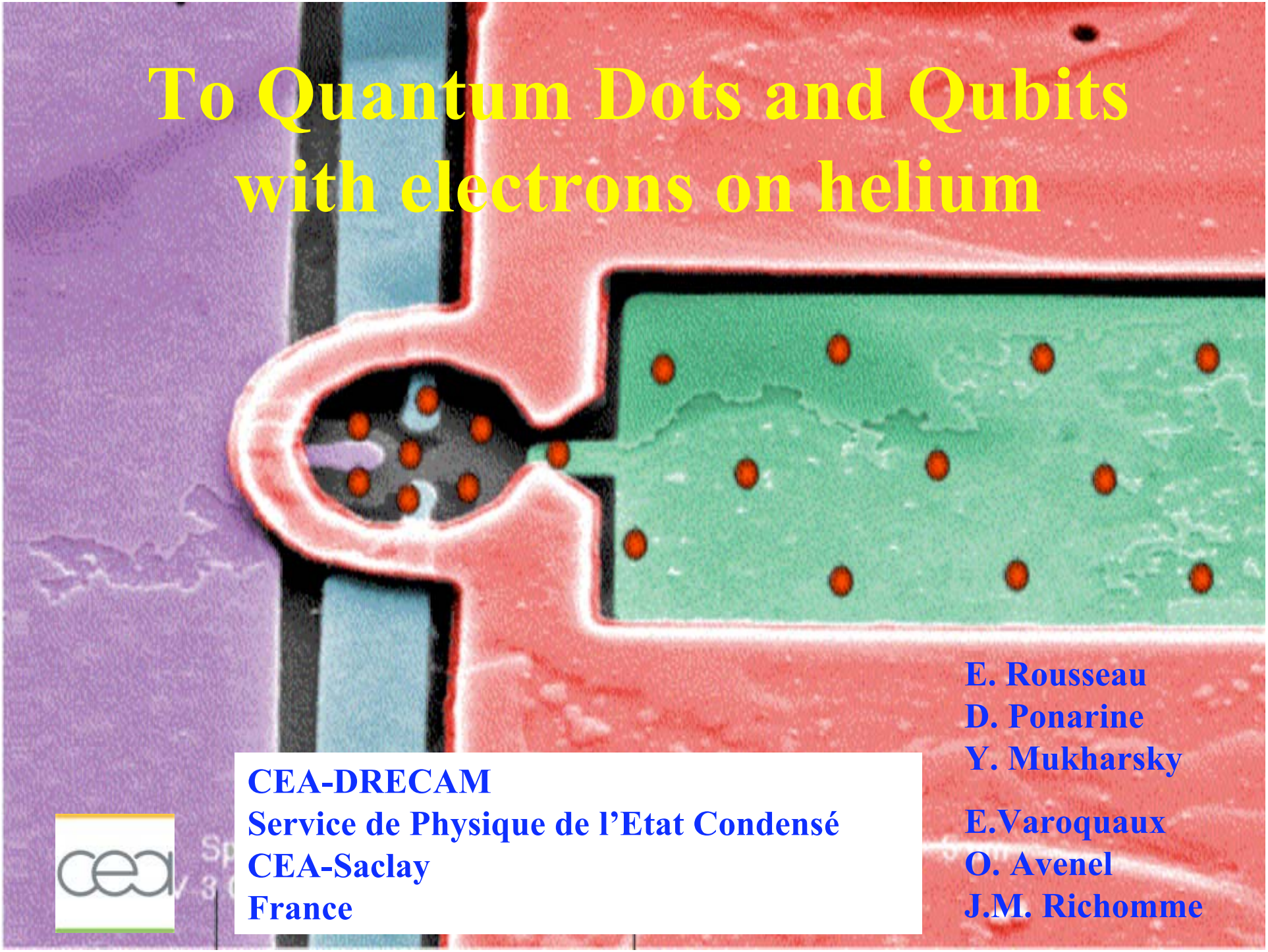
To Quantum Dots and Qubits with electrons on helium

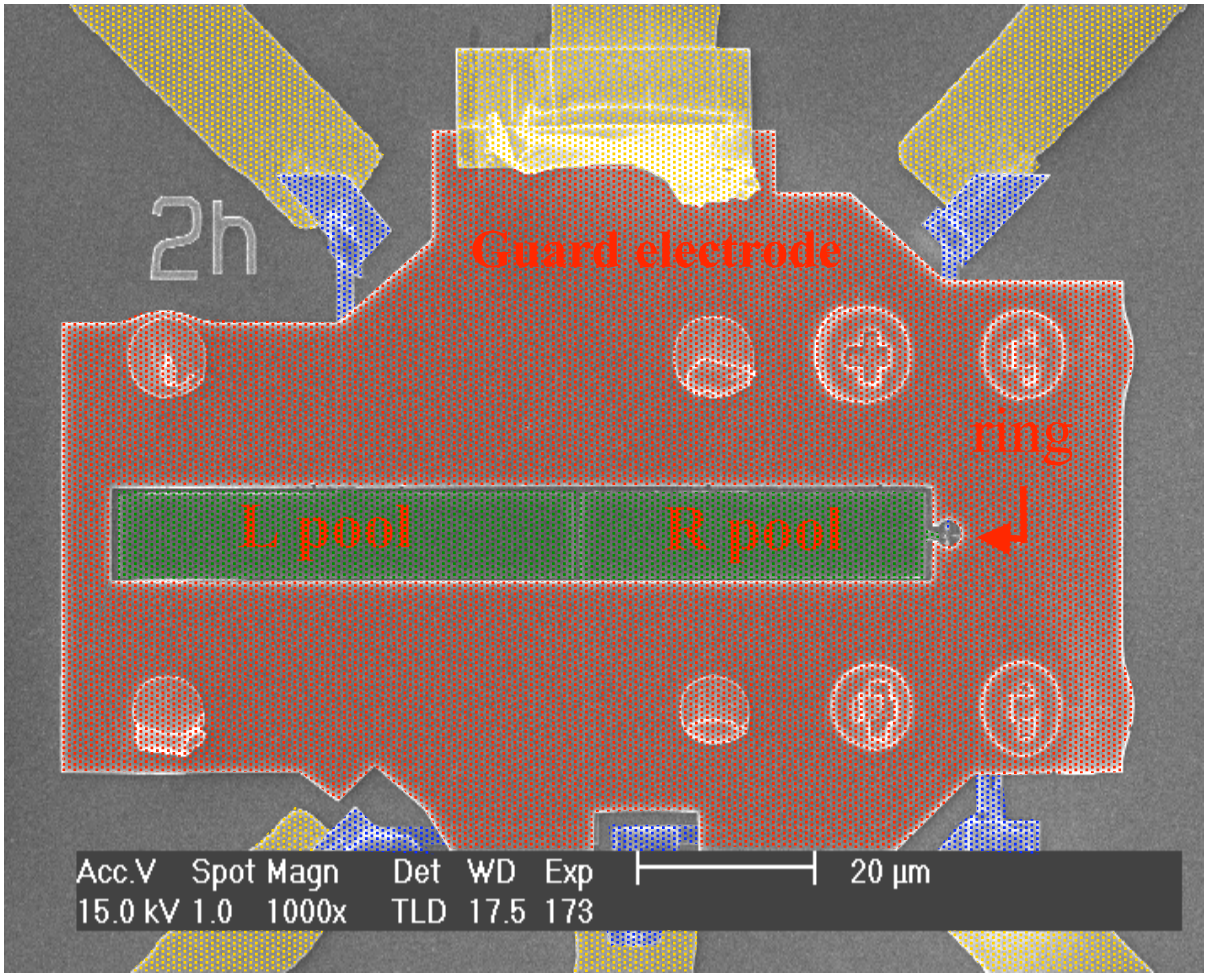


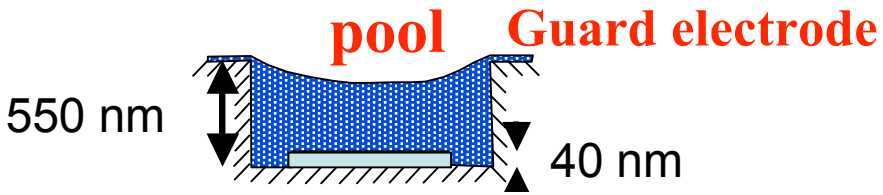
E. Rousseau
D. Ponarine
Y. Mukharsky

E.Varoquaux
O. Avenel
J.M. Richomme

CEA-DRECAM
Service de Physique de l'Etat Condensé
CEA-Saclay
France

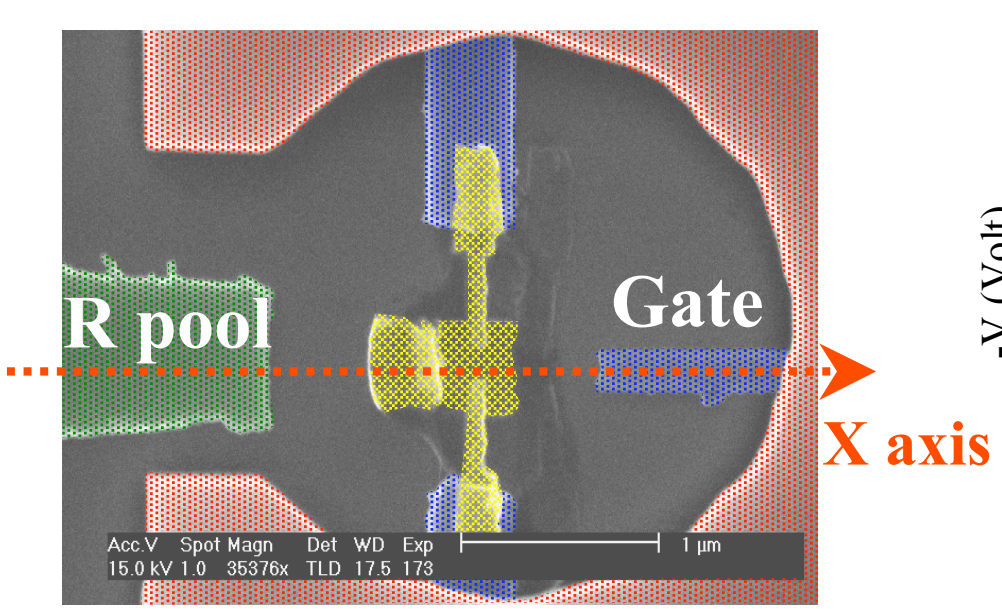
Confine the electrons

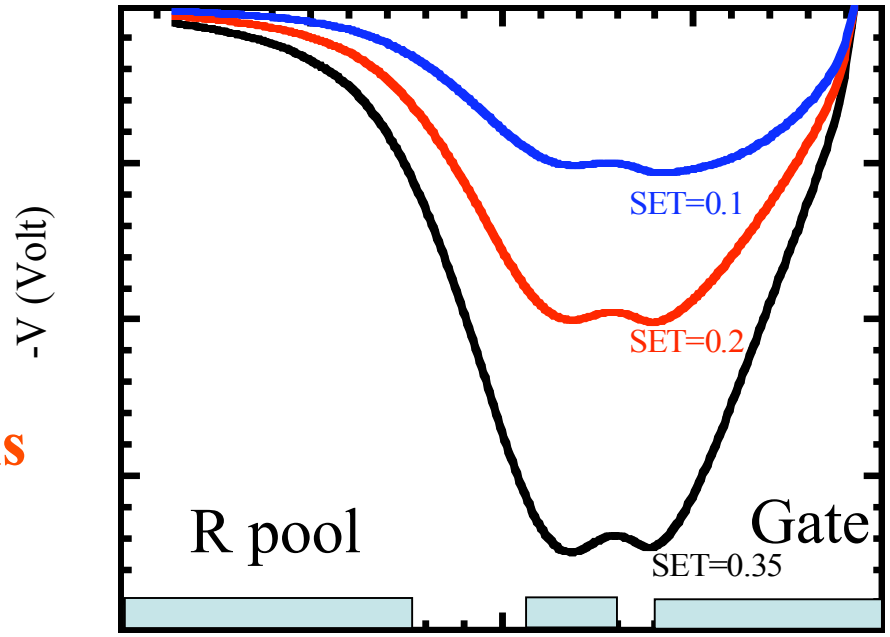




- the exact quantity of helium is added to fill the two pools and the ring.
- electrons are created by a corona discharge.
- Only electrons above pools and ring are mobile.

trapping



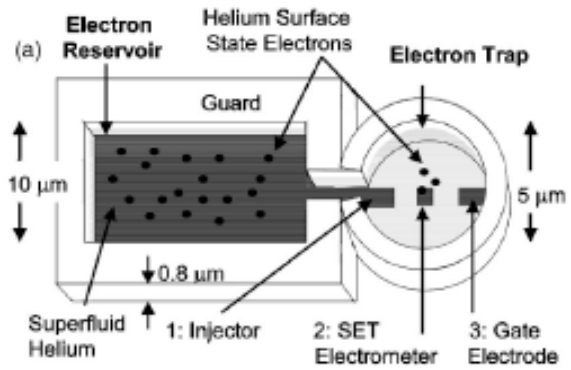


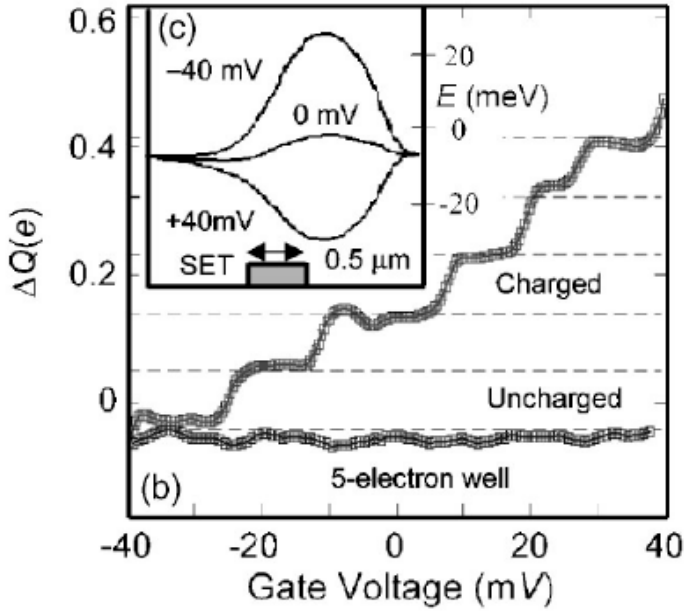
- The electrostatic trap is created by the SET *itself*.

Royal holloway

- Sample more or less similar to RHL one.

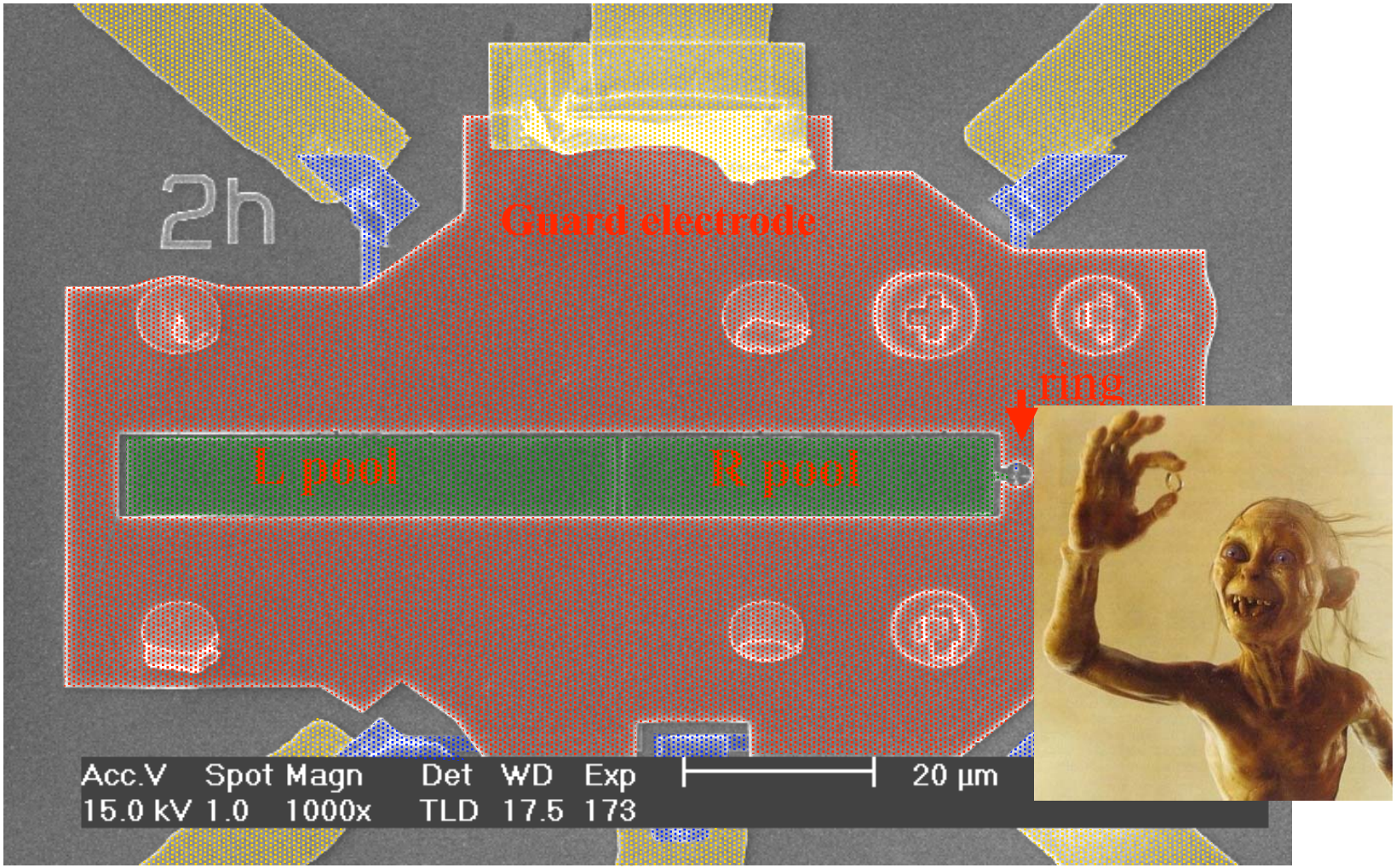
Counting Individual Electrons on liquid Helium .
G.Papageorgiou & al.
Applied physics letters **86**, *153106 (2005)*

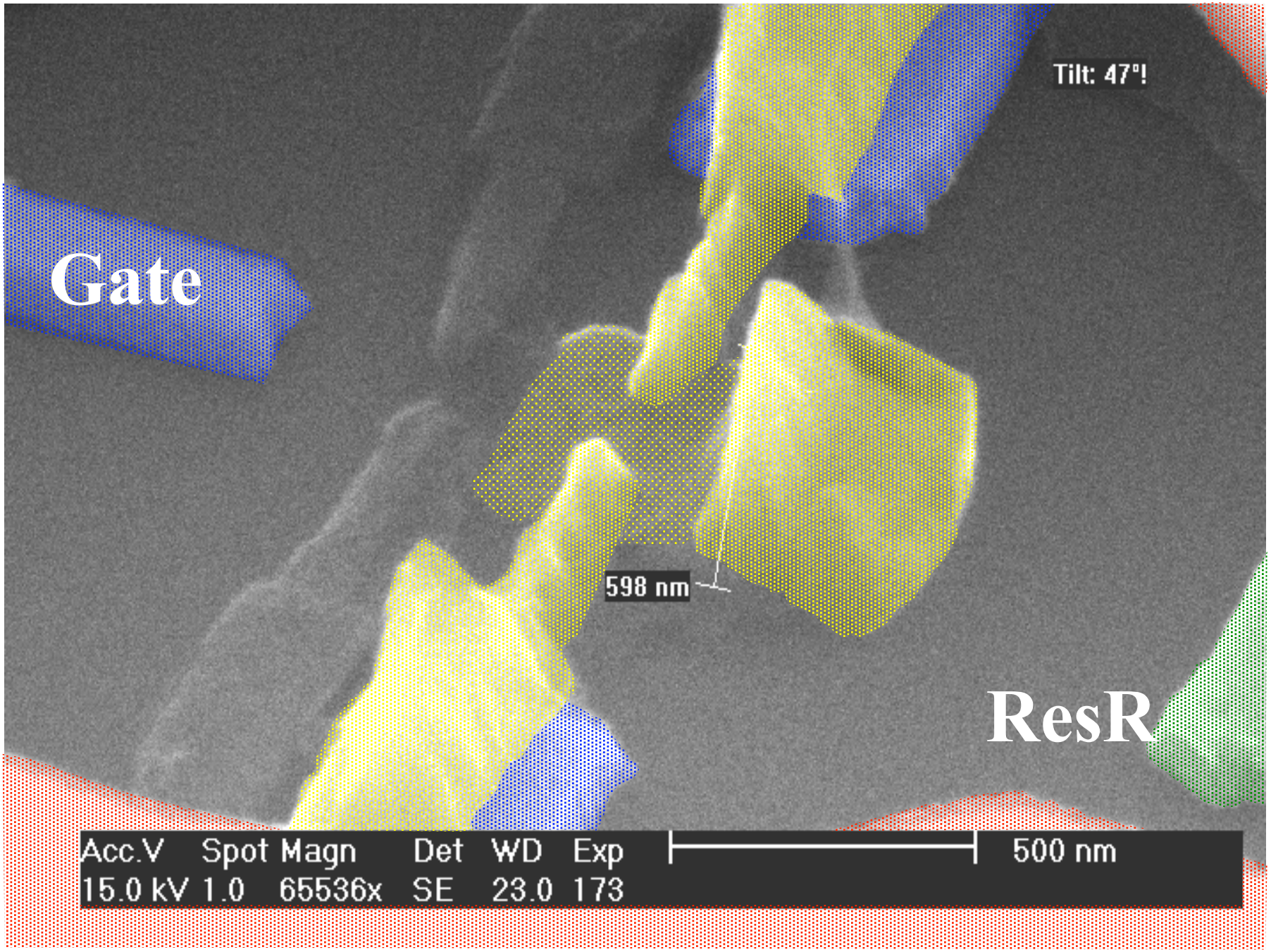




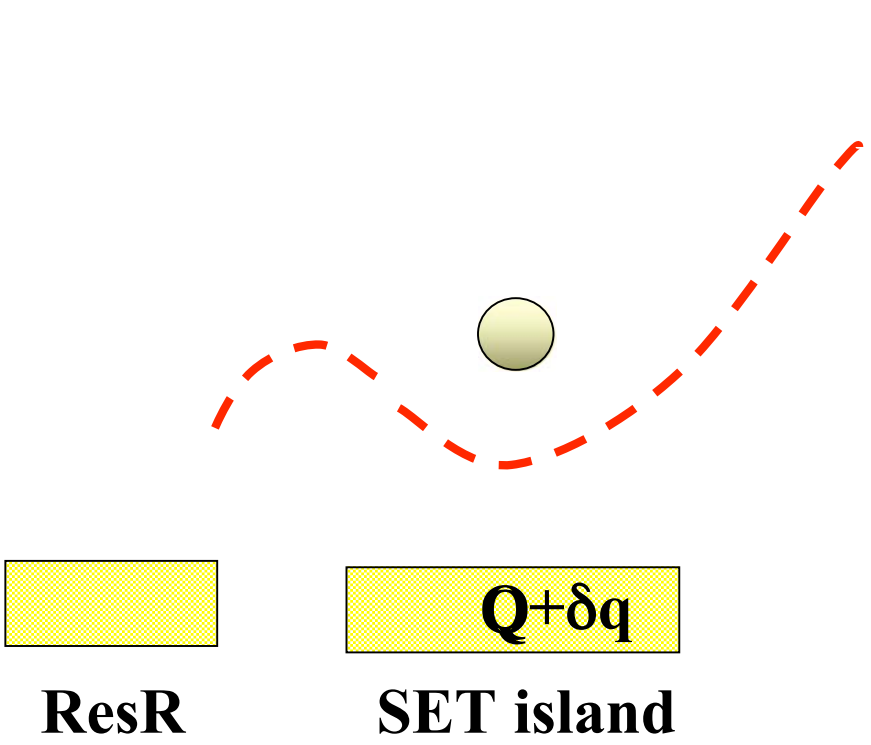
Sample specificity: The Precious

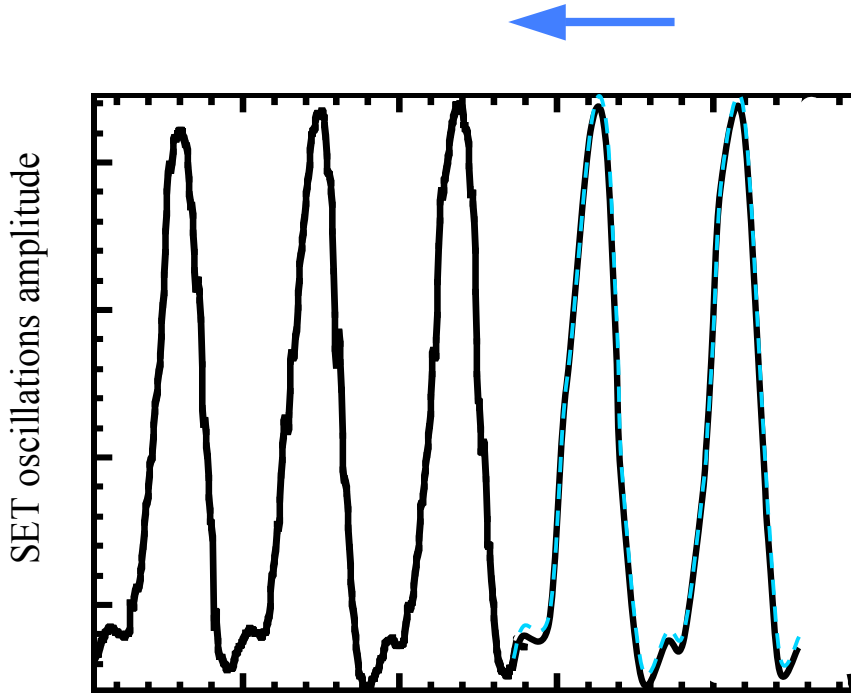
- Ring diameter 3 μm, pyramidal SET island



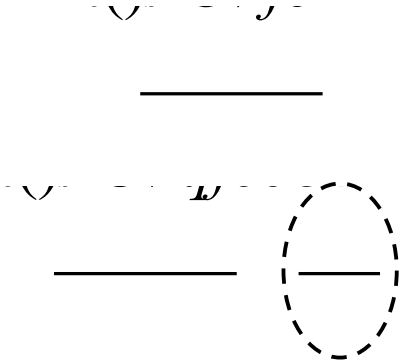

Tilt: 47°!
Gate
598 nm
ResR
Acc.V Spot Magn Det WD Exp
15.0 kV 1.0 65536x SE 23.0 173
500 nm

Detection

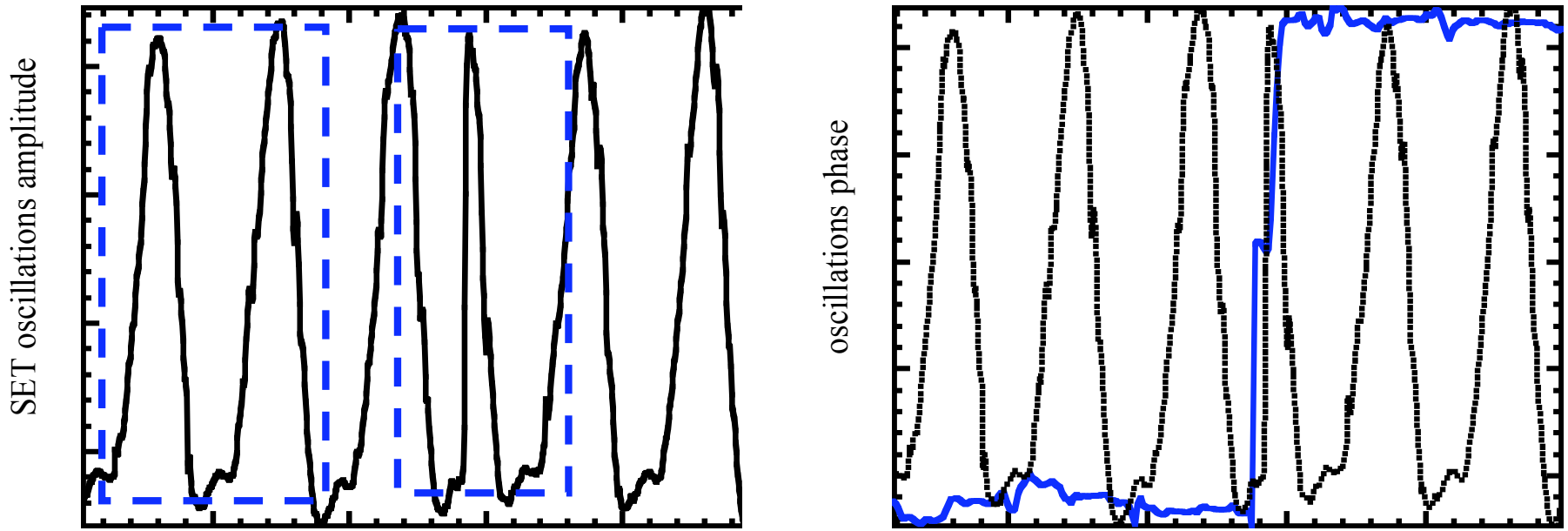




- The voltage across the SET is a periodic function of the island charge.
- When an electron goes in or out of the trap the SET island charge change by δq.



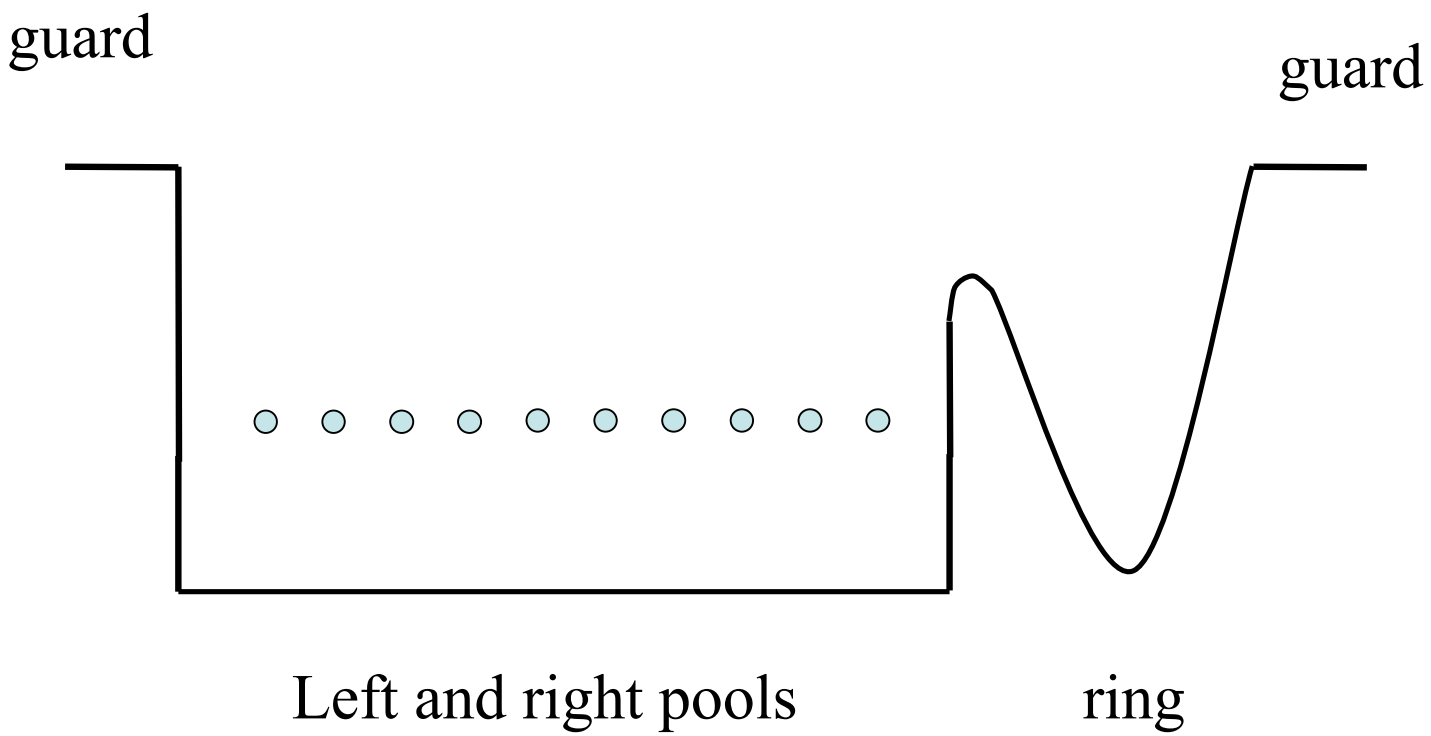
Detection



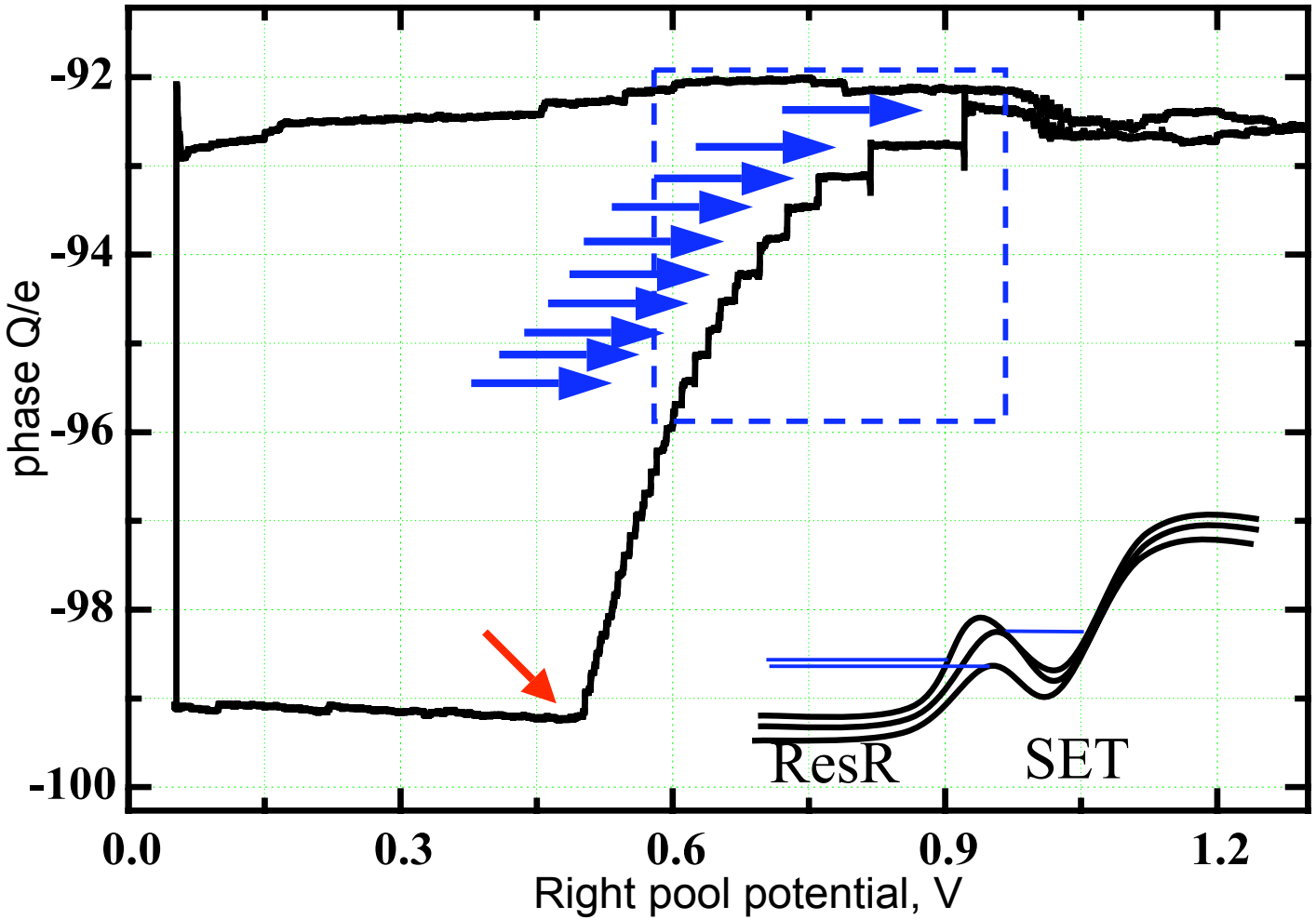
- We fit with a spline function a quiet part of the oscillations.
- The phase of the oscillations changes then by $\delta\phi$.

Charging the ring

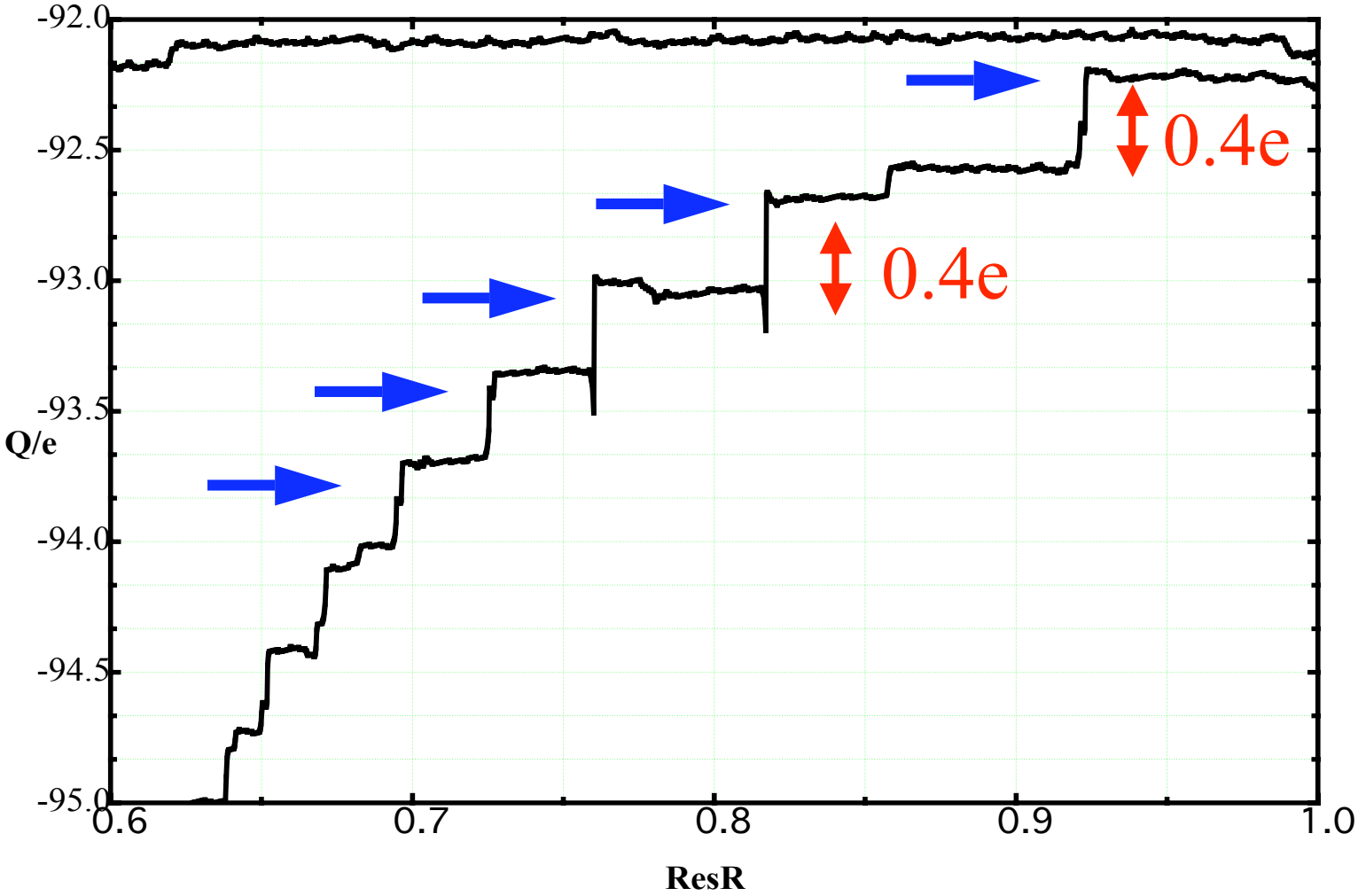
Drawing of the potential profile



One by one observation

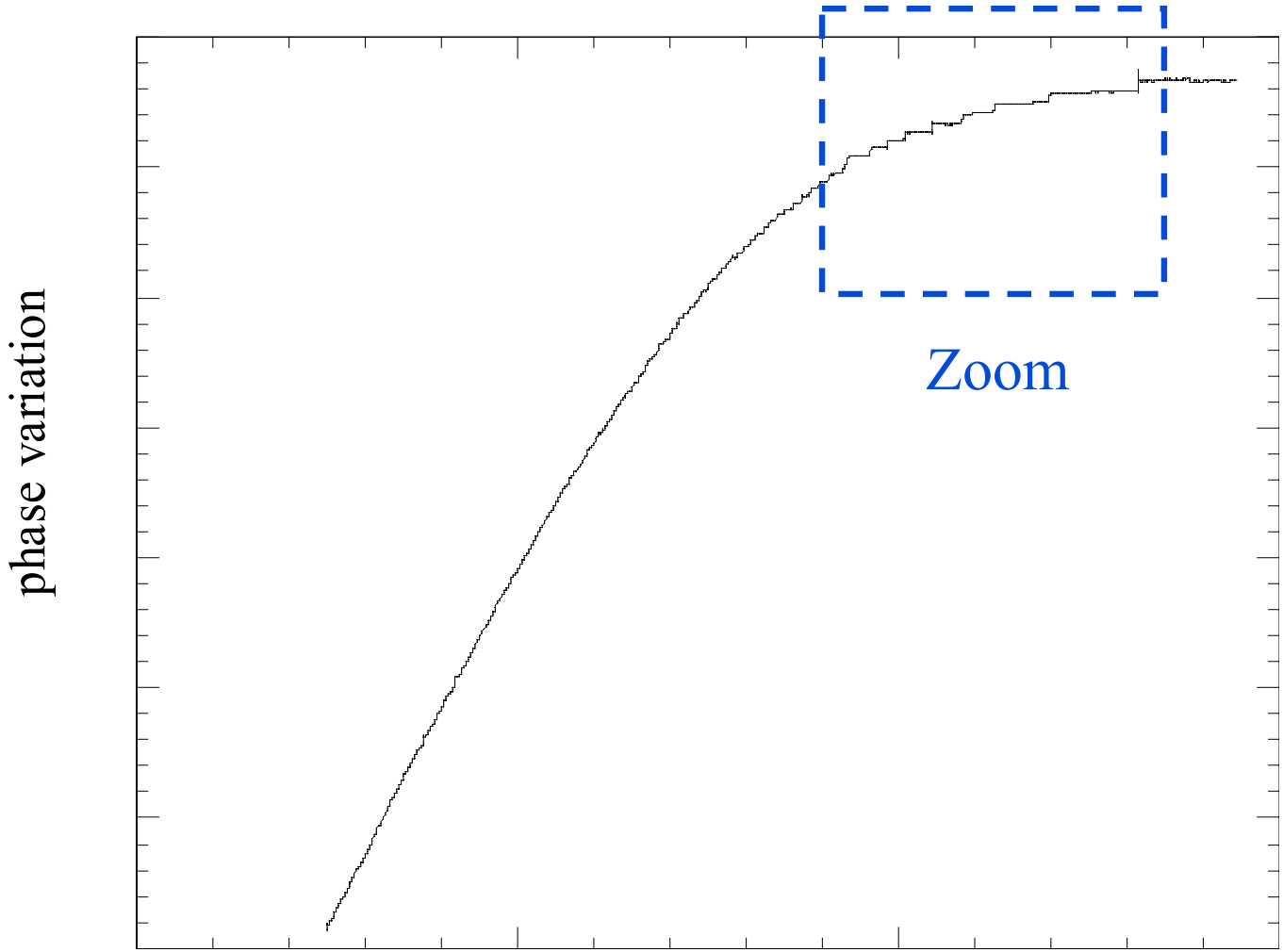


One by one observation

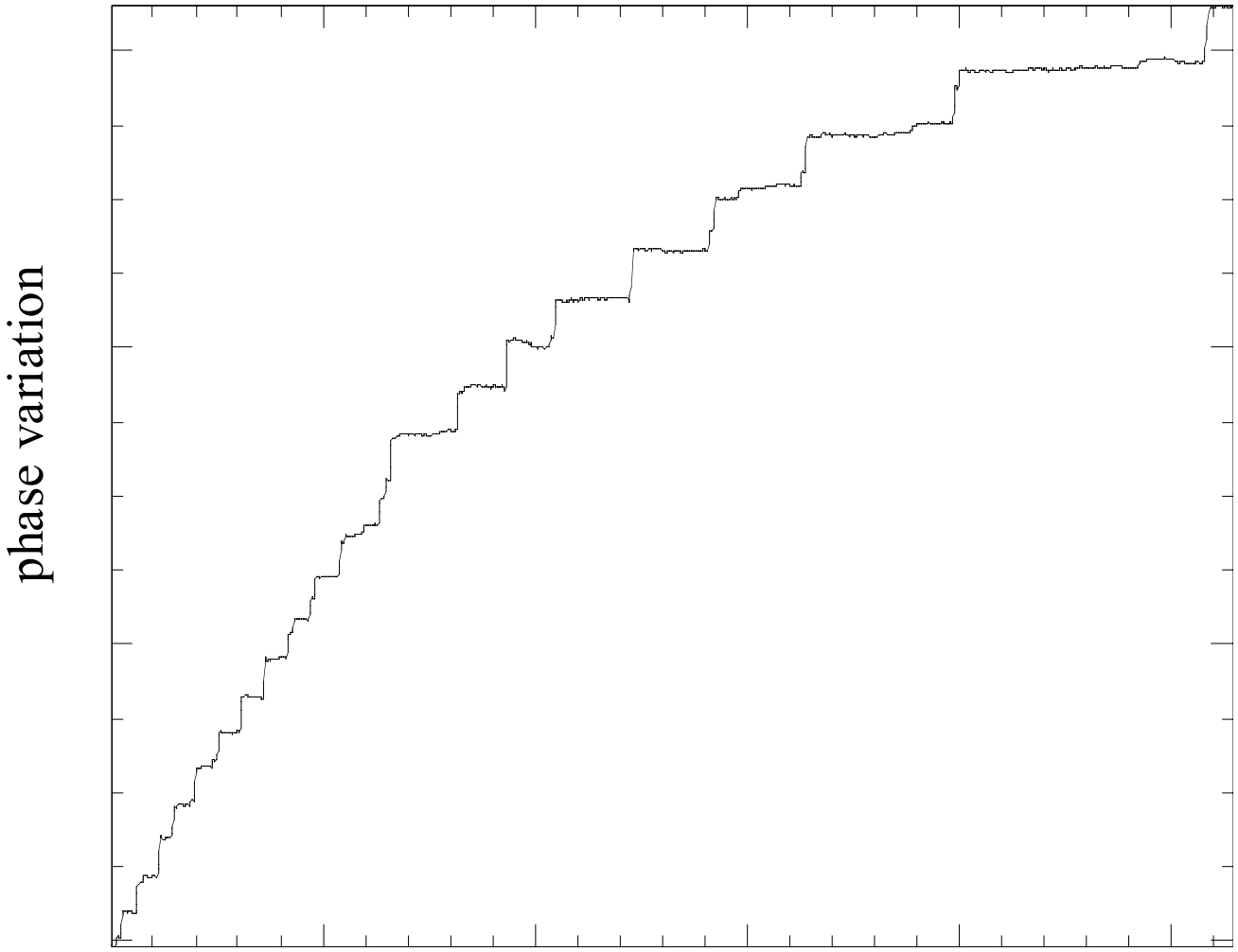


last jumps are around ~0.4 e, value which is reproduced by simulations.

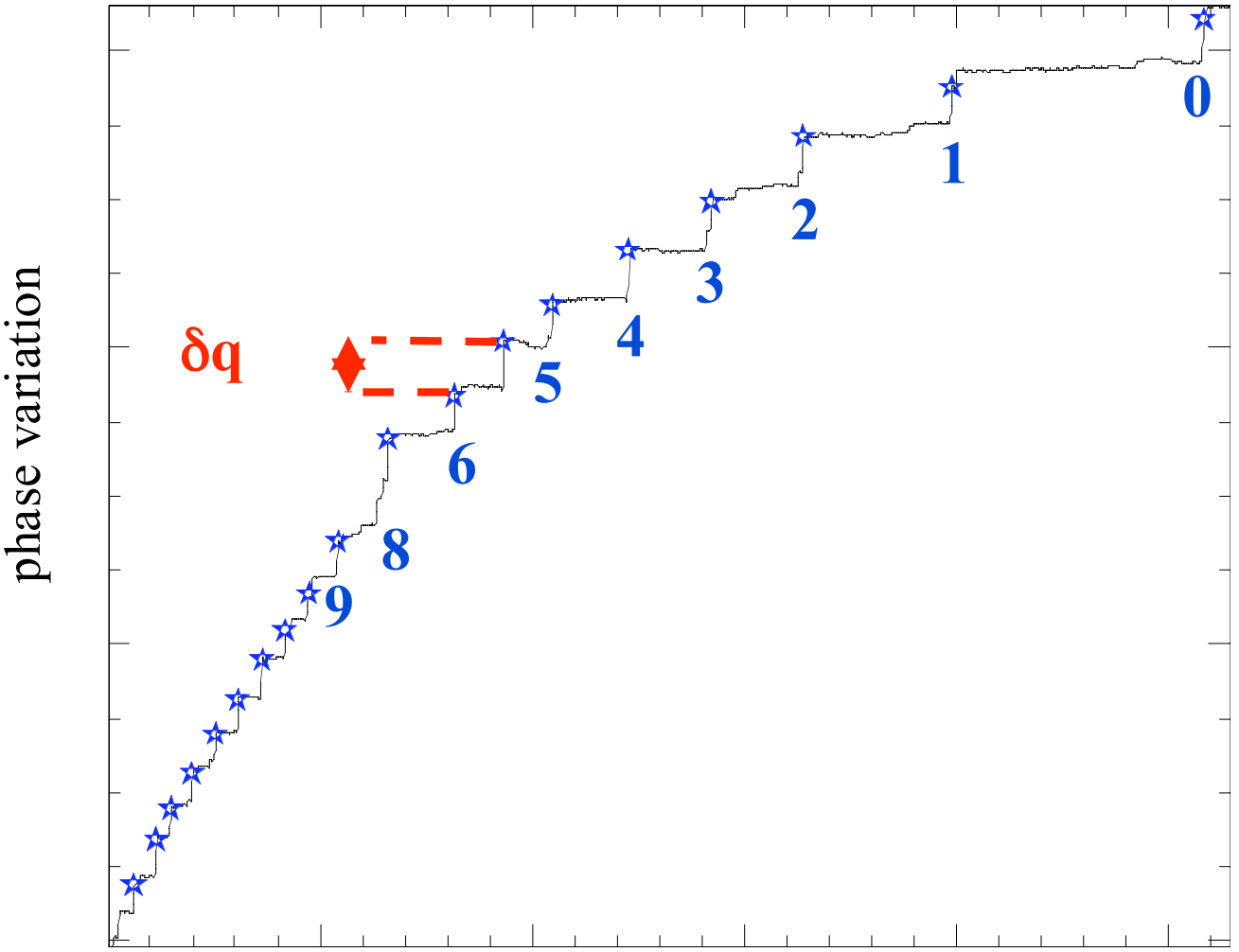
Discharge curve



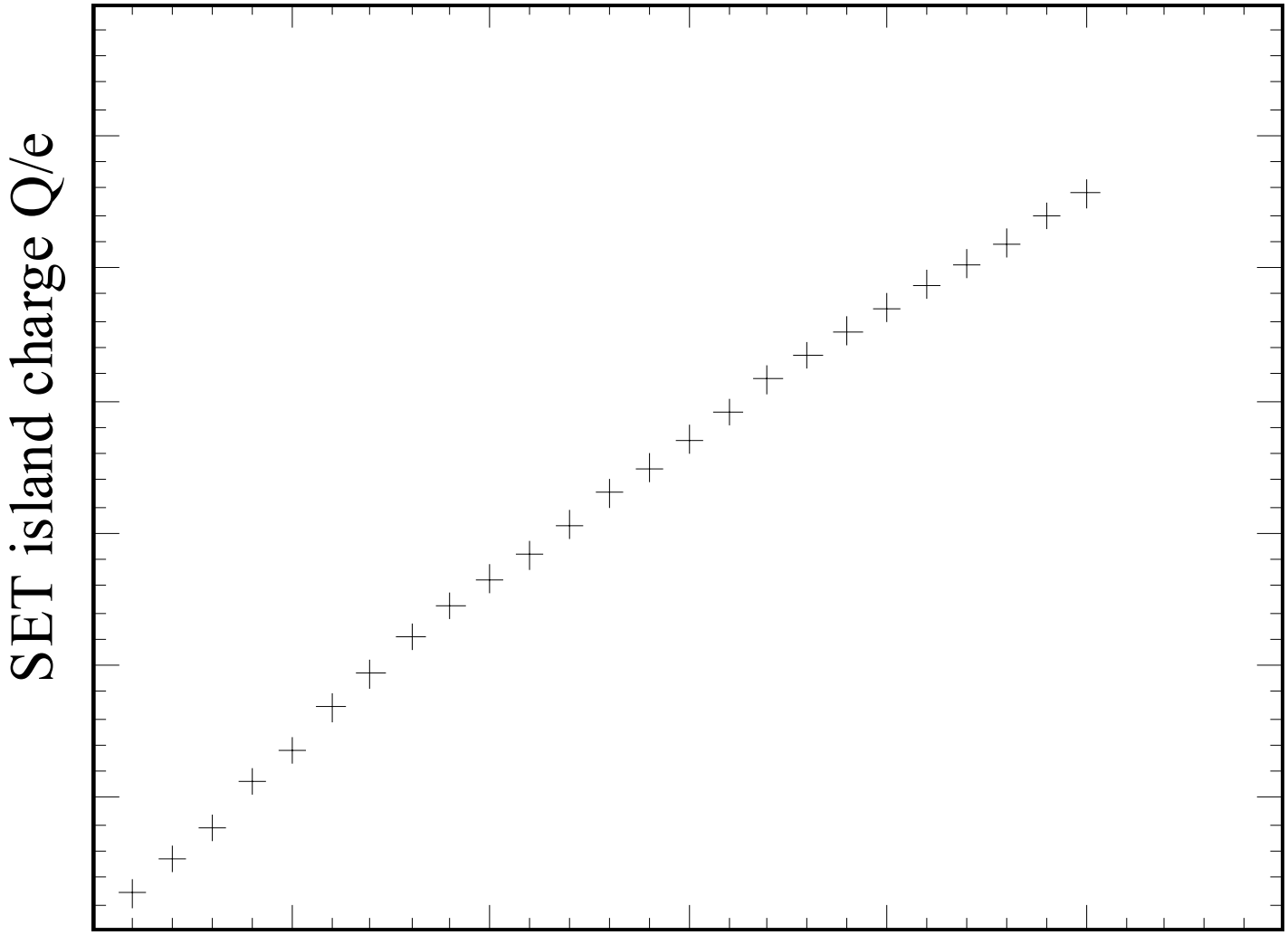
Discharge curve



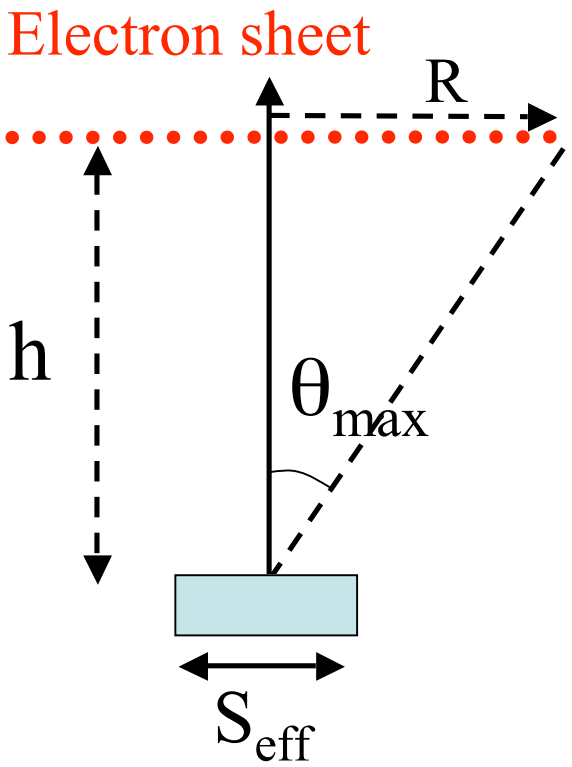
Discharge curve



Discharge curve



Density estimate



- For a small number of electrons, density can be considered as uniform. *A.A.Koulakov, B.I.Shklovskii cond-mat/9705030*
- The electric field is supposed to be constant on SET island.
- The electric charge on the SET island is then given by:

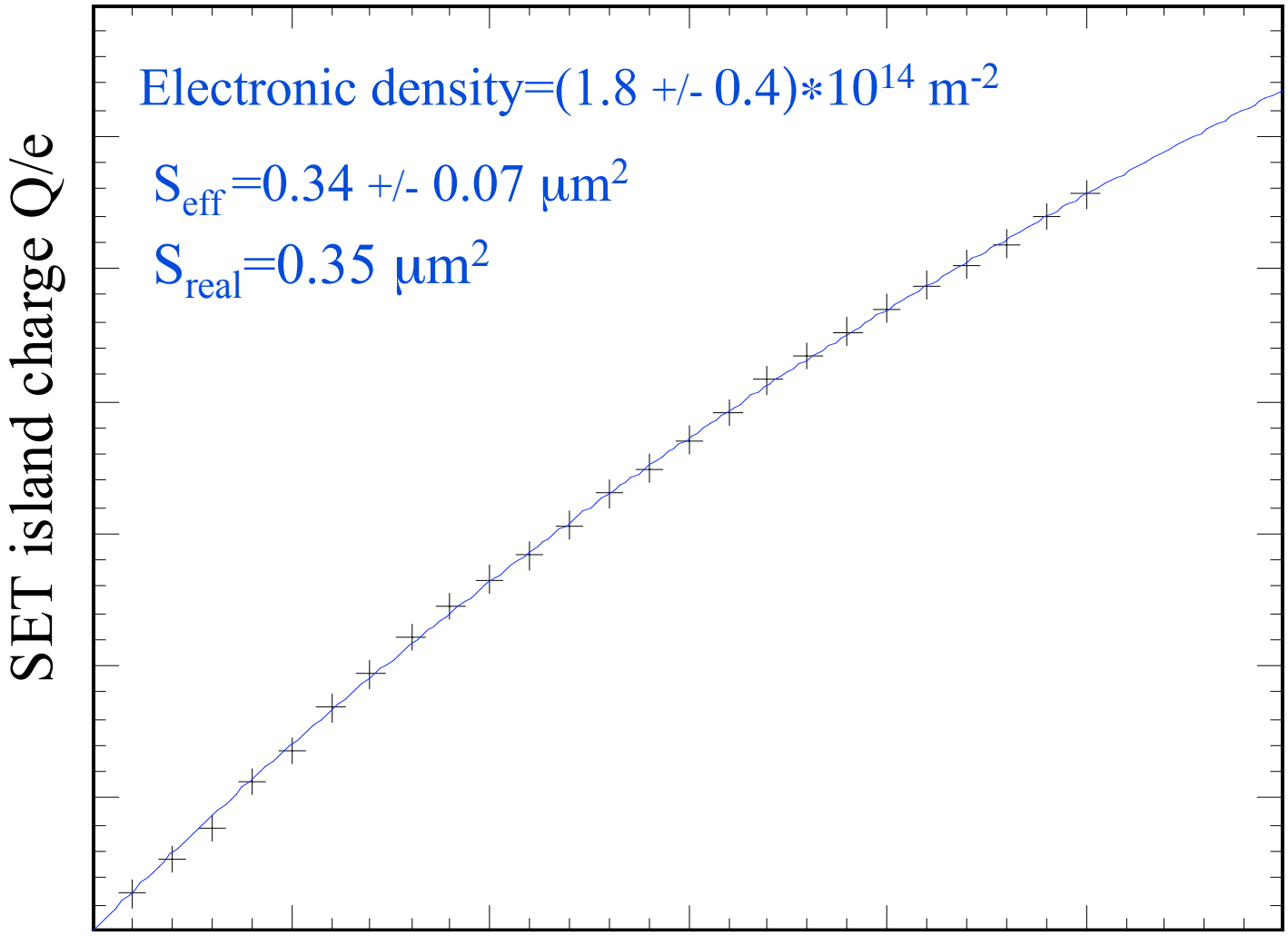
$$\frac{Q}{e} = \frac{nS_{eff}}{2\varepsilon_0}(1-\cos(\theta_{max}))$$

With $\theta_{max}=\arctan\left(\frac{1}{h}\sqrt{\frac{N}{\pi n}}\right)$

$N=n\pi R^2$ number of electron

n electronic density

Density estimate



• The interaction between electrons is not screened by surrounding electrodes.

• From thermal fluctuations:
$n=10^{14}$ transition temperature Tc=2.5 K

• $r_s \sim 2000$ $r_s^{cri} \sim 30$
Coulombic interaction is dominant

• Electrons should form a Wigner crystal.

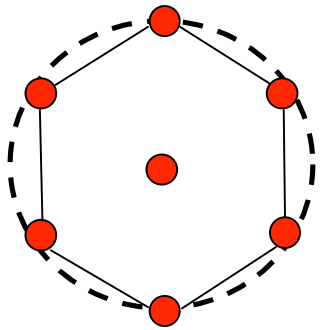
Wigner molecules

Competition
between the symmetry of the trap
(parabolic trap)
→ shell ordering

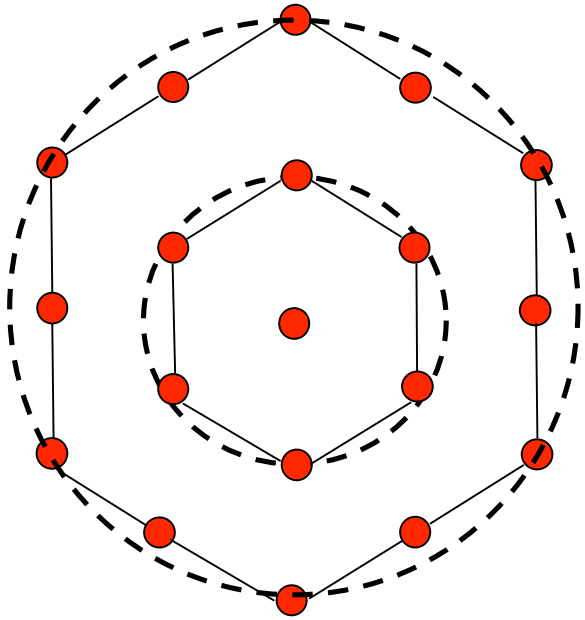
and the symmetry of the Wigner
crystal

→ triangular lattice structure

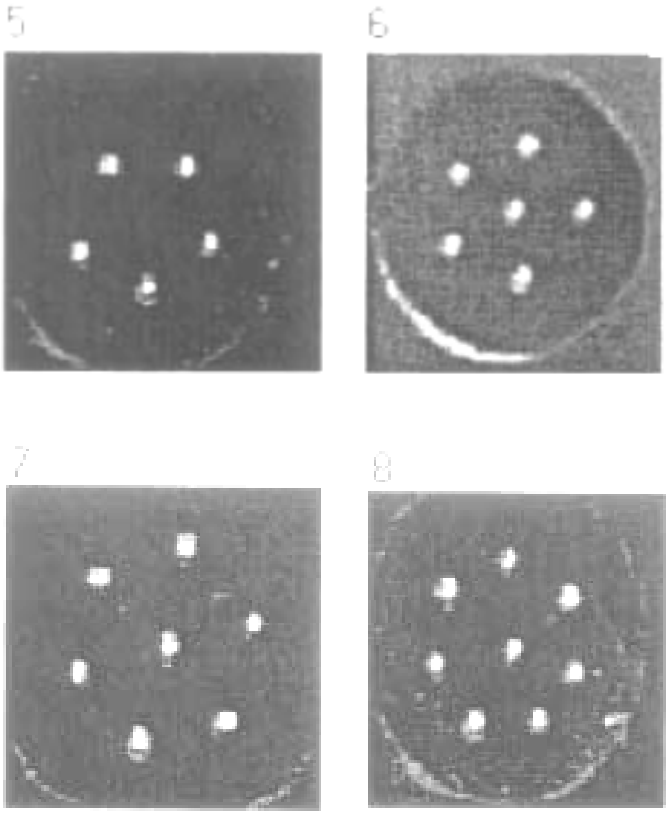
N=7

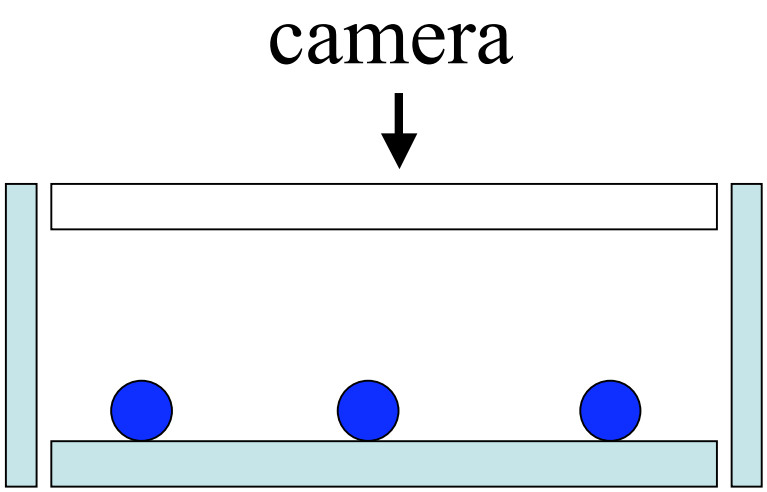


N=19



macroscopic observation





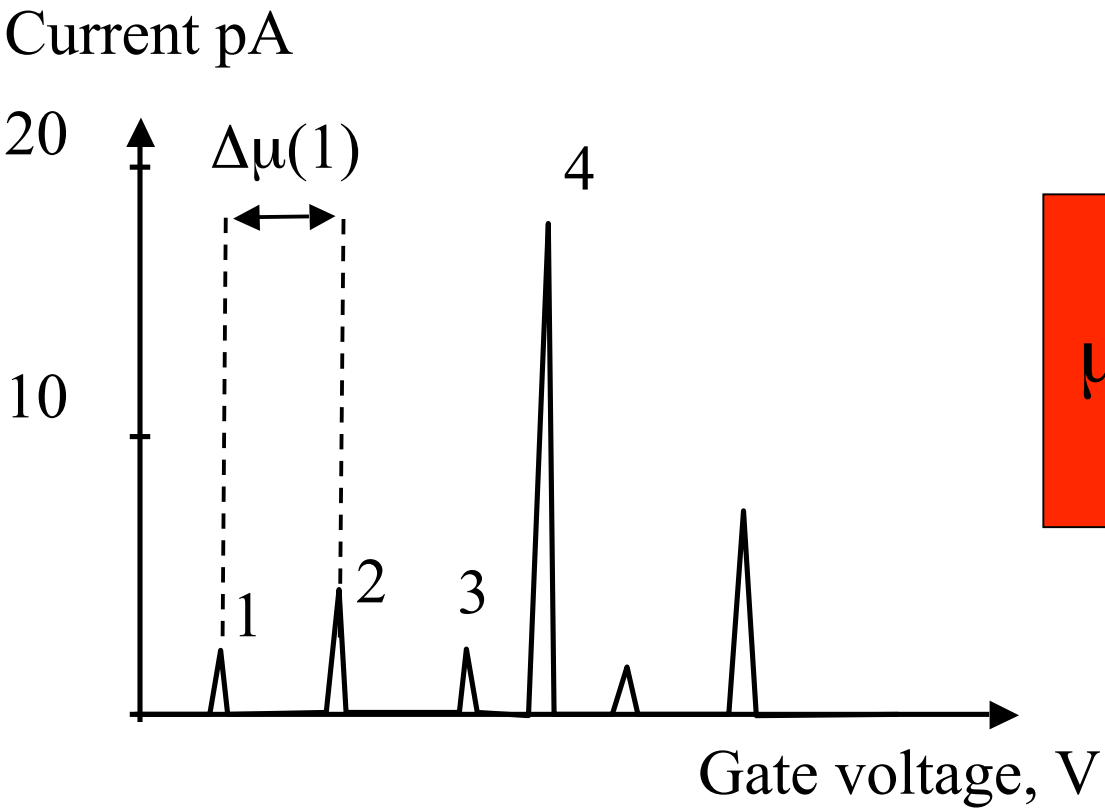
Macroscopic 2D Wigner islands

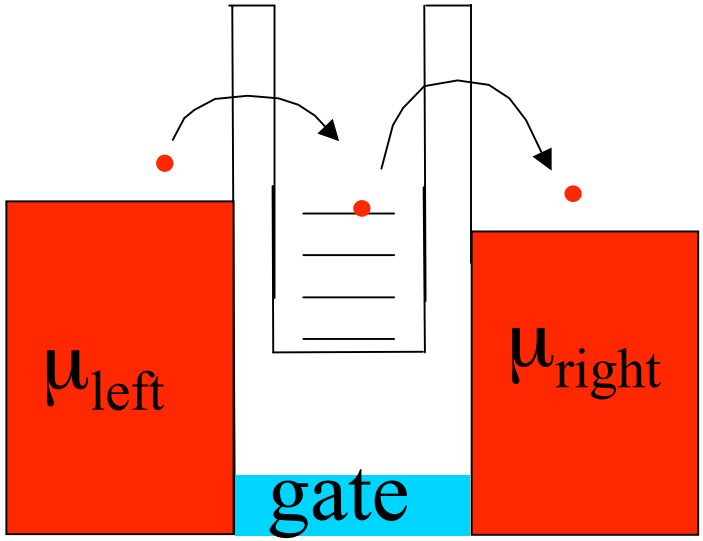
M. Saint Jean(*), C. Even and C. Guthmann

Europhys. Lett., **55** (1), pp. 45–51 (2001)

No observations with electrons on helium.

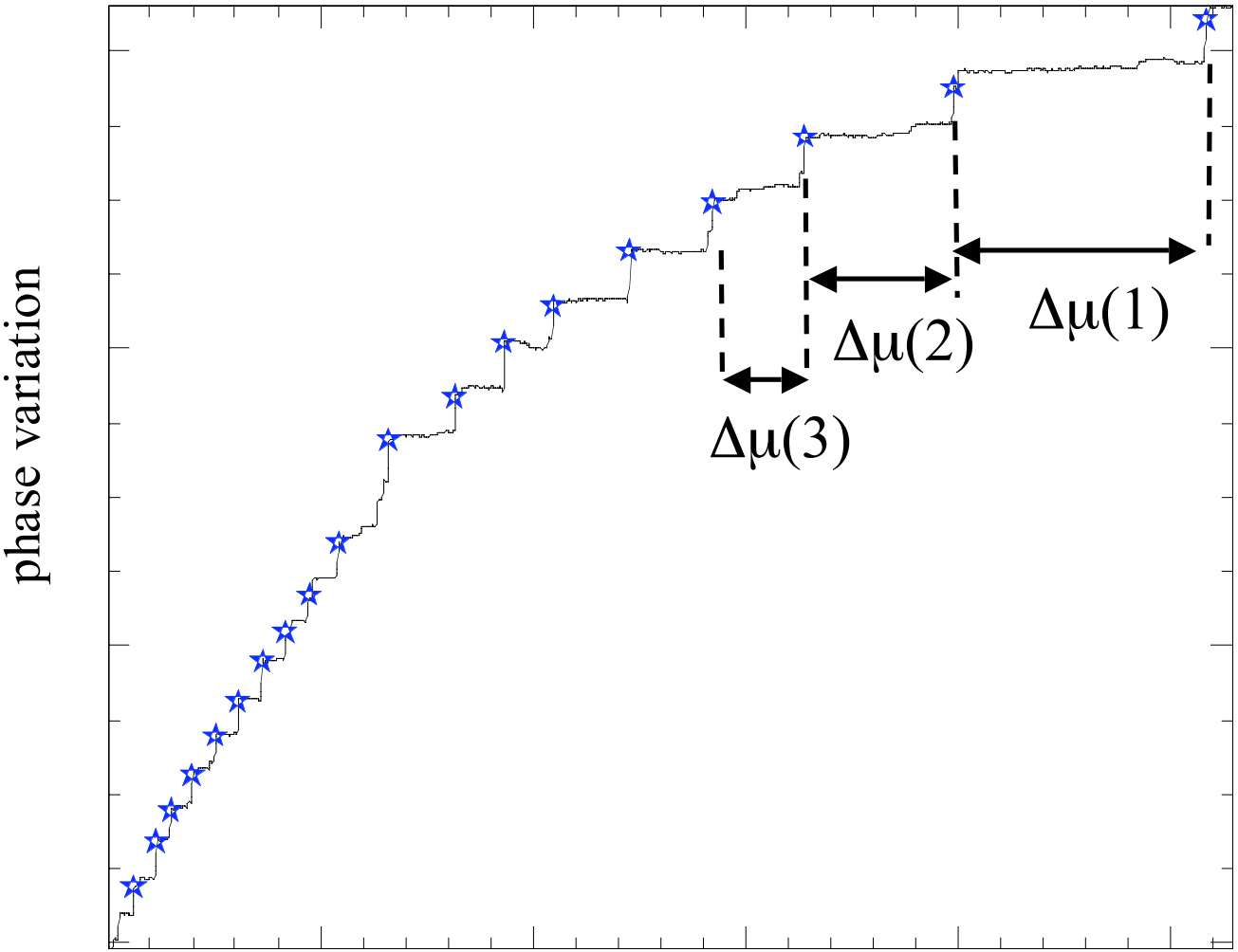
Addition Spectra





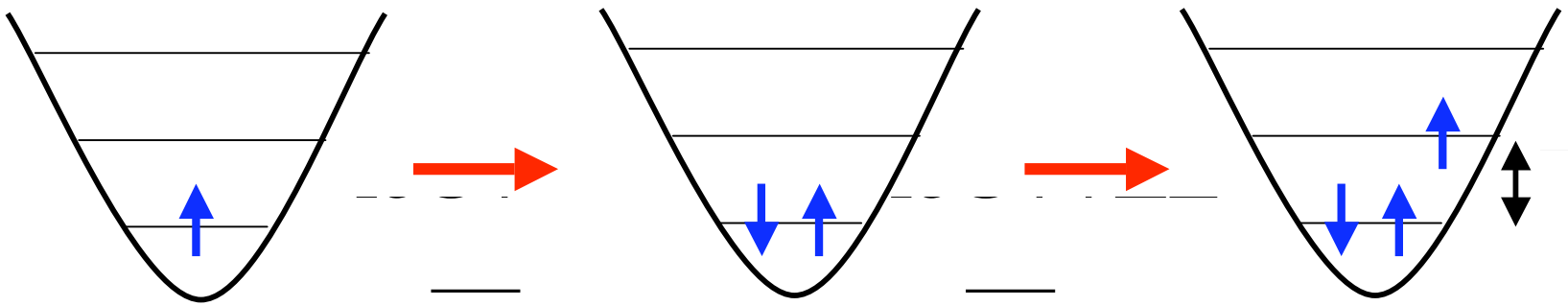
- charging energy: energy required to add one electron
- $\Delta\mu(N) = \mu(N) - \mu(N-1) \sim e\,\Delta V_g$

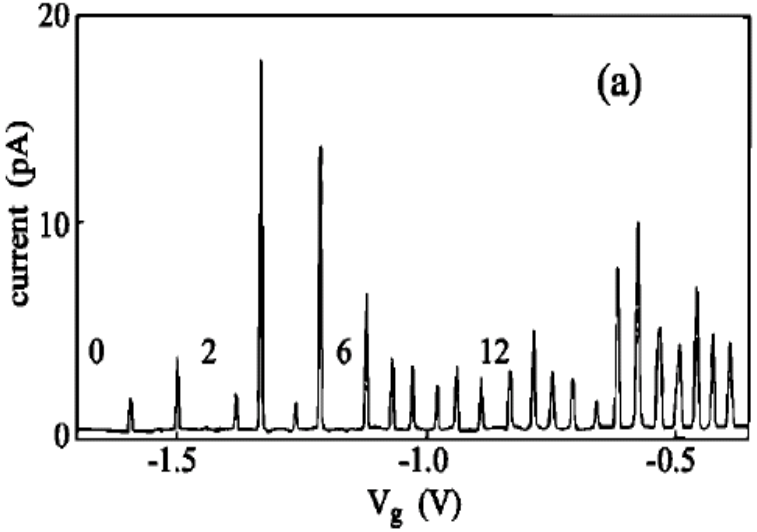
Addition spectra

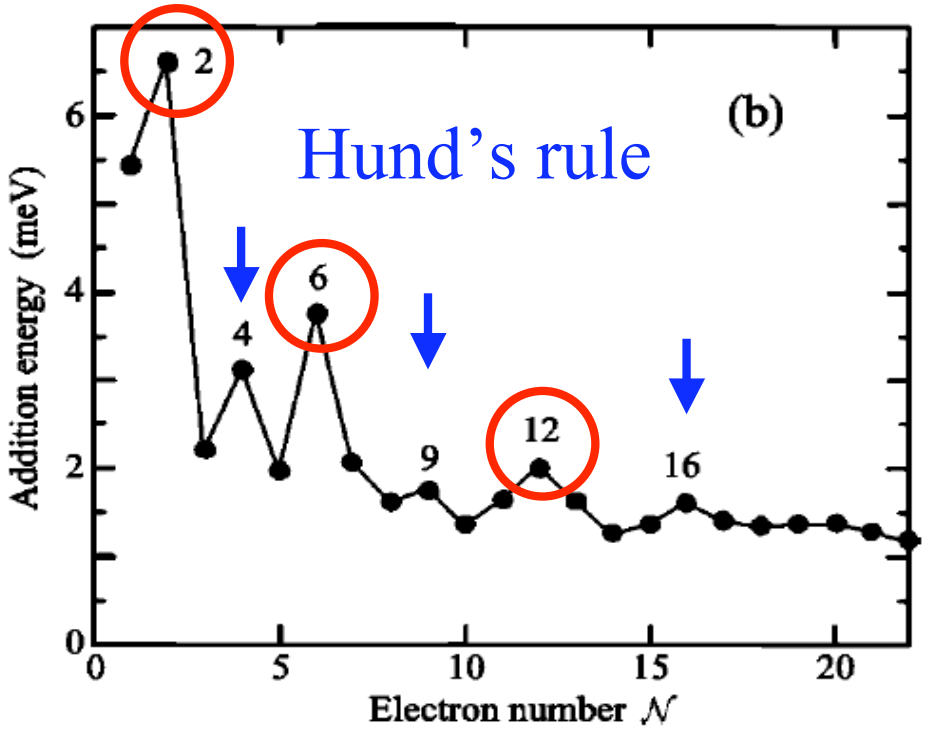


Liquid phase

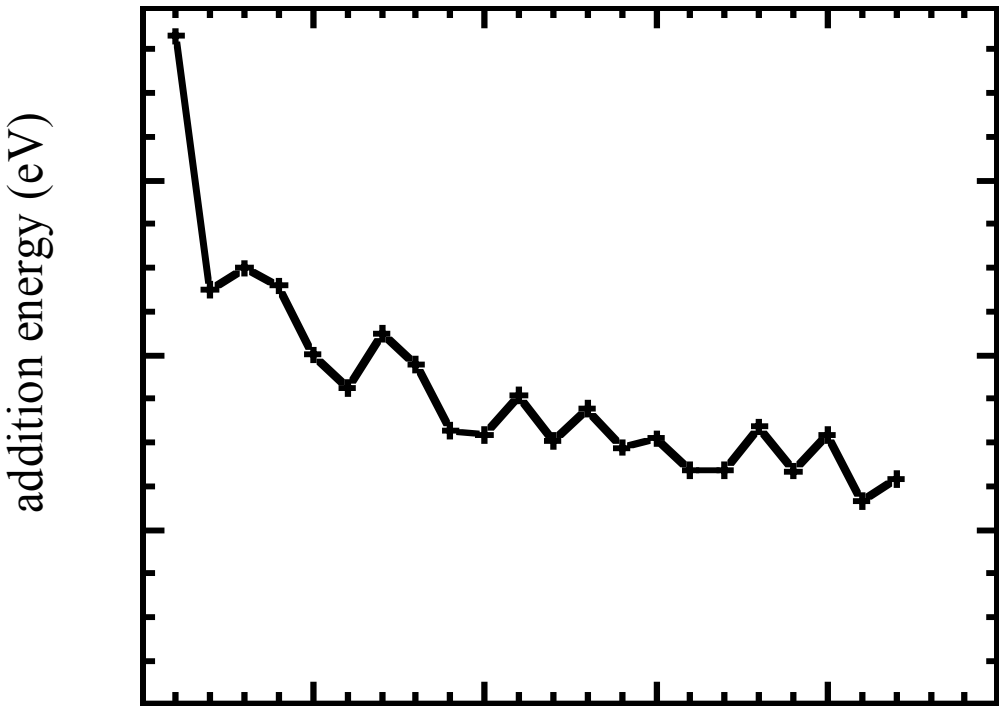
- Average interaction between electrons
  → Constant interaction model
  → 1 particles model in a parabolic trap
- Confinement induce energy shell with magic numbers when a shell is completely filled: 2,6,12 (degeneracy due to spin)




20
10
0
current (pA)
(a)
0
2
6
12
-1.5
-1.0
-0.5
V_g (V)


Hund's rule
(b)
2
4
6
9
12
16
Addition energy (meV)
0
2
4
6
0
5
10
15
20
Electron number $\mathcal{N}$

For a parabolic trap



Vladimir Bedanov and François Peeters
*PRB **49**, 2667*

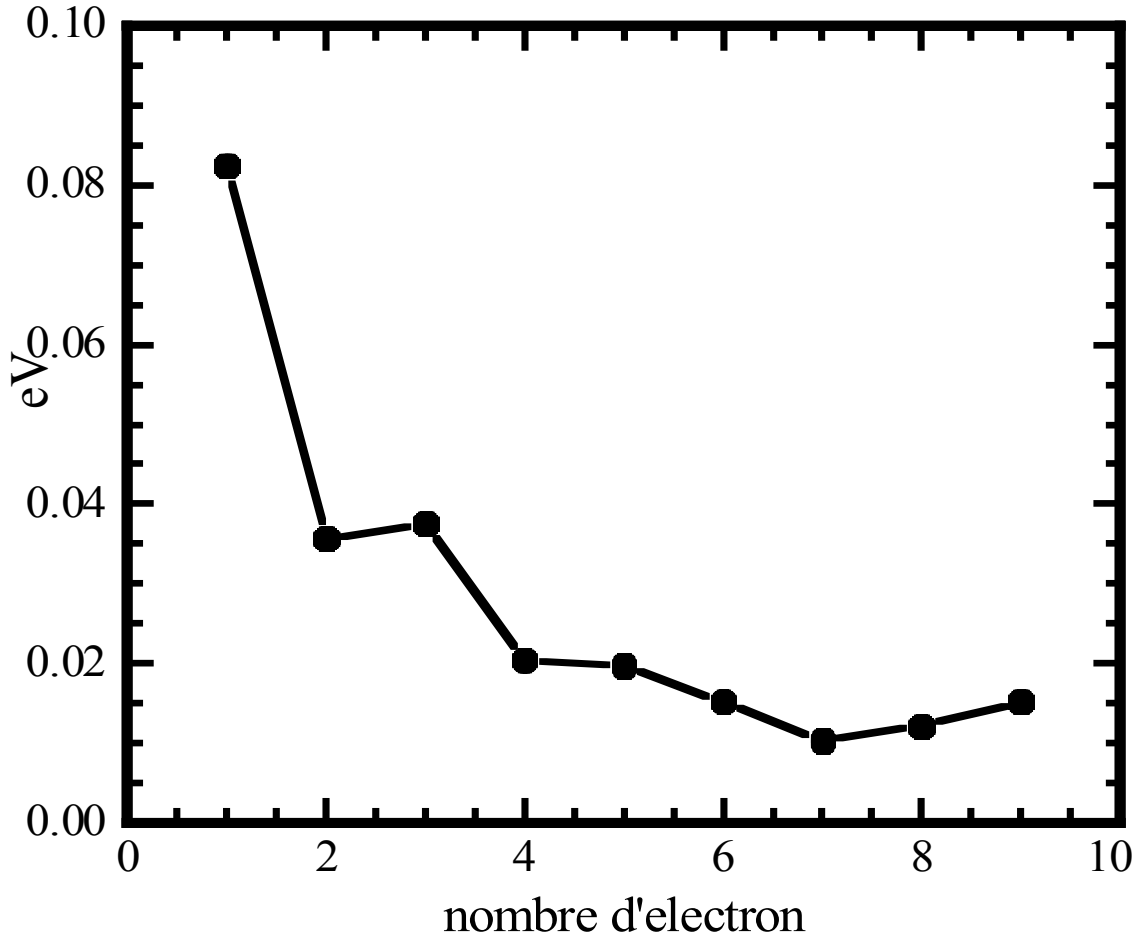
"The numbers of electrons on each ring are not universal and depend on the type and strength of confinement potential."

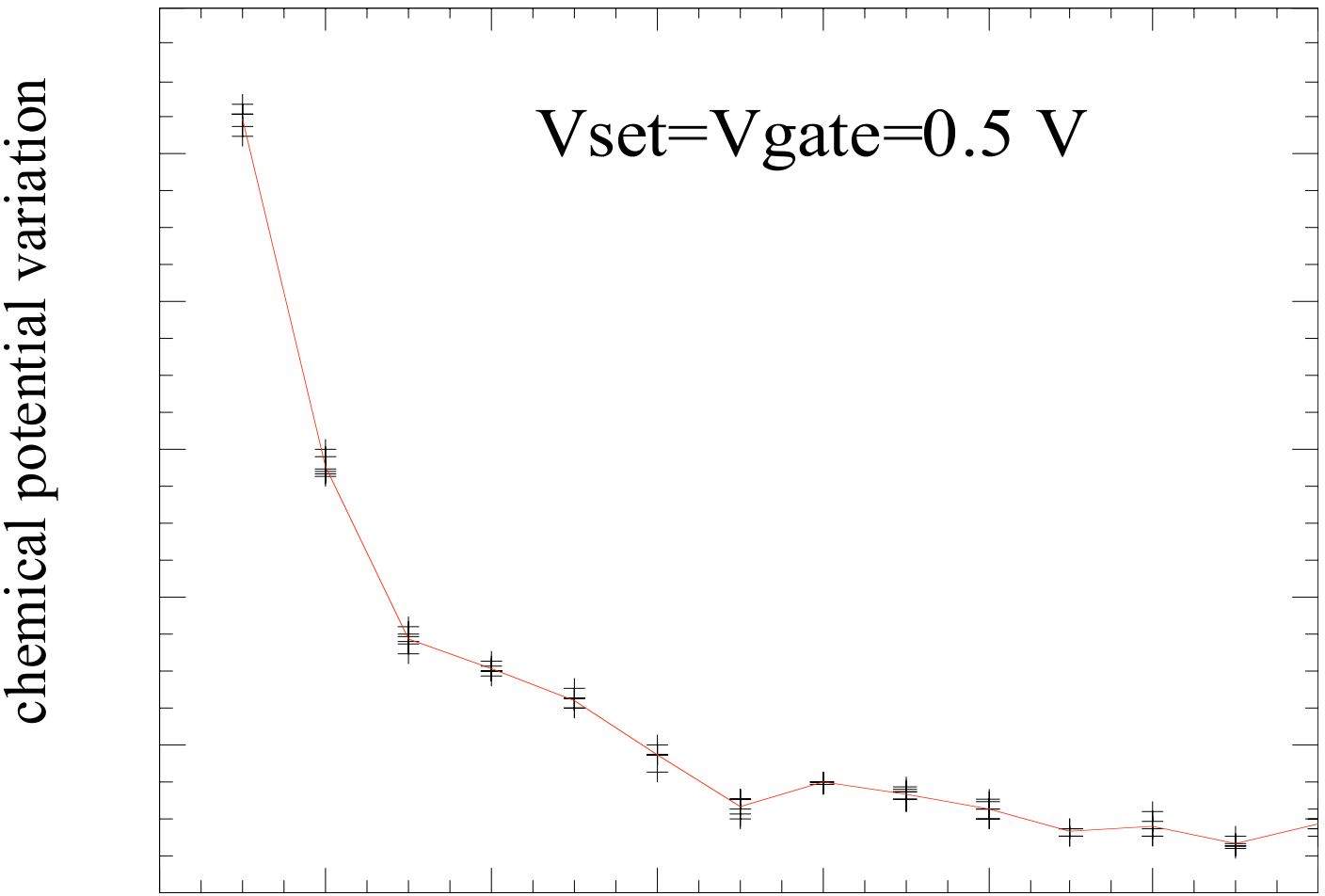
B.Partoens and F.Peeters
*J.Phys:condens matter,**9** 5383 (1997)*

No magic numbers when electrons form Wigner molecules.

Simulations needed to explain addition energy plot

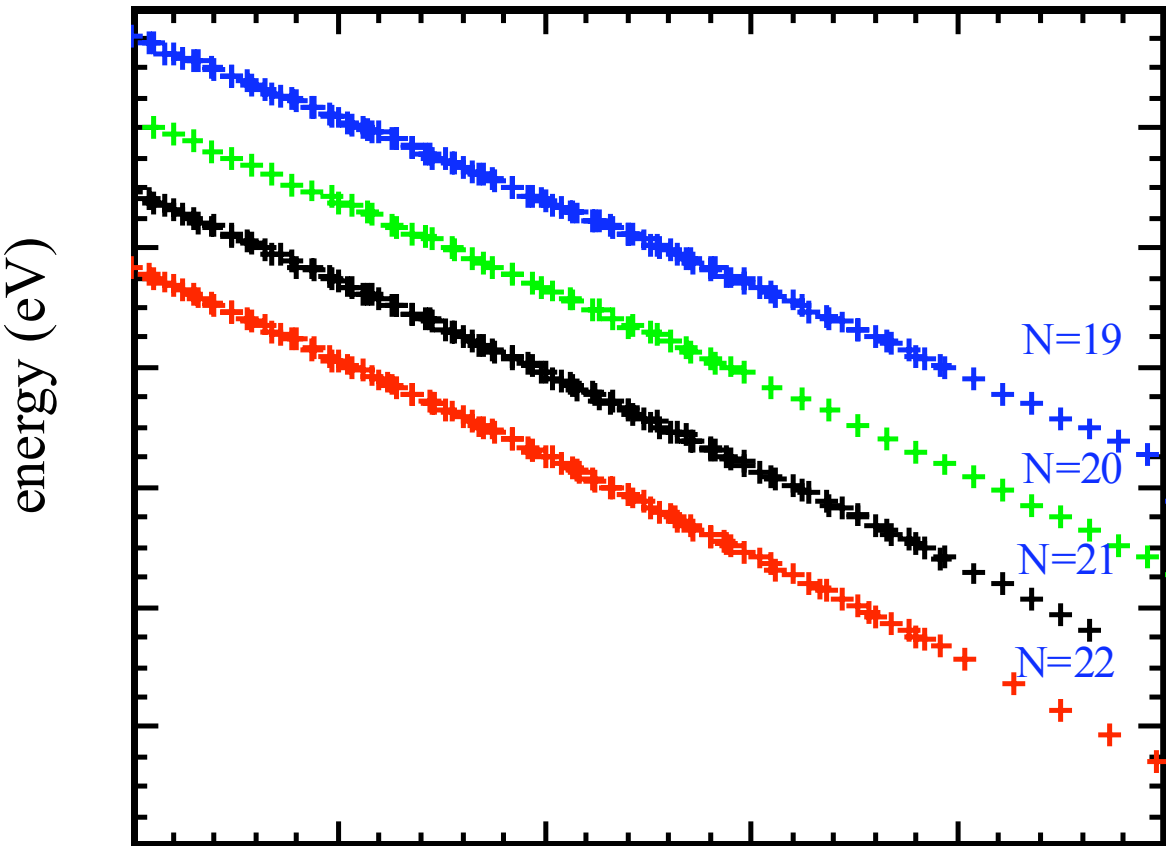
Pour Vset=0.3 Vgate=0 Vground=-0.1




chemical potential variation
Vset=Vgate=0.5 V

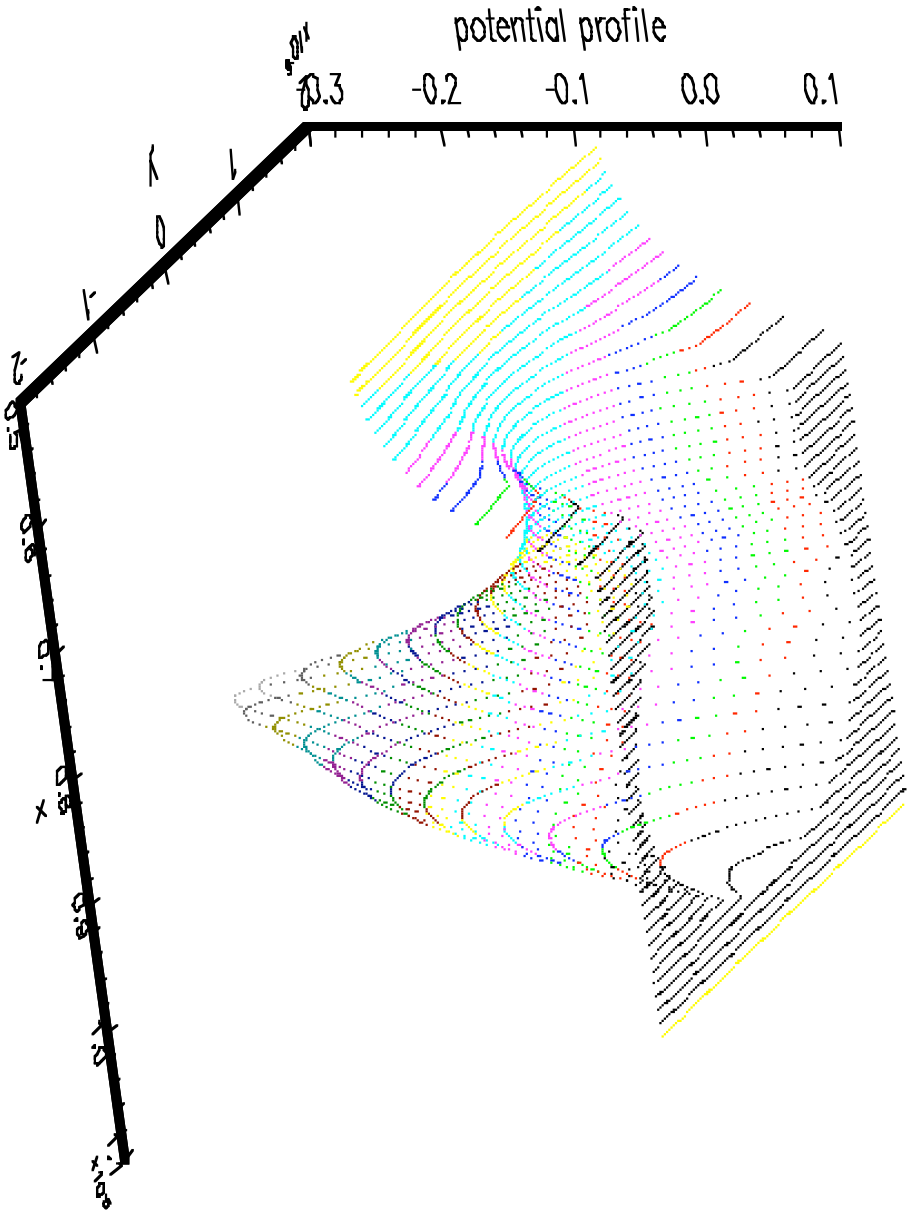
Monte Carlo simulations

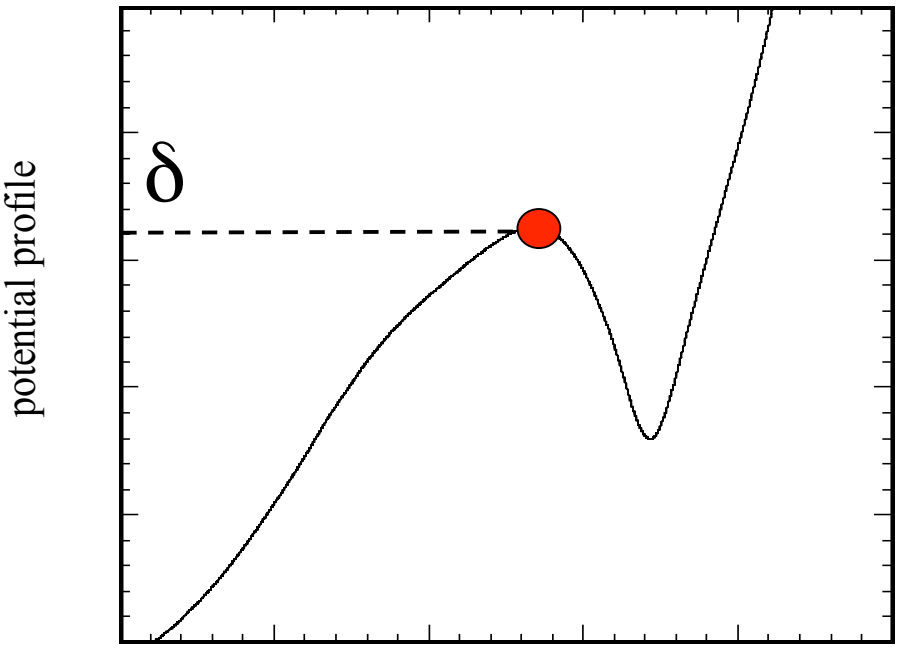
- The model
  potential profile found with simulation
  → simulation of the pyramidal island.
- Ground state of the configuration with N electrons is found with Monte-Carlo Simulations.
- Ground state energy vary linearly with reservoir right potential.


energy (eV)
N=19
N=20
N=21
N=22

Monte Carlo simulations

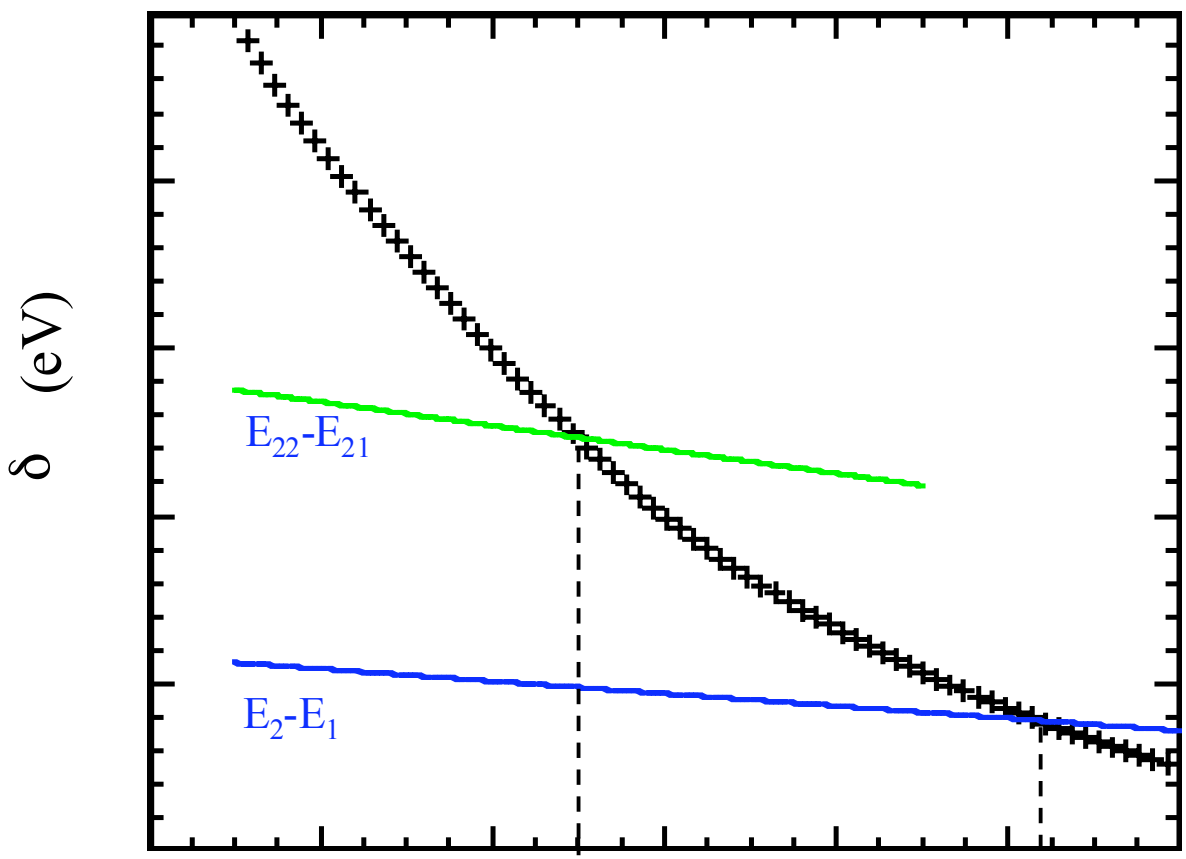
- The model
  potential profile found with simulation
  → simulation of the pyramidal island.
- Ground state of the configuration with N electrons is found with Monte-Carlo Simulations.
- Ground state energy vary linearly with reservoir right potential.
- Criteria when the electron leaves the trap?

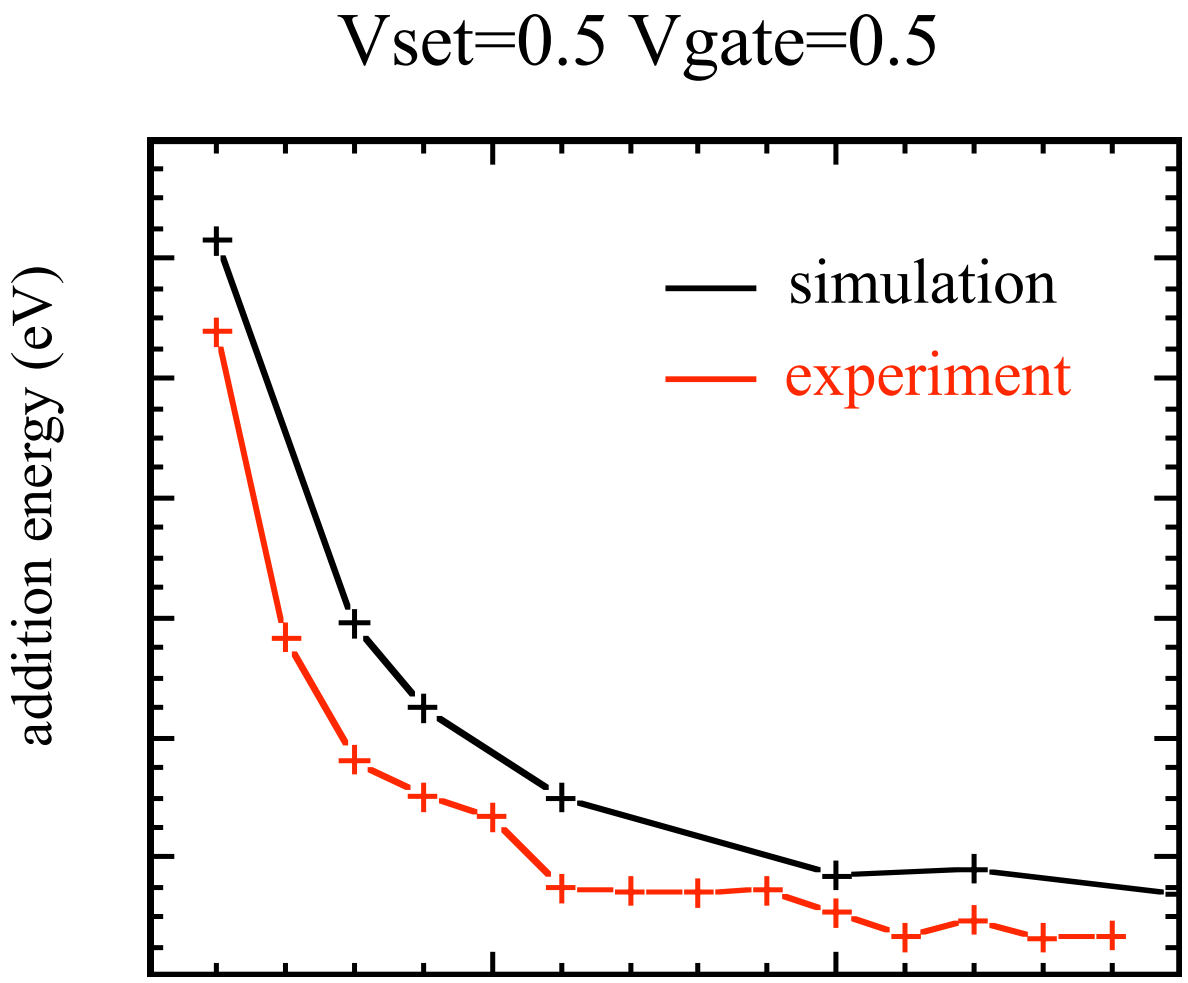

potential profile
-0.3
-0.2
-0.1
0.0
0.1
1
0
-1
-2

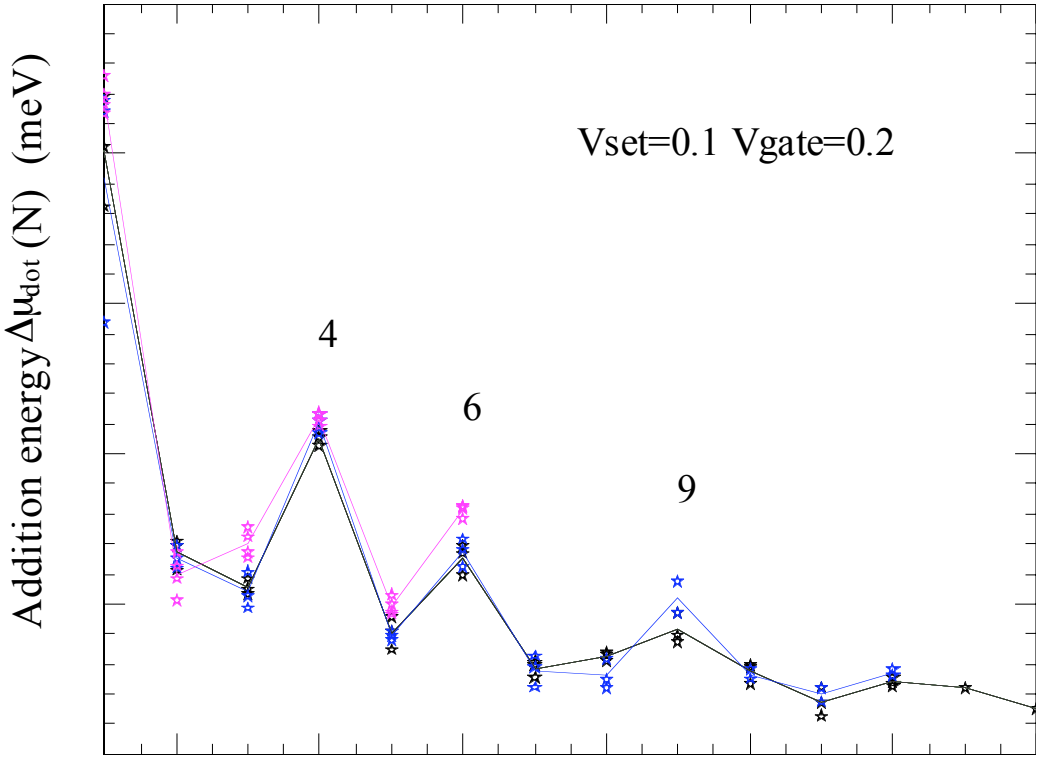


Potential profile = one particule energy

One electron leaves the trap when


δ (eV)
E22-E21
E2-E1


Vset=0.5 Vgate=0.5
addition energy (eV)
simulation
experiment



Clear magic numbers!

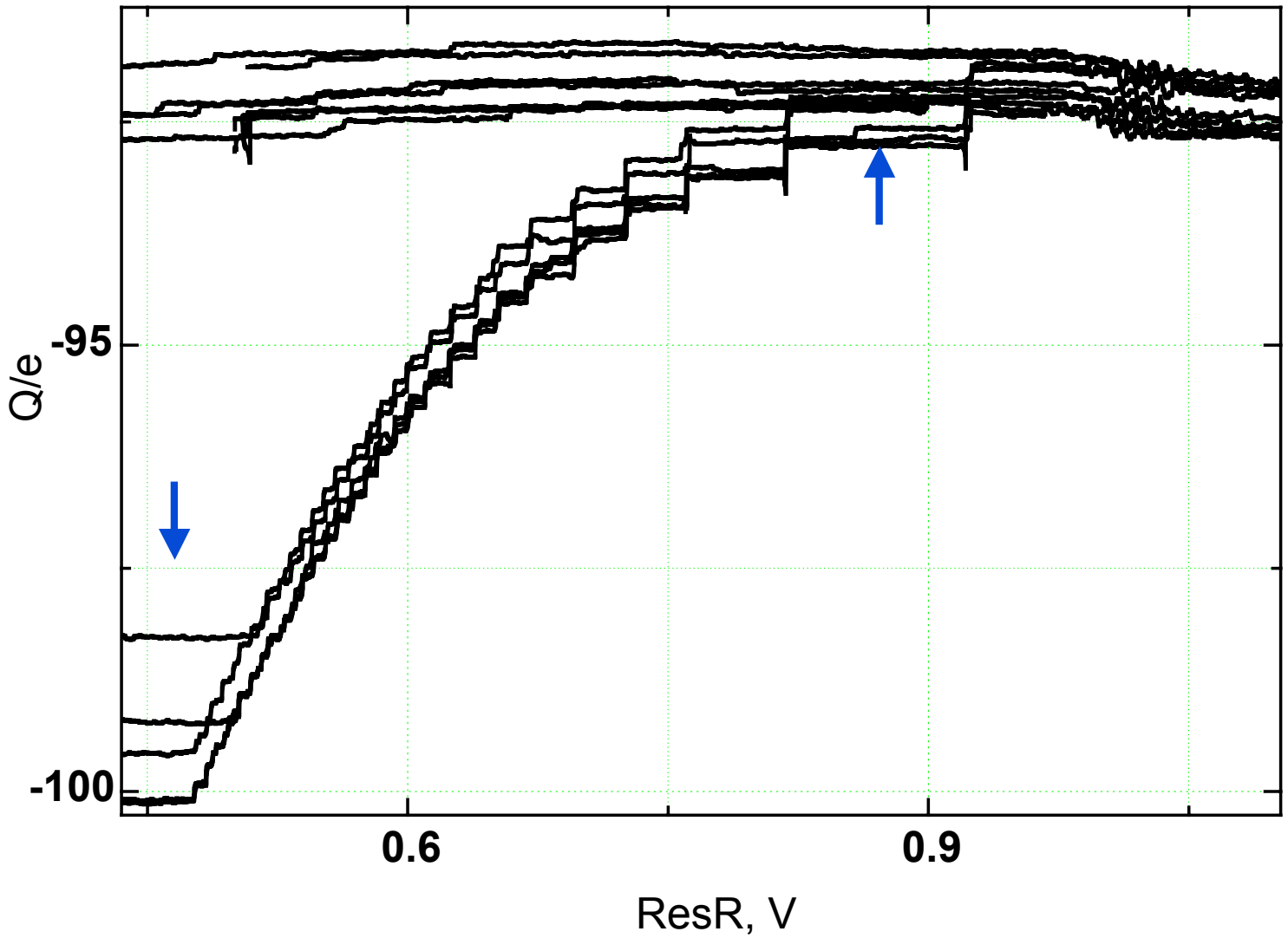
Cannot be explain with M-C simulation

Positive impurity increase locally the density

Structural transition in a finite classical two dimensional system

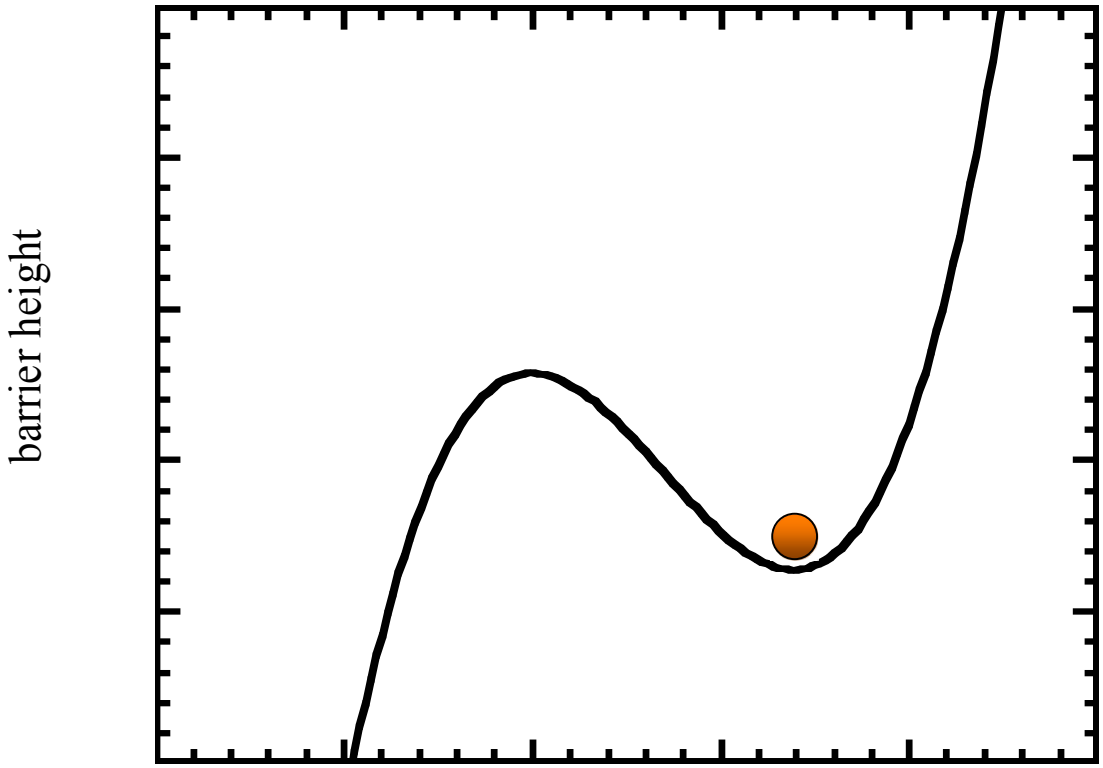
G. A. Farias and F. M. Peeters
solid state communication, **100**, *711 (1996)*

One by one observation

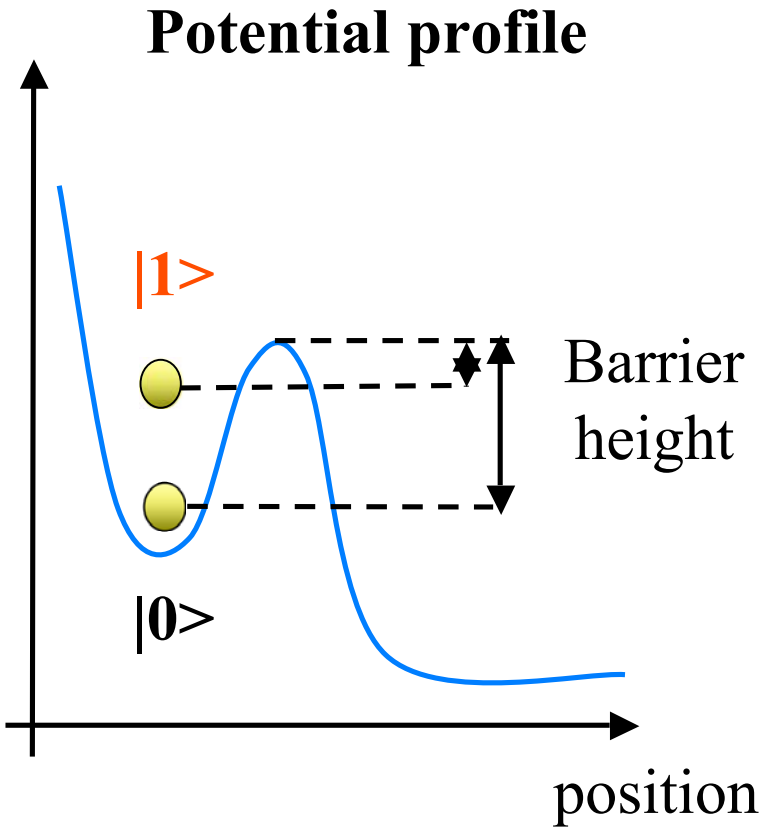


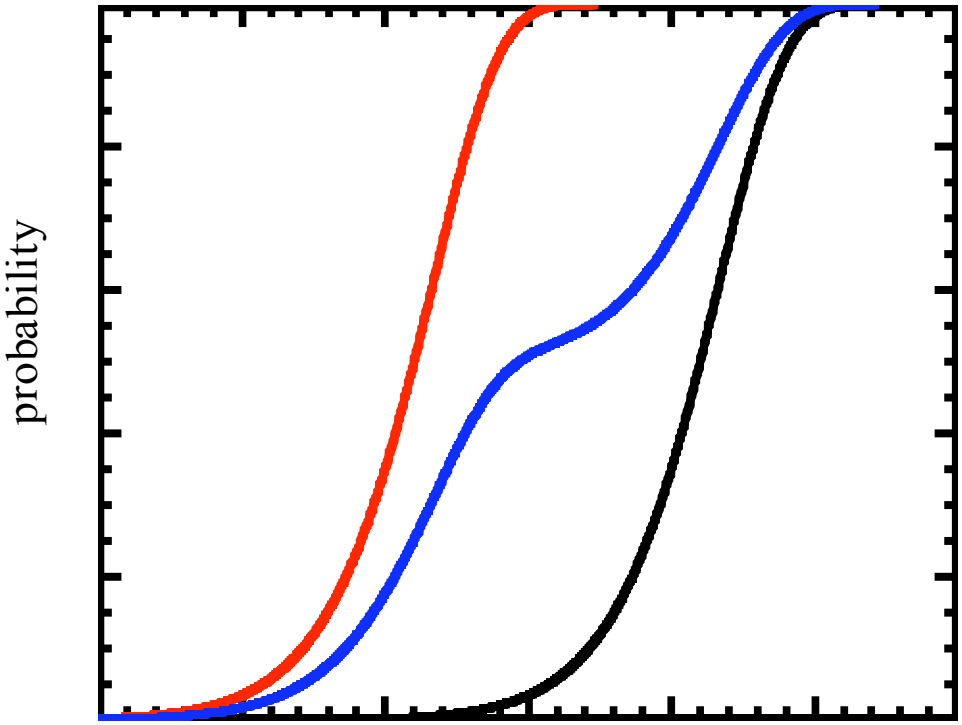
Probability of escape

- If the barrier is thin enough, the electron can tunnel.

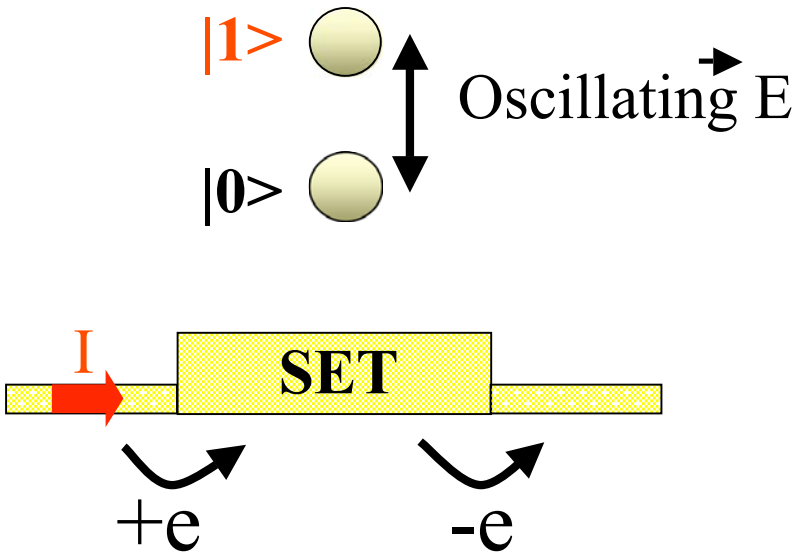


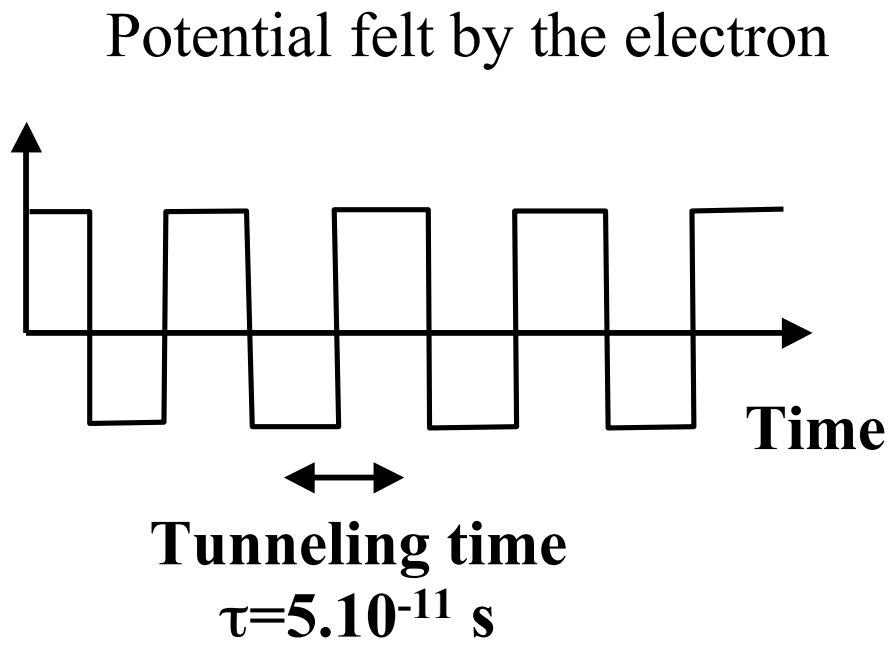
Quantum state evidence?





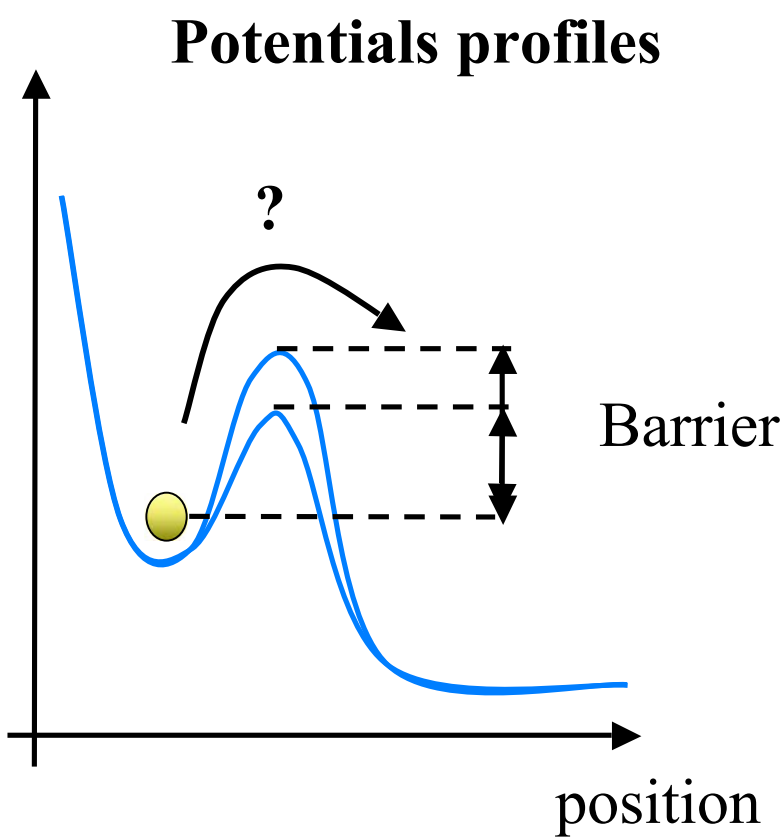
Existing to the first excited state





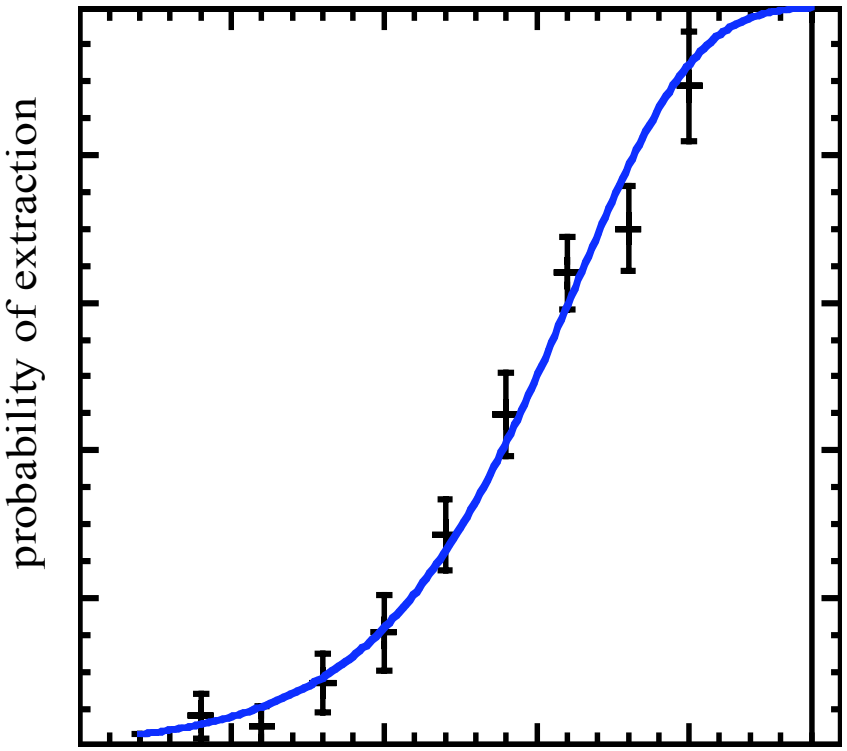
τ_{mix}=75 μs

measurement principles



1. **We choose a SET current value from 0 nAmp (no heating) to 50 nAmps.**
2. **We applied a voltage pulse to the right reservoir: the barrier height is reduce.**
3. **We check whether the electron is still in the trap or not.**
4. **2000-3000 tries for one escape curve.**

Temperature estimate



$p = 1-\exp(-\Gamma_0 \exp(-E_b/k_b T))$

$\Gamma_0 = \omega_0 \tau / 2\pi$

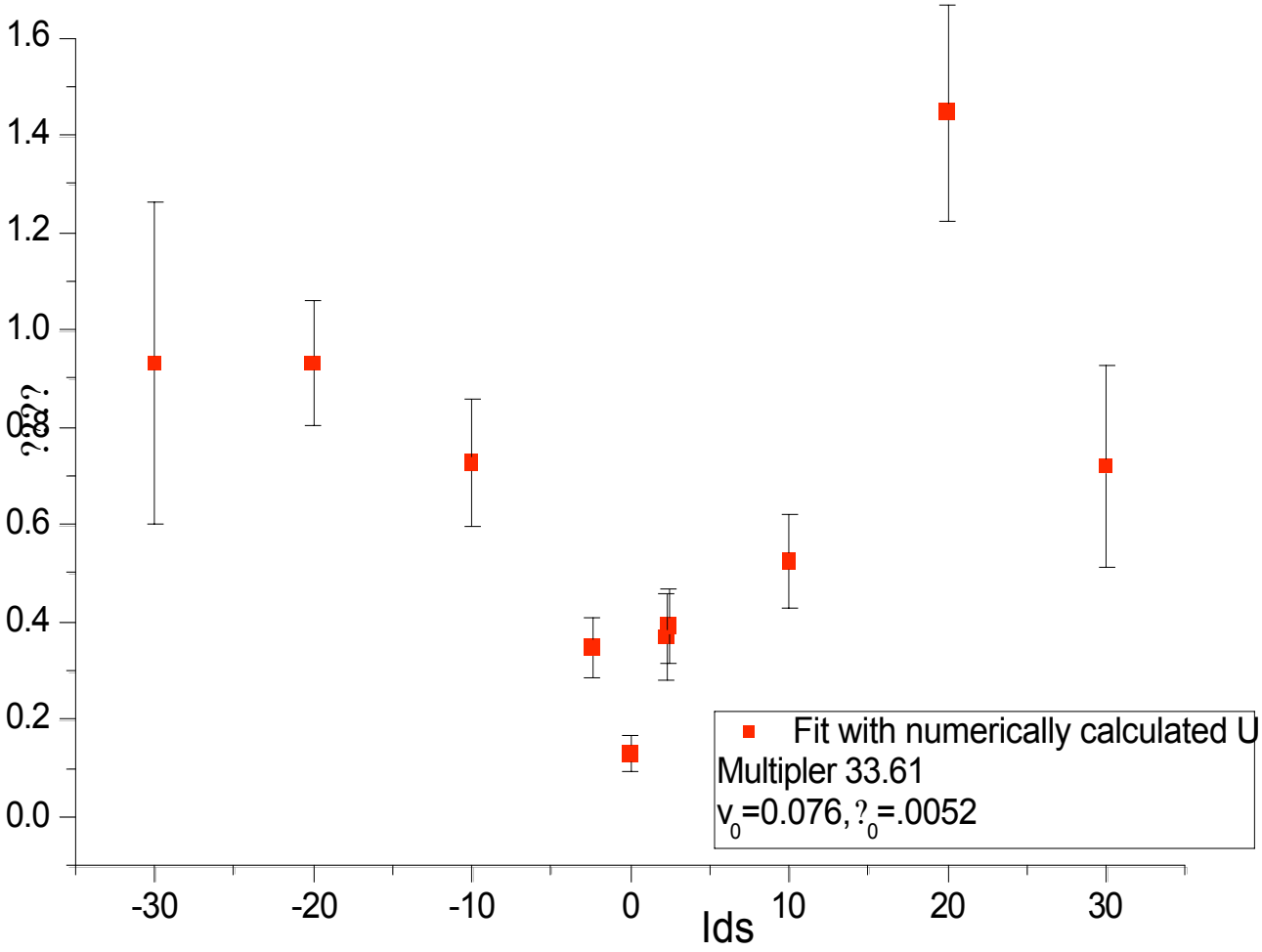
$\omega_0/2\pi \sim 30$ GHz trap frequency

τ pulse length

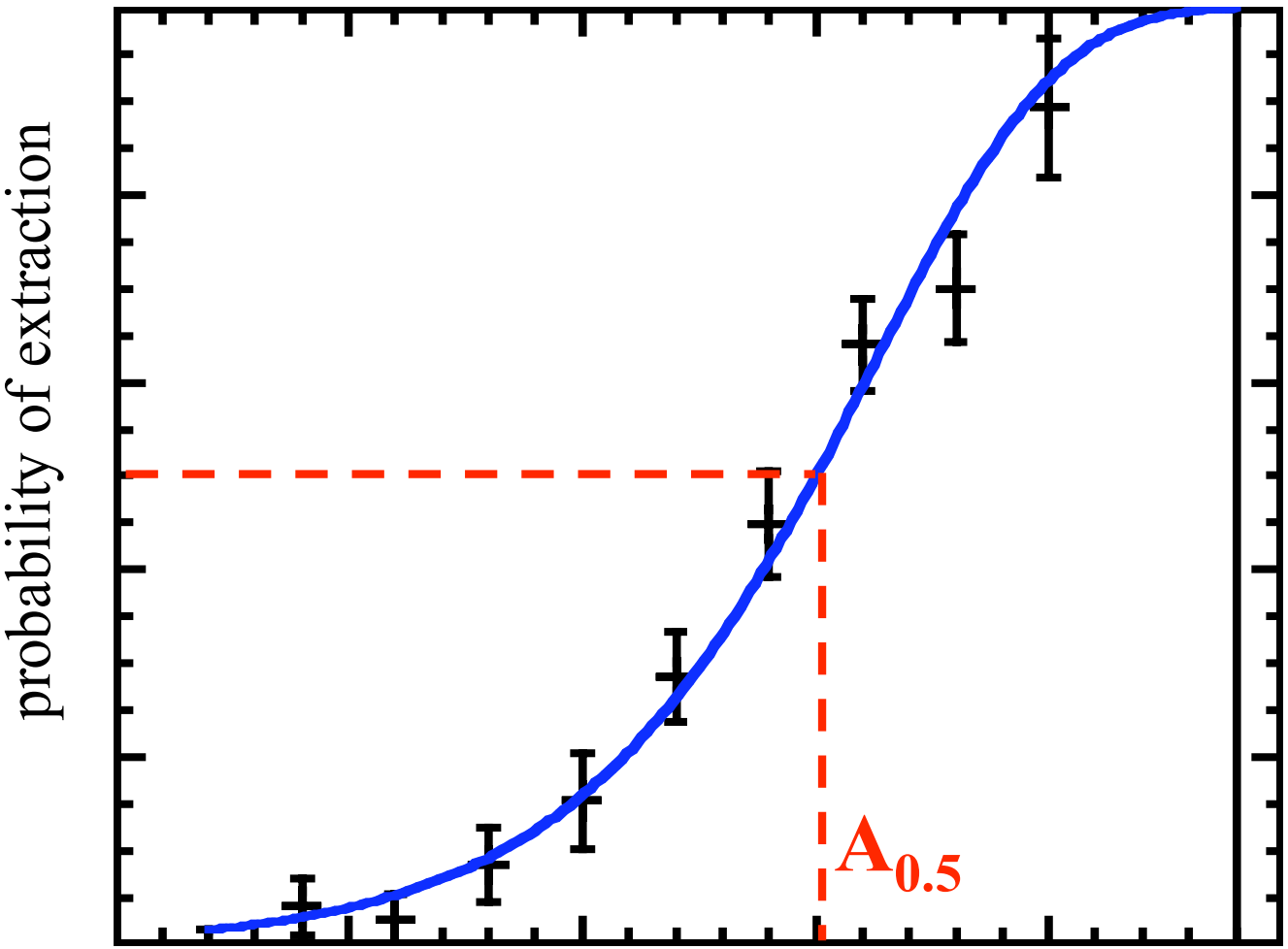
E_b barrier high

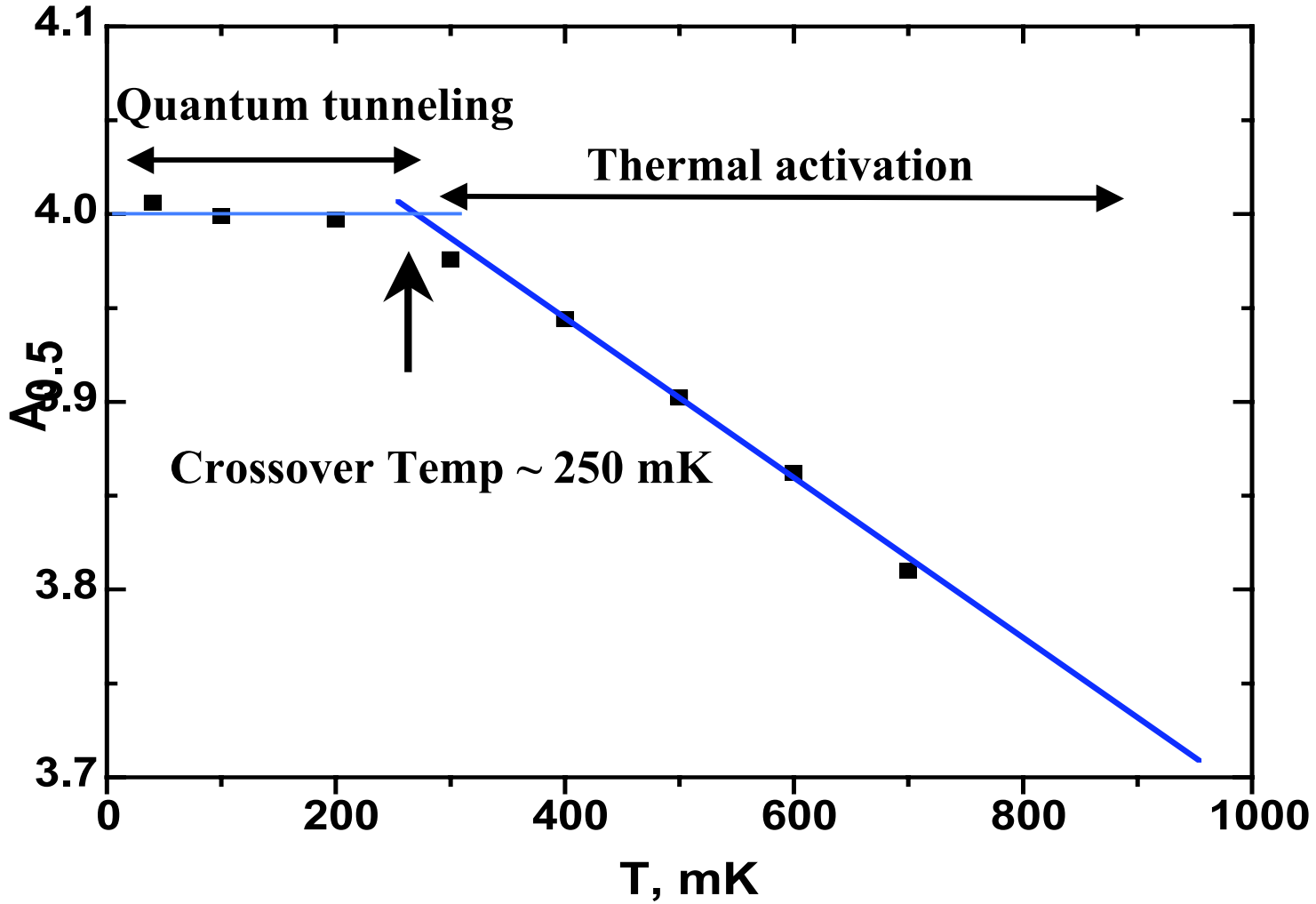
E_b and ω_0 estimated from simulations

Curve width with heating current

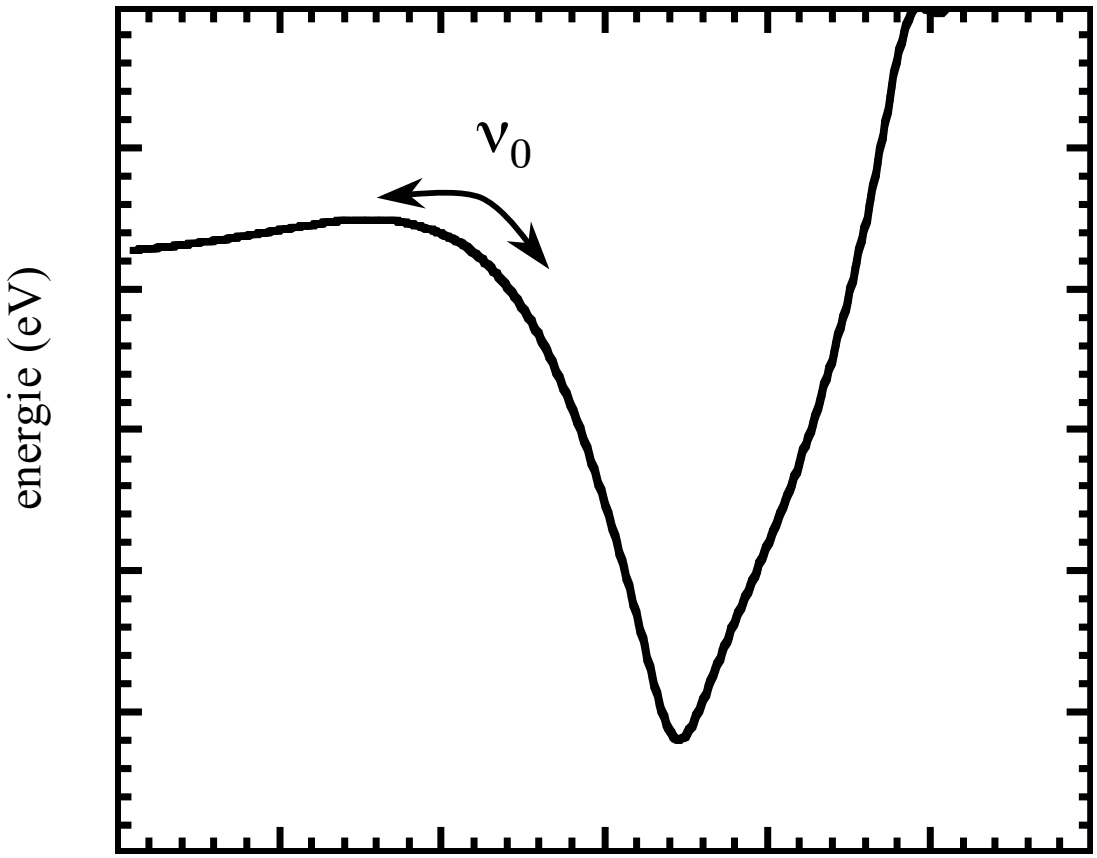


The pulse is applied during heating


probability of extraction
A0.5


Quantum tunneling
Thermal activation
Crossover Temp ~ 250 mK
A
4.1
4.0
3.9
3.8
3.7
0
200
400
600
800
1000
T, mK

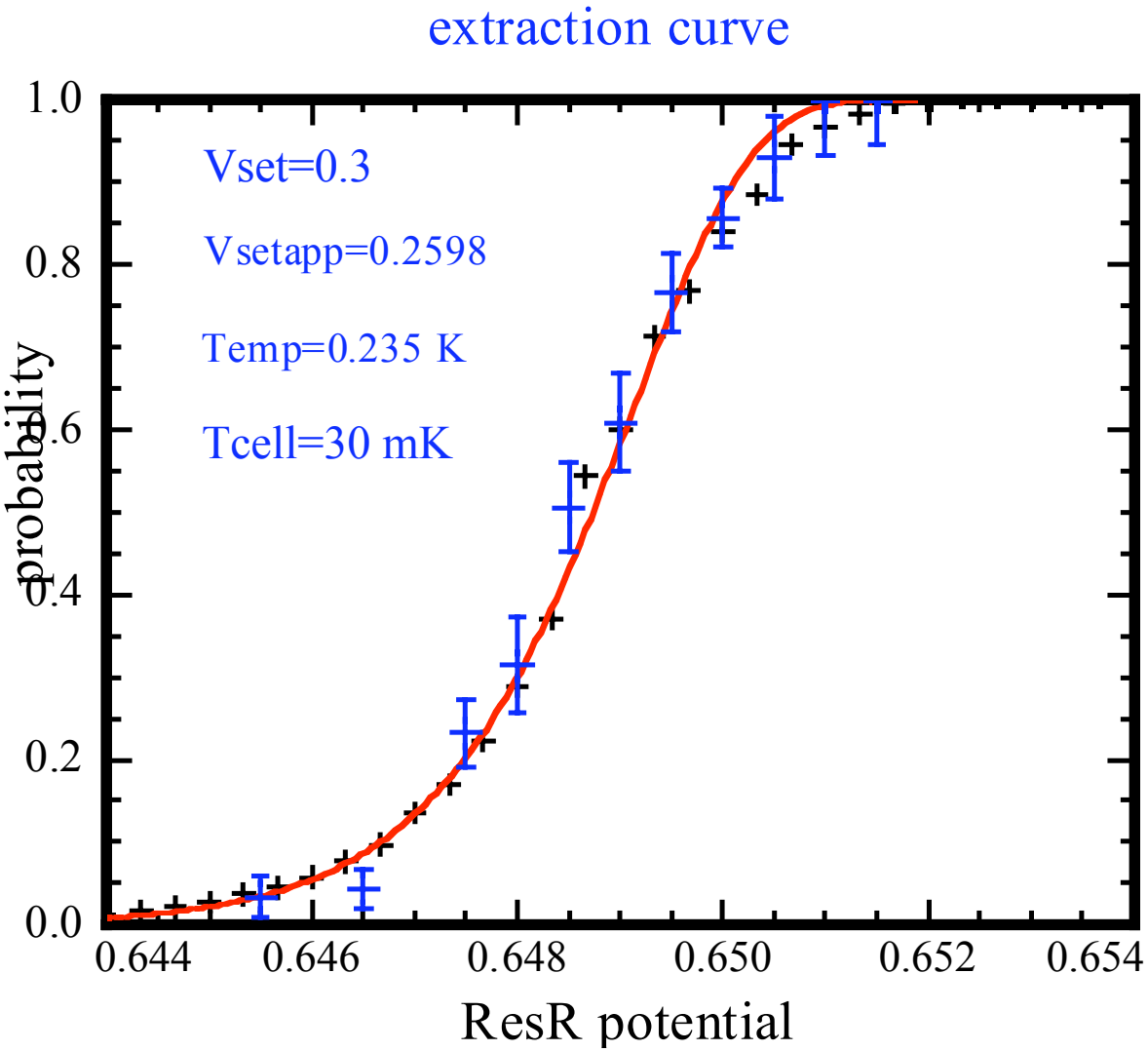
the frequency of the barrier



$\nu_0 \sim 30$ GHz
(before the pulse)

Cross-over temperature

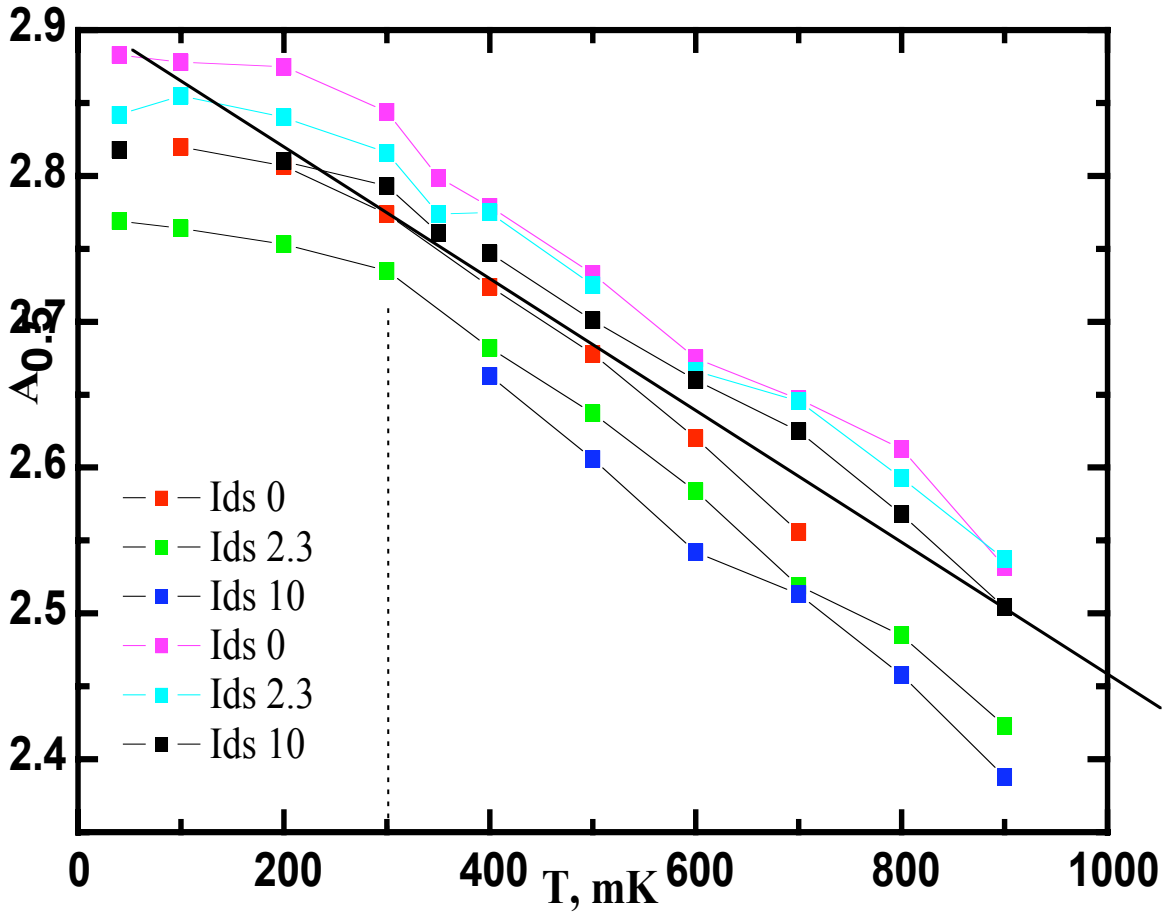
—— ~ 230 mK



Only one parameter is adjusted

→ Vset.

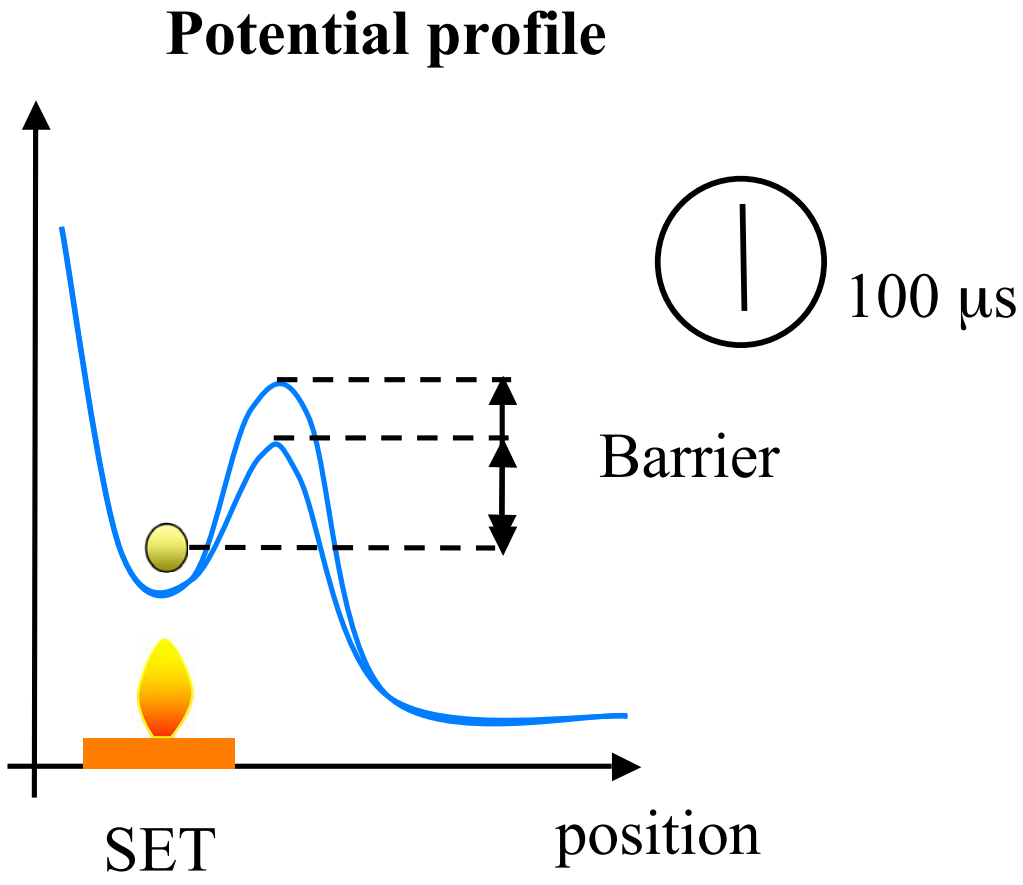
Contact potential between niobium and aluminium
the potential on the SET is not really known



No change when we heat the electron!

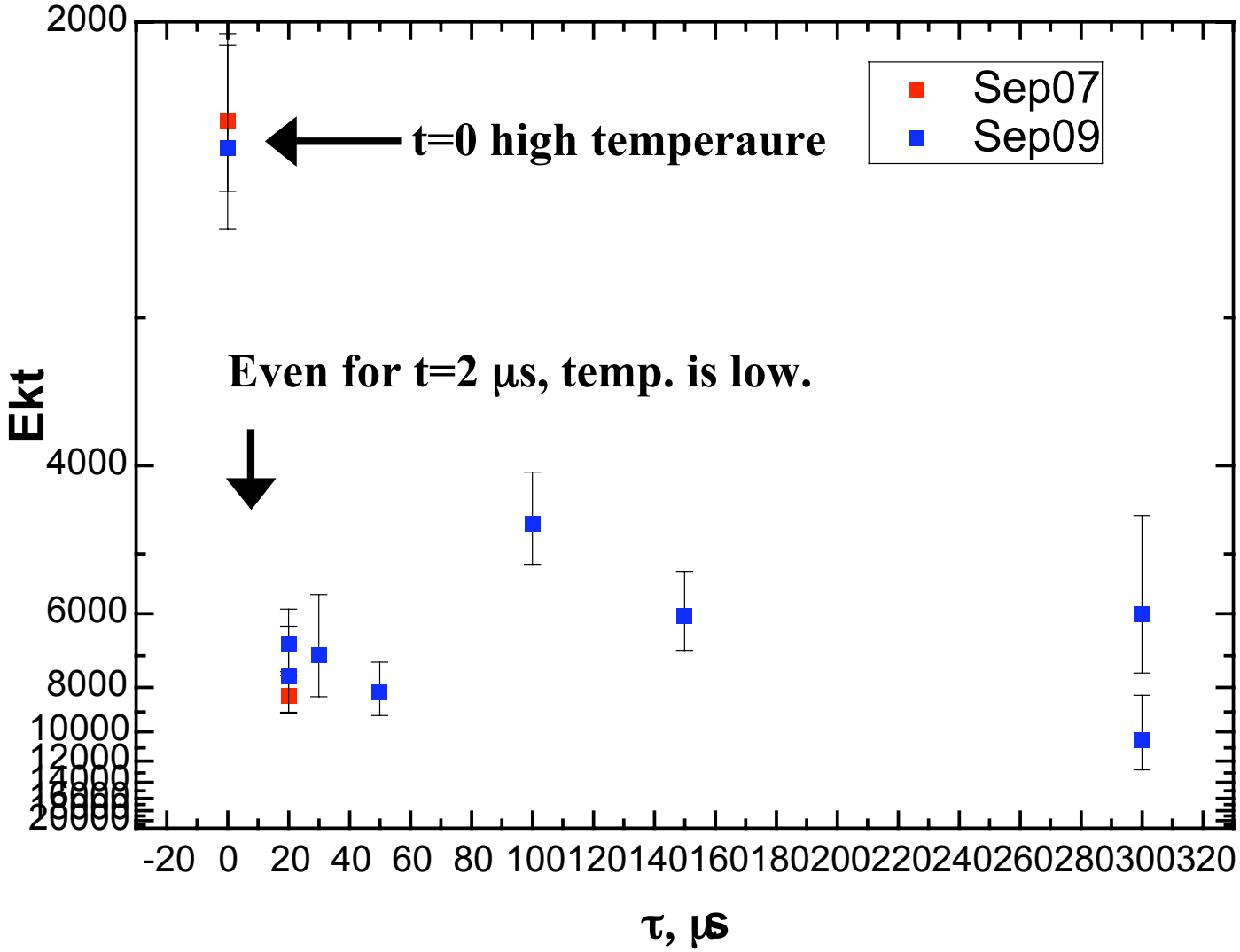
Need to probe the coupling between the electron and its environment

Coupling with environment

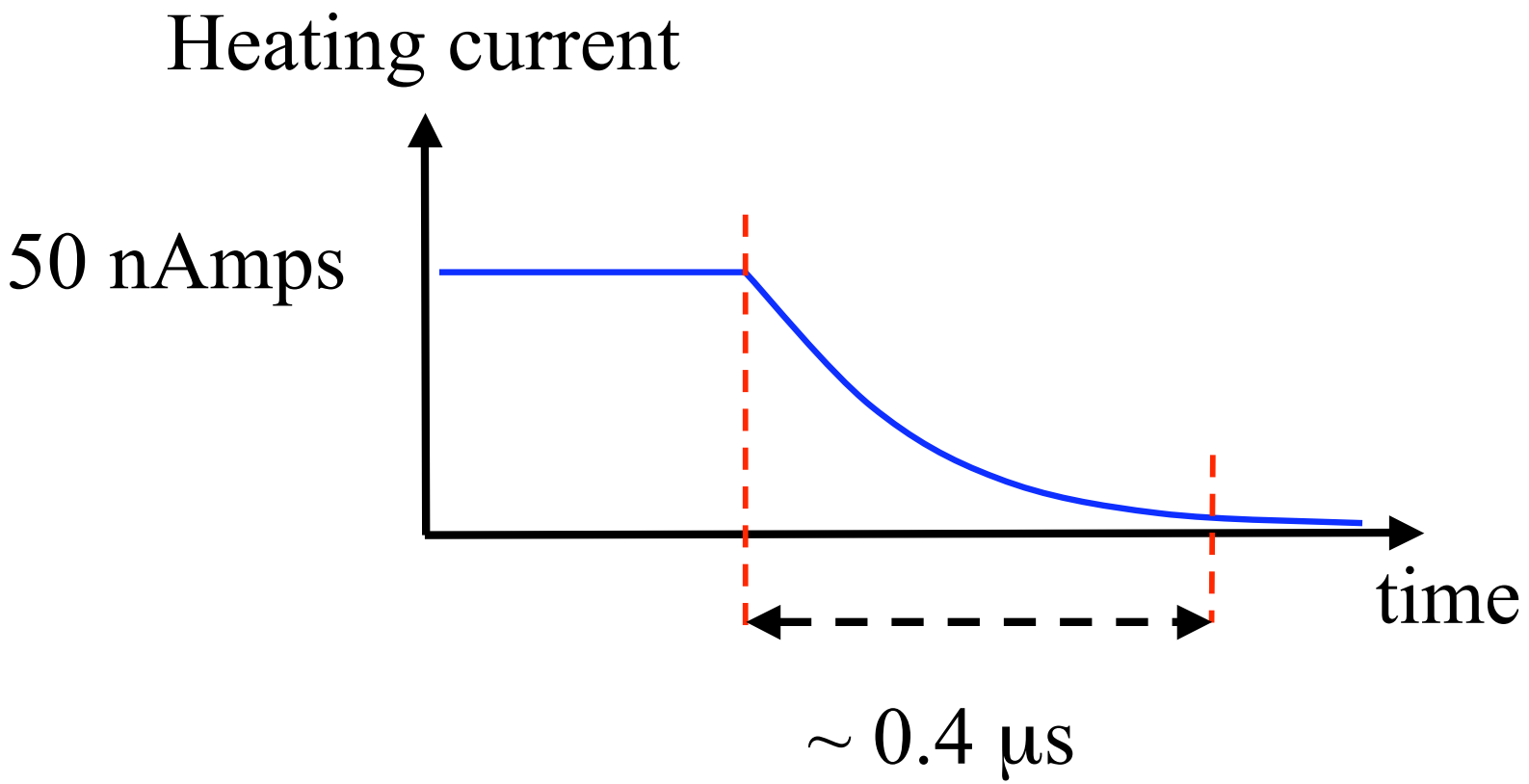


1. Heating for 300 ms with 50 nAmps.
2. Wait between 2 and 100 µs.
3. Applied the pulse on reservoir right.
4. Fit the curve. According to position and width of this curve get a number proportional to the temperature

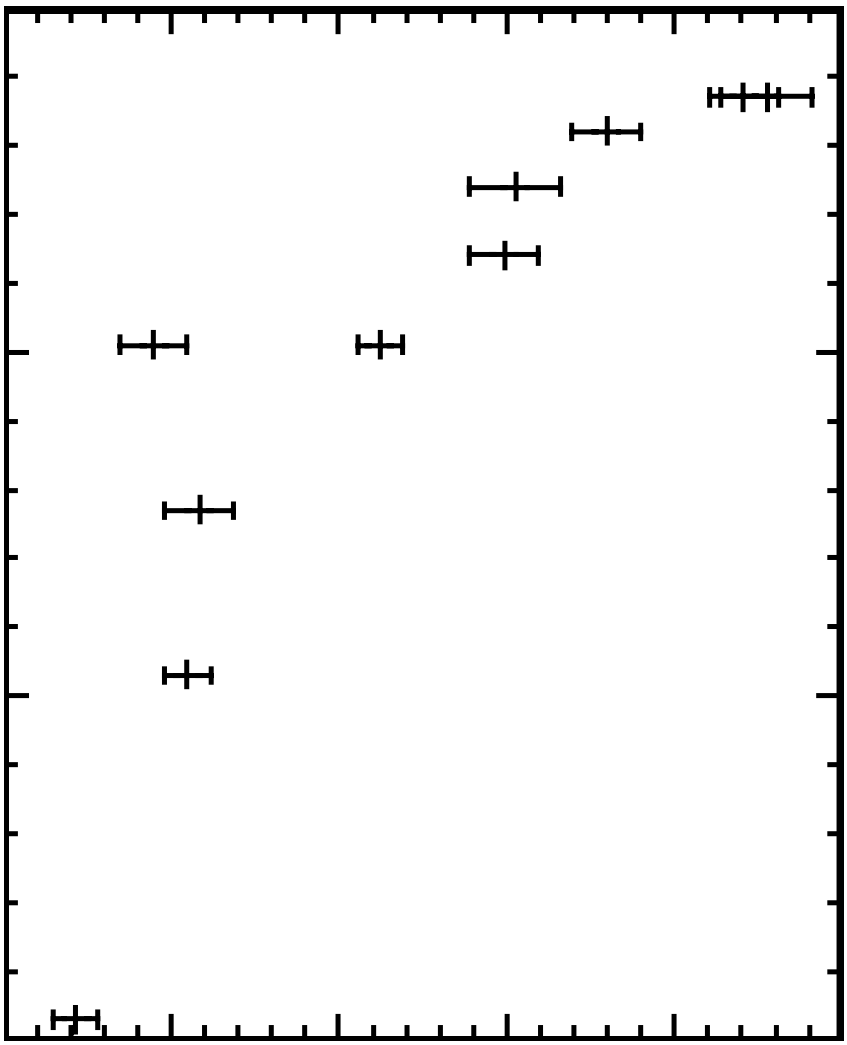
Coupling with the environment

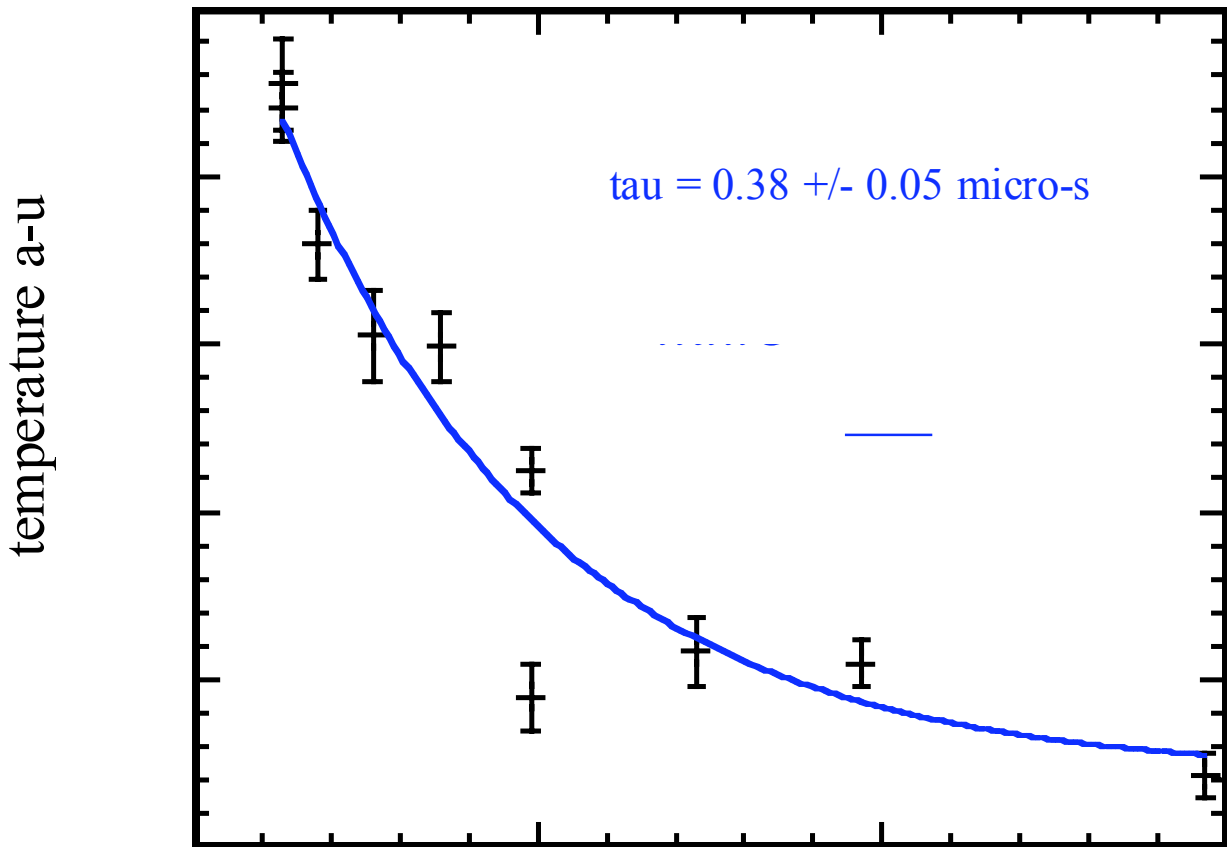


Heating pulse decay



temperature a-u




temperature a-u
tau = 0.38 +/- 0.05 micro-s

What can we say?

- Either the coupling with the environment is huge

Where does it come from?

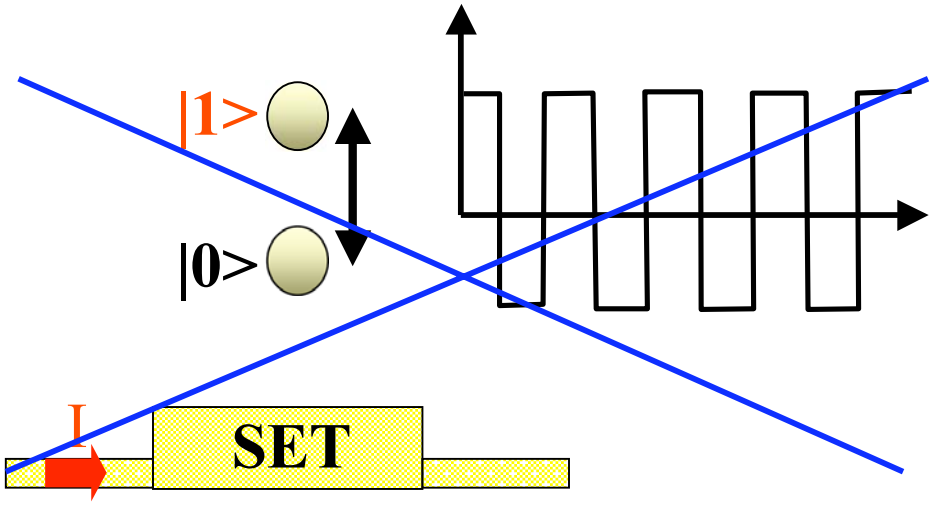
Coupling with phonons

- they induce modulations of the density. So they induce modulation of the image charge.
- This coupling depends highly with the electric field on the electron.
- In our case $\tau \sim 10\ \mu s$

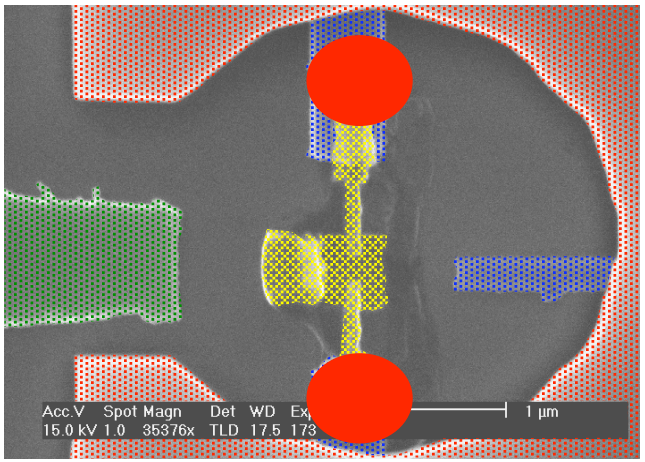
We maybe tried the smallest electric field as we could to keep the electron in the trap!

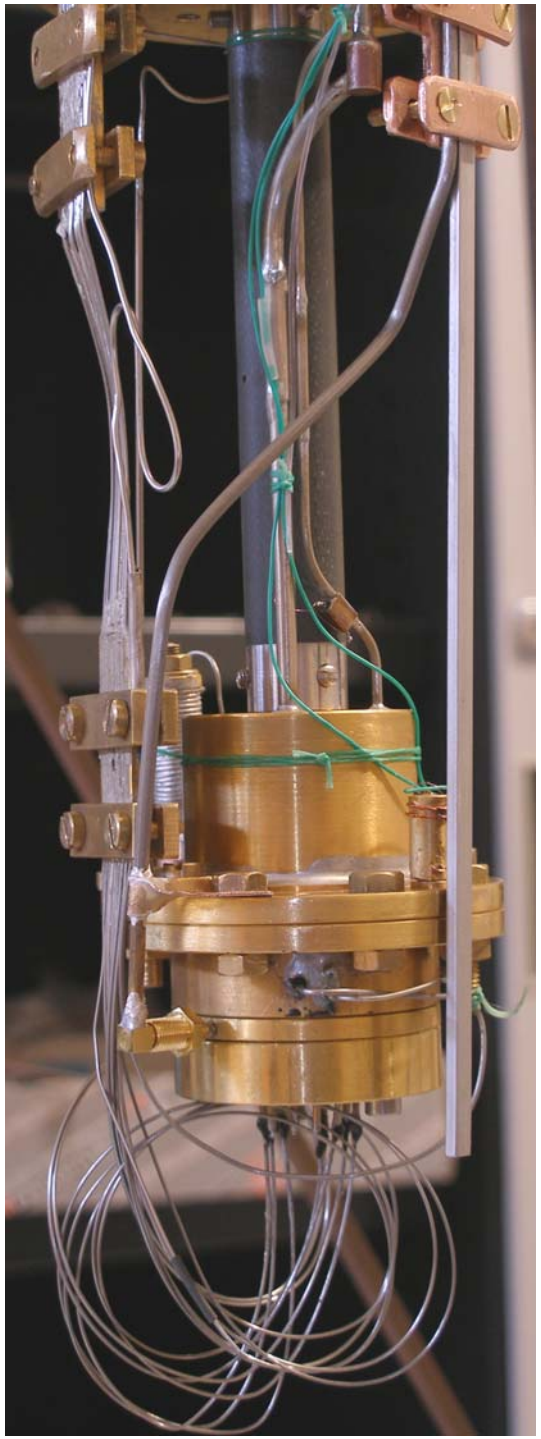
What can we say?

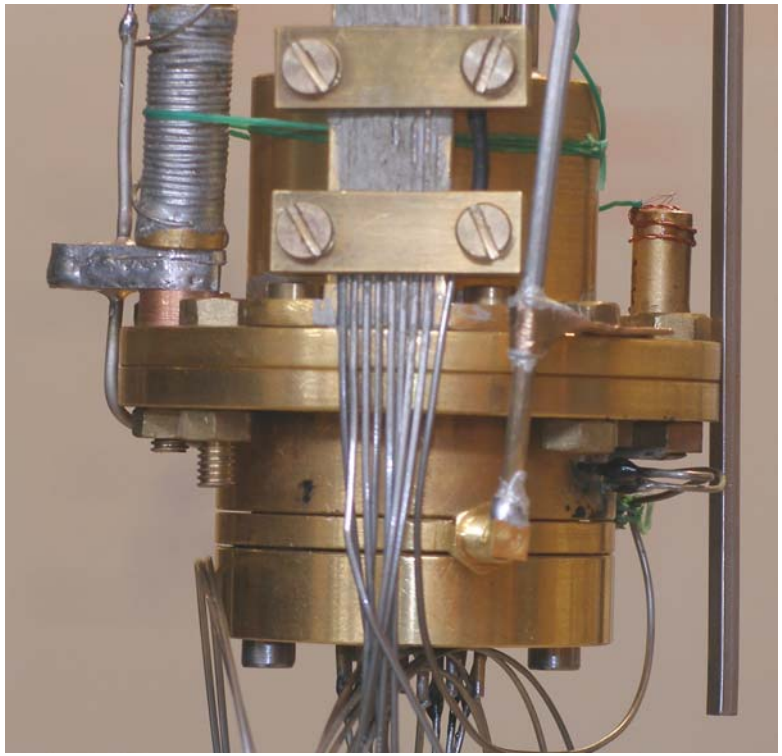
- Either the coupling with the environment is huge
- Or the picture of the heating procedure is too naïve



Dynamical force?



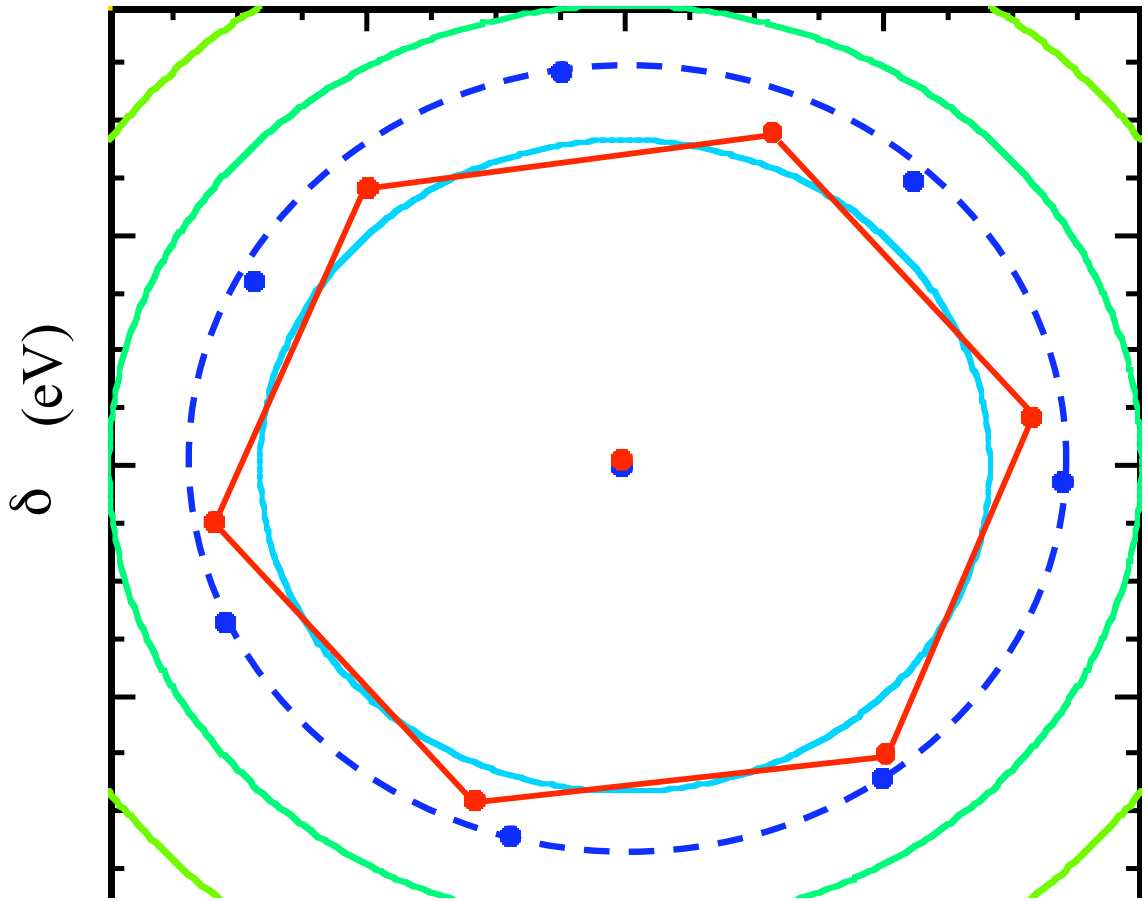




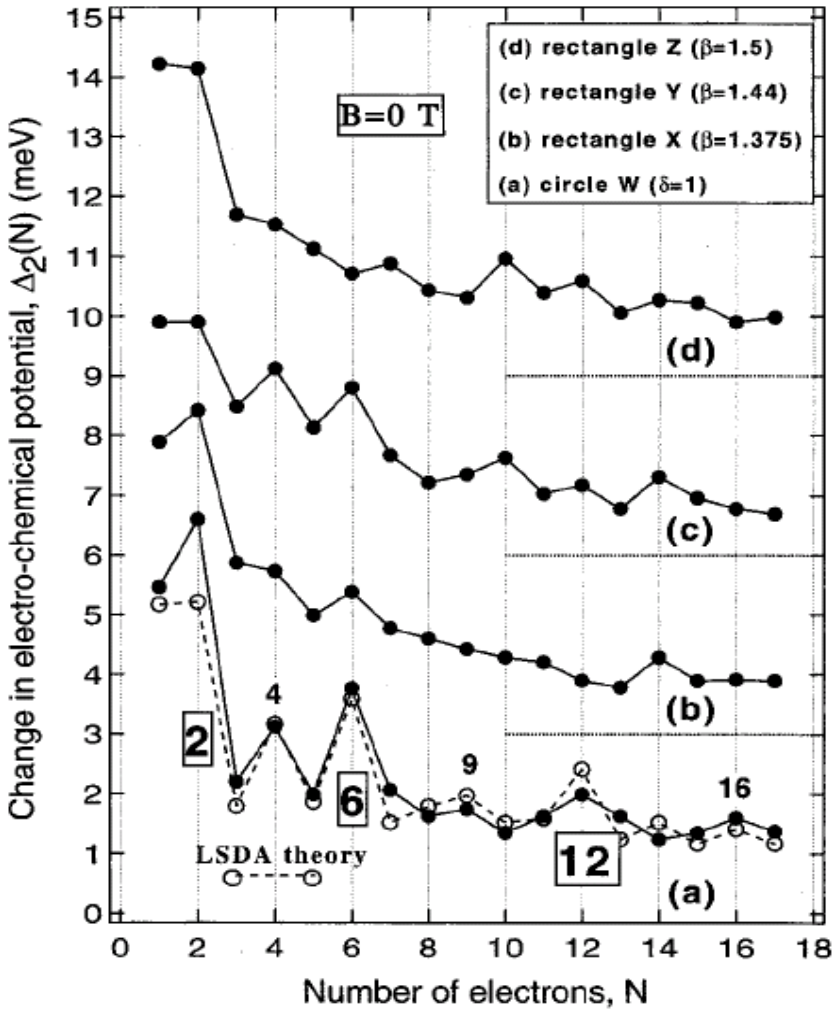
Two wave-guids:

~ 40 GHz → parrallel levels

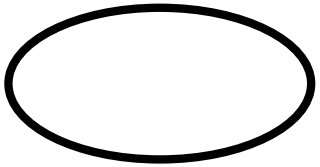
~ 120 GHz → perpendicular levels


δ (eV)

Evolution with deformation

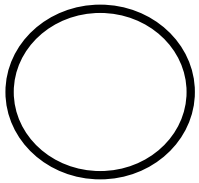


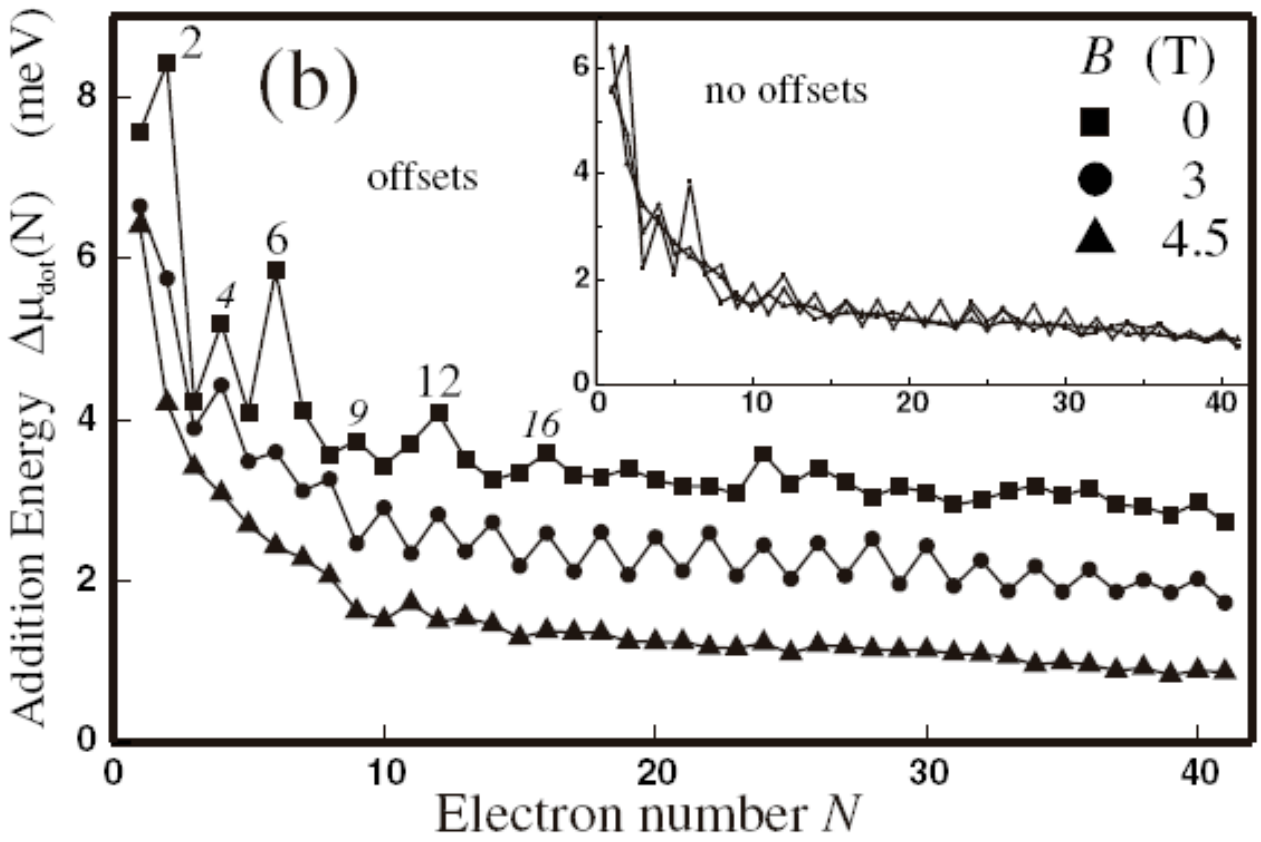
ellipsoïdal



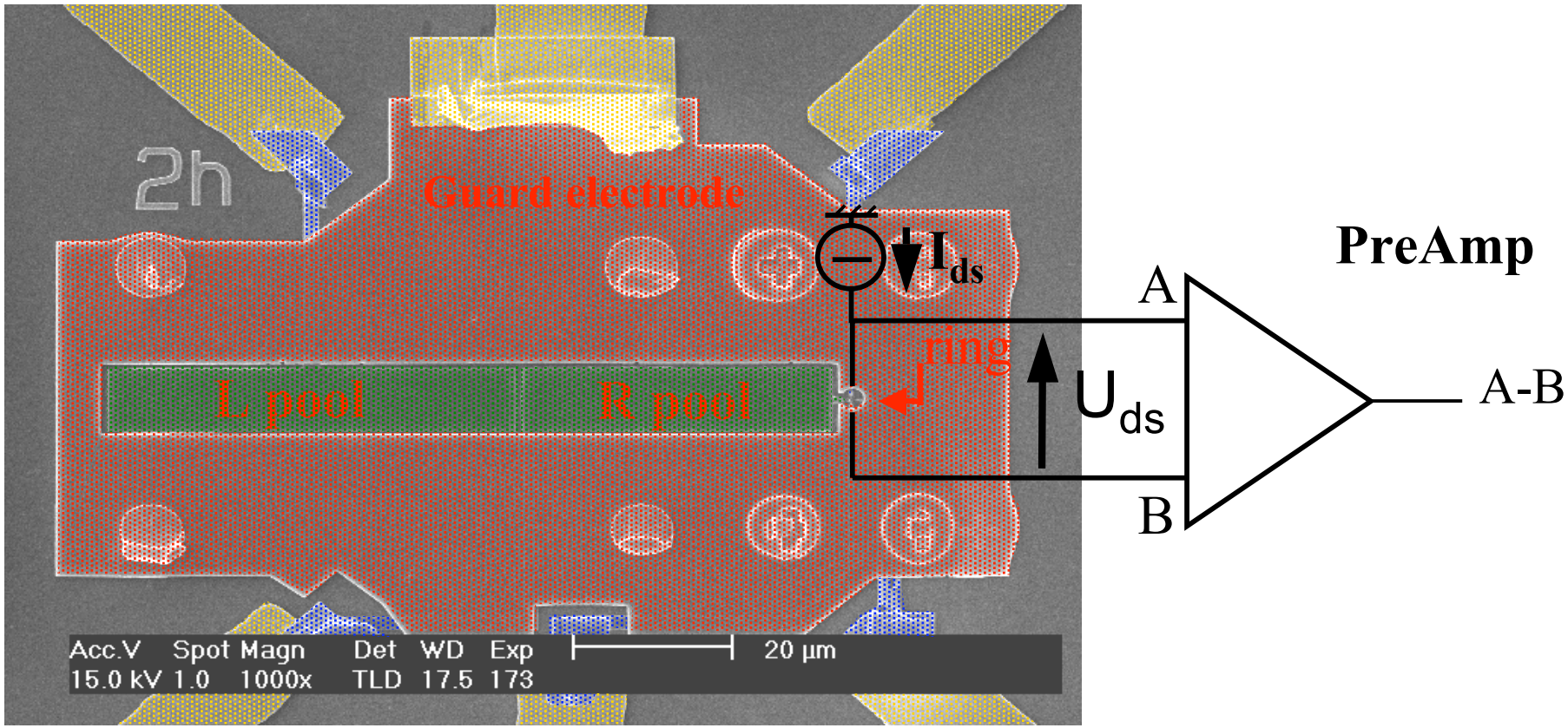
Increase of the deformation

circular



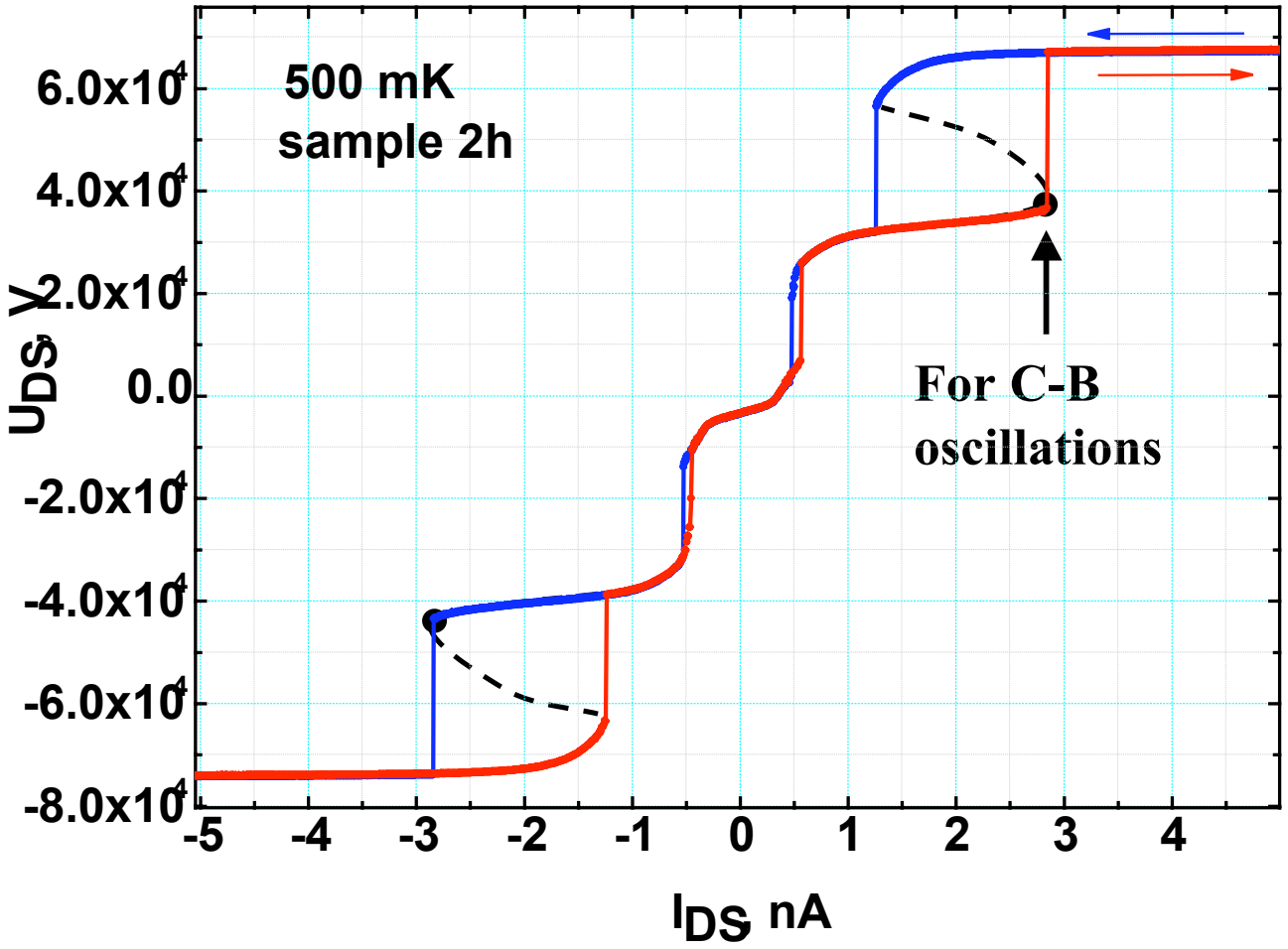

(b)
offsets
no offsets
B (T)
0
3
4.5
2
4
6
9
12
16
Addition Energy Δμdot(N) (meV)
Electron number N
0
2
4
6
8
10
20
30
40

Bias and IV characteristic



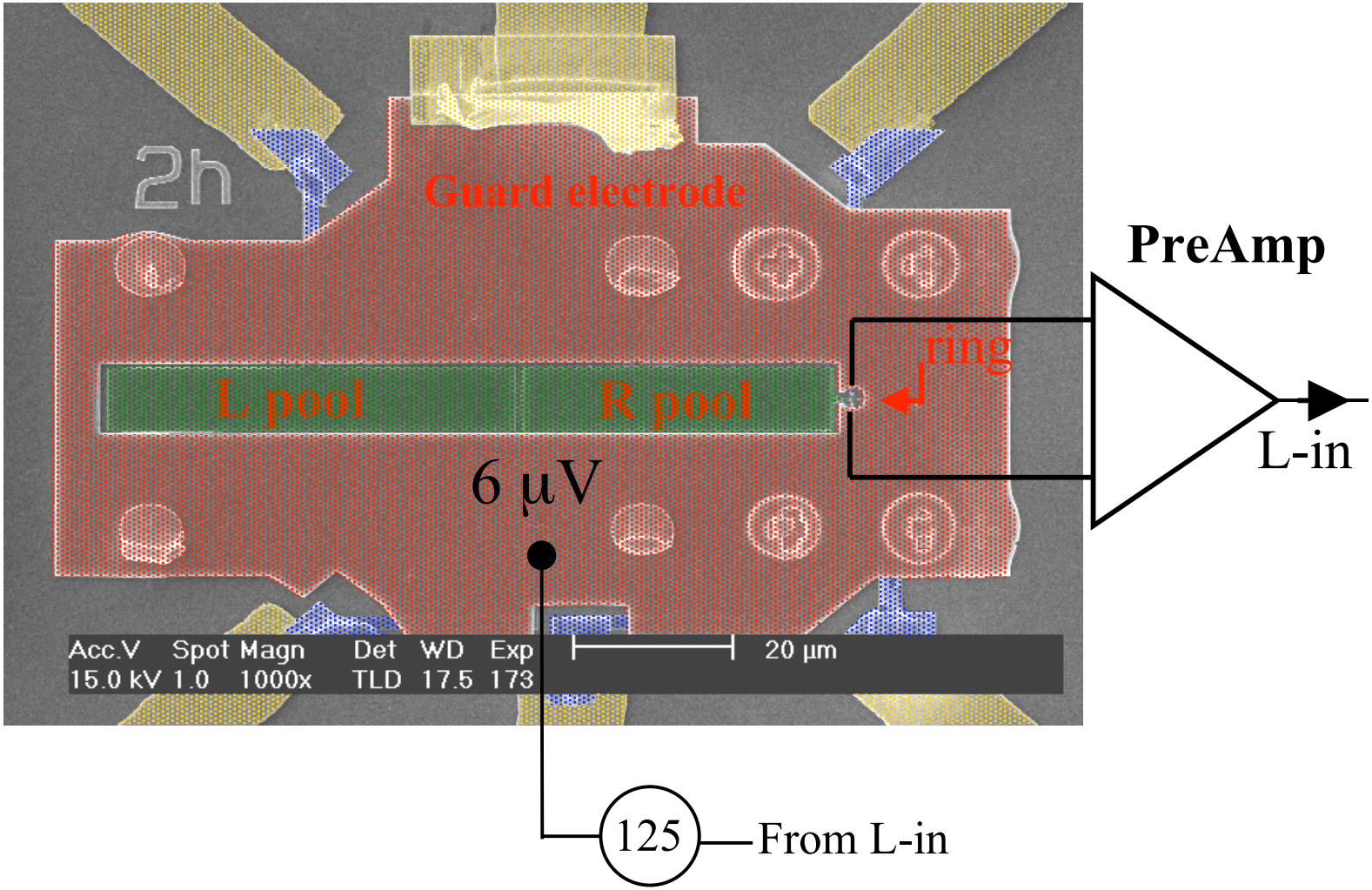
the SET is current bias

IV Characteristic



Measurement

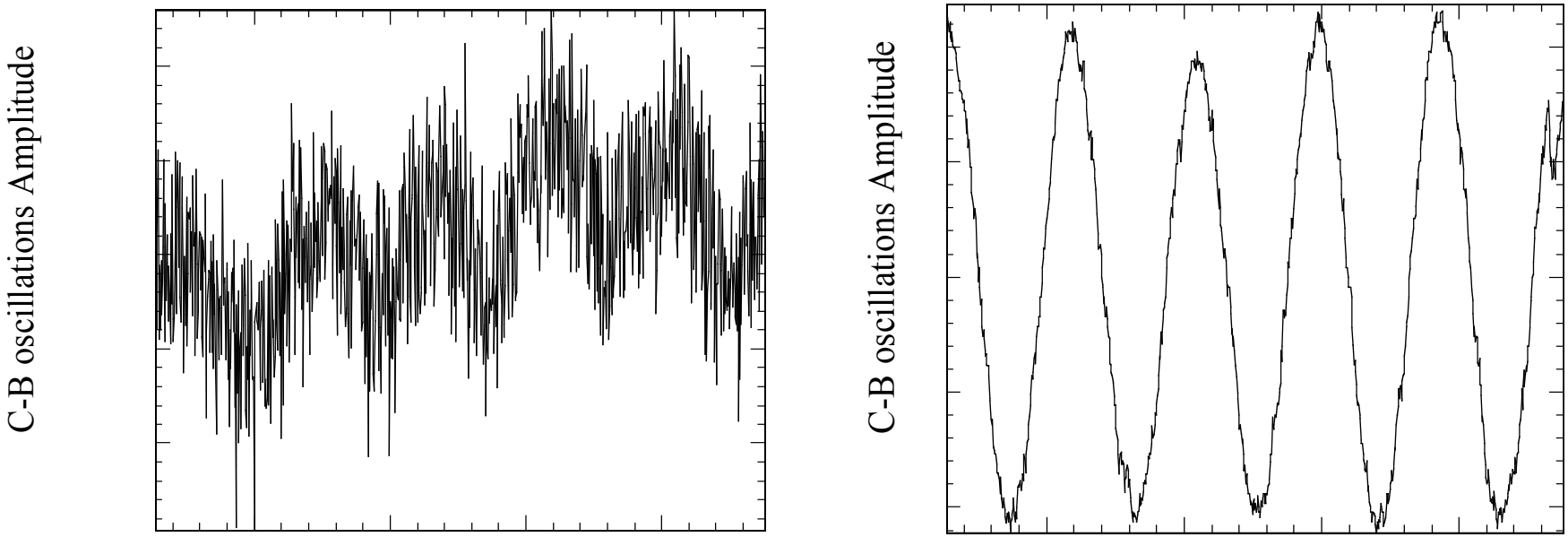
- L-in technique: 125 Hz, 6-30 μV applied to the guard



C-B oscillations

Raw oscillations

From L-in

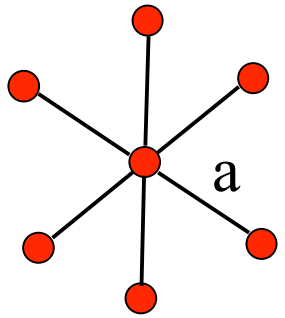


I_{ds}=2.6 nA

Some properties of this kind of quantum dots

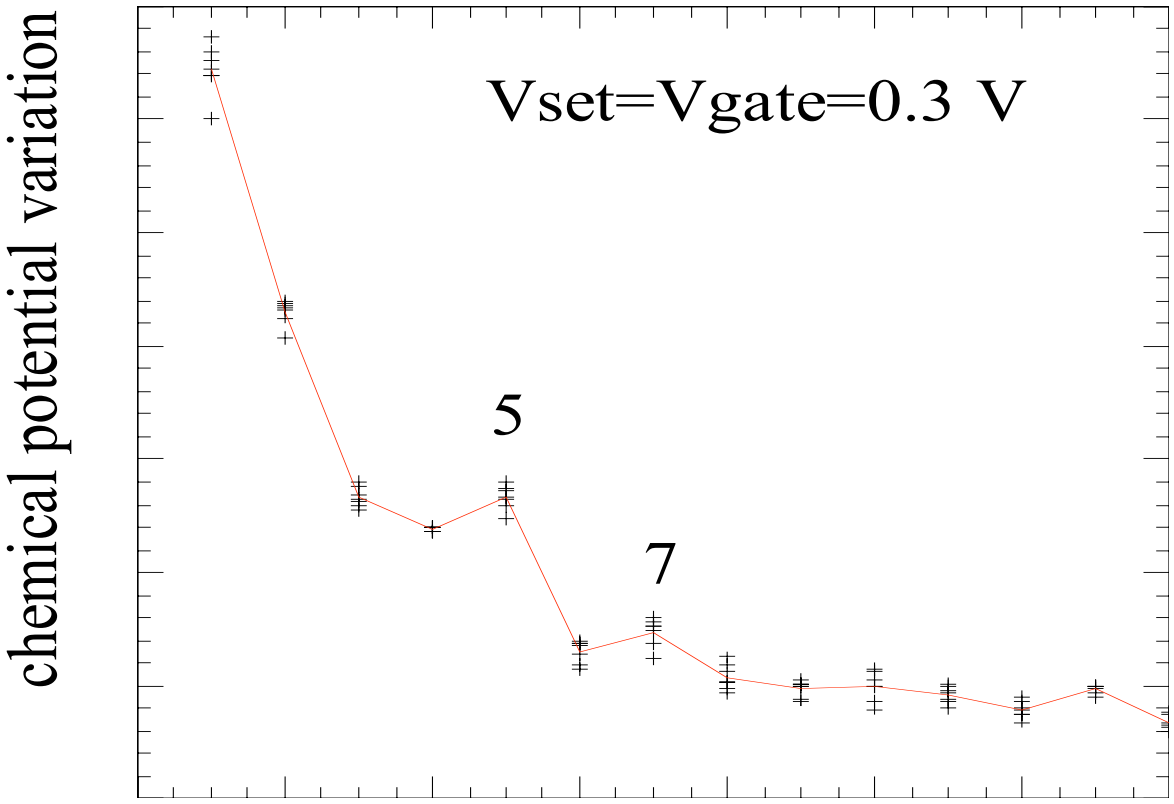
- Classical point of view: competition between thermal fluctuations and coulombian interaction
- for $n=10^{14}$ transition temperature $Tc=2.5$ K
- Working temperature: from 50 mK to 1K

Gas parameter



- Measure the competition between quantum fluctuations and Coulombic interaction
- For $n \sim 10^{14}\ m^{-2}$ $a \sim n^{-1/2} \sim 0.1\ \mu m$
- typical coulomb energy
- Typical kinetic energy (Fermi energy)
- $r_s \sim 2000$ $r_s^{cri} \sim 30$ Coulombic interaction is dominant
- Semiconductors qdots $r_s \sim 2$

potential profile
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
potential profile
1
0
-1
-2
x
0.5
0.6
0.7
0.8
0.9
1.0
1.1


chemical potential variation
Vset=Vgate=0.3 V
5
7