Shot noise in quantum dots

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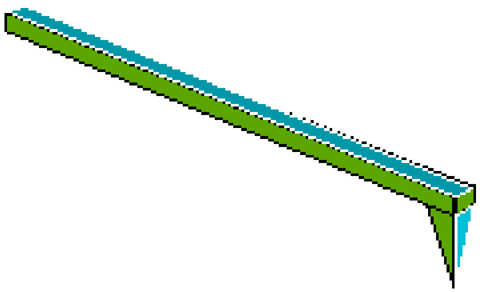
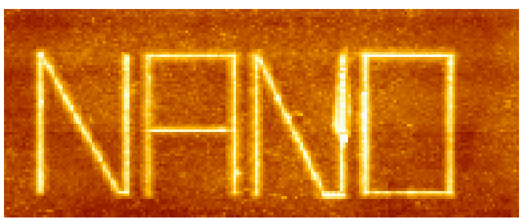
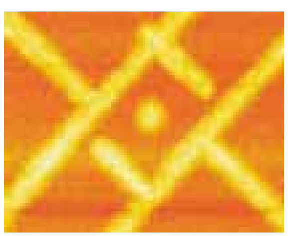
2DEG: A. C. Gossard, UCSB





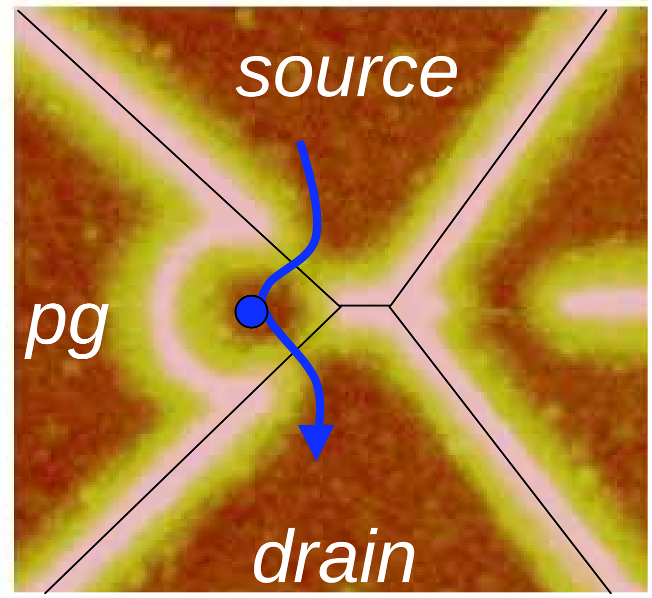


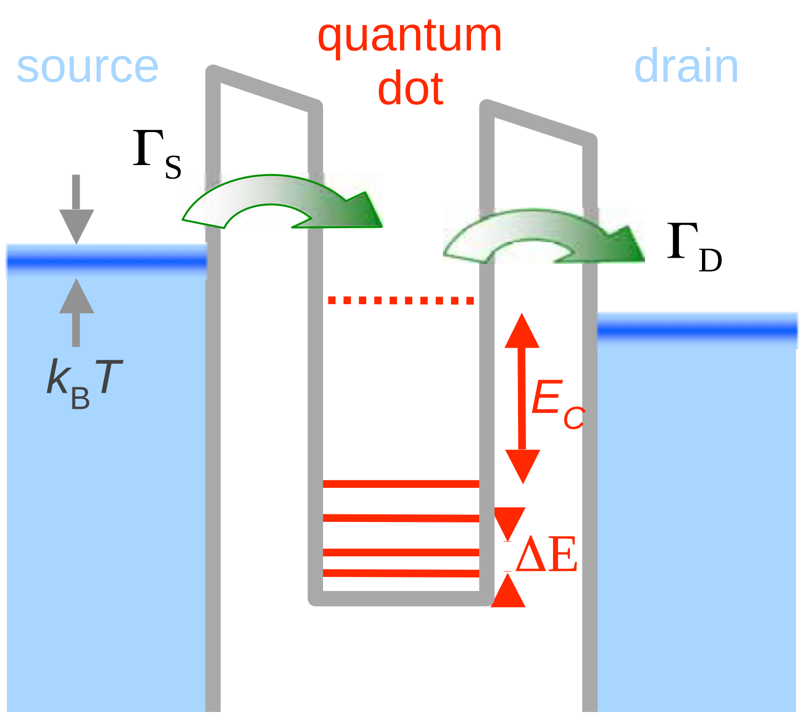
Transport through quantum dots

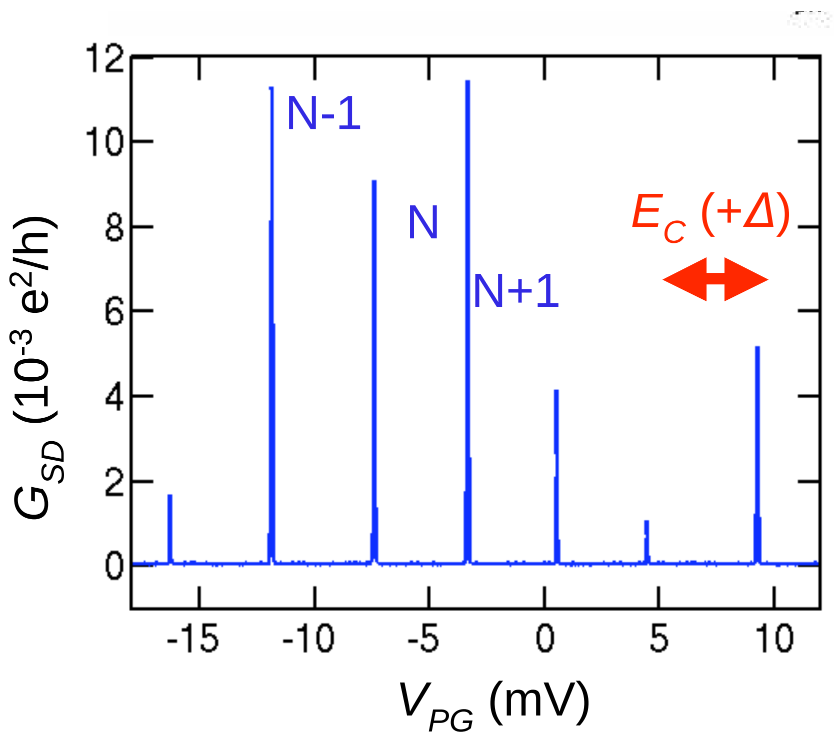
Shot noise in quantum dots

Full counting statistics -> correlations

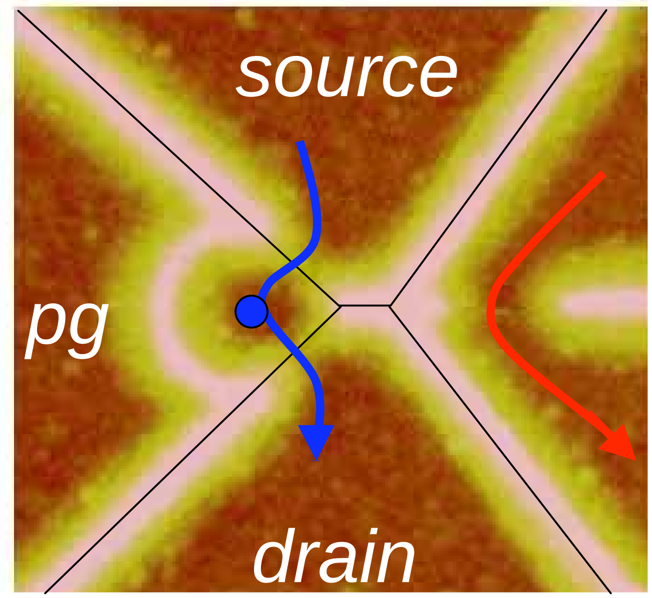
Spectroscopy of electronic states

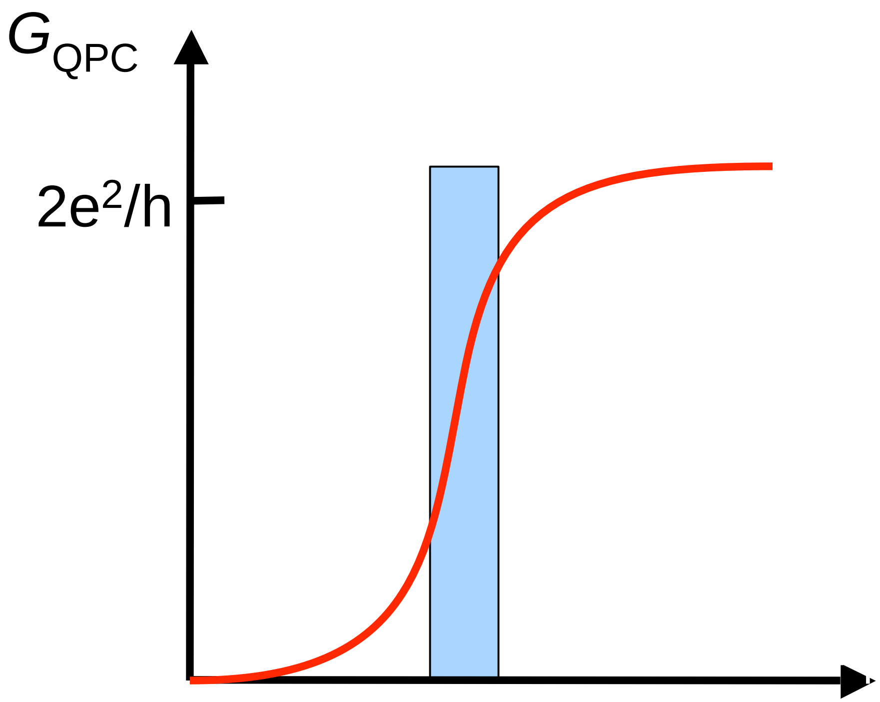


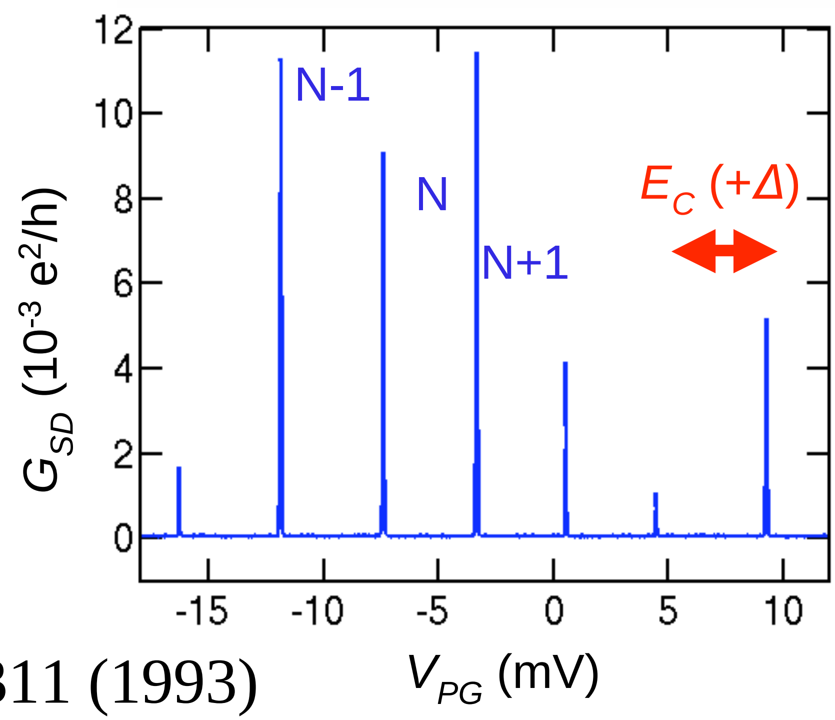




Quantum point contact as a charge detector

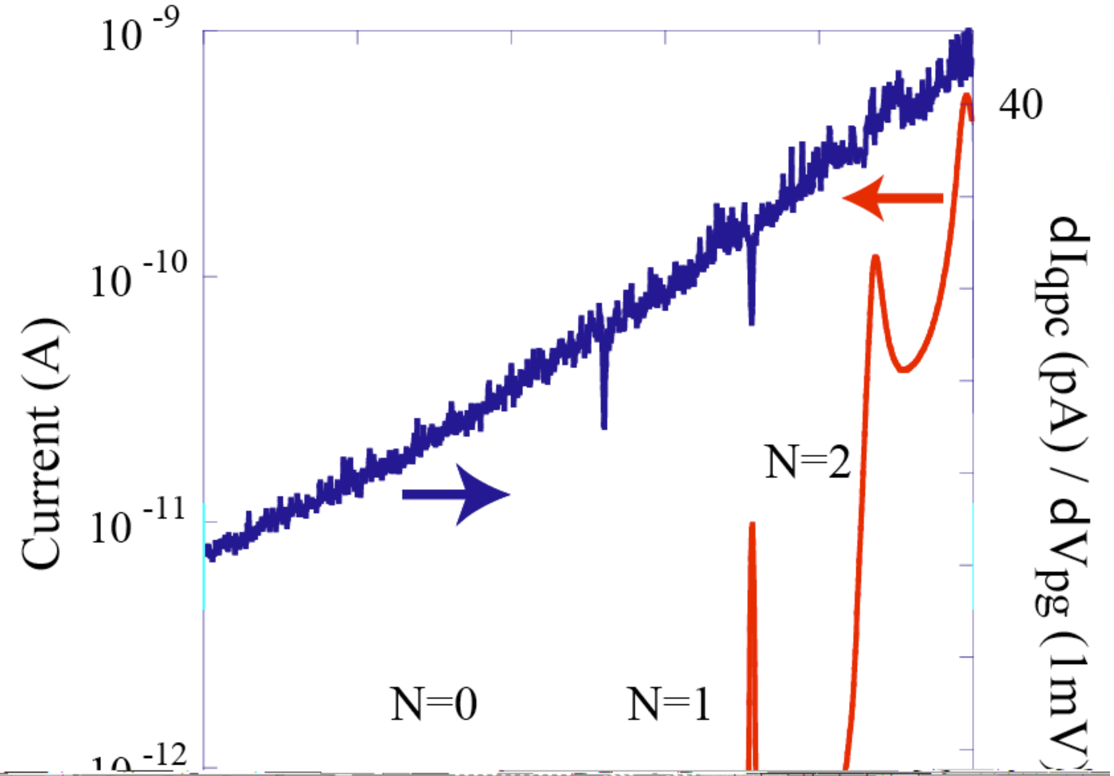


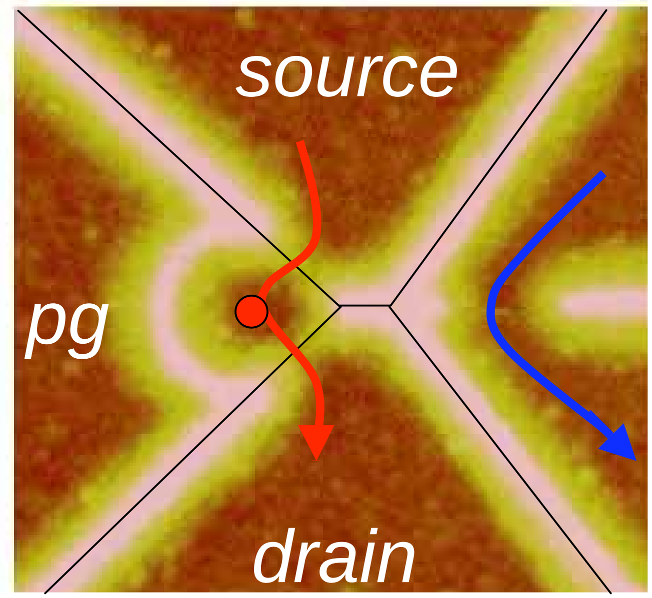




M. Field et al., Phys. Rev. Lett. 70, 1311 (1993)

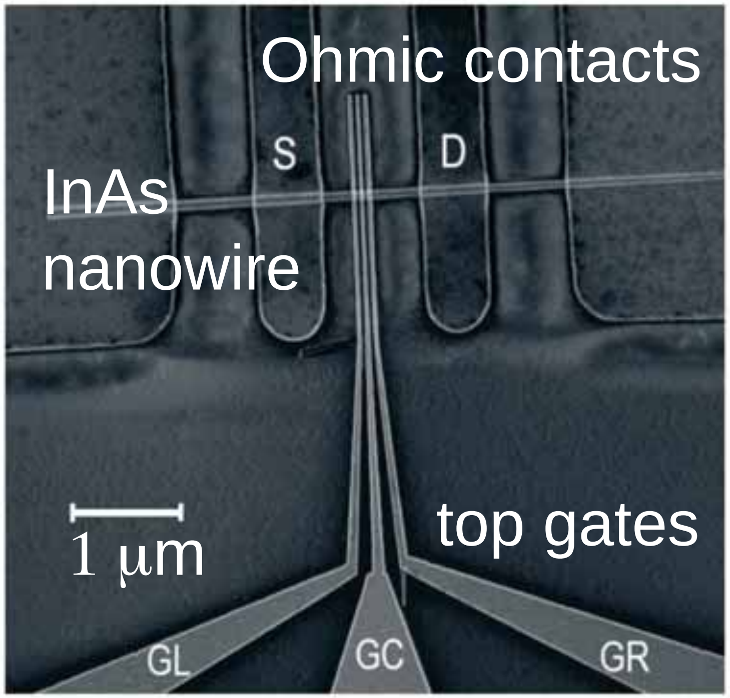
A few electron quantum dot

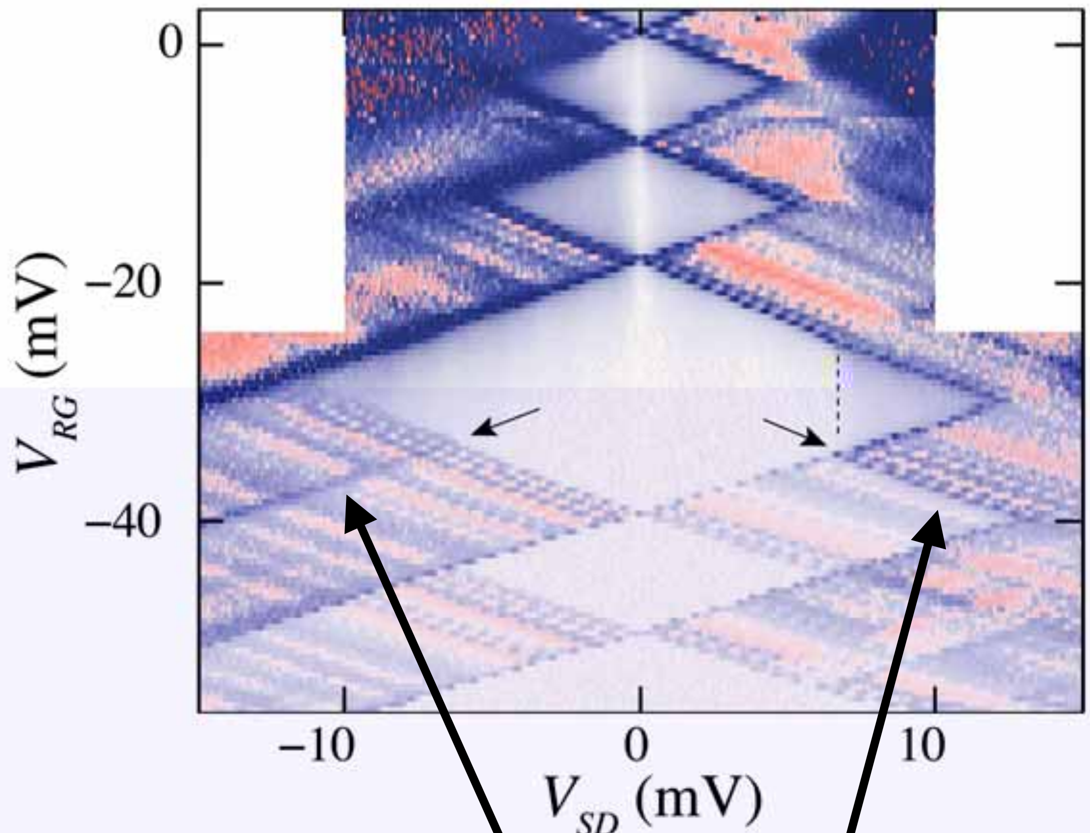




M. Sigrist

Measurement of excited states



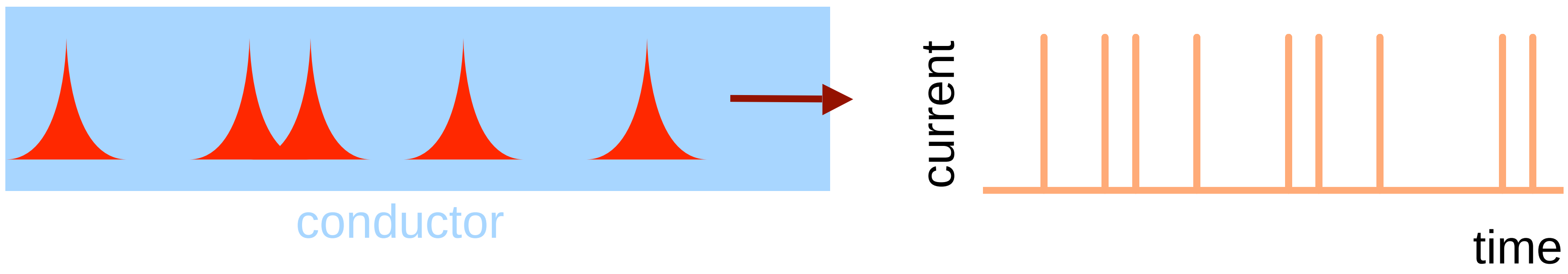


few electron single and
double quantum dot

excited states

A. Pfund, I. Shorubalko, R. Leturcq

Measurement of current fluctuations



- Shot noise due to discreteness of charges
  - classical shot noise for independent particles (Poissonian noise): $S_I = 2eI$
- Usual measurement limited by noise of the current-meter ⇒ $S_I^{min} \approx 10^{-29}$ A^2/Hz

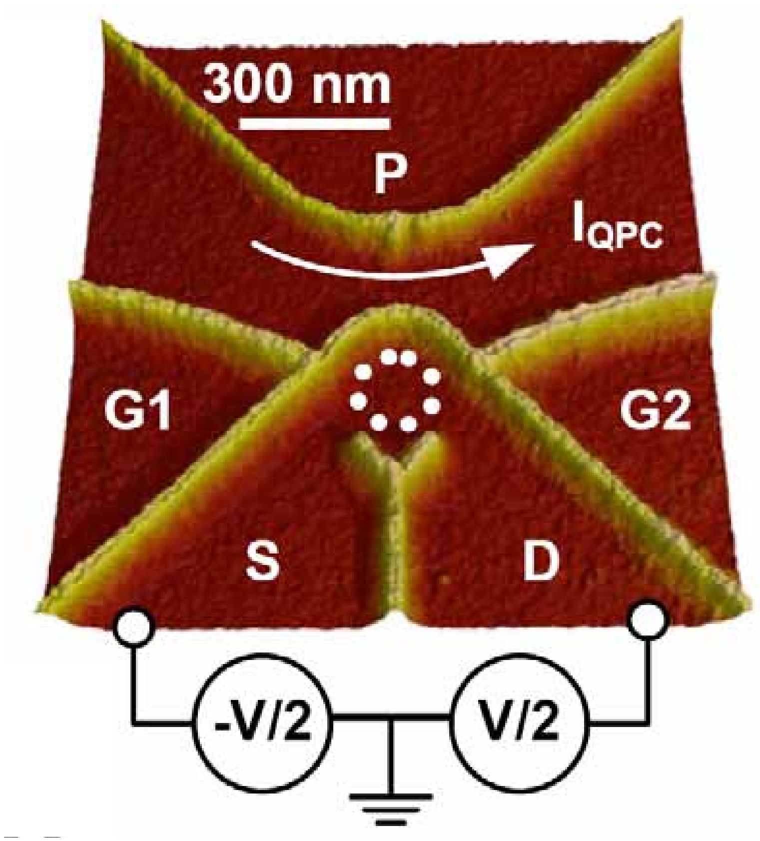
Noise in quantum dots: theoretical predictions

- Sub- vs. super-Poissonian shot noise in quantum dots
  - Beltzig, PRB **71,** 161301(R) (2005)
- Noise correlations in multi-terminal quantum dots
  - Sauret & Feinberg, PRL 92, 106601 (2004)
  - Cottet, Belzig, Bruder, PRL 92, 206801 (2004)
- Probing entanglement with the shot noise in quantum dot systems
  - Loss & Shukorukov, PRL **84,** 1035 (2000)
  - Lesovik, Martin, Blatter, condmat

Noise in quantum dots...

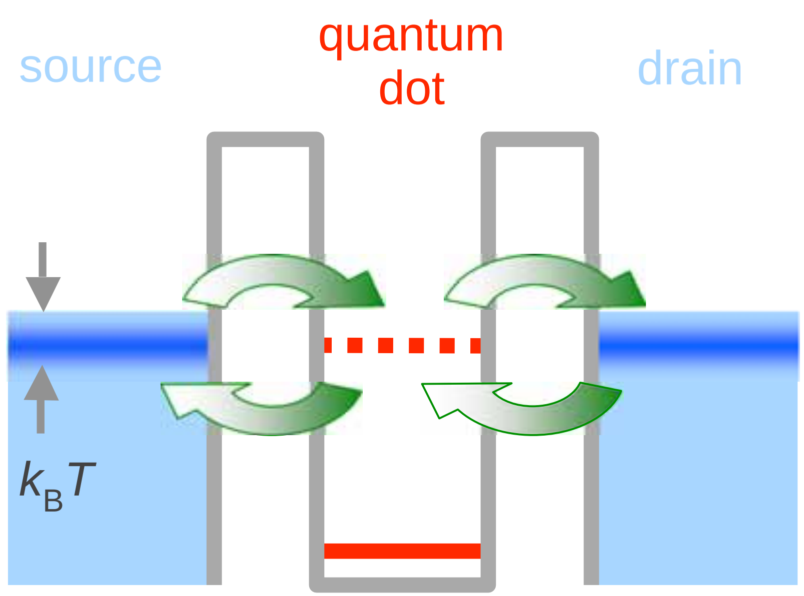
- Noise in interacting systems
  - deviations from Poissonian shot noise
- Early experiments in non-tunable quantum dots showed reduction of the shot noise: $S_I < 2eI$
  - Birk et al., PRL **75,** 1610 (1995), STM
  - Nauen et al., PRB **70,** 033305 (2004), SAQDs
- Challenge in lateral quantum dots
  - very low noise level: I < 1 pA ⇒ $S_I < 10^{-31}$ A^2/Hz !
  - strongly non-linear systems

Detection of single electron transport

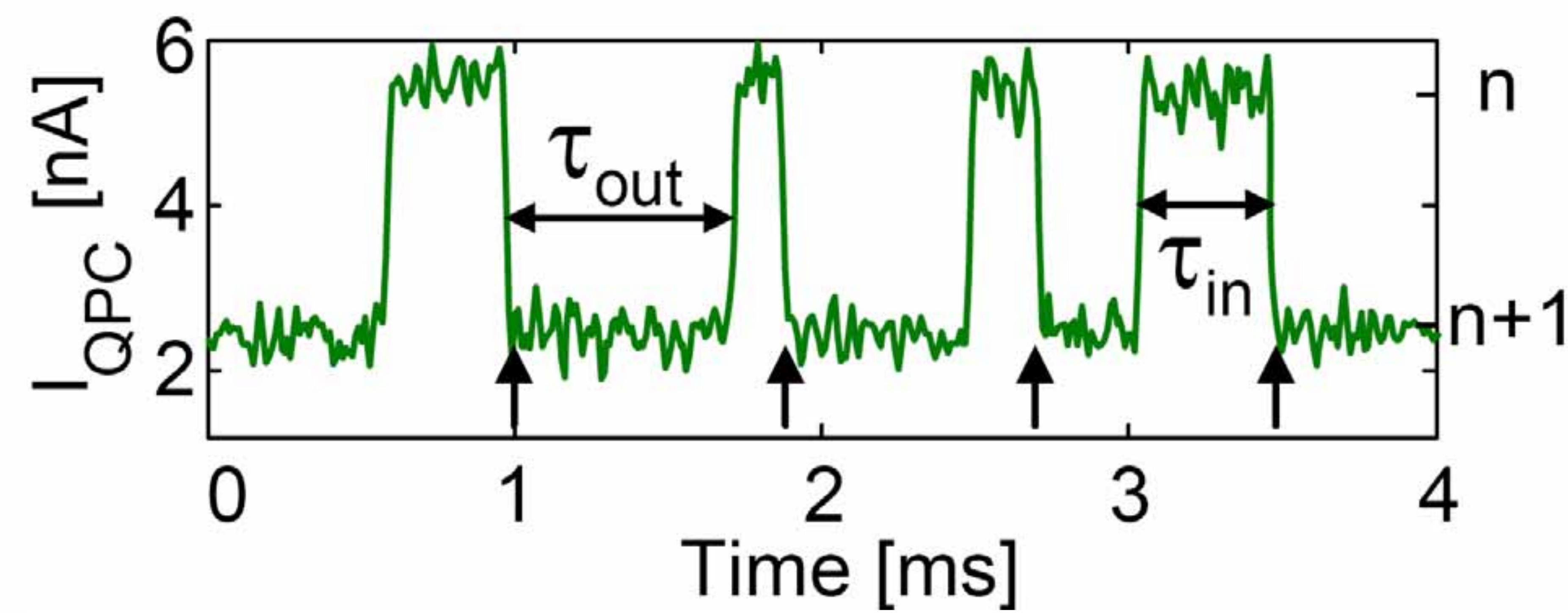


T_e = 350 mK

- Quantum point contact as a charge detector
- Low bias voltage on the quantum dot



Low bias - thermal noise



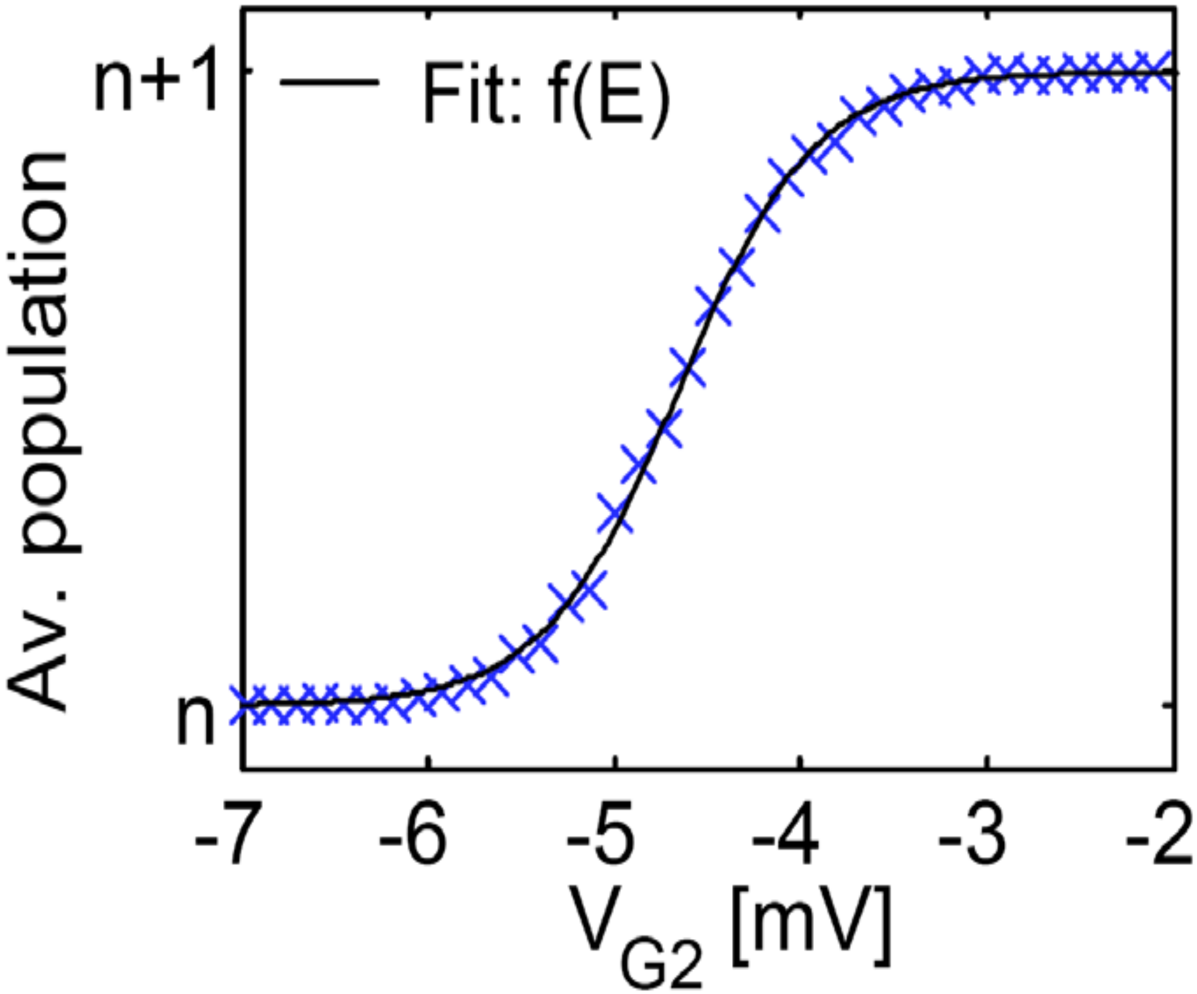
$$\Gamma_{\rm in} = \Gamma \times f(\Delta E/k_B T),\ \Gamma_{\rm out} = \Gamma \times (1 - f(\Delta E/k_B T))$$

Γ: effective dot-lead tunnel coupling

ΔE: energy difference between Fermi level of the lead and electrochemical potential of the dot

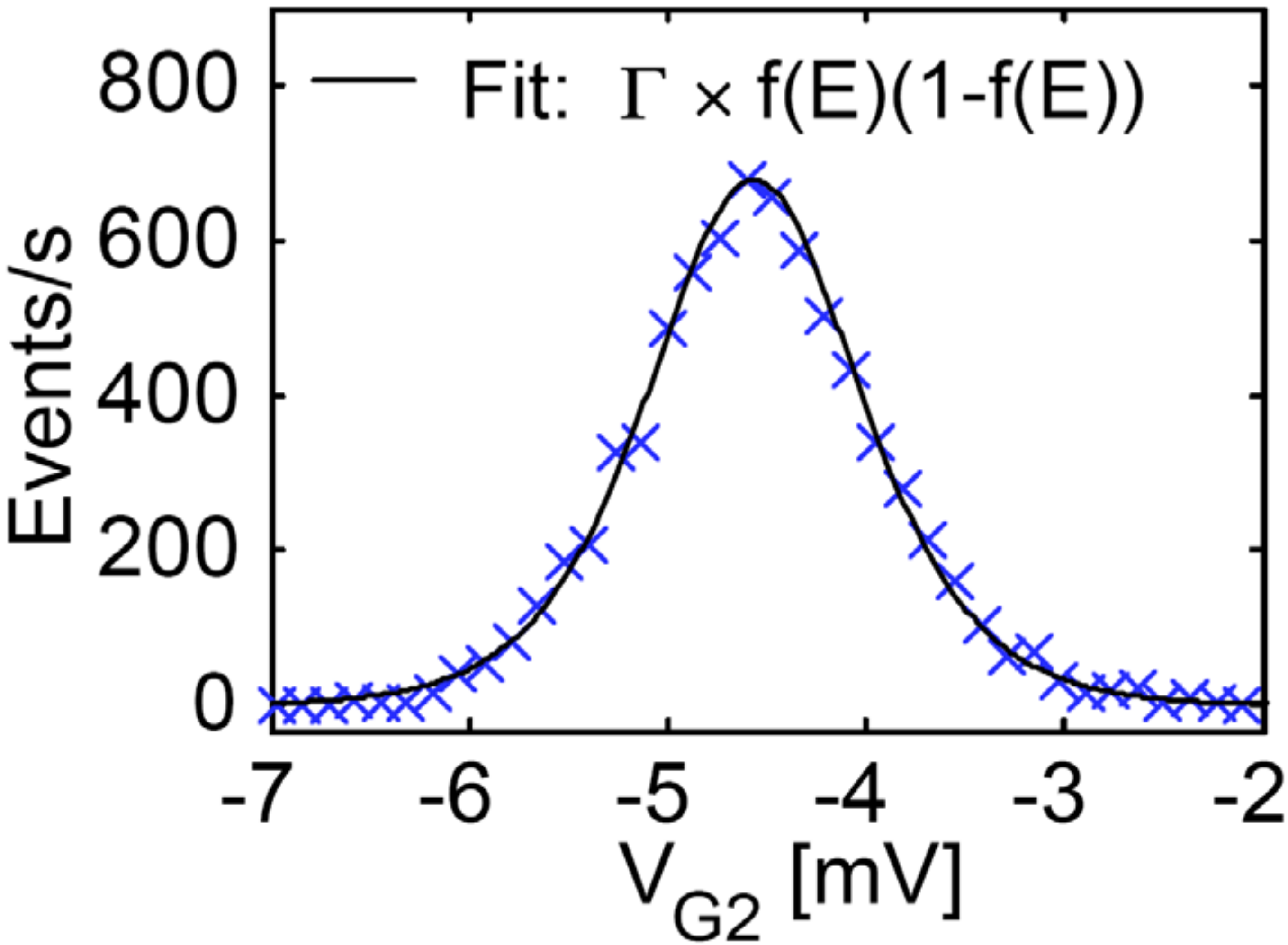
R. Schleser et al., Appl. Phys. Lett. 85, 2005 (2004)
L. M. K. Vandersypen et al., Appl. Phys. Lett. 85, 4394 (2004)

Average dot population



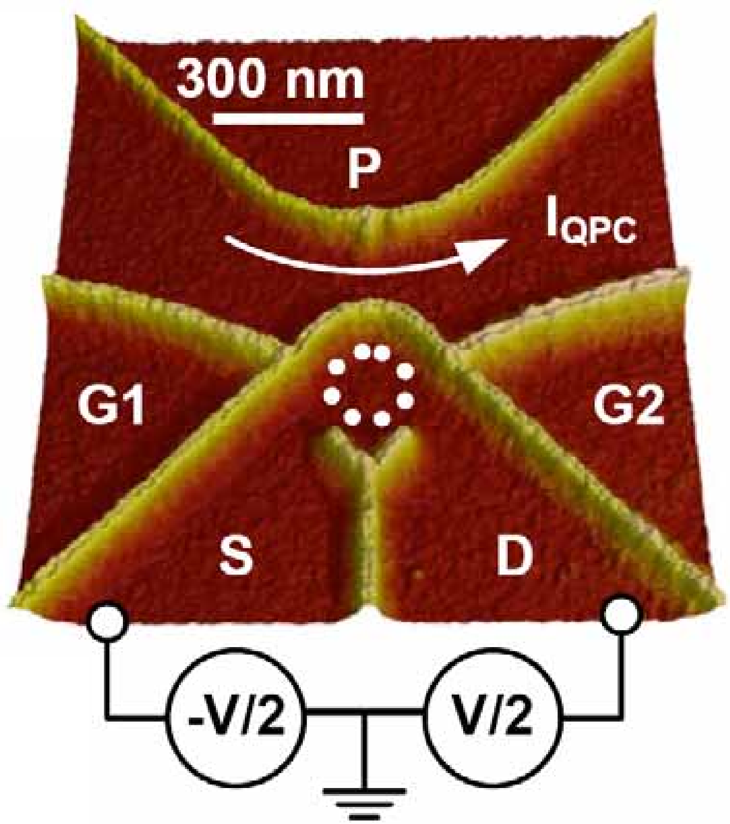
Fitting parameter: T = 230 mK.

Count rate: events per second



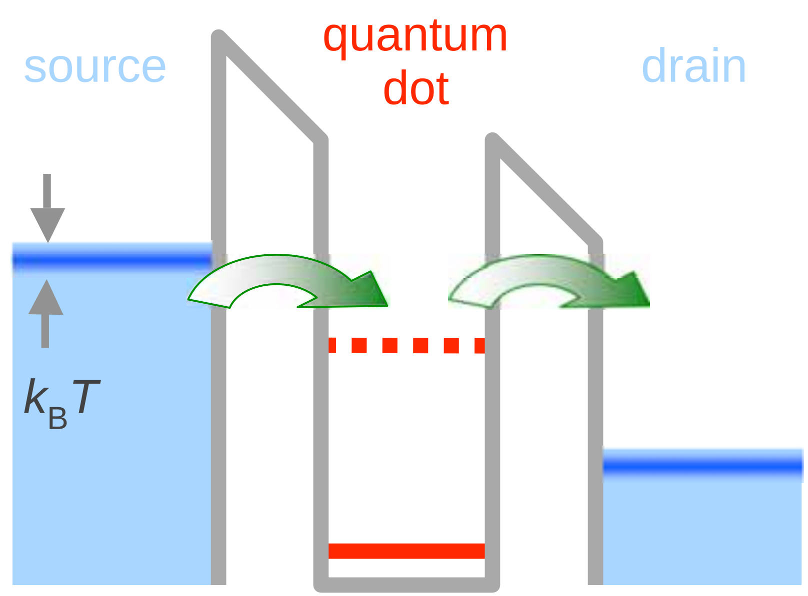
Fitting parameters: Γ= 2.63 kHz and T = 230 mK.

Detection of single electron transport



T_e = 350 mK

- Quantum point contact as a charge detector
- Large bias voltage on the quantum dot



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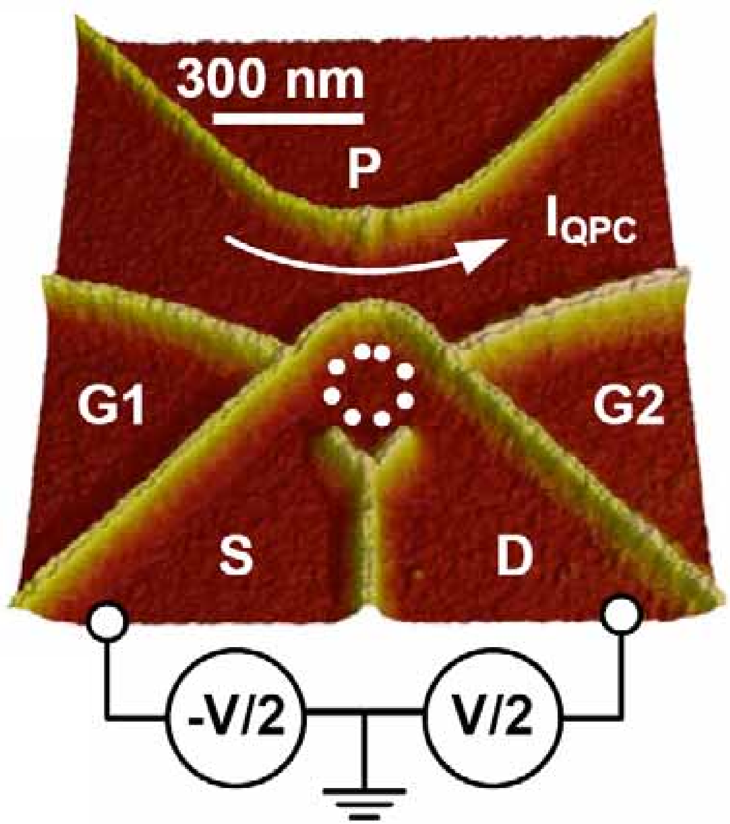
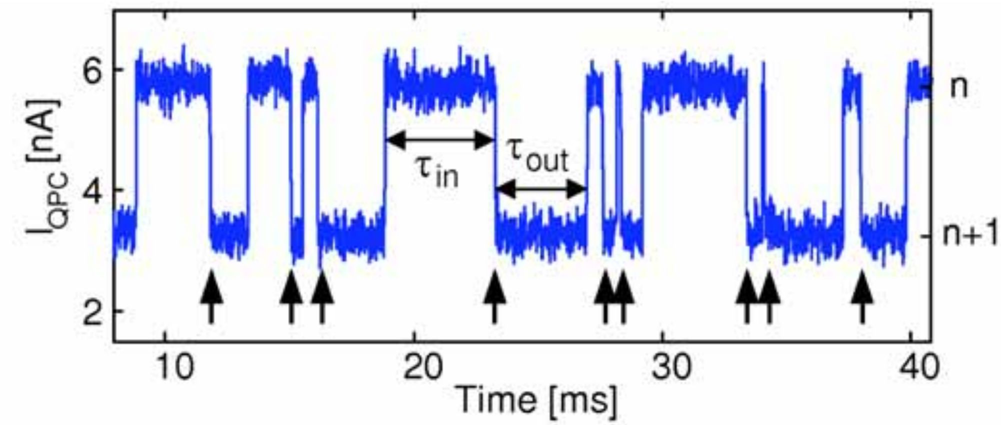
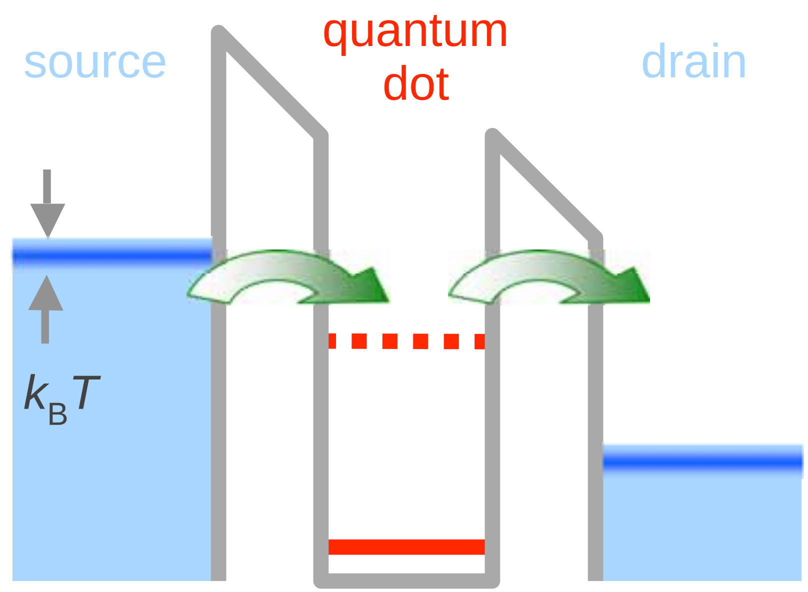


T_e = 350 mK





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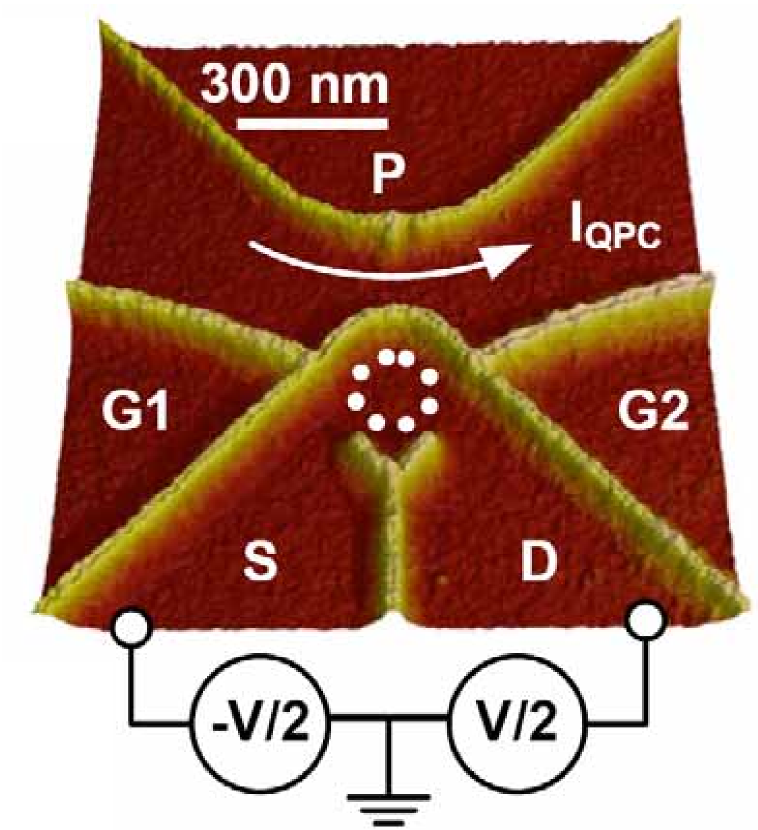
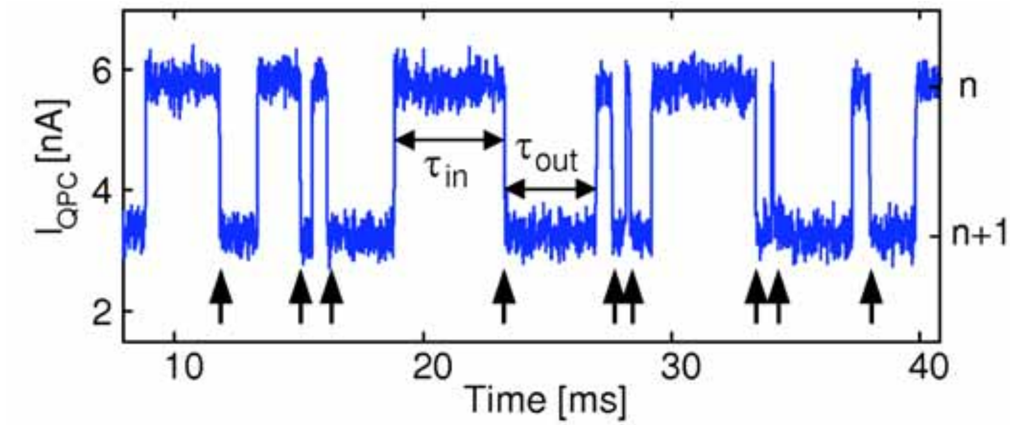
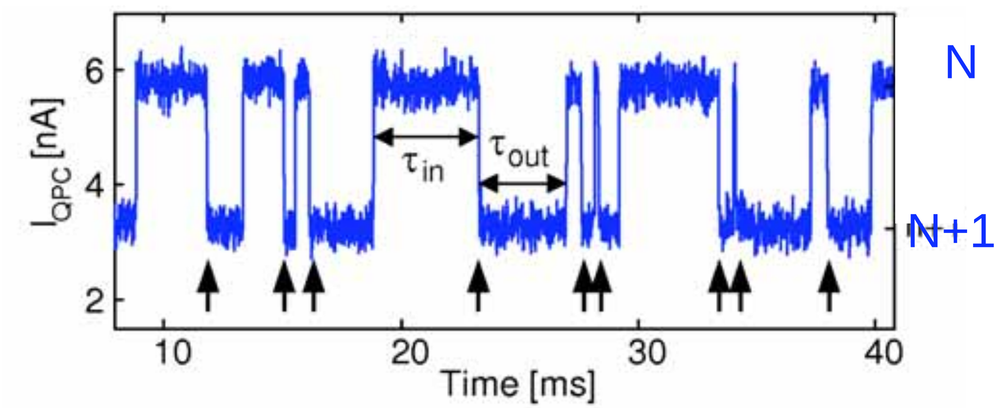


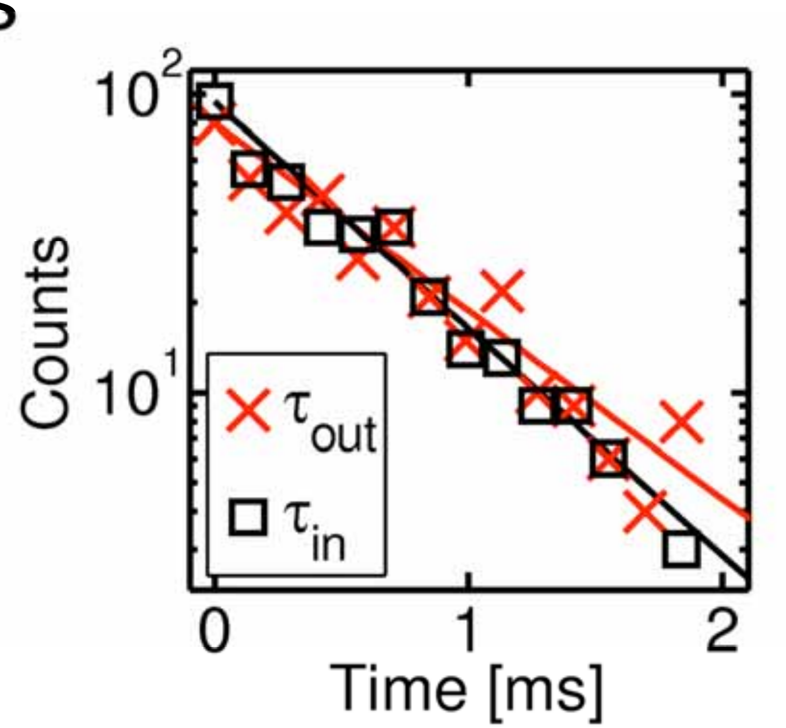


T_e = 350 mK

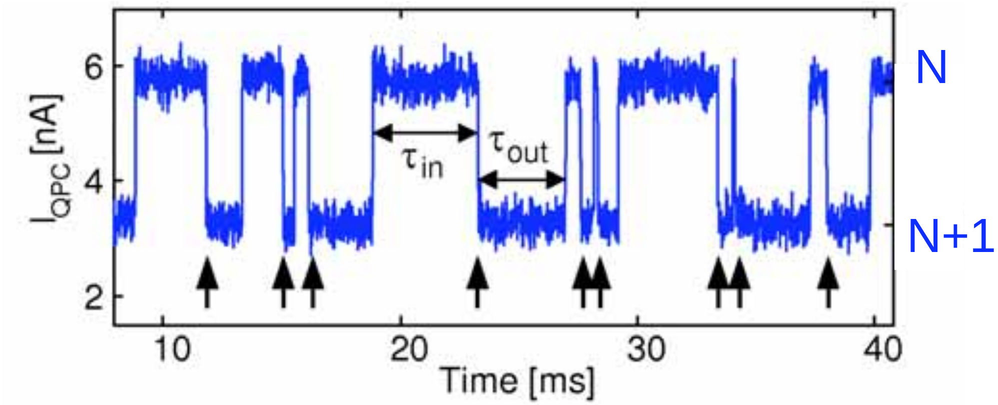
Determination of the individual tunneling rates

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





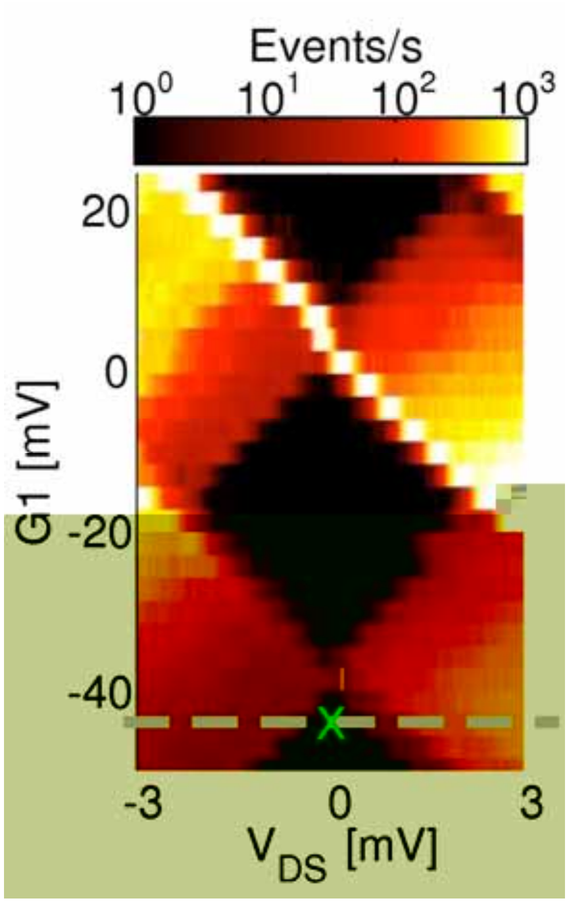
Measuring the current by counting electrons

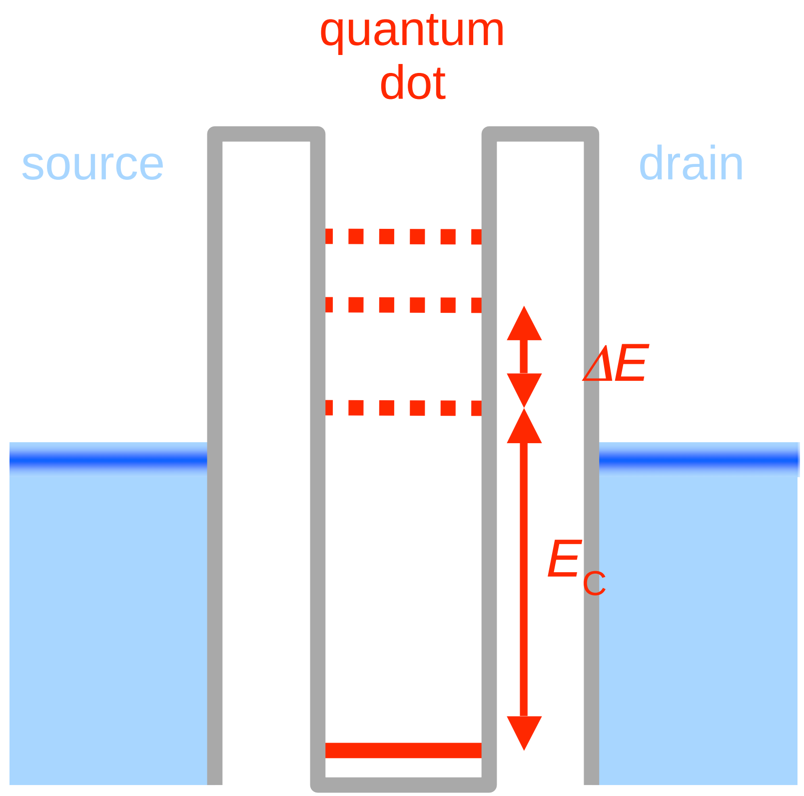


- Count number *n* of electrons entering the dot within a time t_0: $I = e\langle n\rangle/t_0$
- Max. current = few fA (bandwidth = 30 kHz)
- BUT no absolute limitation for low current and noise measurements
  - *we show here:* $I \approx$ few aA, $S_I \approx 10^{-35}$ A^2/Hz

Coulomb diamond measured by electron counting

- $I = e\langle n\rangle/t_0$





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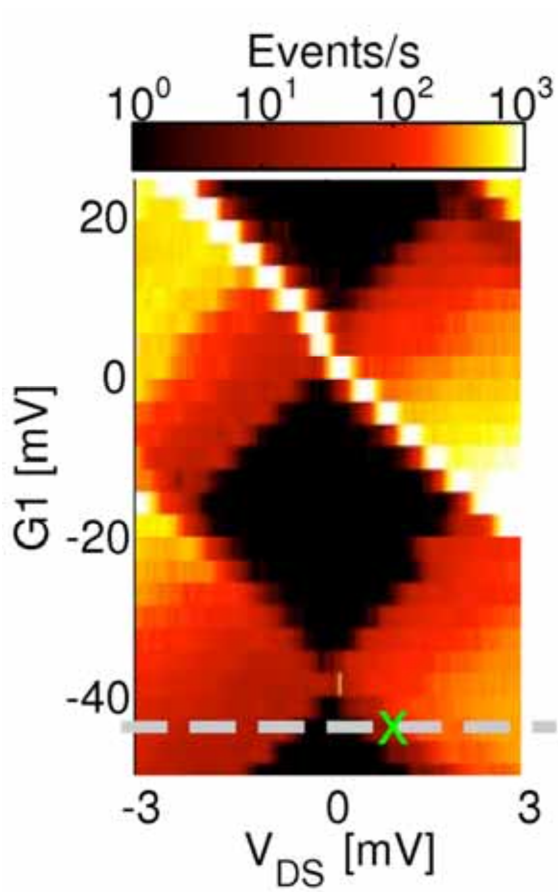

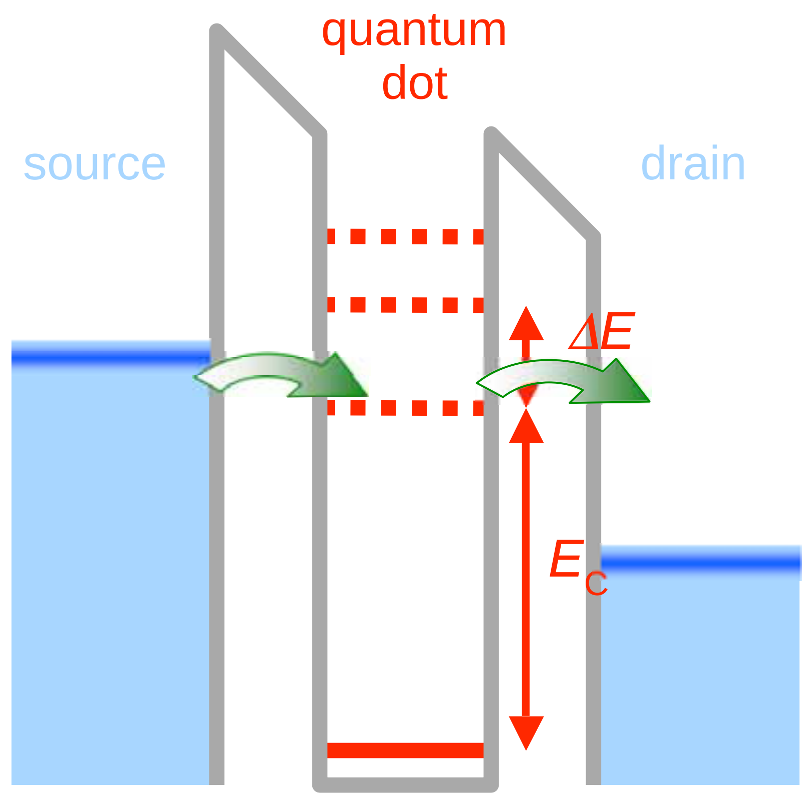

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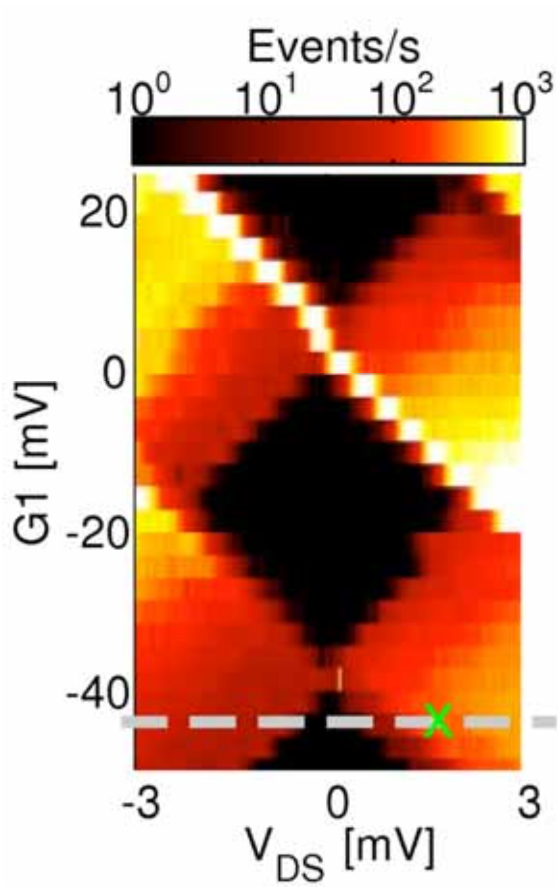

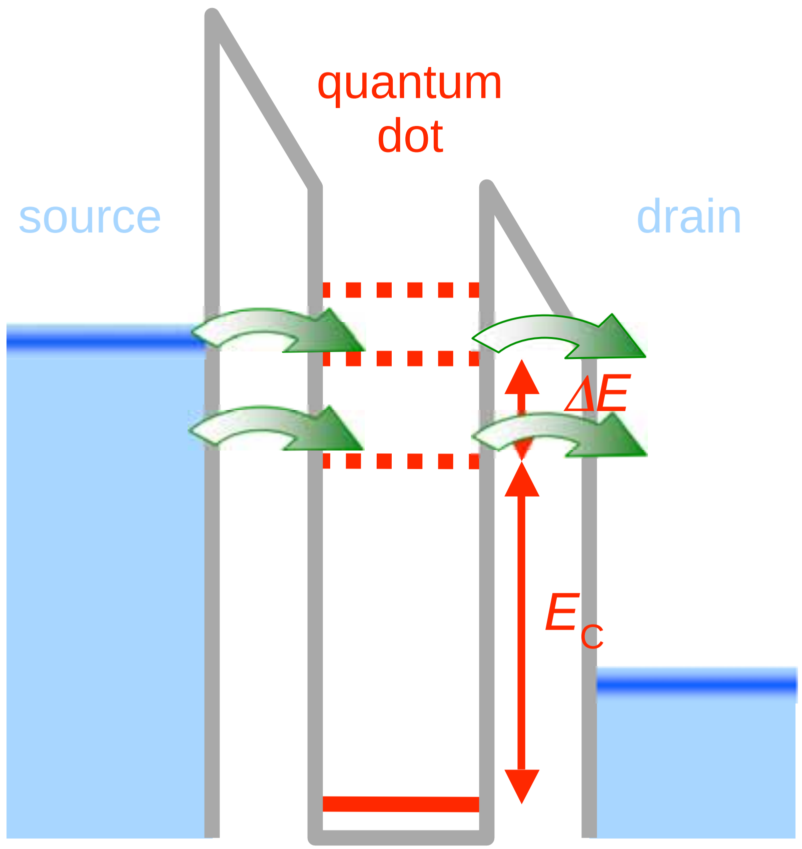

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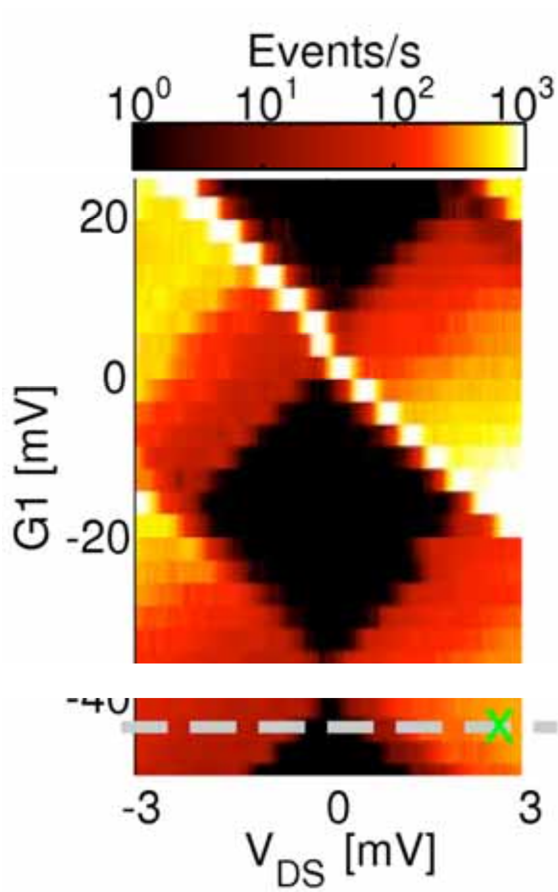

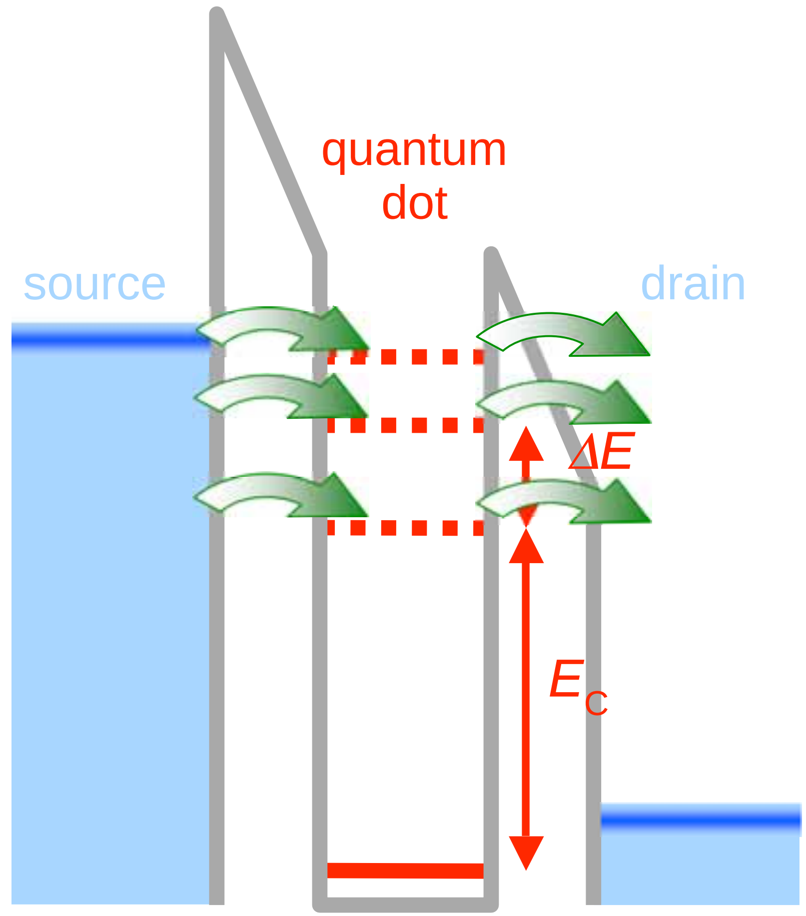

Coulomb diamond measured by electron counting

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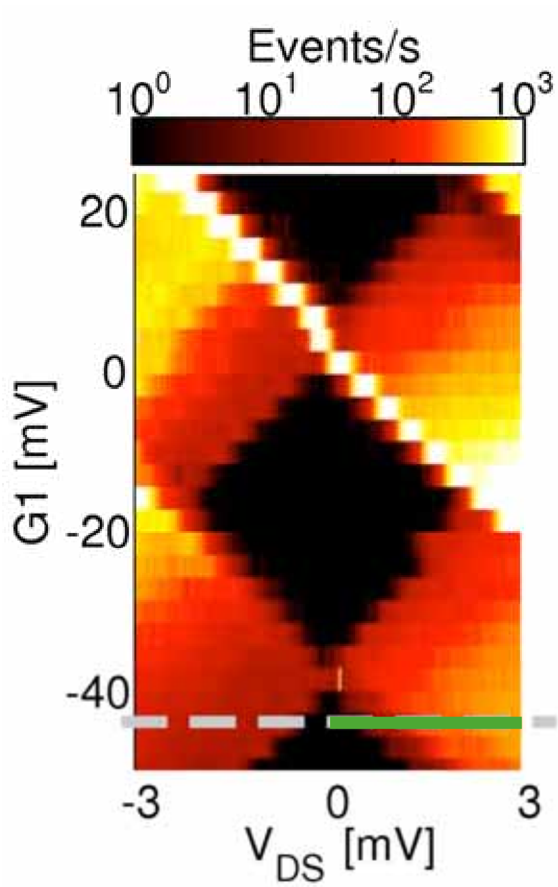
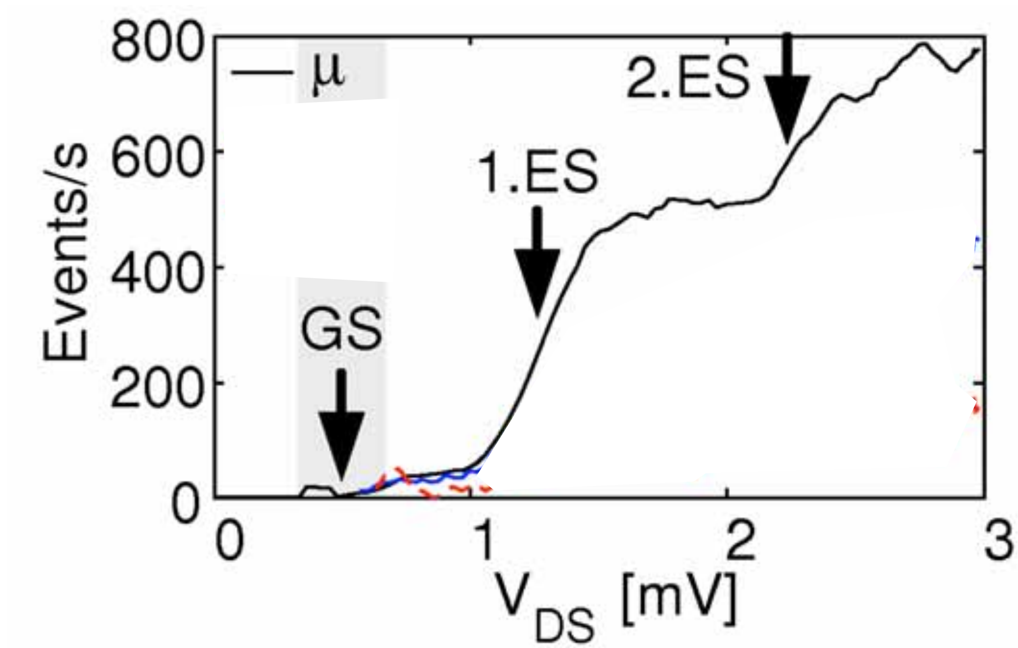
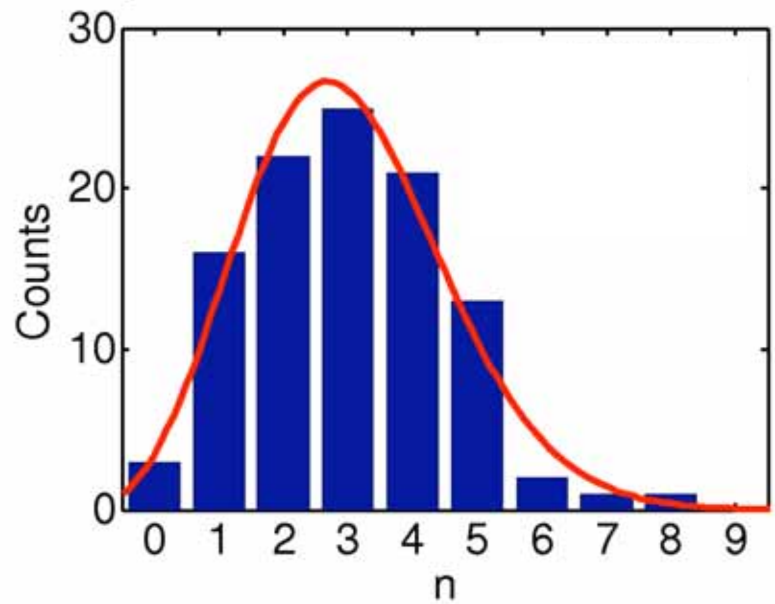




Current fluctuations measured by electron counting

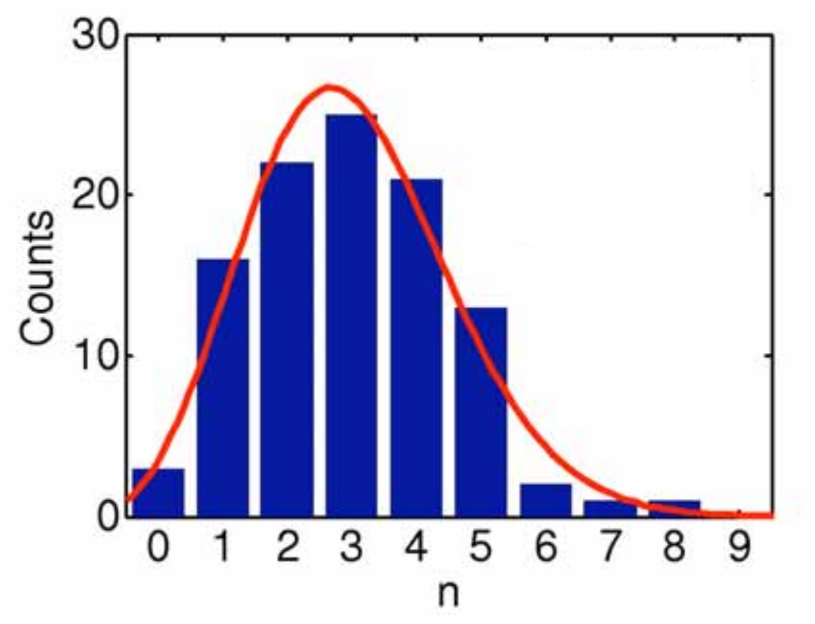
- More than noise: access to the full counting statistics (distribution function)
  - $I = e\mu/t_0$,
    $\mu = <n>$
  - $S_I = 2e^2\mu_2/t_0$,
    $\mu_2 = <(n-<n>)^2>$
  - $S_I^3 = e^3\mu_3/t_0$,
    $\mu_3 = <(n-<n>)^3>$
  - *and many more...*



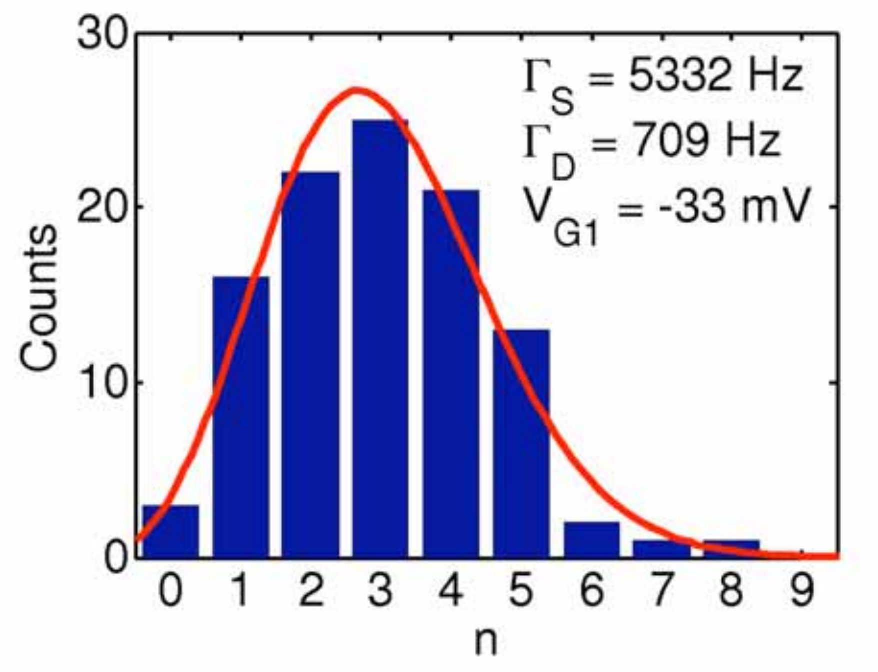
Distribution function for electrons in a conductor

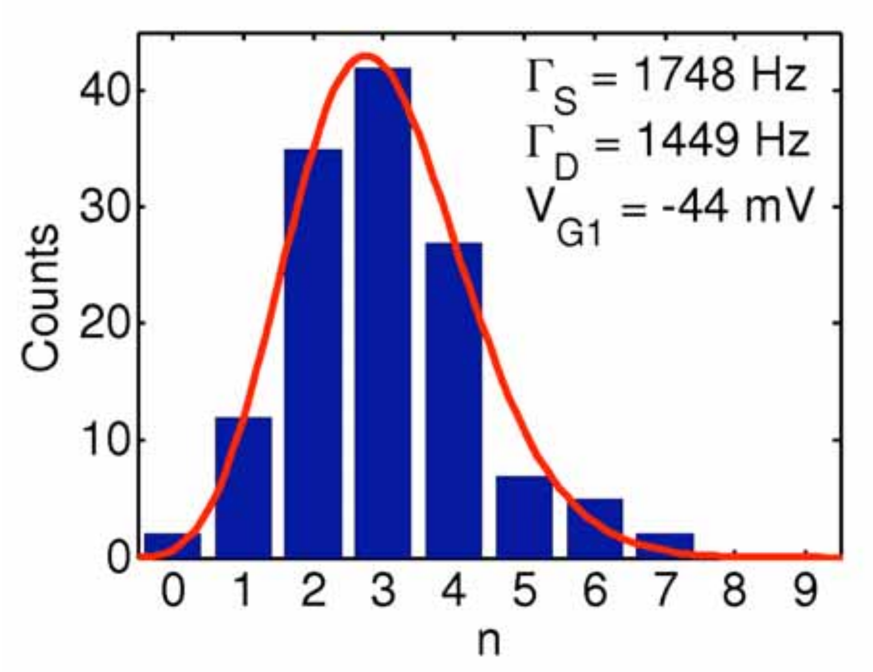
- Classical noise for independent particles

  $\Rightarrow$ Poisson distribution: $\mu = \mu_2 = \mu_3$
- Particles with repulsive interaction $\Rightarrow$ sub-Poissonian distribution: $\mu_2 < \mu$, $\mu_3 < \mu$,...



Histogram of current fluctuations

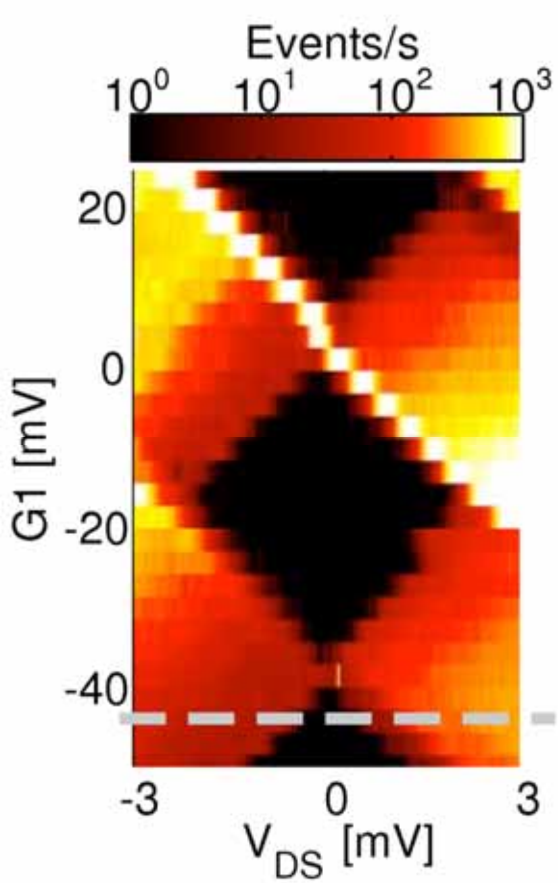


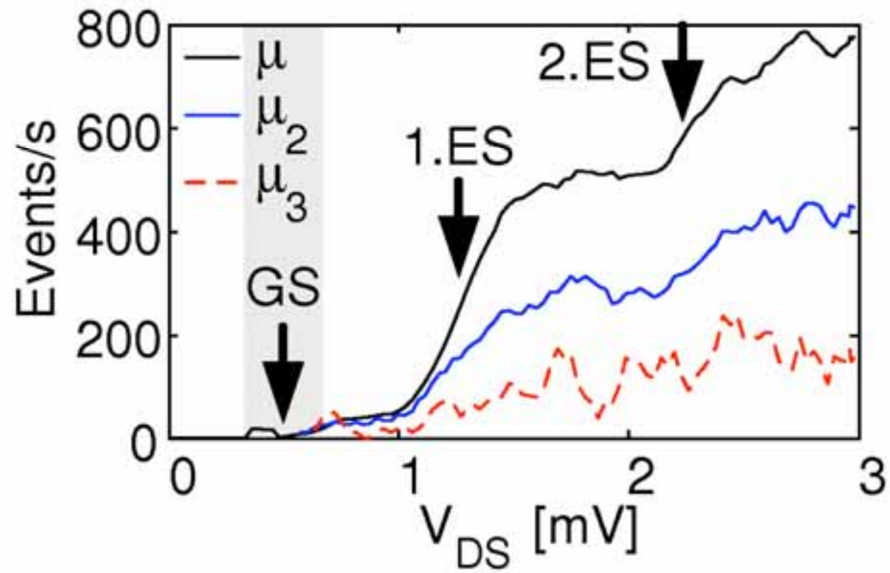


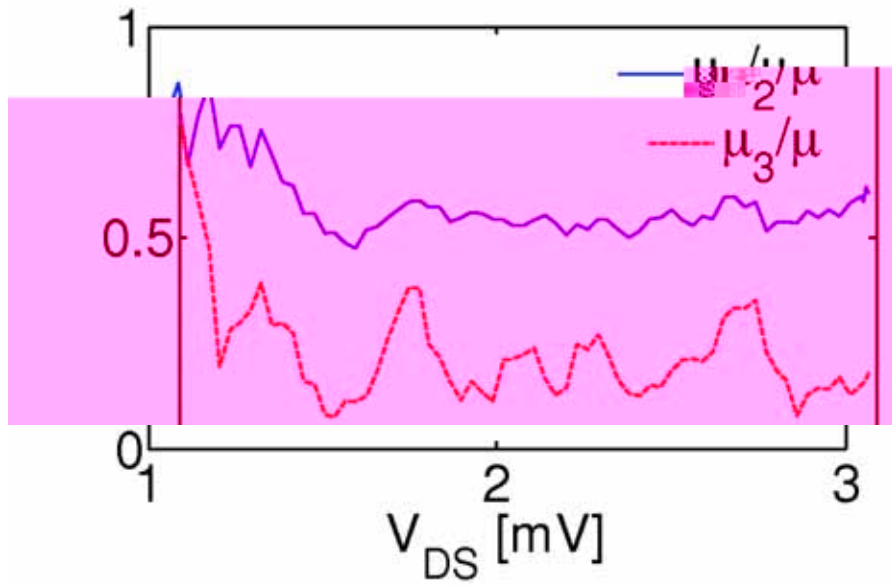
- Poisson distribution for asymmetric coupling
- Sub-Poisson distribution for symmetric coupling

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

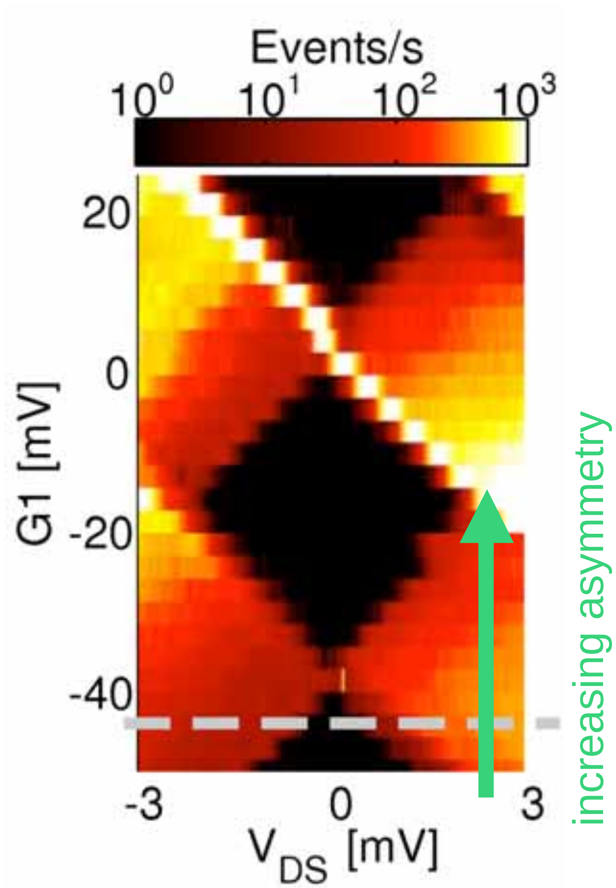
Bias dependence of the fluctuations

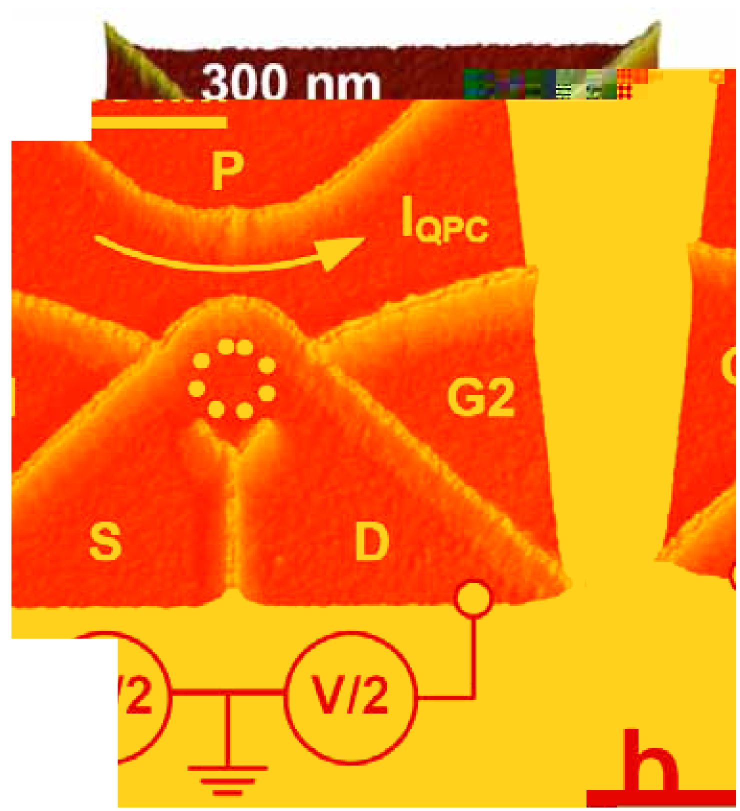




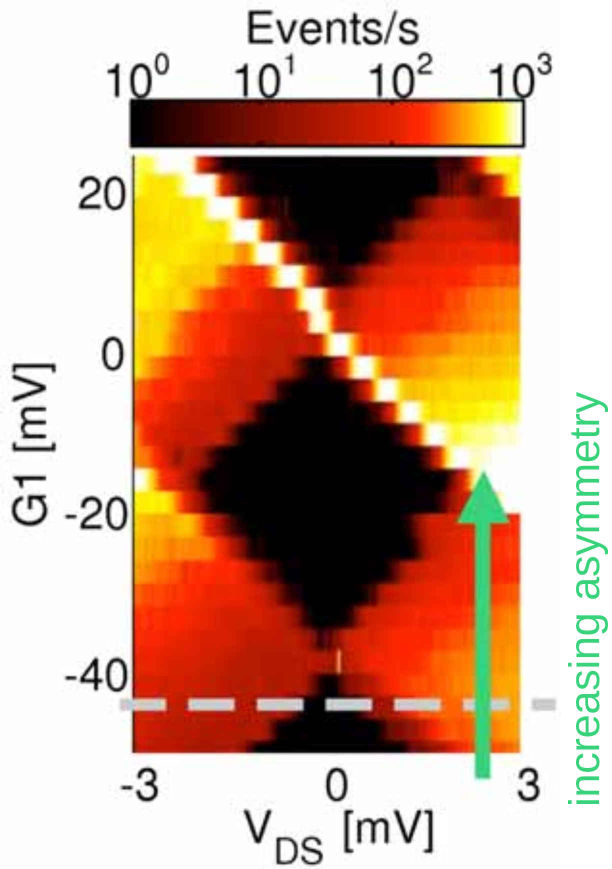


Adjustable asymmetry of the tunneling rates

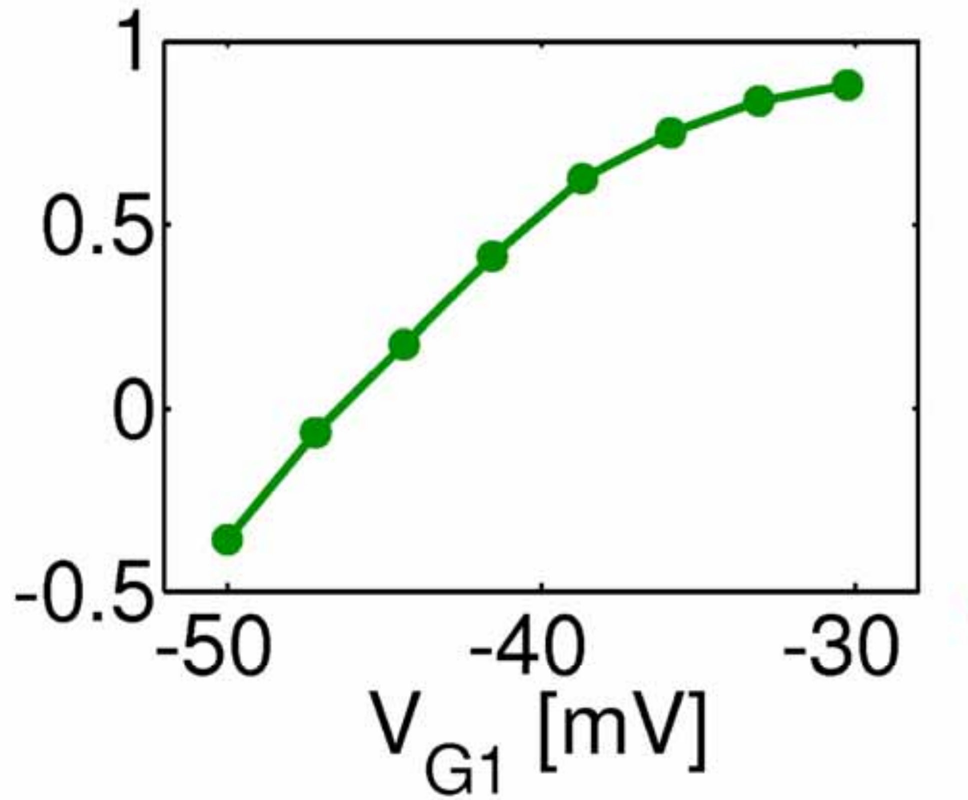




Adjustable asymmetry of the tunneling rates

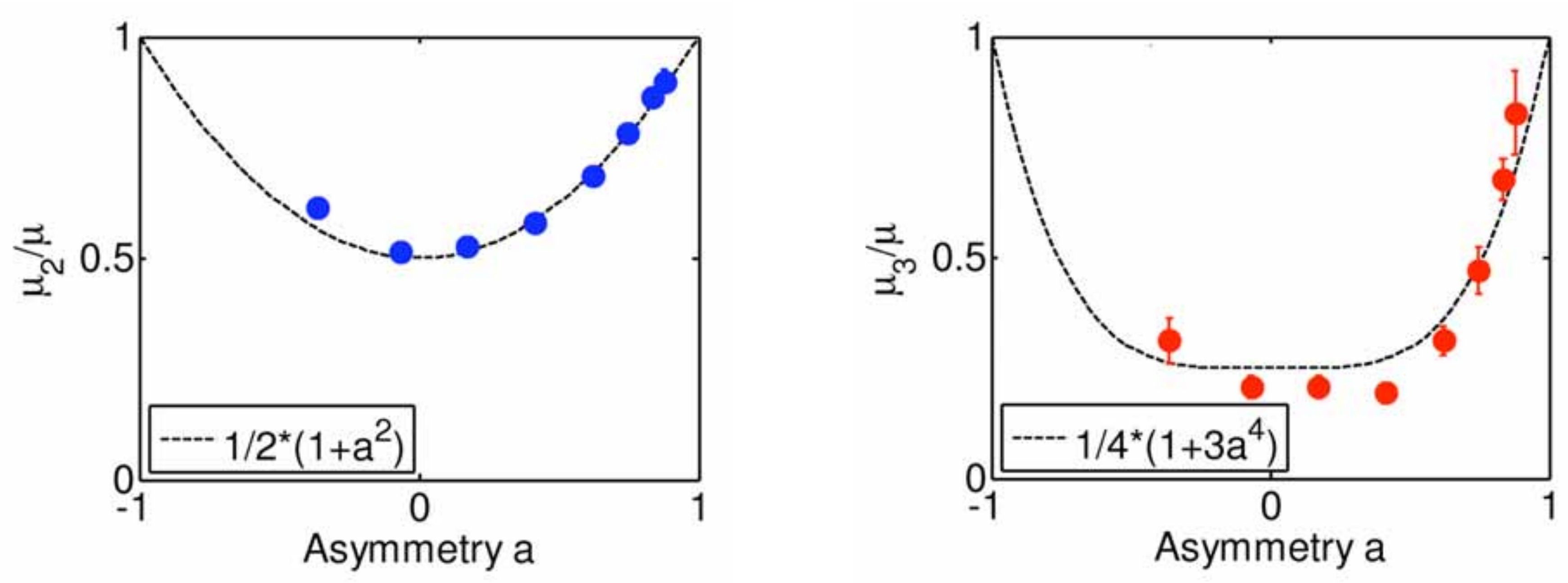


$$a = \frac{\Gamma_S \quad \Gamma_D}{\Gamma_S + \Gamma_D}$$



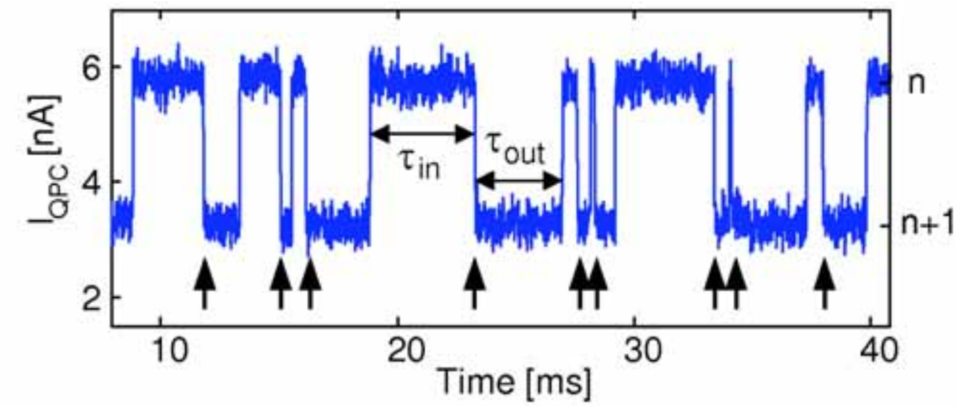
Current fluctuations vs. asymmetry

- Reduction of the second and third moments for symmetric coupling



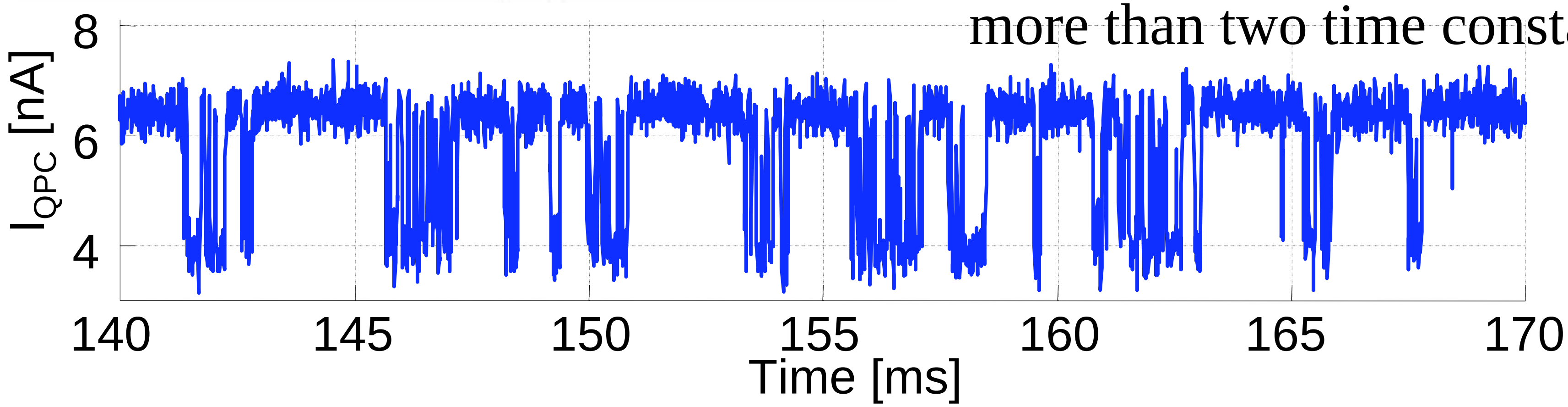
Theory: Hershfield *et al.,* PRB **47,** 1967 (1993)
Bagrets & Nazarov, PRB **67,** 085316 (2003)

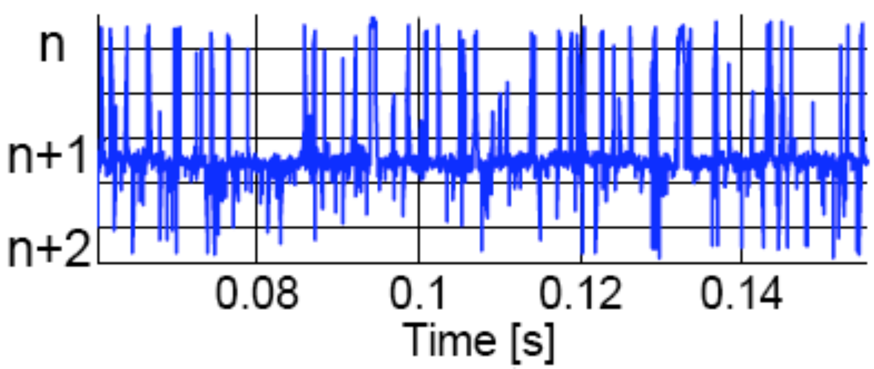
Noisy outlook



<u>Sub</u>poissonian noise
in quantum dots
Higher bandwidth

<u>Super</u>poissonian noise:
more than two time constants?





More than two levels?

Thanks!

Simon Gustavsson

Thomas Ihn

Renaud Leturcq

Roland Schleser

Barbara Simovic