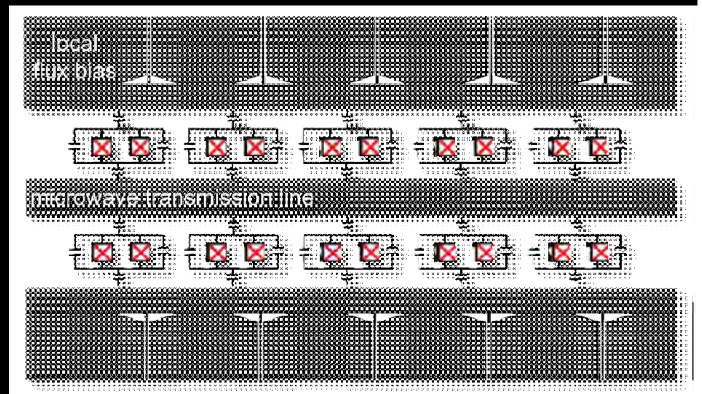
Superconducting quantum circuit research

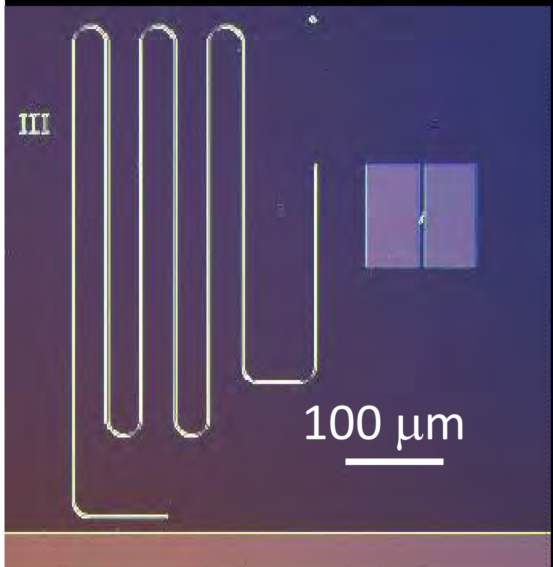
-building blocks for quantum matter-

Status update from the Karlsruhe lab

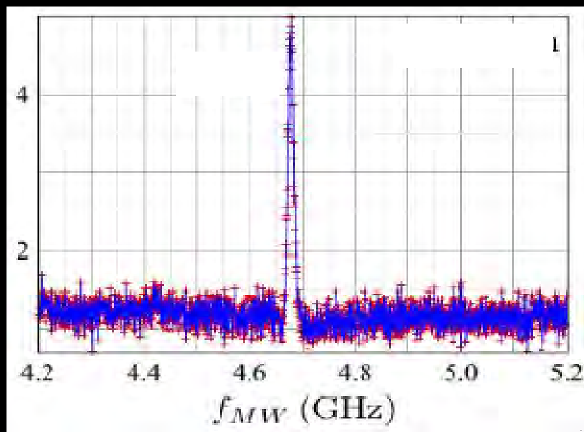
Martin Weides, Karlsruhe Institute of Technology

July 2nd, 2014





$$|0\rangle \leftrightarrow |1\rangle$$



Basic potentials

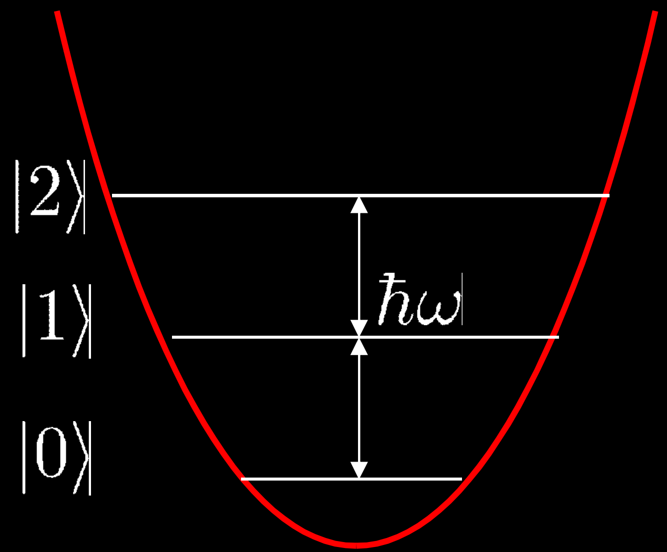
Harmonic oscillator

Photons in cavity, atom oscillation

Energy levels equidistant

Energy eigenstate $|n\rangle$

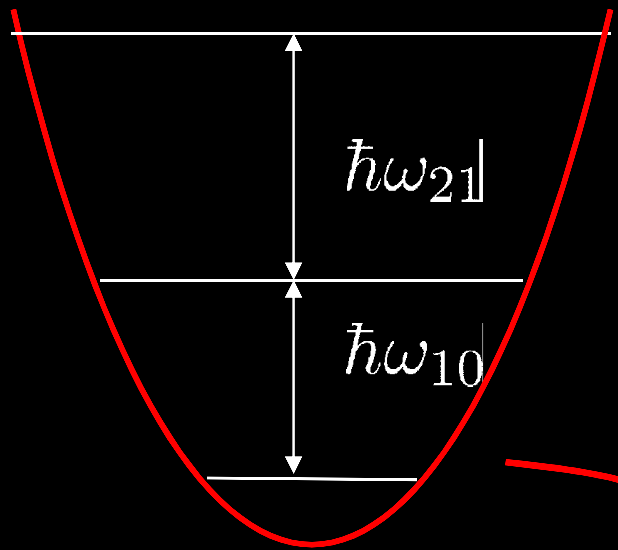
$$\hat{H}_{\mathrm{cavity}} = \left(a^\dagger a + \tfrac{1}{2}\right)\hbar\omega$$



Anharmonic oscillator

Large excitation amplitudes

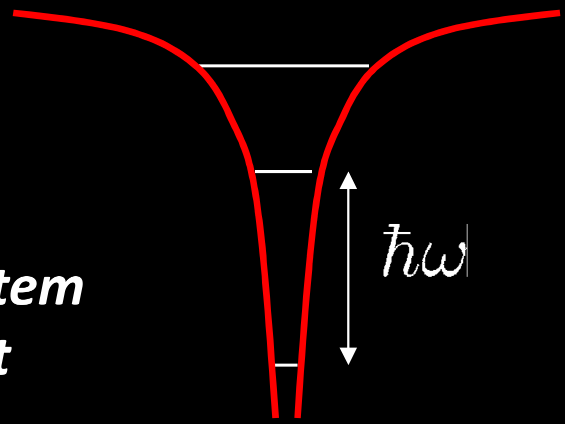
$$\Delta = \omega_{n+1,n} - \omega_{n,n-1}$$



Two level system

if $|\Delta/\omega| >> 0$ → ***two level system***

atomic transition, spin, qubit



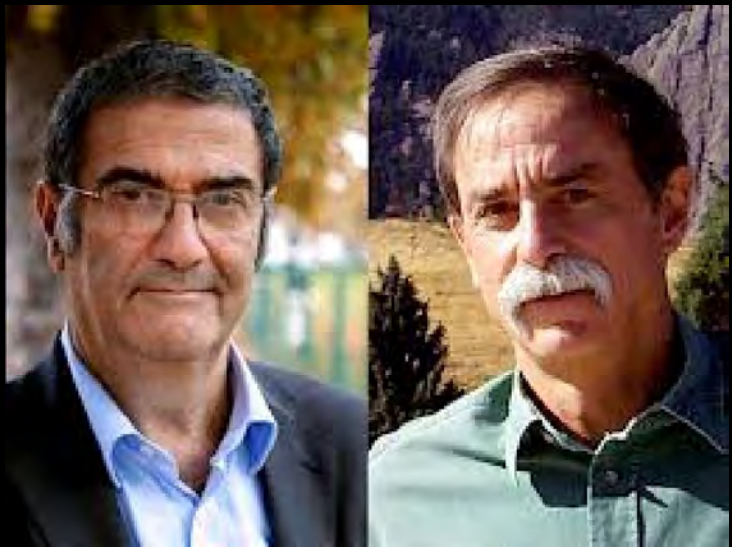
$$\hat{H}_{\mathrm{TLS}} = \hbar\omega\frac{\hat{\sigma}_z}{2}$$

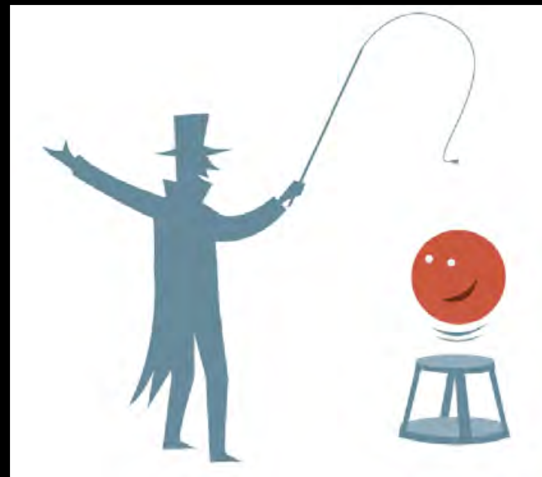
Nobel price 2012

Nobel Prize in Physics 2012 was awarded jointly to

Serge Haroche and David J. Wineland

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"





Controlling a quantum particle (atoms or ions)

$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_a \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}\hat{E}\hat{S}$$

Jaynes–Cummings
Cavity-qubit system

Quantum information processing, Q-simulation, Q-metamaterial

Artificial atoms for quantum matter require

Large interaction strength → ***dipole moment***

Tunability → ***tune transition frequency***

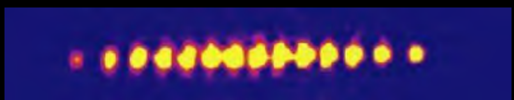
Frequency selection → ***large anharmonicity***

Long coherence → ***low loss***

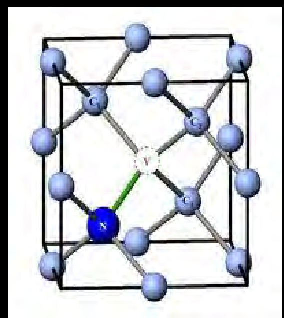
High integration density → ***scalability***

Smaller ⟷ *Bigger*

Atomic
- Ions
- Neutral Atoms
- NMR
- Photons

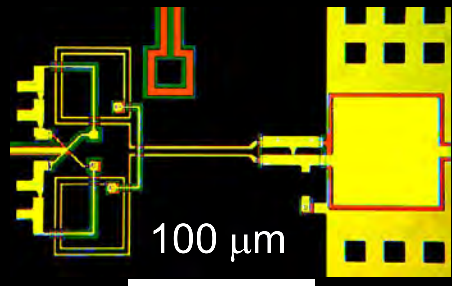


Mesoscopic
- Semiconductor Spins
- Quantum Dots
- Spin

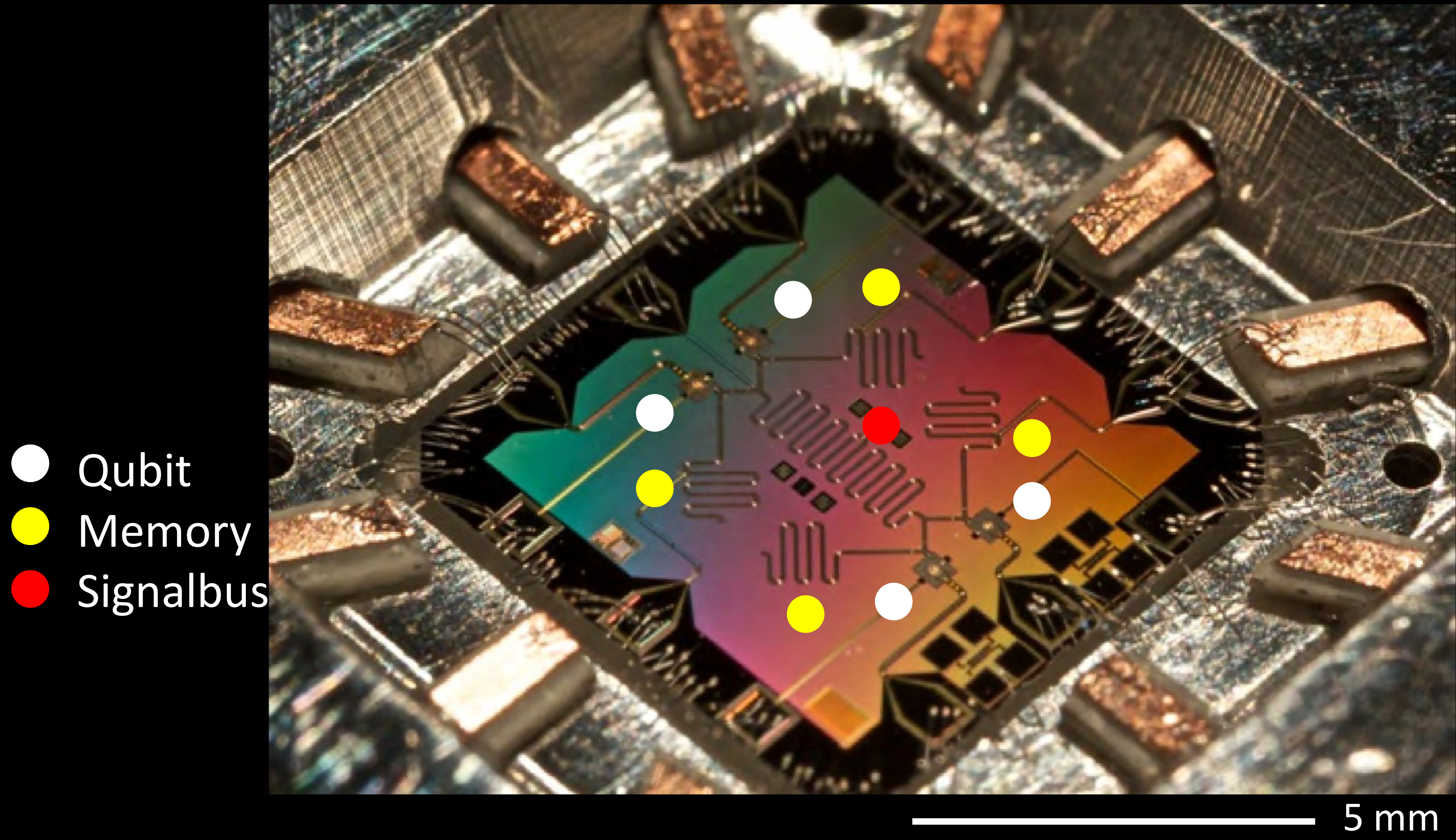


Microscopic
- Superconducting circuits

perfect DC conductor w/ low AC loss



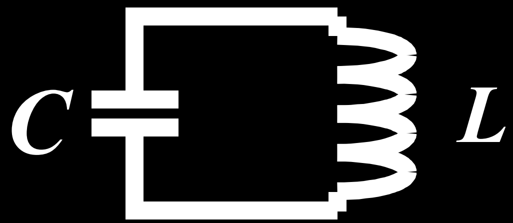
Microstructured quantum processor
(University of California, Santa Barbara)



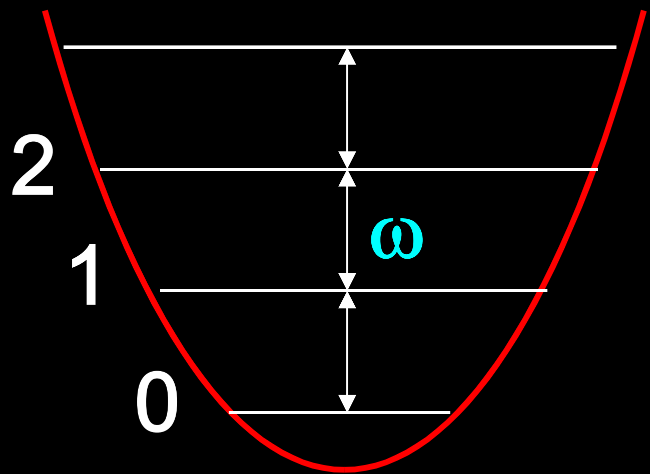
Lucero *et al.*, Nature 2012

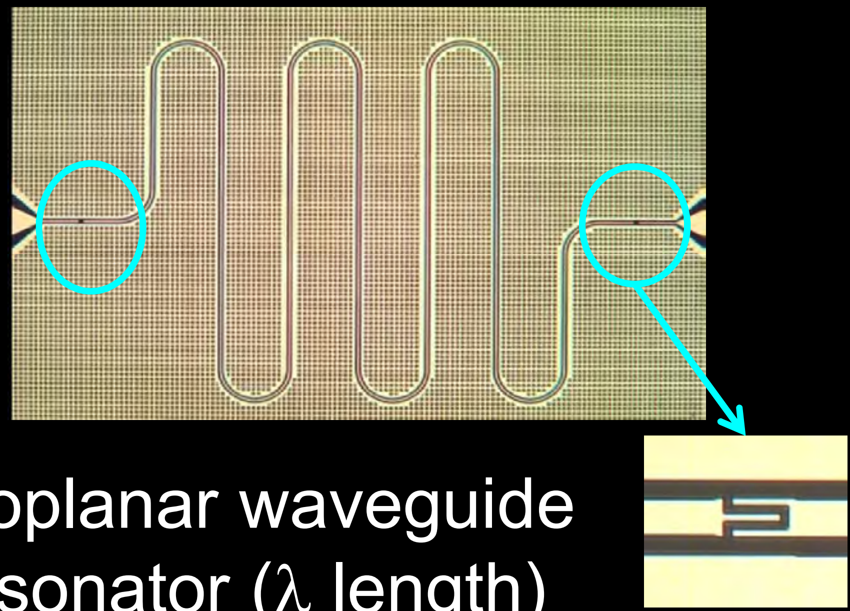
SUPERCONDUCTING RESONATORS AND QUBITS

Harmonic oscillator w/ superconductors



LC (linear) oscillator
→ No atom/qubit





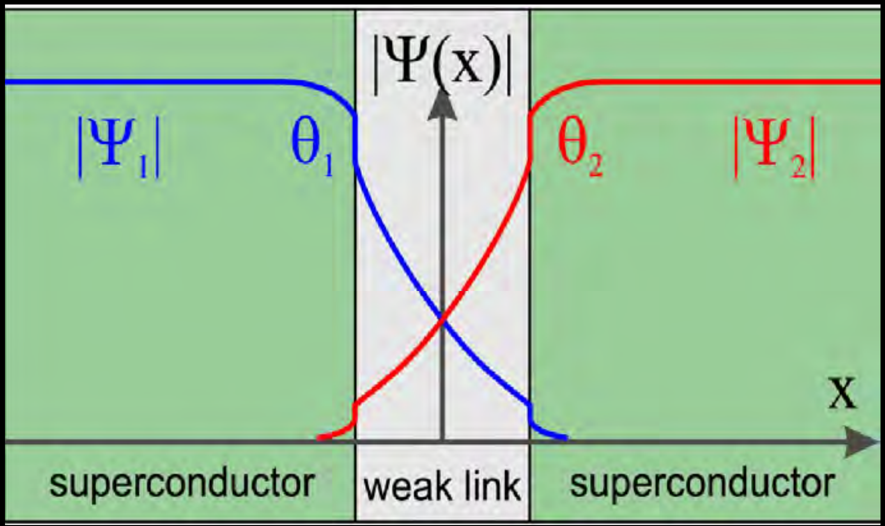
Coplanar waveguide resonator (λ length)

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

$$Q = 1/\tan\delta$$

quality factor Q
loss tangent δ

Josephson junction → non-linear inductor



$$\Psi = |\Psi| \exp(i\theta)$$

Phase difference

$$\phi = \theta_1 - \theta_2$$

1st Josephson eq.: $I_J = I_c \sin\phi$ (DC)

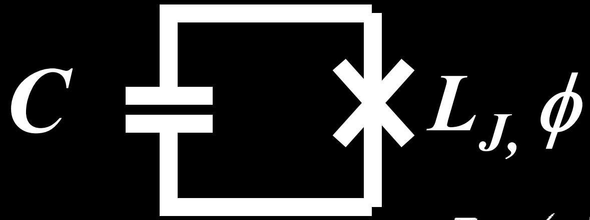
2nd Josephson eq.: $V = \frac{\Phi_0}{2\pi}\frac{\partial\phi}{\partial t}$ (AC)

From DC: $\frac{\partial I_J}{\partial\phi} = I_c \cos\phi$

Insert in AC: $V = \frac{\Phi_0}{2\pi}\frac{1}{I_c\cos\phi}\frac{\partial I_J}{\partial t} = L_J\frac{\partial I_J}{\partial t}$

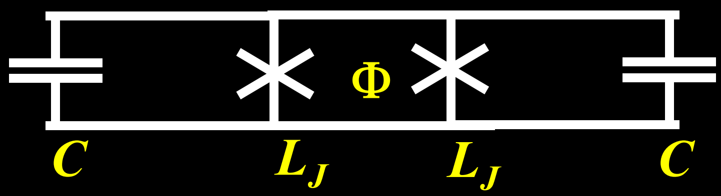
→ non-linear inductance: $L_J(\phi) = \frac{\Phi_0}{2\pi}\frac{1}{I_c\cos\phi}$

Capacitively shunted Josephson junction → Anharmonic oscillator



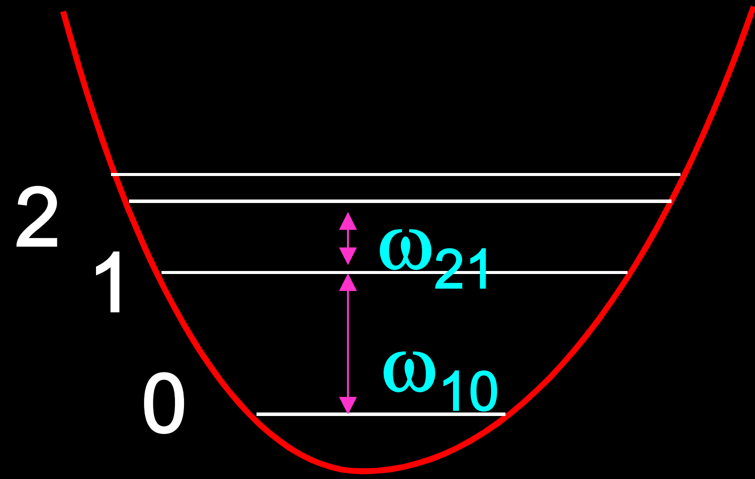
$$L_J(\phi) \propto \frac{1}{I_c \cos\phi}$$

non-linear LC oscillator

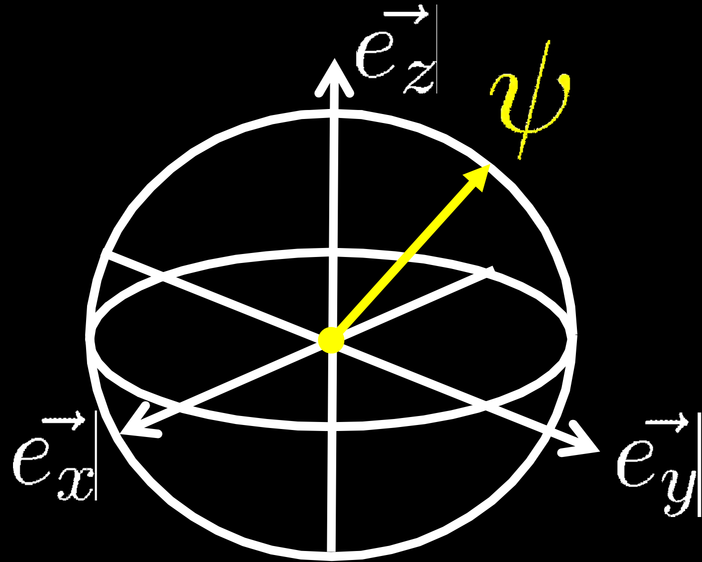


Magnetic flux Φ changes $L_{\mathrm{J}}(\phi)$

$$\omega_{10} = 1/\sqrt{CL_J(\Phi)}$$

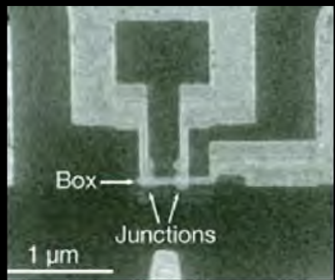


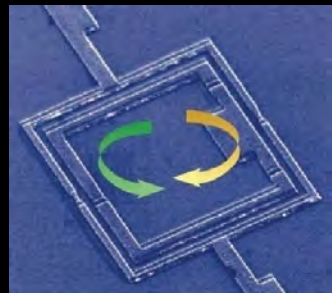
Restrict to two lowest states → **Bloch sphere**

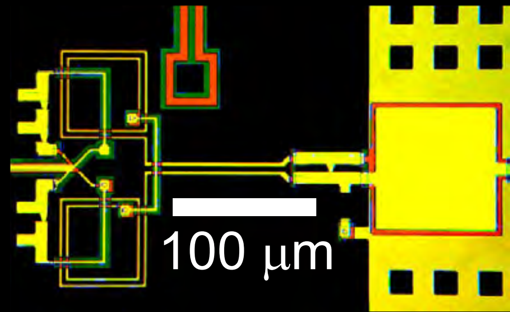


Superconducting qubit ’zoo’

$[\hat{q}, \hat{\phi}] = i\hbar$	Charge	Flux	Phase
$E_J/E_C = \frac{I_c\Phi_0}{2\pi} / \frac{e^2}{2C}$	1	10^2	10^4
Junction area (μm^2)	0.01	0.1-1	1-100

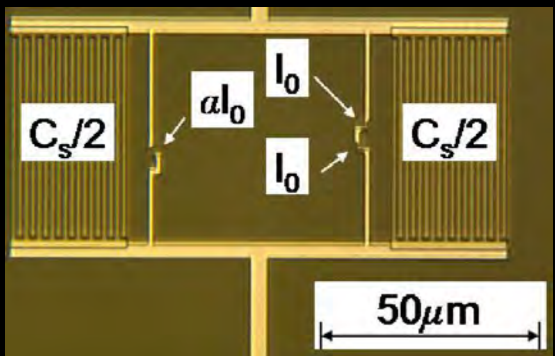




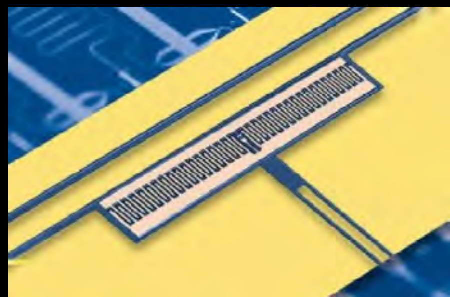


Modern designs

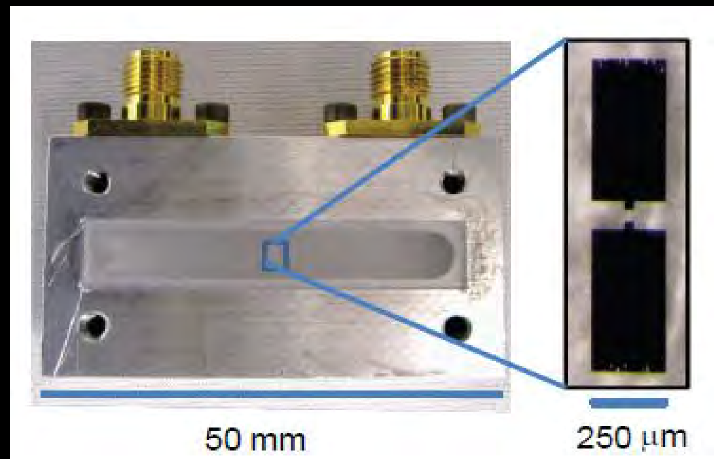
C-shunted flux qubit



Transmon=
C-shunted charge qubit



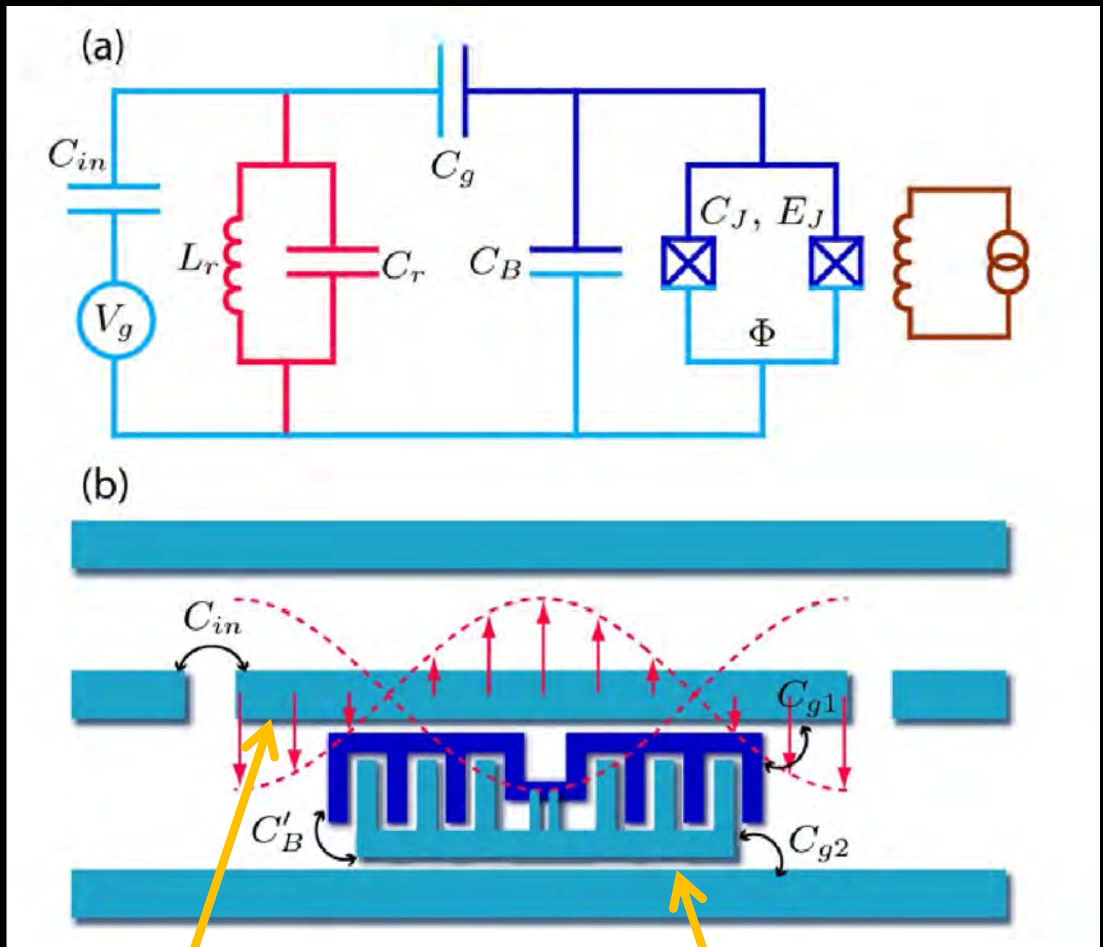
3d transmon



circuit quantum electrodynamics (cQED): artificial atom (qubit) coupled to resonator

$$\hat{H} = \hbar\omega_r \hat{a}^\dagger \hat{a} + \hbar\omega_q \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}\hat{E}\hat{S}$$

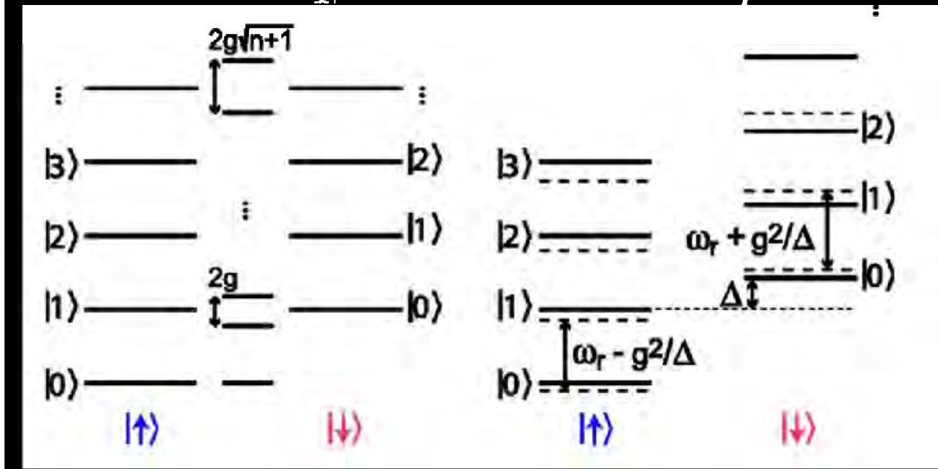
Strong coupling regime possible

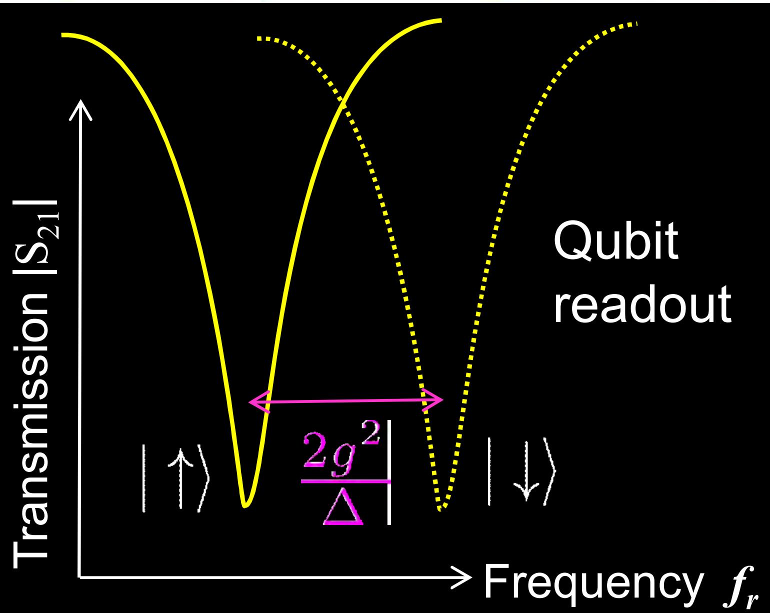


Resonator

Qubit

$\omega_r = \omega_q$ $\quad\quad$ $\omega_r = \omega_q - \Delta$





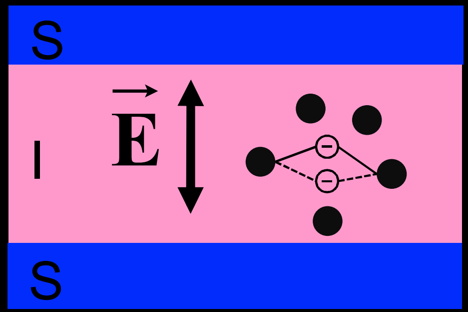
Koch *et al.* PRA 2007, Blais *et al.* PRA 2004

Research goals

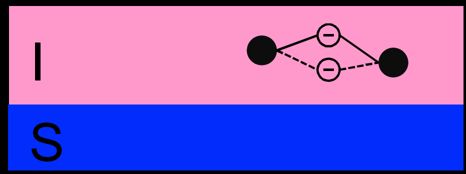
- Quantum material science
  - Junctions, resonators
  - Dynamical control of TLS, monitored with qubit

- Quantum simulation
  - Spin-Boson system
  - Multi-partite entangled systems

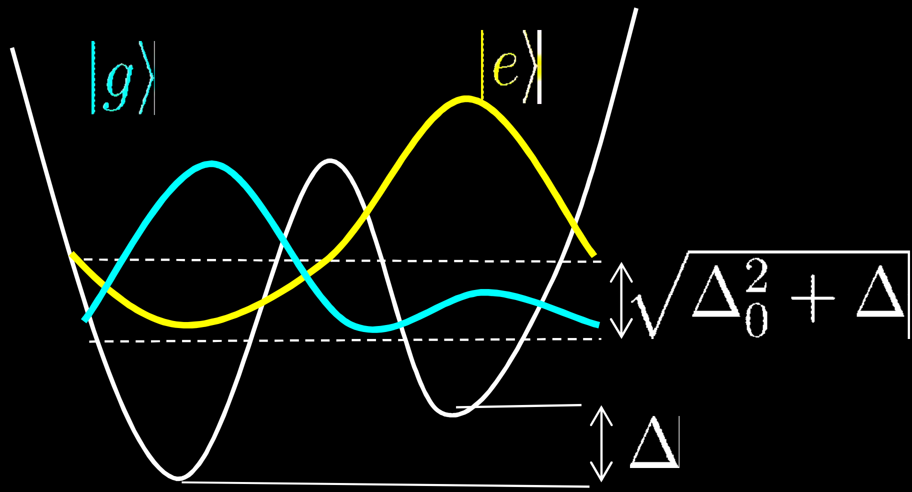
Parasitic two level systems (TLS) in dielectrics



Josephson tunnel junction



resonator



Amorphous oxides loaded with uncompensated charges ~ $10^{16}/\mathrm{cm}^3$

Range of energies, coherence and Rabi frequencies Δ, T_1, T_2, Ω

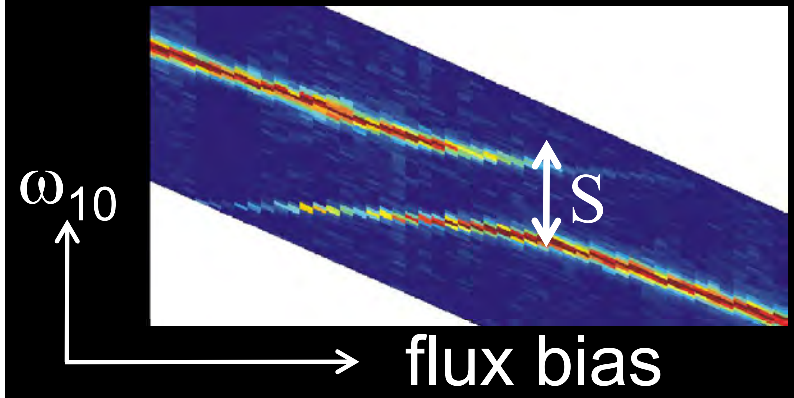
Absorption probability goes as ~ $$\frac{\tanh\left(\frac{\hbar\omega}{2k_BT}\right)}{\sqrt{1+\left(\frac{E}{E_c}\right)^2}}$$

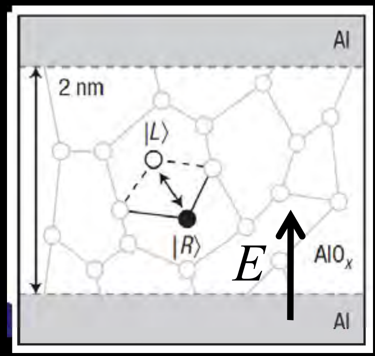
Maximized at low E, T

→ Dominating loss at low T & E

Schickfus, Hunklinger (1975)
Katz *et al.*, PRL (2010)

Decoherence due to TLS

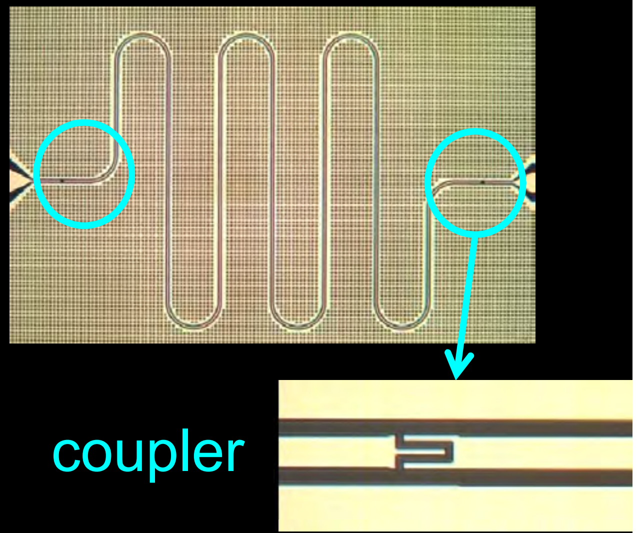




interaction S lifts degeneracy

Qubit spectroscopy and time domain

TLS located in *tunnel barrier oxide*



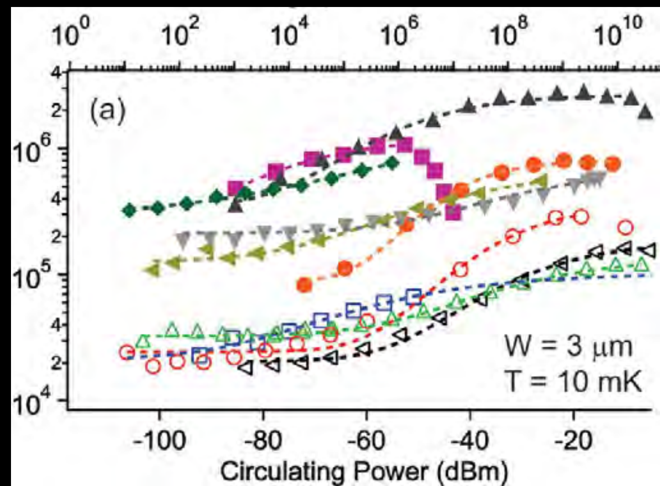
Resonator quality factor

power dependence (TLS saturation)

$$Q^{-1} = Q^{-1}_{\mathrm{TLS}}(E) + Q^{-1}_{\mathrm{P.I.}}$$

$$Q^{-1}_{\mathrm{TLS}} \propto \frac{\tanh\left(\frac{\hbar\omega}{2k_B T}\right)}{\sqrt{1+\left(\frac{E}{E_c}\right)^2}}$$

$$Q = 1/\tan\delta$$

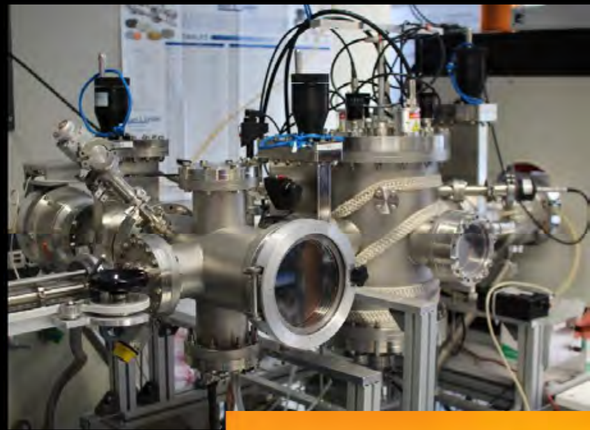


Sage *et al.* JAP '10

GETTING STARTED (2012-) DEPOSITION, FABRICATION MEASUREMENT

Deposition tools

Fast turnaround, flexibility, reliability, good control
Deposition, cleaning, oxidation
Al-AlO$_x$-Al tunnel junctions

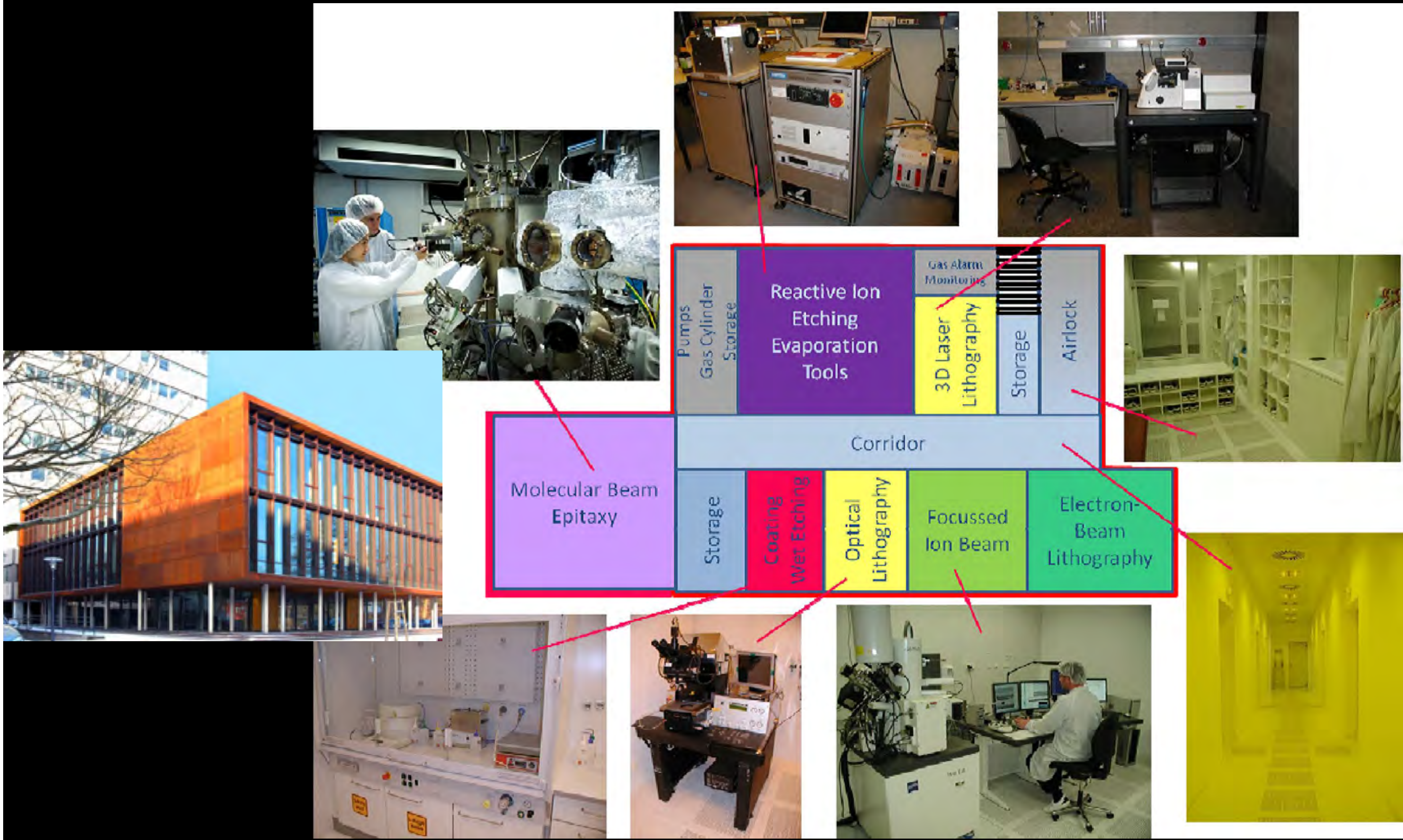


- **Sputter tool** Plasma 1
  - Al, Nb, NbN, AlO$_x$ resonators

- **Shadow evaporation tool** Plassys
  - E-beam evaporator
  - Al-shadow evaporated junctions
  - Ti/Au markers, AuPd resistors

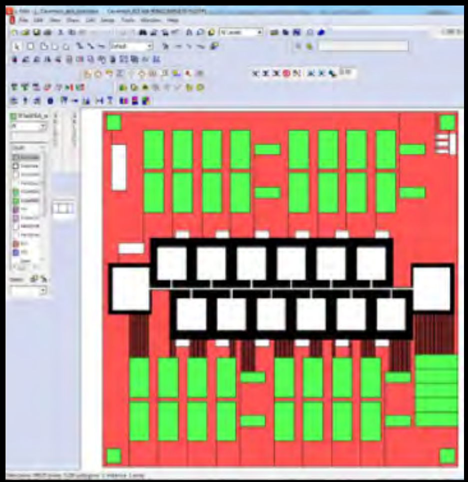
- **Sputter tool** Plasma 2
  - Nitride superconductors
  - Heating stage (500°C)

DFG Center for Functional Nanostructures
Nanostructure Service Laboratory

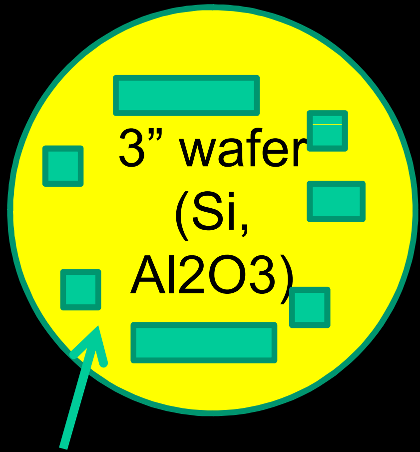


Schematic fabrication

1. Design software

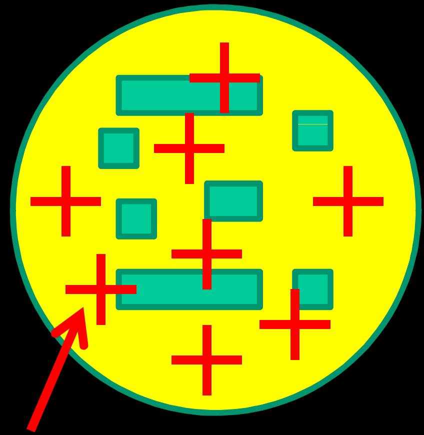


2. Film deposition, optical litho, etch



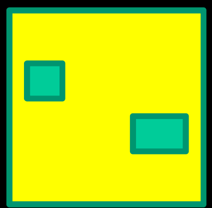
Inductor, capacitor, flux bias…
(1 µm+ feature sizes)

3. E-beam markers optical litho



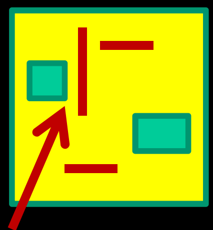
Markers (crosses etc.)

4. Dice into $20 \times 20\ \mathrm{mm}^2$



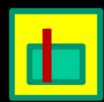
Get 6 chips w/
same designs

5. E-beam litho, Al-$\mathrm{AlO_x}$-Al shadow evaporation



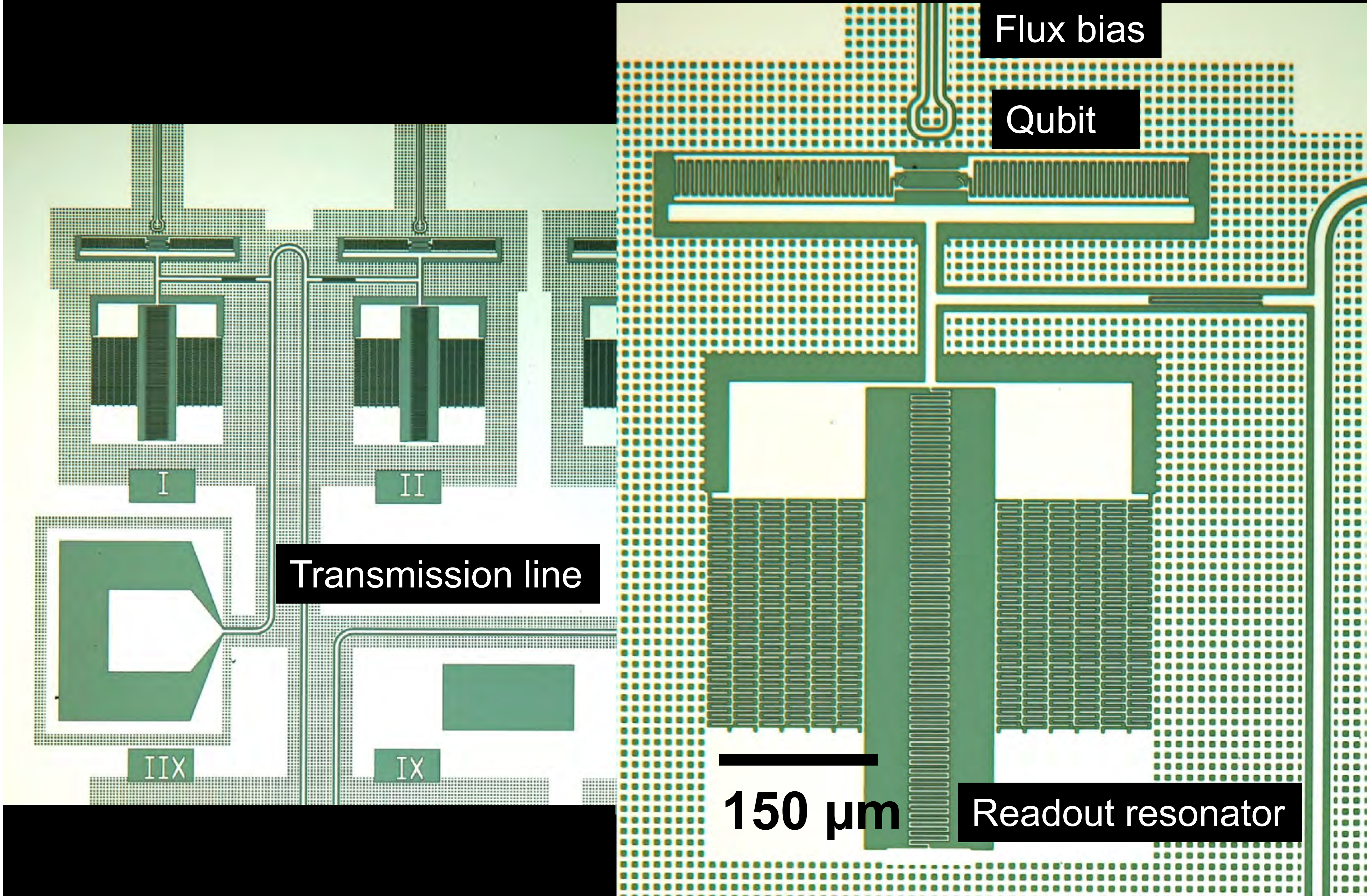
‘Dolan’ bridges,
Tunnel junctions, …

6. Dice into $5 \times 5\mathrm{mm}^2$



Get 9 chips w/
different designs

12 qubit chip 'cavemon'



$^3He/^4He$ dilution refrigerator

400 mm cold plate

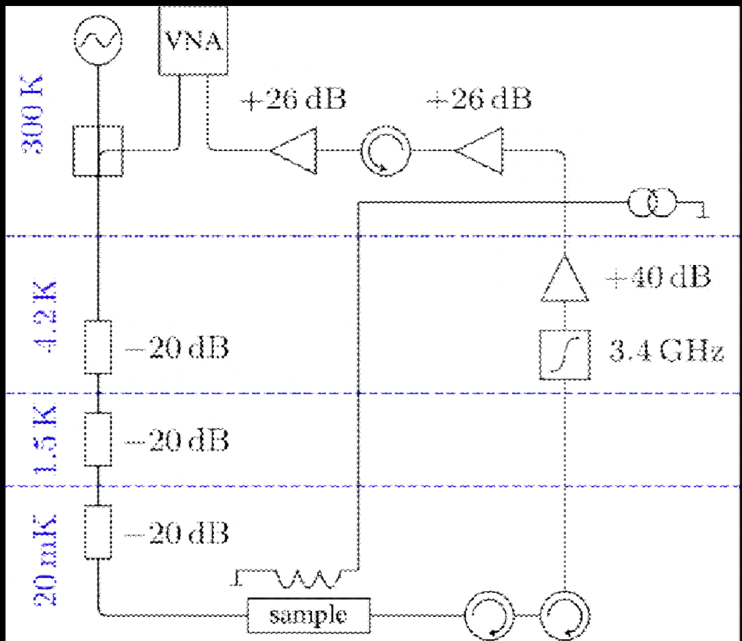
18 coax lines, 24 filtered DC lines

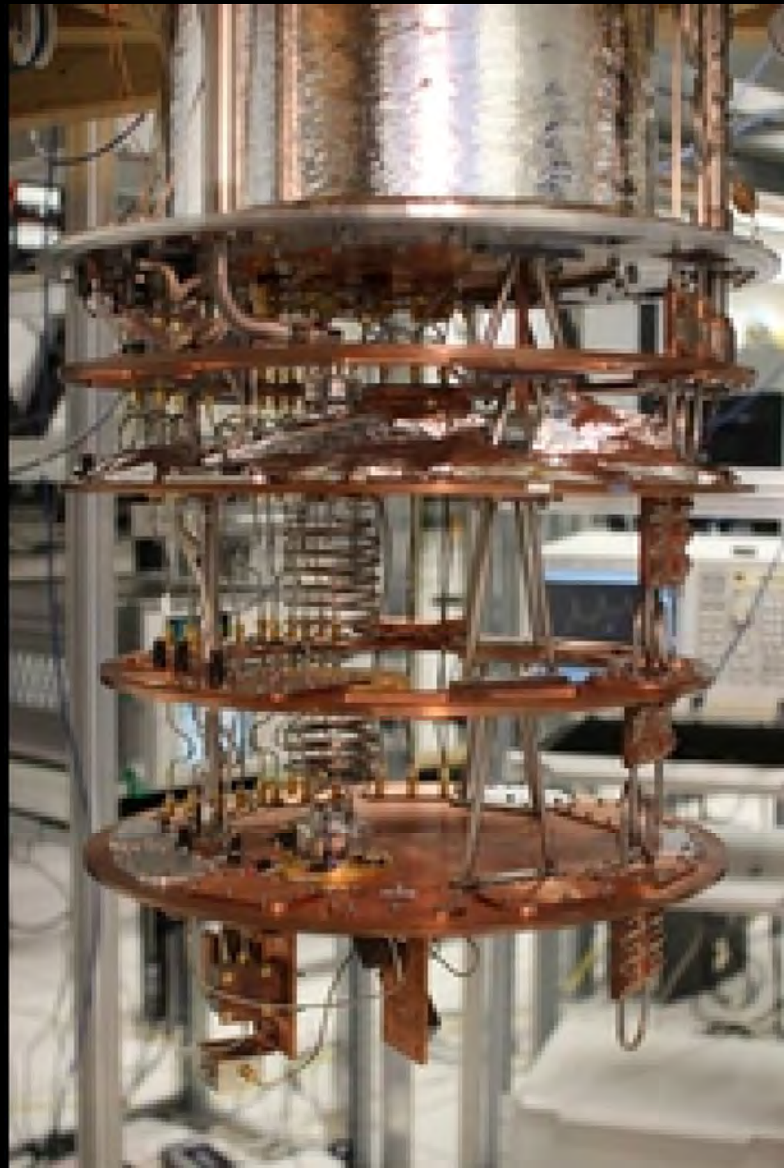
6 HEMTs (2x LNF)

2-port, 4-port microwave switches,
  circulators, filters, infrared shield…

Fits 9 samples

Multi-tone spectroscopy, flux bias,
  time domain measurements



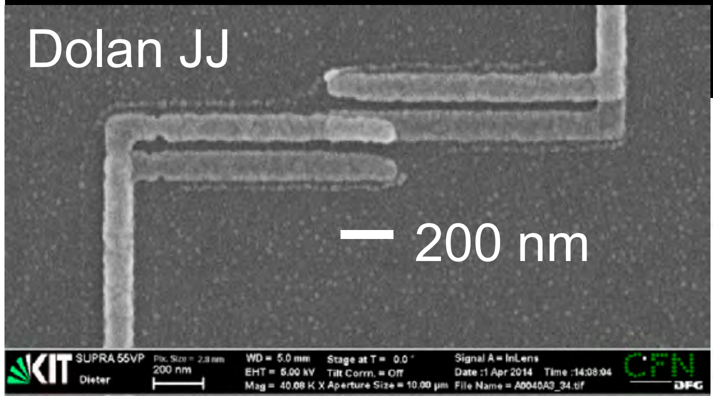


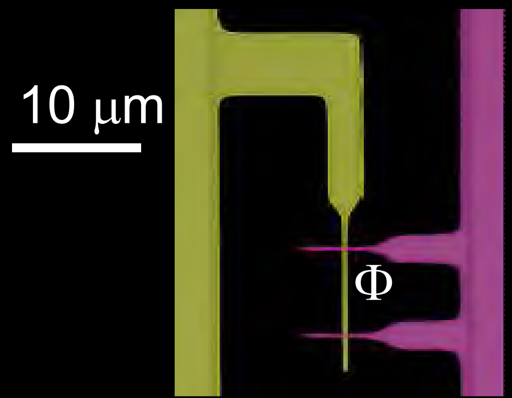
FIRST RESULTS

Josephson tunnel junctions

Al-AlO$_x$-Al junctions

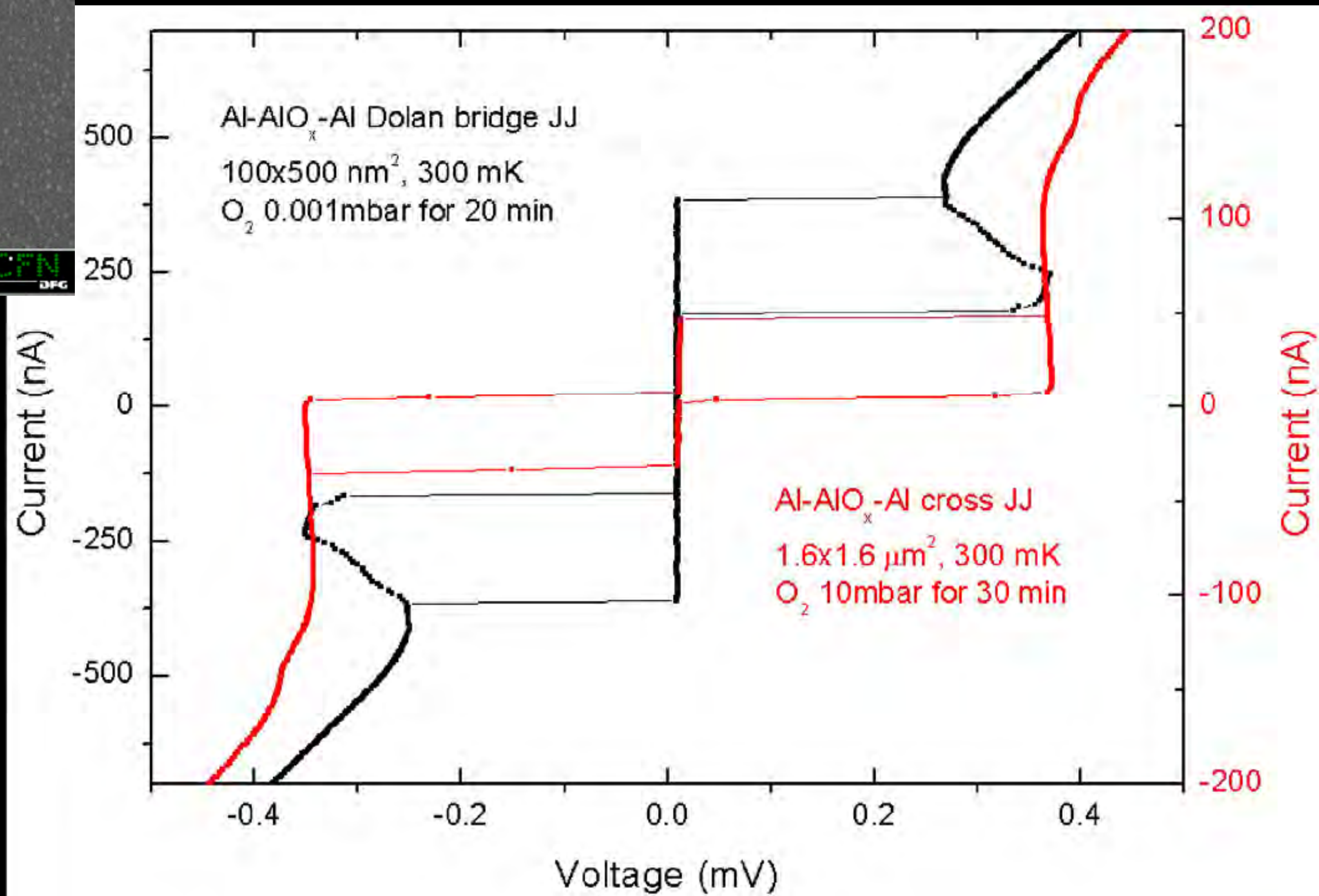
- Ultra-small shadow evaporated (aka *Dolan* JJs)
- Micron-sized *cross* JJs, evaporated and sputtered





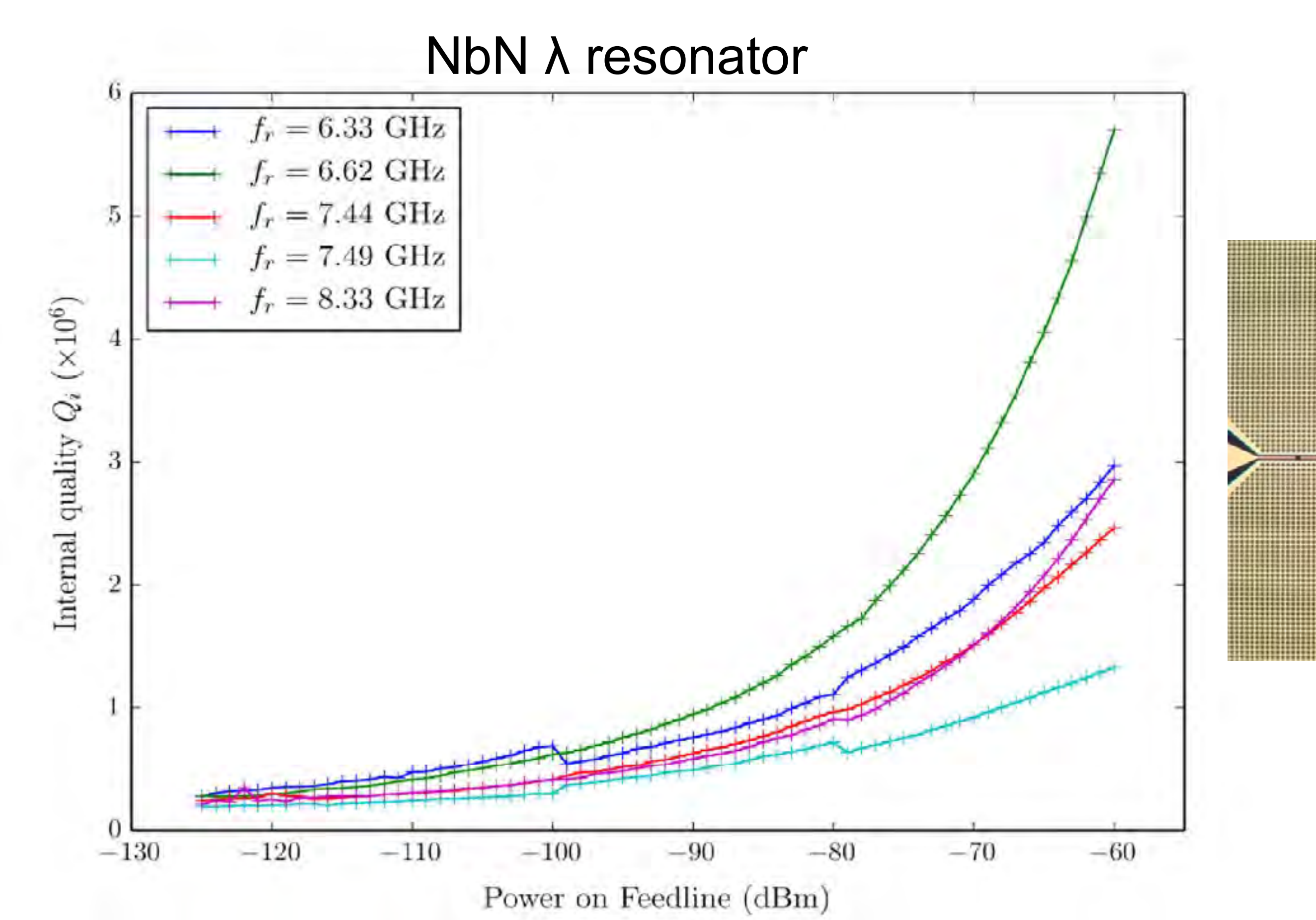
Cross JJ

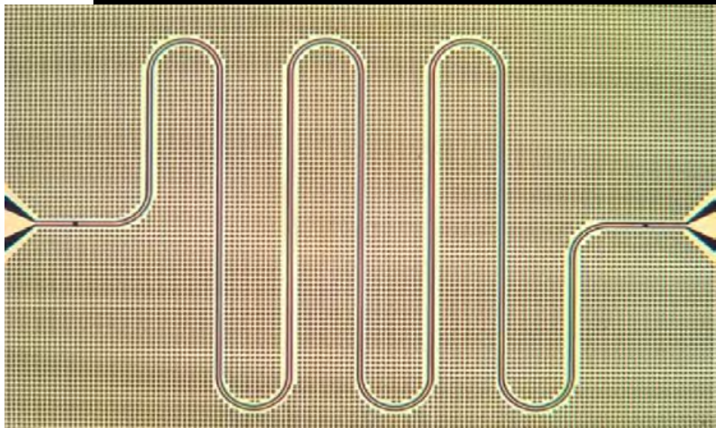
Current-voltage characteristic at 300mK



Microwave resonators

Internal quality factor versus power



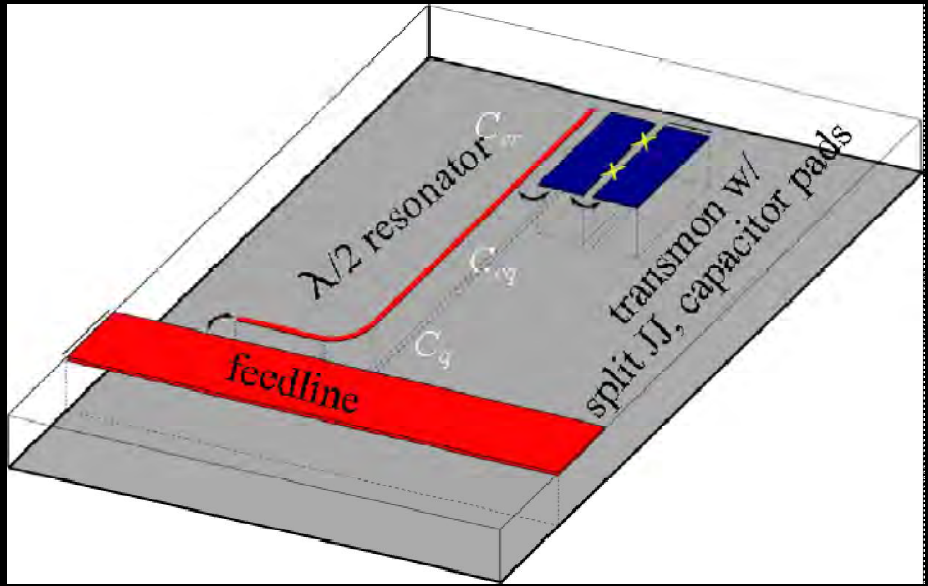


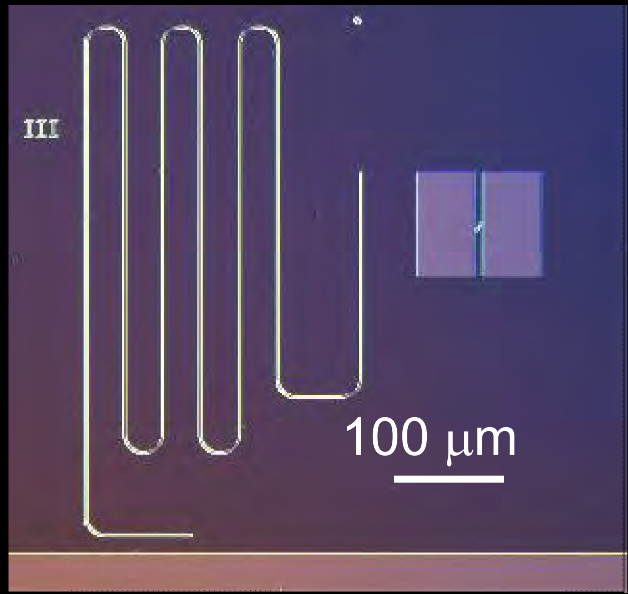
Al, Nb, NbN, and AlO_x resonators

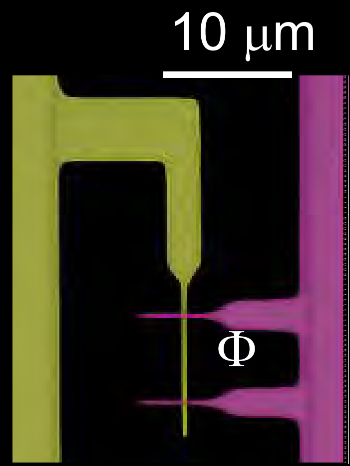
quality factors Q:100k @single photon, 1M+ @high power

Designs: Geometric, lumped element, spiral,
coplanar waveguide, microstrip

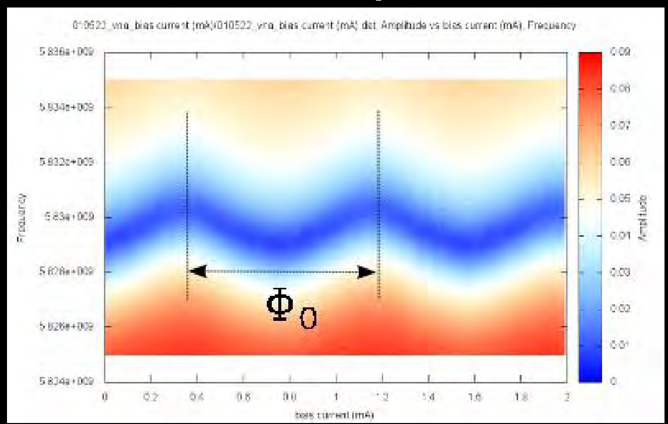
Microstrip transmon qubits (non-tunable and tunable)



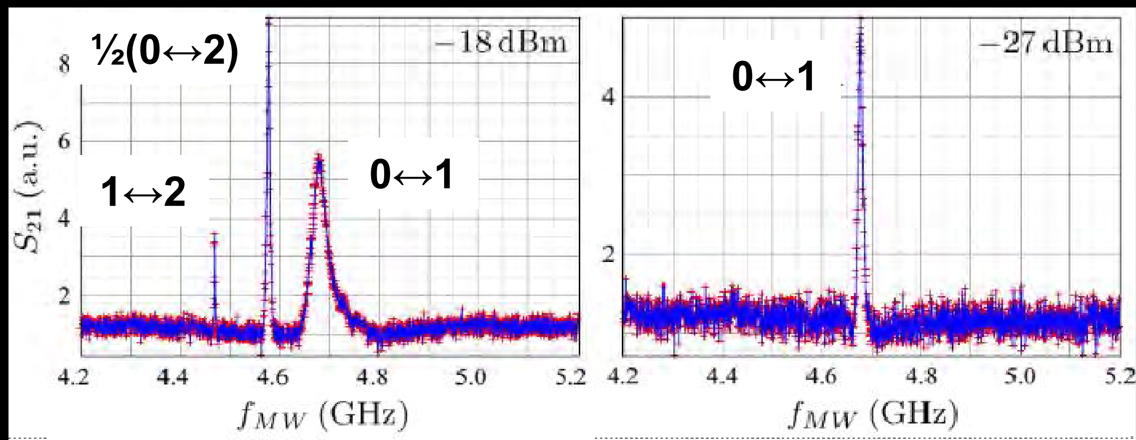




Flux Φ to qubit resonator response



Qubit spectroscopy
Increase drive power → higher level visible



Braumüller, MA thesis '13

The team

Egor Kiselev
Kai Kleindienst
Marcel Langer
Markus Neuwirth
Alexander Stehli

Tobias Bier
Joel Cramer
Amadeus Dieter
Peter Fehlner
Marco Pfirrmann
Steffen Schlör

Jochen Braumüller
Saskia Meißner
Sebastian Skacel
Ping Yang

Lucas Radtke

Hannes Rotzinger
Sasha Lukashenko
Michael Meyer
Roland Jehle

Gernot Goll
Alexey Ustinov
Georg Weiß

Thanks for your attention