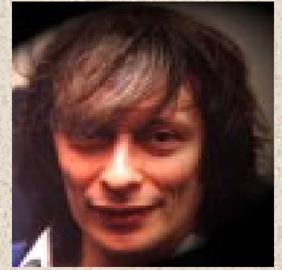
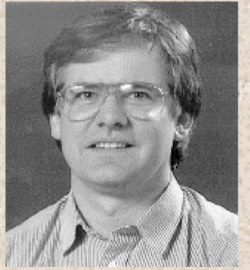
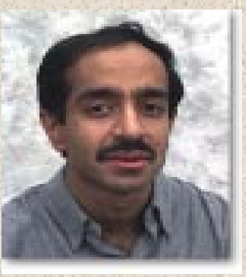


David Deutsch



Richard Jozsa

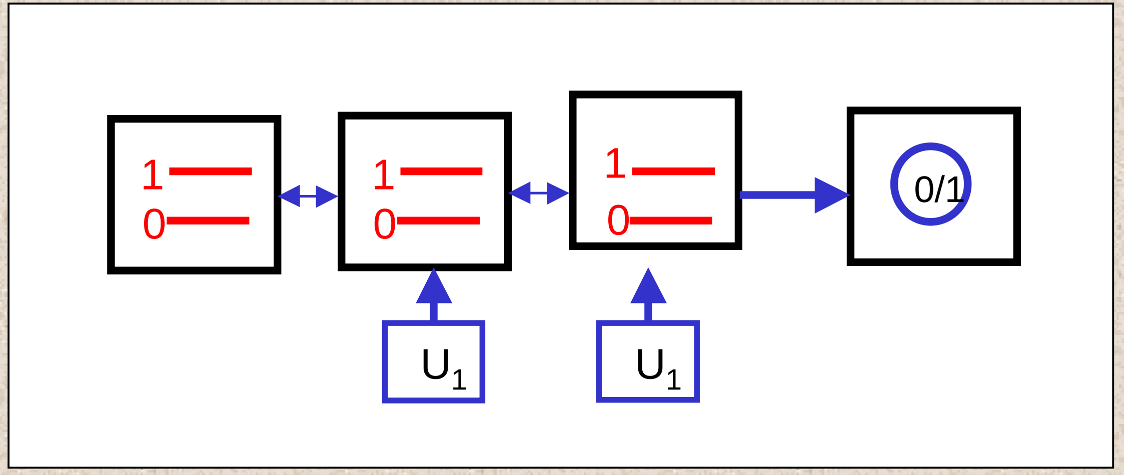
Peter Shor



Lov Grover

powerful quantum algorithms...

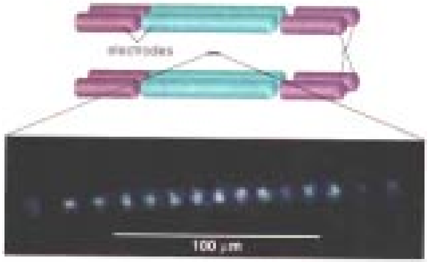
...demanding powerful quantum hardware



micro versus macro

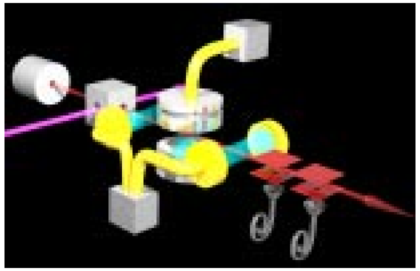
Quantum optics

Trapped ions



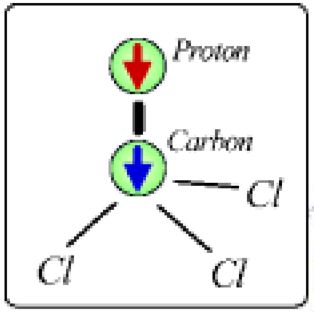
(NIST, Innsbrück...)

Atoms in cavity

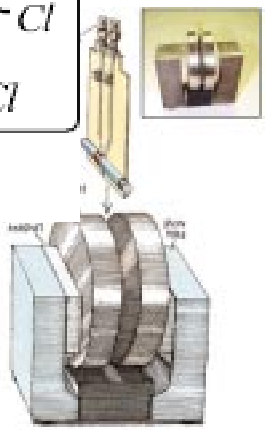


(ENS Paris)

NMR



$|0\rangle|0\rangle$



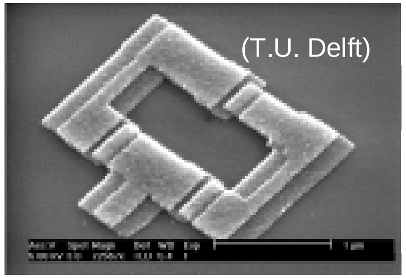
(Oxford, Stanford,
IBM,MIT…)

e / L He atoms on chip

Solid-state devices

semiconductors
P in Si
spintronics →

superconducting circuits



SQUBIT 1-2

Chalmers U.
TU Delft
PTB
Quantronics

CRTBT
NEC
NTT
NIST Boulder
Stony Brook
Kansas U.
Yale
UCB
...

Quantum,
but not easily scalable

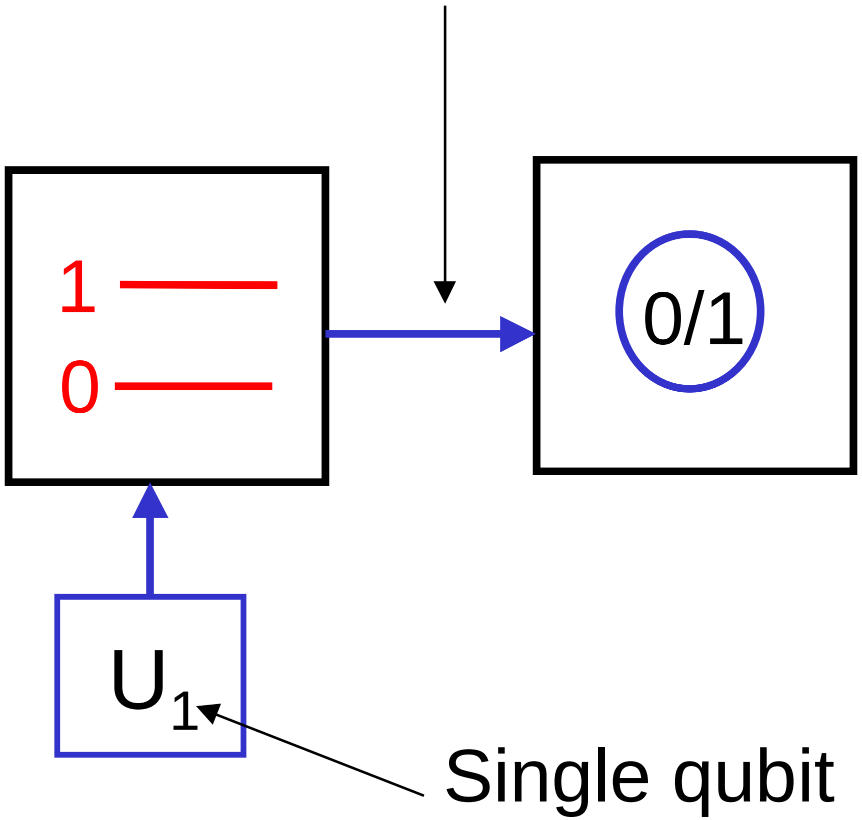
Scalable,
but not easily quantum

Operation of a solid-state quantum-bit

QUANTUM ELECTRONICS GROUP

CEA-Saclay, FRANCE

SQUBIT
collaboration



readout

1

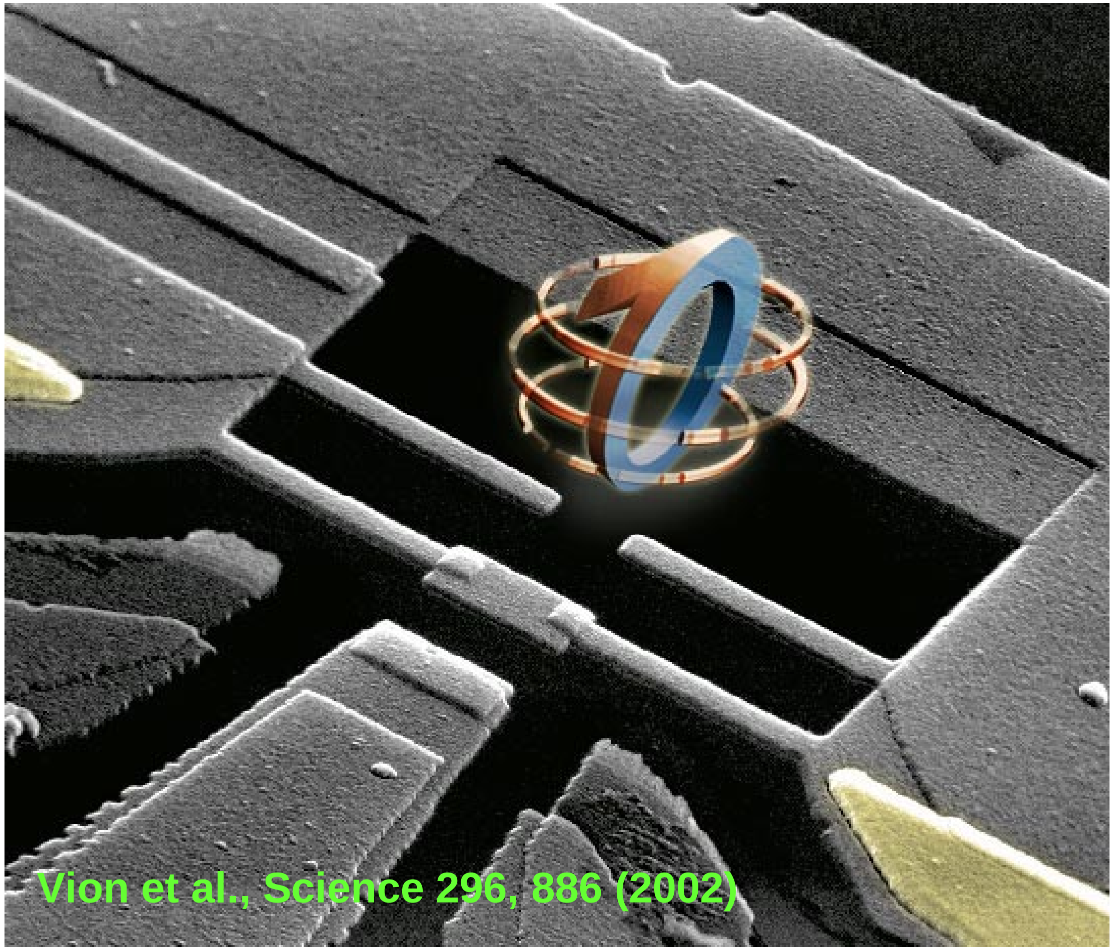
0

0/1

U_1

Single qubit operations

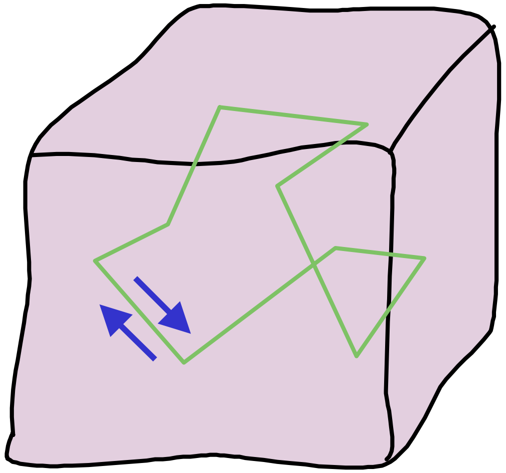
Operation of a solid-state quantum bit



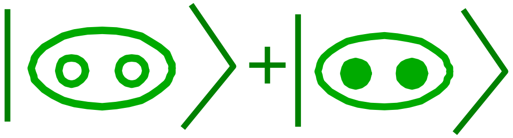
Vion et al., Science 296, 886 (2002)

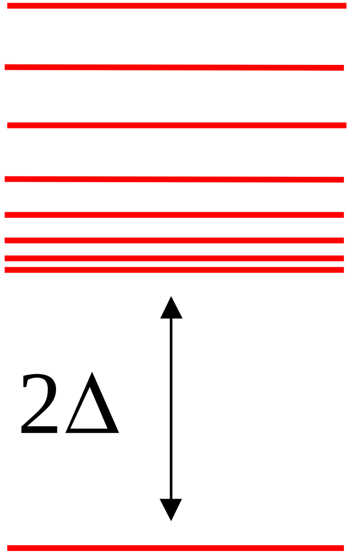
Quantronium superconducting circuit

Why superconductivity ?



All states paired

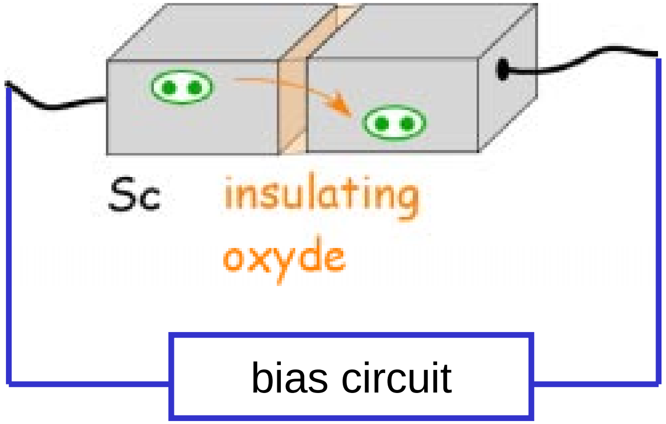


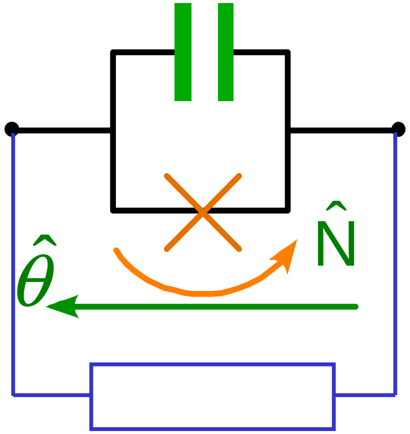


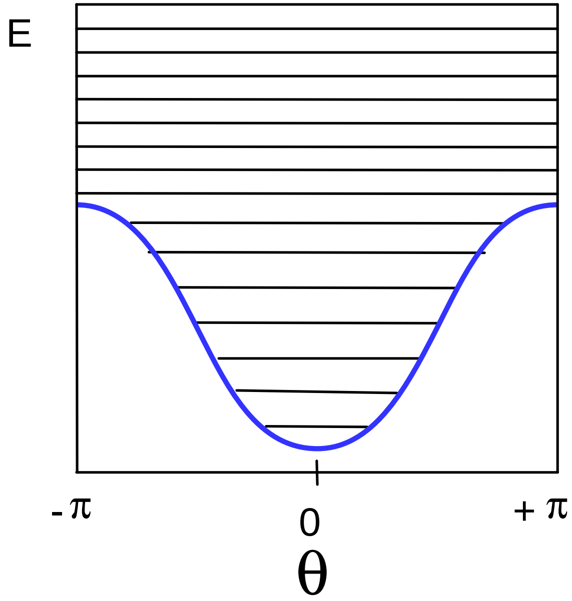
Superconducting Condensate
Ground state

The Josephson junction

A single degree of freedom $[\hat{N},\hat{\theta}]=i$







Josephson hamiltonian:

$$H_J = -E_J \cos\hat{\theta} = -\frac{E_J}{2}\sum_N |N\rangle\langle N+1| + |N+1\rangle\langle N|$$

full hamiltonian:

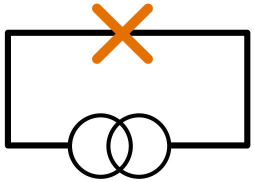
$$H = H_J + H_{elm}$$

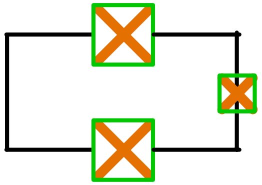
Josephson qubits

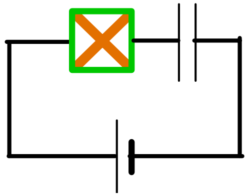
Current-biased large junction

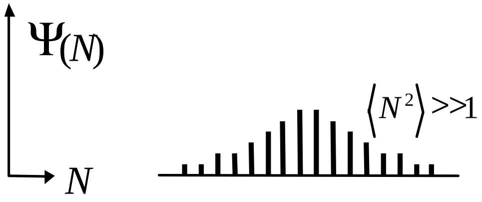
Medium-size junctions in a loop

Small junction in a box geometry



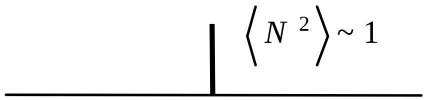




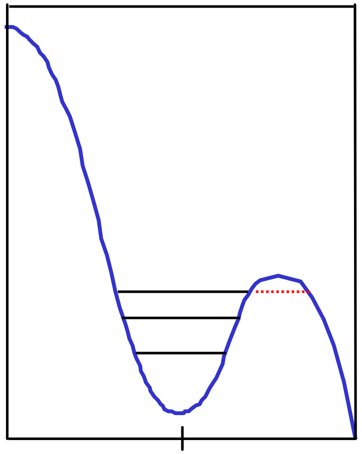


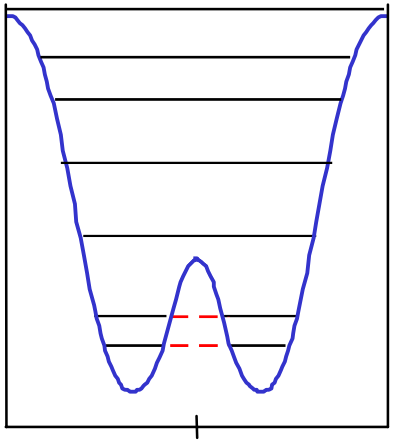
Phase state

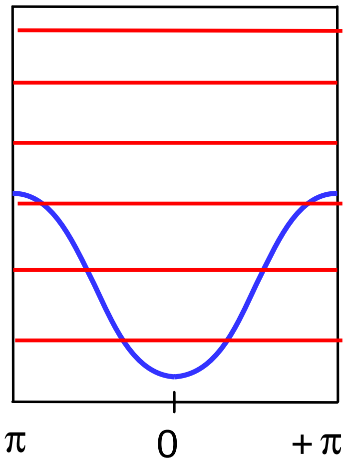
phase → charge



charge state

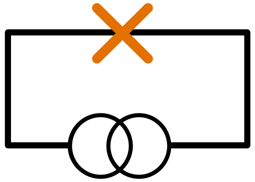


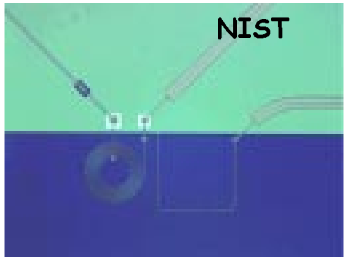


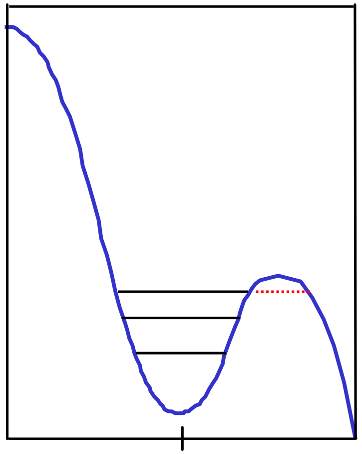


Josephson qubits

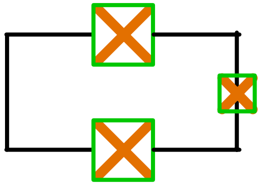
Current-biased large junction

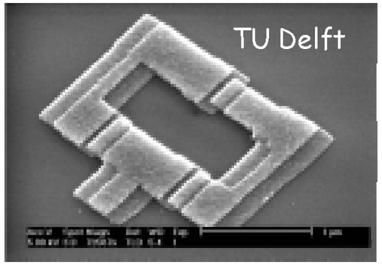


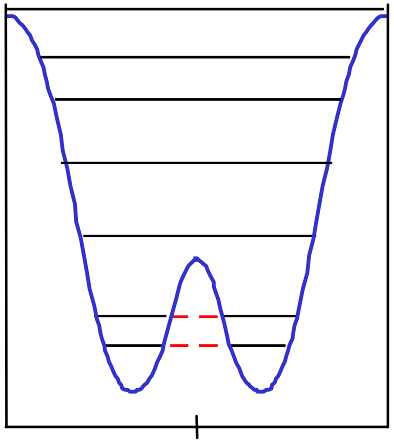




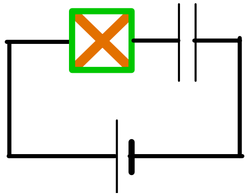
Medium-size junctions in a loop

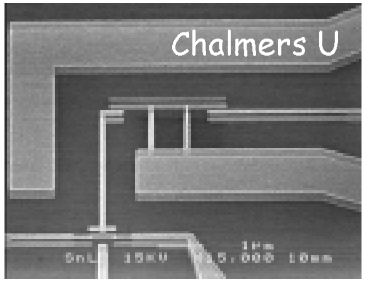


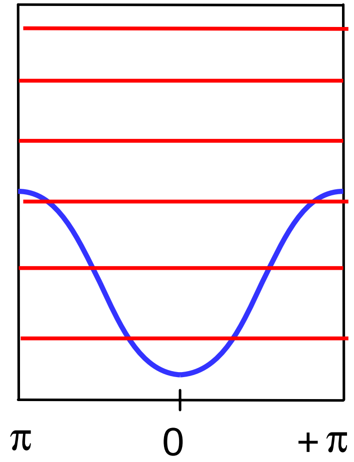




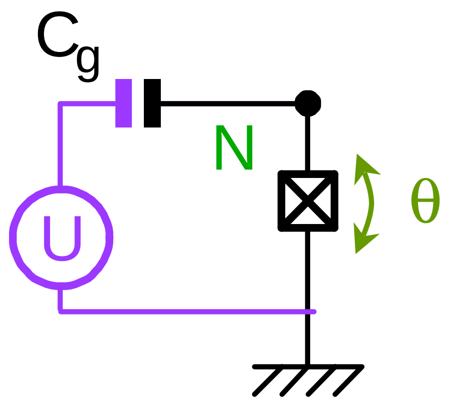
Small junction in a box geometry







The Cooper pair box



Hamiltonian

$$\boxed{\hat{H} = E_c(\hat{N} - N_g)^2 - E_J\cos\hat{\theta}}$$

1 control knob $C_gU/2e$

1 degree of freedom

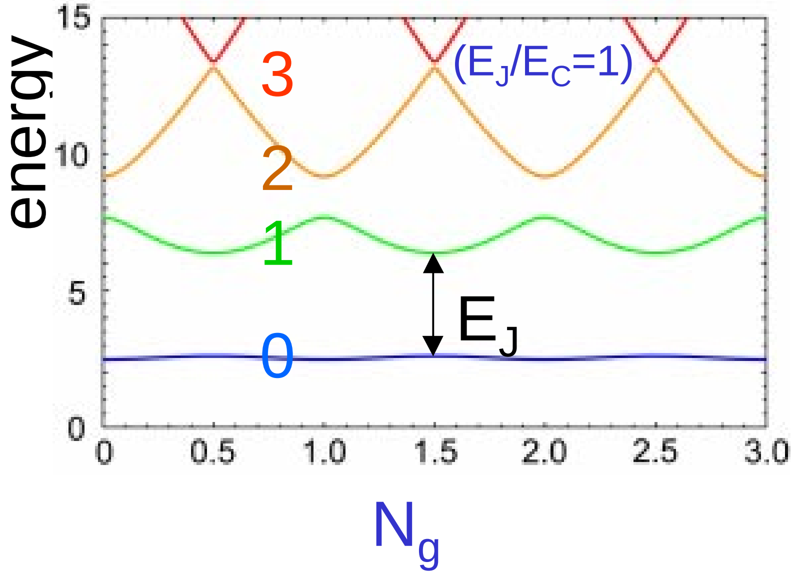
$$[\hat{N},\hat{\theta}] = i$$

2 characteristic energies

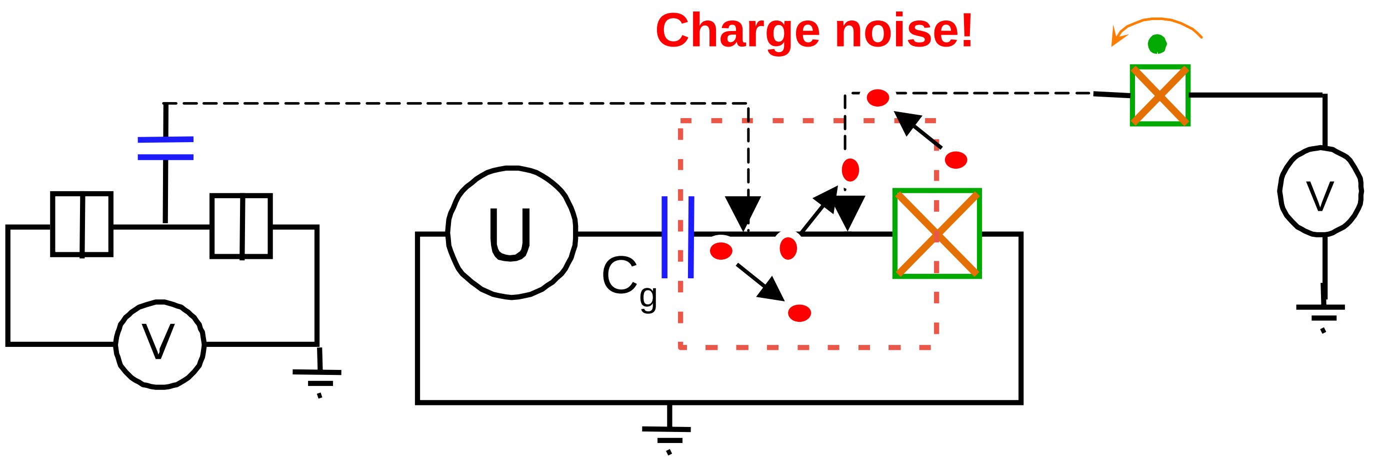
$$E_c = \frac{(2e)^2}{2C_{island}} \qquad E_J = \frac{\Delta h}{8e^2 R_T}$$

"potential" "kinetic"

Spectrum



Measuring the Cooper pair box

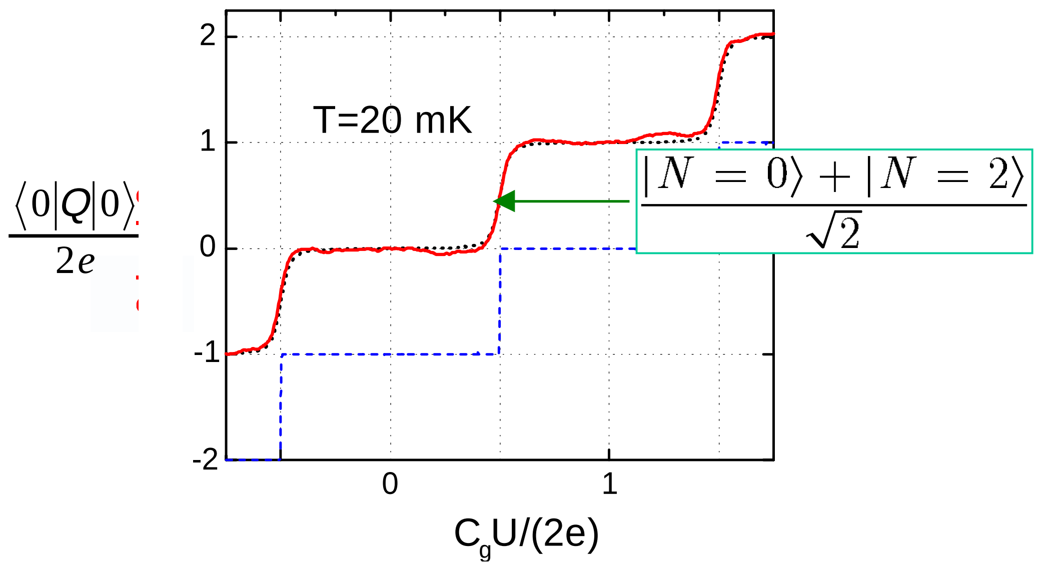


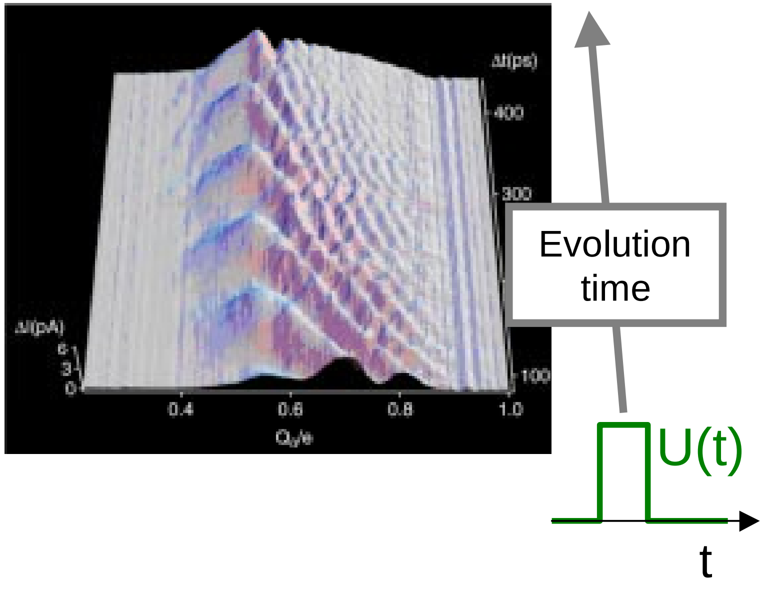
1996 charge of ground state $|0\rangle$

(Bouchiat et al., Quantronics)

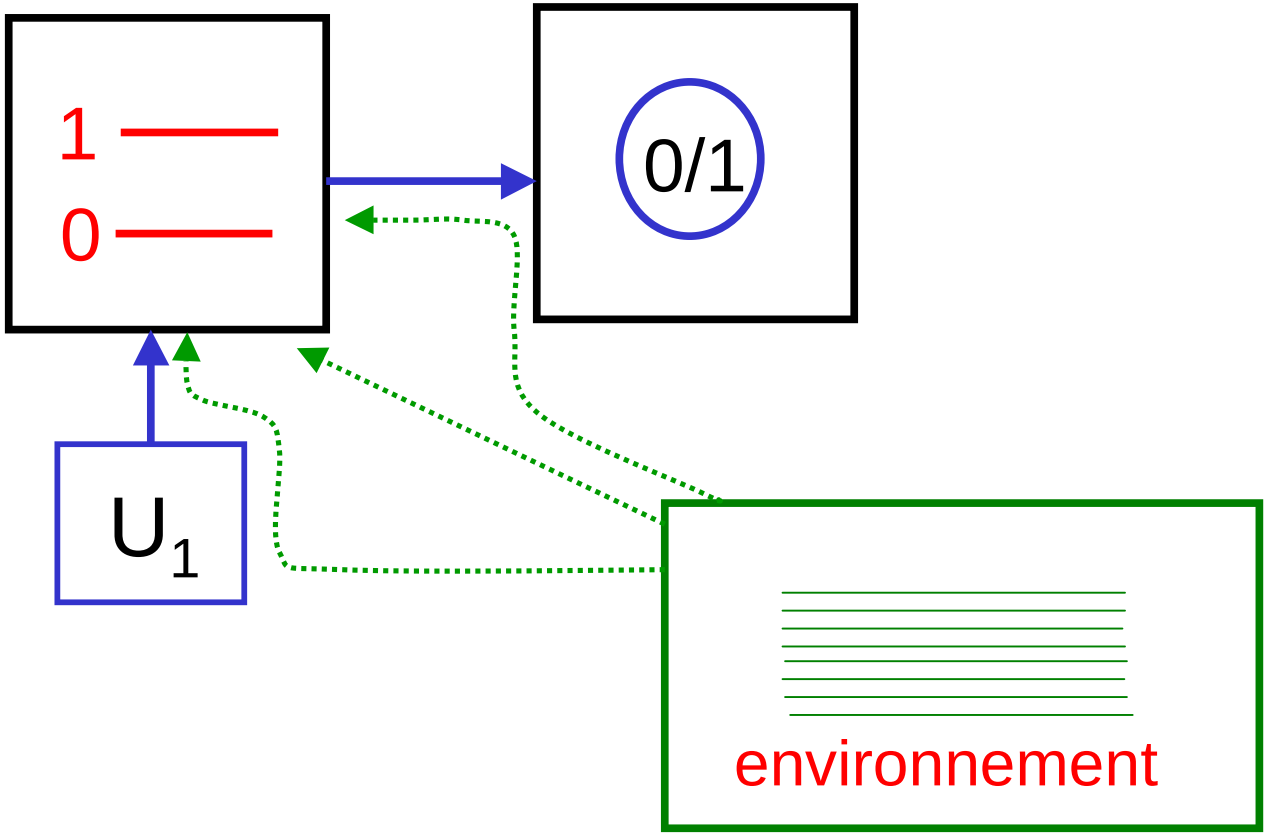
1999 coherent superpositions $\alpha|0\rangle+\beta|1\rangle$

(Nakamura, Pashkin & Tsai, NEC)

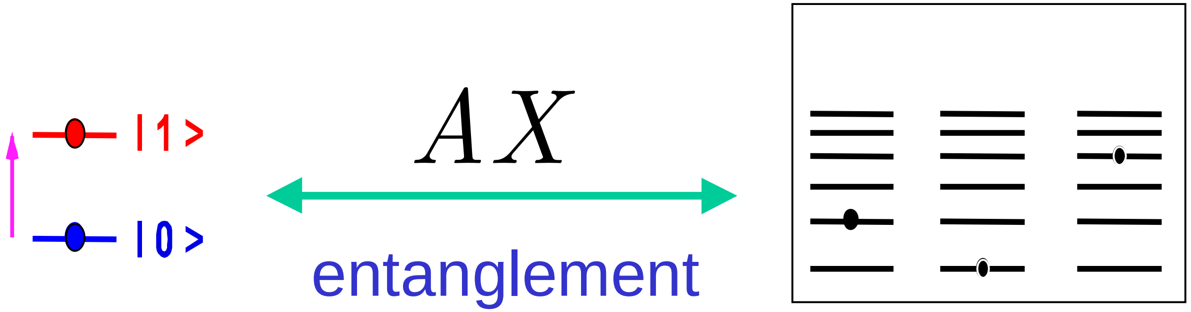




decoherence and readout



decoherence and readout



qubit

readout through X
fluctuating environment

$$AX$$

entanglement

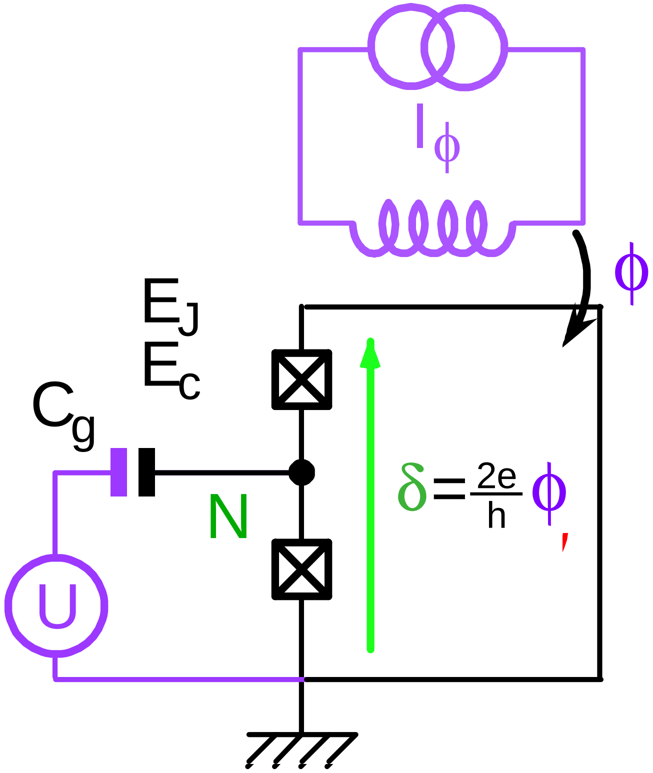
Signal : $$[\langle 1|A|1\rangle - \langle 0|A|0\rangle] = h\frac{\partial \nu_{01}}{\partial X}$$

Dephasing : $$\delta X(t) \longrightarrow \delta\nu_{01}(t) = \frac{\partial \nu_{01}}{\partial X}\,\delta X(t)$$

Readout + environment

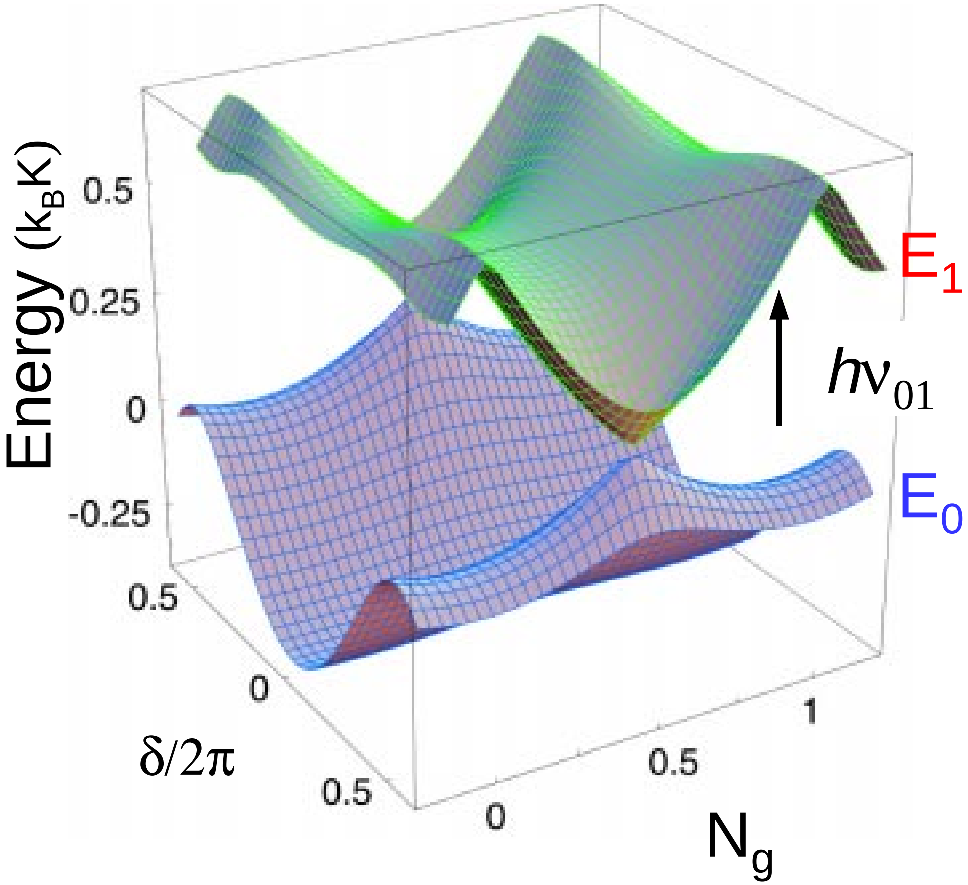
Move adiabatically **then** readout

The Quantronium:
a split junction Cooper pair box

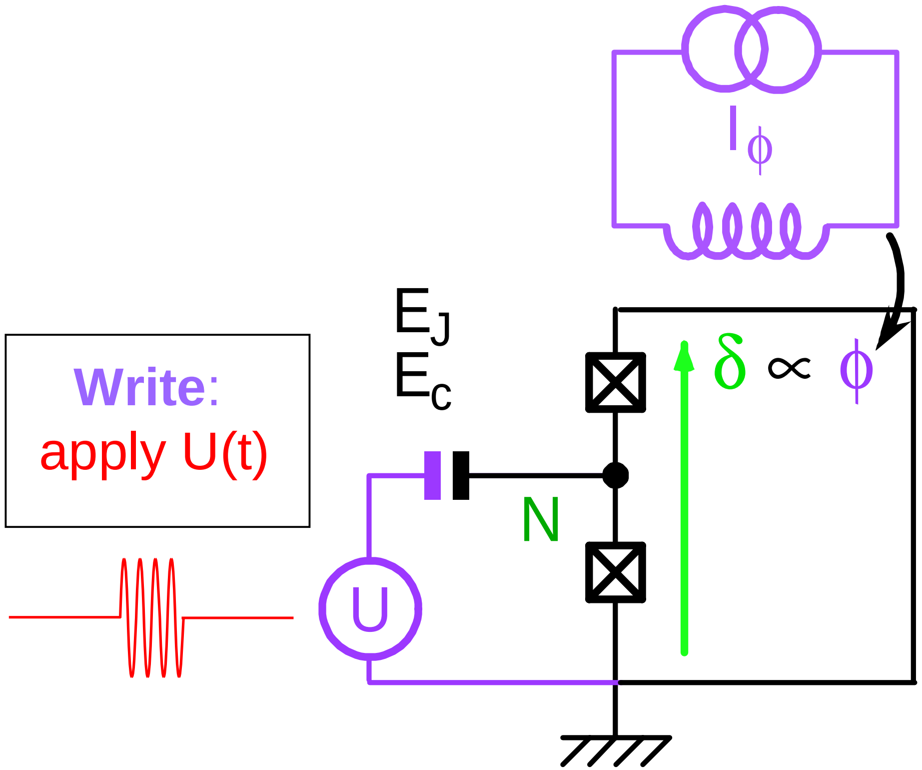


$$E_J^{eff}(\delta) = E_J \cos\frac{\delta}{2}$$

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



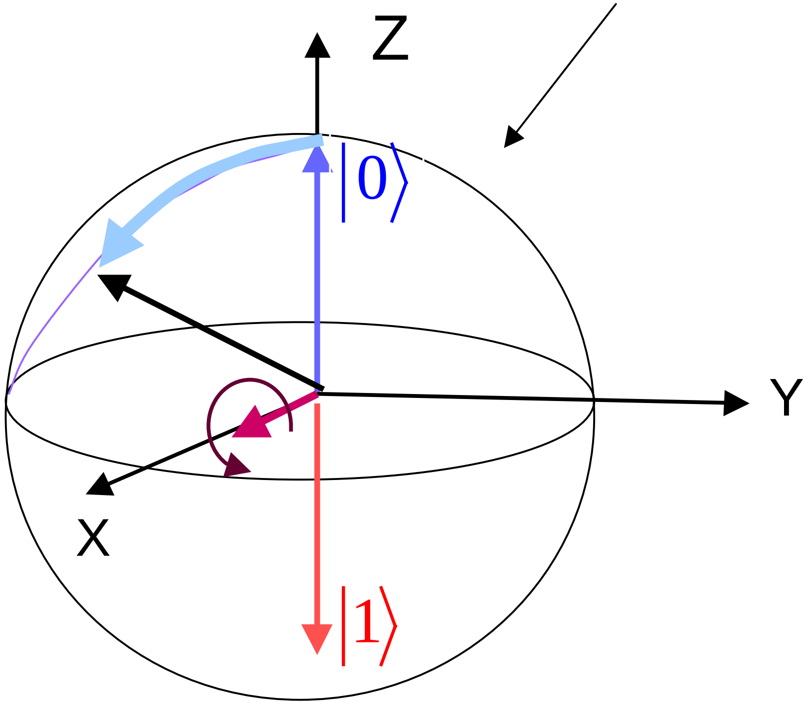
State manipulation using the **charge port**



Microwave drive at

$\nu_{\mu w} \approx \nu_{01}$

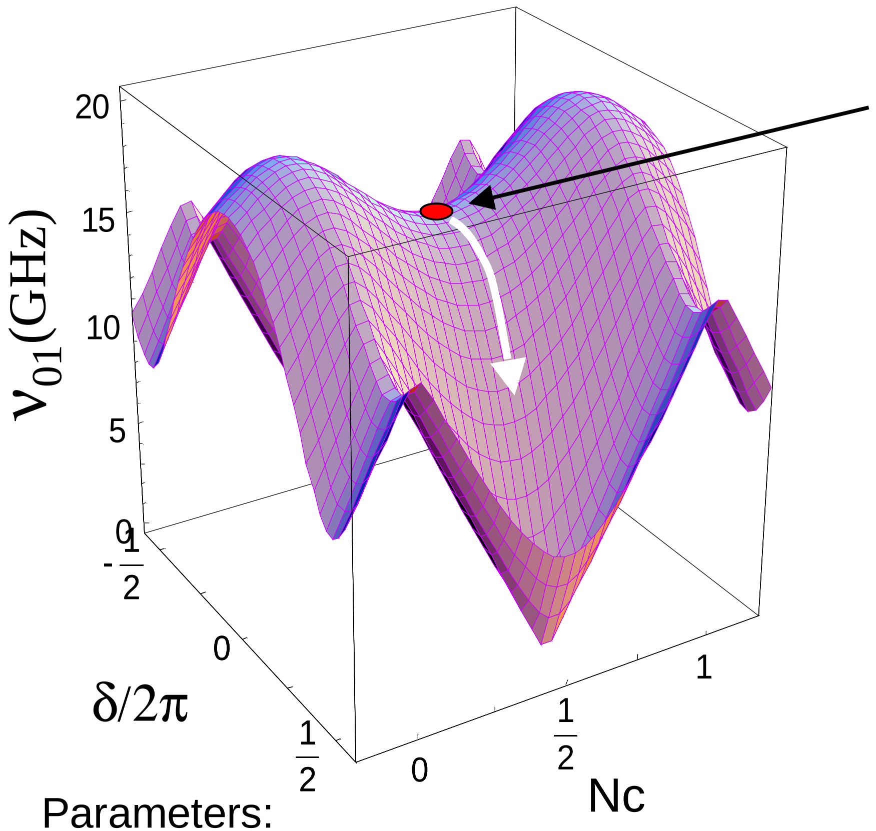
Bloch sphere representation in the rotating frame



Rabi precession

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

Decoherence and readout



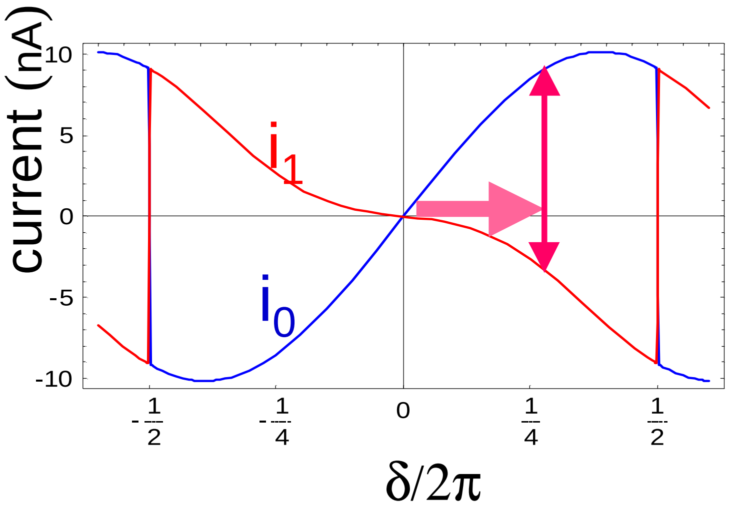
At saddle point :

$$\frac{\partial \nu_{01}}{\partial Ng} = 0$$

$$\frac{\partial \nu_{01}}{\partial \delta} = 0$$

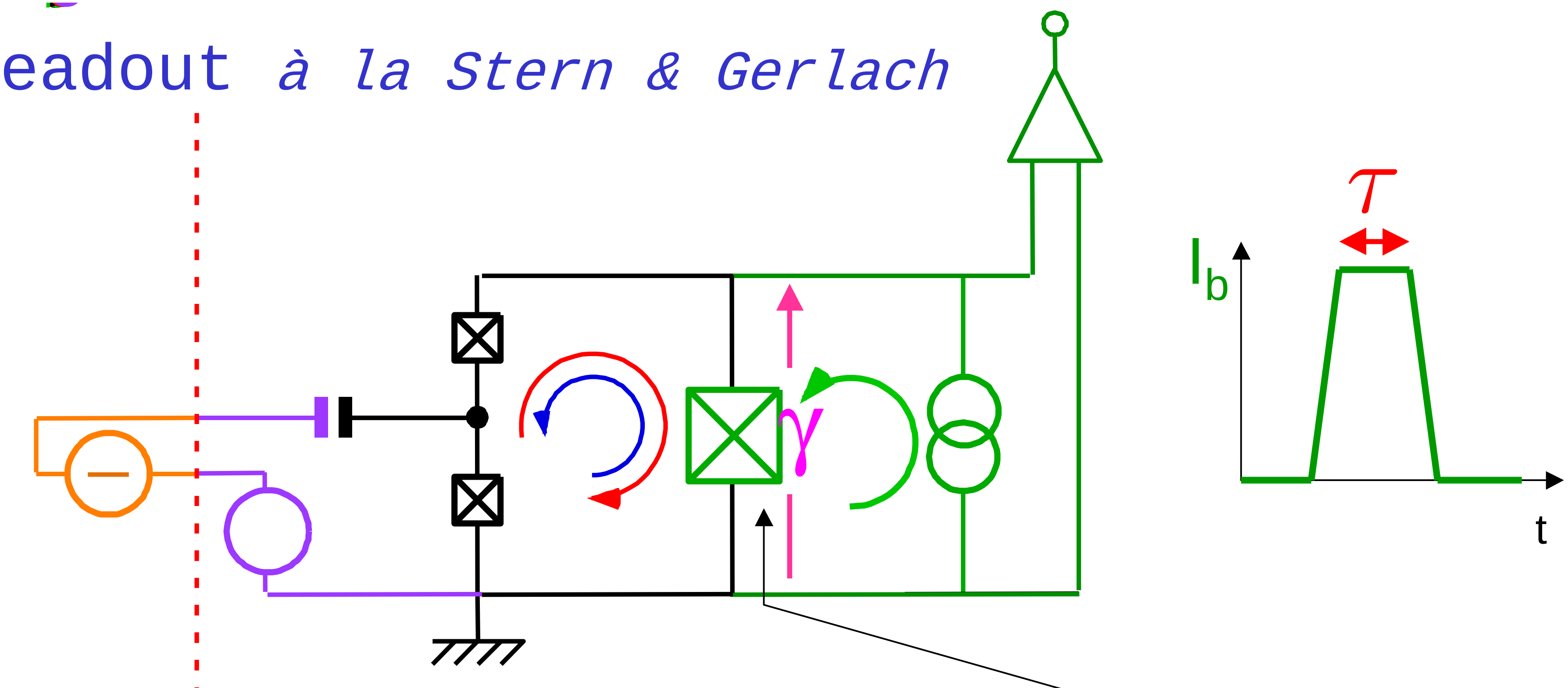
Parameters:
E_J=0.86 k_BK
E_C=0.68 k_BK

no dephasing
...but no signal:



But how ?

Readout *à la Stern & Gerlach*

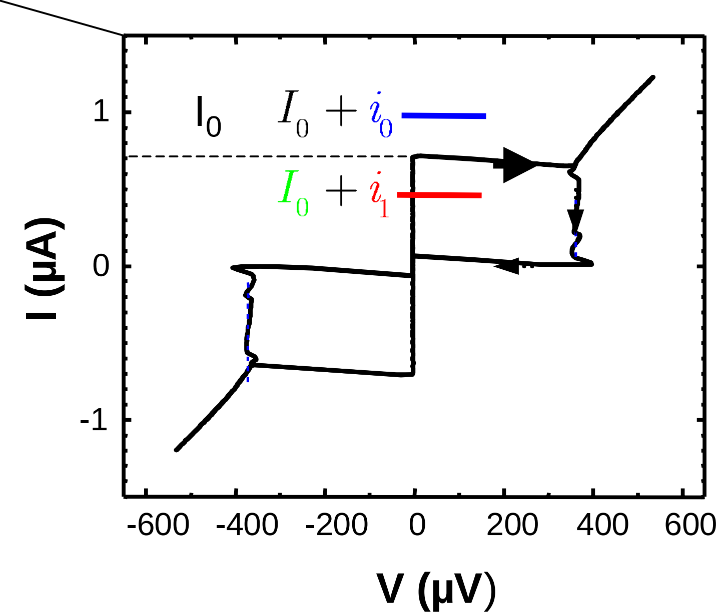


I) phase - bias :

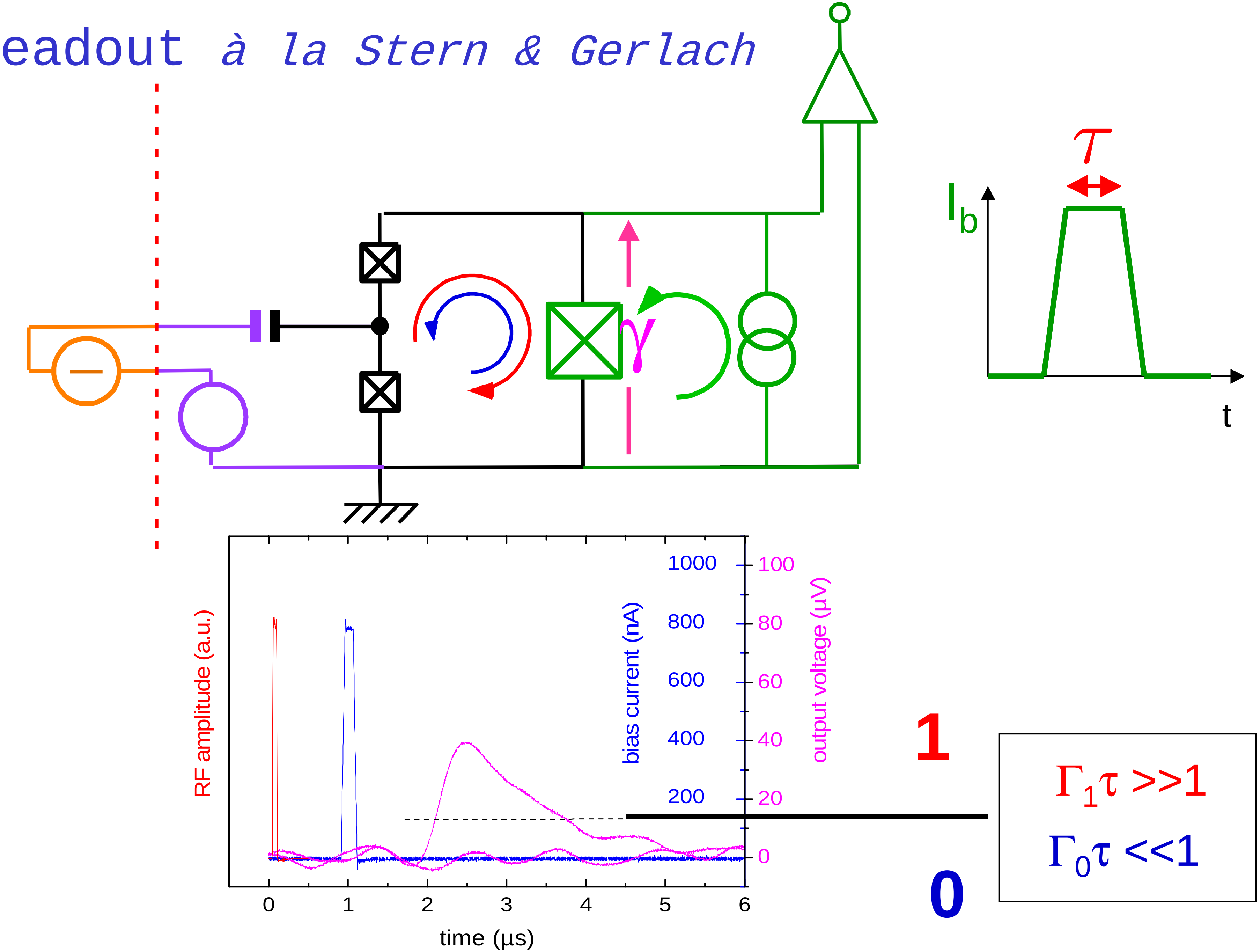
$$I_b < I_0 \quad I_b = I_0 \sin \gamma$$

II) discriminates when : $\gamma \simeq \pi / 2$

$$I_b \simeq I_0 \quad I_b + i_1 < I_0 < I_b + i_0$$



Readout *à la Stern & Gerlach*

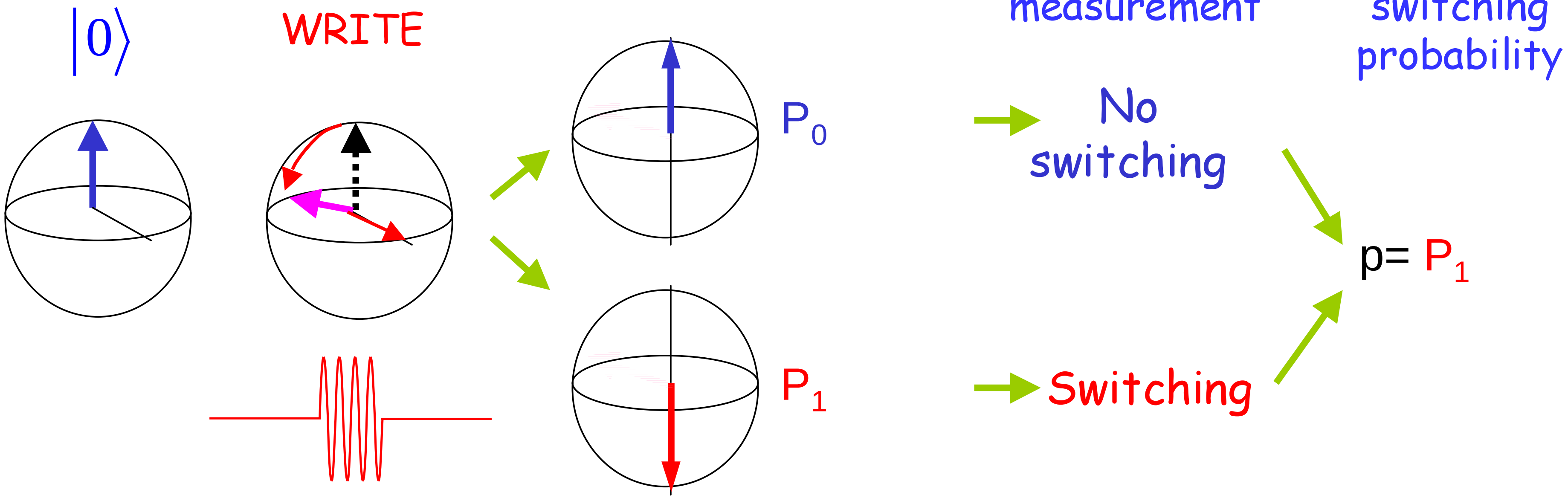


$\Gamma_1\tau >>1$

$\Gamma_0\tau <<1$

Preparation and ideal readout

READ



$|0\rangle$

WRITE

Projection

P_0

P_1

Ideal measurement

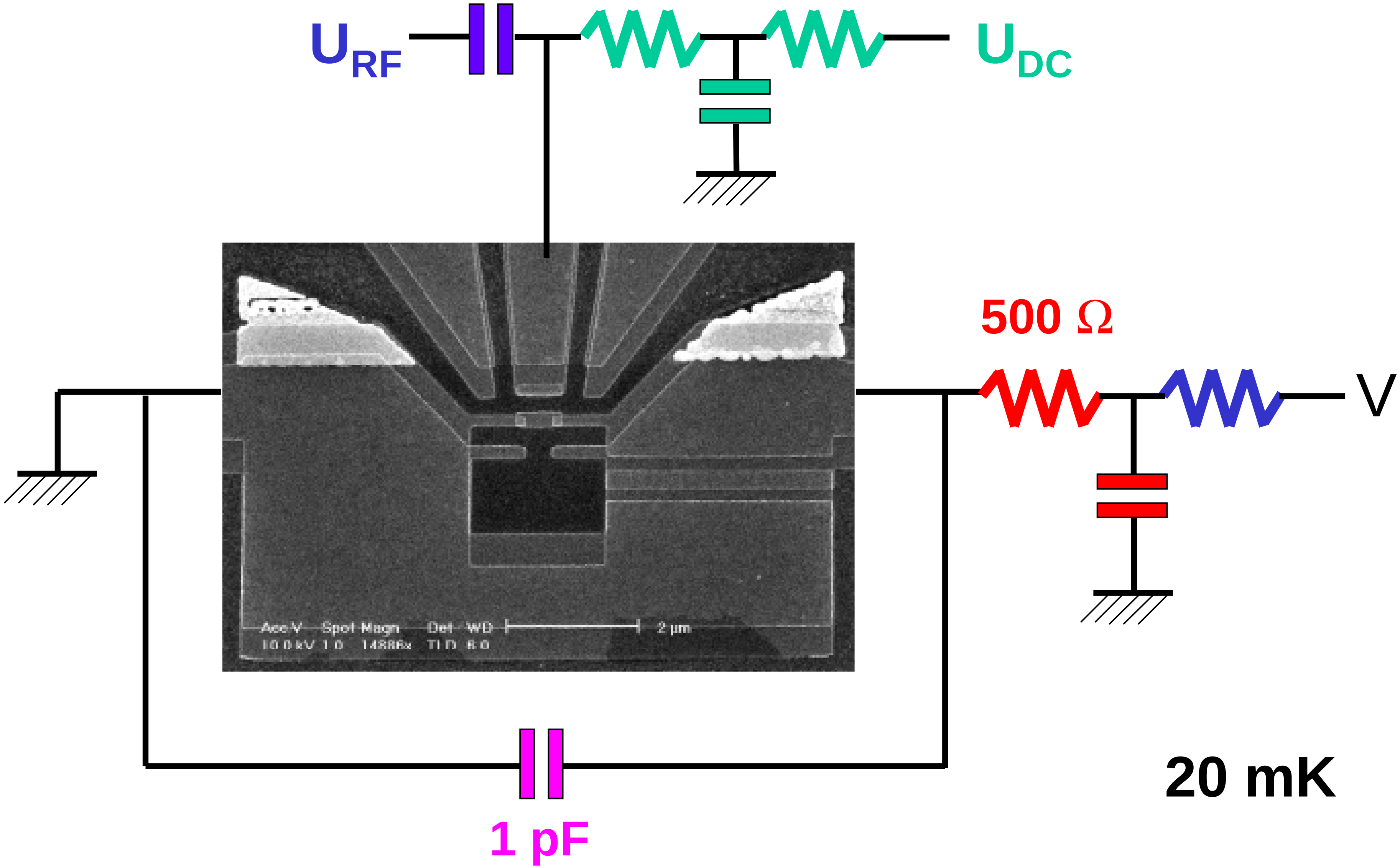
No switching

Switching

Measured switching probability

$p = P_1$

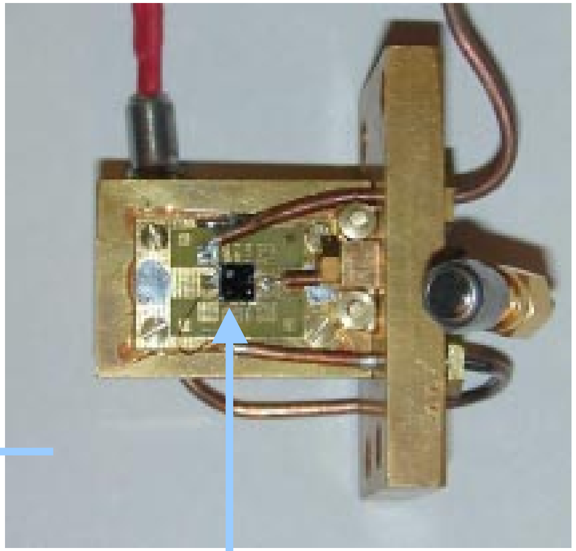
Implementation



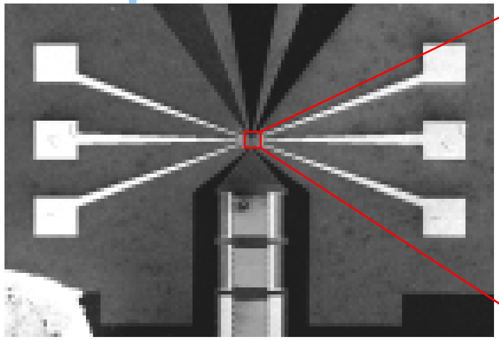
20 mK

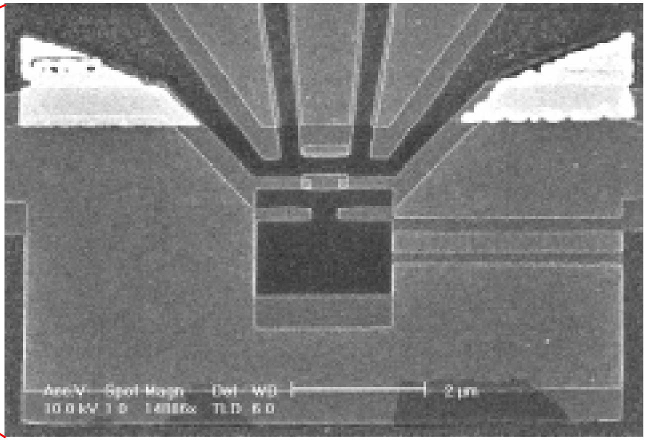
Experimental set-up

Dilution fridge
20 mK



p.c.b.

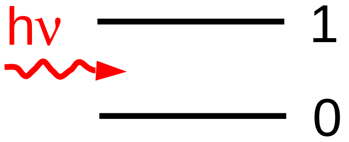


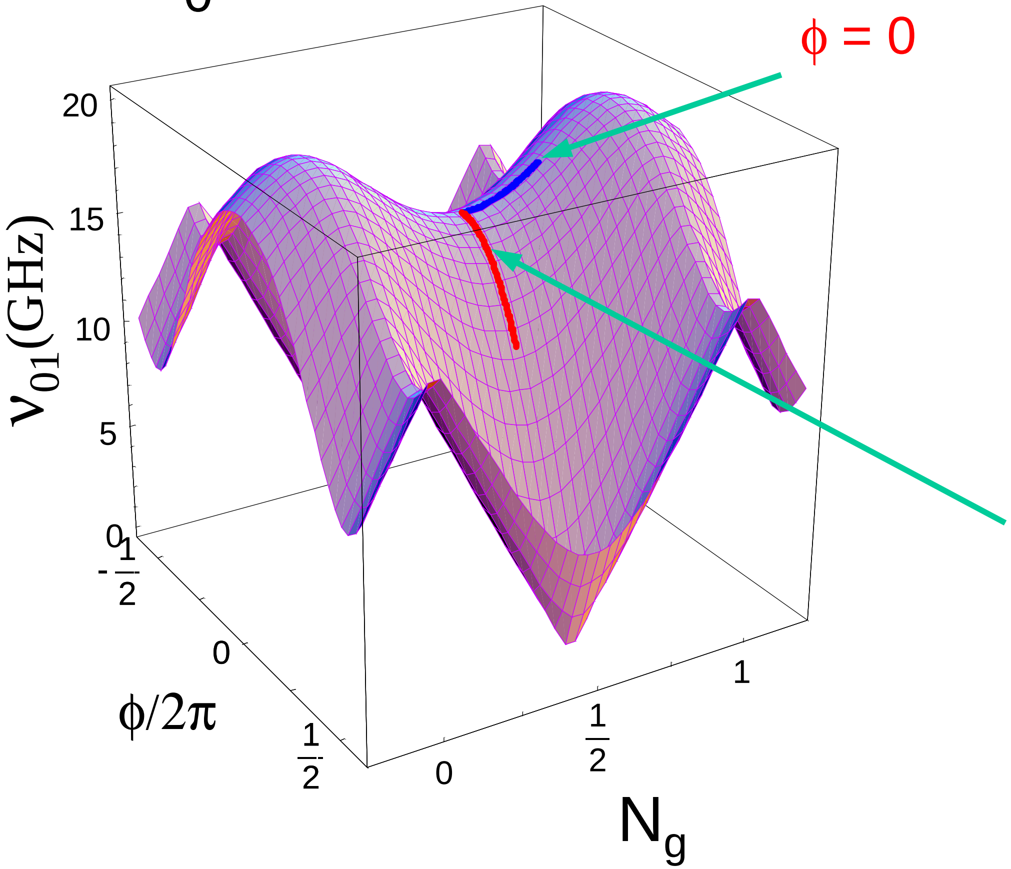


chip

Level spectroscopy

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

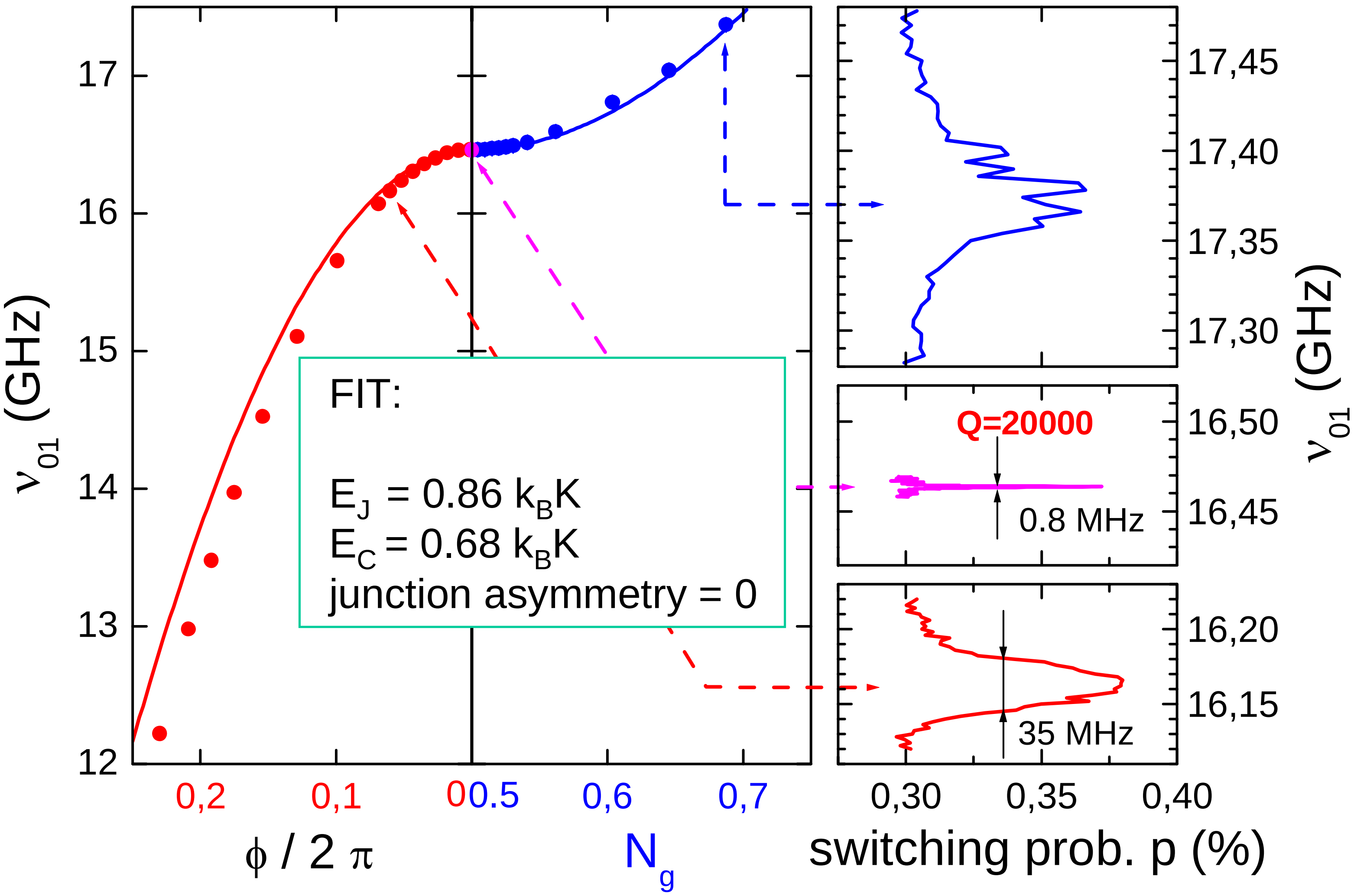




$\phi = 0$

$N_g = 1/2$

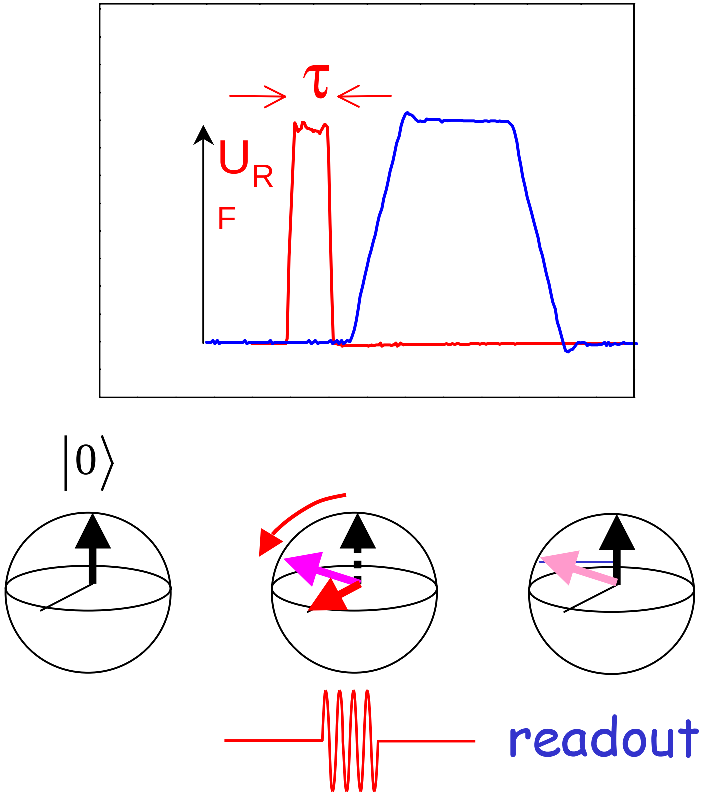
Level spectroscopy $\nu_{01}(Ng, \phi/2\pi)$



FIT:

$E_J = 0.86\ k_BK$
$E_C = 0.68\ k_BK$
junction asymmetry = 0

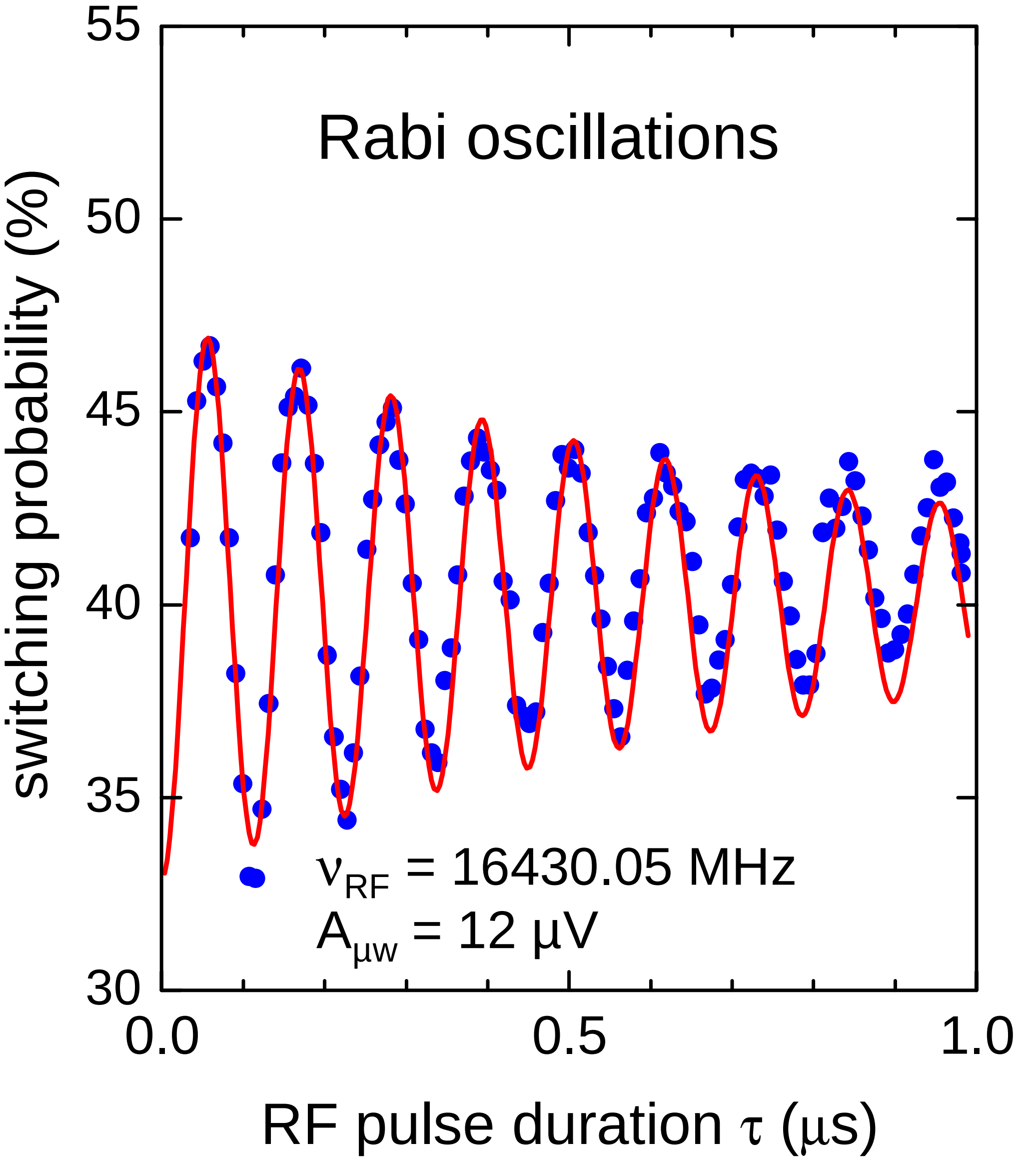
1 pulse: quantum state manipulation



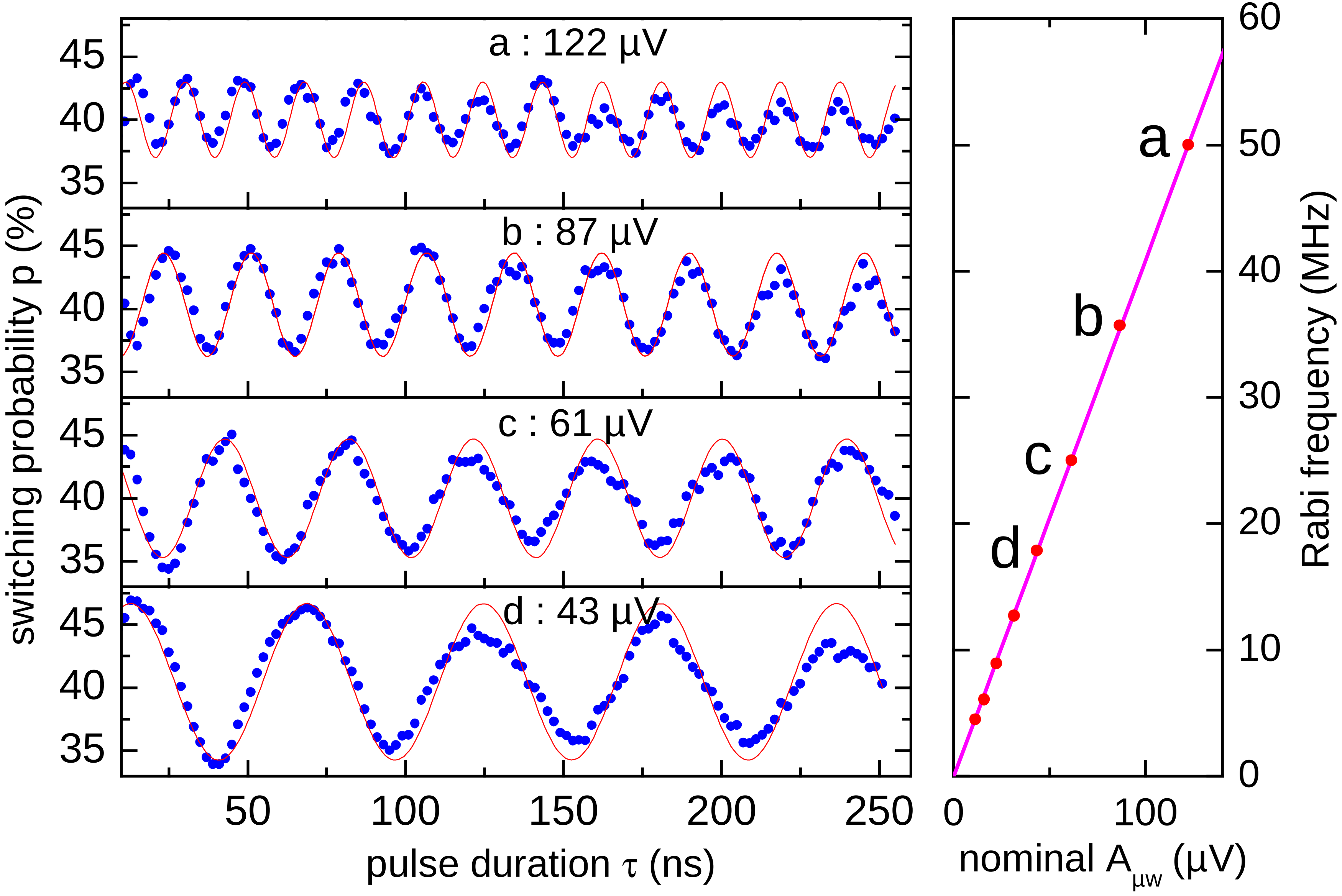
readout

rotation

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

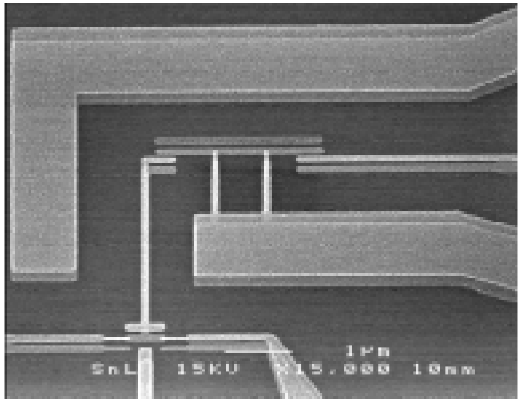


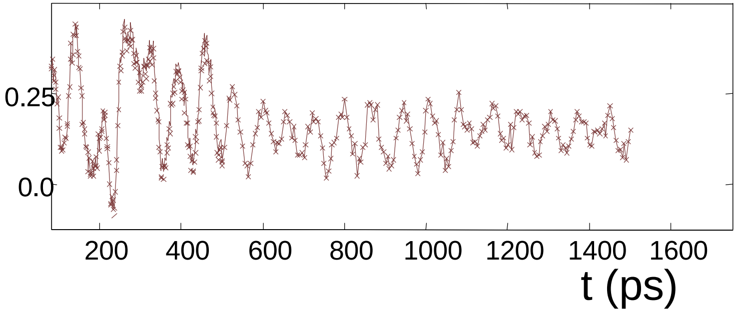
μw amplitude dependence of Rabi frequency



charge qubit

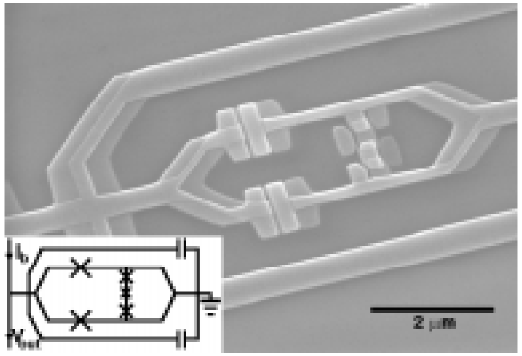
Chalmers U.

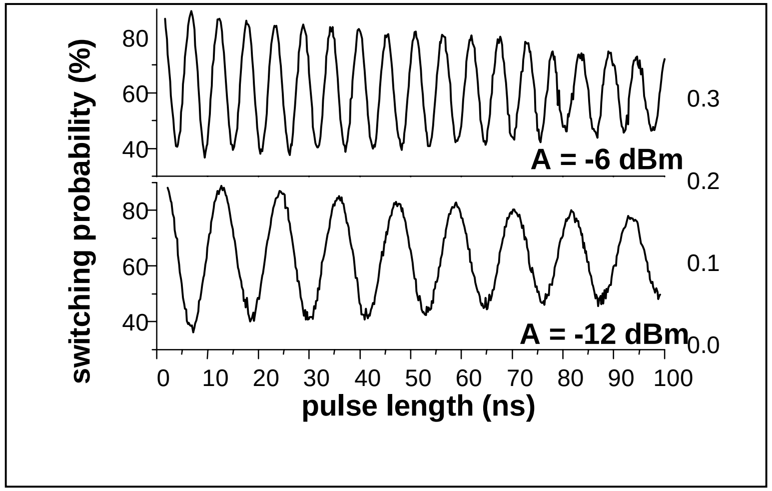




flux qubit

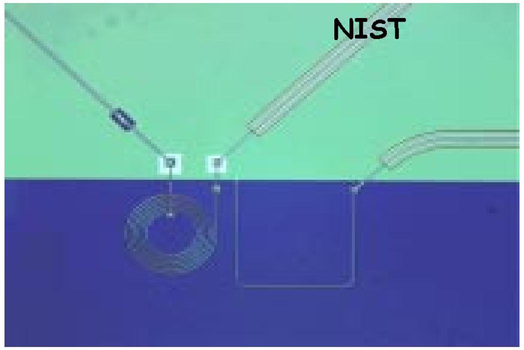
T.U. Delft
(see hot topic
K. Harmans)

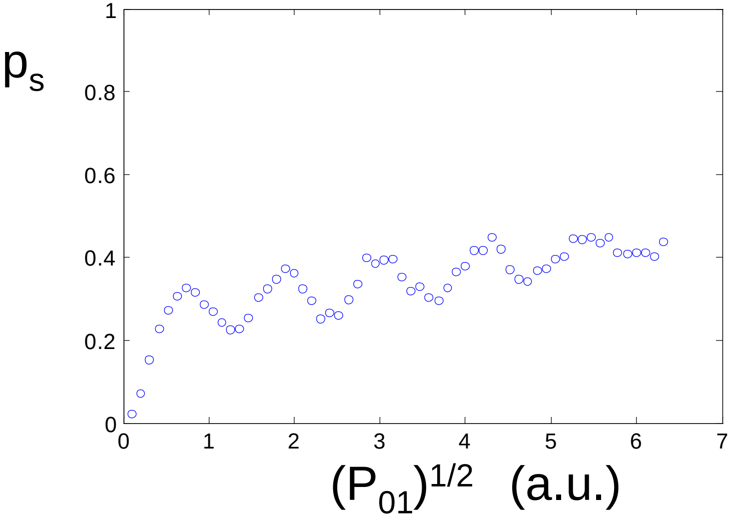




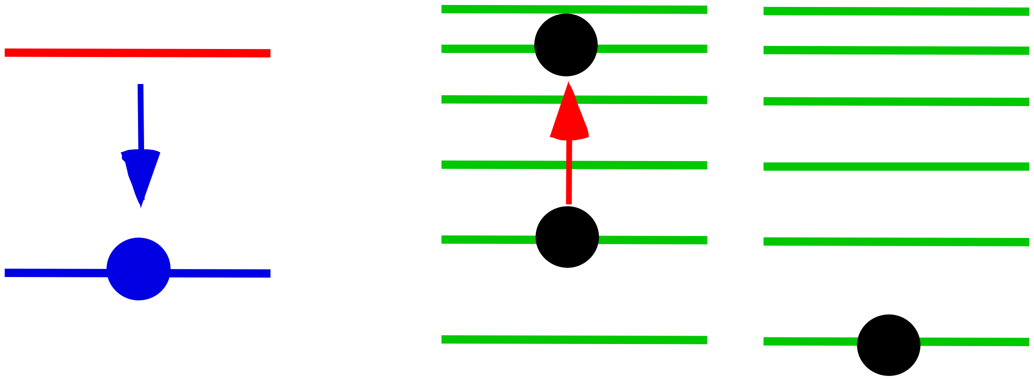
phase qubit

NIST
Martinis et al.





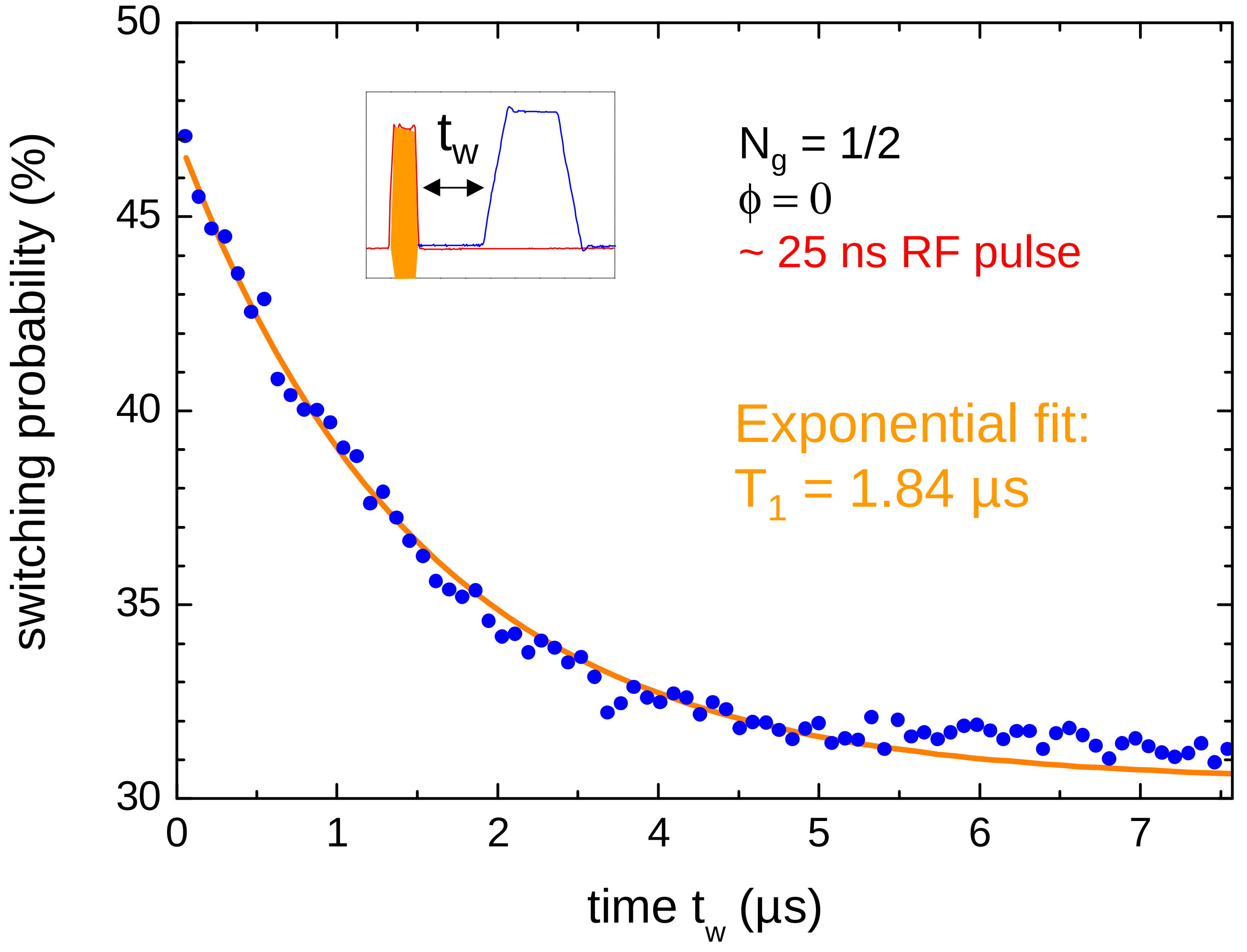
Measurement of the relaxation time



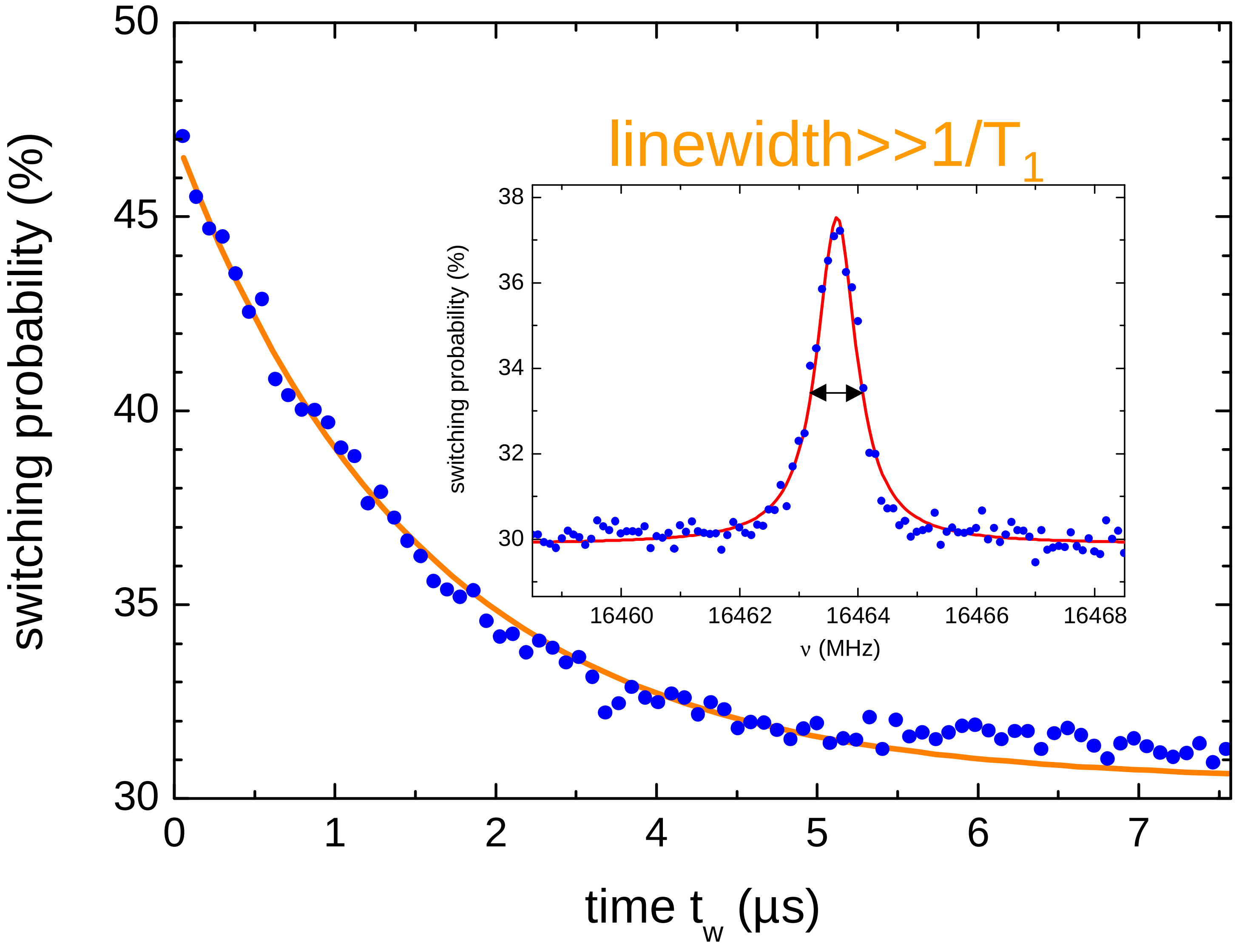
qubit
relaxation

excitation of the
environmemt

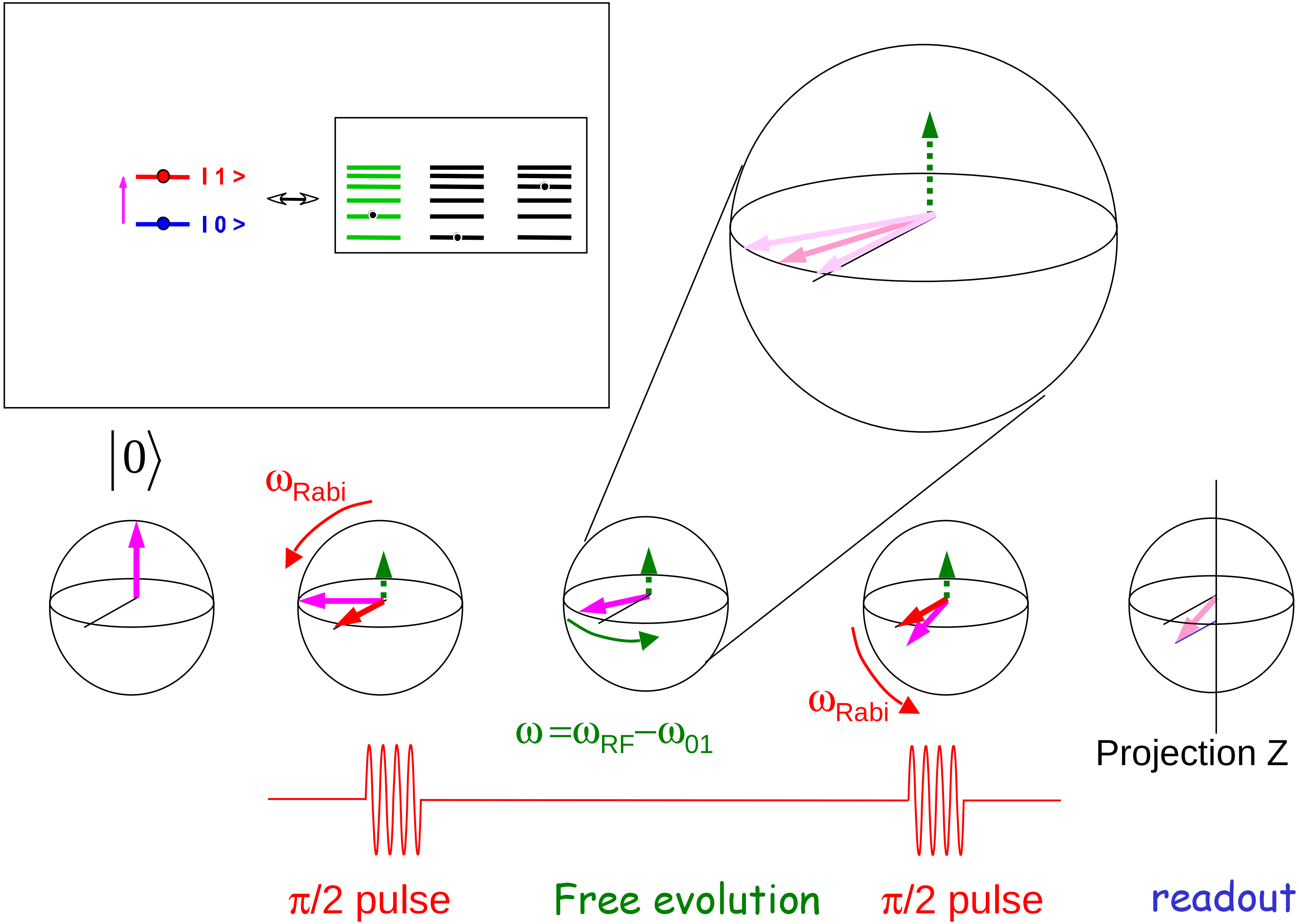
Measurement of the relaxation time



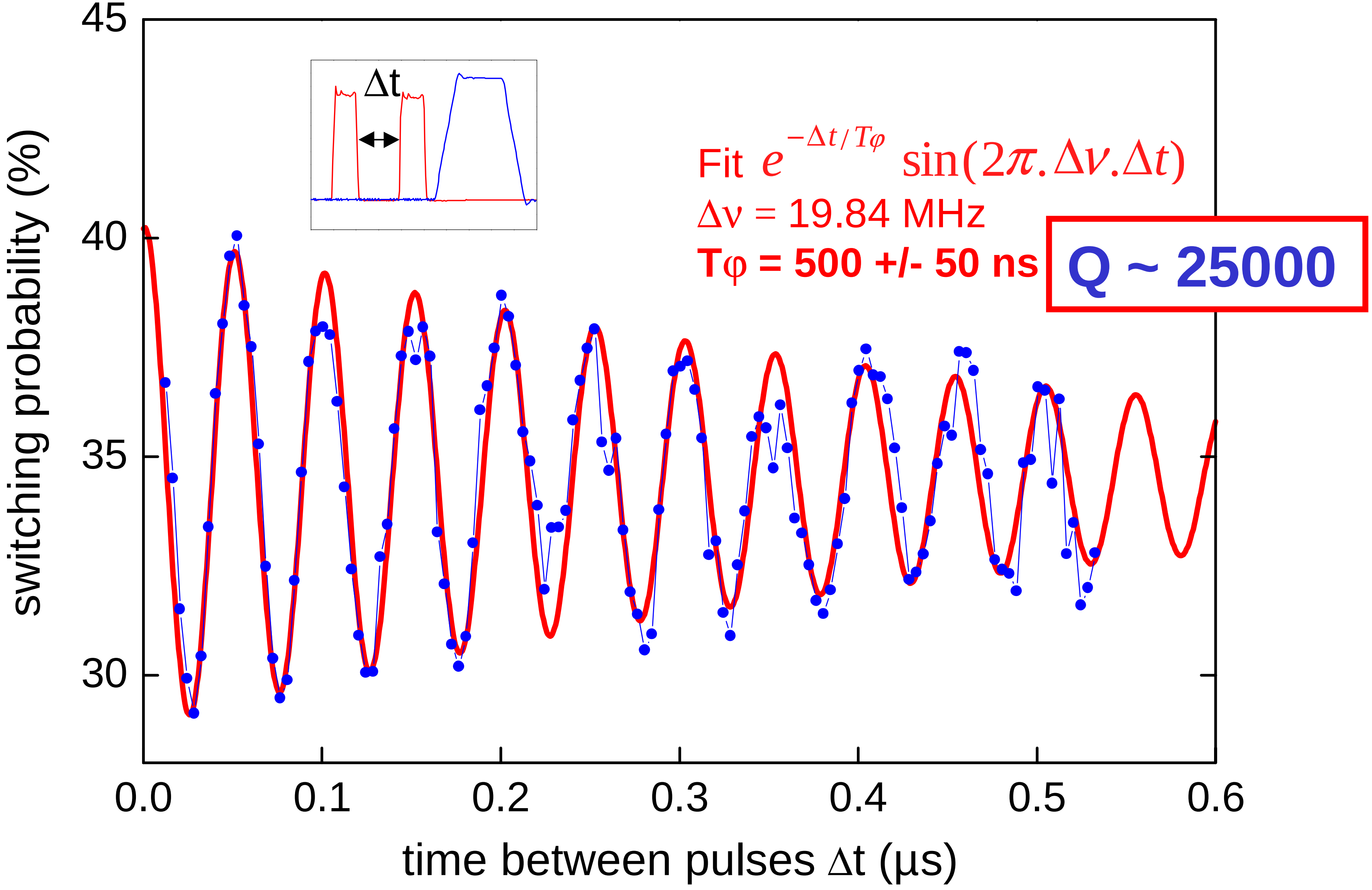
Measurement of the relaxation time



2 pulses: Ramsey interferences



Measurement of the coherence time



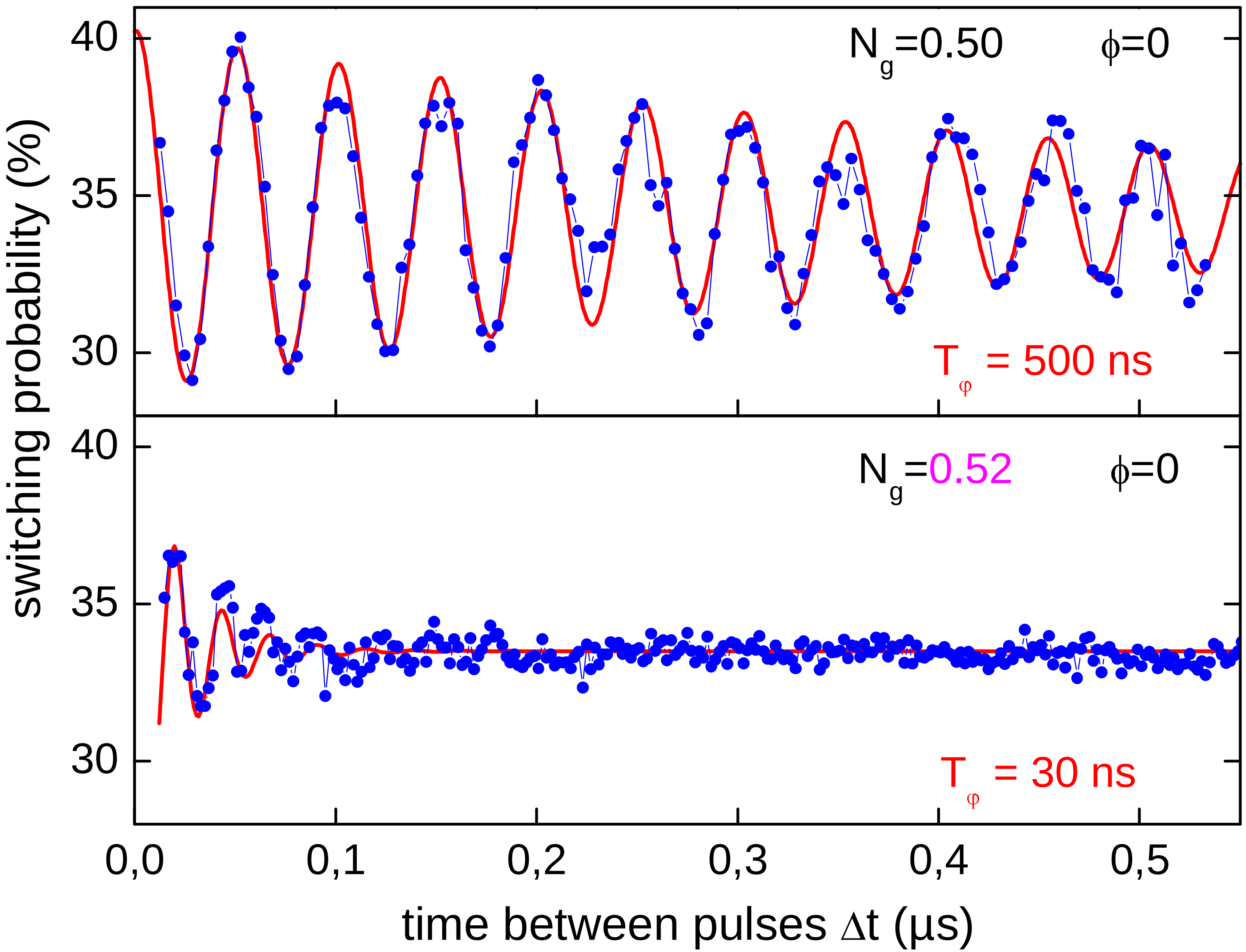
Fit $e^{-\Delta t/T\varphi}\,\sin(2\pi.\Delta\nu.\Delta t)$

Δν = 19.84 MHz

Tφ = 500 +/- 50 ns

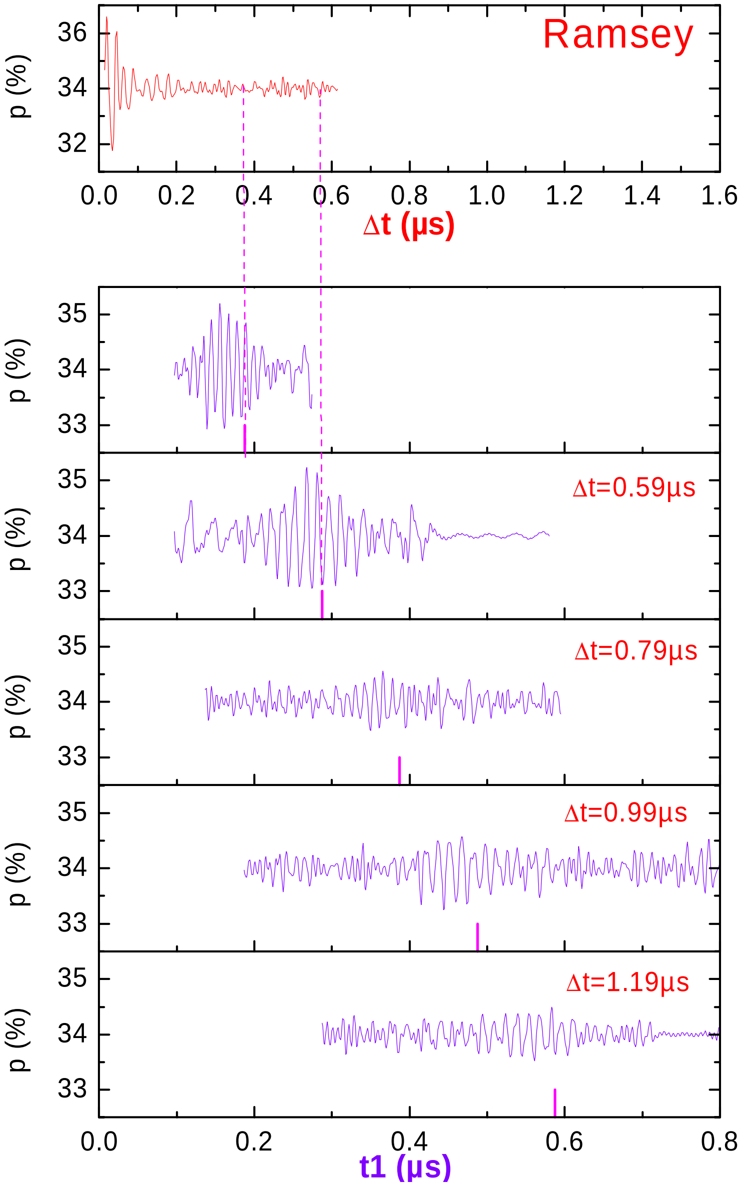
Q ~ 25000

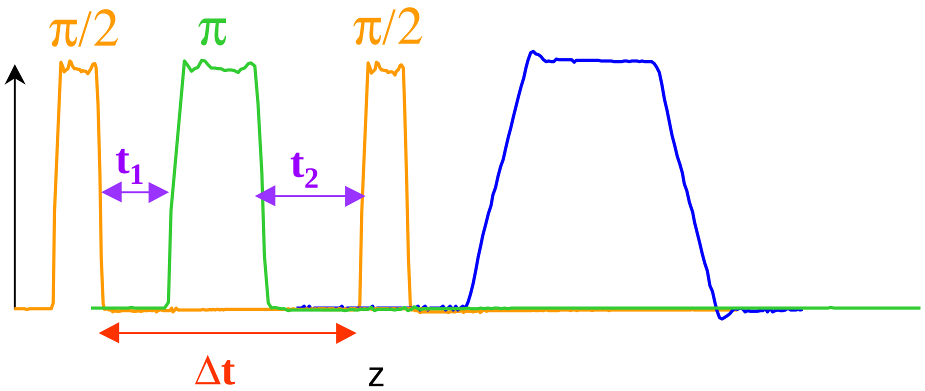
Coherence time at the optimal point...and 2% x 2e away

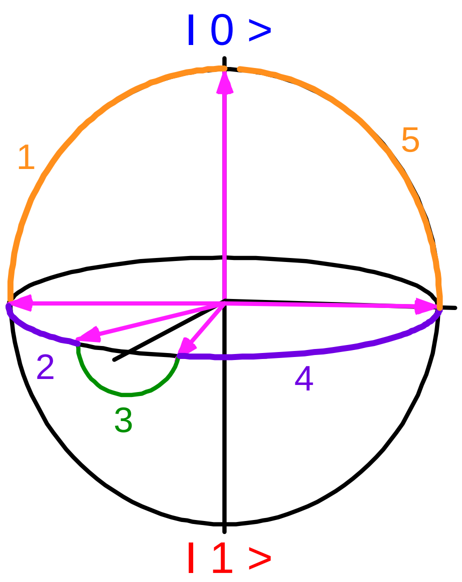


Three pulses:spin-echoes

$\phi = 0$, $\Delta Ng = 2\% \times 2e$

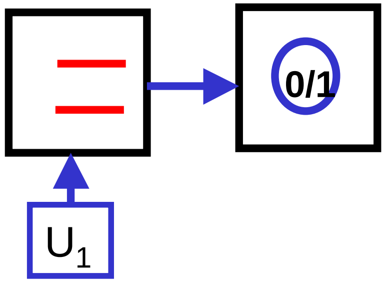


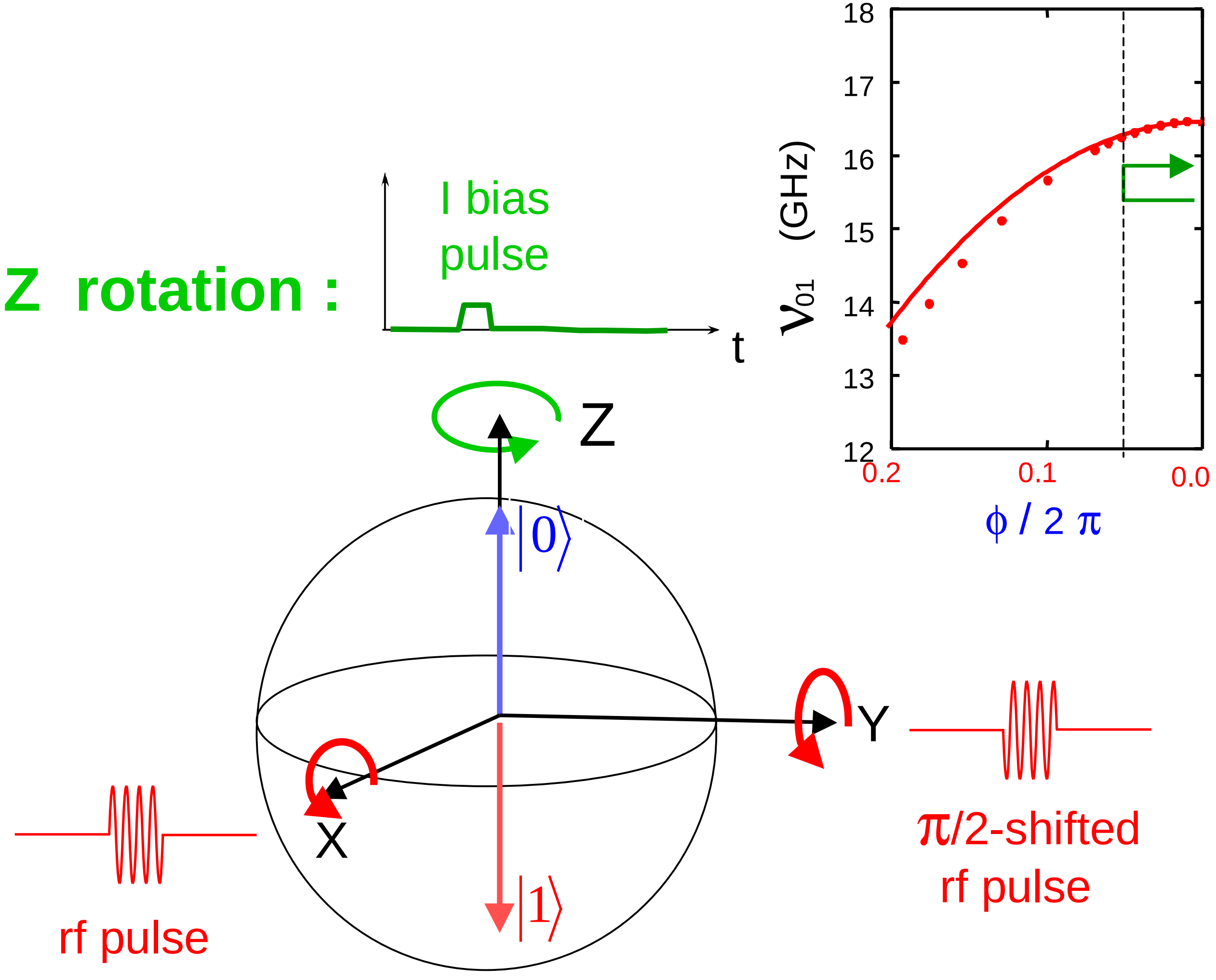




adding ... and removing dephasing

1qubit : full manipulation

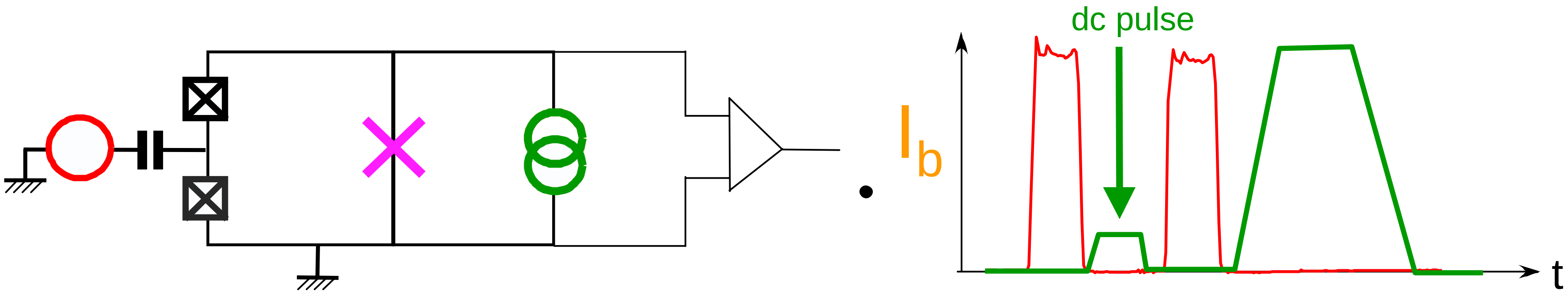


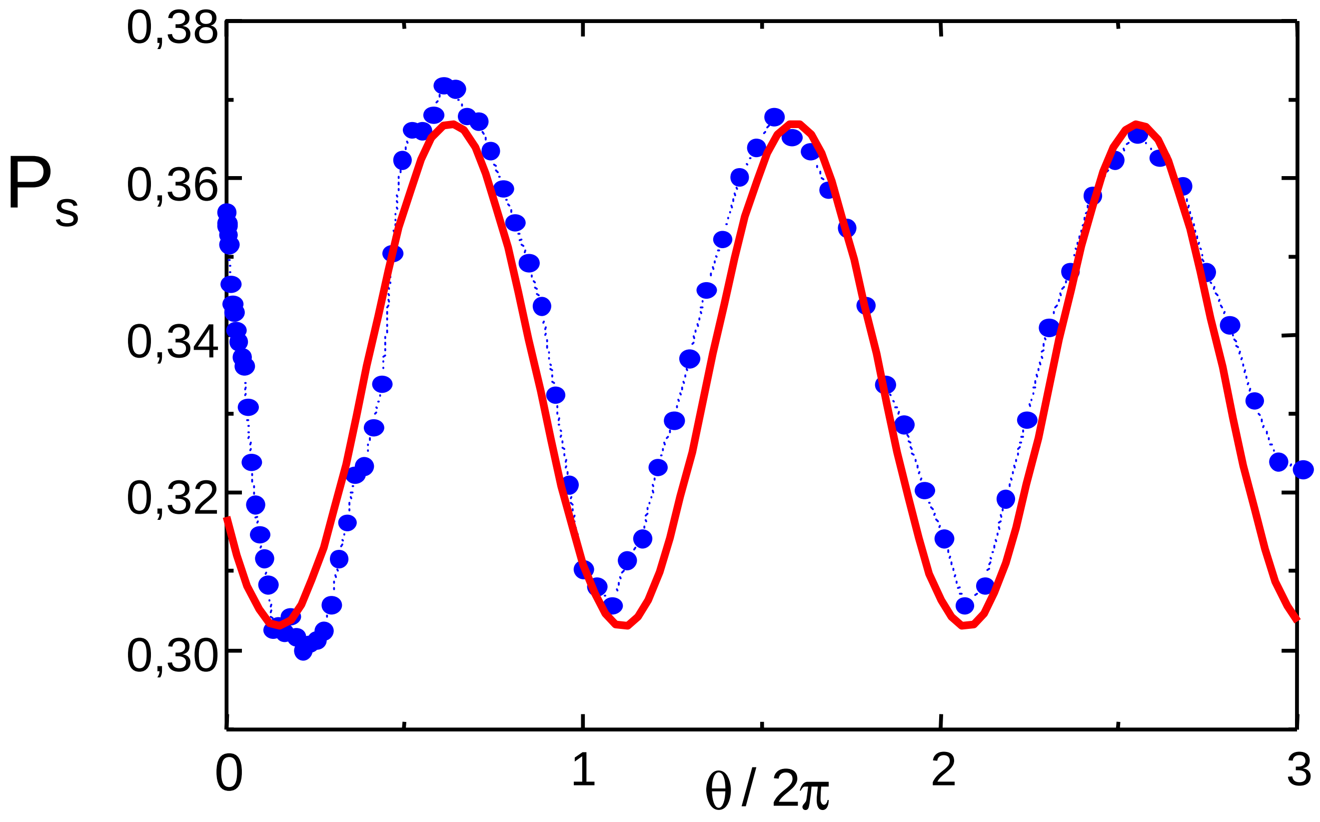


Z rotation :

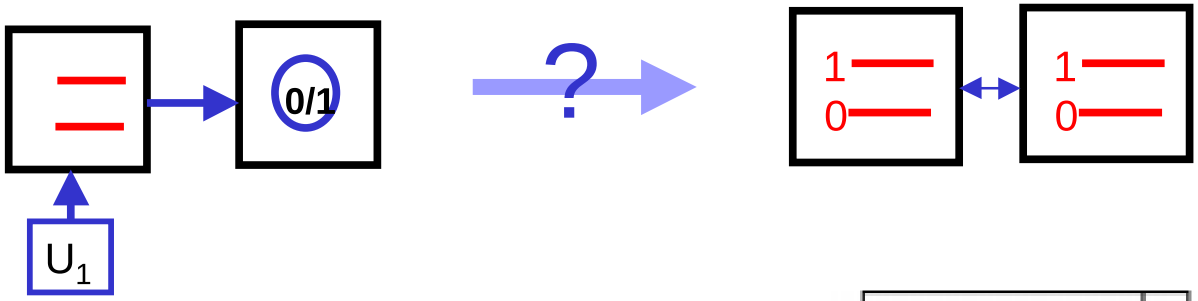
X Y rotations

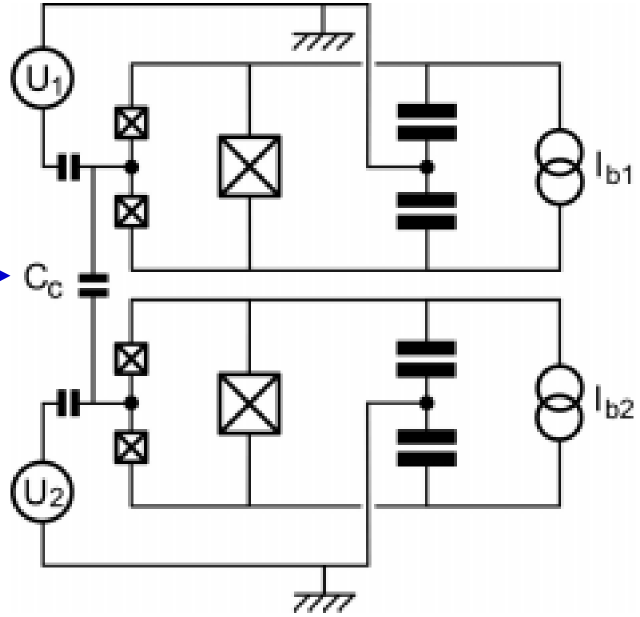
controlled phase-shift





1qubit → 2 qubit gates



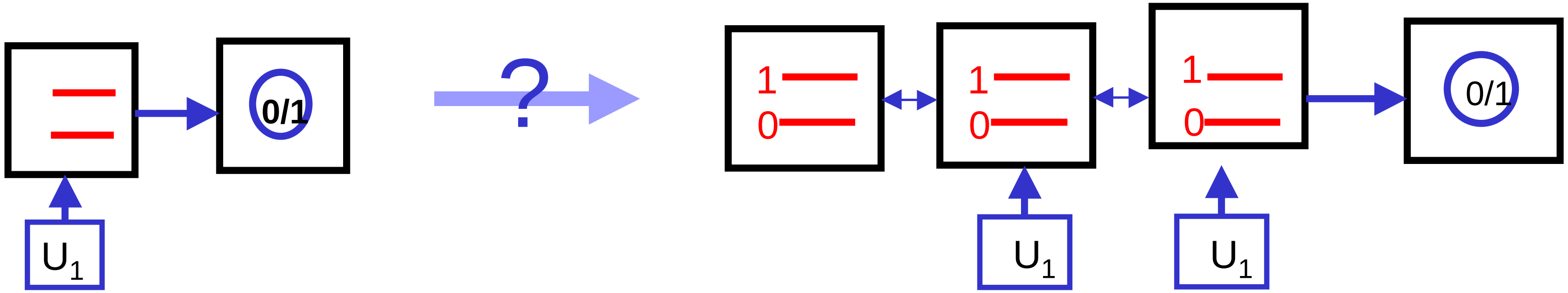


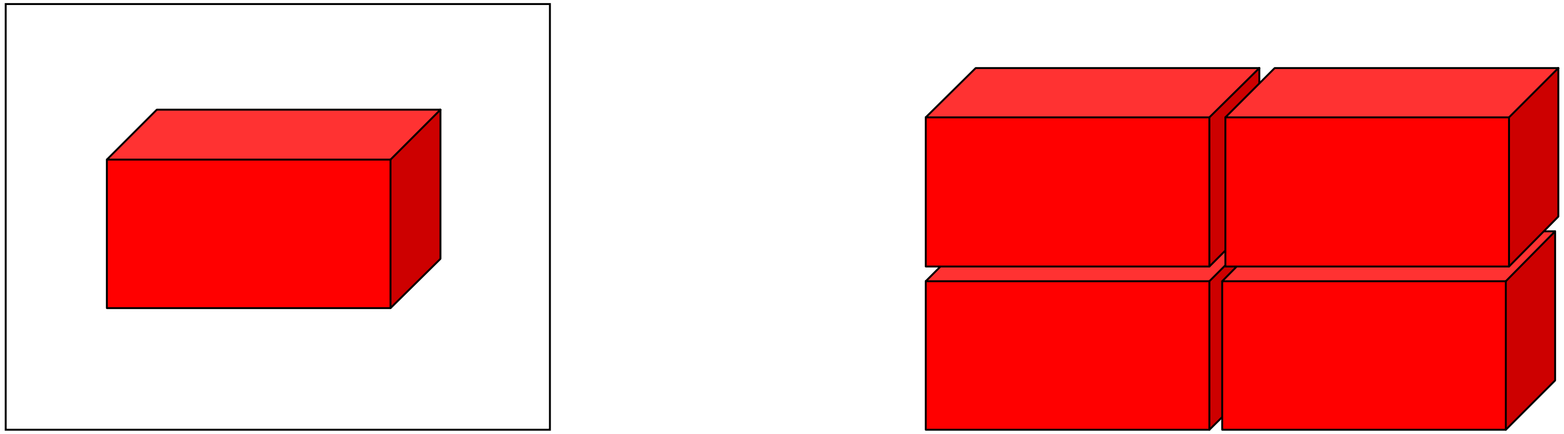
interaction

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

$\sqrt{\text{swap}}$, swap

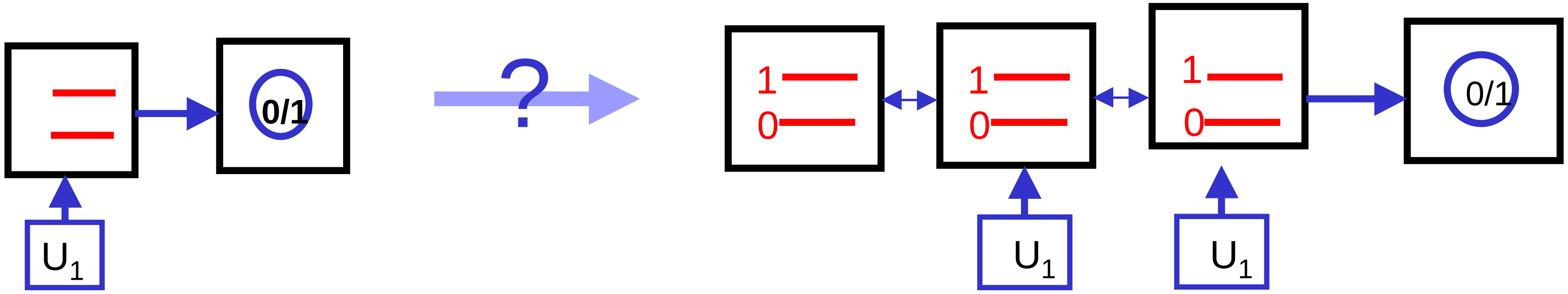
1qubit → 2 qubit gates → processor





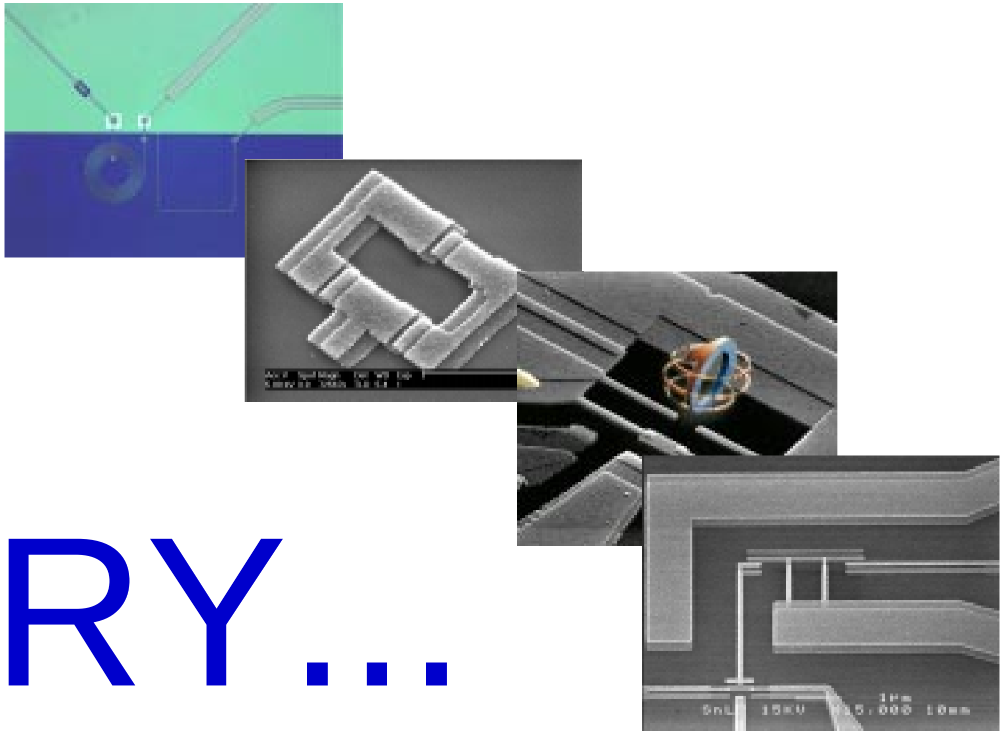
Q=25000

1qubit → 2 qubit gates → processor



NEEDED :

- quantum gates
- high fidelity readout**(s)**
- x100 coherence time



TRY...

QUANTUM
ELECTRONICS GROUP

SPEC CEA-Saclay

D. VION
A. COTTET
A. AASSIME
P. JOYEZ
H. POTHIER
M. DEVORET
(now at Yale)

C. URBINA
D. ESTEVE
P. ORFILA
(technician)

and before:
P. LAFARGE
V. BOUCHIAT