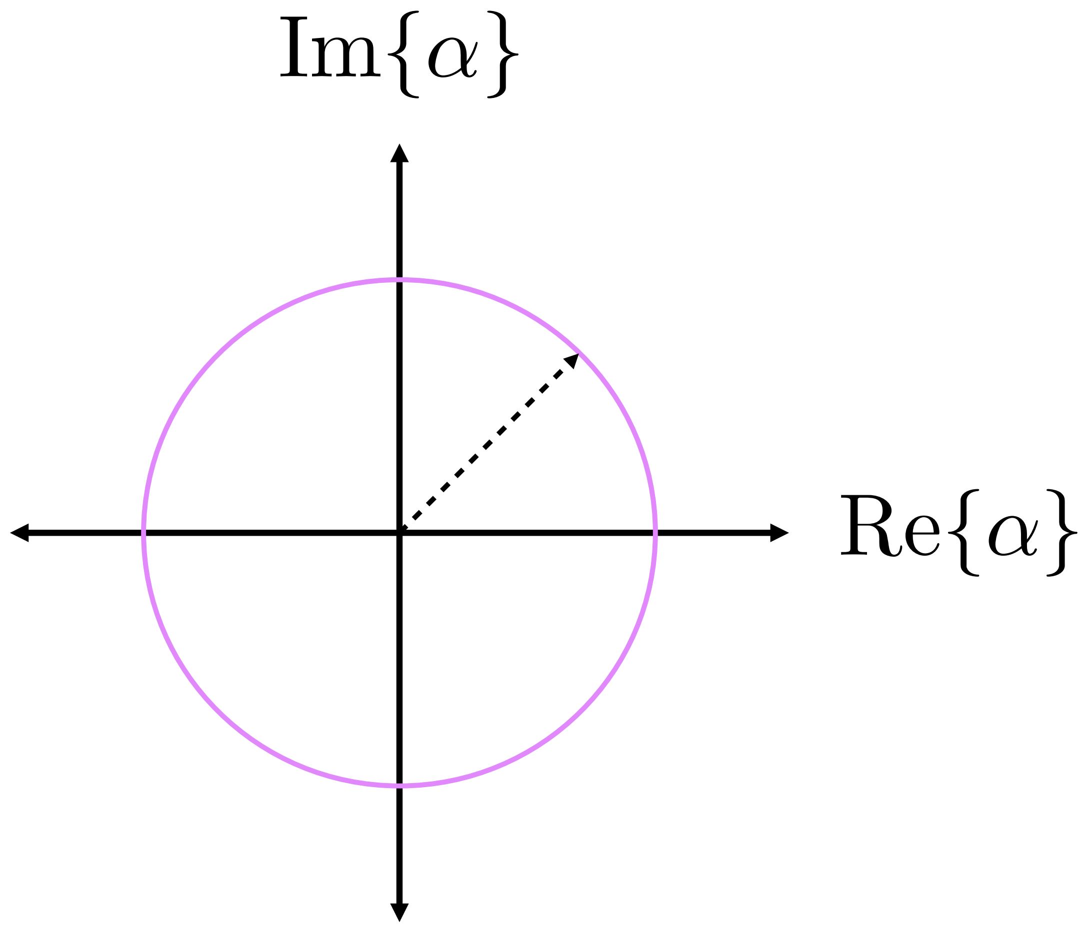
# Count photons to subvert quantum limit

Measure only signal amplitude

No information about phase

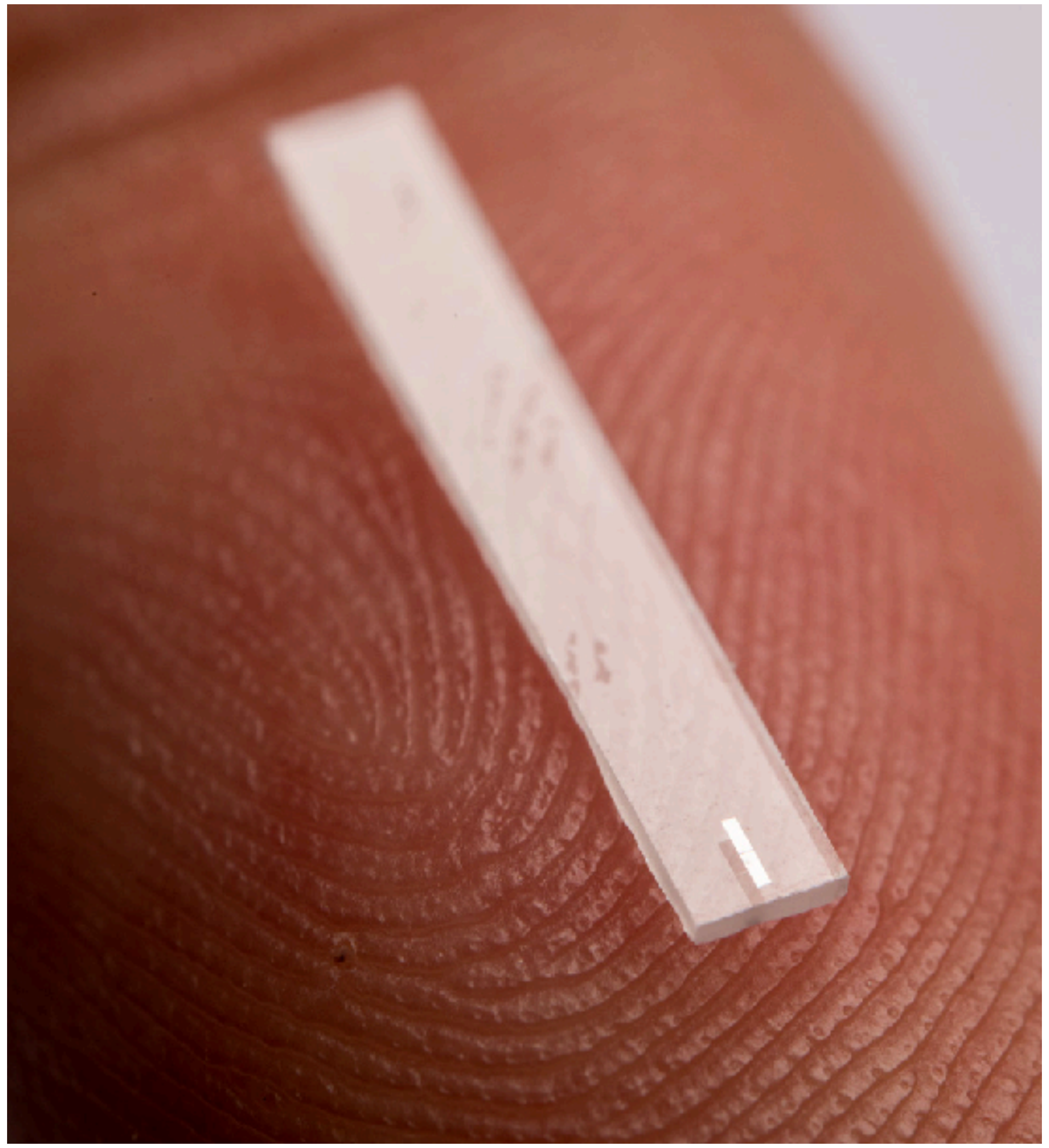
Ideal for determining if dark matter deposited a photon



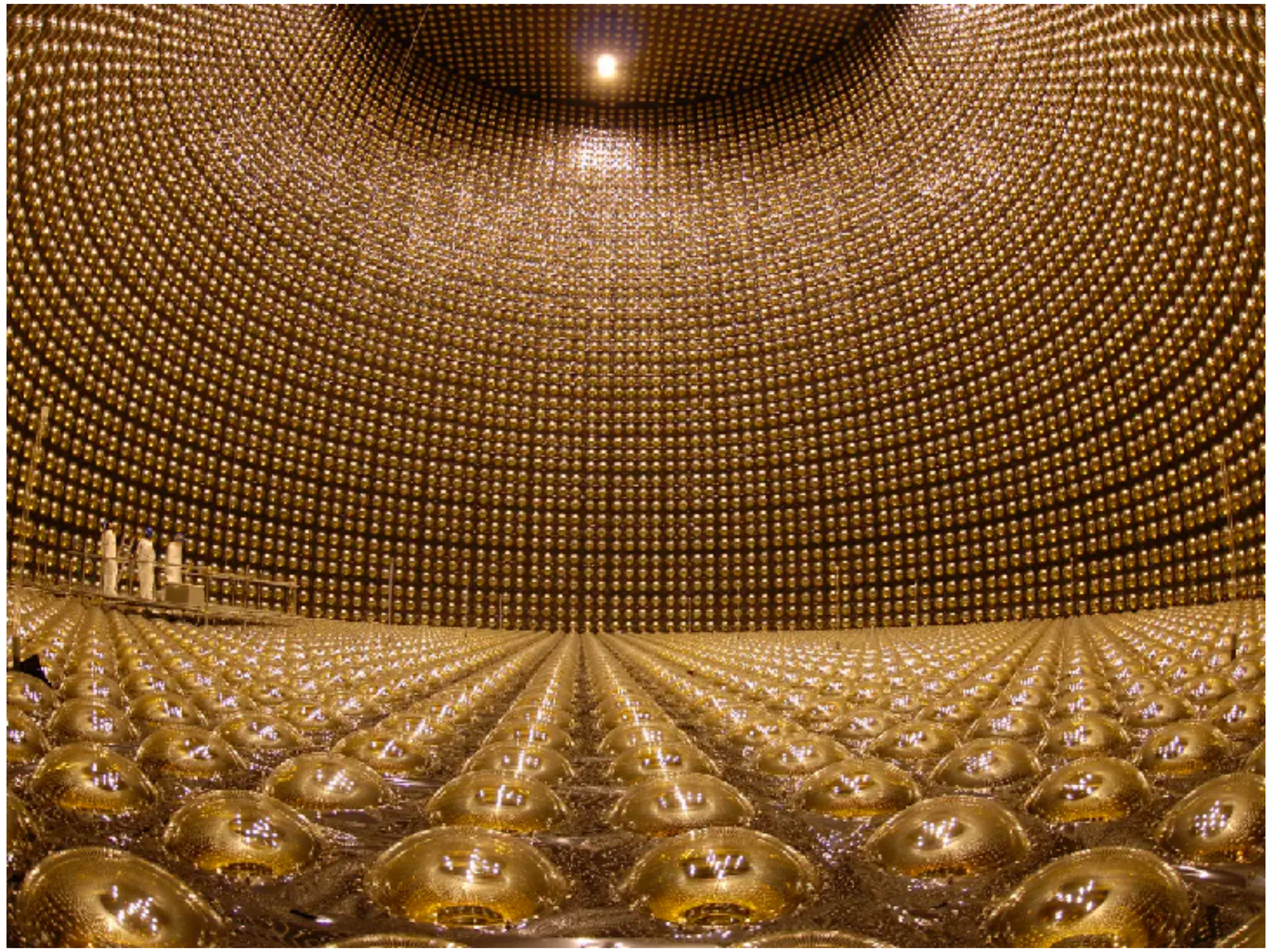



# Outline of talk

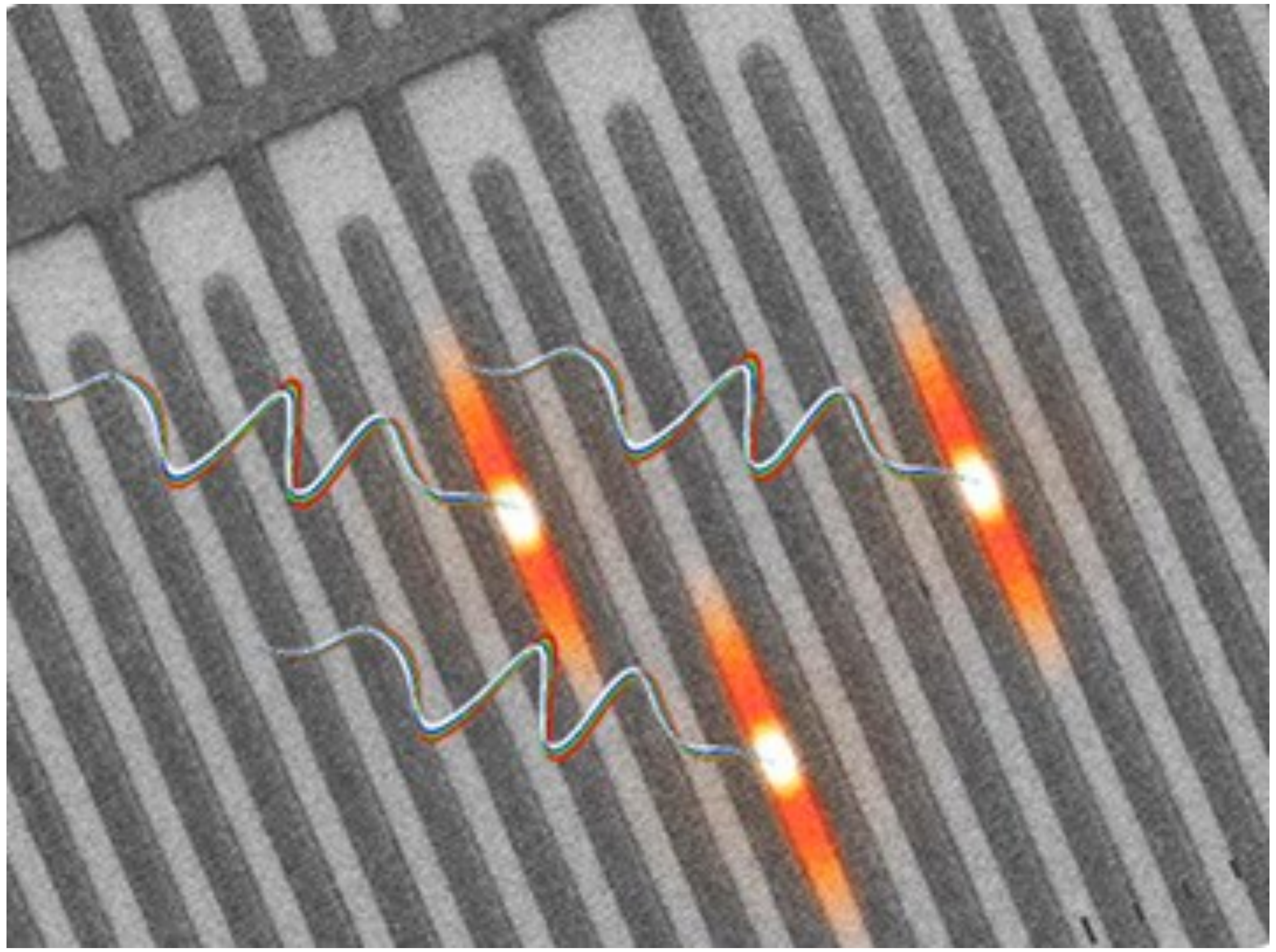
- Dark matter and detection mechanisms
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search
- Improvements and future experiments



# Photon counters exist for high energy photons

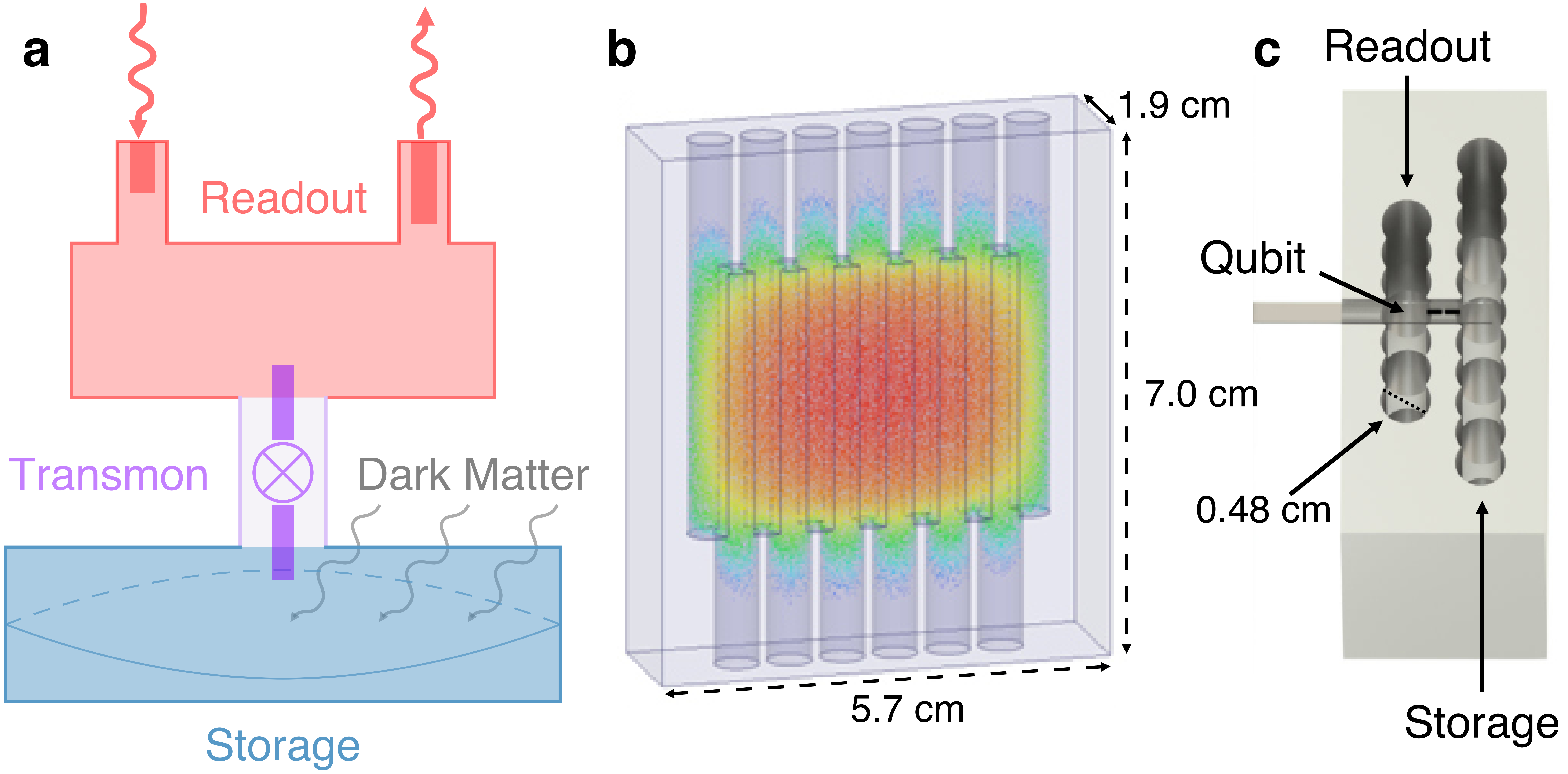


Super Kamiokande



Optica Vol. 4, Issue 12, 1534 (2017)

# Photon counting device




**Storage** 6.011 GHz

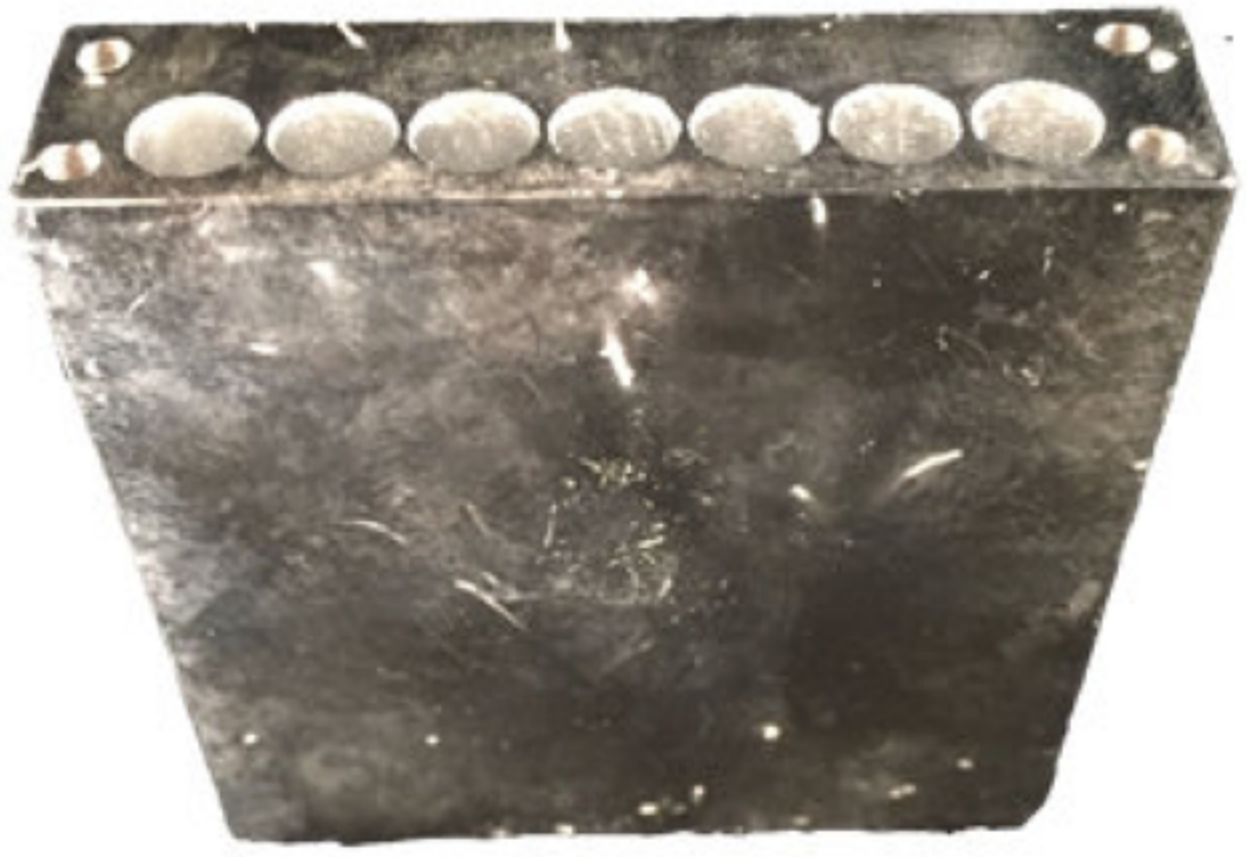
**Readout** 8.052 GHz

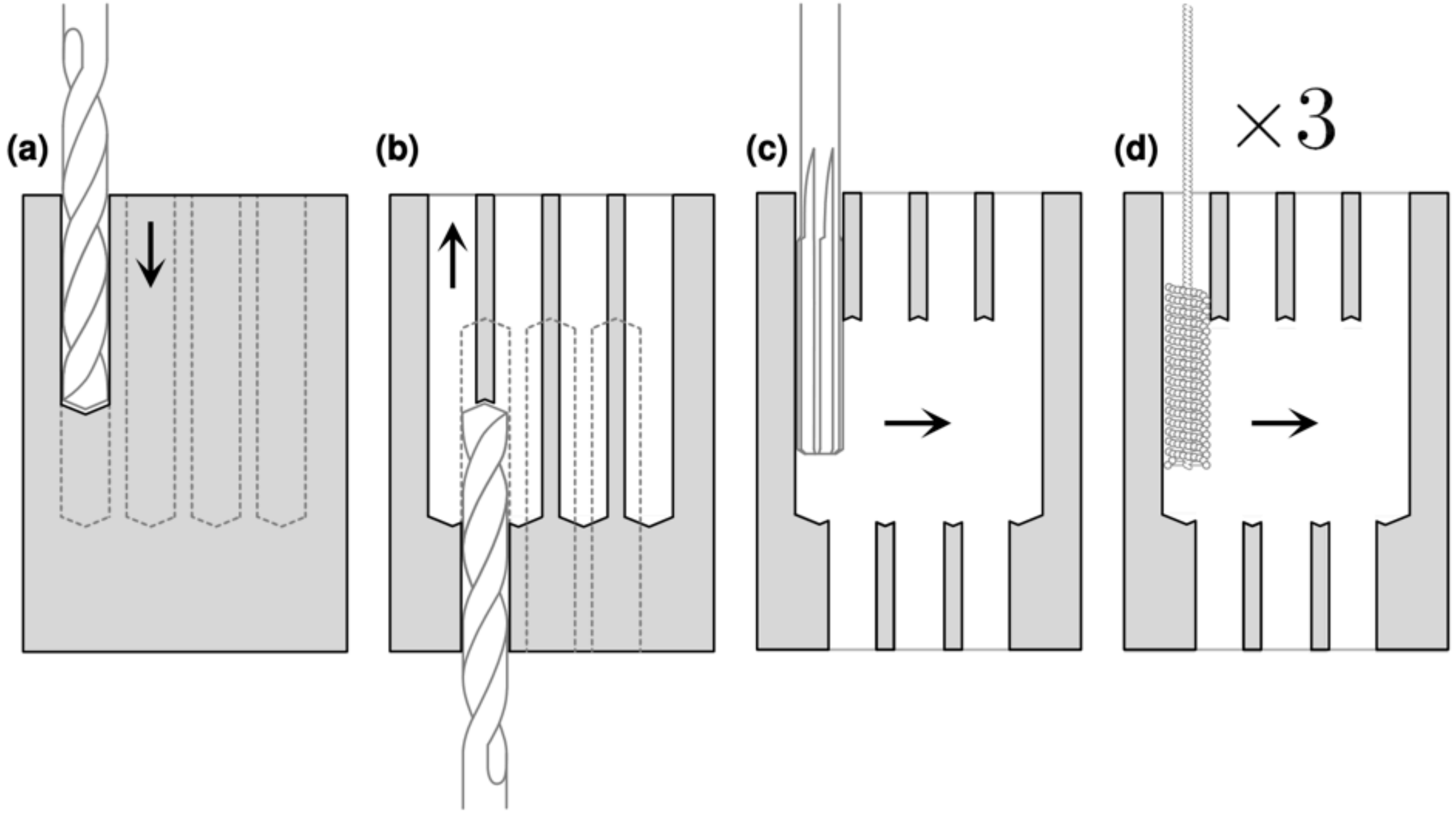
**Qubit** 4.749 GHz

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

# Building a microwave cavity

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

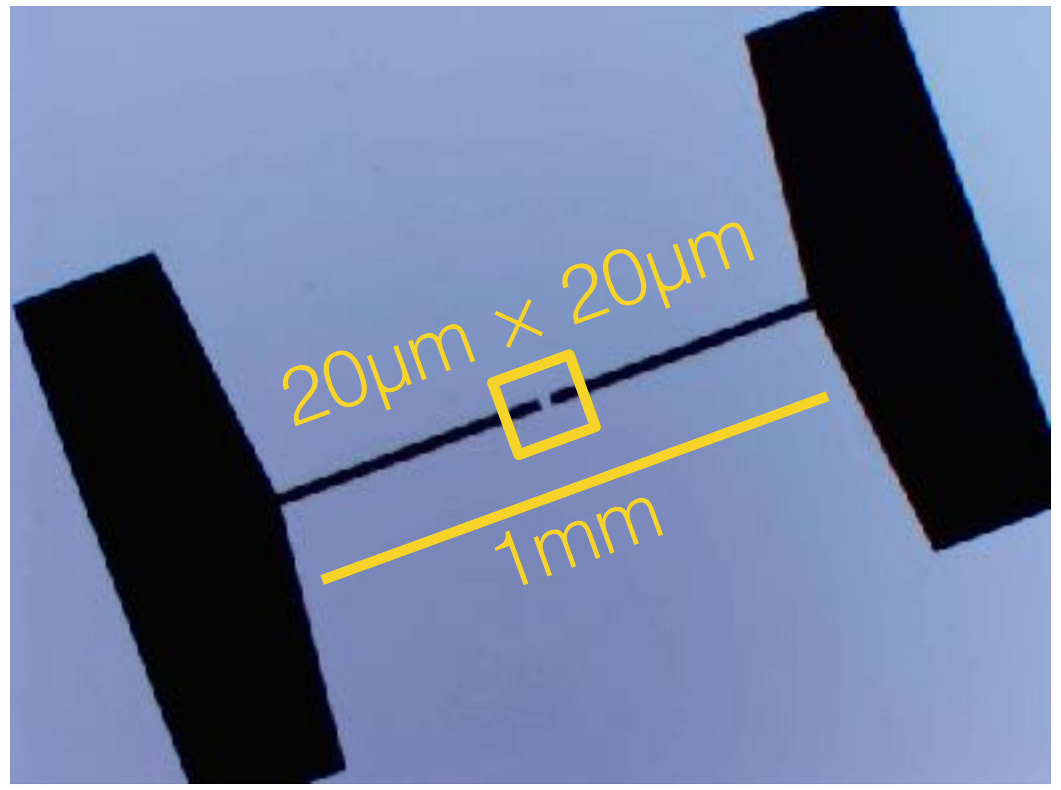




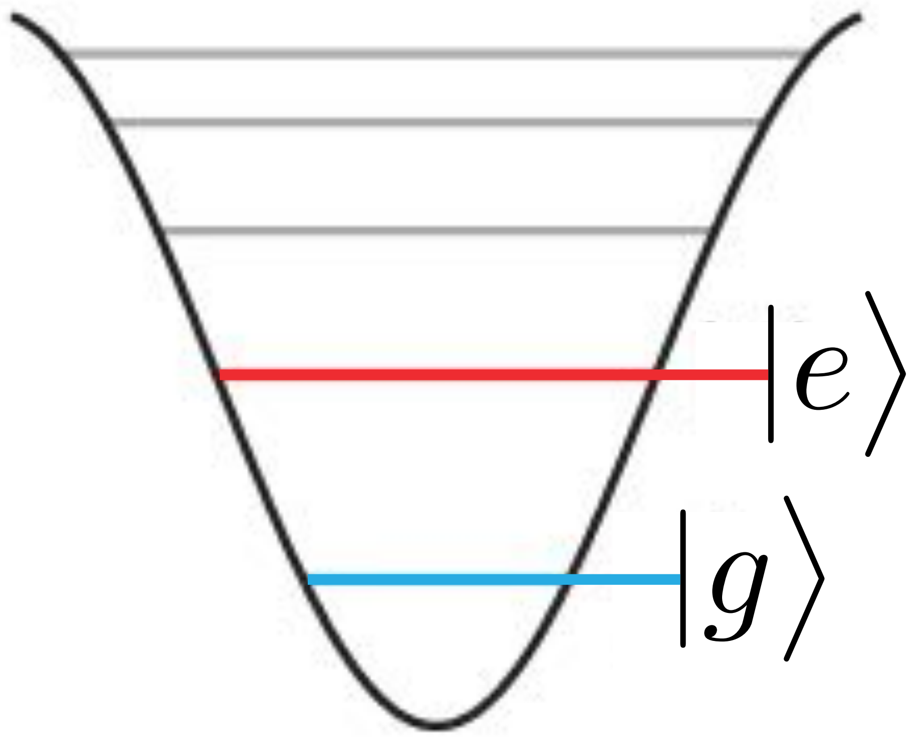



Phys. Rev. Lett. **127**, 107701

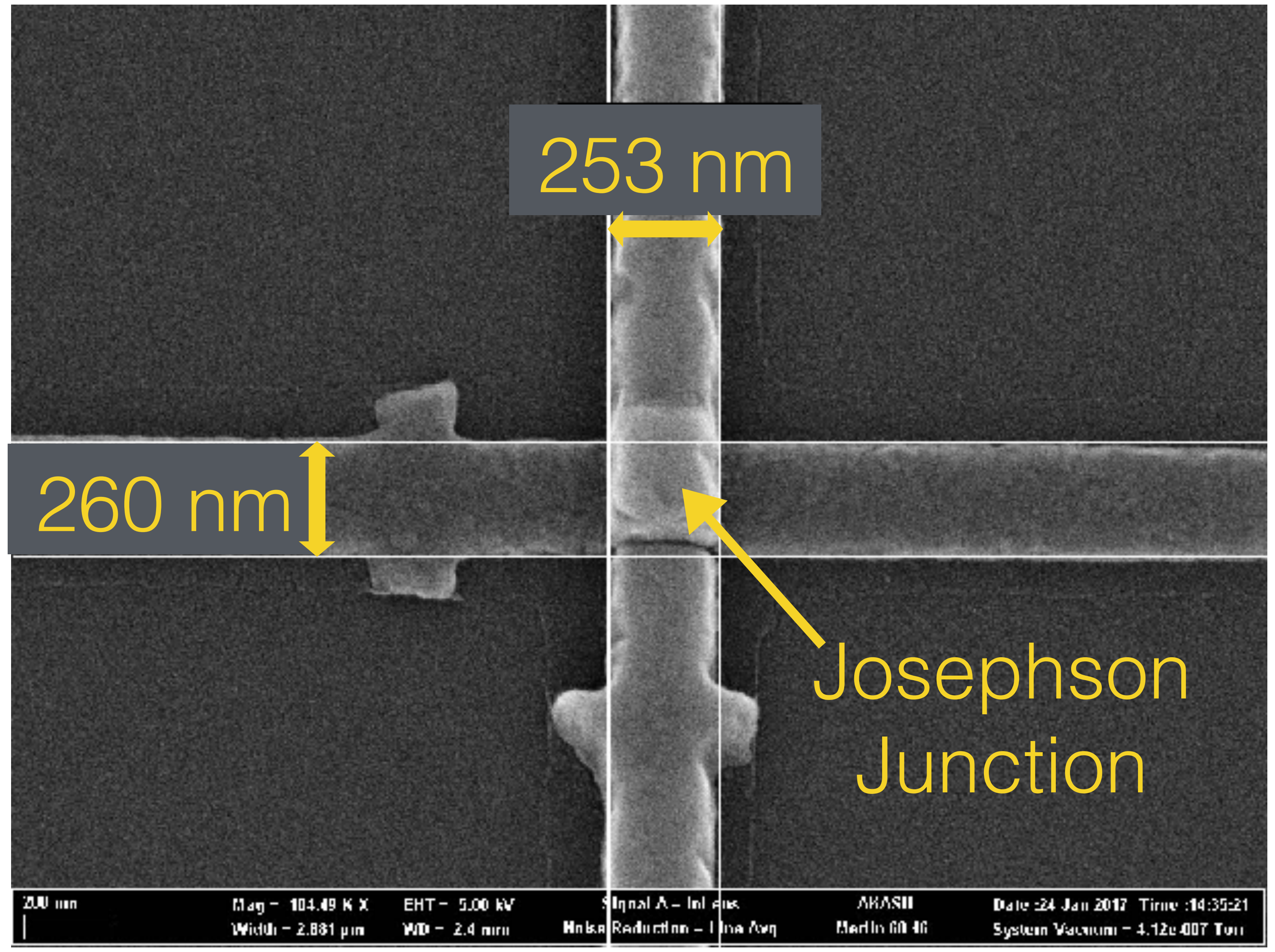
# Building a superconducting qubit




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

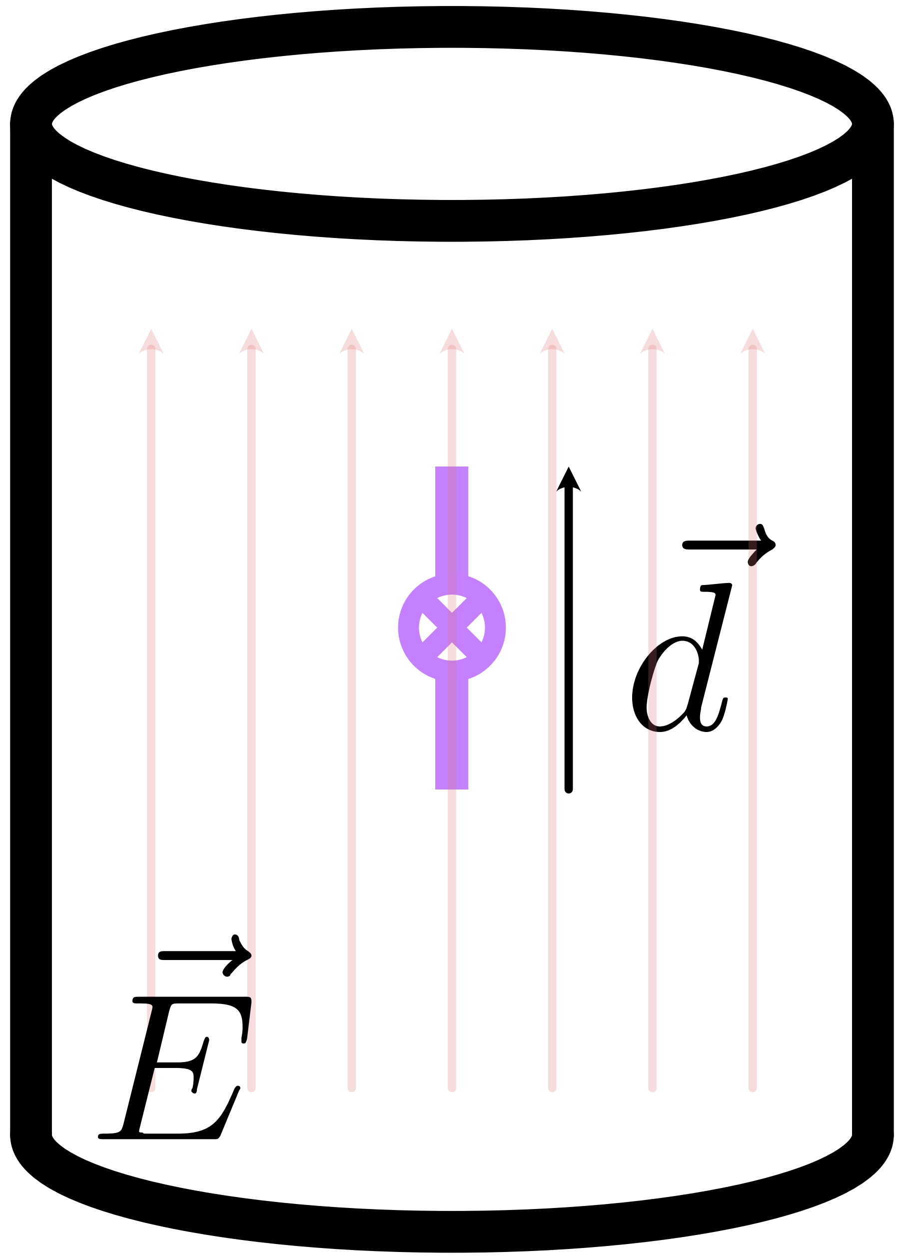



Harmonic Oscillator (LC) +
nonlinearity (Josephson Junction)



# Engineering the qubit-cavity interaction

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




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

$\Delta$ qubit-cavity detuning

$\alpha$ qubit anharmonicity

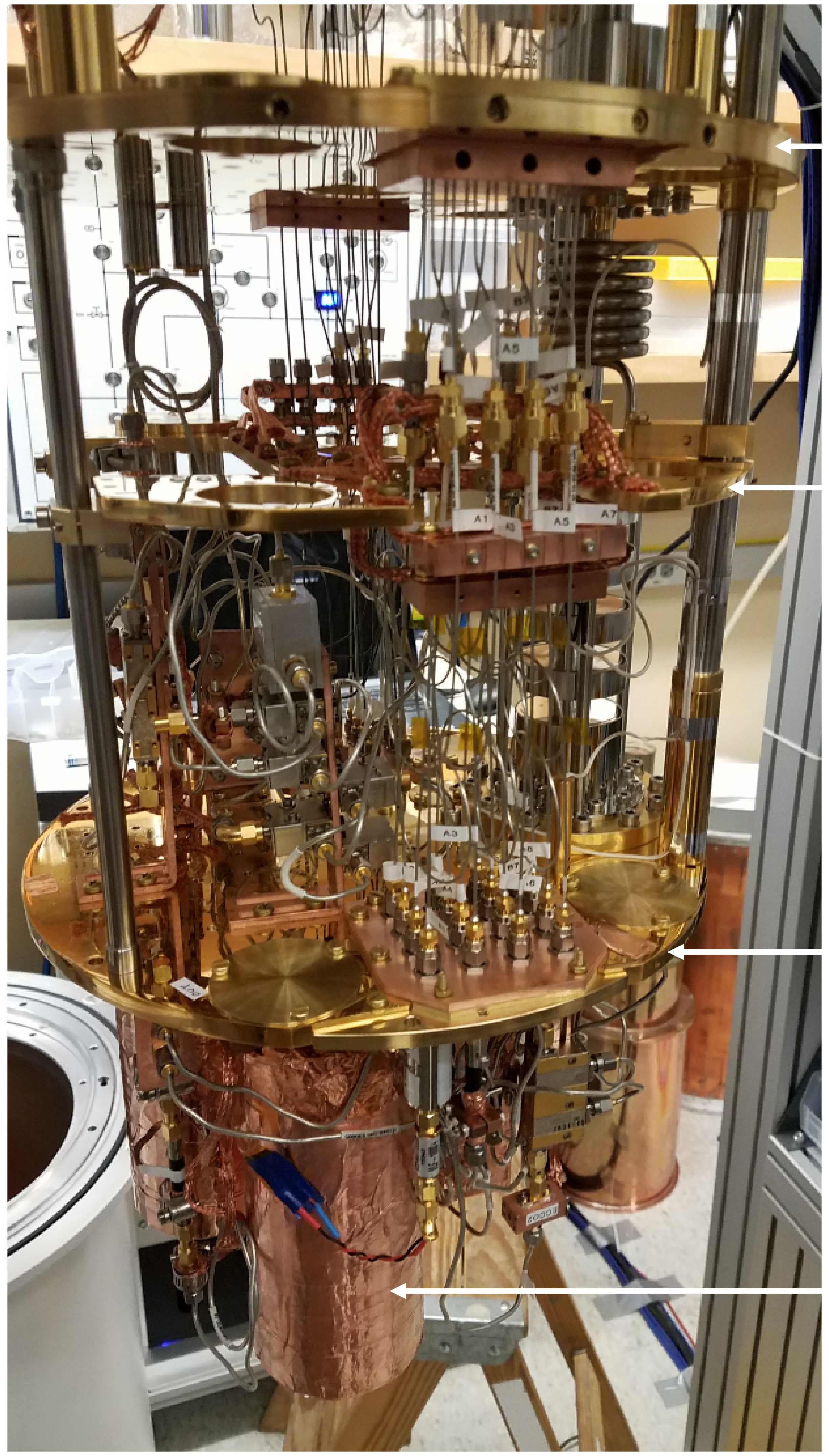
$$\chi = \frac{g^2}{\Delta(\Delta+\alpha)}\alpha$$

# Operate device in very cold environment

Device cooled to 8mK

Required to be below ~1K for materials to go superconducting

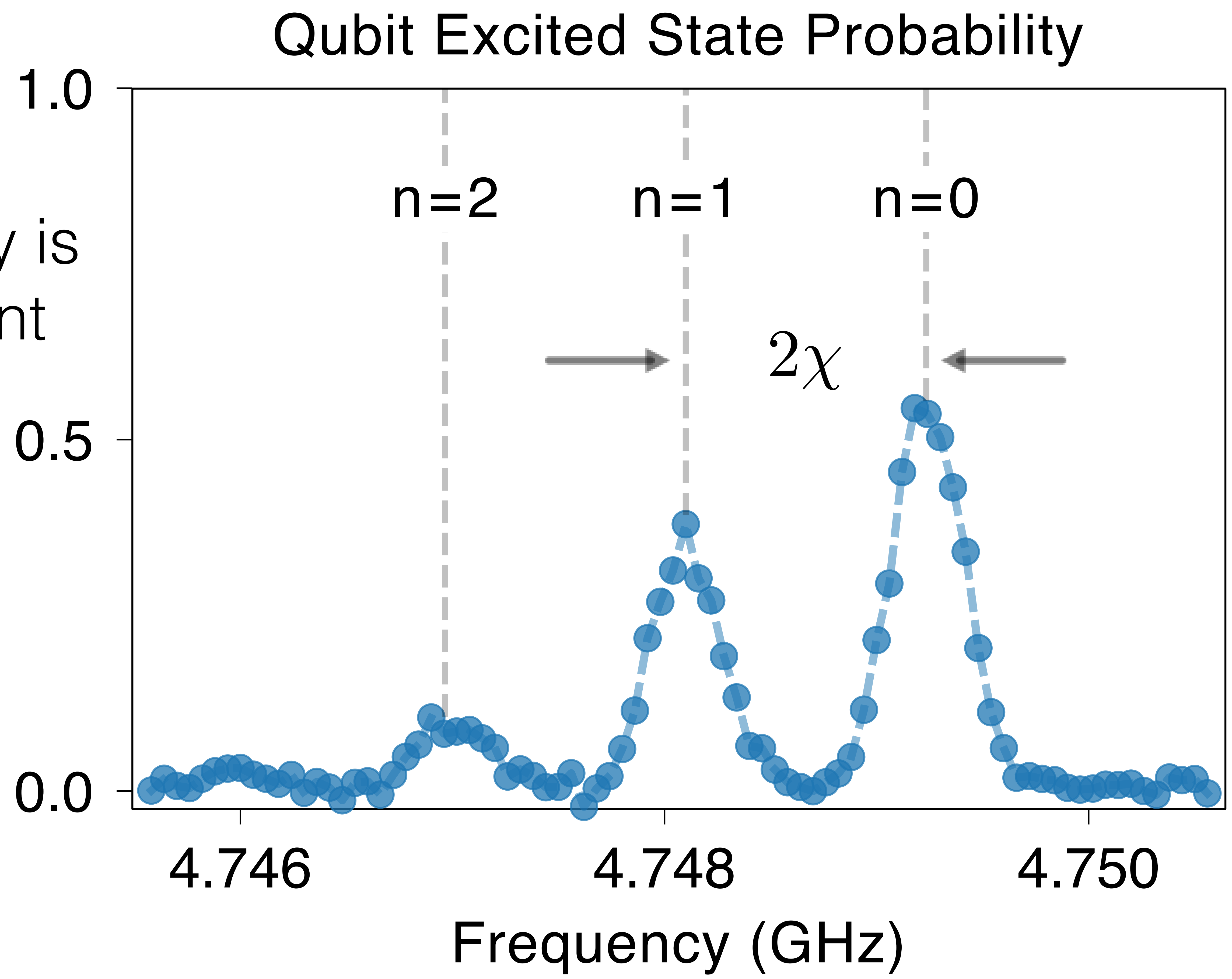
Reduce ambient thermal photons



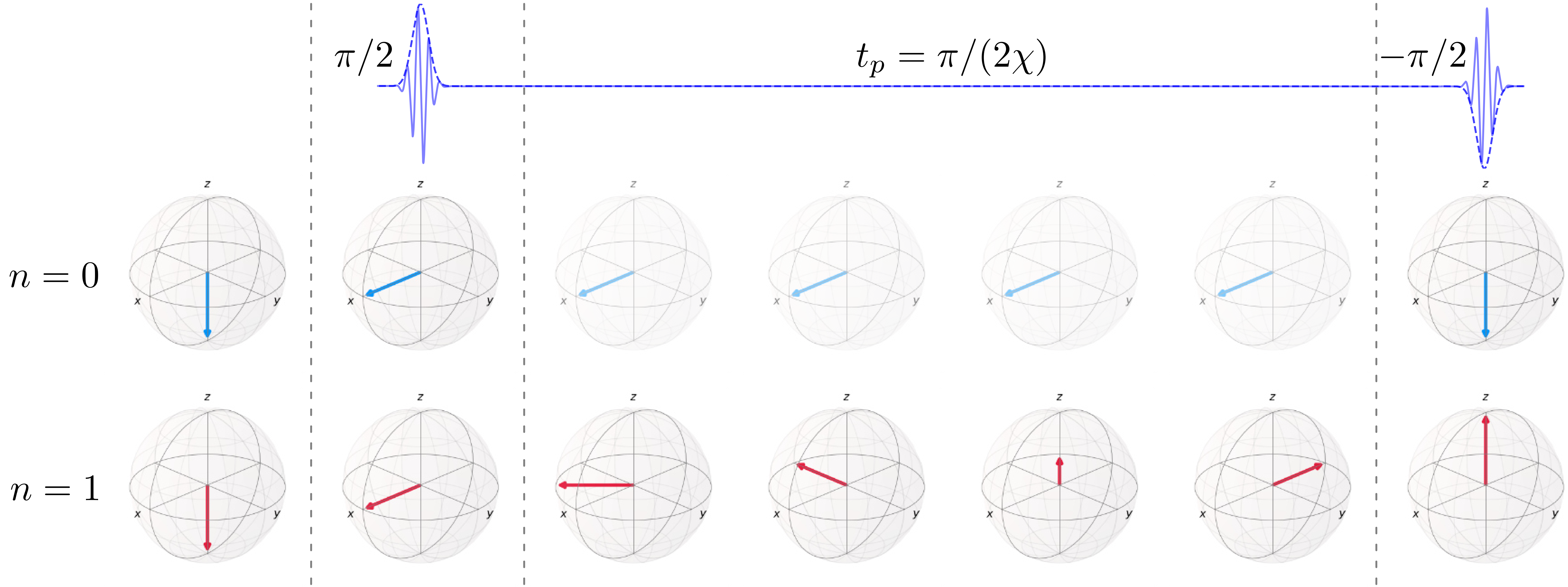
# Cavity occupation imprinted on qubit transition frequency

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

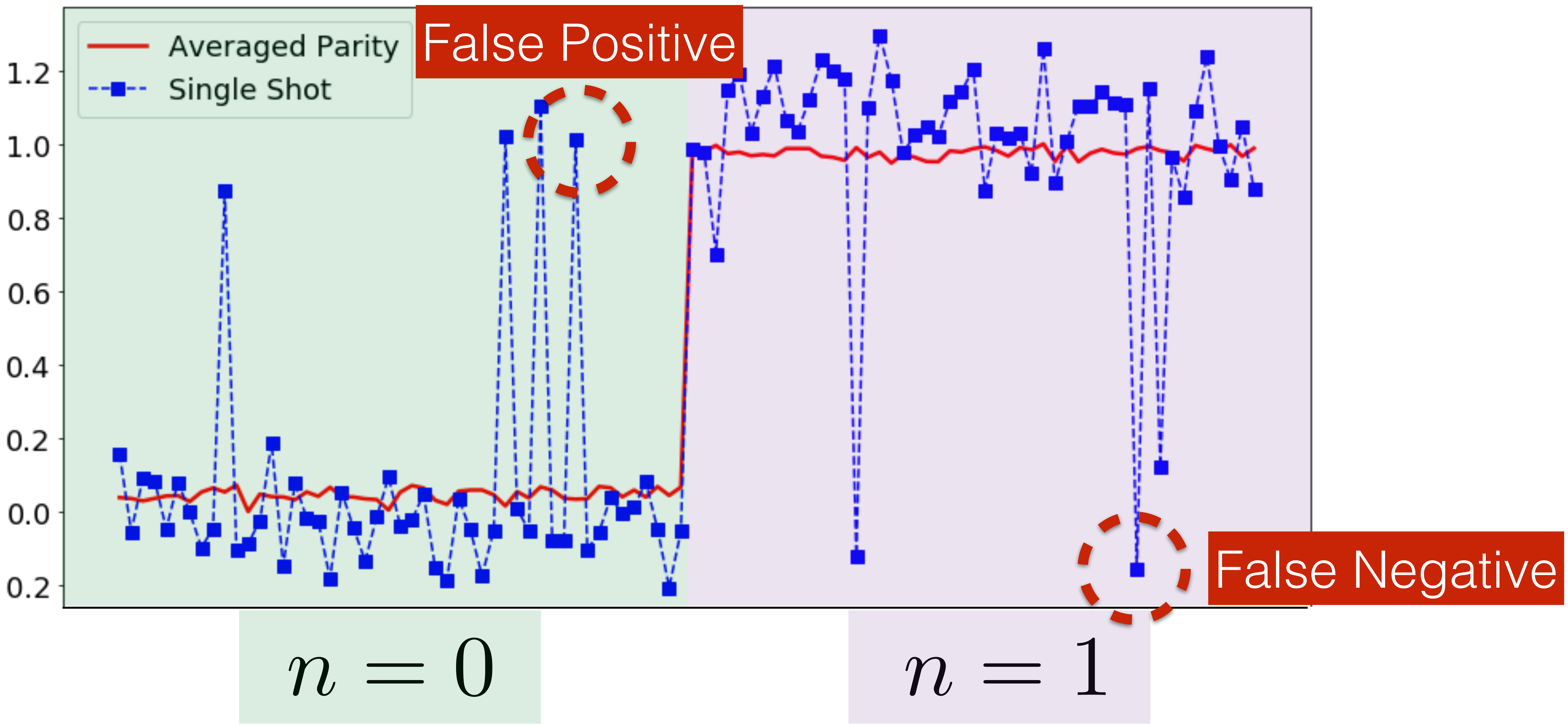
Qubit transition frequency is photon number dependent



# Parity measurement maps cavity state onto qubit



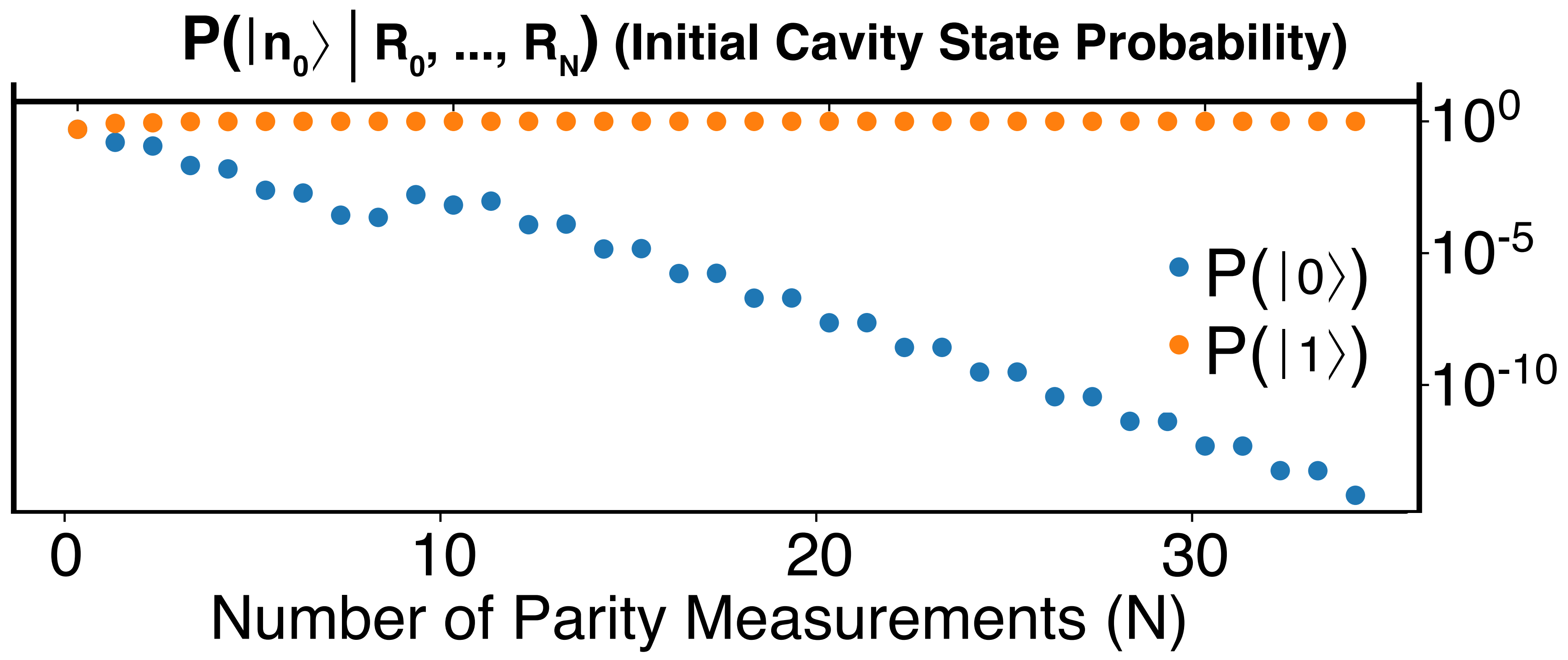
# Qubit makes too many errors




Spurious qubit excitations are dominant source of errors

# Outline of talk

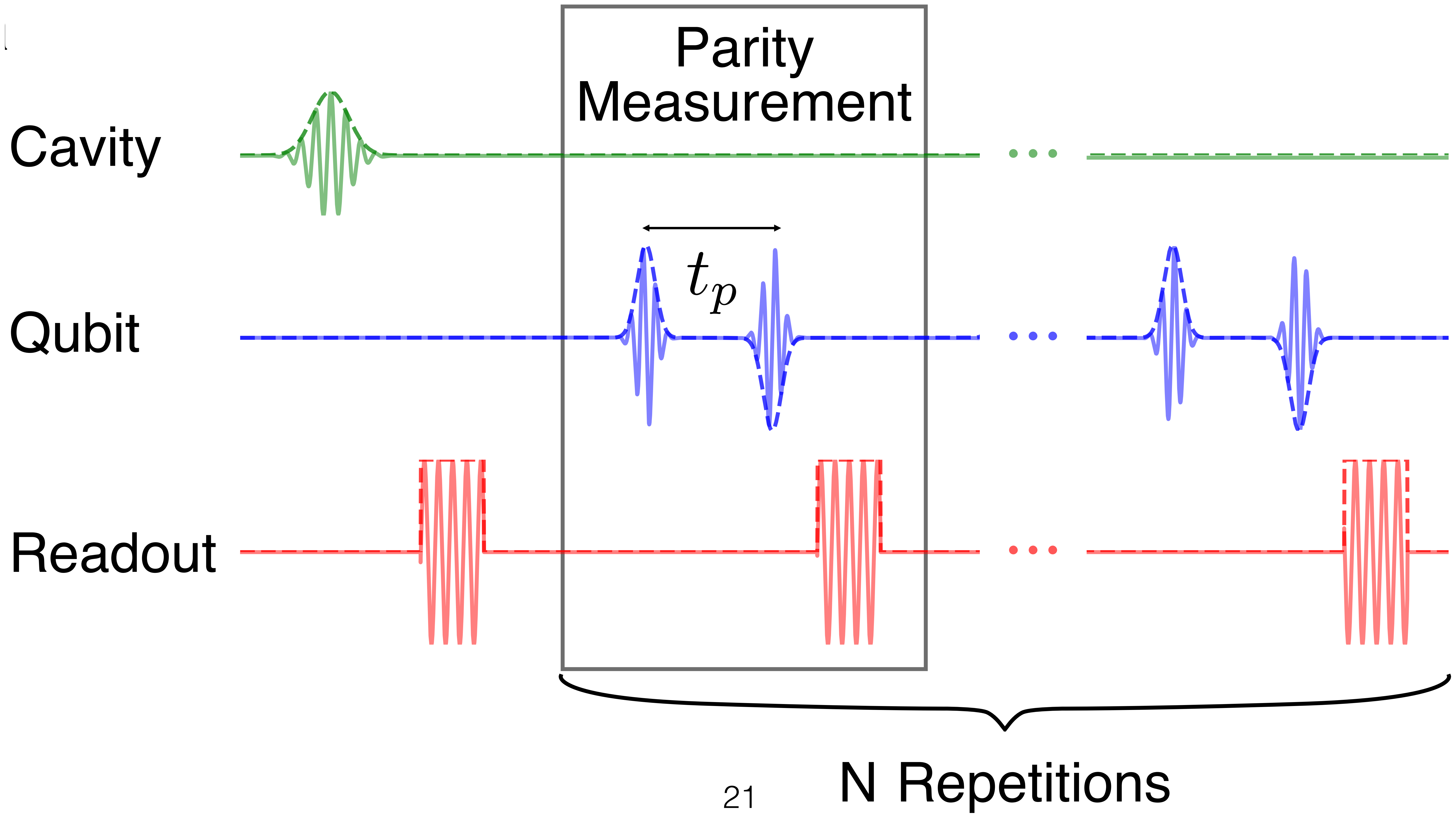
- Dark matter and detection mechanisms
- How to build a photon counter
- Devise a protocol to overcome detector errors
- Characterize photon counting detector
- Use detector to conduct a dark matter search
- Improvements and future experiments



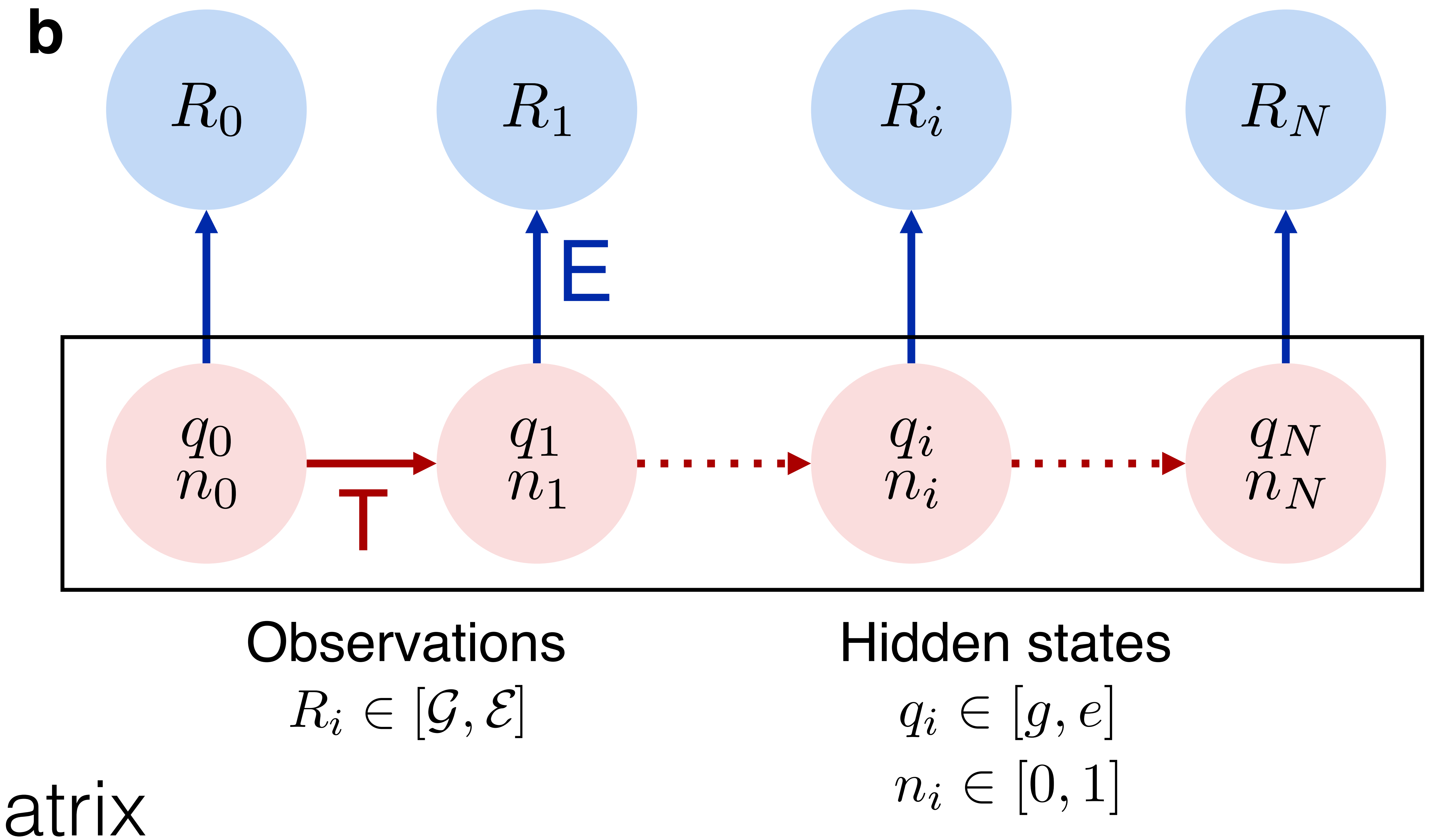
# Mitigate errors by making repeated measurements

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

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



# 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

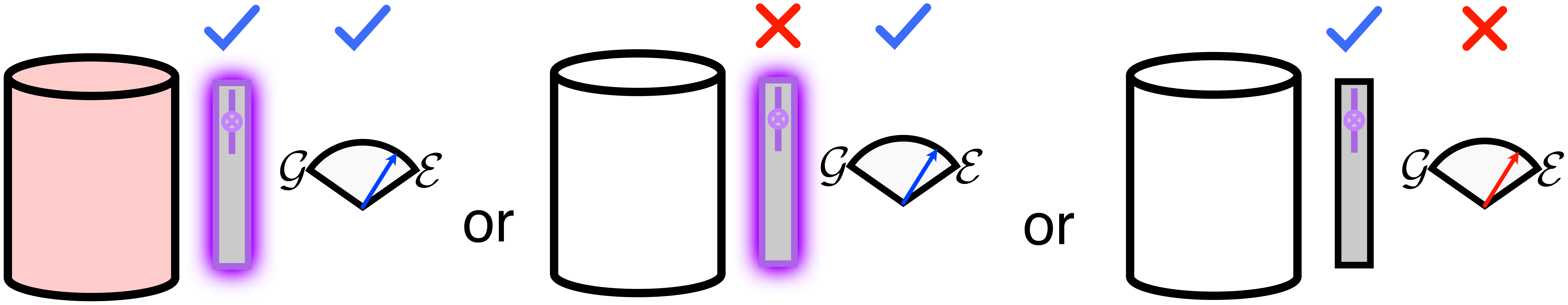
- ground and excited state readout fidelity (~0.95)

arxiv:1607.02529

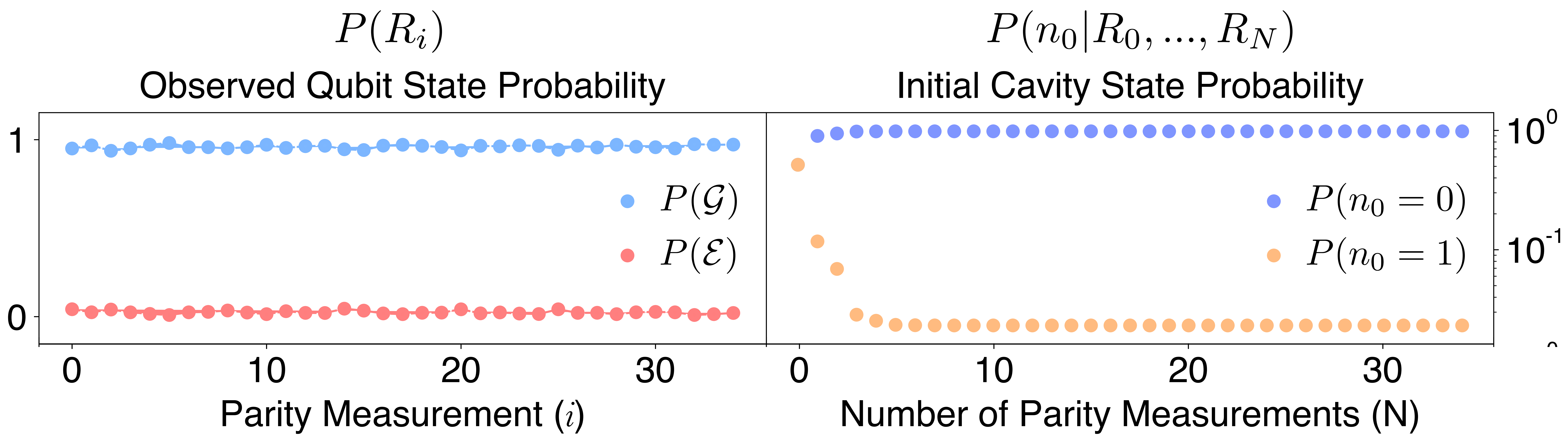
# Reconstructing the cavity state

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

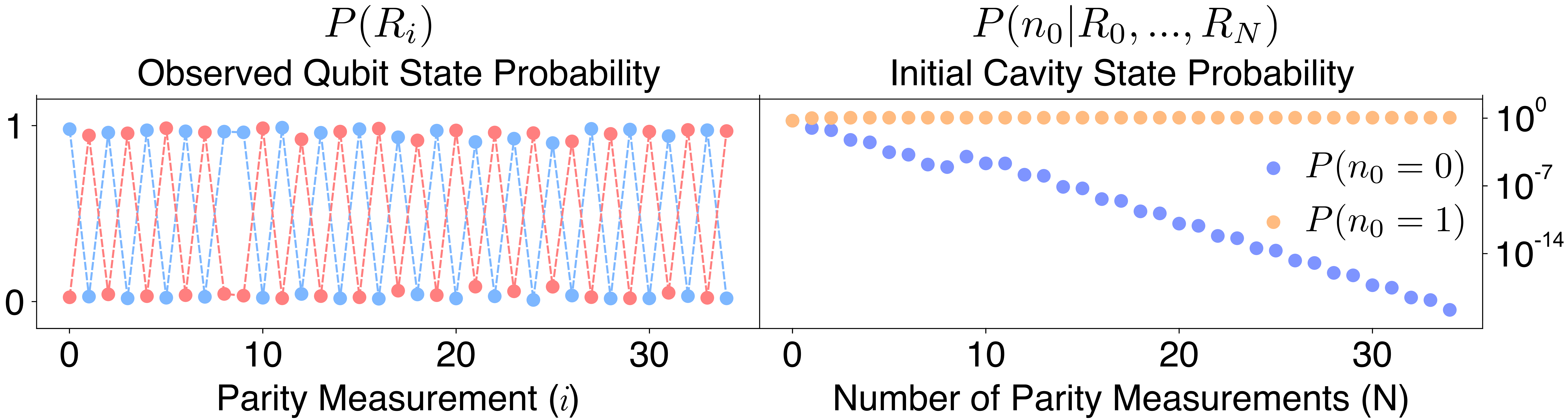
Observed readout sequence: $\mathcal{G} \rightarrow \mathcal{E}$



# Detector response in the presence of zero photons



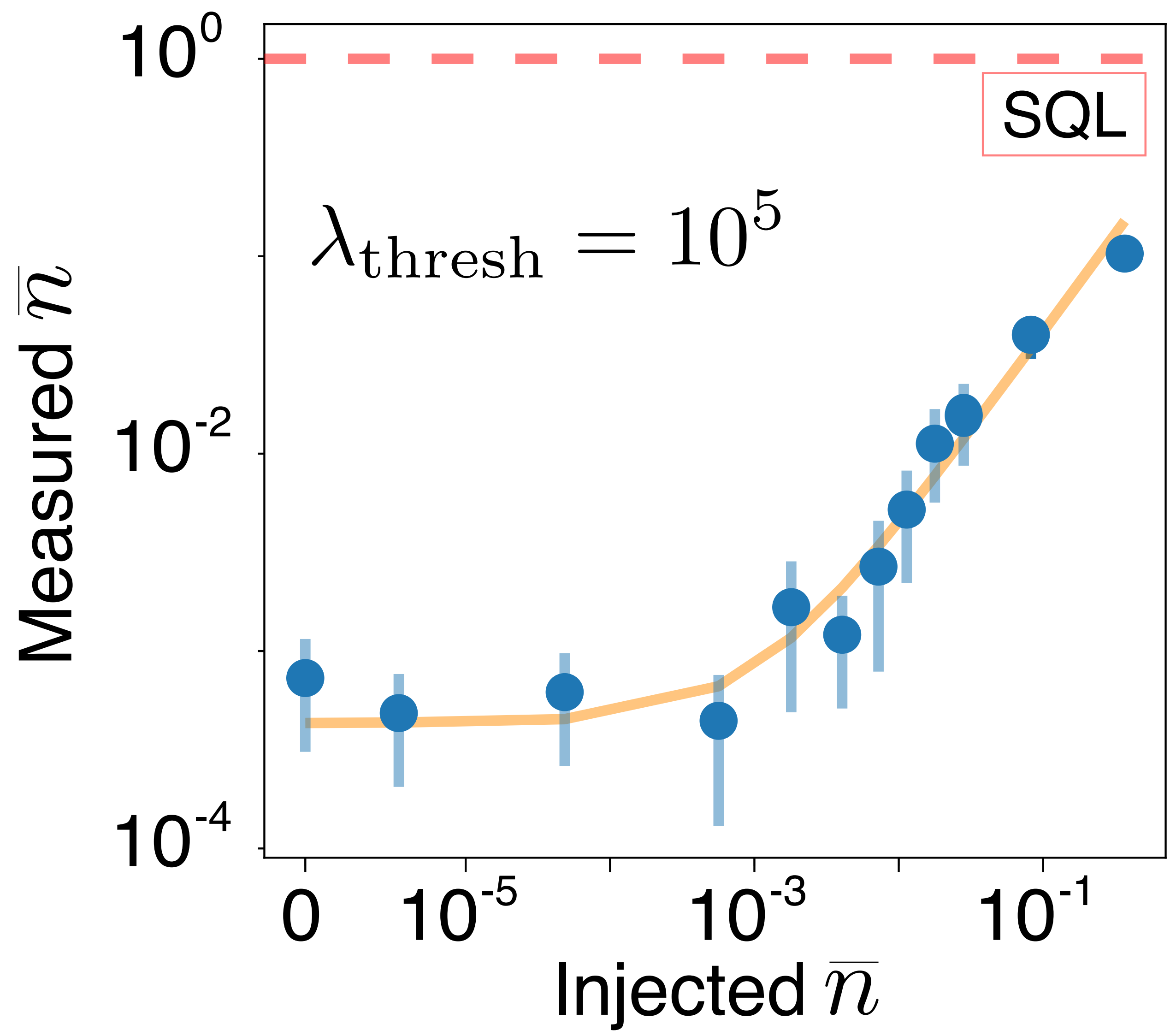
# Detector response in the presence of one photon



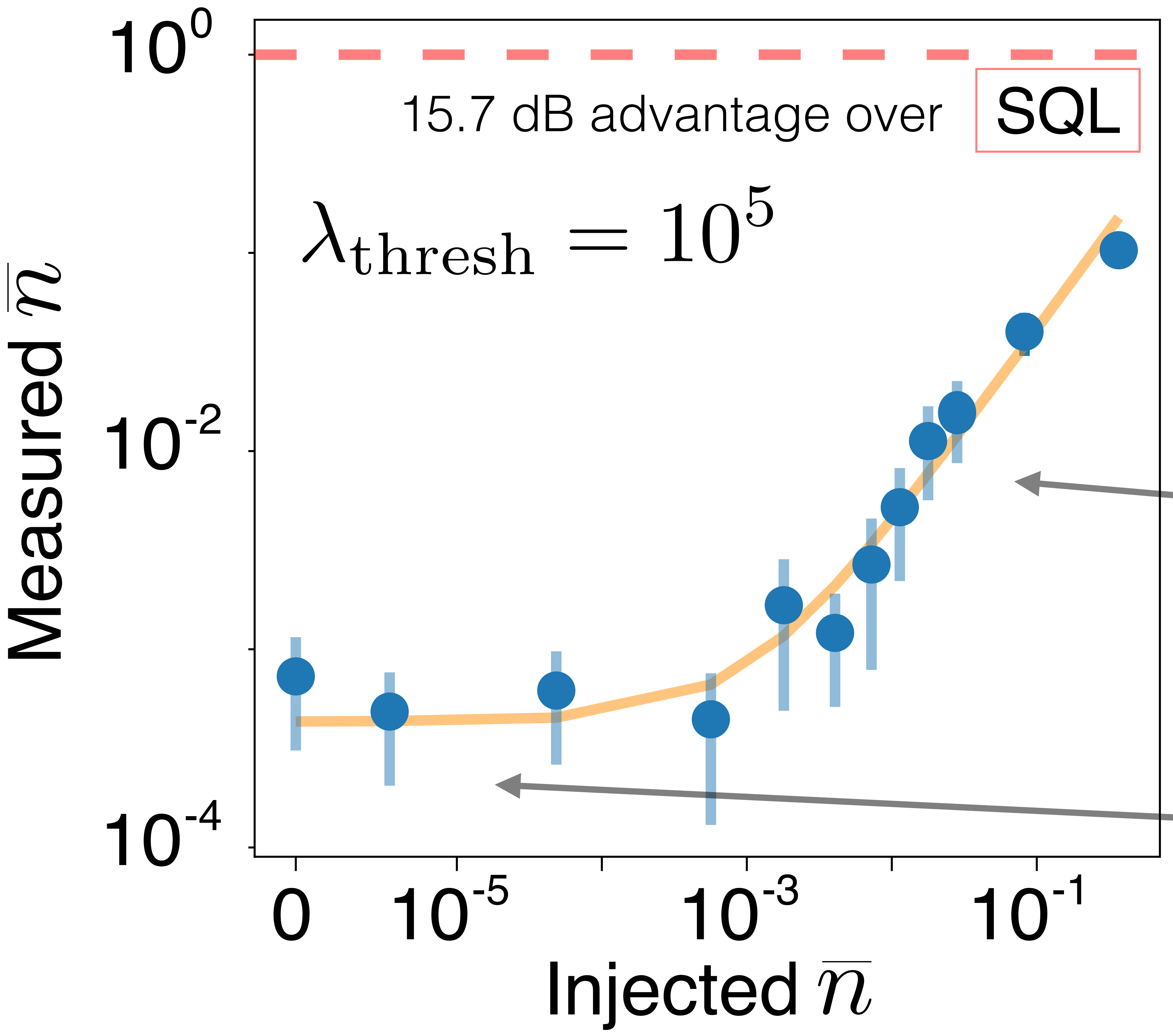

Exponential suppression of detector based false positives

# Outline of talk

- Dark matter and detection mechanisms
- 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
- Improvements and future experiments



# Detected photon occupation vs injected photon occupation



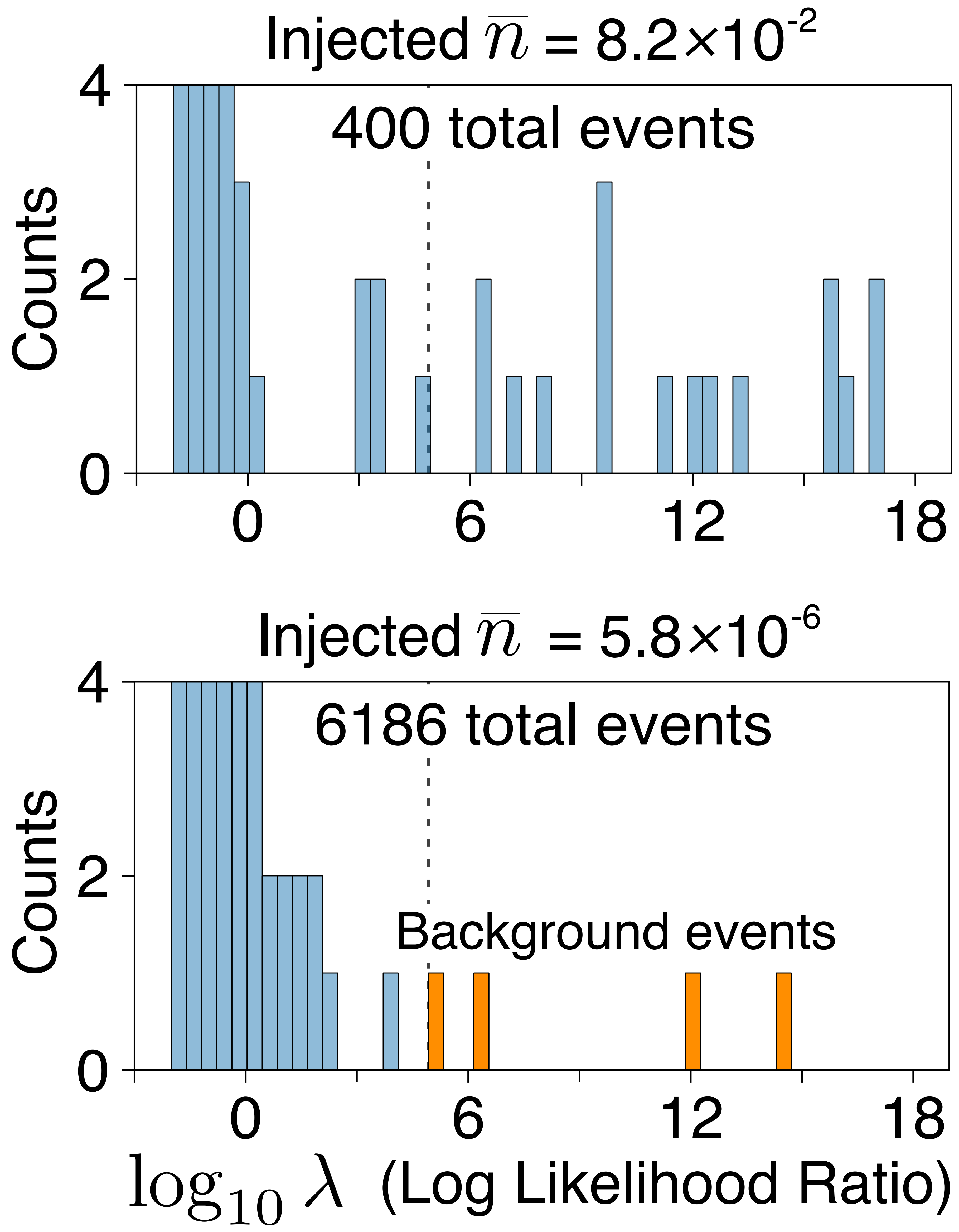

Efficiency

$\eta = 40.9\%$

False positive probability

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

# False positives are background events




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

Photons detected when none are injected

Eliminated detector errors as a source of false positives

Entered a new, background limited regime

# Dark matter search is 1,300 times faster with a qubit

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

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

Integrate until signal is larger than background variance

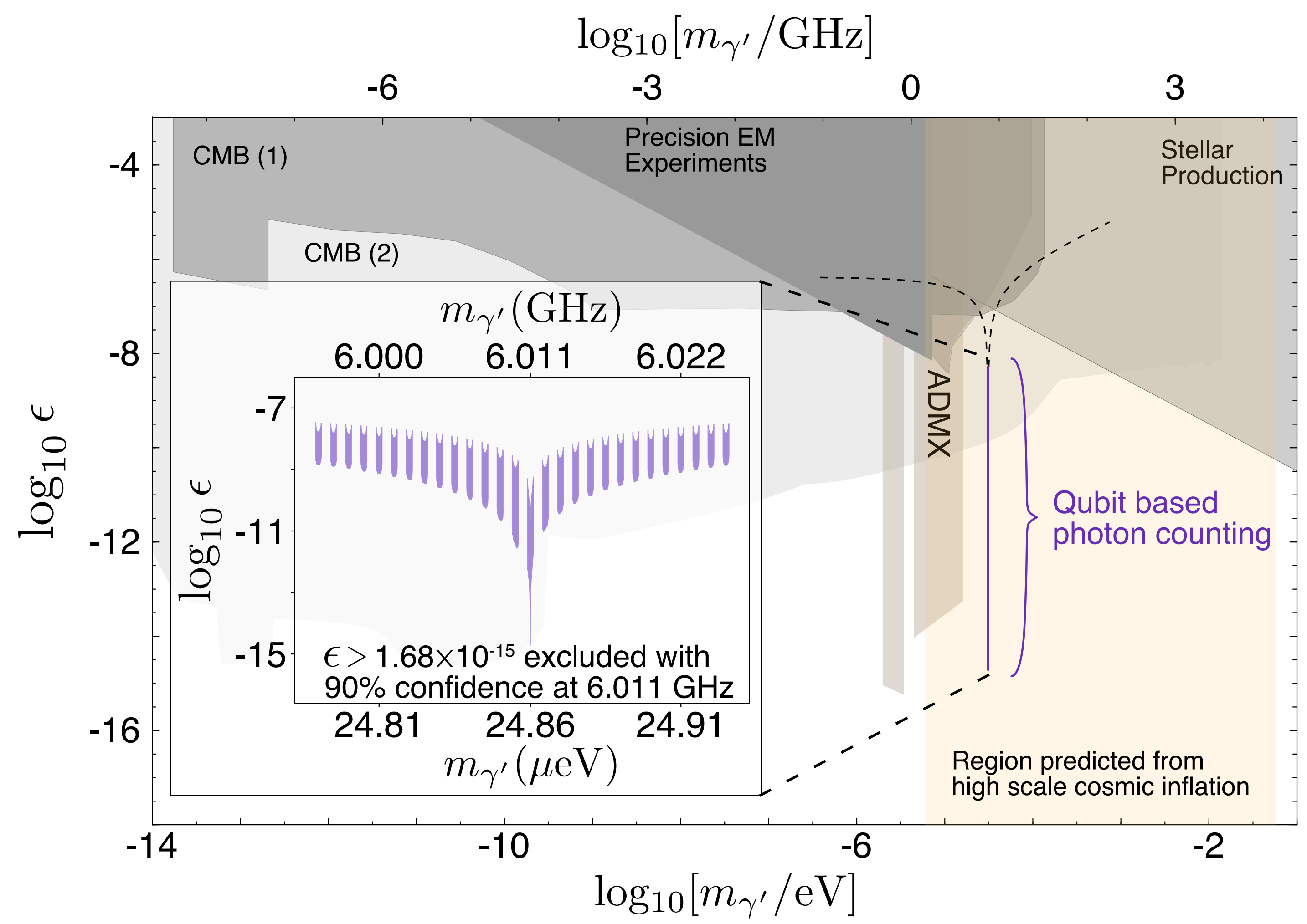
$$\bar{n}_{\mathrm{SQL}} = 1$$

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

1,300 X lower background rate than SQL
⇒ 1,300 X less integration time required

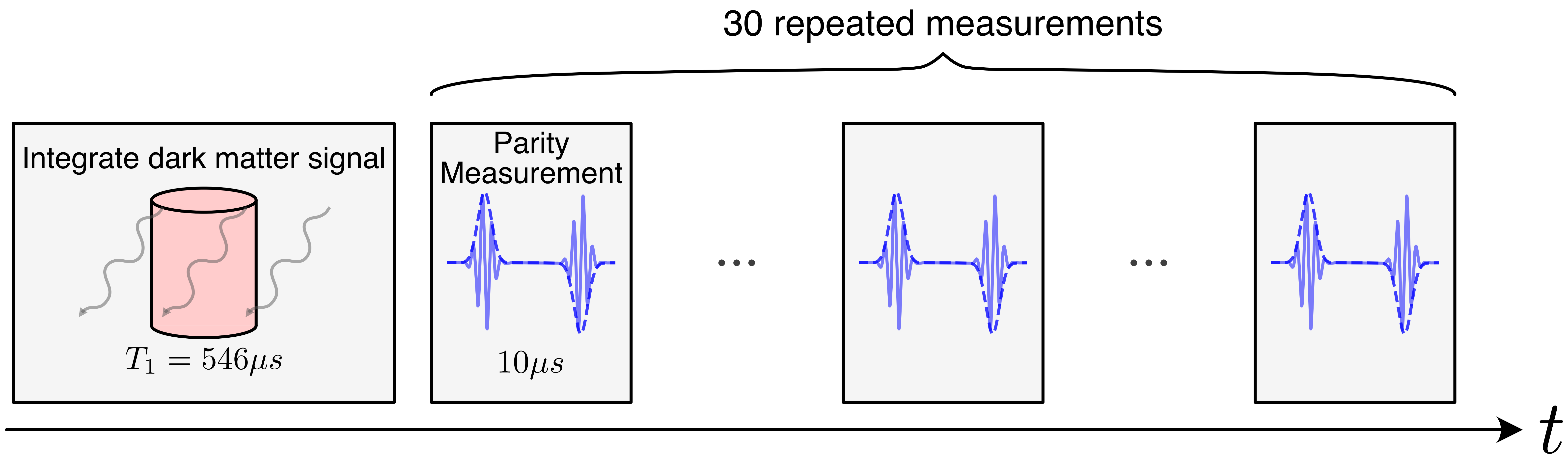
# Outline of talk

- Dark matter and detection mechanisms
- 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**
- Improvements and future experiments



# Dark matter search protocol

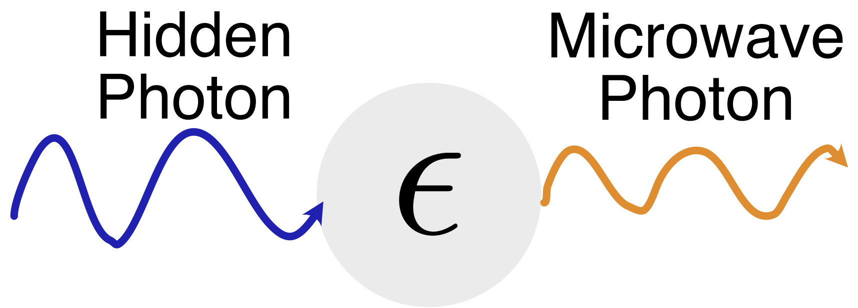
Signal cannot build up while measuring (quantum Zeno effect)

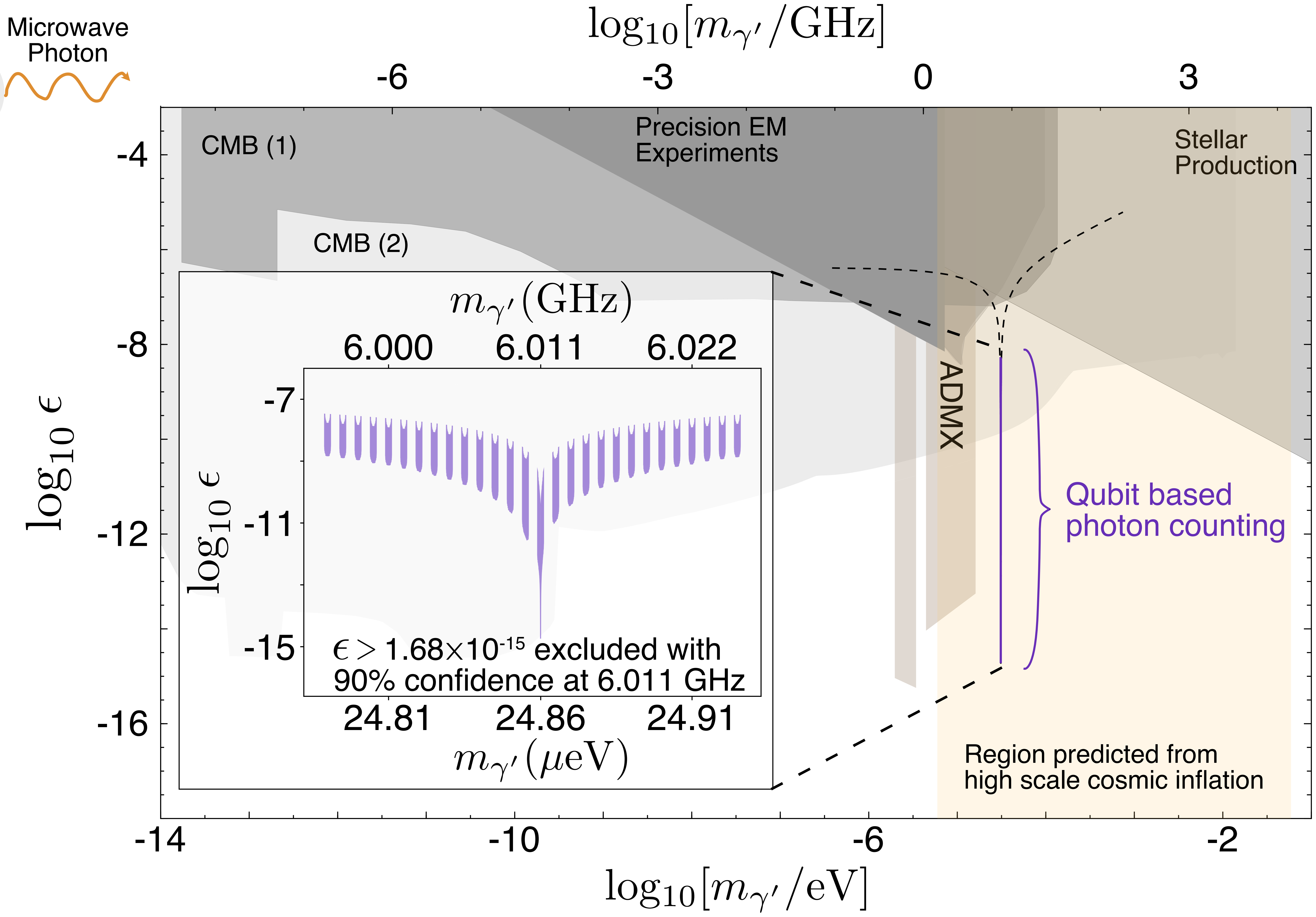



| | |
|---|---|
| **Number of experiments** | 15,141 |
| **Experiment time** | 12.82 s |
| **Integration time** | 8.33 s |
| **Duty cycle** | 65% |
| **Photons counted** | 9 |

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

# Constraining the Hidden Photon Dark Matter



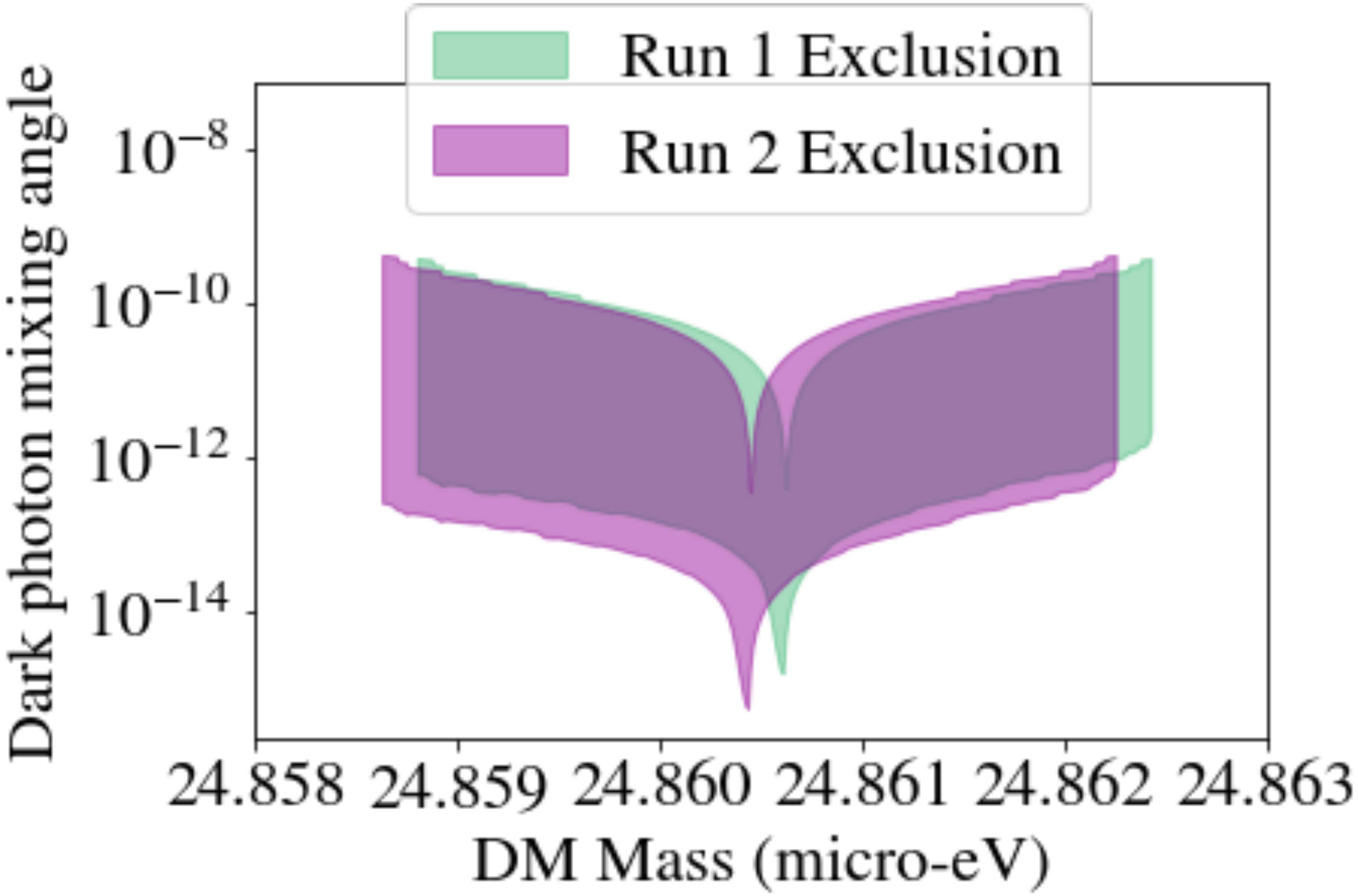






Phys. Rev. D 93, 103520

# Hidden photon search: Run 2

| | Run 1 | Run 2 |
|---|---|---|
| **Background Population** | 7.3 X $10^{-4}$ | 3.7 X $10^{-4}$ |
| **Number of experiments** | 15,141 | 700,000 |
| **Duty cycle** | 65% | 80% |
| **Photons counted** | 9 | 130 |
| **Search speed up** | 1,300 X | 2,700 X |

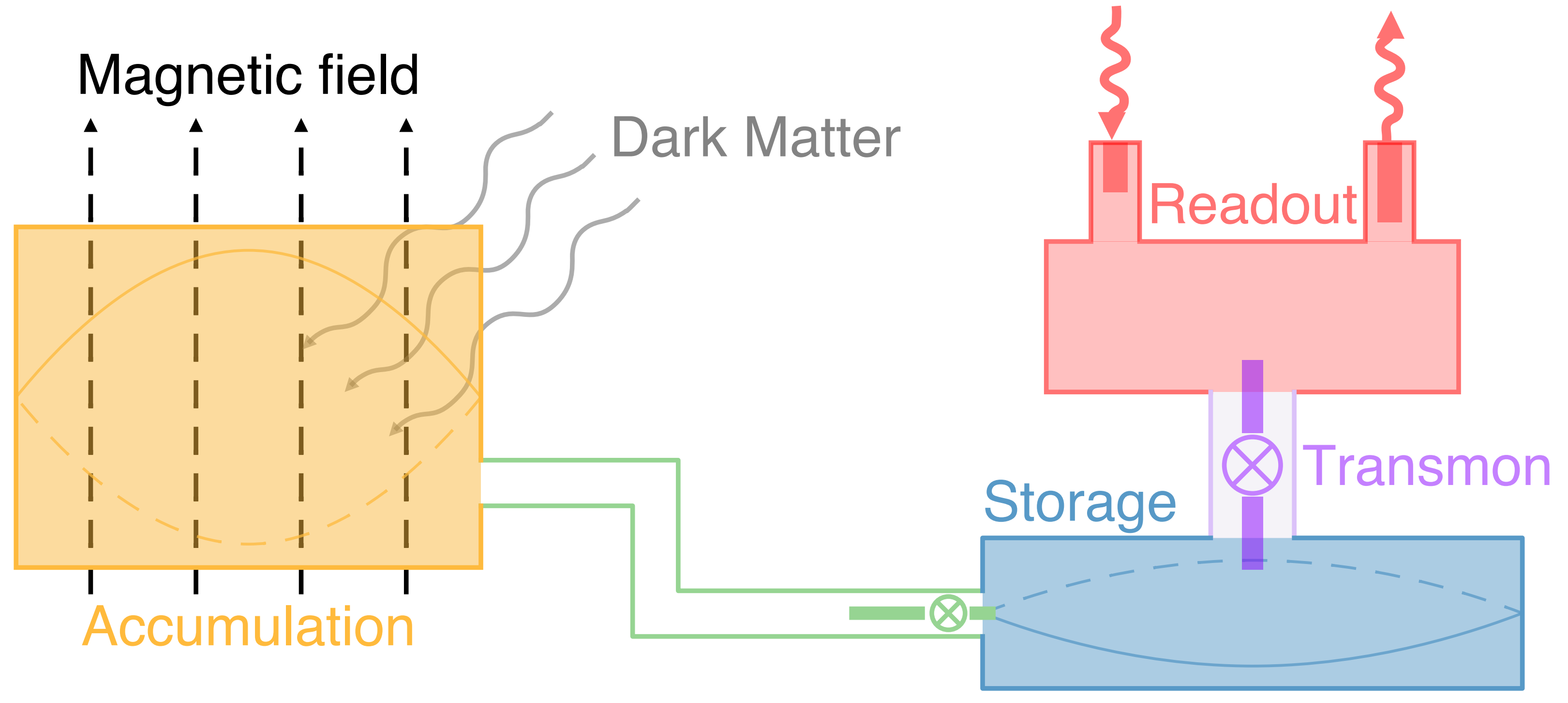



Run 1 constraint $\epsilon \leq 1.68 \times 10^{-15}$

Run 2 constraint $\epsilon \leq 5.22 \times 10^{-16}$

# Outline of talk

- Dark matter and detection mechanisms
- 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
- Improvements and future experiments



# Background sources and mitigation strategies

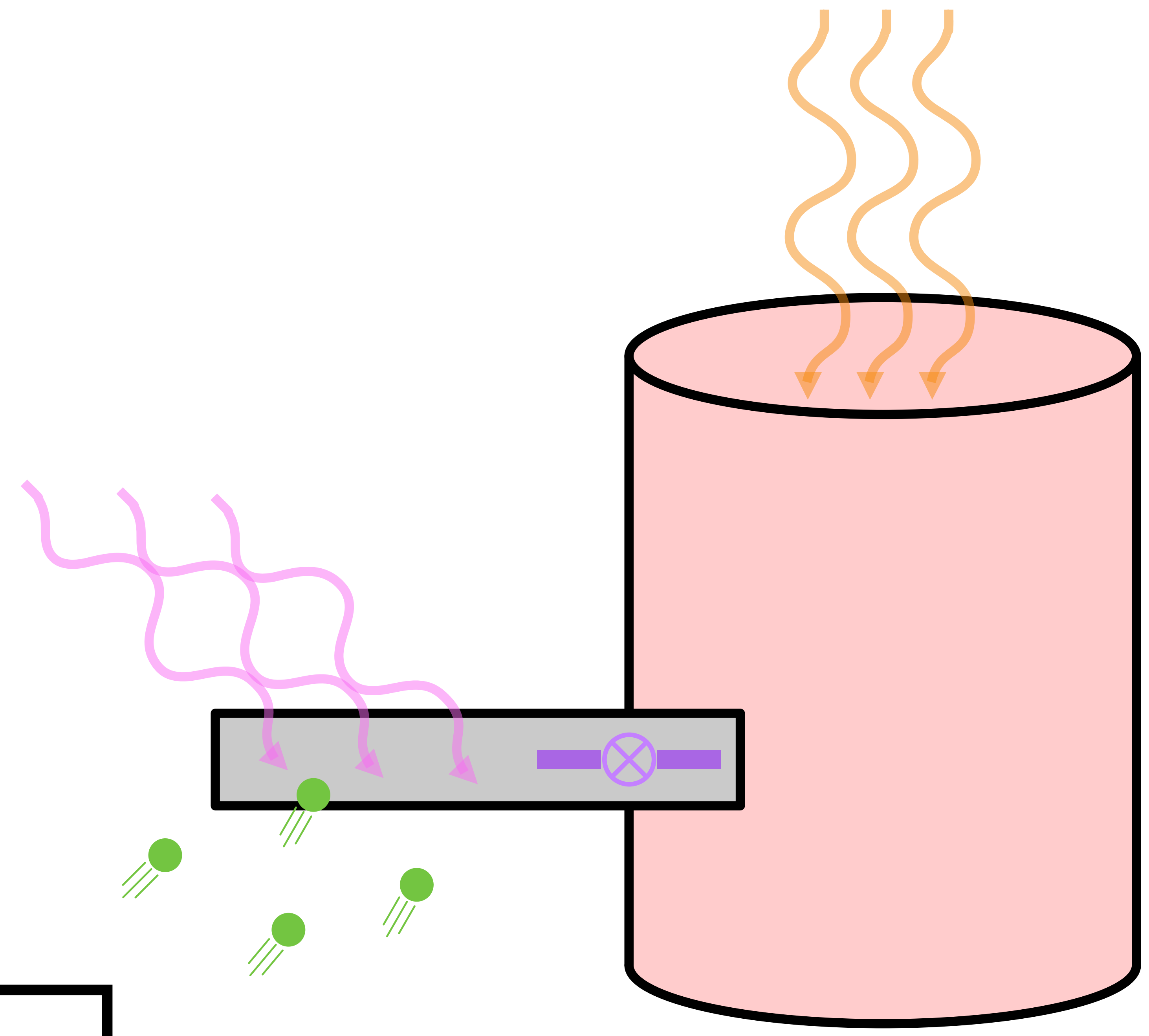
Photons coming down lines

- 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



$$\bar{n}_b \rightarrow 10^{-5}$$

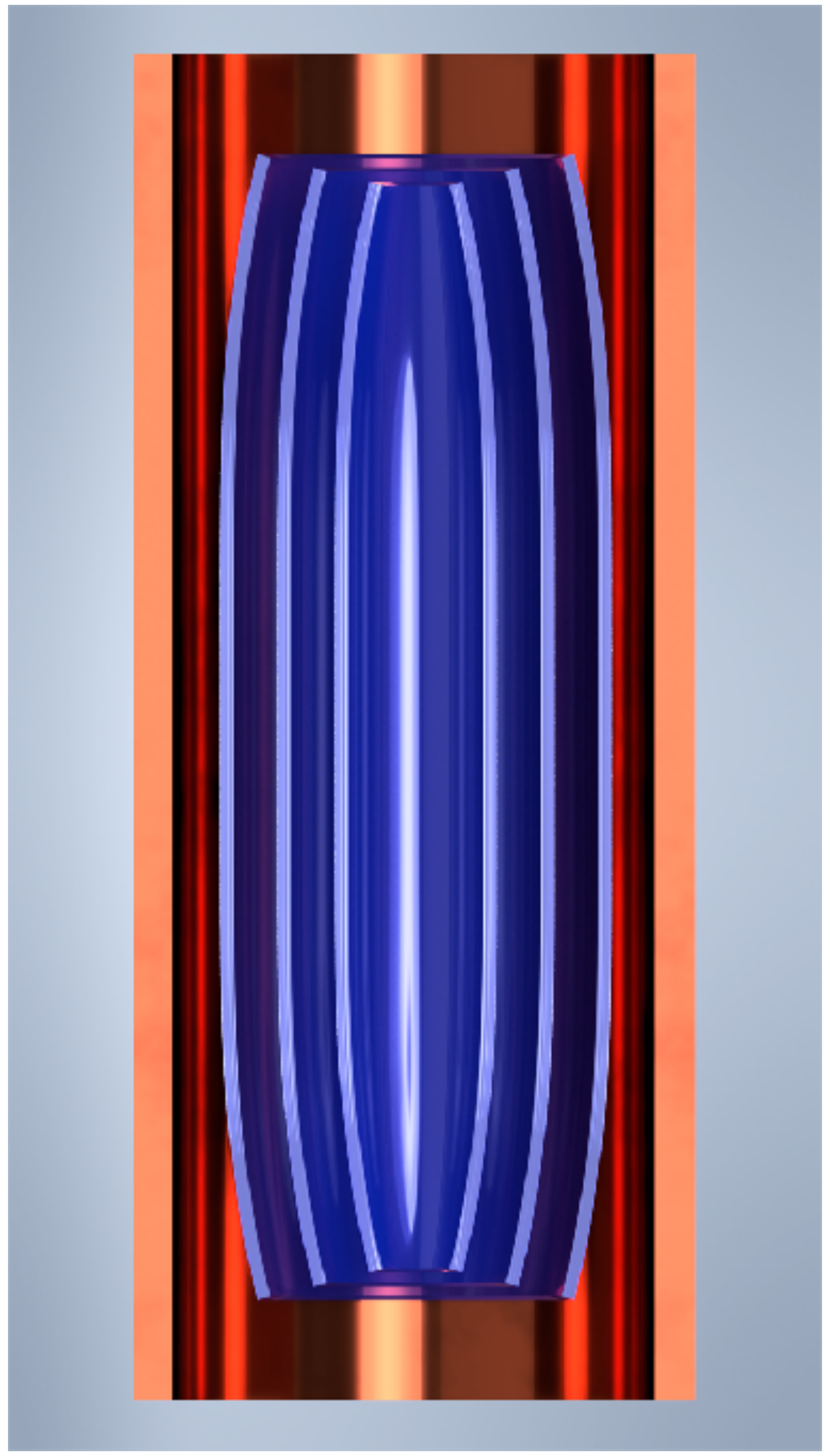
↓

100,000 X
search speed up

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

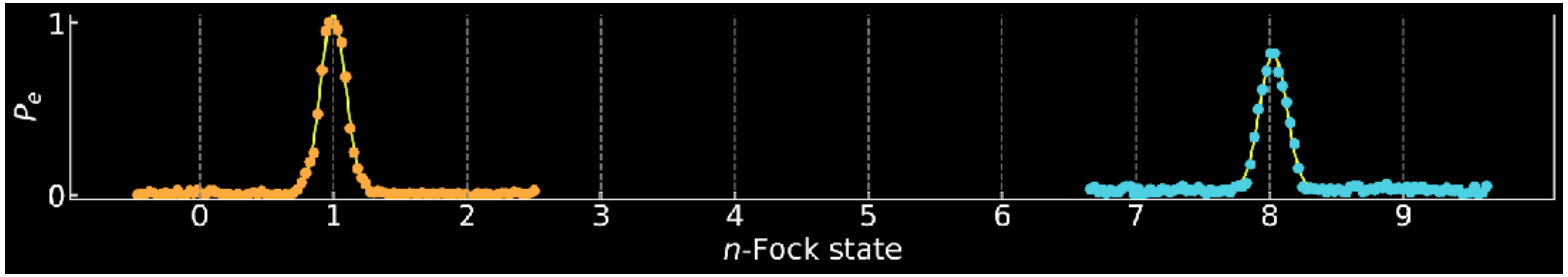
# Boosting the dark matter induced signal

Build high Q cavities
compatible with B-field



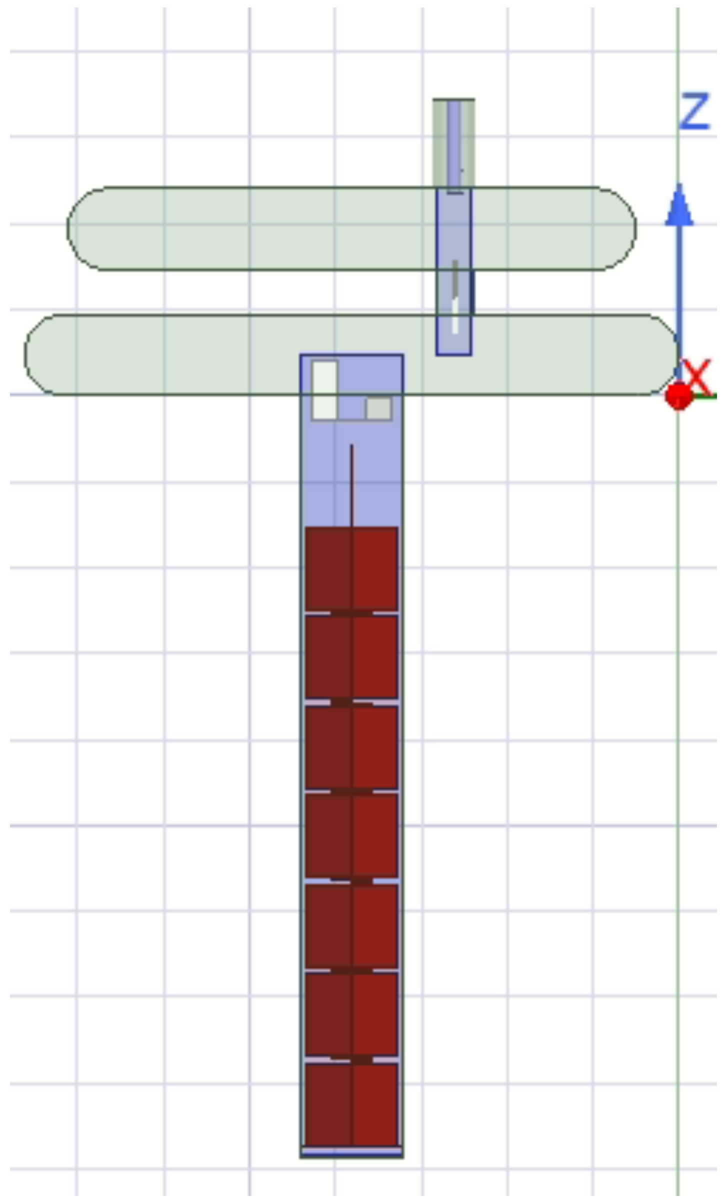
Use nonclassical cavity states
for signal enhancement

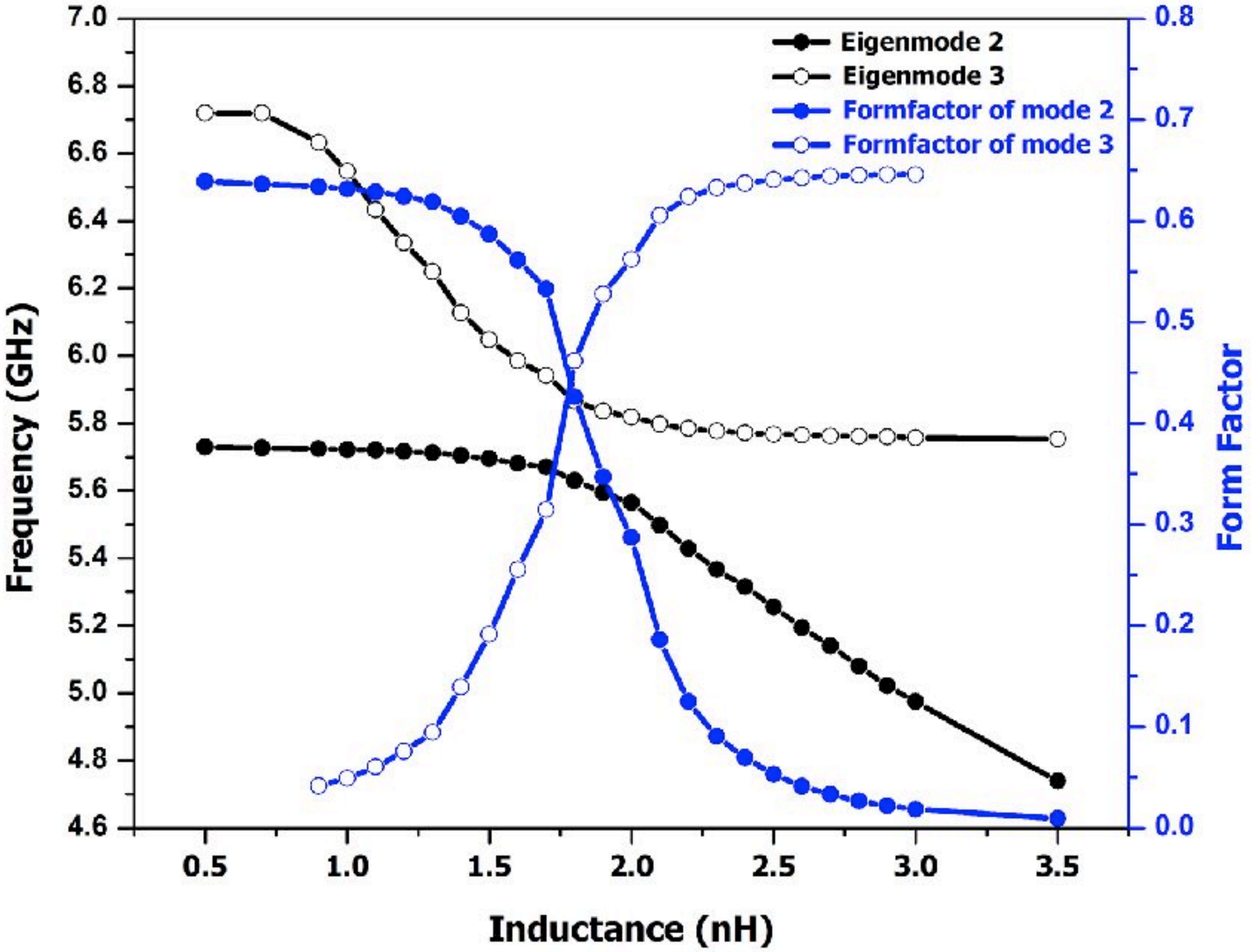
$$| < n+1|\mathcal{D}_\alpha|n > |^2 \sim n\alpha^2$$

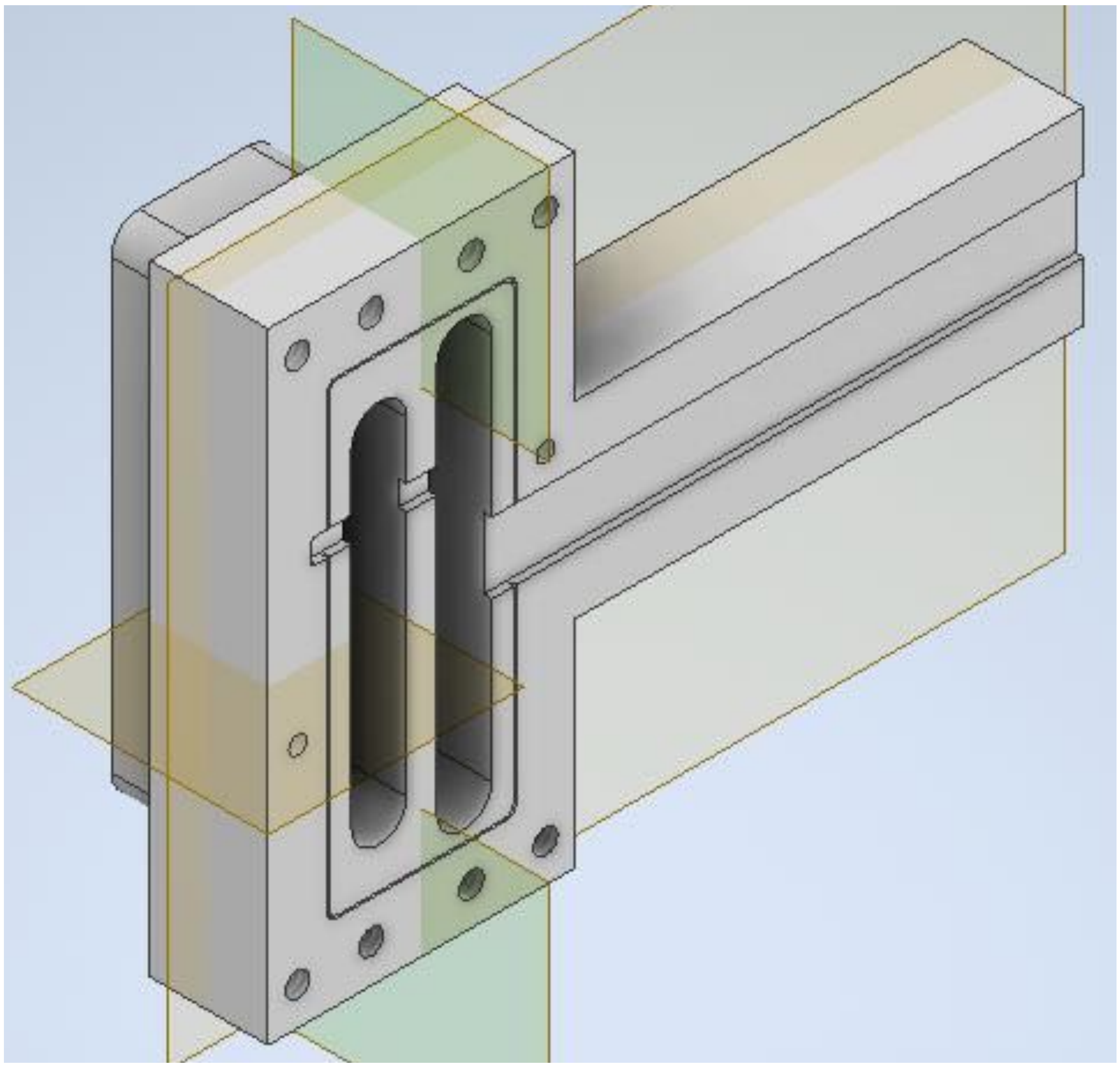



arxiv:2004.02754
Nature Communications volume 10, Article number: 2929 (2019)

# Electronic tuning of cavity for hidden photon search

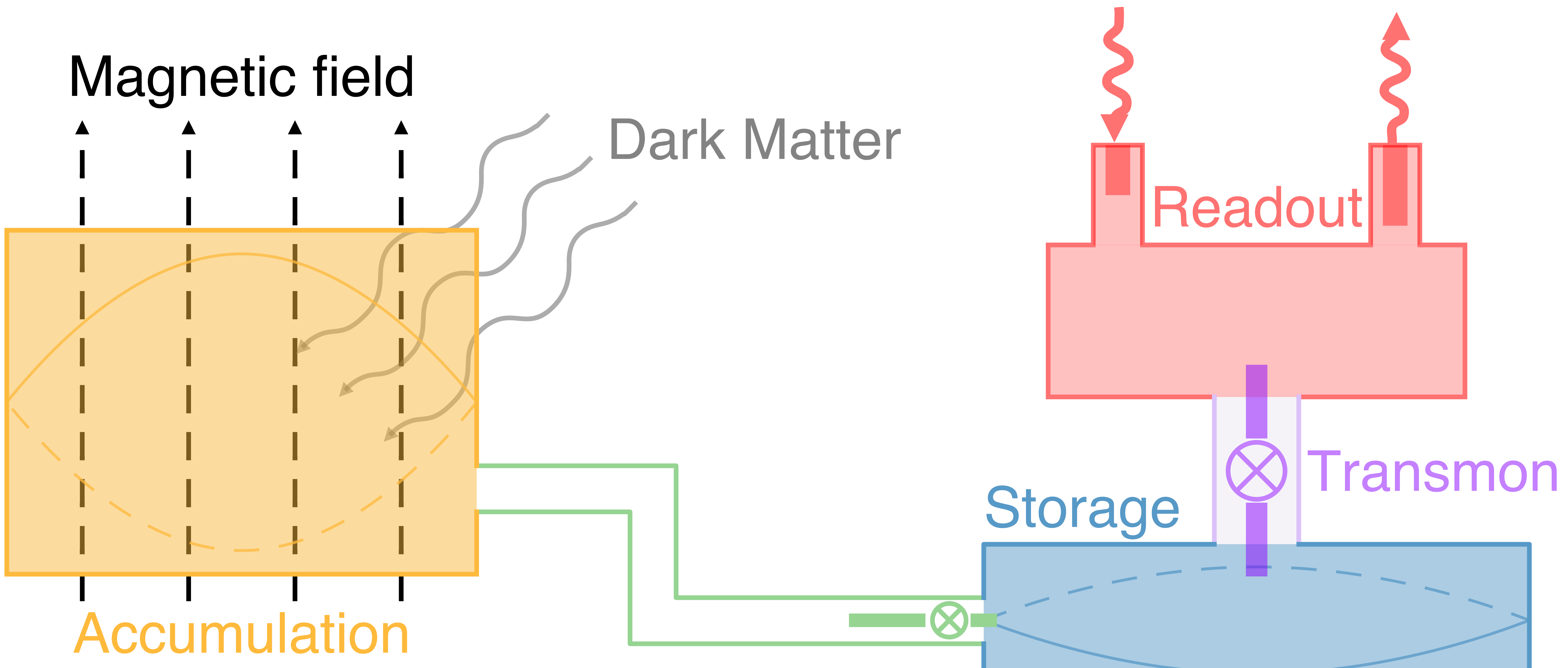


Tuning electronically is much simpler than tuning mechanically

# Searching for axion dark matter



# Conclusions

- Employed quantum information techniques/devices for dark matter cosmology
- Achieved 15.7 dB metrological gain, ~1,300 X speed up of dark matter searches
- Unprecedented sensitivity to hidden photon dark matter
- Manuscript: Phys. Rev. Lett. **126**, 141302

U.S. DEPARTMENT OF ENERGY | Office of Science

Pritzker Nanofabrication Facility

the David & Lucile Packard FOUNDATION

HEISING-SIMONS FOUNDATION

schuster.lab

THE UNIVERSITY OF CHICAGO

Fermilab

# Thank you!