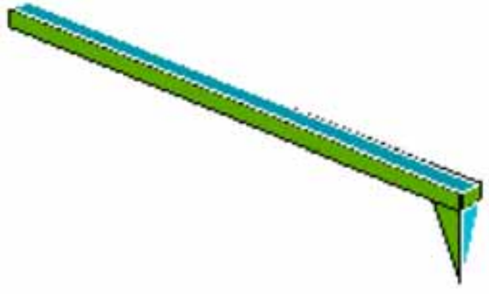
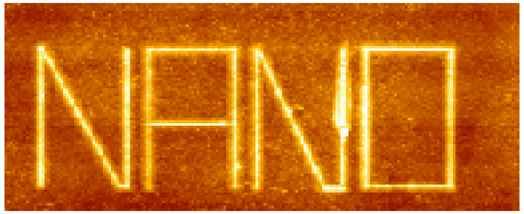
Electron counting with quantum dots



Klaus Ensslin



Solid State Physics ETH ***Zürich***

with
S. Gustavsson
I. Shorubalko
R. Leturcq
T. Ihn

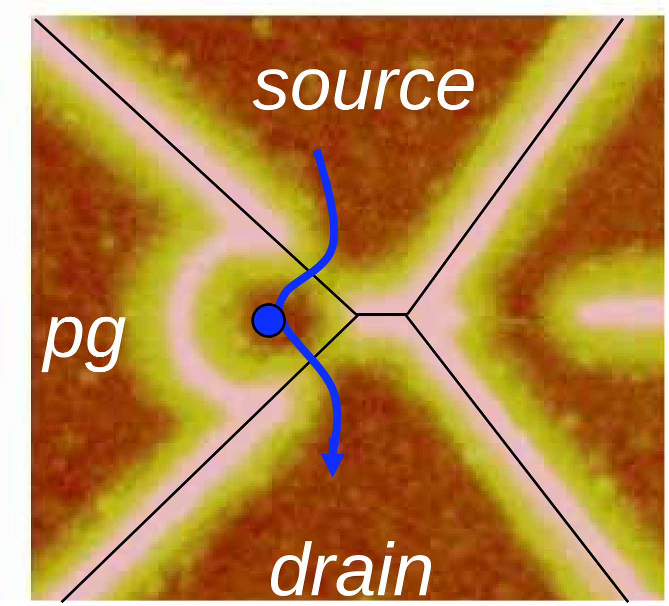
A. C. Gossard UCSB

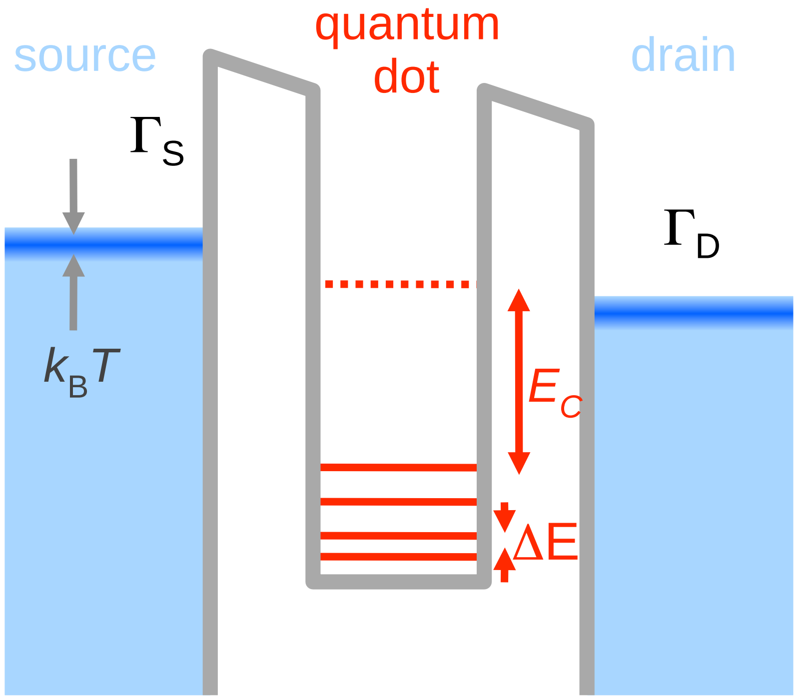
Time-resolved charge detection

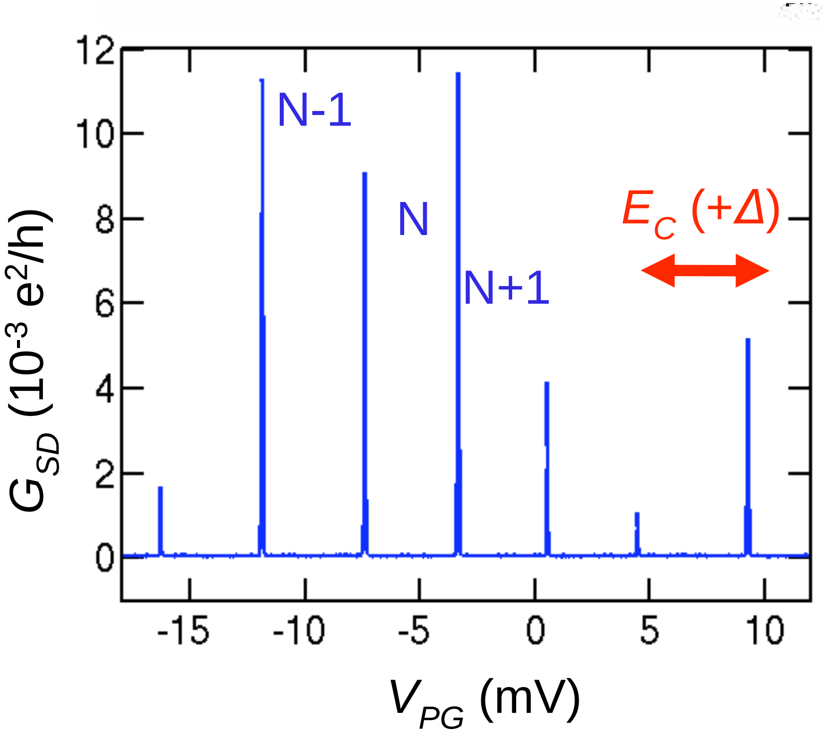
Single photon detection

Time-resolved single electron interference

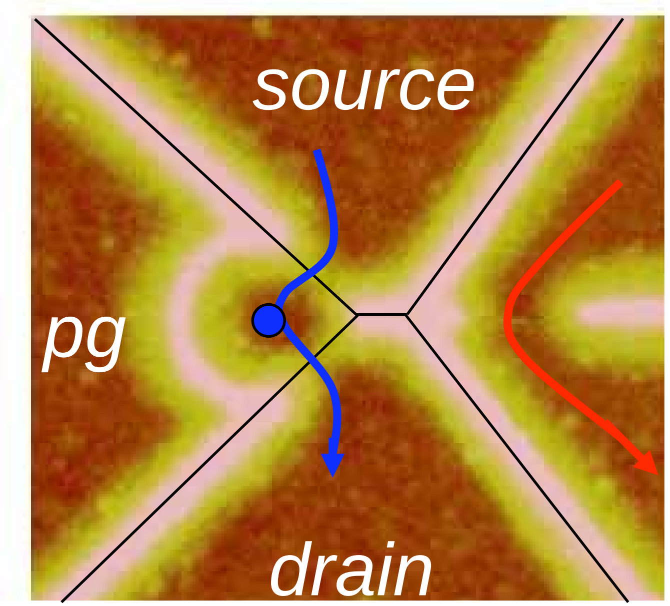
Spectroscopy of electronic states

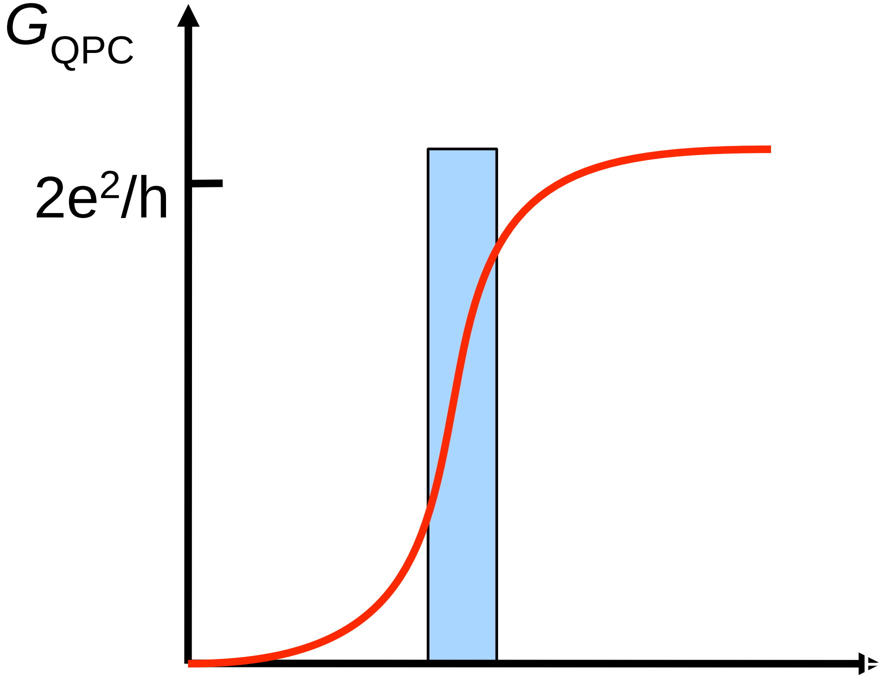


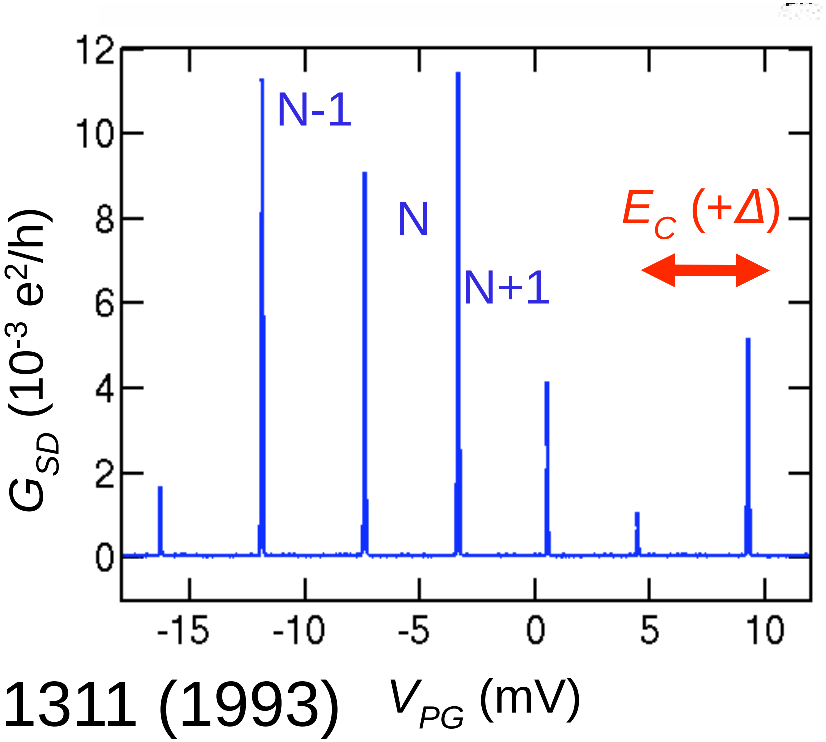




Quantum point contact as a charge detector

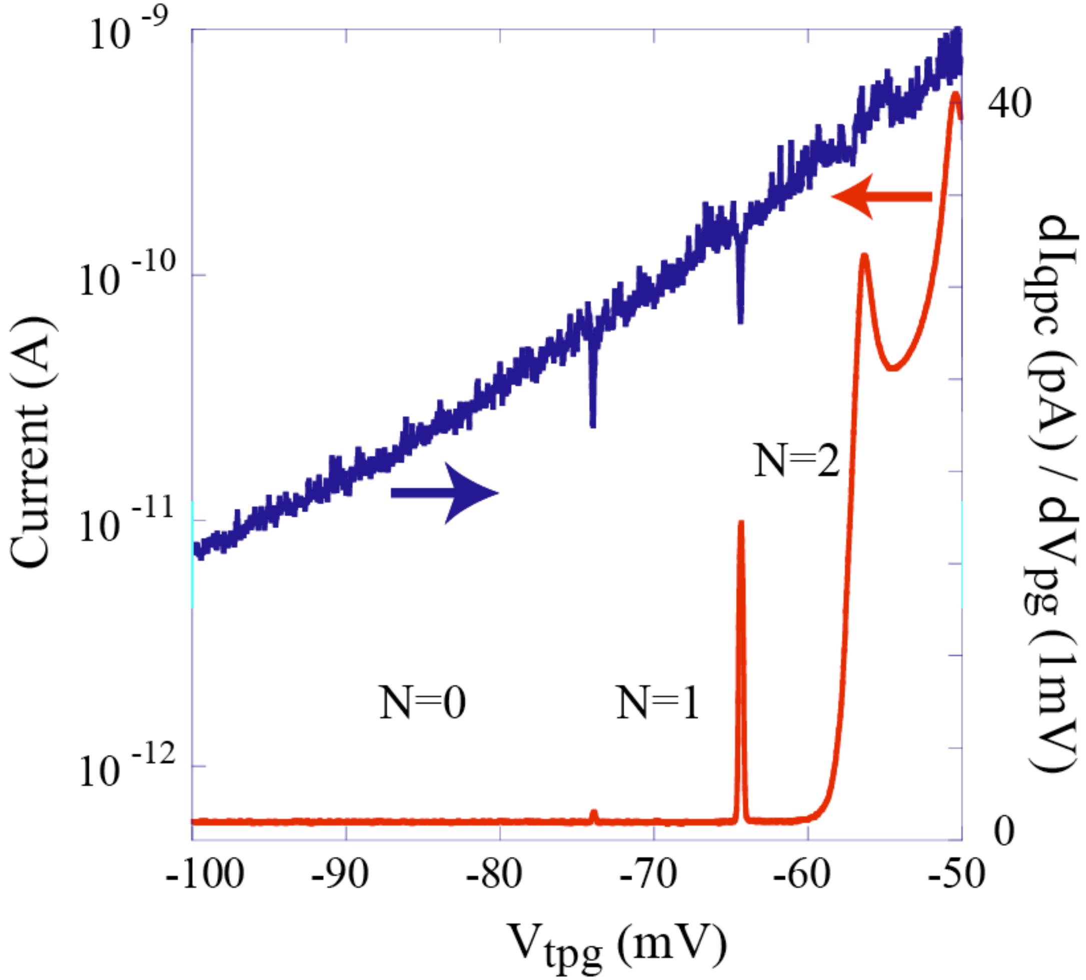


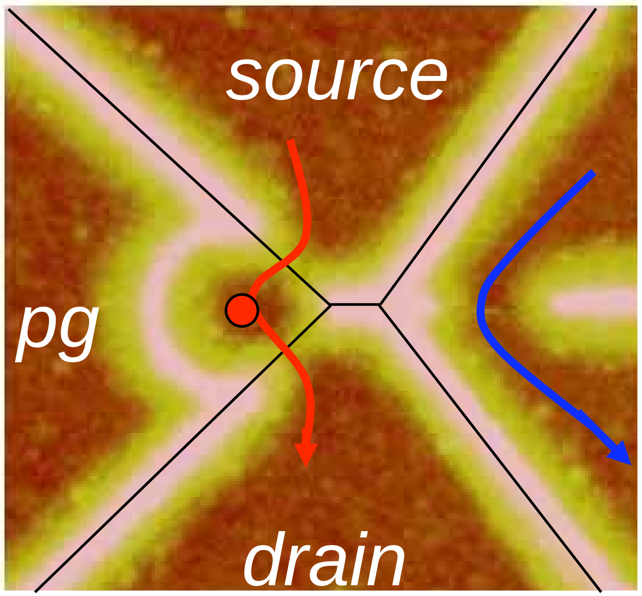




M. Field et al., Phys. Rev. Lett. 70, 1311 (1993)

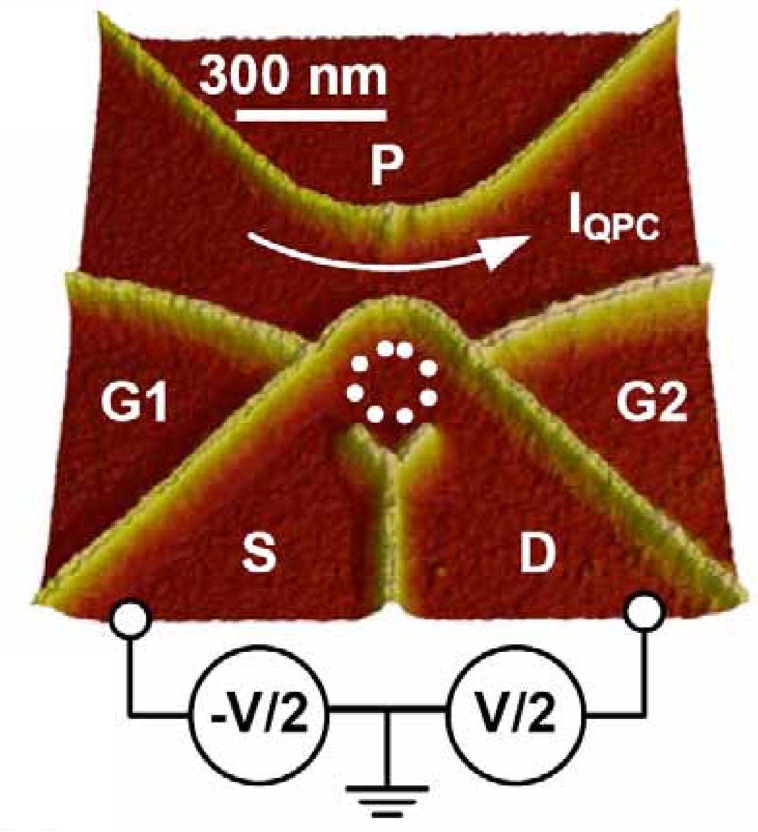
A few electron quantum dot



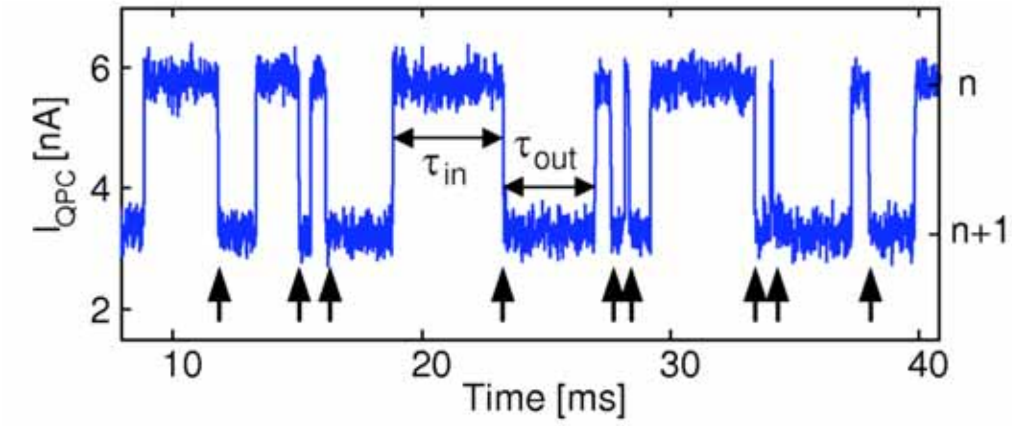


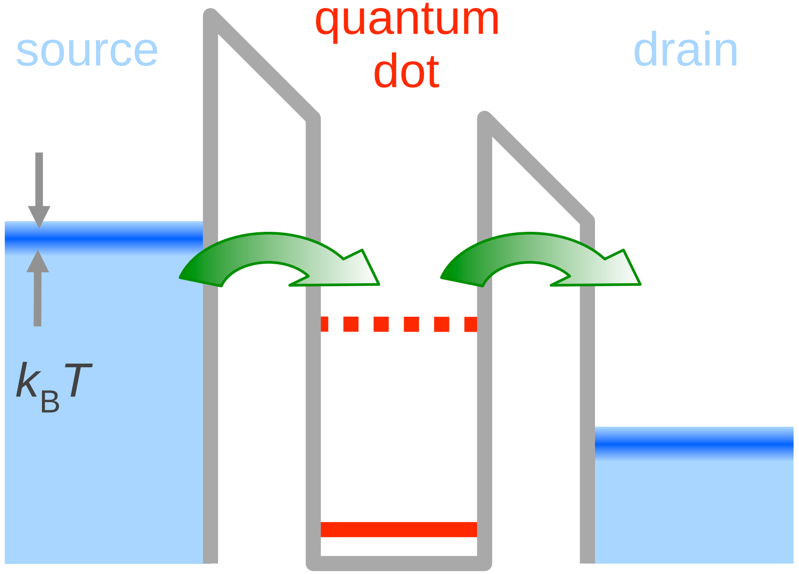
M. Sigrist

Detection of single electron transport



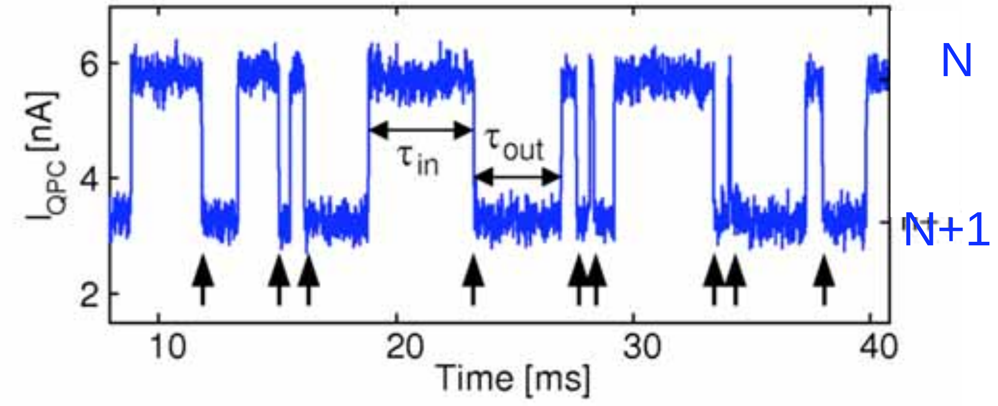
T_e = 350 mK

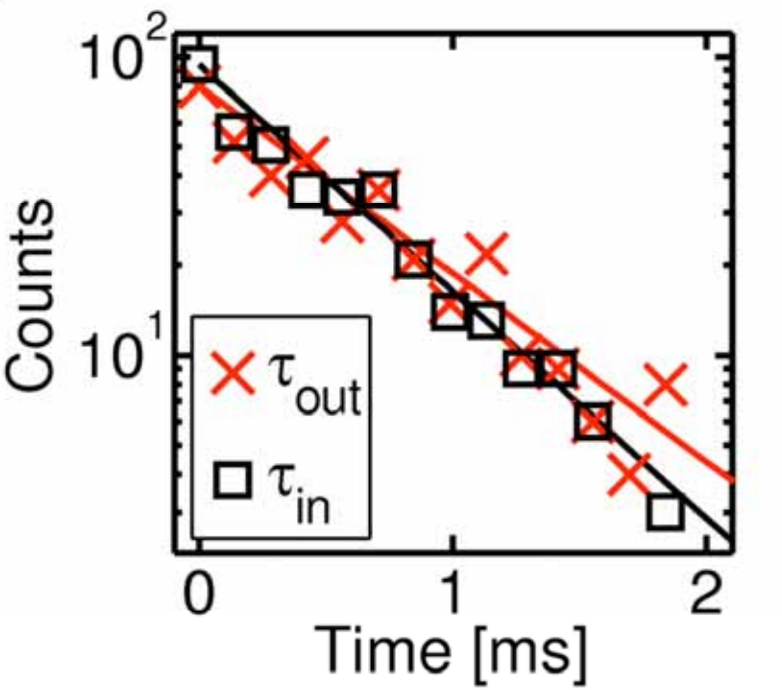




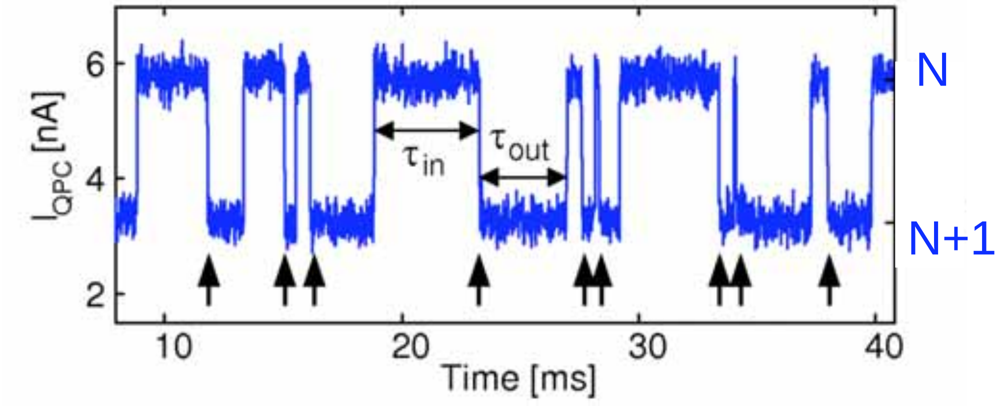
Determination of the individual tunneling rates

- Exponential distribution of waiting times for independent events
- $\Gamma_S = <\tau_{in}>$, $\Gamma_D = <\tau_{out}>$



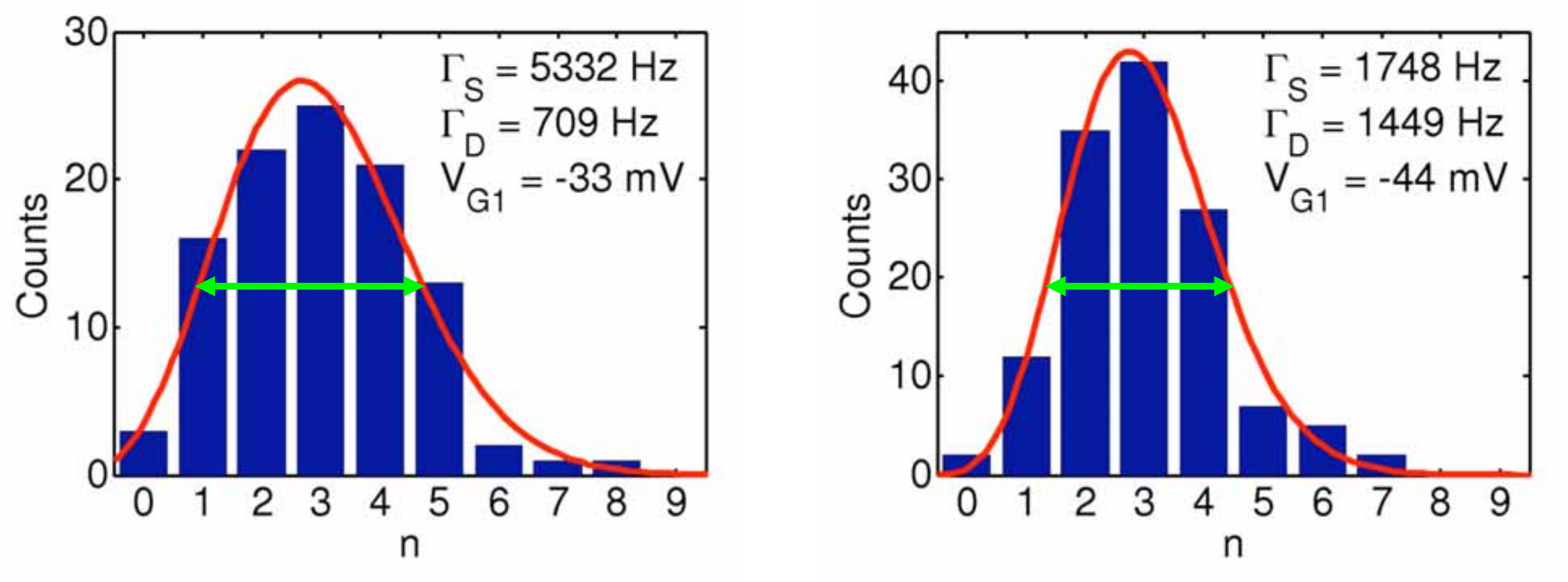


Measuring the current by counting electrons



- Count number *n* of electrons entering the dot within a time t_0: $I = e\langle n\rangle/t_0$
- Max. current = few fA (bandwidth = 30 kHz)
- BUT no absolute limitation for low current and noise measurements
  - *here:* $I \approx$ few aA, $S_I \approx 10^{-35}$ A^2/Hz

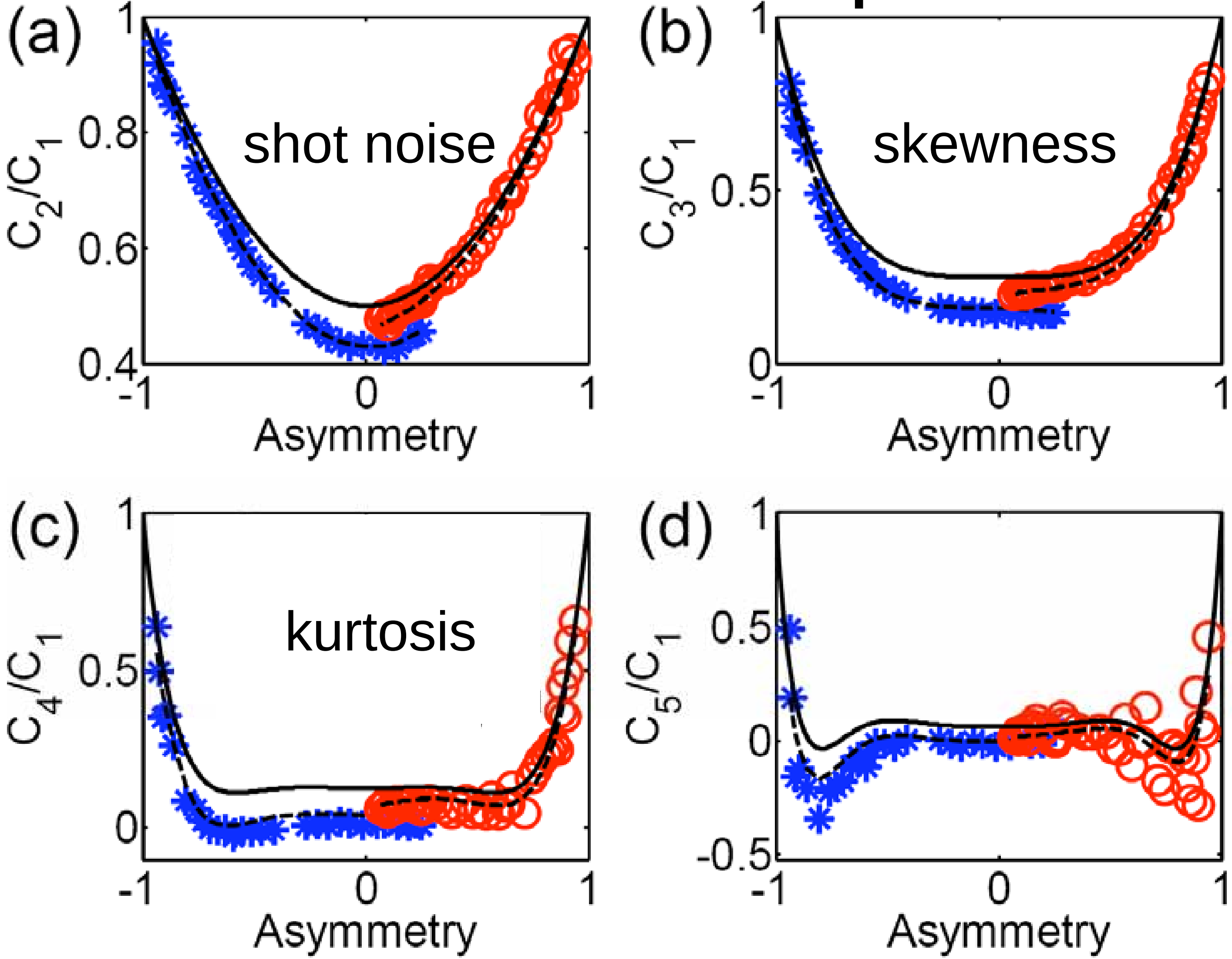
Histogram of current fluctuations



- Poisson distribution for asymmetric coupling
- Sub-Poisson distribution for symmetric coupling

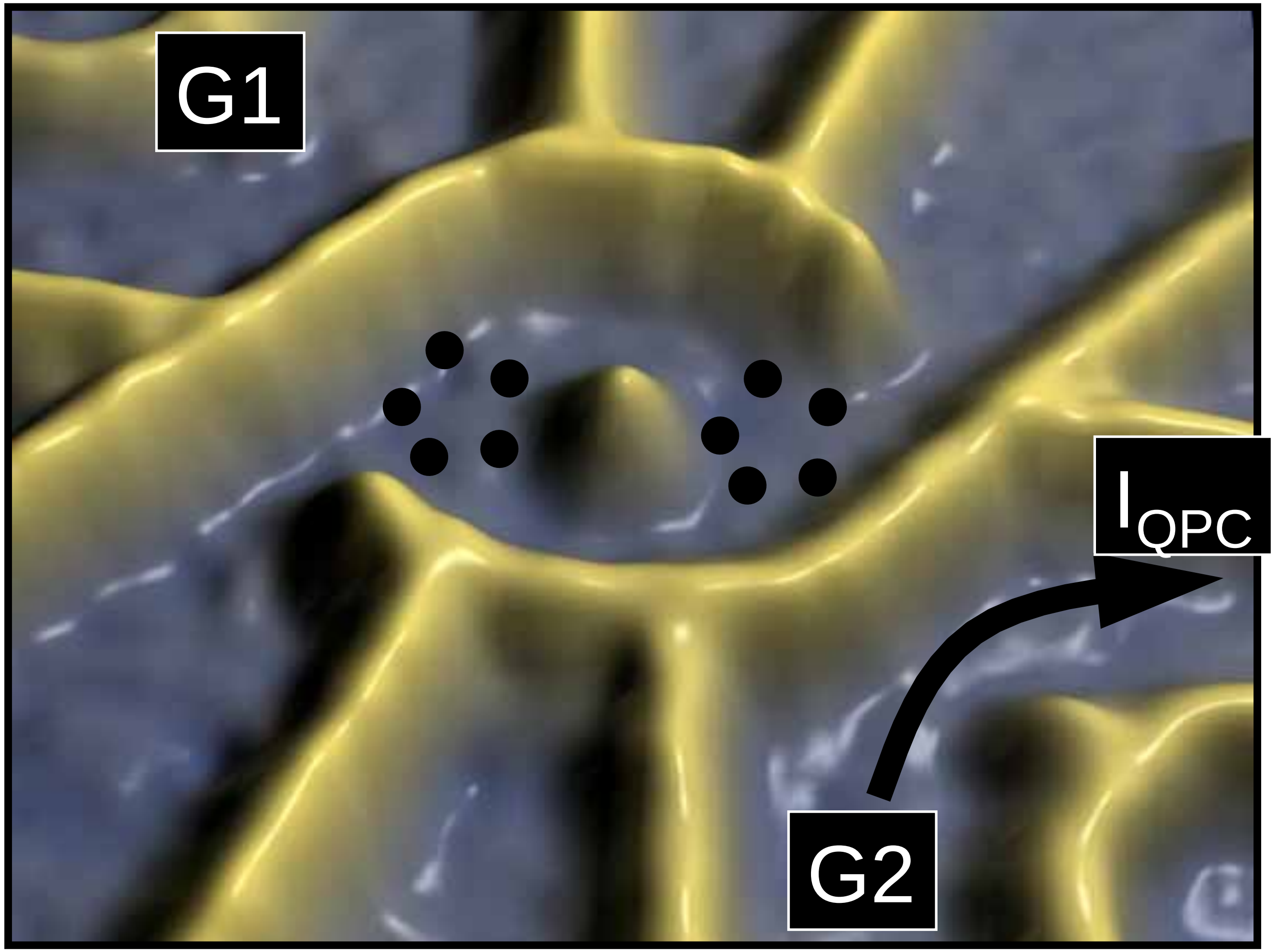
Theory: Hershfield *et al.*, PRB **47,** 1967 (1993)
Bagrets & Nazarov, PRB **67,** 085316 (2003)
Expt: Gustavsson et al., PRL **96,** 076605 (2006)

Higher order correlations of electron transport

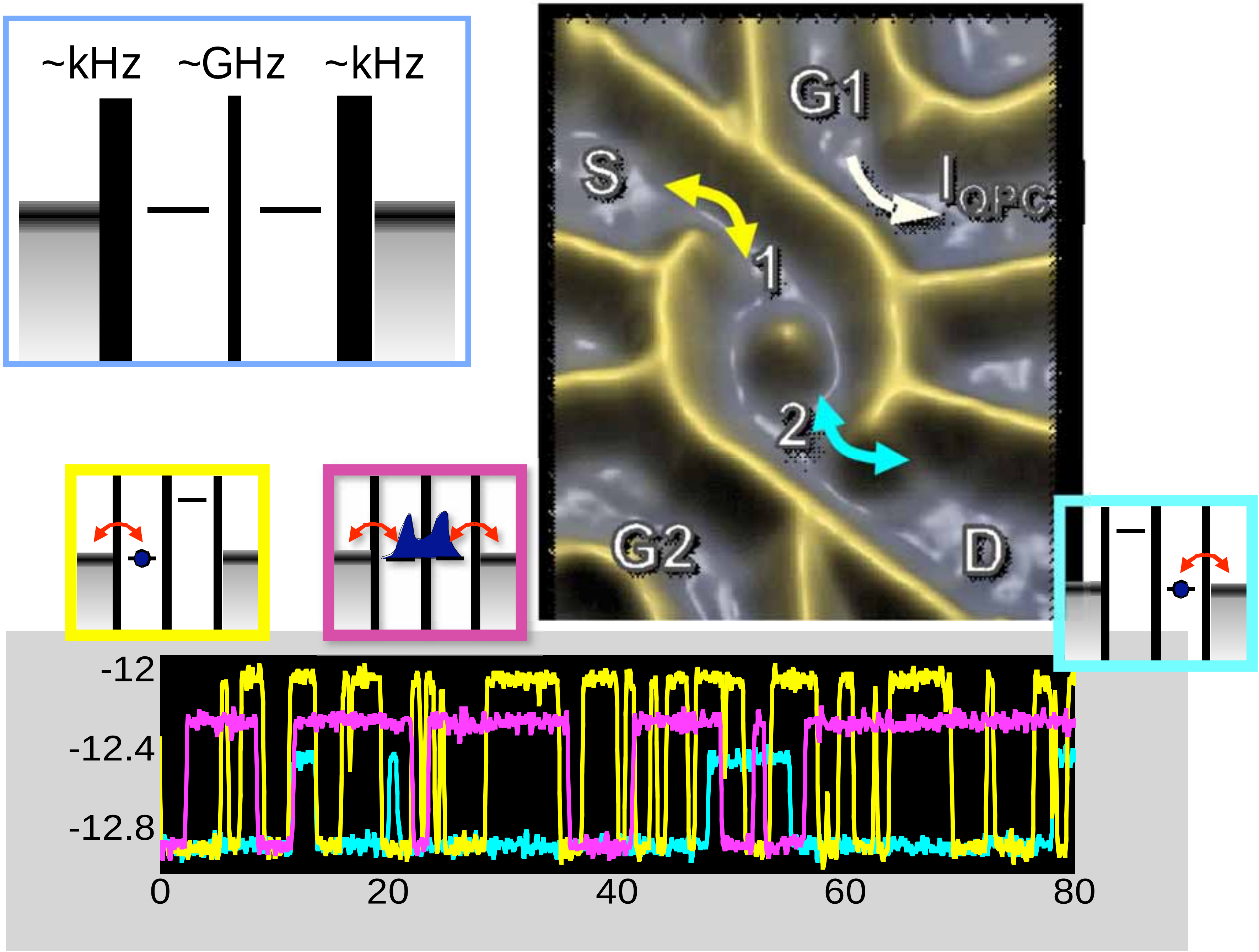


Gustavsson et al, PRB 75, 075314 (2007)

Double quantum dot in a ring



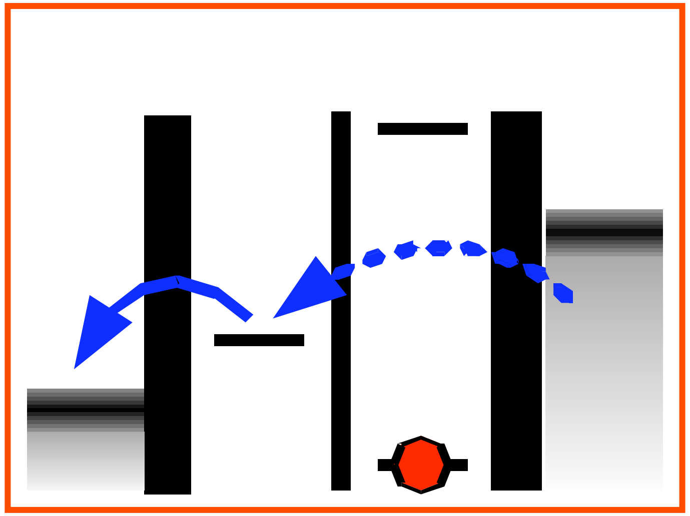
see also: electron counting in double dots: Fujisawa *et al.*, Science **312**, 1634 (2006)

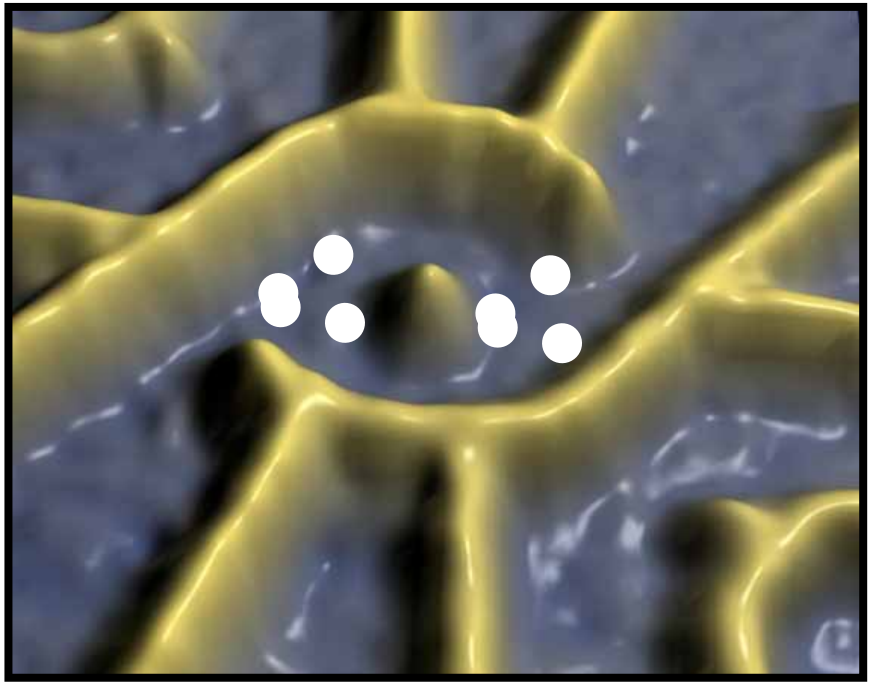

~kHz
~GHz
~kHz
G1
S
I_QPC
1
2
G2
D
-12
-12.4
-12.8
0
20
40
60
80

Aharonov-Bohm with cotunneling

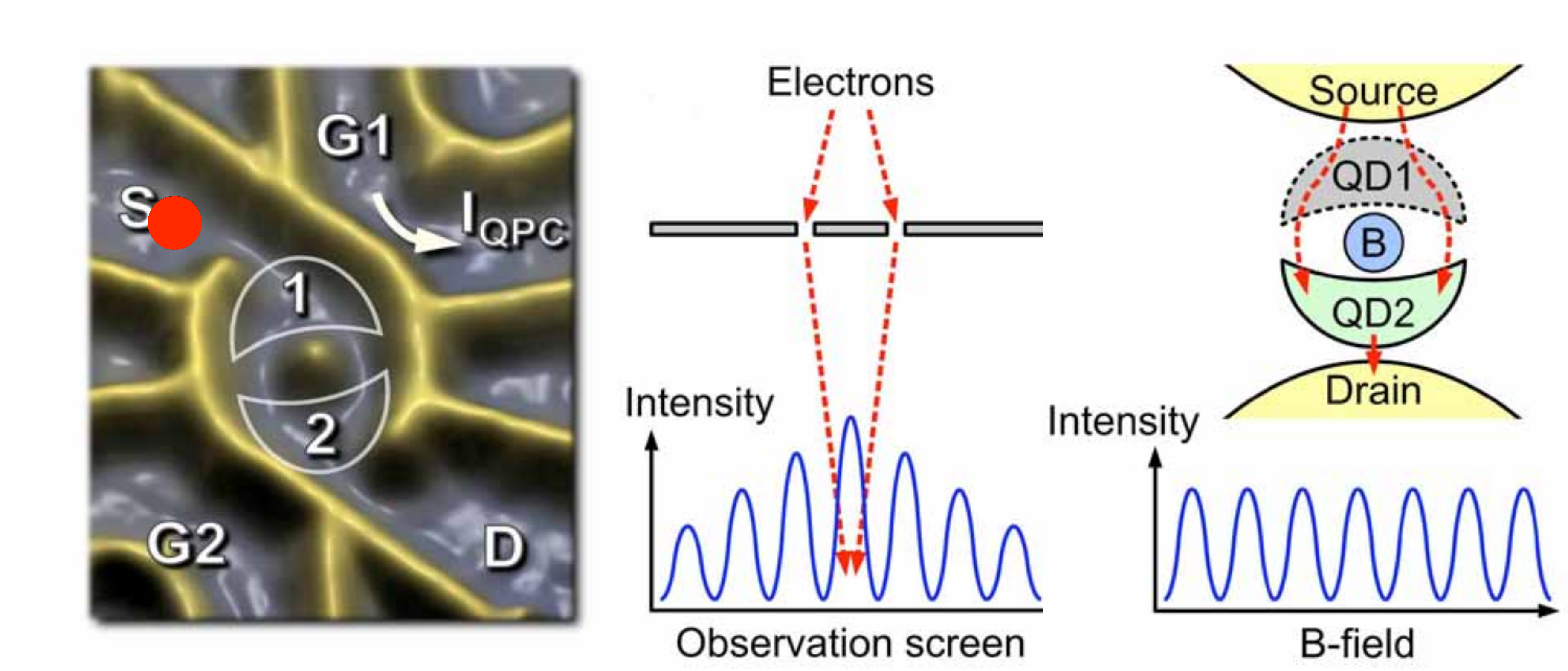
Co-tunneling

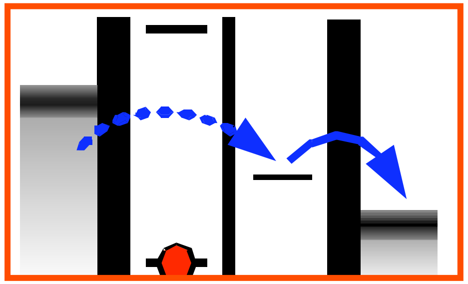
- Electrons are injected from the right lead
- They pass through either the upper or lower arm
- The interference take place in the left QD



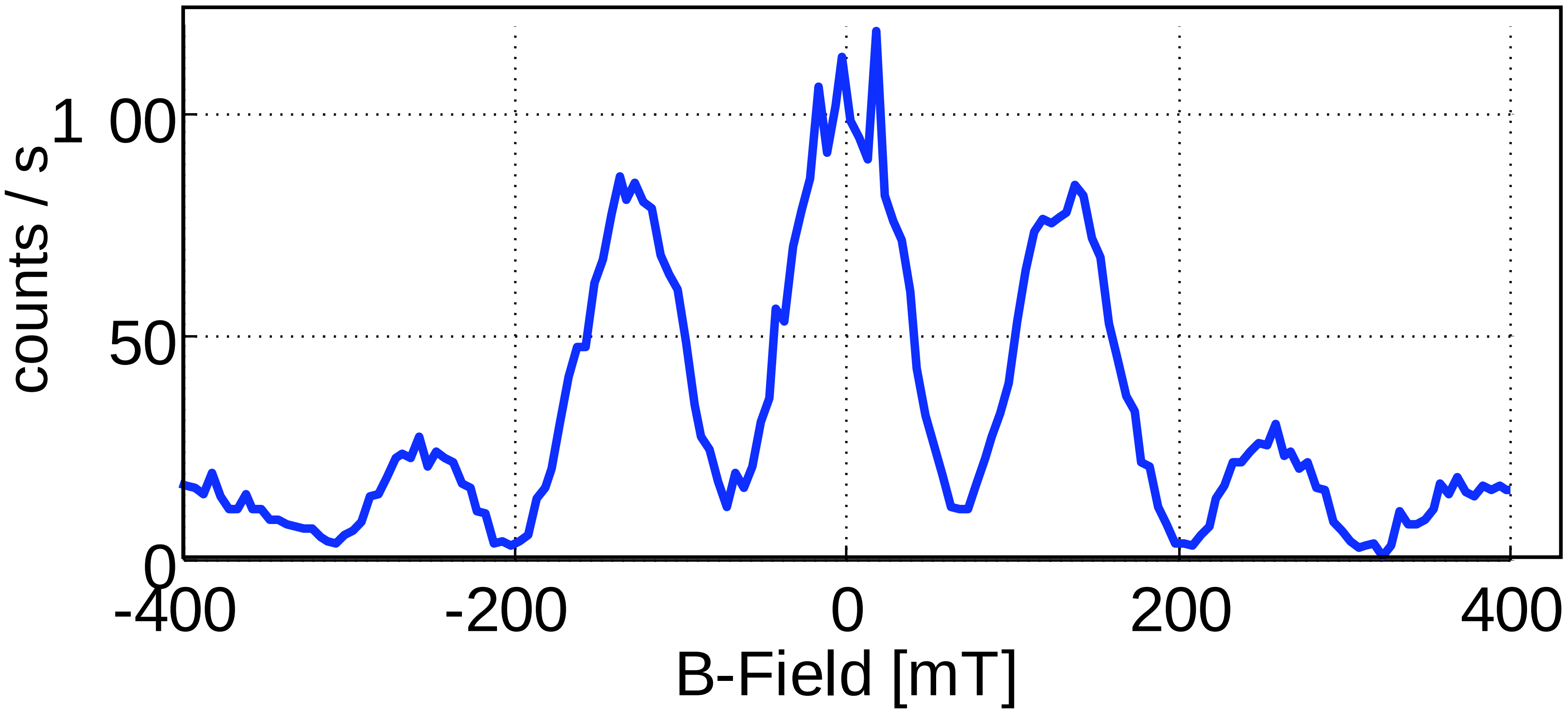


Double slit experiment
<-> Aharonov Bohm





Aharonov-Bohm oscillations

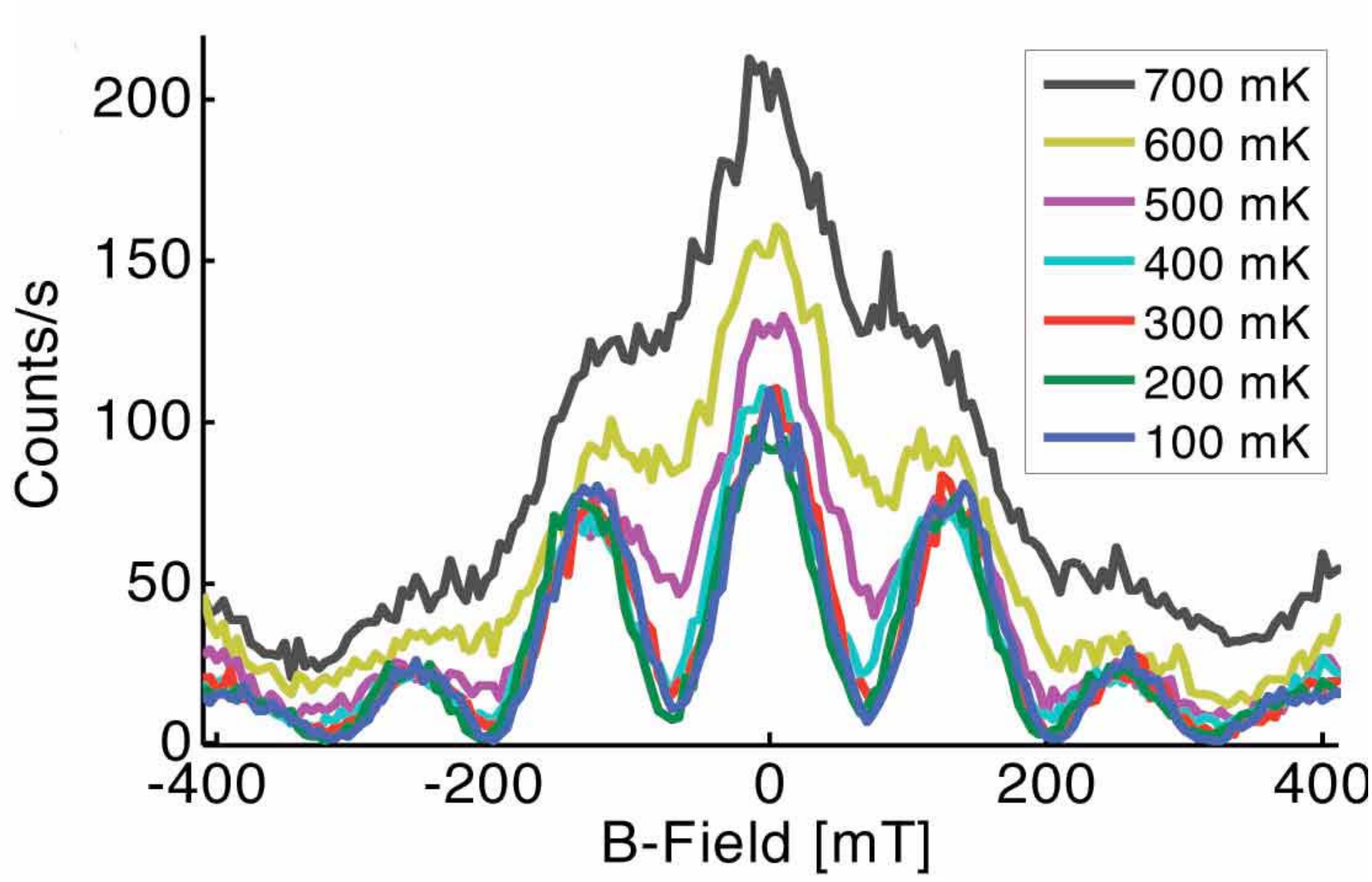


huge visibility! >90%

little decoherence - > due to long dwell time in the collecting dot?

requires the couplings of upper and lower arm to be well symmetrized

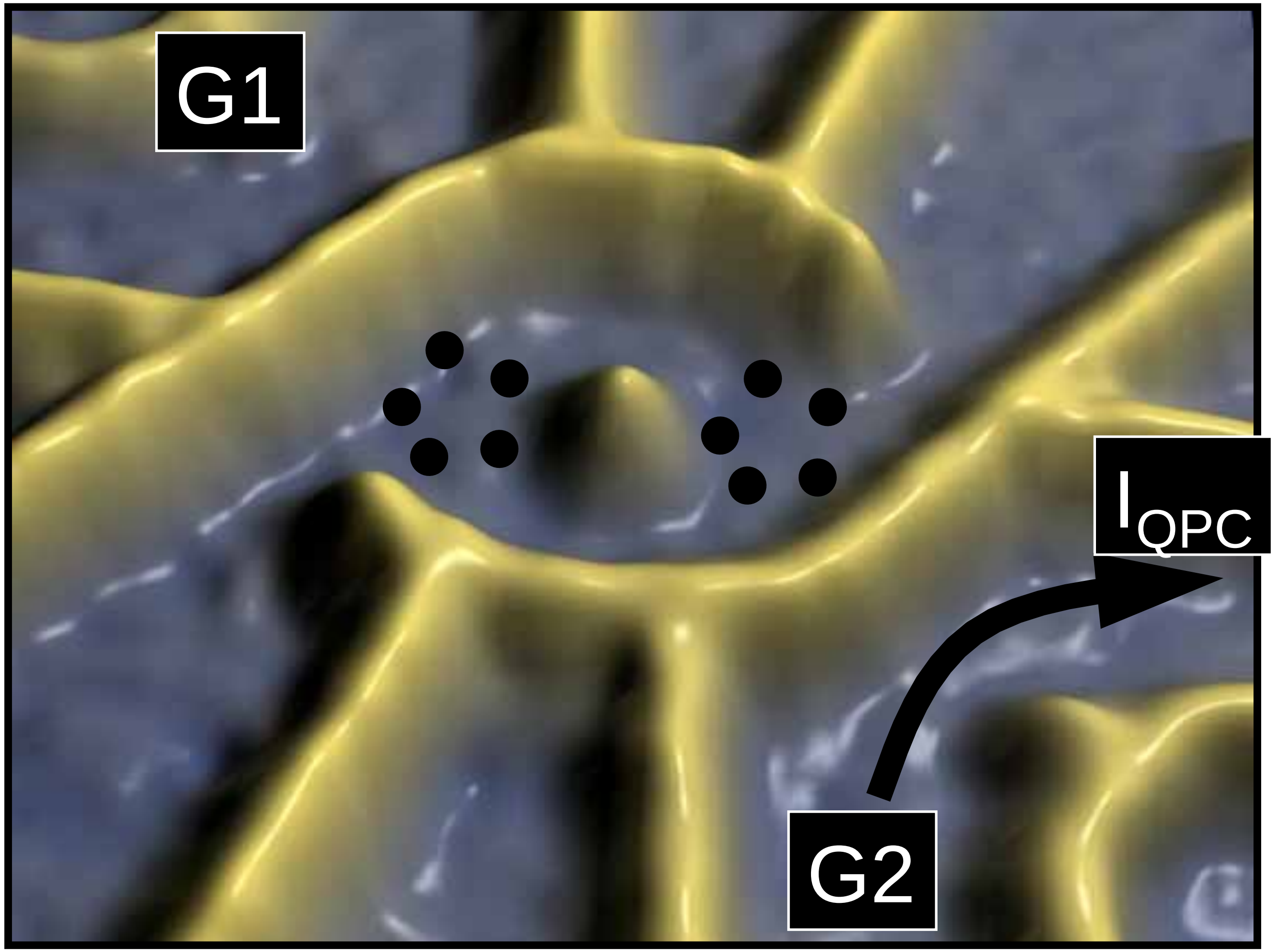
Temperature dependence



AB amplitude stable below T=400mK

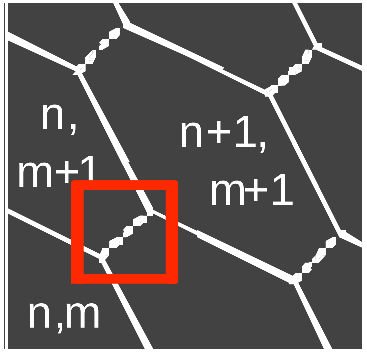
Destruction most likely due to thermal broadening

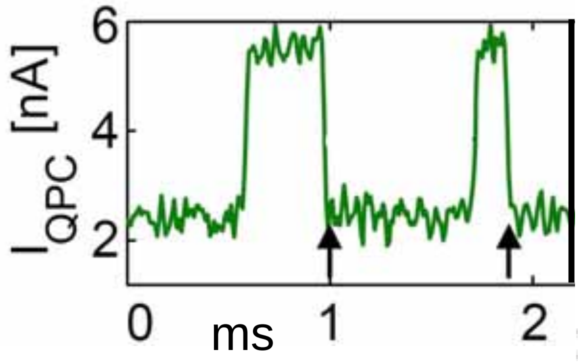
Double quantum dot in a ring

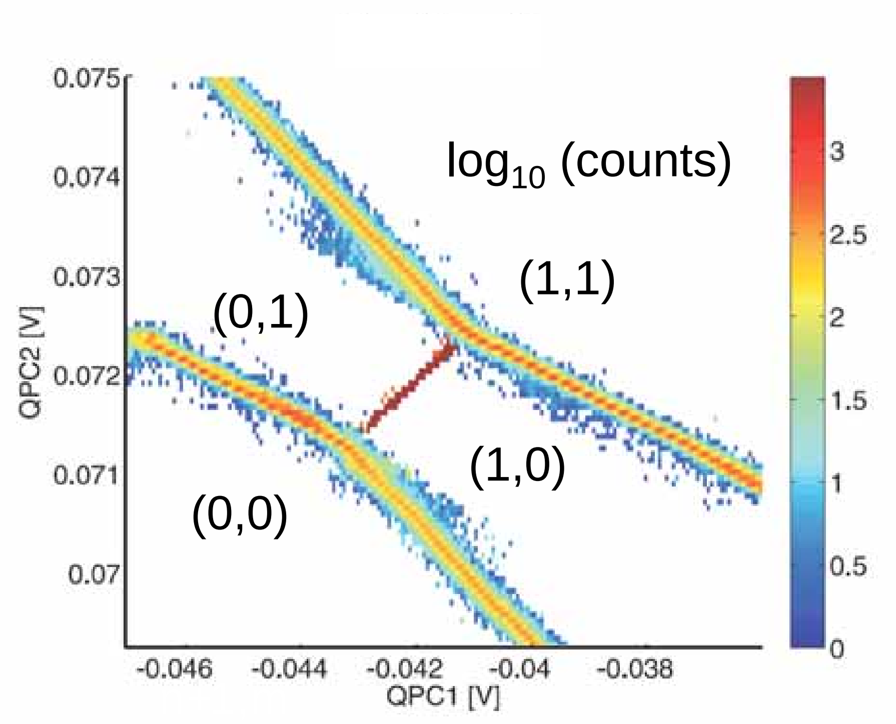


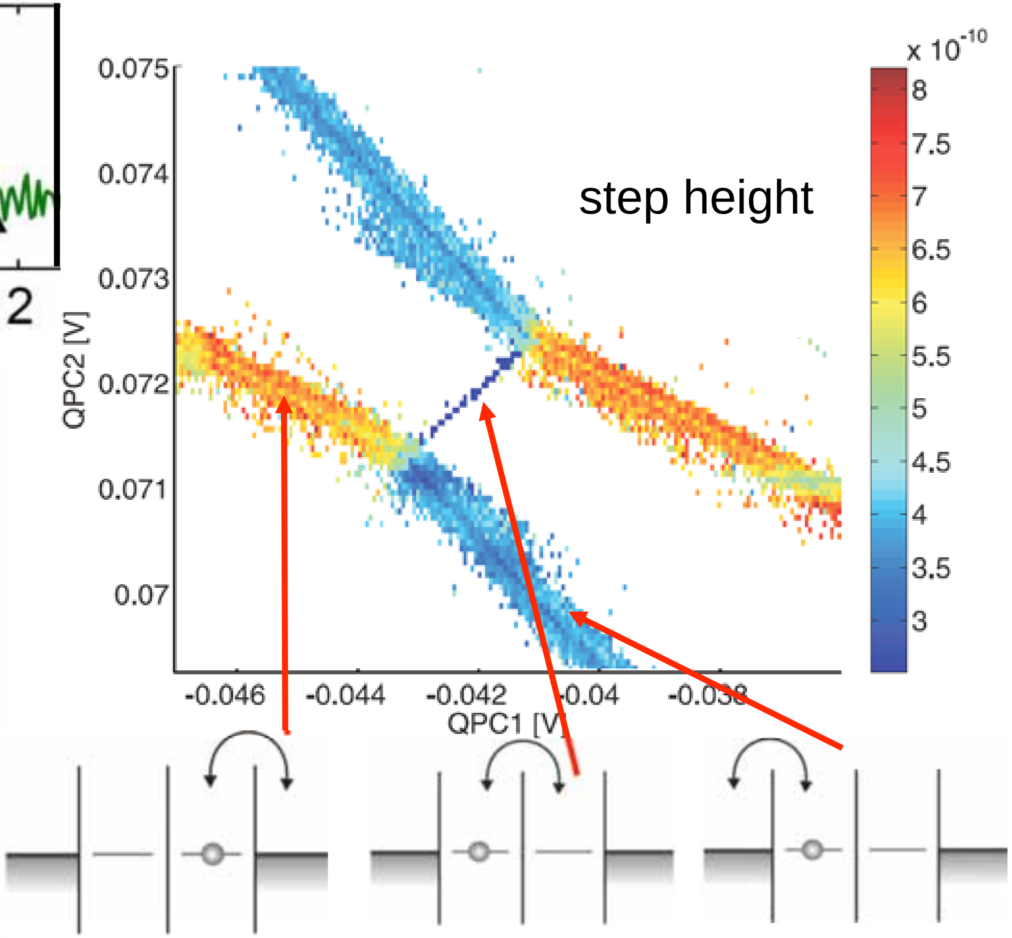
characterization of tunnel rates

Charge stability from counting

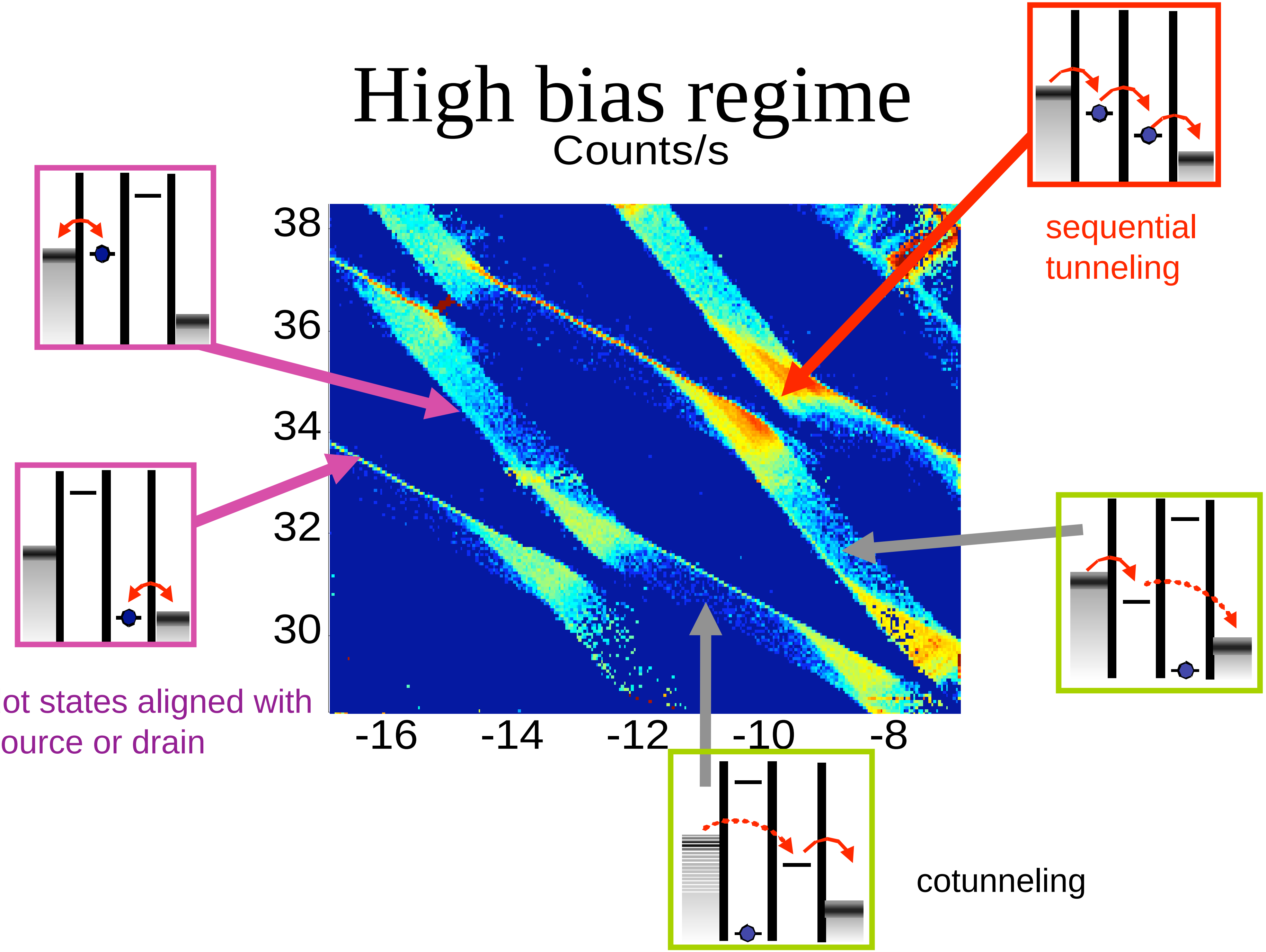








High bias regime



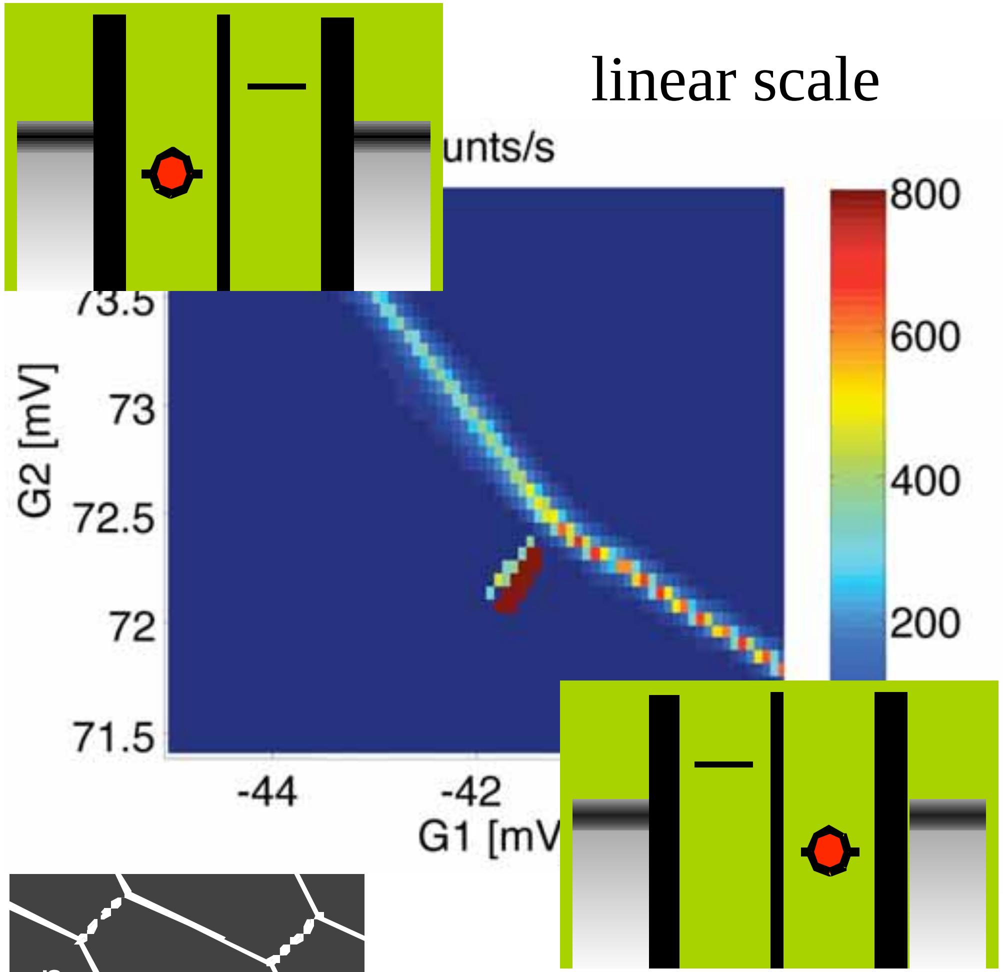
sequential tunneling

dot states aligned with source or drain

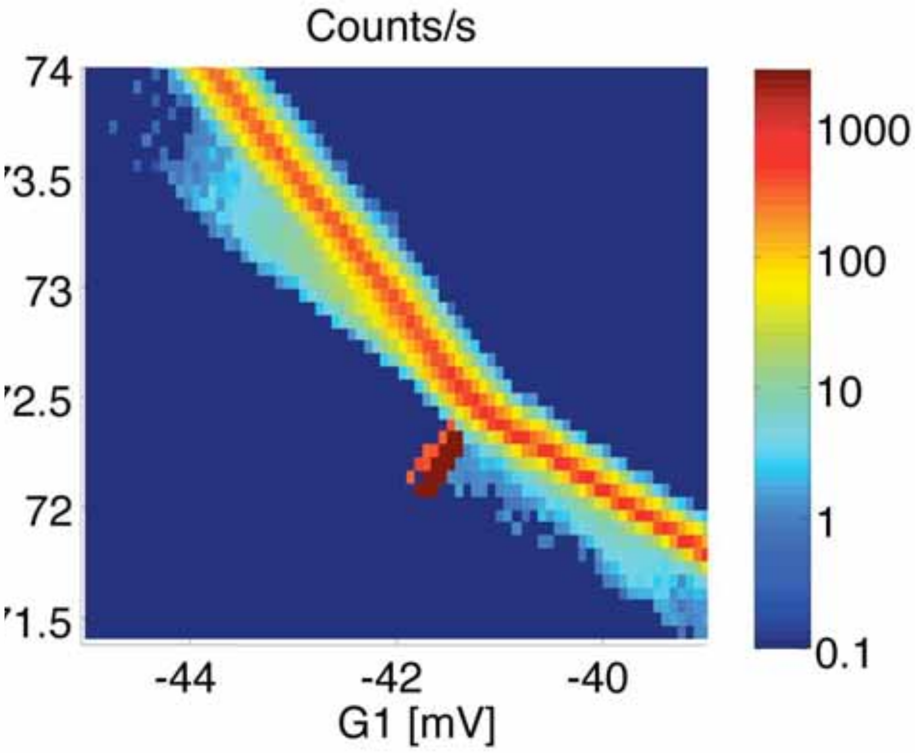
cotunneling

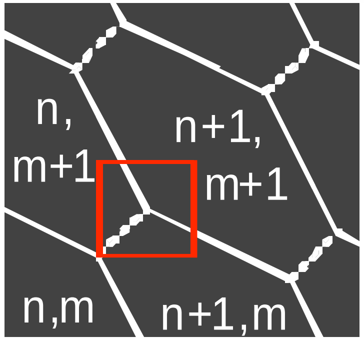
Triangles at zero bias across dot

linear scale



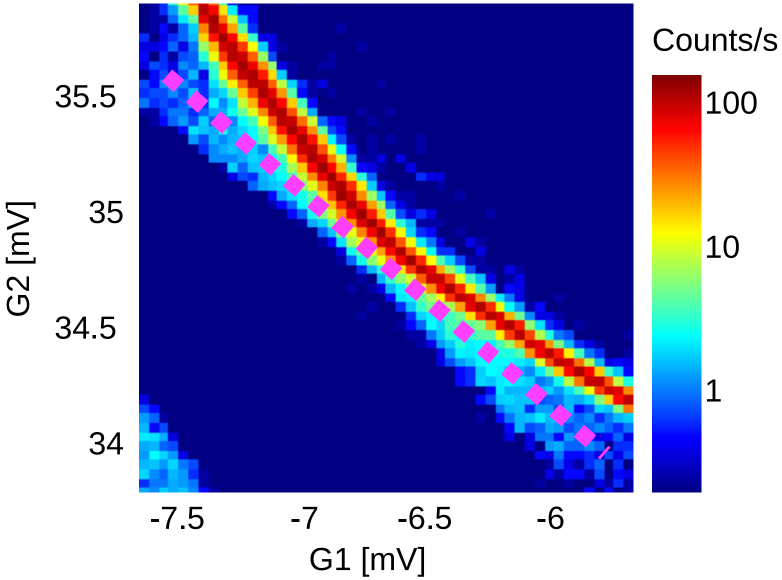
log scale



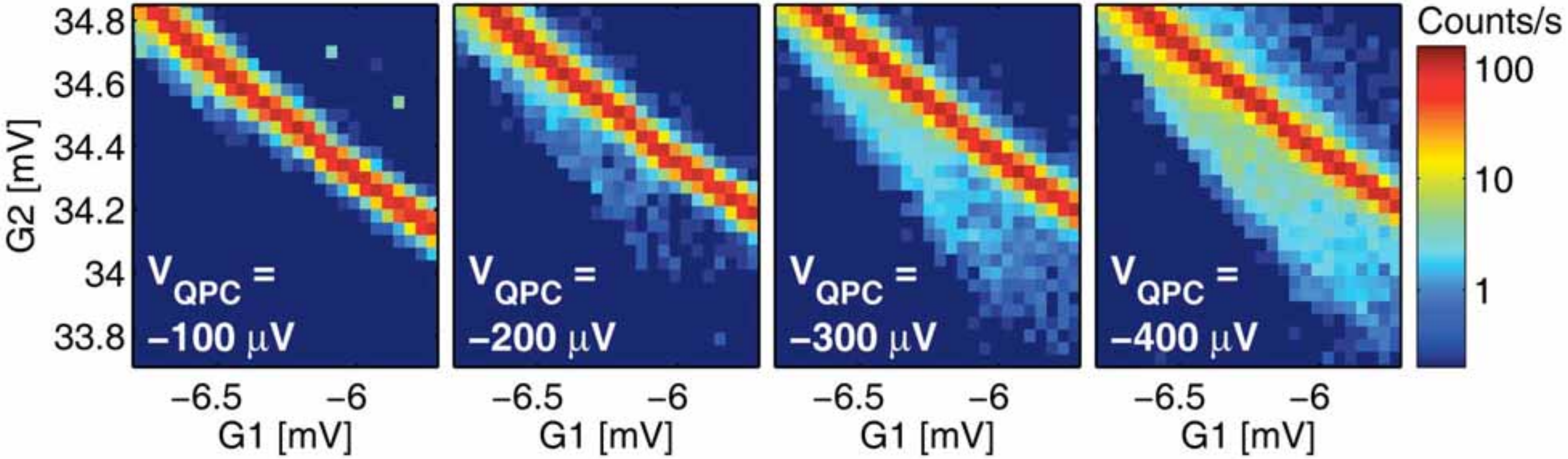


V_{QPC}=300 μV

Different biases across the QPC



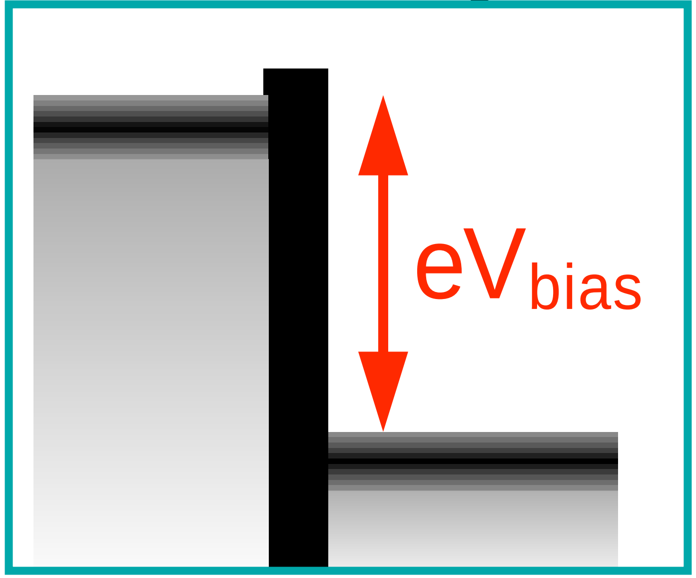
The triangles grow with increasing bias



Microwave emission of a QPC

- Voltage biased tunnel junction

- Emission spectrum
  - Linear increase with bias
  - Cut-off at $f=eV_{bias}/h$



$$S_I(\omega) = \frac{4e^2}{h} T(1-T) \frac{eV - \hbar\omega}{1 - e^{-(eV-\hbar\omega)/k_B T}}$$

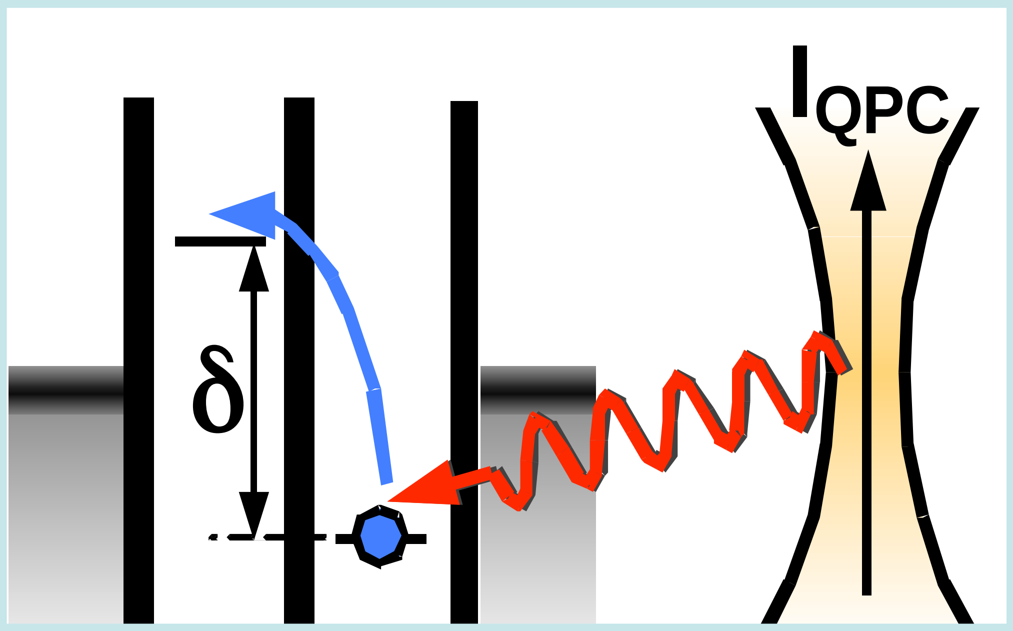
spectral noise density for the emission side ($\omega > 0$)

R. Aguado and L. Kouwenhoven,
PRL **84**, 1986 (2000)

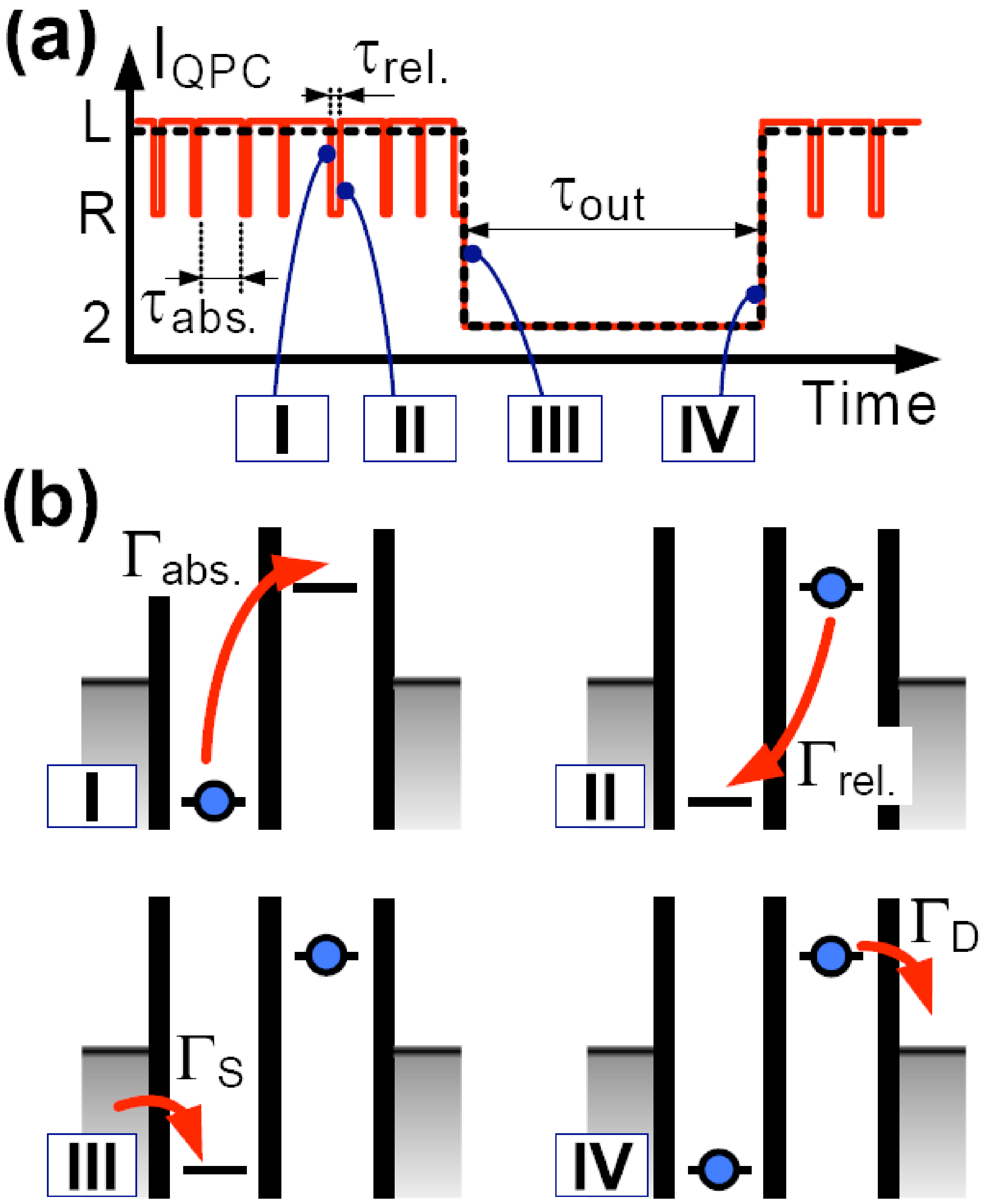
Tunable noise detector

- The detuning of the quantum dots acts as a selective frequency filter

- The detuning is easily changed with gate voltages



R. Aguado and L. Kouwenhoven,
PRL **84**, 1986 (2000)



detector signal

absorption process

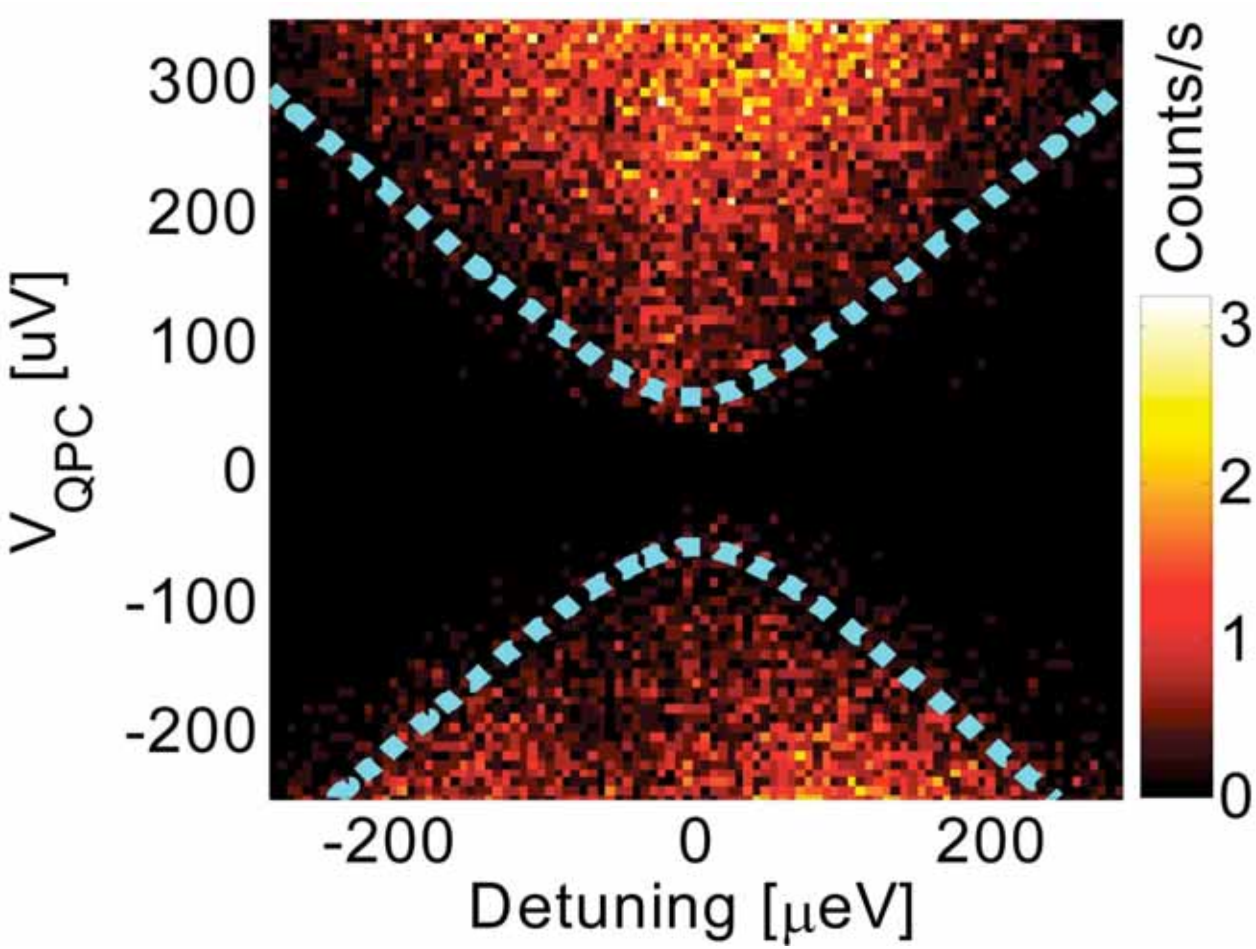
Double dot detuning vs. QPC bias

- Level separation of the DQD dashed line:

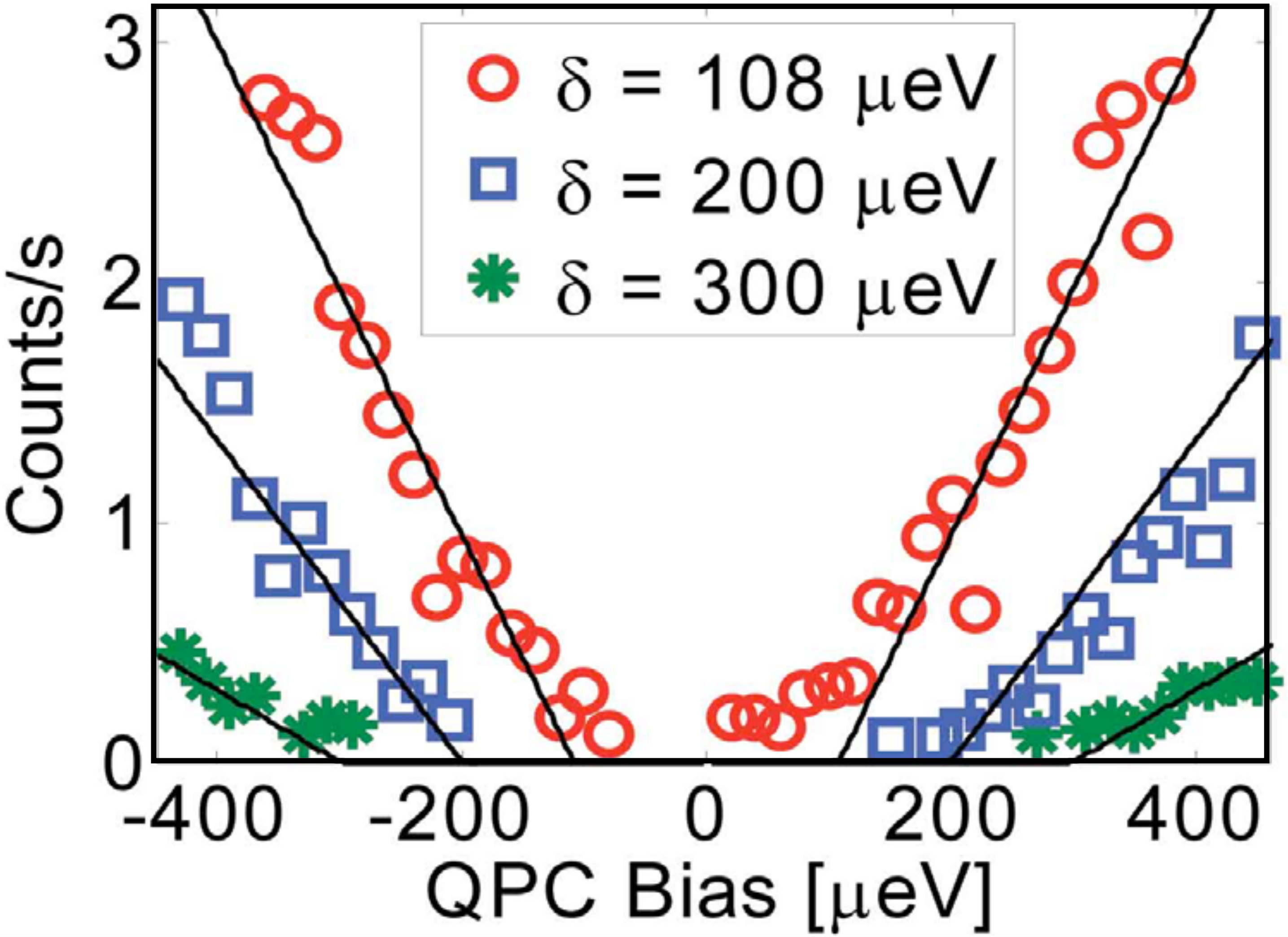
$$\Omega = \sqrt{4\,t^2 + \delta^2}$$

- No counts in the region with $eV_{QPC}<\Omega$!

t : tunnel coupling
δ : detuning



Bias dependence of the count rate

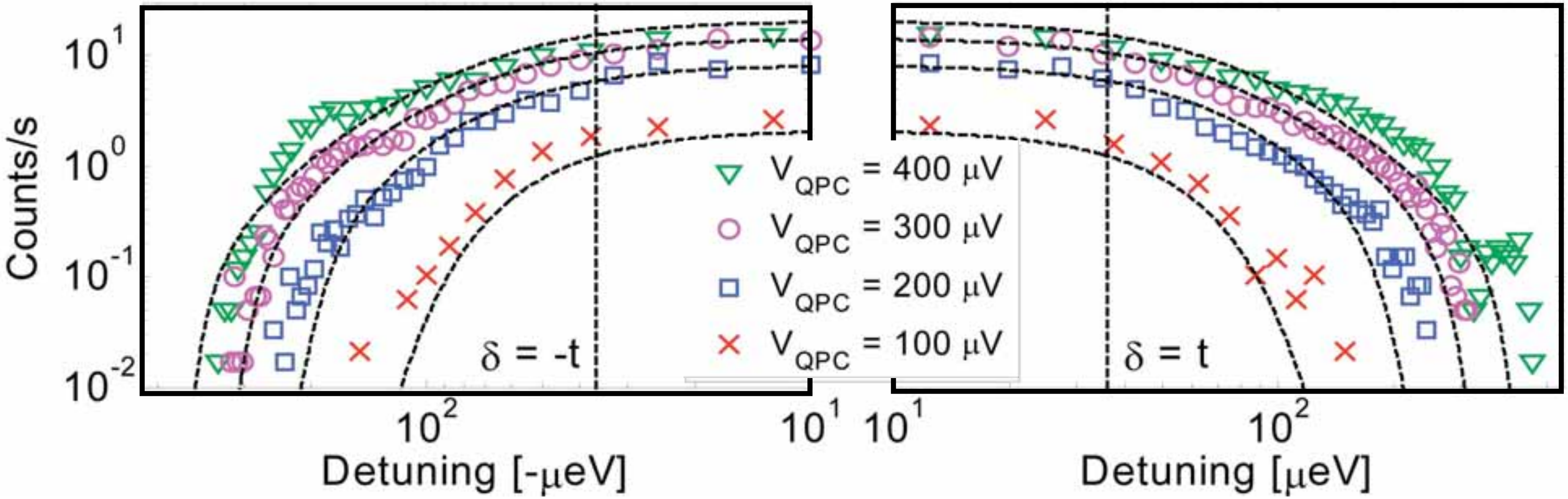


- Linear increase of absorption rate as soon as $eV_{QPC} > \delta$

Measuring the spectrum

absorption rate of the DQD in the presence of the QPC:

$$\Gamma_{abs} = \frac{4\pi e^2 \kappa^2 t^2 Z_l^2}{h^2} \frac{S_I(\Omega/\hbar)}{\Omega^2}$$



κ : capacitive lever arm of QPC on DQD

Z_l: zero frequency impedance of leads connecting QPC to voltage source

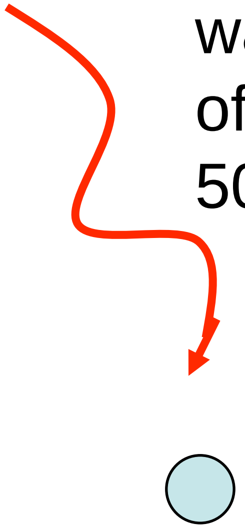
Clear cut-off at δ = eV_{QPC}

Gustavsson et al., PRL **99**, 206804 (2007)

Single photon detection by a quantum dot

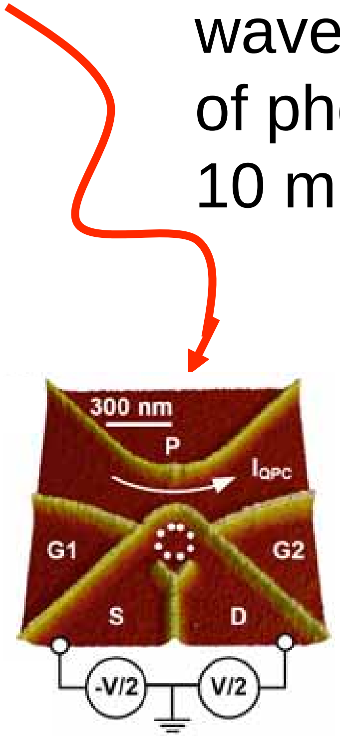
quantum optics

semiconductor nanostructures



wave length
of photon:
500 nm

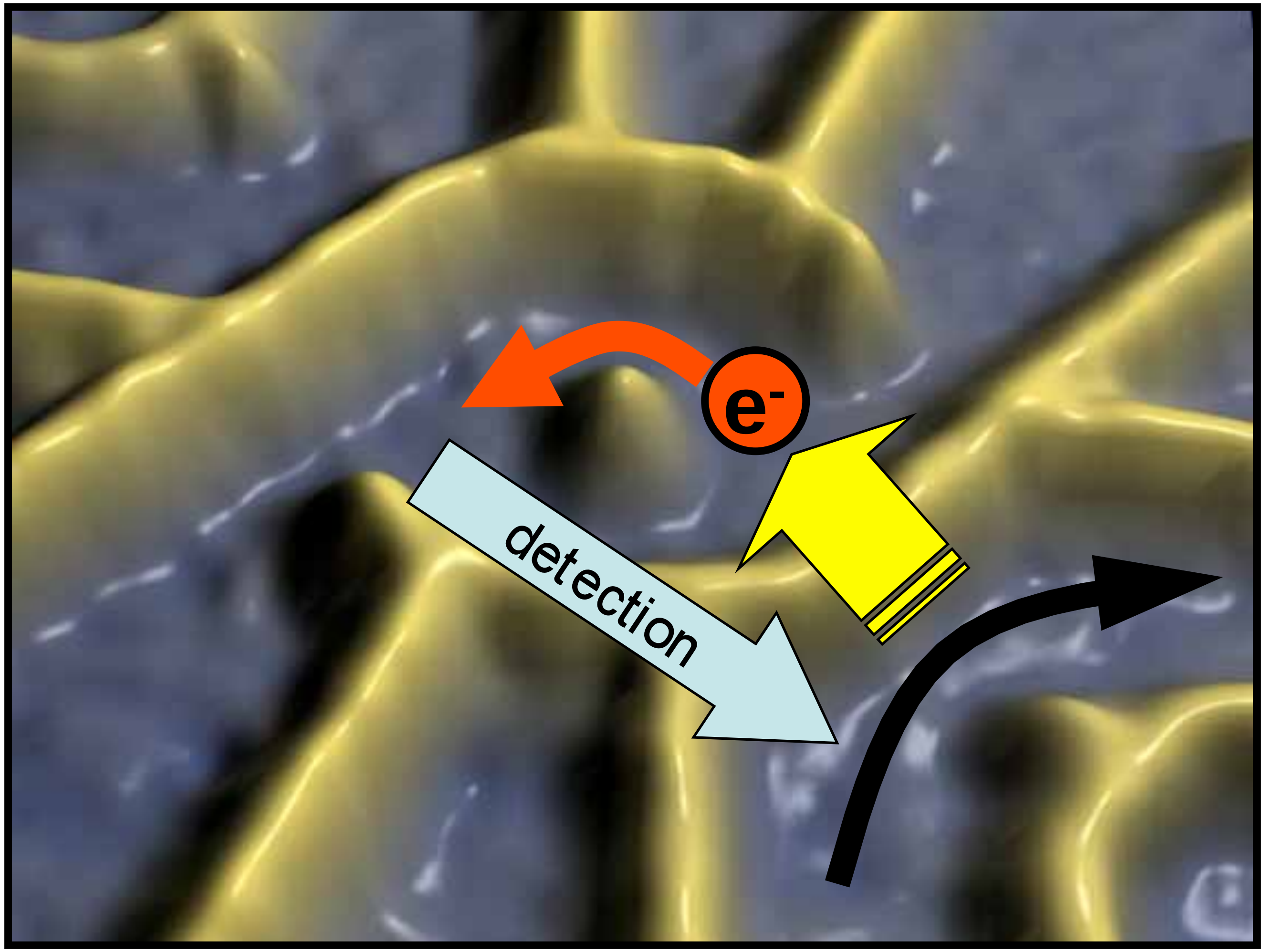
size of atom:
1 nm



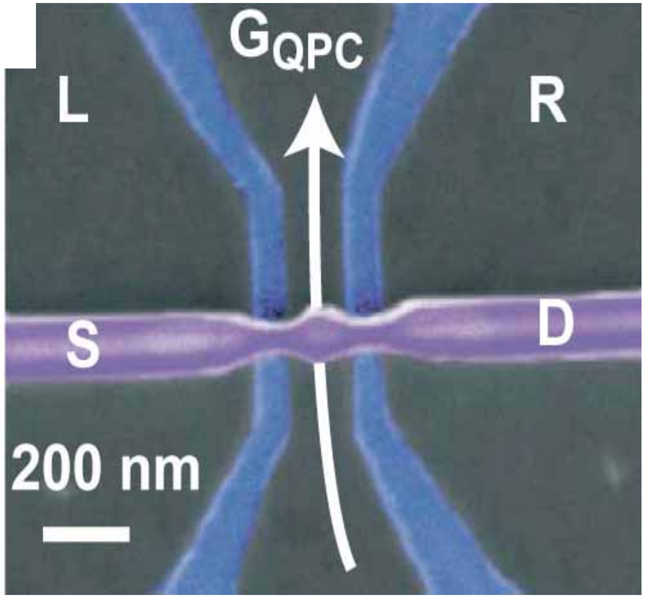
wave length
of photon:
10 mm

size of
quantum dot:
100 nm

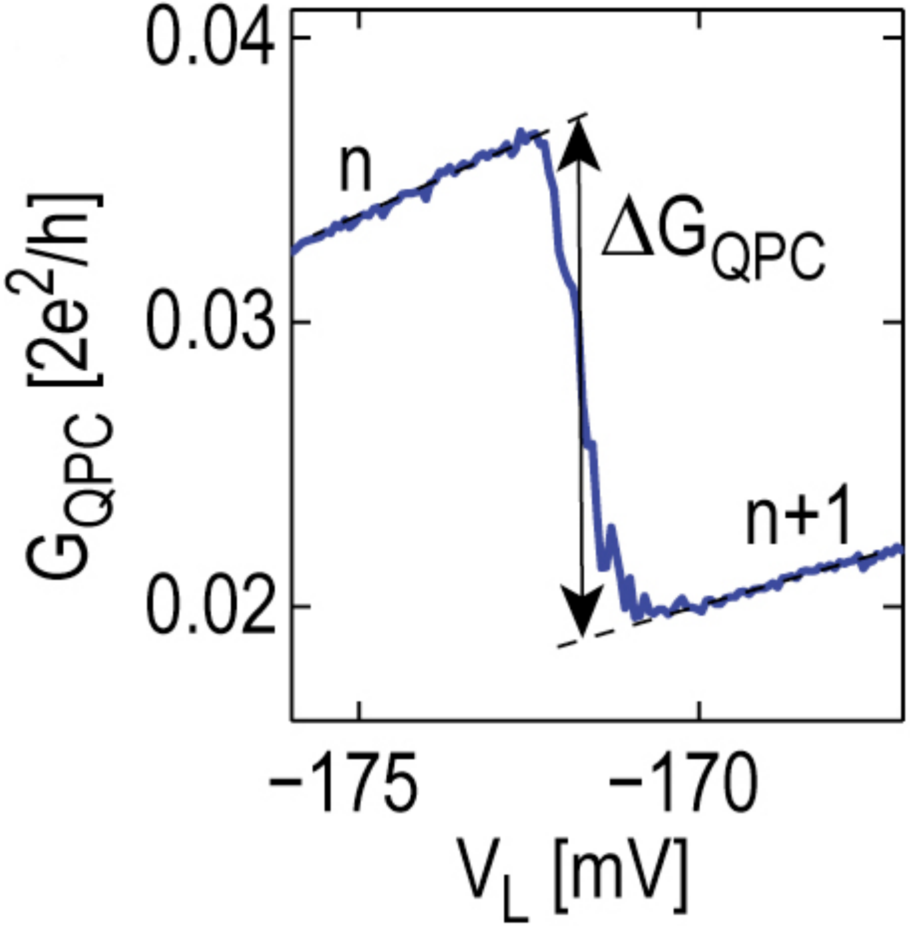
Single-photon, single-electron detection



Towards THZ photons – InAs nanowire dots

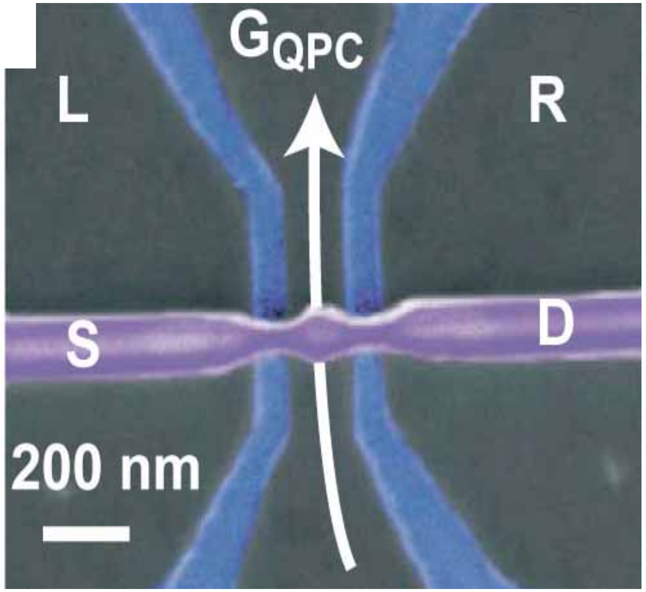


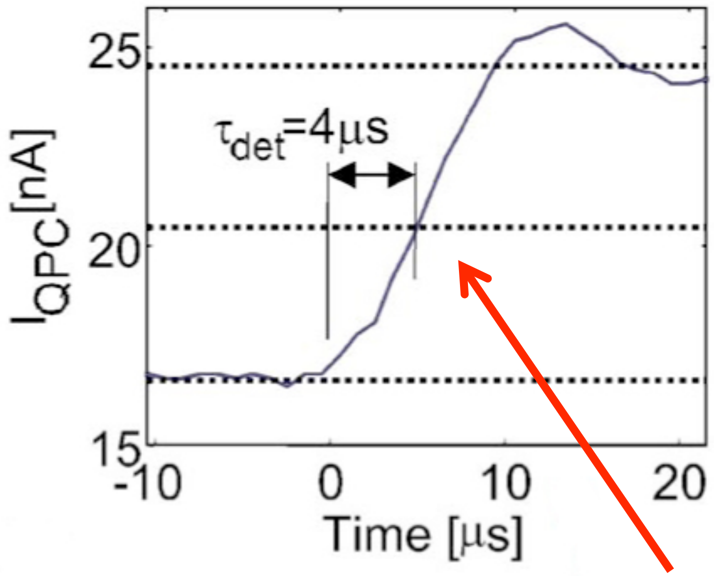
up to 50%
detector signal

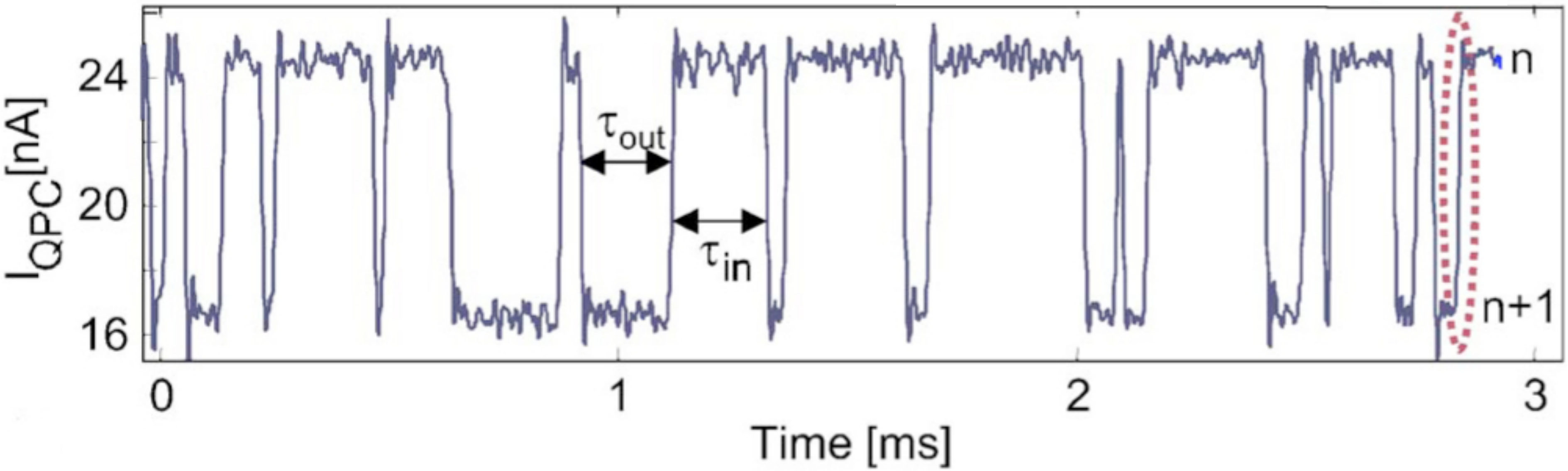


Strong coupling between
dot (InAs) and detector
(GaAs 2DEG)

Time-resolved charge detection in InAs nanowire dots







Thank you

Simon Gustavsson

Renaud Leturcq

Ivan Shorubalko

Thomas Ihn

Plans:
- time resolution
- correlation experiments
- spin blockade
- graphene