Fermi Statistics in Ballistic Conductors

in the light of quantum information

SACLAY

PARIS

Quantum information $\rightarrow$ new way to study quantum systems

single particle interference (probed with current) $\rightarrow$ wave nature

variance of particle flux (quantum shot noise) $\rightarrow$ particle nature

interference with few particles:

(noise correlation, coincidence measurements)

$\rightarrow$ probe entanglement, non-locality problems, ...

Quantum information $\rightarrow$ invent new experimental tools :

to control initial sate of few particles

to record the final state (statistical /single shot readout)

$\rightarrow$ here: review some progresses and approaches using ballistic electrons

Goal of this talk :

show how Fermi statistics provides a ***natural*** mean
to implement quantum correlations
between ballistic electrons

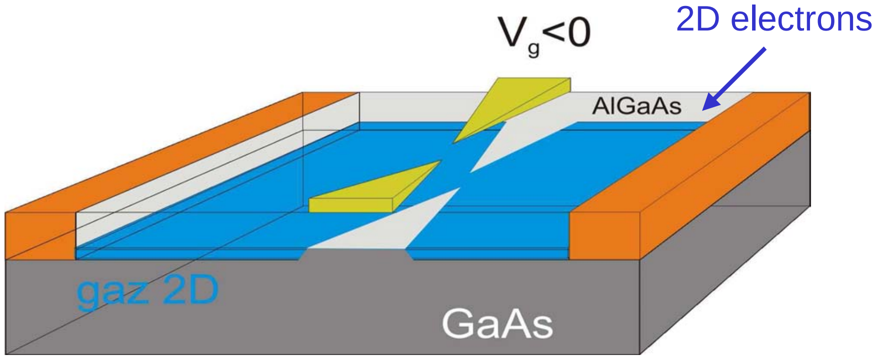
present experimental approaches able to explore new quantum problems

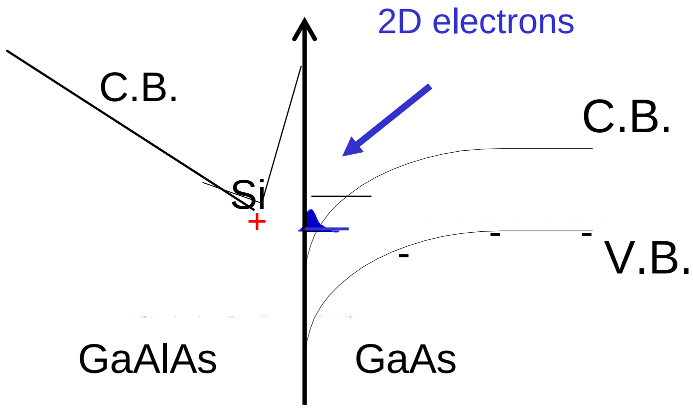
single electron source (running experiment)

few electron sources (starting project) for Full counting statistics

single electron detection (project)

ballistic electron systems in 2D





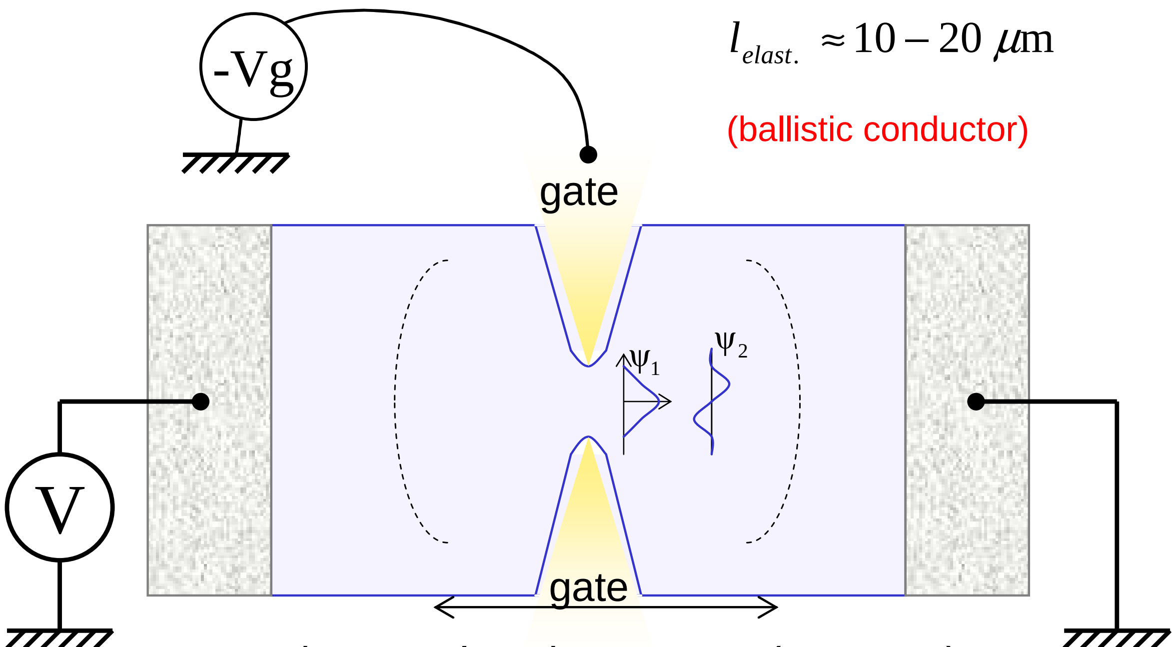
III-V semi-conductor heterojunction GaAs/GaAlAs

quantum Point Contact

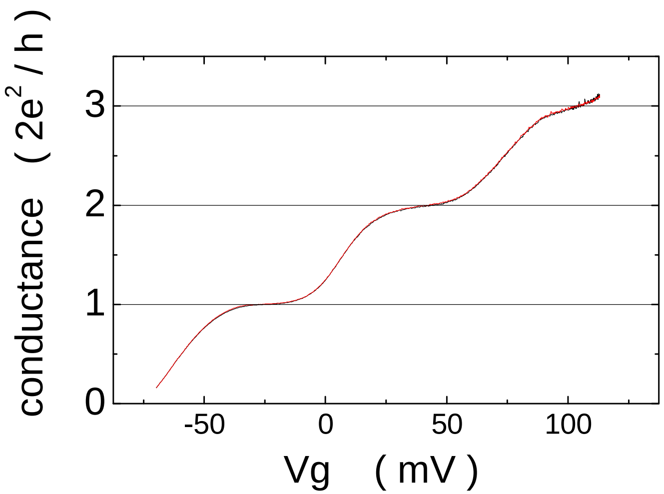
$$\lambda_F \approx 70 \text{ nm}$$

$$l_{elast.} \approx 10 - 20\ \mu\text{m}$$

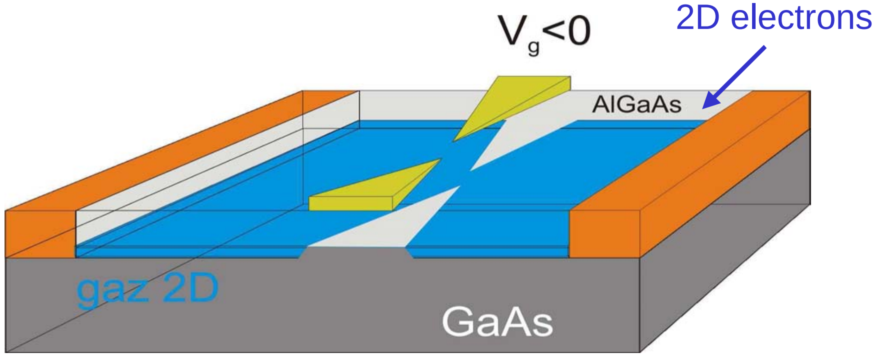
(ballistic conductor)



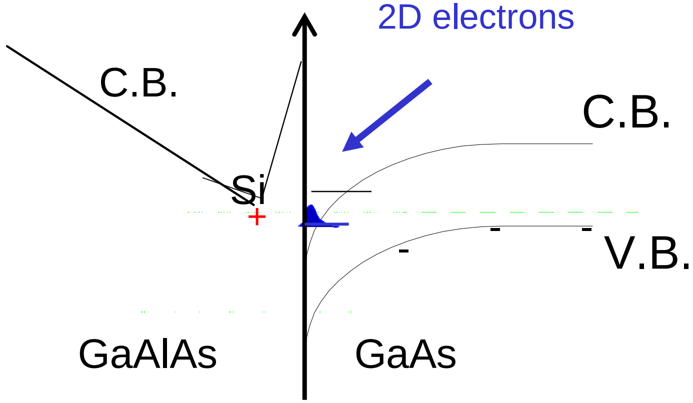
coherence length : >10 µm (T <<1K)



ballistic electron systems in 2D



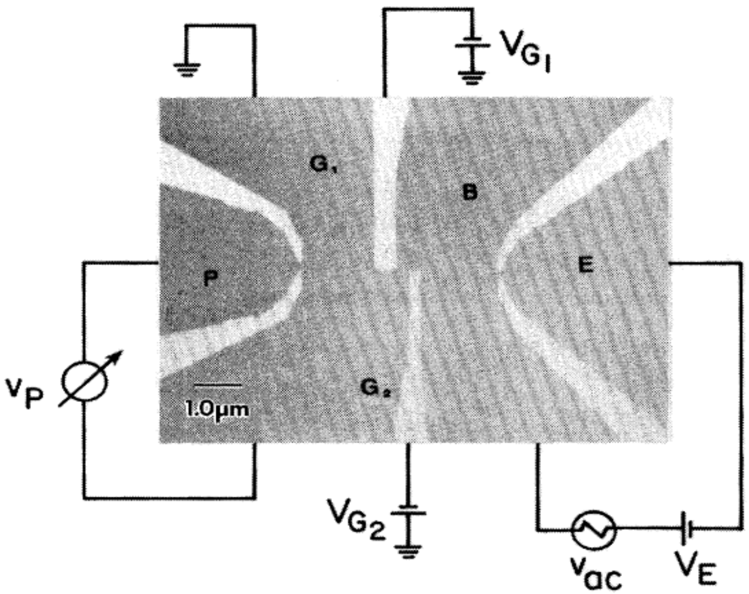
III-V semi-conductor heterojunction GaAs/GaAlAs

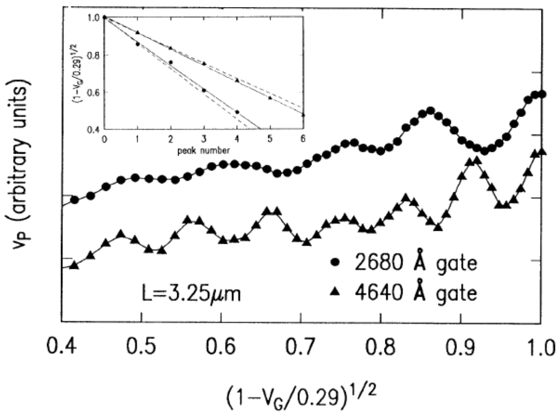


quantum optics with electron waves

electron interferences

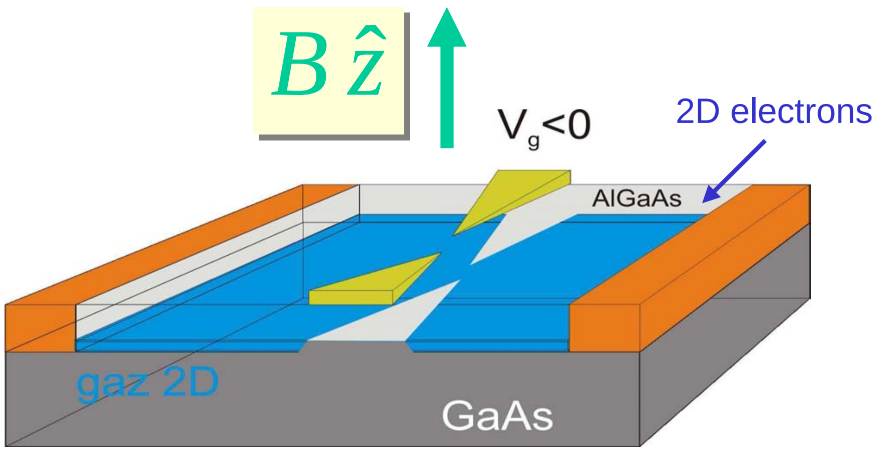
(in 2D)



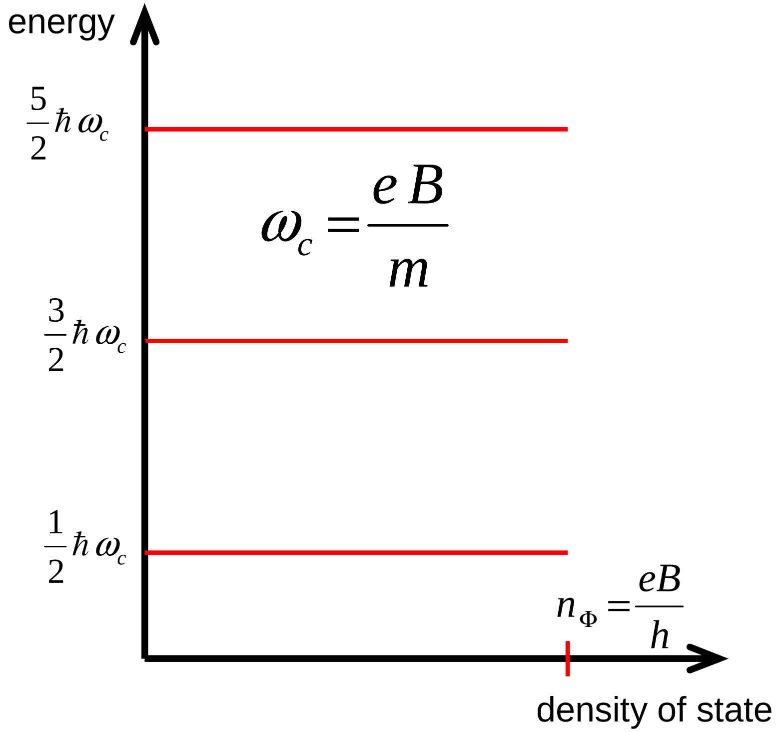


A. Yacoby et al. Phys. Rev. Lett. 66, 1938 (1991)

ballistic electrons: from 2D to 1D :



III-V semi-conductor heterojunction GaAs/GaAlAs

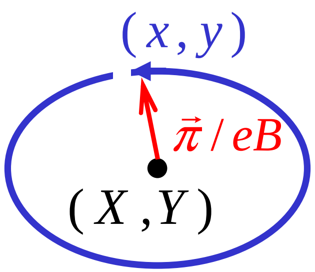


$$\boxed{H=\frac{1}{2m}\left(\vec{p}+e\vec{A}\right)^2=\frac{\vec{\pi}^2}{2m}}$$

$$\left[\pi_x,\pi_y\right]=-i\hbar eB \longrightarrow \boxed{E_n=\hbar\omega_c\left(n+\frac{1}{2}\right)}$$

$$X=x-\frac{\pi_y}{eB}$$

$$Y=y+\frac{\pi_x}{eB}$$

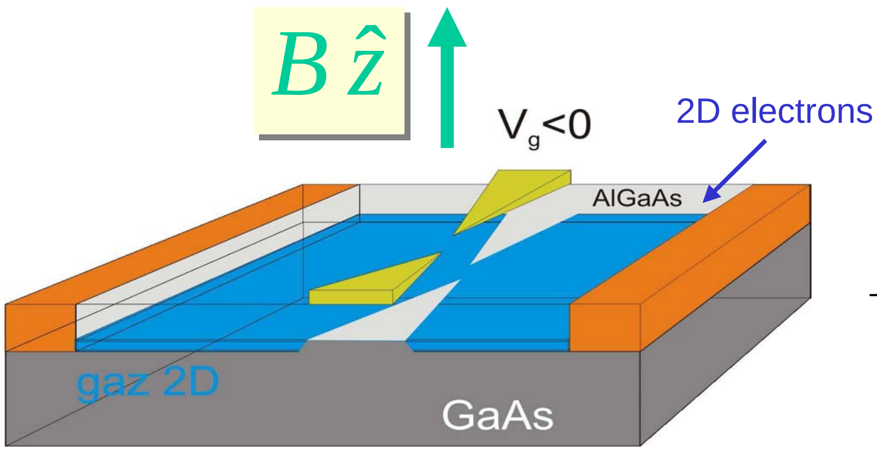


cyclotron motion

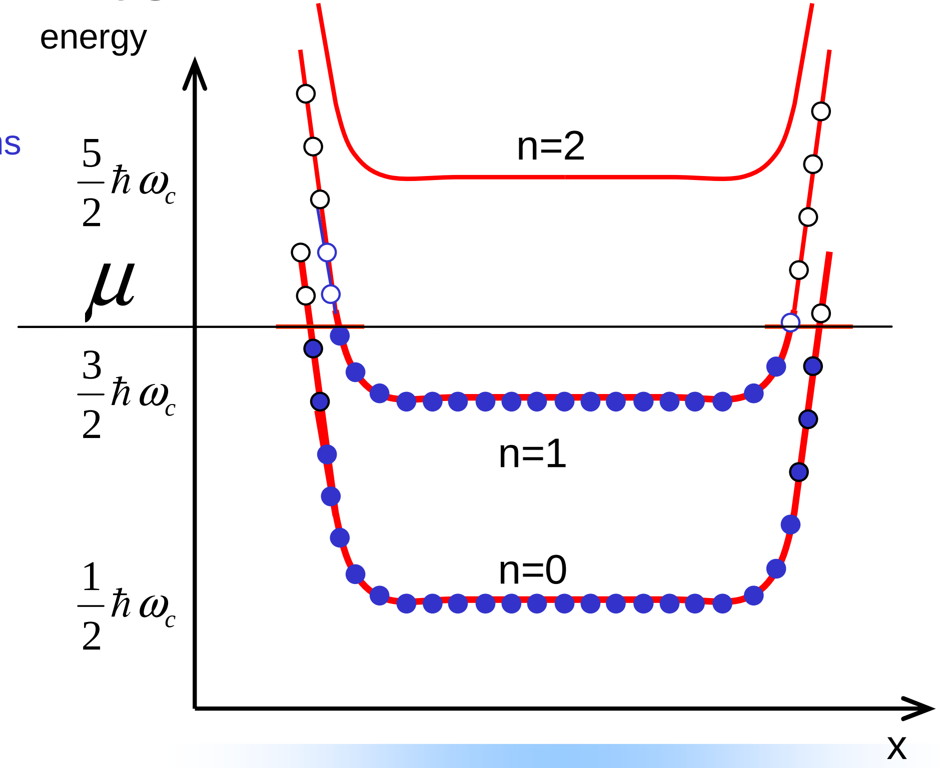
$$\left[X,Y\right]=-i\frac{\hbar}{eB} \longrightarrow B\,\Delta X.\Delta Y=\frac{h}{e}$$

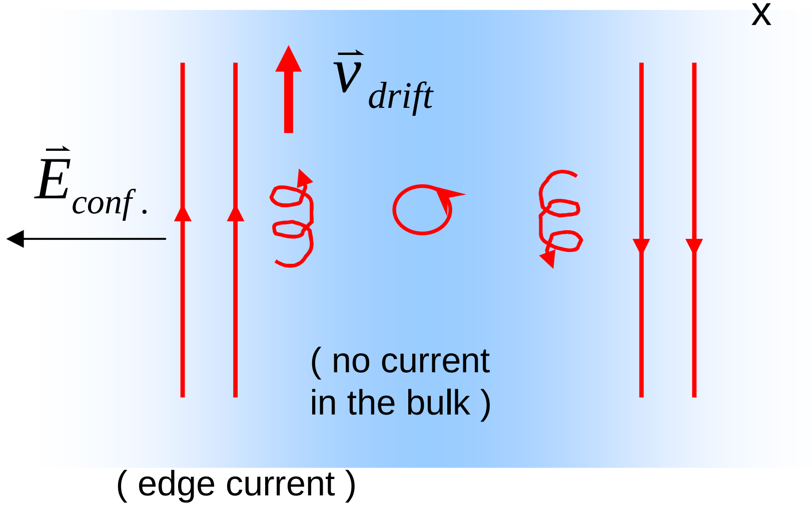
cyclotron motion is frozen → 1D dynamics

ballistic electrons: from 2D to 1D :



III-V semi-conductor heterojunction GaAs/GaAlAs





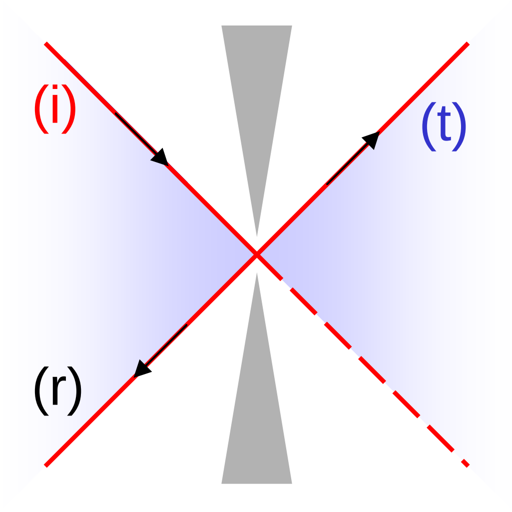
$$\boxed{\vec{v}_{drift} = \frac{\vec{E}_{conf.}}{B} \times \hat{z}}$$

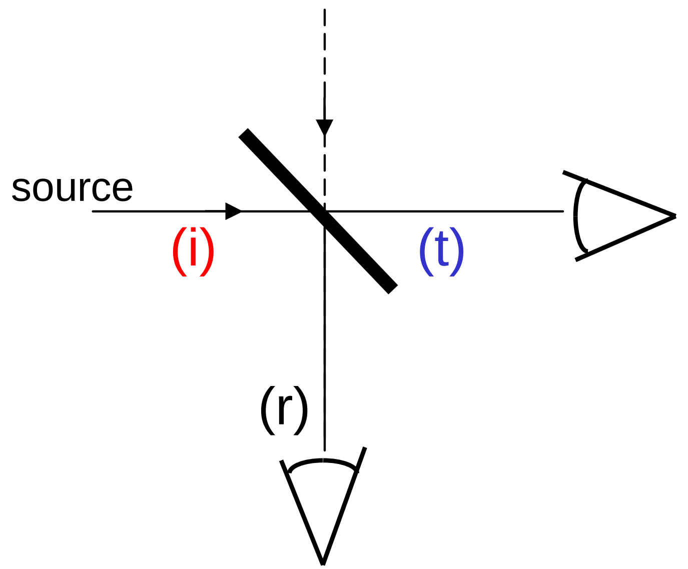
cyclotron motion drift → chiral 1D dynamics

1D chiral ballistic electrons:

elementary quantum gates are realizable:

• beam splitter
• fabry-Pérot interferometer
• Mach-Zehnder interferometer

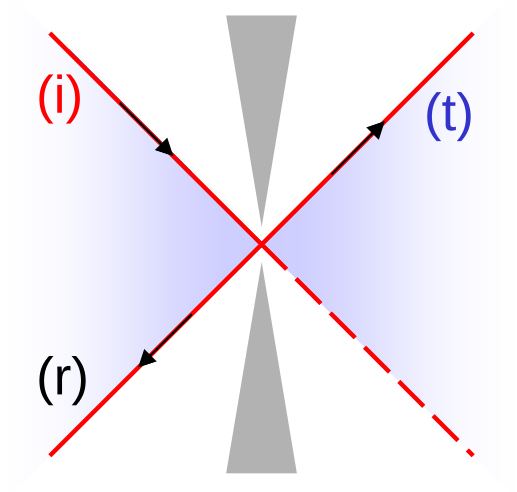


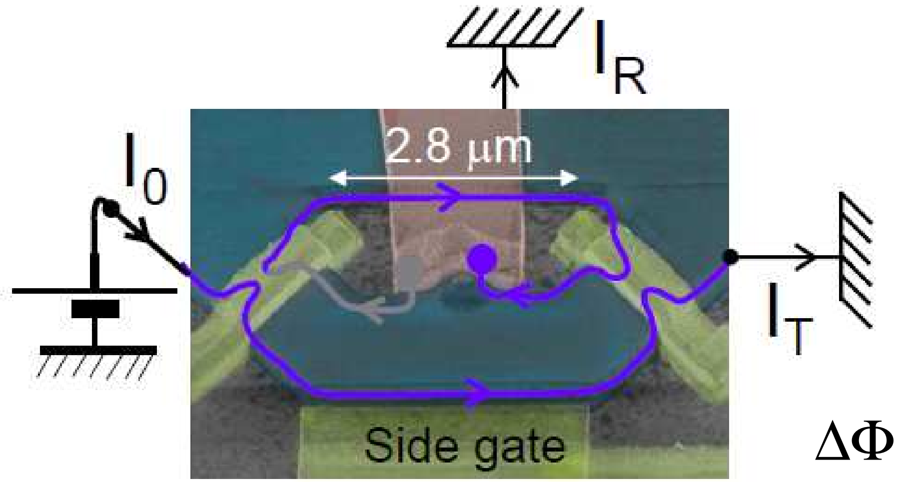


1D chiral ballistic electrons:

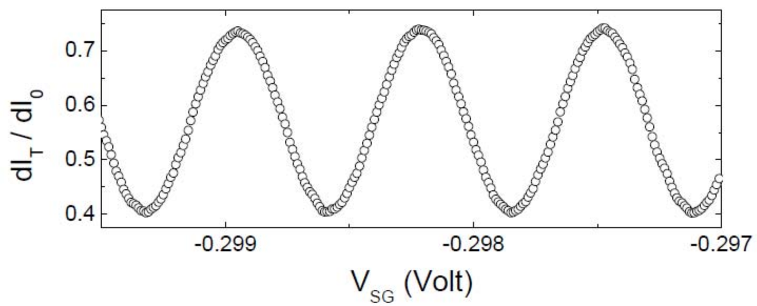
elementary quantum gates are realizable:

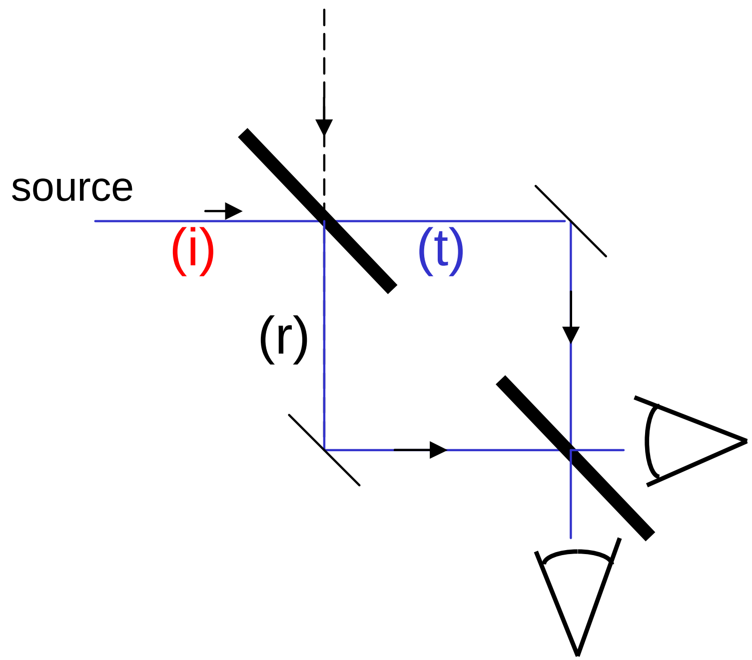
- beam splitter
- fabry-Pérot interferometer
- Mach-Zehnder interferometer (Ji et al. (Nature 2003))





$$\Delta\Phi \approx l_1 - l_2$$



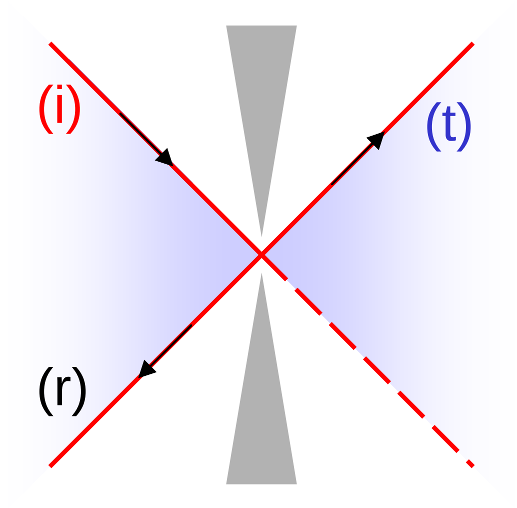


(adapted from: P. Roche, P. Roulleau,F. Portier G. Faini D. Mailly)

1D chiral ballistic electrons:

elementary quantum gates are realizable:

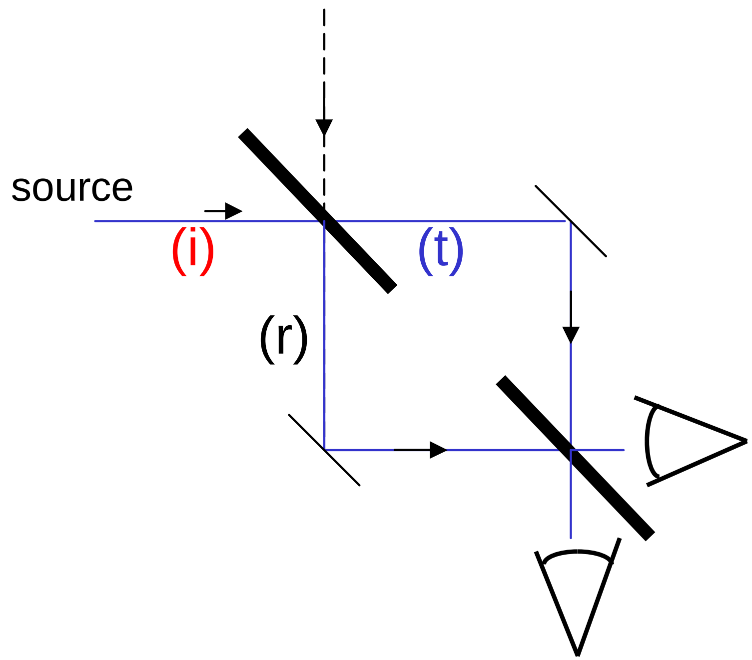
- beam splitter
- fabry-Pérot interferometer
- Mach-Zehnder interferometer



finite coherence requires very low temperature :

``Direct Measurement of the Coherence Length of Edge States in the Integer Quantum Hall Regime ''

P. Roulleau, F. Portier, and P. Roche, A. Cavanna, G. Faini, U. Gennser, and D. Mailly
PRL 100, 126802 (2008)



$$\boxed{l_\Phi \approx \frac{22\,\mu m}{T_{[20\,mK]}}}$$

(P. Roche's talk last year)

… and also : F. Pierre's talk :

(energy relaxation of edge states)

OUTLINE

Magic properties of the Fermi sea

On-demand single electron source for flying qubits **(running experiment)**

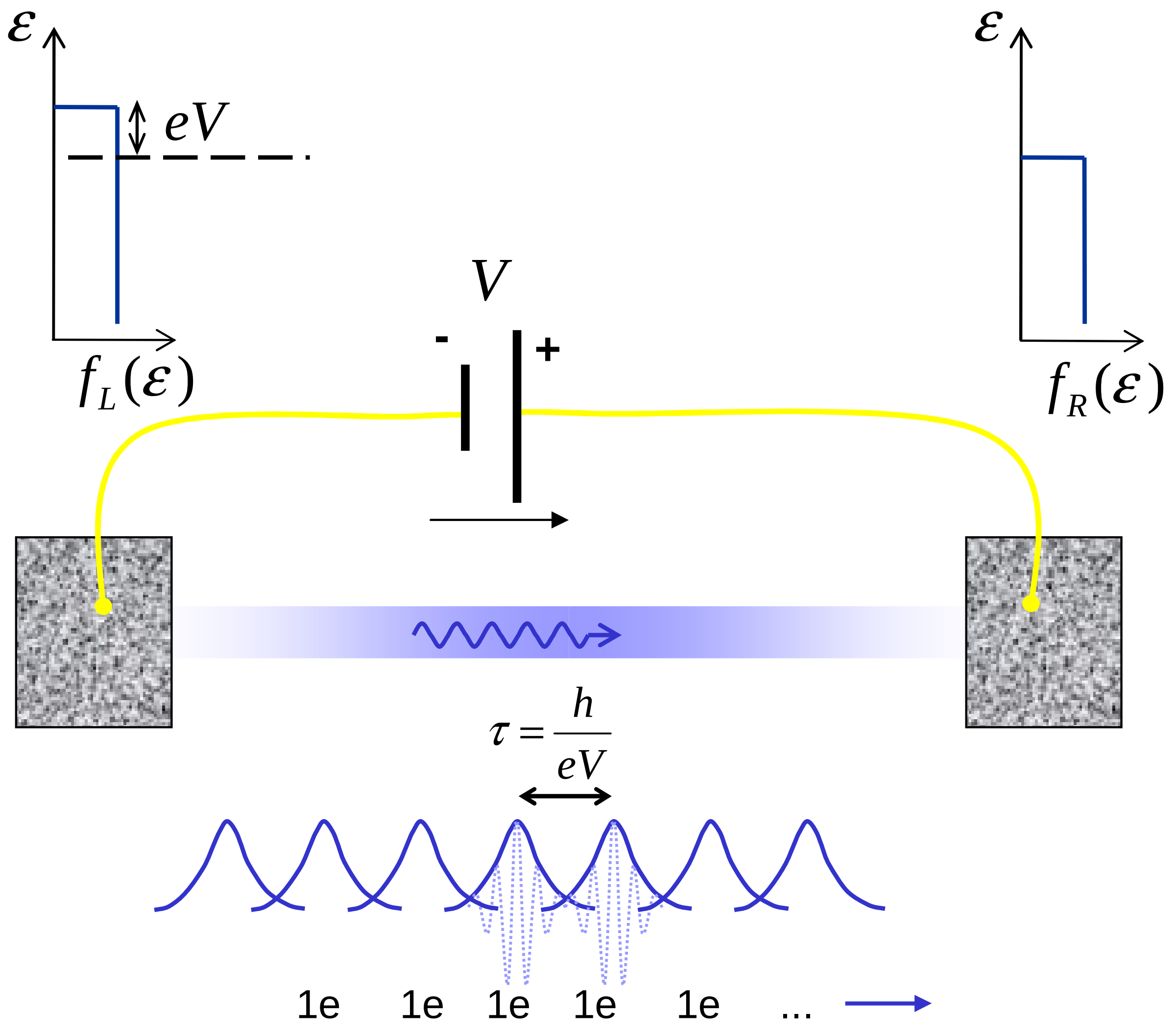
N-electron source for Full Counting Statistics **(new project)**

Counting charges for FCS or quantum information **(new project)**

Conclusion

quantized conductance of a perfect conductor

exemple: single mode (1D)



$$\boxed{G = \frac{e^2}{h}}$$

$$\boxed{R = \frac{h}{e^2}}$$

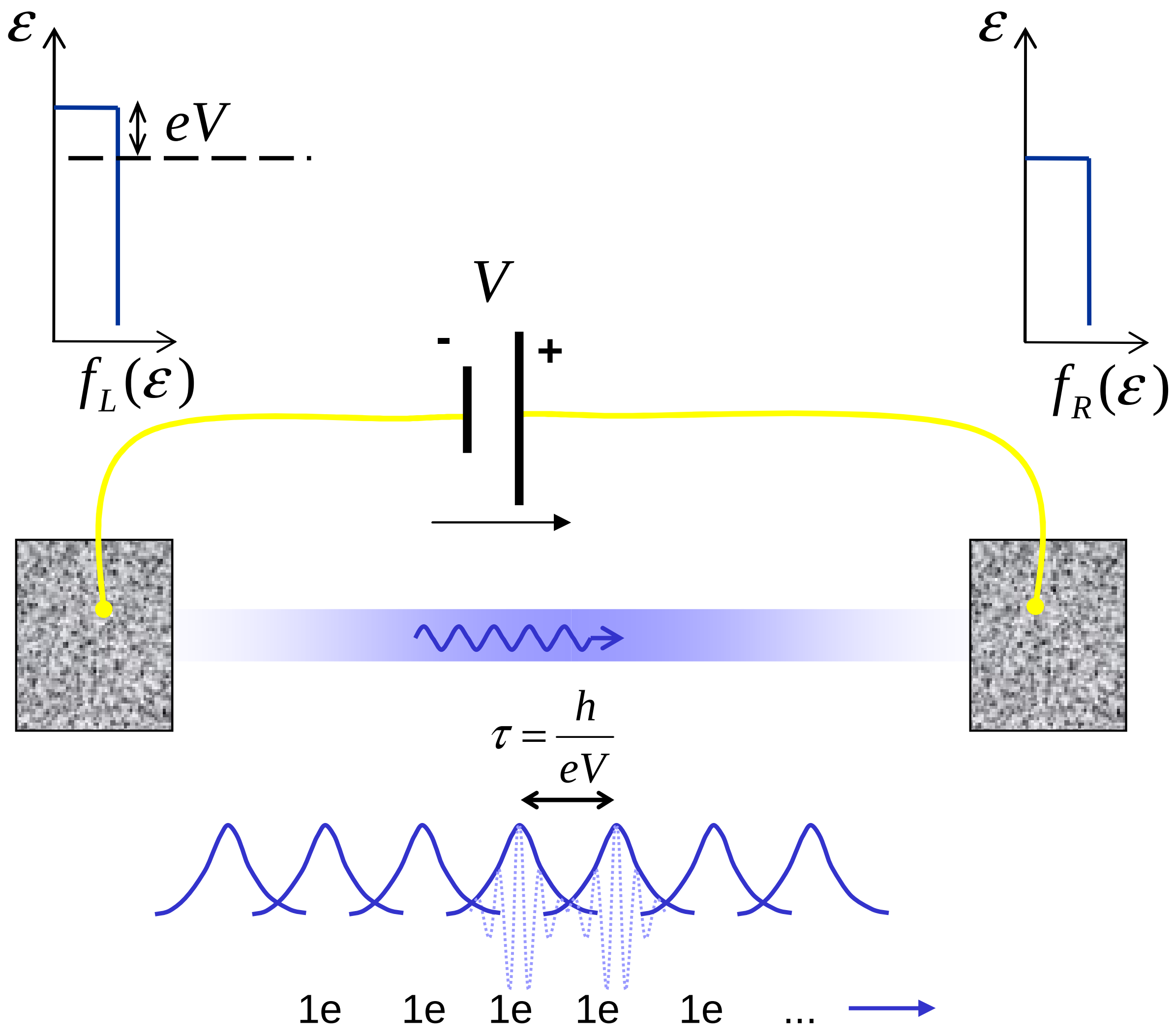
~ 25.8 k Ω

$$I = e.\frac{eV}{h}$$

Pauli

Heisenberg: $eV \,.\, \tau \sim h$

quantized conductance of a perfect conductor



exemple: single mode (1D)

$$G = \frac{e^2}{h}$$

$$R = \frac{h}{e^2}$$ ~ 25.8 k Ω

$$I = e.\frac{eV}{h}$$

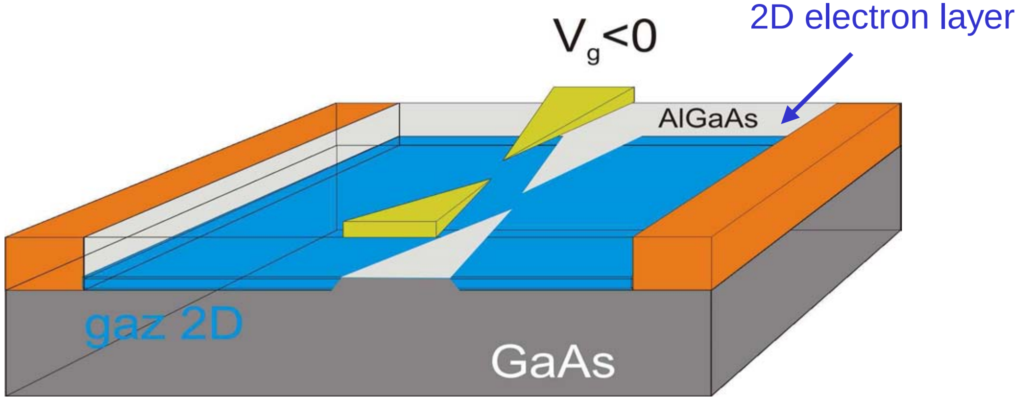
Pauli

Heisenberg: $eV\,.\,\tau \sim h$

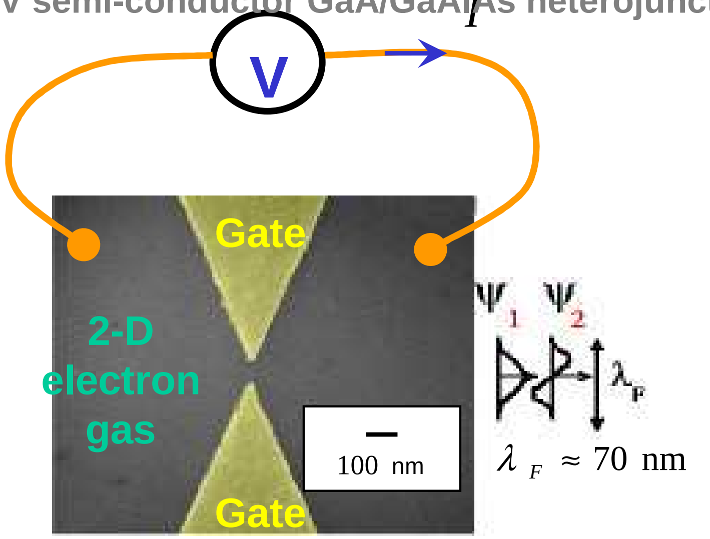
$$\dot{N}_{Ph.} = N_{Ph}\,.\,\frac{\Delta(h\nu)}{h} = N_{Ph.}\,\Delta\nu$$

$\Rightarrow$ conductance quantization

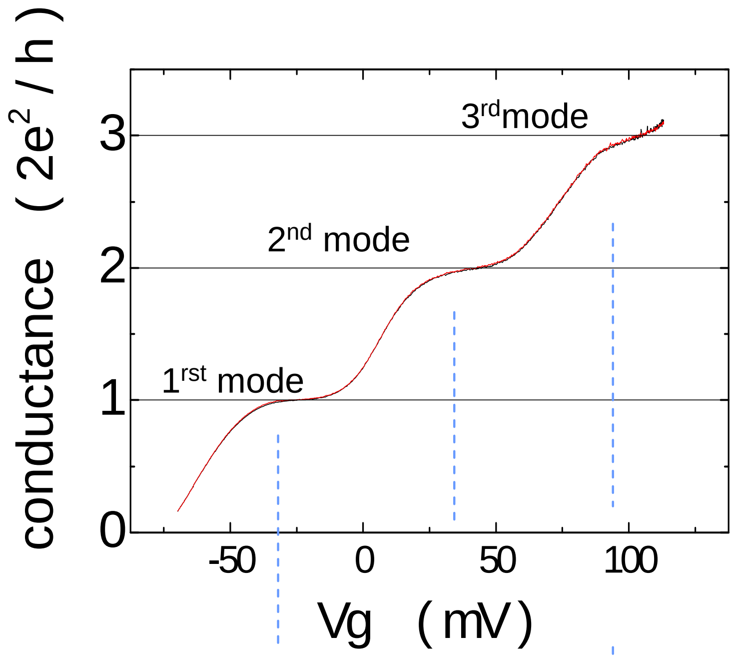
(D. Warrham ; B.J. van Wees 1988)



III-V semi-conductor GaA/GaAlAs heterojunction



Quantum Point Contact QPC



$D_1 = 0 \rightarrow 1$

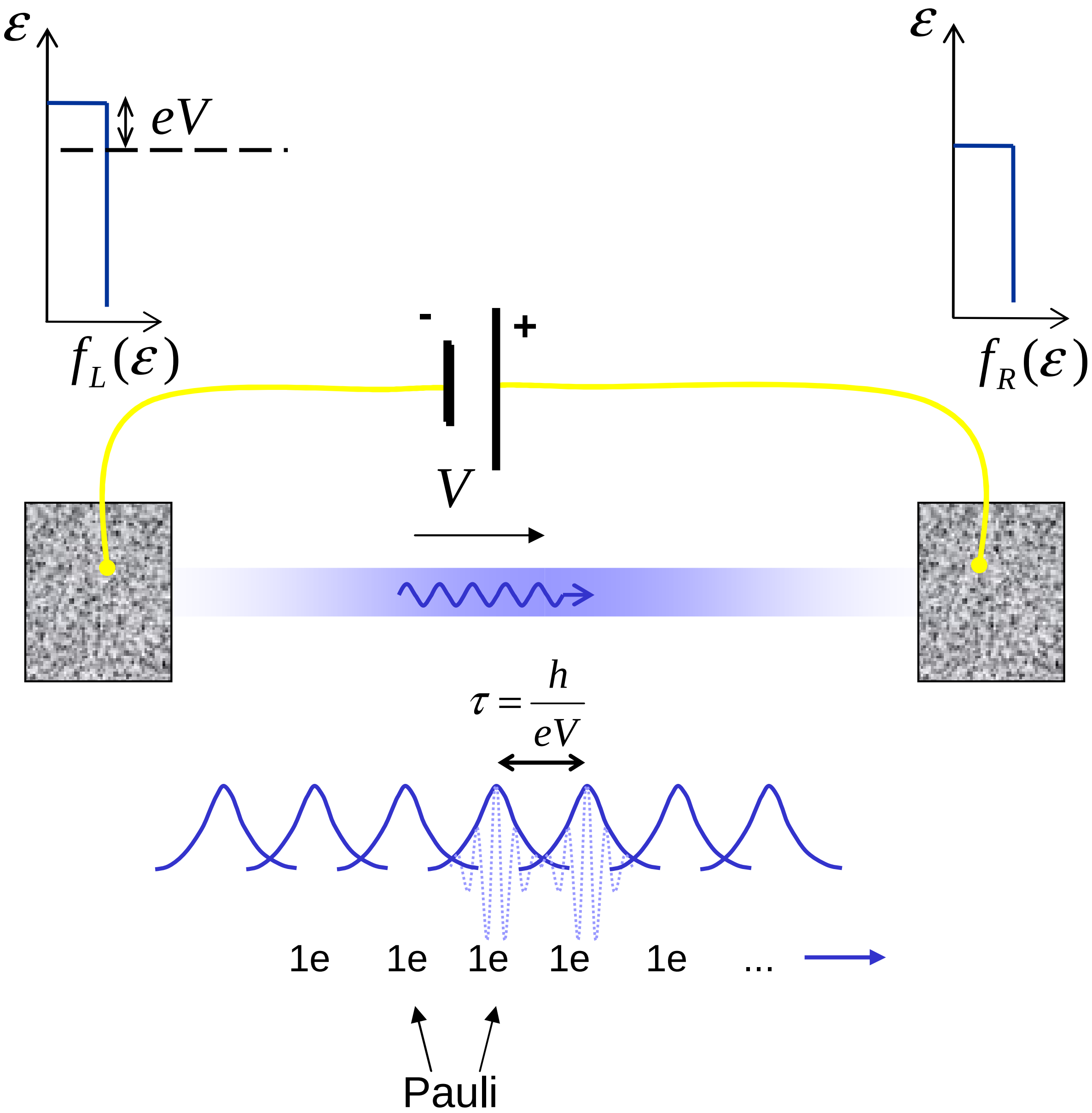
$D_2 = 0 \rightarrow 1$

$D_3 = 0 \rightarrow 1$

$$\boxed{G = \frac{2e^2}{h} . \sum_n D_n}$$

perfect quantum wires are noiseless

here: 1D quantum wires :



Wolfgang Pauli

$$\boxed{\left\langle \Delta I^2 \right\rangle = 0}$$

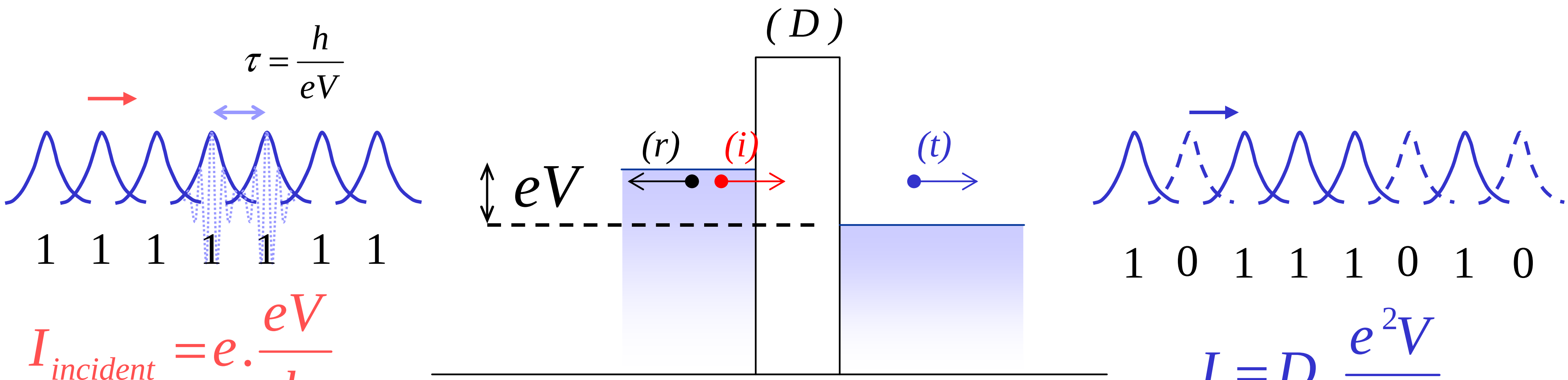
$$I = e.\frac{eV}{h}$$

Pauli

Heisenberg: $eV . \tau \sim h$

$$\dot{N}_{Ph.} = N_{Ph}.\frac{\Delta(h\nu)}{h}$$

shot noise = electron partitioning



$$I_{incident} = e.\frac{eV}{h}$$

$$I = D\,\frac{e^2 V}{h}$$

binomial statistics

Shot Noise < Schottky (Poisson)

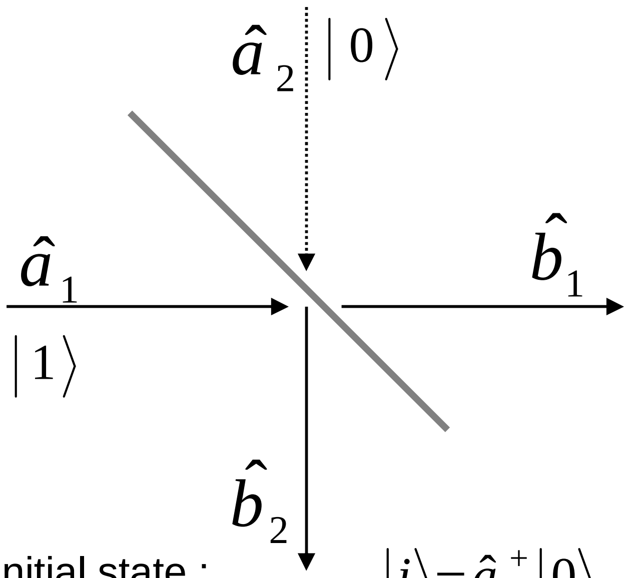
$\boxed{\propto D(1-D)}$

no noise for D = 1 !

$$\boxed{\langle \Delta I^2 \rangle = 2eI(1-D)\Delta f}$$

G. Lesovik 89, M. Büttiker 91
Th. Martin, R. Landauer 92
Khlus (1987)

single particle partitioning



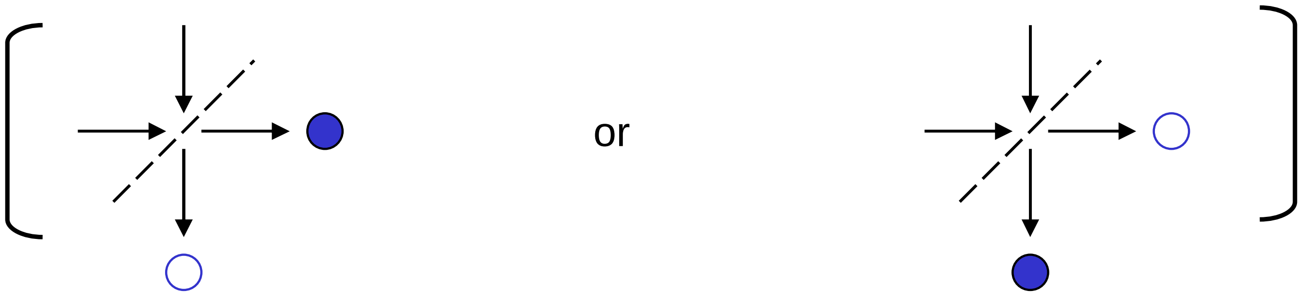
$$\begin{pmatrix} \hat{b}_1 \\ \hat{b}_2 \end{pmatrix} = S \begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix} \qquad S = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\Rightarrow \qquad \begin{pmatrix} \hat{a}_1^{\,+} \\ \hat{a}_2^{\,+} \end{pmatrix} = S \begin{pmatrix} \hat{b}_1^{\,+} \\ \hat{b}_2^{\,+} \end{pmatrix}, \quad \text{as } S^{+}S = 1$$

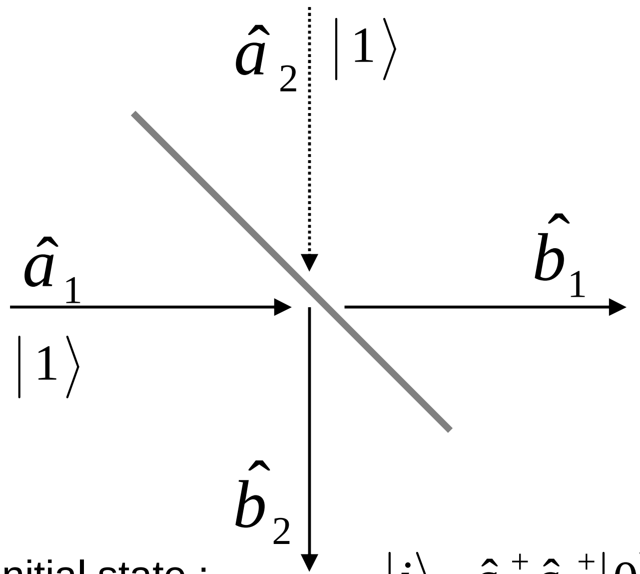
initial state : $\quad |i\rangle = \hat{a}_1^{\,+} |0\rangle_{in}$

final state: $\quad |f\rangle = \frac{1}{\sqrt{2}} \left(\hat{b}_1^{\,+} - \hat{b}_2^{\,+} \right) |0\rangle_{out}$

= superposition of quantum state (transmitted / reflected)



two- particle partitioning



$$\begin{pmatrix}\hat b_1\\ \hat b_2\end{pmatrix} = S\begin{pmatrix}\hat a_1\\ \hat a_2\end{pmatrix} \qquad S=\begin{pmatrix}\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}}\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{pmatrix}$$

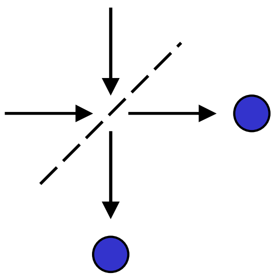
$$\Rightarrow \qquad \begin{pmatrix}\hat a_1^{\,+}\\ \hat a_2^{\,+}\end{pmatrix} = S\begin{pmatrix}\hat b_1^{\,+}\\ \hat b_2^{\,+}\end{pmatrix}, \quad \text{as } S^+S=1$$

initial state : $$|i\rangle = \hat a_1^{\,+}\hat a_2^{\,+}|0\rangle_{in}$$

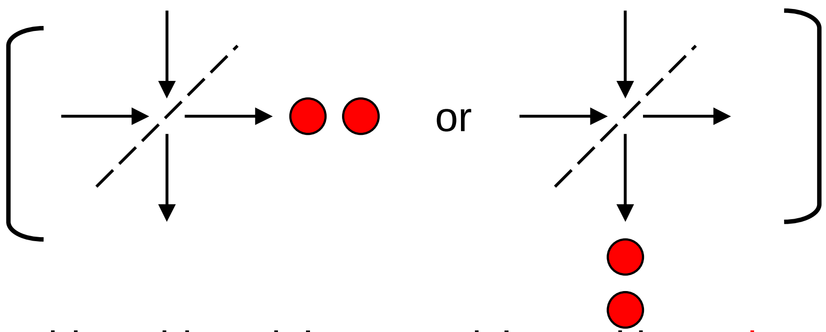
final state: $$|f\rangle = \frac{1}{2}\left(\hat b_1^{\,+}\hat b_1^{\,+} - \hat b_2^{\,+}\hat b_2^{\,+}\right) + \frac{1}{2}\left(\hat b_1^{\,+}\hat b_2^{\,+} - \hat b_2^{\,+}\hat b_1^{\,+}\right)|0\rangle_{out}$$

= 0 (Fermion) = 0 (Boson)

Fermions:



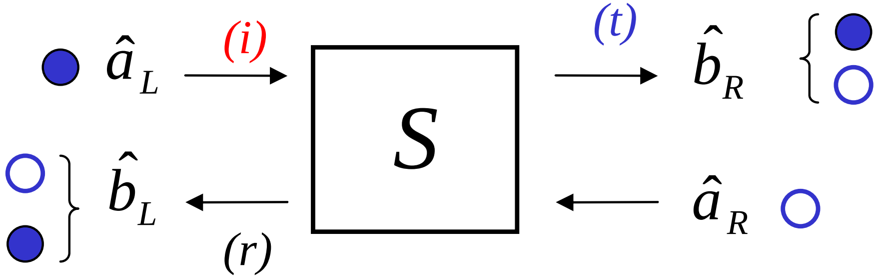
Bosons:



no bunching, no noise

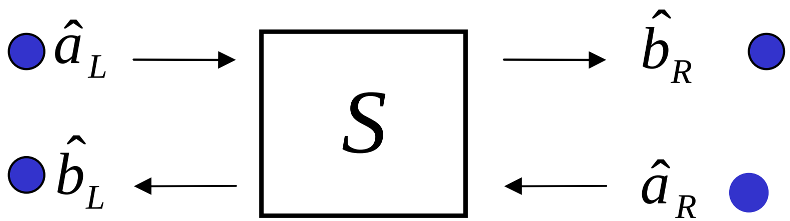
bunching, binomial two-particle partition noise

$E_F < \varepsilon < E_F + eV$

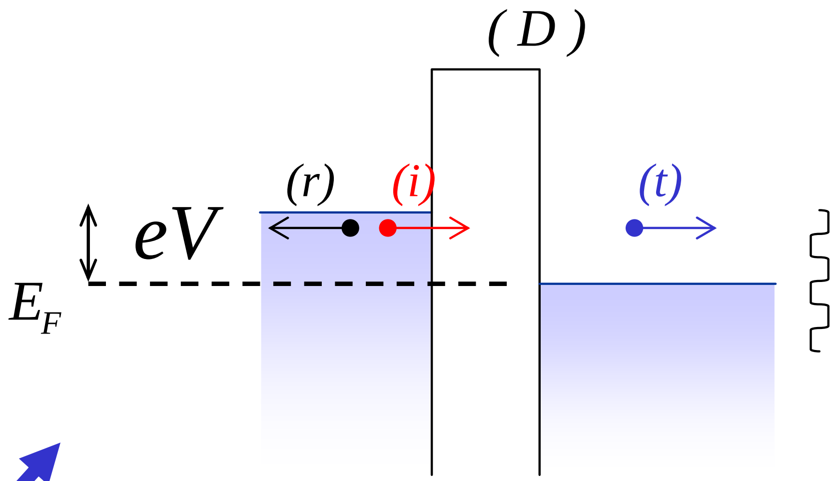


single particle partition noise
= source of shot noise

$\varepsilon \leq E_F$



two-particle partition noise
= no noise (Fermions)

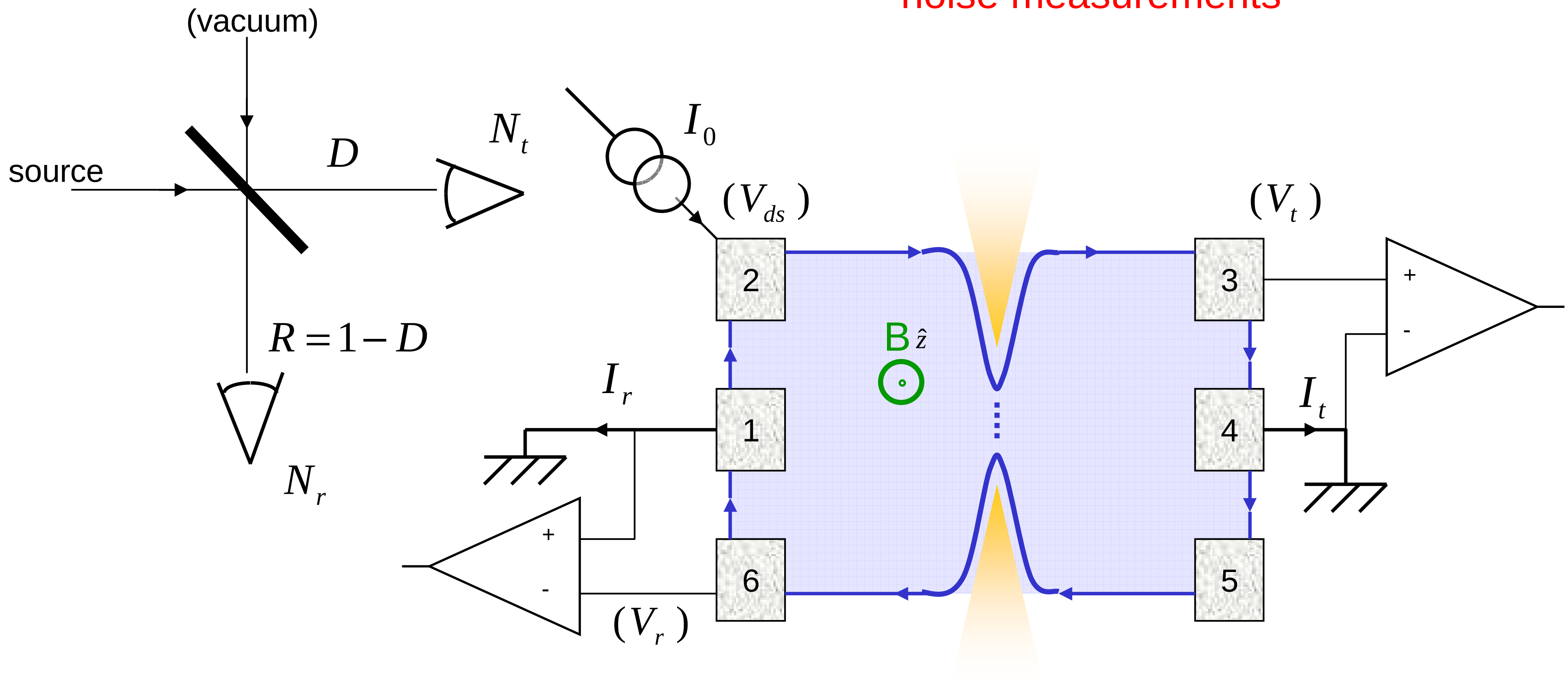


$$\left\langle (\Delta I)^2 \right\rangle = 2eI_0\, \Delta f \cdot D(1-D)$$

$$\boxed{\left\langle \Delta I^2 \right\rangle = 2eI(1-D)\Delta f}$$

the Beam-Splitter

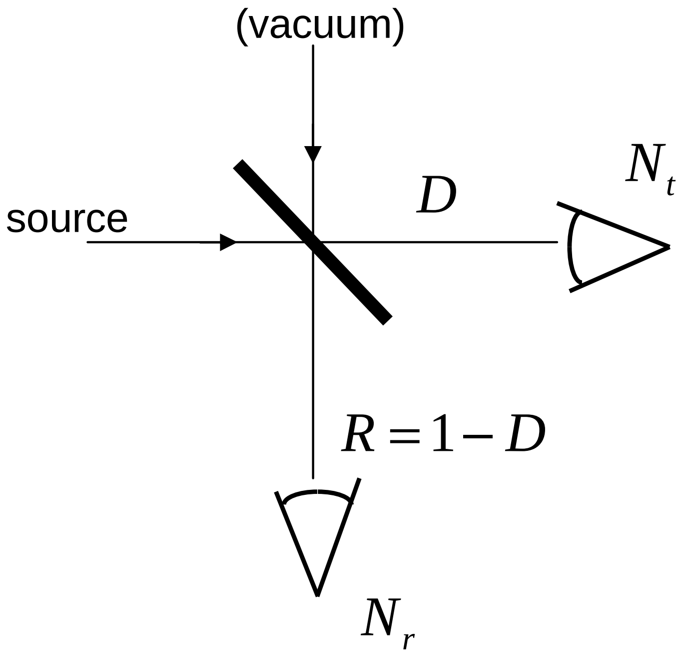
'Hanbury-Brown Twiss' noise measurements

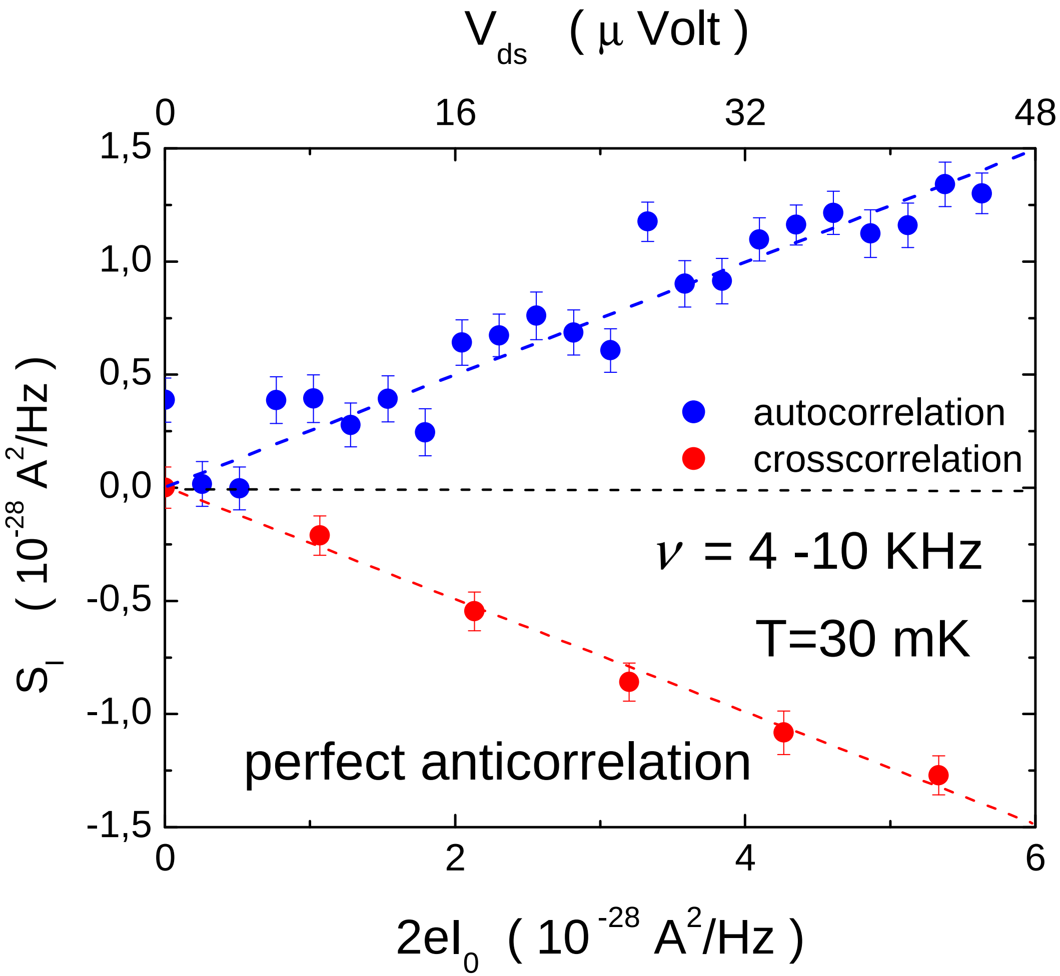


$$V_{ds} = \frac{e^2}{h} I_0 \qquad V_t = \frac{e^2}{h} I_t \qquad V_r = \frac{e^2}{h} I_r$$

$$\langle \Delta V_t . \Delta V \rangle_r = \left(\frac{e^2}{h}\right)^2 \langle \Delta I_t . \Delta I_t \rangle$$

the Beam-Splitter





$$\boxed{\langle \Delta I_t . \Delta I_r \rangle = -\langle (\Delta I_t)^2 \rangle = -S_I \, \Delta\nu}$$

$$2eI_0 = 2e\frac{e^2}{h}V_{DS}$$

$$= \frac{1}{4} \quad (D = 1/2)$$

$$S_I = 2eI_0 \times D(1-D)$$

negative correlation for electrons

exchange effects in cross-correlation current noise

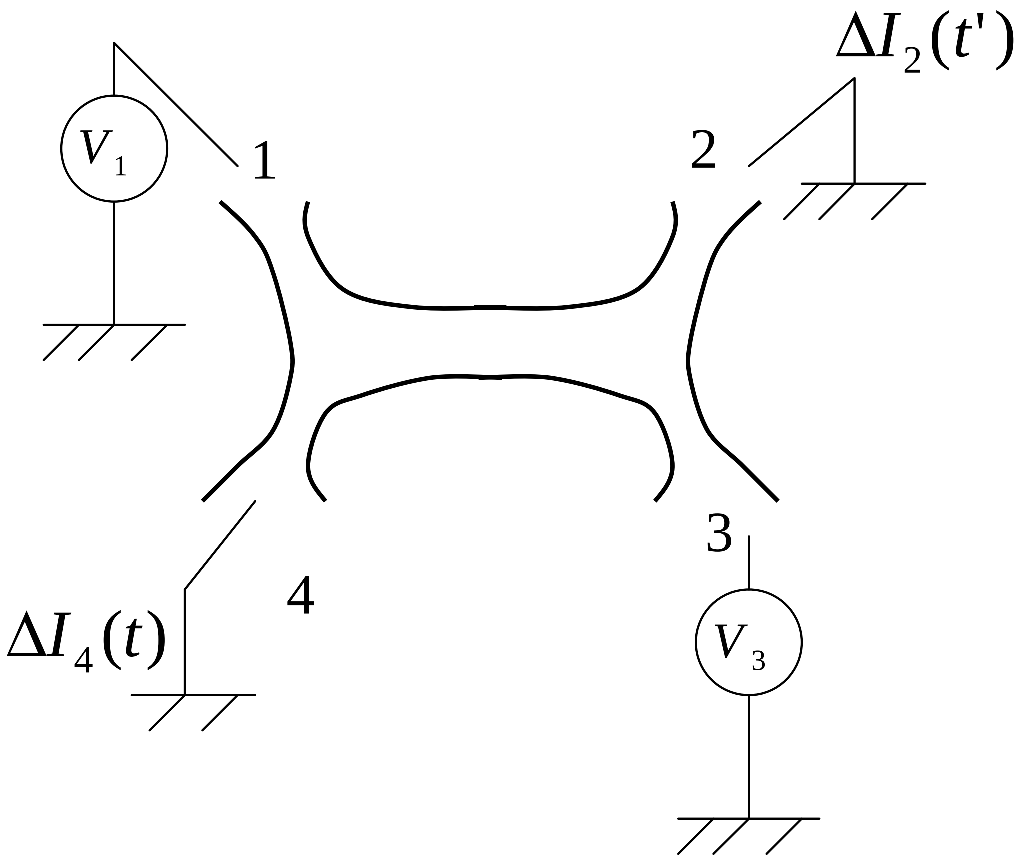
four terminal conductor :

experiments : (A), (B), then (A+B)

(A) $V_1 = V \;\; ; \;\; V_3 = 0$

(B) $V_1 = 0 \;\; ; \;\; V_3 = V$

(A+B) $V_1 = V \;\; ; \;\; V_3 = V$



$$S^{(A)}_{I_2 I_4} = -2\frac{e^2}{h} eV \left(s_{21}\, s^*_{21} s_{41}\, s^*_{41} \right)$$

$$S^{(B)}_{I_2 I_4} = -2\frac{e^2}{h} eV \left(s_{23}\, s^*_{23} s_{43}\, s^*_{43} \right)$$

$$S^{(A+B)}_{I_2 I_4} \neq S^{(A)}_{I_2 I_4} + S^{(B)}_{I_2 I_4}$$

factorizable as a product of transmissions

$$S^{(A+B)}_{I_2 I_4} - S^{(A)}_{I_2 I_4} - S^{(B)}_{I_2 I_4} = -2\frac{e^2}{h} eV \left[s_{21}\, s^*_{23} s_{43}\, s^*_{41} + s_{23}\, s^*_{21} s_{41}\, s^*_{43} \right]$$

exchange terms : non separable

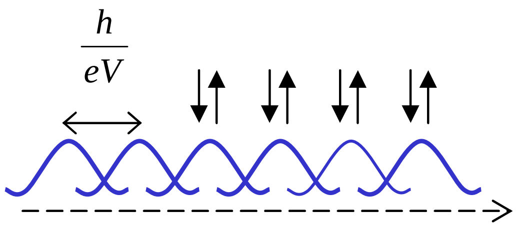
*M. Büttiker, Phys. Rev B **46**, 12 485, (1992).*

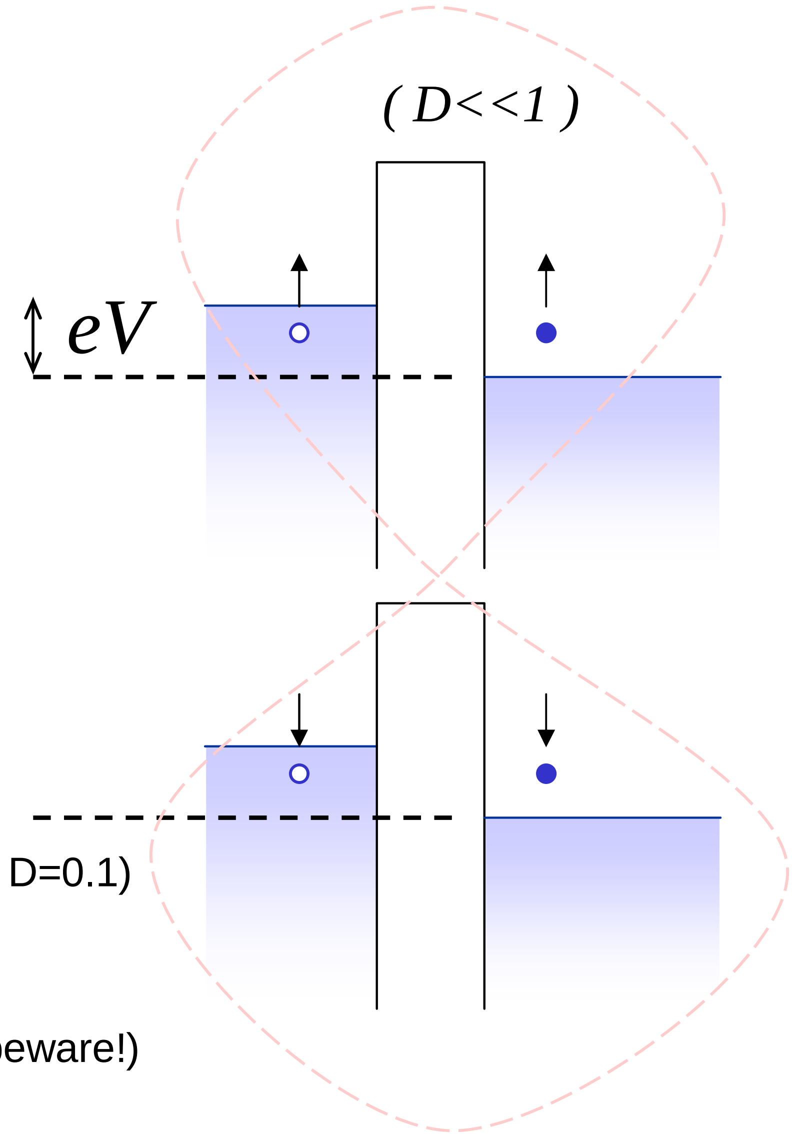
natural entanglement in the Fermi sea

C. Beenakker (2003) :

``in contrast to bosons, fermions can be entangled by single-particle scattering even if the sources are in (local) thermal equilibrium ''

tunnel junction
transmission τ





$$|0\rangle \Rightarrow (1-D)|0\rangle + D|\uparrow\downarrow\rangle_h |\uparrow\downarrow\rangle_e + \dots$$

$$\dots + \sqrt{2D(1-D)}\,2^{-1/2}\left(|\uparrow\rangle_h |\uparrow\rangle_e + |\downarrow\rangle_h |\downarrow\rangle_e\right)$$

entanglement production rate $\approx D\frac{eV}{h}$ (2 GHz for 100 μV, D=0.1)

(Intel® : beware!)

VOLUME 91, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2003

Proposal for Production and Detection of Entangled Electron-Hole Pairs in a Degenerate Electron Gas

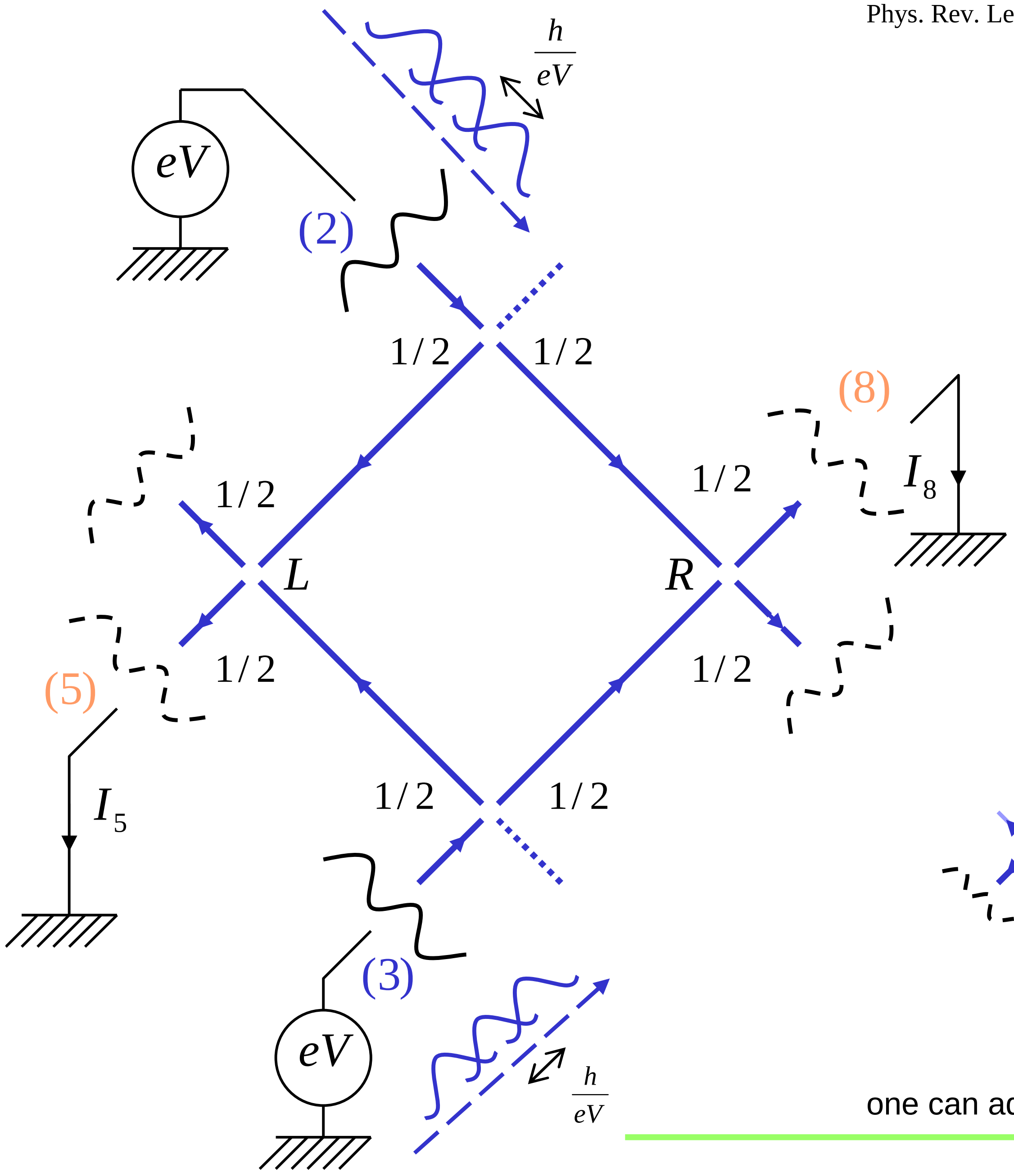
C. W. J. Beenakker, C. Emary, M. Kindermann, and J. L. van Velsen
Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands

(Received 6 May 2003; published 1 October 2003)

two-electron interference / entanglement

(P. Samuelsson, E.V. Sukhorukov, M. Buttiker)

Phys. Rev. Lett. 92, 026805 (2004)

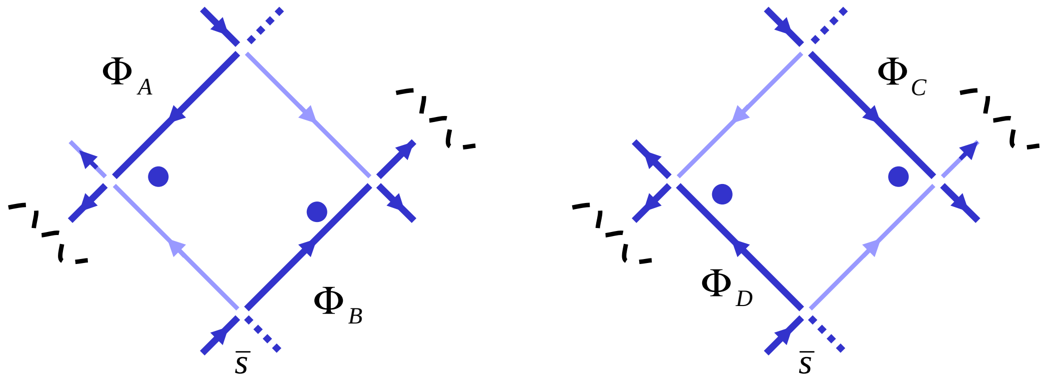


Electrons: injected from (2) and (3)
detected in coincidence at (5) and (8)

two-particle probability
to arrive in 5 and 8 is:

$$P_2 = \frac{1}{4^2}\left| e^{i\Phi_A} e^{i\Phi_B} + e^{i\Phi_C} e^{i\Phi_D} \right|^2$$

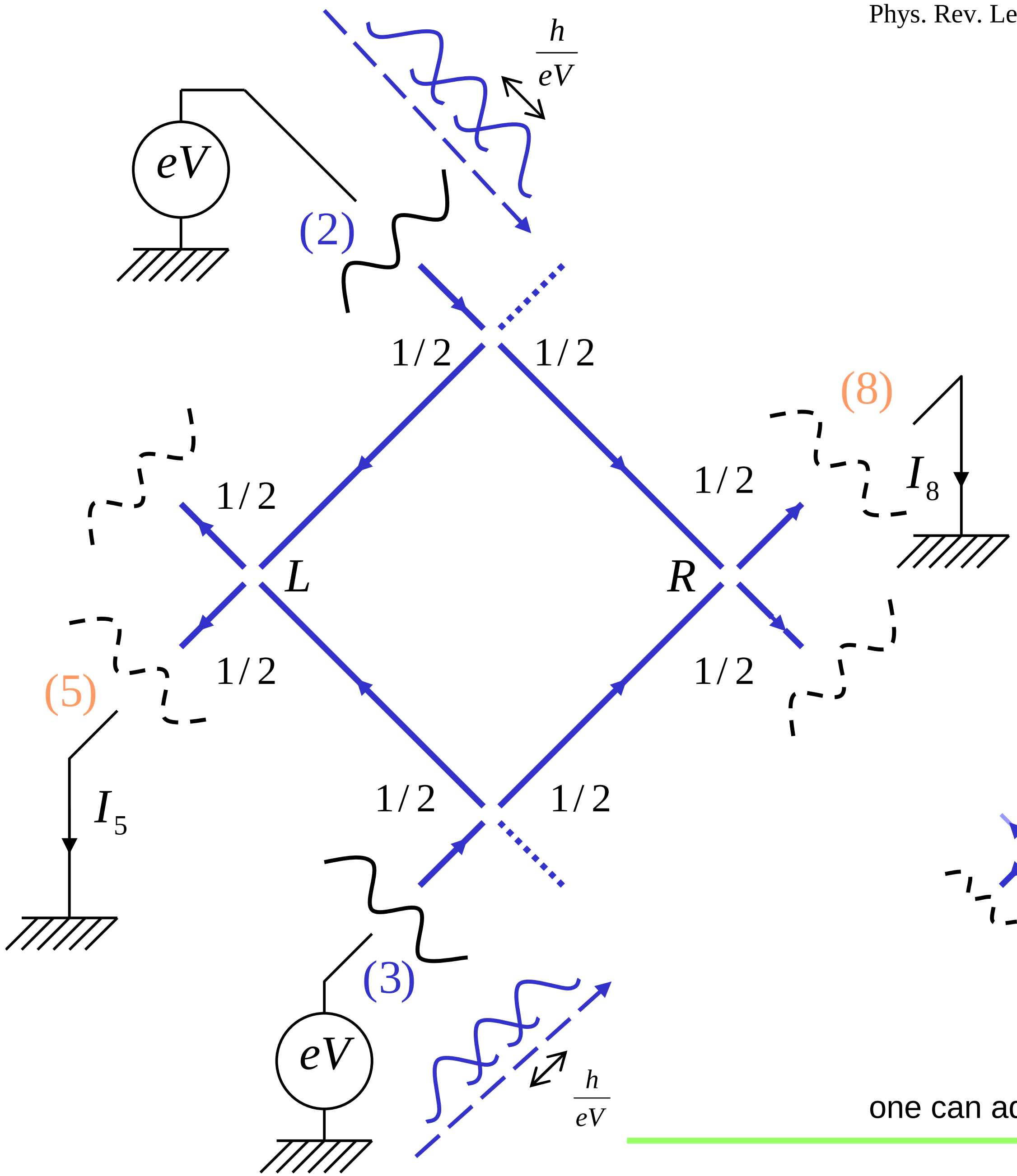
$$= \frac{1}{8}\left(1 + \cos\left(\Phi_A + \Phi_B - \Phi_C - \Phi_D\right)\right)$$



one can add an AB flux through the loop: $\Phi_A + \Phi_B - \Phi_C - \Phi_D + 2\pi \frac{\Phi_{AB}}{\Phi_0}$

two-electron interference / entanglement

(P. Samuelsson, E.V. Sukhorukov, M. Buttiker)
Phys. Rev. Lett. 92, 026805 (2004)

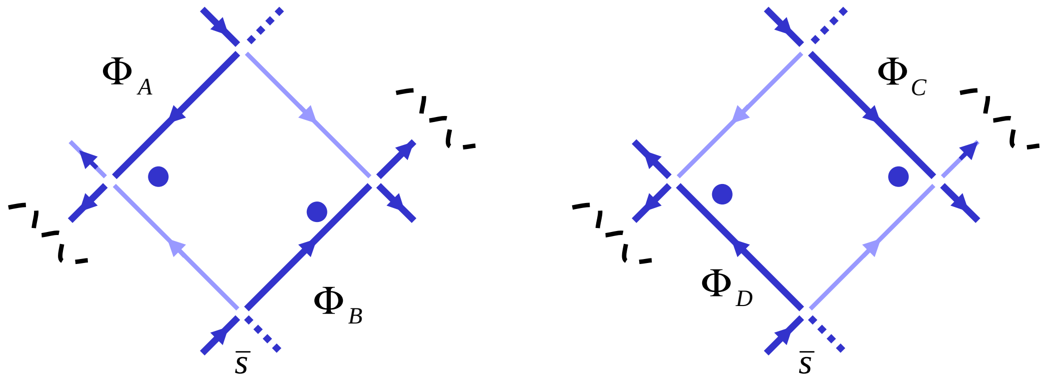


Electrons: injected from (2) and (3)
detected in coincidence at (5) and (8)

Shot noise cross - correlation (5 X 8) :

$$P_2 = \frac{1}{8}\left(1+\cos(\Phi_A+\Phi_B-\Phi_C-\Phi_D)\right)$$

$$\boxed{S_{I_8, I_5} = 2e\frac{e^2}{h}V\times P_2}$$



one can add an AB flux through the loop: $\Phi_A+\Phi_B-\Phi_C-\Phi_D+2\pi\frac{\Phi_{AB}}{\Phi_0}$

need to develop more controlled approaches

• biased contact = continuous source of electrons at rate eV/h

$\rightarrow$ more than 2 e in a MZI $\rightarrow$ interaction may spoil coherence

continuous injection	entanglement	statistical detection

• new approach:

single e injection	entanglement	statistical detection

or better:

single e injection	entanglement	single e detection

OUTLINE

Magic properties of the Fermi sea

On-demand single electron source for flying qubits (running experiment)

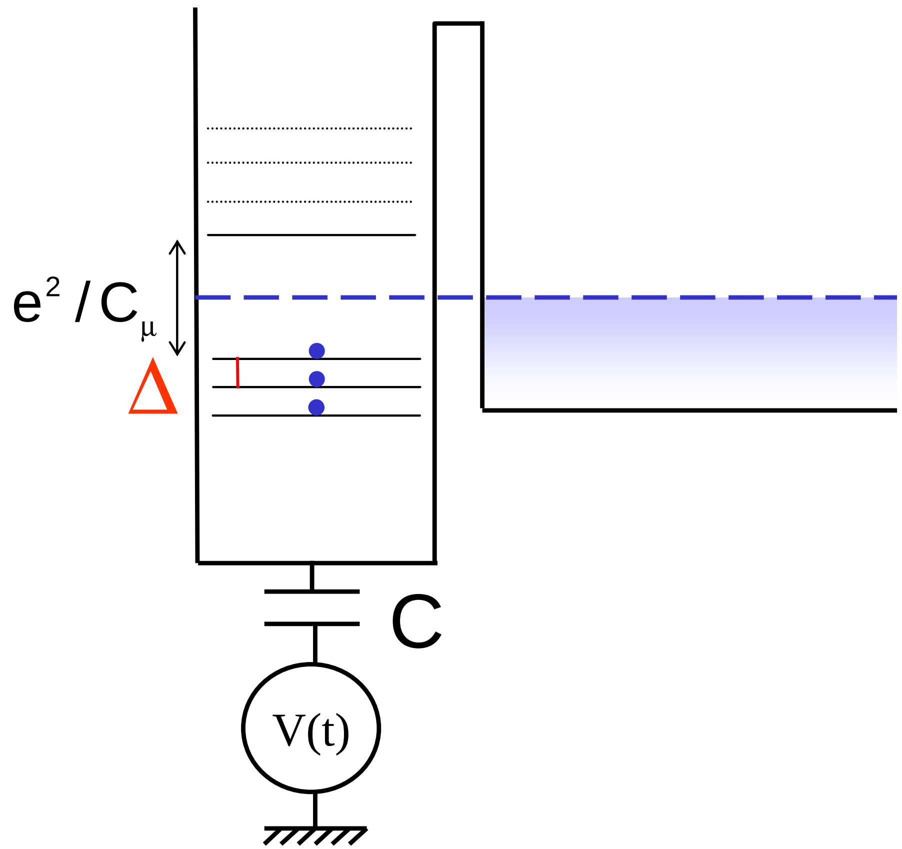
(flying electrons above the Fermi sea)

N-electron source for Full Counting Statistics (new project)

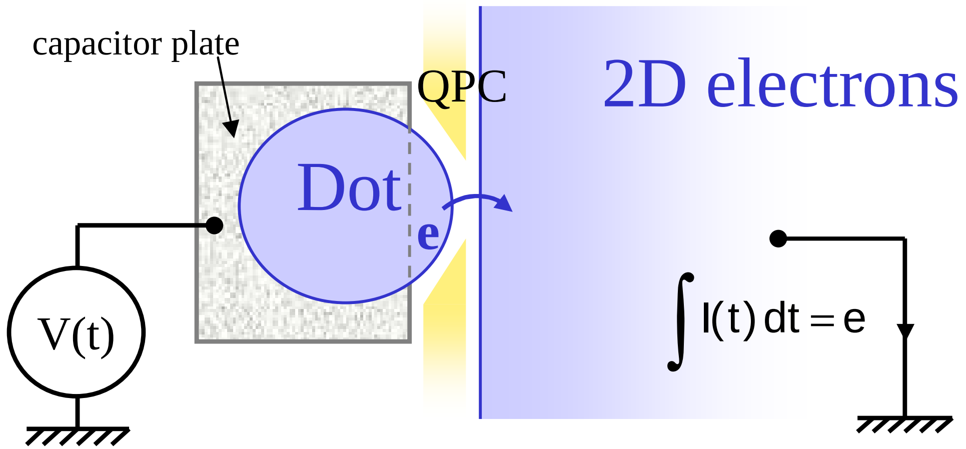
Counting charges for FCS or quantum information (new project)

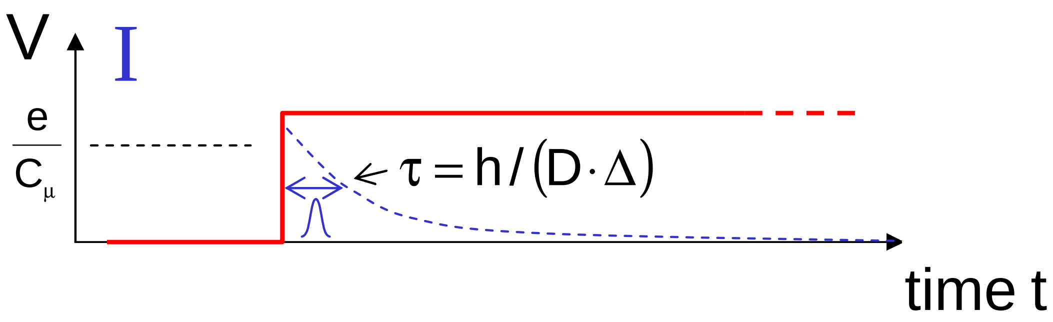
Conclusion

principle of an on-demand Single Electron Source



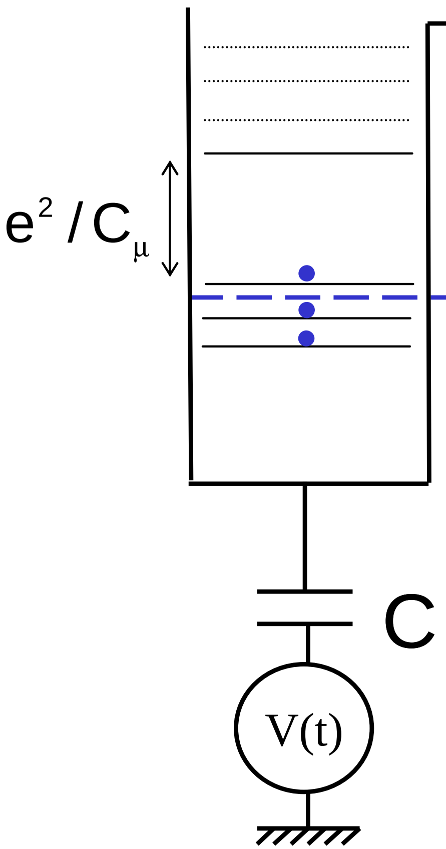
$$C_\mu = C + \frac{e^2}{\Delta}$$

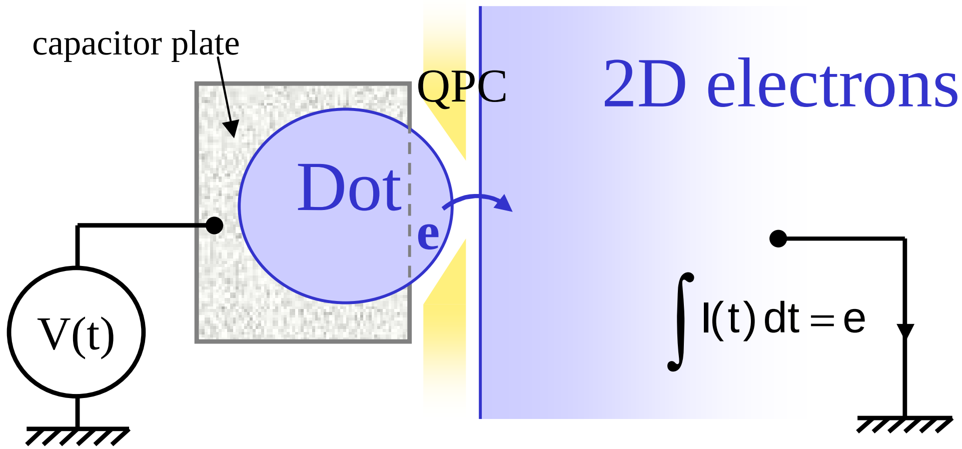


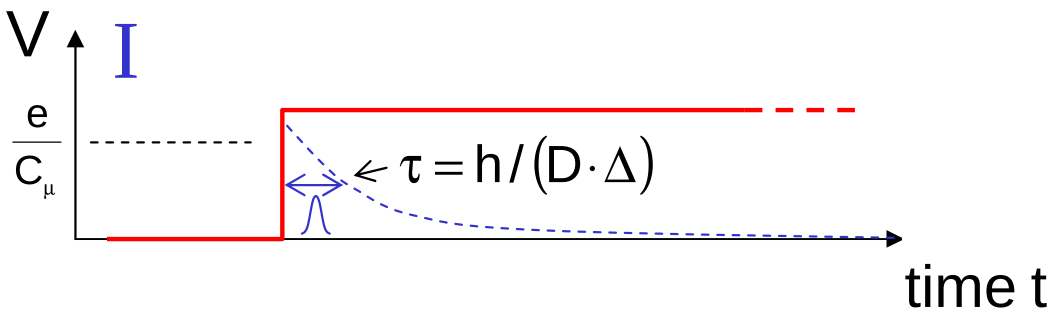


τ =100 ps for Δ=2.5 K and D =0.2

principle of an on-demand Single Electron Source



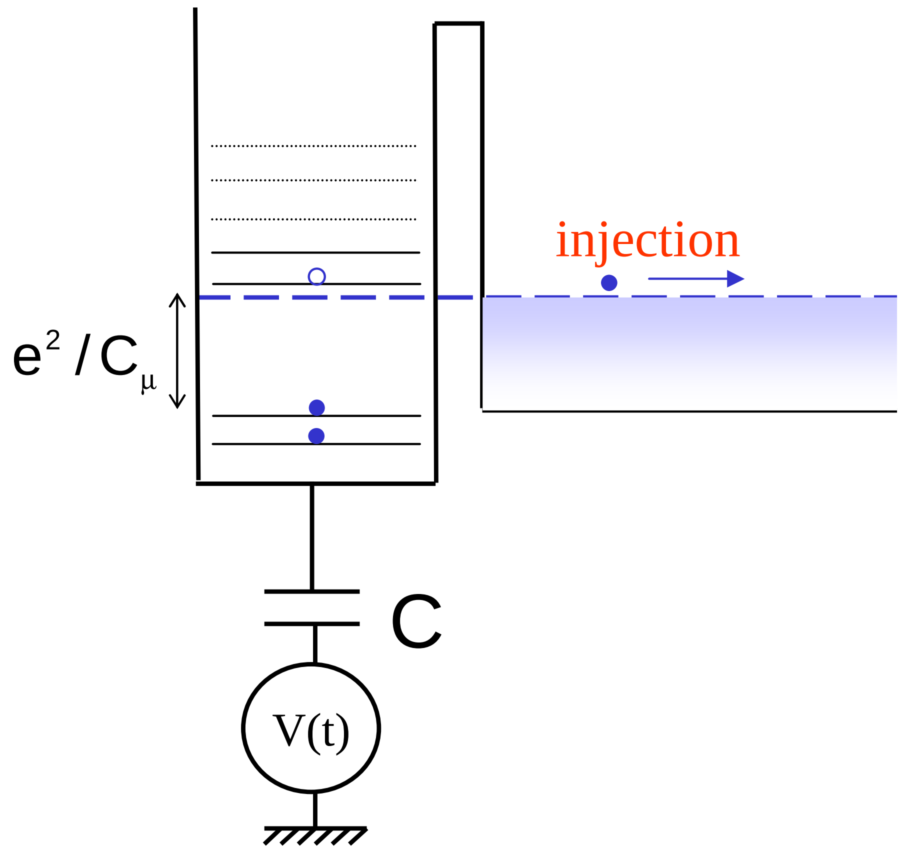




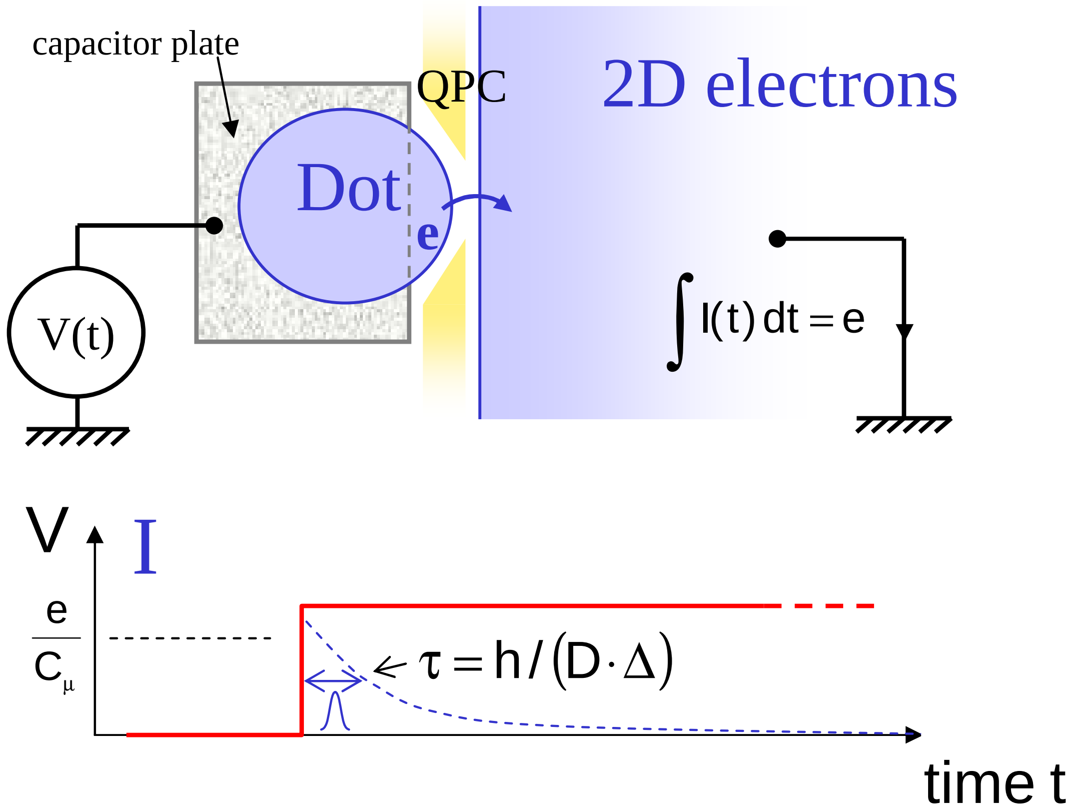
τ =100 ps for Δ=2.5 K and D =0.2

$$C_\mu = C + \frac{e^2}{\Delta}$$

principle of an on-demand Single Electron Source

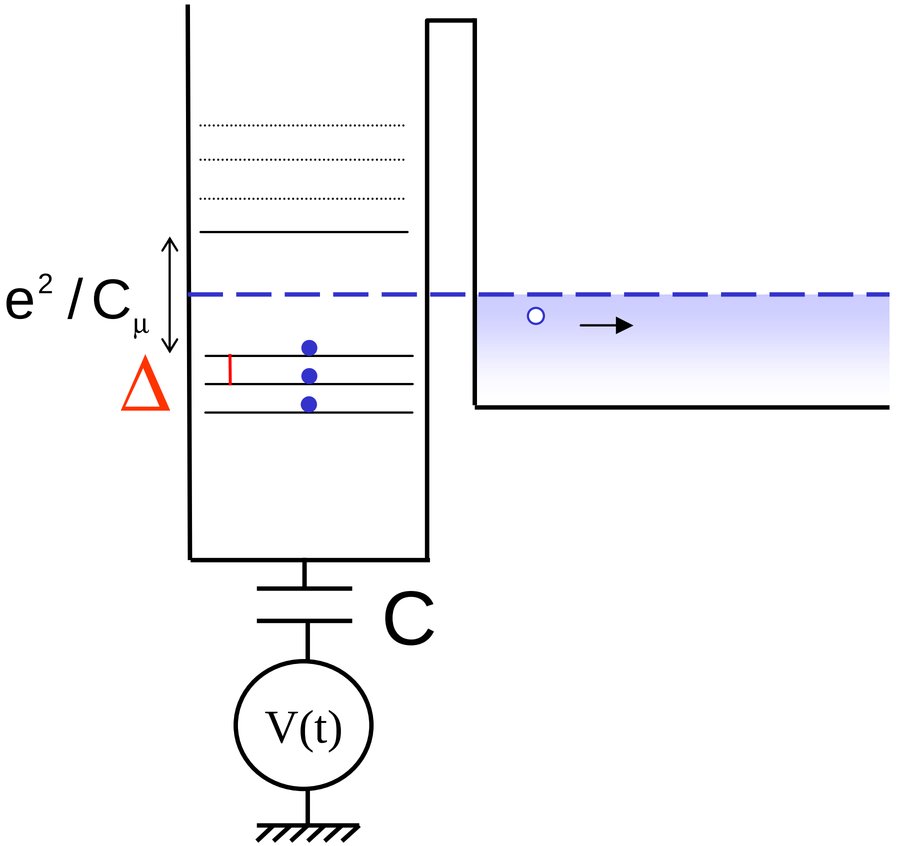


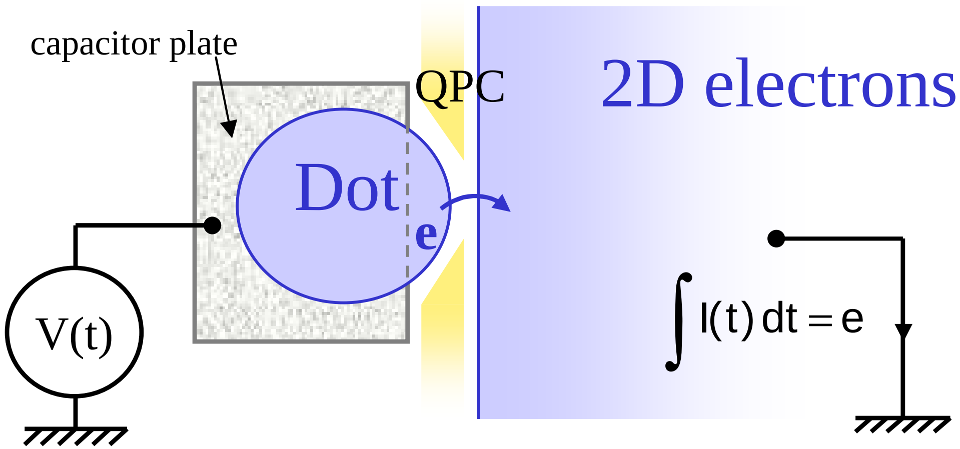
$$C_\mu = C + \frac{e^2}{\Delta}$$

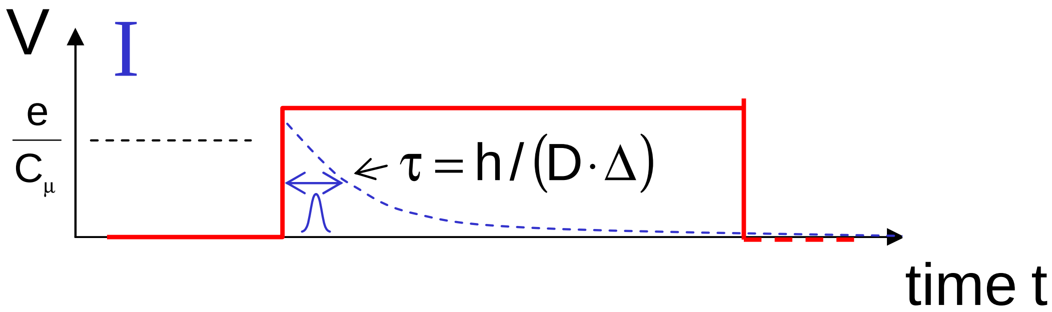


τ =100 ps for Δ=2.5 K and D =0.2

principle of an on-demand Single Electron Source







τ =100 ps for Δ=2.5 K and D =0.2

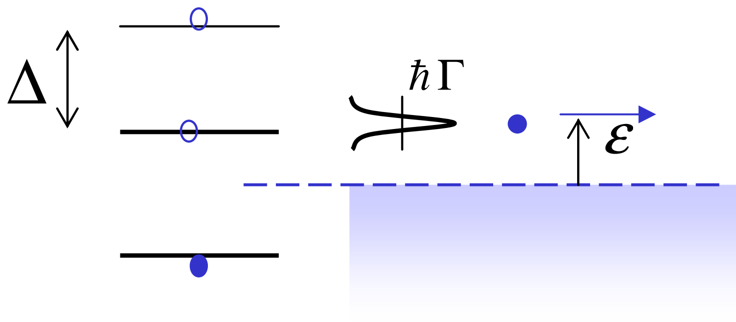
$$C_\mu = C + \frac{e^2}{\Delta}$$

the single electron gun

differences with known (dc) single electron source

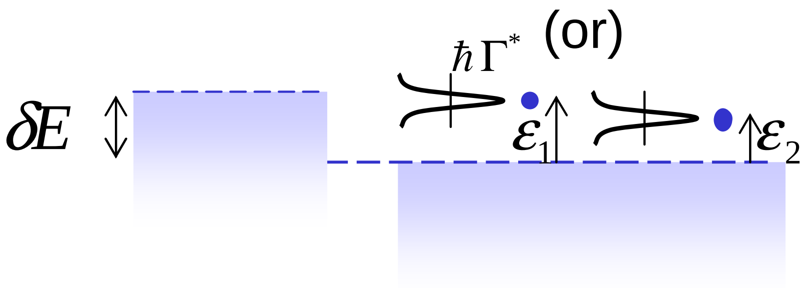
$\hbar\Gamma = D.\Delta$

- (ac electron source)
- energy ε of emitted electron well defined
- energy width $h\Gamma$ = fundamental emission rate
- $\Rightarrow$ suitable for coherent manipulation of electron



… while for a metallic electron box :

- energy ε of electron not well defined
- $\Rightarrow$ energy averaging will smear coherent interference effects

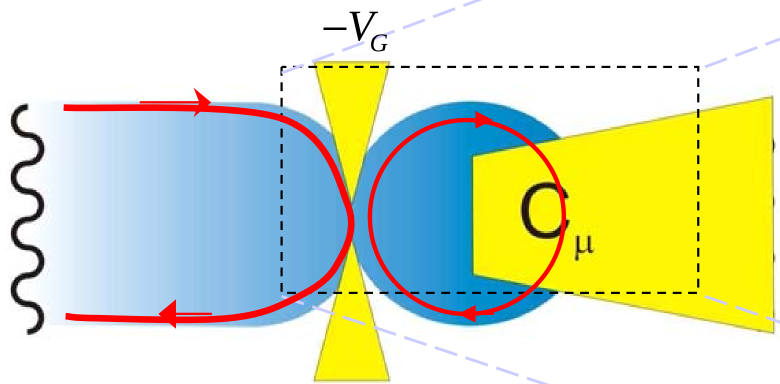


$0 \leq \varepsilon \leq \delta E$

$\Delta = 0$ (continuum)

practical realization

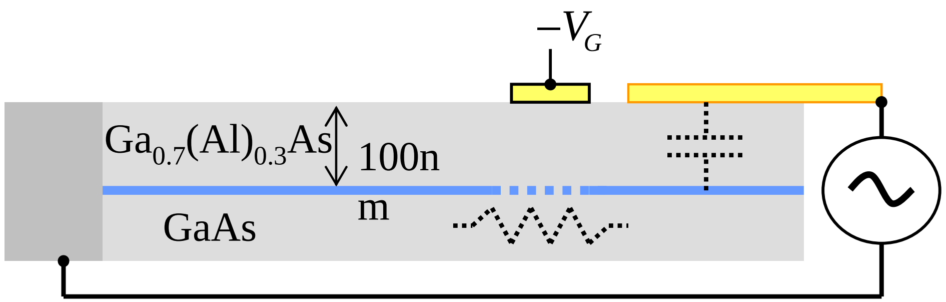
dot in the QHE regime

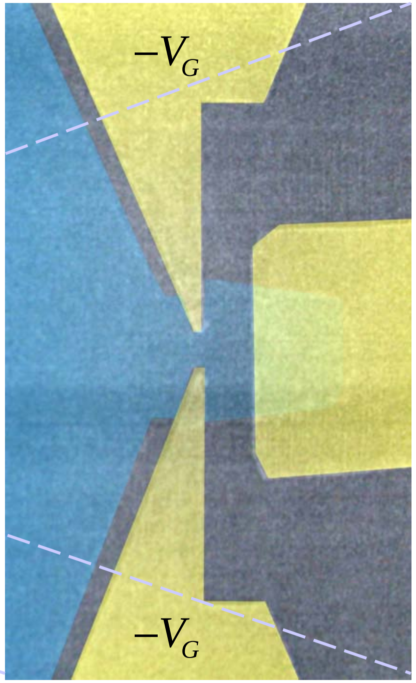


density : 1.7 10^{11} electrons/ cm^{-2}
mobility : 2.5 10^6 $cm^2/(Vs)$

capacitor: C ~ 1 f F
energy level spacing $\Delta = 2.5$ K >> e^2/C

$1/C\omega$ ~ 100 kΩ @ 1.6 GHz

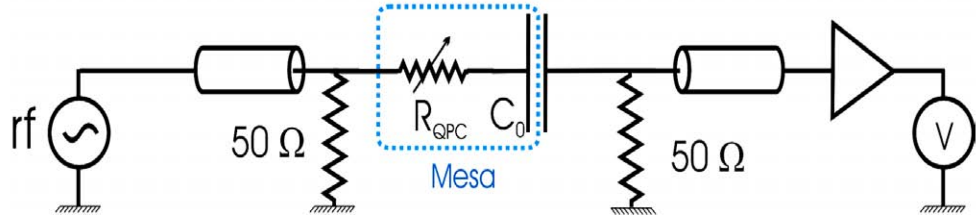




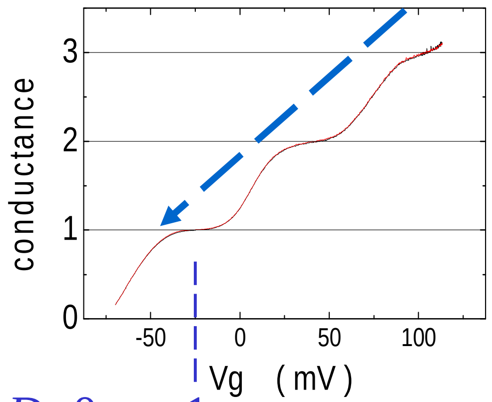
2D electron gaz
in GaAs/Ga(Al)As
heterojunction

300 nm

Photo. Y. Jin, LPN CNRS Marcoussis)

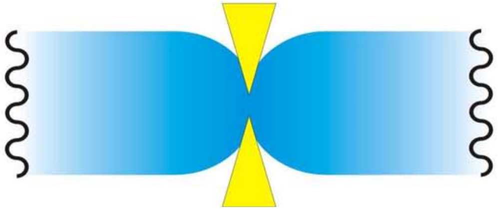


(Linear response) : the Quantum Charge Relaxation Resistance

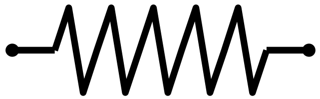


D=0 $\rightarrow$ 1

QPC

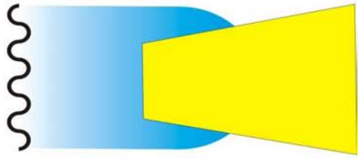


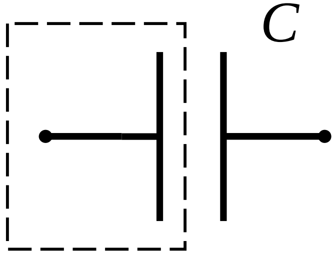
$$R_L = \frac{1}{G_{Landauer}} = \frac{h}{e^2} \cdot \frac{1}{D}$$

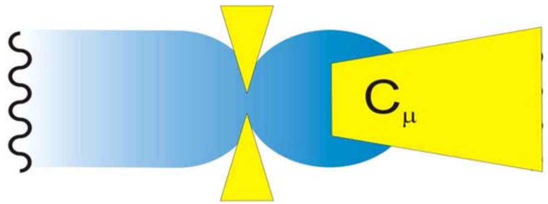


+

Capacitor

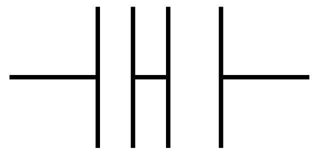






Not new

C_μ



$C_q = e^2 N$

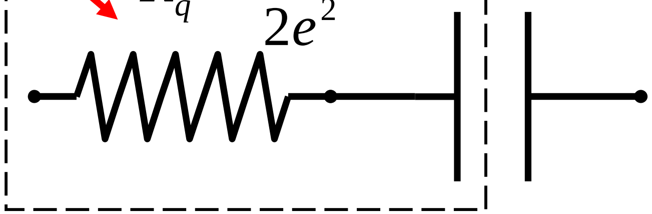
C

N : density of states

New!

$$R_q = \frac{h}{2e^2}$$

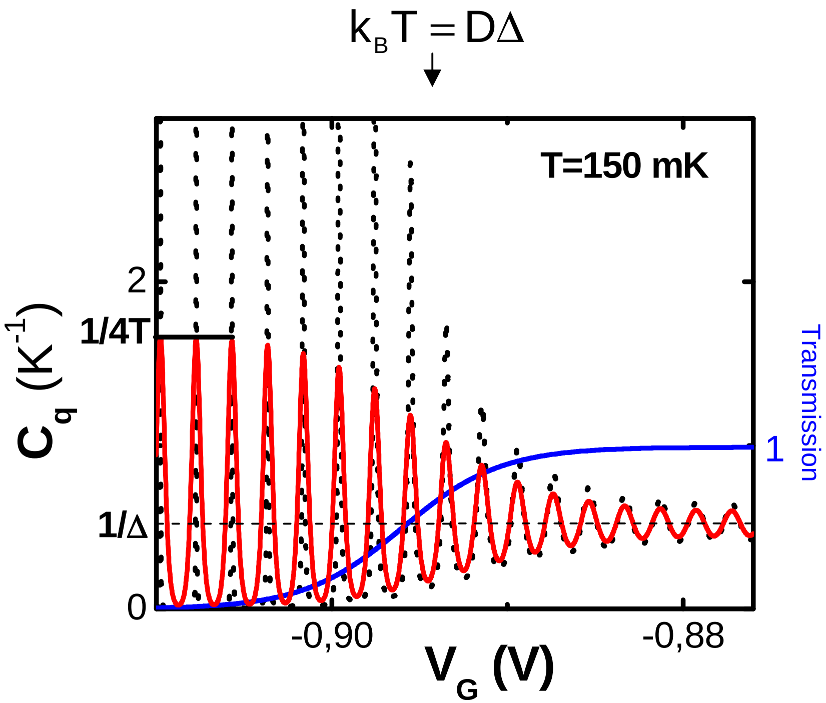
C_μ

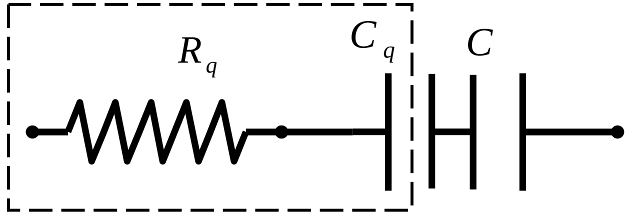


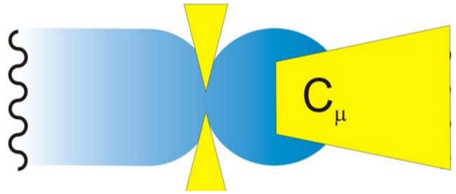
does not depend on transmission D !

(Büttiker, Prêtre, Thomas Phys. Letters A 180 (1993) 364-369)

Linear response : the quantum RC circuit

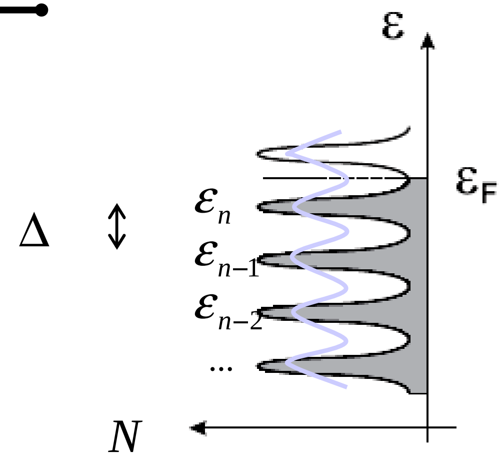




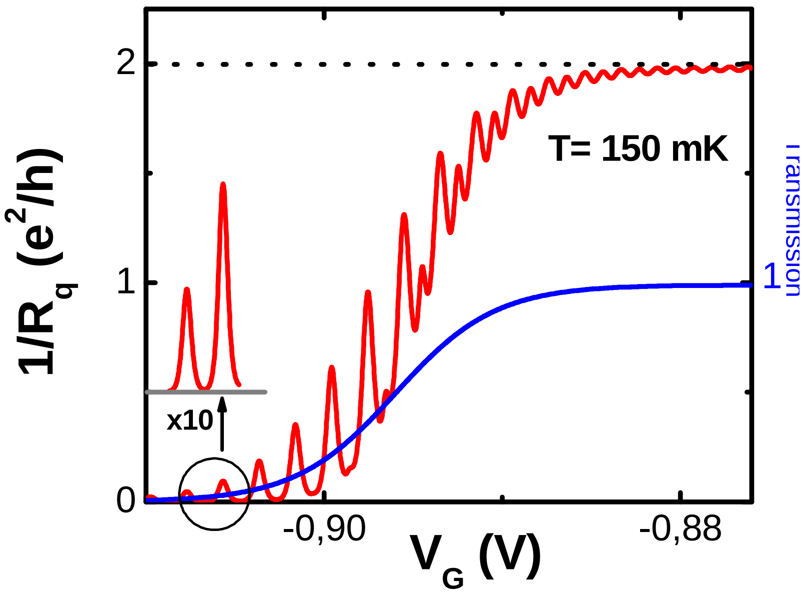


$$C_q = e^2 \int d\varepsilon \, N(\varepsilon) \times \left(-\frac{\partial f}{\partial \varepsilon} \right)$$

$$R_q = \frac{h}{2e^2} \frac{\int d\varepsilon \, N^2(\varepsilon) \times \left(-\frac{\partial f}{\partial \varepsilon} \right)}{\left[\int d\varepsilon \, N(\varepsilon) \times \left(-\frac{\partial f}{\partial \varepsilon} \right) \right]^2}$$



energy level spacing of the mesoscopic capacitor



coherent regime : $D > k_BT/\Delta$

$$\frac{1}{R_q} = \frac{2e^2}{h}$$

NEW !

thermally incoherent regime : $D < k_BT/\Delta$

$$\frac{1}{R_q} = \frac{De^2}{h} \frac{\Delta}{4k_BT} \cdot \frac{1}{\cosh^2\left(\frac{\varepsilon_F - \varepsilon_n}{2k_BT} \right)}$$

(known)

Linear response : the quantum RC circuit

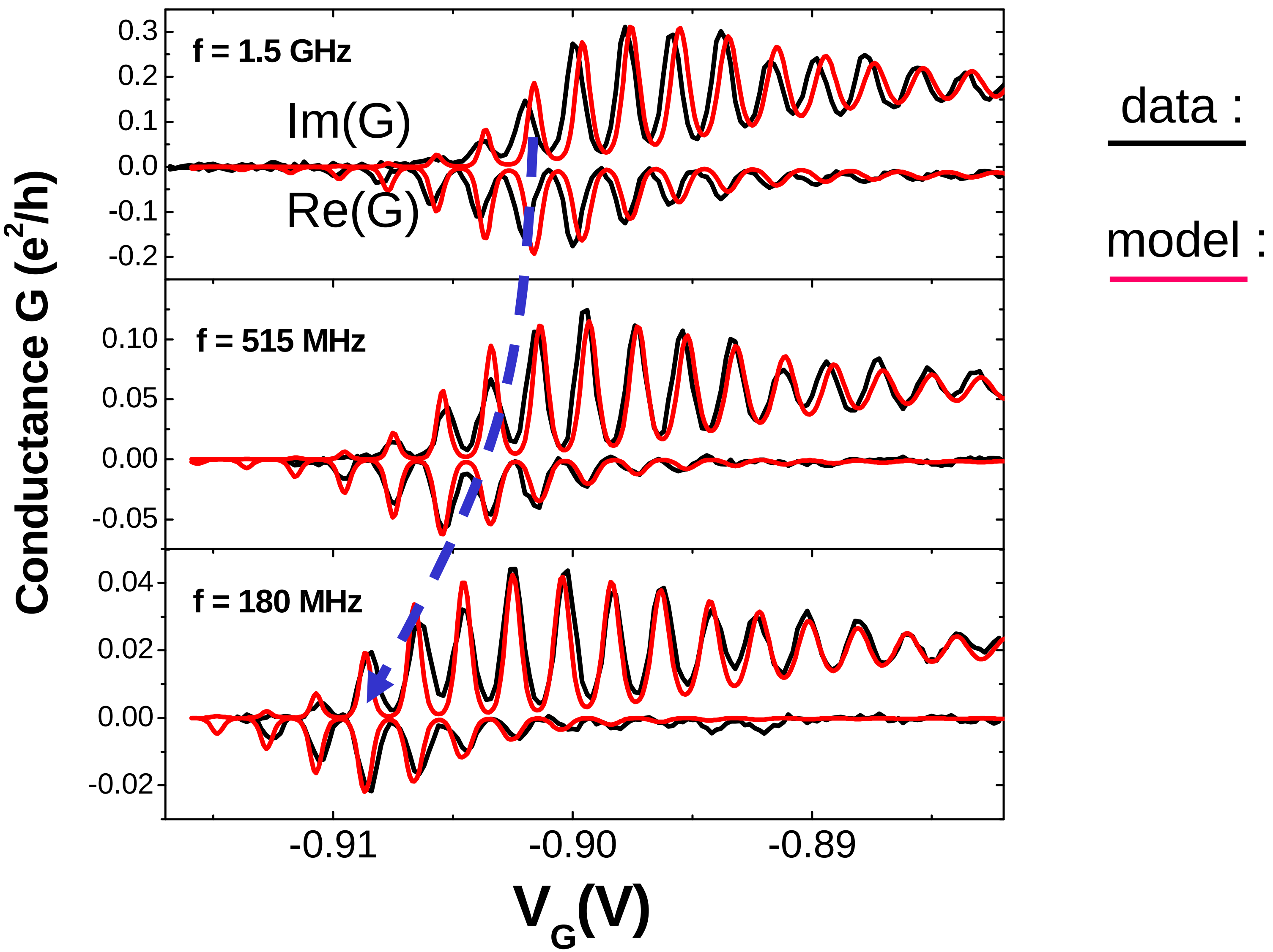
J. Gabelli, et al. Science, 313, 499 (2006)

$$\frac{e^2}{C_\mu} = 2.5K$$

$$\frac{e^2}{C} = 0.5K$$

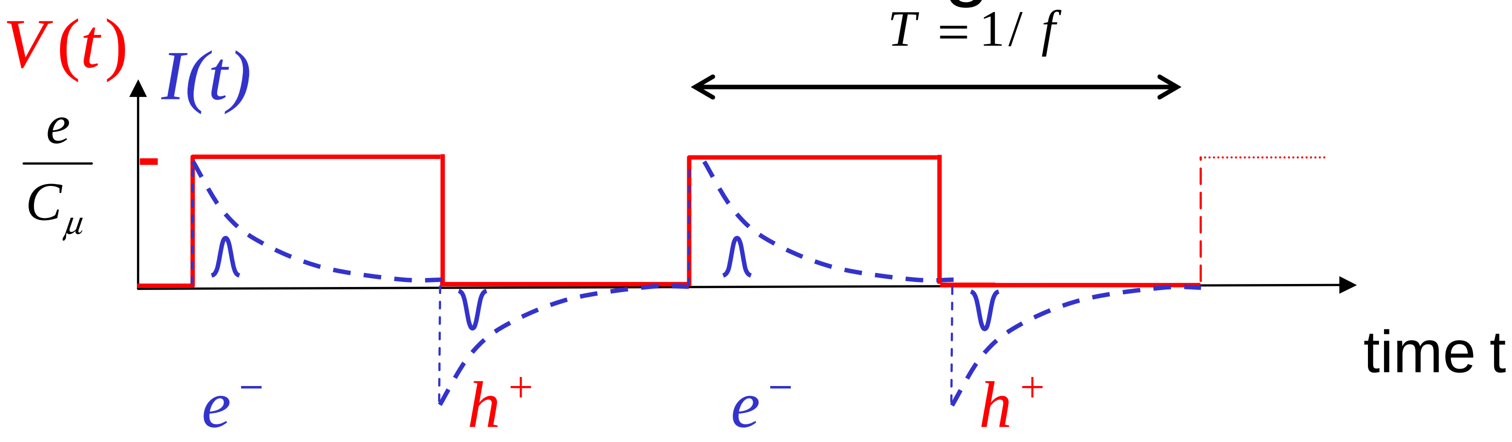
$$\Delta = 2K$$

$$T = 150mK$$



same parameters : C, C_μ, transmission $D(V_G)$ for all data
wide frequency range

measurements :
statistical detection of single electrons



periodic injection of single electrons and single holes

- 2) $\Rightarrow$ **time-domain measurement** of the averaged current spikes

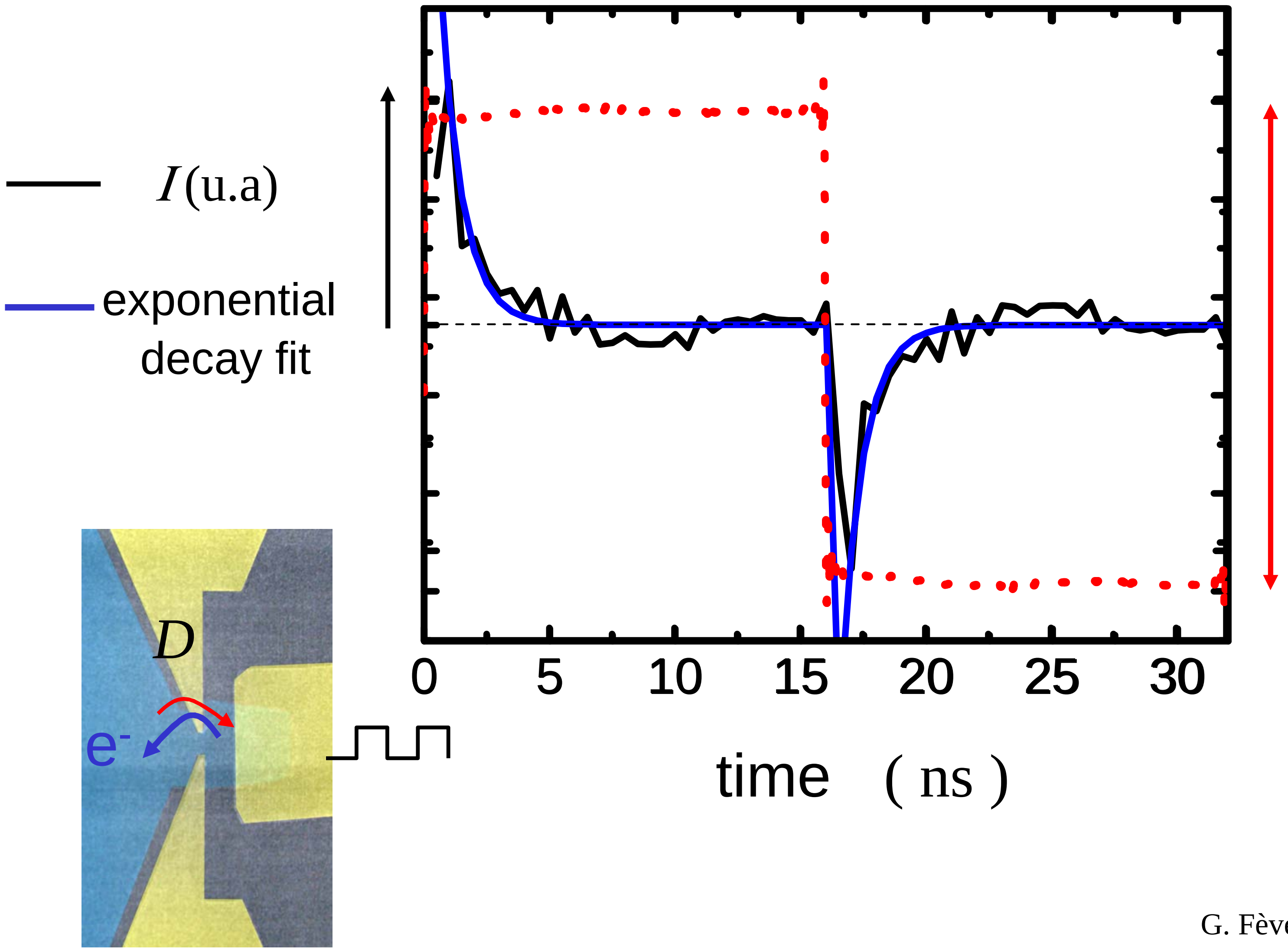
  fast acquistion and signal averaging

- 3) $\Rightarrow$ **phase resolved harmonic response** to a square excitation

  In phase and in quadrature (I-Q) detection of first harmonic

  $\Rightarrow$ quantized ac current $I = 2\,e\,f$

time-domain measurements



$V_G = -907\ mV$

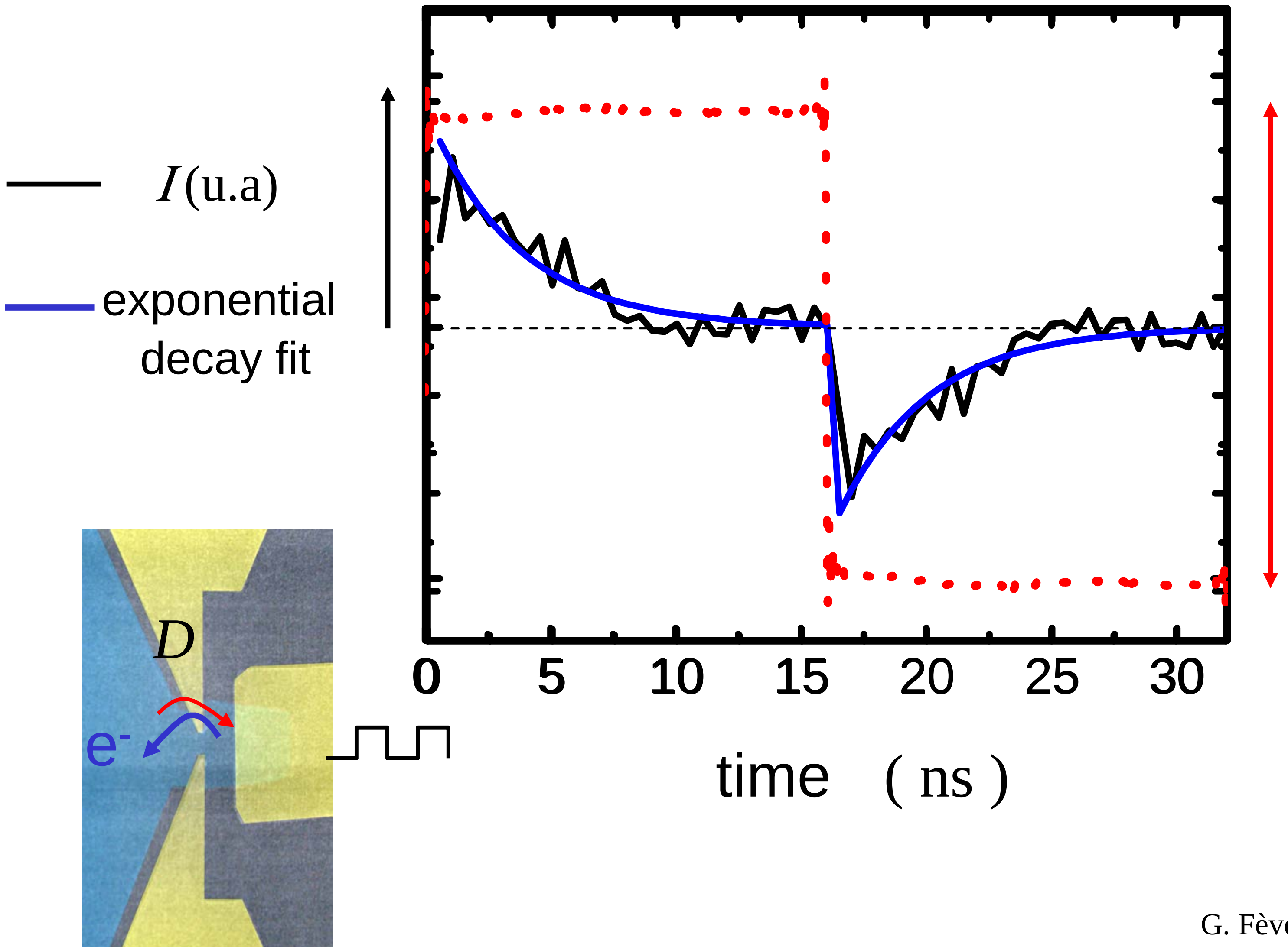
$eV_{exc} = \frac{e^2}{C_\mu}$

$\boxed{\tau = 0.9\ ns}$

$D \approx 0.02$

G. Fève *et al.*, Science ***316,*** *1169 (2 007)*

time-domain measurements



$V_G = -909.2\ mV$

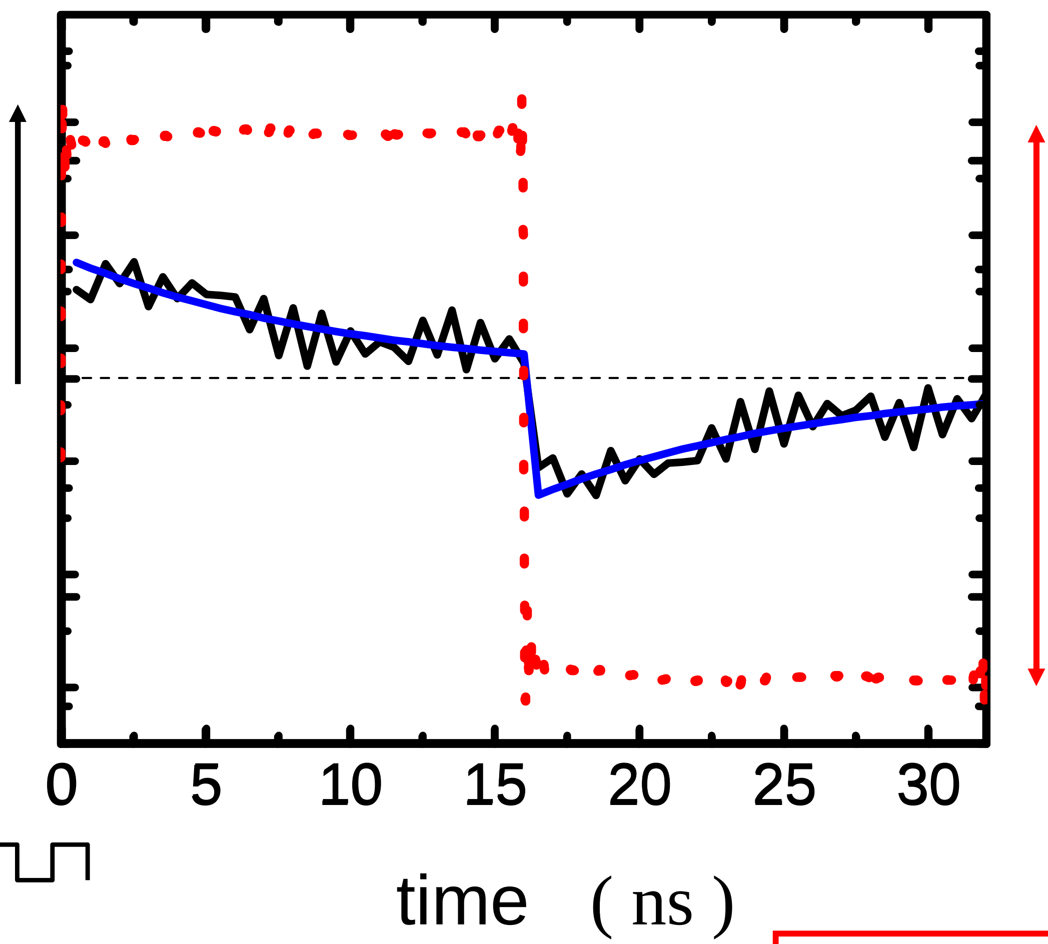
$eV_{exc} = \frac{e^2}{C_\mu}$

$\boxed{\tau = 3.6\ ns}$

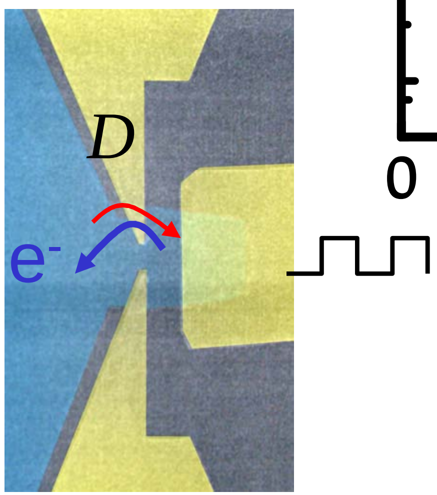
$D \approx 0.005$

G. Fève *et al.*, Science ***316,*** *1169 (2 007)*

time-domain measurements



$V_G = -913\ mV$



$\boxed{\tau = 10\ ns}$

$D \approx 0.002$

$$\boxed{\bar{I}(t) = \frac{q}{\tau} e^{-t/\tau}}$$

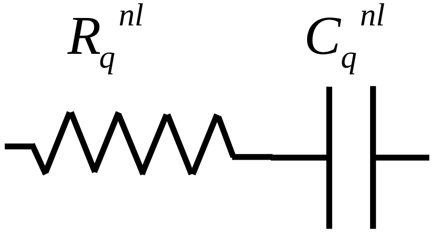
modeling :

Gwendal Fève's *Thesis*

G. Fève *et al.*, Science ***316,*** *1169 (2 007 in S.O.M.)*

for simplicity : $C \rightarrow \infty \qquad \dfrac{e^2}{C_\mu} \rightarrow \Delta$

•  non-linear : $eV_{exc} >> \hbar\omega$ $\longrightarrow$



$$C_q^{nl} = e^2 \int d\varepsilon\, N(\varepsilon) \times \frac{f(\varepsilon - eV_{exc}) - f(\varepsilon)}{eV_{exc}}$$

$$R_q^{nl} = \frac{h}{2e^2} \frac{\int d\varepsilon\, N^2(\varepsilon) \times \dfrac{f(\varepsilon - eV_{exc}) - f(\varepsilon)}{eV_{exc}}}{\left[\int d\varepsilon\, N(\varepsilon) \times \dfrac{f(\varepsilon - eV_{exc}) - f(\varepsilon)}{eV_{exc}}\right]^2}$$

$$\longrightarrow \boxed{\langle I(t) \rangle = \frac{q}{\tau} e^{-t/\tau}}$$

$$q = eV_{exc} C_q^{nl}$$

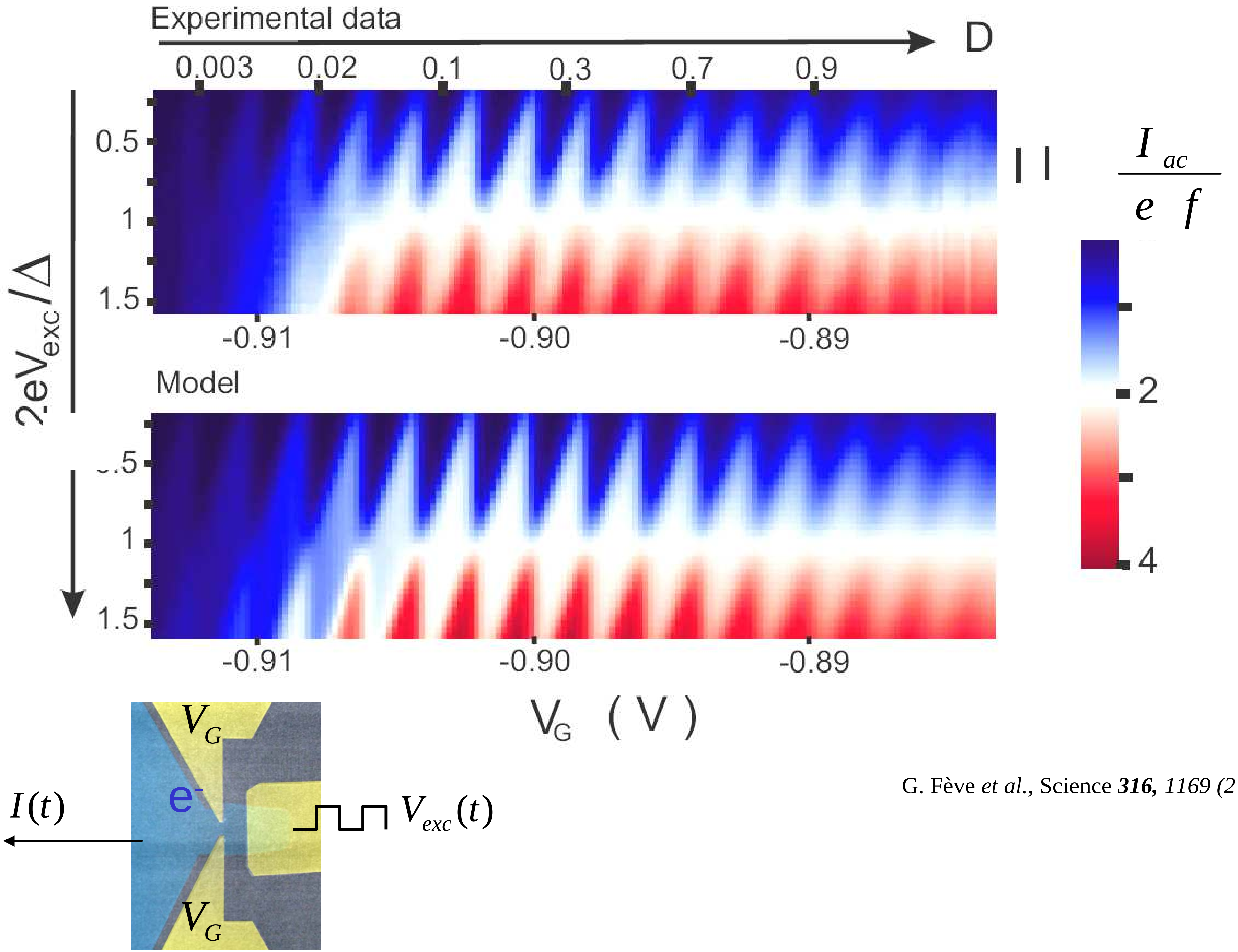
$$\tau = R_q^{nl} C_q^{nl}$$

for : $eV_{exc} = \Delta$

$C_q^{nl} = \dfrac{e^2}{\Delta}$, $\boxed{q = e}$

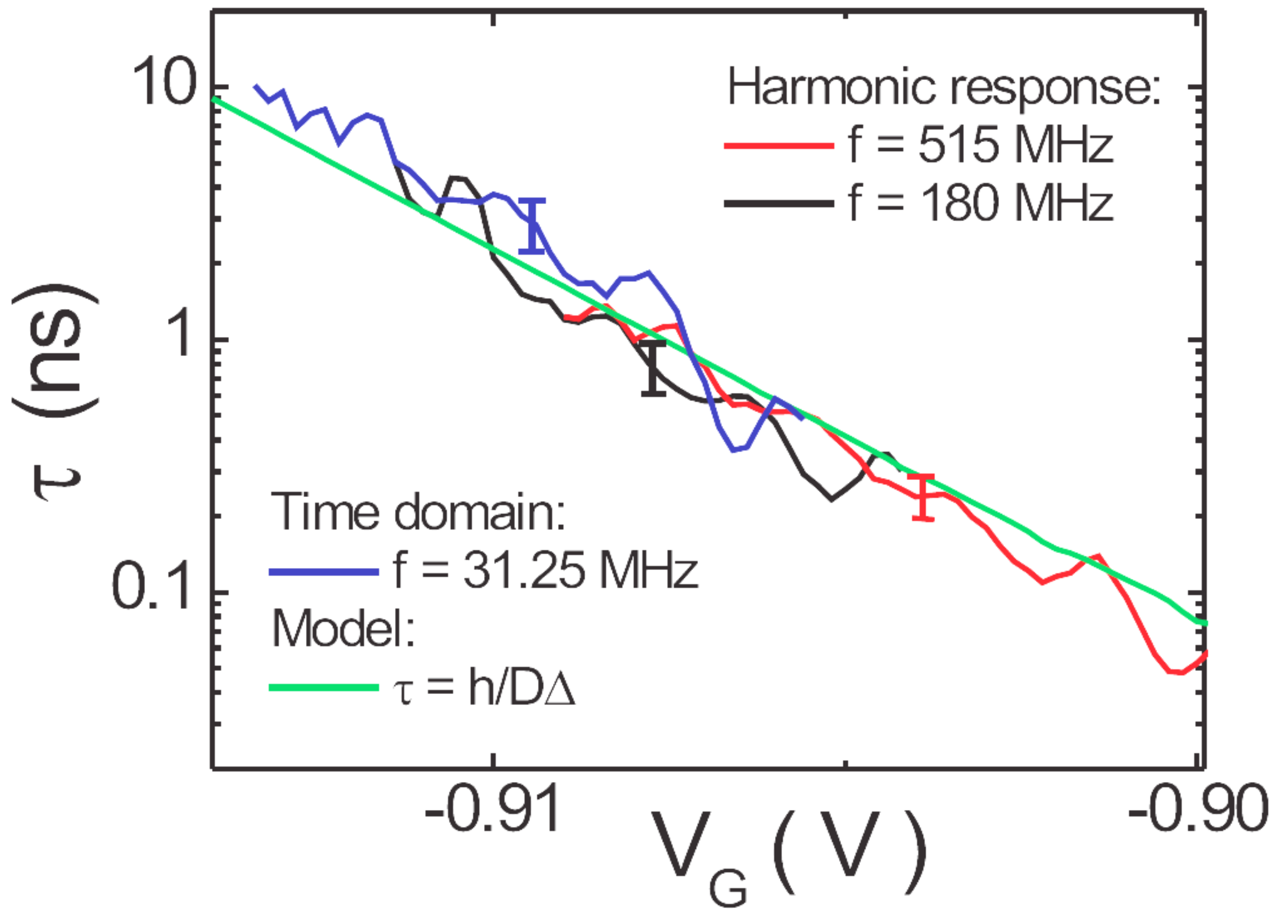
$D << 1, \quad R_q^{nl} = \dfrac{h}{e^2 D}$

$$\boxed{\tau = \frac{h}{D\Delta}}$$



G. Fève *et al.*, Science ***316,*** *1169 (2 007)*

escape (or emission) time



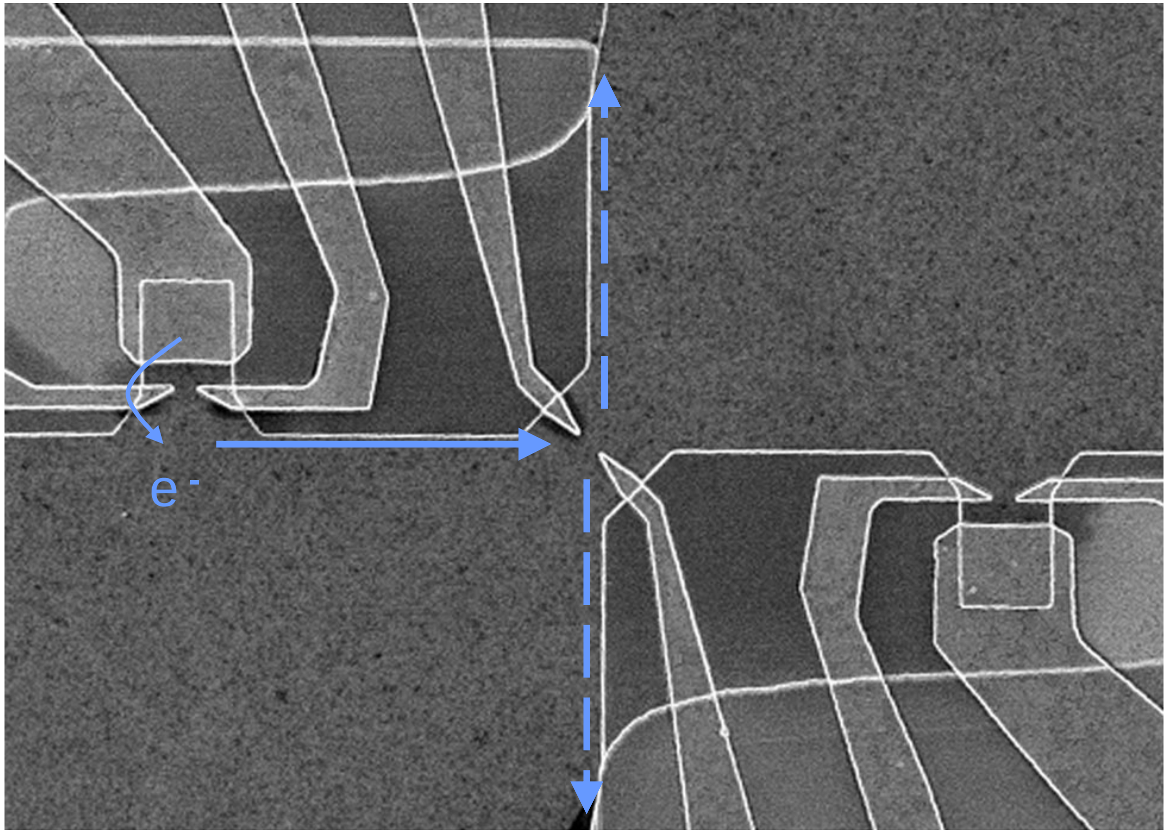
MESURED ESCAPE TIME AGREE WITH : $\tau = h/D\Delta$ (no adjustable parameter)

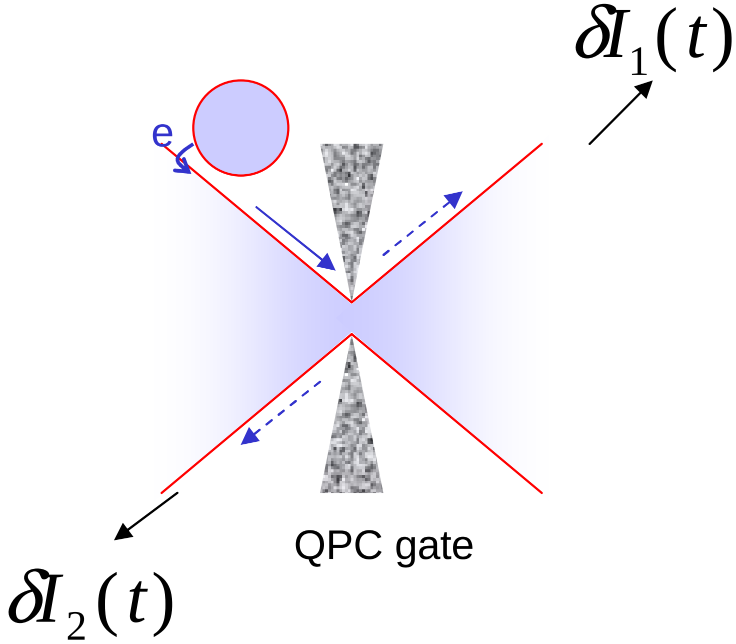
$\Rightarrow$ suitable for coherent manipulation of single electrons

G. Fève *et al.*, Science ***316,*** *1169 (2 007)*

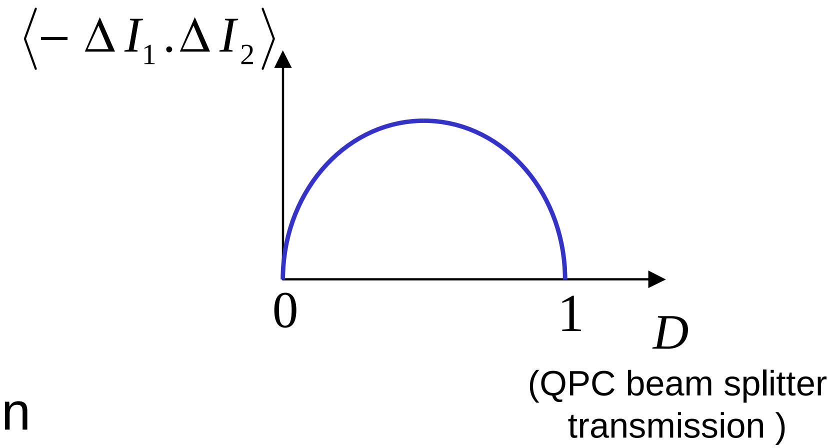
new physics with the on-demand S.E.S.

single electron (hole) partitioning





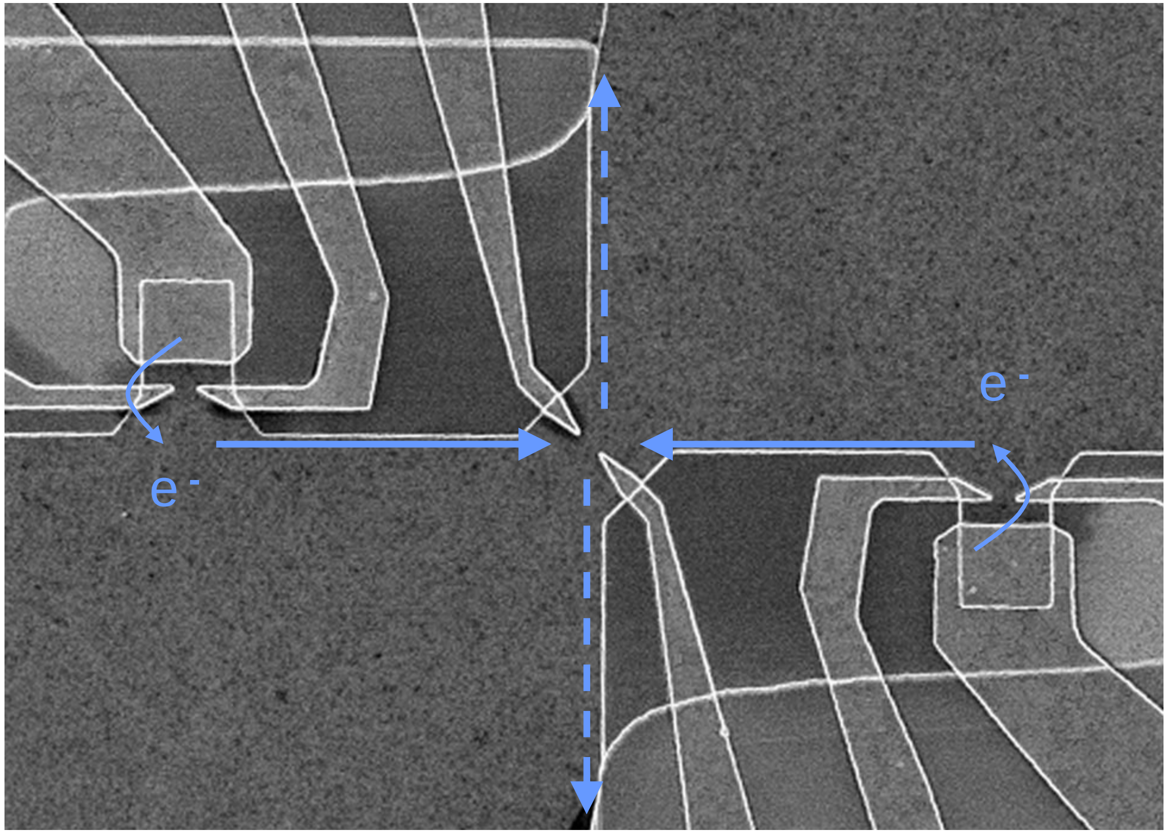
$$\langle \Delta I_1 . \Delta I_2 \rangle \propto -2e\,D(1-D)(2ef)$$

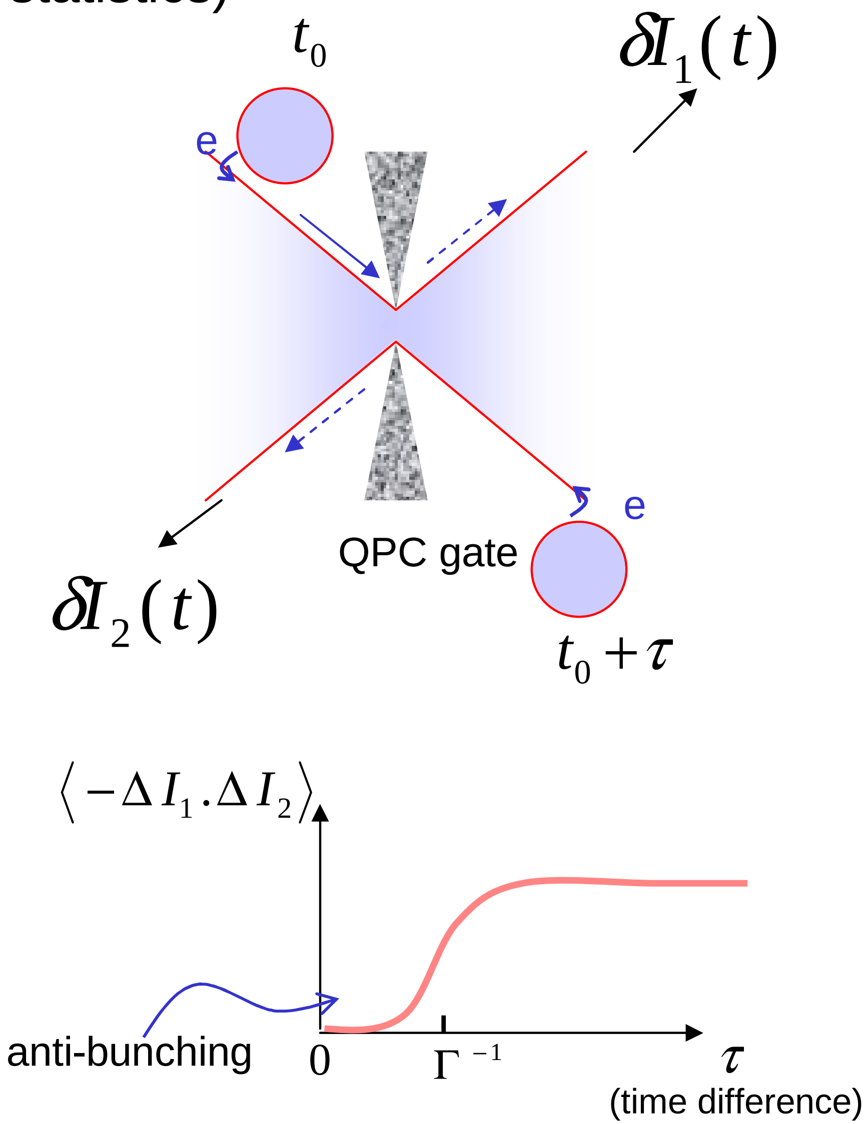


should provide unambiguous electron anticorrelation

new physics with the on-demand S.E.S.

Two- electron (hole) partitioning (probe of Fermi statistics)

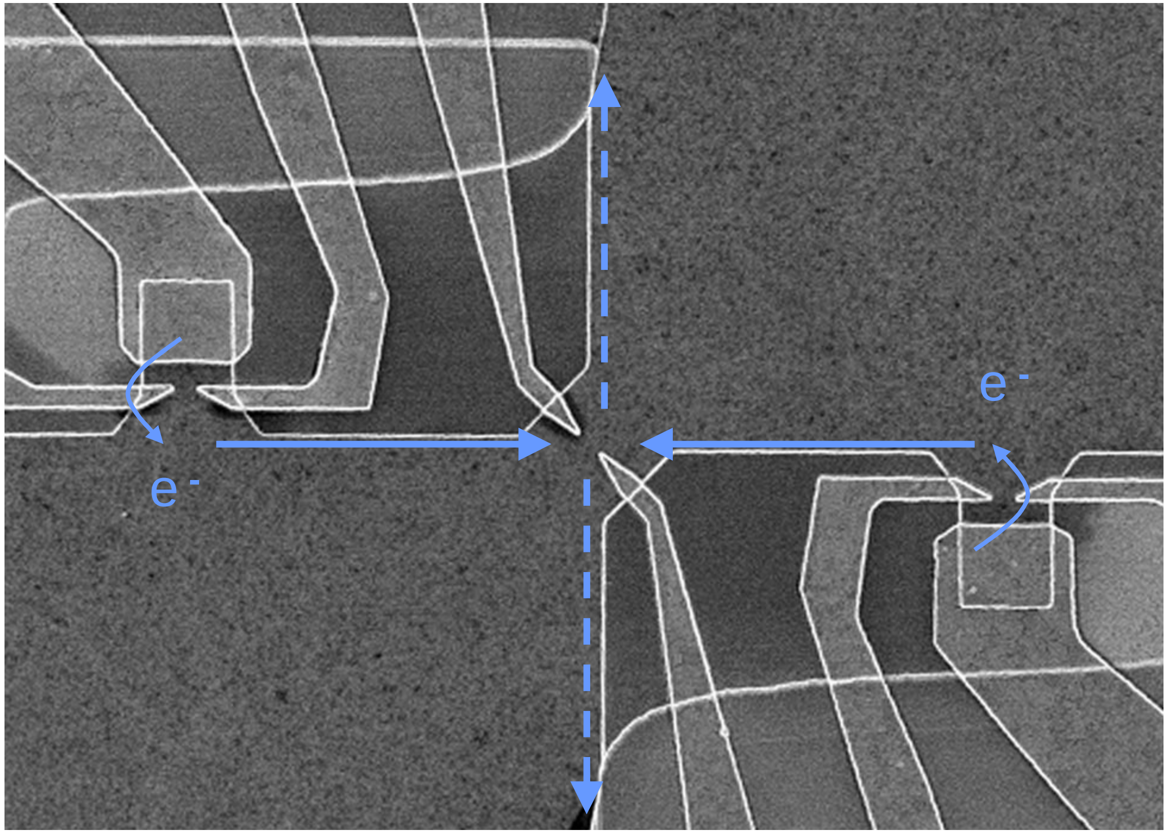


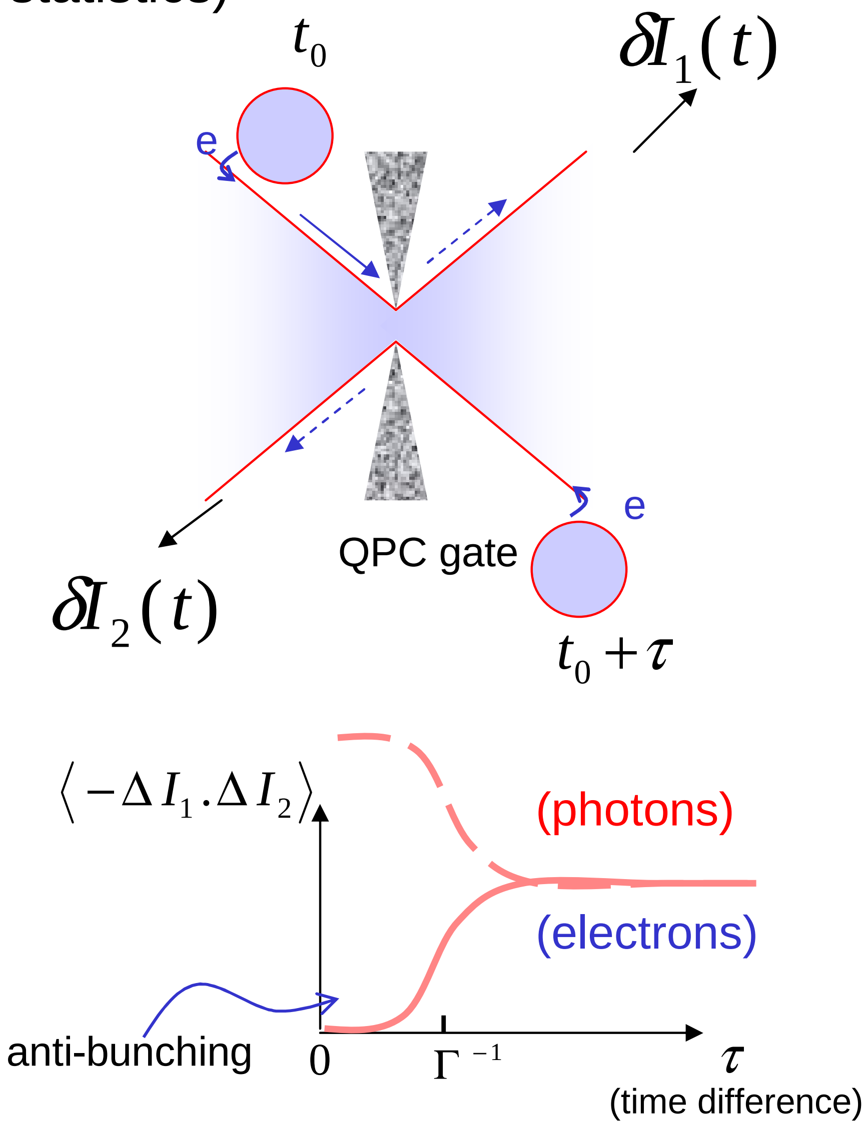


should provide unambiguous electron anti-bunching

new physics with the on-demand S.E.S.

Two- electron (hole) partitioning (probe of Fermi statistics)





(expected results soon ! (next year))

should provide unambiguous electron anti-bunching (analog Hong-Ou-Mandel)

new physics with the on-demand S.E.S.

• measure of electron coherence length with HOM type correlation with electrons

• deviations from Fermi statistics should provide information on e-e interactions

• on-demand S.E.S first step toward implementation of quantum information :
(statistical measurements of flying qubit)

• SES has stimulated many theoretical predictions :

Shot Noise of a Mesoscopic Two-Particle Collider *Ol'khovskaya, Phys. Rev. Lett. 101, 166802 (2008)*

Coherent Particle Transfer in an On-Demand Single-Electron Source, *J. Keeling, A.V. Shytov, and L. S. Levitov, PRL 101, 196404* (2008)

Quantized Dynamics of a Coherent Capacitor, *M. Moskalets P. Samuelsson and M. Büttiker, PRL 100, 086601 (2008)*

Electron counting with a two-particle emitter, *Janine Splettstoesser, Sveta Ol'khovskaya, Michael Moskalets and Markus Büttiker PRB 78, 205110 (2008)*

OUTLINE

Magic properties of the Fermi sea

On-demand single electron source for flying qubits (running experiment)

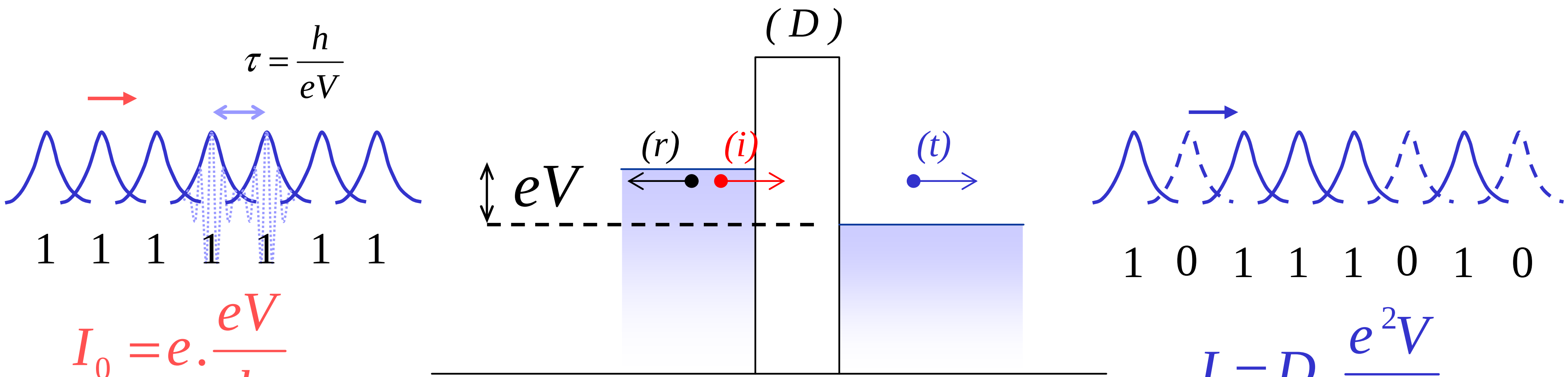
N-electron source for Full Counting Statistics (new project)

Counting charges for FCS or quantum information (new project)

Conclusion

Electron Full Counting Statistics

- $P_{N_0}(n)$: probability of n- transmitted electrons for N_0 emitted electrons



$$I_0 = e.\frac{eV}{h}$$

$$I = D\,\frac{e^2V}{h}$$

Binomial statistics

$$P_{N_0}(n) = C_{N_0}{}^{n}\, D^n\, (1-D)^{N_0-n}$$

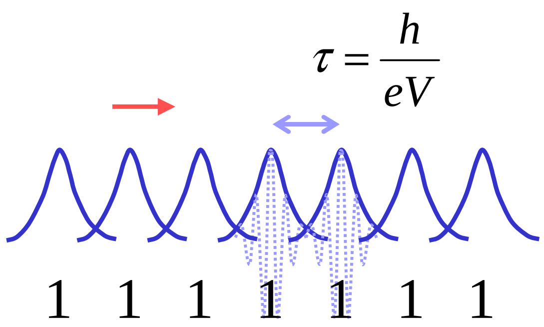
$$N_0 = \frac{eV}{h}\tau_{measurement}$$

N_0 large
(~classical)

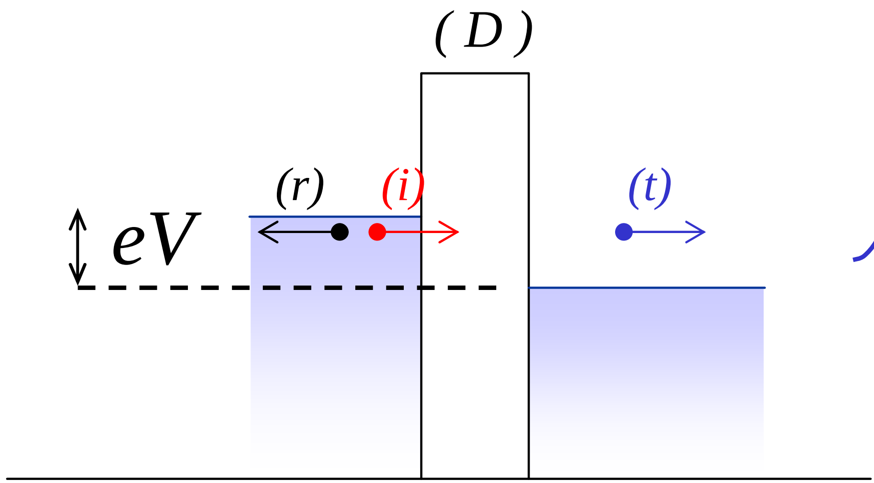
"win or loose game"

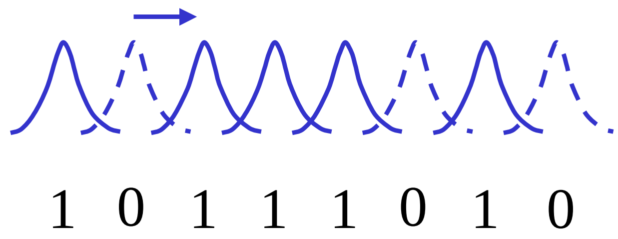
Electron Full Counting Statistics

- $P_{N_0}(n)$: probability of n- transmitted electrons for N_0 emitted electrons



$$I_0 = e.\frac{eV}{h}$$





$$I = D\,\frac{e^2V}{h}$$

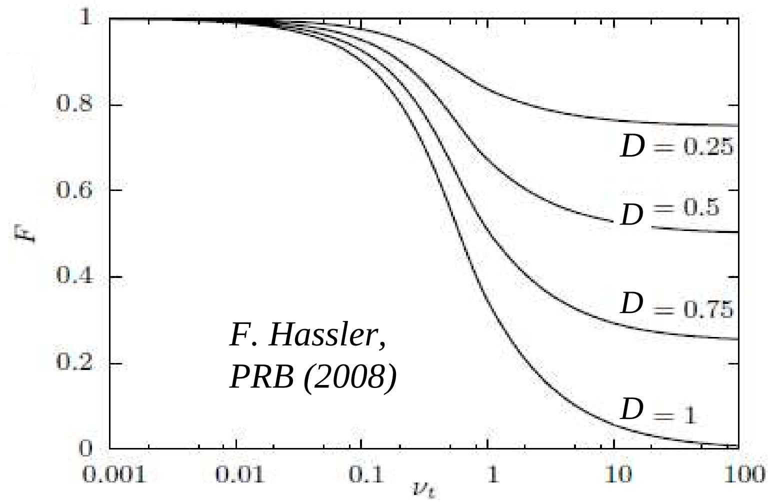
Binomial statistics

$$\boxed{F = \frac{\left\langle (n-\bar{n})^2 \right\rangle}{\bar{n}} = 1 - D}$$

Fano factor may be larger for small N_0 or small timescale

$$\boxed{N_0 = \frac{eV}{h}\tau_{measurement}}$$

N_0 small
(~more quantum)



Present approaches to Full Counting Statistics

- Statistics of flux (current), not of particles.

Measure the p^{th}-moment of current fluctuations

p=1 conductance
p=2 shot noise
p=3 third moment
...

$$G \propto \sum_n D_n$$

$$S_I \propto \sum_n D_n (1 - D_n)$$

$$S_I^{(3)} \propto \sum_n D_n (1 - D_n)(1 - 2D_n)$$

...

- non-unique definition of n-moment current fluctuations at high frequency

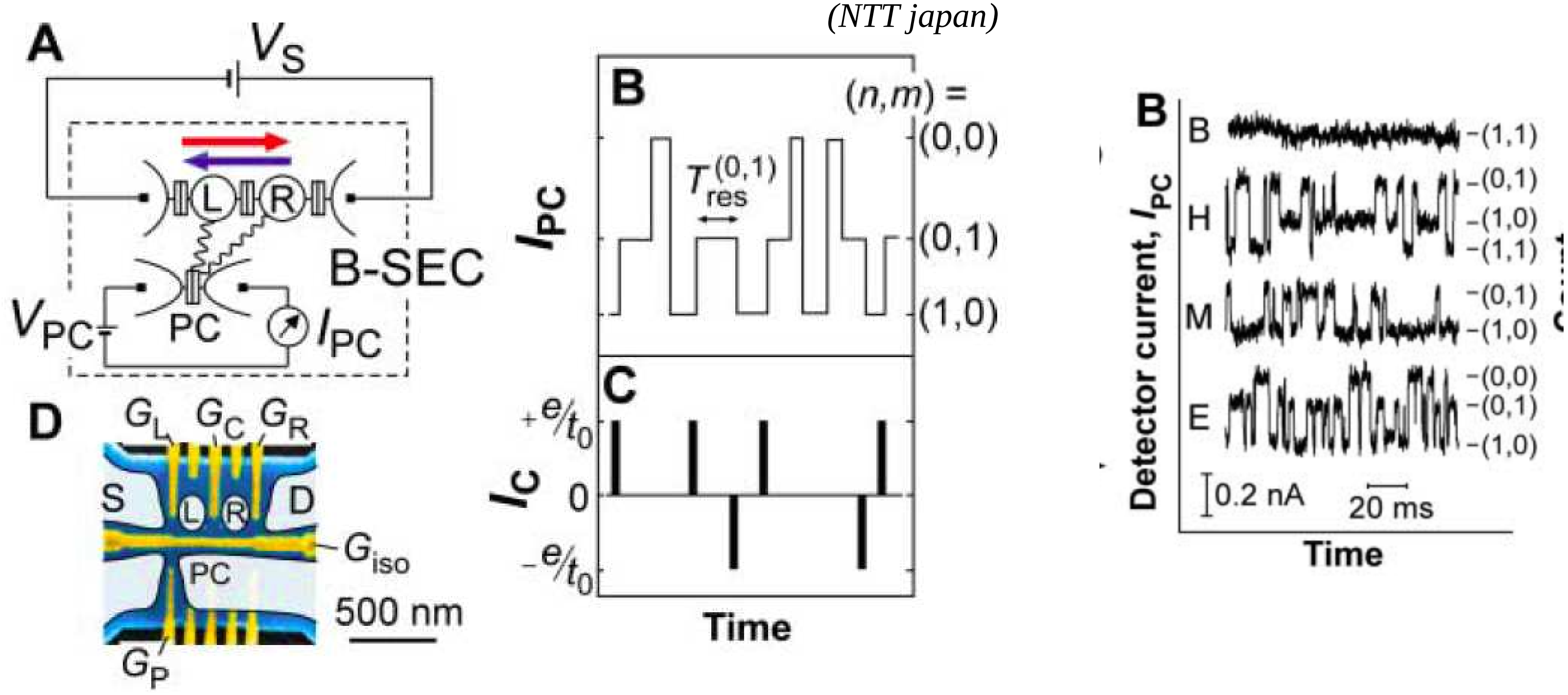
$$S_I^{(p)}(\omega_1, \omega_2, \ldots, \omega_{p-1})$$

- measurements of the low frequency third moment have been done in tunnel junctions (Reulet et al 2003, Reznikov 2005), LeMasne (2009)) and in a QPC (Reznikov 2008).

Present approaches to Full Counting Statistics

• statistics from direct counting of electrons.

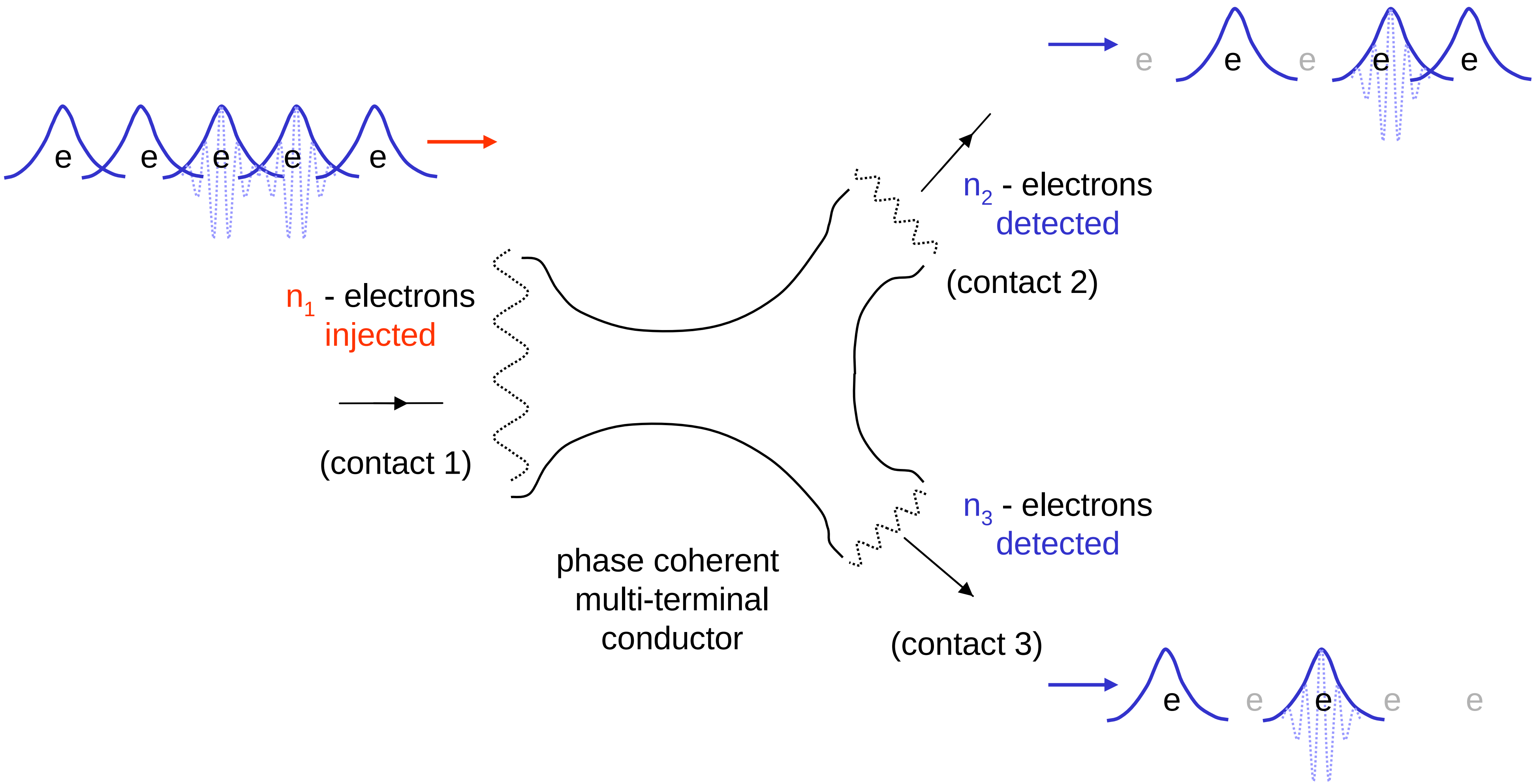
T. Fujisawa et al, Science 312 (2006) (NTT japan)



Also : S. Gustavson, Phys. Rev. Lett. **96**, 076605 (2006) (E.T.H. Zürich)

• non-coherent regime : slow sequential events

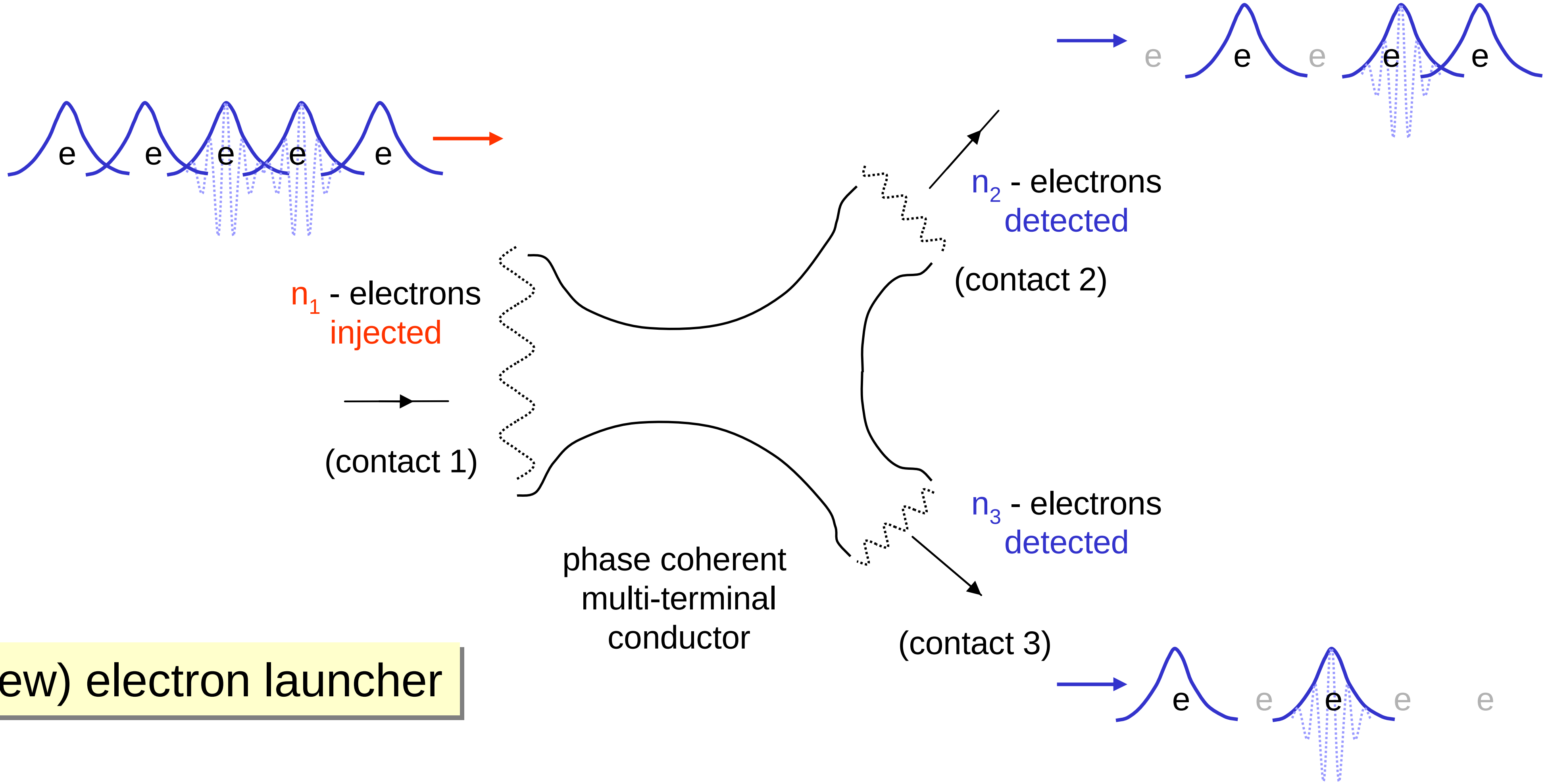
quantum statistics of few electrons



Full Counting Statistics generalised to multi-terminal conductors

n-electron statistics: binomial $\rightarrow$ multi-nomial

invent new tools :



(few) electron launcher

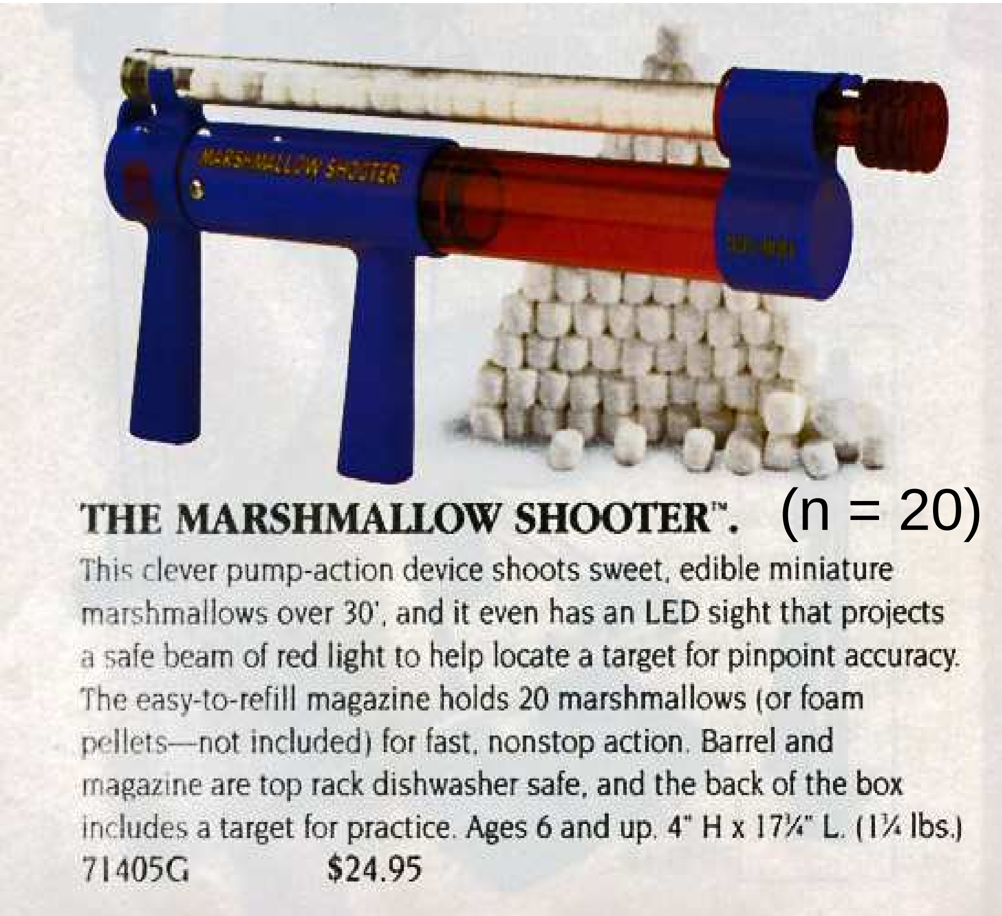
electron playground

electron bunch detector

the n-electron source

(injecting n electrons)

requirement : as simple as possible



(n = 20)

the n-electron source

requirement : as simple as possible … and reliable

Review This Product

Choose a sort order

Customer Review:
lame, October 8, 2008
By frjon (read all my reviews)

"The marshmallows frequently get stuck. Not as fun as I thought it would be"

Was this review helpful to you? **Yes No (Report Inappropriate Review)**
Share this Review:

Customer Review:
look elsewhere, October 1, 2008
By scrappinqueen (read all my reviews)

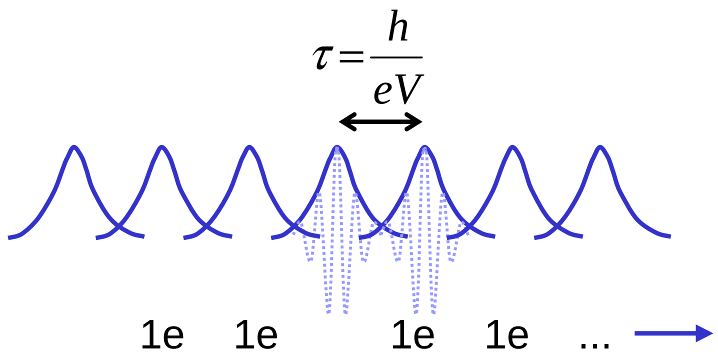
"The marshmallow shooter is poorly made. It was cracked when we received it. Great idea for a child but it needs to be better made. Maybe charge a little more but it should be made with better quality products."

Gender: **Female**
Age: **36-40**

Was this review helpful to you? **Yes No (Report Inappropriate Review)**
Share this Review:

available single electron source

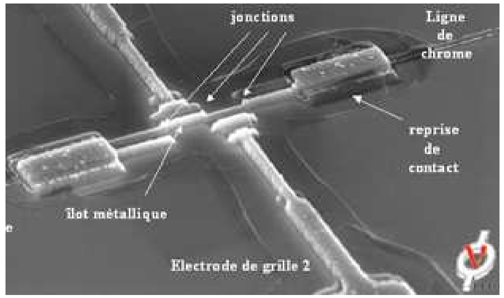
known remarkable electron source :

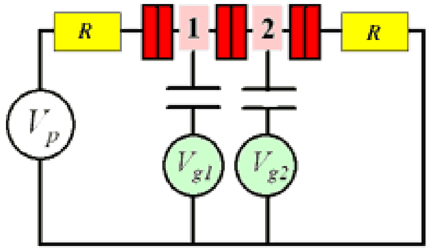


• voltage biased contact :

continuous generation of electrons entangled in a giant Slater determinant at eV/h pace !

But : no time control



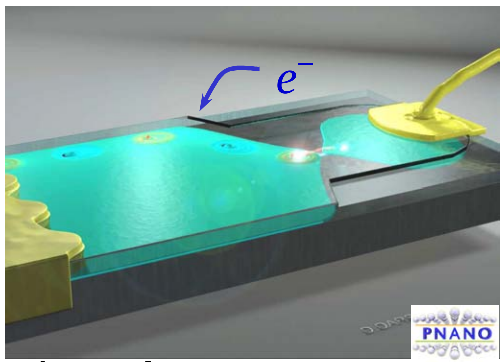


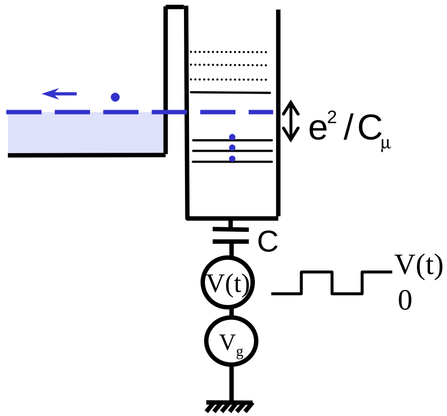
• single electron pumps :

controlled injection of single charge

but : sequential electron injection

(incoherent: not a Slater determinant)





G. Fève et al, Science 2007

• recent single electron gun:

perfect source for flying qubit realisation

coherent single electron source

opens new field of quantum experiments

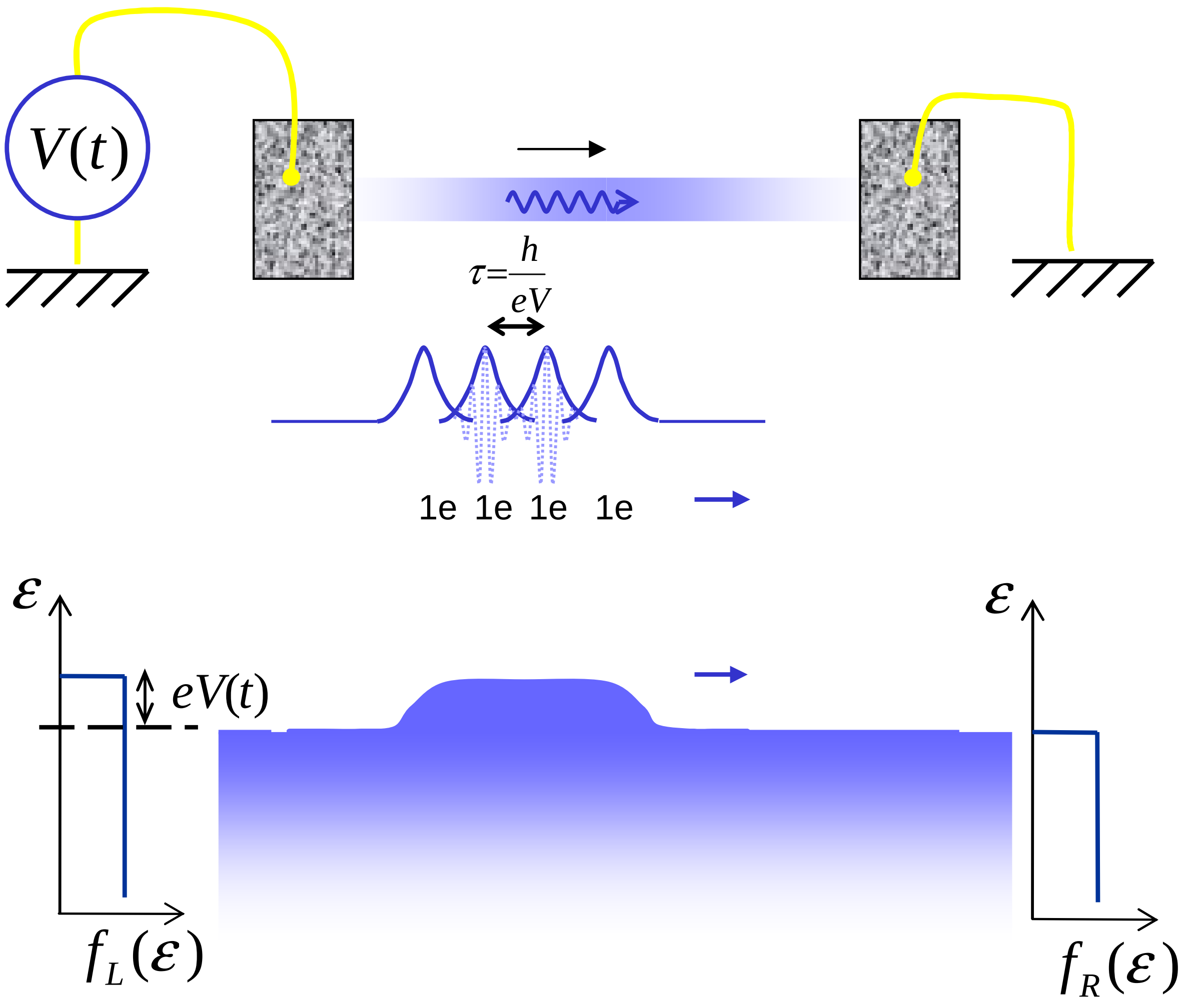
But: difficult to operate for n-electrons

the n-electron source

electrons in a shake !

gentle shake of Fermi sea using voltage pulse

$$\int eV(t)\,dt = n\,h$$



the n-electron source

gentle shake of Fermi sea using voltage pulse

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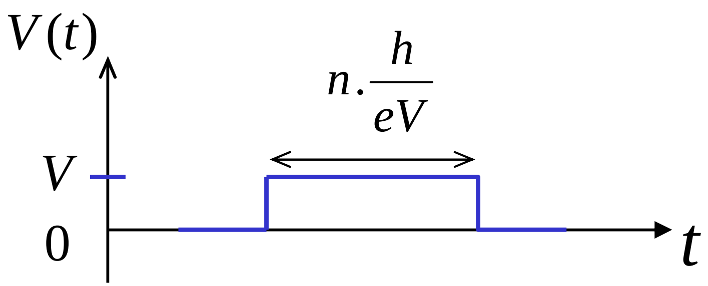
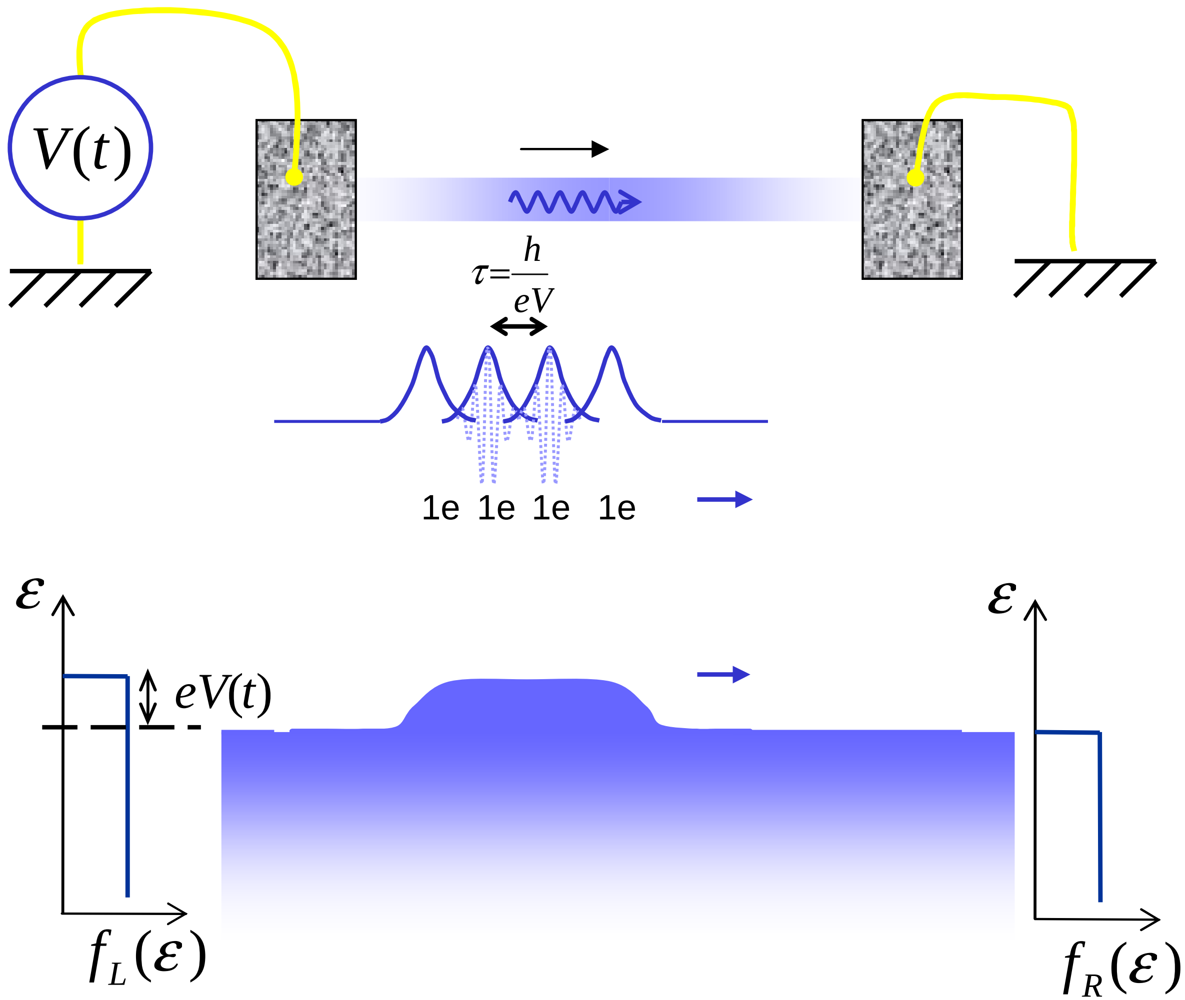
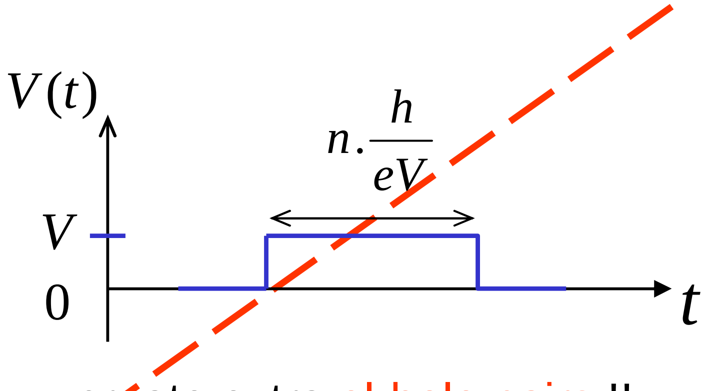


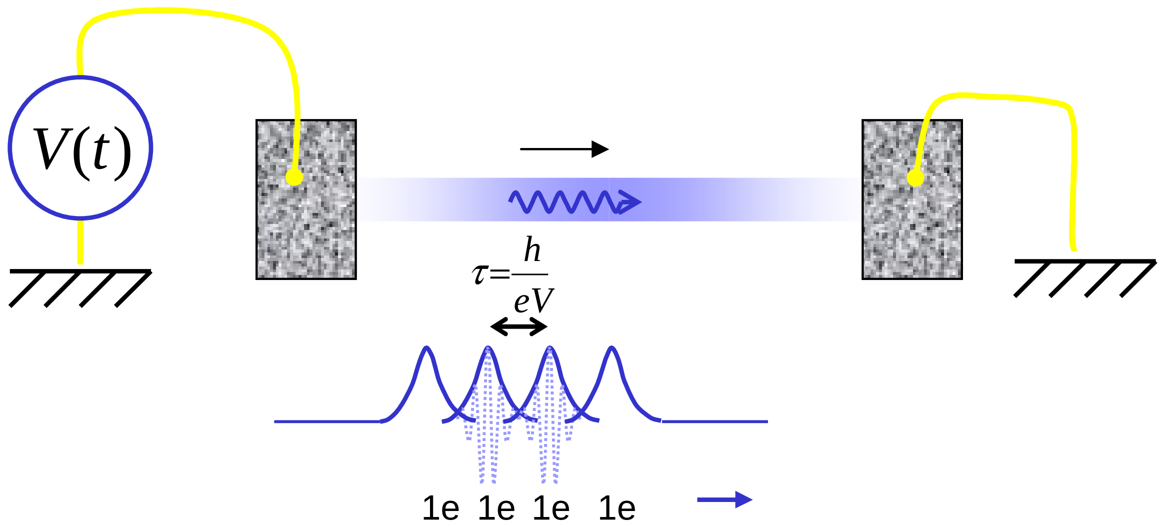


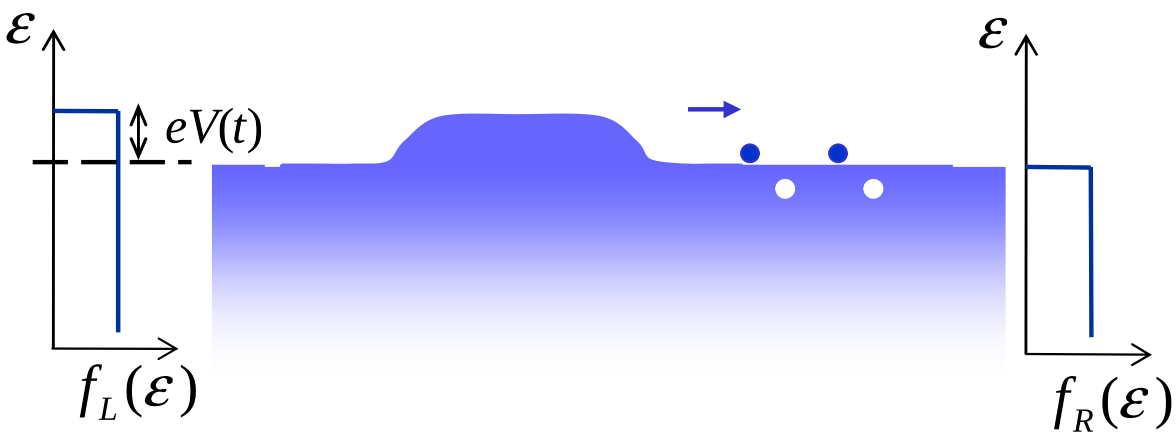
the n-electron Levitov's coherent source

$$\int eV(t)\,dt = n\,h$$



create extra el-hole pairs !!



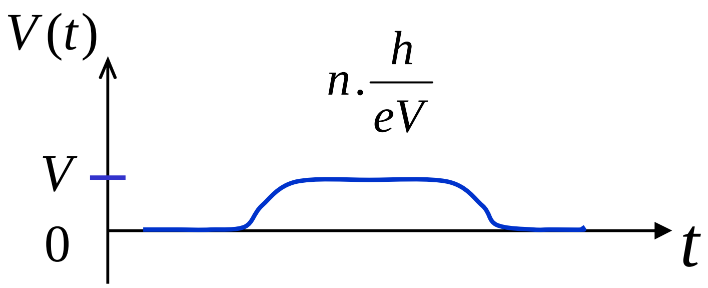


Levitov, Lee and Lesovik, J. Math. Phys. 37, 4845 (1996);Phys. Rev. B 56, 6839 (1997)

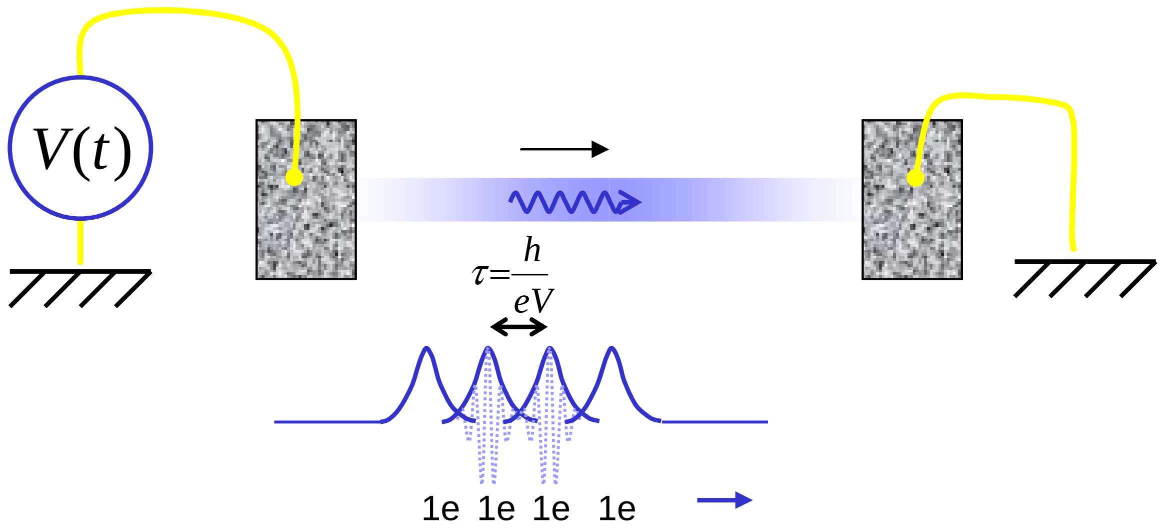
the n-electron Levitov's coherent source

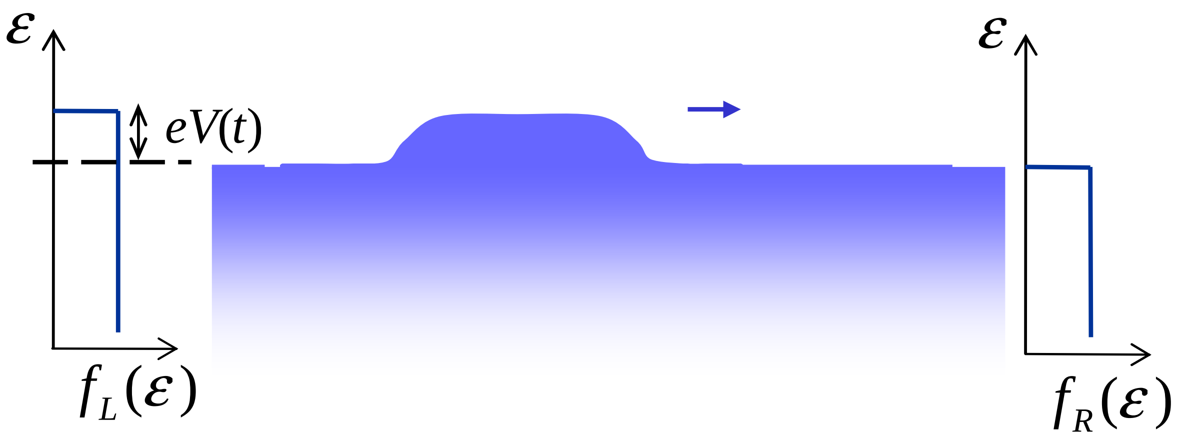
$$\int eV(t)\,dt = n\,h$$

non trivial th. result: minimal excitation pulses must have Lorentzian time dependence



$$V(t) = \pm \frac{h}{\pi e} \sum_{k=1}^{n} \frac{\tau_k}{(t-t_k)^2+\tau_k^2}\ , \tau_k > 0$$





the n-electron Levitov's coherent source

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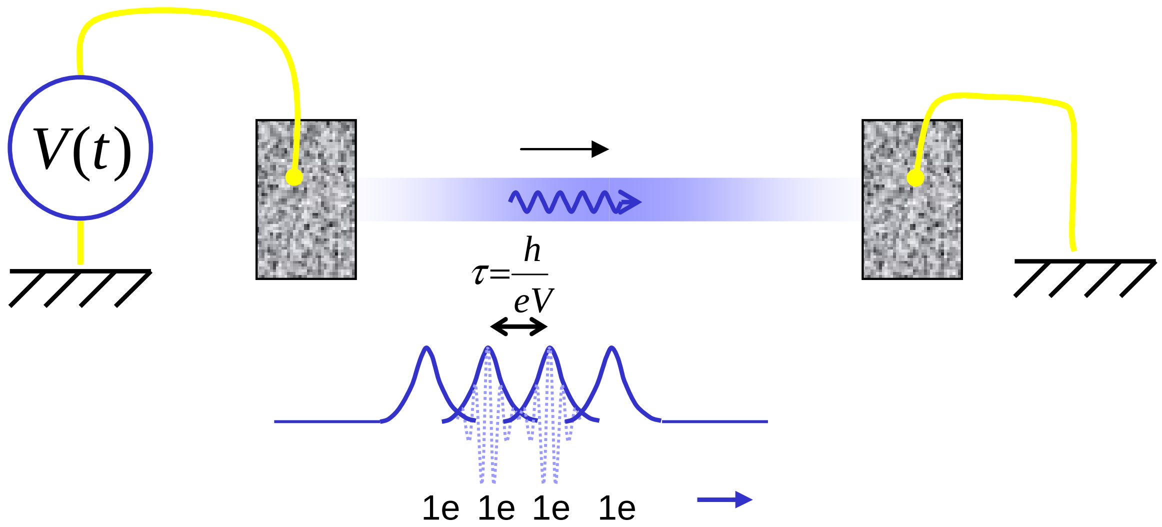

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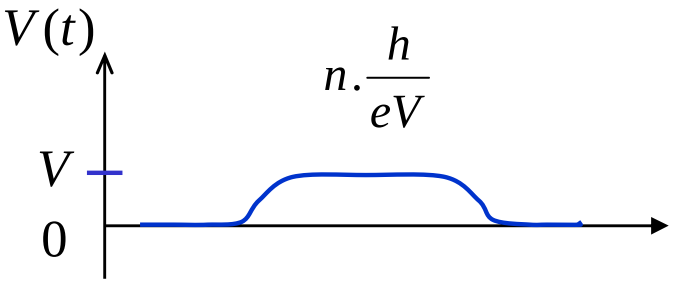


$$V(t) = \pm\frac{h}{\pi e}\sum_{k=1}^{n}\frac{\tau_k}{(t-t_k)^2+\tau_k^2}\ ,\ \tau_k > 0$$

$$\tau_K << \frac{h}{n\pi k_B T}$$

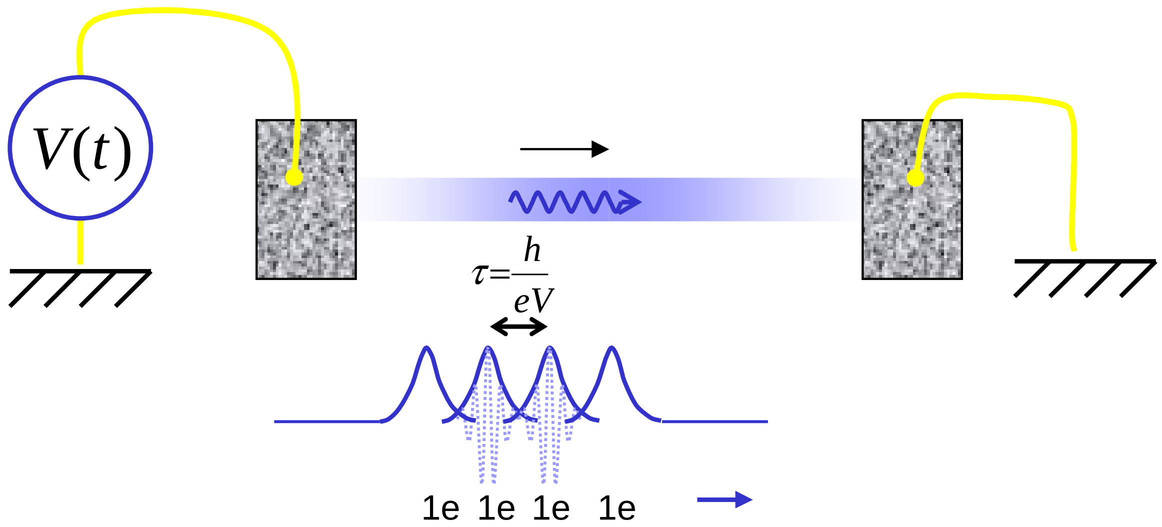
$$\tau_K << \frac{0.5\,\mathrm{ns}}{n}$$

@ 30 mK

(10bit 24Gs/s 9.6GHz bw arbitrary waveform generator)

the n-electron Levitov's coherent source

$$\int eV(t)\,dt = n\,h$$



→ generation of single electrons with voltage pulse
- reveal fundamental properties of the Fermi sea
- allows to investigate few electron FCS

OUTLINE

Magic properties of the Fermi sea

On-demand single electron source for flying qubits (running experiment)

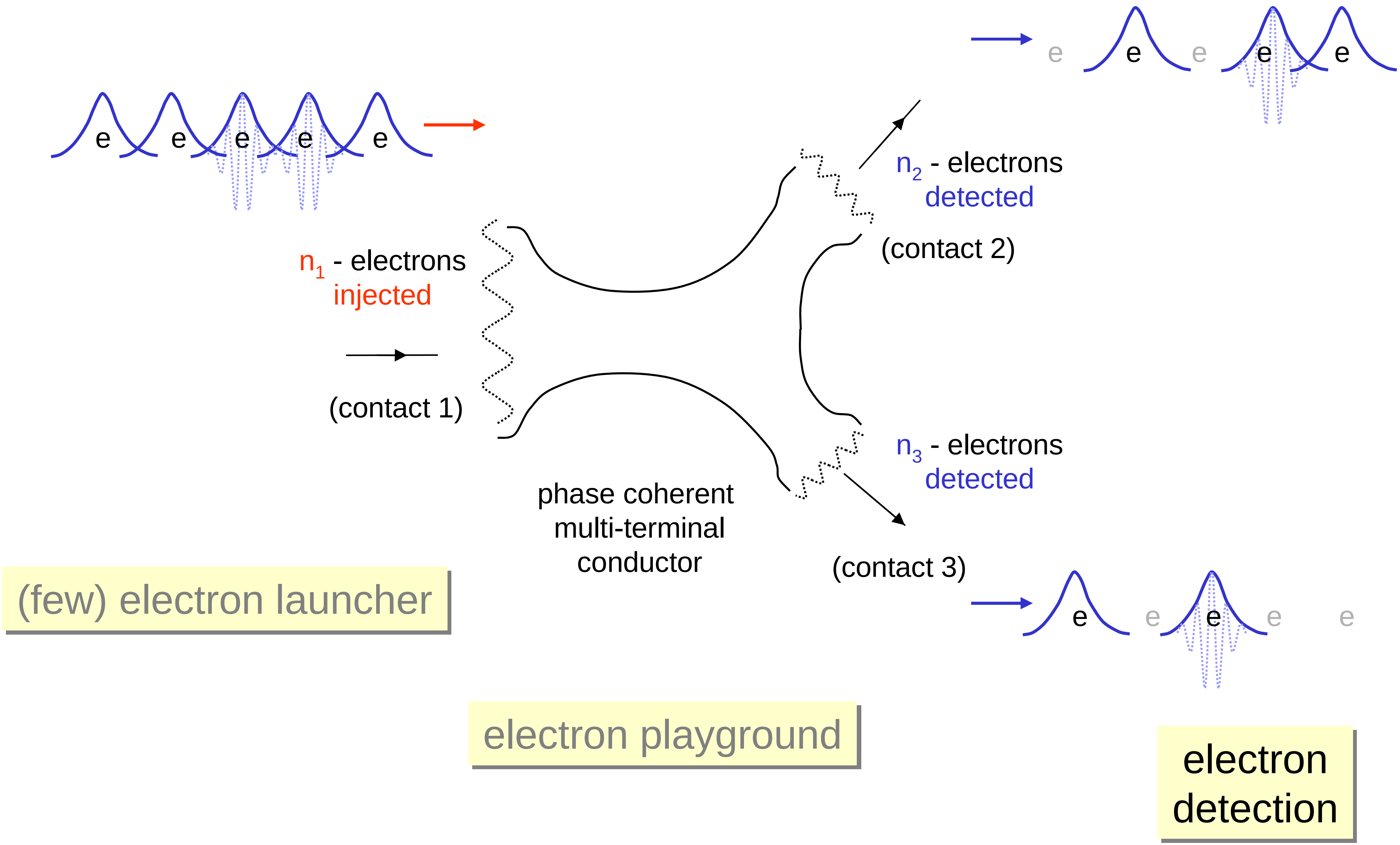
N-electron source for Full Counting Statistics (new project)

Counting charges for FCS or quantum information (new project)

(cutting the Fermi sea)

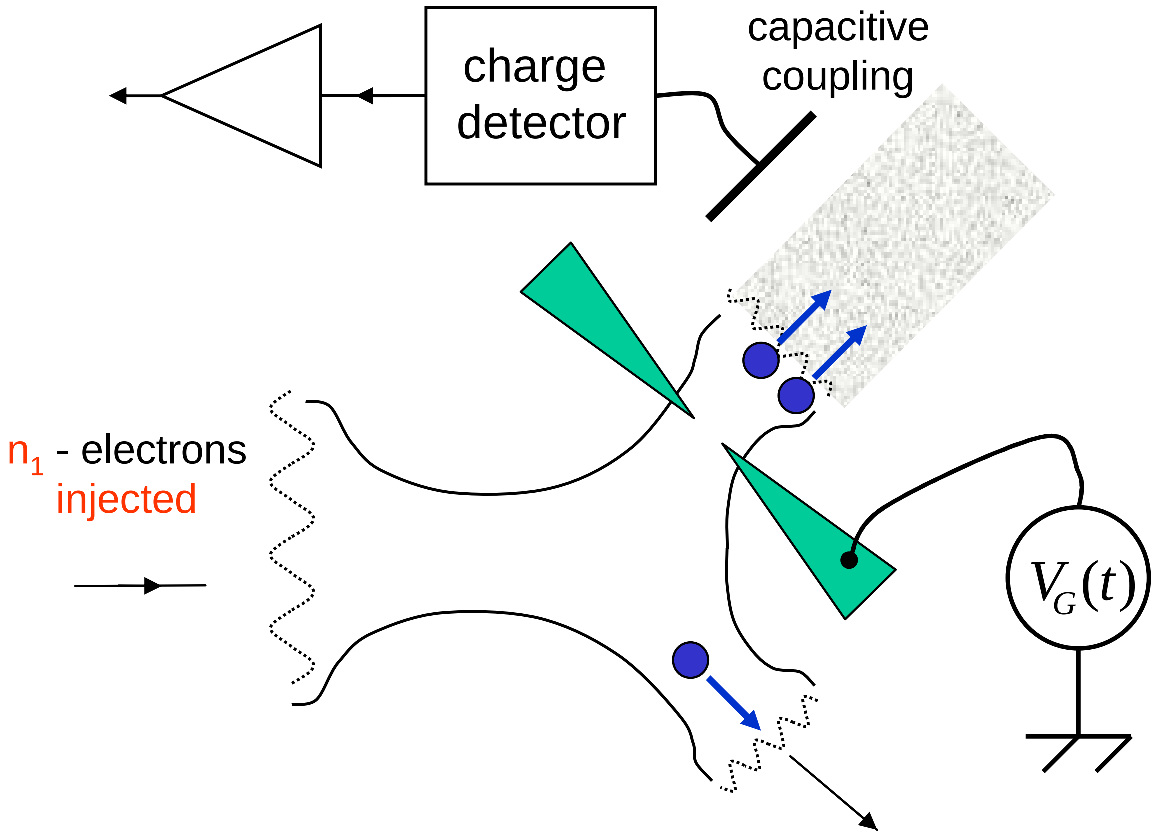
Conclusion

detecting single electrons arriving in contacts :



detecting single electrons arriving in contacts :

possible strategy catching electrons



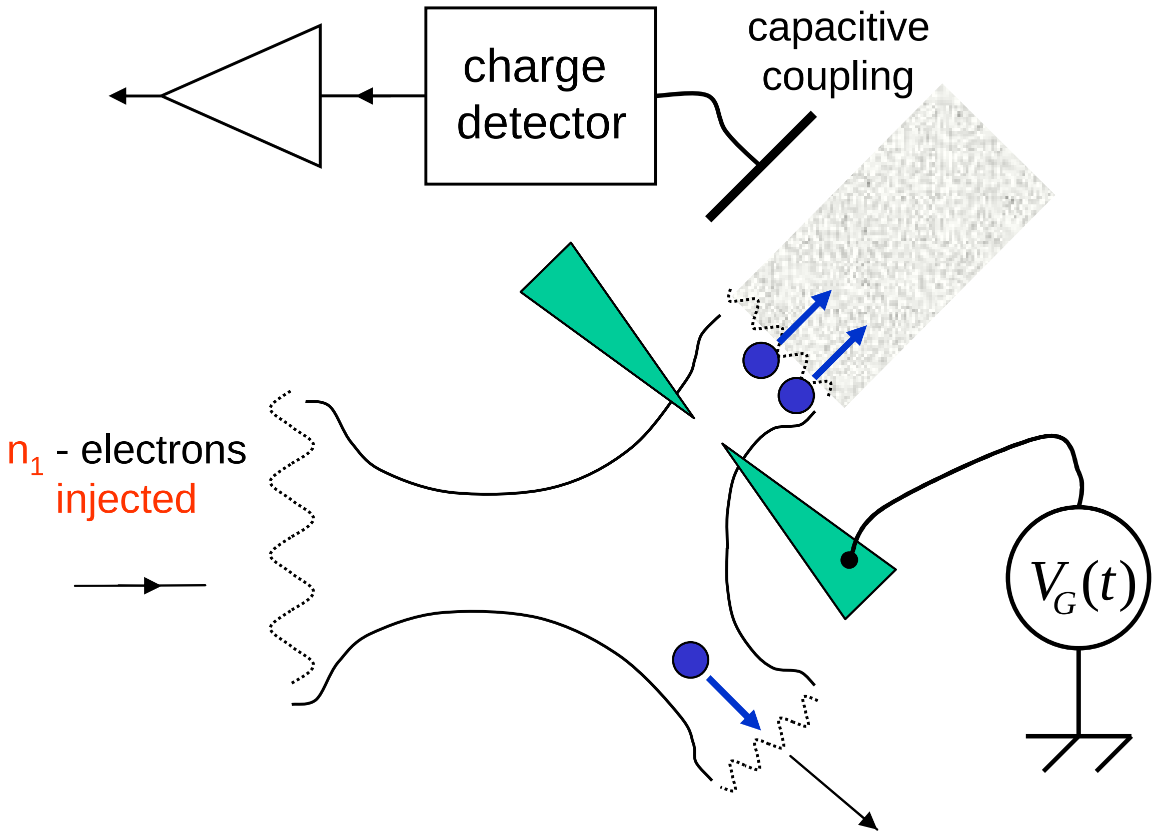
1) isolate electrons in contacts

2) take necessary time for
single charge accuracy

1 e^- over 100fF contact $\rightarrow$ 1.6 μV
$\rightarrow$ easily detectable in 1 μs

new tools : electron detector

possible strategies : … or catching electrons



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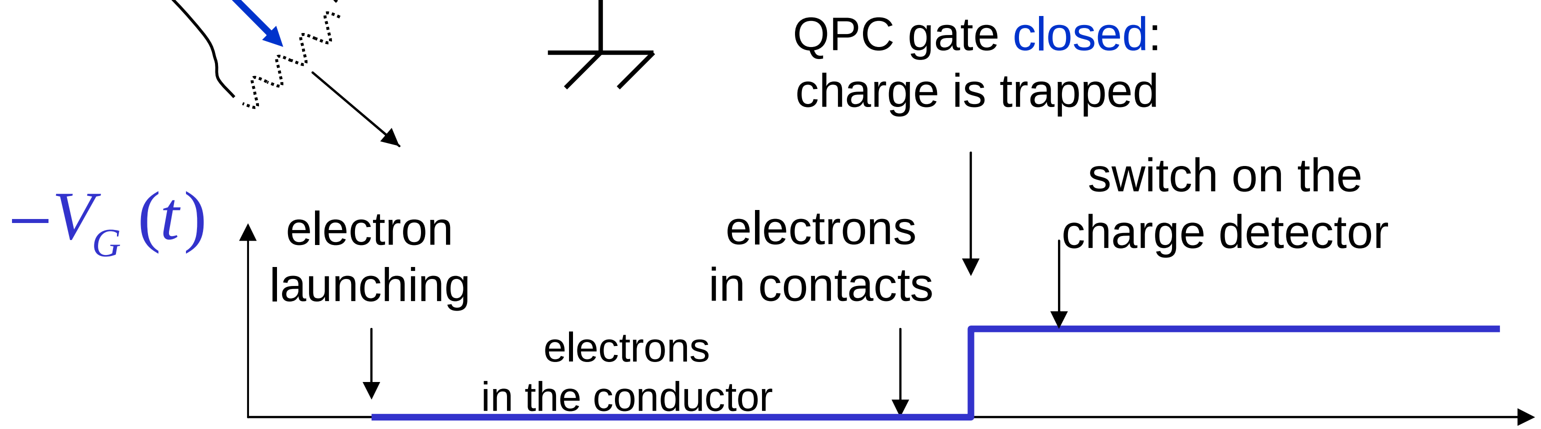
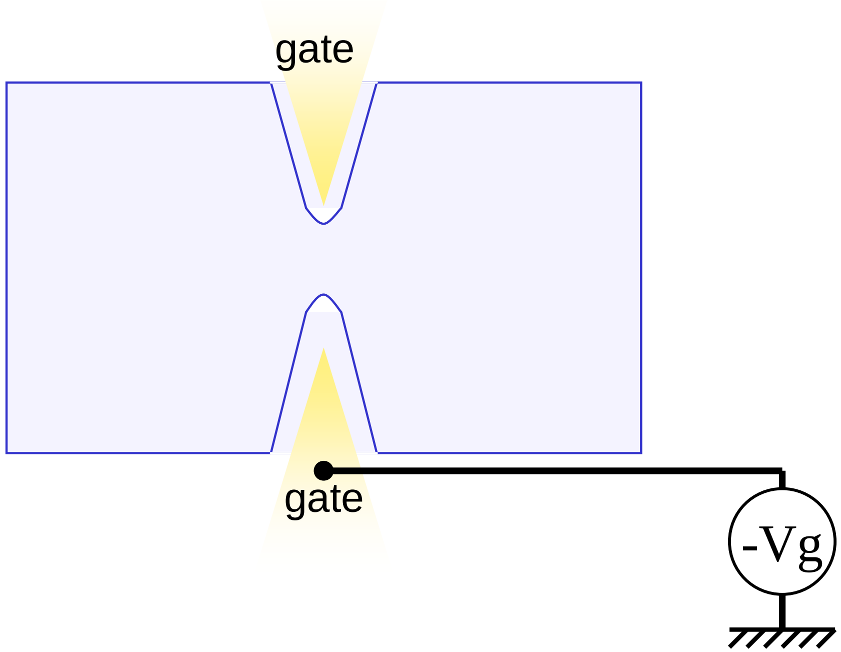
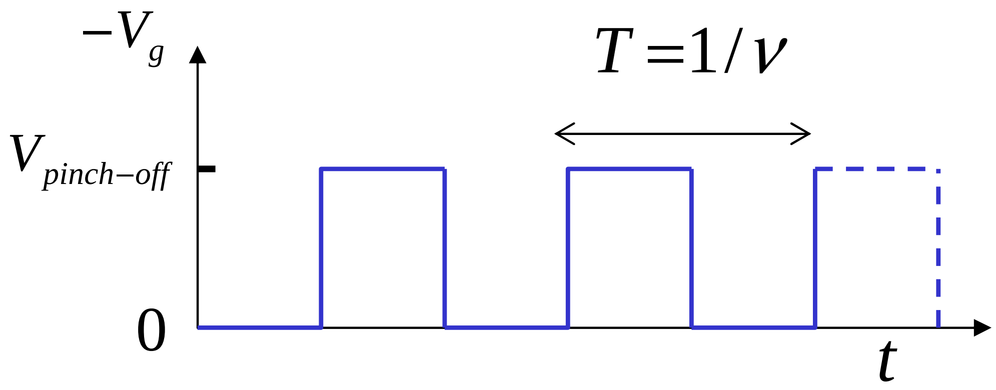
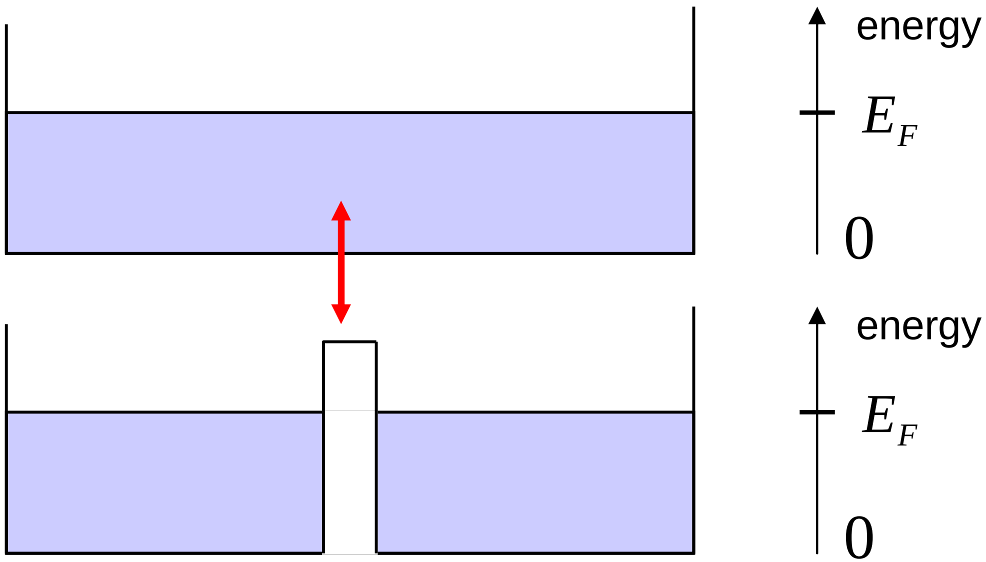


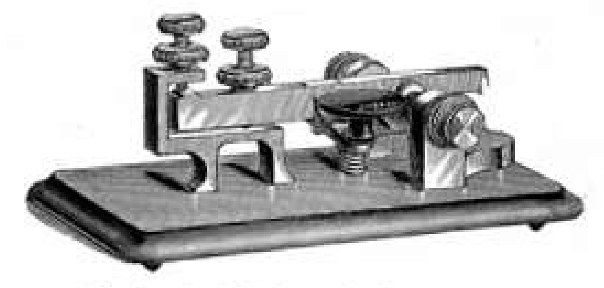
cutting the Fermi sea

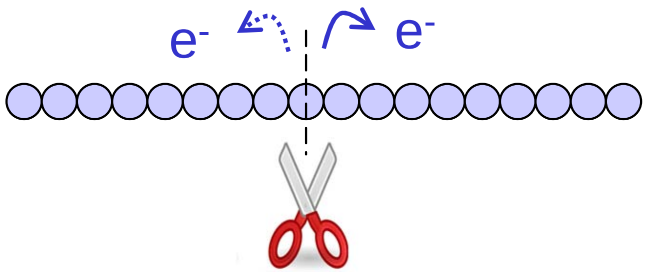




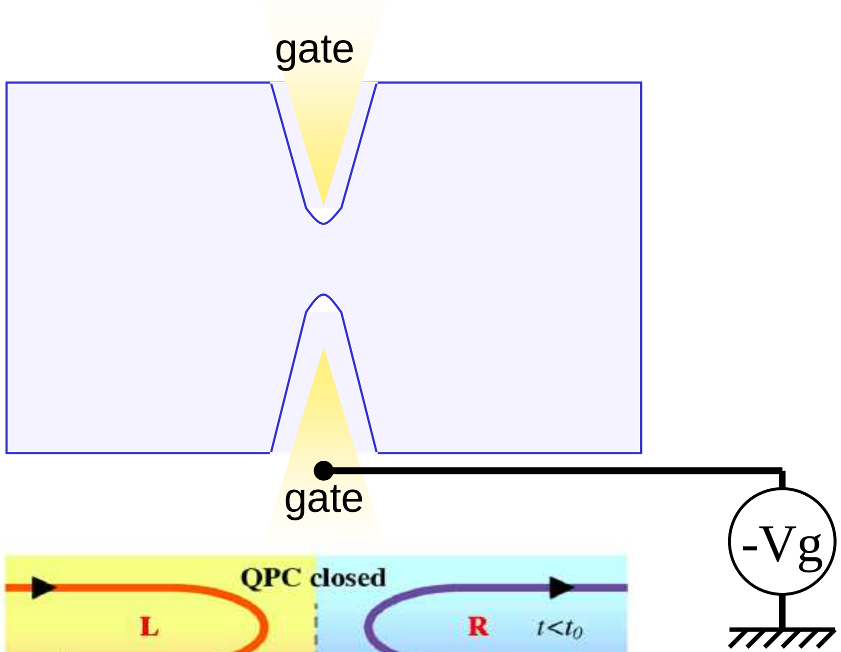


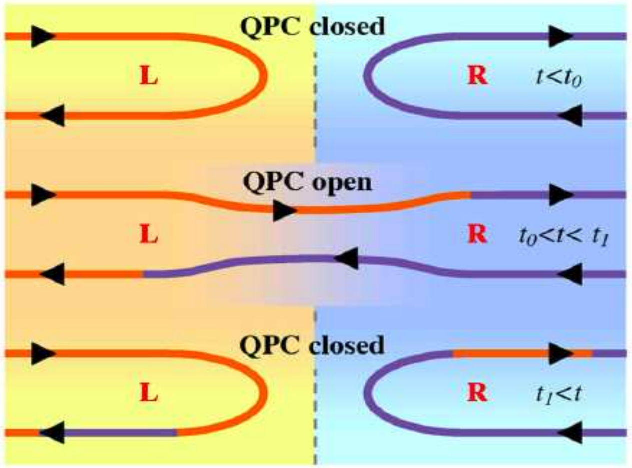
the quantum switch





cutting the Fermi sea





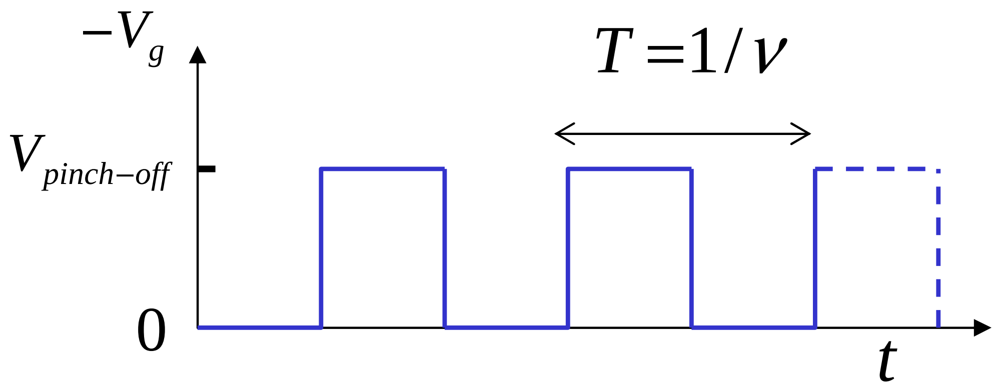
$$\Delta\mathcal{S} = \mathcal{S}[\rho_L(t)] - \mathcal{S}(\rho_0)$$

$$\mathcal{S} = \frac{\pi^2}{3}C_2 + \frac{\pi^4}{15}C_4 + \frac{2\pi^6}{945}C_6 + \ldots$$

PRL 102, 100502 (2009) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2009

Quantum Noise as an Entanglement Meter

Israel Klich[1] and Leonid Levitov[1,2]



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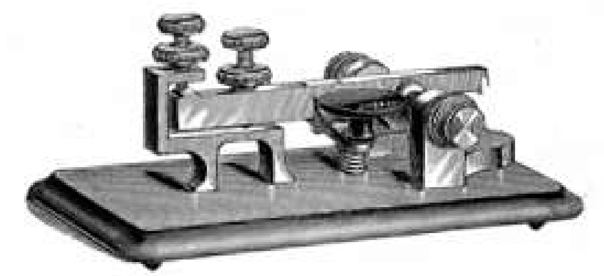
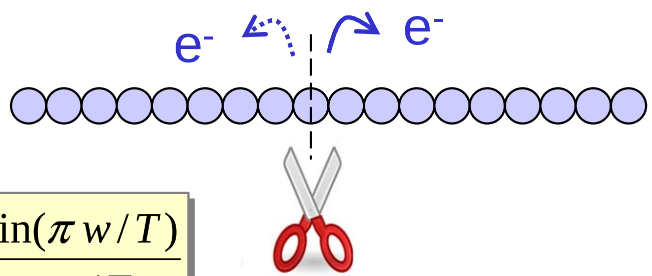




$$\left\langle \Delta Q^2 \right\rangle \sim \frac{e^2}{\pi^2}\log\frac{\sin(\pi w/T)}{\pi\tau/T}$$

cutting the Fermi sea

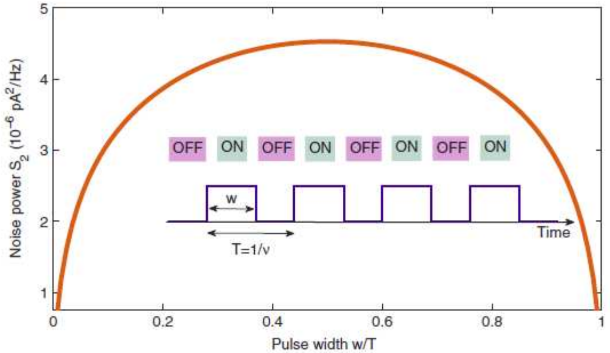
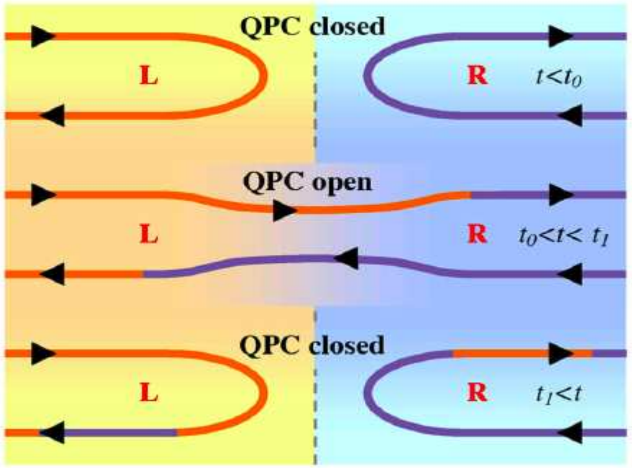


FIG. 2 (color online). Noise power (17) in a QPC driven by a pulse train vs the pulse width. Parameters used: driving frequency $\nu = 500$ MHz, short-time cutoff $\tau = 20$ ps. The noise as well as the entropy production are symmetric under $w \to T - w$. Note that at a narrow pulsewidth $w \ll T$, the dependence (17) reproduces the $\frac{1}{3}\log L$ [2] behavior of the entropy.



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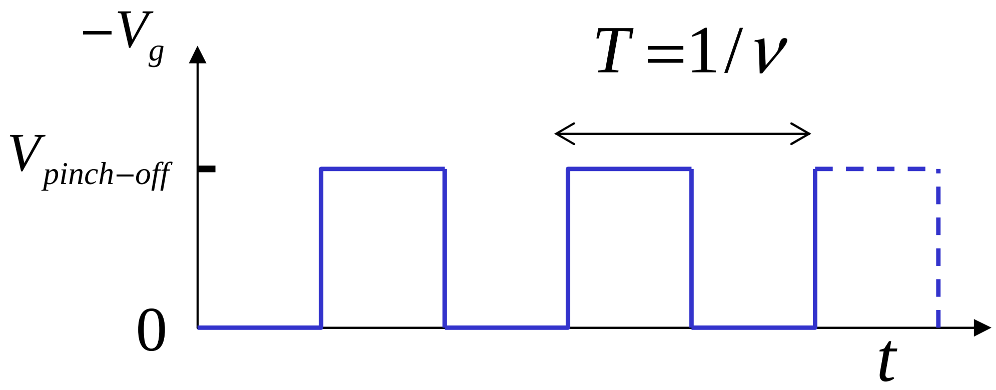
$$\mathcal{S} = \frac{\pi^2}{3} C_2 + \frac{\pi^4}{15} C_4 + \frac{2\pi^6}{945} C_6 + \dots$$

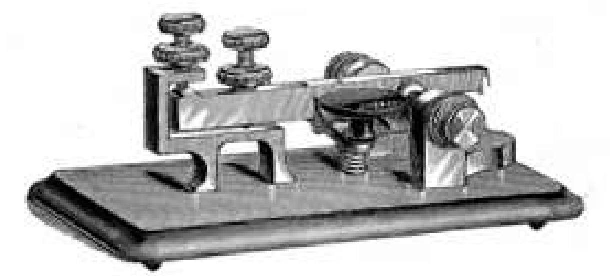
PRL 102, 100502 (2009) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2009

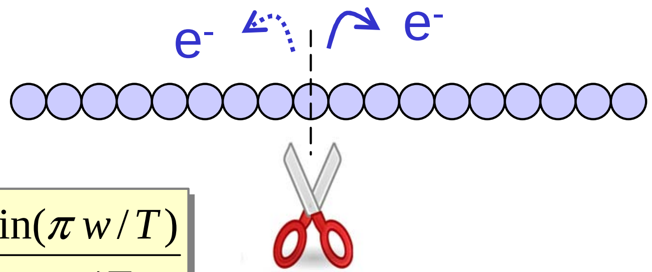
Quantum Noise as an Entanglement Meter

Israel Klich[1] and Leonid Levitov[1,2]



the quantum switch





$$\left\langle \Delta Q^2 \right\rangle \sim \frac{e^2}{\pi^2} \log \frac{\sin(\pi w/T)}{\pi \tau / T}$$

CONCLUSION

the Fermi sea provides :

continuous single electron source
natural entanglement

quantum information with ballistics electrons requires new tools:

On-demand single electron source
for H.O.M. experiments with electrons, flying qubits

Levitov's n-electron source
new Physics of the Fermi sea, allows to study FCS
with few electrons

counting charges for FCS or quantum information
rises new fundamental problems and physics of
the Fermi sea

very rich physics although very few groups are working on these topics !

Weizmann Inst., GNE Saclay, Meso. Phys. Group LPA Paris, Un. Regensburg,
Un. Basel and less related : ETH Zürich, NTT Atsugi, Harvard, Cambridge(UK),...

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L.-H. Bize
J. Segala
J. Dufouleur
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Mesoscopic Physics group
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