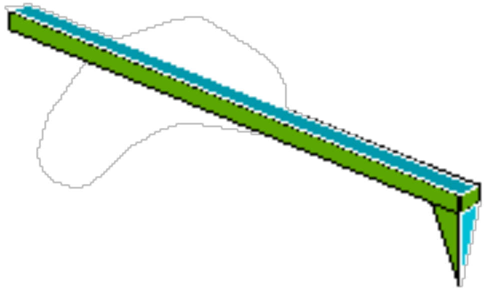
Electrons in quantum dots – one by one



Klaus Ensslin

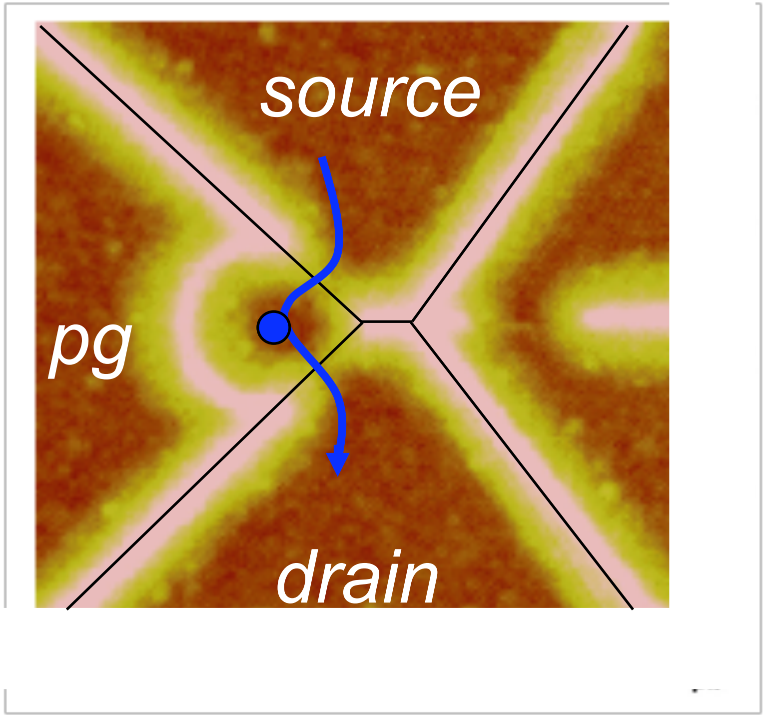
Solid State Physics ETH Zürich

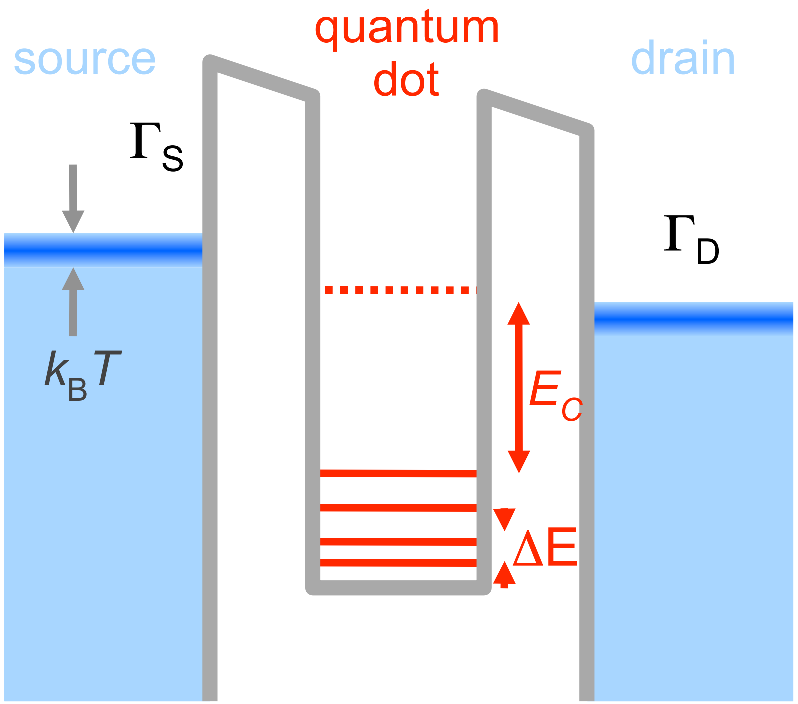
with
S. Gustavsson
I. Shorubalko
R. Leturcq
T. Ihn

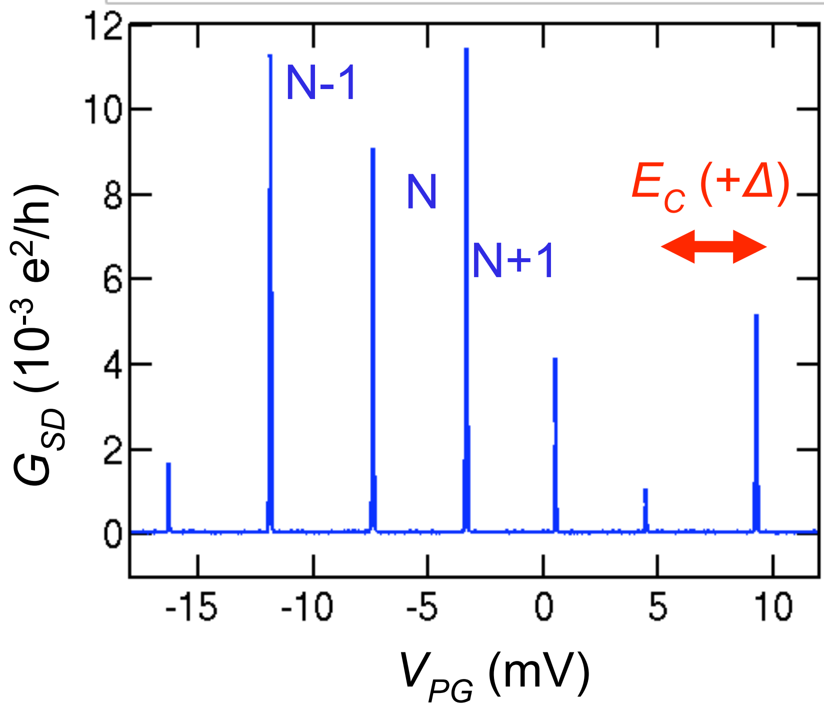
A. C. Gossard UCSB
W. Wegscheider, Regensburg

- Transport through quantum dots
- Charge detection
- Time-resolved charge detection
- Single electron interference
- Single photon detection

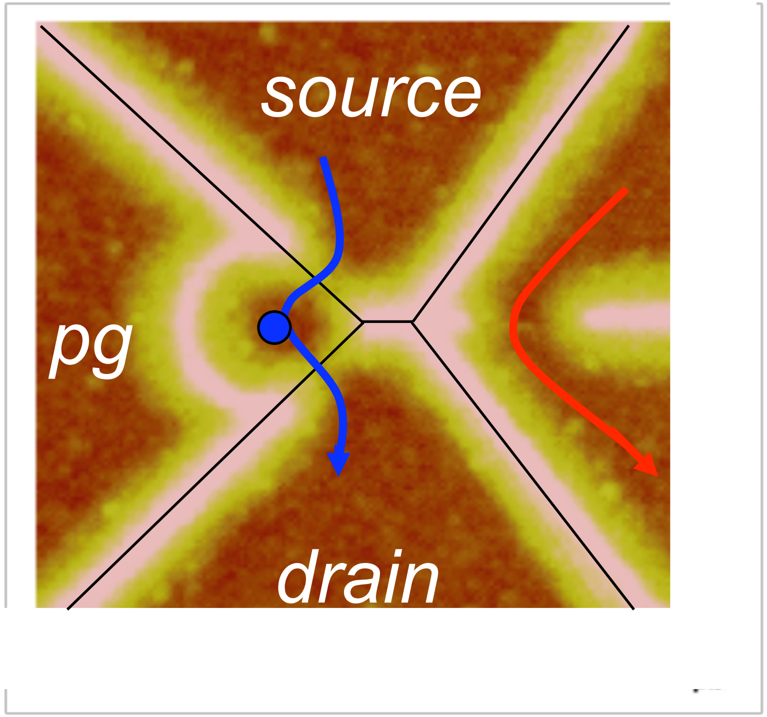
Spectroscopy of electronic states

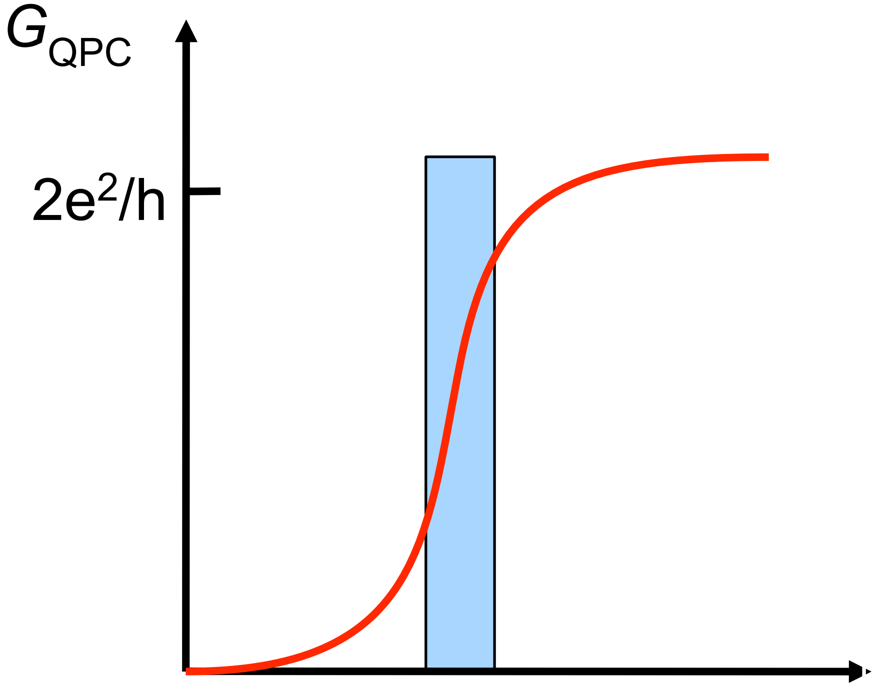


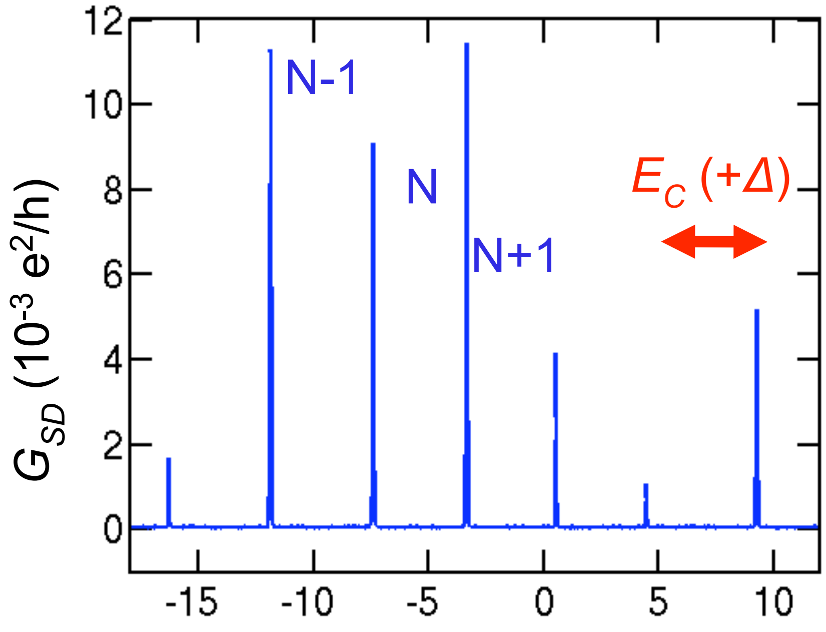




Quantum point contact as a charge detector

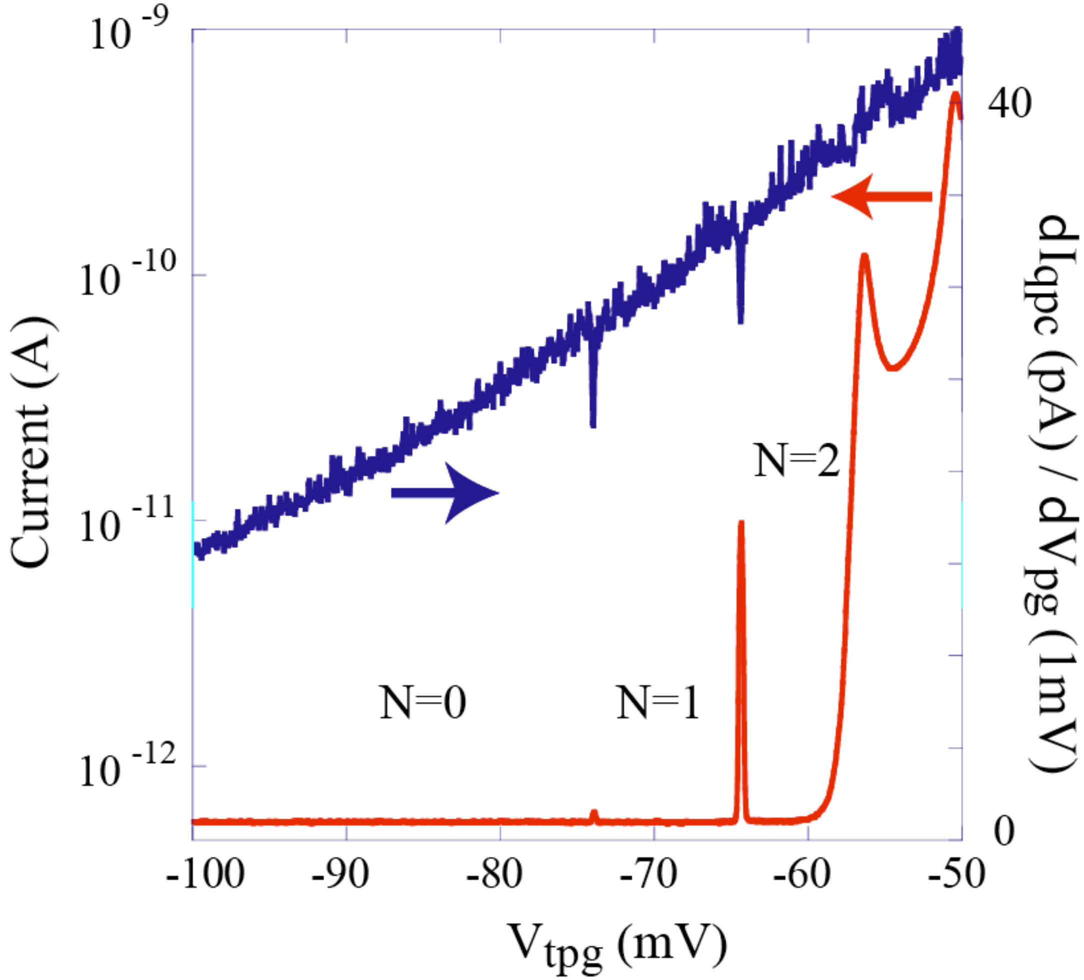


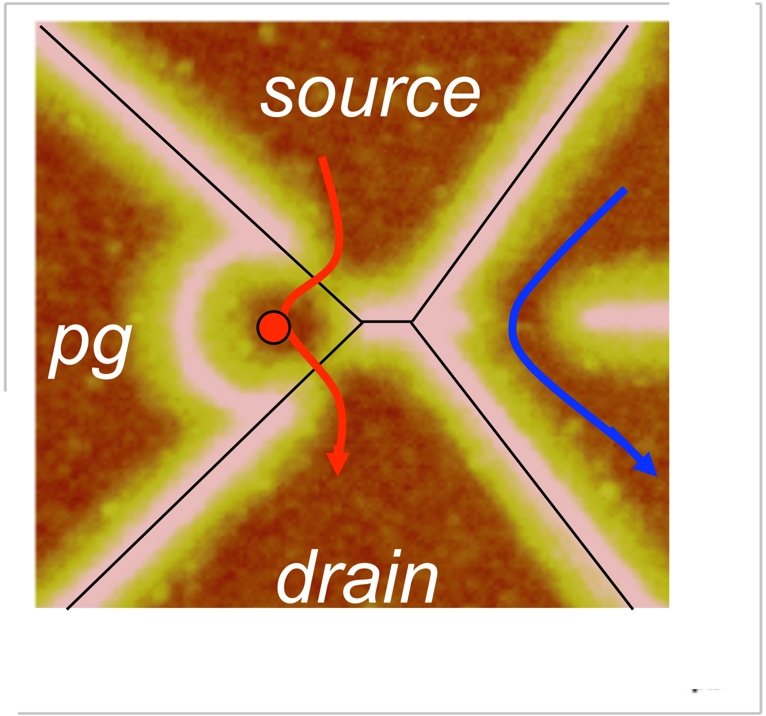




M. Field et al., Phys. Rev. Lett. 70, 1311 (1993)

A few electron quantum dot

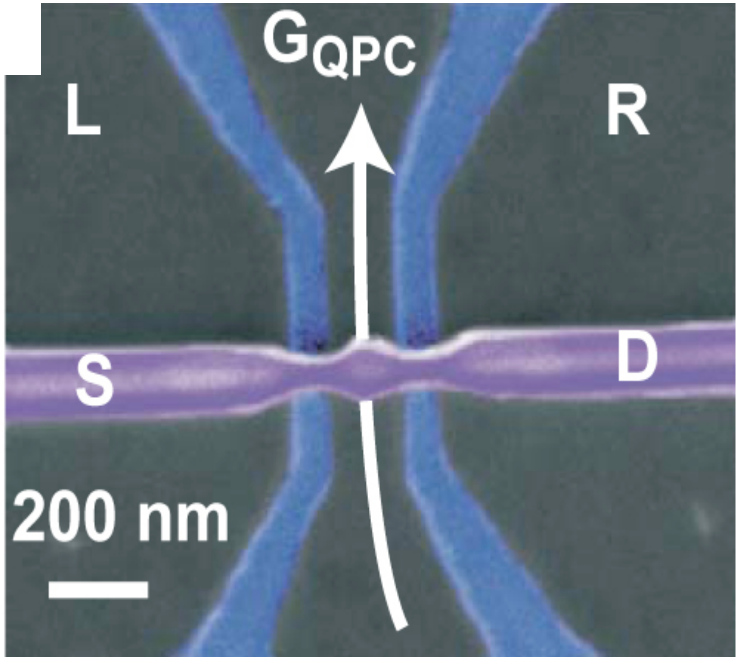


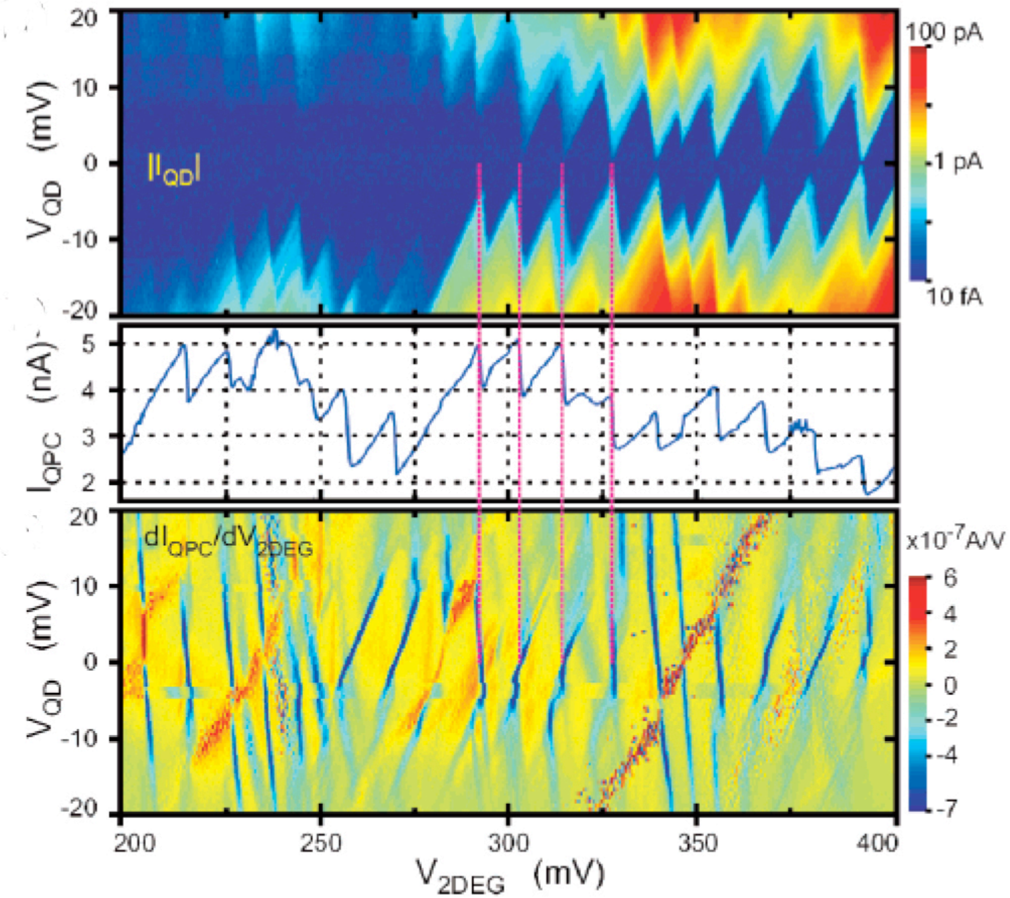


M. Sigrist

Ciorga et al.,
PRB 61, R16315 (2000)
Elzerman et al.
PRB 67, 161308 (2003)

InAs nanowire dot with charge detector in a 2DEG

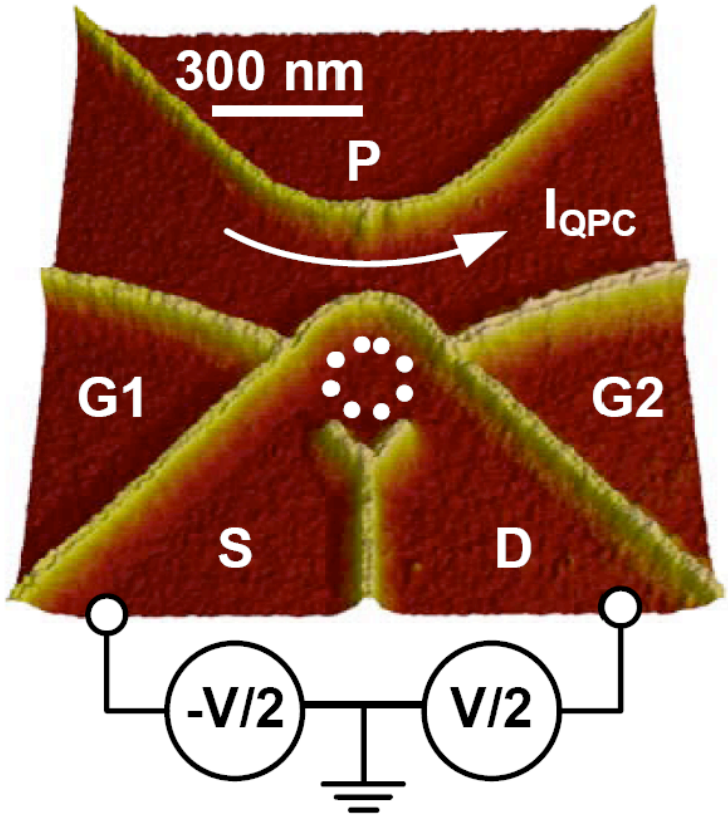


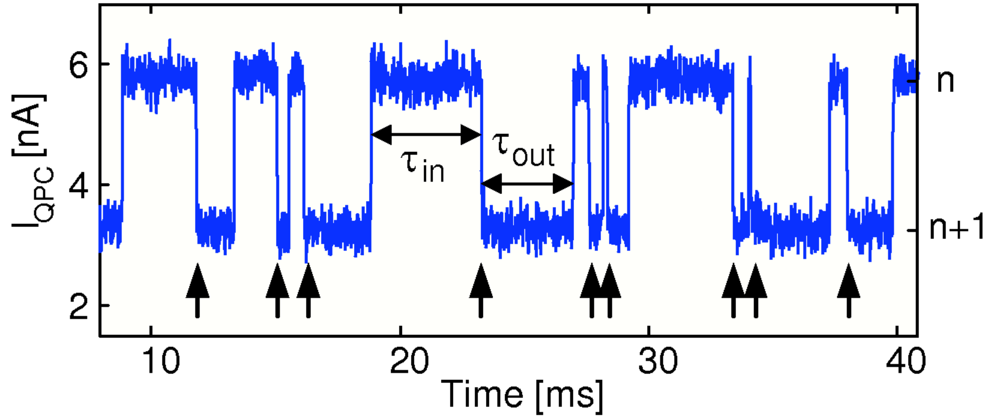


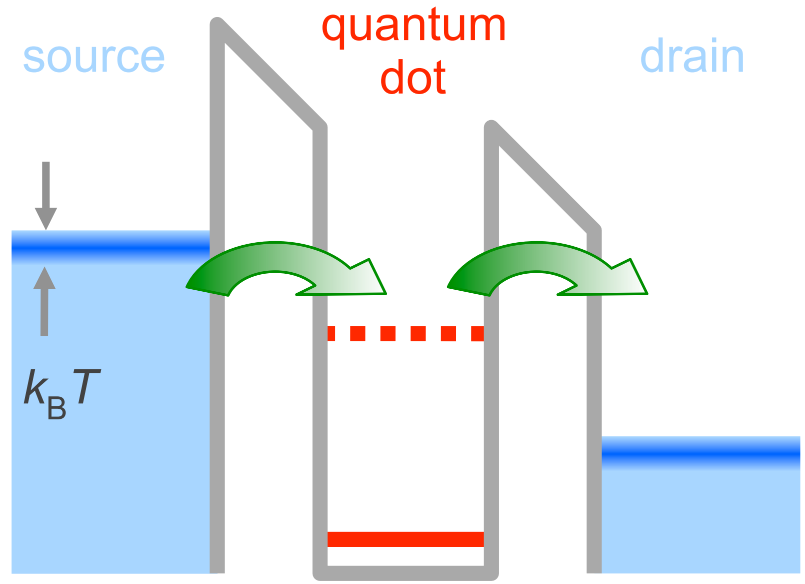
I. Shorubalko, R. Leturcq, A. Pfund

Nanoletters 8, 382 (2008)

Time-resolved detection of single electron transport



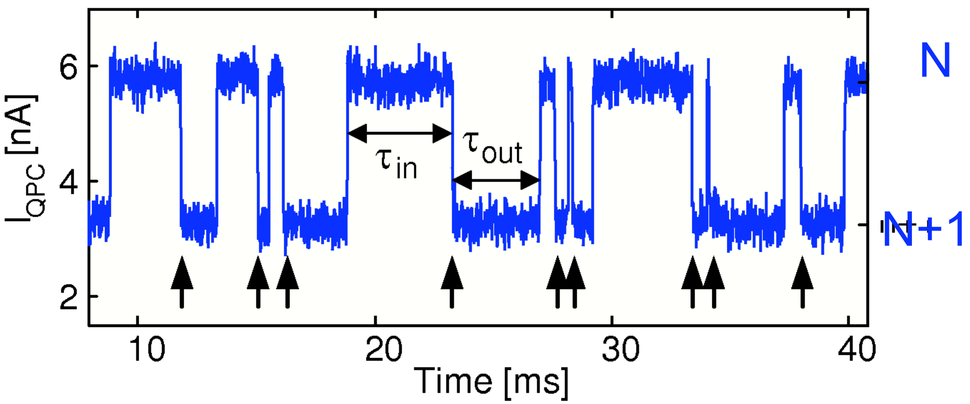


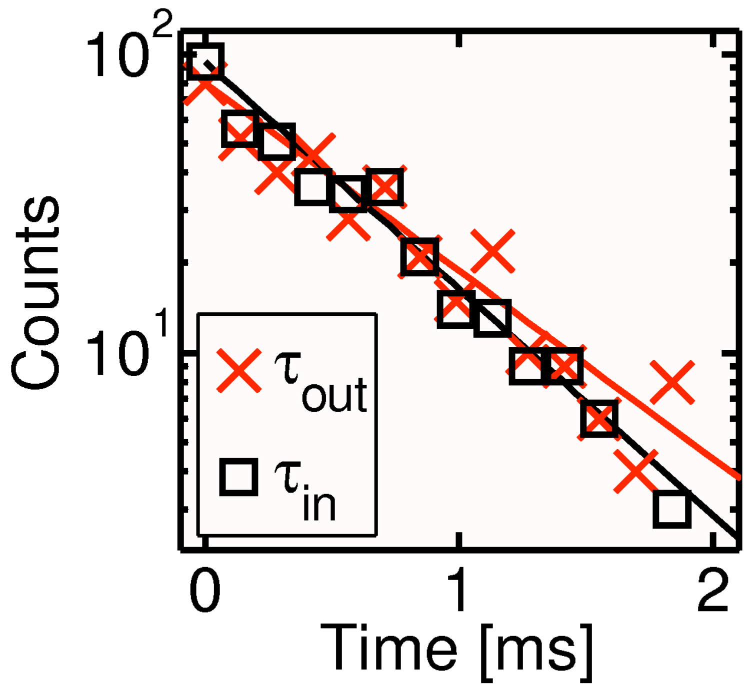


Schleser et al., APL 85, 2005 (2004)
Vandersypen et al., APL 85, 4394 (2004)

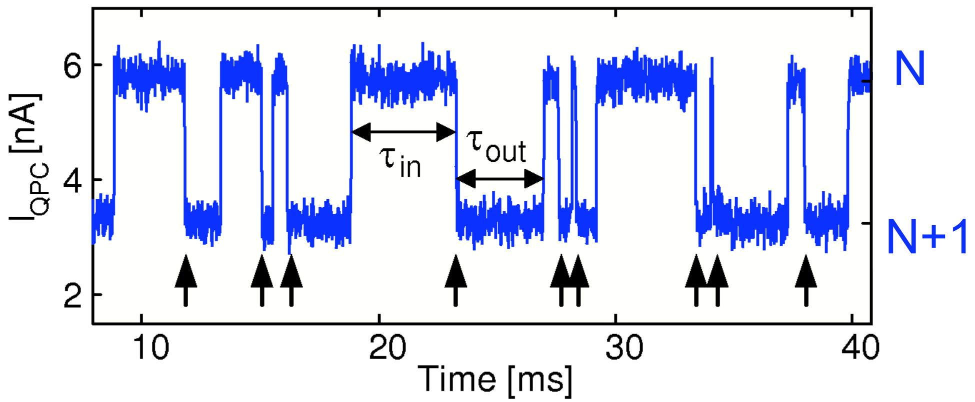
Determination of the individual tunneling rates

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





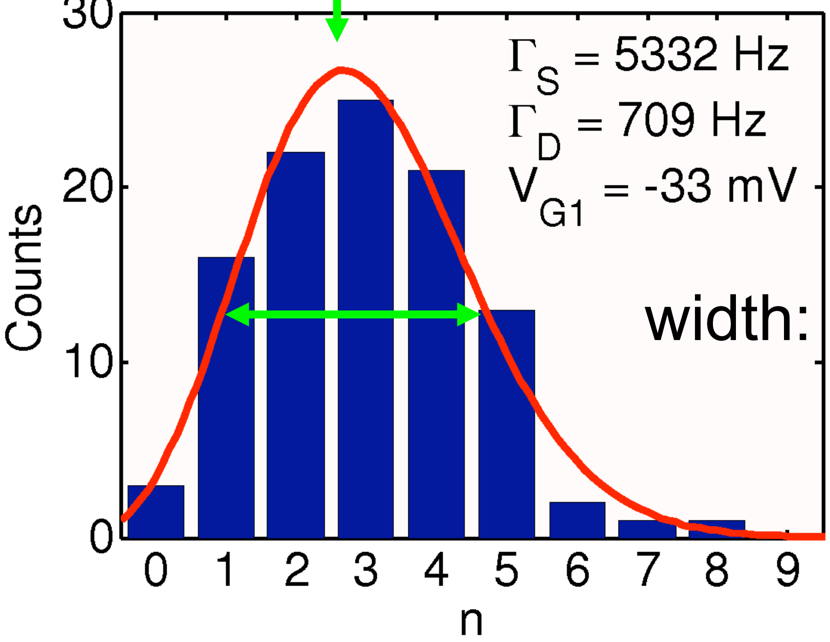
Measuring the current by counting electrons



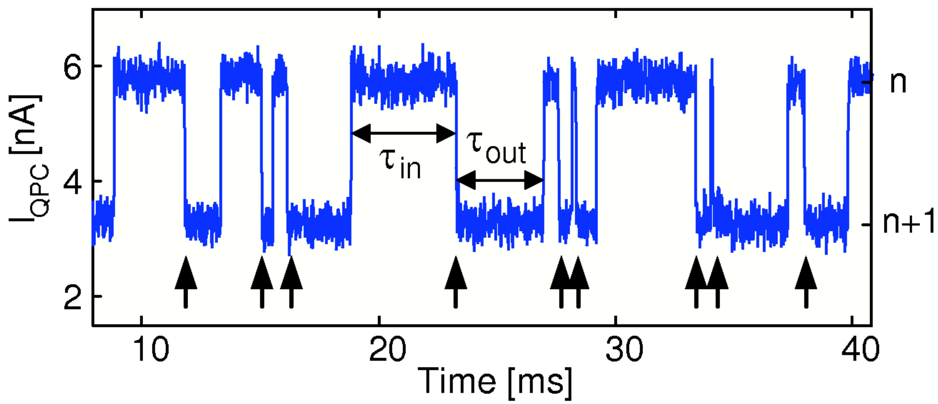
- Count number *n* of electrons entering the dot within a time t_0: $I = e\langle n\rangle/t_0$
- Max. current = few fA (bandwidth = 30 kHz)
- BUT no absolute limitation for low current and noise measurements
  - *here:* $I \approx$ few aA, $S_I \approx 10^{-35}$ A^2/Hz

Histogram of current fluctuations

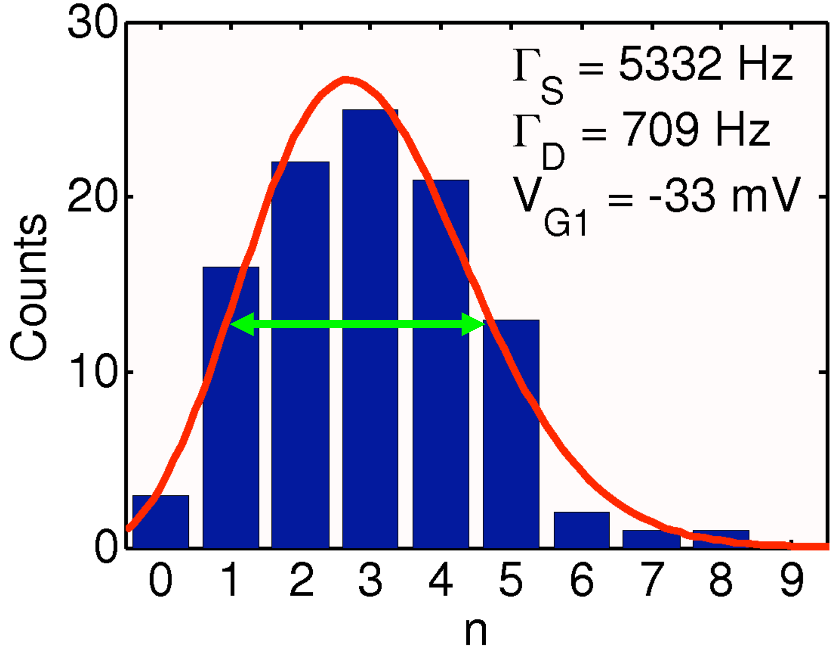
mean: mean current

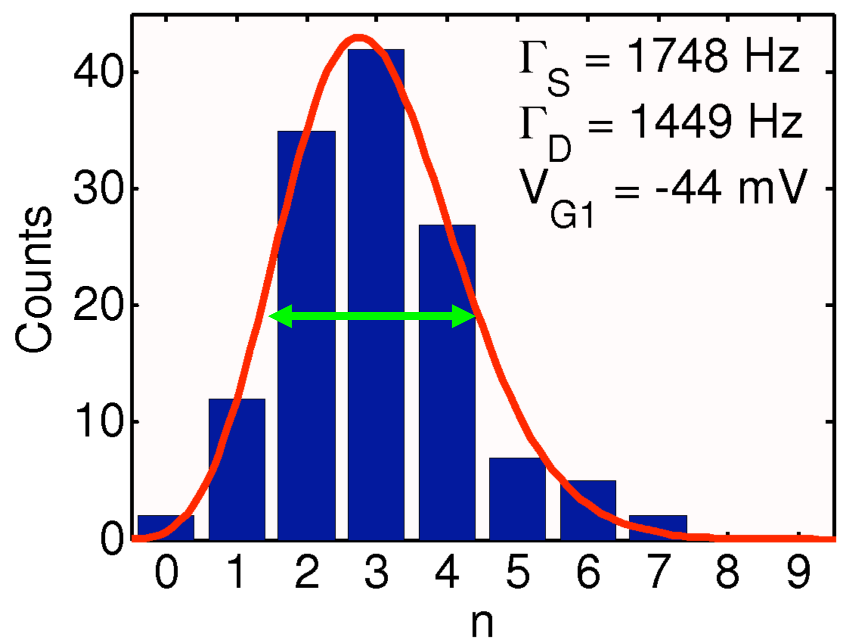


width: fluctuations, noise



Histogram of current fluctuations



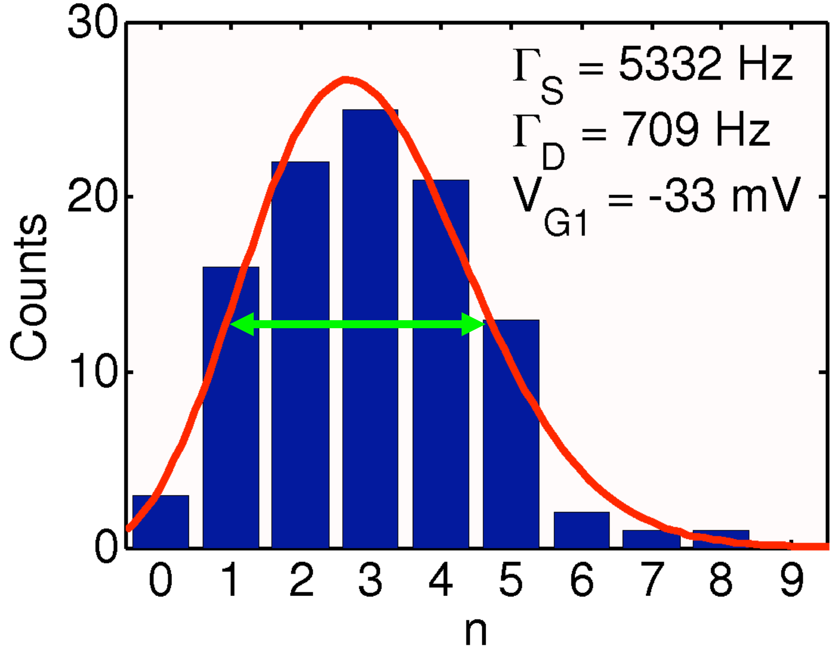


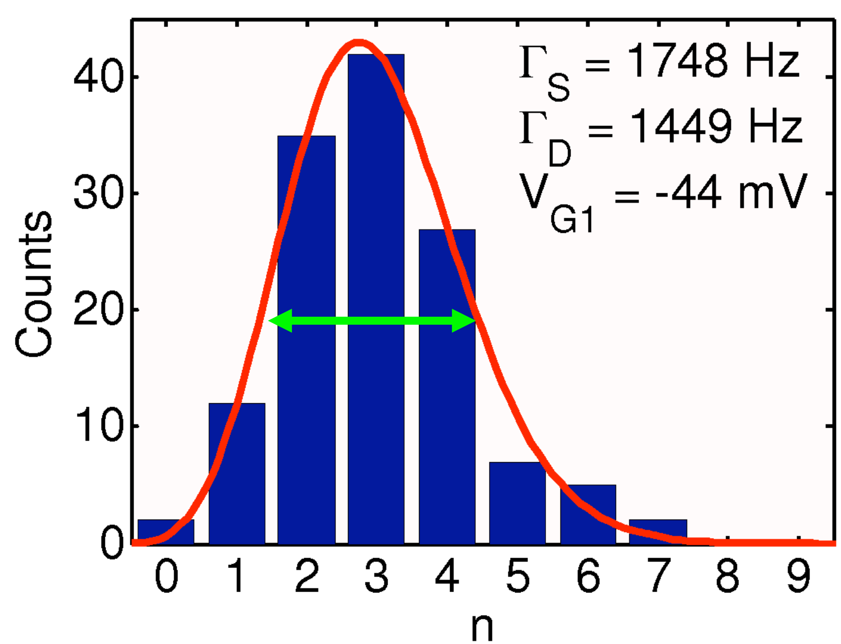
- Poisson distribution for asymmetric coupling
- Sub-Poisson distribution for symmetric coupling

Theory: Hershfield *et al.,* PRB **47,** 1967 (1993)
Bagrets & Nazarov, PRB **67,** 085316 (2003)

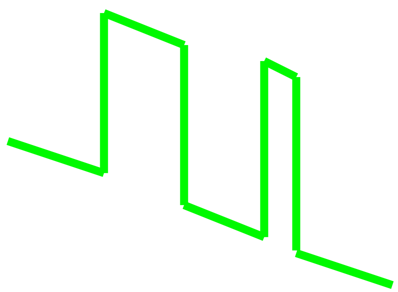
Expt: Gustavsson et al., PRL **96**, 076605 (2006)

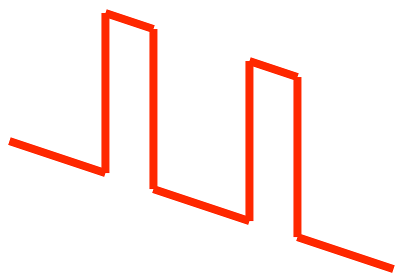
Histogram of current fluctuations





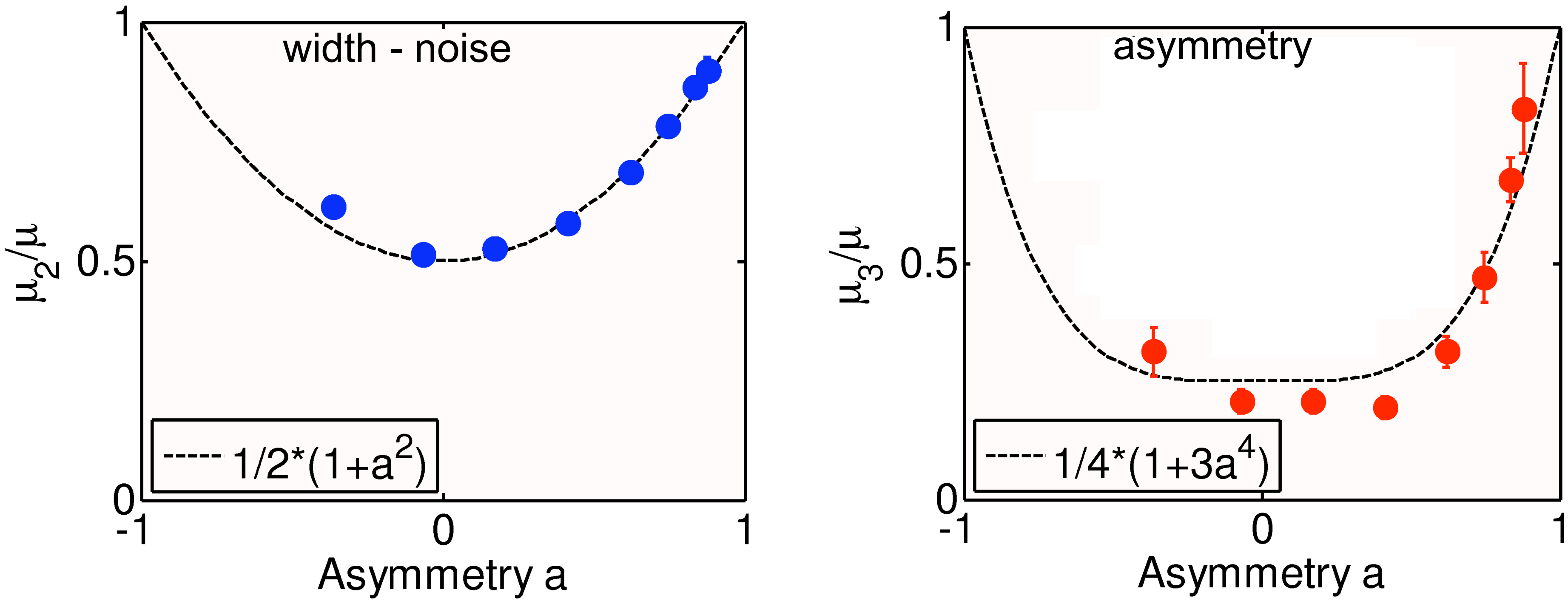
- Poisson distribution for asymmetric coupling
- Sub-Poisson distribution for symmetric coupling





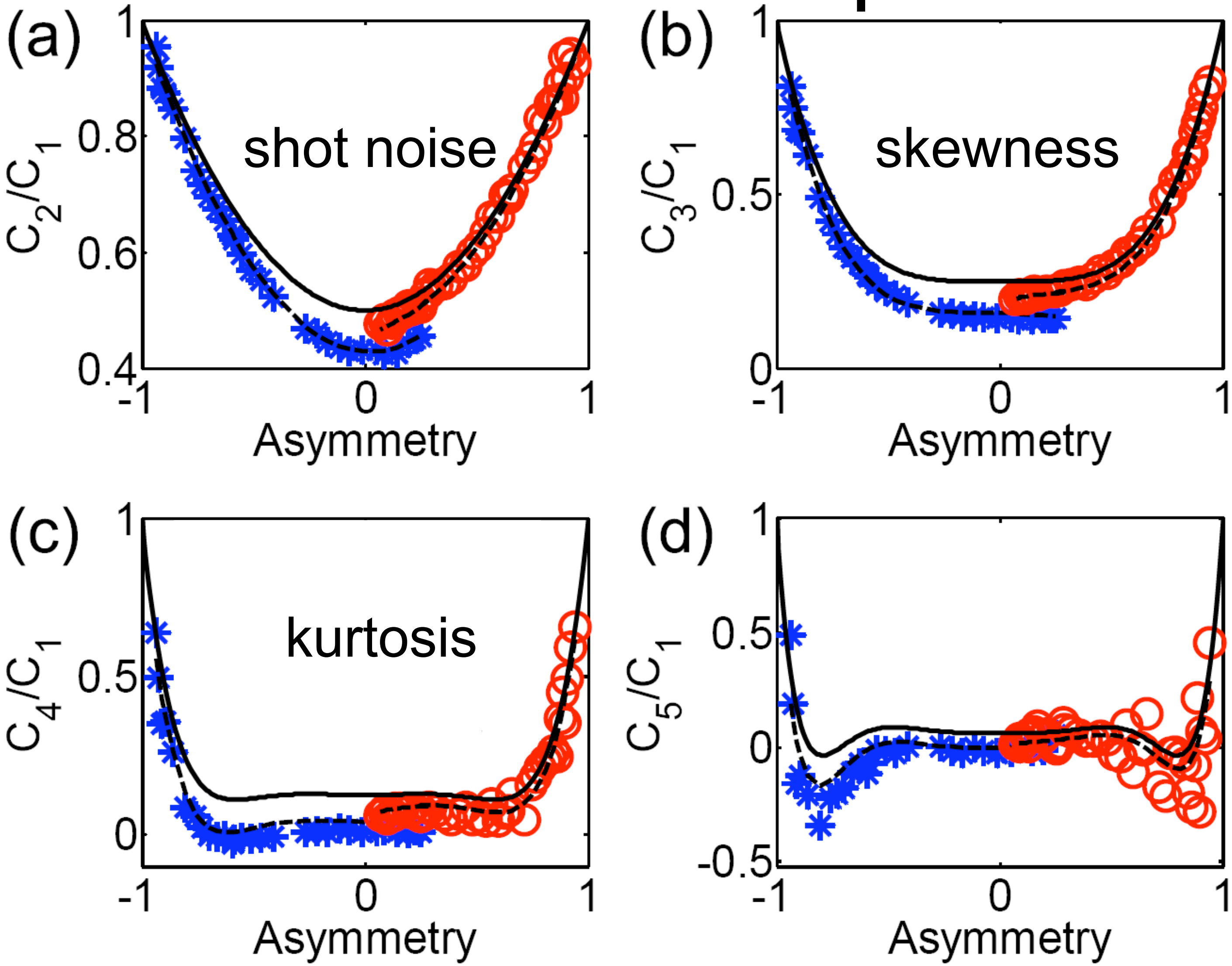
Current fluctuations vs. asymmetry

- Reduction of the second and third moments for symmetric coupling



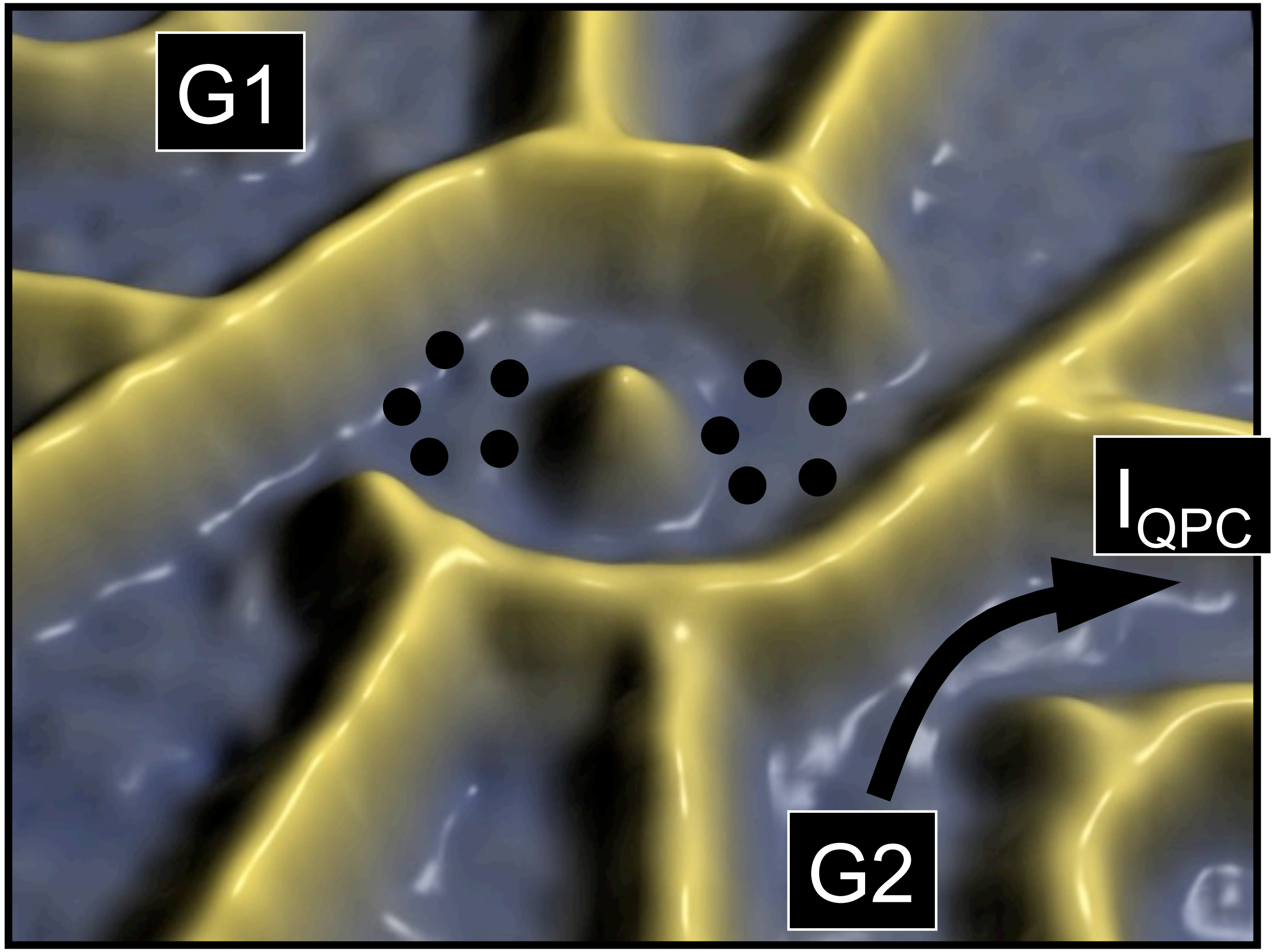
Theory: Hershfield *et al.*, PRB **47,** 1967 (1993)
Bagrets & Nazarov, PRB **67,** 085316 (2003)

Higher order correlations of electron transport

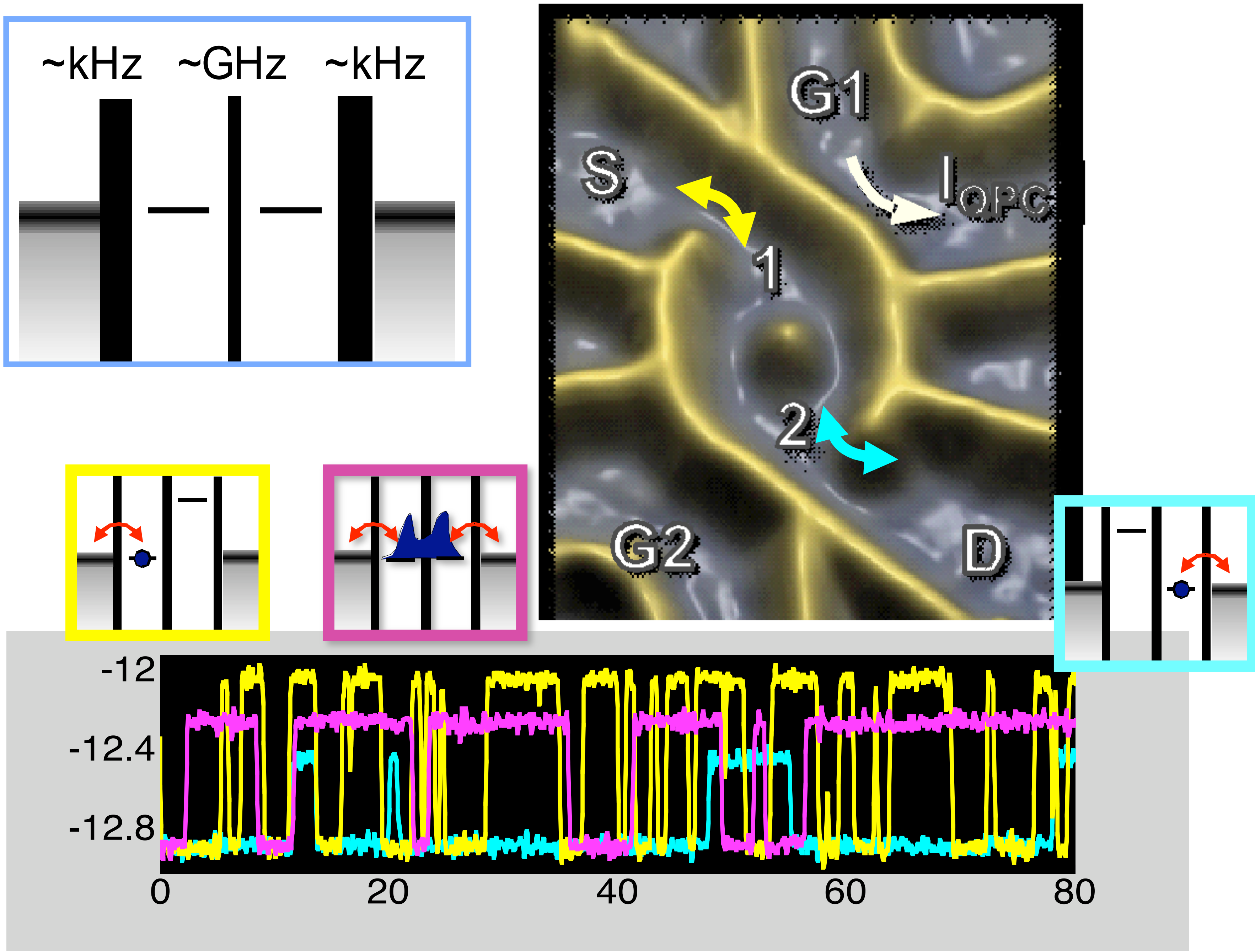


Gustavsson et al, PRB 75, 075314 (2007)

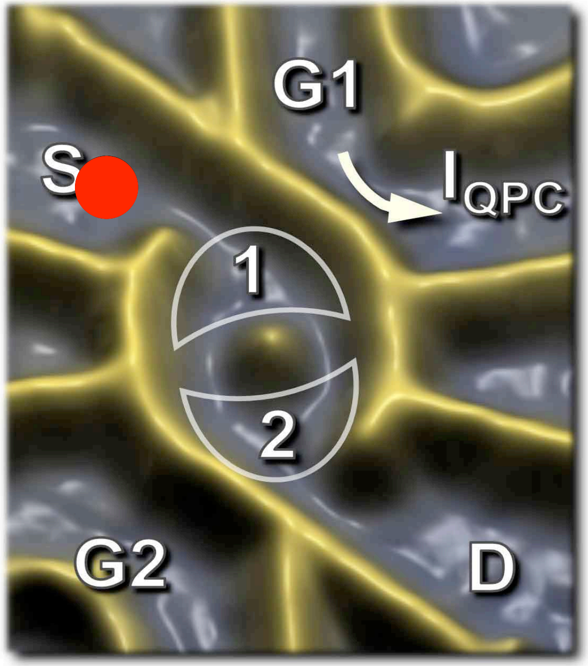
Double quantum dot in a ring

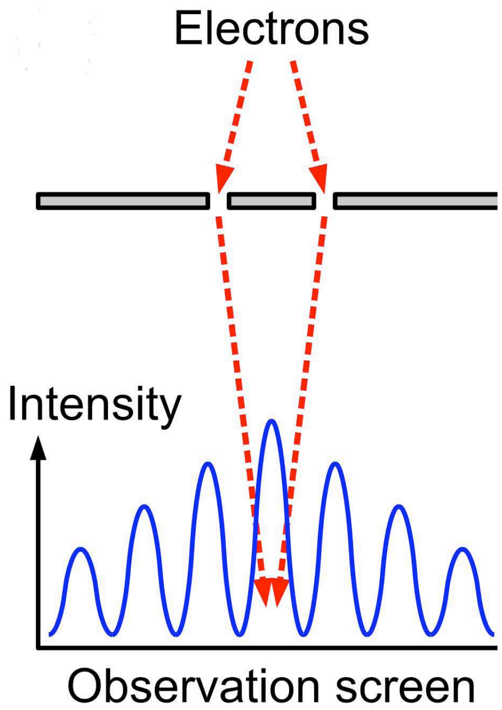


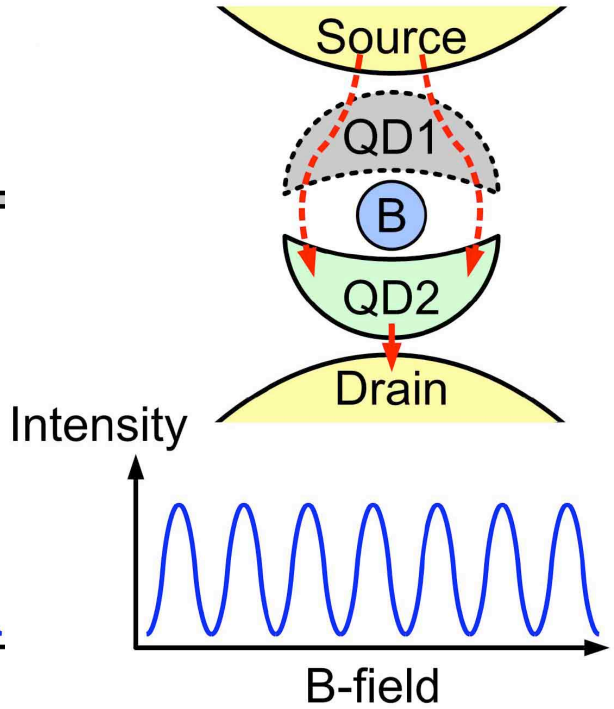
see also: electron counting in double dots: Fujisawa *et al.*, Science **312**, 1634 (2006)

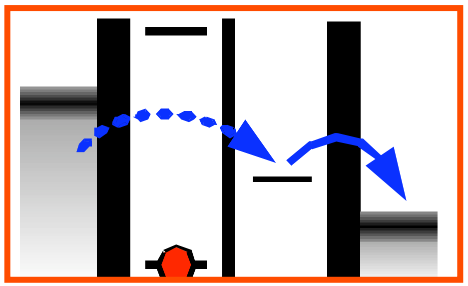

~kHz
~GHz
~kHz
G1
S
I_{QPC}
1
2
G2
D
-12
-12.4
-12.8
0
20
40
60
80

Double slit experiment
<-> Aharonov Bohm



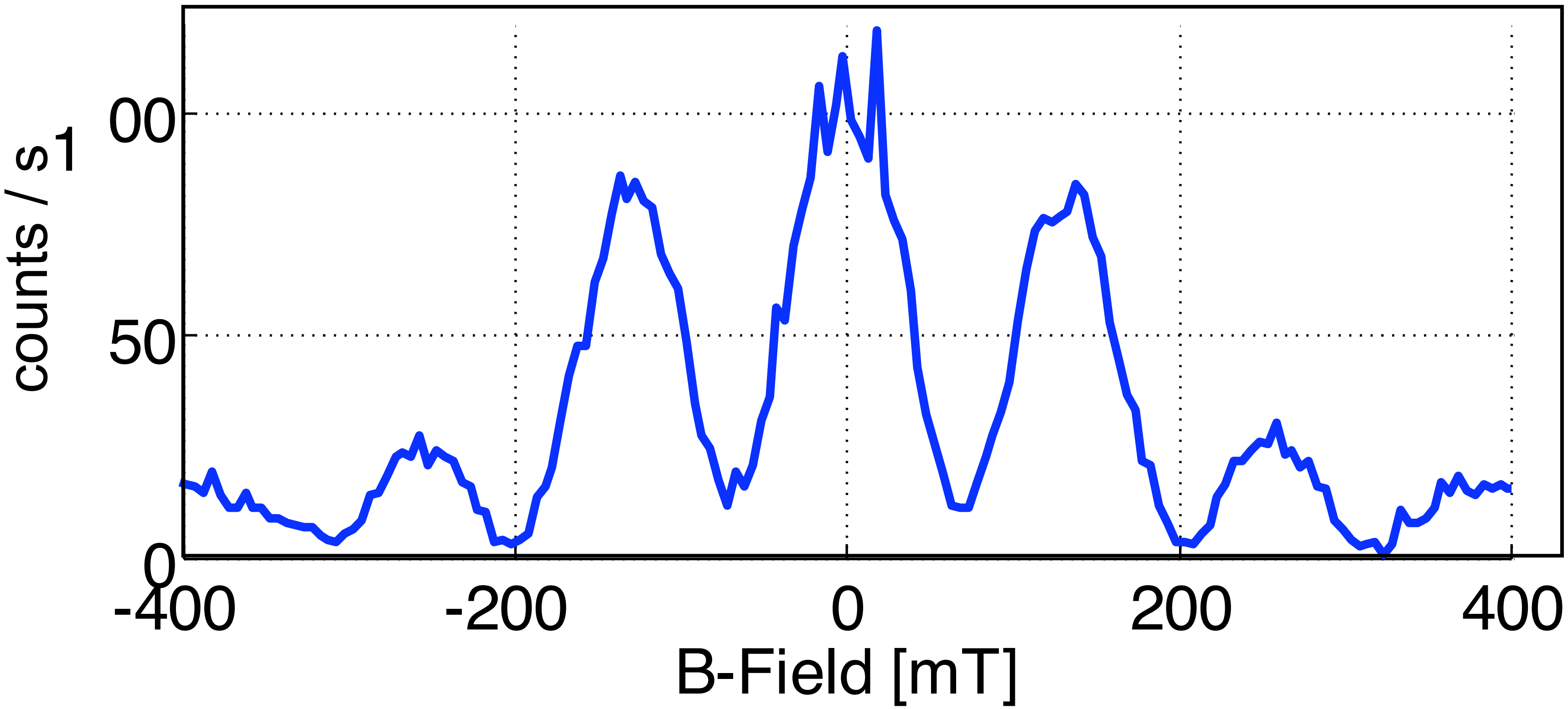






Tonomura et al.,
Amer. J. of Physics **57** 117 (1989)

Aharonov-Bohm oscillations

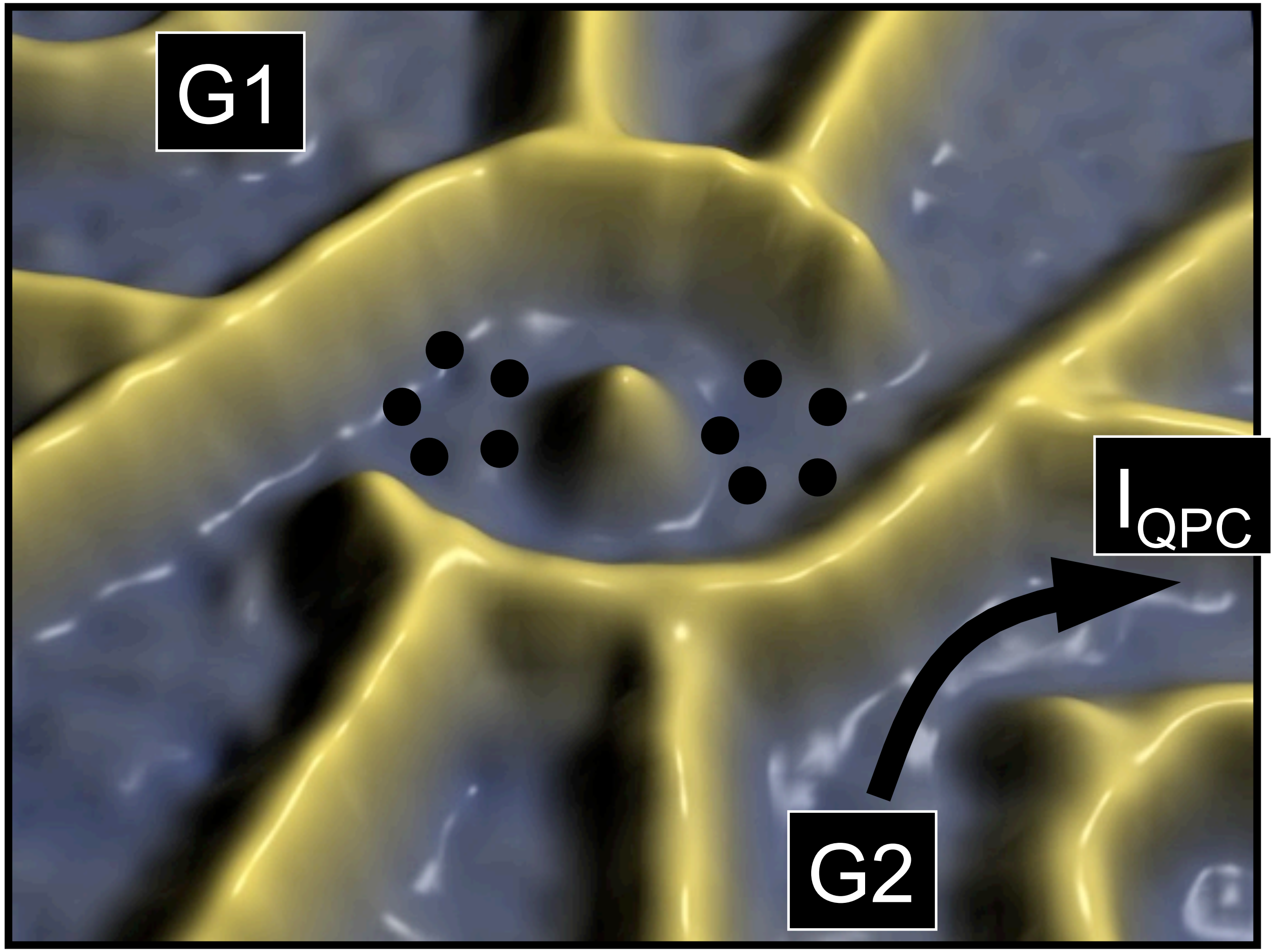


huge visibility! >90%, stable in temperature up to 400 mK

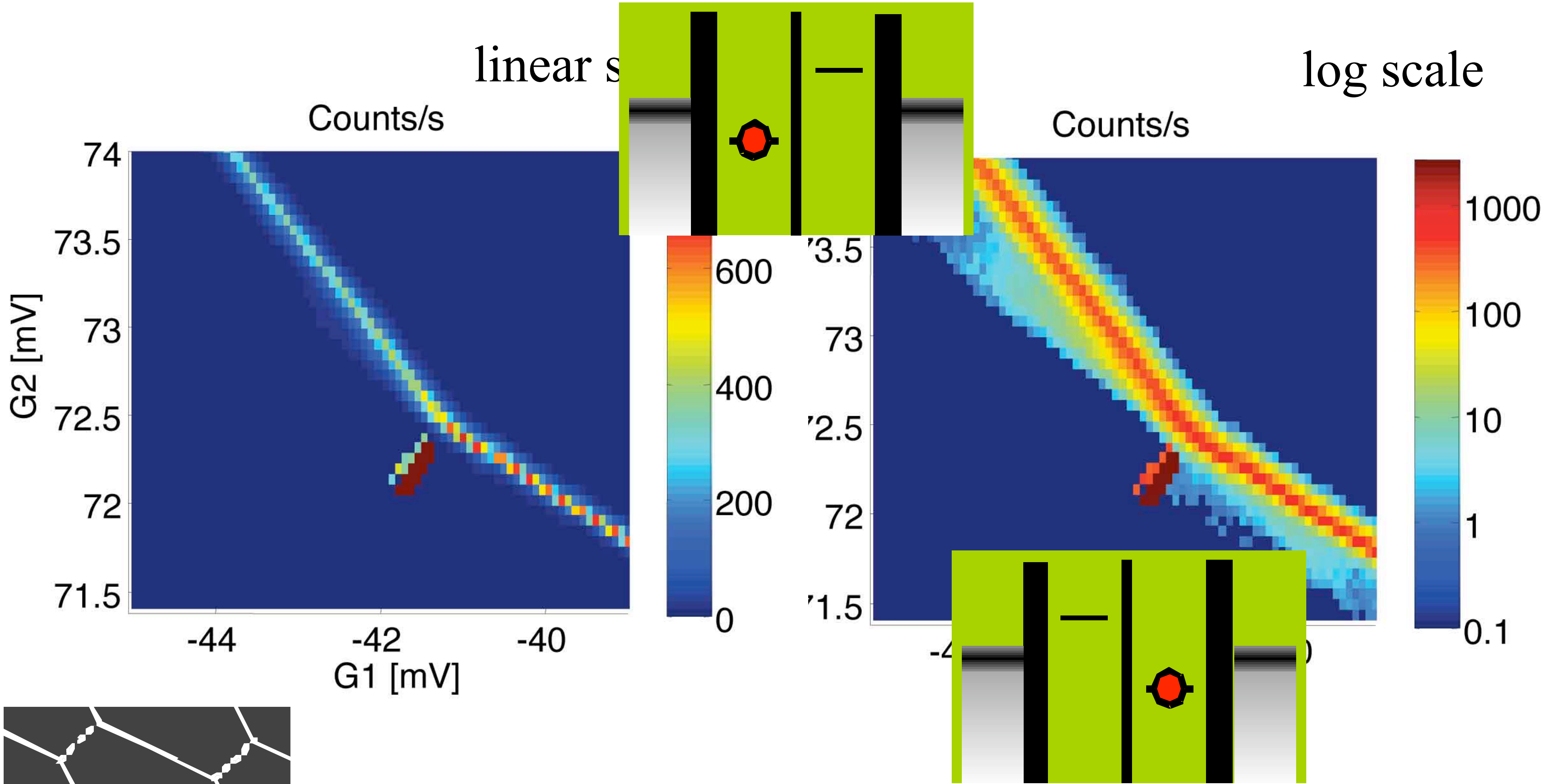
little decoherence - > cotunneling is much faster than decoherence time

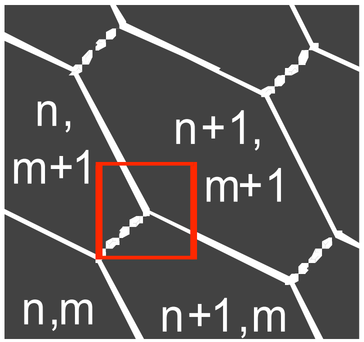
Gustavsson et al., Nanoletters **8**, 2547 (2008)

What about back action?



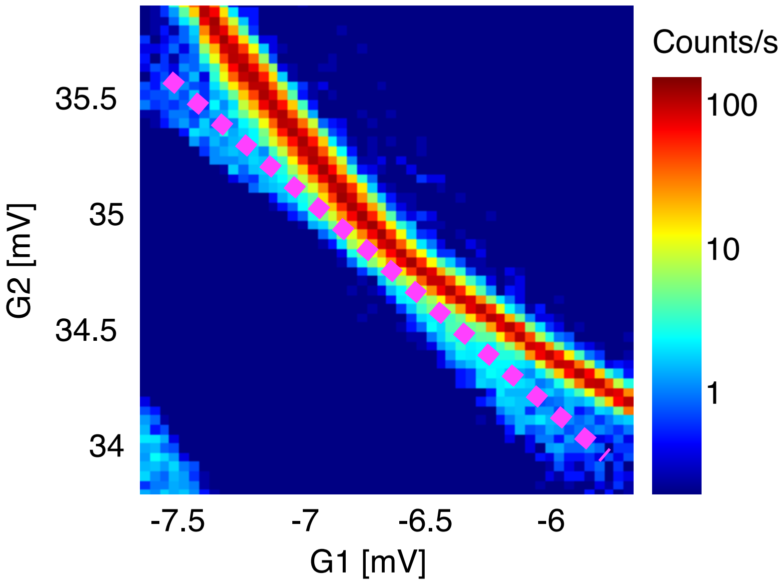
Resonances in double dot



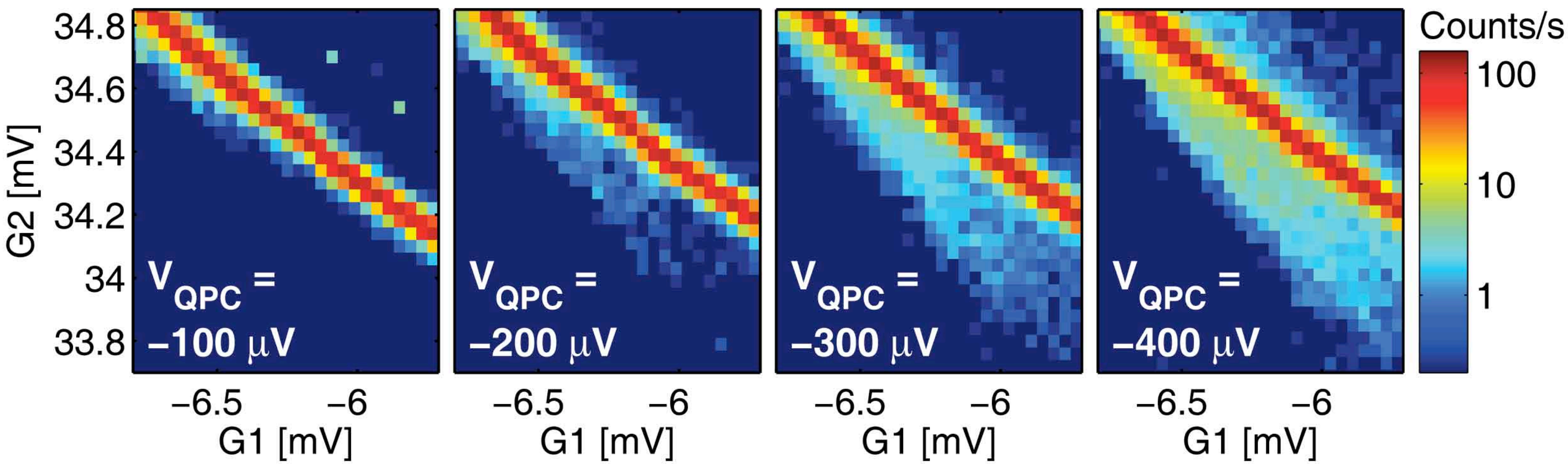


V_{QPC}=300 μV

Different biases across the QPC

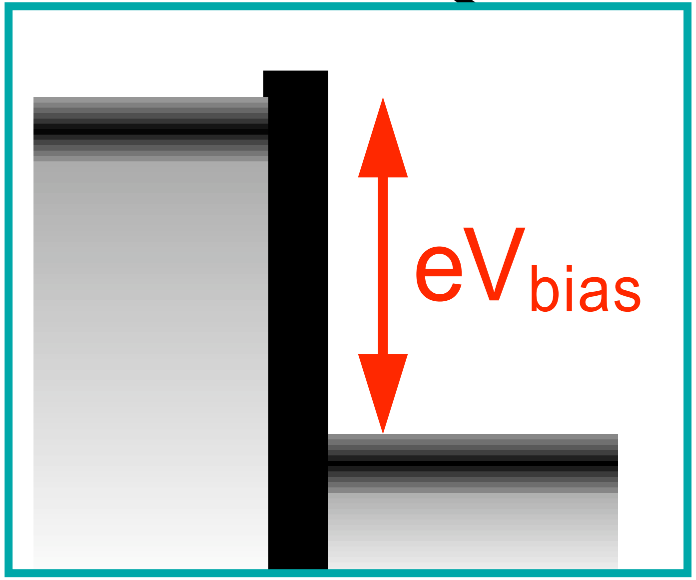


The triangles grow with increasing bias



Microwave emission of a QPC

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



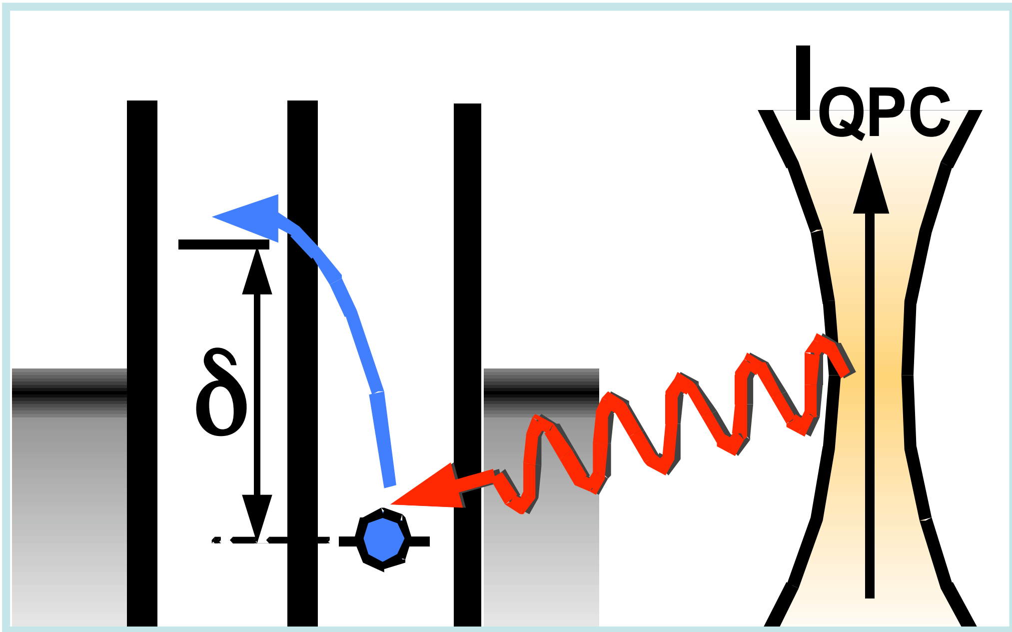
$$S_I(\omega) = \frac{4e^2}{h} T(1-T) \frac{eV - \hbar\omega}{1 - e^{-(eV-\hbar\omega)/k_B T}}$$

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)

Single photon detection by a quantum dot

quantum optics

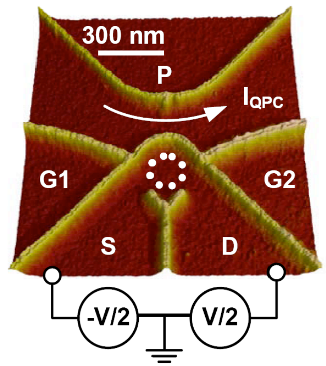
wave length
of photon:
500 nm

size of atom:
1 nm

far field optics

semiconductor nanostructures

wave length
of photon:
10 mm



size of
quantum dot:
100 nm

extreme near field optics

Thank you

Simon Gustavsson

Renaud Leturcq

Ivan Shorubalko

Thomas Ihn

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