Superconducting microwave circuits for quantum computing

NQIT Networked Quantum Information Technologies

OQC Oxford Quantum Circuits

EPSRC Pioneering research and skills

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Kitti Ratter
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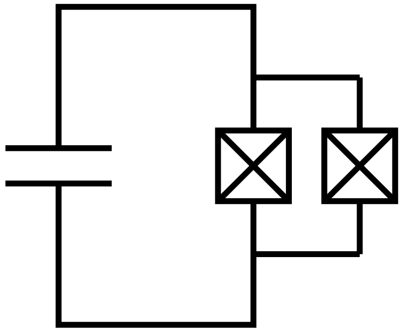
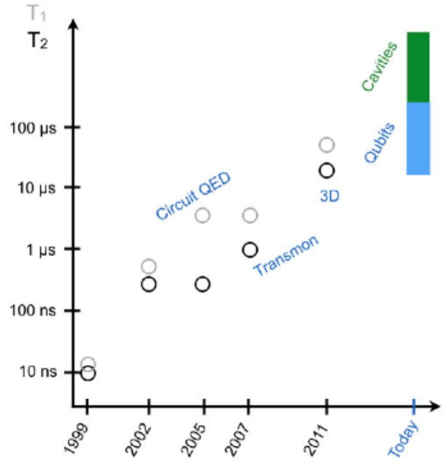
Matthias Mergenthaler
Brian Vlastakis
Peter Spring
Giovanna Tancredi
Salha Jebari
Takahiro Tsunoda
Giulio Campanaro

Condensed Matter Physics,
Clarendon Laboratory,
Oxford, UK

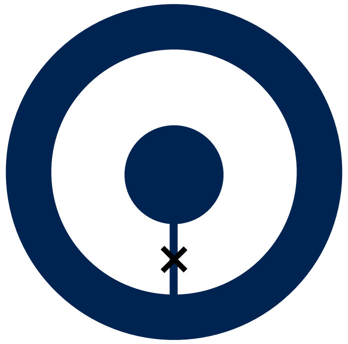
Outline



- Making electric circuits quantum

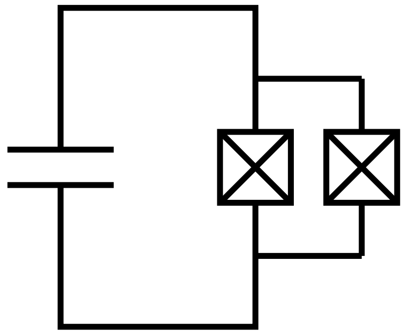


- Development of superconducting circuit quantum computing



- Oxford coaxial circuit architecture

Outline



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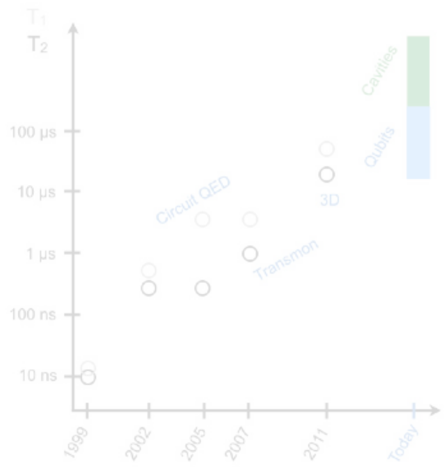
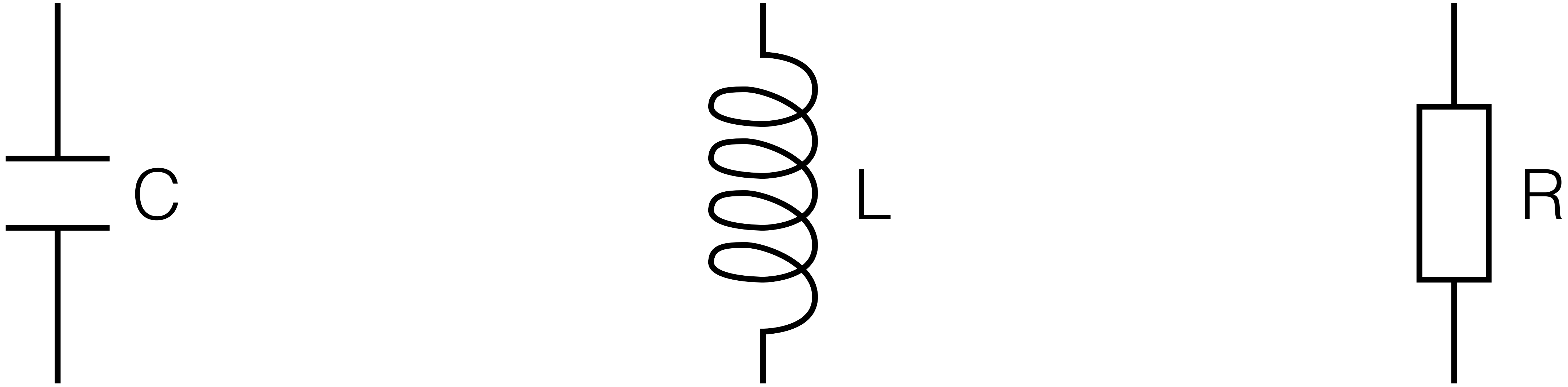


- Development of superconducting circuit quantum computing

- Oxford coaxial circuit architecture

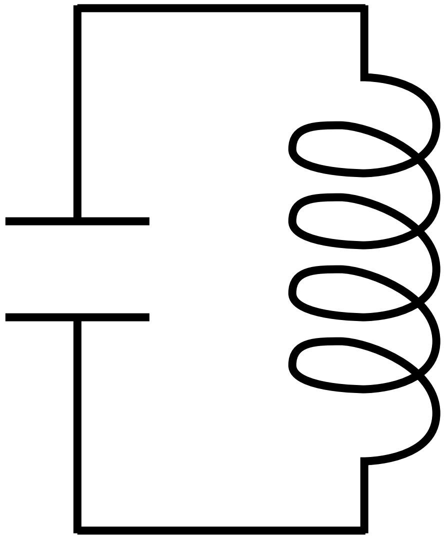
Electric circuits - revision!



$$V = Q/C$$

$$V = L\frac{dI}{dt} = \frac{1}{L}\frac{d\phi}{dt}$$

$$V = IR$$



LC resonator

$$\frac{d^2\phi}{dt^2} + \frac{\phi}{\sqrt{LC}} = 0$$

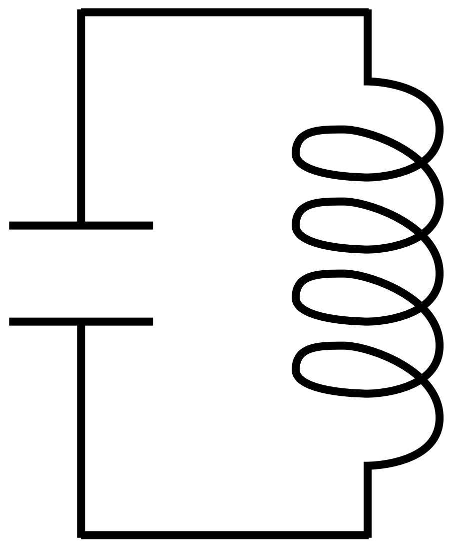
SHO $\omega = 1/\sqrt{LC}$

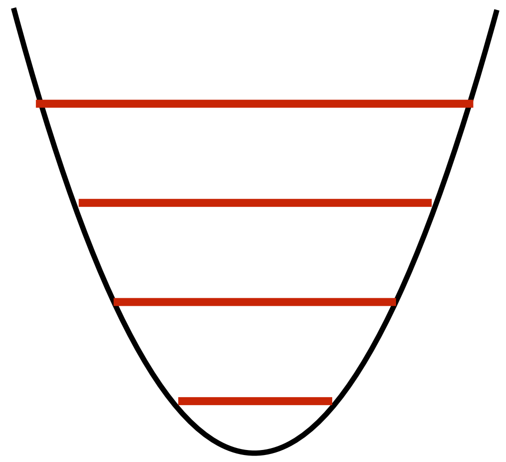
flux, charge ⟷ position, momentum

Typical values for µm-mm-scale circuits

$$C \sim 1\ \mathrm{pF}$$
$$L \sim 1\ \mathrm{nH}$$
$$\omega/2\pi \sim 5\ \mathrm{GHz}$$

Reaching the quantum regime?





$$\hat{H} = \hbar\omega(\hat{n} + \frac{1}{2})$$

- We need high Q circuits (little or no resistance) to have well separated energy levels

- We need ‘low’ temperature $k_B T < \hbar\omega$

Low frequency electromagnetic spectrum

Frequency	50 Hz	1 kHz	1 MHz	1 GHz	10 GHz	1 THz	500 THz

RF *Microwave* *Visible*

EM frequency — Temperature

Frequency	50 Hz	1 kHz	1 MHz	1 GHz	10 GHz	1 THz	500 THz
Temperature	3.5 nK	70 nK	70 uK	70 mK	700 mK	70 K	35,000 K

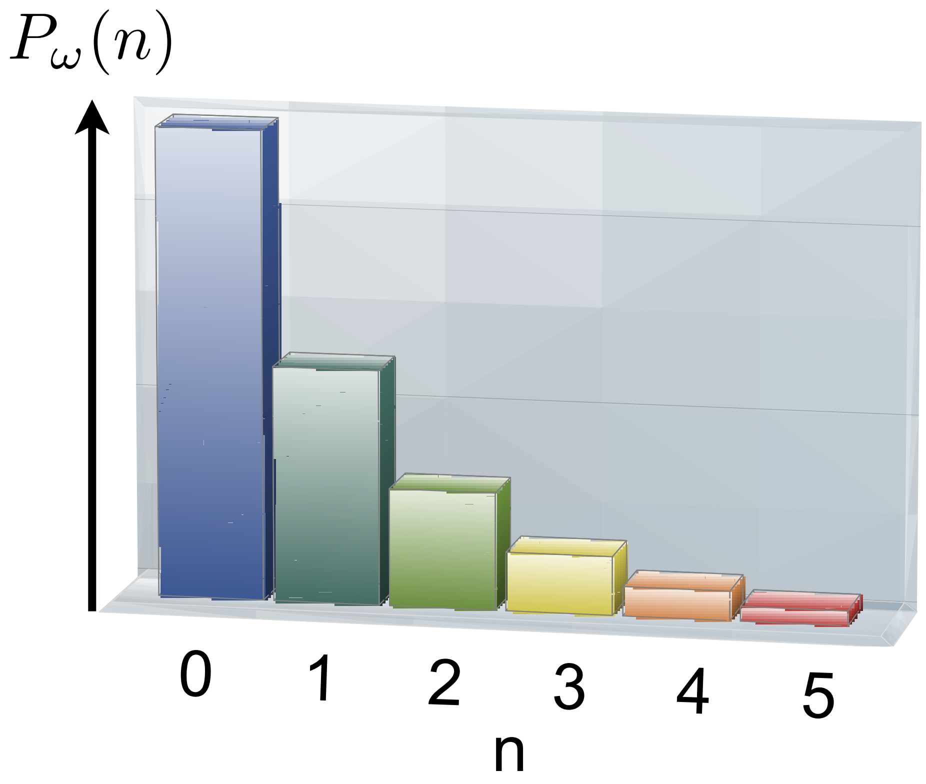
$(\langle \hat{n} \rangle = 1)$

- Average number of thermal photons in the resonator:

$$\langle \hat{n} \rangle = \frac{1}{\exp(\hbar\omega/k_B T) - 1}$$

$\bar{n} = 1$

$P(0) = 0.5$

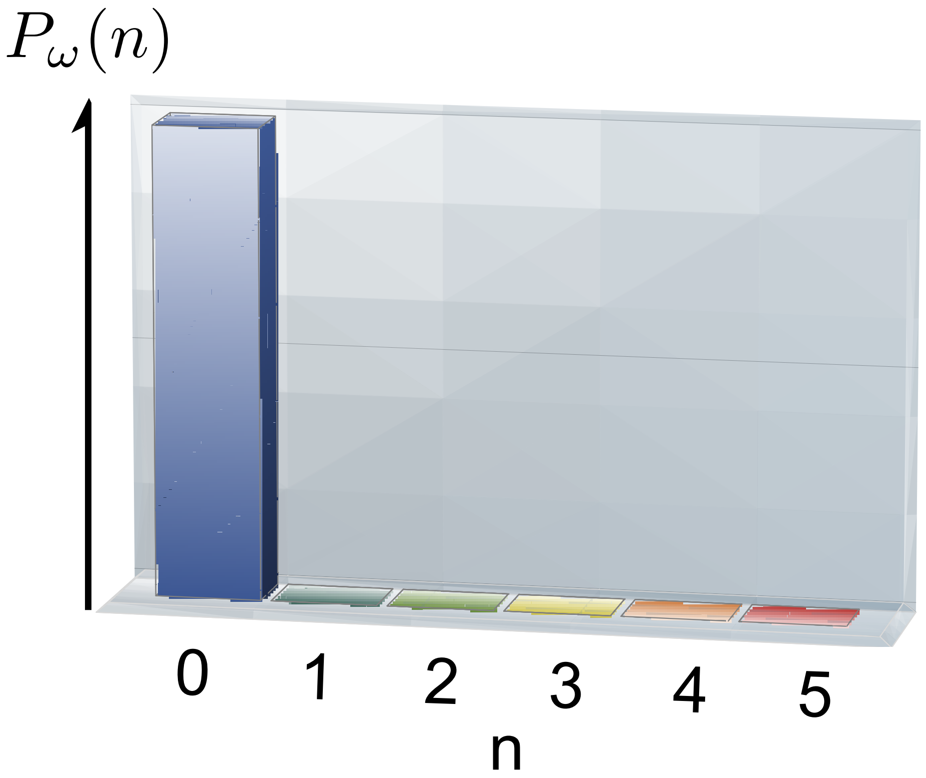


Reaching the ground state

Frequency	1 kHz	1 MHz	1 GHz	10 GHz	1 THz	500 THz
Temperature	5 nK	5 uK	5 mK	50 mK	5 K	2,600 K

$$\bar{n} = 0.0001$$

$$P(0) = 0.9999$$



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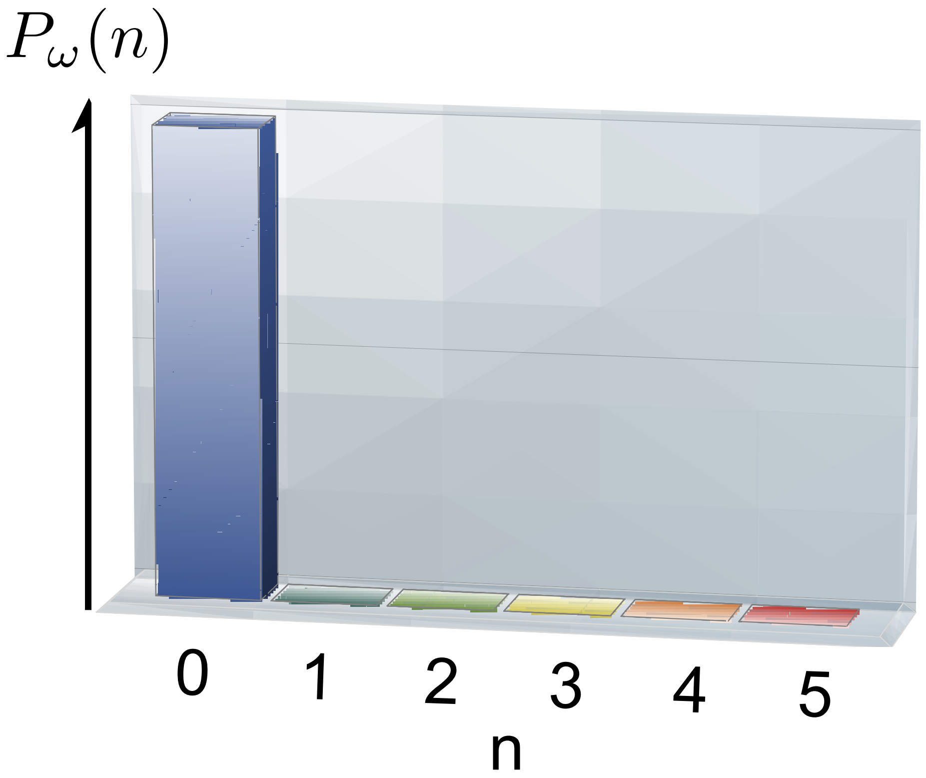
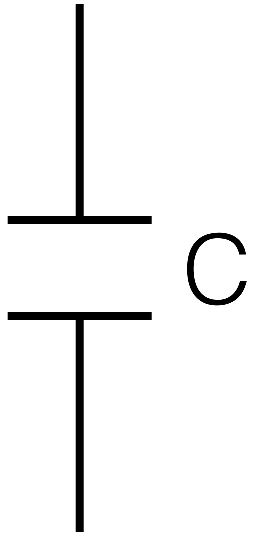
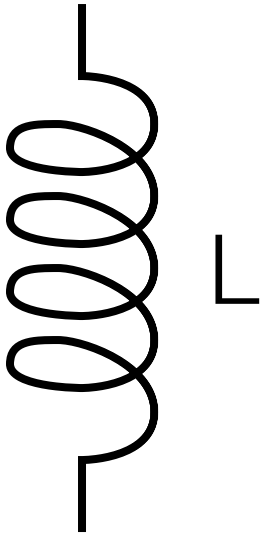


- Microwaves are the *lowest* frequency modes for which one can reach the ground state with a dilution refrigerator (~10 mK)
- Most of the field works in the range 4—12 GHz

Anharmonic electric circuits?





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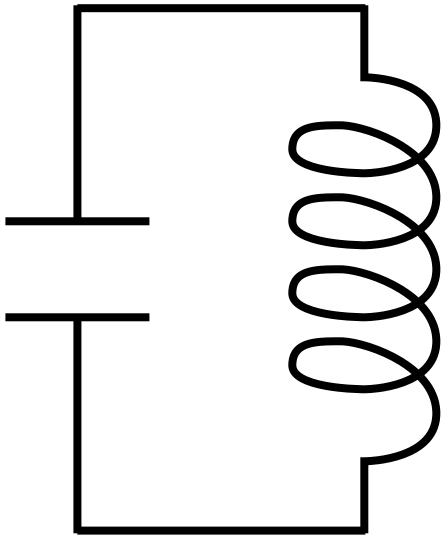

LC resonator

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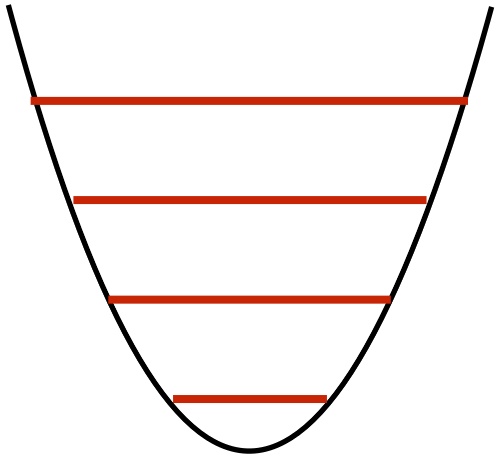
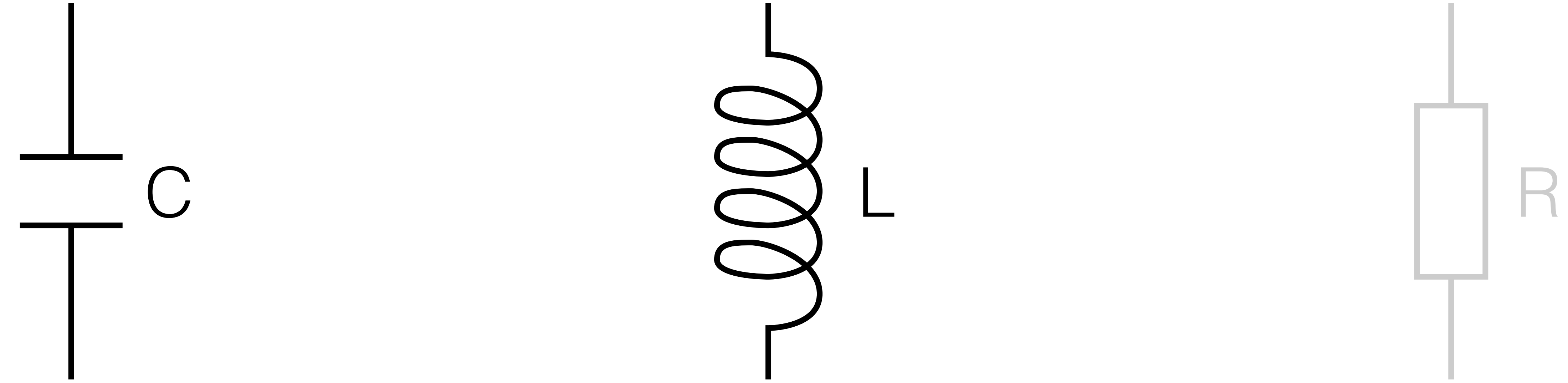
SHO $\omega = 1/\sqrt{LC}$



flux, charge ⟷ position, momentum

Anharmonic electric circuits?



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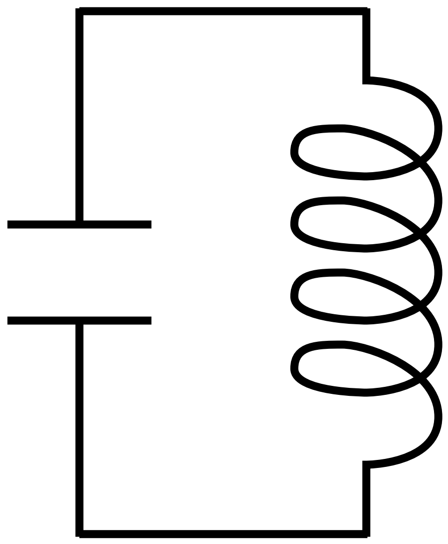


LC resonator

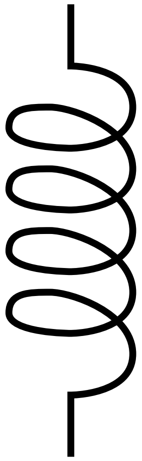
$$\frac{d^2\phi}{dt^2} + \frac{\phi}{\sqrt{LC}} = 0$$

SHO $\quad \omega = 1/\sqrt{LC}$

We need a non-dissipative, non-linear circuit element

flux, charge ⟷ position, momentum

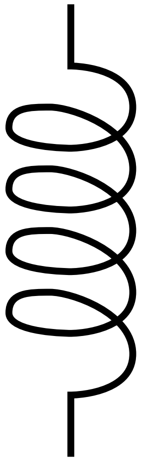
JJ as non-linear inductor



$$V = L\frac{dI}{dt}$$

$$E = \int IV\,dt = \frac{1}{2}LI^2$$

JJ as non-linear inductor



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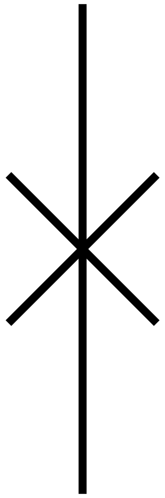


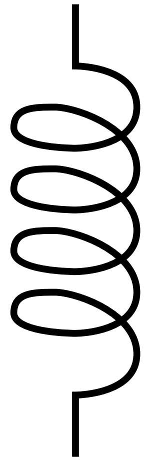
$$V = \frac{\hbar}{2e}\frac{\partial\phi}{\partial t}$$

$$I = I_c\sin(\phi)$$

$$E = -E_J\cos(\phi)$$

$$E_J = \frac{\hbar I_c}{2e}$$

JJ as non-linear inductor



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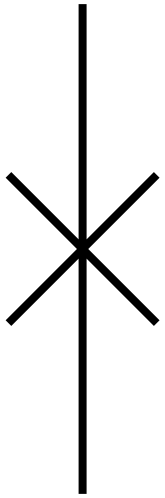

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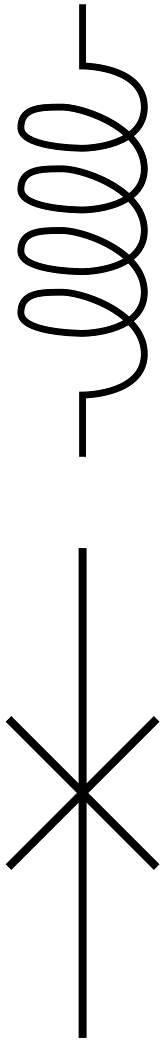
$$L_J = \frac{\hbar}{2eI_c\cos(\phi)}$$

Nonlinear inductance

JJ as non-linear inductor



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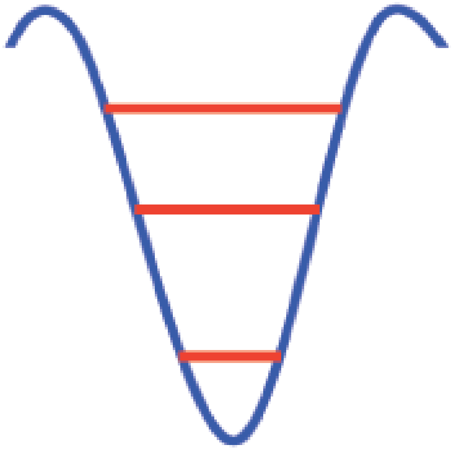
At low energy…

$$L_J = \frac{\hbar}{2eI_c\cos(\phi)}$$

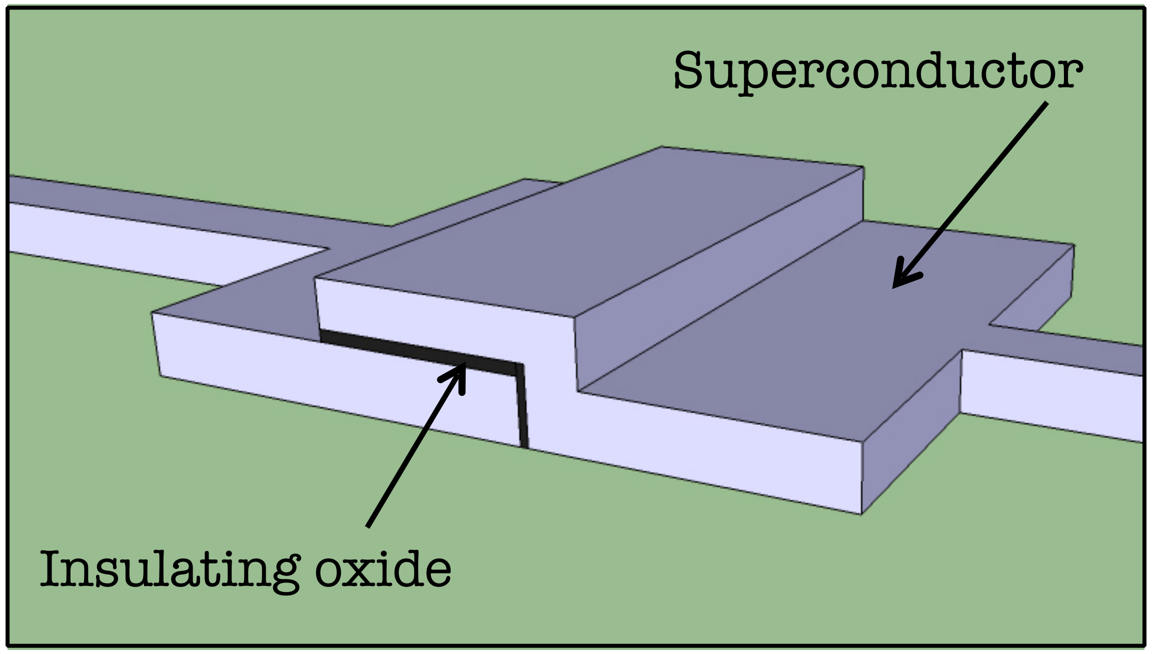
$$E = \frac{1}{2}L_J I^2 + \mathcal{O}(I^4)$$

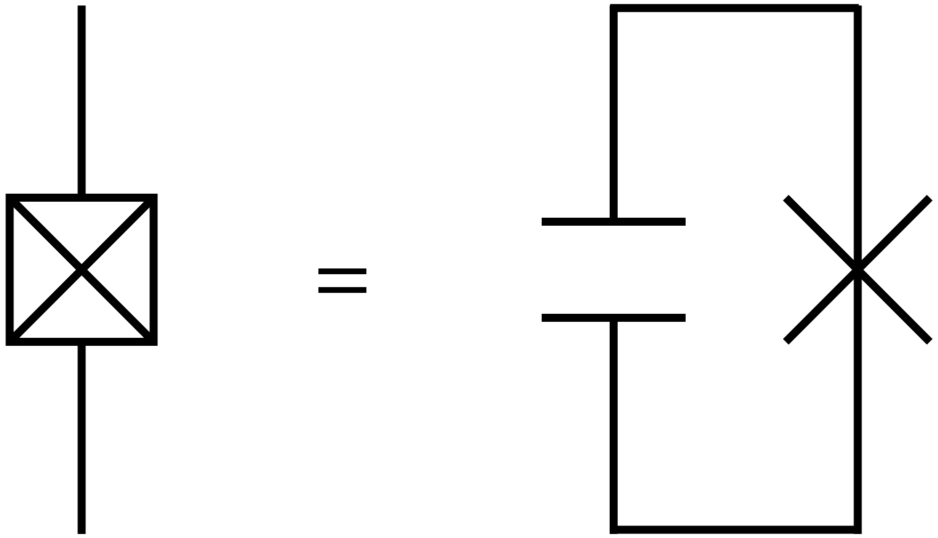


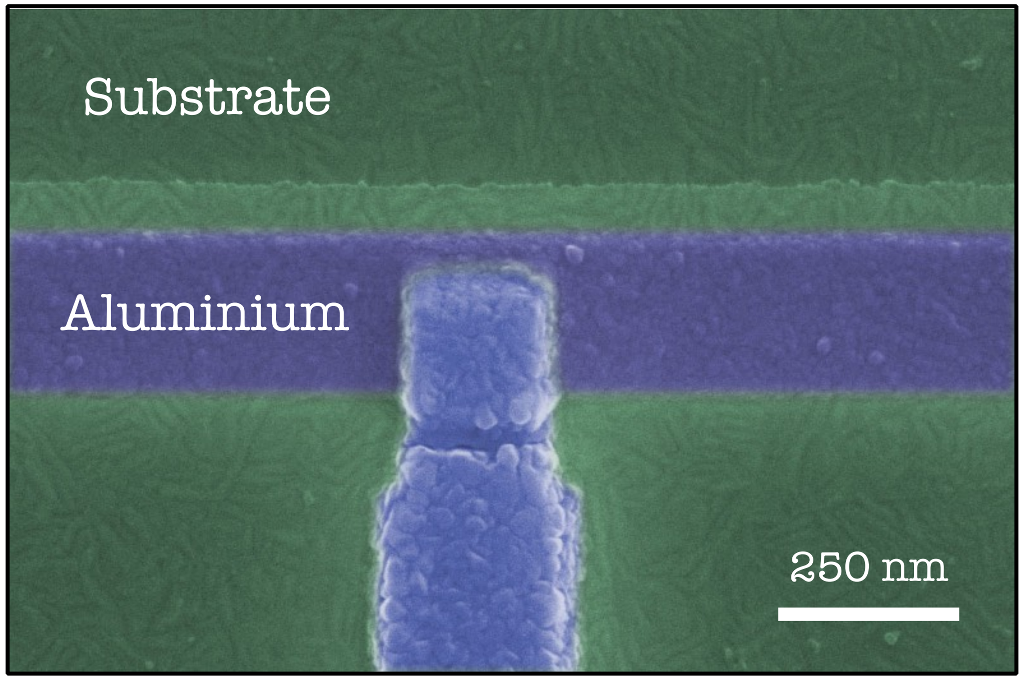
‘anharmonic LC oscillator’

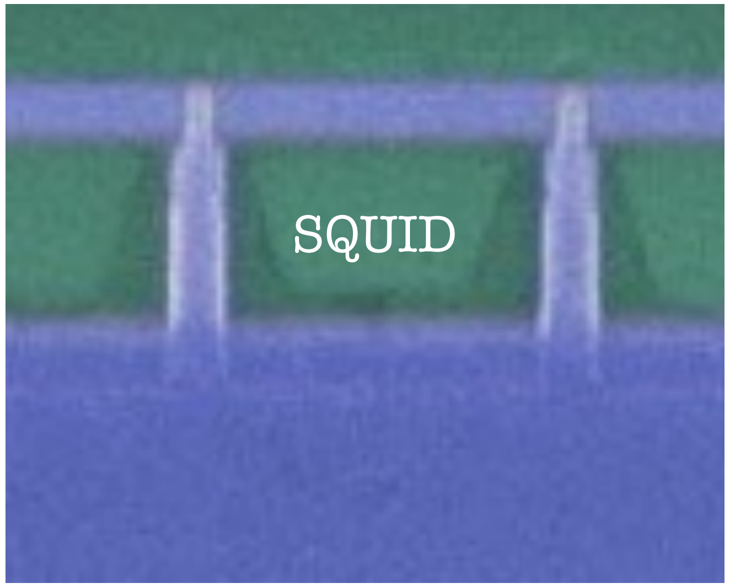
Nonlinear inductance

Real Josephson Junctions



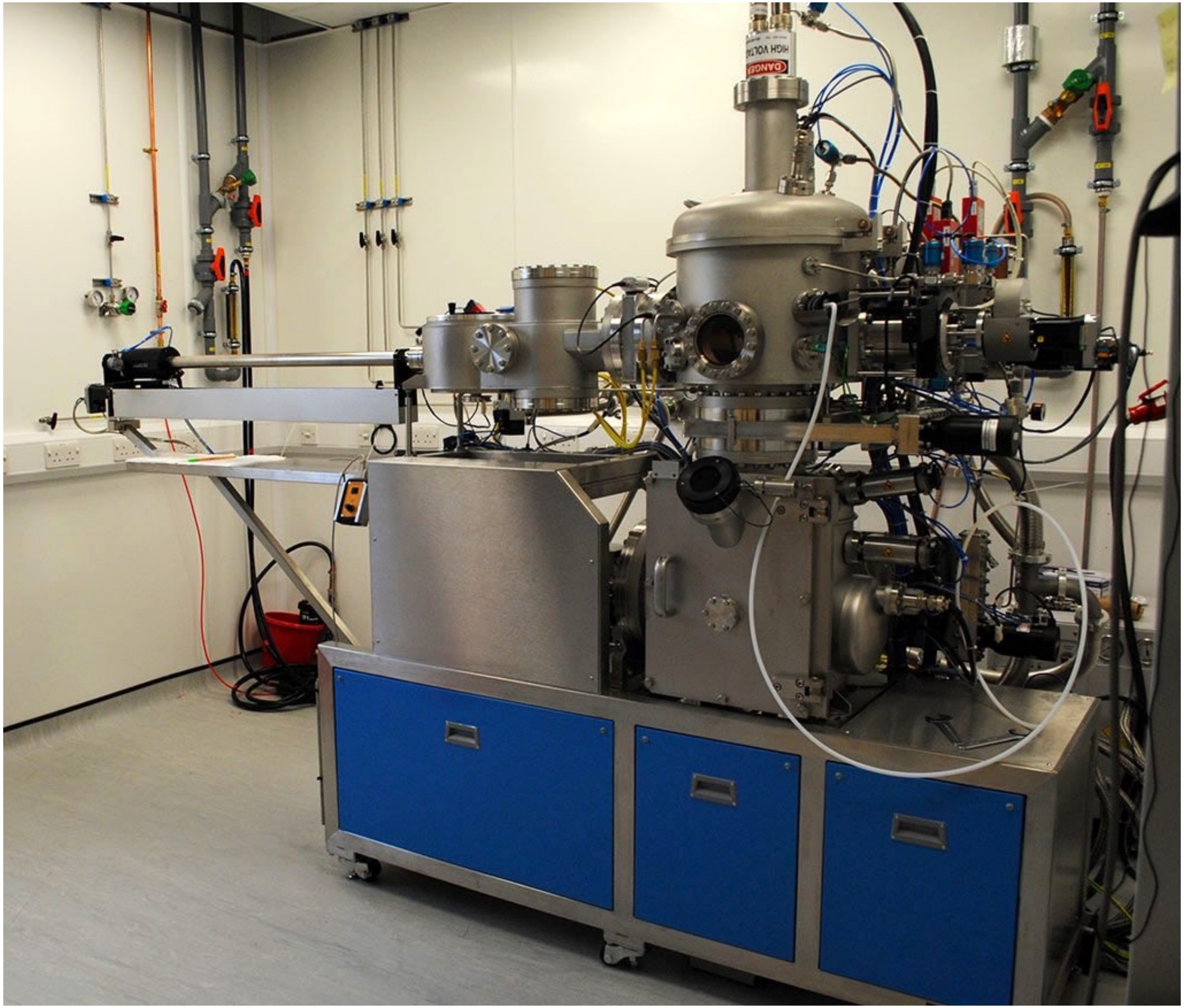




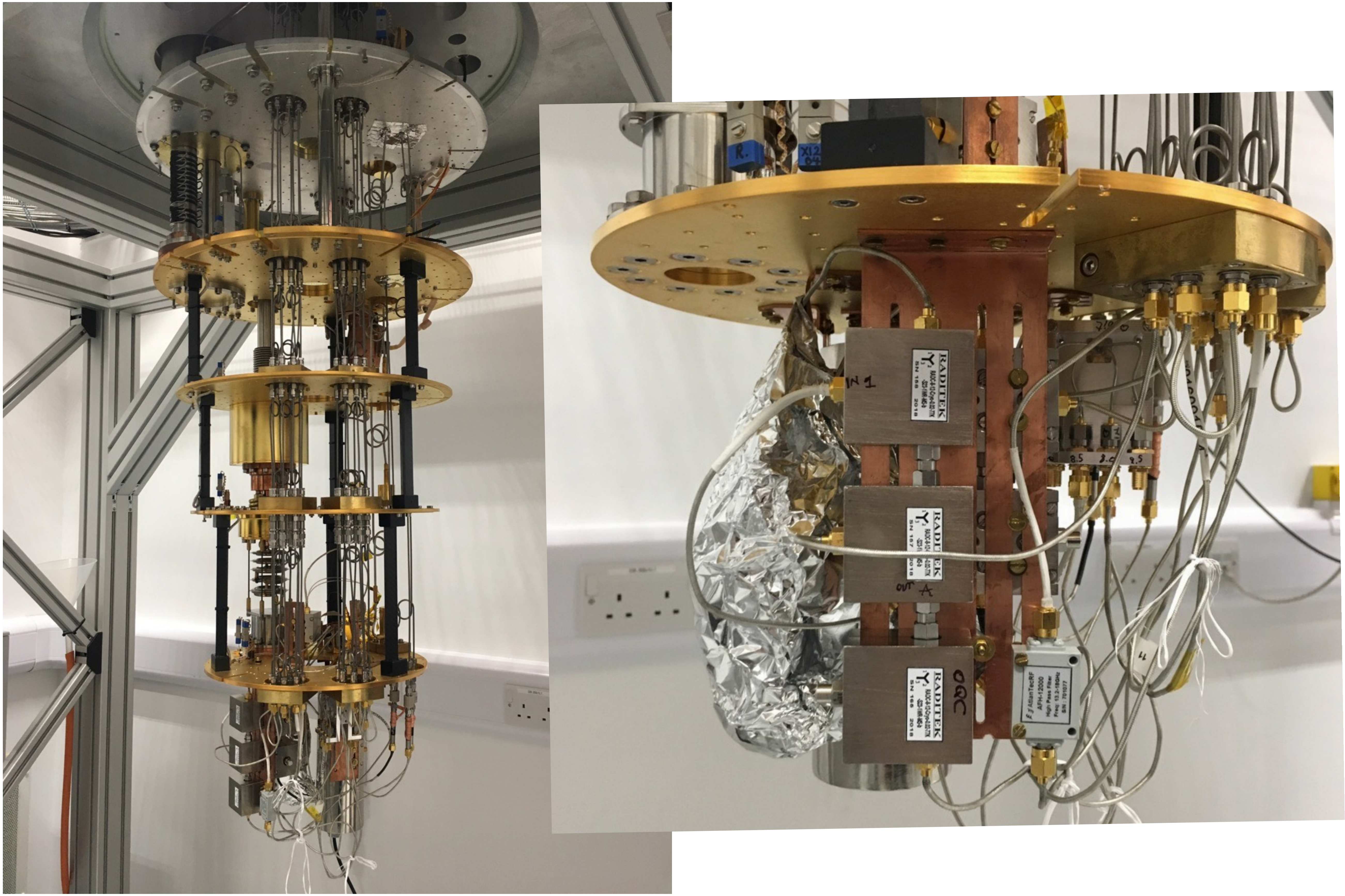


- Fabricated using double angle shadow evaporation and in-situ oxidation of aluminium in vacuum chamber

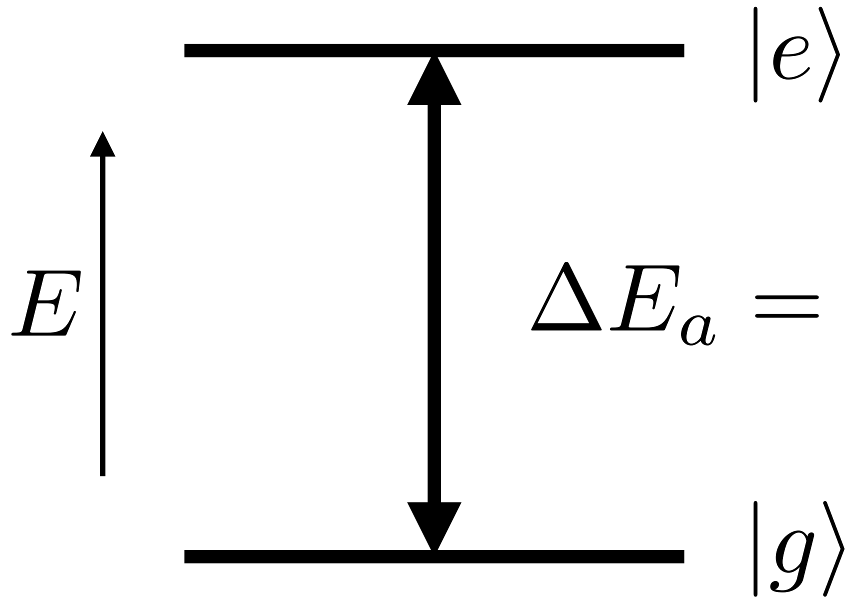
Clean reproducible JJ fabrication



Dilution refrigerators and microwaves



Two-level quantum systems (= ‘qubits’)

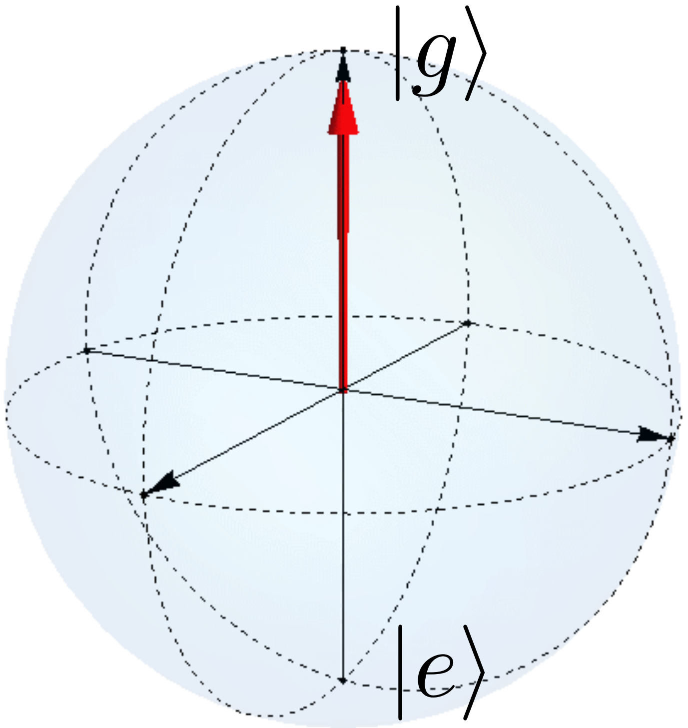


$$\Delta E_a = \hbar\omega_a$$

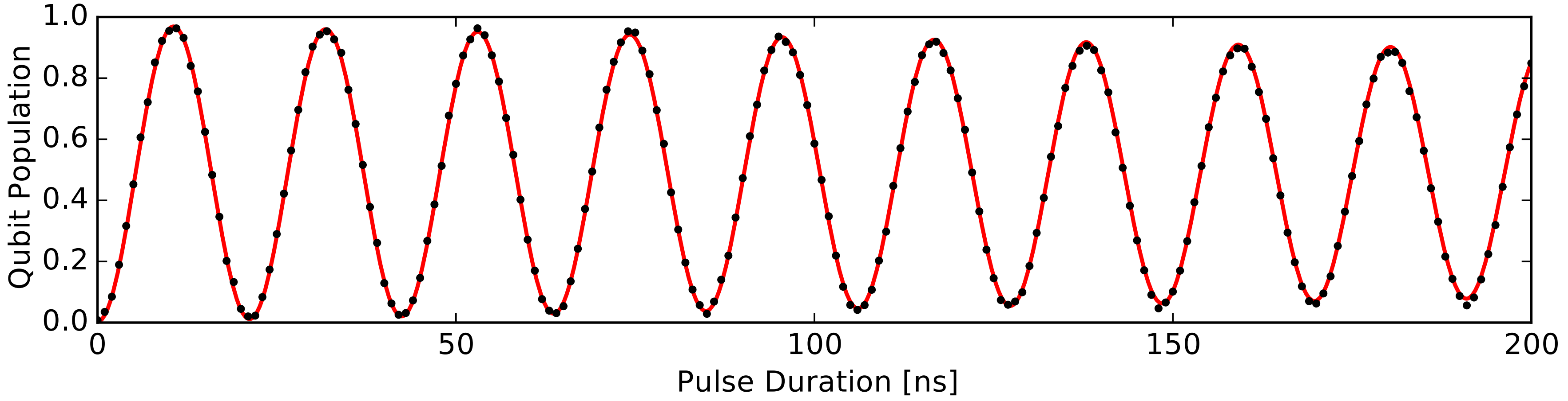
$$|\psi\rangle = c_1|g\rangle + c_2|e\rangle$$

$$\hat{H} = \frac{1}{2}\hbar\omega_a\hat{\sigma}_z$$

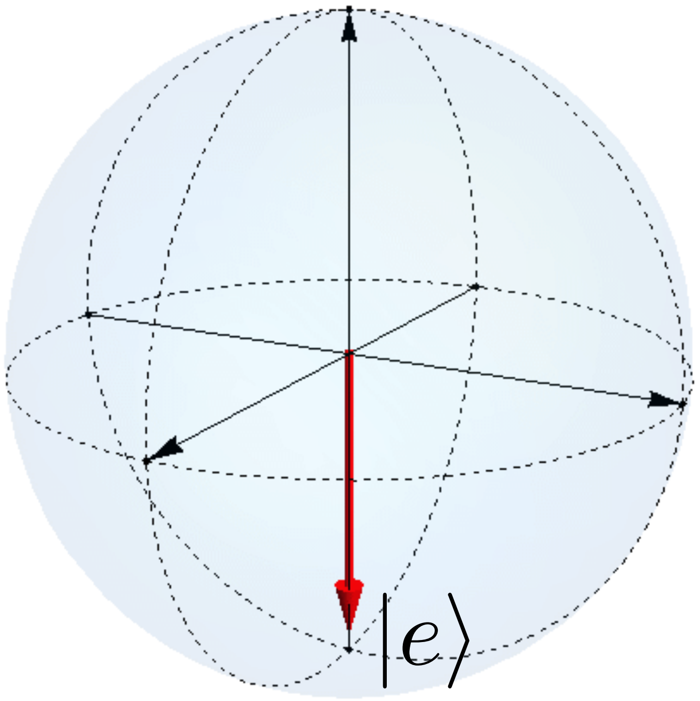
$$\hat{\sigma}_z = |e\rangle\langle e| - |g\rangle\langle g| = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$



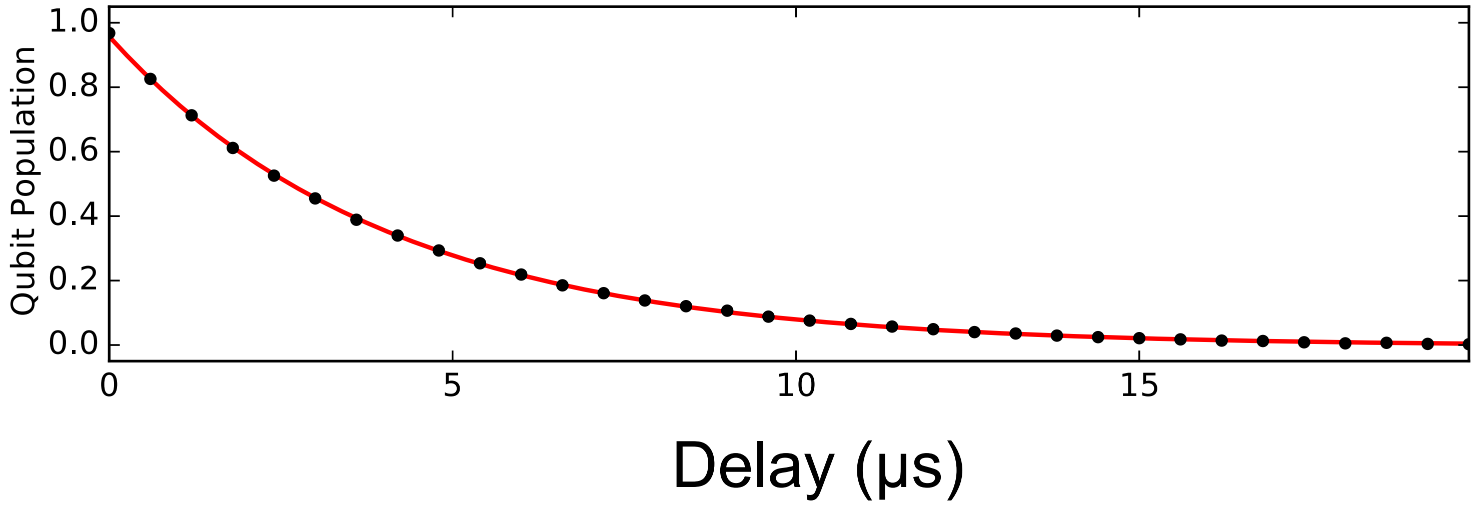
Excite with resonant coherent microwaves:
Rabi oscillations:

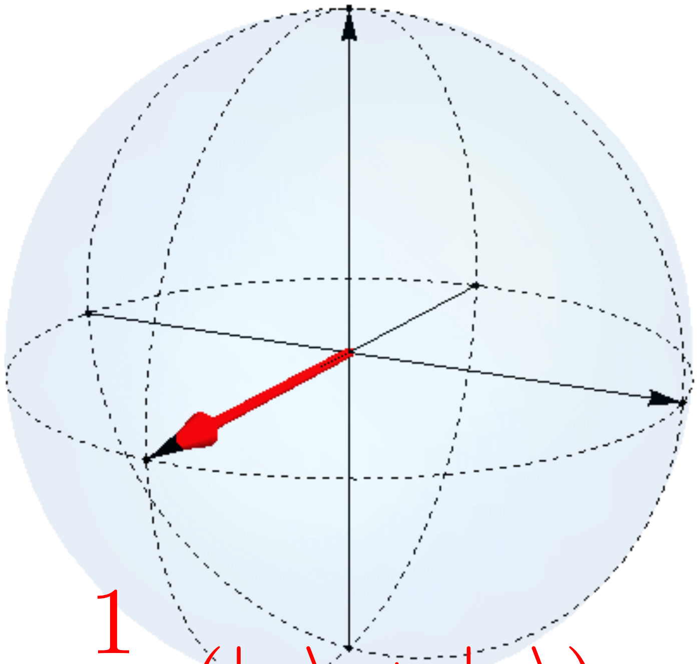


Measuring qubit coherence



Energy relaxation (T1):

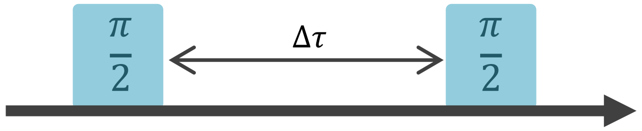


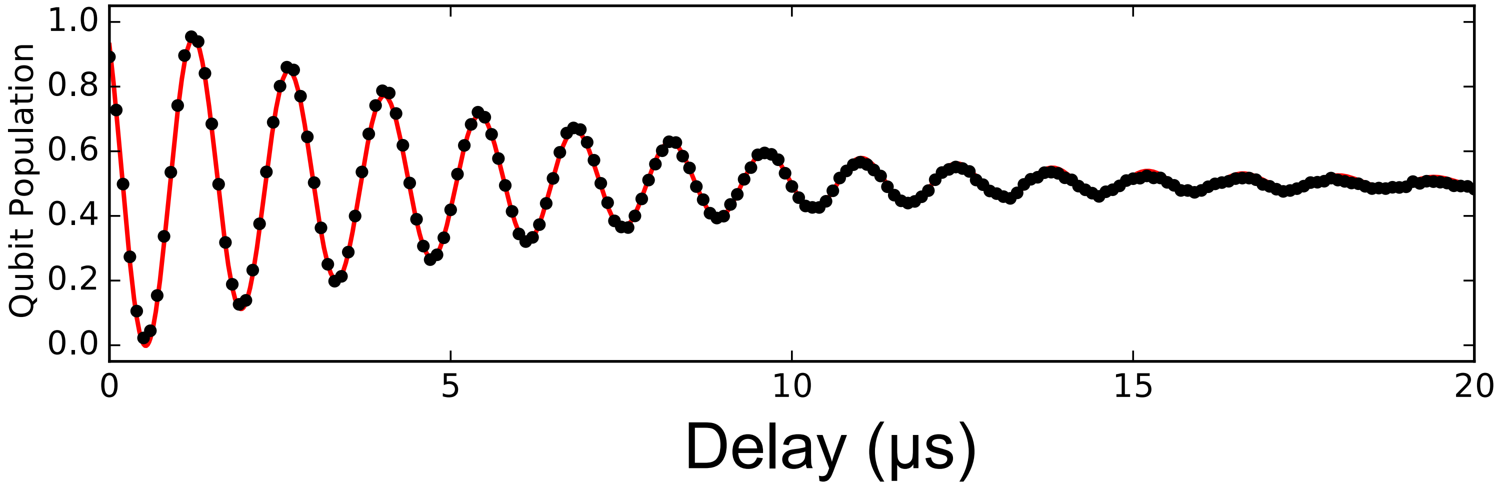


$$\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$$

Phase coherence (T2):

Ramsey interferometry





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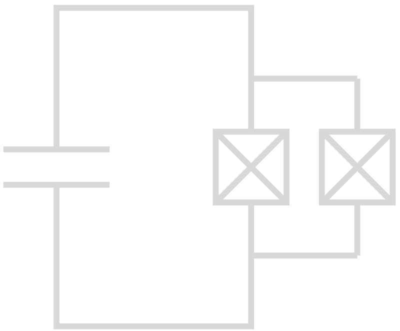
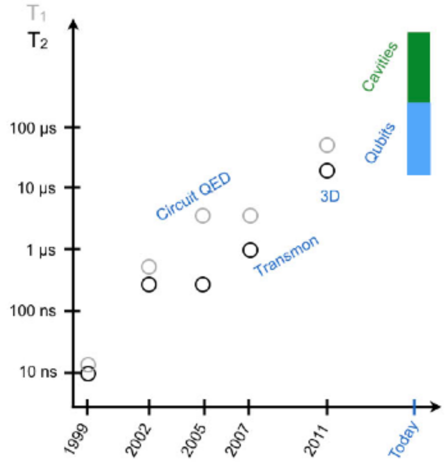


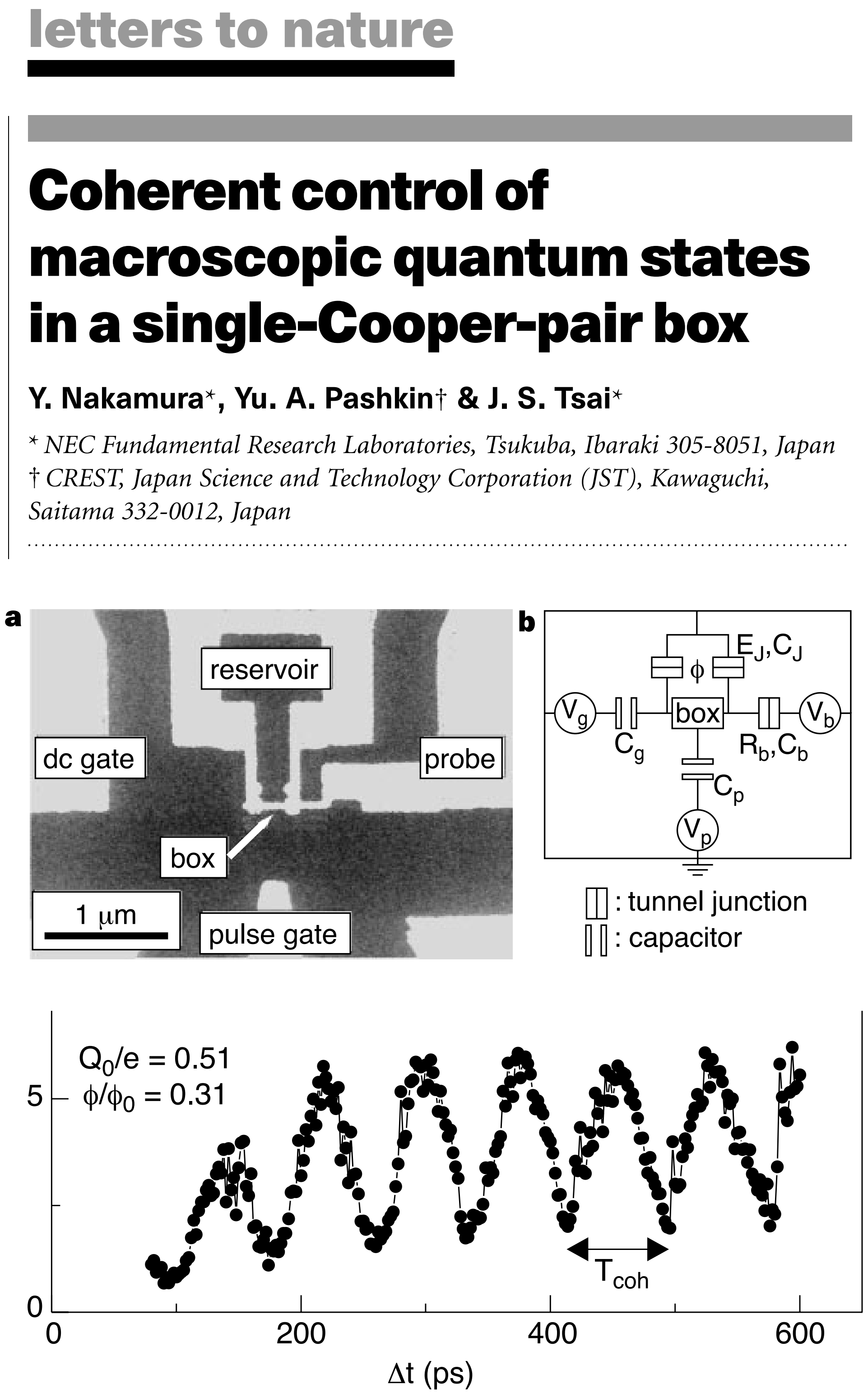
- Making electric circuits quantum



- Development of superconducting circuit quantum computing

- Oxford coaxial circuit architecture

Brief history - the ‘beginning’

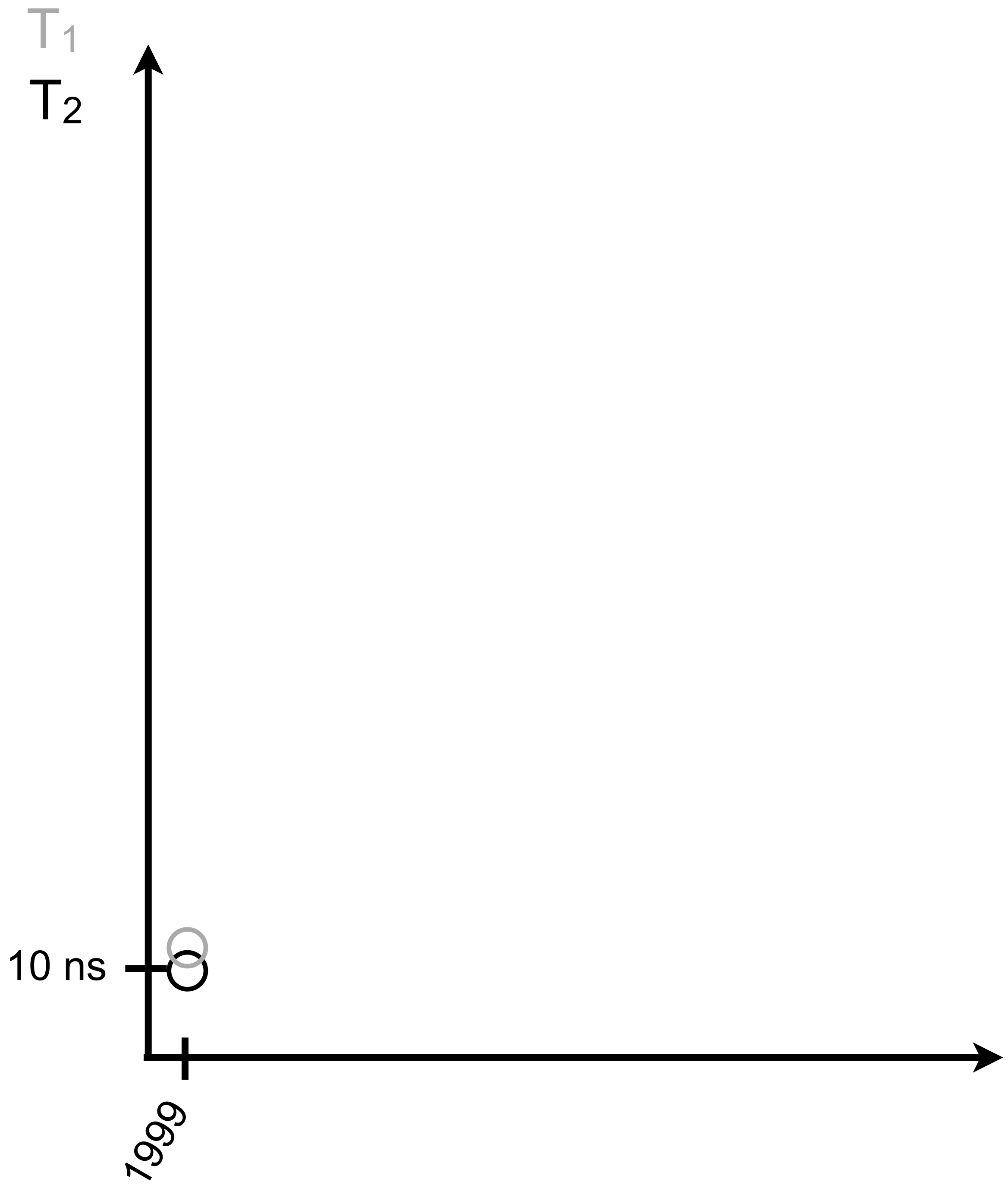


letters to nature

Coherent control of macroscopic quantum states in a single-Cooper-pair box

Y. Nakamura*, **Yu. A. Pashkin**† & **J. S. Tsai***

* *NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305-8051, Japan*
† *CREST, Japan Science and Technology Corporation (JST), Kawaguchi, Saitama 332-0012, Japan*

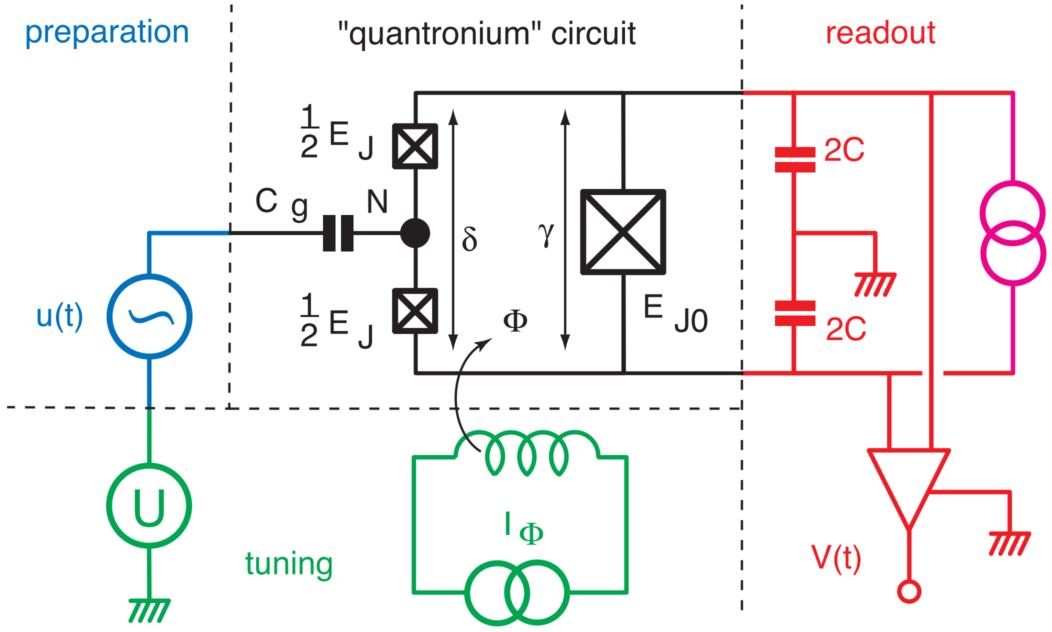


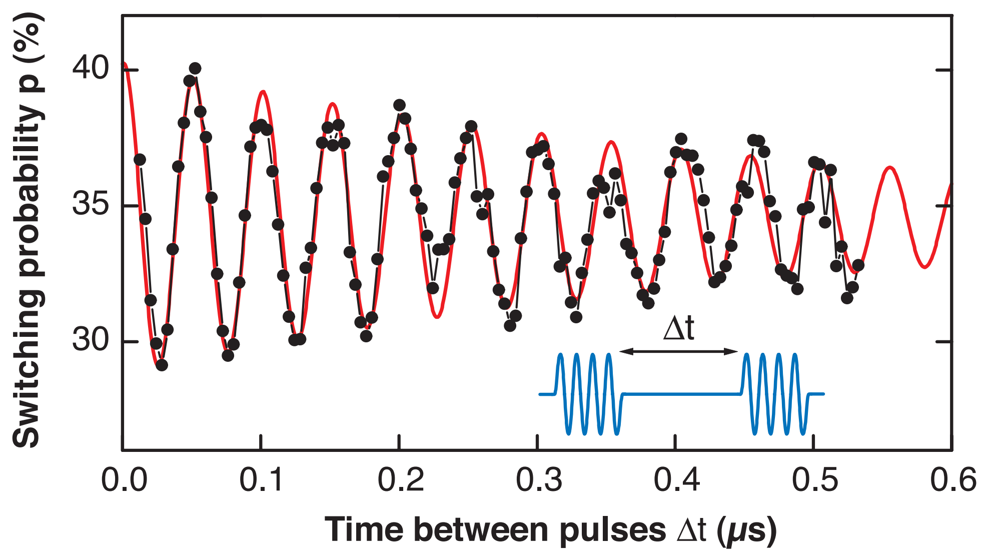
Y Nakamura *et al.*, Nature (1999)

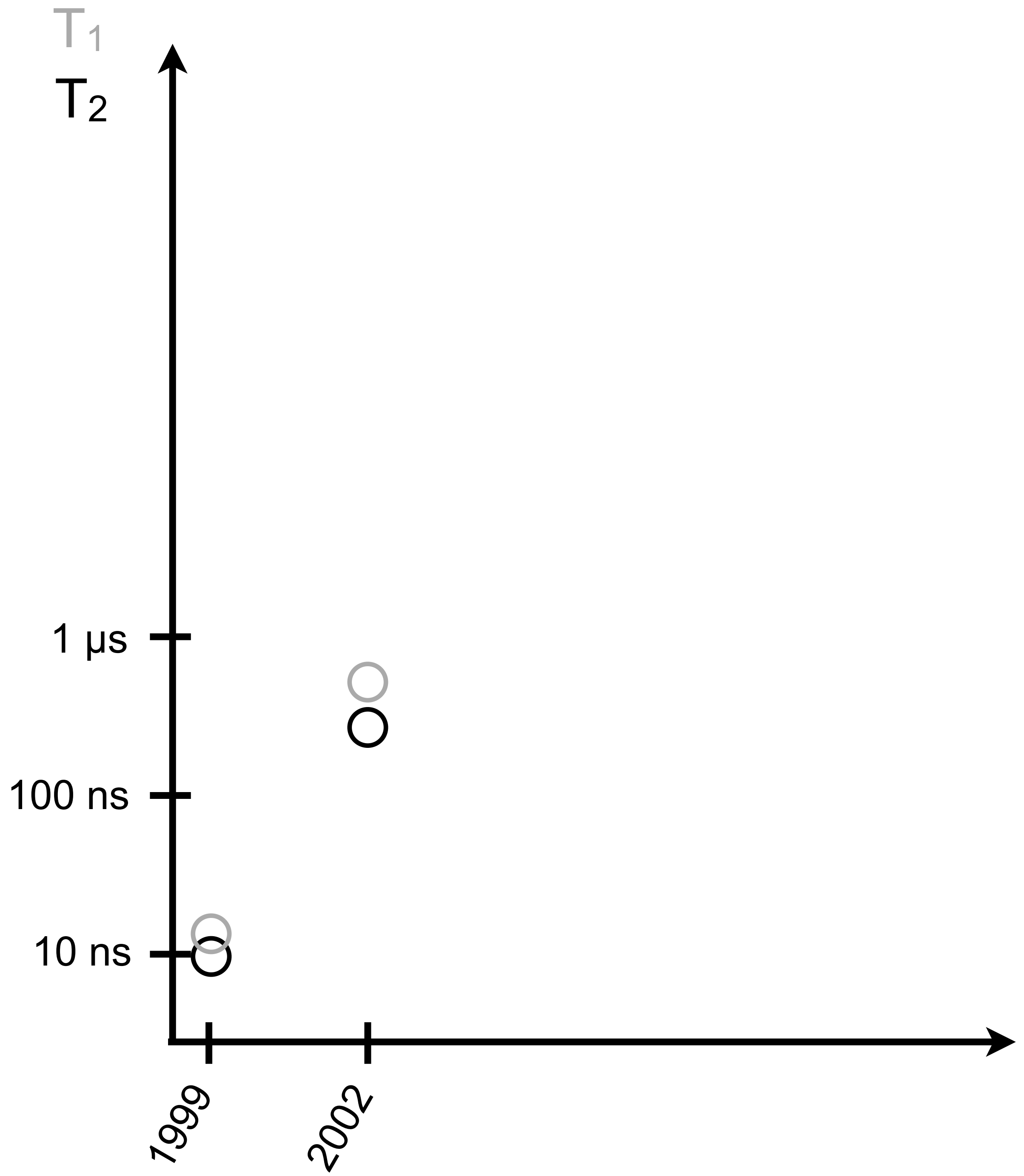
Brief history - improving coherence

Manipulating the Quantum State of an Electrical Circuit

D. Vion,* A. Aassime, A. Cottet, P. Joyez, H. Pothier, C. Urbina,† D. Esteve, M. H. Devoret‡

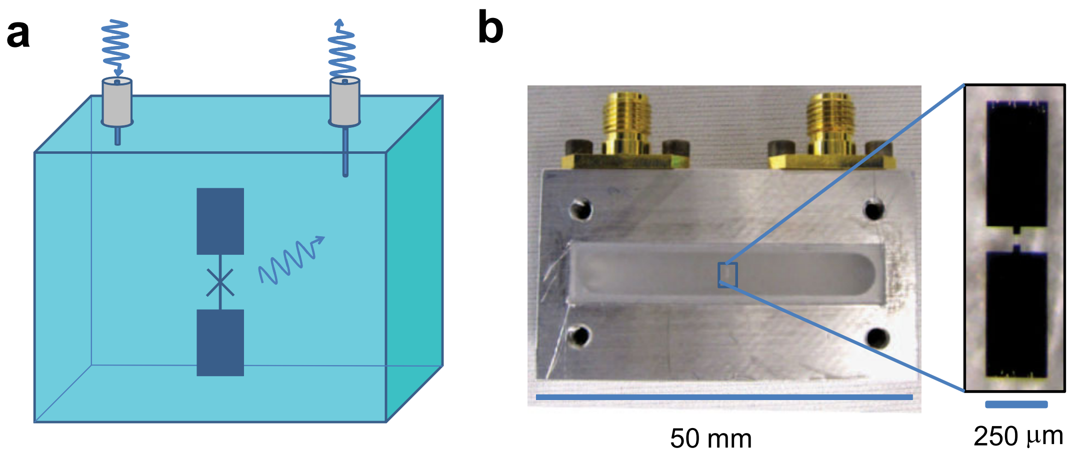


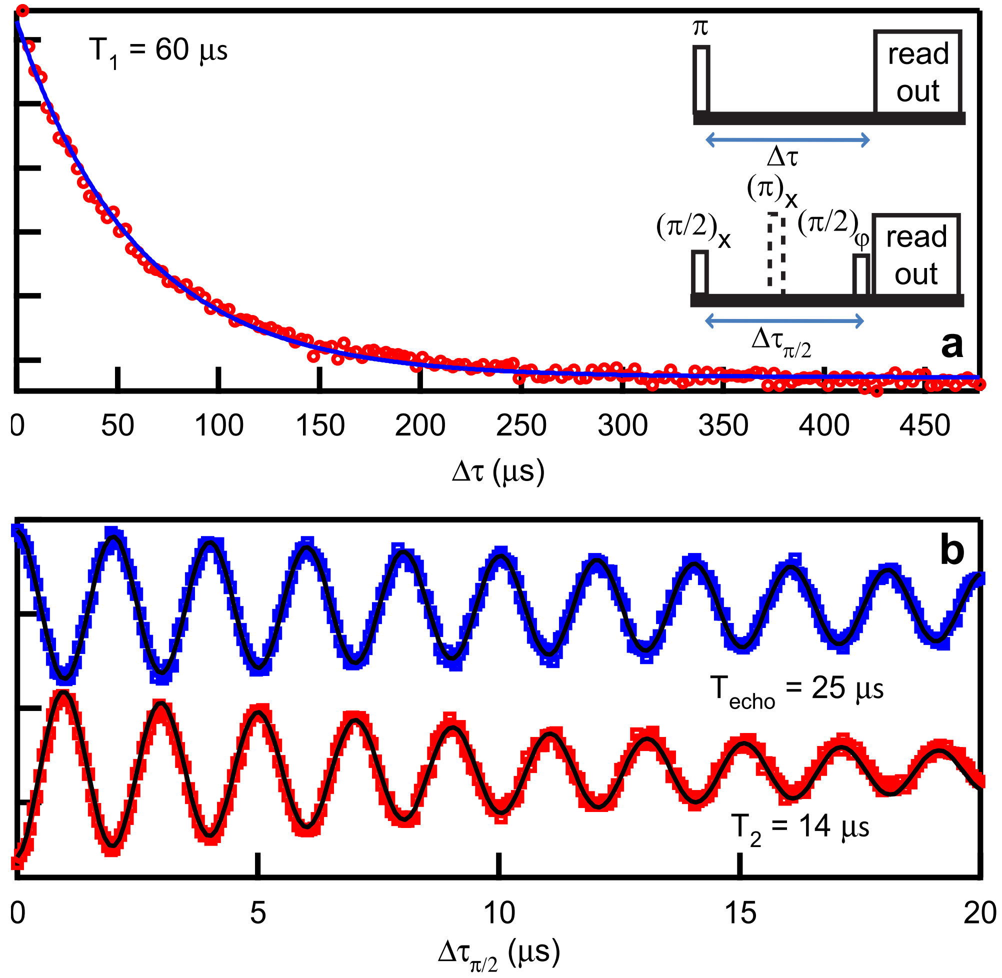


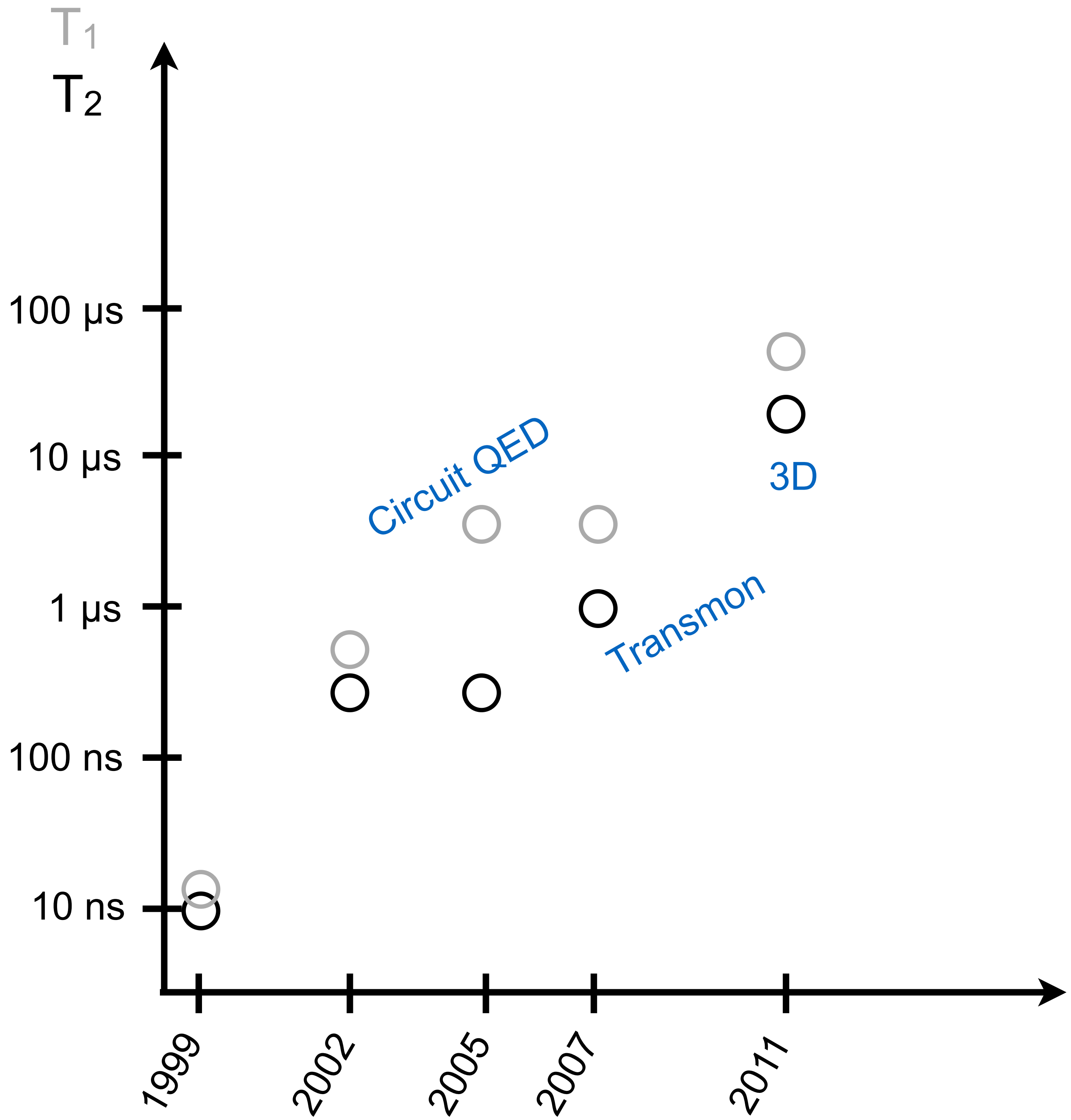


D Vion *et al.*, Science (2002)

Brief history - circuit QED, transmons, 3D







H Paik *et al.*, PRL (2011)

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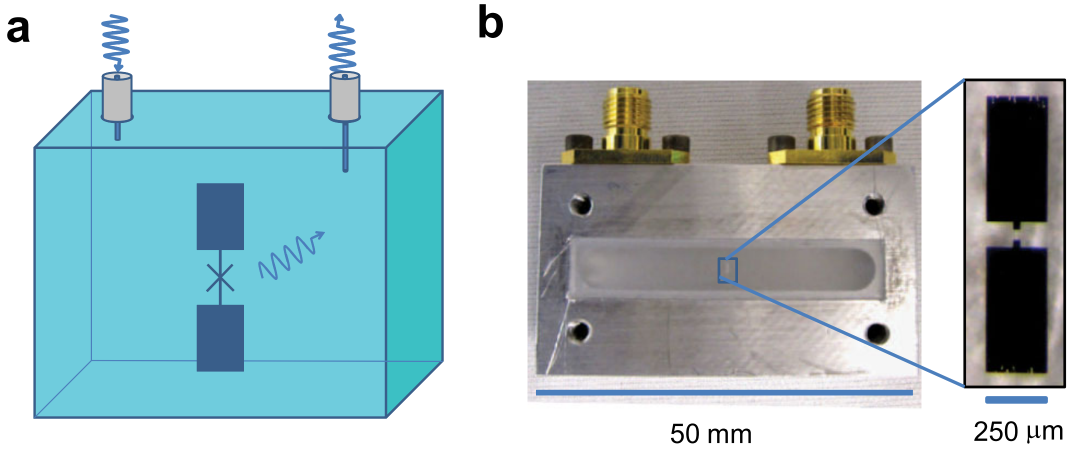
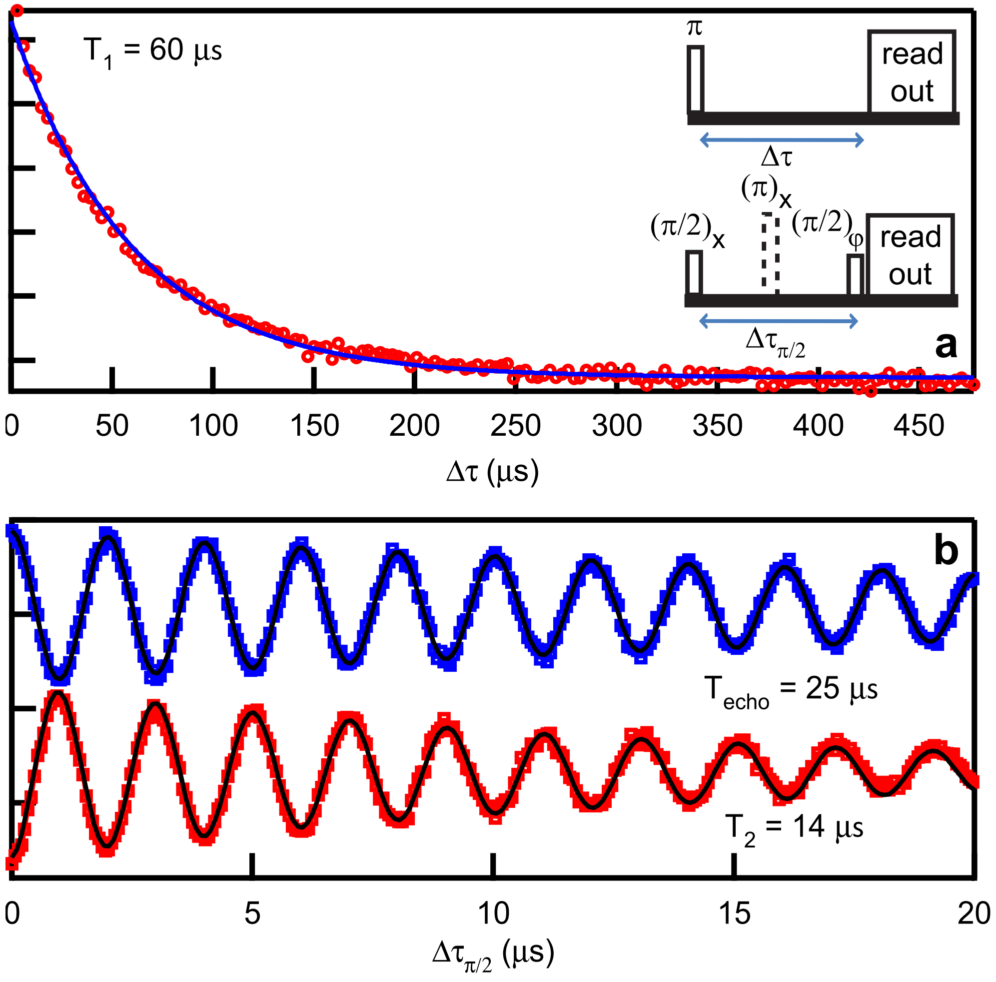
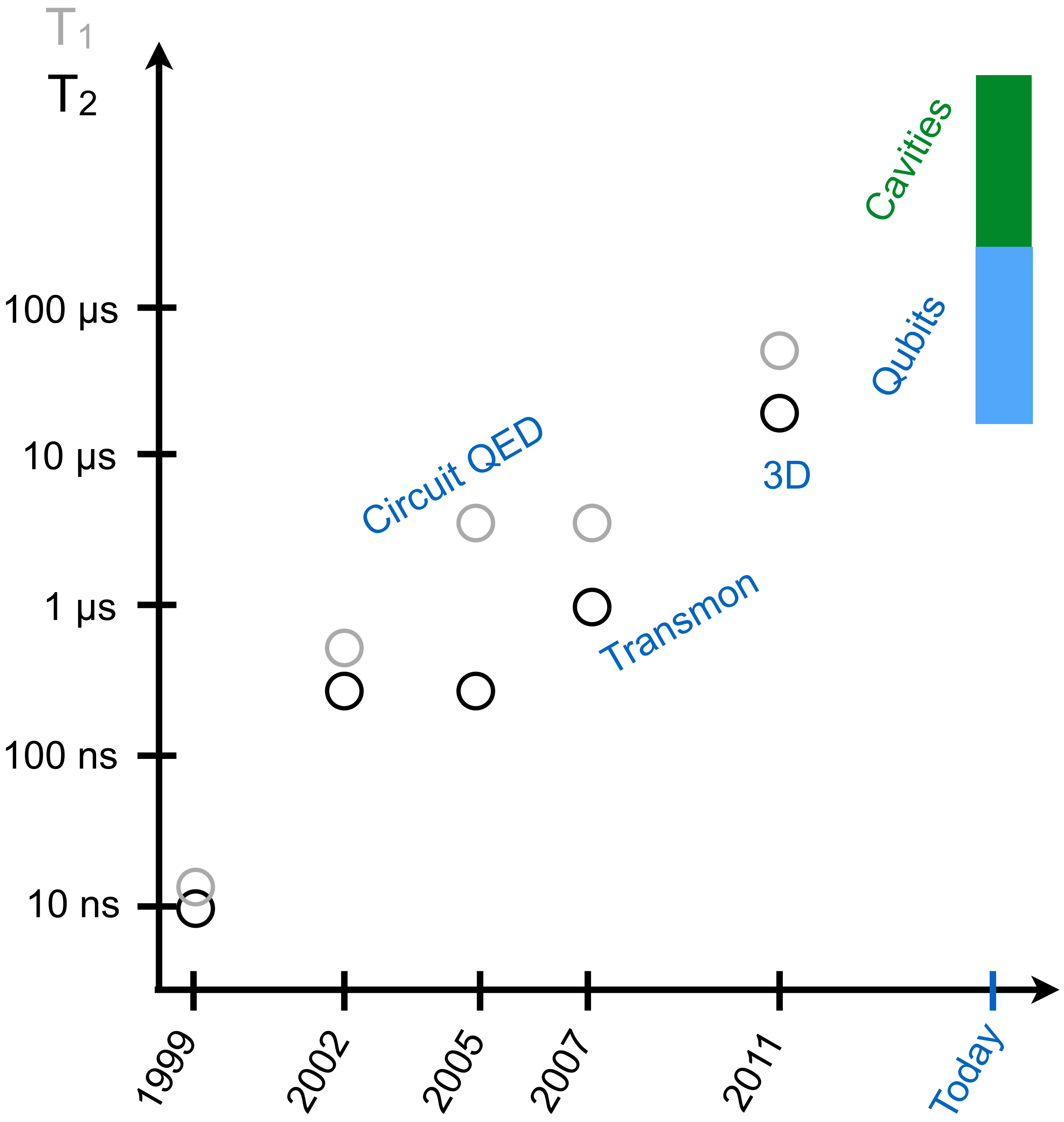
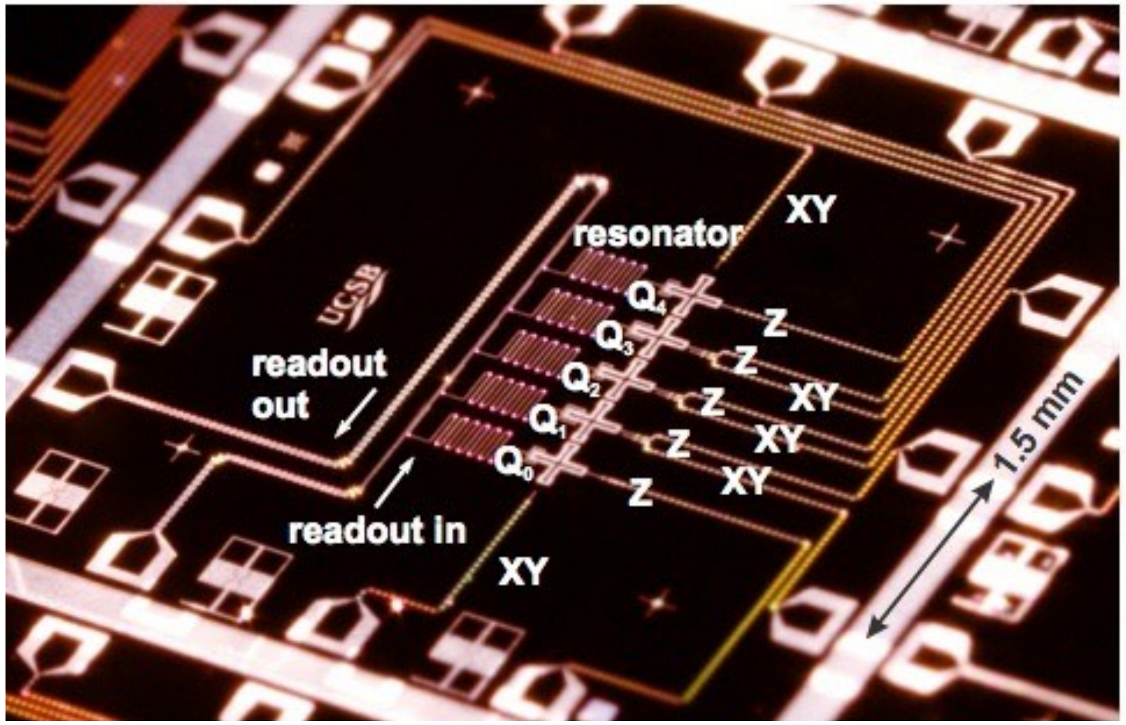


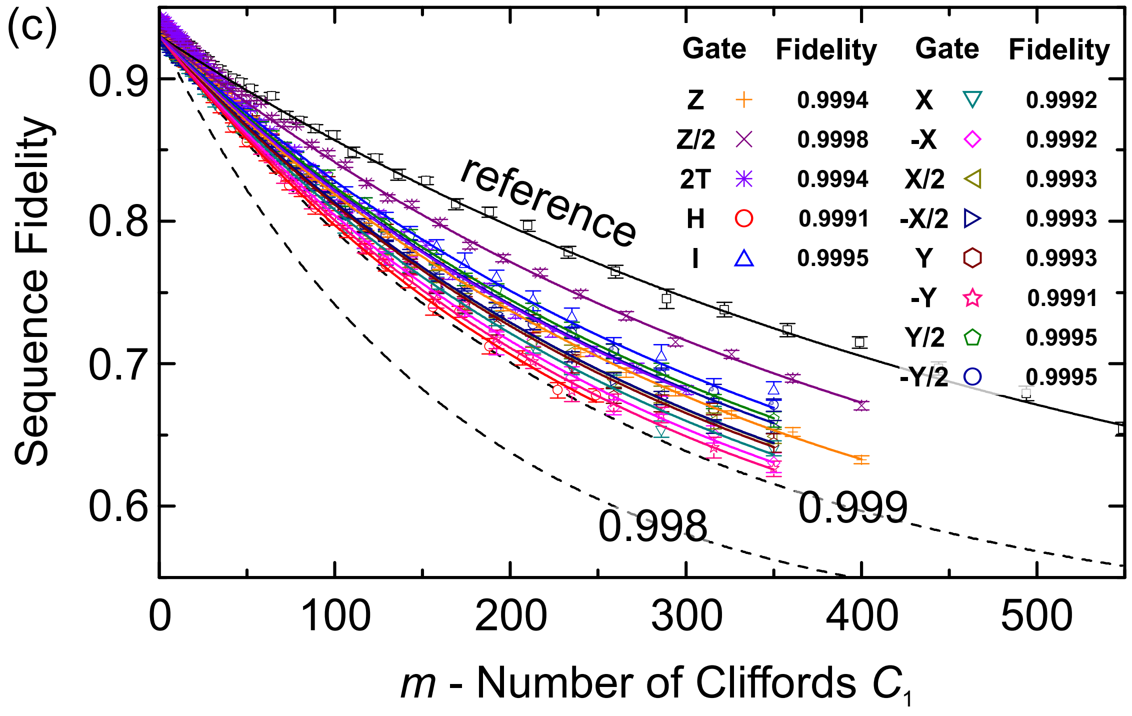


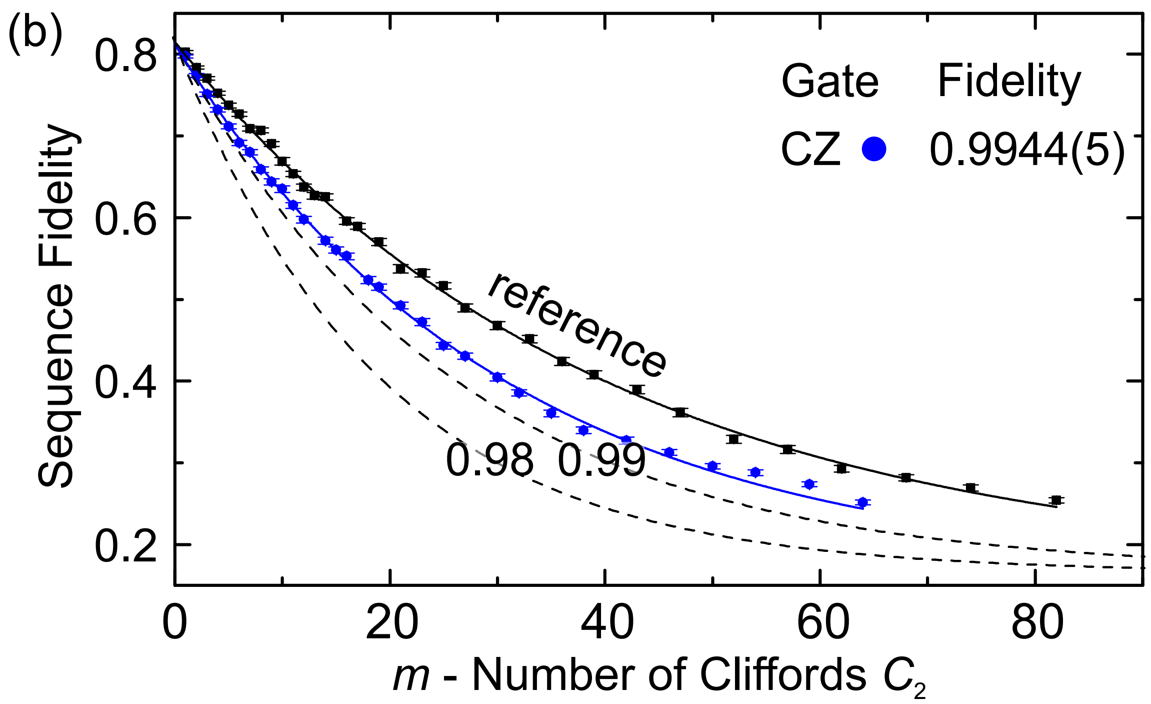


H Paik *et al.*, PRL (2011)

~reaching the ‘fault tolerance threshold’ (UCSB)



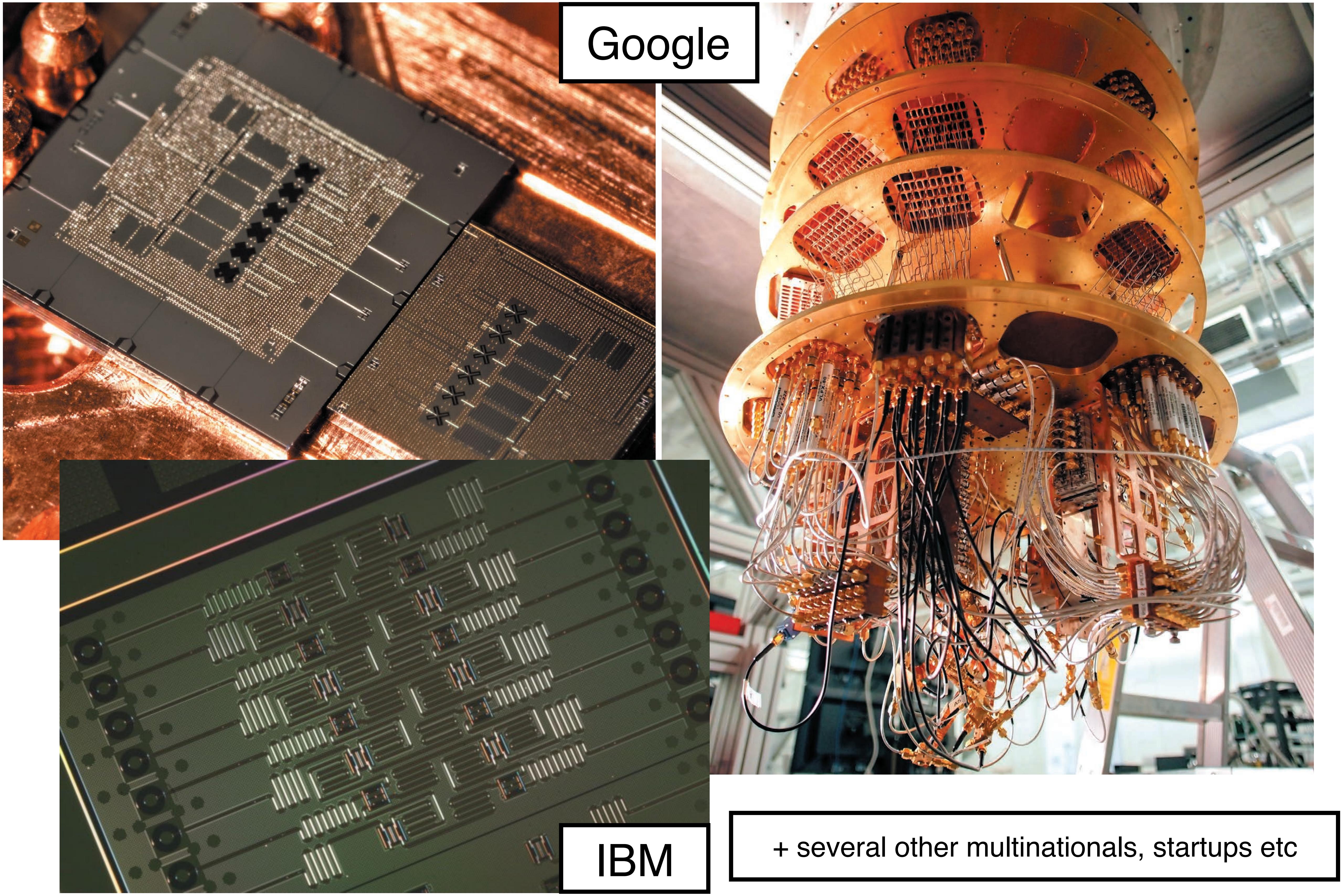




- 5 qubits
- Single qubit gates at F ~ 99.9%
- Two qubit gates at F ~ 99%
- Fidelities at the fault tolerance threshold for the ‘surface code’

Barends *et al.*, Nature **508**, 500 (2014)

Commercial efforts to build quantum computers

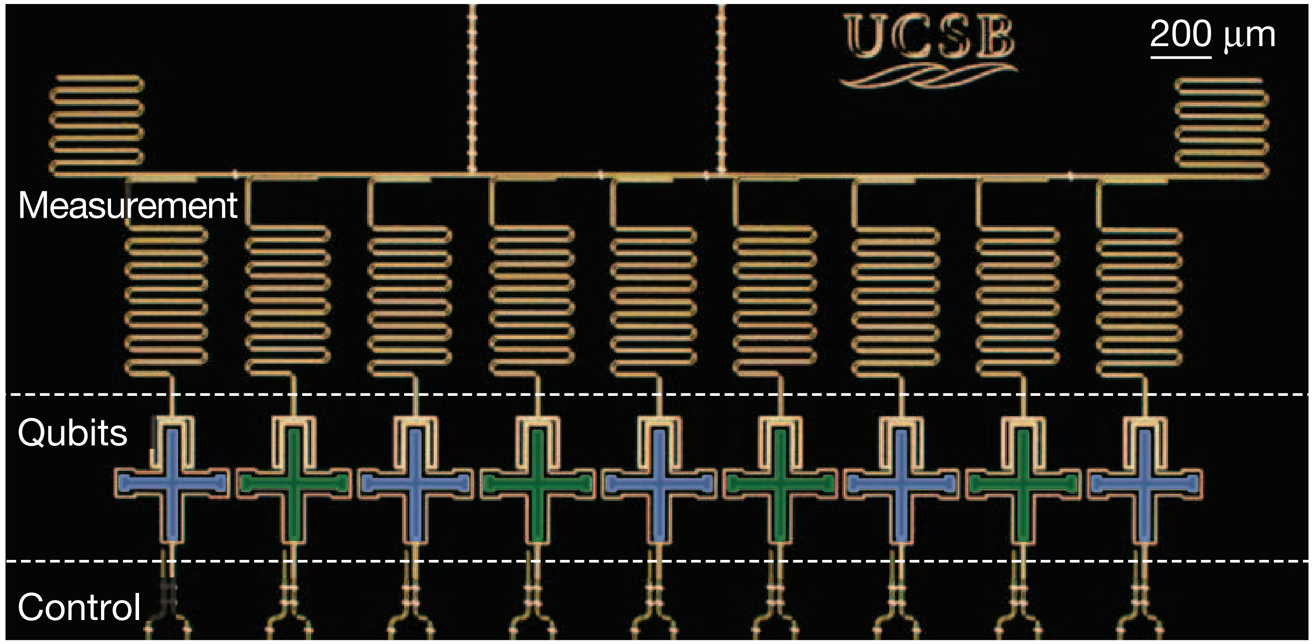


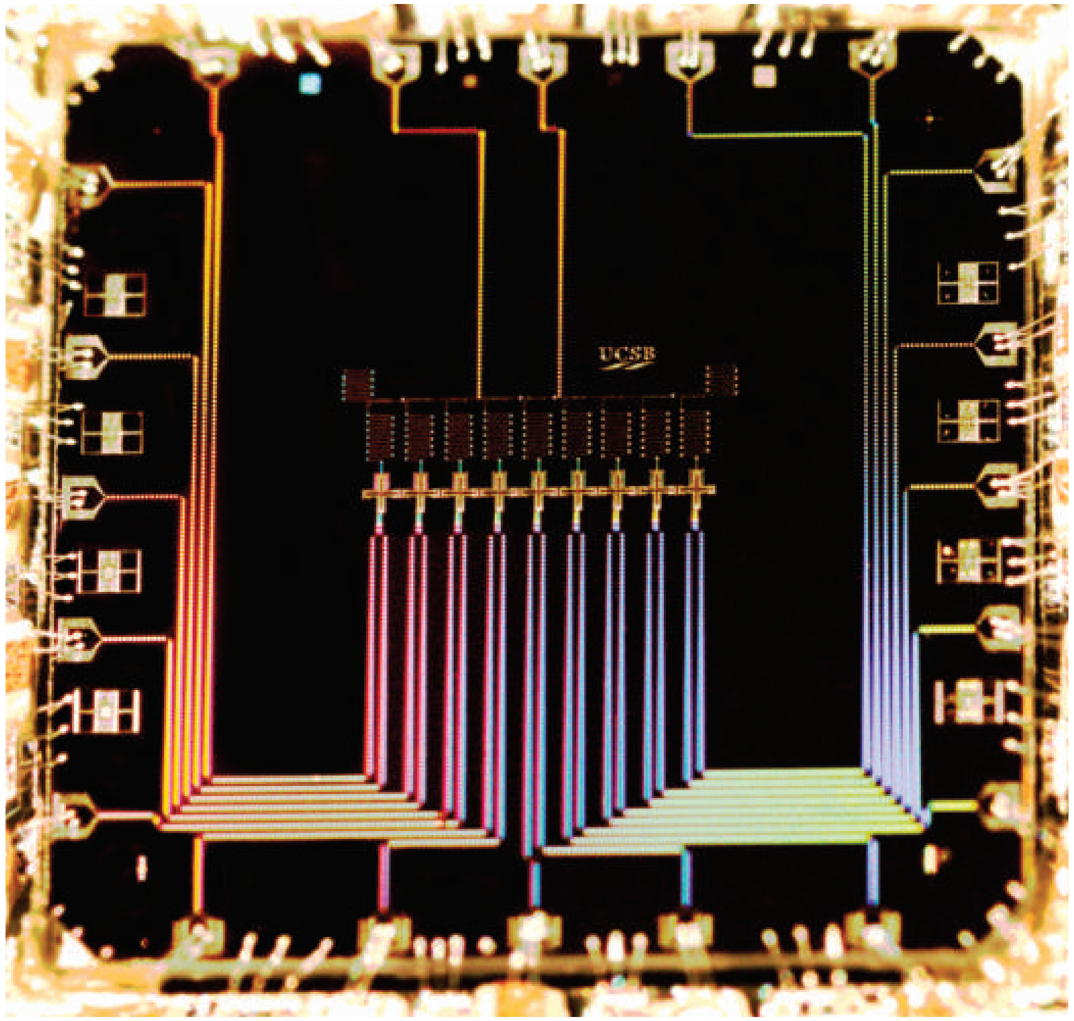
Google

IBM

+ several other multinationals, startups etc

Increasing numbers of qubits

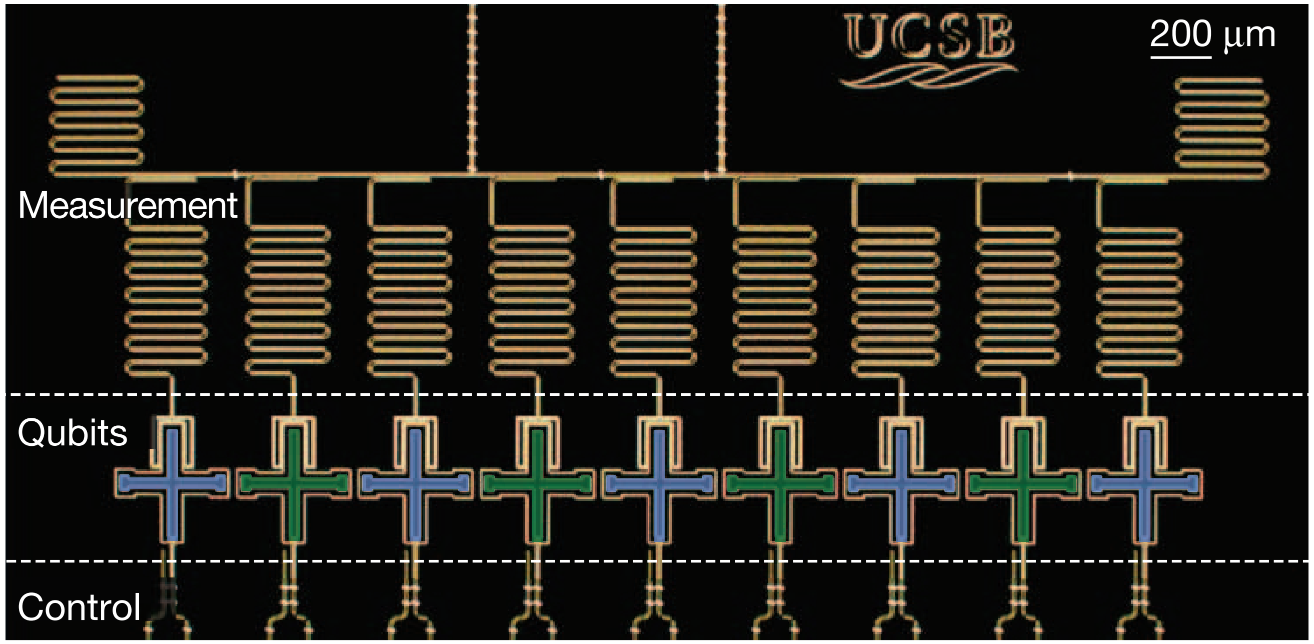




- Qubits in a linear chain
- In-plane control and readout
- Figures of merit (gate fidelities etc) at or near threshold required for scaling up

Kelly *et al.*, Nature **519**, 66 (2015)

Increasing numbers of qubits



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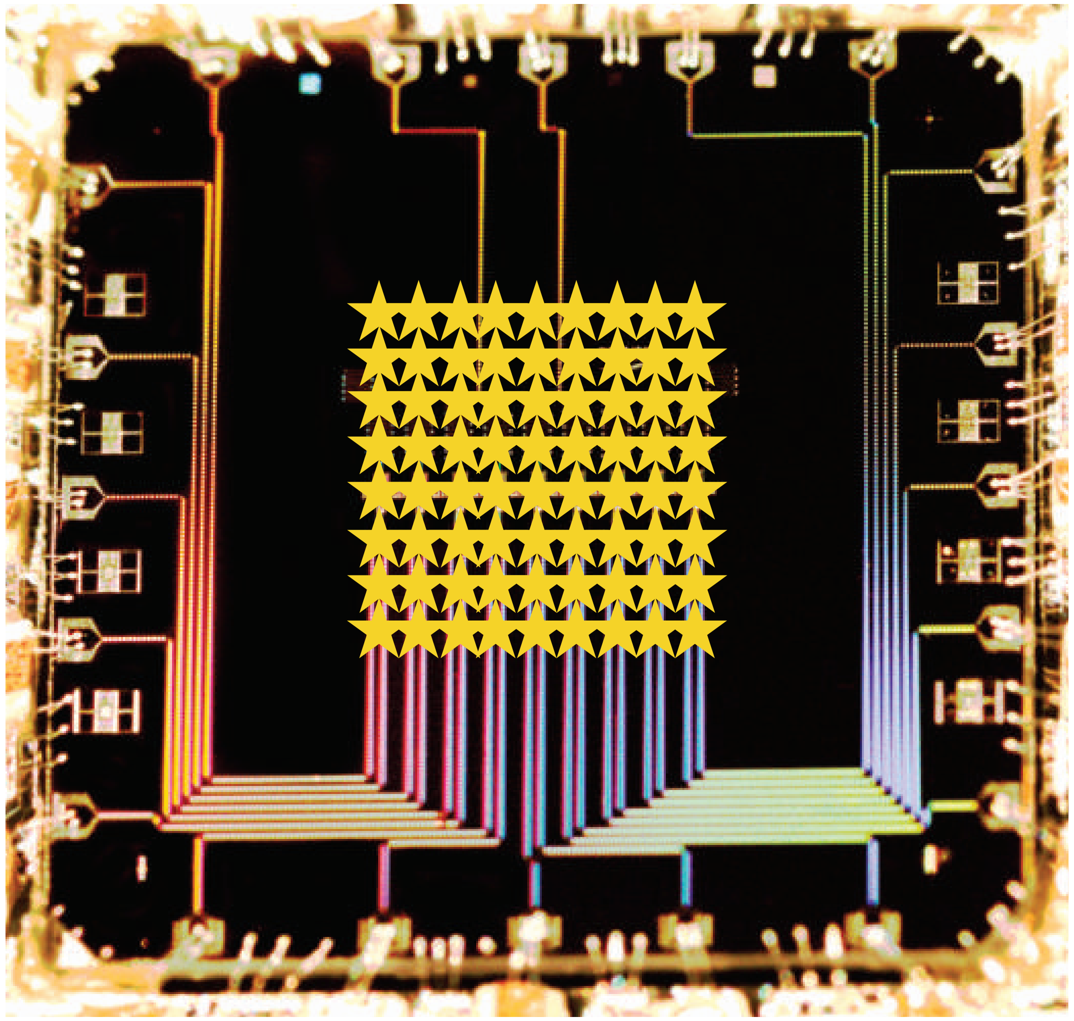
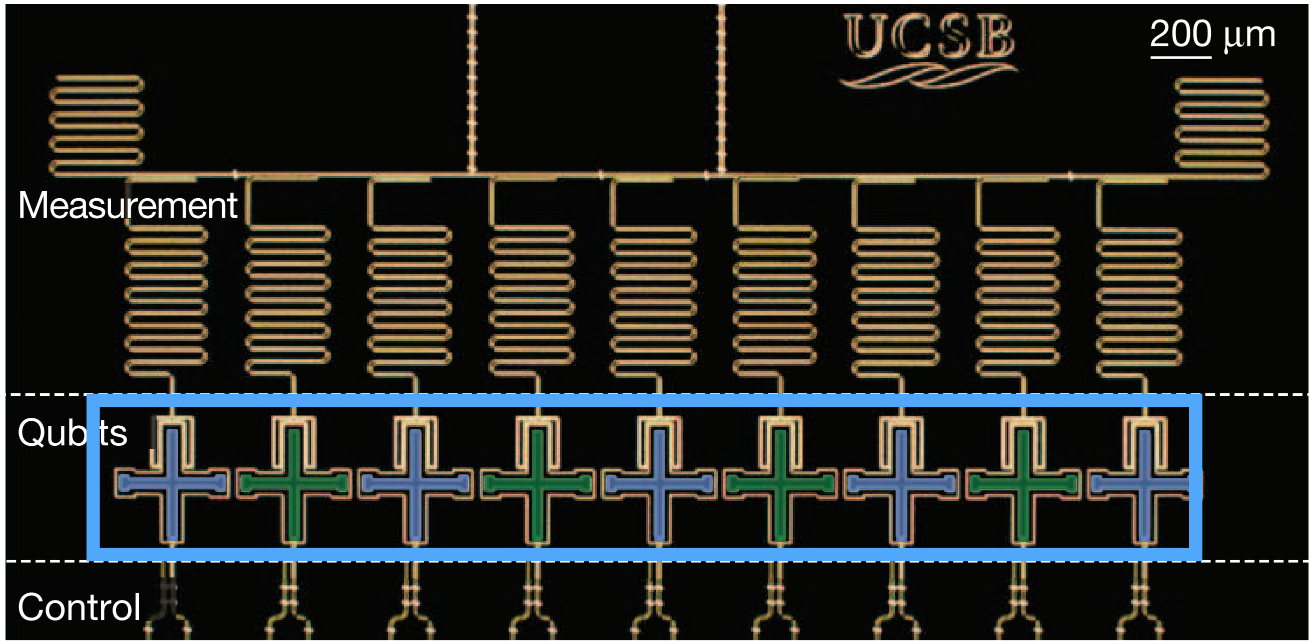


- Scaling up further?
- Need to move to 2D+ array
- Wiring density issue

Increasing numbers of qubits

On chip…



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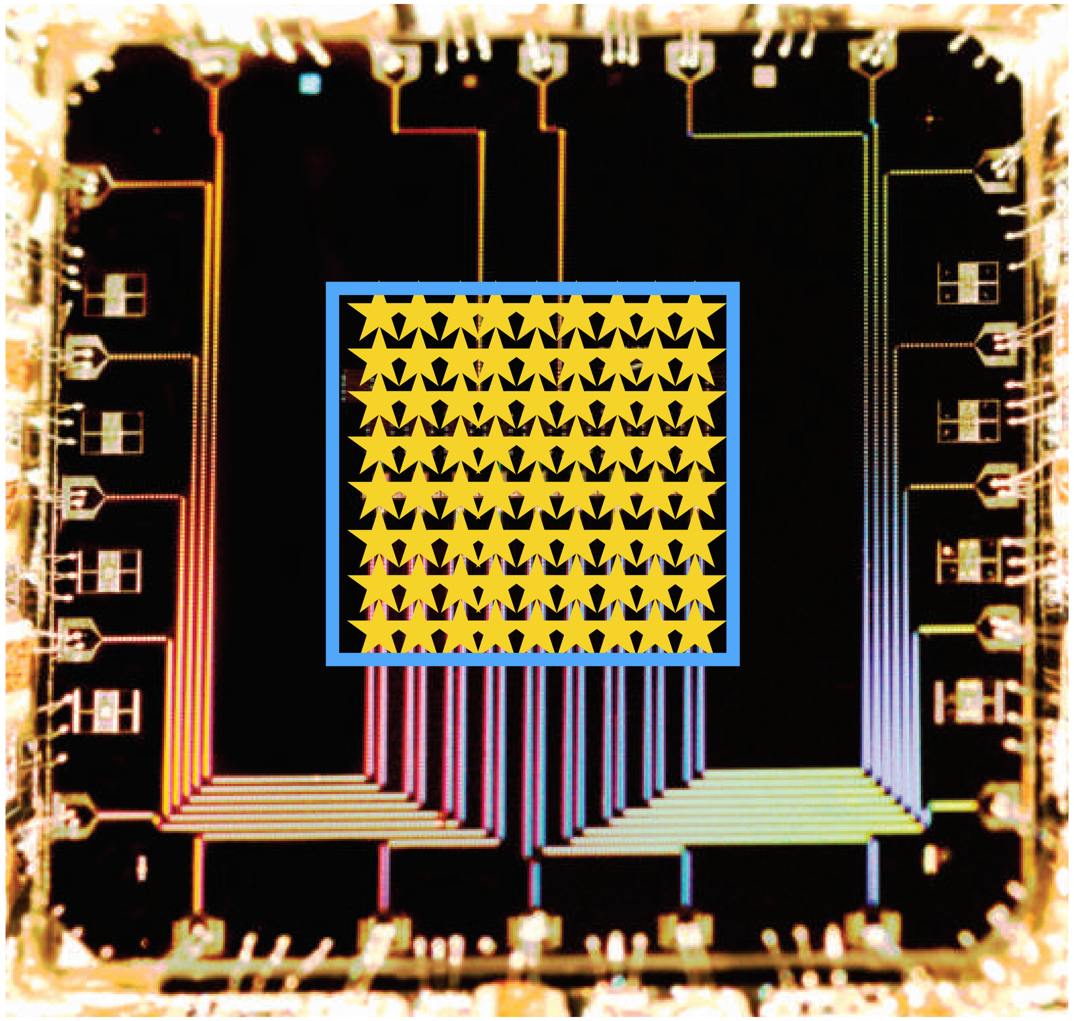
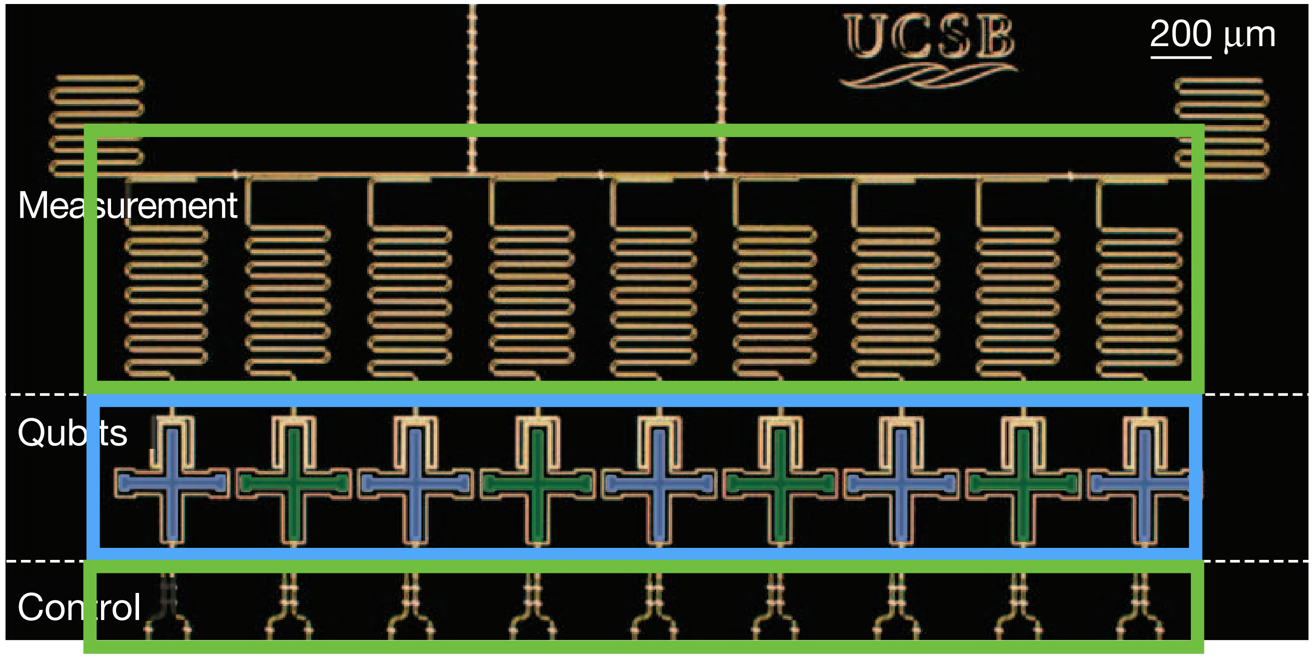
Kelly *et al.*, Nature **519**, 66 (2015)



- Scaling up further?
- Need to move to 2D+ array
- Wiring density issue

Increasing numbers of qubits

On chip… **Out-of-plane?**



- Qubits in a linear chain
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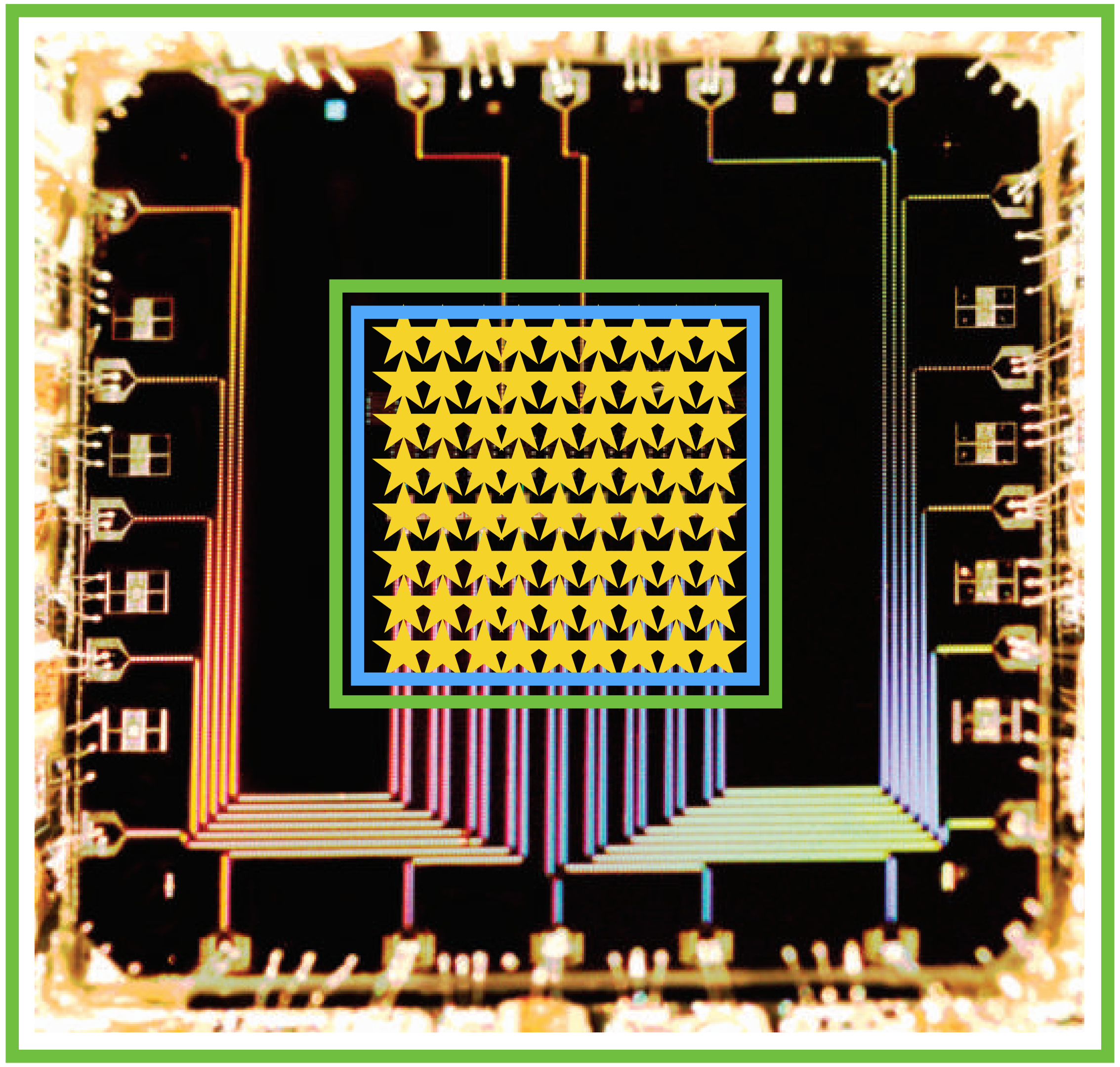
- Figures of merit (gate fidelities etc) at or near threshold required for scaling up

Kelly *et al.*, Nature **519**, 66 (2015)



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- Need to move to 2D+ array
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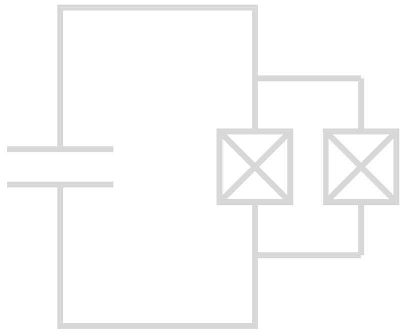
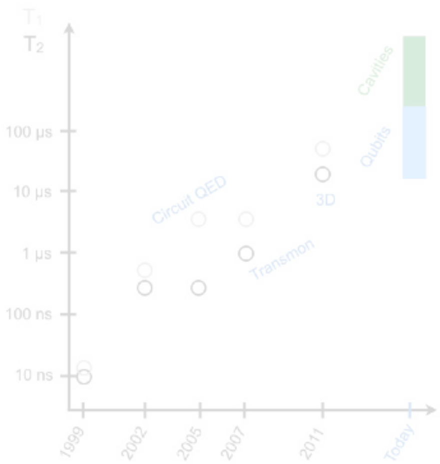
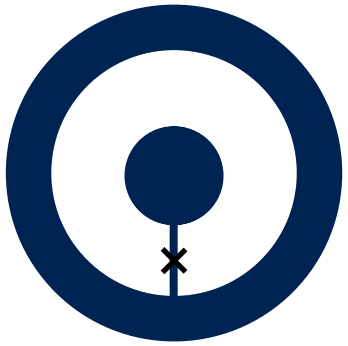
Outline



- Making electric circuits quantum

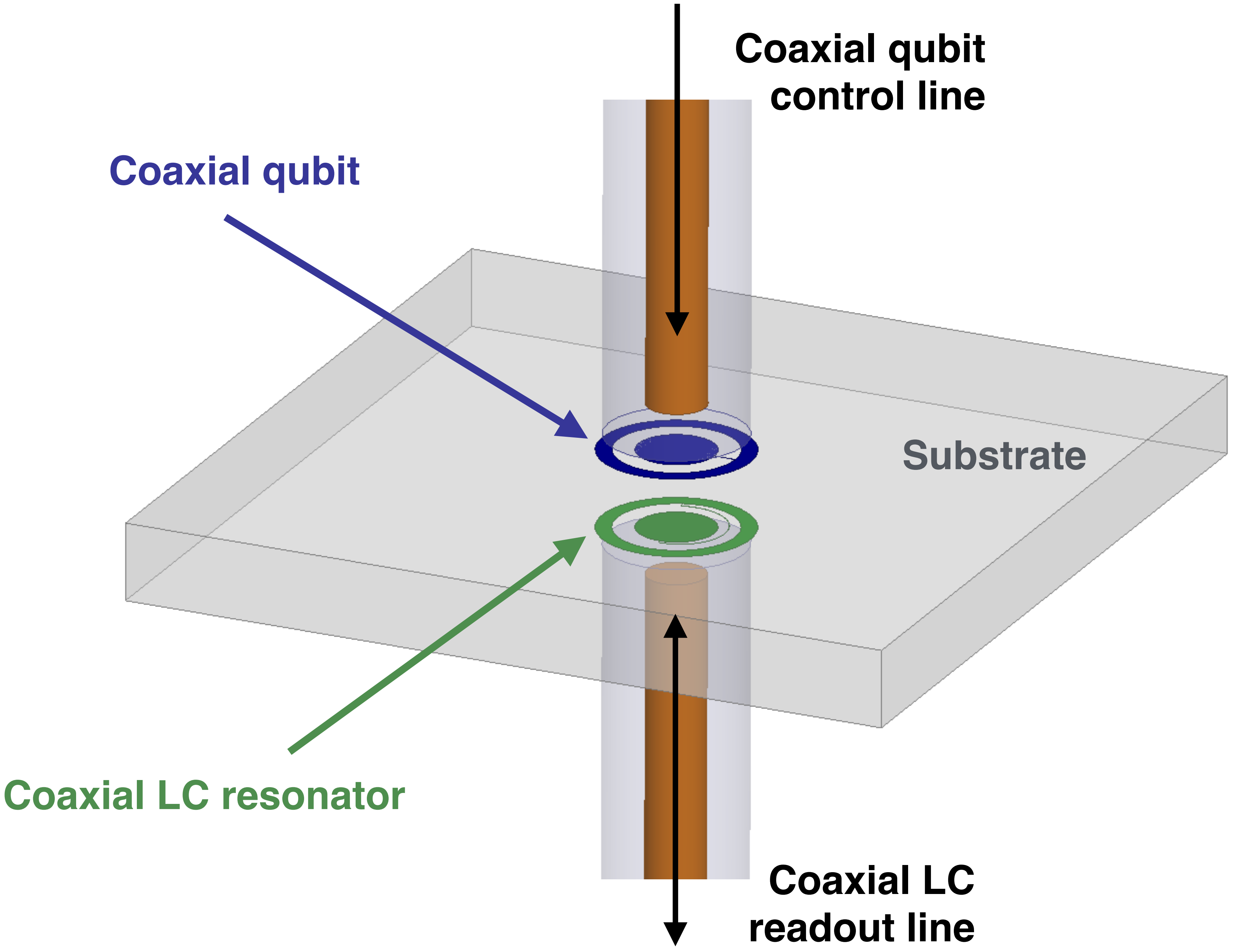


- Development of superconducting circuit quantum computing



- Oxford coaxial circuit architecture

Coaxial 3D-wired architecture



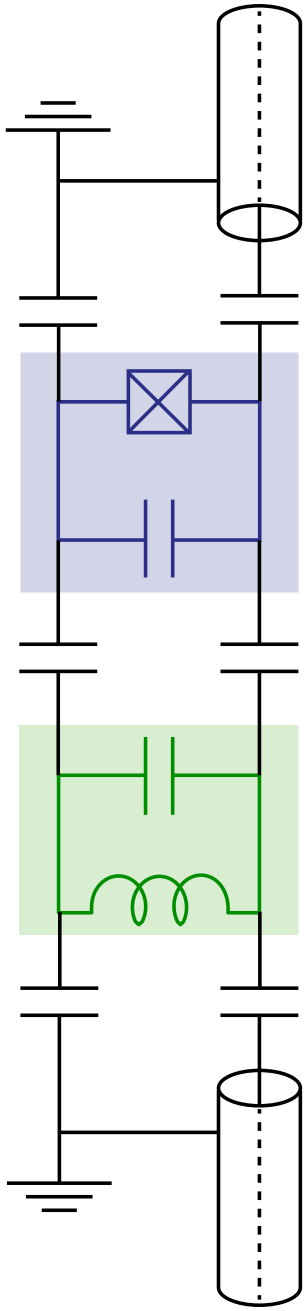
Coaxial qubit control line

Coaxial qubit

Substrate

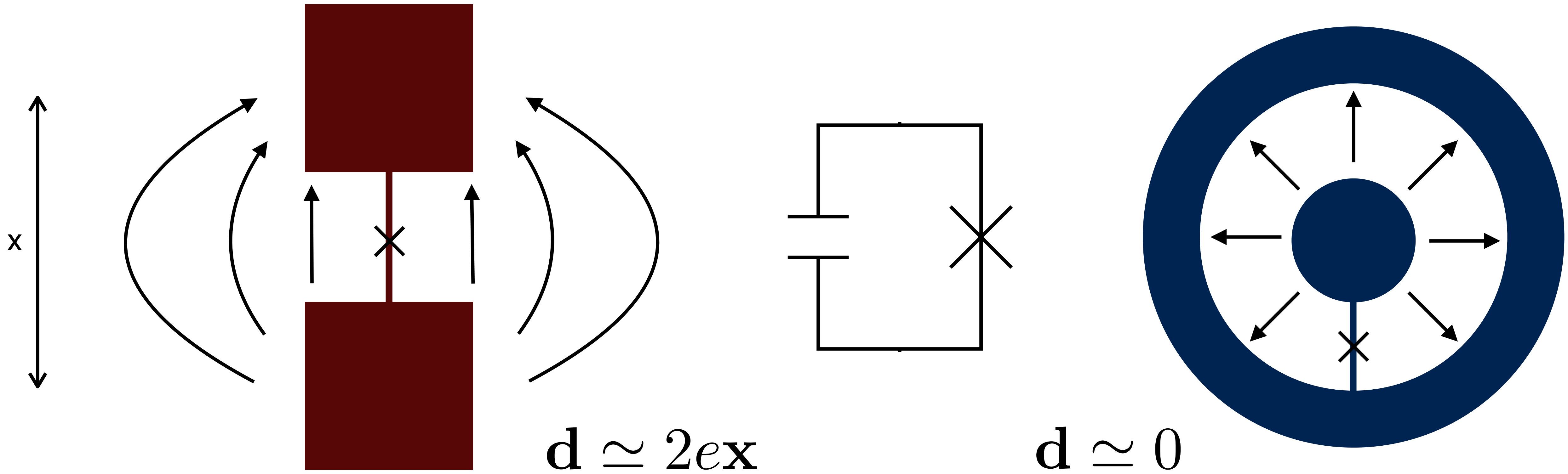
Coaxial LC resonator

Coaxial LC readout line



Rahamim *et al.*, APL **110**, 222602 (2017)

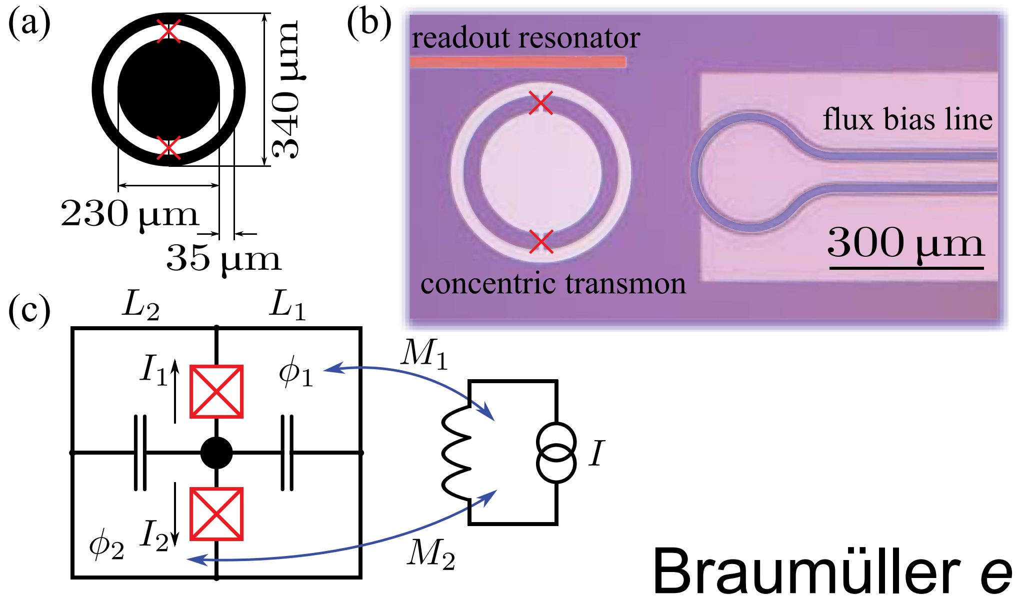
The coaxmon - a transmon with no dipole



$\mathbf{d} \simeq 2e\mathbf{x}$

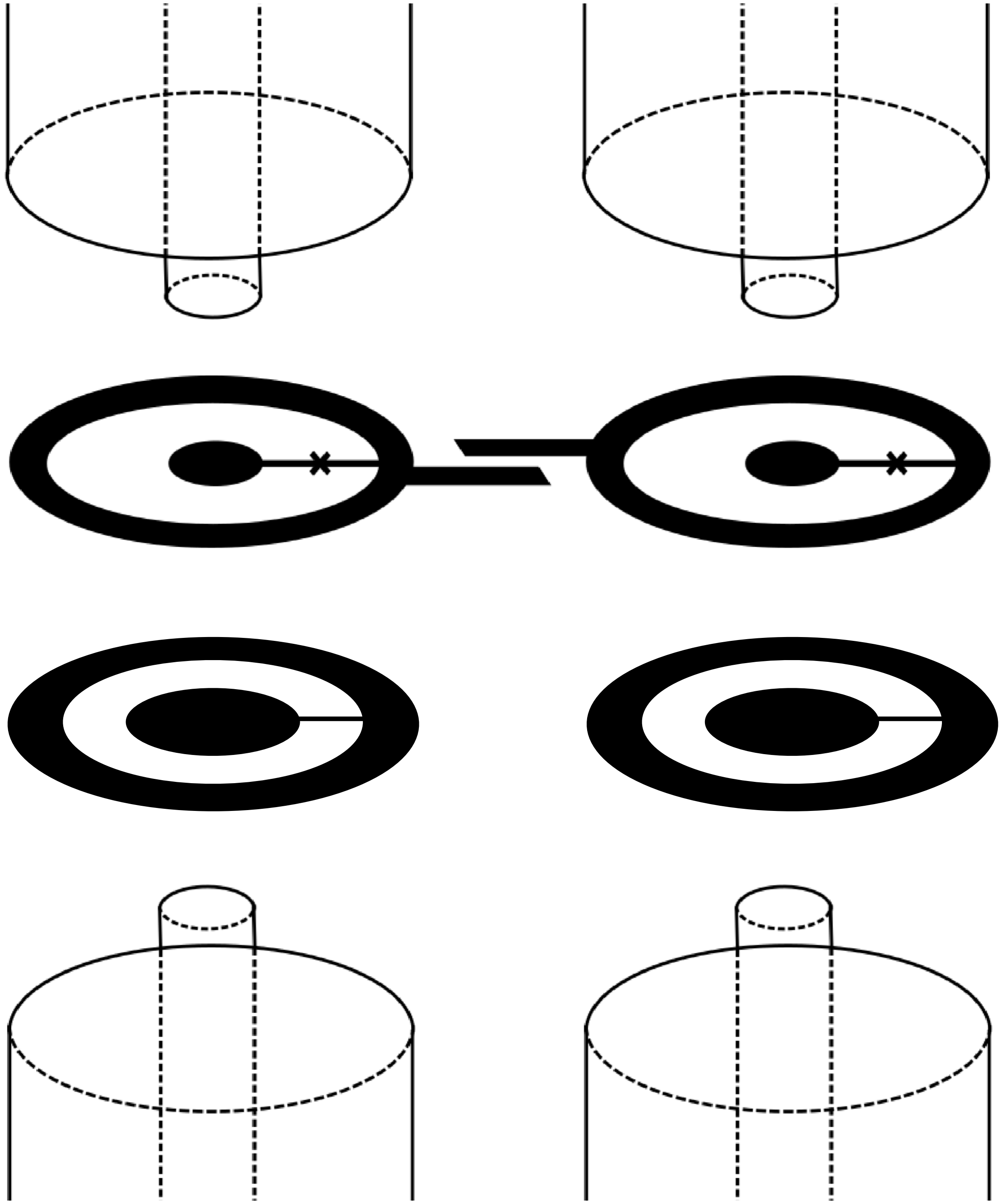
$\mathbf{d} \simeq 0$

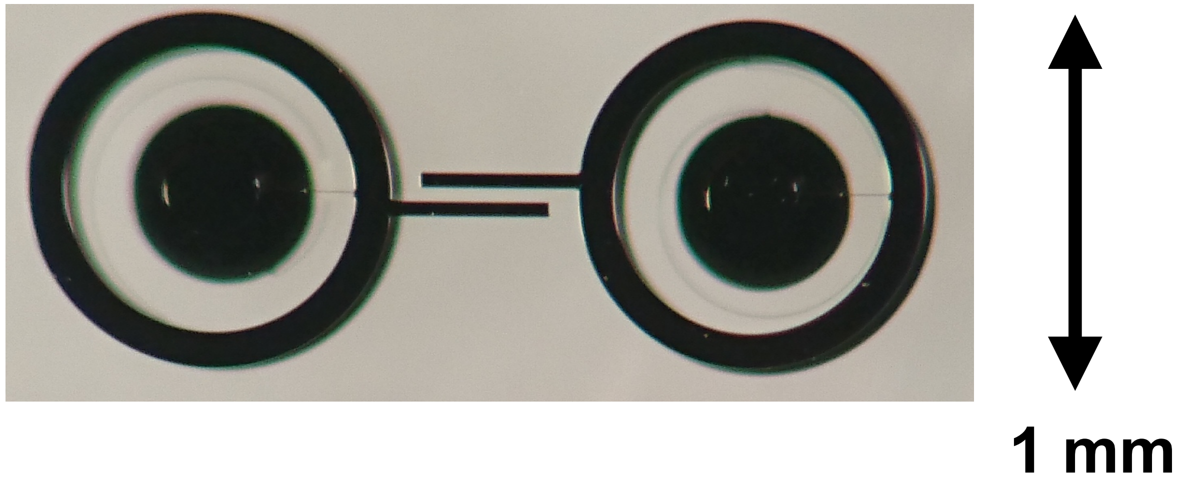
- Conventional transmon has large dipole moment (by design!)
- Symmetry of coaxial transmon results in zero dipole moment
- See also gradiometric SQUID version demonstrated here:



Braumüller *et al.*, APL **108**, 032601 (2016)

A typical two-qubit circuit





$$f_{C,D} = 6.58, 6.07 \text{ GHz}$$

$$\alpha = -0.29, 0.31 \text{ GHz}$$

$$f_R = 10.5, 9.5 \text{ GHz}$$

$$T_1 = 21.4, 26.2 \ \mu\text{s}$$

$$T_2^* = 7.1, 11.7 \ \mu\text{s}$$

$$T_2^E = 25.9, 29.4 \ \mu\text{s}$$

$$H = \frac{\omega_A}{2} ZI + \frac{\omega_B}{2} IZ + JXX$$

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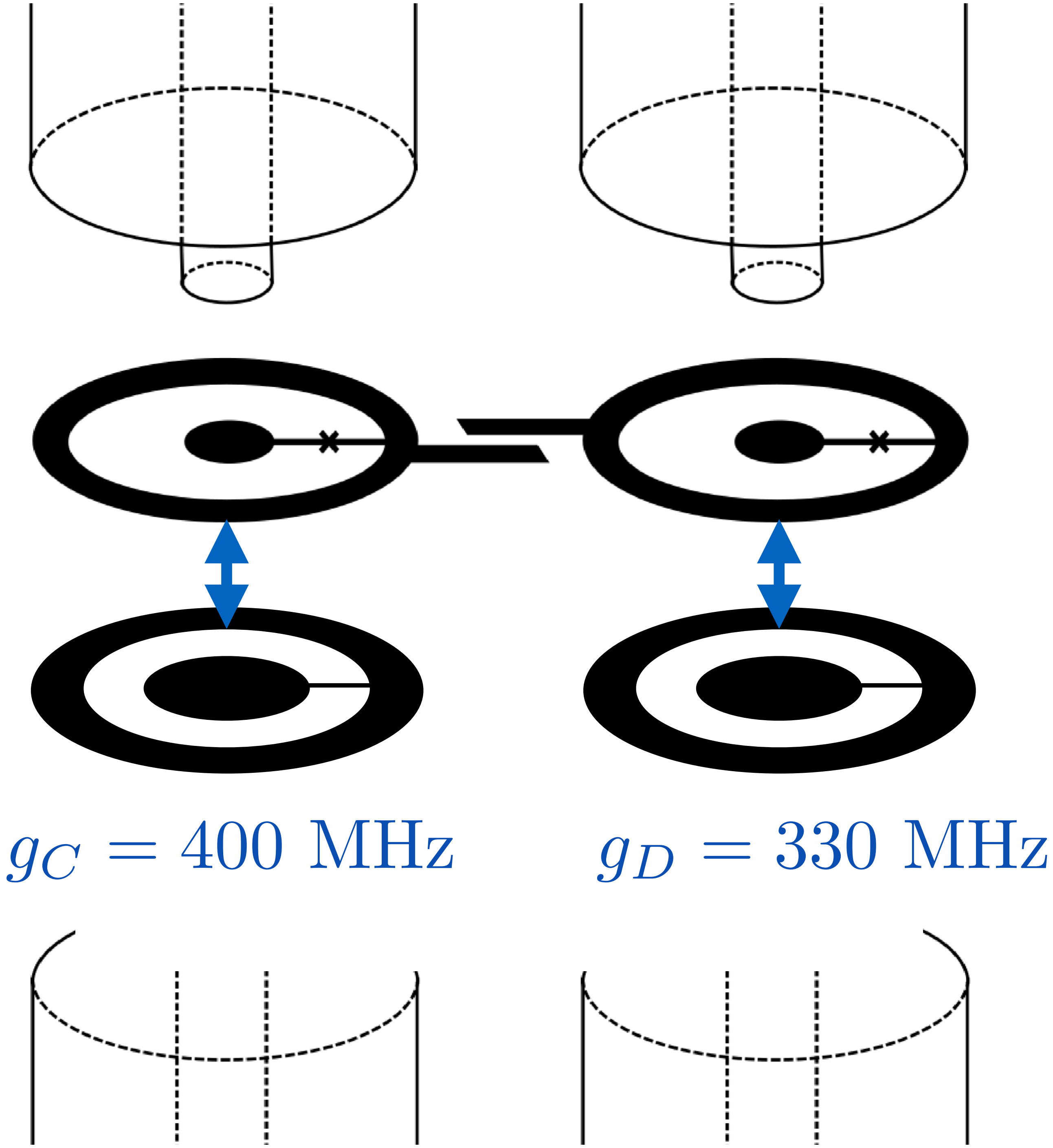
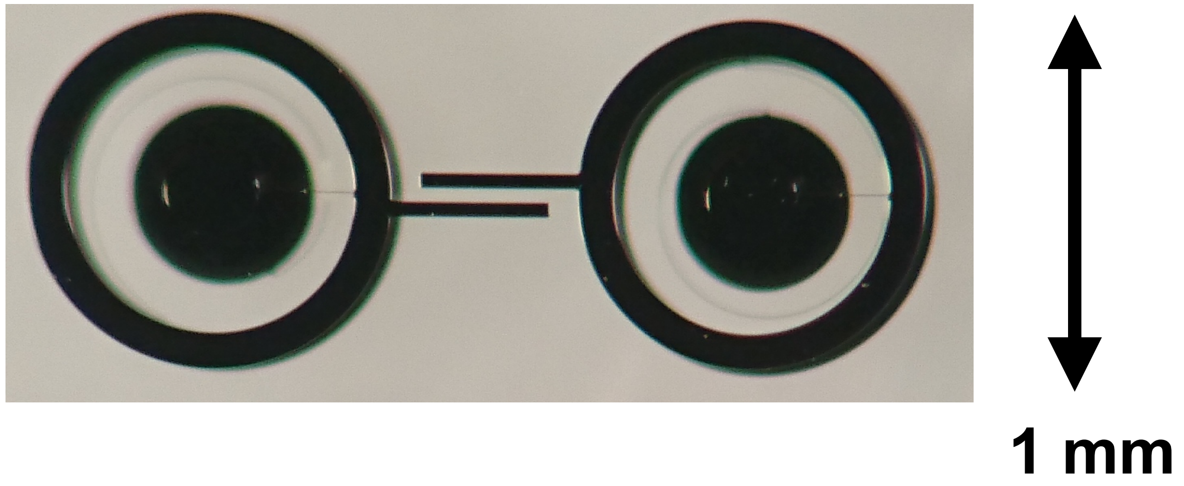


$g_C = 400$ MHz $g_D = 330$ MHz



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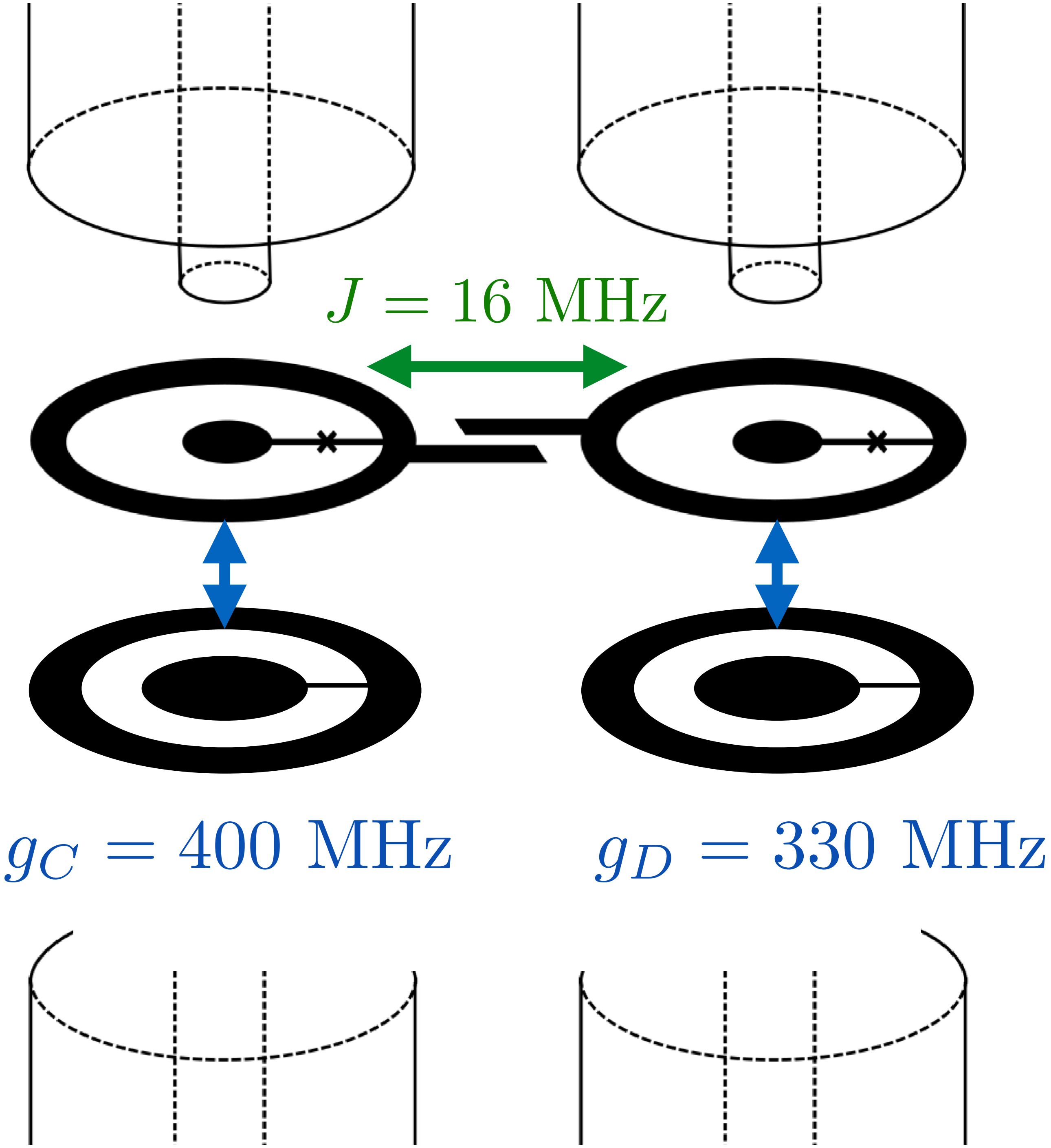
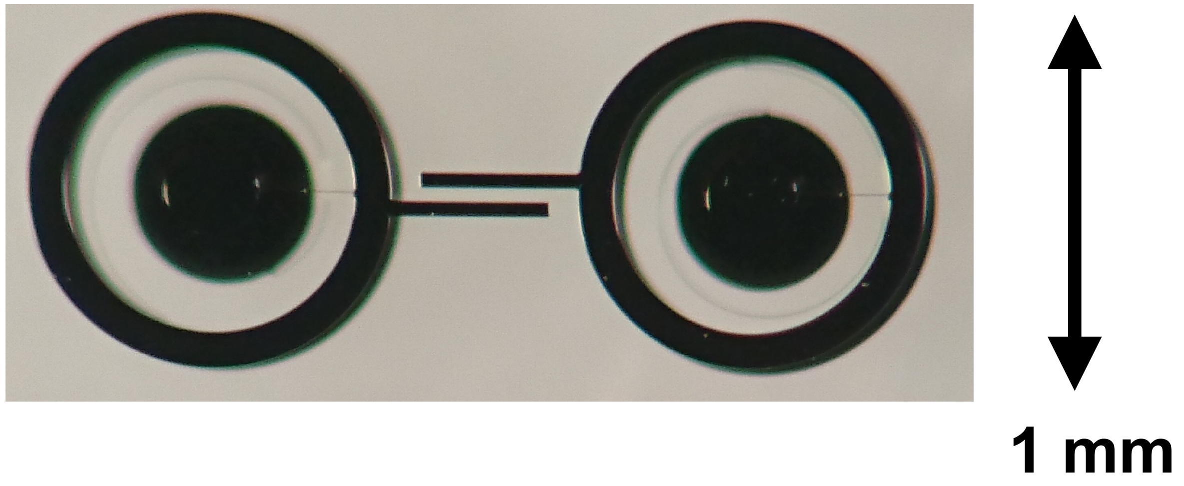
A typical two-qubit circuit



$J = 16\ \text{MHz}$

$g_C = 400\ \text{MHz}$

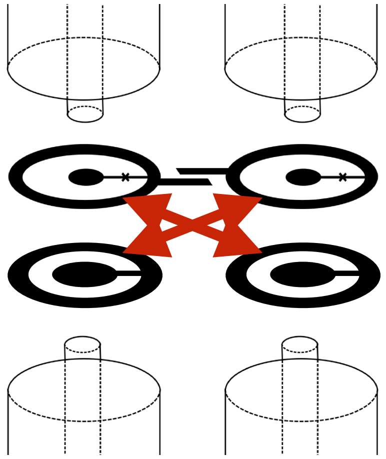
$g_D = 330\ \text{MHz}$



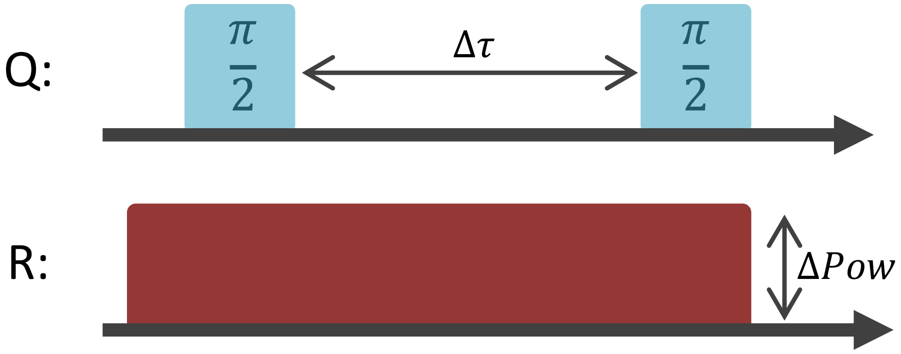
$$\begin{aligned} f_{C,D} &= 6.58, 6.07\ \text{GHz} \\ \alpha &= -0.29, 0.31\ \text{GHz} \\ f_R &= 10.5, 9.5\ \text{GHz} \\ T_1 &= 21.4, 26.2\ \mu\text{s} \\ T_2^* &= 7.1, 11.7\ \mu\text{s} \\ T_2^E &= 25.9, 29.4\ \mu\text{s} \end{aligned}$$

$$H = \tfrac{\omega_A}{2} ZI + \tfrac{\omega_B}{2} IZ + JXX$$

Characterising undesired couplings

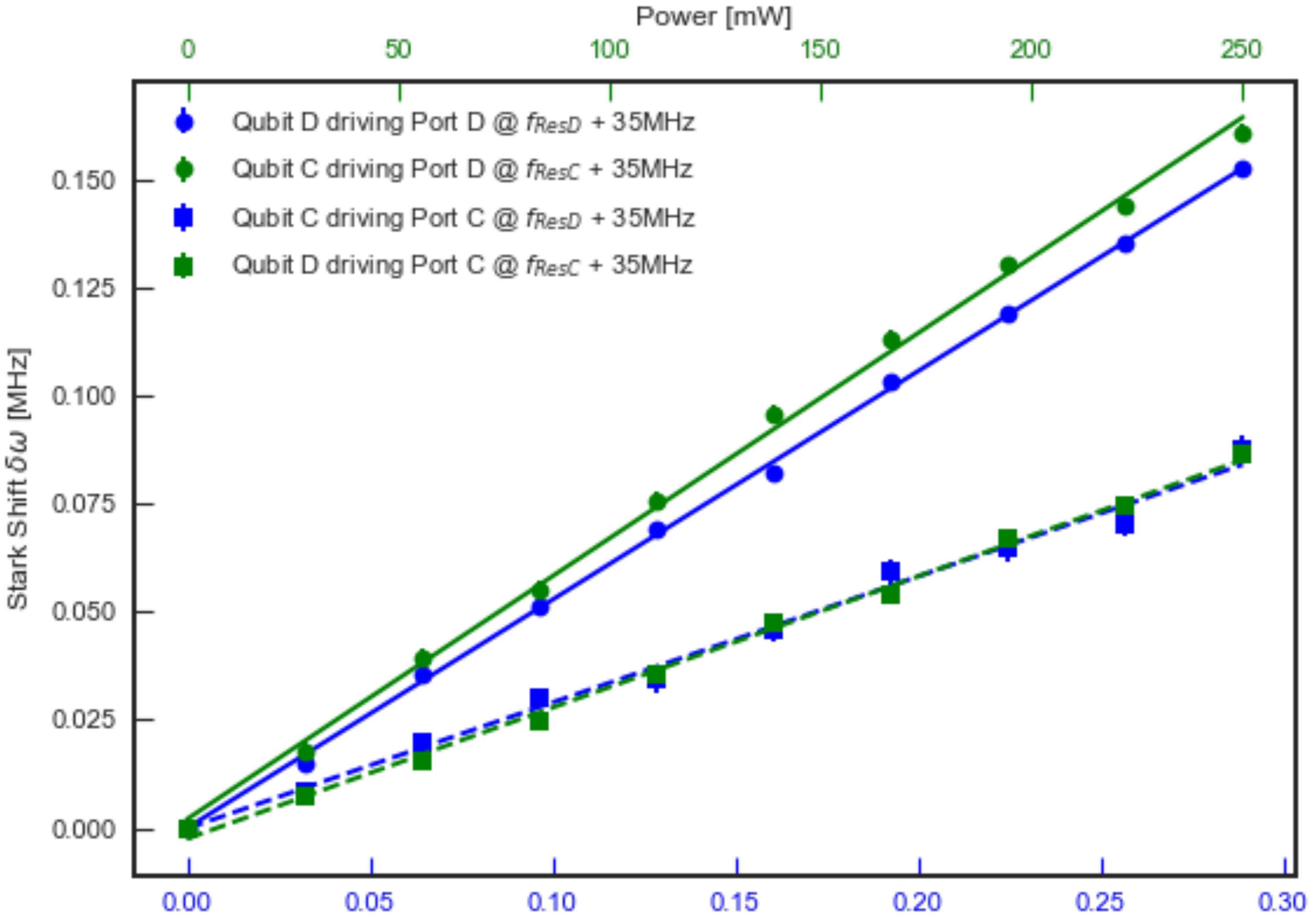


- Do qubits couple to the resonator of the next unit cell?
- Resonator frequency shift is too small to measure easily (good!)
- Instead observe qubit shift due to calibrated resonator drive



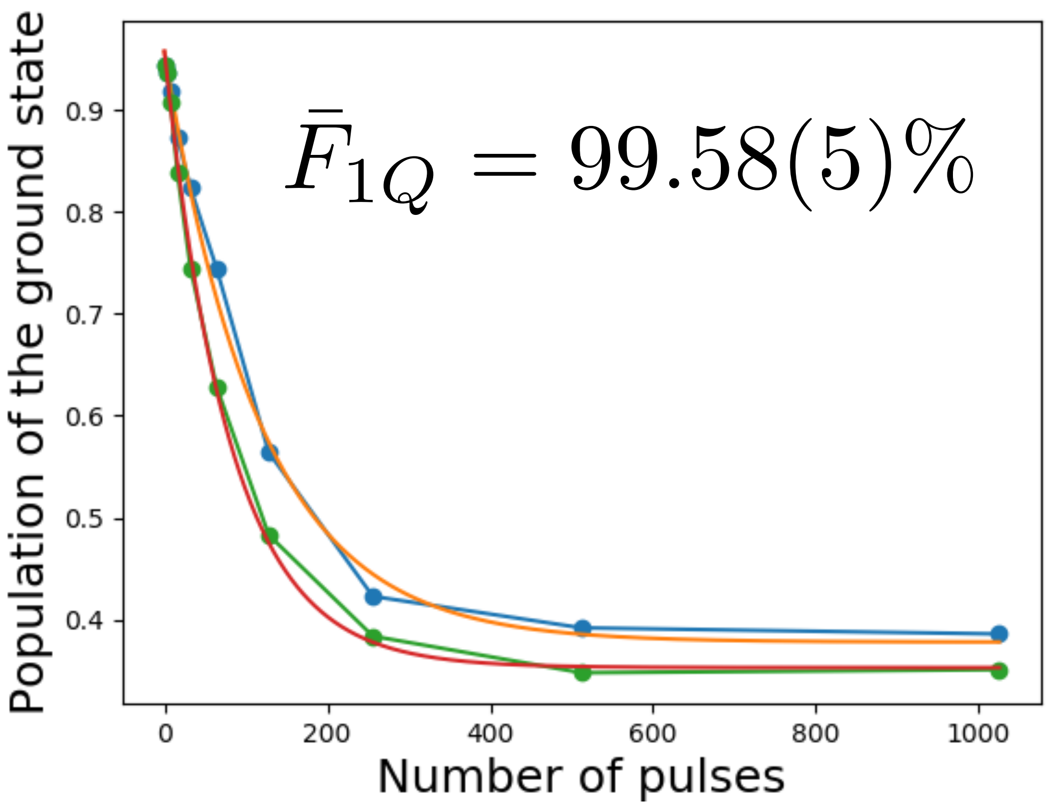
- Results:

$$g_{CC} = 400\ \mathrm{MHz}$$
$$g_{DD} = 330\ \mathrm{MHz}$$
$$g_{CD} = 12\ \mathrm{MHz}$$
$$g_{DC} = 15\ \mathrm{MHz}$$

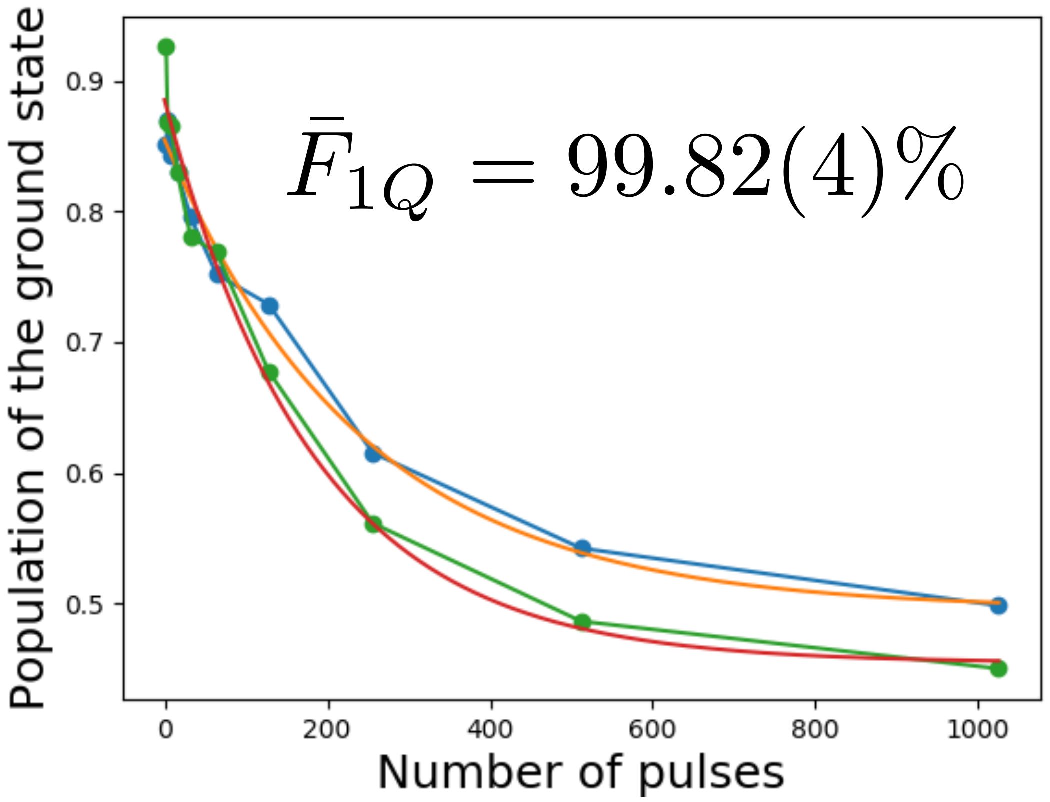


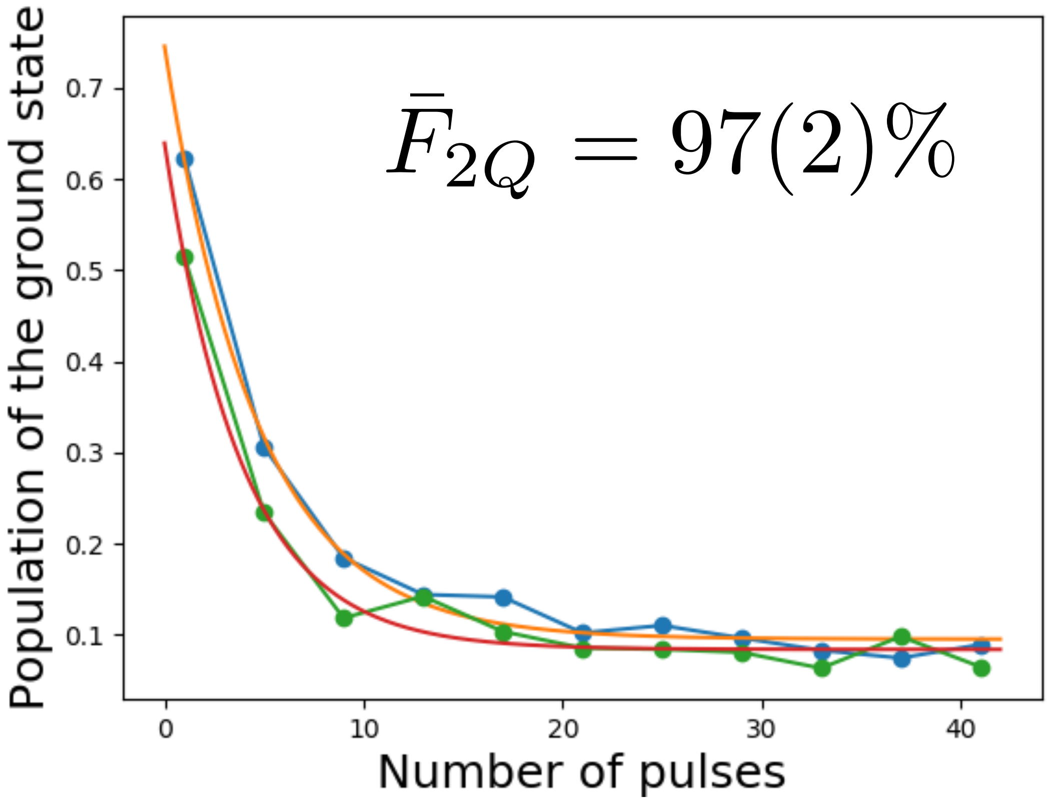
- Implies cross-measurement-induced dephasing time of 10 ms

Gate fidelities

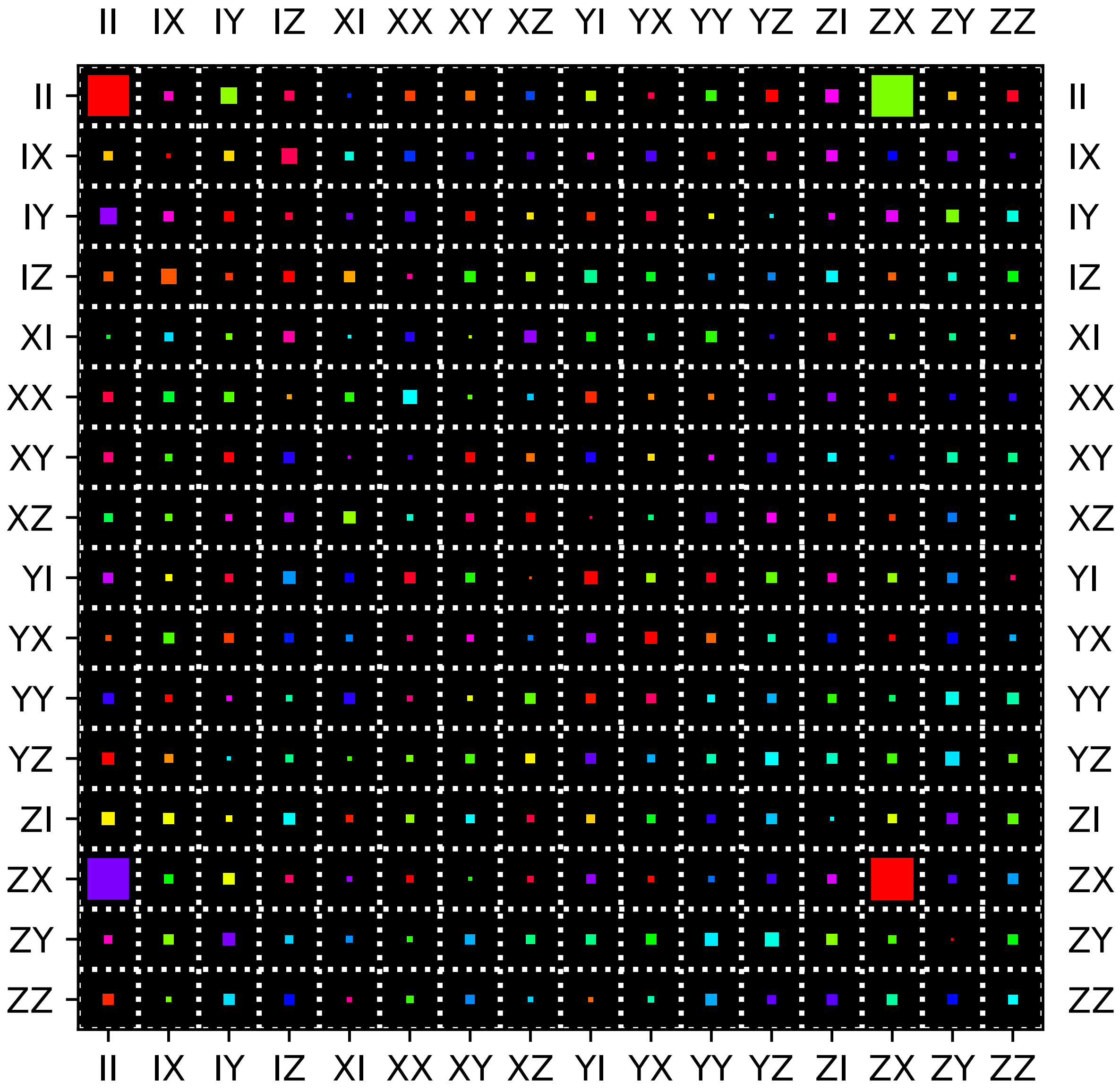


- Single qubit gates using DRAG pulse shapes to minimise driving out of qubit subspace (Motzoi PRL 2009)
- Two-qubit cross-resonance gate utilising echo scheme to reduce residual errors (Sheldon PRA 2016)
- Measured using randomised benchmarking to factor out initialisation and measurement errors

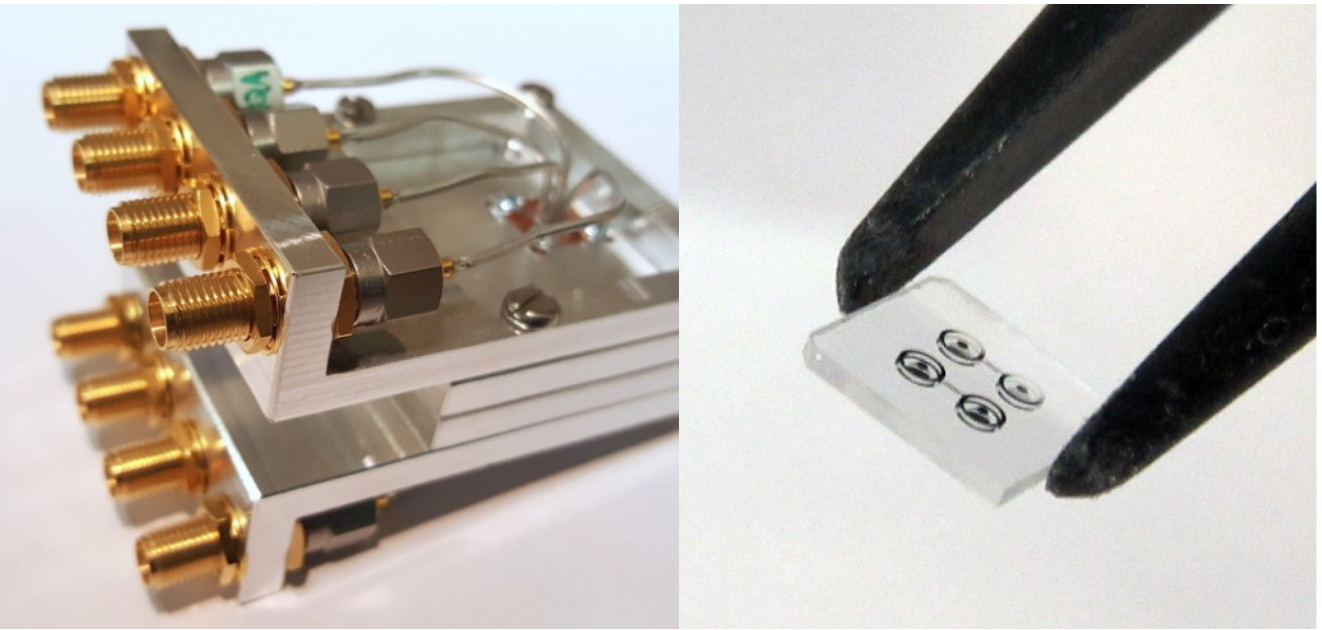




First results on 4-qubit prototypes

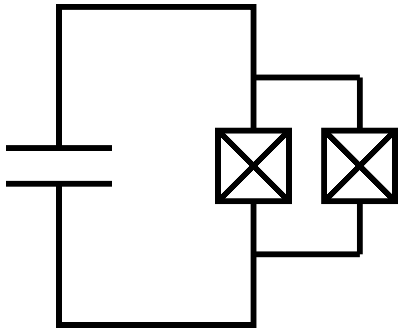


- Process tomography of 2Q gate on 4Q device
- Reduced ZZ error due to refinement of parameters

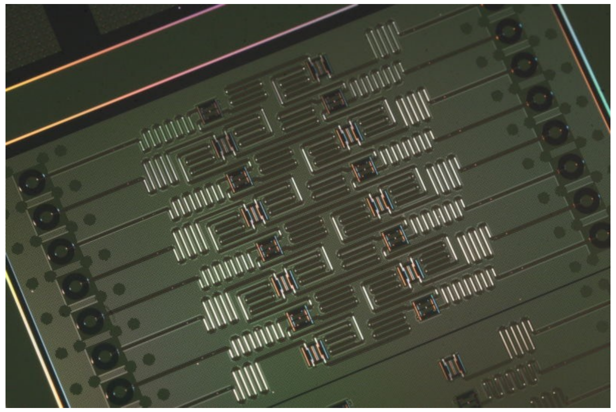


- Static frequency qubits - requires tight control of junction fabrication (<10% std. dev. on E_J)
- Qubits at 5.31, 4.76, 4.21, 3.79 GHz
- Single qubit gate errors at 0.2, 0.3, 0.5, 1.5%
- One two-qubit gate working at 5% error (left) but with significantly reduced ZZ error
- Charge dispersion limiting performance in this case (easy fix)
- 2nd generation devices now in fabrication

Summary

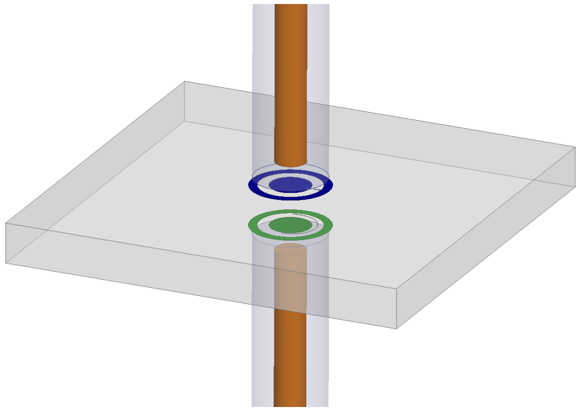


- Microwave electric circuits can be made quantum using superconductors, and millikelvin temperatures



IBM

- Small 'toy' superconducting quantum computers at 20-50 qubits are realised



- Coaxial quantum circuits under development at Oxford for scaling

Rahamim *et al.*, APL **110**, 222602 (2017)

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NQIT Networked Quantum Information Technologies

OQC
Oxford Quantum Circuits

Thanks!

EPSRC
Pioneering research and skills