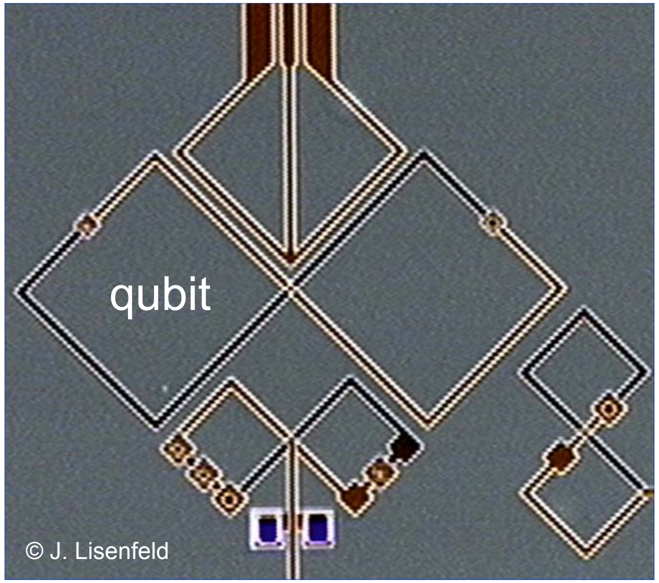
Сверхпроводниковые квантовые биты (эксперимент)



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http://fluxon.physik.uni-erlangen.de

Летняя научная школа
«Нанофизика низких температур»
в Черноголовке

Outline

Lecture 1

- Experiments with Josephson junctions (JJs)
  - making JJs (materials and fabrication)
  - measurements (shielding and filtering)
  - microwave and pulsed experiments
- Macroscopic quantum phenomena in JJs

Lecture 2

  - quantum tunneling
  - energy level quantization
- Experiments with Josephson qubits
  - phase qubits

Lecture 3

  - vortex tunneling and vortex qubit
  - charge qubits
  - cavity quantum electrodynamics (QED) in a circuit
  - ~~quantronium~~
  - flux qubits
  - ~~double-SQUID qubits~~

Lecture 1:
Making experiments with Josephson junctions

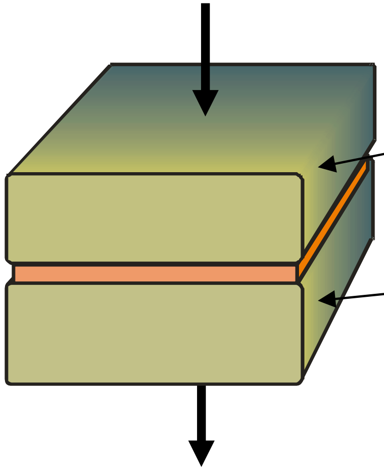
- Fabrication of Josephson junctions
  - Parameters
  - Materials
  - Layout
  - Lithography
- Measurement techniques
  - dc
  - ac (microwaves)
  - pulsed measurements

Josephson effect

superconductor

tunnel barrier

superconductor



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

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

superconducting phase difference: $\varphi = \theta_1 - \theta_2$

Josephson relations

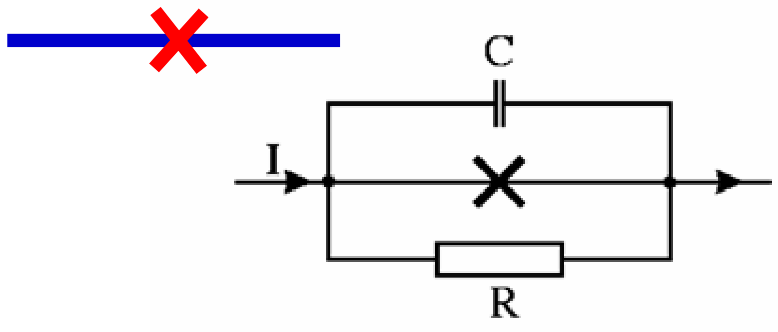
$$\begin{cases} I_s = I_c \sin\varphi \\ V = \dfrac{\hbar}{2e}\dfrac{d\varphi}{dt} \end{cases}$$

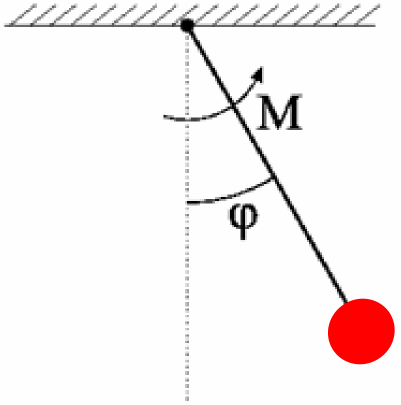
⇒

electromagnetic radiation at the frequency $f = \dfrac{V}{\Phi_0}$

$$\Phi_0 = \frac{h}{2e} \approx 2.07 \times 10^{-15} \mathrm{V \cdot s}$$

Mechanical analog of a Josephson junction: driven underdamped pendulum





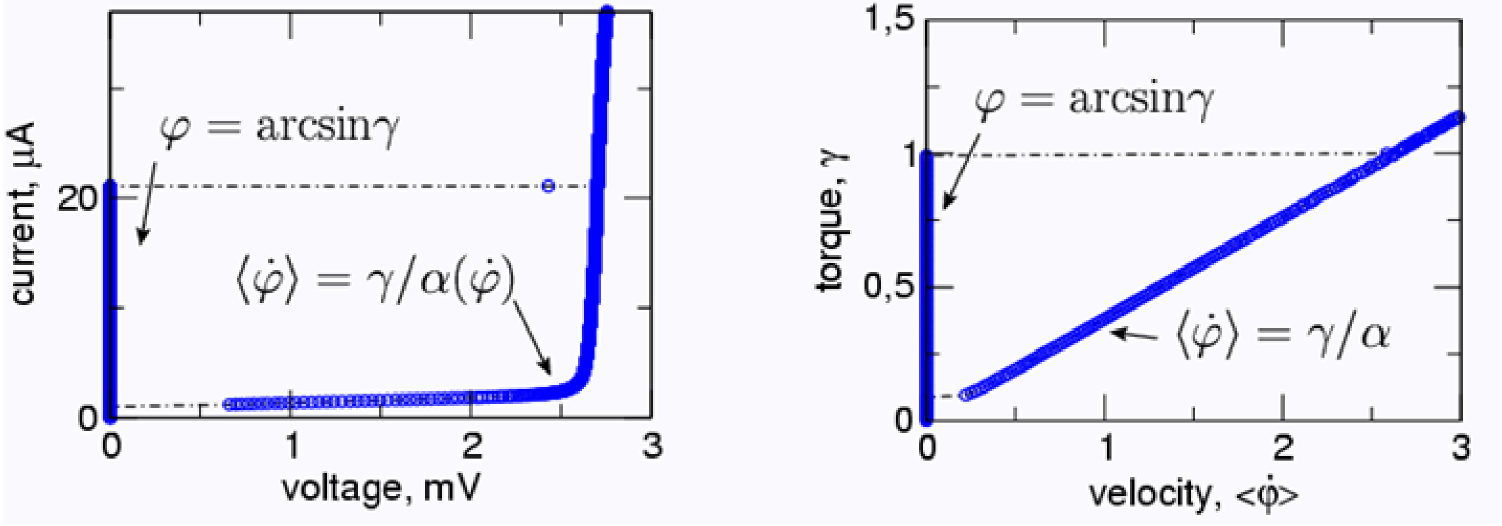
- Mapping:
  - I_C ~ length
  - C ~ mass
  - R^{-1} ~ damping
  - φ ~ angle
  - I ~ ext. torque

Current through the junction

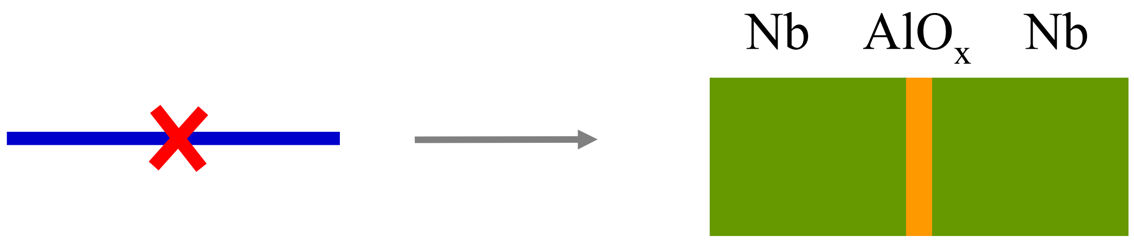
$$\mathcal{N}(\varphi) = \ddot{\varphi} + \alpha\dot{\varphi} + \sin\varphi$$

Josephson junction

pendulum

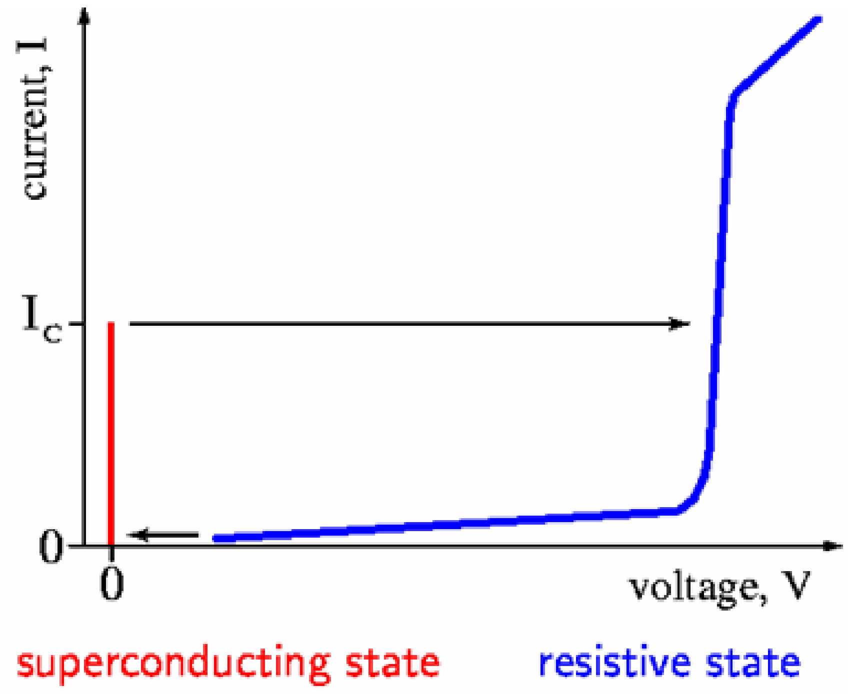


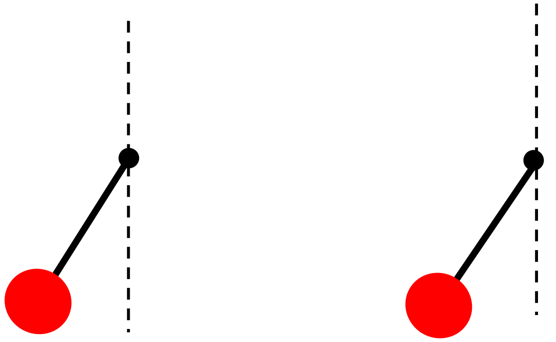
Superconducting and resistive states



Parameters:

- I_C critical current
- C capacitance
- R resistance

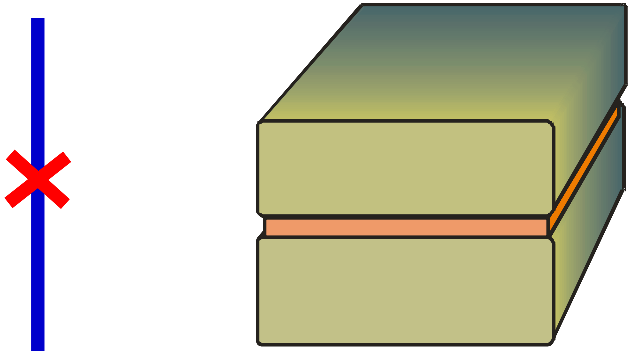




superconducting state

resistive state

Fabrication of Josephson junctions

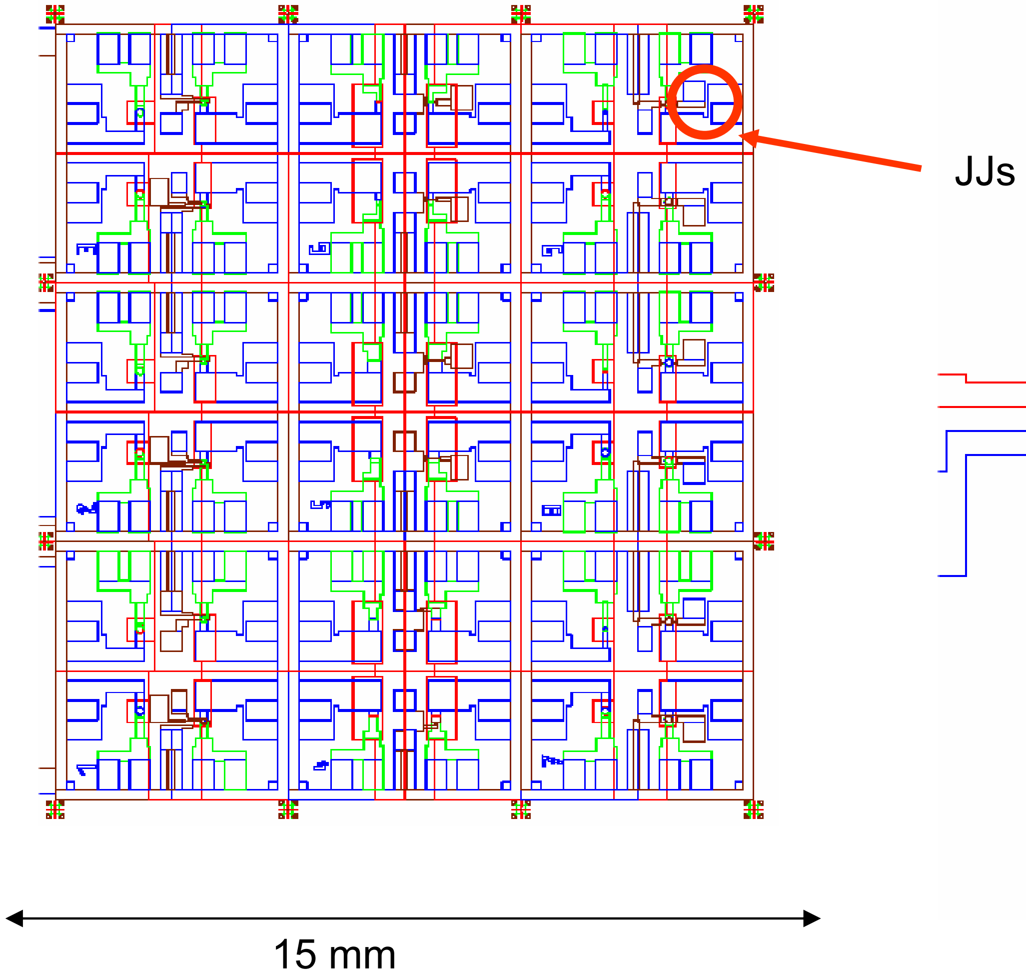


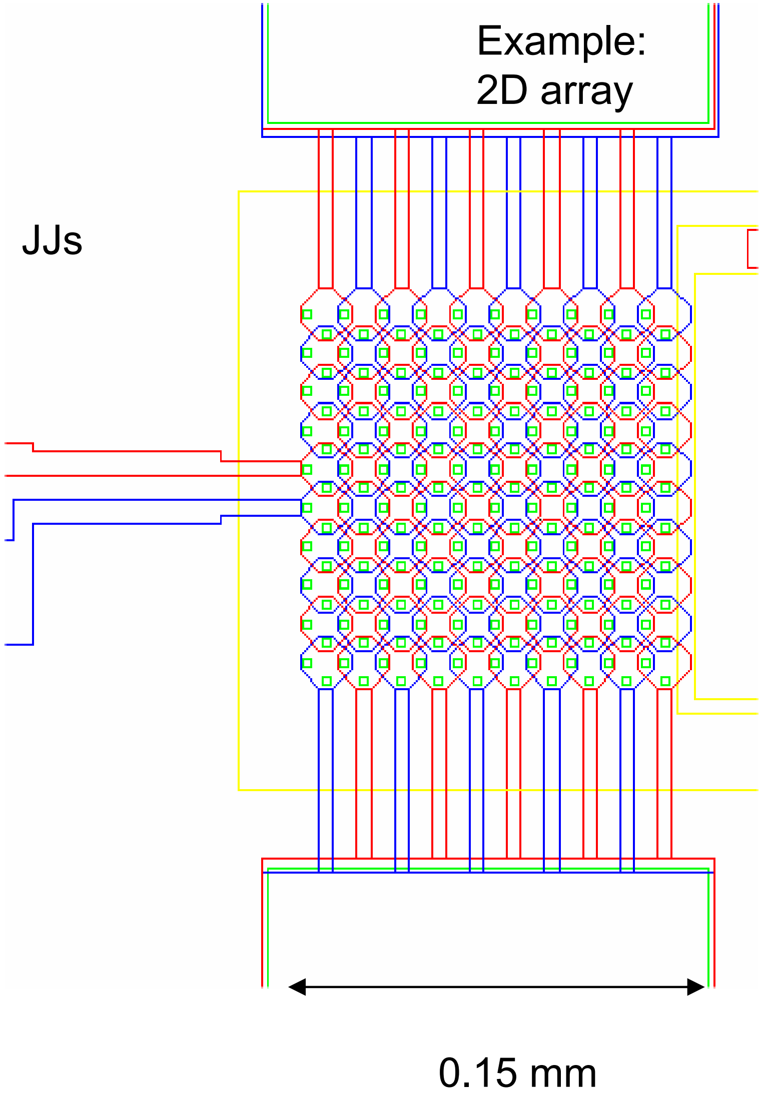
1. circuit layout (CAD)
2. fabrication of photomasks
3. deposition of superconducting and insulating layers on a wafer
4. photo (or e-beam) lithography
5. dicing the wafer into chips

- *Nb-AlO$_x$-Nb*
  - *Nb* sputtering
  - *Al* sputtering and oxidation
  - T_c = 9.2 K
  - J_c from 10^2 to 10^4 A/cm^2
- *Al-AlO$_x$-Al*
  - *Al* evaporation
  - *Al* oxidation
  - T_c = 1.2 K
  - J_c from 1 to 10^2 A/cm^2

Sample layout

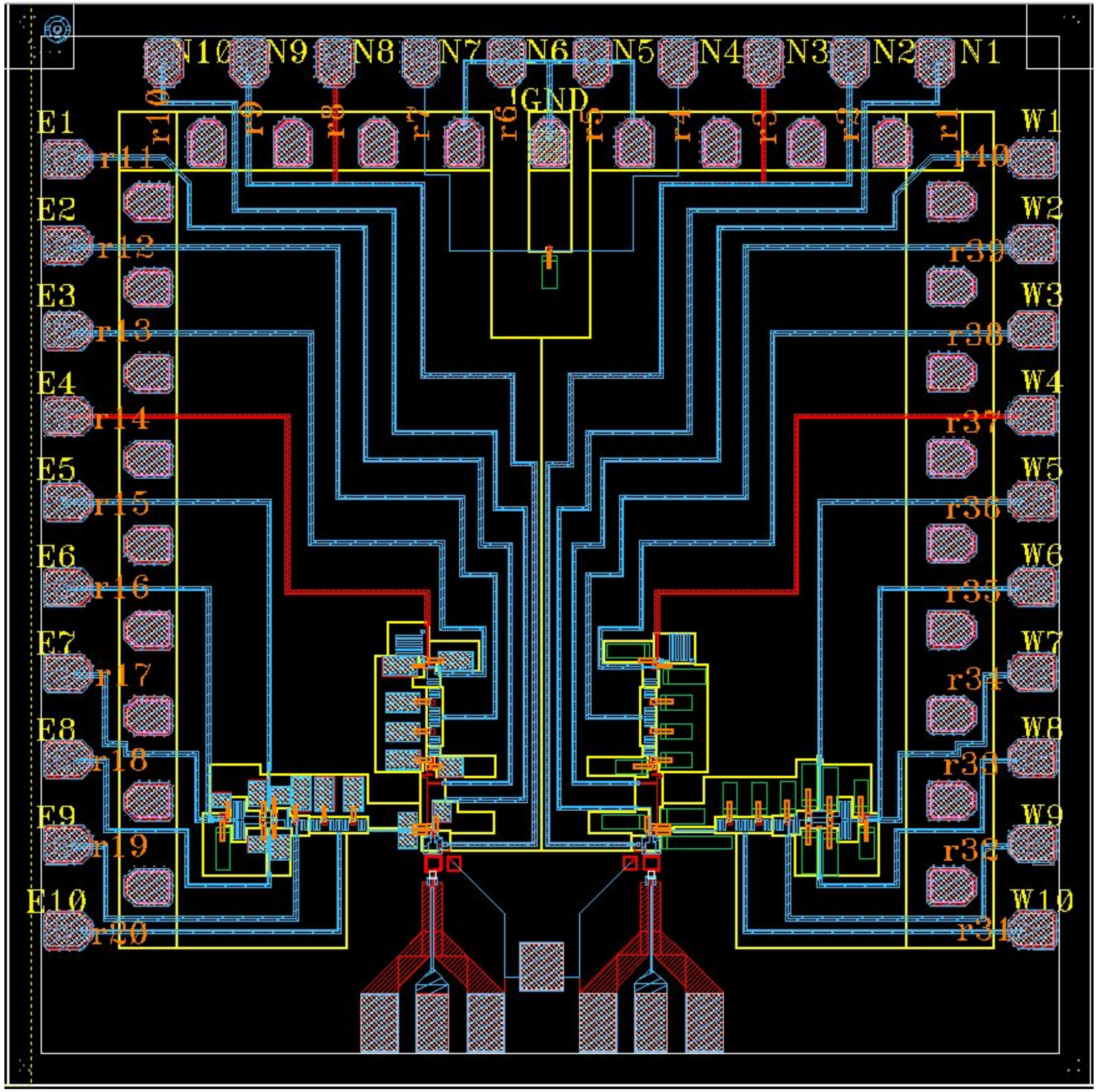
CAD = computer aided design





Example of sample layout (RSFQ)

RSFQ = Rapid Single
Flux Quantum Logic

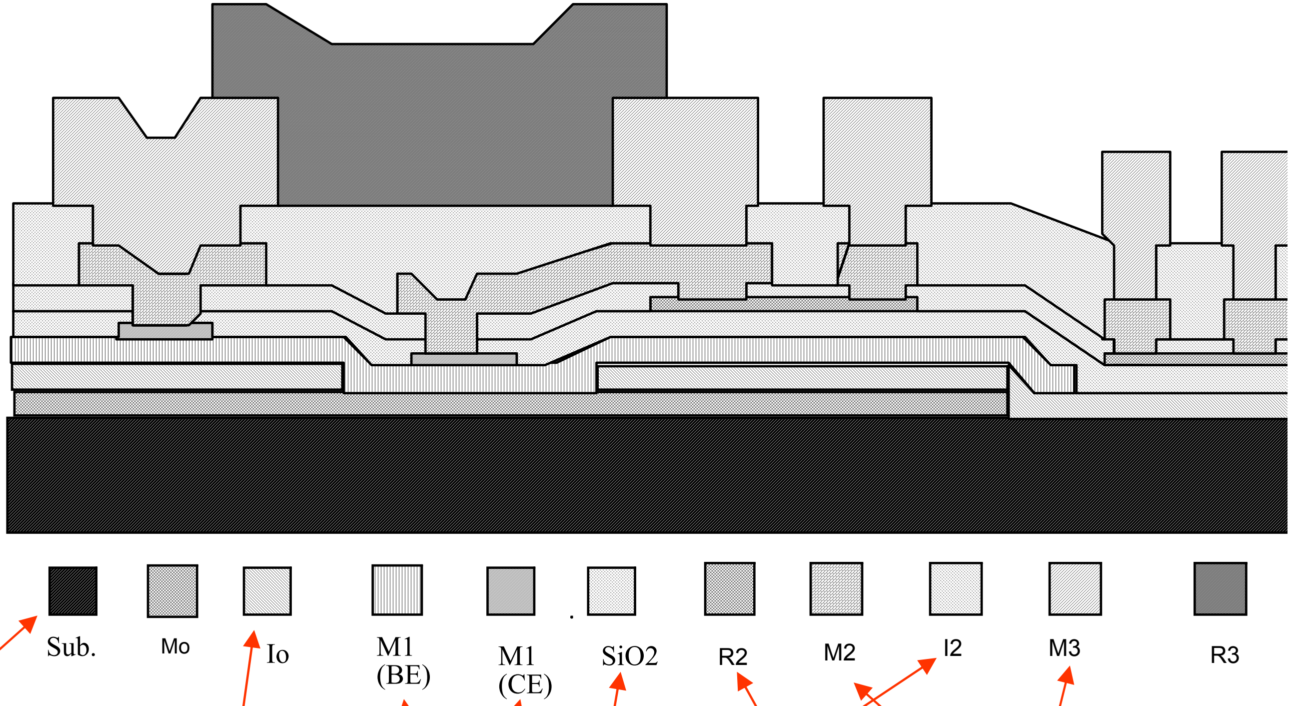


© T. Okhi (Chalmers, 2007)

Foundry rules: Example

design rules of Hypres Inc.

See: http://www.hypres.com



$Nb\text{-}AlO_x\text{-}Nb$

Nb

Si substrate

Insulator (SiO_2)

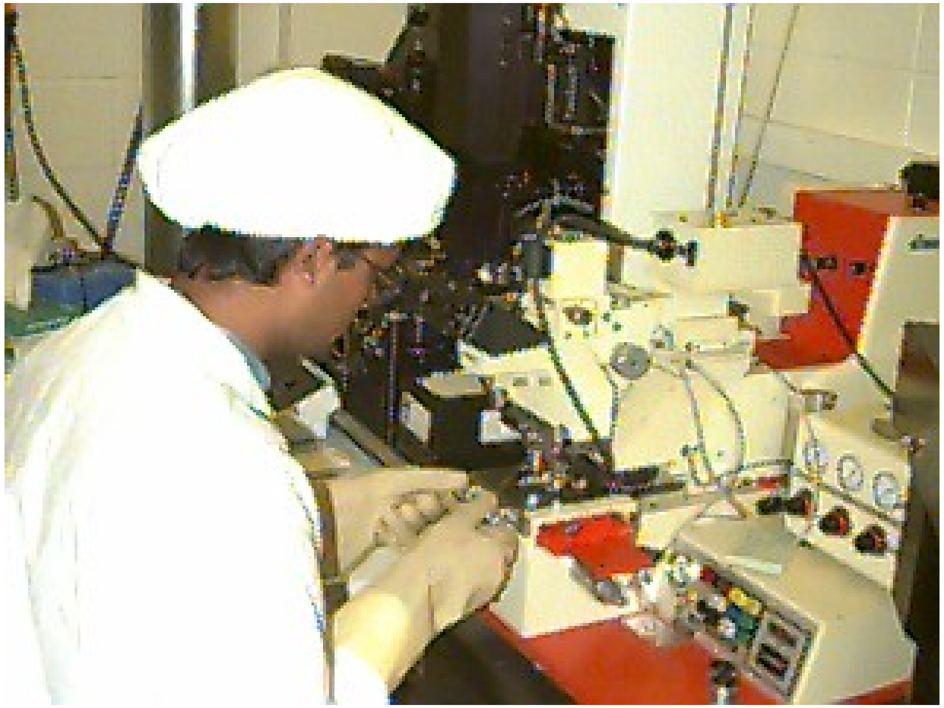
insulator

resistive layer (Mo or $AuPd$)

Wafer processing

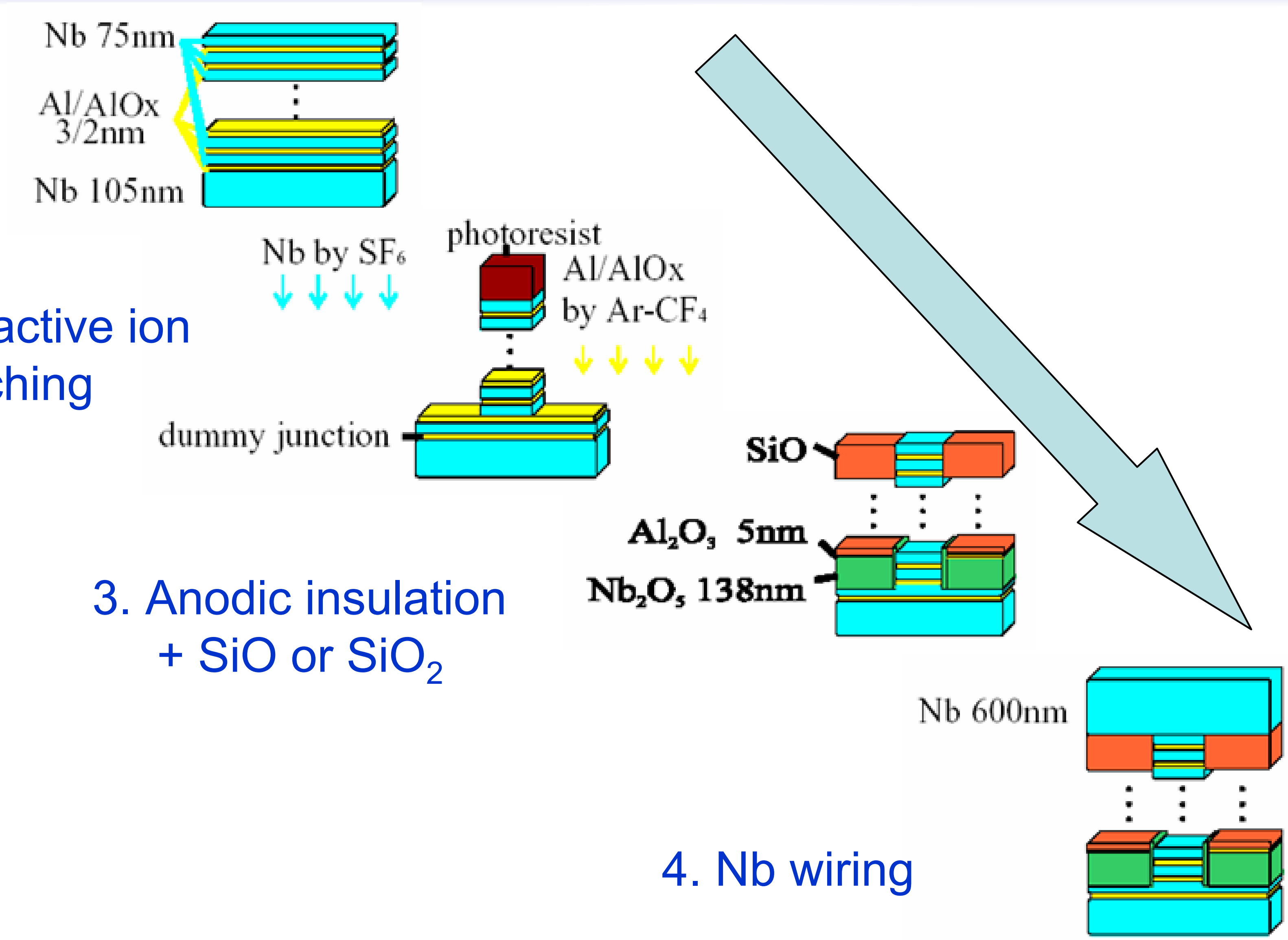
Photolithography can be used for JJ size down to 1 μm

Clean room



mask alignment

Fabrication of Nb-AlO$_x$-Nb junctions



1. Deposition of a multilayer

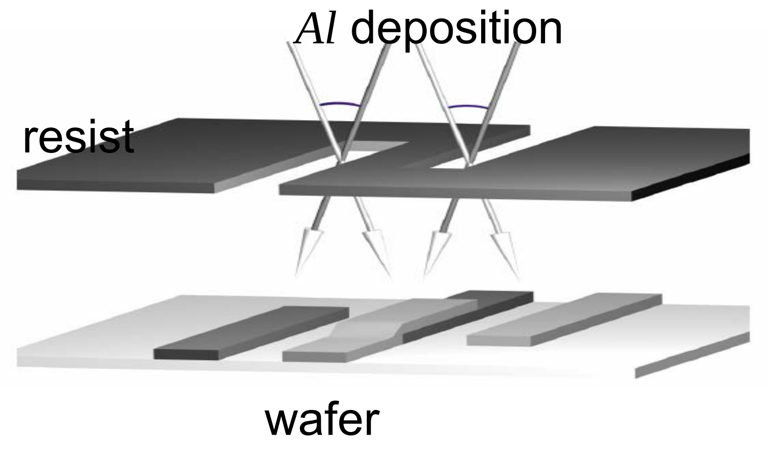
2. Reactive ion etching

3. Anodic insulation + SiO or SiO$_2$

4. Nb wiring

Shadow evaporation technique

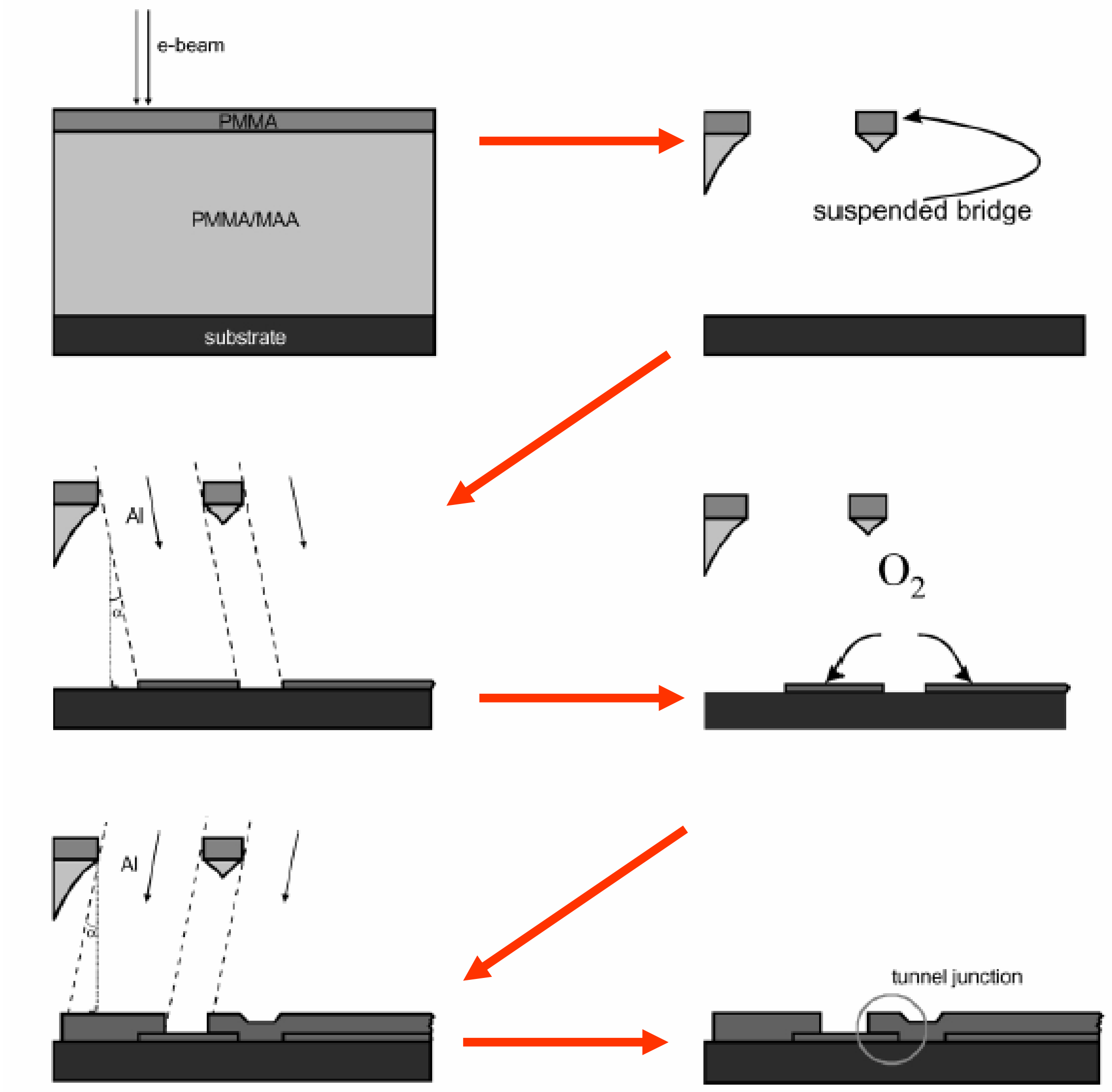
Electron beam lithography can produce JJ size < 0.1 μm



Electrom beam lithography

In a first step metal is evaporated from one angle, indicated by the dark arrows and dark structures on the substrate surface. The evaporation from another angle leads to an overlap of the features in the middle. (Picture by Mattias Urech)

Shadow evaporation of Al-AlO$_x$-Al junctions



Pattern is written in the resist using an electron beam

After the sample is developed, a suspended resist bridge is left

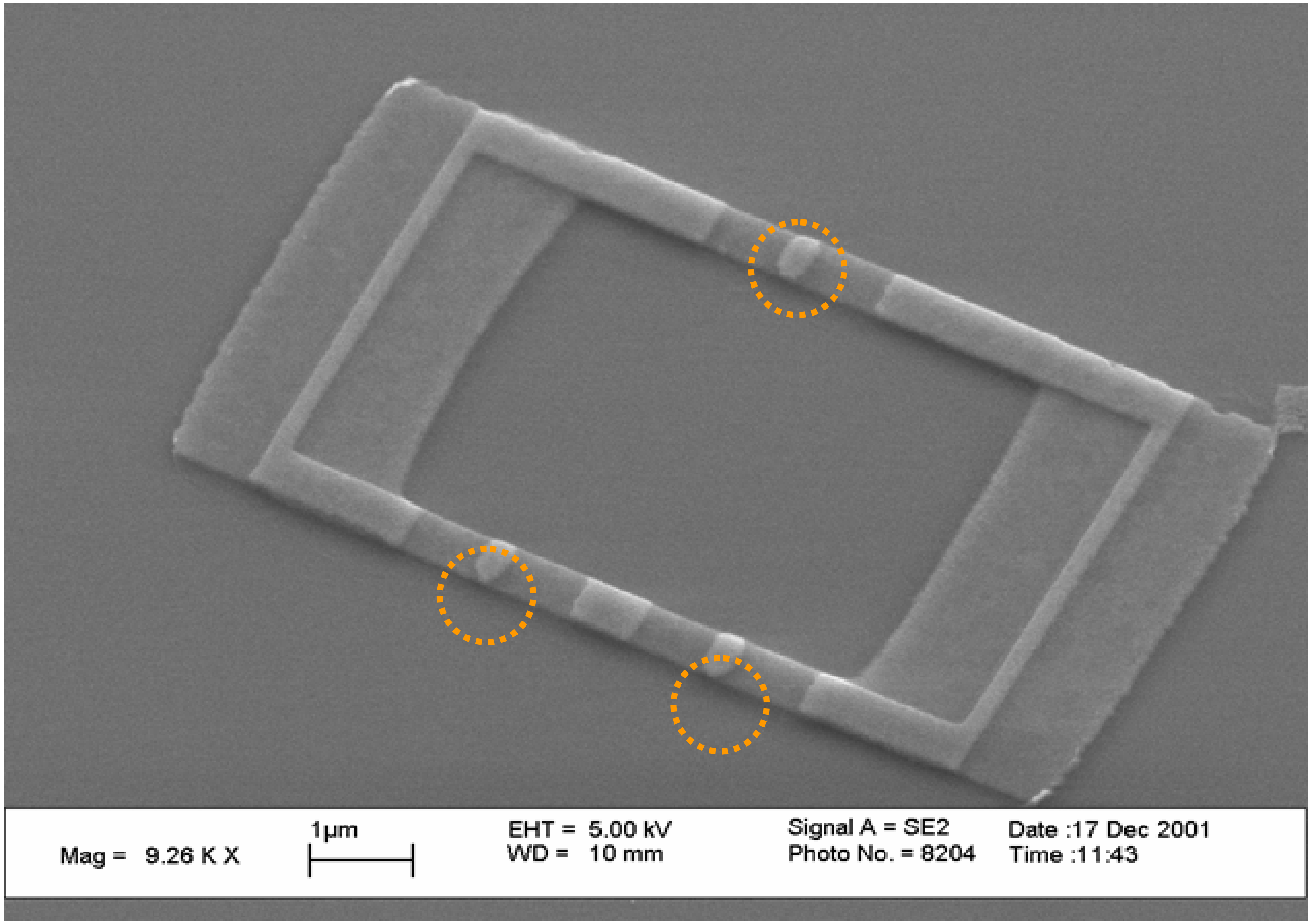
The bottom layer of aluminum is deposited under an angle +α

The sample is exposed to O_2 to form the oxide layer

The top layer of aluminum is deposited under an angle -α

Lift-off in acetone removes the resist and a tunnel junction is left

Sub-micron Al-AlO$_x$-Al JJs produced by electron beam lithography



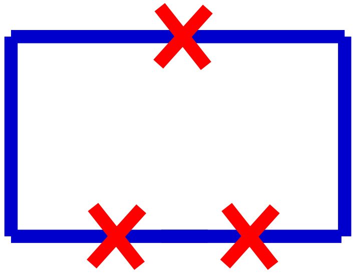
Mag = 9.26 K X

1µm

EHT = 5.00 kV
WD = 10 mm

Signal A = SE2
Photo No. = 8204

Date :17 Dec 2001
Time :11:43

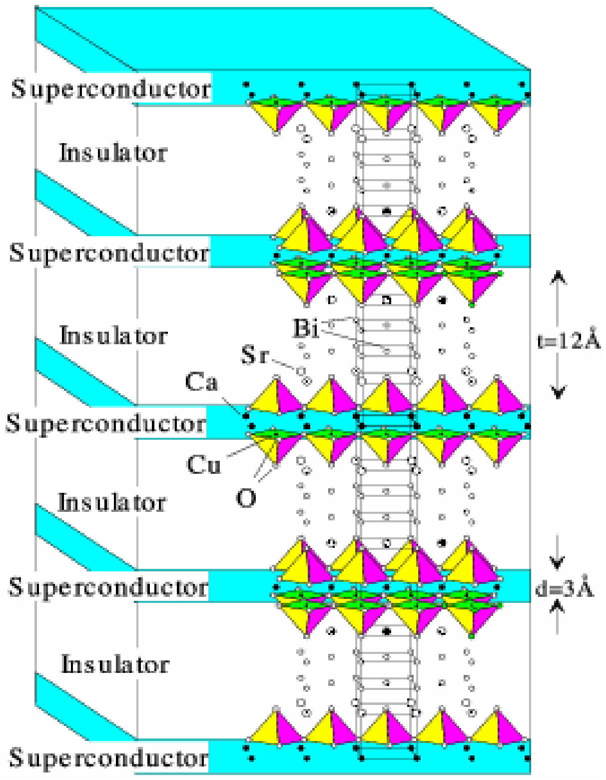


3-JJ flux qubit

Josephson junctions made by nature

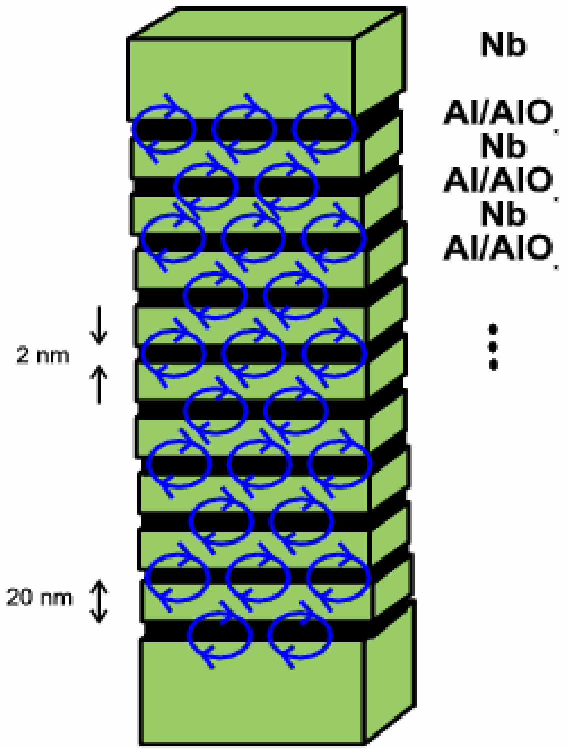
Natural (intrinsic JJs)

$Ba_2Sr_2CaCu_2O_{8-x}$

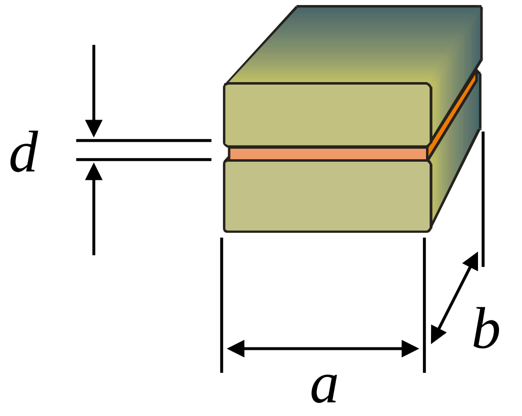


Artificially grown

$(Nb/AlO_x)_N Nb$



Junction parameters



tunnel barrier thickness d

junction area $A = a\,b$

Josephson energy $E_J = \dfrac{I_c \Phi_0}{2\pi}$

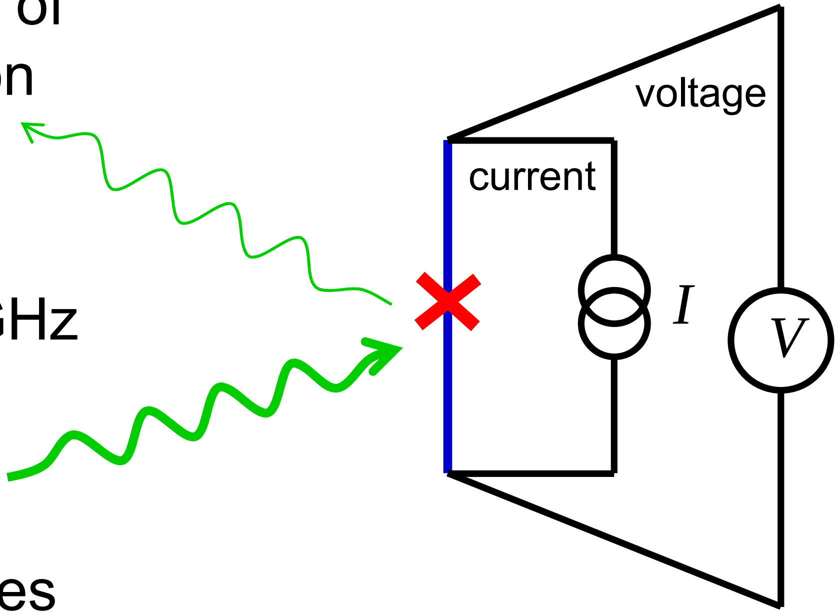
charging energy $E_C = \dfrac{e^2}{2C_J}$

$$I_c = \frac{\Phi_0 \Delta}{2R_n} \sim A \exp\left(-\frac{d}{d_0}\right) \qquad C_J \sim \frac{A}{\varepsilon\, d}$$

$$\Rightarrow \quad \frac{E_J}{E_C} \sim A^2\, d\, \exp\left(-\frac{d}{d_0}\right)$$

Typically, achiving $\dfrac{E_J}{E_C} \sim 1$ requires $A < 0.001\,\mu\mathrm{m}^2$

Measurements of Josephson junctions



Detection of
Josephson
radiation

10 - 600 GHz

applying
microwaves

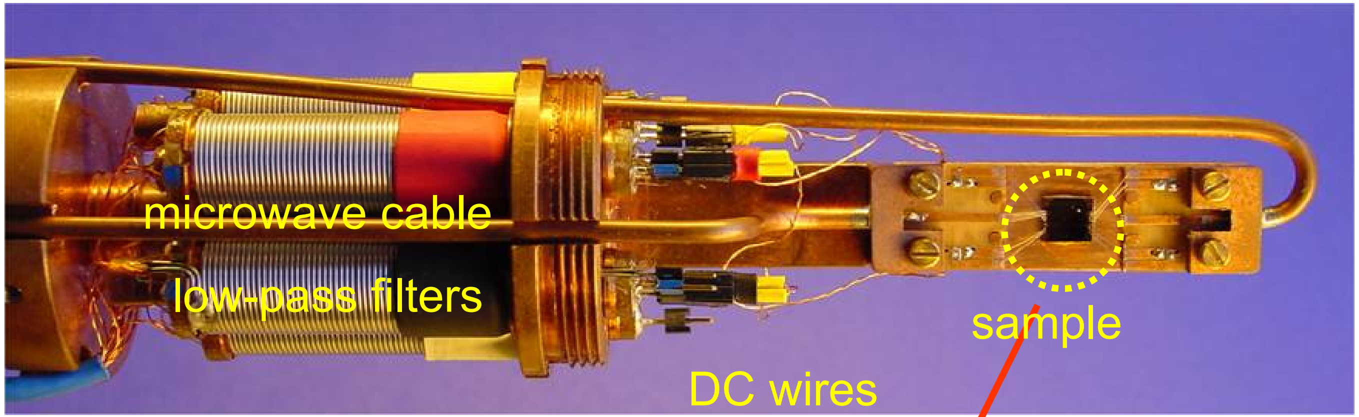
AC techniques

DC techniques

expensive and difficult

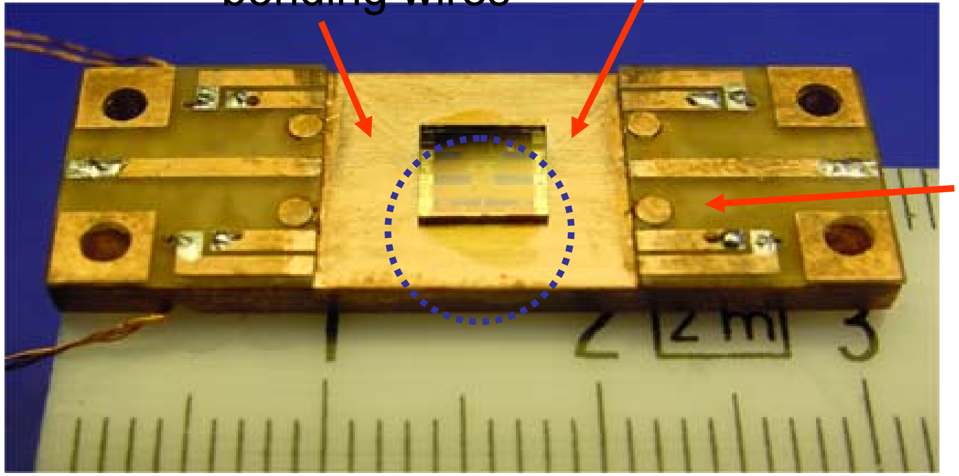
cheap and easy

Sample holder



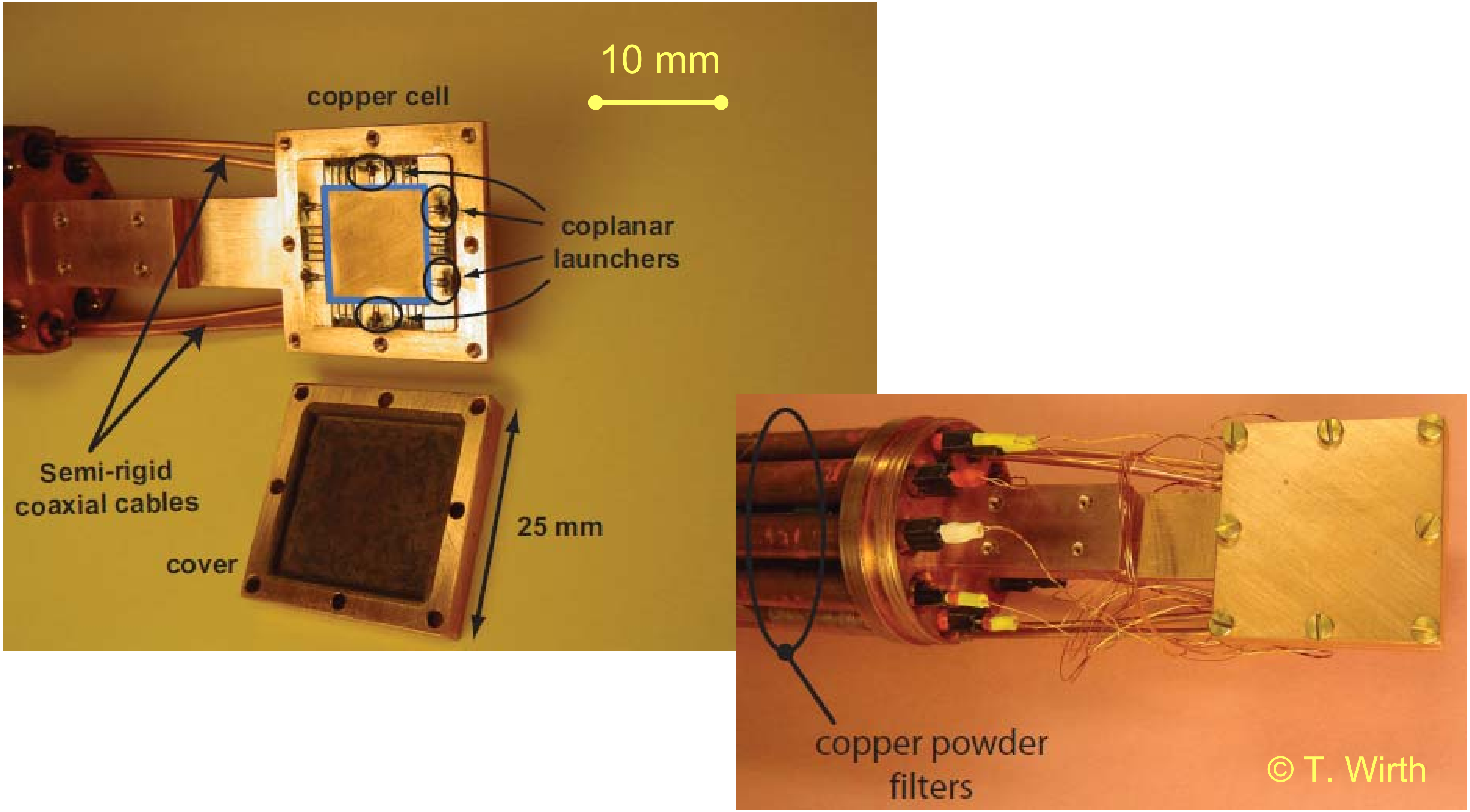
microwave cable

bonding wires

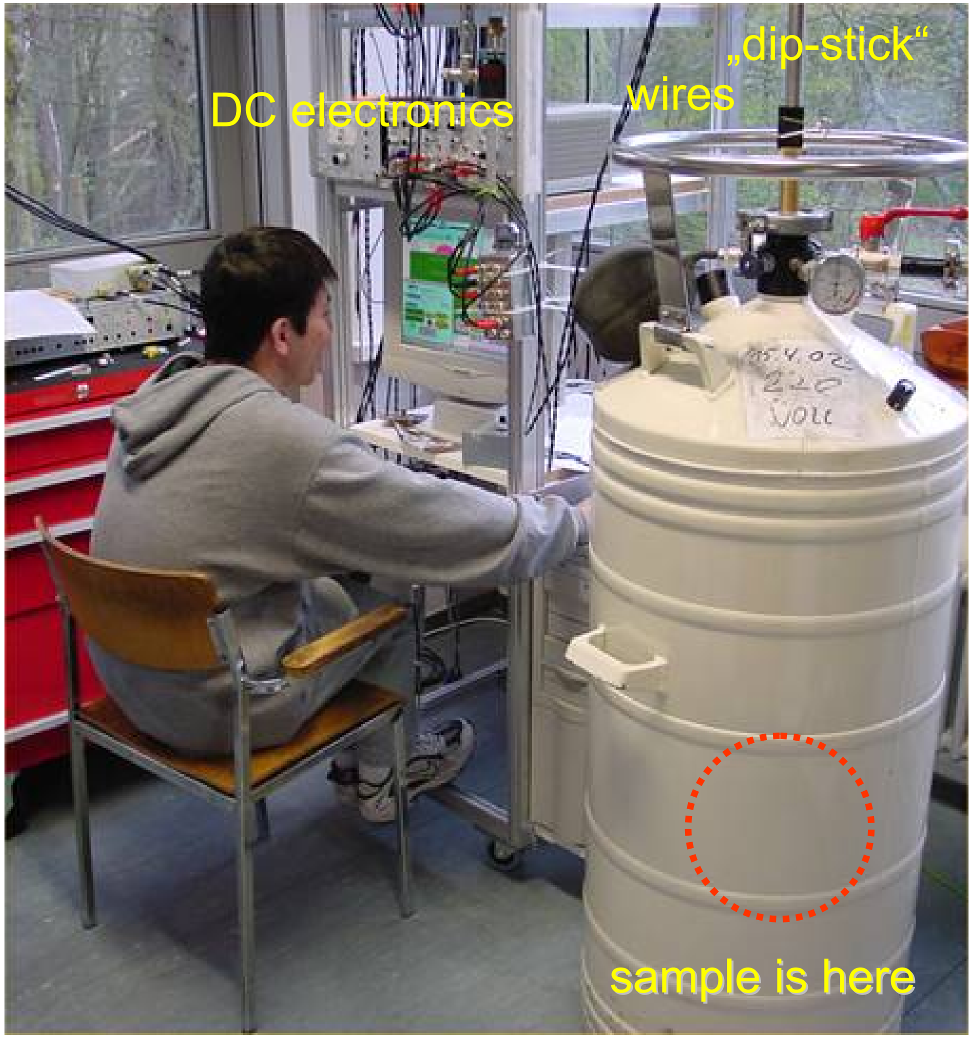


50 Ω stripline

Sample holder (2)



DC measurements place



a dewar with
100 liter of
liquid helium

T = 4.2 K

AC measurement equipment

spectrum analyzer
0.01 – 26 GHz

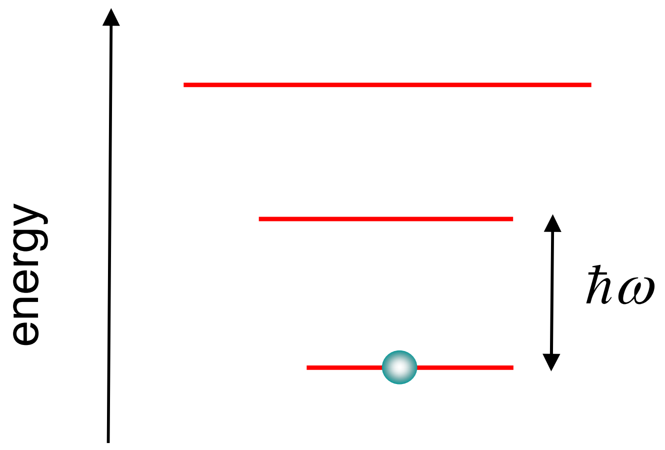
network analyzer
0.05 – 20 GHz

sub-ns pulse generator

microwave sweeper
0.05 – 20 GHz

microwave source
0.5 – 18 GHz

How low should be the temperature?



To see the energy levels we need $\hbar\omega >> k_B T$.

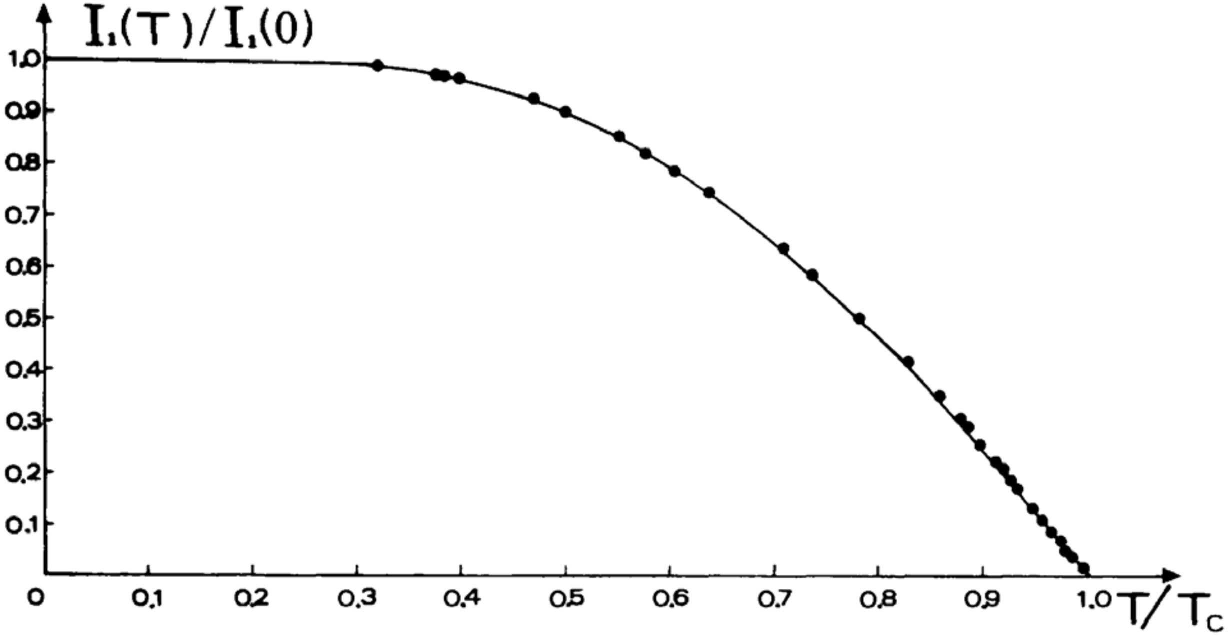
For the level separation frequency of

$$f = \frac{\omega}{2\pi} = 10\,\mathrm{GHz}$$

the condition $T = \frac{\hbar\omega}{k_B}$ corresponds to $T \approx 0.48\,\mathrm{K}$

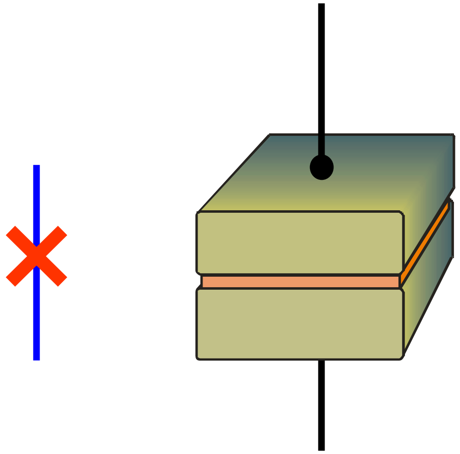
i.e. $1\,\mathrm{GHz} \Longleftrightarrow \sim 50\,\mathrm{mK}$

Temperature dependence of the critical current



© A.Barone data

Sn-SnO$_x$-Sn junction

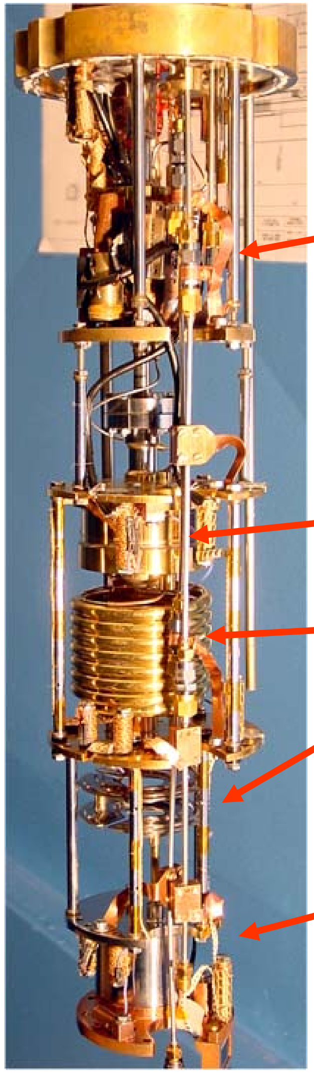


Ambegaokar and Baratoff (1963)

$$I_c(T) = \frac{\pi}{2}\frac{\Delta(T)}{R_n}\tanh\frac{\Delta(T)}{2k_\mathrm{B}T}$$

Measurements at mK temperatures

Dilution Refrigerator (e.g., from Oxford Instruments) with base temperature ~ 15 mK



- 1 K pot (pumped liquid ^{4}He)

- condenser (to liquefy ^{3}He coming from the room temperature pumps)

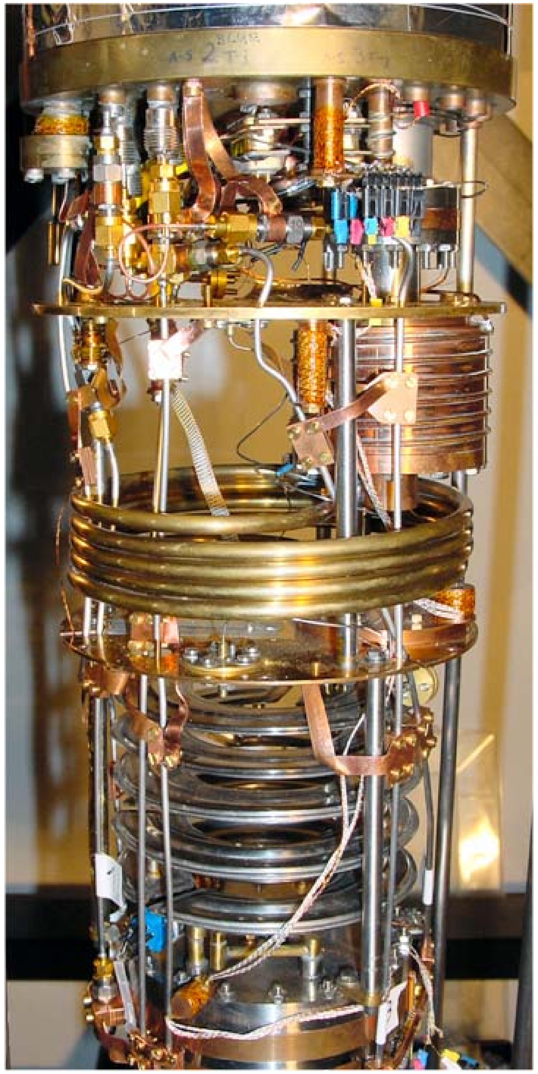
- still (to pump on the dilute ^{3}He-^{4}He mixture)

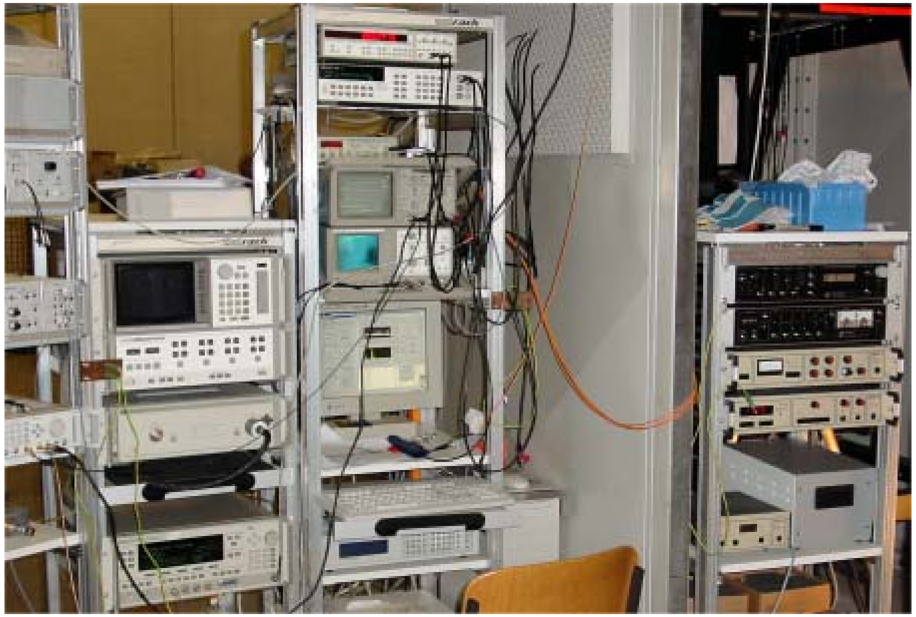
- two sets of heat exchangers (one side of each heat exchanger contains ^{3}He from the condenser while the other side has dilute mixture headed toward the still)

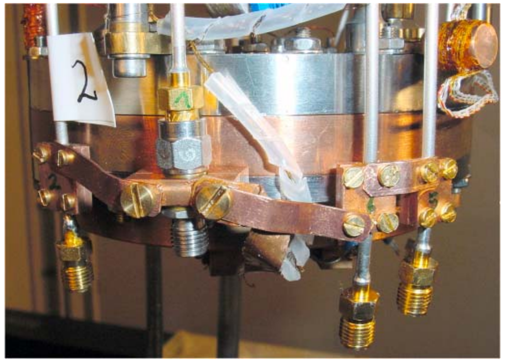
- mixing chamber (which contains the phase boundary between the pure ^{3}He coming from the condenser and the 94% ^{4}He + 6% ^{3}He, the "dilute" phase).

How real measurement looks like …

“old horse”





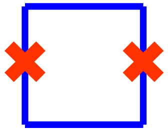


mixing chamber cools down to 10 mK

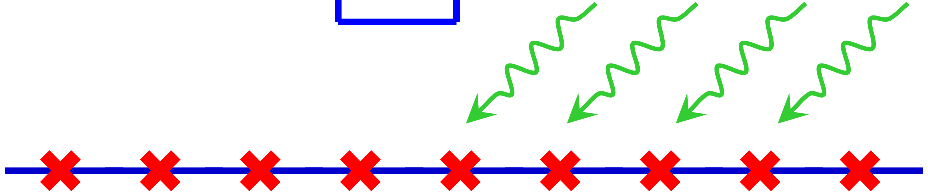
<u>Short experimental quiz:</u>
how to thermally anchor the coaxial line central conductor?

Applications of Josephson junctions

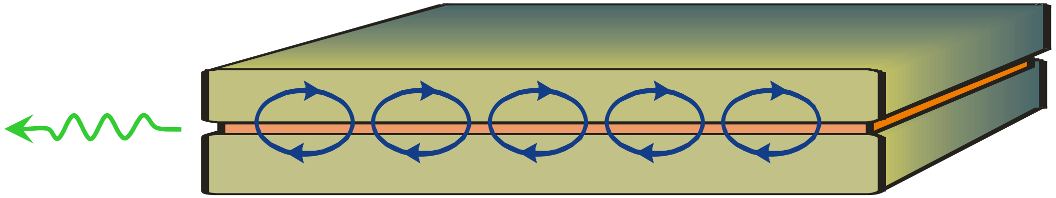
- SQUIDs (magnetometry)



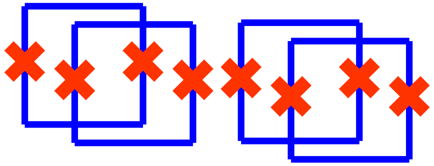
- Voltage standard



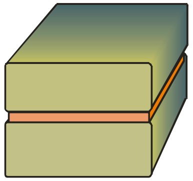
- Microwave generators
  (*1* GHz – *1* THz)



- RSFQ digital electronics

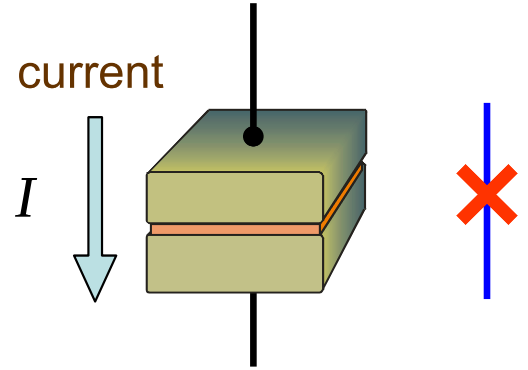


- Qubits



Josephson junction: mapping to a pendulum

Dynamics of a small Josephson junction is equivalent to the motion of a particle



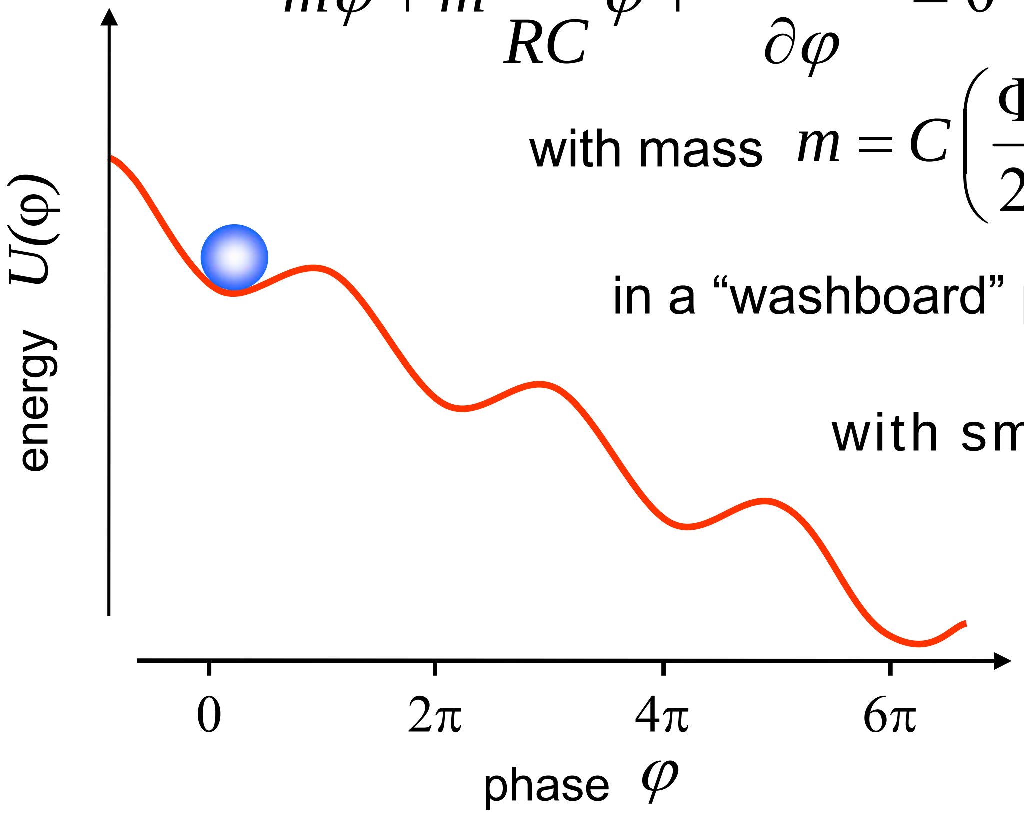
$$m\ddot{\varphi} + m\frac{1}{RC}\dot{\varphi} + \frac{\partial U(\varphi)}{\partial \varphi} = 0$$

with mass $m = C\left(\frac{\Phi_0}{2\pi}\right)^2$

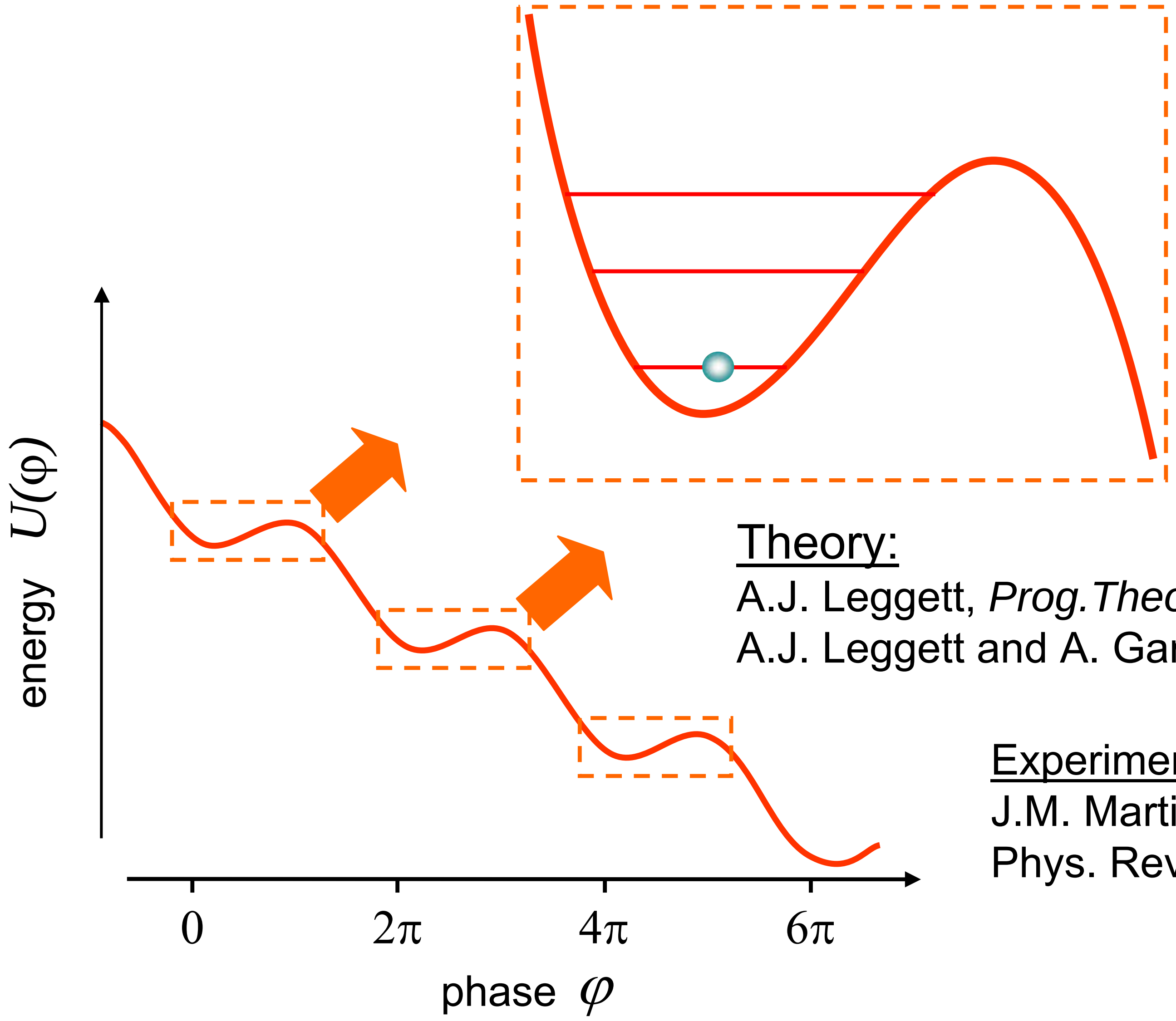
in a “washboard” potential $U(\varphi) = -\frac{I_c\Phi_0}{2\pi}\left(\frac{I\varphi}{I_c} + \cos\varphi\right)$

with small-amplitude oscillation frequency

$$\omega\ (I)\ =\ \omega_0 \sqrt[4]{1-\frac{I^2}{I_c^2}} \quad ; \quad \omega_0 = \sqrt{\frac{2\pi\, I_c}{\Phi_0 C_J}}$$



Macroscopic quantum system



By reducing the
capacitance C
the ´mass`

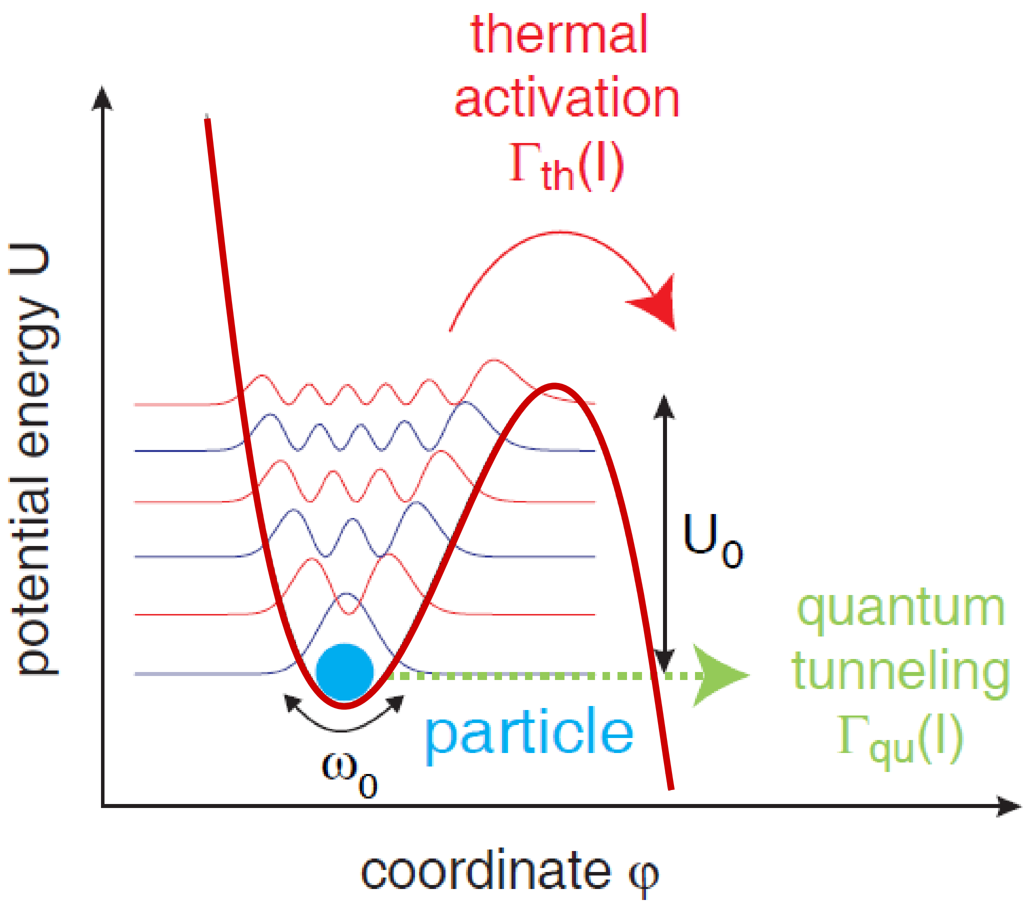
$$m = C\left(\frac{\Phi_0}{2\pi}\right)^2$$

can be made small

Theory:
A.J. Leggett, *Prog.Theor.Phys.Suppl.* **69**, 80 (1980).
A.J. Leggett and A. Garg, *Phys.Rev.Lett.* **54**, 857(1985).

Experiment:
J.M. Martinis, M. H. Devoret, and J. Clarke,
Phys. Rev. B **35**, 4682 (1987).

Thermal and quantum escape of the phase in a Josephson junction



thermal activation rate:

$$\Gamma_{th}(I) = a_t \frac{\omega_0(I)}{2\pi} \exp\left(-\frac{U_0(I)}{k_B T}\right)$$

quantum tunneling rate:

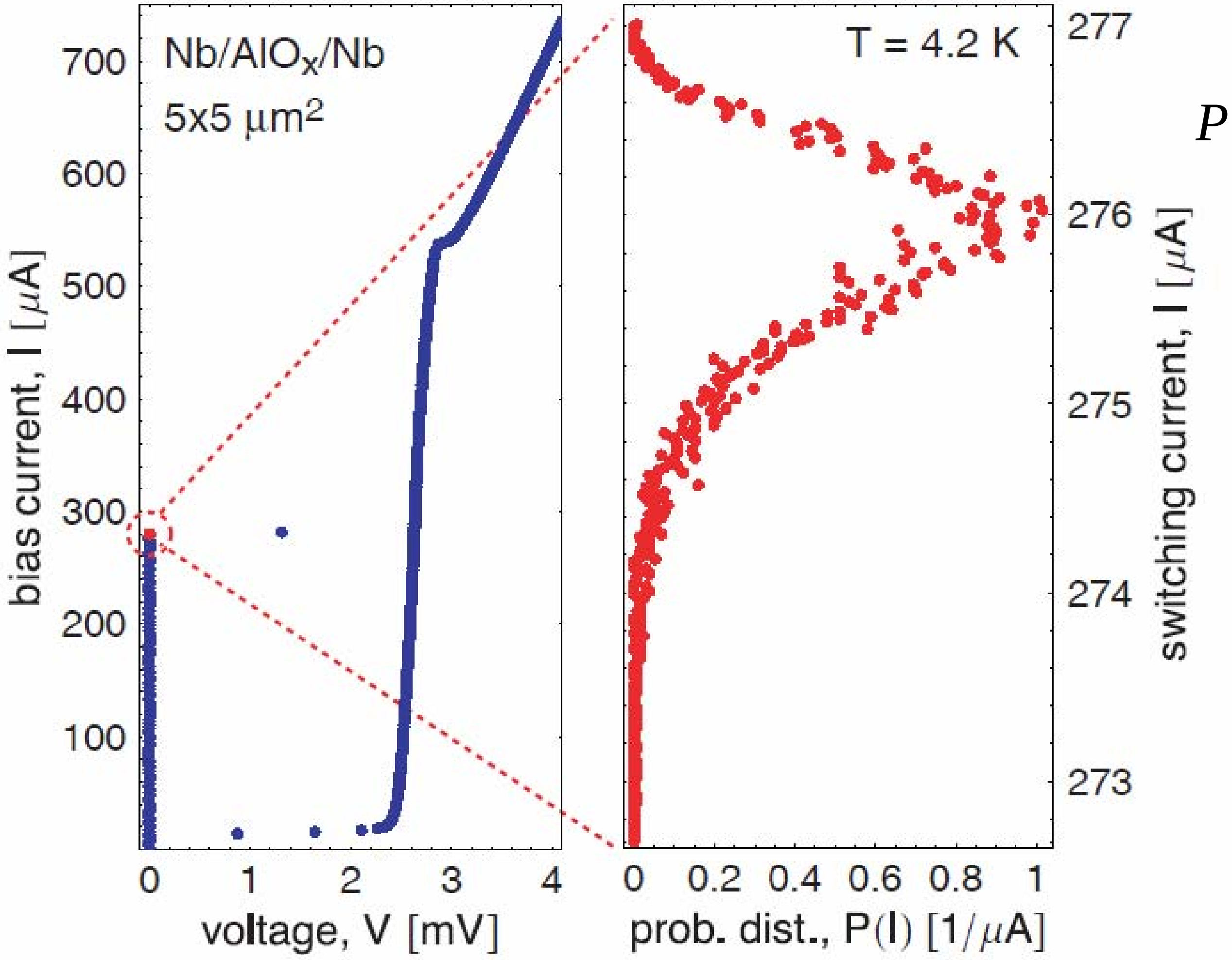
$$\Gamma_{qu}(I) \approx \sqrt{60}\,\omega_0(I) \exp\left(-\frac{36 U_0(I)}{5\hbar\omega_0(I)}\right)$$

where

$$\omega_0 = \sqrt{\frac{2\pi I_c}{\Phi_0 C_J}}$$

is the Josephson plasma frequency of the junction

Measurement procedure

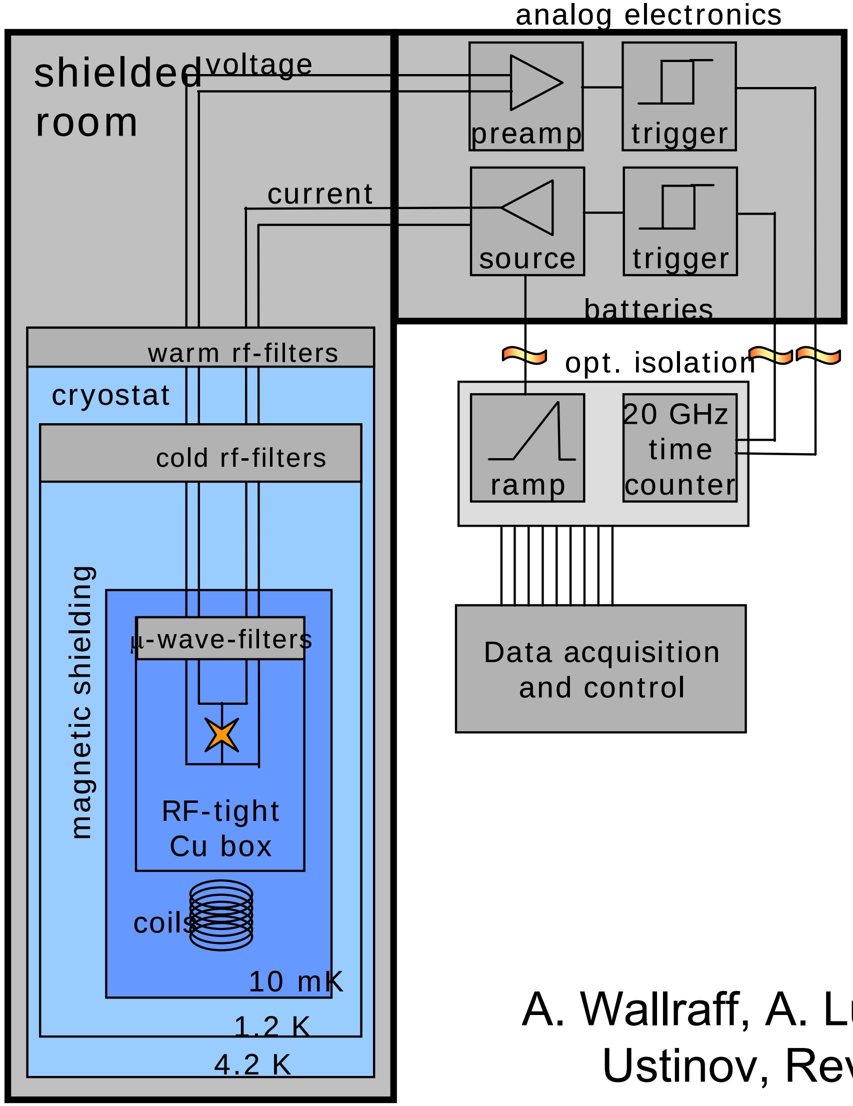


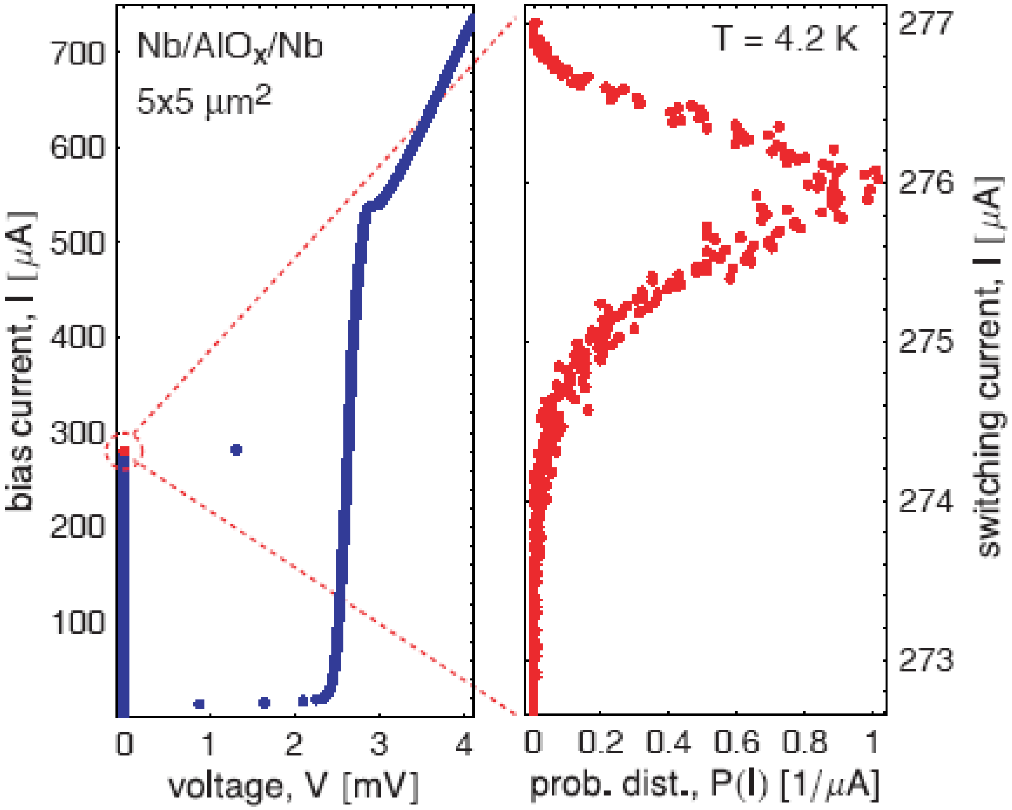
$$P(I)dI = \left|\frac{dI}{dt}\right|^{-1} \Gamma(I)\left(1 - \int_0^I P(I')dI'\right)dI$$

Switching current probability distribution

R.F. Voss et al.,
Phys.Rev.Lett. **47,** 265 (1981)

Electronics for escape measurements





A. Wallraff, A. Lukashenko, C. Coqui, T. Duty, and A. V. Ustinov, Rev. Sci. Inst. **74**, 3740 (2003).

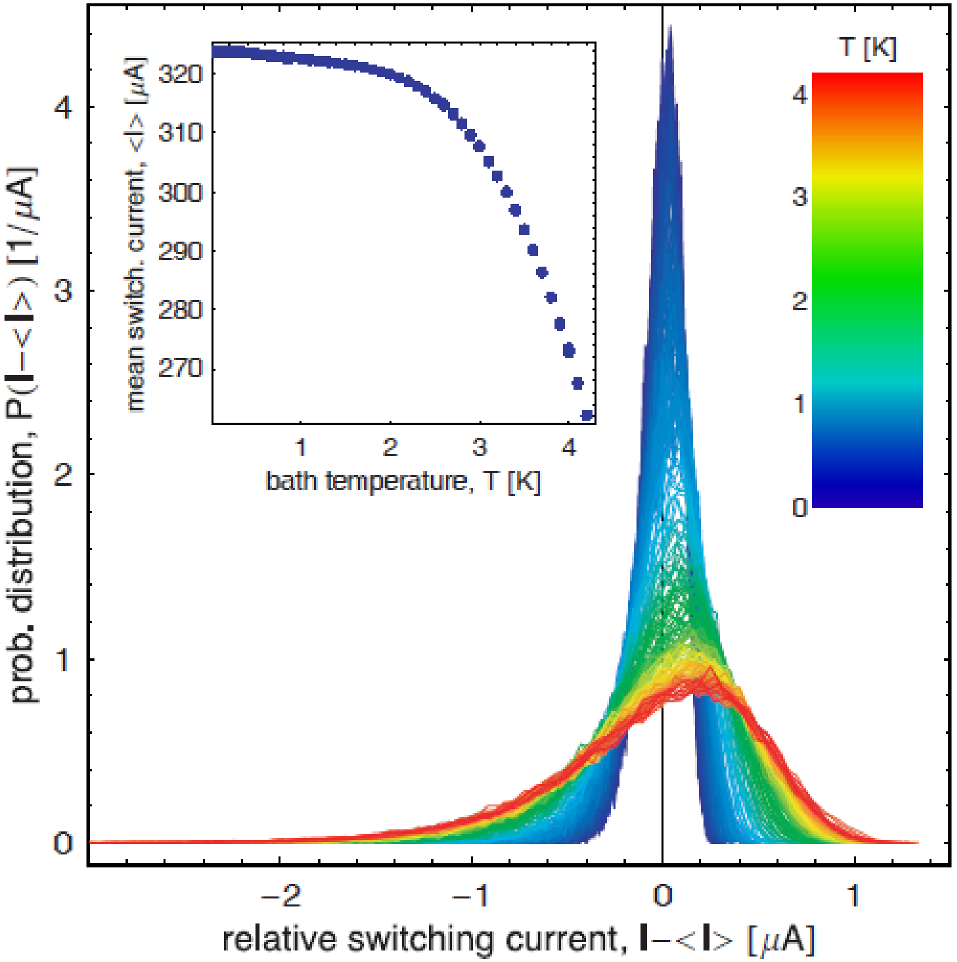
Measured escape histograms

Switching current
probability distribution

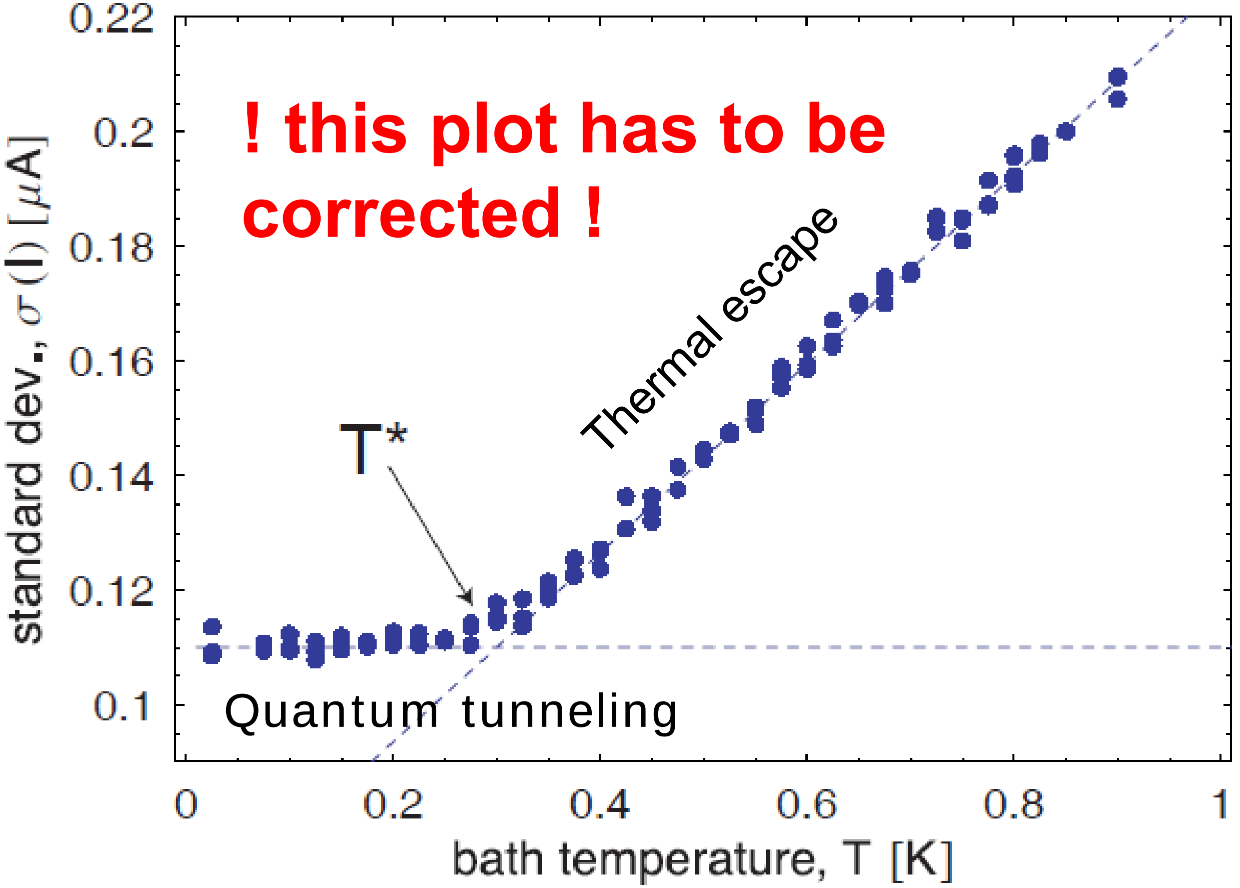
$$P(I)dI = \left|\frac{dI}{dt}\right|^{-1} \Gamma(I)\left(1 - \int_0^I P(I')dI'\right)dI$$

Bath temperature range:

25 mK – 4.2 K



Measured escape temperature



In the major temperature range

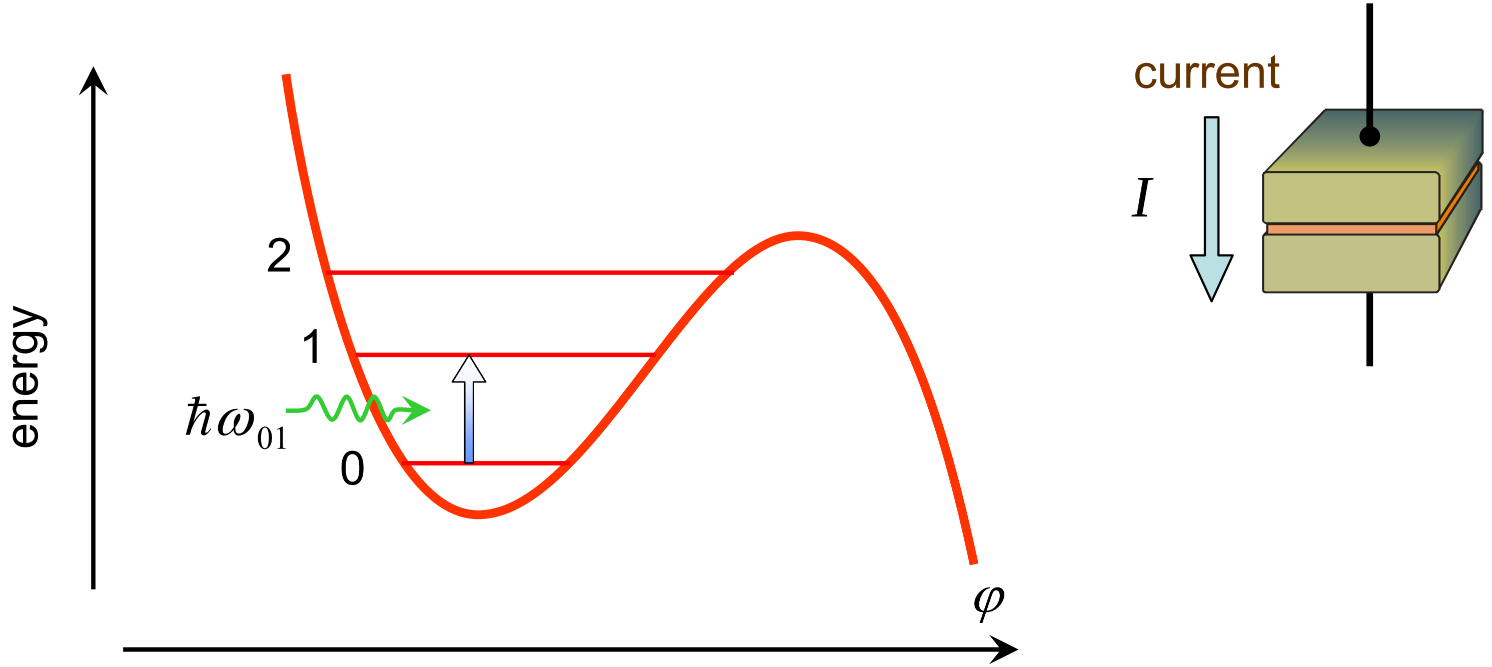
$$T_{\mathrm{esc}} \approx T_{\mathrm{bath}}$$

Crossover from thermal to quantum regime at

$$T^{*} \approx 300\,\mathrm{mK}$$

Washburn et al. (1984); Devoret et al. (1984)

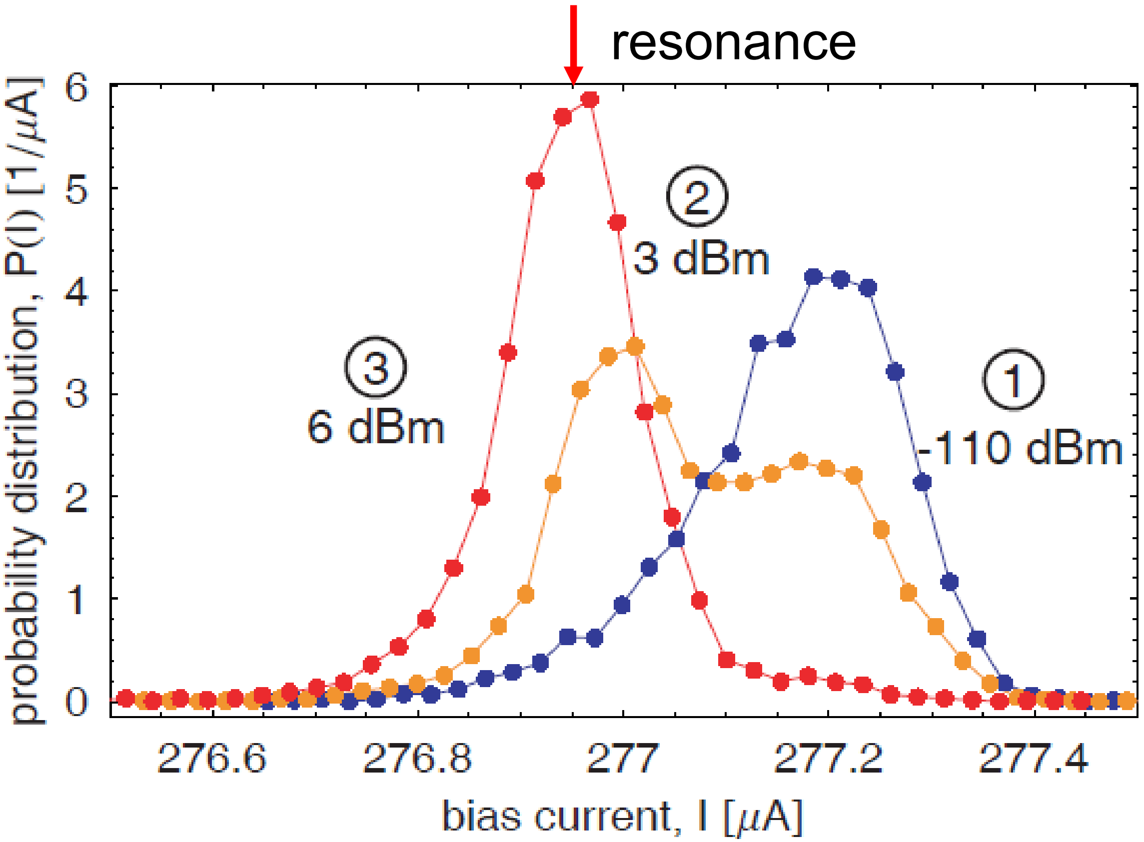
Microwave-induced transitions between quantum levels



J.M. Martinis, M. H. Devoret, and J. Clarke, Phys. Rev. B **35**, 4682 (1987).

Histograms with microwaves

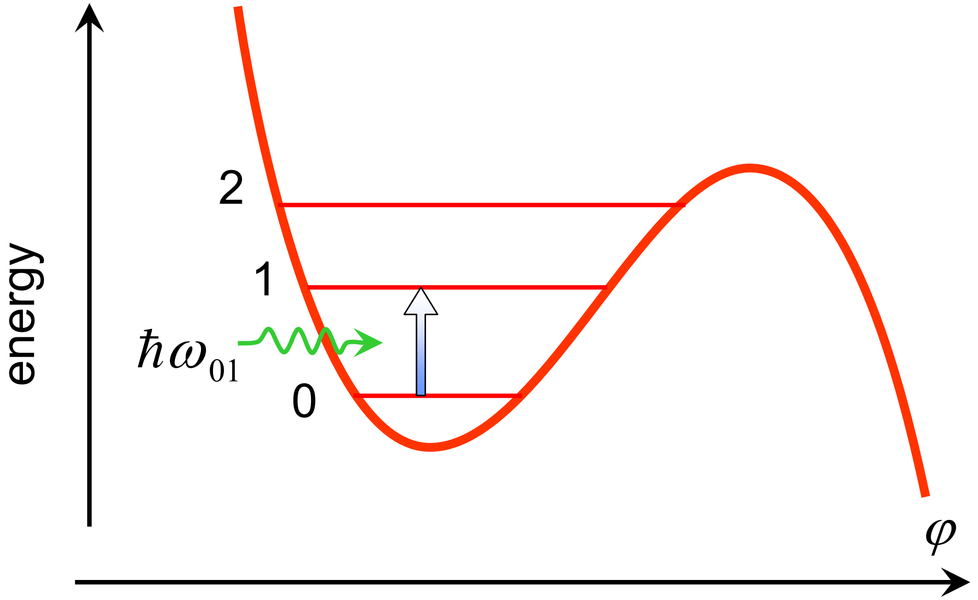
$\nu = 36.554\,\mathrm{GHz}$ at $T = 100\,\mathrm{mK} < \mathrm{T}^\star$:



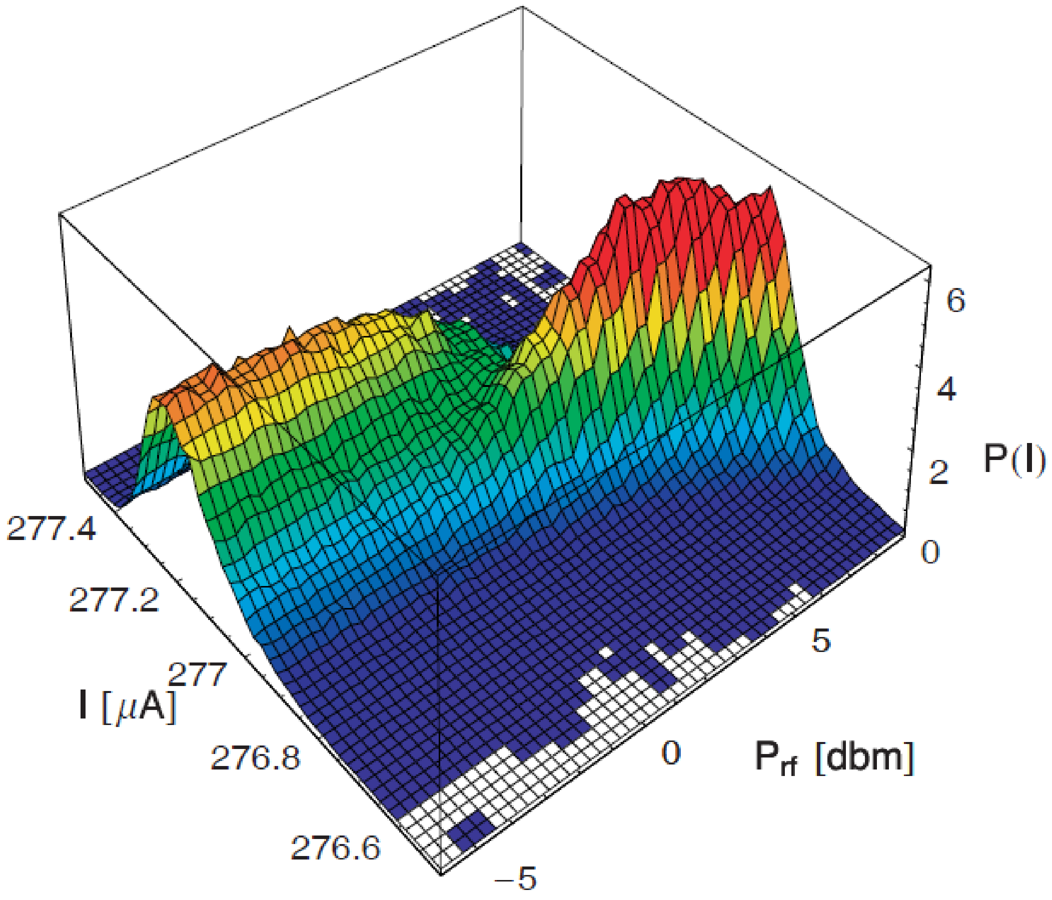
- double-peak structure
- the histogram becomes narrower under microwaves

A. Wallraff, T. Duty, A. Lukashenko, and A.V.Ustinov, Phys. Rev. Lett. **90**, 037003 (2003)

Microwave-induced transitions between quantum levels

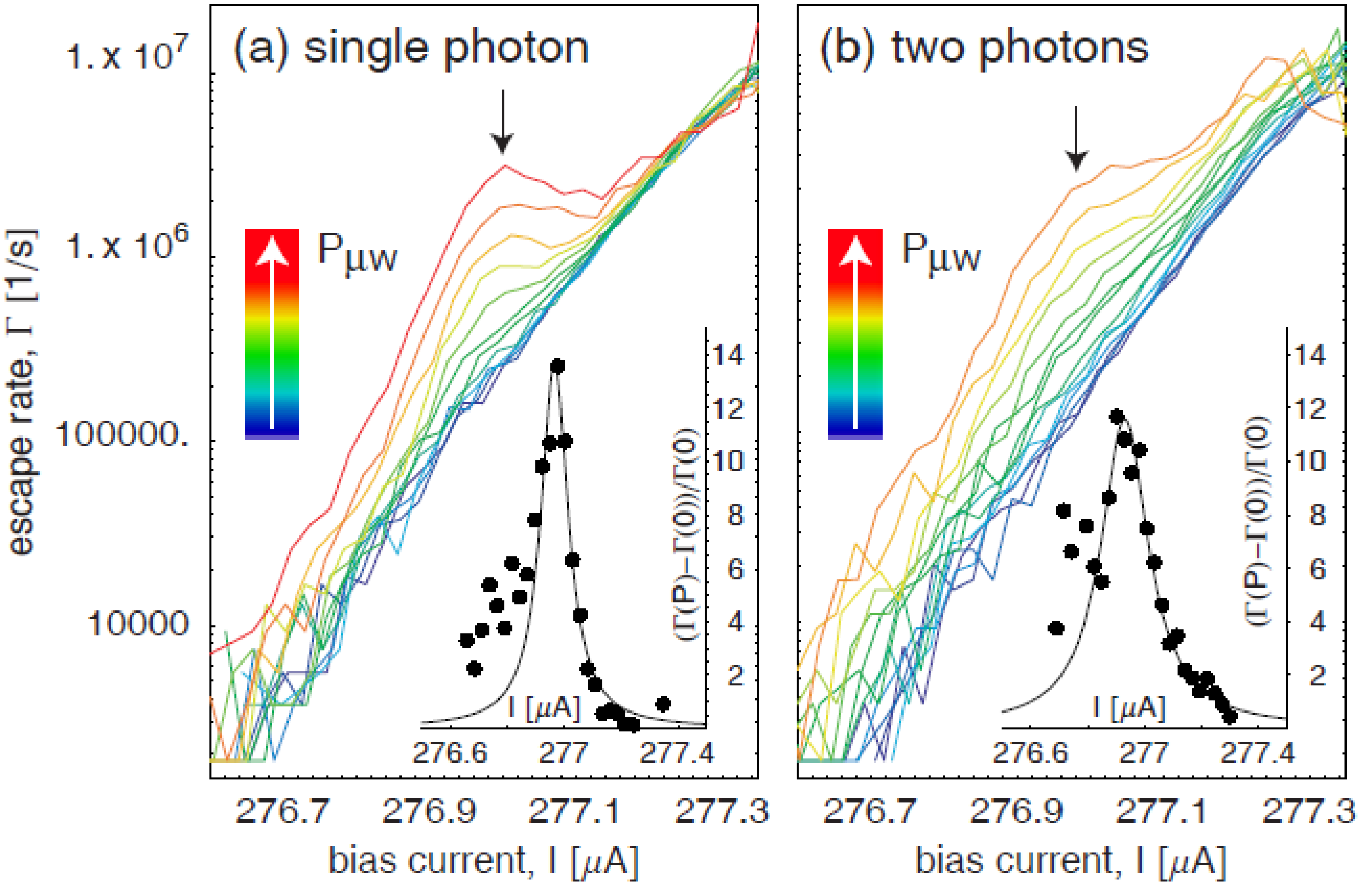


$\nu = 36.554\,\mathrm{GHz}$ and $T = 100\,\mathrm{mK}$:



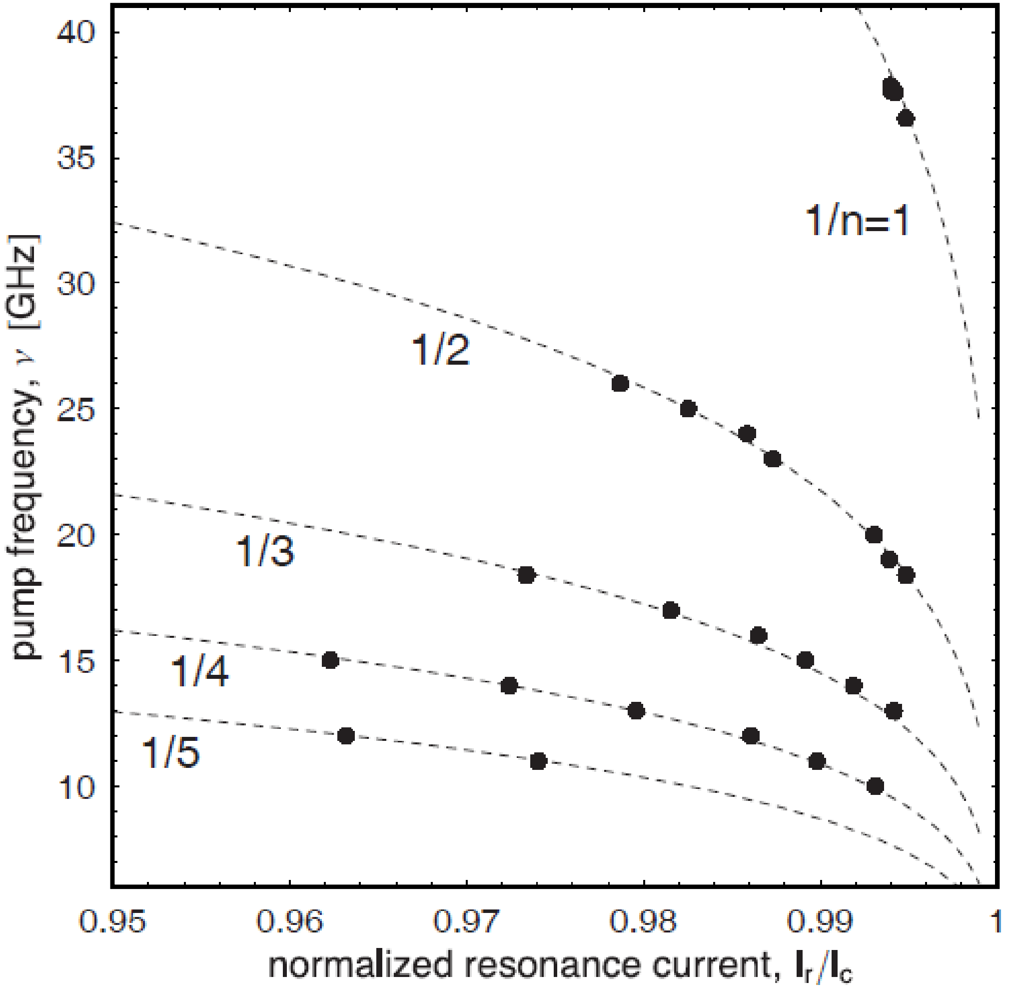
A. Wallraff, T. Duty, A. Lukashenko, and A.V.Ustinov, Phys. Rev. Lett. **90**, 037003 (2003)

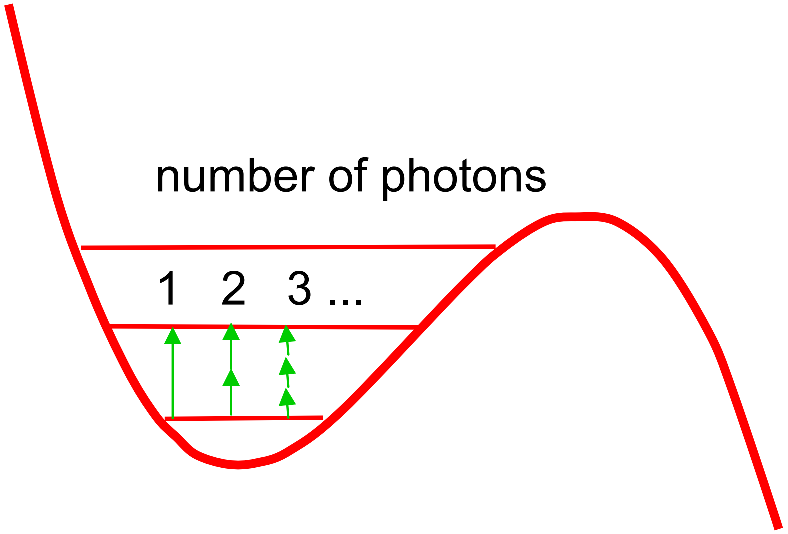
Enhancement of the escape rate



A. Wallraff, T. Duty, A. Lukashenko, and A.V.Ustinov, Phys. Rev. Lett. **90**, 037003 (2003)

Multi-photon transitions between the energy levels





$$\nu\ (I) = \nu_0 \sqrt[4]{1-\frac{I^2}{I_c^2}}$$

A. Wallraff, T. Duty, A. Lukashenko, and A.V.Ustinov, Phys.Rev.Lett. **90**, 037003 (2003)

Summary of the introduction

- Josephson junctions are *nonlinear microwave resonators* with extremely low dissipation
- These junctions can be viewed as `*artificial atoms*´ when operated in the quantum regime
- Pioneering experiments in the 80-s demonstrated *macroscopic quantum tunneling* and energy level quantization

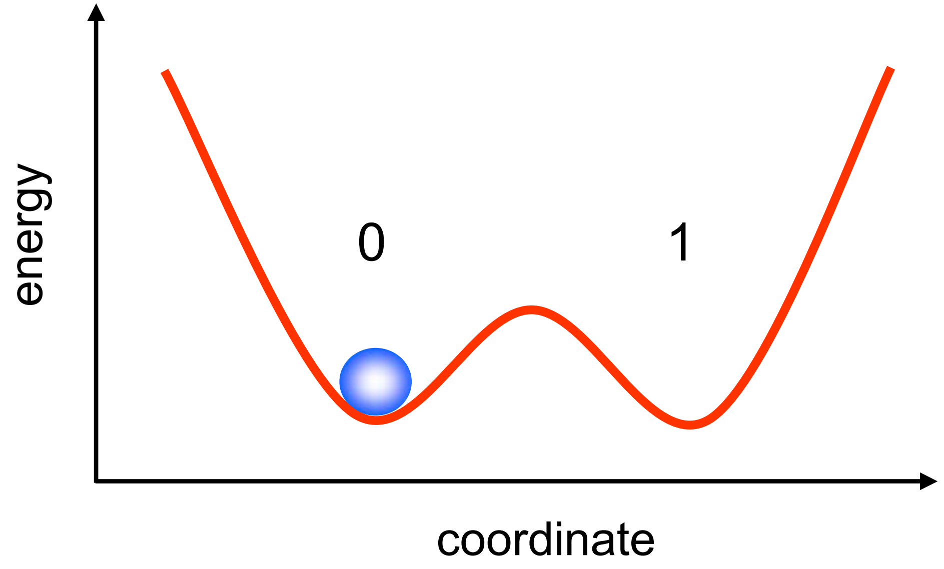
Can one observe *macroscopic quantum coherence*
in Josephson systems?

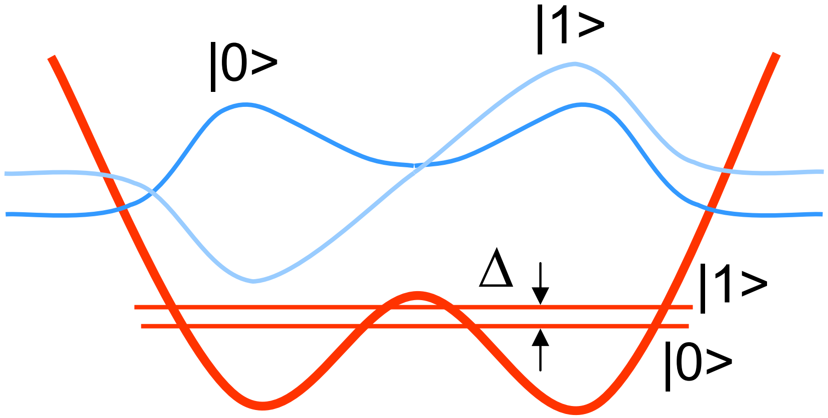
Superconducting qubits

Classical bits and quantum bits

A classical computer operates with bits

A quantum computer operates with quantum bits called qubits





two-level system

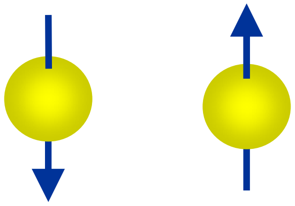
possible states:
0 and 1

possible states:

$$\left|\Psi\right\rangle = \alpha\left|0\right\rangle + \beta\left|1\right\rangle$$

Qubit description as a spin ½ particle

Quantum states



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

two basis states

Wavefunction

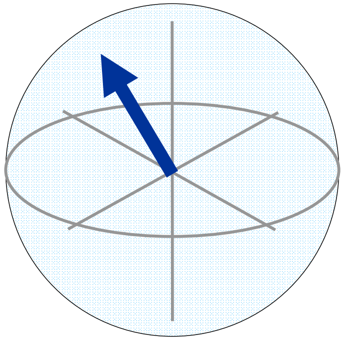
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

α and β are complex numbers

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

The Bloch sphere

$|1\rangle$



$|0\rangle$

In principle, **any two-level system** which acts quantum mechanically **can be used as a qubit**.

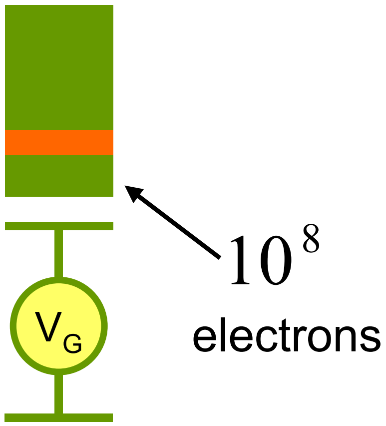
Flux and charge: Two extremes

Uncertainty relation for a superconductor: $\Delta n \cdot \Delta \varphi \geq 1$

Charging energy $E_C = \dfrac{e^2}{2C_J}$

charge qubit

$E_C >> E_J$

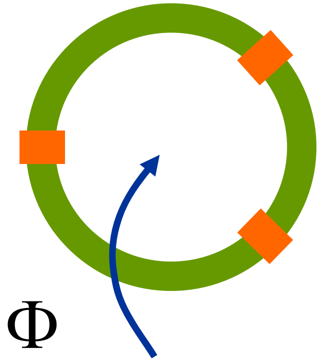


- Makhlin et al., Nature **398**, 305 (1999)
- Nakamura et al., Nature **398**, 786 (1999)

Josephson energy $E_J = \dfrac{I_c \Phi_0}{2\pi}$

flux qubit

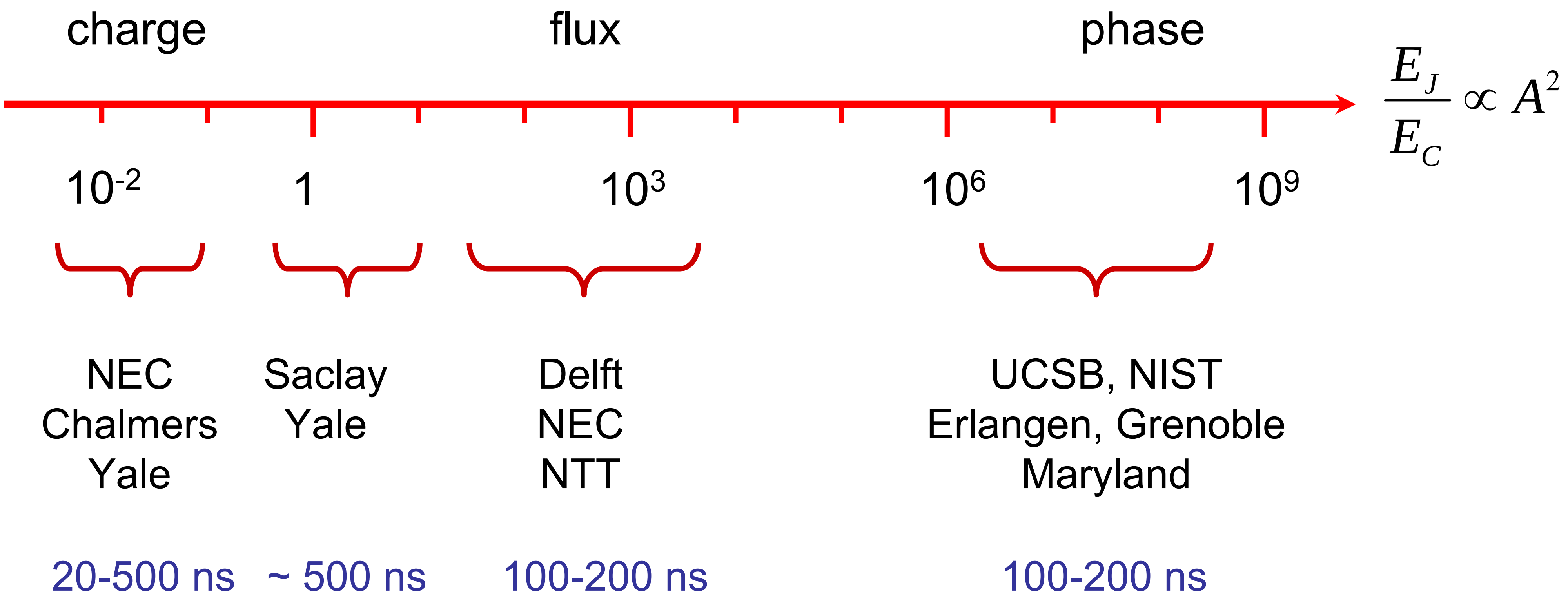
$E_C << E_J$



- Friedman et al., Nature **406**, 43 (2000)
- van der Wahl et al., Science **290**, 773 (2000)

Josephson junction qubits: Energy span

for a chosen J_c , the ratio E_J/E_C depends on the junction area A



charge flux phase

$$\frac{E_J}{E_C} \propto A^2$$

10^{-2} 1 10^3 10^6 10^9

NEC
Chalmers
Yale

20-500 ns

Saclay
Yale

~ 500 ns

Delft
NEC
NTT

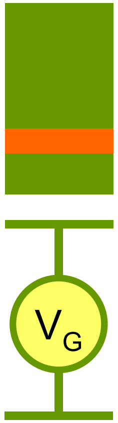
100-200 ns

UCSB, NIST
Erlangen, Grenoble
Maryland

100-200 ns

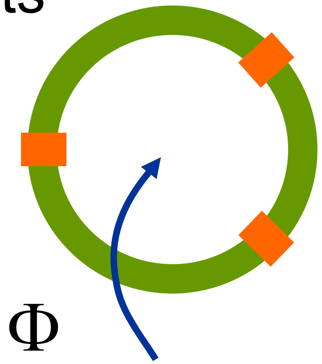
Overview of superconducting qubits

charge qubit



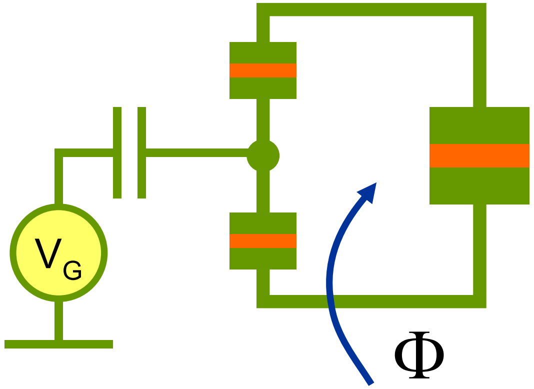
NEC
Chalmers
Yale
Jena

flux qubits



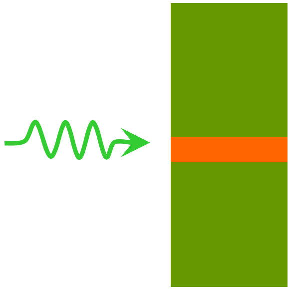
Delft
Jena
MIT
Berkeley
NTT
NEC

charge/flux qubit



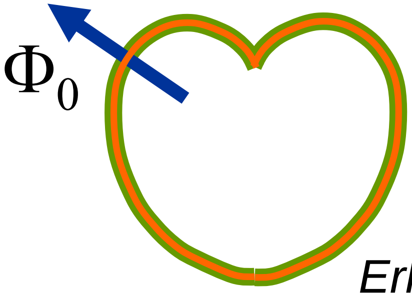
Saclay
Yale
PTB

phase qubit



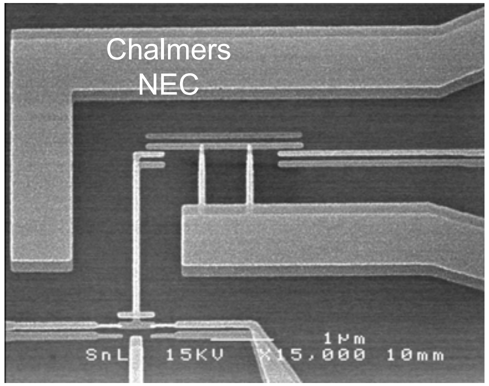
NIST
UCSB
Erlangen
Maryland

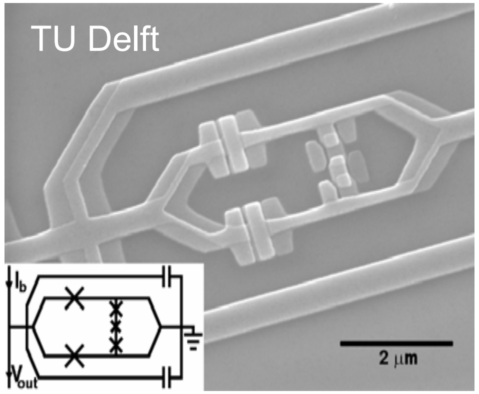
vortex qubit

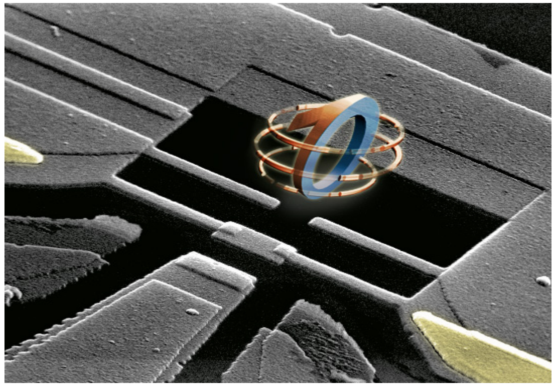


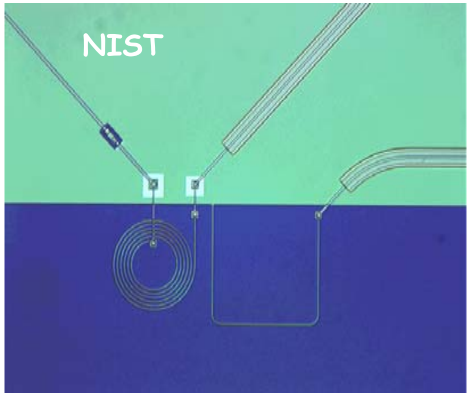
Erlangen
Tübingen

Realizations of Superconducting Qubits









charge	flux	charge/flux	phase
NEC Chalmers Yale	Delft, Jena MIT, Berkeley NTT, NEC	Saclay Yale PTB	NIST, UCSB Erlangen Maryland

Nakamura, Pashkin, Tsai *et al. Nature* **398**, **421**, **425** (1999, 2003, 2003)

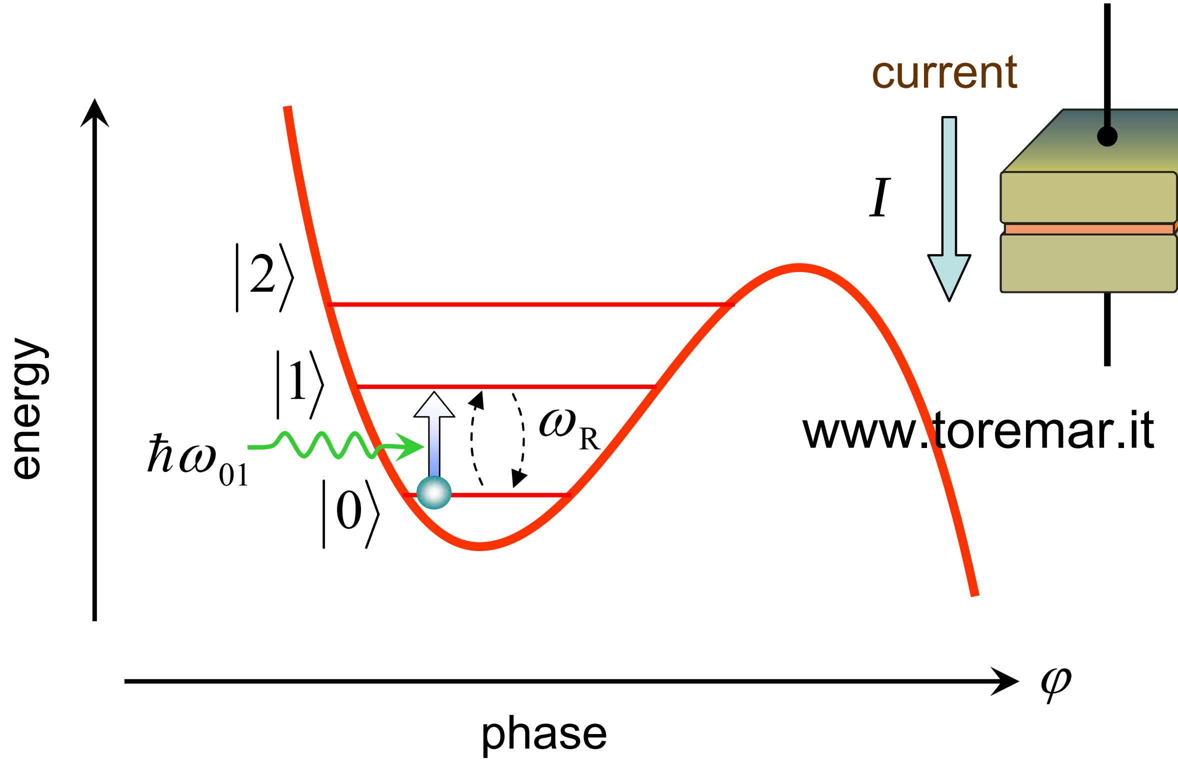
Chiorescu, van der Wal, Mooij, Orlando, S. Lloyd *et al. Science* **285**, **290, 299** (1999, 2000, 2003)

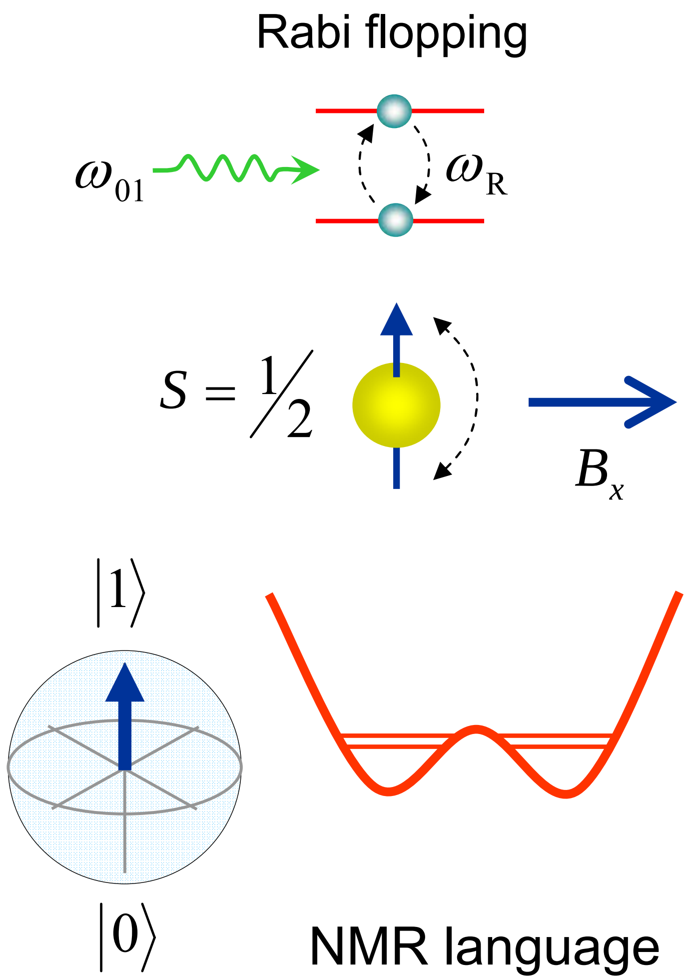
Vion, Esteve, Devoret *et al. Science* **296** (2002)

Martinis, Simmonds, Lang, Nam, Aumentado, Urbina *et al. Phys. Rev. Lett.* **89**, **93** (2002, 2004)

Phase qubits

Josephson phase qubit





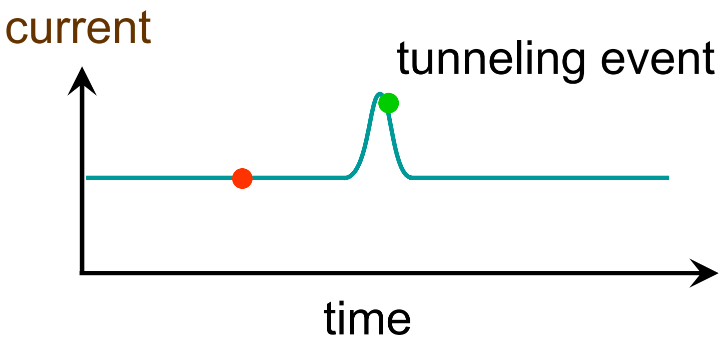
Anharmonic potential - only two levels are involved

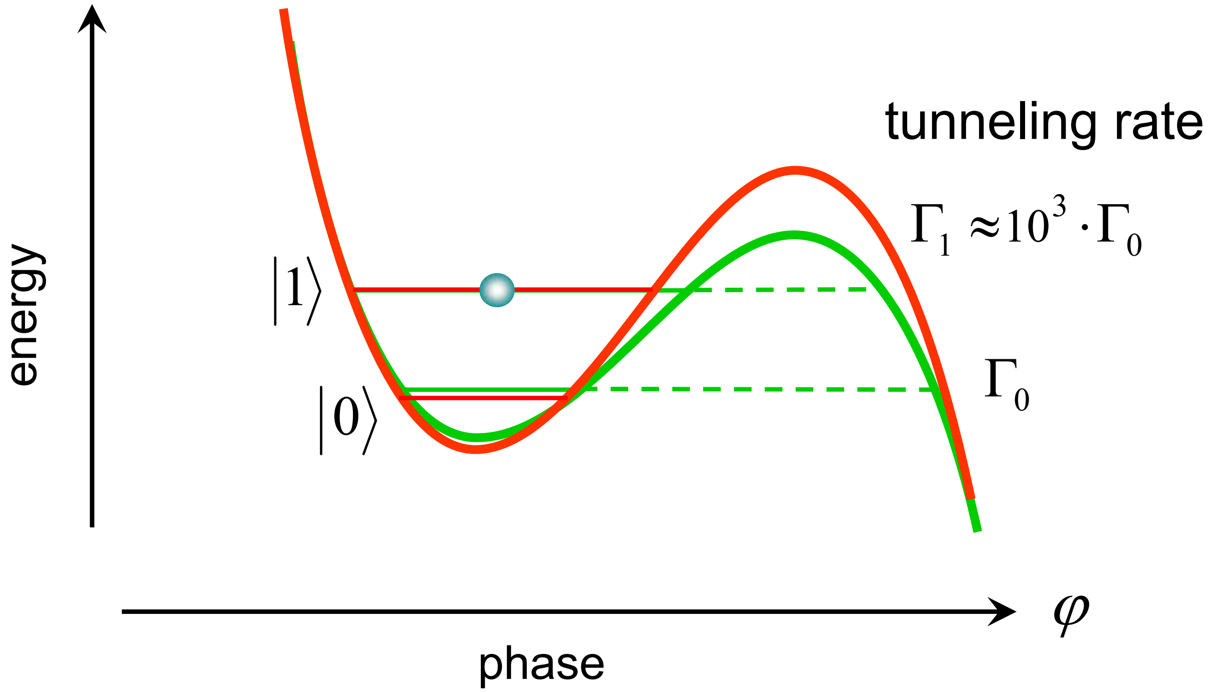
J. M. Martinis et al., Phys. Rev. Lett. **89**, 117901 (2002).

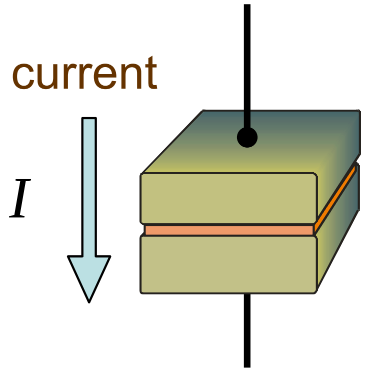
R. McDermott et al., *Science* **307**, 1299 (2005)

Phase qubit readout:
Tunneling from the excited state

Readout by applying a tilt (current) pulse

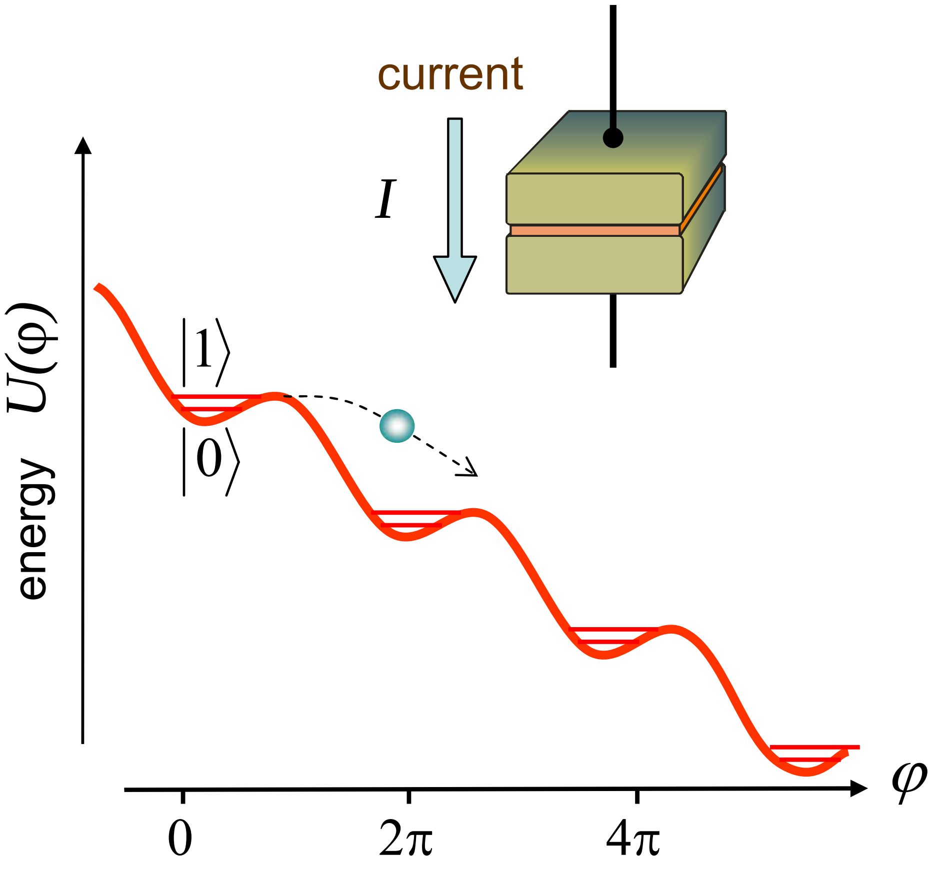




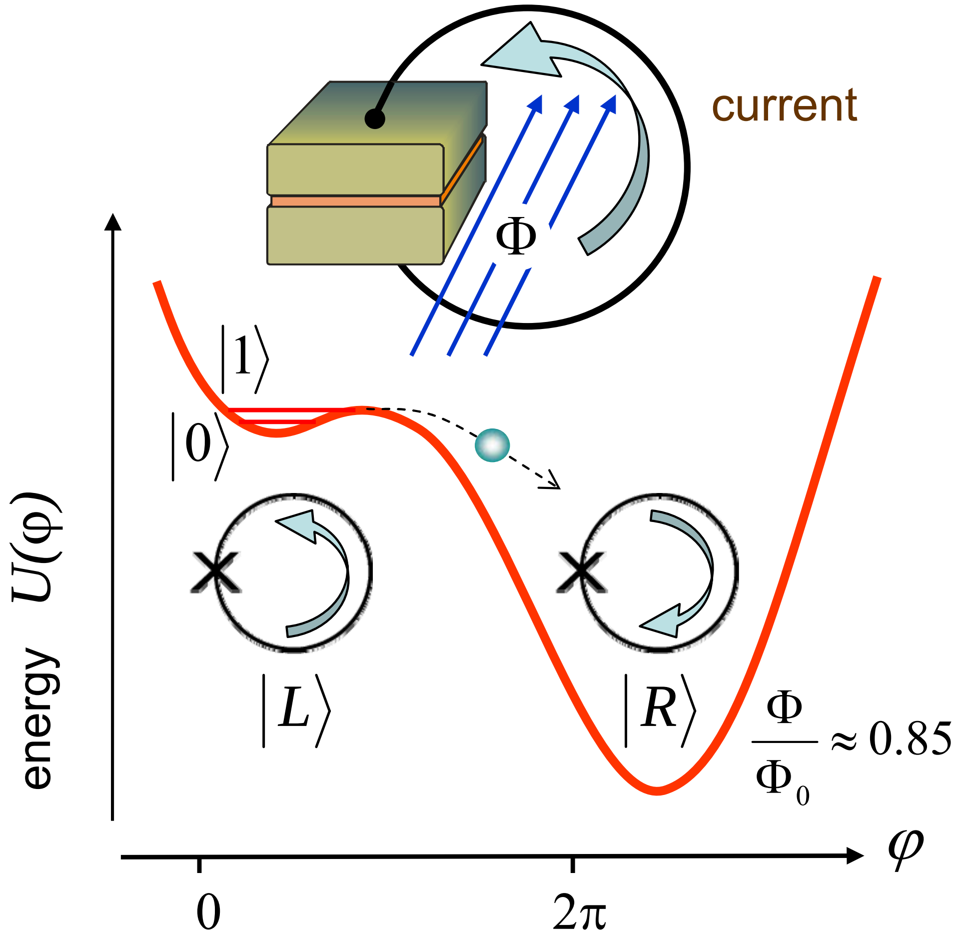


Reducing dissipation by placing the junction in a loop

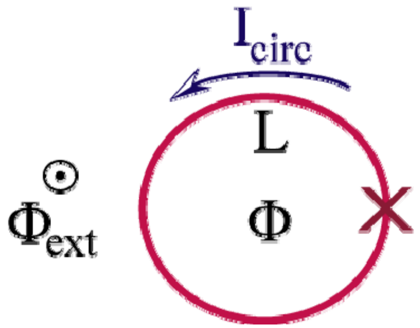
$$U(\varphi)=\frac{I_c\Phi_0}{2\pi}\left(-\frac{I}{I_c}\varphi-\cos\varphi\right)$$



$$U(\varphi)=\frac{I_c\Phi_0}{2\pi}\left[\frac{1}{2\beta_L}\left(\varphi-2\pi\frac{\Phi}{\Phi_0}\right)^2-\cos\varphi\right]$$

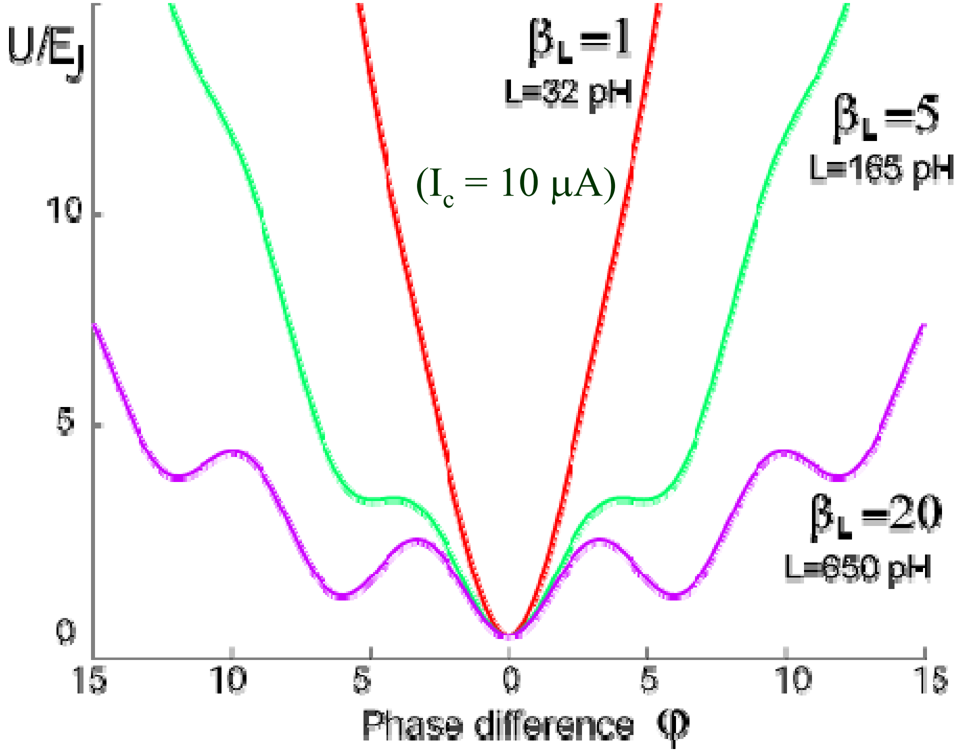


Junction in a loop



potential energy:

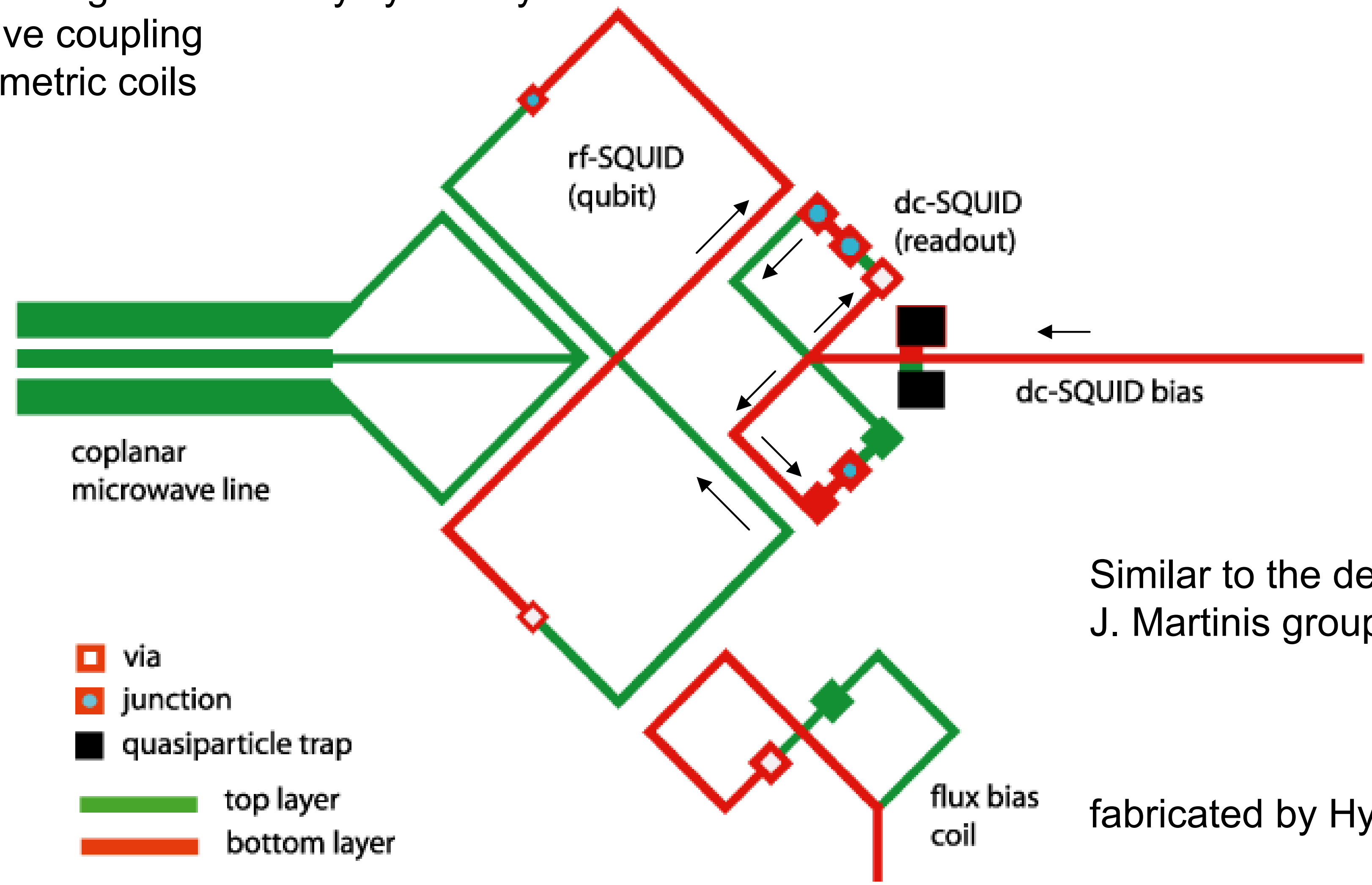
$$U(\varphi)=\frac{I_c\Phi_0}{2\pi}\left[\underbrace{\frac{1}{2\beta_L}\left(\varphi-2\pi\frac{\Phi}{\Phi_0}\right)^2}_{\text{magnetic energy}}\underbrace{-\cos\varphi}_{\text{junction energy}}\right]$$



$$\beta_L\equiv\frac{2\pi L I_c}{\Phi_0}$$

Sample layout

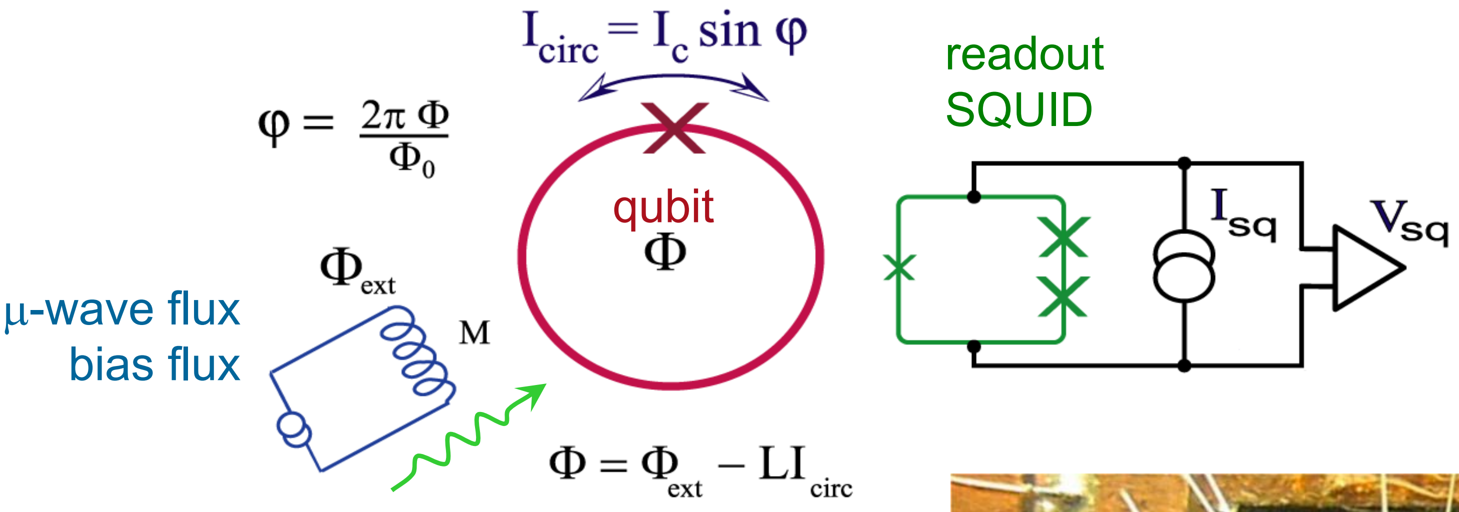
protected against noise by symmetry
inductive coupling
gradiometric coils



Similar to the design of
J. Martinis group at NIST

fabricated by Hypres Inc.

Phase qubit: Measurement



$I_{circ} = I_c \sin \varphi$

$\varphi = \frac{2\pi \Phi}{\Phi_0}$

qubit
Φ

readout
SQUID

I_{sq}

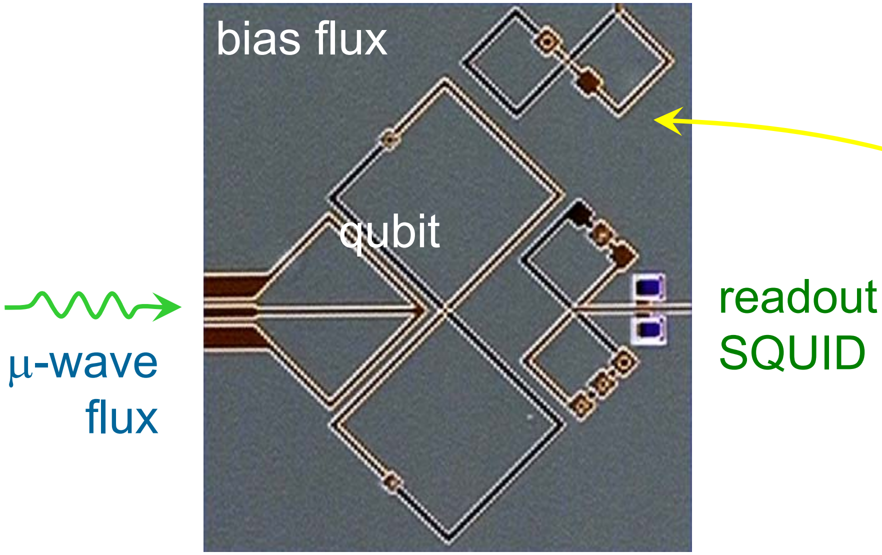
V_{sq}

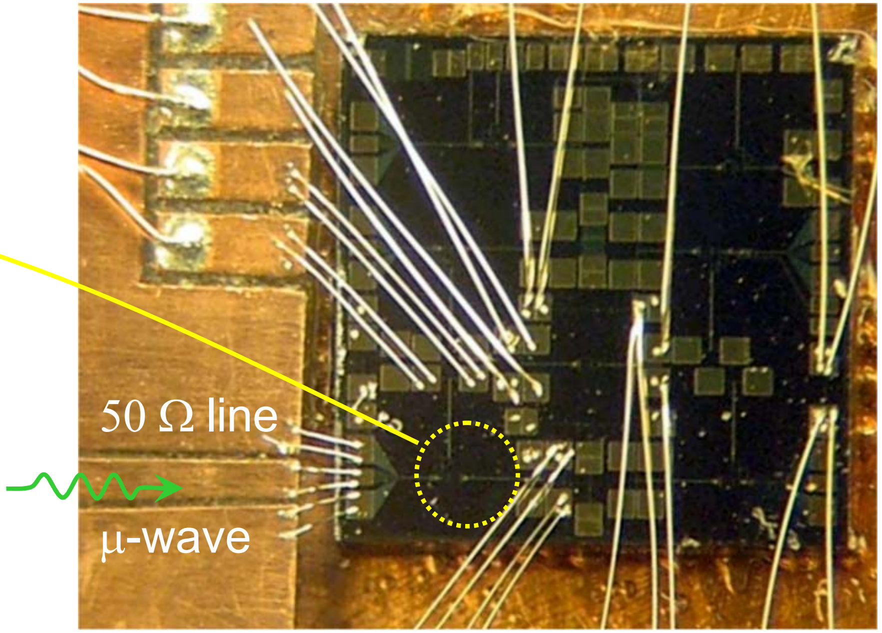
Φ_{ext}

μ-wave flux
bias flux

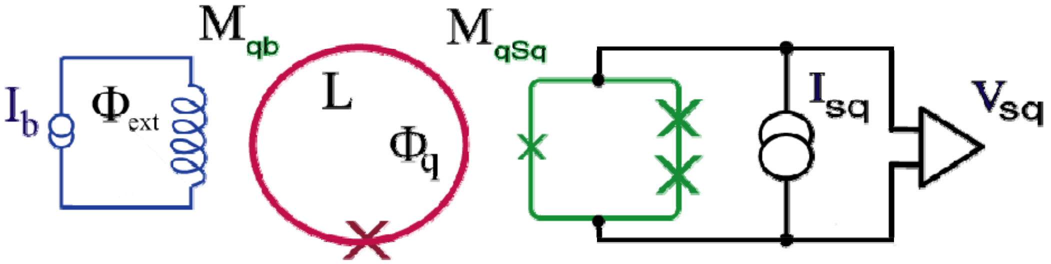
M

$\Phi = \Phi_{ext} - LI_{circ}$



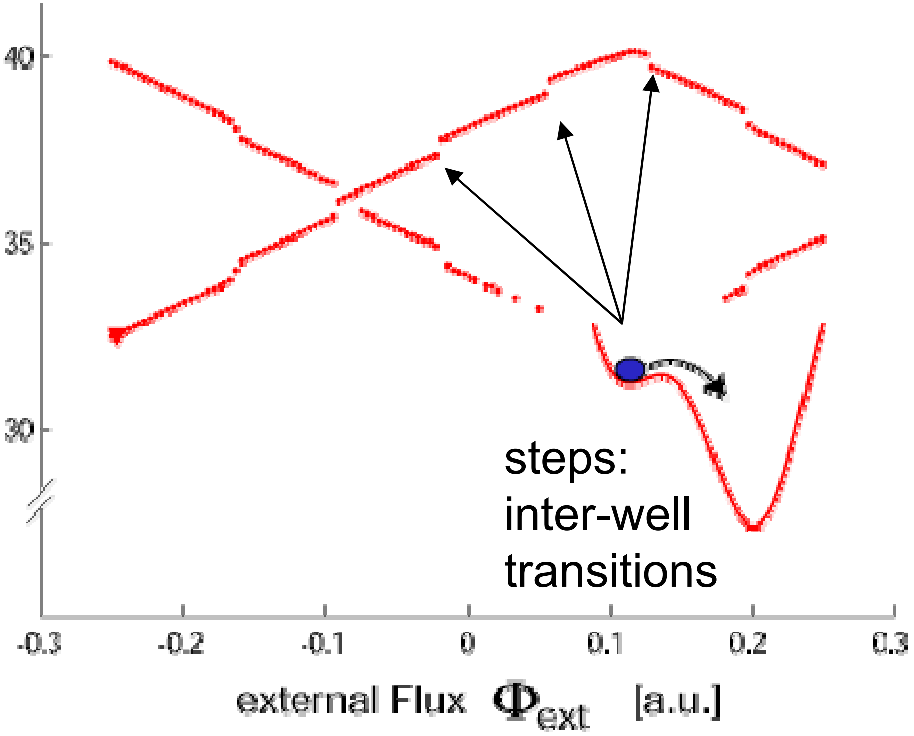


Phase qubit readout using dc-SQUID



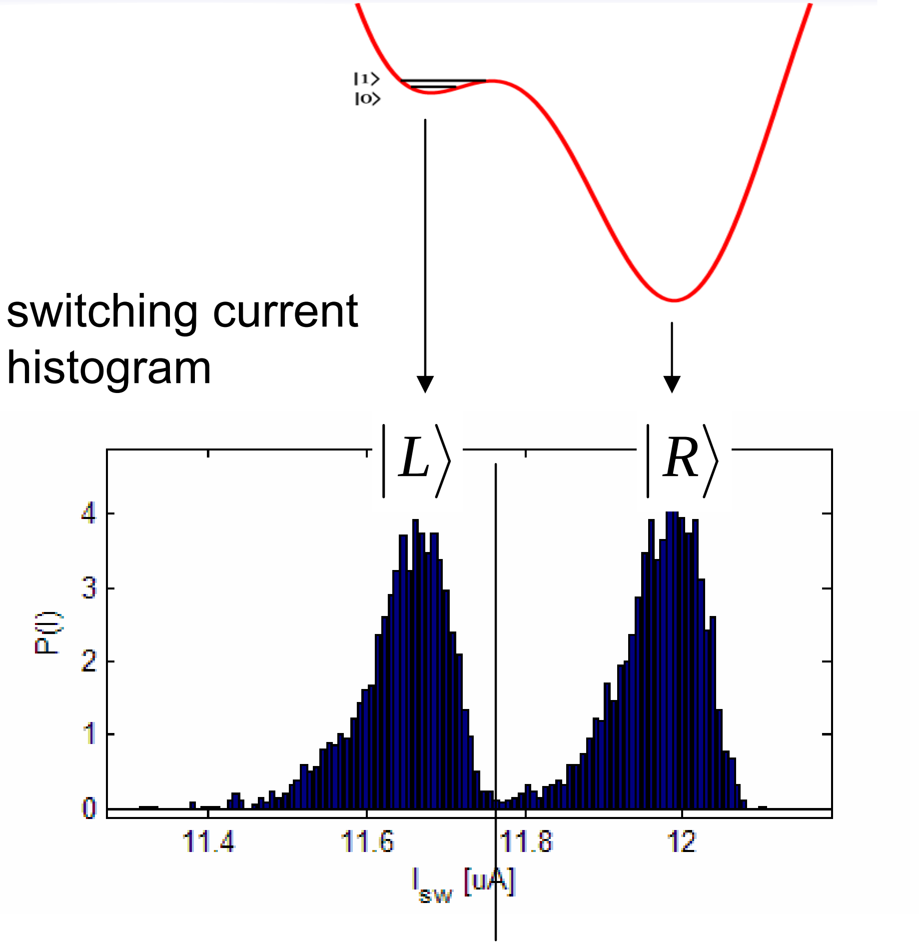
readout dc-SQUID

dc-SQUID I_{sw} (Φ)



steps:
inter-well
transitions

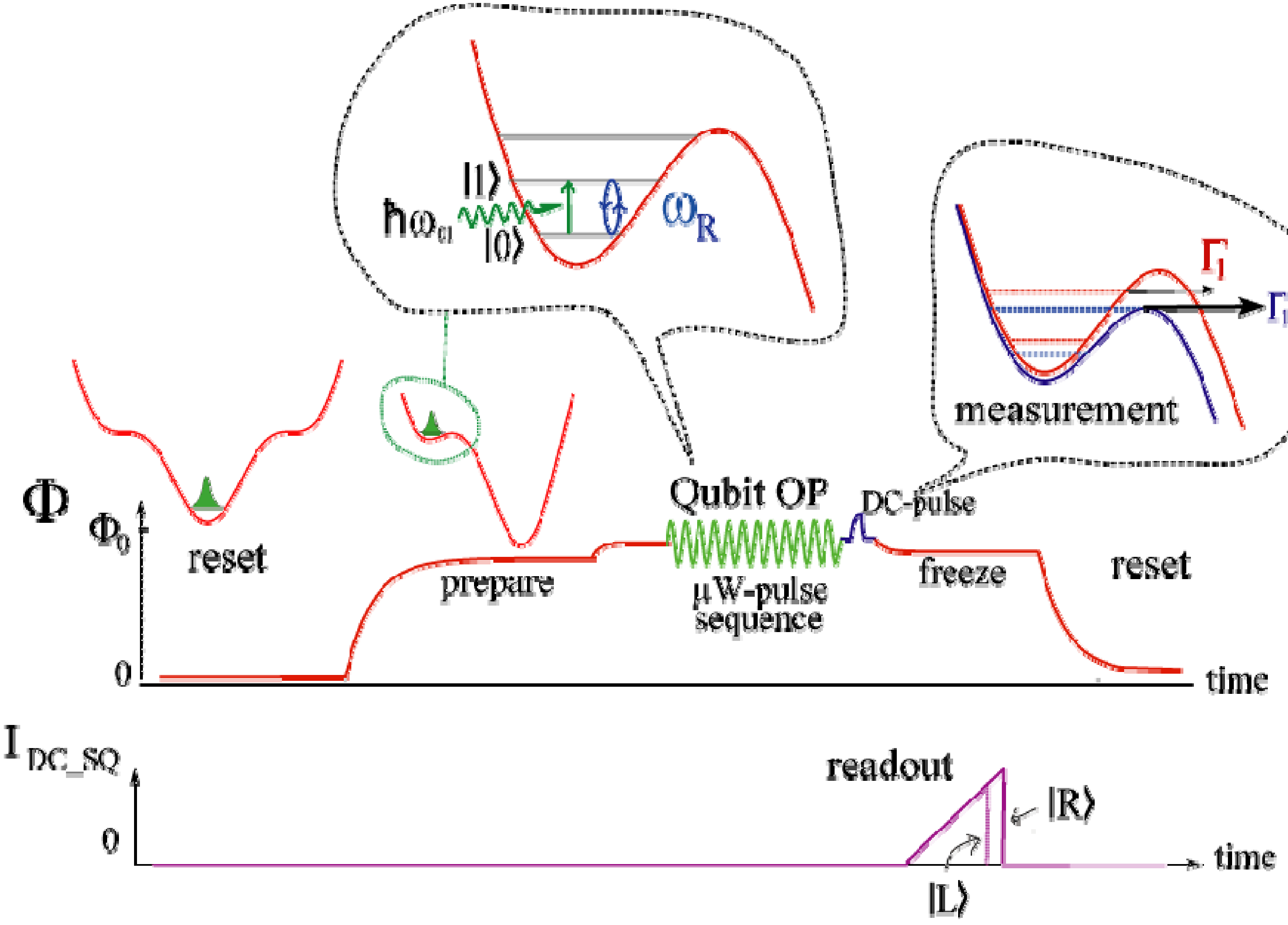
switching current
histogram



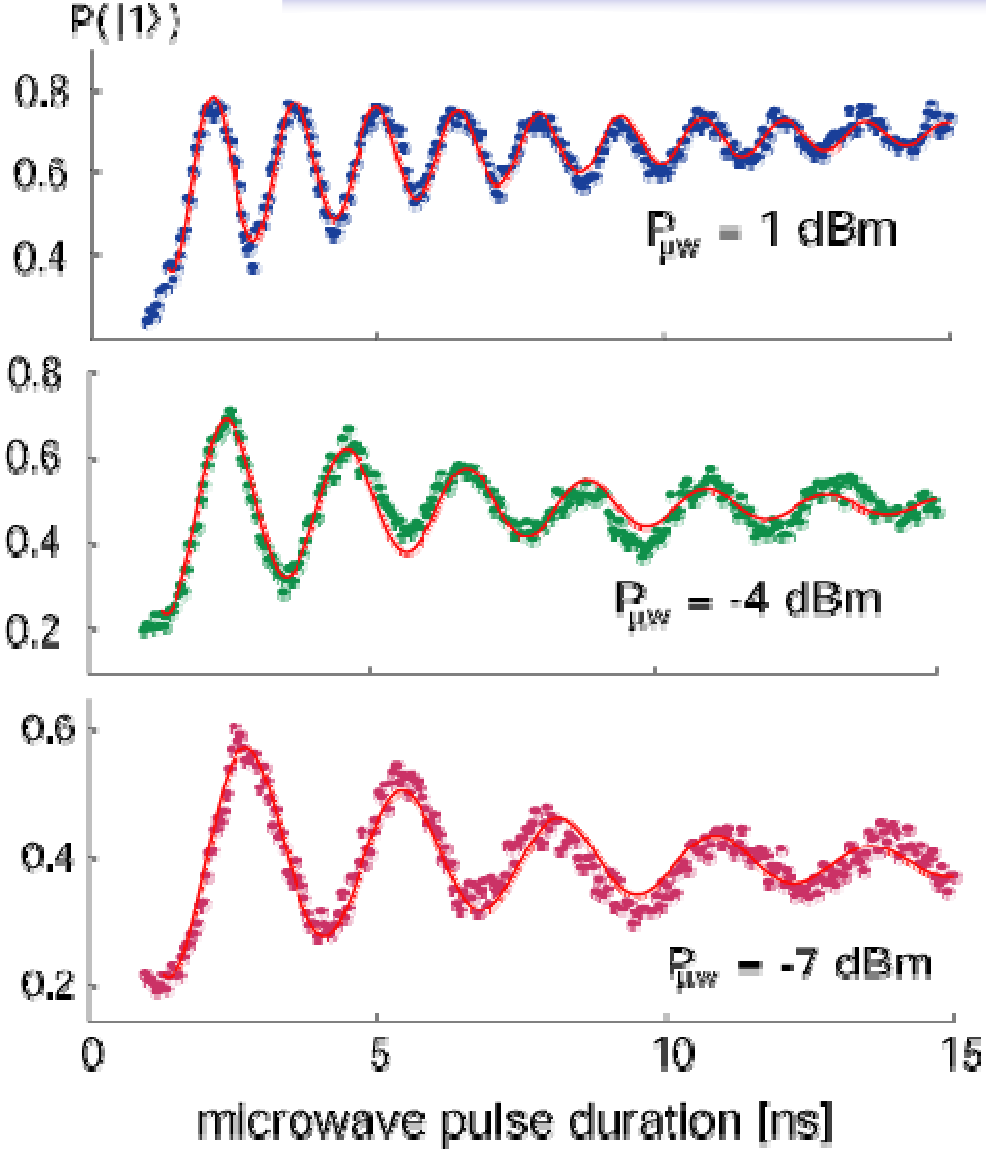
treshold I_{tresh}

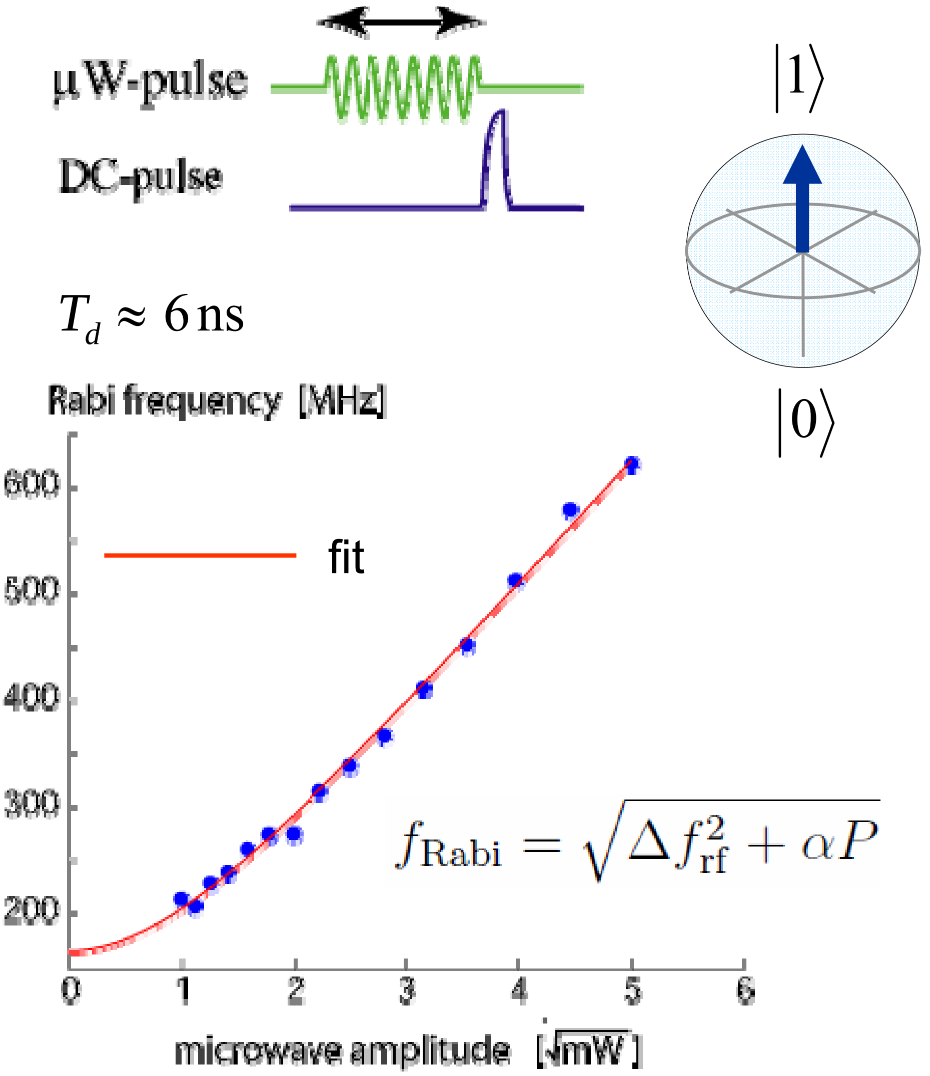
$$P_{esc} = \frac{N_{(I_{sw}>I_{tresh})}}{N_{total}}$$

Qubit operation



Rabi oscillations in a phase qubit

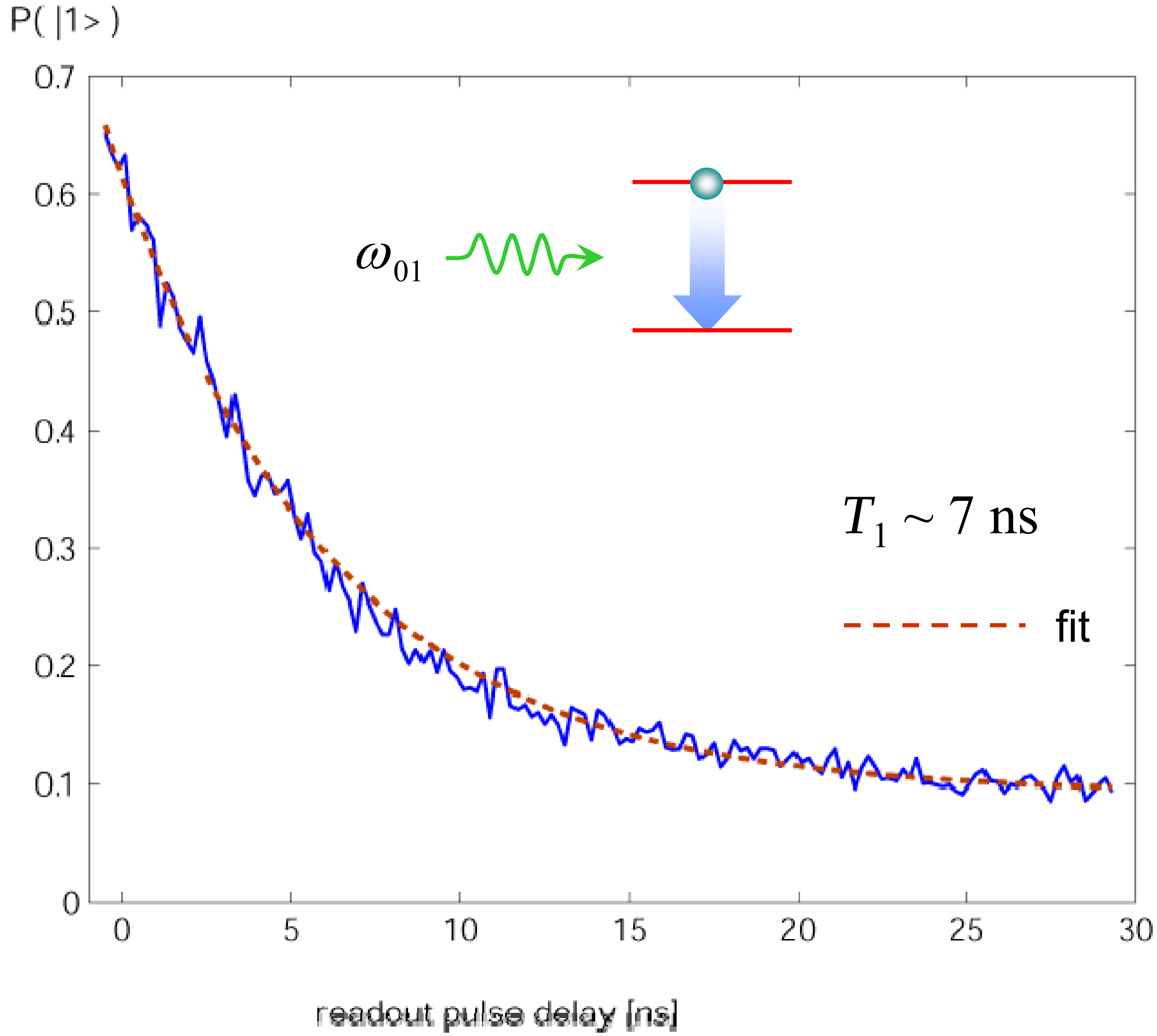




$T_d \approx 6\,\text{ns}$

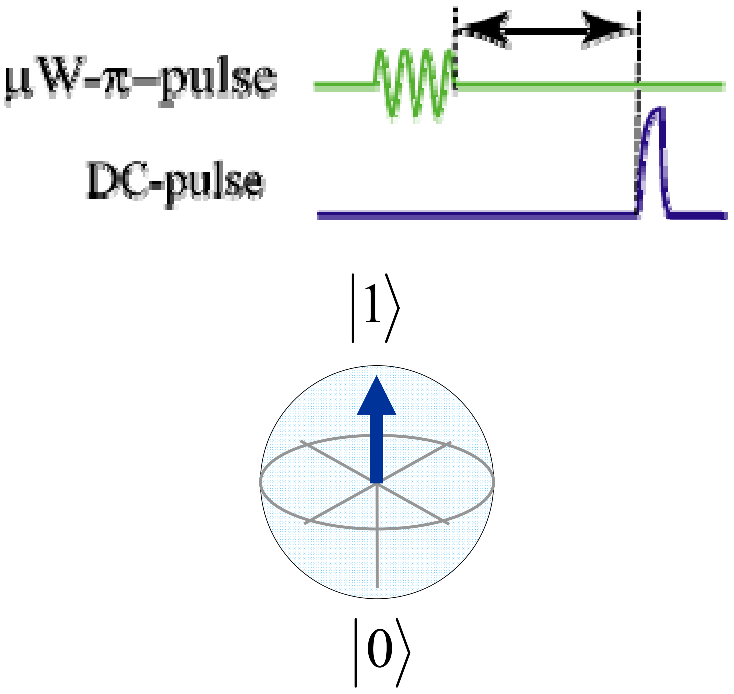
$$f_{\text{Rabi}} = \sqrt{\Delta f_{\text{rf}}^2 + \alpha P}$$

T_1 time: decay of the excited state

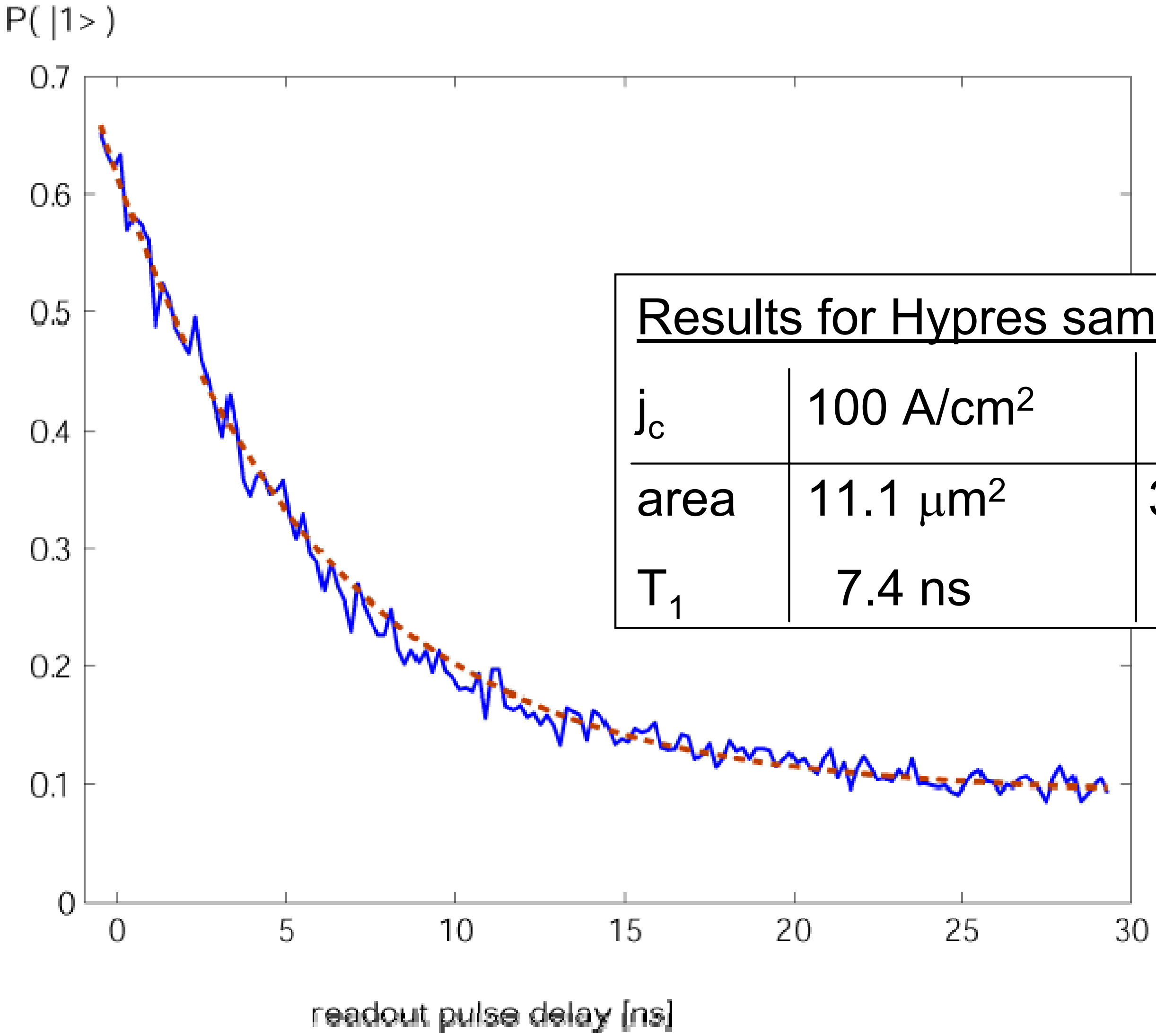


varied time delay between

excitation and readout pulses



T_1 dependence on the junction size



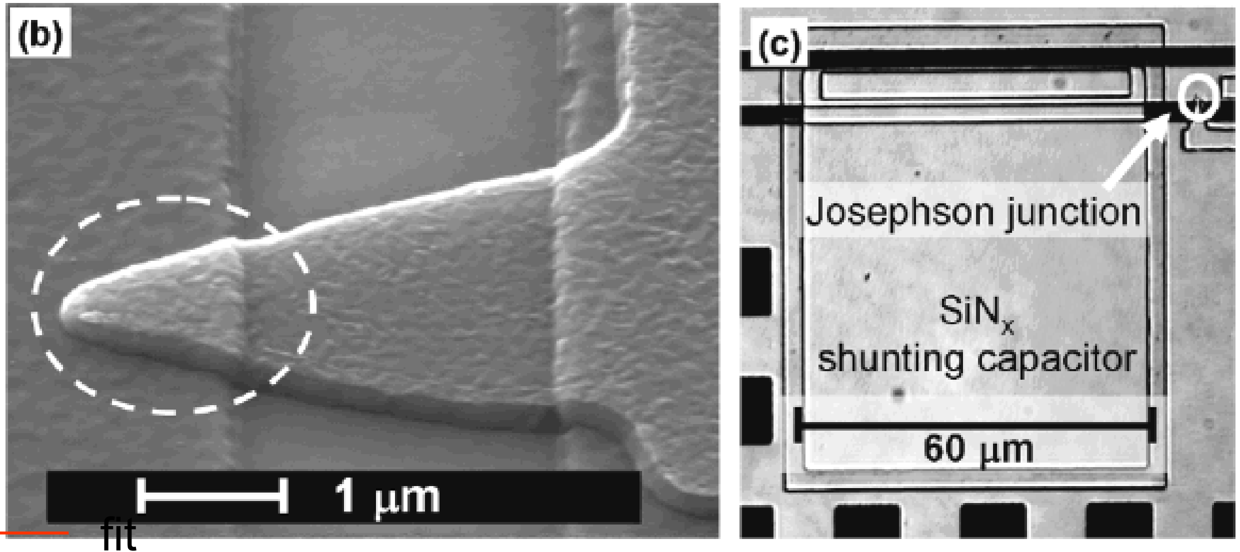
Results for Hypres samples:

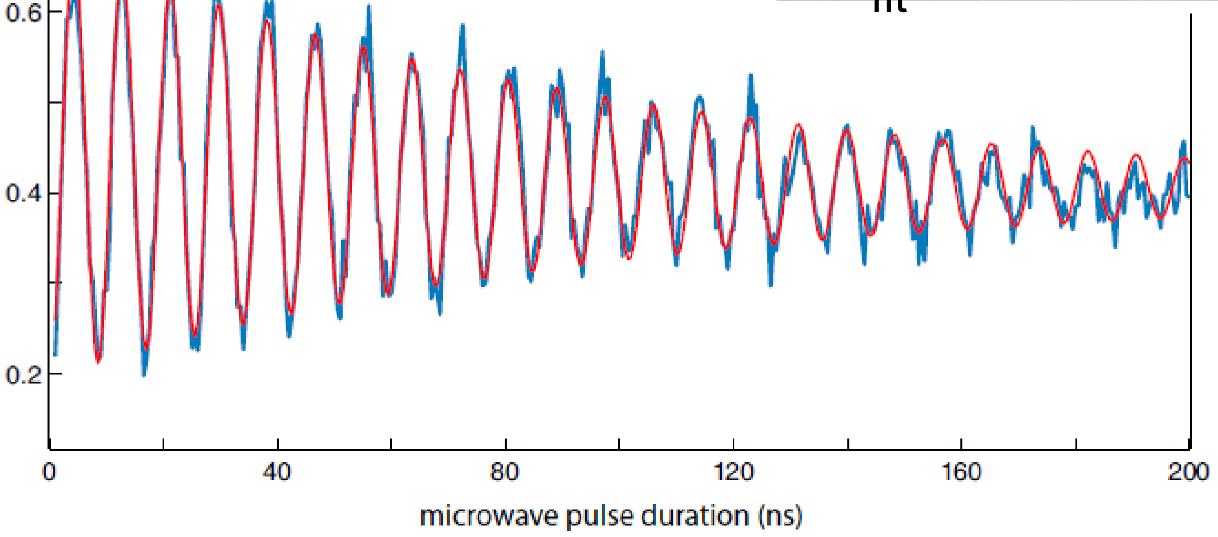
j_c	100 A/cm^2	30 A/cm^2	
area	11.1 μm^2	35.5 μm^2	11.1 μm^2
T_1	7.4 ns	2.5 ns	8.7 ns (15.2 ns)

Trying a better sample (fabricated at UC Santa Barbara)

M.Steffen et al.
Phys.Rev.Lett. **97**, 050502 (2006)

SiO_2 replaced by SiN_x





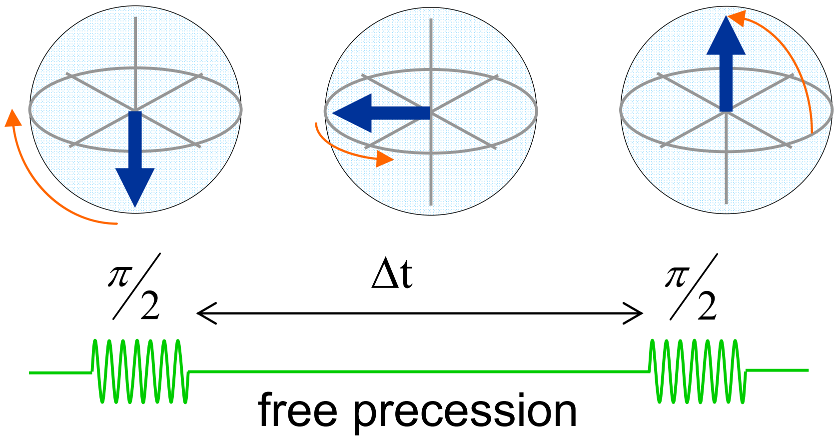
$T_d^{\text{Rabi}} \sim 140\text{ ns}$

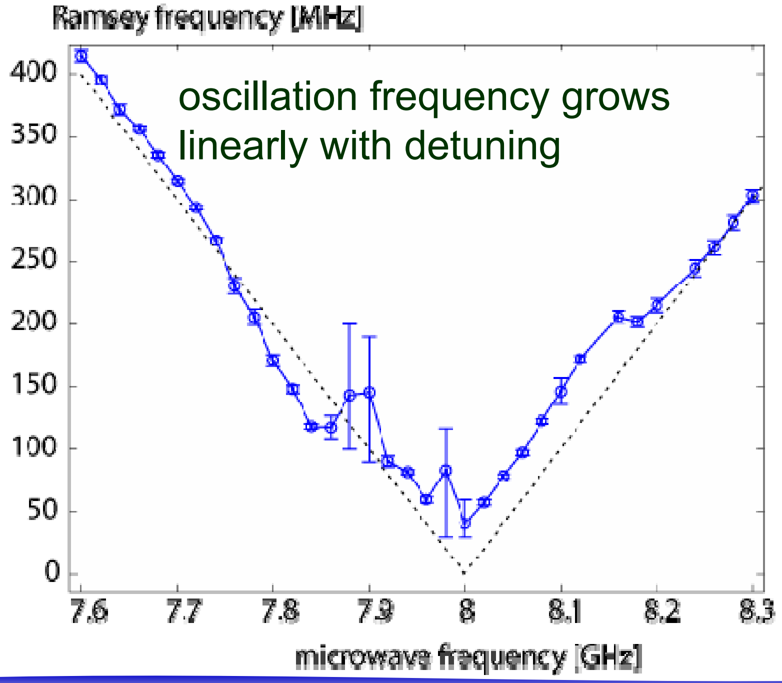
$T_1 \sim 110\text{ ns}$

UCSB sample
measured
in Erlangen

Ramsey fringes

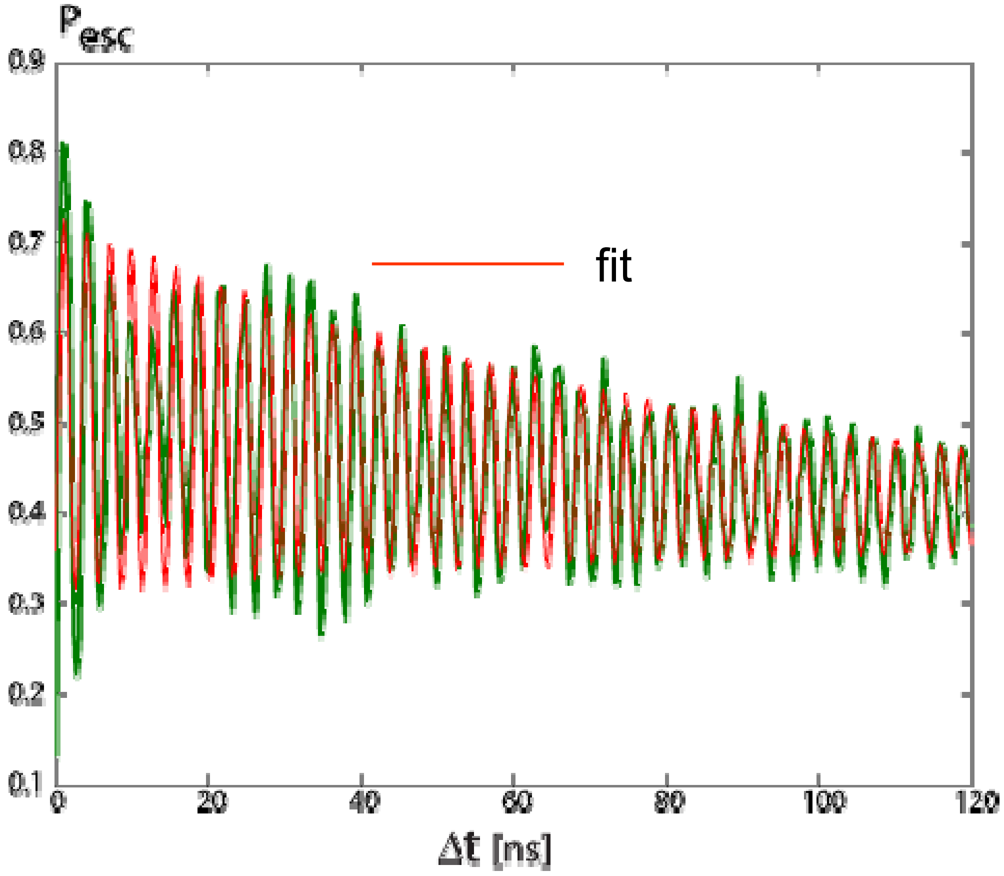
UCSB sample



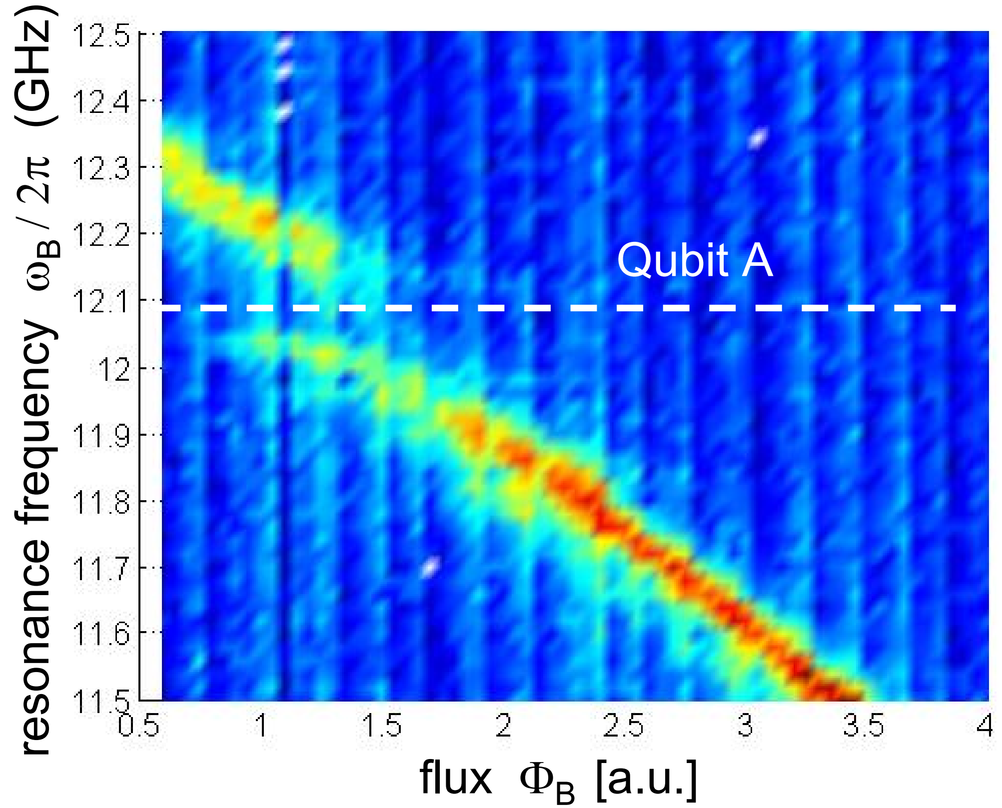


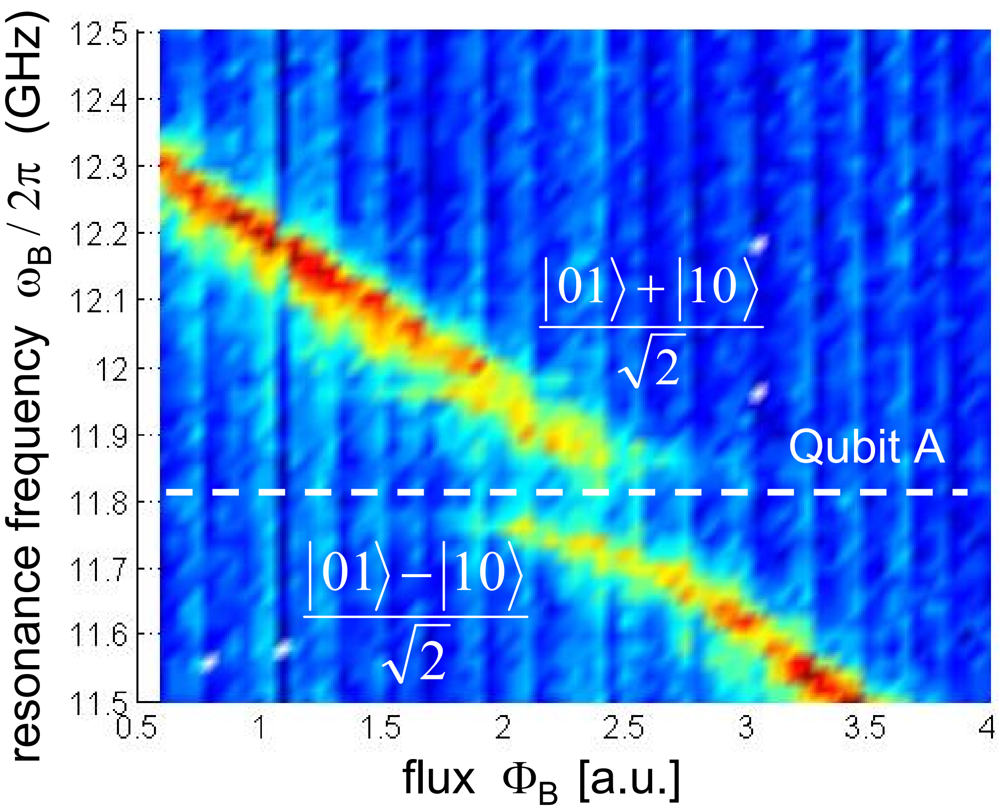
oscillation frequency grows linearly with detuning

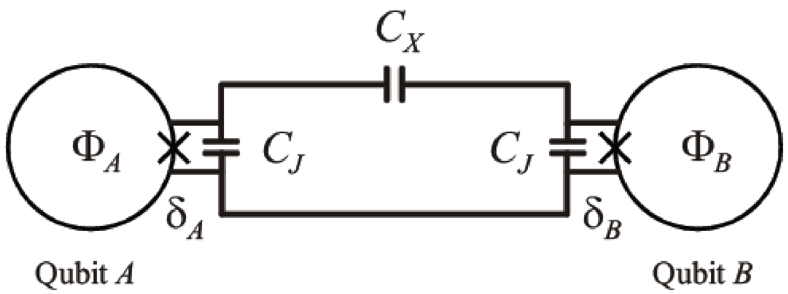
$T_2^{*\,\mathrm{Ramsey}} \sim 90$ ns $\qquad T_2^{\mathrm{echo}} \sim 160$ ns

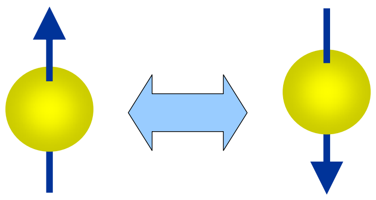


Coupled phase qubits

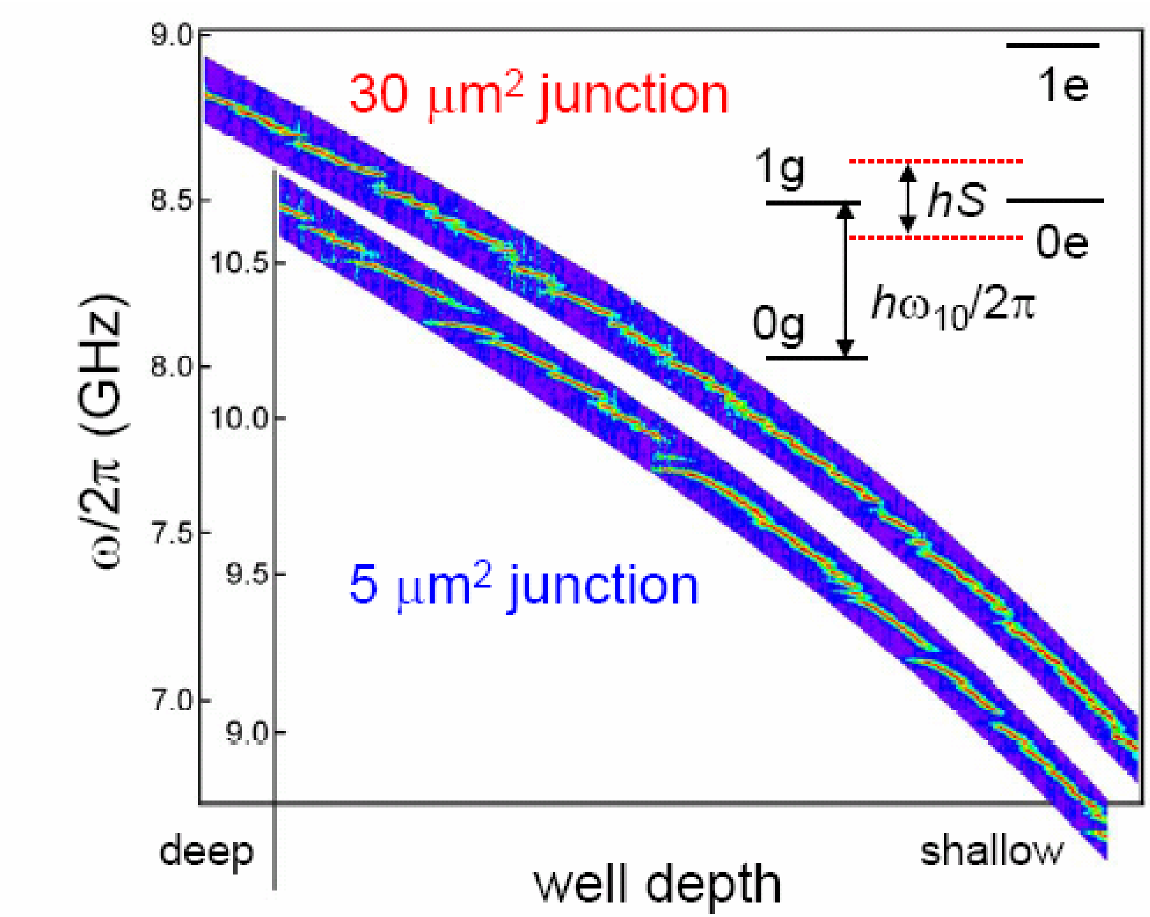






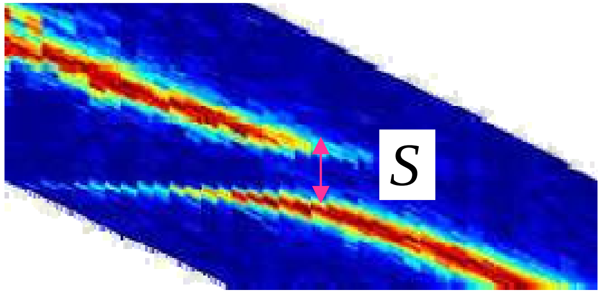


Origin of decoherence in phase qubits: microscopic two-level fluctuators



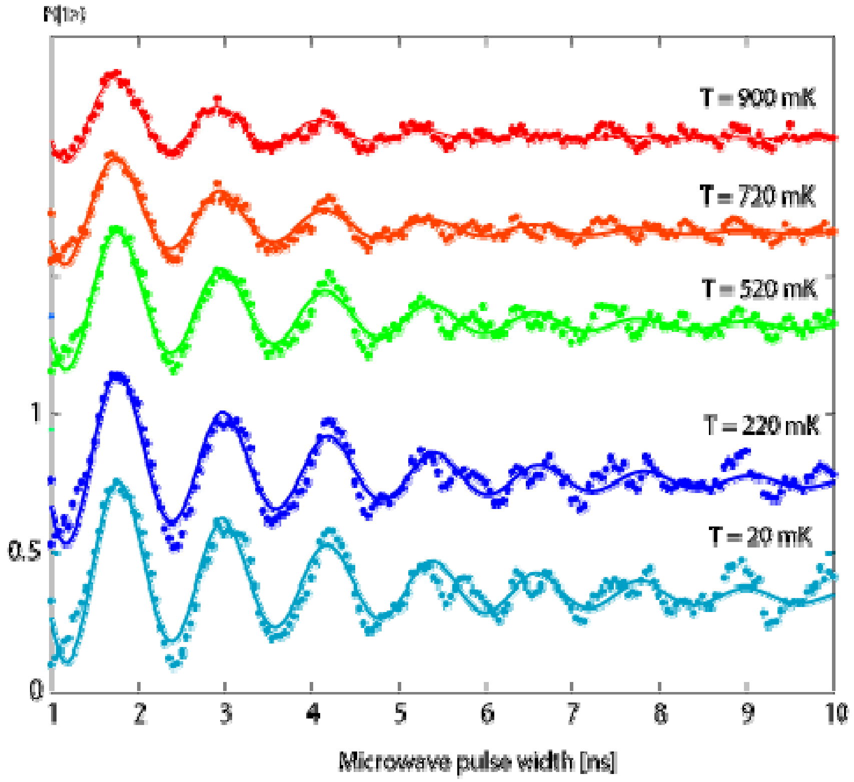
spectroscopy

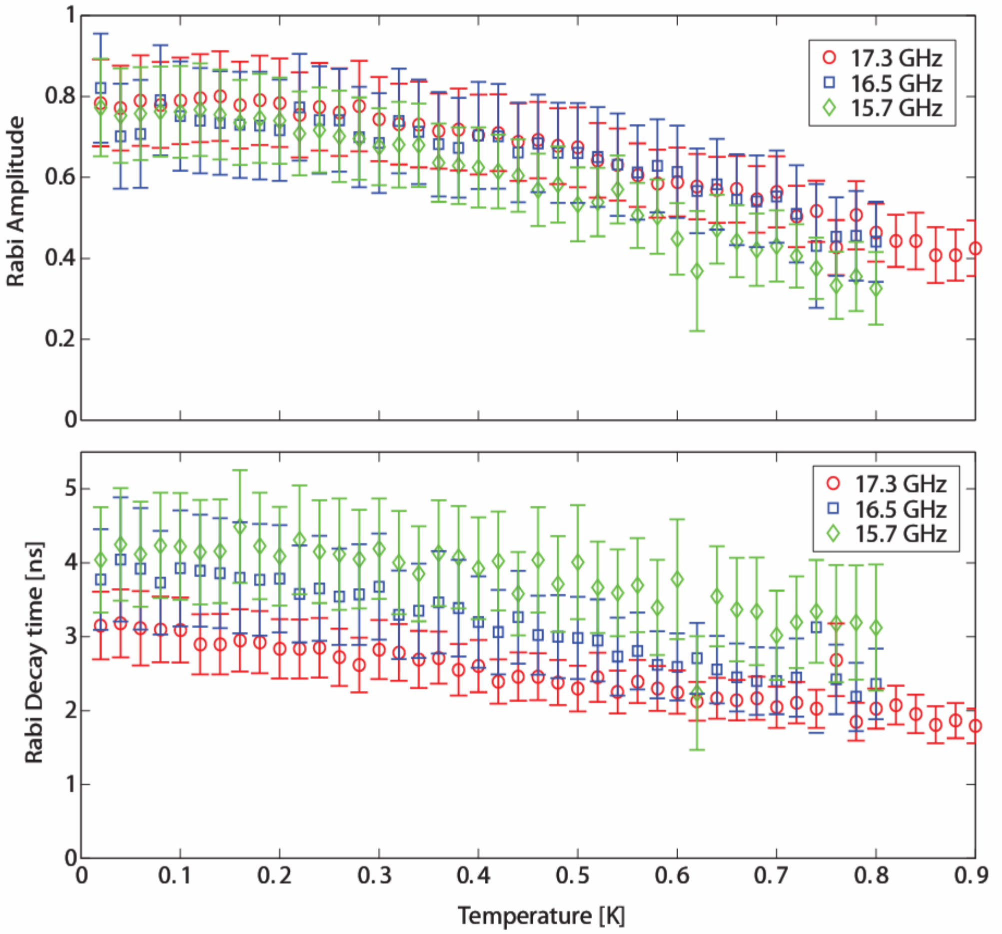
$$S_{\max} \propto \sqrt{\frac{1}{A}}$$



K. B. Cooper, et al., Phys.Rev.Lett. **93**, 180401 (2004).

Bad samples: Multi-level Rabi oscillations up to high temperatures



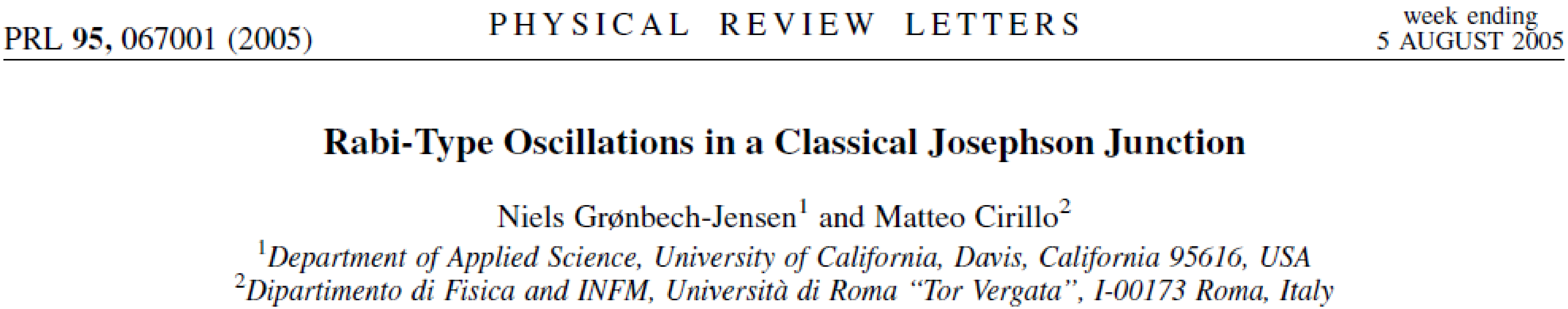


$$\omega_{01} = 16.5\,\mathrm{GHz} \cdot 2\pi$$

$$T_{01} = \frac{\hbar\omega_{01}}{k_B} = 790\,\mathrm{mK}$$

N. Groenbech-Jensen, M. Cirillo, *“Rabi-type oscillations in a classical Josephson junction”*, Phys.Rev.Lett. **95**, 067001 (2005)

Rabi oscillations: quantum or classical?



PRL **95,** 067001 (2005) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2005

Rabi-Type Oscillations in a Classical Josephson Junction

Niels Grønbech-Jensen[1] and Matteo Cirillo[2]
[1]*Department of Applied Science, University of California, Davis, California 95616, USA*
[2]*Dipartimento di Fisica and INFM, Università di Roma "Tor Vergata", I-00173 Roma, Italy*

$$\ddot{\varphi} + \alpha\dot{\varphi} + \sin\varphi = \eta + \varepsilon_s \sin\omega_s t$$

$$\varphi = \varphi_0 + \psi = \varphi_0 + a\sin(\omega_s t + \theta)$$

$$\ddot{\varphi} + \alpha\dot{\varphi} + \sin\varphi = \eta + \Theta(t)\varepsilon_s \sin(\omega_s t + \theta_s)$$

where $\Theta(t)$ is Heaviside's step function

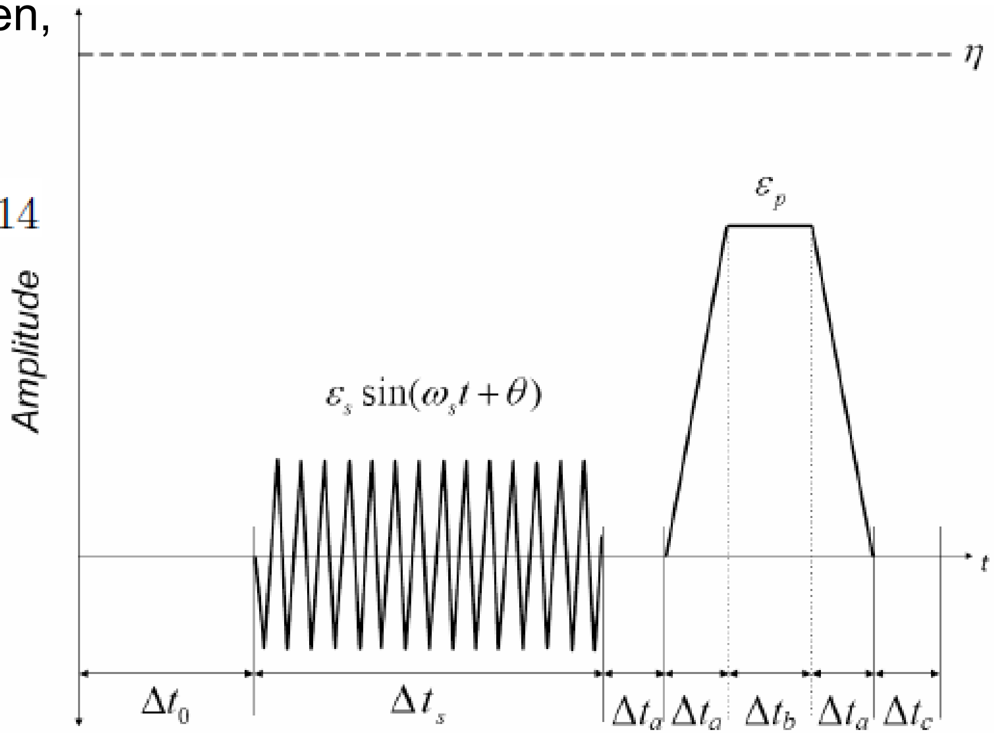
Classical Rabi oscillations

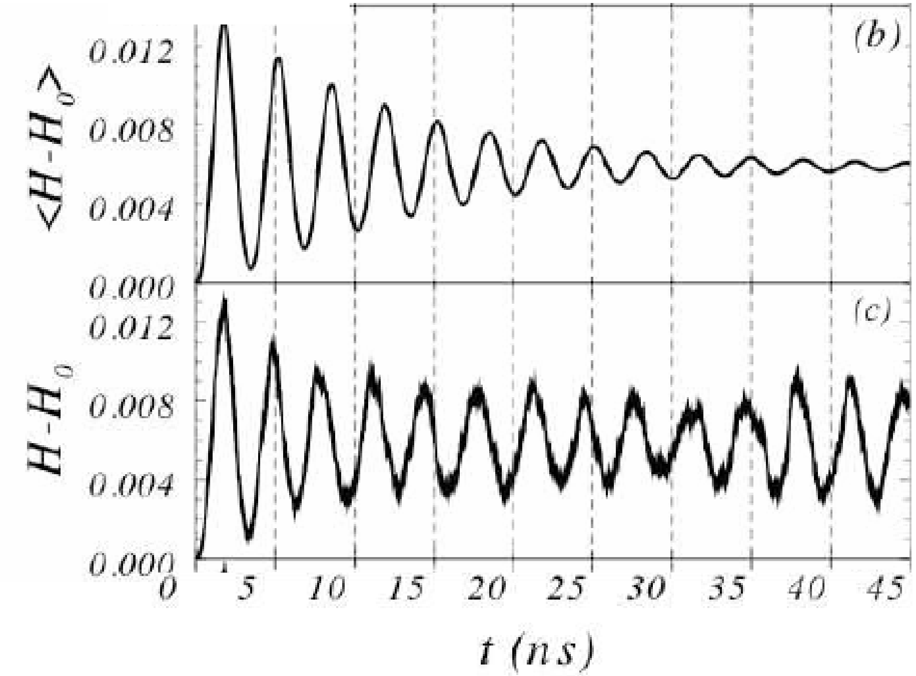
J. E. Marchese, M. Cirillo, and N. Grønbech-Jensen, *Phys. Rev. B* **73**, 174507 (2006).

Parameters are: $T = 30$ mK, $\alpha = 0.00151477$,

$\eta = \sqrt{1-\omega_s^4} = 0.904706$, $\omega_s = 2\pi\nu_{01}/\omega_0 = 0.652714$

$\epsilon_s = 0.00217000$, $\epsilon_p = 0.0847400$





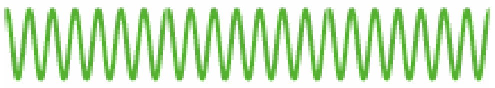
Ensemble average of normalized energy

Single trajectory of energy versus time

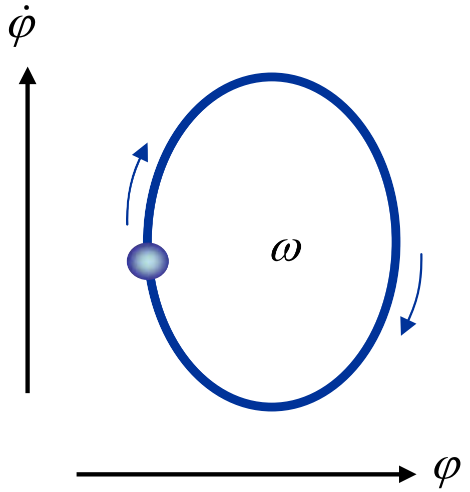
Classical „Rabi“ oscillations: main idea

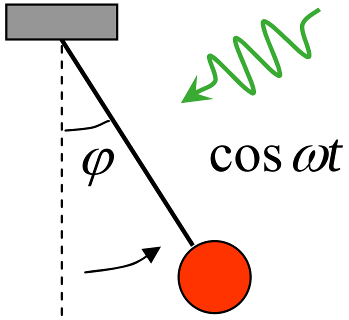
Qualitative picture: transient oscillations approaching phase locking

N. Grønbech-Jensen and M. Cirillo, *Phys. Rev. Lett.* **95**, 067001 (2005)
P.S. Lomdahl and M.R. Samuelsen, *Phys. Lett. A* **128**, 427 (1988)

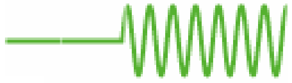


continuous driving
⇨ phase locking

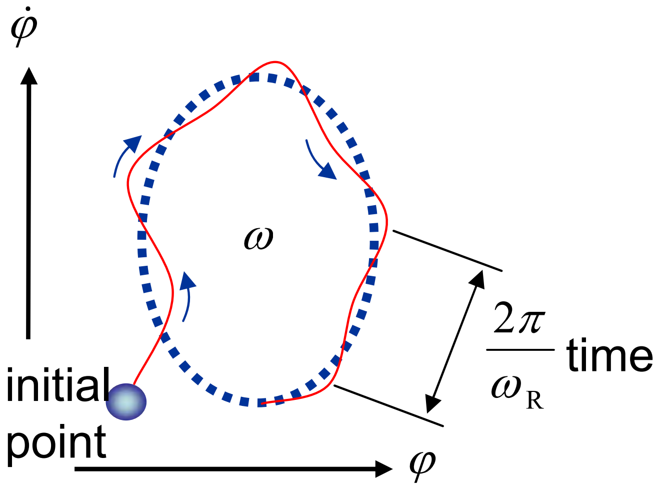




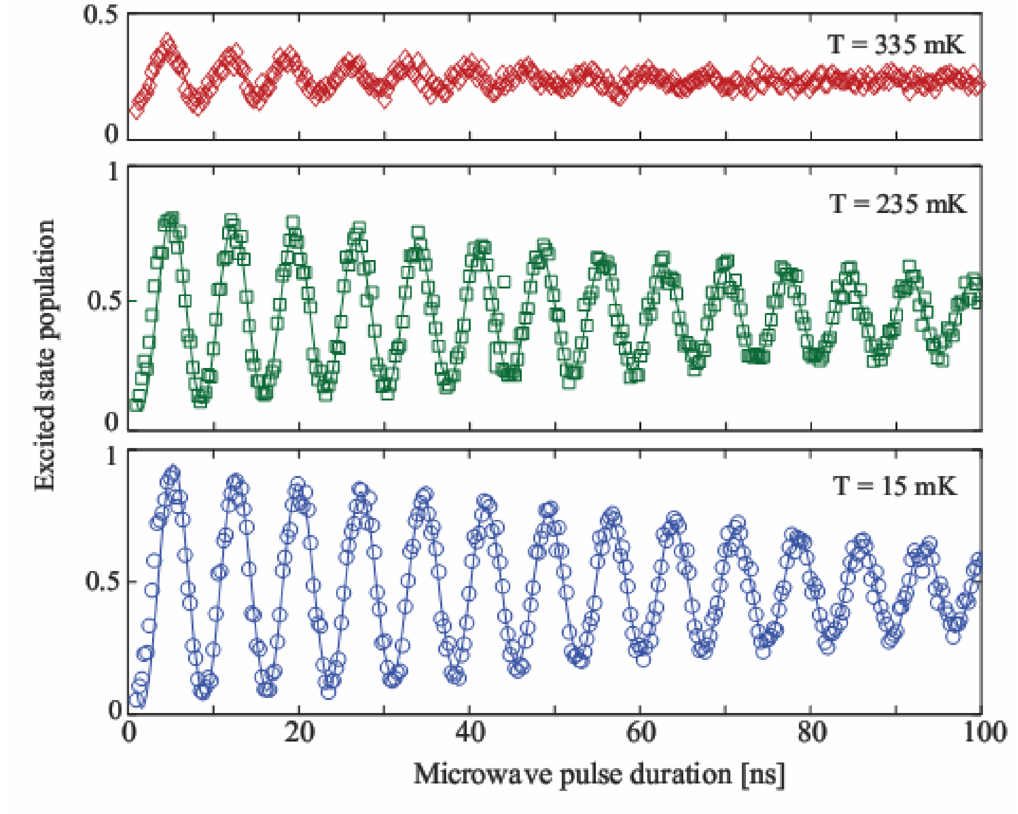
This picture ⇨
is not to scale:
in reality $\omega_R << \omega$

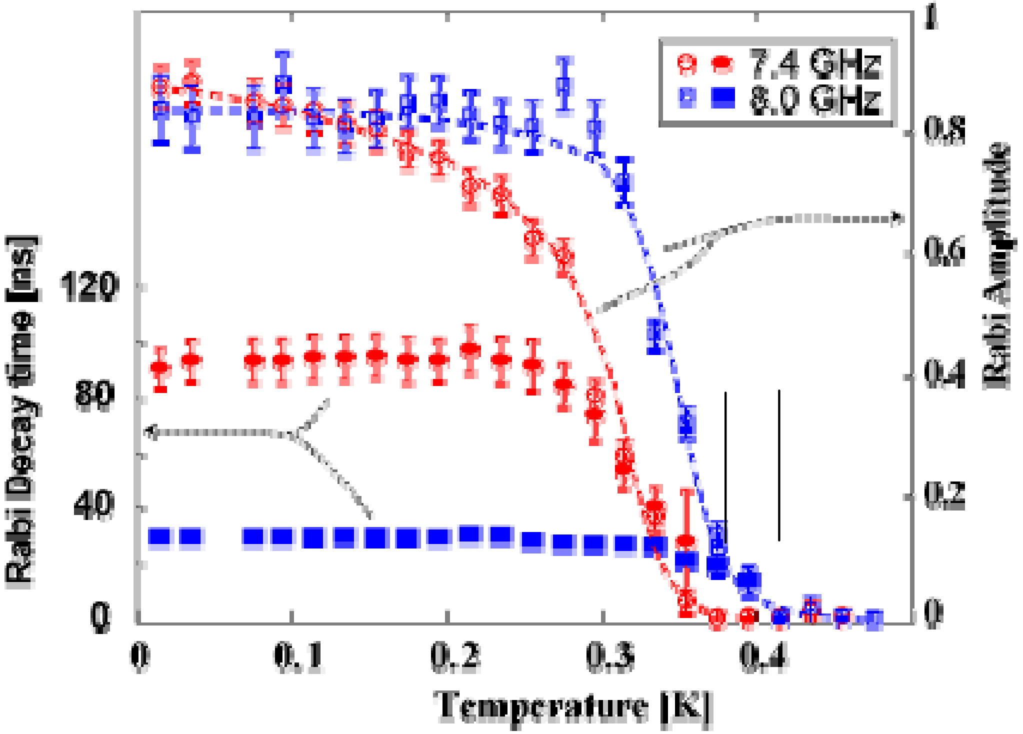


ac-pulse driving
⇨ transient oscillation



Good samples: Two-level Rabi oscillations at high temperatures





Weak temperature dependence up to $T \approx 200\,\mathrm{mK}$

Rabi oscillations vanish at $k_B T \approx \hbar \omega_{01}$

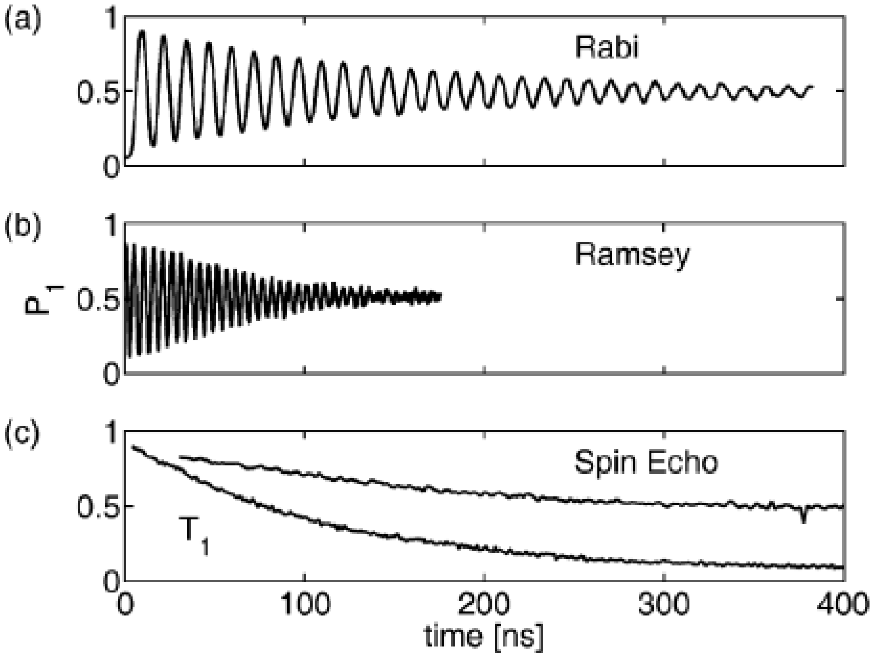
$$T_{01} = \frac{\hbar\omega_{01}}{k_B} = 355\,\mathrm{mK\ at\ 7.4\,GHz}$$

$$T_{01} = 384\,\mathrm{mK\ at\ 8\,GHz}$$

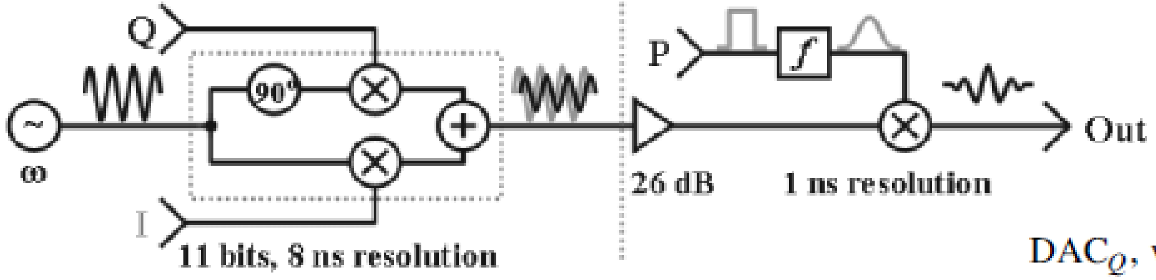
Phase qubits: Summary

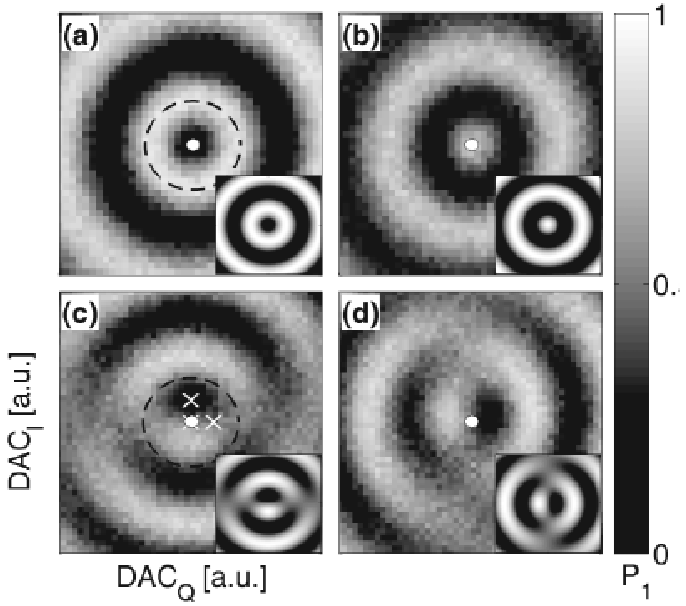
„bad“ samples: **multi-level, nearly classical**	**„good“ samples:** **two-level, quantum**
easy-to-make Nb based junctions	best available Al based junctions
Si-oxide insulator on chip	**Si-nitride insulator on chip**
small junction size > 10 μm^2	small junction size < 1 μm^2
moderate damping Q ~ 50	low damping Q ~ 1000
broad levels	narrow levels
short coherence times < 10 ns	long coherence times > 100 ns

Quantum state tomogrphy



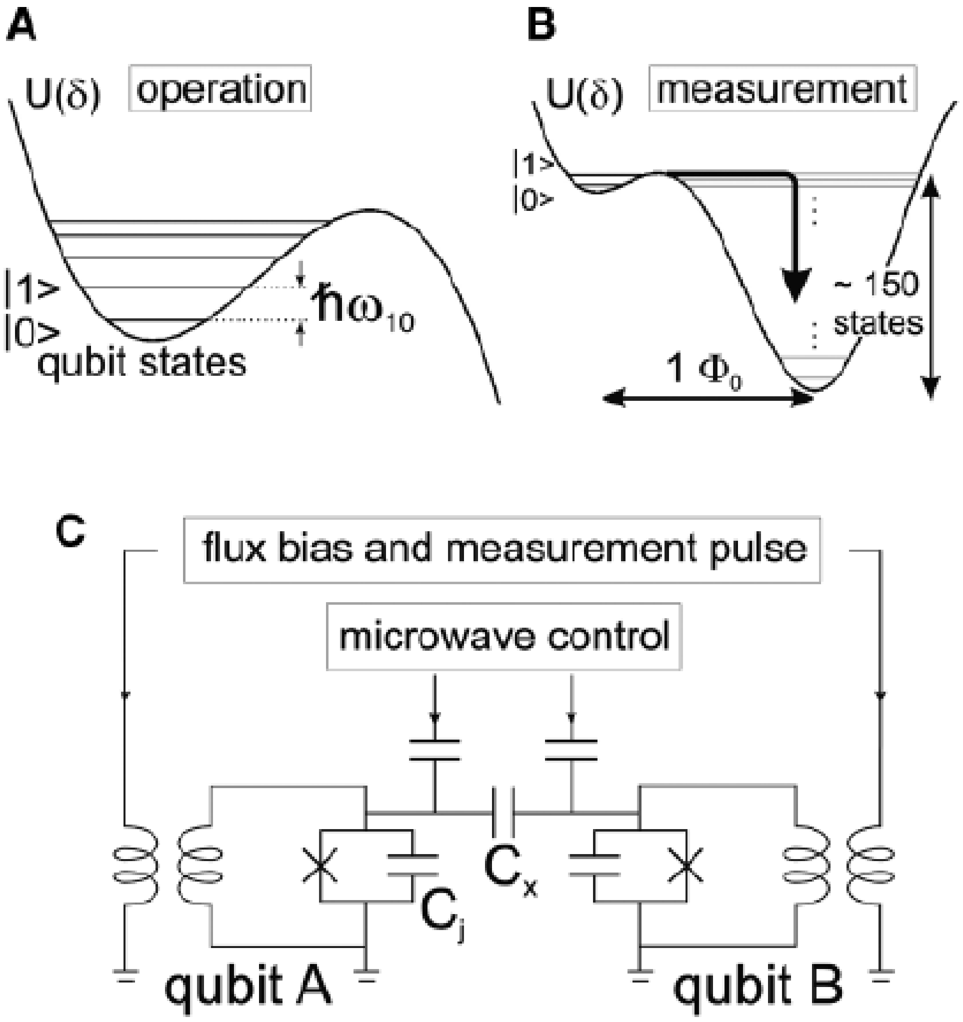
M. Steffen, M. Ansmann, R. McDermott, N. Katz, R. C. Bialczak, E. Lucero, M. Neeley, E.M. Weig, A.N. Cleland, and J.M. Martinis, *Phys.Rev.Lett.* **97,** 050502 (2006)





Probability P_1 of occupying state $|1\rangle$ vs DAC_I and DAC_Q, which control the amplitude of the $\hat{y}$ and $\hat{x}$ tomography rotations, for the input states (a) $|0\rangle$, (b) $|1\rangle$, (c) $(|0\rangle + |1\rangle)/\sqrt{2}$, and (d) $(|0\rangle + i|1\rangle)/\sqrt{2}$. The tomography pulse was 16 ns long

Experiments on coupled phase qubits



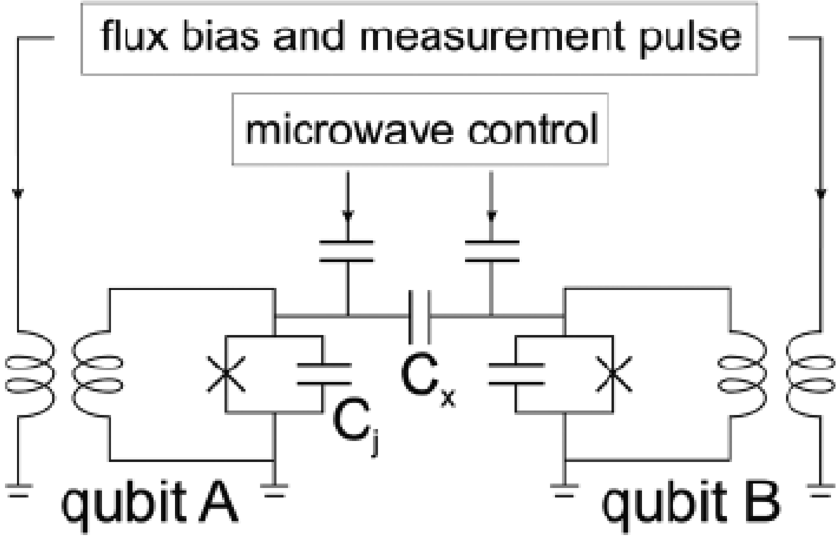
R. McDermott, R. W. Simmonds, M. Steffen, K. B. Cooper, K. Cicak, K. D. Osborn, S. Oh, D. P. Pappas, and J. M. Martinis, *Science* **307**, 1299 (2005).

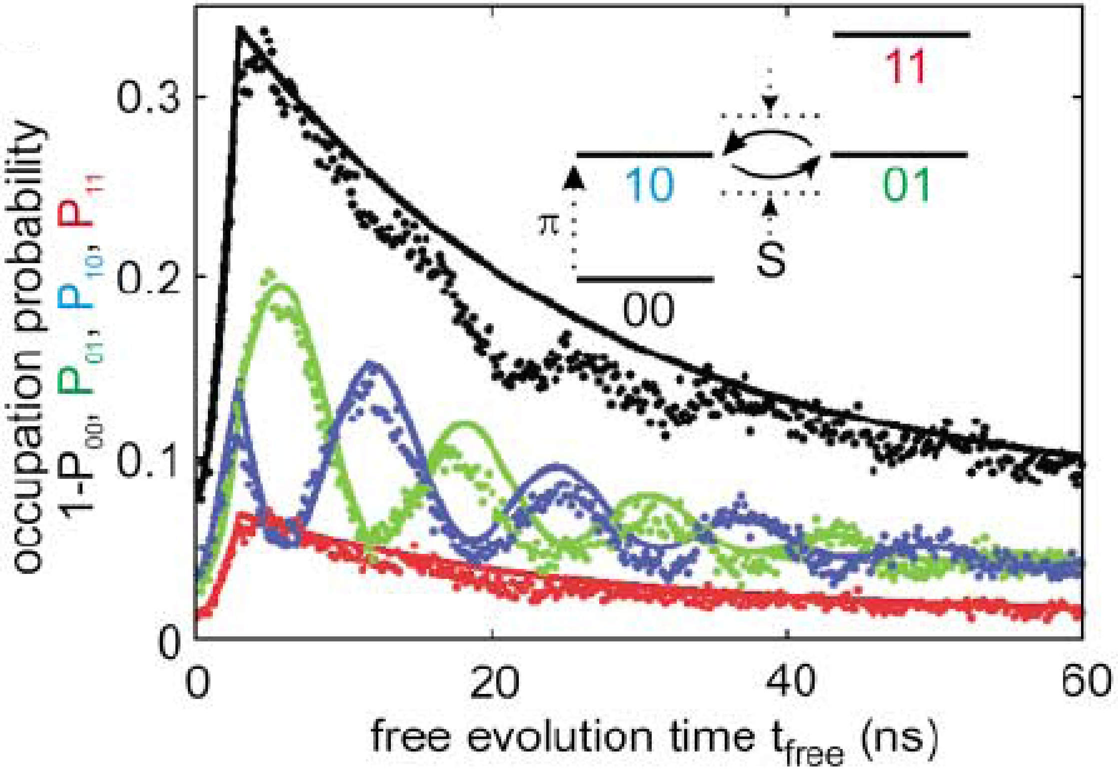
N. Katz, M. Ansmann, R.C. Bialczak, E. Lucero, R. McDermott, M. Neeley, M. Steffen, E.M. Weig, A.N. Cleland, J.M. Martinis, and A.N.Korotkov, *Science* **312**, 1498 (2006).

M. Steffen, M. Ansmann, R. C. Bialczak, N. Katz, E. Lucero, R. McDermott, M. Neeley, E. M. Weig, A. N. Cleland, and J. M. Martinis, *Science* **313**, 1423 (2006).

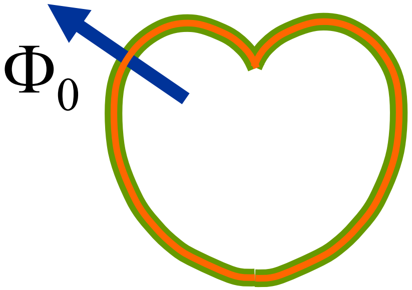
Simultaneous state measurement of coupled Josephson phase qubits

R. McDermott, R. W. Simmonds, M. Steffen, K. B. Cooper, K. Cicak, K. D. Osborn, S. Oh, D. P. Pappas, and J. M. Martinis, *Science* **307**, 1299 (2005).

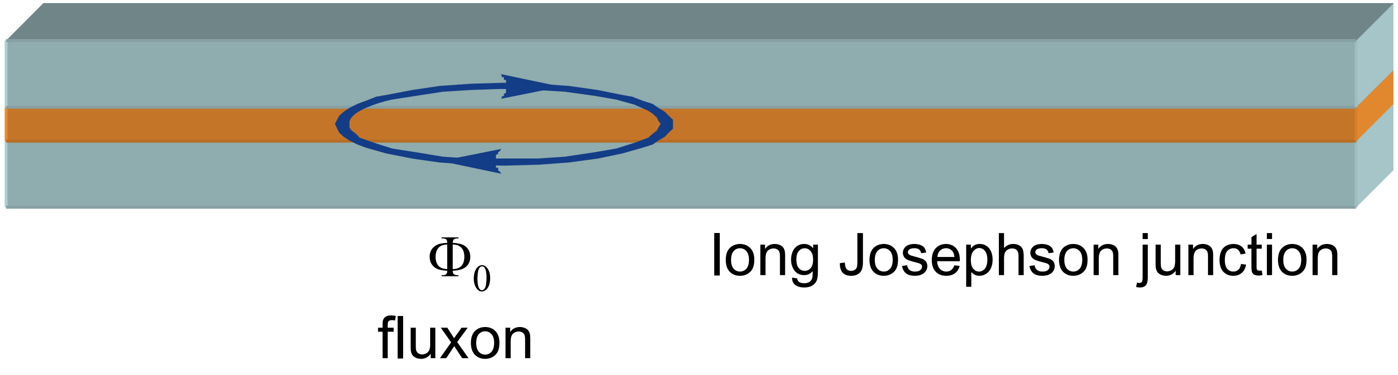


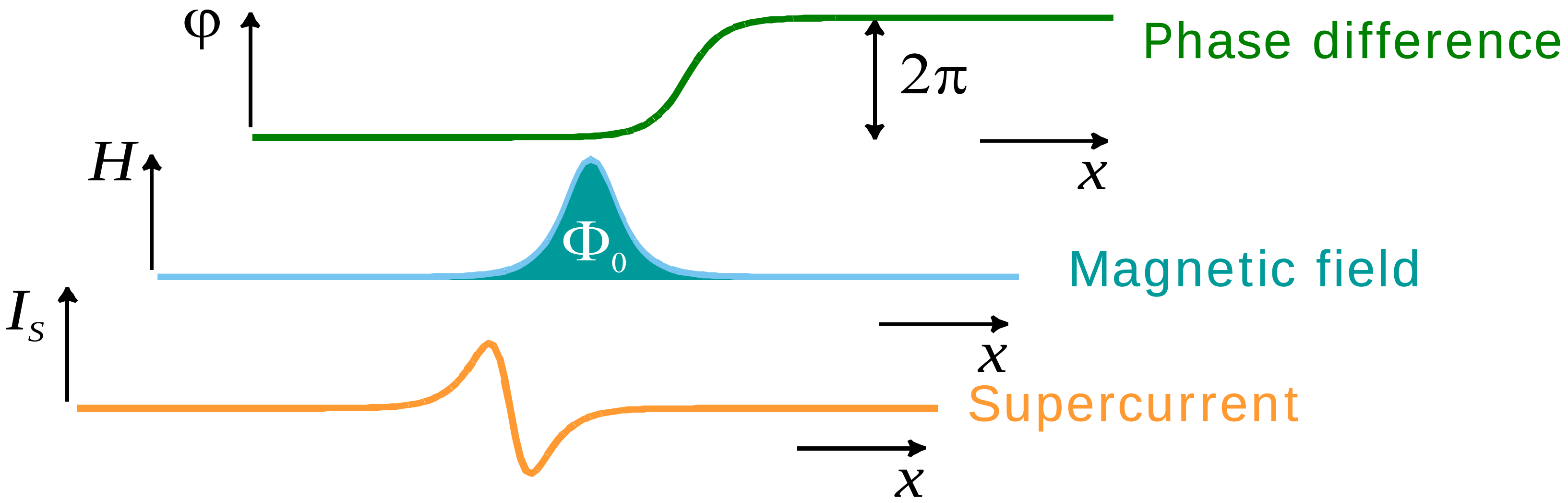


Vortex qubit



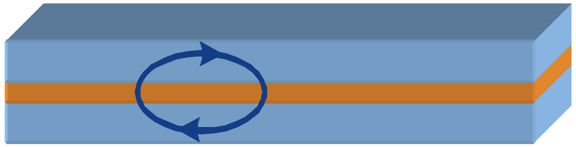
Soliton in a long Josephson junction



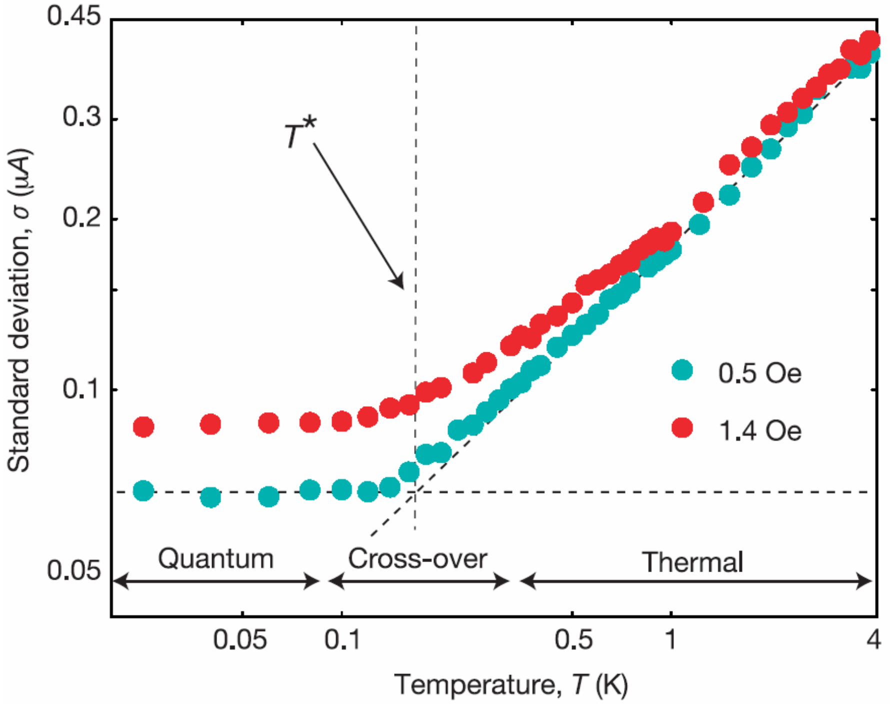


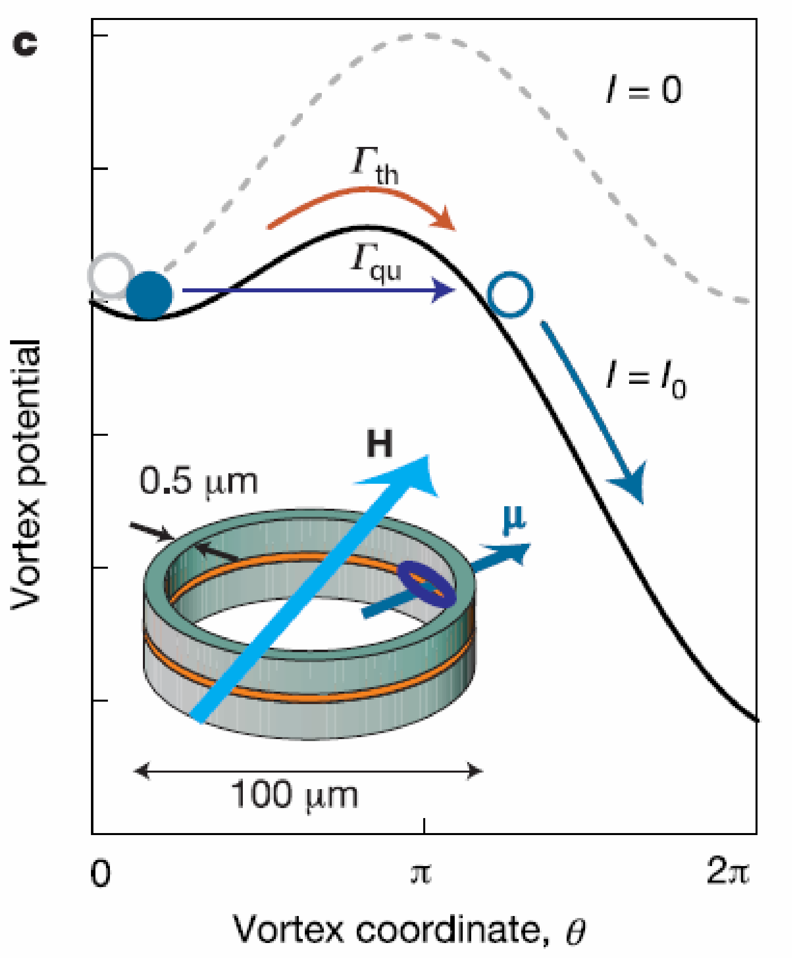
Soliton (fluxon, Josephson vortex, kink, flux quantum)

Quantum tunneling of a single vortex



volume
~ 10 μm^3

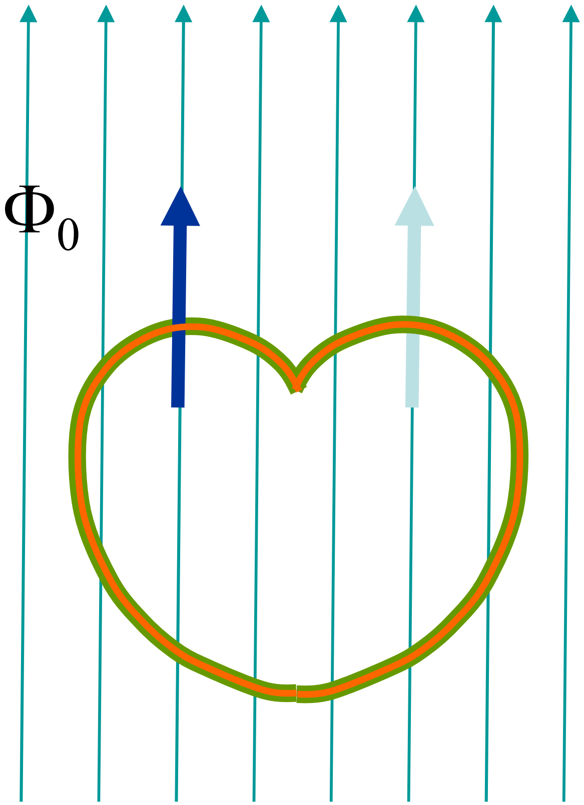




A. Wallraff, A. Lukashenko, J. Lisenfeld, A. Kemp, M.V. Fistul, Y. Koval, and A.V. Ustinov, Nature ***425****, 155 (2003).*

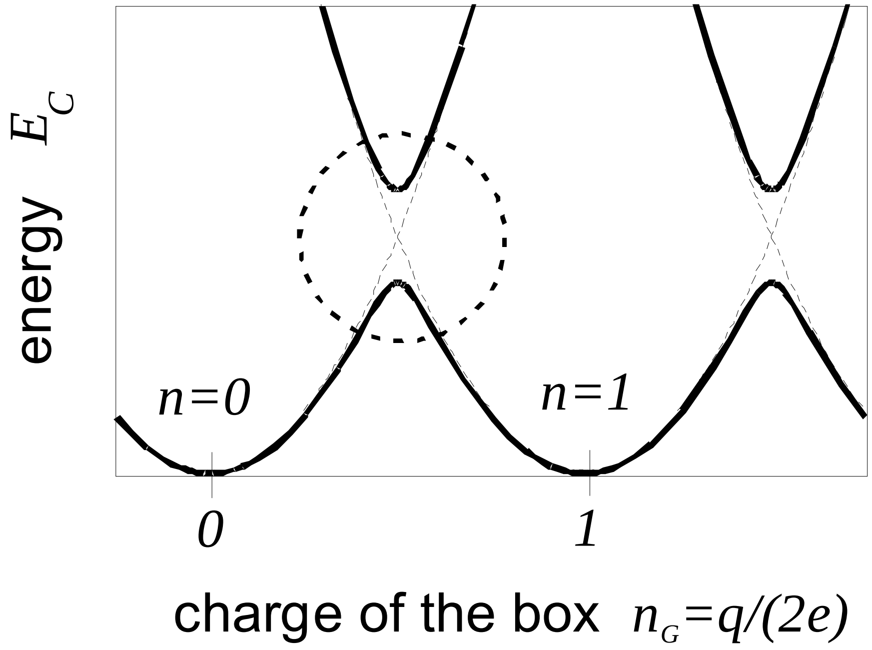
Vortex qubit

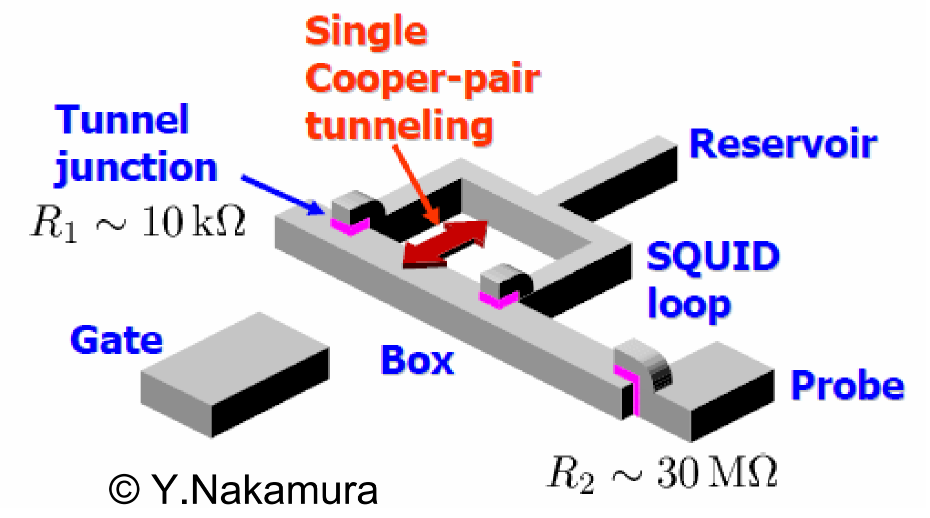
?



Charge qubits

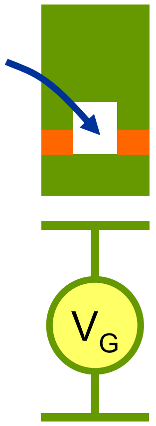
Charge qubit: NEC experiments

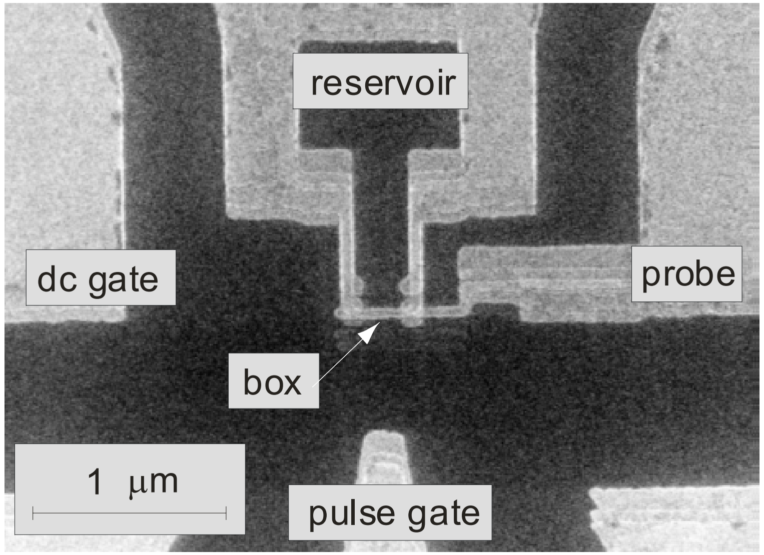




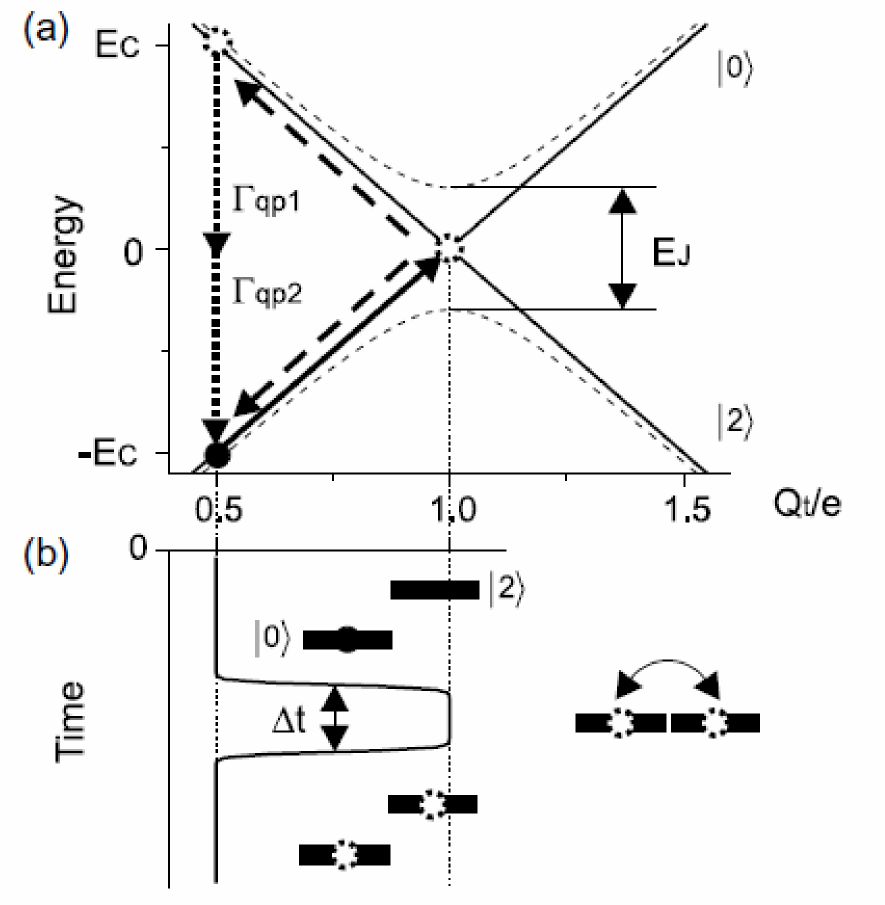
© Y.Nakamura

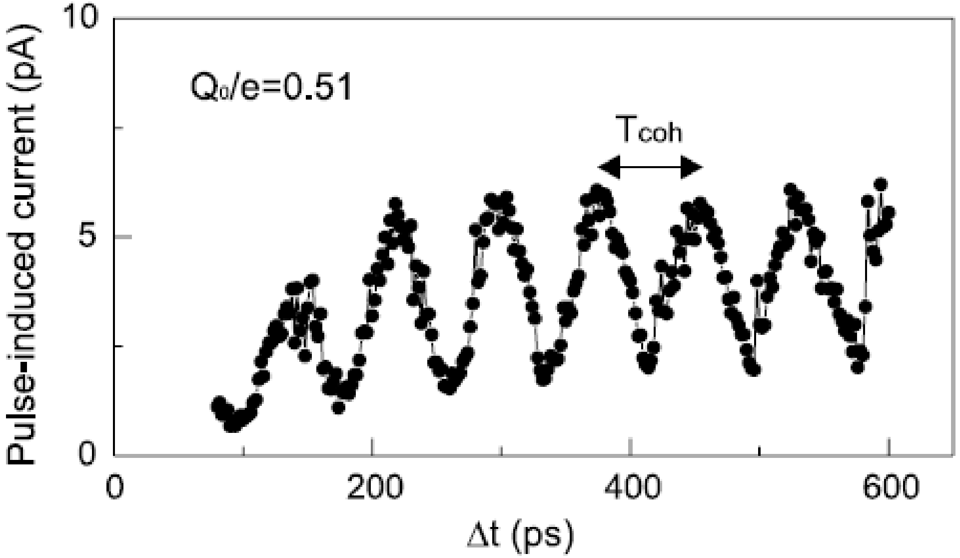
- Nakamura et al., Nature **398**, 786 (1999)
- Nakamura et al., PRL **87**, 246601 (2001)
- Nakamura et al., PRL **88**, 047901 (2002)





Charge qubit: NEC experiments (2)

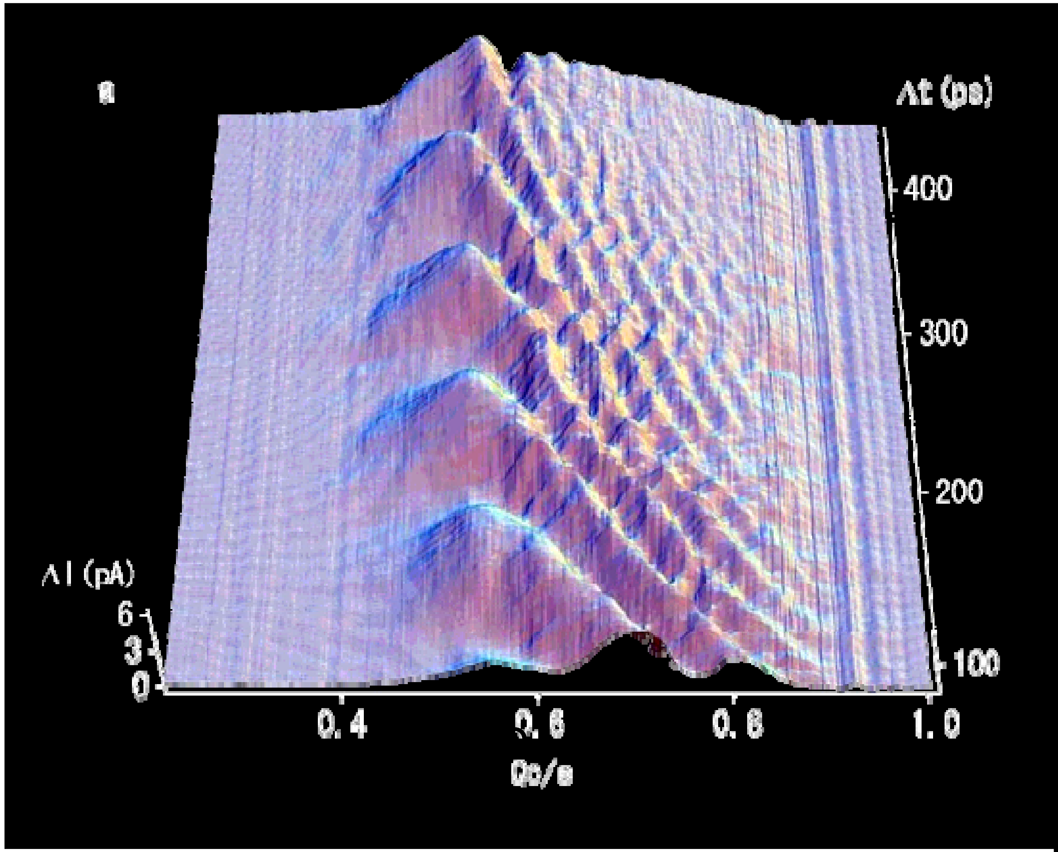




Nakamura, Pashkin and Tsai, *Nature* **398**, 786 (1999)

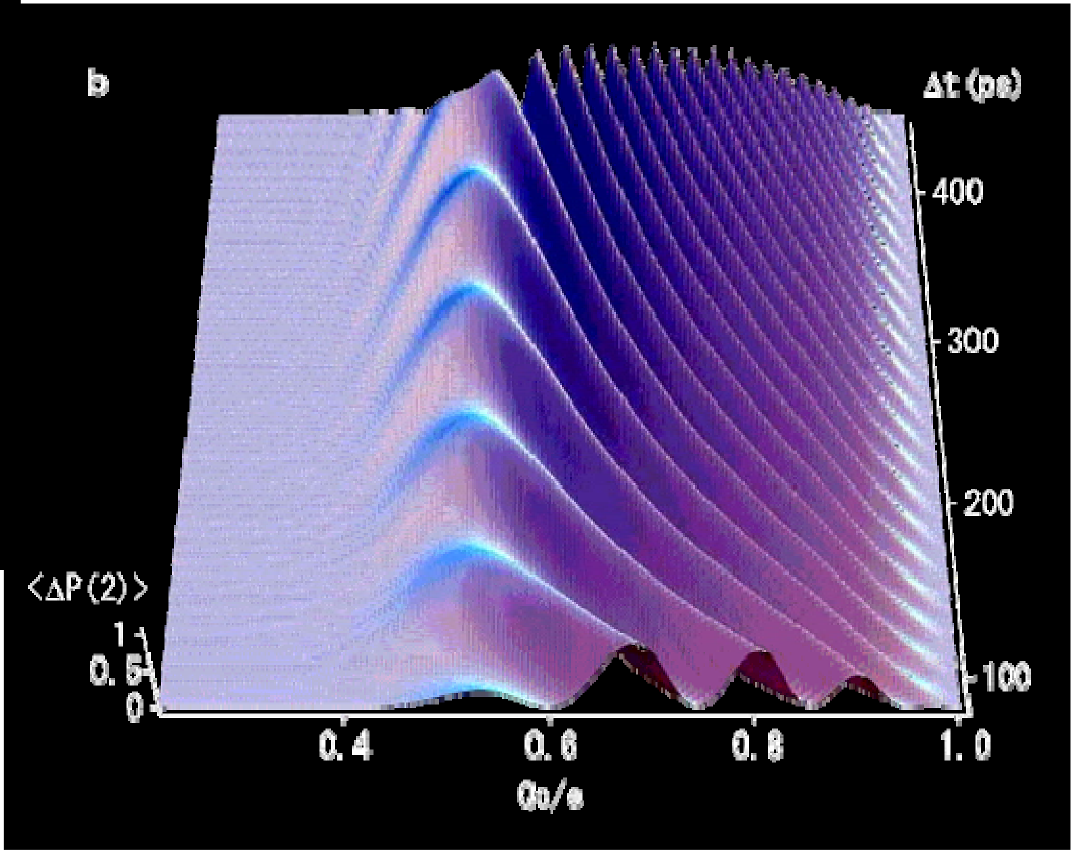
Charge qubit: NEC experiments (3)

- Nakamura et al., Nature **398**, 786 (1999)

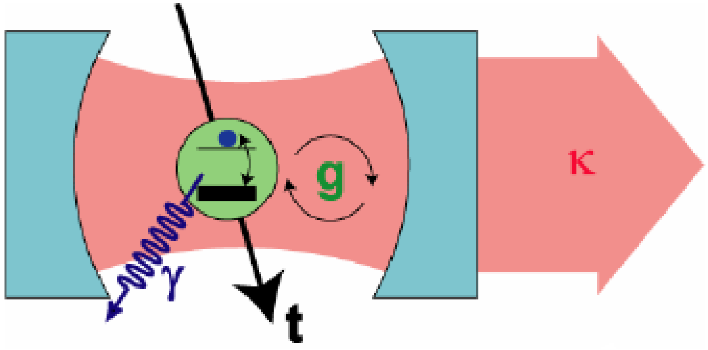


Measurement

Simulation



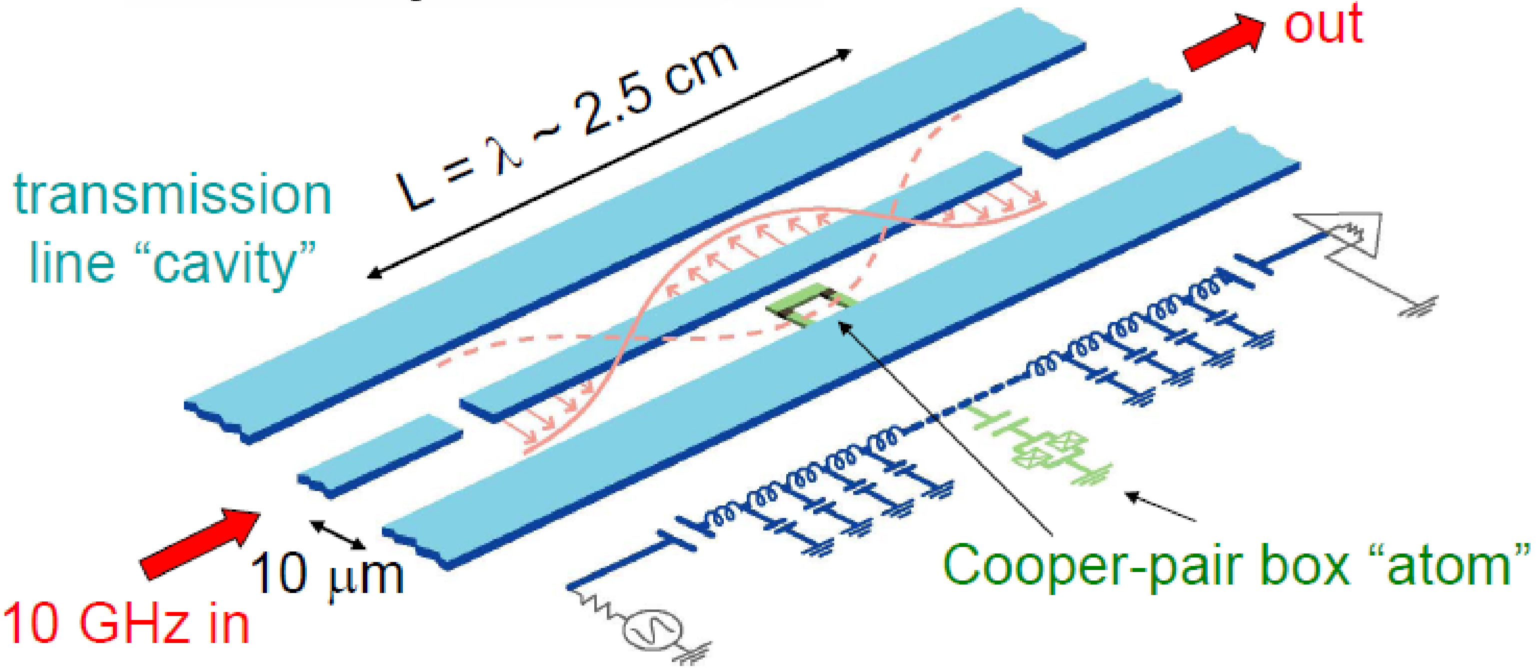
A circuit analog for cavity QED (Yale)



2g = vacuum Rabi freq.

κ = cavity decay rate

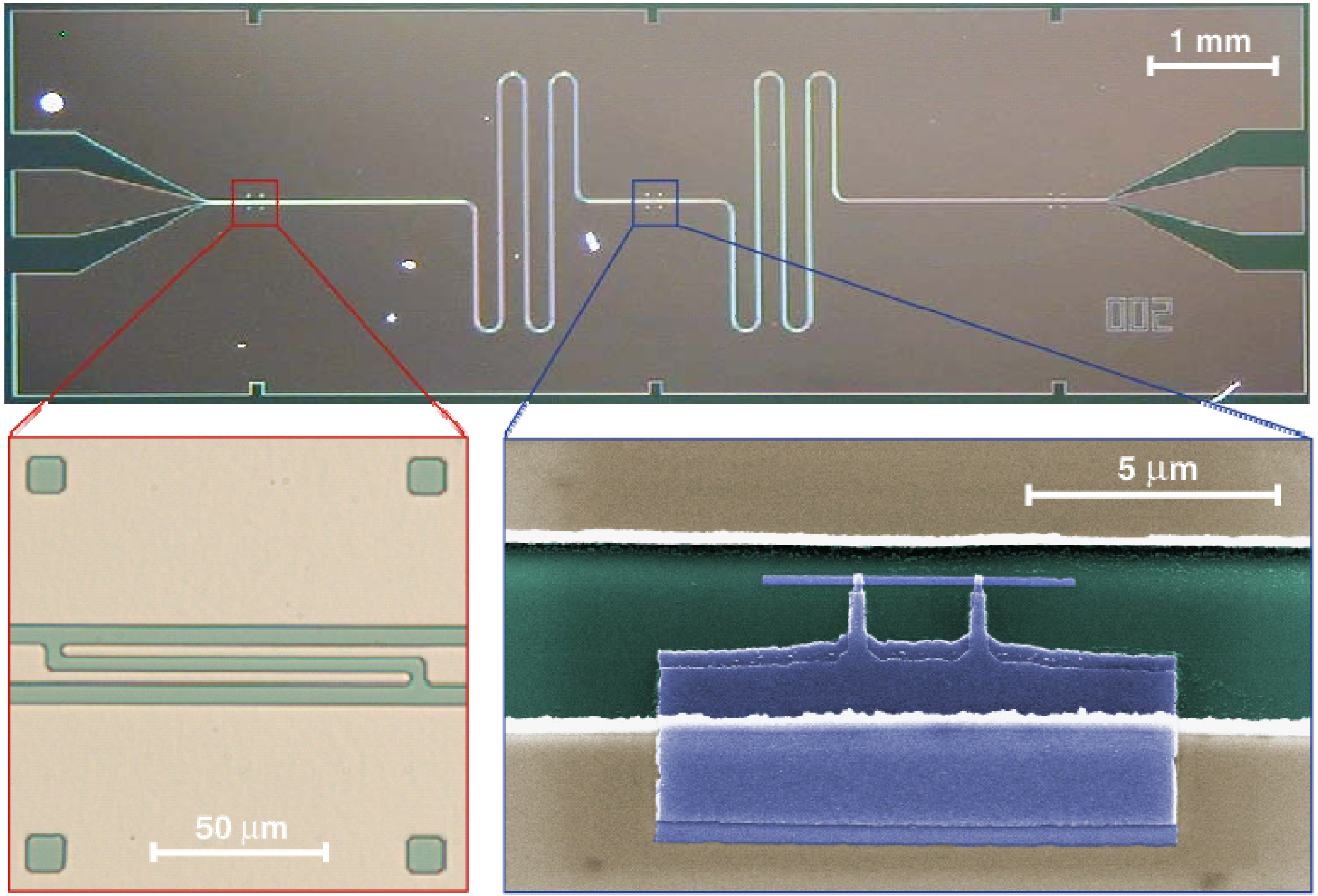
γ = “transverse” decay rate



A. Wallraff, D. I. Schuster, A. Blais, et al., *Nature* **431**, 162 (2004)

© A.Wallraff

Charge qubit in a cavity (Yale)

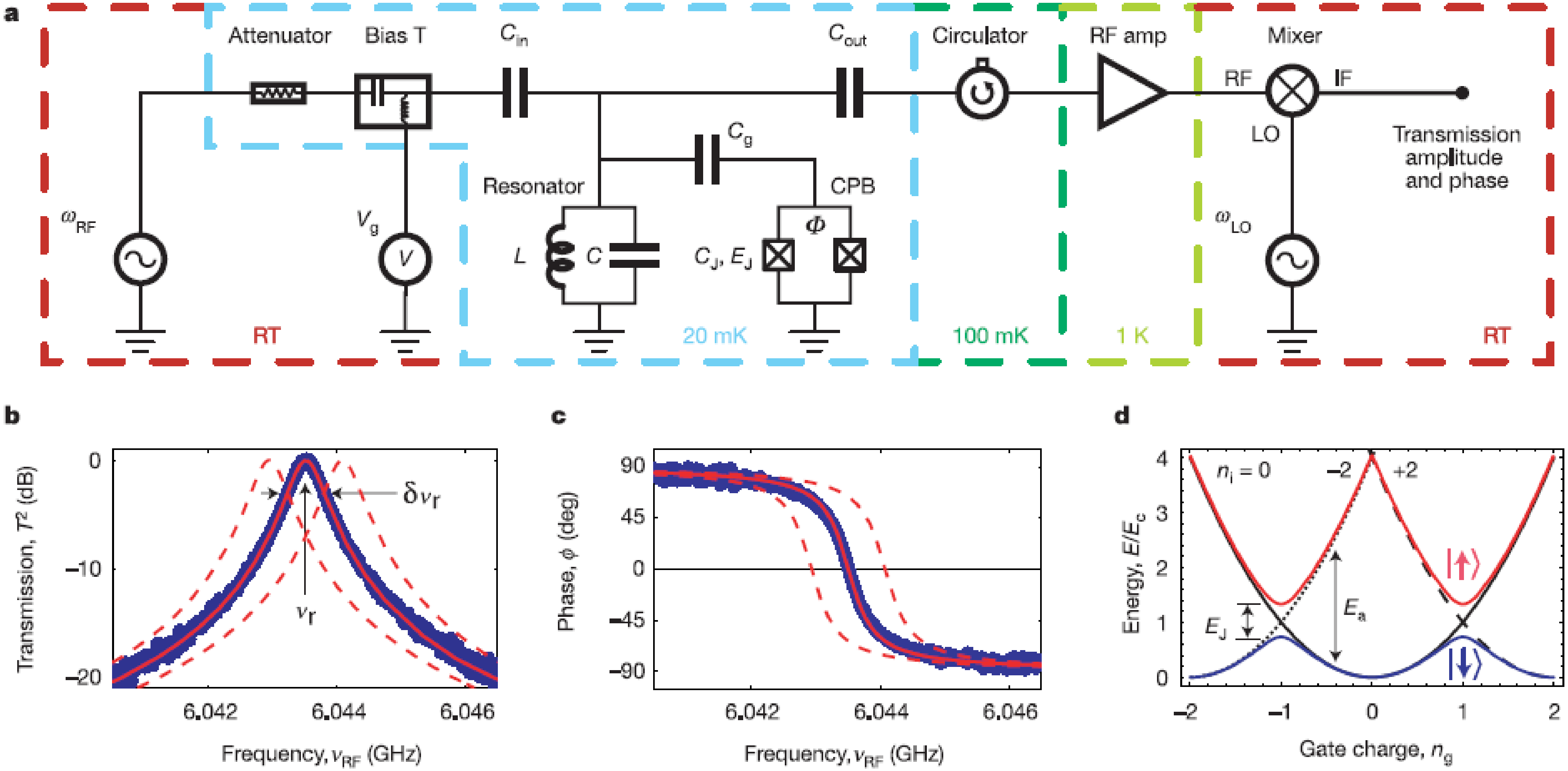


realization of superconducting cavity QED circuit

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

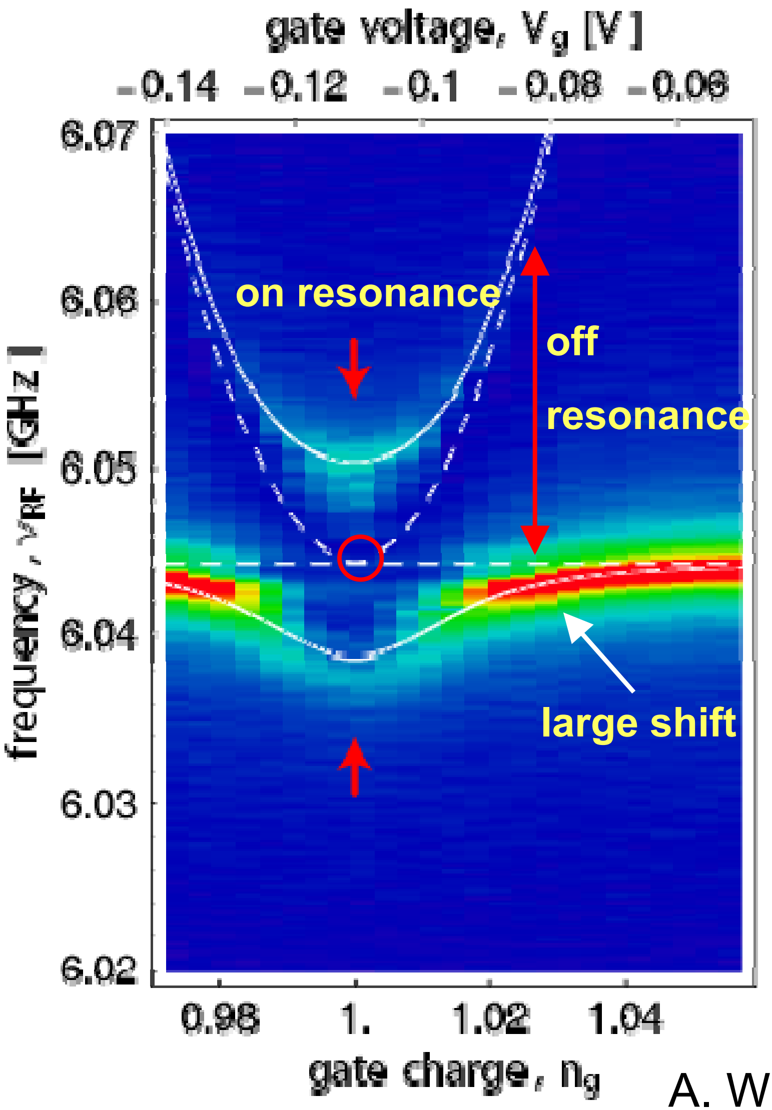
© A.Wallraff

QED experiment @ Yale: scheme, resonator and charge qubit

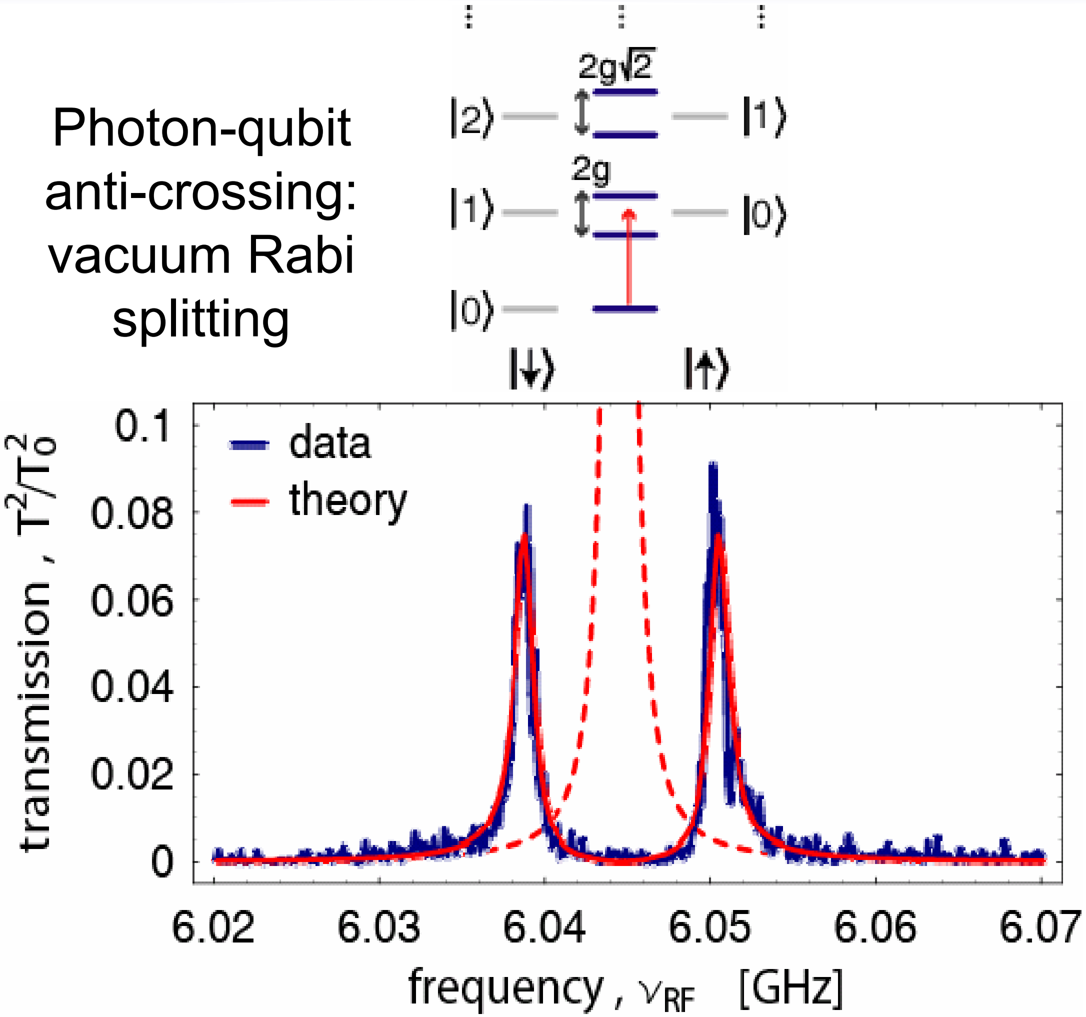


A. Wallraff, D. I. Schuster, A. Blais, et al., *Nature* **431**, 162 (2004)

Dispersive qubit-field interaction

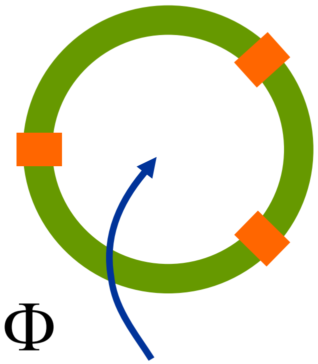


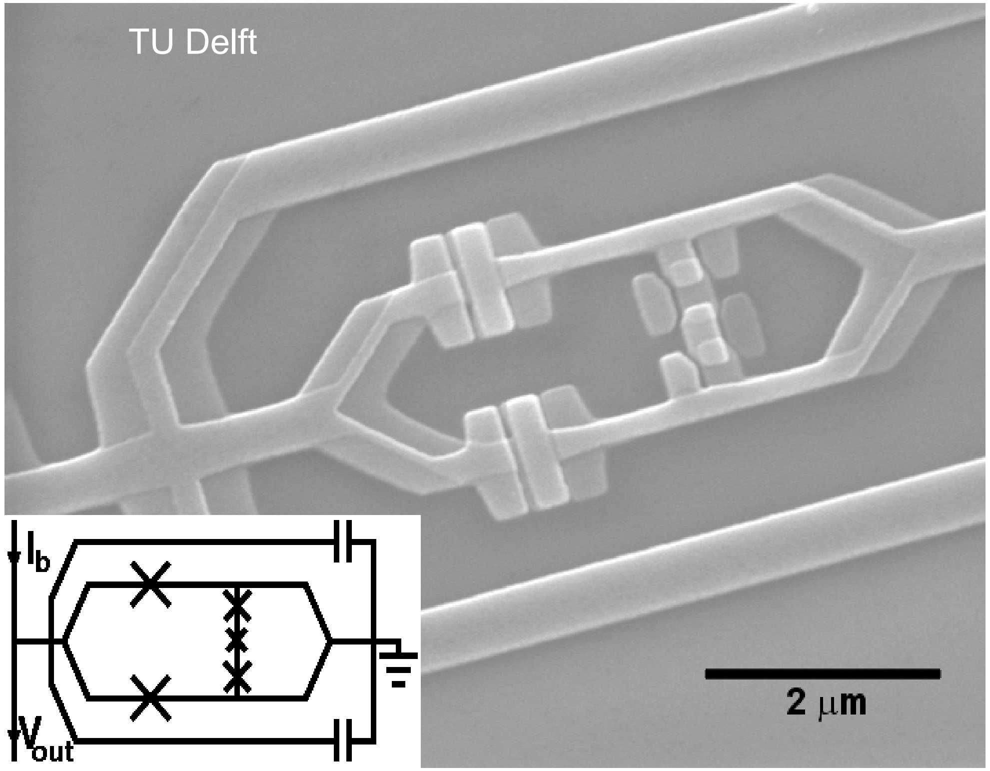
Photon-qubit anti-crossing: vacuum Rabi splitting



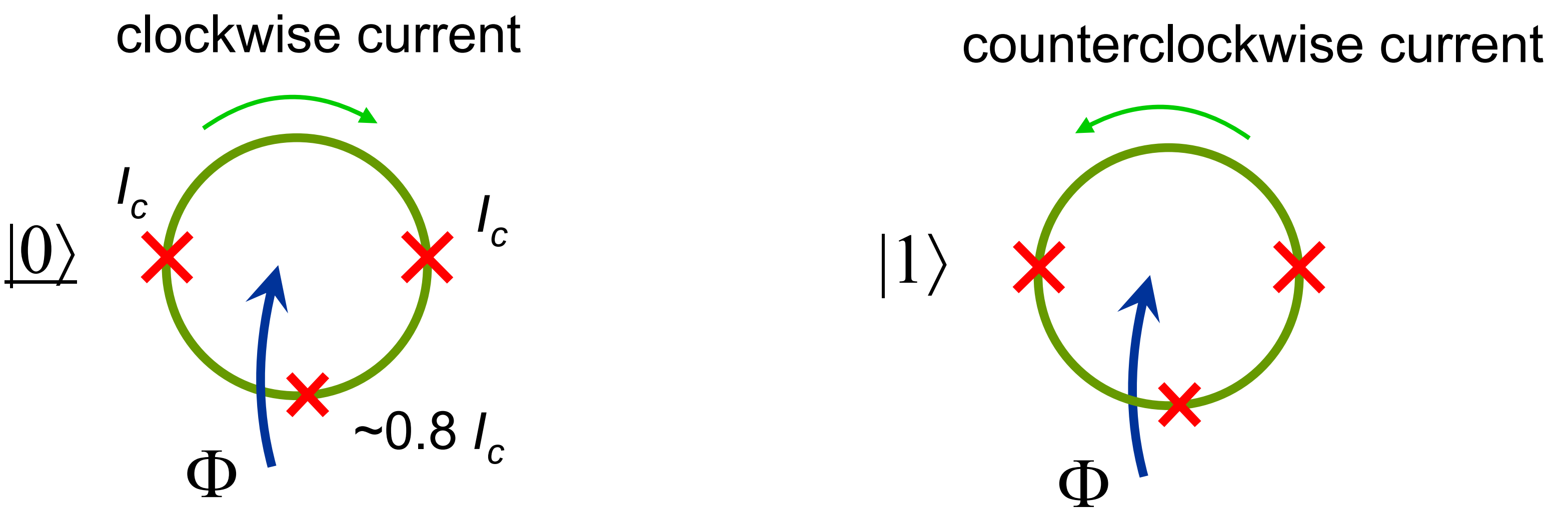
A. Wallraff, D. I. Schuster, A. Blais, et al., *Nature* **431**, 162 (2004)

Flux qubit





Three-junction flux qubit


clockwise current

counterclockwise current

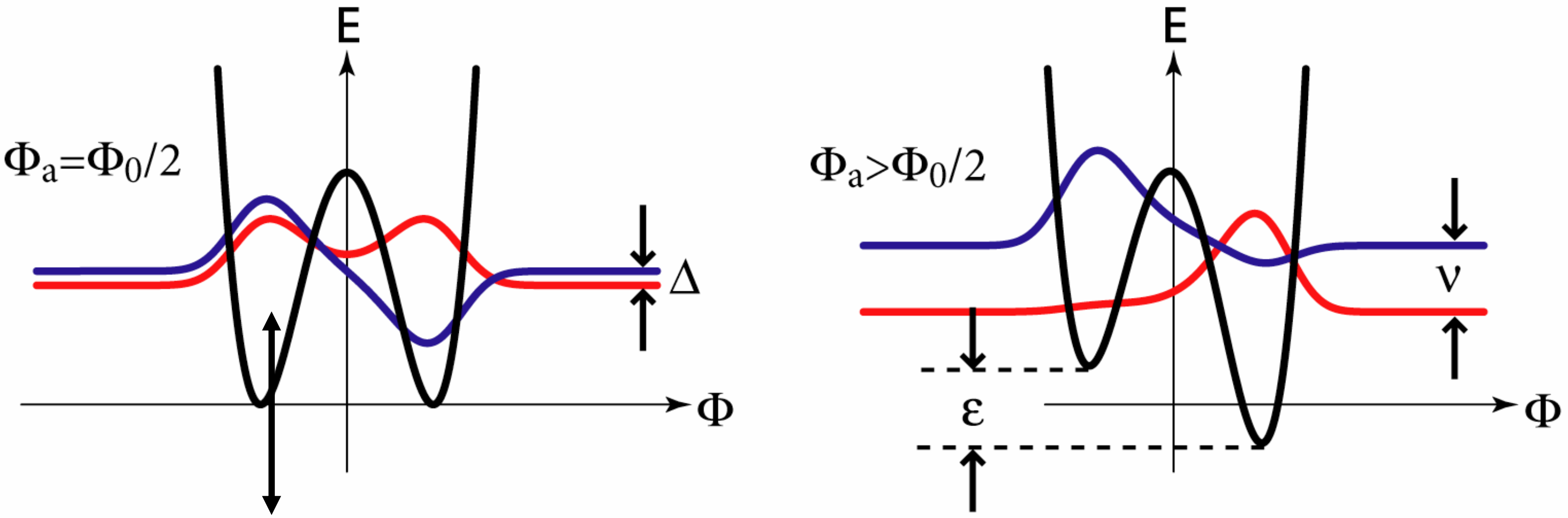
degeneracy point at $\Phi = \Phi_0/2$

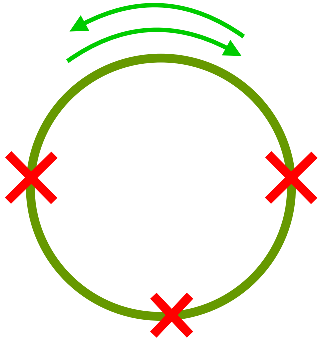
quantum states:

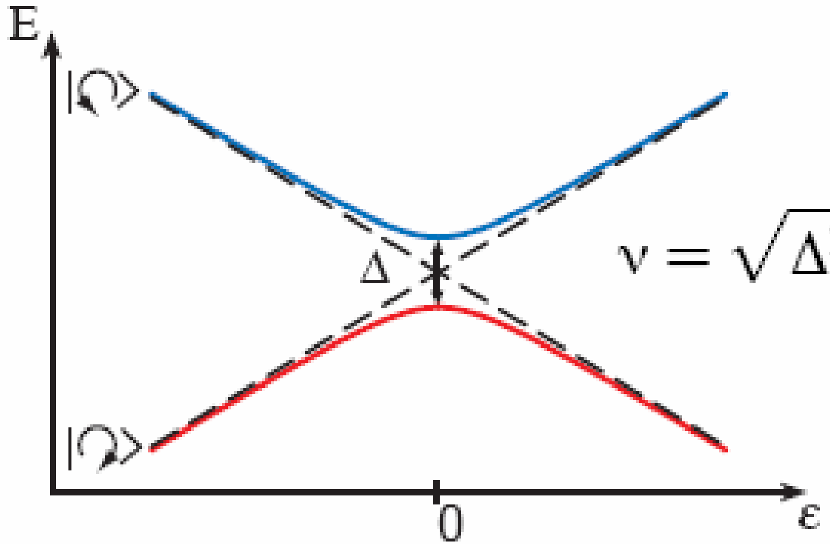
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

J.E. Mooij *et al.*, *Science* **285**, 1036 (1999)
C.H. van der Wal *et al.*, *Science* **290**, 773 (2000)

Energy of the flux qubit

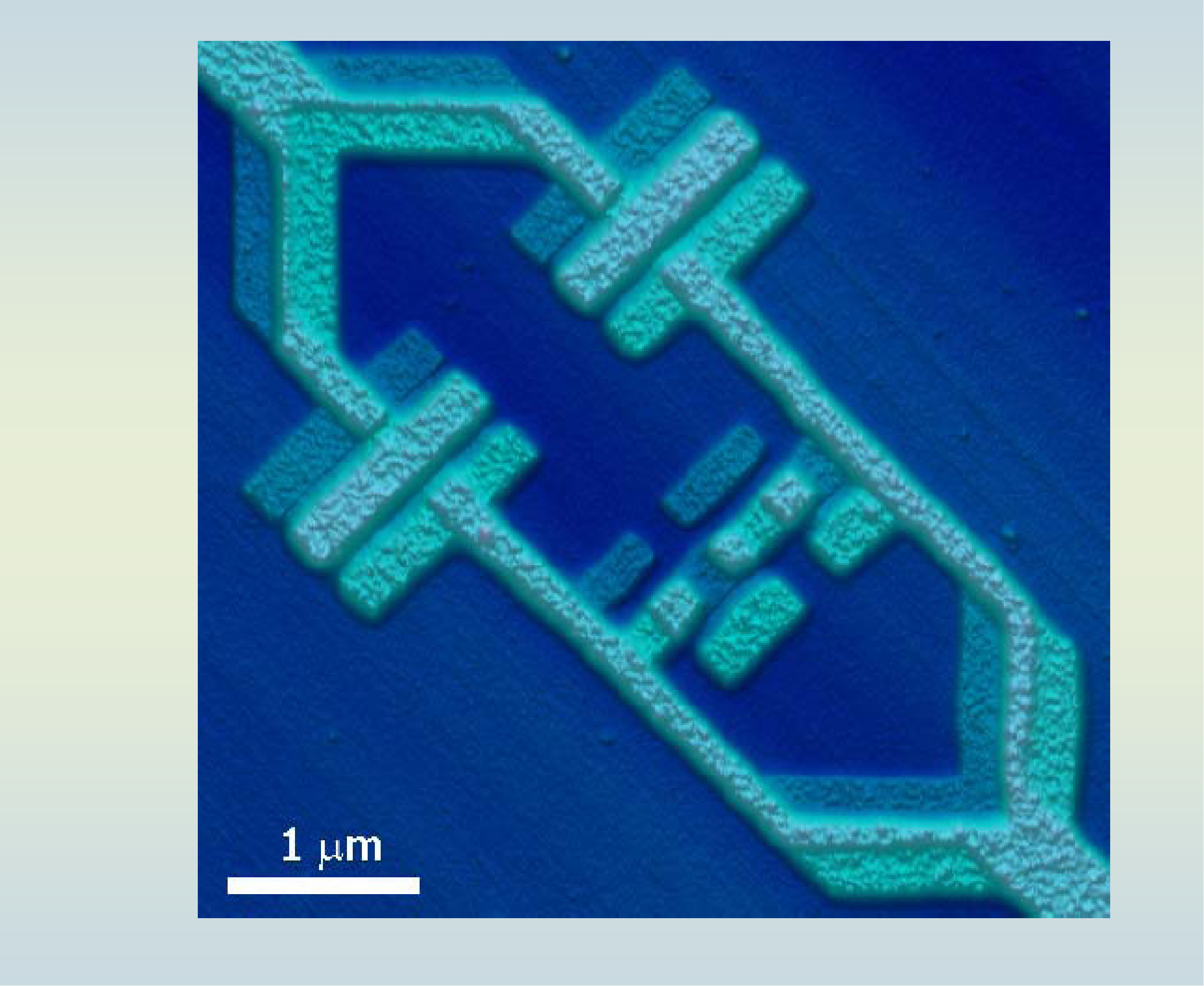




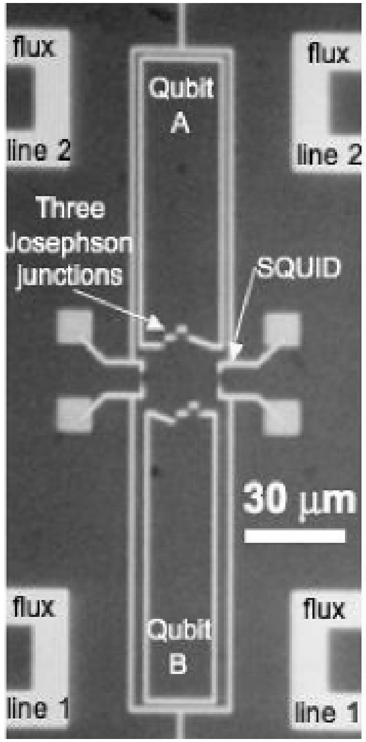


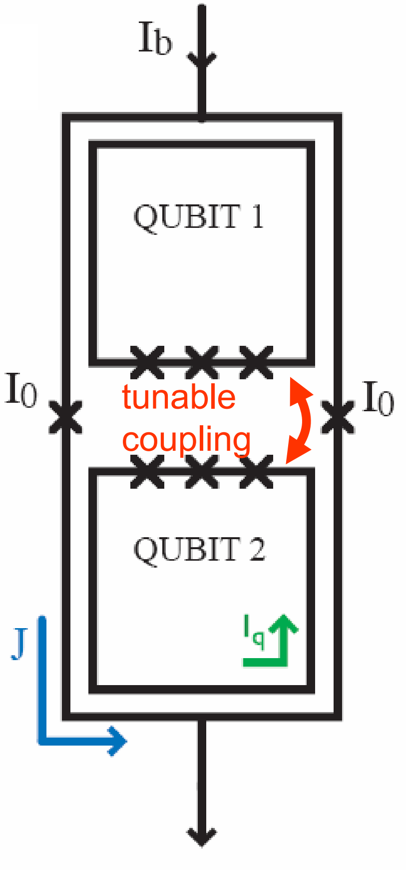
$$\nu = \sqrt{\Delta^2 + \varepsilon^2} = 2I_q(\Phi_q - \Phi_0/2)$$

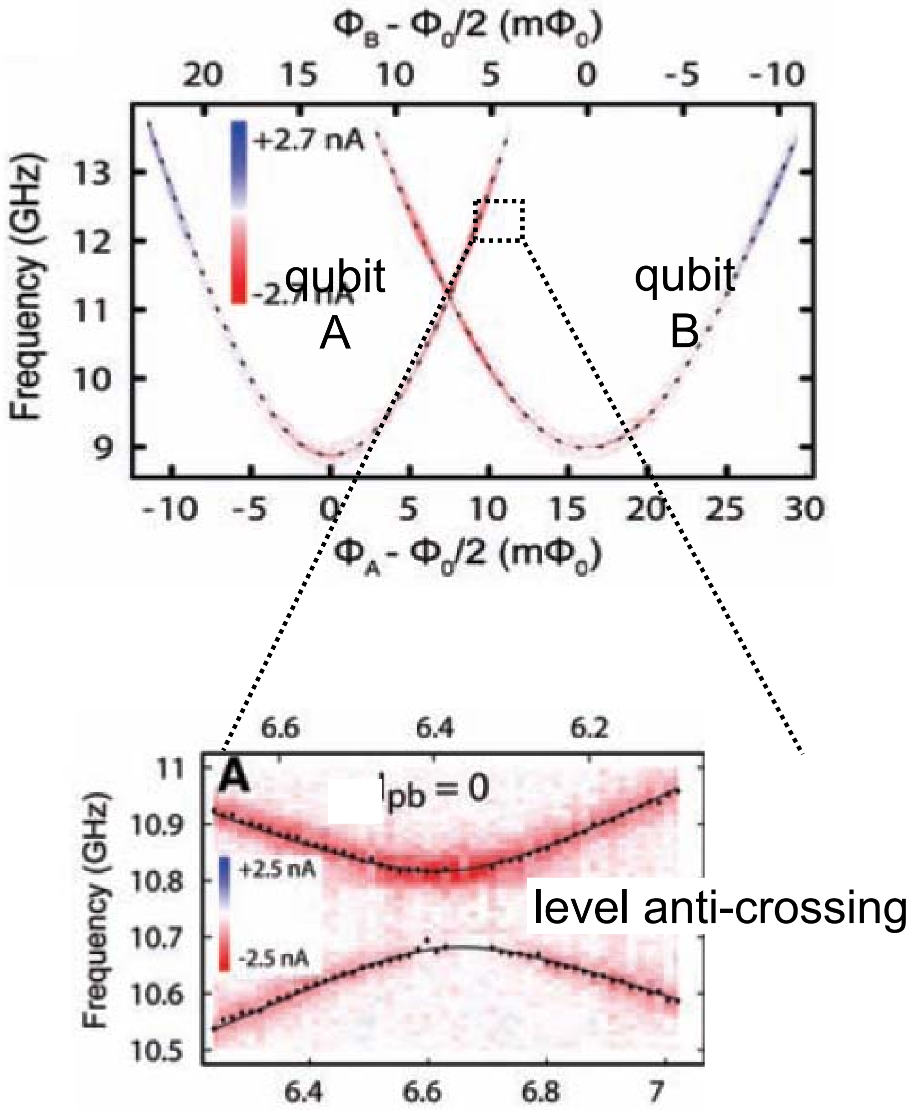
Nakamura design



Flux qubits with current-controlled coupling

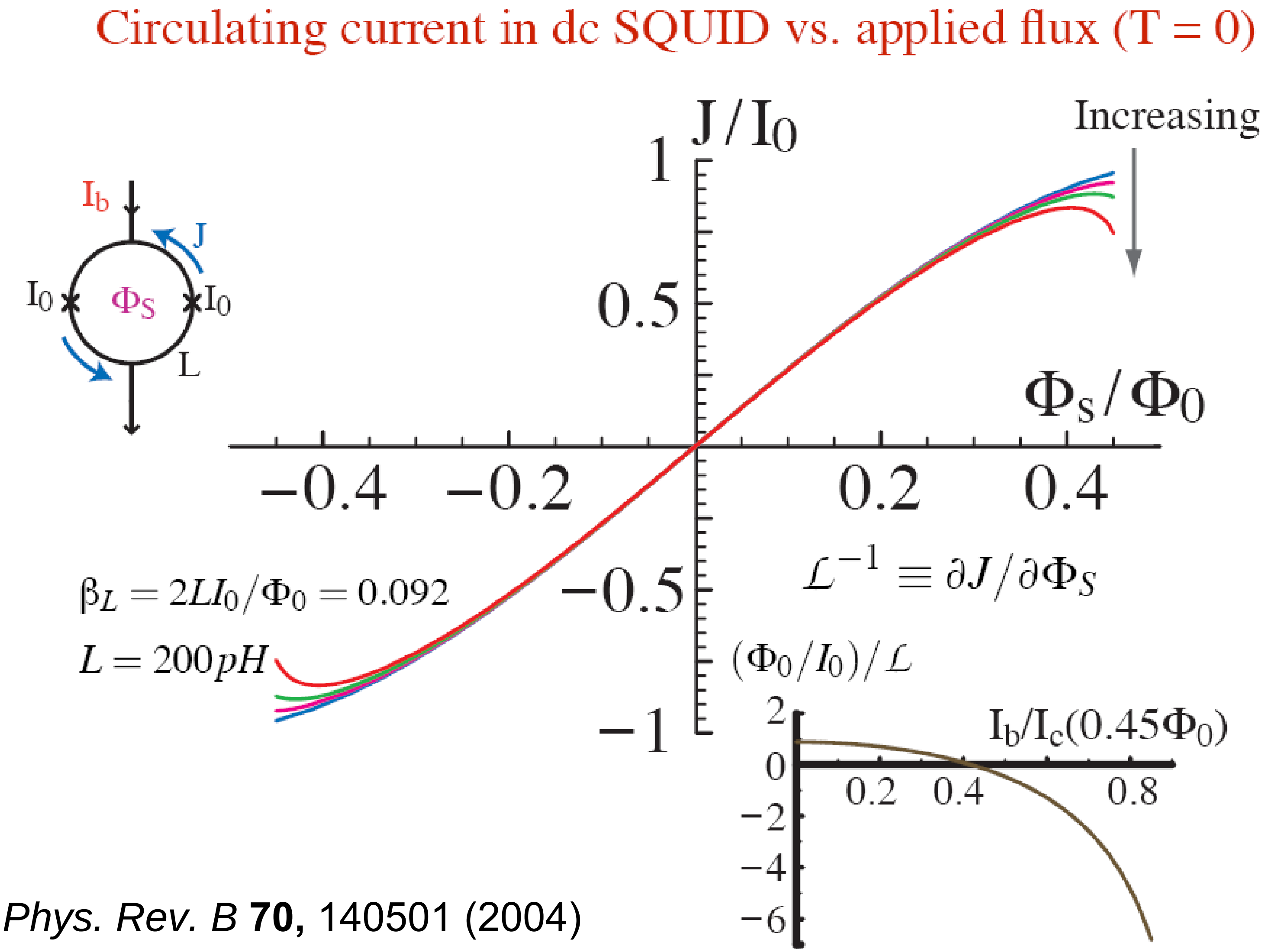






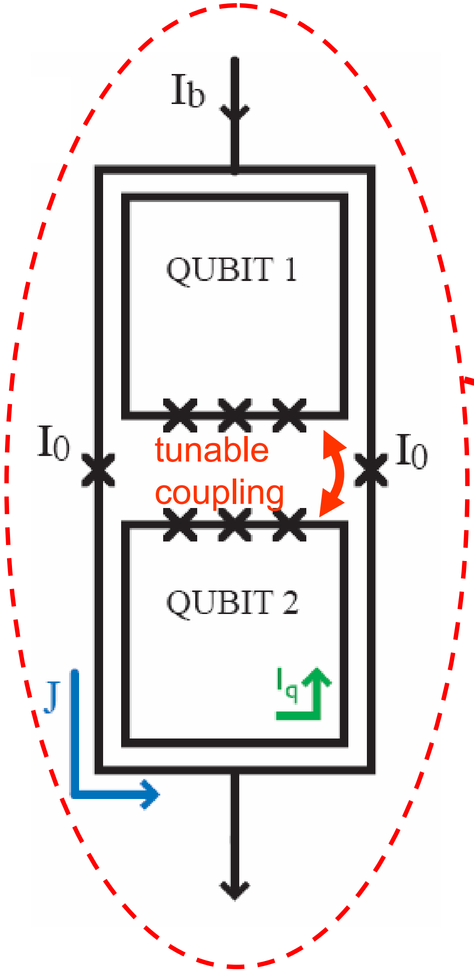
T. Hime, P.A. Reichardt, B.L.T. Plourde, T.L. Robertson, C.-E. Wu, A.V. Ustinov, and J. Clarke, *Science* **314**, 1427 (2006).

Circulating current in dc SQUID vs. applied flux

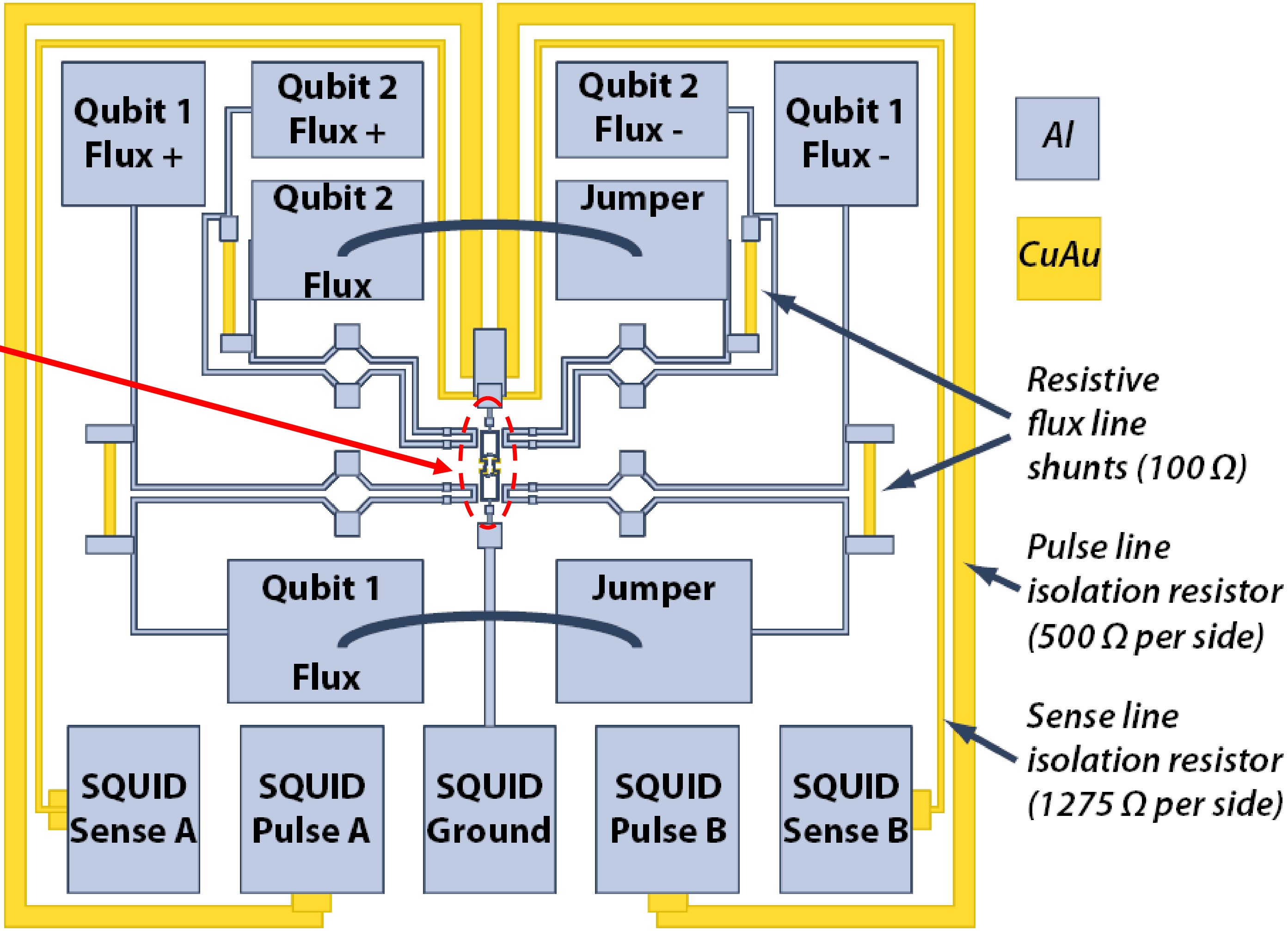


Plourde *et al*. *Phys. Rev. B* **70,** 140501 (2004)

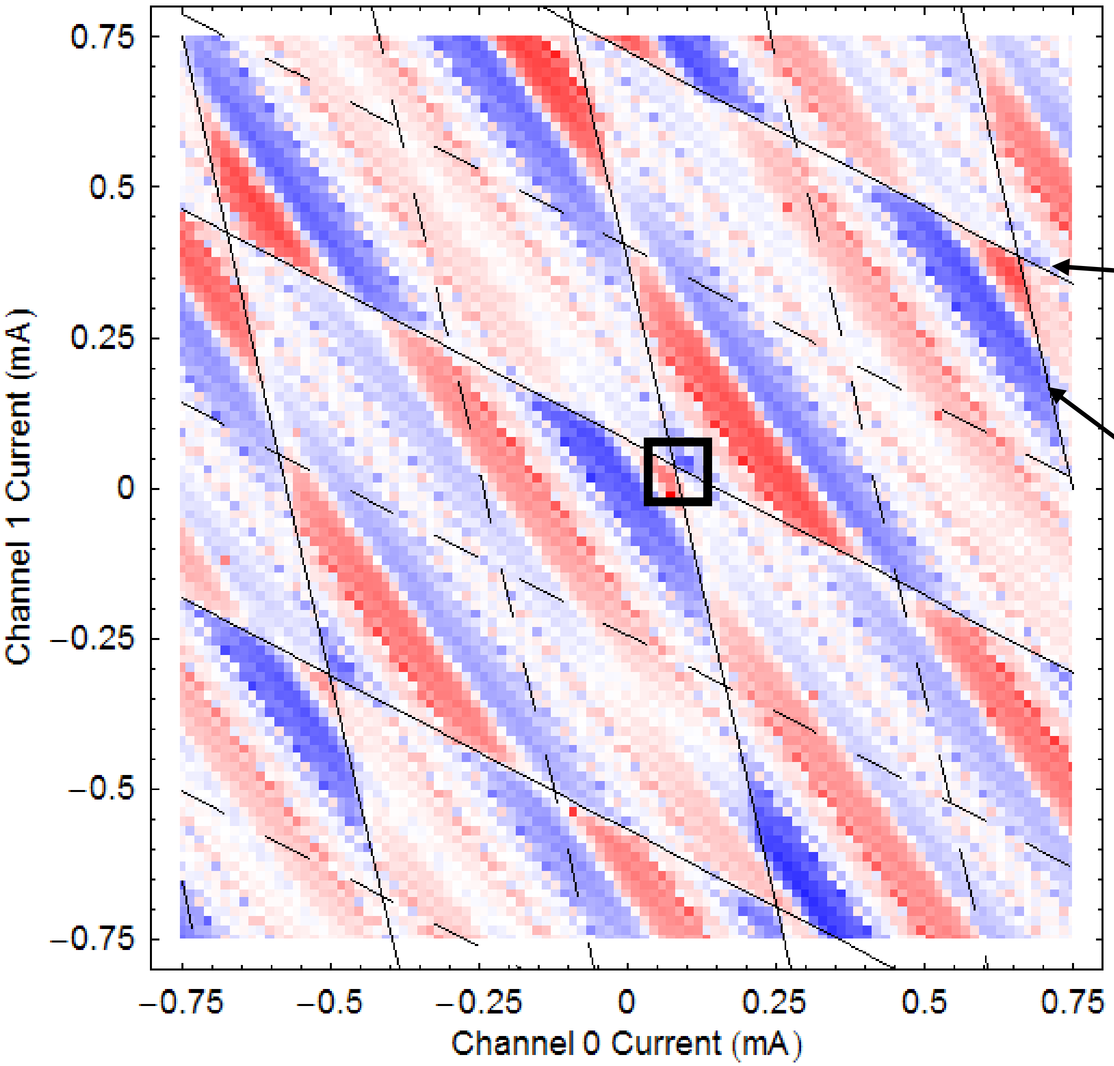
Chip layout



Layout with on-chip flux bias lines



Two-Qubit Flux Map



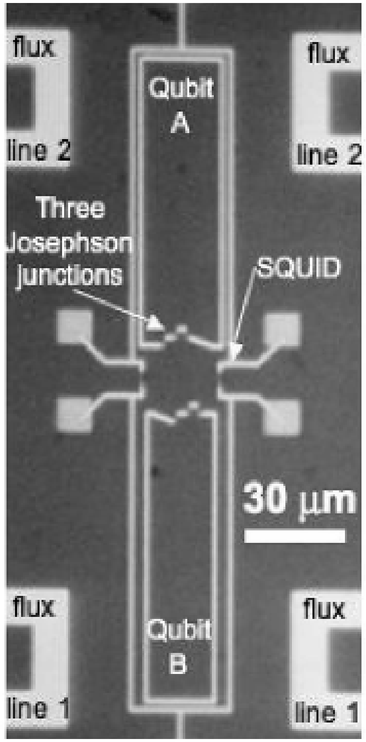
lines of constant flux in qubit A

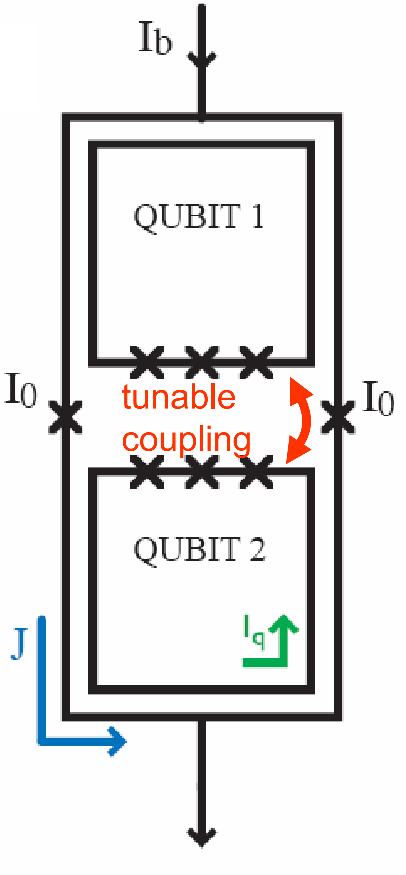
lines of constant flux in qubit B

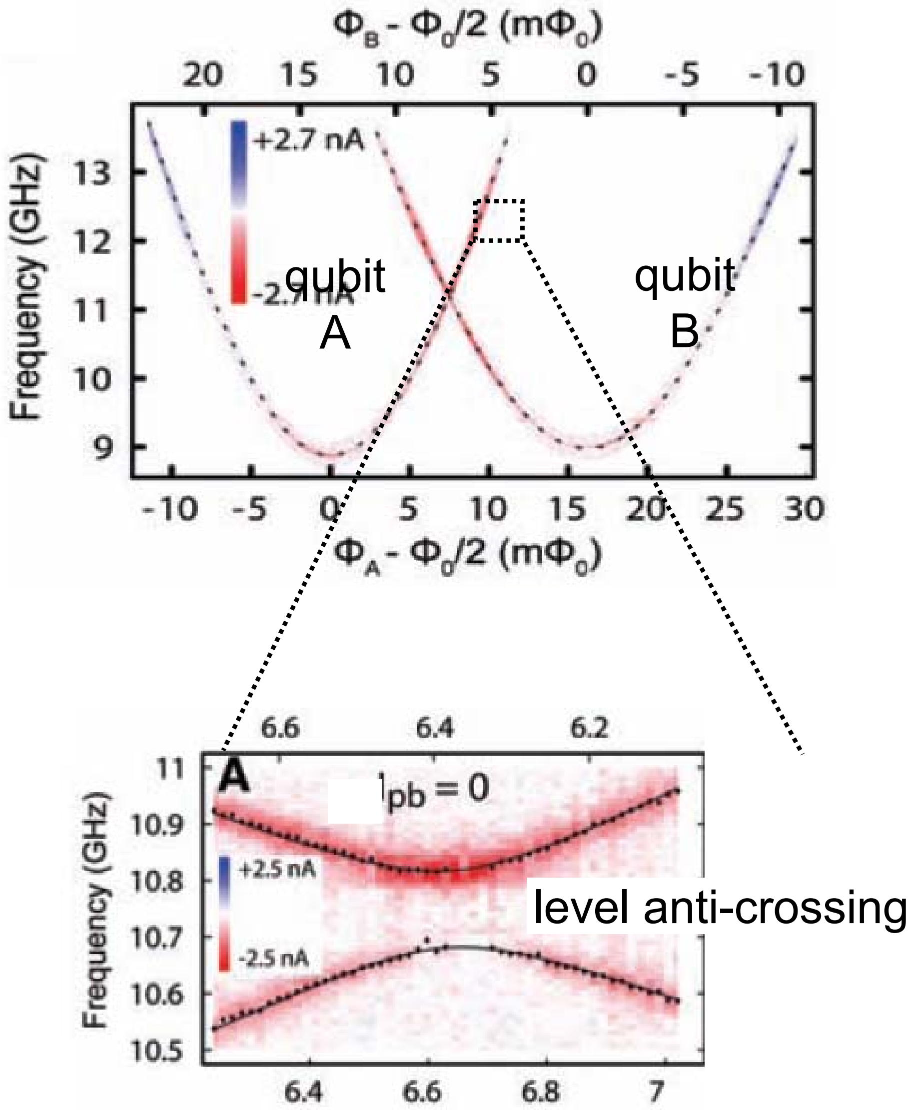
□ typical double degeneracy point

Solid-State Qubits with Current-Controlled Coupling

(in collaboration with UC Berkeley)







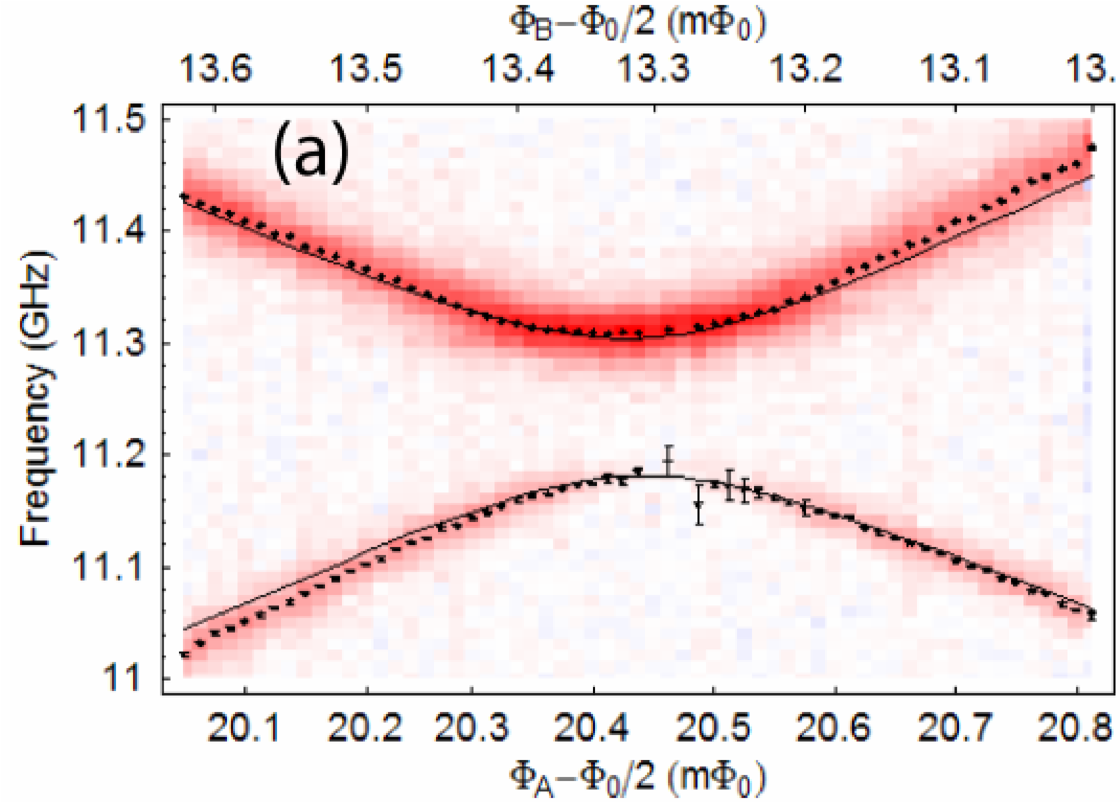
qubit A

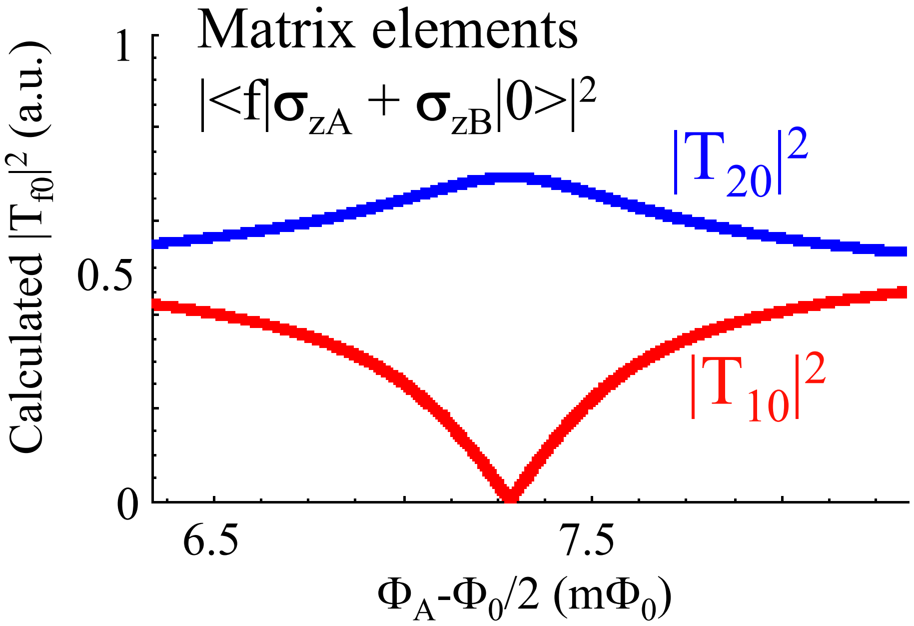
qubit B

level anti-crossing

T. Hime, P.A. Reichardt, B.L.T. Plourde, T.L. Robertson, C.-E. Wu, A.V. Ustinov, and J. Clarke, *Science* **314**, 1427 (2006).

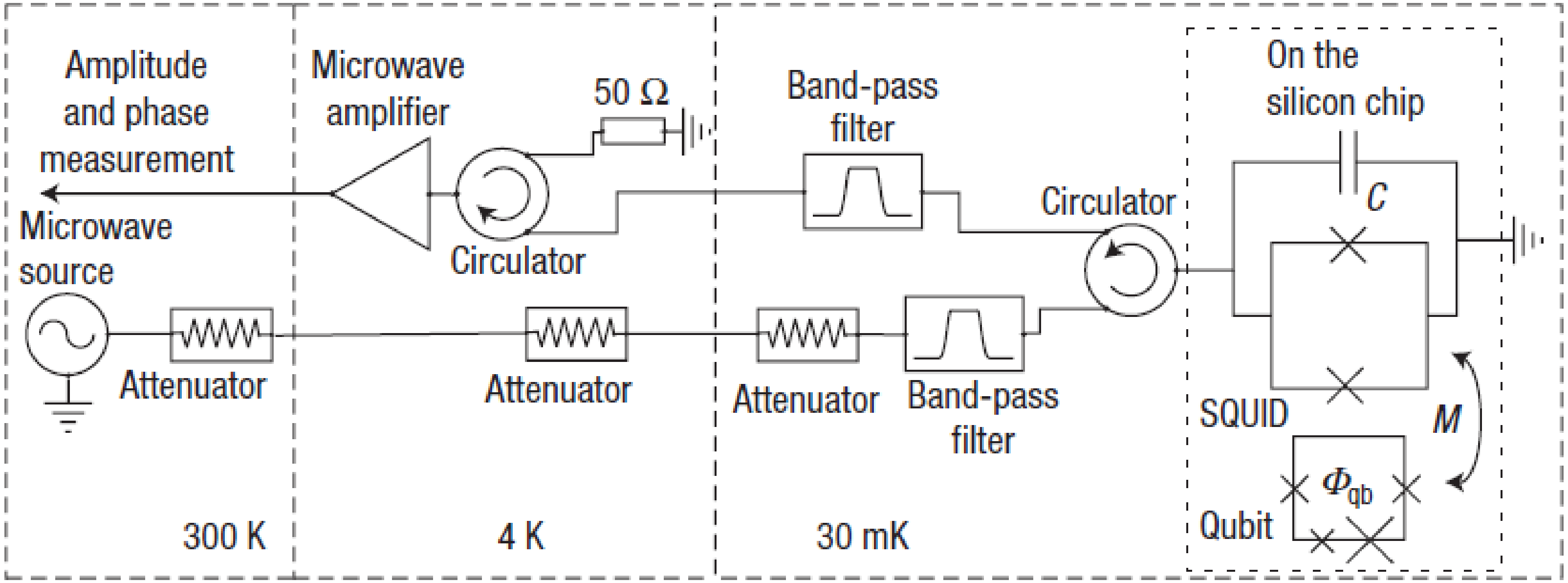
Two coupled flux qubits

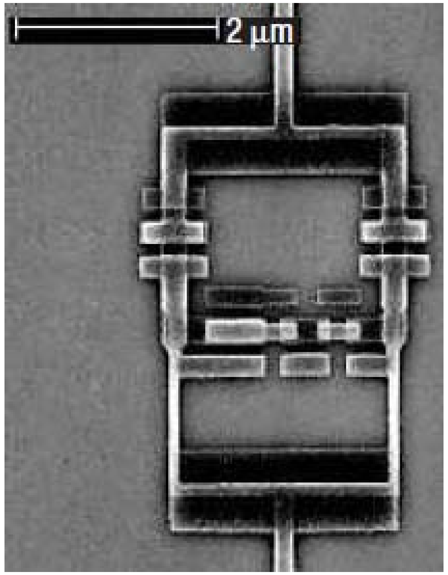




Quantum non-demolition measurement of a flux qubit

A quantum non-demolition (QND) measurement minimizes the disturbance by interaction with a detector that preserves the eigenstates of the quantum system.

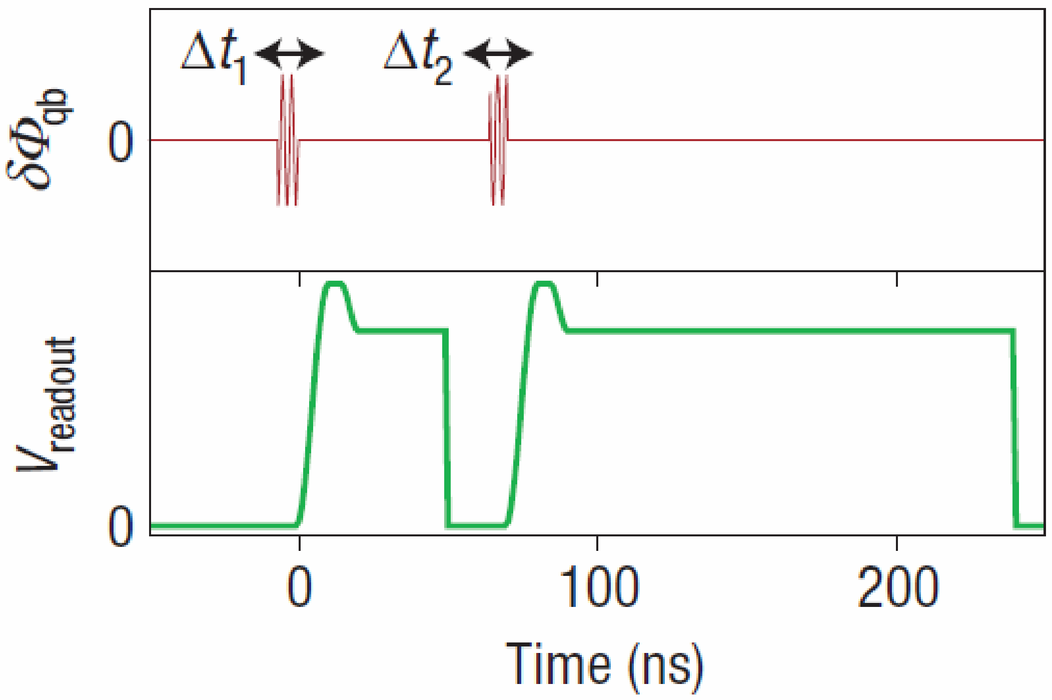


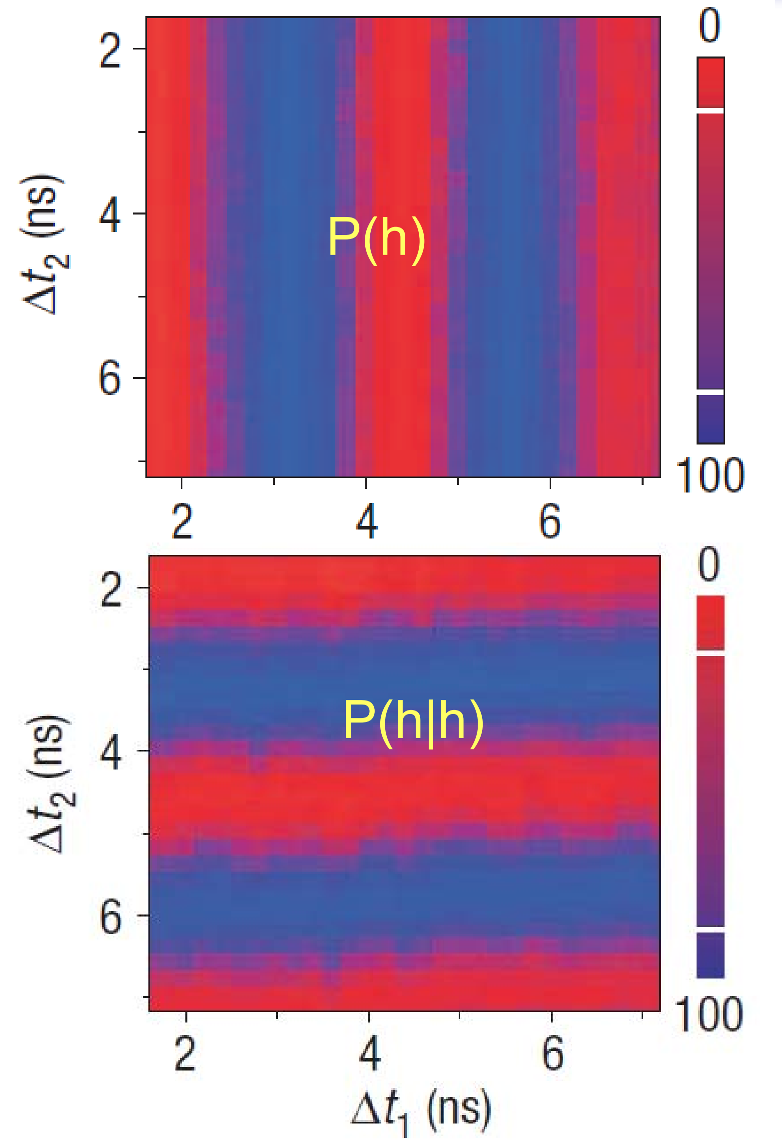


The mutual inductance M=14 pH represents the sum of a geometric inductance and of the kinetic inductance of the narrow lines shared by the qubit and SQUID loops.

A. Lupascu et al. , Nature Physics **3**, 119 (2007)

QND measurement of a flux qubit

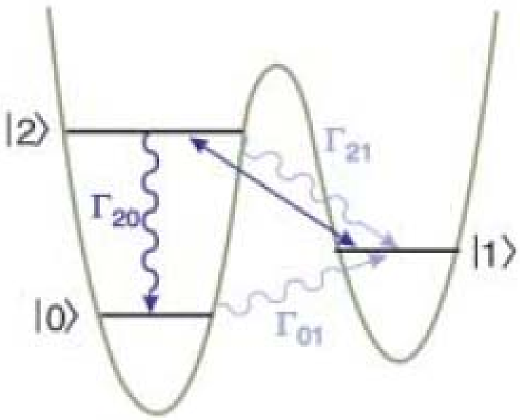


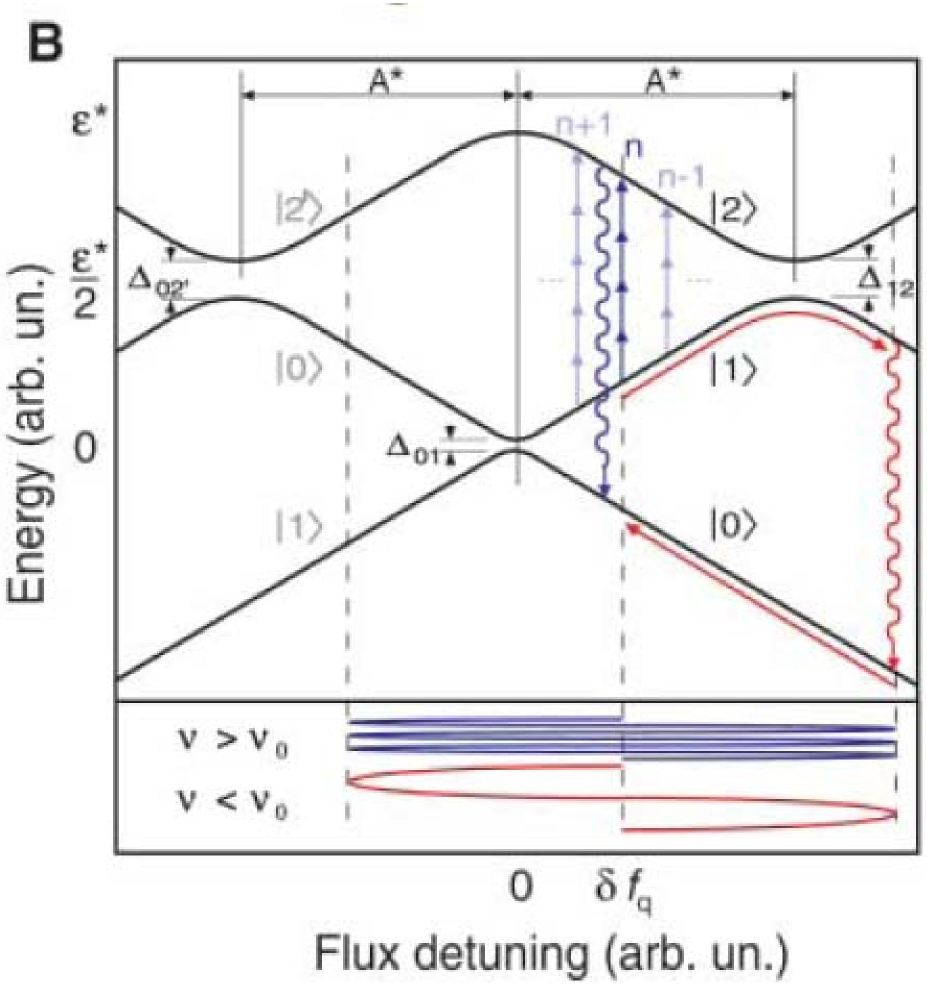


conditional measurement

A. Lupascu et al. , Nature Physics **3**, 119 (2007)

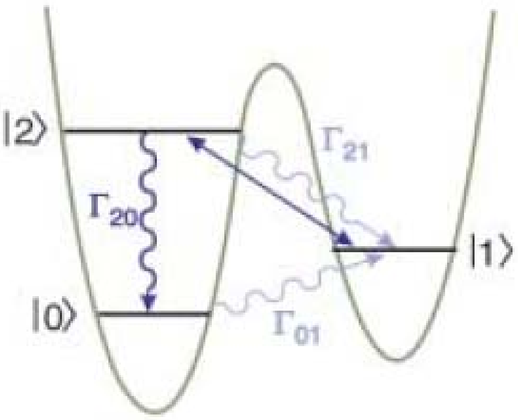
Microwave-induced cooling of a flux qubit

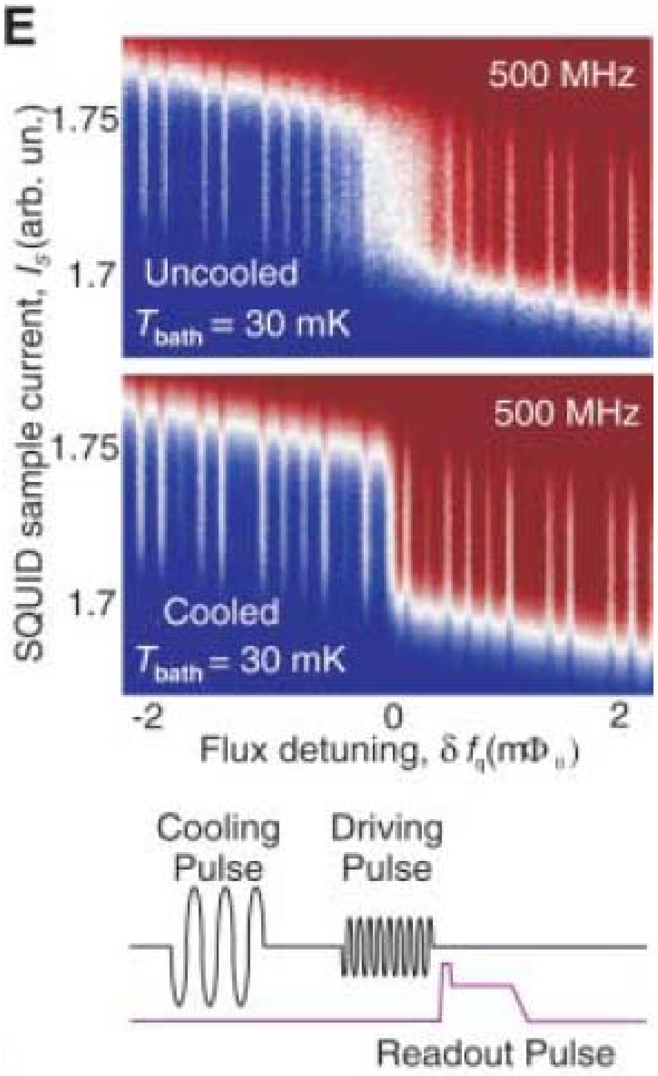




S.O. Valenzuela, *et al. Science* **314**, 1589 (2006)

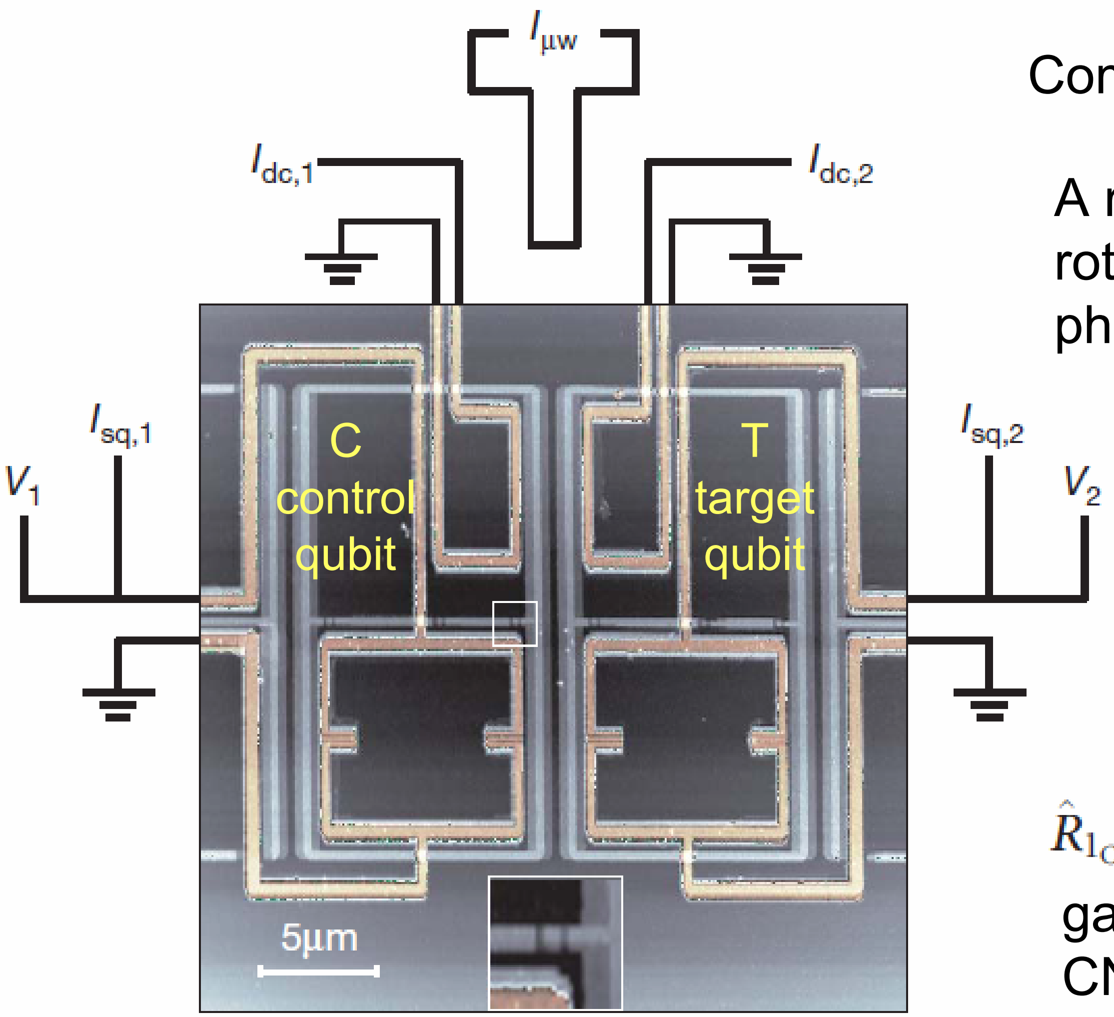
Microwave-induced cooling of a flux qubit





S.O. Valenzuela, *et al. Science* **314**, 1589 (2006)

Demonstration of controlled-NOT quantum gates on a pair of flux qubits



Computational basis: $0_C 0_T,\ 0_C 1_T,\ 1_C 0_T,\ 1_C 1_T$

A resonant microwave pulse induces rotations in this basis, and its microwave phase determines the rotation axis.

A microwave pulse inducing a rotation around the x axis of the $1_C 0_T – 1_C 1_T$ transition:

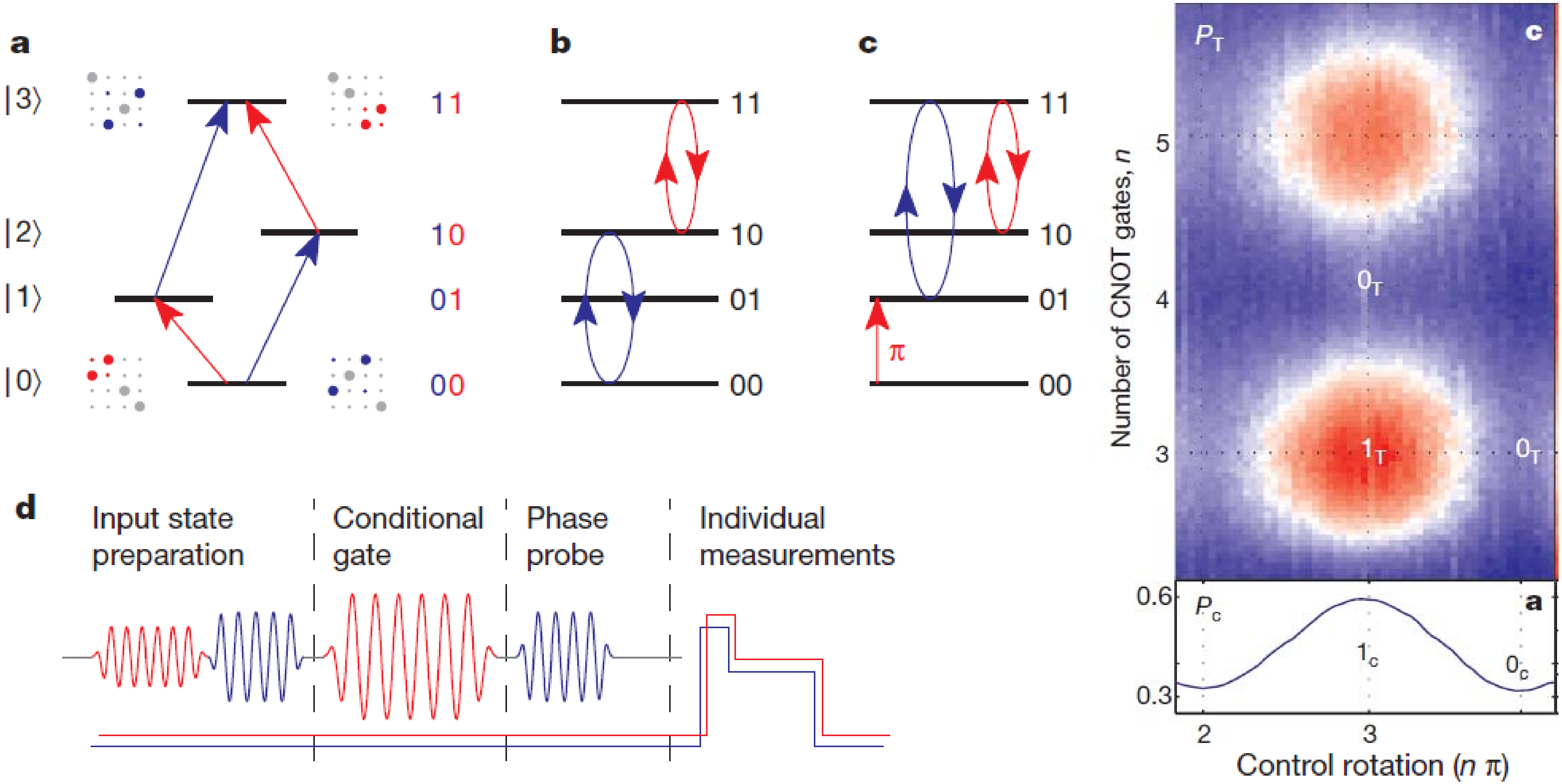
$$\hat{R}_{1_C 0_T - 1_C 1_T}(\omega,\tau) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\frac{\omega\tau}{2} & i\sin\frac{\omega\tau}{2} \\ 0 & 0 & i\sin\frac{\omega\tau}{2} & \cos\frac{\omega\tau}{2} \end{pmatrix}$$

gate matrix

CNOT $\omega\tau = \pi$

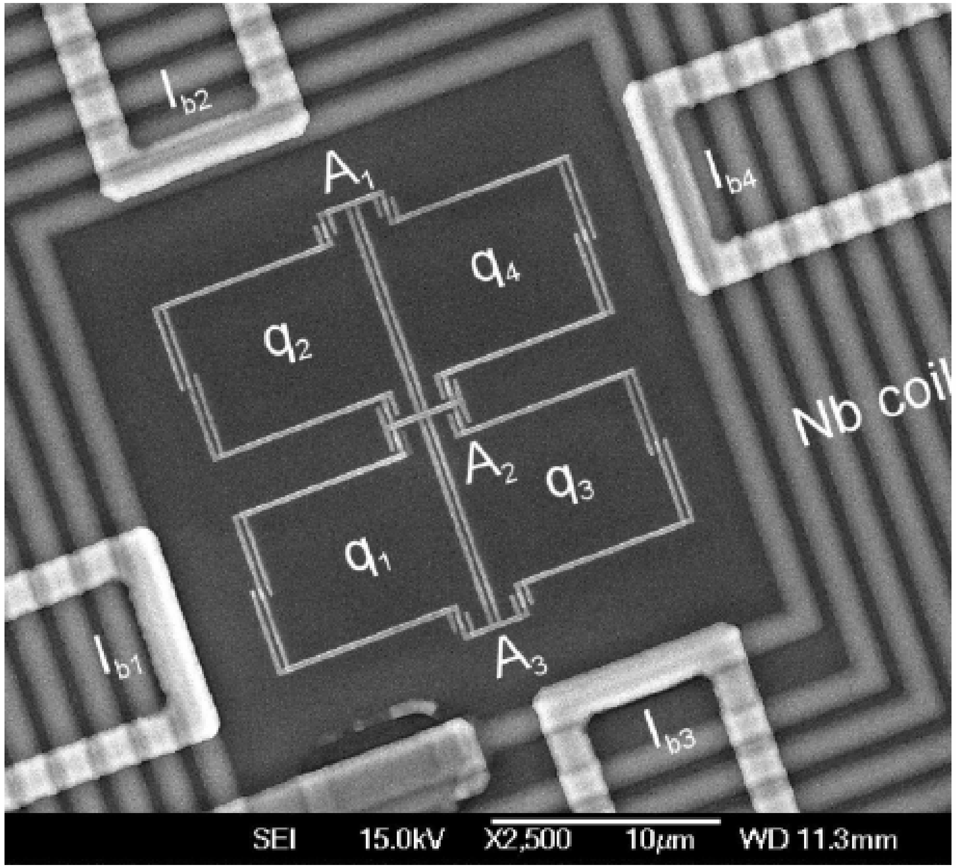
J.H. Plantenberg, P.C. de Groot, C.J.P.M. Harmans and J.E. Mooij, *Nature* **447**, 836 (2007)

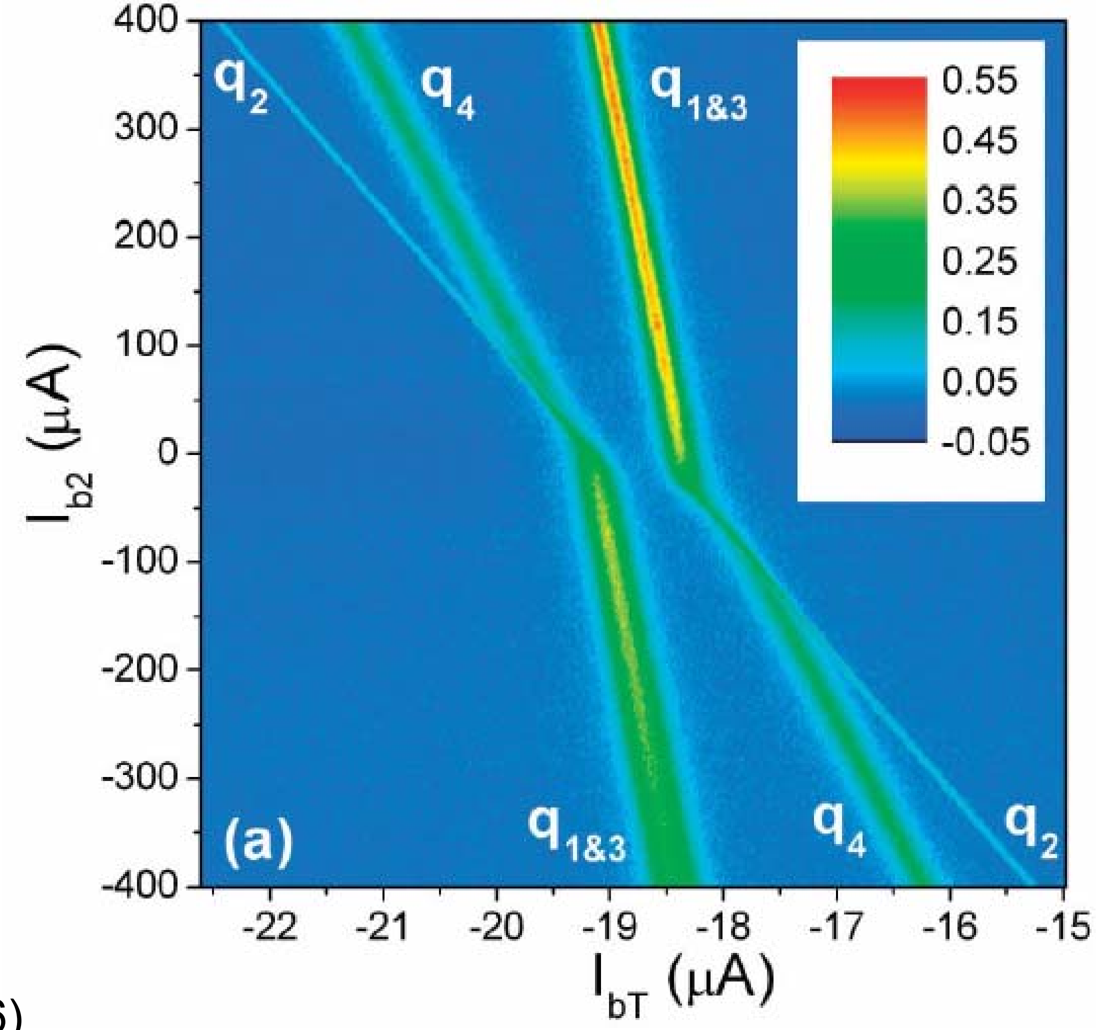
Operation of the coupled-qubits device



J.H. Plantenberg, P.C. de Groot, C.J.P.M. Harmans and J.E. Mooij, *Nature* **447**, 836 (2007)

First 4-qubit experiment: IPHT Jena





M. Grajcar et al, PRL **96,** 047006 (2006)

Forthcoming experiments with superconducting qubits

- Josephson `artificial atoms´ are becoming scalable and reliable qubits
- CNOT-type gates have been reported for charge, flux and phase qubits
- More coupled qubits will be coming soon
- Dispersive QND readout is on the way
- Pactical yield: Cooling by using coherent qubit states
- Challenge for the future:Entangling Josephson qubits with other types of qubits (photons, atoms, spins)