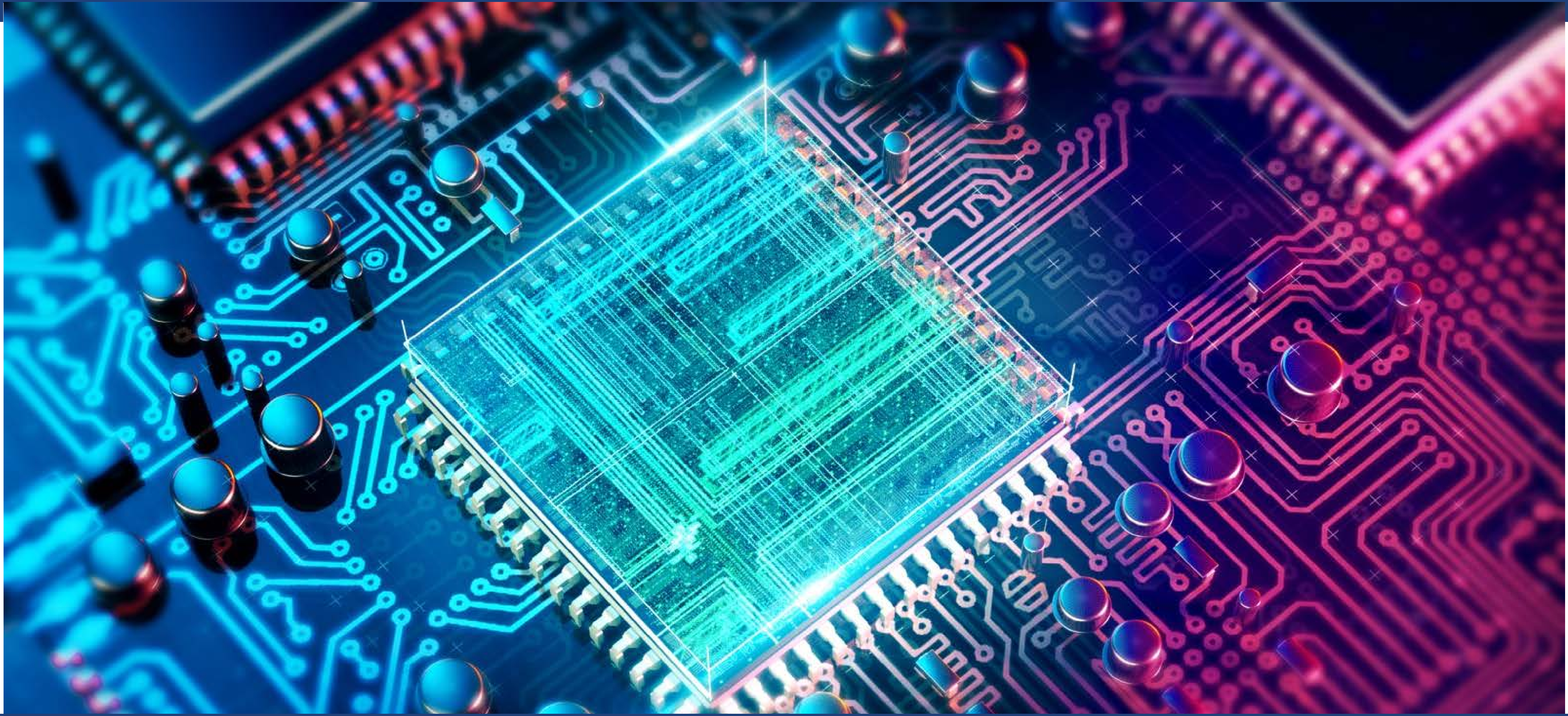
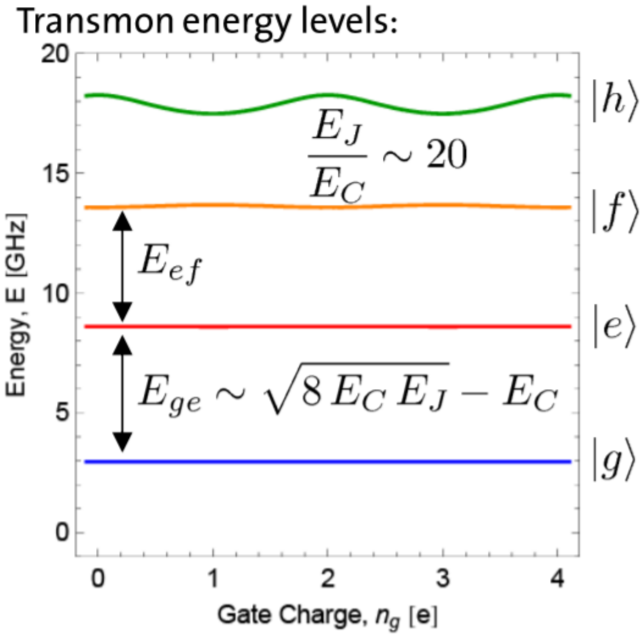
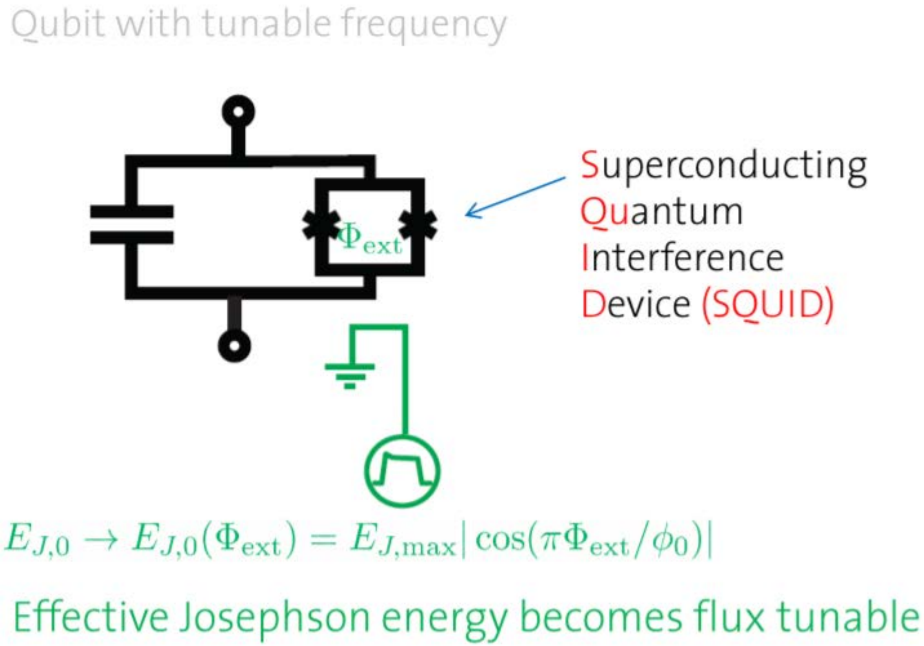
ETH zürich



Demonstration of two-qubit algorithms with a superconducting quantum processor

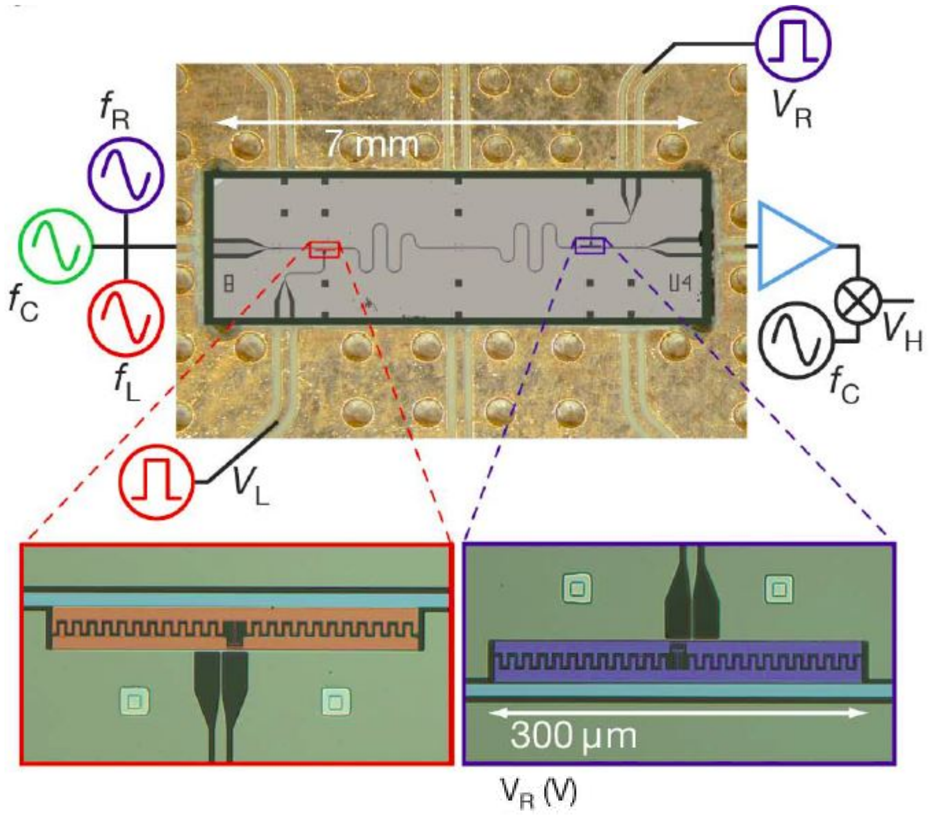
Processor





J.Koch et al., Phys. Rev. A 76, 042319 (2007)

Processor

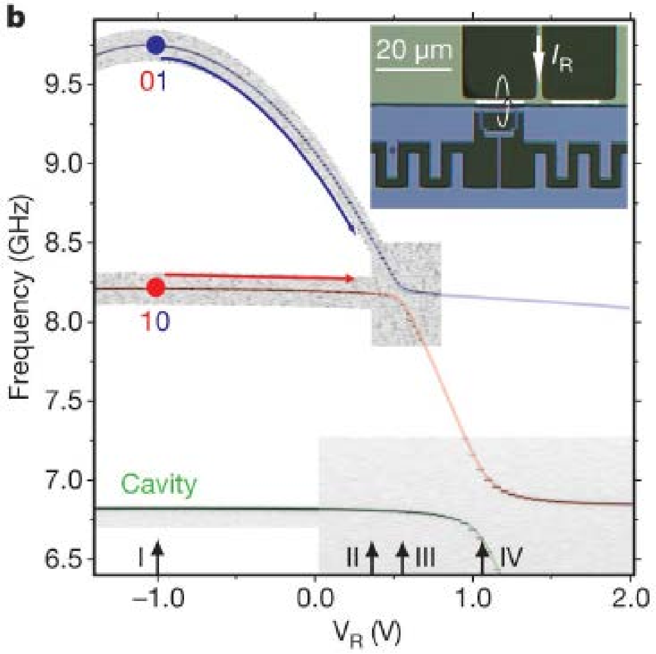


DiCarlo, L. et al. Demonstration of two-qubit algorithms with a superconducting quantum processor. *Nature* **460**, 240–244 (2009)

2 Qubits in a cavity (Dispersive limit)

$$|\Delta_{1,2}| \gg g_{1,2}$$

$$H_{eff} = \frac{\hbar\omega_1}{2}\sigma_1^z + \frac{\hbar\omega_2}{2}\sigma_2^z + \hbar(\omega_r + \chi_1\sigma_1^z + \chi_2\sigma_2^z)a^\dagger a + \hbar J(\sigma_1^- \sigma_2^+ + \sigma_2^- \sigma_1^+)$$



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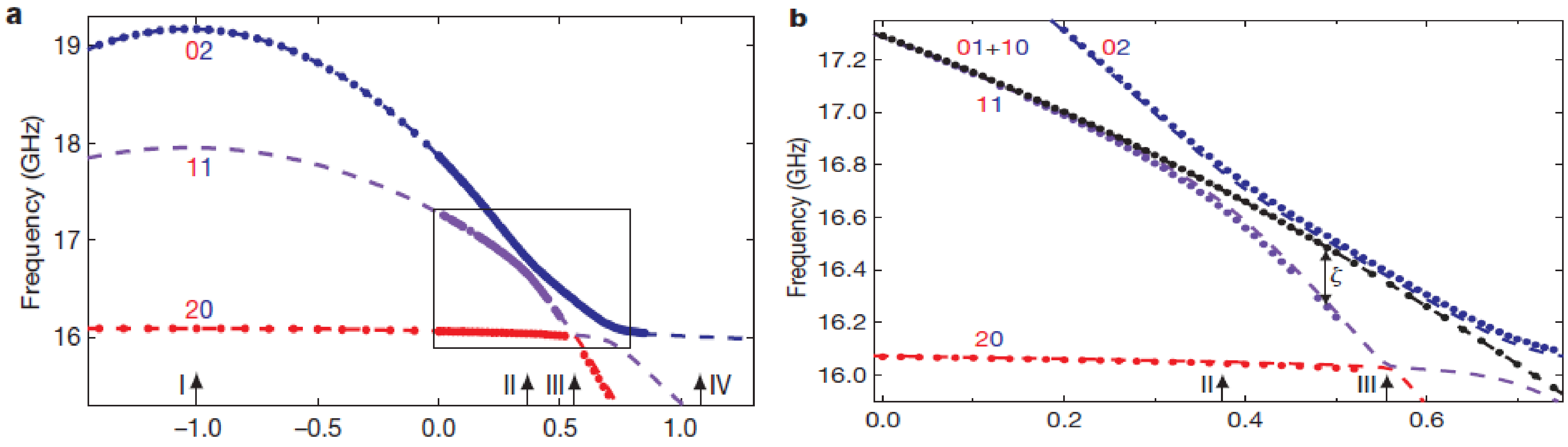
2 Qubits in a cavity



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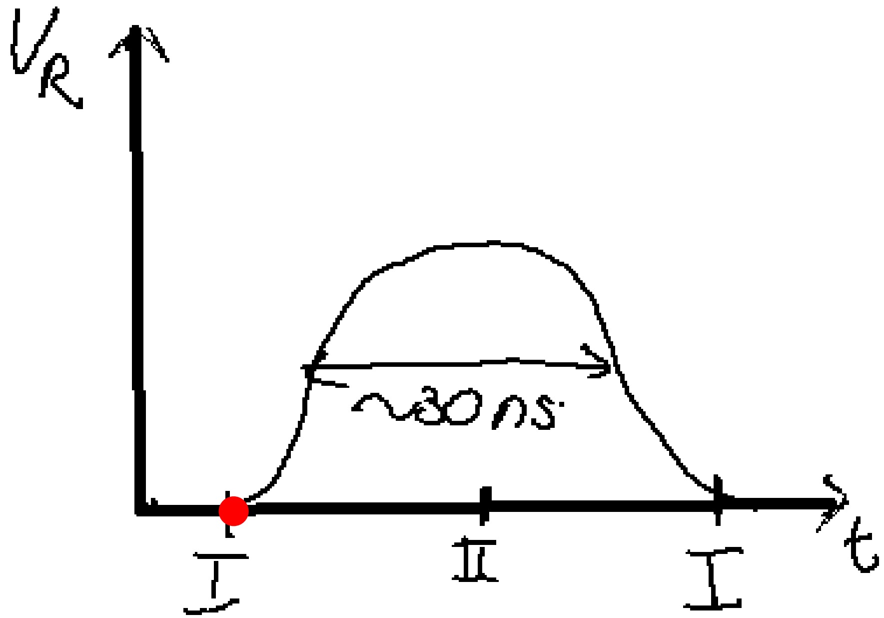
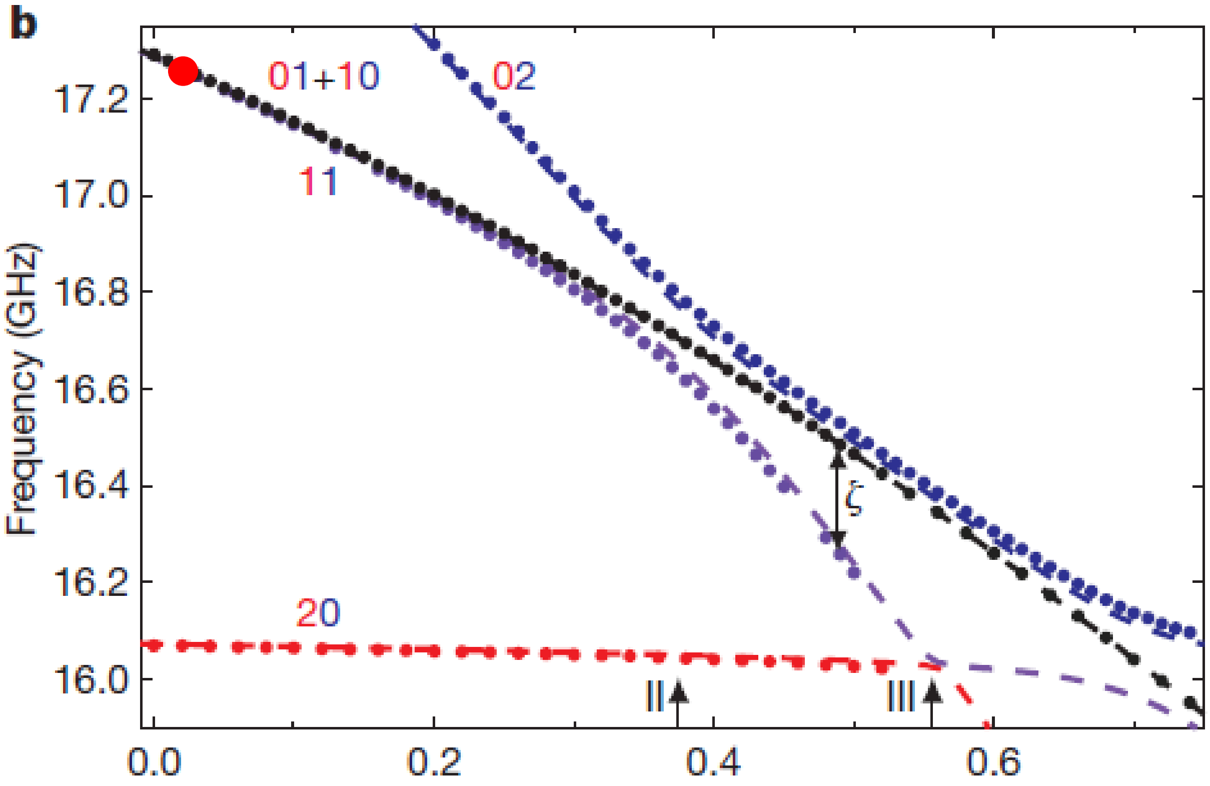
2 Qubits in a cavity

- The Tavis-Cummings generalized to multi-level transmon qubits:

$$H = \omega_c a^\dagger a + \sum_{q \in L,R} \left(\sum_{j=0}^{N} \omega_{0j}^{q} \left|j\right\rangle_q \left\langle j\right|_q + (a + a^\dagger) \sum_{j,k=0}^{N} g_{jk}^{q} \left|j\right\rangle_q \left\langle k\right|_q \right)$$

2 Qubits in a cavity (C-Phase gate)





DiCarlo, L. et al. Demonstration of two-qubit algorithms with a superconducting quantum processor. *Nature* **460**, 240–244 (2009)

2 Qubits in a cavity (C-Phase gate)

- All the computational basis states aquire a relative phase because of the pulse

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\phi_{01}} & 0 & 0 \\ 0 & 0 & e^{i\phi_{10}} & 0 \\ 0 & 0 & 0 & e^{i\phi_{11}} \end{pmatrix}$$

$$\phi_{11} = \phi_{01} + \phi_{10} - \int \zeta(t)dt$$

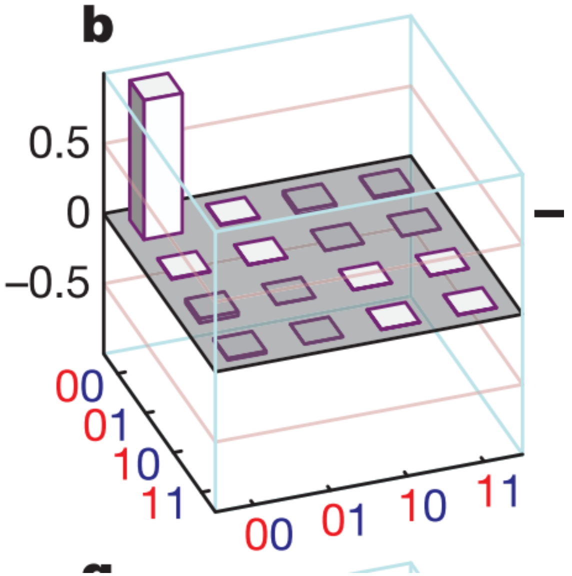
- To realize a C-Phase gate we would like to get

$$U = \mathrm{diag}(1, 1, 1, -1)$$

- Choose the pulse such that $\int \zeta(t)dt = (2n+1)\pi$
- Play with the pulse form and V_L to make ϕ_{01} and ϕ_{10} integer multiples of π.

2 Qubit readout

- Goal: We want to be able to perform a full state tomography of our processor to test it's functionality.
- We need independent measurement operators



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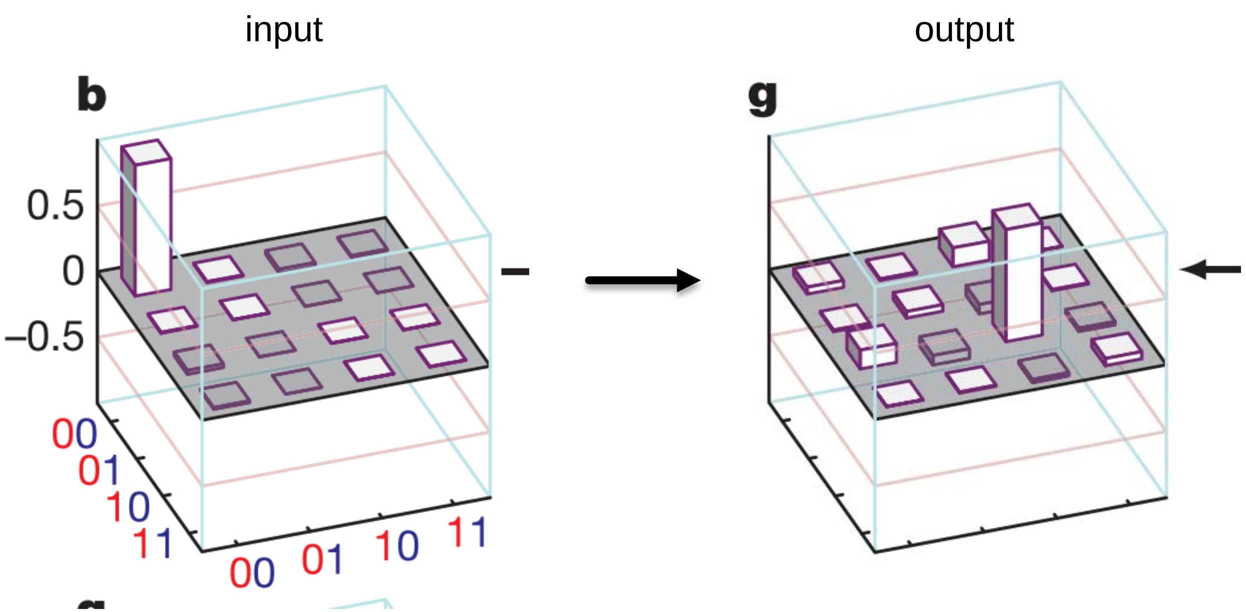
2 Qubit readout

$$H_{eff} = \frac{\hbar\omega_1}{2}\sigma_1^z + \frac{\hbar\omega_2}{2}\sigma_2^z + \boxed{\hbar(\omega_r + \chi_1\sigma_1^z + \chi_2\sigma_2^z)a^\dagger a} + \hbar J(\sigma_1^-\sigma_2^+ + \sigma_2^-\sigma_1^+)$$

- Cavity resonance frequency gets shifted by state of the Qubit.
- A measurement of the homodyne Voltage V_H corresponds to a measurement of the operator $M = \beta_1\sigma_z^L + \beta_2\sigma_z^R + \beta_{12}\sigma_z^L\sigma_z^R$
- Precompose with rotations to get more measurement operators

Filipp et al., Phys. Rev. Lett. **102**, 200402 (2009)

Implementations – Grover & Bell States



DiCarlo, L. et al. Demonstration of two-qubit algorithms with a superconducting quantum processor. *Nature* **460**, 240–244 (2009)

Universal?

We have implemented:

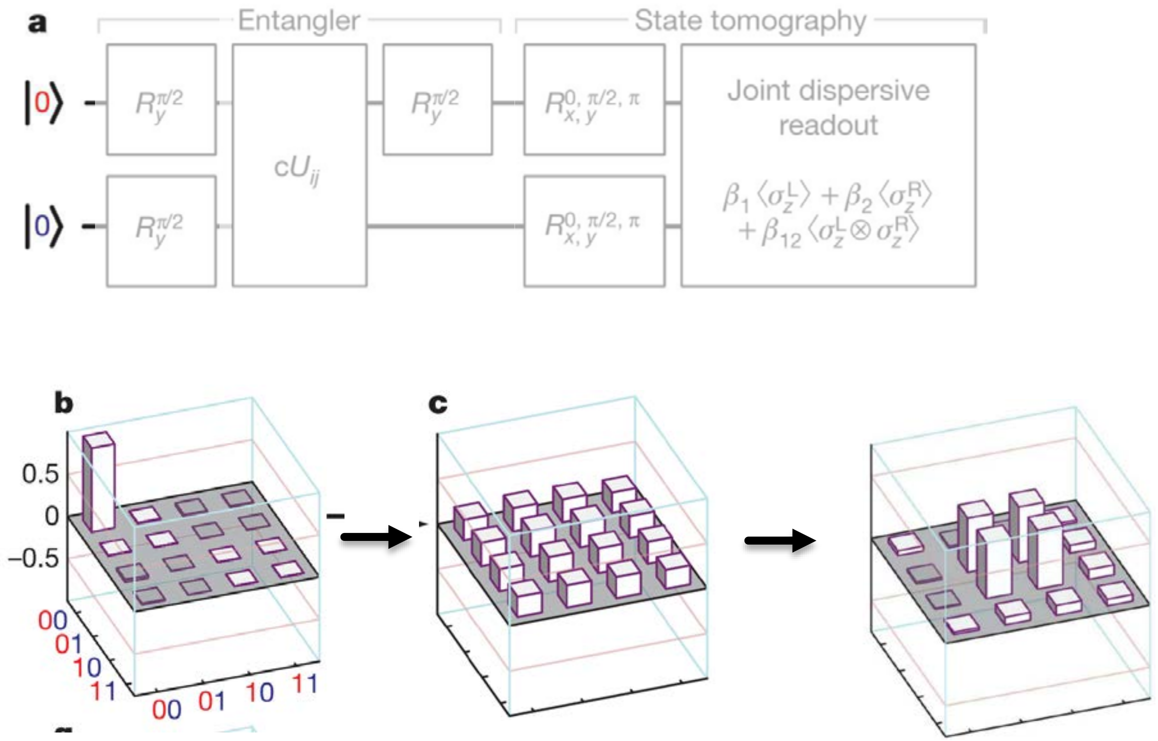
- single qubit rotations
- C-phase gate (two qubit gate)

$\Rightarrow$ Universality!

Testing the processor – Bell States

Density matrix:

$\langle nk | \rho | jl \rangle$



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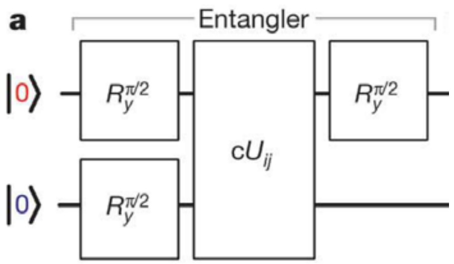
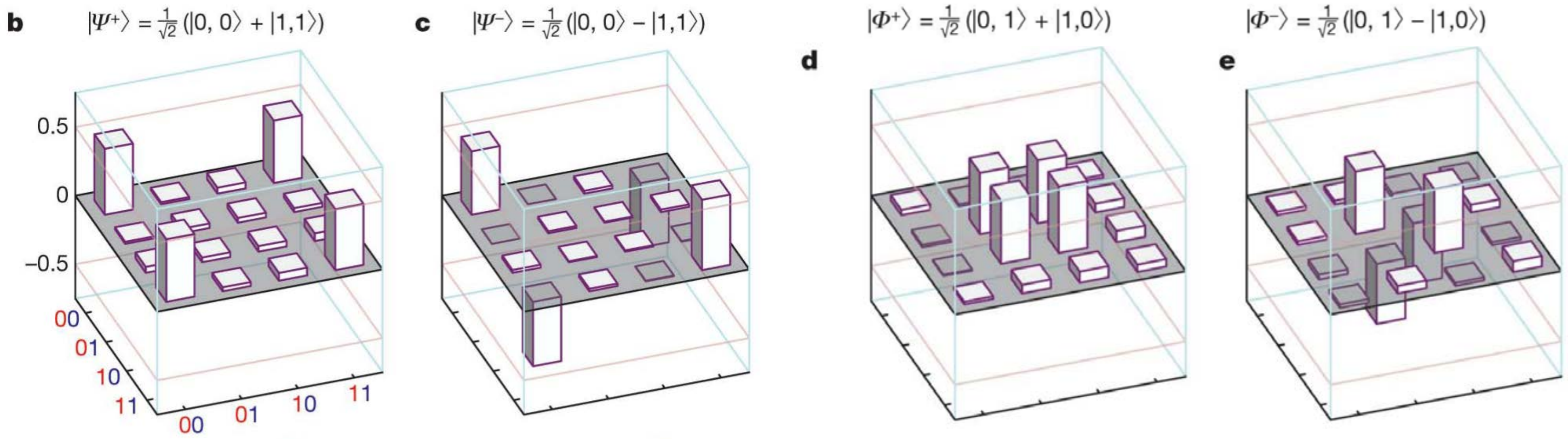
Bell States





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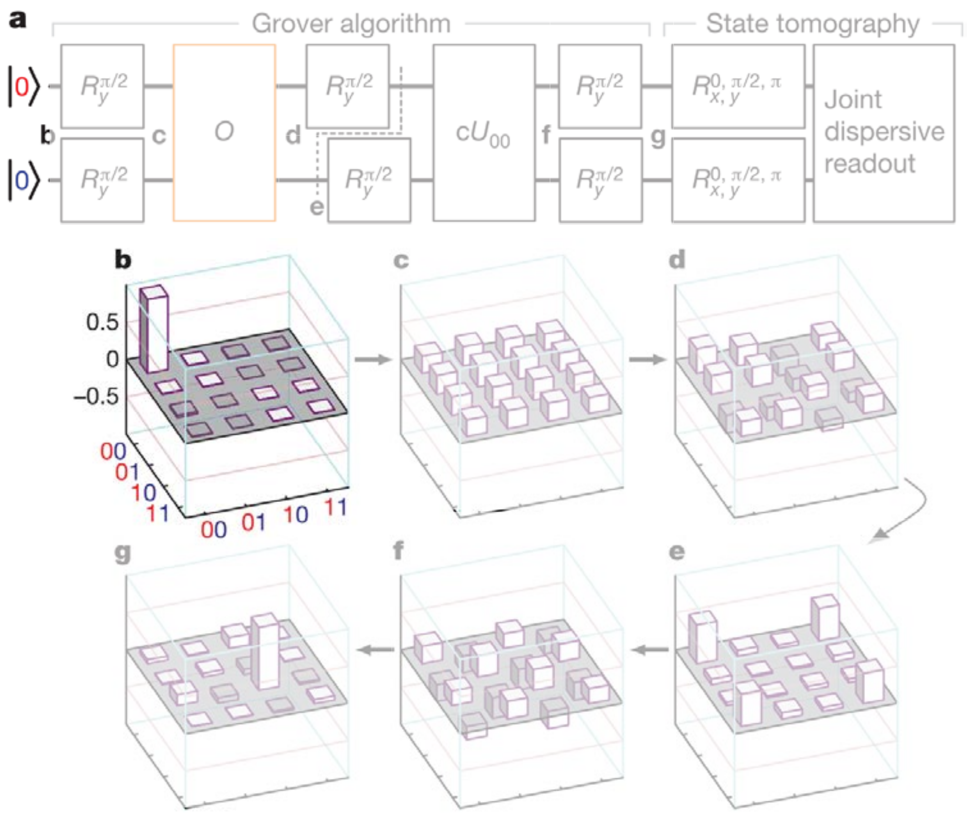
Grover Algorithm



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Algorithmic Performance

Element		Grover search oracle*				Deutsch–Jozsa function†			
		f_{00}	f_{01}	f_{10}	f_{11}	f_0	f_1	f_2	f_3
$\langle 0,0 \vert \rho \vert 0,0 \rangle$	Ideal	1	0	0	0	0	0	1	1
	Measured	0.81(1)	0.08(1)	0.07(2)	0.065(7)	0.010(3)	0.014(5)	0.909(6)	0.841(9)
$\langle 0,1 \vert \rho \vert 0,1 \rangle$	Ideal	0	1	0	0	0	0	0	0
	Measured	0.066(7)	0.802(9)	0.05(1)	0.054(8)	0.012(4)	0.008(4)	0.031(8)	0.04(2)
$\langle 1,0 \vert \rho \vert 1,0 \rangle$	Ideal	0	0	1	0	1	1	0	0
	Measured	0.08(1)	0.05(1)	0.82(2)	0.07(1)	0.93(1)	0.93(1)	0.05(1)	0.04(1)
$\langle 1,1 \vert \rho \vert 1,1 \rangle$	Ideal	0	0	0	1	0	0	0	0
	Measured	0.05(2)	0.07(1)	0.06(1)	0.81(1)	0.05(1)	0.04(1)	0.012(9)	0.07(2)

DiCarlo, L. et al. Demonstration of two-qubit algorithms with a superconducting quantum processor. *Nature* **460**, 240–244 (2009)

Coherence time: 1 μs

→ ~30 operations

1 operation takes ~ 30ns

Nowadays: ~ 50 μs