Quanten-Physik auf einem Chip

Technologie vom Feinsten!!

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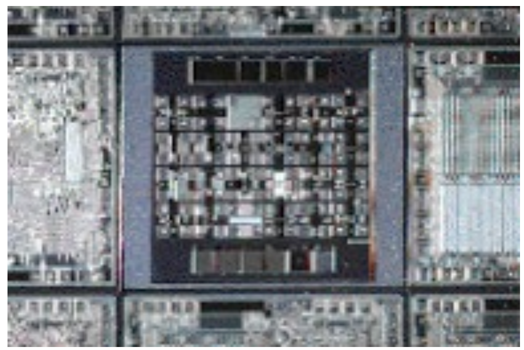
Swiss Federal Institute of Technology Zurich

QSIT Quantum Science and Technology
National Centre of Competence in Research

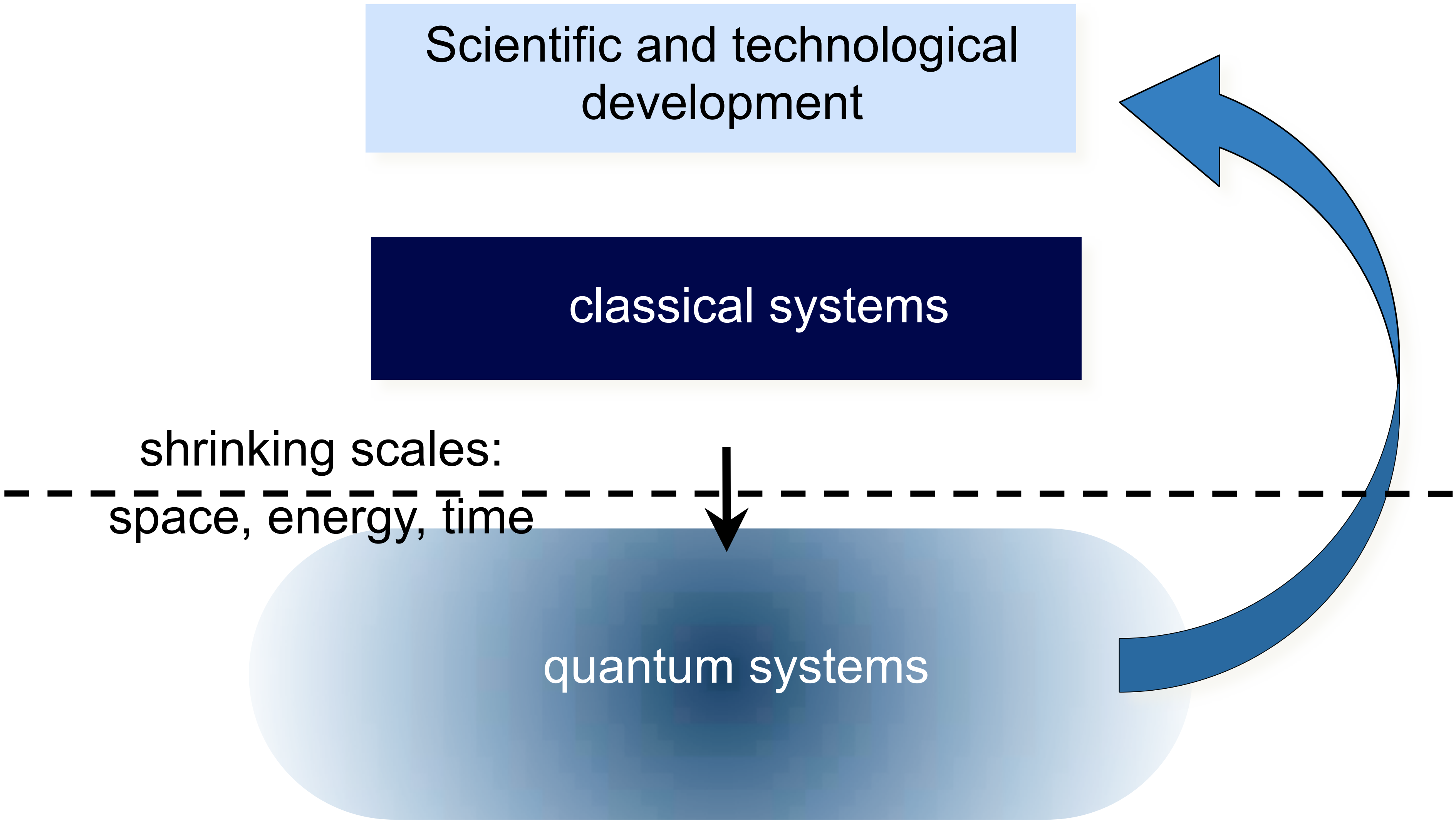
Classical technology

First transistor

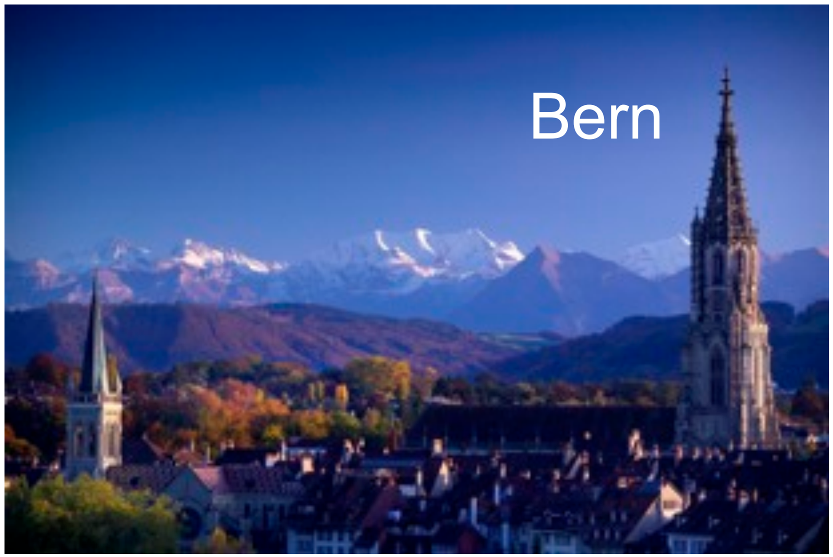
modern
integrated
circuit



Quantum Technology



Waren Sie schon einmal gleichzeitig an zwei Orten, z.B. in Zürich und in Bern?



Waren Sie schon einmal gleichzeitig an zwei Orten, z.B. in Zürich und in Bern?

Elektronen und Atome können das!!!

Wie Wasserwellen, die gleichzeitig an verschiedenen Stellen eines Sees sind

individual quantum objects

interference -> waves

waves -> particles

particles -> electrons, photons, atoms

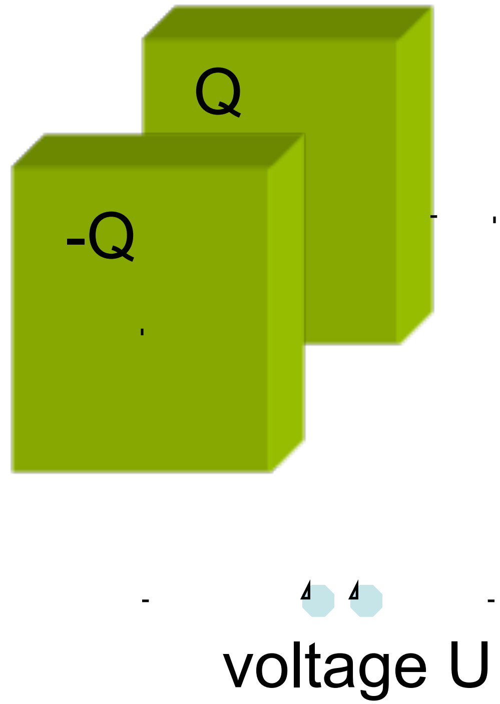
control over individual quantum systems

manipulation of quantum systems

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

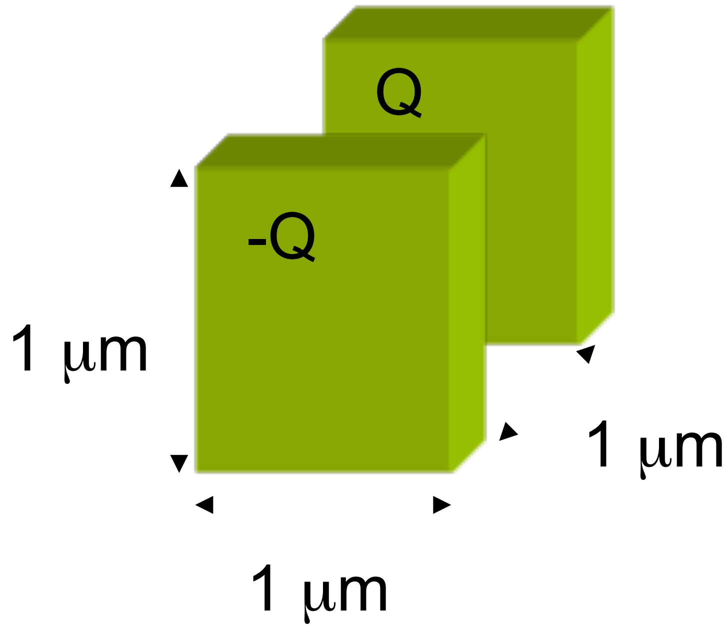
Size of a capacitor

capacitance

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

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

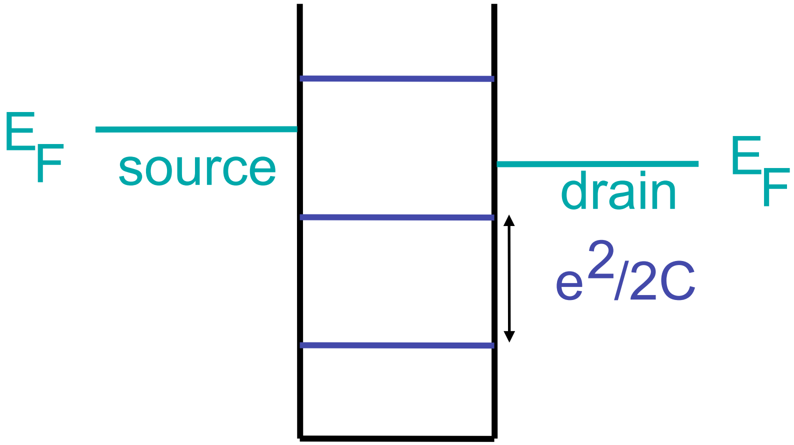
equivalent to temperature $T = 7\ K$



-> use nanotechnology to make a small capacitor

decoupled from its environment

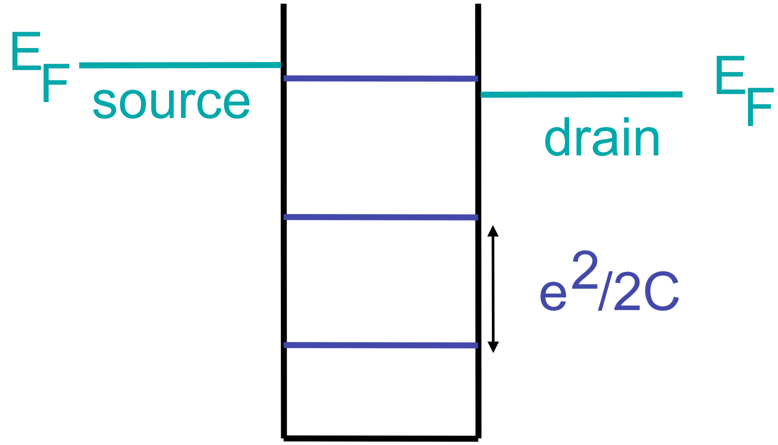
Coulomb blockade



$kT \ll e^2/2C$

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

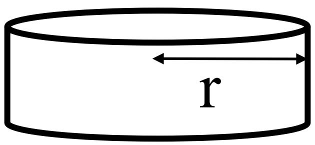
-> no current transport



discrete level between

E_F^{source} and E_F^{drain}

-> coherent resonant tunneling

disk: 

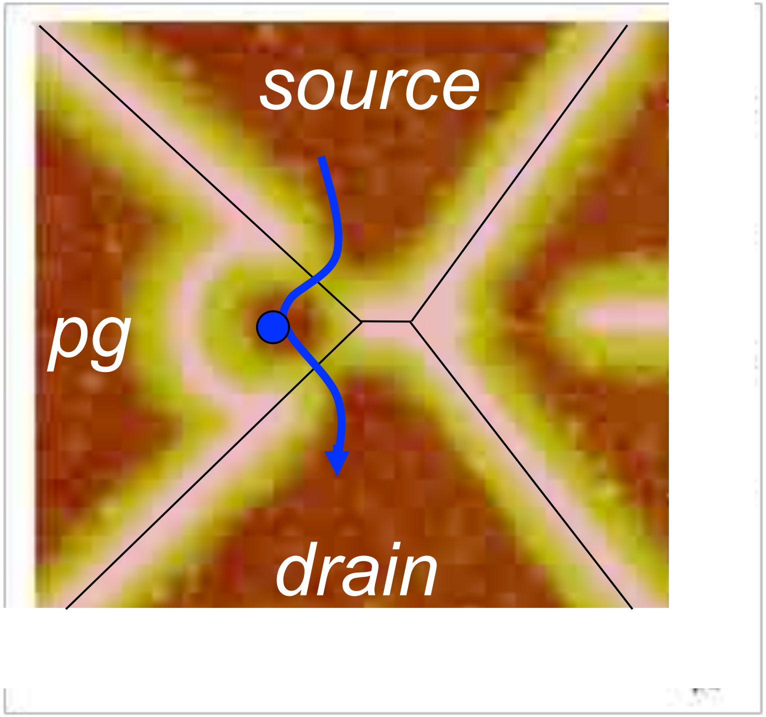
$C = 8\varepsilon\varepsilon_0 r$

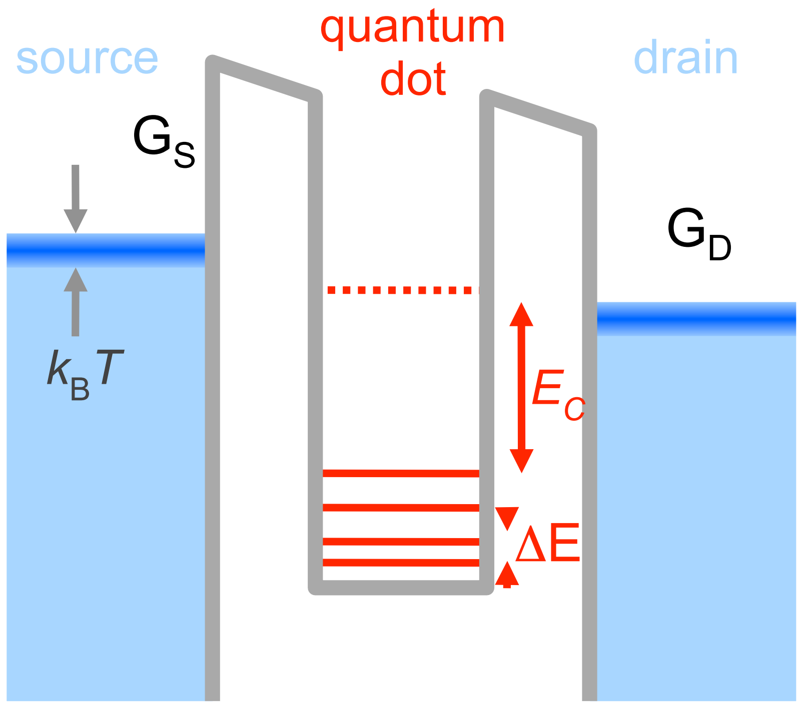
$r = 100\ nm$

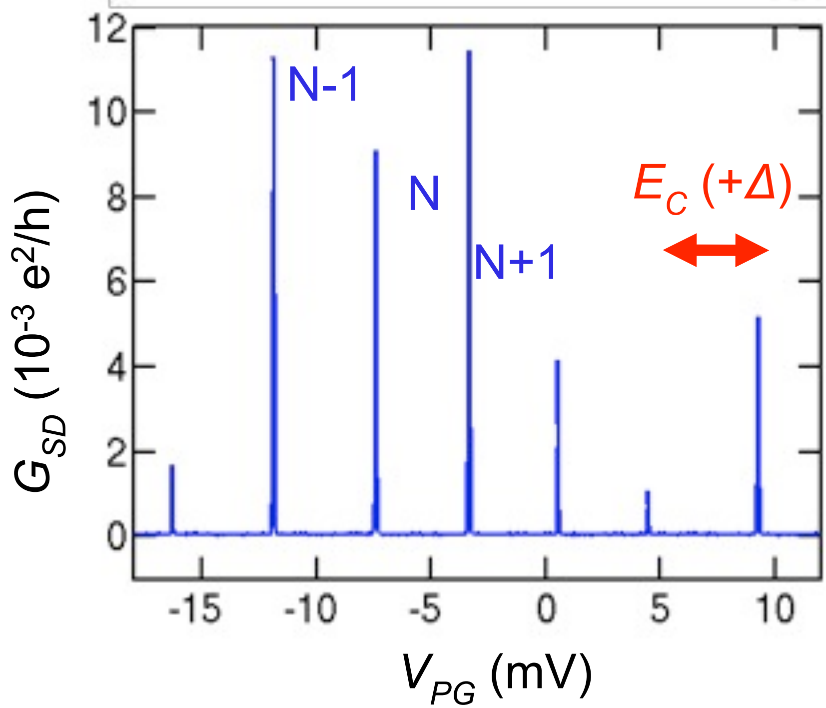
$-> \ C = 84\ aF$

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

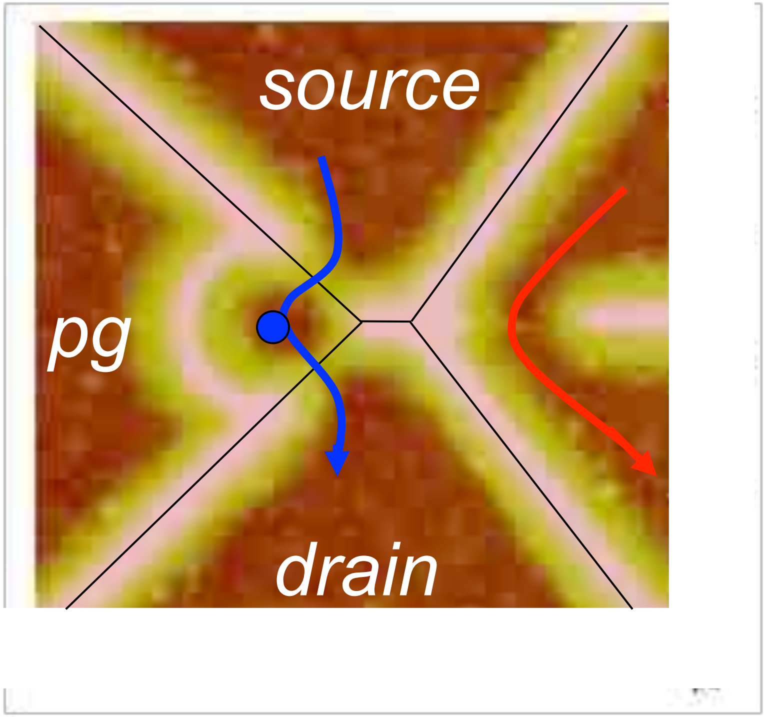
Spectroscopy of electronic states

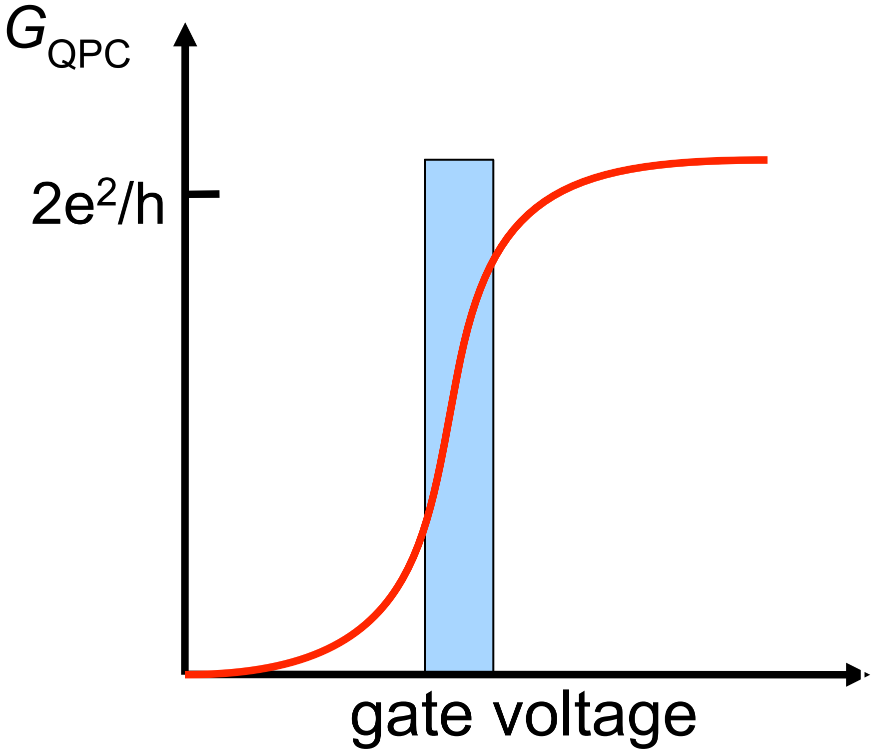


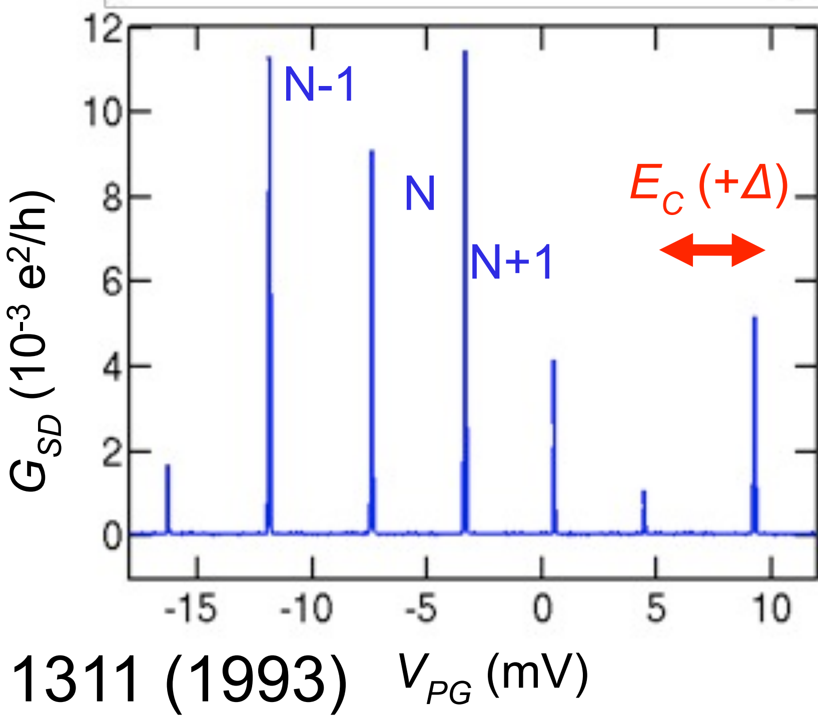




Quantum point contact as a charge detector

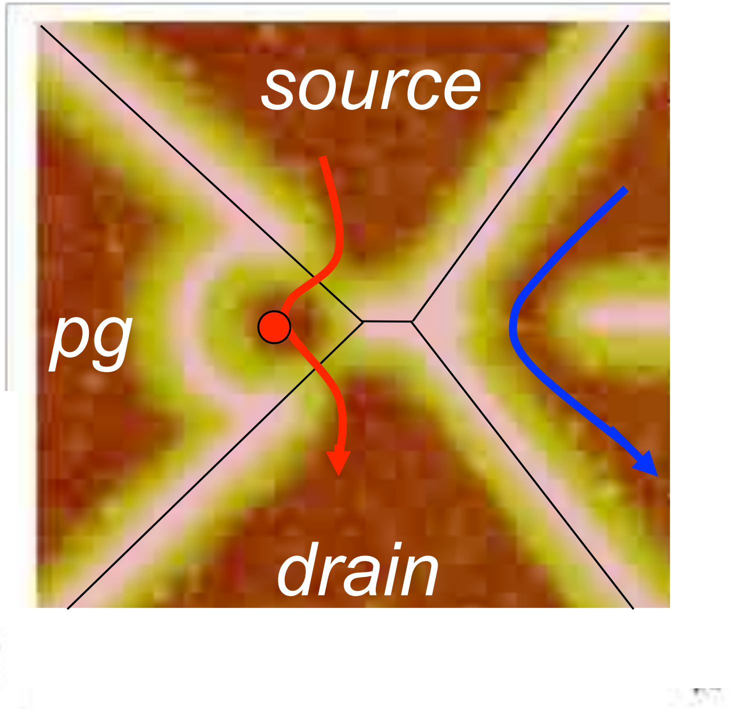




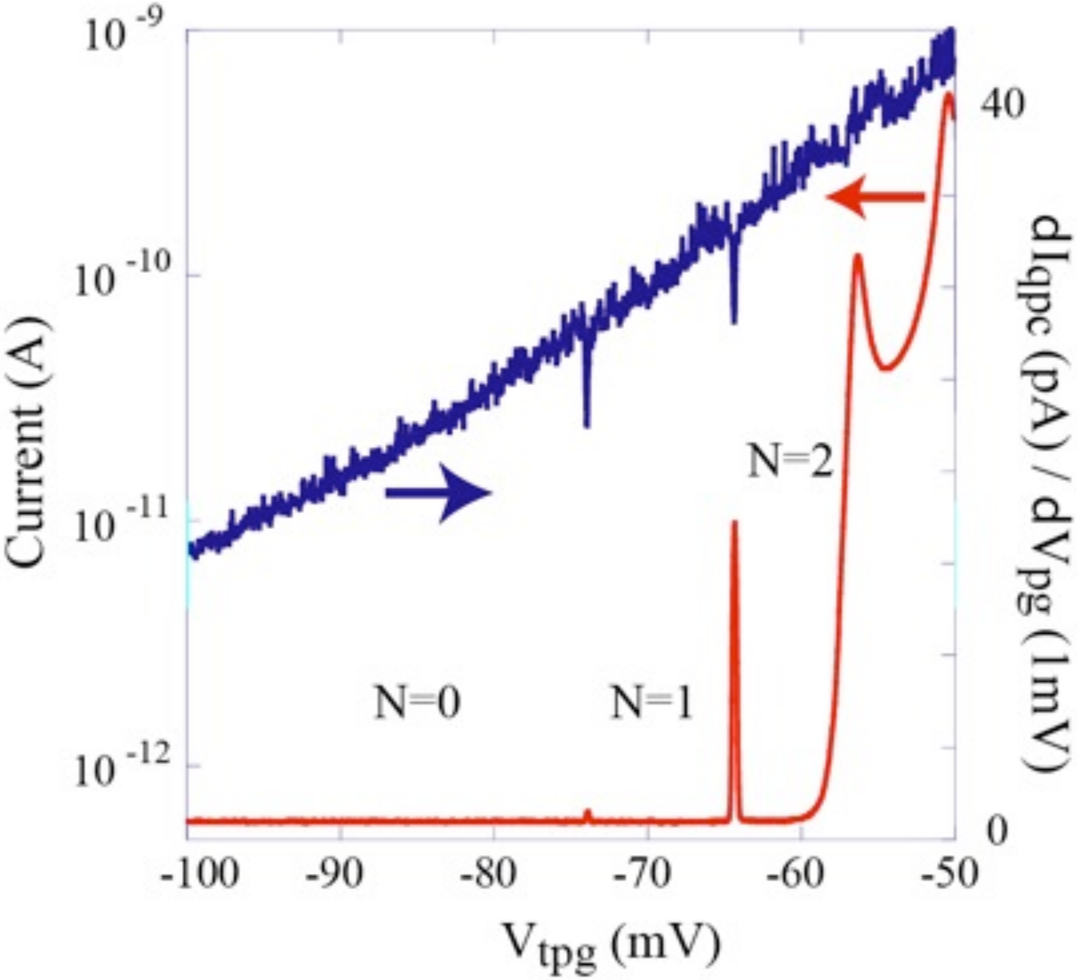


M. Field et al., Phys. Rev. Lett. 70, 1311 (1993)

A few electron quantum dot

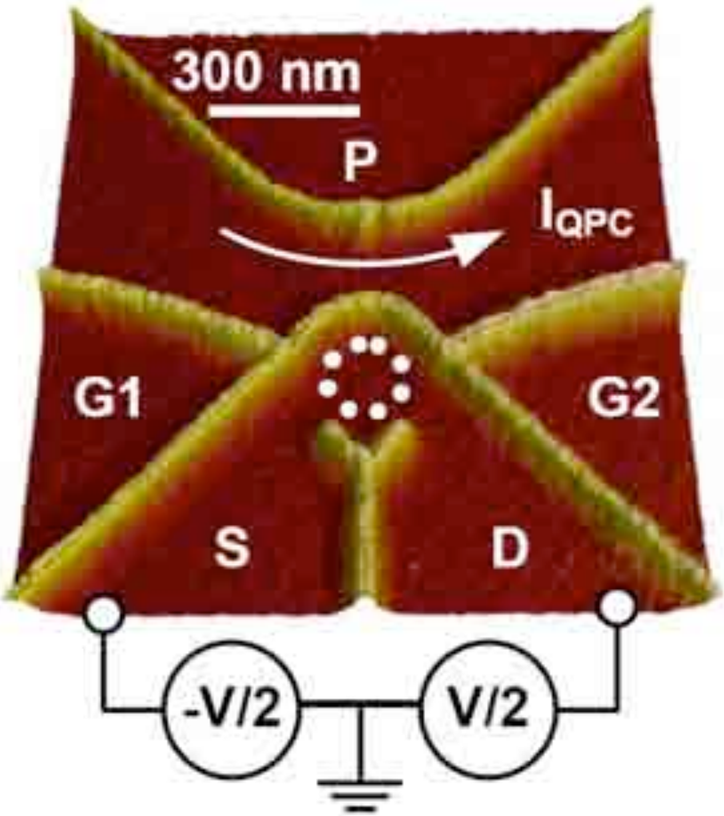


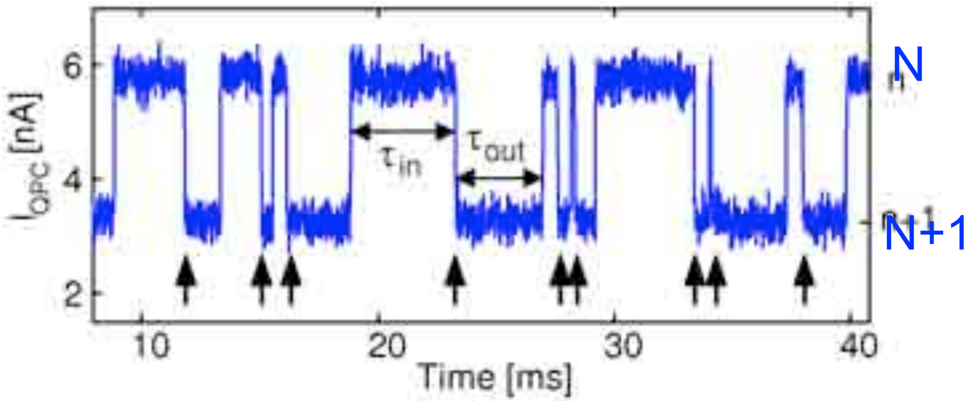
M. Sigrist

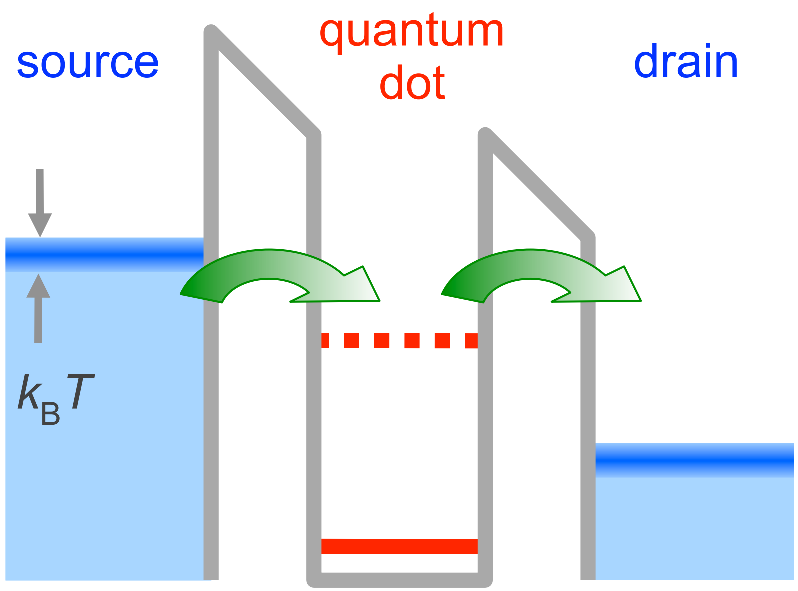


Ciorga et al.,
PRB 61, R16315 (2000)
Elzerman et al.
PRB 67, 161308 (2003)

Time-resolved detection of single electron transport

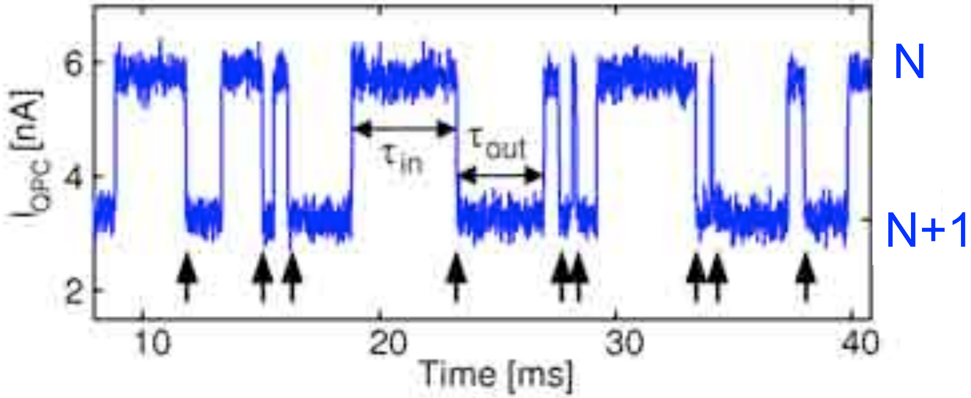






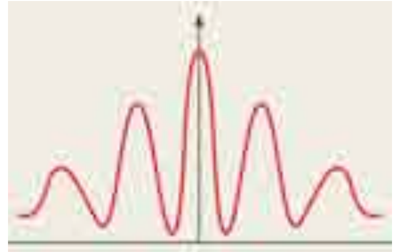
Schleser et al., APL 85, 2005 (2004)
Vandersypen et al., APL 85, 4394 (2004)

Measuring the current by counting electrons



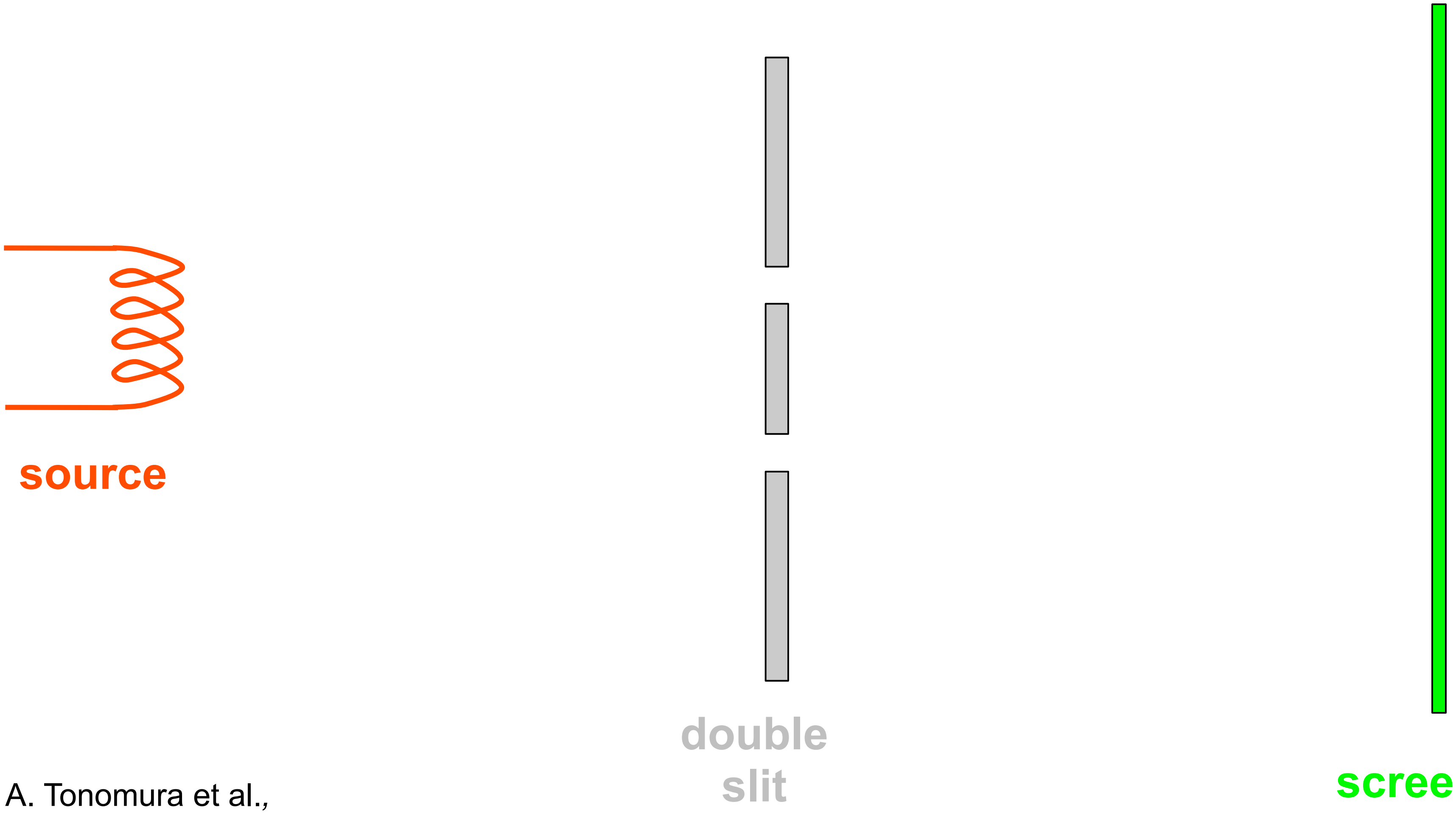
- Count number *n* of electrons entering the dot within a time t_0: $I = e\langle n\rangle/t_0$
- Max. current = few fA (bandwidth = 30 kHz)
- BUT no absolute limitation for low current and noise measurements
  -> *here:* $I \approx$ few aA, $S_I \approx 10^{-35}$ A^2/Hz

The most beautiful experiment in physics

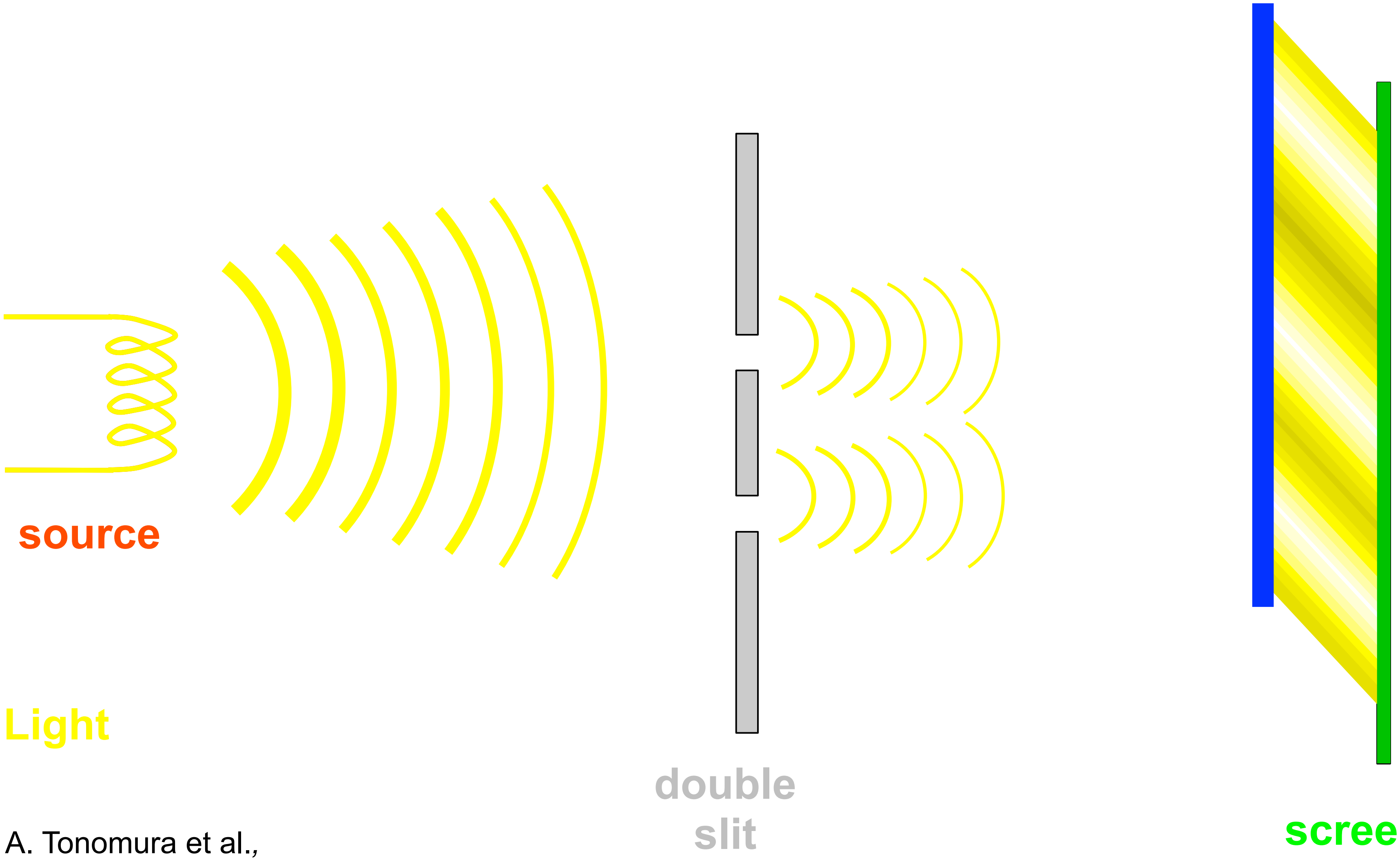


The most beautiful experiment in physics, according to a poll of Physics World readers, is the interference of single electrons in a Young's double slit.
Robert P Crease, Physics World, Sep 1, 2002

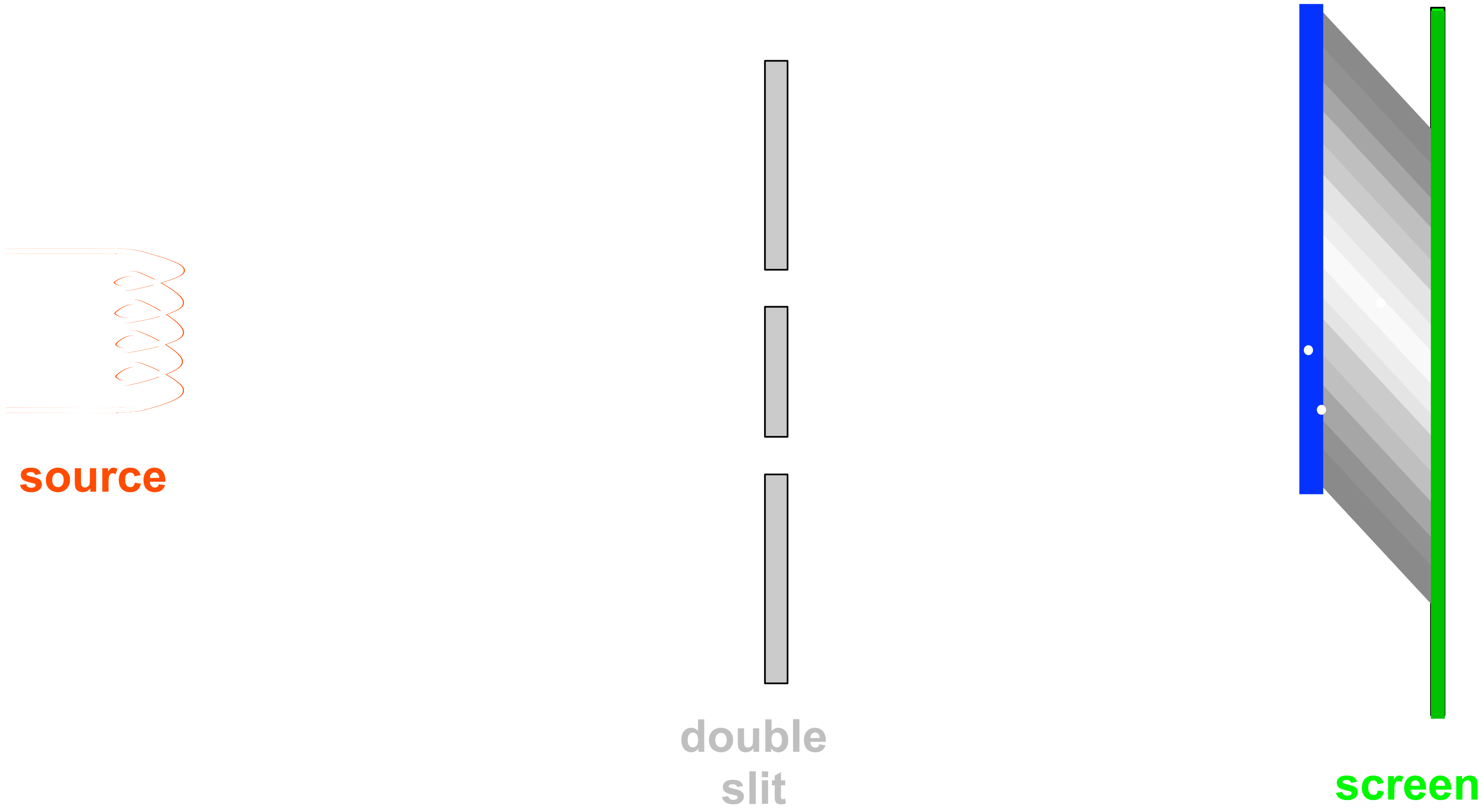
- Young, photons, first decade of the 1800s
- Davisson and Germer, 1927: diffraction of electron beams from a crystal
  ->1937 Nobel prize
- Jönsson (Tübingen), 1961: double-slit experiment with electrons for the first time (*Zeitschrift für Physik* ***161 454).***
- Merli, Pozzi and Missiroli (Bologna), 70's: double-slit interference experiments with single electrons
- Tonomura et al (Hitachi) 1989: experiment with just one electron in the apparatus at any one time (*American Journal of Physics* ***57 117-120).***



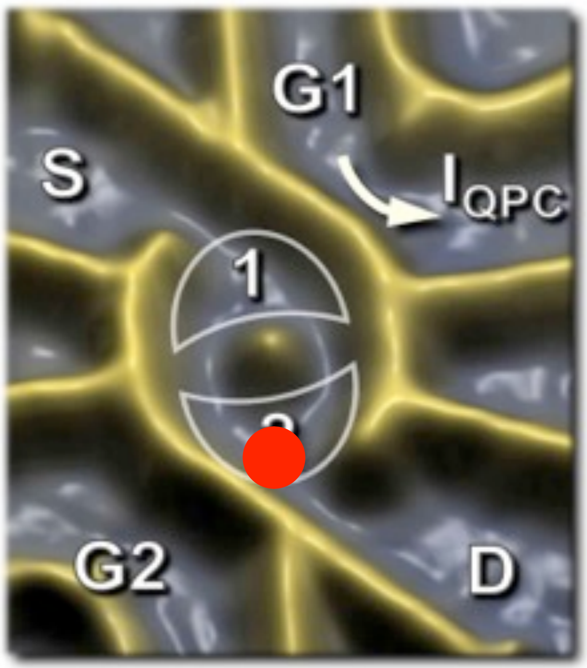
A. Tonomura et al.,
American Journal of Physics **57** 117-120 (1989)

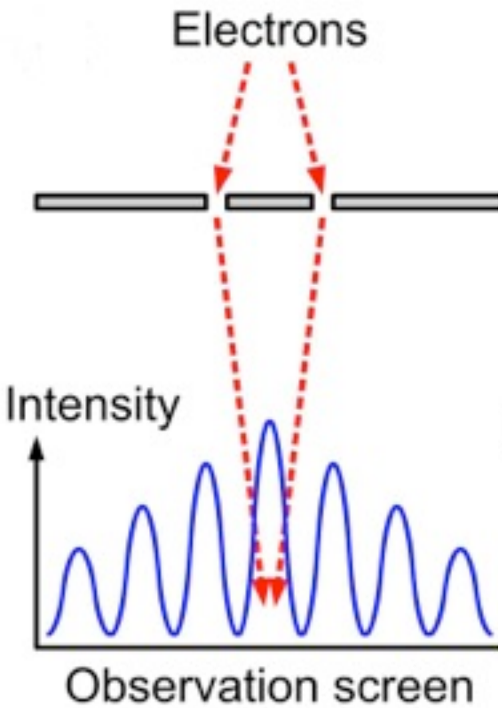


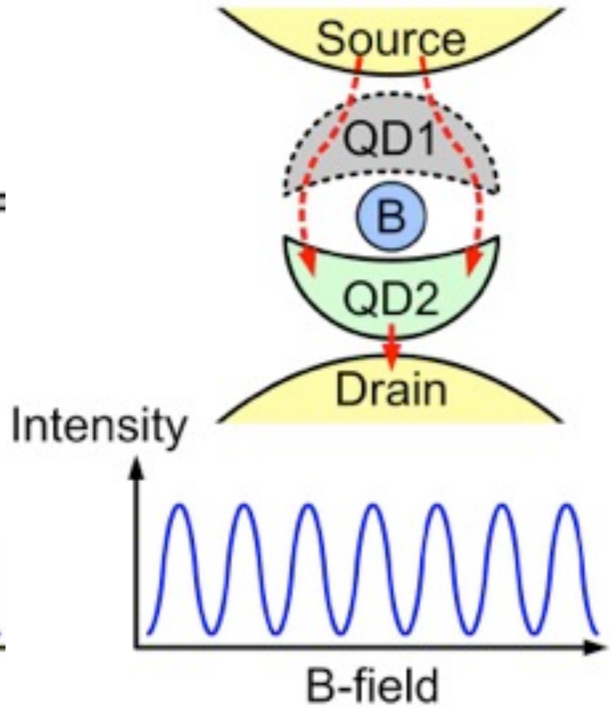
A. Tonomura et al.,
American Journal of Physics **57** 117-120 (1989)

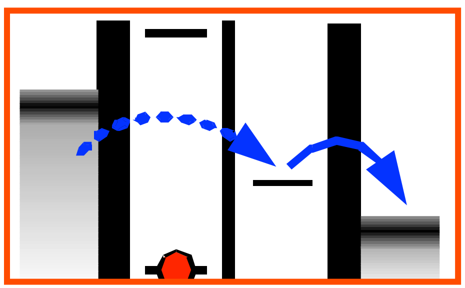

source
double
slit
screen

Double slit experiment
<-> Aharonov Bohm

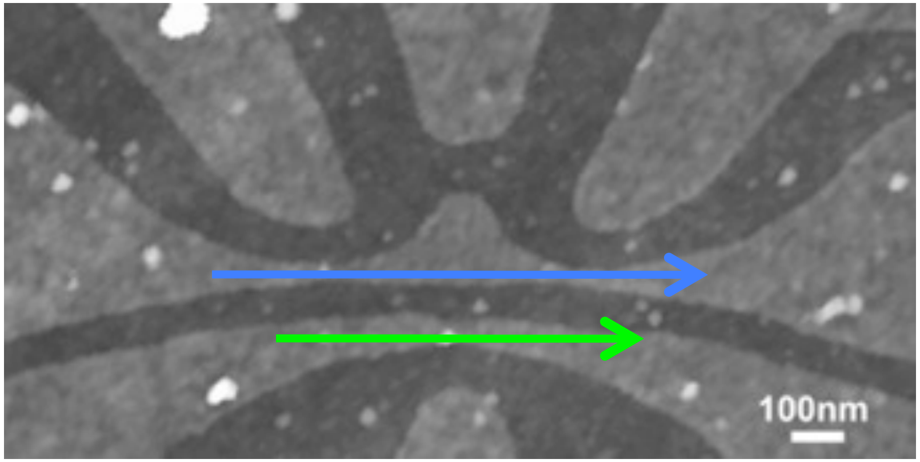








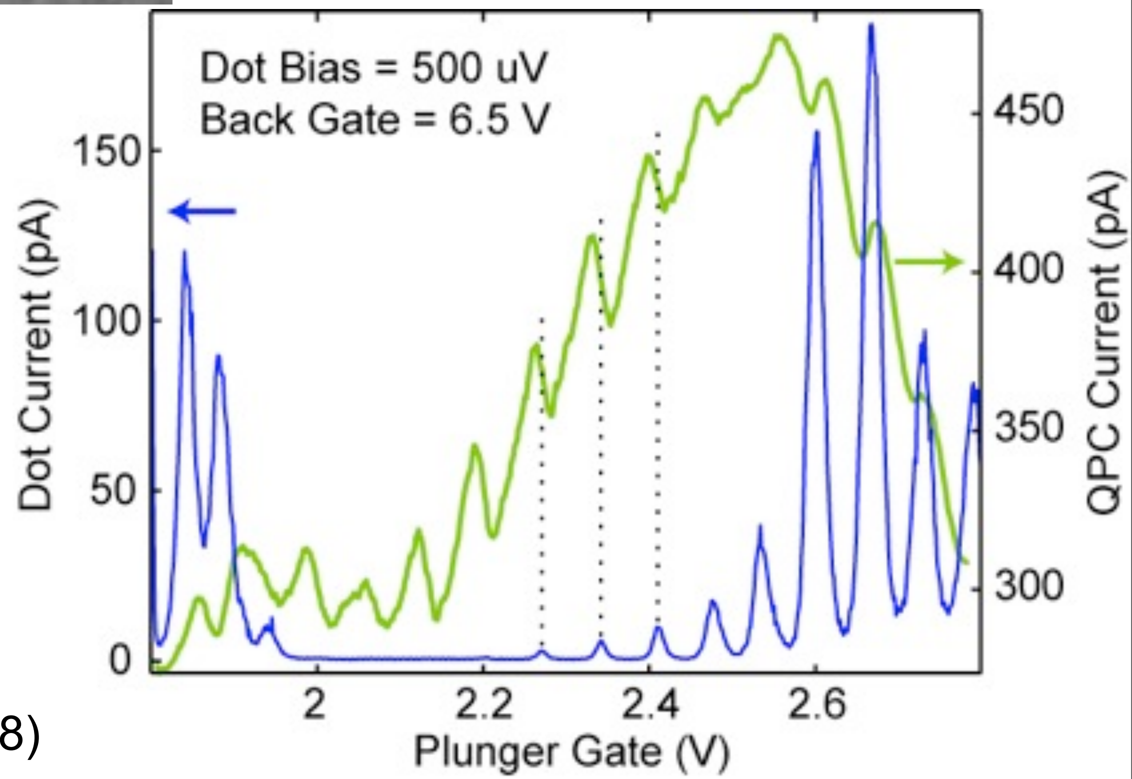
Graphene dot with charge detector



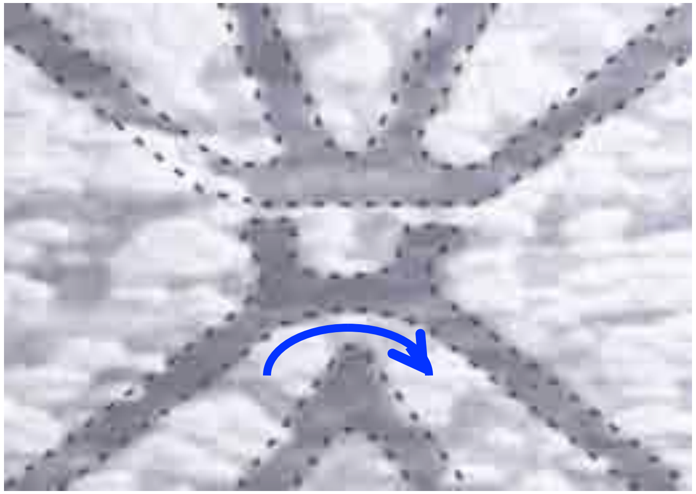
dot

constriction

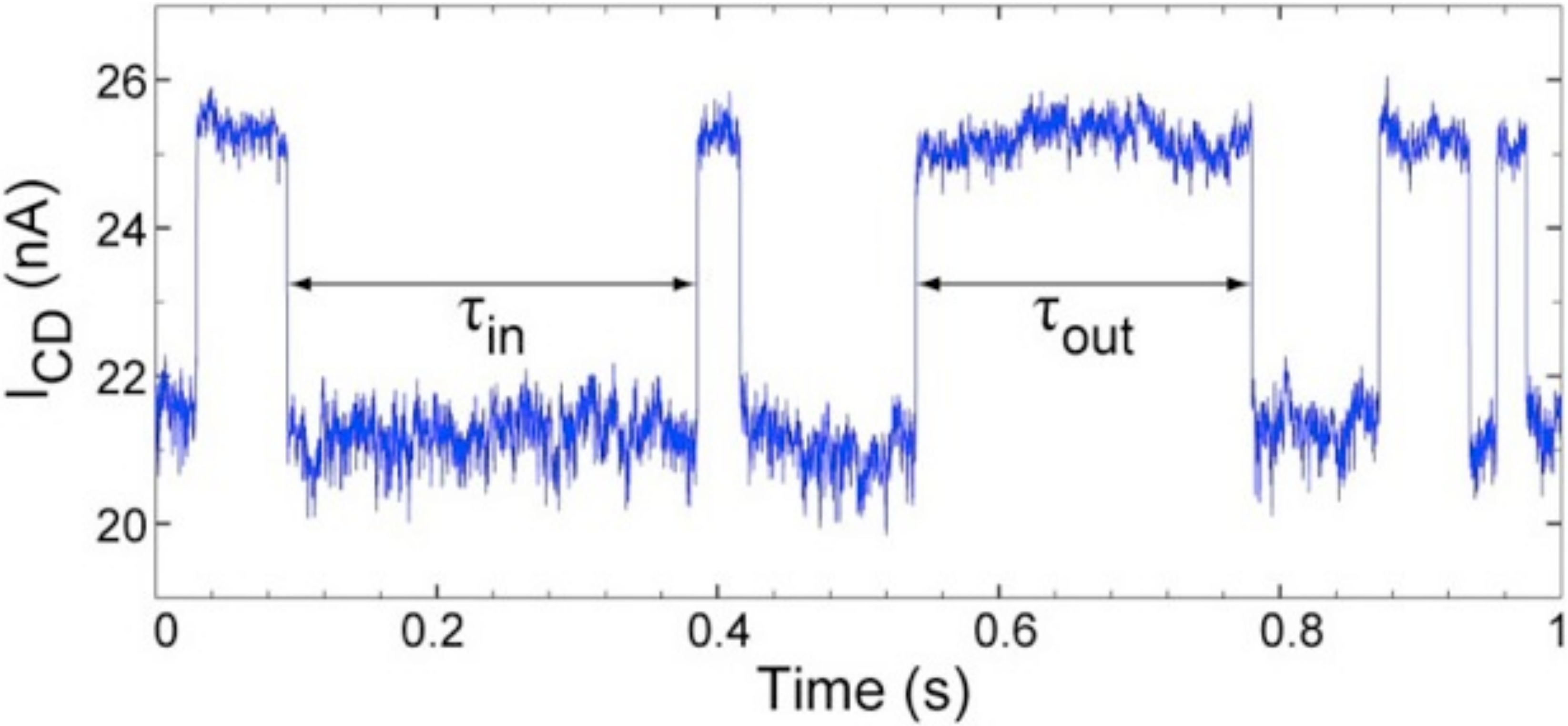
C. Stampfer,
S. Hellmüller,
J. Güttinger,
F. Molitor,
T. Ihn



Güttinger et al. APL **93**, 212102 (2008)



Electron counting



J. Güttinger, C. Achille, C. Stampfer

Klassischer Computer

Information ist in Einheiten von bits gespeichert:
(0) und (1)

Vergleich Dezimal-System – Binärsystem:

0 - 0

1 - 1

$2 = 2 \cdot 10^0$ - $1 \cdot 2^1 + 0 \cdot 2^0$

$3 = 3 \cdot 10^0$ - $1 \cdot 2^1 + 1 \cdot 2^0$

Quanten-Computer

Information ist in Einheiten von qubits gespeichert:
gleichzeitig (0) und (1)

Klassischer Computer

Bits:

Entweder (0) oder (1)

Seriell: addiert eine Nummer nach der anderen

Inkohärent, keine Interferenz (Billard-Kugeln)

Quanten-Computer

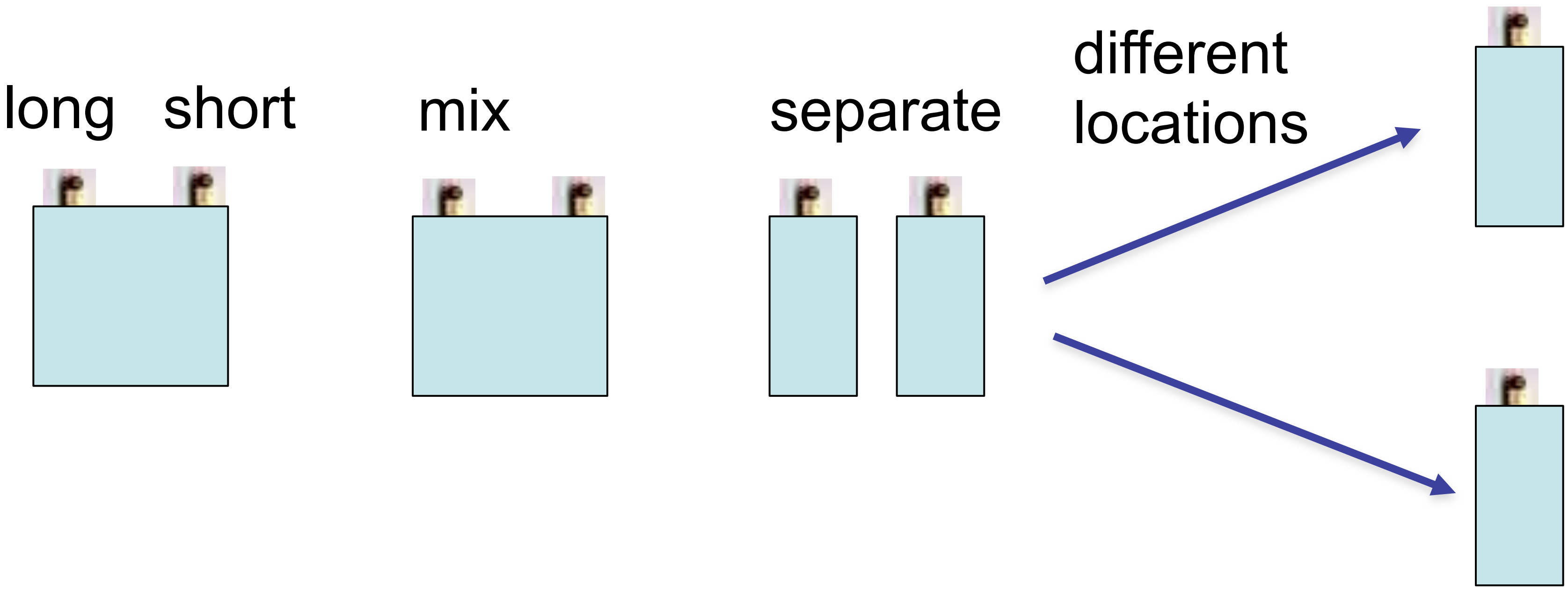
Qubits:

Sowohl (0) als auch (1)

Parallel: verarbeitet Daten gleichzeitig

Kohärent, Überlagerung (Wasserwellen)

Classical correlation



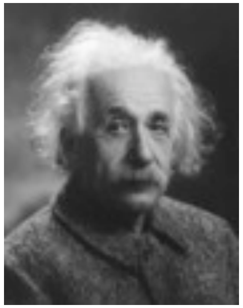
Quantum correlation

Is much stronger and can be measured

application: Quantum cryptography, data decoding

Aussagen über Quantenmechanik

Erwin Schrödinger:
“Ich mag es nicht, und es ist mir unangenehm, dass ich jemals etwas damit zu tun hatte.”



Albert Einstein:
“Wunderbar, welche Ideen die jungen Leute heutzutage haben. Aber ich glaube kein Wort davon.”

Richard Feynman:
“Ich denke, dass man mit Sicherheit sagen kann, dass niemand die Quantenmechanik versteht.”