IMPLEMENTATION D 'UN BIT QUANTIQUE DANS UN CIRCUIT SUPRACONDUCTEUR

QUANTUM ELECTRONICS GROUP

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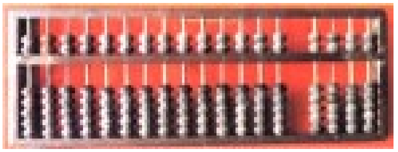
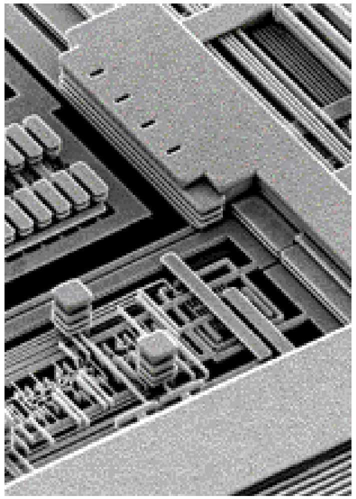
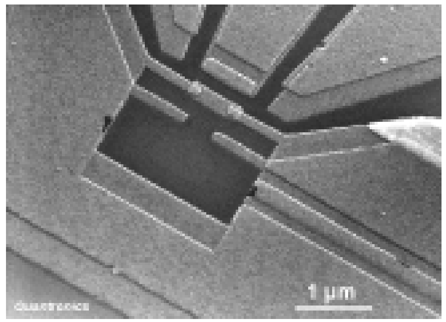
SPEC CEA-Saclay





?

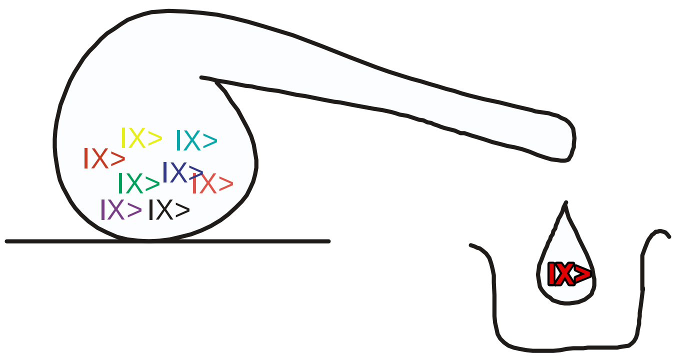


Quantum computing in a nut

Built-in parallelism... ...but readout projects

Ix> + Iy> + Iz> + .. → **Quantum processor U** → U Ix> + U Iy> + U Iz> + .. → **Projection** → Iy>

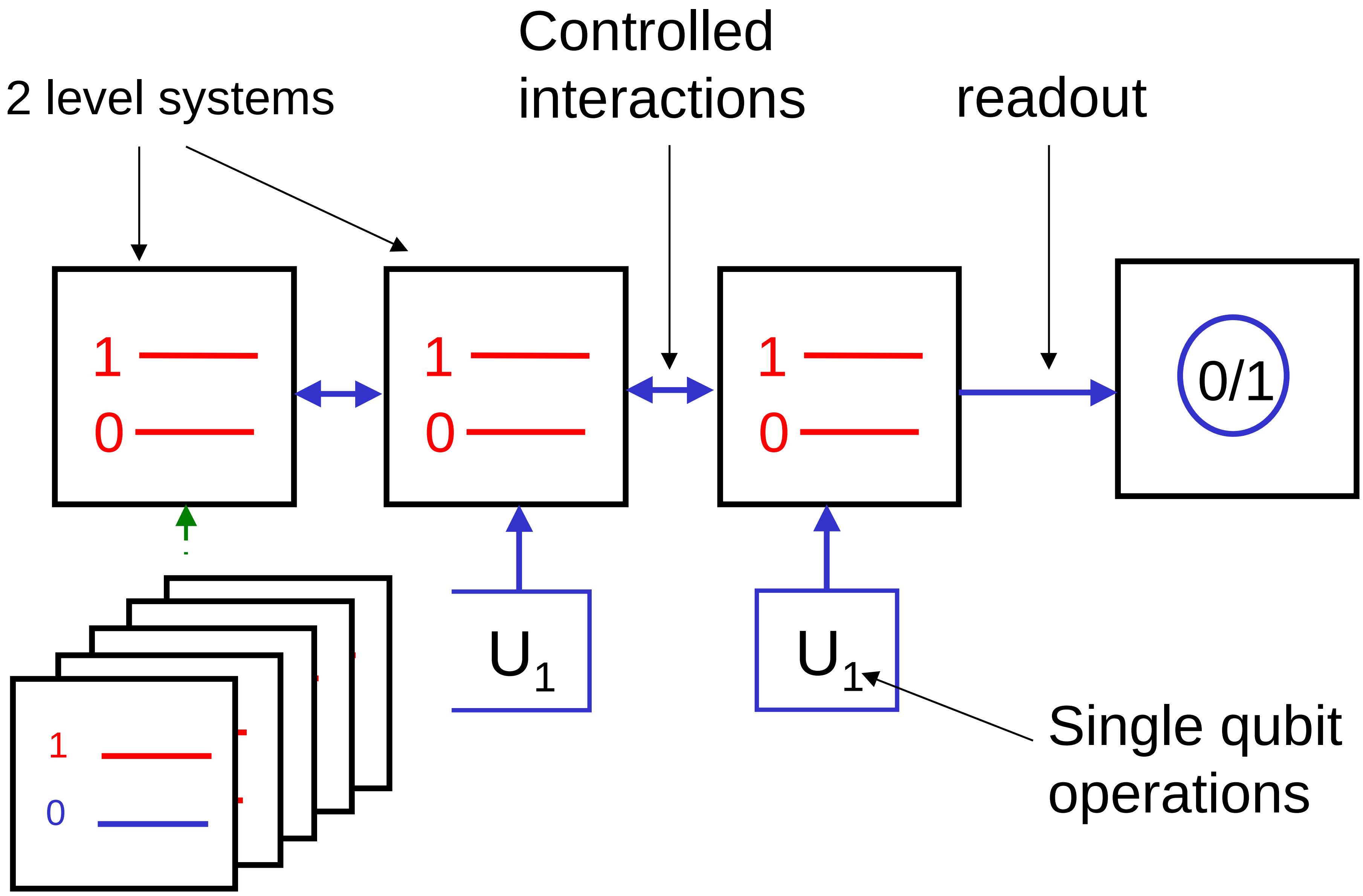
Quantum algorithms AND error correcting codes (Shor,…,1996)



the art of quantum distillation

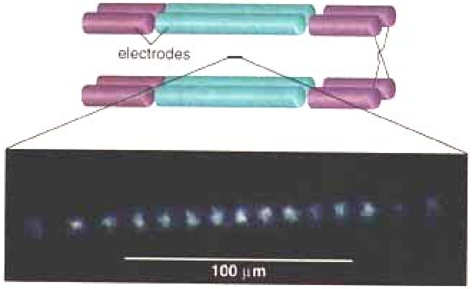
- Factorisation : O[(Log N)^3] (Shor, 1994)
- unstructured data base search O[N$^{1/2}$] (Grover, 1995)

Quantum processor ?



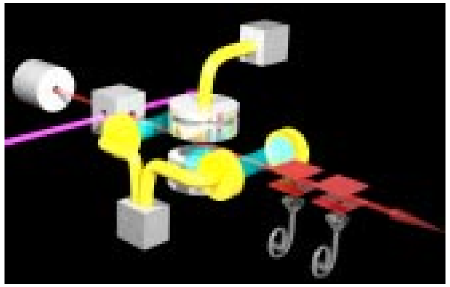
Microscopic objects vs mesoscopic systems

Trapped ions



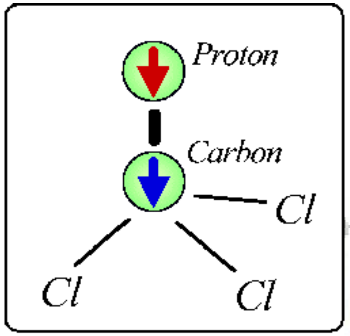
(NIST,...)

Rydberg atoms

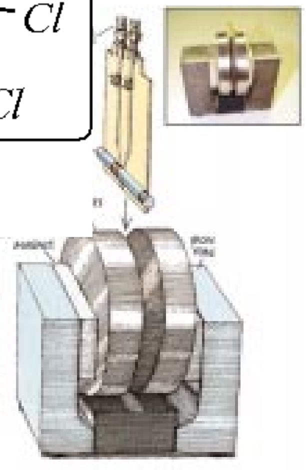


(ENS)

nuclear spins

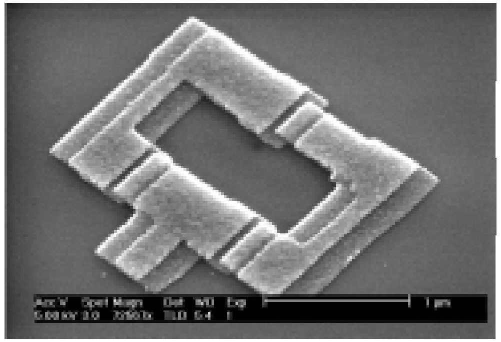


$|0\rangle|0\rangle$



(Stanford, IBM,…)

superconducting circuits

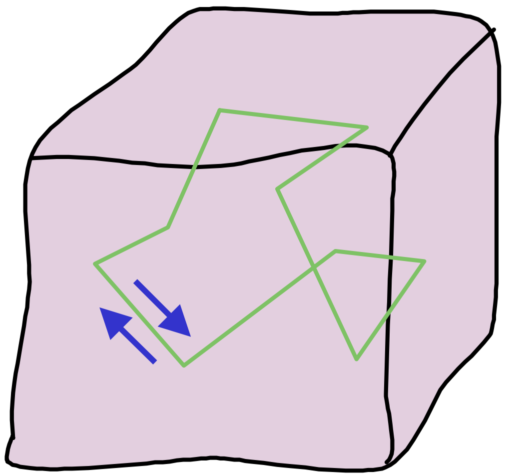


(T.U. Delft)

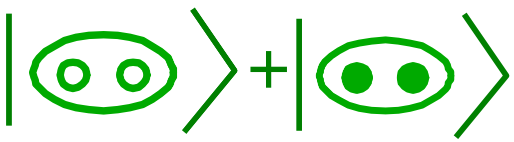
Quantum,
but not easily scalable

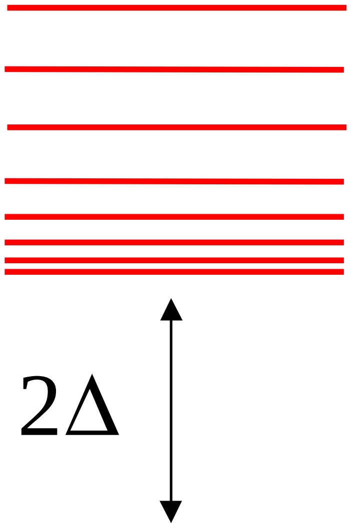
Scalable,
but not easily quantum

Energy spectrum of a superconducting electrode



All states paired

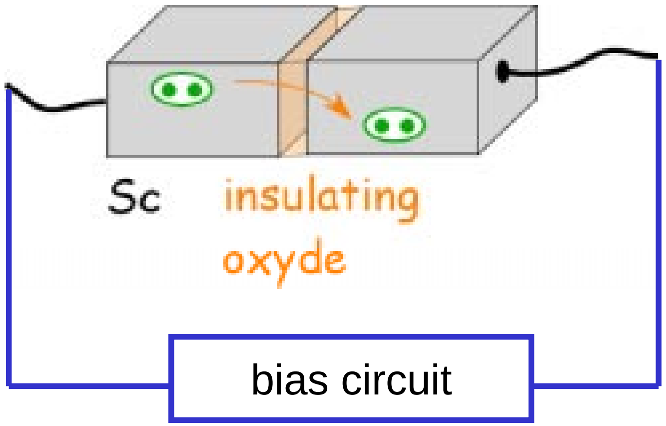


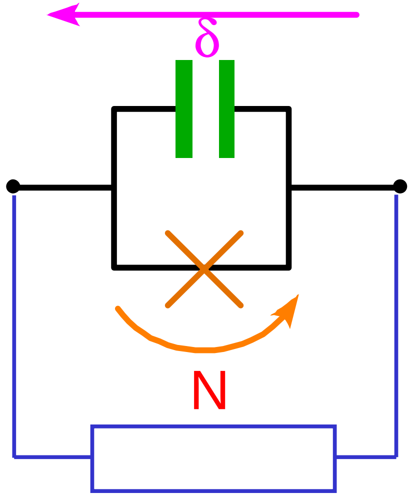


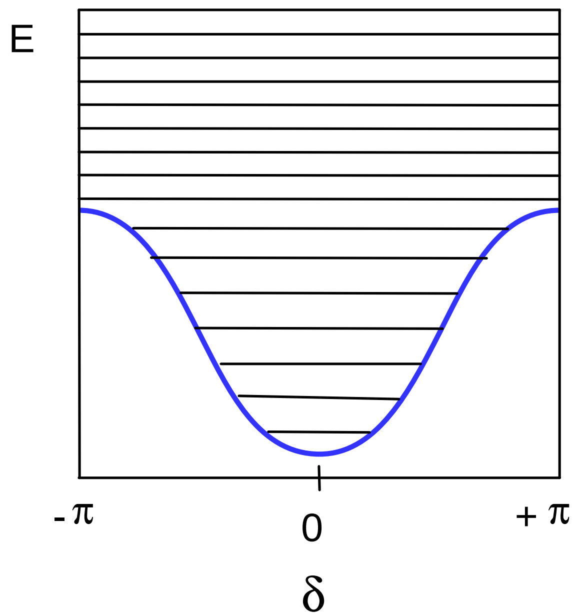
Superconducting
Condensate
Ground state

The Josephson junction

A single degree of freedom: δ $[\delta, N] = i$







Josephson hamiltonian:

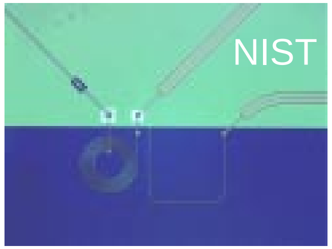
$$H_J = -E_J \cos \delta$$

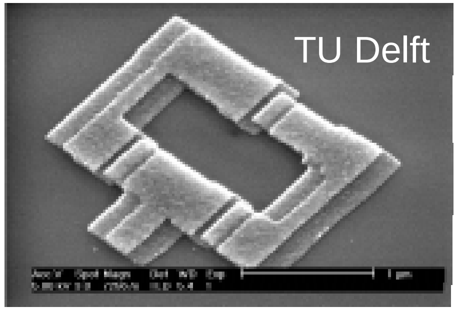
full hamiltonian:

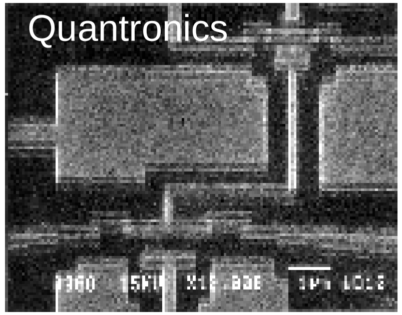
$$H = H_J + H_{elm}$$

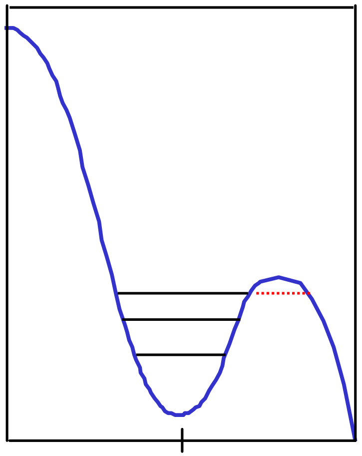
Josephson qubits

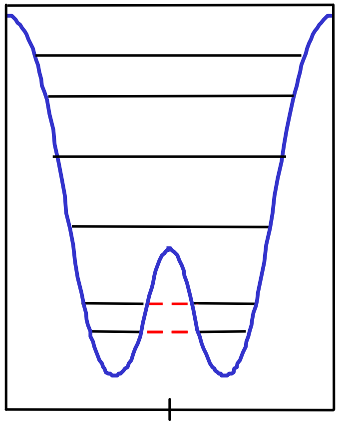
Current-biased large junction | Coupled medium-size junctions | Small junction

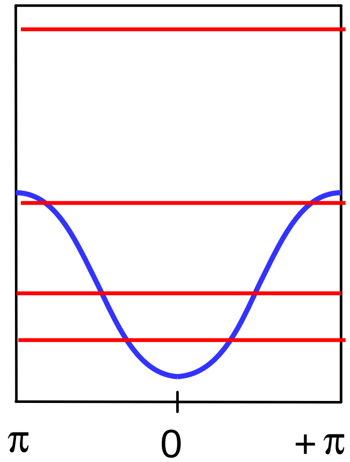


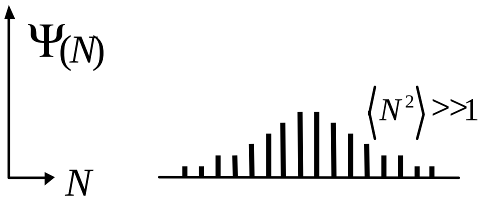




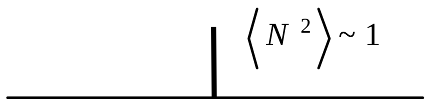








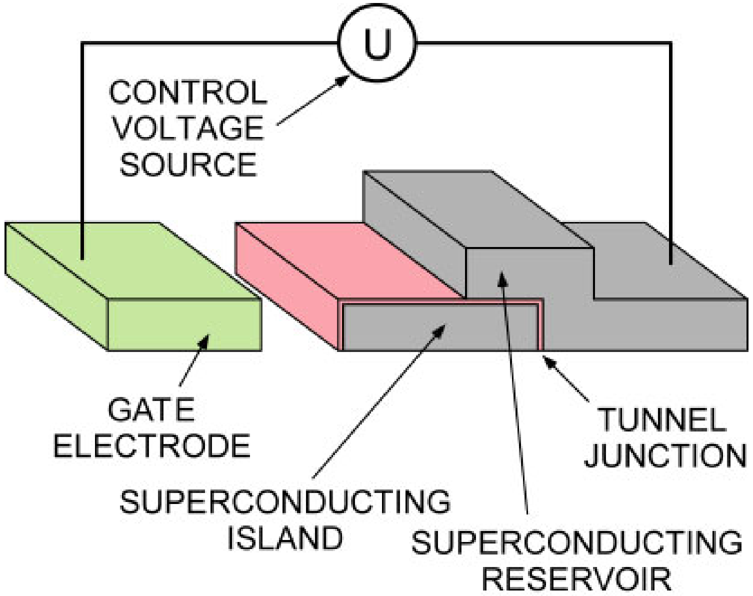
phase → charge

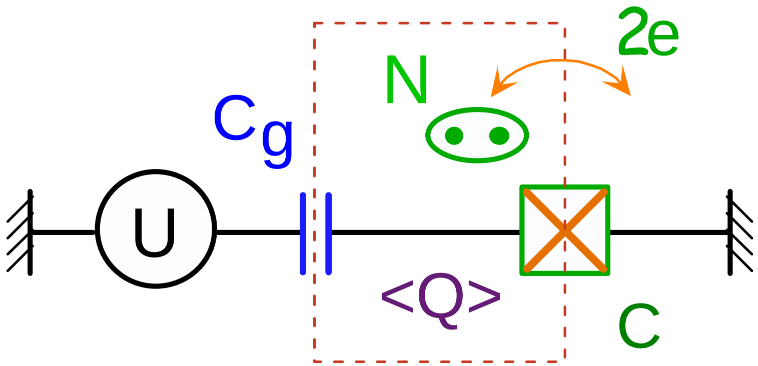


Phase state

charge state

The Cooper-pair box





$$E_c = \frac{(2e)^2}{2(C_g + C_J)}$$

E_J : $|N\rangle \leftrightarrow |N+1\rangle$

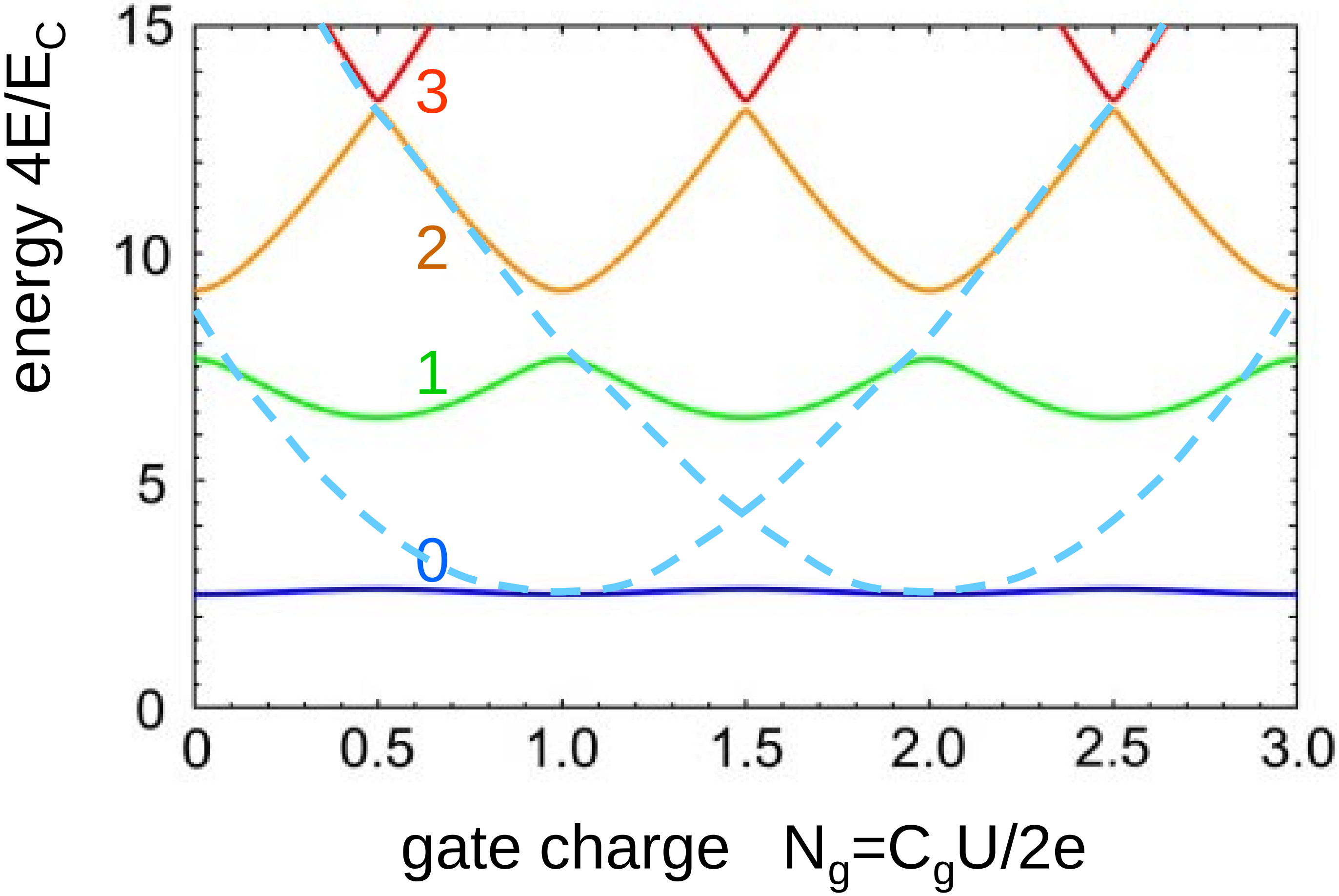
$$H = -E_J \cos\delta + E_c (N - N_g)^2$$

$\cos\delta \rightarrow 1/2 \sum_N |N\rangle\langle N+1| + |N+1\rangle\langle N|$

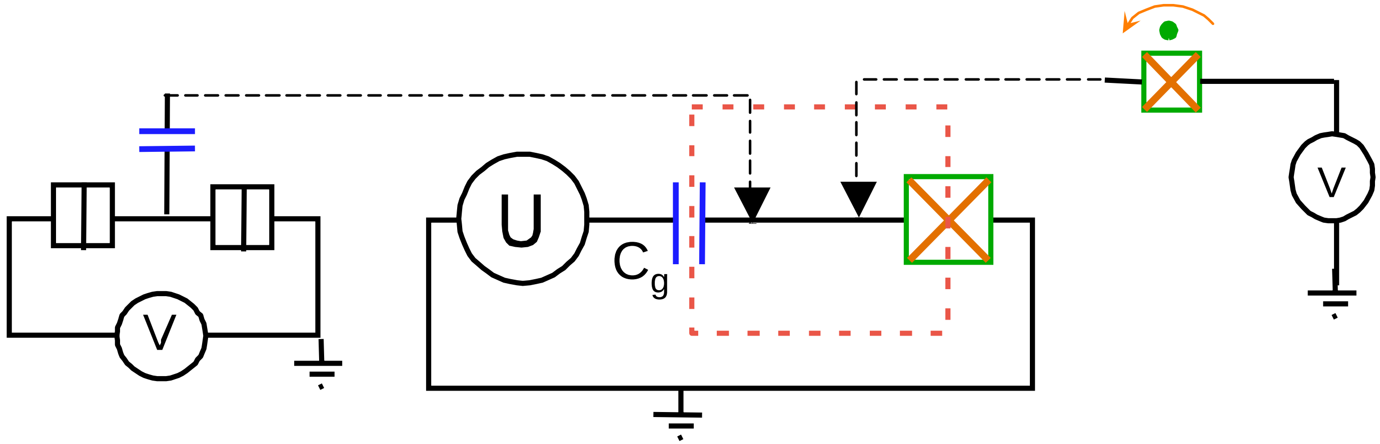
$N_g \rightarrow C_g U / 2e$

Energy levels of the Cooper pair box

($E_J/E_C=1$)

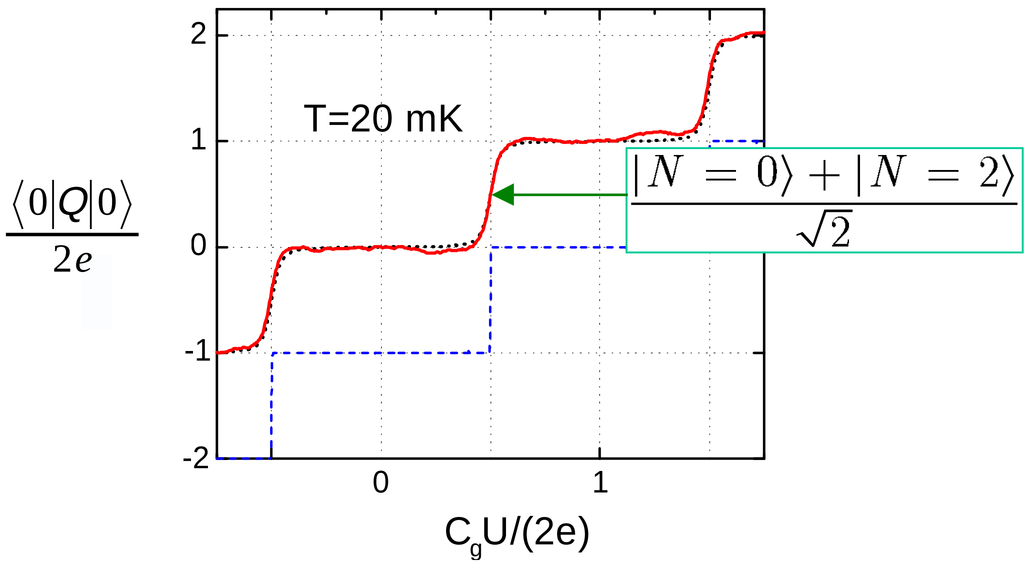


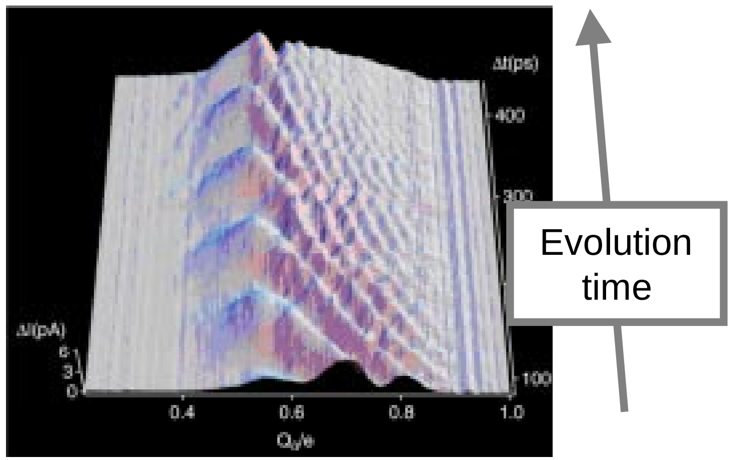
Measuring the Cooper pair box



1996 charge of ground state $|0\rangle$
(Bouchiat et al., Quantronics)

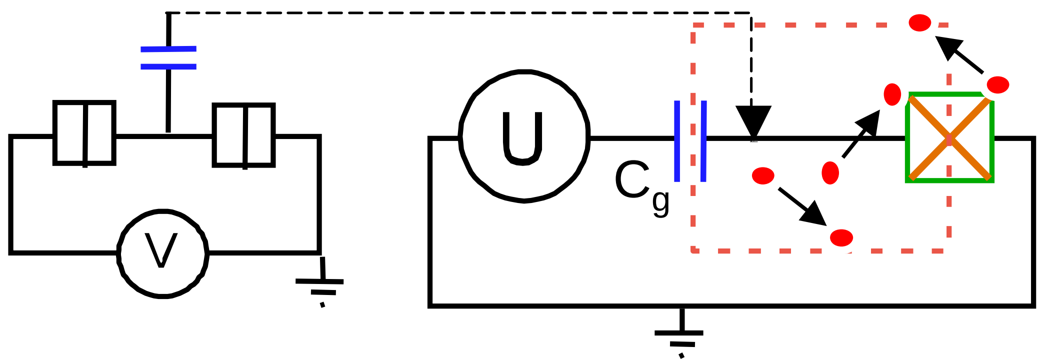
1999 coherent superpositions $\alpha|0\rangle + \beta|1\rangle$
(Nakamura, Pashkin & Tsai, NEC)





2001 ...

The charge-noise issue



$$|\psi\rangle = \frac{|0\rangle + e^{i\varphi}|1\rangle}{\sqrt{2}}$$

$$\varphi(t) = 2\pi\int_0^t \nu_{01}(t')dt'$$

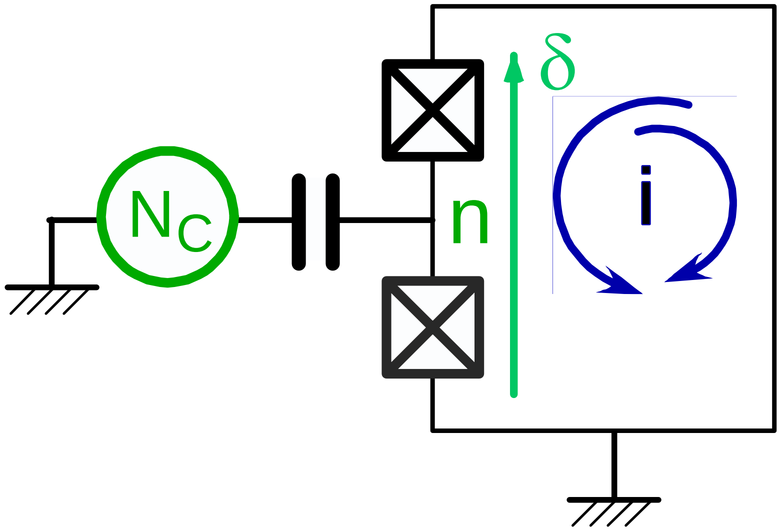
$$\nu_{01} = \bar{\nu}_{01} + \frac{d\nu_{01}}{dN_C}\delta N_C$$

signal

<Q>$_1$ - <Q>$_0$

dephasing

The splitted Cooper-pair box



CHARGE-PHASE QBIT

with
persistent current

Write on charge

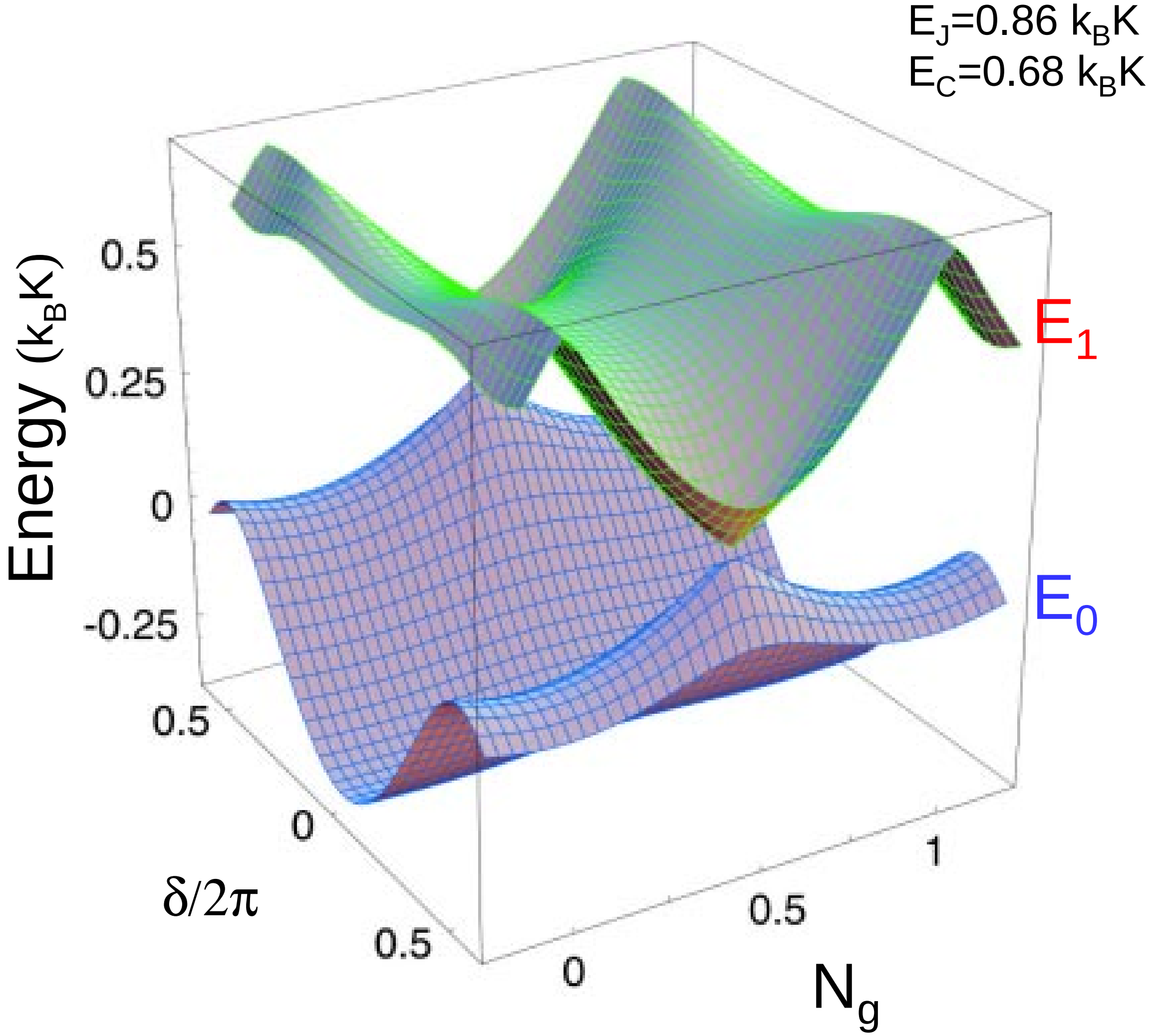
Read current

(Note: similar idea by A.Zorin)

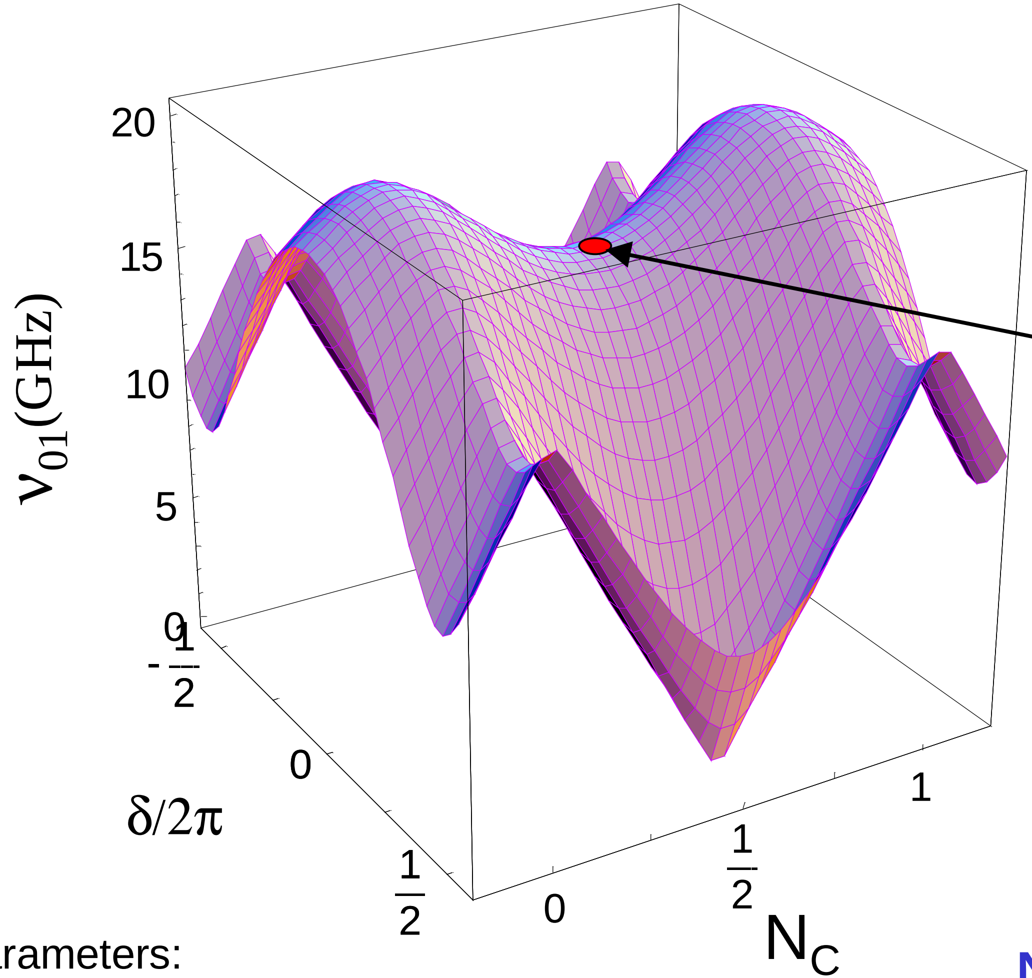
Energy levels of the splitted Cooper pair box

Effective box :

$$E_{Jeff} \simeq E_J \left|\cos(\delta/2)\right|$$



Transition frequency



At saddle point :

$d\nu_{01}/dN_C = 0$
$d\nu_{01}/d\delta = 0$

$$\varphi(t) = \int_0^t \nu_{01}(t')dt' \simeq \nu_{01}\, t$$

No random dephasing
(at 1st order)

Parameters:

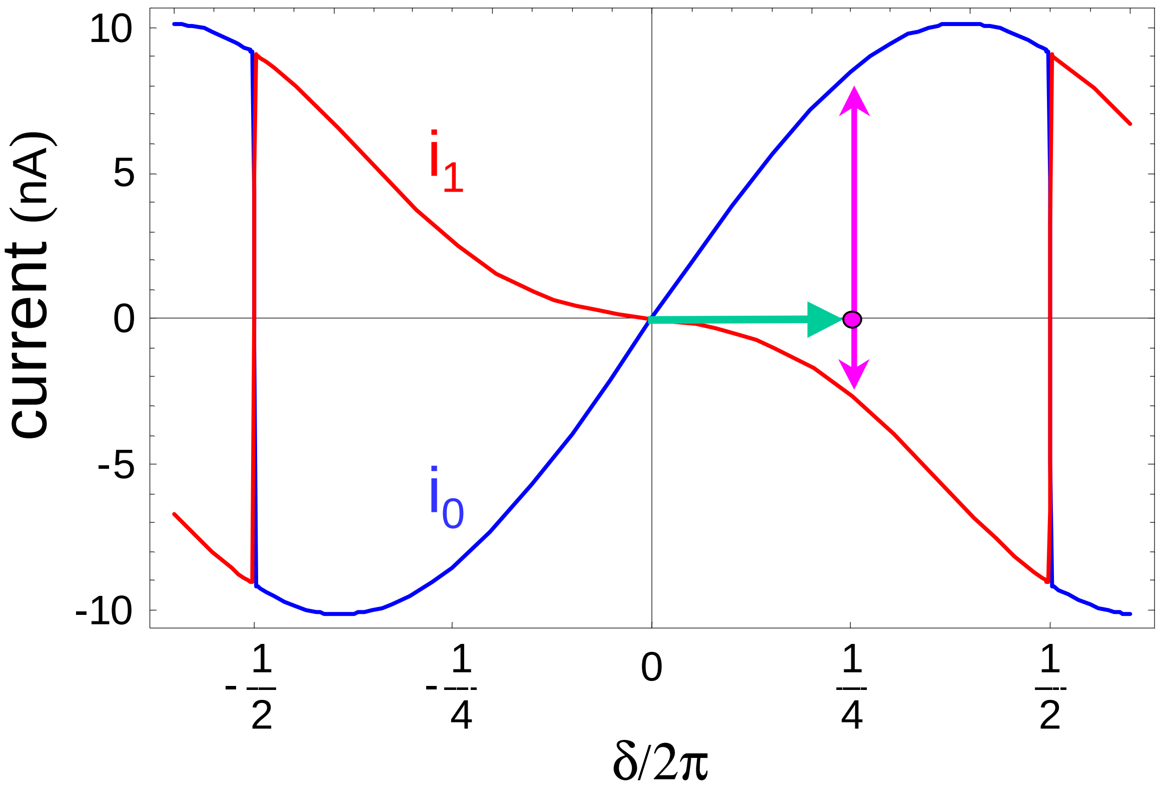
$E_J = 0.86\ k_B K$
$E_C = 0.68\ k_B K$

Measurement strategy

$N_C = 1/2$

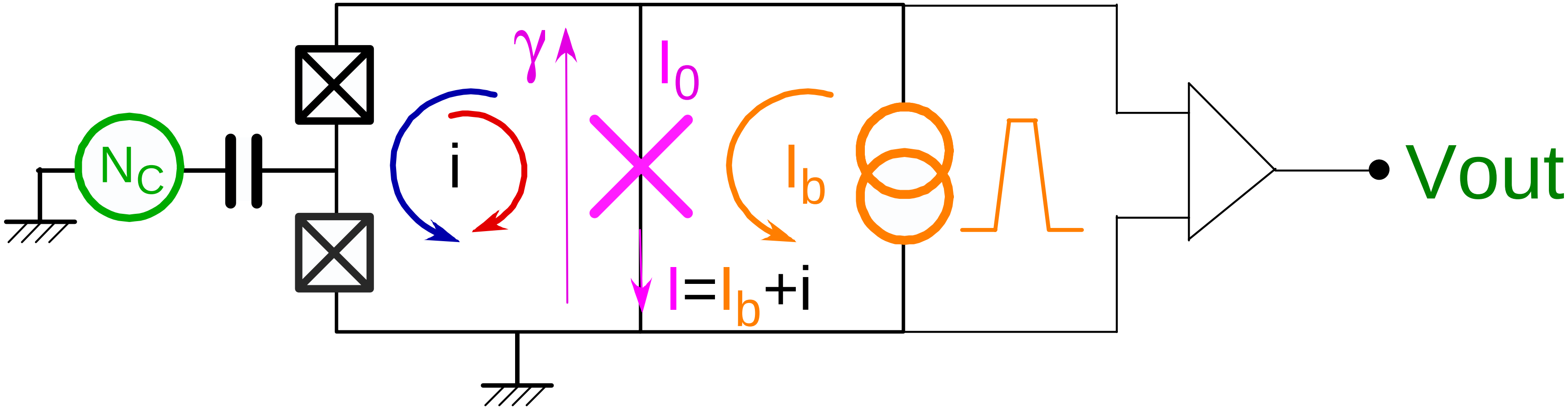
E_J=0.86 k_BK
E_C=0.68 k_BK

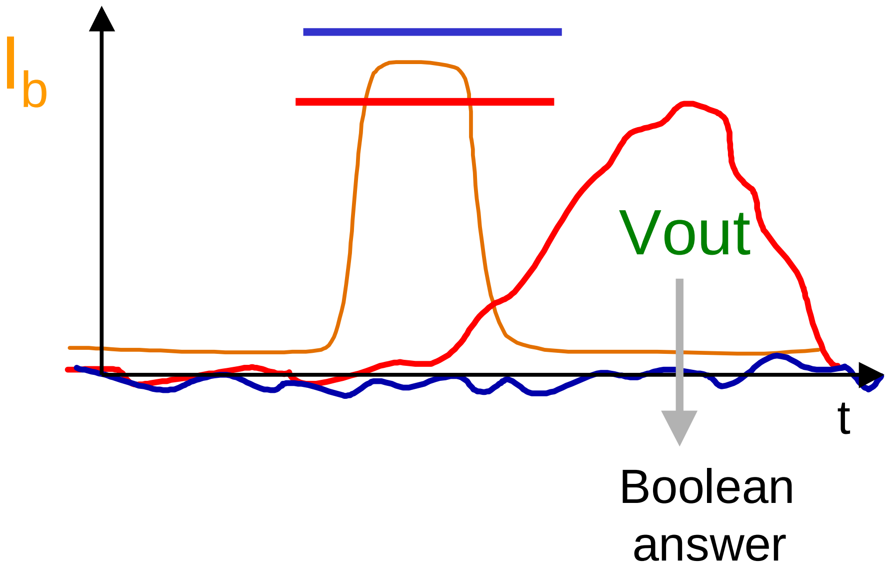
ADIABATIC TRANSFER
TO MEASURING POINT

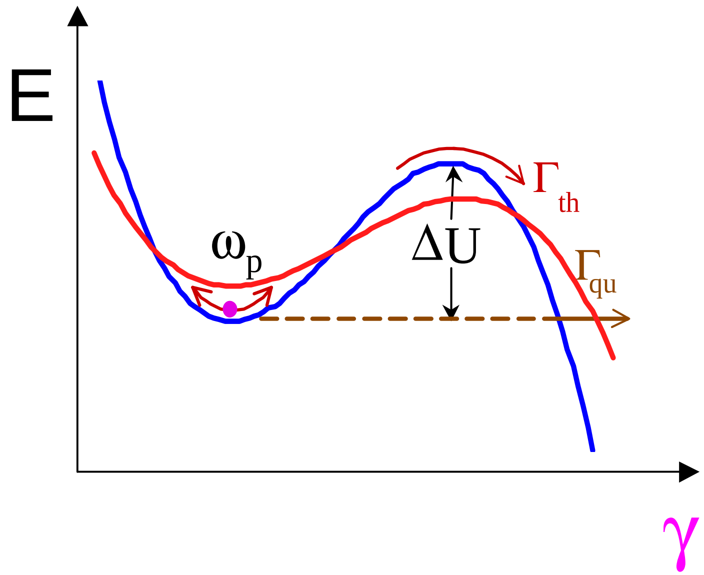


SIGNAL
$i_1 - i_0$
~ 10 - 20 nA

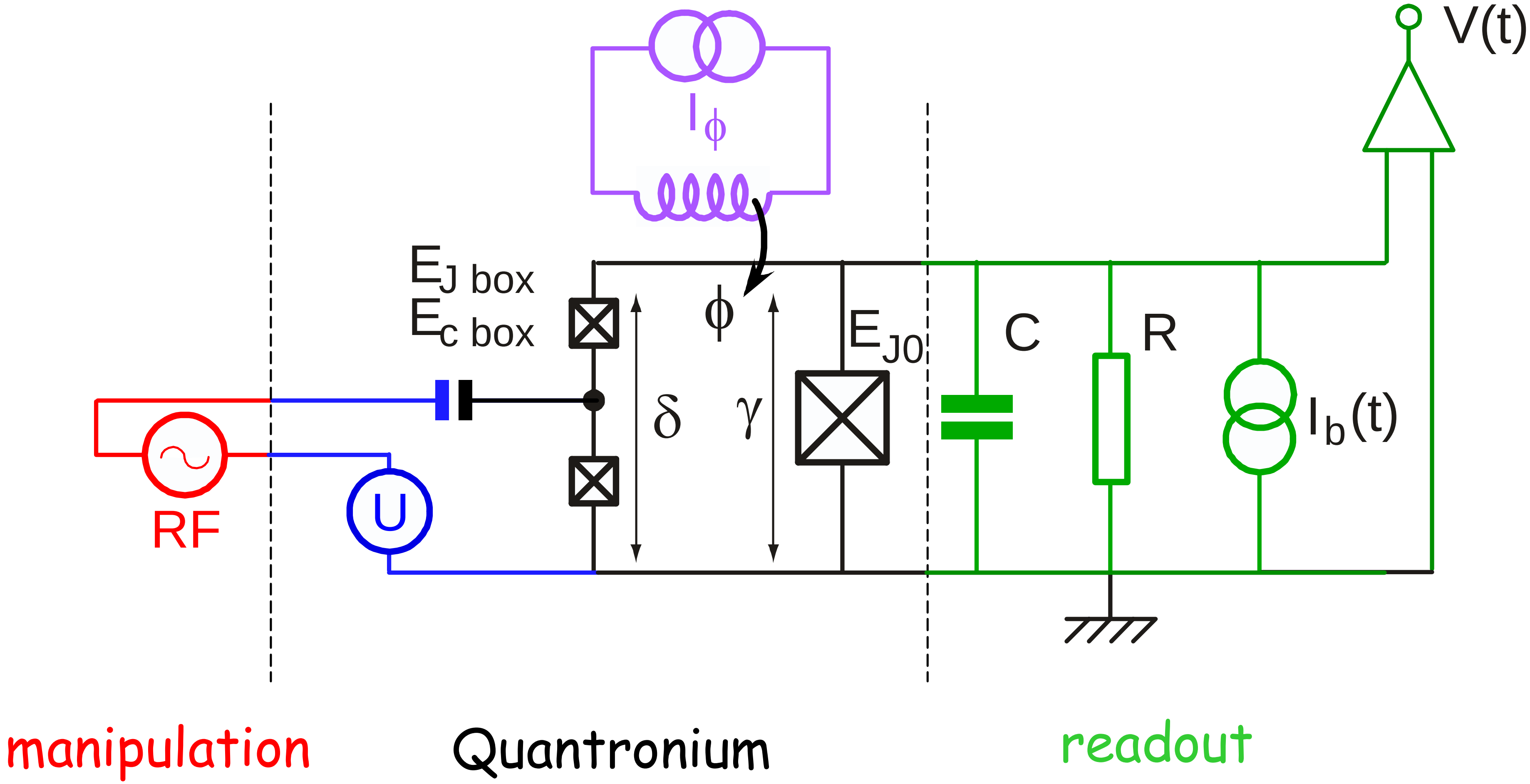
Entangling the qubit with an extra junction



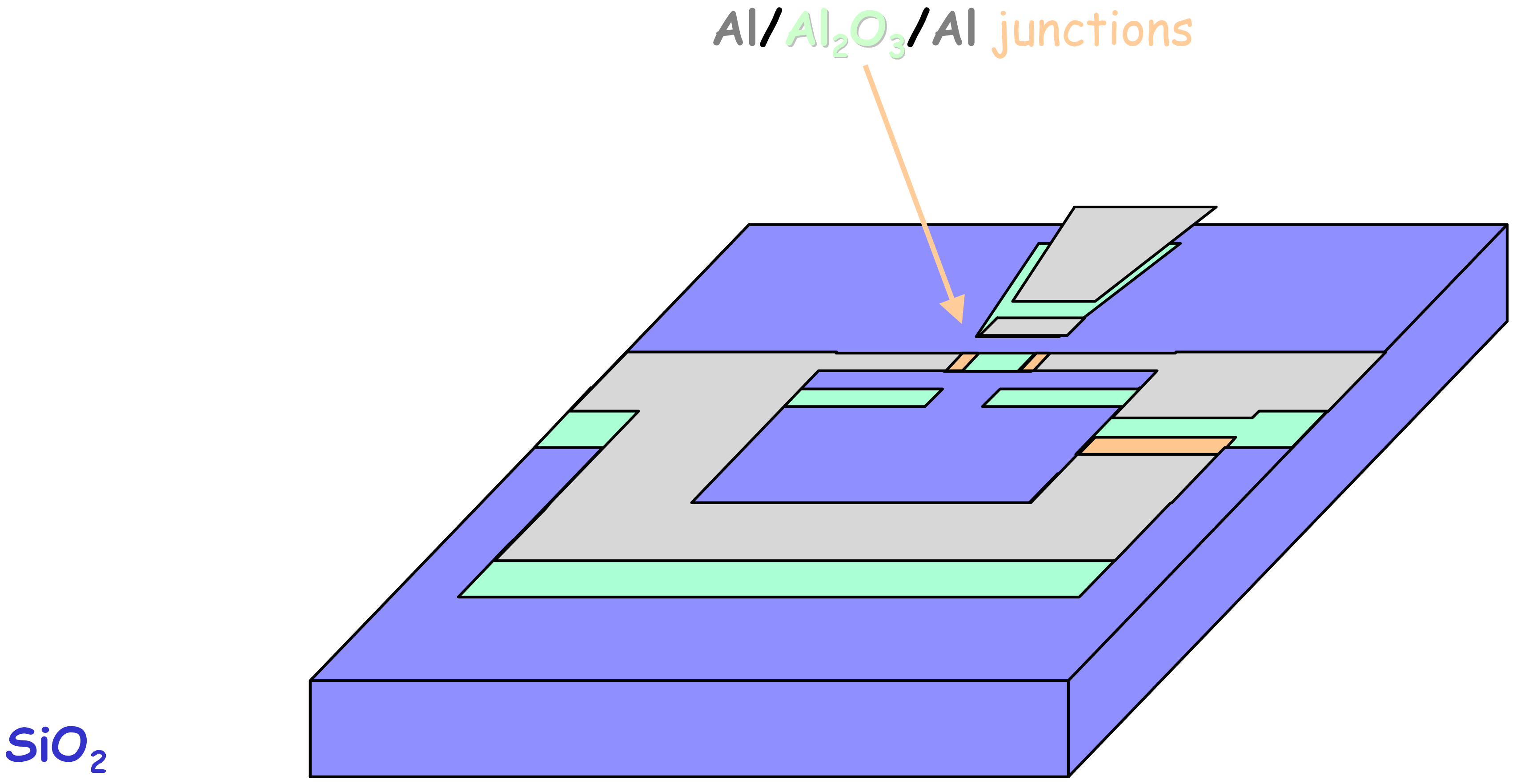




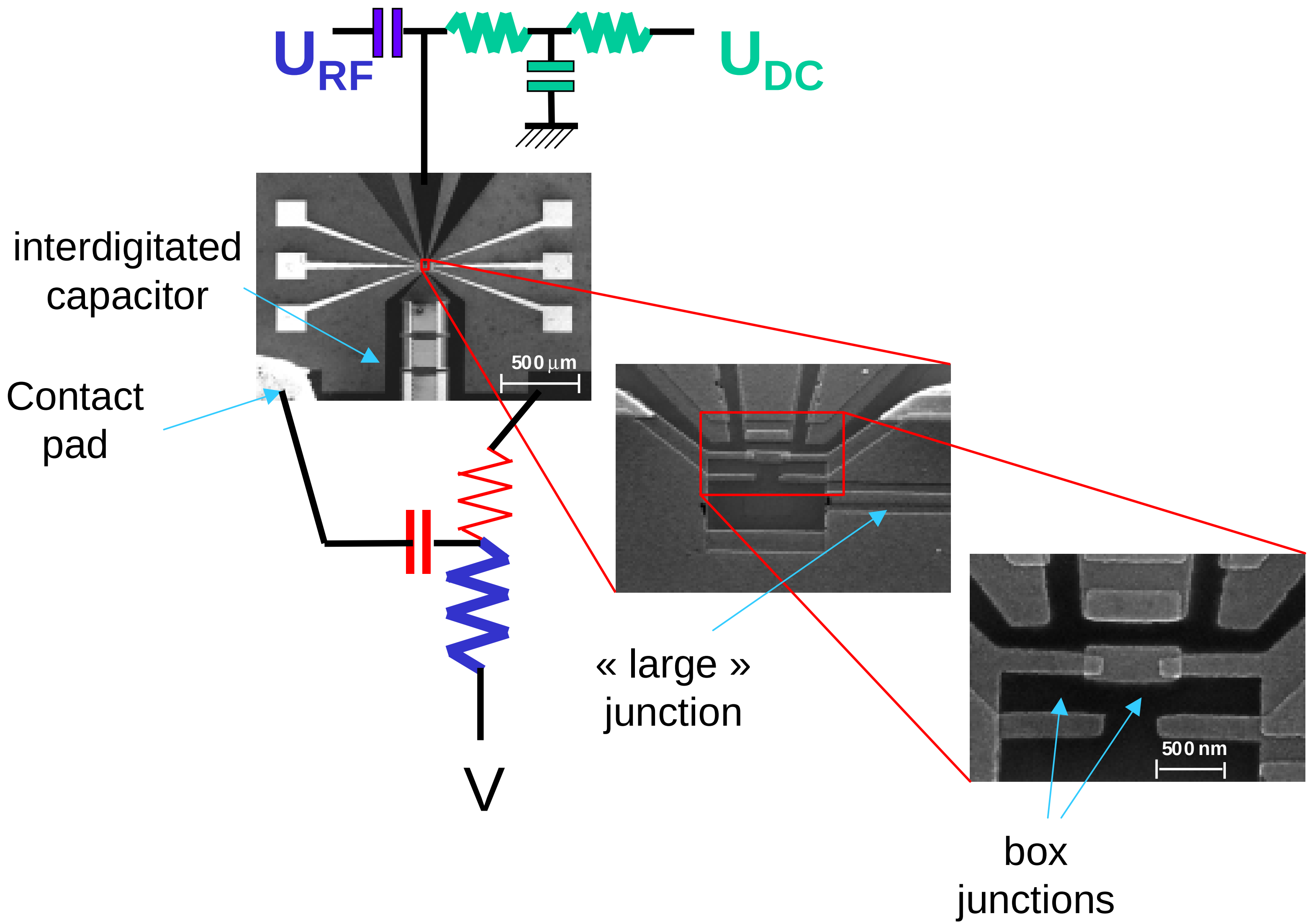
The "Quantronium" circuit



Fabrication process

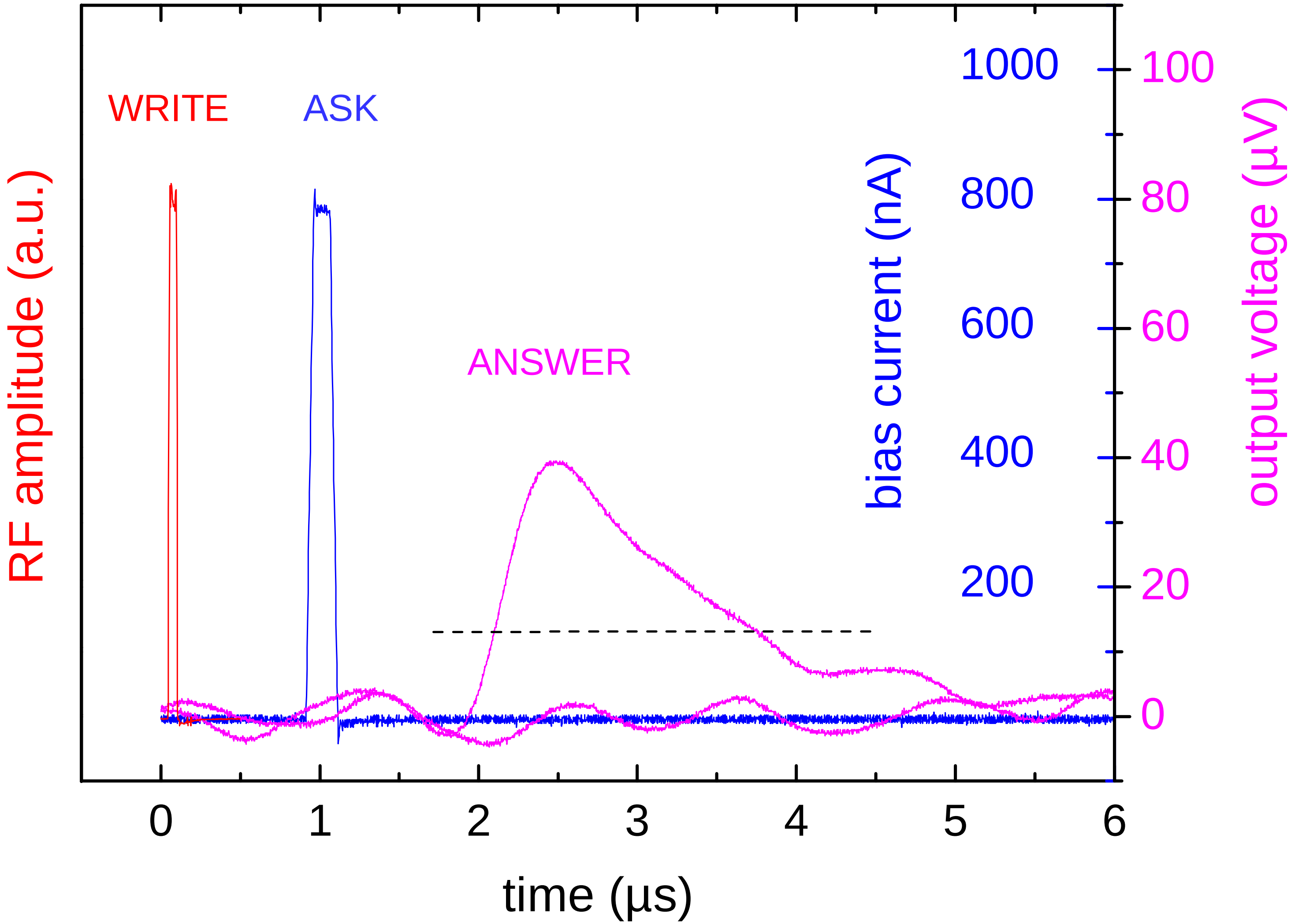


Chip design

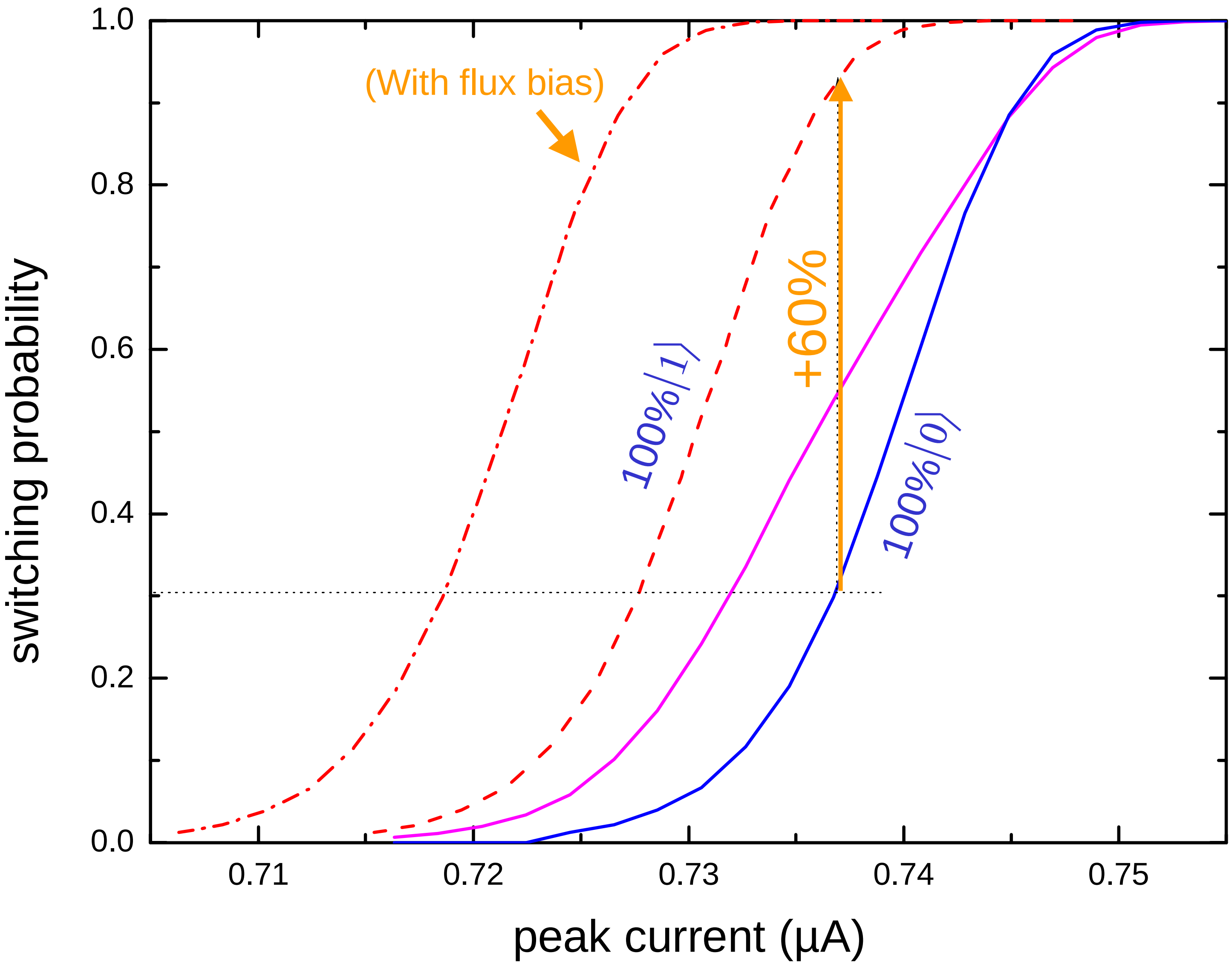


U_{RF}
U_{DC}
interdigitated capacitor
Contact pad
500 µm
V
« large » junction
500 nm
box junctions

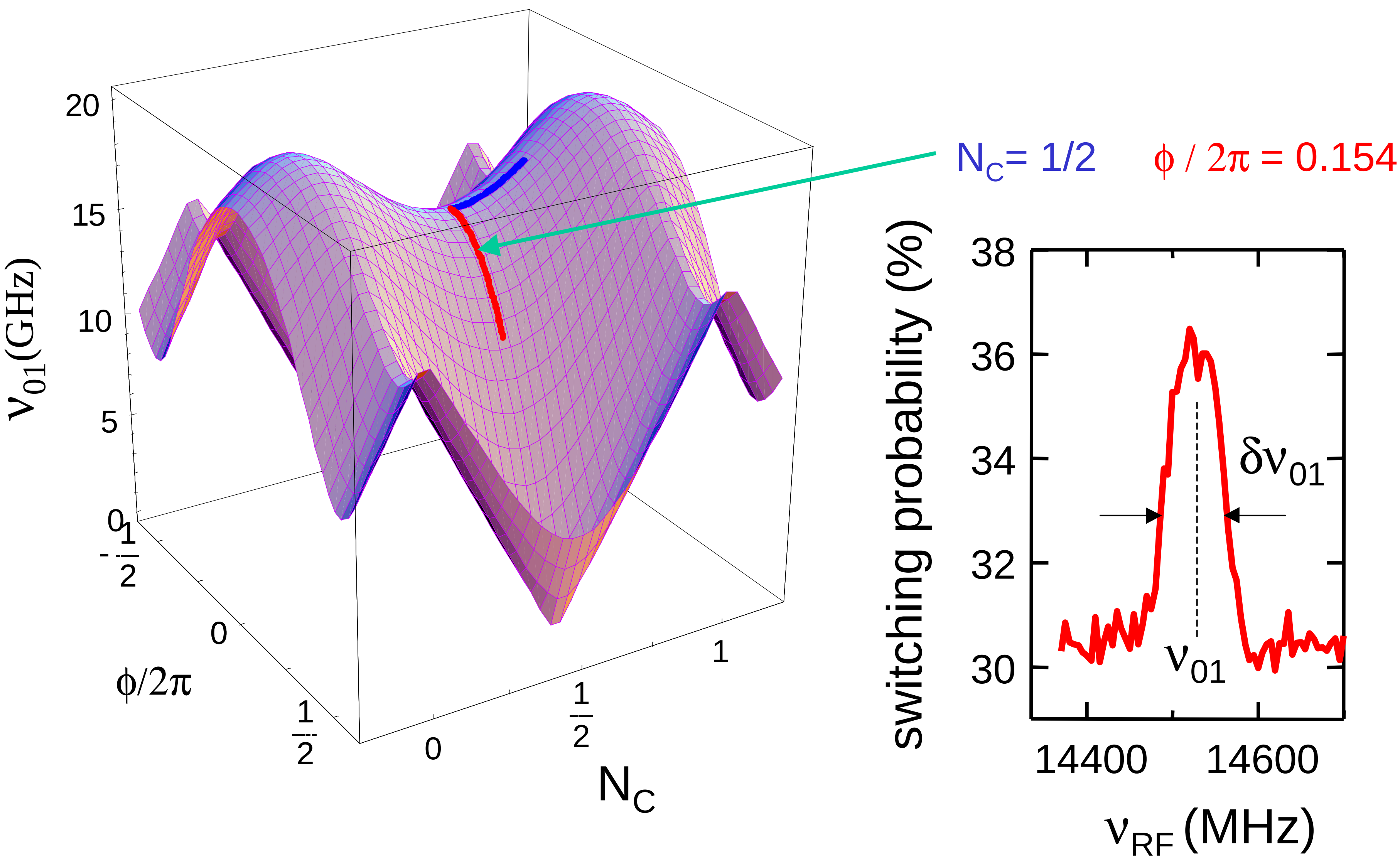
Preparation and readout



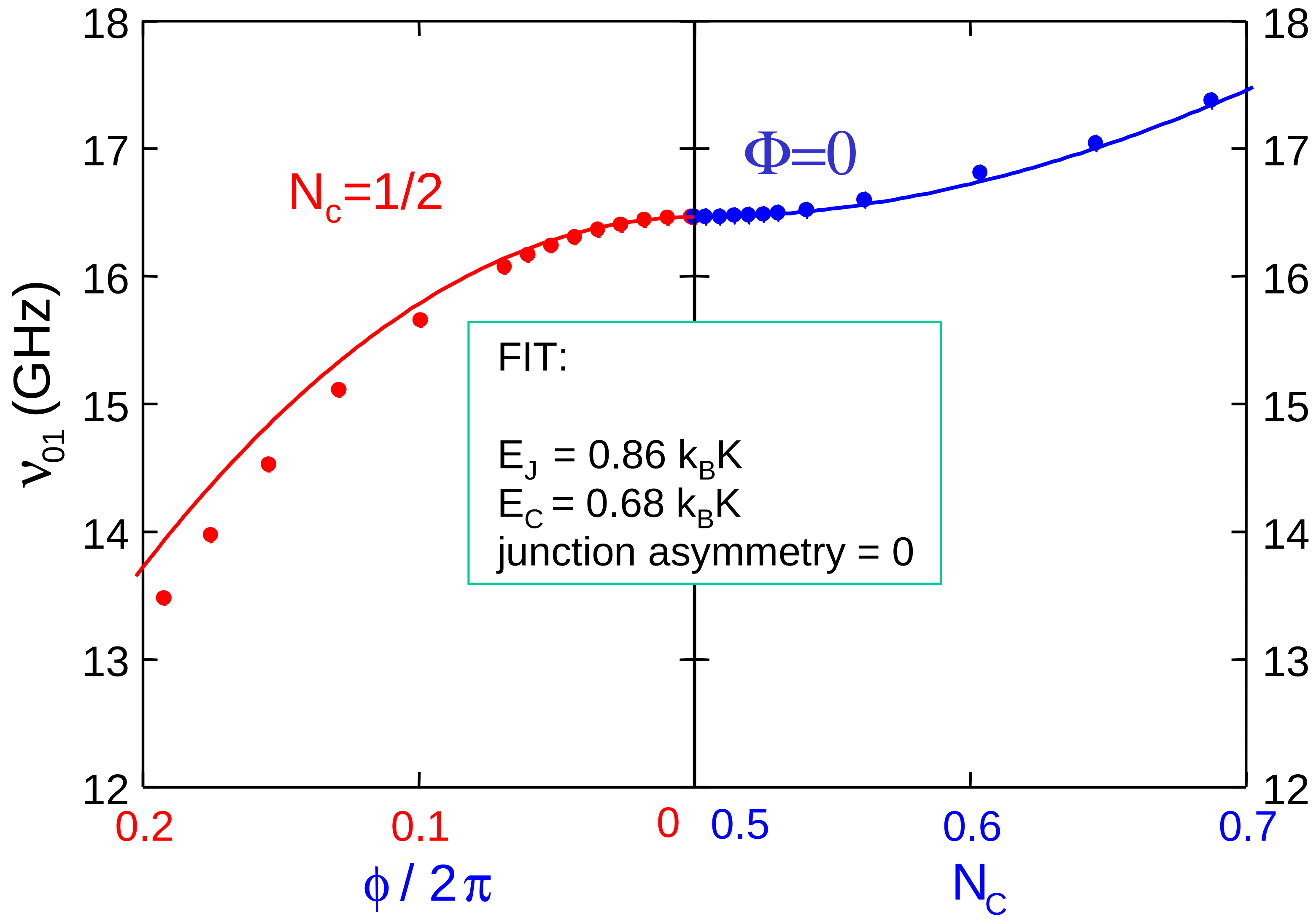
Estimated readout sensitivity



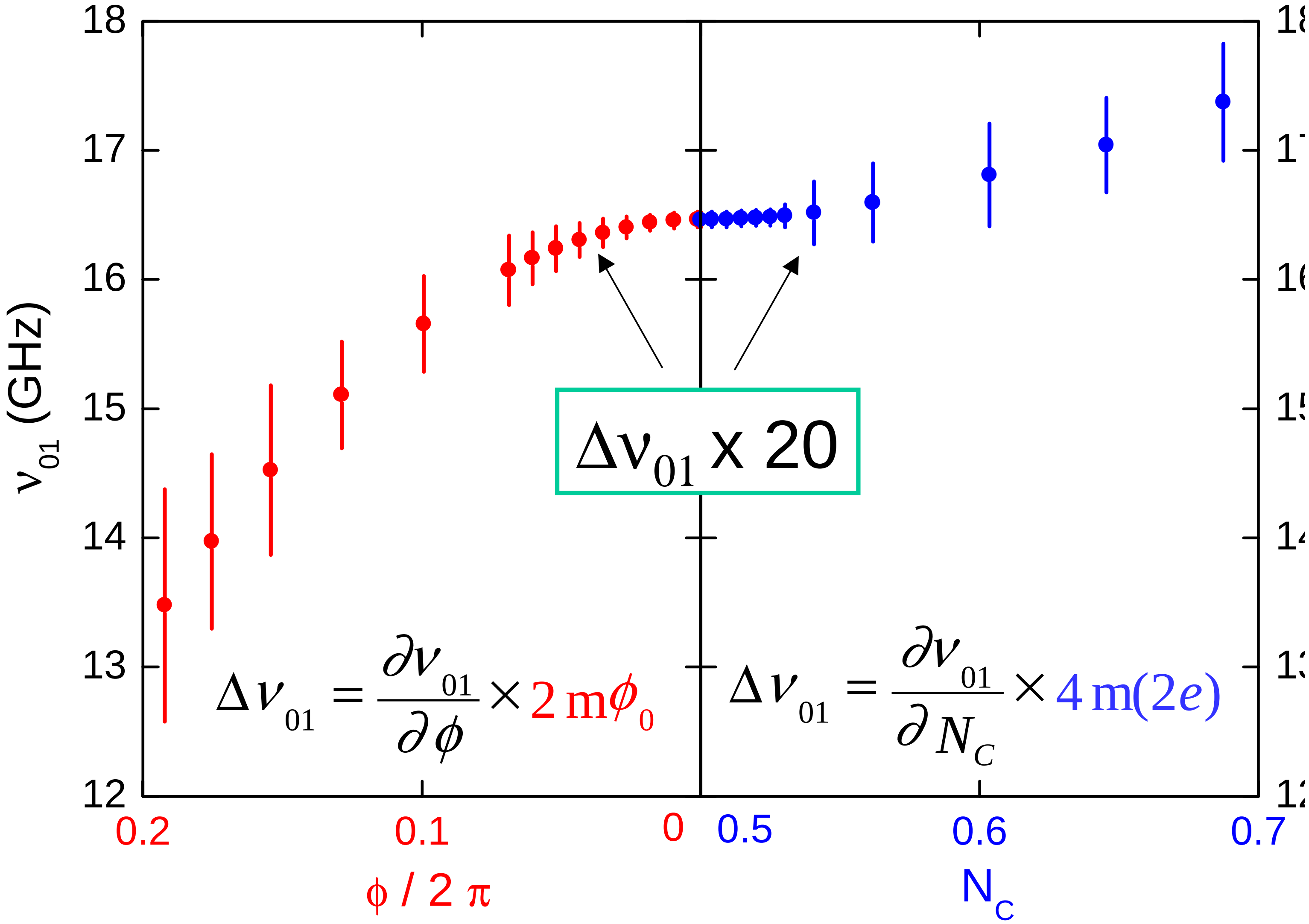
Spectroscopy $\nu_{01}(Ng, \phi/2\pi)$



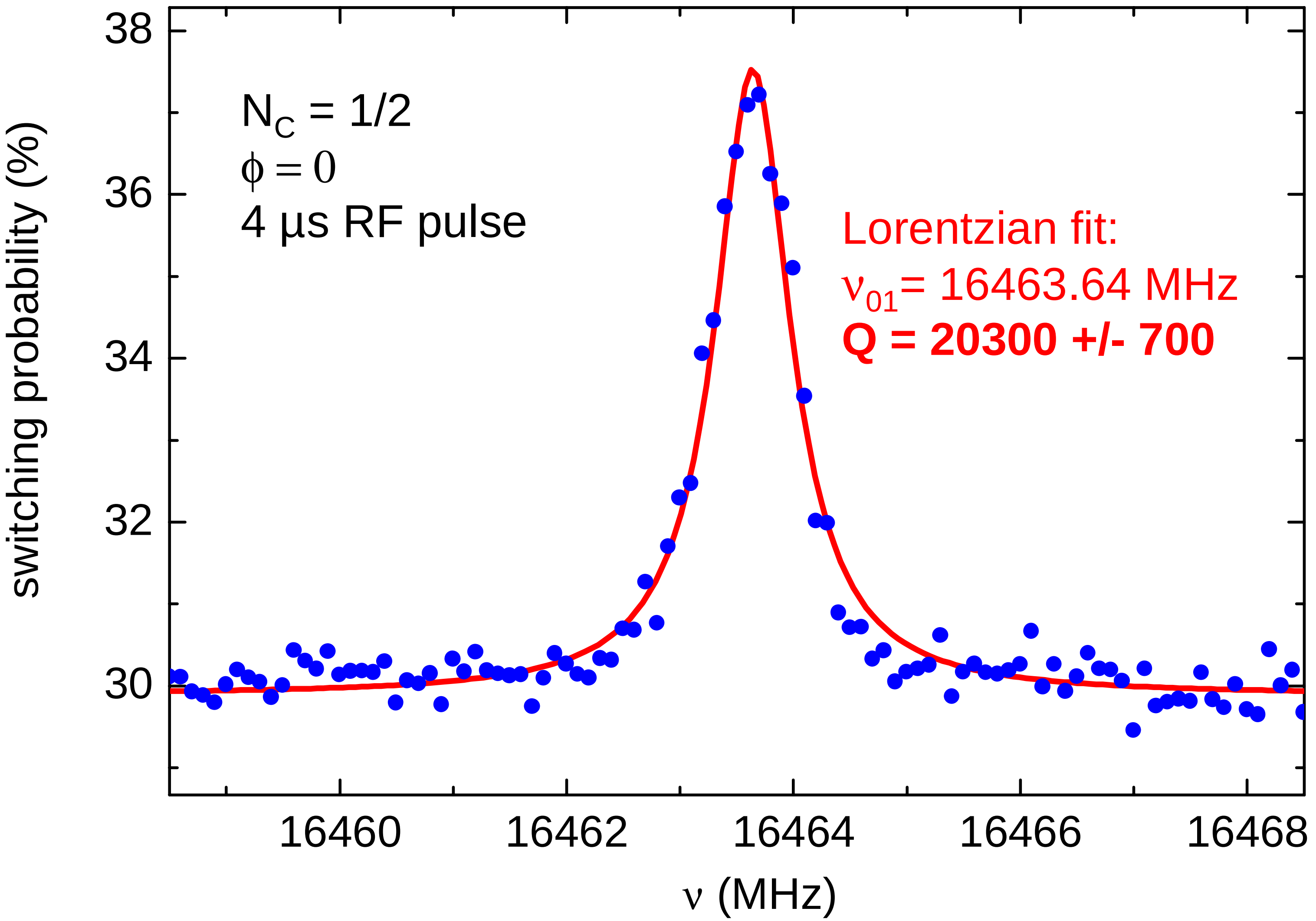
Level spectroscopy close to the saddle point



Line-width close to the saddle point



Line-shape at the optimal point



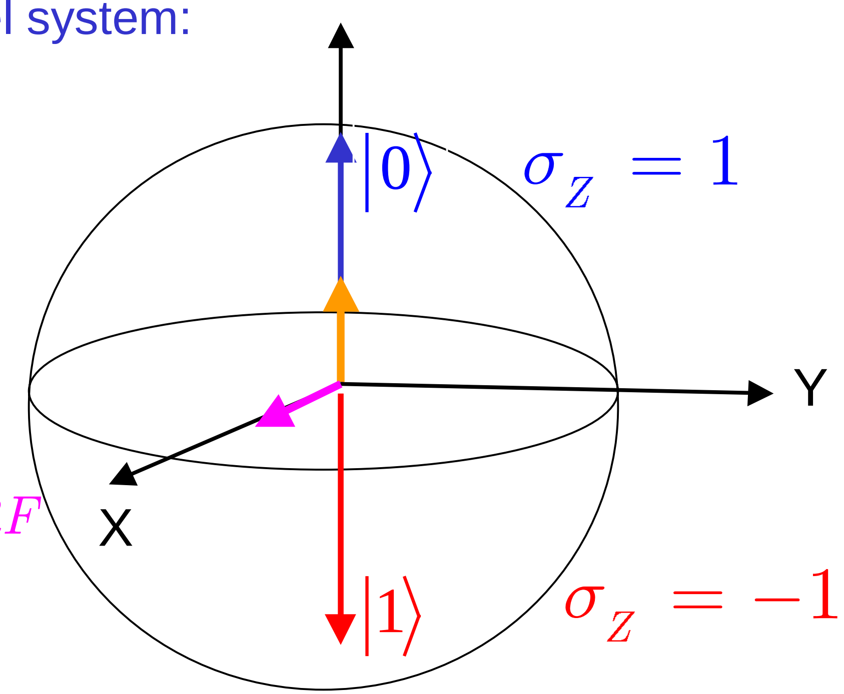
The Bloch sphere in the rotating frame

Fictitious spin 1/2 representation of a 2-level system:

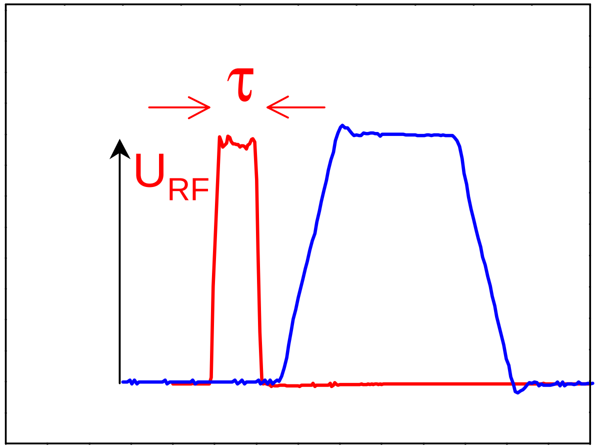
Rotation vector in the rotating frame

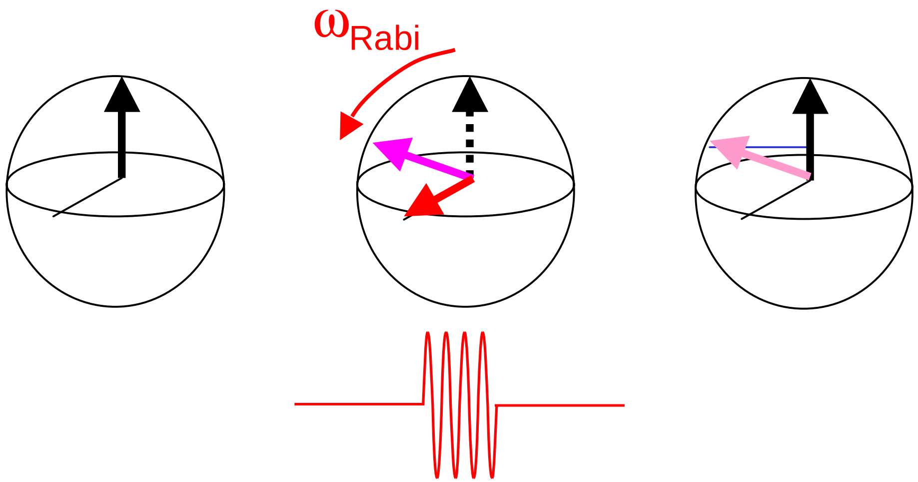
$$\omega_{01} - \omega_{RF}$$

$$\omega_{RABI} \propto A_{RF}$$



Rabi oscillations

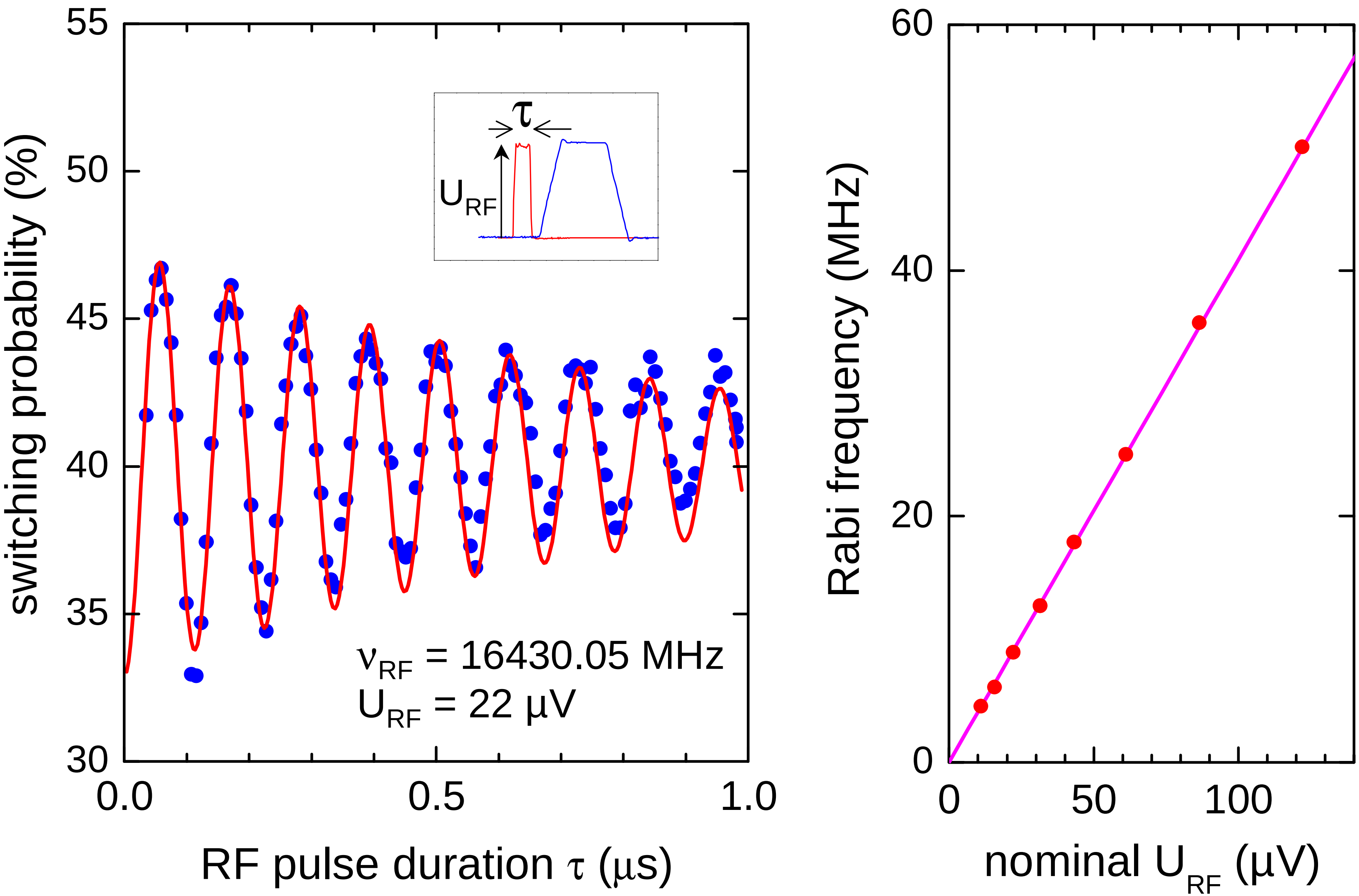




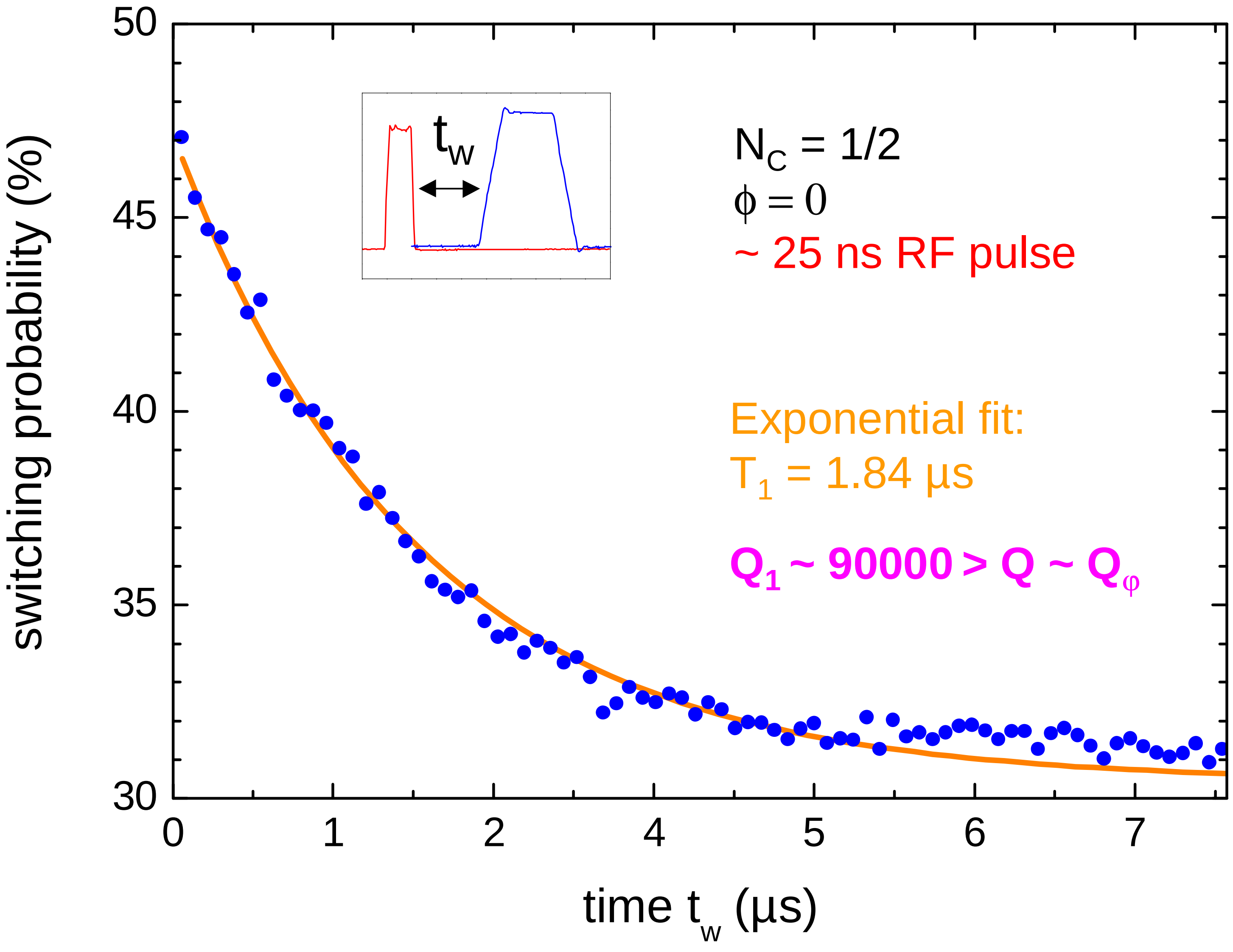
$|0\rangle$ **rotation** **projection**

$\omega_{Rabi} = \alpha U_{RF}$

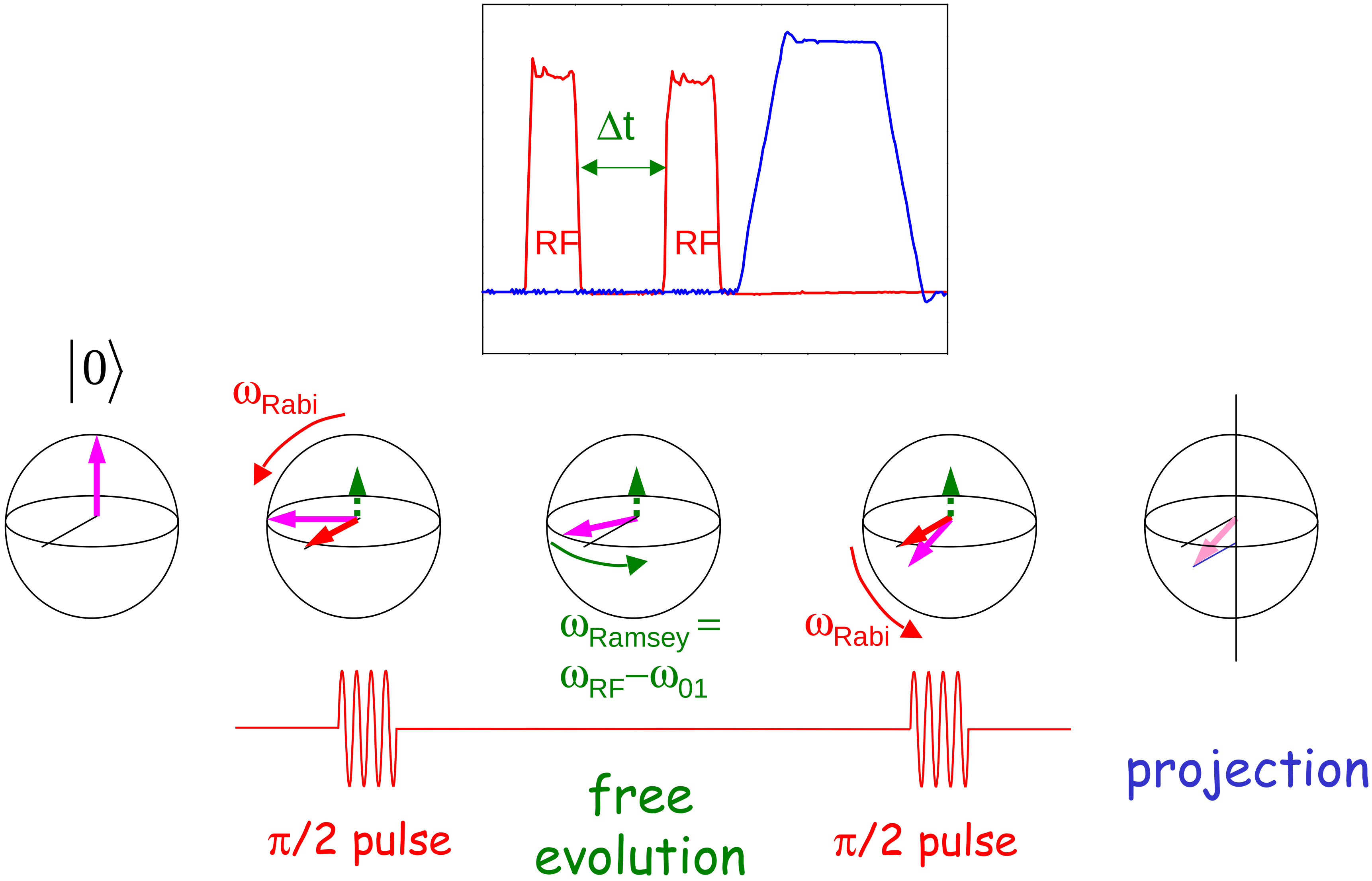
controlled rotations around an in-plane axis



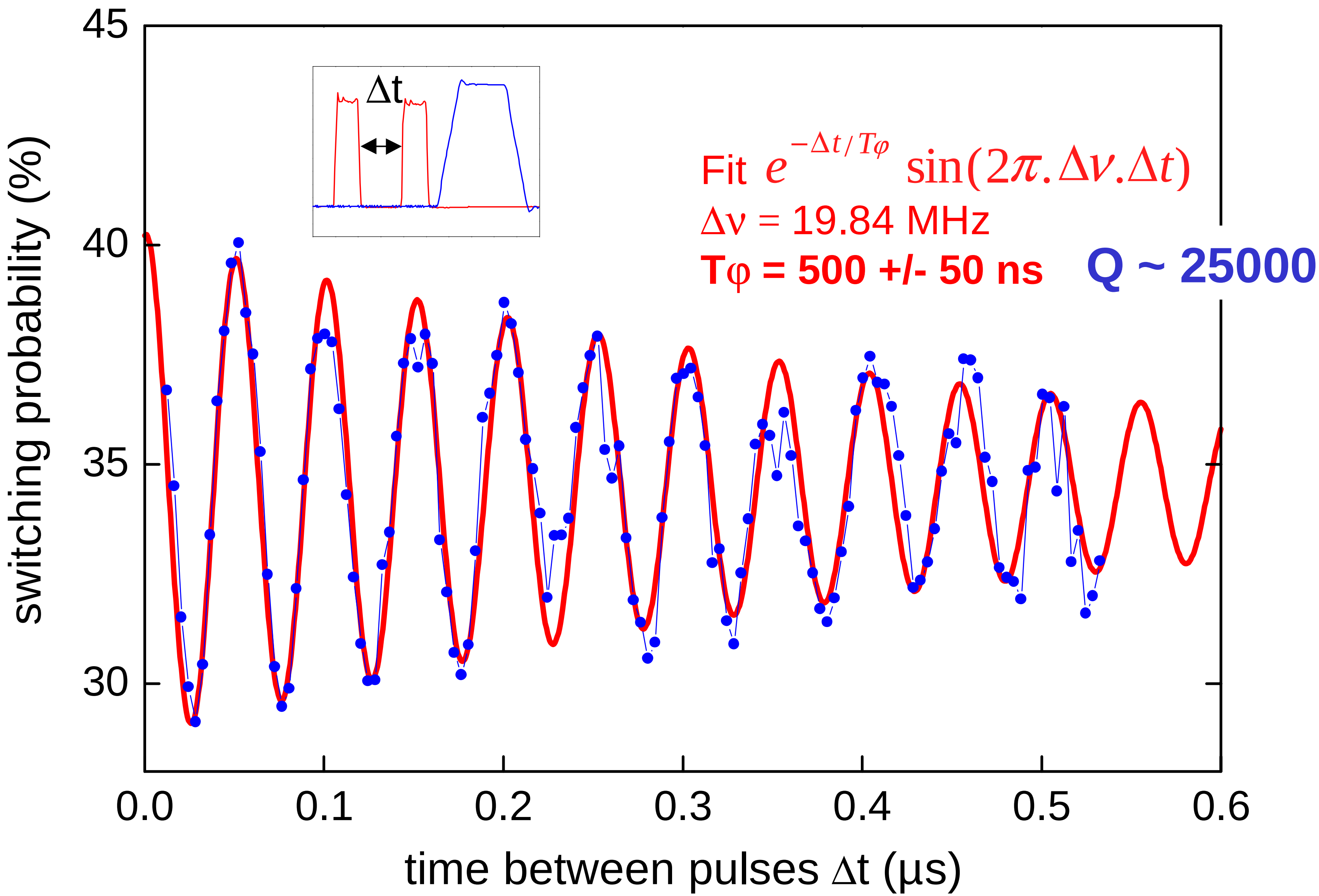
Relaxation at the optimal point



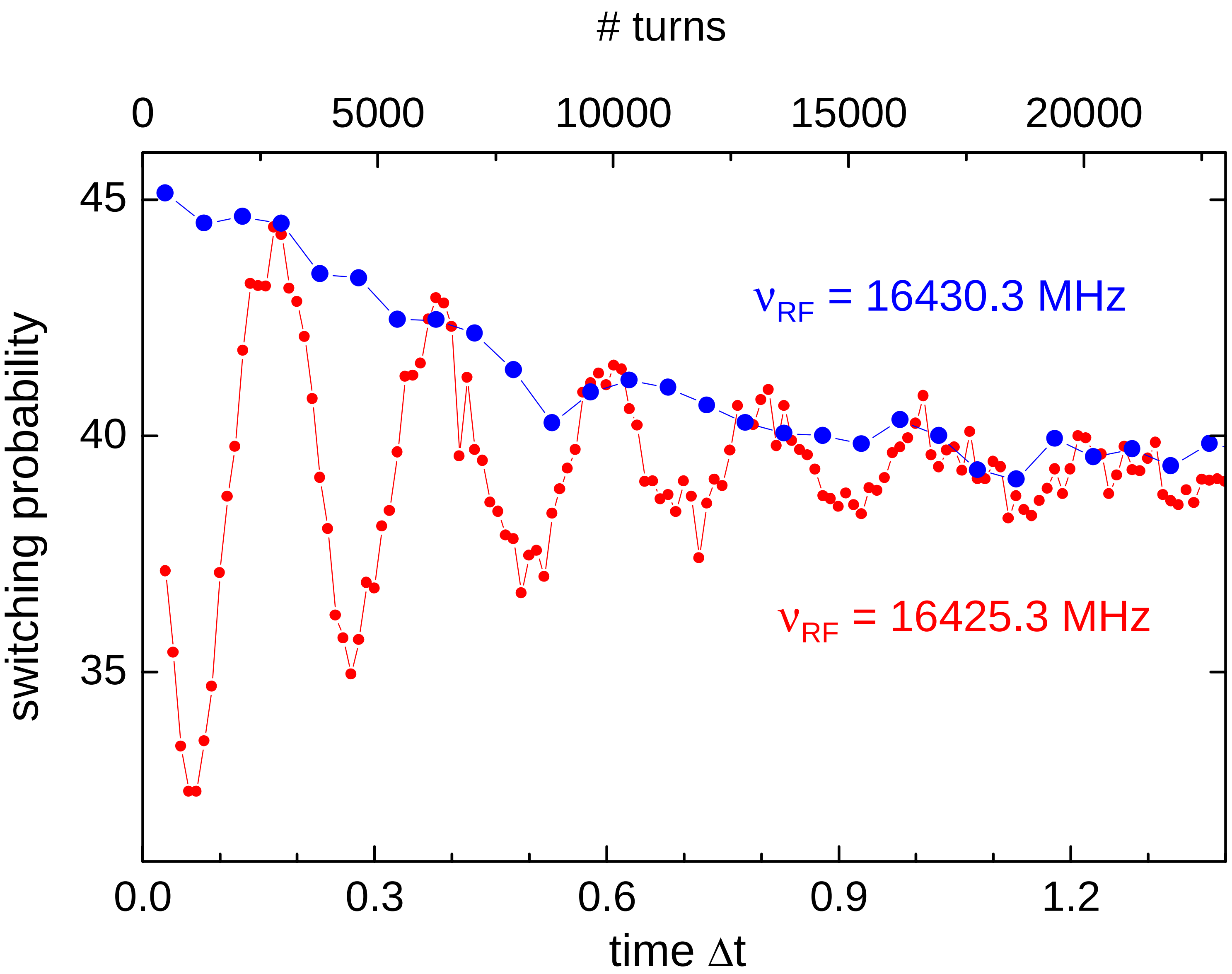
Ramsey interferences



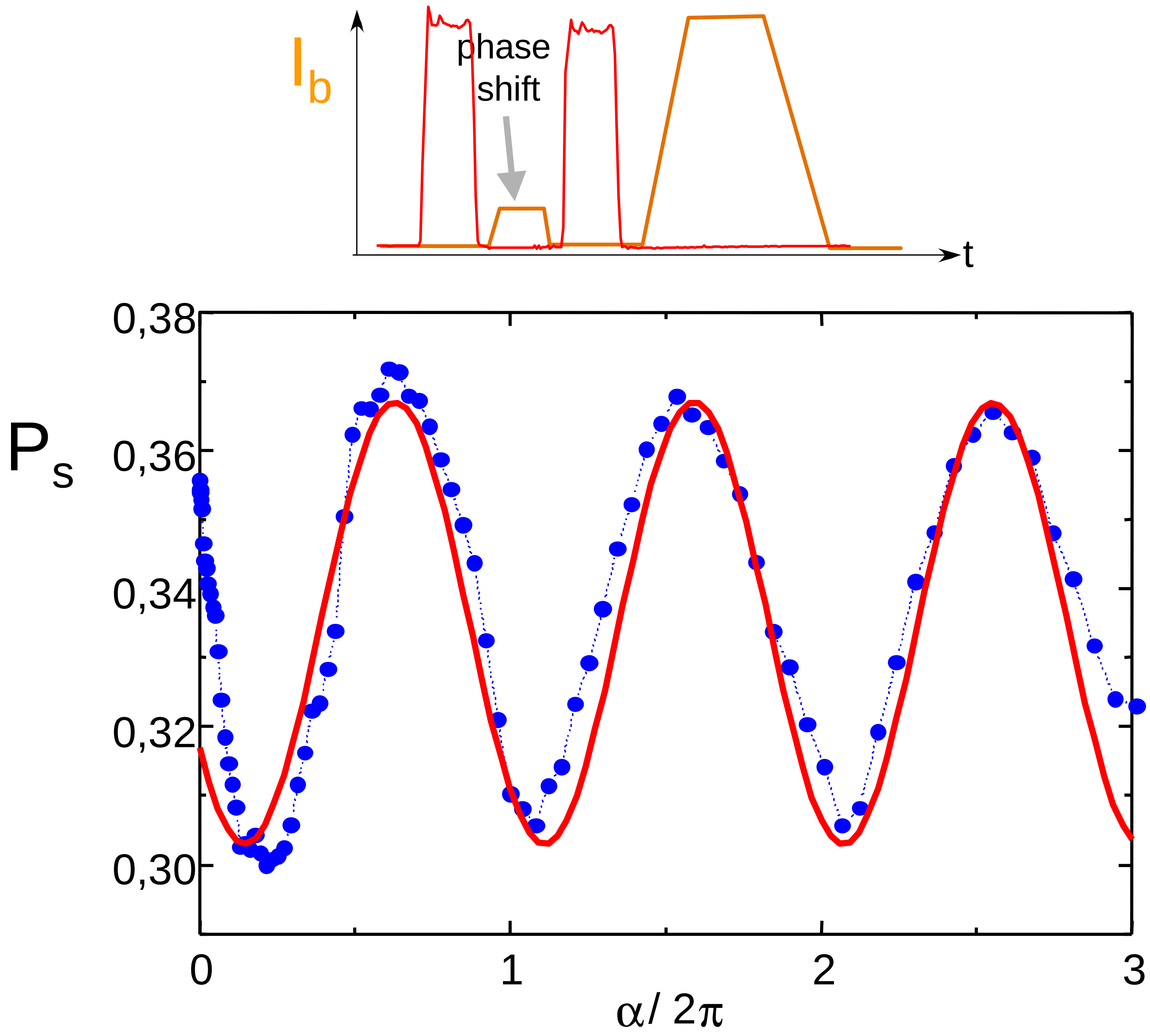
Observations of Ramsey "fringes"



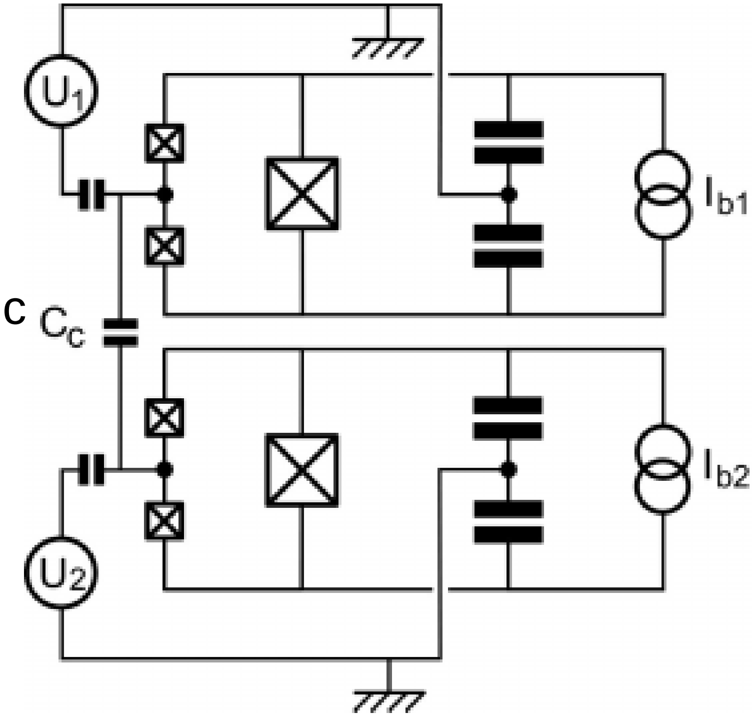
On and off resonance Ramsey experiment



controlled rotations around Z axis



qubit logic gates ?



Electrostatic coupling

Exchange interaction

$$|01\rangle \leftrightarrow |10\rangle$$

Bell's states

$$\frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

logic gates

U_1 & $\sqrt{\text{swap}}$

↓

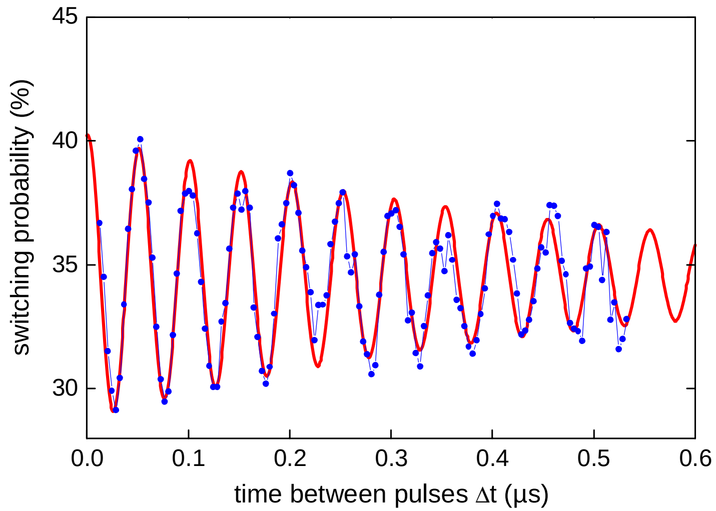
Universal set

Summary

operation of a solid state qubit:

coherence time > 8000 qubit oscillations

imperfect fidelity at readout



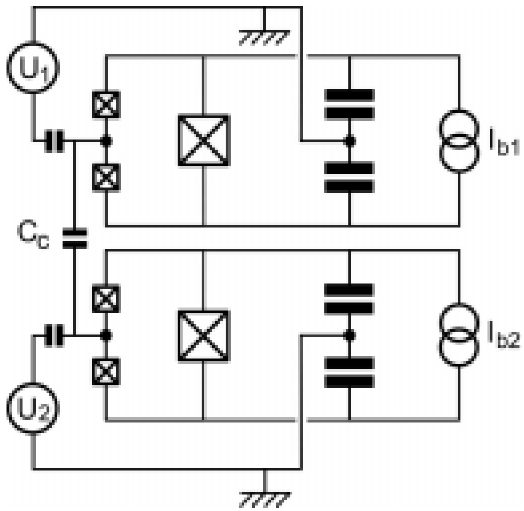
→ ? entanglement

coupled qubits

Bell 's states & logic gates

$\sqrt{\text{swap}}$

Cnot,...



Many other possibilities: atoms on chips, spintronics,...