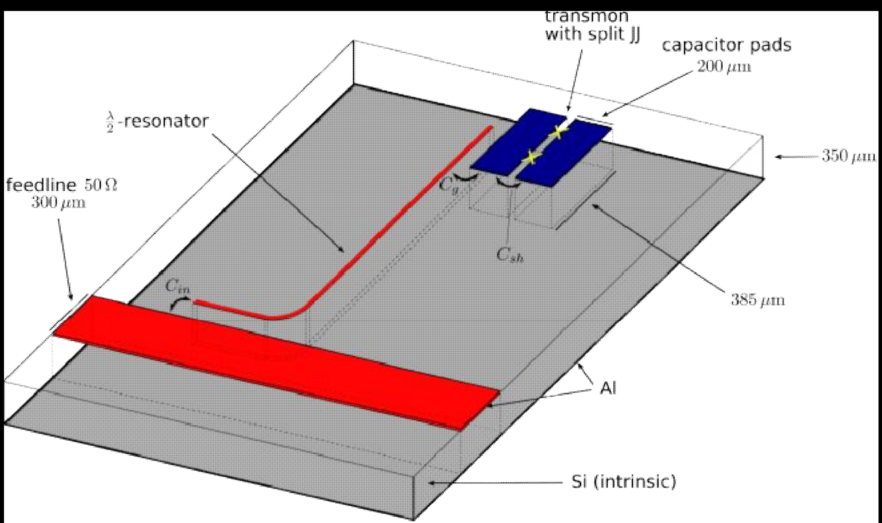
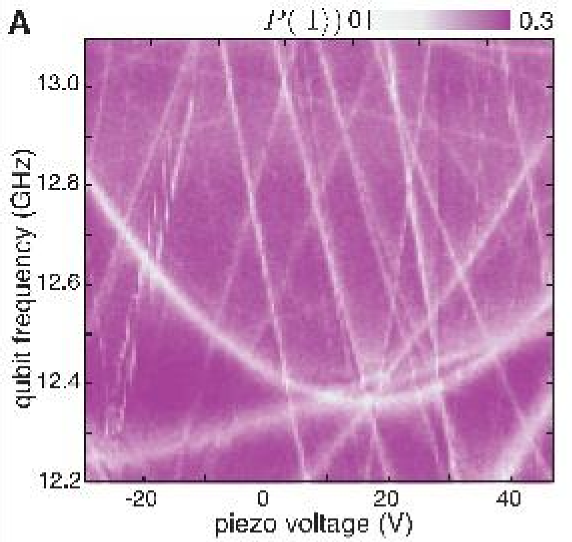
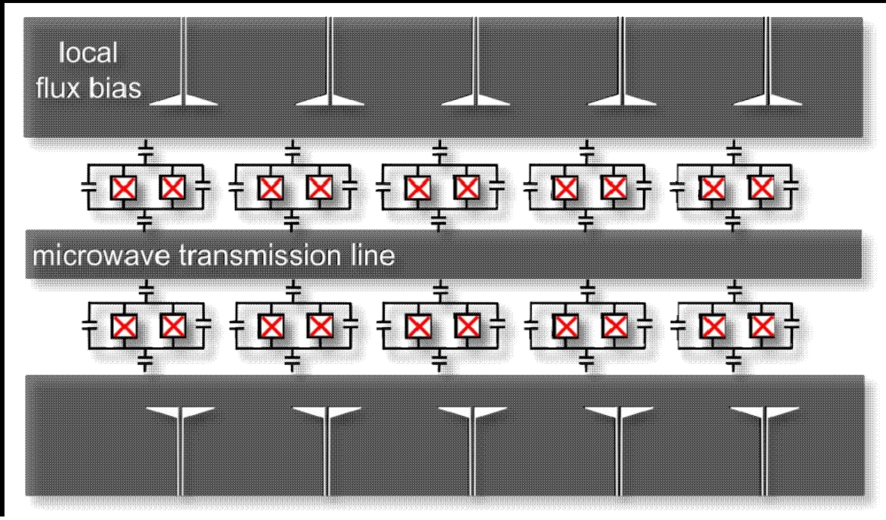
Superconducting quantum bits
-building blocks for quantum matter-





Martin Weides
Karlsruhe Institute of Technology, Germany
QCN Kick-off Meeting Heraklion
Crete, September 5-7, 2013

September 6th, 4:00 pm



Basic potentials

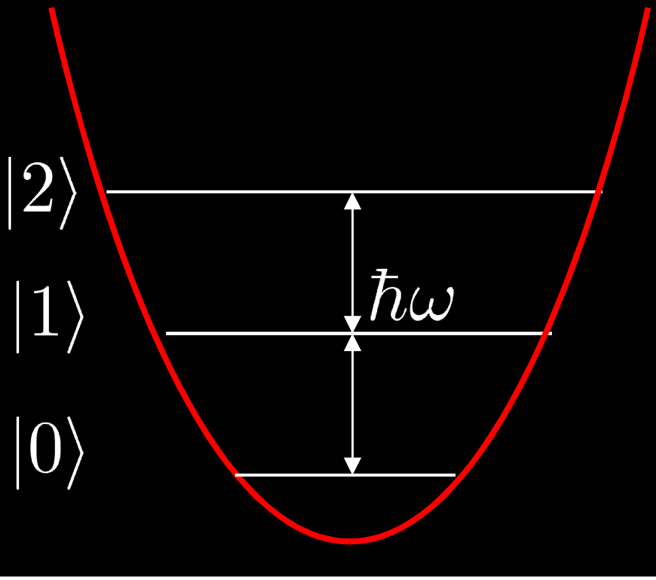
Harmonic oscillator

Photons in cavity, atom oscillation

Energy levels equidistant

Energy eigenstate $|n\rangle$

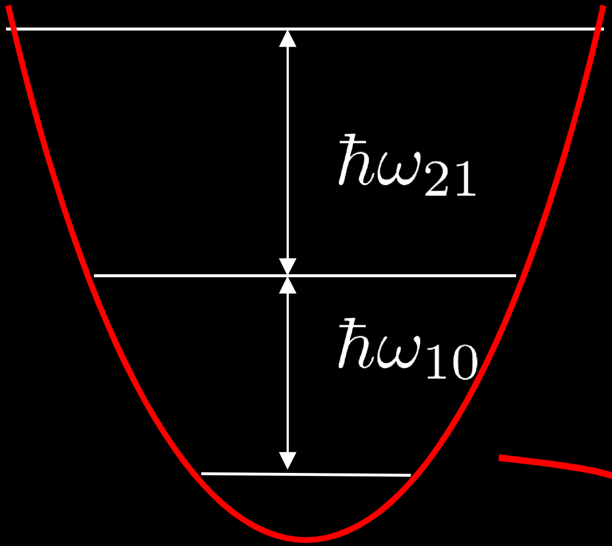
$$\hat{H}_{\text{cavity}} = \left(\hat{a}^{\dagger}\hat{a} + \tfrac{1}{2}\right)\hbar\omega$$



Anharmonic oscillator

Large excitation amplitudes

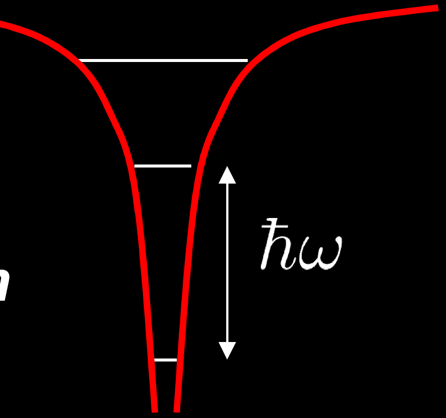
$$\Delta = \omega_{21} - \omega_{10}$$



Two level system

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

atomic transition, spin, qubit



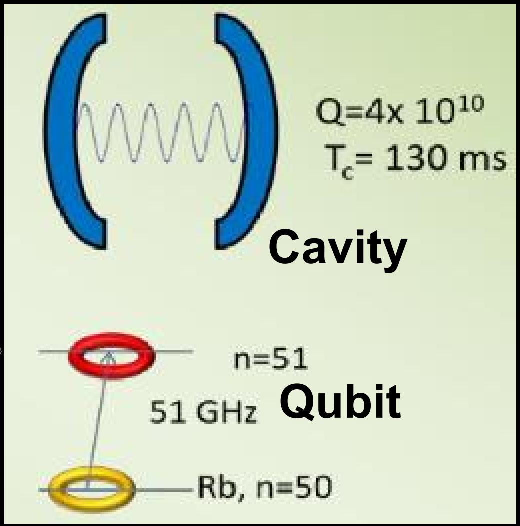
$$\hat{H}_{\text{TLS}} = \hbar\omega\frac{\hat{\sigma}_z}{2}$$

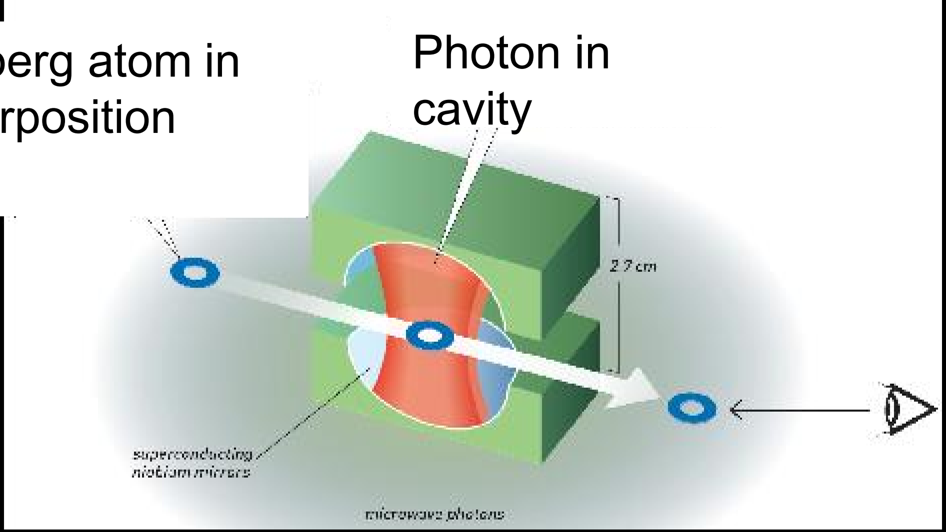
Cavity - two level system coupling

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

Cavity TLS atom (qubit) Interaction

Haroche: Measure one photon in cavity without destroying it

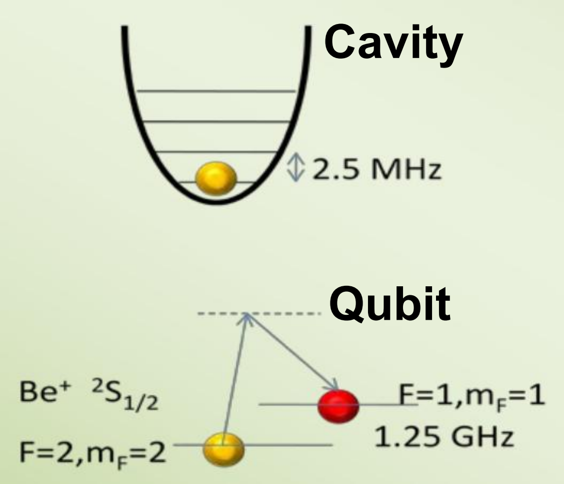


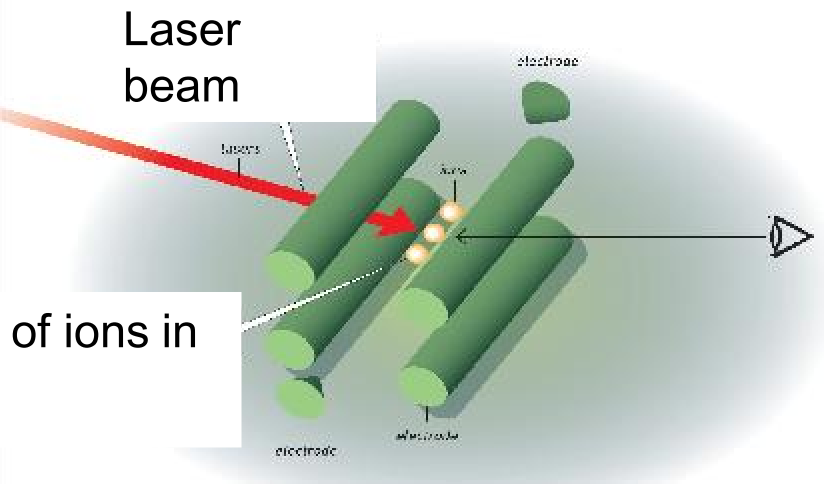


Rydberg atom in superposition state

Photon in cavity

Wineland: Create and transfer superposition of ion states





Laser beam

Chain of ions in cavity

nobelprize.org

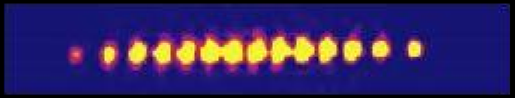
Collective quantum phenomena, quantum simulation, quantum information processing

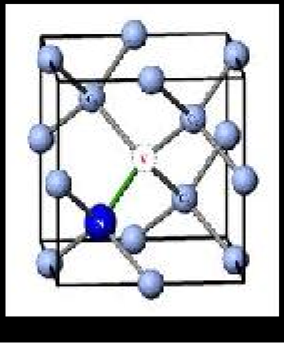
Requirements for quantum matter

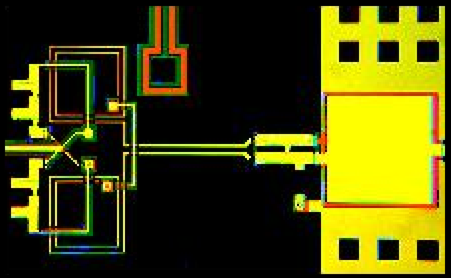
- Tailor atom level and interaction strength (dipole moment)
- Tune level separation (transition frequency)
- Long coherence
- Large anharmonicity (frequency selection)
- High integration density (scalability)

Smaller ⟷ *Bigger*

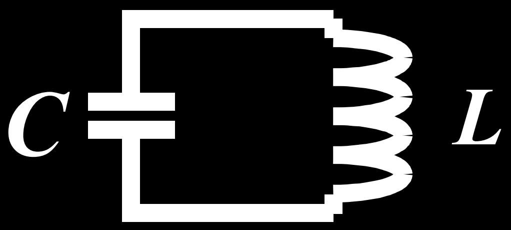
Atomic	Mesoscopic	Microscopic
- Ions	- Semiconductor Spins	- Superconducting circuits
- Neutral Atoms	- Quantum Dots	perfect DC conductor w/
- NMR	- Spin	low AC loss (at GHz)
- Photons		





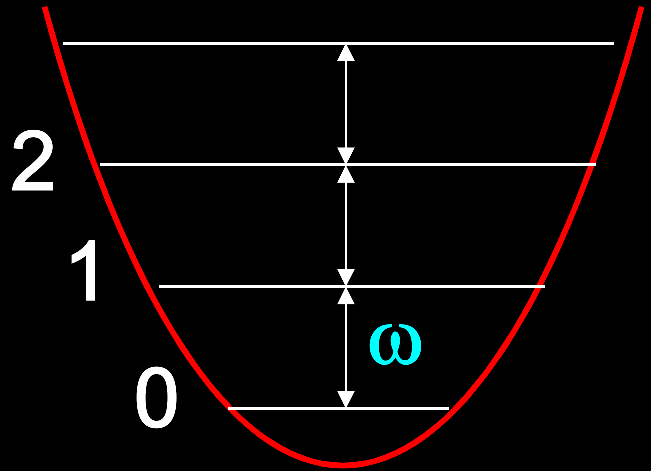


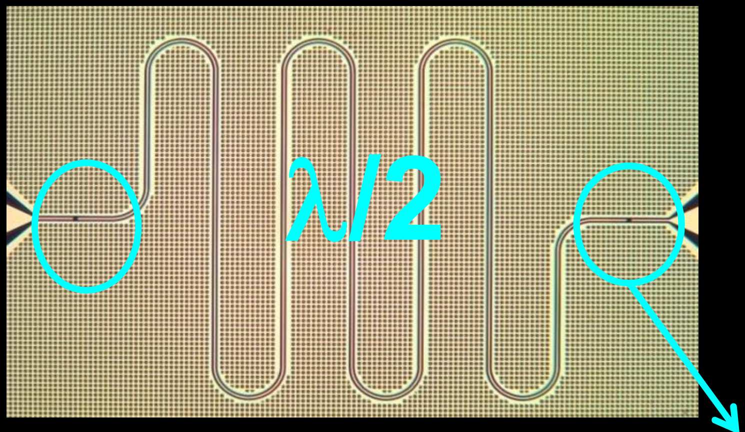
Harmonic oscillator with superconducting circuits



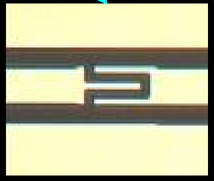
$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{1}{2} L\omega^2 \hat{Q}^2$$

LC (linear) oscillator
→ No atom/qubit





Coplanar waveguide resonator



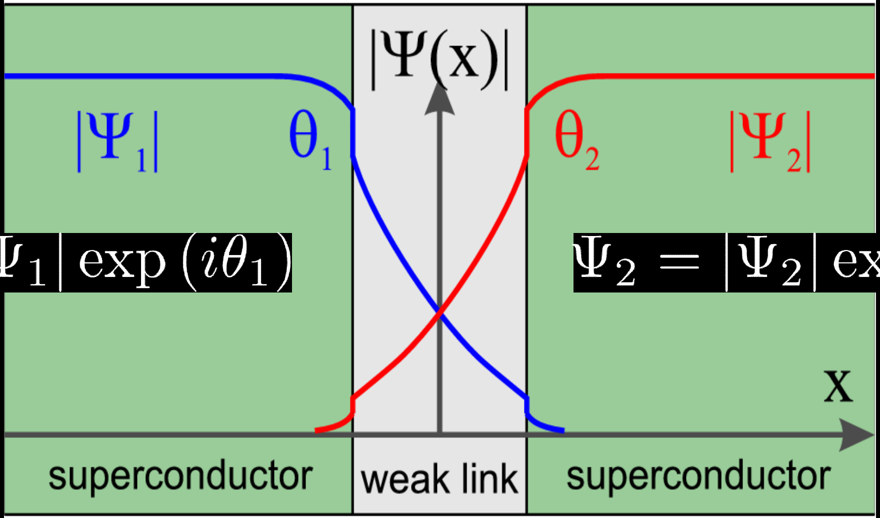
$$\omega = 1/\sqrt{LC}$$

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

$$T_1 = Q/\omega$$

quality factor Q
loss tangent δ

Josephson junction → non-linear inductor



$\Psi_1 = |\Psi_1| \exp{(i\theta_1)}$

$\Psi_2 = |\Psi_2| \exp{(i\theta_2)}$

Phase difference

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

First Josephson equation: $I_J = I_c \sin\phi$ (DC)

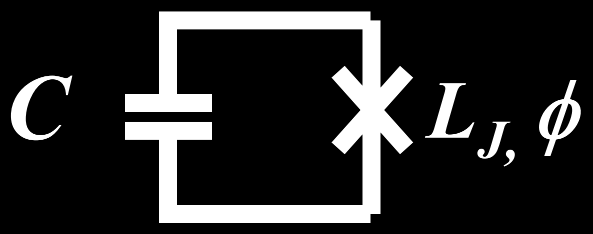
Second Josephson equation: $V = \frac{\Phi_0}{2\pi}\frac{\partial\phi}{\partial t}$ (AC)

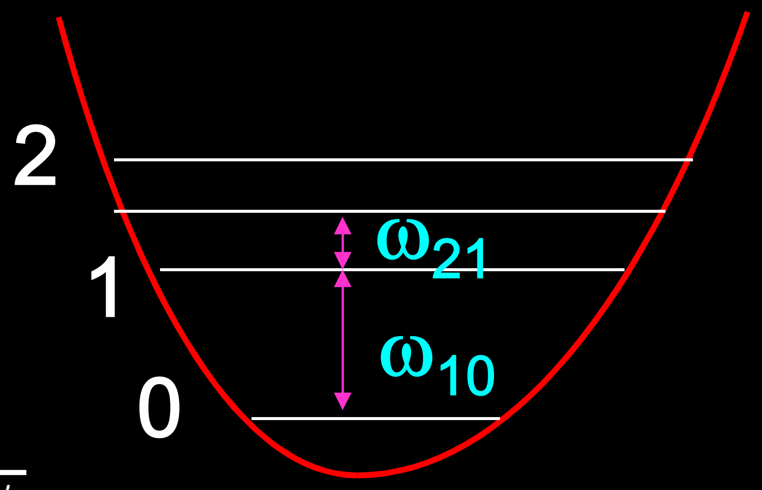
From DC: $\frac{\partial I_J}{\partial\phi} = I_c \cos\phi$

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: $L_J(\phi) = \frac{\Phi_0}{2\pi}\frac{1}{I_c\cos\phi}$

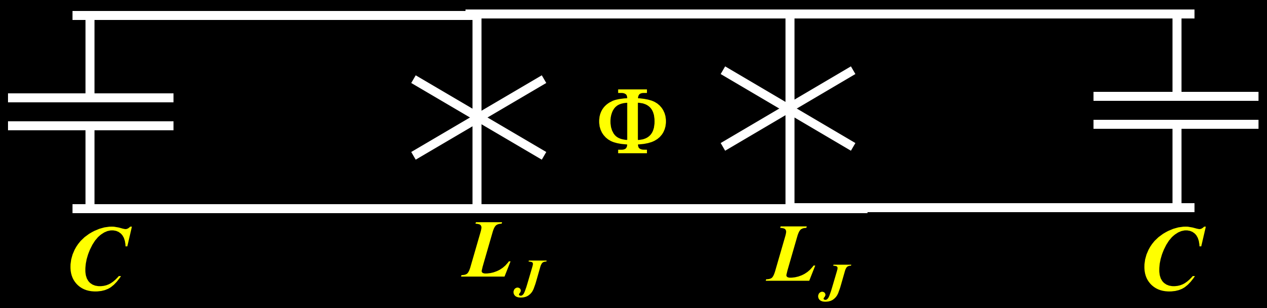
Josephson junction with capacitive shunt → anharmonic oscillator





non-linear LC oscillator

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

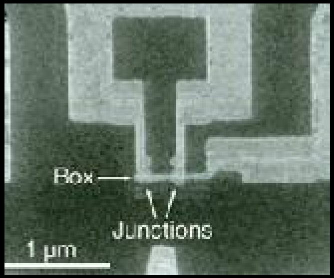


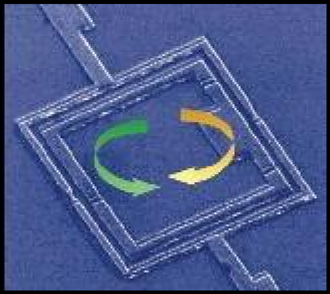
Magnetic flux Φ changes L_J of split Josephson junction

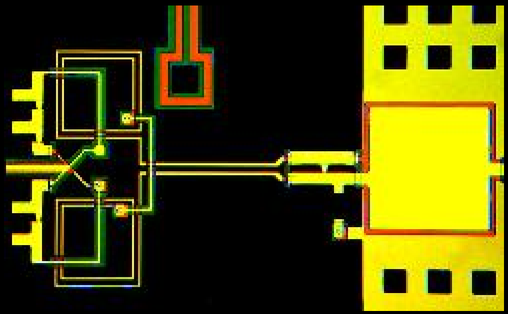
$$\omega_{10} = \omega_{10}(\Phi)$$

Superconducting qubits ‘colors’

$[\hat{q}, \hat{\phi}] = i\hbar$	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

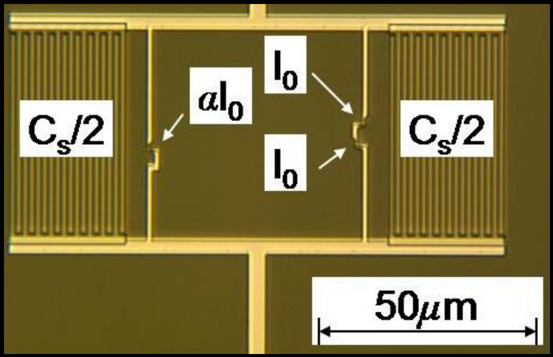




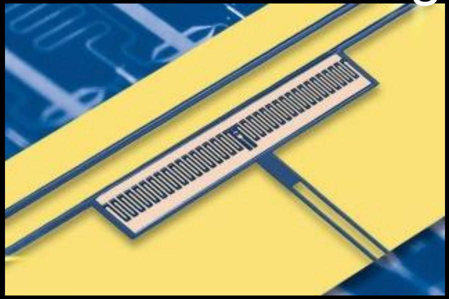


Modern designs

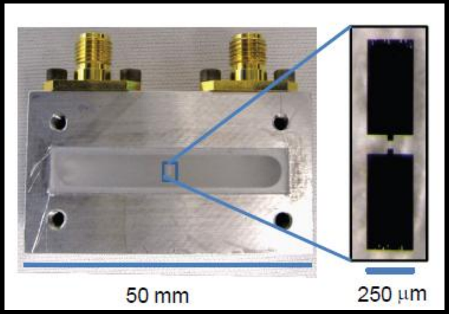
C-shunted flux qubit



Transmon=
C-shunted charge qubit

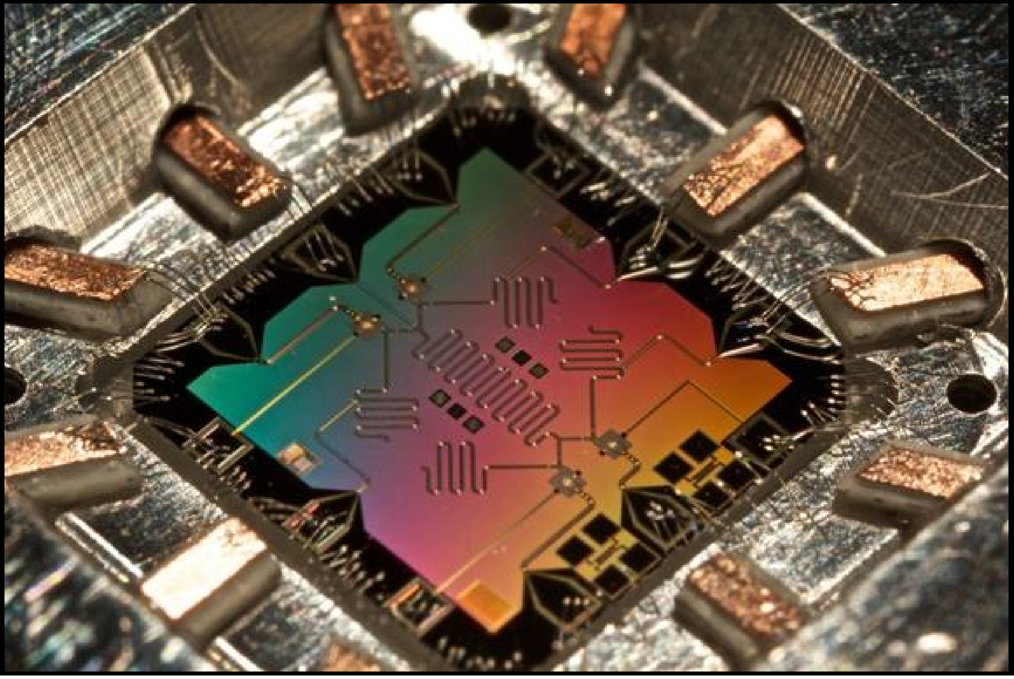


3d transmon



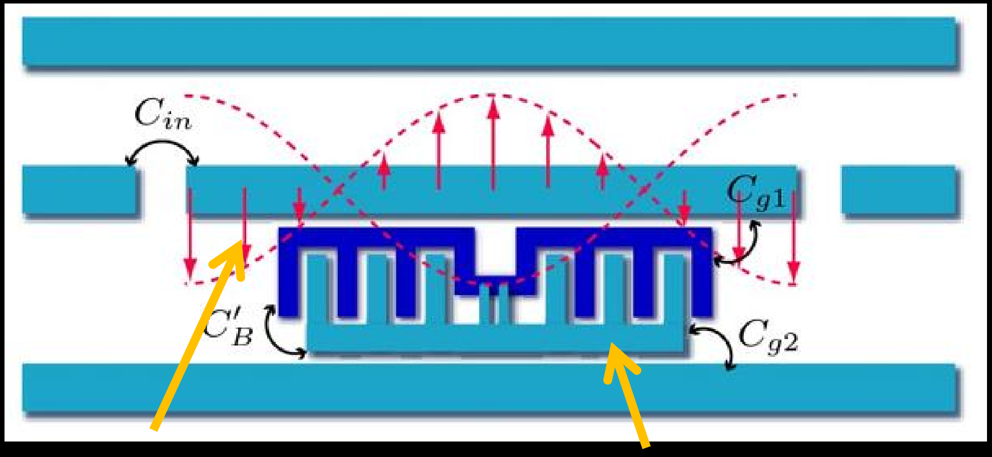
Brief history experimental SC qubits

1999 Charge (NEC), flux (Delft) qubits
2002 Phase qubit (NIST)
2004 cQED with qubits (Yale)
2007 Lasing (NEC)
QND (Delft)
2008 Fock states (UCSB)
2009 Grover and Deutsch–Jozsa (Yale)
Arbitrary quantum states (UCSB)
Bell inequality (UCSB)
2010 3-qubit entanglement
(UCSB & Yale)
2012 4 qubits and
5 resonators (UCSB)



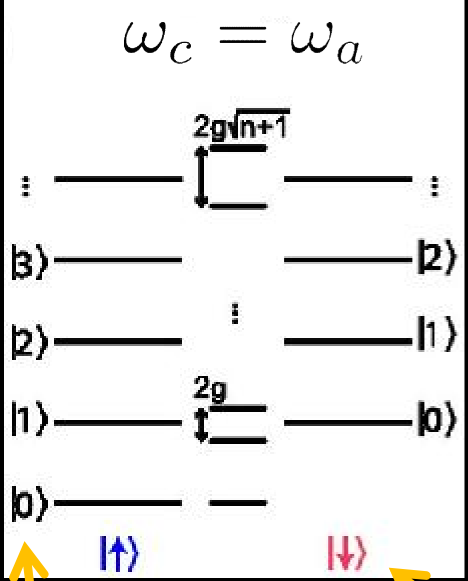
circuit Quantum Electrodynamic
on-chip coupling cavity with qubit

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

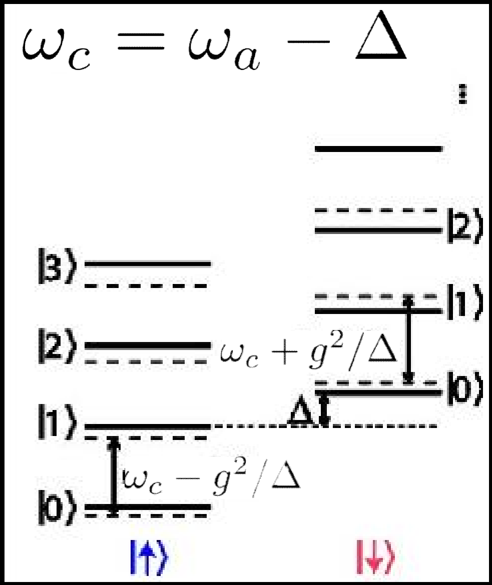


resonator artificial atom/qubit

On resonance



Dispersive



Cavity states artificial atom/qubit states

$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_a \frac{\hat{\sigma}_z}{2} + \hbar g \left(\hat{a}^\dagger \hat{\sigma}^- + \hat{\sigma}^+ \hat{a}\right)$$

On resonance (Δ=0)

→ collective quantum phenomena, quantum simulation

Dispersive limit (large Δ)

→ quantum information processing

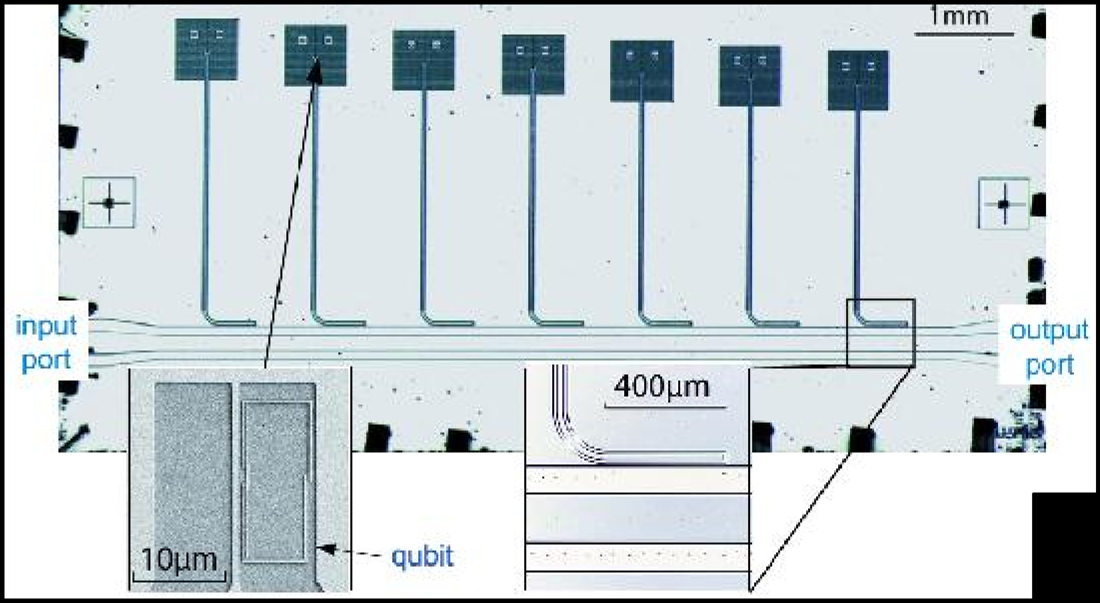
Research at KIT (Ustinov group)

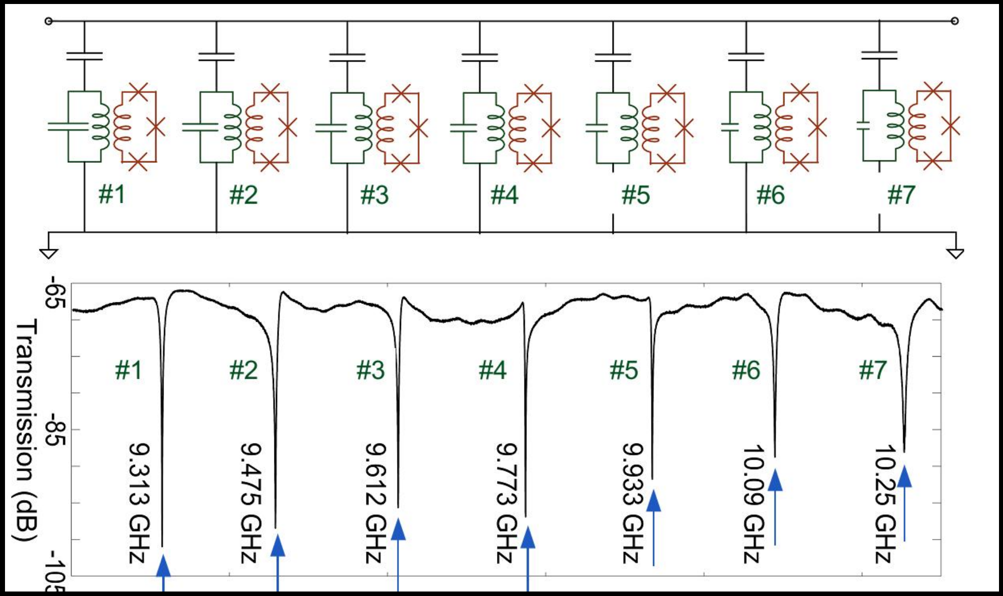
- **Qubits (Phase, flux, transmon)**
  - **Coherence, scalability, dielectric defect states (TLS)**
- Quantum phase slip (w/ H. Mooij)
  - Complementary to Josephson junctions, current standard
- Hybrid spin-solid state qubits
  - Couple optical w/ microwave transitions, memory element
- **Classical metamaterials**
  - **Tailor EM environment, low-loss, tunability**
- **Quantum metamaterials (started)**
  - **quantum matter, multipartite entanglement**

Qubits

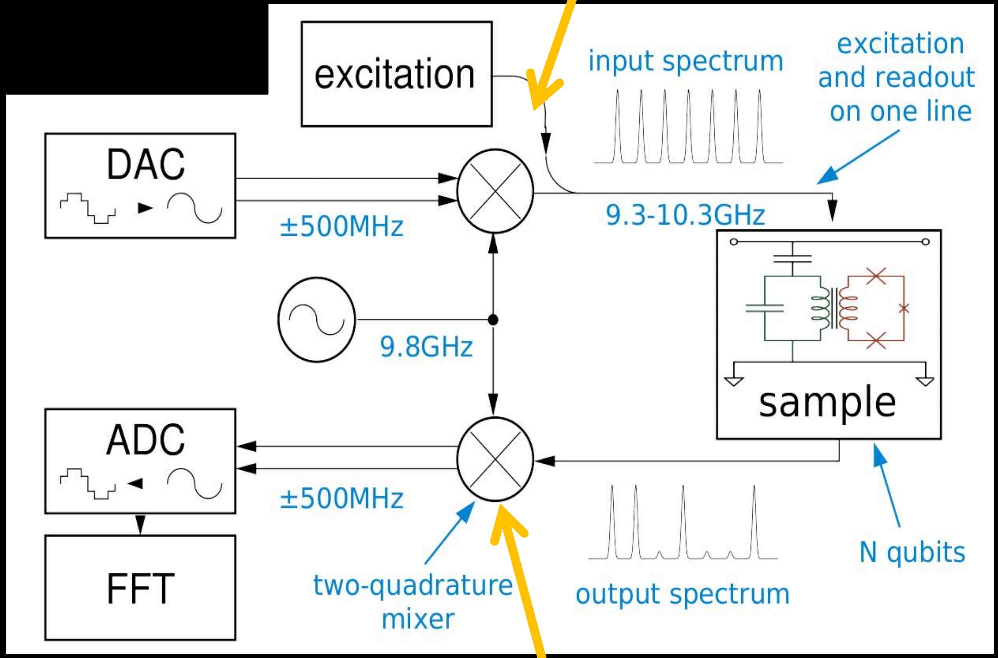
Multi-quantum bit system (seven resonators & qubits)

- Flux qubits inductively coupled to readout resonator
- Frequency multiplexed readout



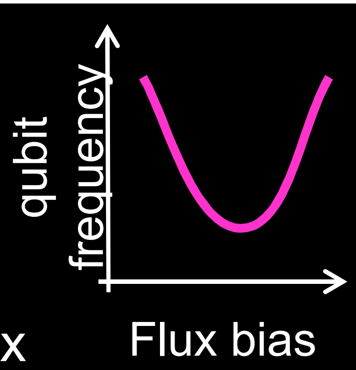


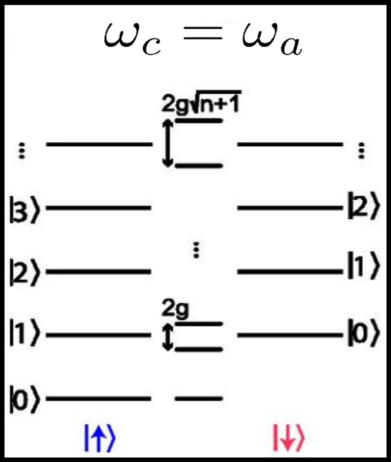
Frequency upconversion f_1+f_{LO0}



Frequency downconversion f_2-f_{LO}

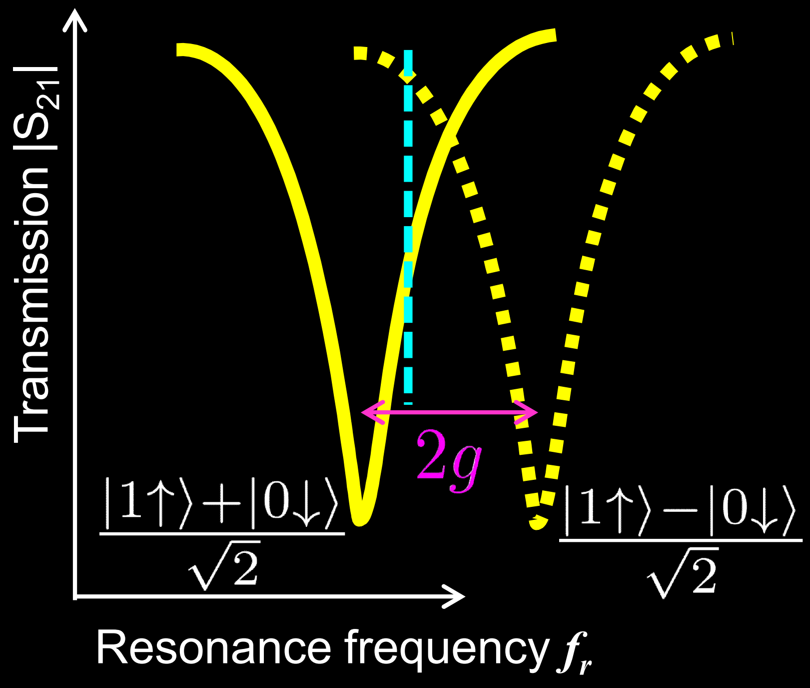
Spectroscopy w/ qubit flux tuning
address and readout qubits

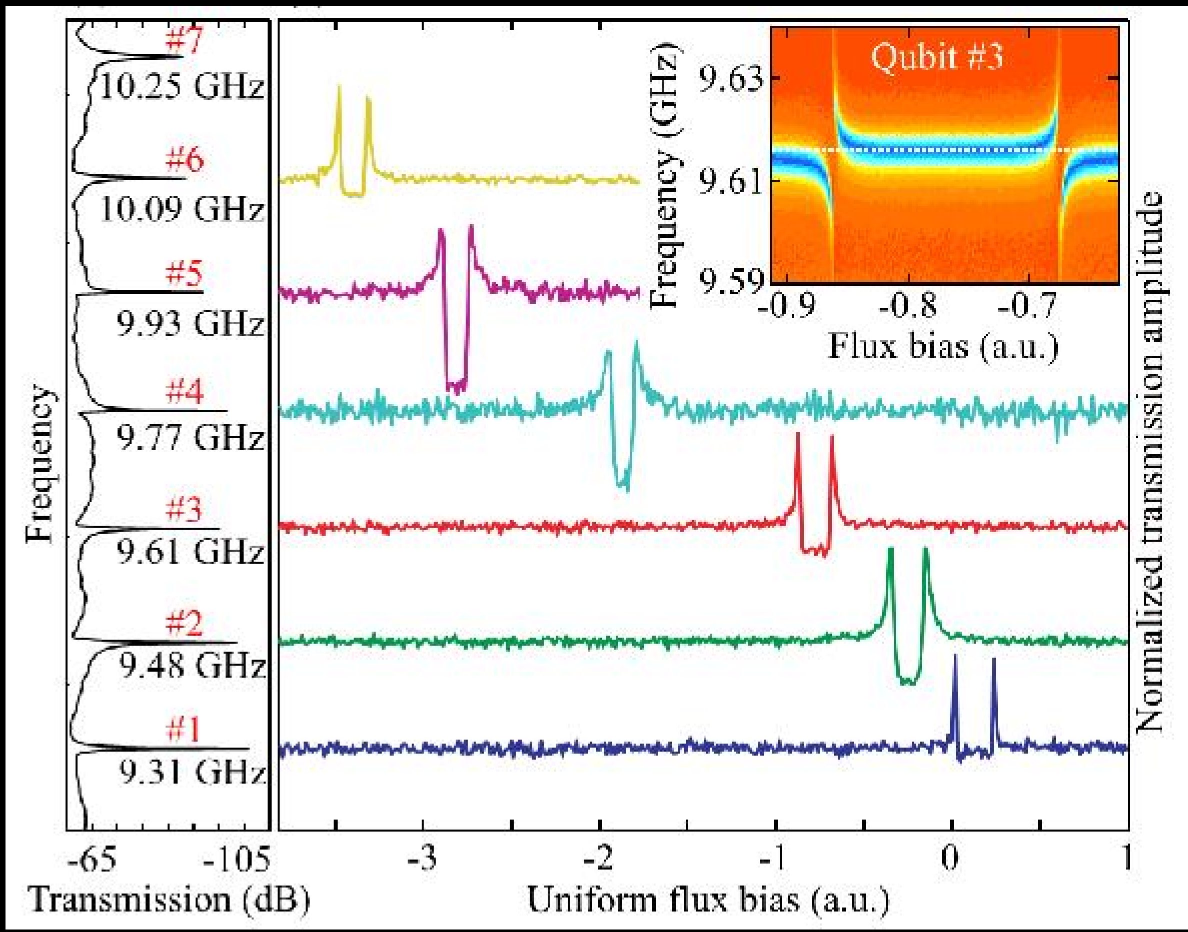




Resonator at fixed frequency while sweeping qubit flux
if on-resonance → level separation

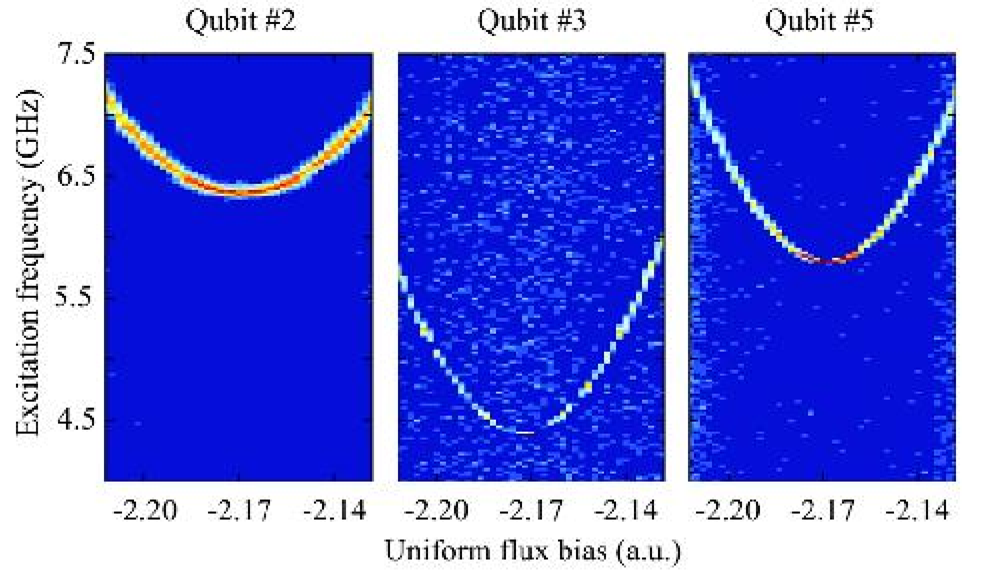
Qubits have random magnetic states

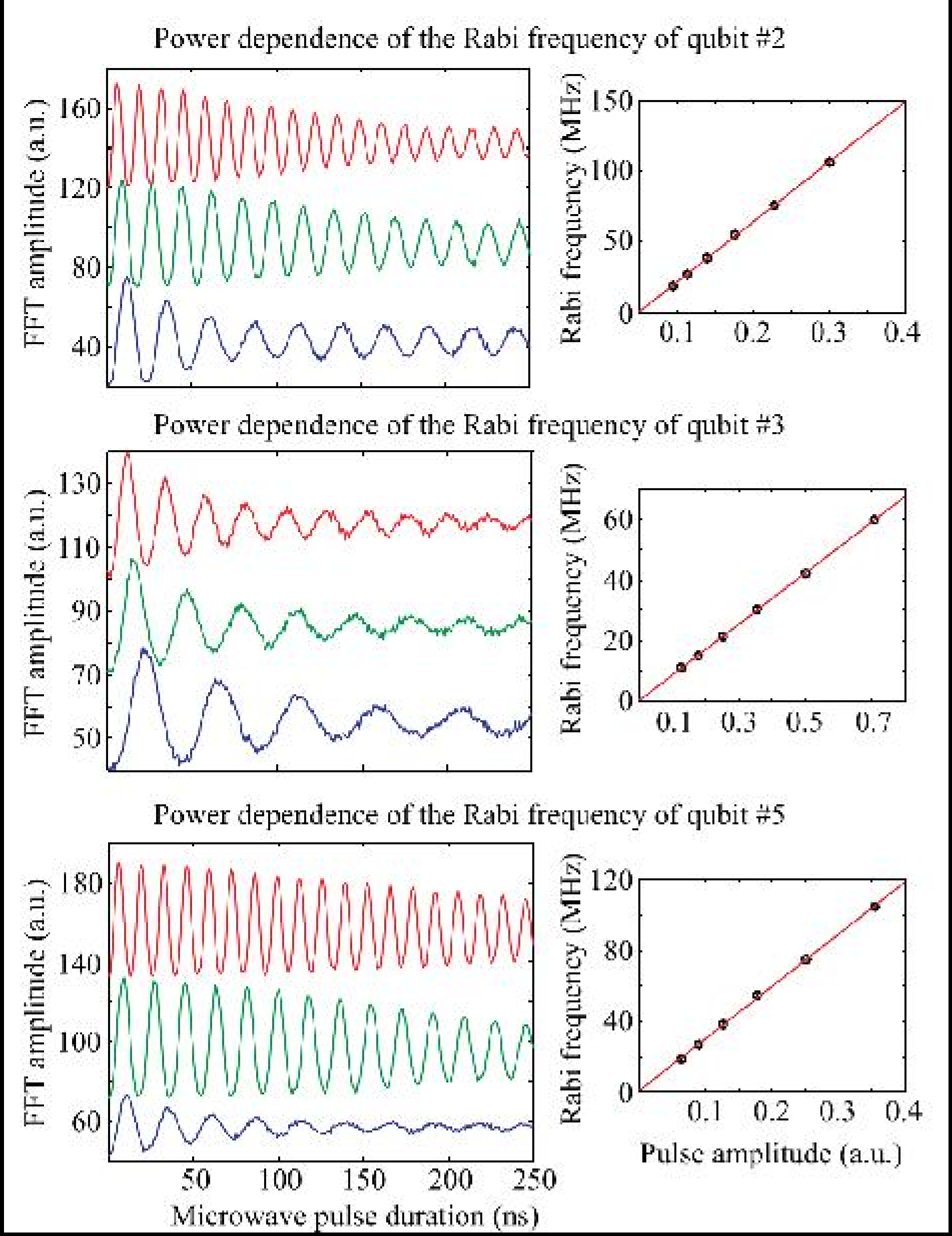




Jerger *et al.* APL 2012

Simultaneous spectroscopy, manipulation and detection on three qubits





- simultaneous manipulation and time resolved measurement of 3 qubits
  - Power Rabi
  - $T_1 \approx 1$ µsec, $T_2 \approx 200$ nsec

Jerger *et al.* APL 2012

Parasitic microscopic two level states

Coherence for quantum error correction

Min. requirement: 0.1‰ error per gate (10 nsec)→ 100 μsec

Relaxation T_1

$$|1\rangle \rightarrow |0\rangle$$

Limited by: *Capacitive and inductive loss, quasiparticles, environmental coupling, microscopic defect states (TLS)*

Dephasing T_2^*, T_2

$$|\psi\rangle \rightarrow |\psi\rangle e^{i\phi}$$

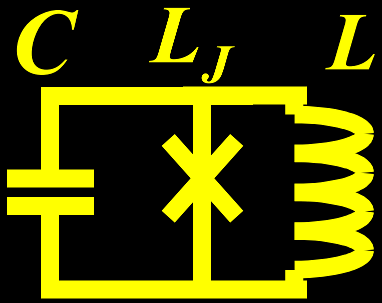
$T_2 \approx 2T_1$ (@ sweet spot), usually shorter

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{\tau_\phi}$$

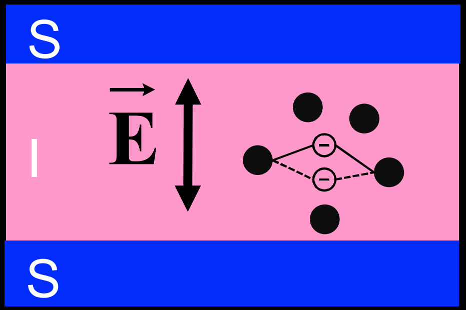
Limited by: *1/f noise (charge, flux)*

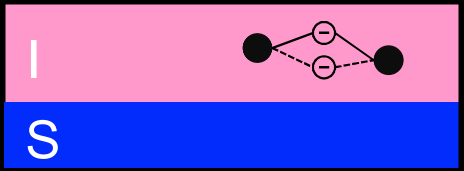
→ **Material science**

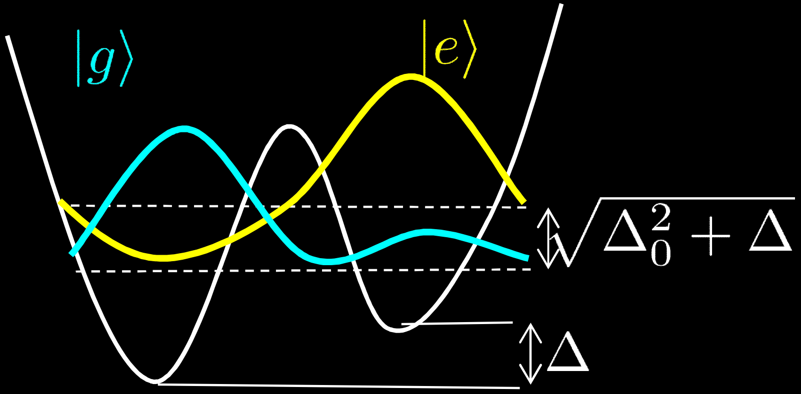
Junctions, inductors, capacitors



Parasitic two level systems (TLS) in dielectrics





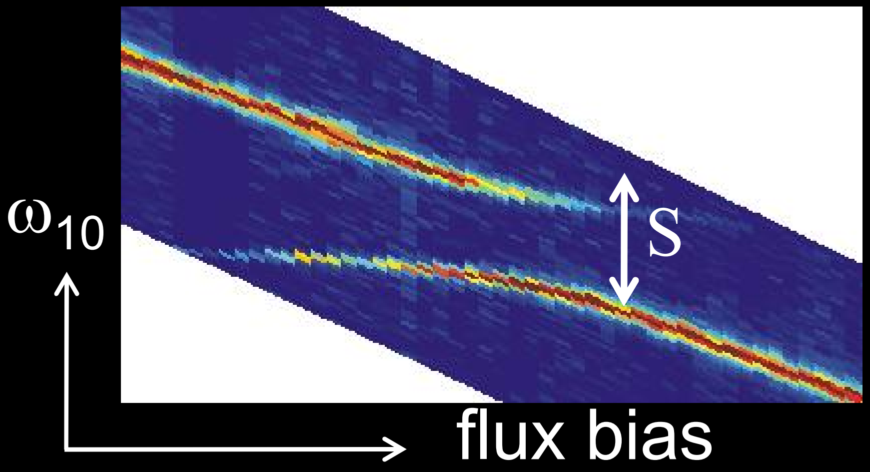


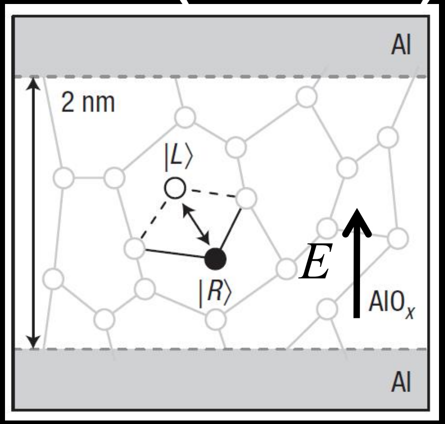
- Amorphous oxides loaded with uncompensated charges ~ 10^{16}/cm^3
- Range of energies, coherence and Rabi frequencies Δ, T_1, T_2, Ω
- Absorption probability goes as ~ $\frac{1}{E}\tanh\left(\frac{hf}{2k_BT}\right)$
  - Maximized at low E, T

→ Dominating loss at low T & E

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

Decoherence in junctions: Coupling to two level systems (TLSs)

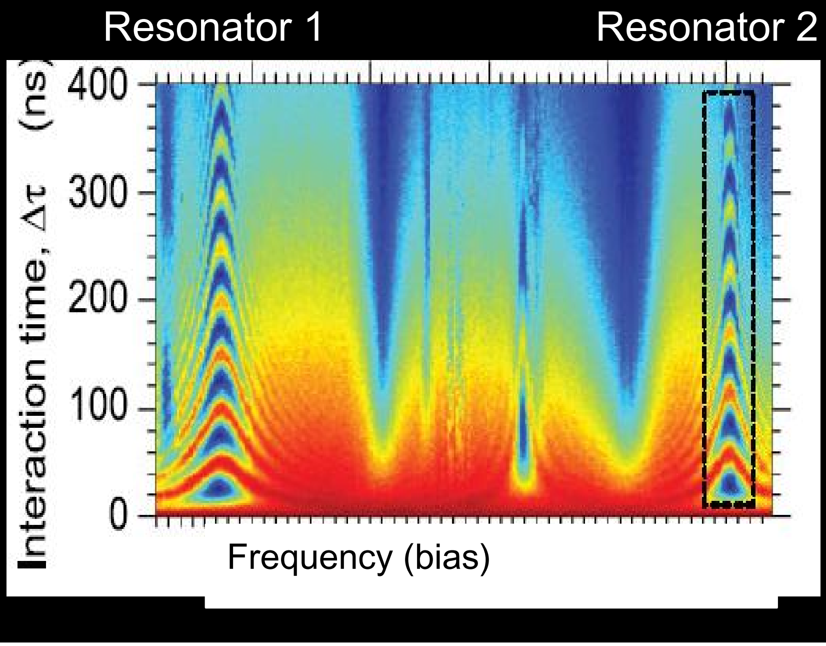




interaction S lifts degeneracy

- TLS *dipole moment* couples to E-field
- Located in *tunnel barrier oxide*

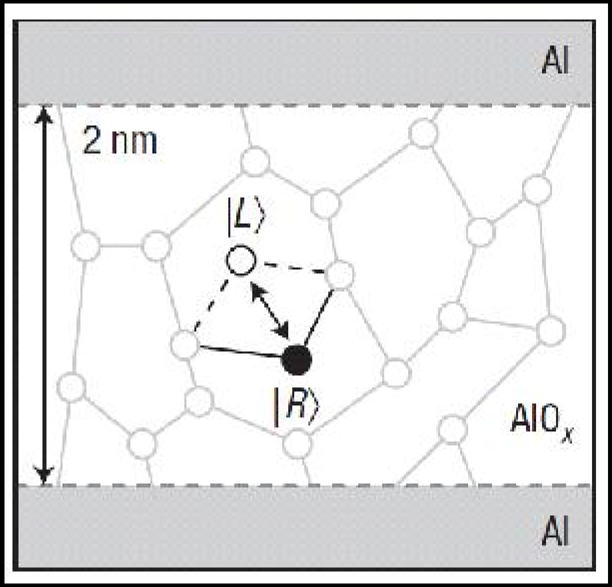
- Time domain: *beating, absorption*
- Scale: *Frequency crowding*
- Tune qubit: *Landau-Zehner*



Mariantoni *et al.*, Nat. Phys. 11

Test of Two-Level-systems

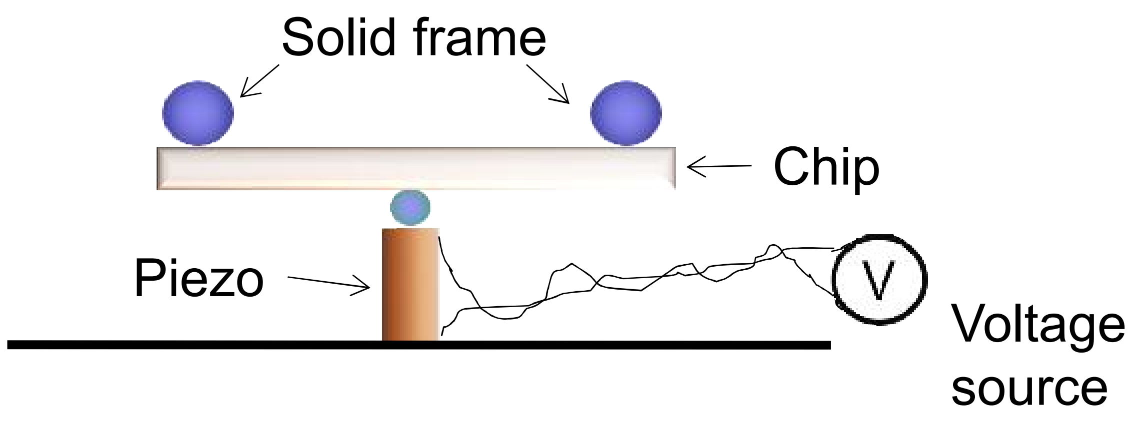
are they really atoms moving in the lattice?



if yes, their properties change under mechanical stress on crystal

→**bending the chip** changes **forces between atoms**

→ TLS’s local strain potential changes, and alter their **resonance frequency**.

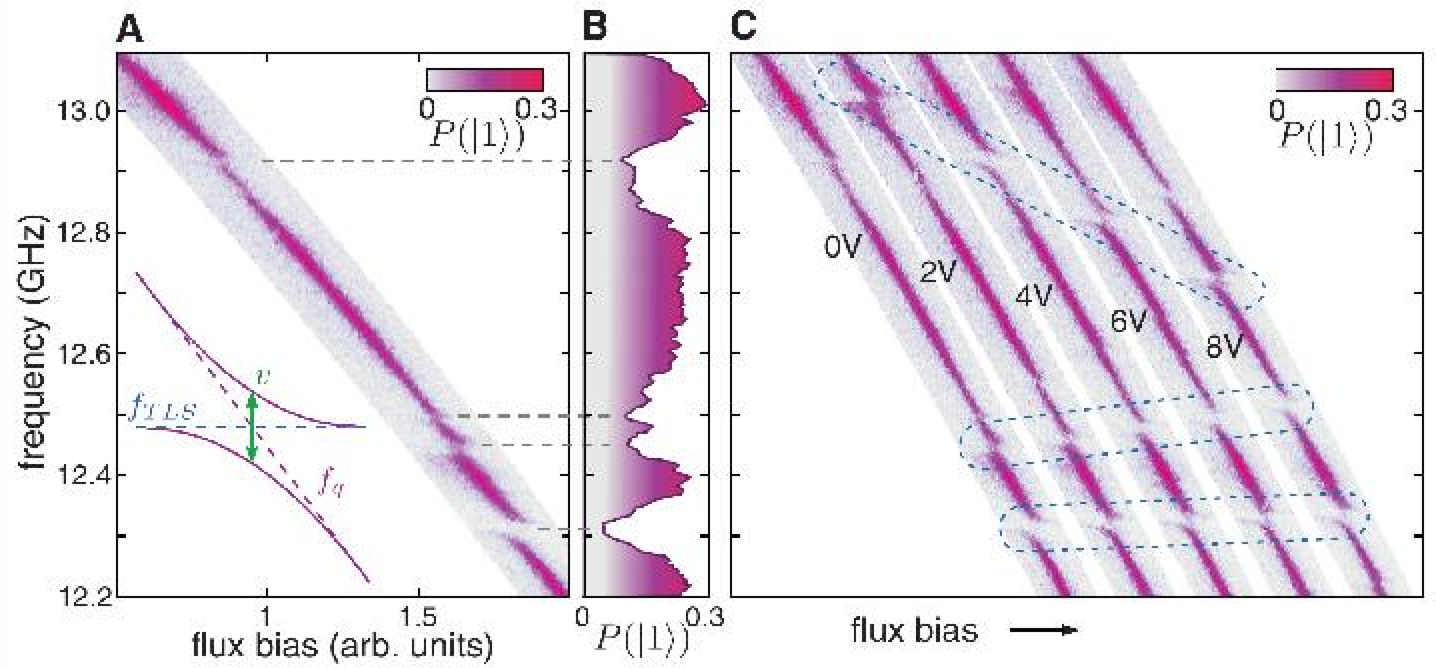


Idea:

Piezo which expands under applied voltage

monitor TLS resonances vs. applied voltage

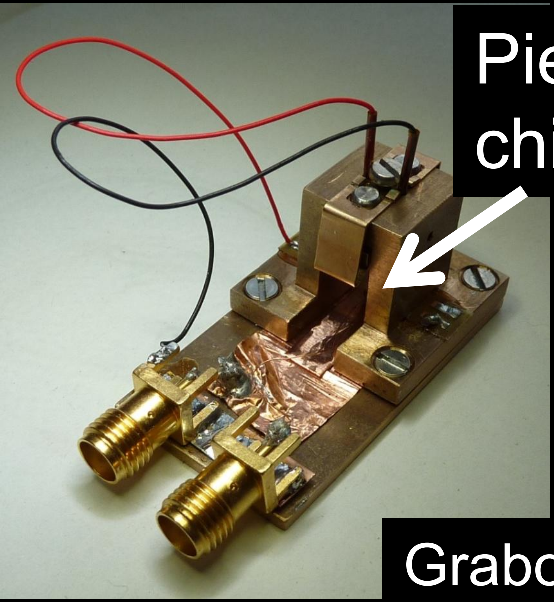
Chip under stress, spectroscopy



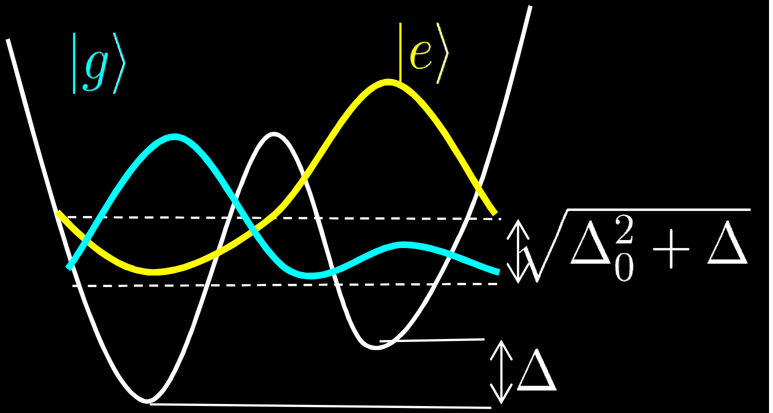
bending the chip

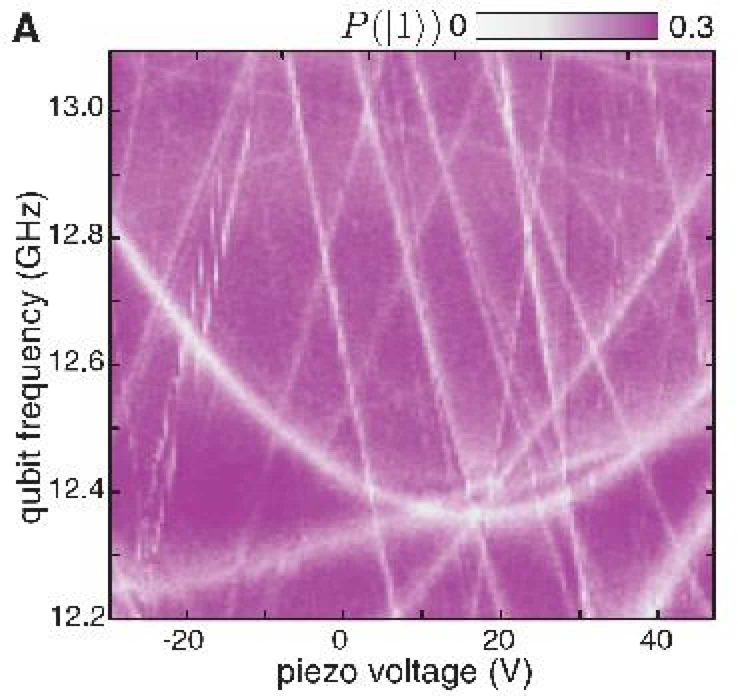
2d spectroscopy

P_1 (f_q, V_{piezo})



Piezo under chip





Grabovskij *et al.*, Science 2012

Improve coherence

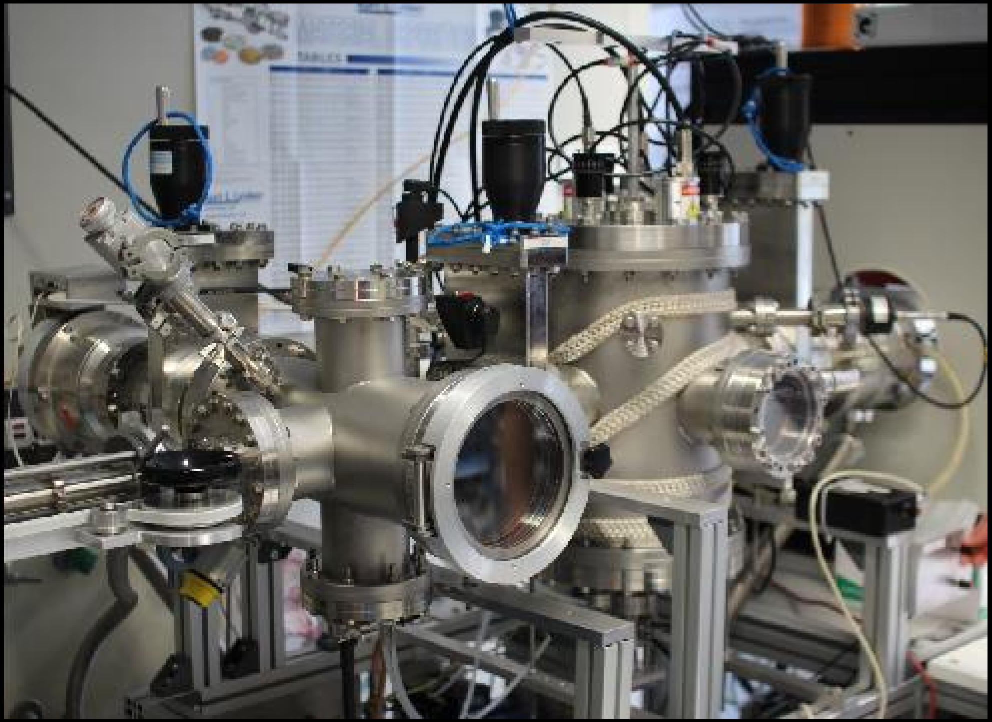
Adding resonant quantum circuit fab

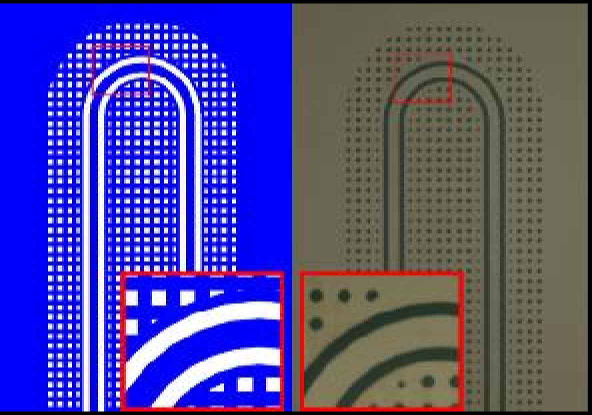
- Fast turnaround, flexibility, reliability, high coherence

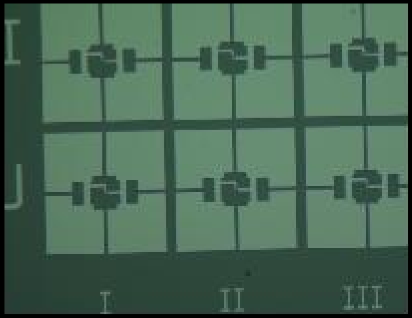
- Deposition
- Optical and e-beam lithography
- Etching

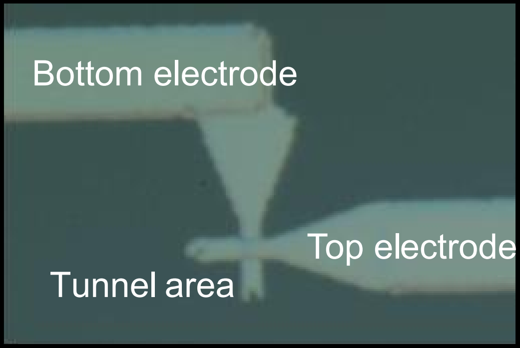
- Al-AlO$_x$-Al tunnel junctions
- Al, Nb, NbN, TiN resonators

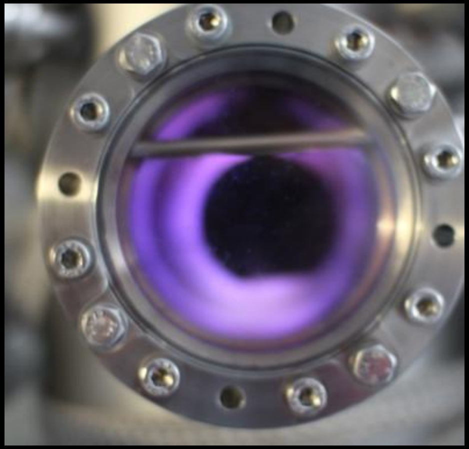
- Toolbox of designs and materials





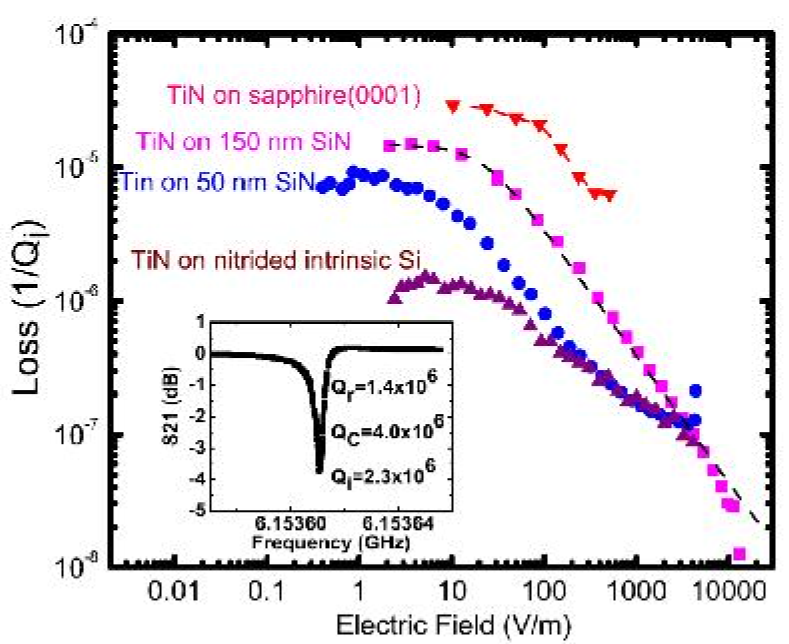




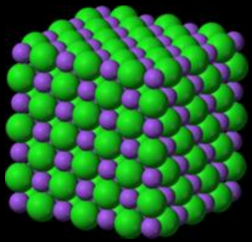


Low-loss TiN resonators

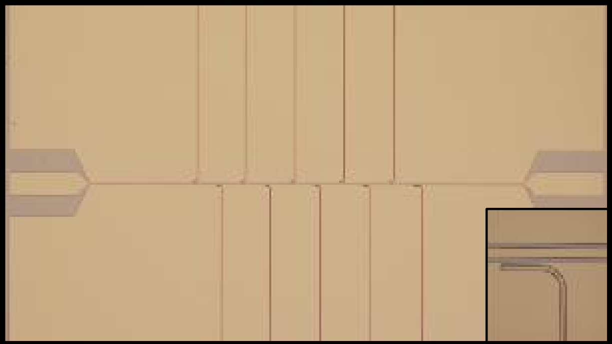
- High kinetic inductance & adjustable T_c →Photon detector applications (MKIDs)



NaCl



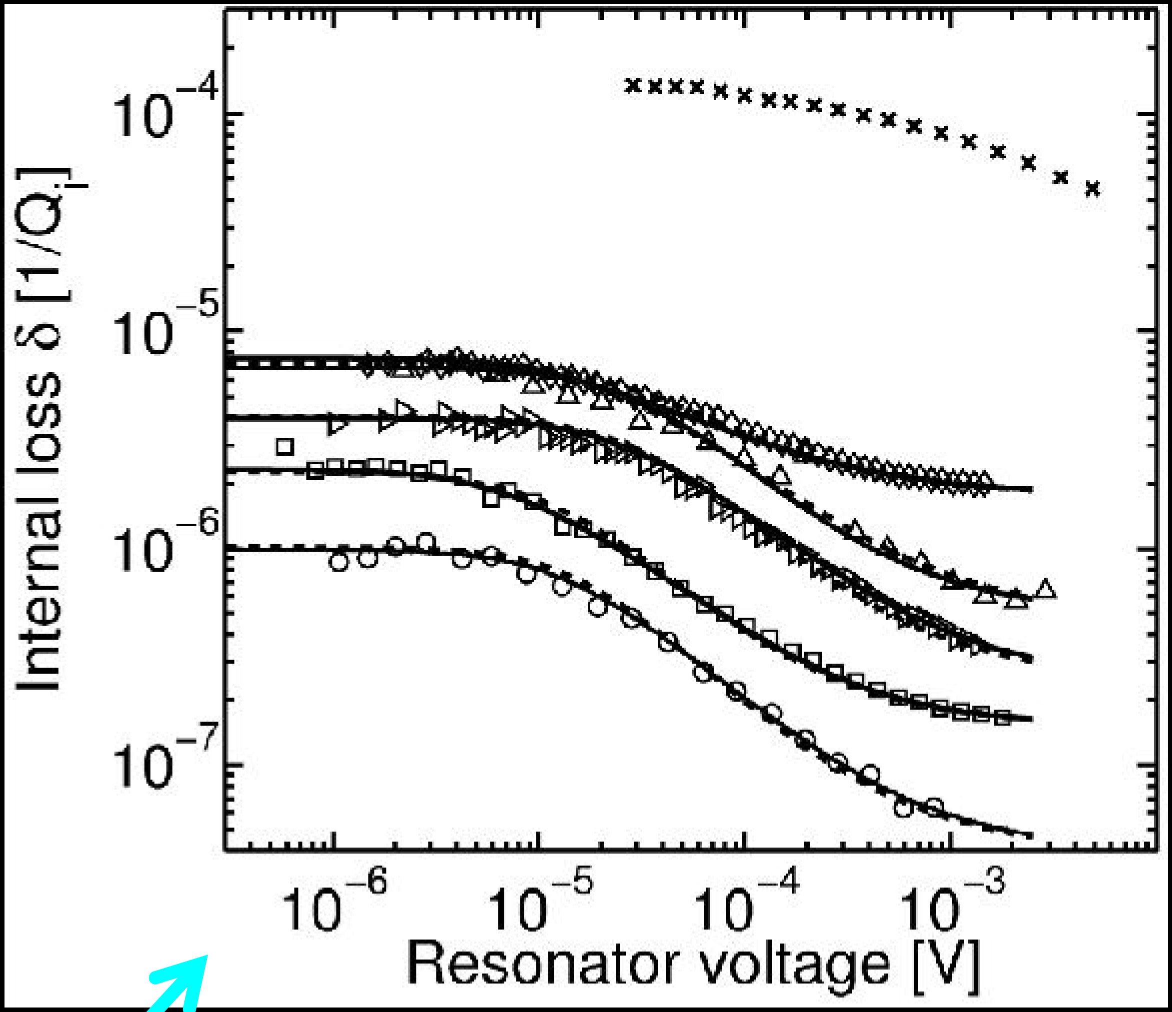
λ/4 resonator



- 111- metastable face nucleates on xtals & at low T → porous film, high loss
- 200-low energy face for “NaCl”-structure grows at high T
  - Need to grow on amorphous substrate, low defects
  - Pre-nitrided H:Si substrate for ultra-thin, 2 nm buffer Si-rich buffer

→ TiN microwave resonators: *quality factor >1M*

Etching & Trenching affect loss in 40nm TiN



Etch, Etch depth

Ion milled, 650nm

Chlorine #3, 40nm
Chlorine #2, 200nm
Chlorine #1, 270nm

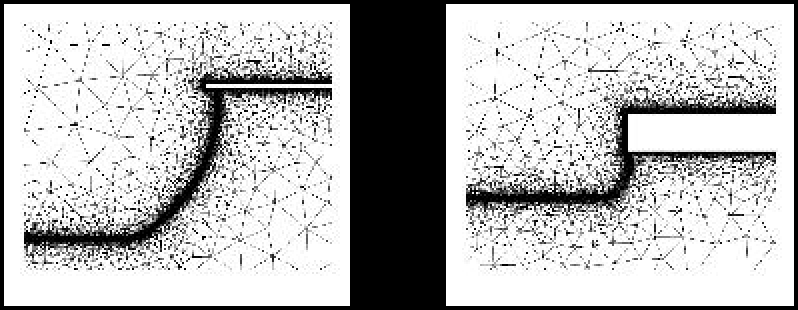
Fluorine #2, 200nm
Fluorine #1, 1200nm

Single photon limit

Field distribution, filling factor of stored energy

→ Etched surface matters, microscopic structure, E-field

→ Implications for resonant quantum circuits



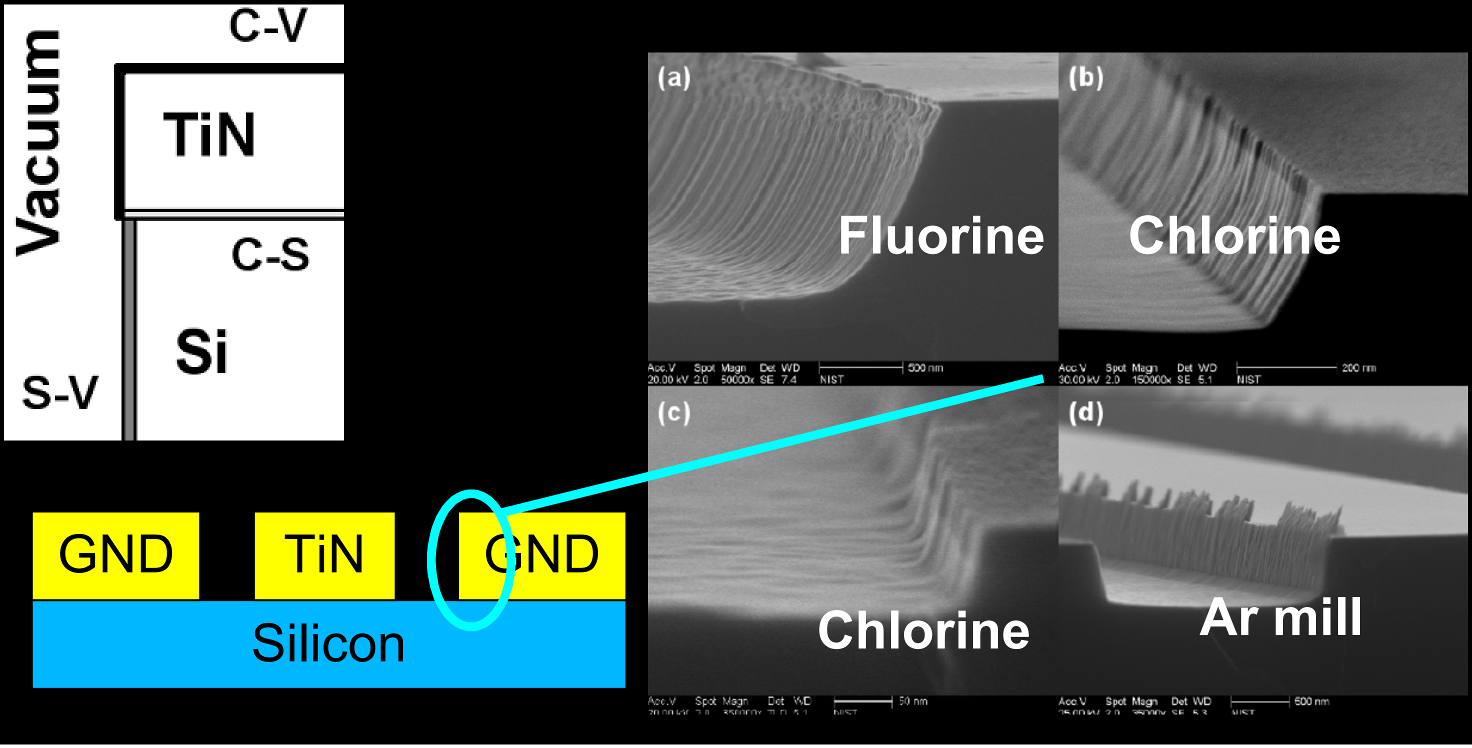
vacuum

conductor

substrate

Filling factor:

$$F_V = \frac{\int_V \epsilon_V |E(r)|^2 dv}{\int_{V_{tot}} \epsilon(r) |E(r)|^2 dv}$$

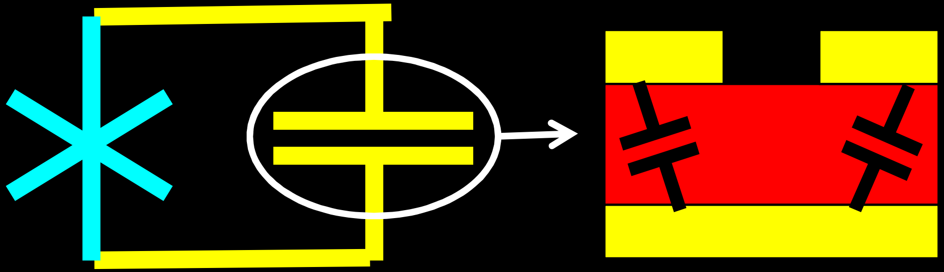


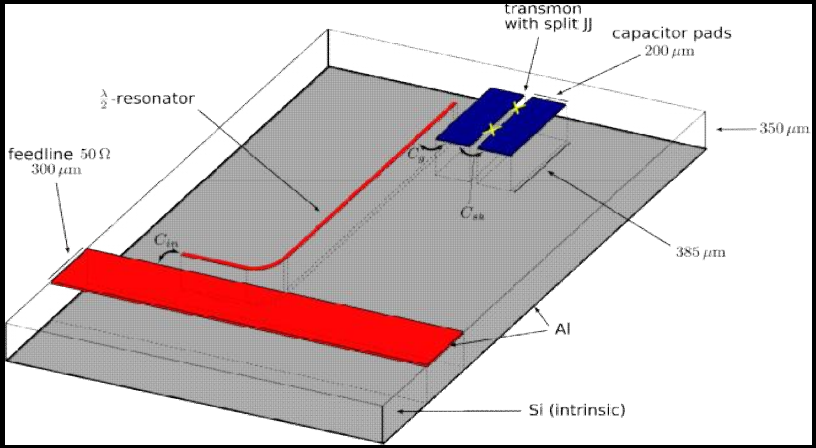
Sandberg *et al.*
APL 2012

Microstrip transmon qubit

1. Best Josephson junction (T_1) → Sub-micron Al-AlO$_x$-Al
2. Best capacitor (δ) → TiN microstrip w/ low loss silicon substrate
3. Negligible Al/TiN interface loss → Merge sub-micron junctions and TiN capacitor

Loss participation analysis: → expected lifetime dominated by TiN (T_1 > 100 µsec)



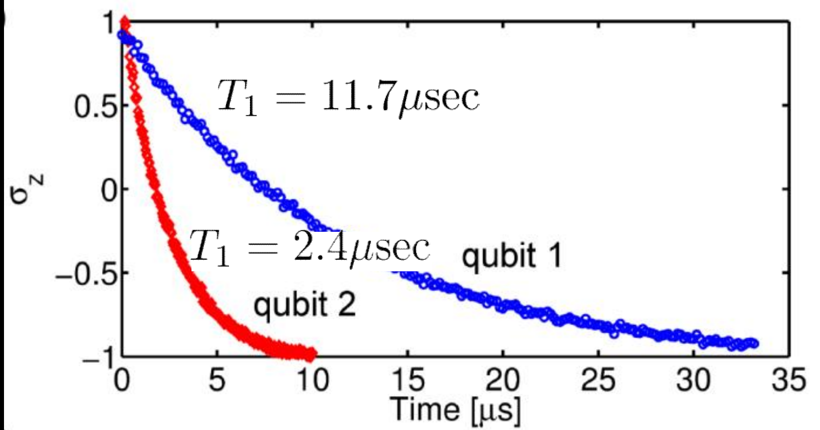


qubit 1: Purcell limit 20 µsec

Radiation limit 17 µsec

Combined limit 9.7 µsec

qubit 2: Purcell limited



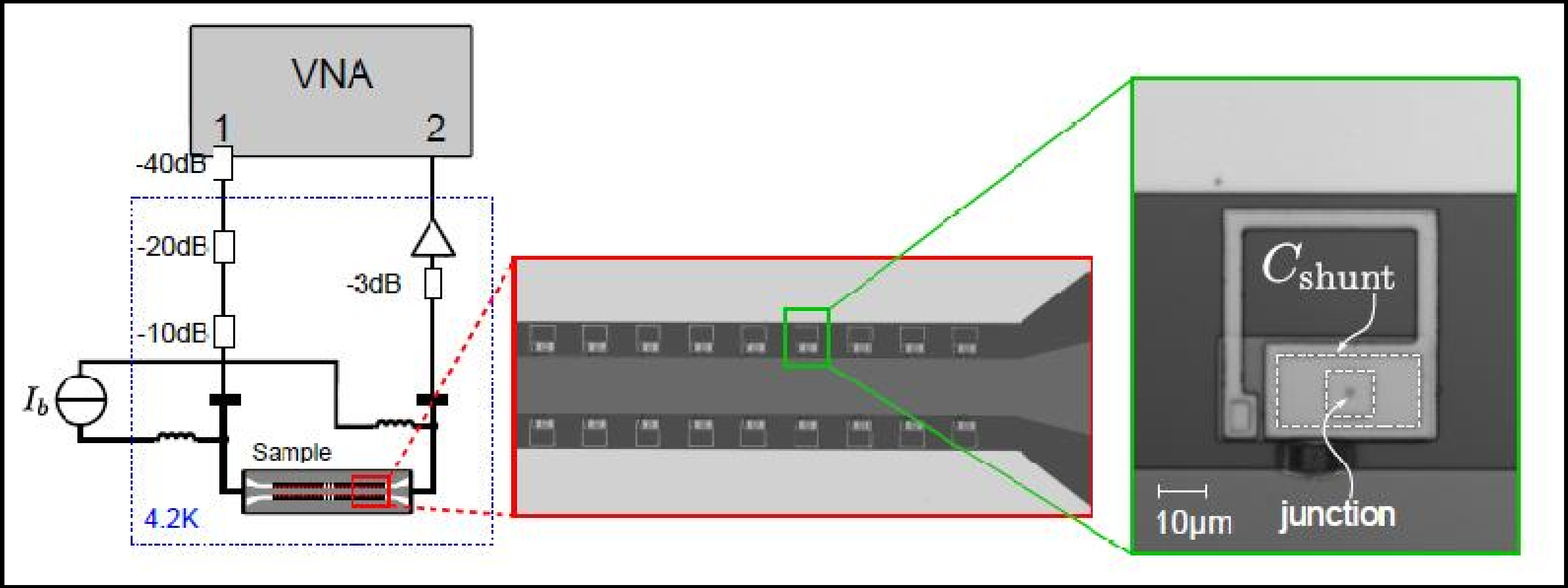
Re-designed qubit T_1=40 µsec

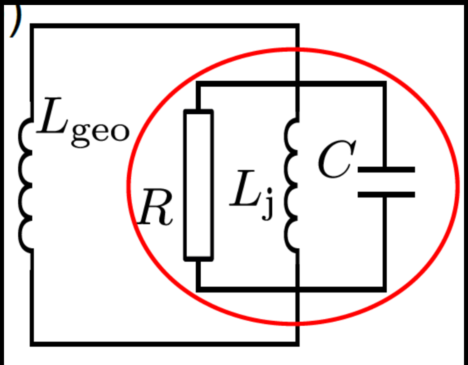
Aim at 100 µsec threshold (error correction)

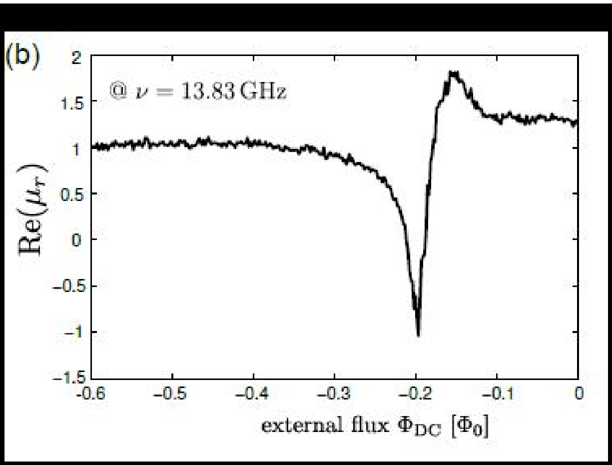
Sandberg *et al.*, APL 2013

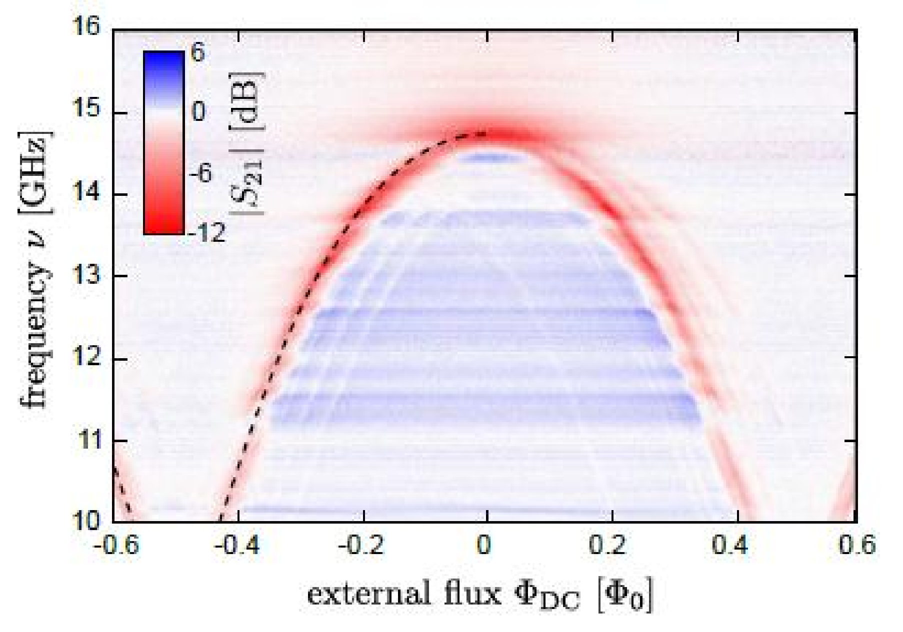
Classical meta-materials

Tunable 54 SQUID-loaded transmission line









Negative magnetic permeability

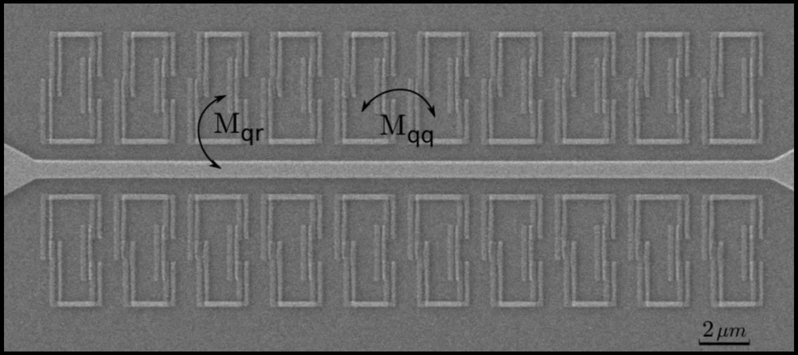
1d SQUID array modify properties of coplanar waveguide

Butz *et al.* Metamaterials 2013

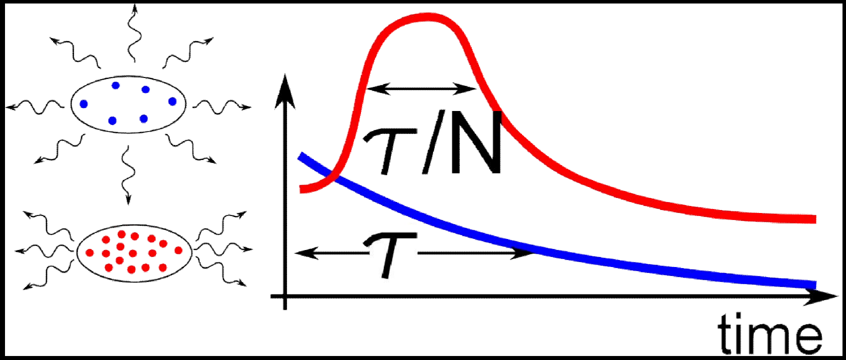
Quantum metamaterials

Quantum meta-materials

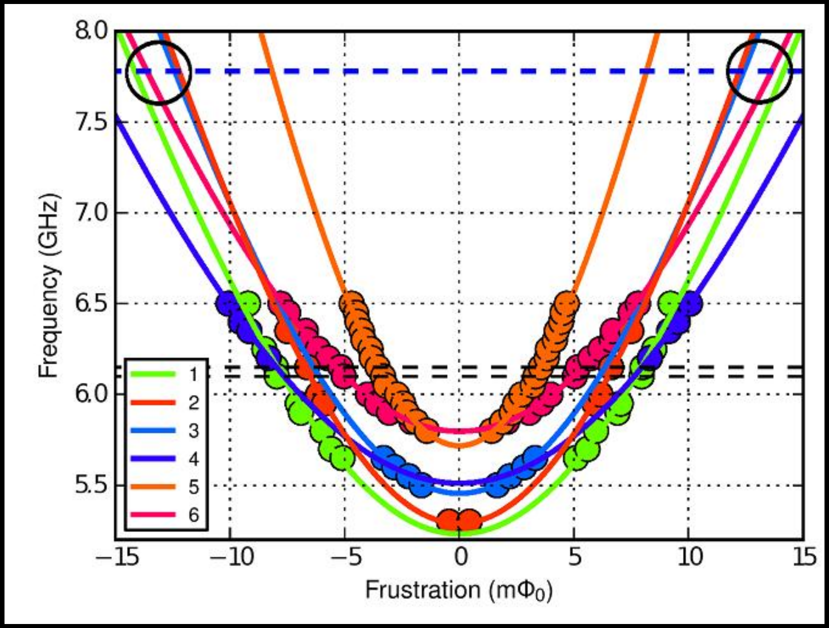
Manipulate light by periodic qubit structures strongly and coherently coupled to EM field of transmission line/cavity



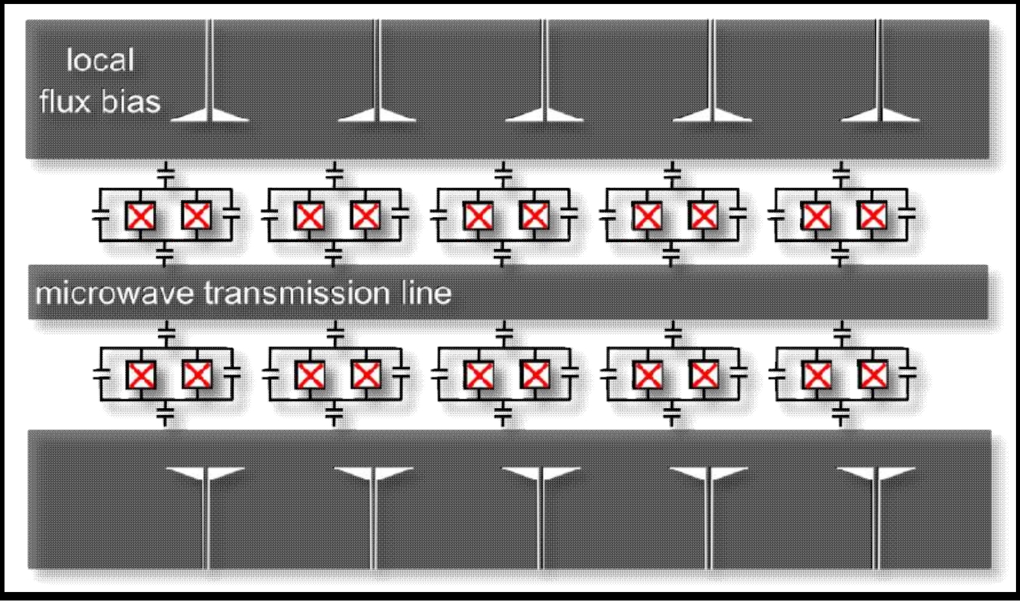
cooperative radiation phenomena (phase locking)
superradiance and super-fluorescence
Field-intensity ~ N^2, radiation burst ~ τ/N



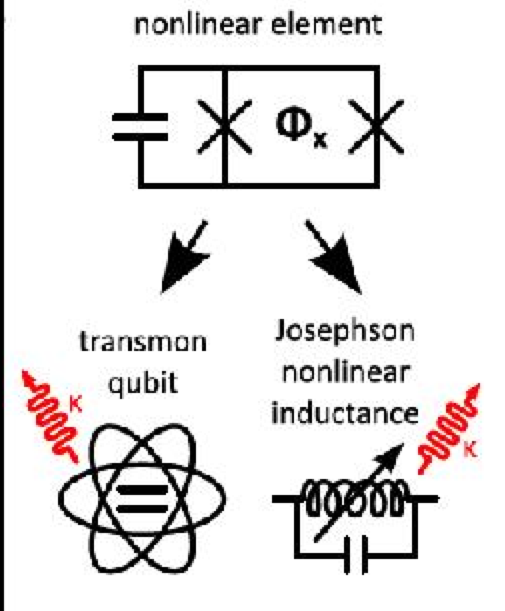
Two-tone spectroscopy on qubit chain
individual sets of qubits

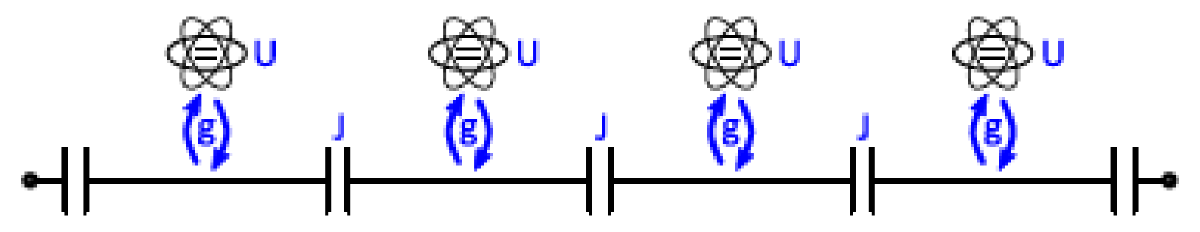


Macha PhD thesis ‘13



Quantum chains → quantum simulator





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

$$\hat{H} = \sum_j \hat{H}^{JC} - J \sum_{<i,j>} (\hat{a}_j^\dagger \hat{a}_i + \hat{a}_i^\dagger \hat{a}_j)$$

- Highly integrated multi-partite quantum system, cooperative radiation phenomena in qubit chain/resonator systems
- Bose Hubbard dynamics of polaritons in quantum chains delocalization (photon hopping) versus localization (on-site interaction)
- Transmission, collective phenomena, localization, correlation, dynamics

Ustinov group (at KIT)

Thanks for your attention

NIST

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Jeffrey Kline

Martin Sandberg

Michael Vissers

David Wisbey

David Pappas (PI)