Quantum optics with edge states

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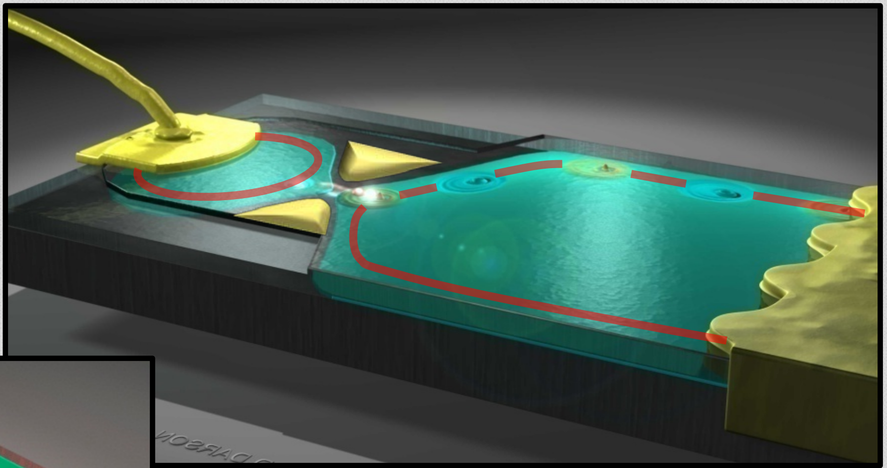
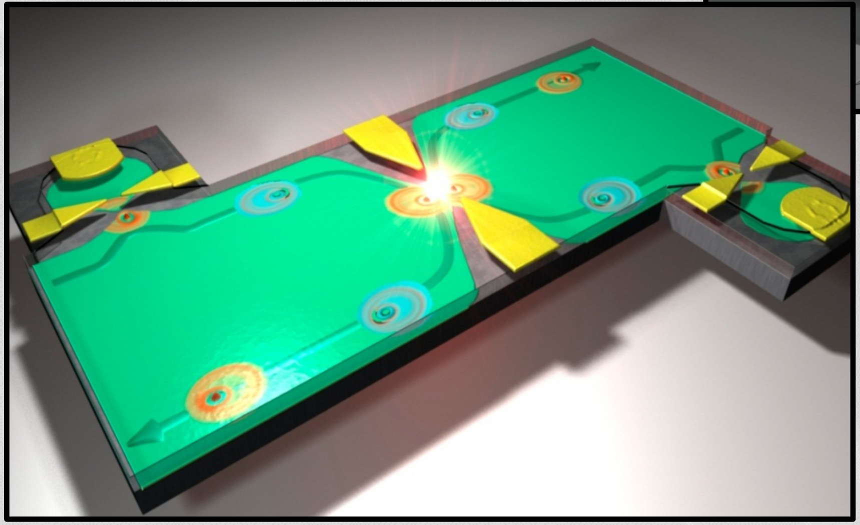




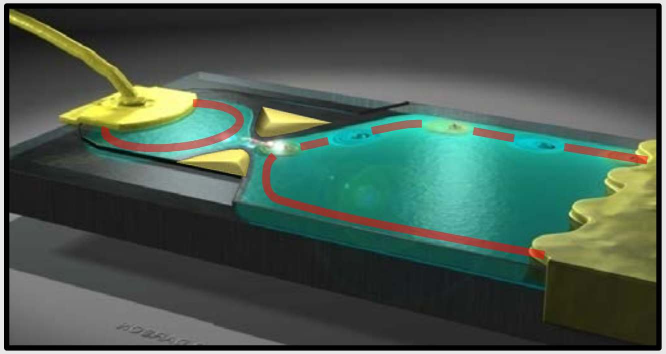
Gwendal Fève

Jean-Marc Berroir

Theory : P. Degiovanni et al. (ENS-Lyon), T. Martin et al. (CPT-Marseille)
M. Butttiker et al. (Uni Genève)

laboratoire pierre aigrain
électronique et photonique quantiques

Summary (quantum optics with edge states)



Part 3 : Introduction to electrons optics

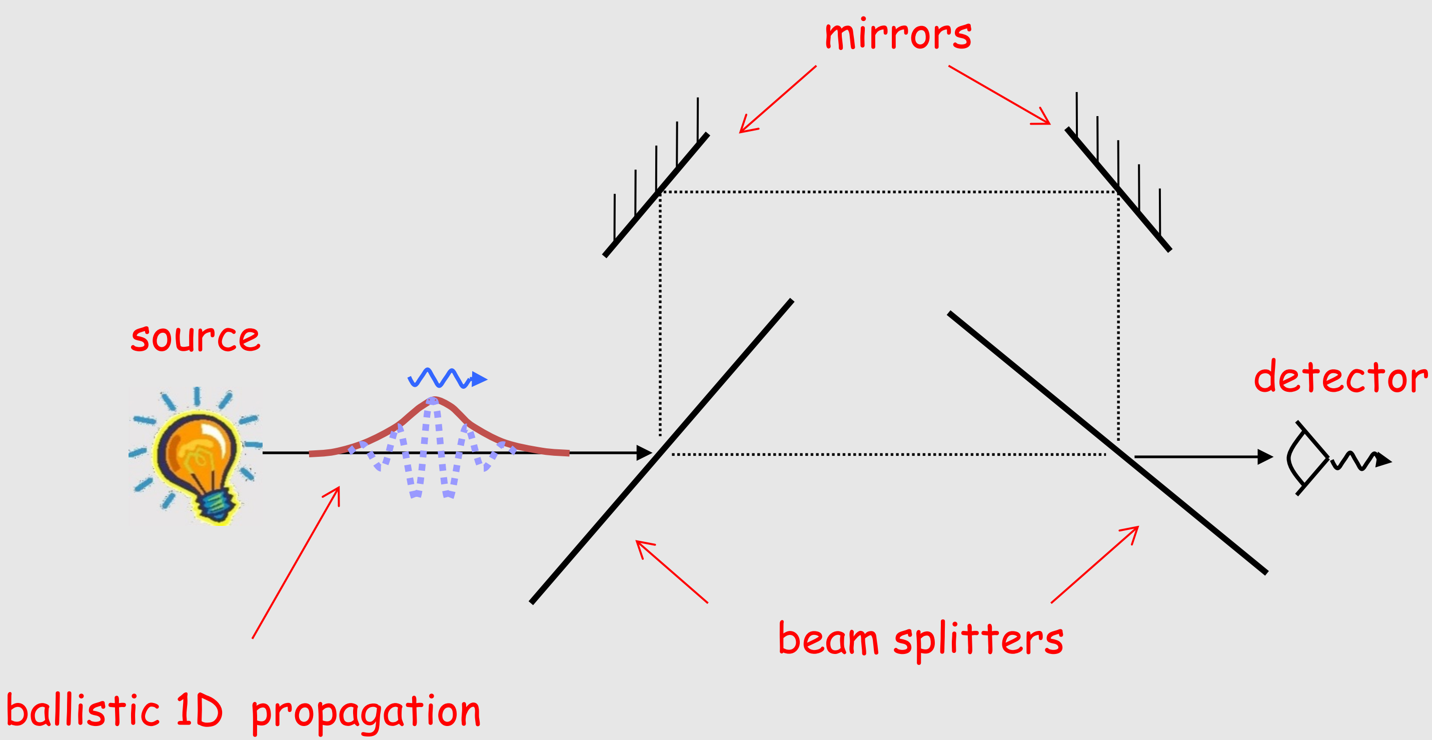
- Electron optics principles
- Single electron sources
- Mesoscopic capacitor : average current and noise

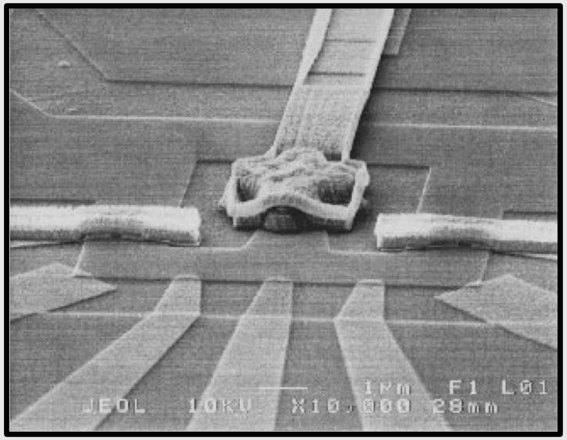
Part 4 : Quantum optics experiments

- Partitioning single electrons
- Colliding indistinguishable electrons
- Decoherence and charge fractionalization

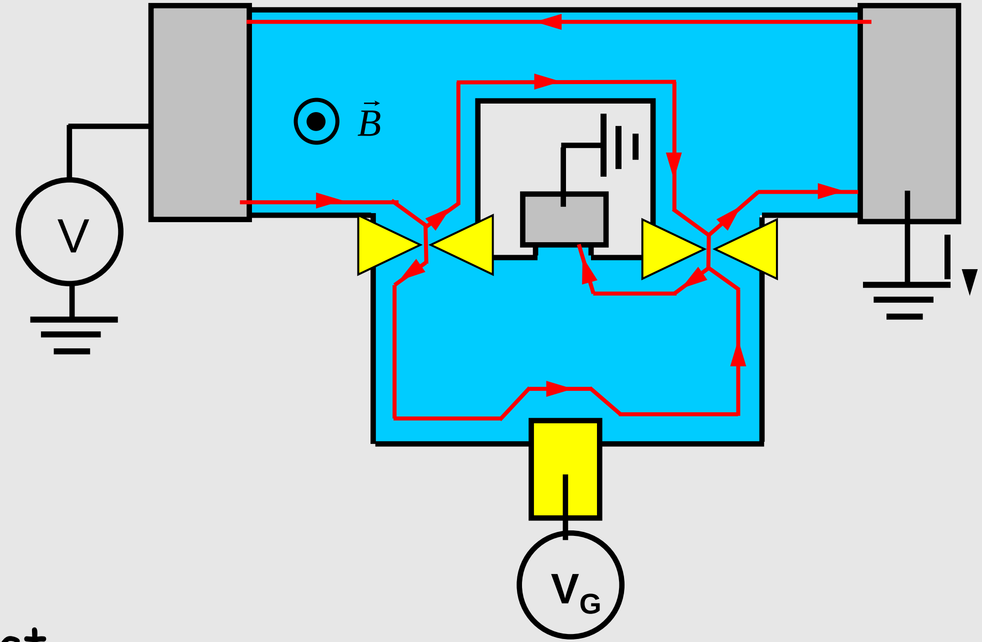
Electron quantum optics in ballistic chiral conductors,
Bocquillon et al., Annalen der Physik 526, 1 (2014)

What do we need to realize an interferometer ?





Y. Ji et al., Nature 422, 415 (2003)

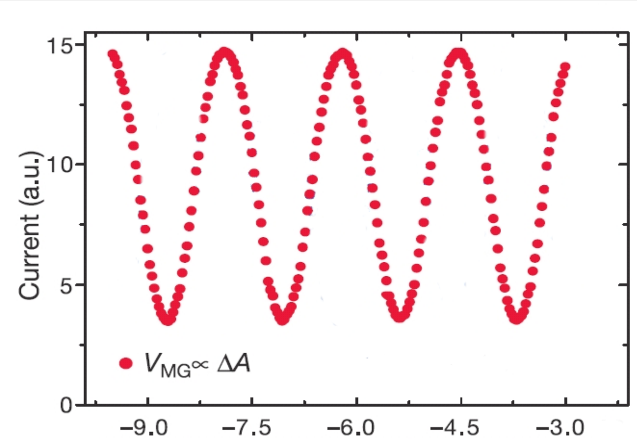


Coherent source = biased contact

« Natural source » not noisy

Coherence length = contrast

$$L_\varphi = 20\ \mu m \quad at \quad 20\ mK$$
$$\tau_\varphi \approx 200\ ps \quad \text{for} \quad v_D \approx 10^5\ ms^{-1}$$

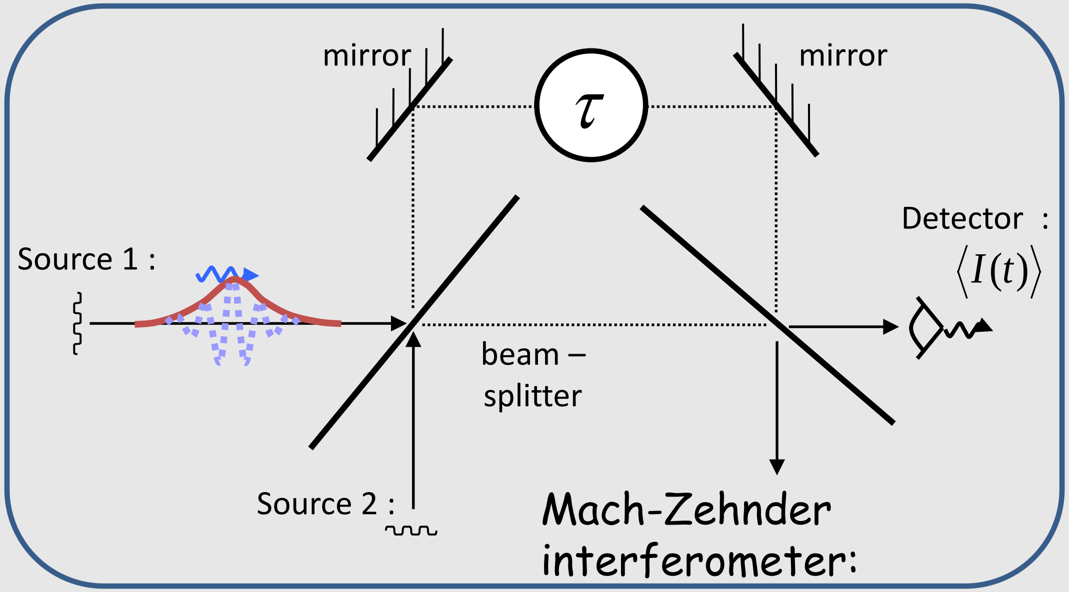


Coherence properties of light

Wavelike description encoded in the first order coherence of the electromagnetic field

$$G^{(1)}(t, t+\tau) \propto \langle E(t)E(t+\tau) \rangle$$

Measured by e.g. Mach-Zehnder interferometry

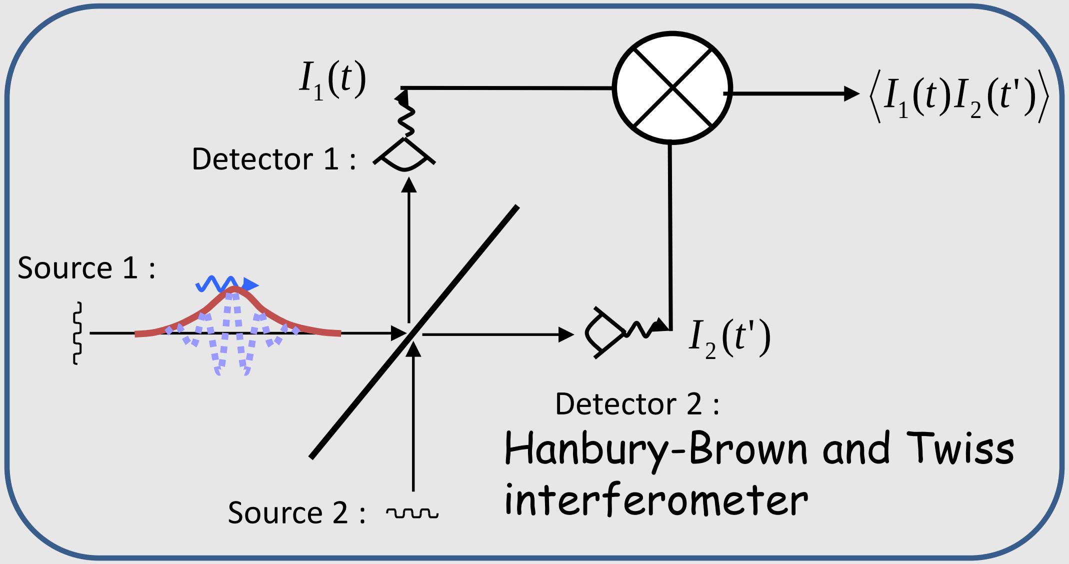


Statistical properties of light

Corpuscular description encoded in intensity corrrelations

$$G^{(2)}(t, t+\tau) \propto \langle I_{ph}(t)I_{ph}(t+\tau) \rangle$$

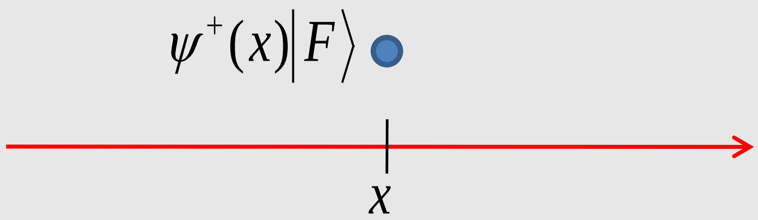
Measured by Hanbury-Brown and Twiss (HBT) interferometry



Electron optics in edge channels : formalism

Electron field operator

$$\psi(x) = \frac{1}{\sqrt{h v_F}} \int d\epsilon \, a(\epsilon) e^{i\epsilon x/(\hbar v_F)}$$



Chiral, 1D, propagation

$$\psi(x,t) = \psi(x - v_F t) \qquad \psi(x) \leftrightarrow E^{+}(x) \qquad \psi^{\dagger}(x) \leftrightarrow E^{-}(x)$$

Charge density and electrical currrent

$$I_{el}(\mathrm{x},\mathrm{t}) = \mathrm{e} v_F \, \psi^{\dagger}(x,t)\psi(x,t) \qquad I_{ph}(\mathrm{x},\mathrm{t}) \propto E^{+}(x,t)E^{-}(x,t)$$

$$G^{(1)}(\epsilon,\epsilon') = \langle a^{\dagger}(\epsilon) a(\epsilon') \rangle$$

Vacuum is the Fermi sea ! transport subtracts the Fermi sea

$$G^{(1)}(x,x') = {G_F}^{(1)}(x,x') + \Delta G^{(1)}(x,x') \qquad {G_F}^{(1)}(\epsilon,\epsilon') = \theta(\epsilon - \epsilon_F)\,\delta(\epsilon - \epsilon')$$

$$I(x) = \mathrm{e} v_F \Delta G^{(1)}(x,x)$$

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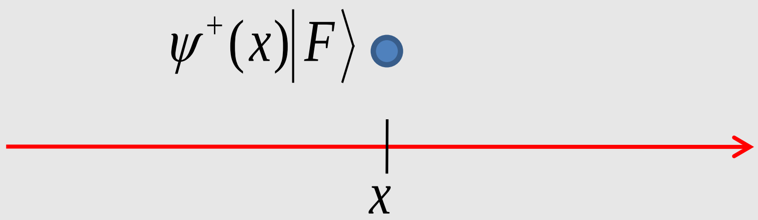

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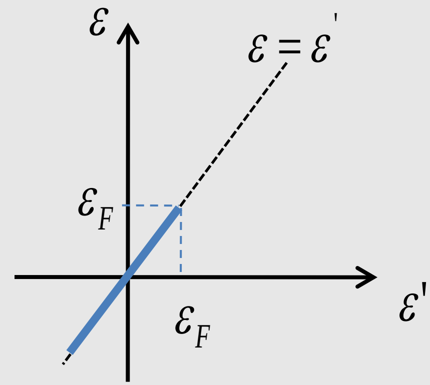

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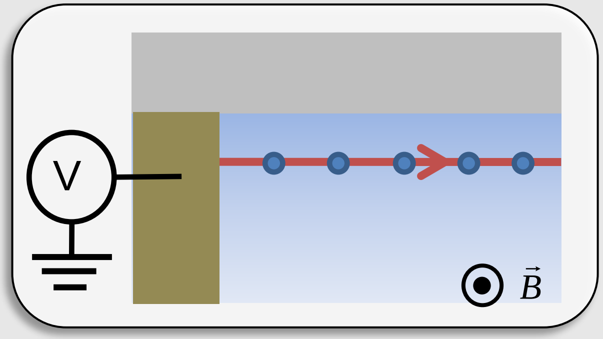
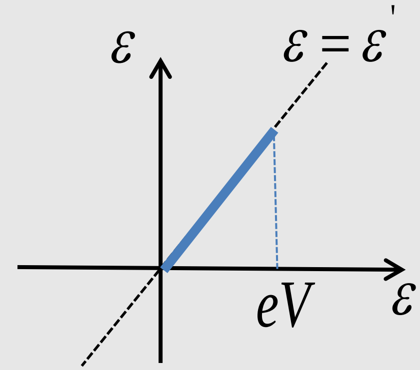
$$I(x) = \mathrm{e} v_F \Delta G^{(1)}(x,x)$$

Stationary versus single electron emitters

Stationary emitters :



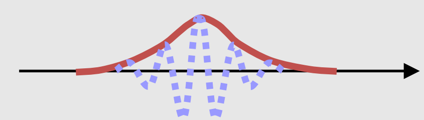


$$\Delta G^{(1)}(x, x') = \Delta G^{(1)}(x - x')$$

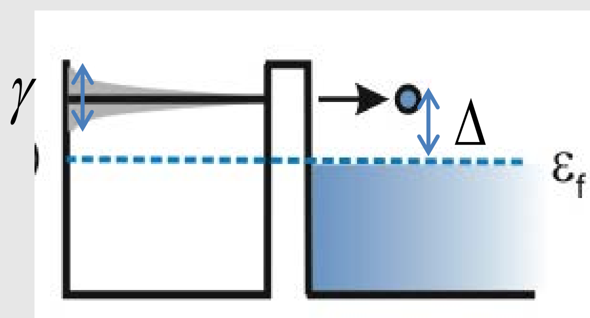
$$\Delta G^{(1)}(\epsilon, \epsilon') \propto \delta(\epsilon - \epsilon')$$

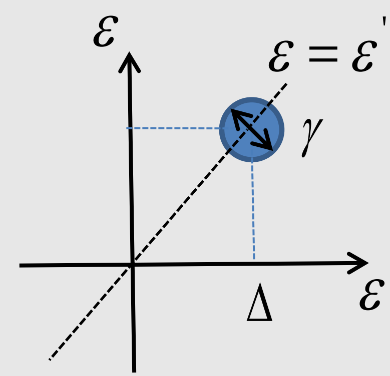
control of the populations (no off − diagonal element in ΔG *!)*

Single electron state, wave packet $\varphi(x)$, « a Landau QP »



$$\psi^{\dagger}[\varphi]|F\rangle = \frac{1}{\sqrt{hv_F}} \int dx \ \varphi(x)\psi^{\dagger}(x)\,|F\rangle$$





$$\Delta G^{(1)}(x, x') = \varphi^{*}(x)\varphi(x')$$
$$\Delta G^{(1)}(\epsilon, \epsilon') = \varphi^{*}(\epsilon)\varphi(\epsilon')$$

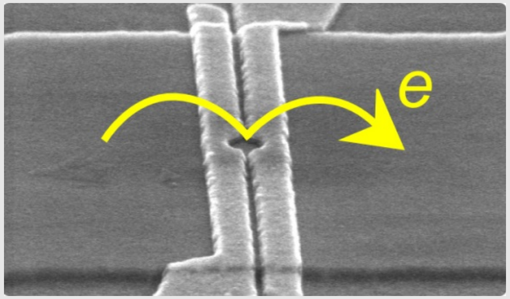
electrons $(\epsilon > 0)$ *holes* $(\epsilon < 0)$
acces to the coherence (fragile off − diagonal terms in ΔG*)*

Triggerred electron emitters (2DEGs)

J. Pekola et al., Rev. Mod. Phys. 85, 1421 (2013)

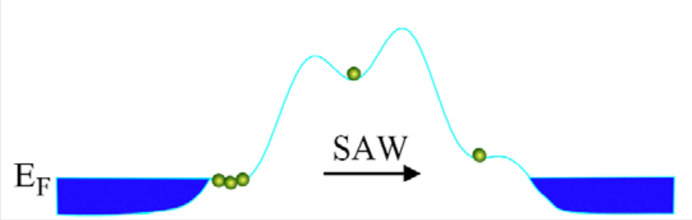
Electron pumps

M.D. Blumenthal et al., Nature Physics 3, 343 (2007)
F. Hohls et al., Phys. Rev. Lett. 109, 056802 (2012)
J. Fletcher et al., Phys. Rev. Lett. **111**, 216807 (2013)



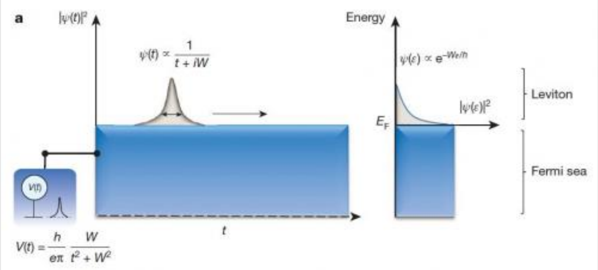
Electrons flying on SAW (flying Q-dot)

R. McNeil et al., Nature 477 (7365), 439 (2011)
S. Hermelin et al., Nature 477 (7365), 435 (2011)



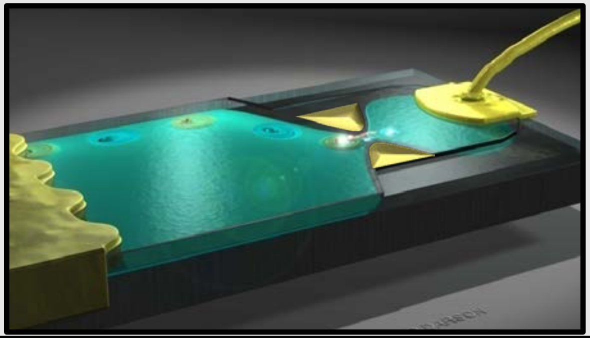
Lorentzian voltage pulse (Levitons)

D. A. Ivanov, et al., Phys. Rev B 56, 6839 (1997)
J. Dubois et al., Nature 502, 659 (2013)

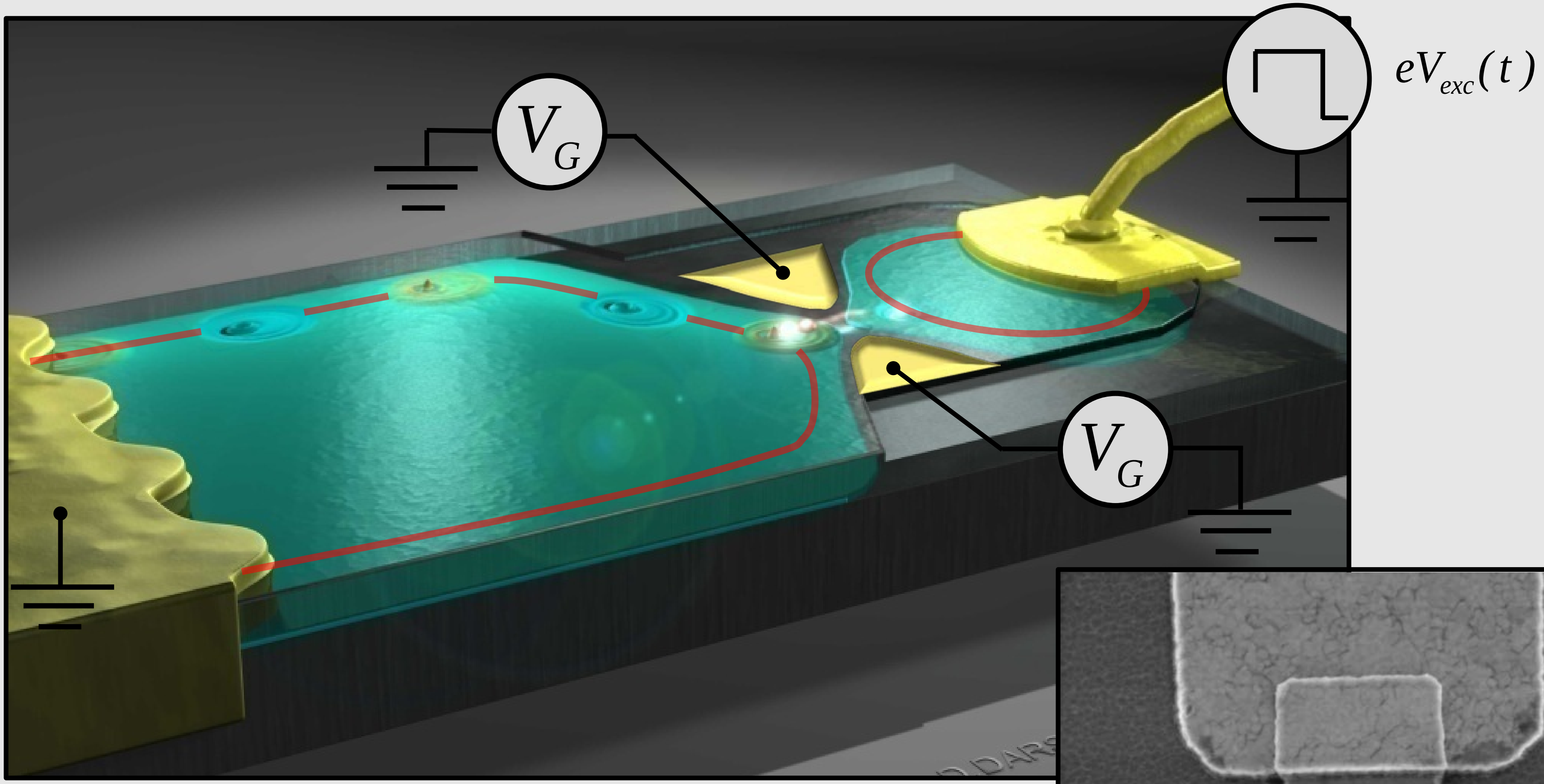


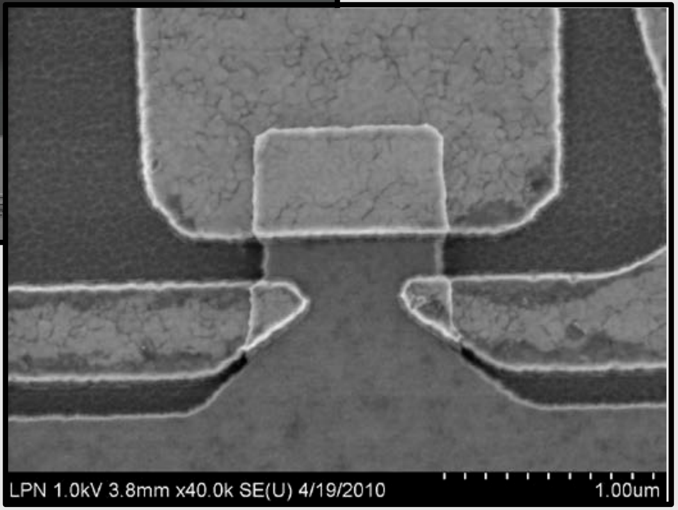
Mesoscopic capacitor (electron/hole, energy resolved)

G. Fève et al., Science 316, 1169 (2007)

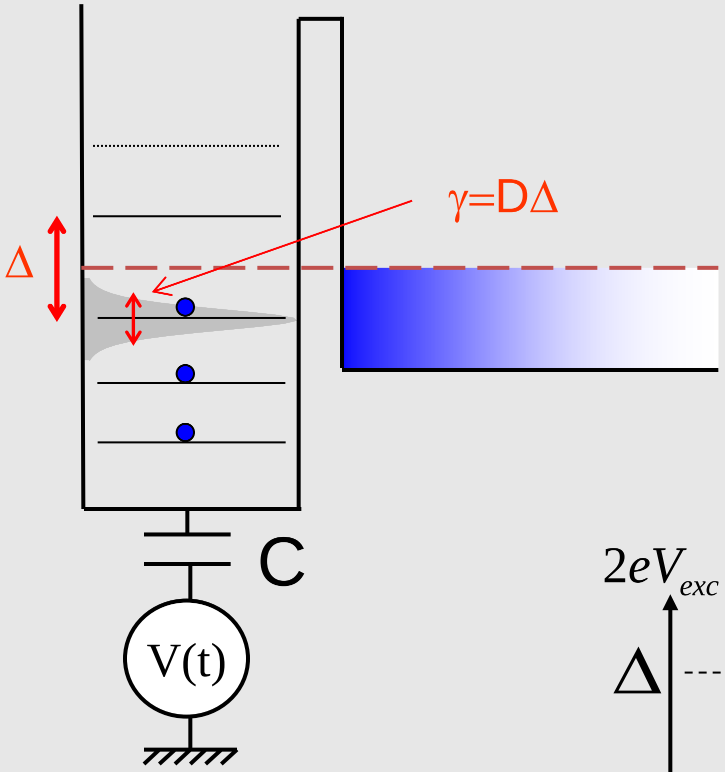


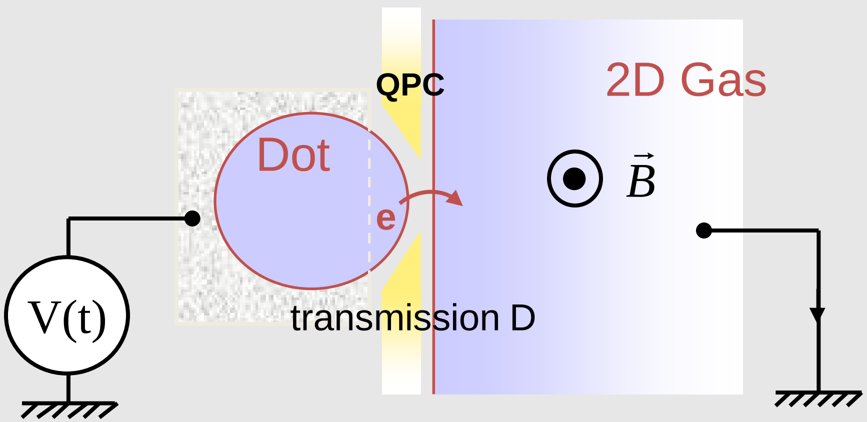
Mesoscopic capacitor : A single eletron/hole emitter

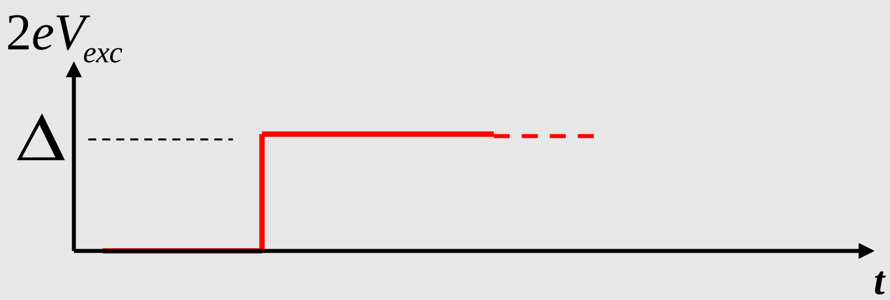


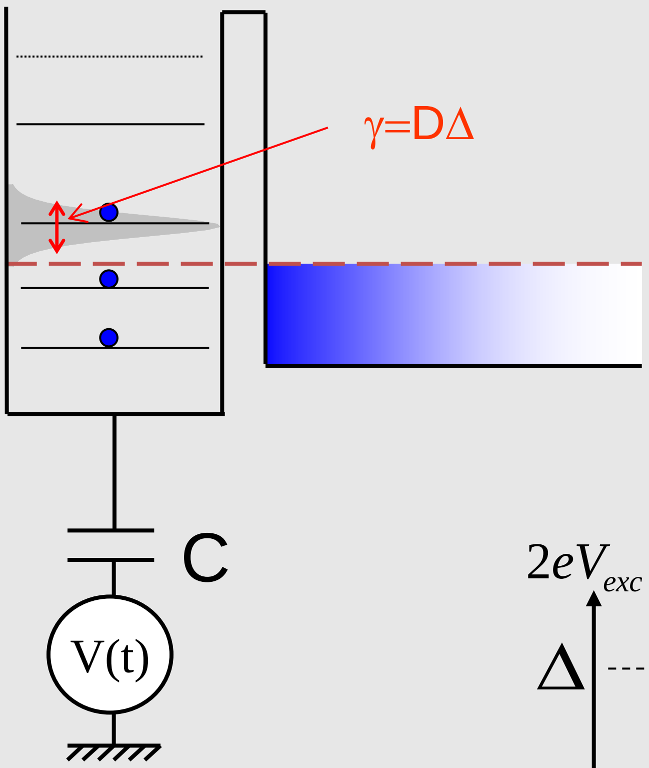


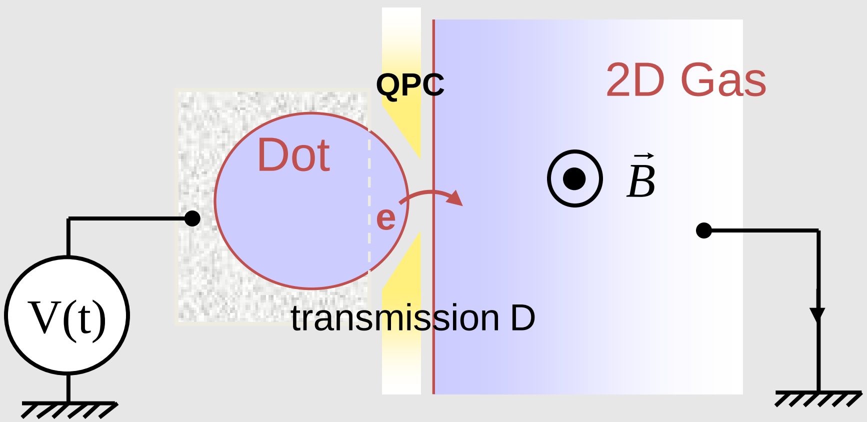
Cartoon of single charge injection

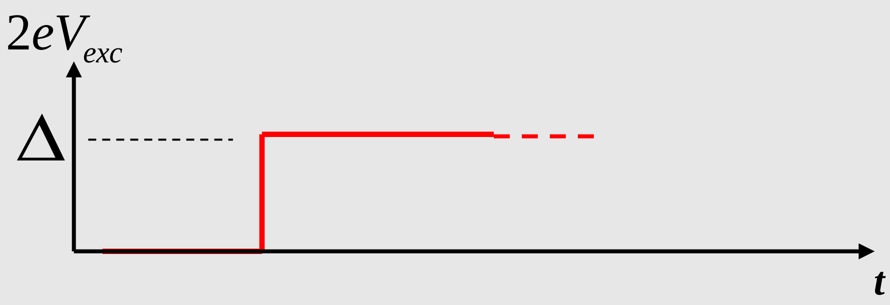




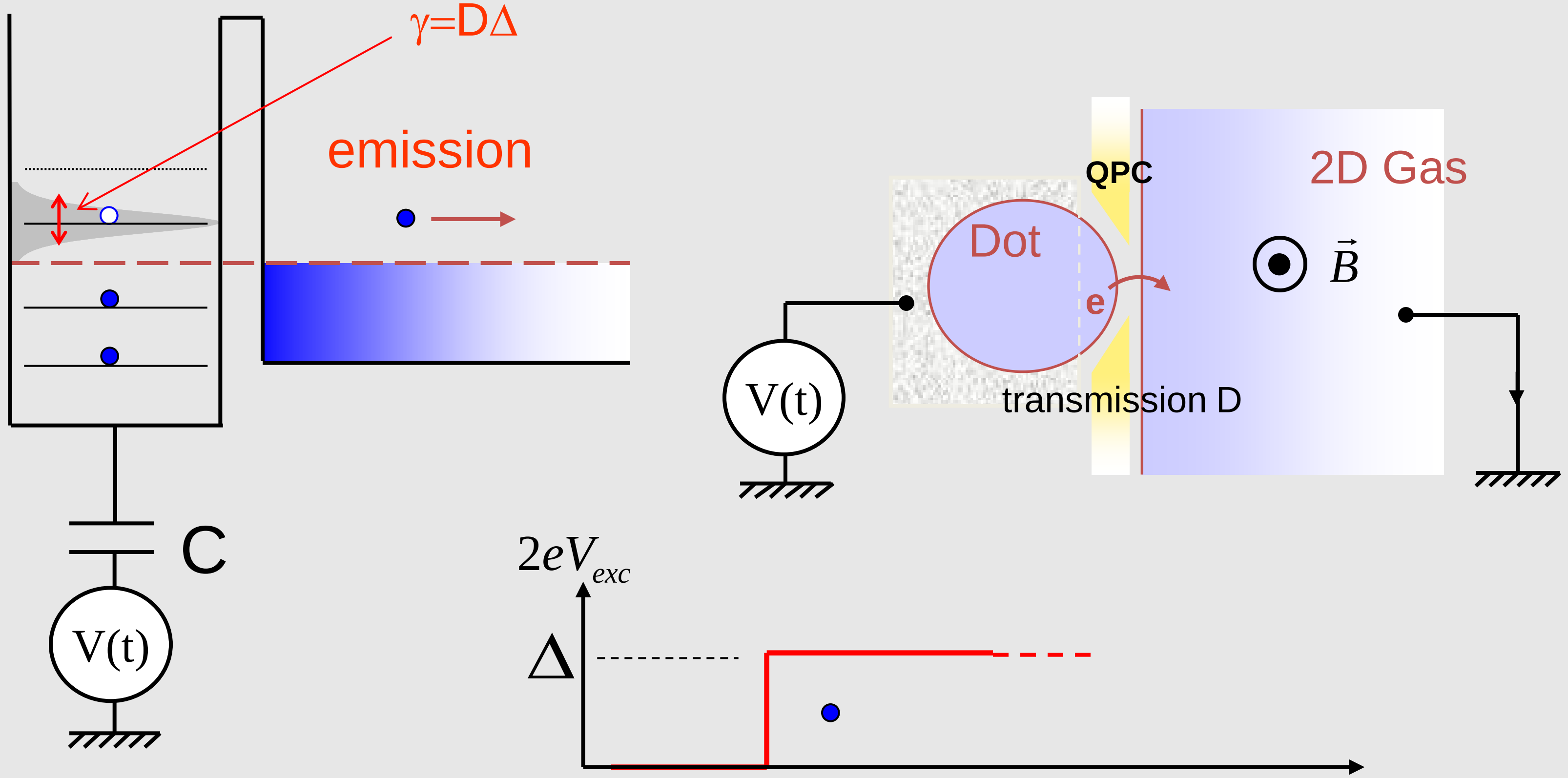



γ=DΔ
C
V(t)


QPC
2D Gas
Dot
e
B
V(t)
transmission D

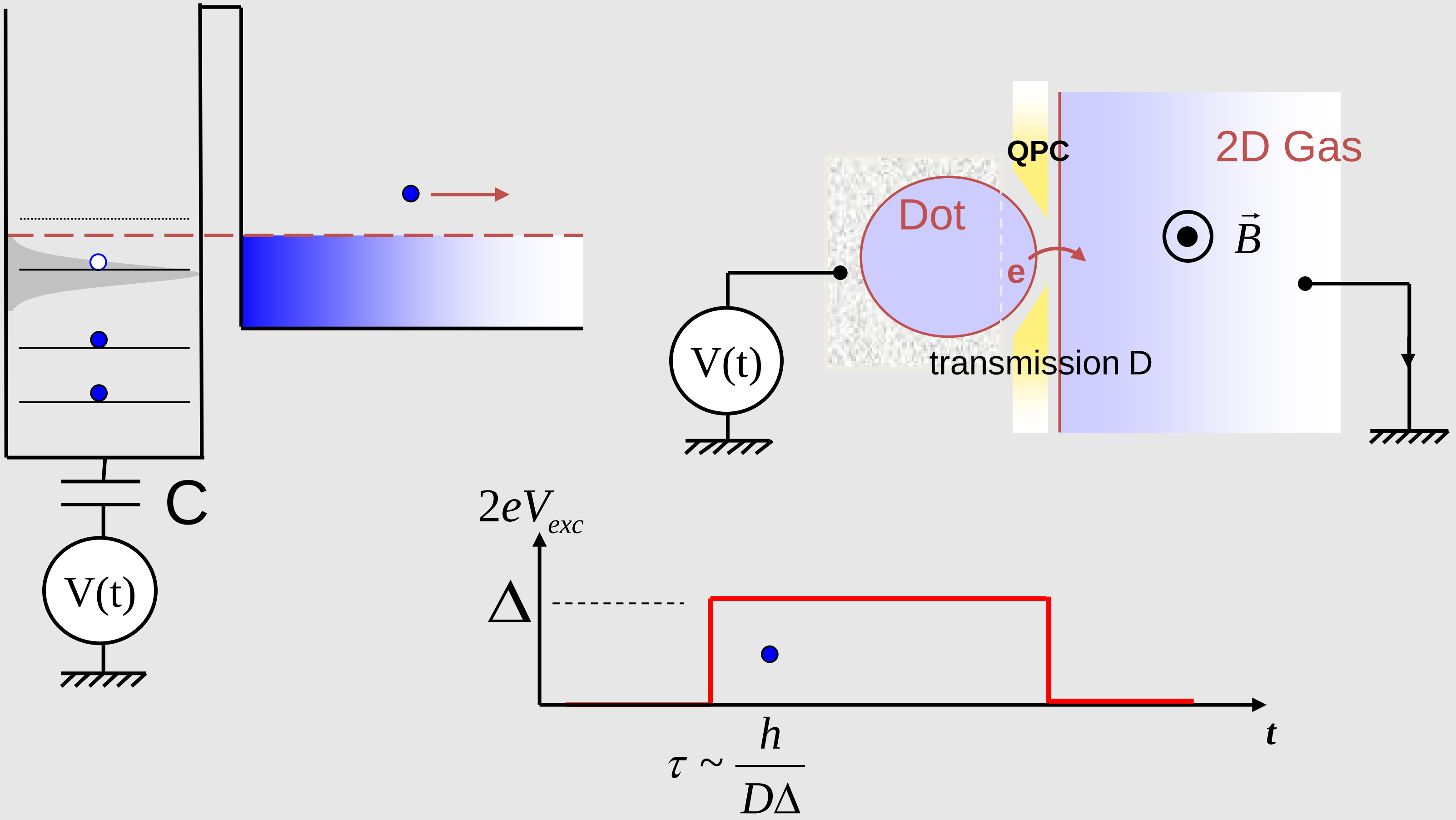

$2eV_{exc}$
Δ
t

Cartoon of single charge injection

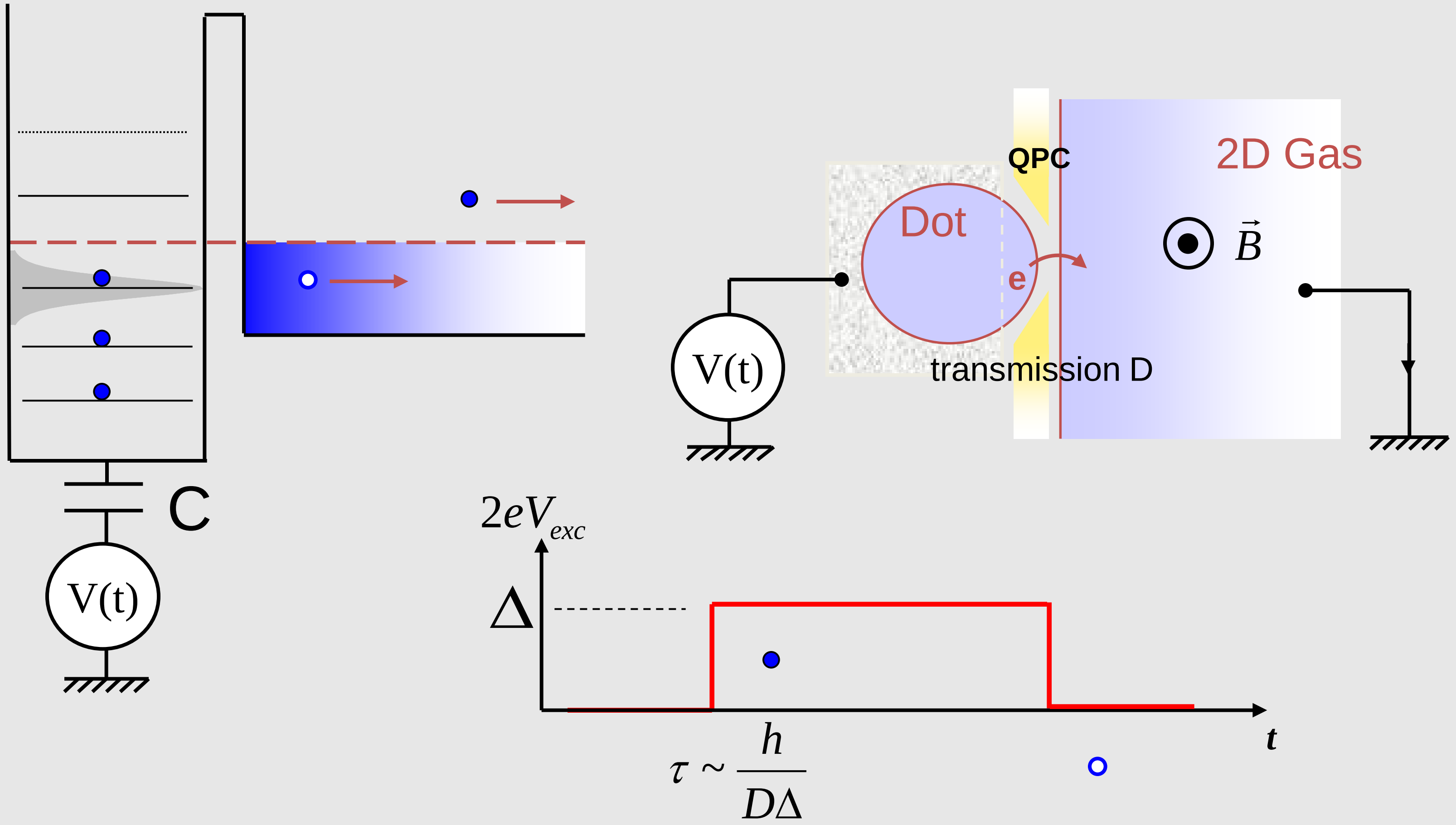


$$\tau \sim \frac{h}{D\Delta}$$ typically 100 ps

Cartoon of single charge injection



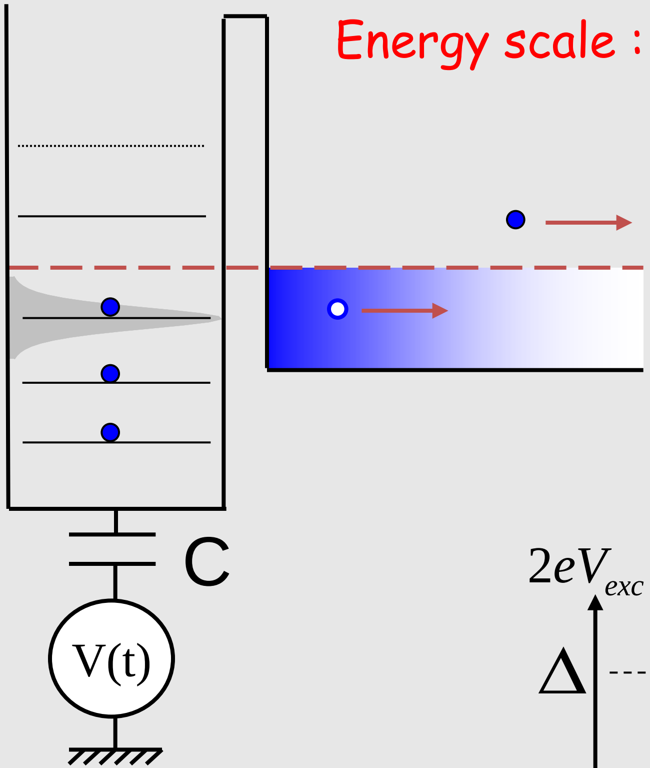
Cartoon of single charge injection

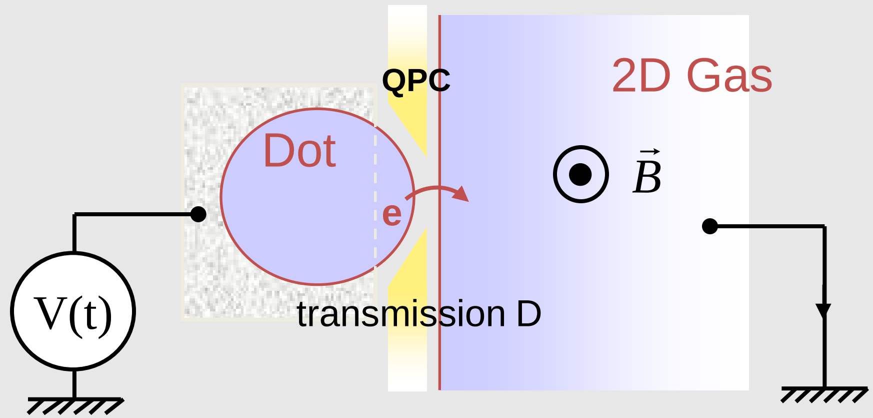


Statistical averaging

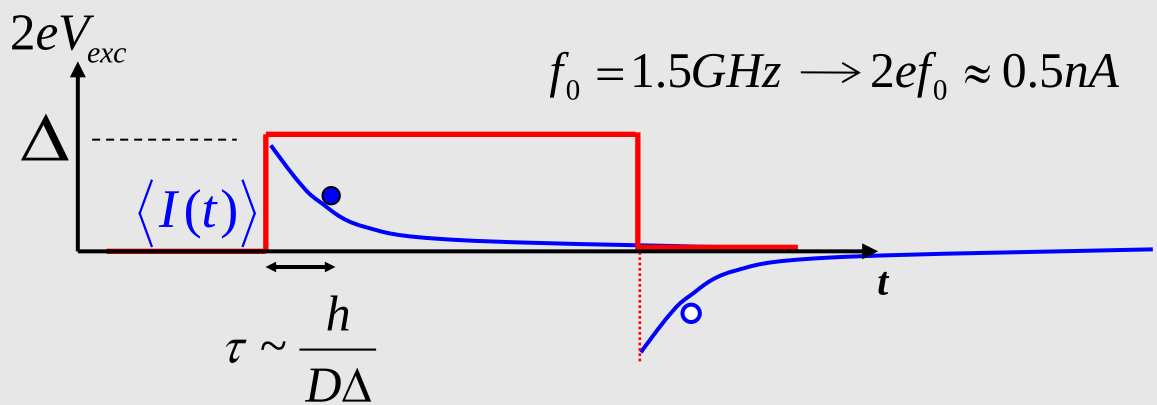
Energy scale (1 Kelvin ≡ 86 μeV ≡ 20.8 GHz) : $\Delta \approx 2\ Kelvin$

Energy scale : $\tau = \hbar / D\Delta \approx 50 - -500$ ps





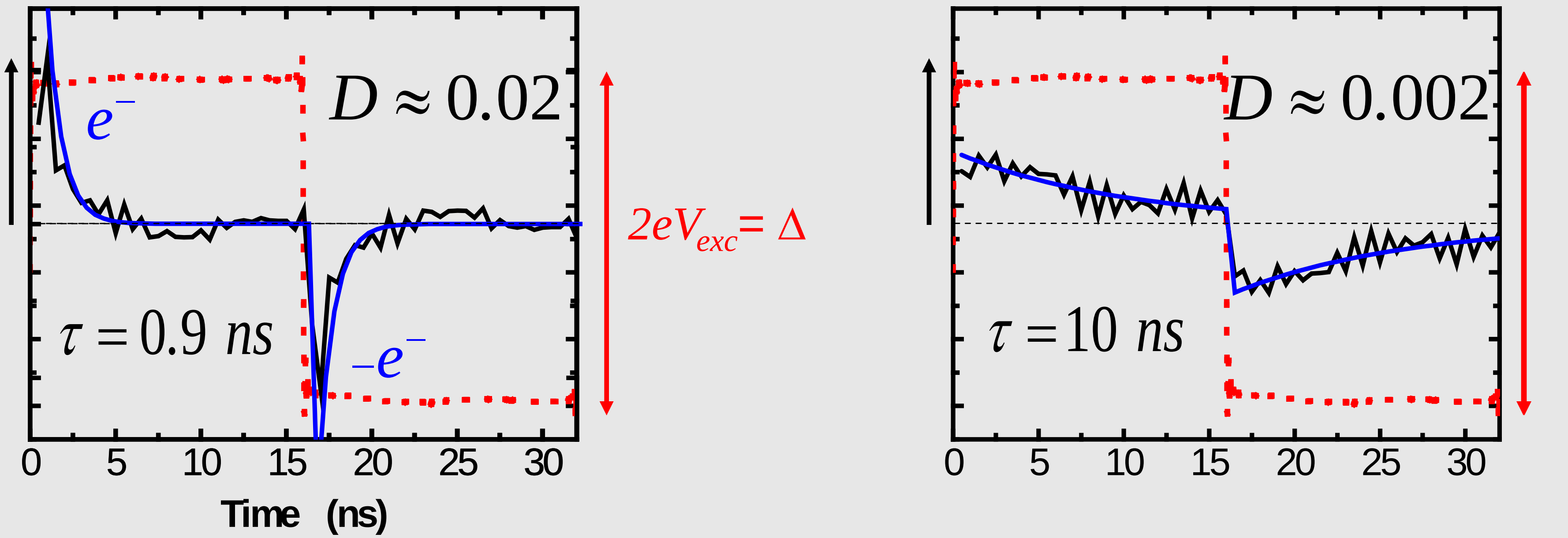
$f_0 = 1.5GHz \longrightarrow 2ef_0 \approx 0.5nA$



Single electron current pulses

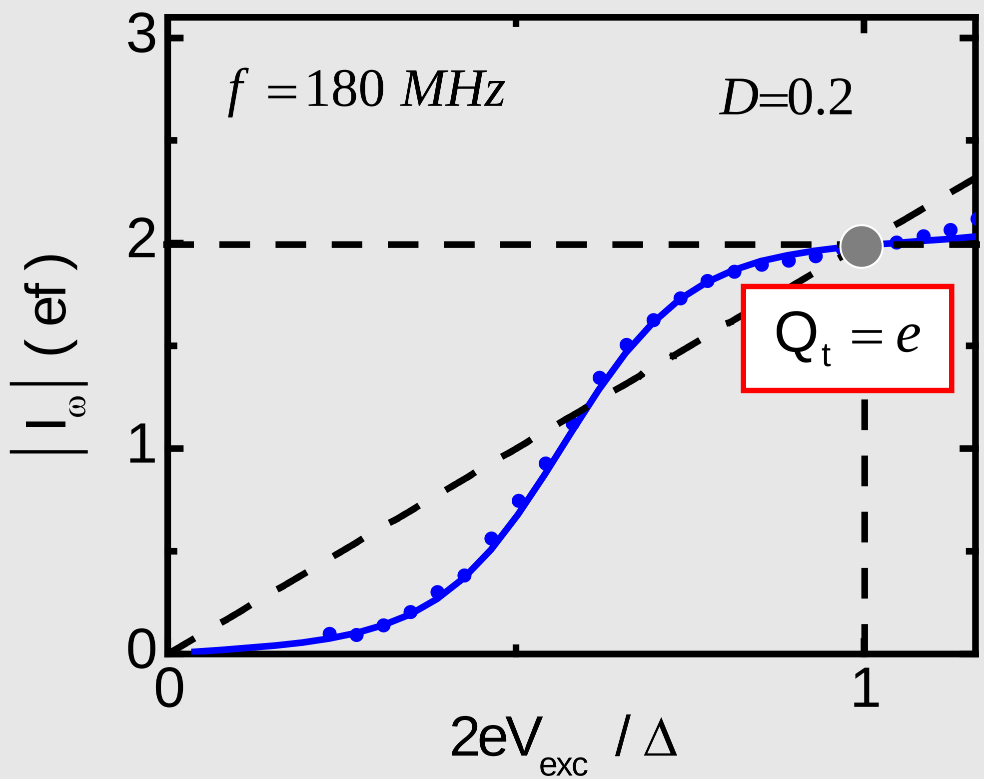
Measuring single electron current pulses ?

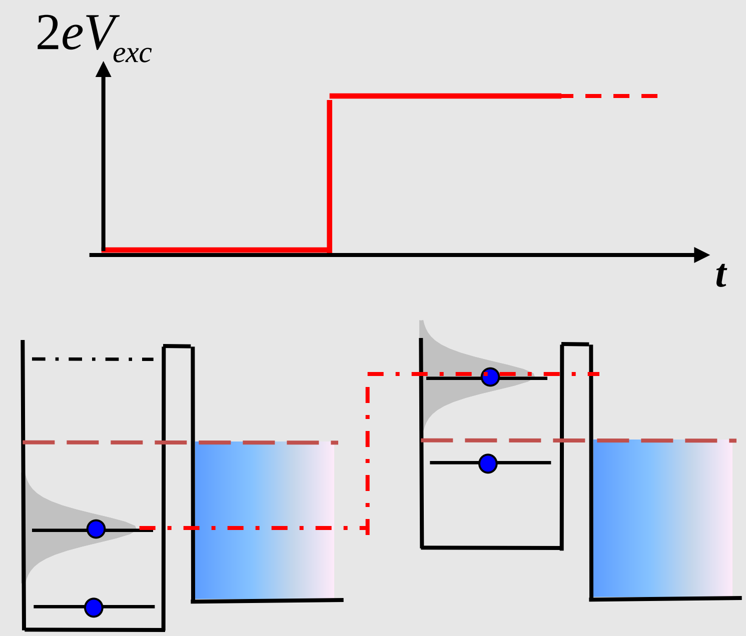
Use a slow 32 MHz clock and a 1GHz fast averaging card (Acquiris)



Quantization of the AC current ?

Use homodyne detection at large clock frequency : $\langle I_\omega \rangle = {}^{(2iQf)}/_{(1-i\omega\tau)}$

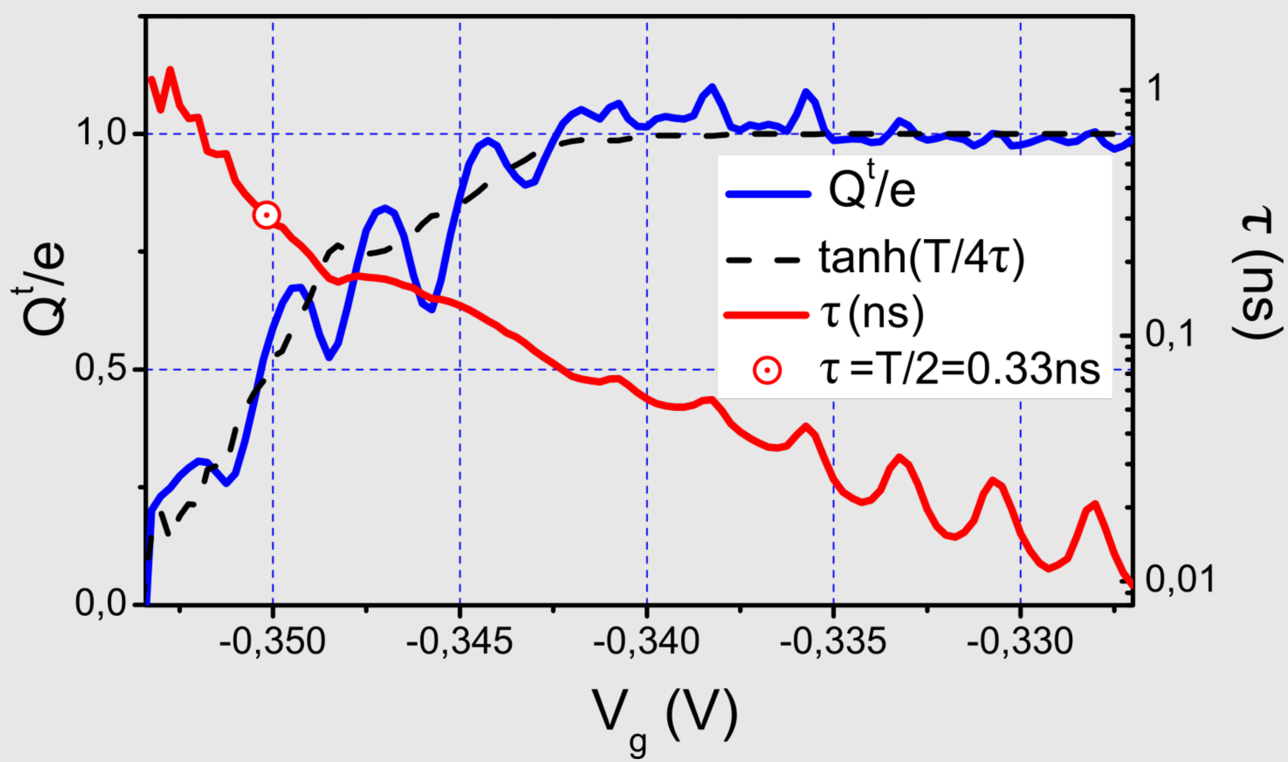




Cartoon or reality ?

Subnanosecond control of the emission time

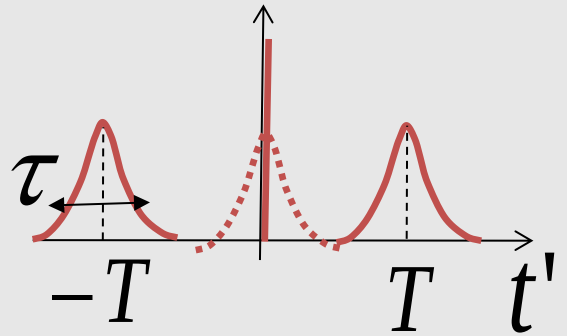
Use homodyne detection at large clock frequency : $\langle I_{\omega} \rangle = {}^{(2iQf)}/_{(1-i\omega\tau)}$



Short time current correlations

Single electron emission is characterized by current correlator

$$\overline{\langle I(t)I(t')\rangle} = \frac{Q^2}{T}\delta(t'-t)$$



AC noise correlations

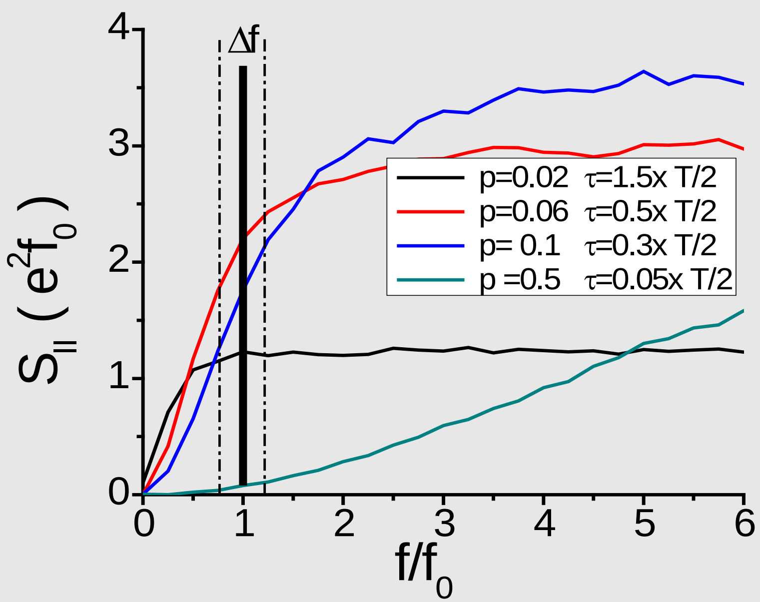
$$\overline{\langle \delta I(t)\delta I(t')\rangle} = \overline{\langle I(t)I(t')\rangle} - \overline{\langle I(t)\rangle\langle I(t')\rangle}$$

where $\overline{\langle I(t)\rangle\langle I(t')\rangle} = \frac{Q^2}{T}\ \frac{e^{-(t'-t)/\tau}}{\tau}$

Whence the AC noise spectrum

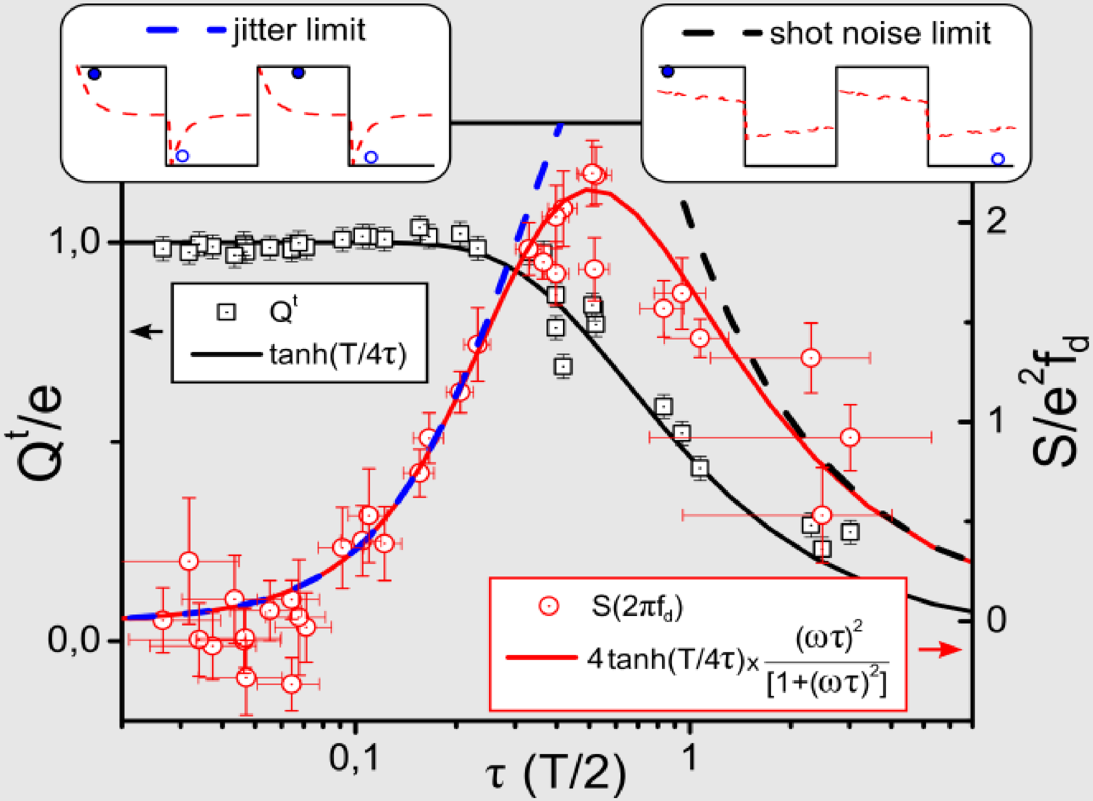
$$S_{II}(\tau,\omega) = 2\frac{e^2}{T}\frac{(\omega\tau)^2}{1+(\omega\tau)^2}$$

Experiment → $S_{II}(\tau,\omega = 2\pi f_0)$



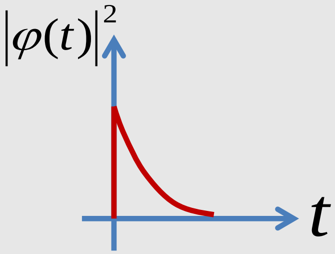
Cartoon or reality ?

Single electron source, beyond average current, average noise



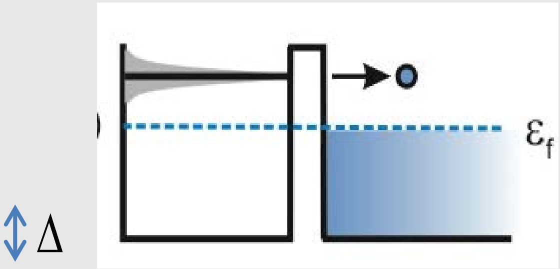
Beyond current and noise, 2 particle interference

average current : $\langle I(t)\rangle = e\,|\varphi(t)|^2$



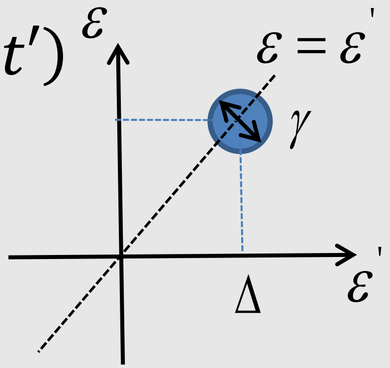
current noise : $\langle I(t)I(t+\tau)\rangle = e^2|\varphi(t)|^2\,\delta(\tau)$

sensitive to *wave packet envelop* : $|\varphi(t)|^2$



How to access wave coherence ? $\rho(t,t') = \varphi(t)\varphi^*(t')$

Asses decoherence: $\rho(t,t') = \varphi(t)\varphi^*(t')D(t-t')$



Part 4 (quantum optics with edge states)

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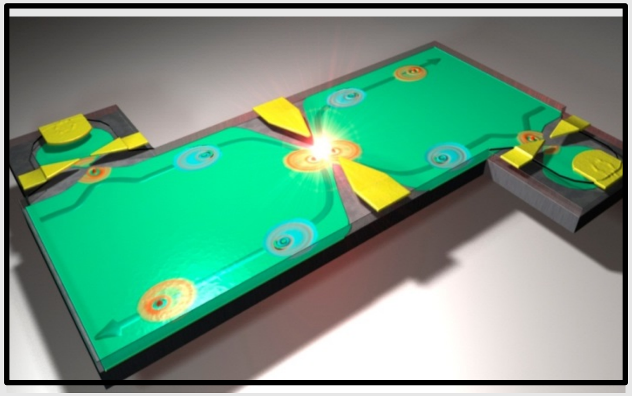


Hanbury-Brown and Twiss partioning (classical AC source)

Input channel 1 noise

$Q_1 = N_e - N_h \qquad \overline{\langle \delta Q_1{}^2 \rangle} = 0 \qquad S_{11}(\omega = 0) = 0$

AC source is noise free at DC

DC noise correlations at outputs

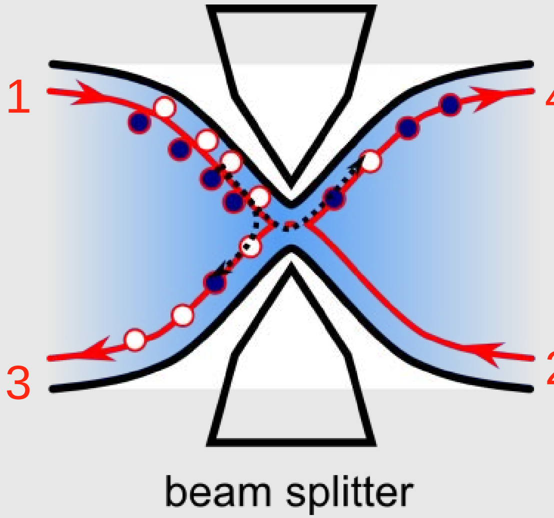
$$\overline{\langle \delta Q_3 \delta Q_4 \rangle} = -e^2 T(1-T) \times (\langle N_e \rangle + \langle N_h \rangle)$$

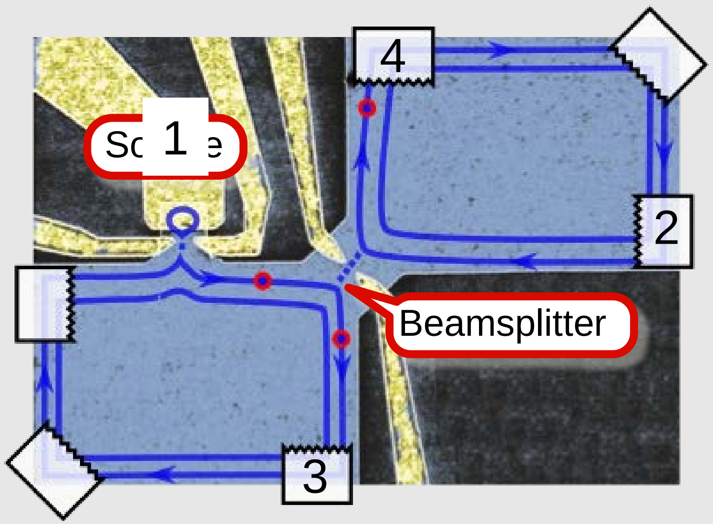
Measures the average number of electron-hole pairs

Low frequency noise spectrum

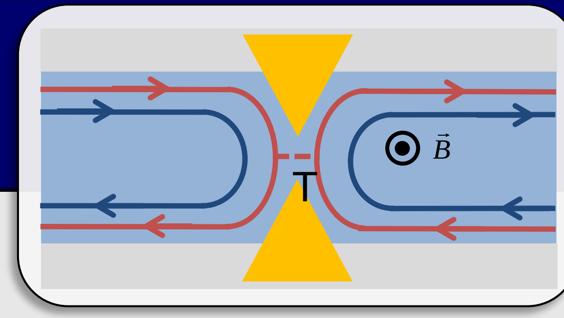
$$S_{33}(\omega = 0) = -S_{34}(\omega = 0) = 4e^2 f\, T(1-T) \times \langle N_{e/h} \rangle$$

Enough to measure noise at output 3





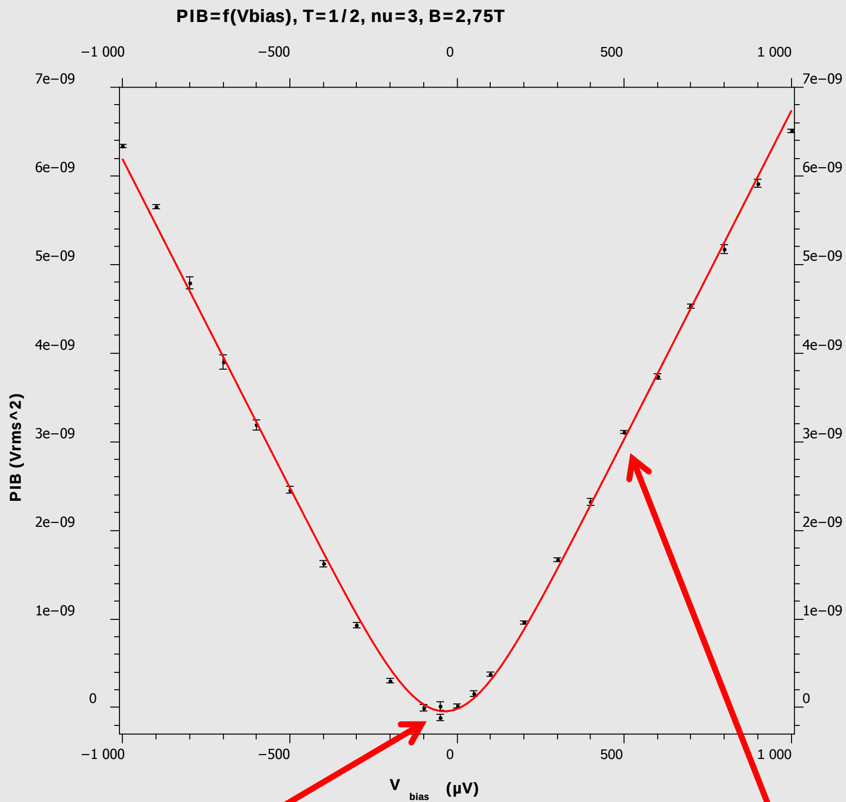
Exemples of QPC noise

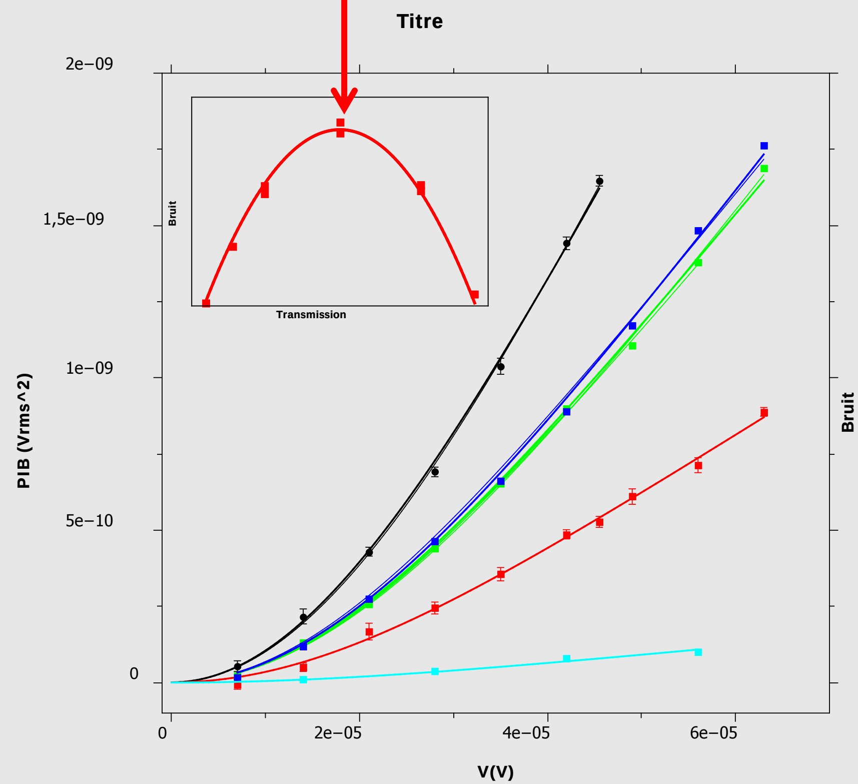


Thermal crossover

$$S_I = 2eI \tanh^{-1} \frac{eV}{2k\theta_e}$$

partition noise : $S_I \propto T(1-T)$



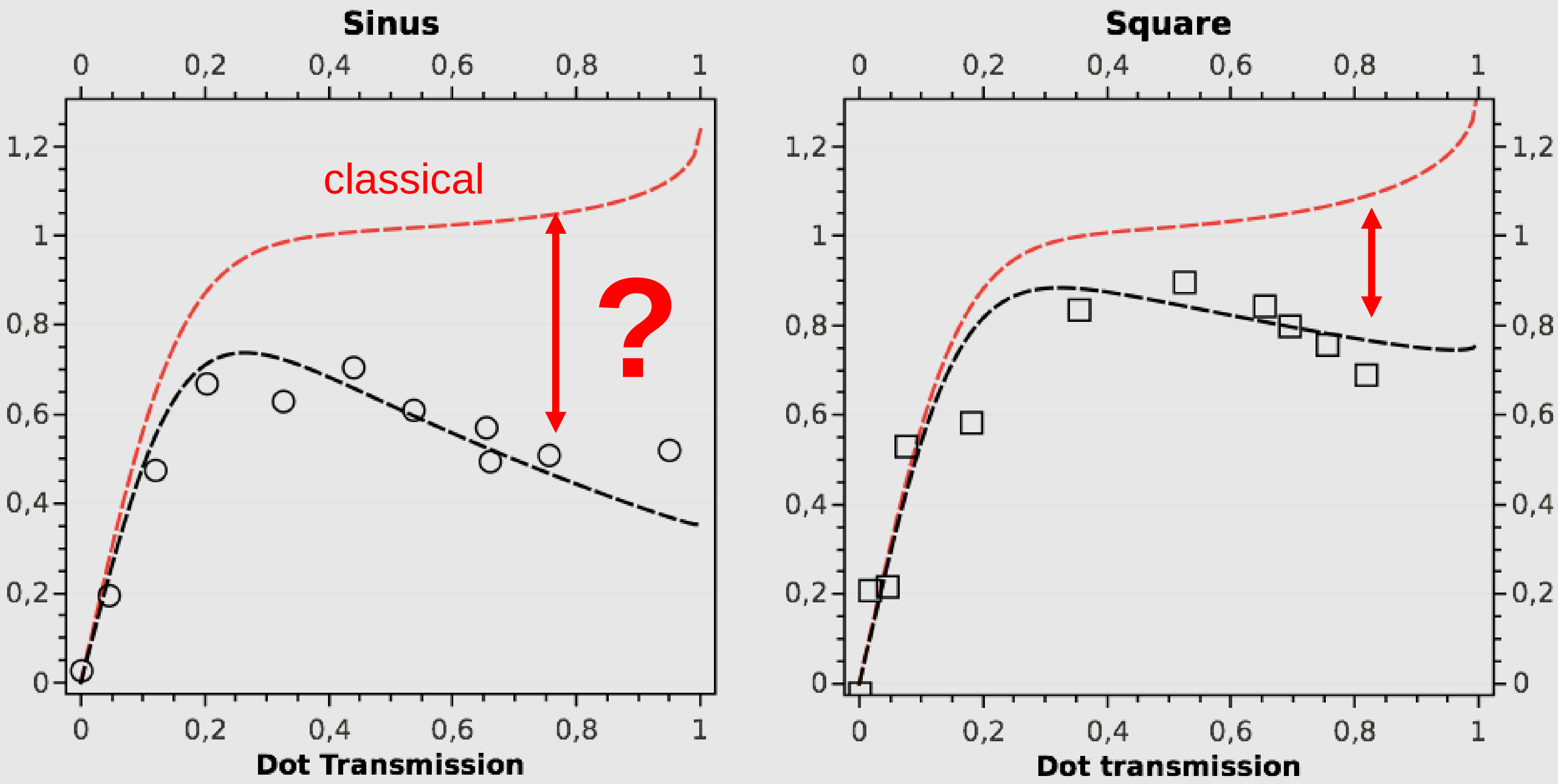


Thermal noise

partition noise

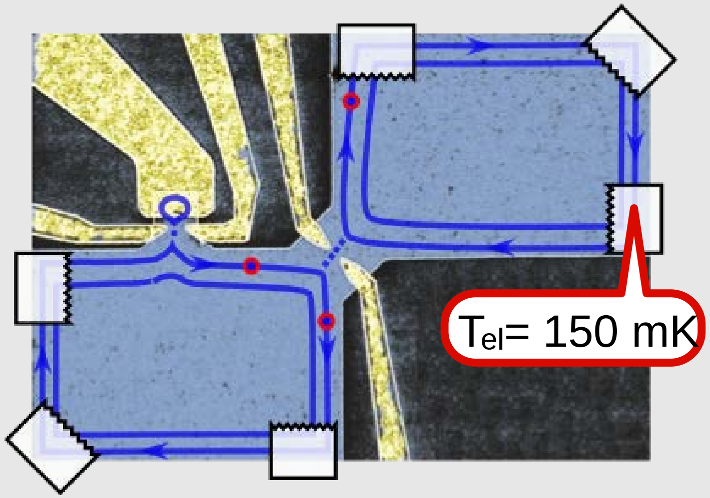
Partitioning single electrons : Experiment ?

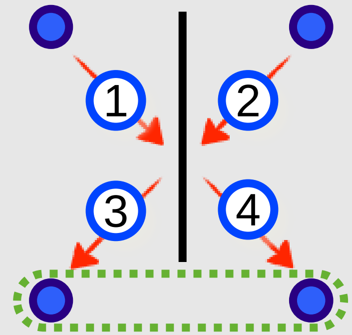
HBT noise is smaller than classical prediction, why ????



The explanation :

Antibunching with thermal excitations emitted by auxiliary entry 4 !!!!

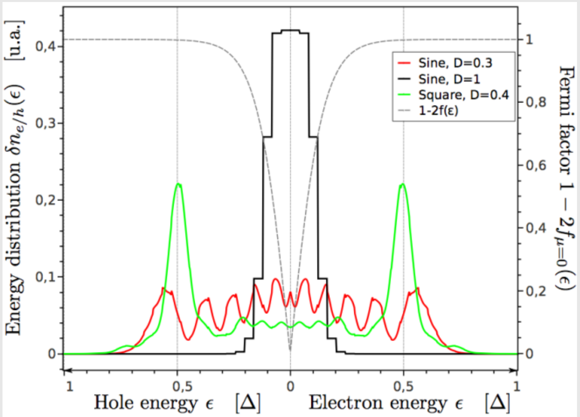




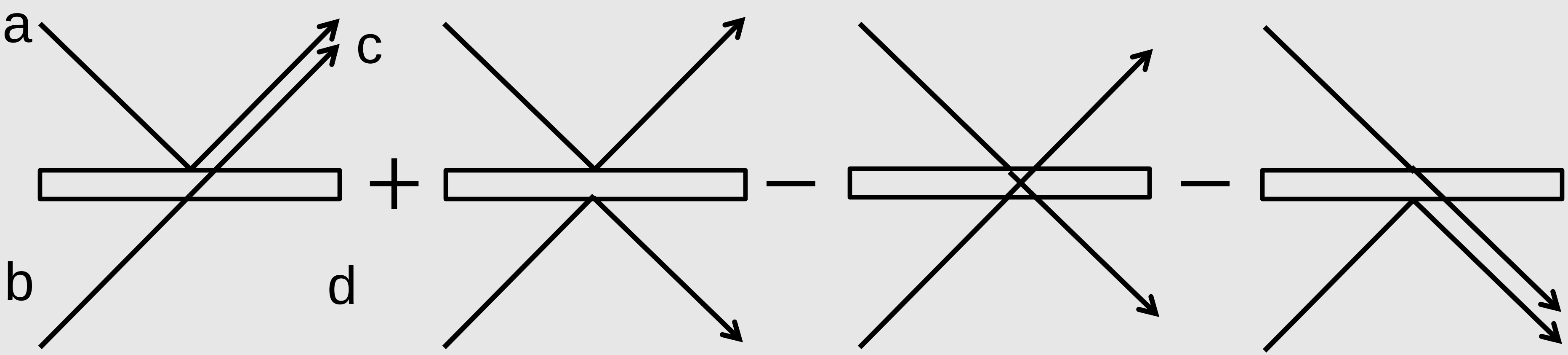
fermions

$$\delta N_{HBT} = \frac{\langle N_e\rangle + \langle N_h\rangle}{2} - \int_0^\infty d\epsilon[\delta n_e(\epsilon) + \delta n(\epsilon)]f(\epsilon)$$

$$\langle N_{e,h}\rangle = \int_0^\infty d\epsilon\ \delta n_{e,h}(\epsilon)$$



Two indistinguishable particles interference



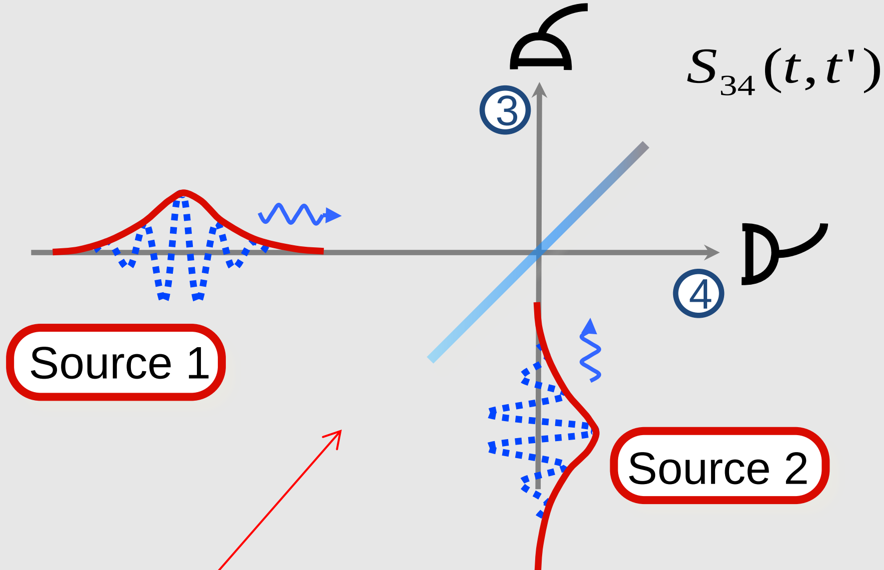
Splitter scattering matrix : $\begin{pmatrix} a \\ b \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{pmatrix} c \\ d \end{pmatrix}$

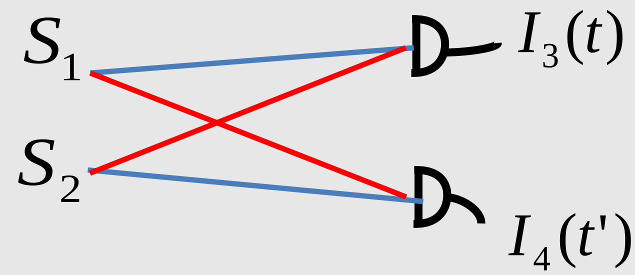
$$a^+b^+\,|0{,}0\rangle_{ab} = \frac{1}{2}(c^+ + d^+)(c^+ - d^+)|0{,}0\rangle_{cd}$$

bosons (destructive 2 − part. interference) : $a^+b^+\,|0{,}0\rangle_{ab} = \frac{1}{2}(\,|2{,}0\rangle_{cd} - |0{,}2\rangle_{cd})$

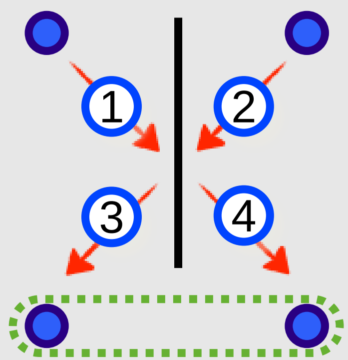
fermions (constructive 2 − part. interference): $a^+b^+\,|0{,}0\rangle_{ab} = |1{,}1\rangle_{cd}$

Two particle Hong-Ou-Mandel interferences

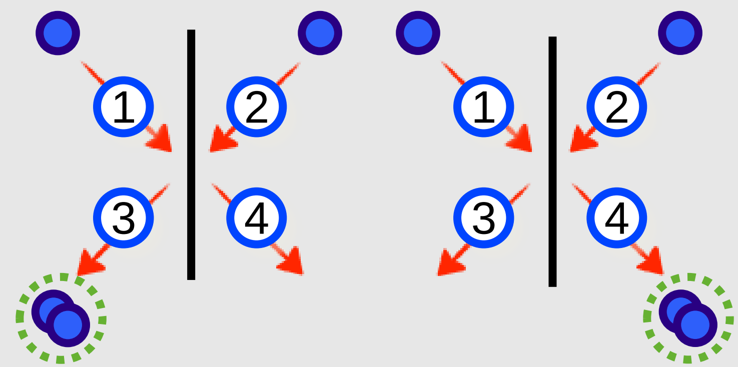




Hanbury Brown & Twiss experiment

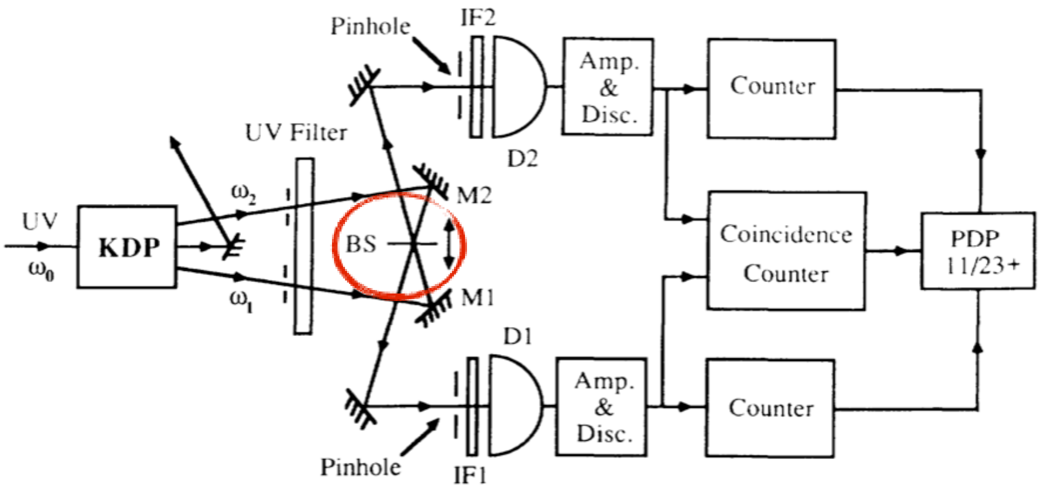


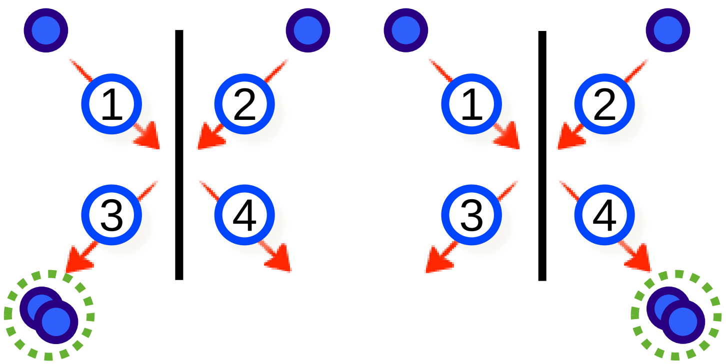
antibunching



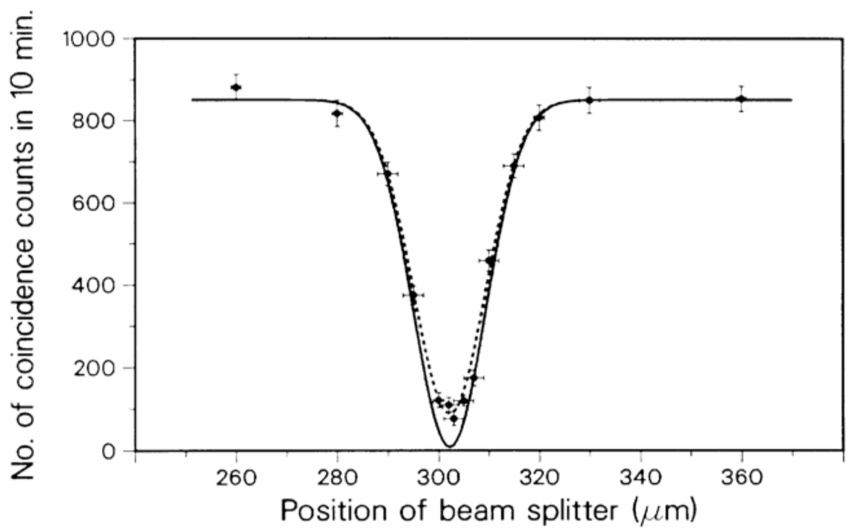
bunching

How indistinguisahble are photons ?



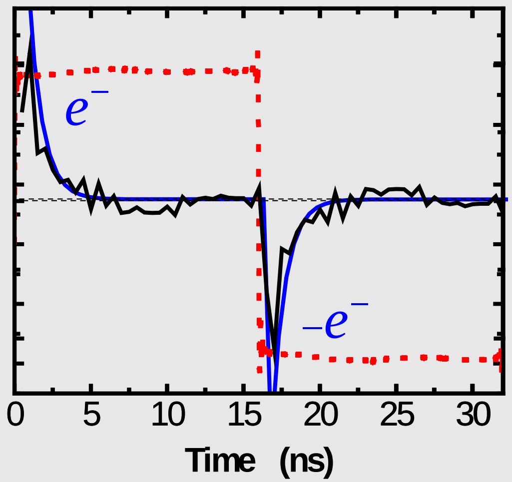


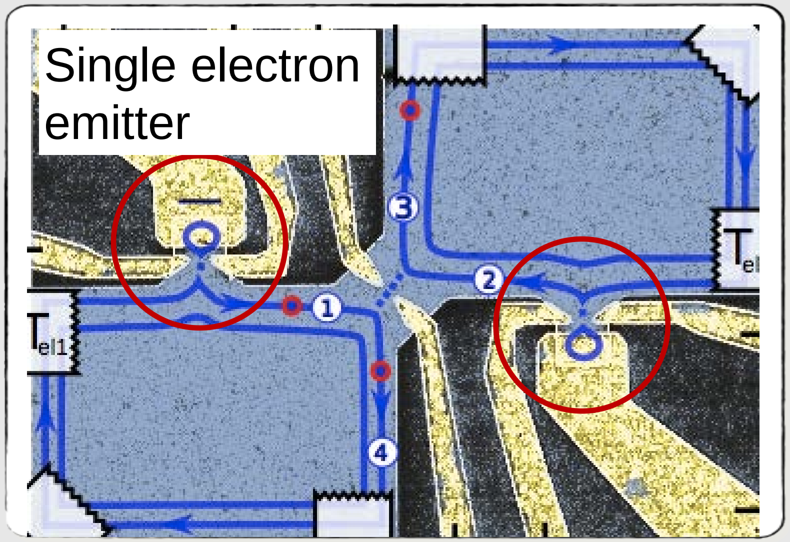
Undistinguishable photons

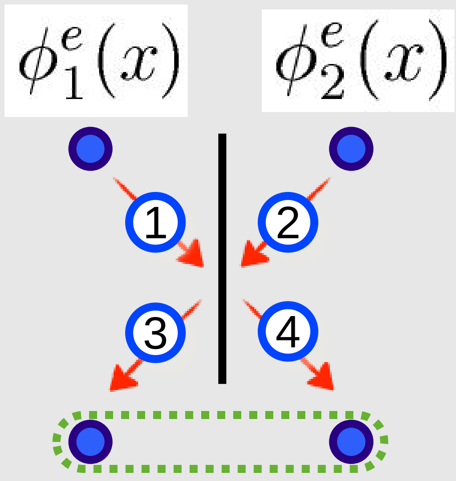


Photons pairs :
C. Hong *et al.,* PRL **59**(18), 2044 (1987)
Independent emitters :
J. Beugnon *et al.*, Nature **440**, 779 (2006)
P. Maunz *et al.*, Nature Physics **3**, 538 (2007)
E. B. Flagg *et al.*, PRL **104,** 137401 (2010)
C. Lang *et al.*, Nature Physics **9**, 345 (2013)

2 particle interferences with 2 single electron sources







From joint probability :

$$P(1,1) = \frac{1}{2}\left[1 + |\langle \varphi_1{}^e | \varphi_2{}^e \rangle|^2\right]$$

To normalized noise :

$$\frac{S_{HOM}}{S_{HBT}} = 1 - \left| \int dt \;\; \varphi_1(t+\tau)\varphi_2{}^*(t) \right|^2$$

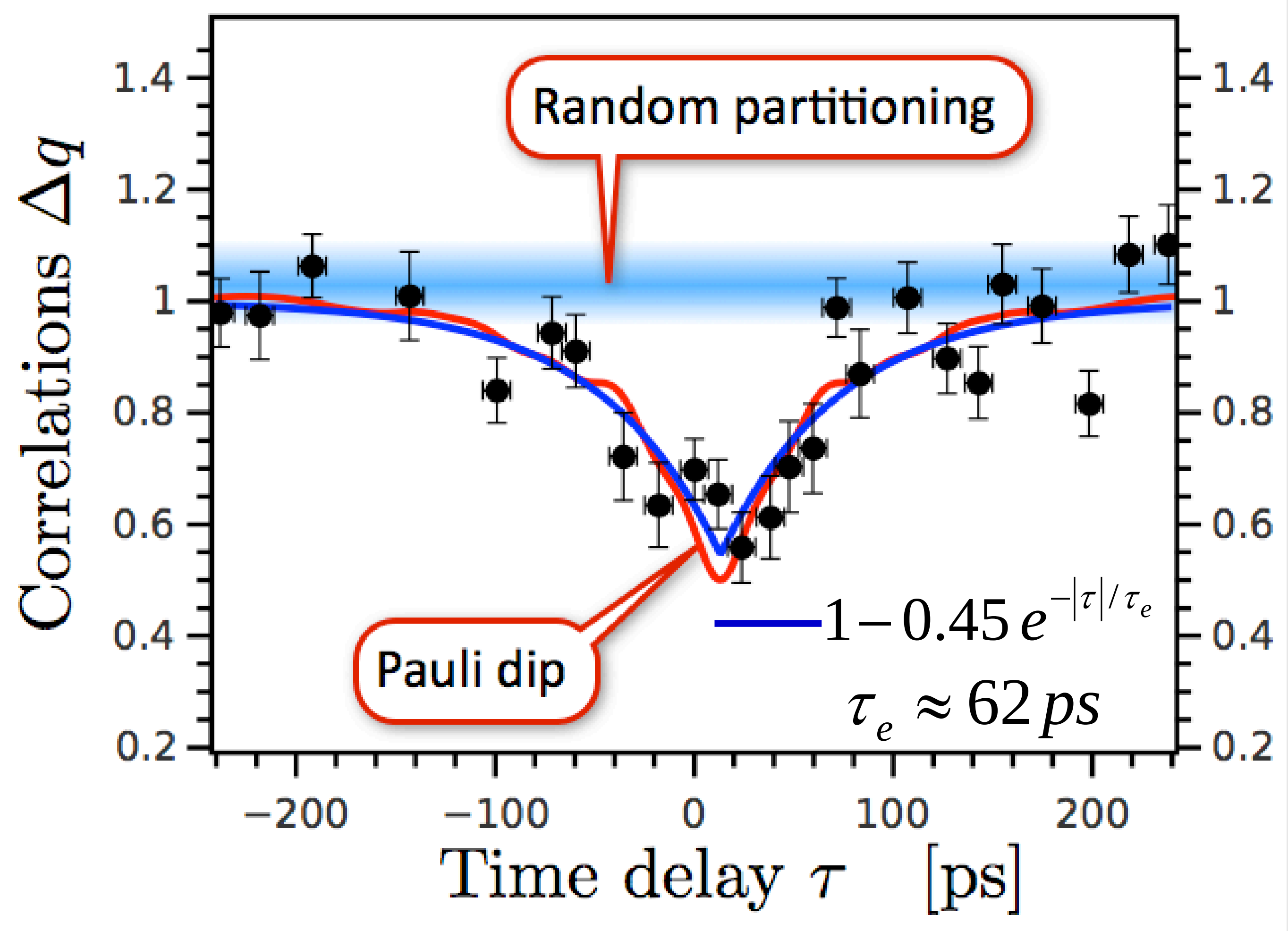
$$= 1 - e^{-|\tau|/\tau_e}$$

First order coherence

First electronic HOM Experiment (2013)

$D_1 = D_2 \approx 0.4$

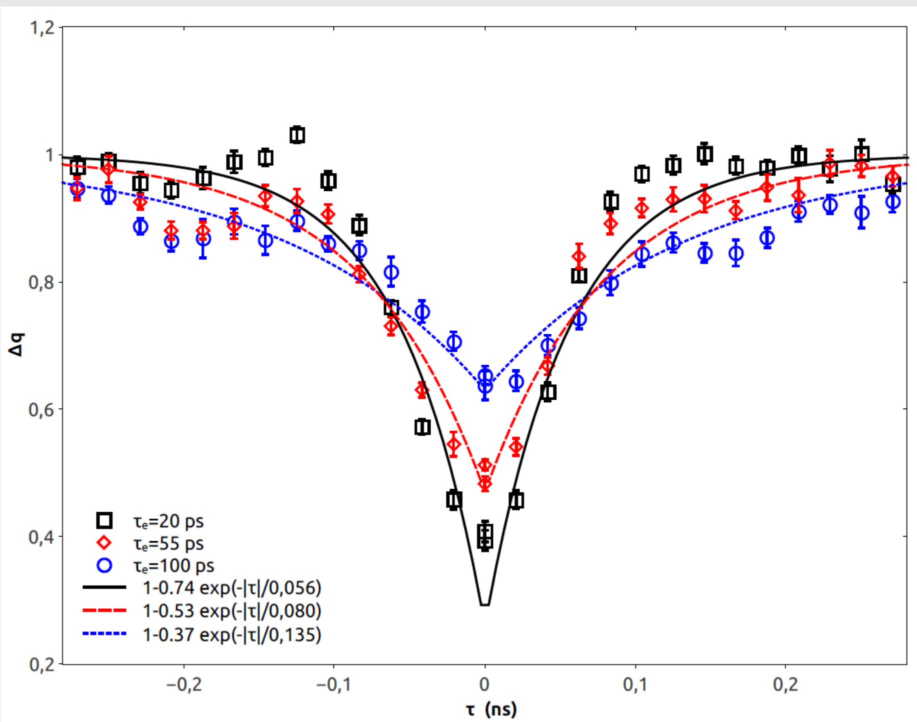
$\tau_e \approx 58\,ps$

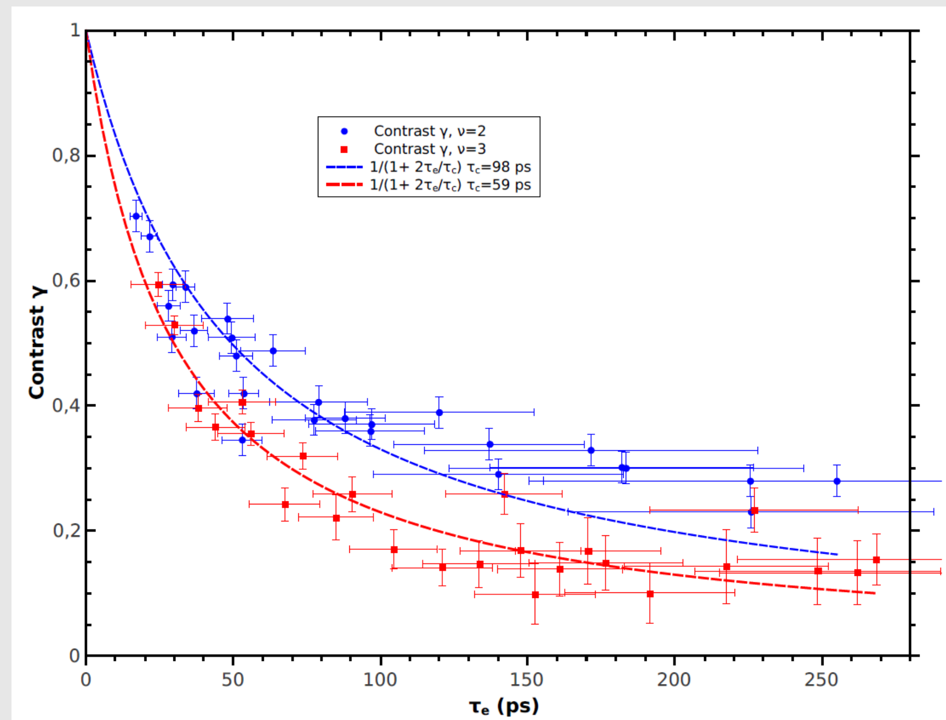


Decoherence of the single electron wave packet

‼ *HOM experiment combines particle and wave aspects* ‼

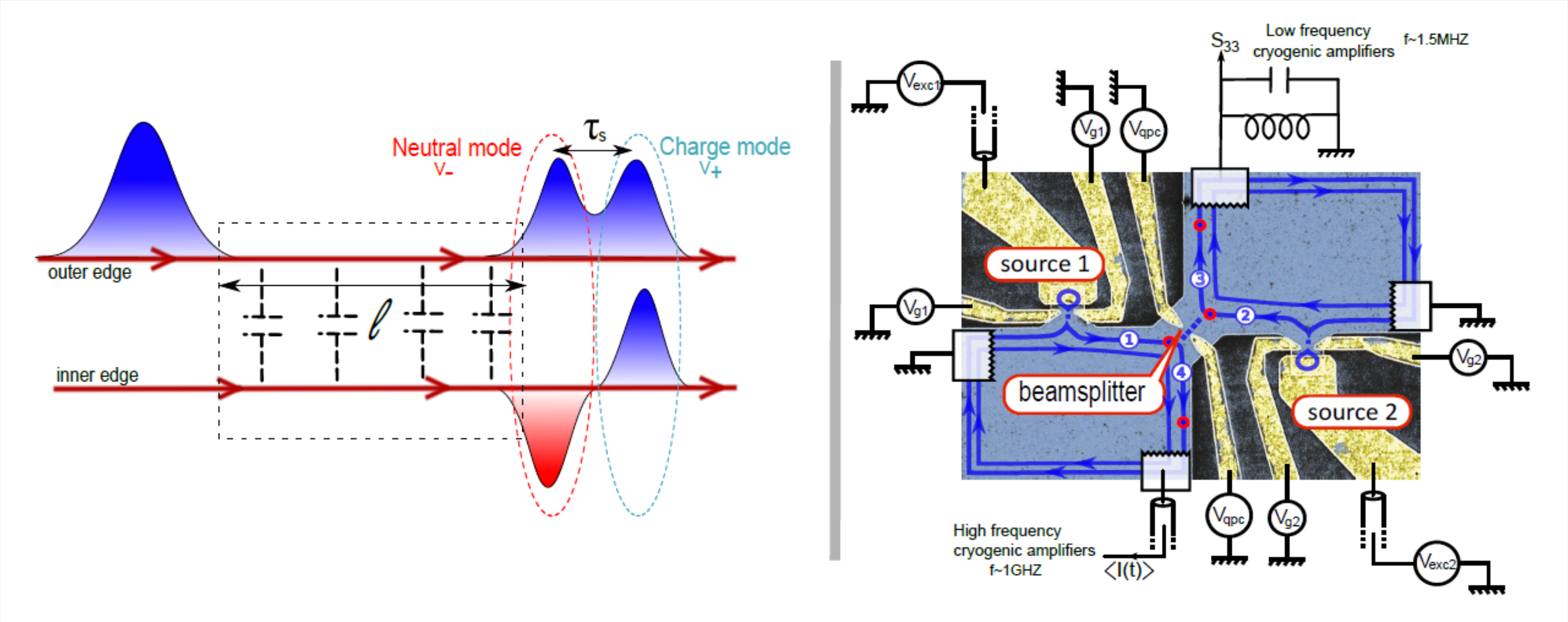
$$\frac{S_{HOM}}{S_{HBT}} = 1 - \left| \int dt \;\; \varphi_1(t+\tau) D(\tau) \varphi_2{}^*(t) \right|^2 \approx \left(1 - e^{-|\tau|/\tau_e}\right) \times \left(\frac{1}{1 + 2\,\tau_e/\tau_\varphi} \right)$$





Autopsy of the quasi-particle (QP)
HOM in the environment

QPs are not eigenstates in 1D; they degrade into collective e − h excitations



Input of the interaction region : single electron state in outer channel

$$|\psi_{in}\rangle = \left(\int dx\, \varphi(x) \otimes |\lambda(x)\rangle_{outer} \right) \otimes |0\rangle_{inner}$$

Output : the electron gets entangled with environment e − h excitations

$$|\psi_{out}\rangle = \int dx\, \varphi(x) \otimes \left(|t \times \lambda(x)\rangle_{outer} \right) \otimes |r \times \lambda(x)\rangle_{inner})$$

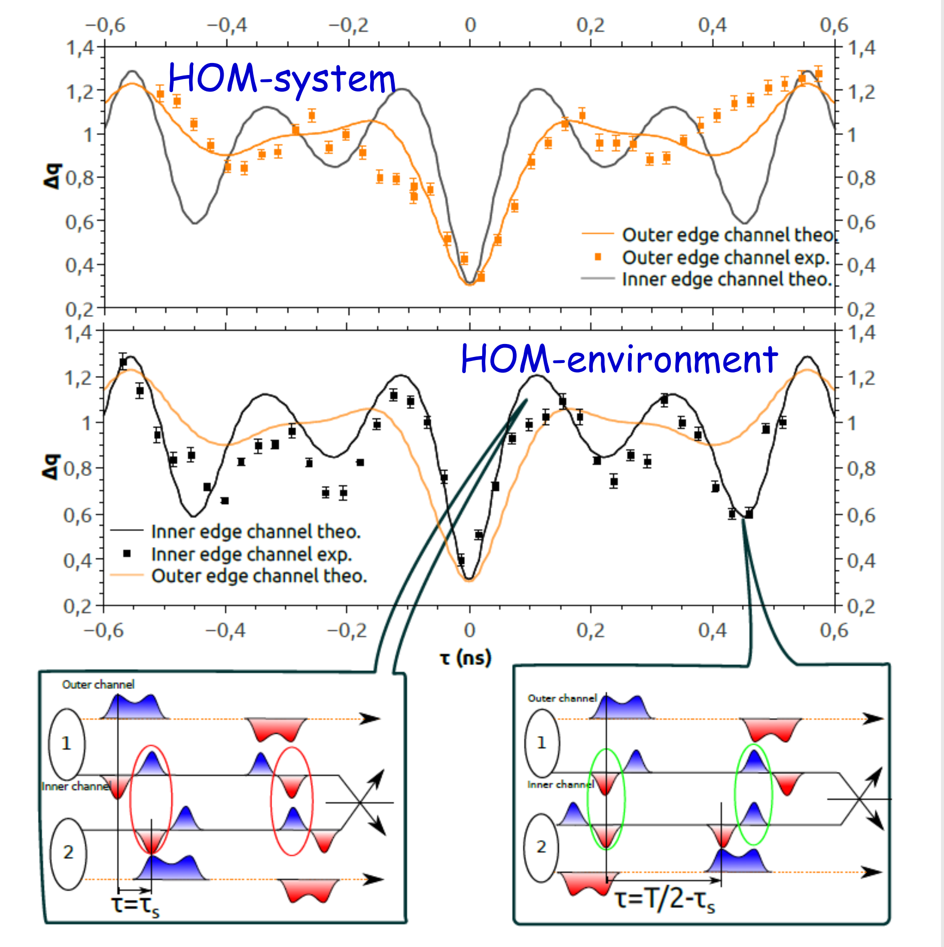
HOM experiment in the environment evidence for electron-fractionalization

Output : the electron gets entangled with environment excitations

$$|\psi_{out}\rangle = \int dx\, \varphi(x) \otimes (|t \times \lambda(x)\rangle_{outer}) \otimes |r \times \lambda(x)\rangle_{inner})$$

$\rightarrow$ *electron – hole antidips.*

$\rightarrow$ *electron – electron satellites*



Conclusion

- Is single particle description relevant ? (YES, to some extent !)
- Learn about particle statistics and coherence
- Role of the Fermi sea
- Many-body effects

perspectives

- Quantum tomography of the single particle states
- Implementation in other systems (graphene ? TI's ?)
- Use for quantum information (Flying qubits ?)