Quantum Computing and Why We Need Your Help

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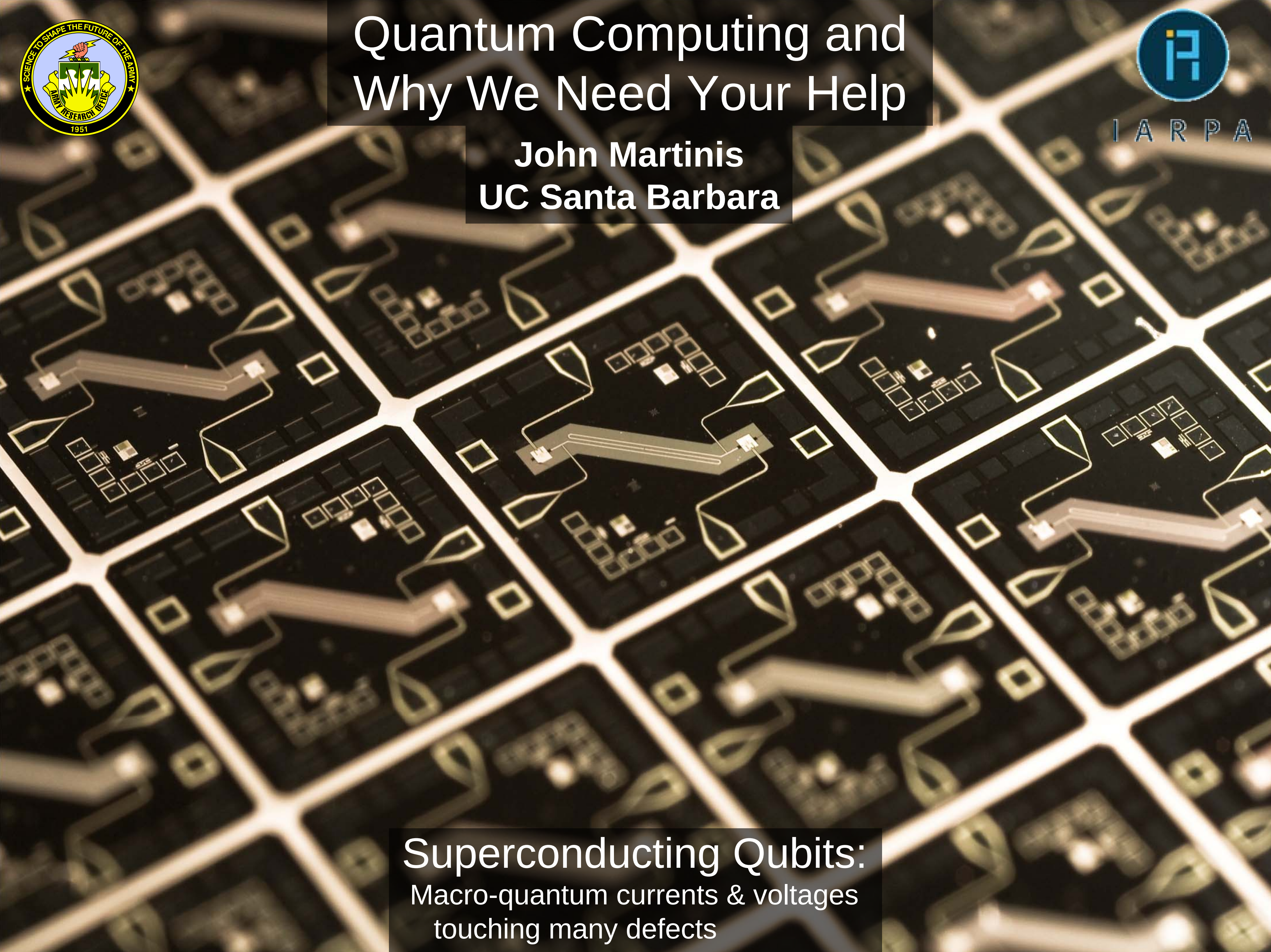


Superconducting Qubits:

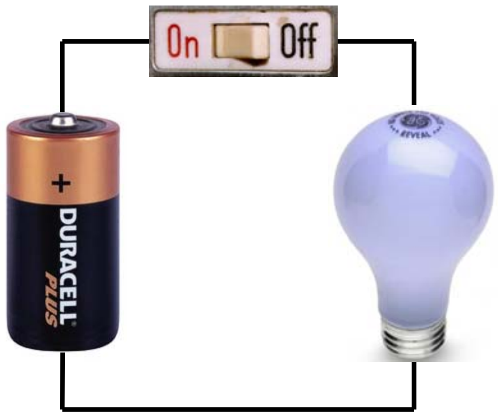
Macro-quantum currents & voltages
touching many defects

Outline

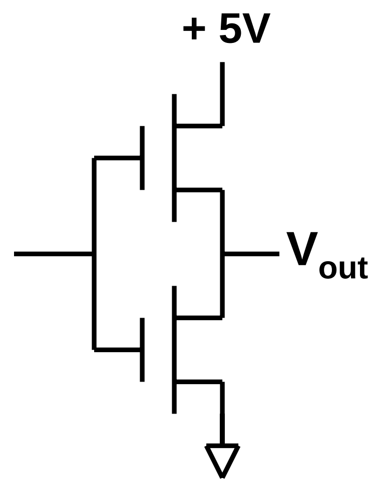
- Quantum computing
- Superconducting qubits
- Example defect: two-level states
- Qubit as new nano-probe of individual defects
- Correlation of defects with materials

Storage of Information: Bits

- **Classical bits: 0 <u>or</u> 1**



Light bulb:
0 = off
1 = on



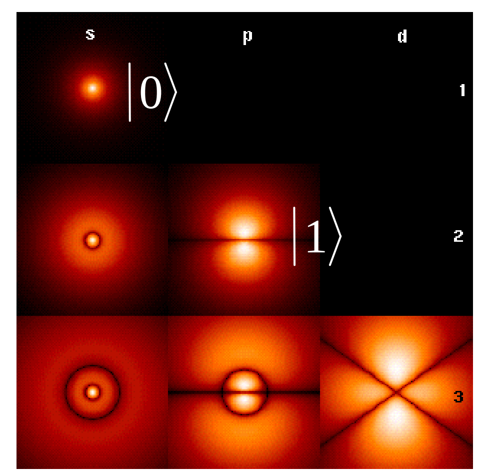
Transistor Logic:
0 = 0 volts
1 = 5 volts

- **Quantum bits: 0 <u>and</u> 1**

$$|0\rangle + |1\rangle$$

(Not "dim", or "2.5 volts" !)

H atom wavefunctions:



Exponential Computation Power

- Classical computation power scales <u>linearly</u>:
  speed (GHz), size (RAM Mbytes), number processors

1 GHz

2 GHz

2 GHz, Dual Processor

- Quantum computer scales <u>exponentially</u>!

qubit 1 qubit 2 qubit 3

$$\left(|0\rangle+|1\rangle\right)\left(|0\rangle+|1\rangle\right)\left(|0\rangle+|1\rangle\right)$$

3 qubits :
<u>parallel</u> <u>processing</u> of 2^3=8 states

$$=|0\rangle|0\rangle|0\rangle+|0\rangle|0\rangle|1\rangle+|0\rangle|1\rangle|0\rangle+|0\rangle|1\rangle|1\rangle+|1\rangle|0\rangle|0\rangle+|1\rangle|0\rangle|1\rangle+|1\rangle|1\rangle|0\rangle+|1\rangle|1\rangle|1\rangle$$

Q-box 64 —2x→ Q-box 65

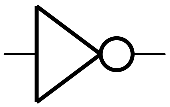
200 bit quantum computer: More states than atoms in universe!

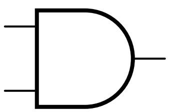
- HOWEVER: Only *measure* n qubits!
  Use only for certain algorithms (quantum simulation, factoring, optimization?)

Operations for Quantum Computation (DiVincenzo criteria)

Classical Computation:

- Initialize state
- Logic

not  0 –> 1
1 –> 0

and  00 –> 0
01 –> 0
10 –> 0
11 –> 1

- Output result
- Logic errors:

Error correction possible

Quantum Computation:

- Initialize state $\Psi_i = |000..0>$
- Logic via series of operations:

State Manipulation (1 qubit)

$|0> \to |1>$
$|1> \to |0>$
$|0> \to (|0>+|1>)/2^{1/2}$

Controlled not (2 qubit)

$|00> \to |00>$
$|10> \to |10>$
$|01> \to |11>$
$|11> \to |01>$

} + linear superposition

bit control

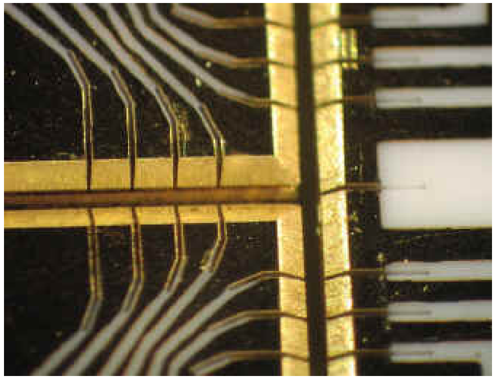
- Final state measurement

Measure qubits of state Ψ_f

- Coherence:

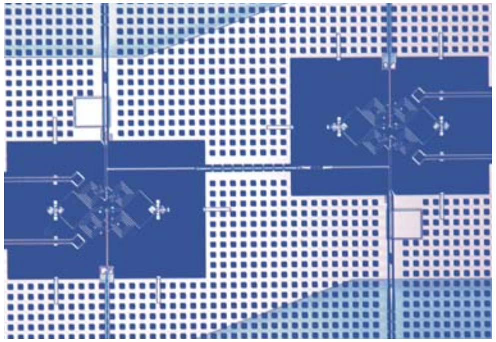
$\tau_{coherence} / \tau_{logic} \sim$ number logic operations
$> 10^4$ for error correction

Qubit Experimental Systems



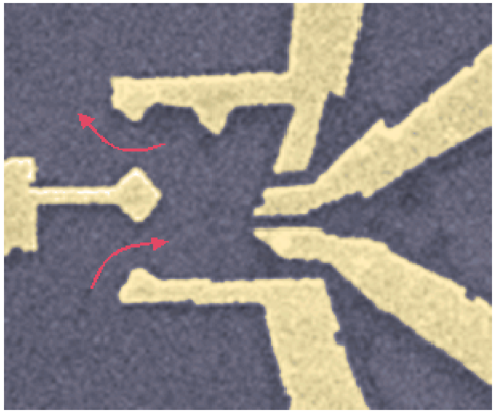
Ion Trap

"Atomic Clock" ions
manipulated with electrodes



Superconductor

Electrical quantum states
connected via wires



Semiconductor Spin

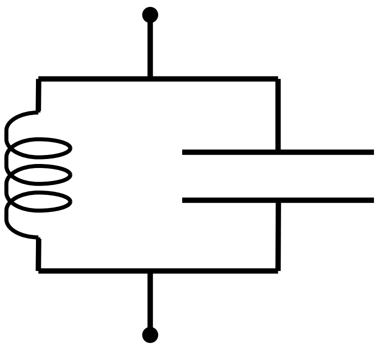
Electron spins moves through
semiconductor substrate

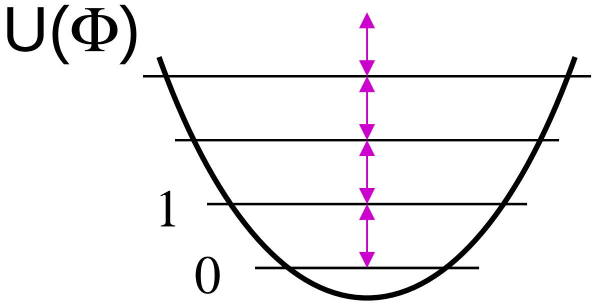
Use macroscopic wires to control quantum states

Couples to many defects!

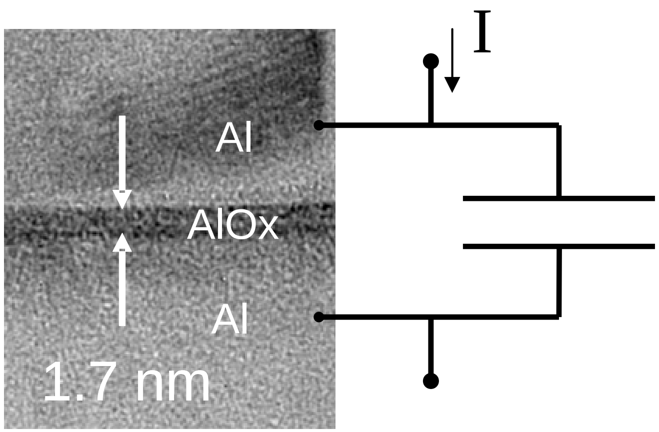
Superconducting Qubits

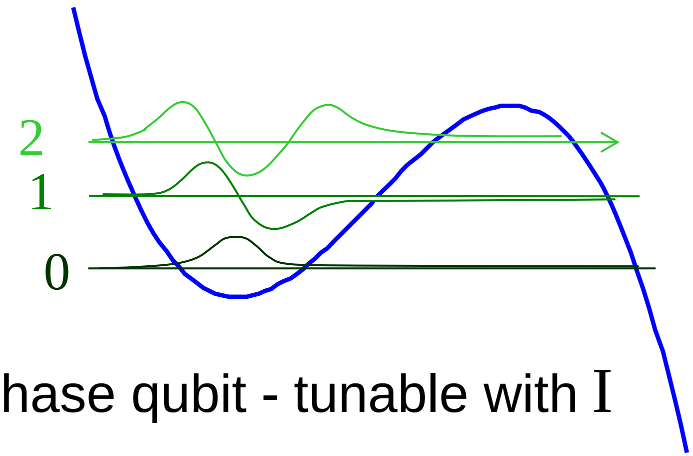
- LC oscillator (linear): no qubit possible





- Josephson junction: non-linear inductance with 1 photon (low loss)

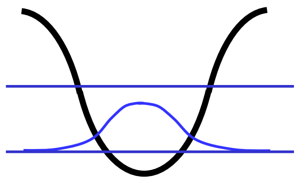


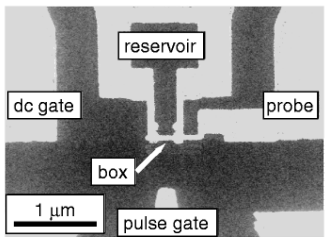


Phase qubit - tunable with I

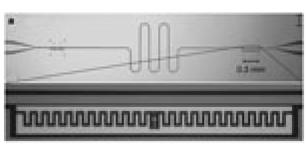
Period Table of SC Qubits

Charge

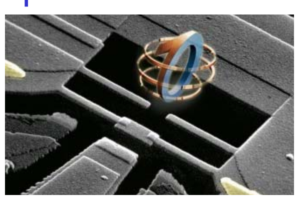




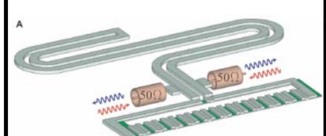
Tr
transmon



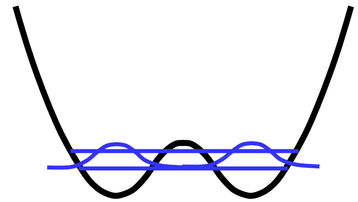
Qu
quantronium

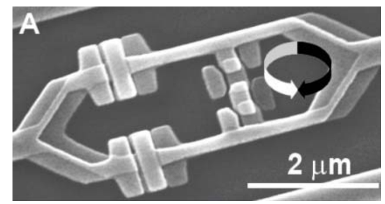


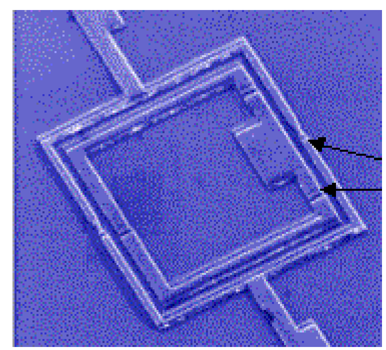
Fx
fluxonium



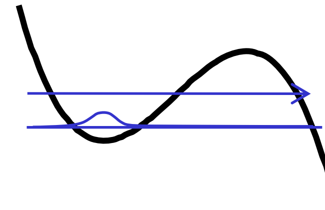
Flux

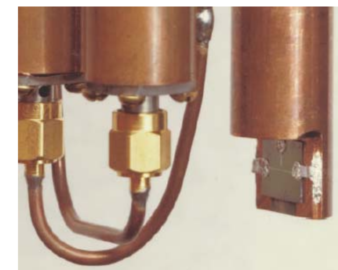


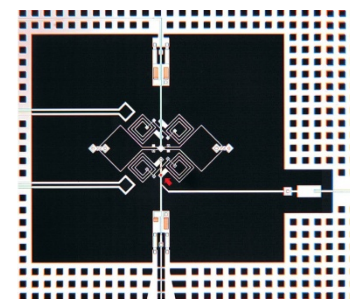




Phase



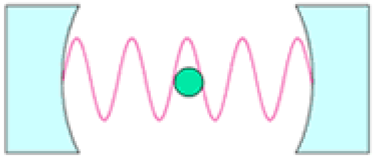




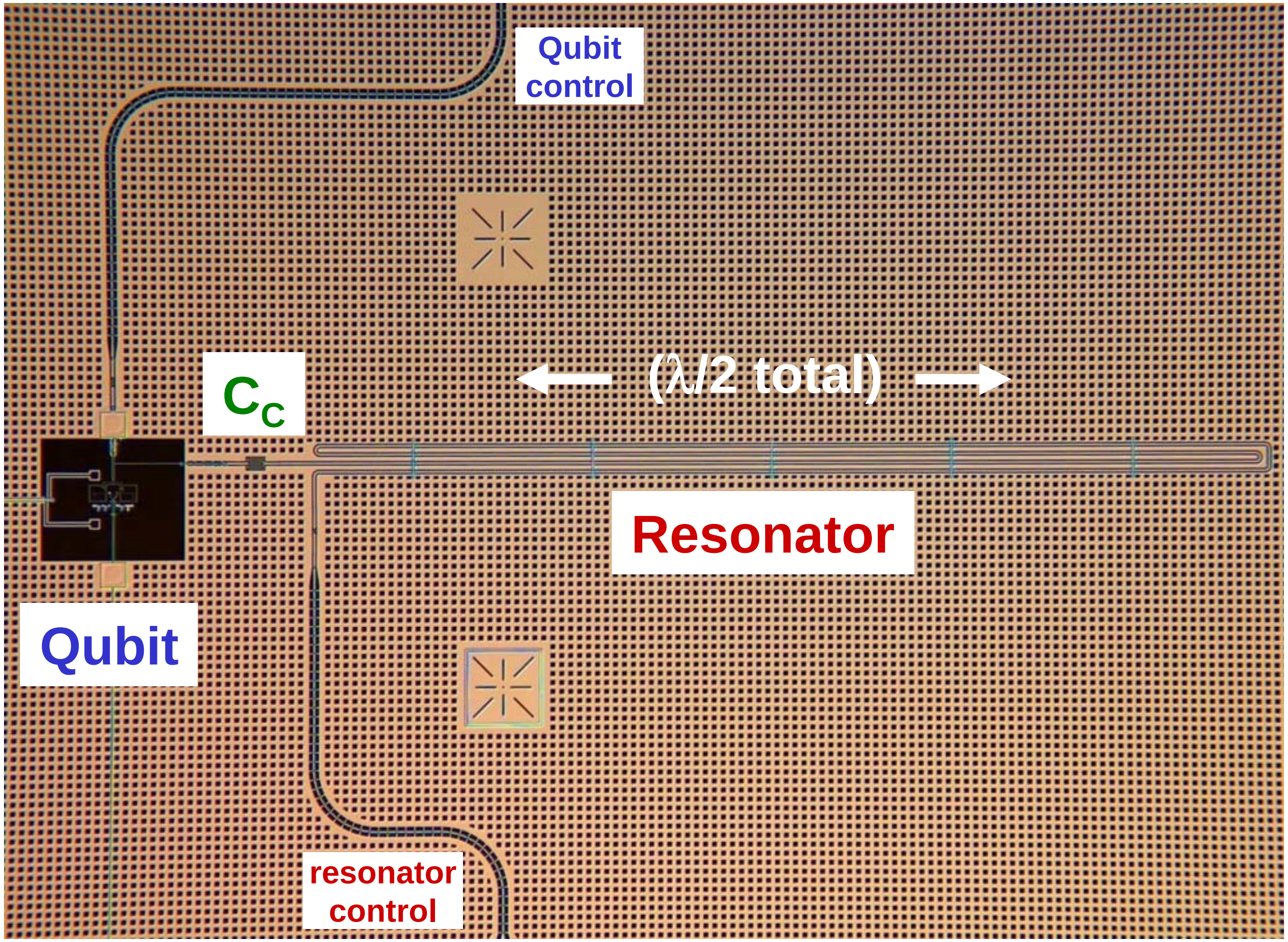
Convention: Name = encoding of state

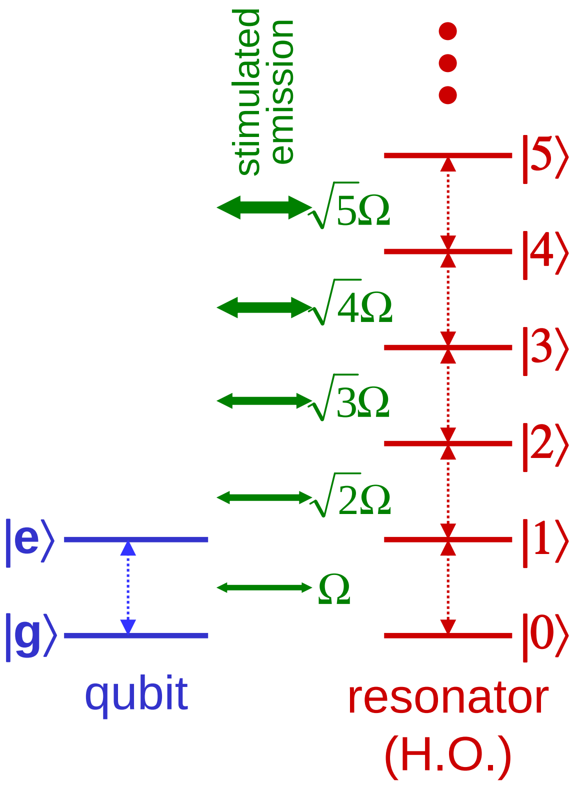
Professional Secret: = sensitivity to noise, what to avoid/fix

Qubit Coupled to Photons (Harmonic Oscillator)



atom state == ground and excited states of superconducting qubit
optical cavity == standing wave in microwave transmission line

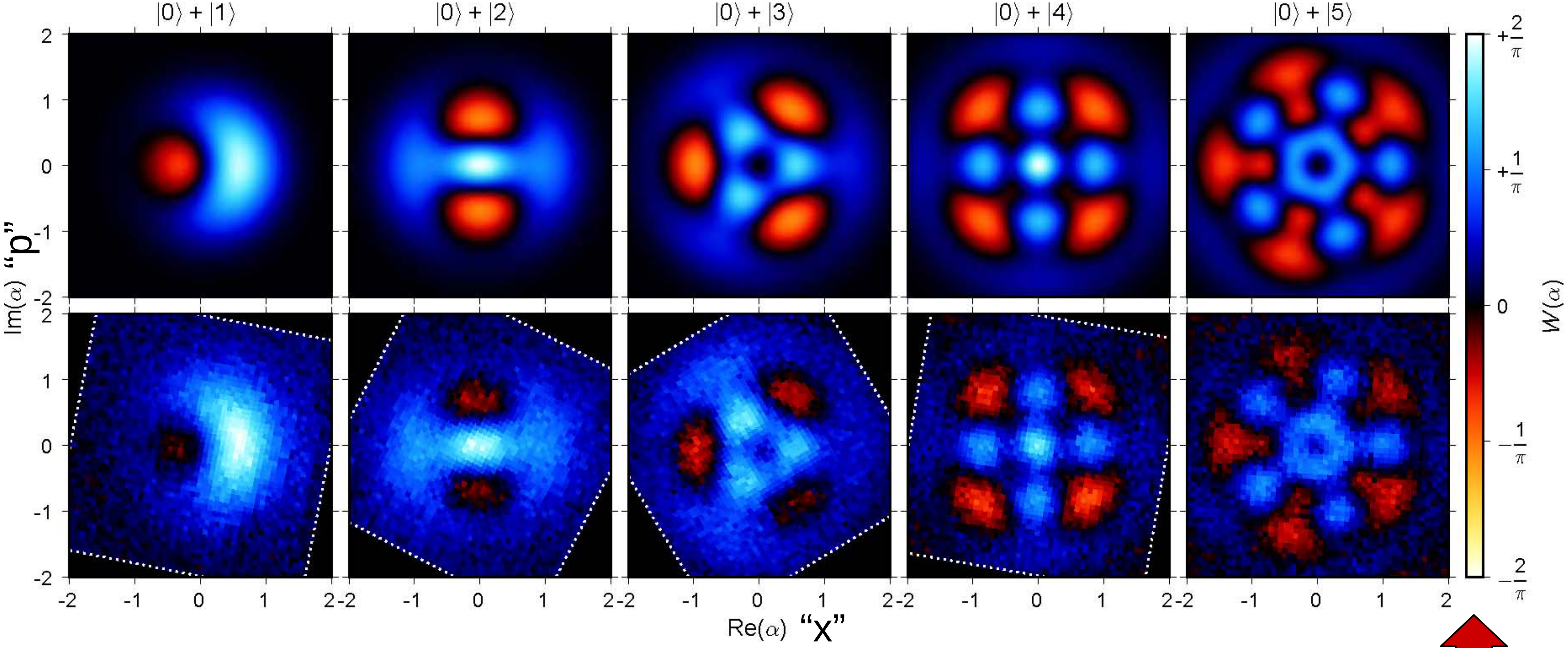




Generating non-Classical States of Light

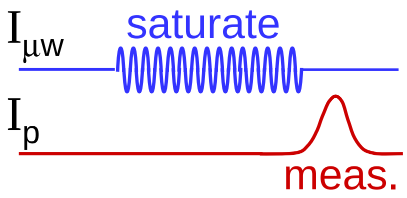
$$\Psi = |0\rangle + |N\rangle$$

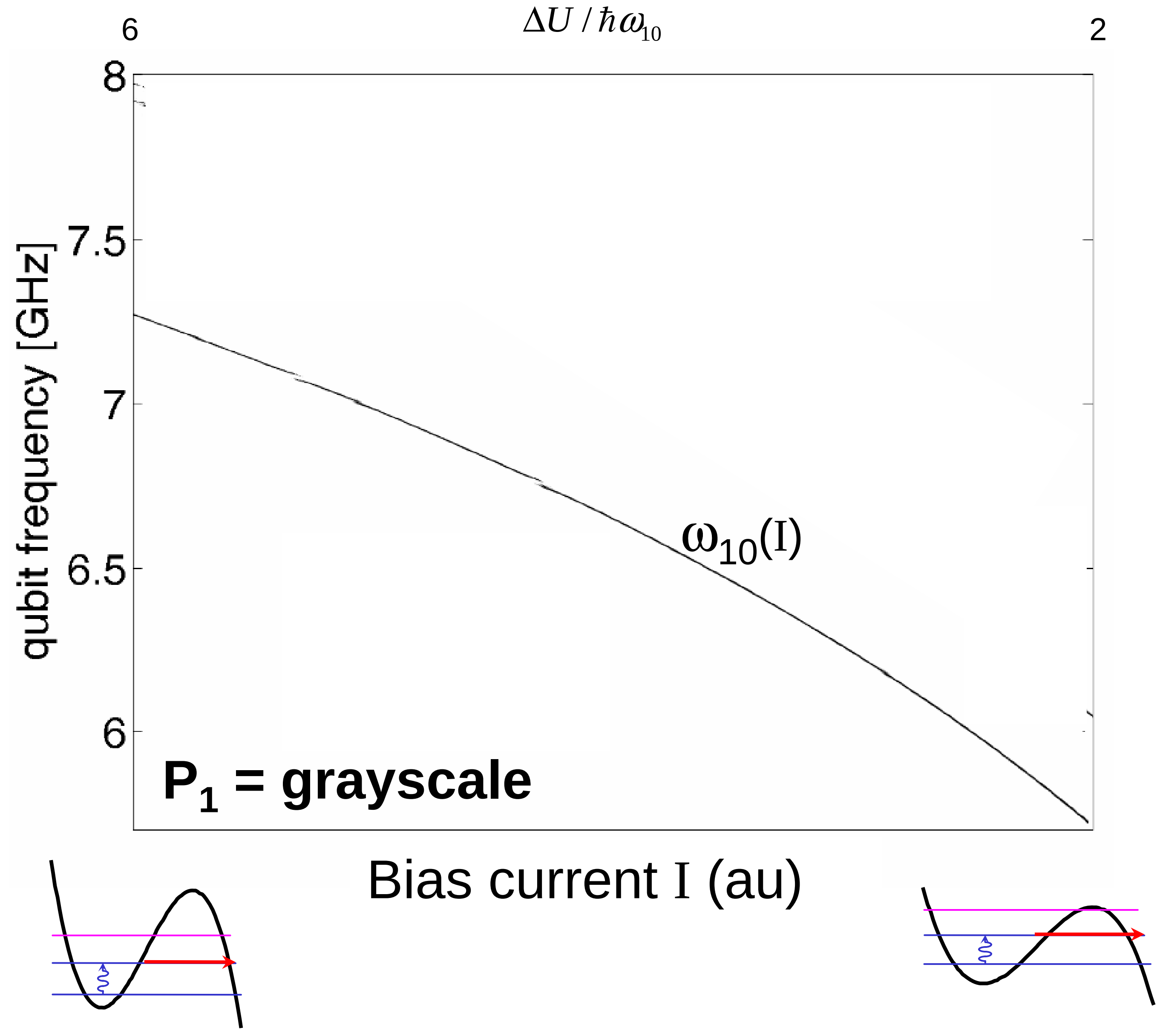
Phase-space (“x” and “p”) probabilities obtained using Wigner tomography



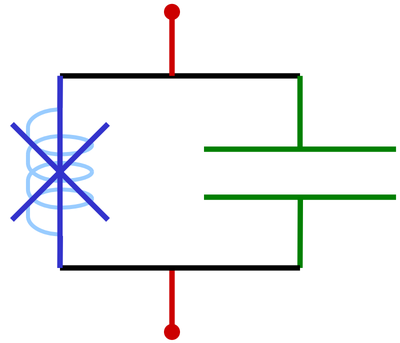
Red is negative quasi-probability

Spectroscopy

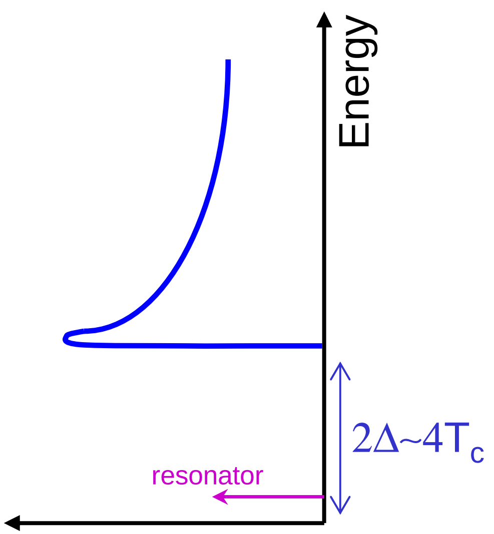




Decoherence: Where's the Problem?

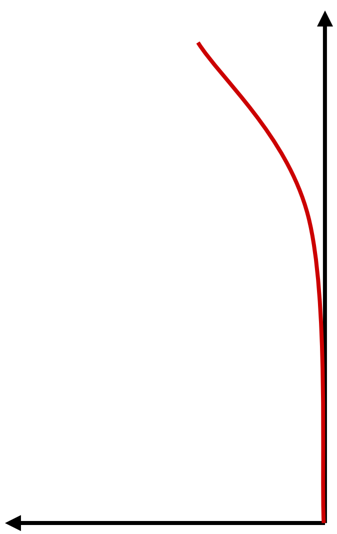


Inductors & Junctions



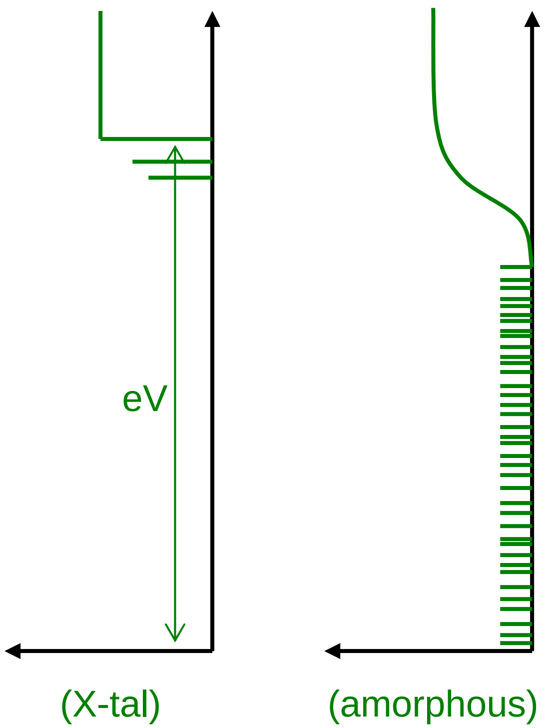
Superconductors:
- Gap protects from dissipation
- X-tal or amorphous metal
- Protected from magnetic defects

Circuits



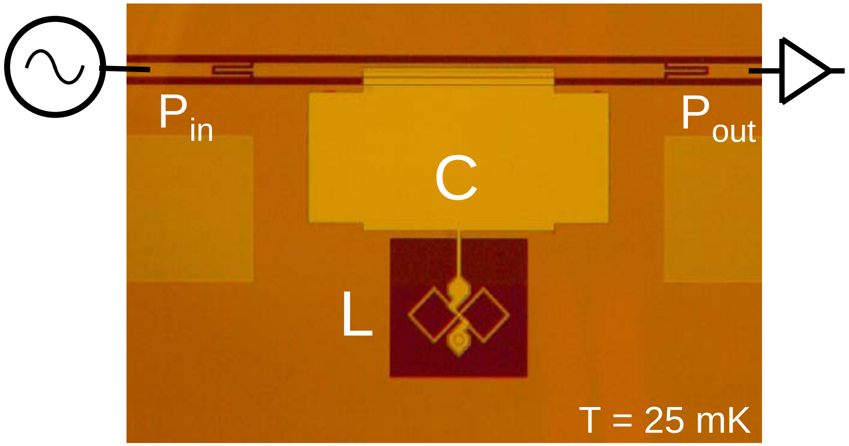
Good circuit design
(μwave engineering.)

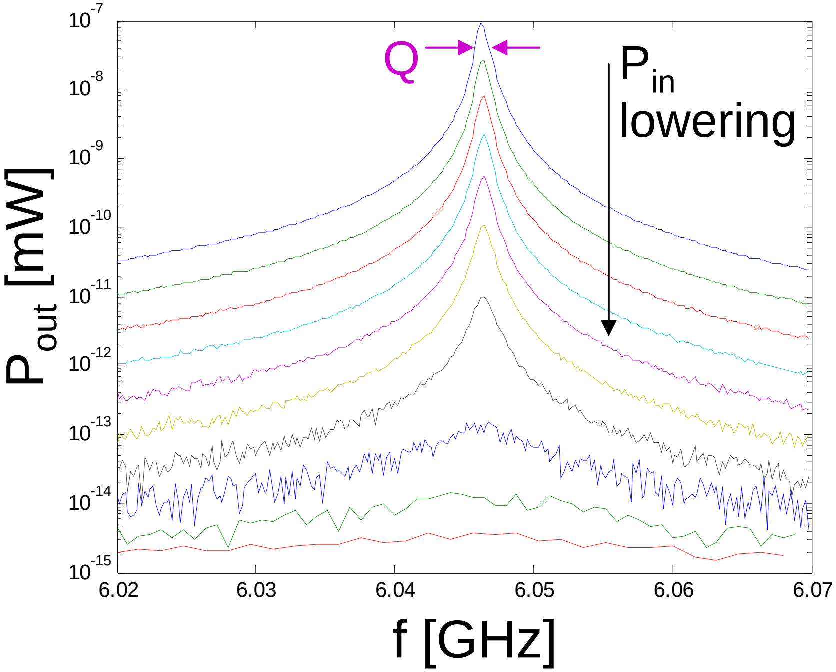
Capacitors



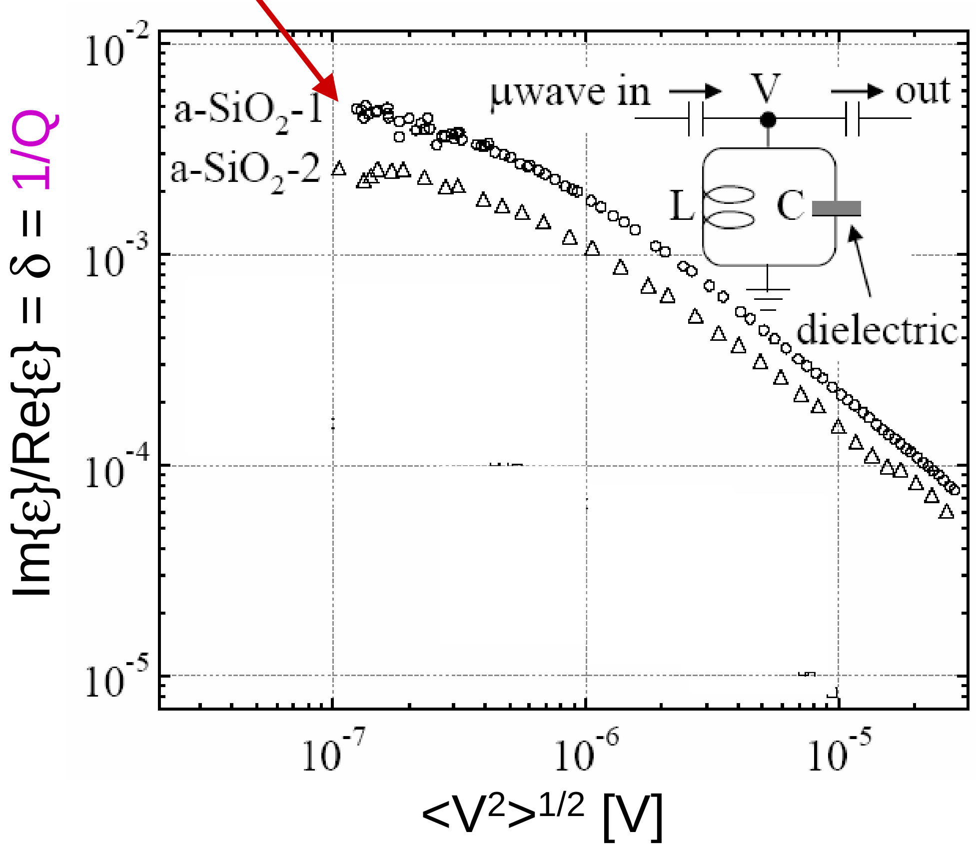
Many low-E states
Only see at low T

Dielectric Loss in CVD SiO_2

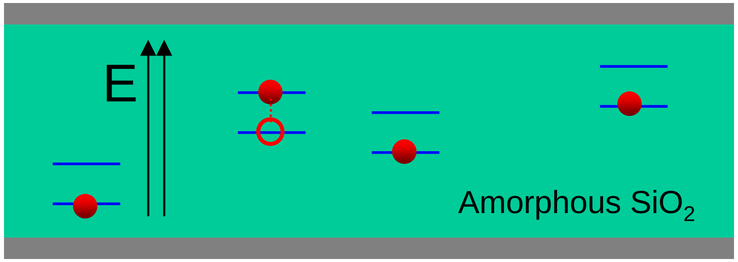




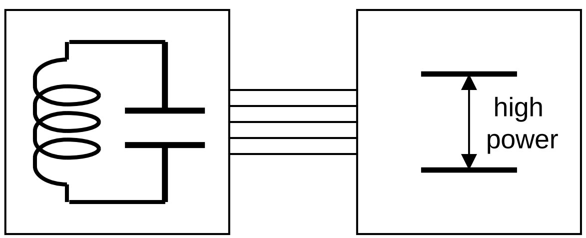
HUGE Dissipation



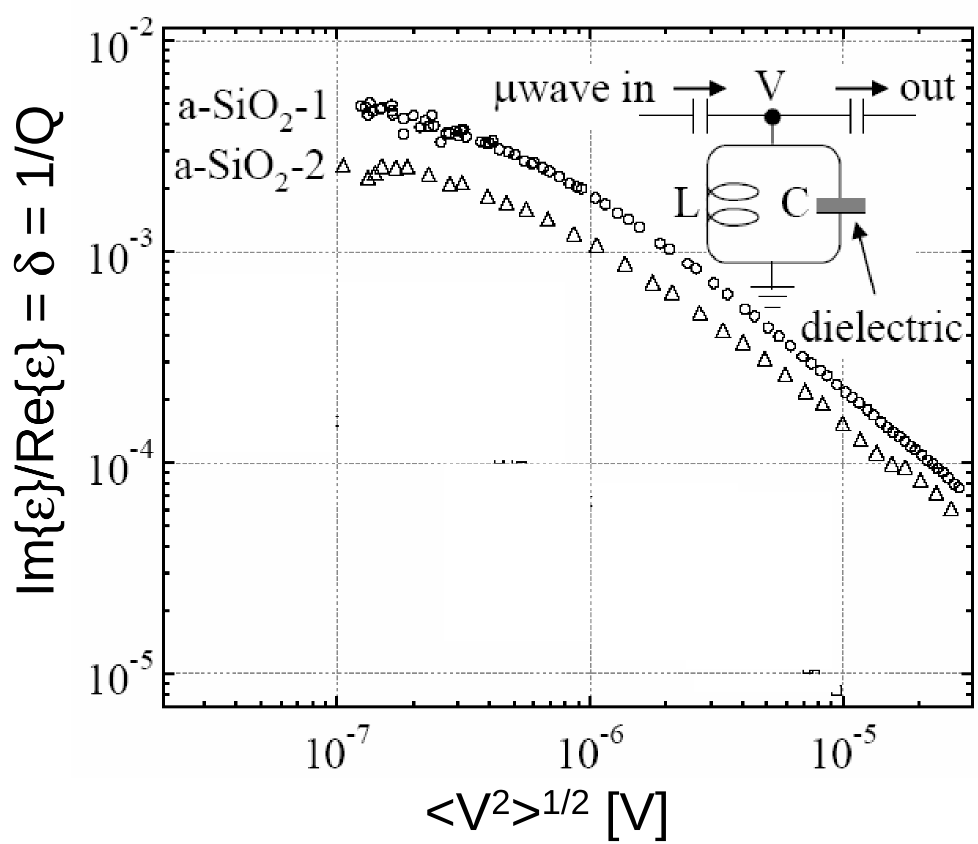
Theory of Dielectric Loss



Two-level (TLS) bath: saturates at high power, decreasing loss



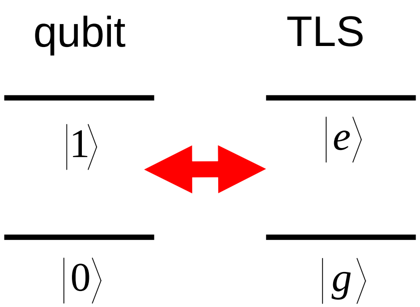
von Schickfus and Hunklinger, 1977

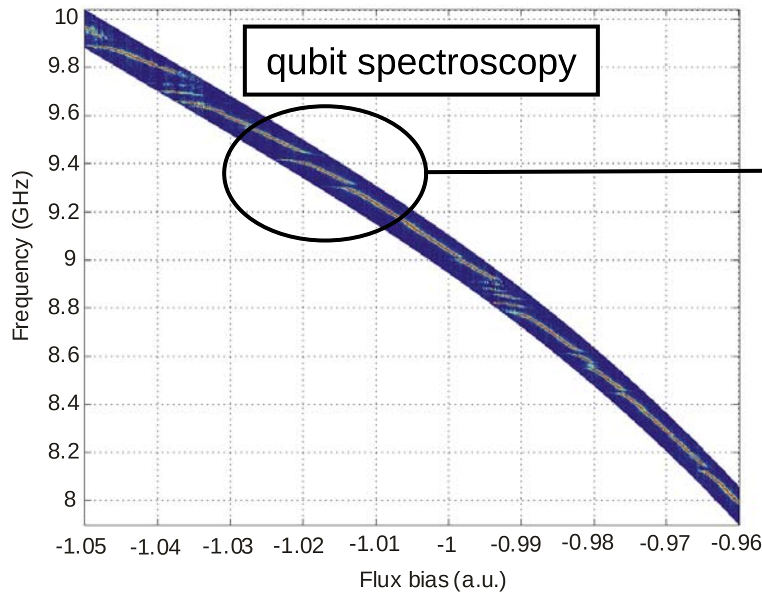


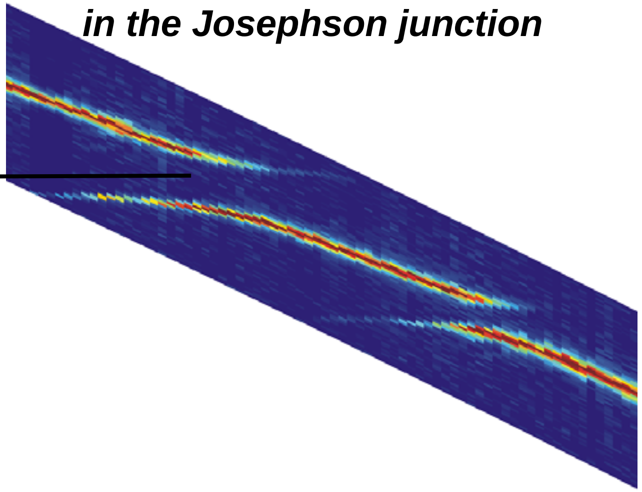
Qubit Interaction with Resonant TLS

avoided level crossings - qubit interaction with resonant two-level defect states (TLS) in the Josephson junction

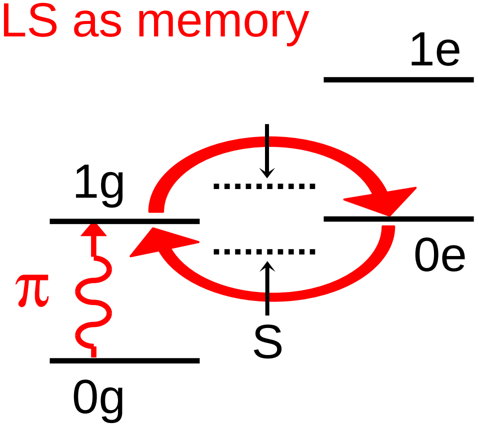
interaction
S

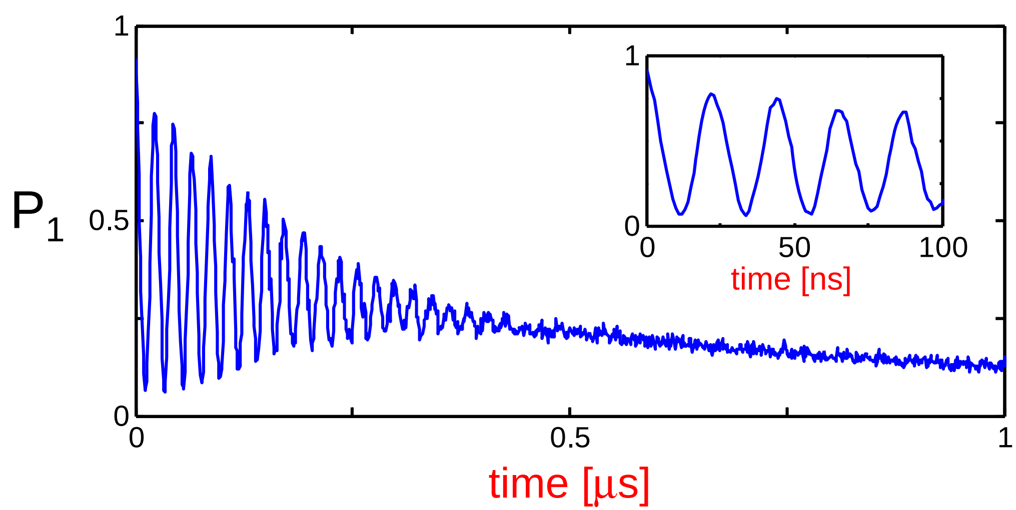




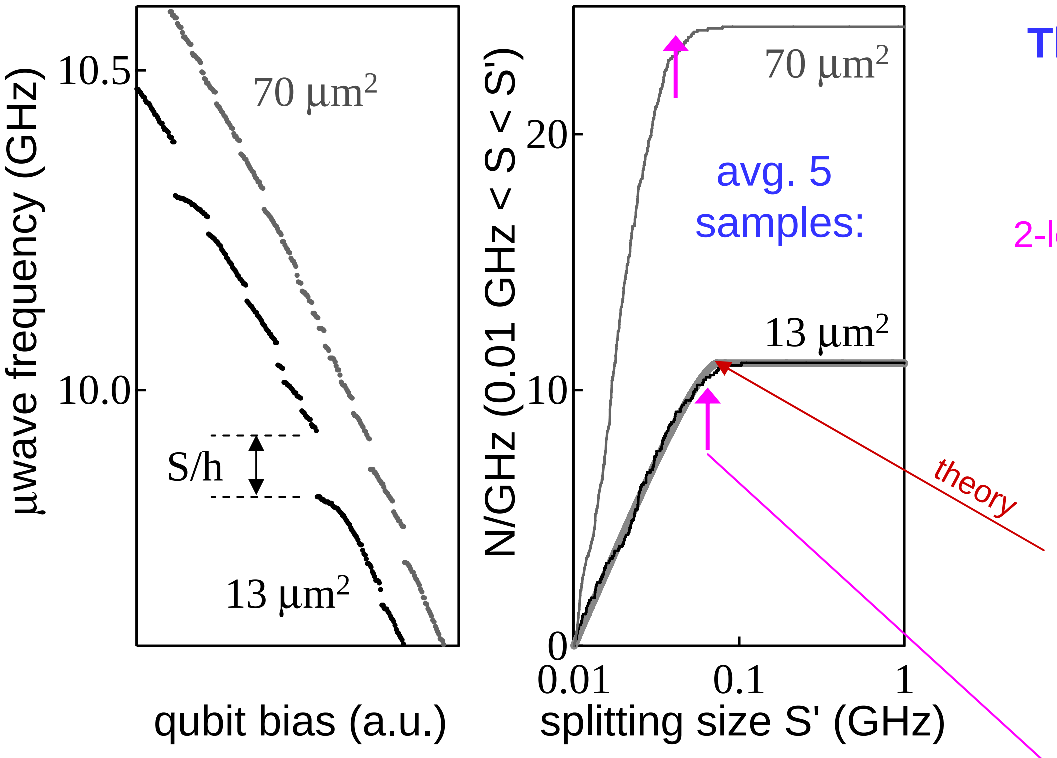


time experiments:
TLS as memory

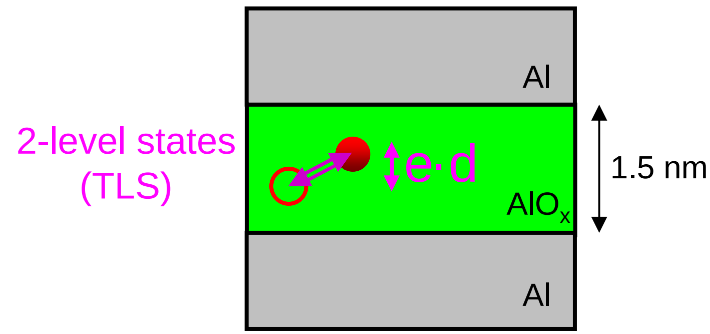




Junction Resonances: Dielectric Loss at the Nanoscale



Theory (Martin *et al*, Martinis *et al*):



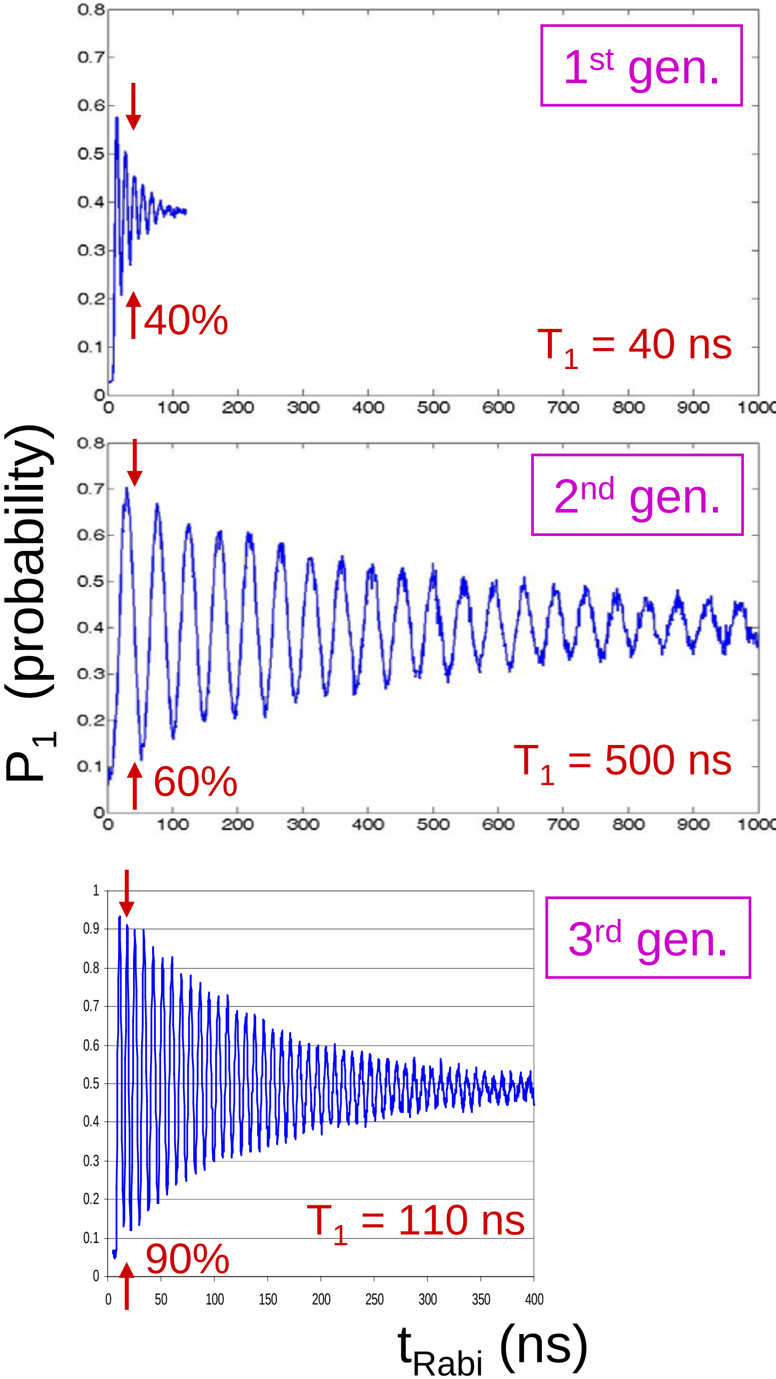
$$\frac{d^2N}{dEdS} = \sigma A \frac{[1-(S/S_{max})^2]^{1/2}}{S}$$

$$S_{max} = \frac{d}{1.5\text{nm}} 2\sqrt{E_{10}e^2/2C}$$

Explains sharp cutoff
d=0.13 nm (bond size of OH defect!)

S_{max} in good agreement with TLS dipole moment:
Charge fluctuators at ~10 GHz explain resonances

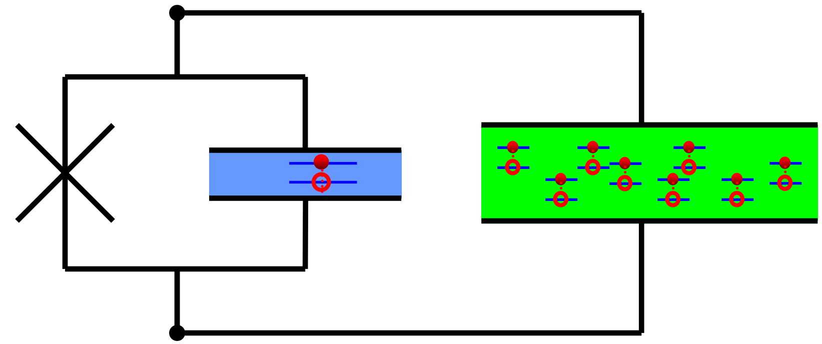
Qubit Improvements

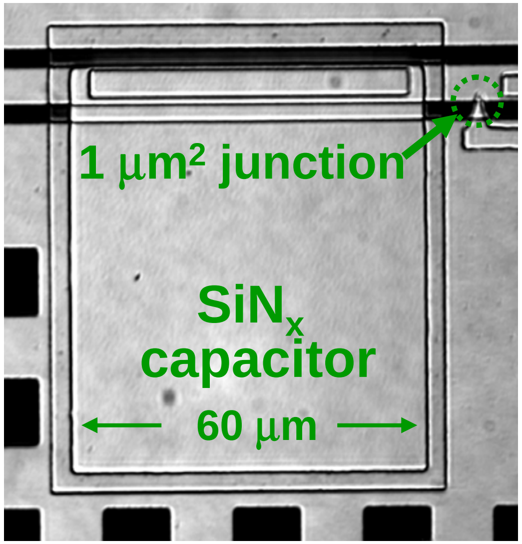


SiO_2 -> SiN_x

Small junction
+ shunting C

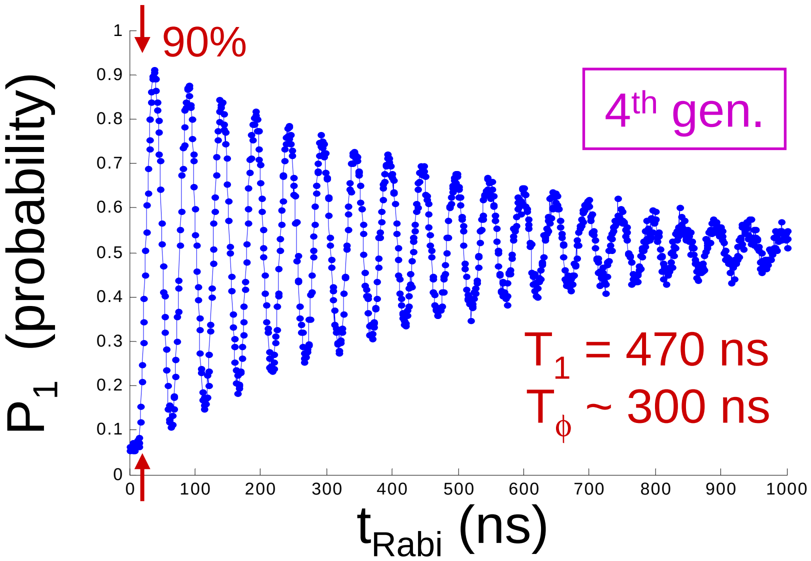
$\delta_i = \delta_i(AlO_x) / 10$

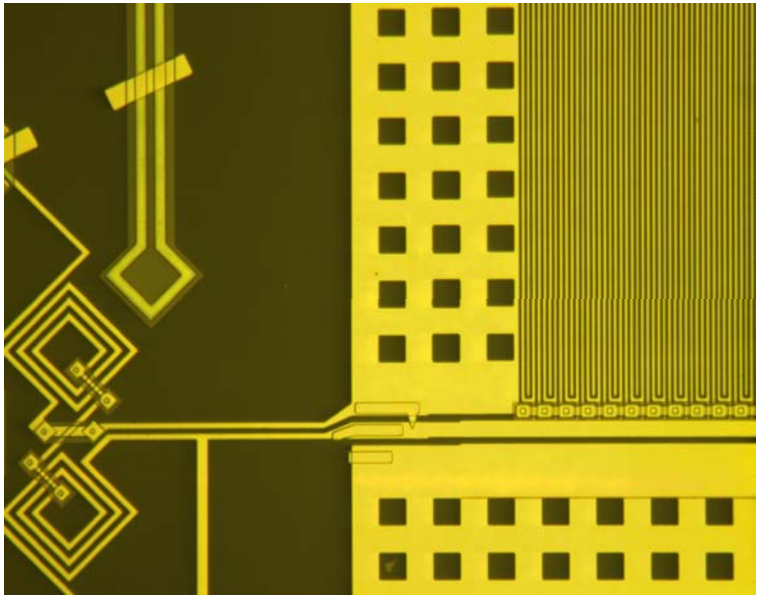




(loss of SiN_x limits T_1)

Outsourcing the Capacitor



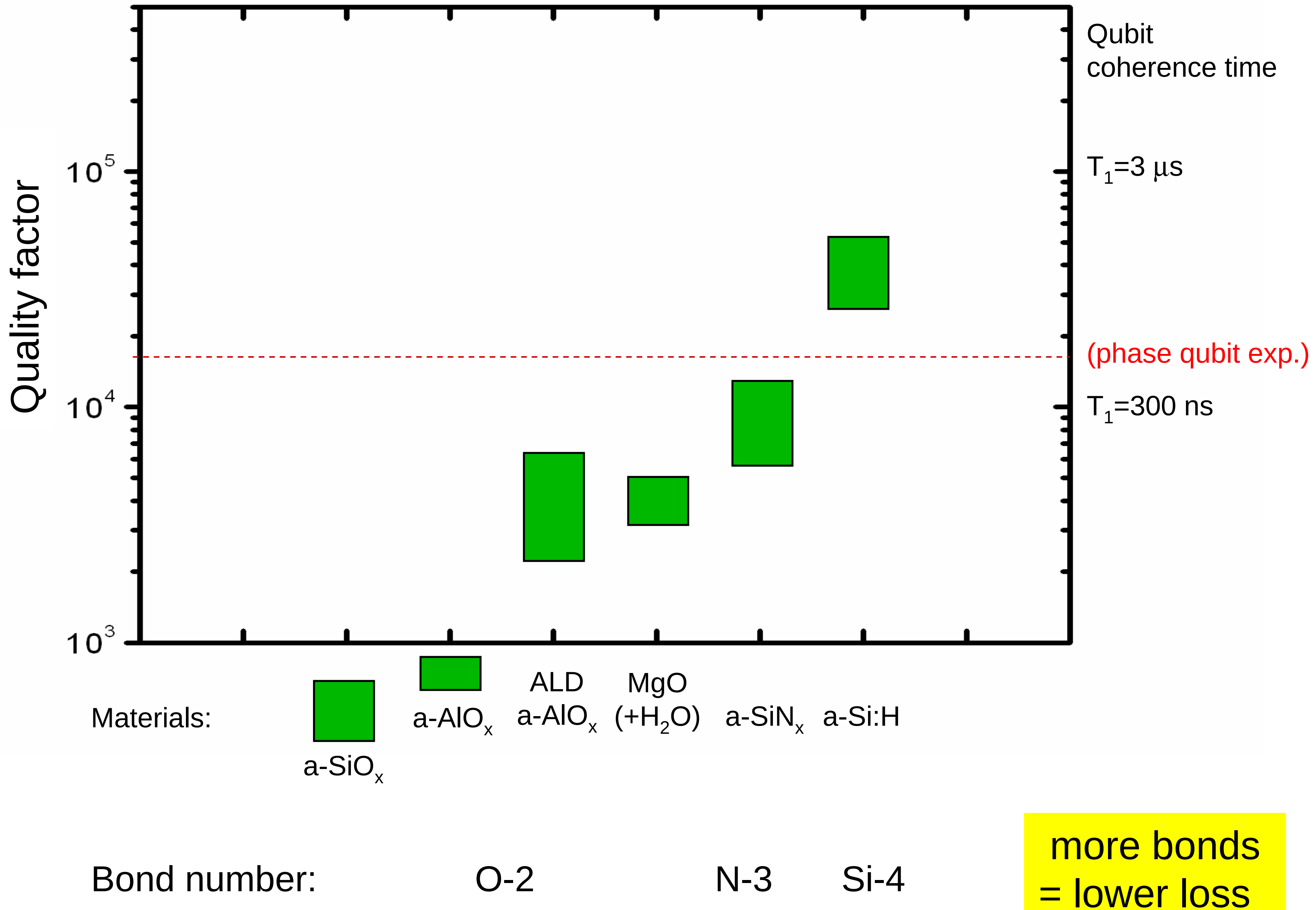


Interdigitated C (and a-Si:H) gives lower loss

Optimistic for further dramatic improvements

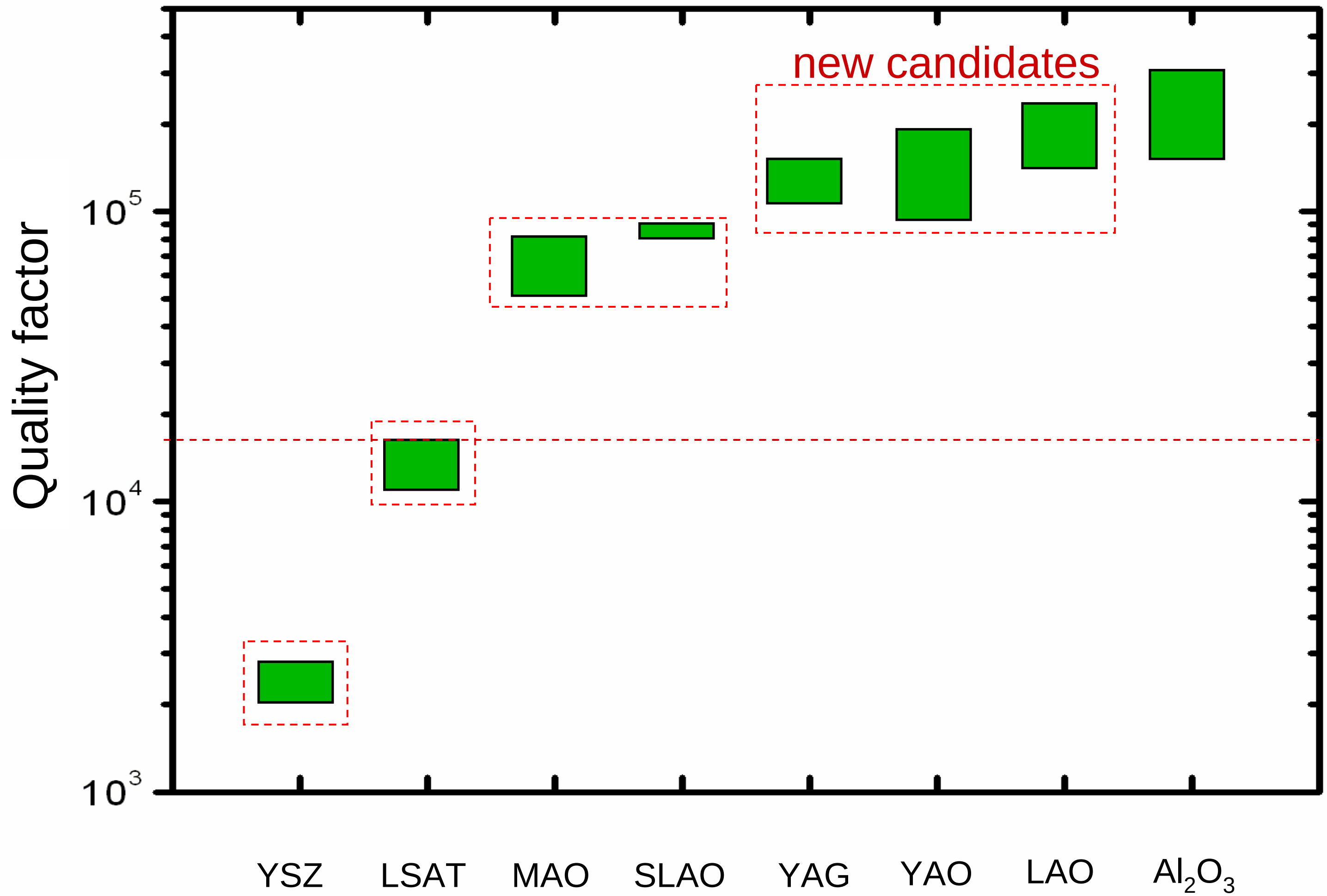
- We know crystals are “superinsulators”
- How to fabricate?

Dielectric Loss from Amorphous Insulators



more bonds
= lower loss

Dielectric Loss from Crystalline Substrates



Other dielectrics besides Si and sapphire are good candidates

Open Questions & Summary

- Although TLS (phonon loss) is well established research,

  little understanding of dielectric loss, correlation with materials
- TLS also produces surface inductance noise, need theory
- Other noise and non-equilibrium sources of decoherence

  Quasiparticles (superconductivity)

  Surface spin noise (2-d spin glass?)

  Josephson junction critical-current noise (electronic defects?)
- Qubits are a sensitive probe of defects

  – new experiments now possible