# OUTLINE

Lecture I

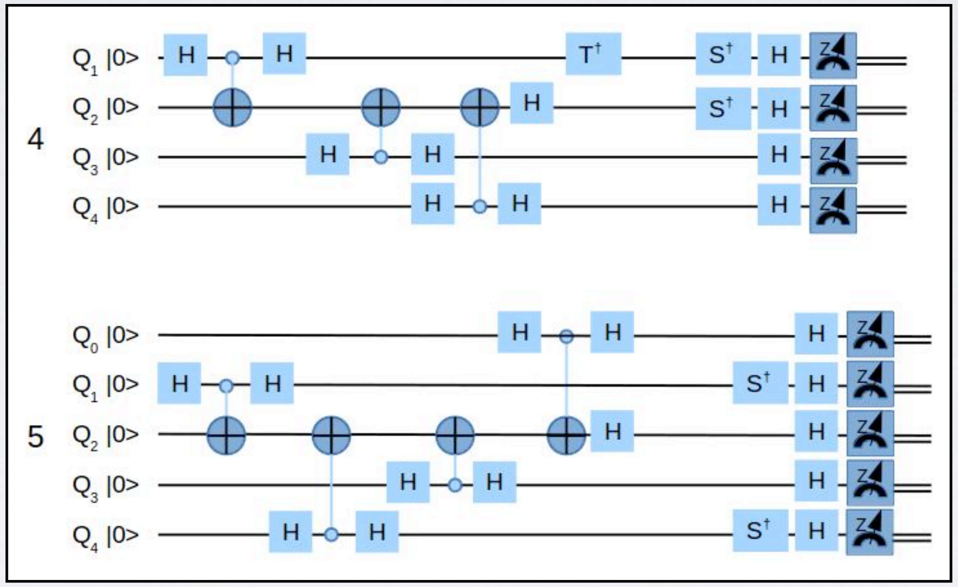
- Quantum computation
- Circuit quantization
- Superconducting qubit zoo
- Qubit state control

**Lecture II**

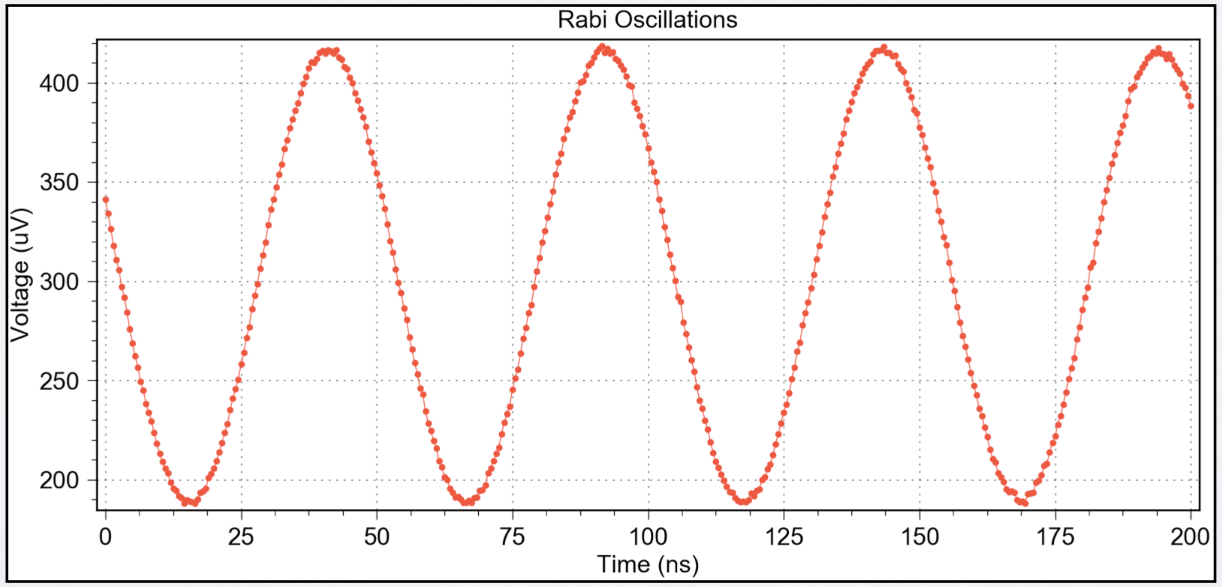
- **Resonators for quantum computation**
- Circuit quantum electrodynamics
- Qubit-qubit couplings and 2-qubit gates
- State of the art in quantum computers

# RESONATORS FOR Q COMPUTATION

Qubits process quantum information

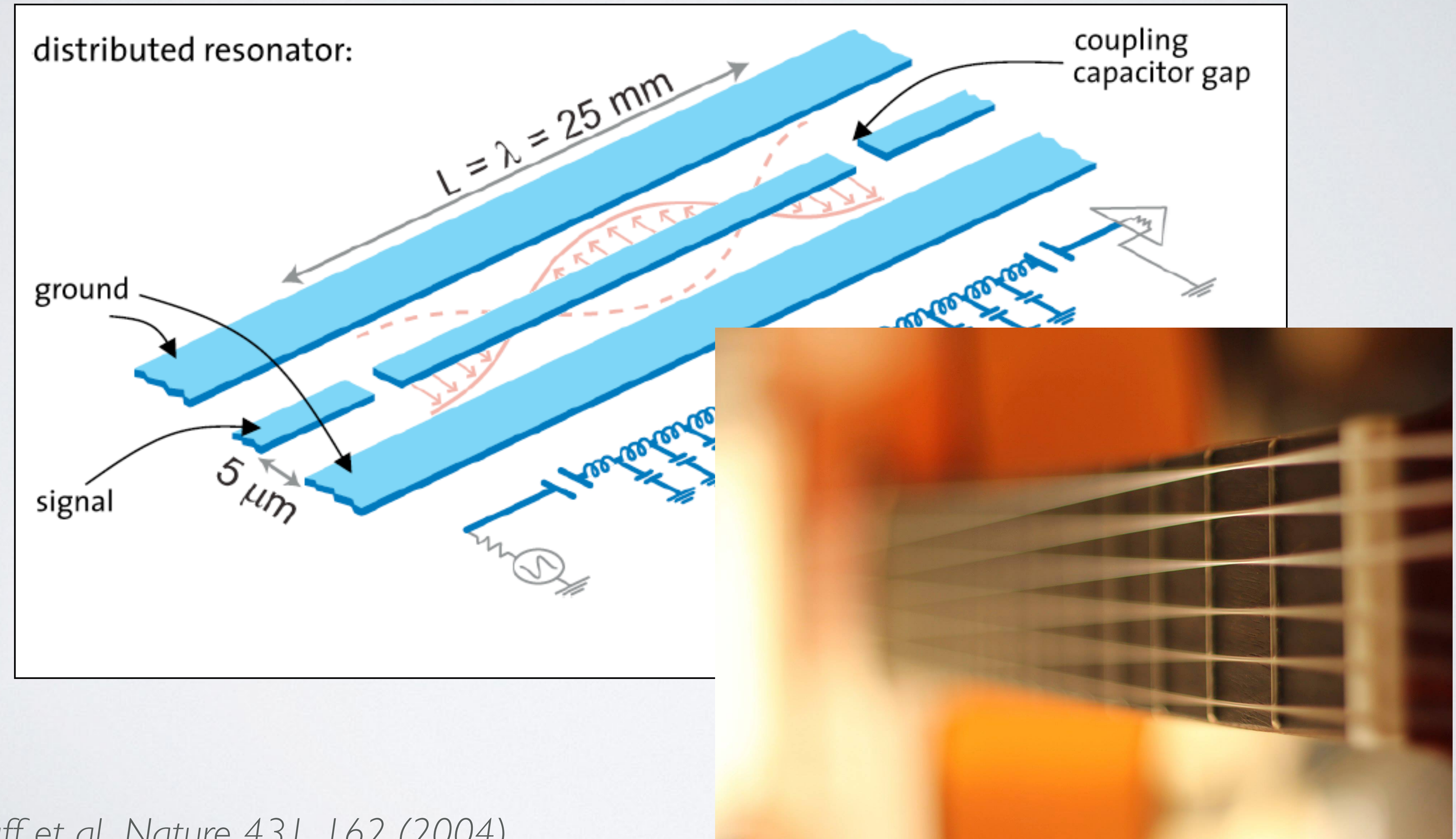



How do we "wire-up" qubits to process their signals?



# RESONATORS FOR Q COMPUTATION

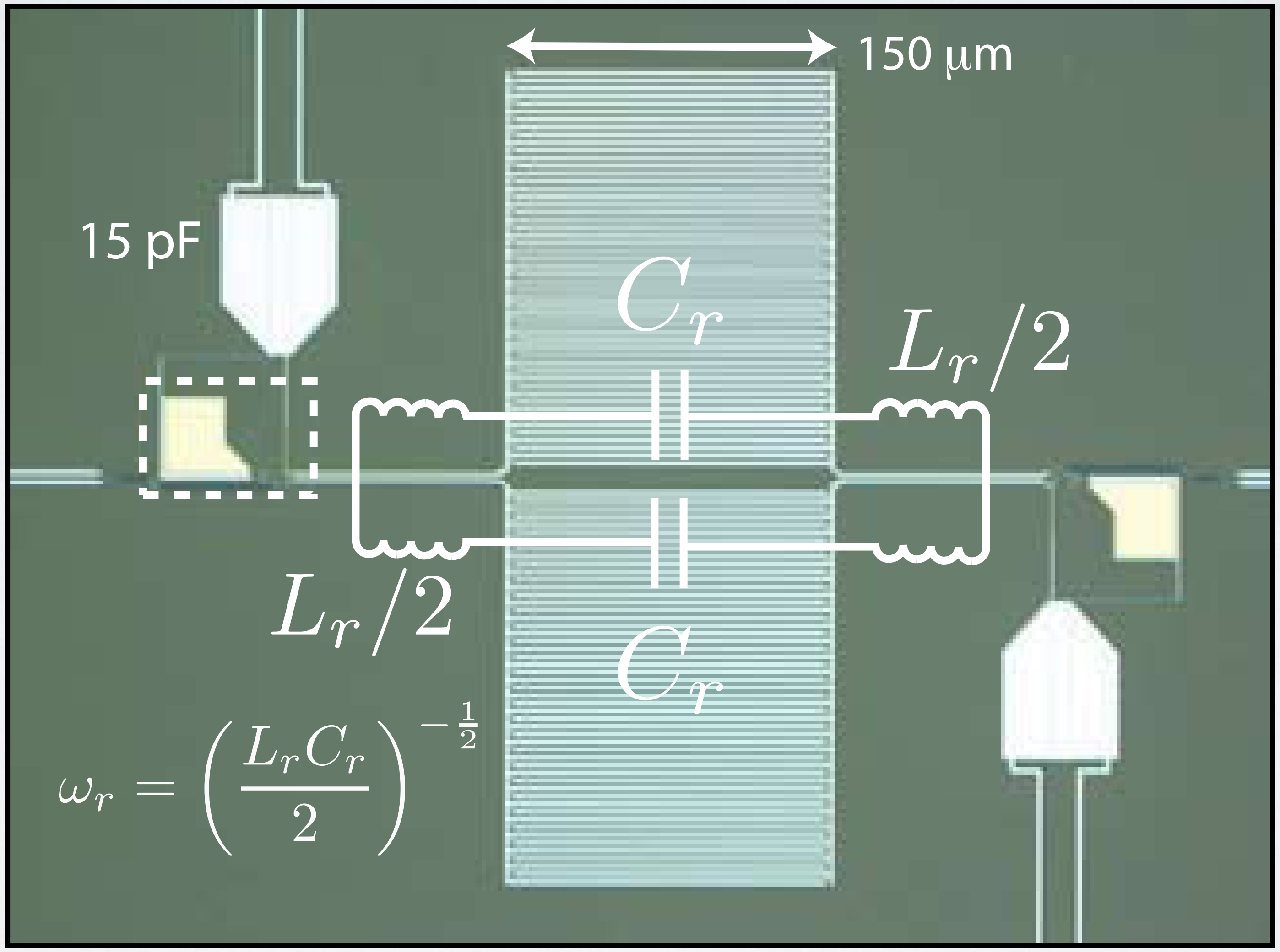
Coplanar waveguide resonator: photon "box"




*A. Wallraff et al., Nature 431, 162 (2004)*

# RESONATORS FOR Q COMPUTATION

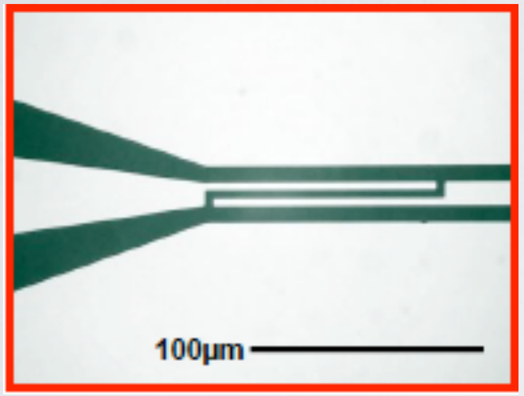
Lumped-element resonator: photon "box"



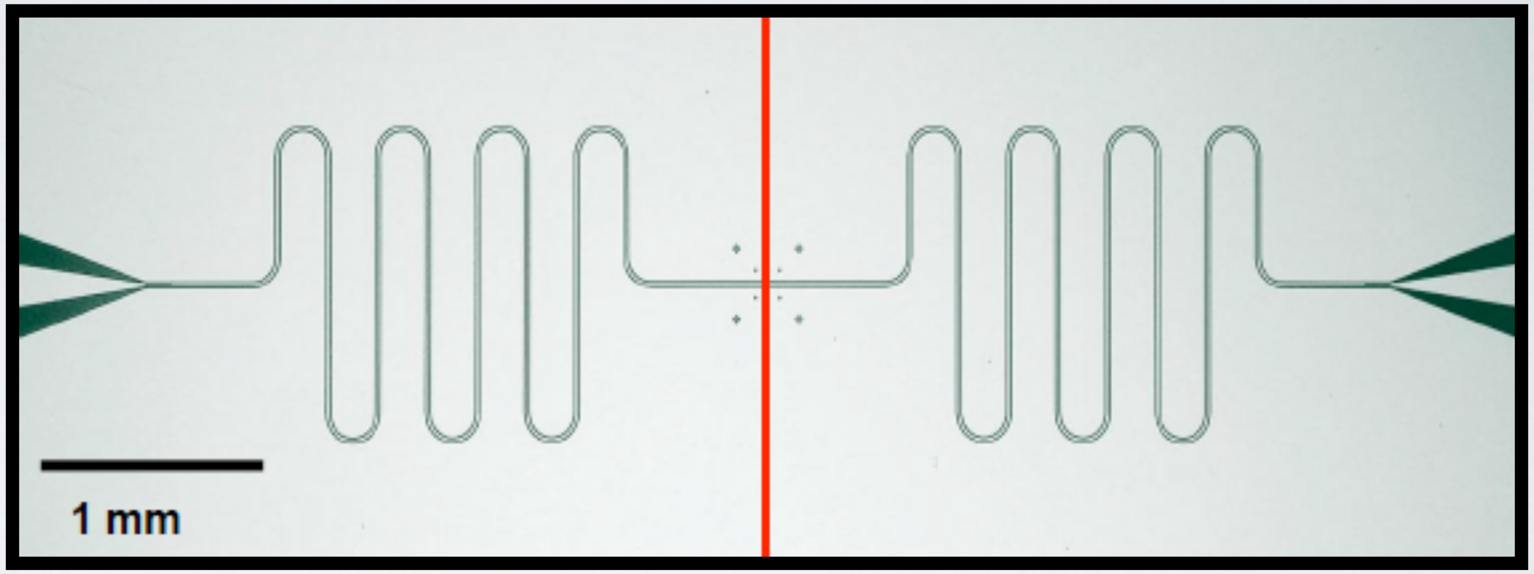

*P. Forn-Díaz et al., PRL 105, 237001 (2010)*

# RESONATORS FOR Q COMPUTATION

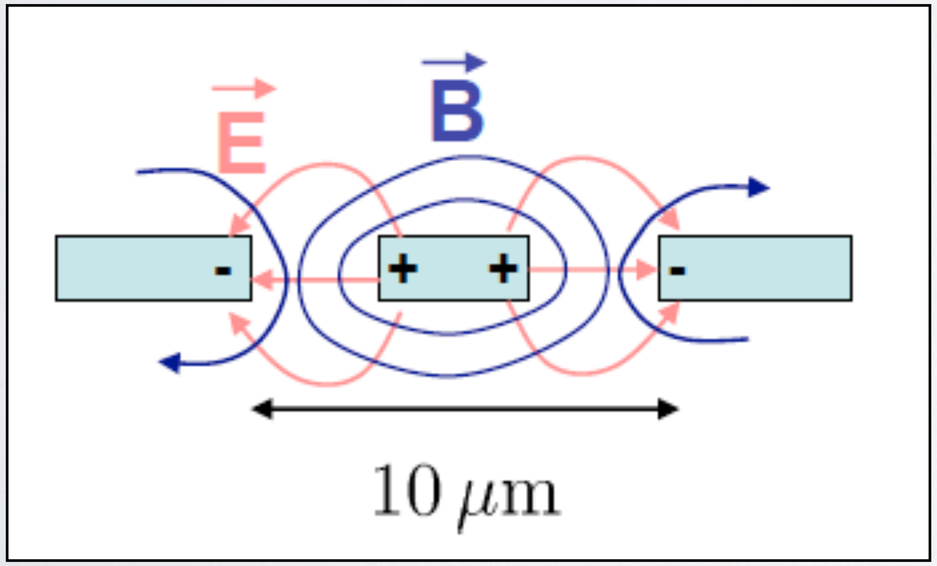
Input capacitor



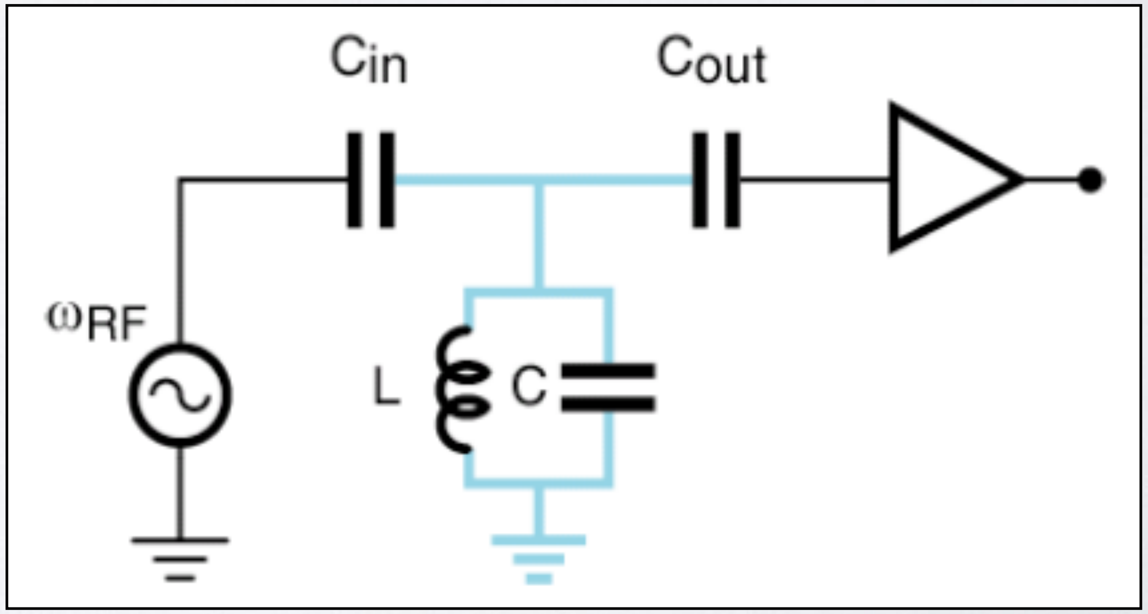

Coplanar waveguide resonator chip




Field distribution

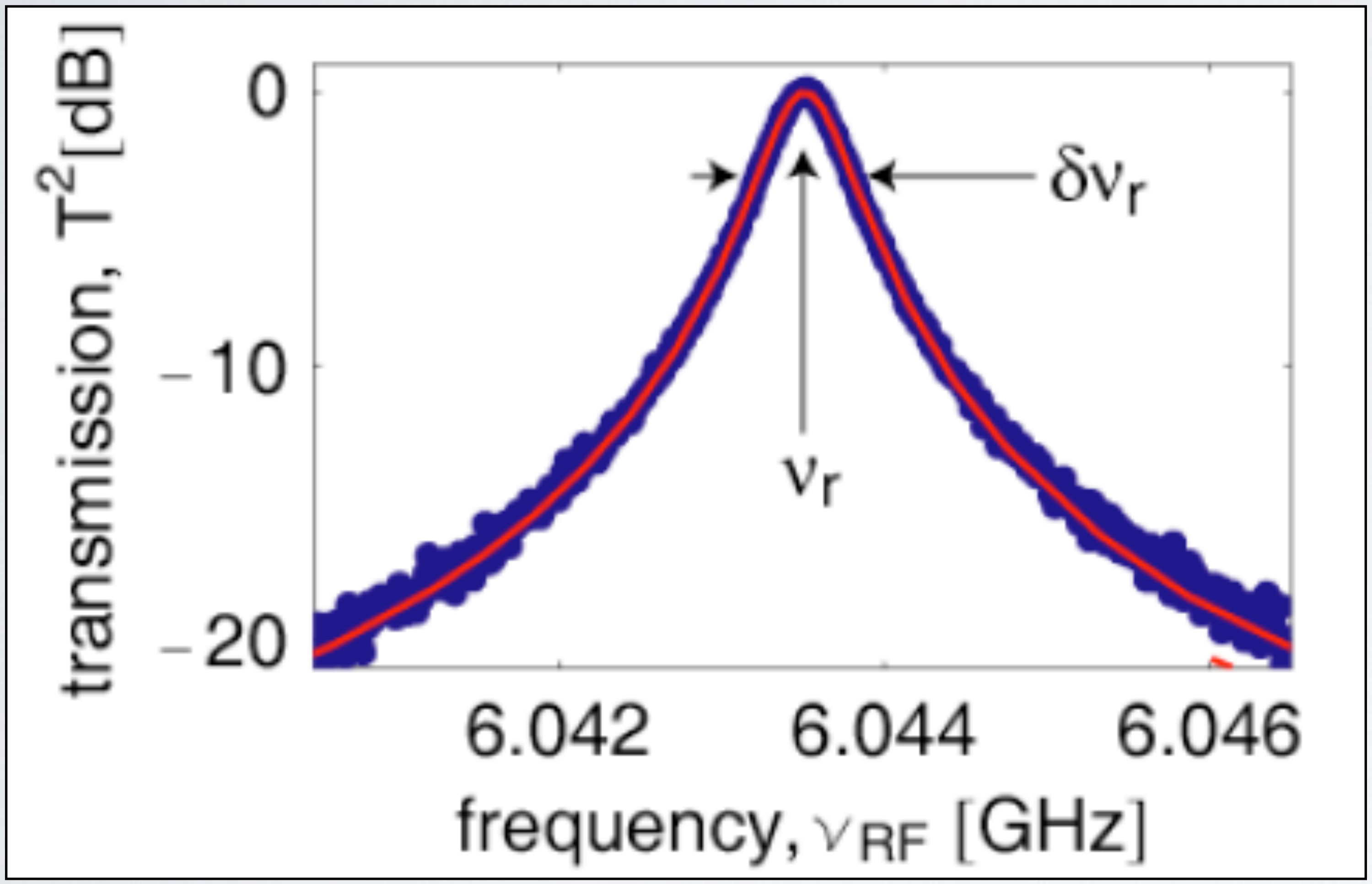



Electrical circuit schematic




*A. Wallraff et al., Nature 431, 162 (2004)*

# RESONATORS FOR Q COMPUTATION




resonance frequency:

$$\nu_r = 6.04\,\mathrm{GHz}$$

quality factor:

$$Q = \frac{\nu_r}{\delta\nu_r} \approx 10^4$$

photon decay rate:

$$\frac{\kappa}{2\pi} = \frac{\nu_r}{Q} \approx 0.8\,\mathrm{MHz}$$

photon lifetime:

$$T_\kappa = 1/\kappa \approx 200\,\mathrm{ns}$$

*A. Wallraff et al., Nature 431, 162 (2004)*

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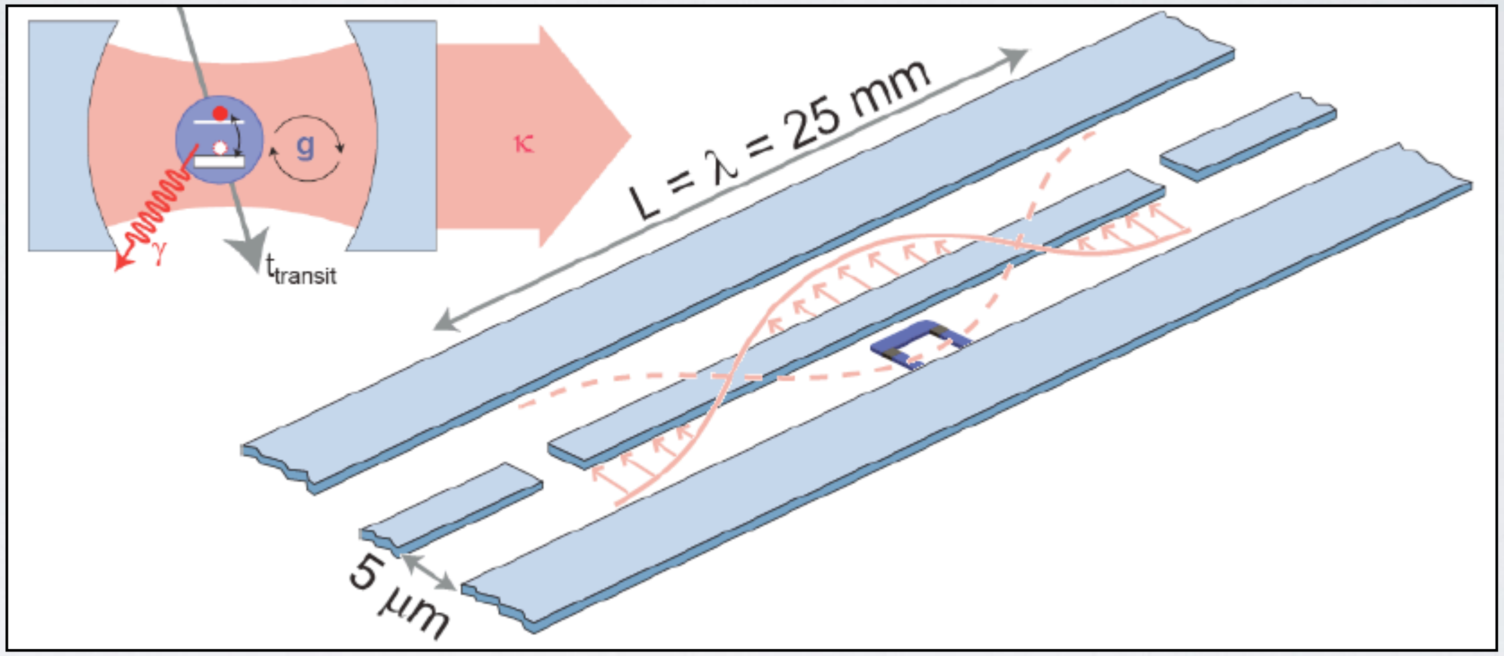
# CIRCUIT QED

Quantum optics on a chip




$E_{0,\mathrm{rms}} \approx 0.2\,\mathrm{V/m}$

for $\omega_r/2\pi \approx 6\,\mathrm{GHz}$

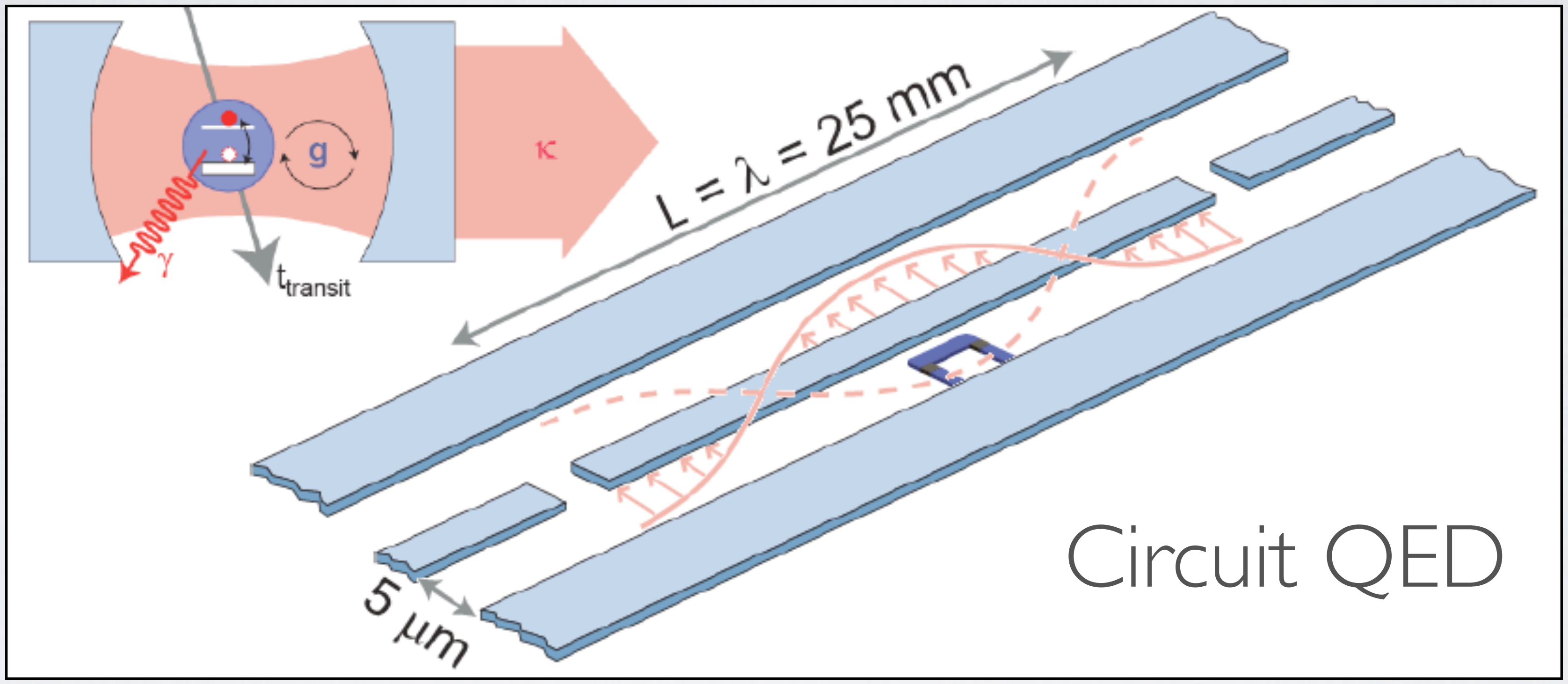
$\times 10^6$ larger than $E_0$ in 3D microwave cavity

| | Photon propagation | Frequency range (Hz) | Two-level systems | Photon storage | Cavity lifetime | Atom dipole | Coupling strength |
|---|---|---|---|---|---|---|---|
| Optics | Free space, fibers | $10^{14}$ | atoms | cavities | 10 ns | 1 a.u. | 200 MHz |
| Microwave | Transmission lines | $10^{9}$ | qubits | resonators | 100 ns | $10^4$ a.u. | 7 GHz |

*A. Wallraff et al., Nature 431, 162 (2004)*

*Atomic physics and quantum optics using superconducting circuits, JQ You, F. Nori, Nature 474, 589. arxiv:1202.1923*

# CIRCUIT QED




$E_{0,\mathrm{rms}} \approx 0.2\,\mathrm{V/m}$

for $\omega_r/2\pi \approx 6\,\mathrm{GHz}$

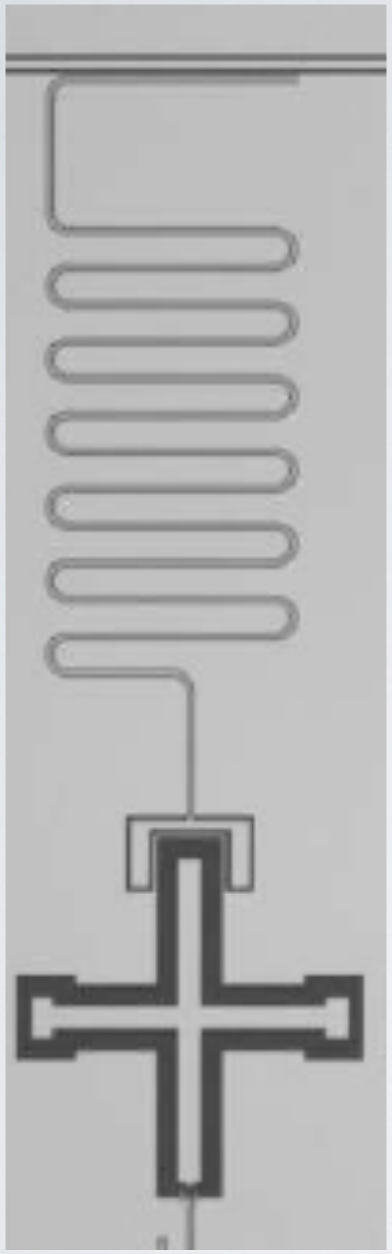
$\times 10^6$ larger than $E_0$ in 3D microwave cavity

Jaynes-Cummings model

$$\mathcal{H}_{\mathrm{JC}}/\hbar = \frac{\omega_q}{2}\sigma_z + \omega_r\left(a^\dagger a + \frac{1}{2}\right) + g(a^\dagger\sigma^- + a\sigma^+)$$

*Atomic physics and quantum optics using superconducting circuits, JQ You, F. Nori, Nature 474, 589. arxiv:1202.1923*

# CIRCUIT QED



Dispersive limit: $g \ll \Delta \equiv \omega_q - \omega_r$

$$\mathcal{H}_{\mathrm{JC}}/\hbar \approx \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{1}{2}\left(\omega_q + \frac{g^2}{\Delta}\right)\sigma_z$$

Stark shift Lamb shift

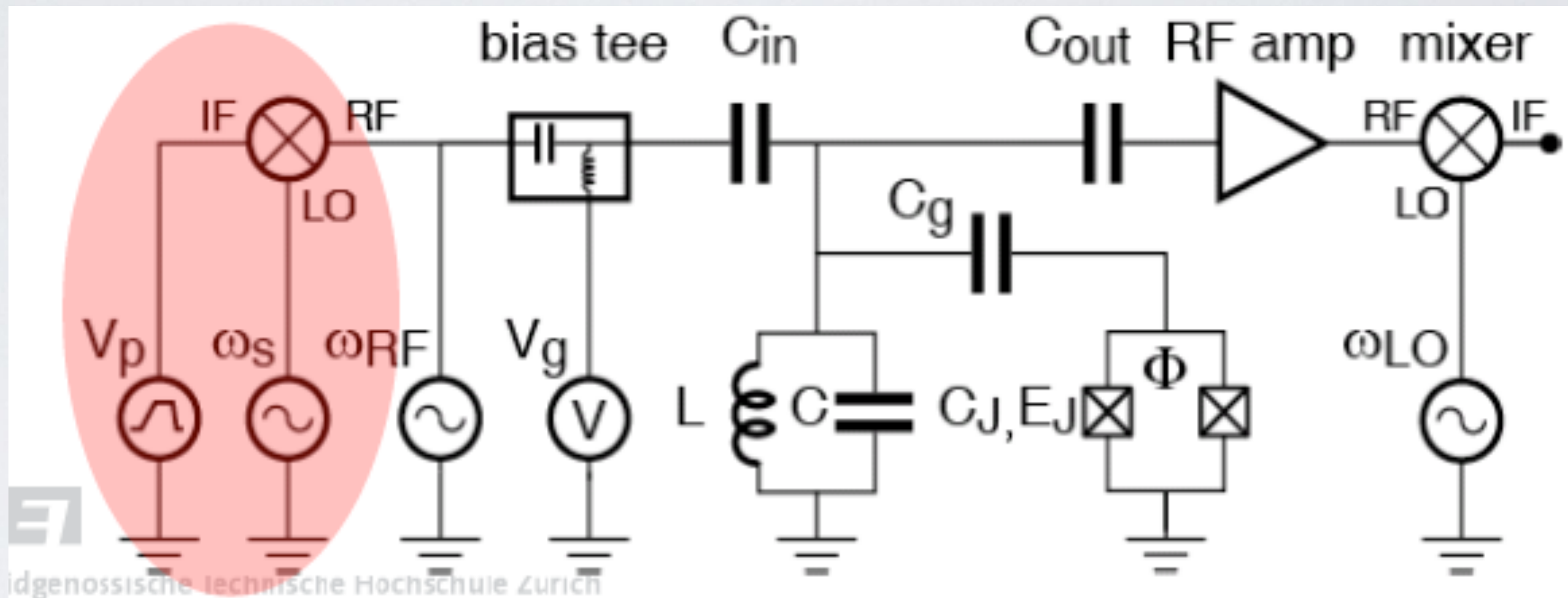
- Resonator frequency depends on qubit state
- Nondestructive readout, as operators commute
- As there is no energy exchange: dispersive readout

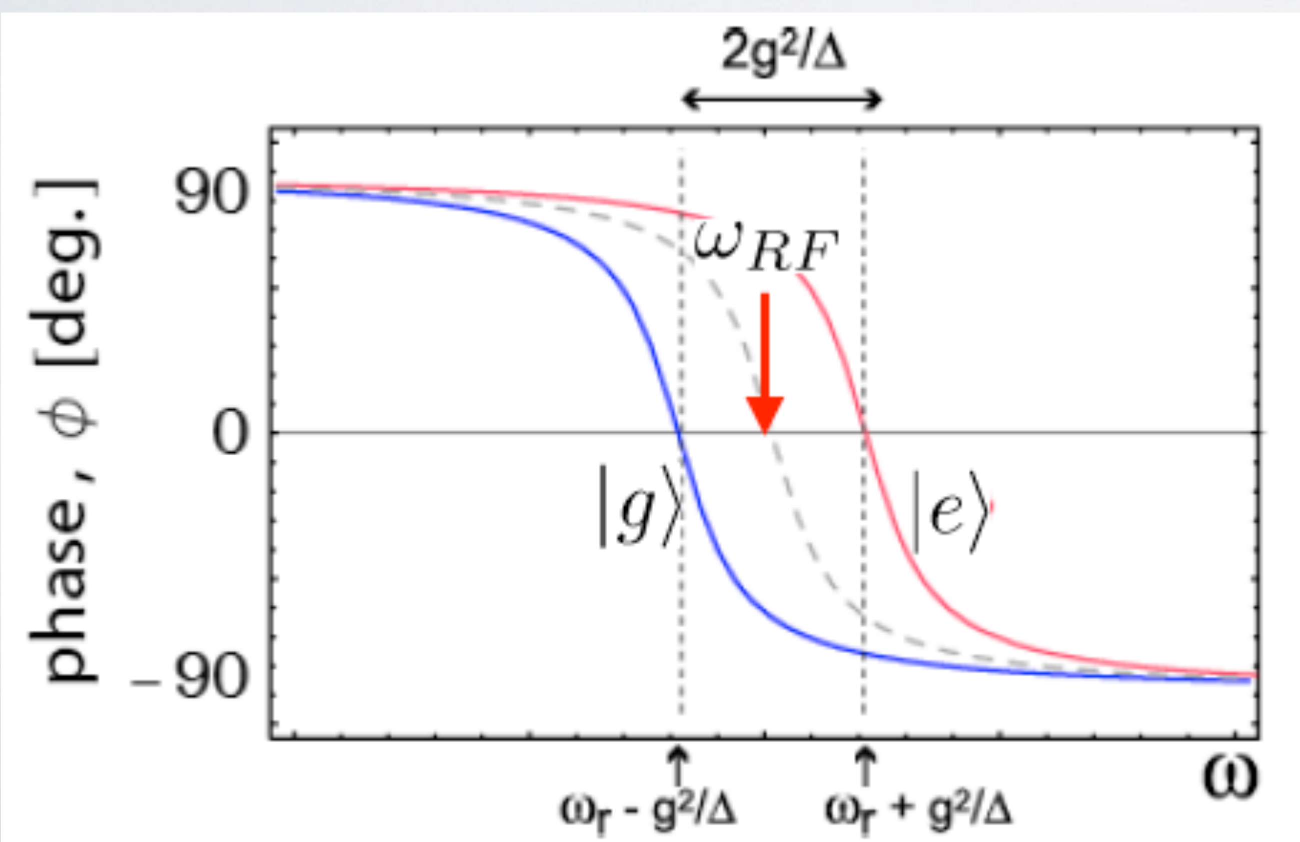
*A. Blais et al., PRA 69, 062320 (2004)*

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

# CIRCUIT QED

Dispersive readout:



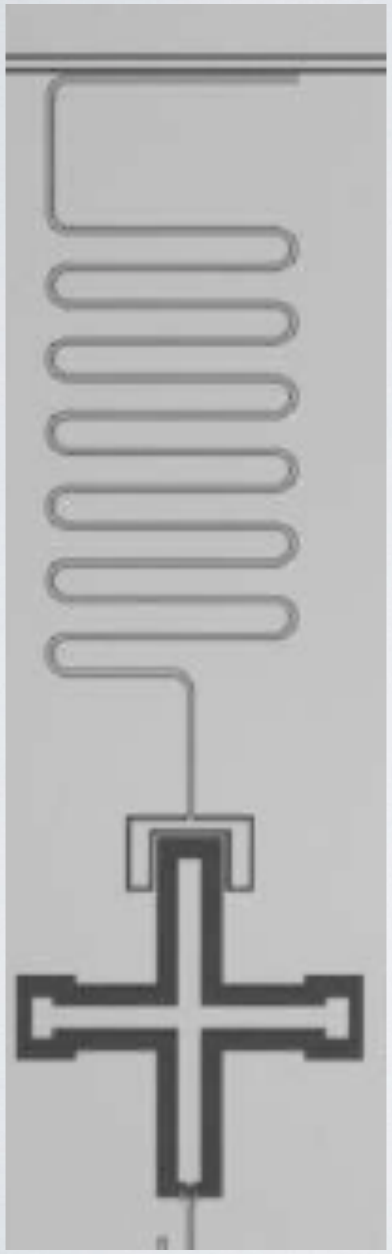



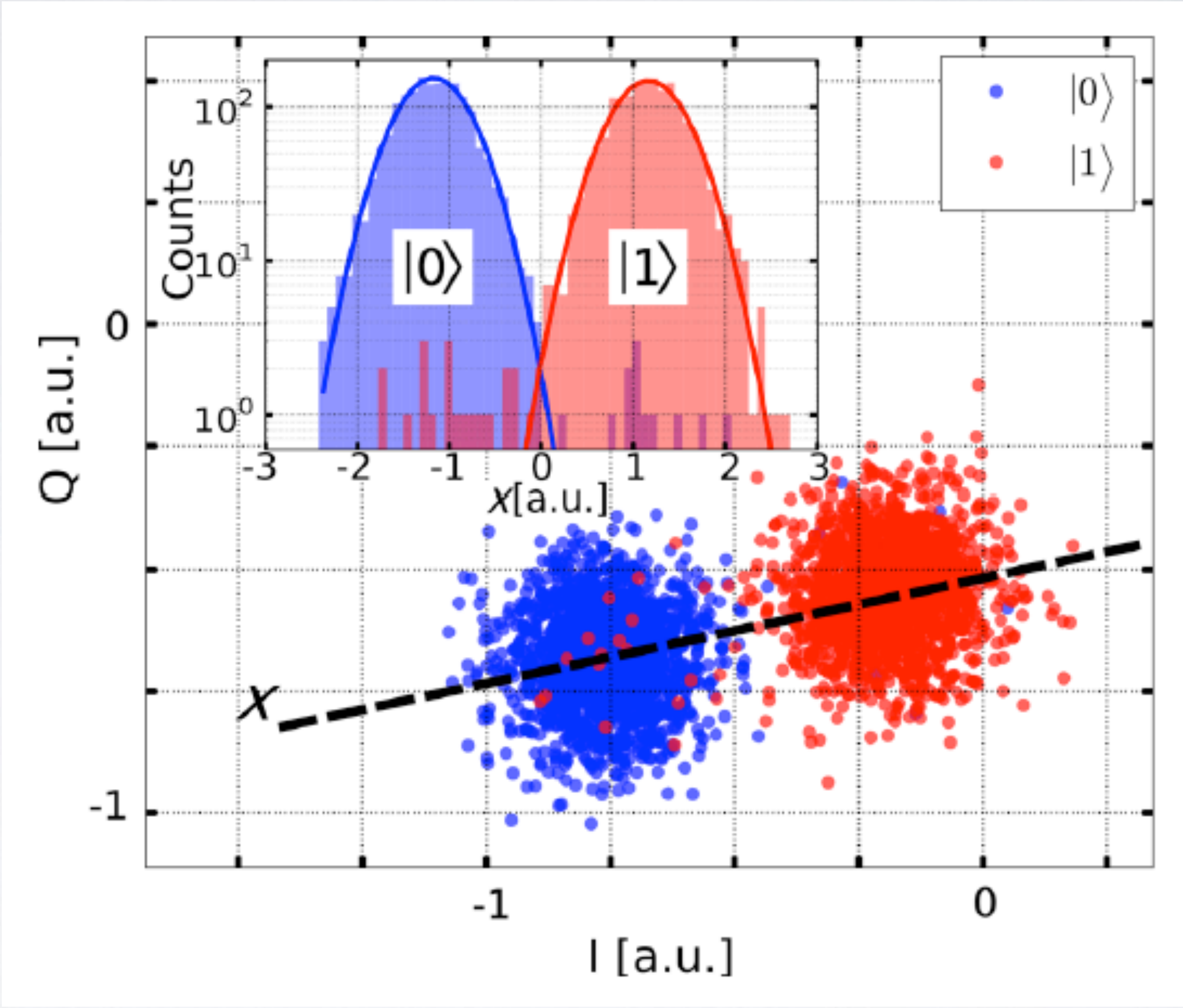

1. Probe tone rings up resonator
2. Qubit state determines resonant frequency
3. Probe tone experiences qubit-dependent phase shift
4. Readout electronics chain amplify pulse
5. At RT, signal is downconverted and digitized

*J. Fink et al., Nature 454, 315 (2008)*

# CIRCUIT QED

Dispersive readout:

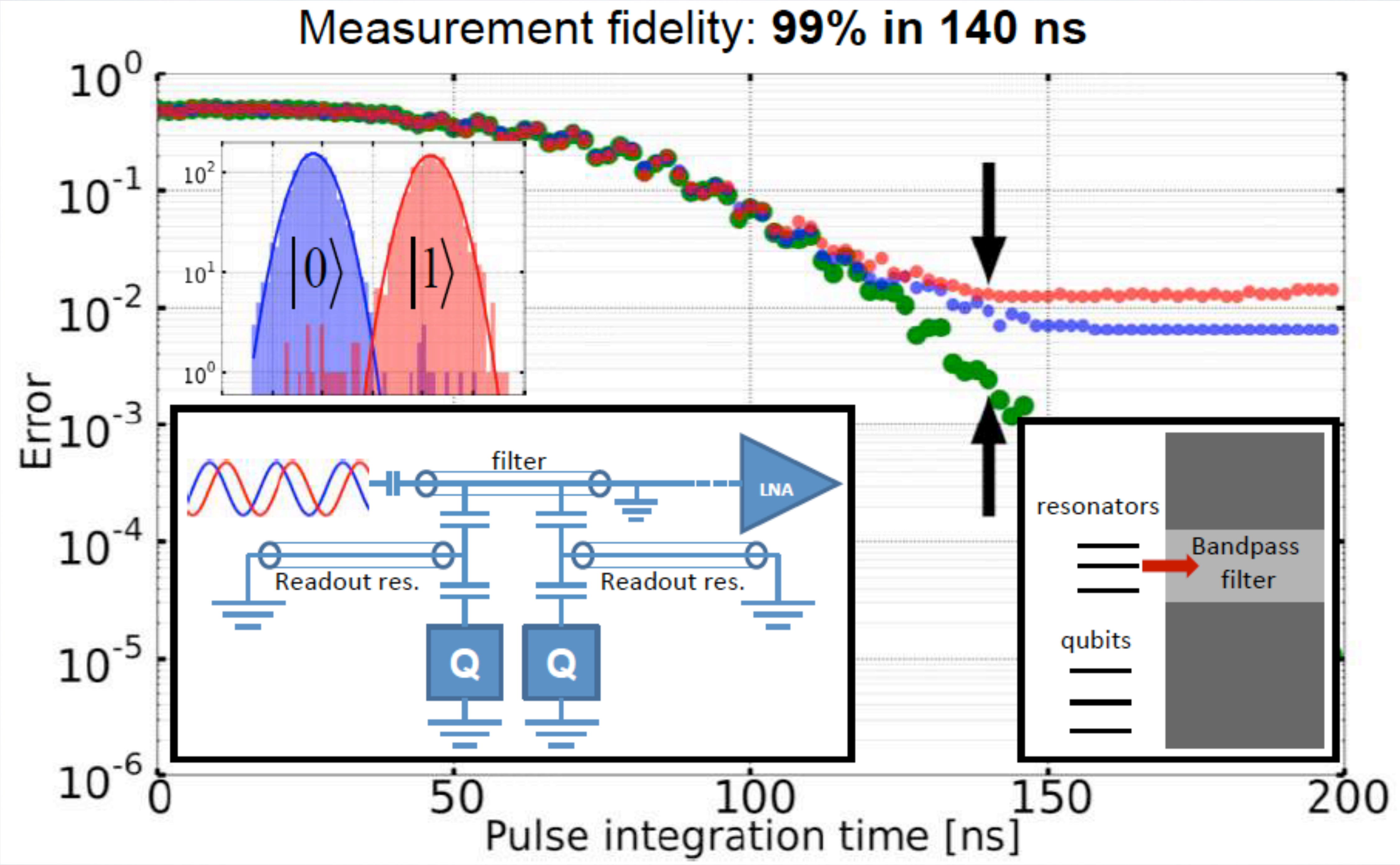





- Phase response produces count distribution on the IQ plane
- Readout contrast is determined by separation between distributions

*E. Jeffrey et al., PRL 112, 190504 (2014)*

# CIRCUIT QED



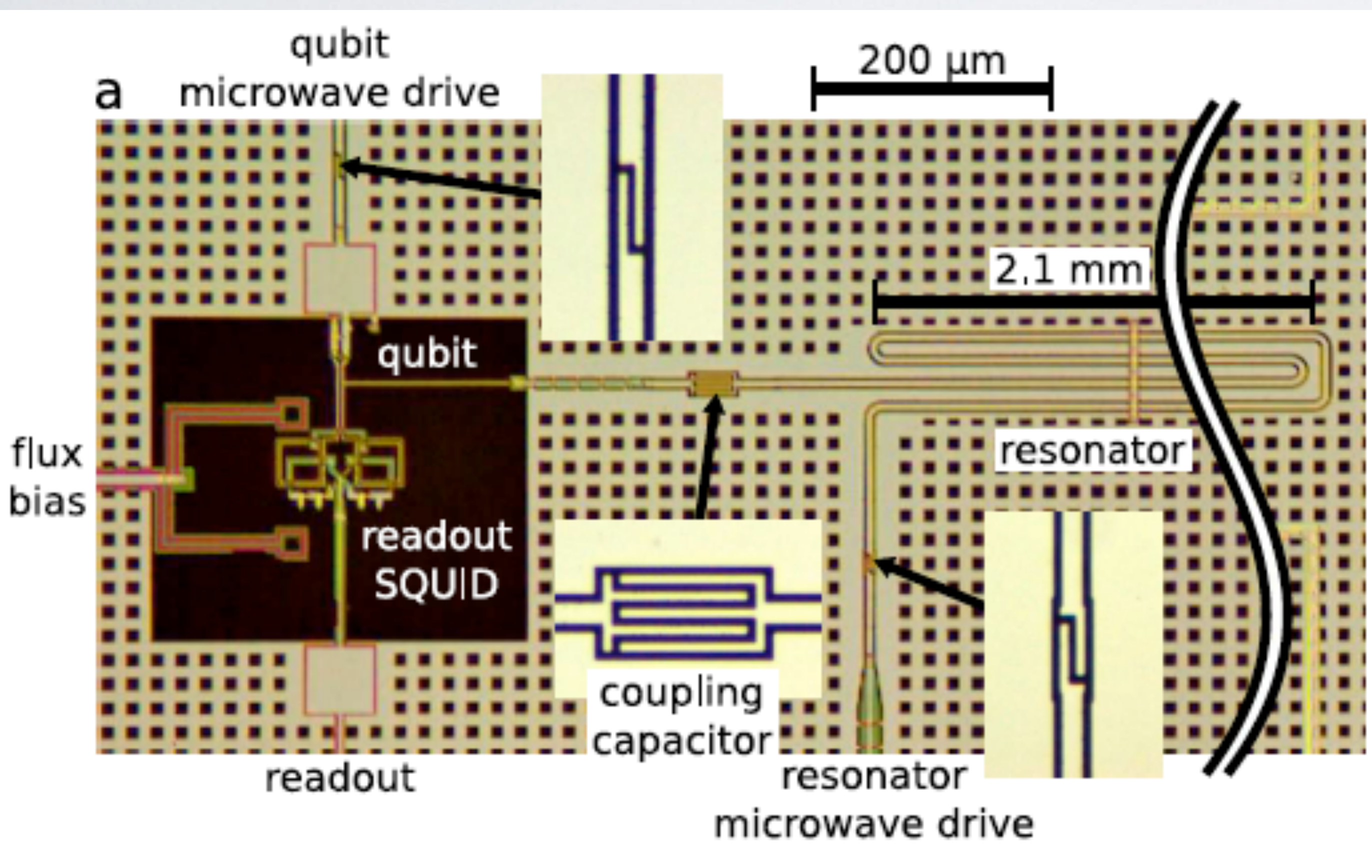

*E. Jeffrey et al., PRL 112, 190504 (2014)*

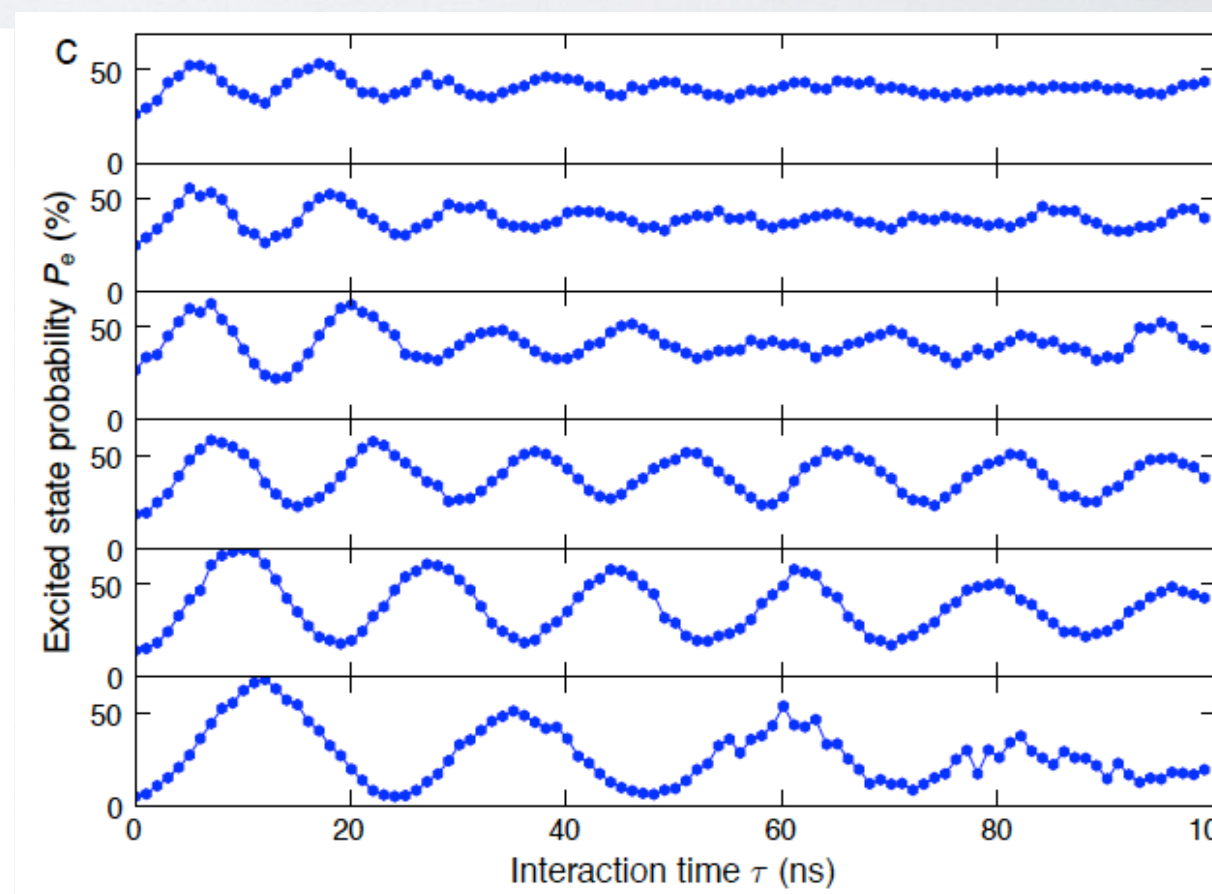
# CIRCUIT QED

Quantum optics on a chip

$$\mathcal{H}_{\mathrm{JC}}/\hbar = \frac{\omega_q}{2}\sigma_z + \omega_r\left(a^\dagger a + \frac{1}{2}\right) + g(a^\dagger\sigma^- + a\sigma^+)$$

swap interaction




*M. Hofheinz et al., Nature 454, 310-314 (2008)*

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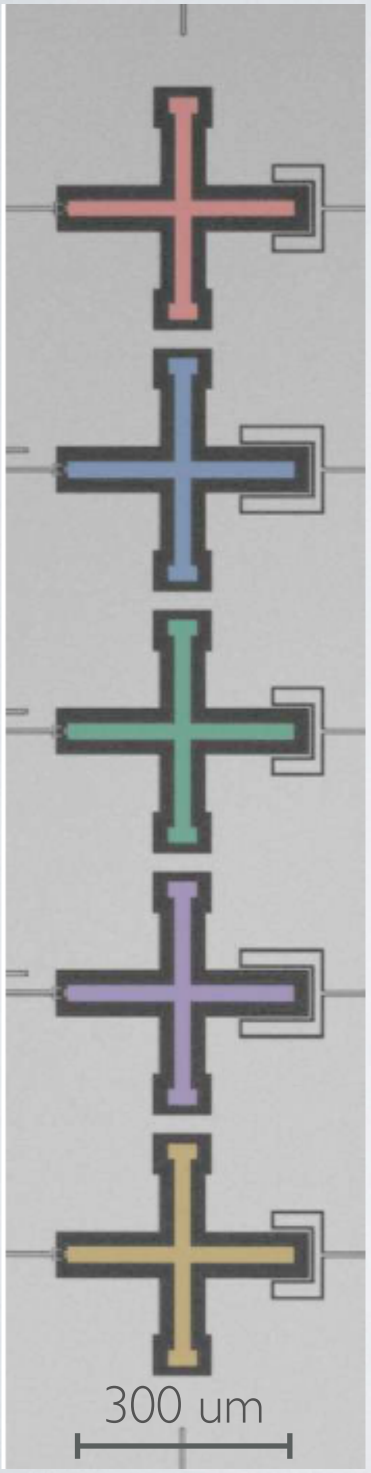
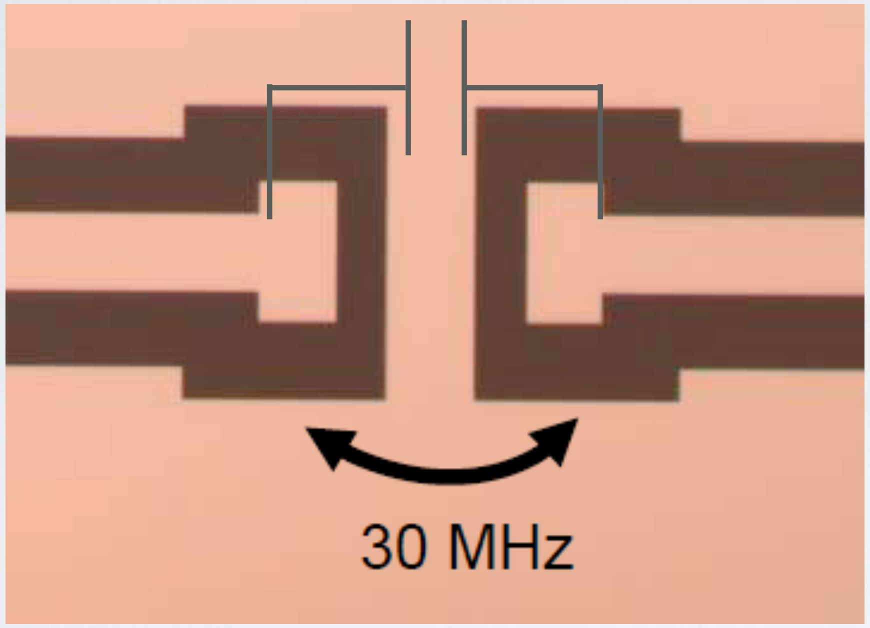
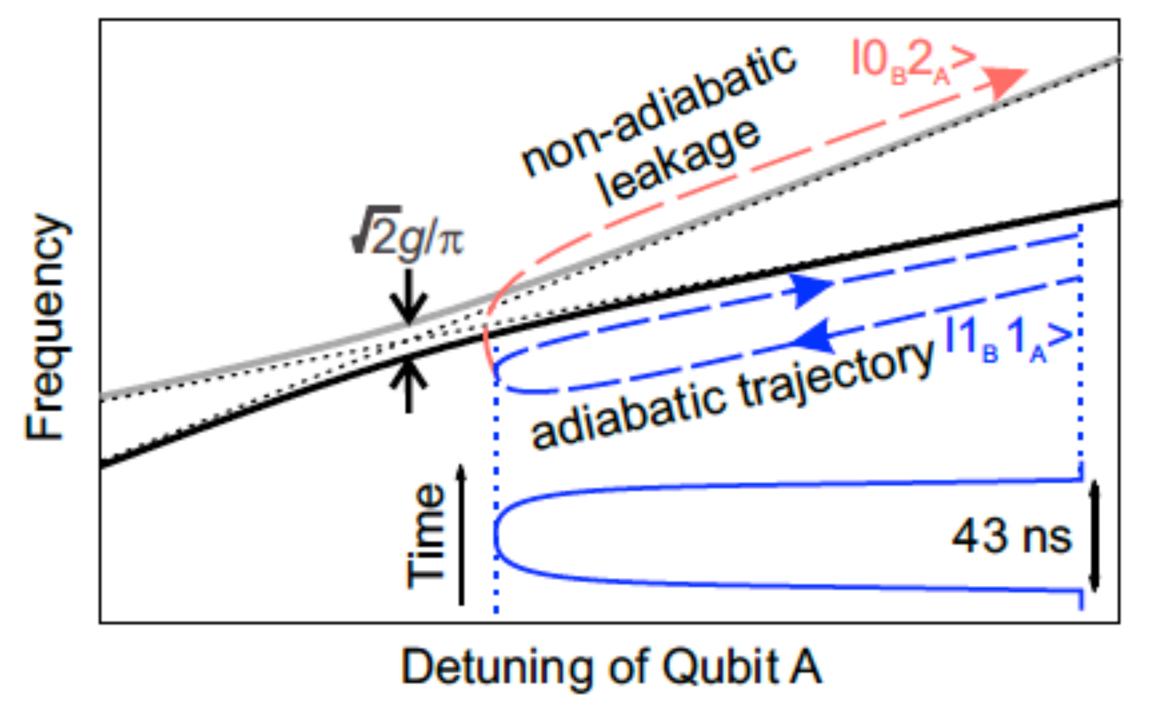
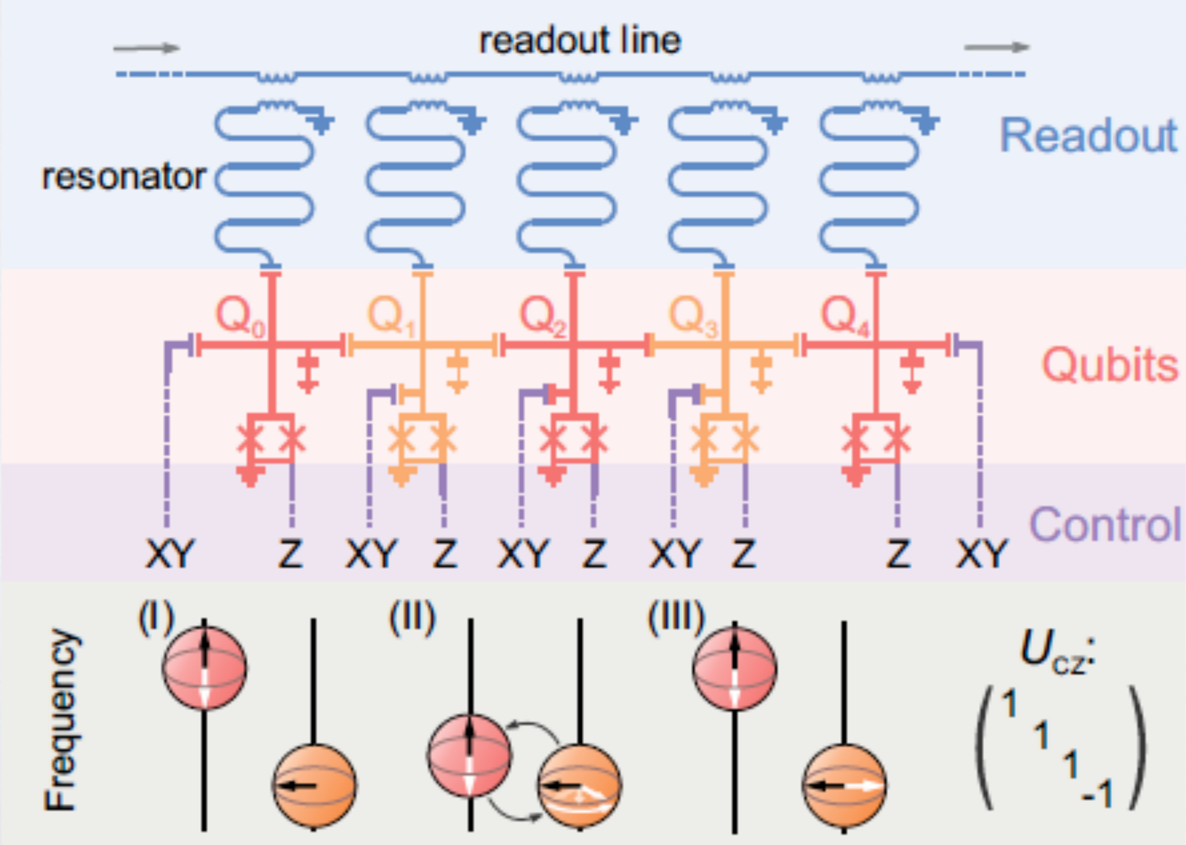
# 2-QUBIT GATES




Geometric capacitive coupling



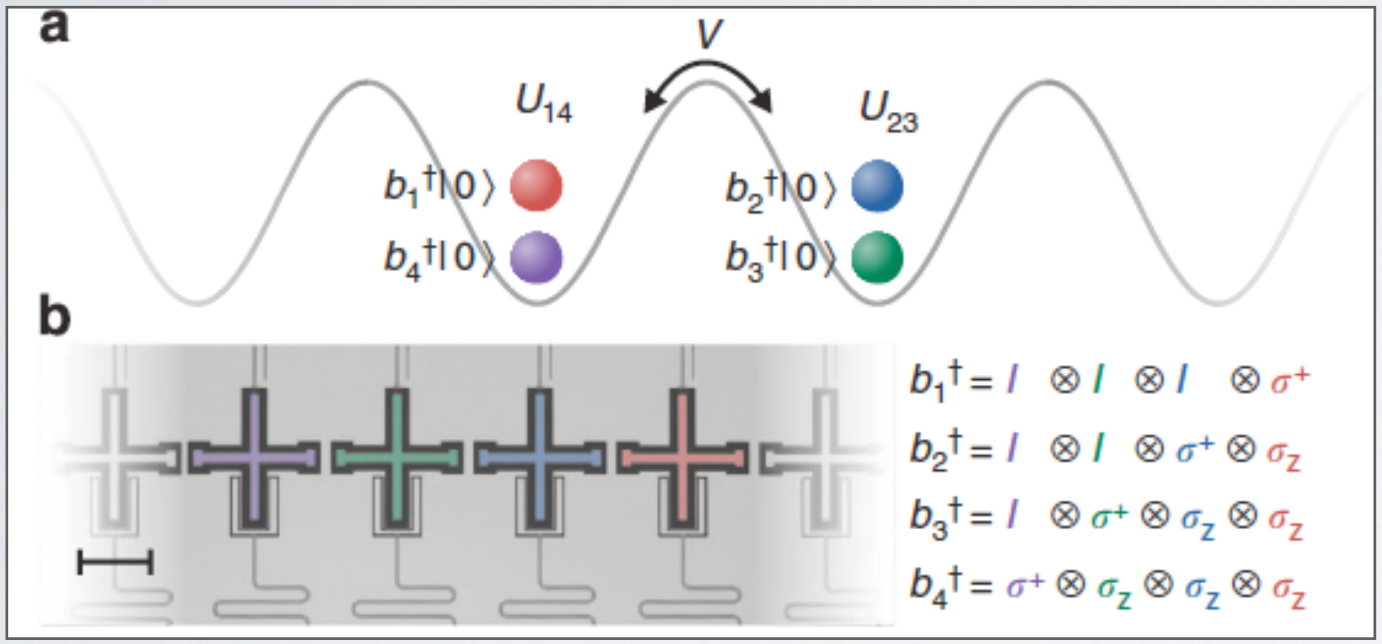

- Tuning qubit frequency close to resonance produces controlled-phase gate.
- C-phase gate is universal (any 2-qubit operation can be decomposed into C-phase and single qubit rotations.
- Gate time can be fast, under 100 ns
- Gate fidelity measured at 99.3%

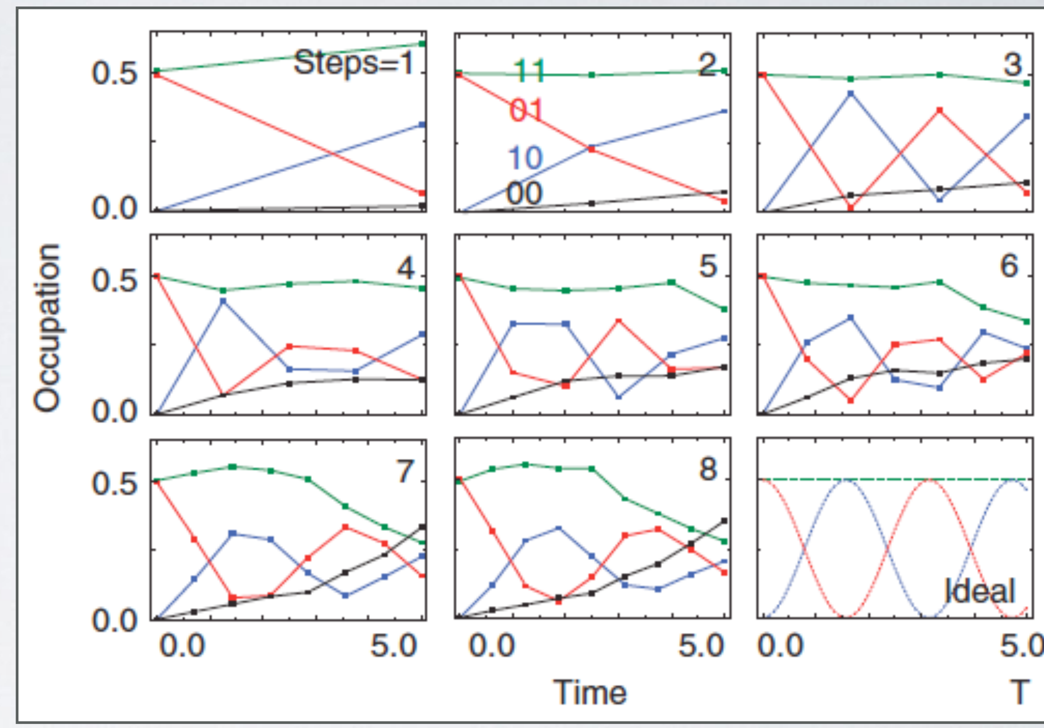
*R. Barends et al., Nature 508, 500 (2014)*

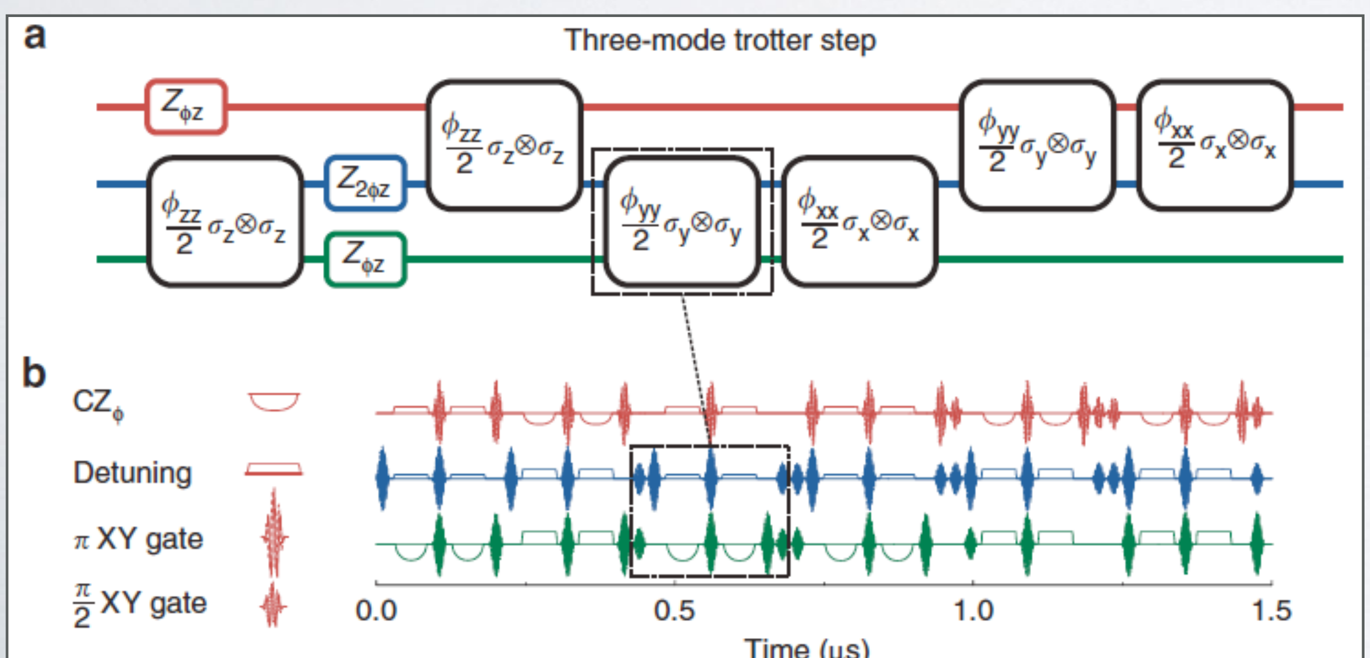
# 2-QUBIT GATES

## What can we do with so many qubits?

Simulation of Hubbard model (fermion scattering)



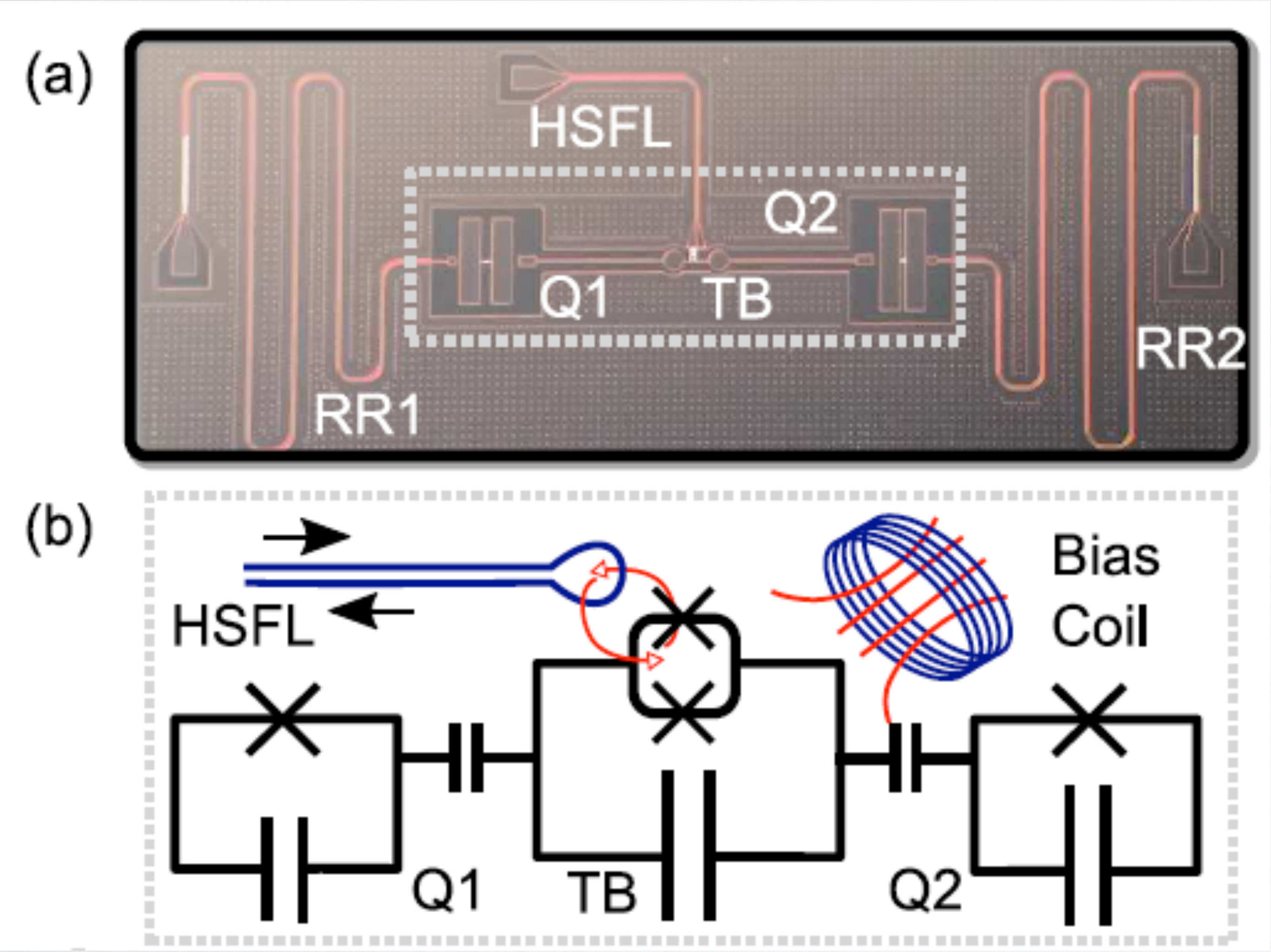



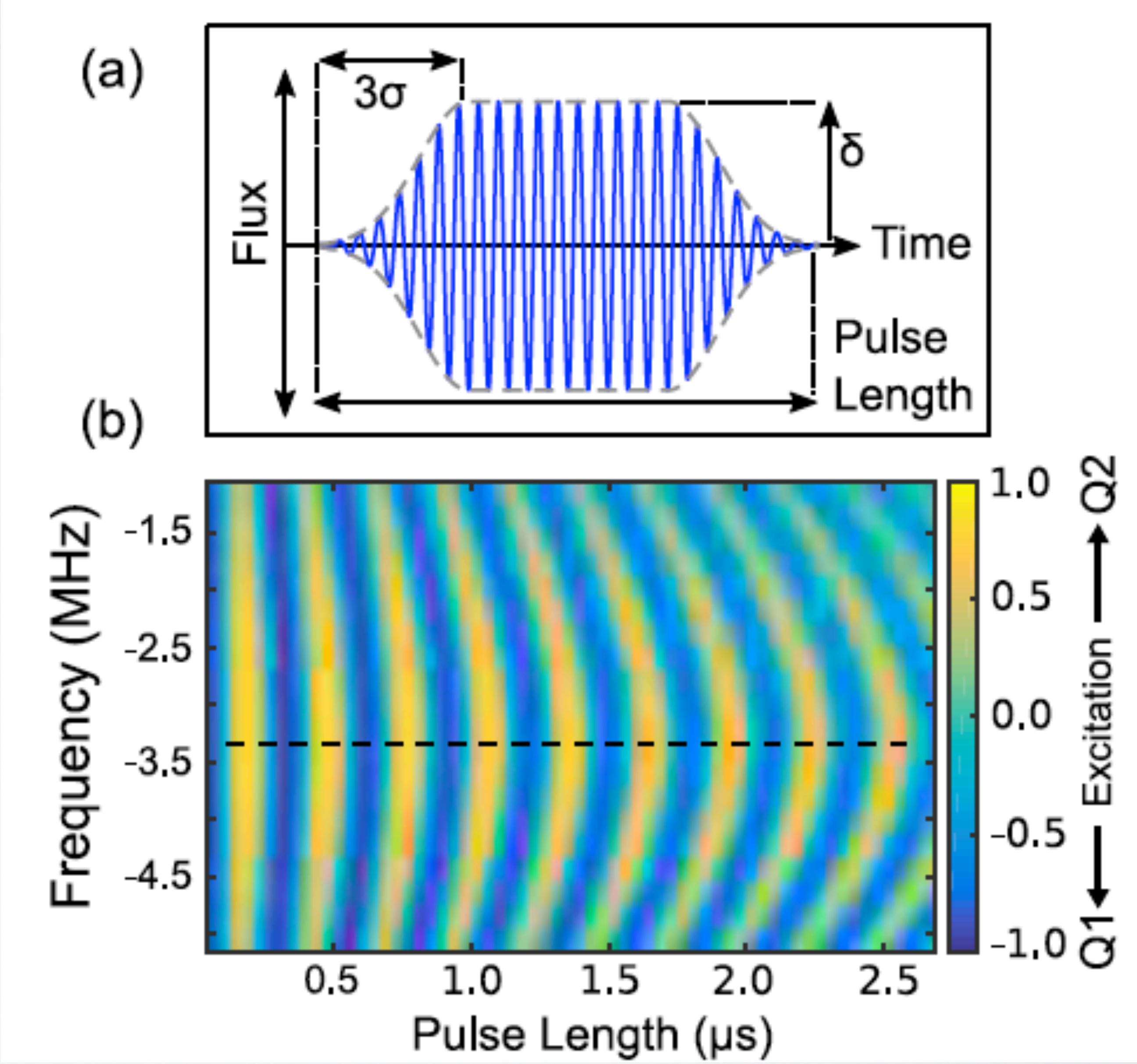

- Simulation infidelity consistent with single errors per gate
- Longest gate sequence contains 1000 gates

*R. Barends et al., Nature Comm. 6, 7654 (2015)*

# 2-QUBIT GATES

Resonator-induced 2-qubit gates

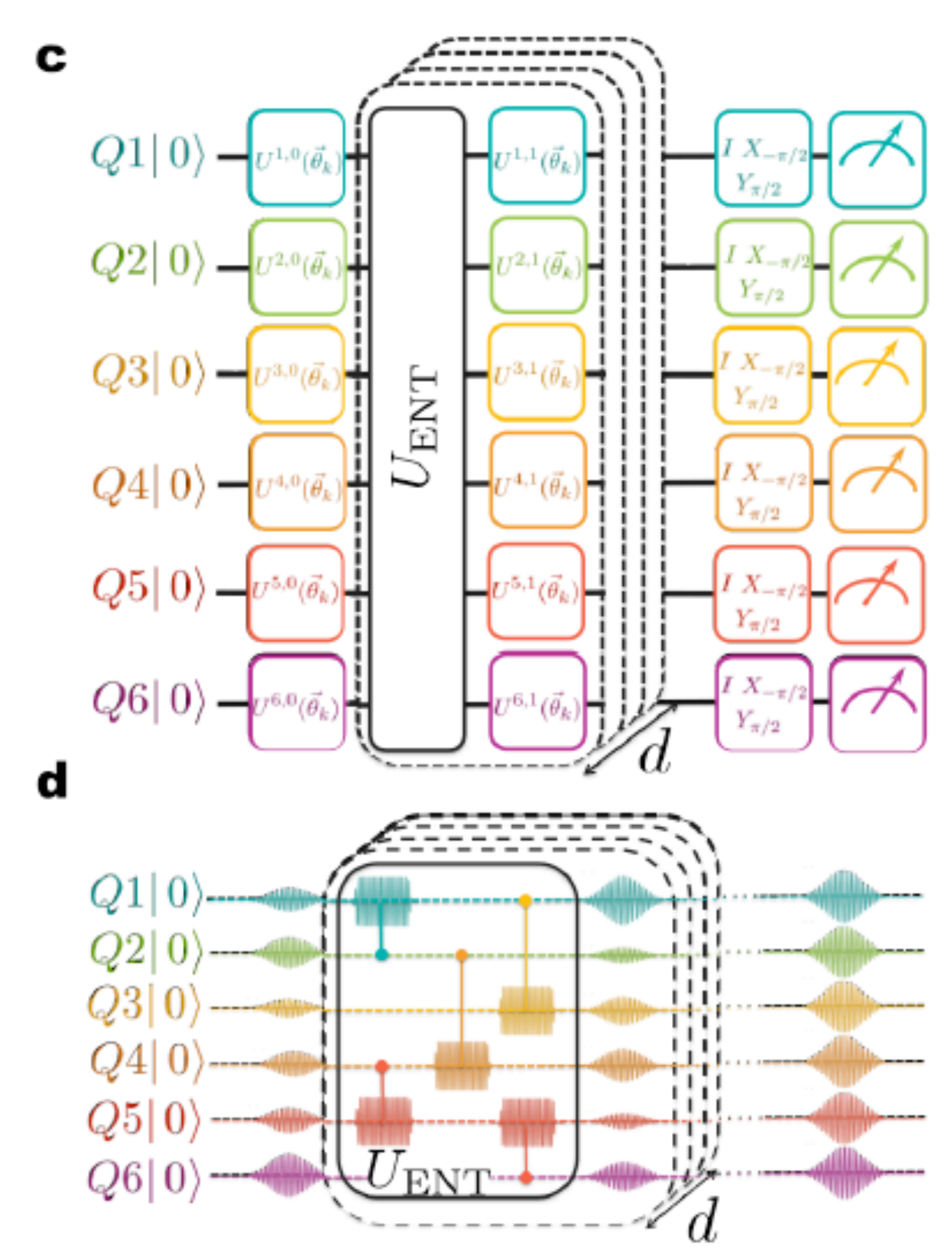


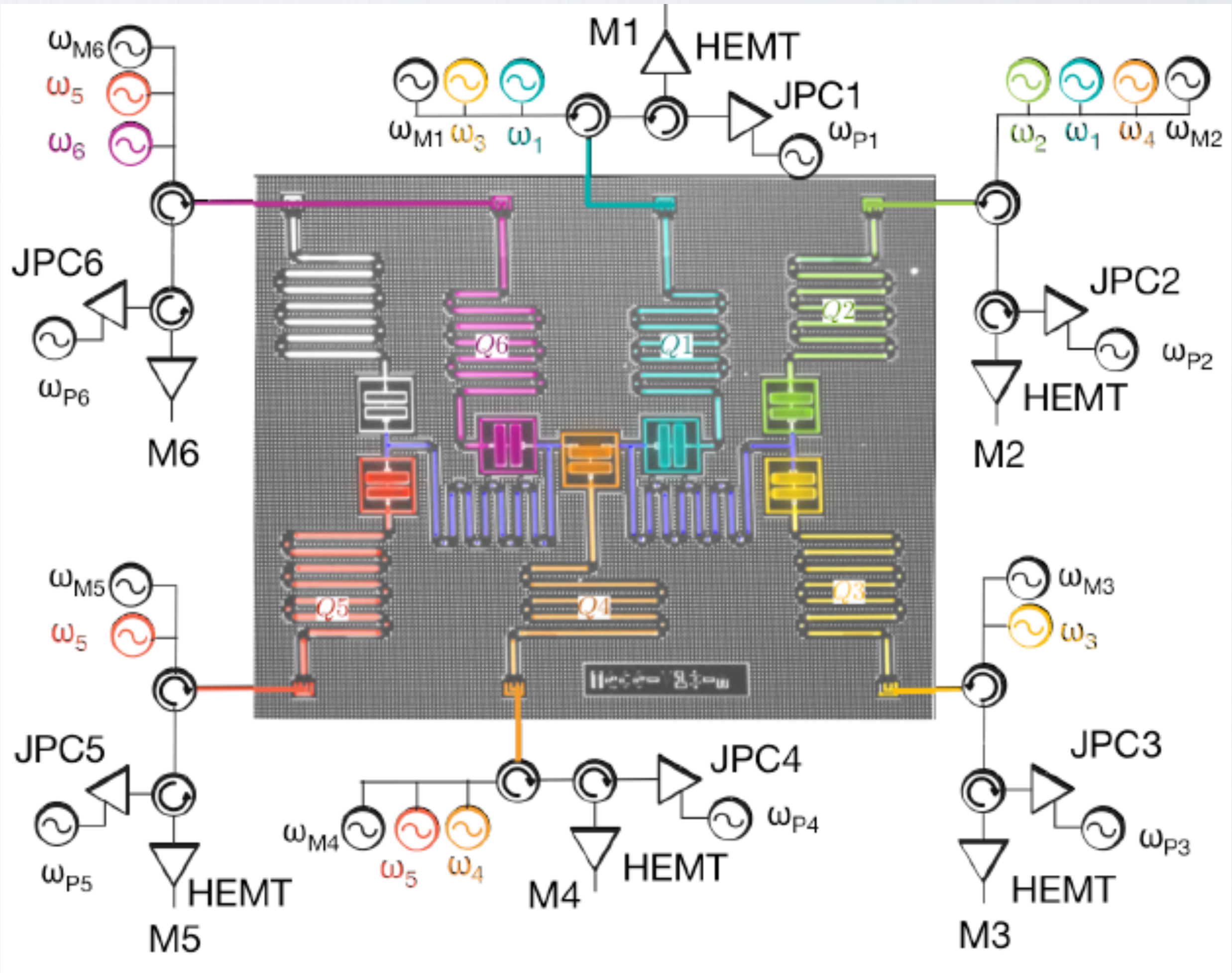

D. McKay et al., Phys. Rev. Applied 6, 064007 (2016)

# 2-QUBIT GATES

Hybrid classical-quantum algorithms:
Variational quantum eigensolvers



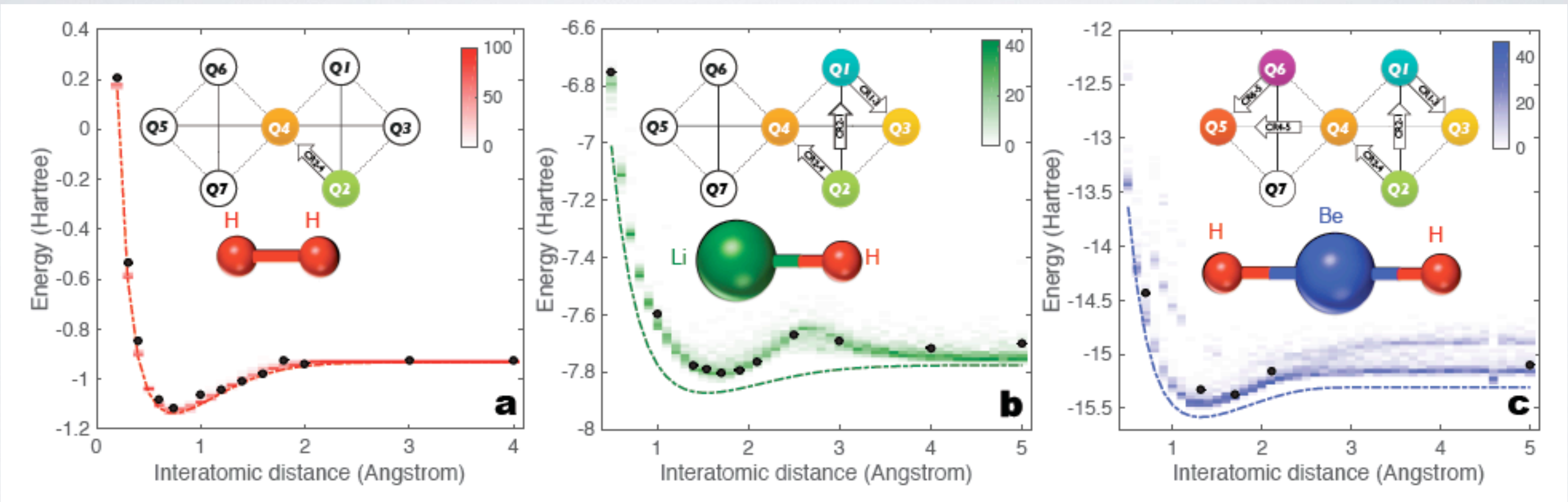

Classical calculation of orbitals needs estimation of system energy, performed by quantum processor




A. Kandala et al., Nature 549, 242 (2017)

# 2-QUBIT GATES

Hybrid classical-quantum algorithms:
Variational quantum eigensolvers




*A. Kandala et al., Nature 549, 242 (2017)*

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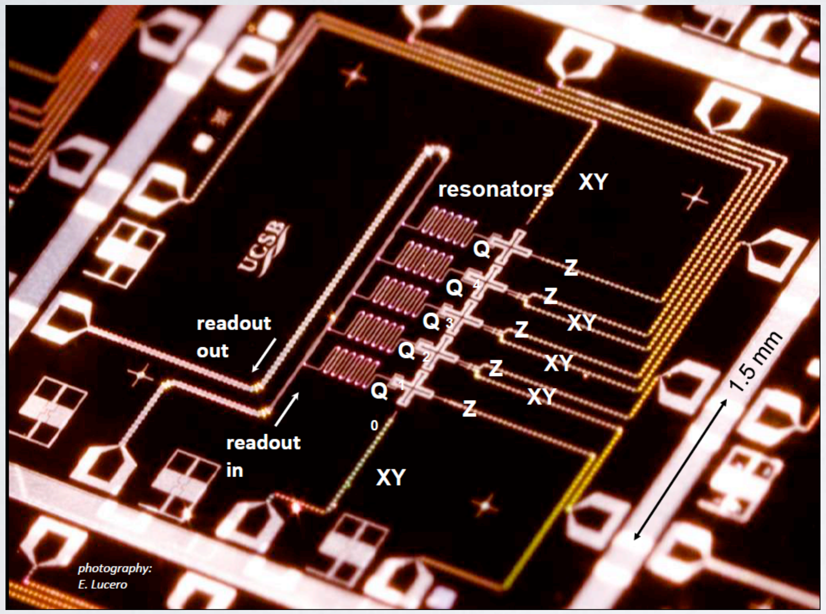
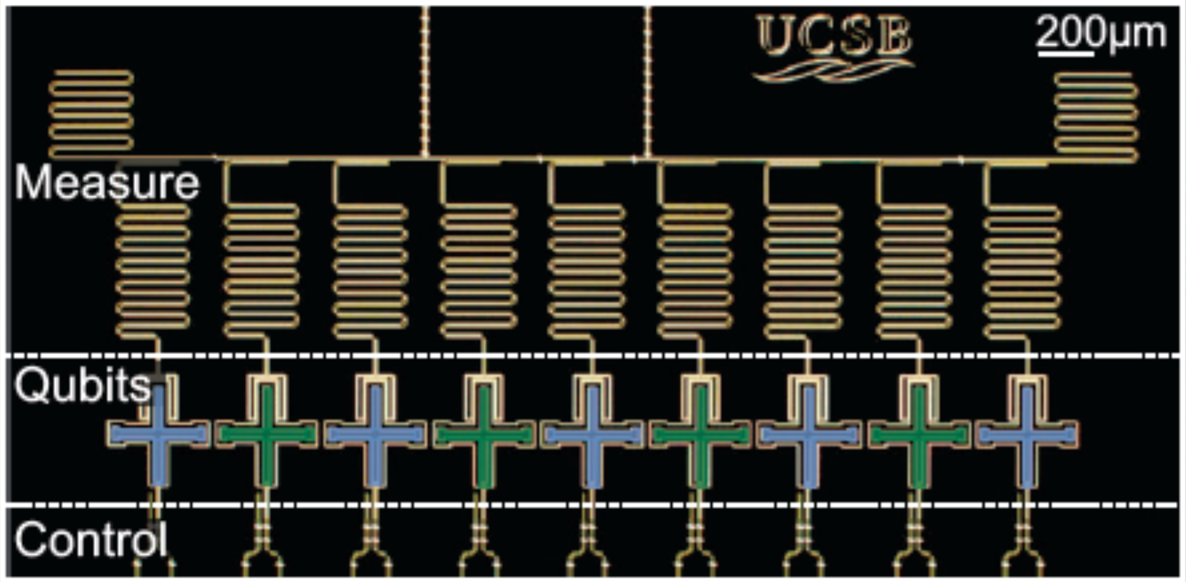
# STATE OF THE ART (SC)

5-qubit (2013)



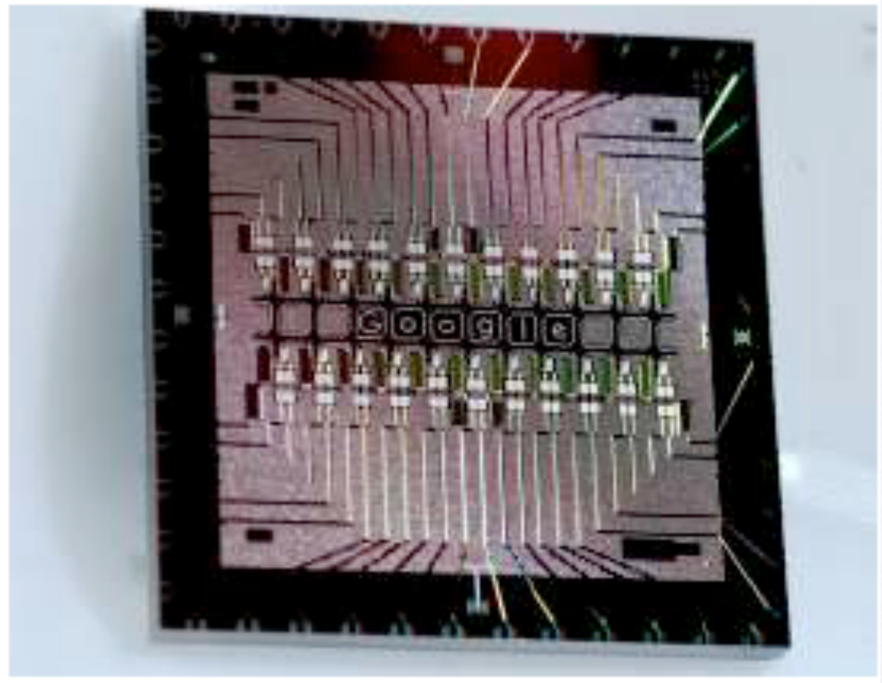

Nature 508, 500-503 (2014)

9-qubit (2015)

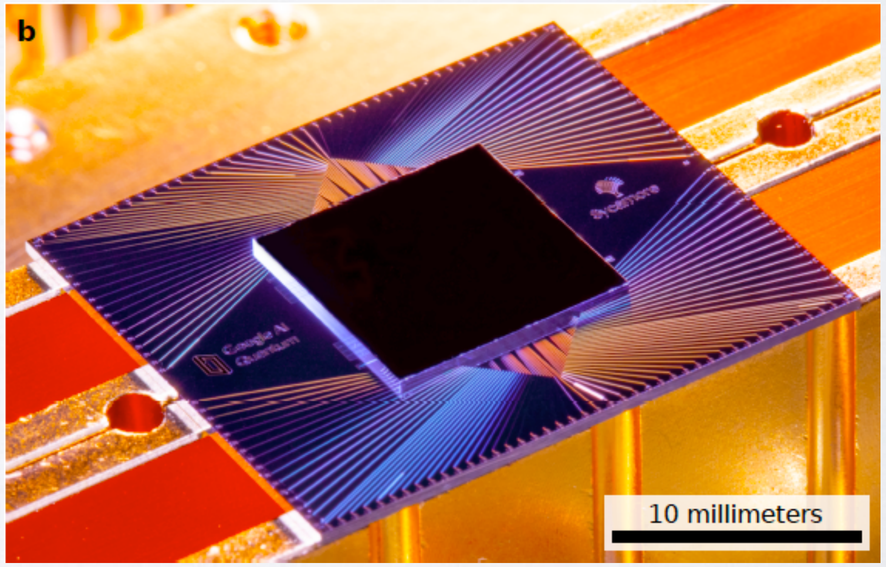



Nature 519, 66-69 (2015)

22-qubit (2017)




54-qubit (2019)




Nature 574, 505 (2019)

*Google/UCSB group evolution*

# STATE OF THE ART

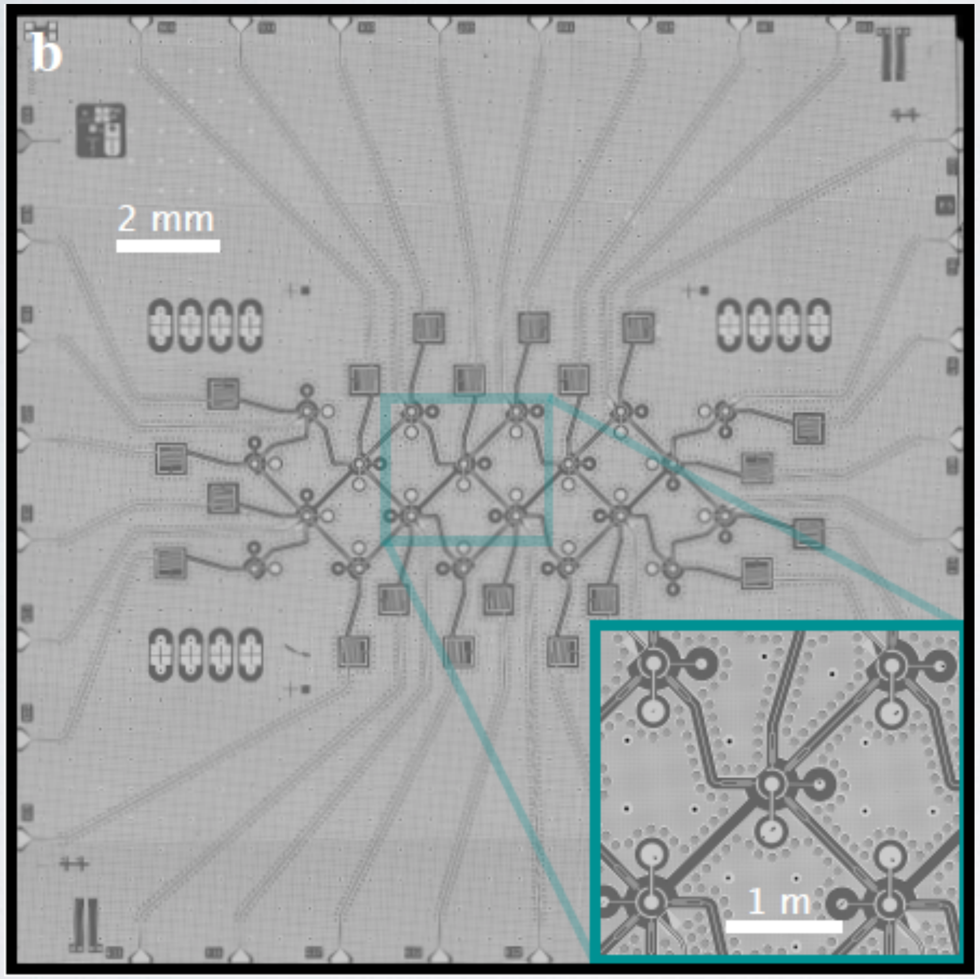
| gates | $Q_0$ | $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ |
|---|---|---|---|---|---|
| I | 0.9990 | 0.9996 | 0.9995 | 0.9994 | 0.9991 |
| X | 0.9992 | 0.9996 | 0.9992 | 0.9991 | 0.9991 |
| Y | 0.9991 | 0.9995 | 0.9993 | 0.9992 | 0.9991 |
| X/2 | 0.9992 | 0.9993 | 0.9993 | 0.9994 | 0.9993 |
| Y/2 | 0.9991 | 0.9993 | 0.9995 | 0.9994 | 0.9994 |
| -X | 0.9991 | 0.9995 | 0.9992 | 0.9989 | 0.9991 |
| -Y | 0.9991 | 0.9995 | 0.9991 | 0.9987 | 0.9991 |
| -X/2 | 0.9991 | 0.9992 | 0.9993 | 0.9990 | 0.9995 |
| -Y/2 | 0.9991 | 0.9992 | 0.9995 | 0.9990 | 0.9994 |
| H | 0.9986 | 0.9986 | 0.9991 | 0.9981 | 0.9988 |
| Z | 0.9995 | 0.9988 | 0.9994 | 0.9991 | 0.9993 |
| Z/2 | 0.9998 | 0.9991 | 0.9998 | 0.9995 | 0.9996 |
| 2T [a] | | 0.9989 | 0.9994 | 0.9989 | 0.9990 |
| average over gates | 0.9992 | 0.9992 | 0.9994 | 0.9991 | 0.9992 |
| average over qubits | | | 0.9992 | | |

| qubits | $Q_0$ | $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ |
|---|---|---|---|---|---|
| $CZ_{Q_0-Q_1}$ | $0.9924 \pm 0.0005$ | | | | |
| $CZ_{Q_1-Q_2}$ | | $0.9936 \pm 0.0004$ | | | |
| $CZ_{Q_2-Q_3}$ | | | $0.9944 \pm 0.0005$ | | |
| $CZ_{Q_3-Q_4}$ | | | | $0.9900 \pm 0.0006$ | |

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

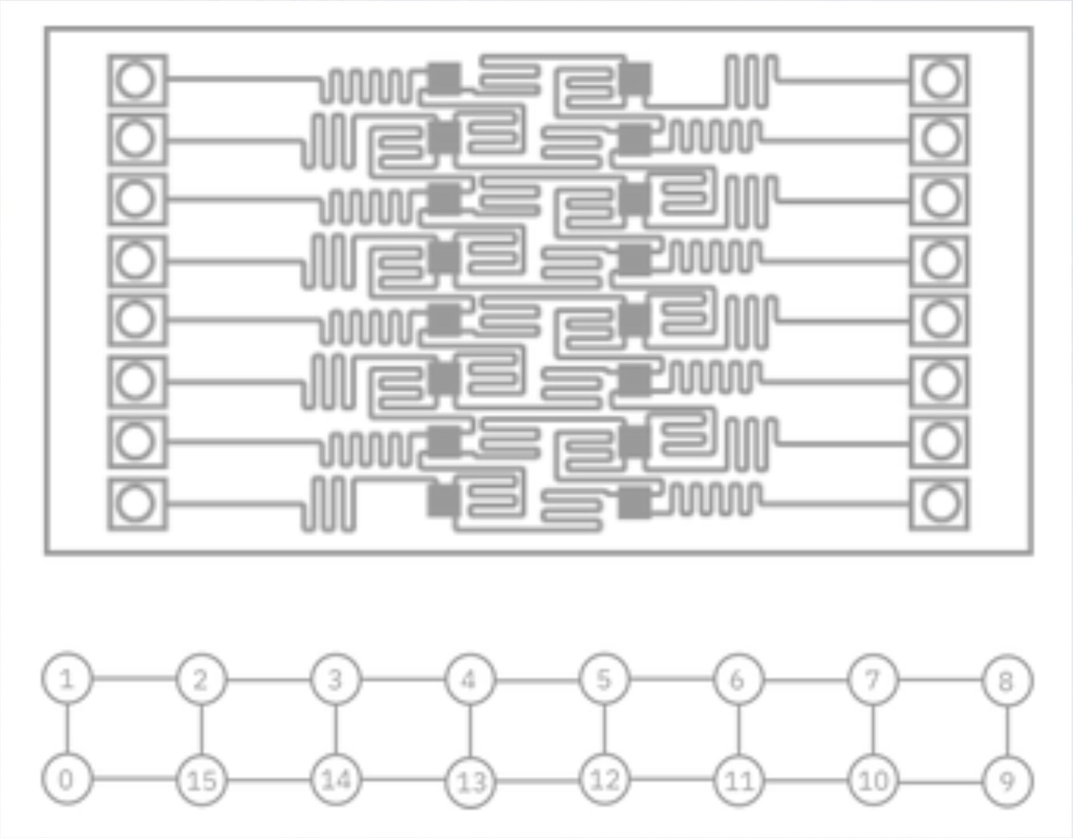
# STATE OF THE ART (SC)

Rigetti, 19 qubits (2017)




Open cloud service available

IBM, 16 qubits (2016)

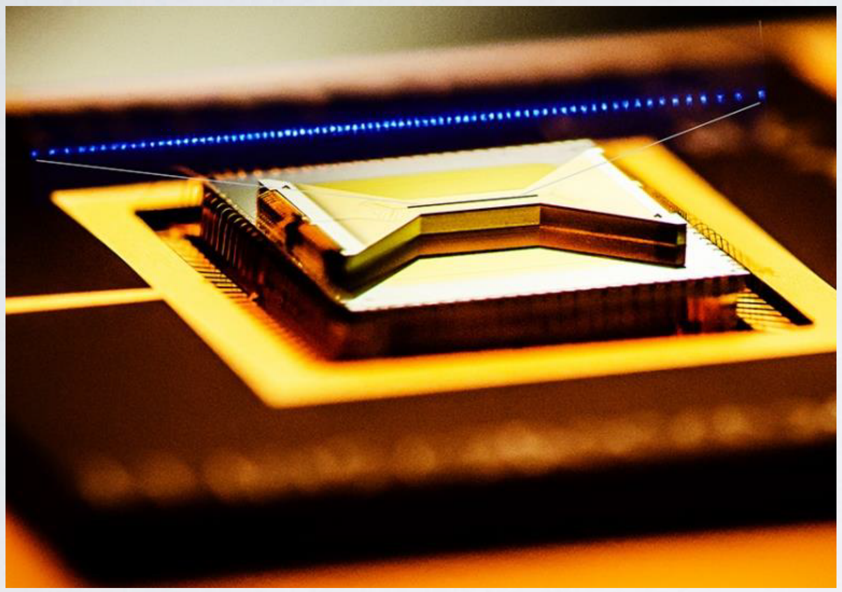



IBM Quantum experience
Online free access to quantum processor

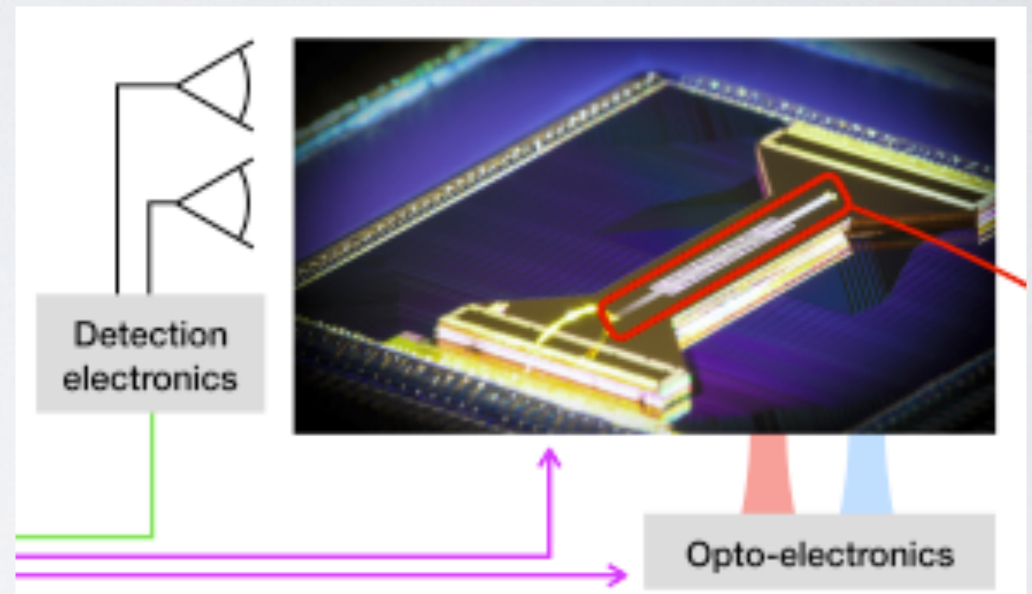
Recently launched a 65 qubit device called Hummingbird

# STATE OF THE ART (IT)

IonQ



Honeywell




Alpine QT

**Performance Benchmarks†**

**Qubits**
Single-qubit gates on
**79 Qubits**
Two-qubit gates on all pairs up to
**11 Qubits**

**Average Fidelity**
Single-qubit gates
**>99%**
Two-qubit gates
**>98%***

**Best Fidelity**
Single-qubit gates
**>99.97%**
Two-qubit gates
**>99.3%***

From IonQ's website

# STATE OF THE ART

## What's next?

-Quantum supremacy / advantage (achieved in 2019)

5-10 years

-Real world optimization problems with annealers

-Simulation of small molecules

-Partial error-corrected quantum computation

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**End of lecture II!**

# ACKNOWLEDGEMENTS


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AGENCIA ESTATAL DE INVESTIGACIÓN

"la Caixa" Foundation

MISTI — MIT International Science & Technology Initiatives

European Commission | Horizon 2020 European Union funding for Research & Innovation

QUANTERA


# Thank you!


pforndiaz@ifae.es

https://qct.ifae.es

@pforndiaz

@_IFAE

# BACKUP SLIDES

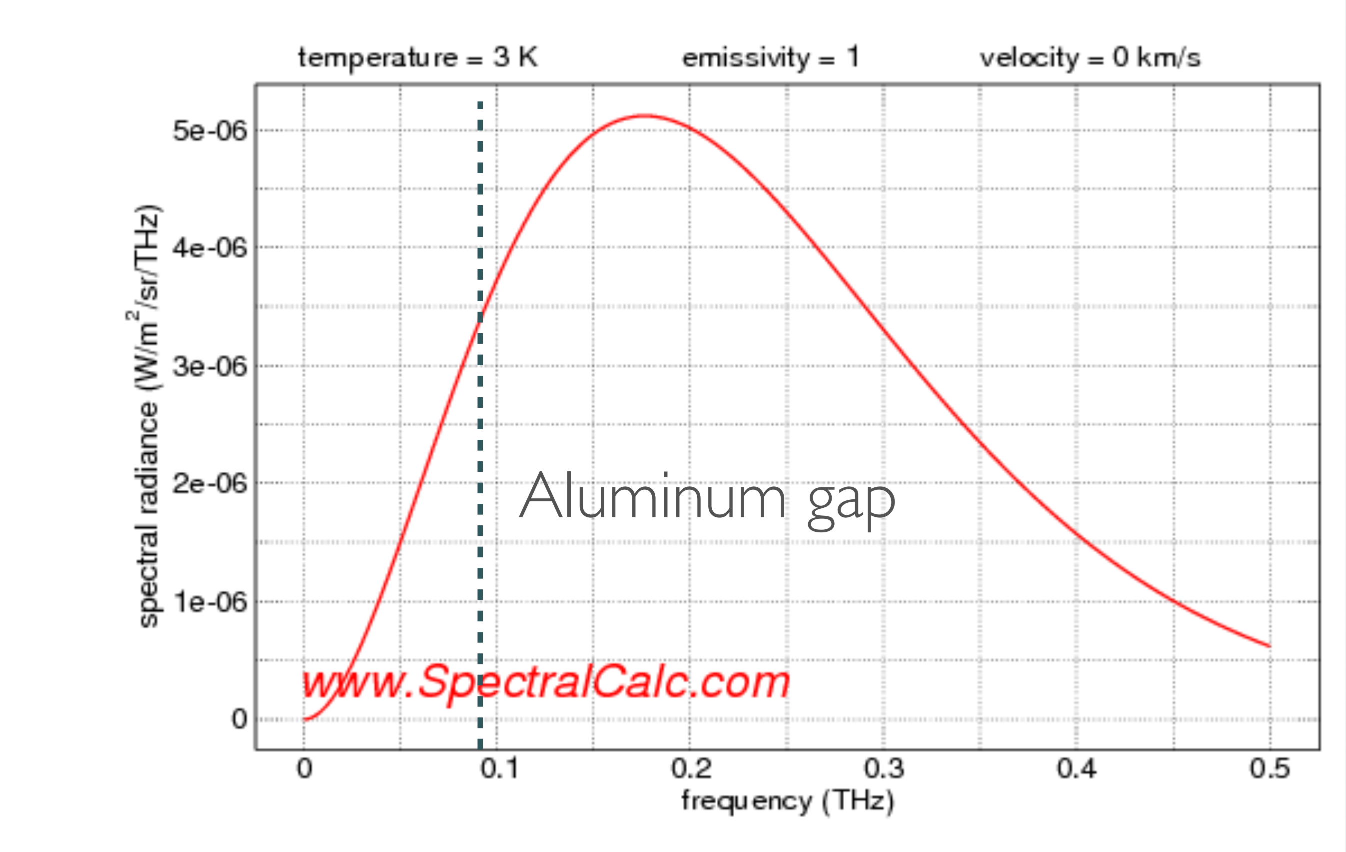
# QUBIT STATE CONTROL

## Absolute control?

Multiple sources of noise:

- ~~Control/readout circuit noise (white)~~ LPFs, circuit design, etc.
- Infrared radiation (Planck)
- Two-level systems (1/f)
- Quasiparticles (Poisson)
- Cosmic rays (??)

Fridge background thermal photons



# QUBIT STATE CONTROL

## Absolute control?

Multiple sources of noise:

- ~~Control/readout circuit noise (white)~~
- Infrared radiation (Planck)
- Two-level systems (1/f)
- Quasiparticles (Poisson)
- Cosmic rays (??)

IR absorptive material (SiC) in MCh can, 90% absorption

Picture courtesy of R. Barends

# QUBIT STATE CONTROL

## Absolute control?

Multiple sources of noise:

- ~~Control/readout circuit noise (white)~~
- ~~Infrared radiation (Planck)~~
- Two-level systems (1/f)
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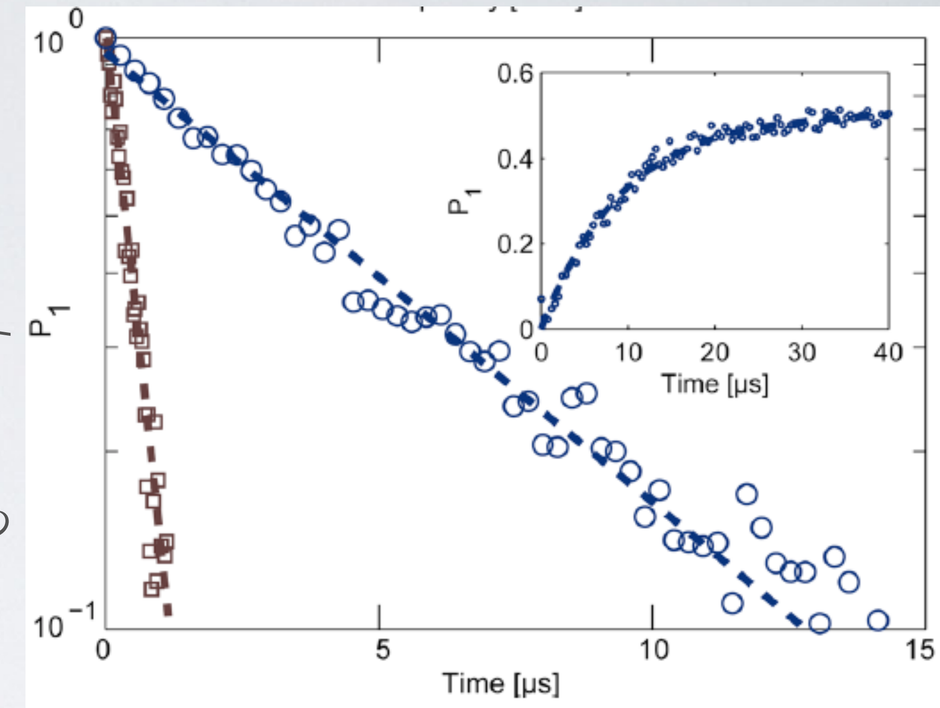
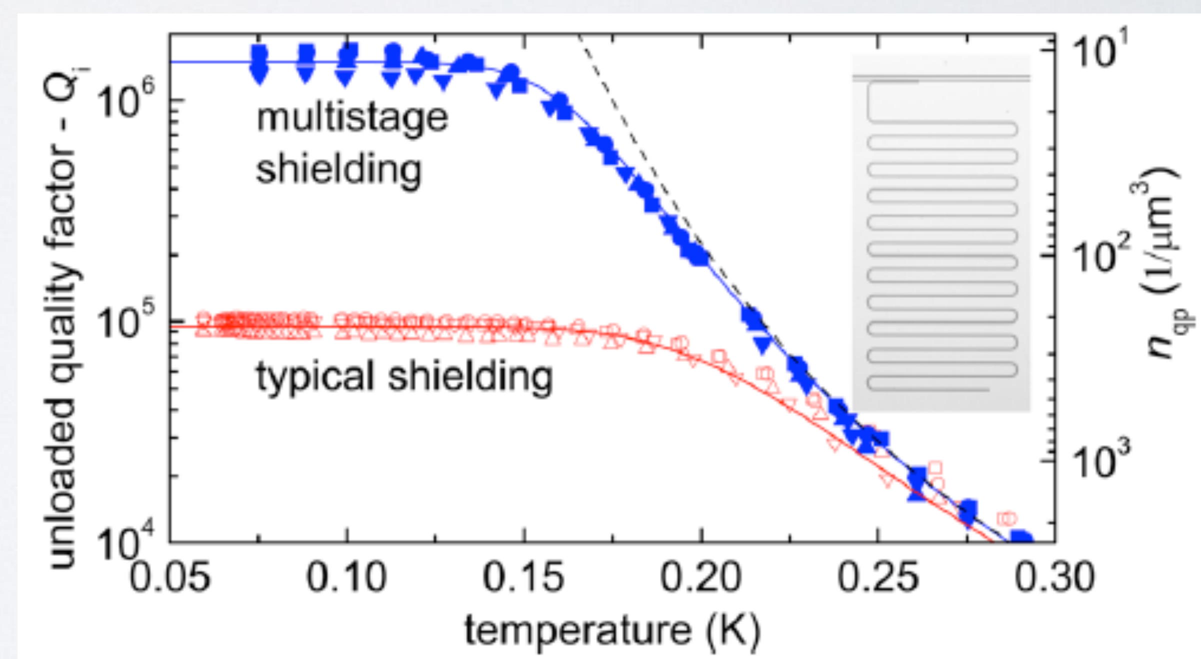
*Qubit improvement*




*Córcoles et al., APL 99, 181906 (2011)*

*Resonator improvement*




*Barends et al., APL 99, 113507 (2011)*

# QUBIT STATE CONTROL

## Absolute control?

Multiple sources of noise:

- ~~Control/readout circuit noise~~ (white)
- ~~Infrared radiation~~ (Planck)
- Two-level systems (1/f)
- Quasiparticles (Poisson)
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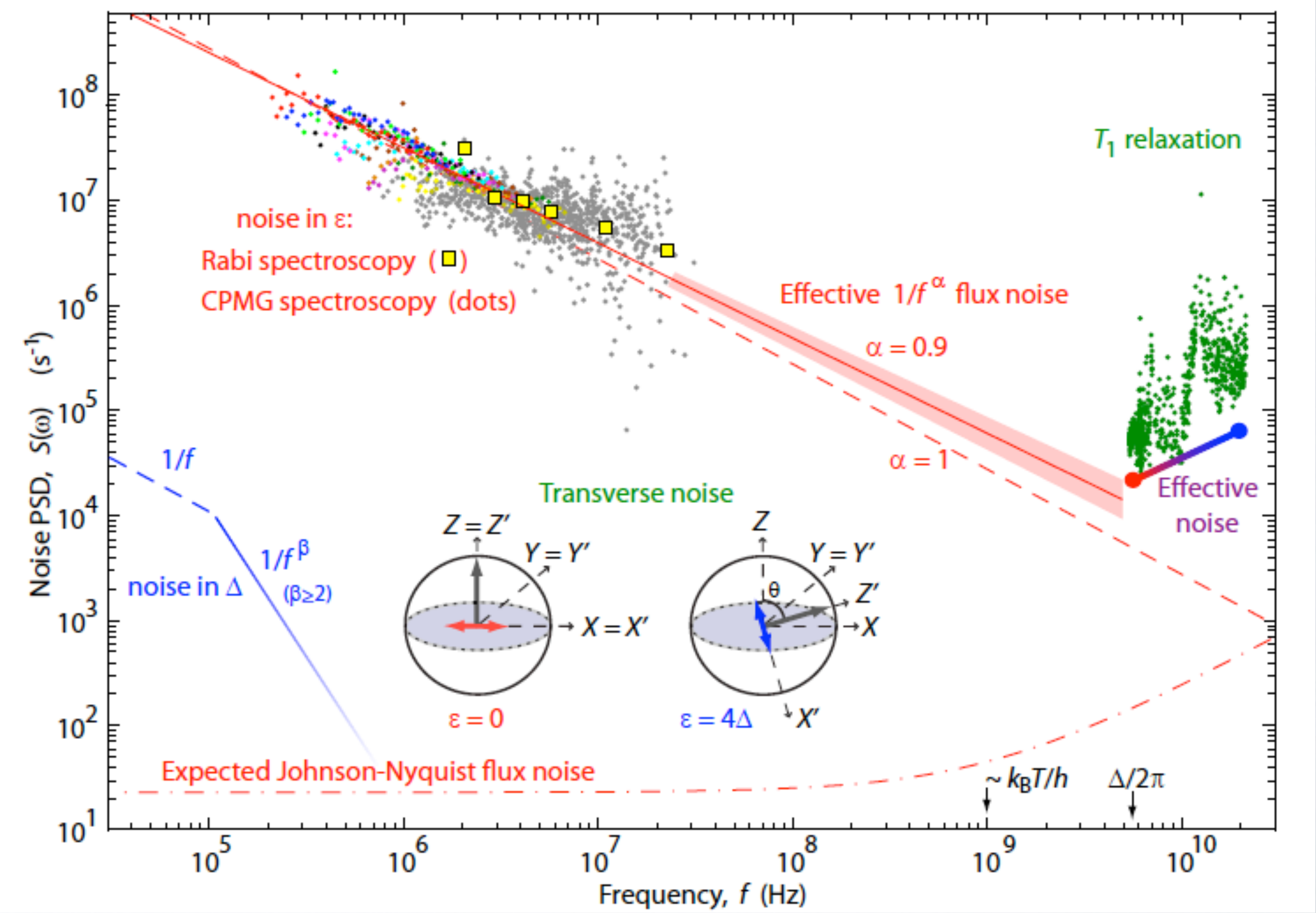
Same type of flux noise observed in SQUIDs!

$$S_\Phi(f) = \frac{\mu\Phi_0}{f}$$



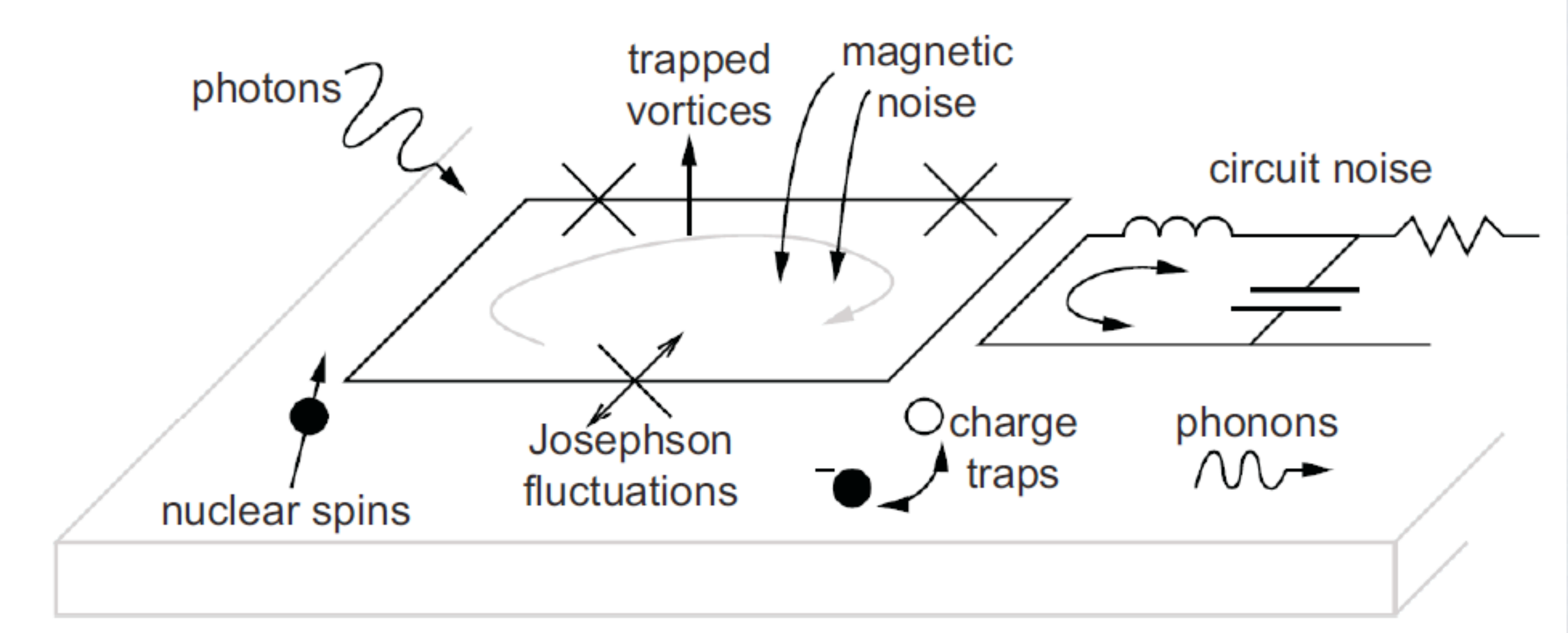

*Bylander et al., Nature Phys. vol. 7, pp. 565-570 (2011)*

# QUBIT STATE CONTROL

## Absolute control?

### Multiple sources of noise:

- ~~Control/readout circuit noise (white)~~
- ~~Infrared radiation (Planck)~~
- Two-level systems (1/f)
- Quasiparticles (Poisson)
- Cosmic rays (??)




*Plantenberg, PhD thesis (Delft)*

# QUBIT STATE CONTROL

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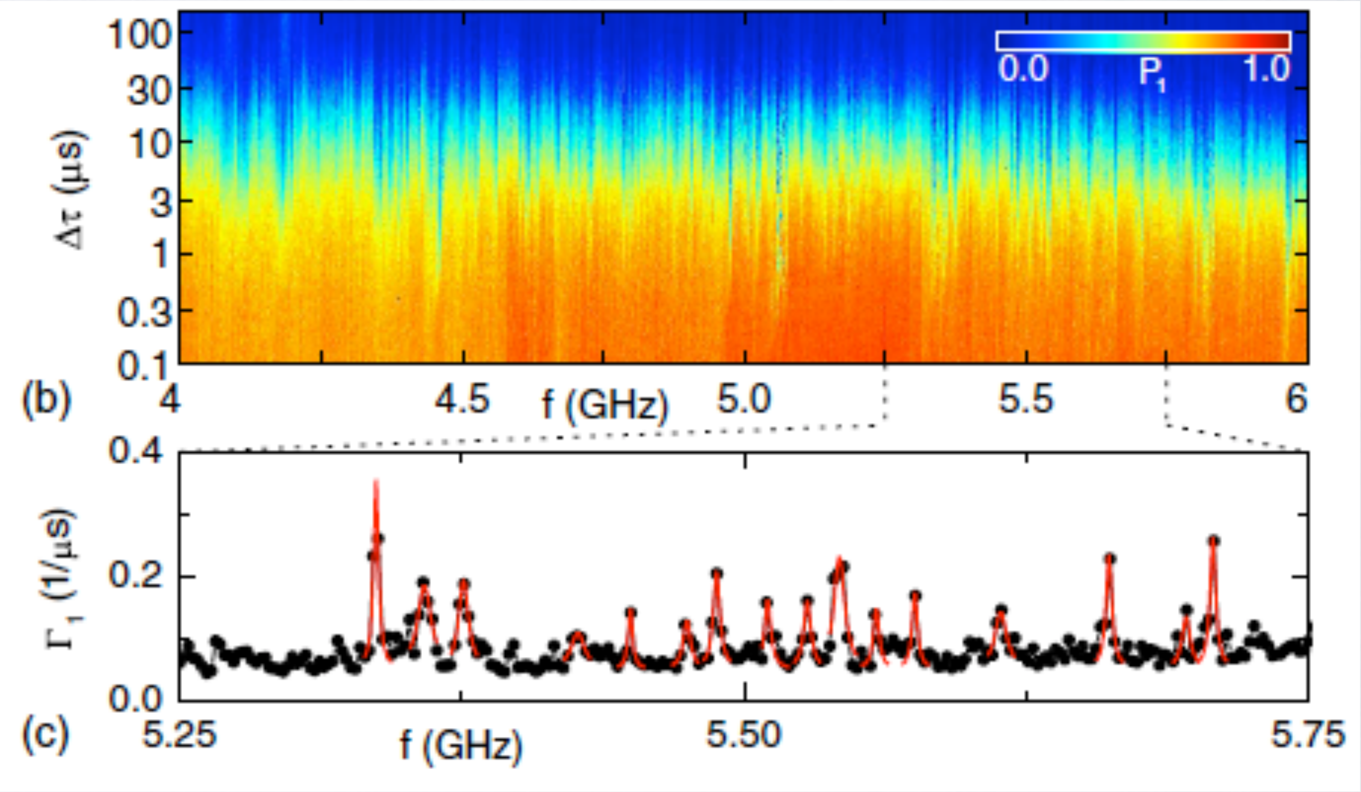
*T1 fluctuations, consistent with TLSs*




*Barends et al., PRL 111, 080502 (2013)*

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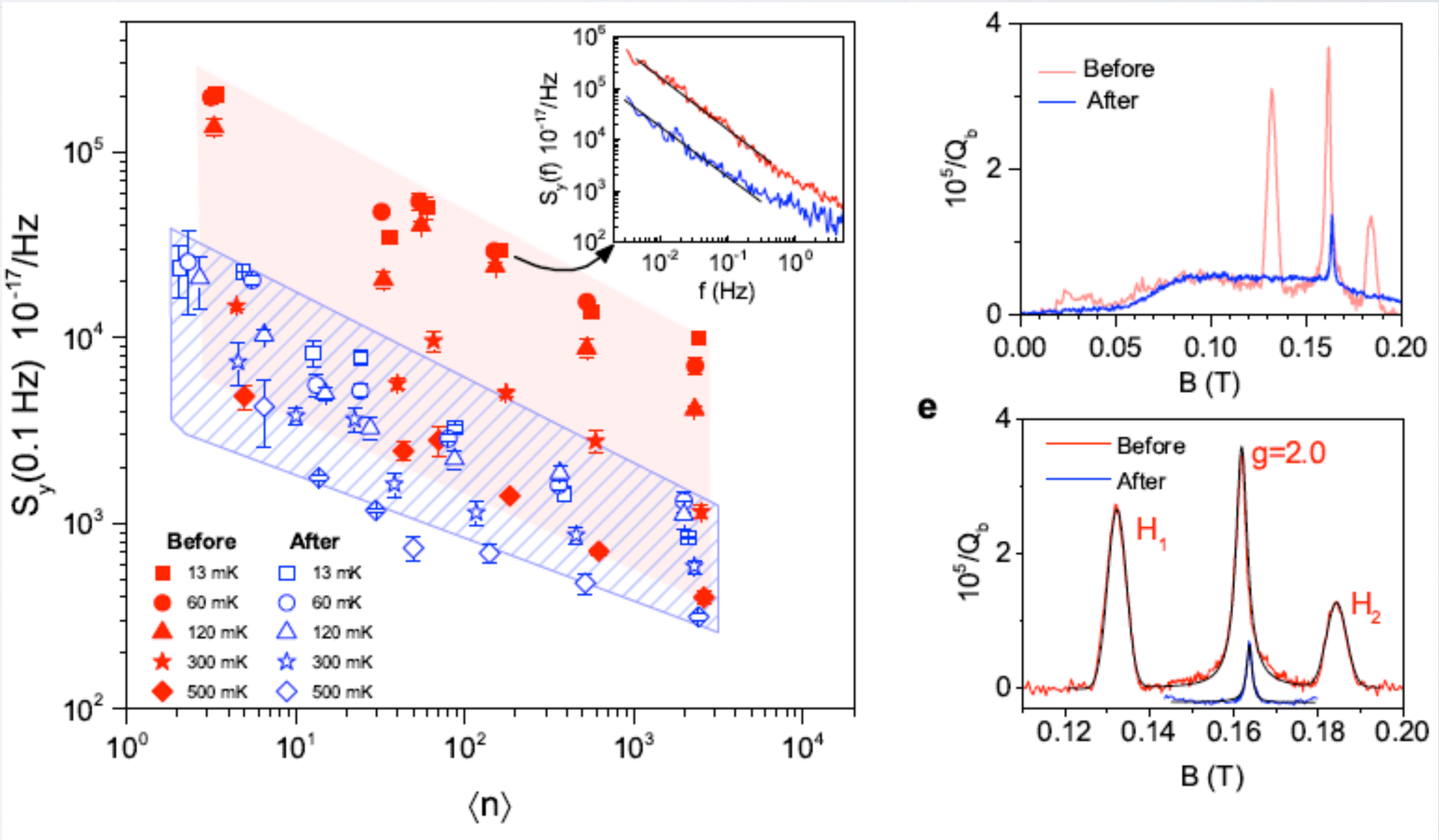
$$\Gamma(\omega) = \frac{1}{\hbar^2}|\langle 0|\hat{O}|1\rangle|^2\delta(\omega - \omega_{\mathrm{qb}})$$




S. E. de Graaf et al., *Nature Communications, 9:1143 (2018)*

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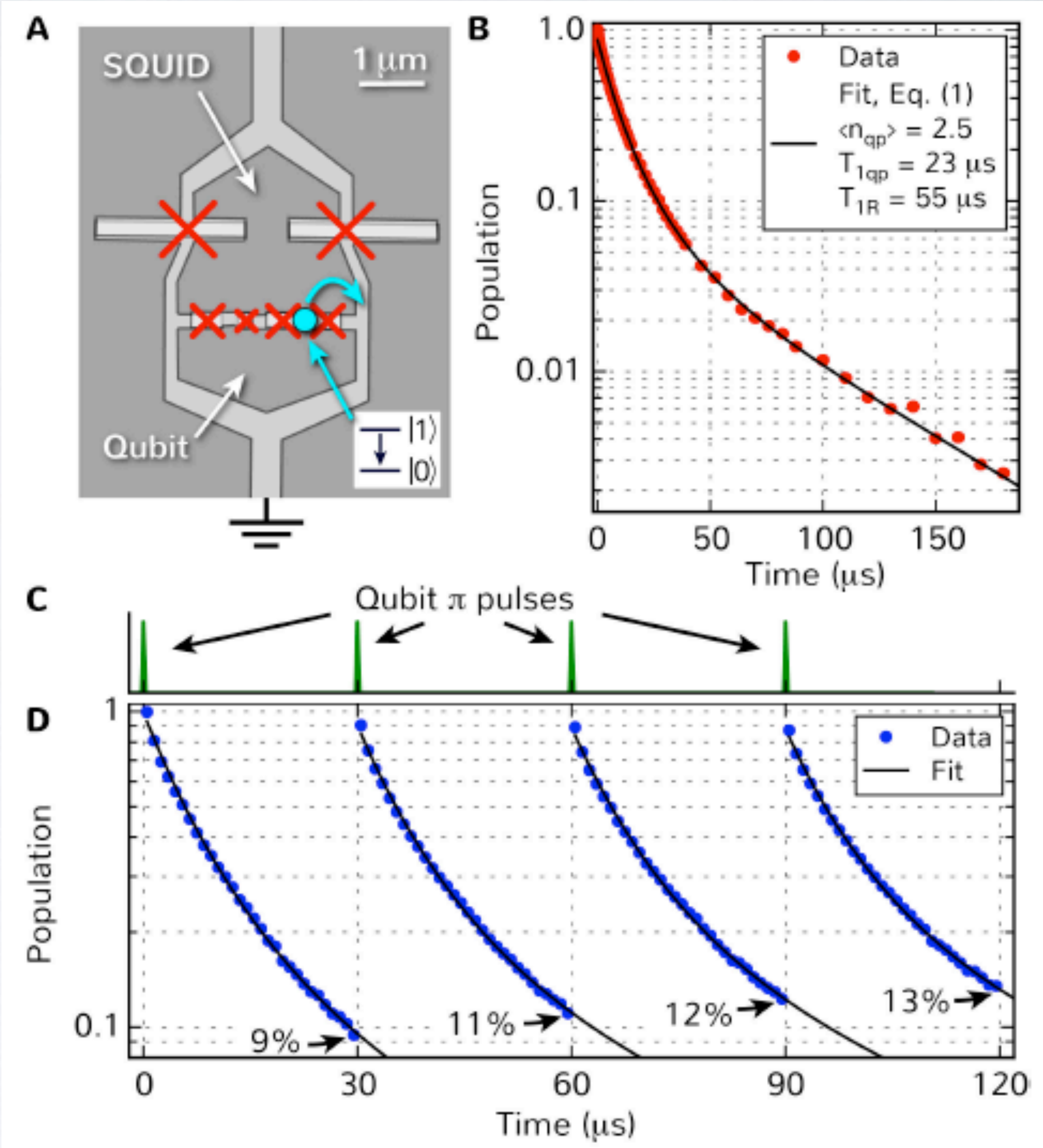


*Gustavsson et al., Science 354, 1573-1577 (2016)*

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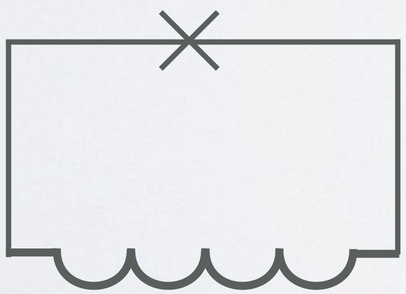
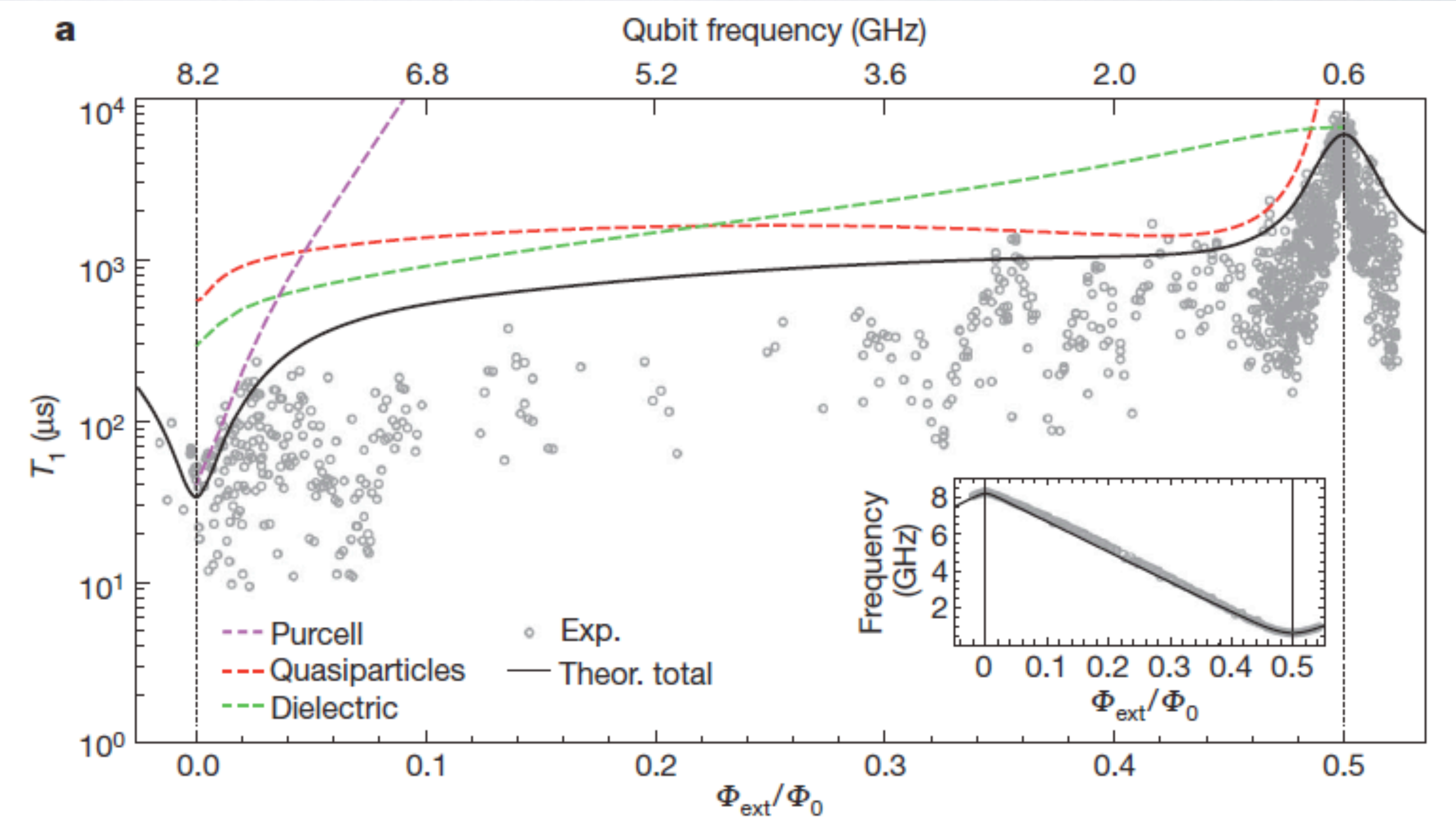
Solving $1 + \epsilon \cos \varphi$ debate

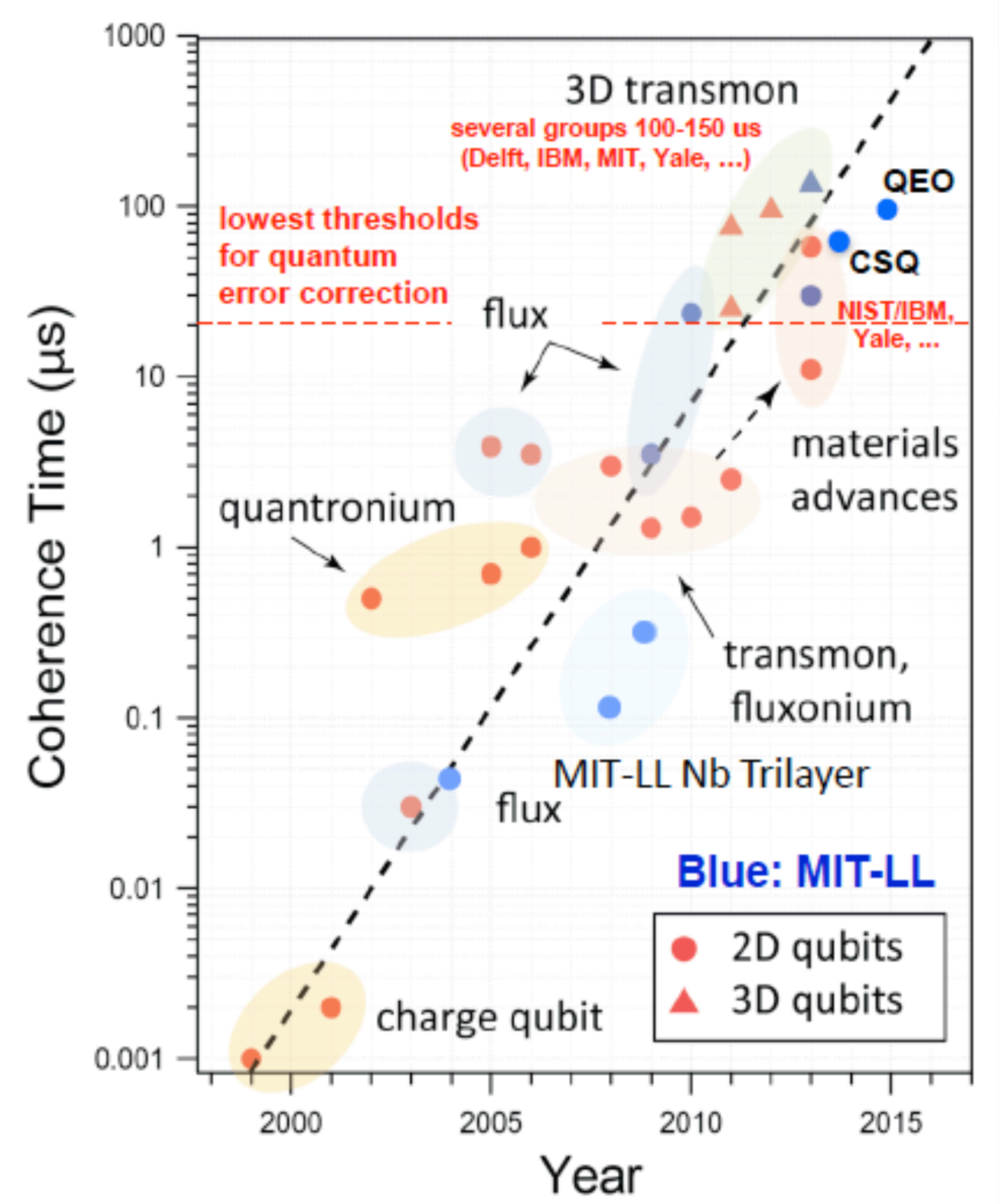
fluxonium qubit






*I. Pop et al., Nature 508, 369 (2014)*

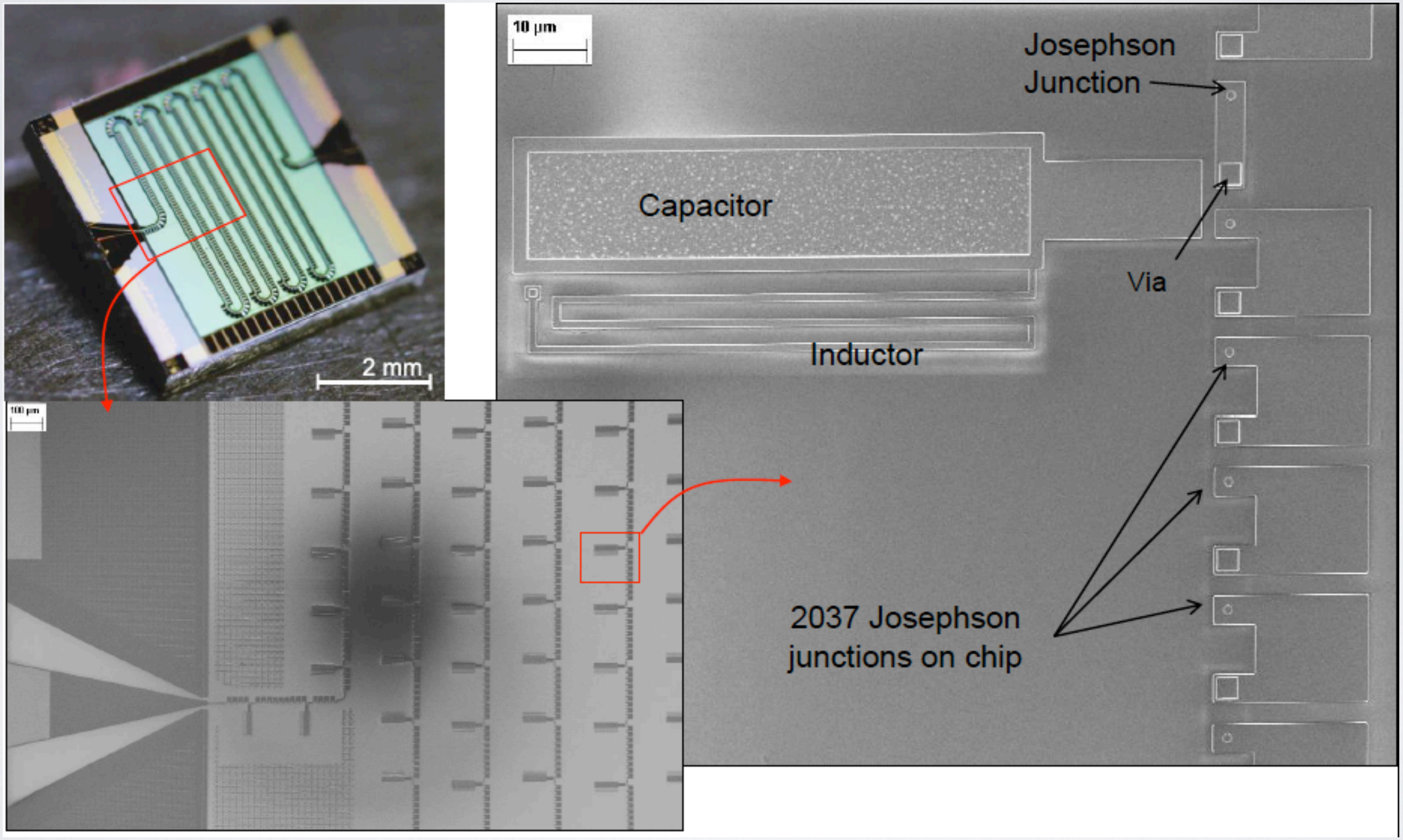
# QUBIT STATE CONTROL




*W. Oliver & Welander, MRS Bulletin (2013)*

# STATE OF THE ART

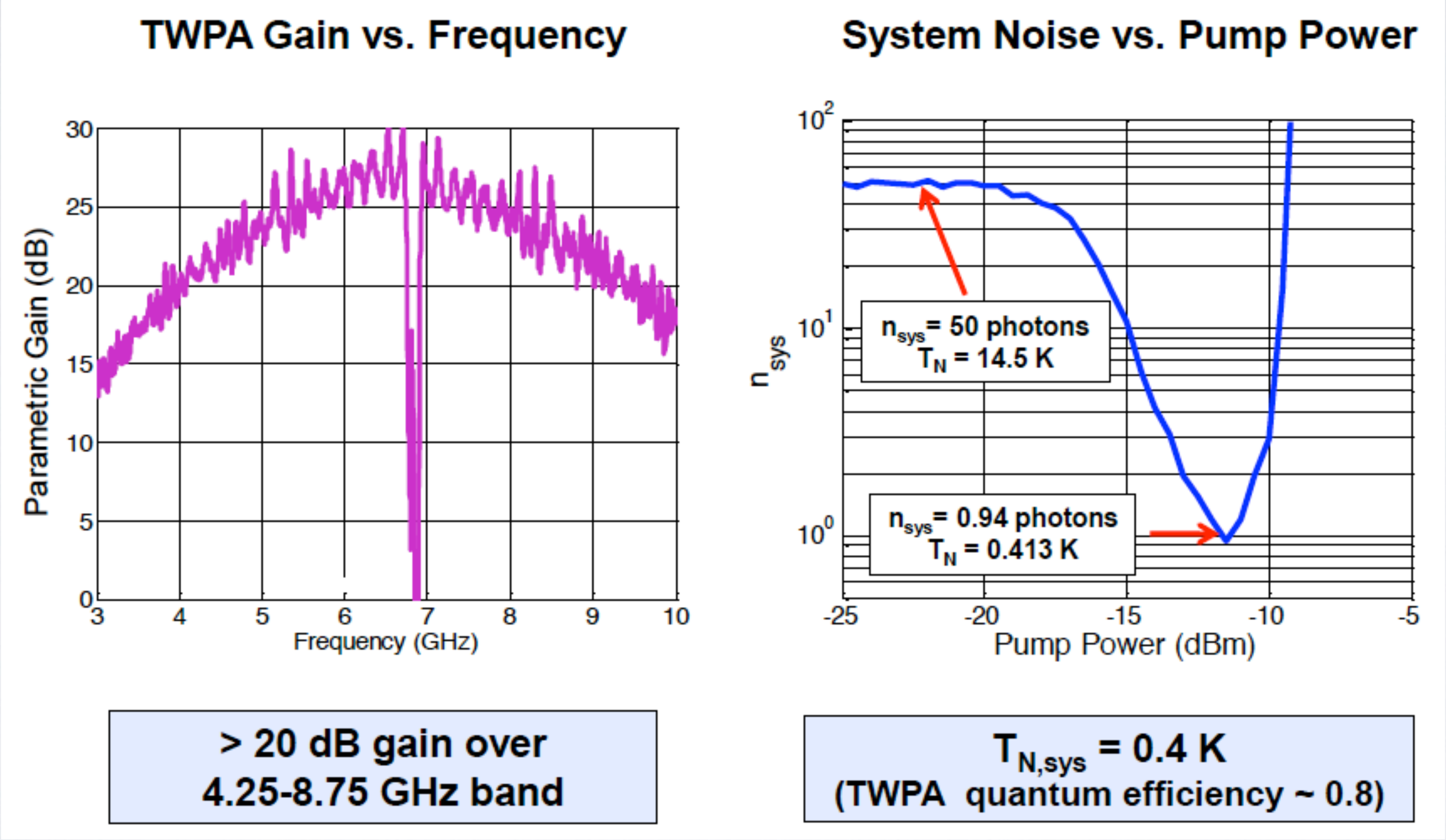
Traveling wave Josephson parametric amplifier




*C. Macklin et al., Science 350, 307 (2015)*

# STATE OF THE ART

Traveling wave Josephson parametric amplifier




P1B < -100 dBm

*C. Macklin et al., Science 350, 307 (2015)*