M. G. Castellano, MQC collaboration

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SQUIDs for macroscopic quantum coherence experiments

MQC: testing the superposition principle for macroscopically distinct states "Schroedinger's cat with SQUIDs"

This work presents the results obtained in the MQC project, supported in Italy by INFN. The project is being performed by two groups, in Rome and Naples.

Rome: Universita' La Sapienza, and CNR-IESS (Istituto di Elettronica dello Stato Solido)

Naples: CNR-IC (Istituto di Cibernetica)

Outline

quantum behavior of a two-level systems

MQC: Macroscopic Quantum Coherence the INFN experiment (Rome, Naples)

Josephson systems as macroscopic quantum states

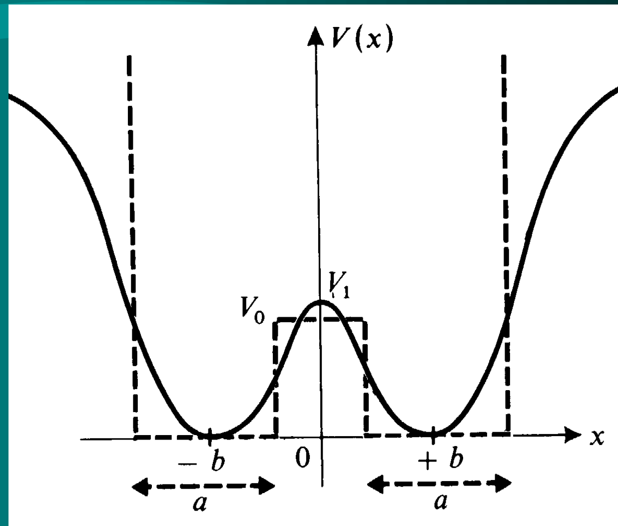
recent experiments on MQC

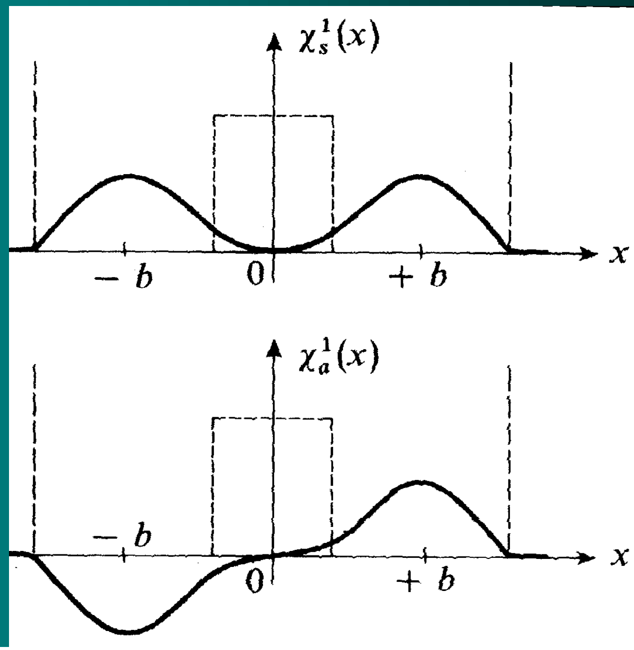
Quantum behavior of a two-level system (the ammonia molecule)

- double well potential with finite barrier

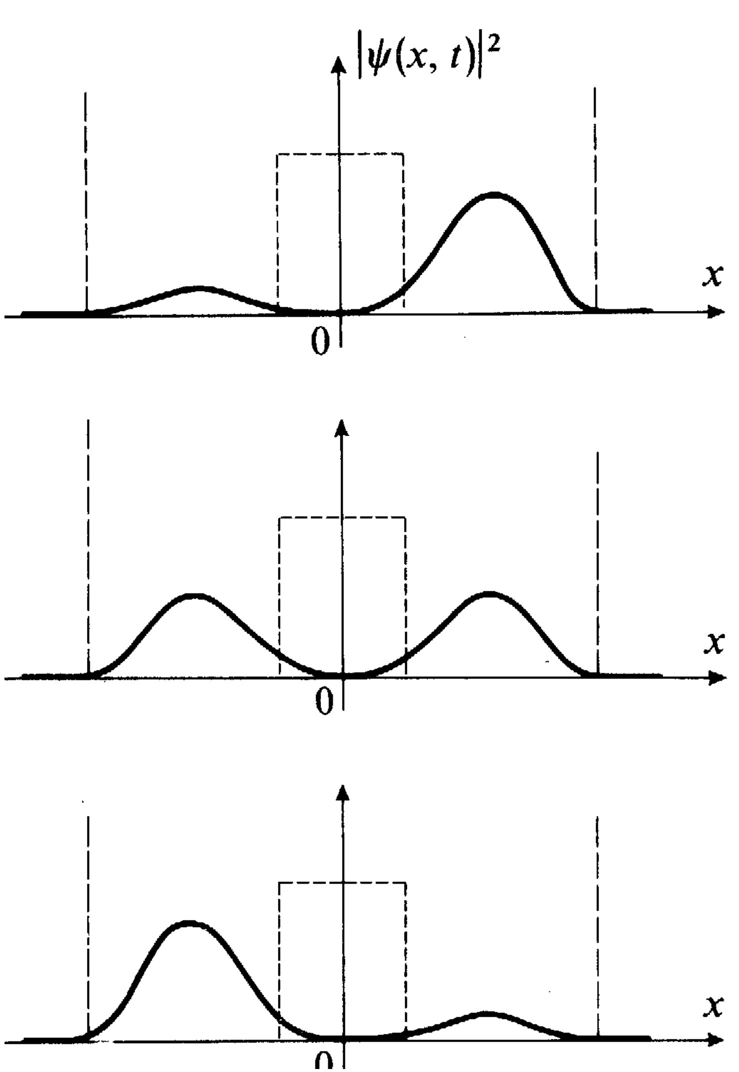
- classically: equilibrium states are localized in the bottom of the two wells (left or right) with energies E_L and E_R

- eigenfunctions: symmetric and antisymmetric functions of the coordinate x

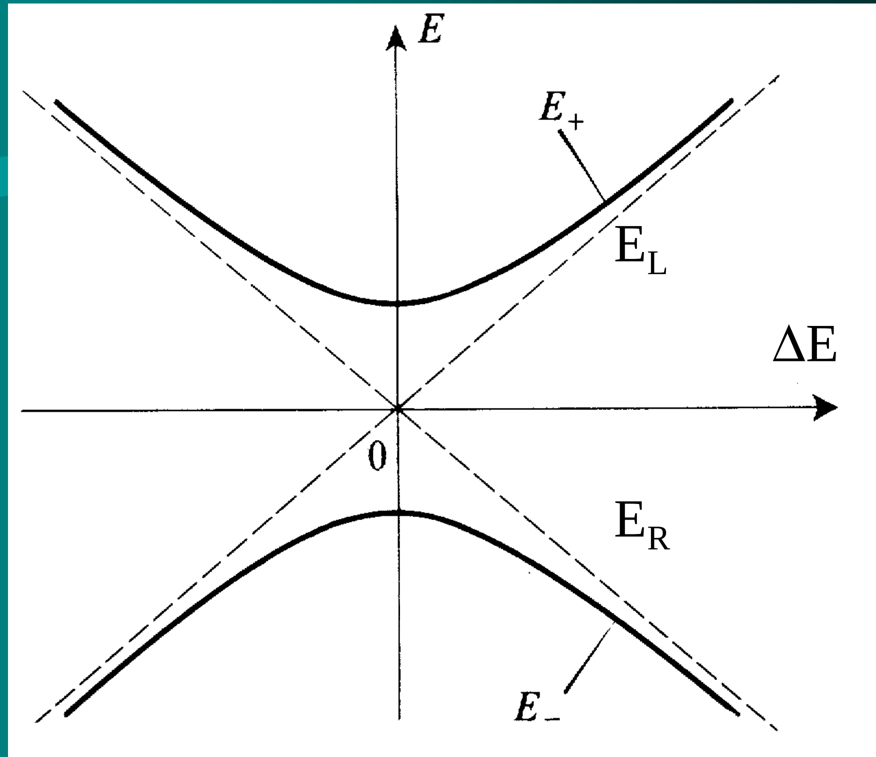




- a wavepacket prepared in either well does tunnel from one well to the other coherently



- energy eigenvalues:



- uncoupled values: E_L, E_R
- the transparency of the potential barrier removes the energy level degeneracy
- repulsion of energy levels (anticrossing)

Josephson systems as sources of Macroscopic Quantum States

A suitable system must satisfy two conditions:

1) systems described by a macroscopic degree of freedom

- Josephson junction $\Rightarrow$ superconducting phase across the junction
- SQUIDs (superconducting ring with one or more Josephson junctions) $\Rightarrow$ magnetic flux through the ring

2) energy scale on a microscopic order of magnitude

- $E \sim I_0 \Phi_0$, contains Planck's constant

Dissipation in MQC

- we want to observe oscillations back and forth from one well to the other with tunneling freq. ϖ
- tunneling probability is exponentially depressed by dissipation (Caldeira, Leggett, *Phys. Rev. Lett.* **46**, 211 -1981; Garg, *Phys. Rev. Lett.* **32**, 4746 -1985)
- $P(t) = 1/2[1+\cos(\varpi t)\exp(-\gamma t)]$

$$\gamma = \varpi \frac{T}{T^*}$$

$$T^* \cong \frac{\hbar\varpi}{\pi k \alpha} \qquad \alpha = \frac{\delta\phi^2}{2\pi\hbar R}$$

→

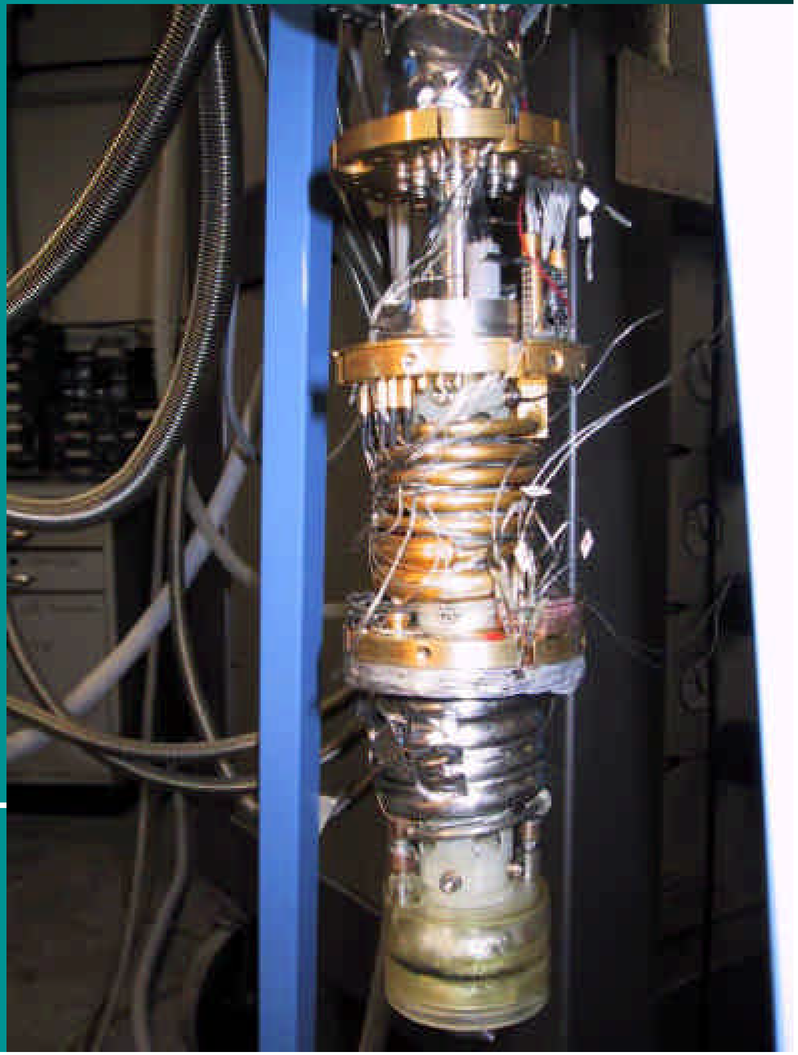
low temperature

low dissipation

low temperature: ^{3}He-^{4}He dilution refrigerator

Rome group
Leiden cryogenics

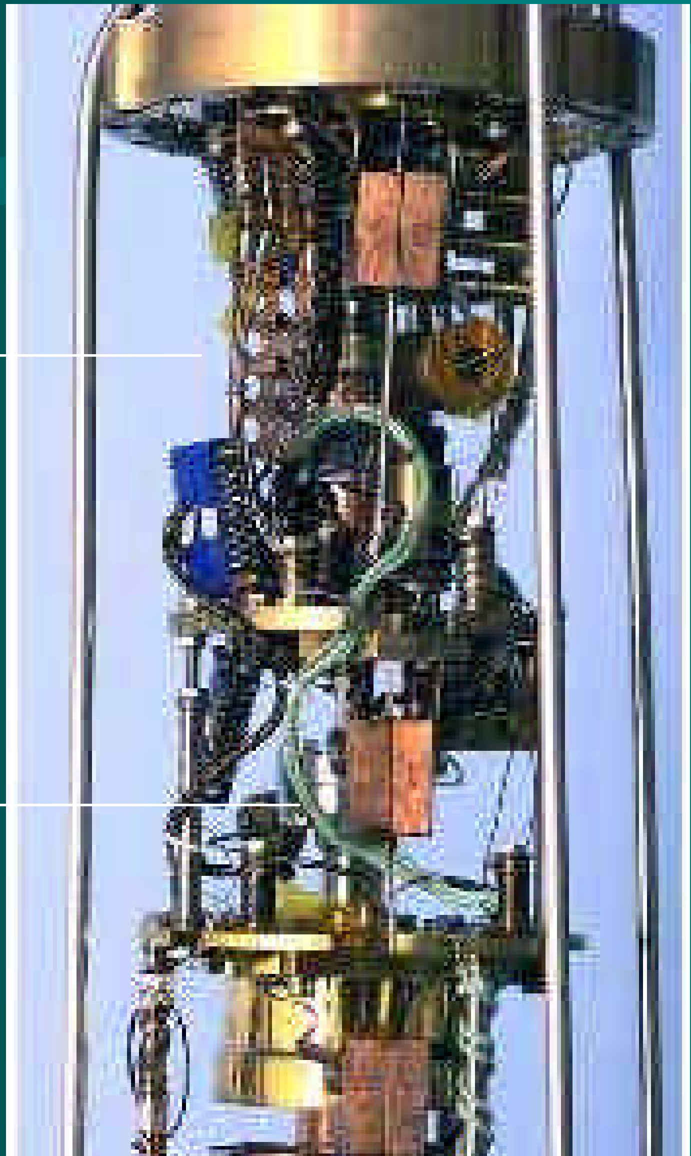
- T=9 mK, power= 200 μW at 120 mK
- 3 μ-metal shields (> 40 dB between dc and 100 Hz)
- 2 Al shields (> 90 dB at 1 MHz)
- Set of Helmoltz coils 1.5x1.5x1.5 m^3 (34 dB attenuation of Earth magnetic field within 1 dm^3)
- Magnetically levitated turbo pump
- Vibration Isolation platform, frequency cut ~1 Hz.
- Sample immersed in the liquid ^{3}He-^{4}He mixture.



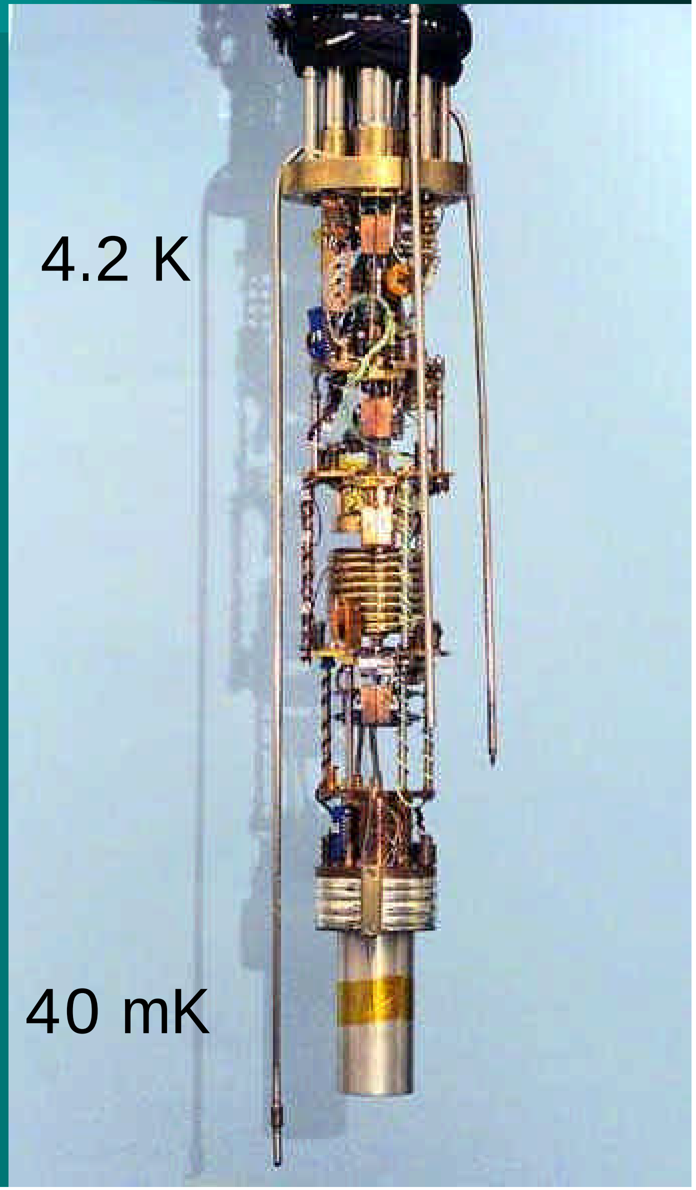
low temperature:
^3He-^4He dilution refrigerator

Naples, CNR-IC
Oxford Instruments

RF filtering stage (R-p)
4.2 K



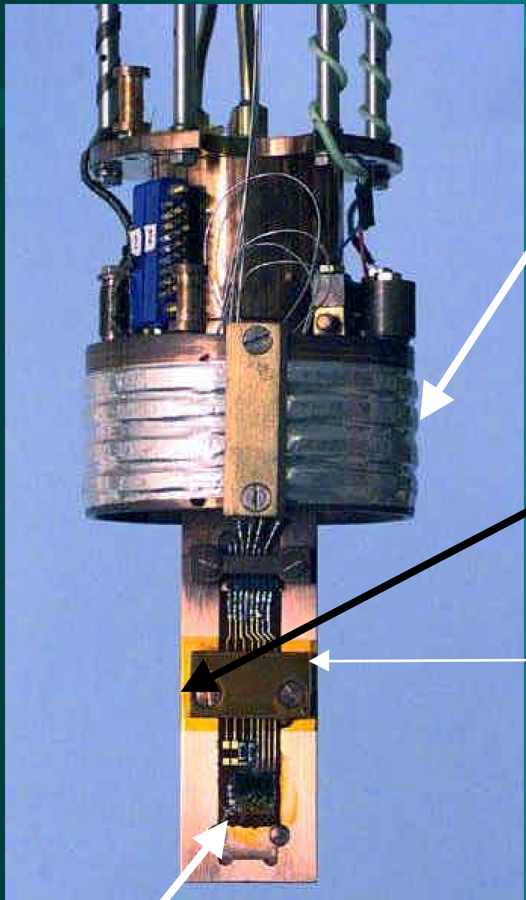
Thermocoax
(Zorin, Rev. Sci. Instr. 66, 4296-1995)
4.2 K-40 mK



filters and shielding

NAPLES, CNR-IC

ROME

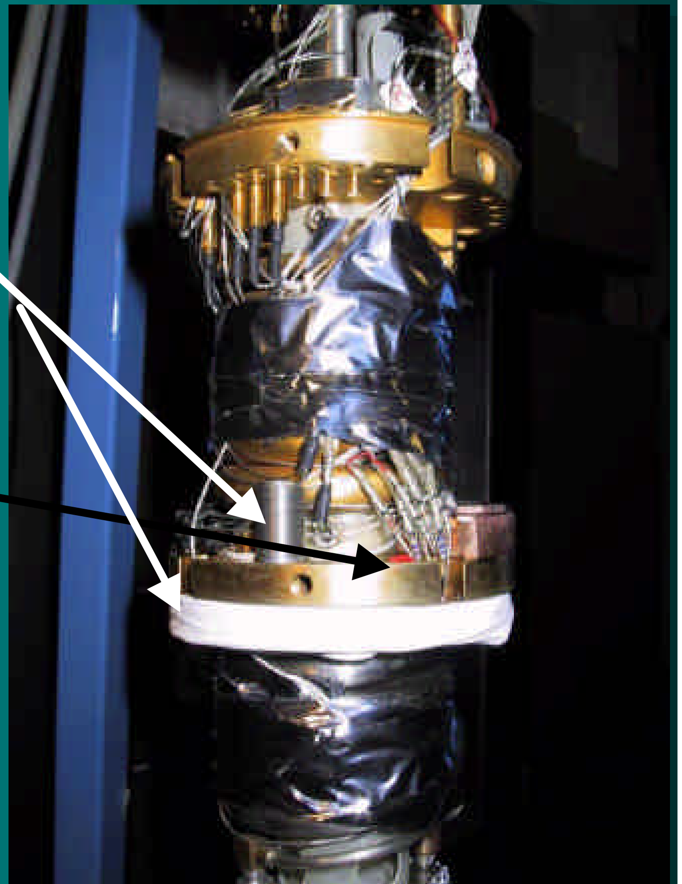


Thermocoaxes filtering stage (Zorin)

Filtering stage

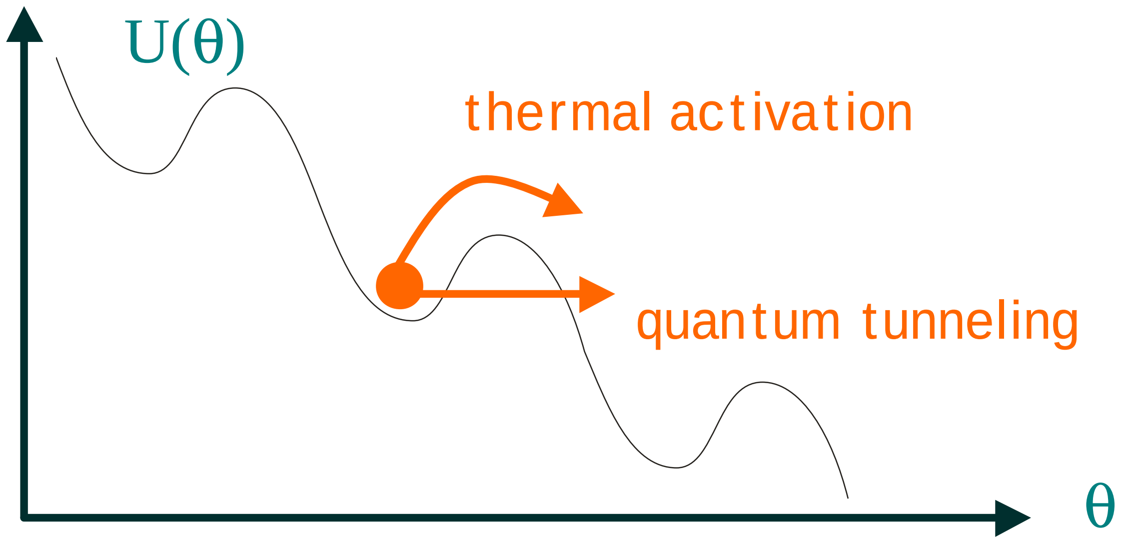
Chip carrier

Josephson sample



Josephson junctions

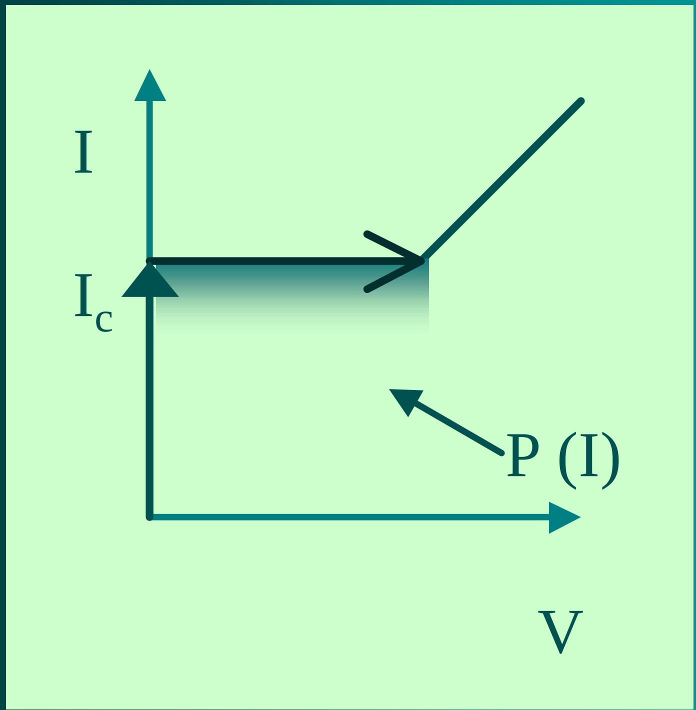
- Nb/AlOx/Nb trilayer
- parameters: I_c, R_N, C
- dissipation: subgap resistance
- equivalent to a fictitious particle moving in a tilted washboard potential
- coordinate: phase θ



use to test:

- experimental setup
- noise
- thermal escape from metastable well
- quantum tunneling
- dissipation

The escape from a metastable well: thermal and quantum regimes



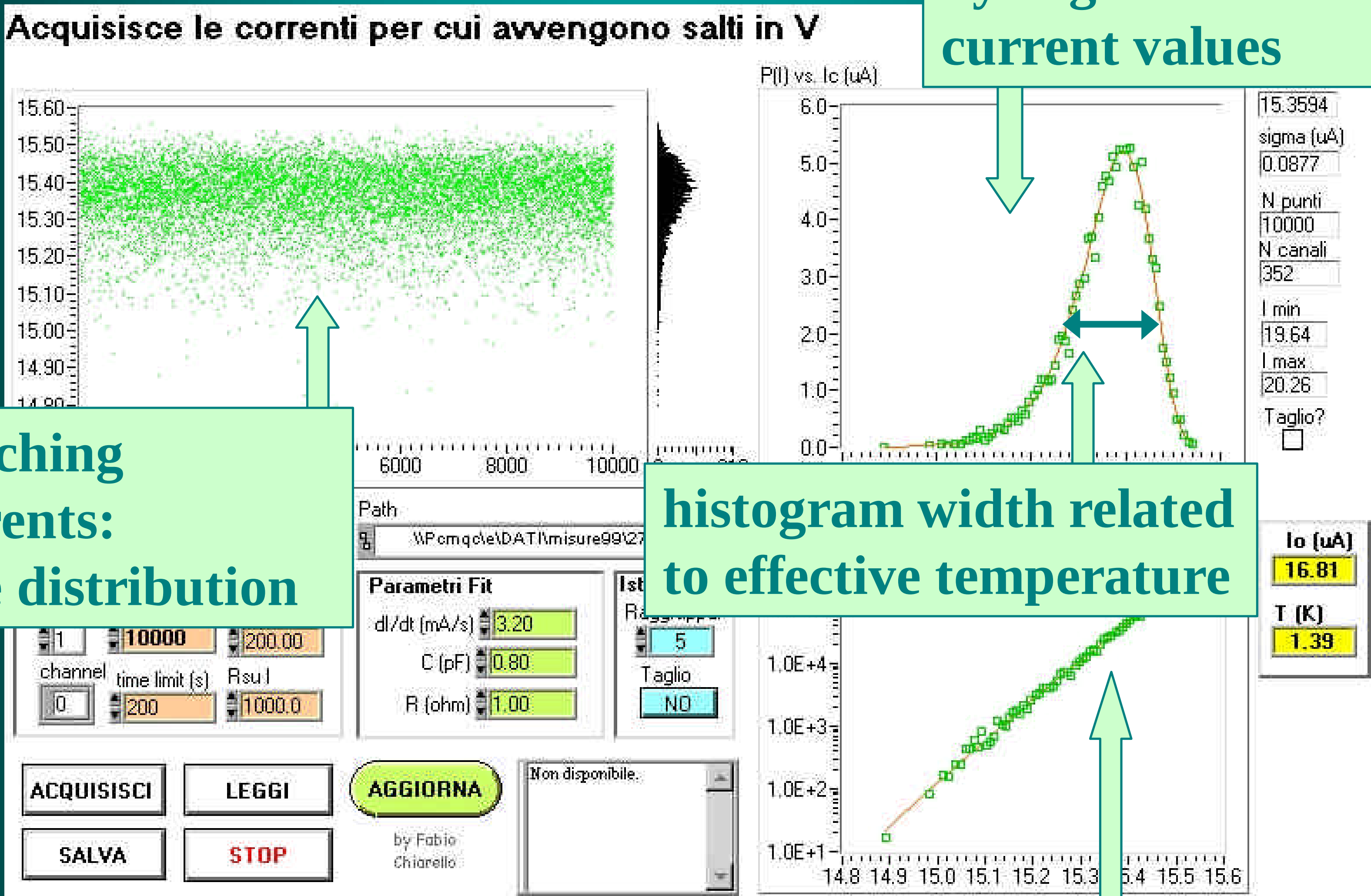
- increase the bias current: voltage goes from V=0 to V ≠0
- thermal fluctuations or quantum tunneling → stochastic process of activation
- distribution of current values

- for many cycles (10^4), collect the current values for switch and make a histogram

information on: noise, critical current value, dissipation

T.A. Fulton, L.N. Dunkleberger, *Phys. Rev.* **B 9**, 4760 (1974)

Analysis program (Rome)

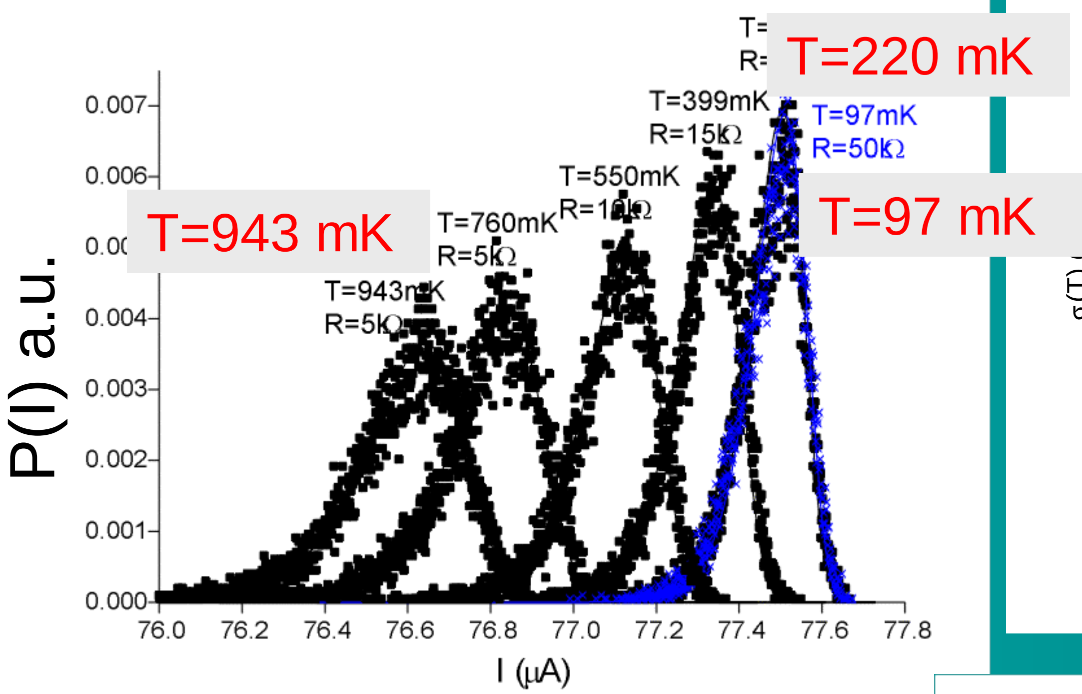


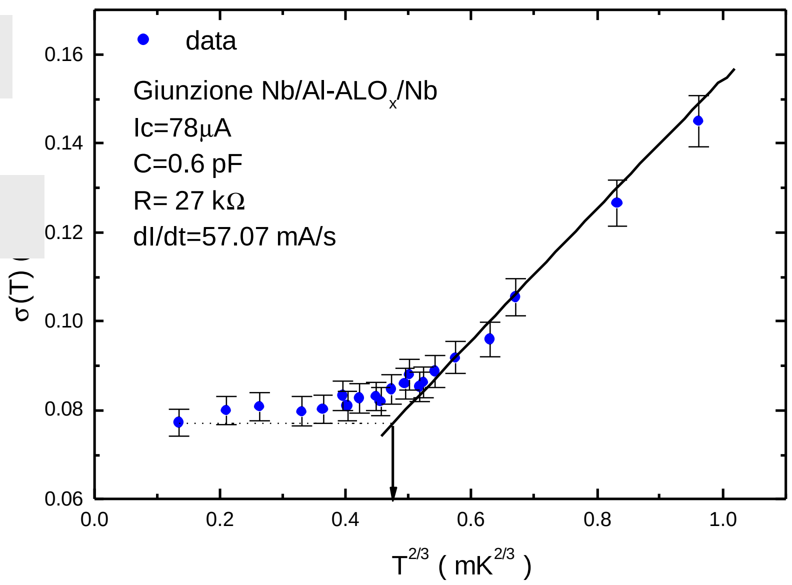
hystogram of the current values

switching currents: time distribution

histogram width related to effective temperature

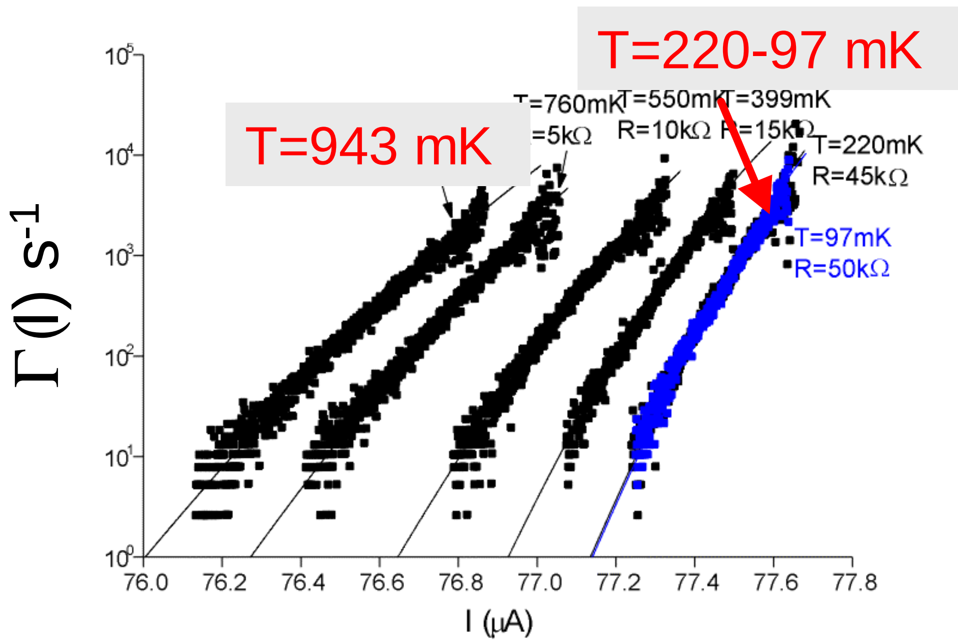
escape rate vs current



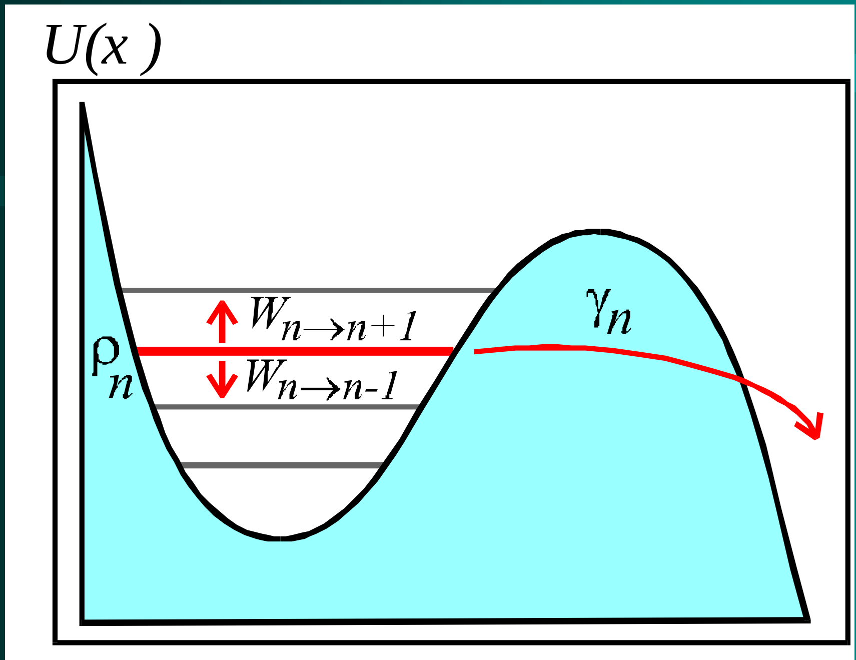


Data CNR-IC : MQT
1999/2000
V.Corato, D.Thesis
(Univ. Roma e CNR-IC)

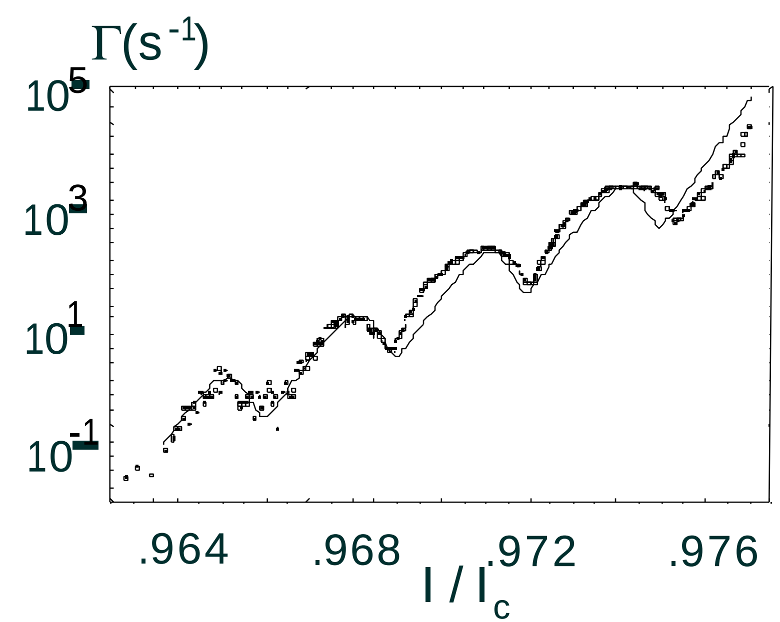
Macroscopic Quantum Tunneling



Energy level quantization at low temperature



- there are quantized levels in the metastable well
- the effect of single levels is seen as peaks in the escape rate



by fitting the escape rate curve, we can find the value of the effective resistance and therefore the related decoherence time

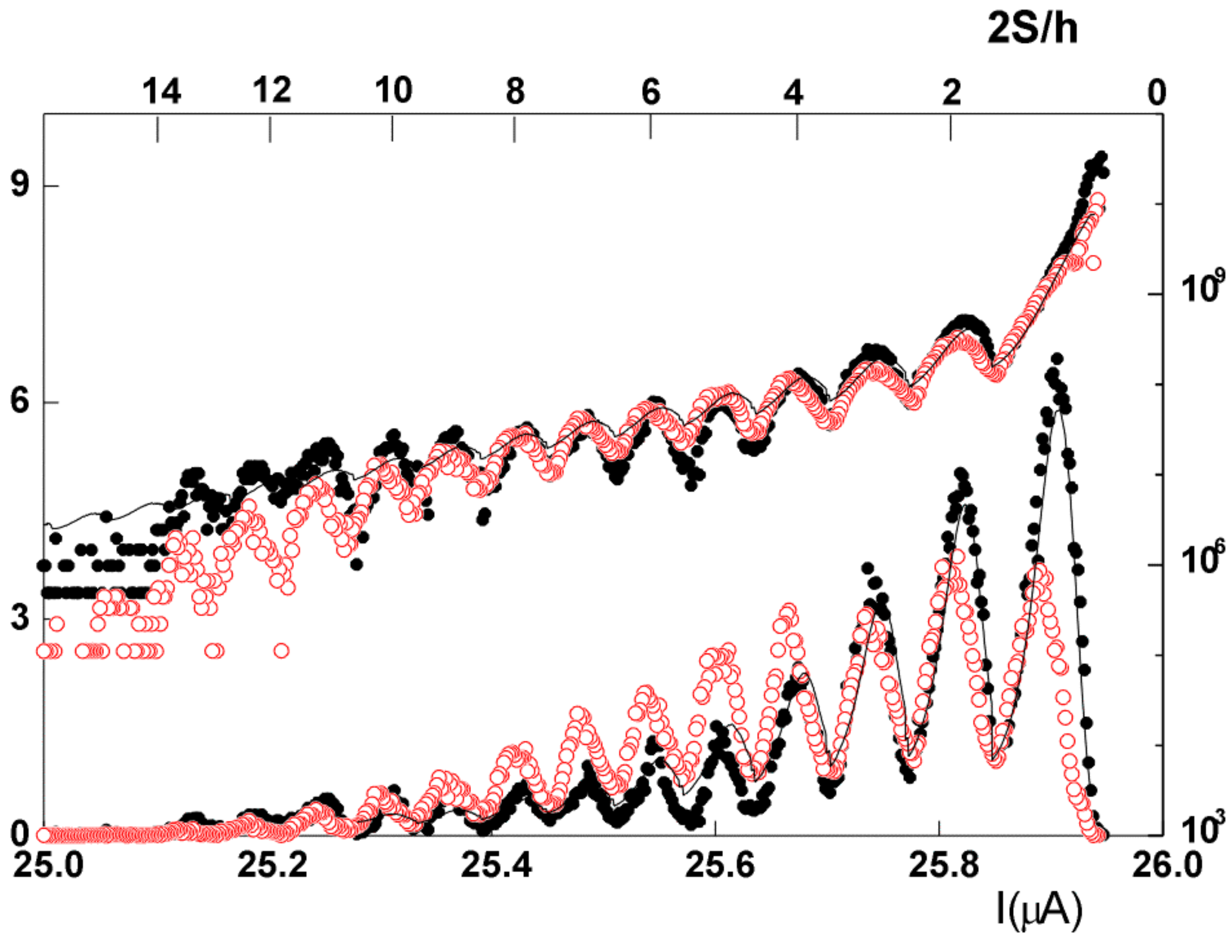
C.Cosmelli, F. Chiarello, G.D'Agosta, M. G. Castellano, G. Torrioli, *IEEE Trans. on Appl. Supercond.* **9**, 4123-4126 (1999)

- T= 20 mK (Rome)
- fit gives $R \approx 1 \ M\Omega$

Energy level quantization in thermal regime

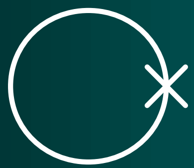
fast sweeping of the current, non-stationary regime, $T > T_{crossover}$

P.Silvestrini, V.G. Palmieri, B. Ruggiero, M. Russo, *Phys. Rev. Lett.* **79**, 3046 (1999)

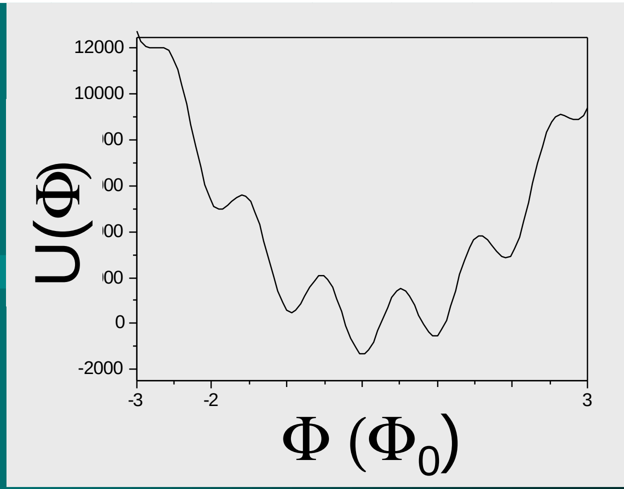


T=1.3 K

(Naples)

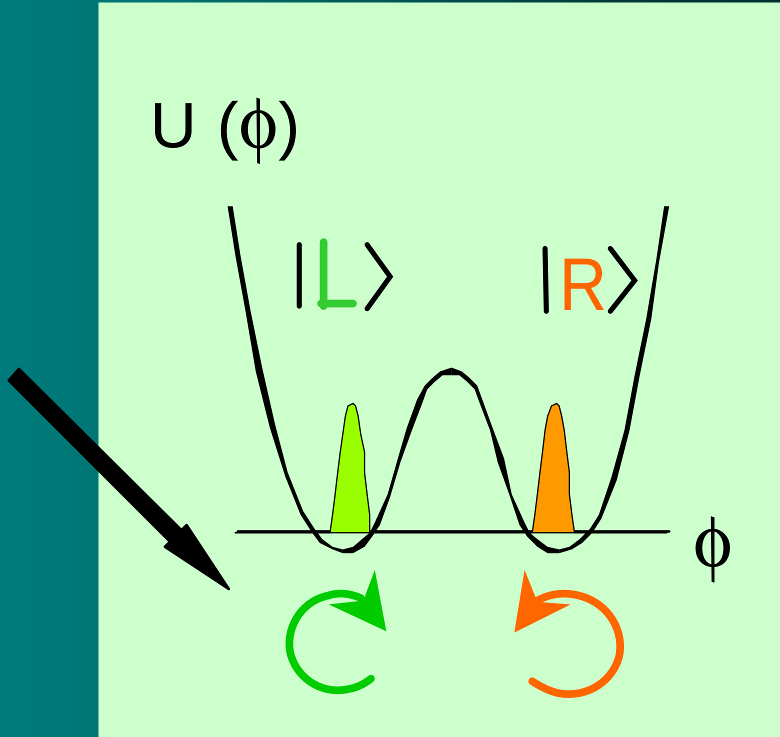


the rf-SQUID



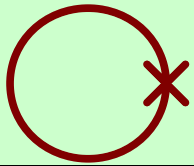
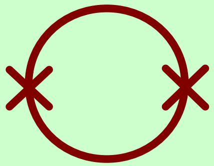
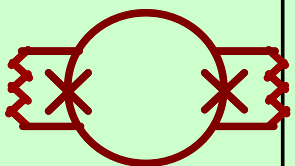
- superconducting ring with one JJ
- coordinate: magnetic flux Φ threading the ring
- potential shape allows studying tunneling and coherence
- double-well potential under proper bias ($\Phi_0/2$)

direction of the shielding current

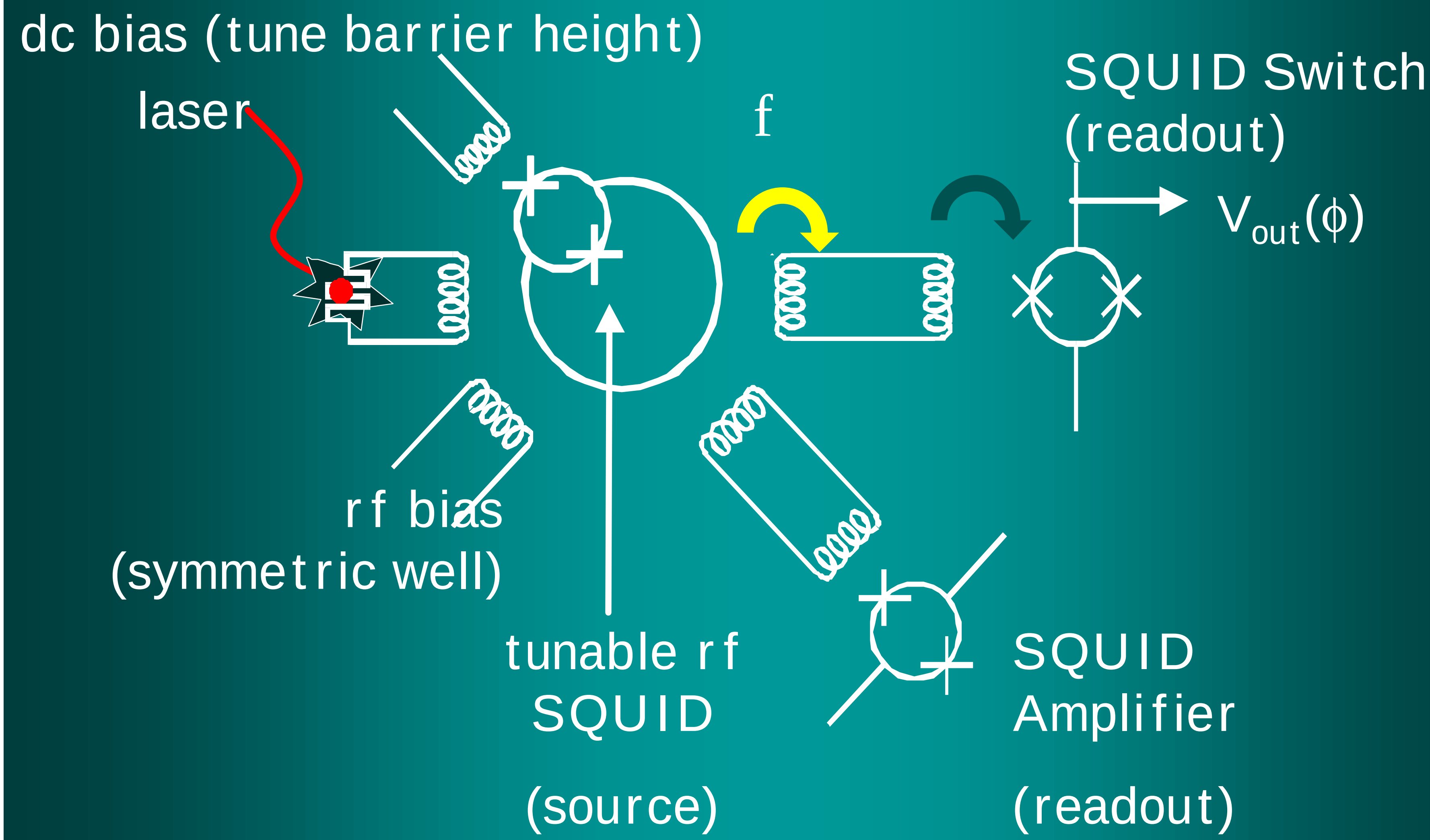


- look for ***coherent oscillations*** back and forth from Φ_L and Φ_R
- $\Phi_L - \Phi_R \sim 0.25\,\Phi_0$

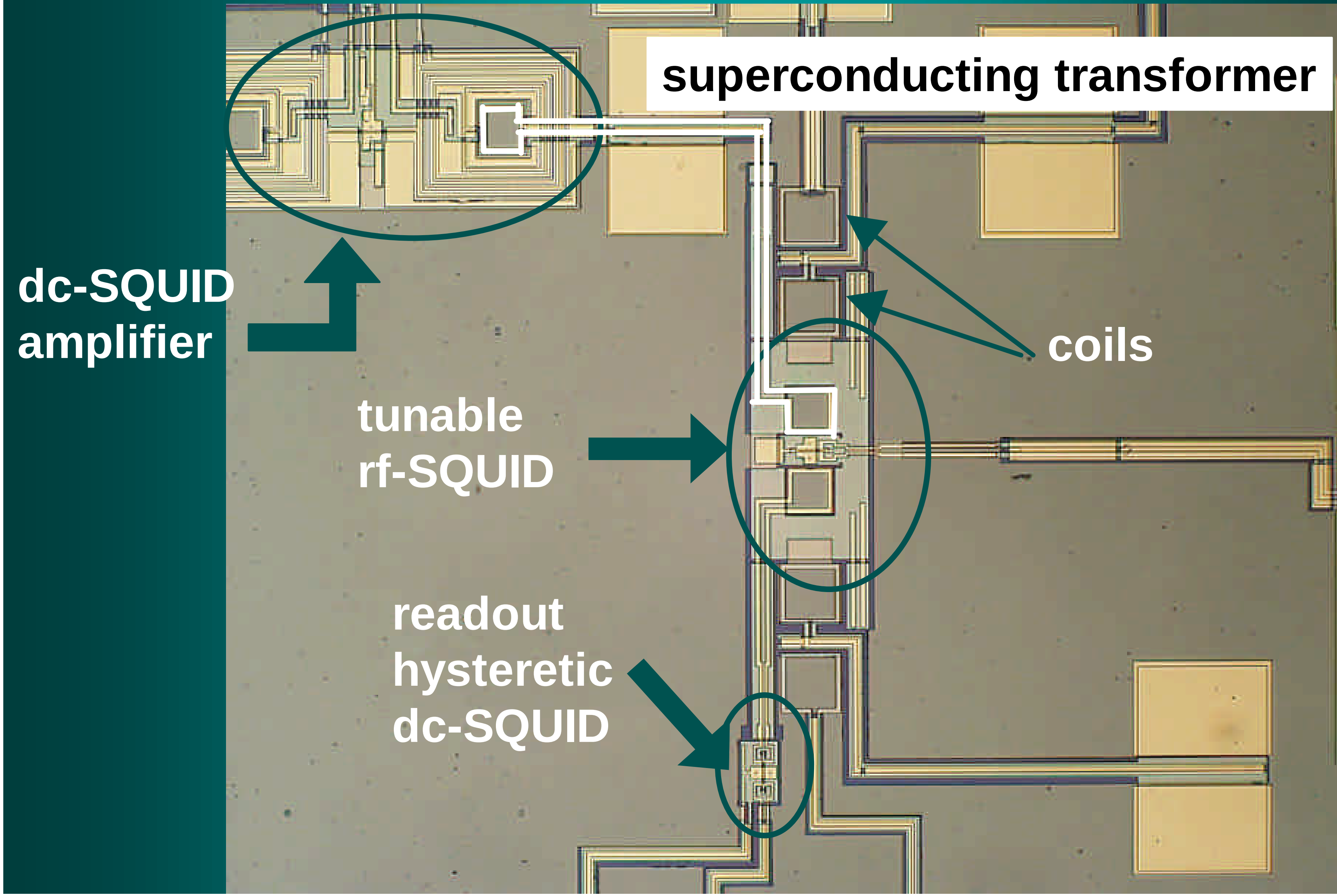
SQUID: several types are needed for the MQC experiment

type	schematic	dissipation source	use
rf-SQUID		intrinsic	source of the macroscopic state
hysteretic dc-SQUID		intrinsic	1. tuning the barrier height (inside rf-SQUID) 2. readout of the rf-SQUID (non-dissipative)
non-hysteretic dc-SQUID		external shunt resistors	readout of rf-SQUID (dissipative)

Scheme of the experimental SQUID system for MQC (Rome group)



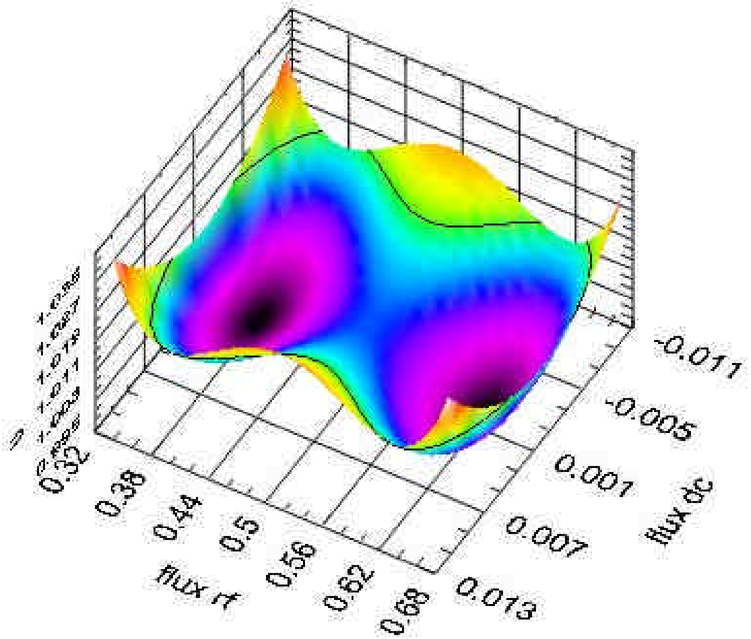
Chip for the MQC experiment(CNR-IESS, Rome)



The tunable rf-SQUID

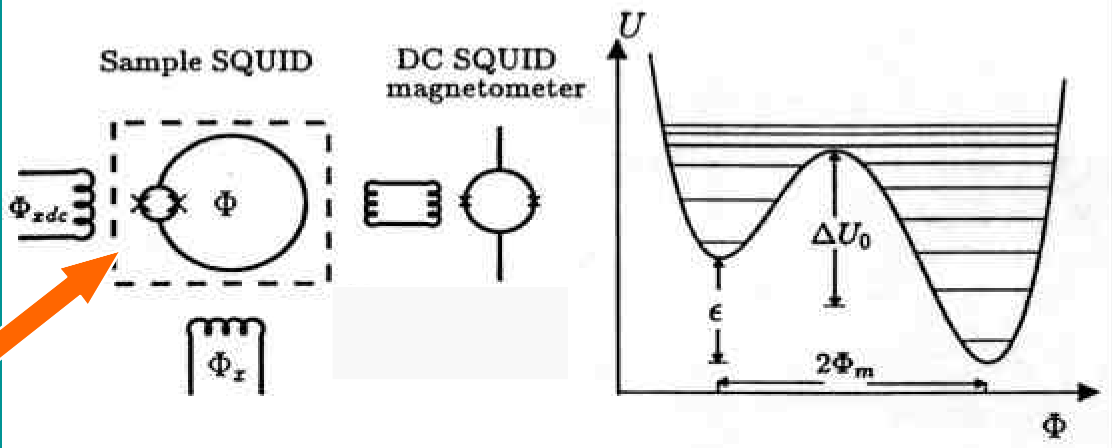
Han, Lapointe, Lukens, PRL, 1712 (89)

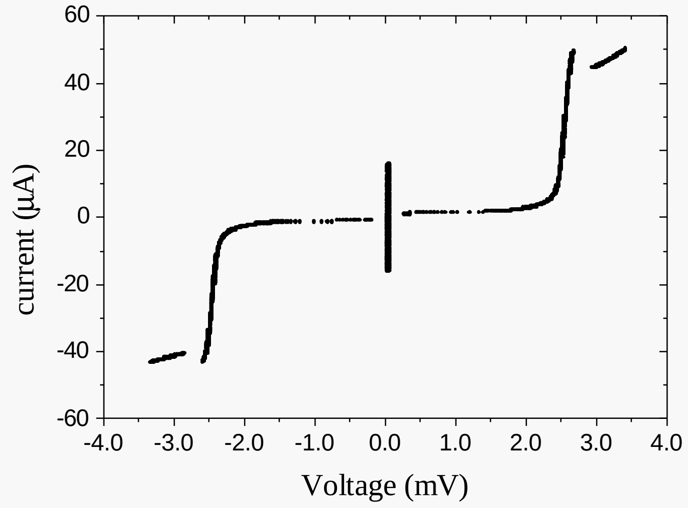
- we need to control very precisely the barrier height between wells (up to 1 part in 10^3) to control the tunneling frequency
- barrier height: $\approx I_0\Phi_0 \rightarrow$ vary I_0
- tune critical current of the device with some external parameter



equivalent potential

the solution is using a hysteretic dc-SQUID instead of single JJ



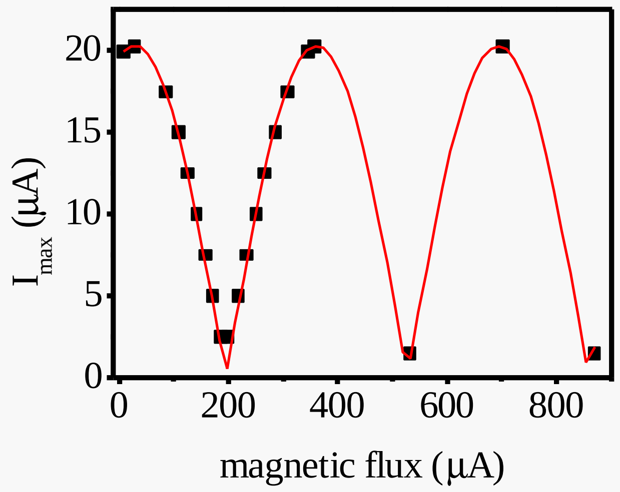


The hysteretic dc-SQUID

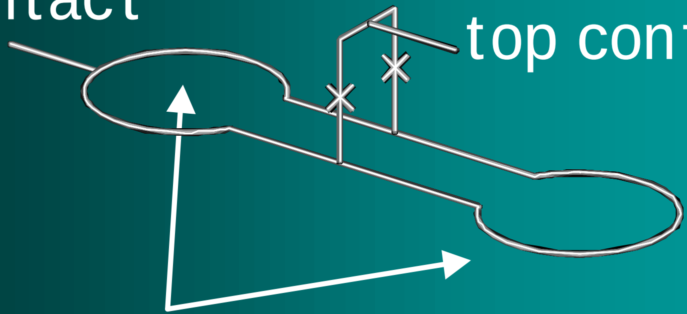
I-V characteristics
like a single Josephson junction

- coupling factor $\beta_L = 2\pi L I_0 / \Phi_0$
- $\beta_L >> 1$
  - 2-dim dynamics
  - small I_0 modulation
- $\beta_L << 1$
  - 1-dim dynamics
  - like single junction
  - complete I_0 modulation

critical current modulated by magnetic field $\Rightarrow$ magnetometer

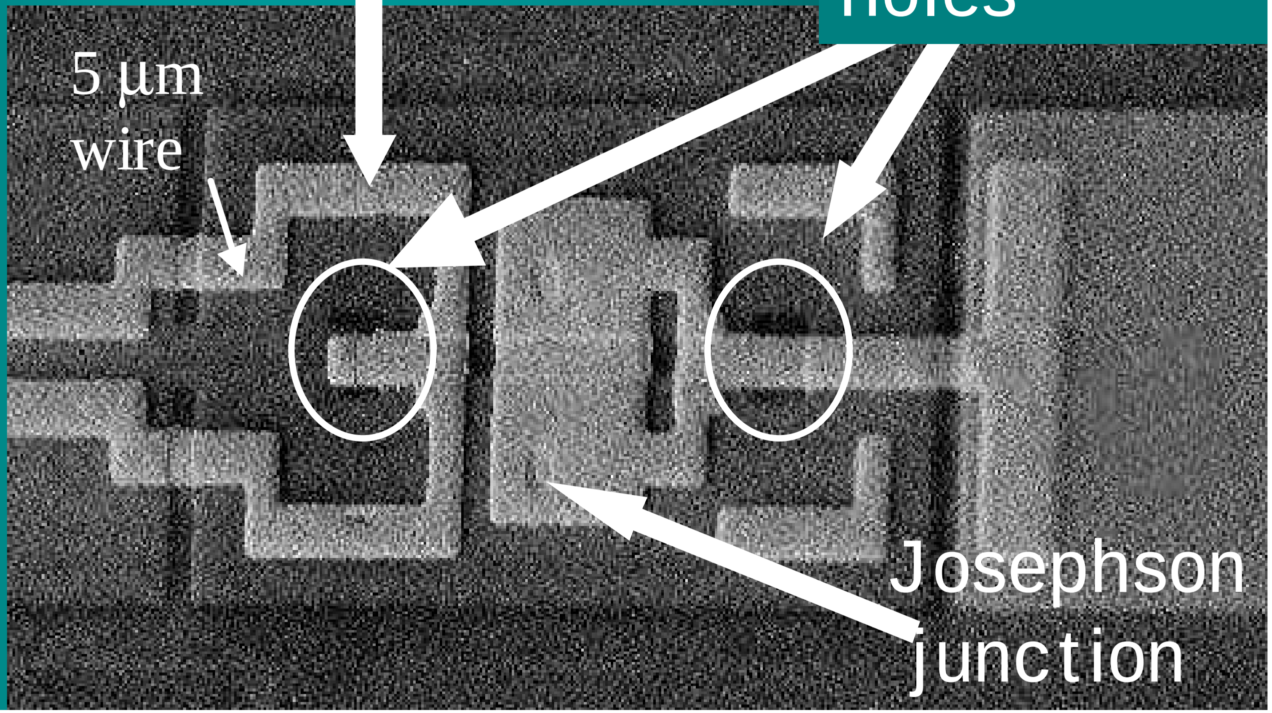


A two-hole hysteretic dc-SQUID

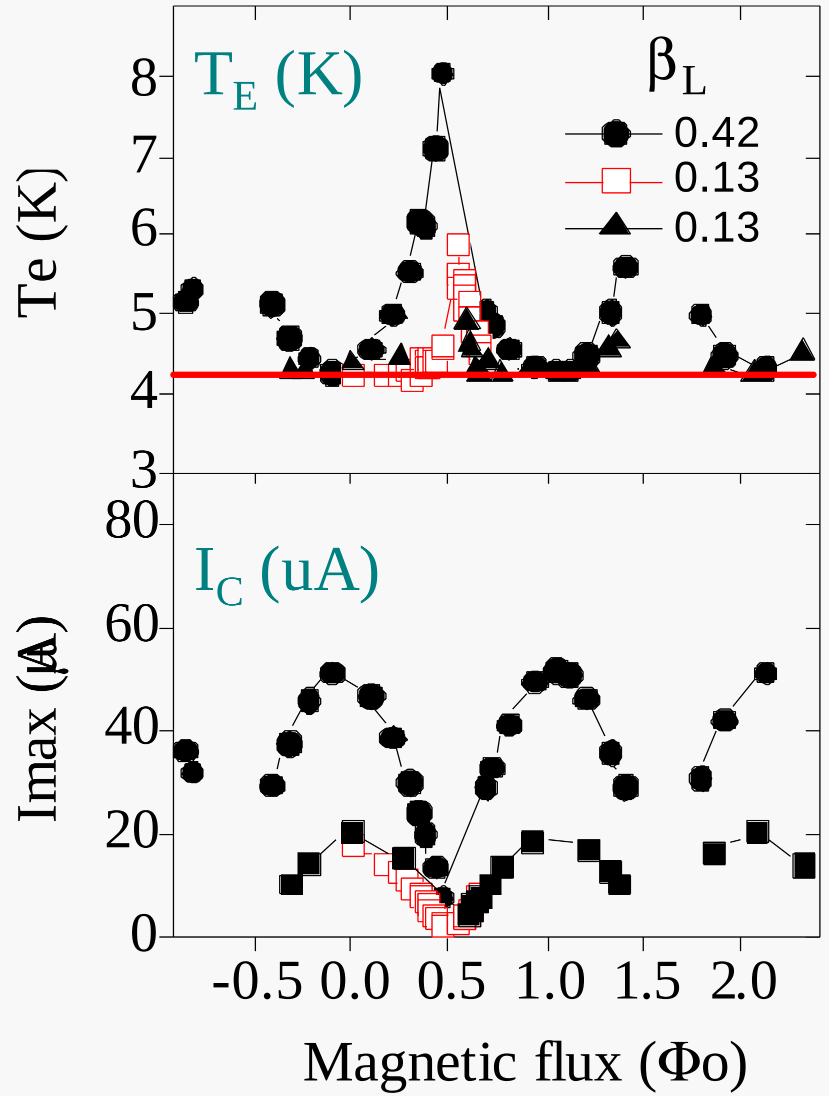


- Nb/AlOx/Nb trilayer
- L=5pH
- hole size: 10 µm
- I_0 = 4-25 µA
- JJ size: 3 µm

coil for magnetic flux coupling and tune current

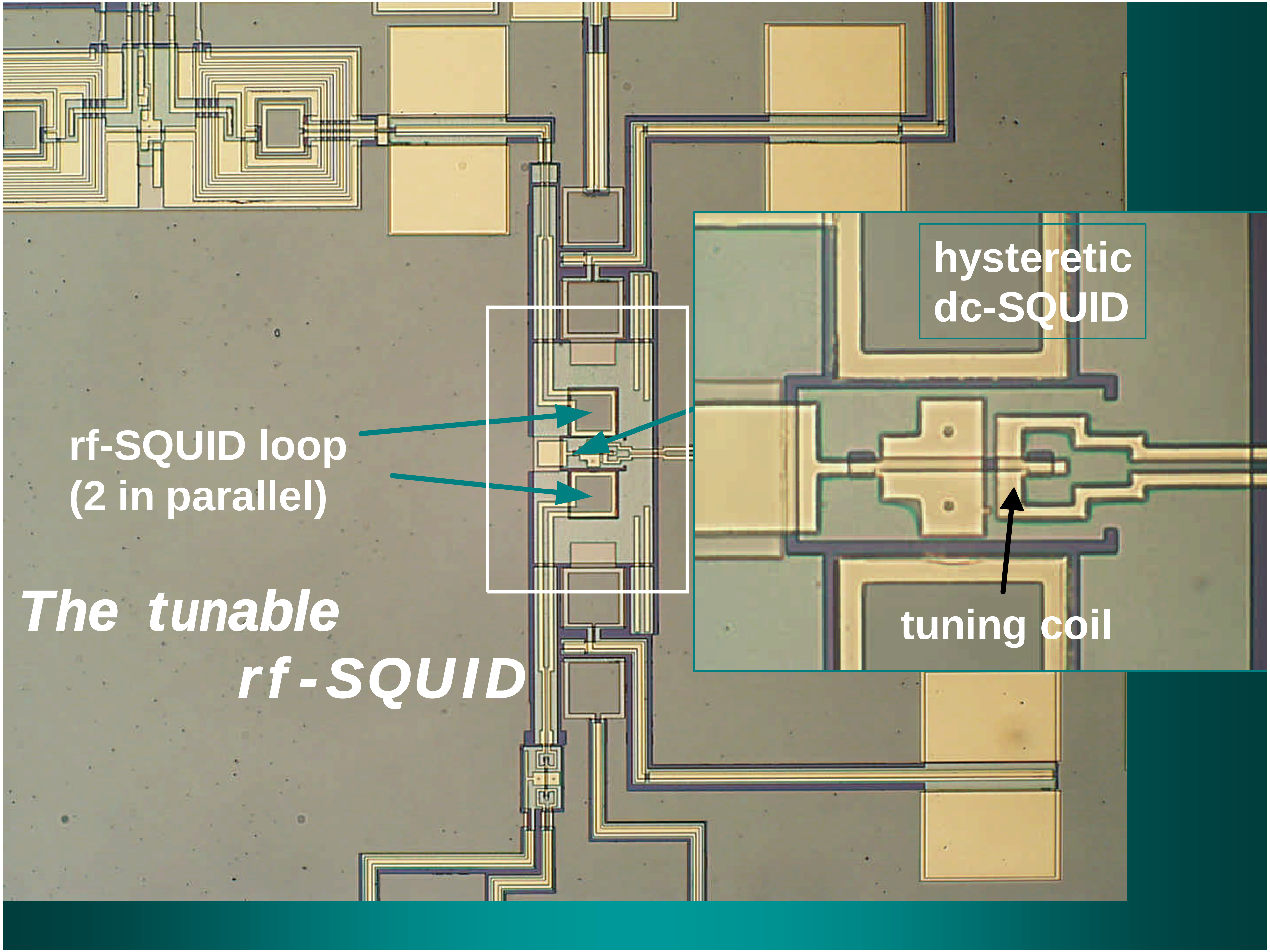


Escape of the hysteretic dc-SQUID from the zero-voltage state at 4.2 K



Results:
our hysteretic dc-SQUID is like a single JJ with tunable I_0

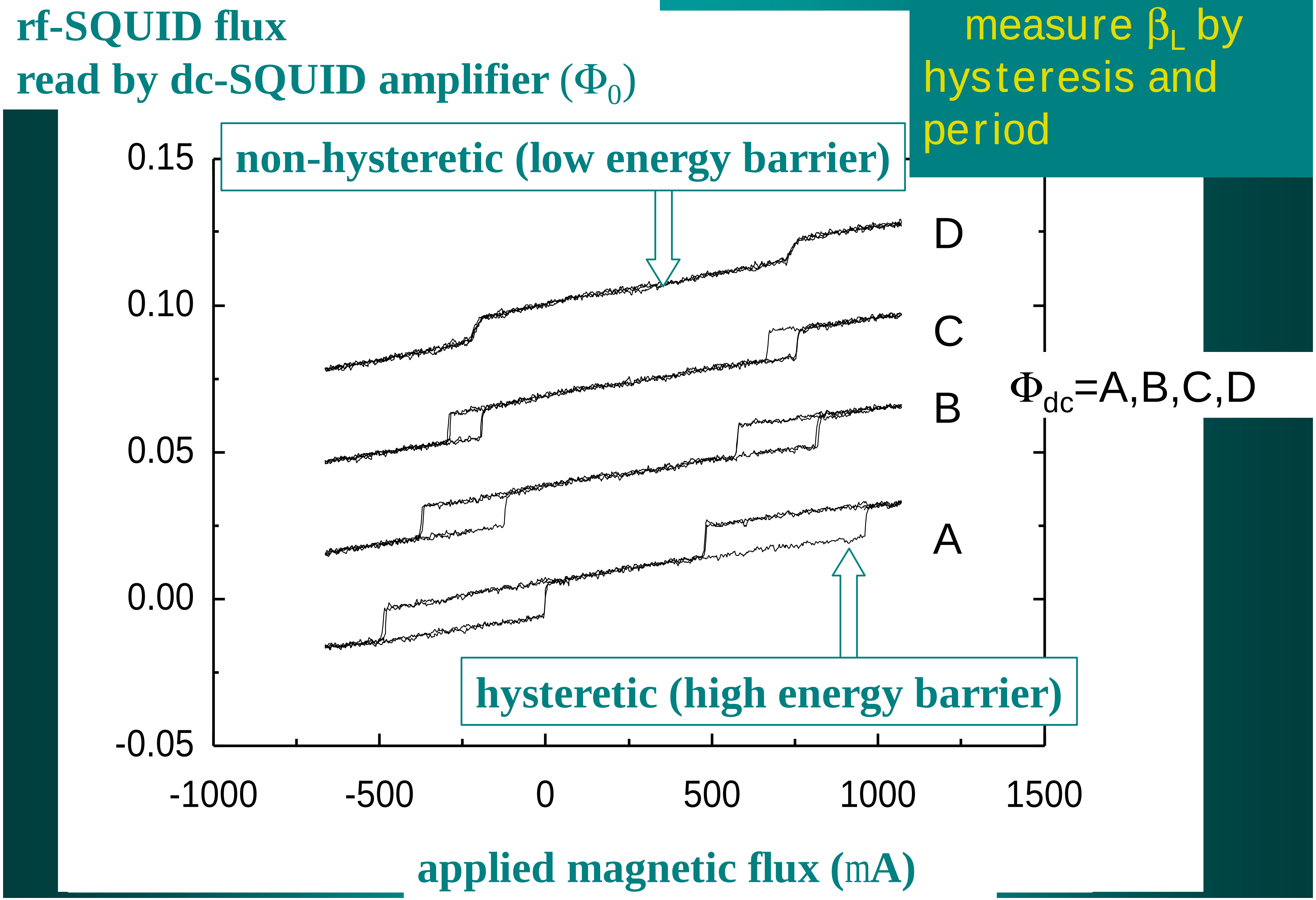
- for small enough β_L (0.13)
- in a specific range of flux values



hysteretic
dc-SQUID
rf-SQUID loop
(2 in parallel)
tuning coil
The tunable
rf-SQUID

Tuning of the rf-SQUID: experimental results

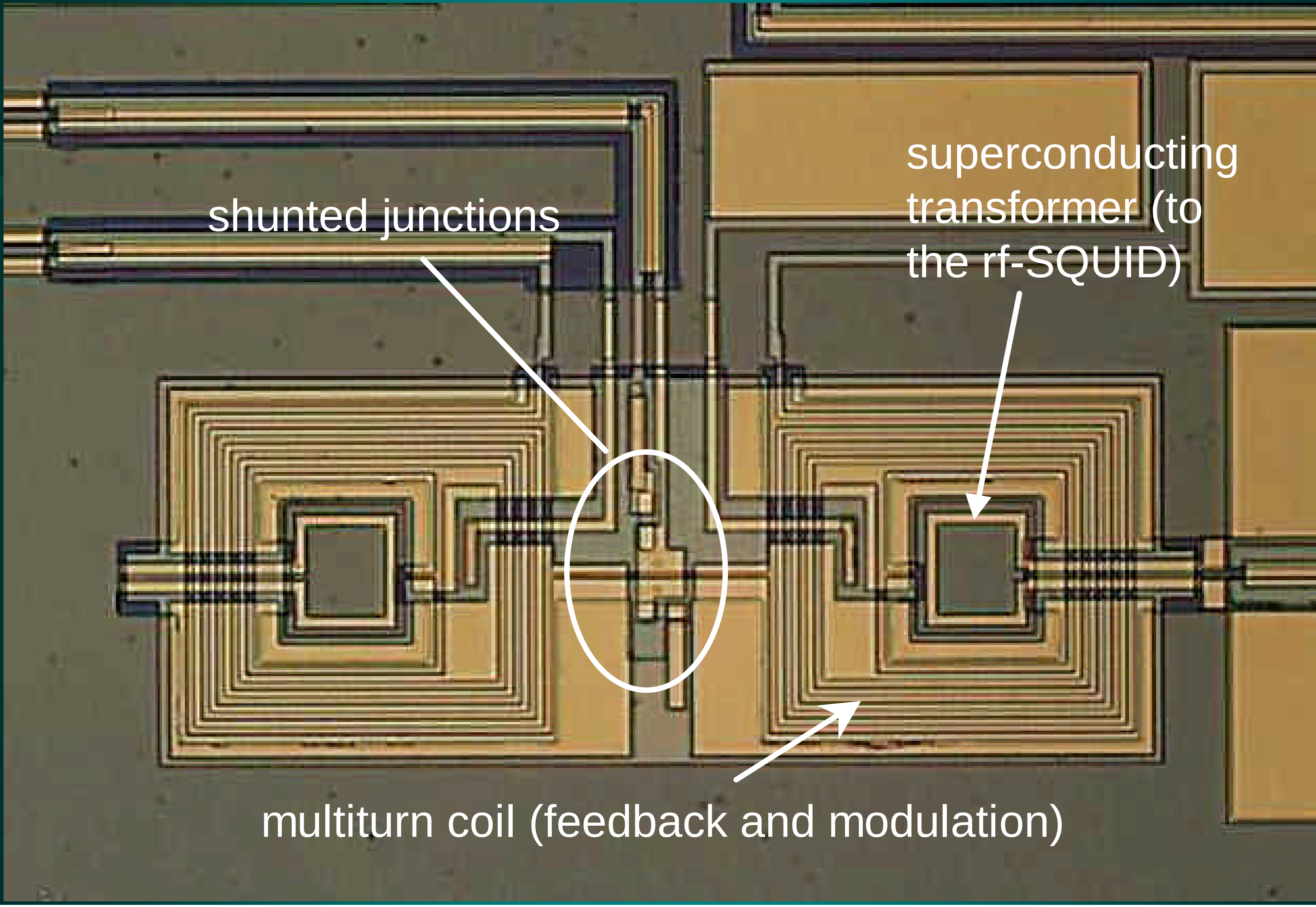
measure β_L by hysteresis and period



readout of the rf-SQUID

- Read the flux in the tunable rf-SQUID with a suitable magnetometer
    - dc-SQUID amplifier (invasive, due to dissipation in the device)
    - hysteretic dc-SQUID (used to read only the direction of the circulating current)

dc-SQUID amplifier (two-hole)



Experimental results

Escape rate for an rf SQUID (β_L=8)

T=35mK - R≈ 4 MΩ

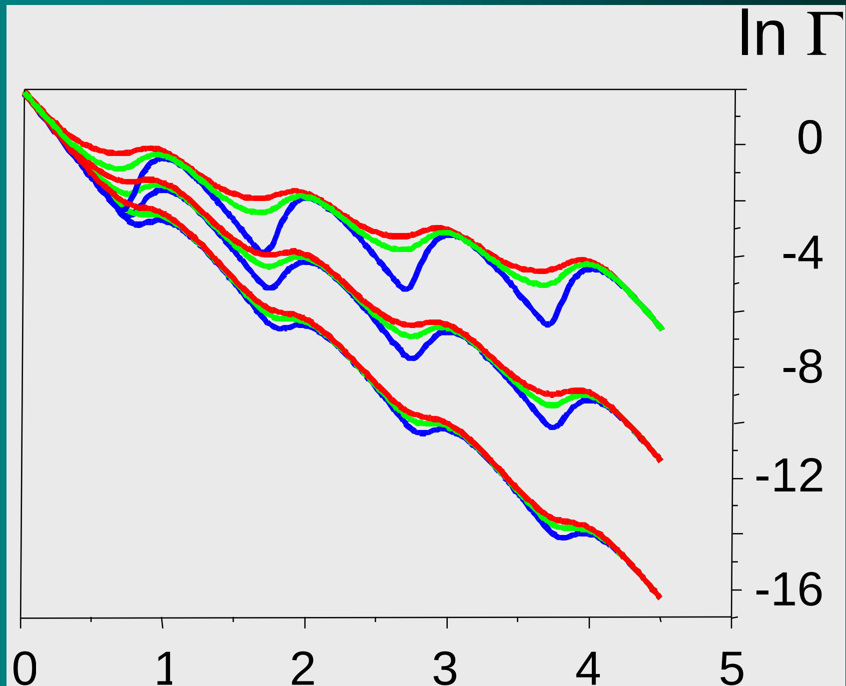
Measurement of the intrinsic dissipation of a macroscopic system in the quantum regime

P. Carelli, M.G. Castellano, F. Chiarello, C. Cosmelli, G. Diambrini-Palazzi, R. Leoni, G. Torrioli

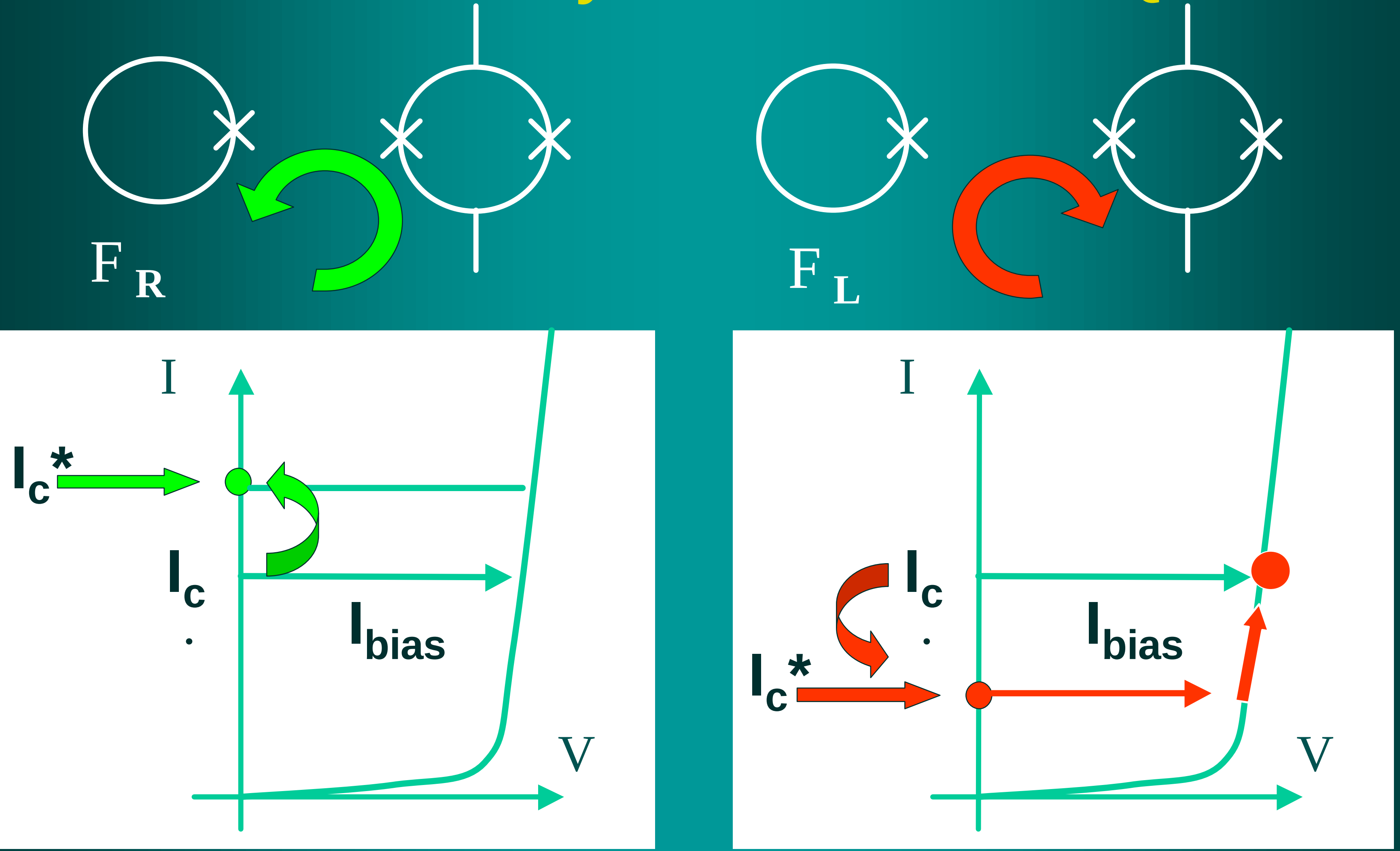
Physical Review Letters, **82**, 5357-5360 (1999)

example of fit:

- 3 different temperatures → different slopes
- 3 different resistances (red, green, blue curve) → modulation depth



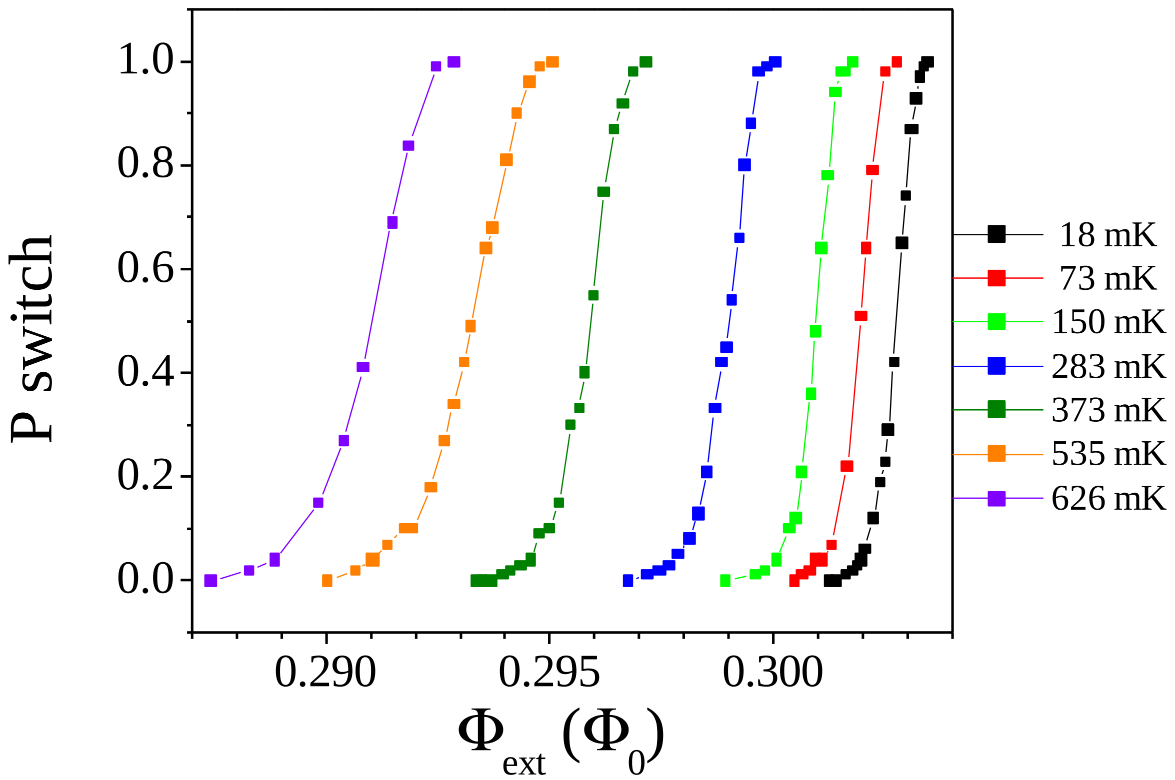
Readout with a hysteretic dc-SQUID



- $I_{bias} < I_c^* \rightarrow$ no transition
- dc SQUID remains at V=0

- $I_{bias} > I_c^* \rightarrow$ transition to $V^{1}\ 0$

Choose working point of hysteretic dc-SQUID so that Φ_L causes transition, while Φ_R does not

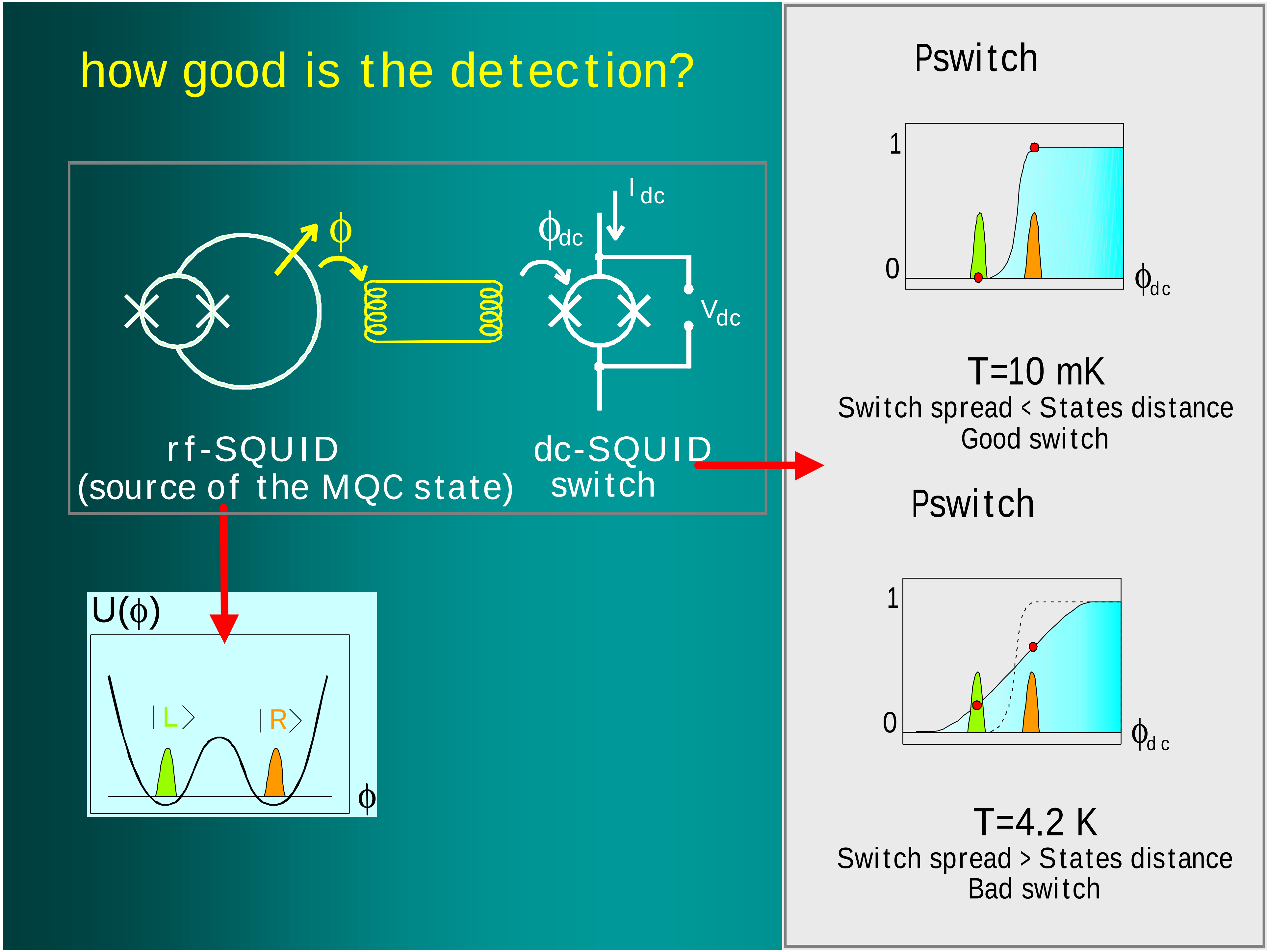


BUT

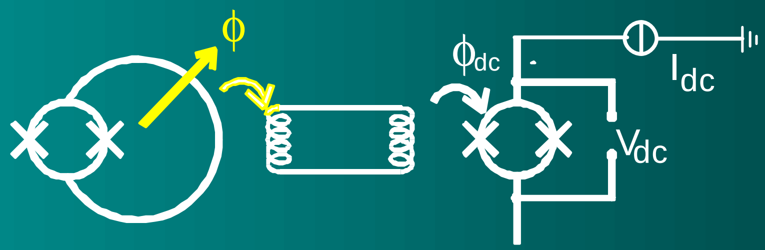
thermal or quantum effects spread the transition of dc-SQUID

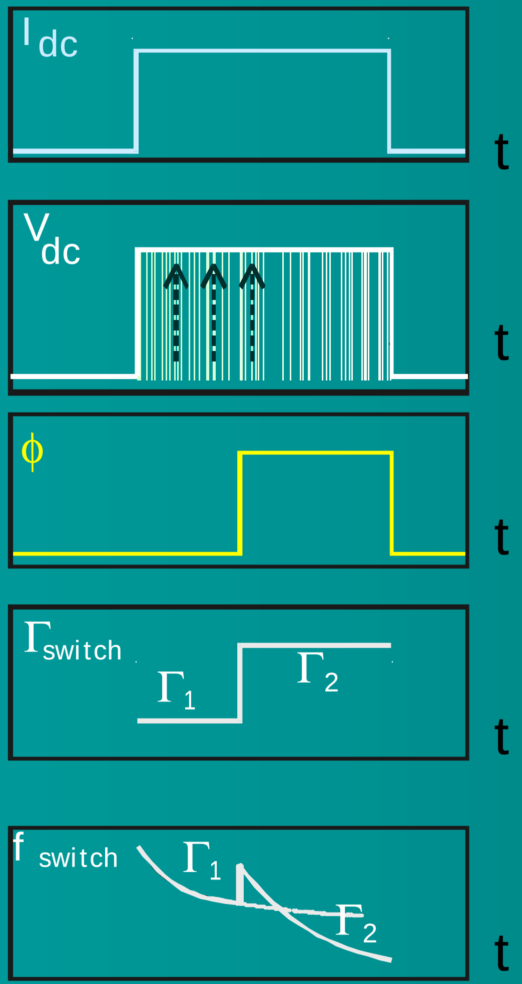
Switch probability of hysteretic dc-SQUID as a function of applied magnetic flux and temperature

how good is the detection?



Read-out of rf-SQUID state with a dc-SQUID at 4.2K





The dc-SQUID switch is turned on for a time Δt

The dc-SQUID can switch to the normal state after a time t (exponential distribution, rate Γ_1)

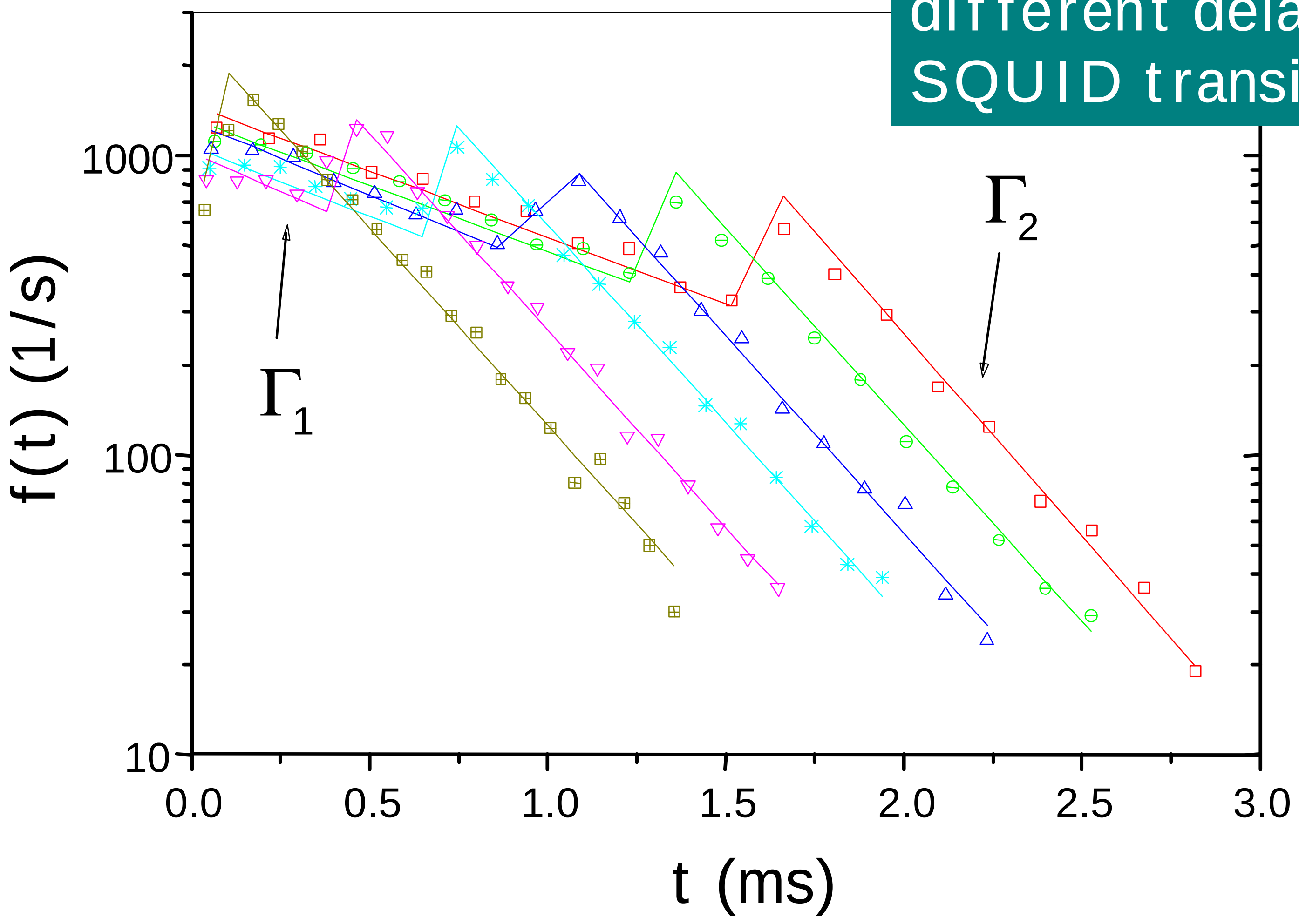
During this time, one induces the rf-SQUID flux transition

The flux from rf-SQUID modifies the dc-SQUID switching rate into Γ_2

The probability distribution presents a double rate exponential decay

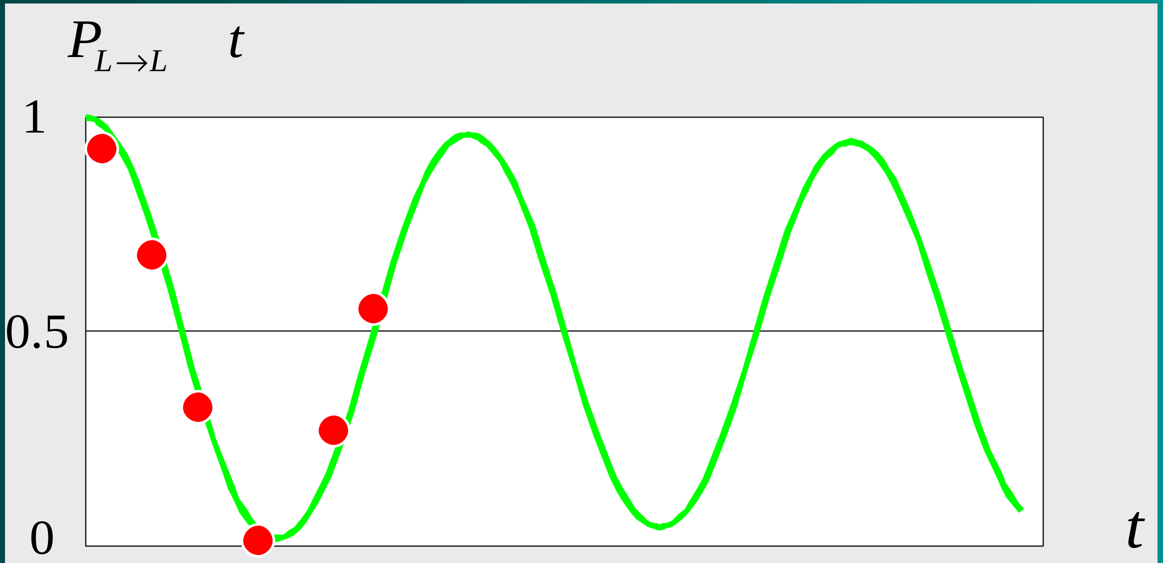
Read-out of rf-SQUID state with a dc-SQUID at 4.2K

for each curve, different delay for rf-SQUID transition

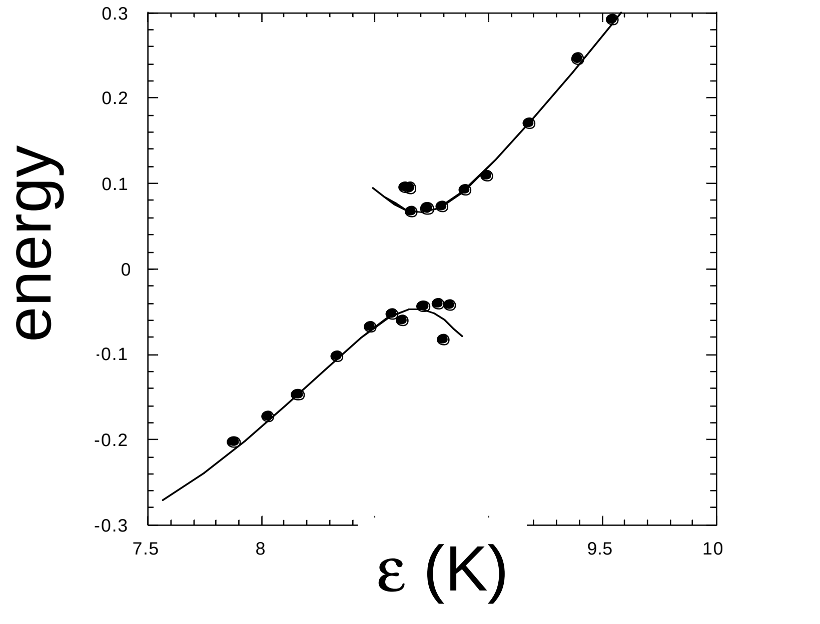


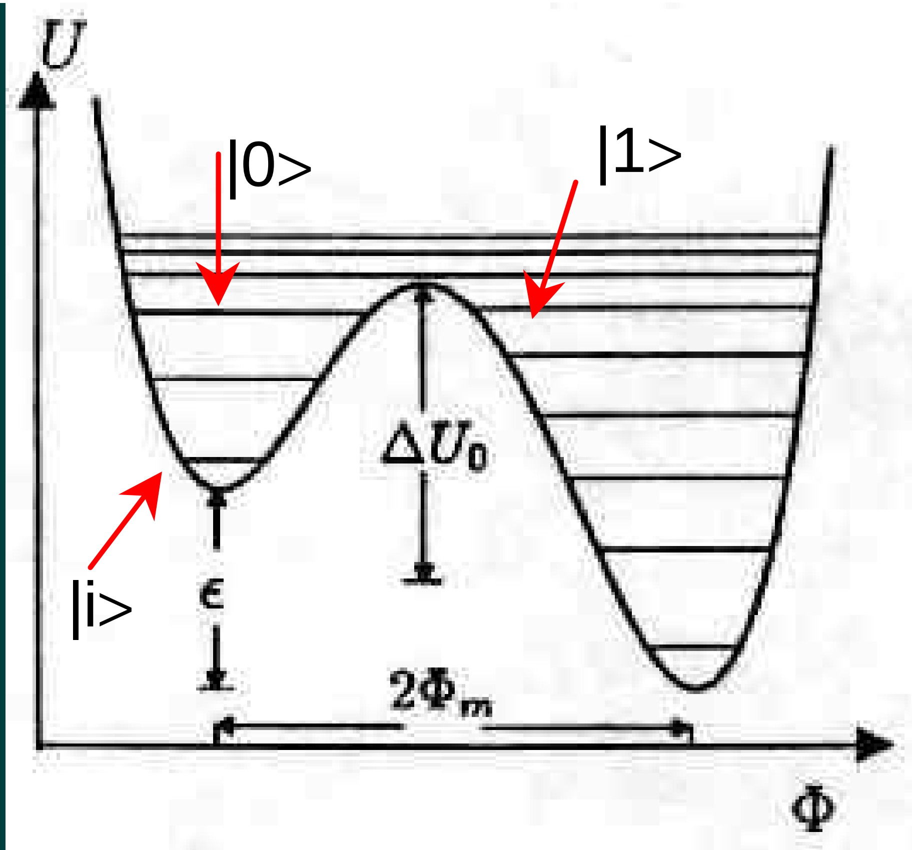
Plan of future measurements:

- Direct detection of coherent oscillations with the following scheme:
  - Preparation of the flux state (L)
  - Flux Measurement after Δt
  - Repeat for differents Δt
  - Evaluate the Probability P(L,L)



Recent results on MQC





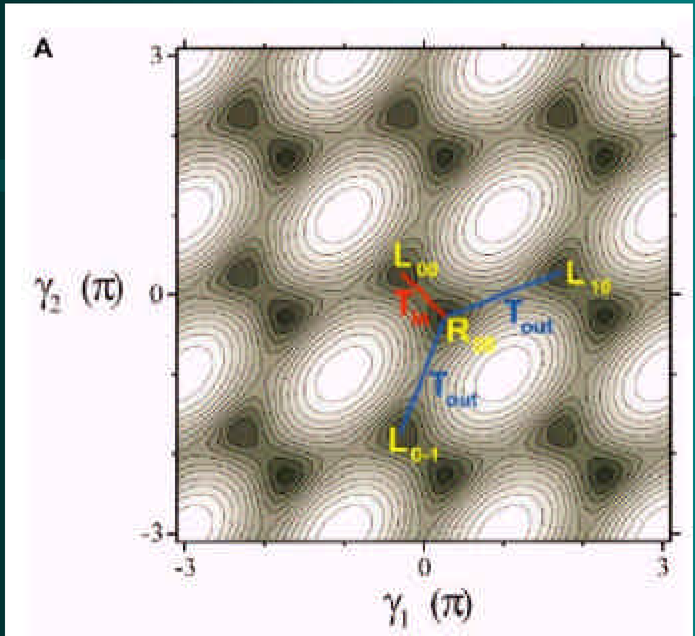
J. R. Friedman, V. Patel, W. Chen, S. K. Tolpygo and J. E. Lukens

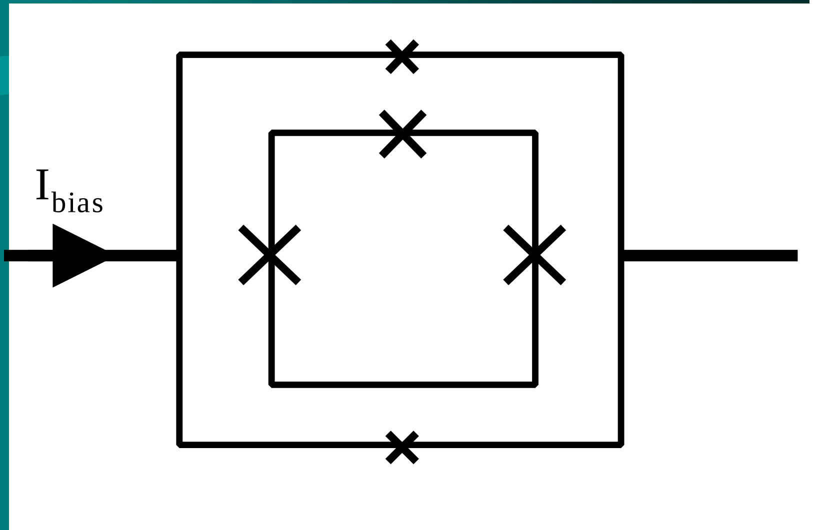
Nature **406**, 43 (2000)

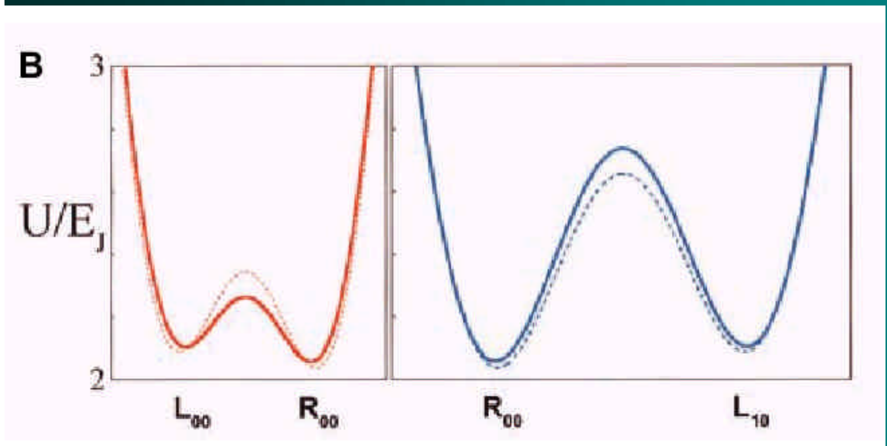
- tunable rf-SQUID
- superposition of two excited states |0> and |1>
- look for interwell transitions caused by photon absorption
- spectroscopic measurement

Superconducting vortex qubit

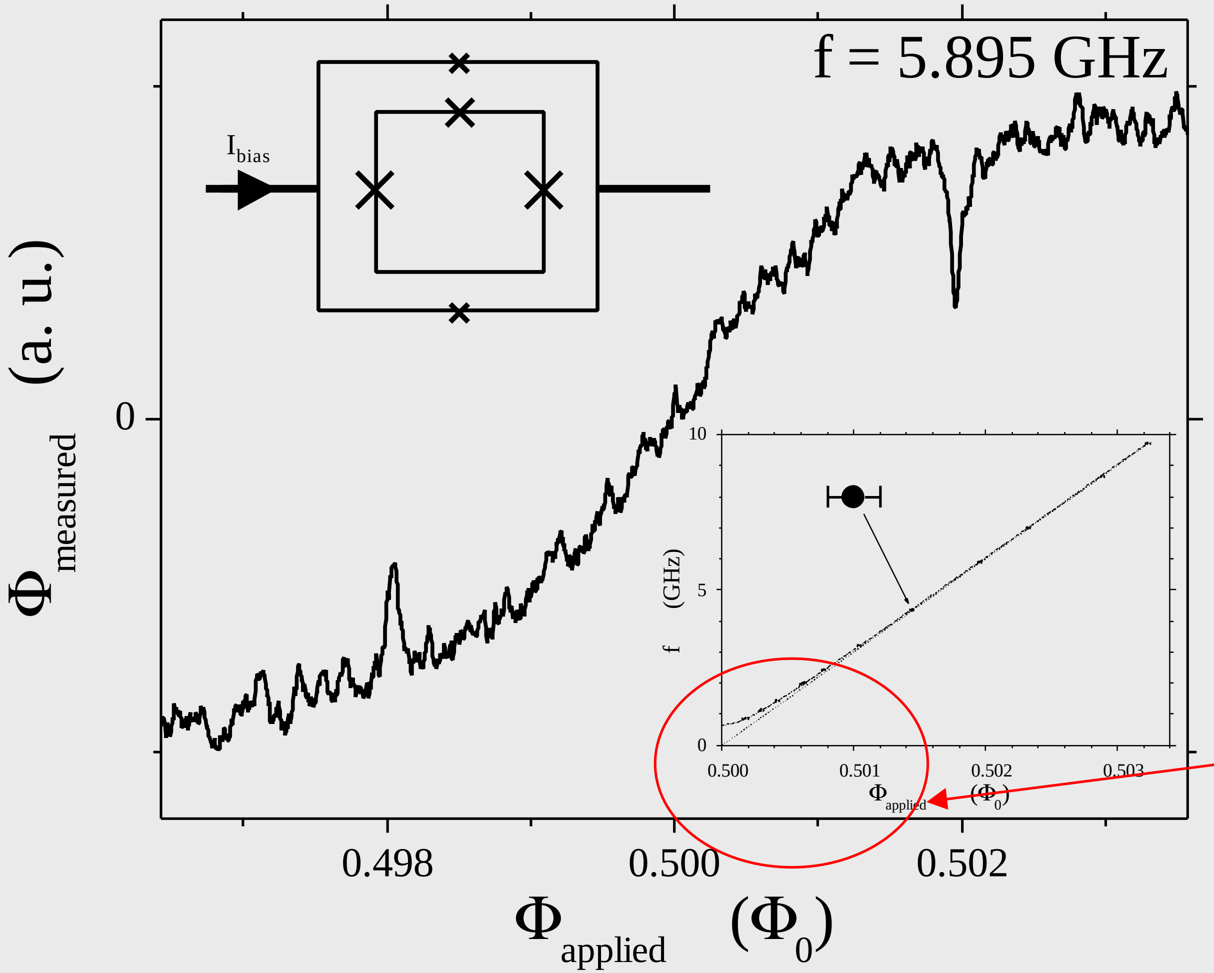
J. E. Mooij, T.P. Orlando, T. Levitov, C. van der Wal, S. Lloyd, Science **258,** 1036 (1999)







- 3 junctions, one with different E_J
- double well potential
- read with surrounding underdamped dc-SQUID



peak and dip under μ-wave

resonance between photon and energy spacing between lowest quantum states

level repulsion

C. van der Wal et al., new results
(proc. Int. Workshop on Macroscopic Quantum Coherence and Computing, Naples, June 14-17, 2000)

Conclusions

- recent spectroscopic measurements have shown the existence of energy doublets, due to quantum superposition of states
- the measured dissipation in SQUIDs (R~MΩ) should allow direct measurement of coherent oscillations
- a hysteretic dc-SQUID can read out the rf-SQUID flux states with a non-invasive procedure
- next step: probing of the coherent oscillation with stroboscopic time measurements

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