VSRP-2019
Tata Institute of Fundamental Research, Mumbai

Inter-qubit coupling in the circular bus architecture

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Basic Quantum Computing

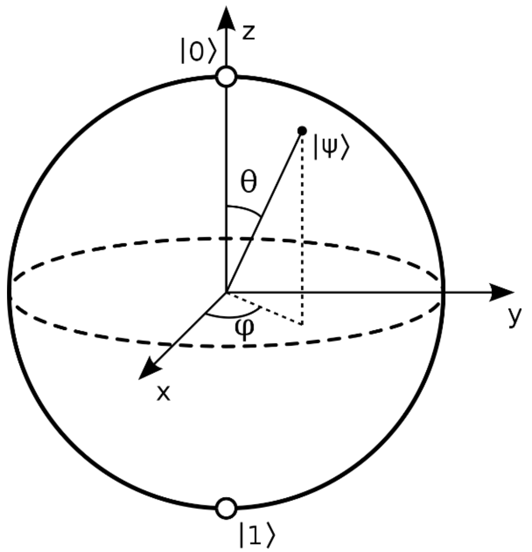
Qubit

$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

$$0 \le \theta, \phi \le 2\pi,$$

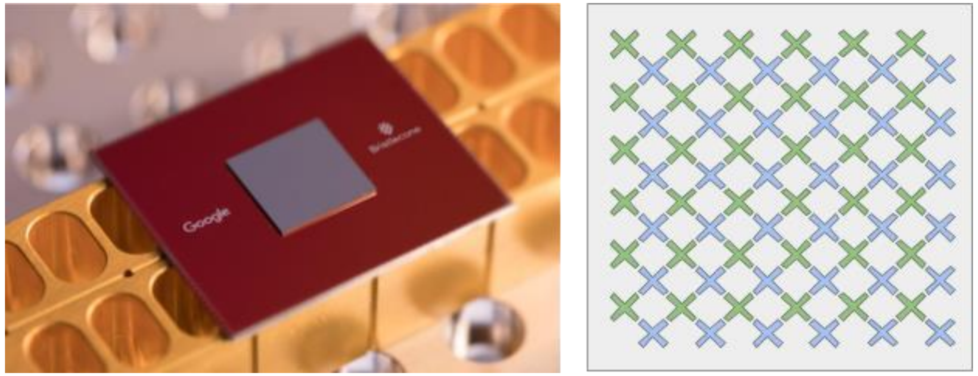


- **Measurement**: $|0\rangle$ or $|1\rangle$ with probabilities $\cos^2\left(\frac{\theta}{2}\right)$ or $\sin^2\left(\frac{\theta}{2}\right)$

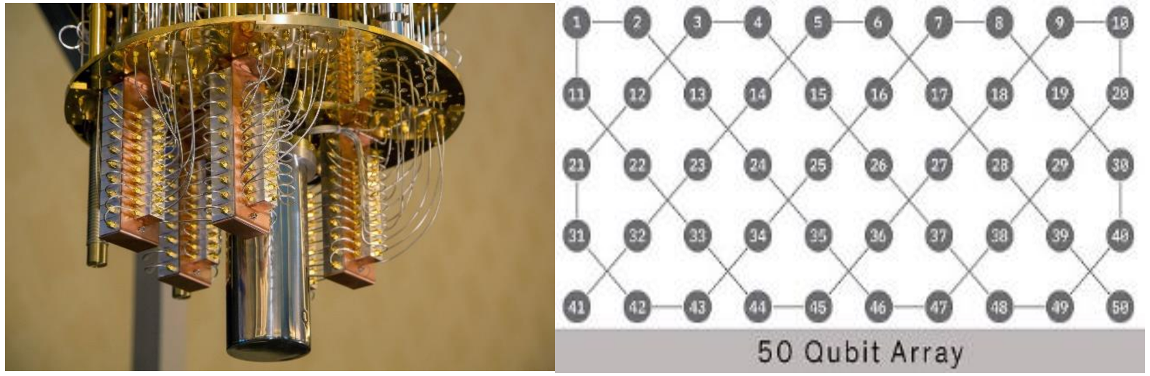
- **Gate**: $U|\psi\rangle$ - Rotation in the Bloch sphere.

Superconducting quantum processors

- Edge in **scalability.**
- **Connectivity** a major challenge.



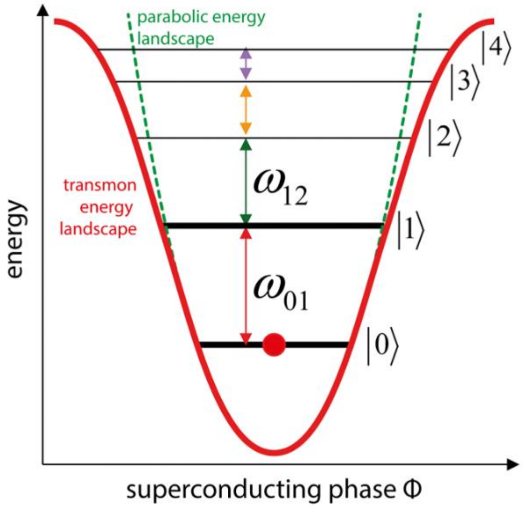
Google Bristlecone, a 72 qubit processor



IBM-Q, a 50 qubit processor

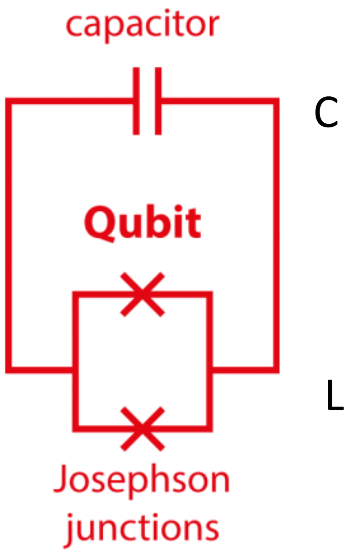
Basics of superconducting qubits

- **Non-linear Quantum LC oscillators.**
  - ➢ Quantized energy levels with decreasing level spacing.
  - ➢ Made of **Josephson Junctions**: dissipationless *non-linear inductors.*

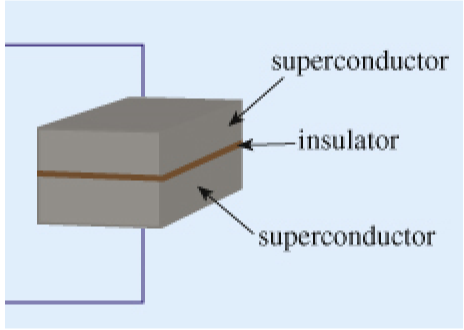


Energy levels of a superconducting qubit

$$\omega_{01} = \frac{1}{\sqrt{LC}}$$



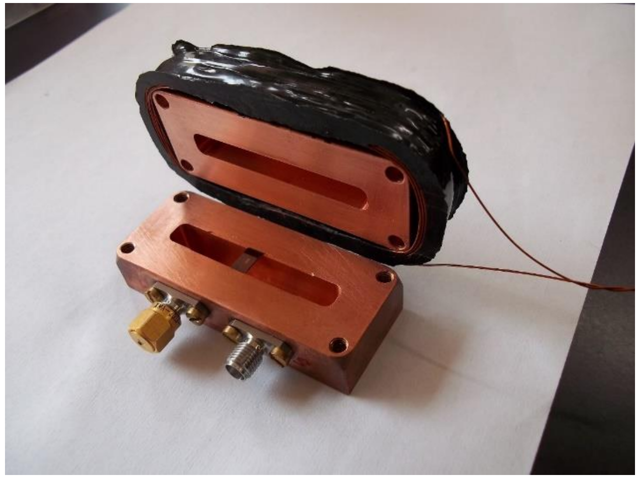
The transmon qubit



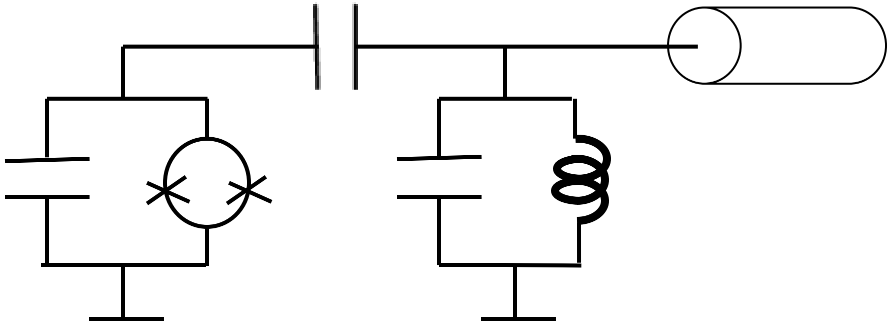
A Josephson Junction

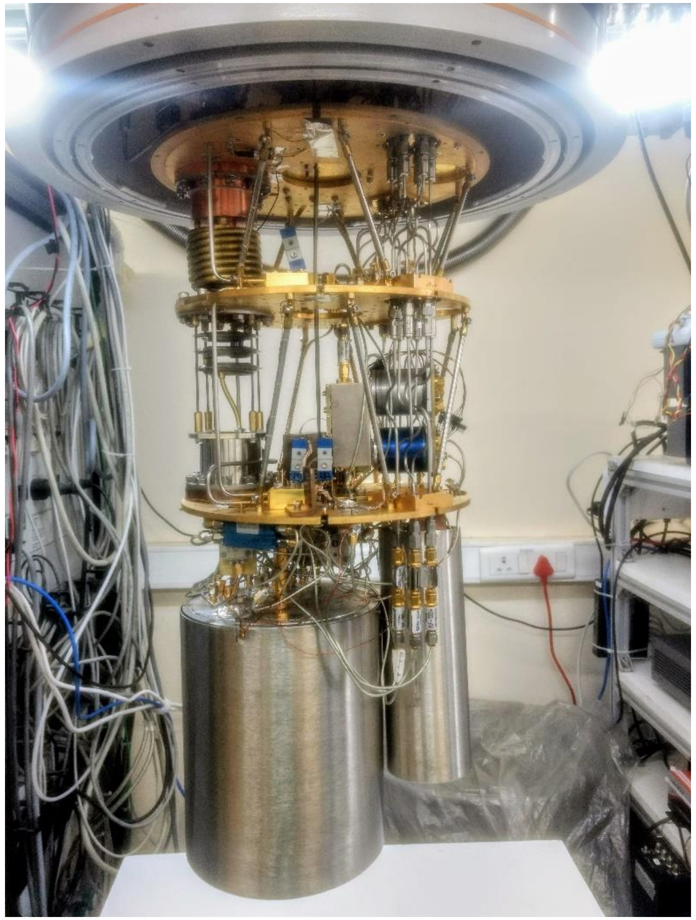
Circuit QED

$k_B T \ll \hbar\omega_{01}$



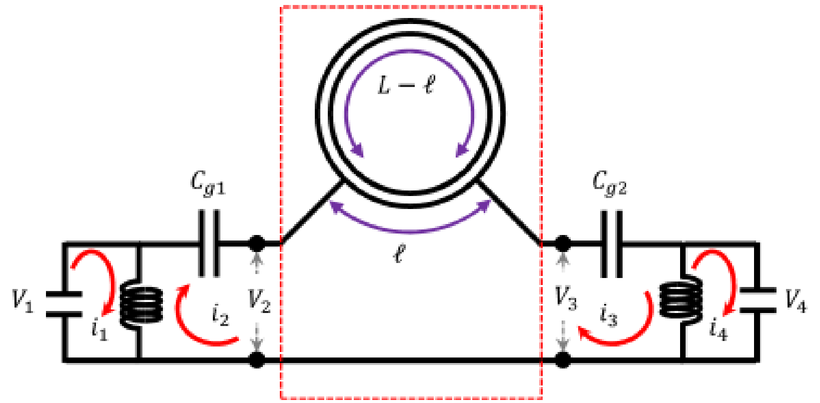
Transmon coupled to a copper cavity





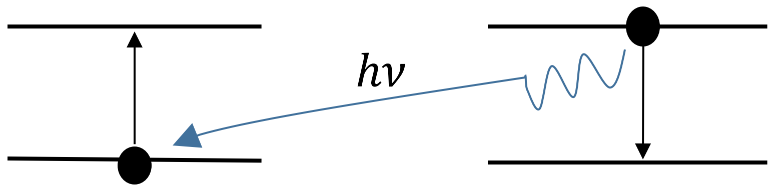
40 milli Kelvin Dilution refrigerator at QuMaC

Qubit-Qubit coupling

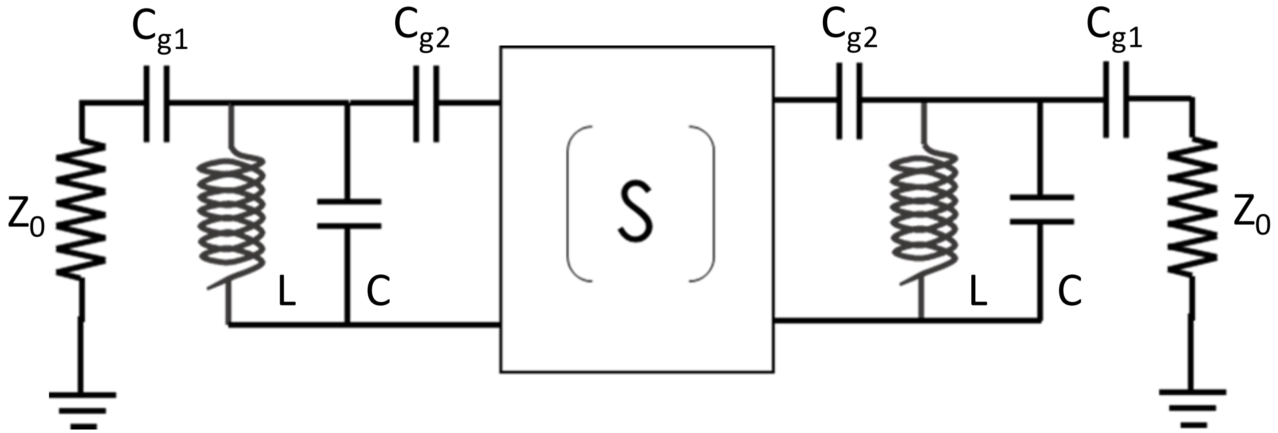


Jaynes-Cummings Hamiltonian

$$H = \frac{\hbar\Omega_{01}}{2}(\sigma_z)_a + \frac{\hbar\Omega_{01}}{2}(\sigma_z)_b + \boxed{\hbar g(\sigma^-\sigma_+ + \sigma^+\sigma_-)} + H_{drive} + H_{damping}$$



Frequency of coupled oscillations = g



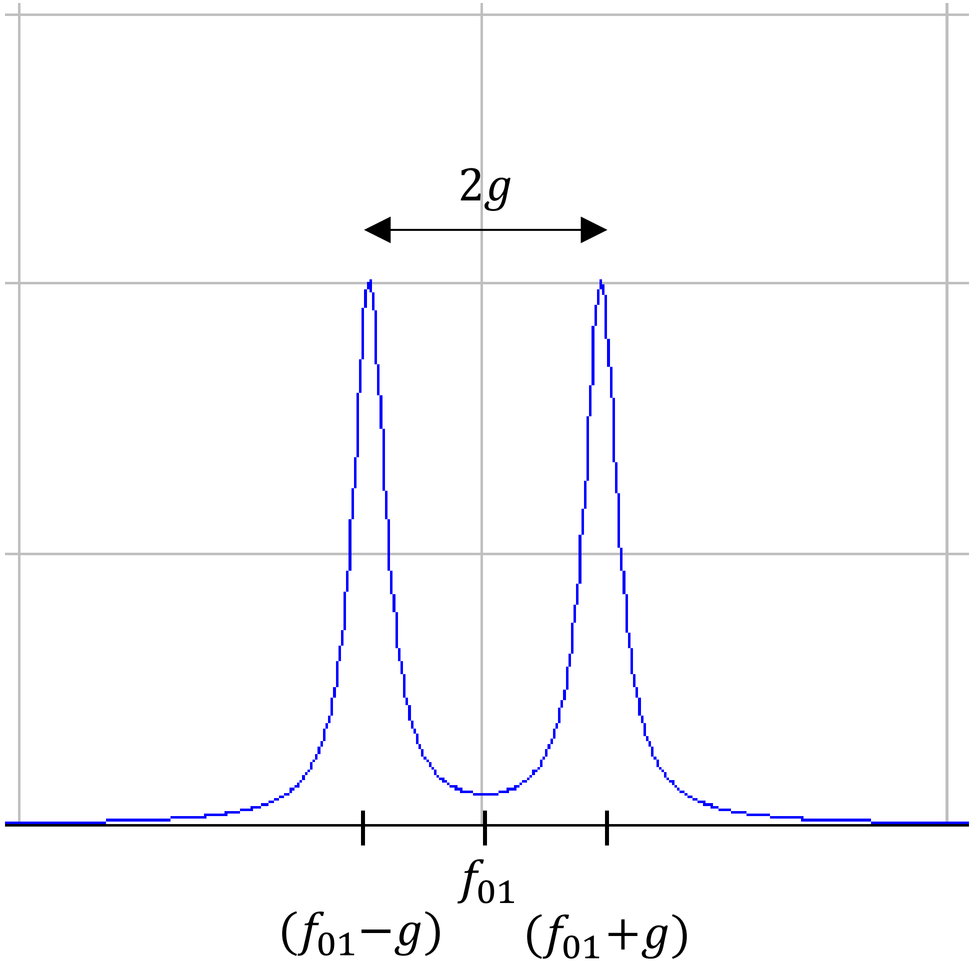
Two qubits, each coupled to a cavity and a coaxial line

Cavity modes: f_{c1}, f_{c2}

Qubit transition frequency: f_{01}

$$f_{c1} < f_{01} < f_{c2}$$

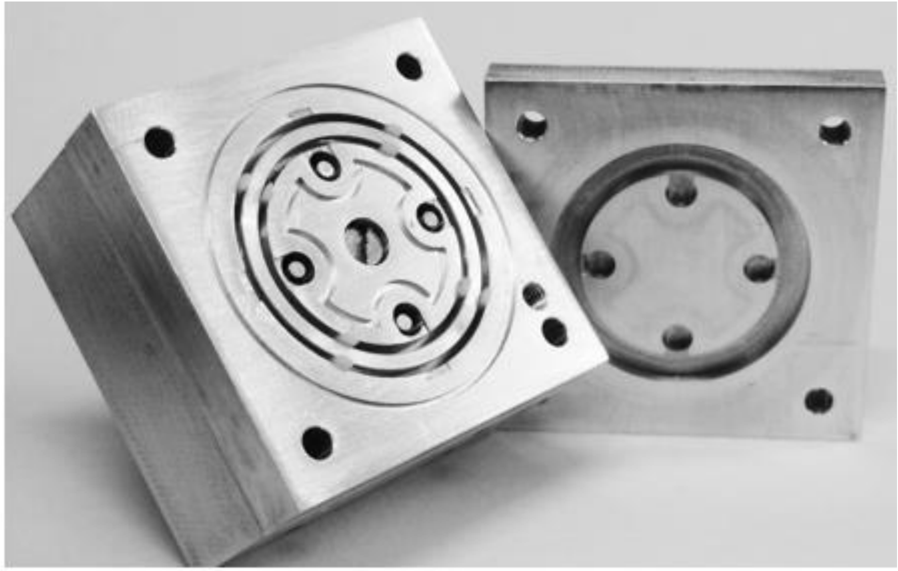
Avoided level crossing

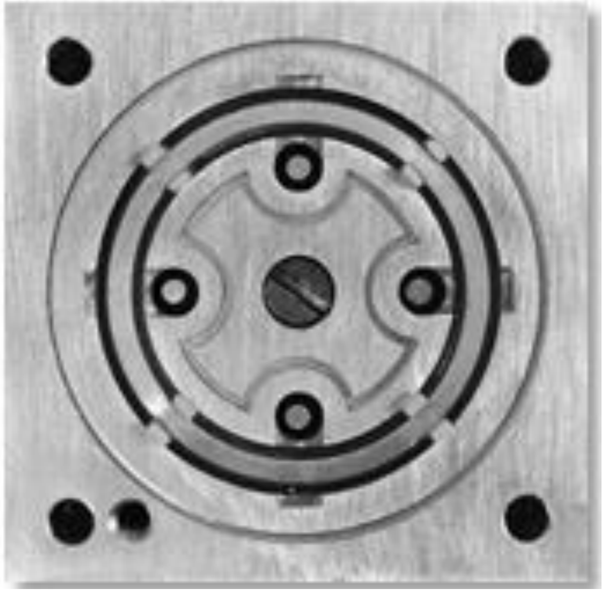


Why do we see two modes _around_ f_{01} rather than a single mode _at_ f_{01}?

Effective qubit-qubit coupling!

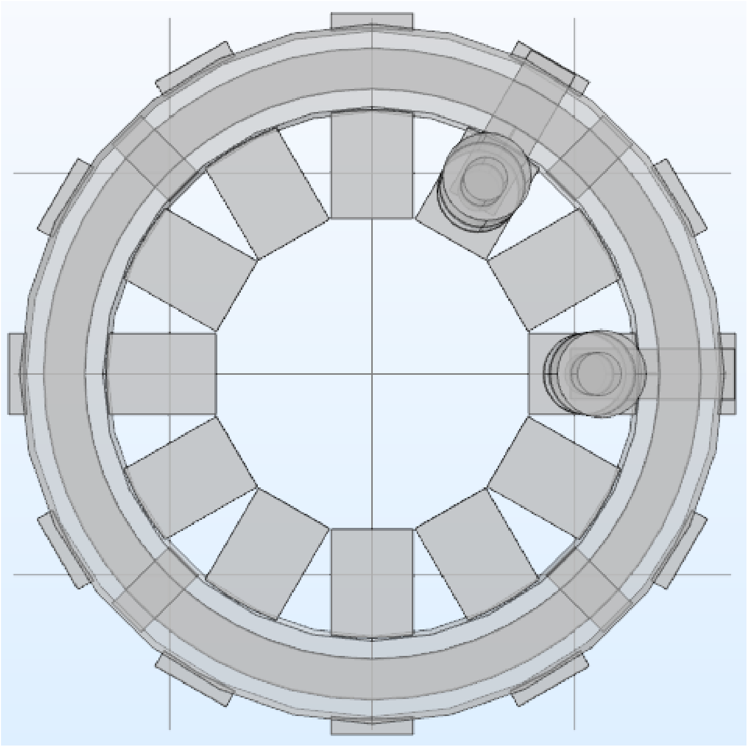
Circular bus architecture



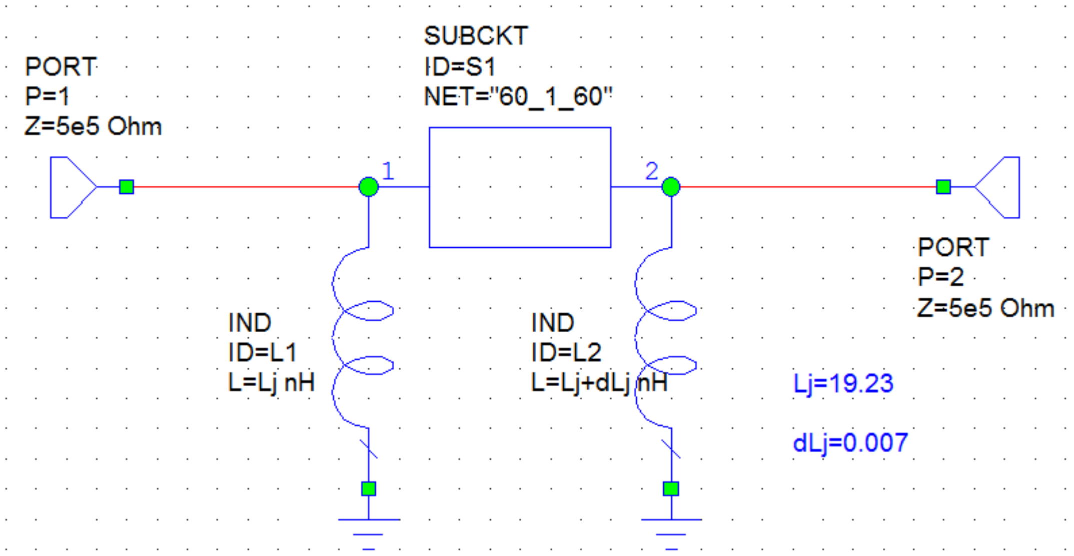


Currently fabricated circular bus architecture, built at QuMaC

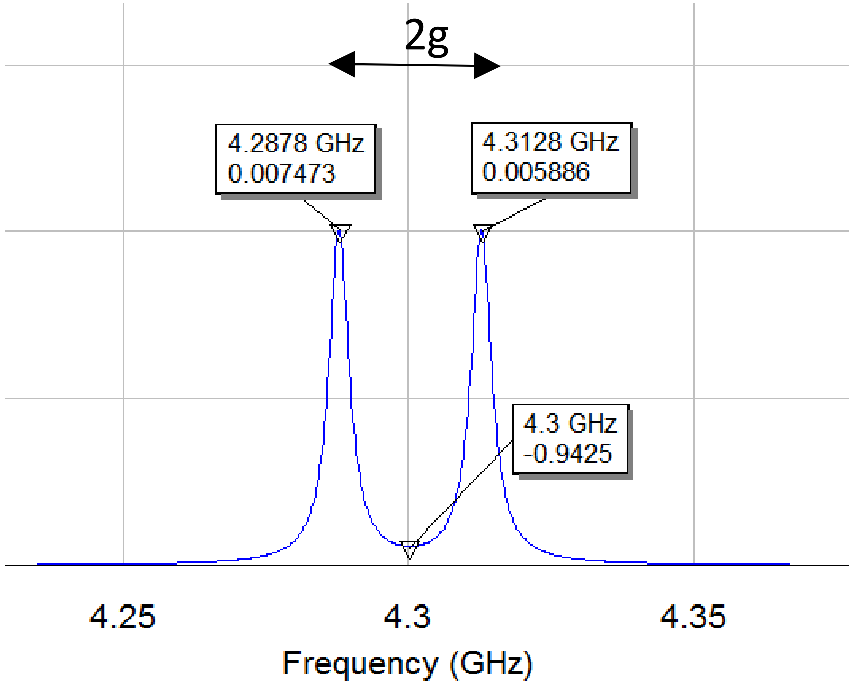
Simulations



COMSOL geometry



AWR Circuit

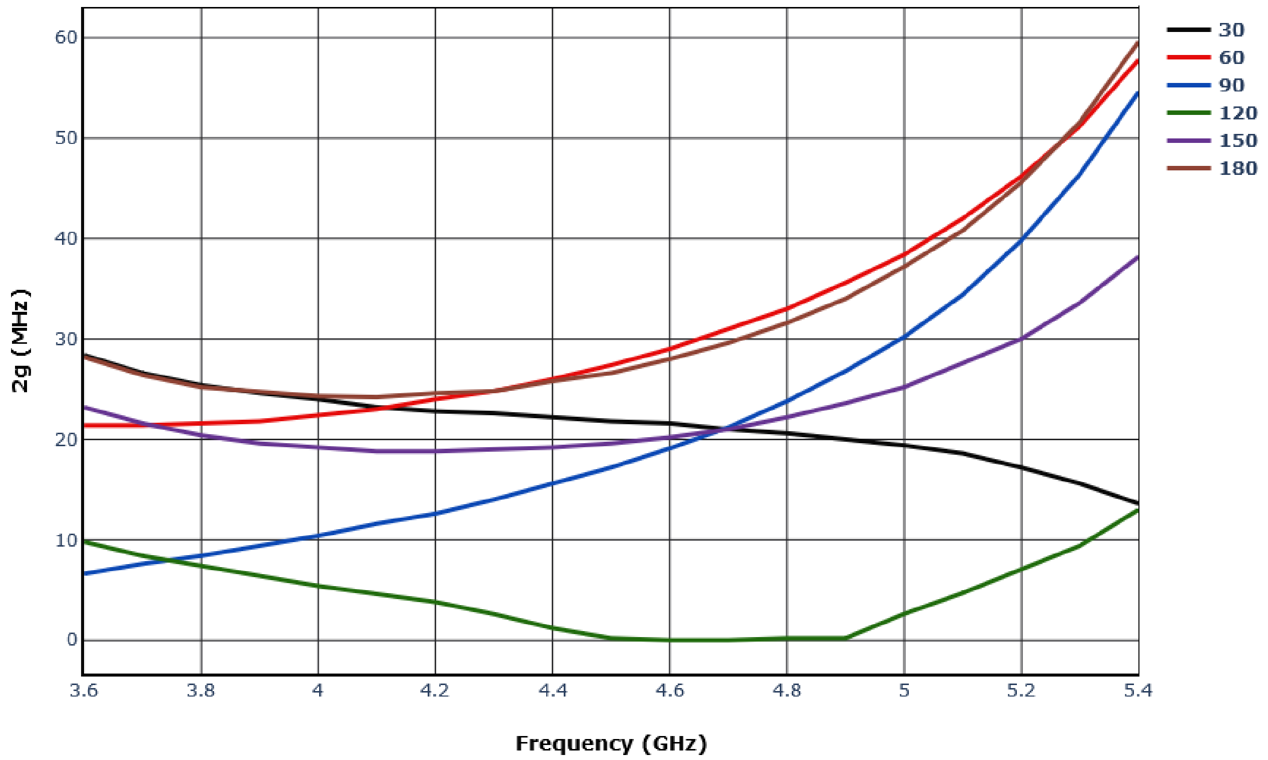


Sample avoided crossing in AWR

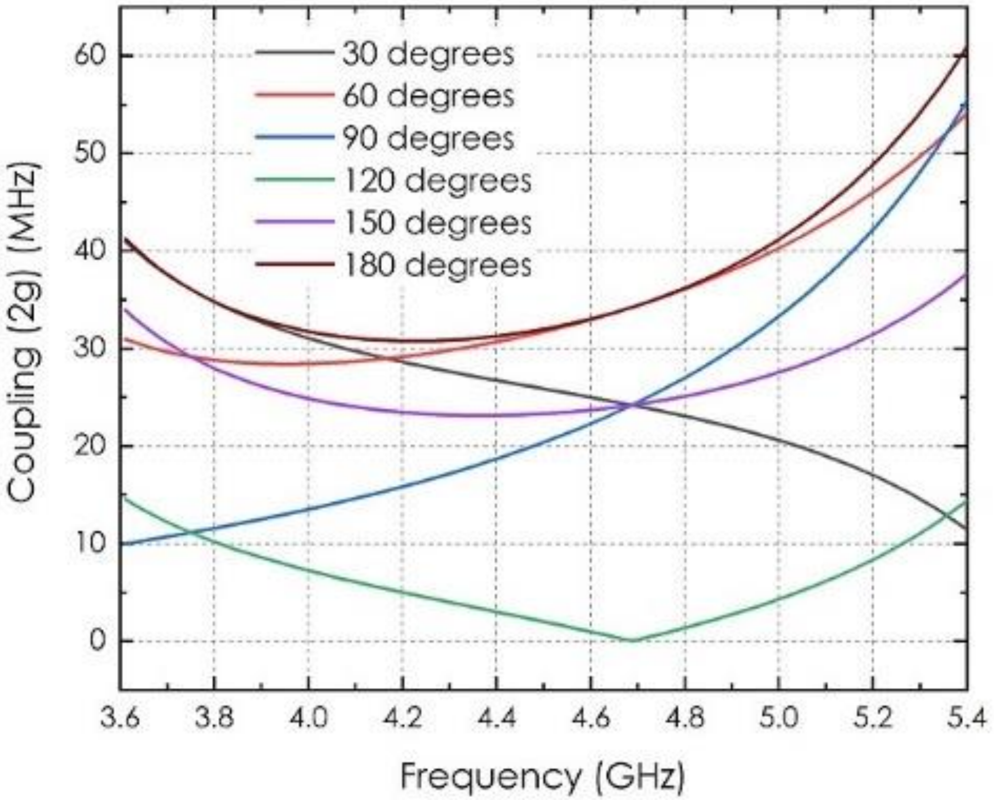
Simulation range: 3.5 to 5.5 GHz in steps of 0.02 GHz

Results

2g vs f_{01} for six relative angles

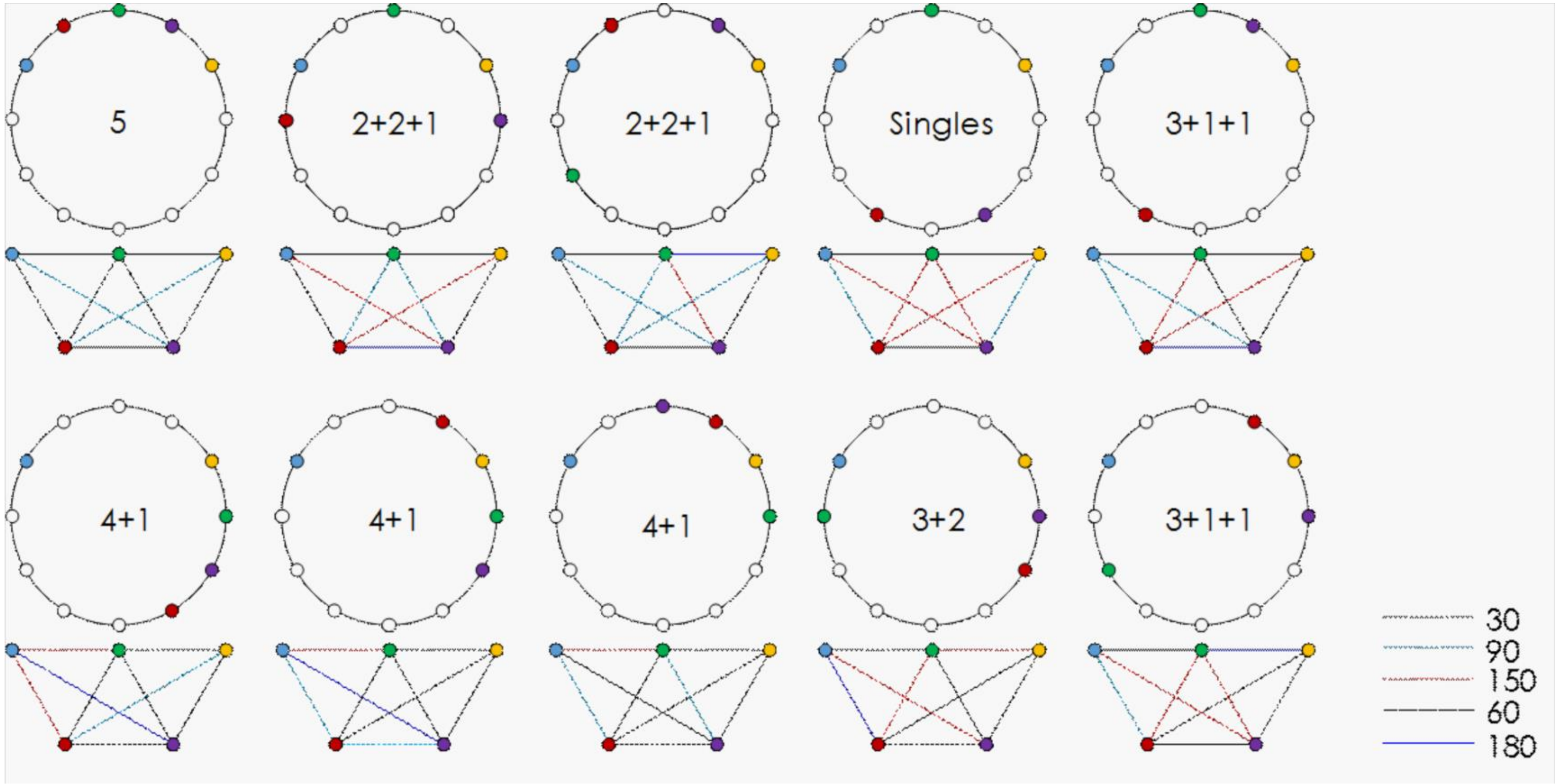


Based on COMSOL and AWR simulations



Based on theoretical calculations

Prospective 5 qubit networks



Summary & Future directions

- Key observations:
  - ➢ Equal coupling at relative angles of 30, 90 and 150 degrees if qubits are used at 4.7 GHz.
  - ➢ Very small coupling for relative angle of 120 degrees over the entire frequency range. Negligible between 4.5 and 4.9 GHz.
  - ➢ Relative angles of 60 and 180 degrees exhibit nearly equal coupling above 4.2 GHz.
- Future directions:
  - ➢ Coupling 5 qubits efficiently in the cavity.
  - ➢ Scaling the architecture.

References

- David M Pozar. *Microwave engineering*. John Wiley & Sons, 2009.

- Steven M Girvin. *“Circuit QED: superconducting qubits coupled to microwave photons*". In: Quantum Machines: Measurement and Control of Engineered Quantum Systems (2011)

Thank You