# Modular Superconducting Quantum Computing

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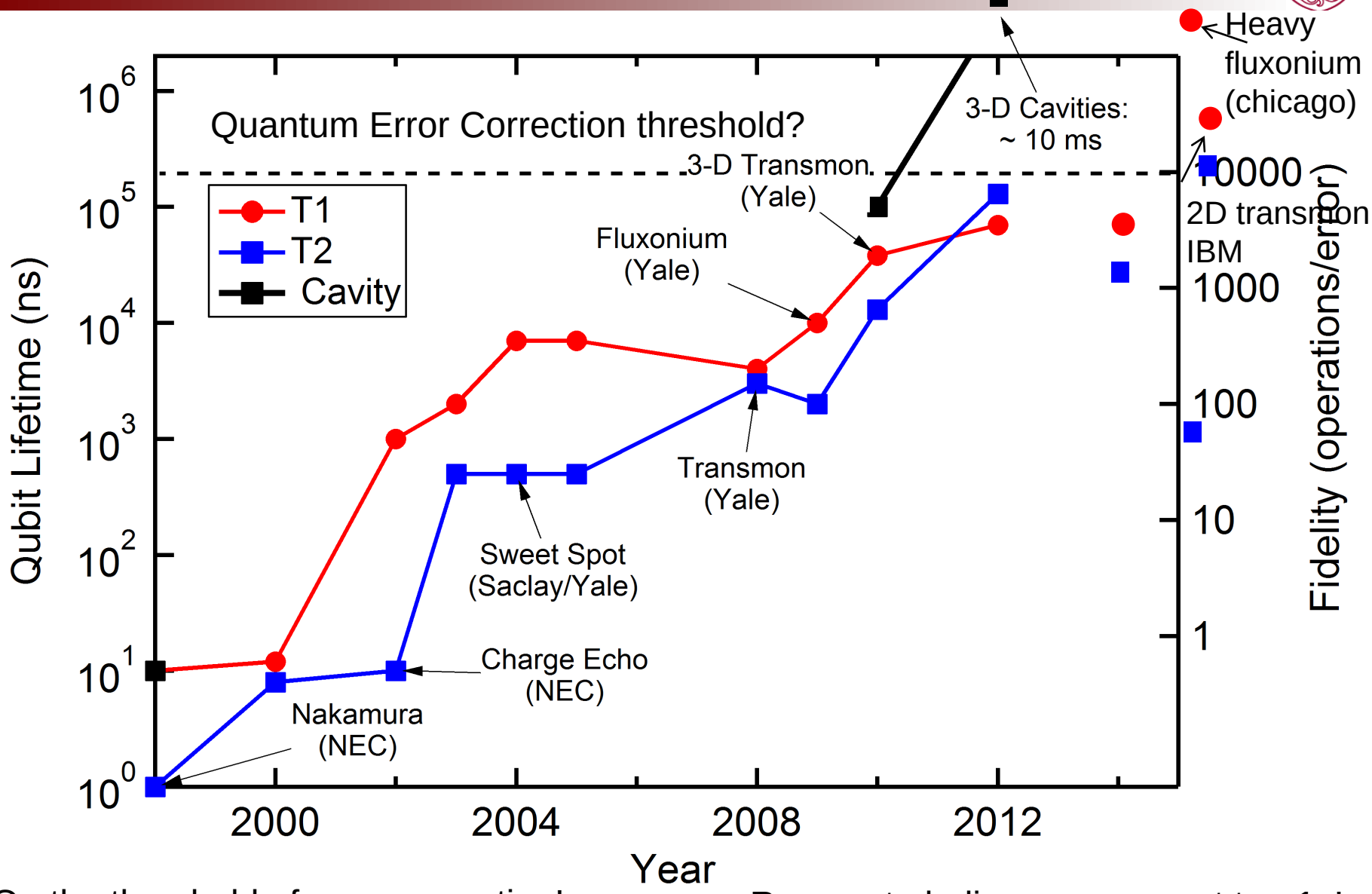
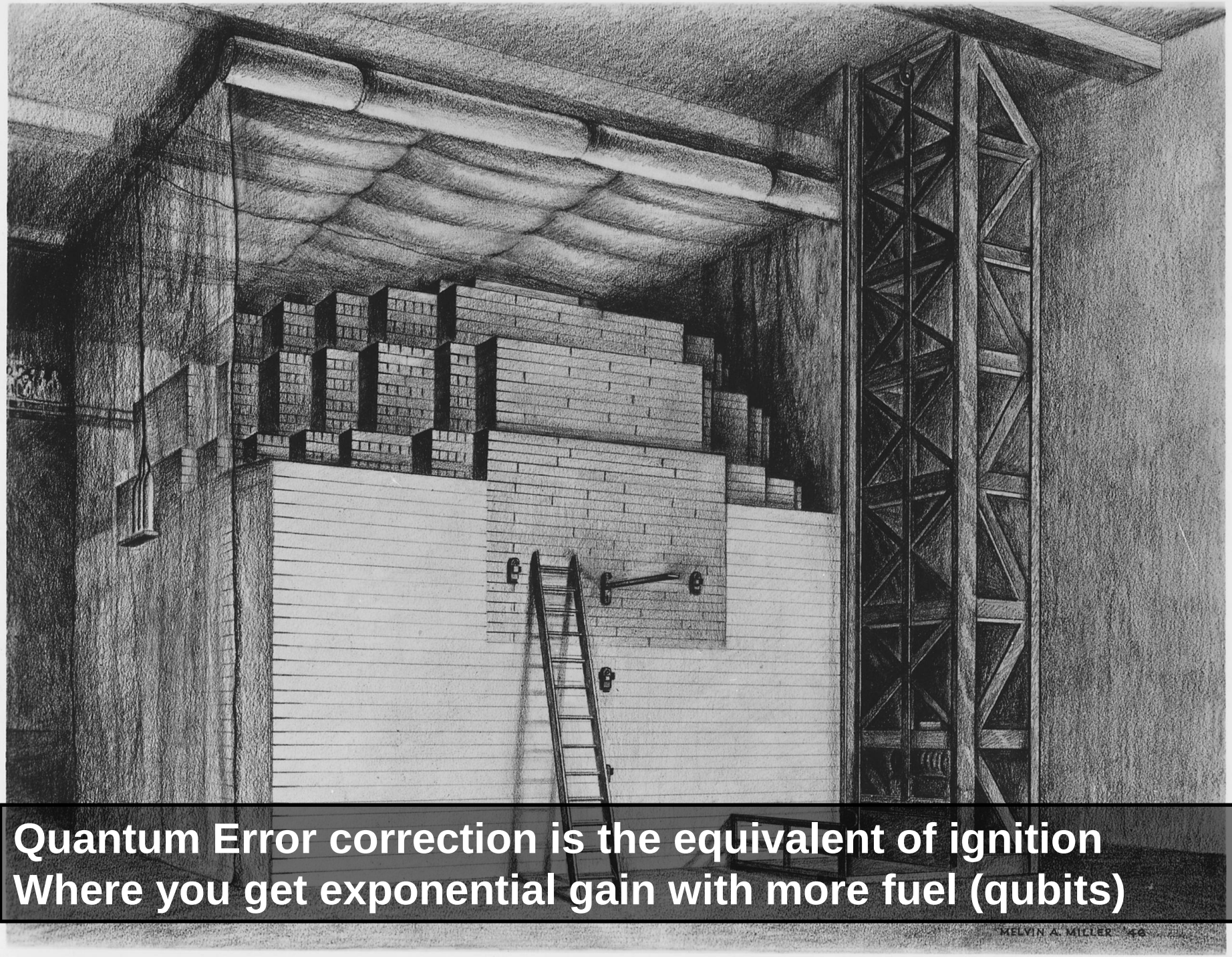
# *Schoelkopf's law – Coherence 10x every 3 yrs!*




On the threshold of error correction!

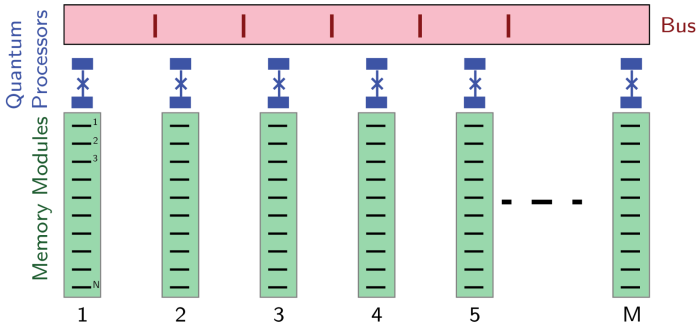
Reason to believe we can get to >1s!



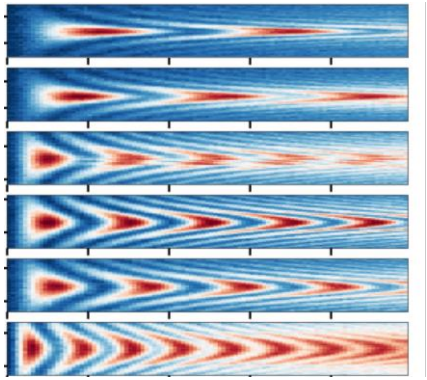

**Quantum Error correction is the equivalent of ignition**
**Where you get exponential gain with more fuel (qubits)**

# Outline

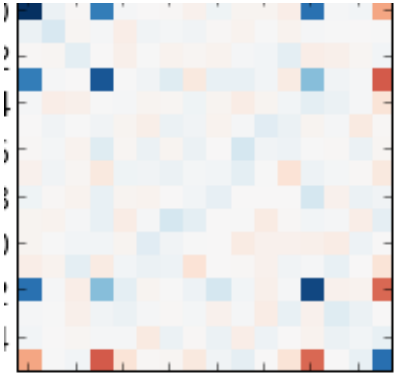
- A modular architecture for superconducting quantum computing

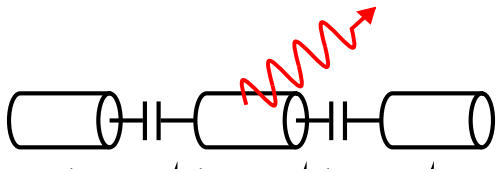



- Multimode Circuit QED



- Universal local operations

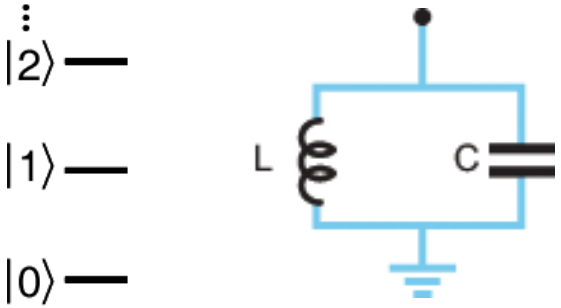




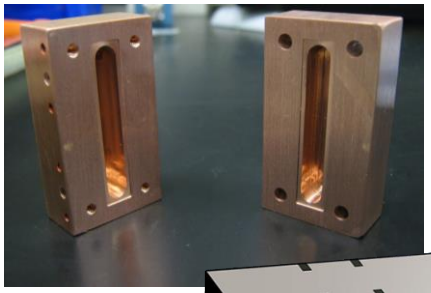
- Deterministically transmitting quantum information

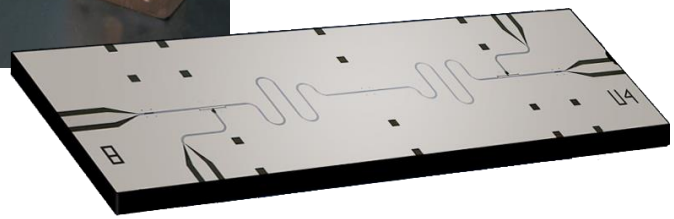
# *Microwave photons in a superconducting box*

- If we take a single resonant mode of any of these boxes it looks like a harmonic oscillator




- Many types of “boxes”

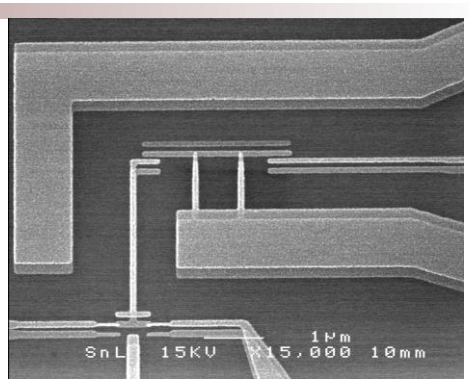




# *Superconducting qubits (two level system)*

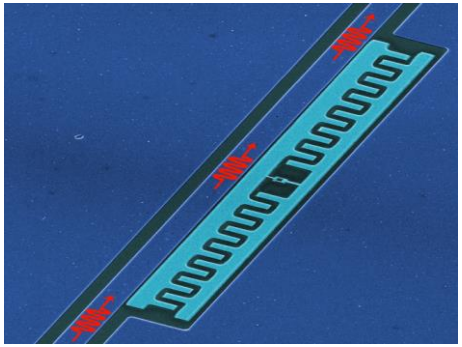
- Many flavors of qubit
- Key element is the Josephson Junction

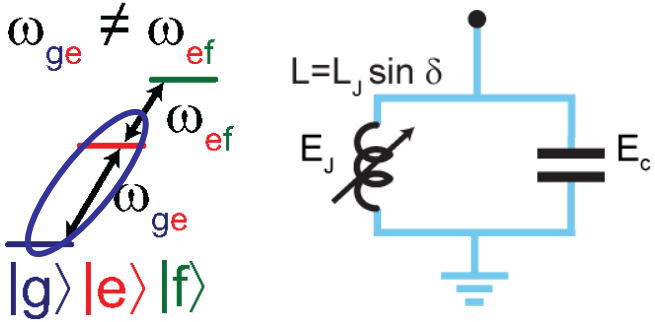
Charge



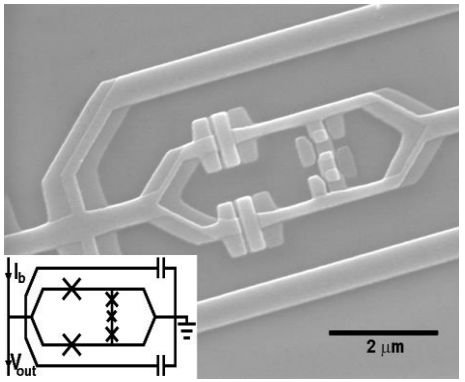

## Anharmonic Oscillator

Transmon



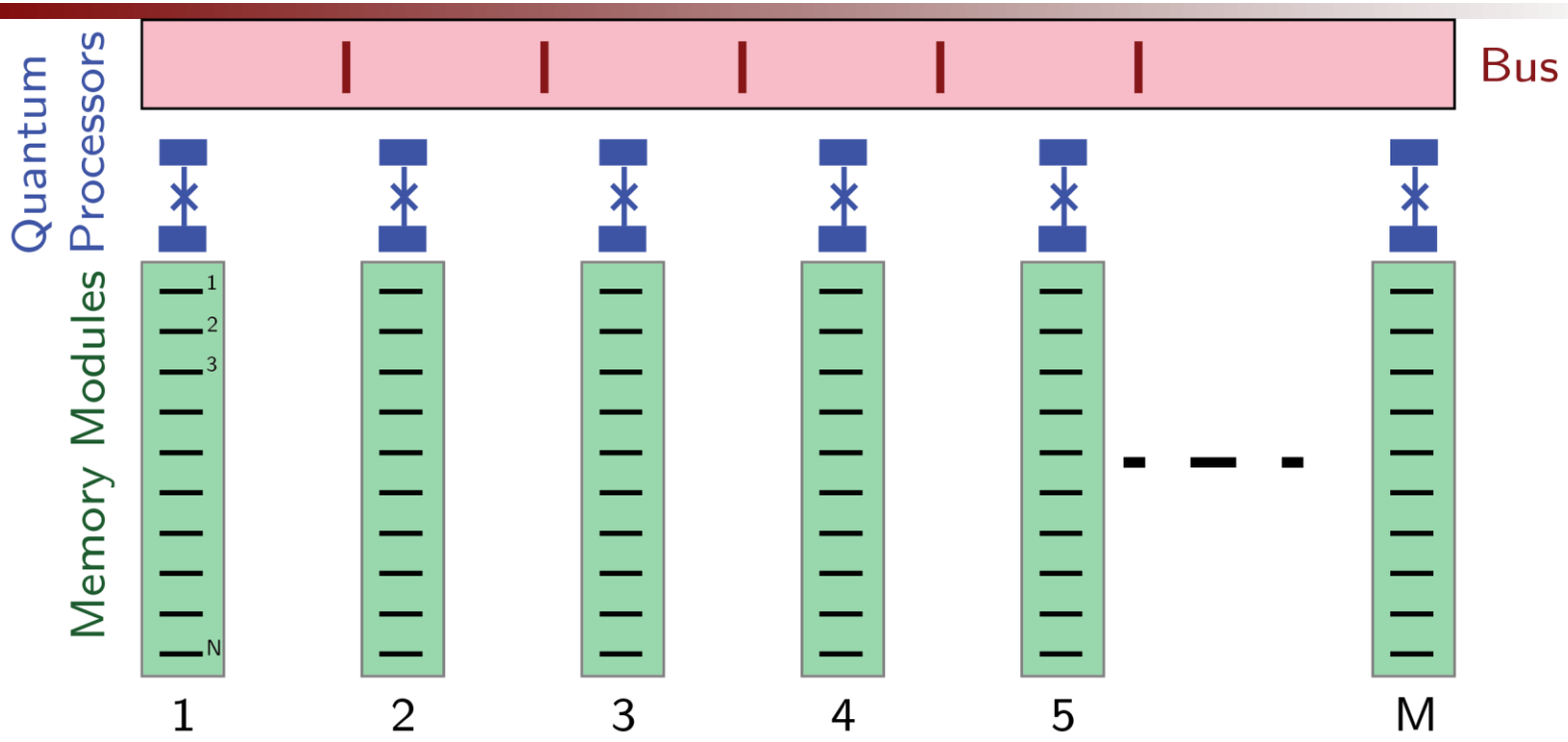



Flux




- Junction acts as non-linear inductor
- Bottom two (or several) individually addressable

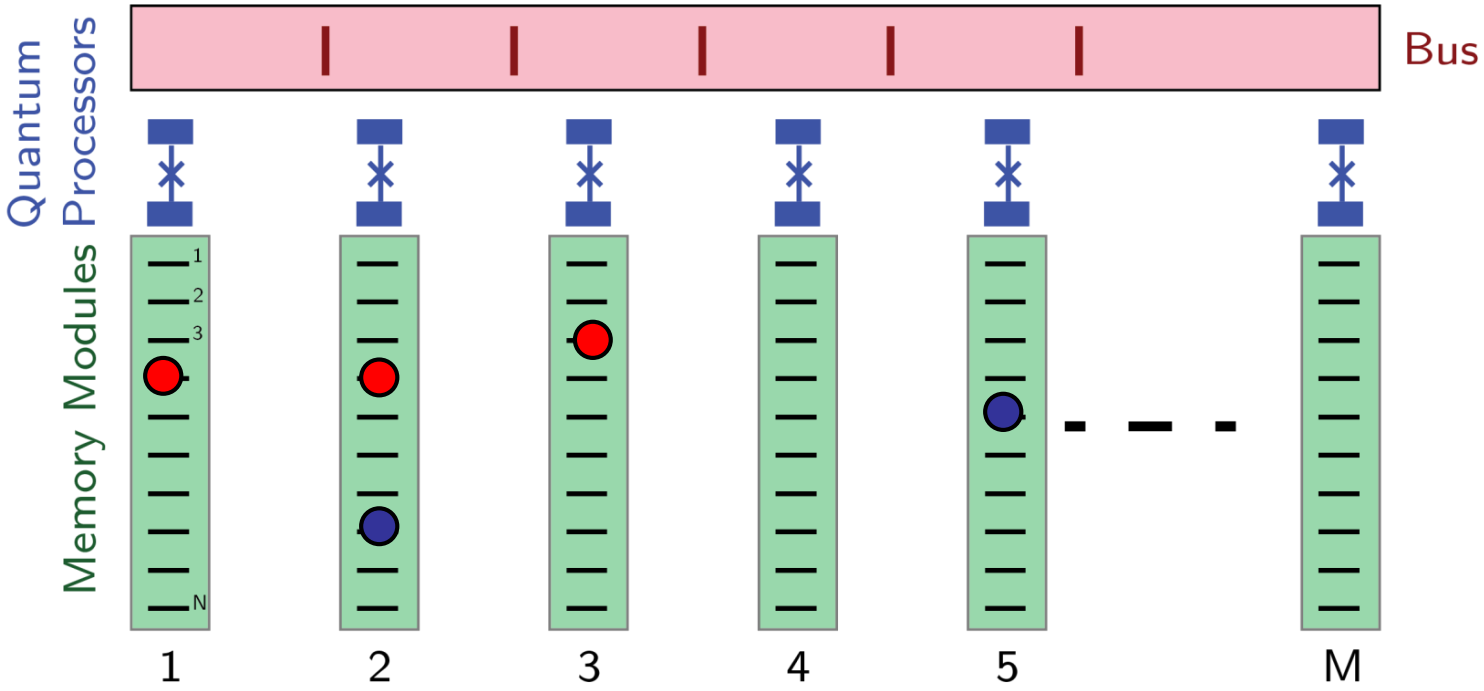
# *A photonic modular architecture for SC qubits*




Advantages:

- 10-100 qubits per module
- 10x fewer transmons, 10x less classical hardware
- Fully connected: 2 hops between any pair of bits, M-bits in parallel
- Compatible with hardware efficient error correction

# Modular Universal Quantum Logic




- Single qubit gate (2 swaps)
- Intra-module two qubit gate (4 swaps)
- Inter-module two qubit gate (8 swaps)

- Only two types of operations (rotation and swap)
- Inter-module almost as fast as intra-module
- Can run M instructions in parallel

# A network of two multimode-processors

**2 chips each with:**

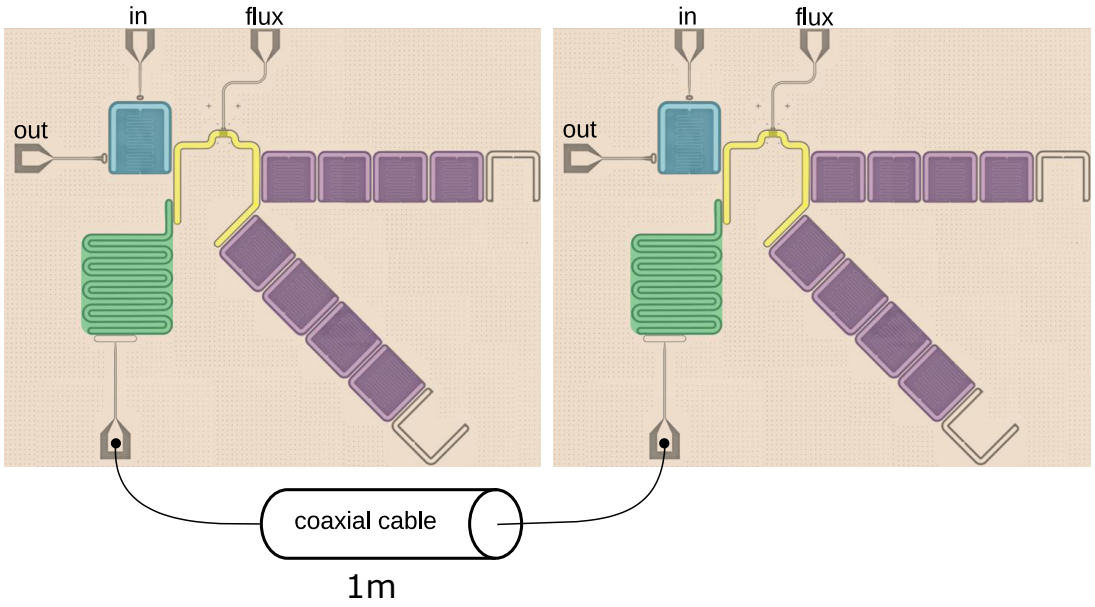
1 Transmon control

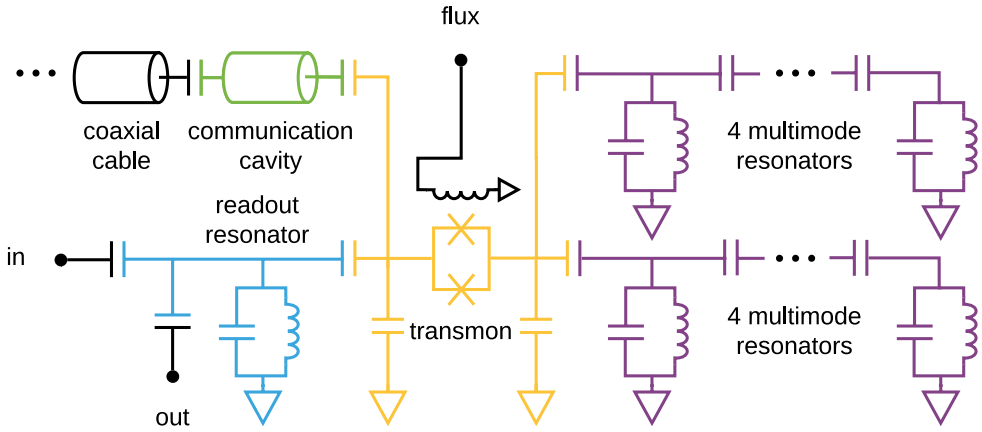
1 Measurement channel

8 data qubit modes

1 communication link

- ✓ Many photonic qubits
- ✓ Multiplexed control
- ✓ Universal Multimode Ops
- ✓ Modular architecture



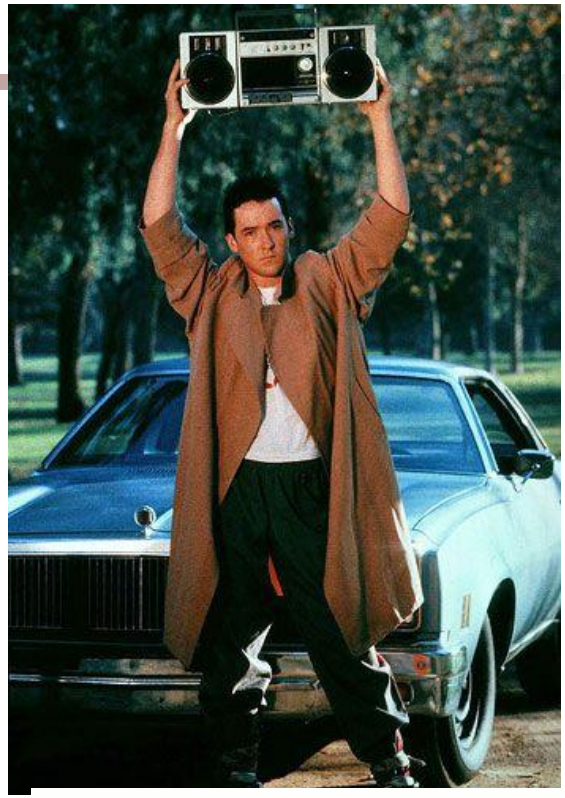



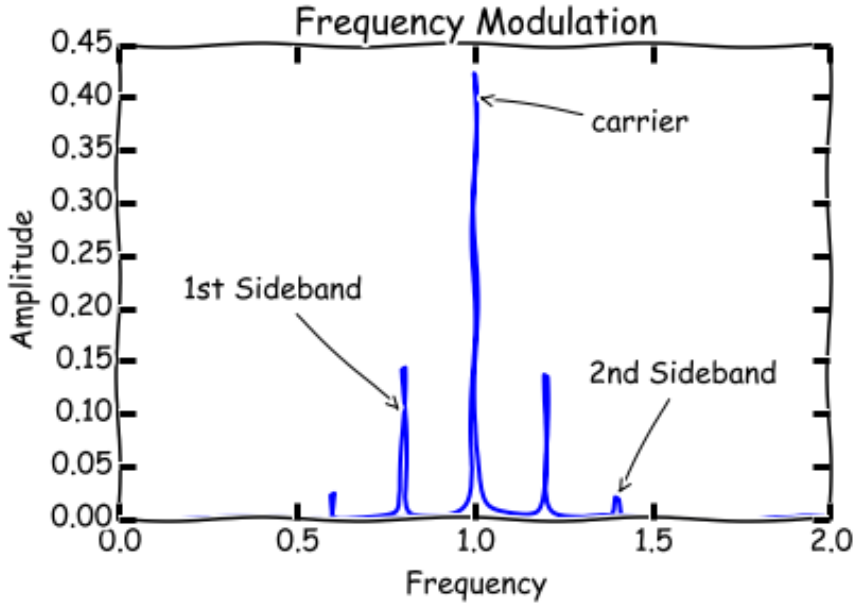
# How does an FM radio work?

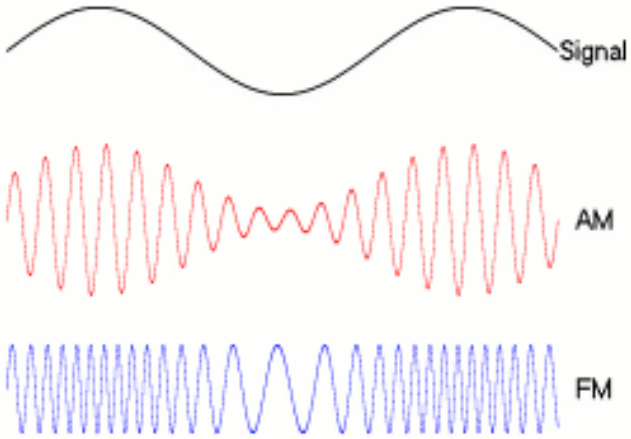
Carrier Frequency

Modulation signal

$$\sin\left(\omega_c t + \int_0^t \epsilon_m(\tau)d\tau\right)$$

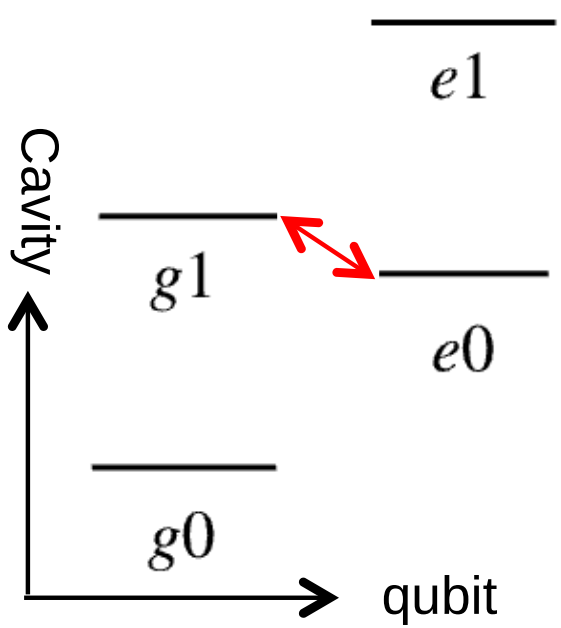


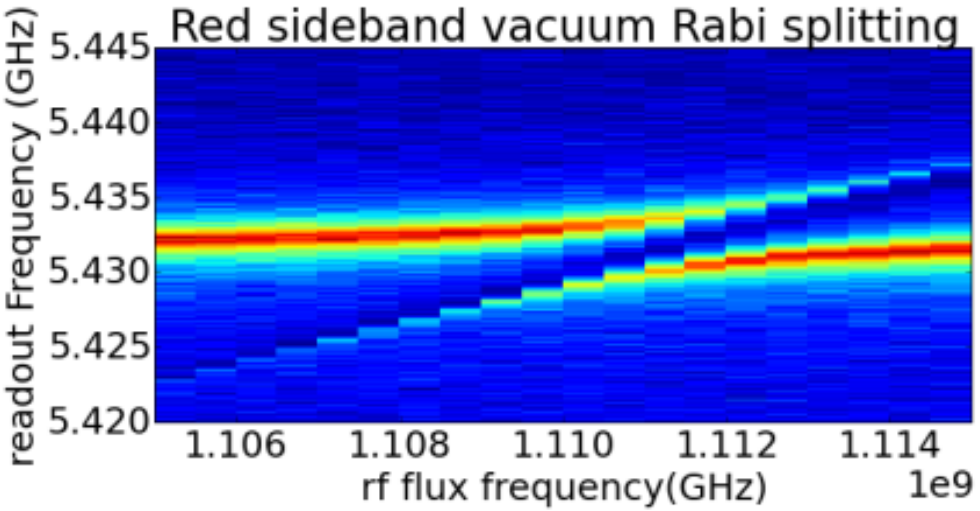


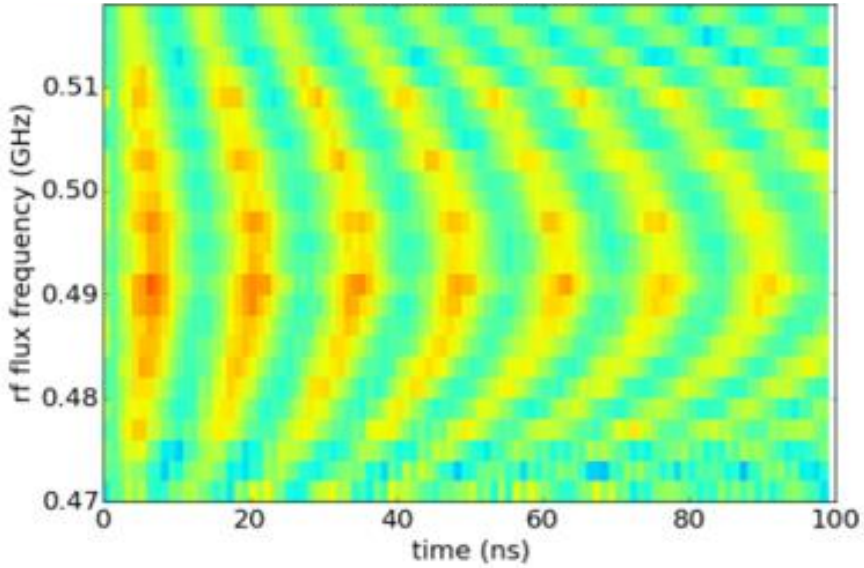



# Stimulated Vacuum Rabi Oscillations

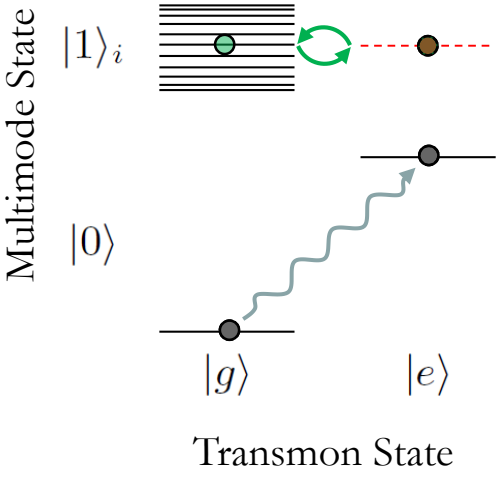
$$H_{int} = \frac{g_1}{2}(a^\dagger \sigma^- + a\sigma^+)$$

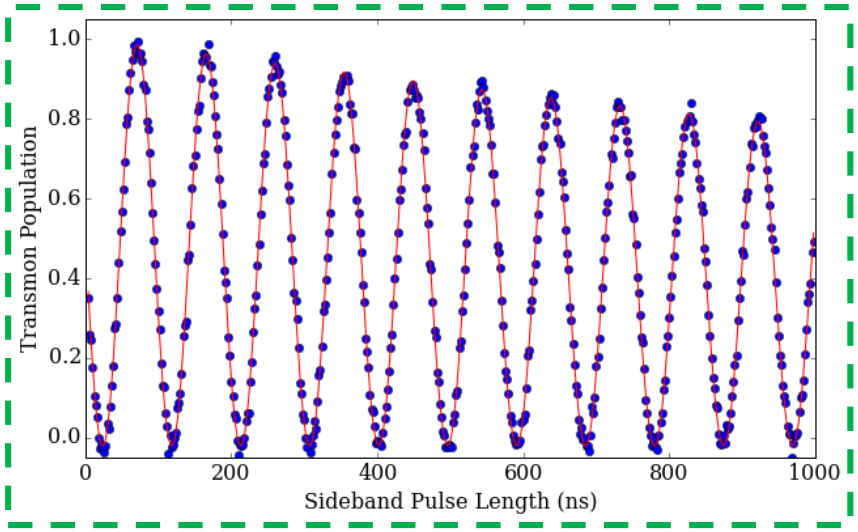


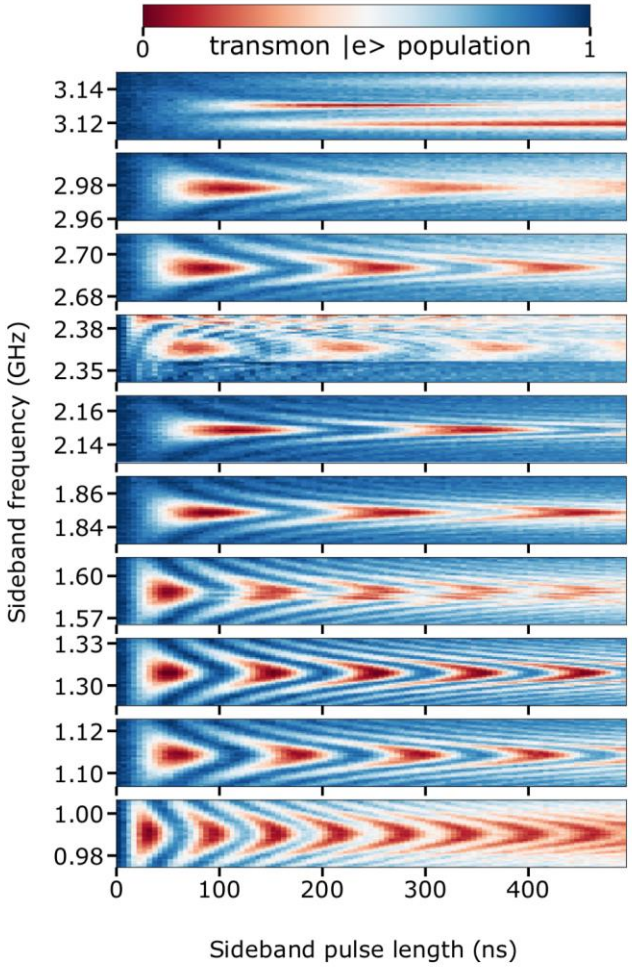



# Stimulated Vacuum Rabi Oscillations

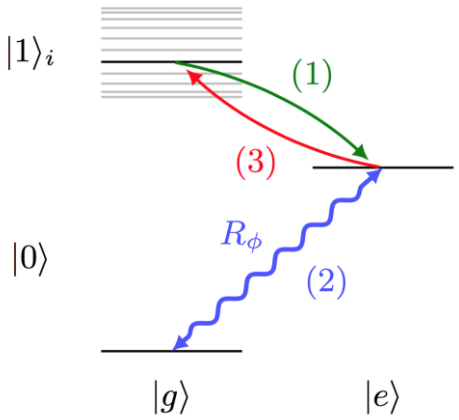


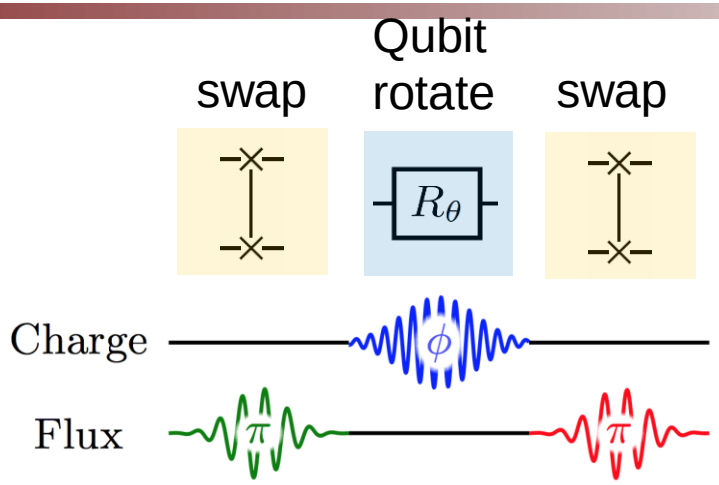




- We use a parametric drive to stimulate a vacuum Rabi Oscillation with any mode
- Address many modes with just a single transmon and set of controls

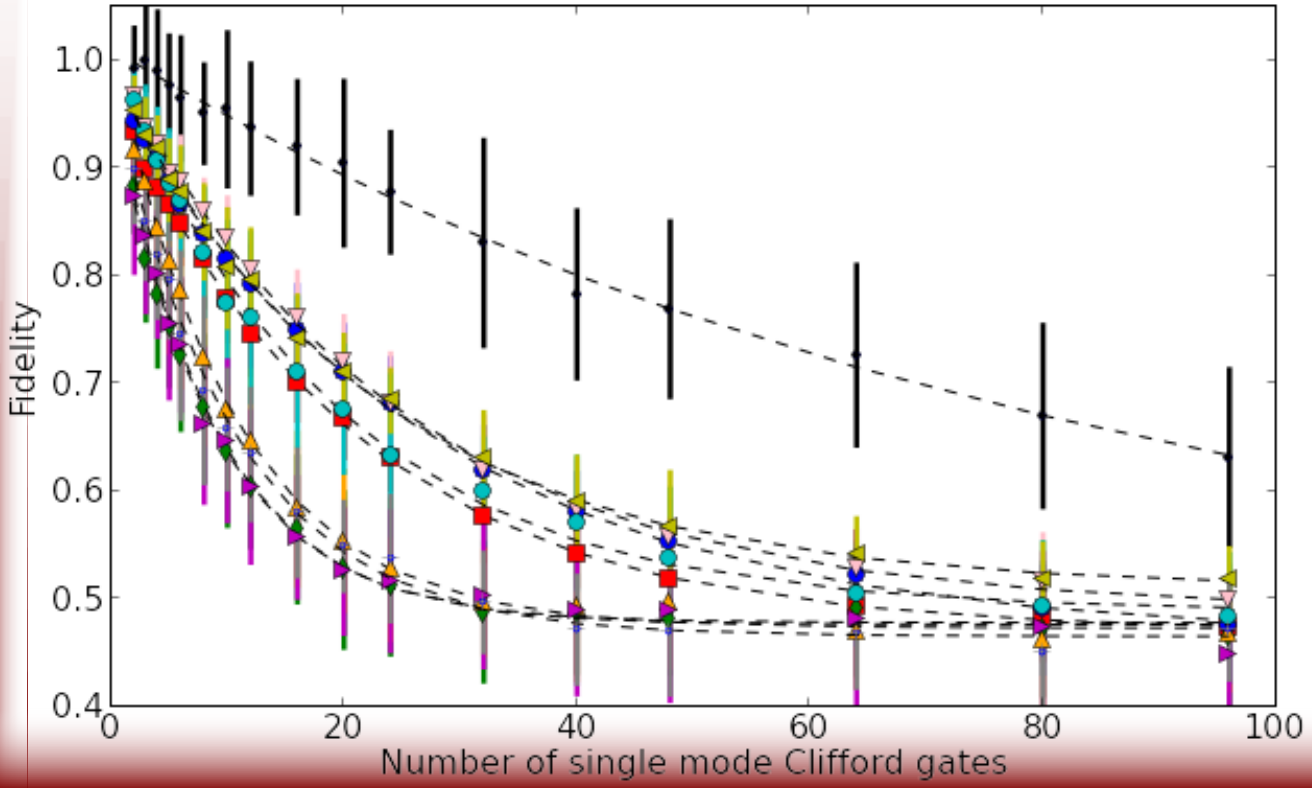
# Randomized Benchmarking of light

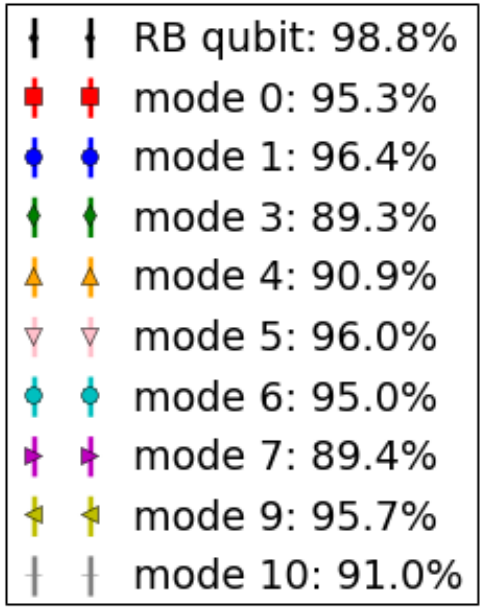


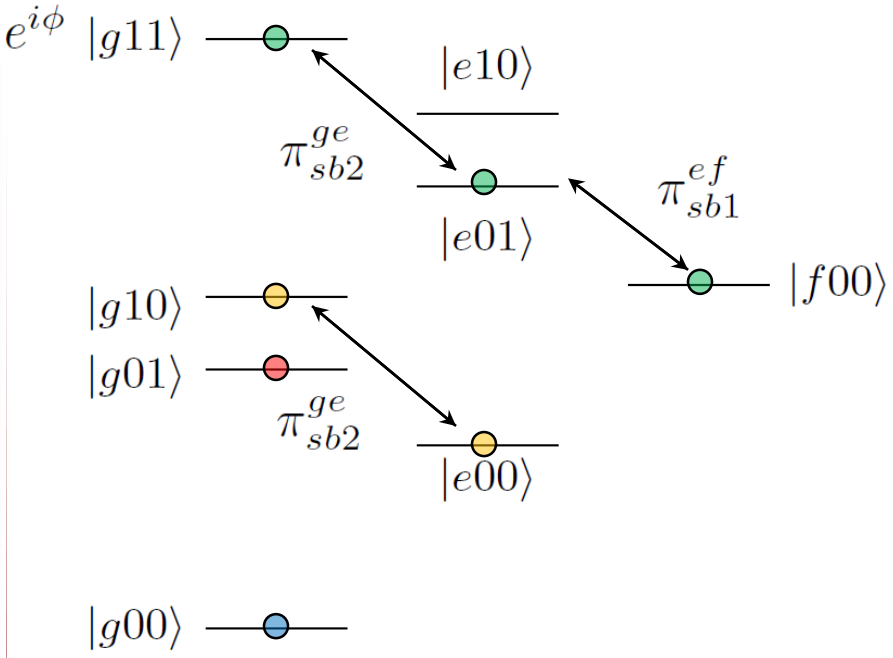

Qubit: >98%

Cavity mode Fidelity: 90-97%



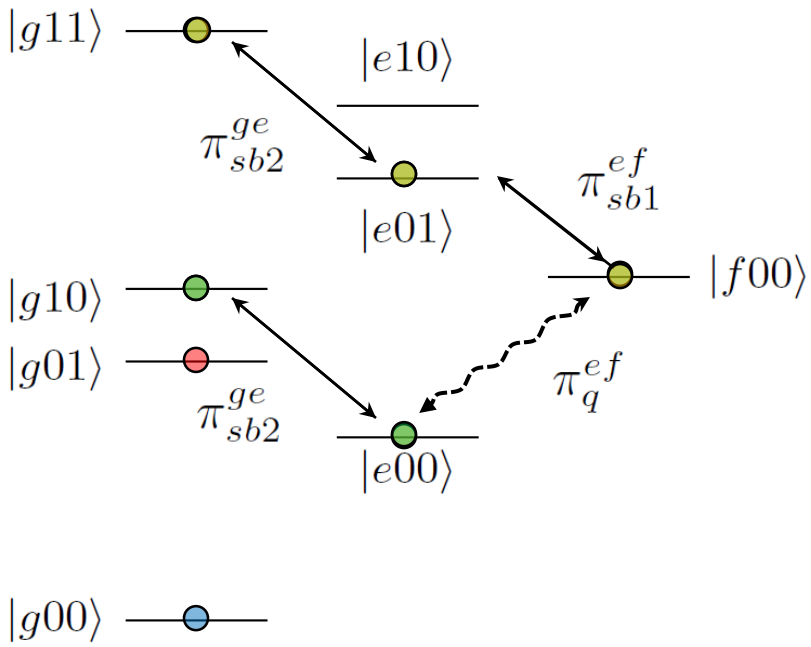
# Anatomy of a multimode gate




CZ

$$\pi^{ge}_{sb2} + \pi^{ef}_{sb1} + \pi^{ef}_{sb1} + \pi^{ge}_{sb2}$$

# Anatomy of a multimode gate



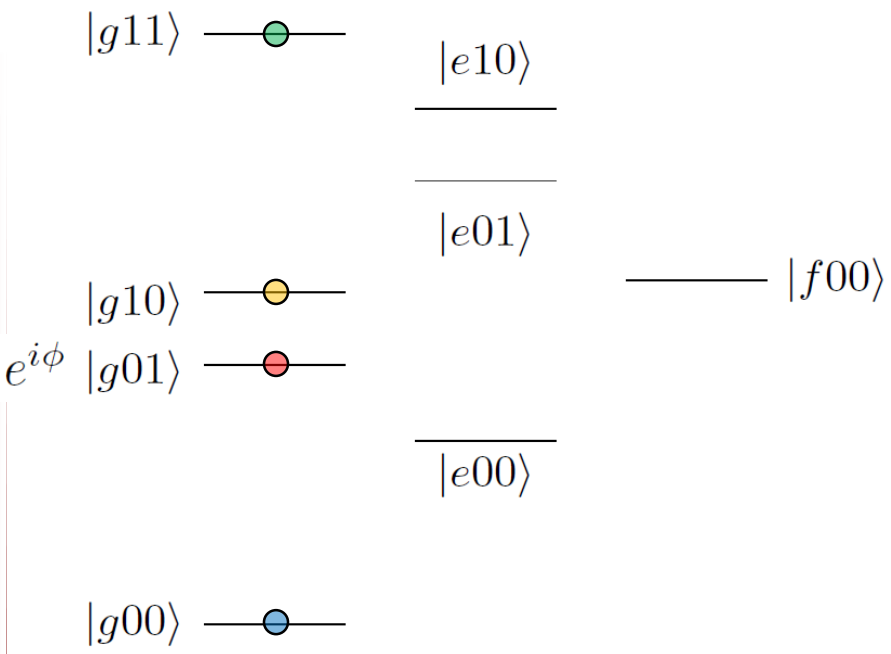

CZ

$$\pi^{ge}_{sb2} + \pi^{ef}_{sb1} + \pi^{ef}_{sb1} + \pi^{ge}_{sb2}$$

CNOT

$$\pi^{ge}_{sb2} + \pi^{ef}_{sb1} + \pi^{ef}_{q} + \pi^{ef}_{sb1} + \pi^{ge}_{sb2}$$

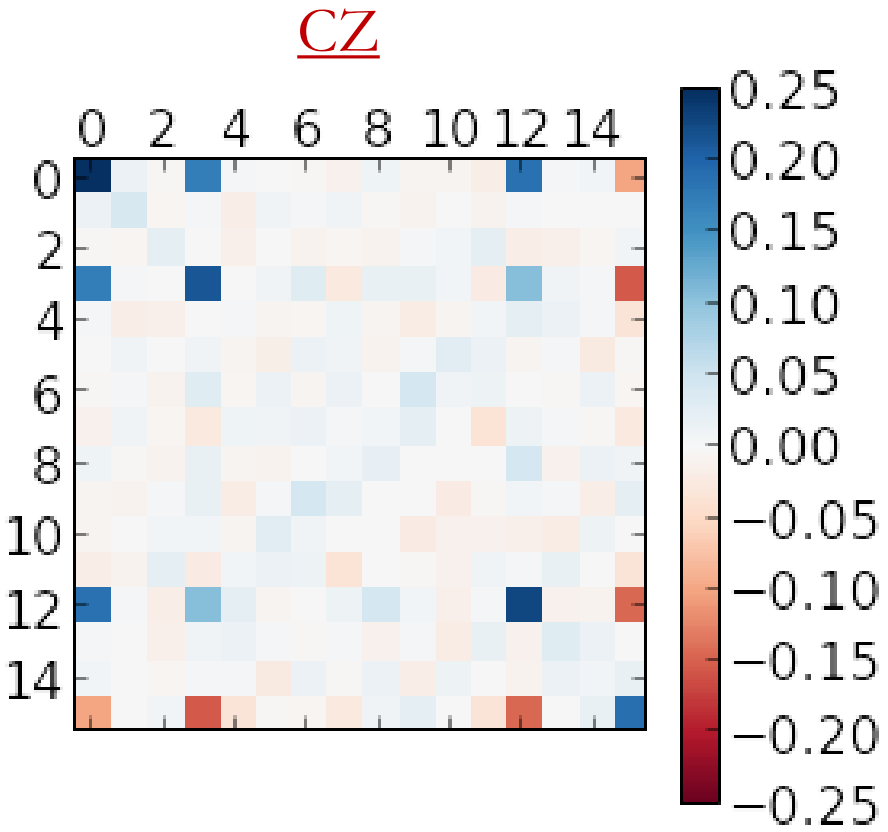
# Anatomy of a multimode gate

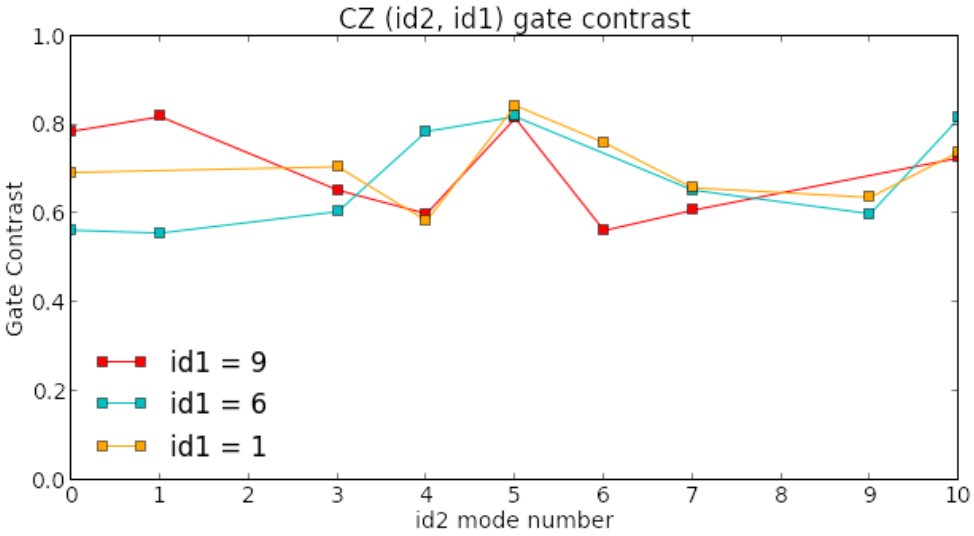



- Dispersive shift
- Stimulated AC Stark shift
- Qubit DC offset during Gate

- Working to model, compensate these higher order terms

# Process tomography of multimode gates

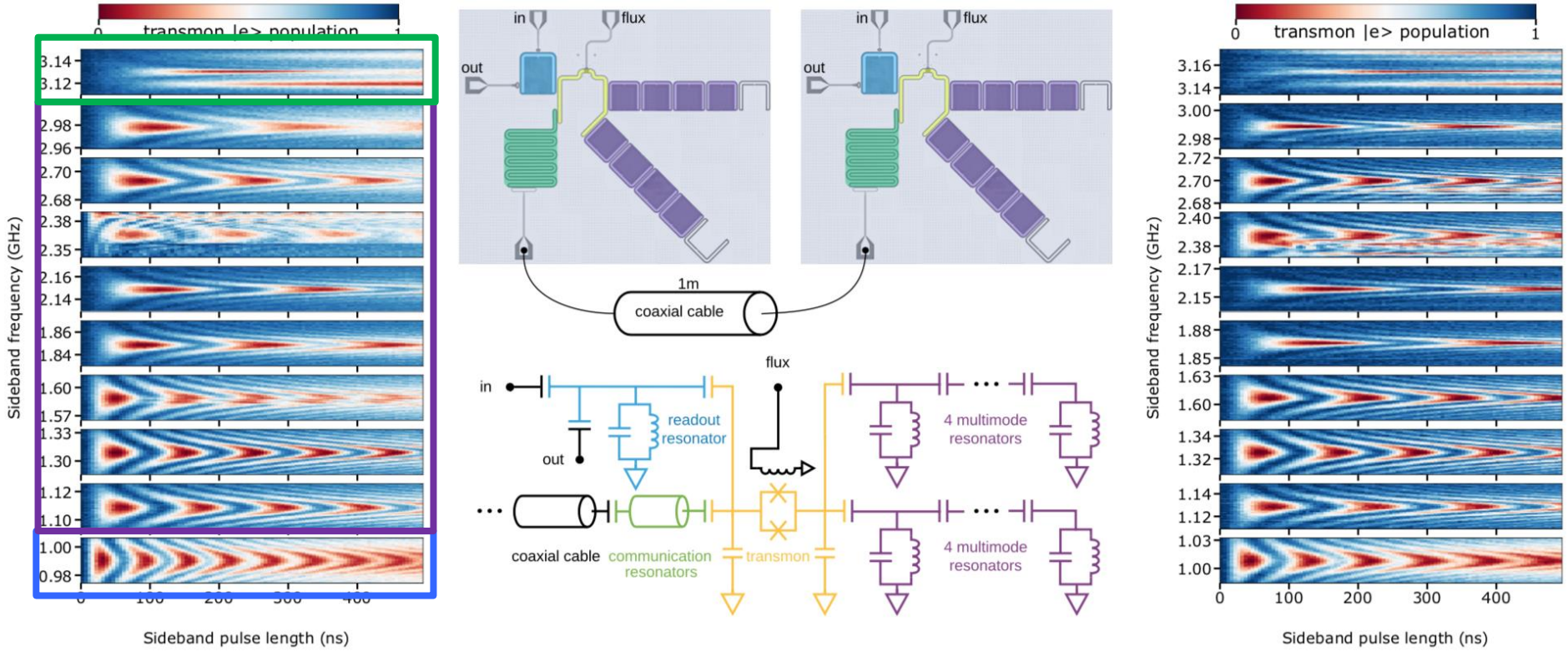



- Fidelity ~80% for gate

Random access quantum information processors. Nat. Comm. 8, 1904 (2017)

# Shuttling single photons




**Readout**

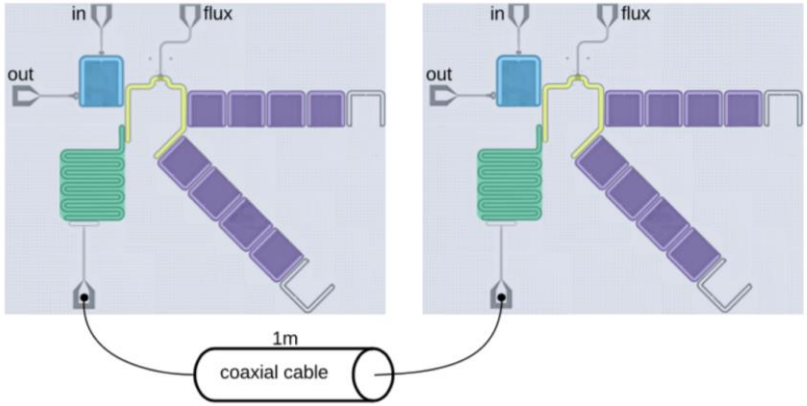
**Multimode Memory**

**Communication**

Everything is accessed with sideband swaps.

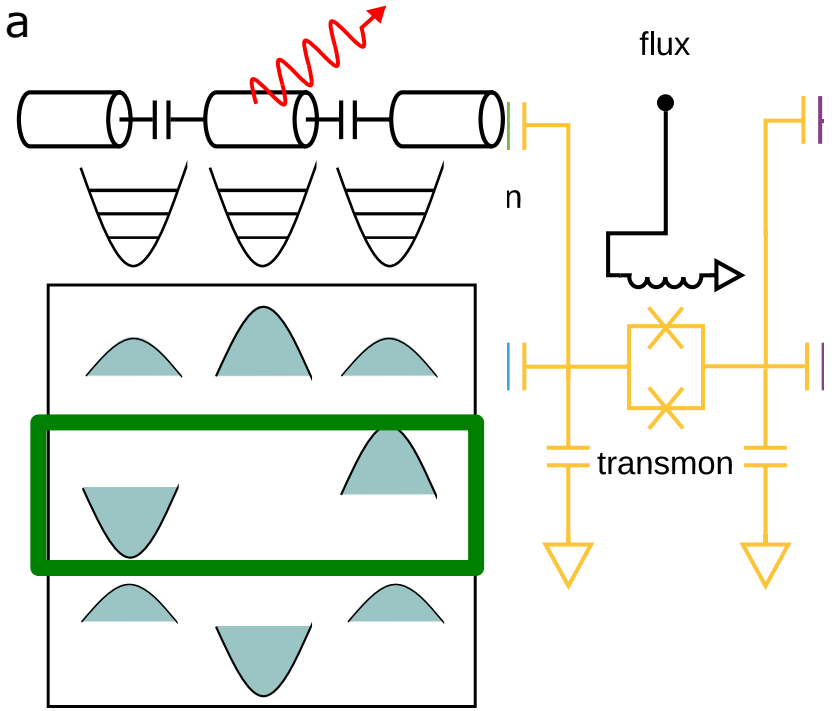
Communication looks just like memory!

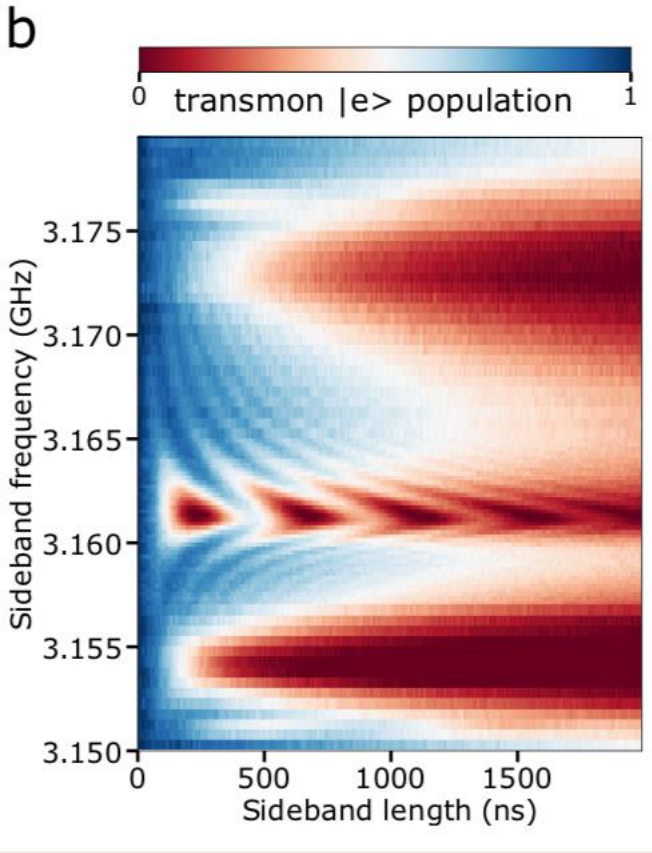
# Low loss communication channel




Model as 3 modes in series
Comm – cable – Comm

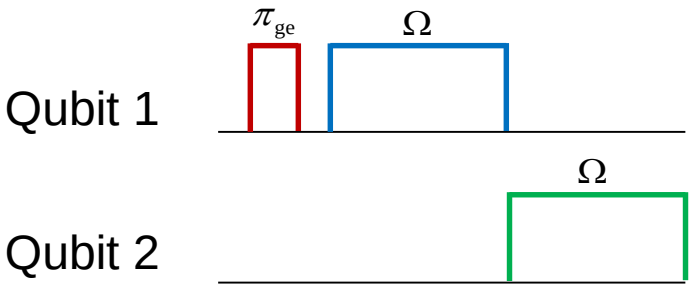
Dark mode is protected against loss in cable!

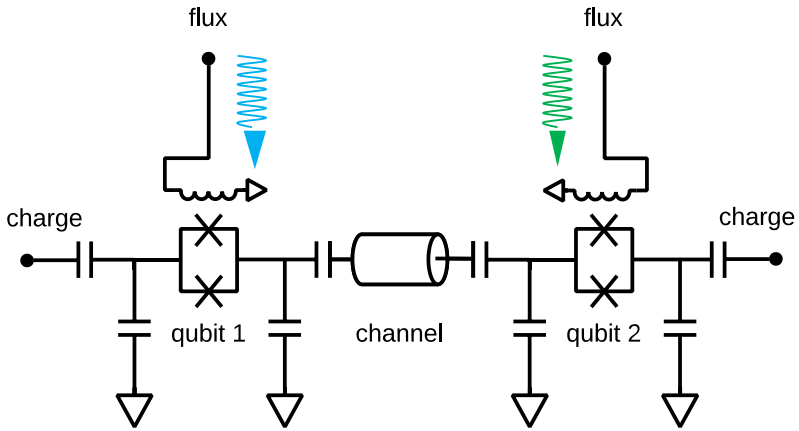


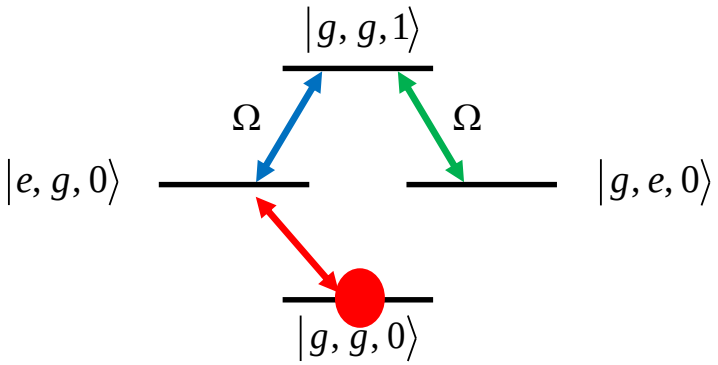




T1 = 550ns

# Bi-directional photon transfer




$|\text{qubit 1, qubit 2, channel}\rangle$

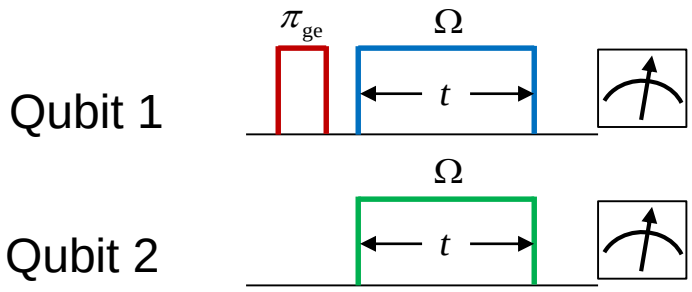
1. Put single photon in sender

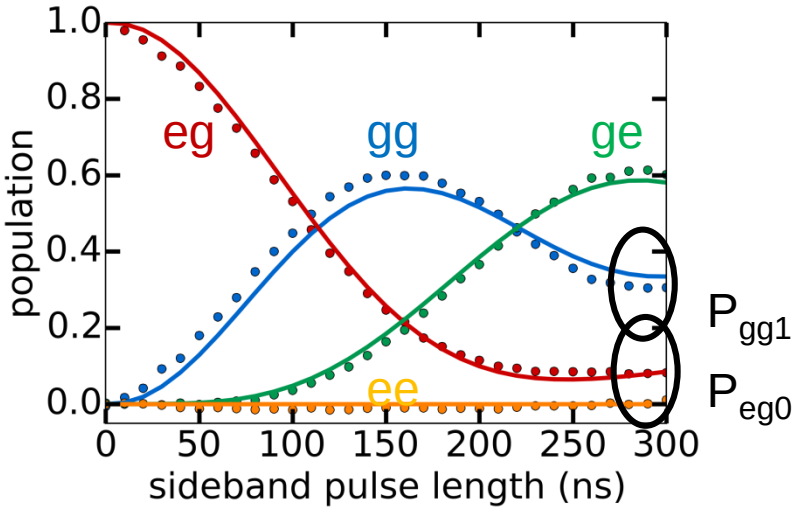
2. Swap into “dark” mode

3. Swap into receiver

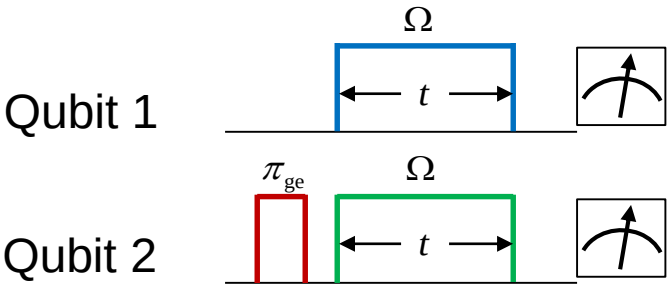
Can speed things up by sending and receiving simultaneously.

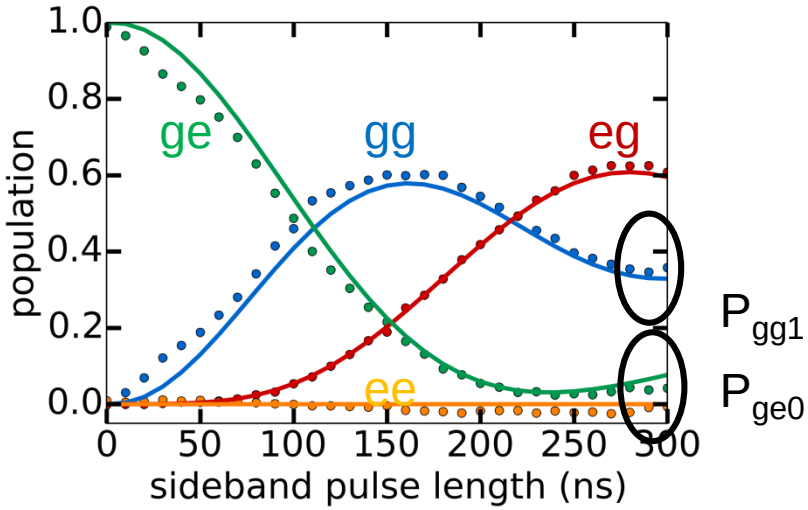
# Bidirectional photon transfer



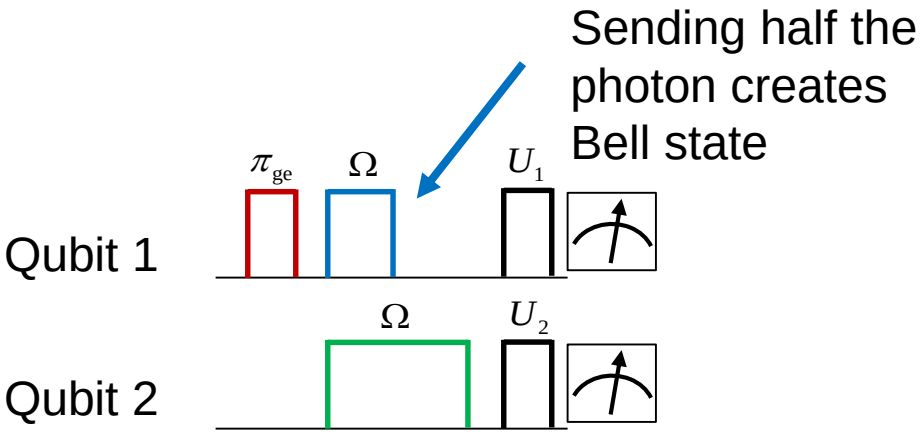

- 1 to 2 fidelity: $P_{ge0} \approx 61\ \%$
- Loss mechanism:
  - qubit and channel decay: $P_{gg0} \approx 24\%$
  - qubit dephasing: $P_{gg1} + P_{eg0} \approx 15\%$

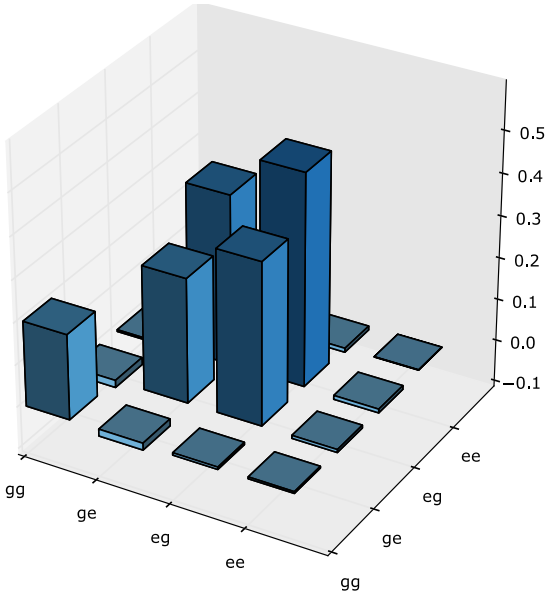



- 2 to 1 fidelity: $P_{eg0} \approx 62\ \%$
- Loss mechanism:
  - qubit and channel decay: $P_{gg0} \approx 24\%$
  - qubit dephasing: $P_{gg1} + P_{eg0} \approx 14\%$

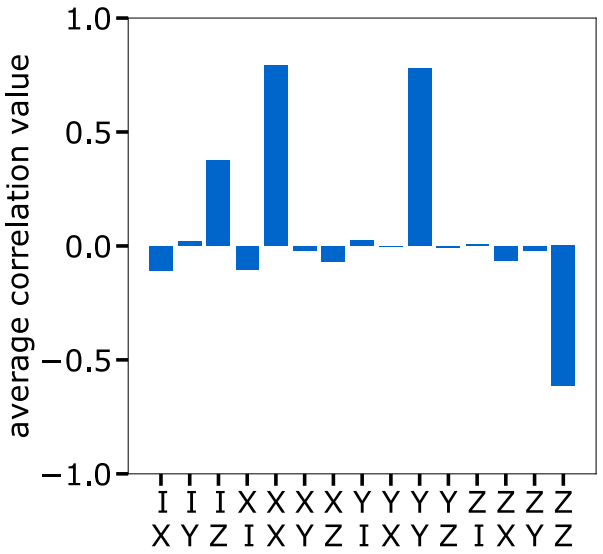
# Bell state generation



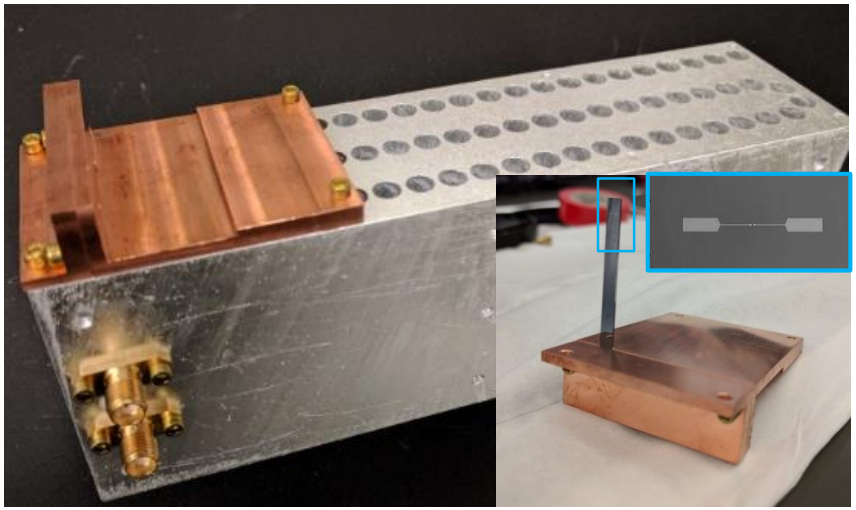



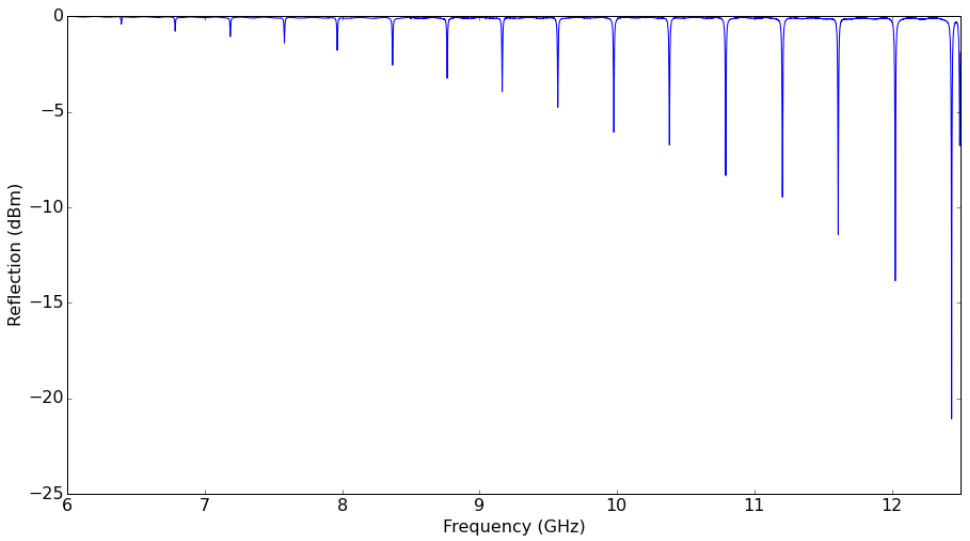

- $F = \mathrm{Tr}\left(\rho_{\mathrm{Bell}} \cdot \rho_{\mathrm{measure}}\right) = 0.793 \pm 0.002$

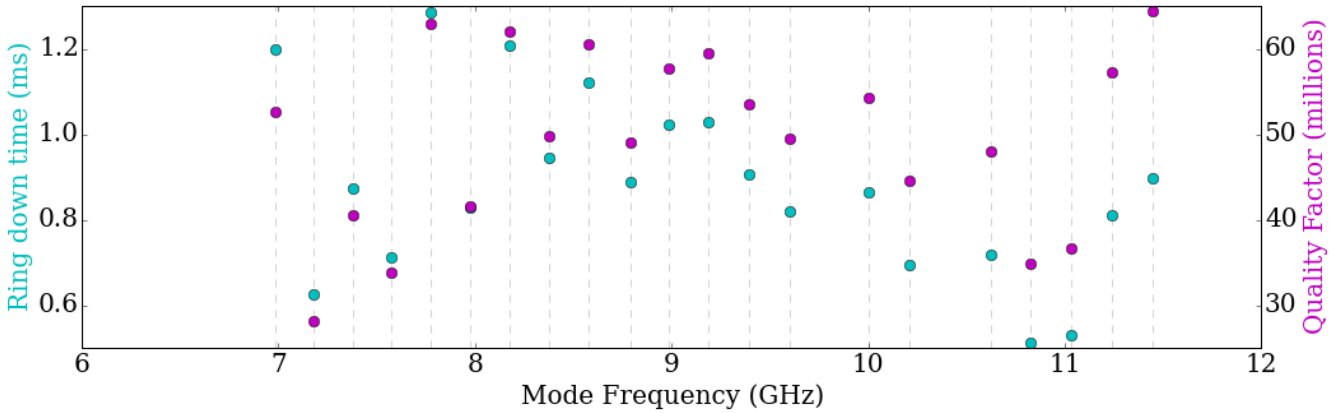
- Loss mechanism:
  - qubit and channel decay: 0.1
  - qubit dephasing: 0.1



# Realizing higher Q - 3D modules

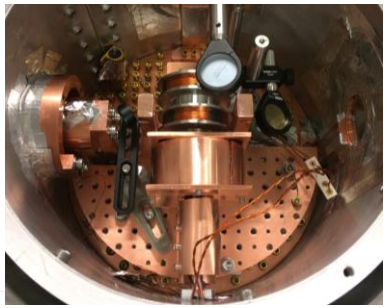




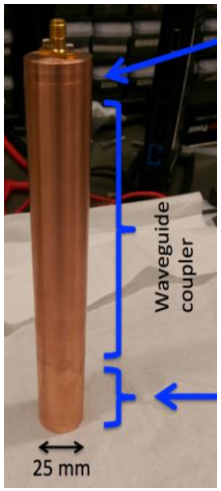




- A box with no seams.
- 10-50 Modes
- Engineered dispersion uniformly spaced (400MHz)

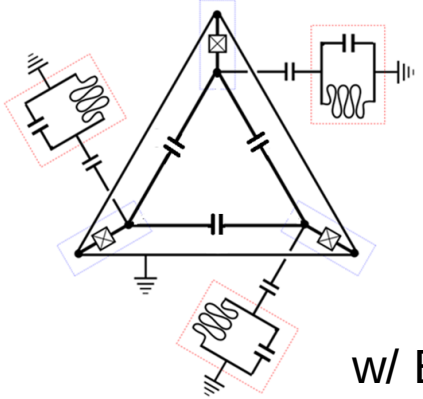
# Other exciting projects in the lab



Rydberg Optical/Microwave CQED w/ Jon Simon



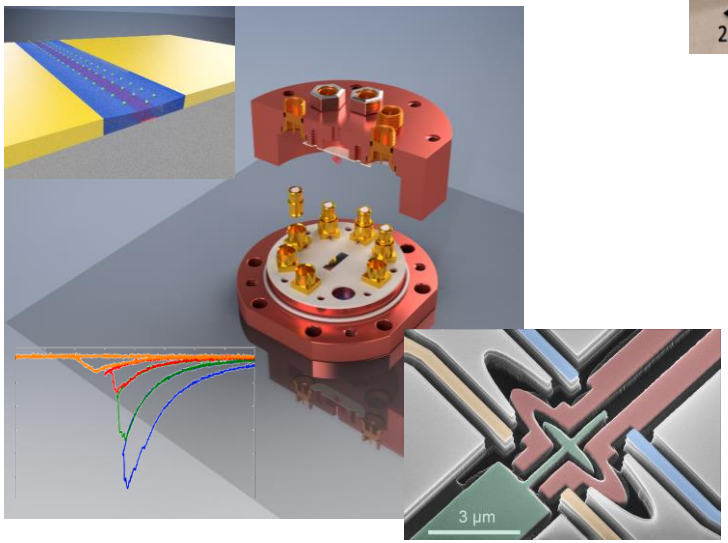

Autonomous error correction



w/ E. Kapit

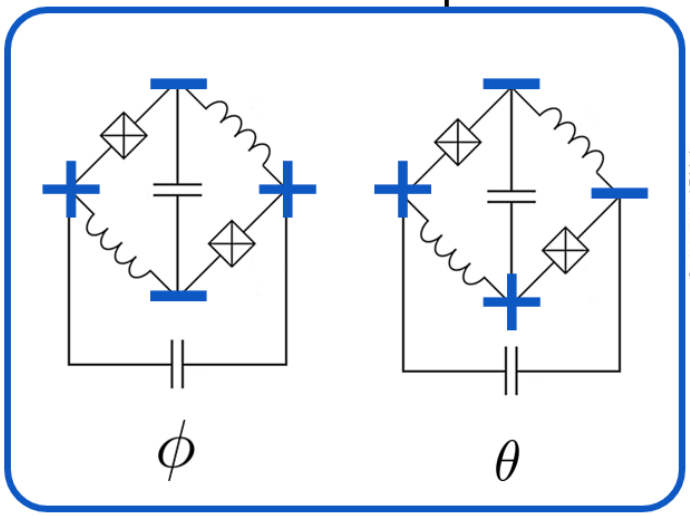
Searching for Dark Matter w/ Aaron Chou, and others at FNAL

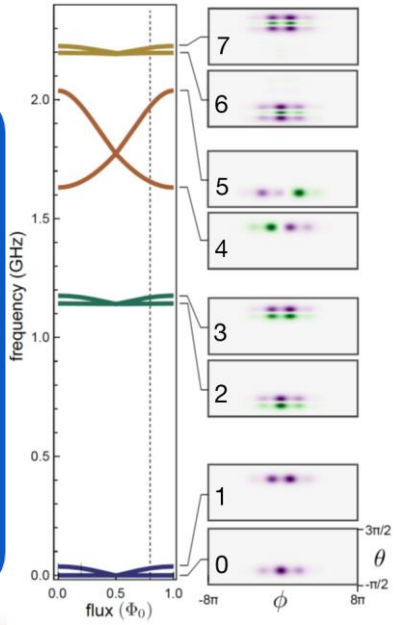
cQED with electrons on helium




PRX 6, 011031 (2016)

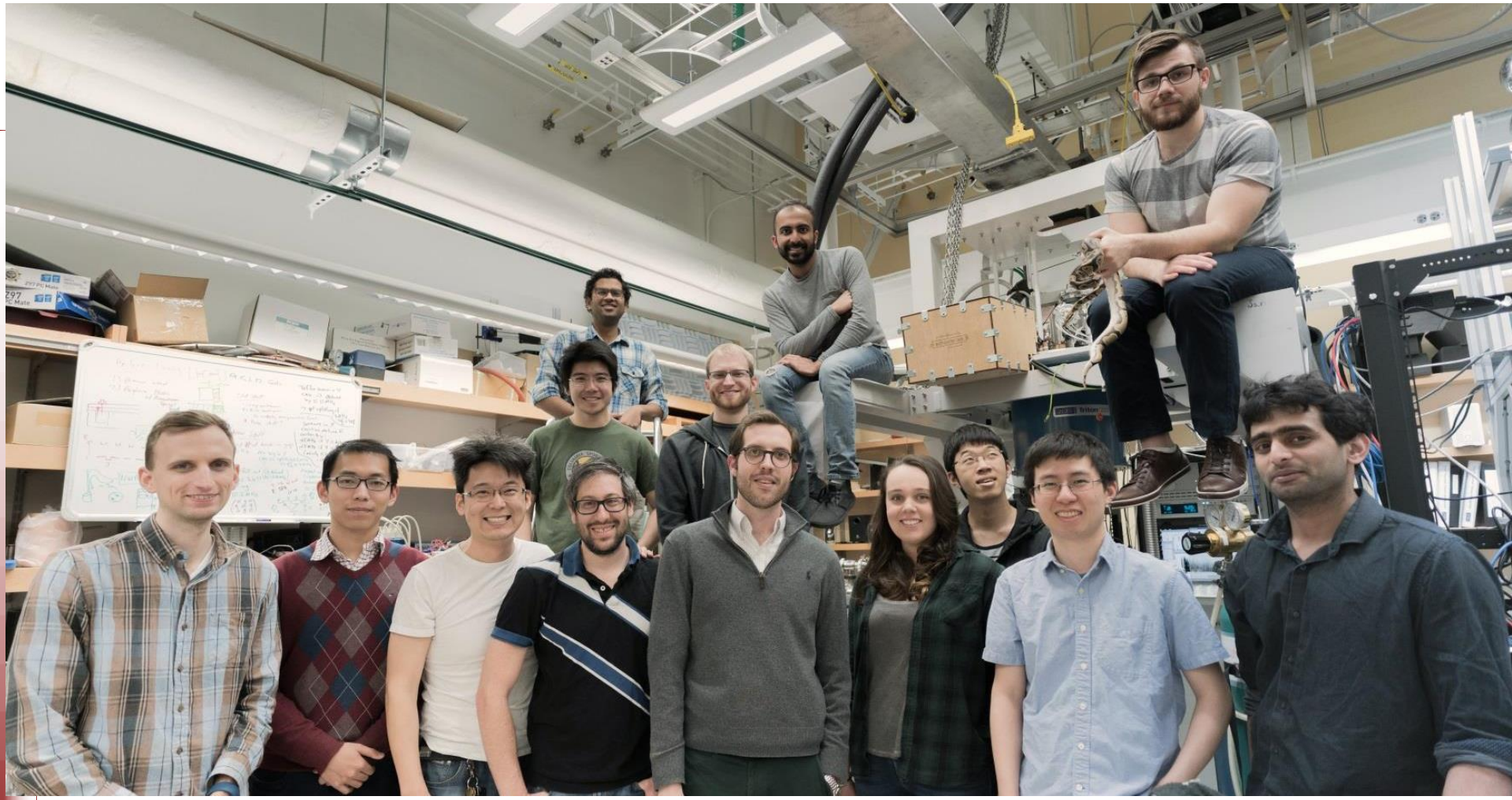
Protected qubits



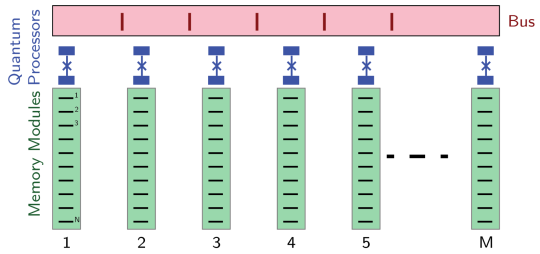

PRB 90, 094518 (2014)

# The group

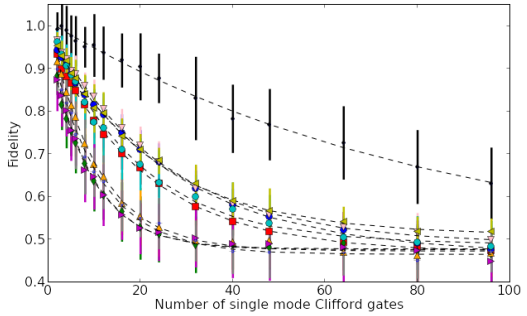


# Conclusions

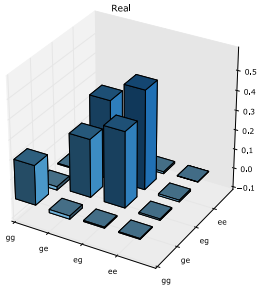
- Modular superconducting architecture with random access, reduced resources



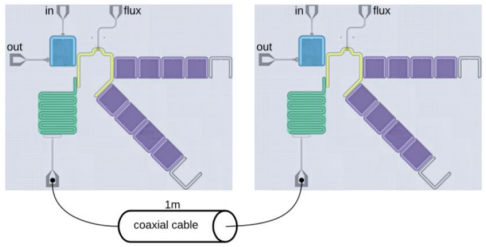

- Universal quantum logic within a module

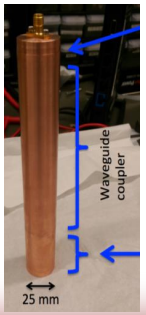



- Bi-directional coherent communication
  ~60% single photon fidelity




- Remote Bell state generation
  ~80% Bell state fidelity




- Higher Q 3D implementations soon
- Superconducting Qubits can be used directly as sensors