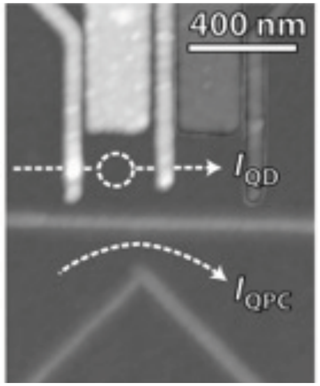
Time-dependent single-electron transport: irreversibility and out-of-equilibrium

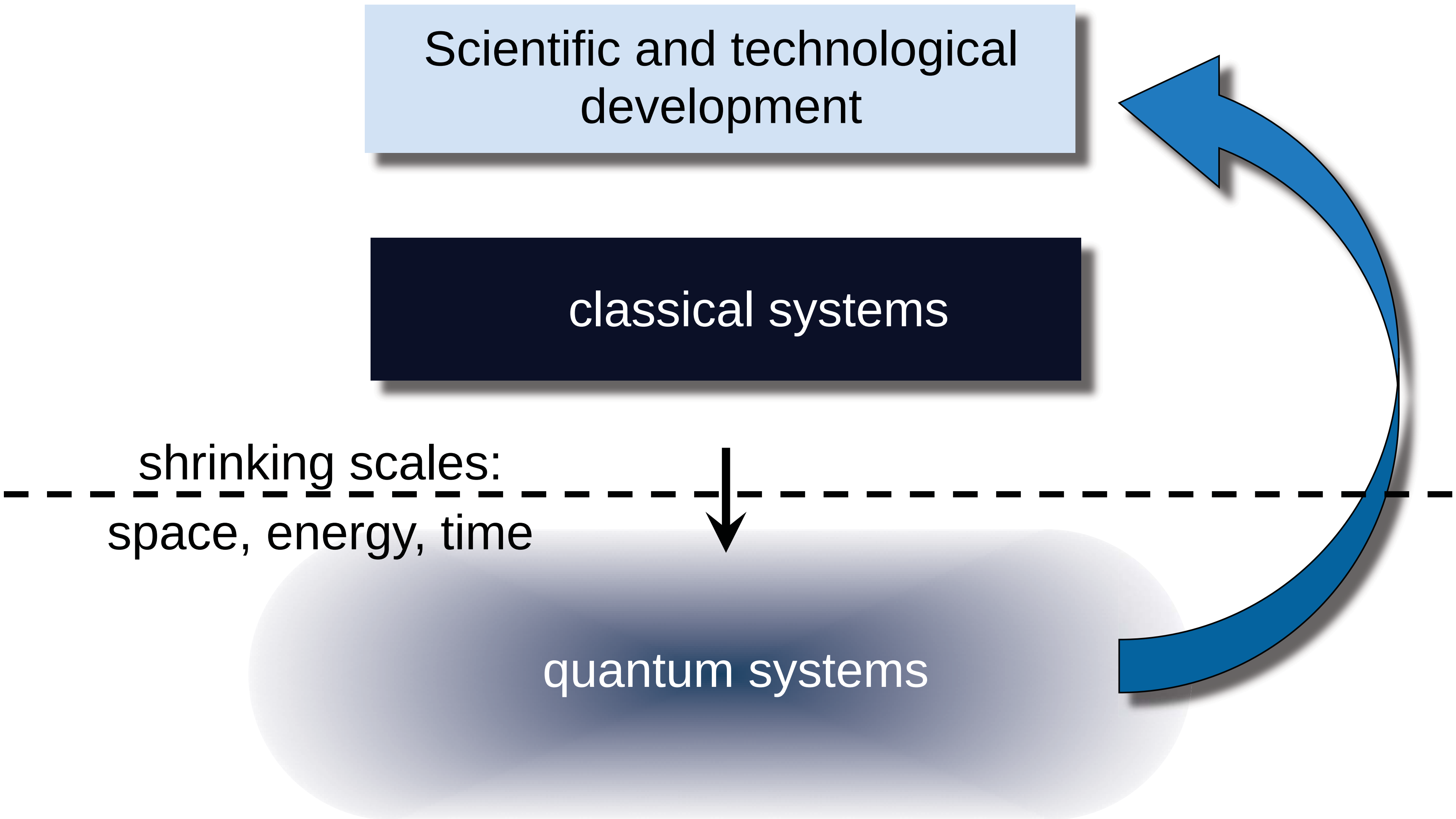


Klaus Ensslin

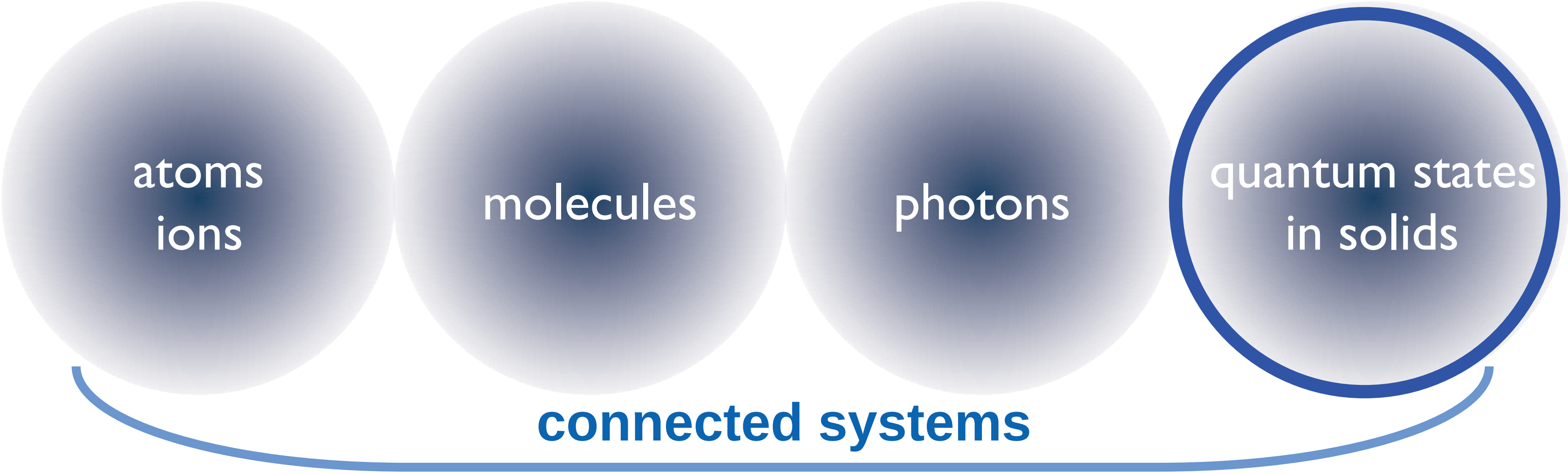
Solid State Physics ETH Zürich

1. quantum dots
2. electron counting
3. counting and irreversibility
4. Microwave resonantor coupled to quantum dots

Quantum Technology

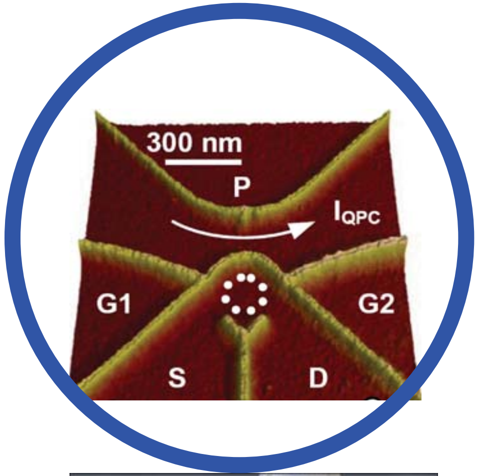


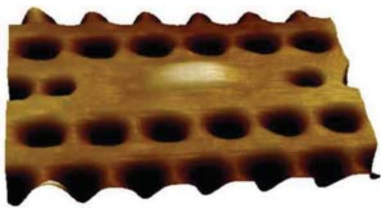
Engineering of Quantum Systems

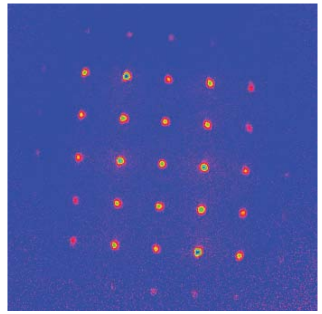


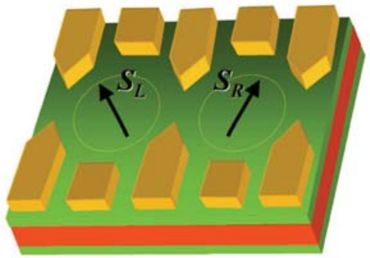
1. quantum computing, quantum simulation, quantum cryptography
2. matter wave sensors, optical frequency synthesizer
3. super-chemistry and quantum materials
4. interference-based devices

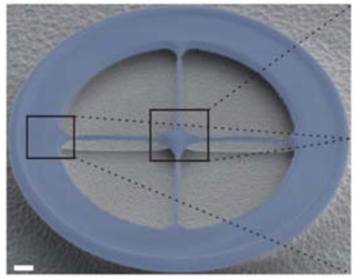
Quantum Science and Technology in Switzerland

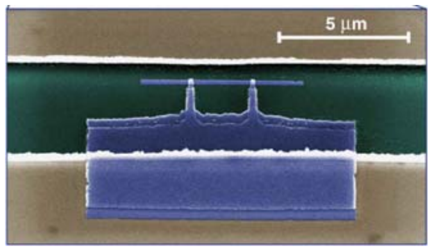


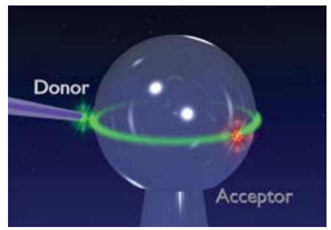


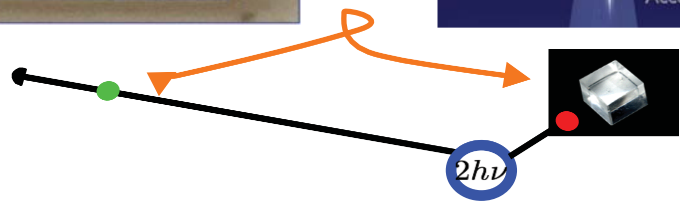












QSIT-Quantum Science and Technology www.nccr-qsit.ethz.ch

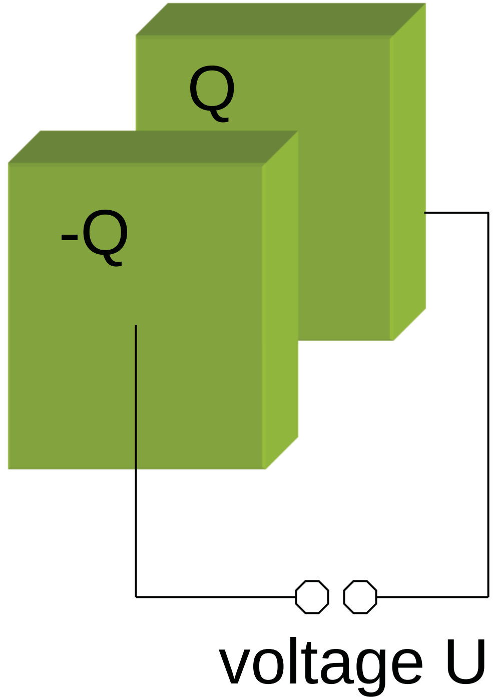
Quantized Charge

Capacitance of a capacitor:

$$C = \frac{|Q|}{U} = \frac{\text{charge}}{\text{voltage}}$$

Energy to charge the capacitor:

$$E = \int_0^Q U\,dQ = \int_0^Q \frac{Q}{C}\,dQ = \frac{Q^2}{2C}$$



Energy to put one electron (*Q*=*e*) on a capacitor with *C = 1 nF*

$$E = \frac{\left(1.6\cdot 10^{-19}\ As\right)^2}{2\cdot 10^{-9}\ F} = 1.3\cdot 10^{-29}\ Joule = 8\cdot 10^{-9}\ eV$$

Equivalent to temperature $T = 0.1\ mK$

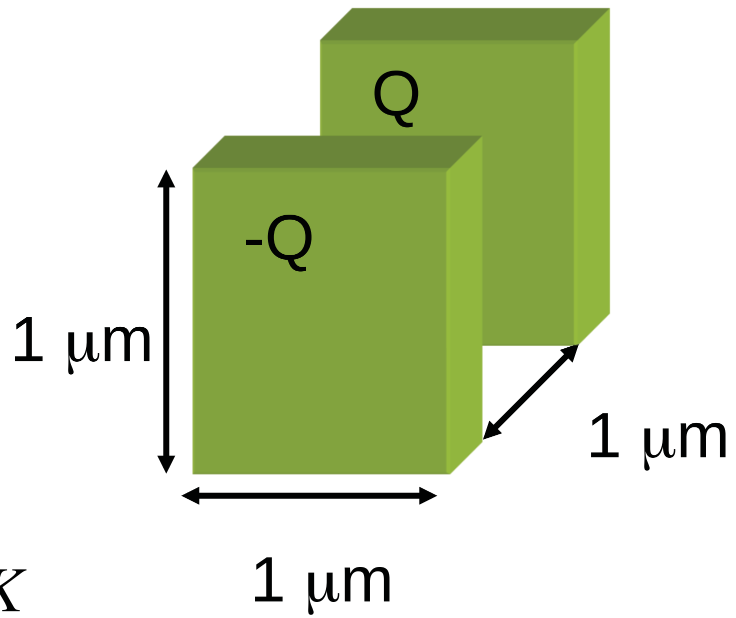
Size of a Capacitor

Capacitance

$$C = \varepsilon\varepsilon_0 \frac{area}{separation} =$$

$$= \varepsilon\varepsilon_0 \frac{(1\ \mu m)^2}{1\ \mu m} = 10^{-16}\ F$$

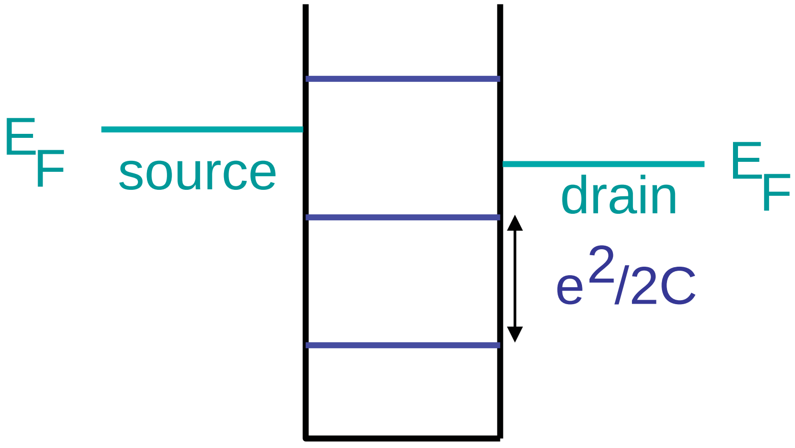
Equivalent to temperature $T = 7\ K$



-> use nanotechnology to make a small capacitor

decoupled from its environment

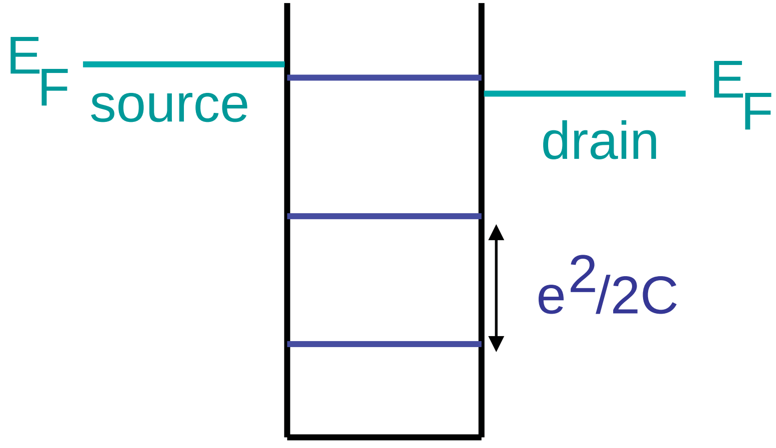
Coulomb Blockade



$kT << e^2/2C$

$eU = E_F^{source} - E_F^{drain} << e^2/2C$

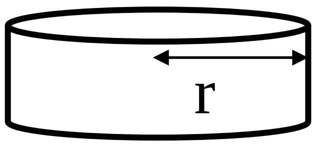
➔ no current transport



discrete level between

E_F^{source} and E_F^{drain}

➔ coherent resonant tunneling

disk: 

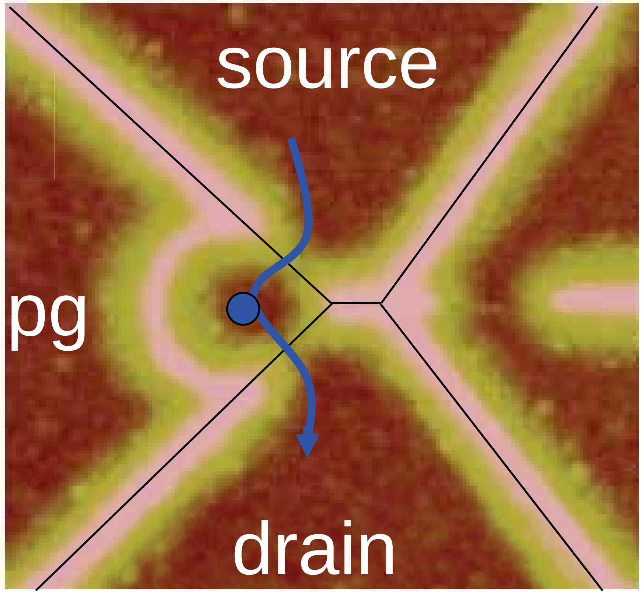
$$C = 8\varepsilon\varepsilon_0 r$$

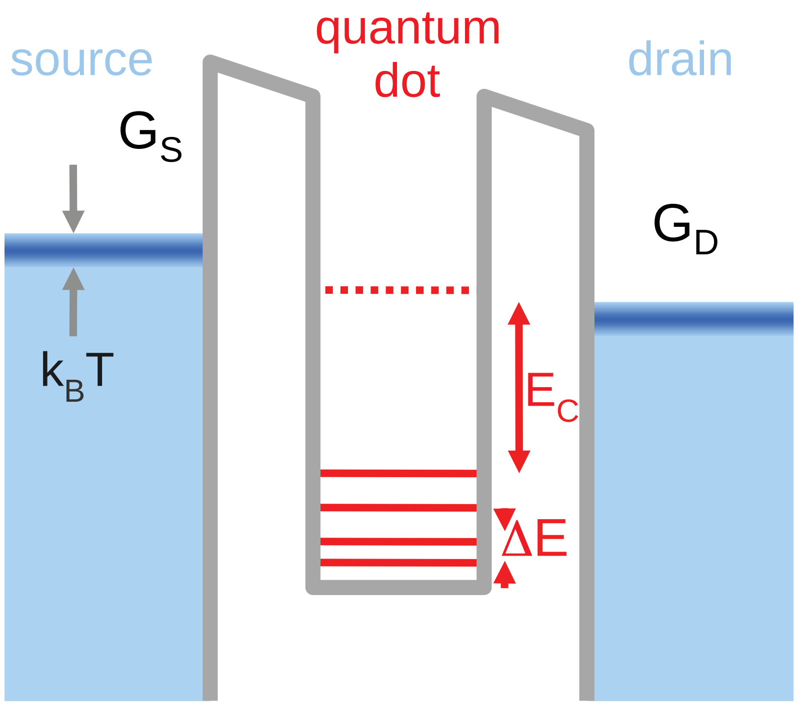
$$r = 100\ nm$$

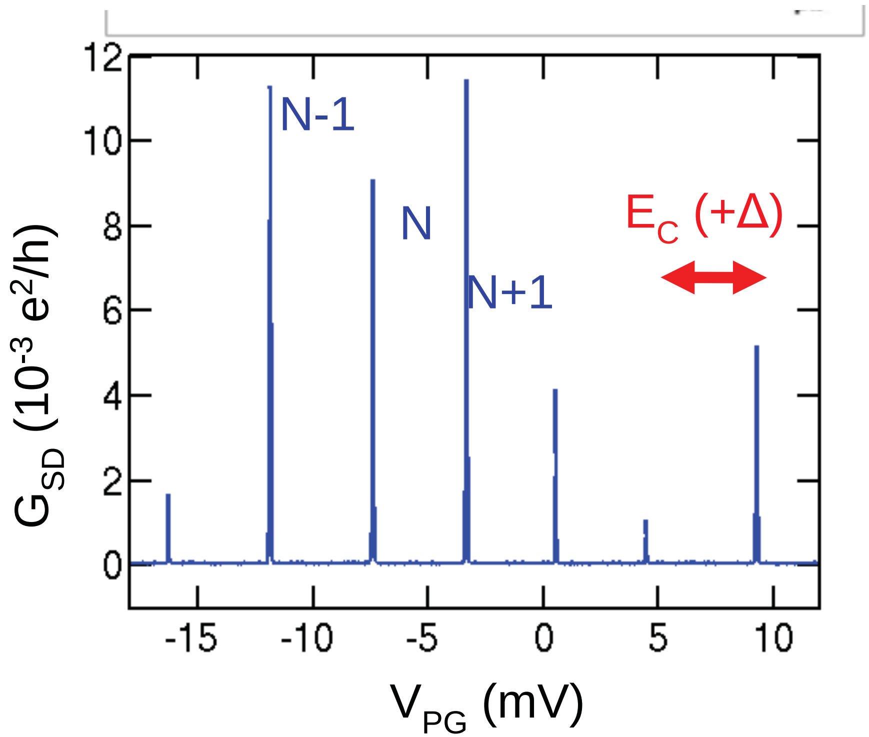
$$-> \ C = 84\ aF$$

$$-> \ e^2/2C = 900\ \mu eV \ \cong \ 11\ K$$

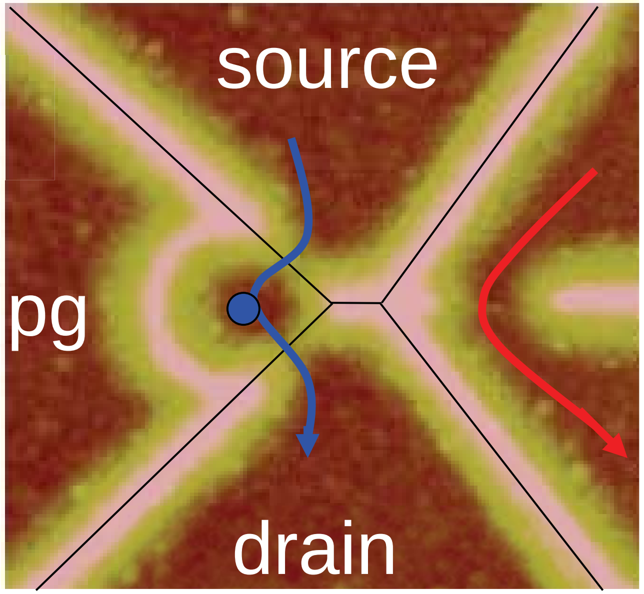
Spectroscopy of electronic states

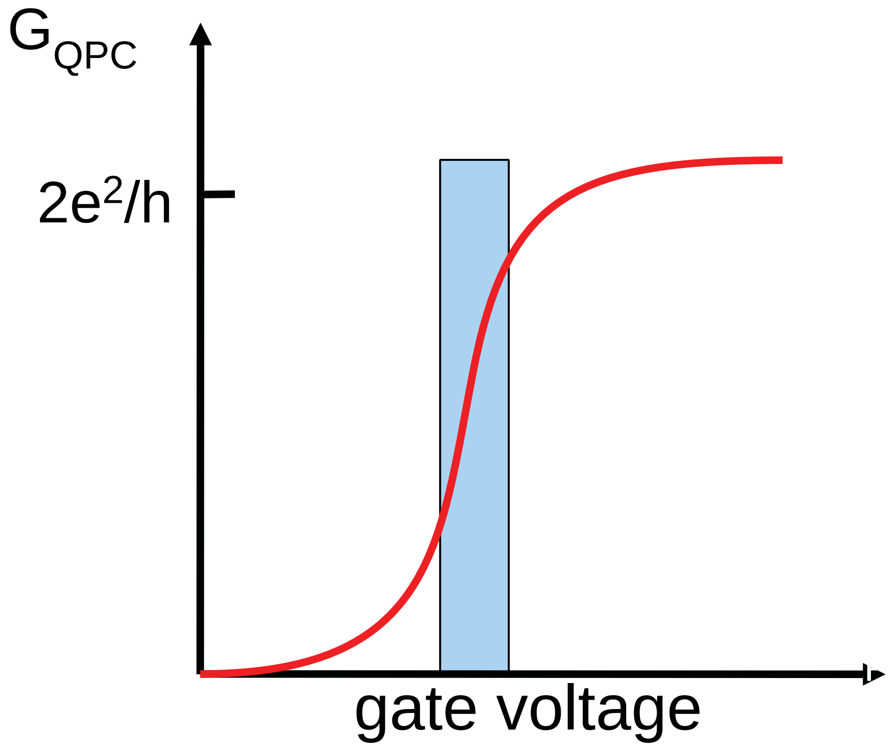


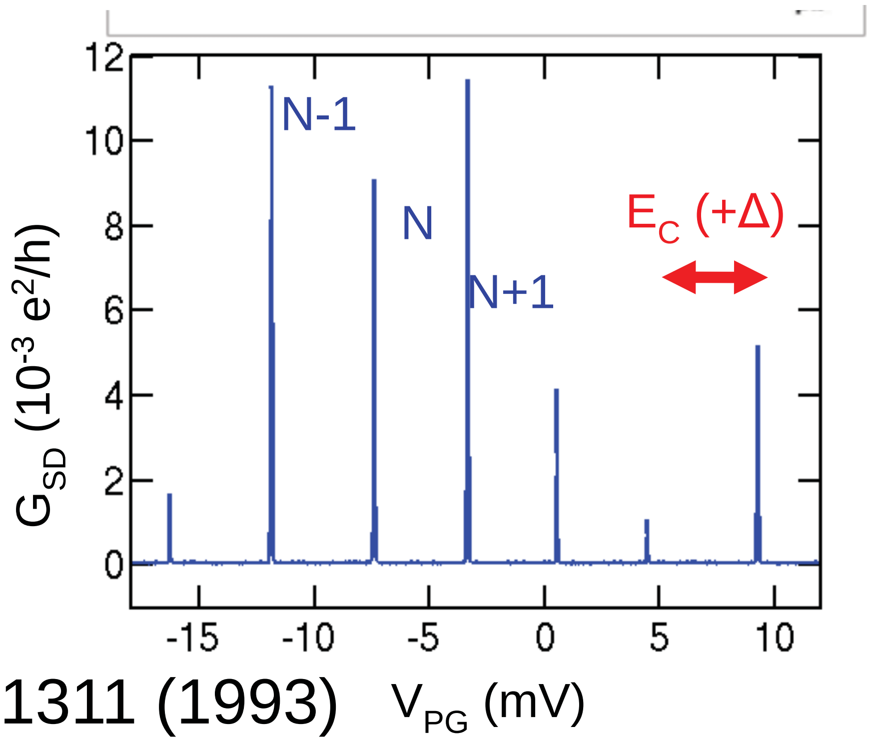




Quantum point contact as a charge detector

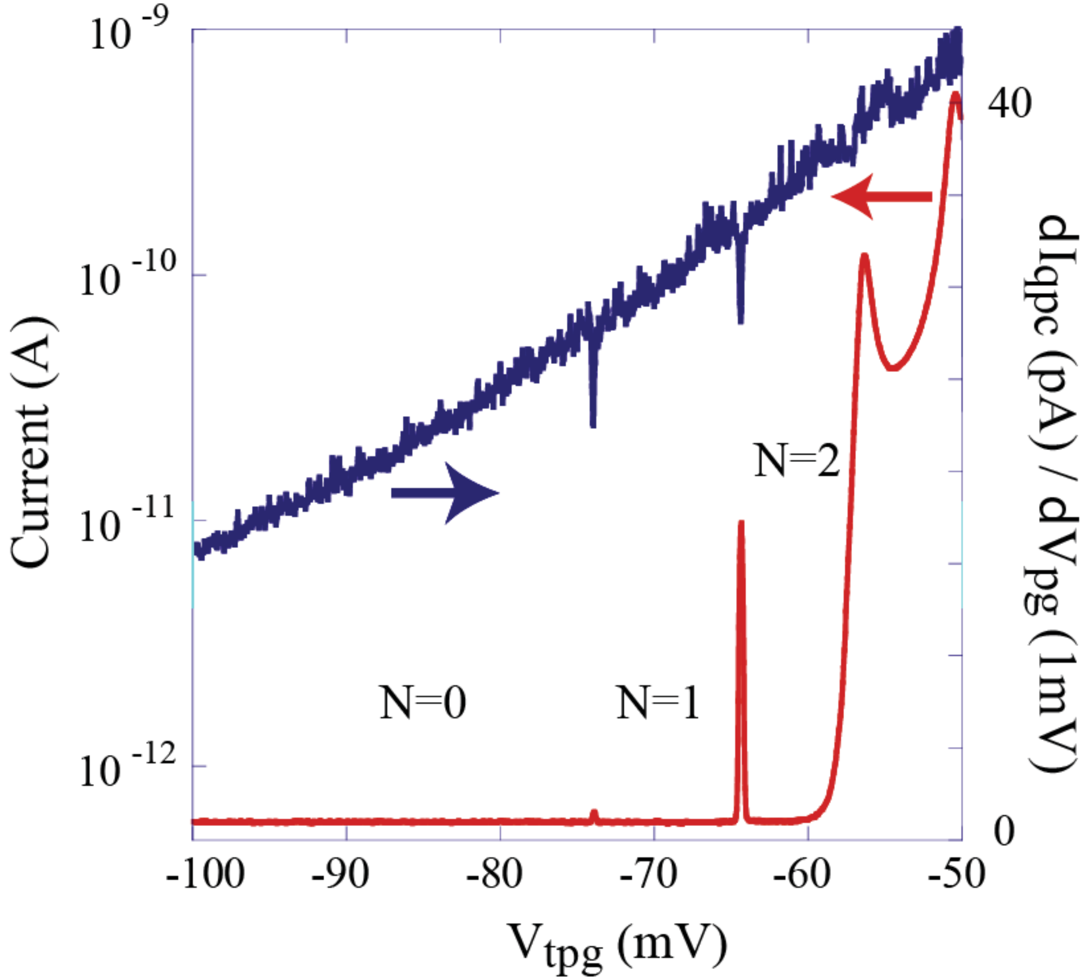


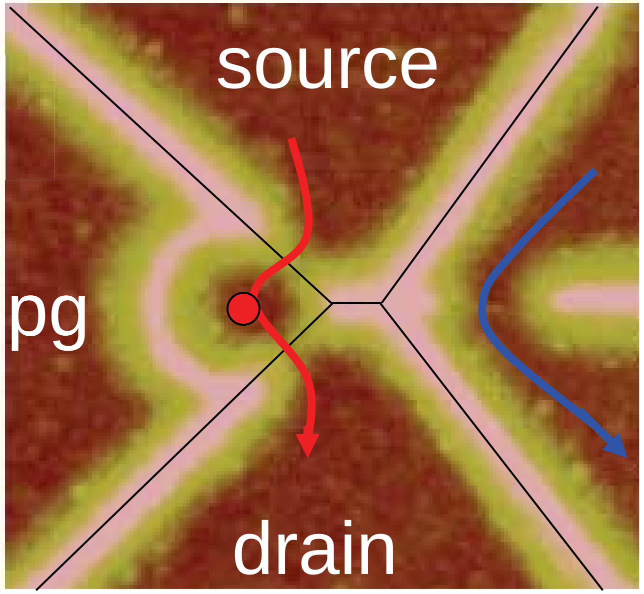




M. Field et al., Phys. Rev. Lett. 70, 1311 (1993)

A few electron quantum dot

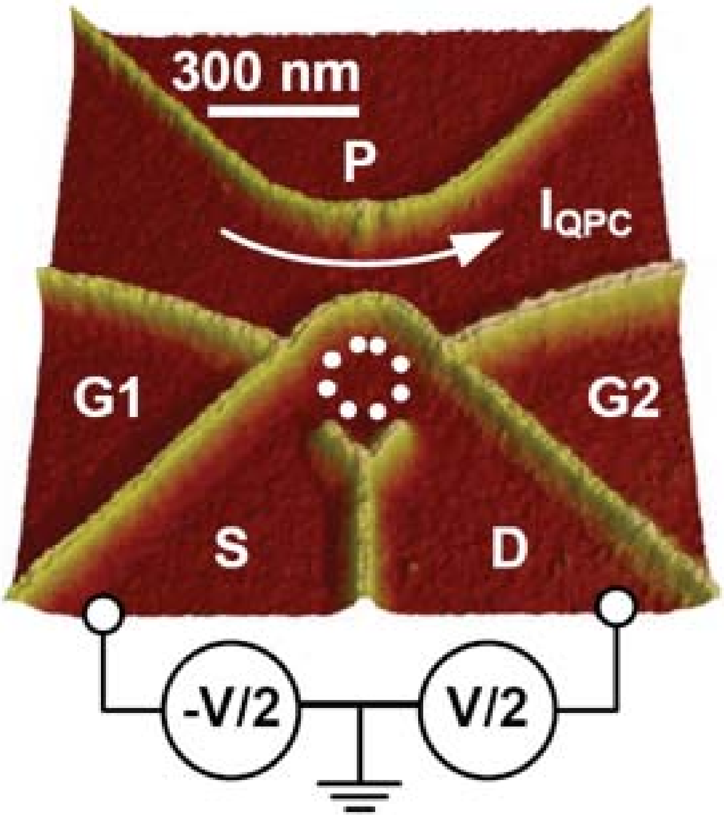


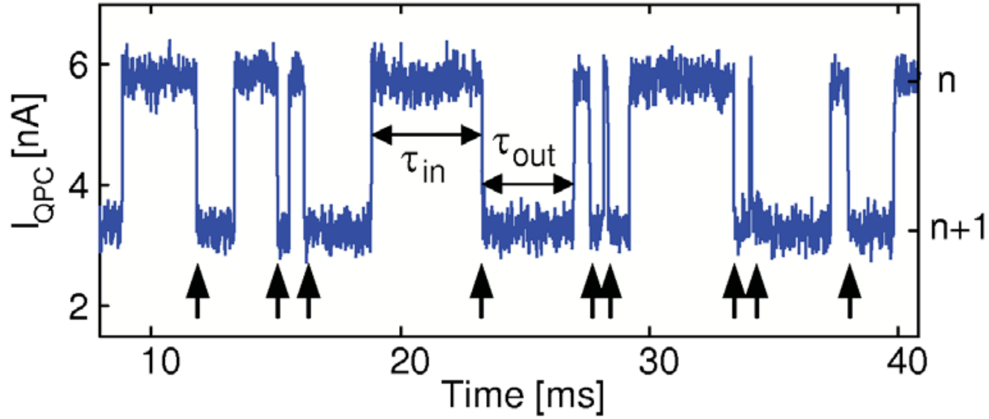


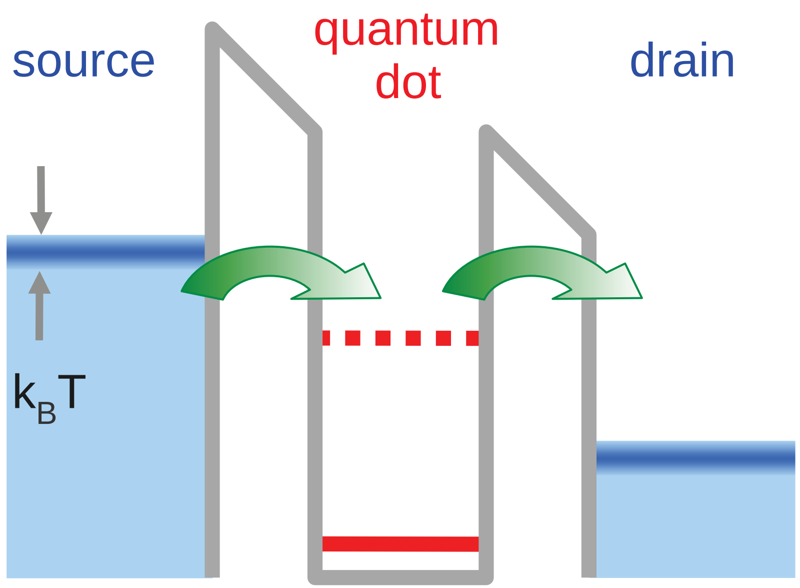
M. Sigrist

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

Time-resolved detection of single electron transport

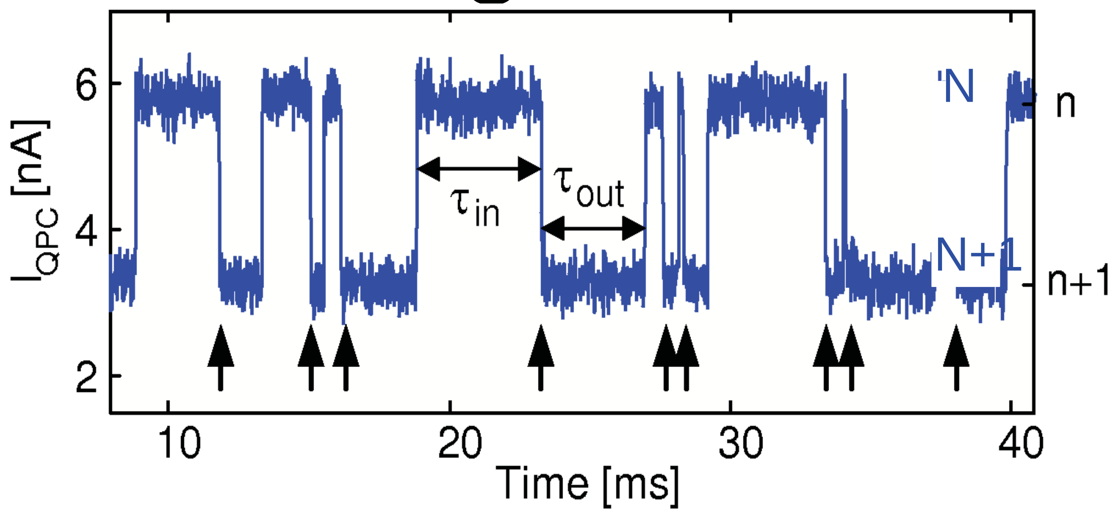






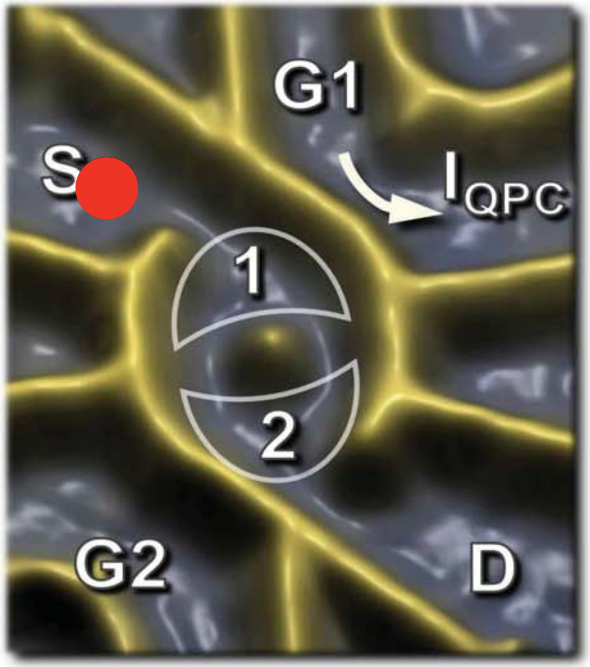
Schleser et al., APL 85, 2005 (2004)
Vandersypen et al., APL 85, 4394 (2004)

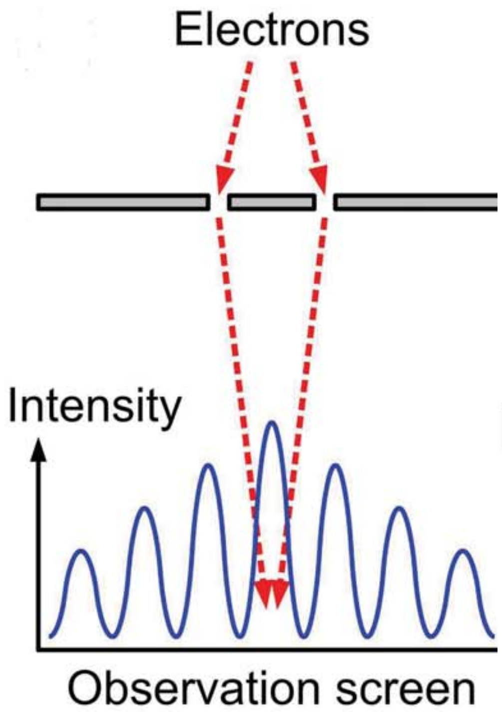
Measuring the current by counting electrons

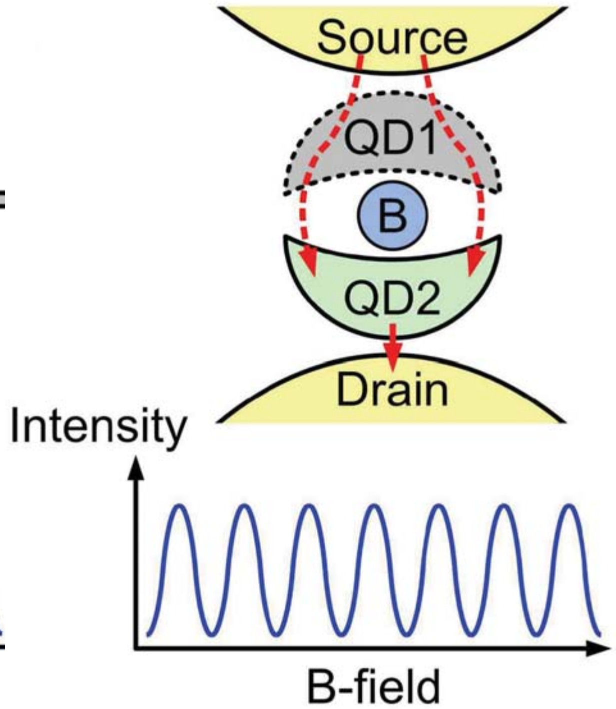


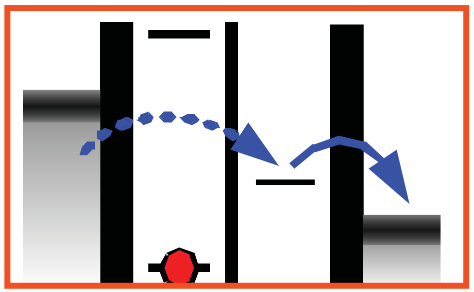
- Count number n of electrons entering the dot within a time t_0: $I = e\langle n\rangle/t_0$
- Max. current = few fA (bandwidth = 30 kHz)
- BUT no absolute limitation for low current and noise measurements
  -> here: $I \approx$ few aA, $S_I \approx 10^{-35}$ A^2/Hz

Double slit experiment
<-> Aharonov Bohm

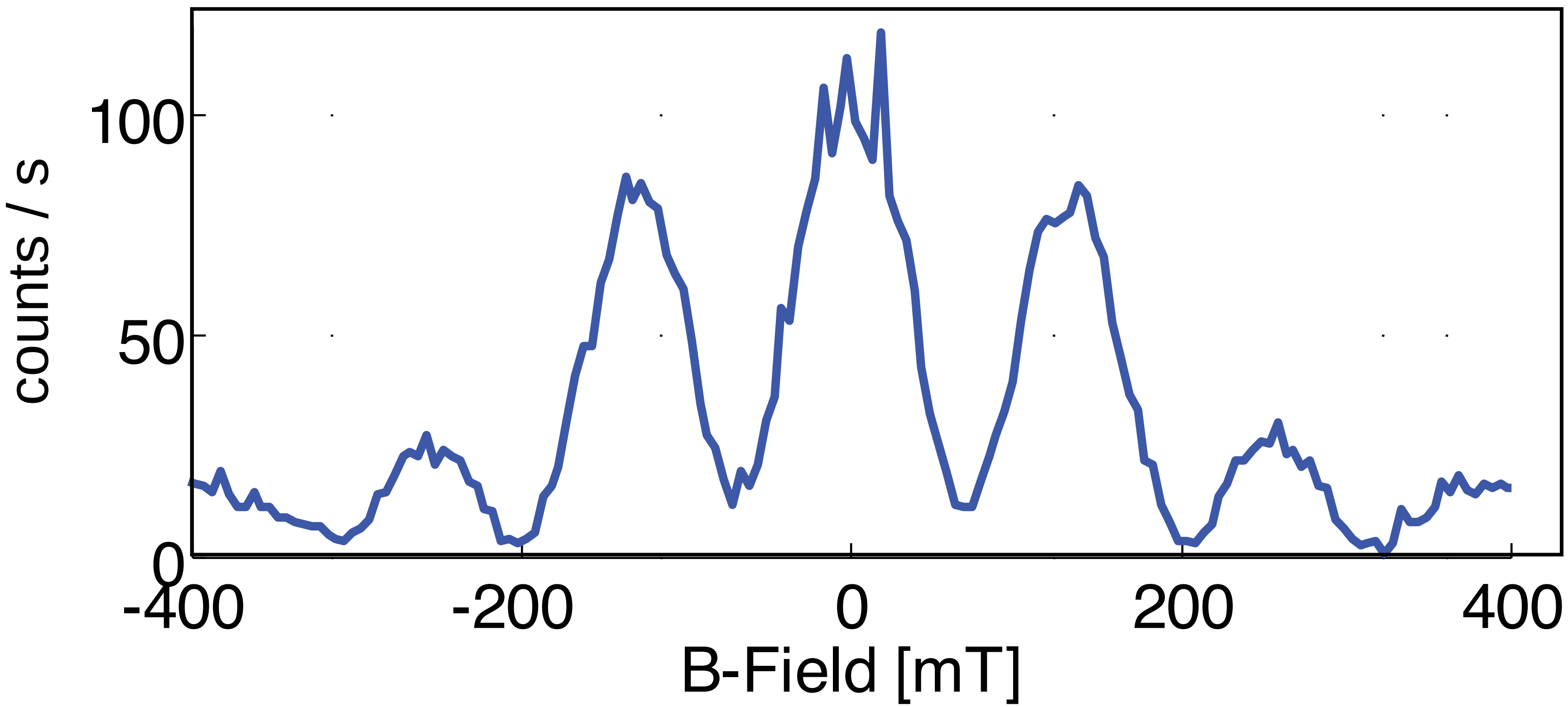








Aharonov-Bohm oscillations

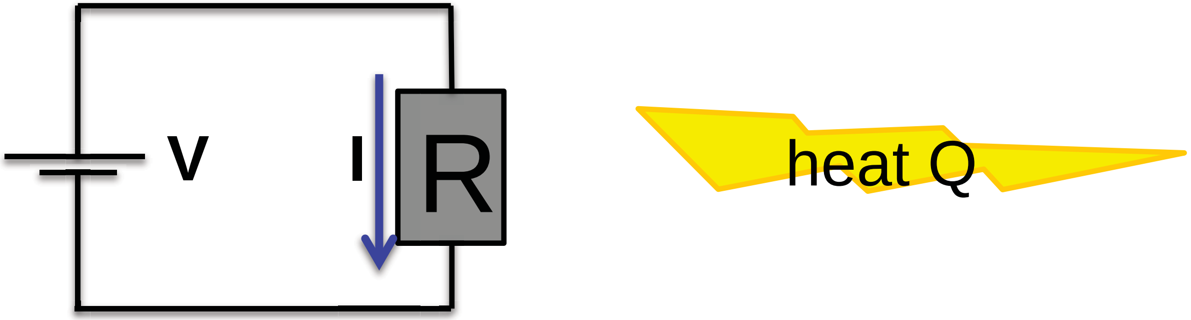


huge visibility! >90%,   stable in temperature up to 400 mK

little decoherence - > cotunneling is much faster than decoherence time

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

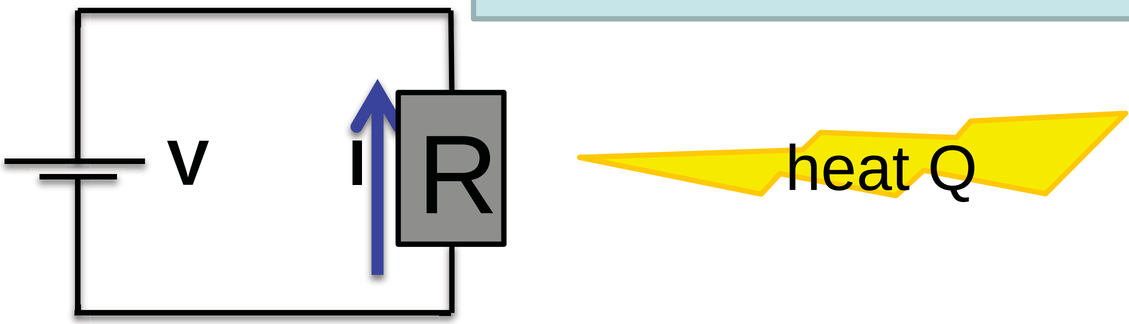
Dispersive current: Macroscopic non-equilibrium process



environment, temperature T

$P_\tau(\Delta S)$

But: reverse processes are not forbidden!



environment, temperature T

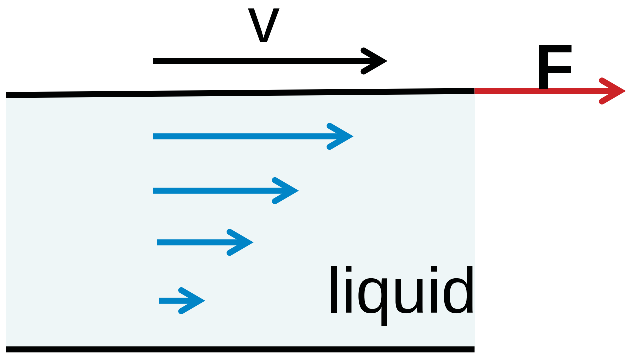
$P_\tau(-\Delta S)$

Entropy is **fluctuating variable**, probability $P_\tau(\Delta S)$

Fluctuation theorem:

quantitative statement about $P_\tau(\Delta S)$

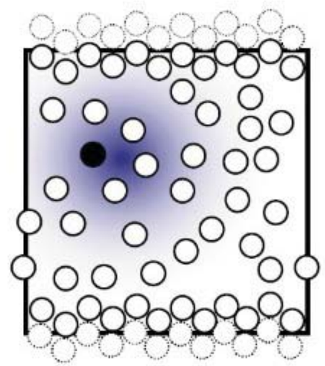
$$\frac{P_\tau(\Delta S)}{P_\tau(-\Delta S)} = \exp\left(\frac{\Delta S}{k_B}\right)$$



*D.J. Evans, E.G.D. Cohen, G.P. Morriss, PRL **71**, 2401 (1993).*

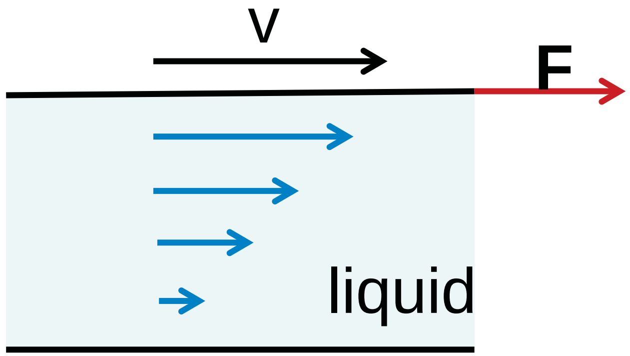
First experimental test: Latex bead moving in a liquid

*G.M. Wang et al., PRL **89**, 050601 (2002).*



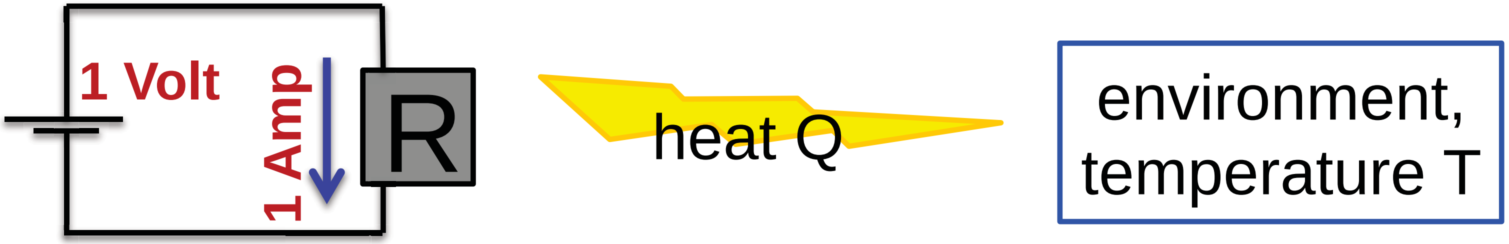
Fluctuation theorem: quantitative statement about $P_\tau(\Delta S)$

$$\frac{P_\tau(\Delta S)}{P_\tau(-\Delta S)} = \exp\left(\frac{\Delta S}{k_B}\right)$$



D.J. Evans, E.G.D. Cohen, G.P. Morriss, PRL ***71****, 2401 (1993).*

Not relevant for macroscopic systems: $\Delta S<0$ just does not occur



$$\exp\left(\frac{\Delta S}{k_B}\right) = \exp\left(\frac{1V\cdot 1A\cdot 1s}{k_B\cdot 300K}\right) \approx 10^{\left(10^{20}\right)}$$

Realization

A different system: Fluctuations of the charge across a **mesoscopic conductor**

$$\frac{P_\tau(n)}{P_\tau(-n)} = \exp\left(\frac{neV}{k_B T}\right)$$

Thermal equilibrium: $V = 0 \rightarrow P_\tau(n) = P_\tau(-n)$

High-bias regime: $eV >> kT \rightarrow P_\tau(n) >> P_\tau(-n)$

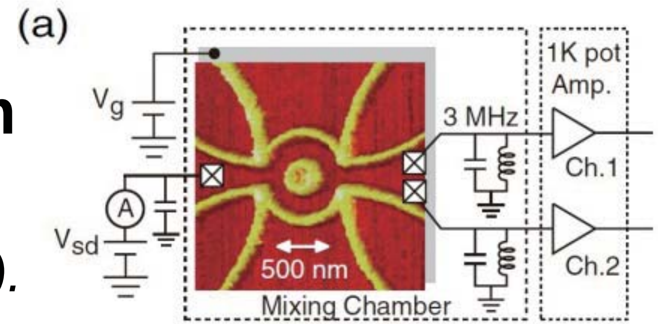
Realization

A different system: Fluctuations of the charge across a **mesoscopic conductor**

$$\frac{P_\tau(n)}{P_\tau(-n)} = \exp\left(\frac{neV}{k_B T}\right)$$

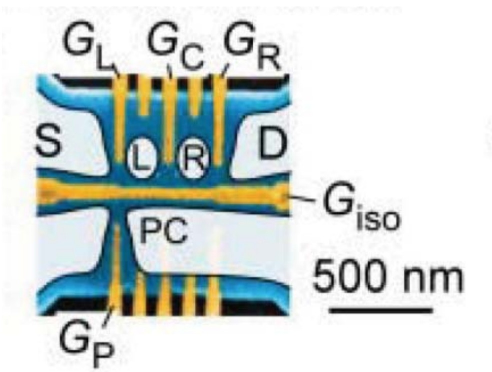
→ Low temperatures and **quantum coherence**

*S. Nakamura et al., PRL **104**, 080602 (2010).*



→ Observing a dissipative **current flow as individual electrons**

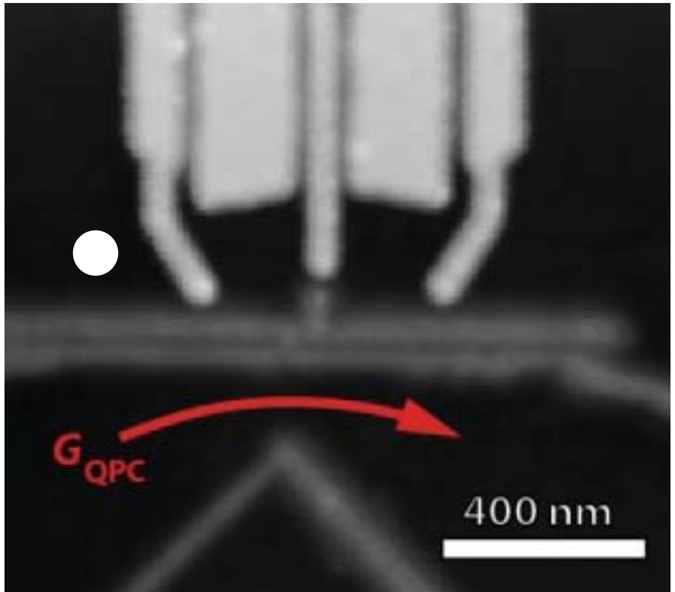
*Y. Utsumi et al., PRB **81**, 125331 (2010).*
*T. Fujisawa et al., Science **312**, 1634 (2006).*



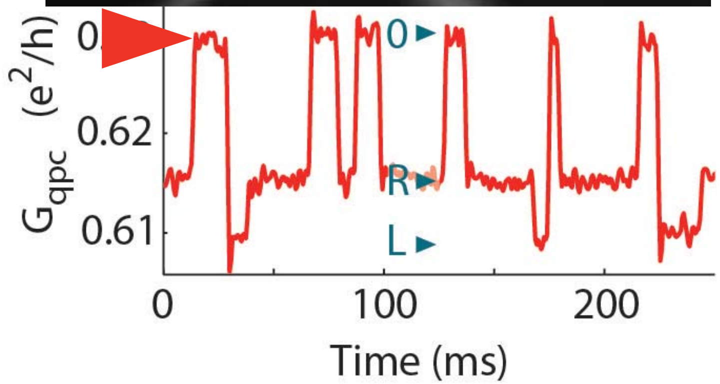
Microscopic approach

Microscopic: ability to measure extremely small currents, by **counting electrons**

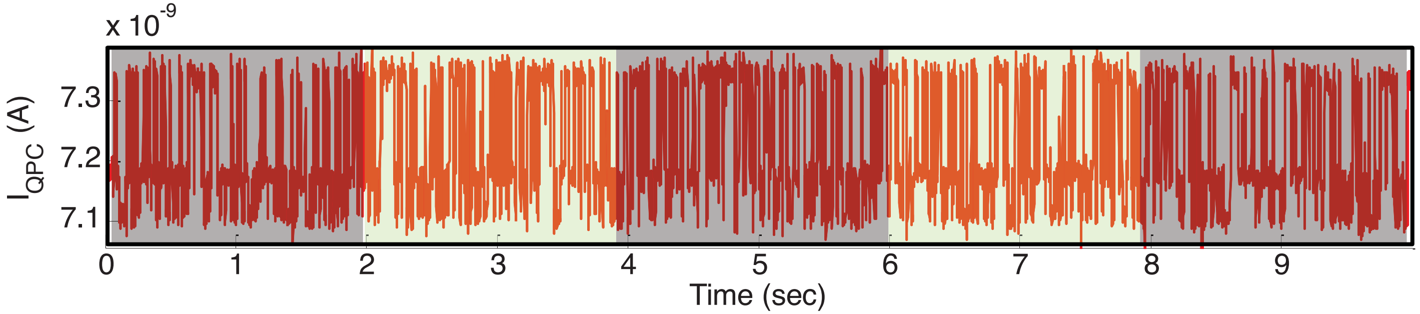
QPC sensor detects the position of electrons inside the structure



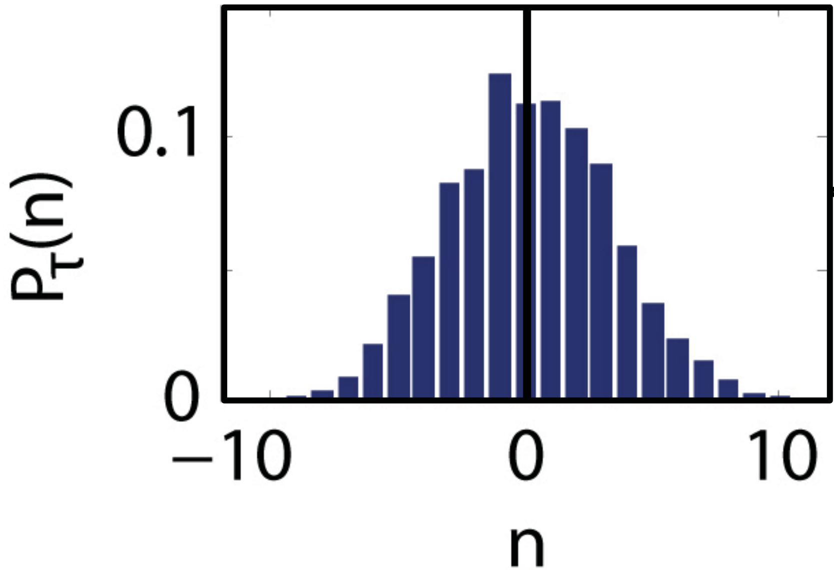
detect the number and direction of electrons passing the structure



Counting electrons



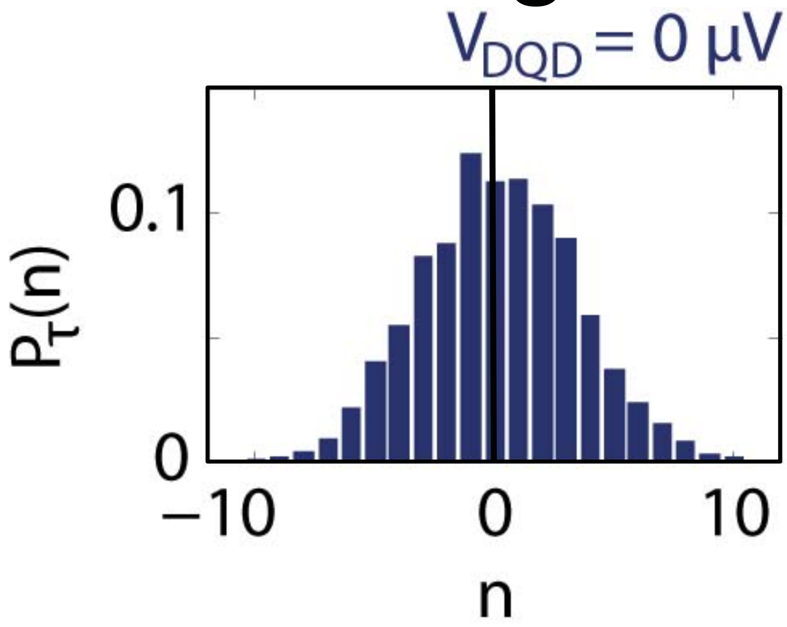
$V_{DQD}=0$, thermal equilibrium
→ $P_\tau(n)$ should be symmetric



$\langle n \rangle = 0.09 \pm 0.09$

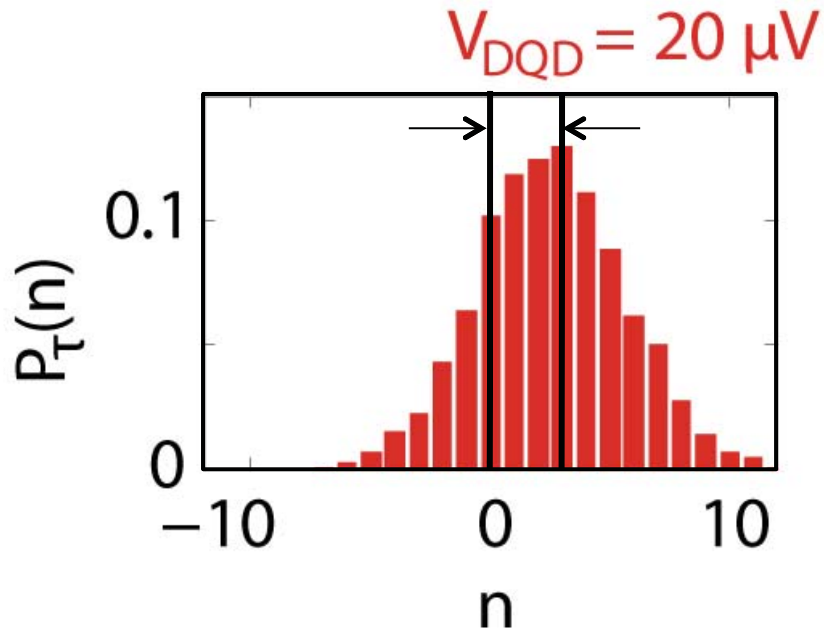
3000 time bins,
length τ=2sec

Counting electrons: finite bias



$V_{DQD} = 0$
→ no charge flow

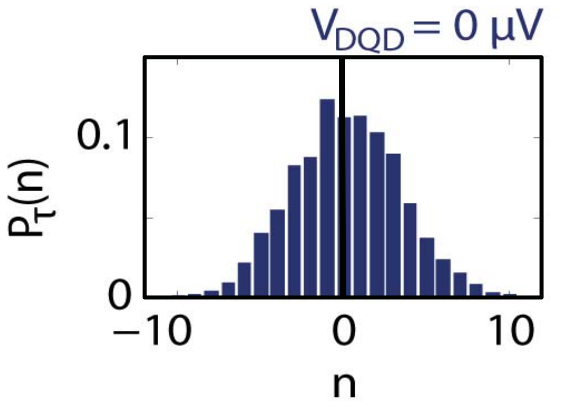
<n> = 0.09 ± 0.09

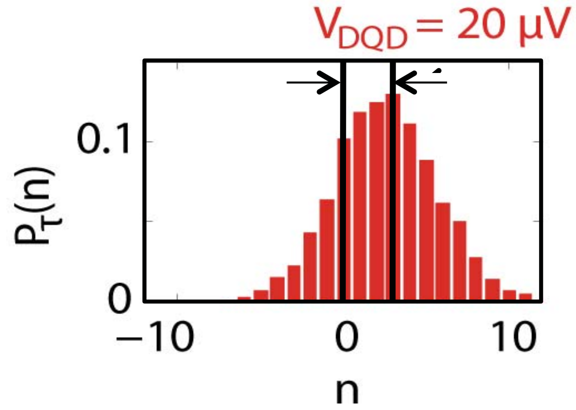


$V_{DQD} = 20\ \mu V$
→ finite charge flow

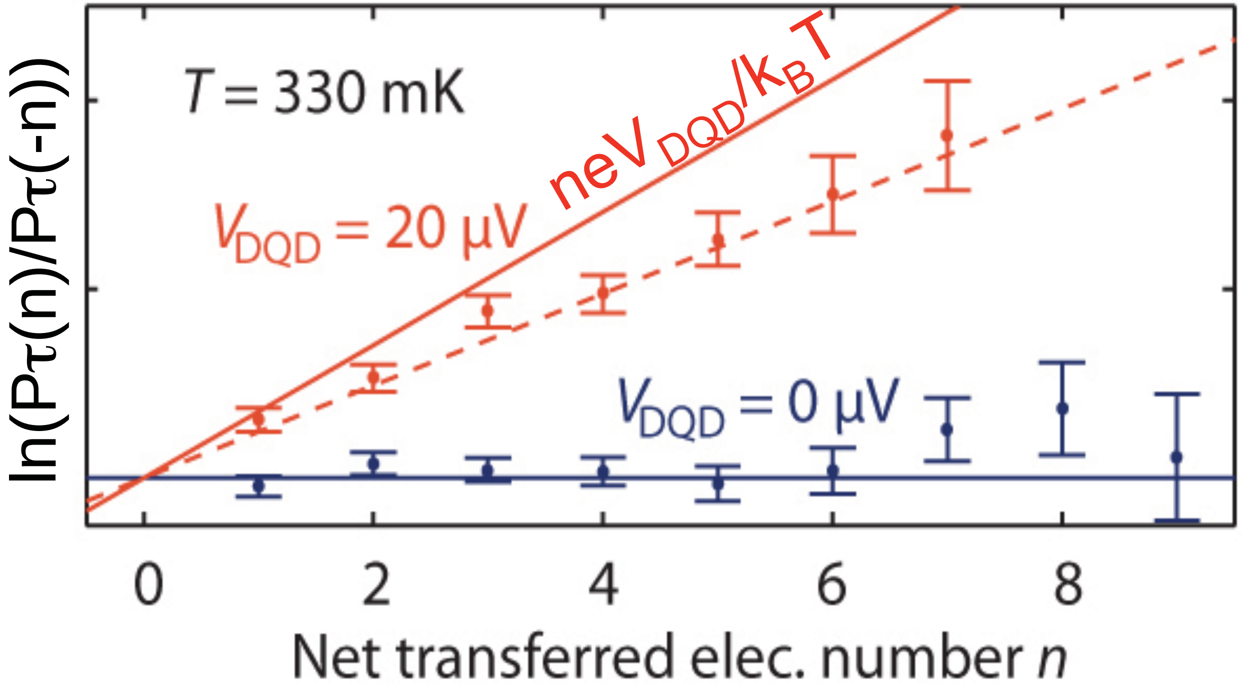
<n> = 2.39 ± 0.09

Counting electrons: finite bias





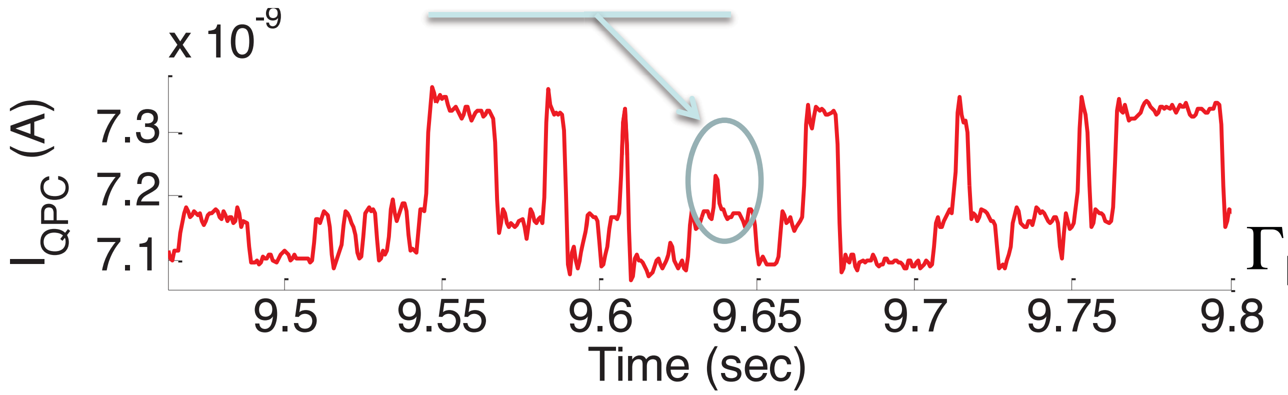
$$\frac{P_\tau(n)}{P_\tau(-n)} = \exp\left(\frac{neV}{k_B T}\right)$$



slope about 20% smaller than expected from theory (solid line)

Counting electrons: finite bias

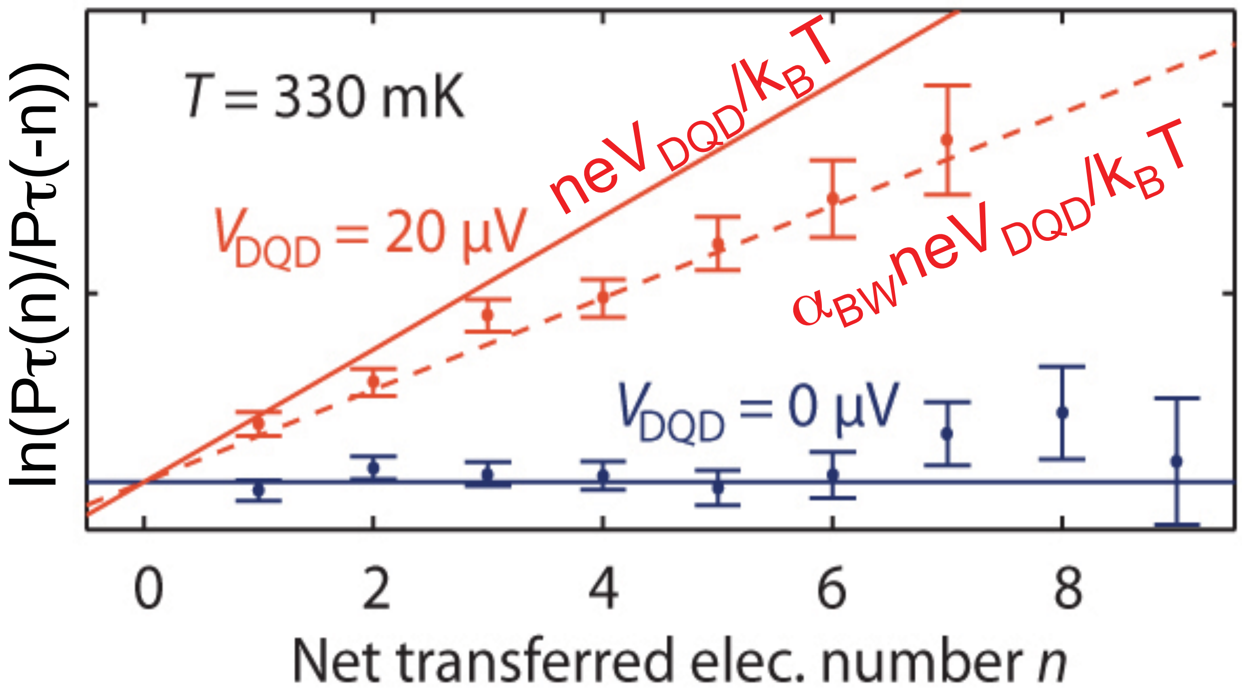
Detector can miss fast events due to limited bandwidth



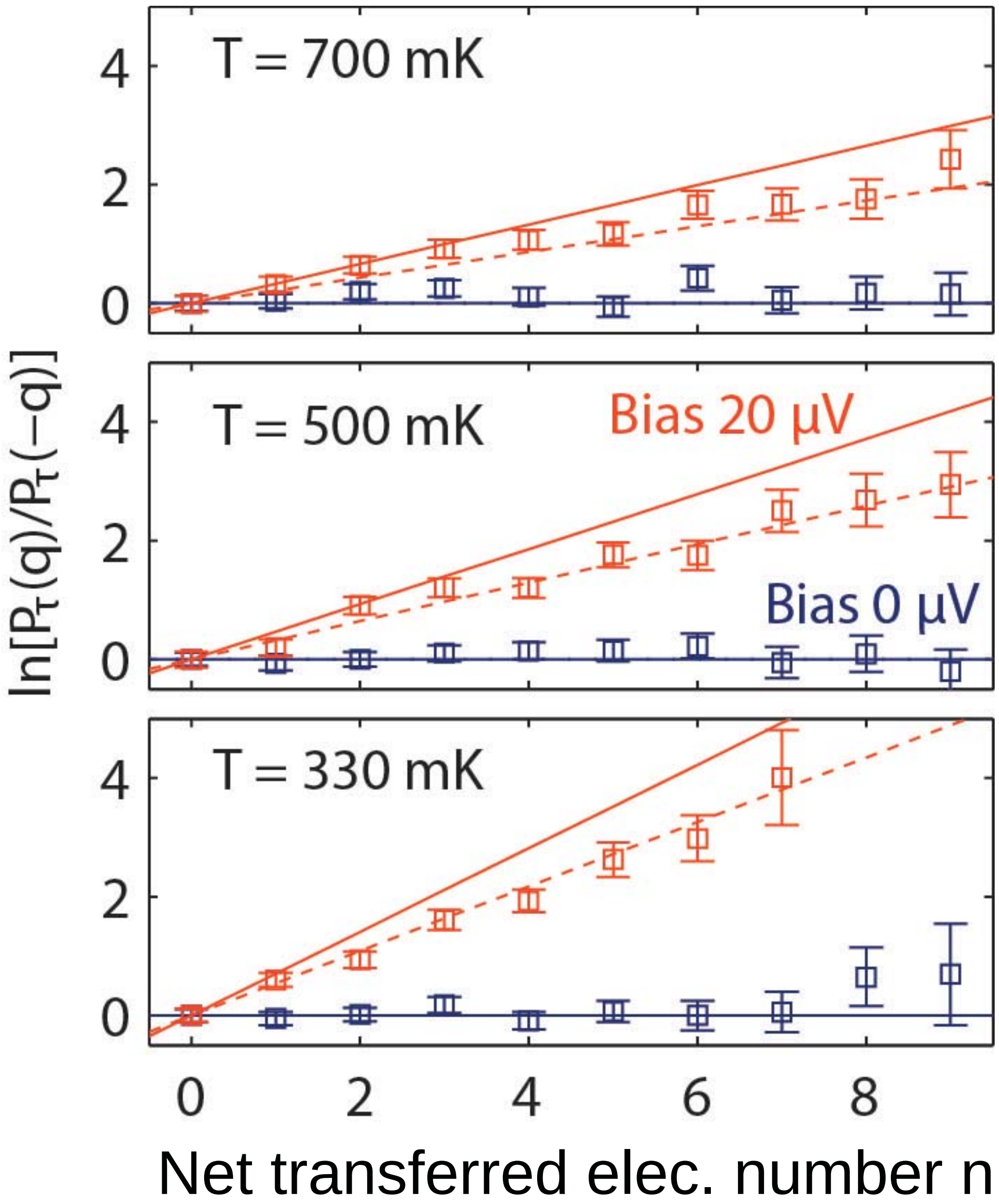
Γ_{det} = 700 Hz
Γ_{DQD} = 50…100 Hz

Theoretical modeling (rate-equations): α_{BW}

O. Naaman and J. Aumentado, PRL ***96****, 100201 (2006).*
Y. Utsumi et al., (World Scientific, 2010), pp. 397-414



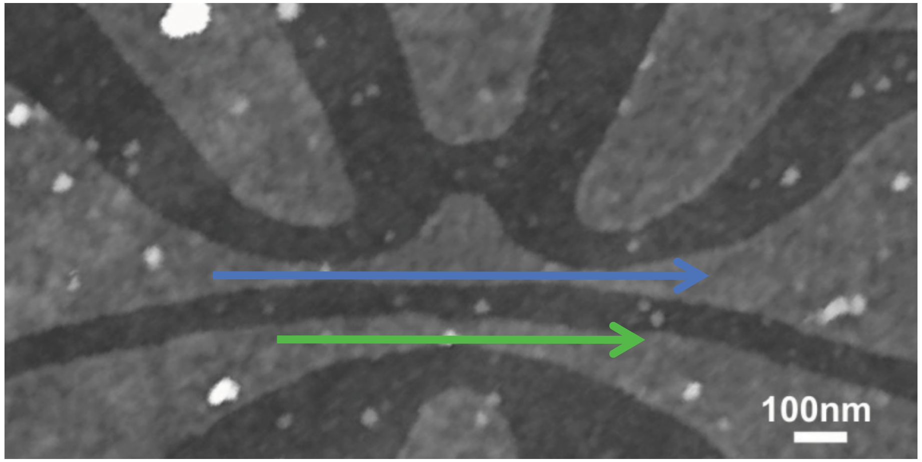
Counting electrons: finite bias



different temperatures

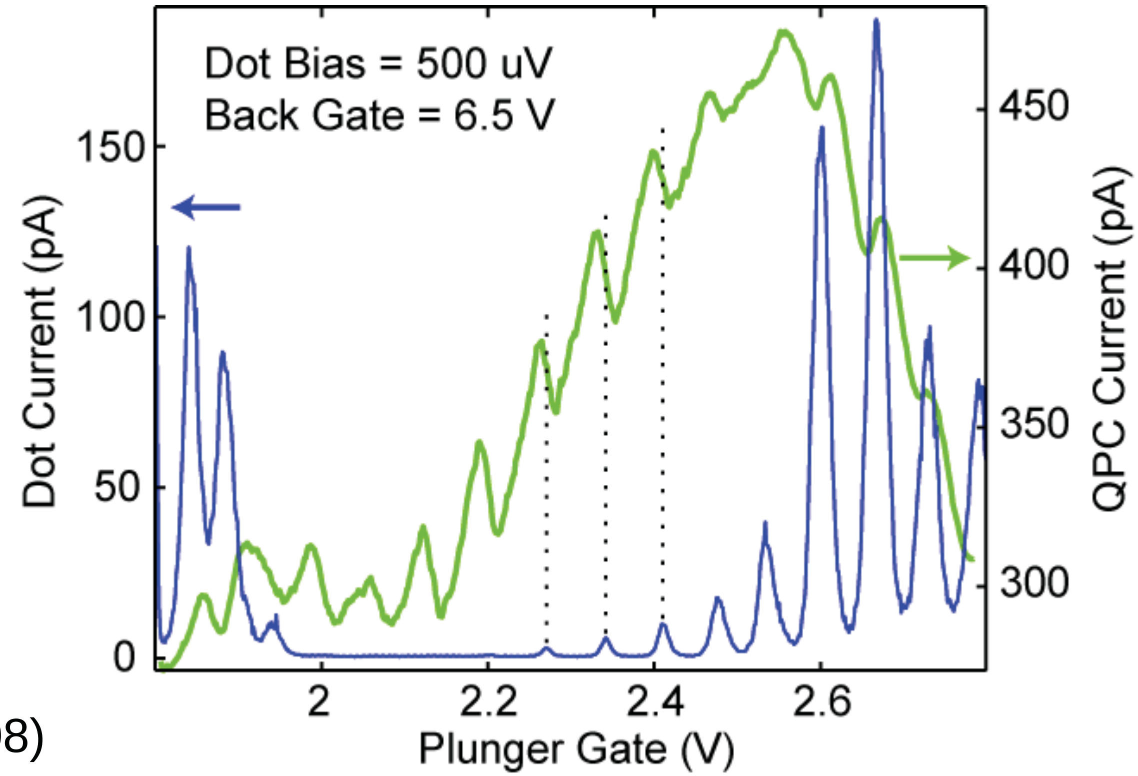
$$\frac{P_\tau(n)}{P_\tau(-n)} = \exp\left(\frac{neV}{k_B T}\right)$$

Graphene dot with charge detector



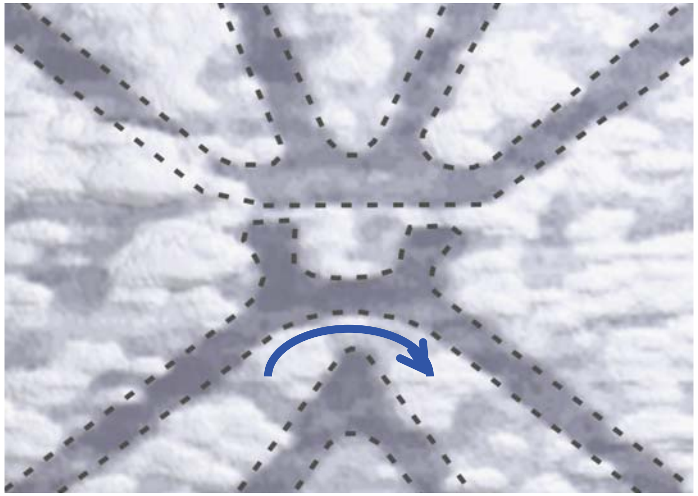
dot

constriction

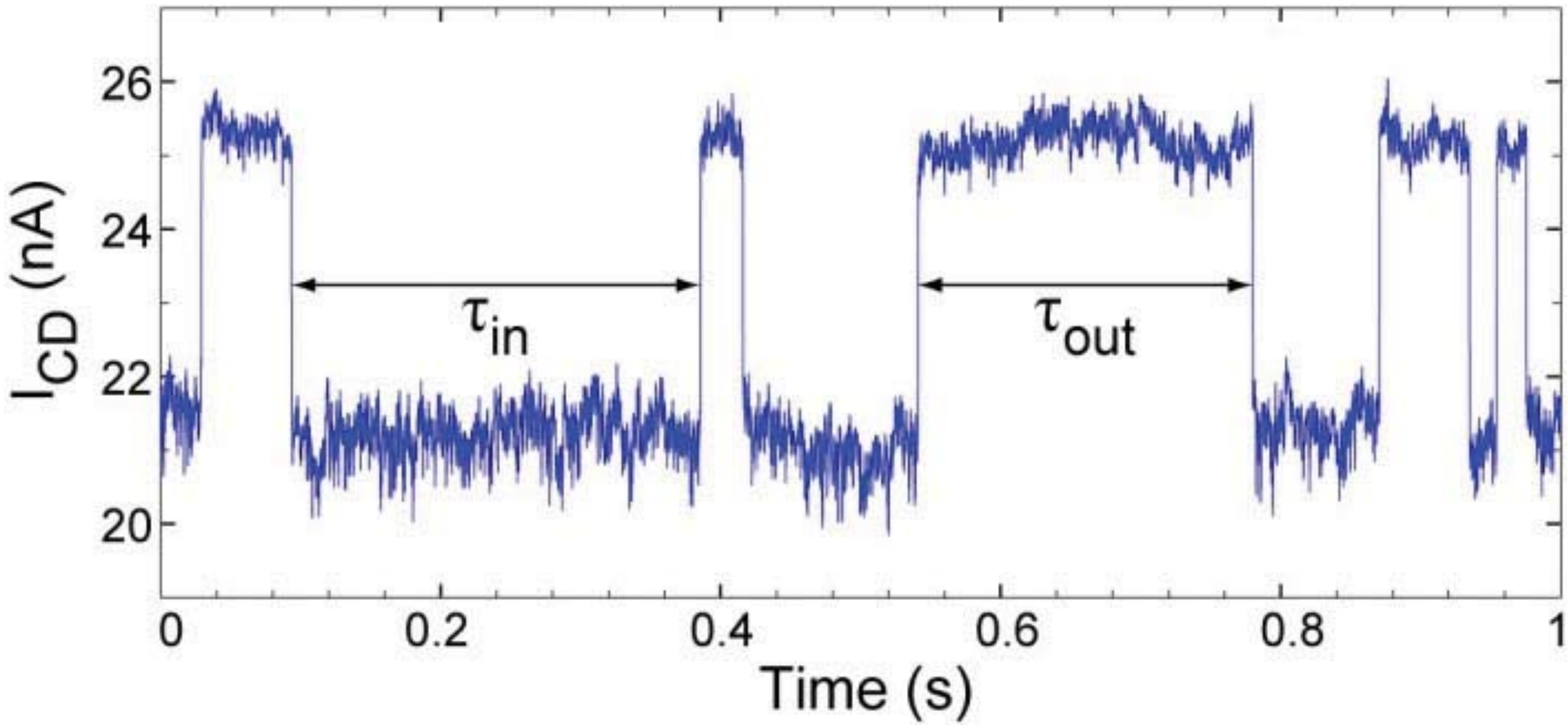


C. Stampfer,
S. Hellmüller,
J. Güttinger,
F. Molitor,
T. Ihn

Güttinger et al. APL 93, 212102 (2008)



Electron counting in graphene



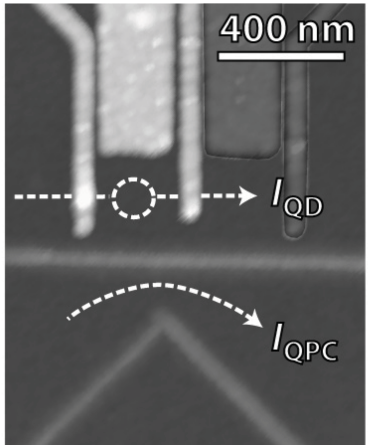
J. Güttinger, C. Achille, C. Stampfer

Thank you

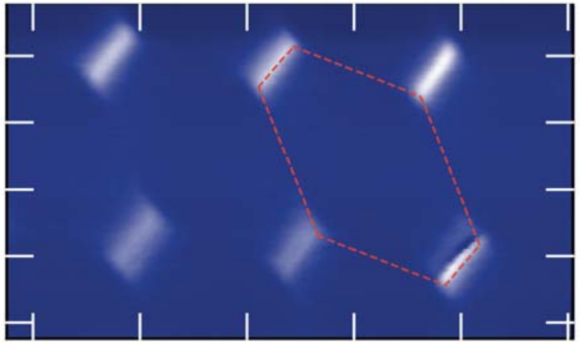
Bruno Küng

Tobias Frey

Thomas Ihn



PRX **2**, 011001 (2012)



PRL **108**, 046807 (2012)

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