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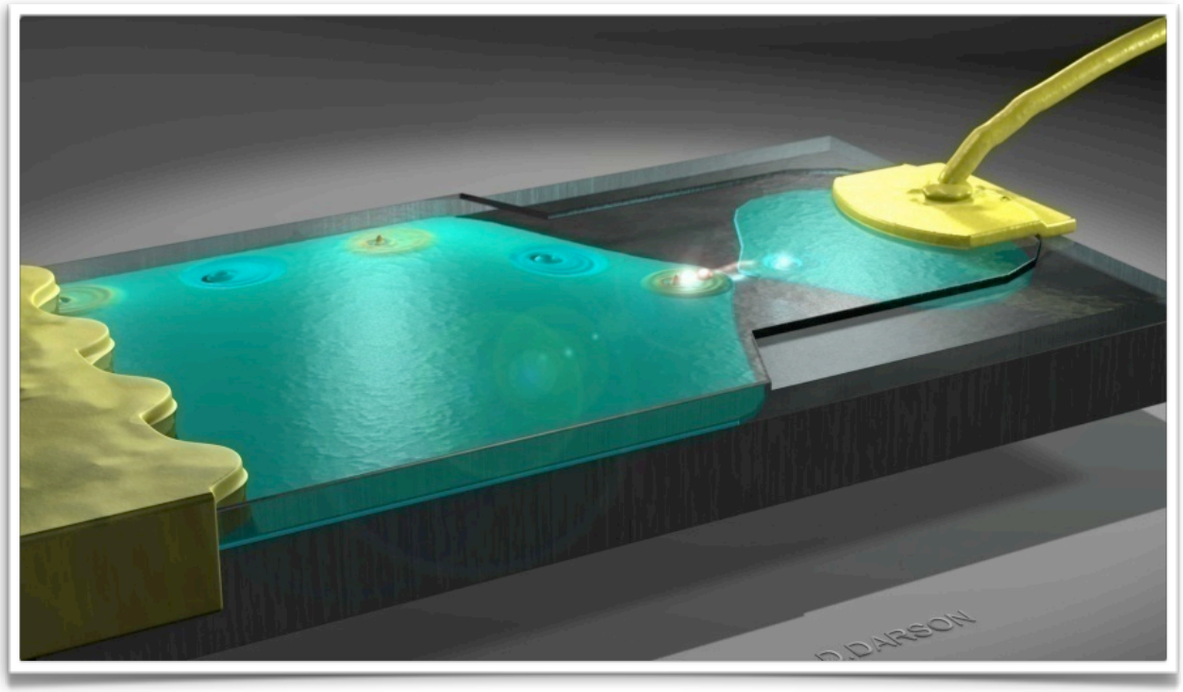
électronique et photonique quantiques

Erwann Bocquillon

Intensity correlations of a single electron beam

Charge and heat dynamics in nanosystems - Orsay - 10/11/2011



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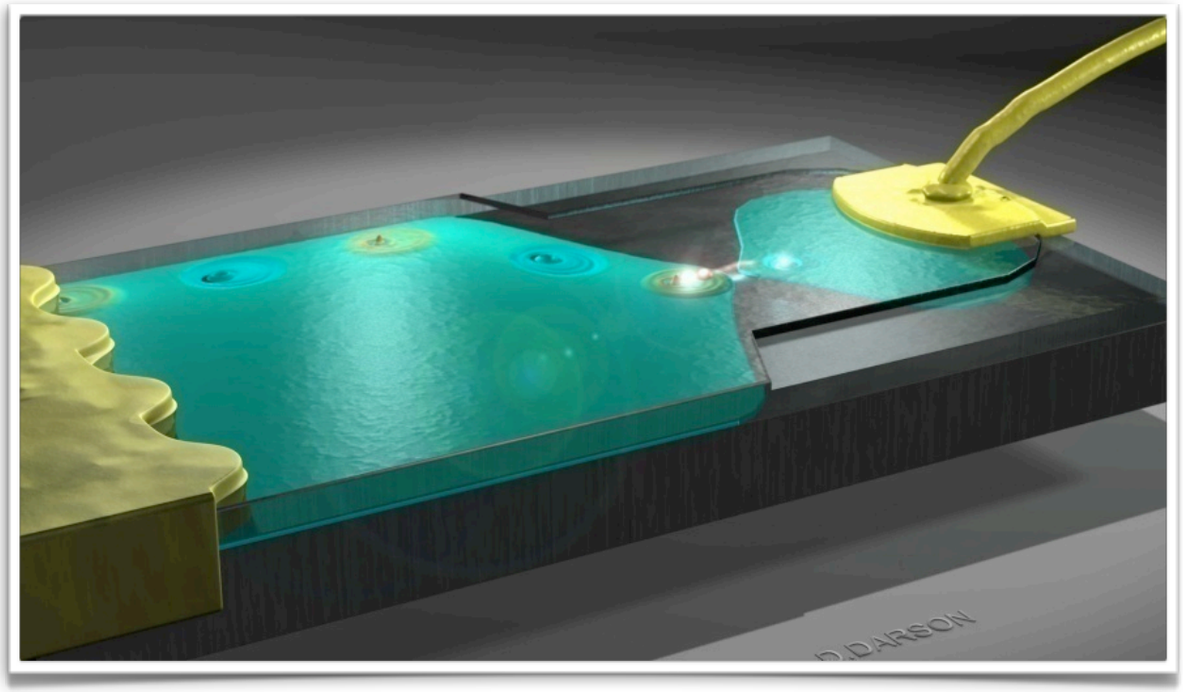

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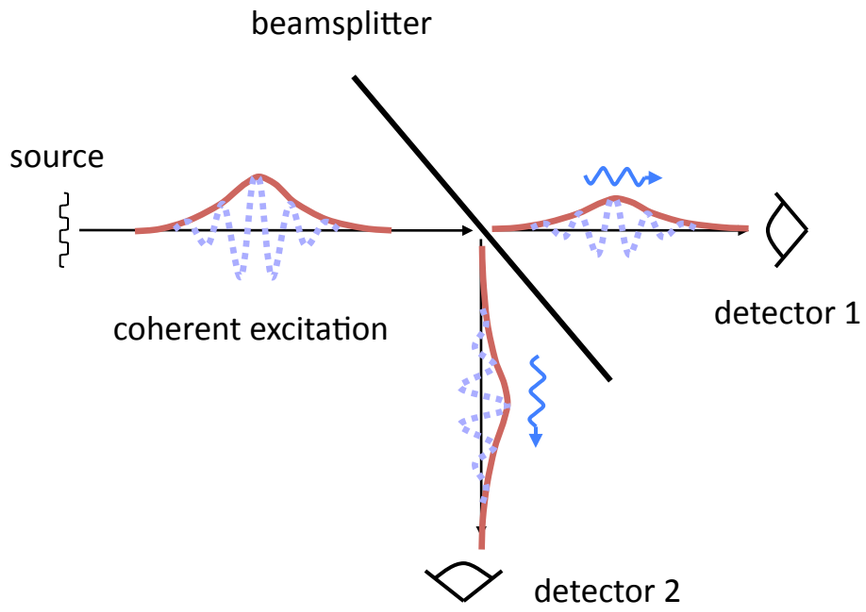
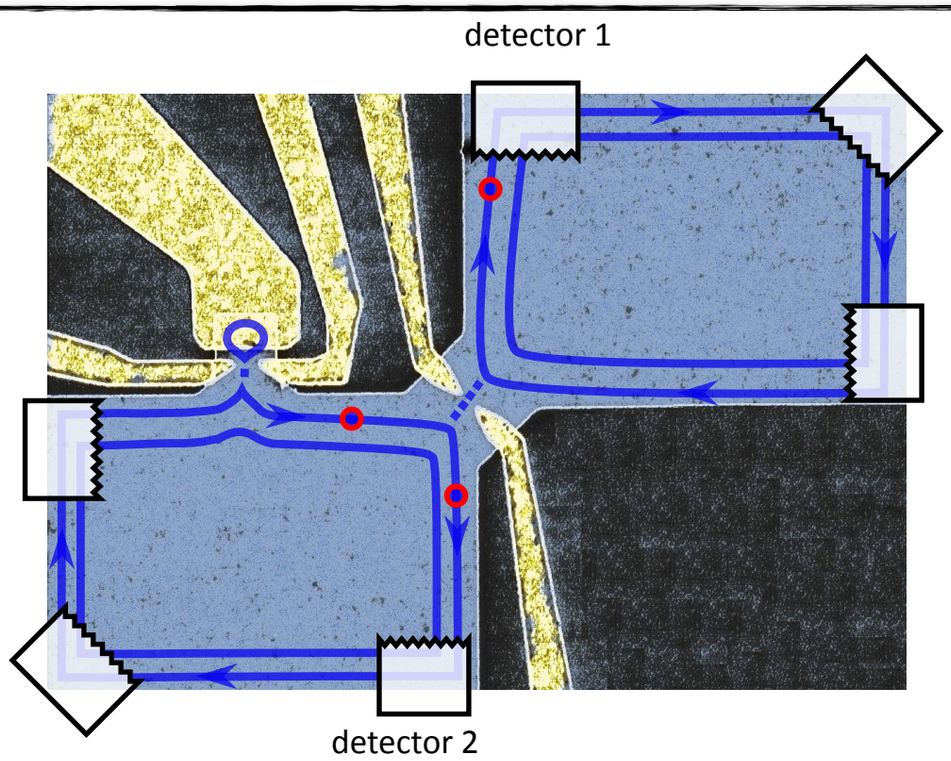
Electron Optics



HBT correlations in optics



HBT correlation in a ballistic conductor

- ballistic propagation in vacuum ⇔ spin polarised 1-D edge channel of IQHE
- beamsplitter ⇔ quantum point contact (QPC)

Most experiments : DC sources
≠ AC single electron source

W. Oliver *et al.*, Science **284**, (5412), 299-301, (1999)
Y. Ji *et al.*, Nature, ***422***(6930), 415-8 (2003)
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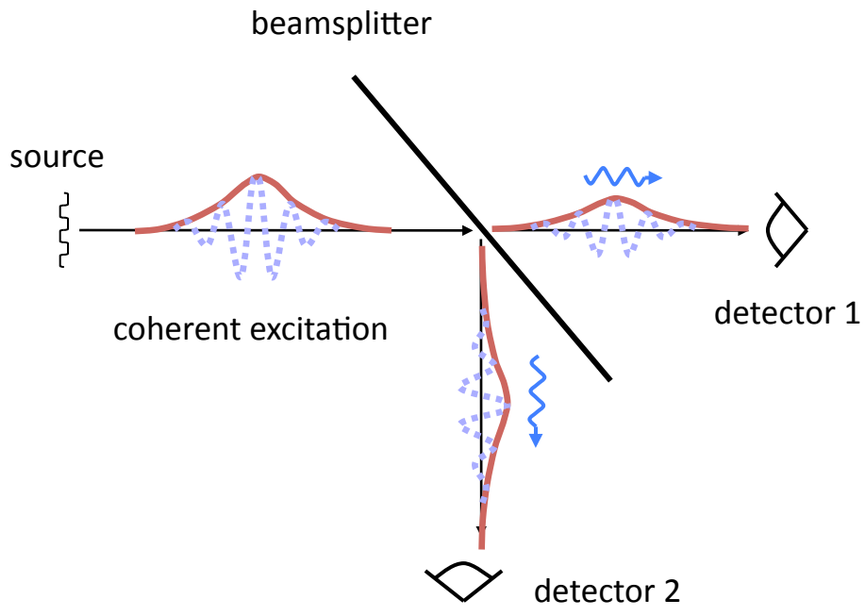

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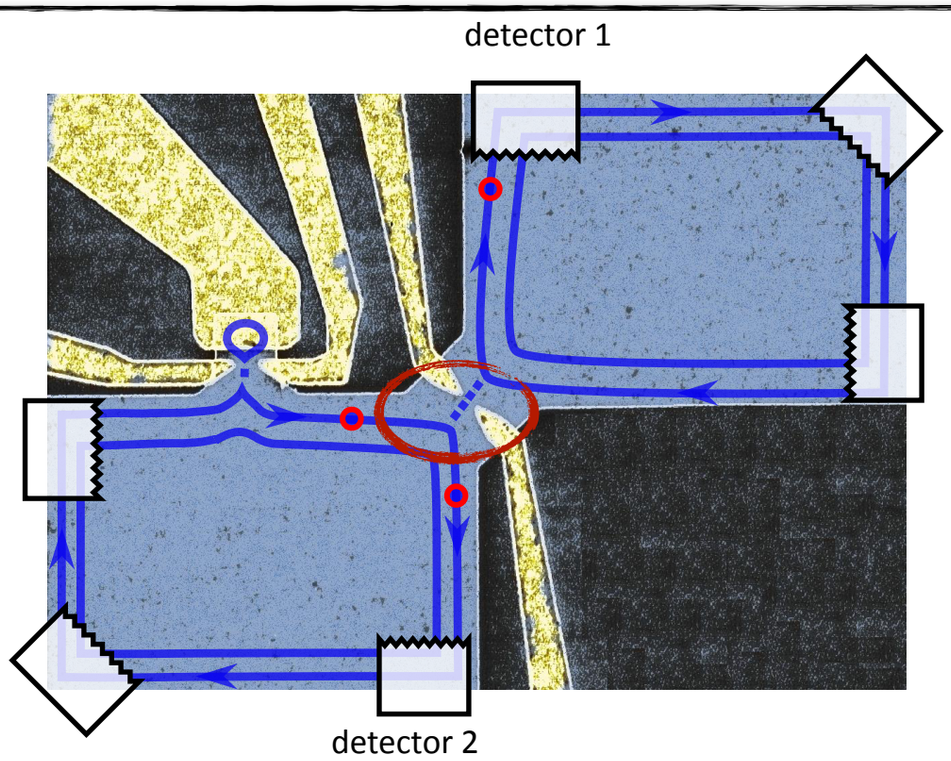

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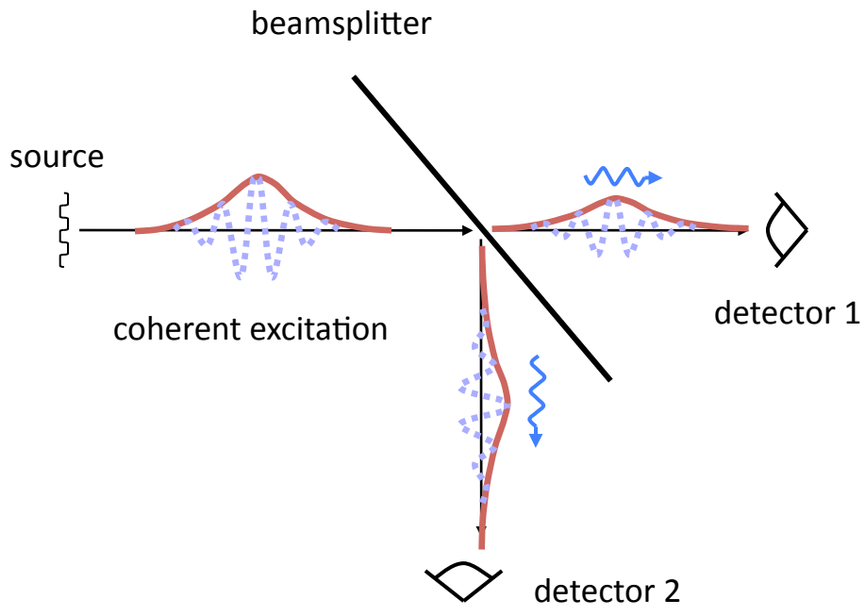

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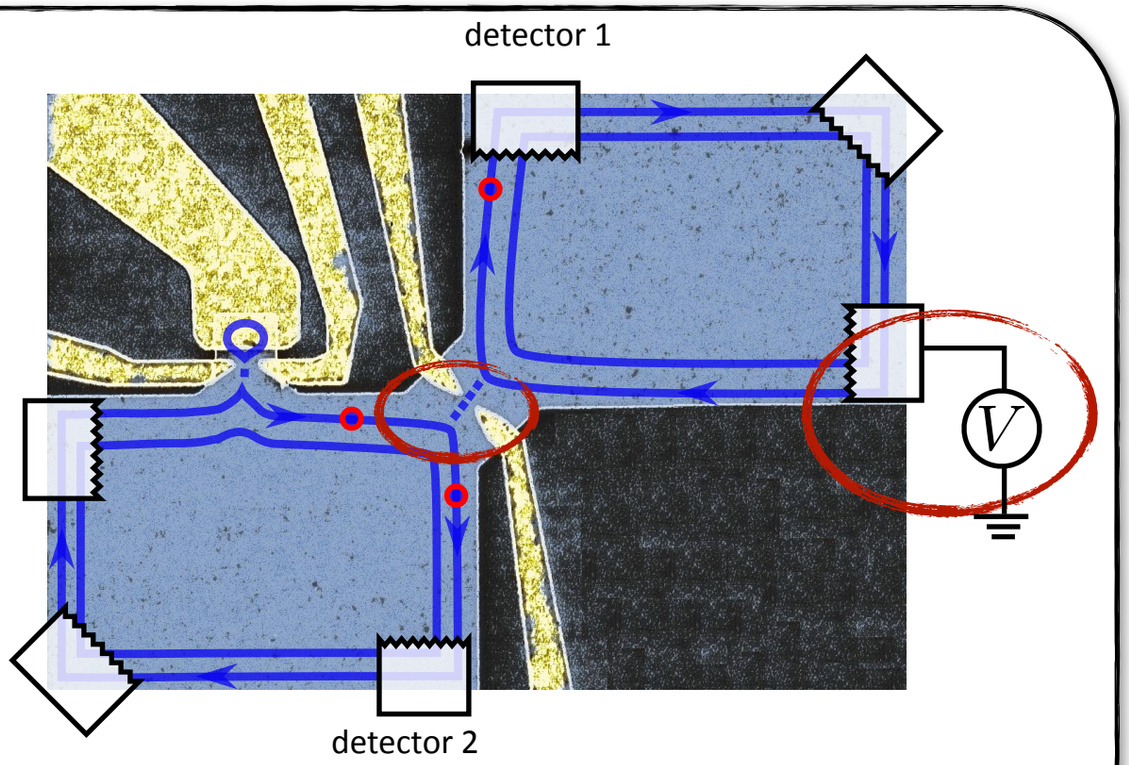

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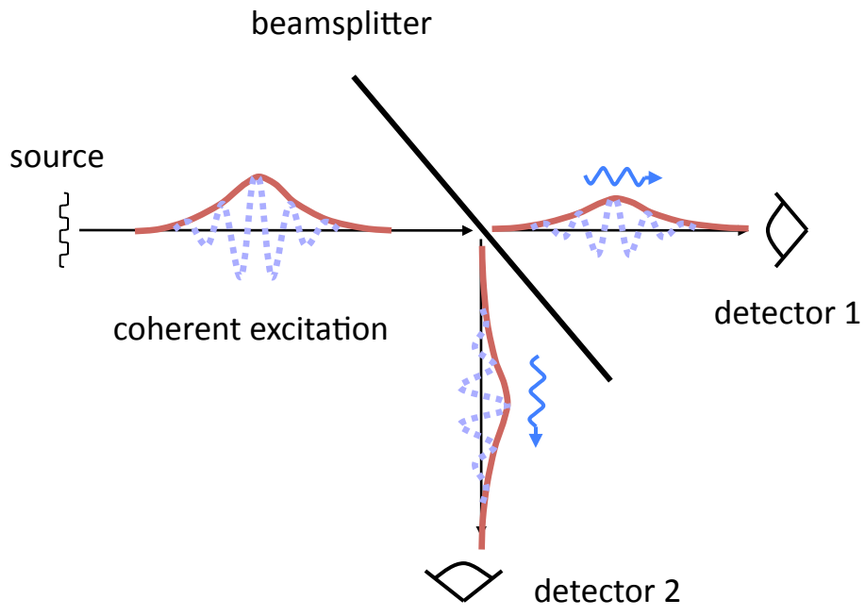

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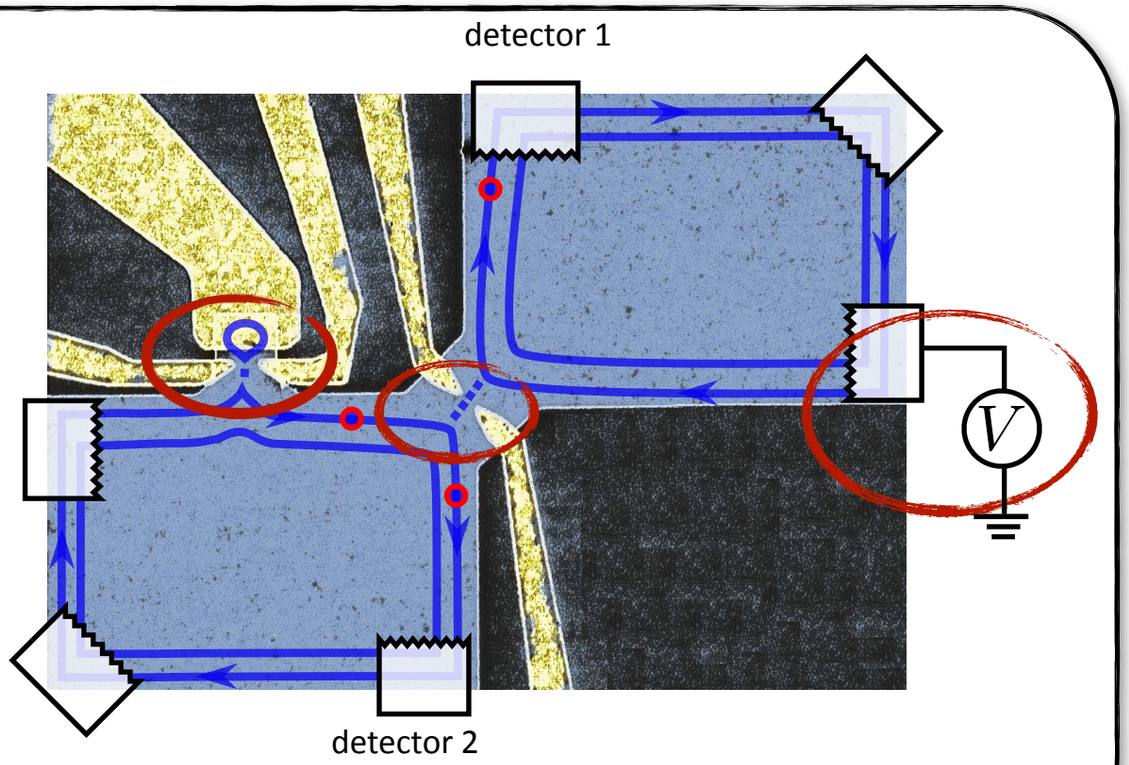

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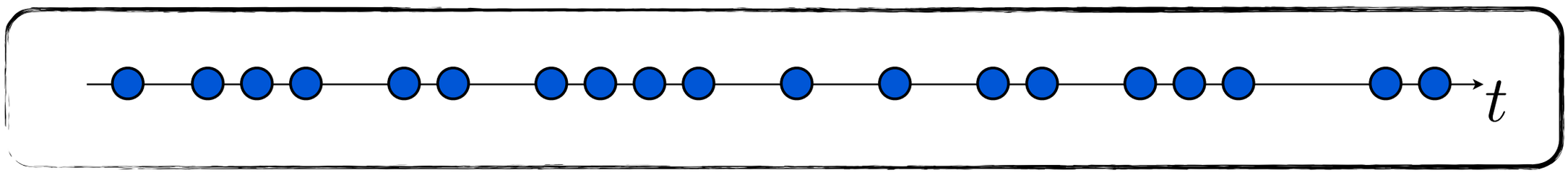
C. Altimiras *et al.*, Nature Physics, ***6***(1), 34–39 (2009)

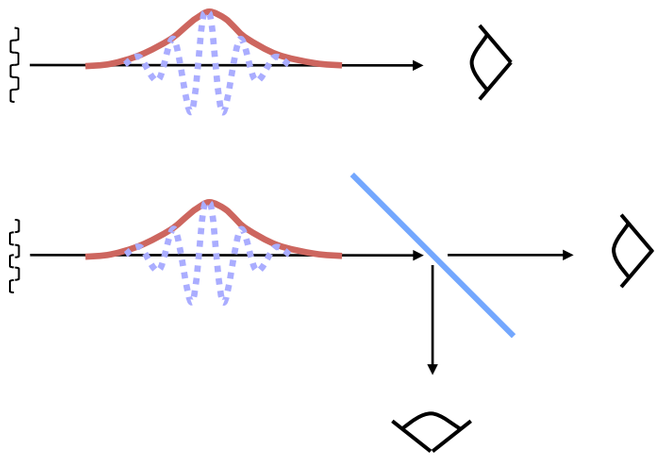
Beyond average current - DC sources

Source with 1 type of carrier :

- photon source
- biased contact at T=0

Average current : $\langle \hat{I} \rangle = e \dfrac{\langle N_e \rangle}{T_{meas}}$





Autocorrelations

HBT correlations

$S(\omega = 0)$ gives $\langle \delta N_e^2 \rangle$

M. Reznikov *et al.,* PRL **75,** 3340 (1995)

A. Kumar *et al.*, PRL **76**, 2778 (1996)

W. Oliver *et al.*, Science **284**, (5412), 299-301, (1999)

S. Oberholzer *et al.*, Science **284**, (5412), 296-298, (2001)

G.B. Lesovik, JETP Lett. **70**, 208 (1999)

T. Martin *et al.*, PRB **45**(4), 1742-1755 (1992)

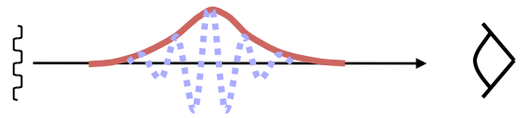
Y. Blanter *et al.*, *Physics* Reports, **336**(1-2), 1–166 (2000)...

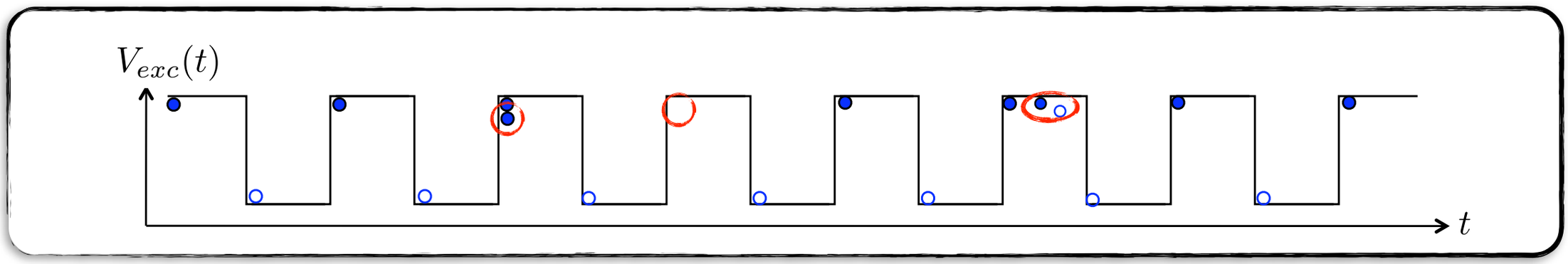
Beyond average current - AC sources

Autocorrelations : Statistics of emitted charge

charge counted in **high-frequency noise**

demonstrates **single charge emission**

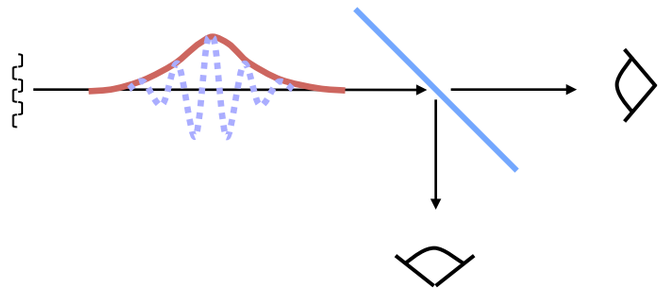


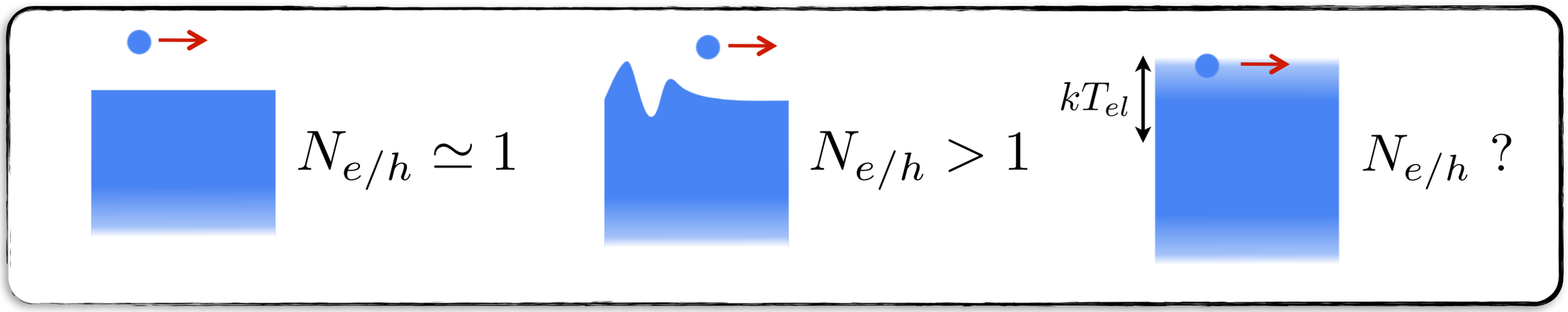


HBT correlations : Counting of emitted quasiparticles

each particle counted in **low-frequency noise**

reveal **extra e/h pairs** and effect of **thermal excitations**





Outline

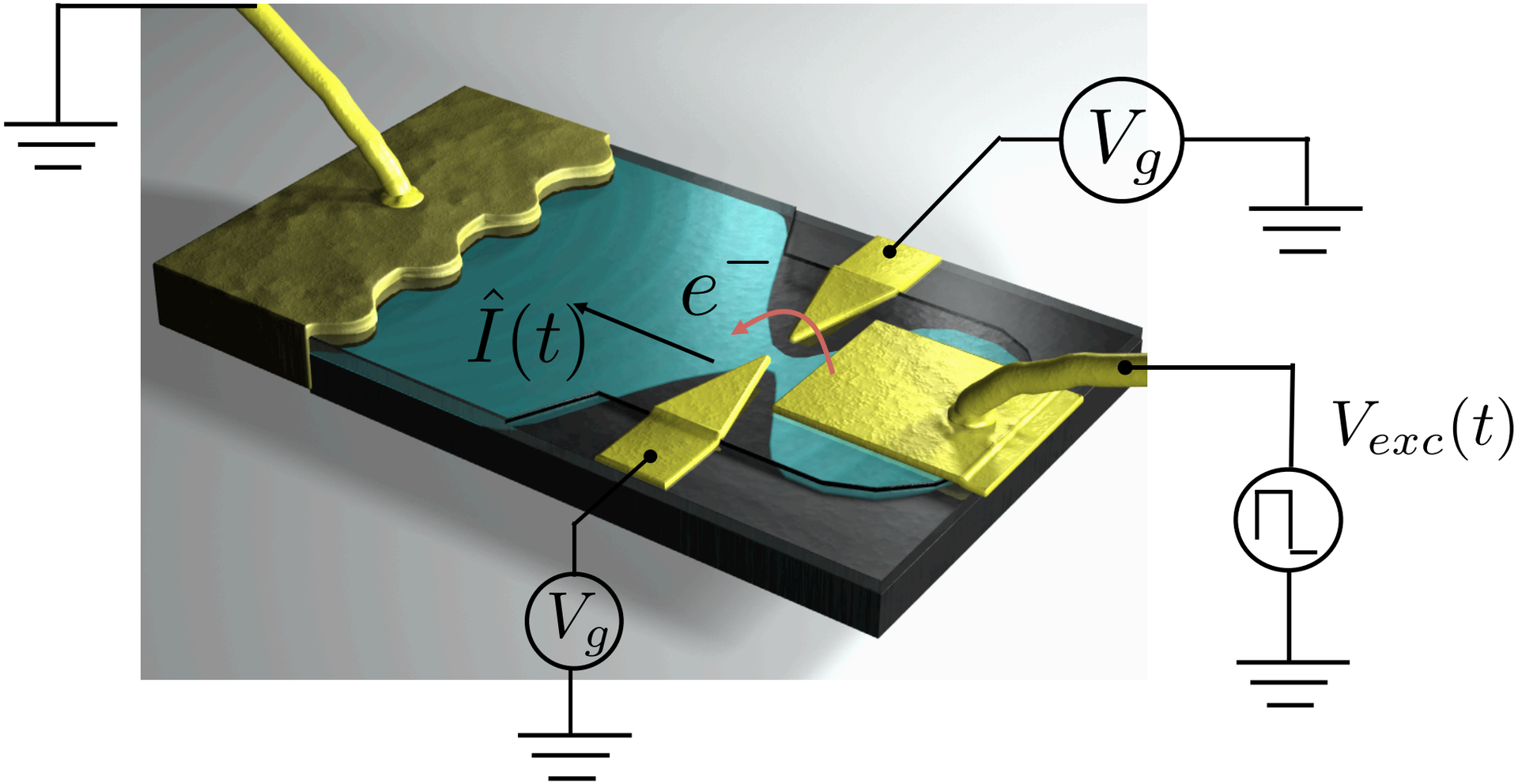
Short time autocorrelations of the current

- single electron source
- high-frequency noise measurement
- phase noise : evidence of single charge emission

Hanbury-Brown & Twiss experiment with single electrons

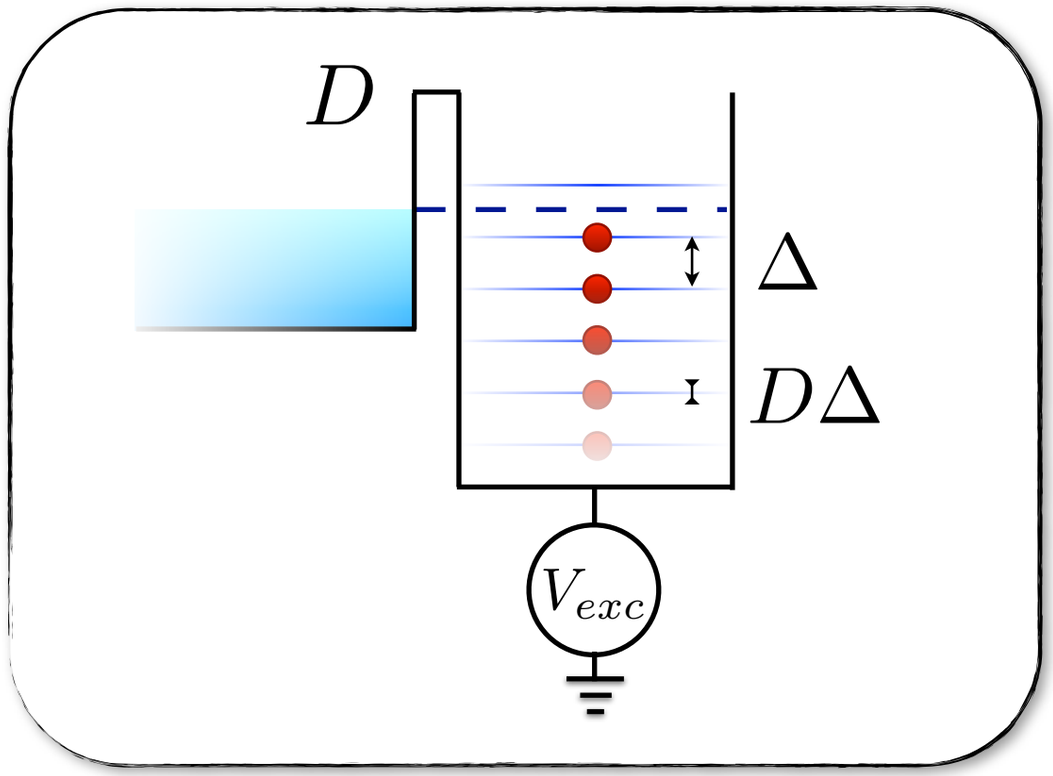
- counting quasiparticles with partition noise
- effect of the Fermi sea
- engineering of the wavepacket

Mesoscopic capacitor as single electron source



M. Büttiker *et al.*, Phys. Lett. A **180**, 364 (1993)
J. Gabelli *et al.*, Science **313**, 499 (2006)

Principle of single charge emission

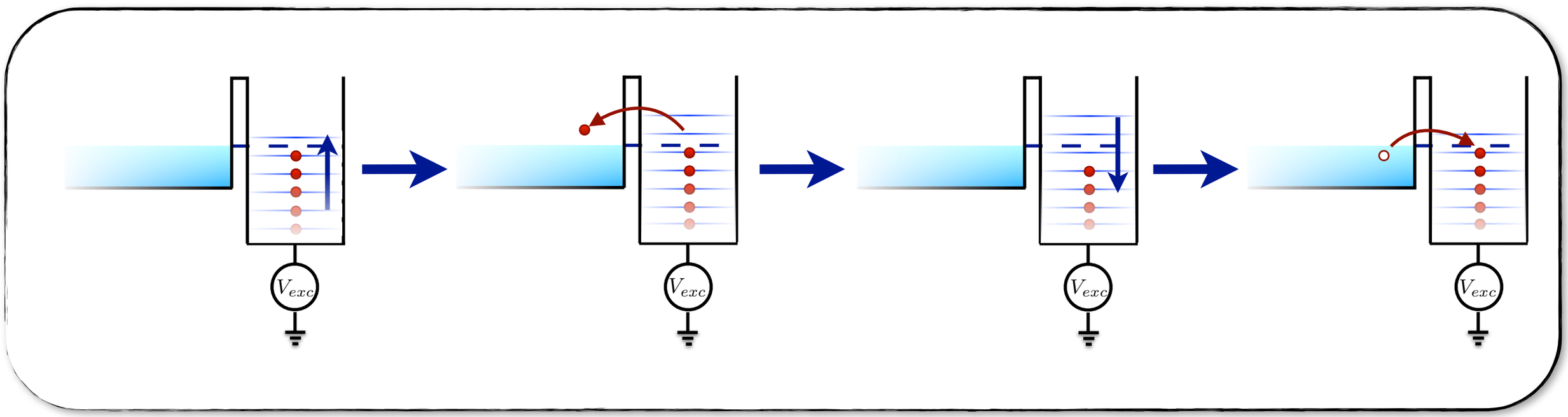


level spacing : $\Delta \simeq 2.1K$

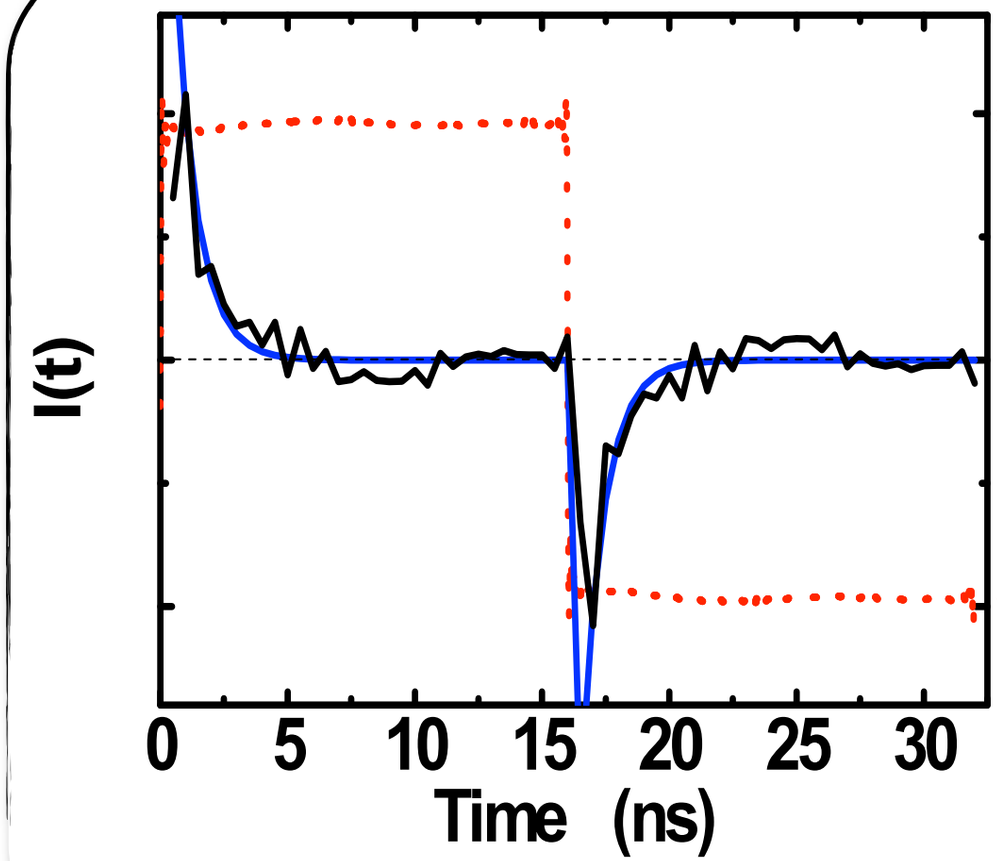
level broadening : $D\Delta$

escape time : $\tau \simeq \dfrac{h}{D\Delta}$

driving frequency : $f = \dfrac{1}{T} \simeq 1.7\,\mathrm{GHz}$



Average current measurement



I (u.a)

exponential fit

square excitation

$$f = 31.25\ \mathrm{MHz}$$

$$T = 32\ \mathrm{ns}$$

$$D \simeq 0.02$$

$$\tau \simeq \frac{h}{D\Delta} \simeq 0.9\,\mathrm{ns}$$

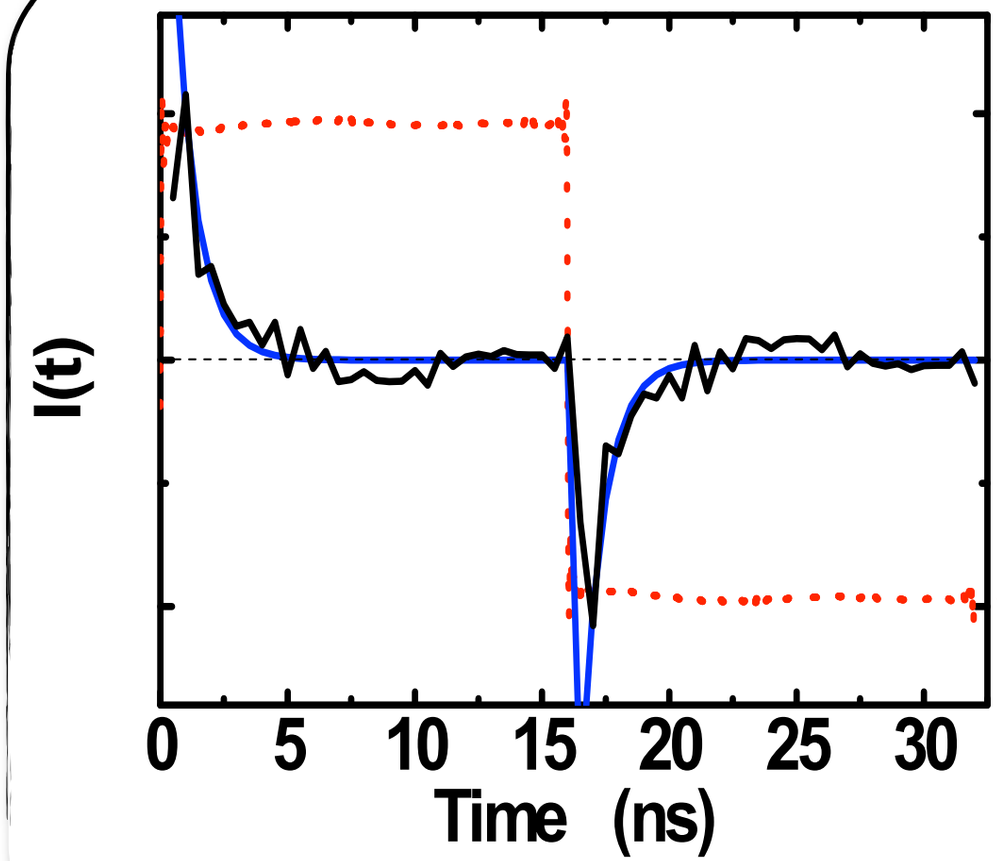
$$Q^t = e$$

A. Mahé *et al.*, JLTP **53**, 339-349 (2008)
G. Fève *et al.*, Science **316**, 1169 (2007)

$$\left.\begin{array}{r} \tau \ll T/2 \\ \Rightarrow Q^t = e \end{array}\right\}$$ ⇒ **single charge emission on average**

$$\left.\begin{array}{r} \tau \geq T/2 \\ \Rightarrow Q^t < e \end{array}\right\}$$ ⇒ charges not emitted during each cycle

Average current measurement



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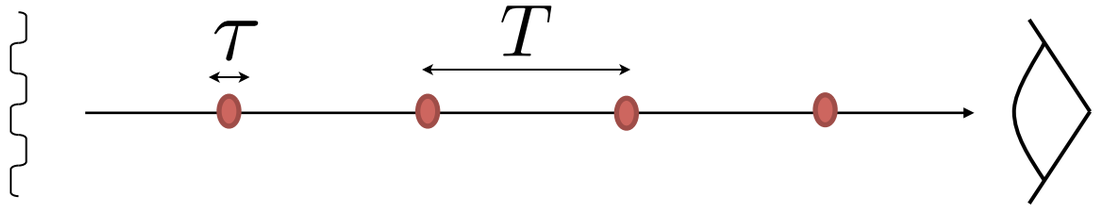
RF noise of a perfect single charge emitter



F.D. Parmentier *et al,* RSI **82**(1), 013904 (2011)
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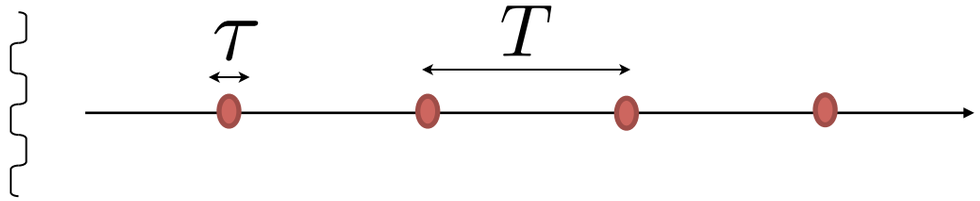

$$\overline{\langle \delta\hat{I}(t)\delta\hat{I}(t+t')\rangle}^{t} = \overline{\langle \hat{I}(t)\hat{I}(t+t')\rangle}^{t} - \overline{\langle \hat{I}(t)\rangle\langle \hat{I}(t+t')\rangle}^{t}$$

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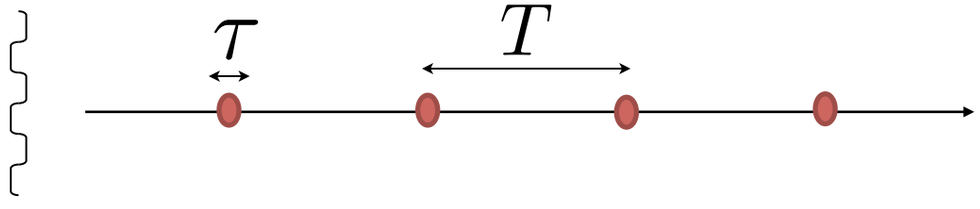

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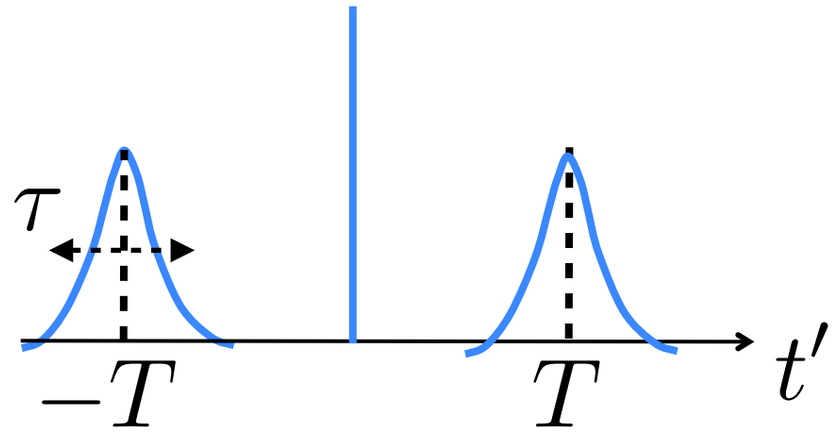
for $t' < T$ $\quad -\overline{\langle \hat{I}(t)\hat{I}(t+t')\rangle}^{t} = \frac{e^2}{T}\delta(t')$



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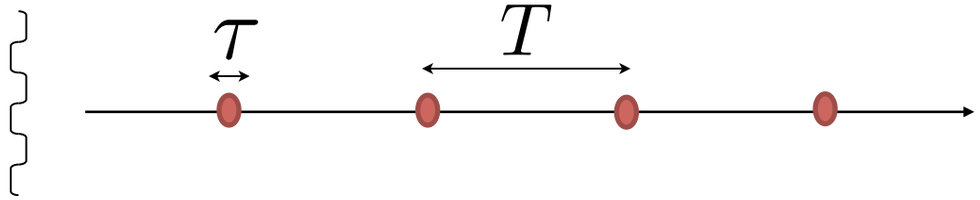

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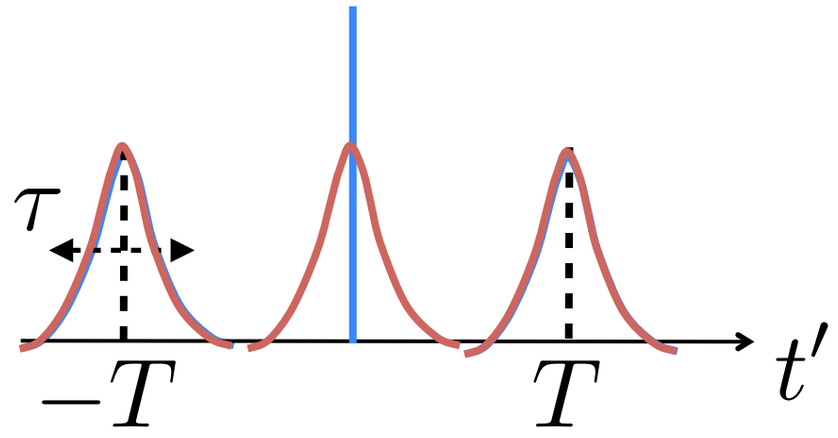
for $t' < T$

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

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



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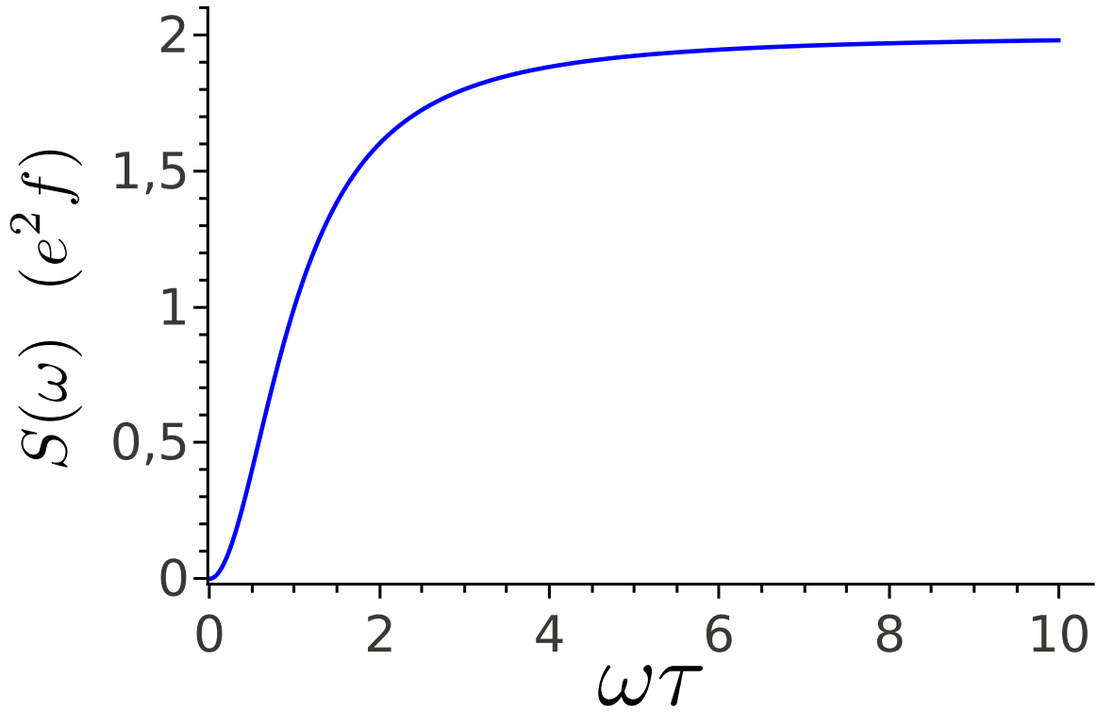
RF noise of a perfect single charge emitter

$$S(\omega) = 2e^2 f \frac{(\omega\tau)^2}{1+(\omega\tau)^2}$$



Fundamental noise : phase noise
High frequency noise : $\omega\tau \simeq 1$
τ-dependence probed, at fixed $\omega \simeq 2\pi f$

$S(\omega) \simeq e^2 f \simeq 4.10^{-29}\,\mathrm{A^2 Hz^{-1}}$
at $f = 1.5\,\mathrm{GHz}$

F.D. Parmentier *et al,* RSI **82**(1), 013904 (2011)
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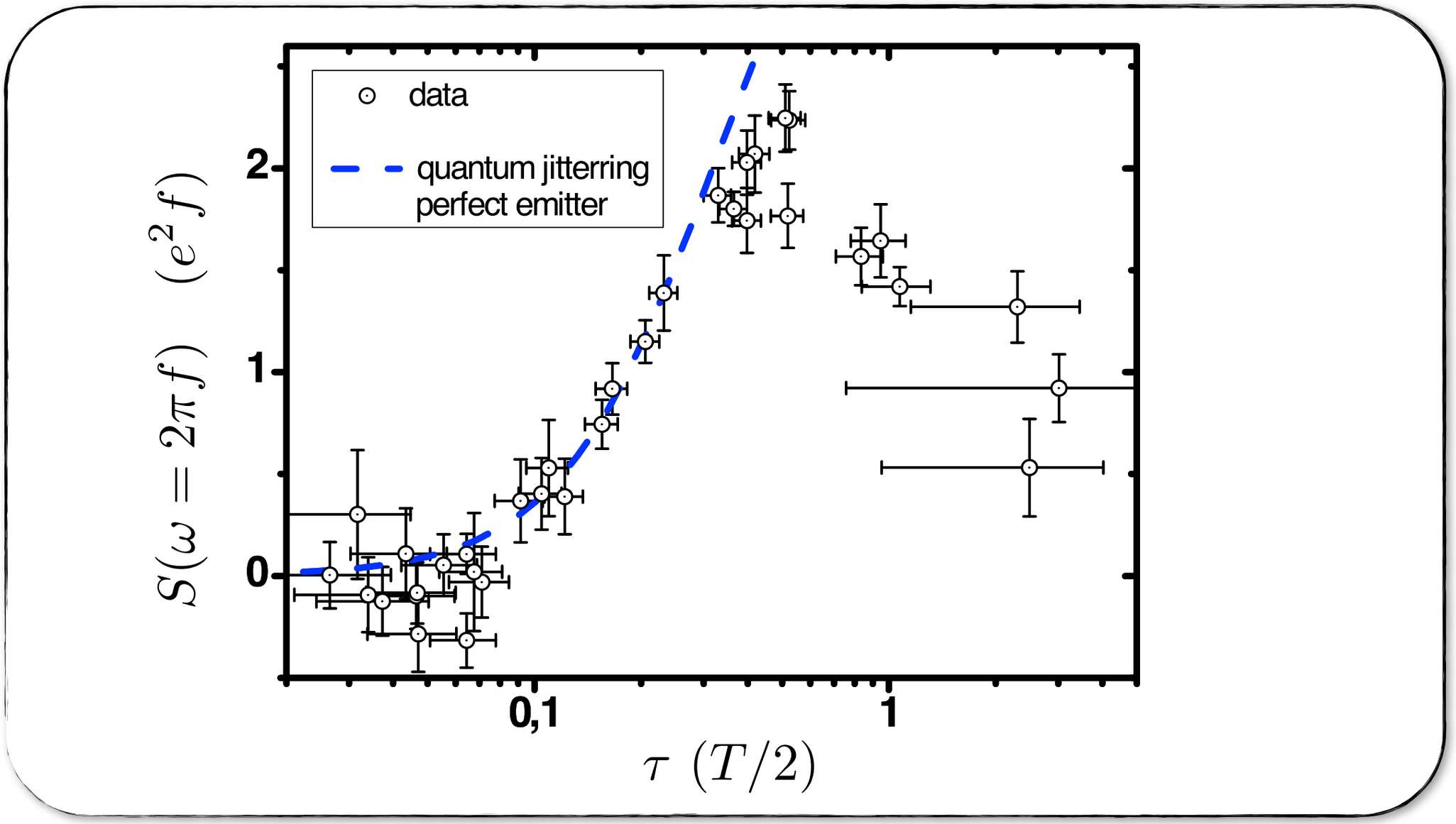
M. Albert *et al.*, PRB **82**(4), 41407 (2010)

Noise of the ‘on demand’ single electron source



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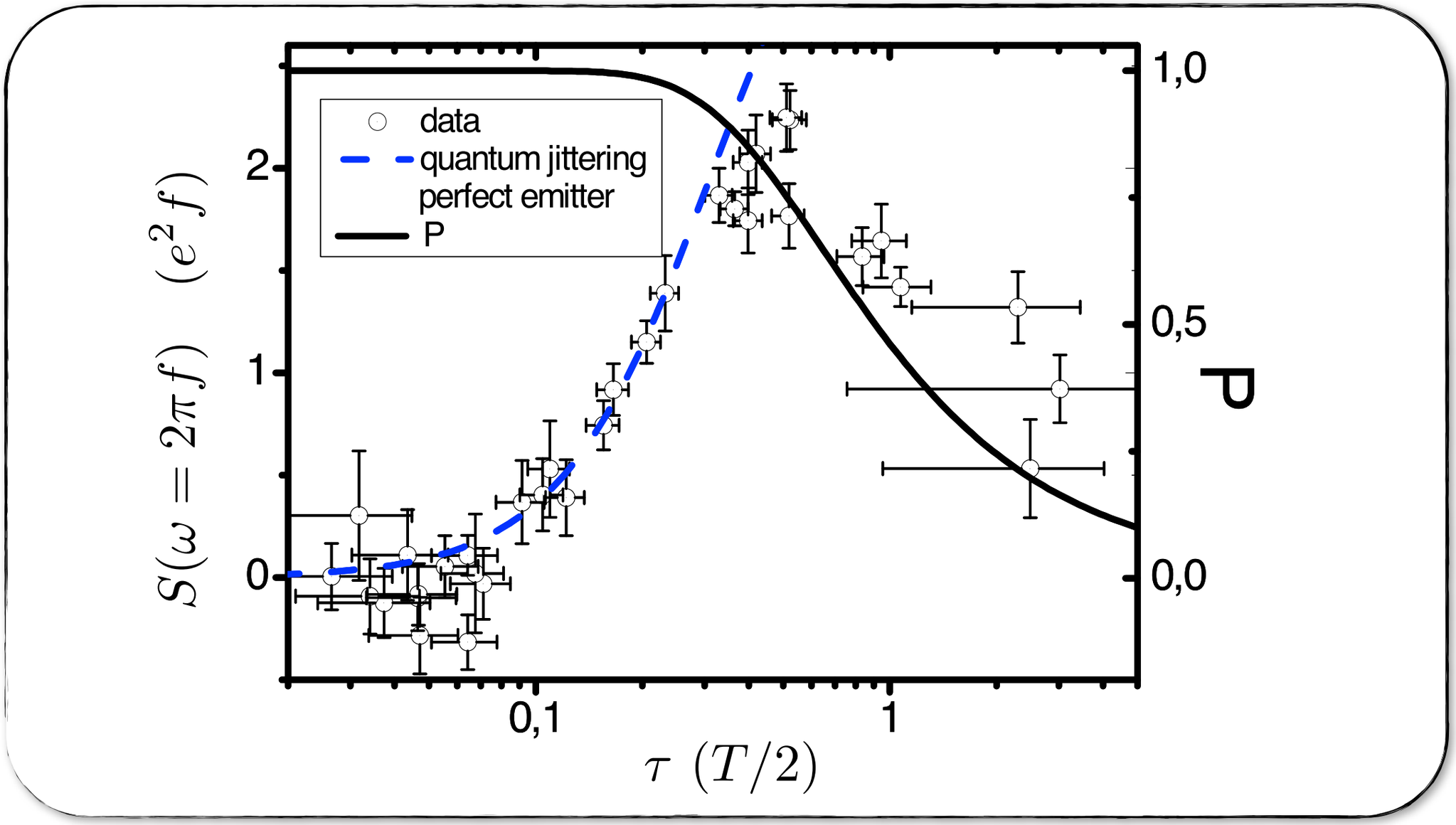

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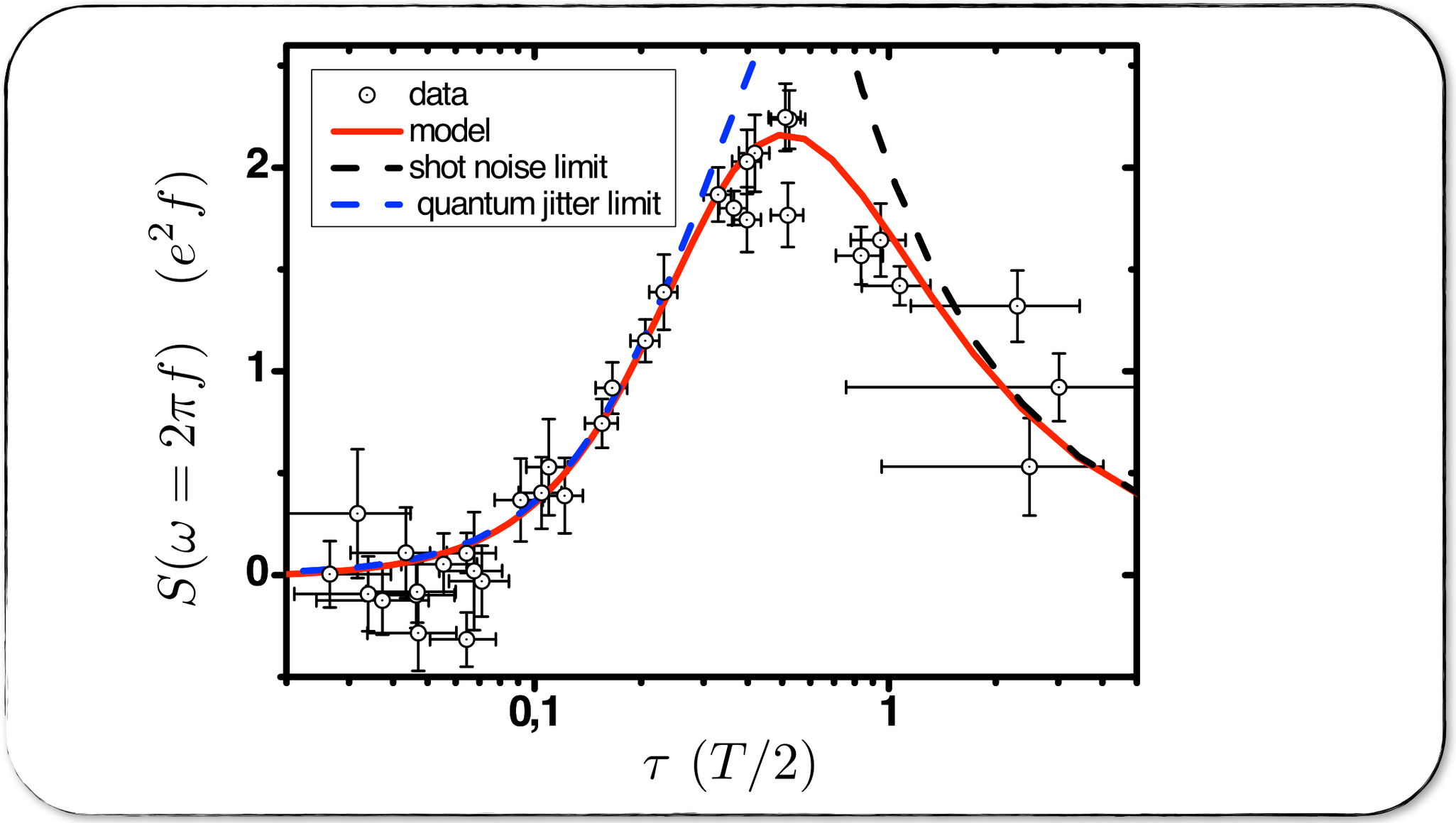

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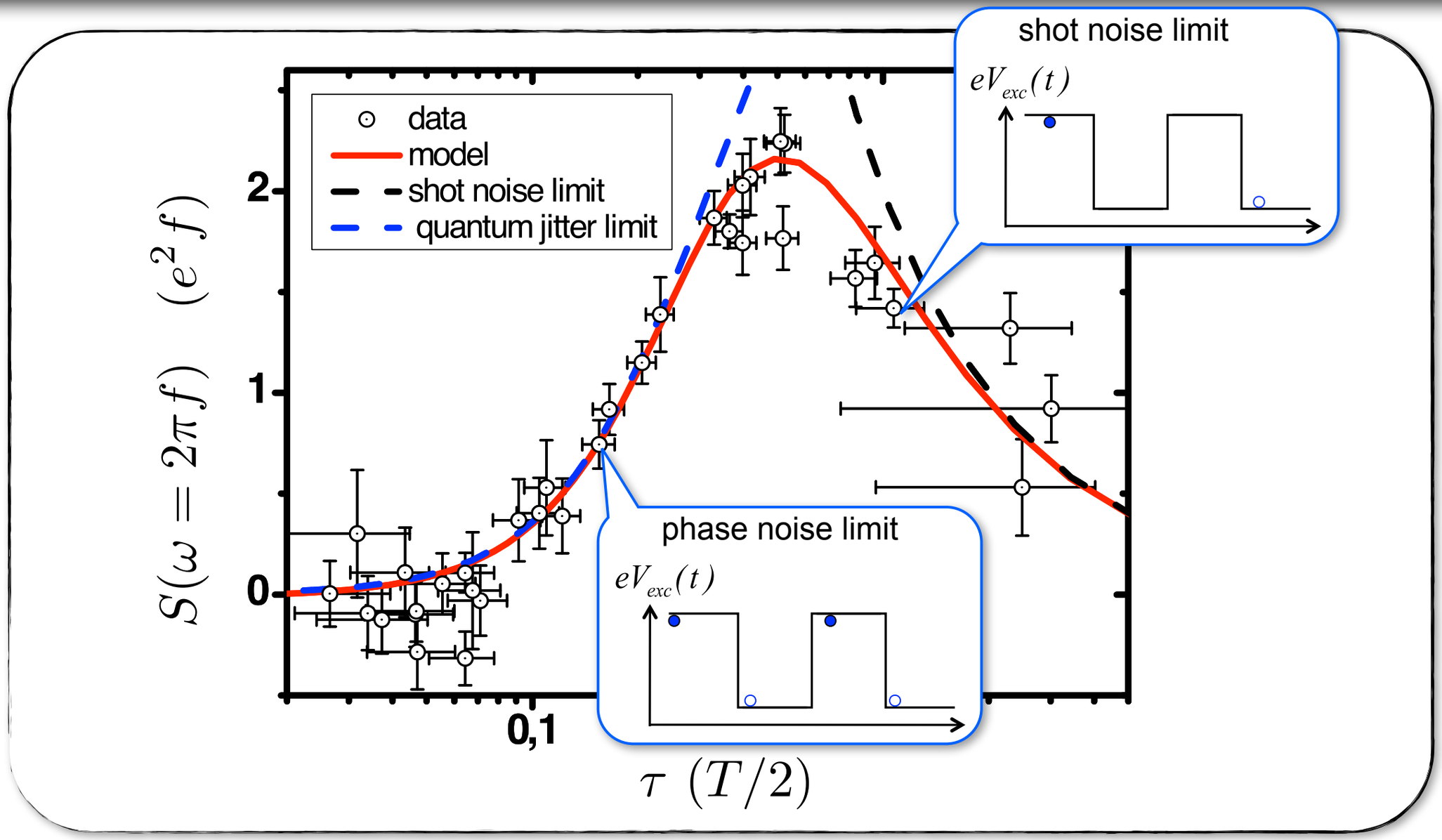
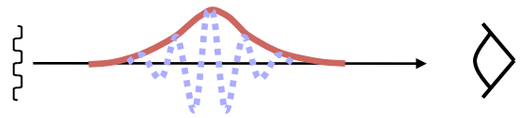


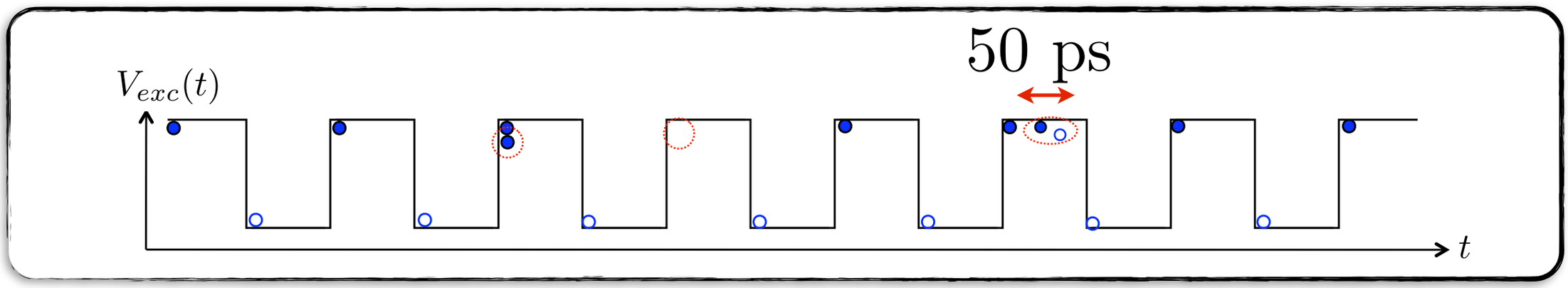
Noise reduced to phase noise ⇒ demonstration of **single charge emission** !
Fully described by 2 models : Floquet scattering theory & heuristic model

M. Moskalets *et al.*, PRB **66**, 205320 (2002)
A. Mahé *et al.*, PRB **82**(20), 201309 (2010)
M. Albert *et al.*, PRB **82**(4), 41407 (2010)

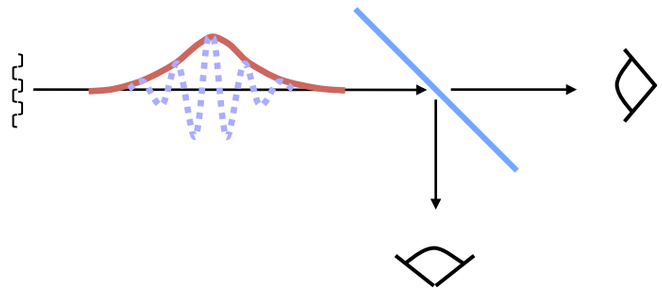
Beyond average current - AC sources

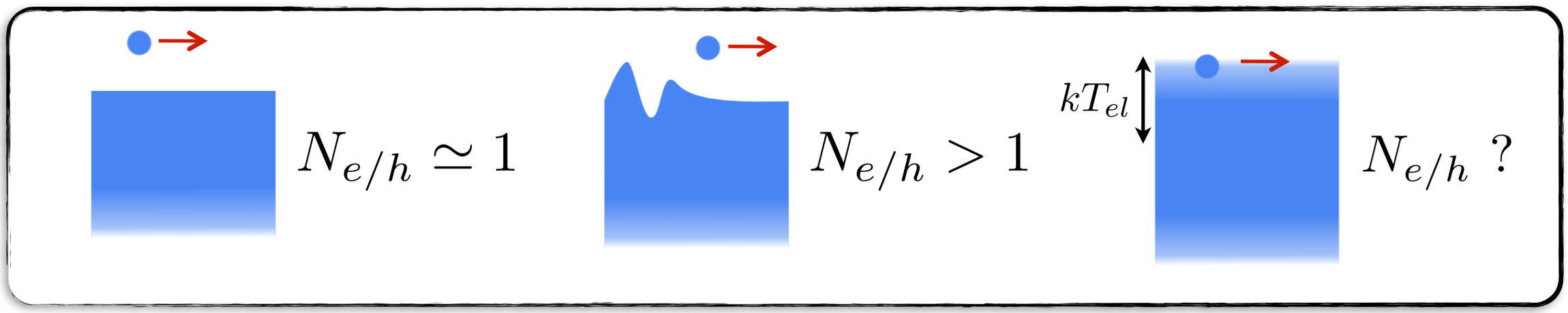
Autocorrelations : Statistics of emitted charge





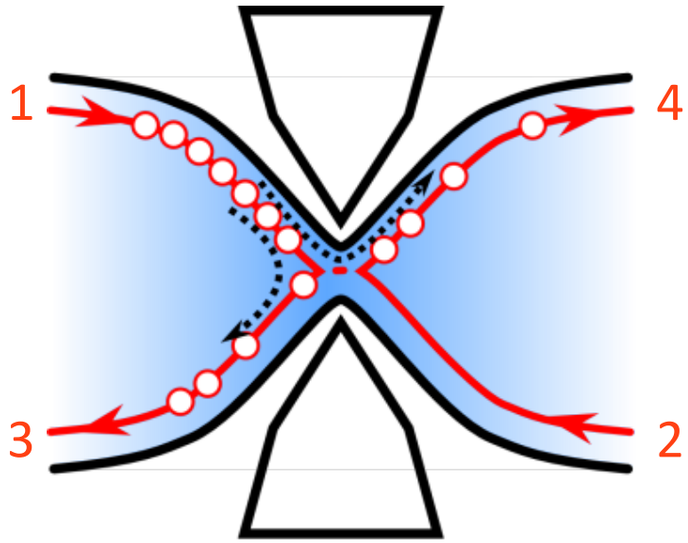
HBT correlations : Counting of emitted quasiparticles





Counting excitations with HBT correlations

continuous source



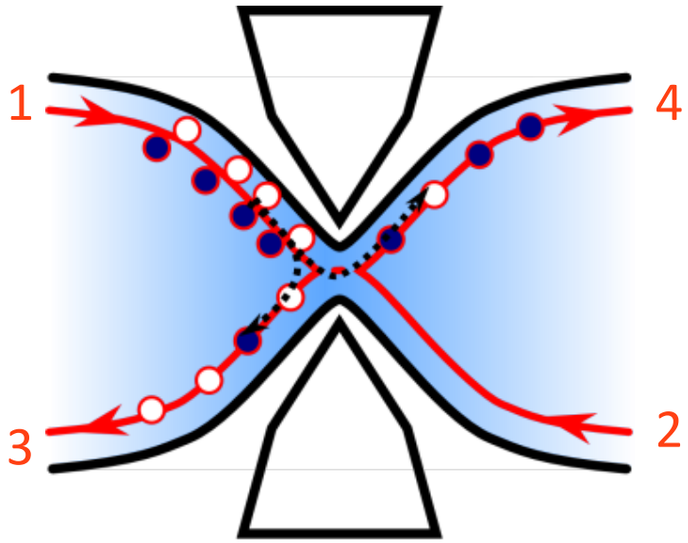
beam splitter

$$S_{3,4}(\omega=0) = 2e\langle\hat{I}\rangle \times T(1-T)$$

$$\langle\hat{I}\rangle = e\frac{\langle N_e\rangle}{T_{meas}}$$

M. Reznikov *et al.,* PRL **75,** 3340 (1995)
A. Kumar *et al.*, PRL **76**, 2778 (1996)
G.B. Lesovik, JETP Lett. **70**, 208 (1999)
T. Martin *et al.*, PRB **45**(4), 1742-1755 (1992)
Y. Blanter *et al.*, *Physics* Reports, **336**(1-2), 1–166 (2000)

e/h pairs



beam splitter

$$S_{3,4}(\omega=0) = 2e\langle\hat{I}_{part}\rangle \times T(1-T)$$

$$\langle\hat{I}_{part}\rangle = e\frac{\langle N_e\rangle + \langle N_h\rangle}{T_{meas}}$$

L.-H Reydellet *et al.*, PRL **90**, 176803 (2003)
V. S. Rychkov *et al.,* PRB **72**, 155326 (2005)

Partition noise (in units e^2f) classically yields the **number of excitations** $\langle N_e\rangle + \langle N_h\rangle$

Measurement of HBT autocorrelations

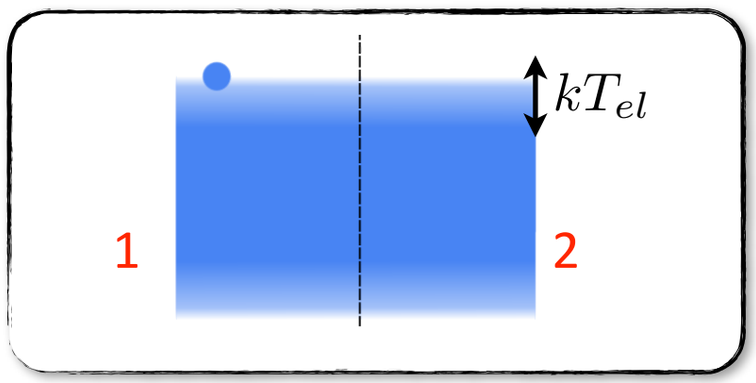
- Autocorrelation on Output 3 :

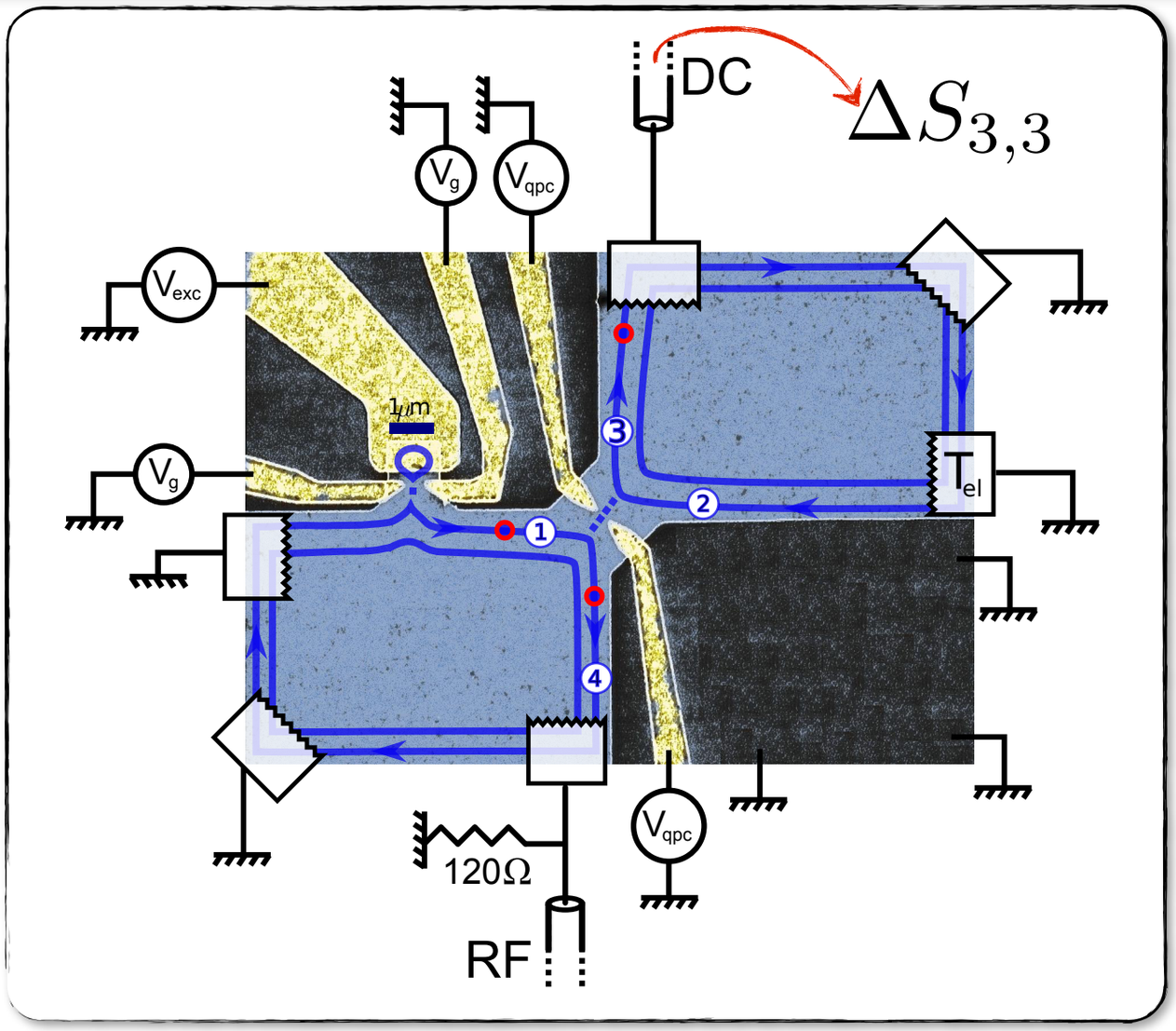
$$\Delta S_{3,3} = -S_{3,4} = 2e^2 f \times T(1-T)\Delta Q$$

- Resolution :

$$0.05\, e^2 f \simeq 2.10^{-30}\mathrm{A}^2\mathrm{Hz}^{-1}$$

- Input 2 : **Fermi sea at T_{el}= 150 mK** ≠ vacuum !





- HBT signal :

$$\Delta Q = \langle N_e \rangle + \langle N_h \rangle - 2\int_0^\infty d\epsilon (n_e(\epsilon) + n_h(\epsilon)) f(\epsilon)$$

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

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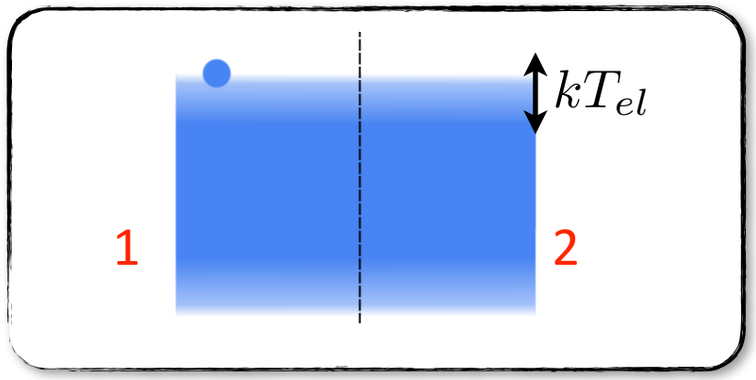

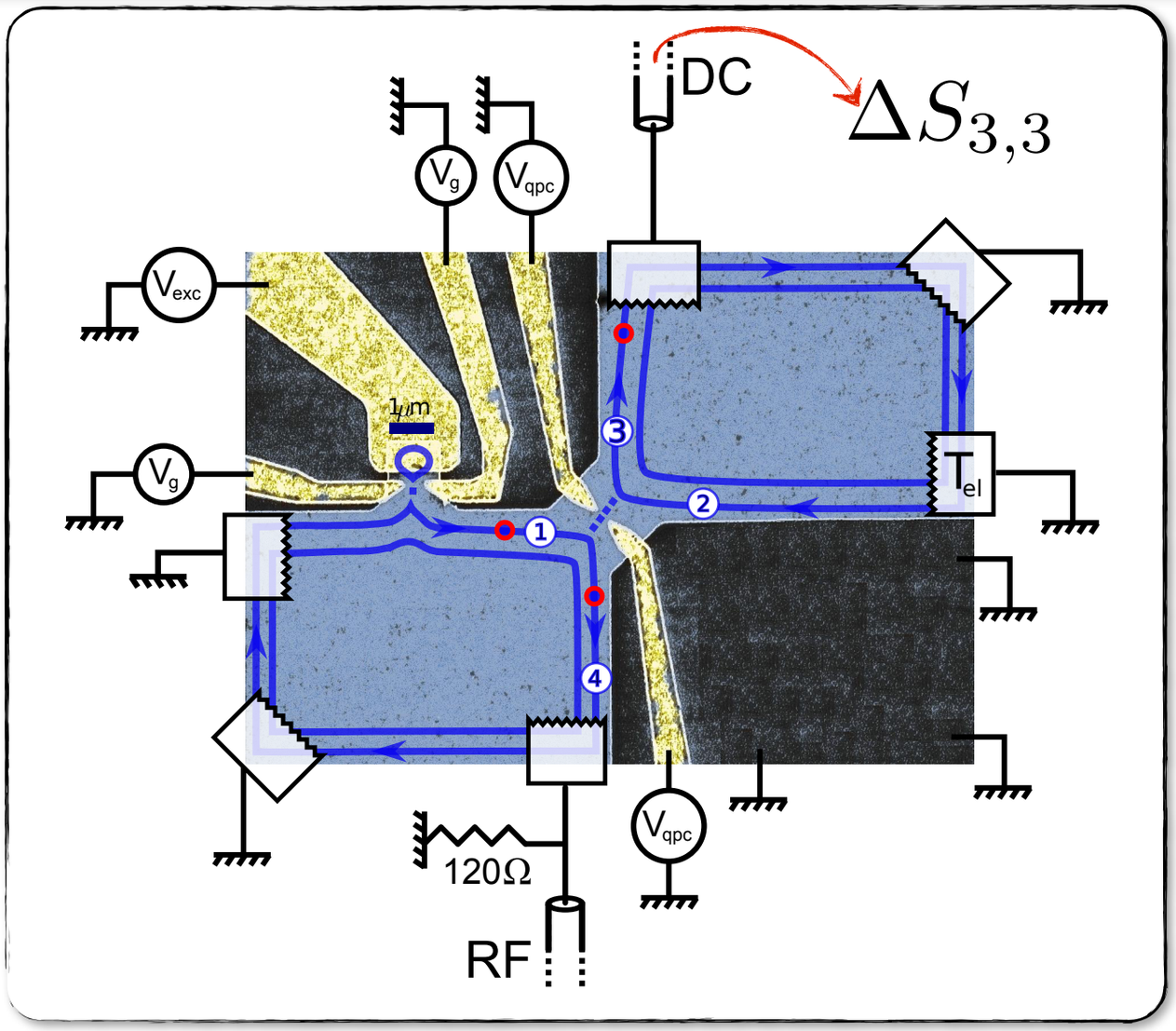

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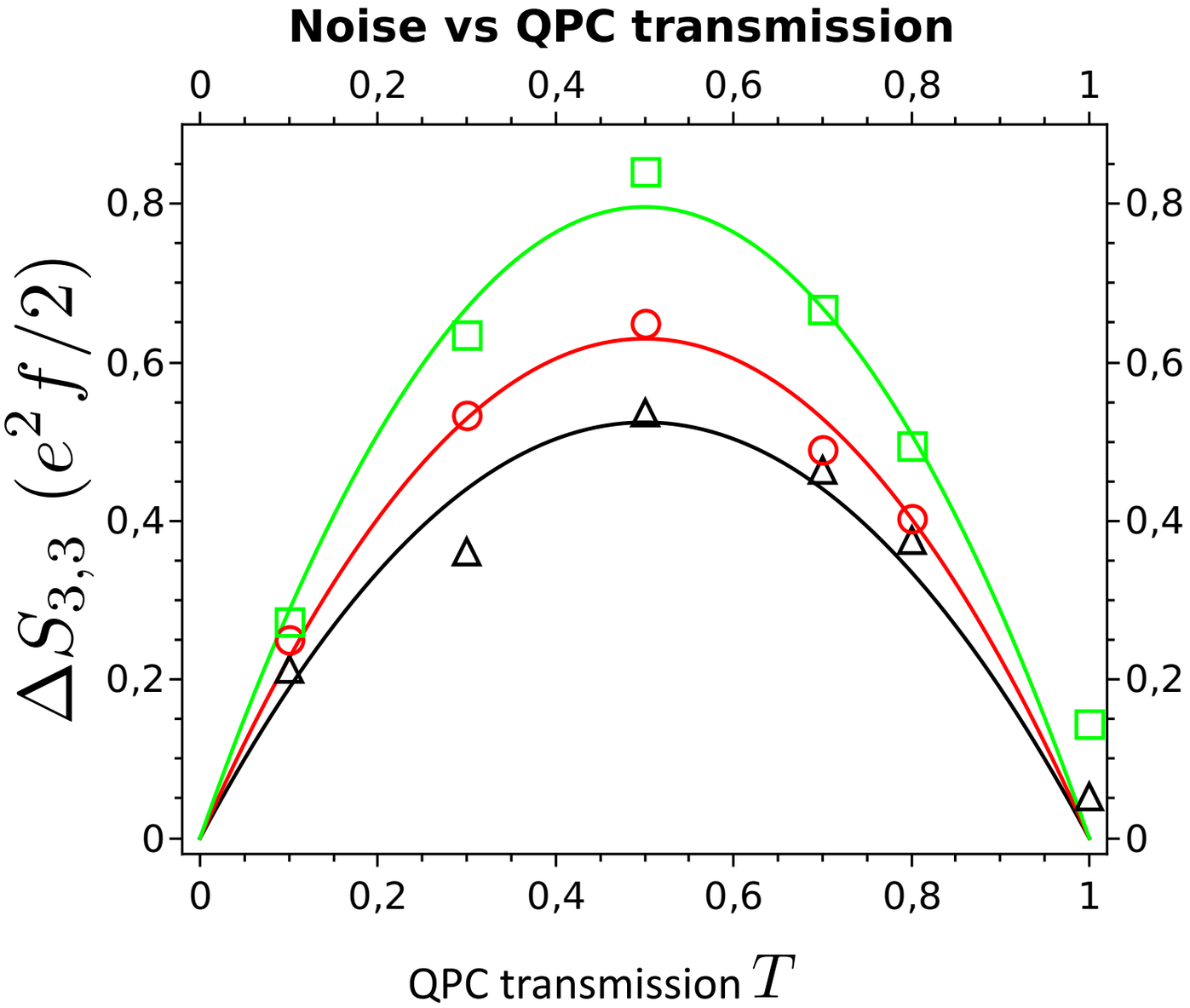
overlap between Fermi sea and single quasiparticles

HBT autocorrelations

$$\Delta S_{3,3} = 2e^2 f T(1-T)\Delta Q$$



— Sine, $D = 1$

$Q^t = 1.27 \qquad \Delta Q = 0.51$

— Sine, $D = 0.3$

$Q^t = 0.93 \qquad \Delta Q = 0.63$

— Square, $D = 0.4$

$Q^t = 1 \qquad \Delta Q = 0.80$

HBT autocorrelations

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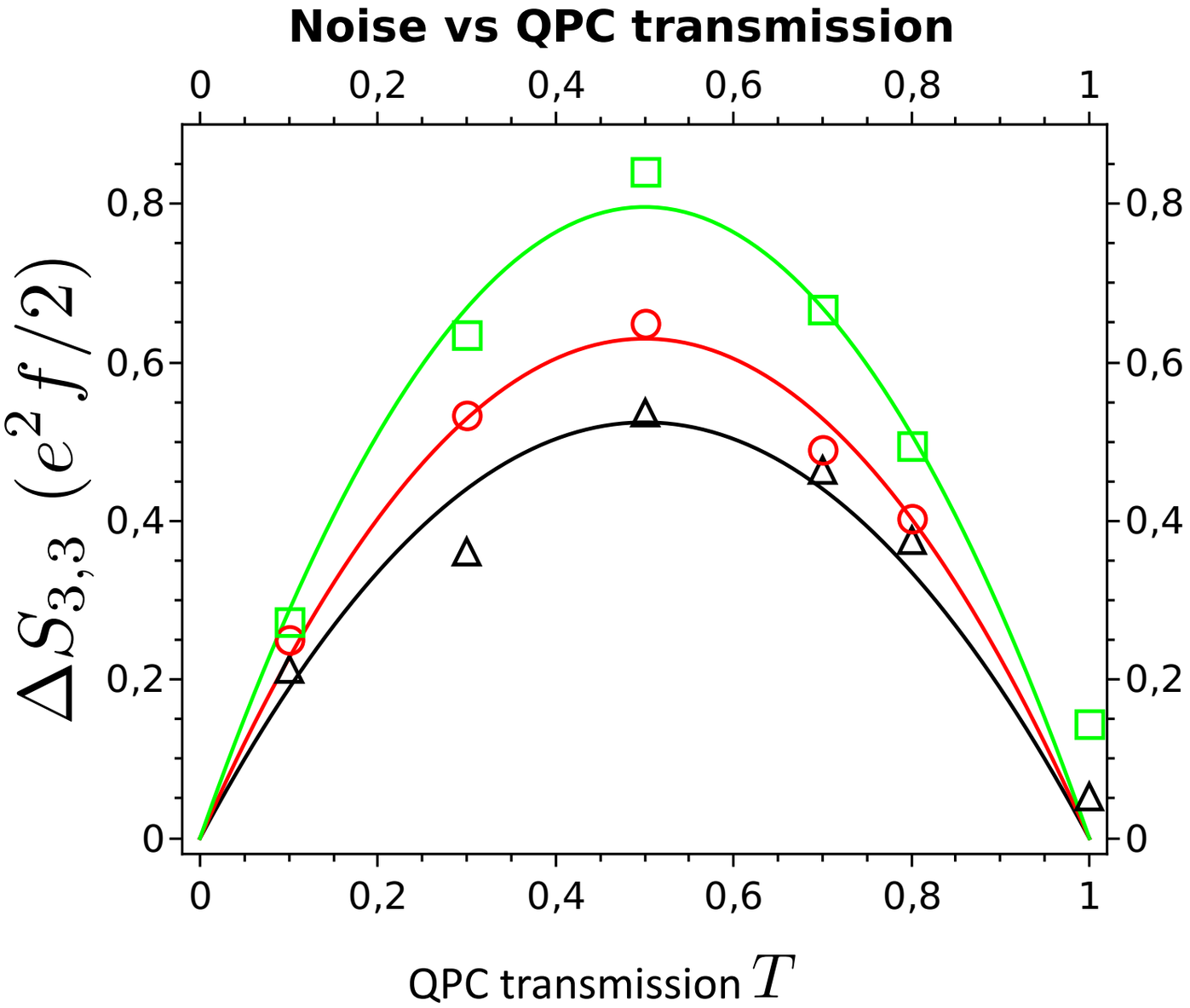

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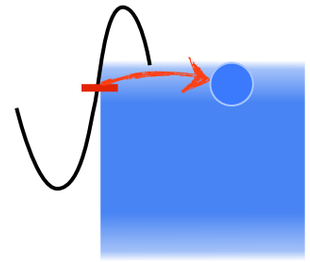

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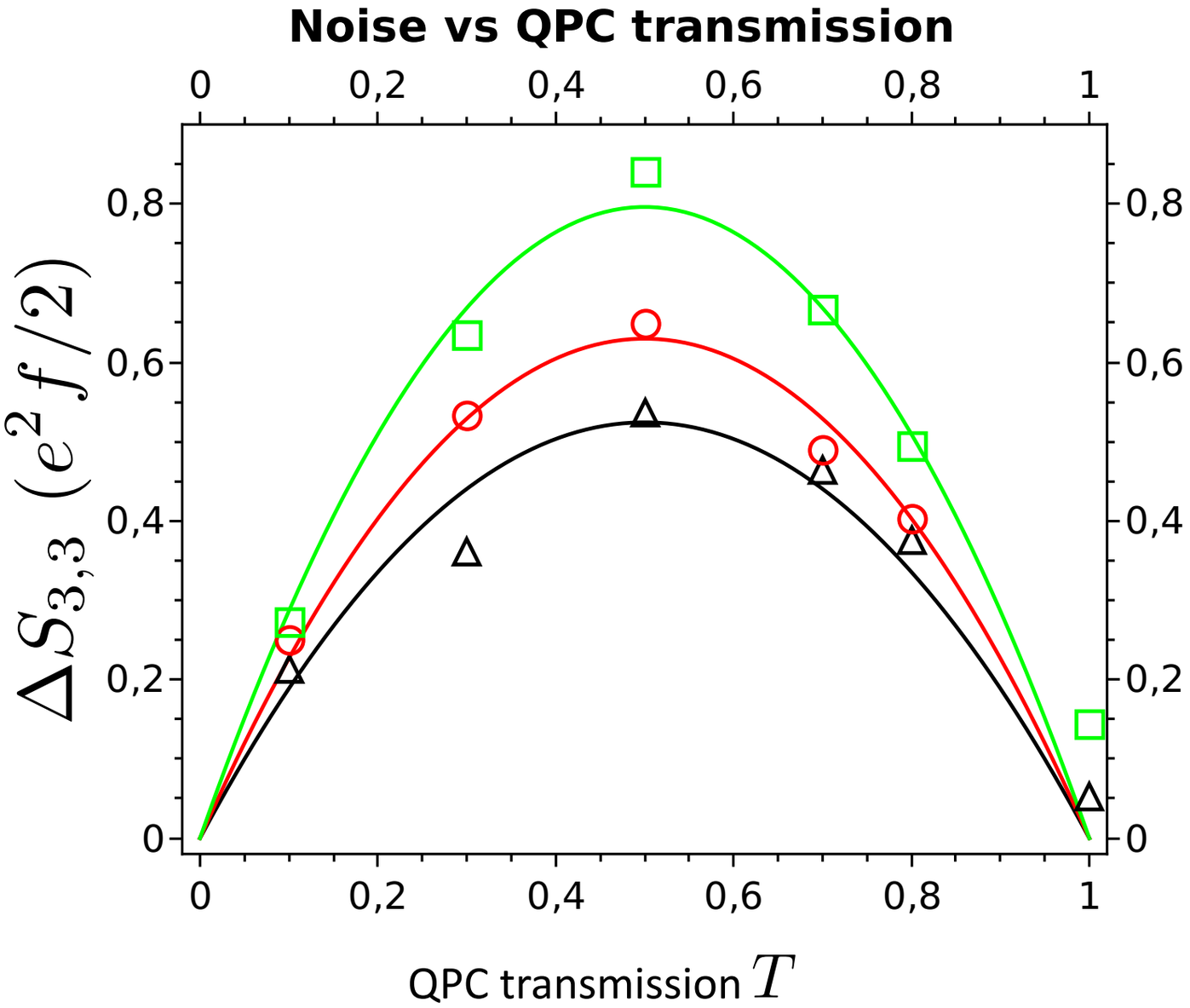

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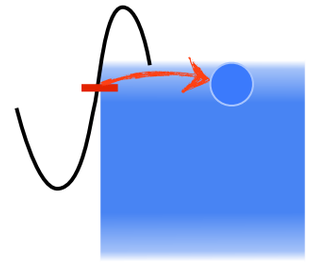

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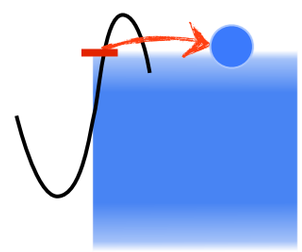

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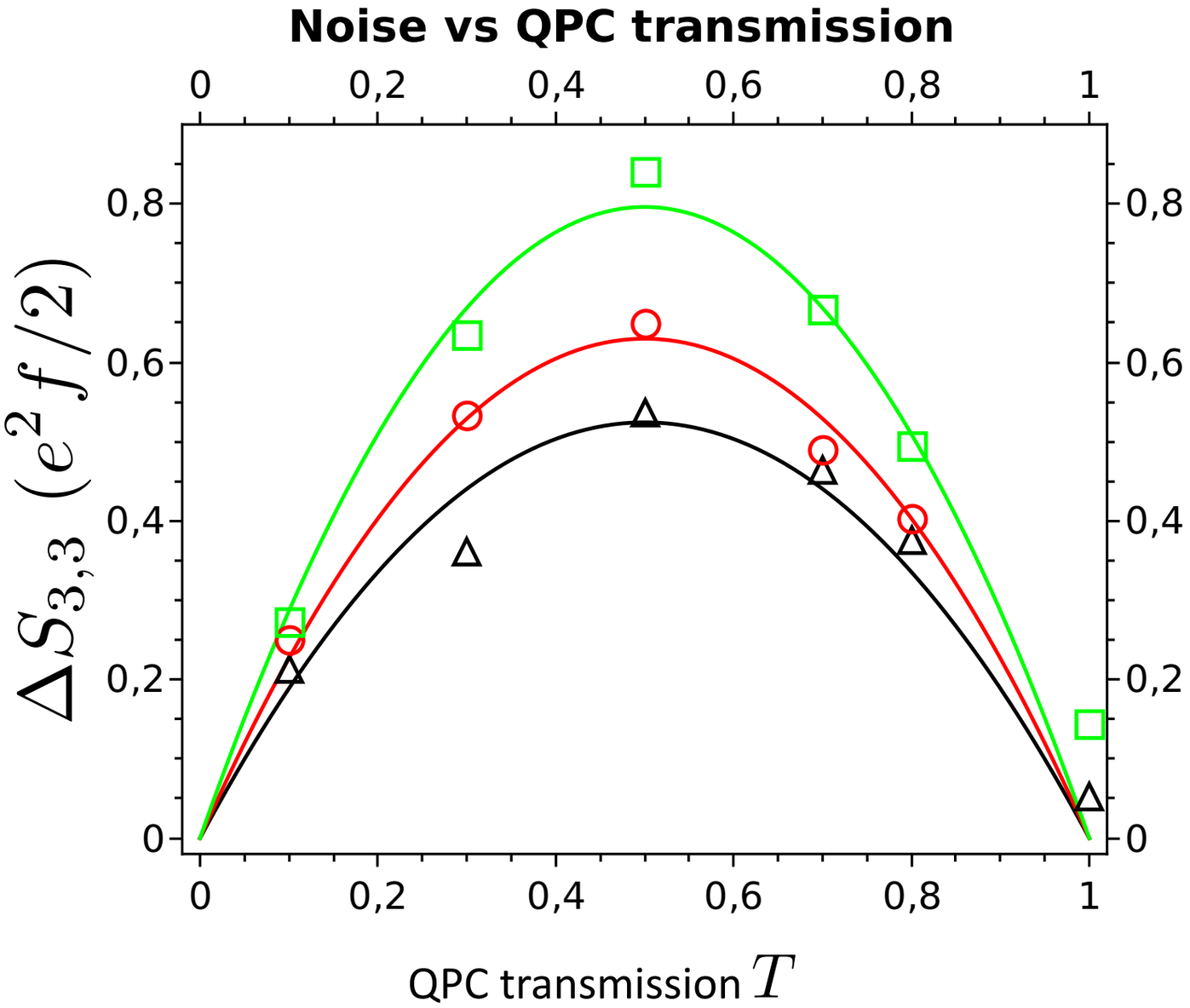

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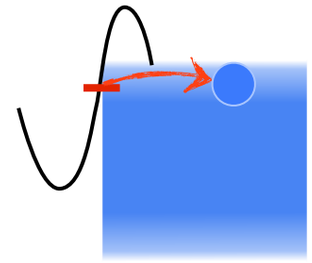
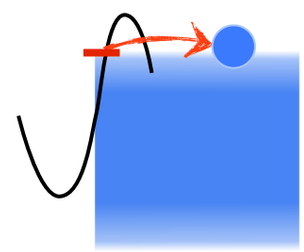


— Sine, $D = 0.3$



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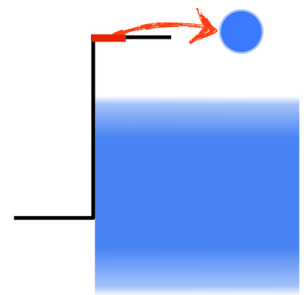
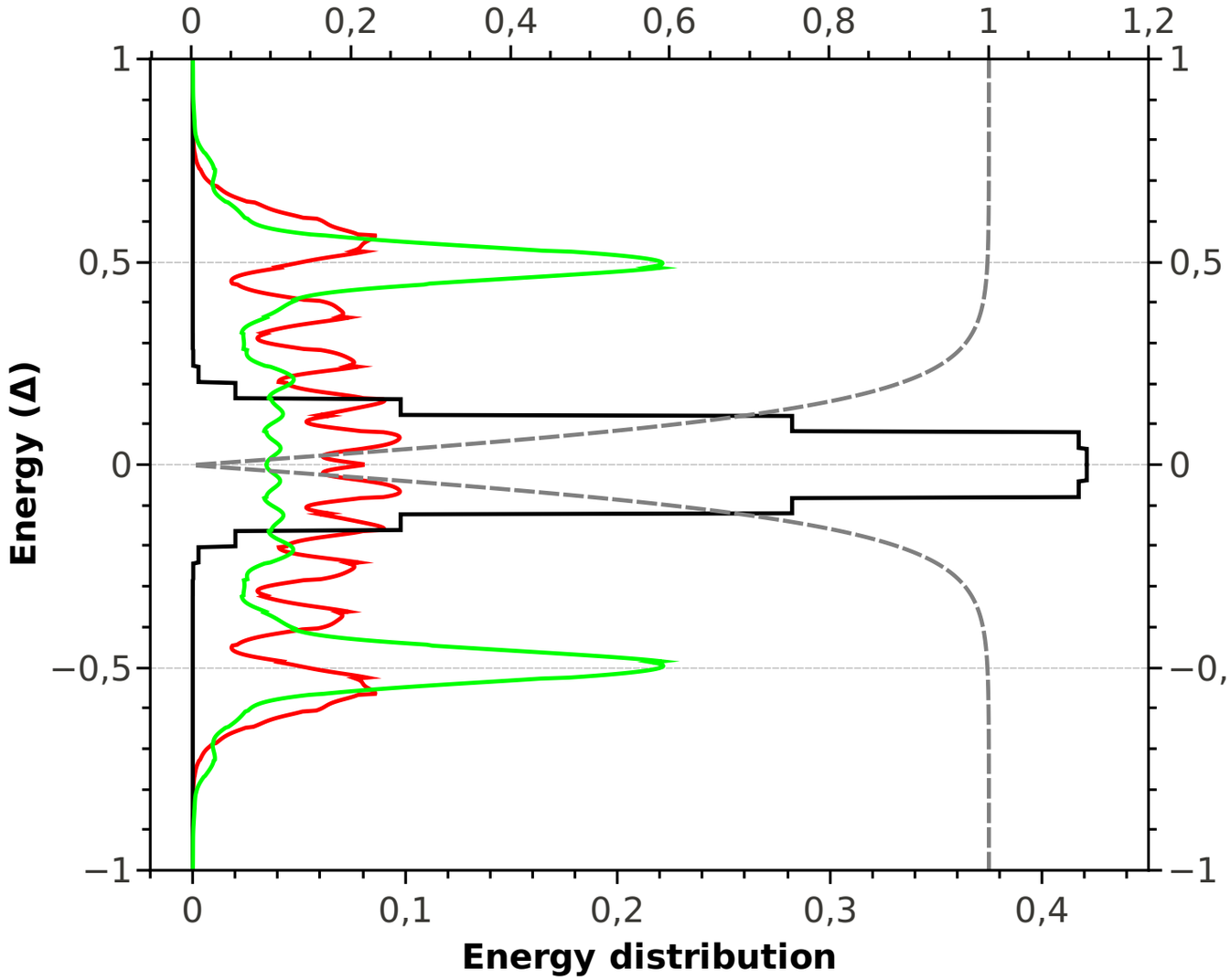


Engineering the wavepacket



Simulated energy distribution (T=0)

- Sine, $D = 1$
- Sine, $D = 0.3$
- Square, $D = 0.4$

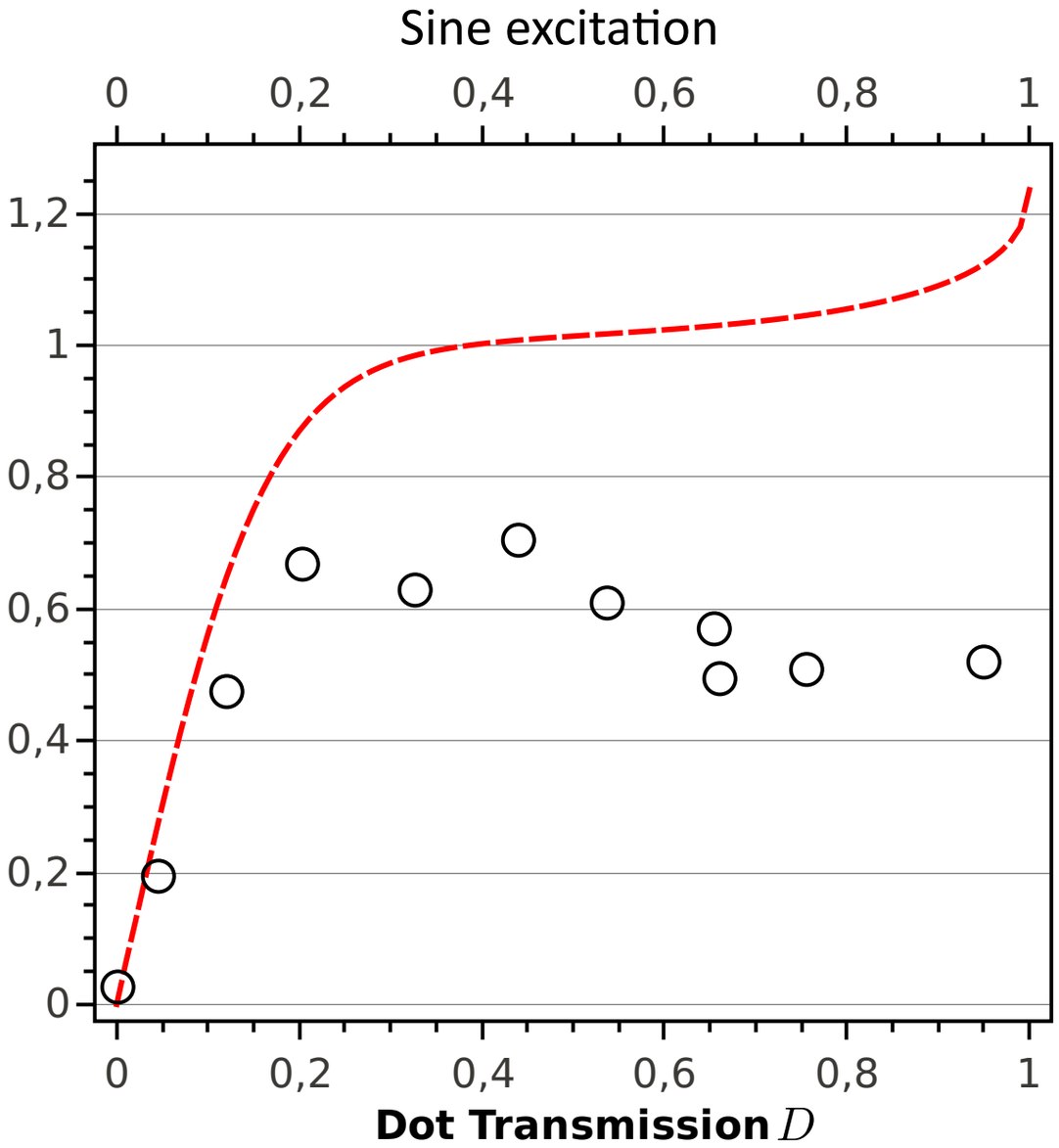
Effect of temperature at 150mK

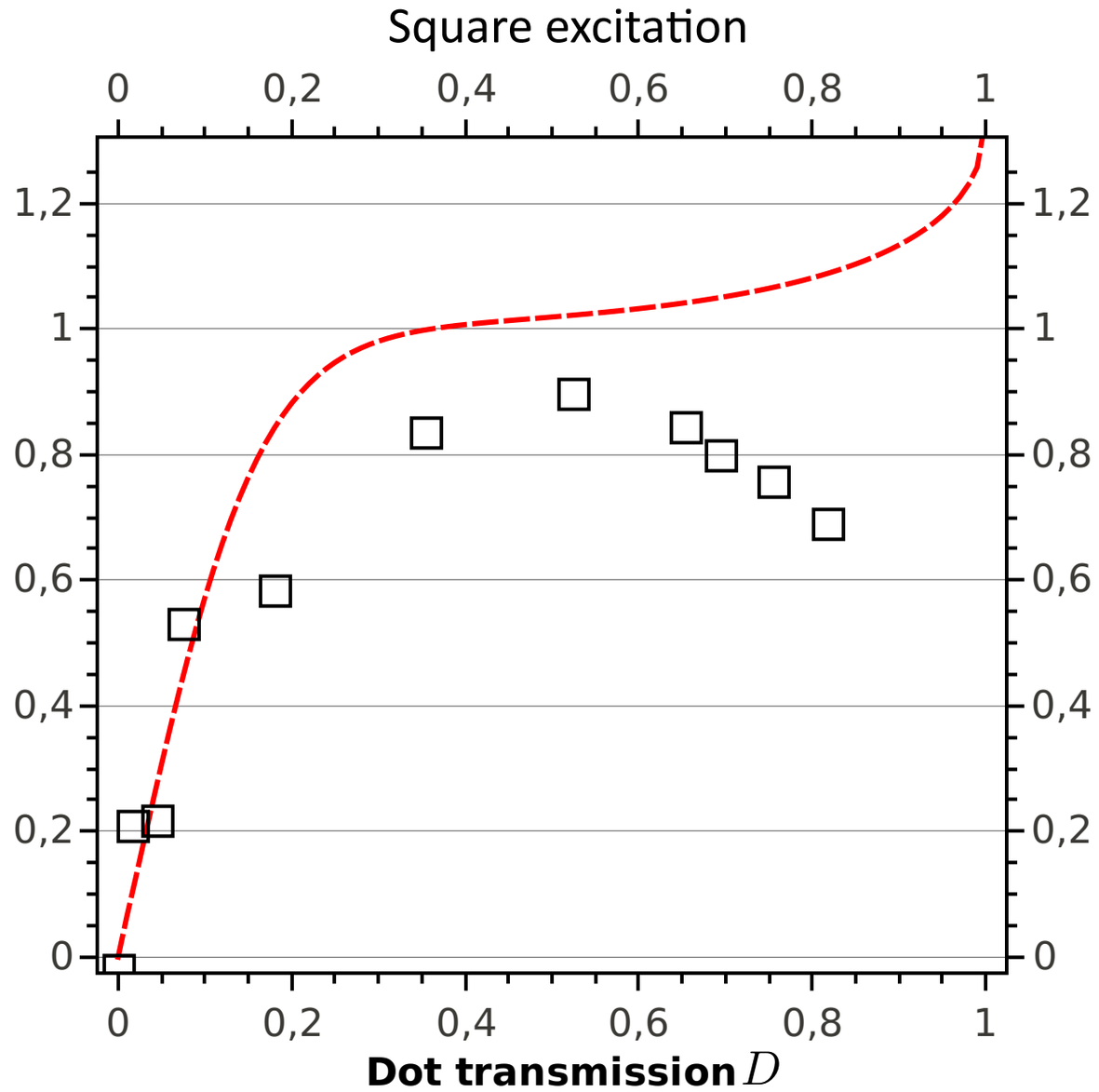
- ----- $|1 - 2f(\epsilon)|$

Engineering of the wavepacket through :

- excitation : sine, square
- dot transmission

Effect of dot transmission

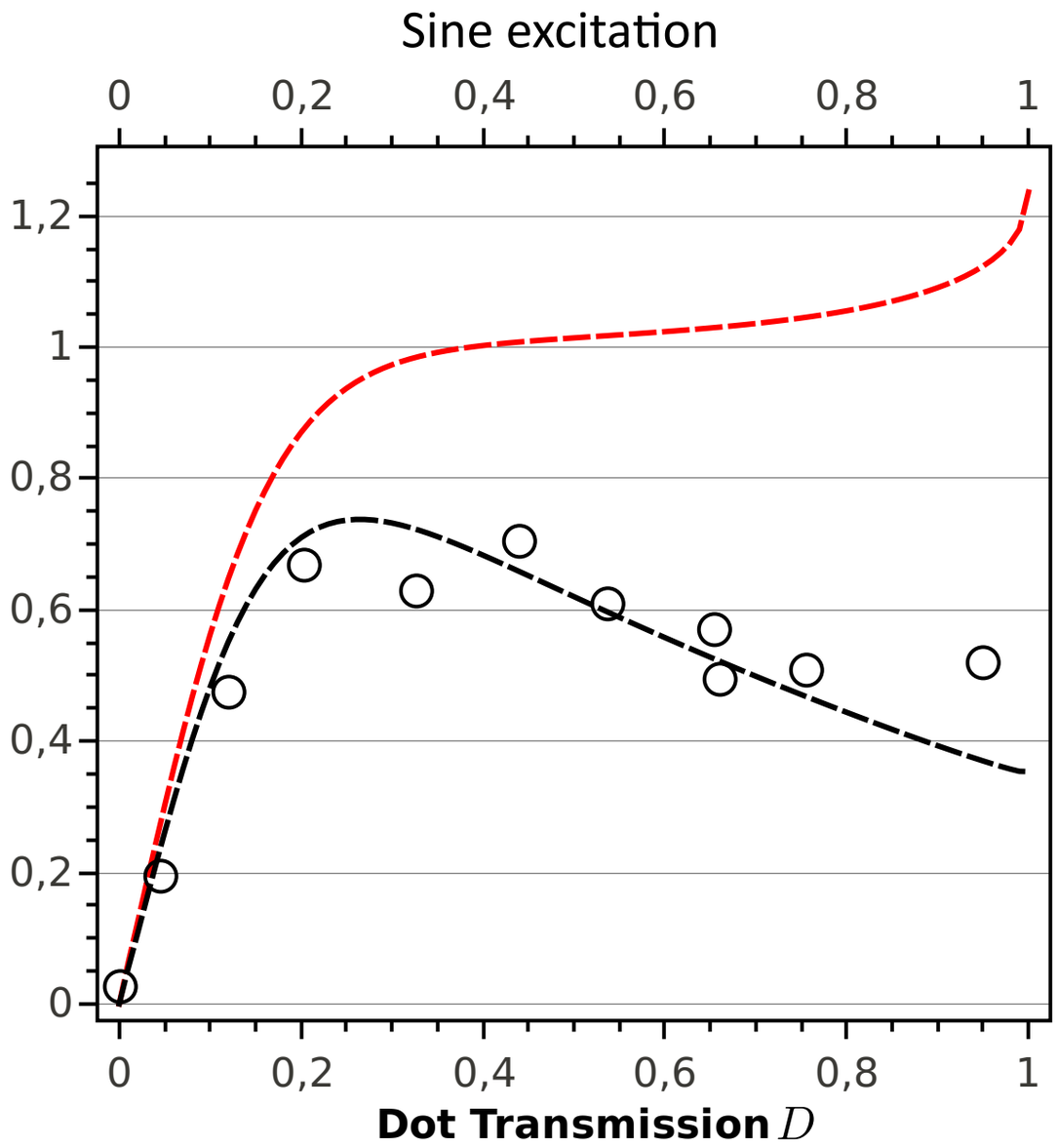


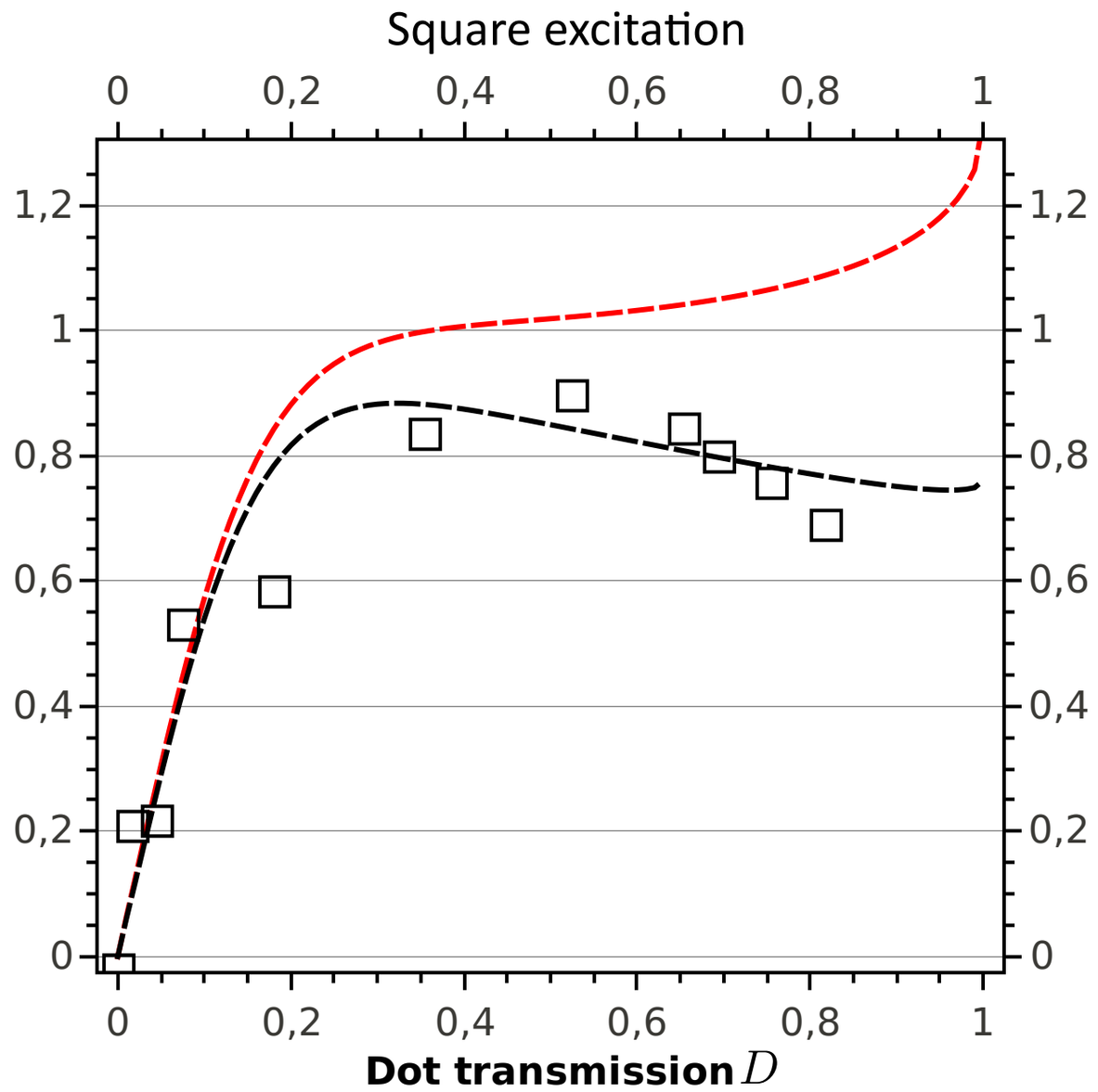


Experimental data

Simulation of $\Delta Q,\ T_{el} = 0\ \mathrm{mK}$

Effect of dot transmission





Experimental data

Simulation of $\Delta Q,\ T_{el} = 0$ mK

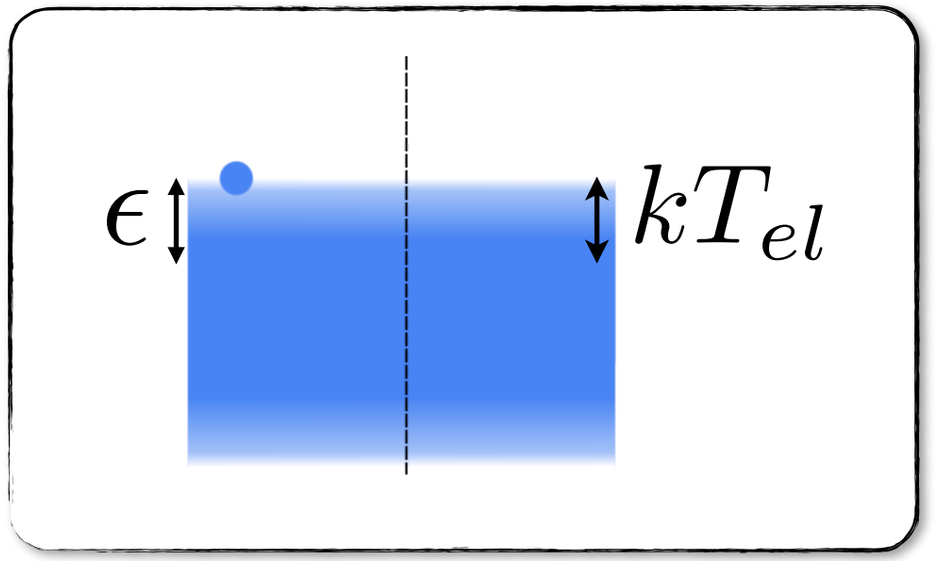
Simulation of $\Delta Q,\ T_{el} = 150$ mK

Conclusion

Autocorrelations proves **single charge emission**

HBT correlations :

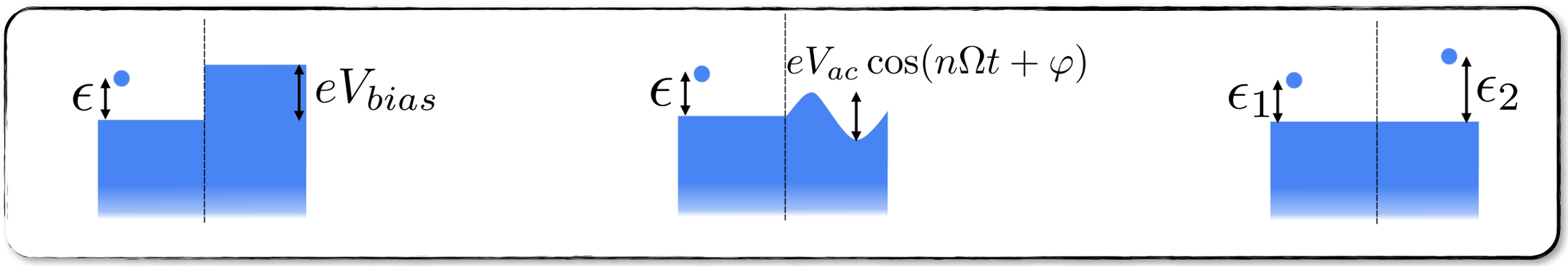
- reveal the effect of **thermal excitations**
- evidence of **engineering of the wavepacket**



Perspectives :

Energy distribution of emitted quasiparticles
Complete tomography protocol (cf. P. Degiovanni's talk)
Hong-Ou-Mandel experiment

C. Grenier *et al.*, NJP ***13***(9), 093007 (2011)
G. Haack *et al.*, PRB **84**, 081303(R) (2011)



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G. Fève

J.-M. Berroir

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B. Plaçais

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- C. Grenier
- R. Hervé

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- T. Jonckheere
- T. Martin
- J. Rech

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Univ. Geneva

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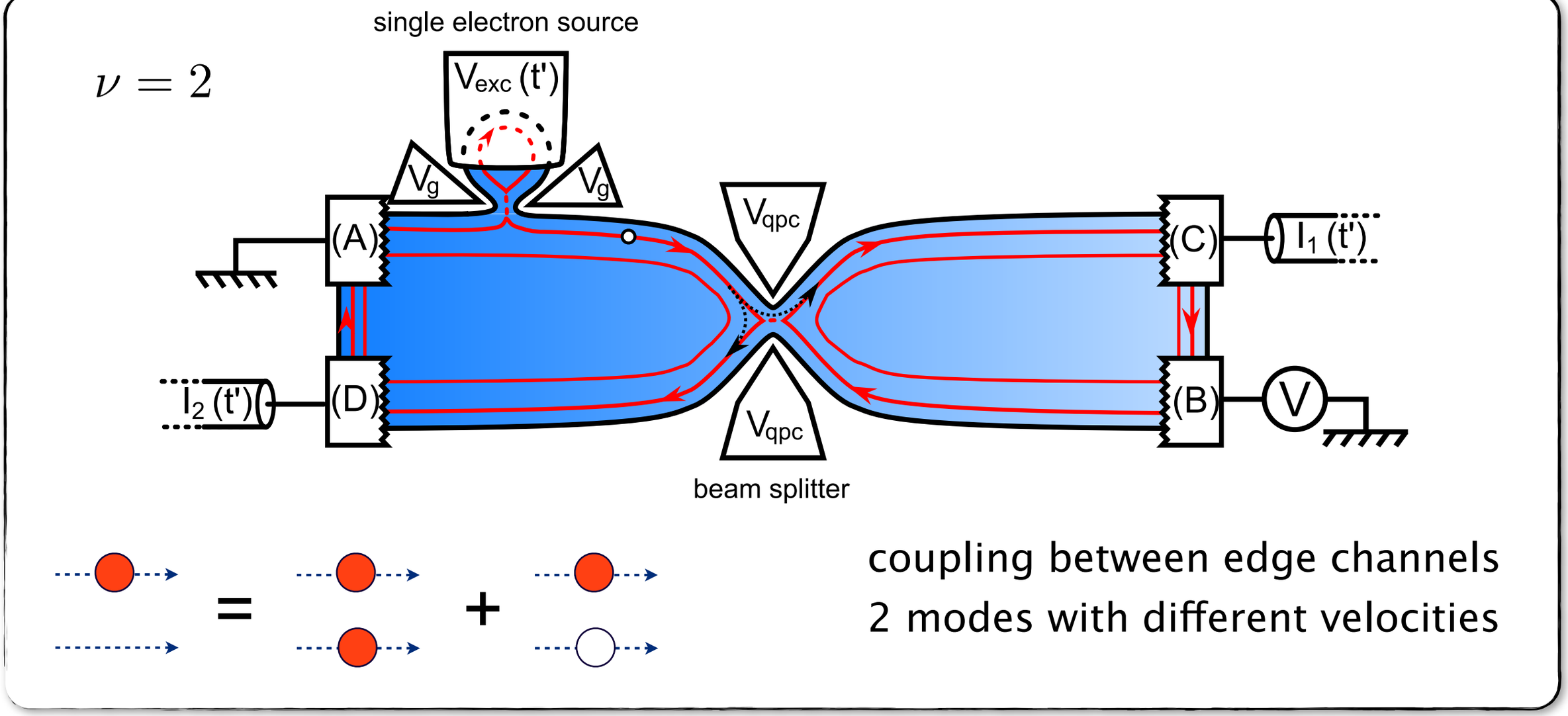
- M. Büttiker
- C. Flindt

Relaxation between channels



C. Altimiras *et al.*, Nature Physics **6**, 34 (2009)

P. Degiovanni *et al.*, PRB **81**, 121302(R) (2010)

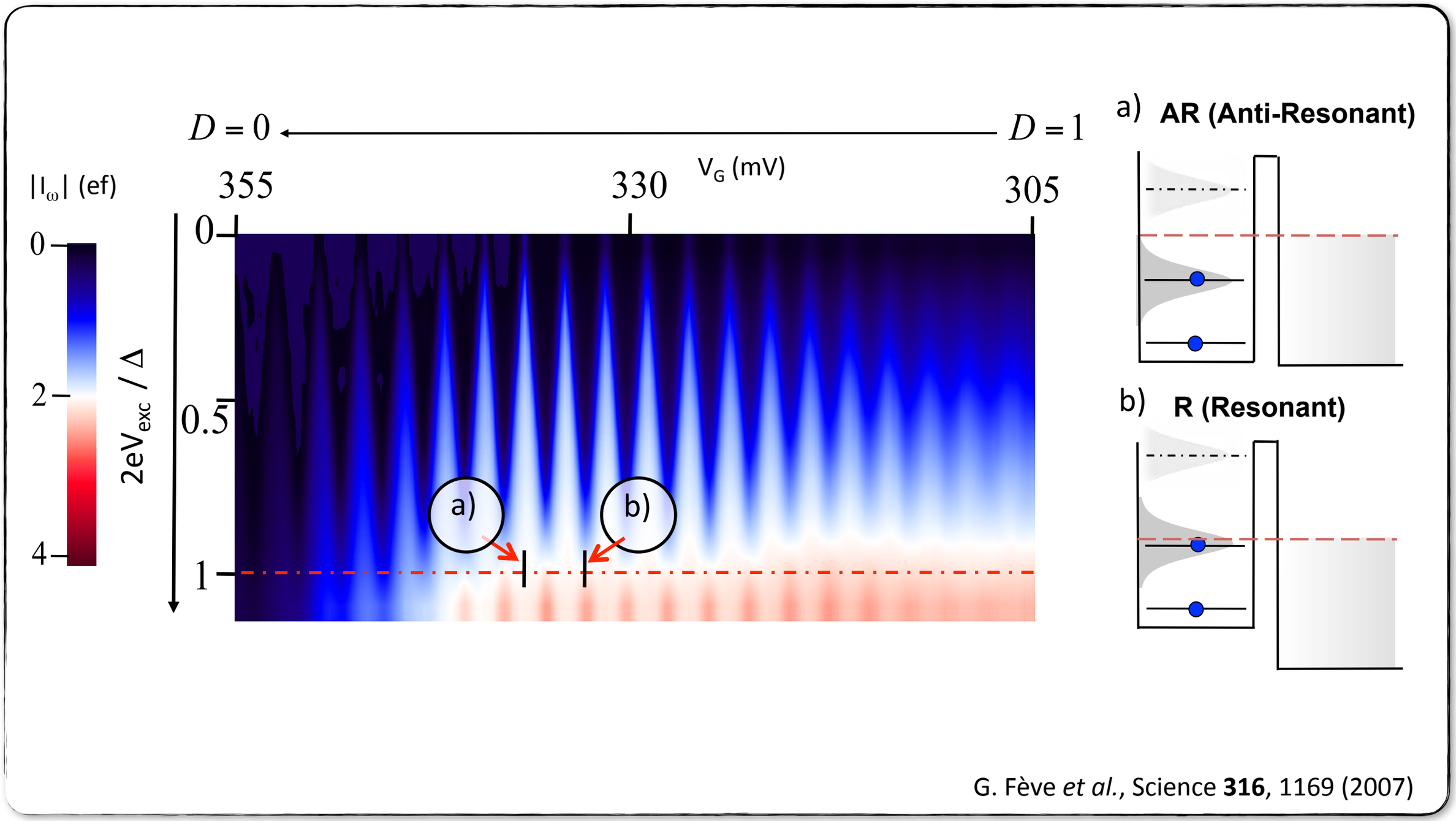
P. Degiovanni *et al.*, PRB **80**, 241307(R) (2009)

D.L. Kovrizhin *et al.*, PRB **81**, 155318 (2010)

I.P. Levkivskyi *et al.*, PRB **78**, 045322 (2008)

A. Lunde *et al.*, PRB, **81**(4) 041311 (2010)...

Average current in frequency domain



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