Manipulation and coupling of Josephson qubits

Fabio Chiarello
Istituto di Fotonica e Nanotecnologie CNR (Rome)
QMFPA Conference - Bertinoro, Dec. 2006

-M. G. Castellano, F. Chiarello,
-S. Poletto, G. Torrioli
(IFN –CNR, Rome, Italy)
-C. Cosmelli
(University "La Sapienza", Rome, Italy)
- P. Carelli
(University of L'Aquila, Italy)

-M. Cirillo
(Univ. "Tor Vergata", Roma, Italy)

- D. V. Balashov, M. I. Kabipov, A. B. Zorin
(PTB, Braunschweig, Germany)

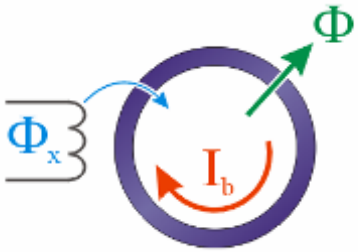
Outline:

- The double SQUID qubit
- Catastrophe Theory
- Improvements
- Controlled entanglement
- RSFQ logic for the qubit control

IFN

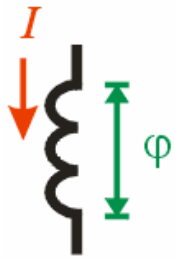
Superconducting electronics

Flux quantization



$$\Phi = \Phi_x - LI = n\Phi_0$$

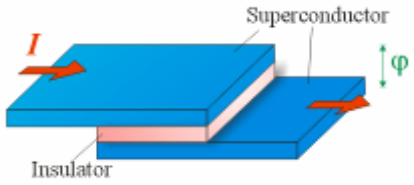
Inductance

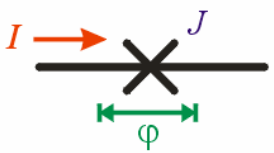


$$I = \Phi_b \varphi / L$$

$$E_L = \frac{\Phi_b^{\,2}}{2L}\varphi^2$$

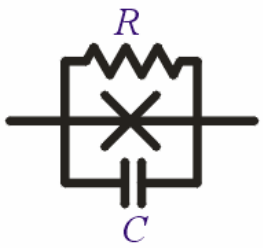
Josephson junction





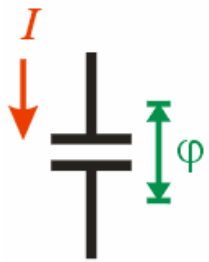
$$\begin{cases} V = \Phi_b \dot{\varphi} \\ I = J\sin\varphi \end{cases}$$

$$E_J = -J\Phi_b \cos\varphi$$



$$I = J\sin\varphi + C\Phi_b\ddot{\varphi} + \frac{\Phi_b}{R}\dot{\varphi}$$

Capacitance



$$I = C\Phi_b\ddot{\varphi}$$

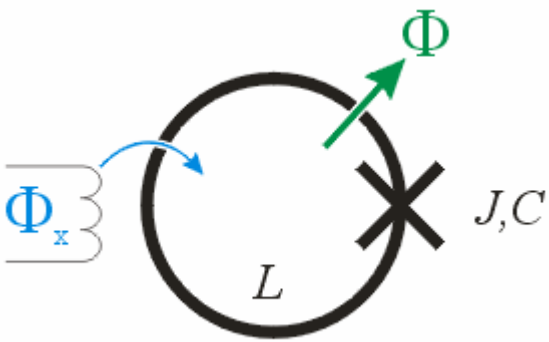
$$E_C = \frac{1}{2}C\Phi_b^{\,2}\dot{\varphi}^2 = \frac{p^2}{2M}$$

$$M = C\Phi_b^{\,2} \qquad p = M\dot{\varphi}$$

$$\Phi_0 = h/2e \cong 2.068\times10^{-15} Wb$$

$$\Phi_b = \Phi_0/2\pi = \hbar/2e \cong 3.291\times10^{-16} Wb$$

rf SQUID

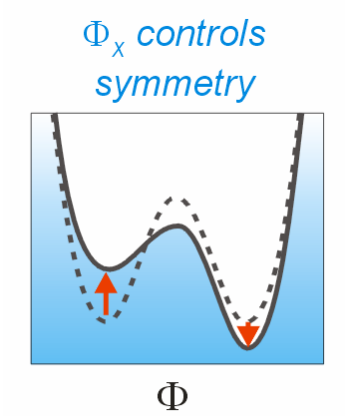


$$H = \frac{Q^2}{2C} + U$$

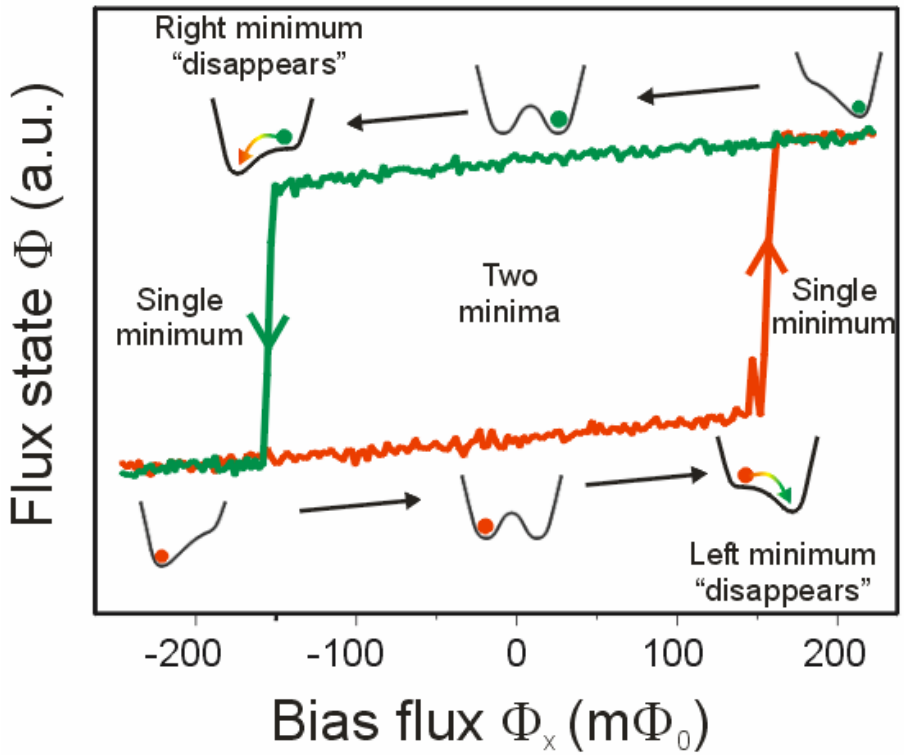
$$[Q, \Phi] = -i\hbar$$

$$\Phi_b = \frac{\hbar}{2e} \cong 3.291 \times 10^{-16} Wb$$

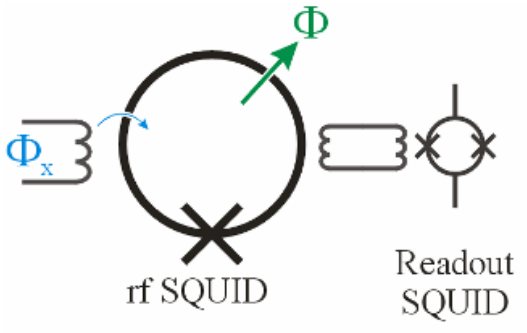
$$U = \frac{1}{2L}(\Phi - \Phi_x)^2 - J\Phi_b \cos\left(\Phi/\Phi_b\right)$$



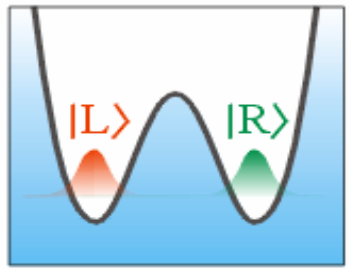
Symmetry: $\Phi_x = \Phi_0/2$



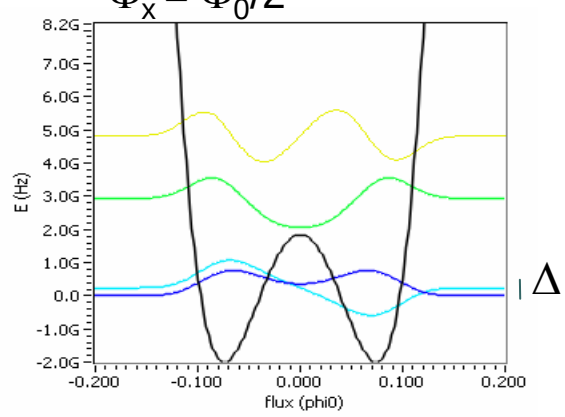
rf SQUID flux Qubit



Flux states ⇒ Qubit states

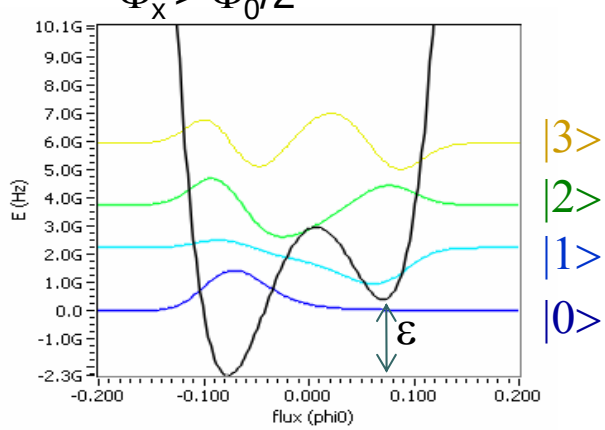


$\Phi_x = \Phi_0/2$



$$|L\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$$
$$|R\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$$
$$\hbar\Omega = E_1 - E_0 = \Delta$$

$\Phi_x > \Phi_0/2$

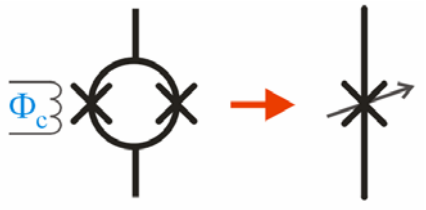


$$|L\rangle = |0\rangle$$
$$|R\rangle = |1\rangle$$
$$\hbar\Omega = E_1 - E_0 = \sqrt{\Delta^2 + \varepsilon^2}$$

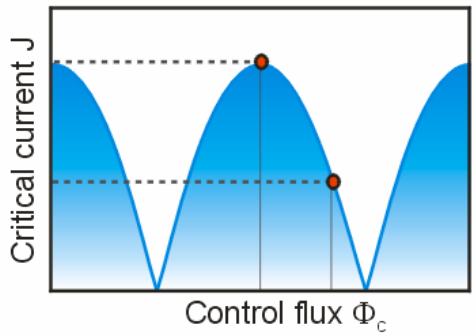
Double SQUID qubit

dc SQUID

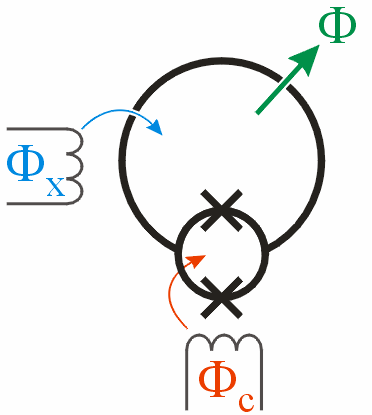
Small inductance dc SQUID ≅ Tunable Josephson junction

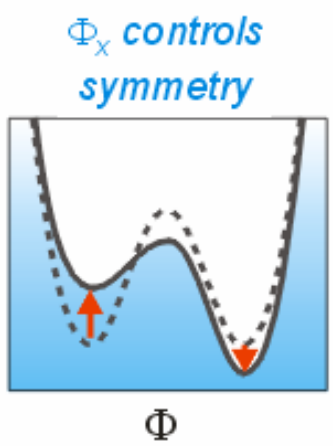


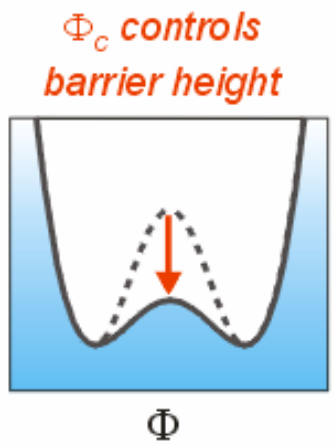
$$J(\Phi_c) = 2J_0 \left| \cos\left(\pi \frac{\Phi_c}{\Phi_0} \right) \right|$$



Double SQUID

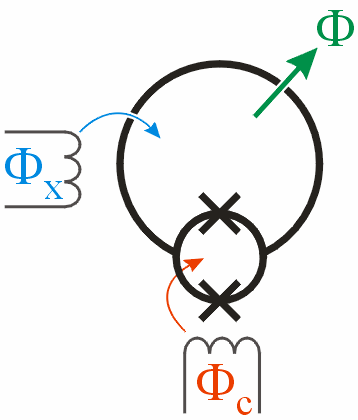


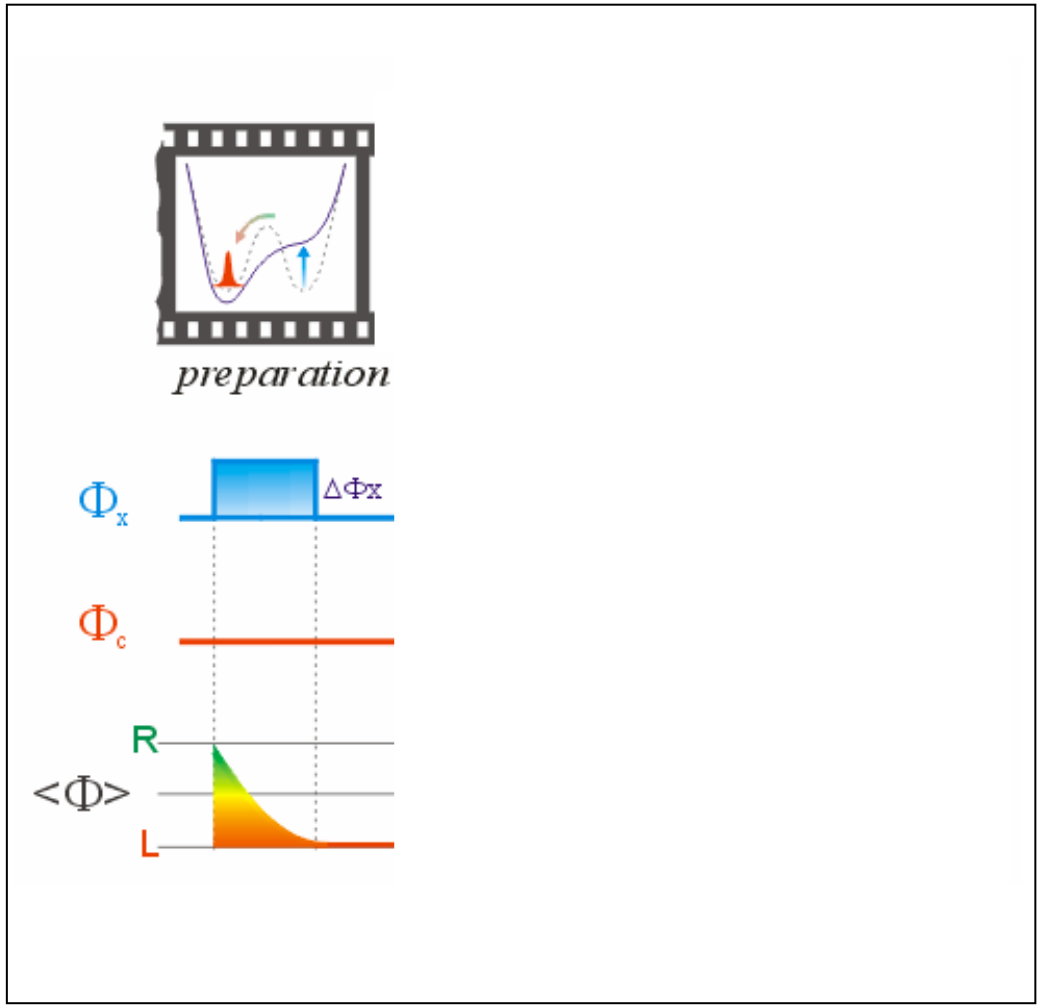




Double SQUID qubit: manipulation

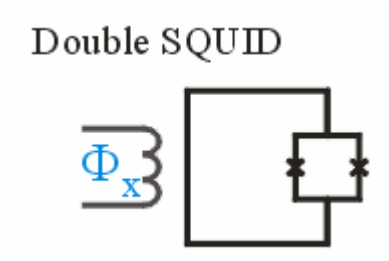
Example of qubit manipulation

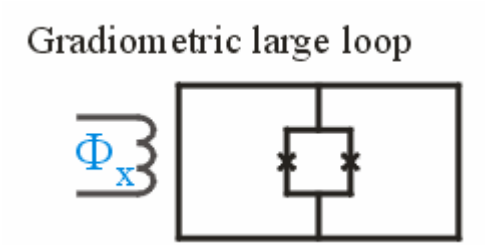


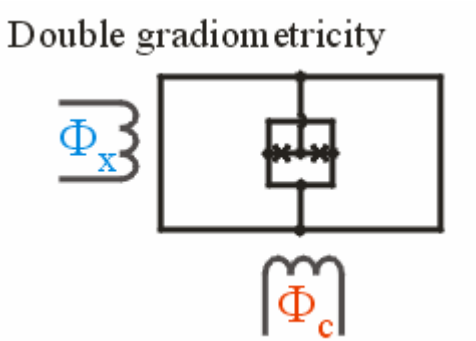


Double SQUID: gradiometric configuration

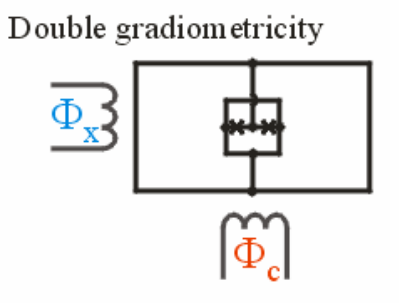
Double gradiometricity:
- Reduction of noise pick-up
- Reduction of fluxes cross-coupling





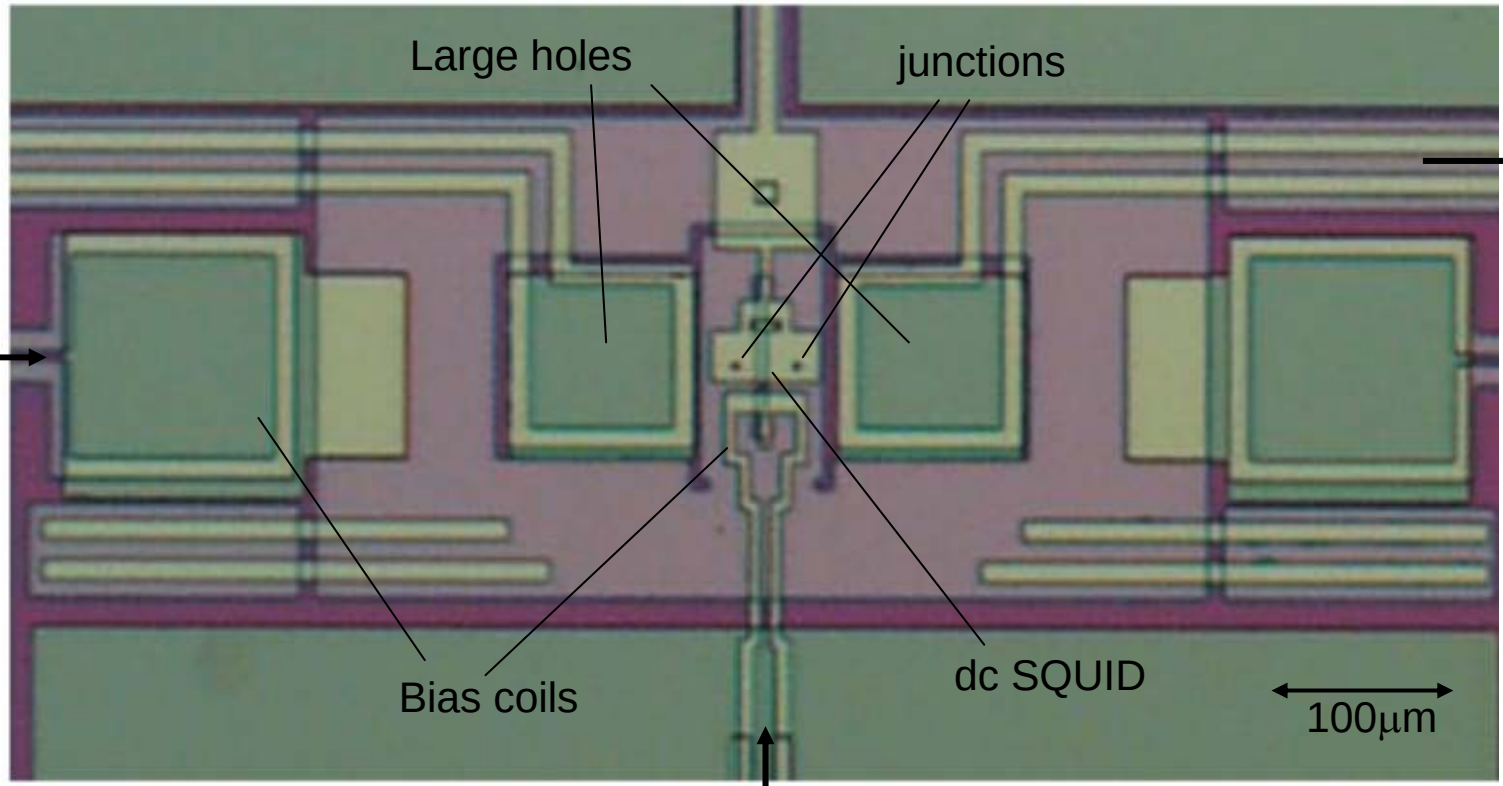


Double SQUID qubit: the device



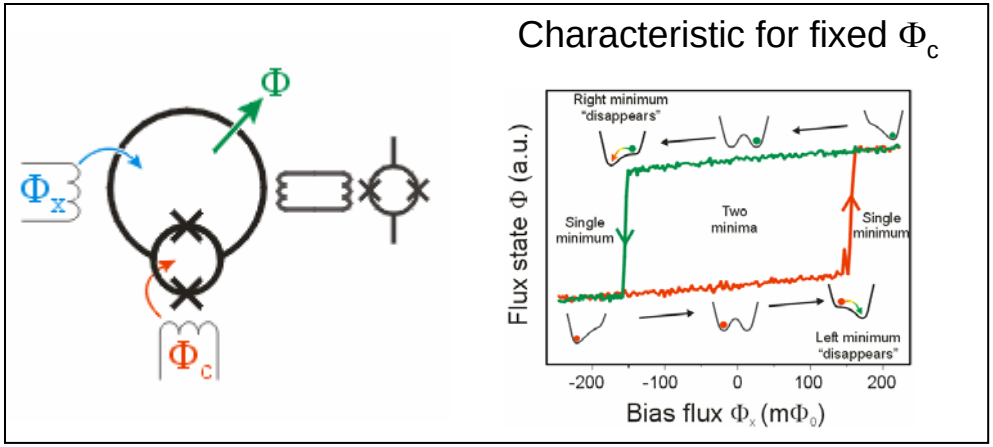
$Nb/AlO_x/Nb$
Trylayer technology

Different samples
From:
- IFN-CNR
- PTB
-Hypres
-VTT

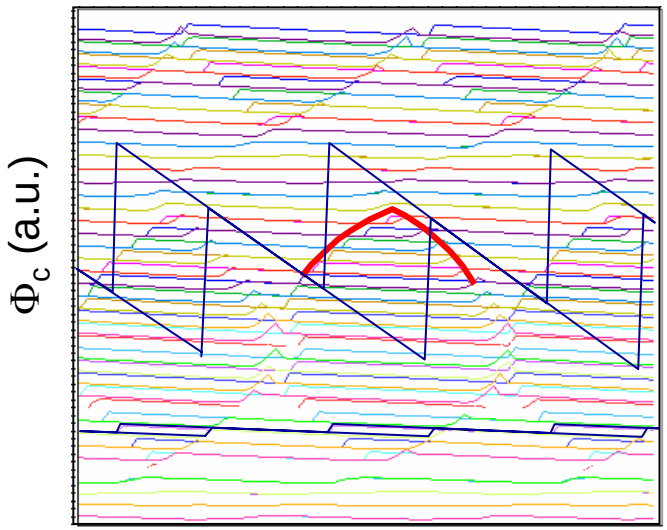


(IFN–CNR)

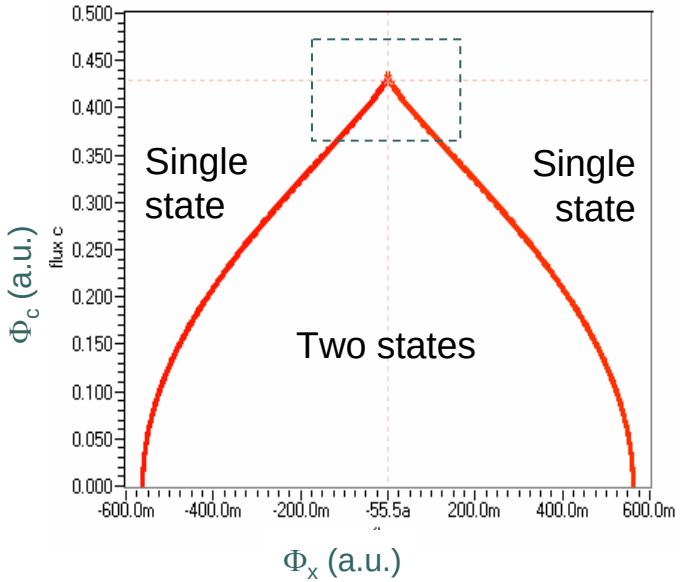
Double SQUID characteristics



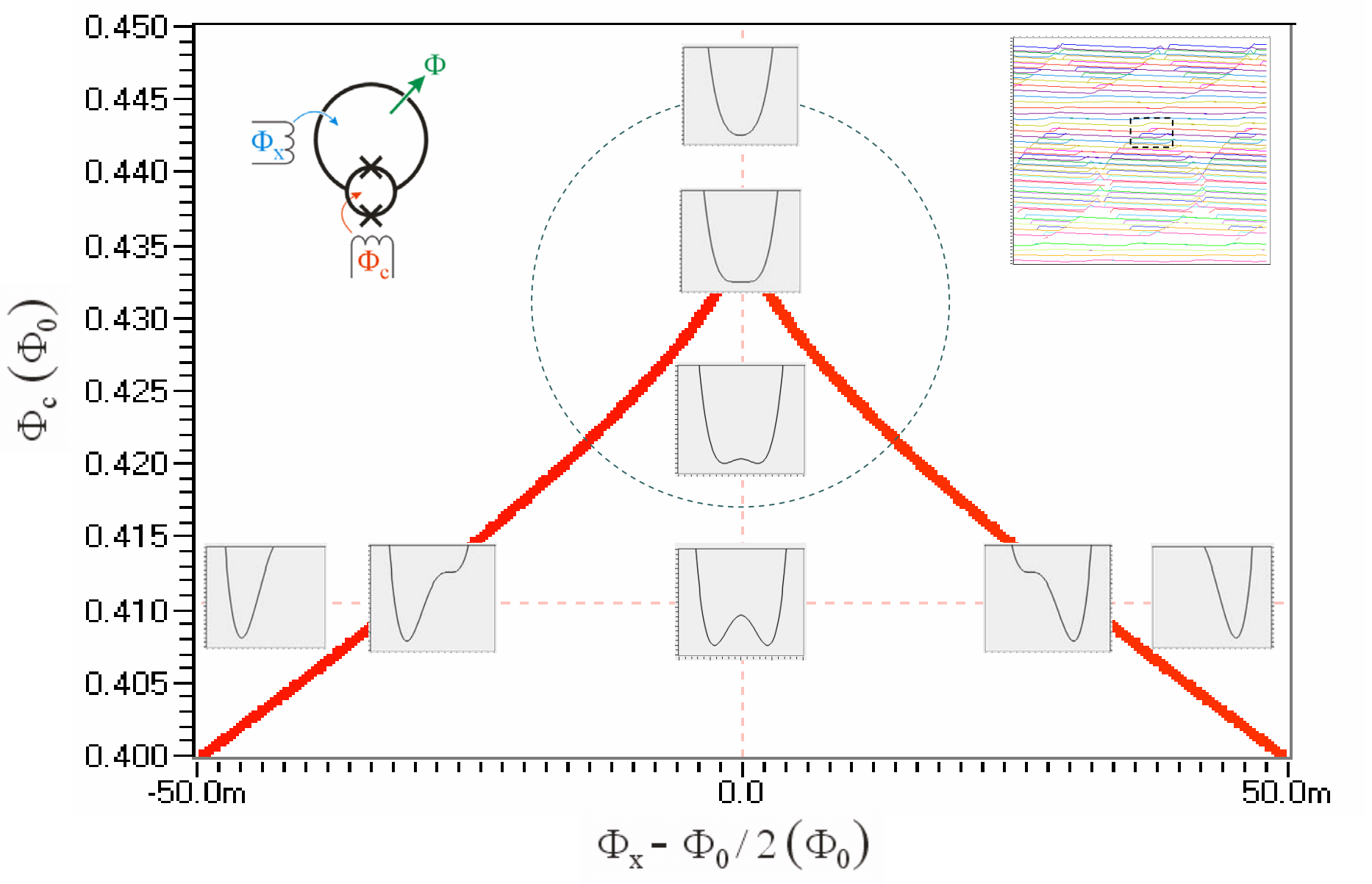
Waterfall graph for different Φ_c



Positions of jumps in the Φ_x – Φ_c plane



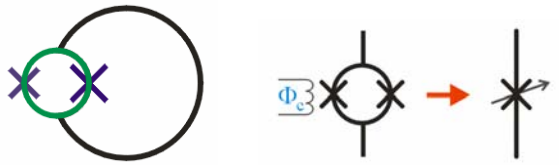
Double SQUID characteristics



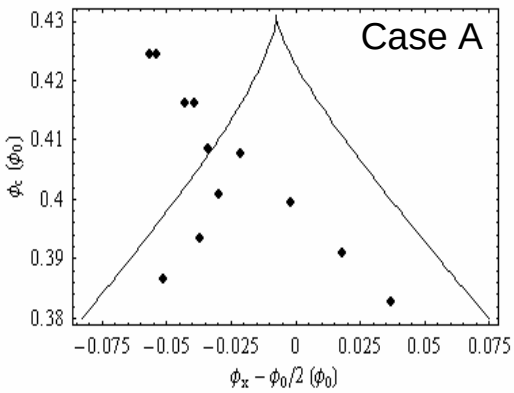
Non ideal behaviour

Non-ideal behaviour:
Visible near the cusp at low temperature (20mK).

Due to junctions asymmetry (J1≠J2)
and non zero small inductance ($\ell \neq 0$)

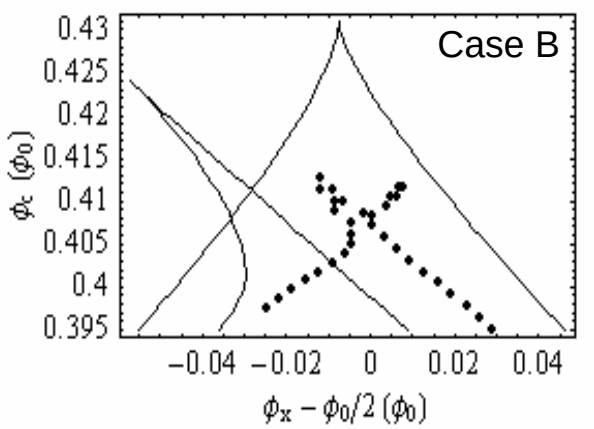


$J_1 \neq J_2$ and $\ell \neq 0$



Shallowtail catastrophe

J1≅J2 and $\ell \neq 0$



Butterfly catastrophe

Manipulation not possible

Can be solved with an optimized design (smaller J and ℓ)

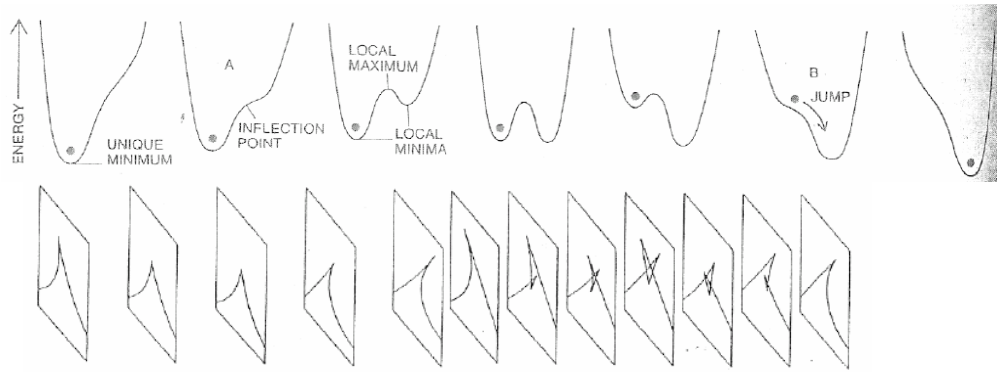
Catastrophe theory

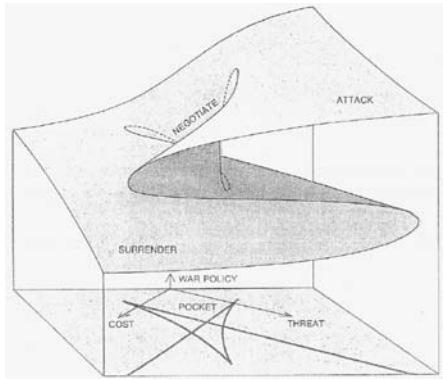
Double SQUID: Excellent and flexible catastrophe machine

Zeeman, "Catastrophe Theory", Scientific American 4, 65 (1976)

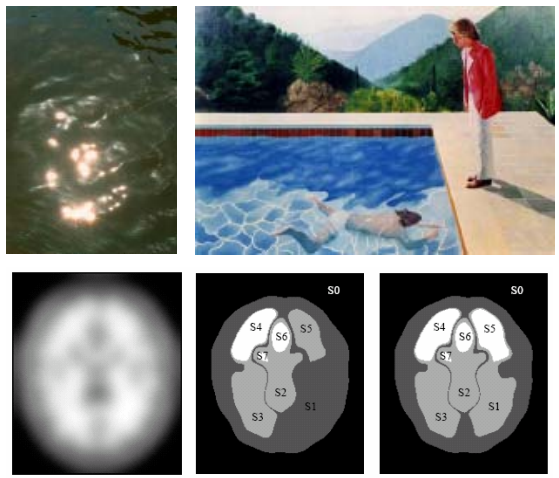
Catastrophe Theory

Zeeman, "Catastrophe Theory", Scientific American 4, 65 (1976)

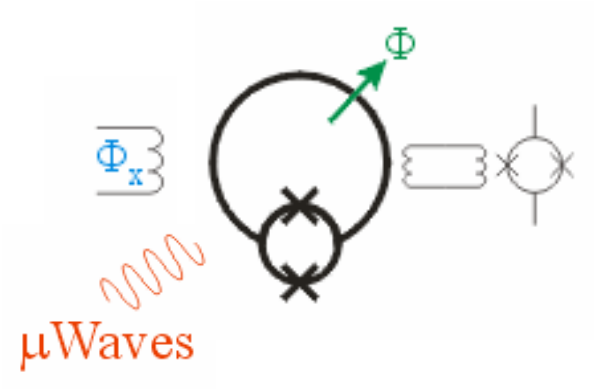


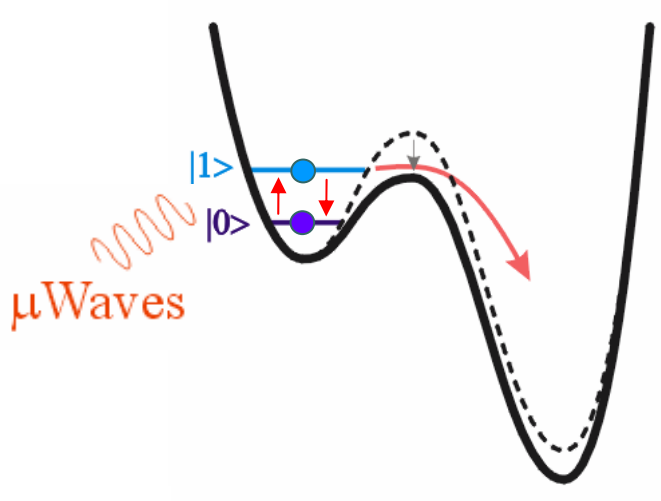


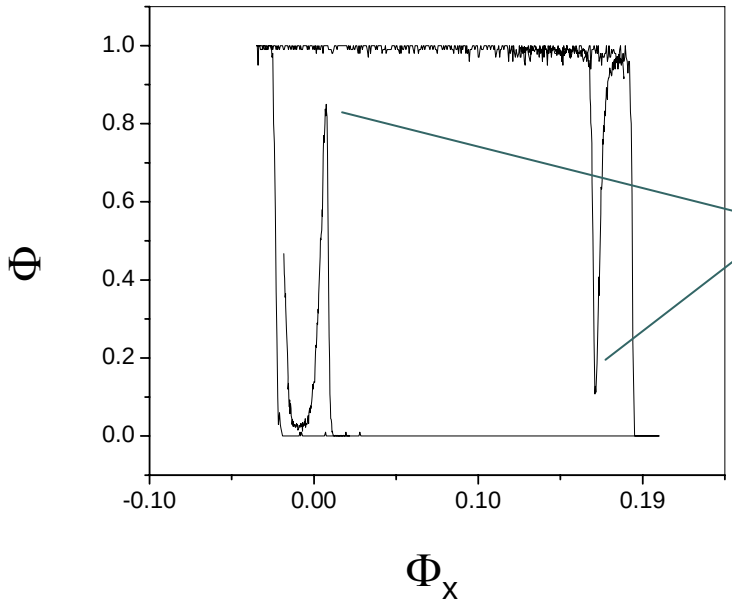
- Model of aggression (fear-rage)
- Human behavior (anxiety-frustration)
- Stock market (demand-speculation)
- Anorexia nervosa (hunger-abnormality)
- War policy (cost-threat)
- Optics (rainbow, swimming-pool caustic networks)
- Phase transitions
- Effects in colliding storage rings
- Symmetry breaking
- Electromagnetic Induced Transparency, slow-light
- Black holes
- Bose Einstein Condensates
- Image analysis
- …



rf SQUID "phase" qubit







Resonances
$h\nu=E_1-E_0$

⇒ T2~5ns ⇒

1. Bad filtering (can be improved)
2. Noise on Φ_x
3. Noise on Φ_c

Improvements: flux trapping circuit

-**Problem:**

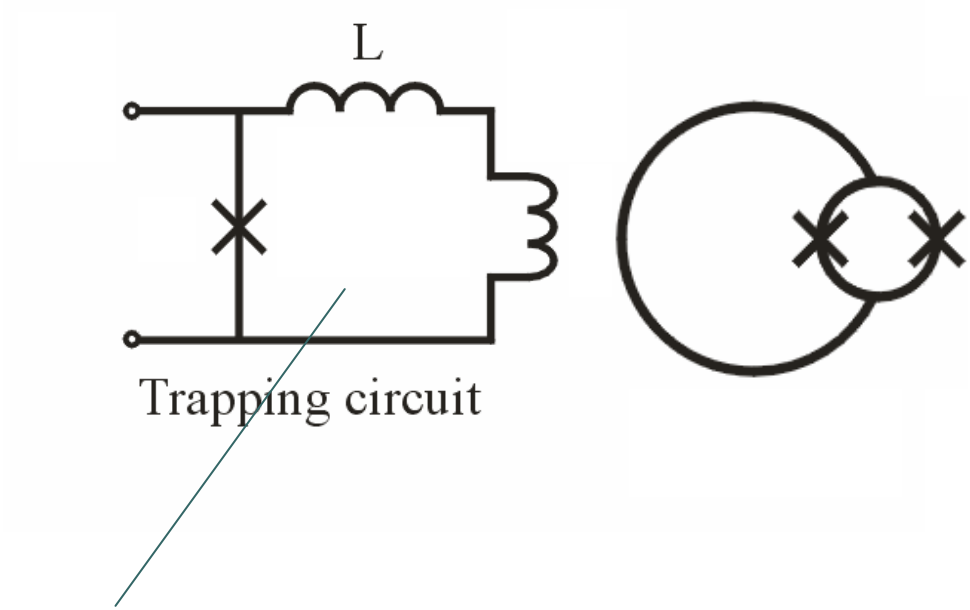
-double SQUID very sensitive to small fluxes

small control signal $\Rightarrow$ weak coupling $\Rightarrow$ coherence ☺

large ($\Phi_0/2$) bias required $\Rightarrow$ strong coupling $\Rightarrow$ decoherence ☹

-**Solution:**

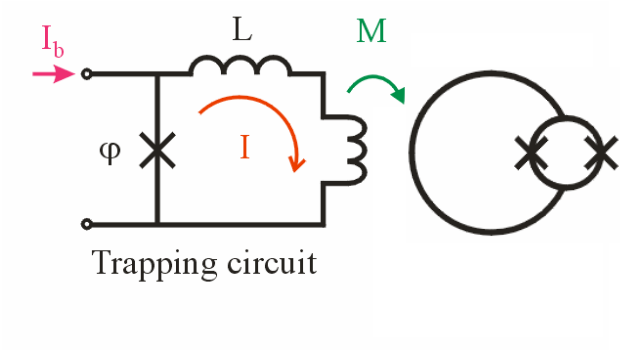
-superconducting trapping circuit for the constant bias

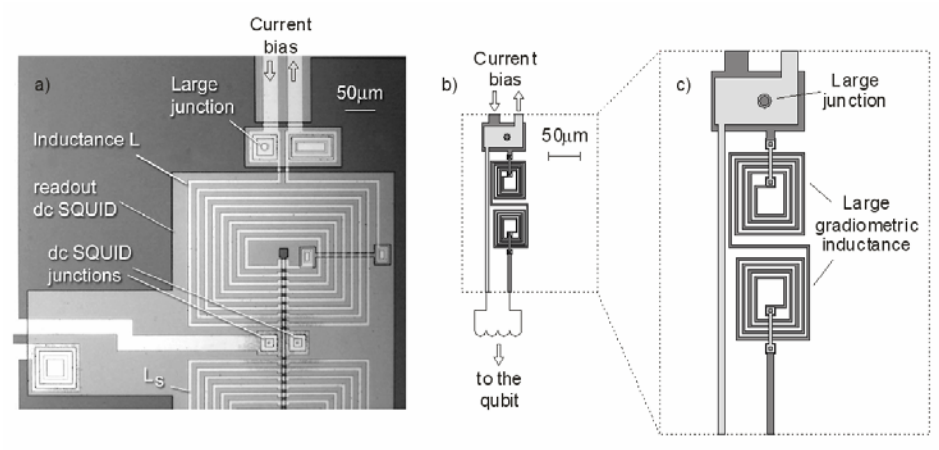


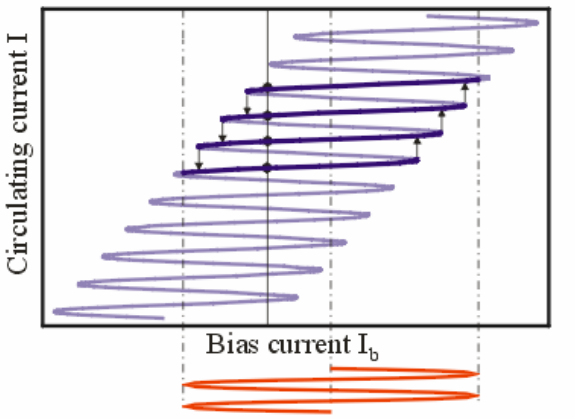
$LJ >> \Phi_b$

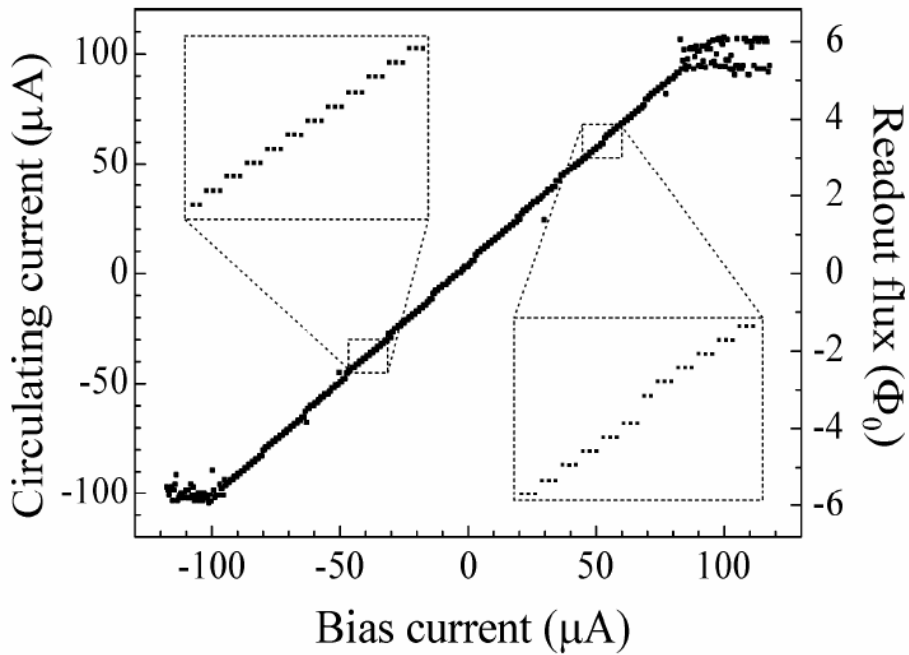
-Constant supercurrent I trapped in the circuit with no external bias

Improvements: flux trapping circuit







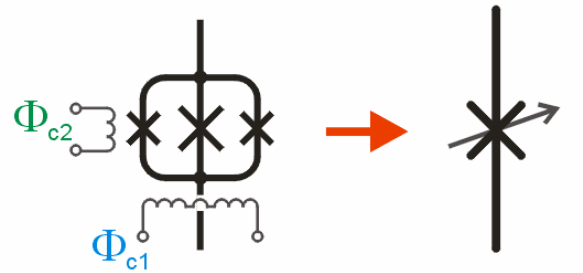


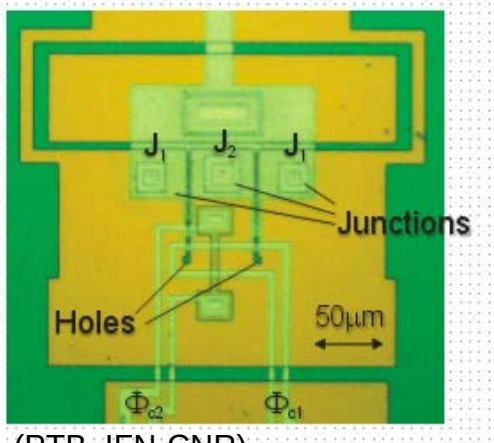
Improvements: Tunable Josephson device

Improvement of the tunable element:

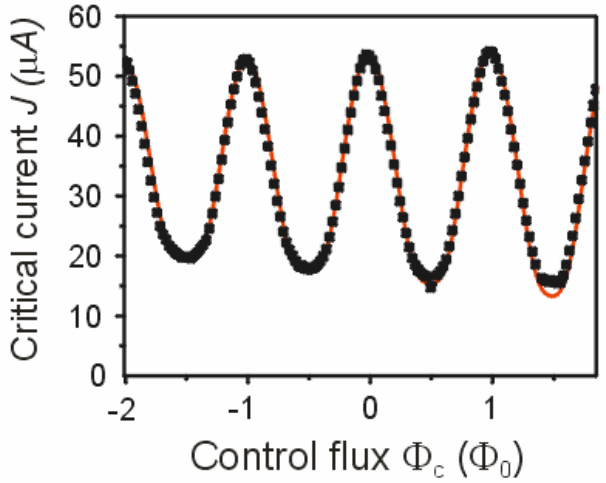
Switching between flat “quiet” points

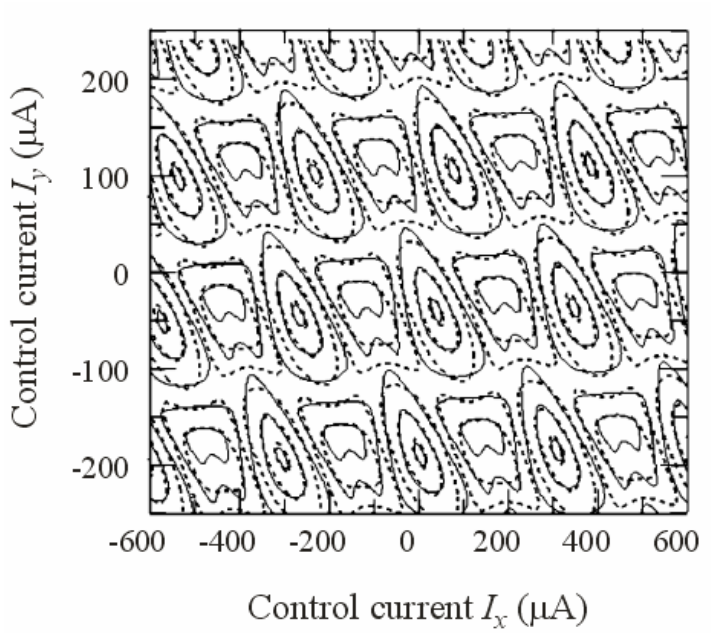
Improvements: Tunable Josephson device



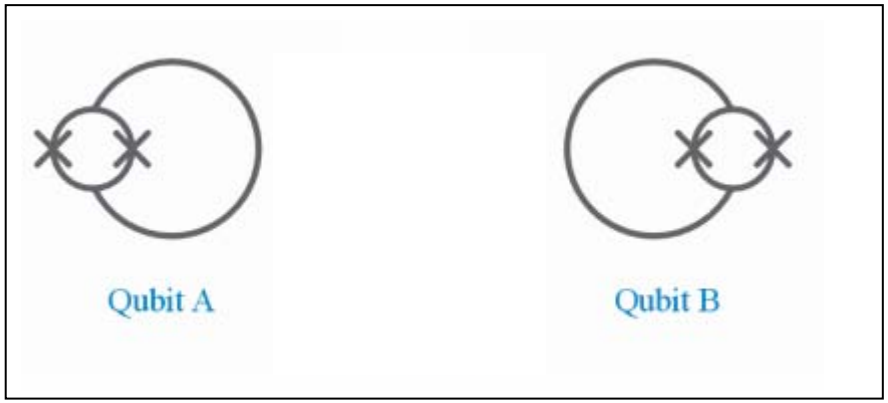


(PTB, IFN-CNR)

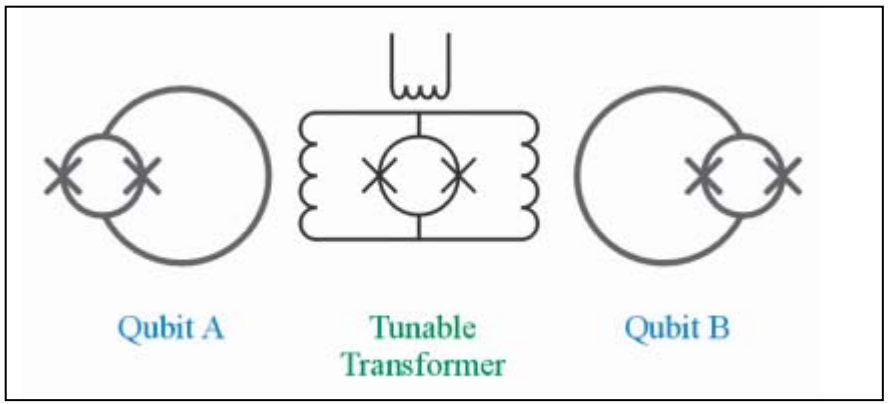




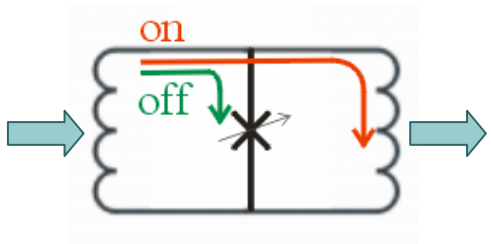
Coupling/entanglement of flux qubits



Coupling of two qubits by a superconducting transformer

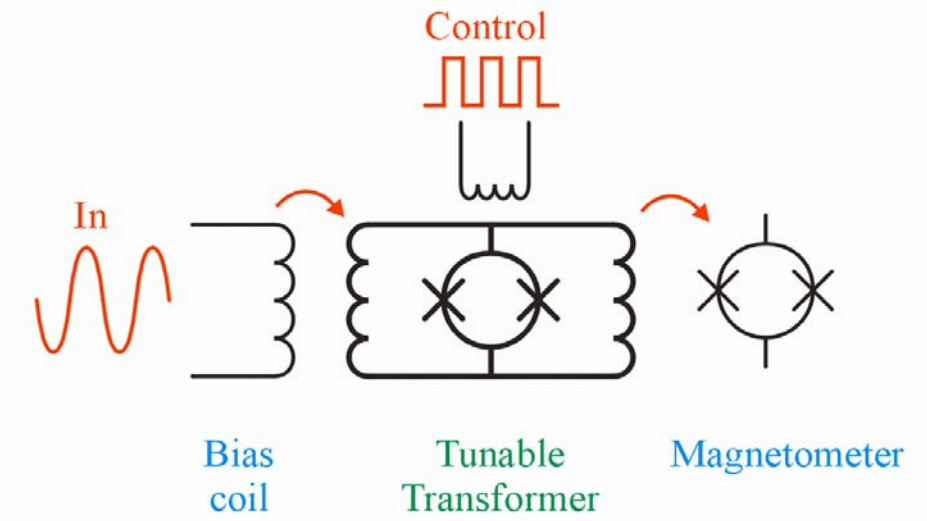


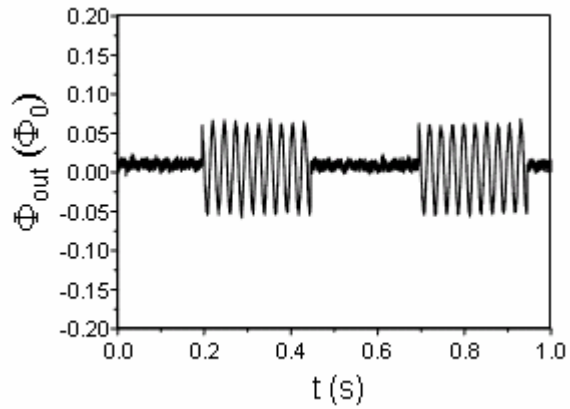
Switchable Coupling of two qubits by a tunable superconducting transformer

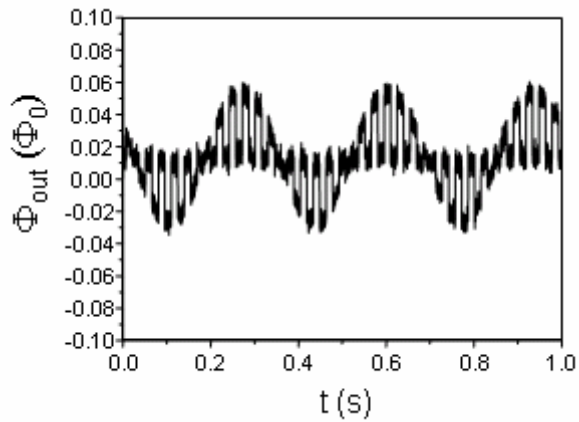


Switchable coupling

Tunable transformer tested at 4.2K
Measured On/Off ratio ~ 40

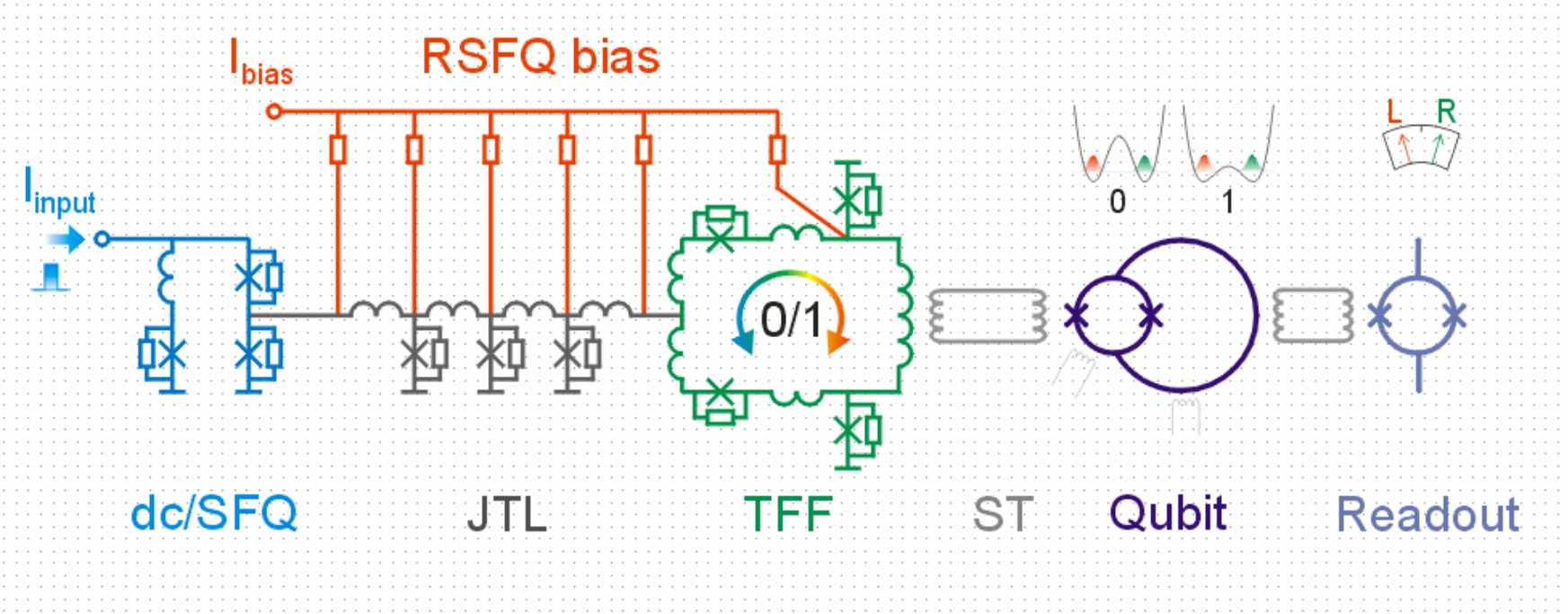




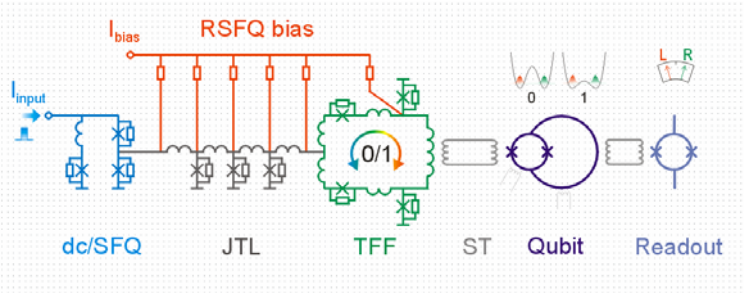


RSFQ quantum computing

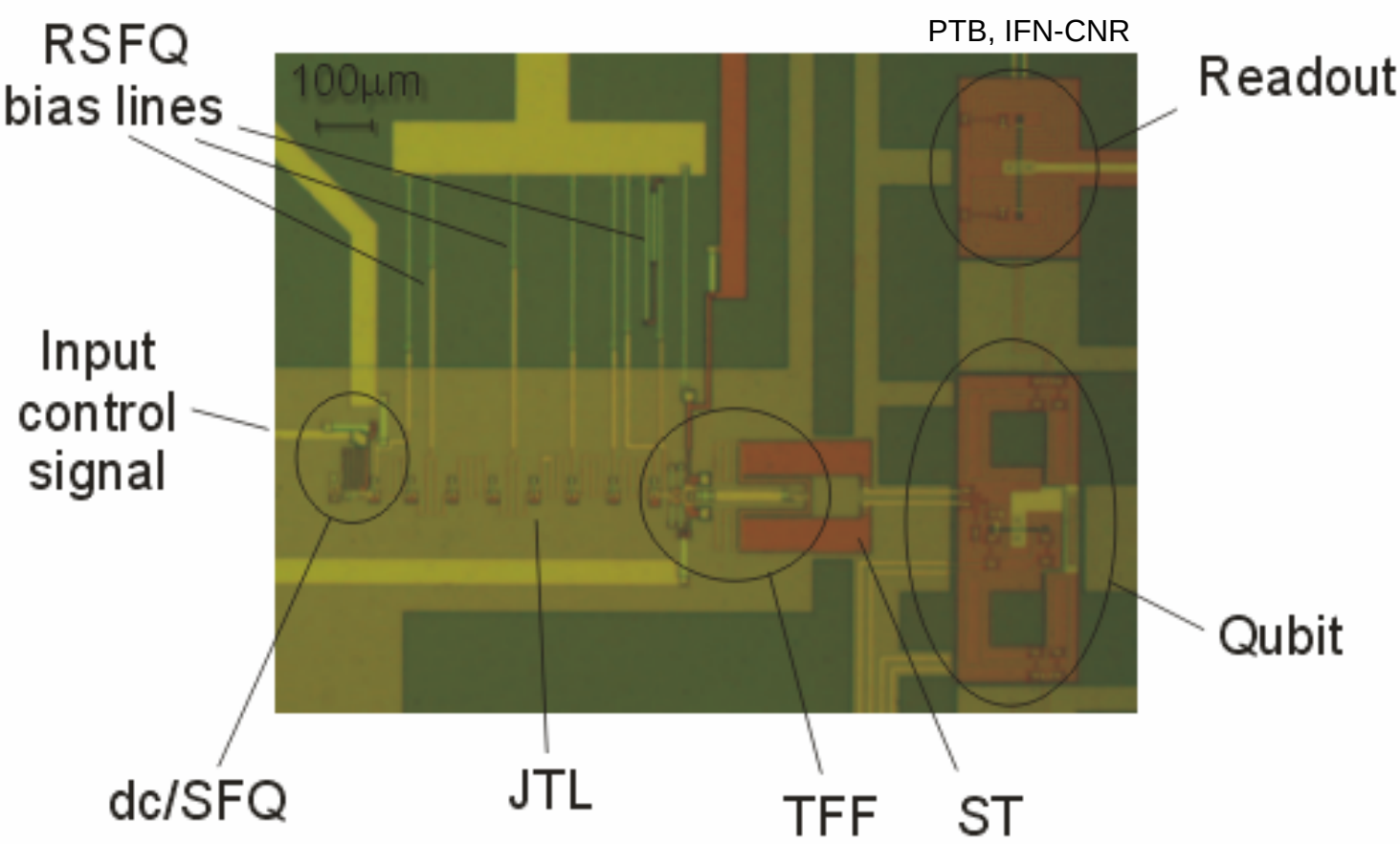
- Rapid Single Flux Quantum (RSFQ) logic: well developed ultrafast (~100GHz) classical digital logic based on Josephson devices and single flux quanta
- Ideal for the control of Josephson qubits



RSFQ quantum computing



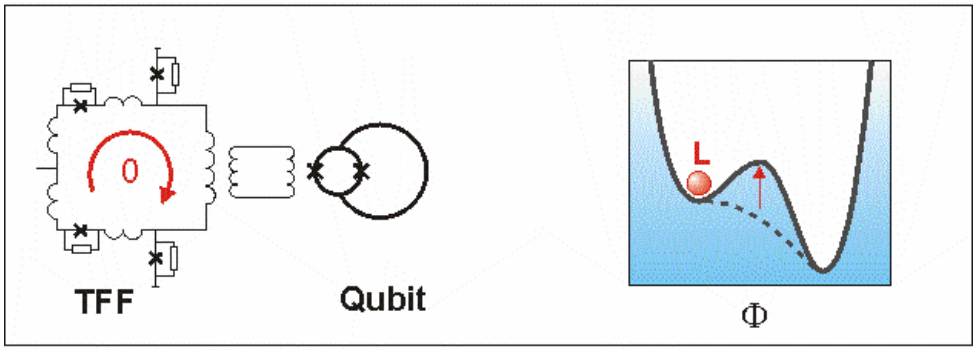
PTB, IFN-CNR

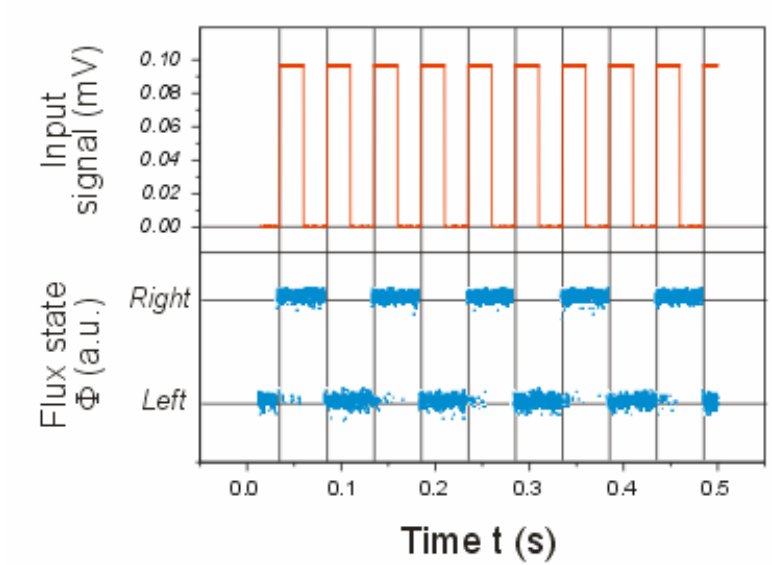


RSFQ control of a double SQUID qubit

- Devices tested at 300mK

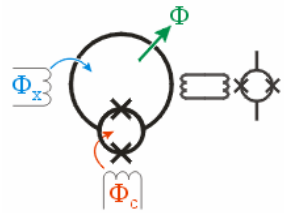
Barrier enhanced by the TFF state “0”
System remains in left state.

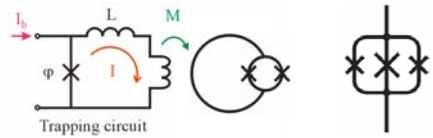


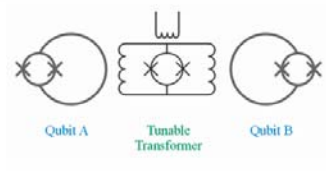


Conclusions

- **The double SQUID qubit**
  - ☺: manipulation, readout, large scale integration
  - ☹ : insulation from the environment, decoherence
  - Technological improvements...
- **Catastrophe theory**
  - No applications, but conceptually very interesting
- **Improvements**
  - Superconducting trapping circuit
  - Three junctions switch for noise reduction
- **Couplings**
  - Switchable transformer works
- **RSFQ**
  - Interface between classical and quantum electronics
  - First encouraging results







Now put all together...

Thank you