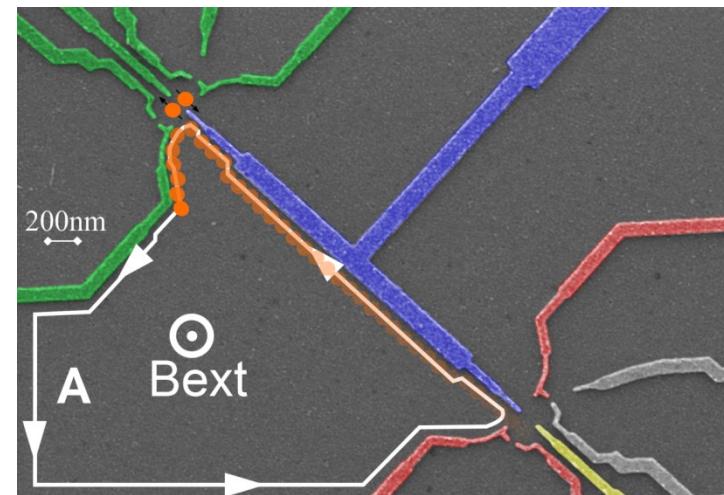
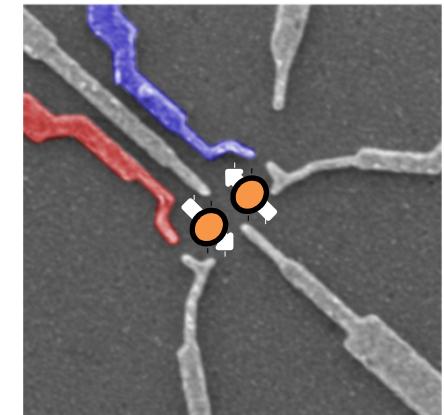
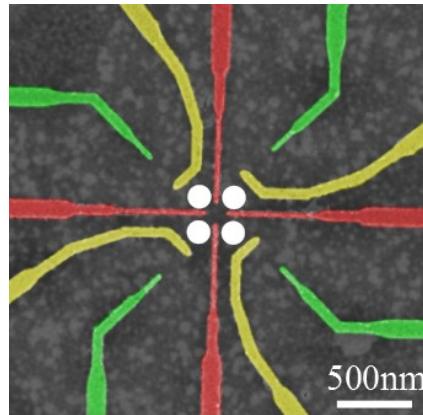


Using spin qubits to detect individual flying electrons.

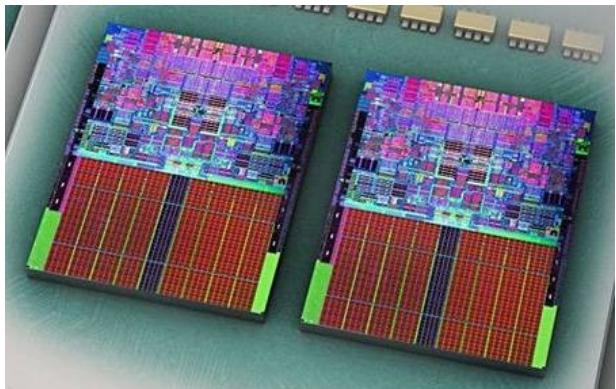
Romain THALINEAU

Supervisor : Tristan MEUNIER
Quantum coherence group
Institut Néel, CNRS-UJF-INPG
December 7th 2012

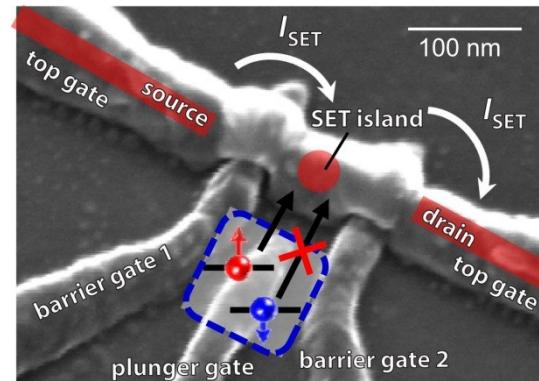


Toward electronic with a single electron

Electronic with ensemble of electrons

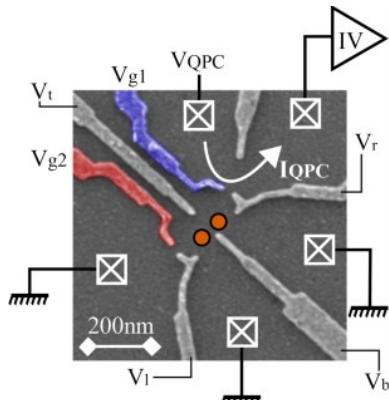


Nanocircuit at the single electron level :



Isolate a single electron in an electrostatic trap

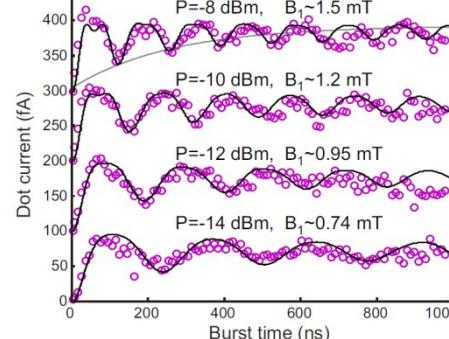
Ciorga et al, PRB(2000)



Manipulate -its charge - its spin

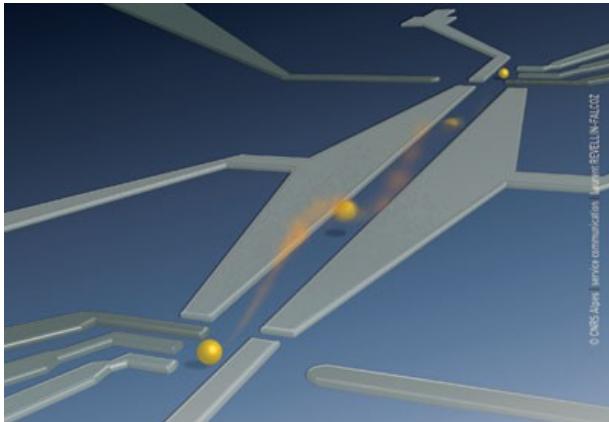
Hayashi et al, PRL(2003)

Koppens et al, Nature(2006)

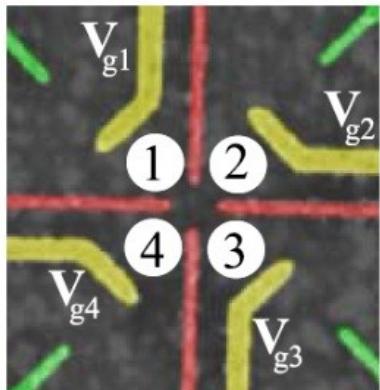


Single electron displacement

Displacement by moving quantum dots

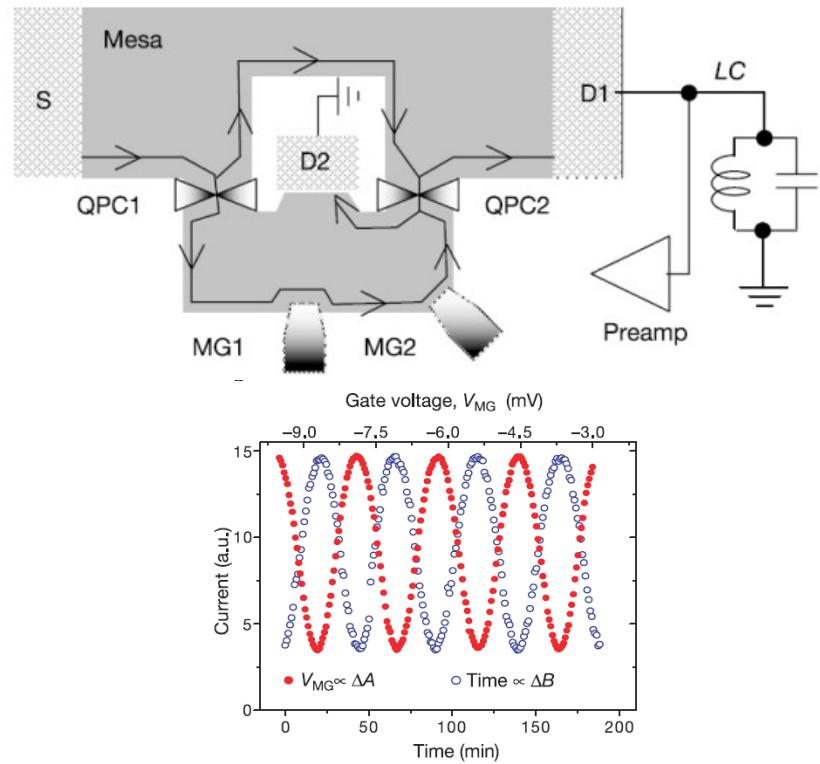


Hermelin et al, Nature(2011)



Thalineau et al, APL(2012)

Displacement by edge-states



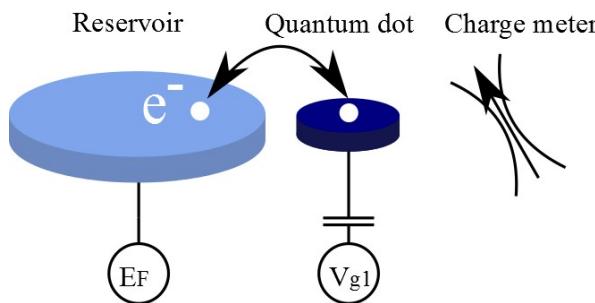
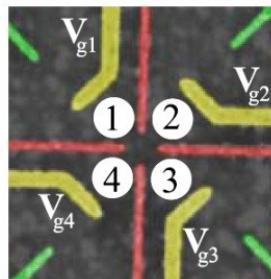
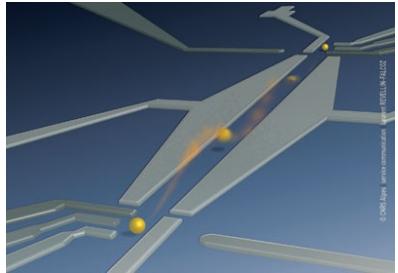
Ji et al, Nature (2003)

I_φ $2\sim20\mu\mu m$

Rouleau et al, PRL (2008)

Single electron detection

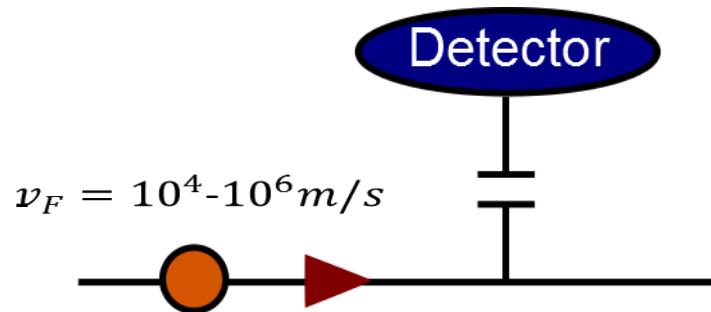
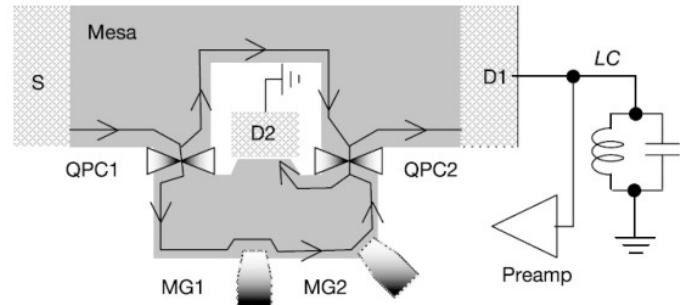
Displacement by moving quantum dots



Elzerman et al, PRB(2003)
Reilly et al, APL(2007)
Barthel et al, PRL(2009)

$$\$ \approx 10^{-4} e/\sqrt{\text{Hz}}$$

Displacement by edge-states



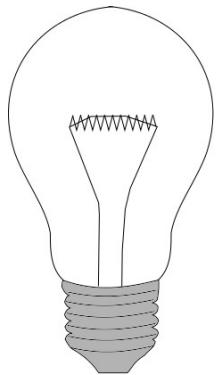
The time of interaction between a flying electron and a detector is short.



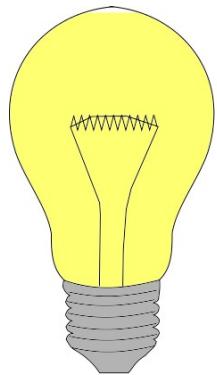
Not accessible to a classical detector

A qubit : a two level quantum object

Two level system :

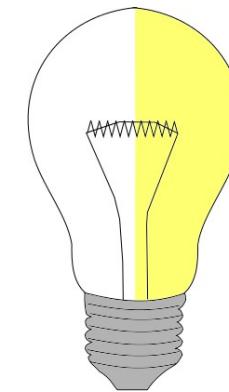


$|0\rangle$



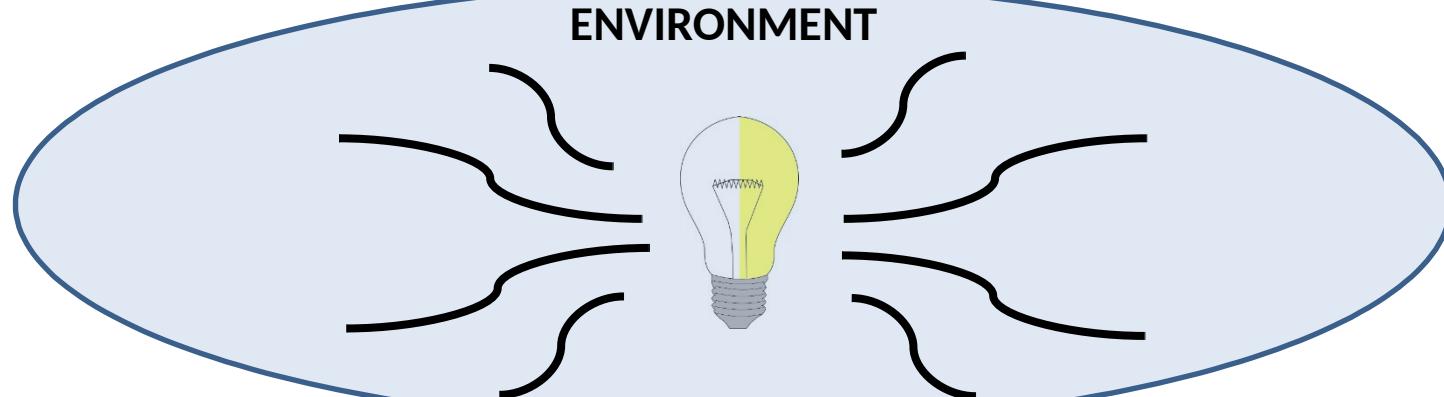
$|1\rangle$

Quantum object :



$|0\rangle + |1\rangle$

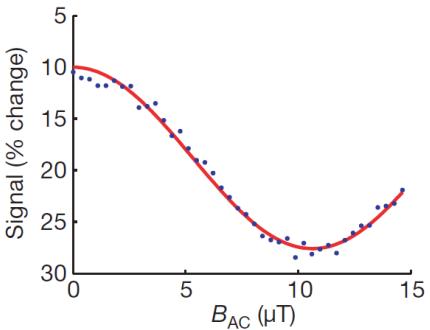
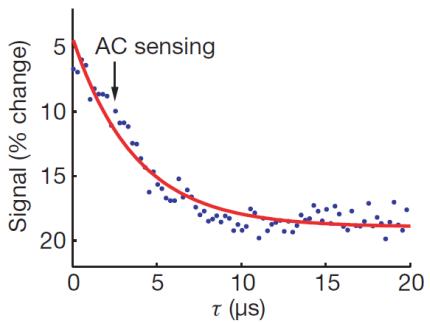
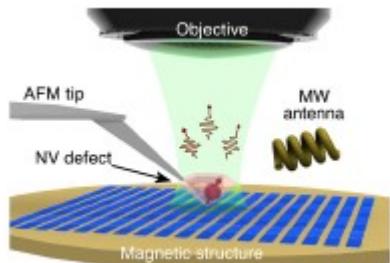
Microscopic object : extremely sensitive to the environment



Qubits as highly sensitive detector

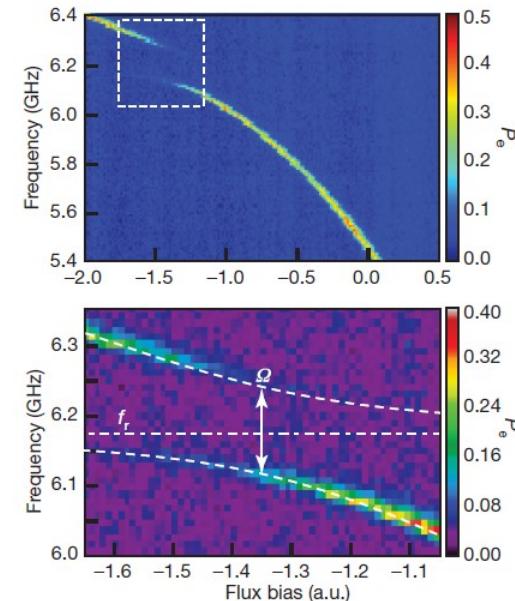
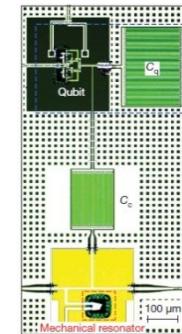
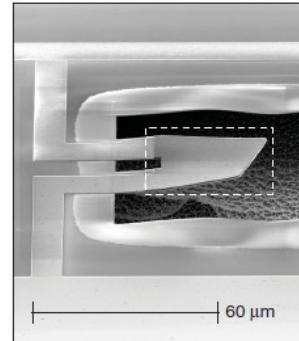
NV center magnetometer

Maze et al, Nature(2008)
Rondin et al, APL(2012)



Superconducting qubit to detect mechanical quantum ground state :

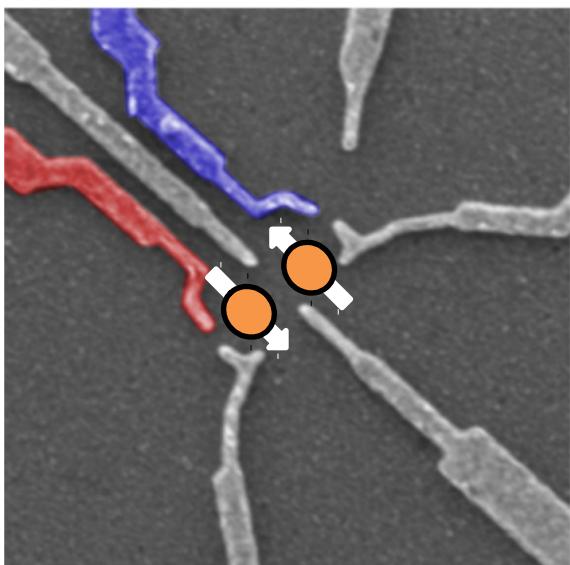
O'Connell et al, Nature(2010)



Singlet-Triplet qubit as an extremely sensitive electrometer

Singlet-Triplet qubit :

Two electron spins trapped in a double quantum dot



Charge-like qubit

Highly sensitive to the electrostatic environment

Interaction~100ps

Petta et al, Science
(2005)

Spin-like qubit

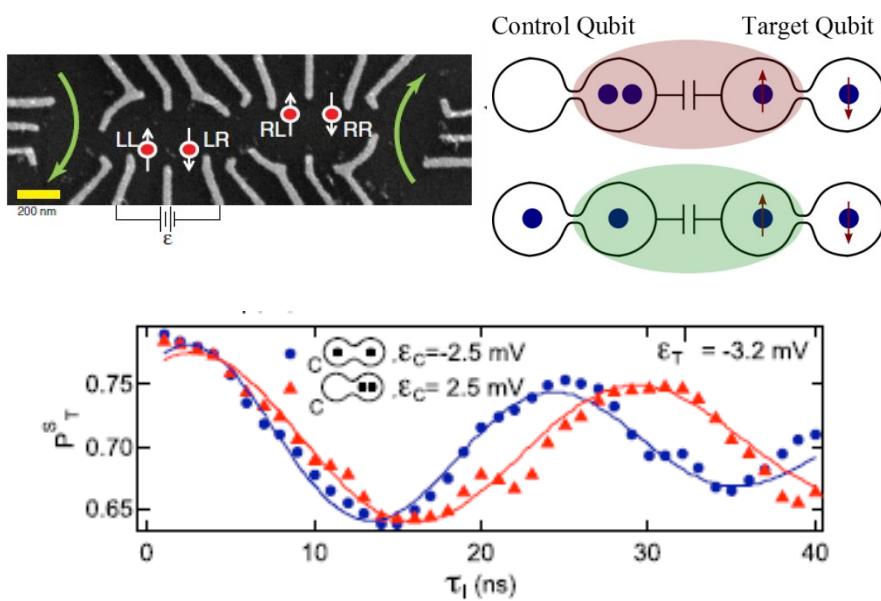
Well protected from the electrostatic environment

Coherence>100μs

Bluhm et al, Nat Phys
(2010)

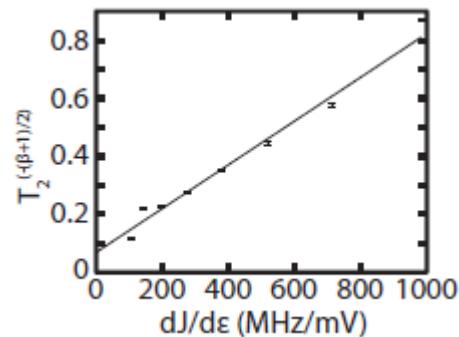
Singlet-Triplet qubit as an extremely sensitive electrometer

Entanglement of two qubit using electrostatic interaction



Van Weperen et al, PRL(2010)
Shulman et al, Science (2012)

Extremely sensitive electrometer



Sensitivity $> 10^{-8} e/\sqrt{\text{Hz}}$

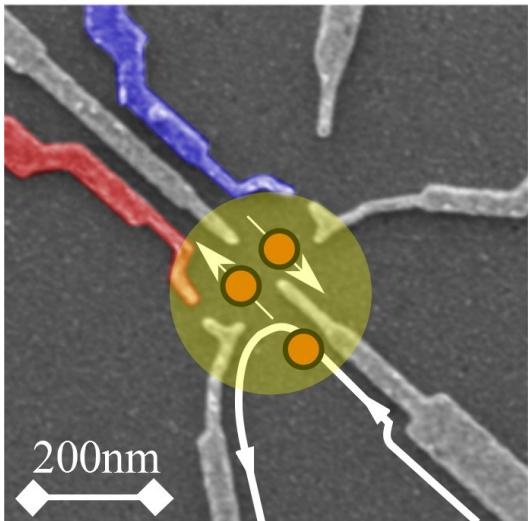
Dial et al, Arxiv (2012)

Excellent charge detector !

Singlet-Triplet qubit as a single electron detector

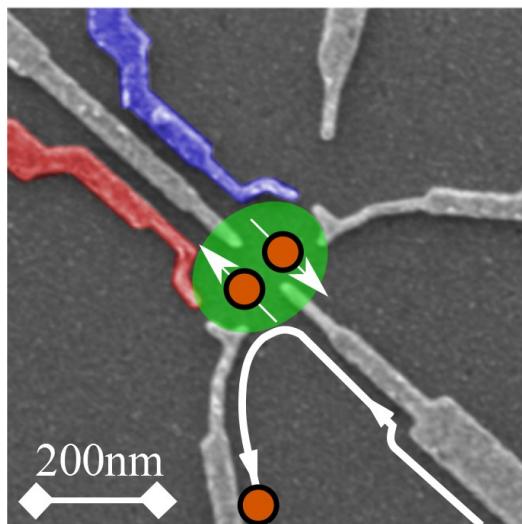
Charge-like qubit :

Strong interaction with a single electron



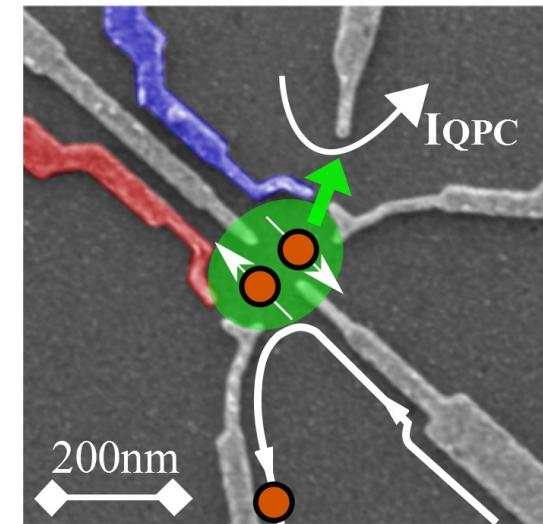
Spin-like qubit :

Storage of the resulting effect on the population of the qubit



Single shot readout :

Measurement of the qubit population



Outline

I) Singlet-Triplet qubit in a double quantum dot

II) Quantum Hall Effect (QHE) and quantum optics with electrons

III) Characterization of the detector device

IV) Single electron detection

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II) Quantum Hall Effect (QHE) and quantum optics with electrons

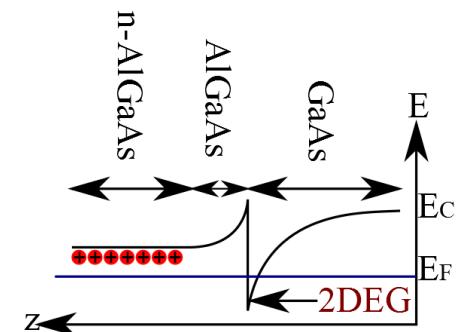
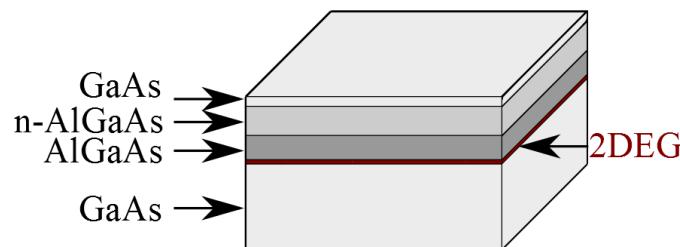
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Quantum dot systems

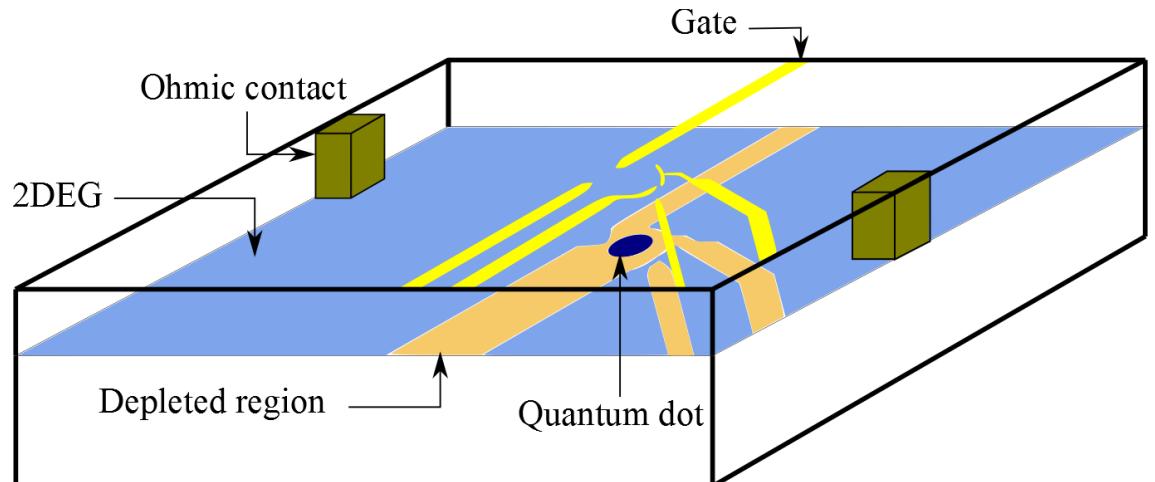
AlGaAs semiconducting heterostructure with a 2DEG :

Electrons confined in a plane

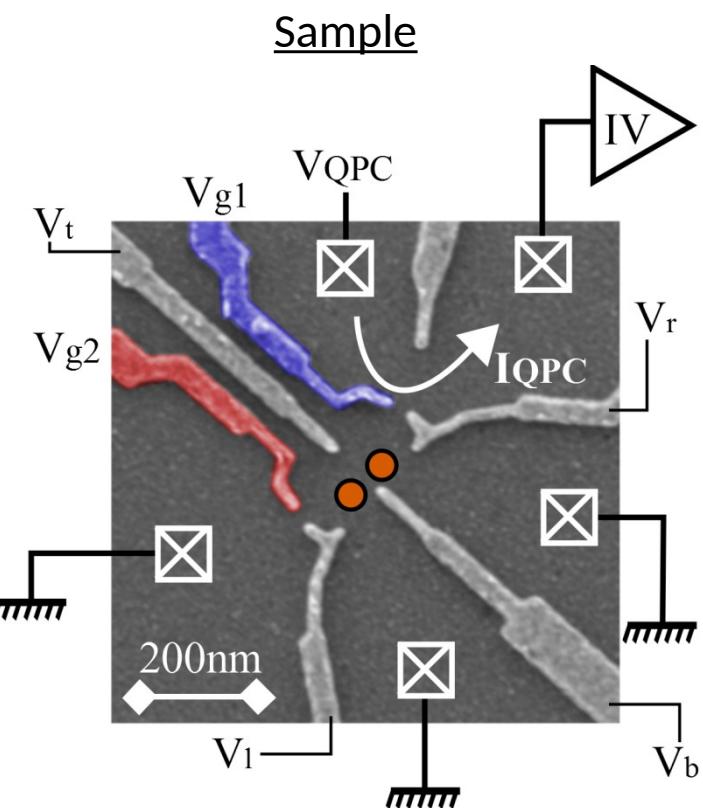


Electrostatic trap engineered by means of electric fields :

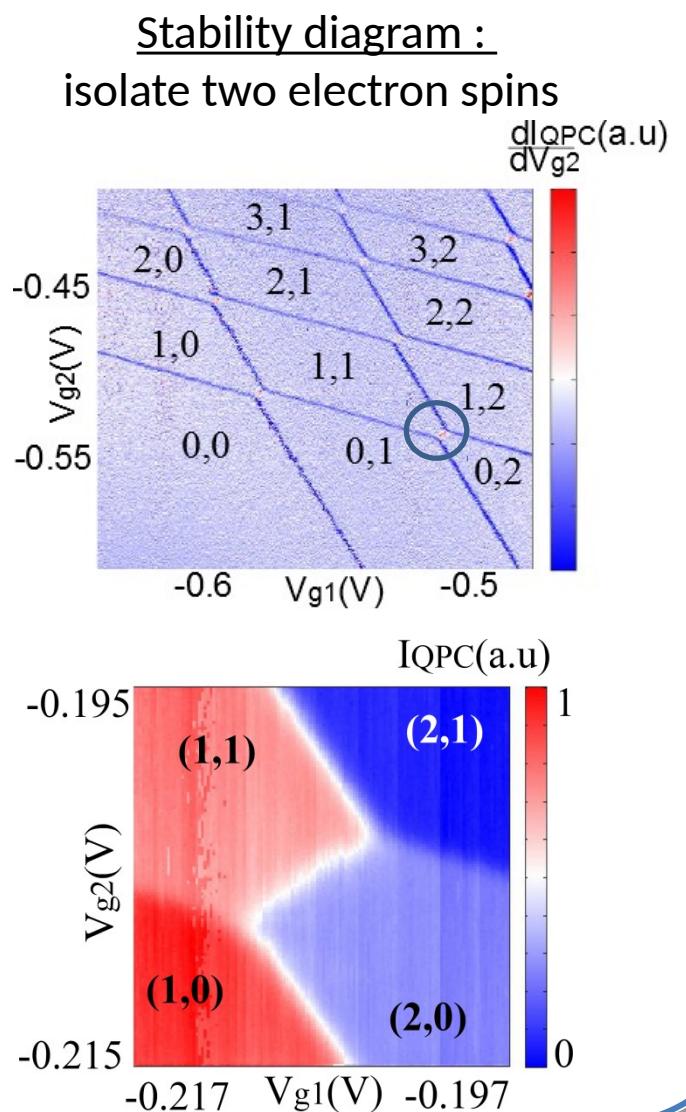
Negative voltages applied to metallic gates



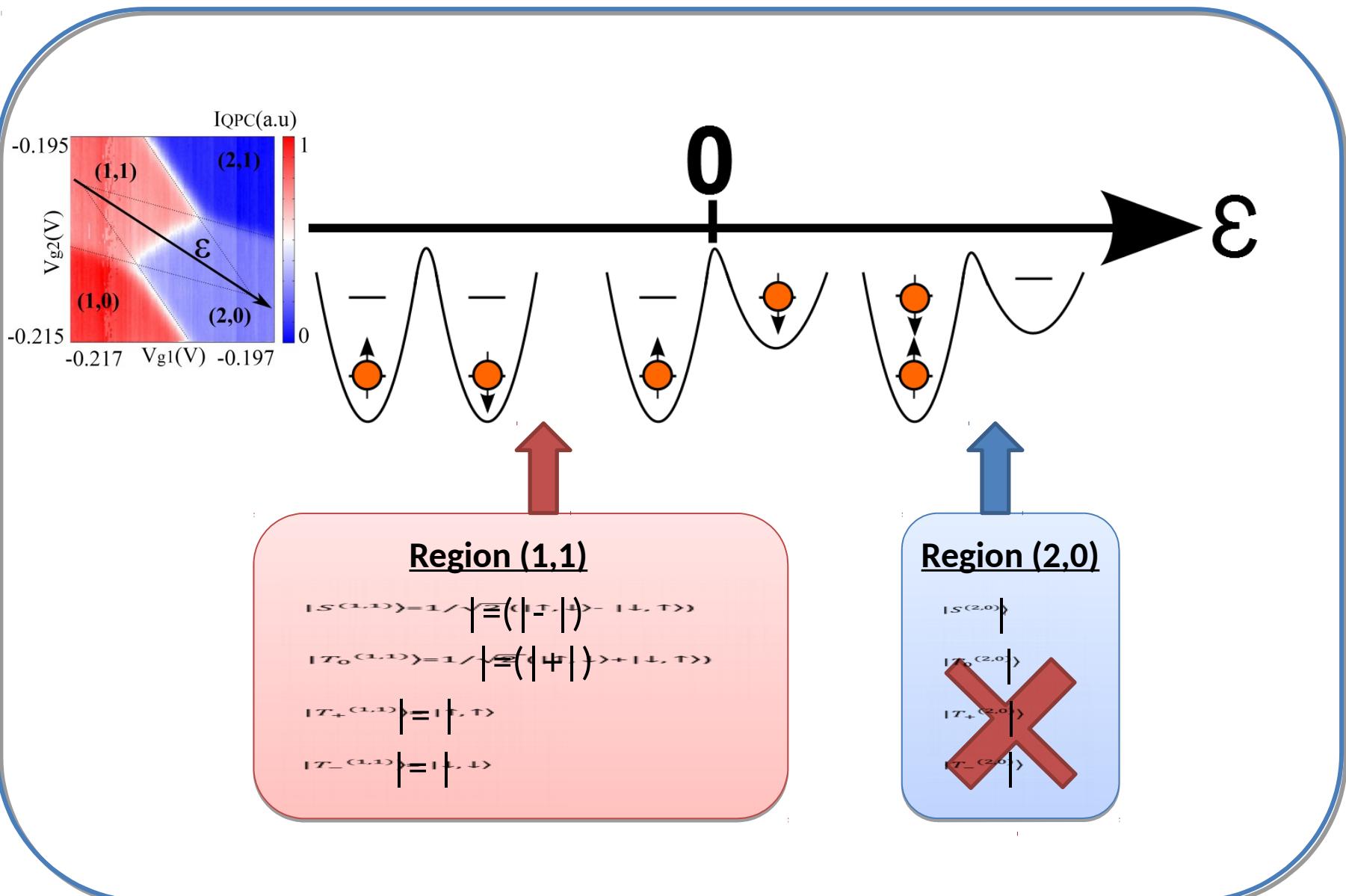
Double quantum dot



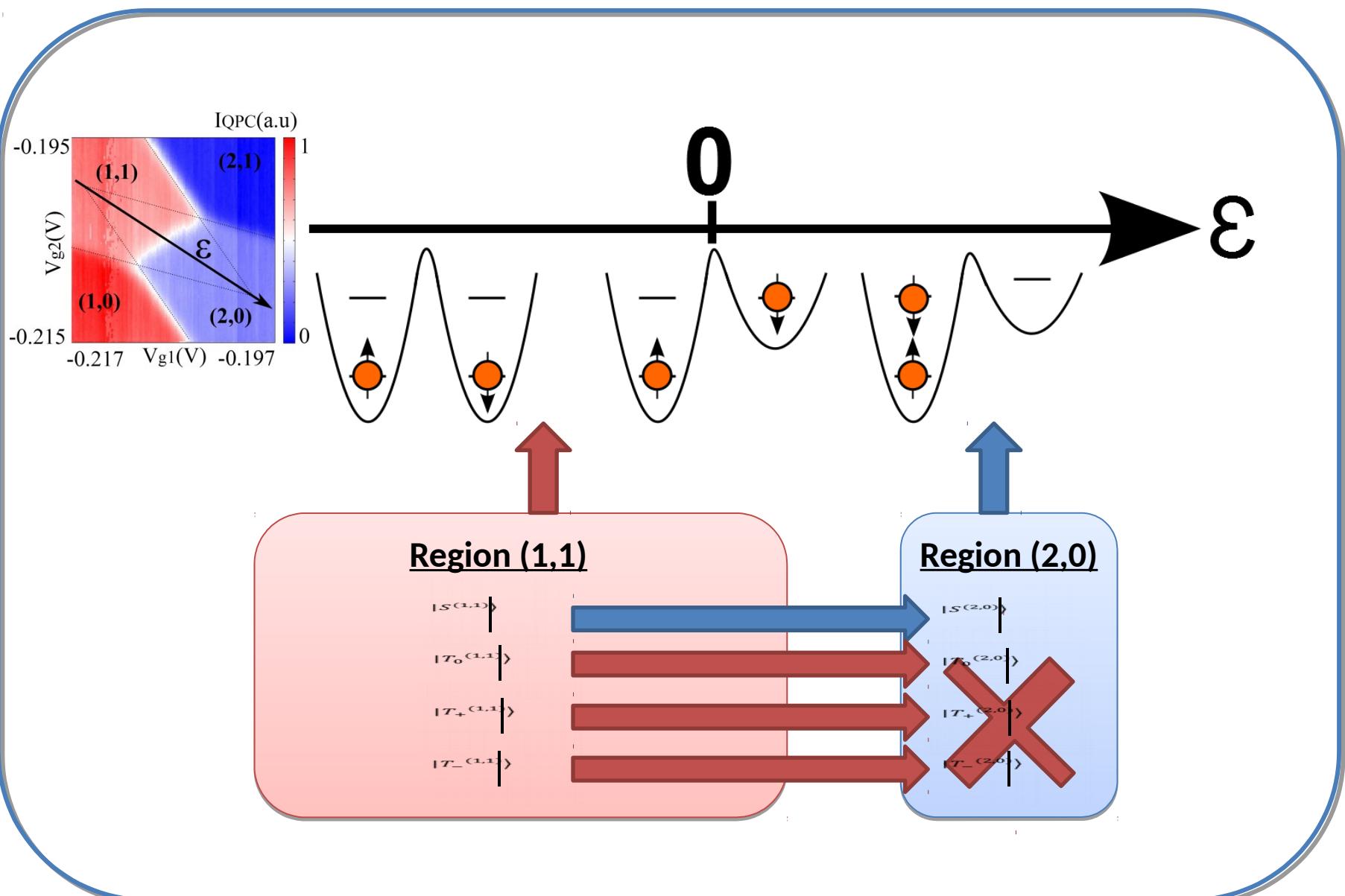
V_{g1} and V_{g2} : control of the dot potentials
 V_t and V_r : tunnel barriers with the reservoirs
 V_b and V_t : tunnel barrier between the dots



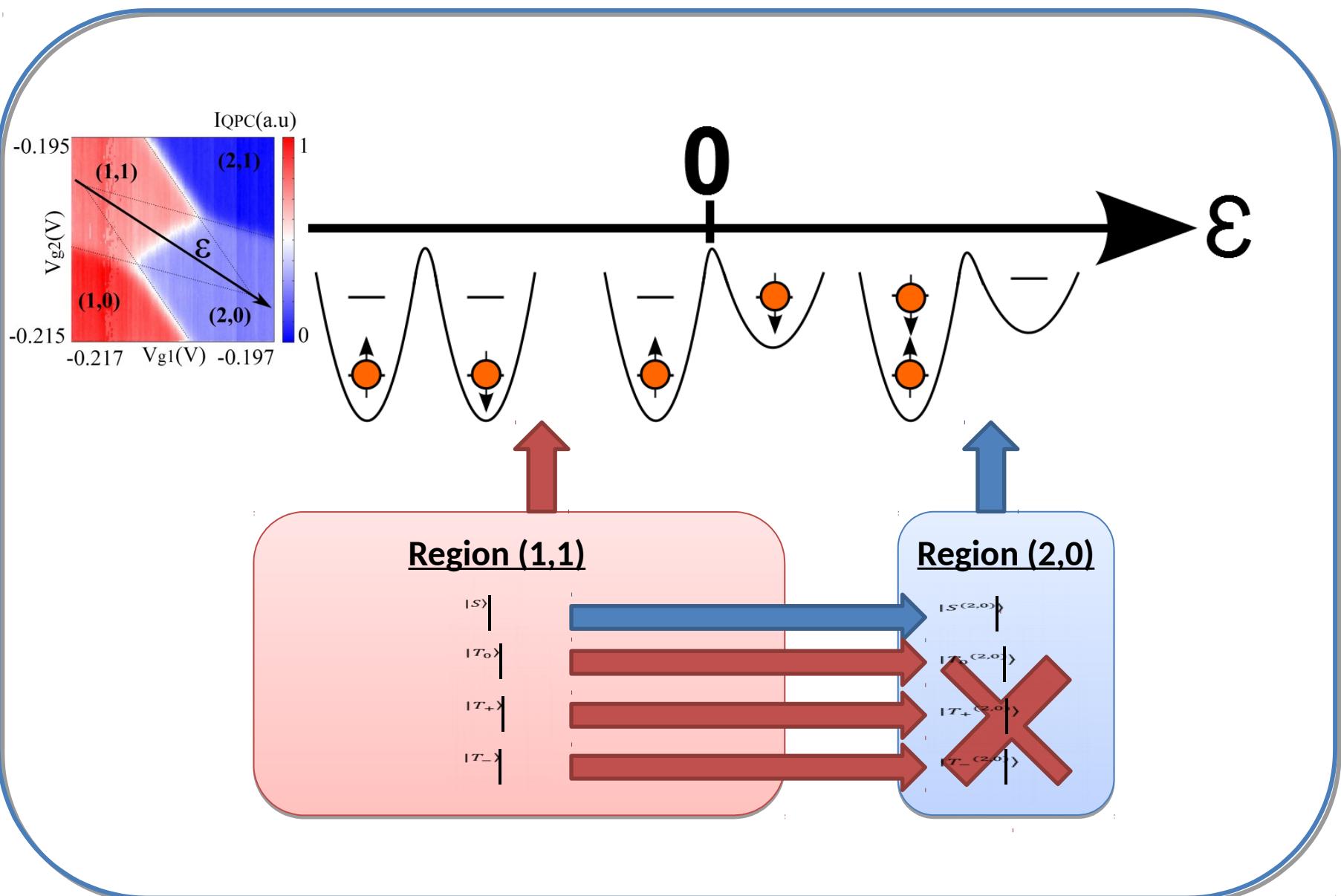
Two electron spin states



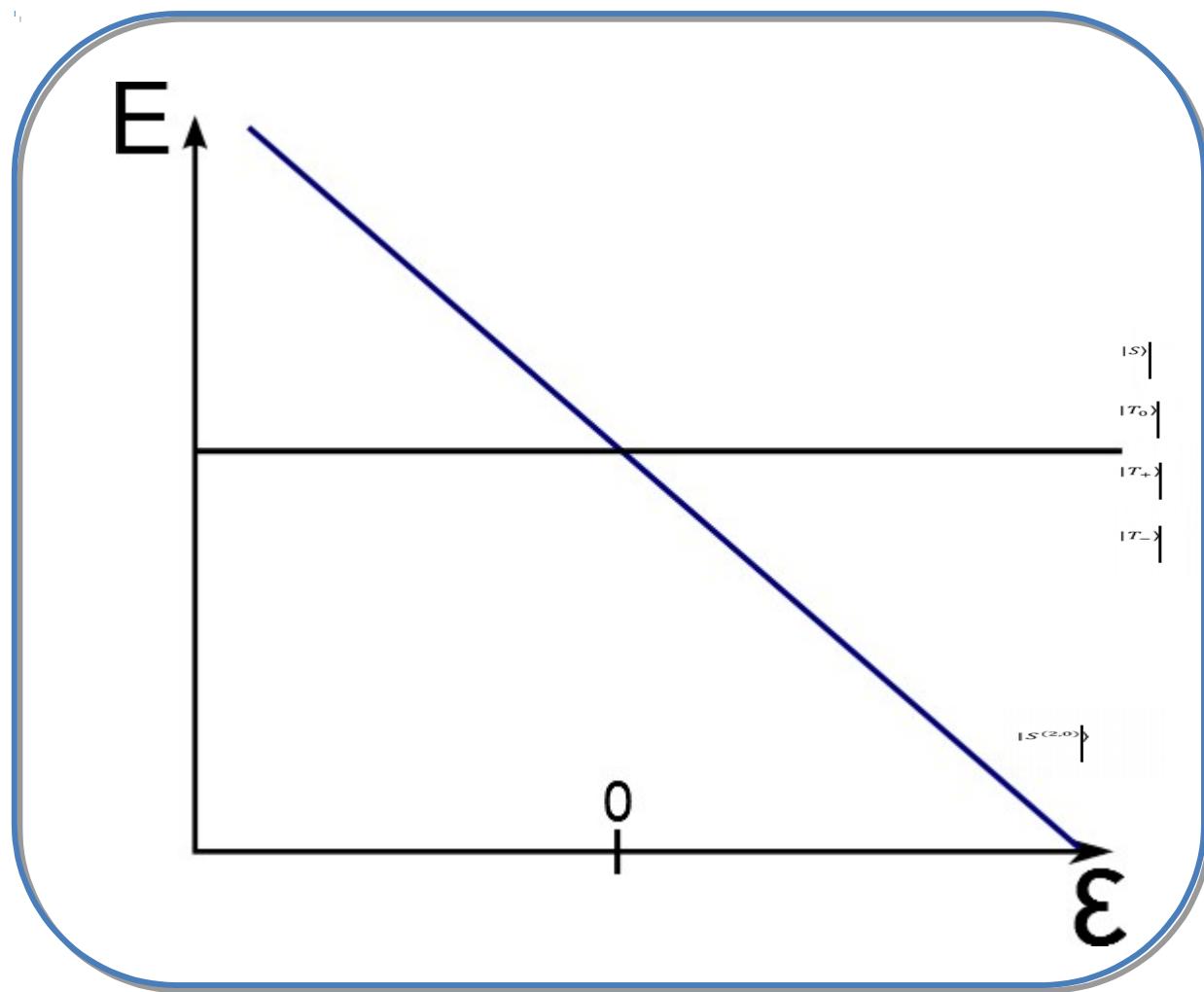
Two electron spin states



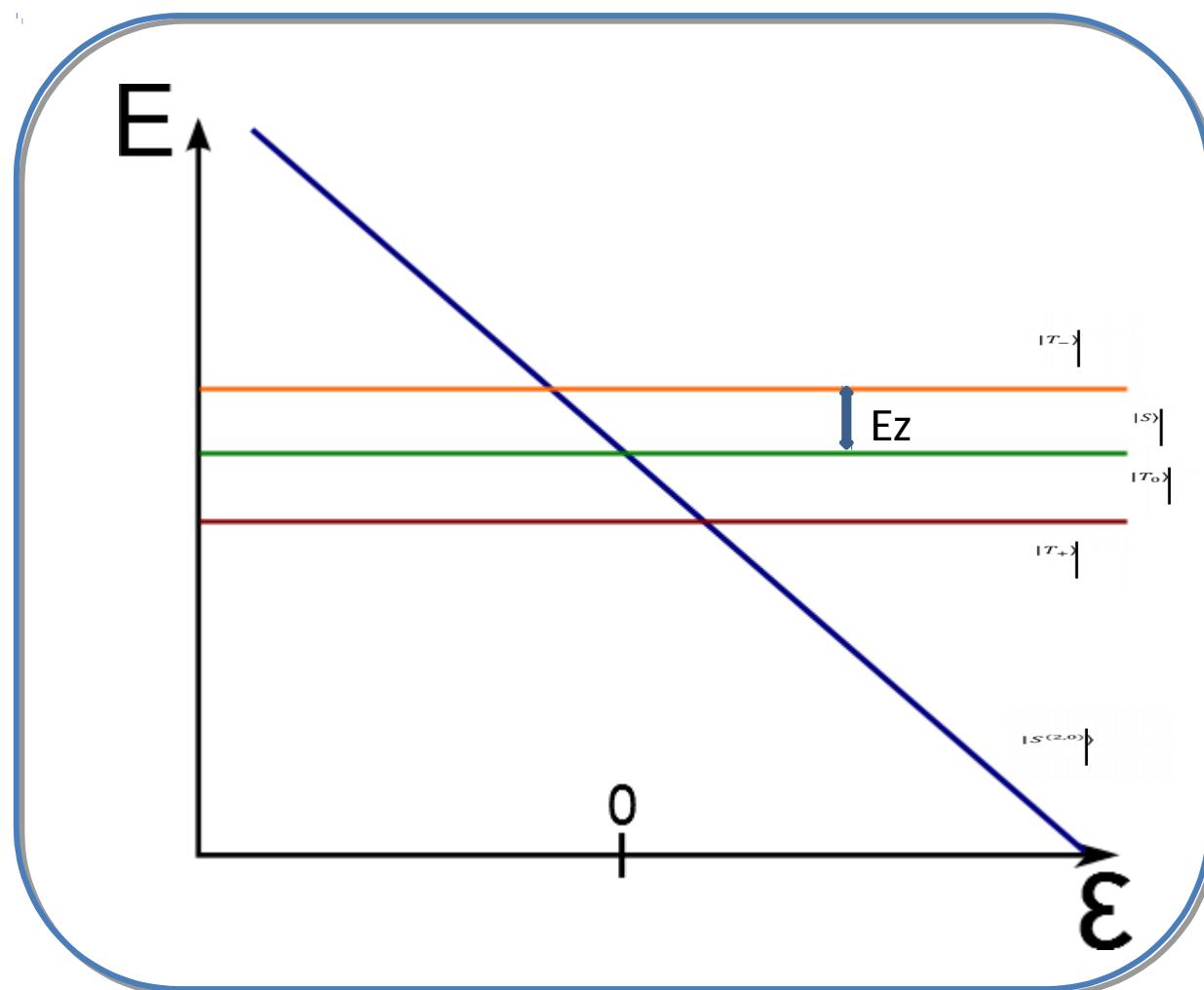
Two electron spin states



Two electron spin states

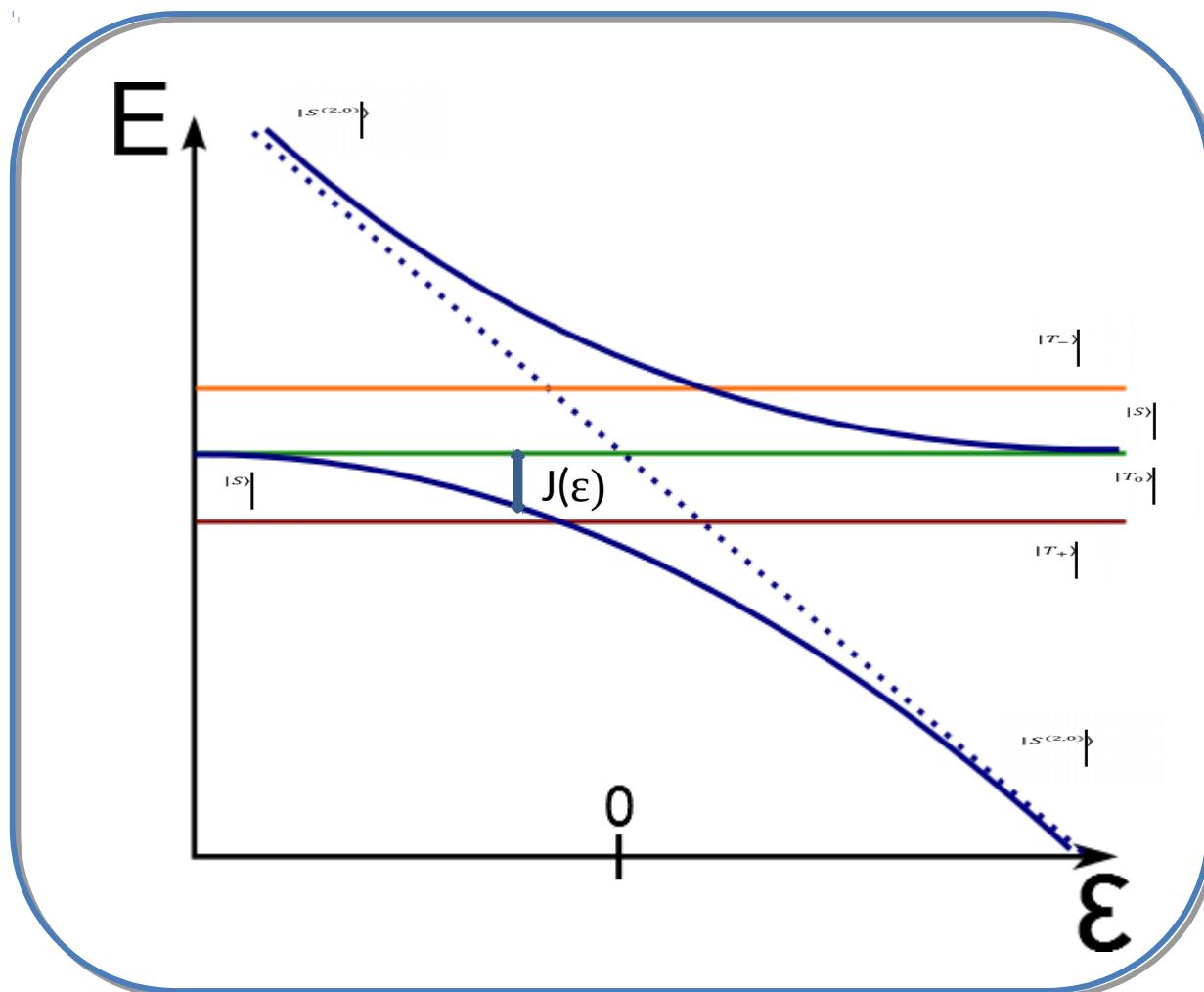


Two electron spin states



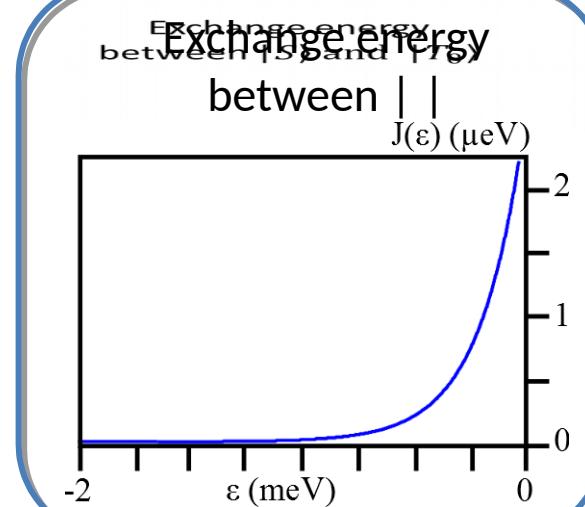
1) A magnetic field splits in energy the triplets states :
 $B_{ext}=700\text{mT} \rightarrow 15.5\mu\text{eV}$

Two electron spin states

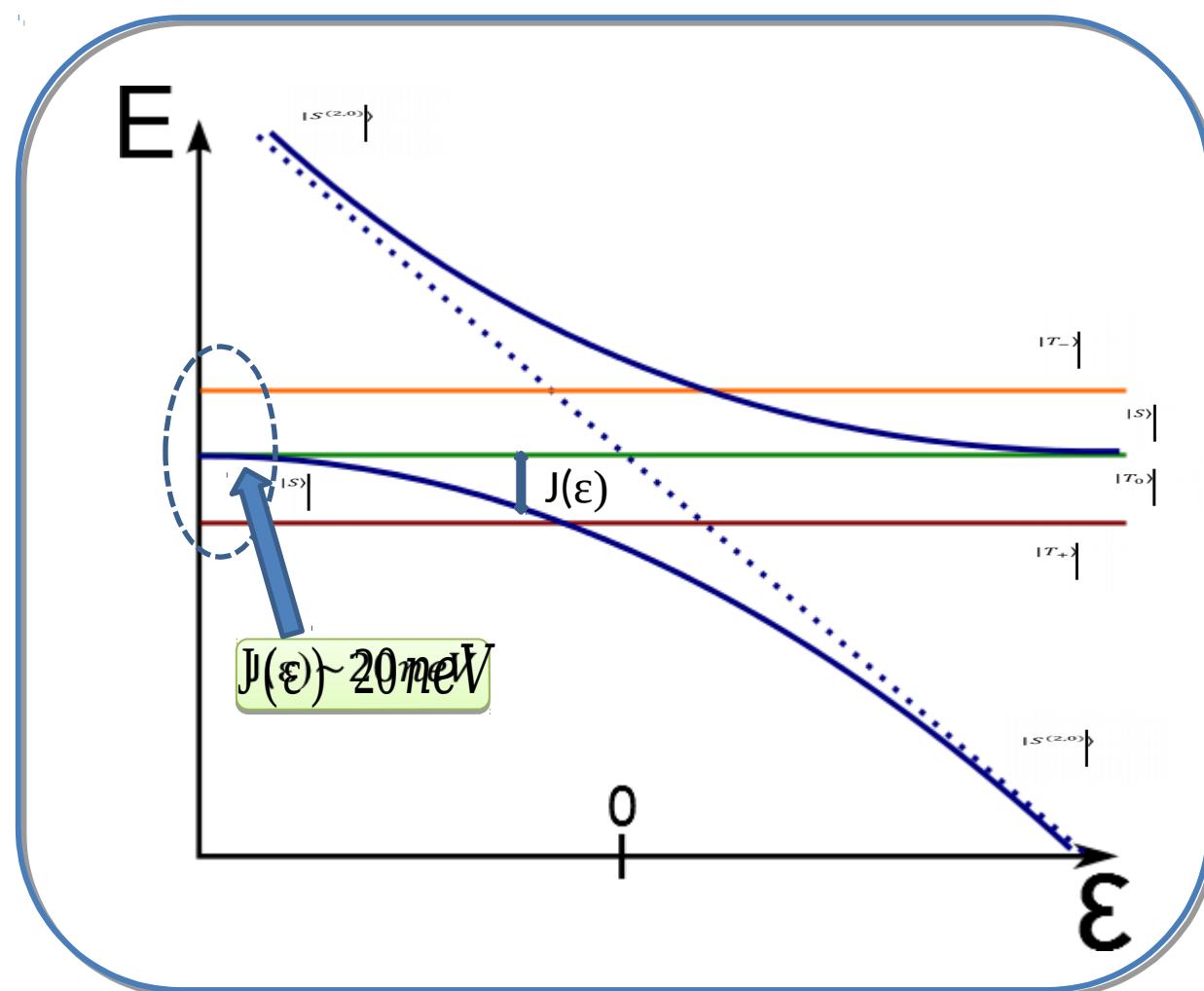


1) A magnetic field splits in energy the triplets states :
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2) Tunnelling couples the two singlet states $t=2,5\mu\text{eV}$



Two electron spin states



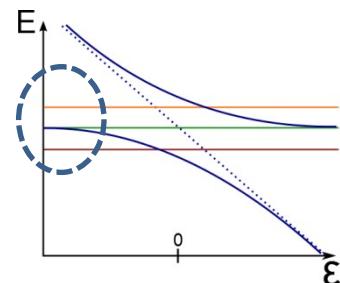
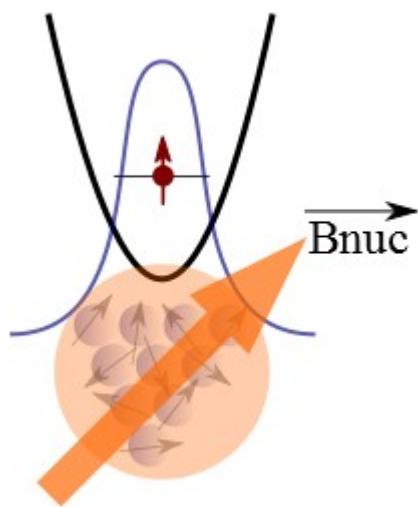
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2) Tunnelling couples the two singlet states $t=2,5\mu\text{eV}$

3) Before the exchange interaction vanishes : the spin are now independant

Two electron spin states

Hyperfine interaction with the host nuclear spins



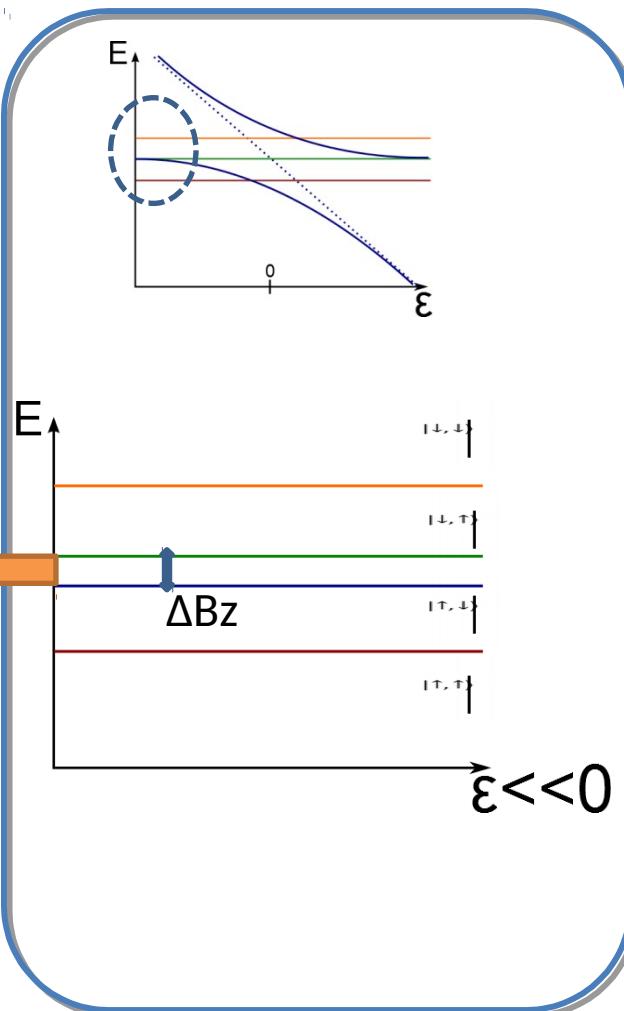
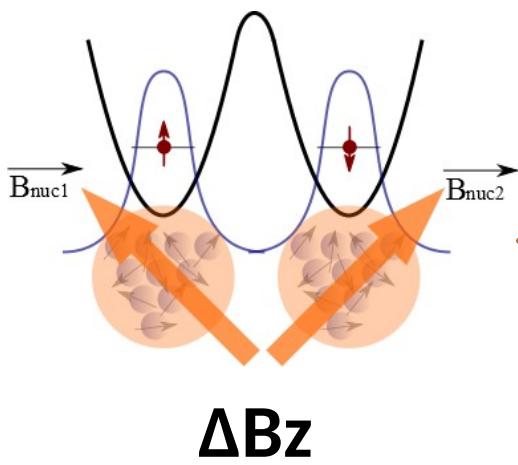
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Two electron spin states

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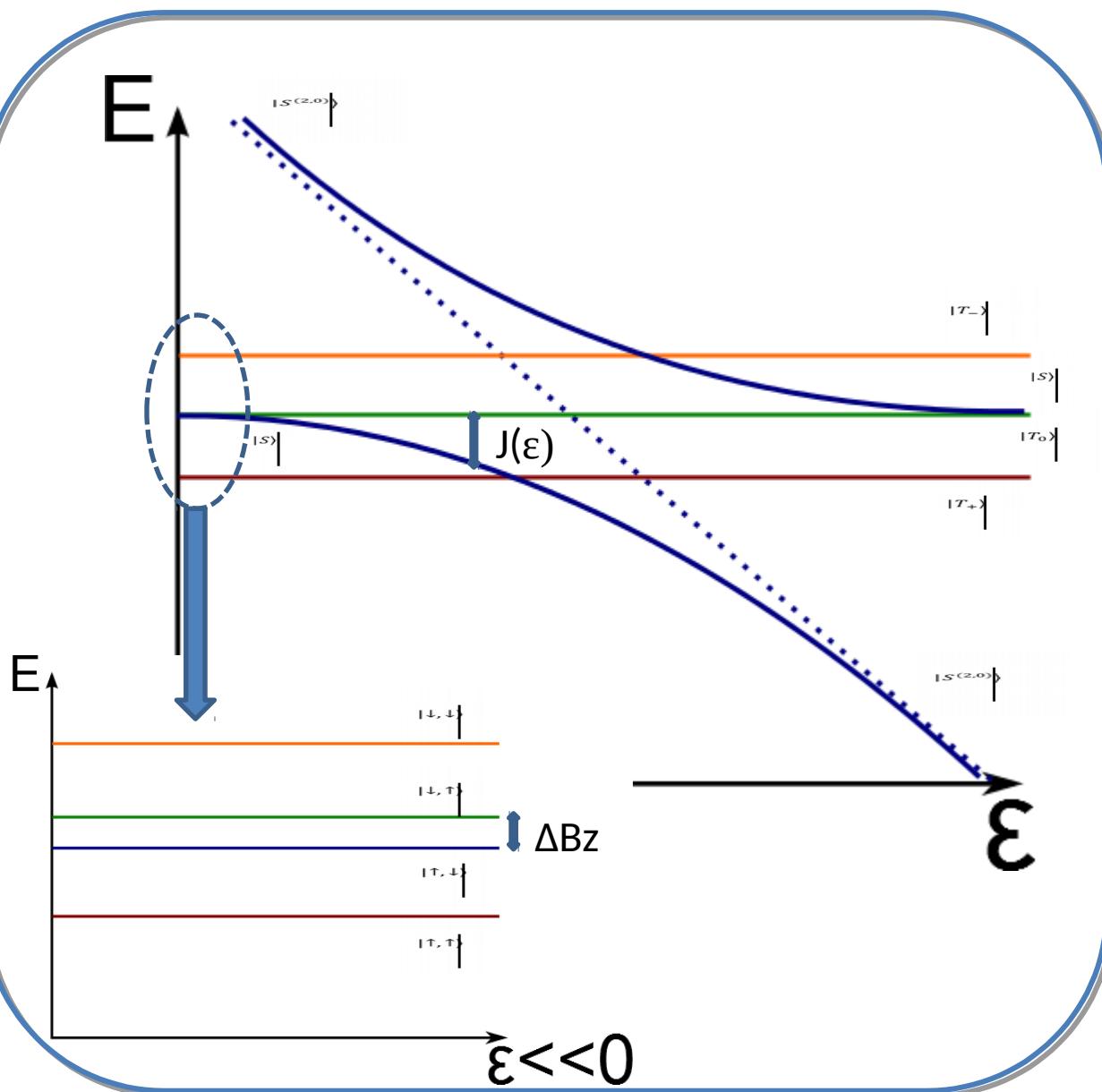
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4) Non uniformity of the nuclear magnetic field :
 $\Delta B_z \sim 4\text{mT} \rightarrow 0,1\mu\text{eV}$

Two electron spin states



1) A magnetic field splits in energy the triplets states :
 $B_{ext}=700\text{mT} \rightarrow 15.5\mu\text{eV}$

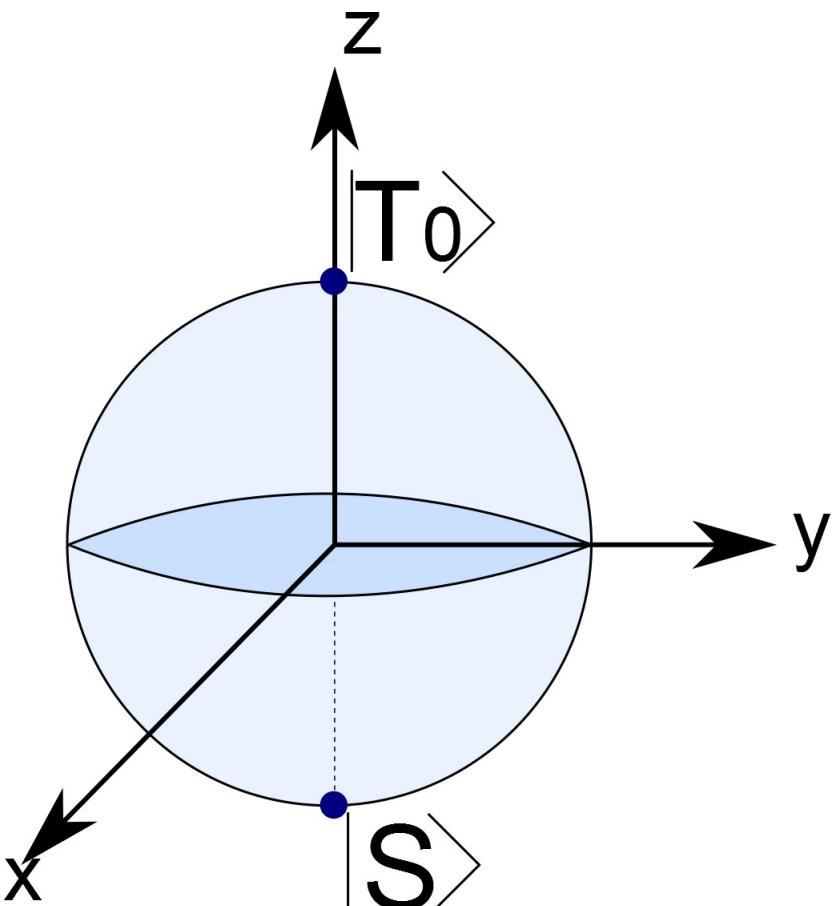
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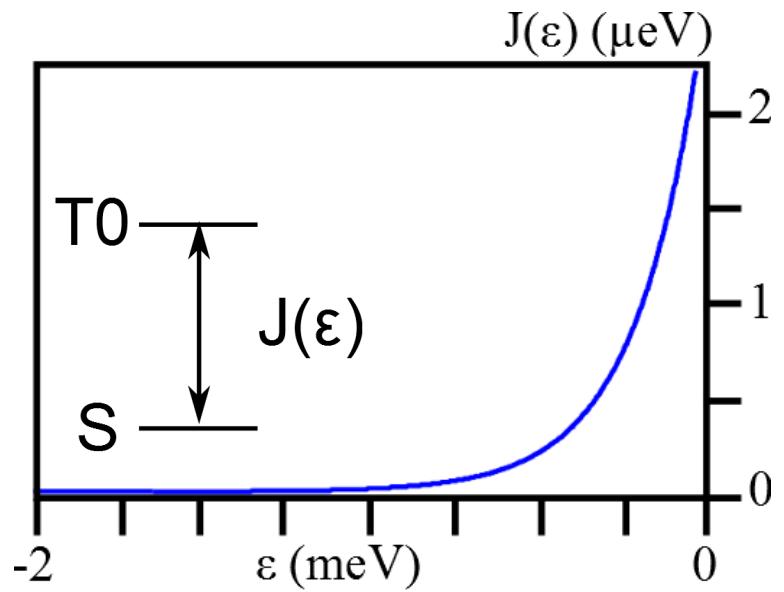
4) Non uniformity of the nuclear magnetic field :
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Qubit subspace

Two level system:
Singlet | and triplet |



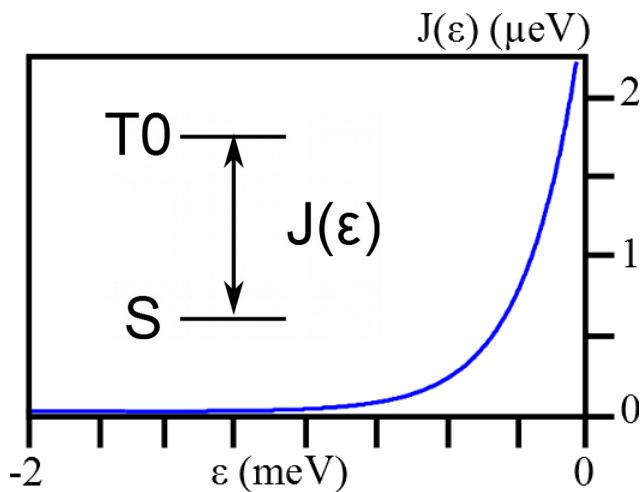
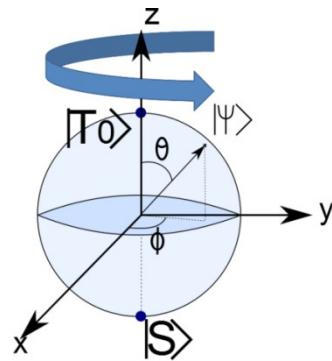
Qubit splitting:
Exchange energy $J(\varepsilon)$



Universal quantum control of S-T₀ qubit

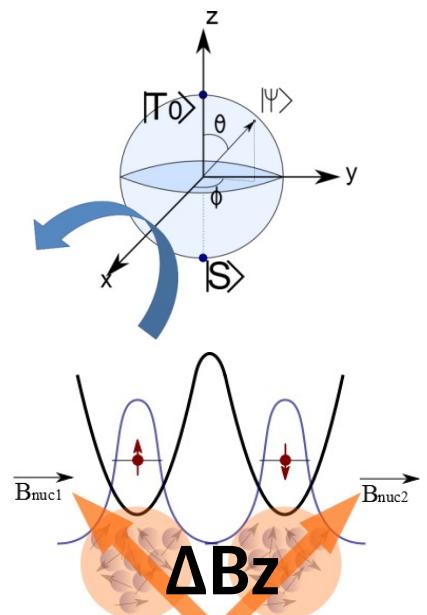
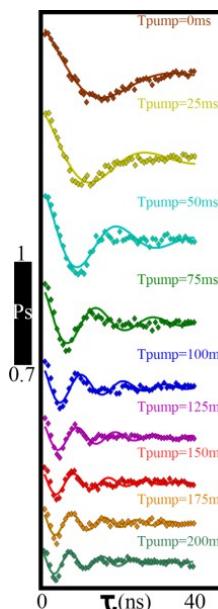
Qubit rotation around the z axis

Exchange $J(\varepsilon)$
Petta et al, Science(2005)



Qubit rotation around the x axis

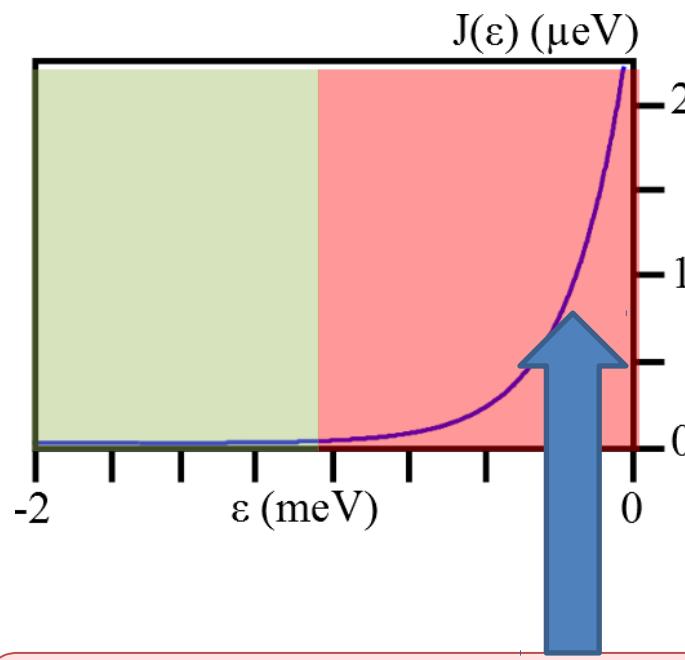
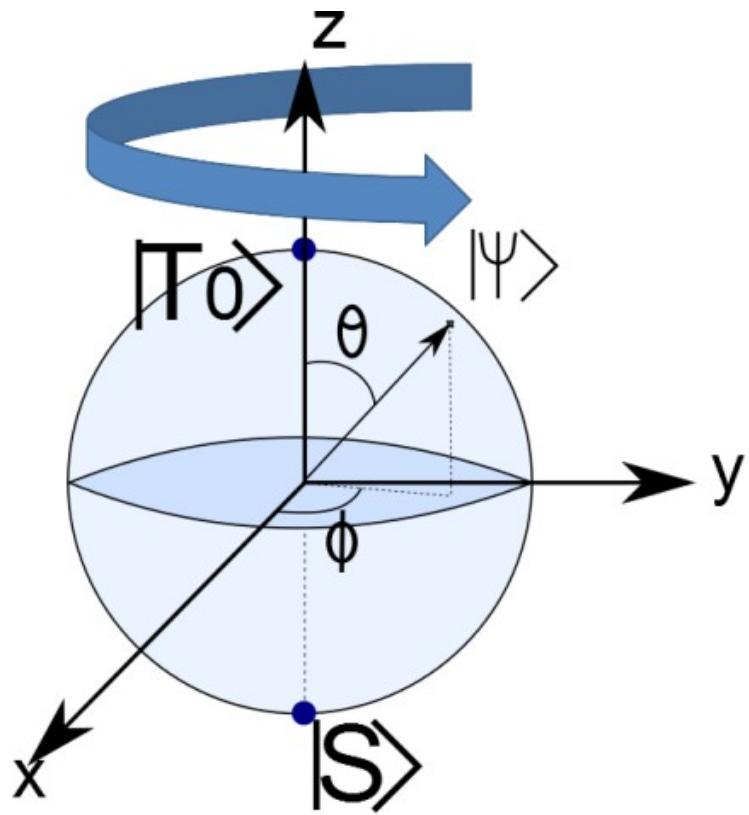
Gradient ΔB_z
Foletti et al, Nat Phys(2009)



Can be used in order to engineer a C-phase gate with single spin qubits

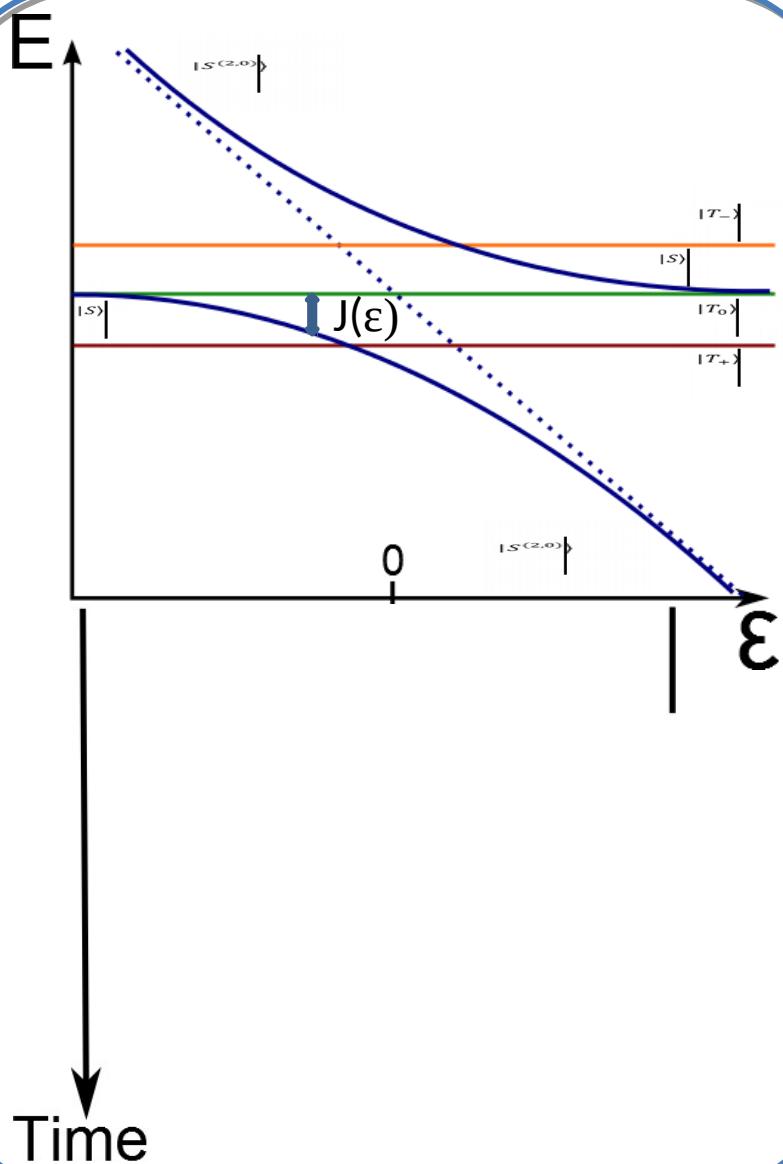
Thalineau et al, In preparation

Electrostatic dependence of S-To qubits

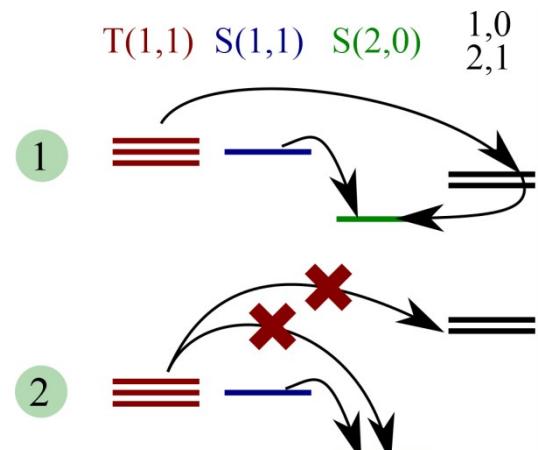
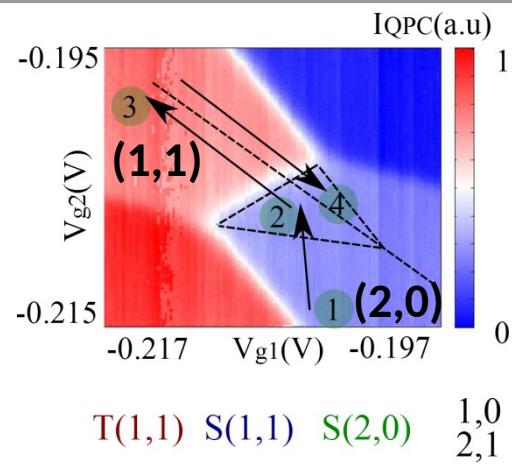


Charge-like qubit :
Highly sensitive to the electrostatic environment on timescale $\sim 100\text{ps}$

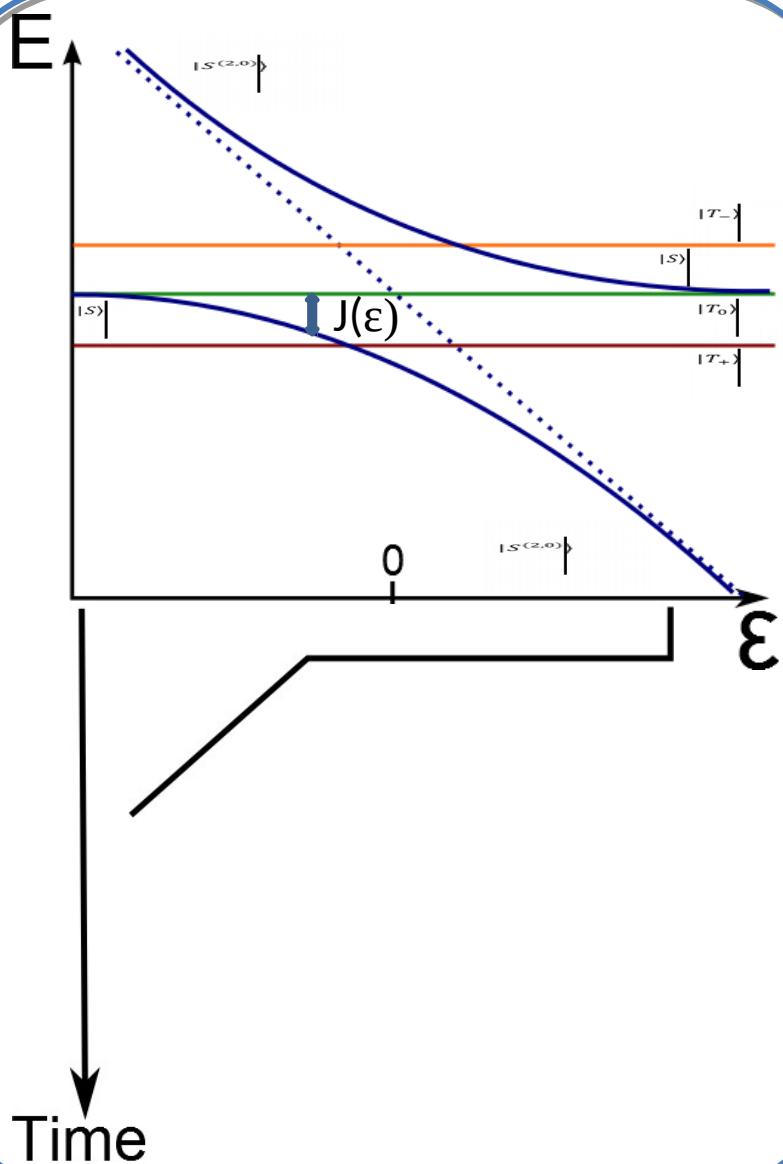
Coherent exchange oscillations



1) Initialization of $|S^{(2,0)}\rangle$
Relaxation through the reservoirs

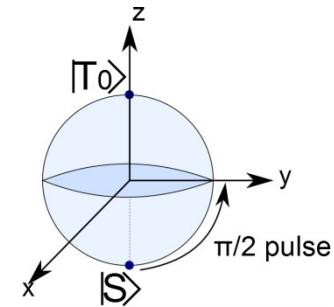


Coherent exchange oscillations

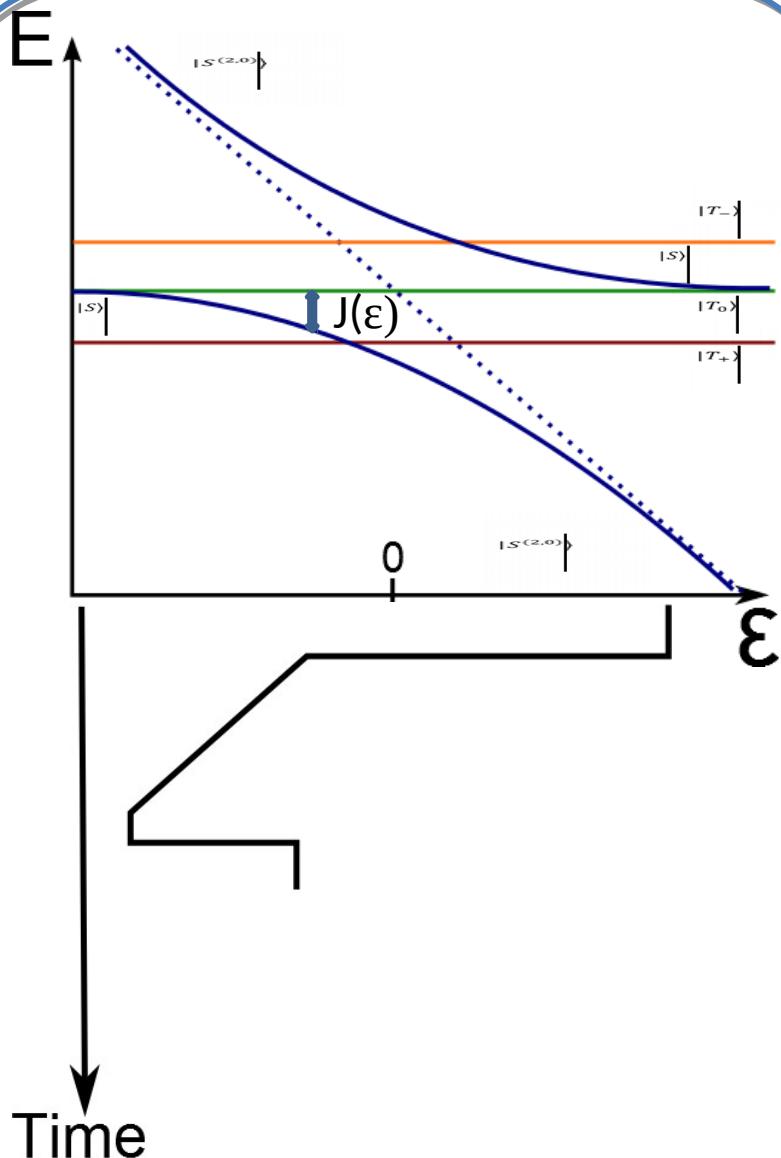


Initialization of $|S\rangle$
Initialization of $|S^{(2,0)}\rangle$
Relaxation through the reservoirs
through the reservoirs

$\pi/2$ rotations around the x axis



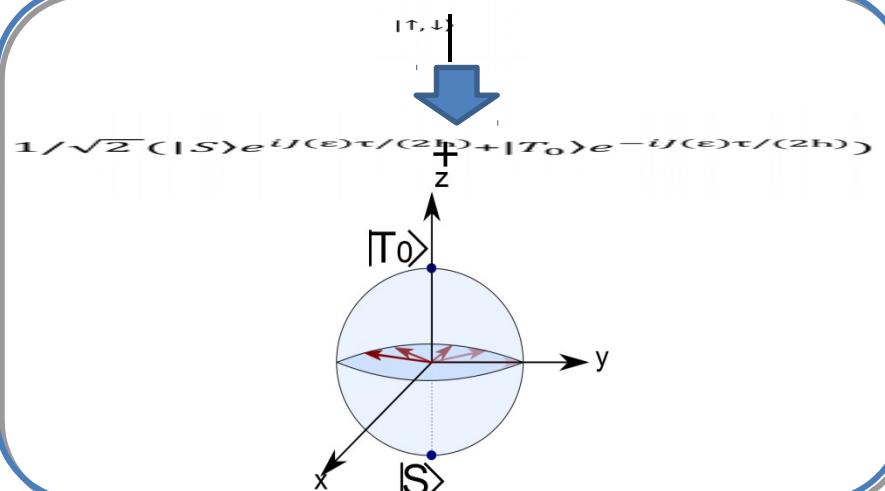
Coherent exchange oscillations



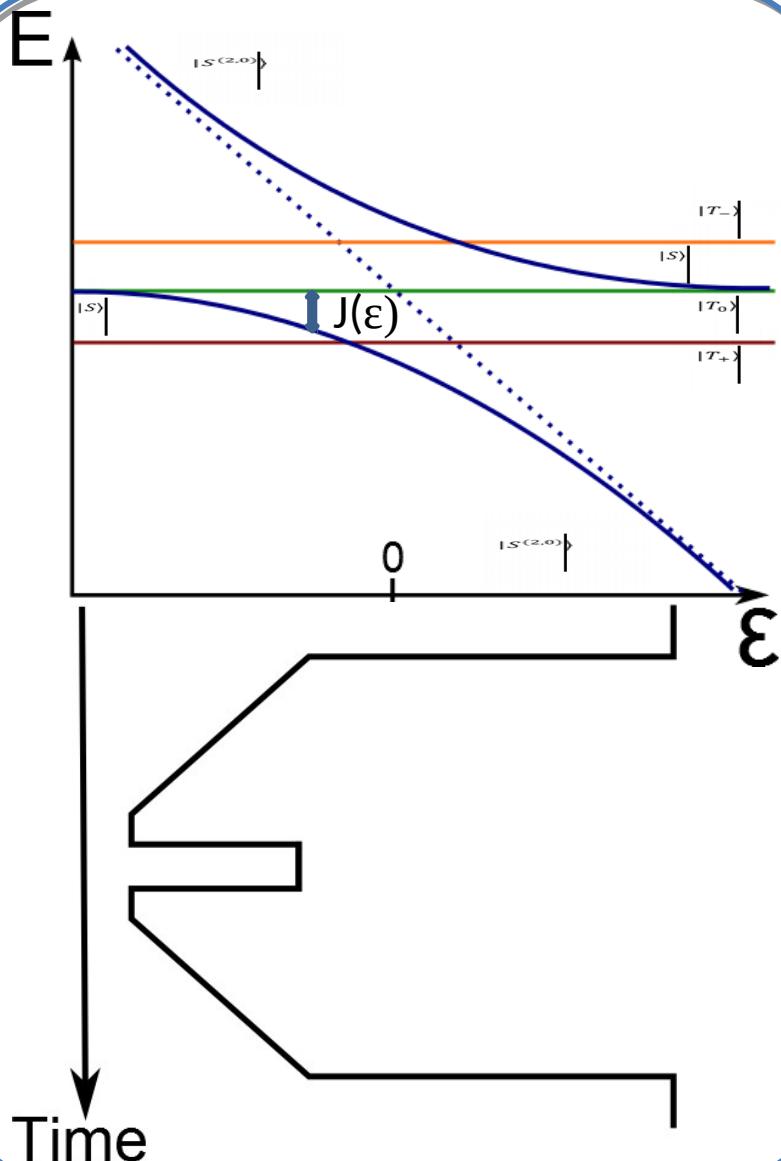
Initialization of | Relaxation
Initialization of $|S^{(2,0)}\rangle$
Relaxation through the reservoirs
through the reservoirs

$\pi/2$ rotations around the x axis

Exchange pulse
Non adiabatic vs ΔB_z



Coherent exchange oscillations



Initialization of | Relaxation
Initialization of $|S^{(2,0)}\rangle$
Relaxation through the reservoirs
through the reservoirs

$\pi/2$ rotations around the x axis

Exchange pulse
Non adiabatic vs ΔB_z

Measurement :
Follow the way back

$$\frac{1}{\sqrt{2}}(|S\rangle e^{iJ(\epsilon)\tau/(2\hbar)} + |T_0\rangle e^{-iJ(\epsilon)\tau/(2\hbar)})$$

$$\cos(J(\epsilon)/2) \cos(J(\epsilon)\tau/(2\hbar)) |\uparrow, \downarrow\rangle + i \sin(J(\epsilon)\tau/(2\hbar)) |\downarrow, \uparrow\rangle$$

$$P_S(\tau) = (1 + \cos(J(\epsilon)\tau/\hbar))/2$$

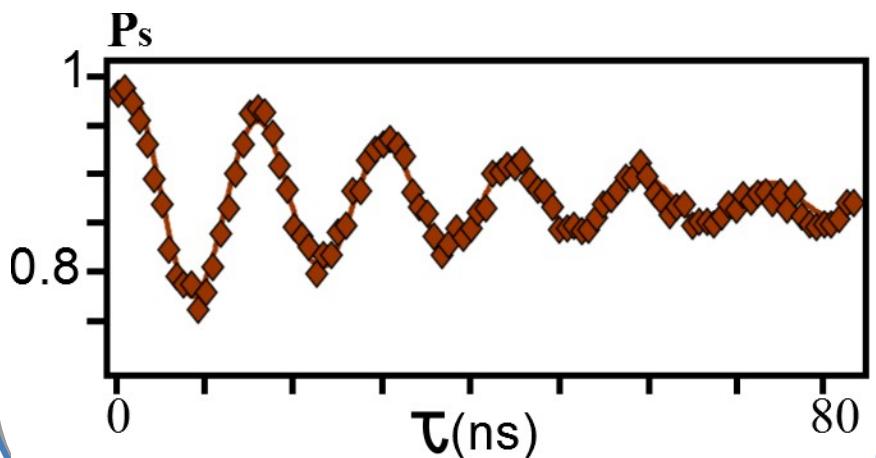
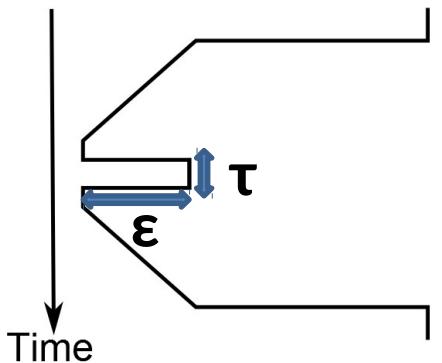


Blocked

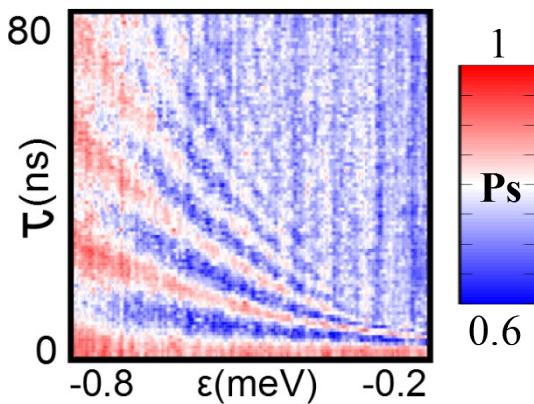
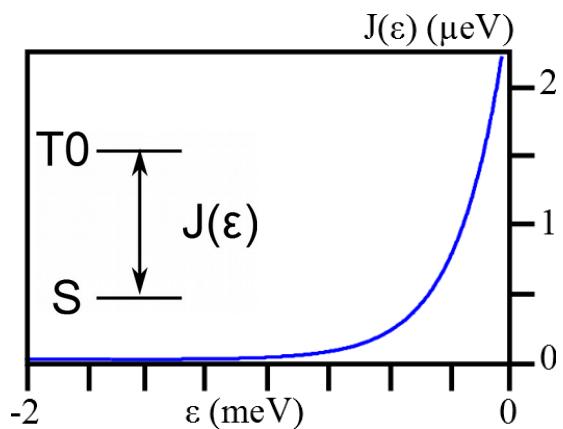
Electrostatic environment dependent coherent oscillations

Exchange coherent oscillations

$$P_S(\tau) = (1 + \cos((\frac{J(\epsilon)}{\hbar})\tau)) / 2$$

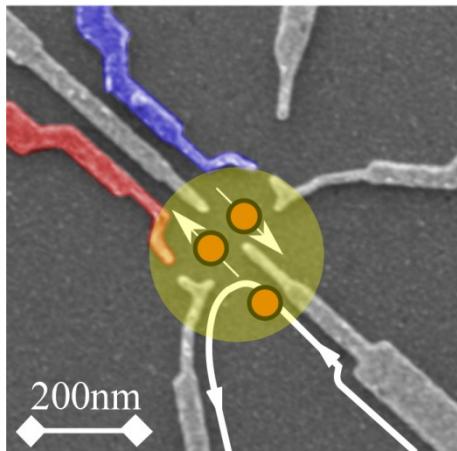


The frequency of the oscillations
depends on the detuning parameter

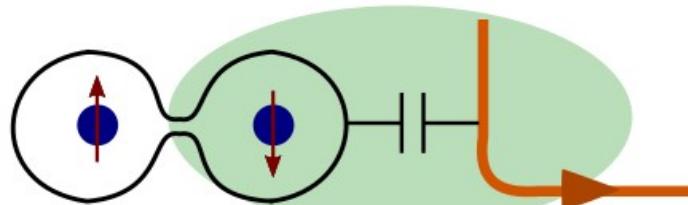
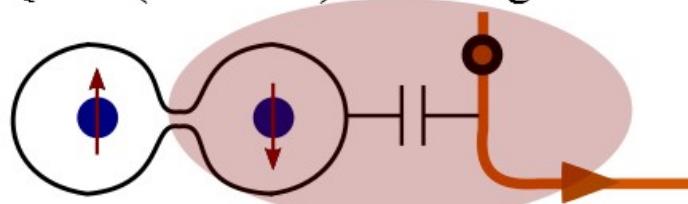


Electrostatic environment dependent coherent oscillations

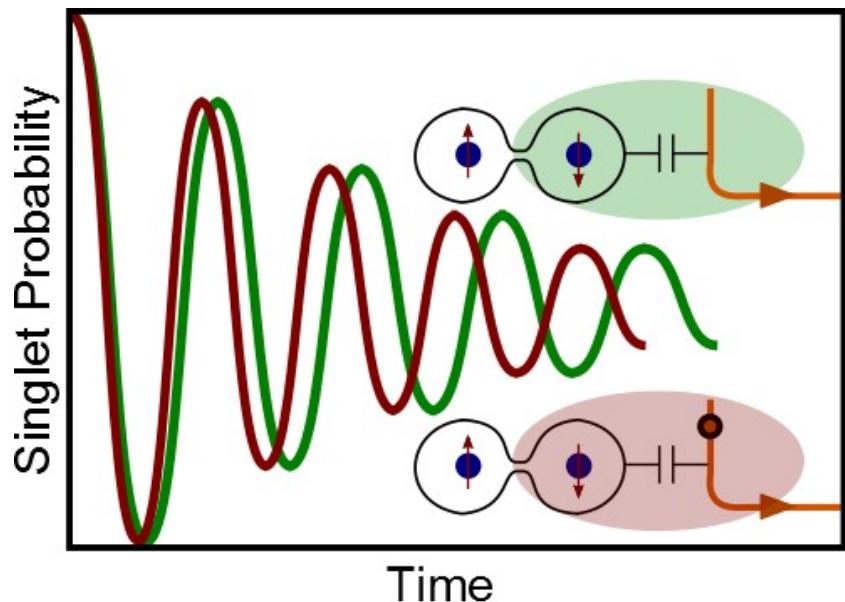
Singlet-Triplet qubit capacitively coupled to edge states



Qubit (detector) Edge



The passage of the electron should change the qubit population



Outline

I) Singlet-Triplet qubit in a double quantum dot

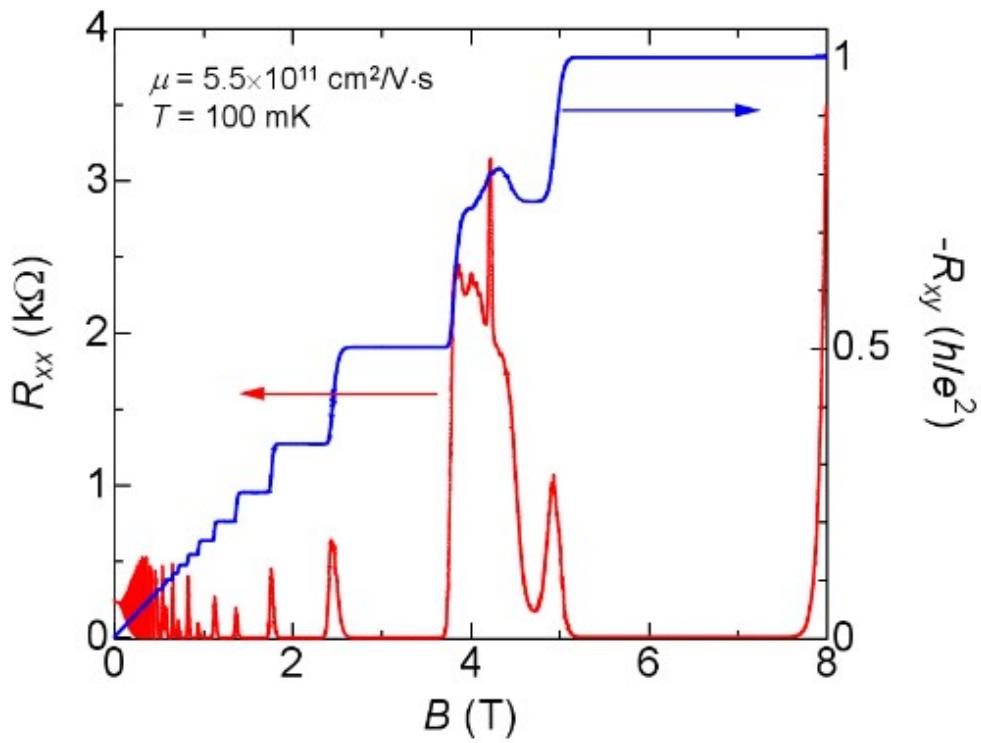
II) Quantum Hall Effect (QHE) and quantum optics with electrons

III) Characterization of the detector device

IV) Single electron detection

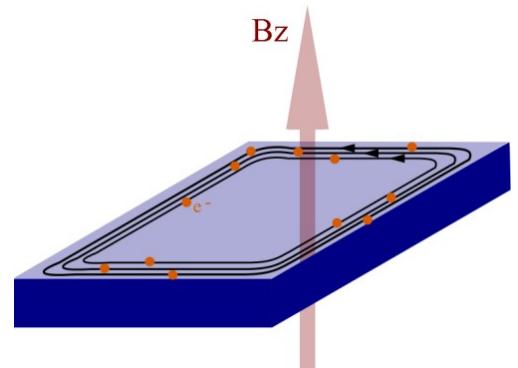
Quantum Hall Effect

Quantum Hall Effect :

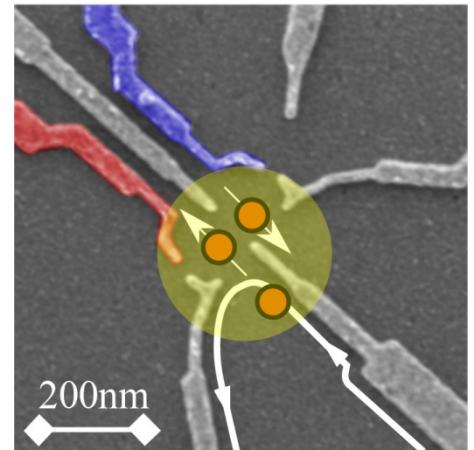


Klitzing et al, PRL(1980)

Edge-states



Halperin et al, PRB(1982)



Quantum optics with electrons

Analogy between quantum optics with photons and electrons

Photons

Bosons, no interaction

Electrons

Fermions, interaction e-e

Optical fiber

Edge states, Flying quantum dots

Single photon source :
Optical quantum dots, Atoms...

Single electron source :
Lateral quantum dot
Feve et al, Science(2007)

Single photon detector :
Avalanche photodiode

Single electron detector :
Singlet-Triplet qubit

Outline

I) Singlet-Triplet qubit in a double quantum dot

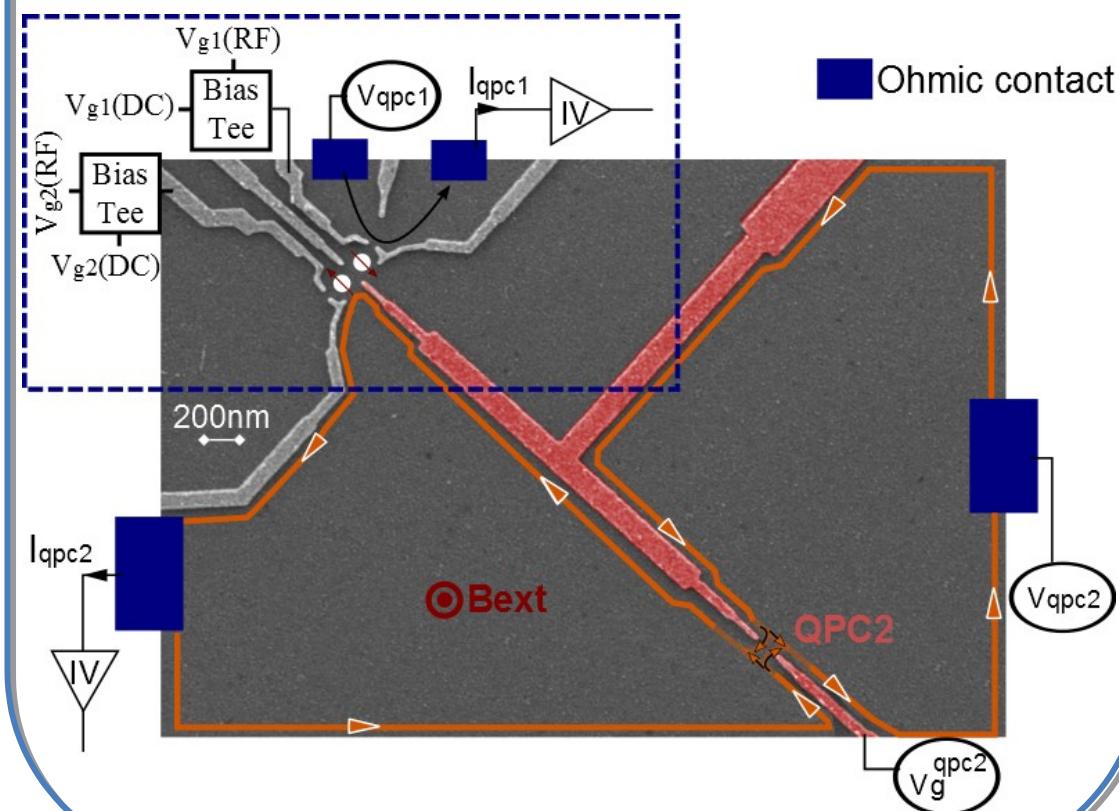
II) Quantum Hall Effect (QHE) and quantum optics with electrons

III) Characterization of the detector device

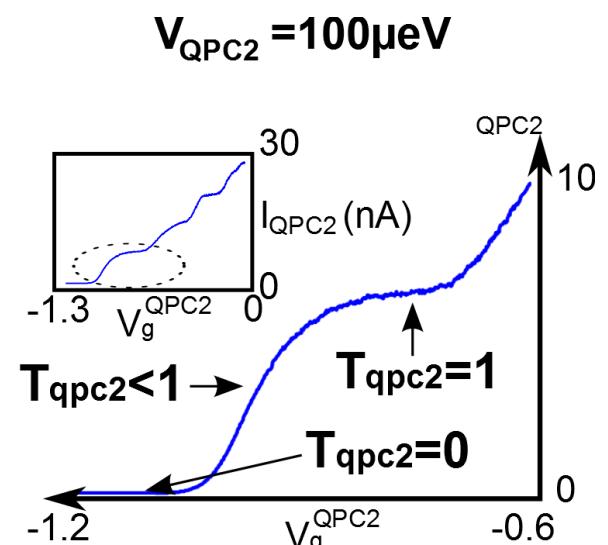
IV) Single electron detection

Sample

Control of the electron injection into the edge-states by means of QPC2



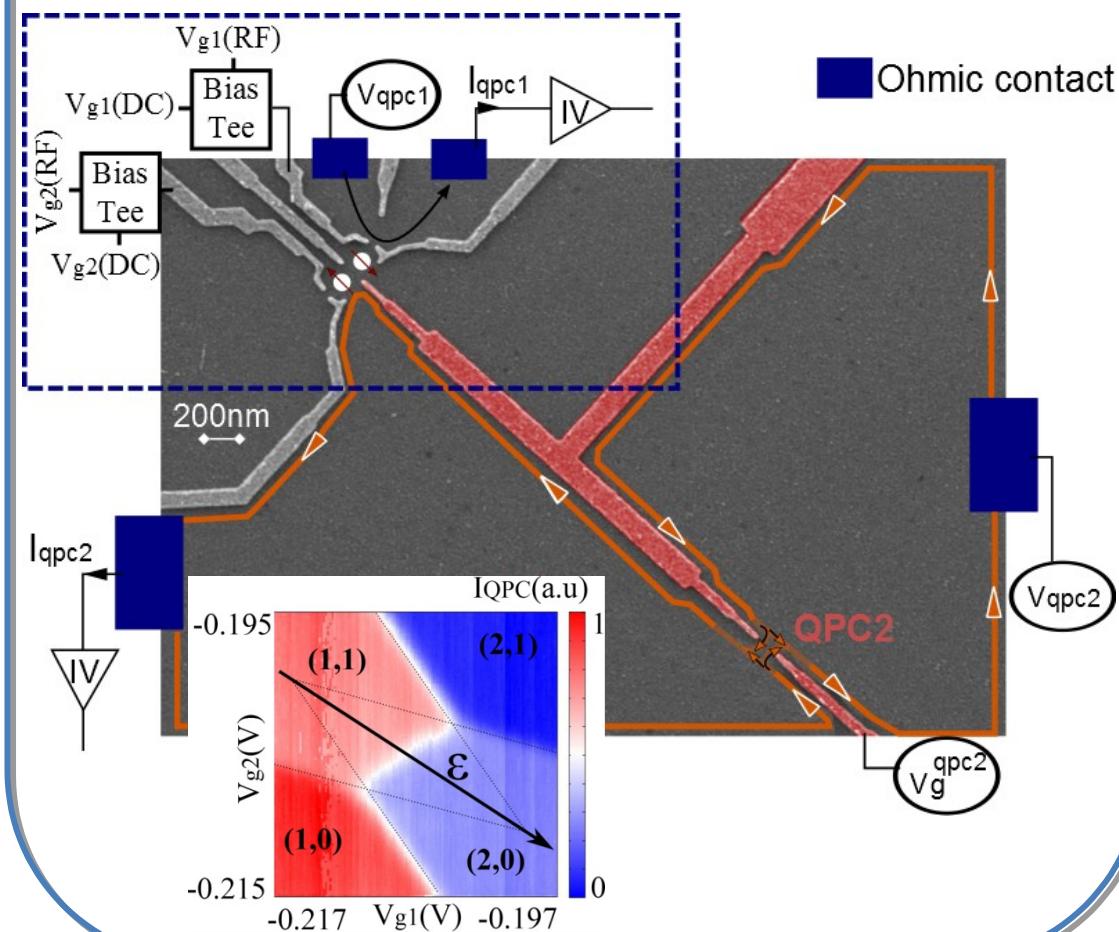
Calibration of QPC2 :



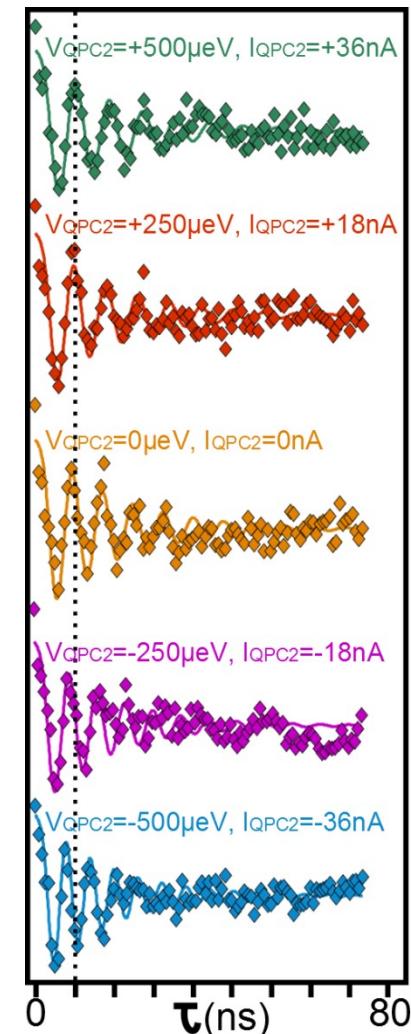
Detection of the edge electrochemical potentials

$T_{QPC2} = 1$

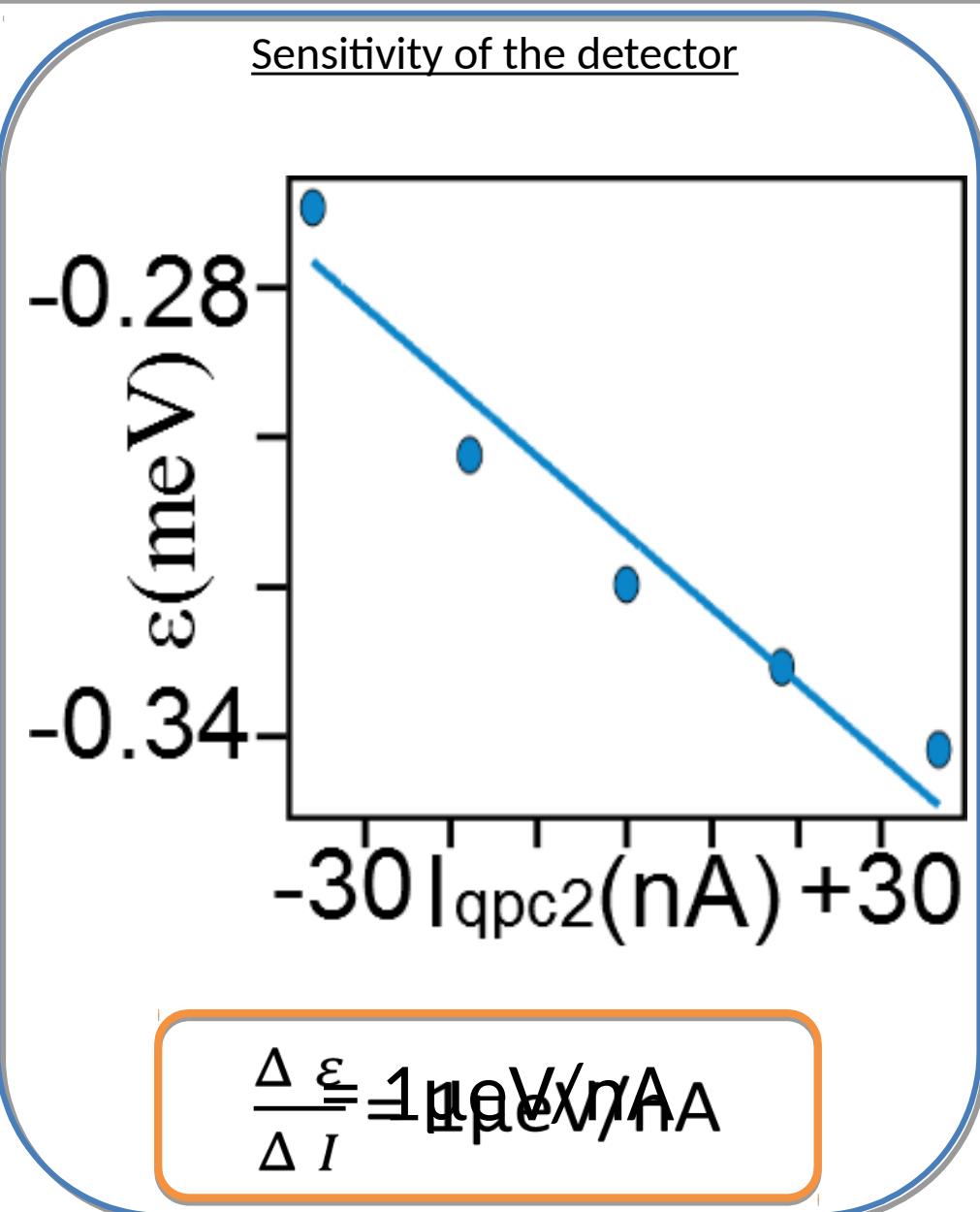
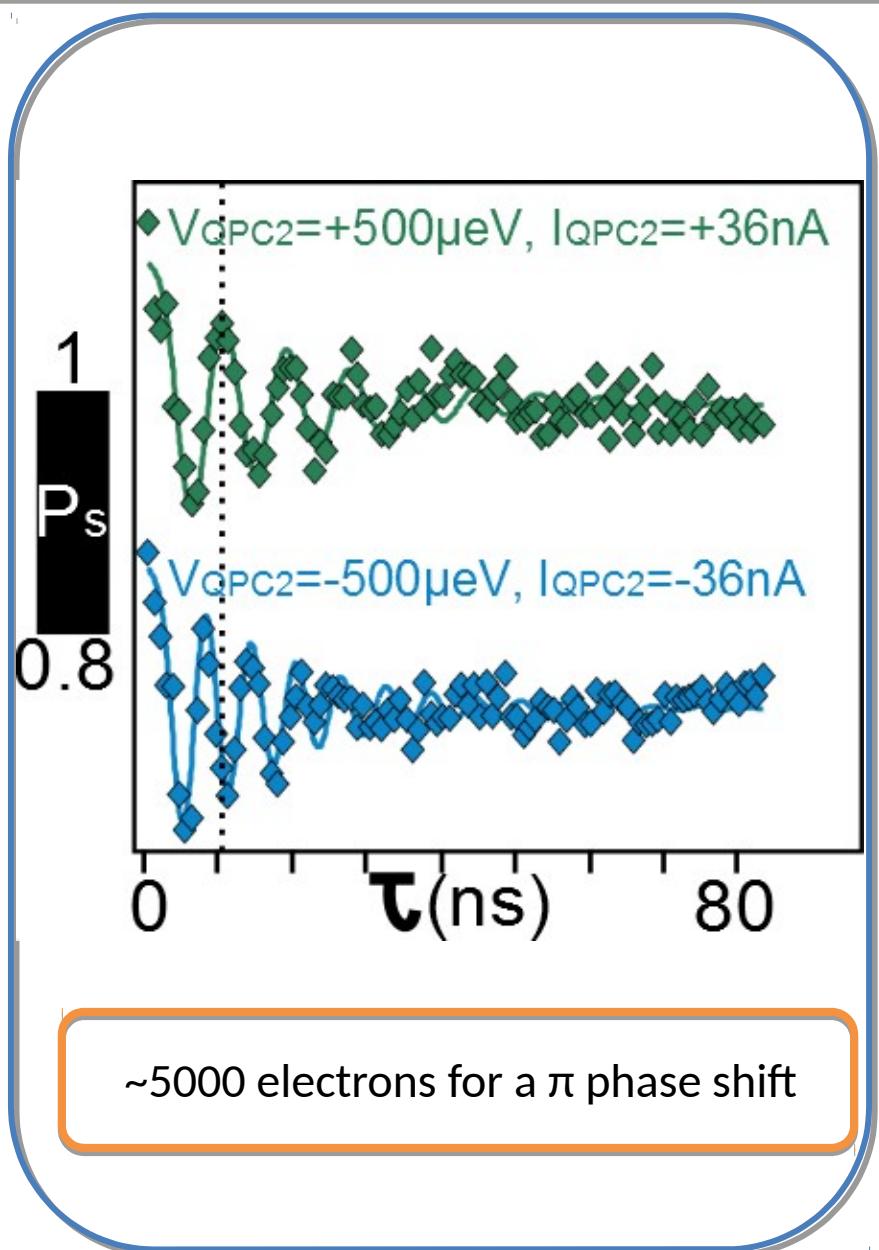
V_{QPC2} is changed in order to change the edge potential



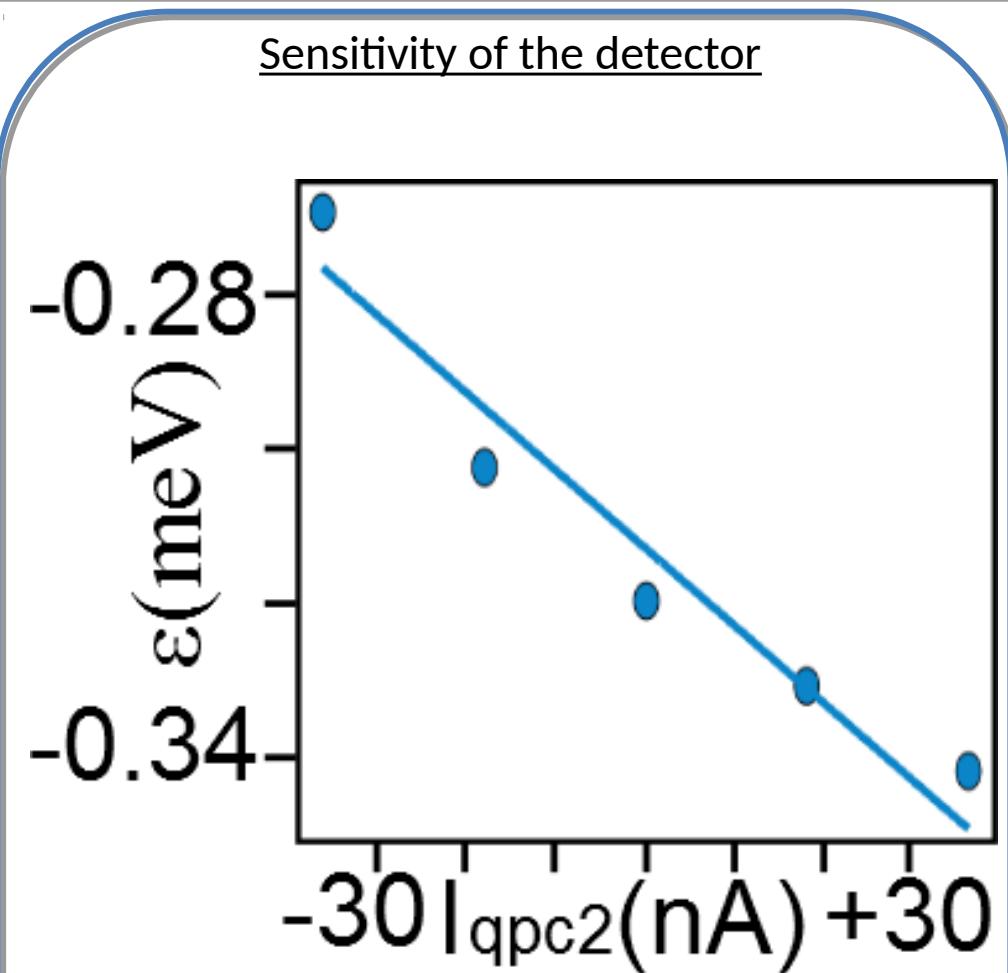
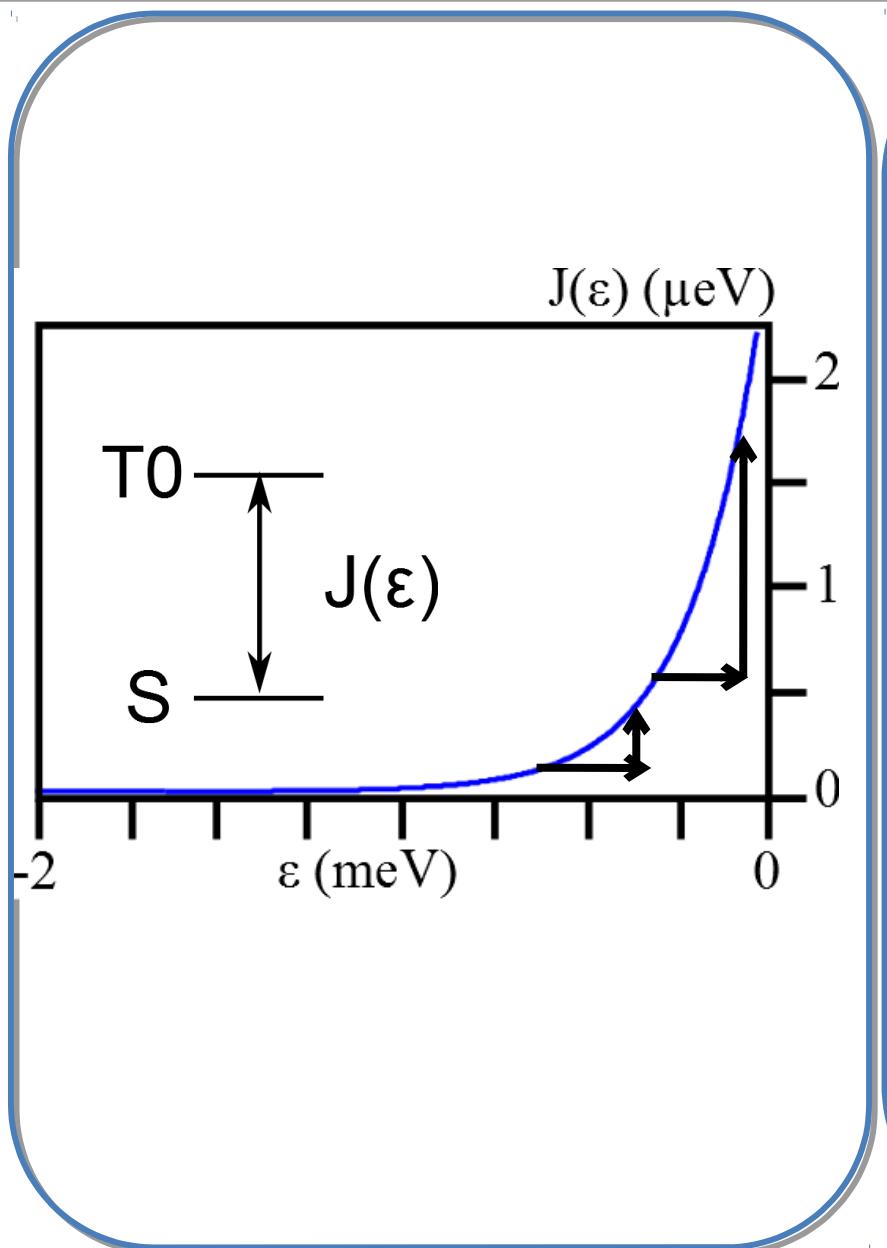
The detector is sensitive to the edge electrochemical potential



Detection of the electron density of the edge-states



Detection of the electron density of the edge-states



$$\frac{\Delta \varepsilon}{\Delta I} = 1 \text{ meV/nA}$$

Outline

I) Singlet-Triplet qubit in a double quantum dot

II) Quantum Hall Effect (QHE) and quantum optics with electrons

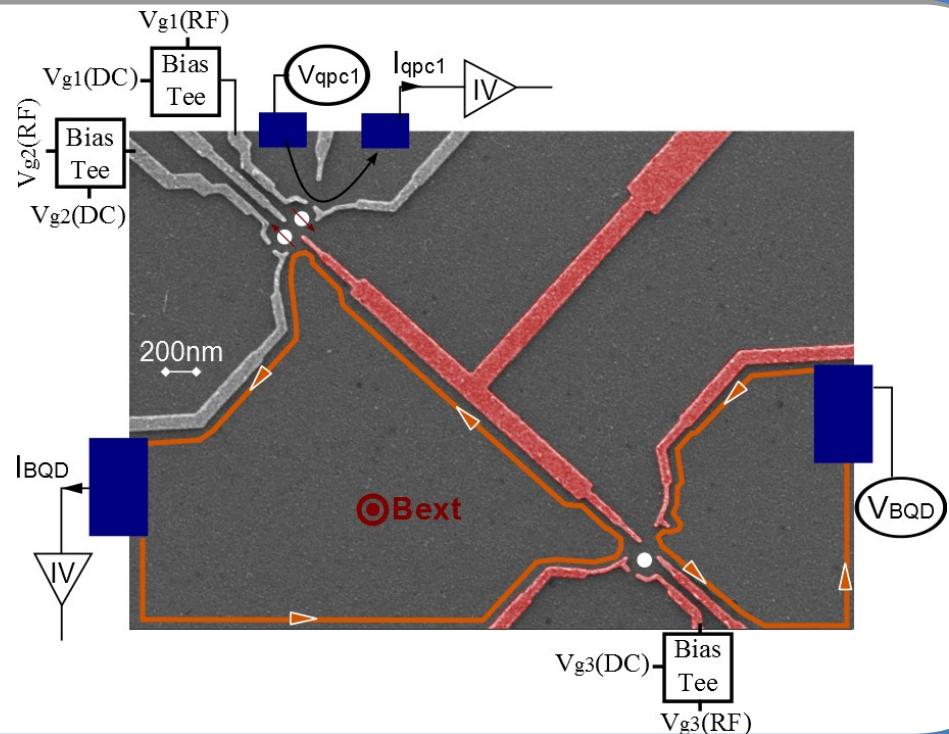
III) Characterization of the detector device

IV) Single electron detection

Single electron source

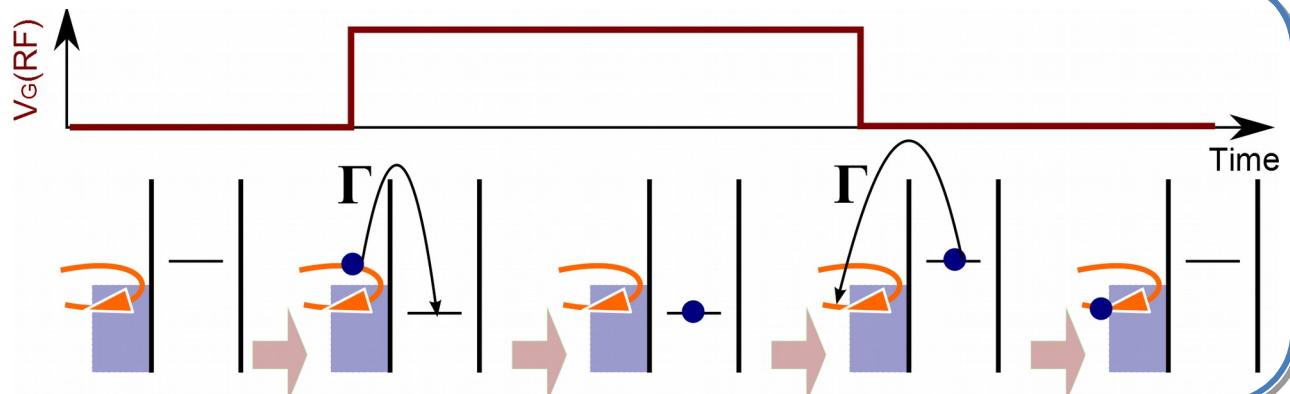
Sample :

Instead to use the QPC to inject electrons, we use now a quantum dot tunnel coupled to the edge-states

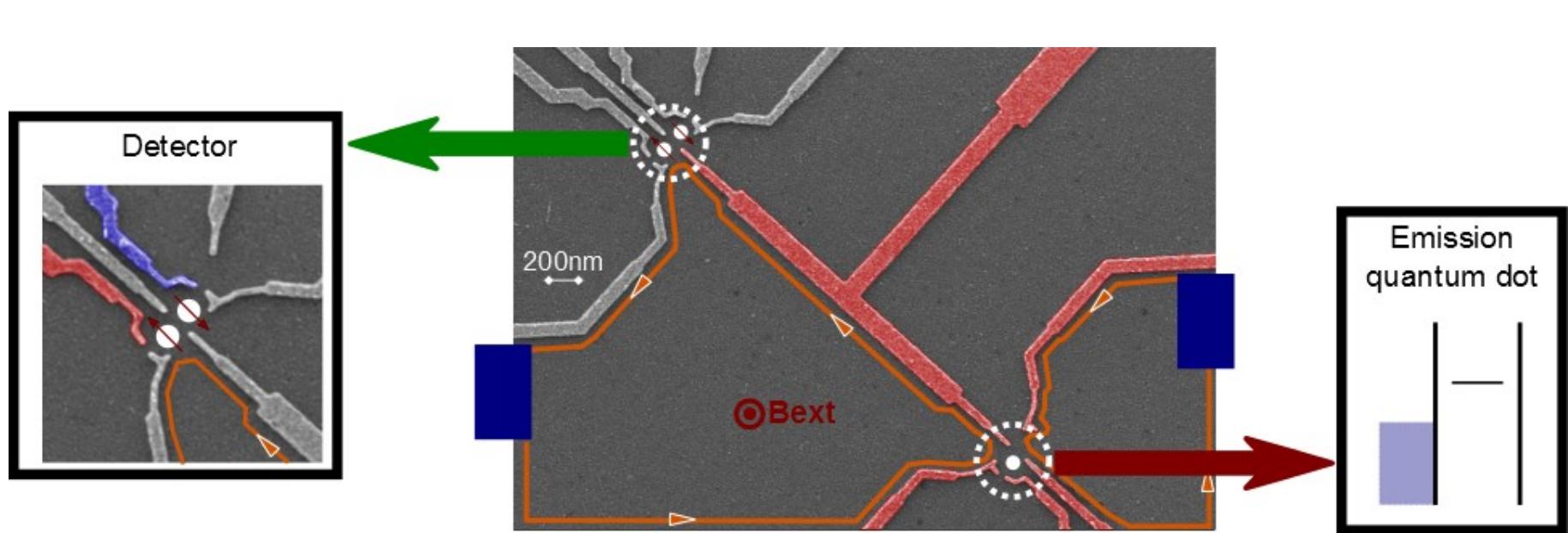


A quantum dot as an on demand electron source

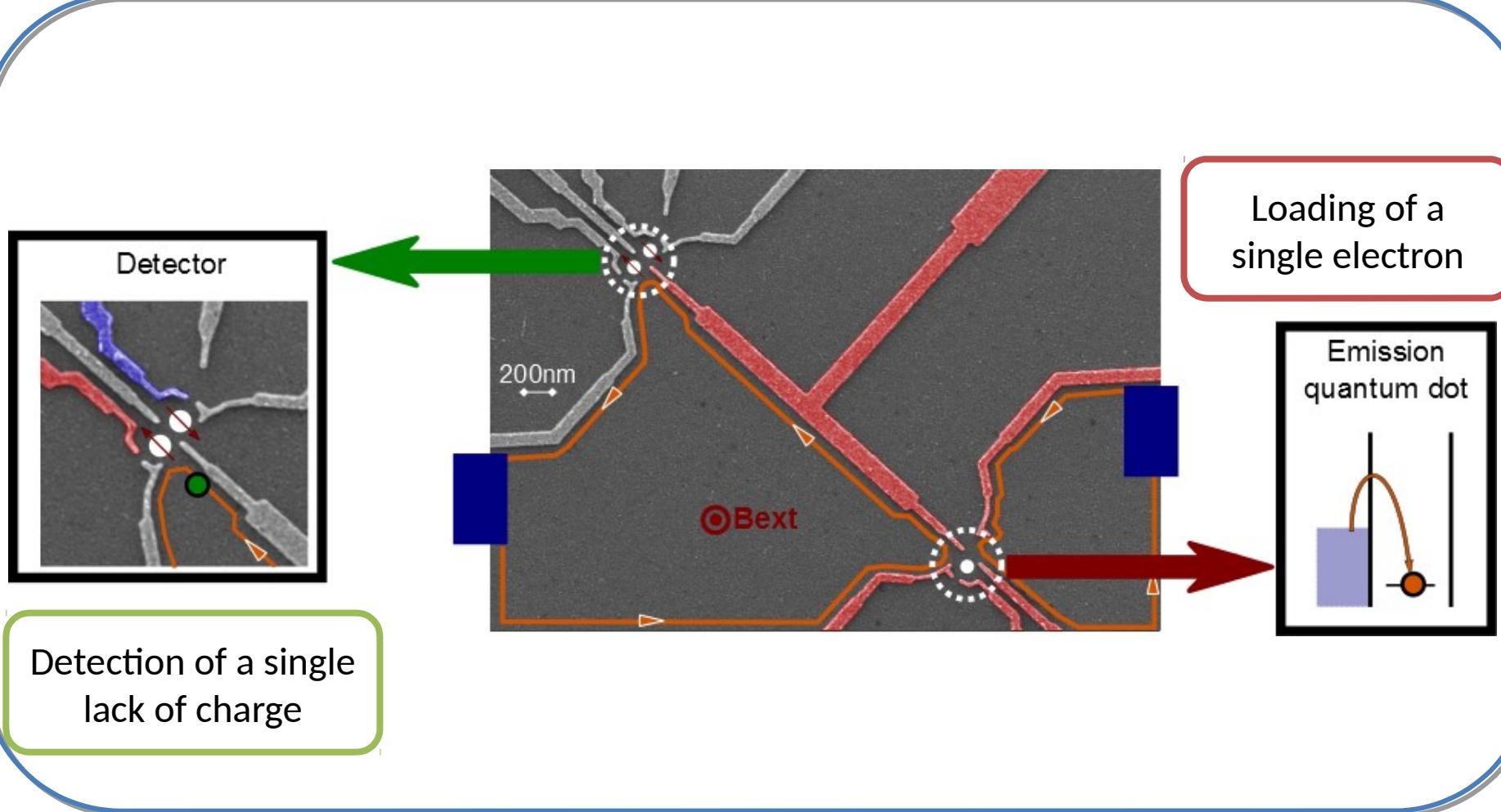
Feve et al, Science(2007)



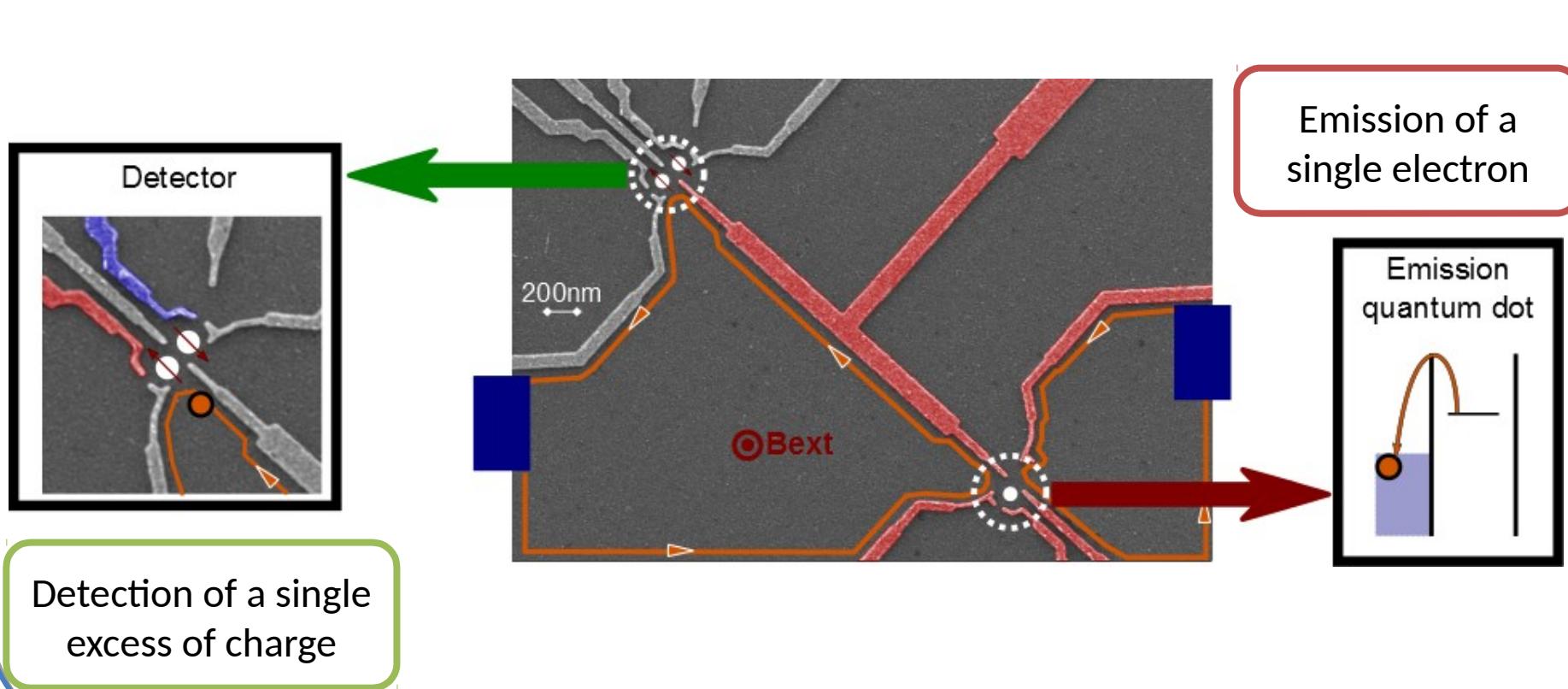
Principle of the experiment



Principle of the experiment

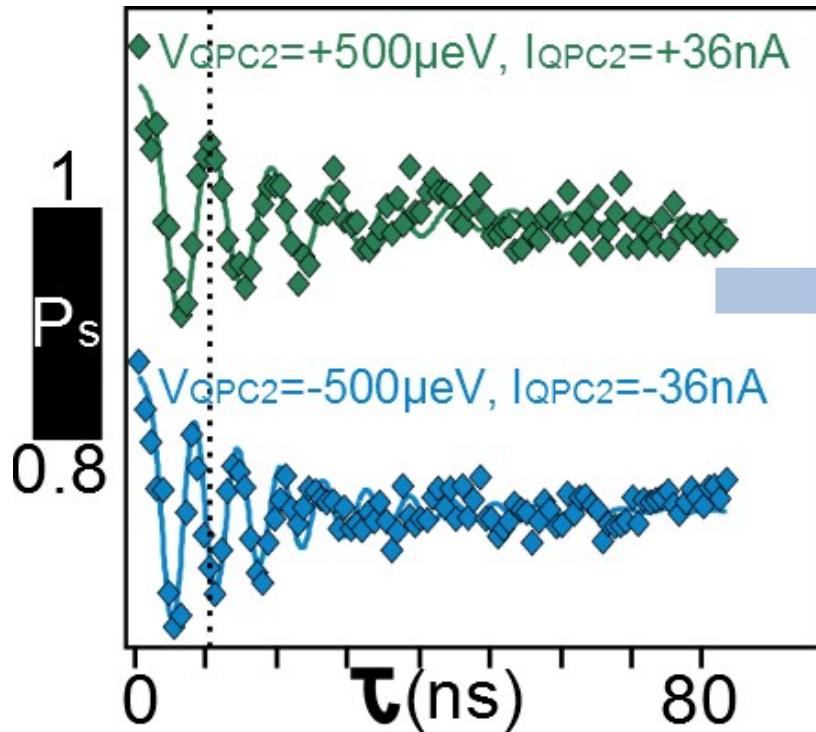


Principle of the experiment

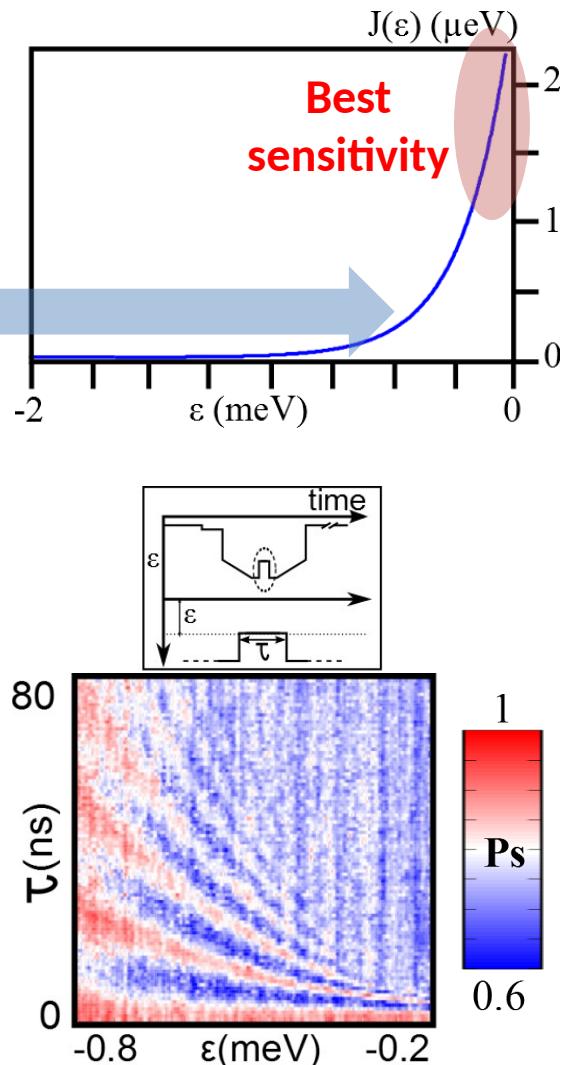


Problematic of the single electron detection

Detection efficiency :



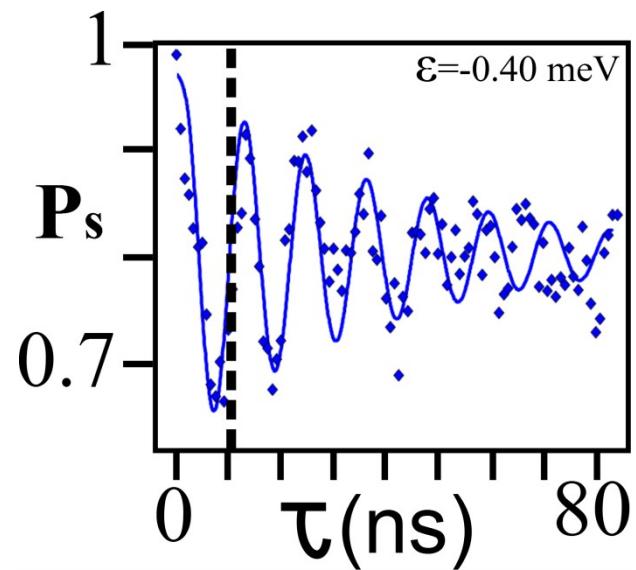
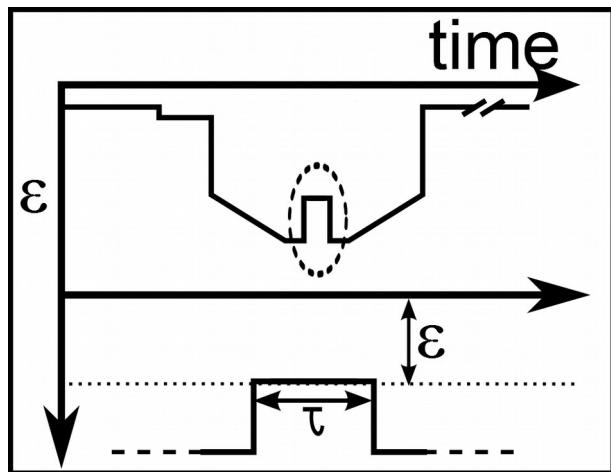
Towards higher sensitivity :



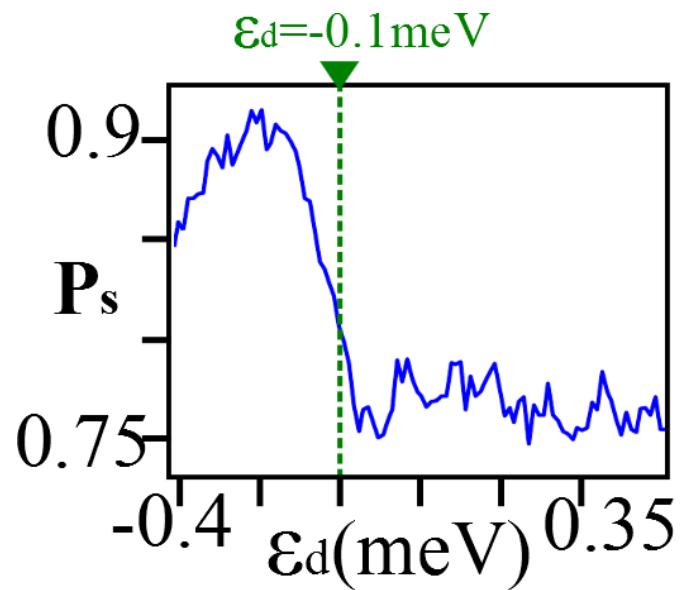
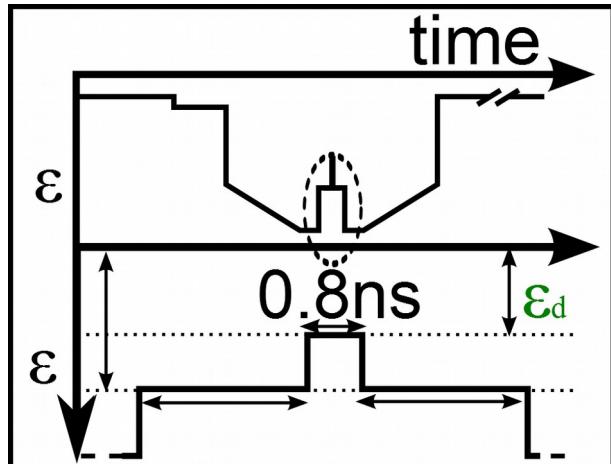
~5000 electrons for a π phase shift

Single electron detection pulse

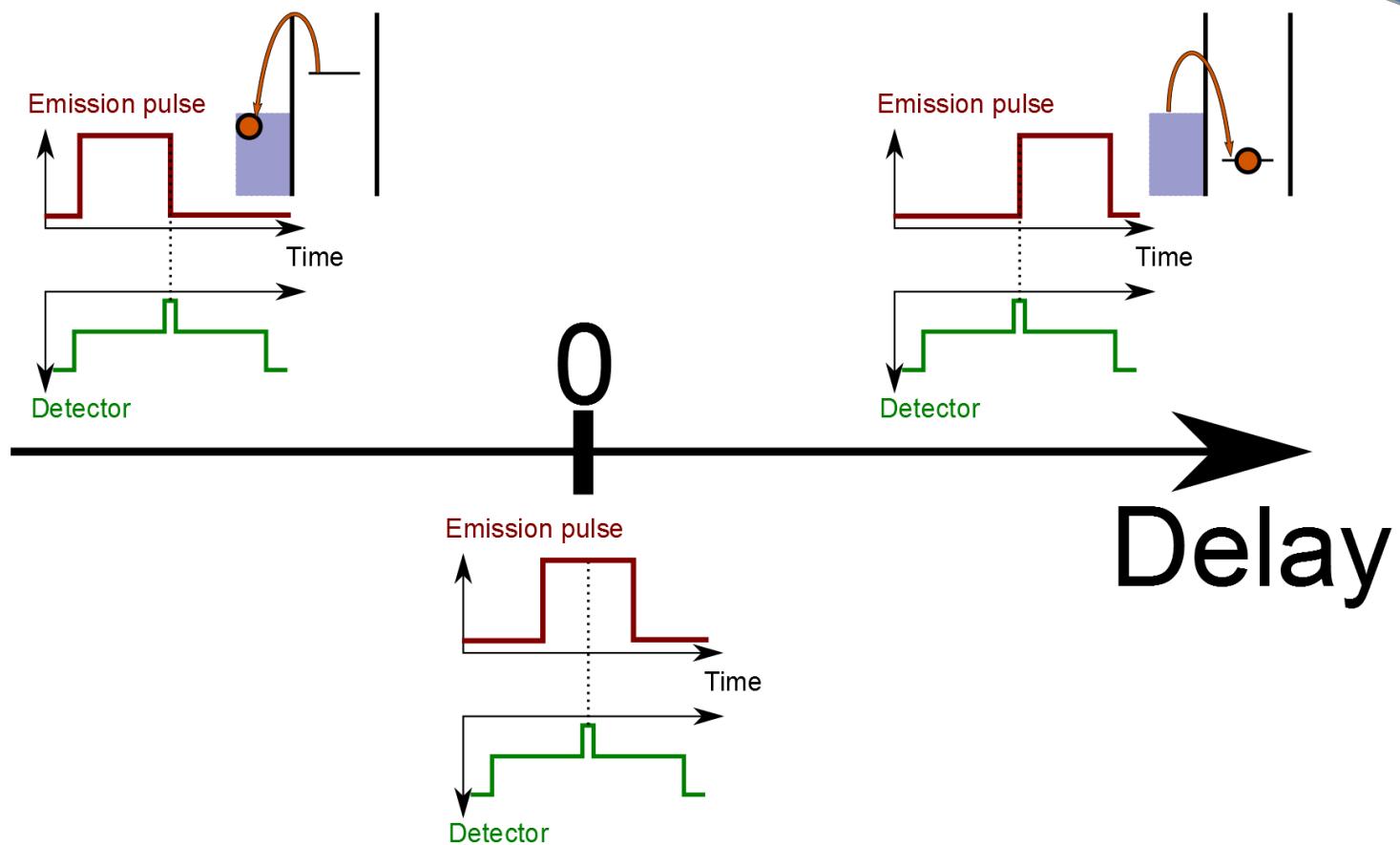
Standard exchange pulse :



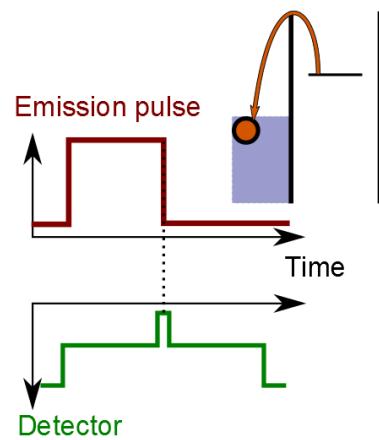
Detection pulse :



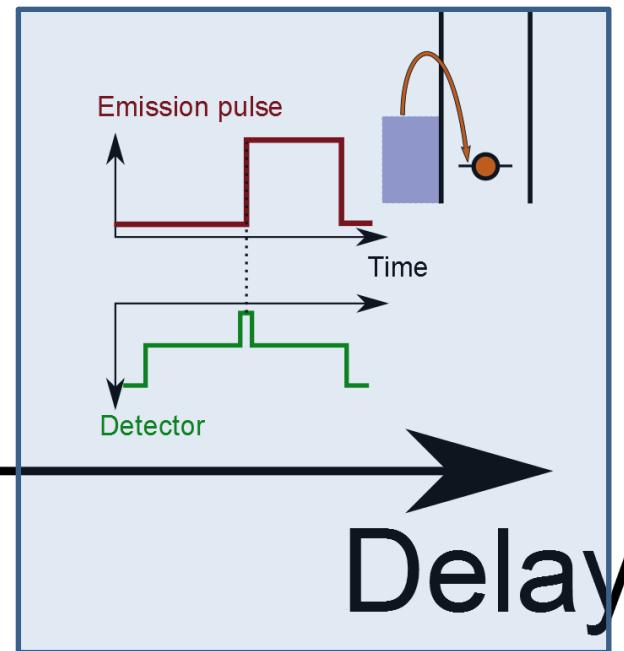
Single electron detection pulse



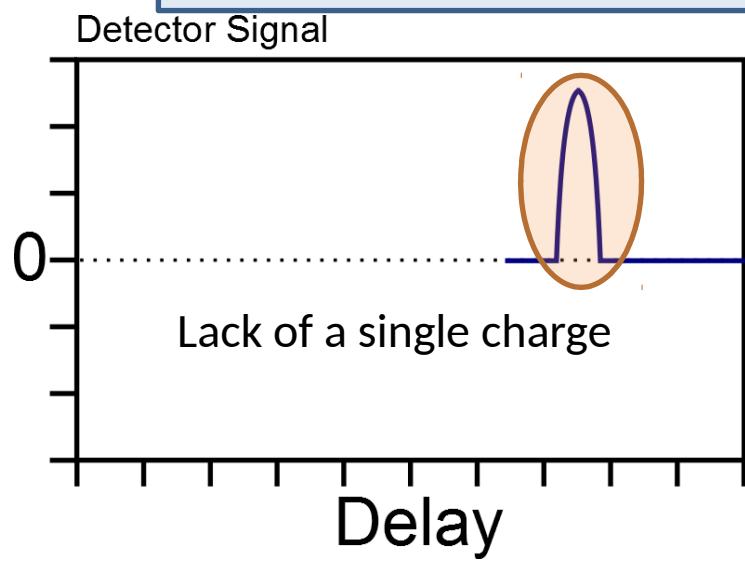
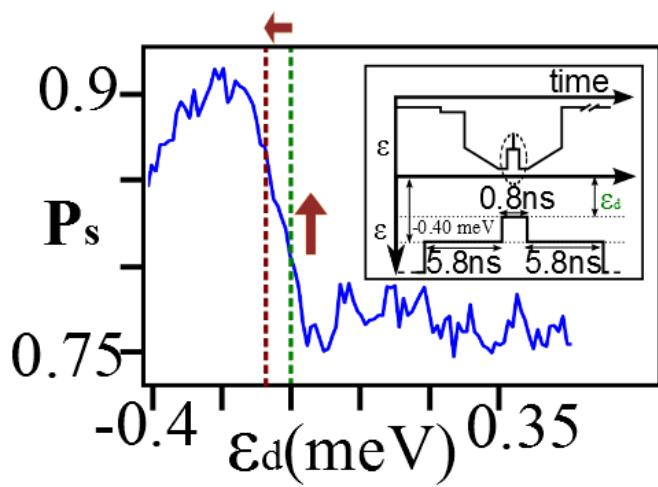
Single electron detection pulse



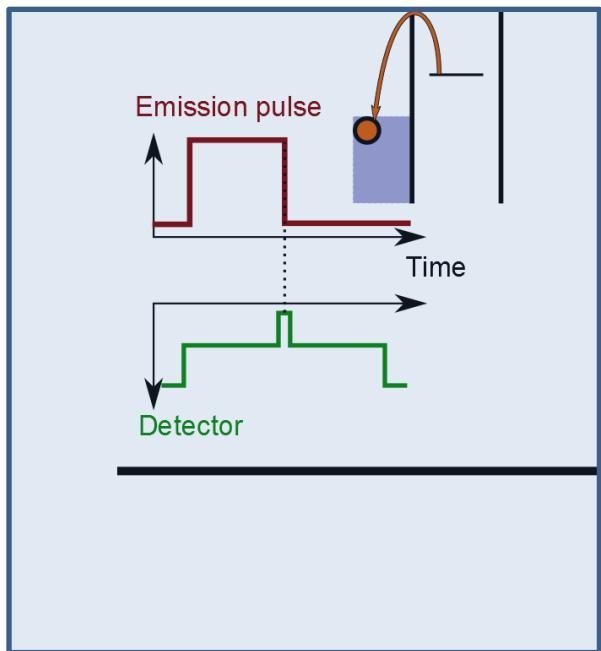
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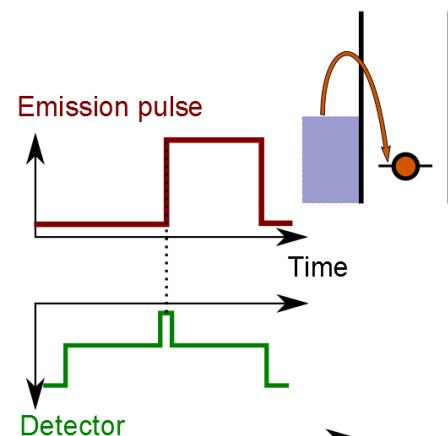
Delay



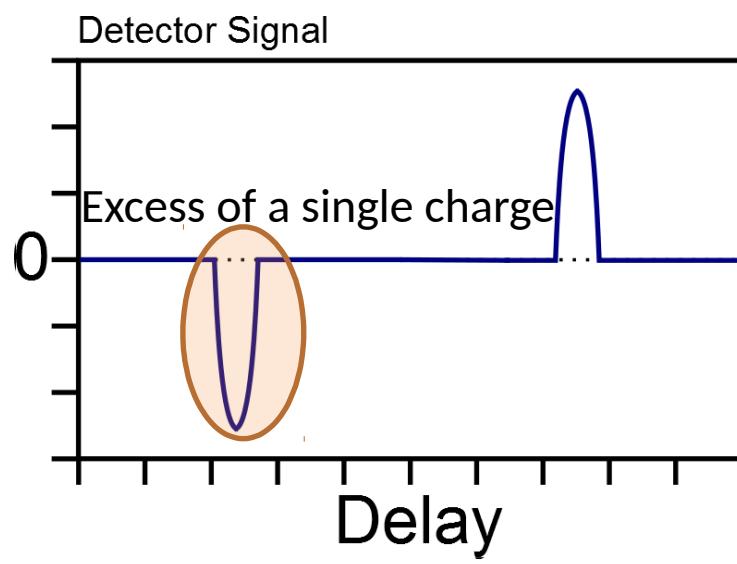
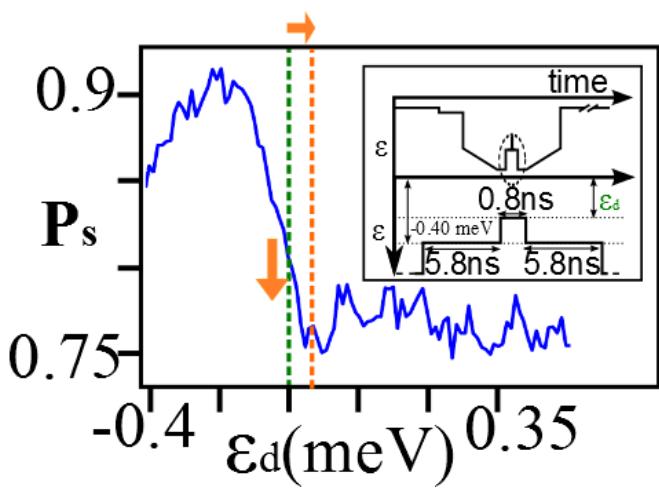
Single electron detection pulse



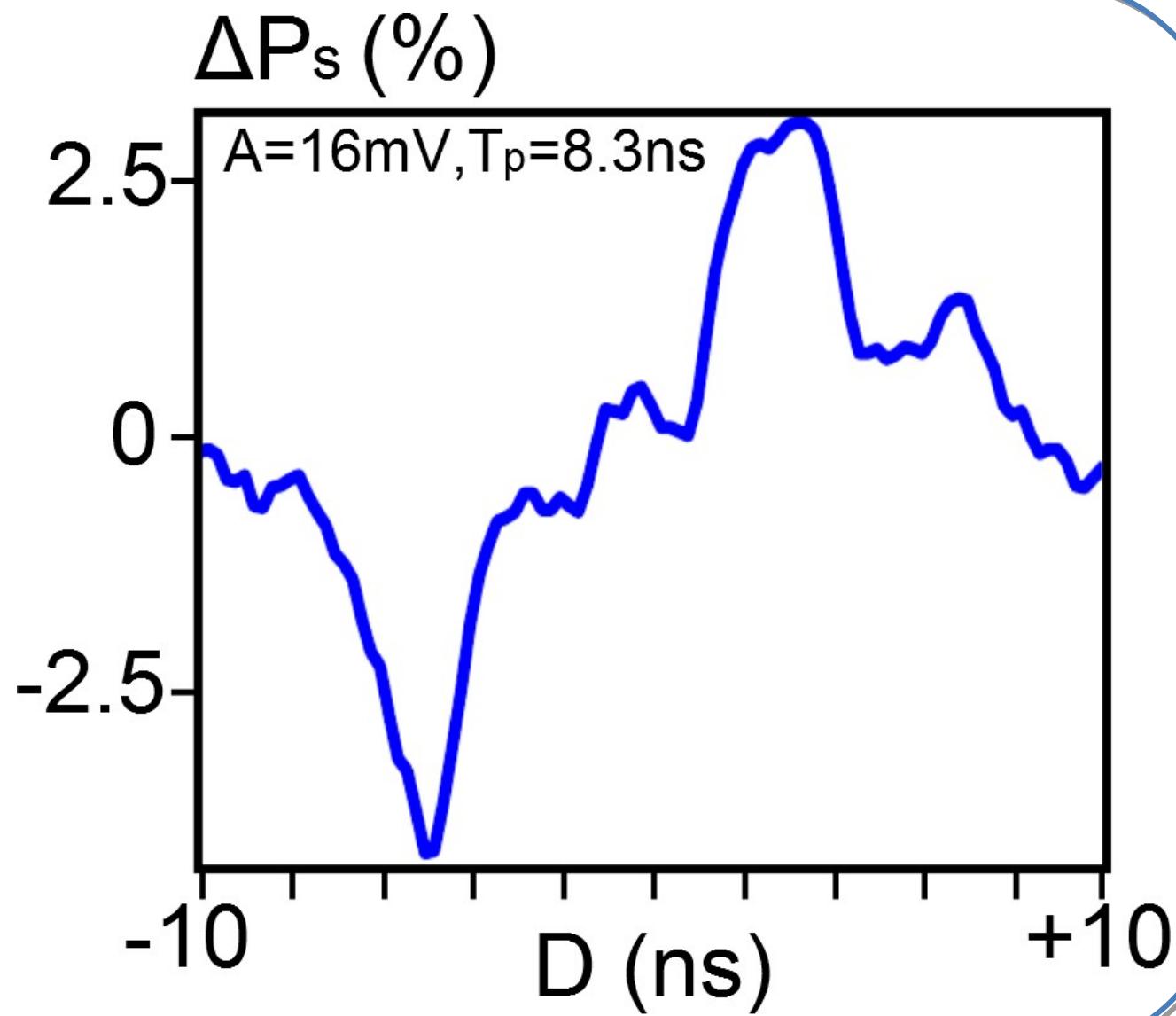
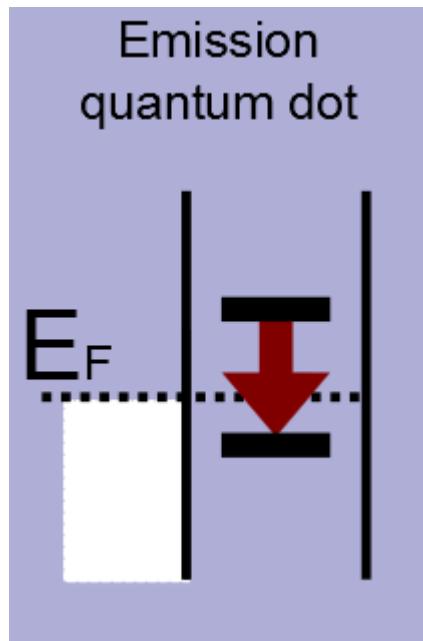
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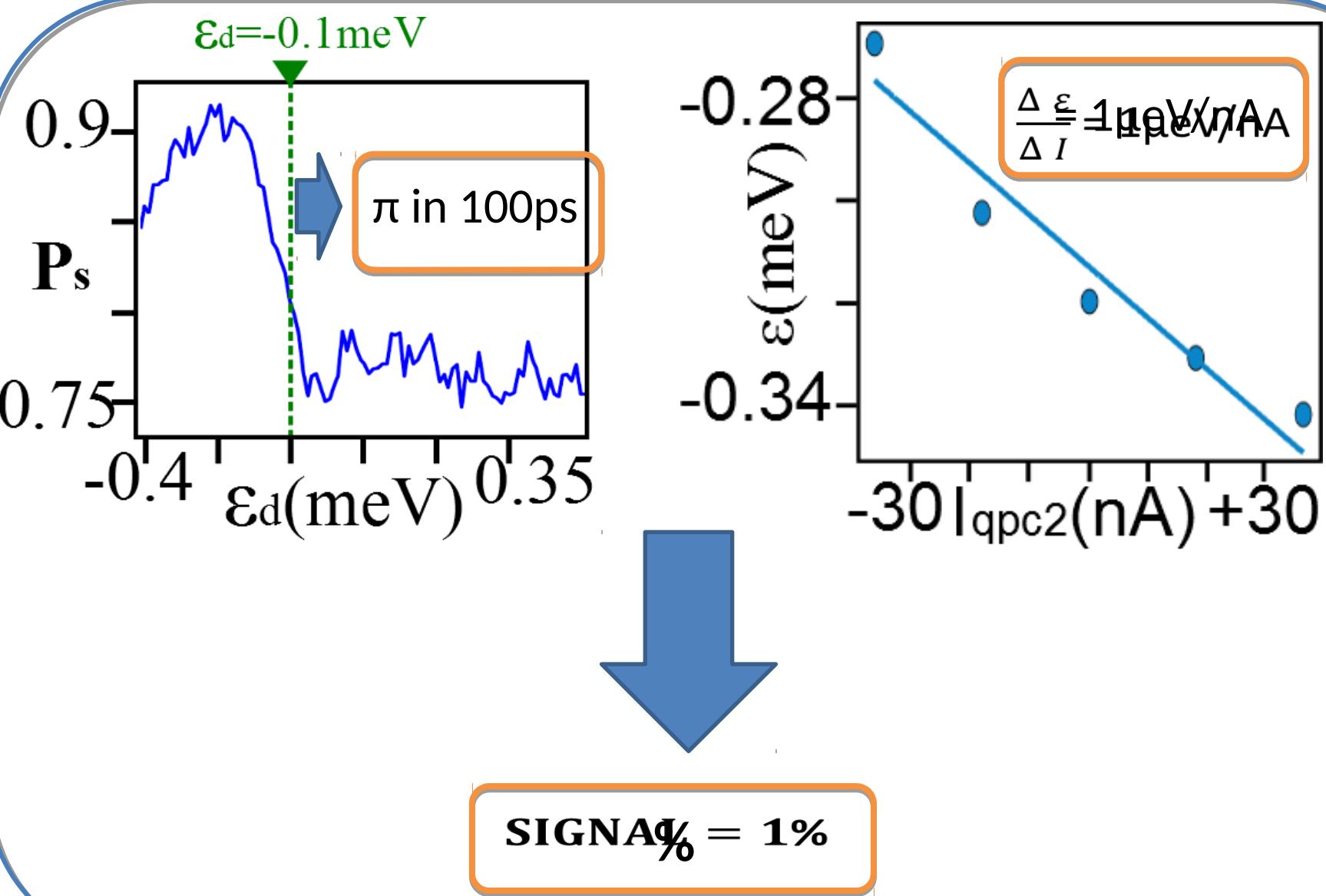
Delay



Detection

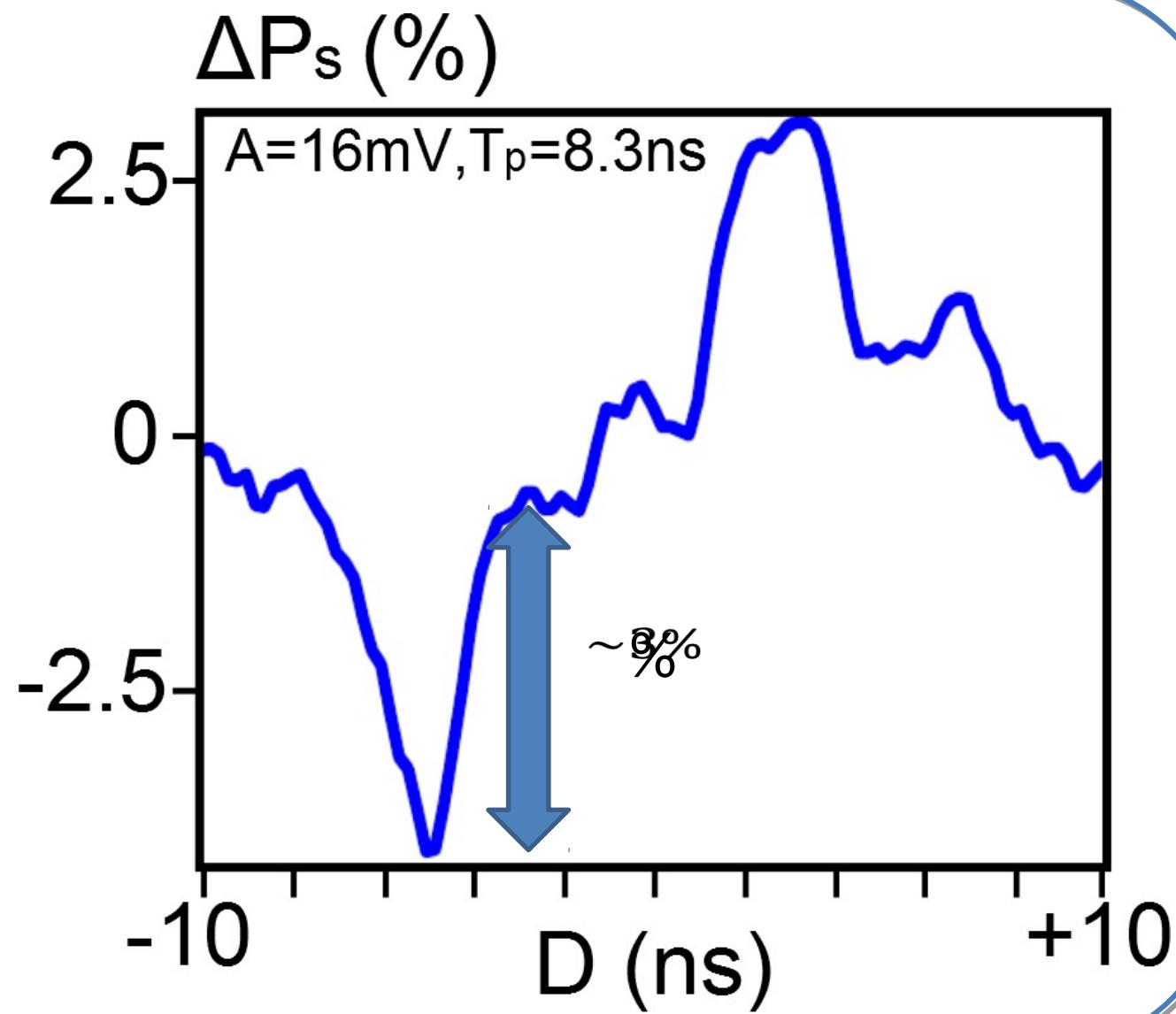


Analyse of the signal amplitude

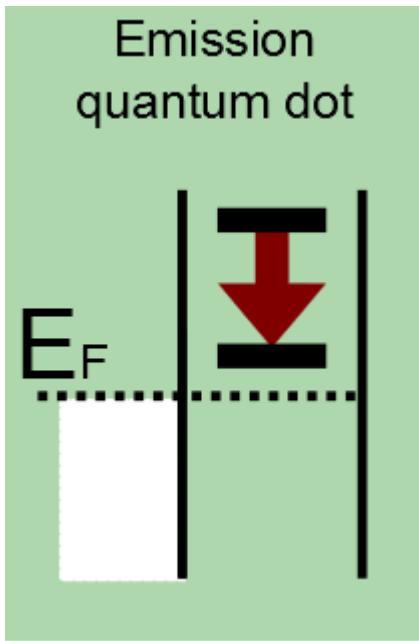
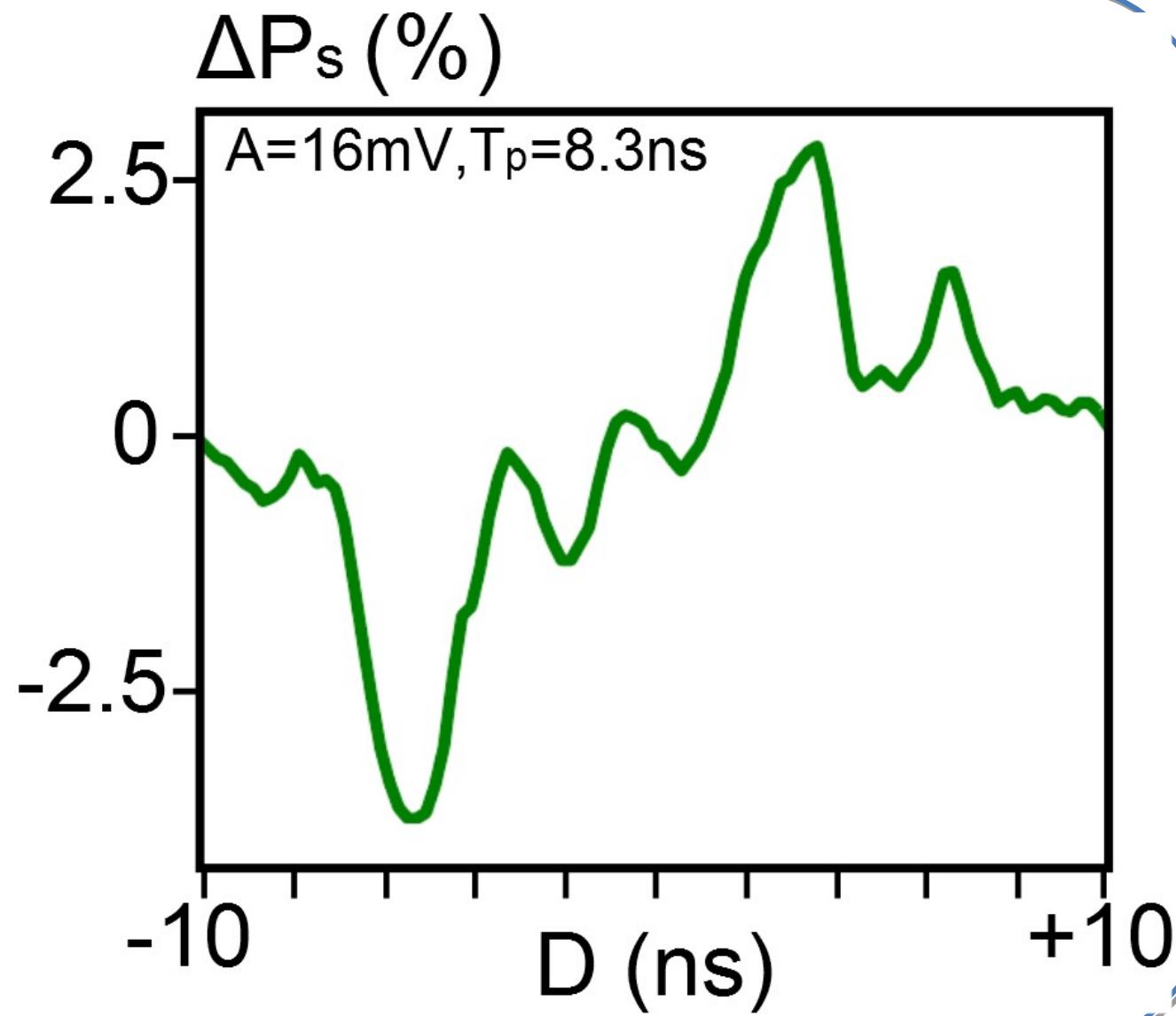


Detection

$\sim 3\%$

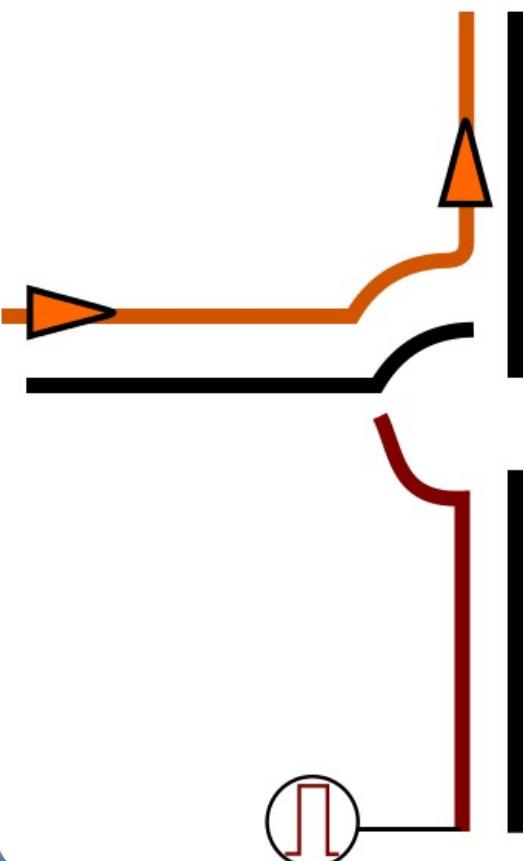


Detection

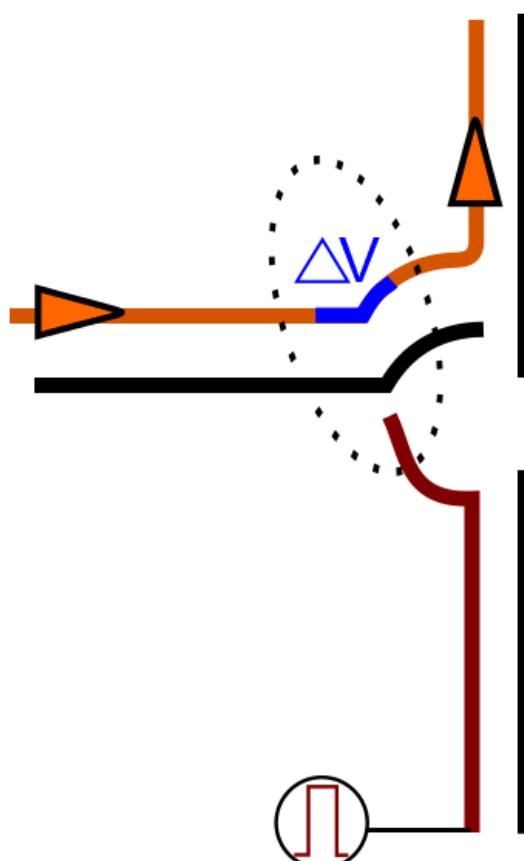


Edge excitations

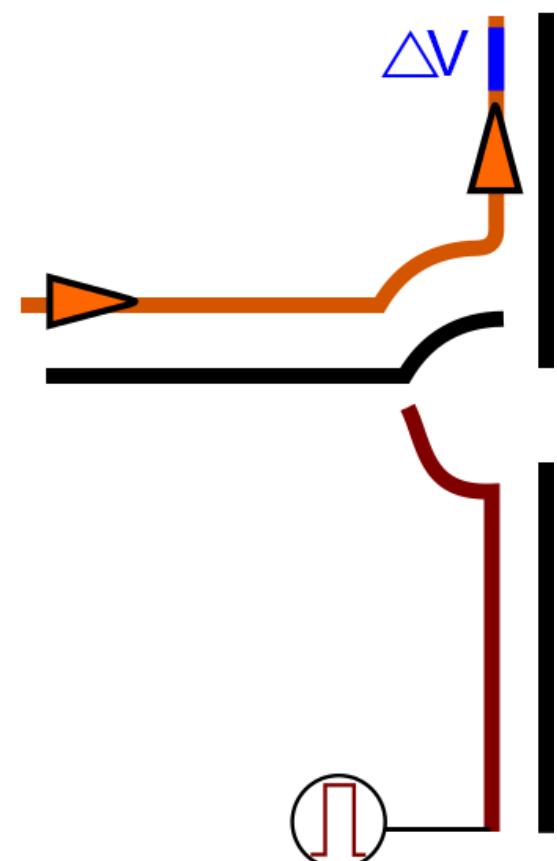
Capacitive coupling between the gate (red) and the edge-states (orange)



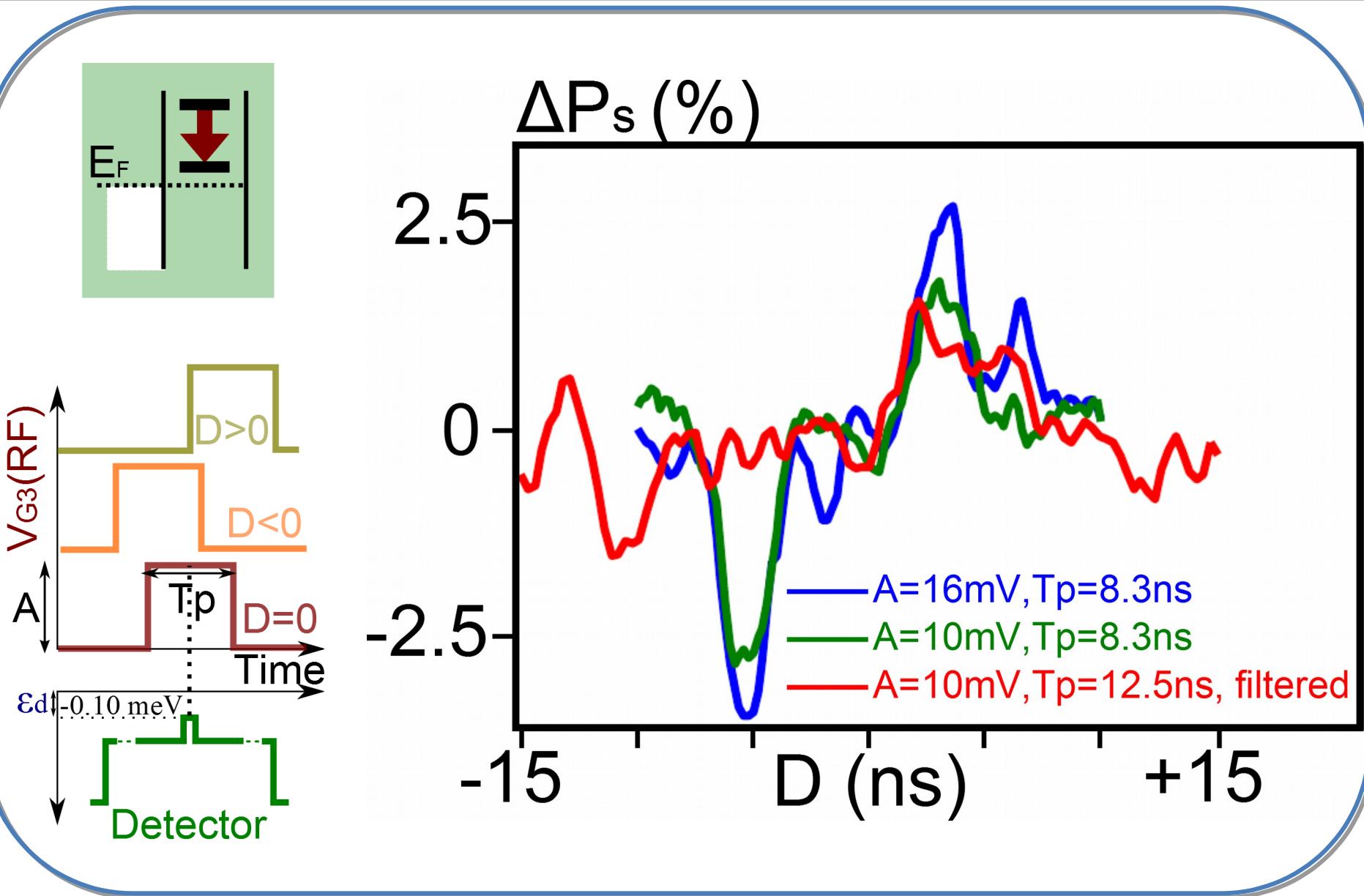
A pulse generates a local change of the edge-state potential



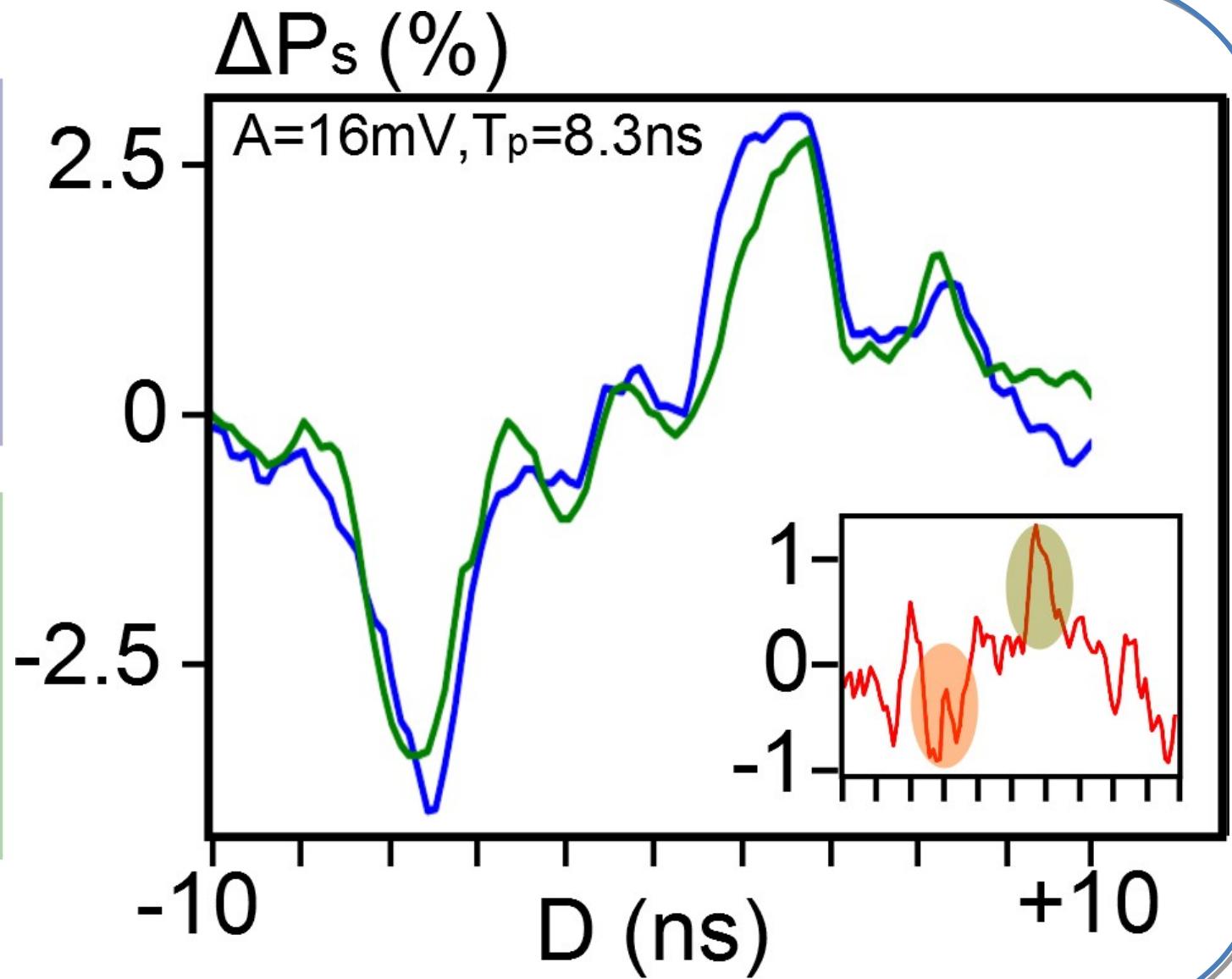
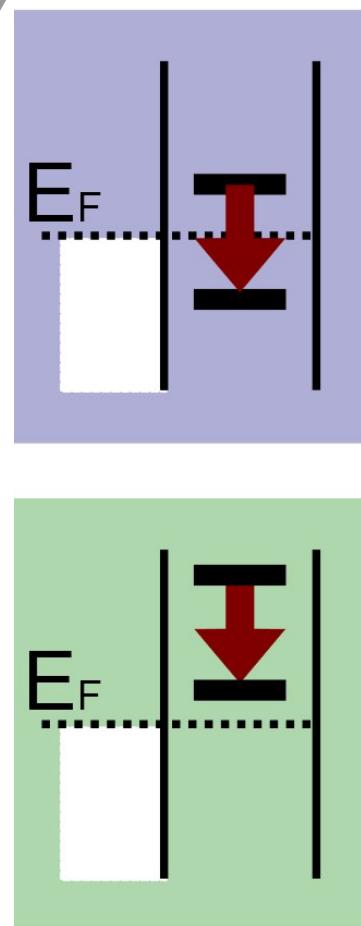
This propagates with the electrons and is finally detected



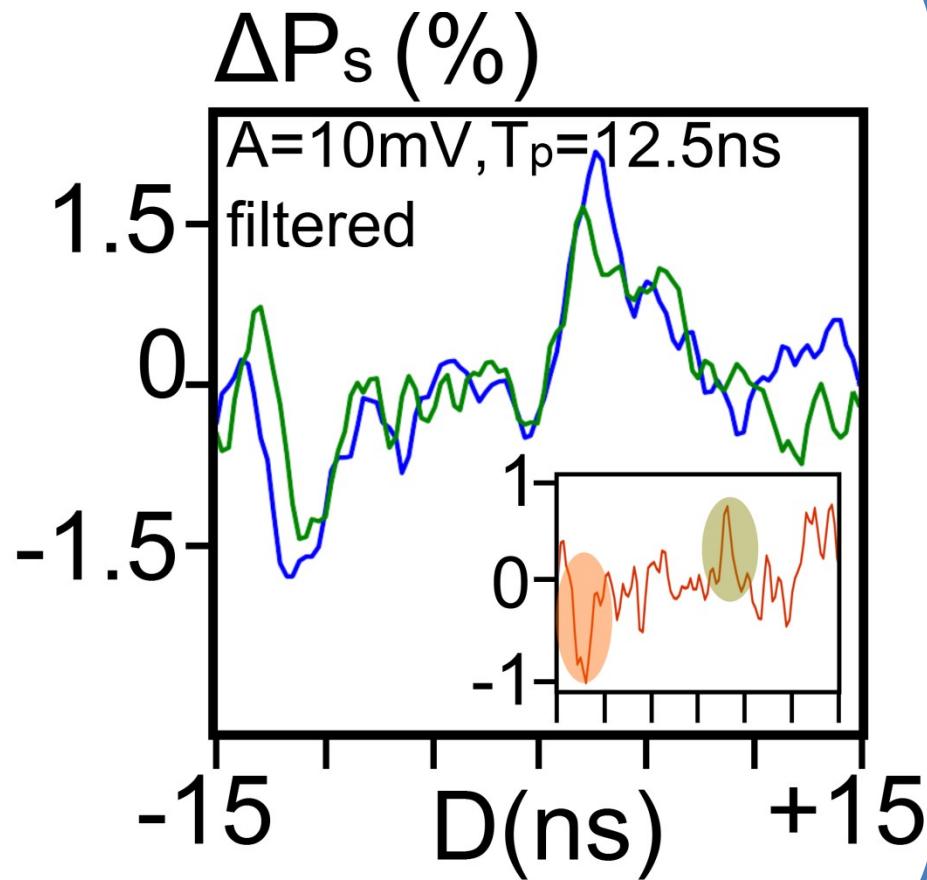
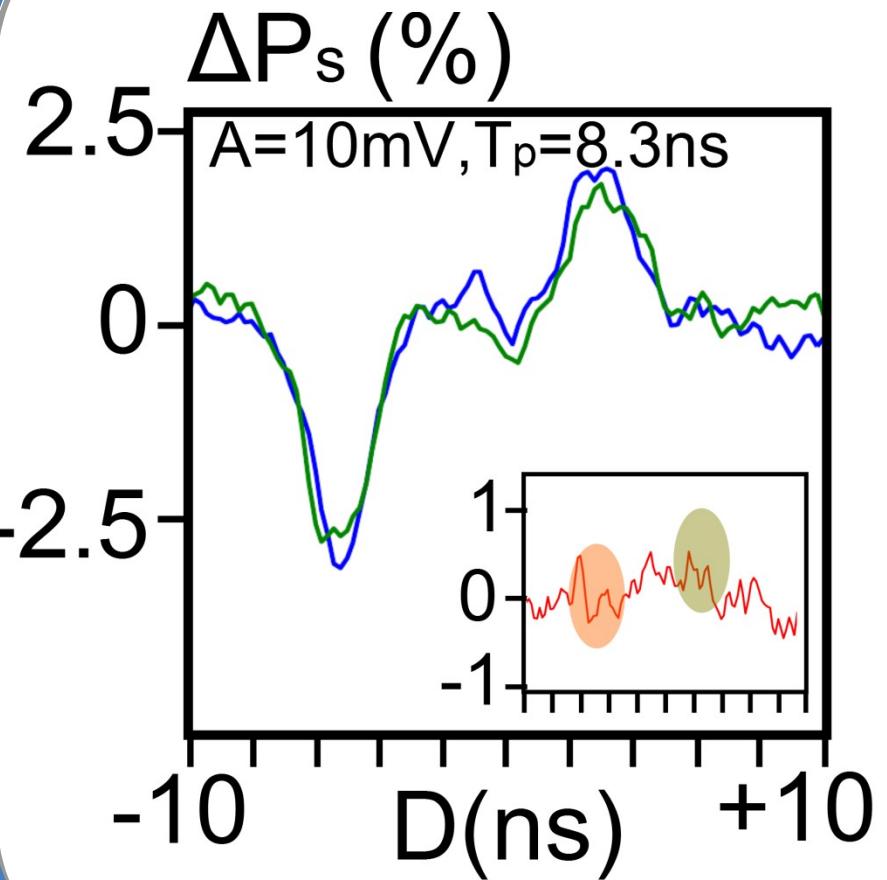
Edge excitations



Single electron detection

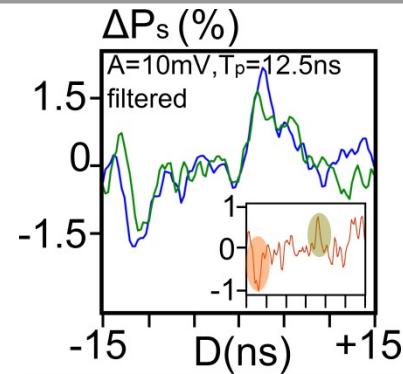


Single electron detection

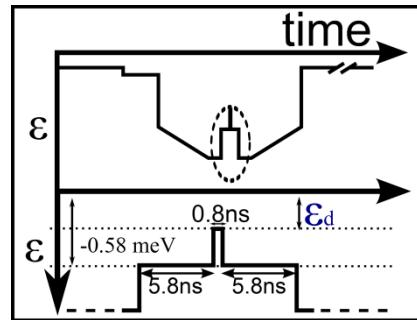


Conclusion and perspectives

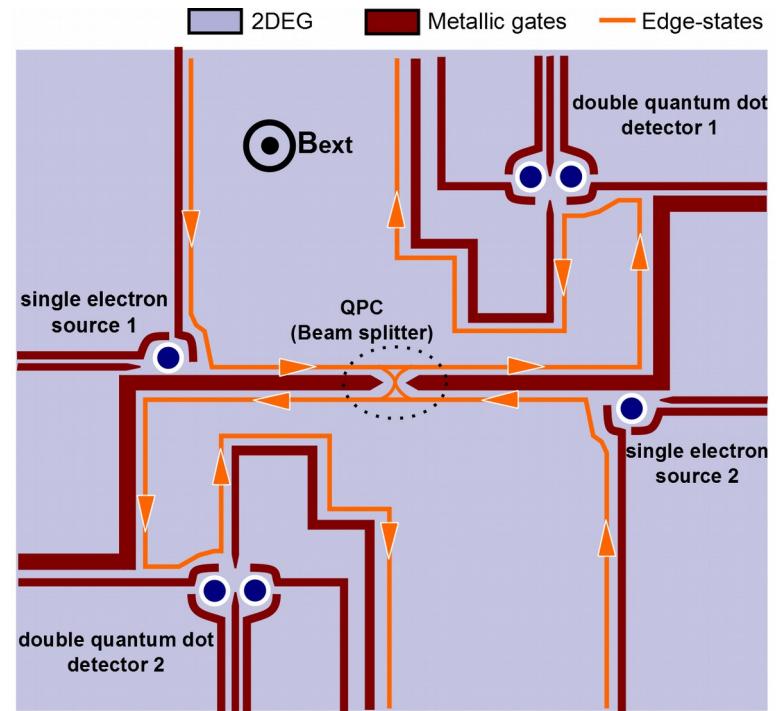
Demonstration of a single flying electron detection



Increase
the set-up bandwith



Hanbury-Brown and
Twiss experiment at the
single electron level



Remerciements

***Cryogenic support :** Pierre PERRIER

***Electronic support :** pole
électronique NANO & MCBT, Christophe
GUTTIN, Christophe HOARAU, Daniel
LEPOITTEVIN

***NanoFab team**

***Liquefactor team**

***Administrative team**

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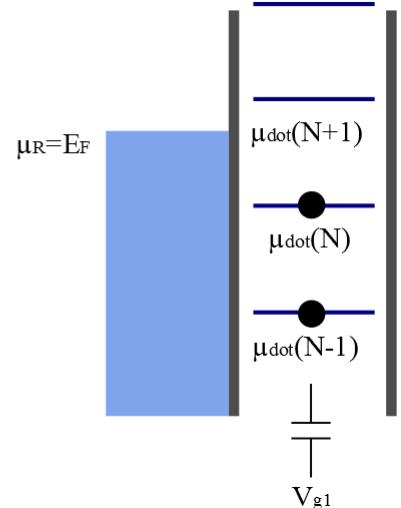
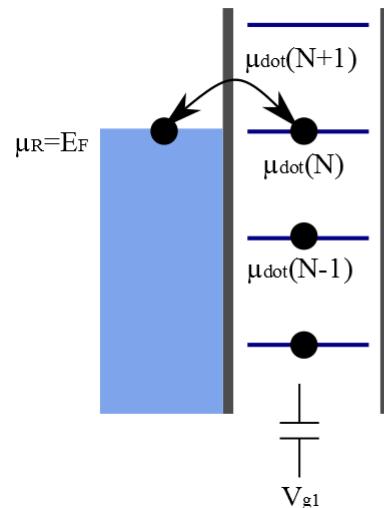
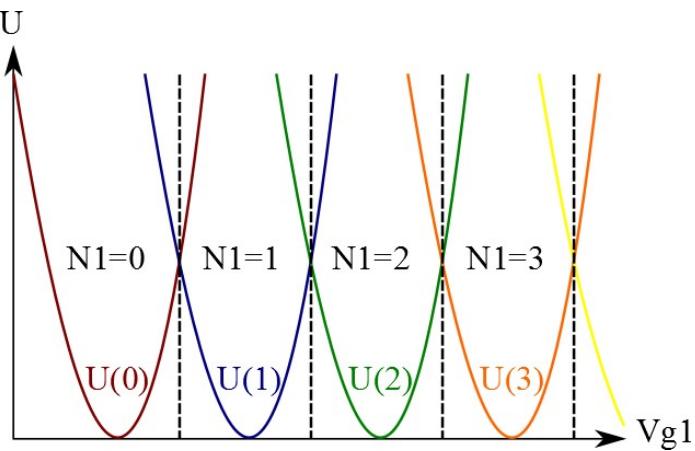
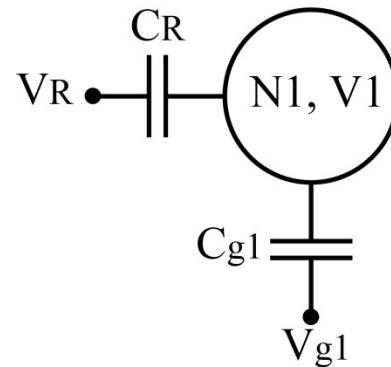
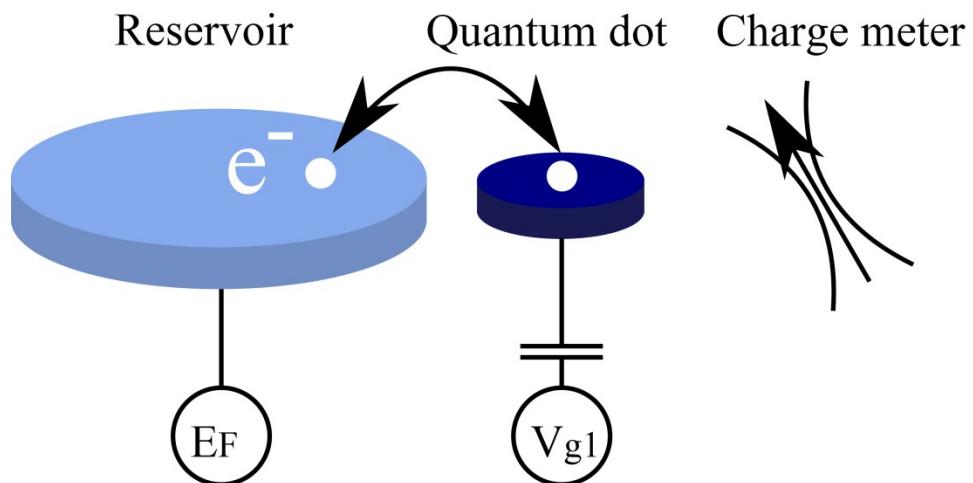
Grégoire ROUSSELY

Post-Doc :

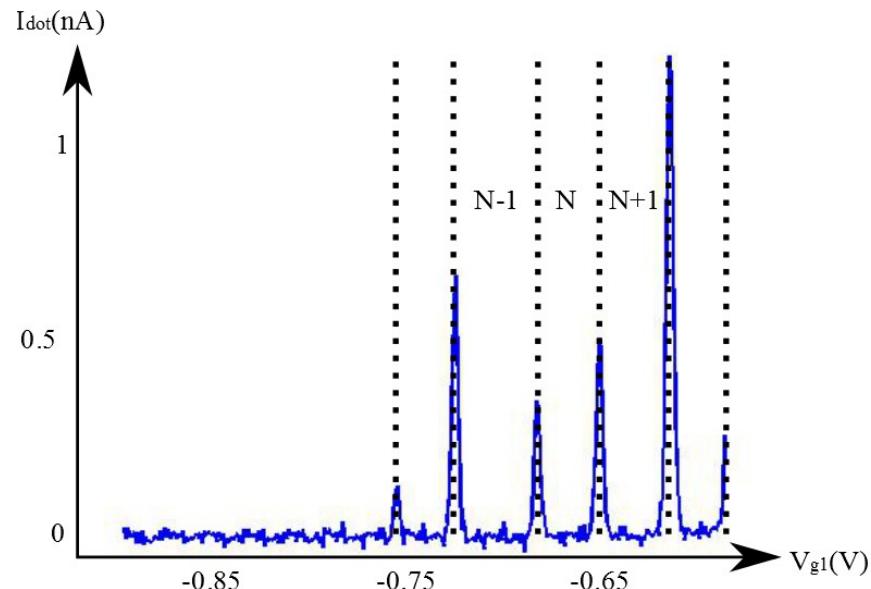
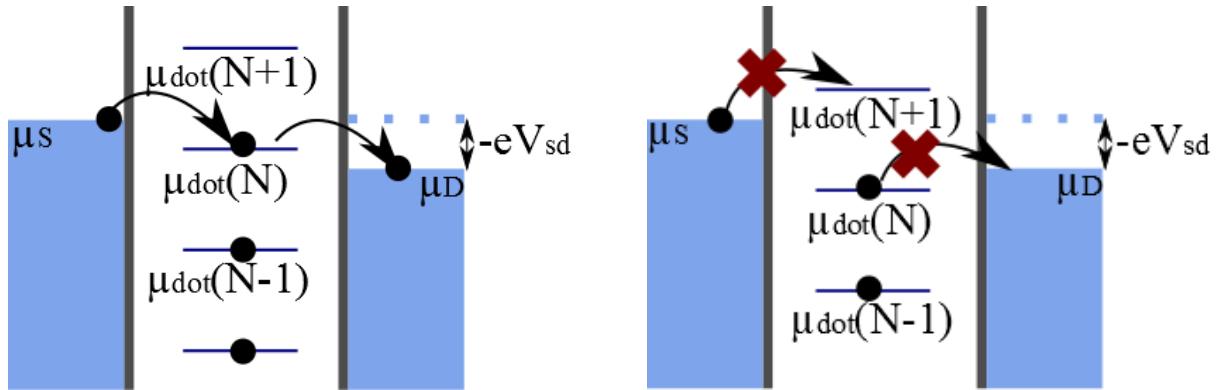
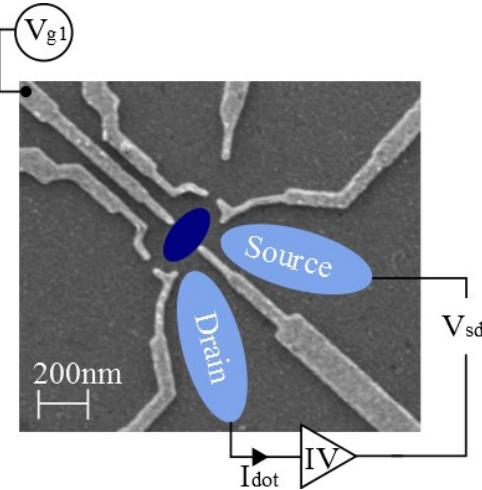
Soumen MANDAL

And to all the **Quantum Coherence team**

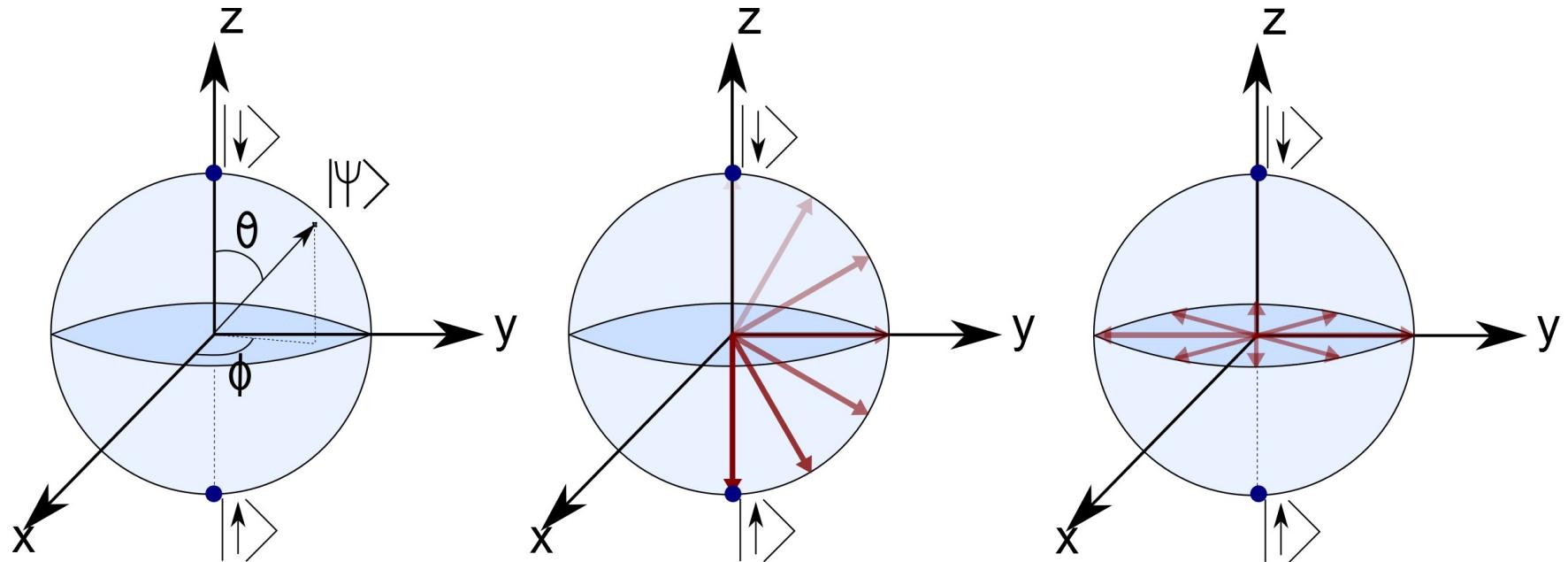
CI model



Transport

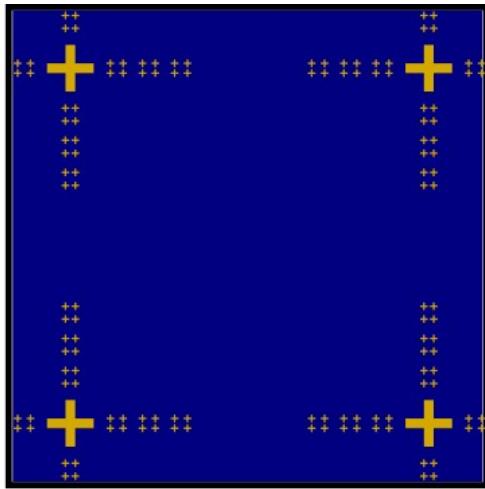


Relaxation and decoherence

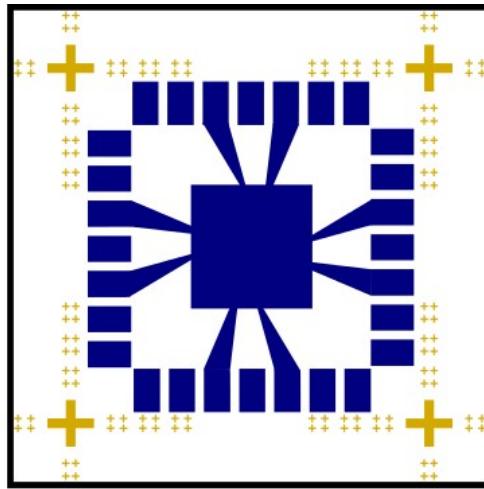


Nanofabrication

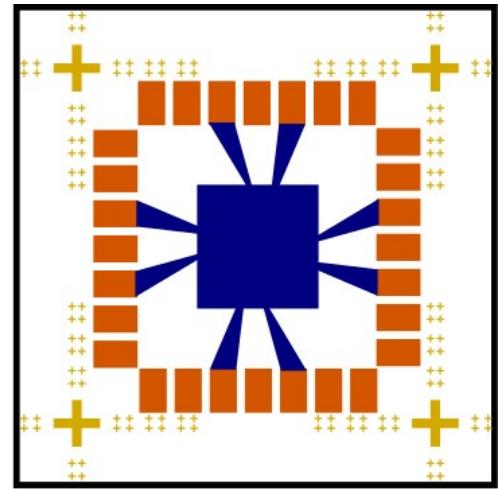
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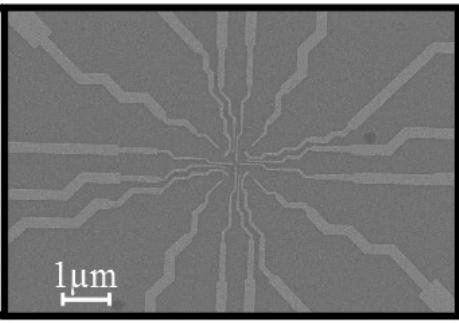
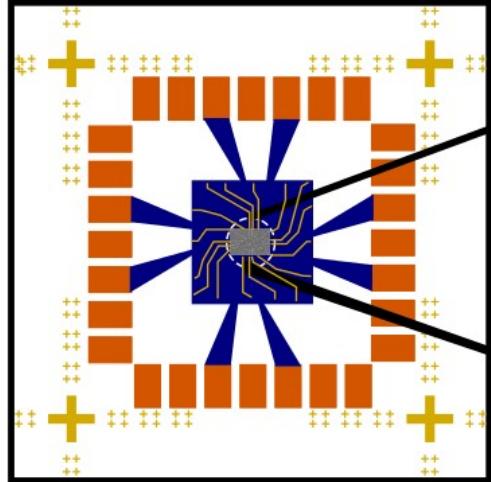
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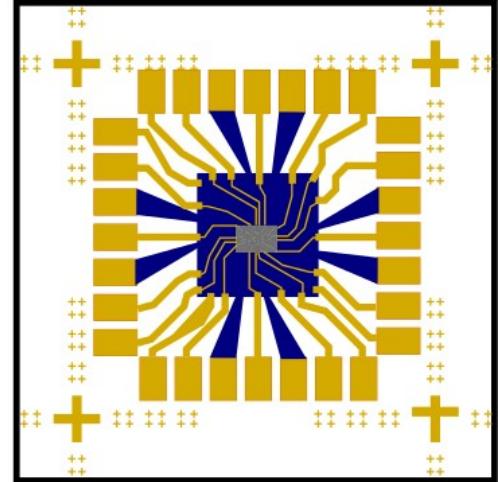
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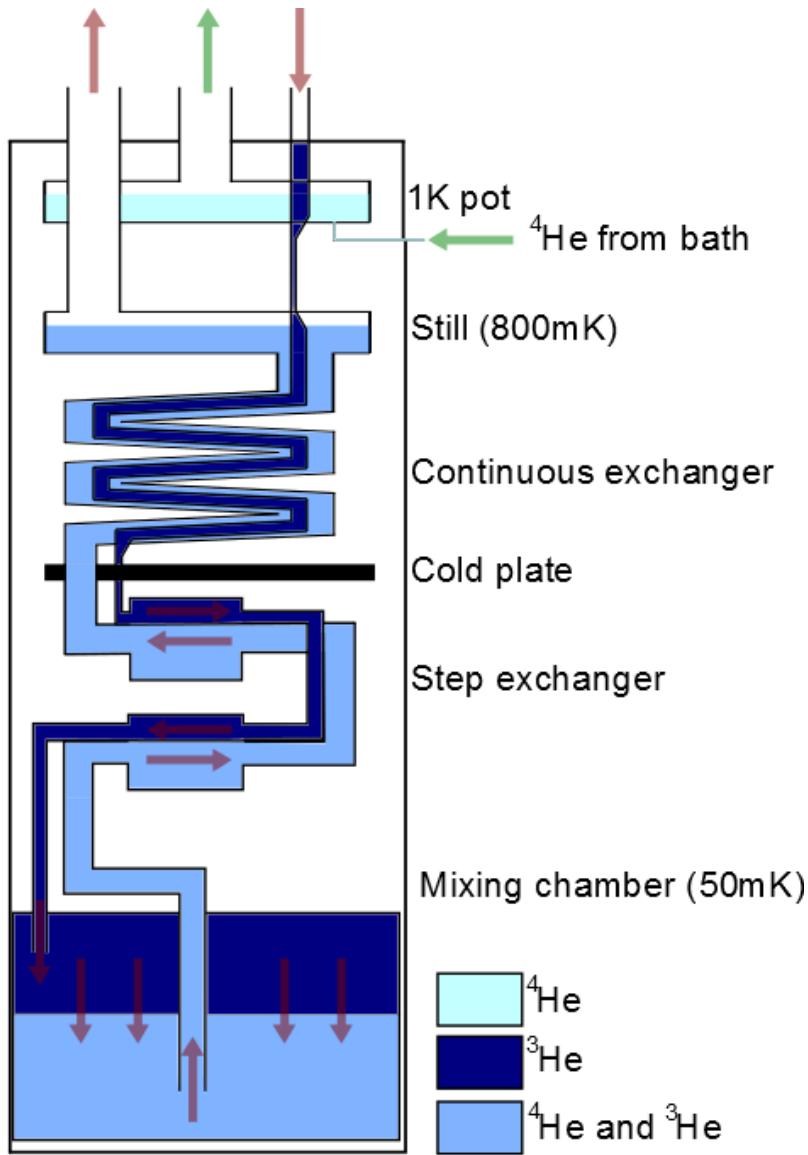
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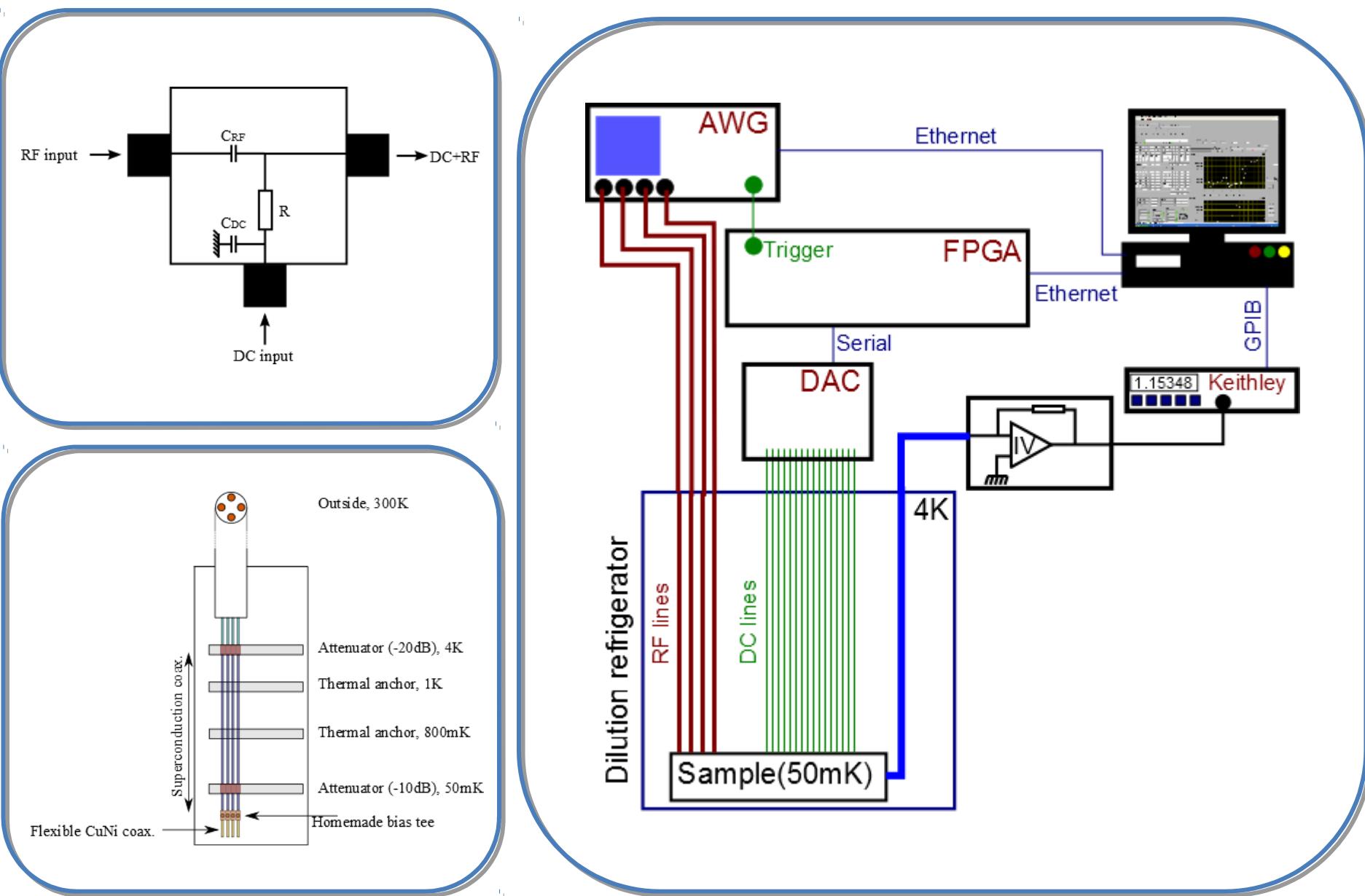
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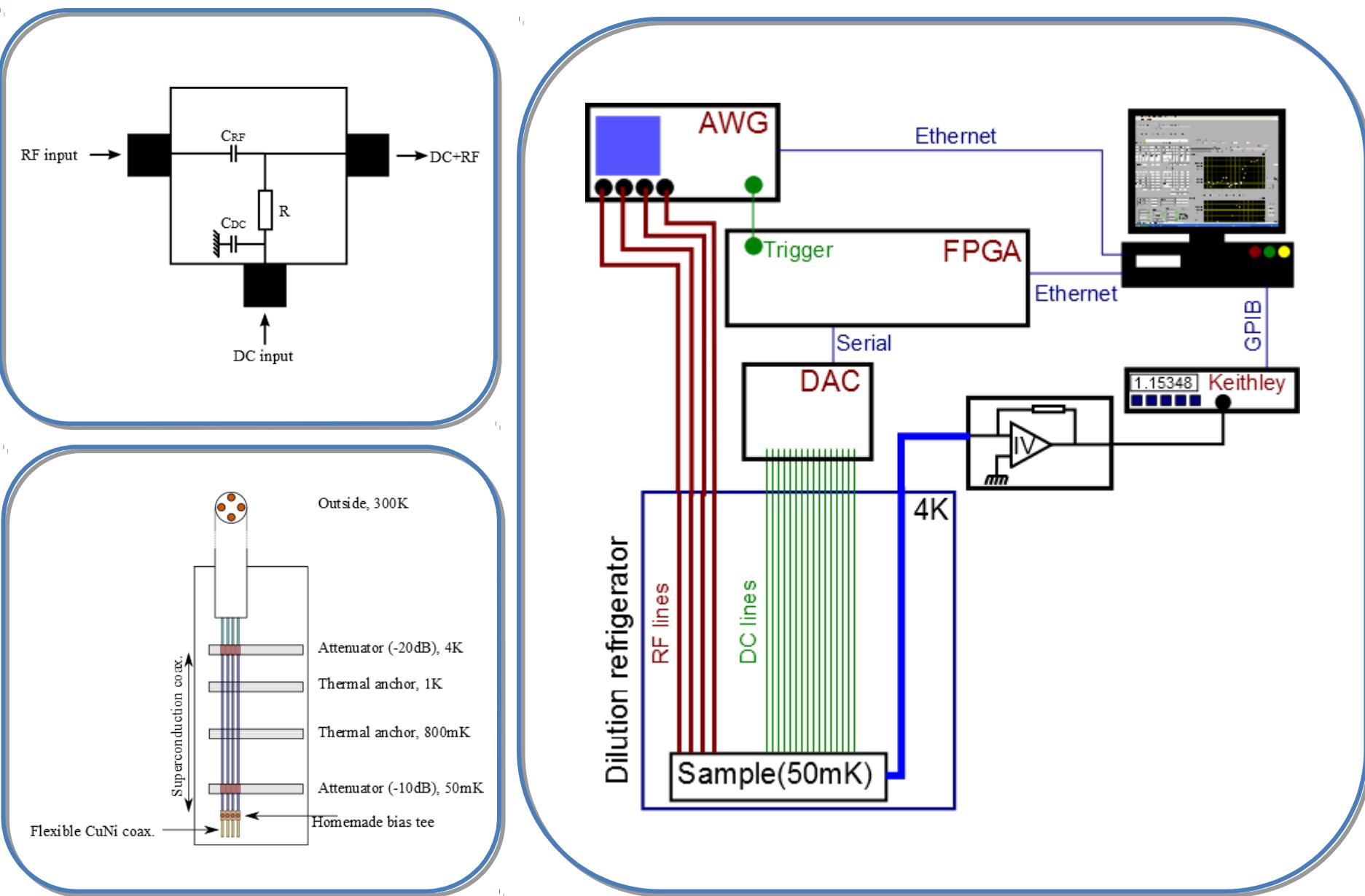
Cryogenics



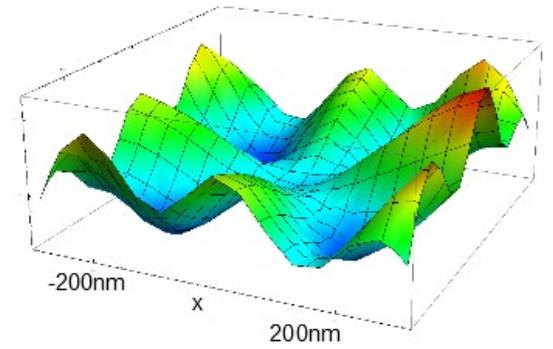
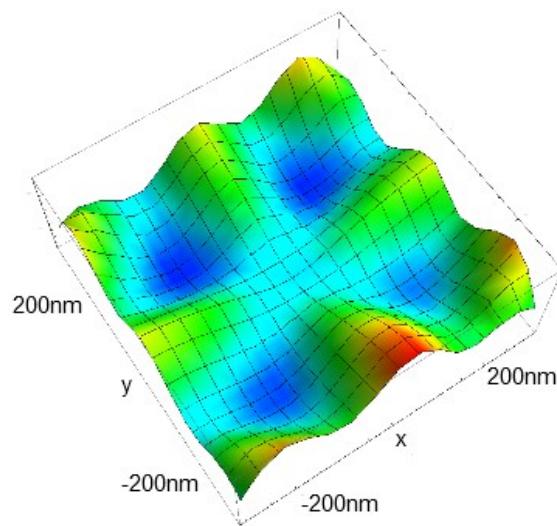
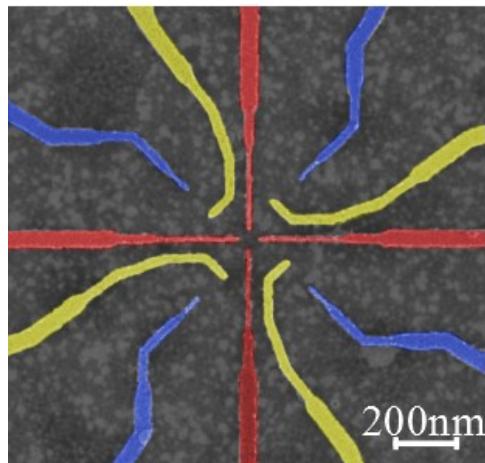
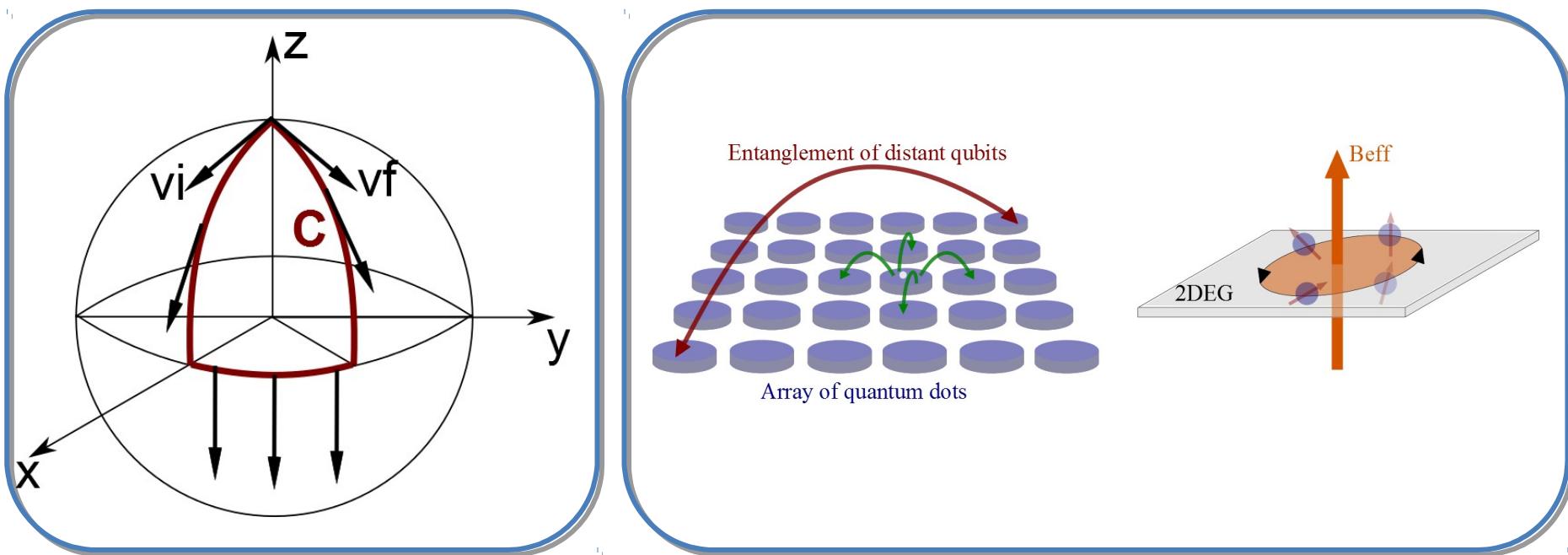
Experimental Set-up



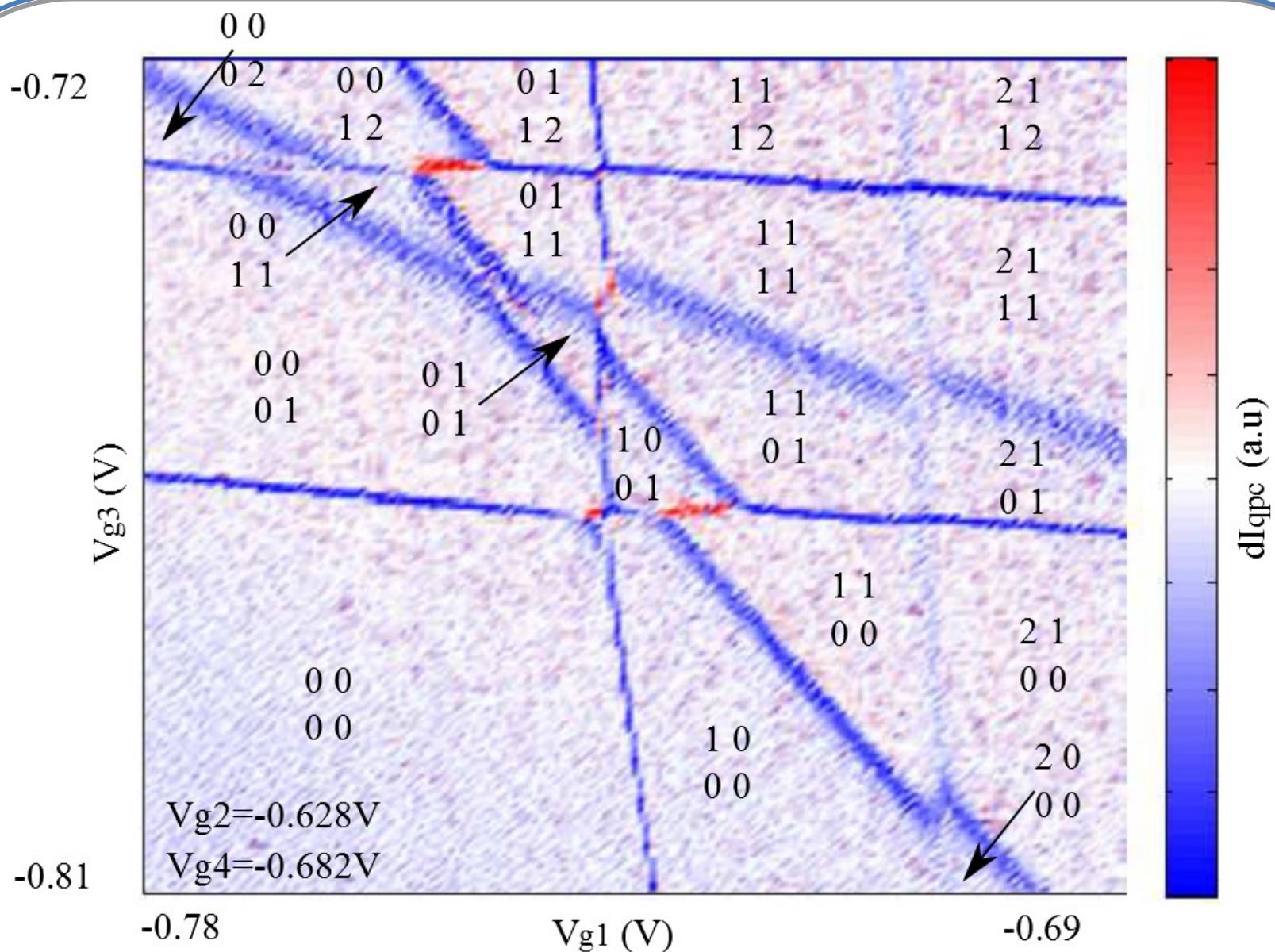
Experimental Set-up



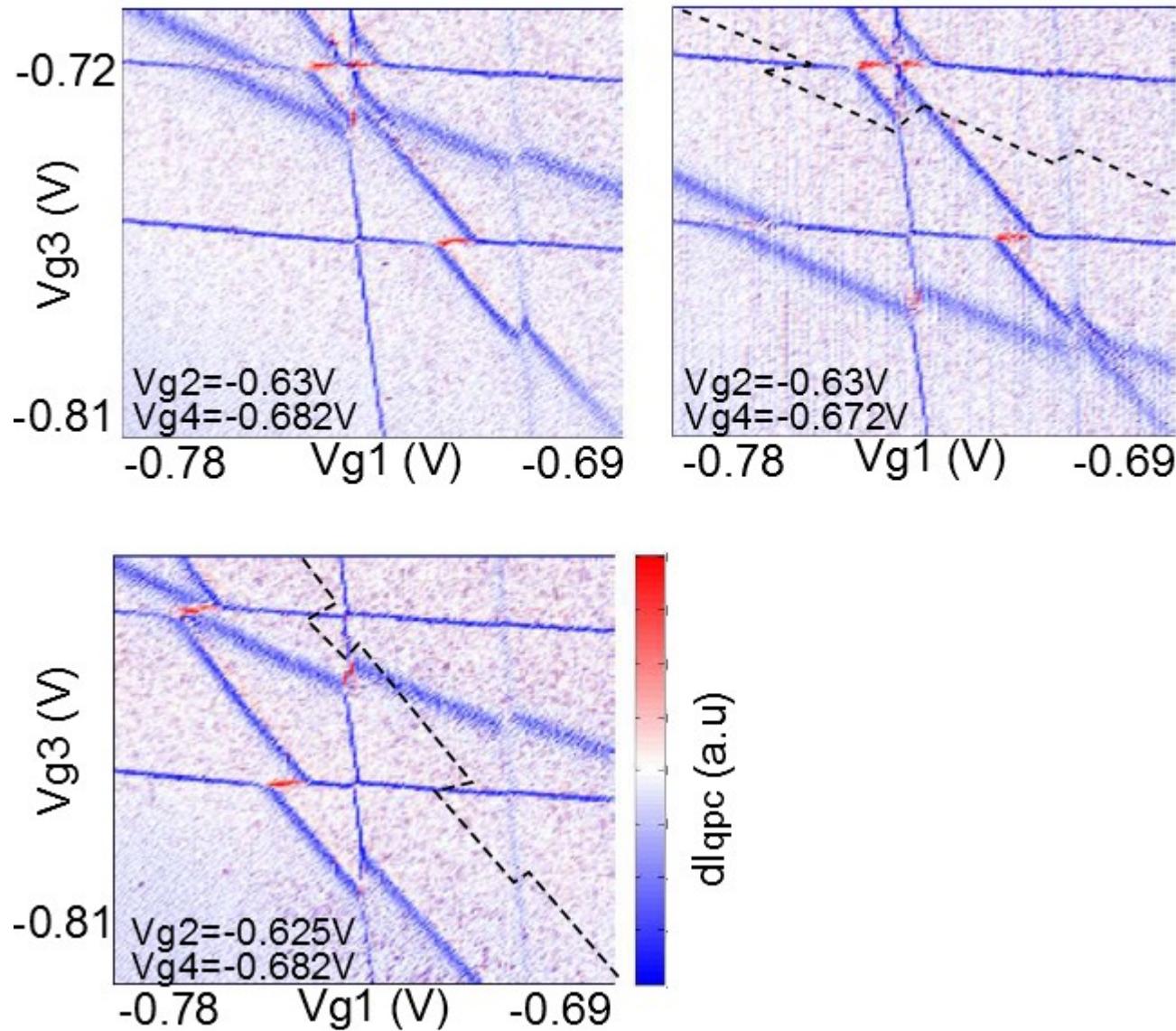
Quadruple quantum dot



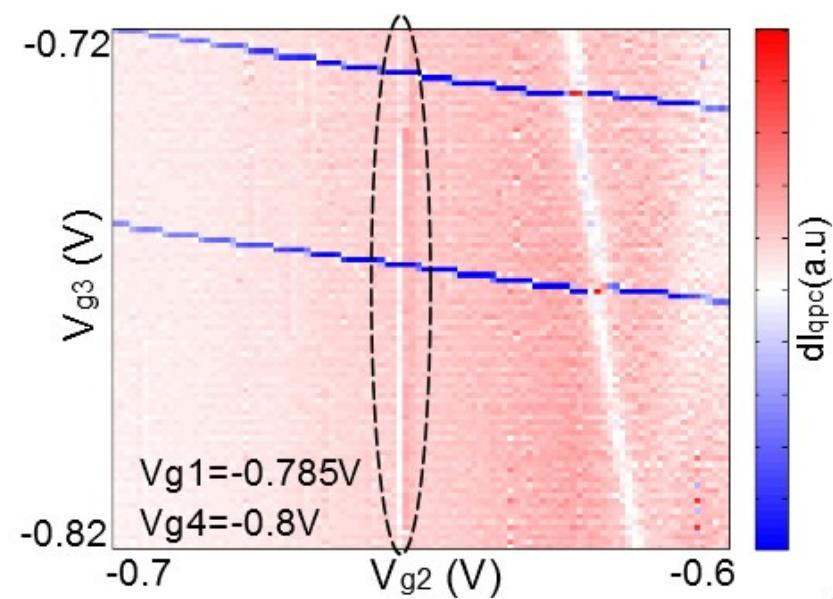
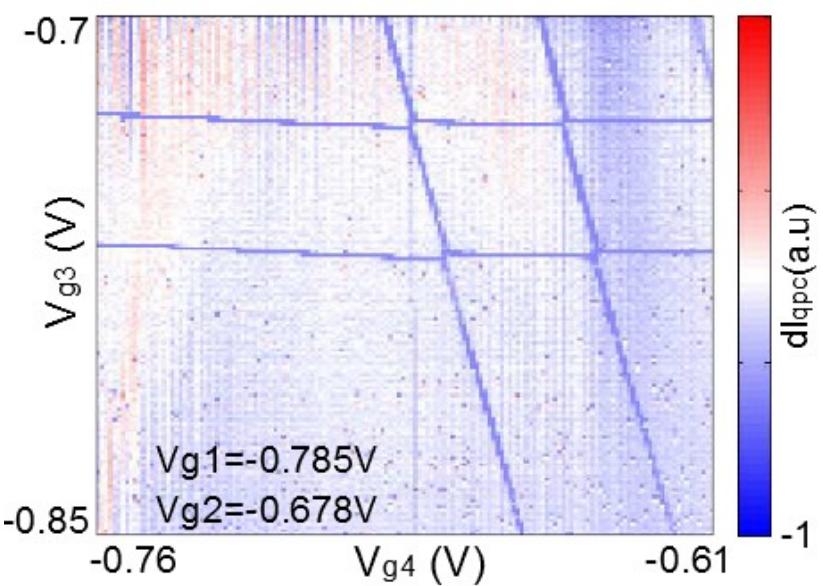
Quadruple quantum dot



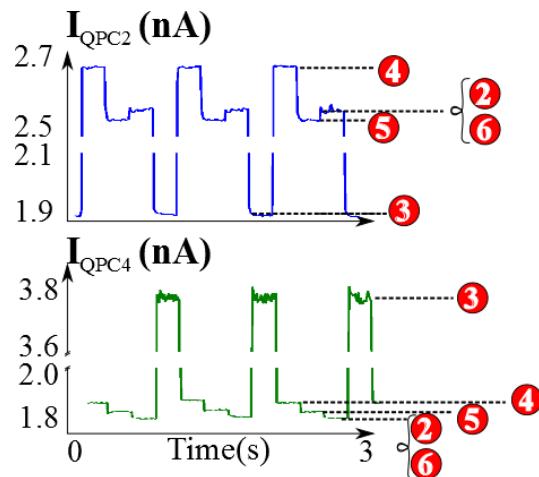
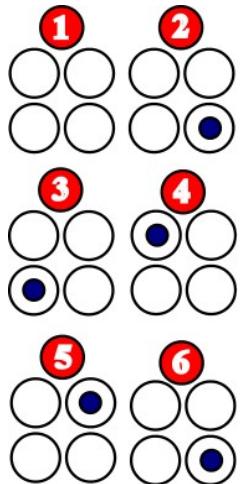
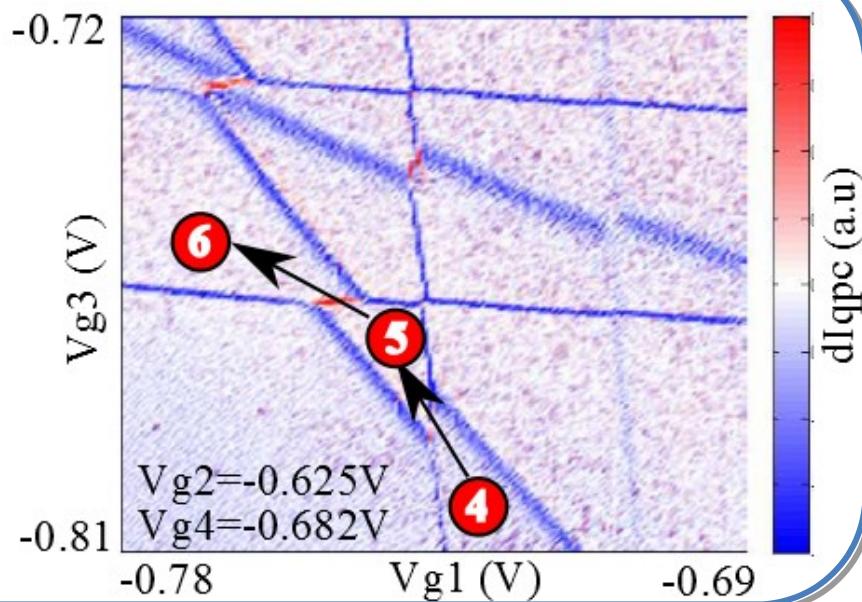
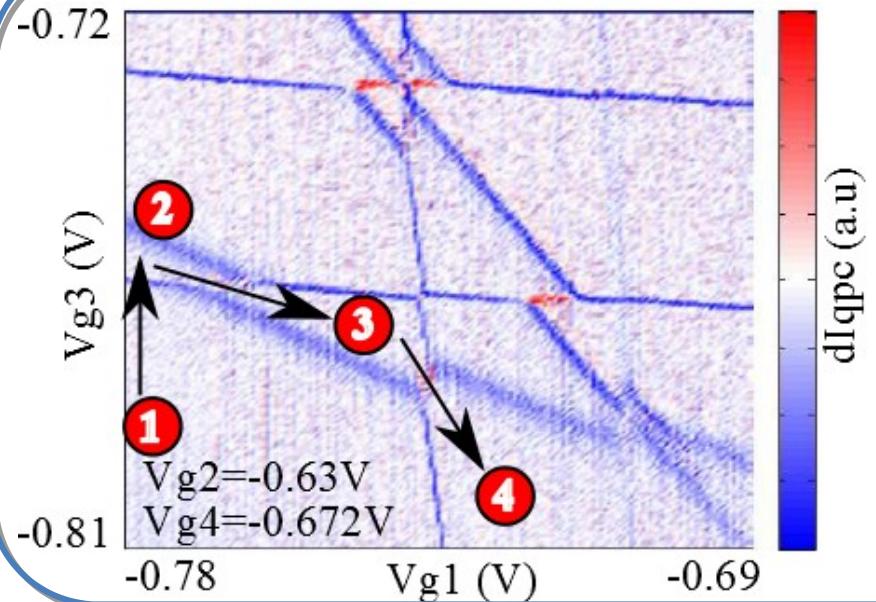
Quadruple quantum dot



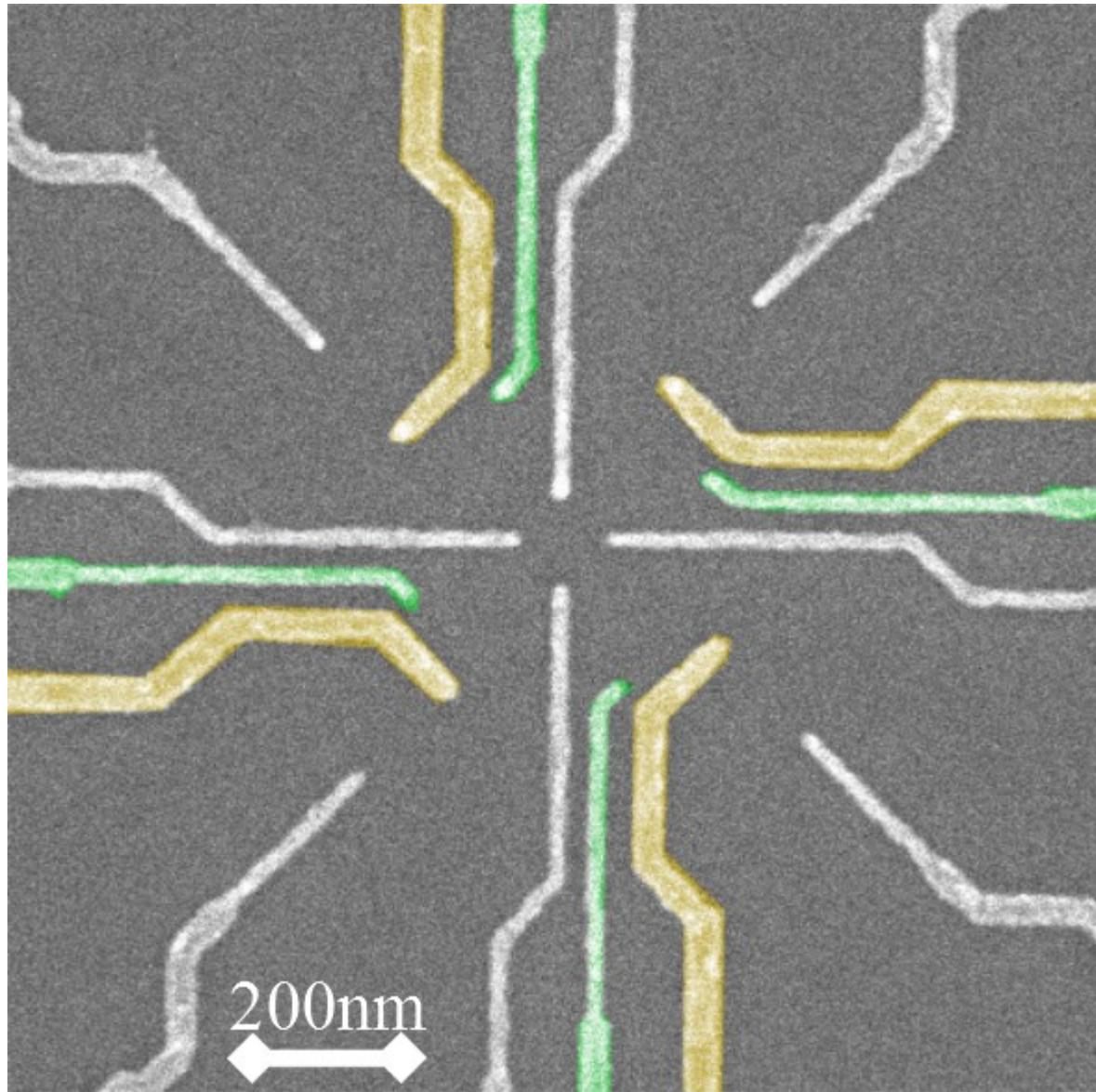
Quadruple quantum dot



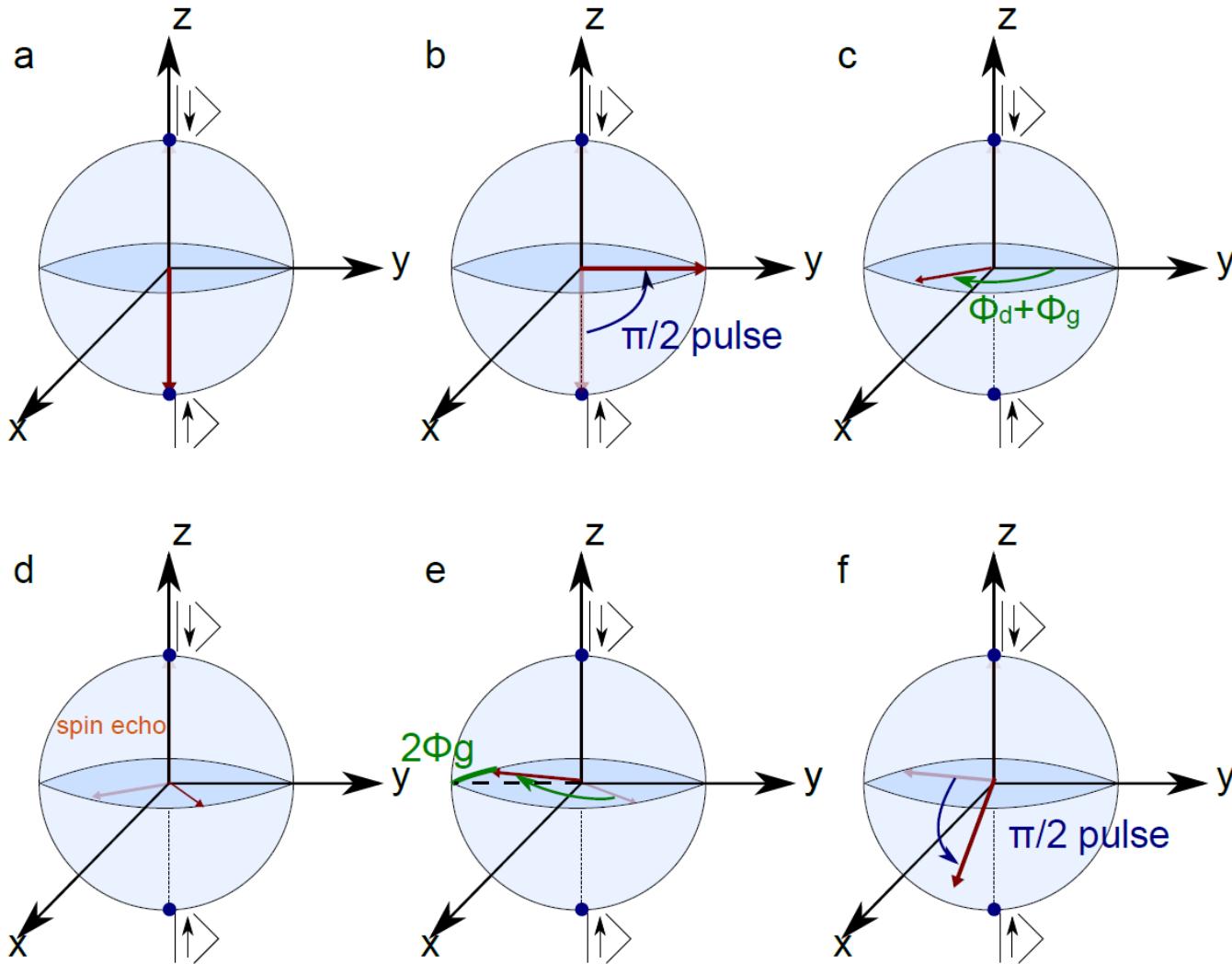
Quadruple quantum dot



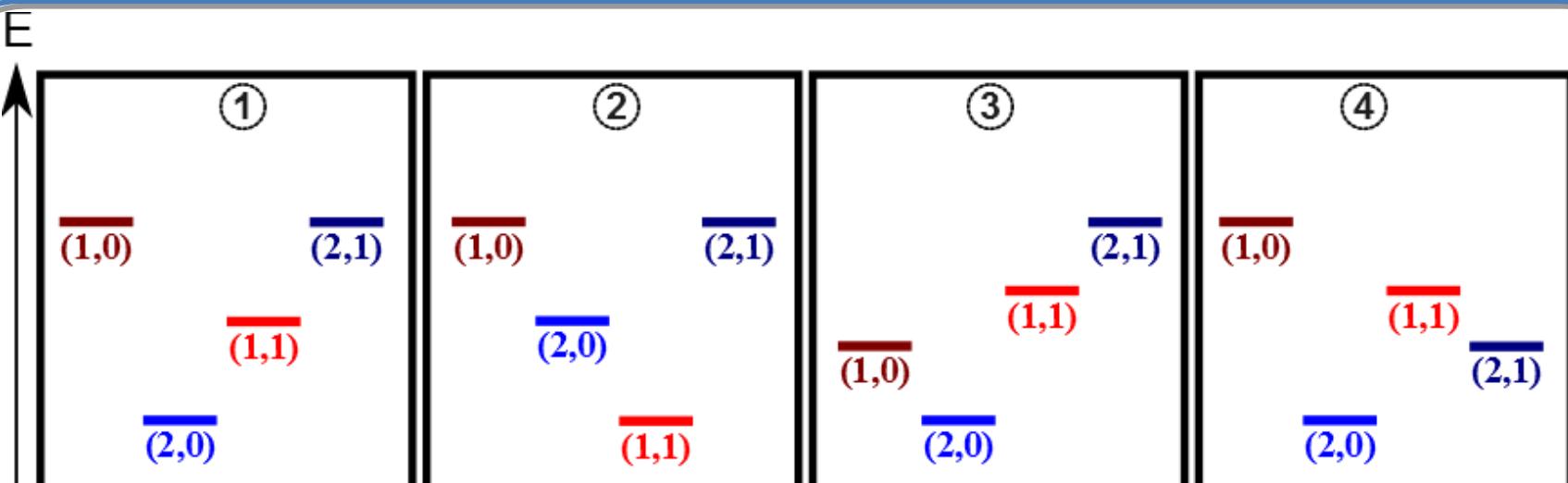
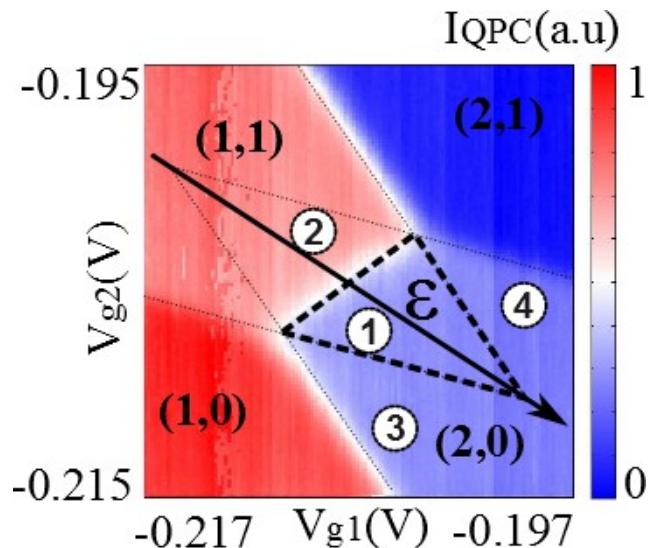
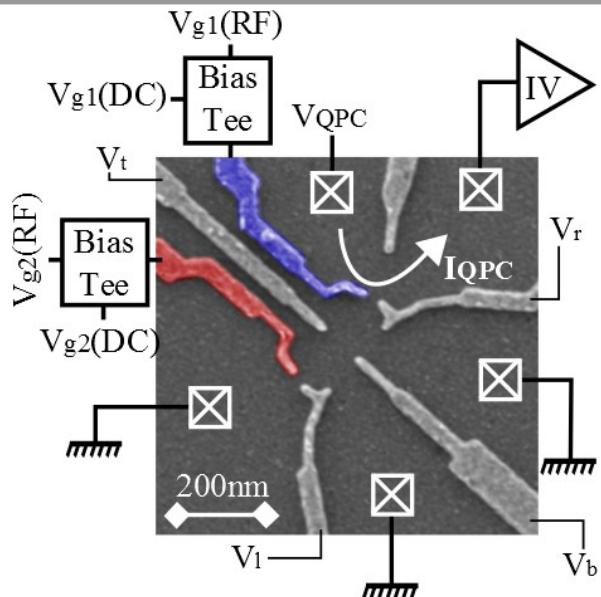
Quadruple quantum dot



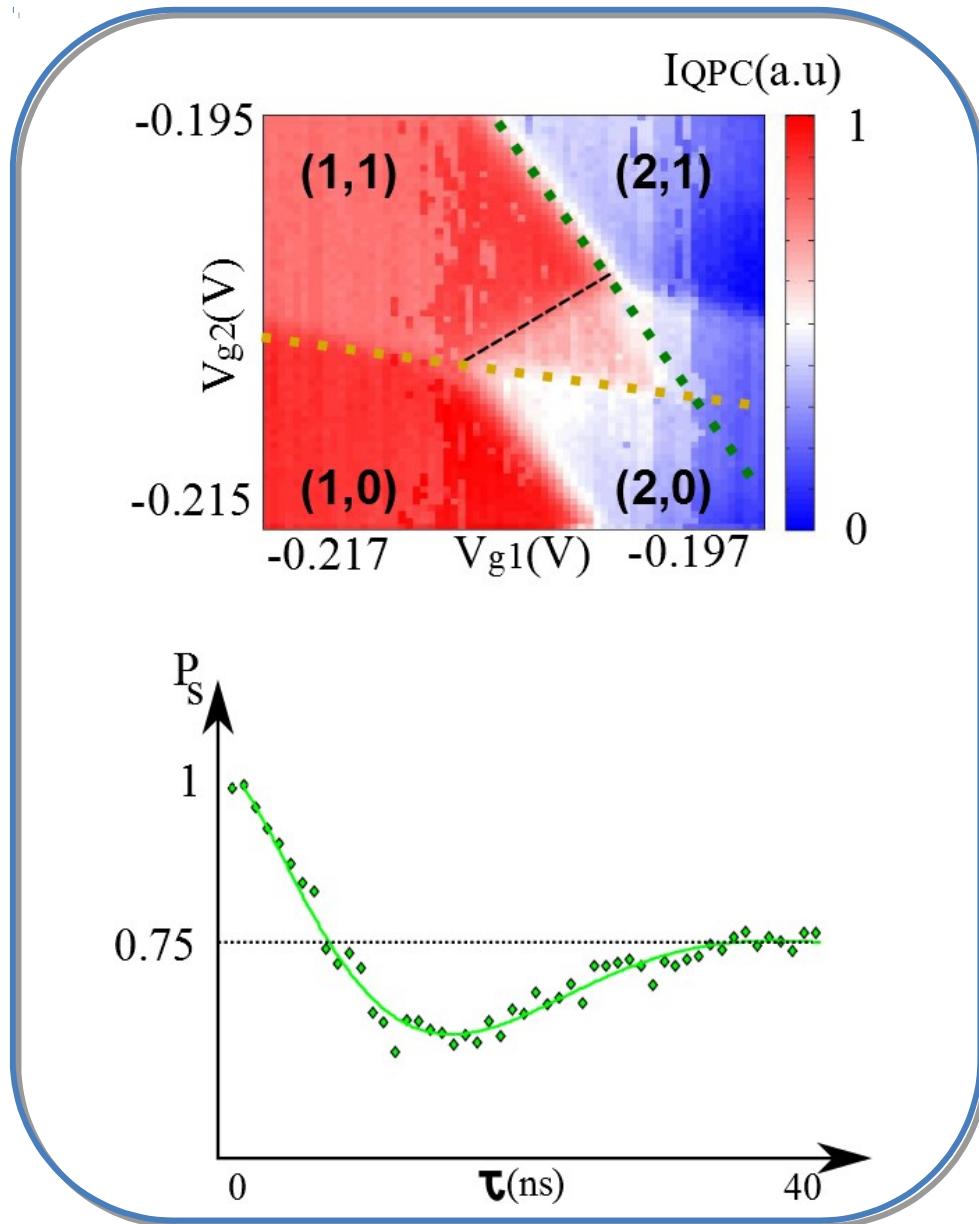
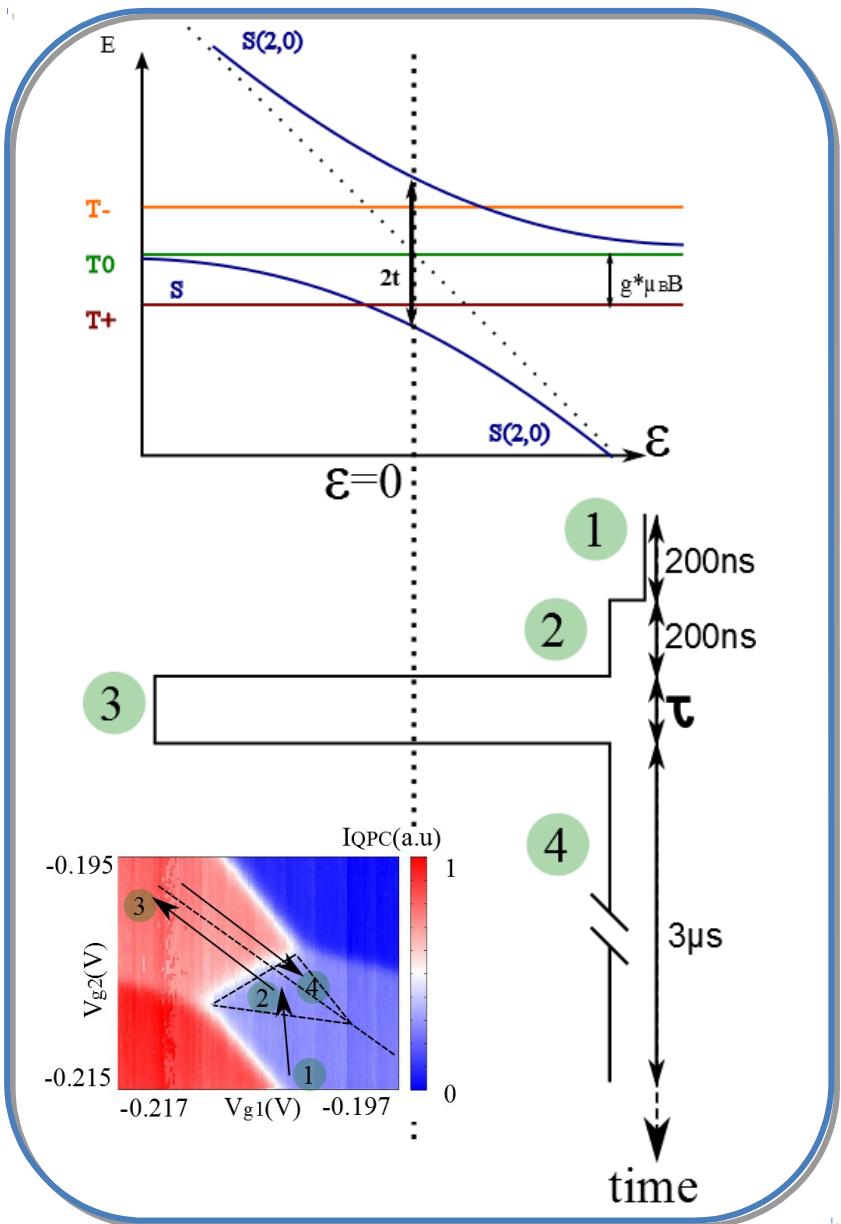
Quadruple quantum dot



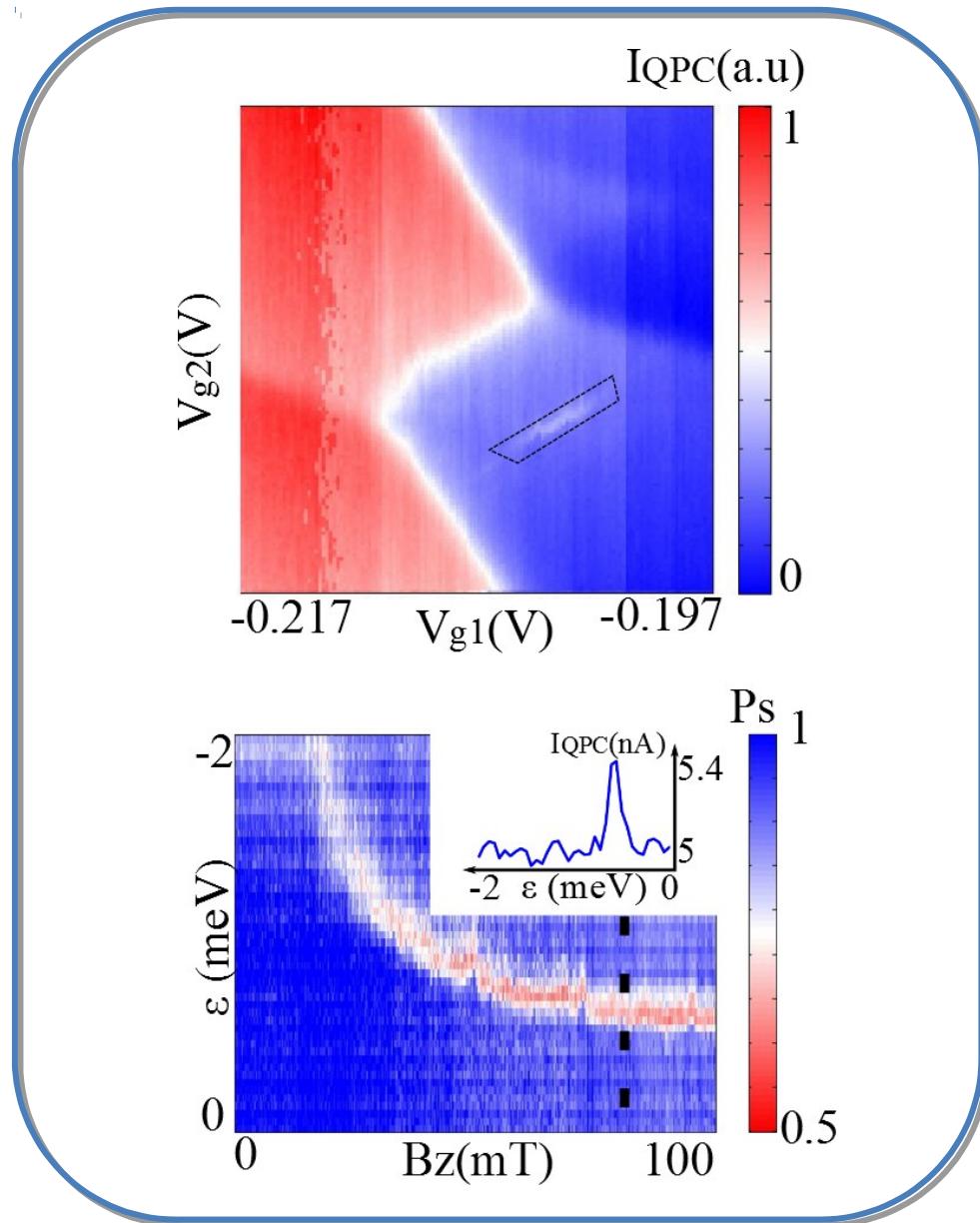
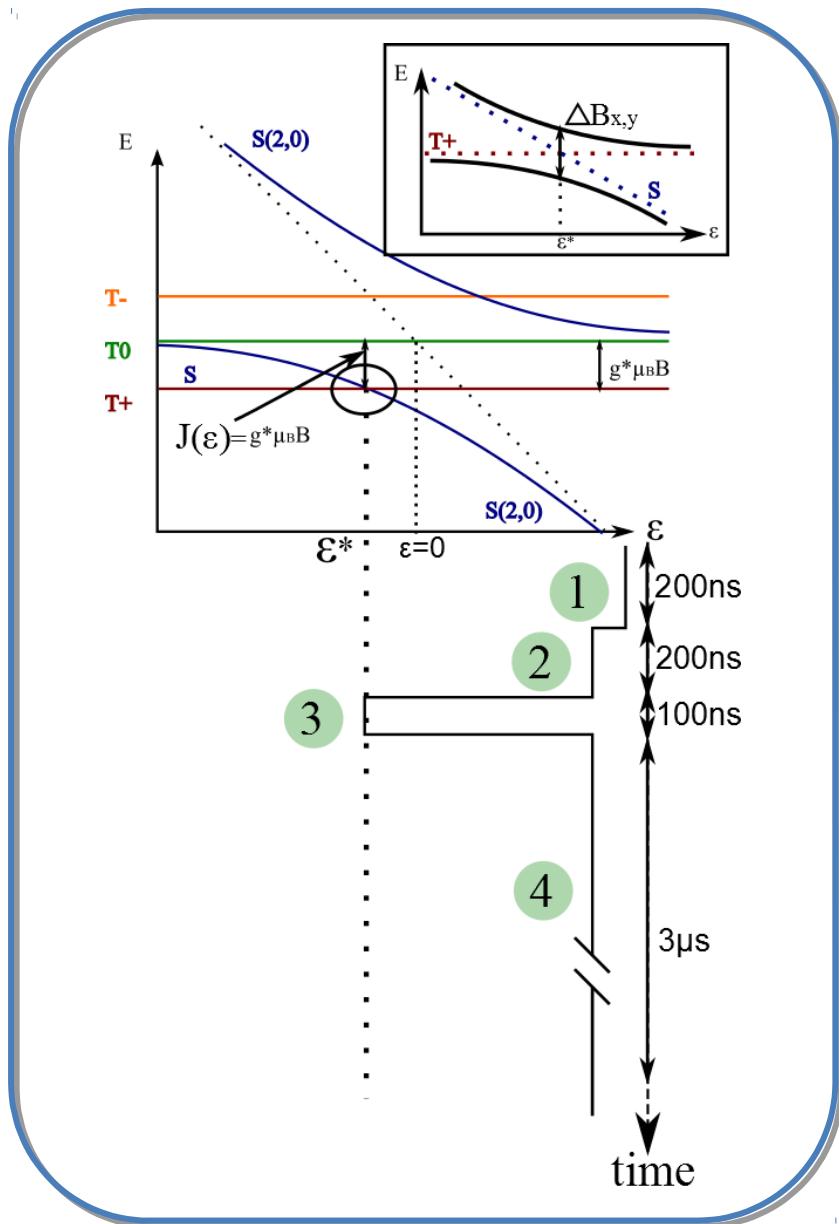
From SWAP to C-phase gate



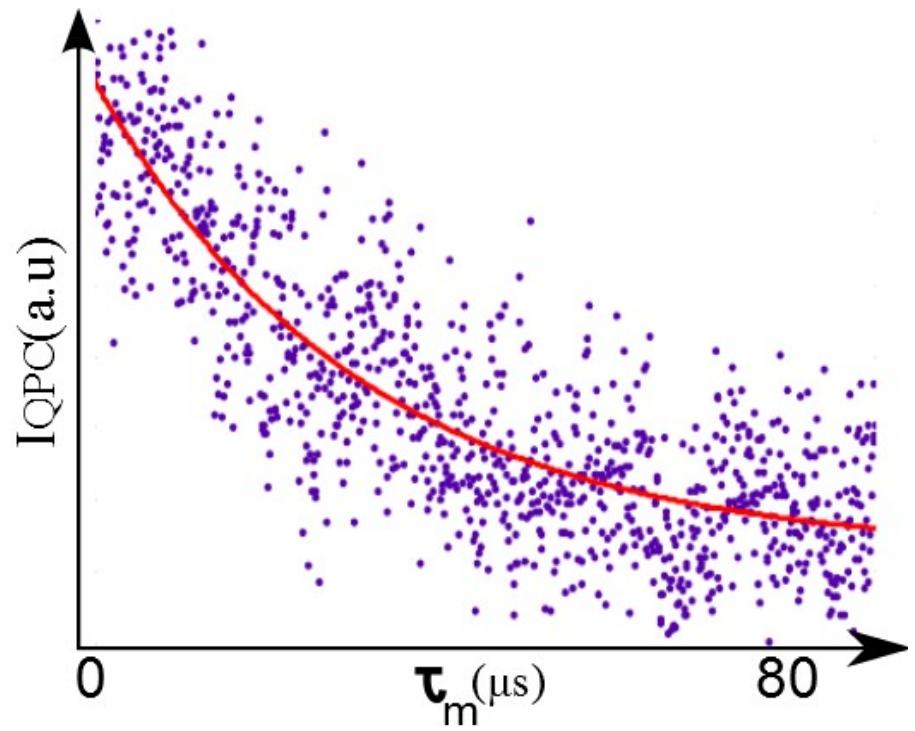
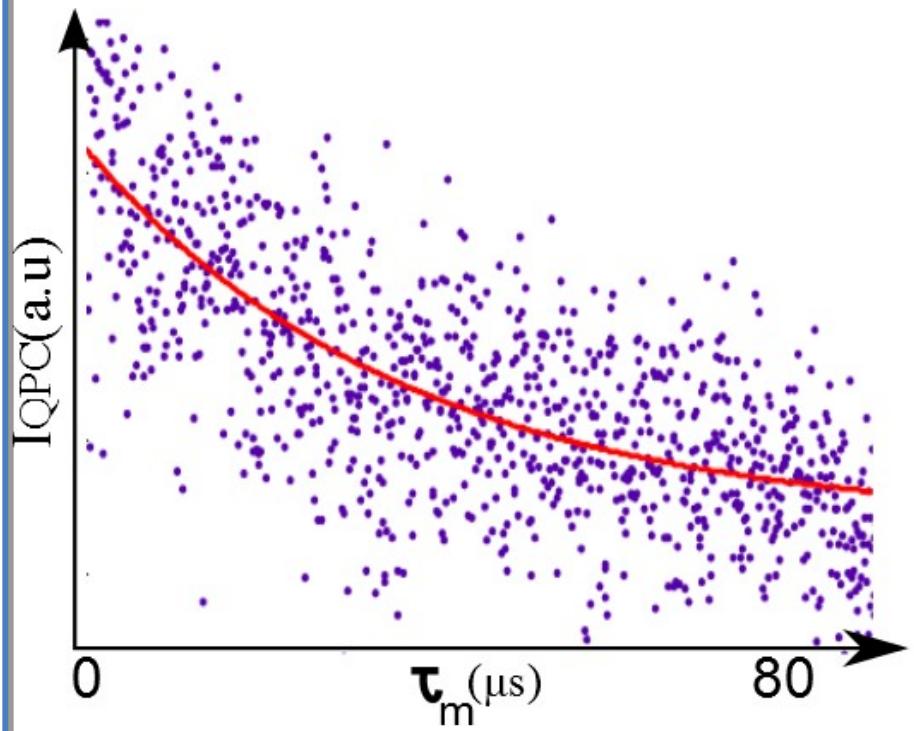
From SWAP to C-phase gate



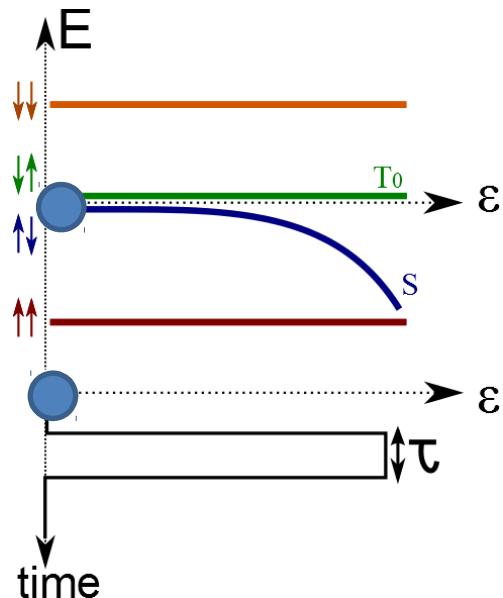
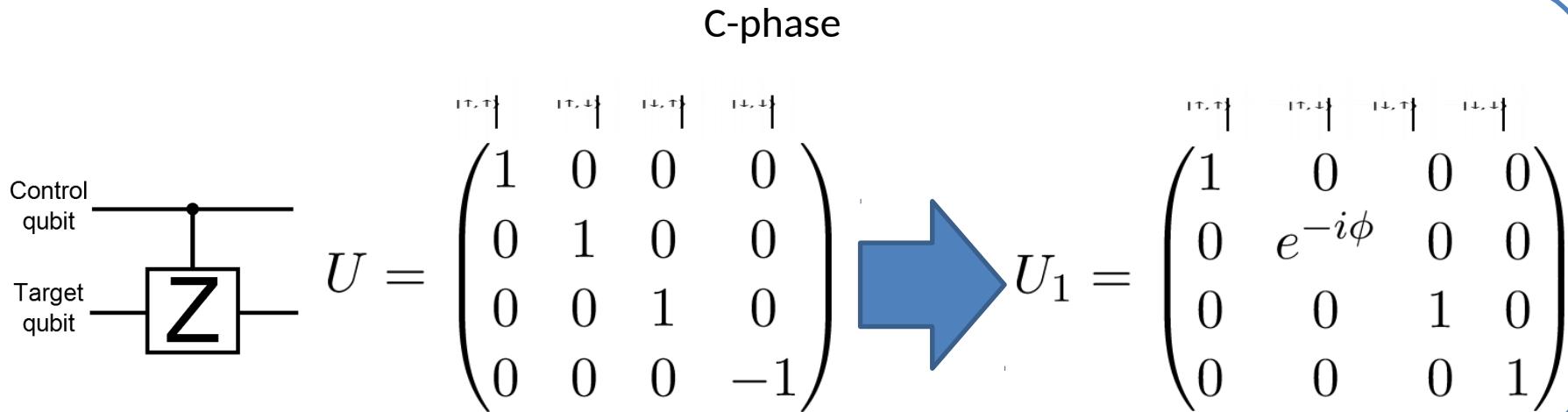
From SWAP to C-phase gate



From SWAP to C-phase gate



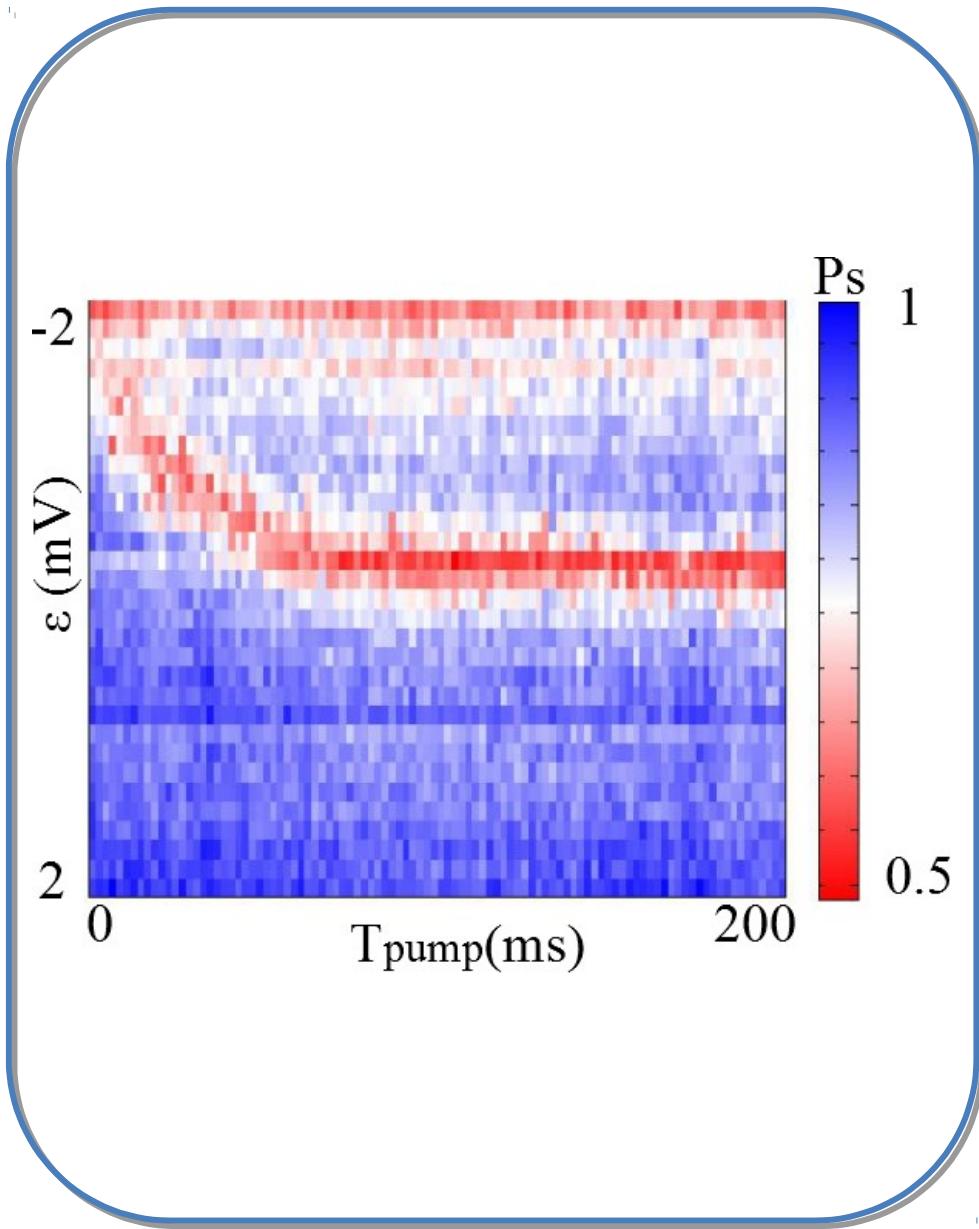
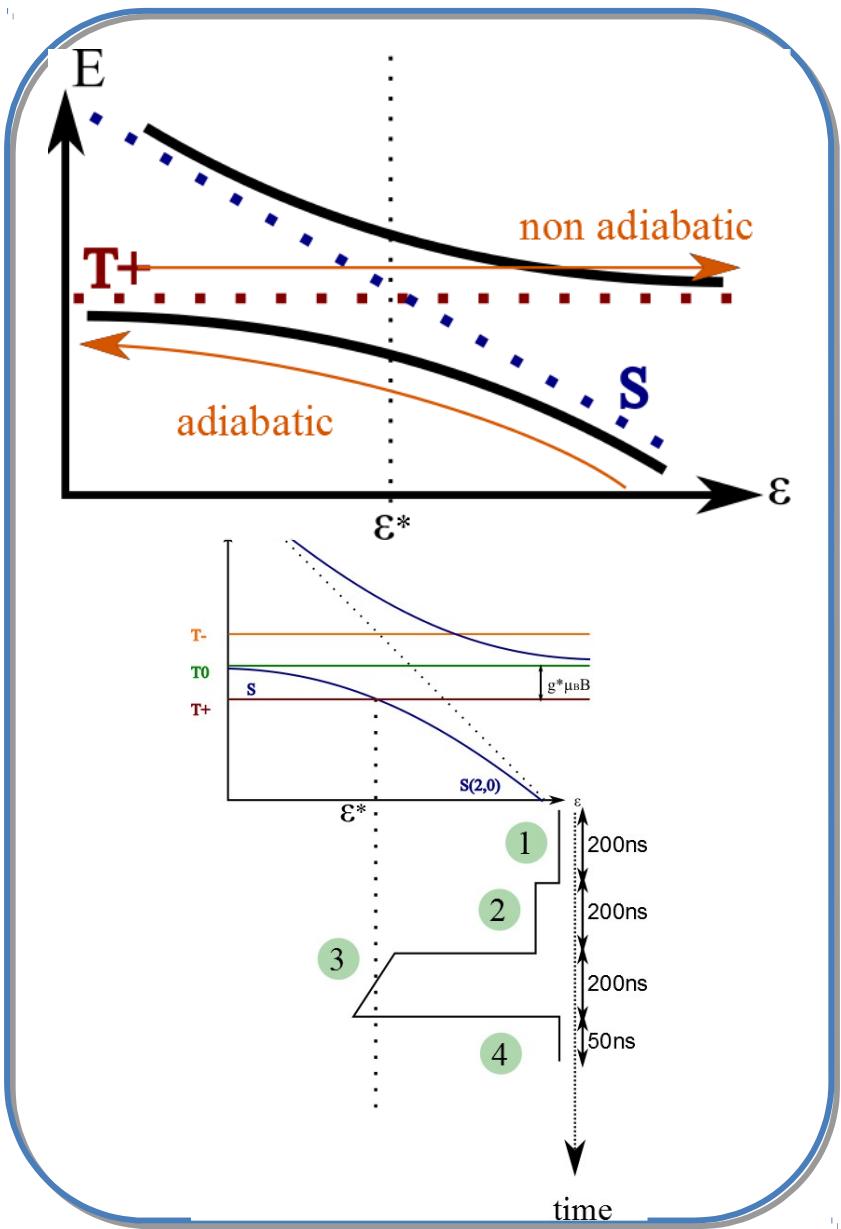
From SWAP to C-phase gate



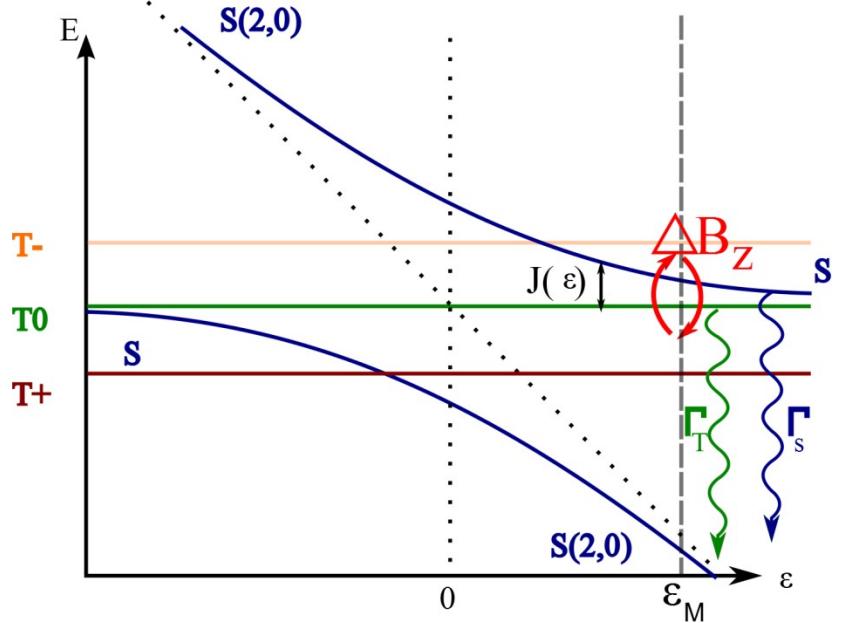
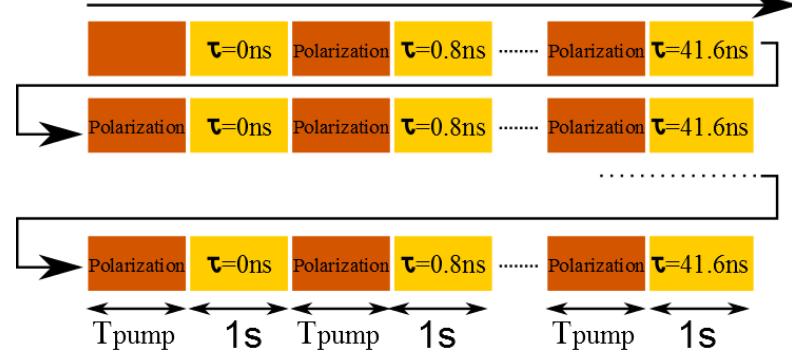
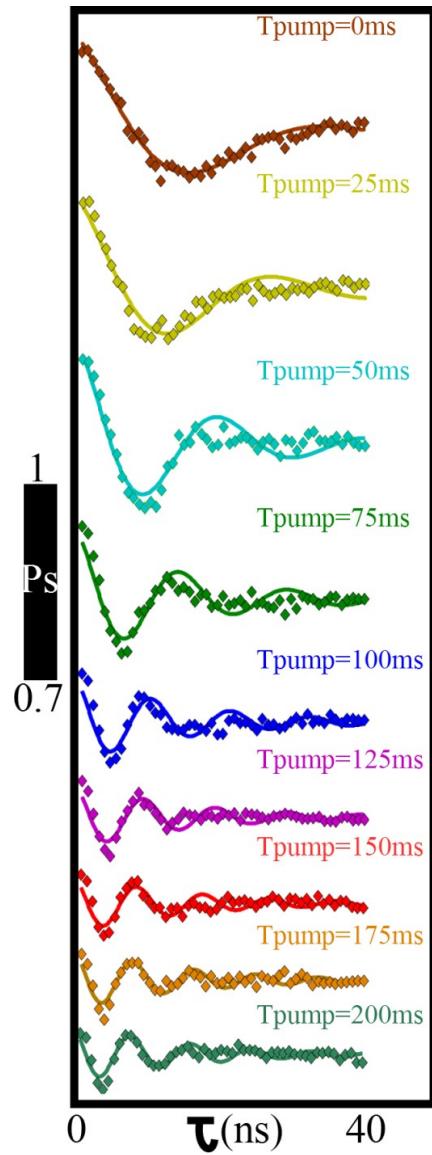
Adiabatic pulse vs ΔB_z

$$U_1 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{-i\phi} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

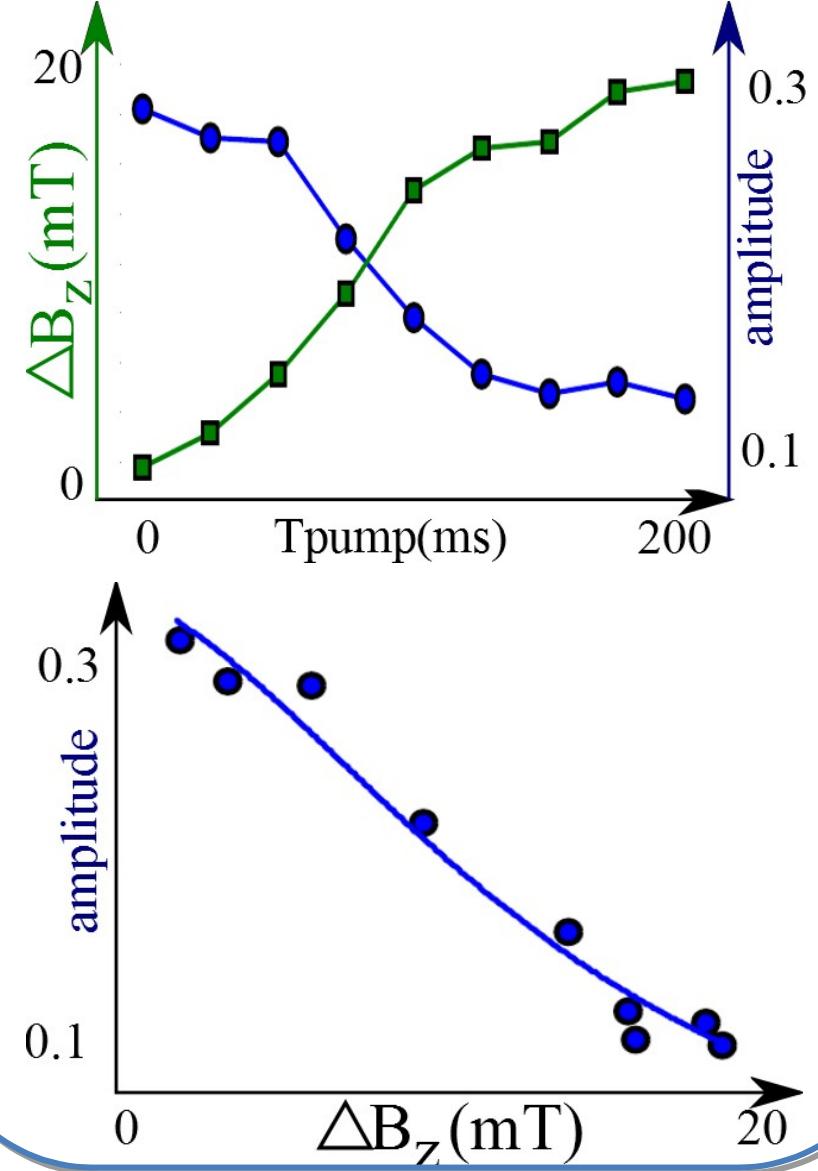
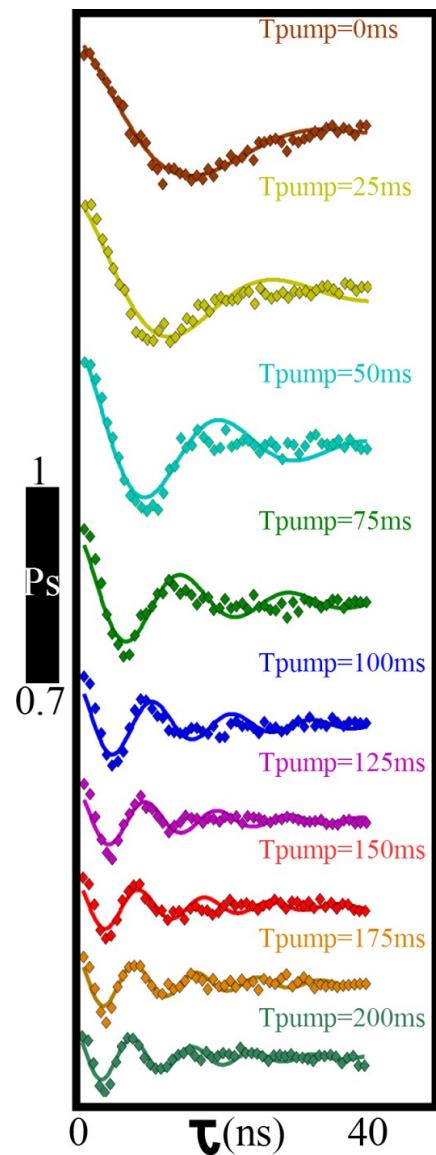
From SWAP to C-phase gate



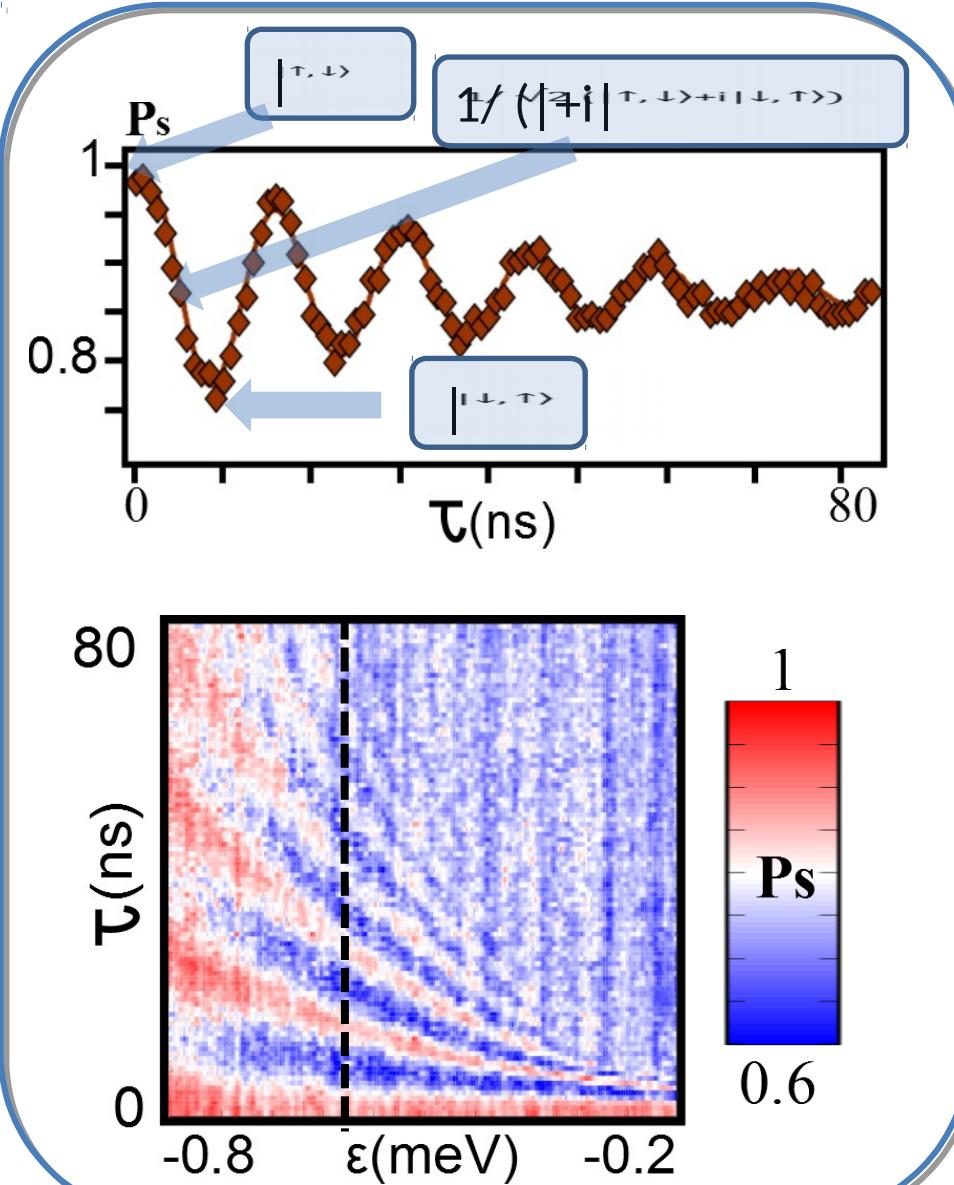
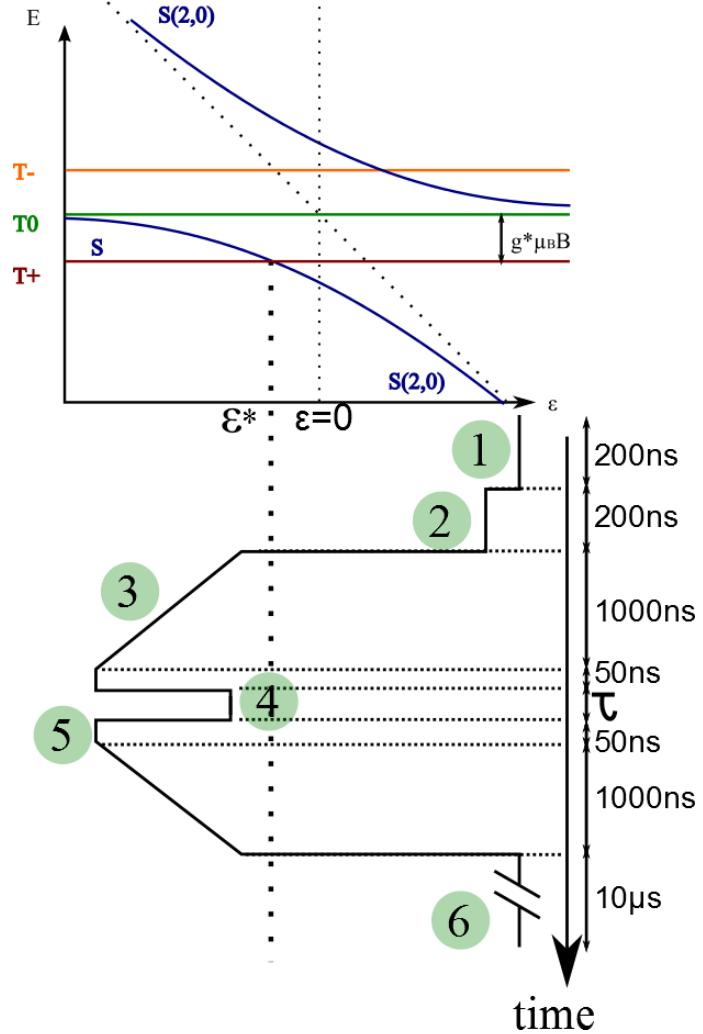
From SWAP to C-phase gate



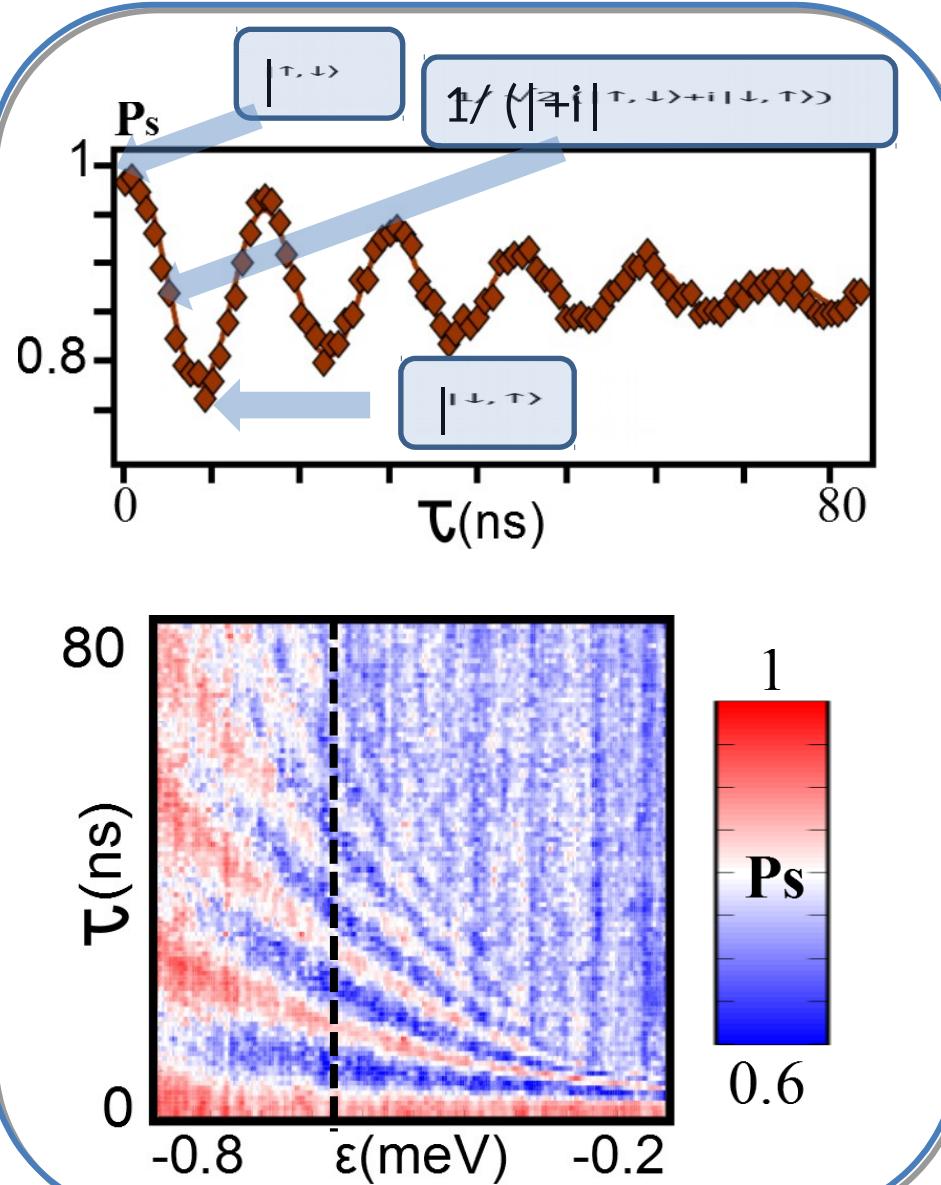
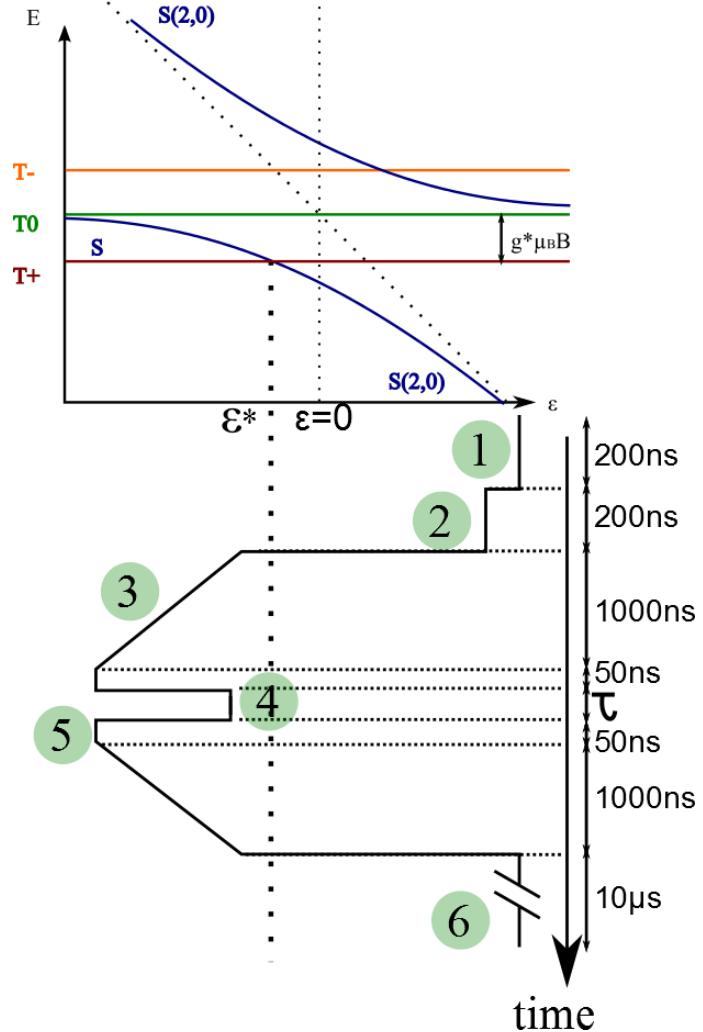
From SWAP to C-phase gate



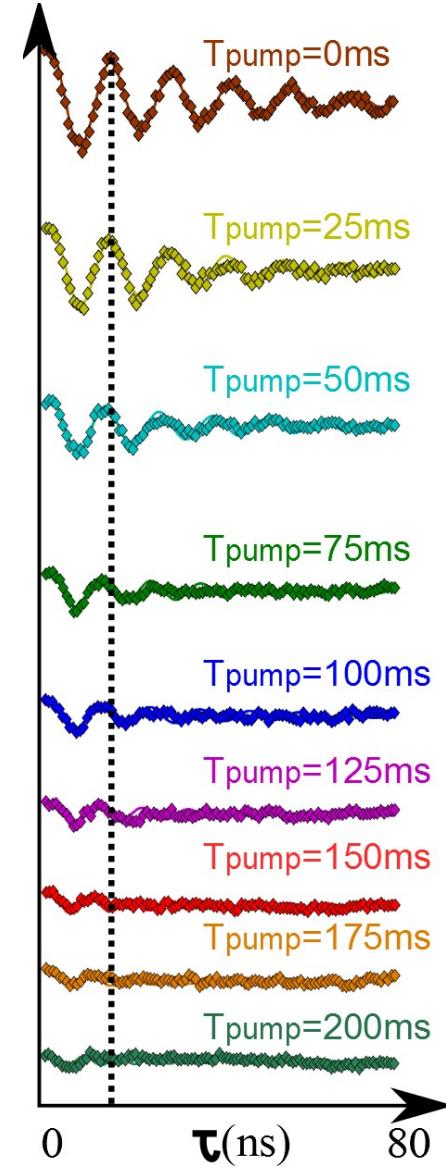
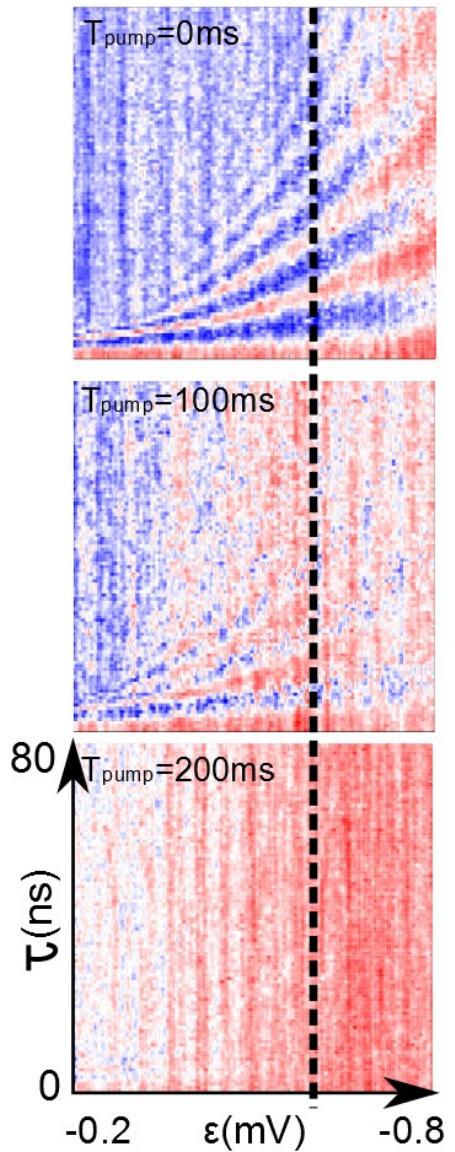
From SWAP to C-phase gate



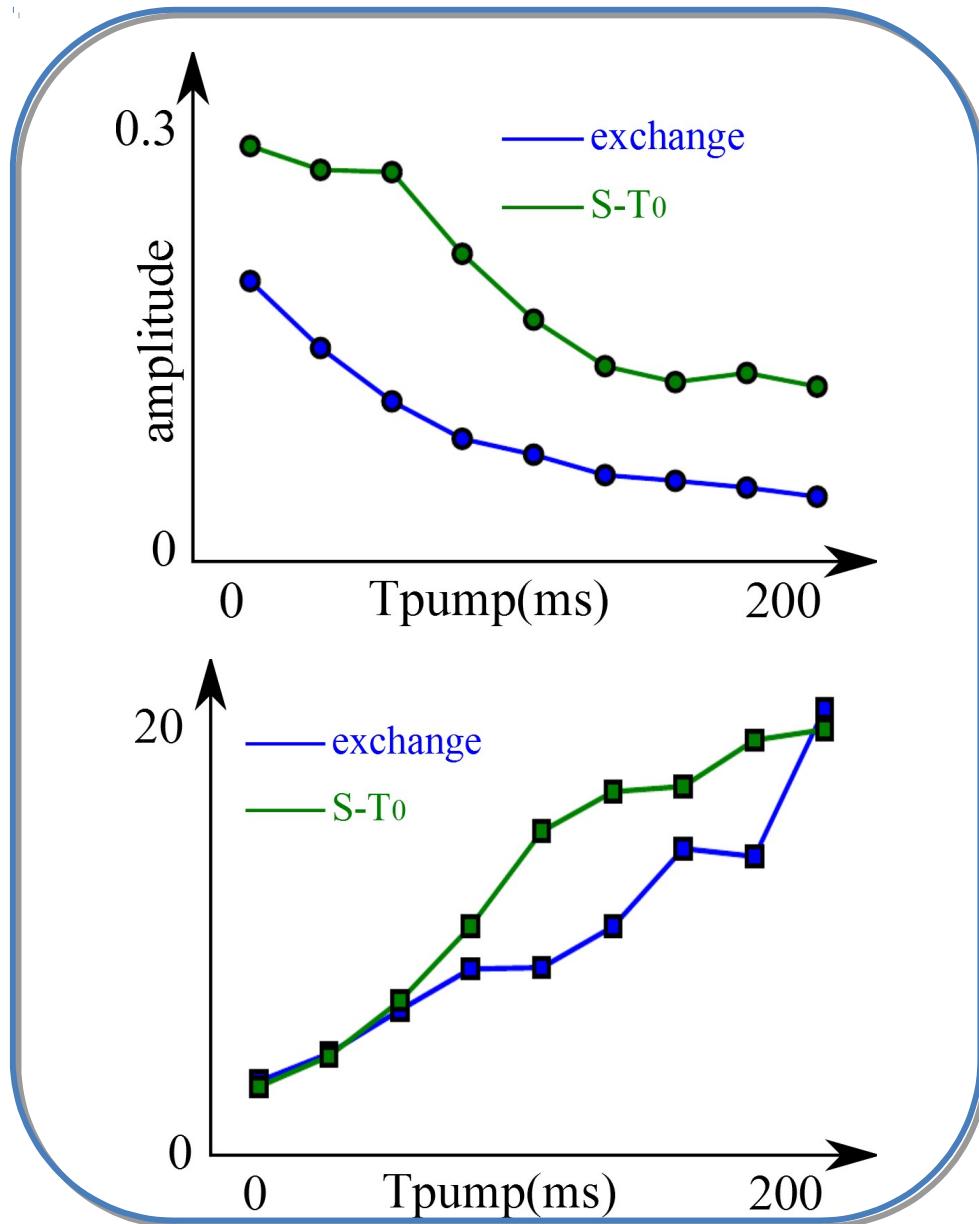
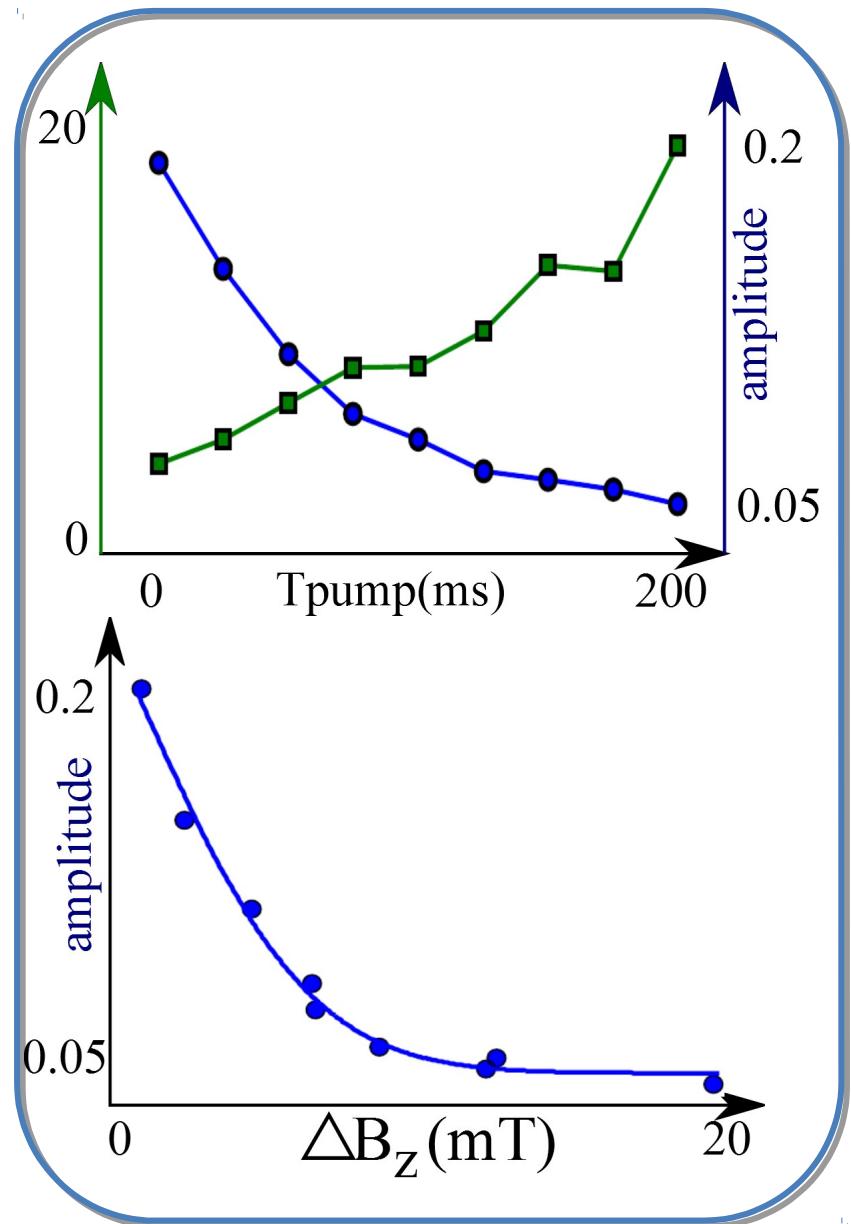
From SWAP to C-phase gate



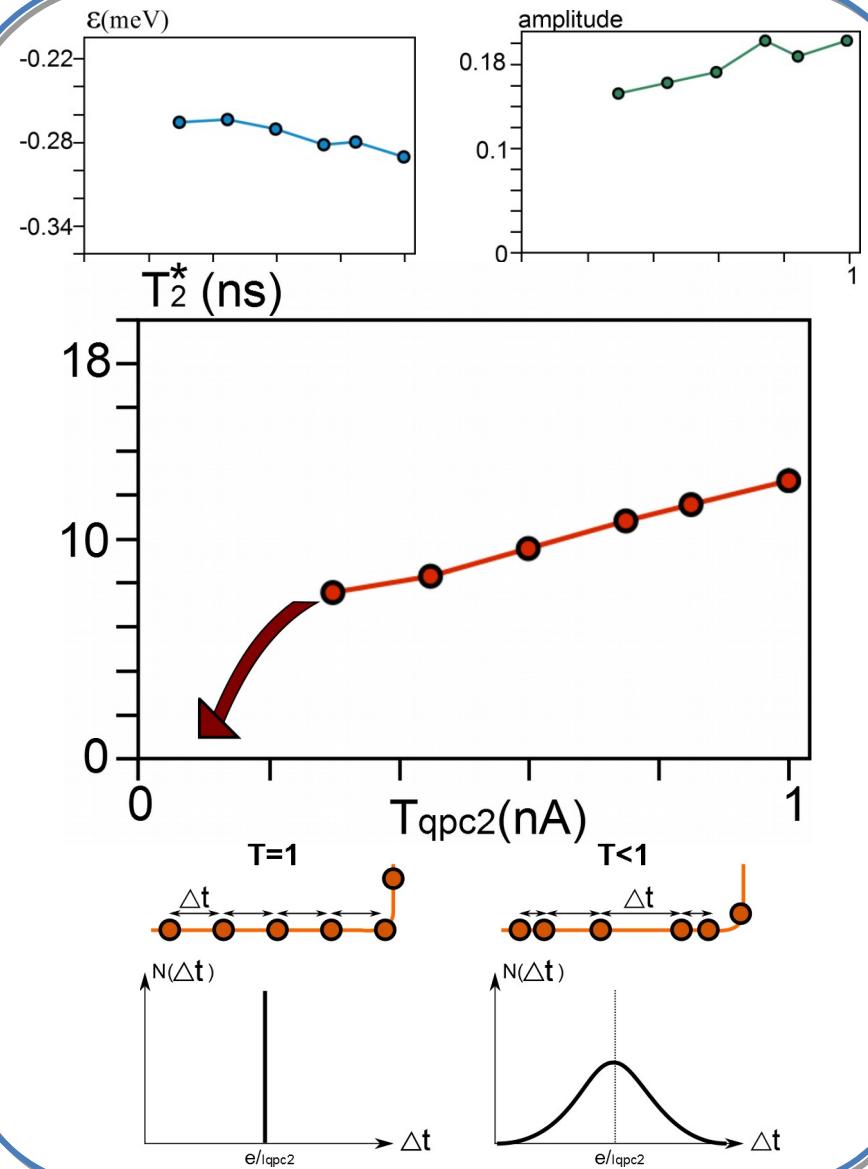
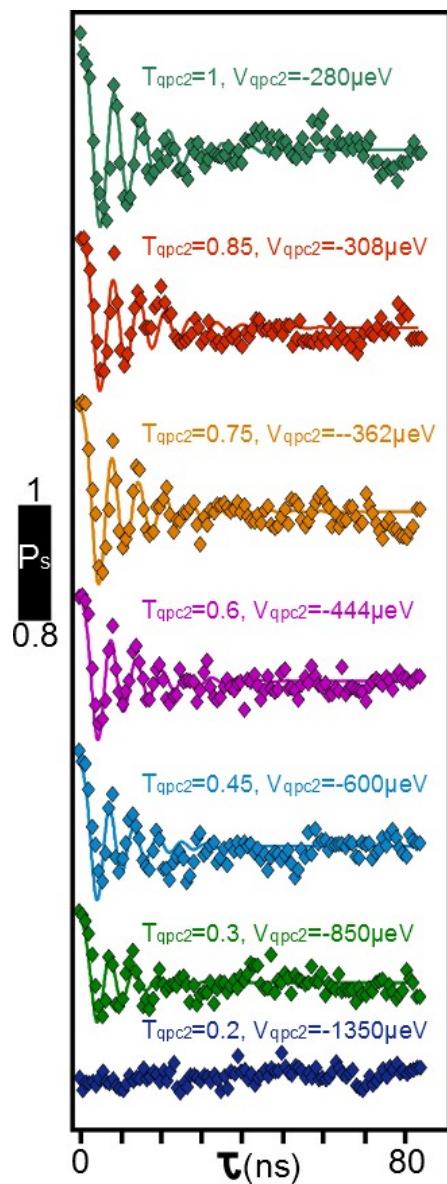
From SWAP to C-phase gate



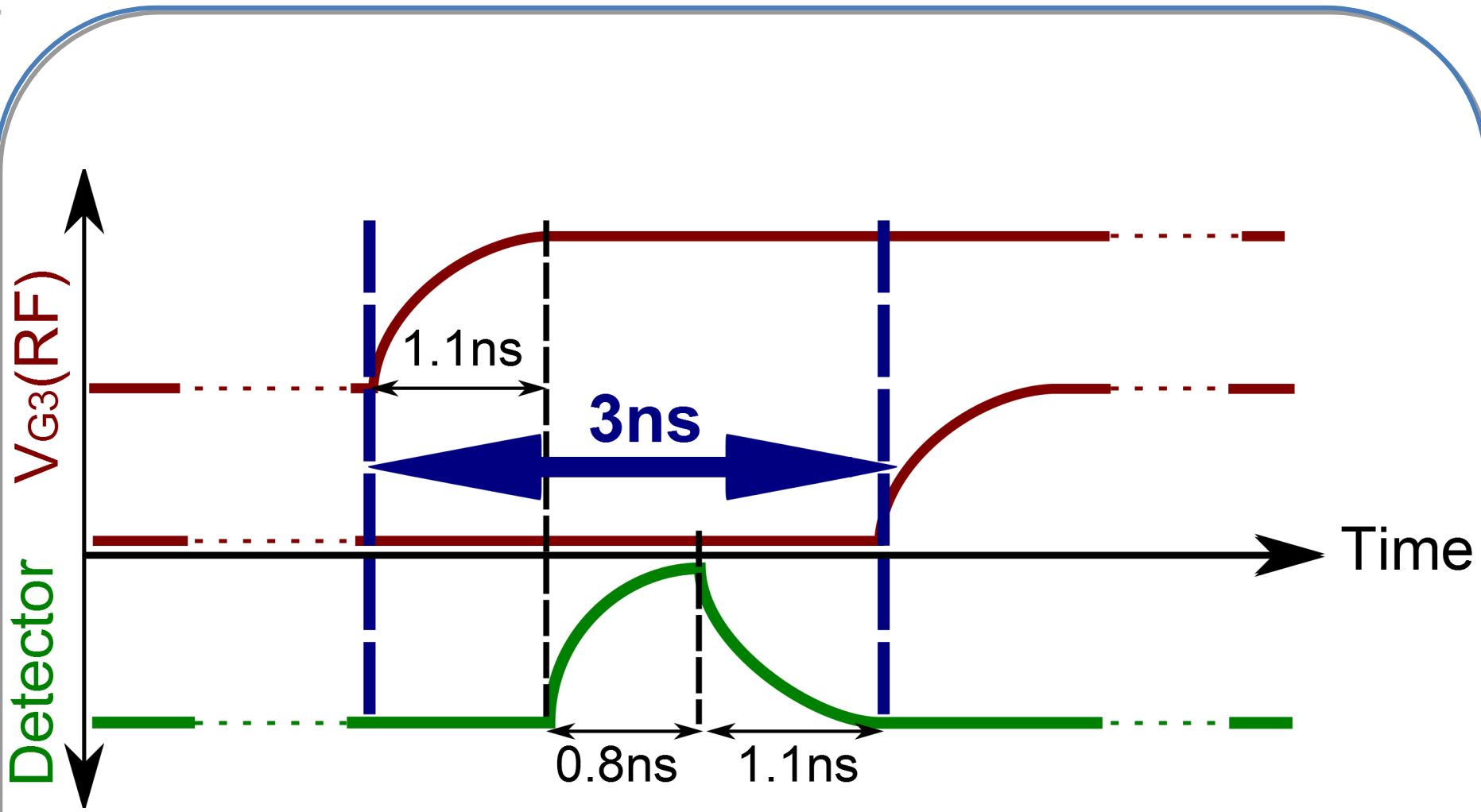
From SWAP to C-phase gate



Stochastic events



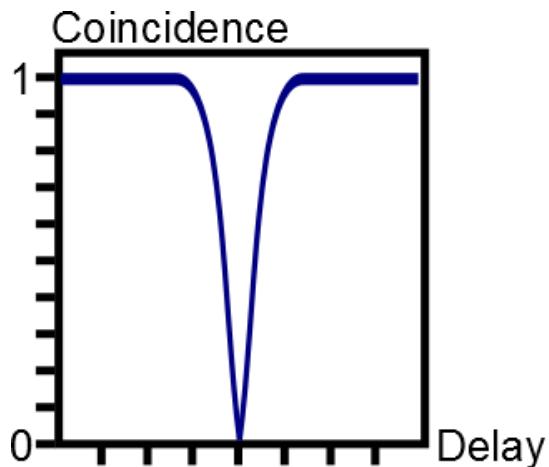
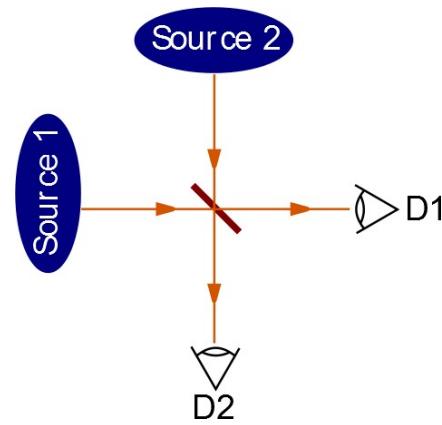
Peak broadening



Quantum optics with electrons

Hanbury Brown and Twiss experiment
with photons :

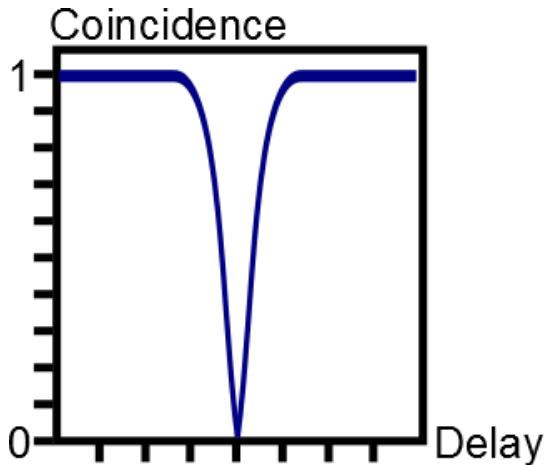
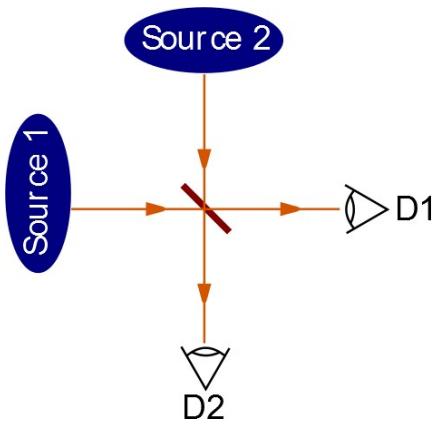
Brown and Twiss, Nature (1956)



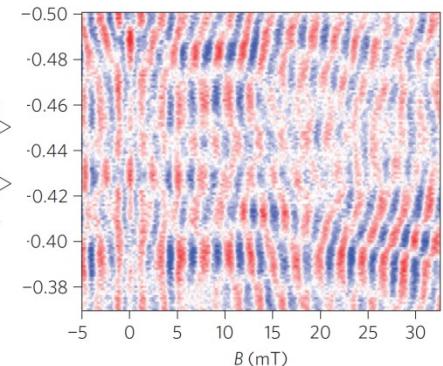
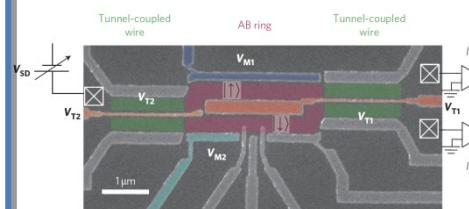
Quantum optics with electrons

Hanbury Brown and Twiss experiment with photons :

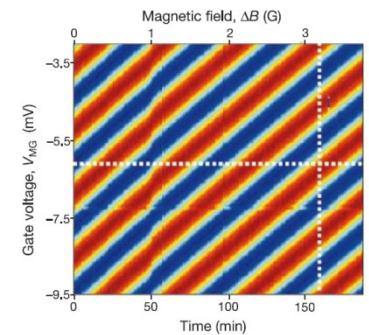
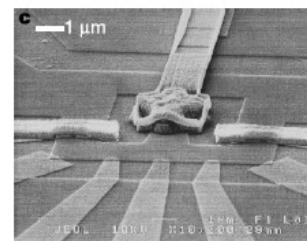
Brown and Twiss, Nature (1956)



Quantum optics with electrons :
Yamamoto et al, Nature Nano (2012)



Ji et al, Nature (2003)

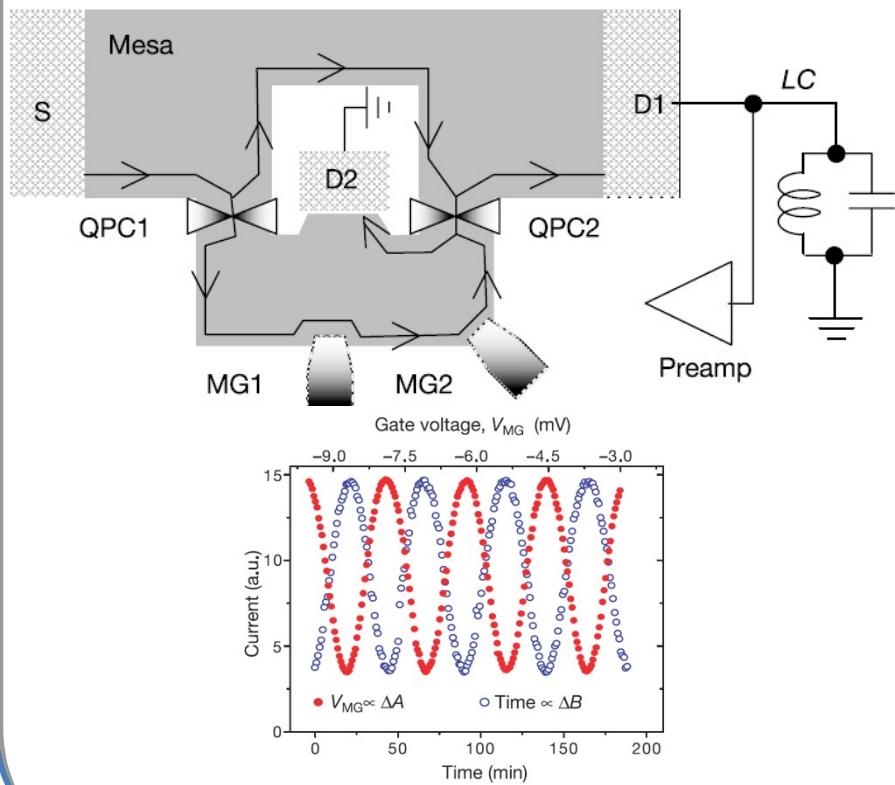


I_φ $2\sim 20 \mu\text{m}$ m
Rouleau et al, PRL (2008)

Singlet-Triplet qubit as a single electron detector

Detection principle :

Detection done by means of the current generated by an ensemble of electrons

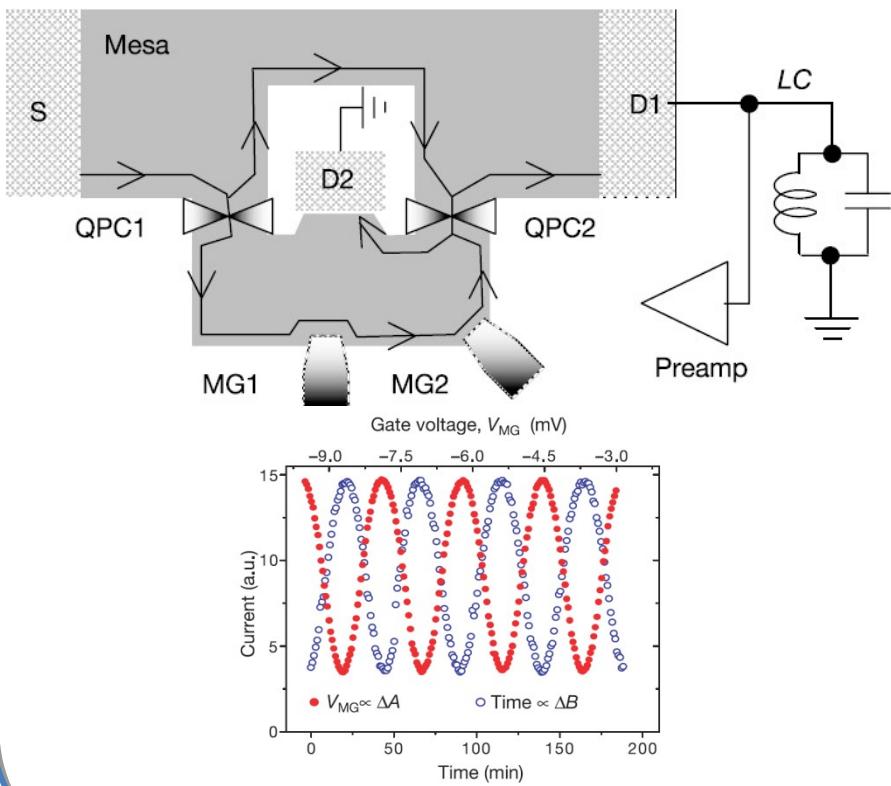


Ji et al, Nature (2003)

Singlet-Triplet qubit as a single electron detector

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Detection done by means of the current generated by an ensemble of electrons

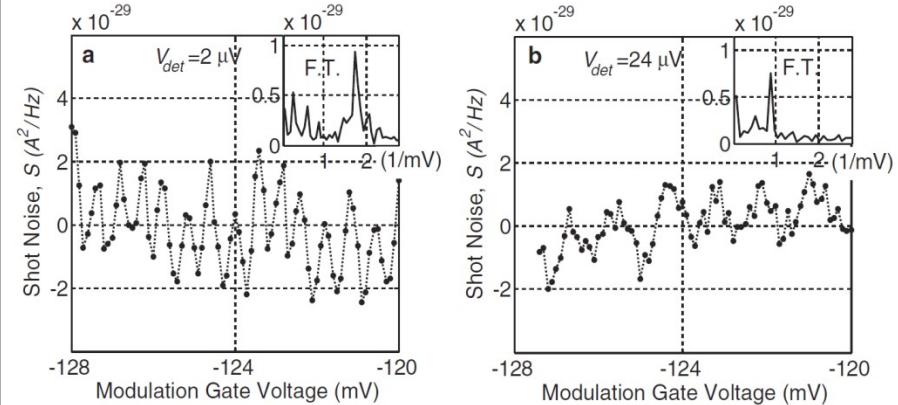


Ji et al, Nature (2003)

Single electron detection :

Not yet engineered !

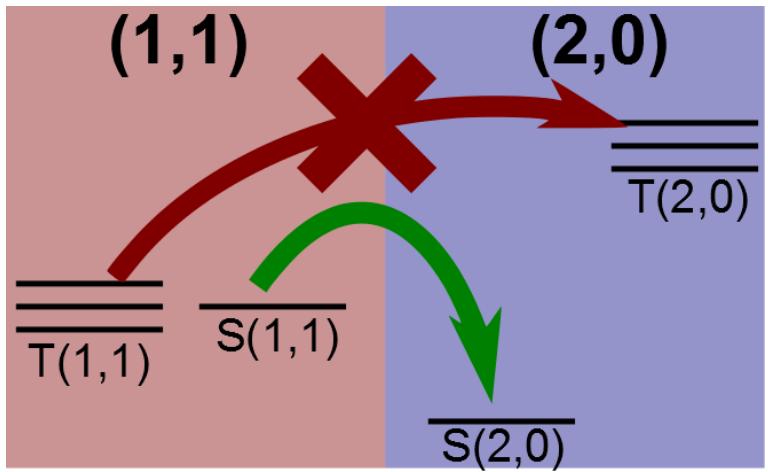
Electron correlations encrypted in the current noise



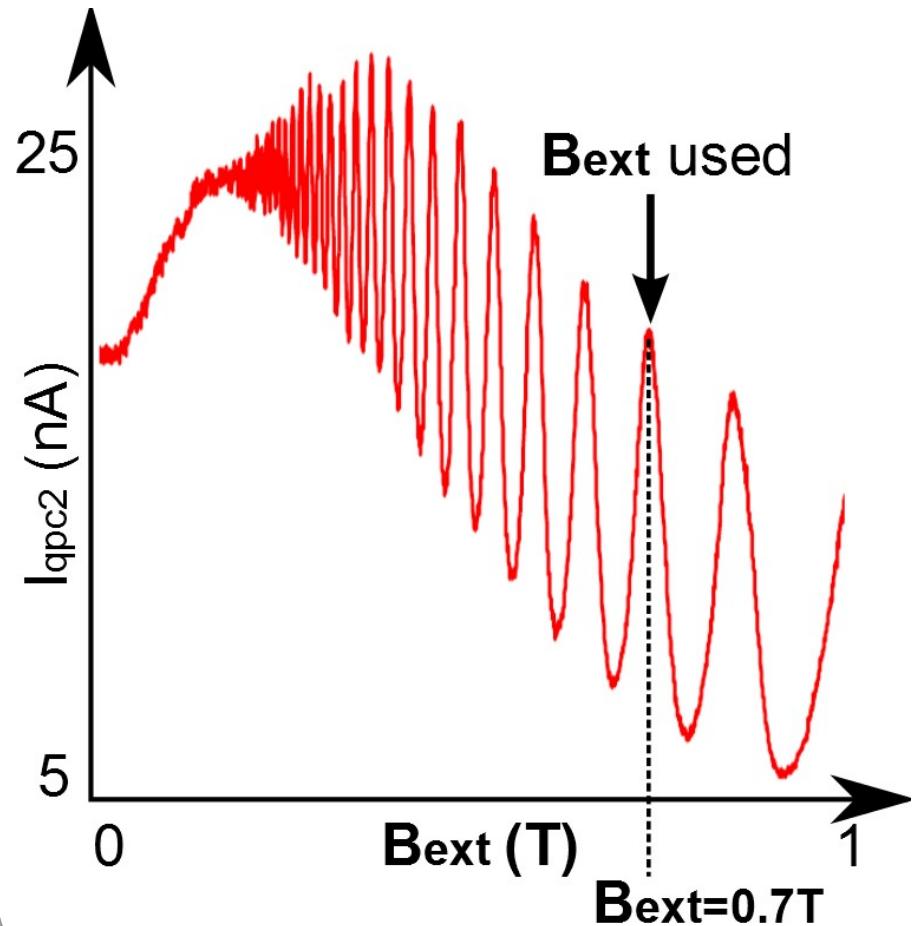
Neder et al, PRL (2007)

Quantum Hall regime and spin measurements

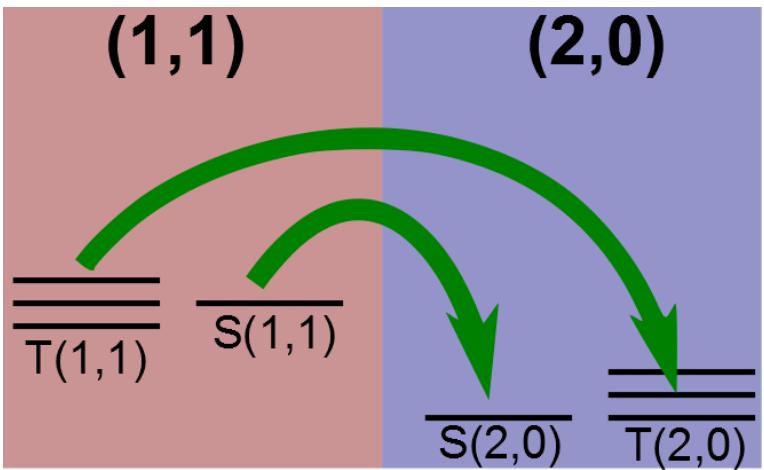
Spin measurements at low magnetic fields



Shubnikov de Haas oscillations



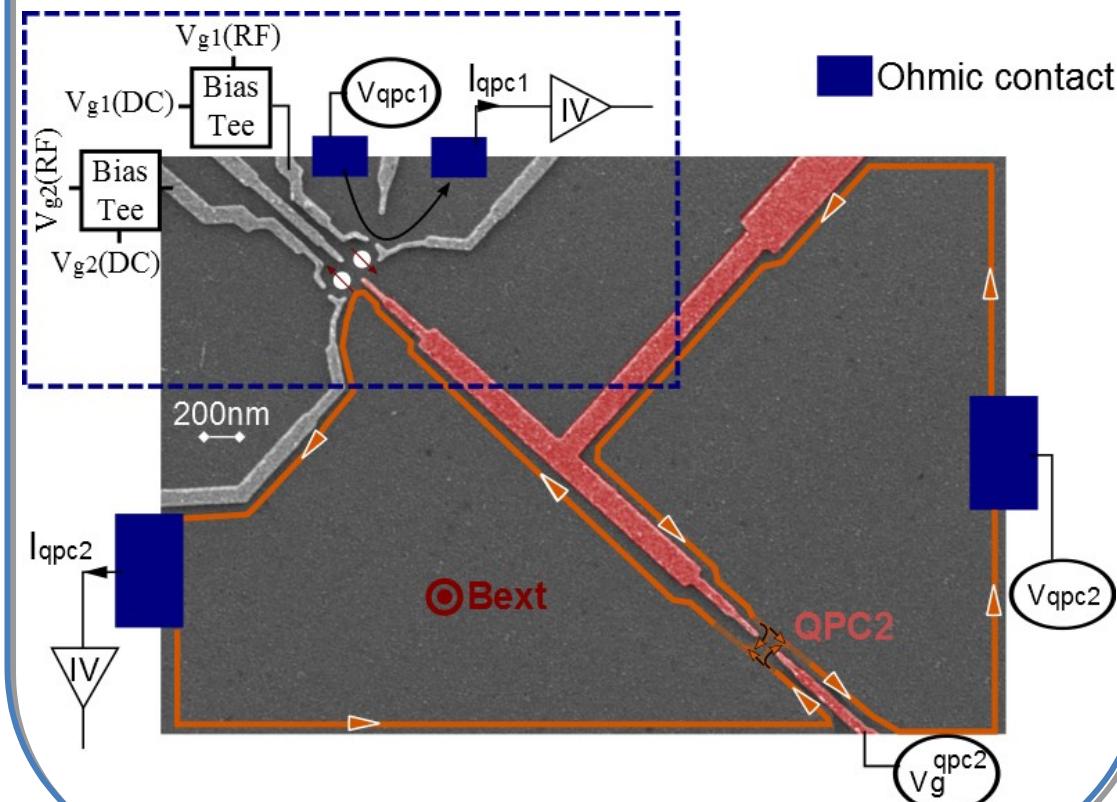
Spin measurements at high magnetic fields



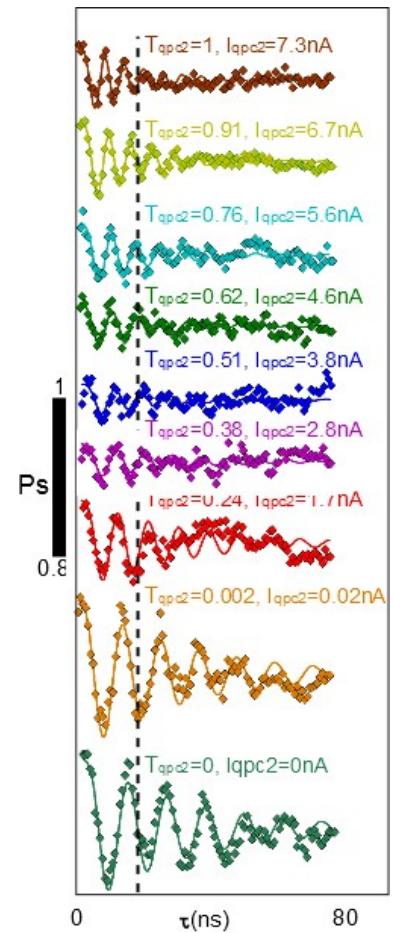
Detector visibility

$$V_{QPC2} = -1\text{meV}$$

T_{QPC2} is changed in order to « partitione » the edge potential

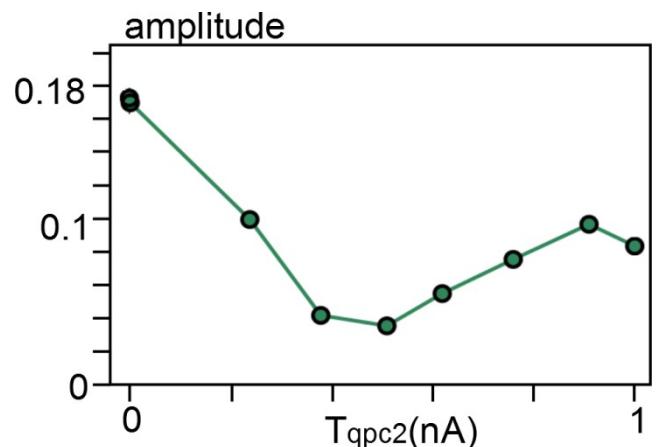


The amplitude decays until $T_{QPC2}=0,5$ and then increases

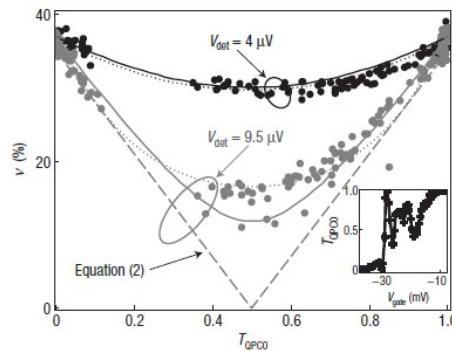
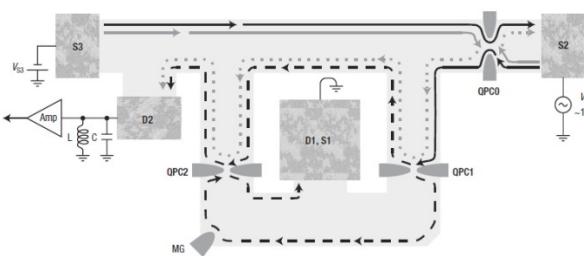


Detector visibility

Partitioning of the edge potential

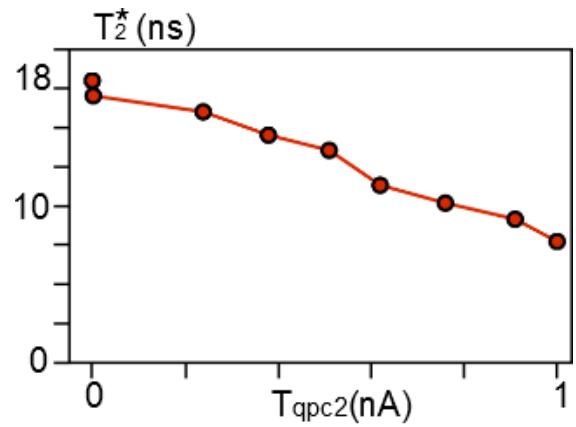
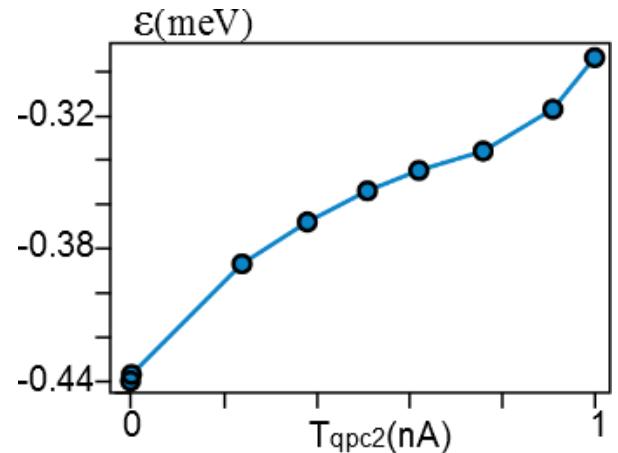


Scrambling of the detector interferences



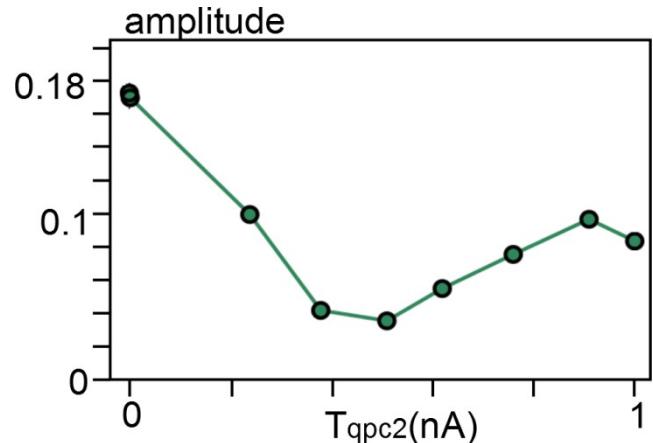
Neder et al, Nat Phys (2007)
Rouleau et al, PRB (2007)

$$\mathcal{E}_T = T \cdot \mathcal{E}_{T=1} + (1 - T) \cdot \mathcal{E}_{T=0}$$

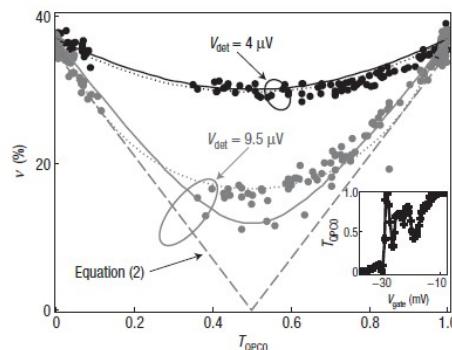
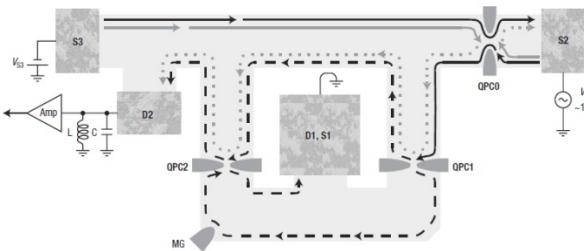


Detector visibility

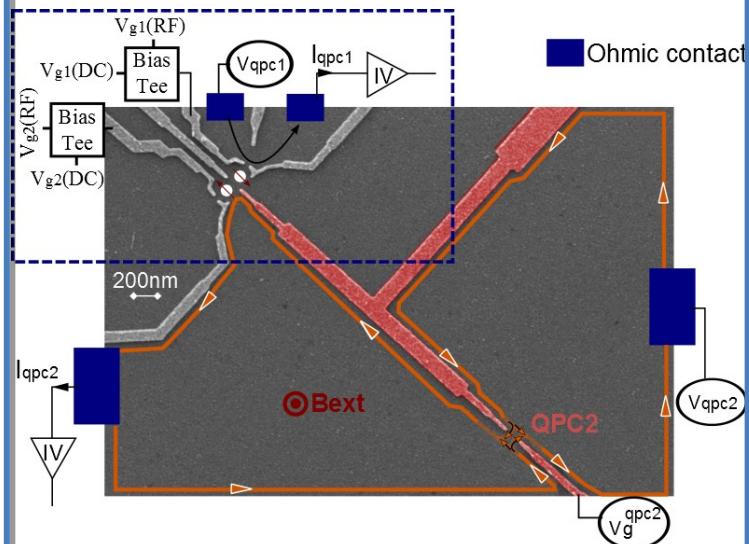
Partitioning of the edge potential



Scrambling of the detector interferences



Neder et al, Nat Phys (2007)
Rouleau et al, PRB (2007)



Pulse shape

