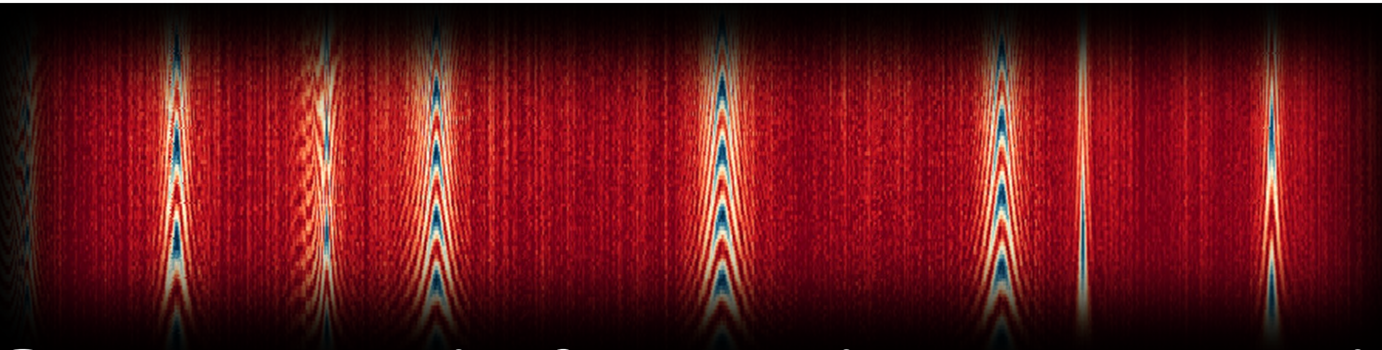
schuster.lab

THE UNIVERSITY OF CHICAGO

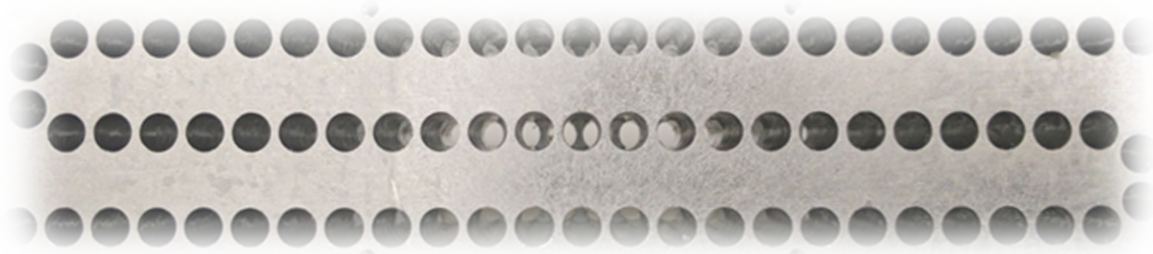


Quantum information processing using multimode cavities

Srivatsan Chakram, Kevin He, Akash Dixit, Ravi Naik, Andrew Oriani,
Nelson Leung, Yao Lu, Wen-Long Ma, Liang Jiang,
Akash Dixit, Ankur Agarwal, Aaron Chou,
Gustavo Cancelo, Leoandro Steffanazzi, Chris Stoughton, Ken Treptow, Shefali Saxena, Sara Sussman

David Schuster

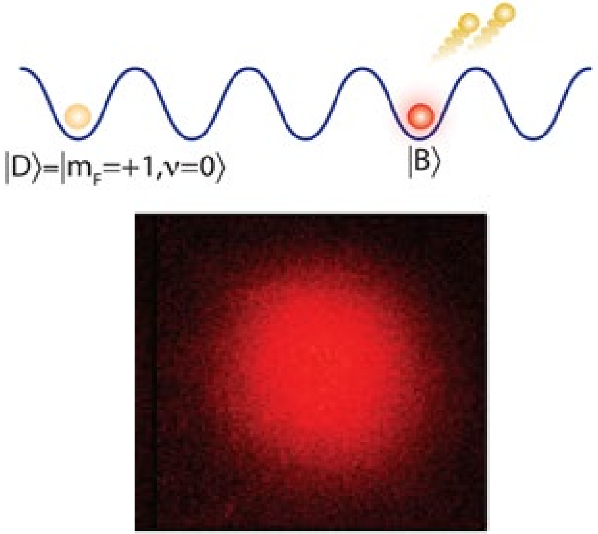
University of Chicago



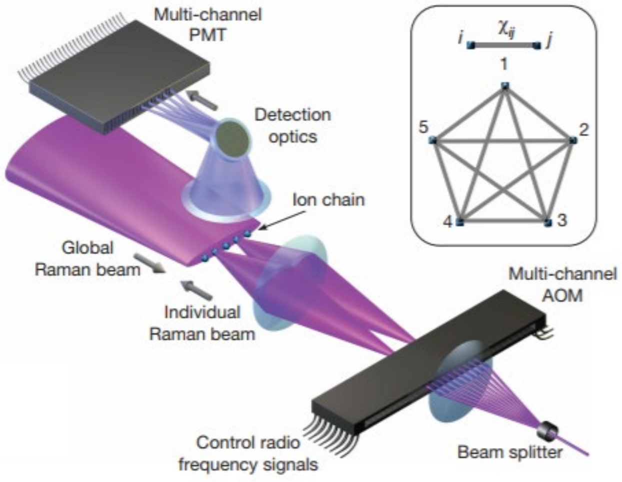
SAMSUNG

SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY

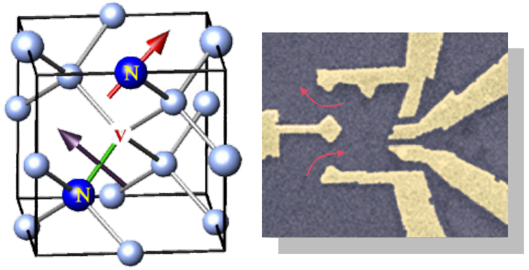
The garden of experimental quantum science



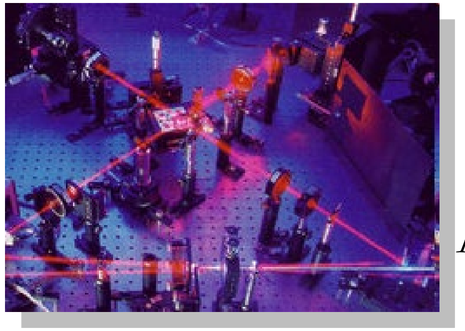
Ultracold atoms



Trapped ions

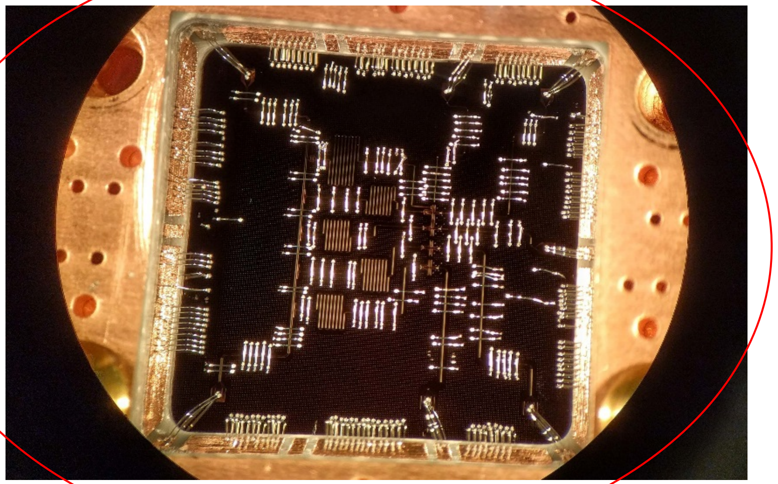


Electron/nuclear spins

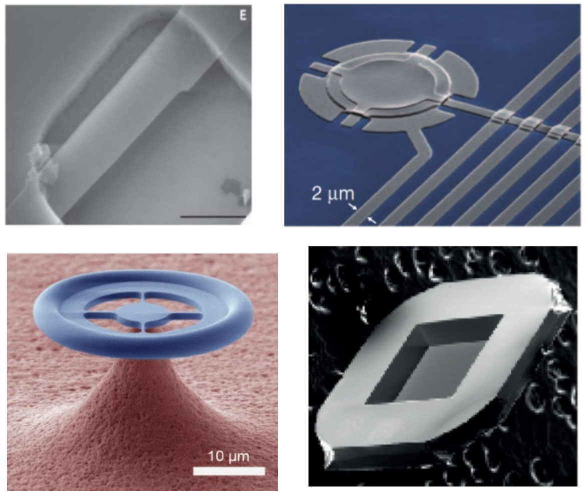


Optical photons

. . .



Superconducting circuits

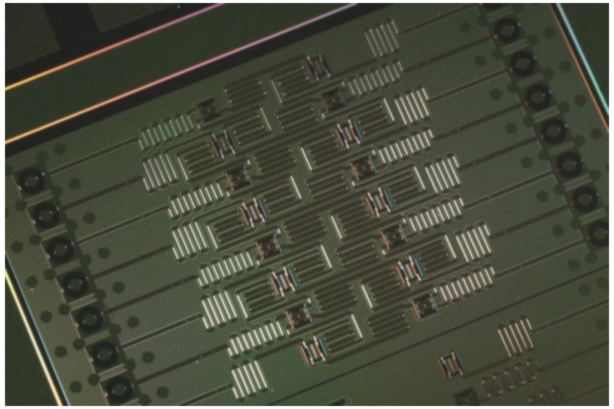


Opto/Electro Mechanical Sytsems

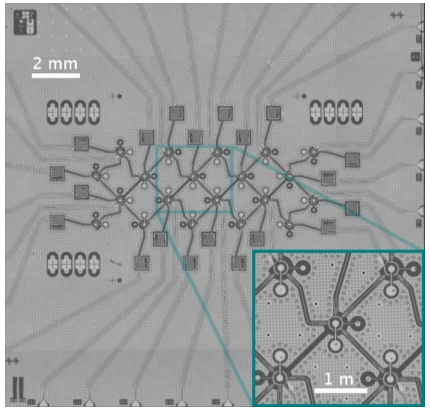
- Wide variety of experimental quantum systems.
- Different applications in quantum technologies

Quantum computing with superconducting circuits

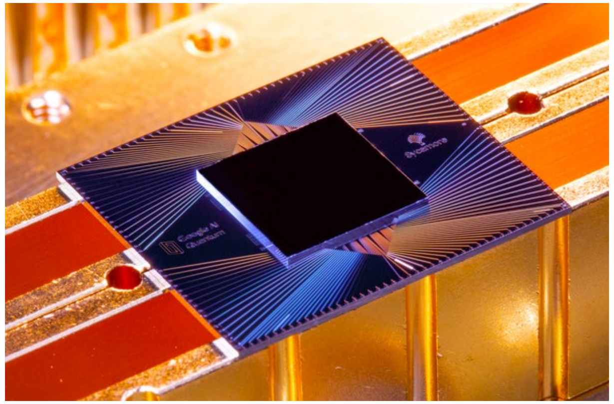
- Rapidly scaling to larger systems (10's of qubits)
- First demonstration of quantum supremacy
- 2D lattice of qubits with nearest neighbor interactions
- Readout using circuit-QED
- Qubits are based on the transmon circuit

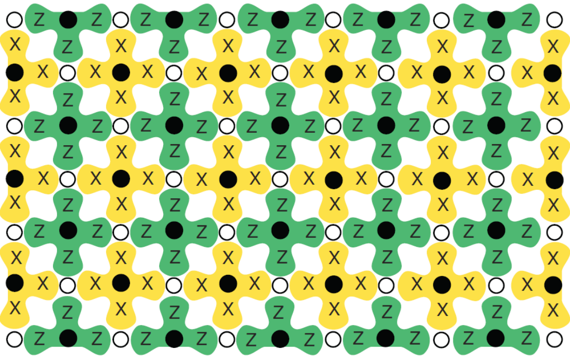


IBM Q Experience



Rigetti





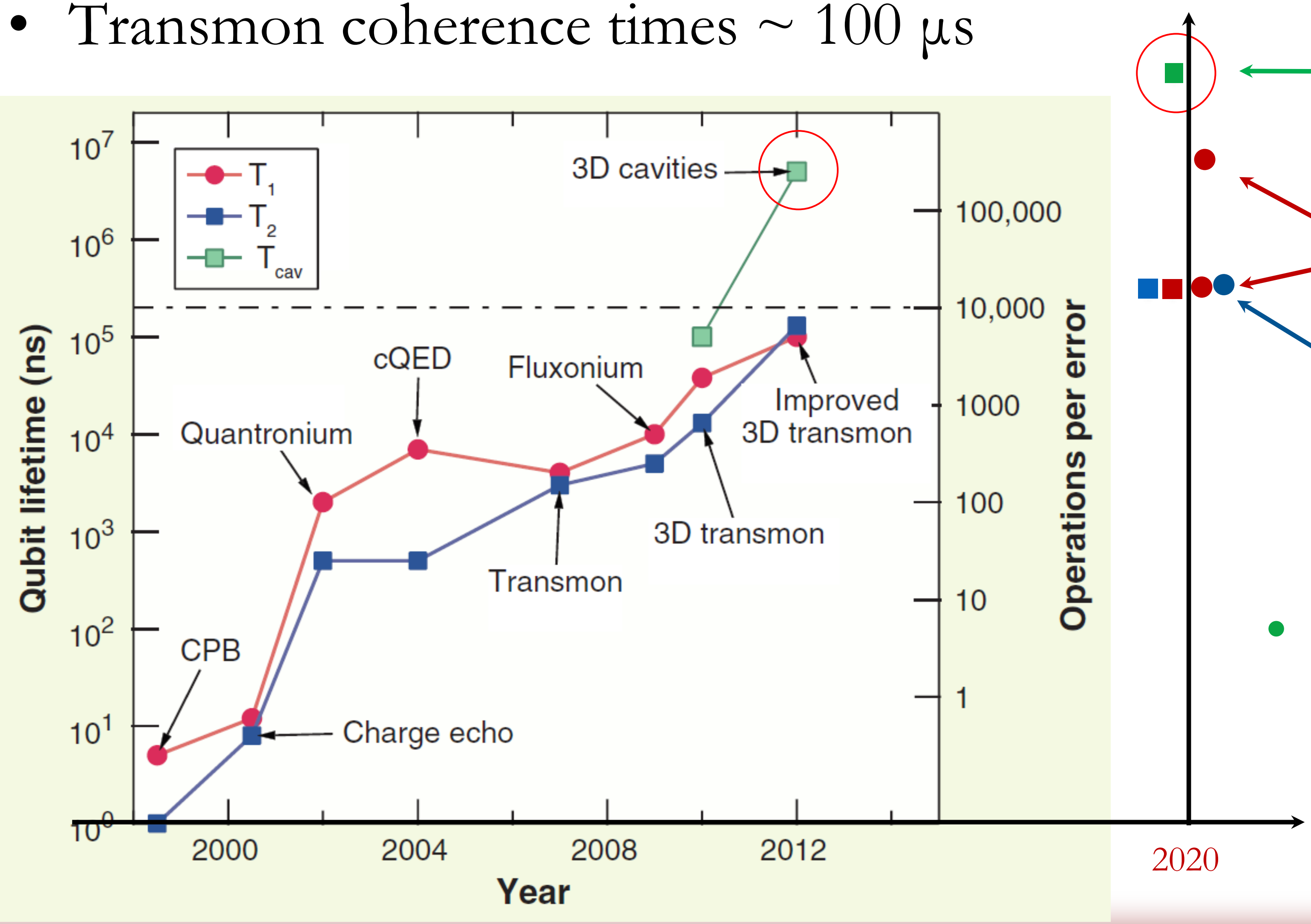
Google/UCSB

Moore's law for superconducting qubits

- 10x improvement in coherence every 3 years

Devoret, Schoelkopf, Science (2013)

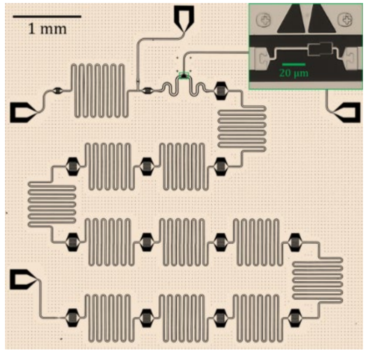
- Transmon coherence times ~ 100 μs

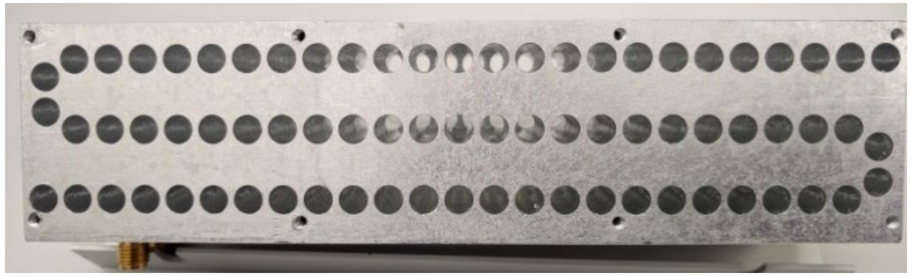


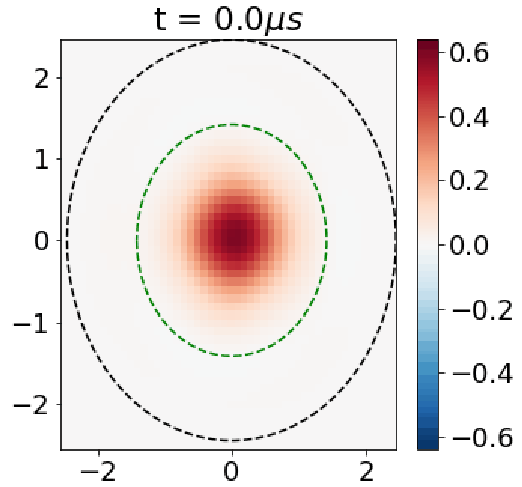
- Cavities still have the best coherences

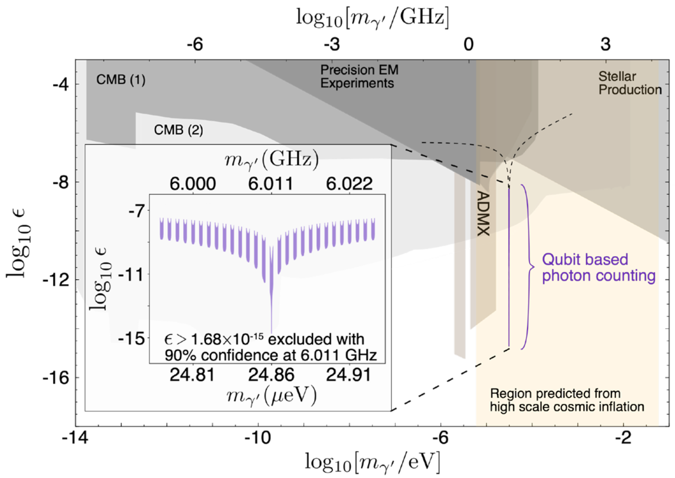
Outline

- Physics of superconducting qubits
- Random Access Quantum computer with cavities
- Controlling single microwave photons with a qubit
- Detecting single (dark) photons with a qubit



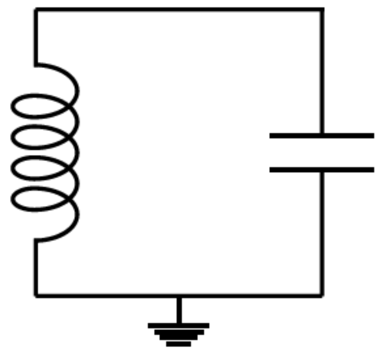


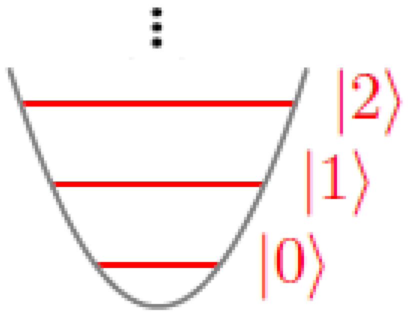


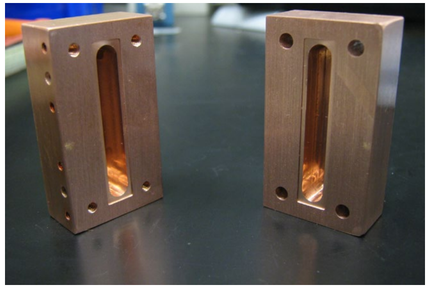


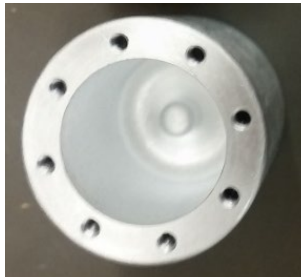
Microwave photons in a superconducting box

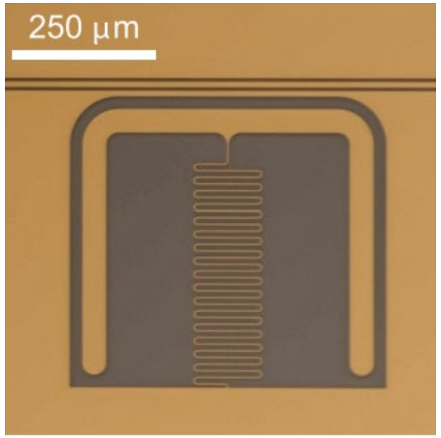
- Simplest superconducting circuit
  → LC oscillator
- Single resonant mode of any box
- Many types of "boxes"

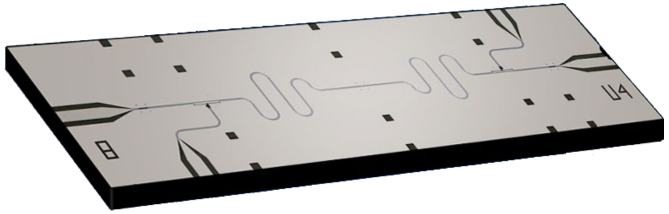


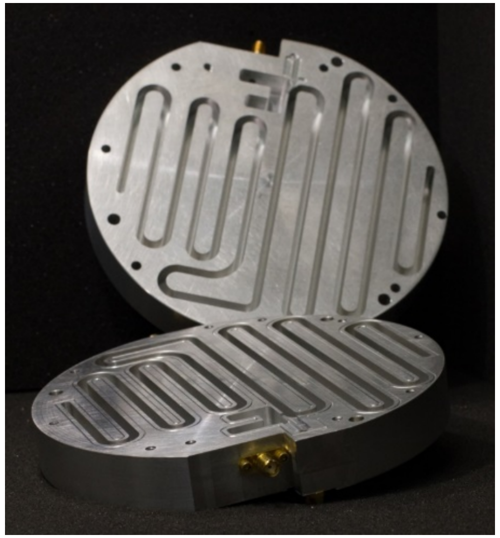


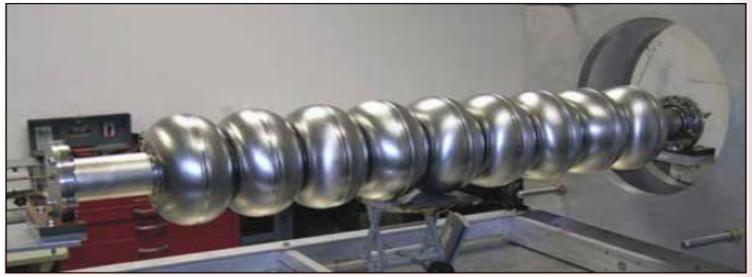


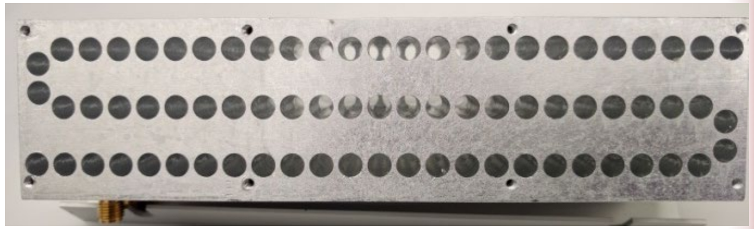






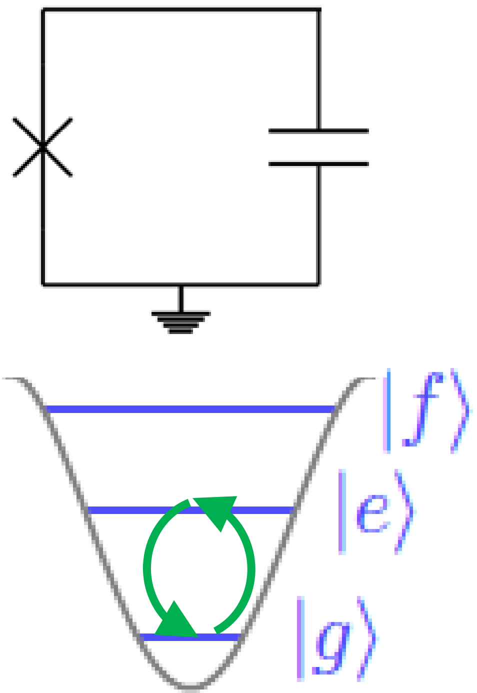




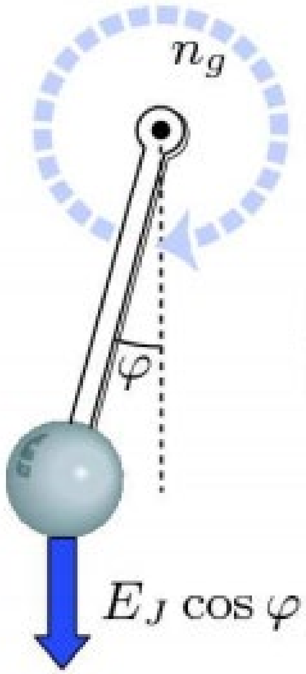


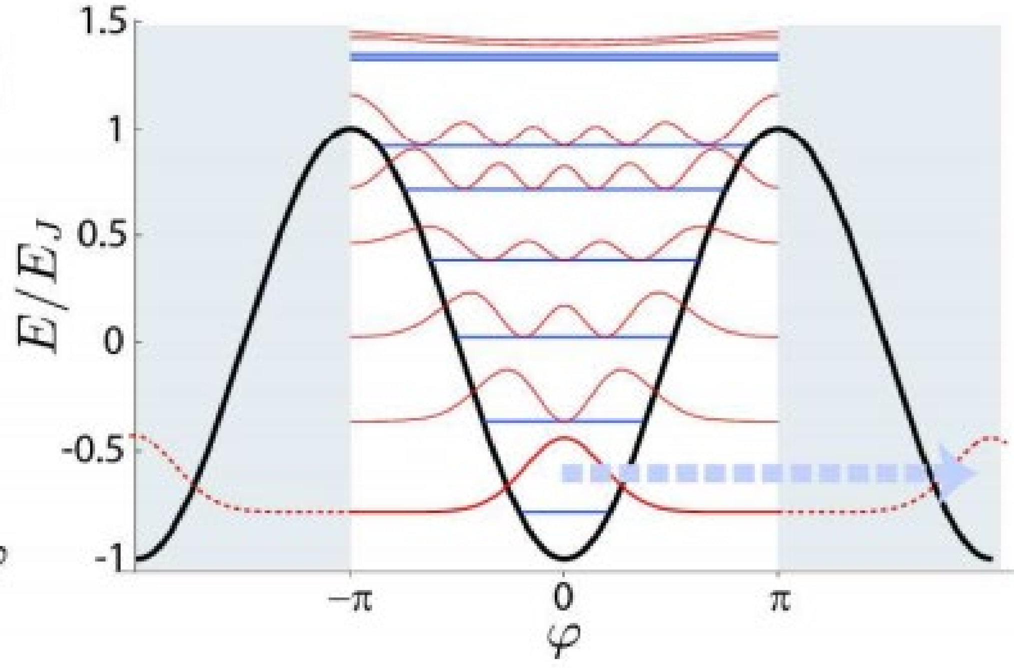
Superconducting qubits

- Transmon the simplest superconducting qubit
- Key element – Josephson junction
- Phase difference – macroscopic quantum DOF
- Junction acts as a nonlinear inductor



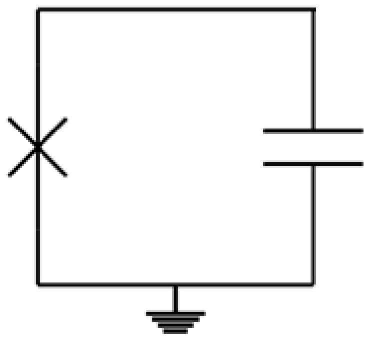
$\omega_{ge} \neq \omega_{ef}$

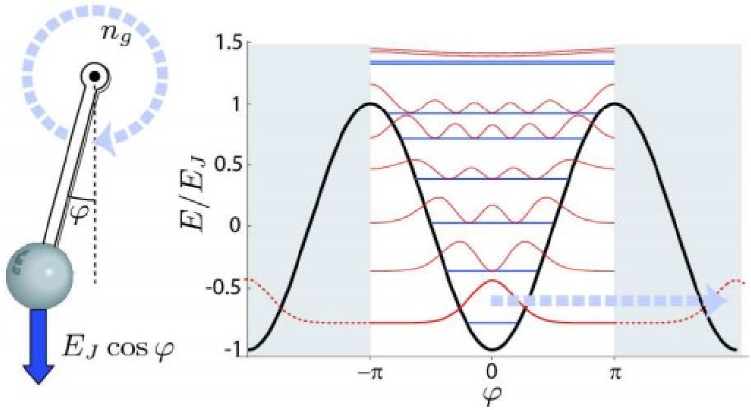


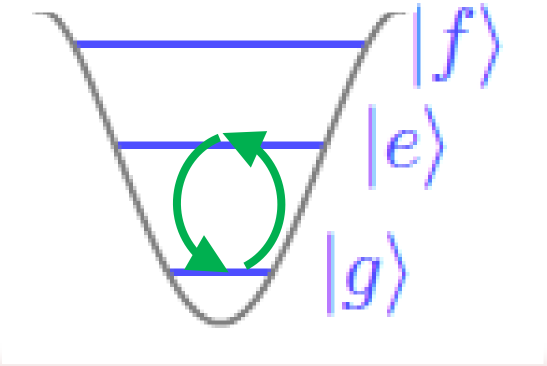


Superconducting qubits

- Transmon is the simplest superconducting qubit
- Key element is the *Josephson Junction*
- Phase difference – macroscopic quantum DOF
- Junction acts as a nonlinear inductor

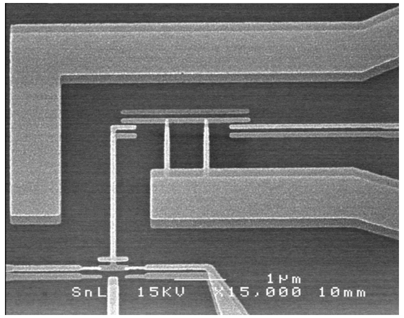




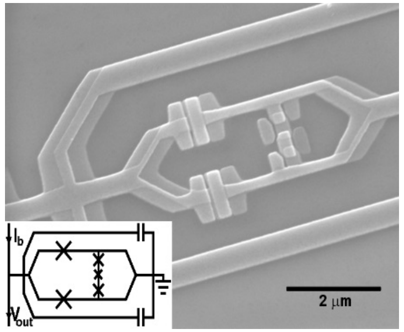


$$\omega_{ge} \neq \omega_{ef}$$

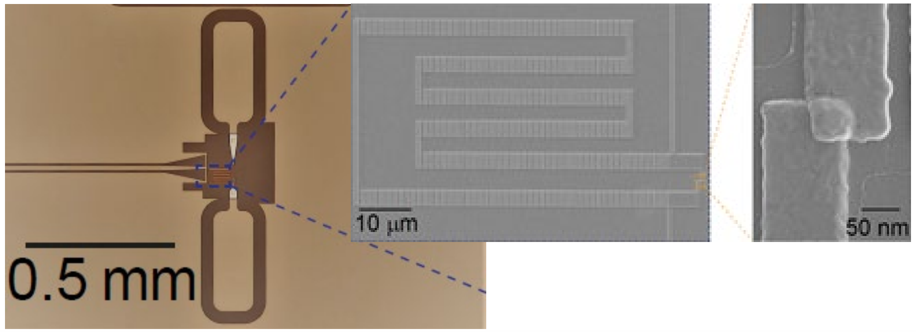
Many flavors of qubits



Charge



Flux qubit

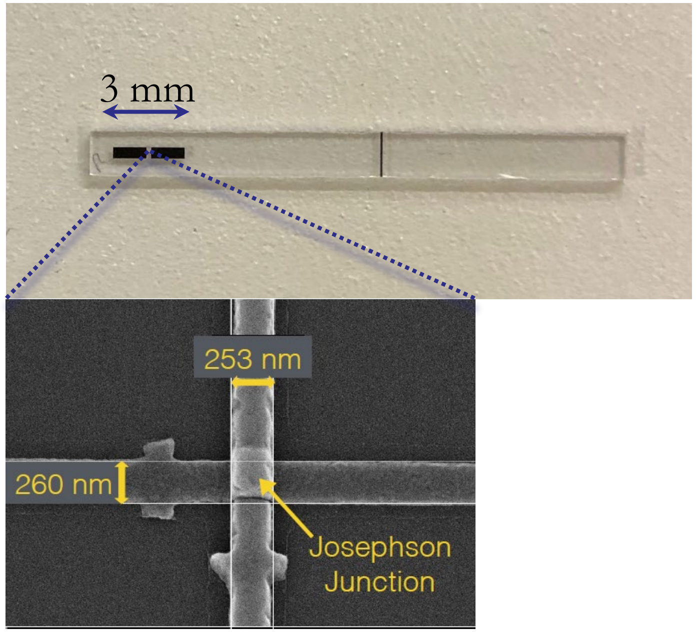


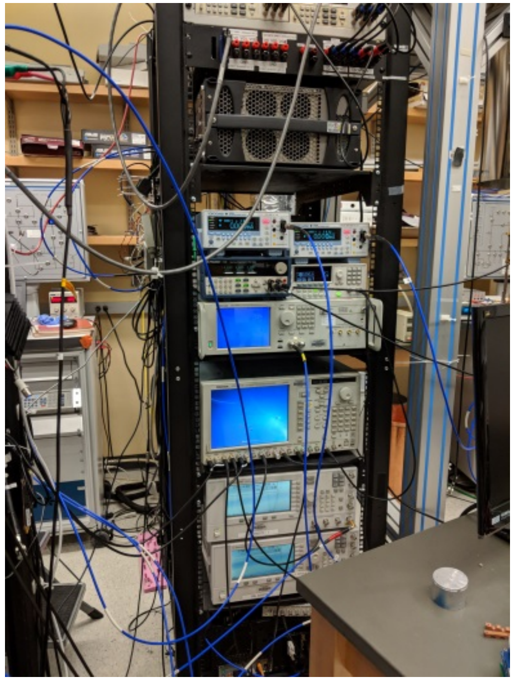
Fluxonium

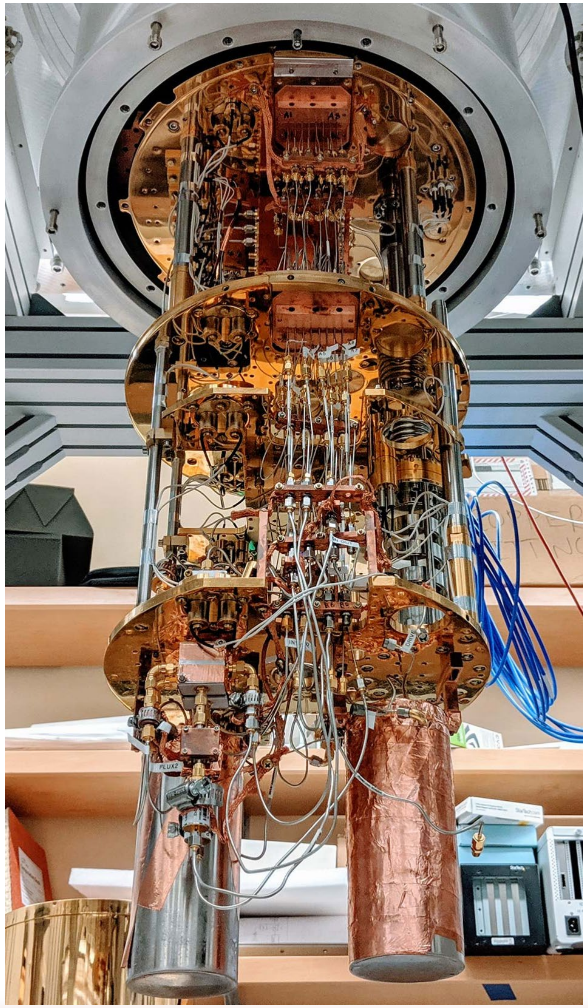
Ingredients for superconducting quantum information

- Macroscopic artificial atoms
- Large dipole moments/fast operations
- Operate at cellphone frequencies
- Sophisticated microwave control
- Cooled in a dilution refrigerator to 10 mK

5-10 GHz = 250-500 mK





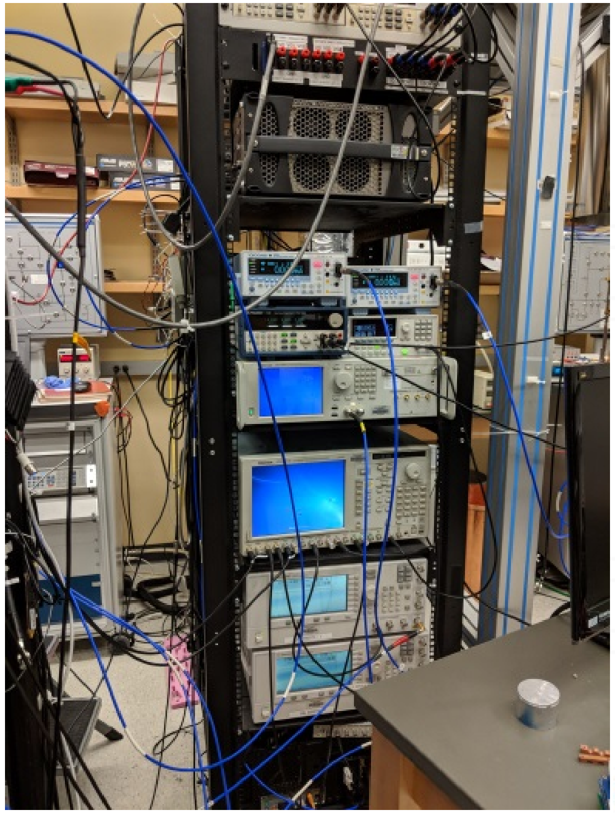


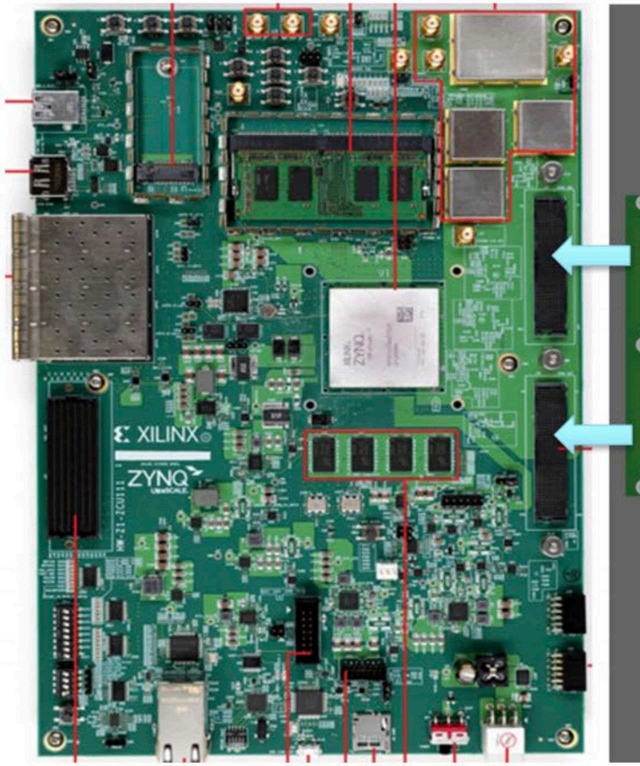
Scaling control electronics with FNAL

Control for 1 qubit ~ $100k

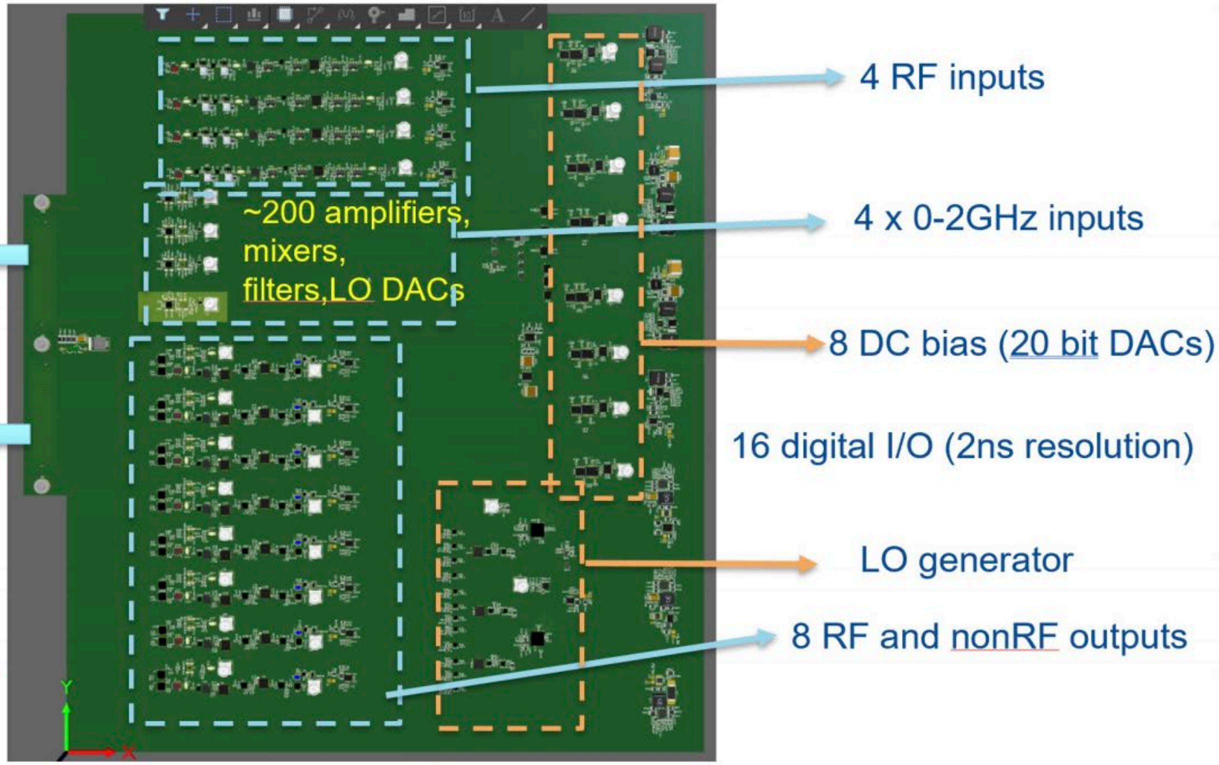
Control for 8 qubits ~ $15k

Future plans for 32 qubits ~ $20k





FPGA+ADC+DAC+memory+interfaces



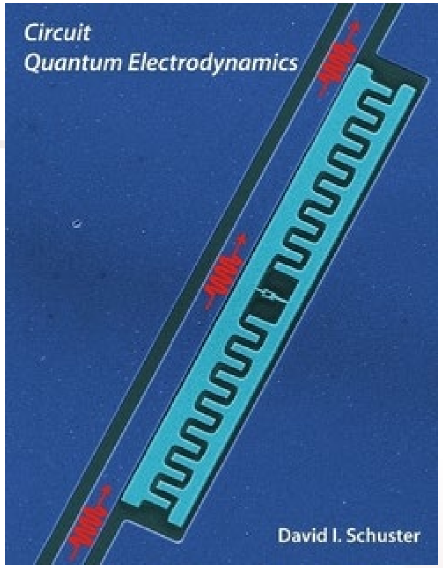
RF inputs, outputs, LO, fast flux control, high precision bias

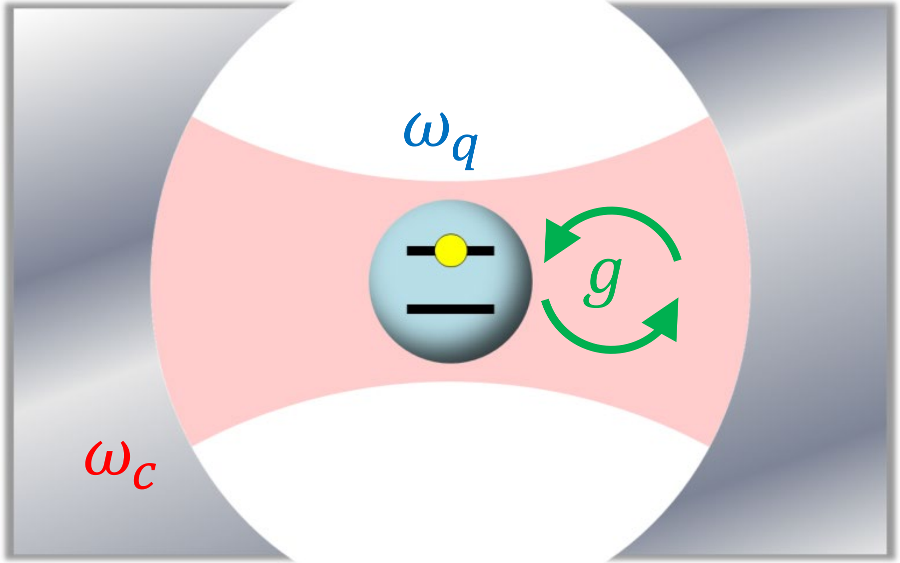
Gustavo Cancelo, Leoandro Steffanazzi, Chris Stoughton, Ken Treptow, Shefali Saxena, Sara Sussman

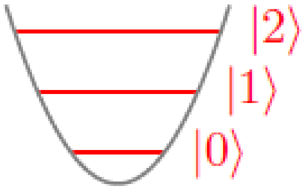
Circuit quantum electrodynamics

- Couple a superconducting qubit to a microwave cavity
- Readout the quantum state of the qubit
- Protects the qubit from the environment

$$H = \omega_c\left(a^\dagger a + \tfrac{1}{2}\right) + \tfrac{1}{2}\omega_q\sigma_z + g\left(\sigma_+ a + \sigma_- a^\dagger\right)$$



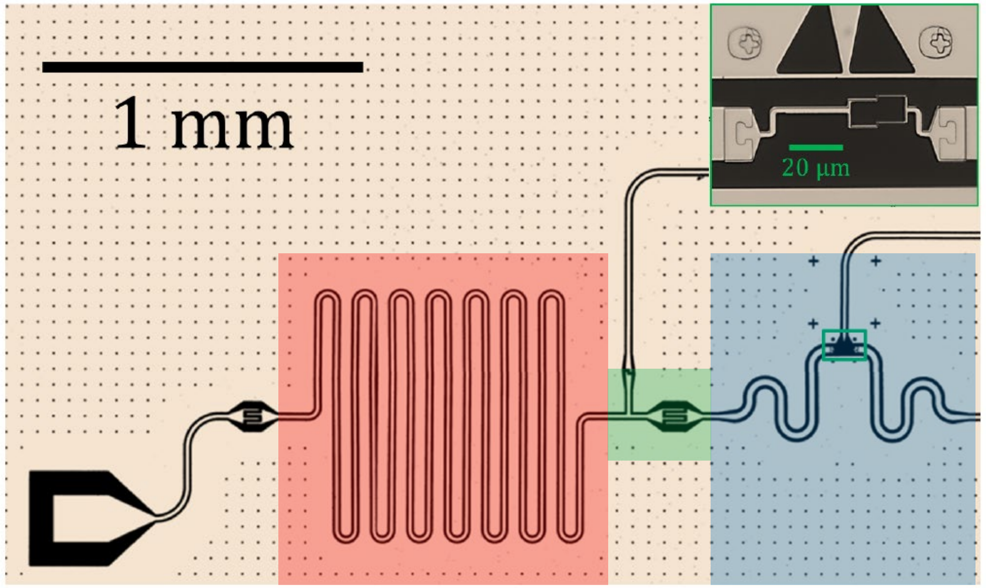


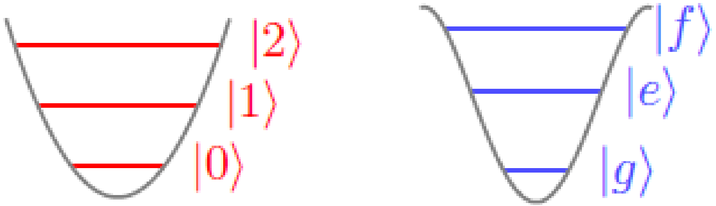


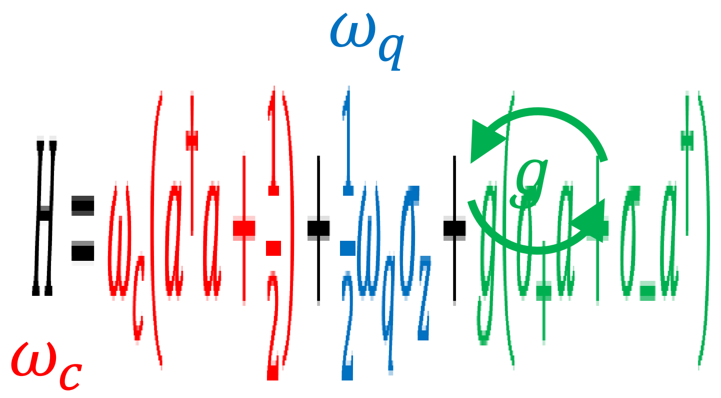
Circuit quantum electrodynamics

- Cavity-QED with a macroscopic atom
- Cavity size ~ wavelength

$$H = \omega_c\left(a^\dagger a + \tfrac{1}{2}\right) + \tfrac{1}{2}\omega_q\sigma_z + g\left(\sigma_+ a + \sigma_- a^\dagger\right)$$



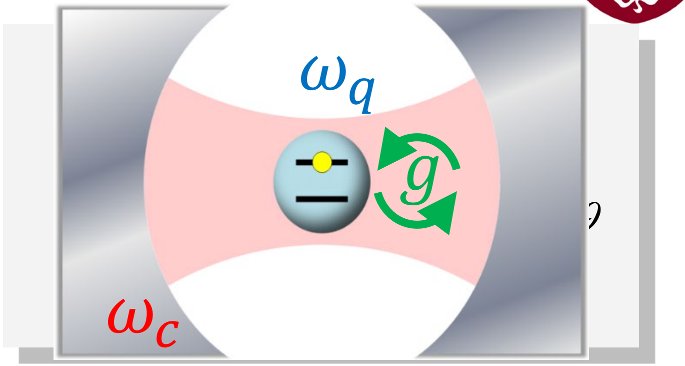




Circuit quantum electrodynamics

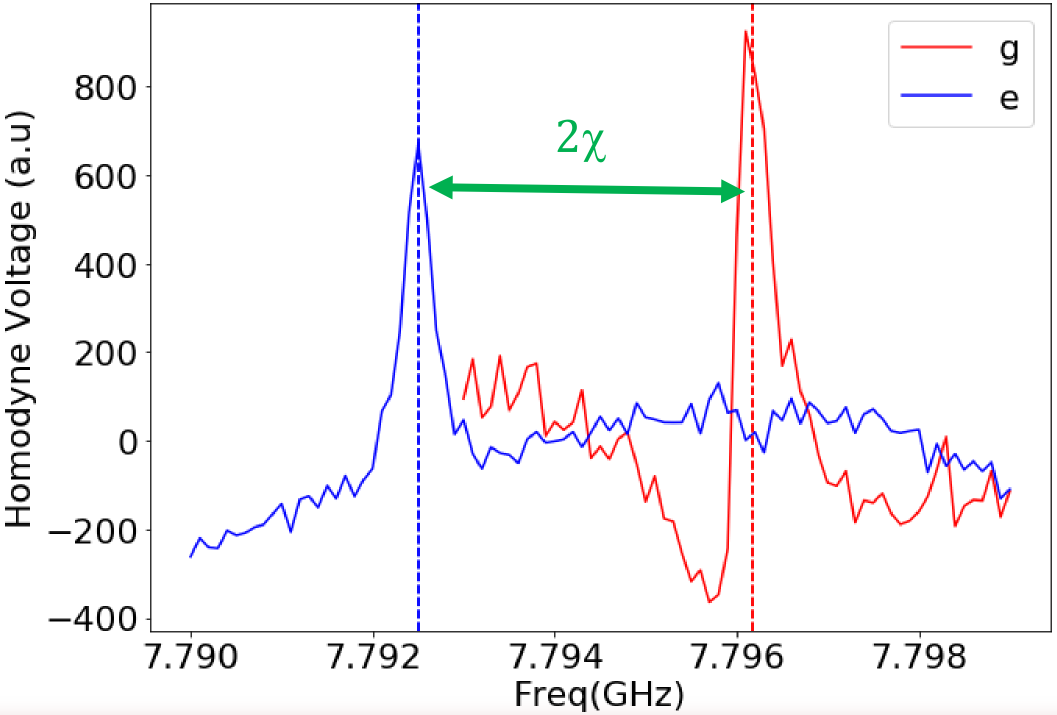
- Dispersive limit - qubit and cavity are off-resonant

$$H_I = \omega_c\left(a^\dagger a + \frac{1}{2}\right) + \frac{1}{2}\omega_q \sigma_z + g\left(\sigma_+ a + \sigma_- a^\dagger\right)$$

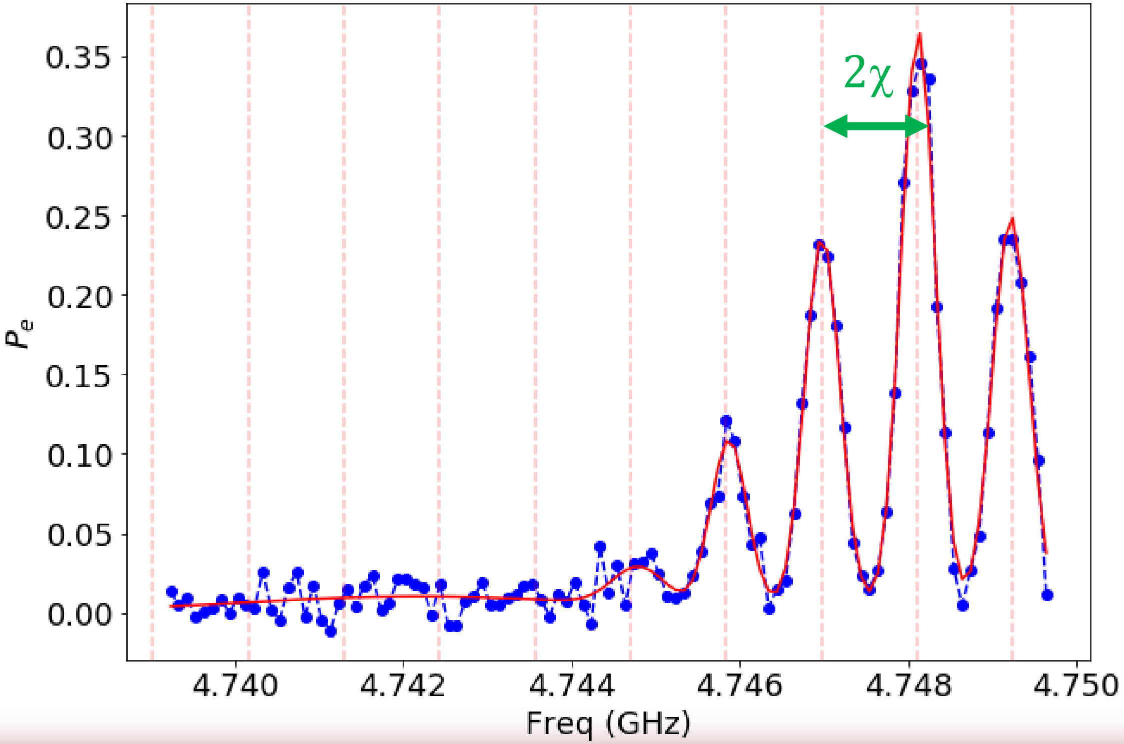


- Quantum non-demolition readout

Cavity frequency shift based on qubit state

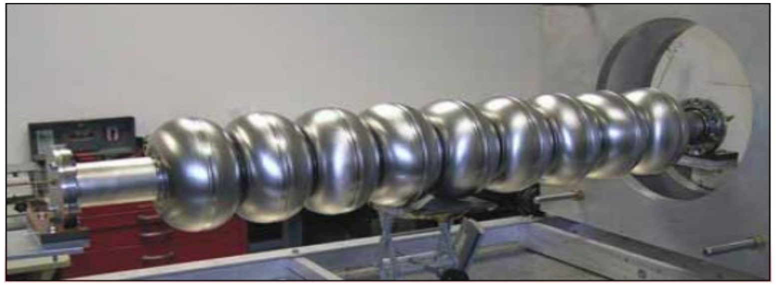


Qubit frequency shift due to photon number

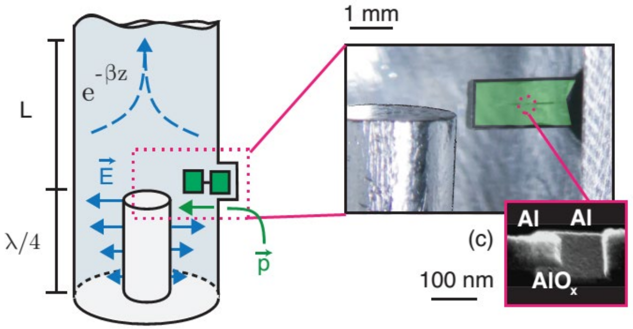


Microwave cavities as quantum memories

- Large single photon lifetimes
  - ➢ Coaxial quarter wave cavities
  - – Q ~ 100 million
  - – T_1 ~ 1-2 milli seconds
  - ➢ Fermilab accelerator cavities
  - – Q = 20 billion @ 1.3 GHz
  - – T_1 ~ seconds
- Controlled with superconducting qubits



A. Romanenko et al., arXiv:1810.03703v1
D. Gonella et al., JoAP (2016)



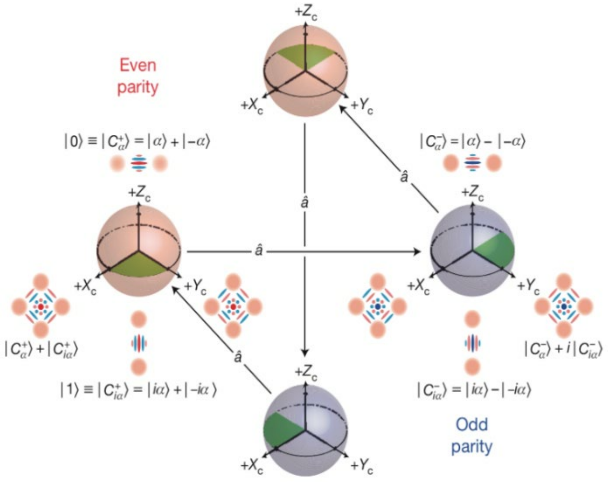
M. Reagor et al., PRB (2016)

Microwave cavities as quantum memories

- ➢ Large single photon lifetimes
- ➢ Control with superconducting qubits
- ➢ Restricted set of decay channels
- ➢ Bosonic quantum error correction

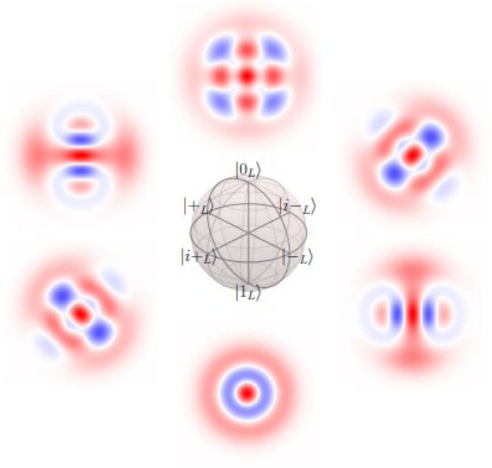
- Logical qubit - multiphoton states
  - – Same mean photon number
  - – Same parity
- Parity = Error syndrome

Cat code



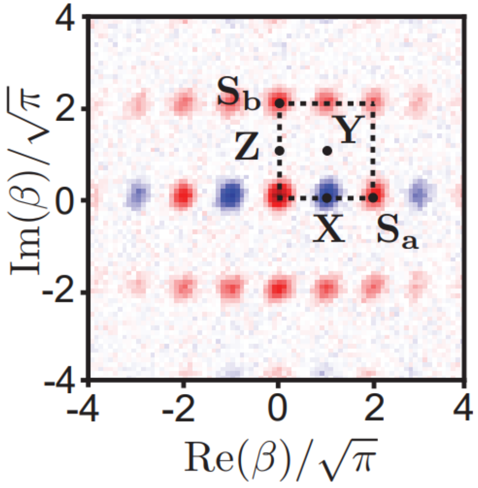
N. Ofek et al., Nature (2016)

Binomial code



S. Rosenblum, P. Reinhold et al., Nat. Comm. (2017)

GKP code



Pioneered @ Yale

P. *Campagne-Ibarq et al., arXiv:1907.12487*

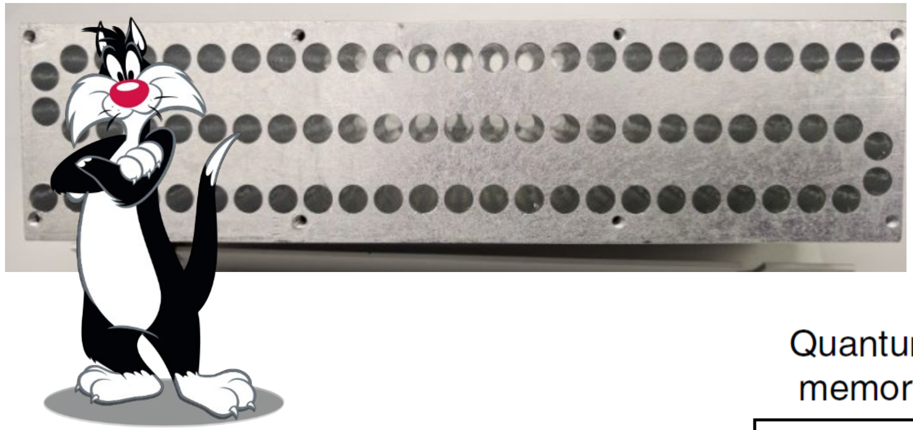
Multimode cavities as a quantum resource

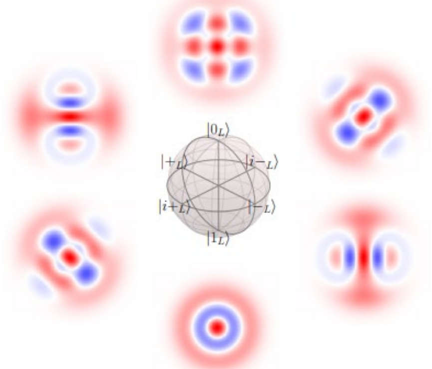
- Large Hilbert space
- High coherence
- Hardware efficient control of 10's of bits
- Multiplexed control using single transmon

➢ Random access quantum information processors

➢ Multimode bosonic quantum error correction

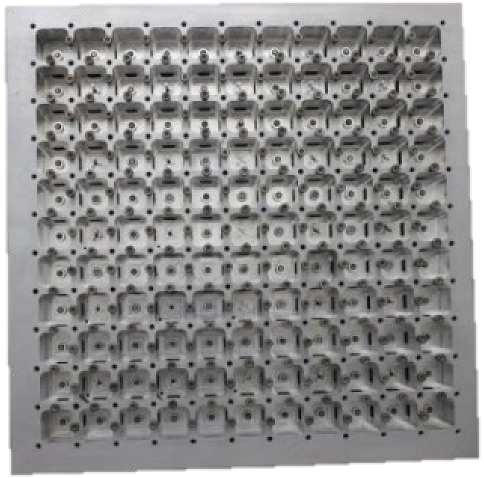
➢ Quantum simulations with photons

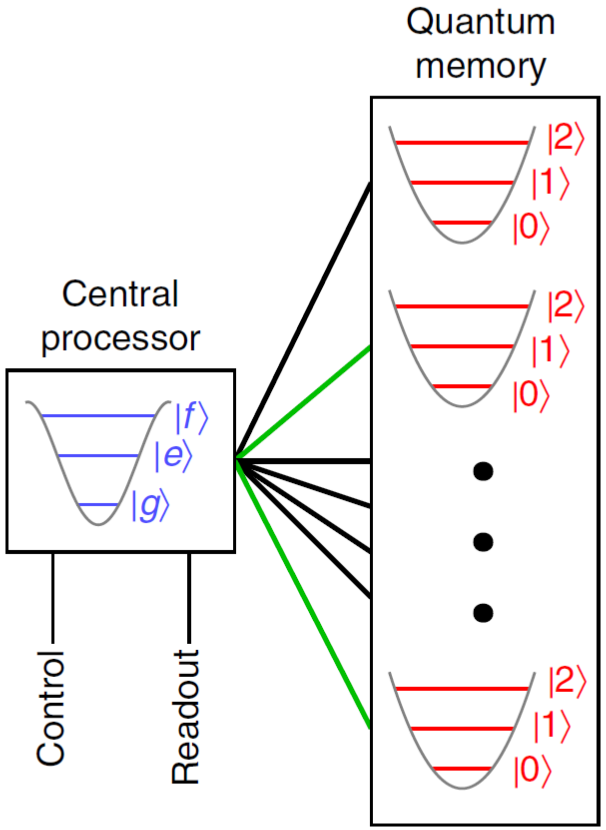




Topological lattices:

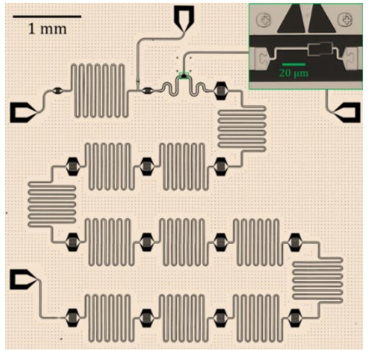
C. Owens et. al, Phys. Rev. A (2018)

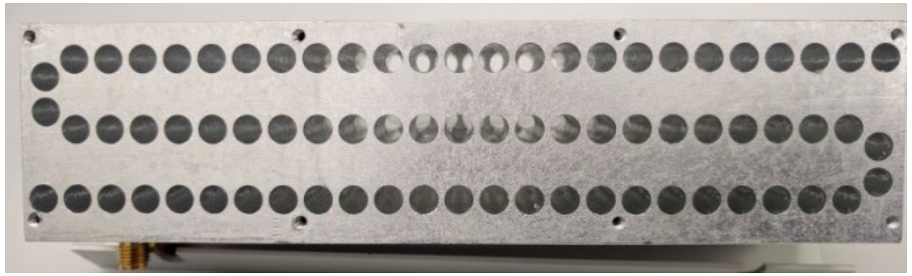


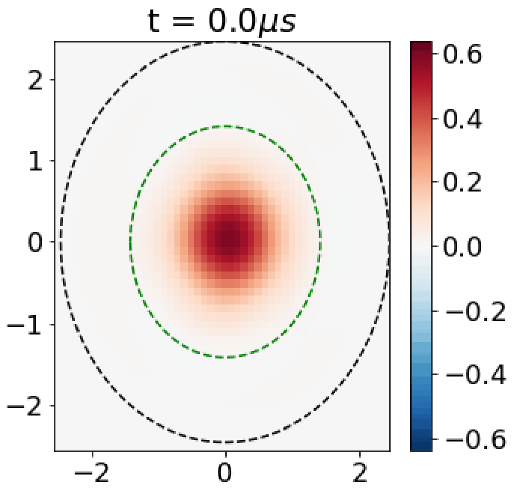


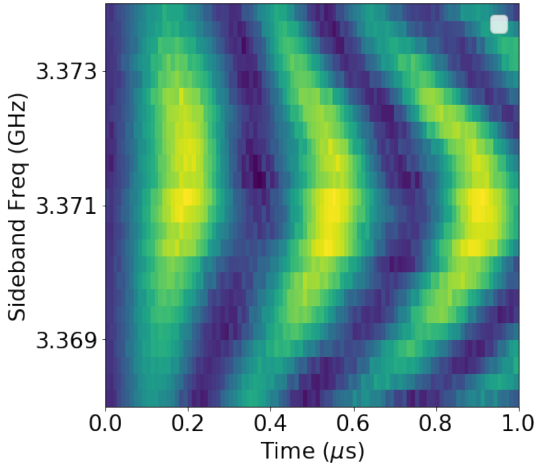
Outline

- Random access quantum information processor
- Seamless multimode flute cavities
- Quantum control using a transmon
  - Resonant sideband interactions
  - Photon blockade
  - Optimal control
  - Dressed multimode interactions

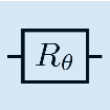
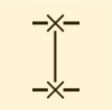




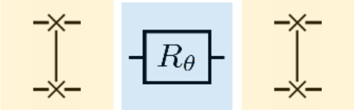




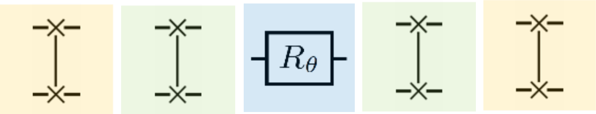
Schematic outline of how a quantum computer from multimode cavities

- Only two types of operations
  - Transmon rotation 
  - Transmon-cavity SWAPs 

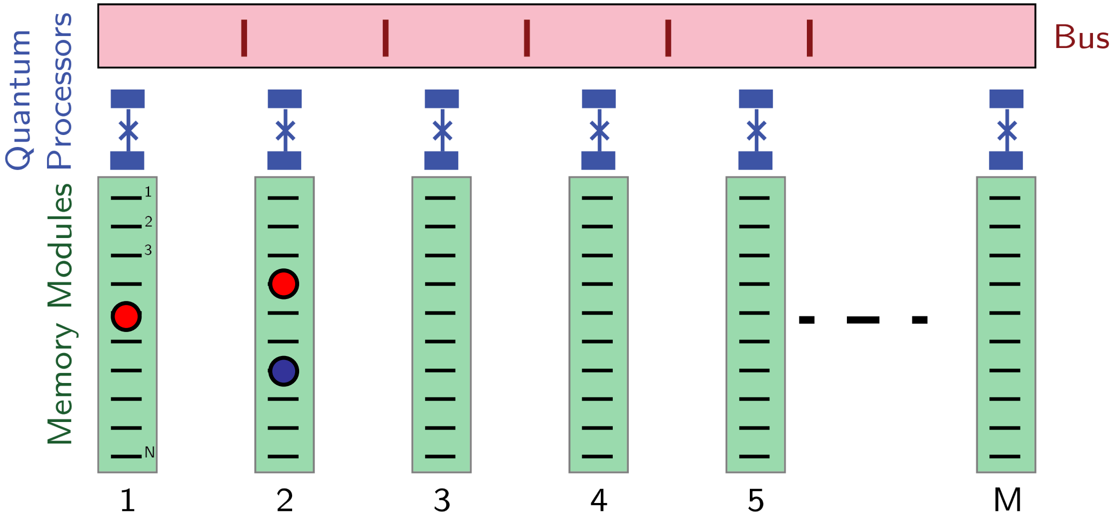
- Single qubit gate



- Intra-module two qubit gate



$|e1\rangle$ - $|f0\rangle$ $|e1\rangle$ - $|f0\rangle$

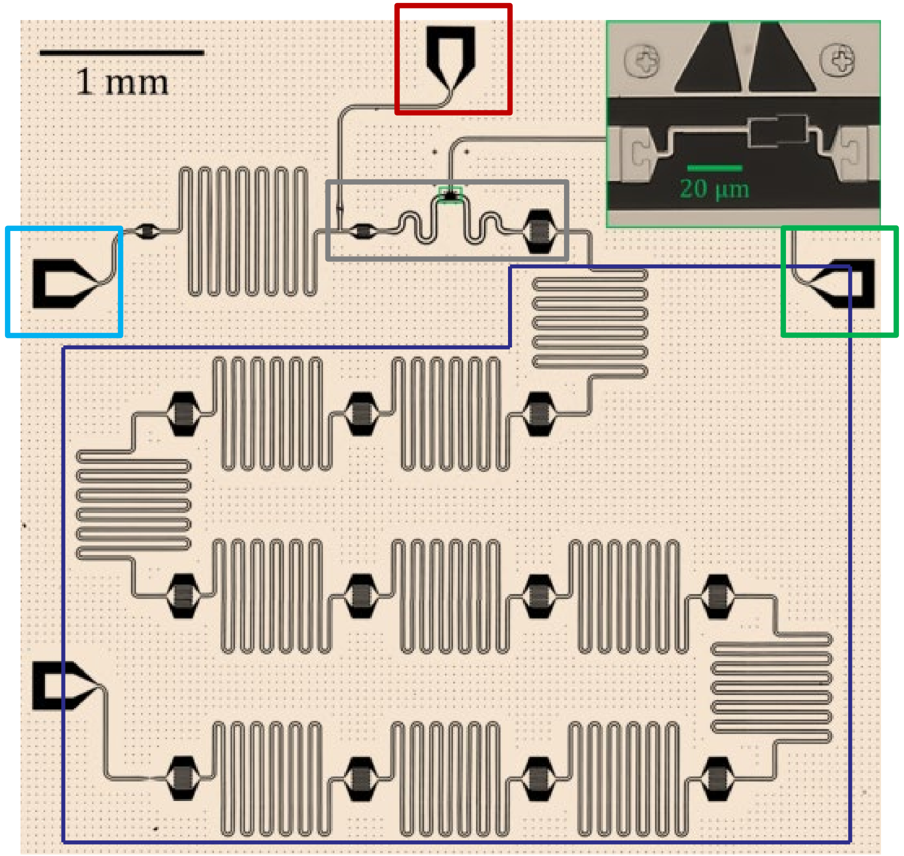


Platform for understanding how memory works in quantum computers

- Qubits are at most 2 hops away from another
- Can run M instructions in parallel
- Inter-module almost as fast as intra-module

Random access quantum information processor

- Strongly coupled chain of resonators
- Memory bits are photons in *momentum* states
- Multiplexed control from the chain edge
  - ➢ 1 Transmon
  - ➢ 1 Charge port
  - ➢ 1 Flux port
  - ➢ 1 Measurement channel
- Universal Operations



R. Naik, N. Leung*, **S.Chakram**** *et. al., Nat. Comm. (2017)*

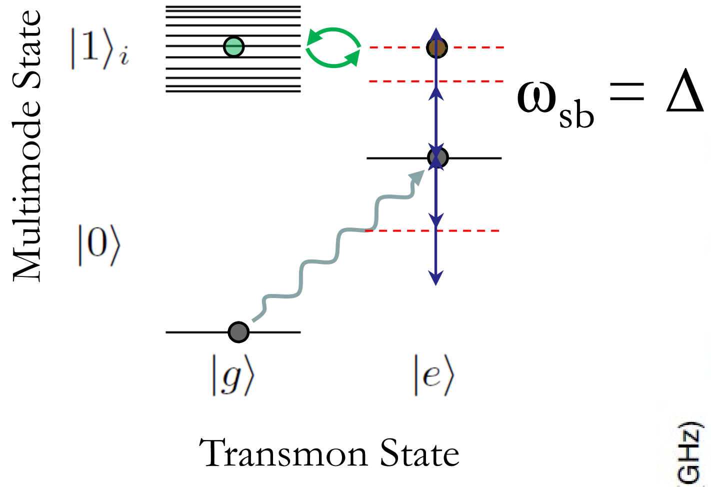
Stimulated Vacuum Rabi Oscillations

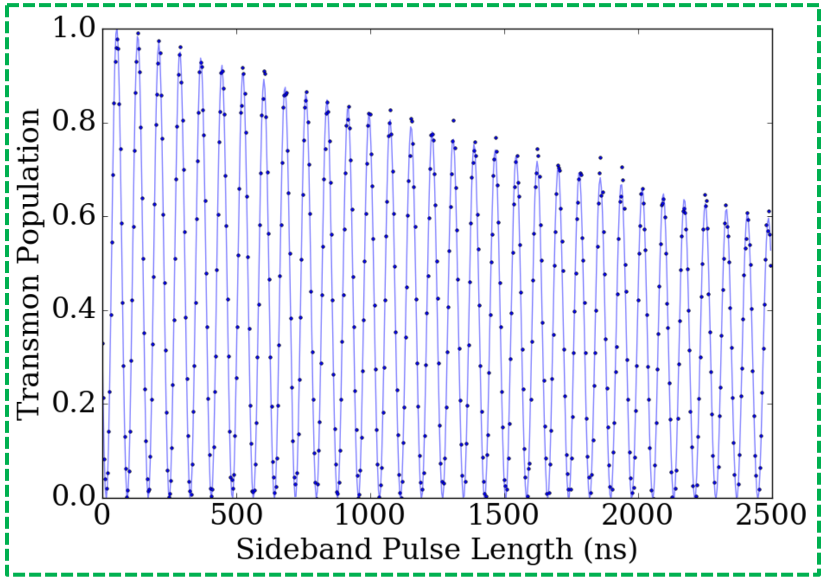
- RF flux modulation

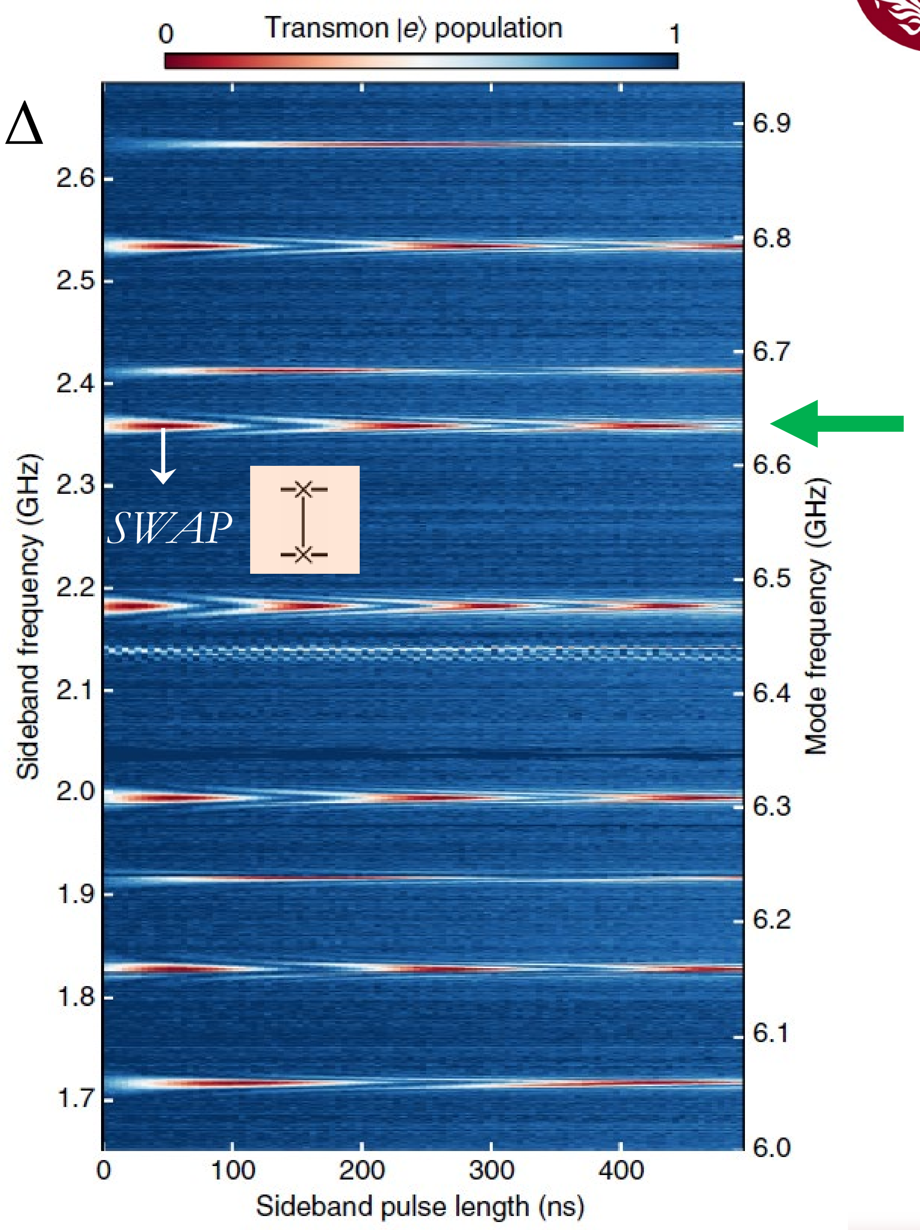
$$\omega_q(t) = \omega_q^0 + \epsilon \sin(\omega_{sb} t)$$

- Resonant interactions

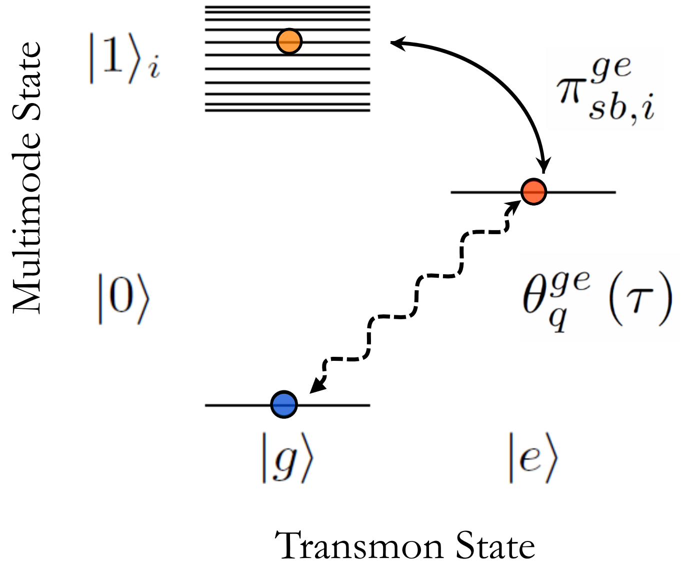
$$g_{\text{eff}} = g J_1 \left(\frac{\epsilon}{2\omega_{sb}} \right)$$



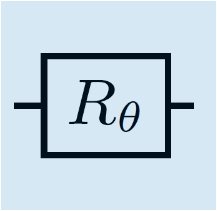




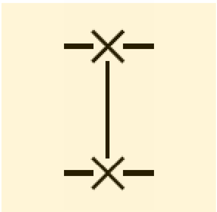
Single mode gate operations

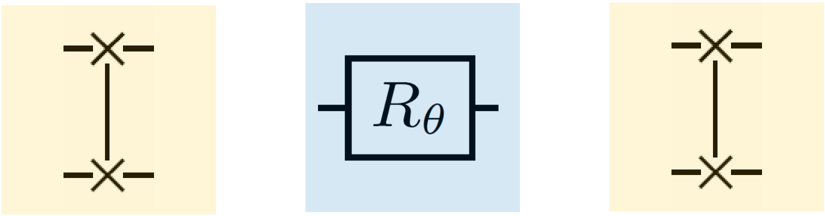


- Transmon rotations



- Sideband SWAPs



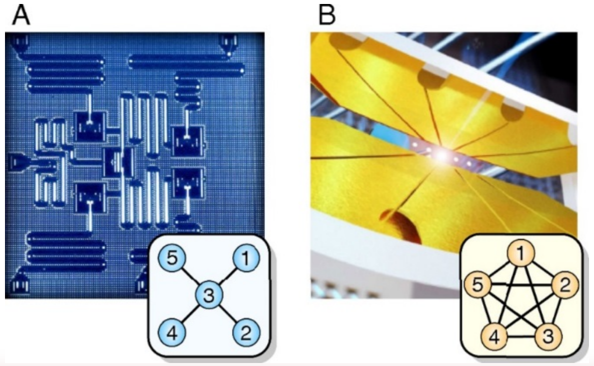


Two mode gates

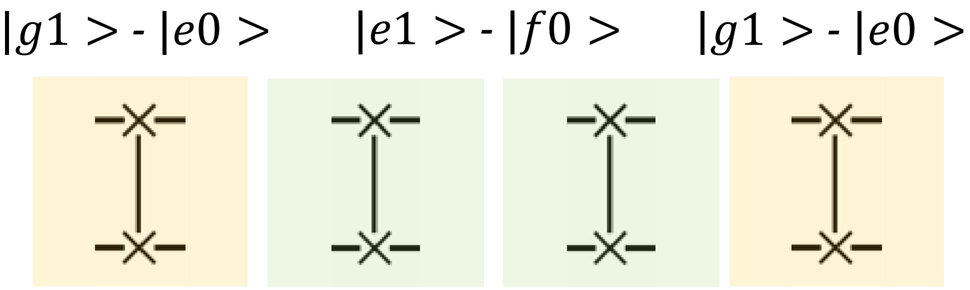
- Conditional operation using $|e1>$ - $|f0>$ SWAPS

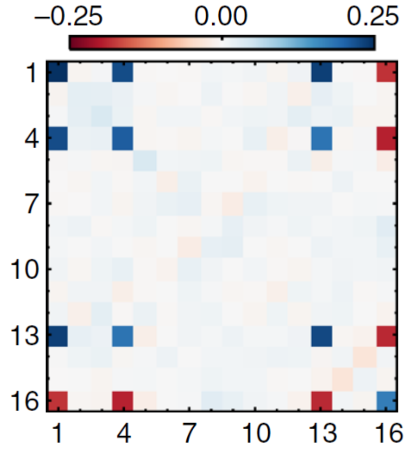
- Reconfigurable 2-qubit gates
  - CZ
  - CNOT
  - iSWAP

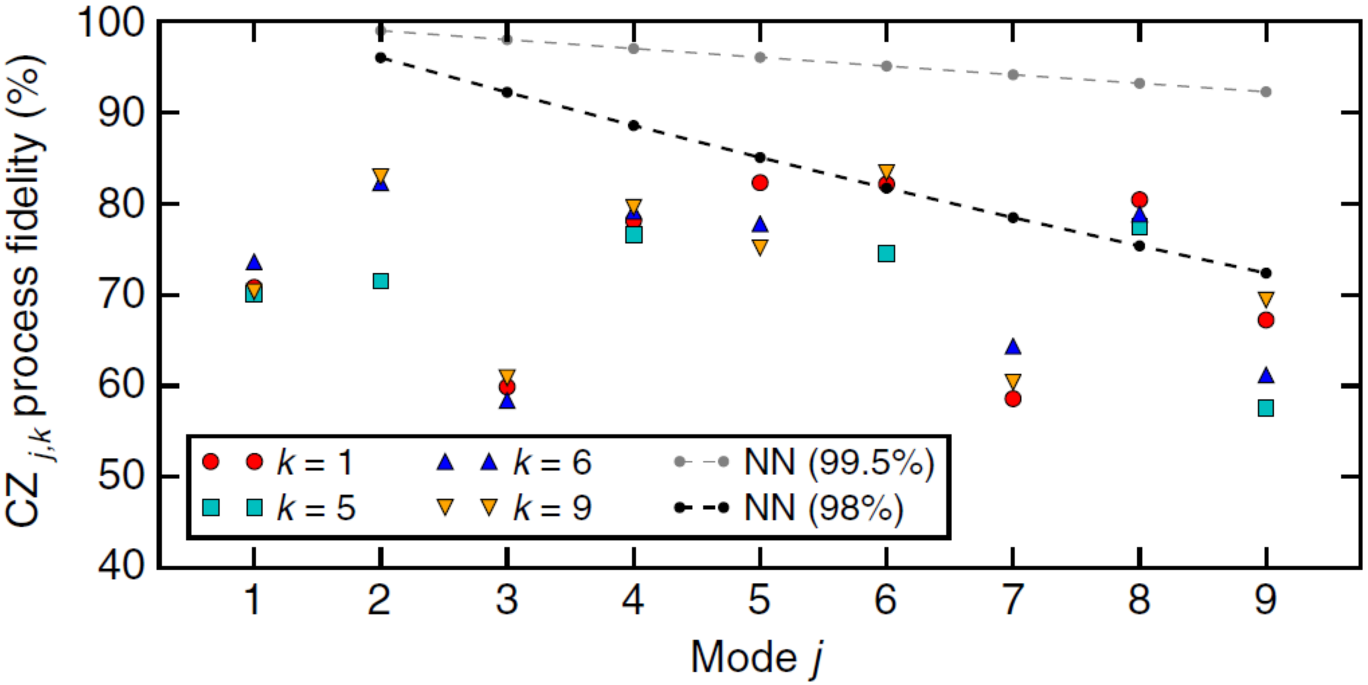
- Random access advantage



Linke, Norbert M., et al. PNAS (2017)







Two mode gates

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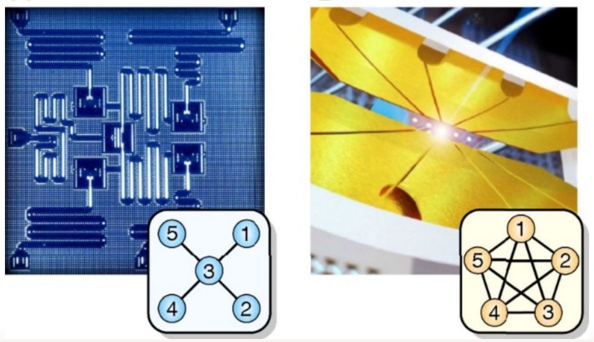
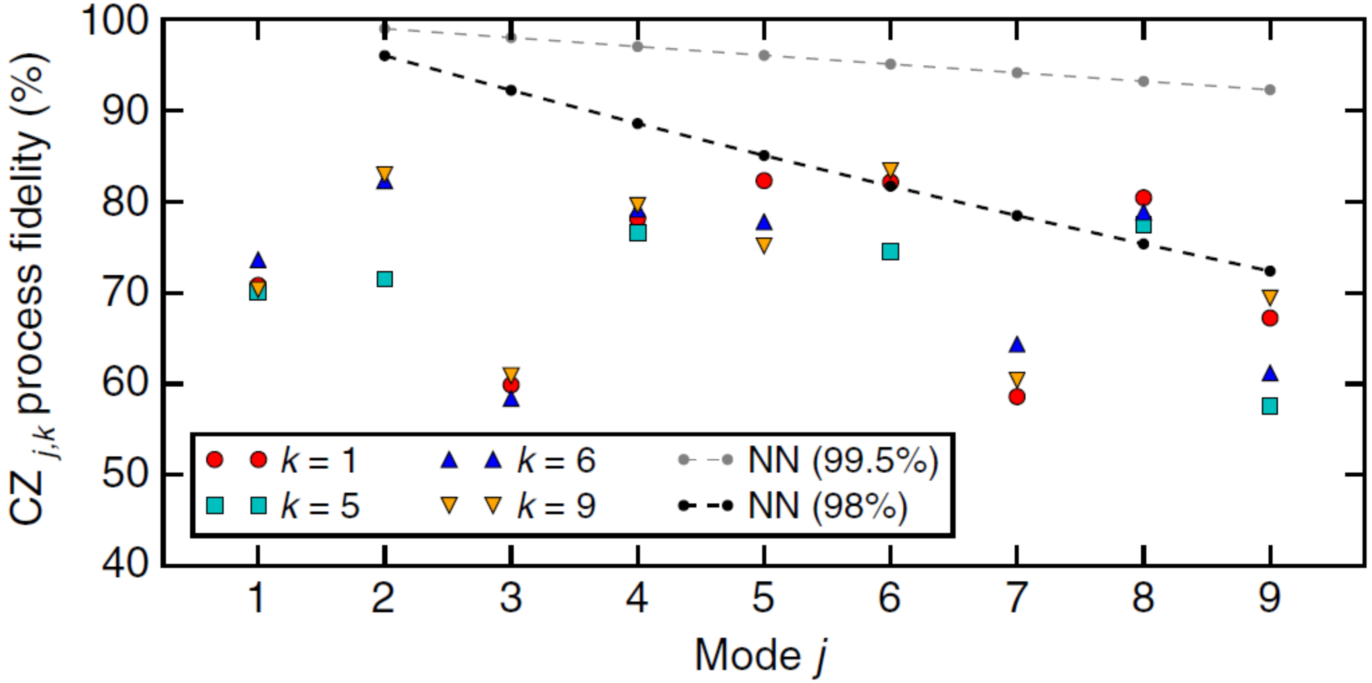


Linke, Norbert M., et al. PNAS (2017)

- Limited by the coherence times of the cavity modes.

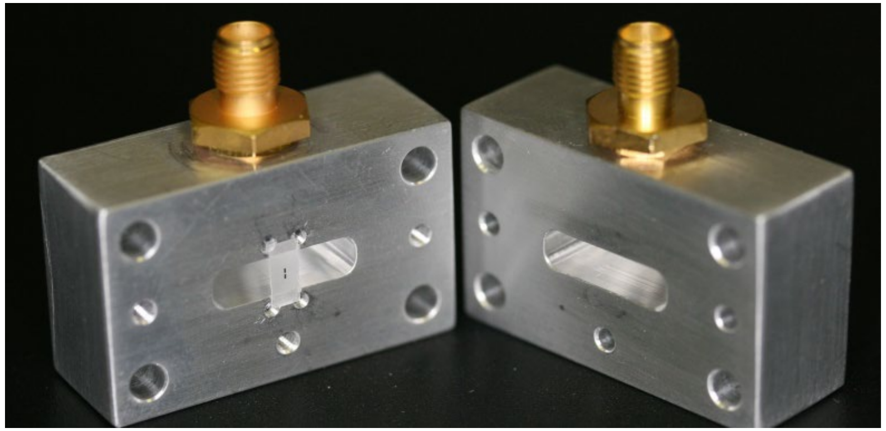
T_1^{mm} = 1-8 μs, T_2^{mm} = 5-8 μs
T_1^{q} = 10 μs, T_2^{*q} = 1.2 μs

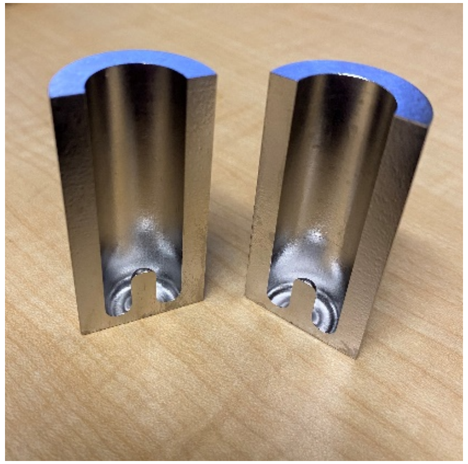
Use 3d cavities!

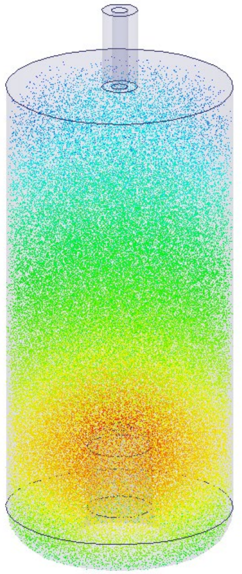


Seamless cavities

- Three principle sources of loss in 3D cavities:
  - Dielectric
  - Conduction
  - Seam
- Traditional 3D cavities suffer from loss at seam between pieces of the cavity
- Monolithic coaxial quarter-wave cavities minimize seam loss
- How to create arbitrary geometries seamlessly?





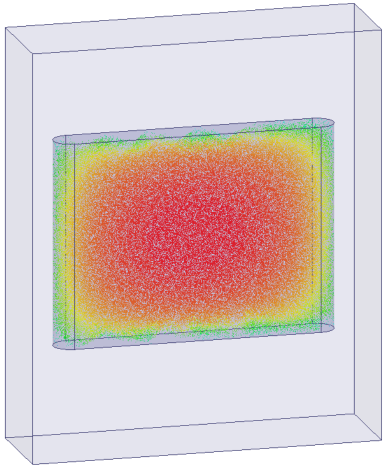


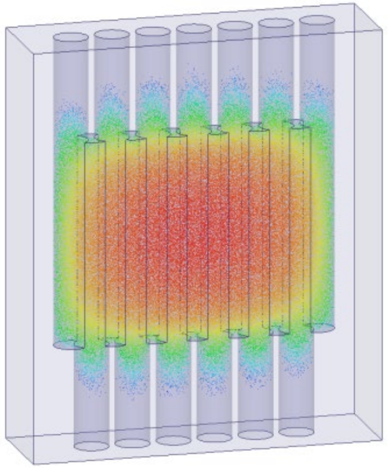
Q ~ 100-200 million
T_1 ~ 1-5 milliseconds

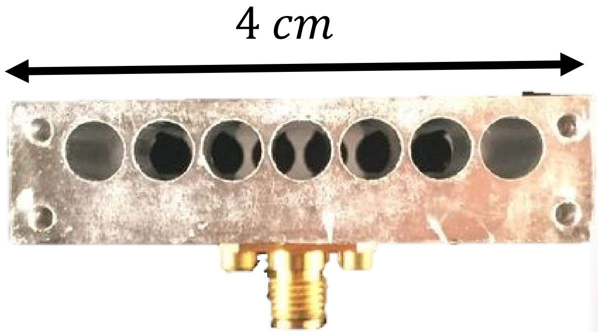
The Flute Method for Fabricating Seamless Cavities

- Rectangular waveguide

Q ~ 20-95 million

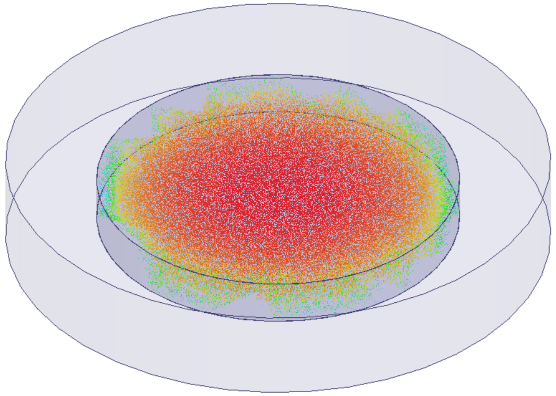


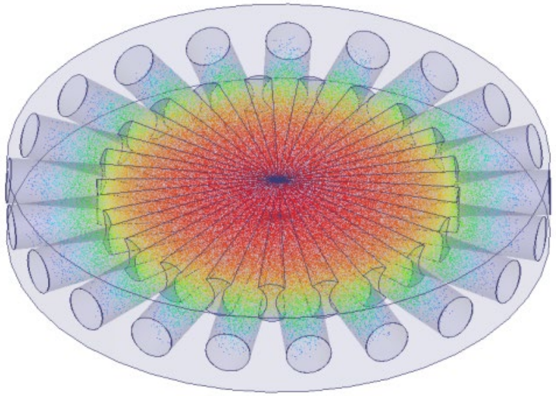




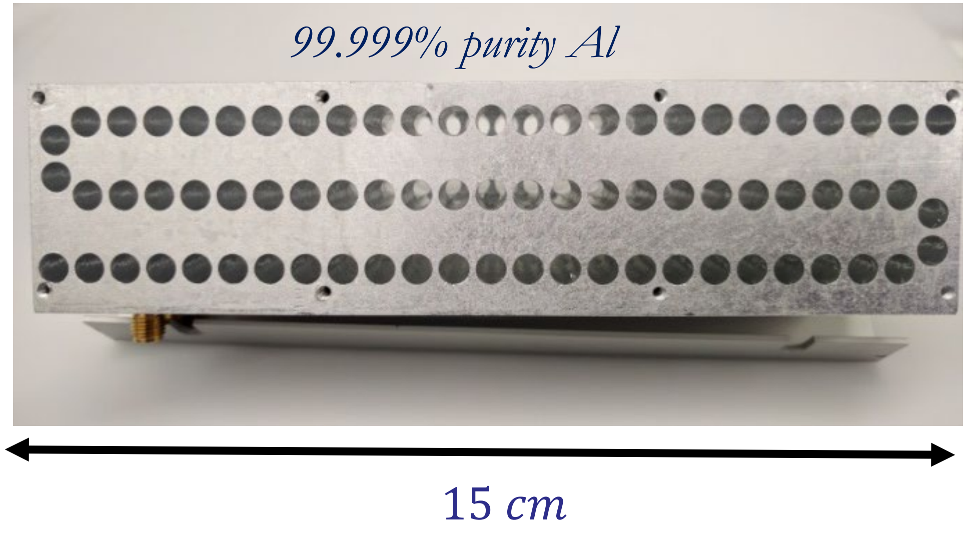
- Cylindrical Disk

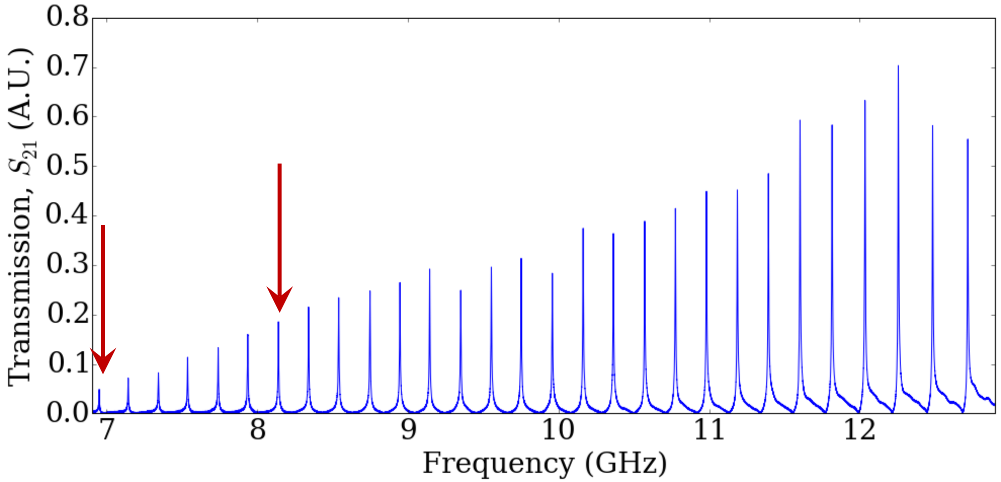
Q ~ 25 million

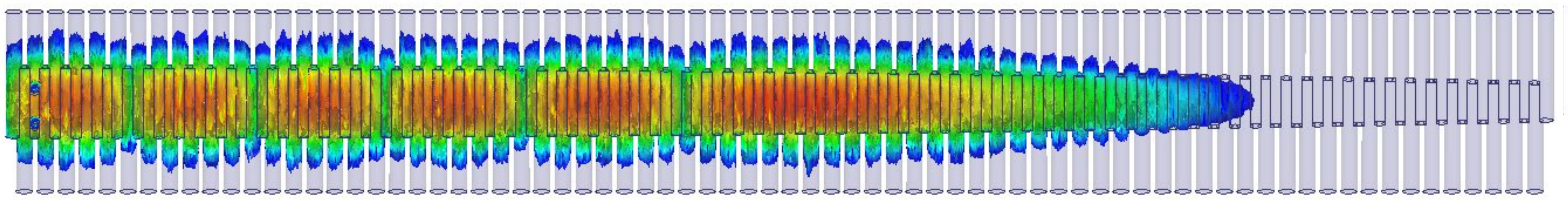




Multimode rectangular flute cavity

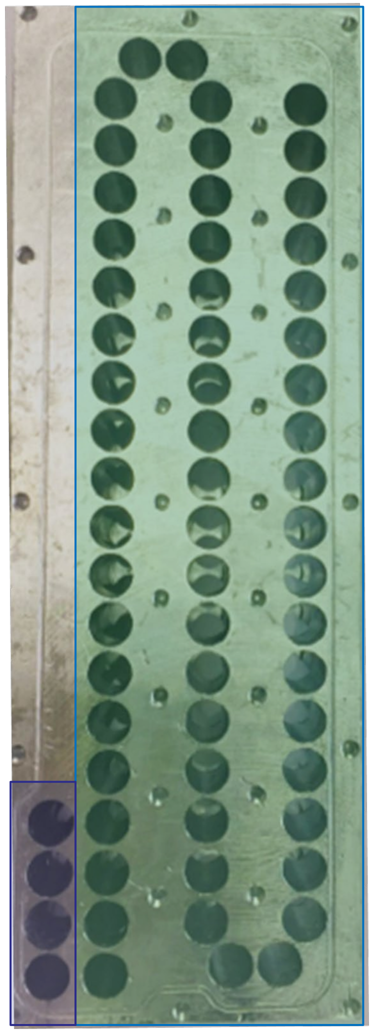






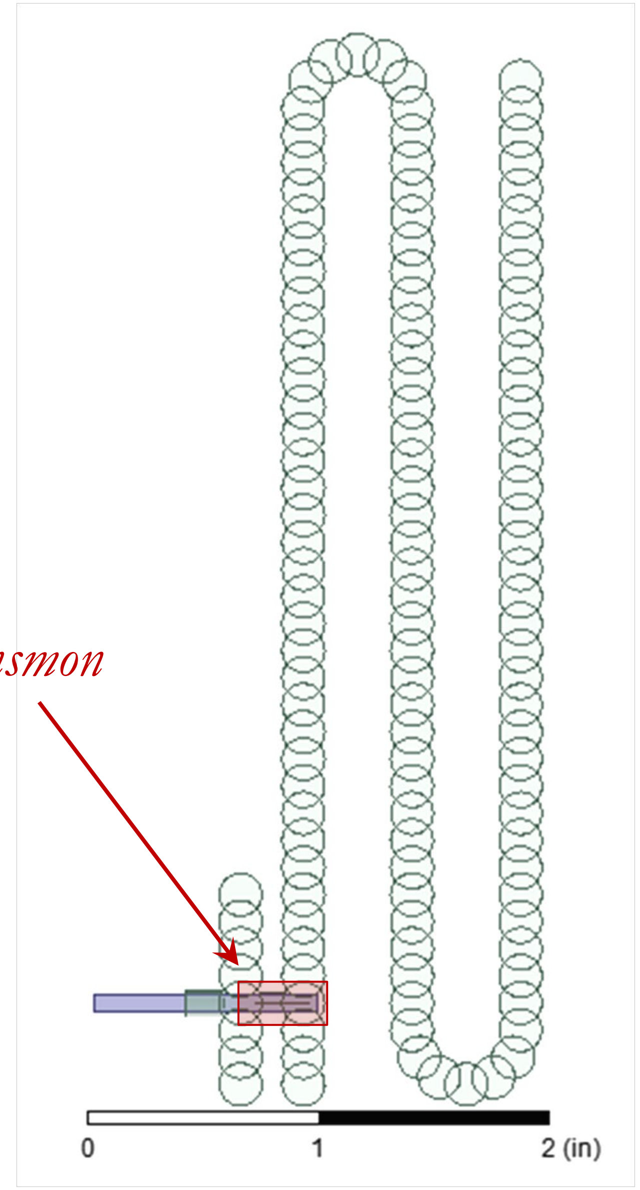
- Straightforward design of a variety of spectra and spatial distributions
- Taper the cavity to create equally spaced modes

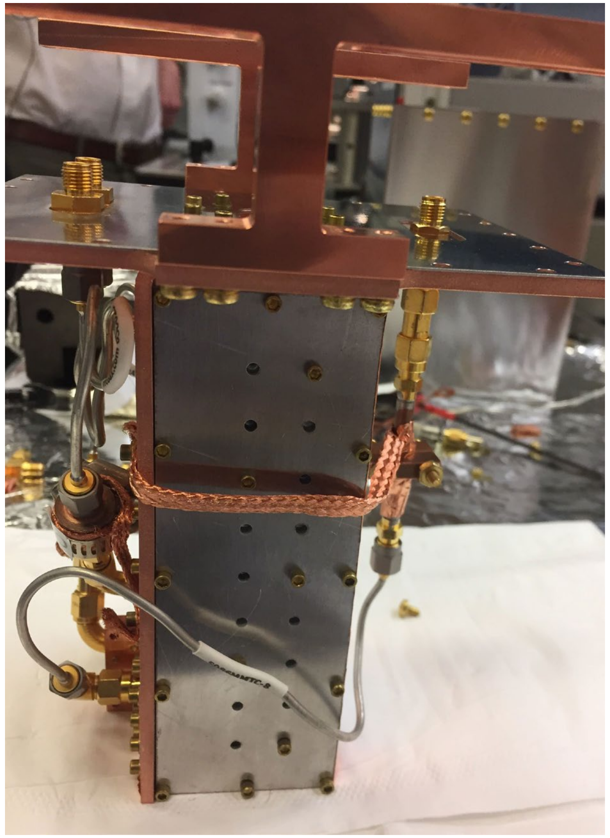
Coupling a multimode cavity to a transmon



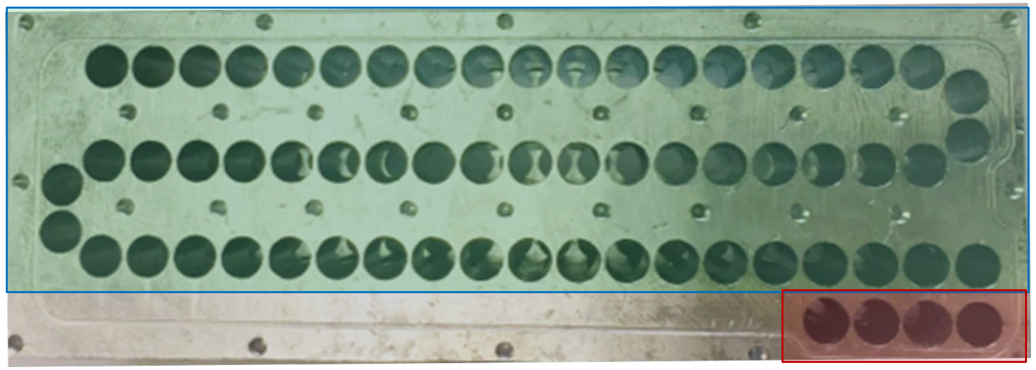
Readout

Storage cavity





Coupling a multimode cavity to a transmon

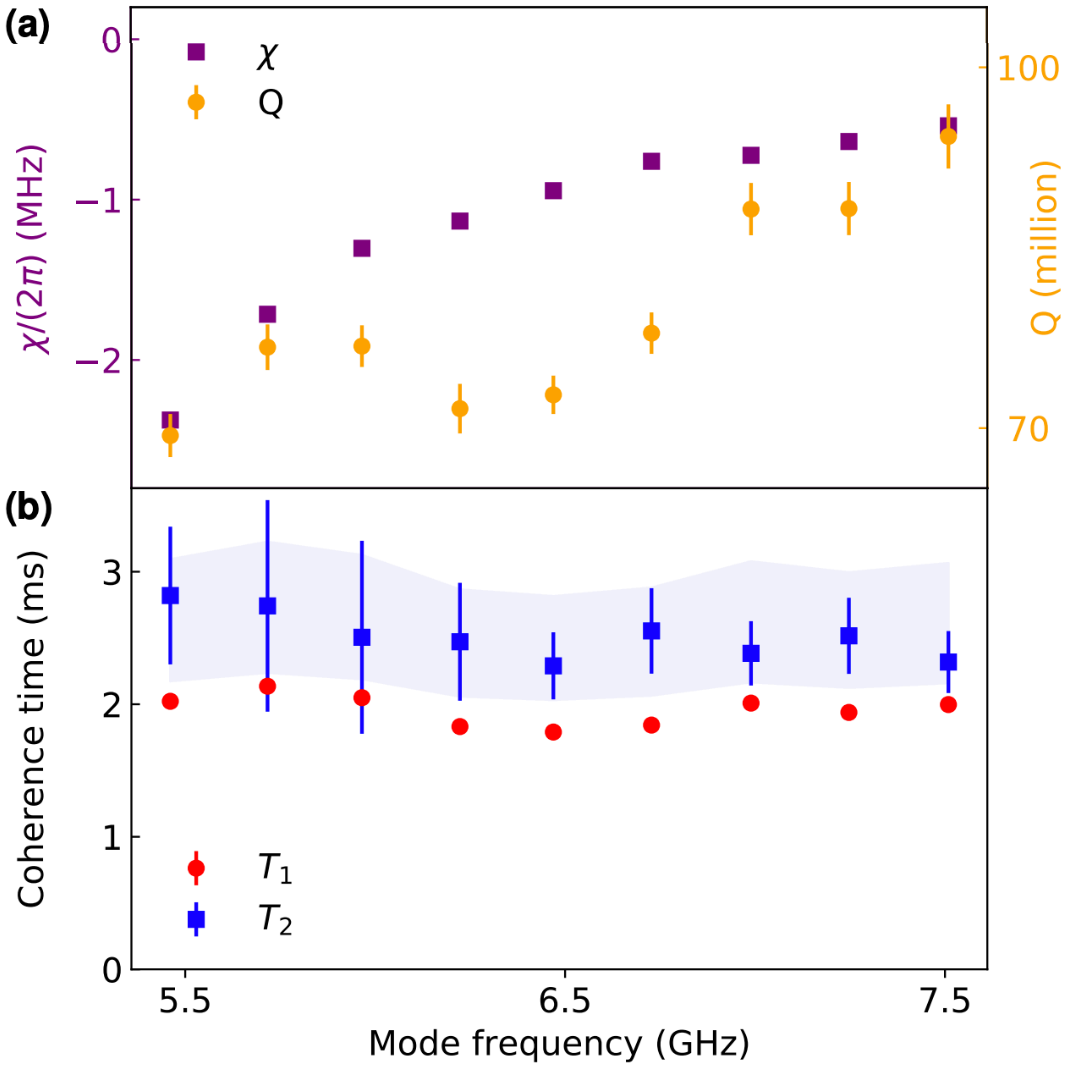


Storage cavity

Readout

- ➢ For 9 modes
- Q ~ 70-95 million
- T_1 ~ 2 ms
- T_2 ~ 2 - 3.5 ms

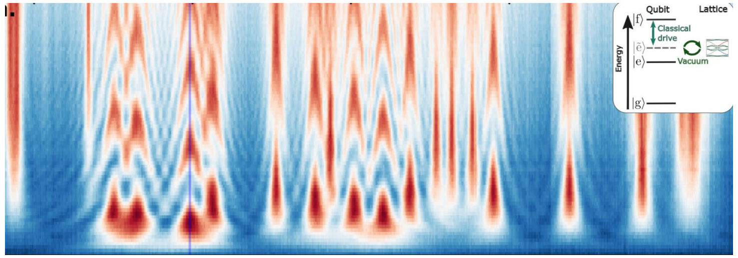
200 times better than in 2d!



arXiv:2010.16382 (2020)

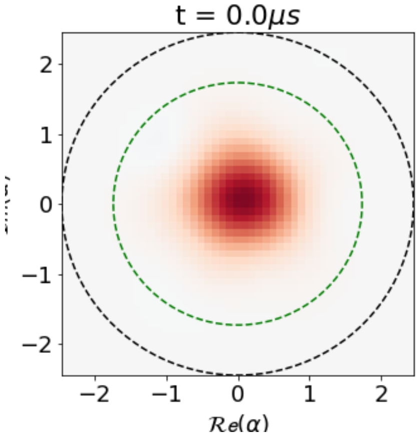
Engineering interactions of photons in a (multimode) resonator

- Resonant charge sideband interactions

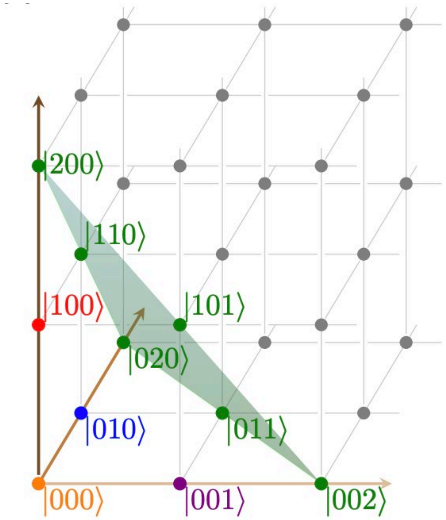


*Heeres, Vlastakis, Holland,…,Schoelkopf, PRL, **115**, 13, 137002, (2015))*

- Control using SNAP gates



- Photon blockade



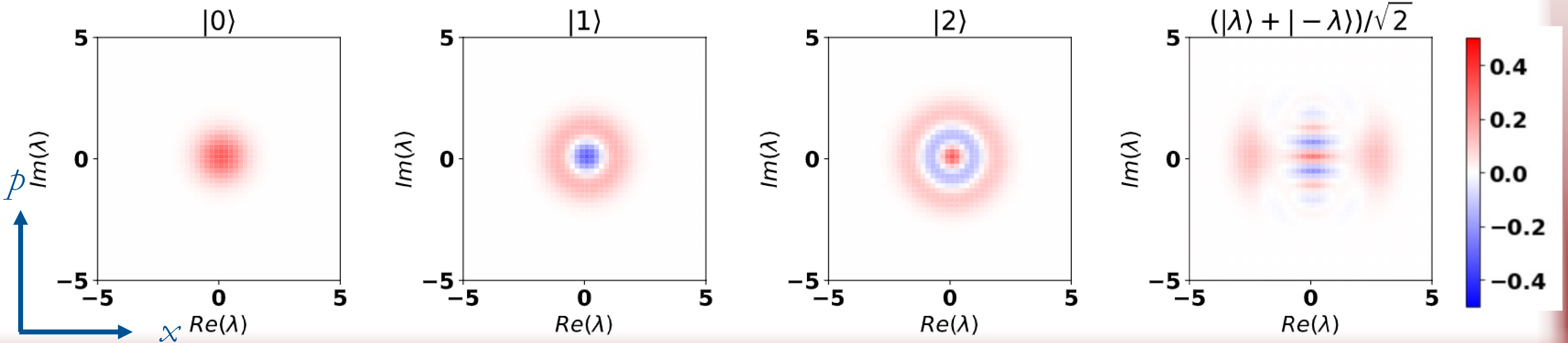
- Multimode photon blockade

Parity measurements and Wigner tomography

- Partial fourier transform of density matrix
- Negativity - *non-classicality*

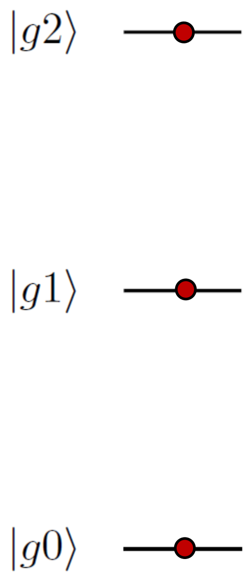
Wigner Tomography

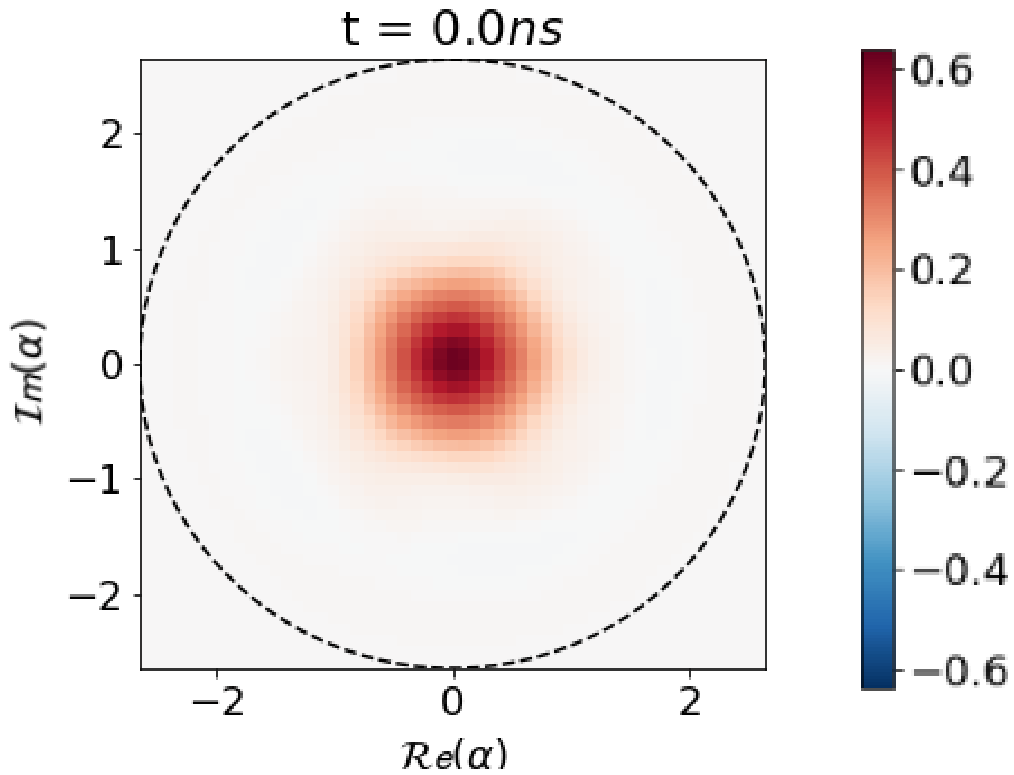
- ➢ Displace cavity
- ➢ Measure Parity



Dynamically engineering photon blockade

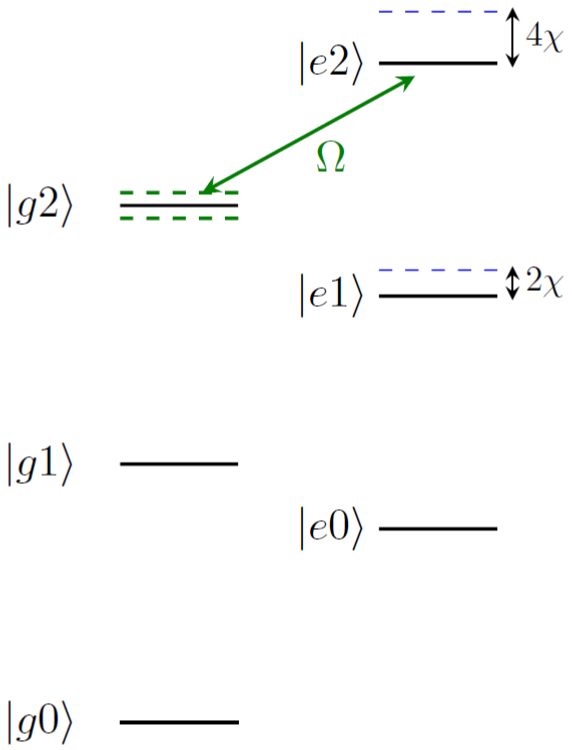
- A pure cavity drive can only generate classical states

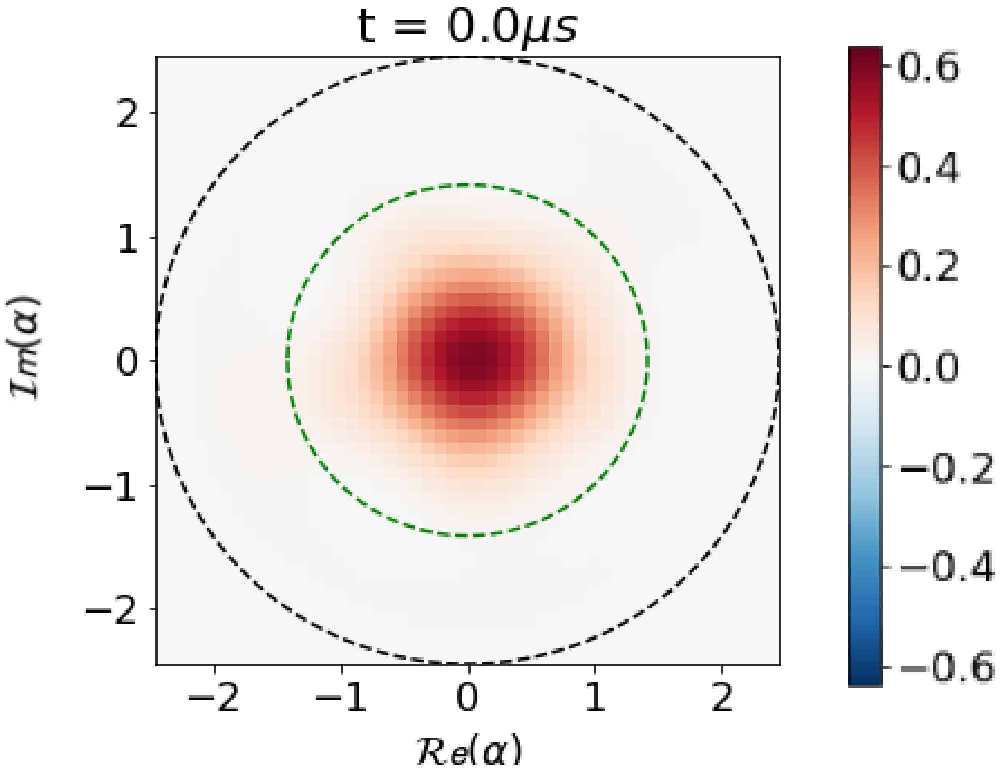




Dynamically engineering photon blockade

- Use a number selective transmon pulse
- Blockade of specific photon numbers





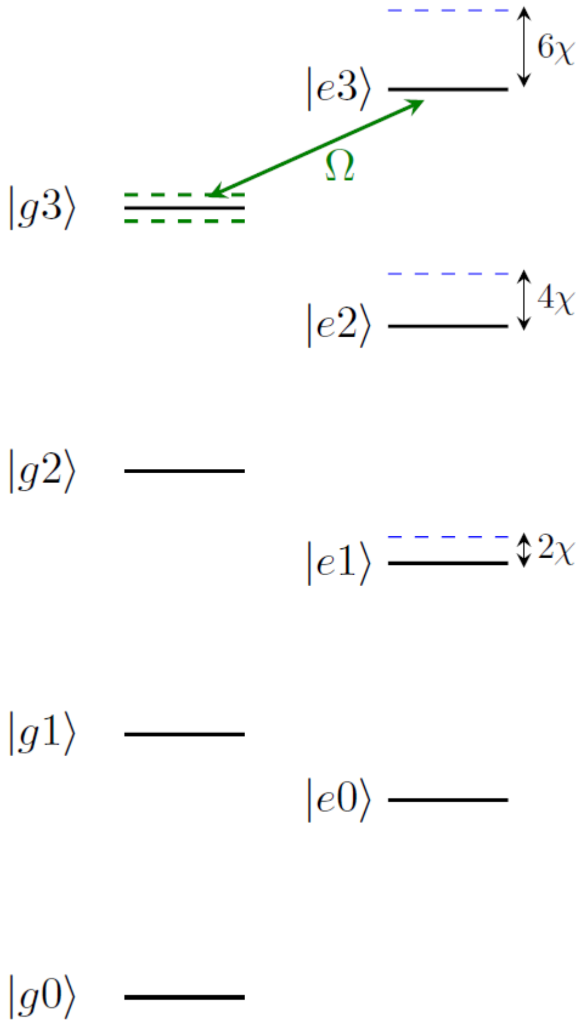
Cavity drive results in a Rabi oscillation!

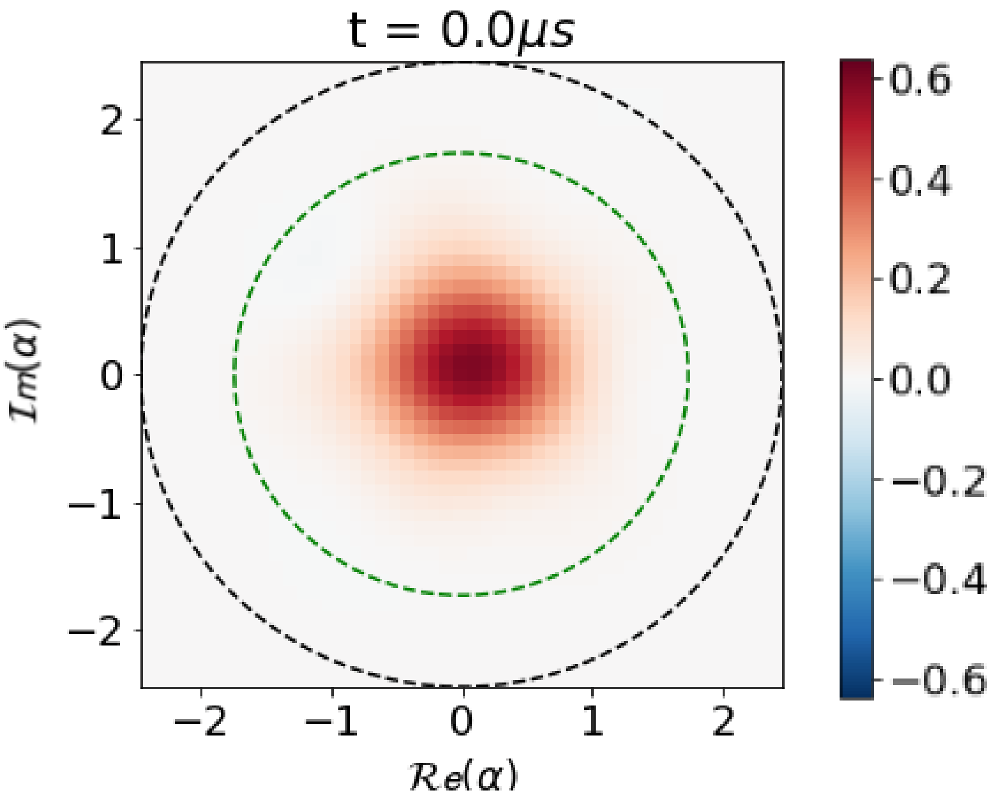
Similar to L. Bretheu,…,B.Huard, Science, 348, 6236 (2015)

arXiv:2010.15292 (2020)

Dynamically engineering photon blockade for higher N

- Blockade of higher photon numbers

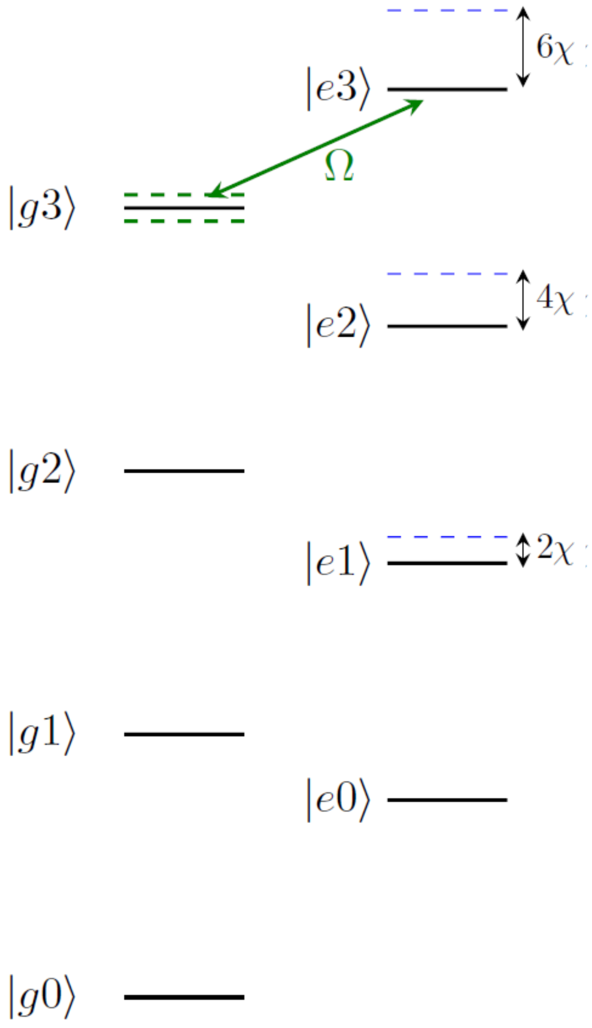




- Blockade radius increases as $\sqrt{n}$

Universal qudit control with cavity drive and blockade

- Can achieve arbitrary qudit control just by driving the cavity

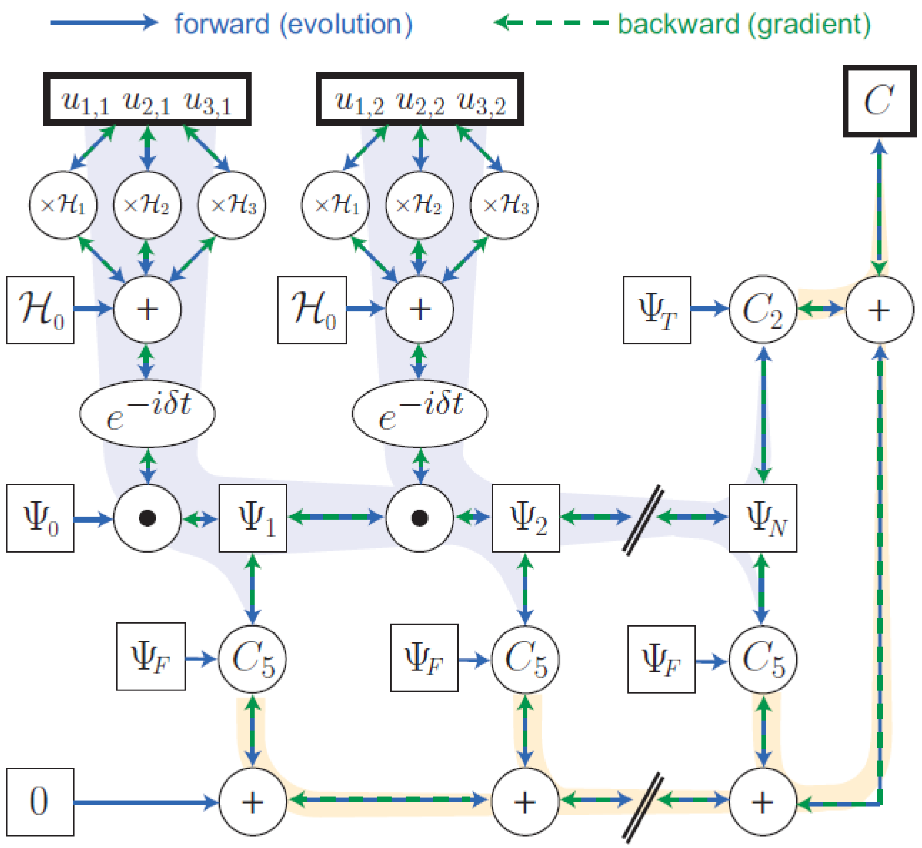


S. G. Schirmer, H. Fu, C. Solomon, Phys. Rev. A, 63, 063410 (2001)

Optimal control

Numerically find pulses using gradient descent

N. Leung, M. Abdelhafez, J. Koch, and D.Schuster,
Phys. Rev. A ***95****, 042318 (2017)*



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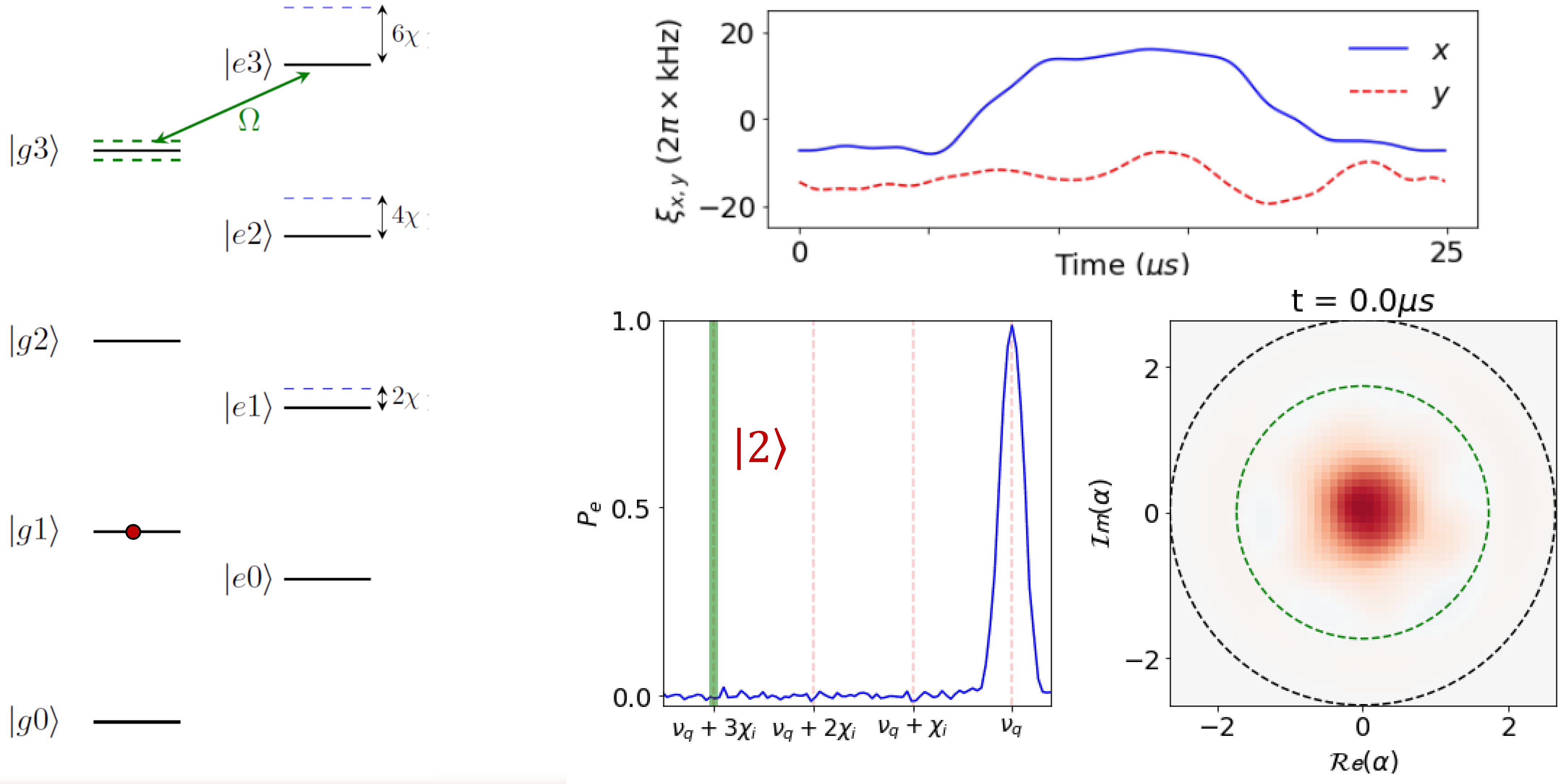
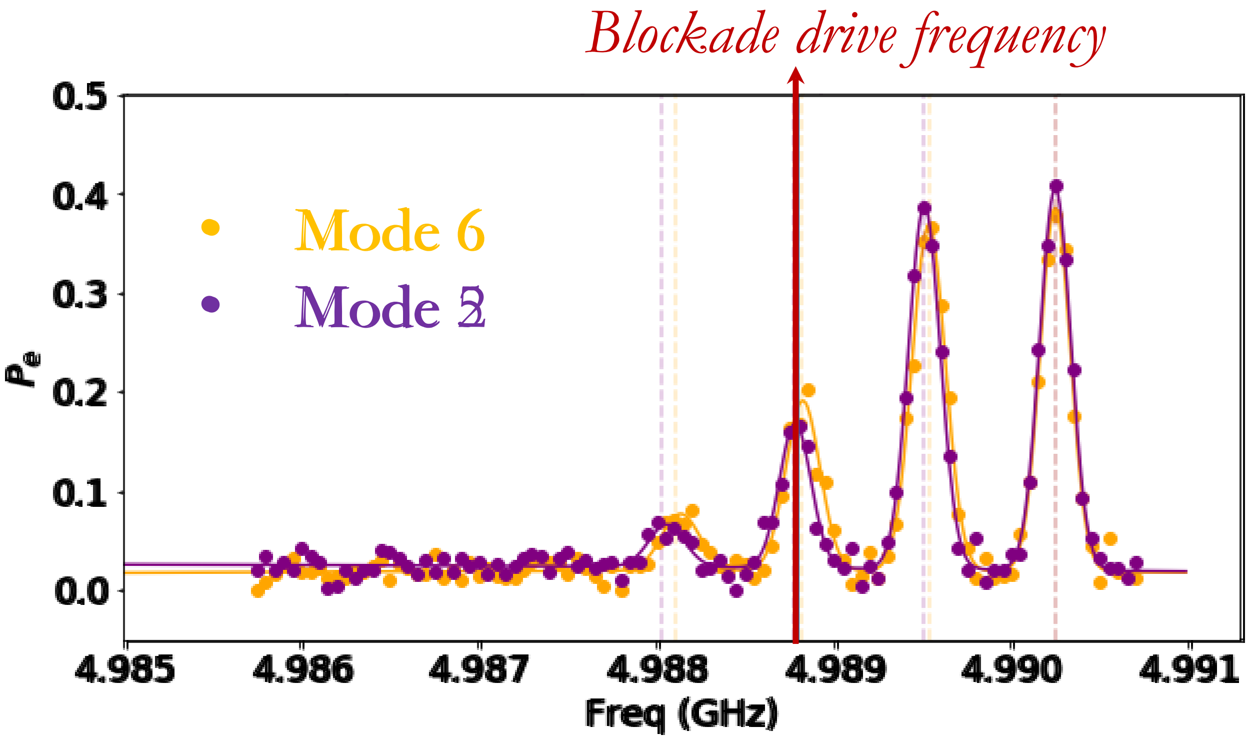


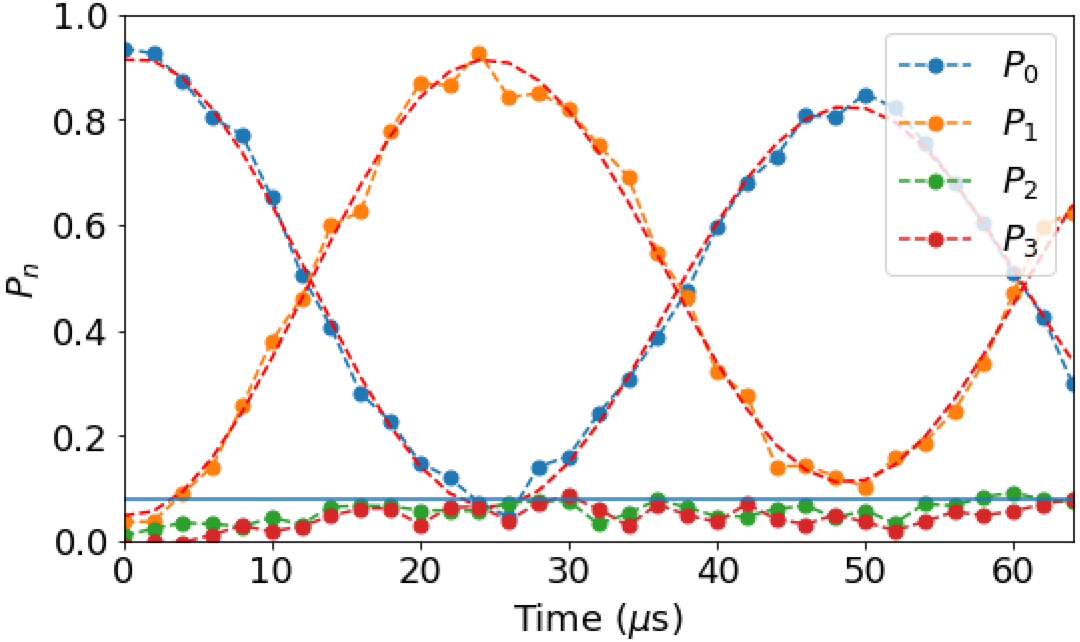
arXiv:2010.15292 (2020)

Multimode interactions through photon blockade

- Modes typically have different χ shifts
- Qubit cannot distinguish between modes if χ shifts are the same
- Blockade drive generates interactions between modes



- Drive mode 6



- Disallows $|20\rangle, |02\rangle$ and $|11\rangle$

Multimode interactions through photon blockade

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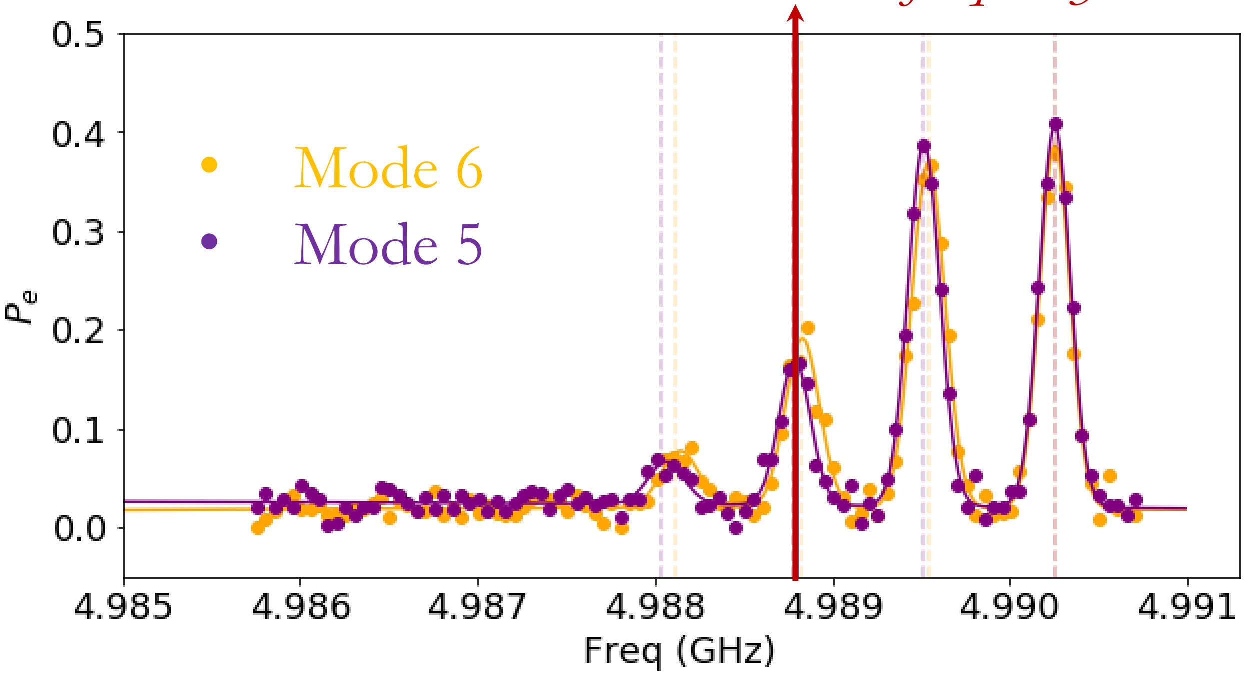
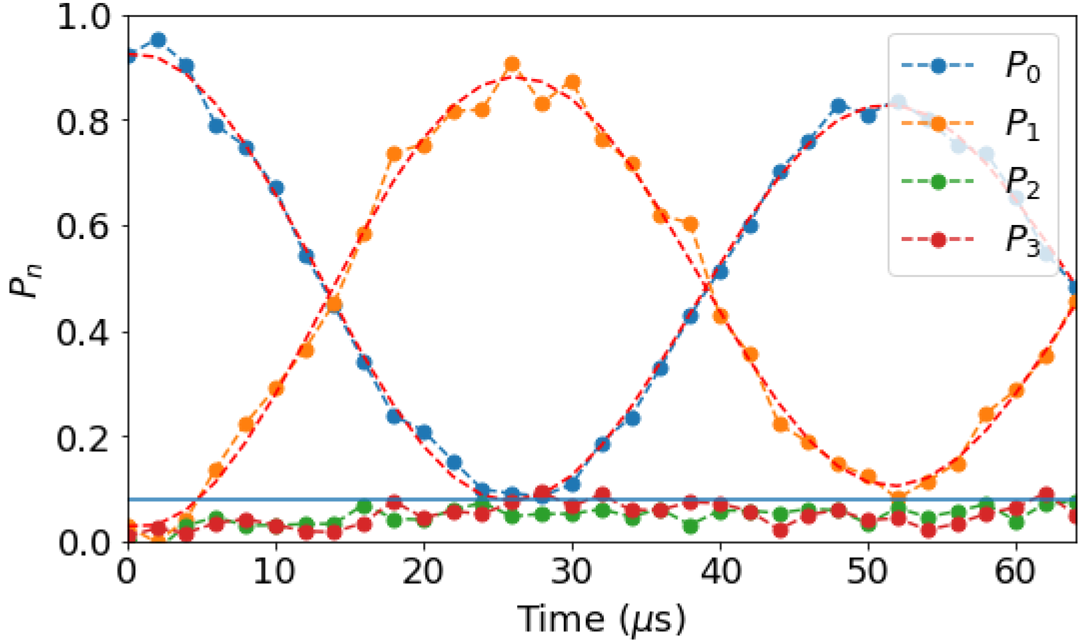
Blockade drive frequency



- Drive mode 5



- Disallows $|20\rangle, |02\rangle$ and $|11\rangle$

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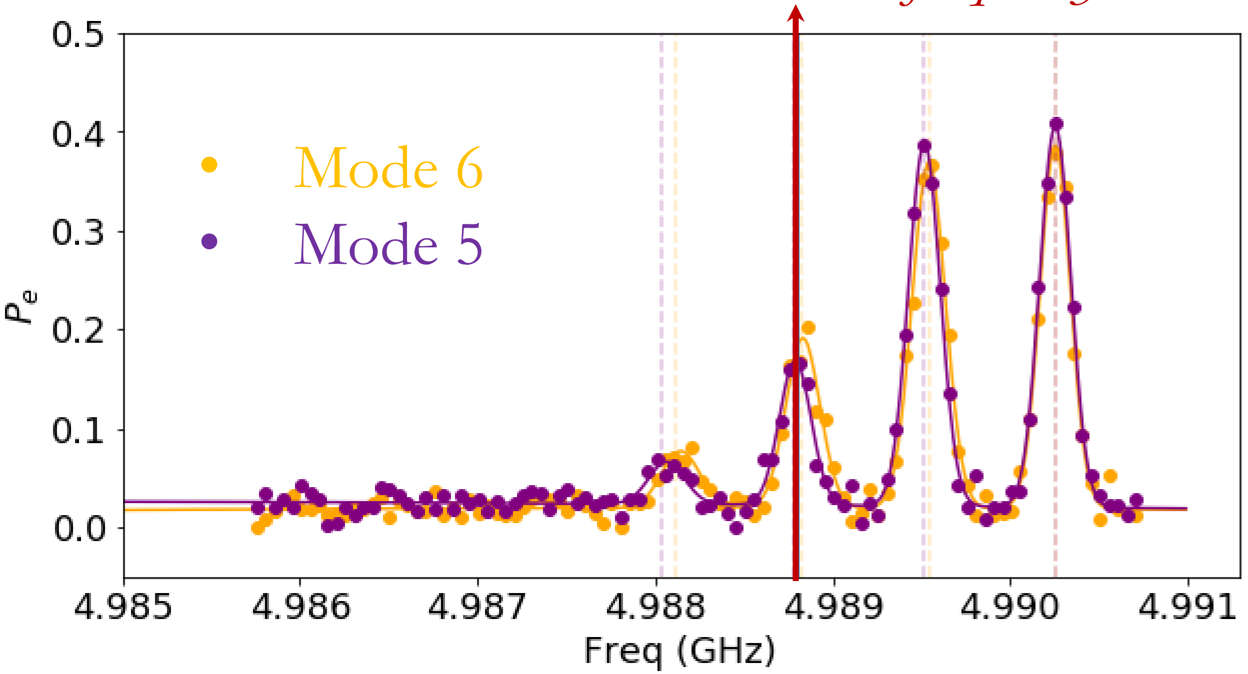
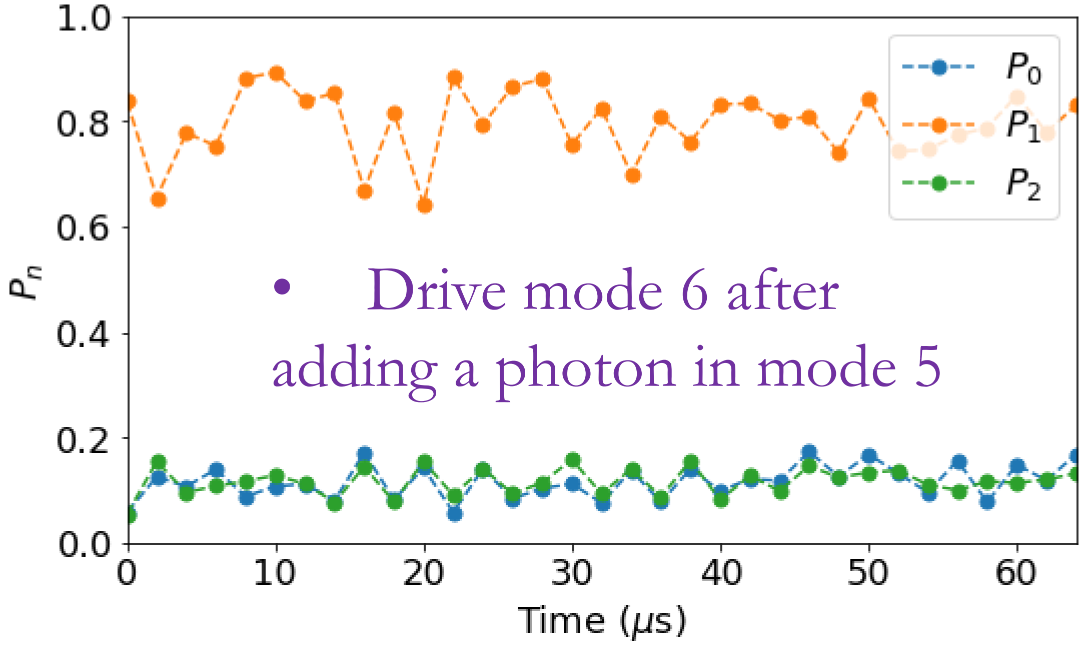


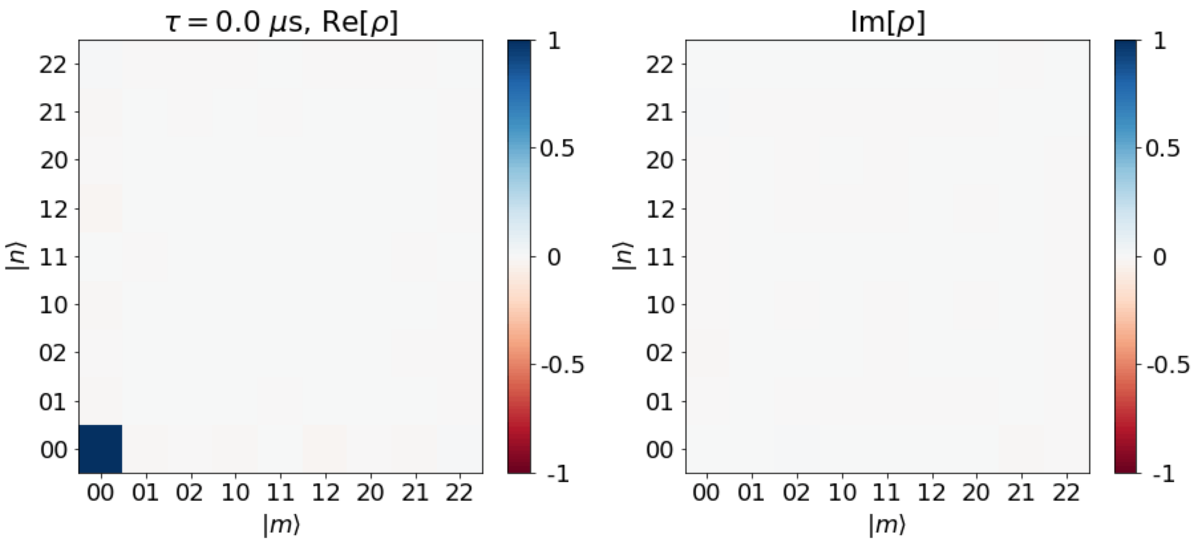
- Entangling gate



- Drive mode 6 after adding a photon in mode 5

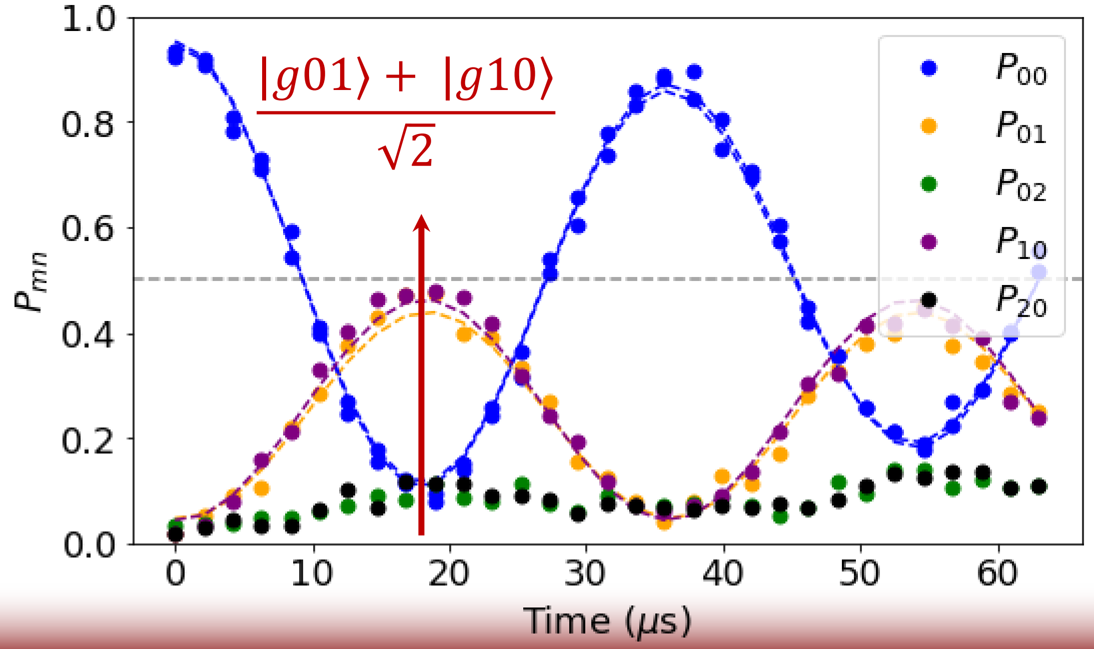
- Disallows $|20\rangle, |02\rangle$ and $|11\rangle$

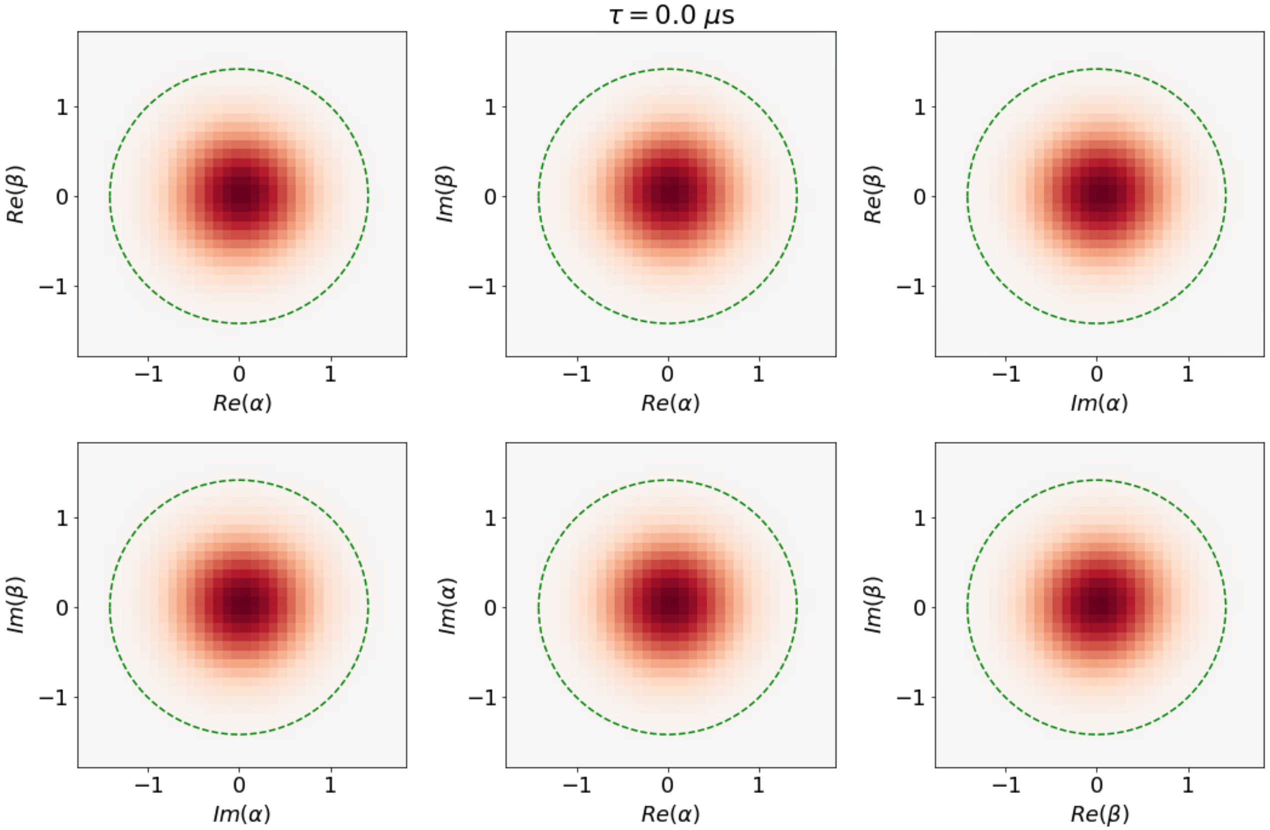
Time resolved two-mode entanglement generation



$$\mathcal{W}(\{\alpha_i\}) = \prod_{\otimes} \mathcal{D}(\alpha_i)\left[\cos\left(\sum_i \theta_i N_i\right)\right]\prod_{\otimes} \mathcal{D}(-\alpha_i)$$

$$\theta_i = 4\pi\chi_i\tau_m$$

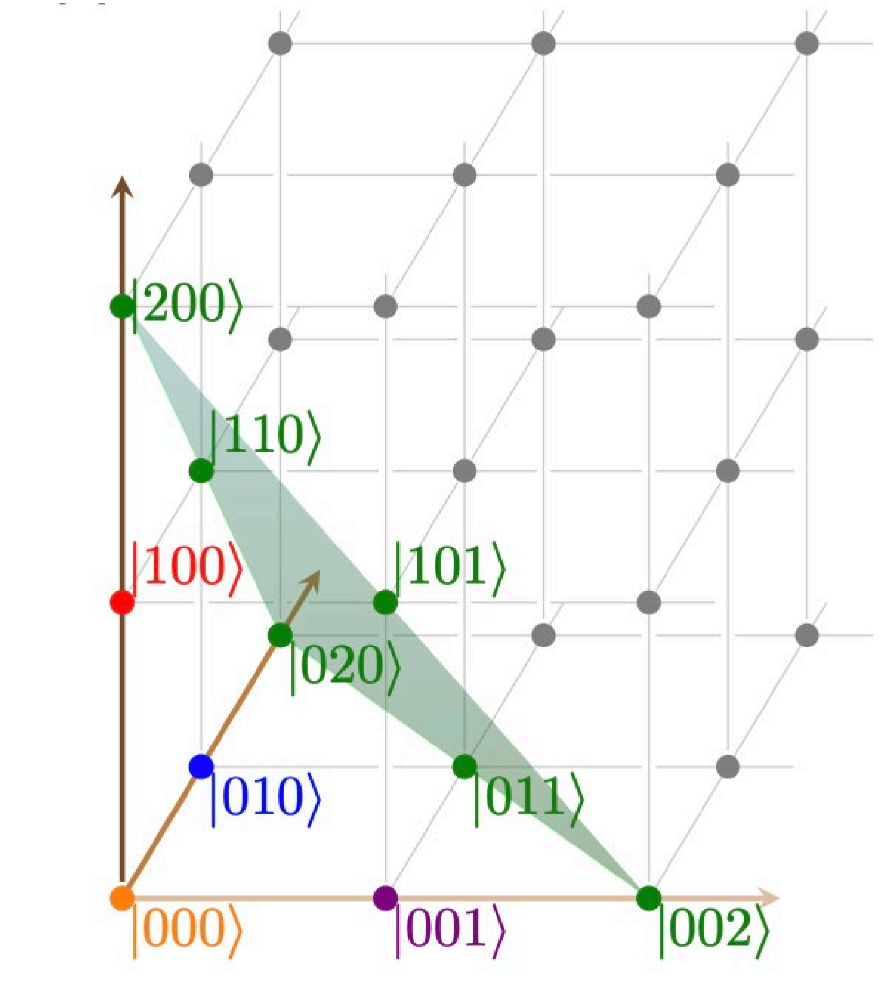




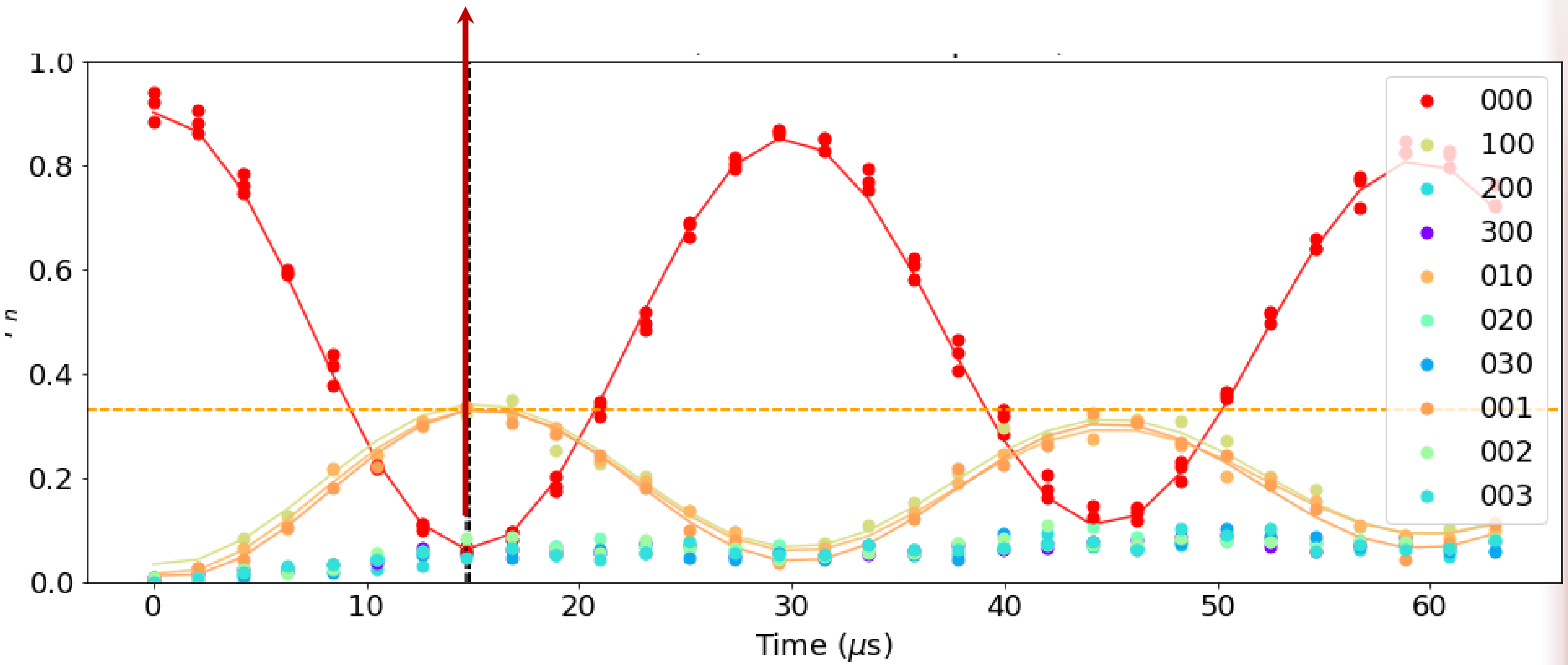
Drive both cavities simultaneously

Generating pure multi-photon, multi-mode interaction

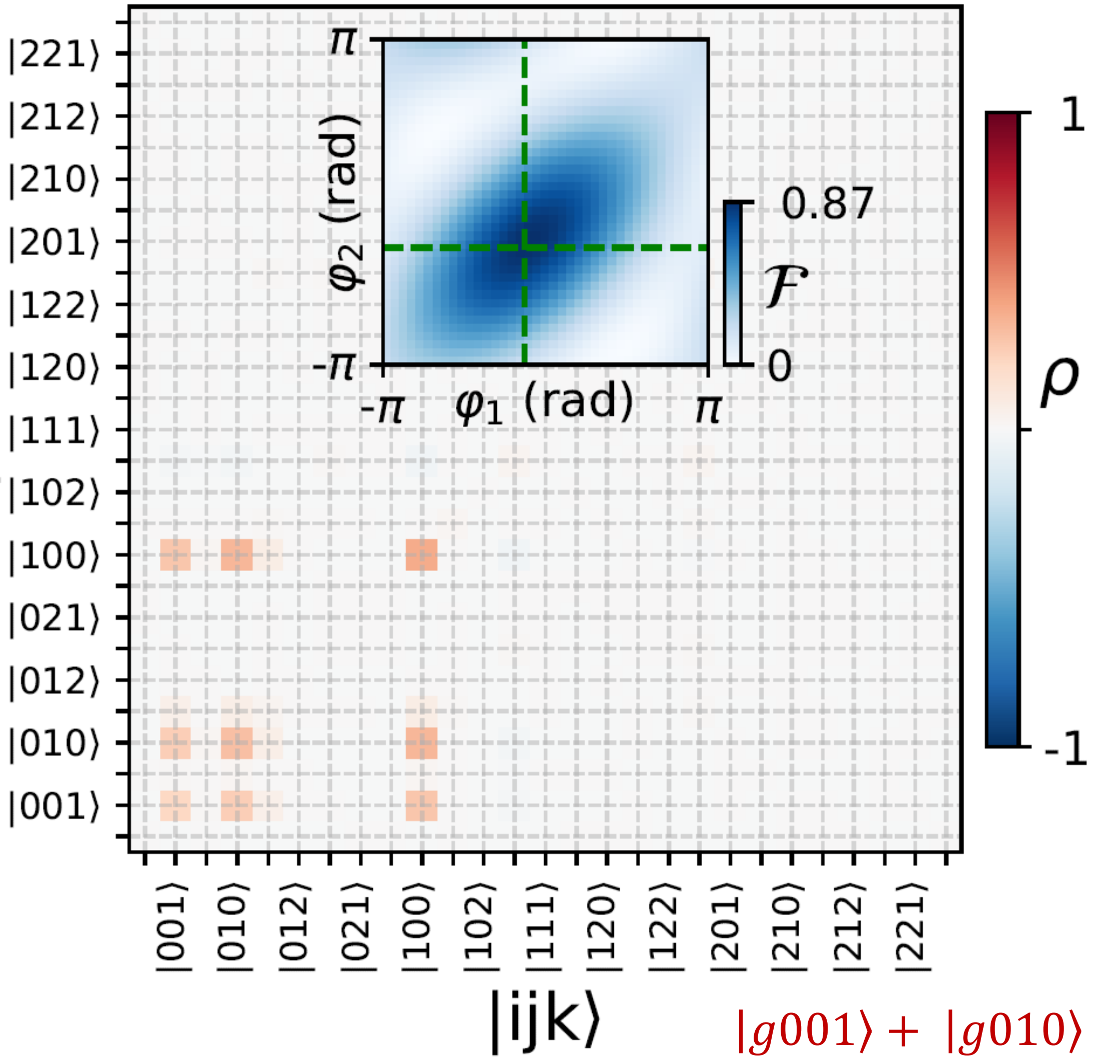
- Drive at mean of $|g110\rangle \rightarrow |e110\rangle, |g101\rangle \rightarrow |e101\rangle, |g011\rangle \rightarrow |e011\rangle$ of the transmon, and all 3 cavity modes simultaneously

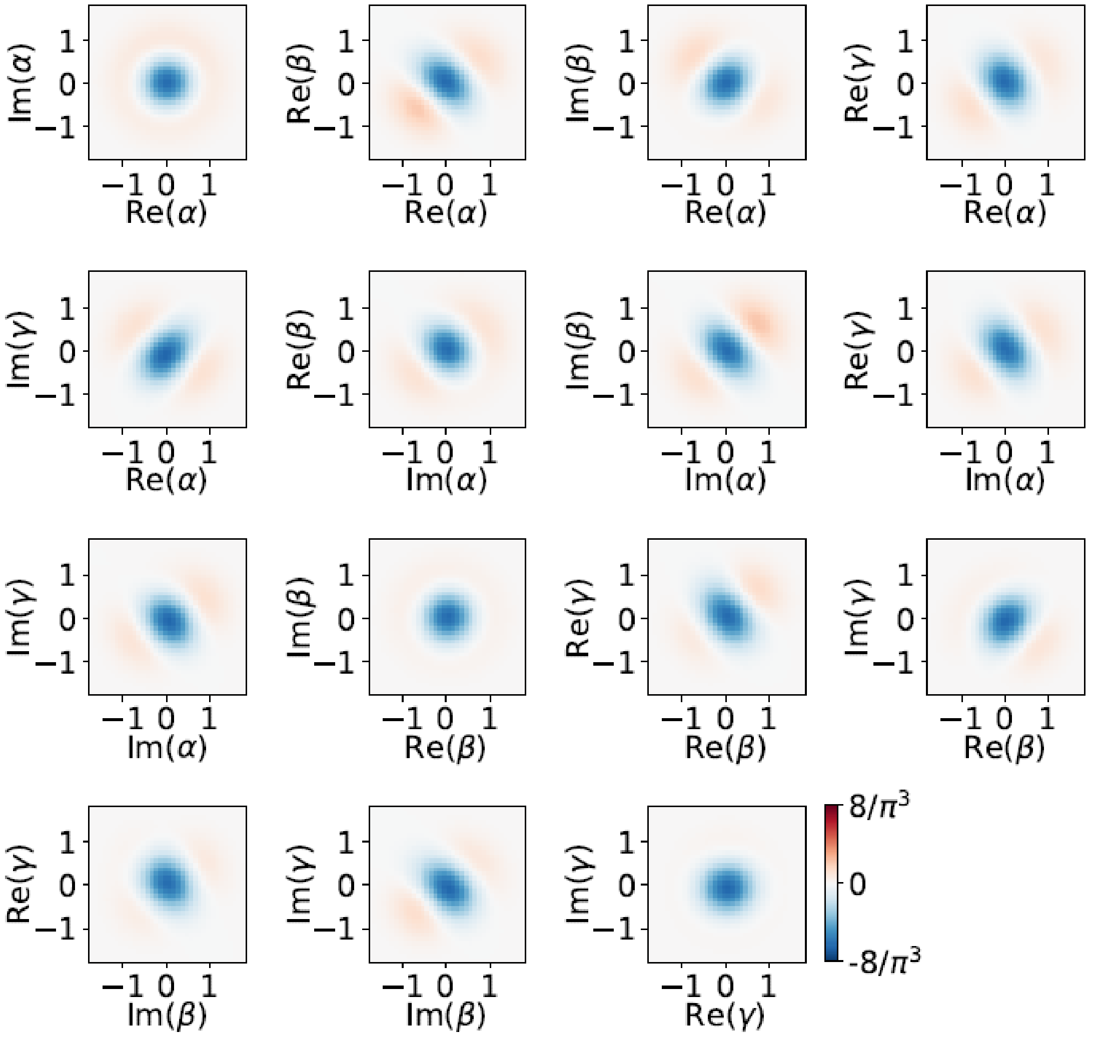


$$\frac{|g001\rangle + |g010\rangle + |g100\rangle}{\sqrt{3}}$$



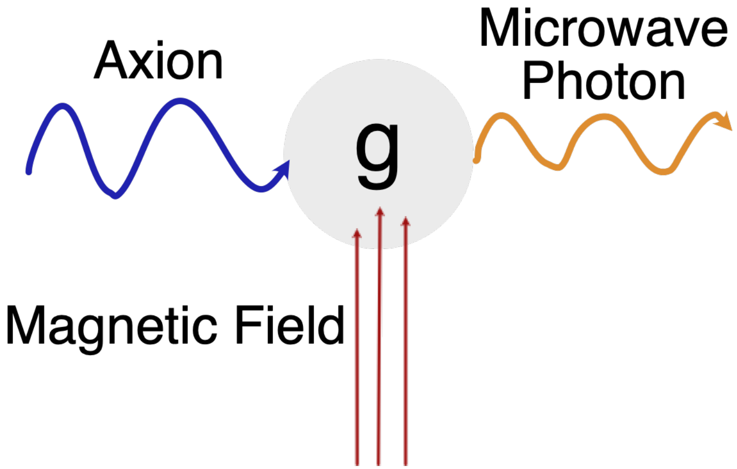
Using multimode photon blockade to create W state

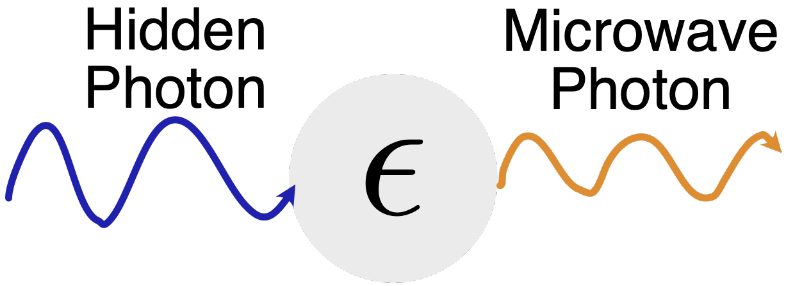




$$\frac{|g001\rangle + |g010\rangle + |g100\rangle}{\sqrt{3}}$$

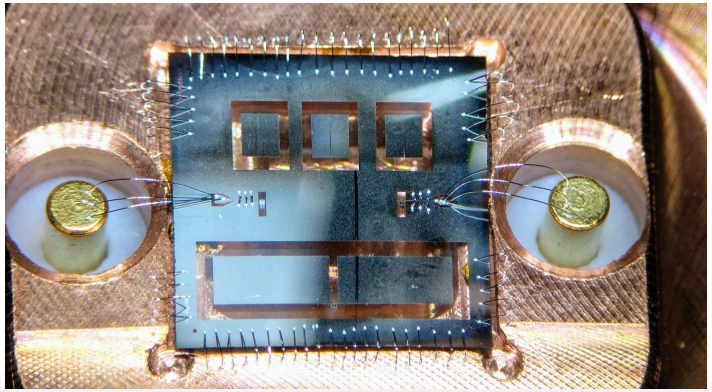
Detecting Axion-like dark matter with qubits



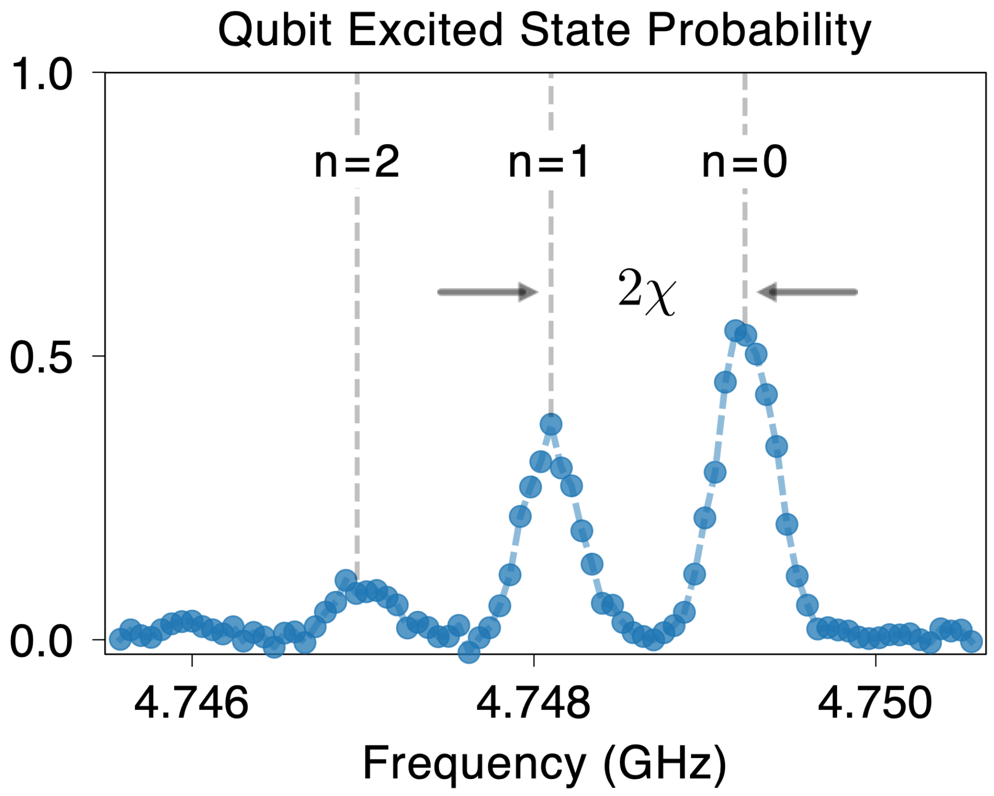


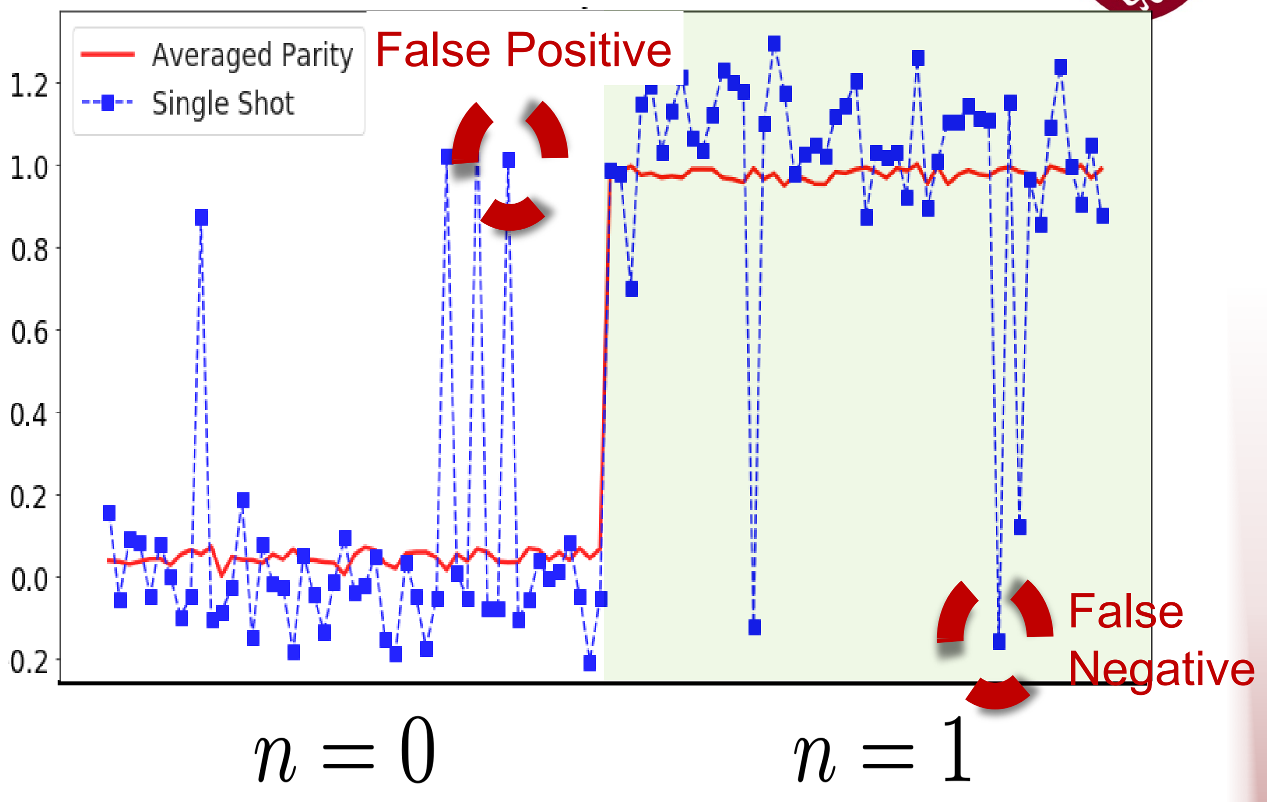
Resonant cavity to capture signal

Quantum limited amplifier for readout

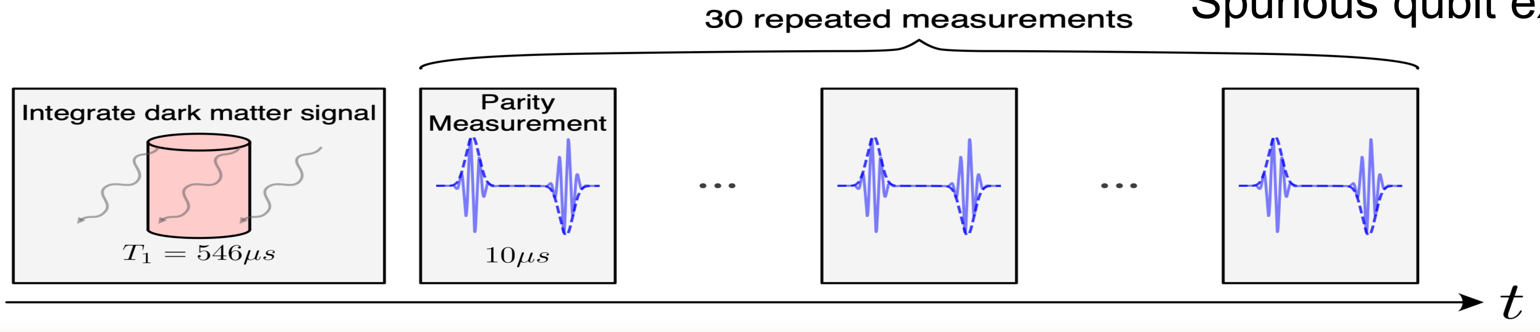


Using a qubit to measure a single photon



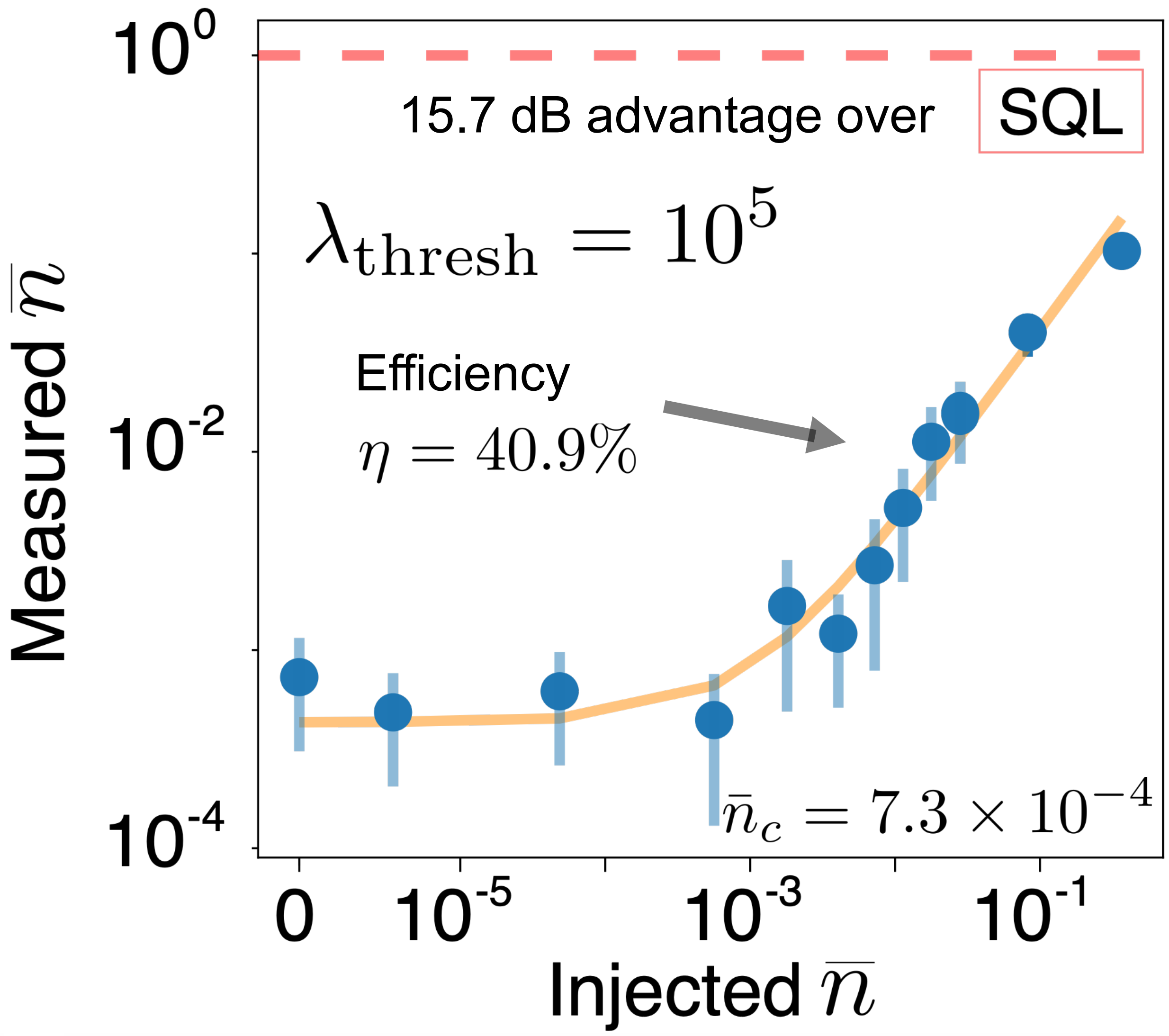


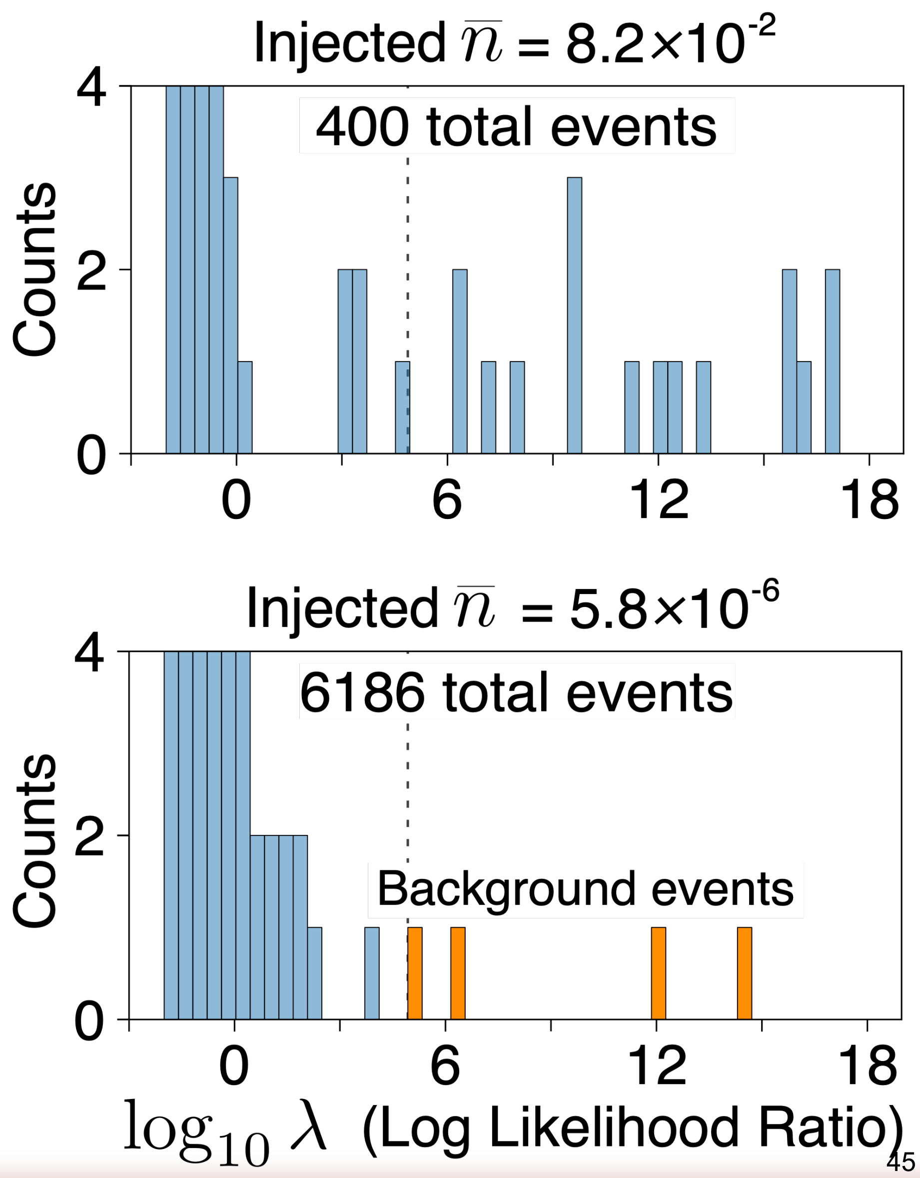
Spurious qubit excitations are dominant source of errors



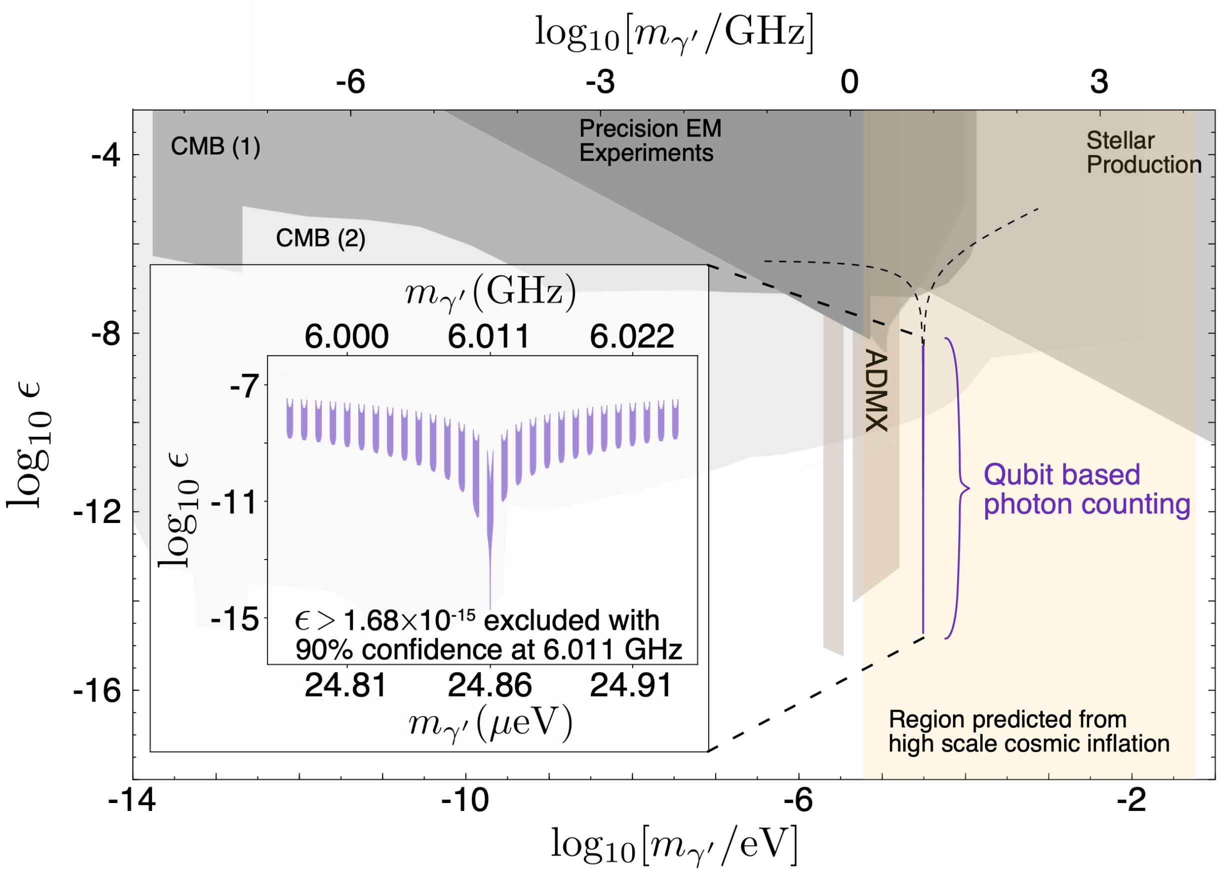
Suppress false qubit positives by repeated measurement and voting (Markov chain)

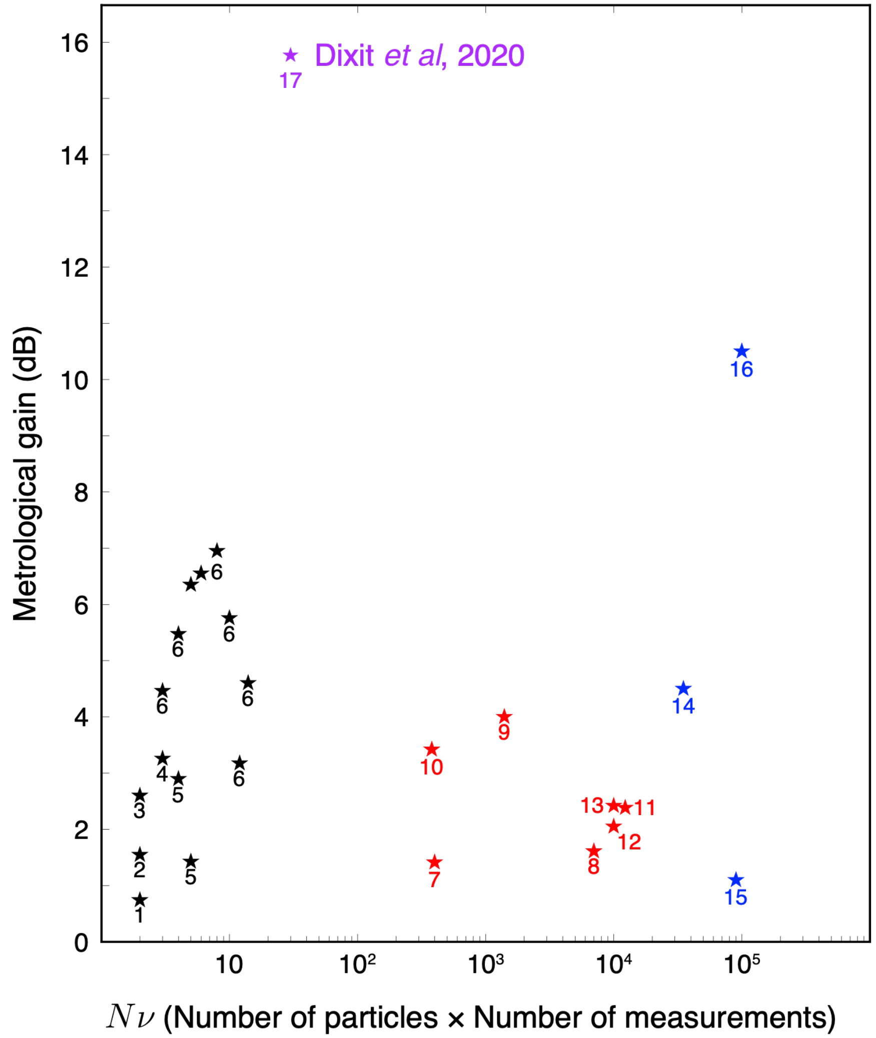
Detected photon occupation vs injected photon occupation





Searching for dark photons below the Standard Quantum Limit





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

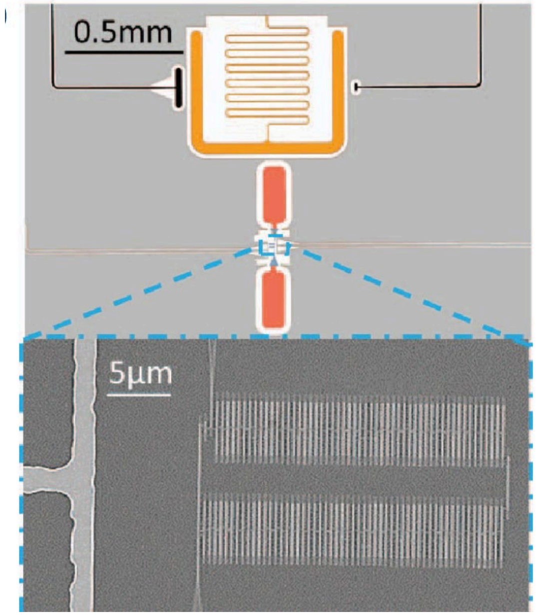
Cold Thermal Atoms
[14] Leoroux, 2010a
[15] Louchet-Chauvet, 2010
[16] Hosten, 2016

Superconducting Qubit
[17] Dixit, 2020

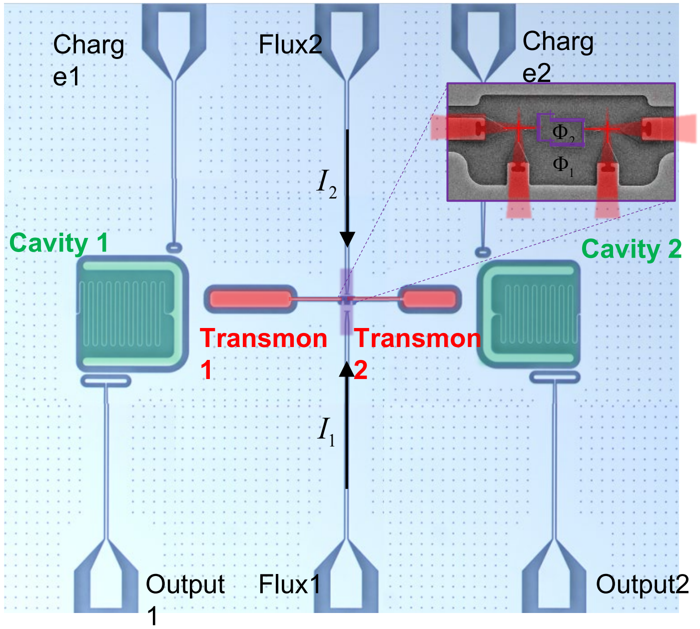
- Already functioning at limits where one can exclude well-motivated theories
- Need to develop ability to tune detection cavity
- Need to be able to operate detection cavity in large B field for Axions

Other efforts in the lab

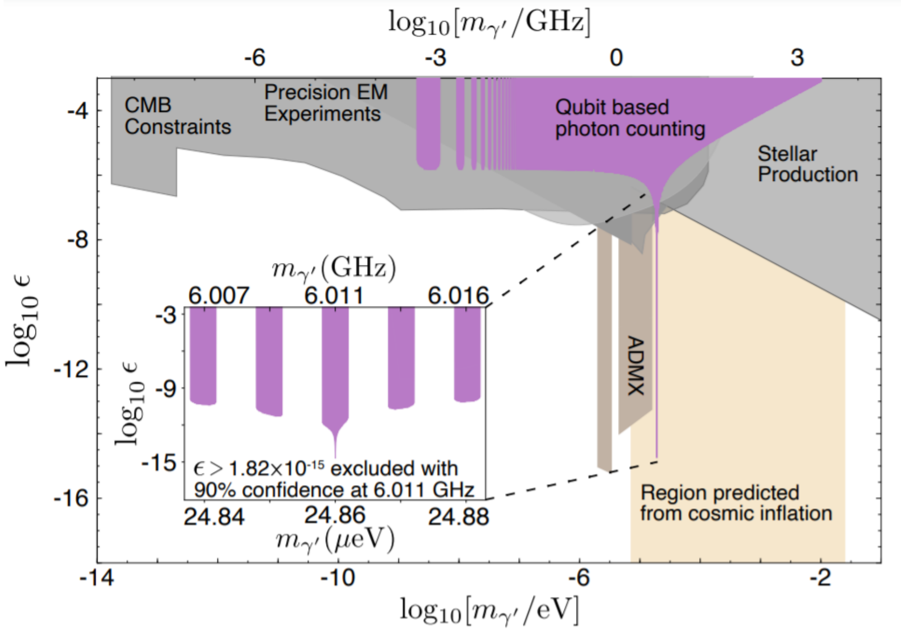
Novel qubits



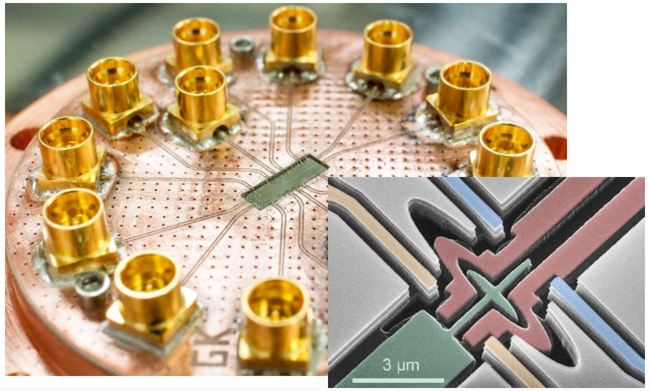
Autonomous QEC



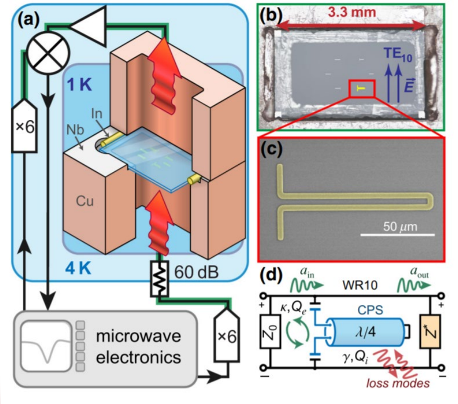
Axion DM search



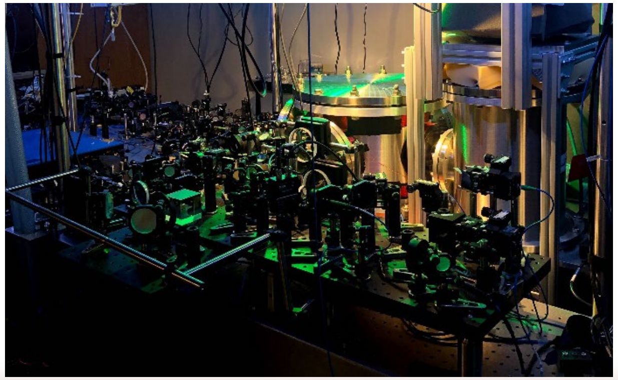
Electrons on helium



Mm-wave circuits

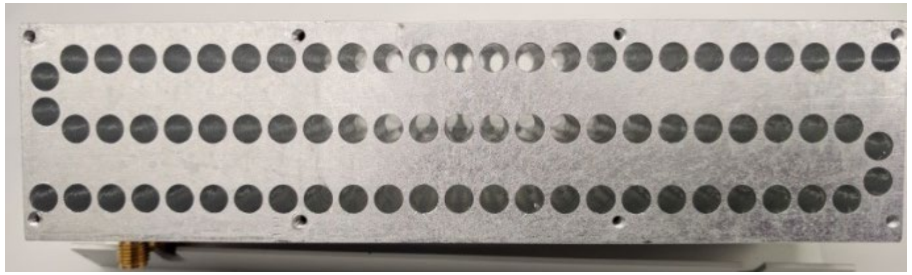


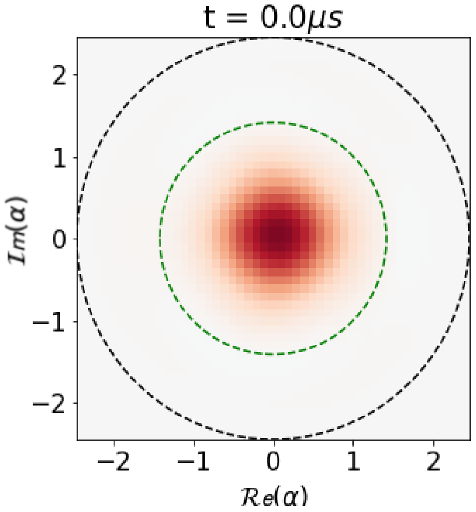
Hybrid Rydberg CQED

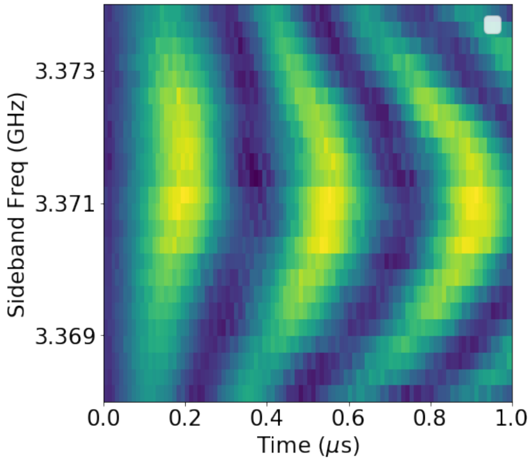


Conclusions

- 2D random access quantum information processor
- Seamless multimode flute cavities
- Quantum control using a transmon
  - Resonant sideband interactions
  - Photon blockade
  - Optimal control
  - Dressed multimode interactions







- Qubits can accelerate detection of microwave energy particles

Thank you!

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