videos are available on the powerpoint version, ask for it: vincent.talbo@gmail.com

Frequency-dependent shot noise in single-electron devices interpreted by means of waiting time distributions

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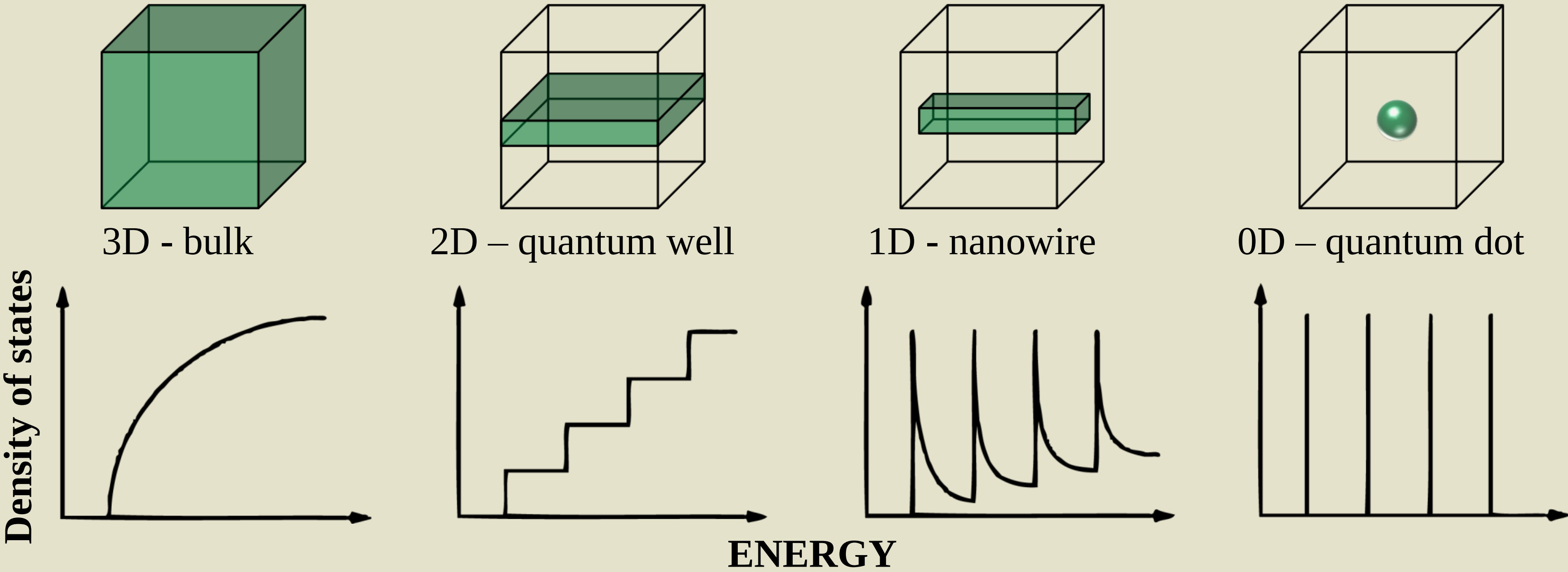
Introduction

COULOMB BLOCKADE AND APPLICATIONS

From micrometric to nanometric



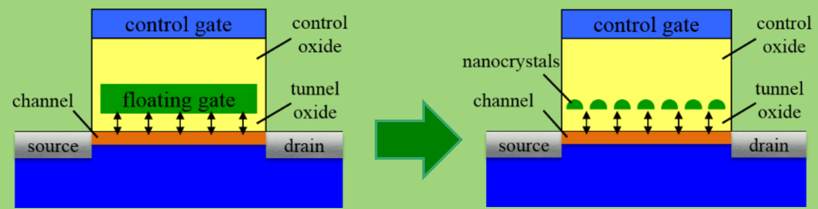
- discretization of energy levels

- gap broadening with reduction of size
  - ➢ blue shift

size of the dot

Applications in electronics

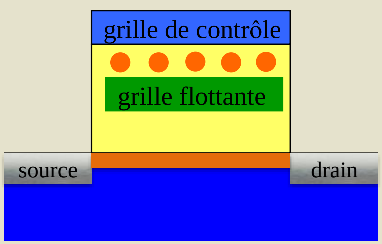
Granular floating gate FLASH memories



- Tiwari, IEDM, 1995
- Freescale

Coulomb Blockade

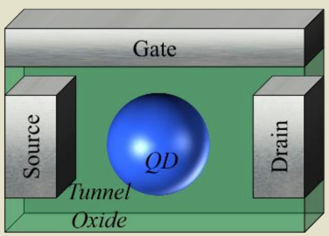
Multiple-tunnel junction FLASH memory

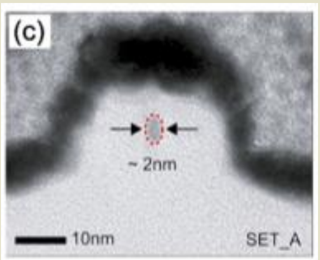


Deleruyelle, *Microelec Eng.*, 2004

- Writing through nanocrystals
- Writing/Reading decoupled

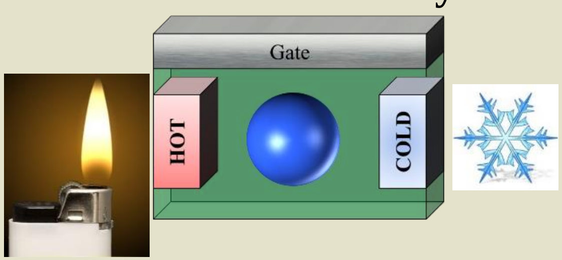
Single-Electron Transistor (SET)



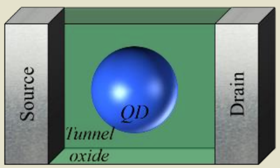


Shin, *APL*, 2010

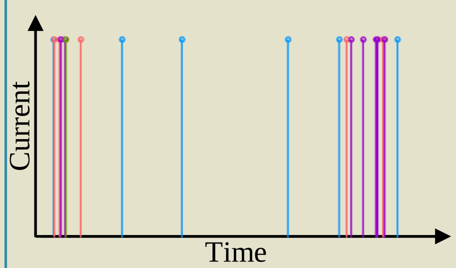
Thermoelectricity



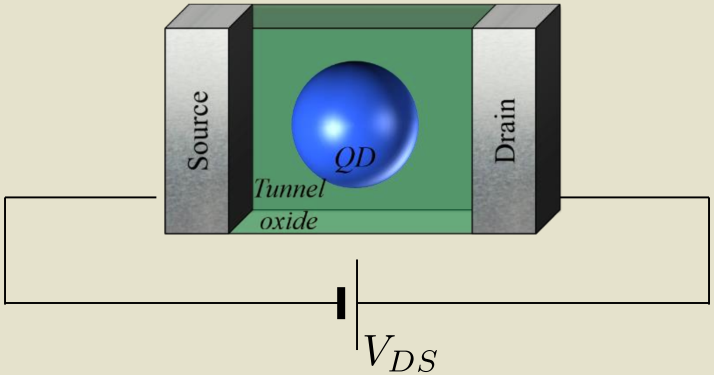
Double-Tunnel junction (DTJ)



Shot Noise in DTJ

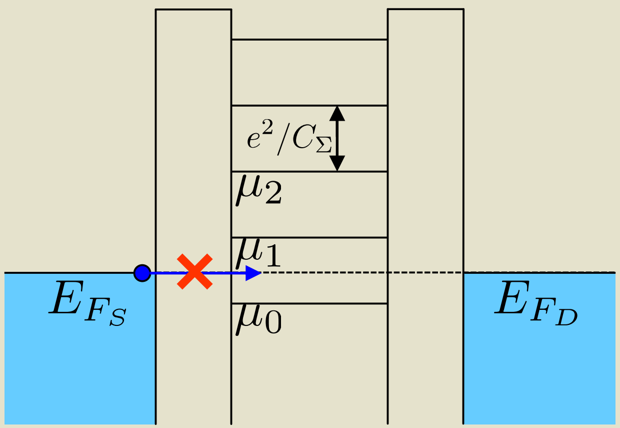


double-tunnel junction: simple case of Coulomb blockade

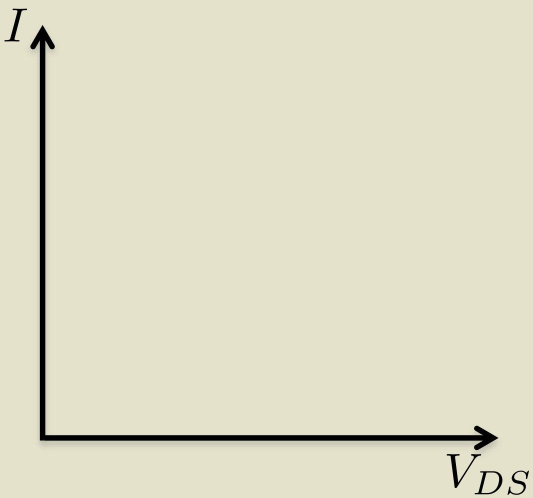


Charging energy: $E_{\text{charge}} = \frac{e^2}{C_\Sigma}$

(energy to bring to add an electron in the dot)

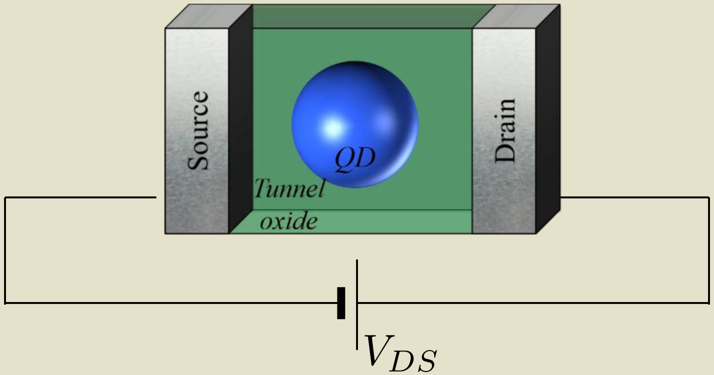


$V_{DS} = 0$



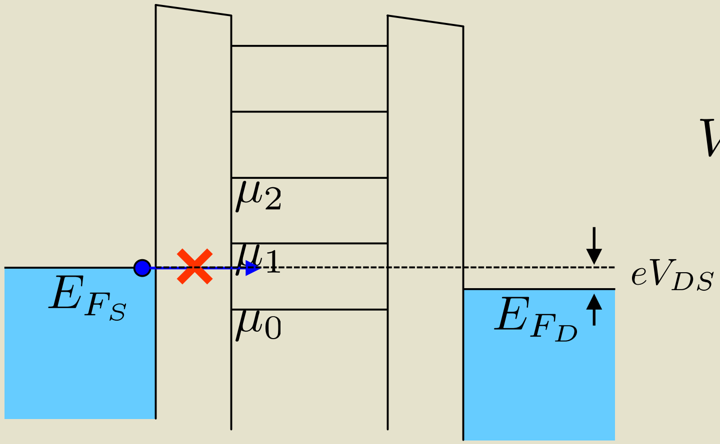
Coulomb blockade

double-tunnel junction: simple case of Coulomb blockade

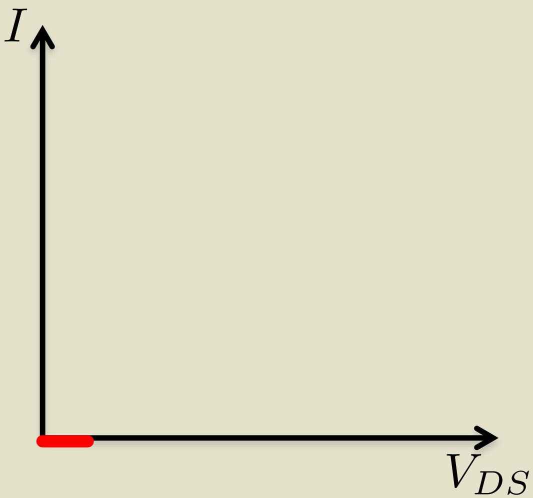


Charging energy: $E_{\text{charge}} = \frac{e^2}{C_\Sigma}$

(energy to bring to add an electron in the dot)



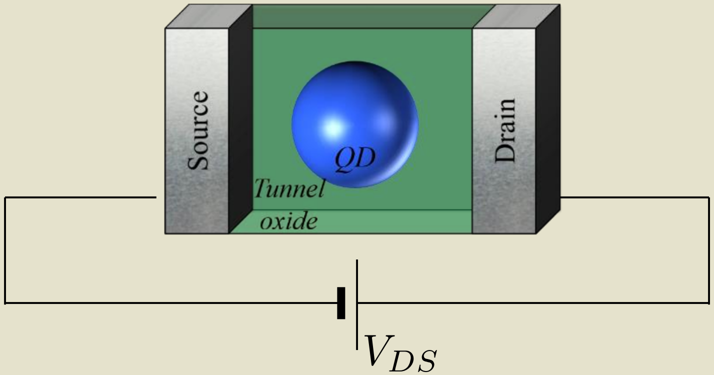
$$V_{DS} < \frac{e}{C_\Sigma}$$



COULOMB BLOCKADE

Coulomb blockade

double-tunnel junction: simple case of Coulomb blockade



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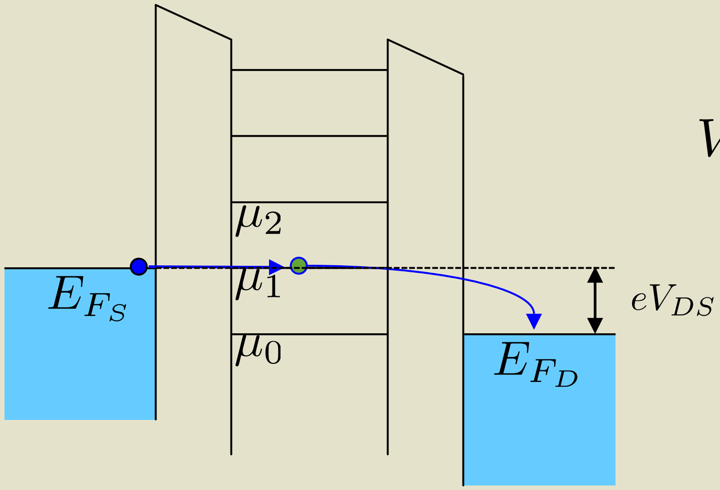
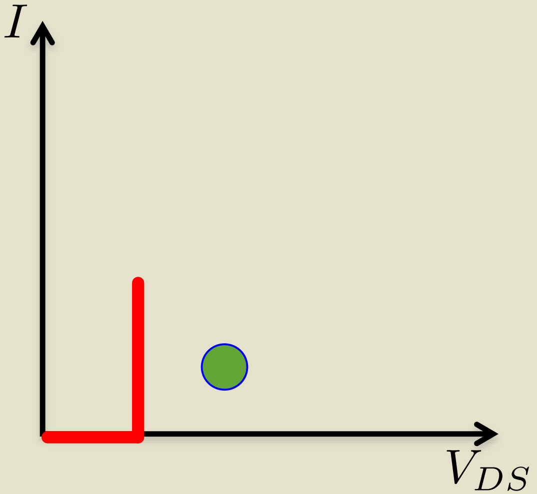
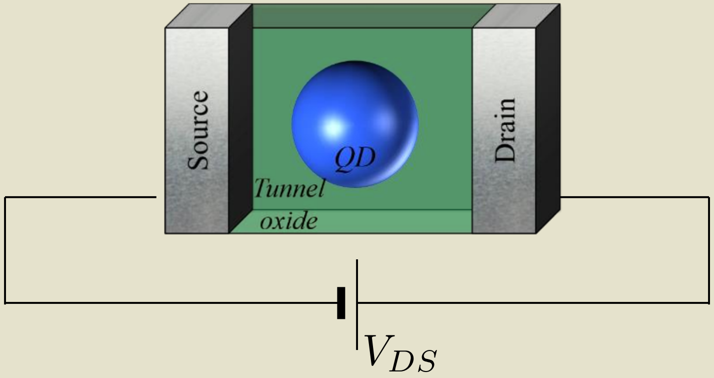


$$V_{DS} = \frac{e}{C_\Sigma}$$

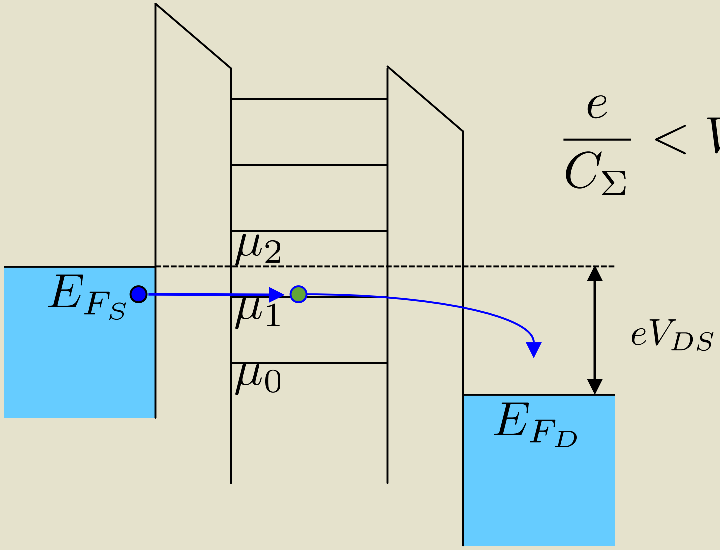


double-tunnel junction: simple case of Coulomb blockade

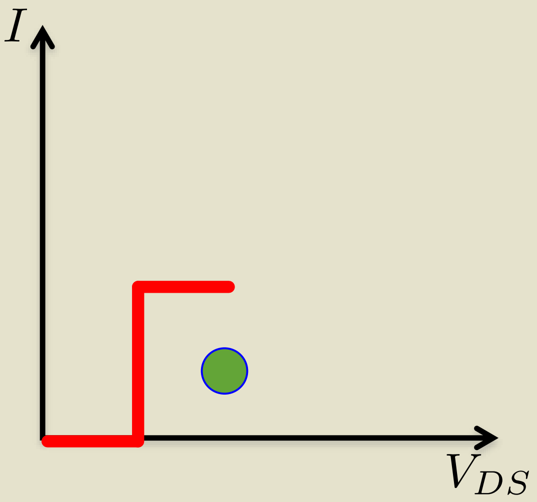


Charging energy: $E_{\text{charge}} = \frac{e^2}{C_\Sigma}$

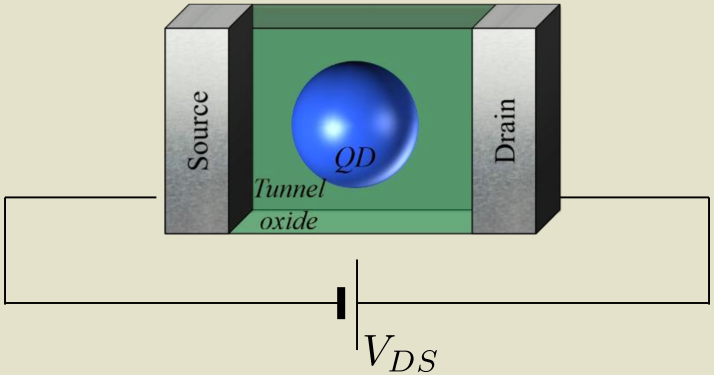
(energy to bring to add an electron in the dot)



$$\frac{e}{C_\Sigma} < V_{DS} < \frac{3e}{C_\Sigma}$$

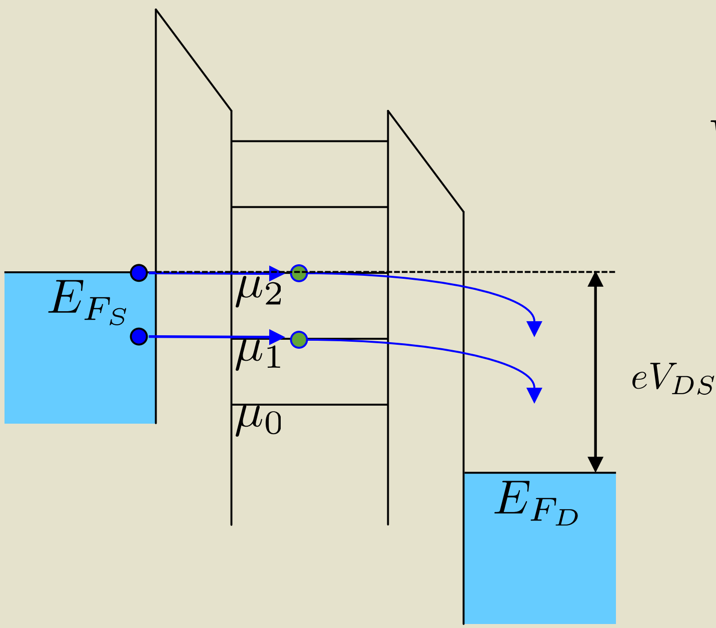


double-tunnel junction: simple case of Coulomb blockade

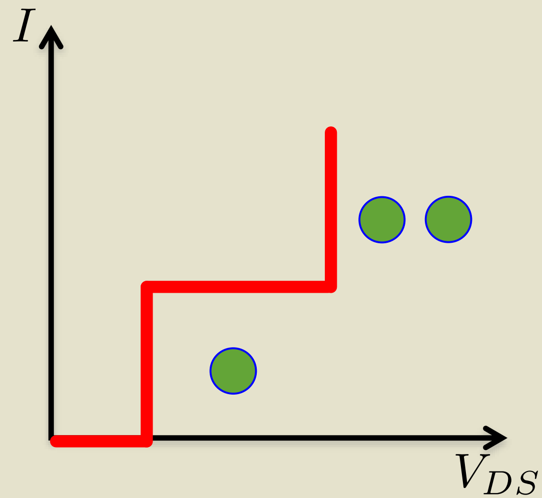


Charging energy: $E_{\text{charge}} = \frac{e^2}{C_\Sigma}$

(energy to bring to add an electron in the dot)

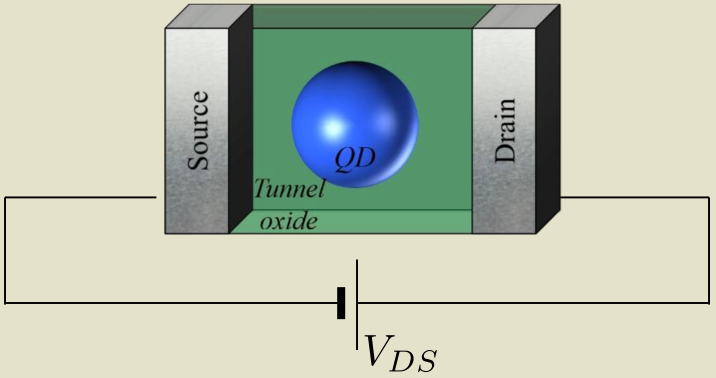


$$V_{DS} = \frac{3e}{C_\Sigma}$$



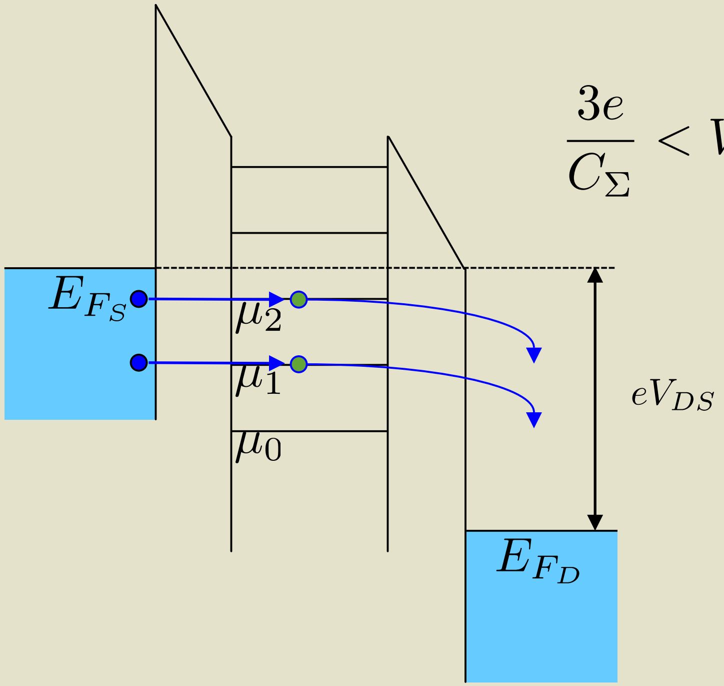
Coulomb blockade

double-tunnel junction: simple case of Coulomb blockade

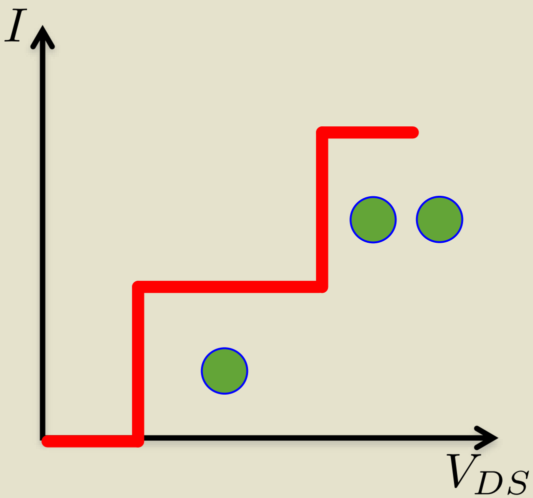


Charging energy: $E_{\text{charge}} = \frac{e^2}{C_\Sigma}$

(energy to bring to add an electron in the dot)

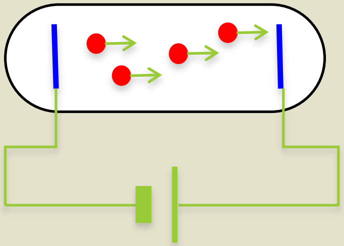


$$\frac{3e}{C_\Sigma} < V_{DS} < \frac{5e}{C_\Sigma}$$



COULOMB STAIRCASE

Shot Noise in double-tunnel junction



- **Shot noise (SN)**: Consequence of charge granularity
  → **more information of the electronic transport**
  Between two electrodes: **Poissonian transport**

- **Comparison with Poissonian transport**

$$S(f)/2e\langle I\rangle$$

$S\,(\,f\,)$ current spectral density at frequency f
$2e$ $<I>$ current spectral density of a Poissonian process

- at $f = 0$, **Fano factor** $F = S(0)/2e\langle I\rangle$
  < 1 : sub-Poissonian noise
  = 1 : Poissonian noise
  > 1 : super-Poissonian noise

➢ **Behaviour at *f* = 0 already well understood**

Sub-Poissonian noise : *Birk et al., Phys. Rev. Lett, 1995*
Super-Poissonian noise in multi-levels QDs: *W. Belzig, Phys. Rev. B, 2005*
Shot Noise in double-tunnel junction: *V. Talbo et al., Fluct. Noise Lett., 2012*

SENS Simulation

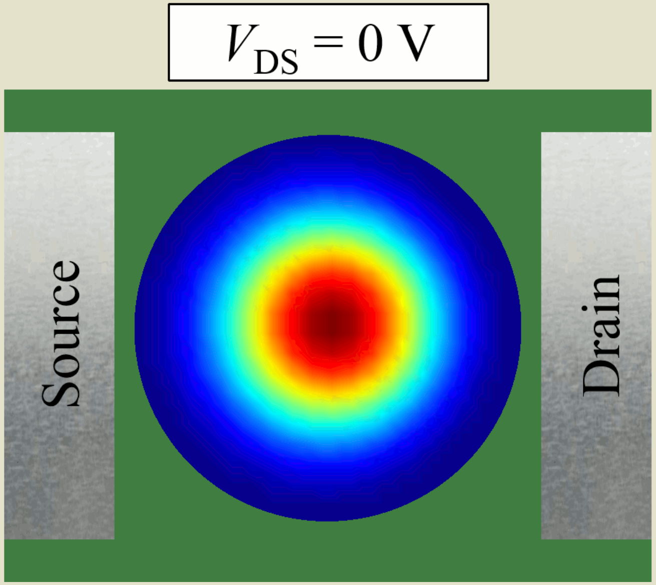
MODEL AND RESULTS

SENS model – Single-Electron Nanodevice Simulation

Electronic structure of Si QDs(wave-function *ψ*, energy *E*)

- 3D solver for Poisson and Schrödinger equations (geometry, bias, number of electrons)
- Hartree method, access to the electronic wave-function

➢ **delocalization of the wavefunction with bias**



double-tunnel junction: *J.Sée et al., IEEE TED, 2006*
double-dot structure: *A. Valentin et al., J. Appl. Phys., 2009*
single-electron transistor: *V. Talbo et al., IEEE TED, 2011*

SENS model – Single-Electron Nanodevice Simulation

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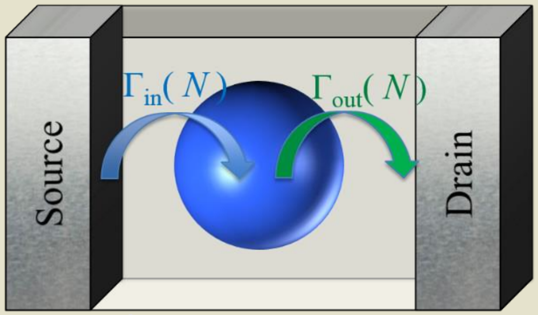
- 3D solver for Poisson and Schrödinger equations (geometry, bias, number of electrons)
- Hartree method, access to the electronic wave-function

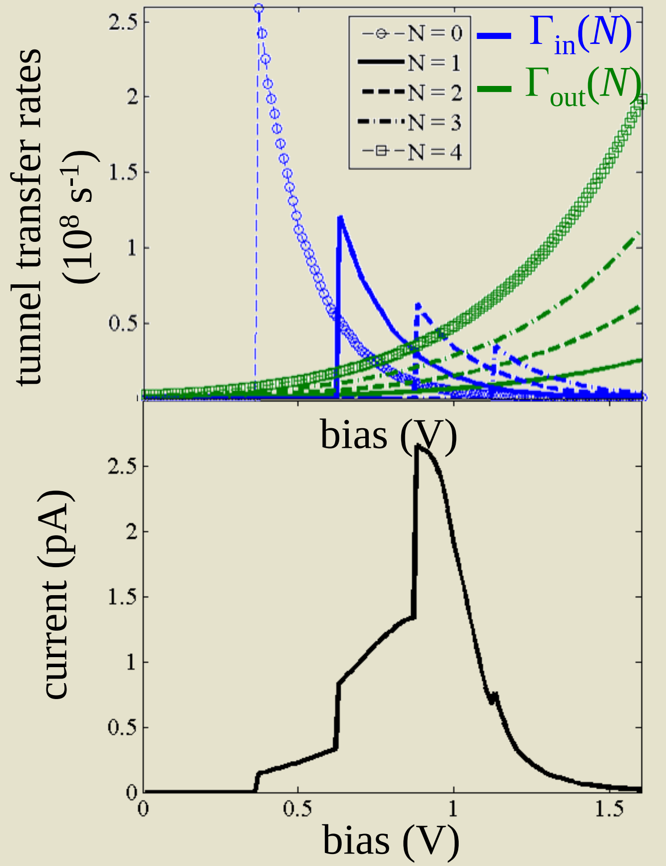
Tunnel transfer rates Γ(*Bias*, *Temperature*) from wave functions

- weak **coupling**
- Fermi golden rule and Bardeen formalism
- ➢ **decrease (increase) of Γ_{in} (Γ_{out}) with as consequence of delocalization of the wavefunction with bias**



Electronic characteristics

- **Monte-Carlo algorithm:** probability to find N electrons in the dot(*P(N)*)
- and / or **master equation**, linked with **Korotkov** formalism for noise
- ➢ **negative differential conductance when $\Gamma_{in}(N) < \Gamma_{out}(N+1)$**



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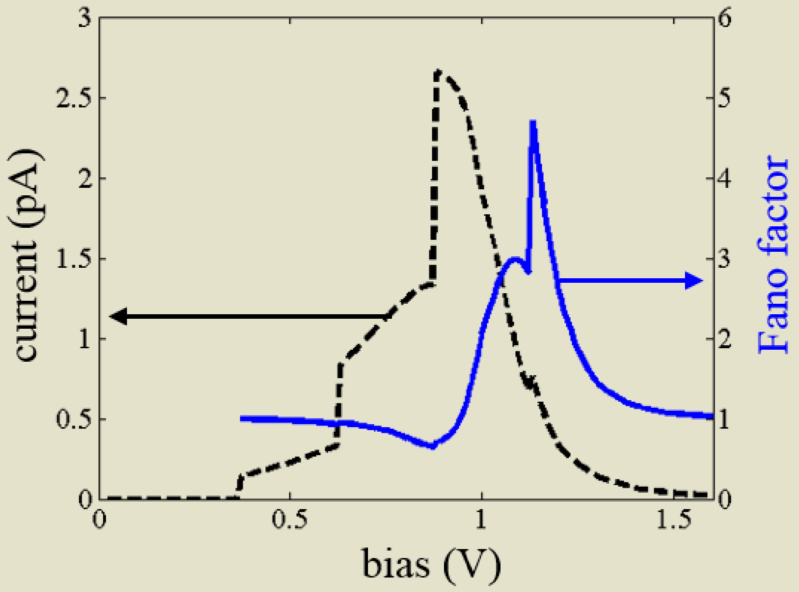
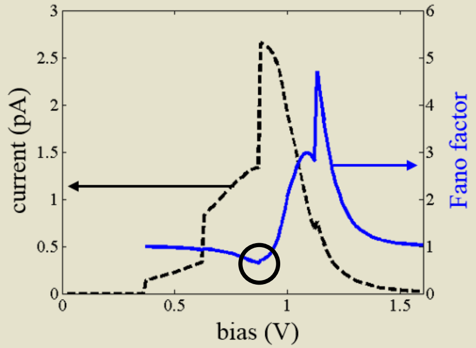
single-electron transistor: *V. Talbo et al., IEEE TED, 2011*

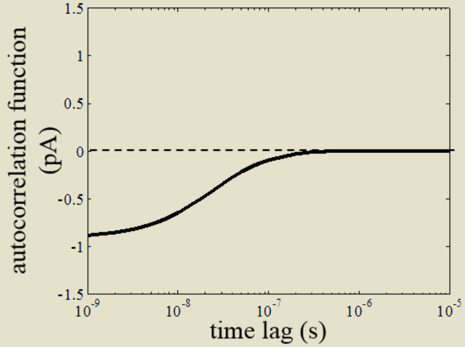
Results

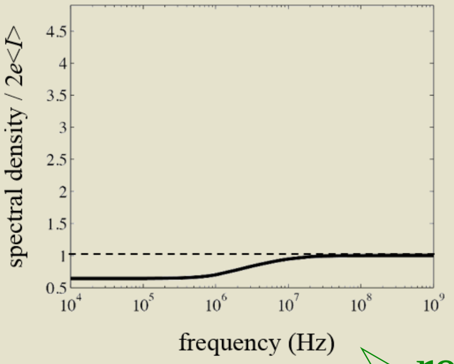
Ø = 10 nm h_S = 1.2 nm h_D = 1.8 nm T = 0 K

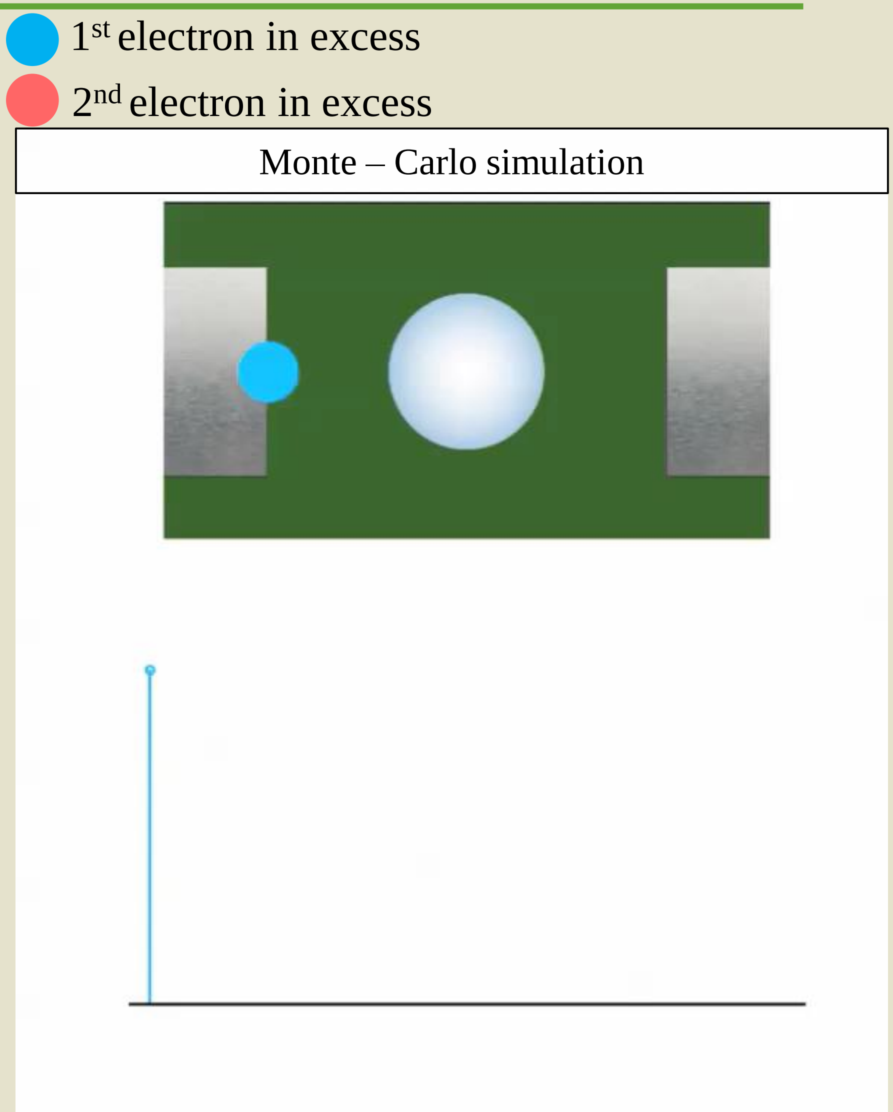


Results – Sub-Poissonian case



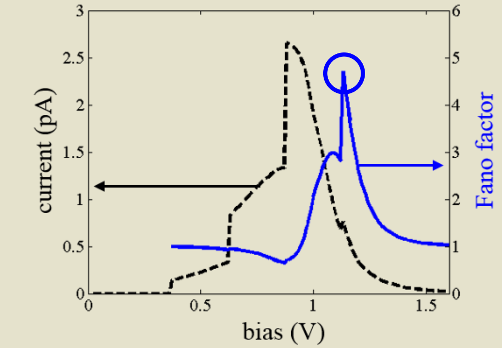


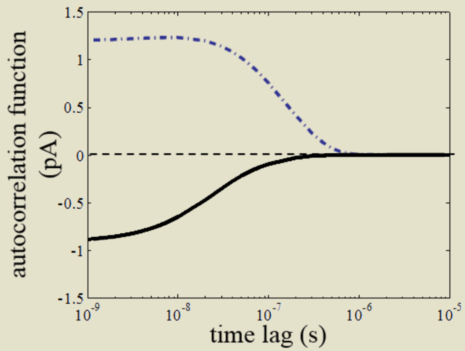


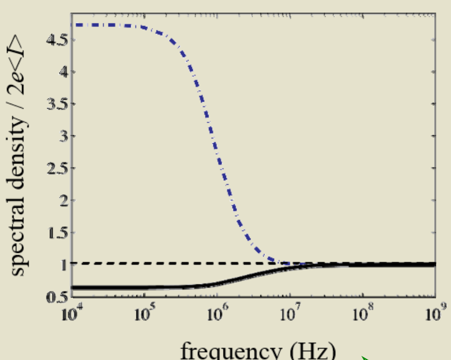


- ➢ remains sub-Poissonian with frequency

Results – Super-Poissonian “bunching”

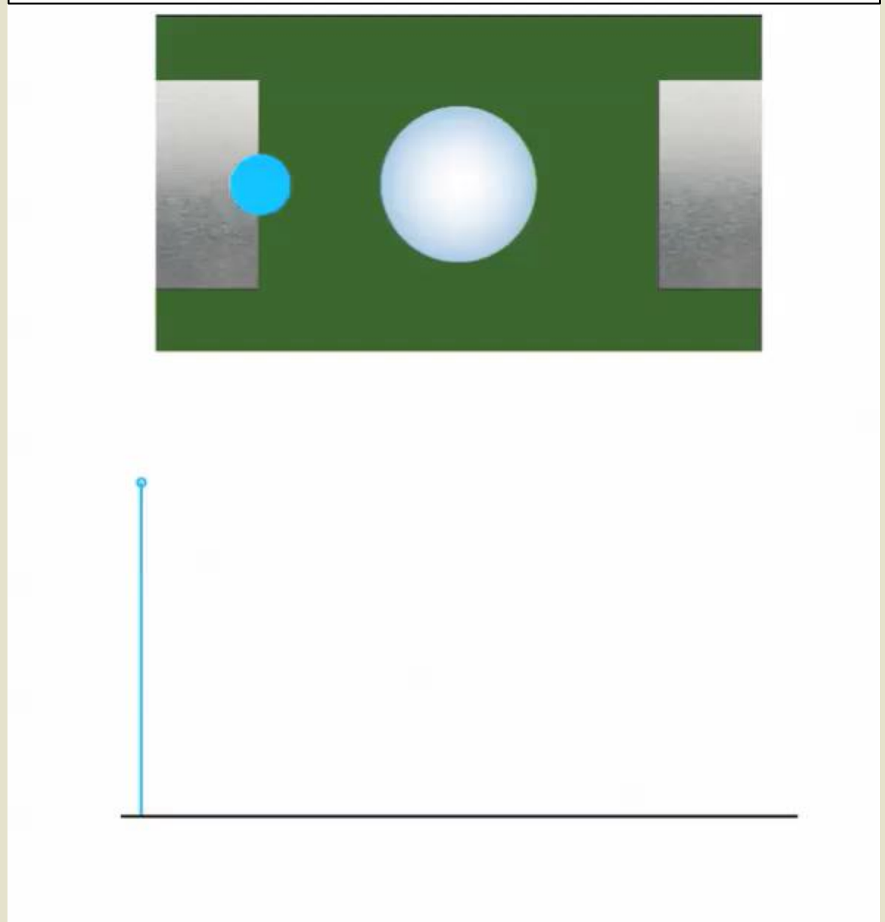






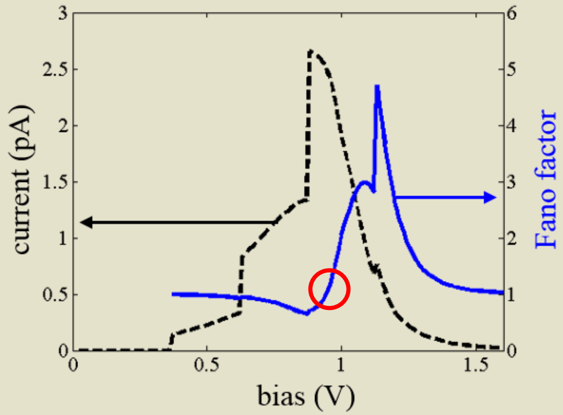
1st electron in excess
2nd electron in excess
3rd electron in excess
4th electron in excess

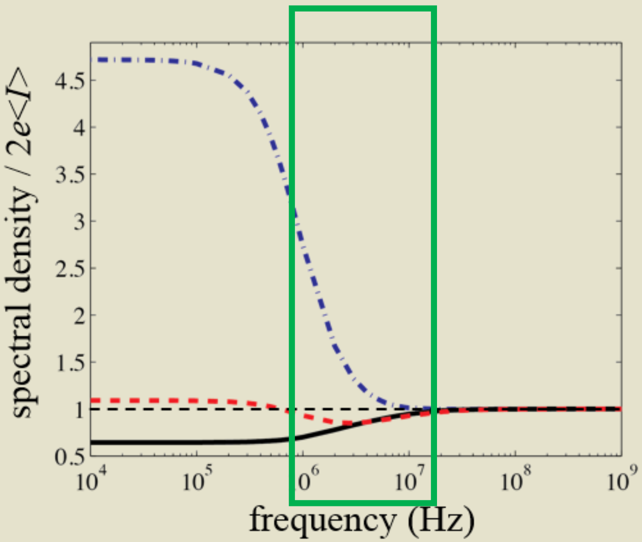
Monte – Carlo simulation

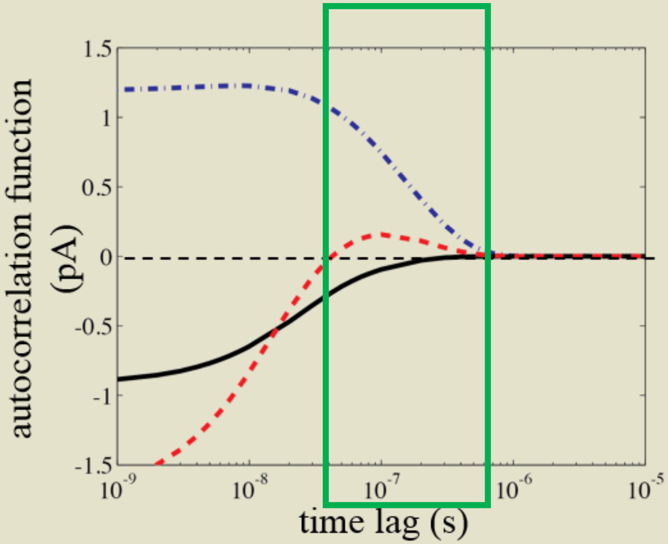


➢ remains super-Poissonian with frequency

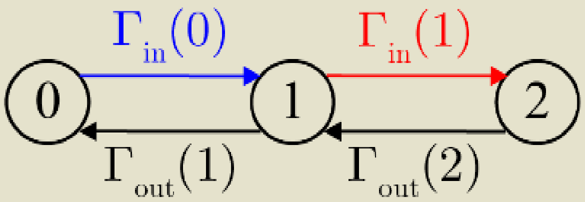
Results – Near-Poissonian (F = 1.01)







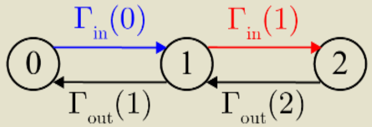
Where this specific dynamics is coming from ?

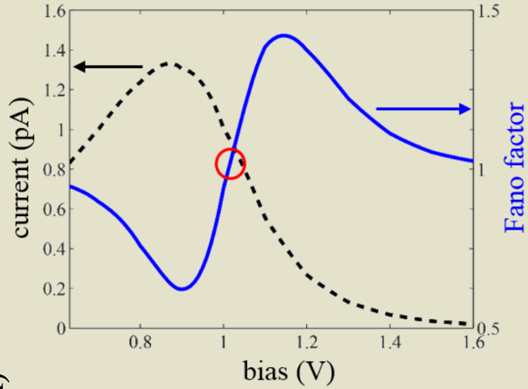


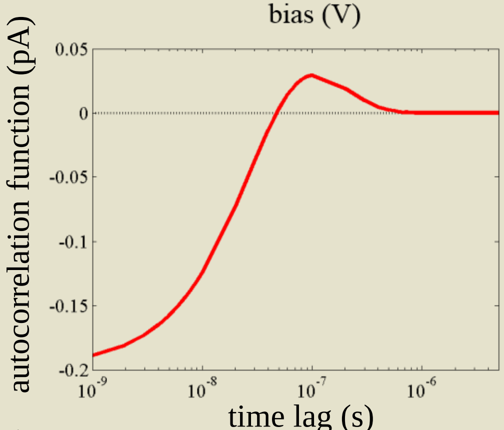
3-state case

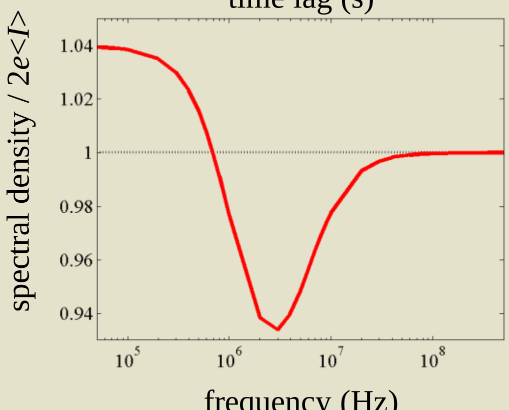
CORRELATIONS AND WAITING TIME DISTRIBUTIONS

Results





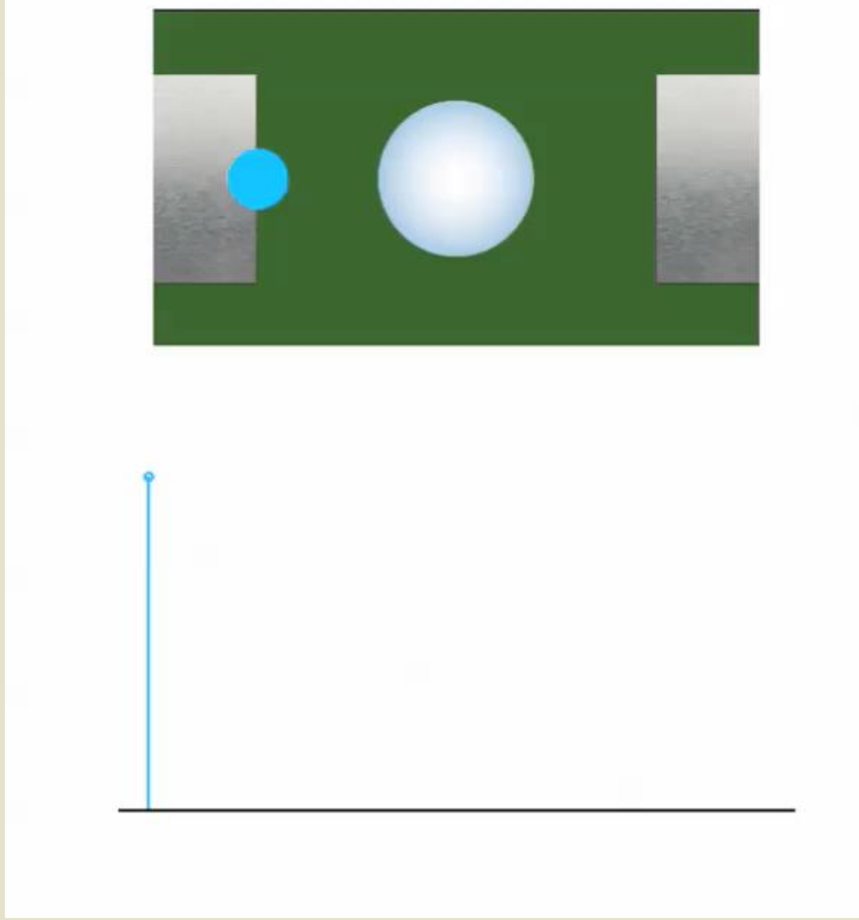




1st electron in excess

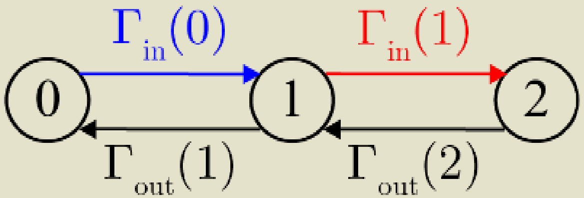
2nd electron in excess

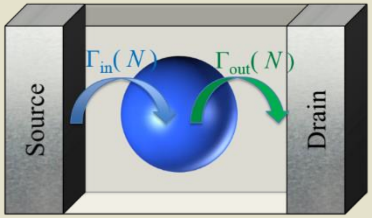
Monte – Carlo simulation

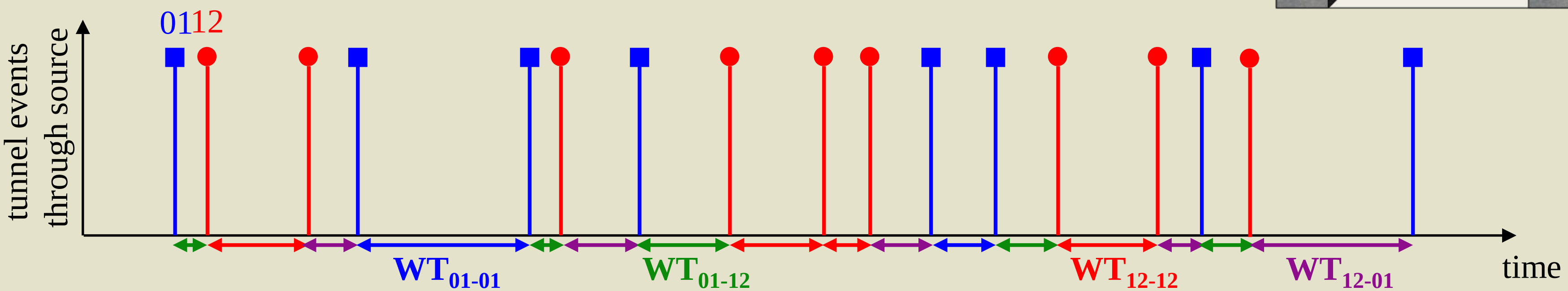


How to understand the behaviour of auto-correlation functions ?

tunnel events through source:
01 and 12







Probabilities of 01 and 12 peaks

partial AUTO-CORRELATIONS

C_{01-01} C_{12-12}

+

partial CROSS-CORRELATIONS

C_{01-12} C_{12-01}

=

total auto-correlation C_{II}

WAITING TIME DISTRIBUTIONS

↔ WT_{01-01}

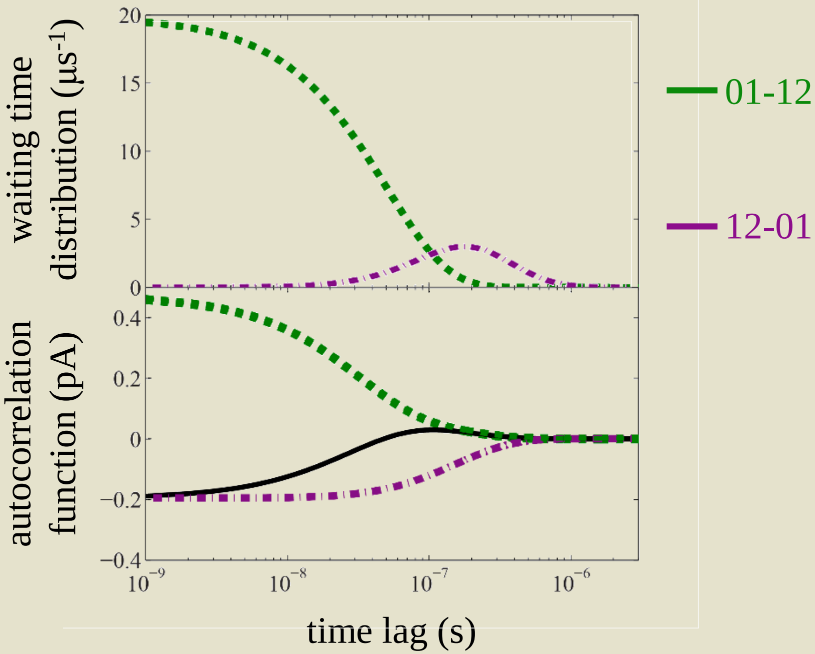
↔ WT_{12-12}

↔ WT_{01-12}

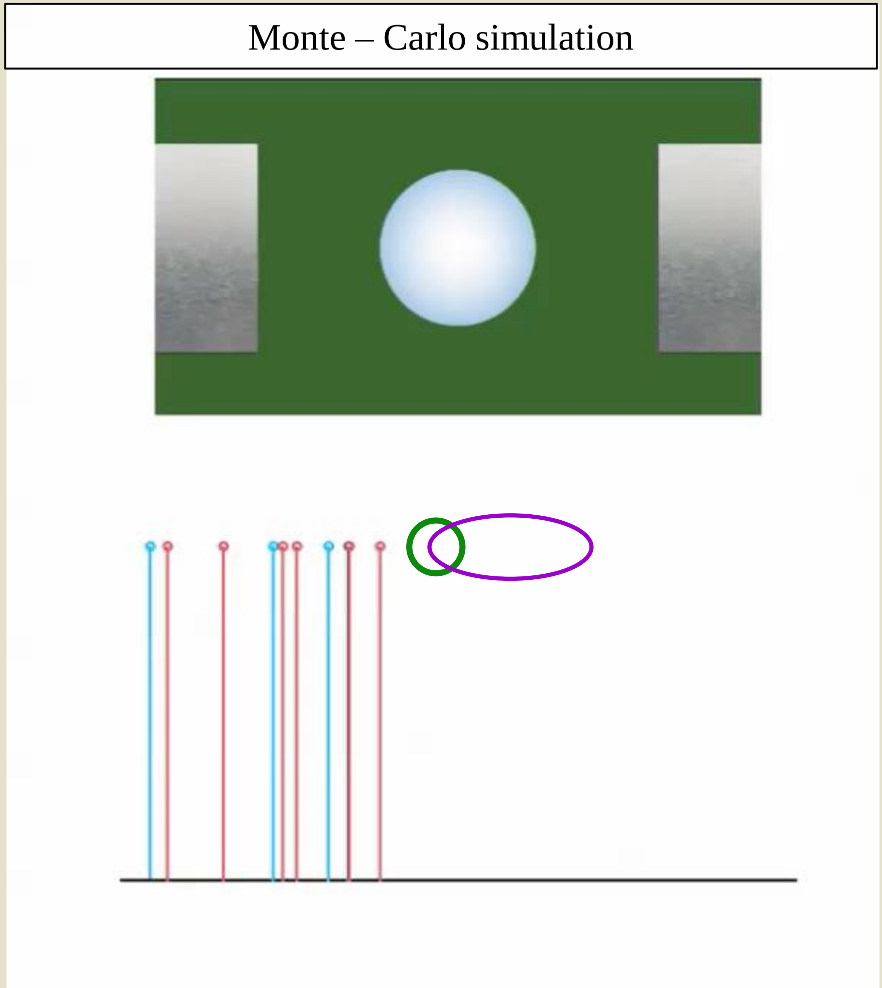
↔ WT_{12-01}

Electron Waiting Times in Mesoscopic Conductors
M. Albert, G. Haack, C. Flindt, and M. Büttiker
Phys. Rev. Lett. 2012

Cross-correlations $C_{01\text{-}12}$ and $C_{12\text{-}01}$



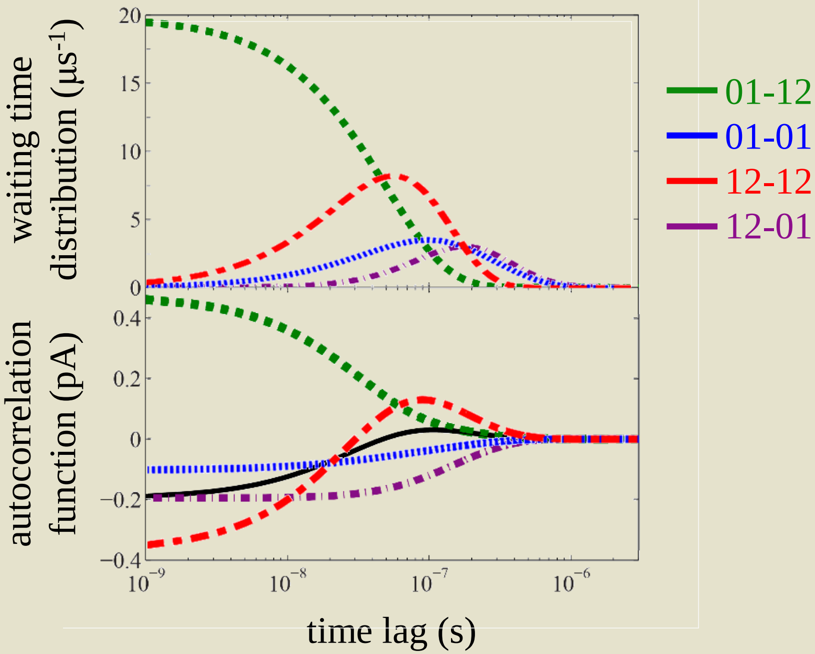
$\text{Prob}_{01\text{-}12}$ = $\text{Prob}_{12\text{-}01}$ = 23 %



- No tunnel event between consecutive 01 and 12
  - Poissonian WTD (maximum at 0)
  - High correlation $C_{01\text{-}12}$ at low times

- 2 tunnel events (drain side) between 12 and 01
  - WTD = 0 at short times
  - Negative correlation $C_{12\text{-}01}$

Auto-correlations $C_{12\text{-}12}$ and $C_{01\text{-}01}$



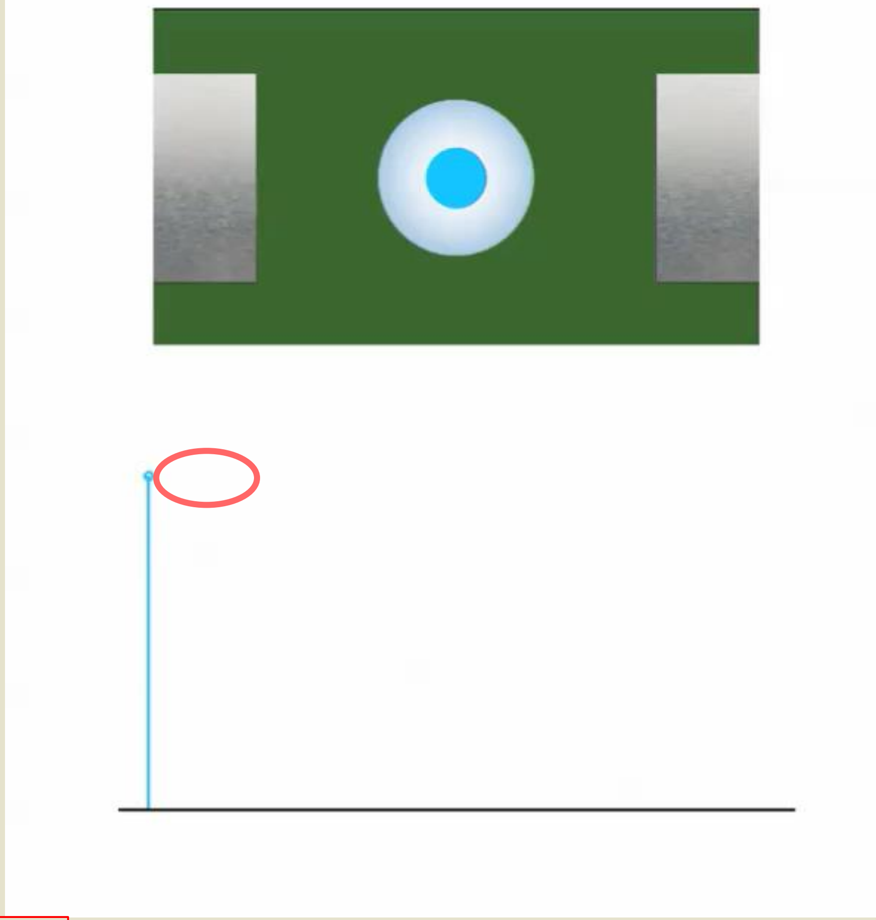
- one tunnel event between consecutive peaks
  - WTD = 0 at short times, increases after
  - negative correlation at low times, increasing later

- $P_{12\text{-}12}$ is not high enough for $C_{12\text{-}12}$ to remain negative when WTD increases

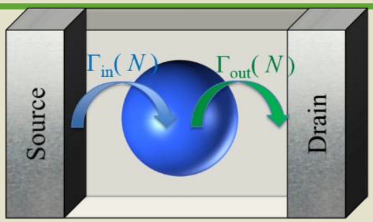
→ **ORIGIN OF SPECIFIC DYNAMICS**

$Prob_{12\text{-}12}$ = 43 % , **$Prob_{01\text{-}01}$ = 12 %**

Monte – Carlo simulation



Conclusion



The time-dependent physics of electronic transport in double-tunnel junction

✓Obtained from SENS simulator: tunnel transfer rates

✓Understood through the study of the link between:

auto- and cross-correlations, probabilities and waiting time distributions

High-majority of a given tunnel event: negative correlation

➢Equality of tunnel events: positive correlation

➢"in between": specific dynamics, going from negative to positive correlation

Thank you !