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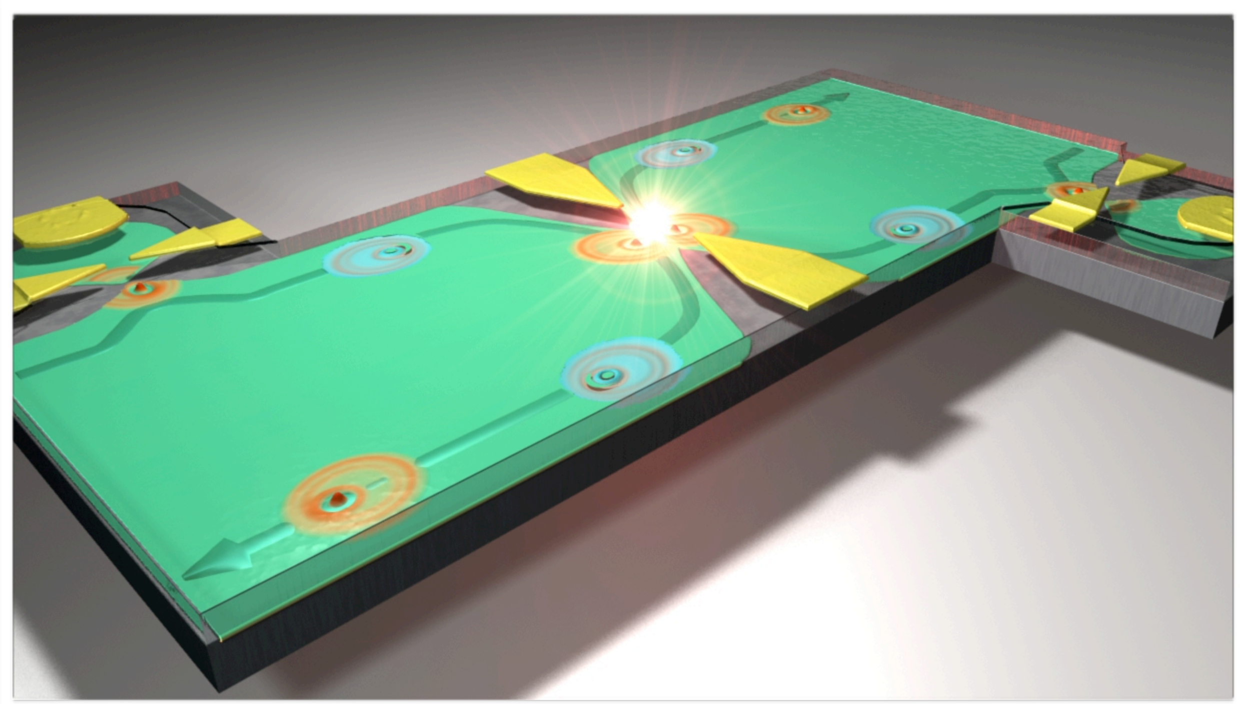
électronique et photonique quantiques

Erwann Bocquillon

Electron quantum optics in quantum Hall edge channels

EP2DS - Wrocław - 02/07/2013



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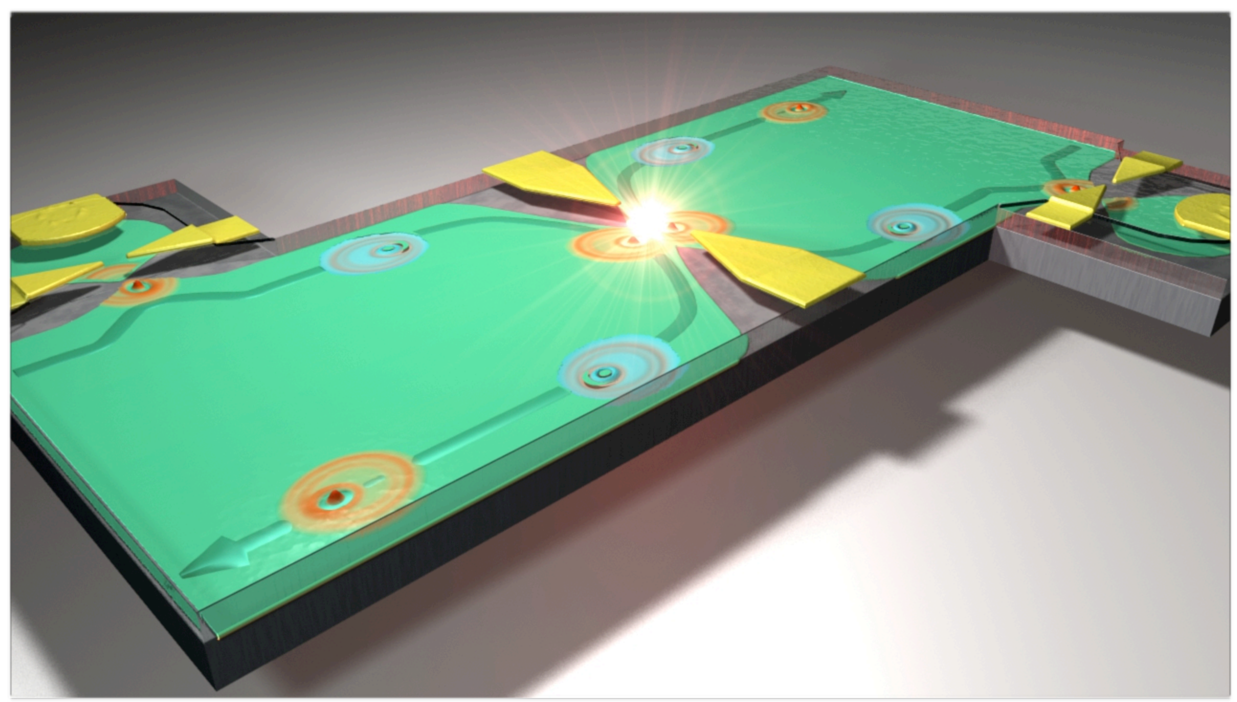

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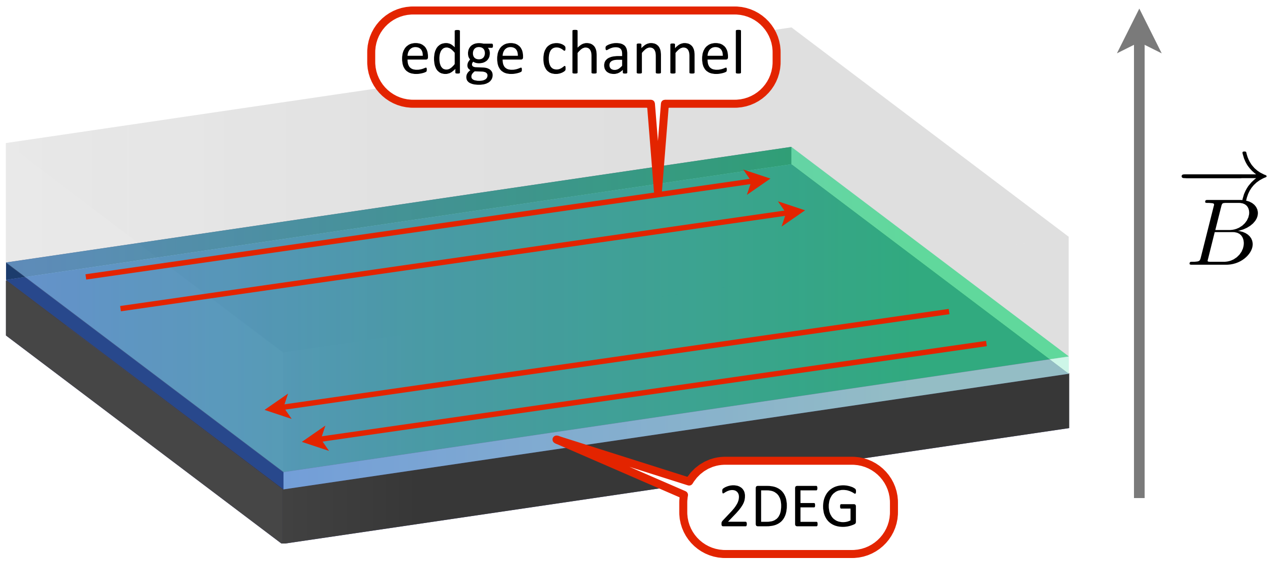
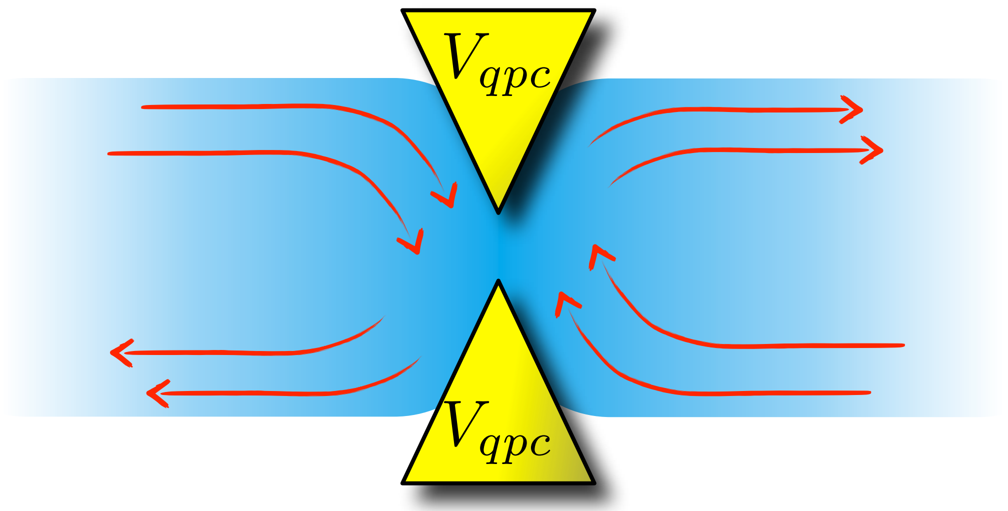
Toolbox for electron optics





Quantum Hall edge channels

- ballistic chiral propagation
- long coherence length
- filling factor 2 or 3
- spin polarised 1D edge channel

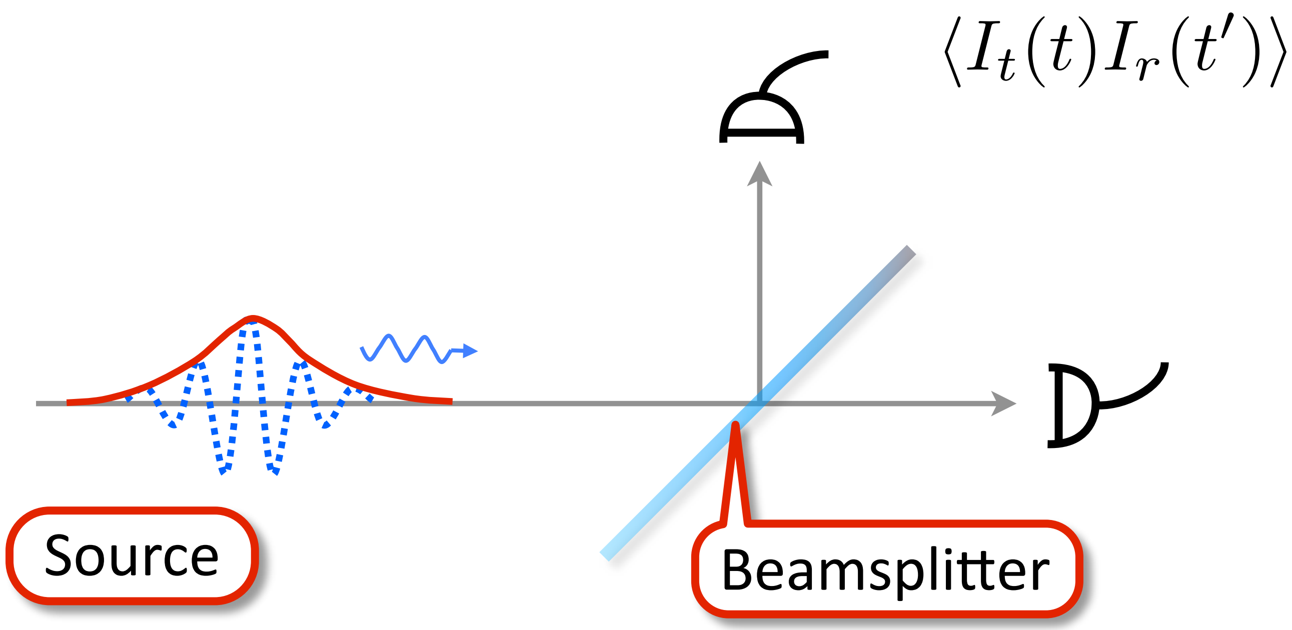
Quantum Point Contact (QPC)

- electronic «beamsplitter»
- variable transmission via gate voltage V_{qpc}

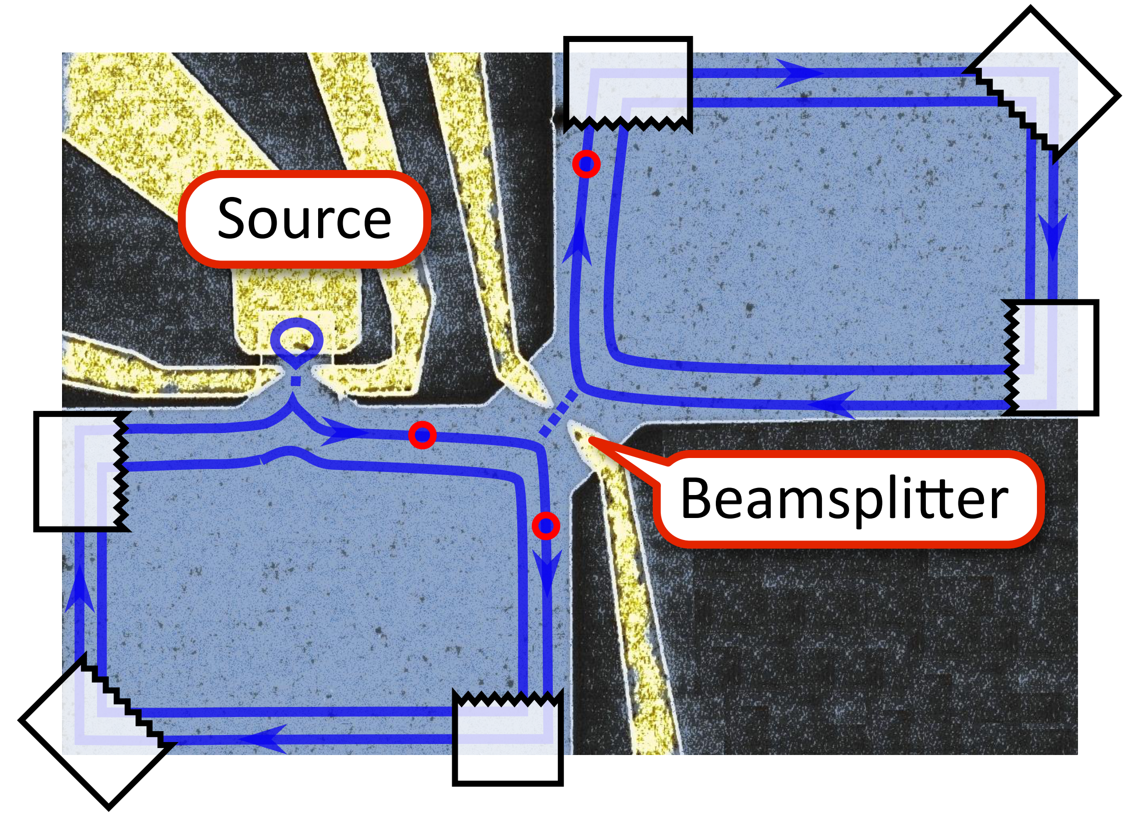
⇒ Mach-Zehnder interferometers

Y. Ji et al., Nature **422**, 415 (2003)
P. Roulleau et al., Phys. Rev. Lett. **101**, 186803 (2008)

Electron optics in quantum conductors



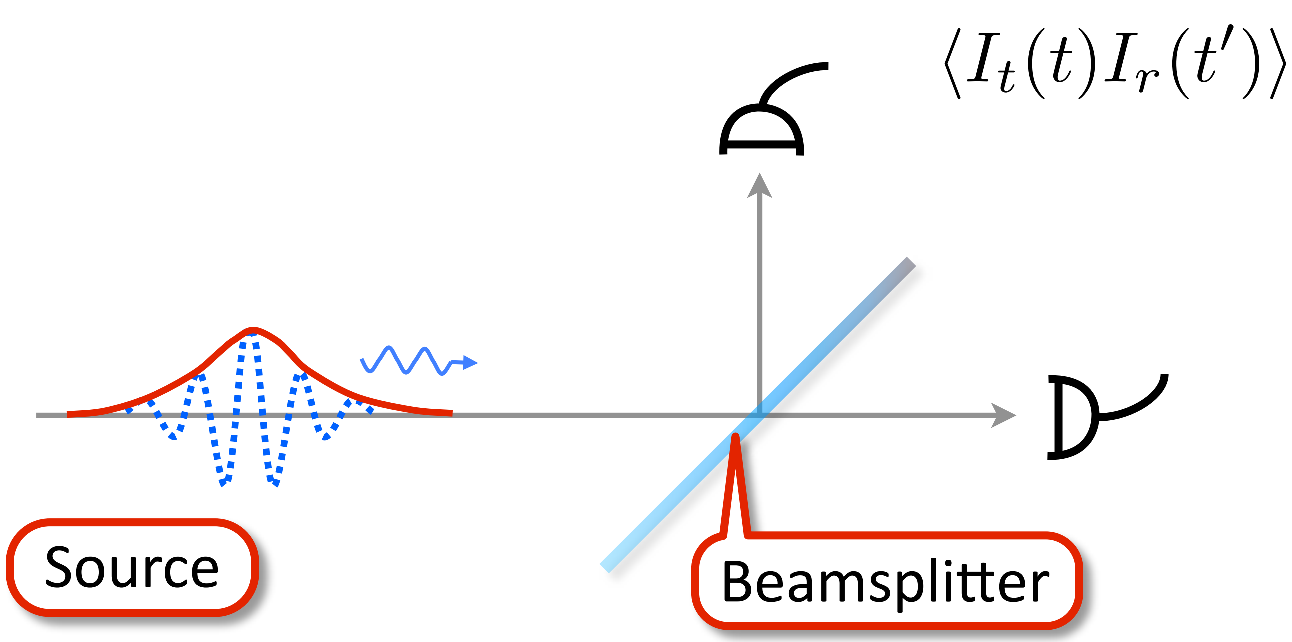
Hanbury-Brown & Twiss correlations in optics



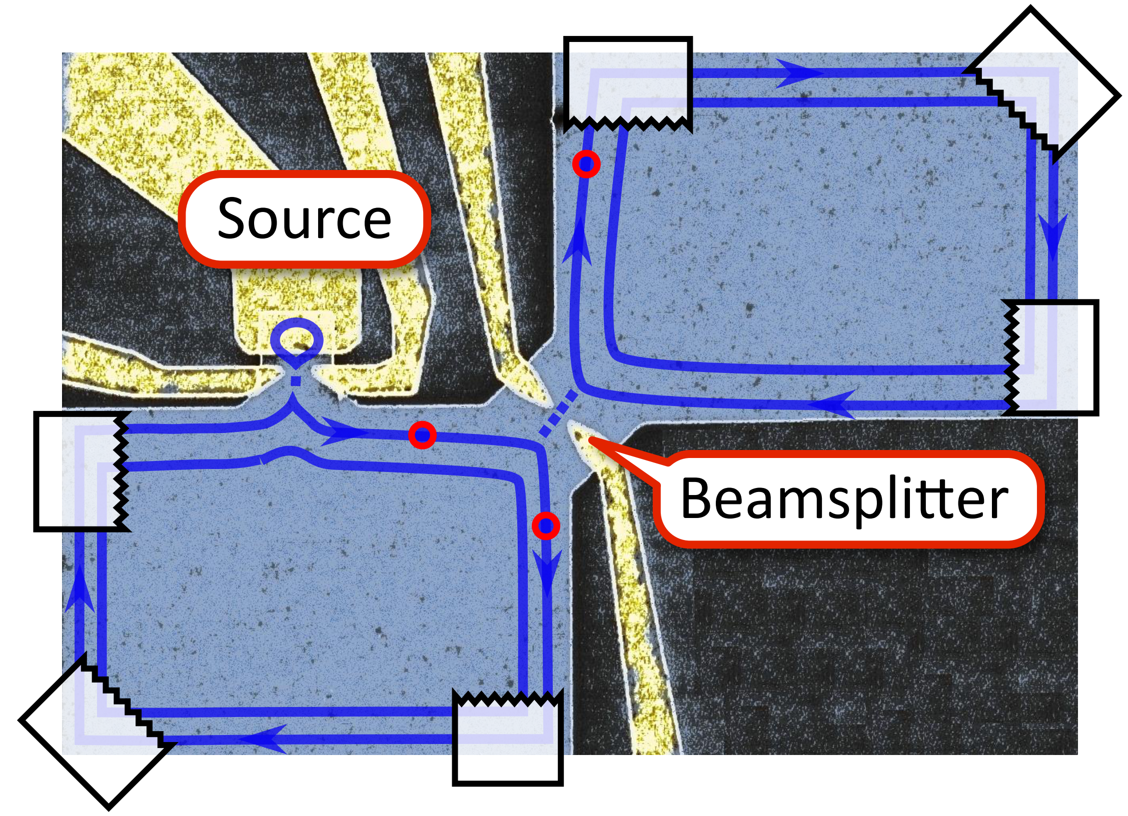
HBT correlations in a ballistic conductor

Samples : Y. Jin, A. Cavanna, LPN Marcoussis

W. Oliver *et al.*, Science **284** (5412), 299-301, (1999)
M. Henny *et al.*, Science **284** (5412), 296 (1999)



Hanbury-Brown & Twiss correlations in optics



HBT correlations in a ballistic conductor

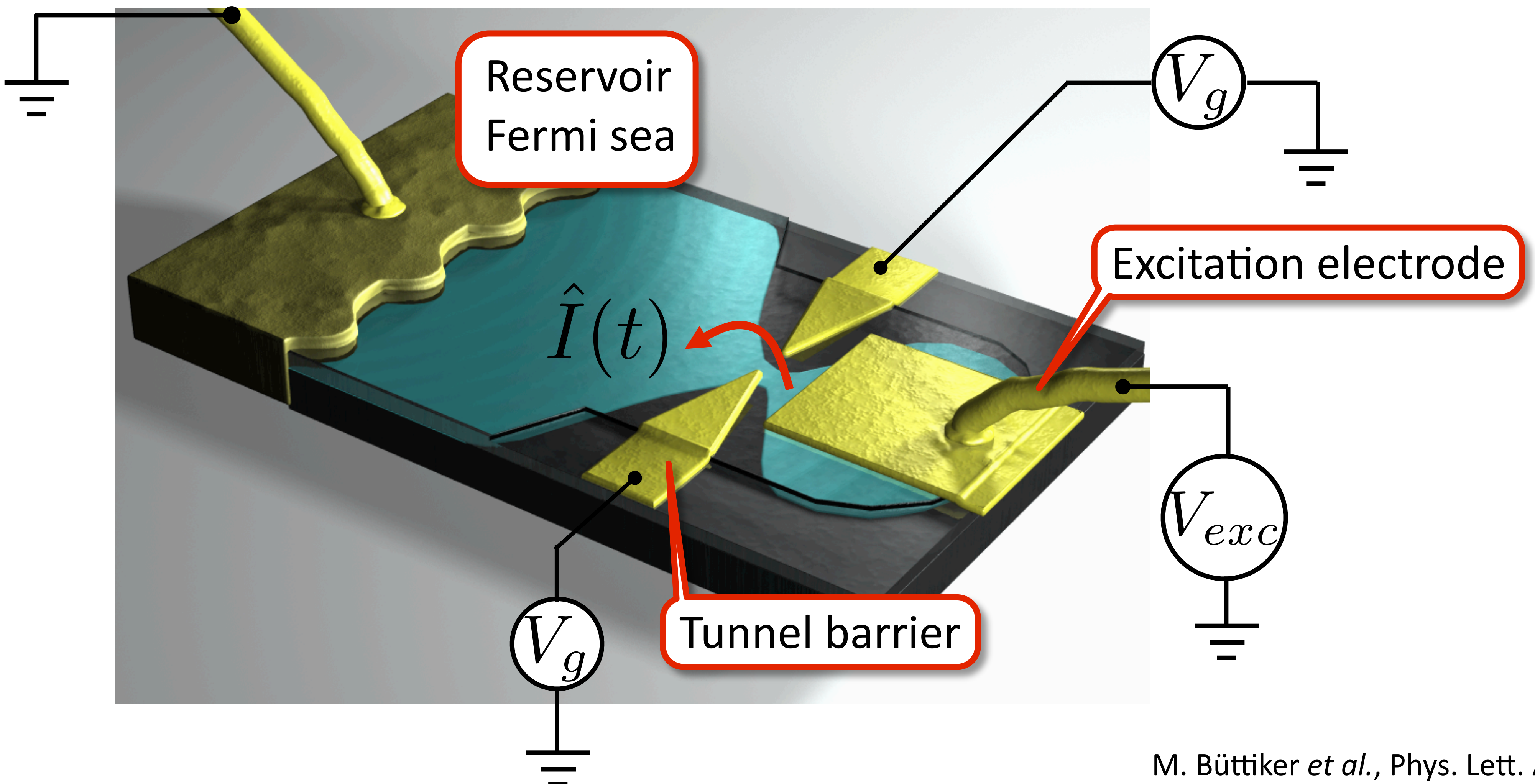
Motivations :

- analogies between photons and electrons in ballistic quantum conductors
- generate/manipulate/characterize single particle states
- Fermi sea & Coulomb interaction

Samples : Y. Jin, A. Cavanna, LPN Marcoussis

W. Oliver *et al.*, Science **284** (5412), 299-301, (1999)
M. Henny *et al.*, Science **284** (5412), 296 (1999)

Mesoscopic capacitor as single electron source



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

Other triggered sources

- Electron turnstiles/pumps

M.D. Blumenthal *et al.*, Nature Physics **3,** 343 (2007)
P. Mirovsky *et al.,* APL **97**, 252104 (2010)
S. Giblin *et al.,* Nature Comm. **3**, 930 (2012)

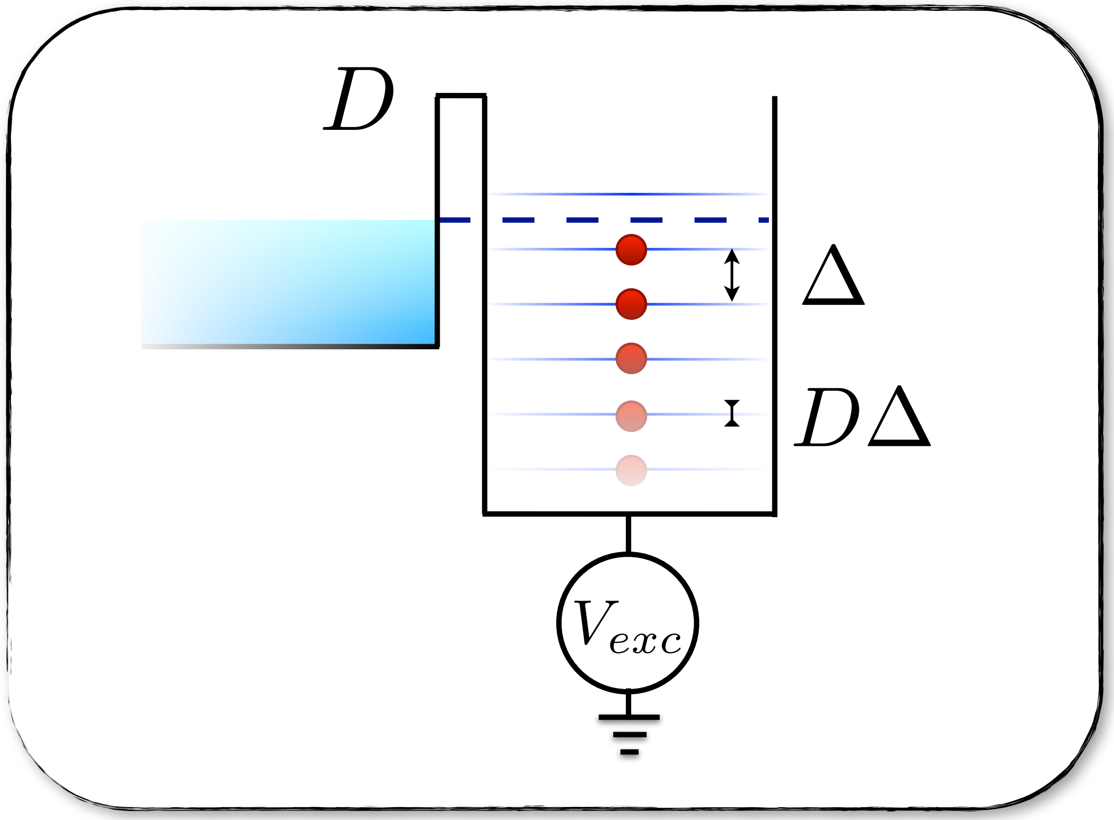
- Levitov pulses

L.S. Levitov *et al.*, J. Math Phys. **37** (10), 43 (1996)
J. Keeling et al., PRL **97**, 116403 (2006)
J. Dubois *et al.*, ArXiv:1212.3921

- Electrons flying on SAW

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

Principle of single charge emission



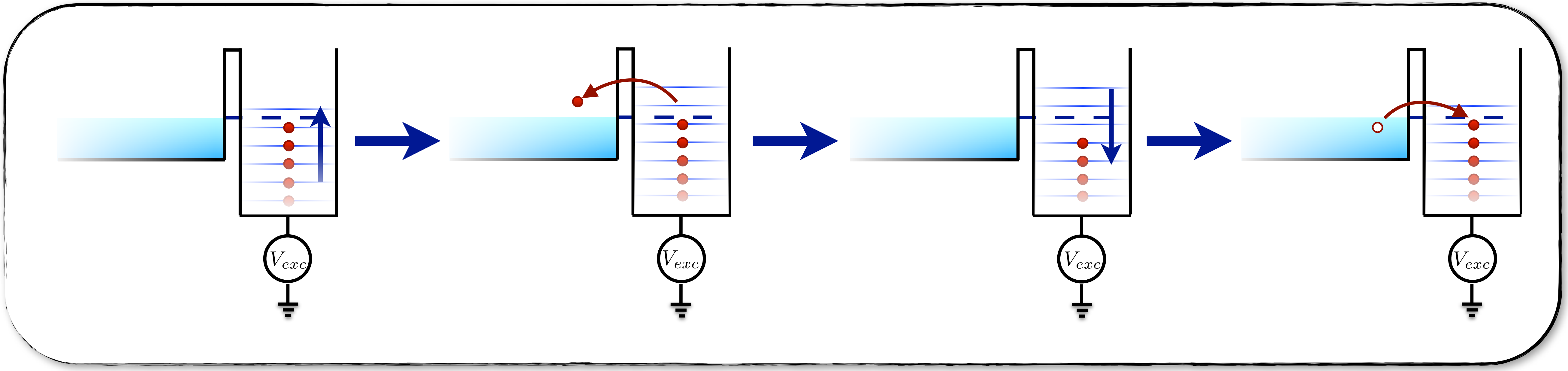
level spacing : $\Delta \simeq 1 - 2\,\mathrm{K}$

level broadening : $D\Delta$

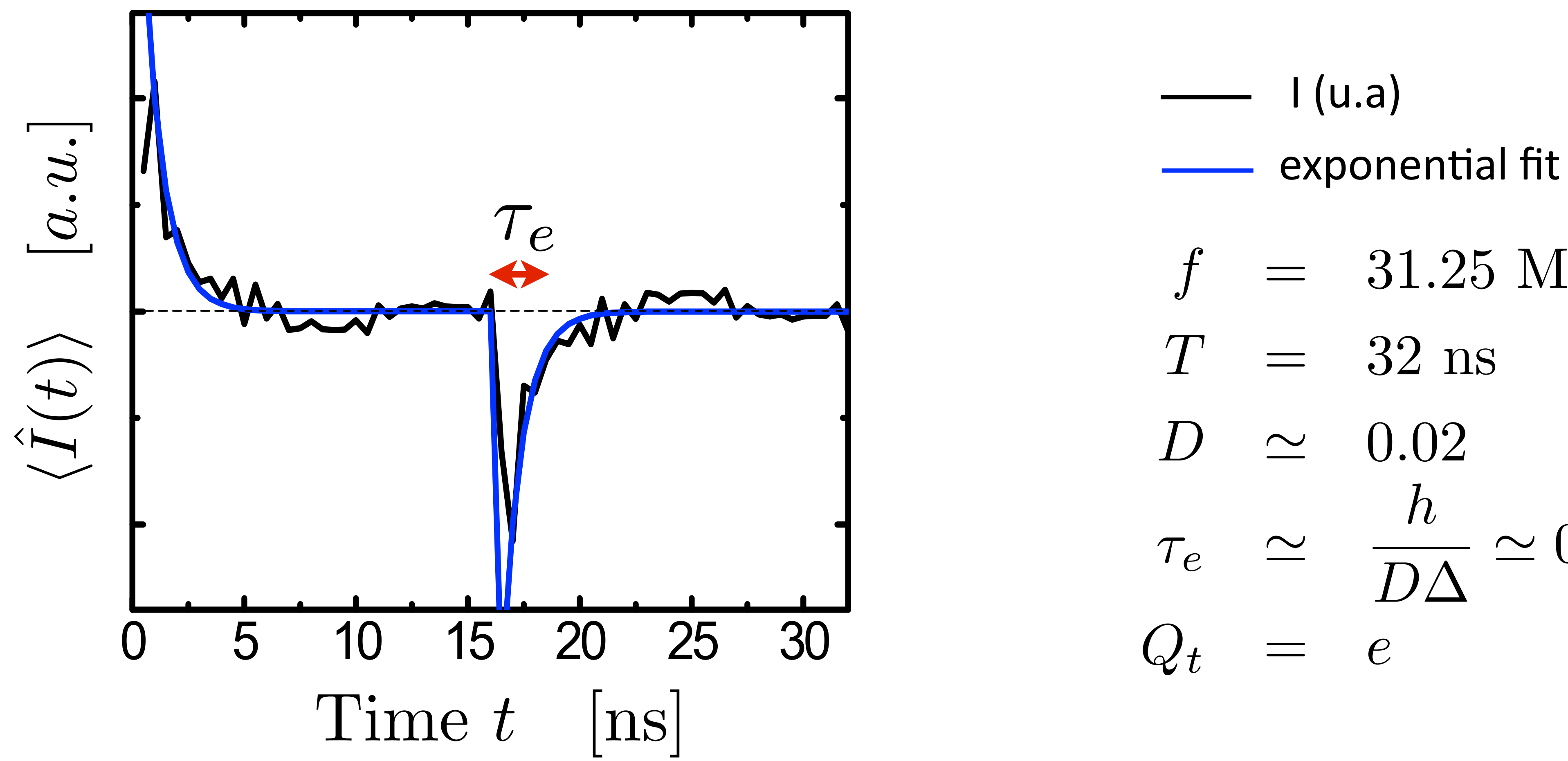
escape time : $\tau_e \simeq \dfrac{h}{D\Delta}$

driving frequency : $f = \dfrac{1}{T} \sim 1 - 2\,\mathrm{GHz}$

single charge emission : $2eV_{exc} = \Delta$



Single charge emission



$$f = 31.25\ \mathrm{MHz}$$
$$T = 32\ \mathrm{ns}$$
$$D \simeq 0.02$$
$$\tau_e \simeq \frac{h}{D\Delta} \simeq 0.9\,\mathrm{ns}$$
$$Q_t = e$$

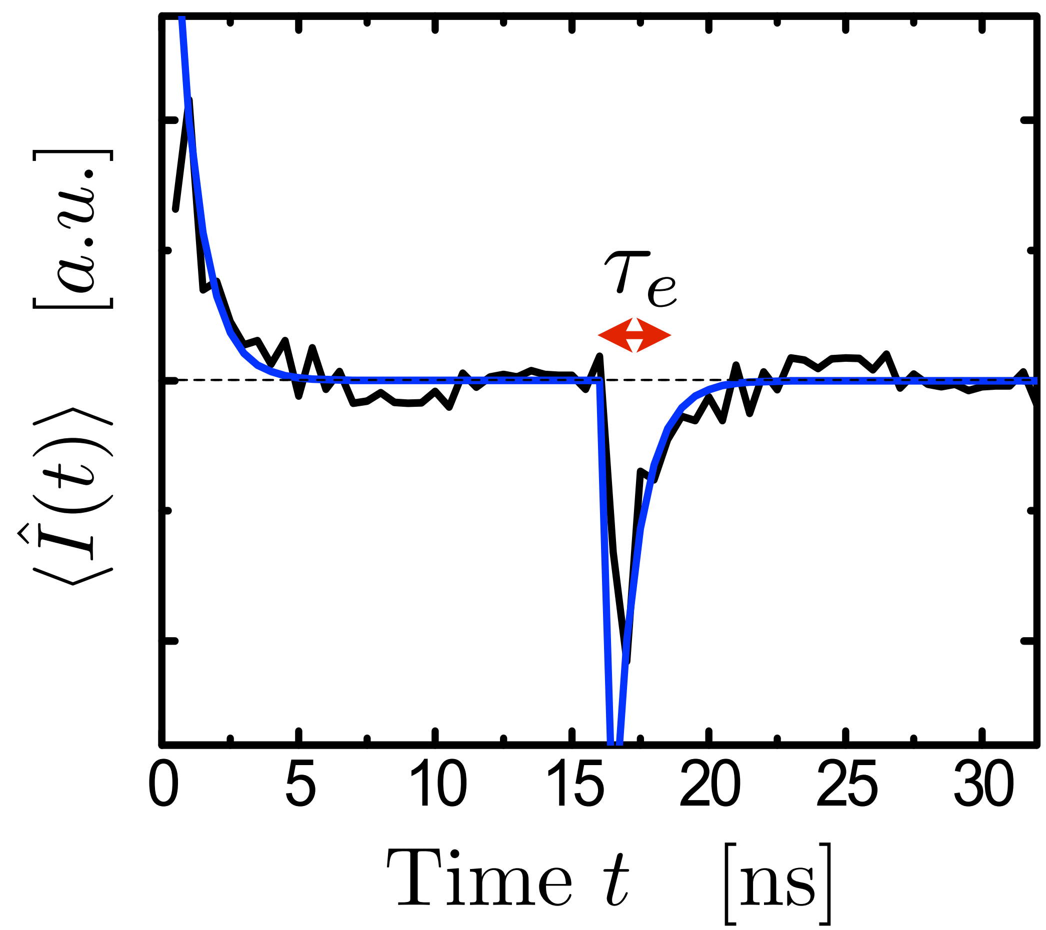
$$\left.\begin{array}{l} \tau_e \ll T/2 \\ \Rightarrow Q_t = e \end{array}\right\}$$

$\Rightarrow$ **single charge emission on average**

G. Fève *et al.*, Science **316**, 1169 (2007)
A. Mahé *et al.*, JLTP **53**, 339-349 (2008)
M. Moskalets *et al.*, PRL **100** (8) (2008)

A. Mahé *et al.*, PRB **82**(20), 201309 (2010)
M. Albert *et al.*, PRB **82**(4), 41407 (2010)
T. Jonckheere *et al.*, PRB **85**(4) 045321 (2012)
F.D. Parmentier *et al.*, PRB **85**, 165438 (2012)

Single charge emission



I (u.a)

exponential fit

$$
\begin{aligned}
f &= 31.25 \text{ MHz} \\
T &= 32 \text{ ns} \\
D &\simeq 0.02 \\
\tau_e &\simeq \frac{h}{D\Delta} \simeq 0.9 \,\text{ns} \\
Q_t &= e
\end{aligned}
$$

$$
\left.\begin{aligned}
&\tau_e \ll T/2 \\
&\Rightarrow Q_t = e
\end{aligned}\right\}
$$

⇒ single charge emission on average

confirmed by current autocorrelations

G. Fève *et al.*, Science **316**, 1169 (2007)
A. Mahé *et al.*, JLTP **53**, 339-349 (2008)
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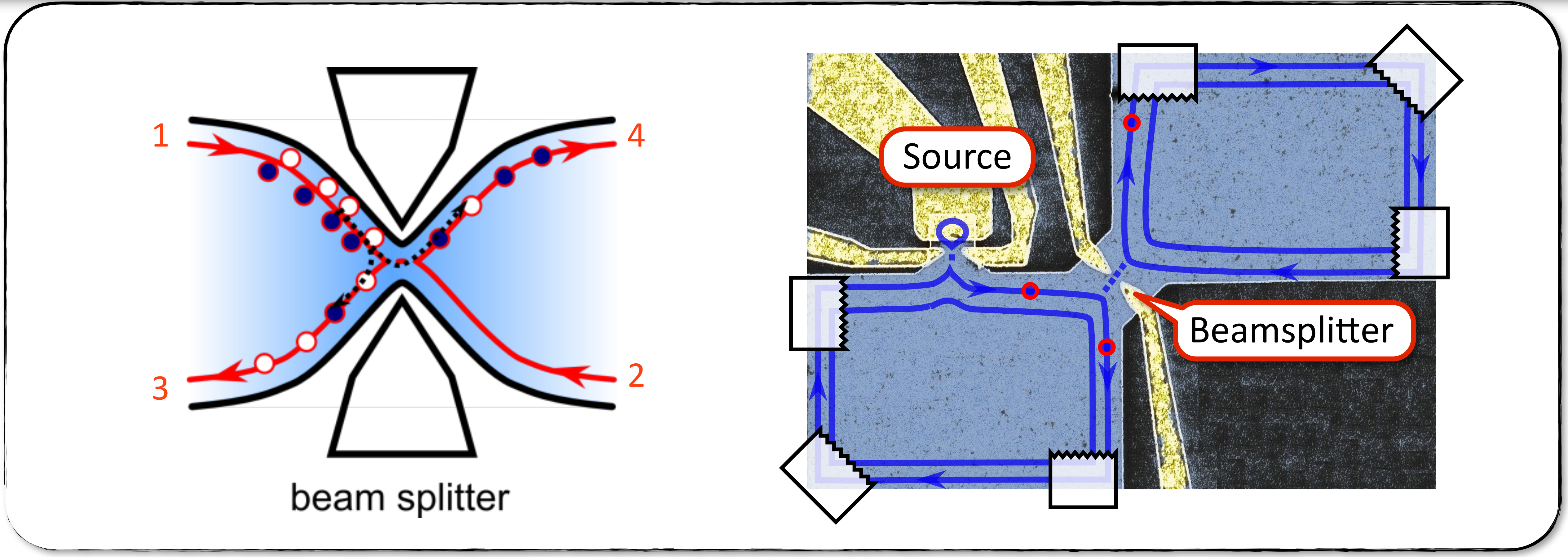
T. Jonckheere *et al.*, PRB **85**(4) 045321 (2012)
F.D. Parmentier *et al.*, PRB **85**, 165438 (2012)

Partition noise



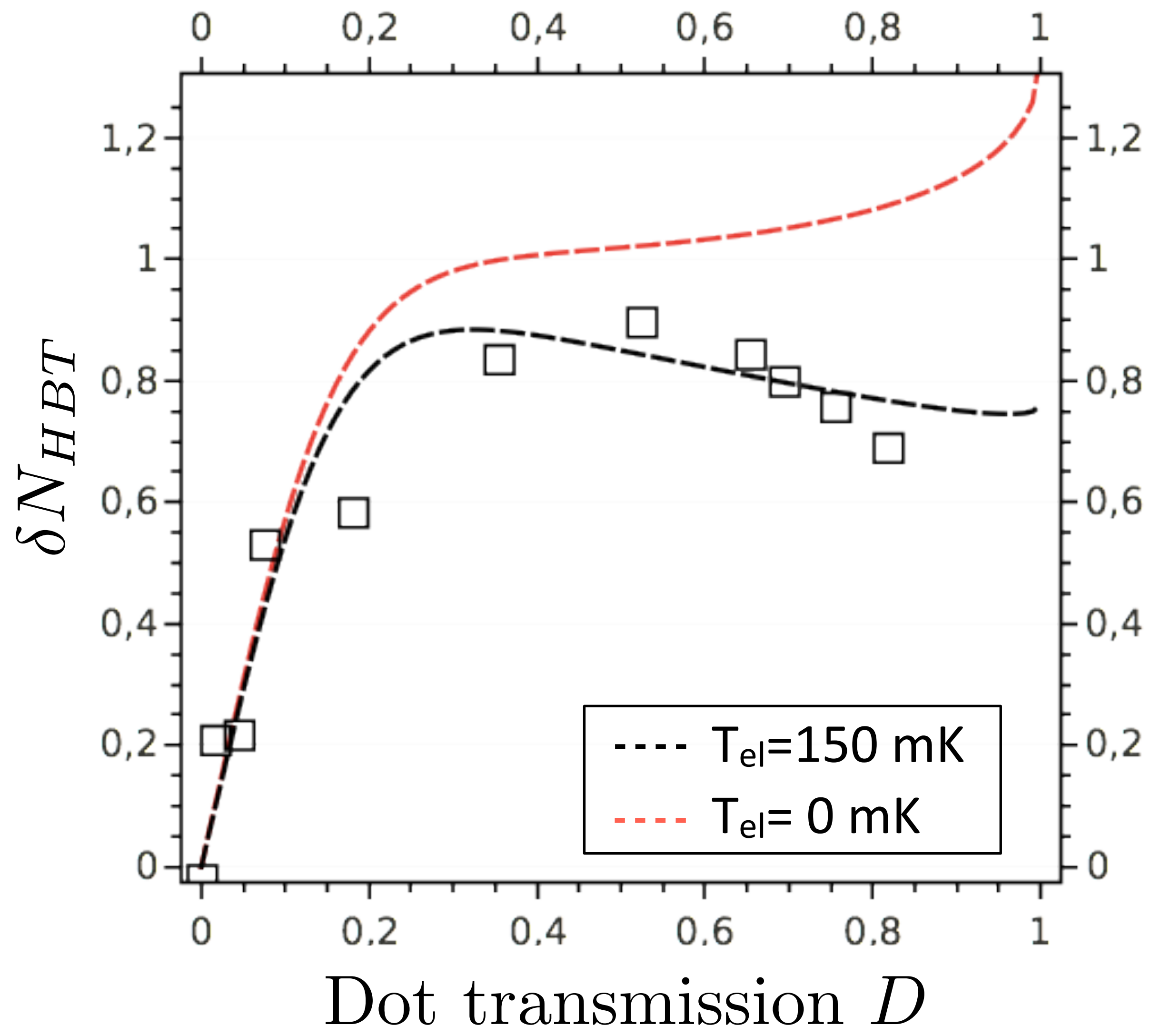
- random partitioning ⇒ **zero-frequency noise**
- access to neutral events ⇒ **counting quasiparticles**

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

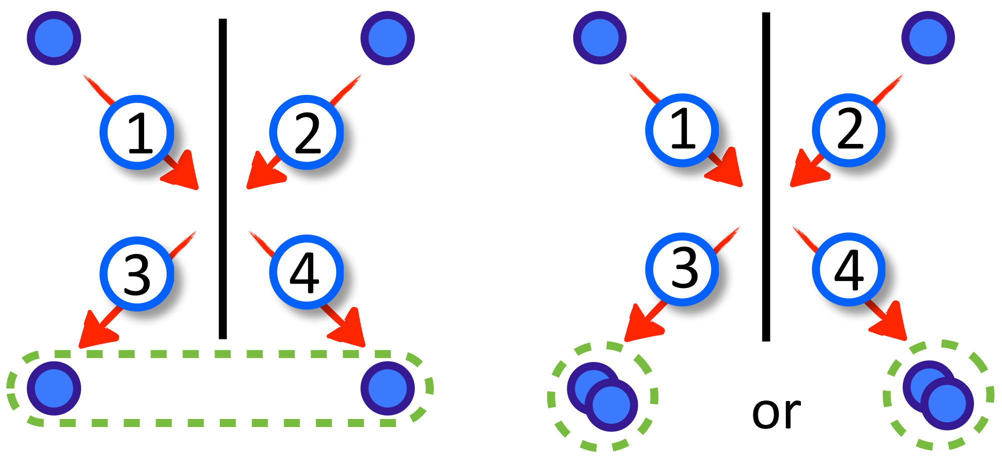
$$\langle \hat{I}_{part}\rangle = ef\big(\langle N_e\rangle + \langle N_h\rangle\big) = 2ef\,\delta N_{HBT}$$

M.H. Pedersen *et al.*, PRB **58**, 12993 (1998)
G.B. Lesovik, JETP Lett. **70**, 208 (1999)
L.-H Reydellet *et al.*, PRL **90**, 176803 (2003)
V. S. Rychkov *et al.*, PRB **72**, 155326 (2005)
J. Keeling *et al.*, PRL **101**, 196404 (2008)
M. Vanević *et al.*, PRB **78**, 245308 (2008)

Measurement of HBT autocorrelations



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



E. Bocquillon *et al.*, PRL **108** 196803 (2012)

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

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

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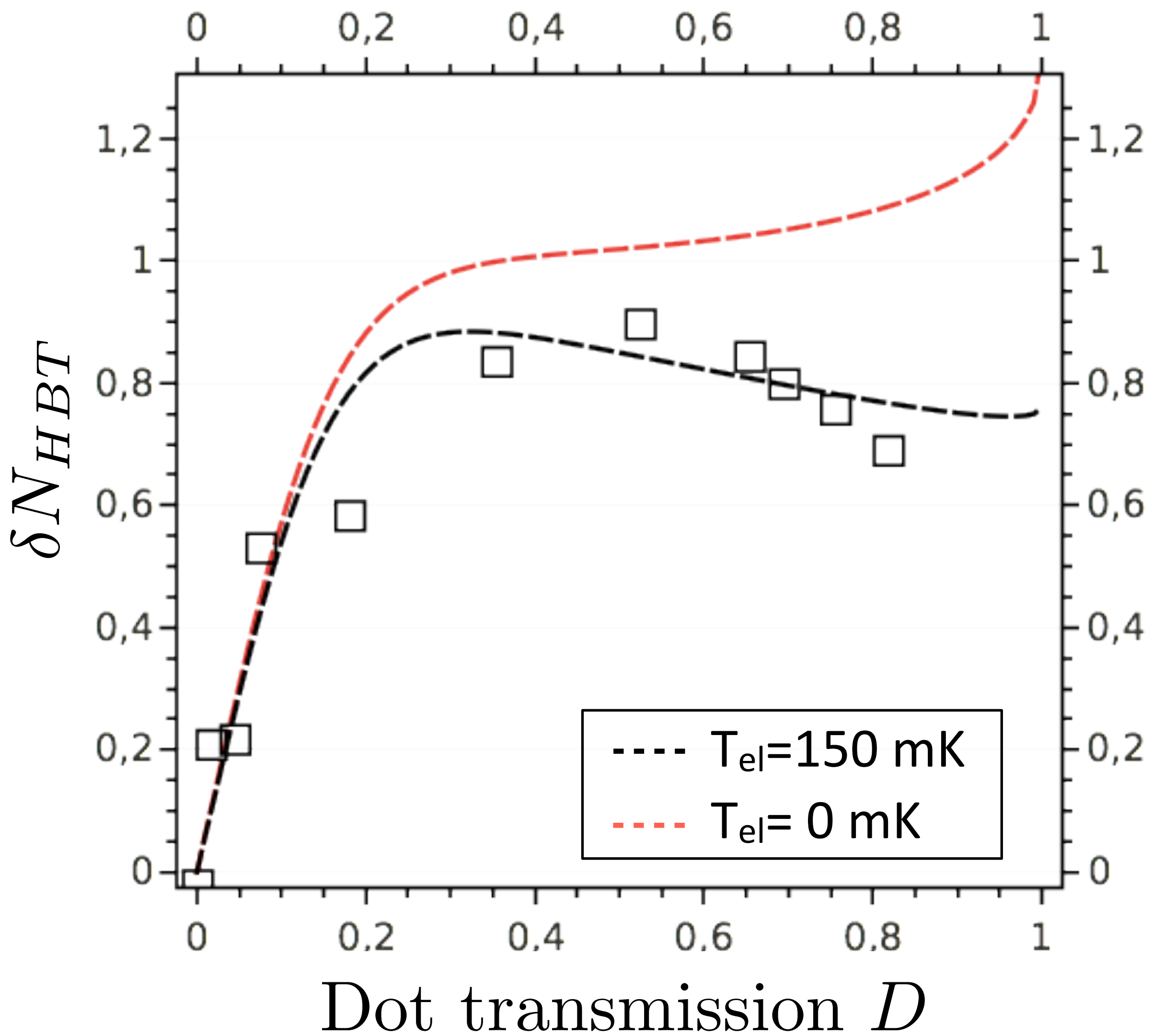

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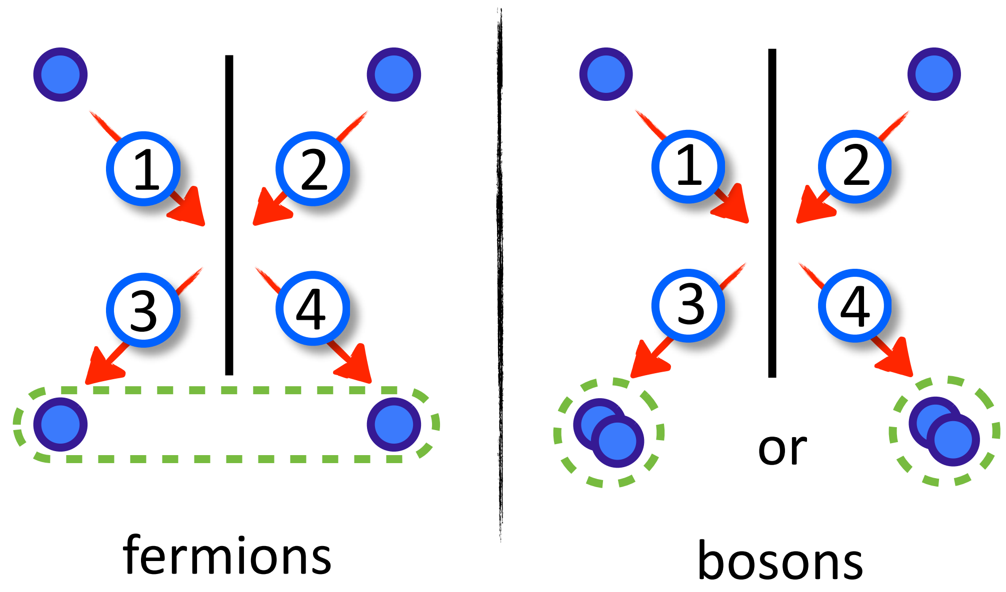

E. Bocquillon *et al.*, PRL **108** 196803 (2012)

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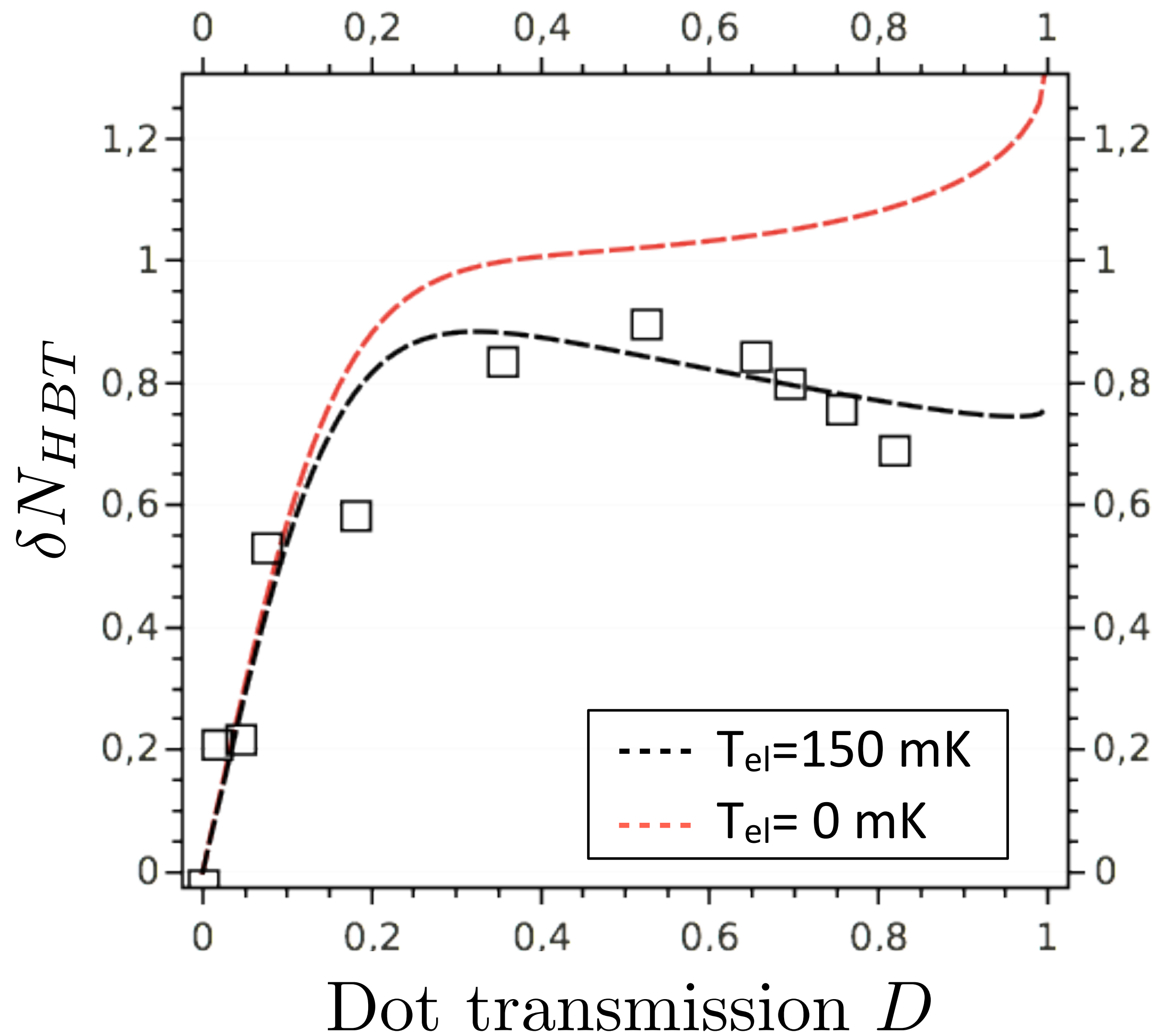

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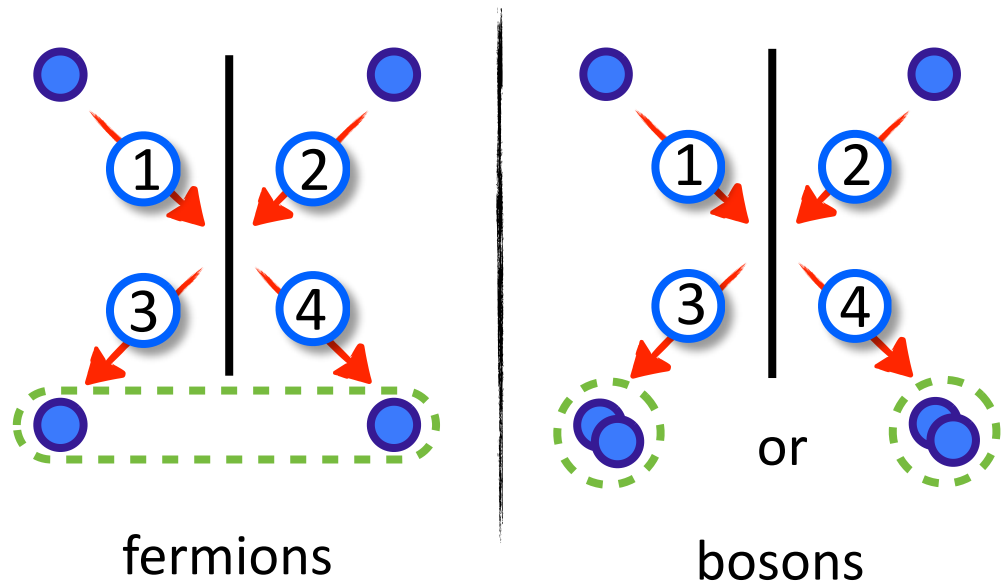

E. Bocquillon *et al.*, PRL **108** 196803 (2012)

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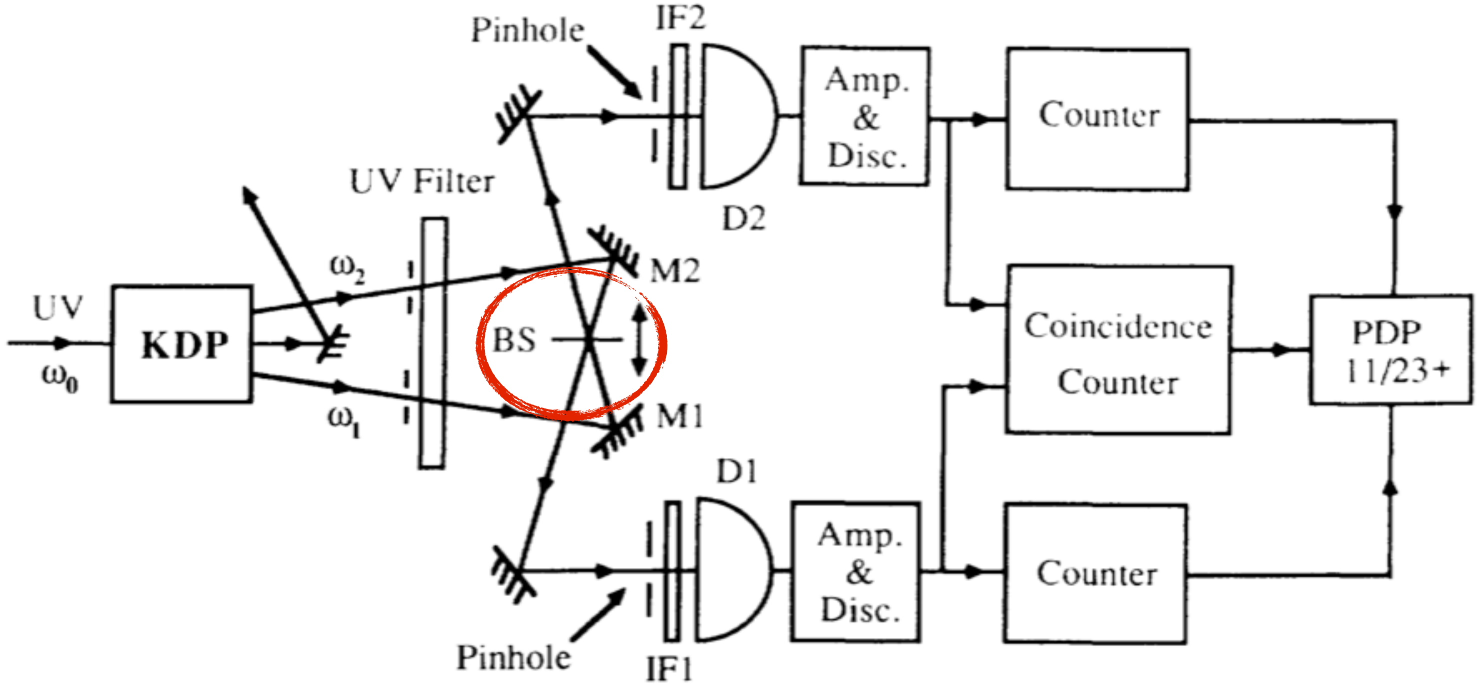
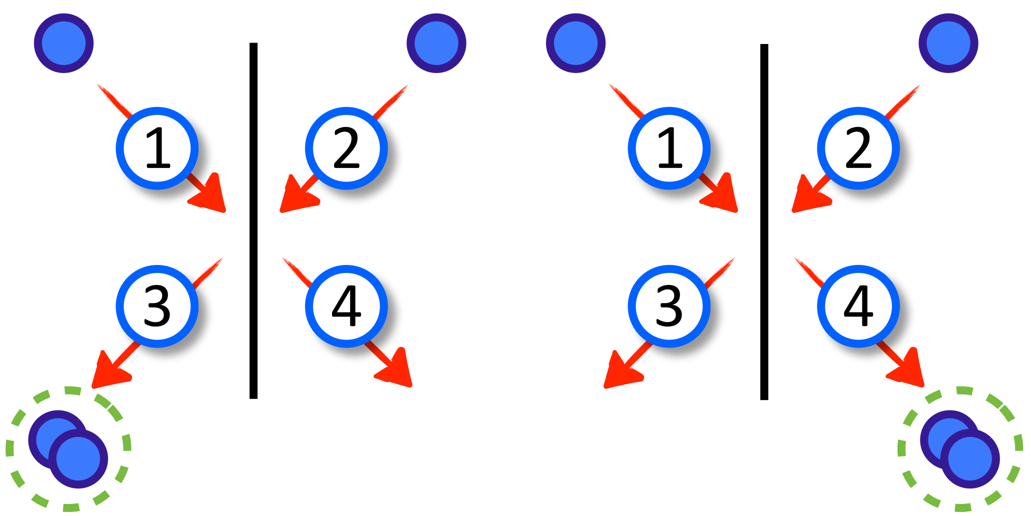
$$\langle N_{e/h} \rangle = \int_0^\infty d\epsilon \; \delta n_{e/h}(\epsilon)$$

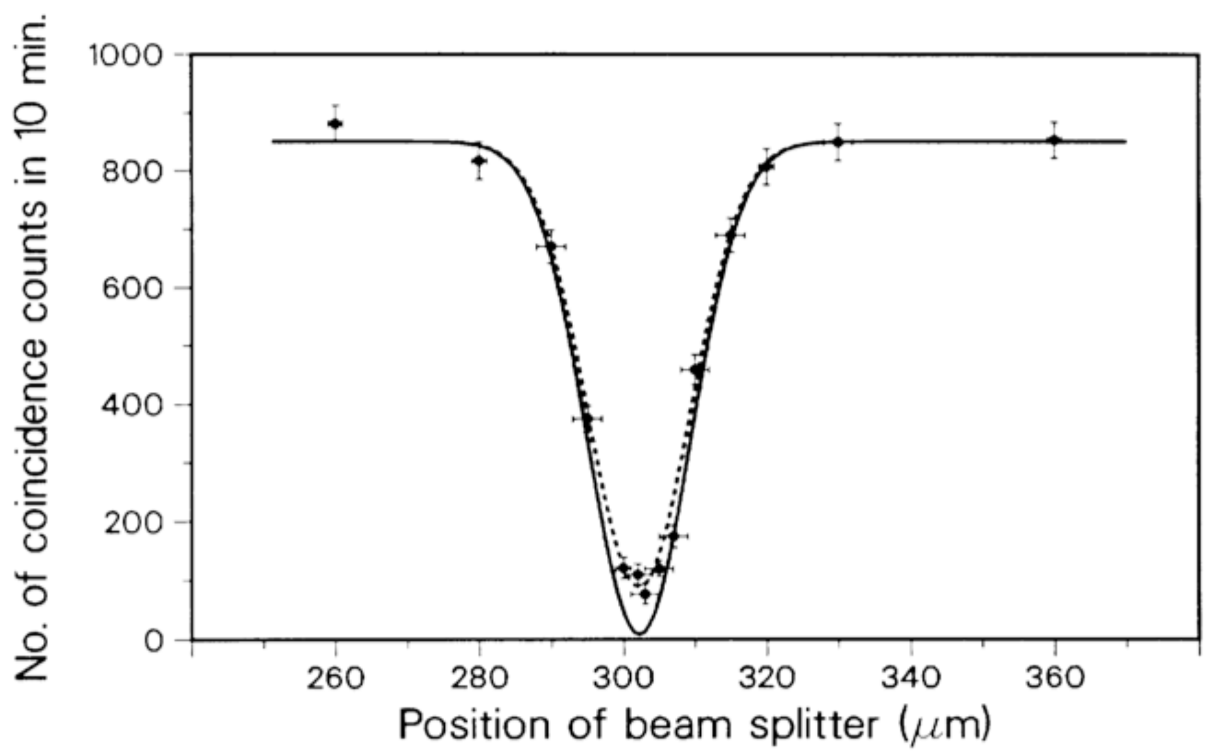
antibunching
with thermal excitations

Undistinguishability of generated particles

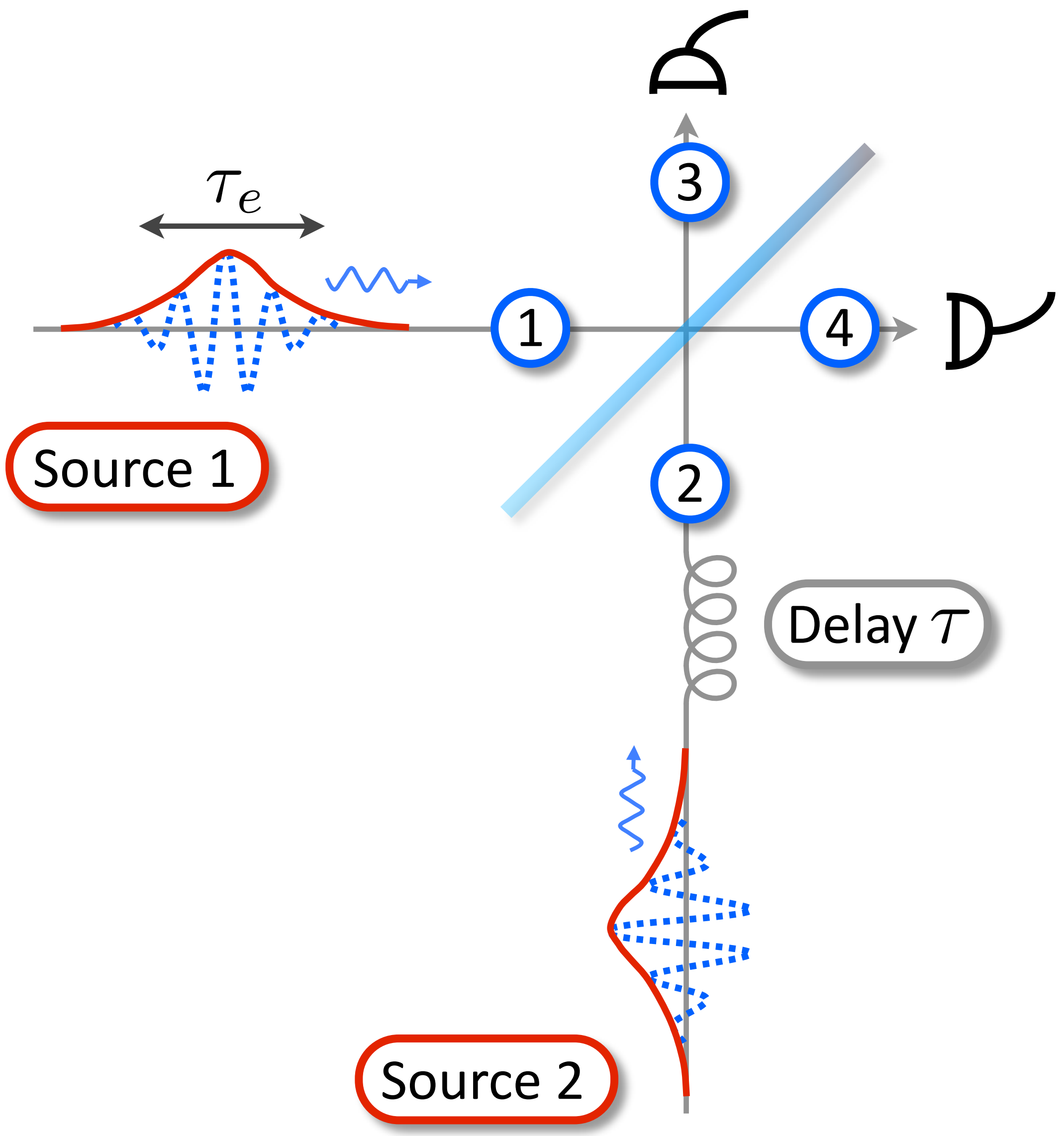


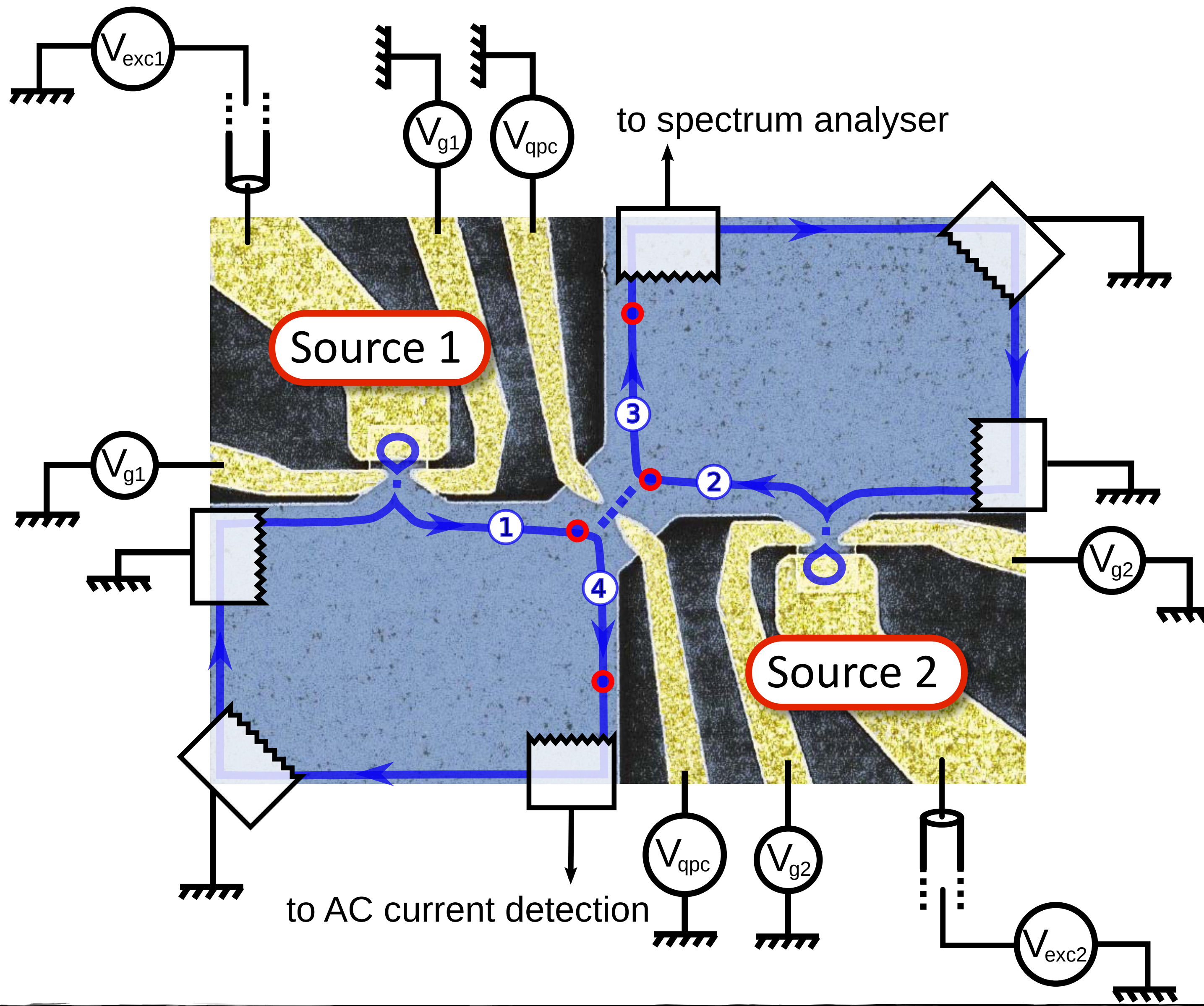


Undistinguishable photons



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)



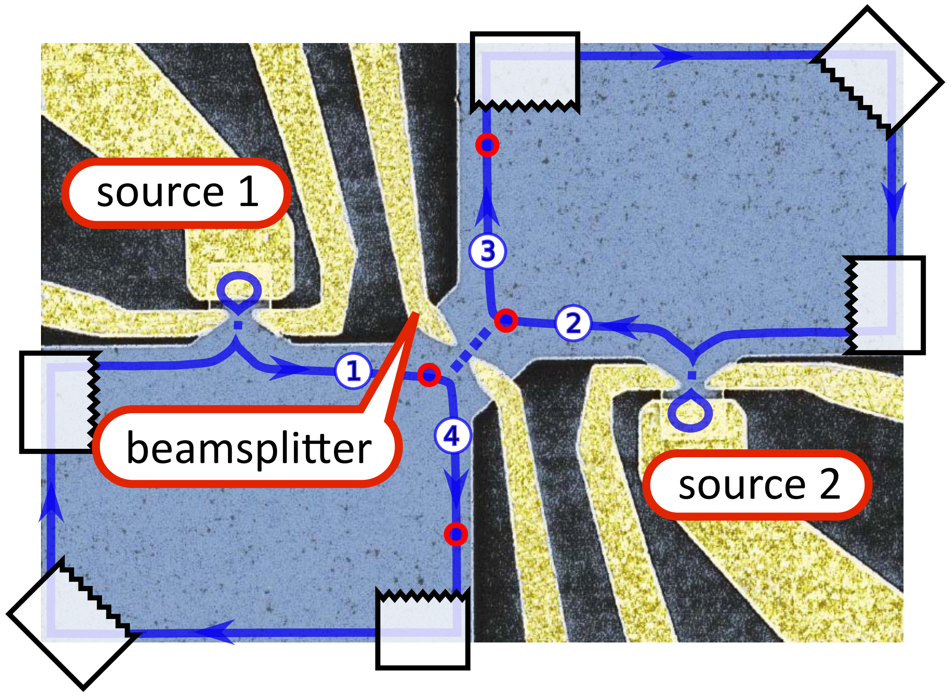


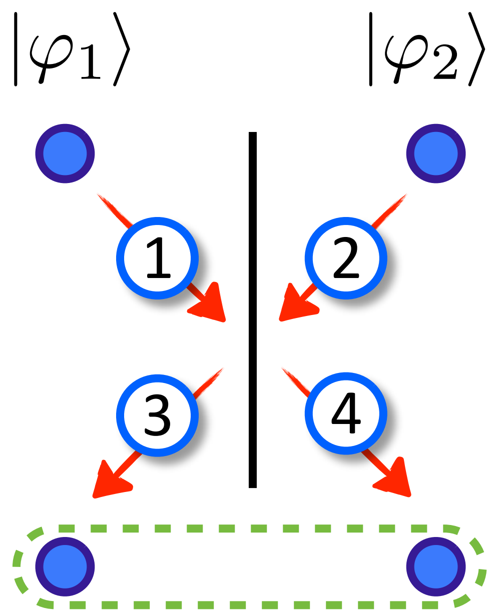
Two sources:

- independently tuned parameters
- synchronized excitations, with tunable delay τ (within a ±7 ps error)

P. Samuelsson *et al.*, **PRL** 92, 026805 (2004)
I. Neder *et al.*, Nature **448** 333 (2007)

S. Ol'khovskaya *et al.*, PRL **101**, 166802 (2008)
G. Fève *et al.*, PRB **77**, 035308 (2008)
T. Jonckheere *et al.*, PRB **86**, 125425 (2012)





Two-particle interference at zero delay if **undistinguishable particles!**

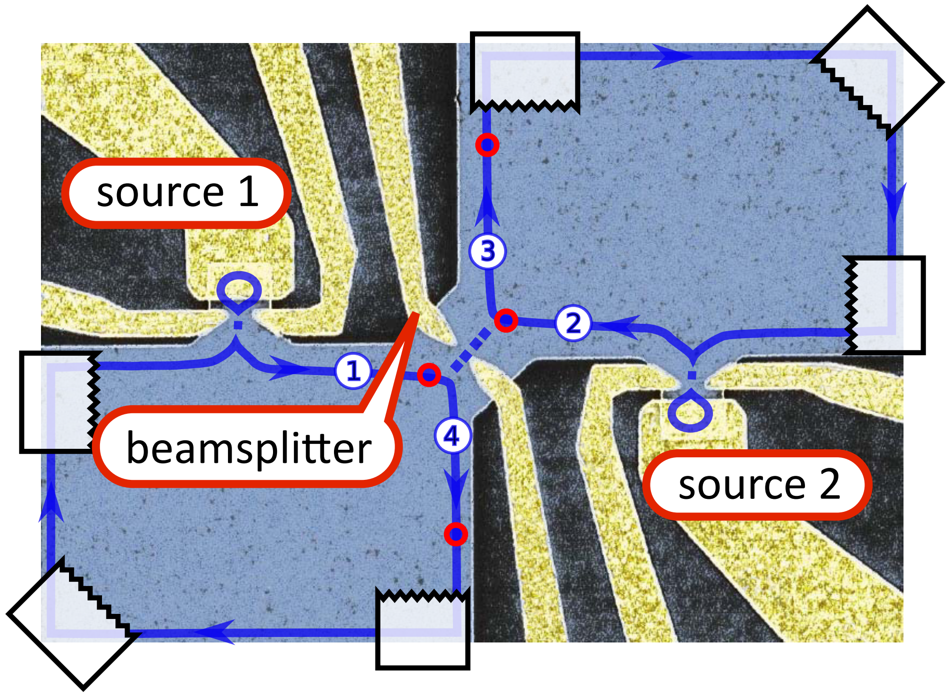
$$P(1,1) = \frac{1}{2}\left(1 + |\langle\varphi_1|\varphi_2\rangle|^2\right)$$

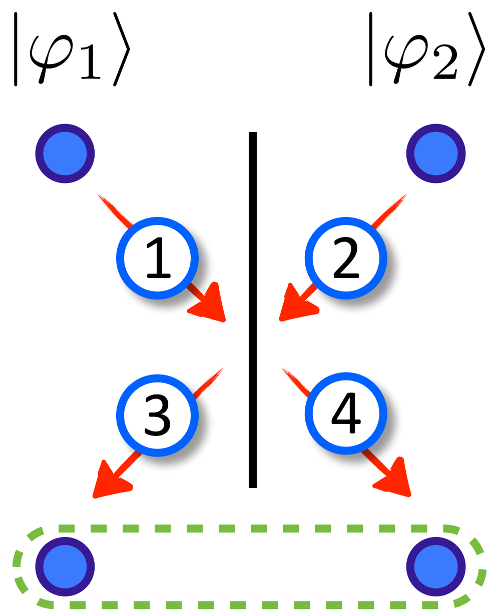
Undistinguishability probed through correlations:

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

- antibunching at delay $\tau = 0$
- independent random partitioning for $\tau \gg \tau_e$

$\Rightarrow$ "Pauli dip"





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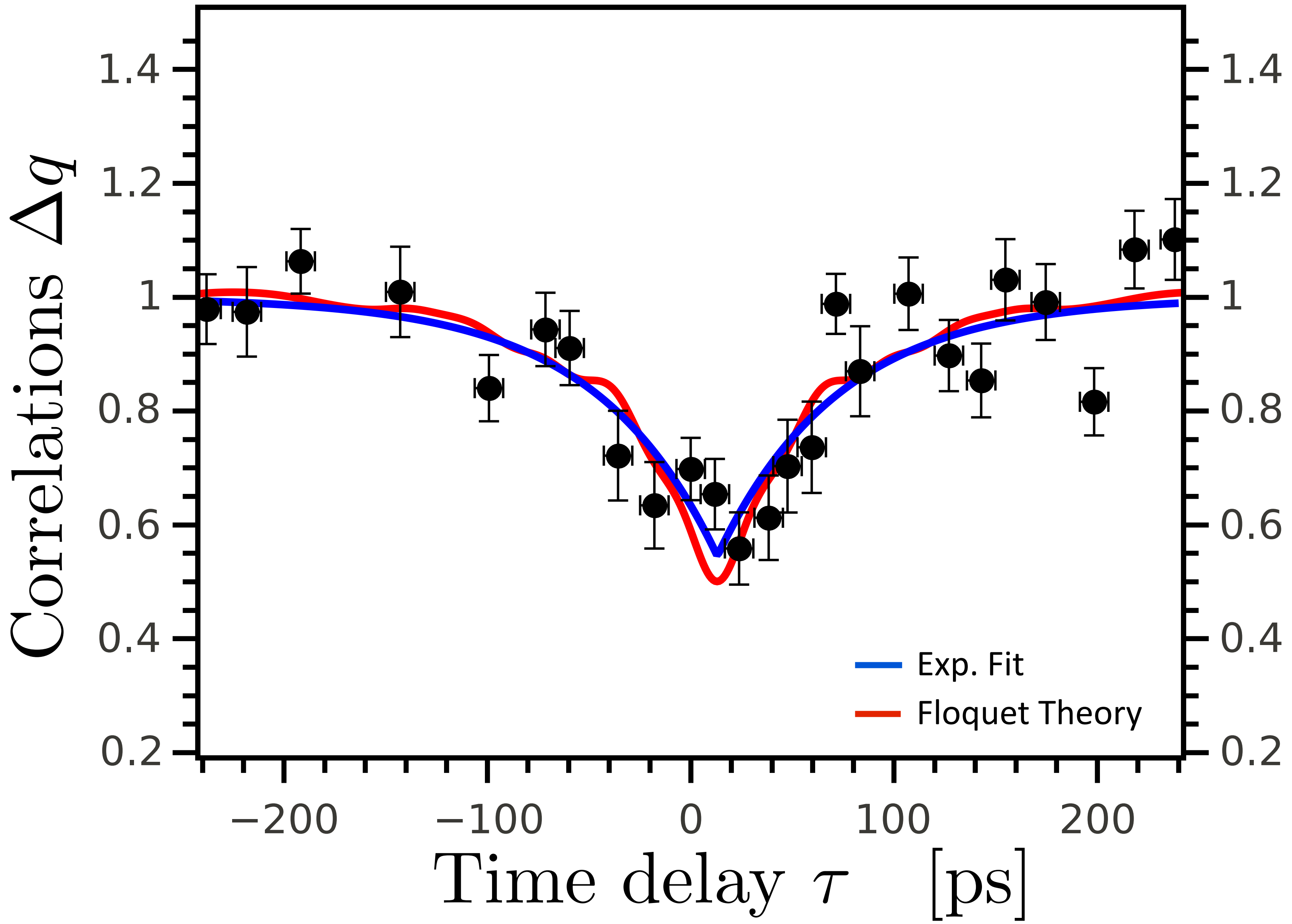
- independent random partitioning for $\tau \gg \tau_e$

$\Rightarrow$ "Pauli dip"

Generate undistinguishable fermions?

Decoherence?

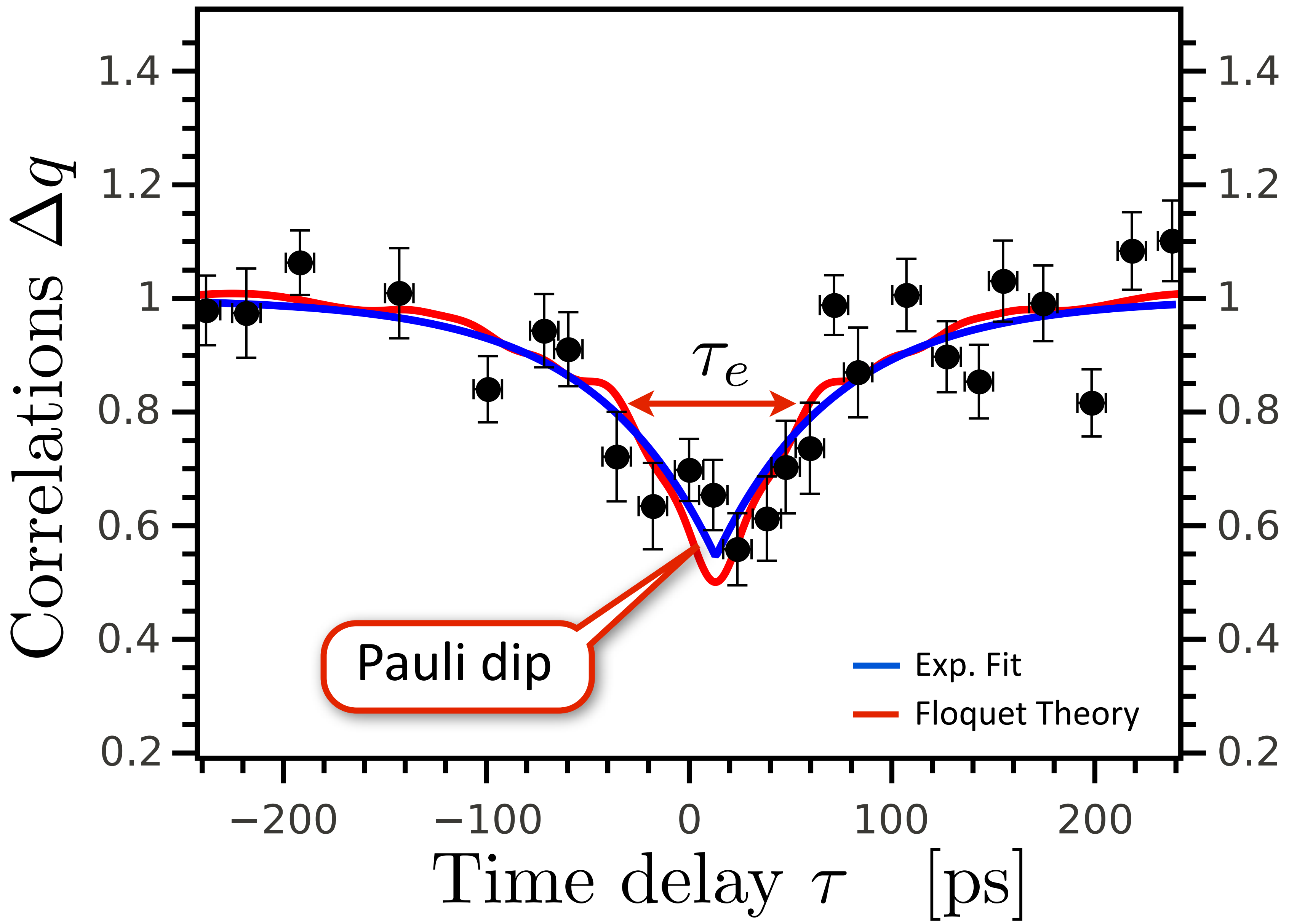
Triggered 2-particle interference



For $D_1 = D_2 = 0.4$

E. Bocquillon *et al.*, Science **339**, 1054 (2013)

Triggered 2-particle interference



For $D_1 = D_2 = 0.4$

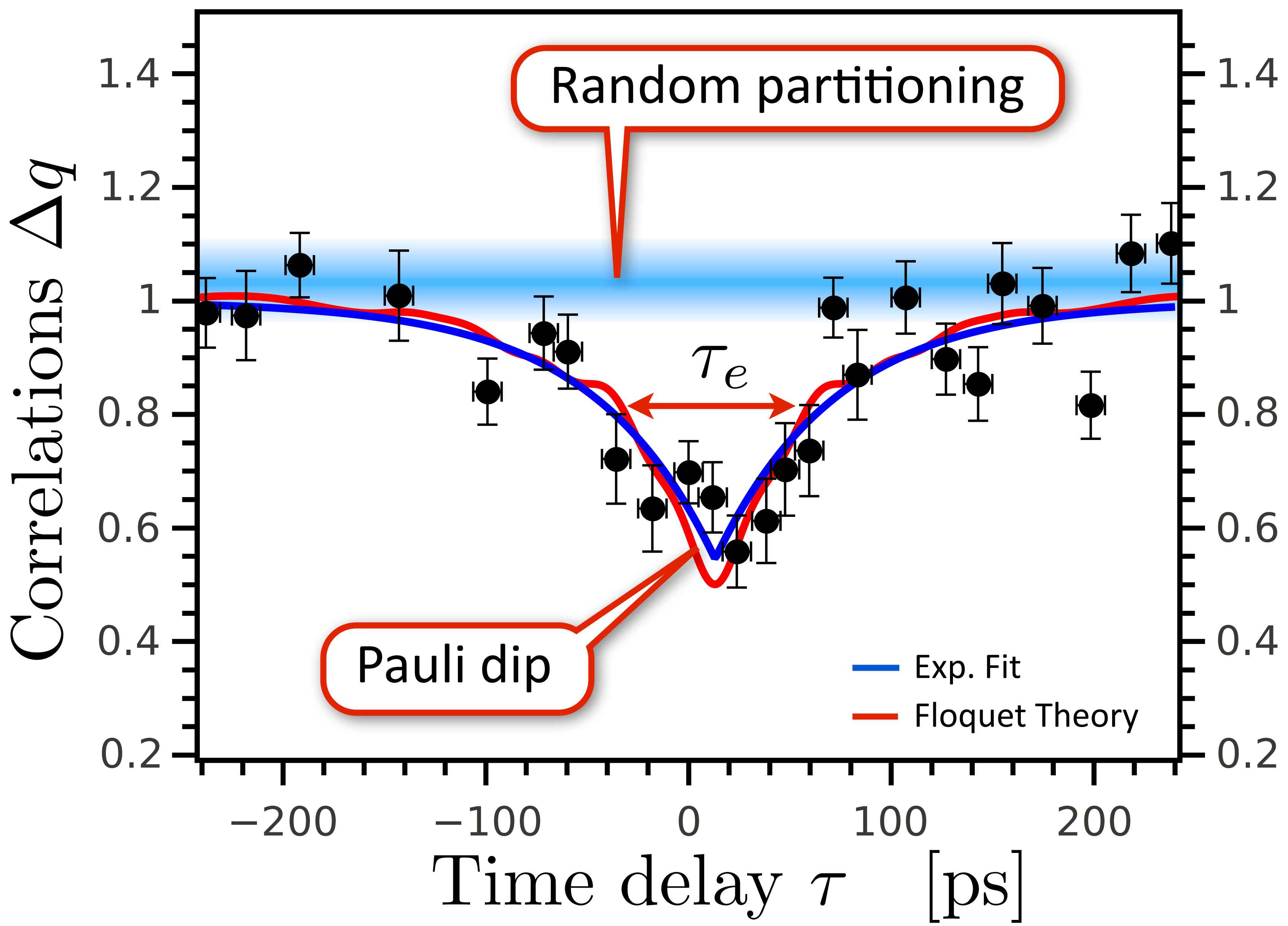
- antibunching at $\tau = 0$

$\Rightarrow$ "Pauli dip"

$\tau_e = 62 \pm 10\,\mathrm{ps}$

E. Bocquillon *et al.*, Science **339**, 1054 (2013)

Triggered 2-particle interference



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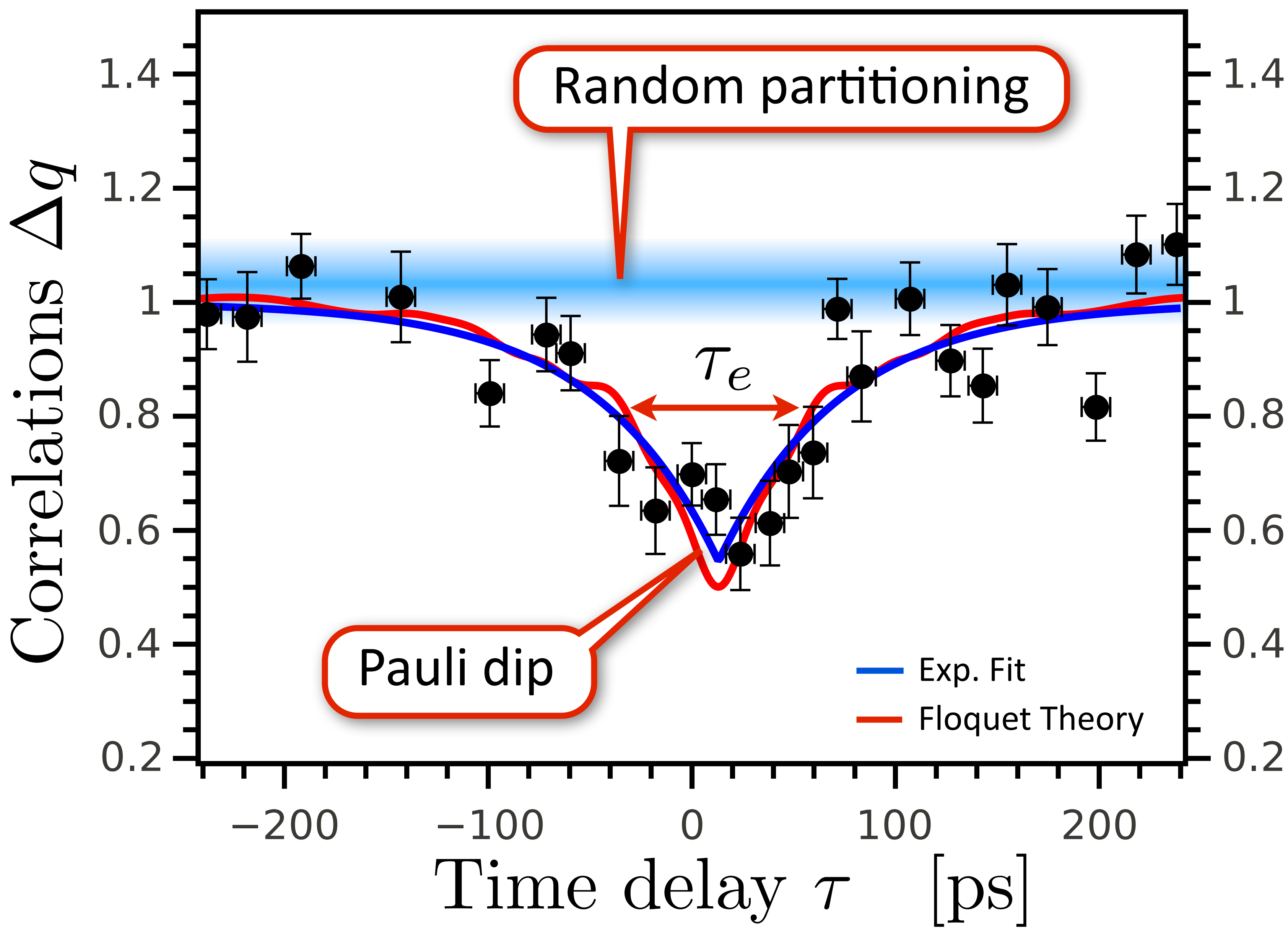
for $\tau \gg \tau_e$

HBT contributions

E. Bocquillon *et al.*, Science **339**, 1054 (2013)

Triggered 2-particle interference



For $D_1 = D_2 = 0.4$

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- independent partitioning

  for $\tau \gg \tau_e$

  HBT contributions

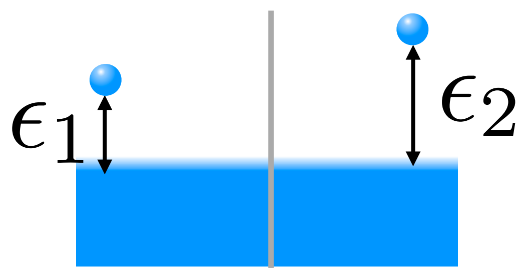
E. Bocquillon *et al.*, Science **339**, 1054 (2013)

Finite visibility (≃50 %)

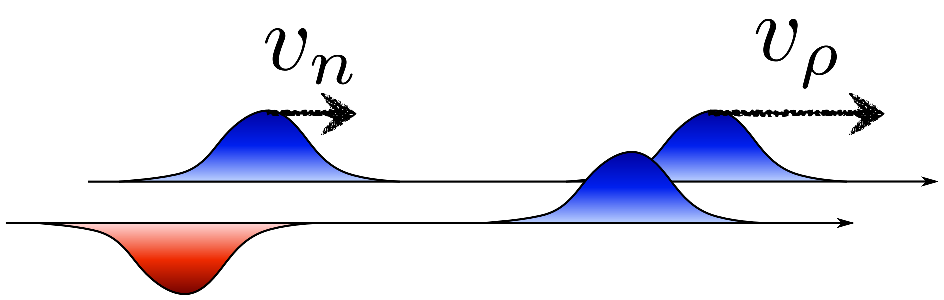
- partial undistinguishability of produced excitations
- decoherence due to interactions?

Electron quantum optics

- antibunching between triggered excitations
$\Rightarrow$ (partial) undistinguishability



- decoherence : effect of interactions between edge channels?



I. Neder *et al.*, PRL **96**, 016804 (2006)
I.P. Levkivskyi et al., Phys. Rev. B **78**, 045322 (2008)

P. Roulleau et al., Phys. Rev. Lett. **101**, 186803 (2008)
H. Le Sueur et al., Phys. Rev. Lett. **105**, 056803 (2010)

Imaging a single-electron wavepacket

- tomography in energy domain (HBT geometry)
- tomography in time domain (MZI)

C. Grenier *et al.*, NJP **13**(9), 093007 (2011)
M. Moskalets *et al.*, PRB **83**, 035316 (2011)
G. Haack *et al.*, PRB **84**, 081303(R) (2011)

People involved

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- T. Martin
- J. Rech
- C.Wahl