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Quantum tomography of single electron excitations in quantum Hall edge channels

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

CENTRE DE PHYSIQUE THÉORIQUE

Agence Nationale de la Recherche ANR

Outline

- Introduction and motivation
- Quantum tomography...
- and its applications
- Conclusion

What is quantum tomography ?

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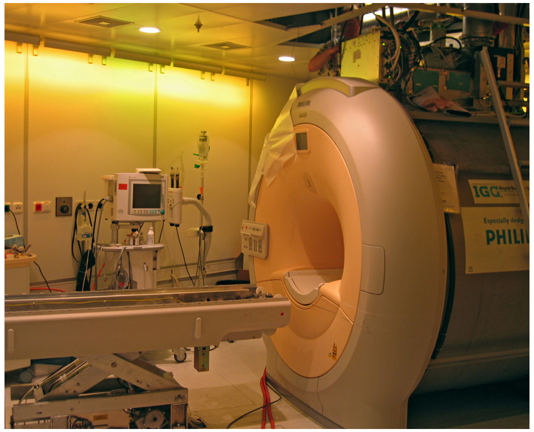
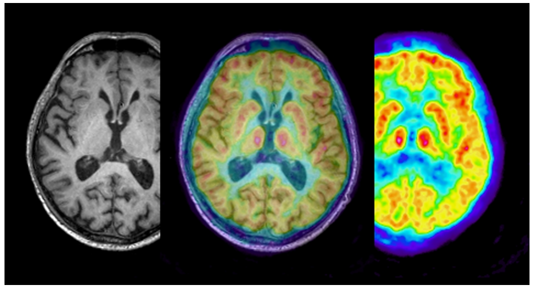
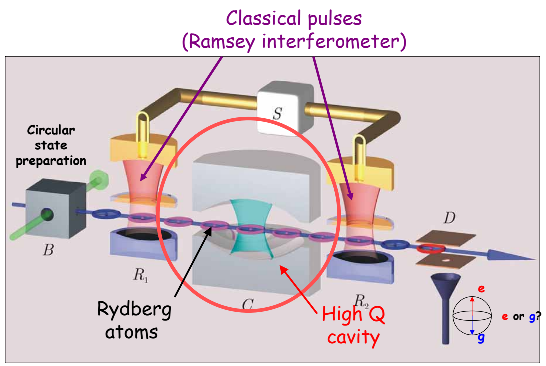
Classical tomography



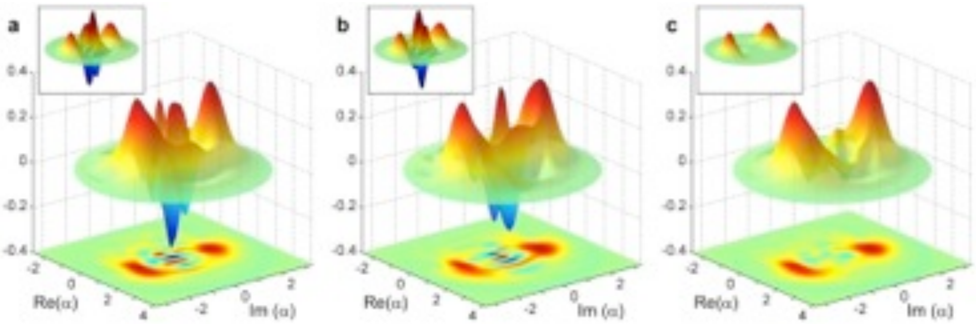


Density reconstruction from many measurements on a single system.

Quantum tomography

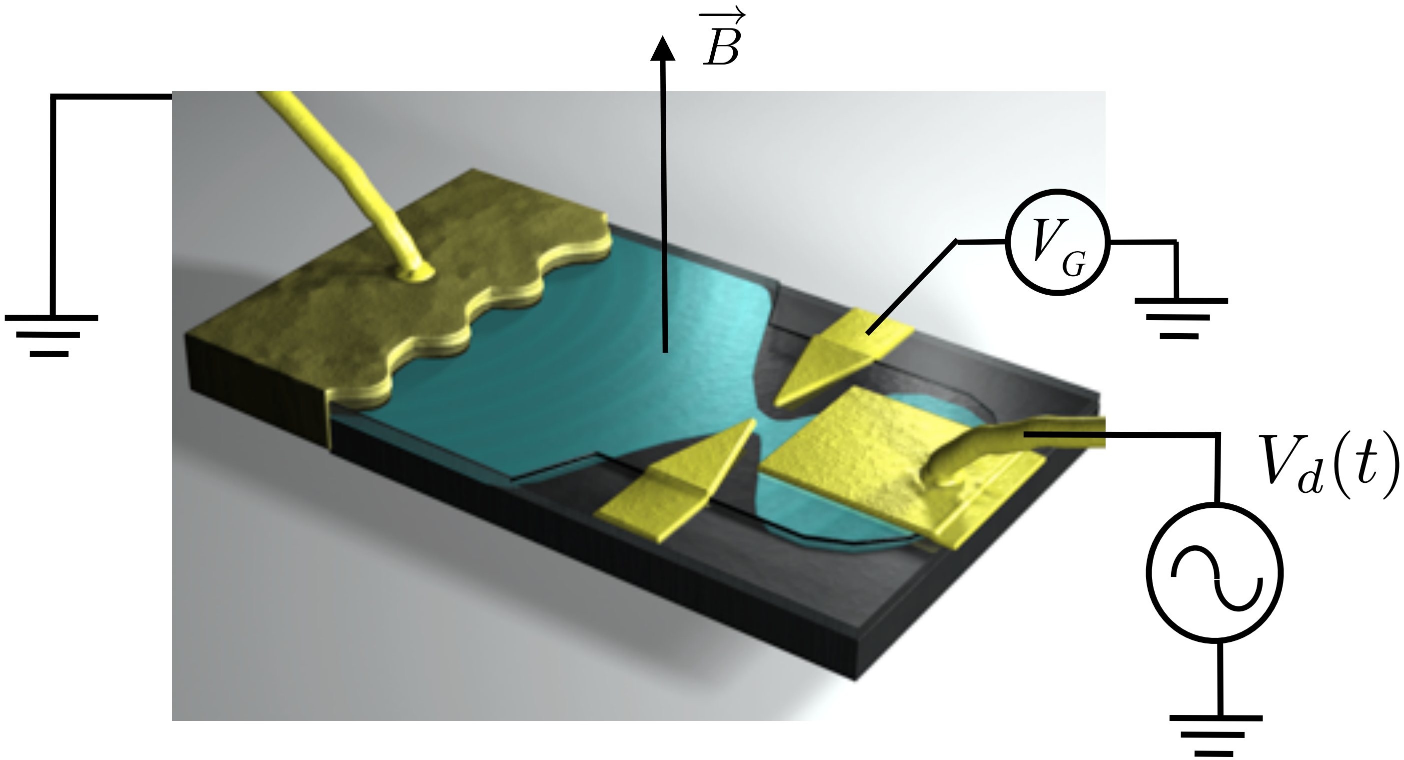


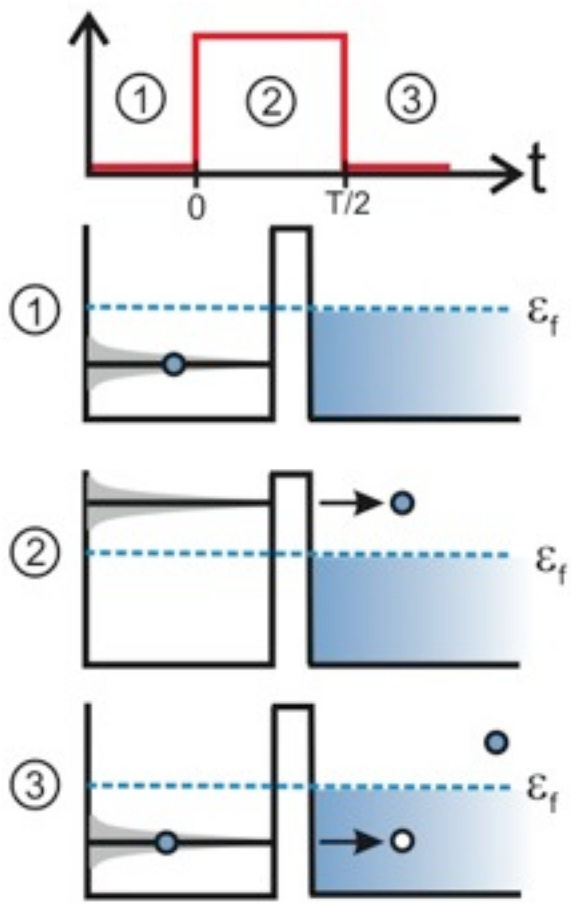
High Q cavity



It requires many realizations of the state (*no cloning theorem*).

The single electron source



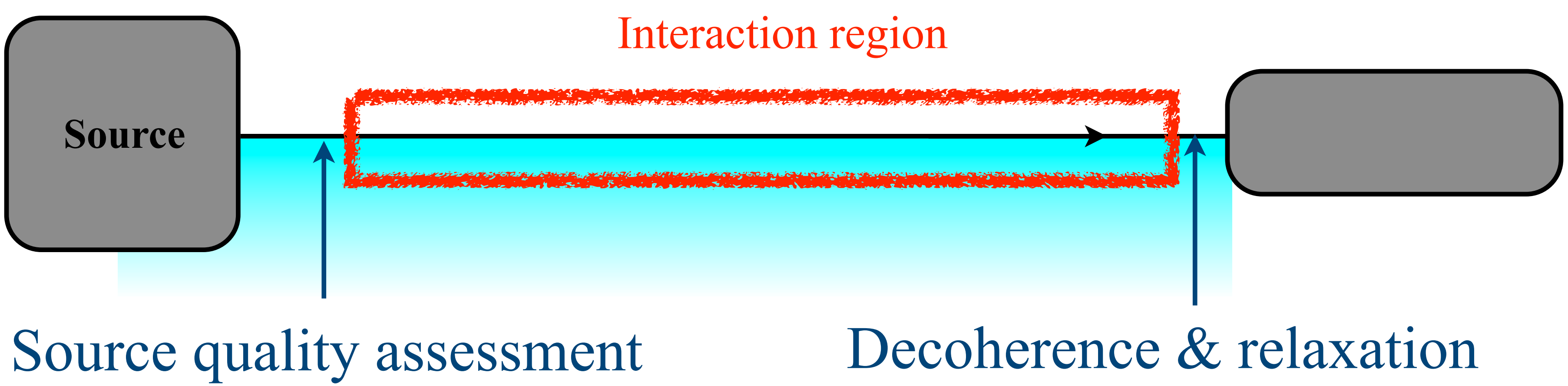


Emits single electron excitations!

G. Fève *et al*, Science **316**, 1169 (2007)
A. Mahé *et al*, Phys. Rev. B **82**, 201309 (2010)

See M. Büttiker's talk and M. Albert et al, Phys. Rev. B **82**, 041407 (2010) and Phys. Rev. Lett. **107**, 086805 (2011)

Our problem...



Statistical properties: average current, noise, full counting statistics

See Ch. Glattli and M. Büttiker talks

Coherence properties: can we access single electron wave packets ?

Single electron coherence: $\mathcal{G}_\rho^{(e)}(x,\tau|x',\tau') = \mathrm{Tr}(\psi(x,\tau)\rho\,\psi^\dagger(x',\tau'))$

Single electron coherence

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Single electron coherence: $\mathcal{G}^{(e)}_{\rho}(x,\tau|x',\tau') = \mathrm{Tr}(\psi(x,\tau)\rho\,\psi^{\dagger}(x',\tau'))$

Electronic analogue of Glauber's correlators

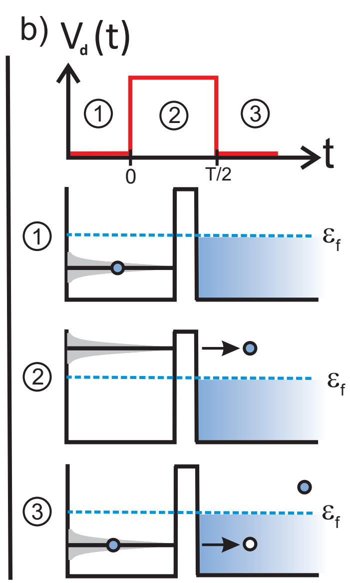
$$\mathcal{G}^{(1)}_{\rho}(x,t|x't') = \mathrm{Tr}(E^{+}(x,t)\,\rho\,E^{-}(x't'))$$

The Quantum Theory of Optical Coherence*

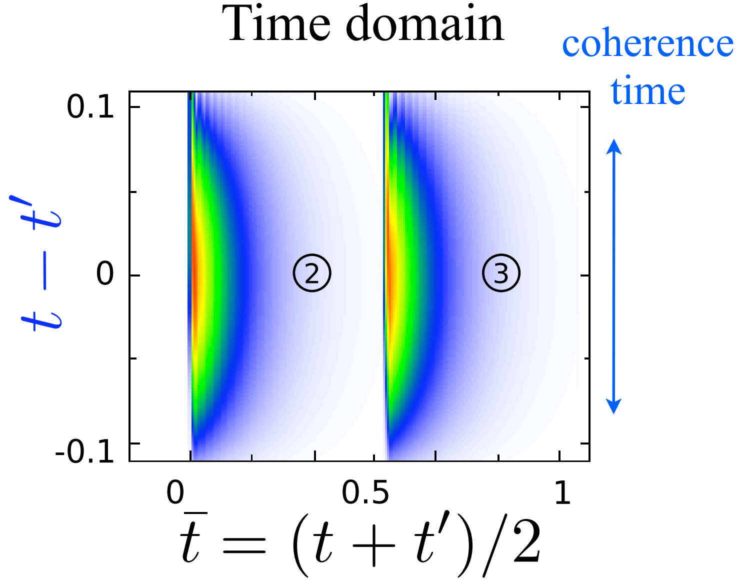
Roy J. Glauber
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts

(Received 11 February 1963)

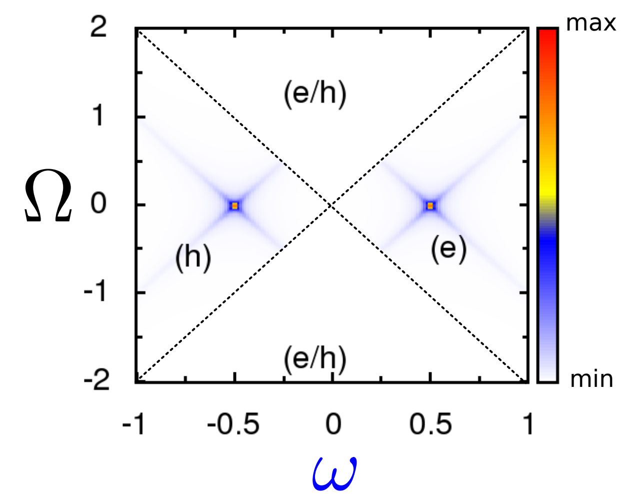
Phys. Rev. **130**, 2529 (1963)



Time domain



Frequency domain



Quantum vs classical signals

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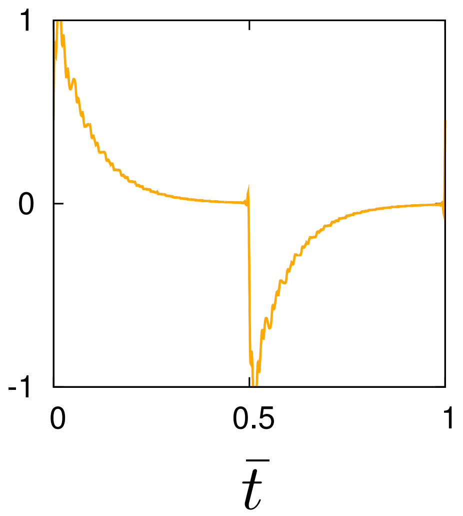
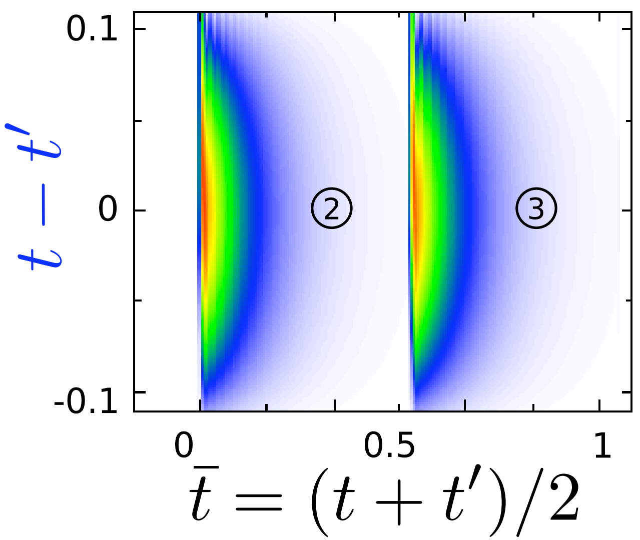
Classical signal	Quantum signal
$\langle i(t) \rangle$	$\lvert \Delta \mathcal{G}^{(e)}(t,t') \rvert$





Measured directly

How to measure it ?

Ch. Grenier *et al*, New Journal of Physics **13**, 093007 (2011)

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Measuring single electron coherence

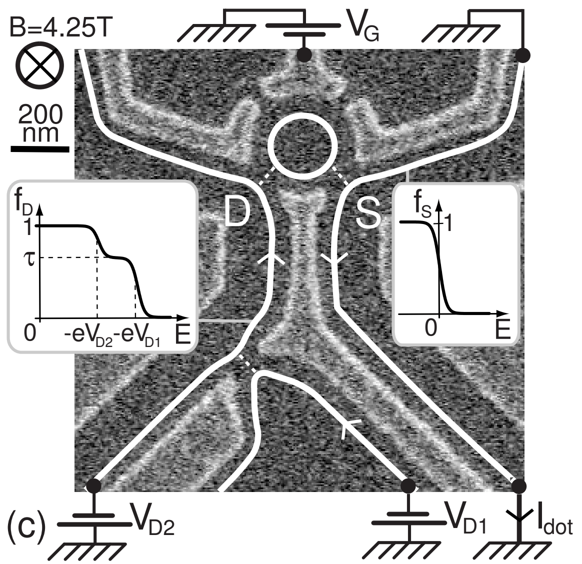
Single electron coherence: $\mathcal{G}^{(e)}_{\rho}(x,\tau|x',\tau') = \mathrm{Tr}(\psi(x,\tau)\rho\,\psi^{\dagger}(x',\tau'))$

First idea: spectroscopy experiment

$$\overline{I} = e\int (n_S - n_D)(\omega)\, g_d(\omega)\,\frac{d\omega}{2\pi}$$

$$n_D(\omega) = \int \overline{\mathcal{G}^{(e)}(x,t|x,t')}^{\bar{t}}\, e^{i\omega(t-t')} d(t-t')$$

$$\bar{t} = (t+t')/2$$



C. Altimiras *et al*, Nature Physics **6**, 34 (2010)

Only captures the stationary part: well suited to stationary sources...

Used to study relaxation of a non equilibrium energy distribution: Phys. Rev. B **81**, 121302(R) (2010)
Phys. Rev. Lett. **105**, 056803 (2010)
Phys. Rev. Lett. **105**, 226804 (2010)

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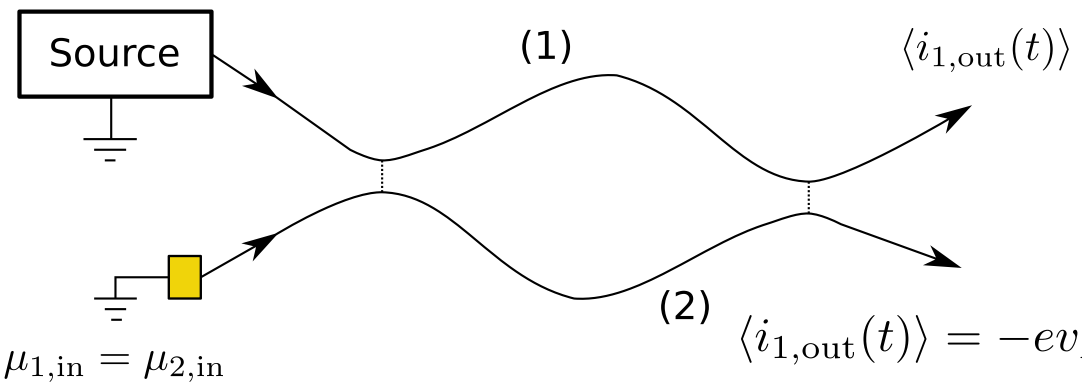
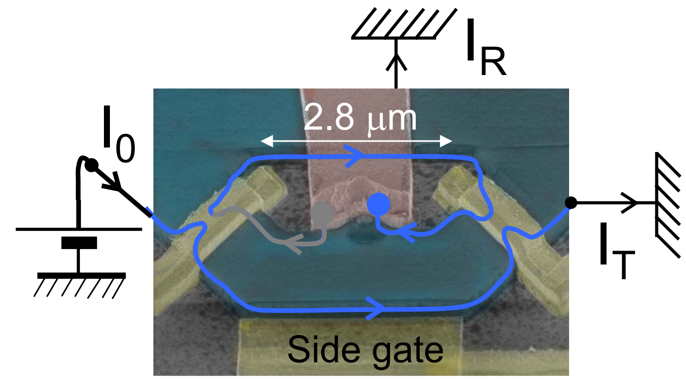
Second idea: Mach Zehnder interferometry





Courtesy P. Roche

$$\langle i_{1,\mathrm{out}}(t)\rangle = -ev_F\Delta\mathcal{G}^{(e)}_{1,\mathrm{out}}(t,t)$$

$$\Delta\mathcal{G}^{(e)}_{1,\mathrm{out}}(t,t') = \sum_{\alpha,\beta}\mathcal{A}_{\alpha,\beta}\,\Delta\mathcal{G}^{(e)}_{1,\mathrm{in}}(t-\tau_\alpha, t'-\tau_\beta)$$

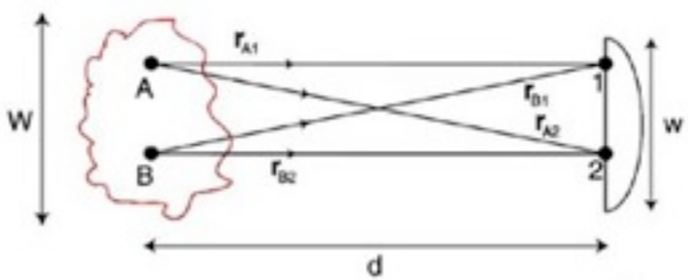
- Classical contributions $\alpha = \beta$
- Quantum contributions $\alpha \neq \beta$

Quantum contributions to $\langle i^{(dc)}_{1,\mathrm{out}}\rangle \simeq \mathcal{A}_{12}\overline{\Delta\mathcal{G}^{(e)}_{1,\mathrm{in}}(t-\tau_1,t-\tau_2)}^{t} + \mathcal{A}_{21}\overline{\Delta\mathcal{G}^{(e)}_{1,\mathrm{in}}(t-\tau_2,t-\tau_1)}^{t}$

G. Haack *et al*, Phys. Rev. B **84**, 081303(R) (2011)

Relies on a simple measurement but decoherence within the MZI may be a problem!

Our idea: HBT interferometry

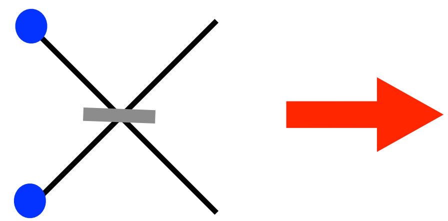


$$P = |\psi_A e^{i\phi_{A1}} \psi_B e^{i\phi_{B2}} \pm \psi_A e^{i\phi_{A2}} \psi_B e^{i\phi_{B1}}|^2$$

Nature **178**, 1046 (1956)

Two particle interference interpretation

U. Fano, Am. J. Phys. **29**, 539 (1961)



(2,0)

(1,1)

(0,2)

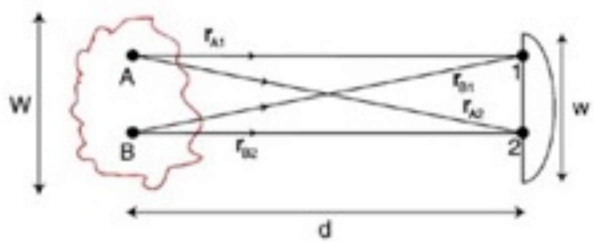
Classical	Bosons	Fermions
(0,2) (1,1) (2,0)	(0,2) (2,0)	(1,1)

HBT effect with electrons:

Liu *et al*, Nature **391**, 263 (1998)
Henny *et al*, Science **284**, 396 (1999)
Oliver *et al*, Science **284**, 299 (1999)

Homodyne tomography

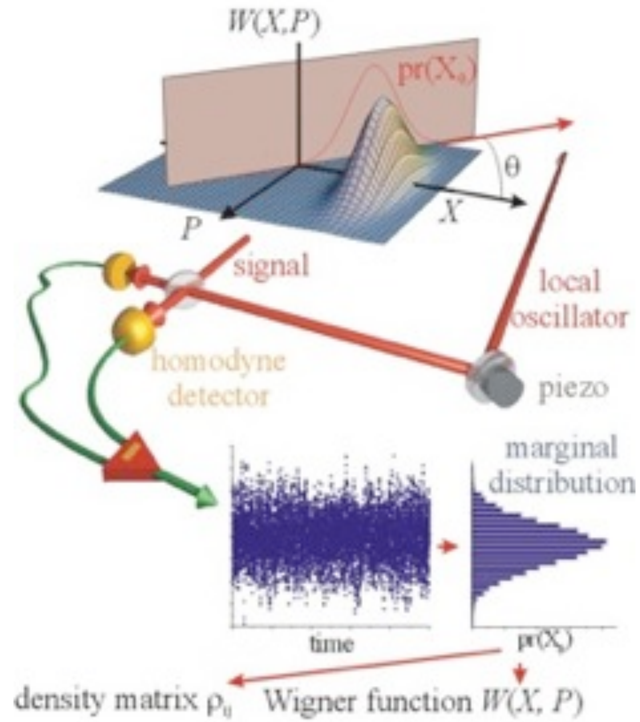
From stellar diameter measurements...



$$P = |\psi_A e^{i\phi_{A1}}\psi_B e^{i\phi_{B2}} \pm \psi_A e^{i\phi_{A2}}\psi_B e^{i\phi_{B1}}|^2$$

Nature **178**, 1046 (1956)

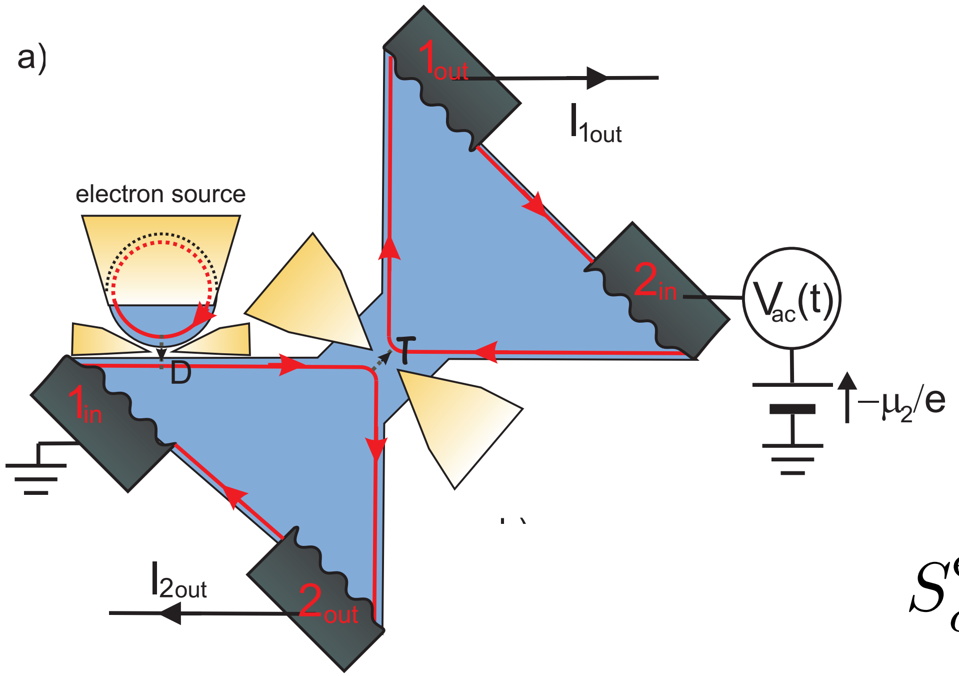
to quantum tomography in quantum optics!



Smithey *et al*, Phys. Rev. Lett. **70**, 1244 (1993)

Lvovsky & Raymer, Rev. Mod. Phys. **81**, 299 (2009)

Homodyne tomography



Input: two sources

Beam splitter: QPC with

$$G = (e^2/h)\mathcal{T}$$

What can we measure ?

$$S^{\text{exp}}_{\alpha\beta} = 2\int \overline{S^{\text{out}}_{\alpha,\beta}(\bar{t}+\tau/2,\bar{t}-\tau/2)}^{\bar{t}}\, d\tau$$

$$S^{\text{out}}_{11} = \mathcal{T}^2 S^{\text{in}}_{11} + \mathcal{R}^2 S^{\text{in}}_{22} + \mathcal{R}\mathcal{T}\mathcal{Q}_0$$

Classical terms (partitioning)

Quantum terms (HBT & HOM)

$$\mathcal{Q}_0 = (ev_F)^2 \int \overline{(\mathcal{G}^{(e)}_1\mathcal{G}^{(h)}_2 + \mathcal{G}^{(h)}_1\mathcal{G}^{(e)}_2)(t,t')}^{\bar{t}}\, d(t-t')$$

Overlap between single particle coherences!

Comparing sources through HBT correlations: see Moskalets and Büttiker, Phys. Rev. B **83**, 035316 (2011)

What will we reconstruct ?

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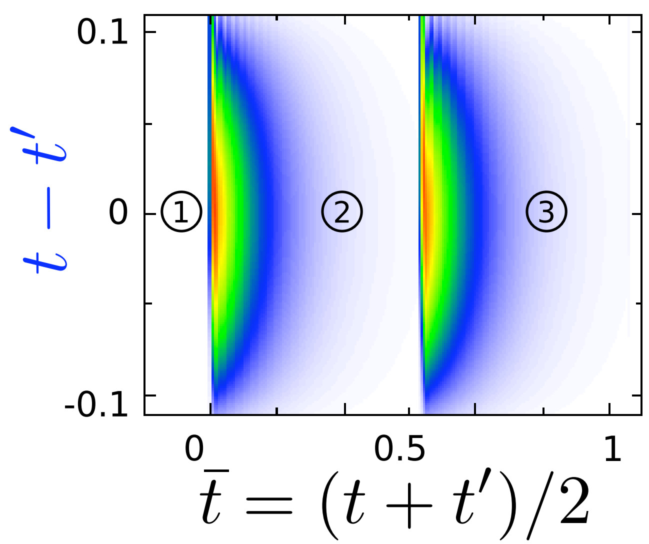
$$\mathcal{G}^{(e)}(t,t') = \mathcal{G}^{(e)}_F(t-t') + \Delta\mathcal{G}^{(e)}(t,t')$$

Fermi sea | Source contribution

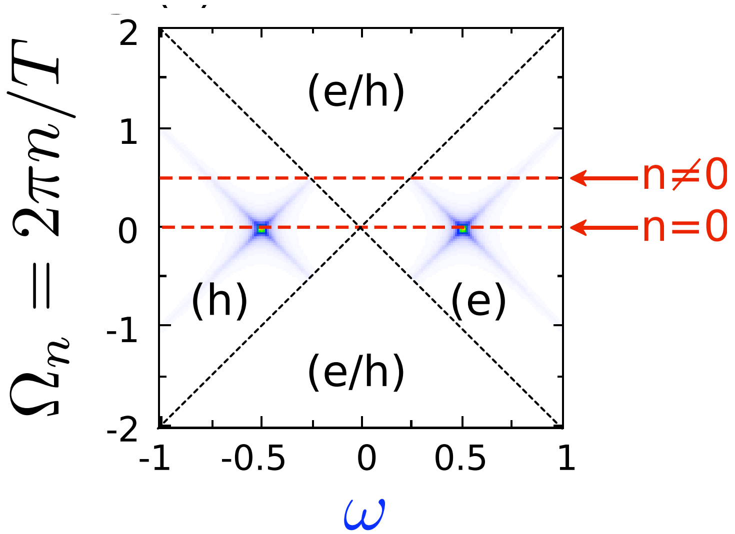
Time domain

$$|\Delta\mathcal{G}^{(e)}(t,t')|$$



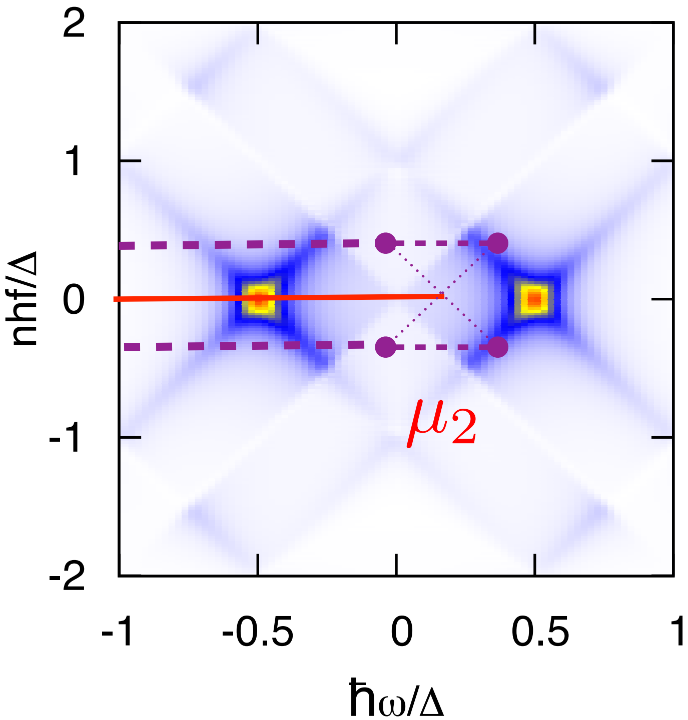
Frequency domain

$$|\Delta\mathcal{G}^{(e)}_n(\omega)|$$



$$\Delta\mathcal{G}^{(e)}(t,t') = \sum_{n\in\mathbb{Z}} e^{-2\pi i n\,\bar{t}/T} \int \Delta\mathcal{G}_n(\omega) e^{-i\omega(t-t')}\,\frac{d\omega}{2\pi}$$

Homodyne tomography



DC bias: $V_{\mathrm{dc}} = -\mu_2/e$

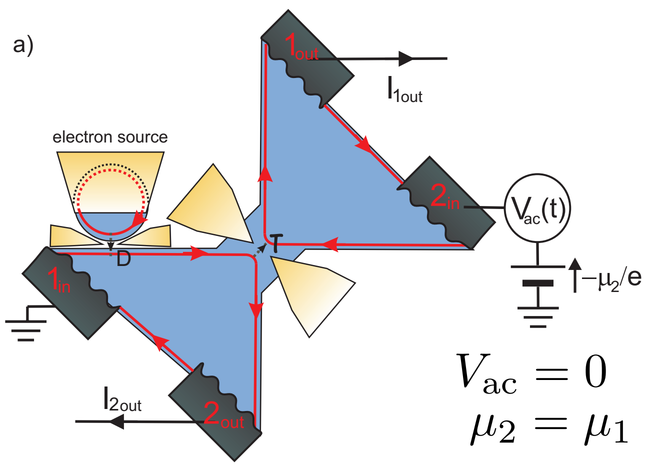
AC drive: $V_{\mathrm{ac}}(t) = V\cos\left(2\pi n f t + \phi\right)$

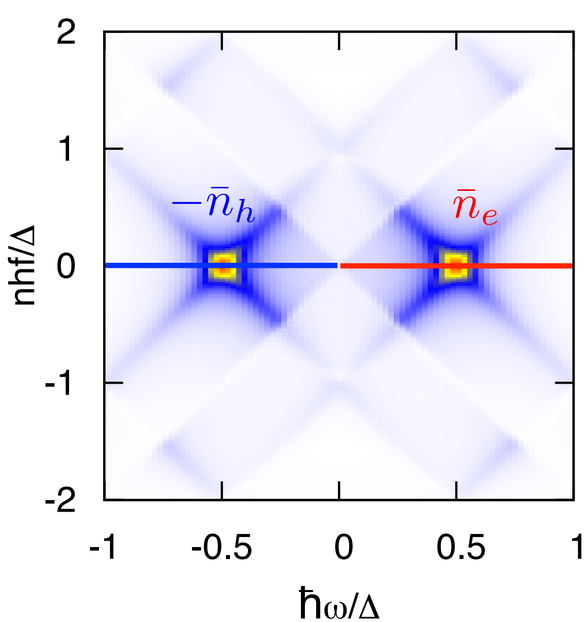
Current noise *vs* DC bias: $\Delta\mathcal{G}^{(e)}_{n=0}(\omega)$

Current noise response to AC drive: $\Delta\mathcal{G}^{(e)}_{n\neq 0}(\omega)$

«*The noise is the signal* » (R. Landauer 1998)

Counting electrons and holes





No AC drive, no DC bias:

$$\Delta\mathcal{Q}_0 = e^2 \int \tanh\left(\frac{\hbar\omega}{2k_BT_2}\right) v_F \Delta\mathcal{G}^{(e)}_{1,0}(\omega)\frac{d\omega}{2\pi}$$

Known source

Source to be characterized

Vanishing temperature ($T_2 = 0$ K)

$$\Delta\mathcal{Q}_0(\mu_2 = 0) = e^2 f\,(\bar{n}_e + \bar{n}_h)$$

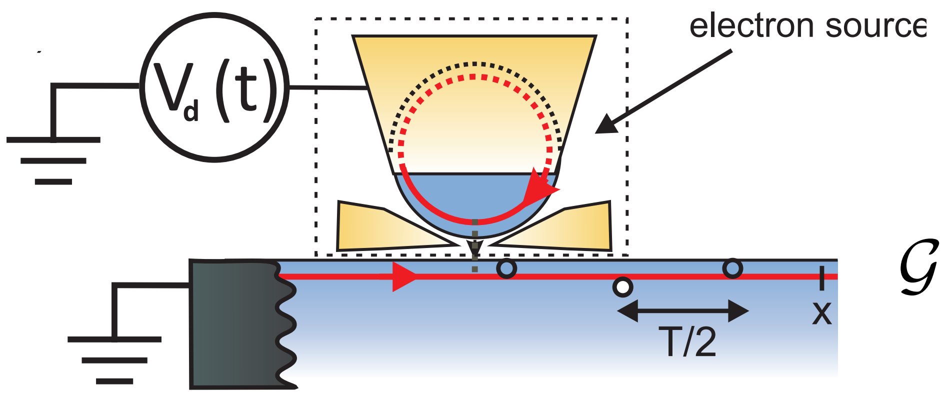
$\bar{n}_{e/h}$ = # of electron (resp. hole) excitations per period

Non zero temperature

Excitations below k_BT_2 antibunch with thermal excitations from the reservoir #2.

See E. Bocquillon's talk!

The single electron source



Controls: QPC transparency D

Driving frequency $f = T^{-1}$

Drive amplitude V_d

$2eV_d = \Delta$ (level spacing)

$$\mathcal{G}^{(e)}(t,t') = ?$$

Modeling the source

Floquet scattering approach

Büttiker & Moskalets,
Phys. Rev. B **66**, 205320 (2002)
Phys. Rev. Lett. **100**, 086601 (2008)

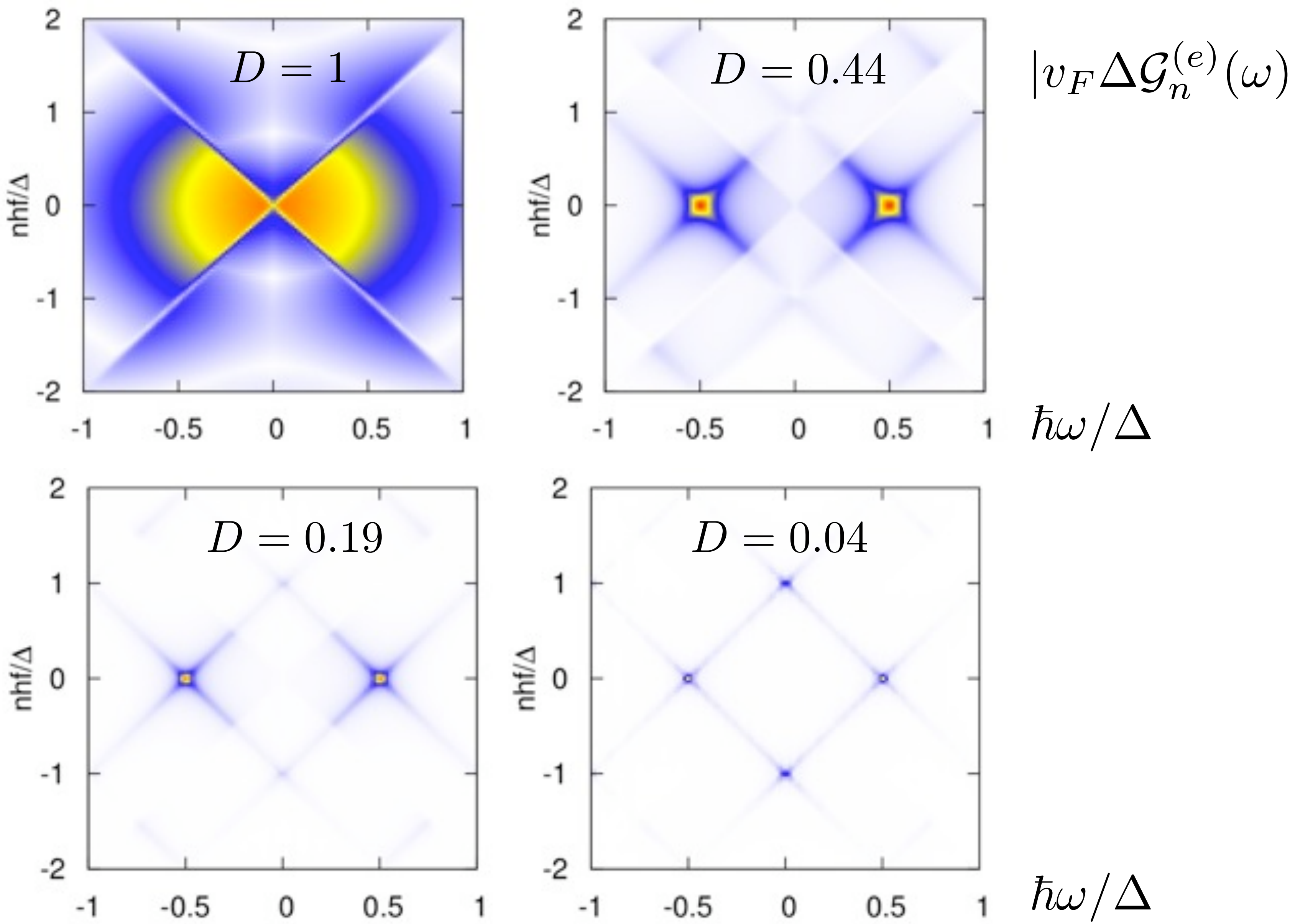
Neglects interactions within the dot (experimentally OK)

Evaluation of $\Delta\mathcal{G}_n^{(e)}(\omega)$ and of the excess HBT contribution of the source to the noise (*expected experimental signal*)

Single electron coherence

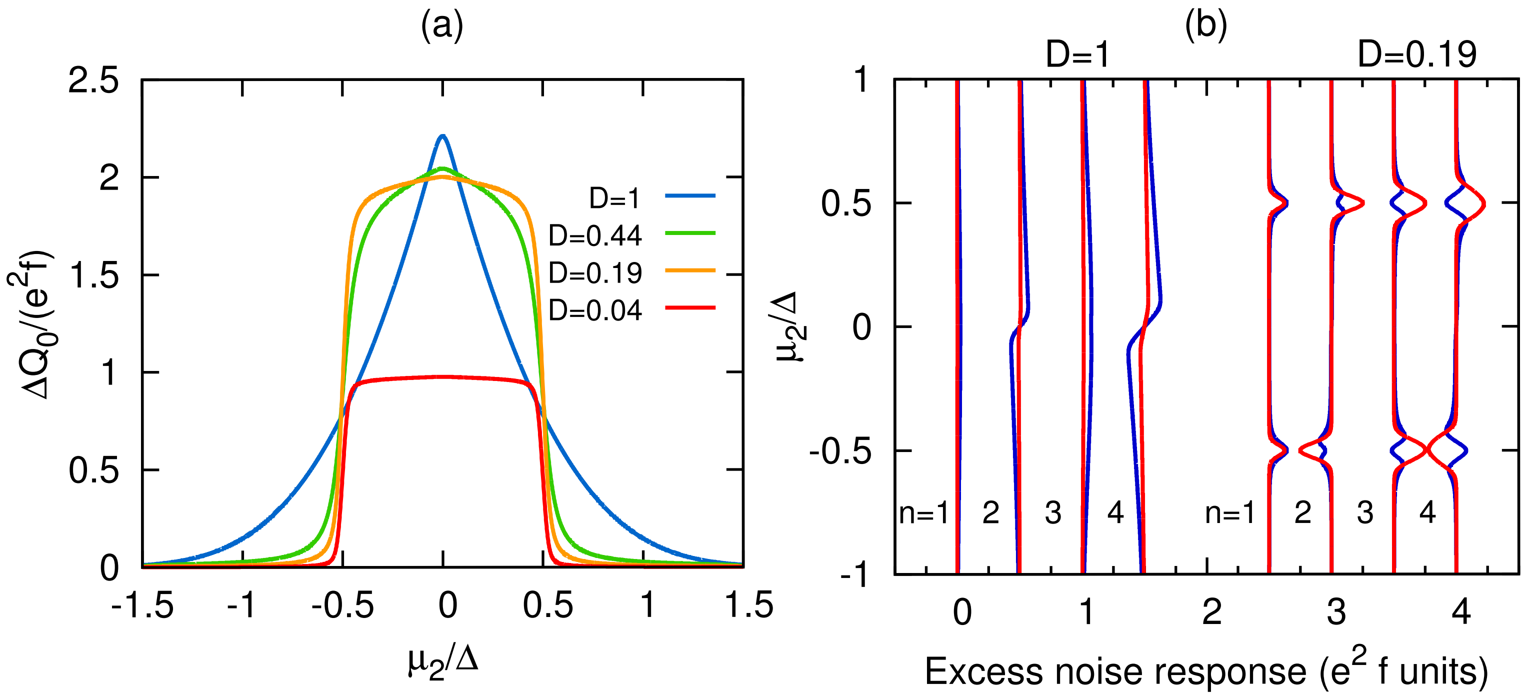
$f = 3$ GHz

$T_{\mathrm{el}} = 40$ mK



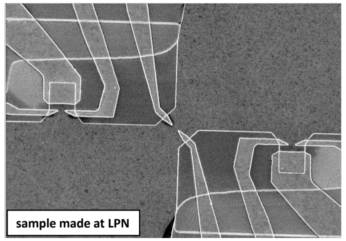
Expected experimental signals

$f = 3$ GHz $\qquad T_{\mathrm{el}} = 40$ mK



Exp. requirement: sensitivity $\simeq 0.05 \times e^2 f = 4 \times 10^{-30}\ \mathrm{A}^2/\mathrm{Hz}$

Ongoing experimental effort at ENS Paris:
see Erwann Bocquillon's talk!



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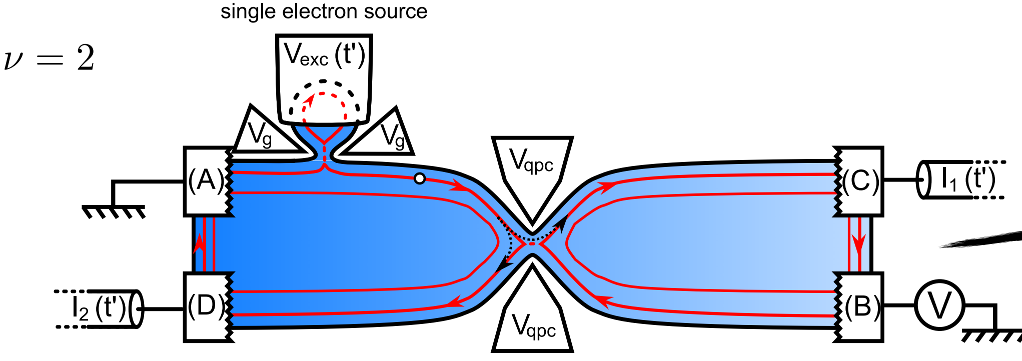
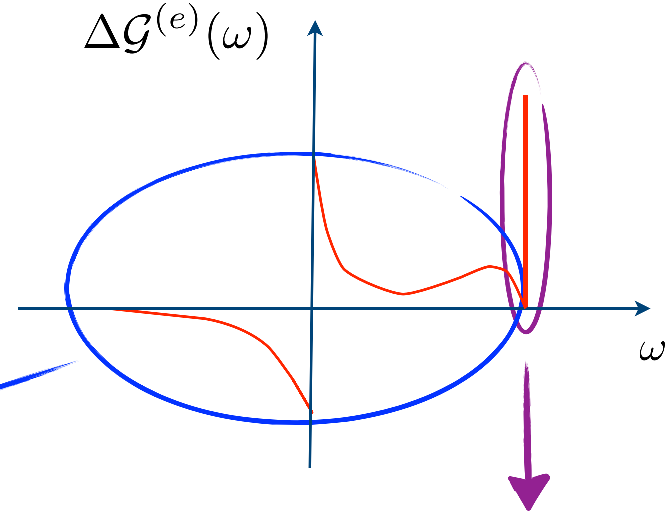
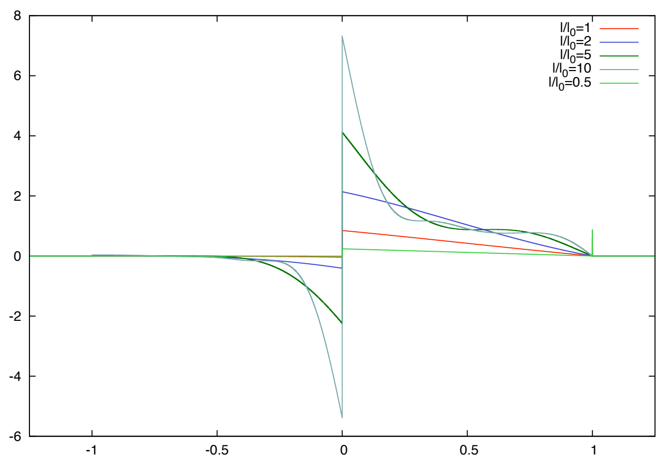
Quasiparticle relaxation

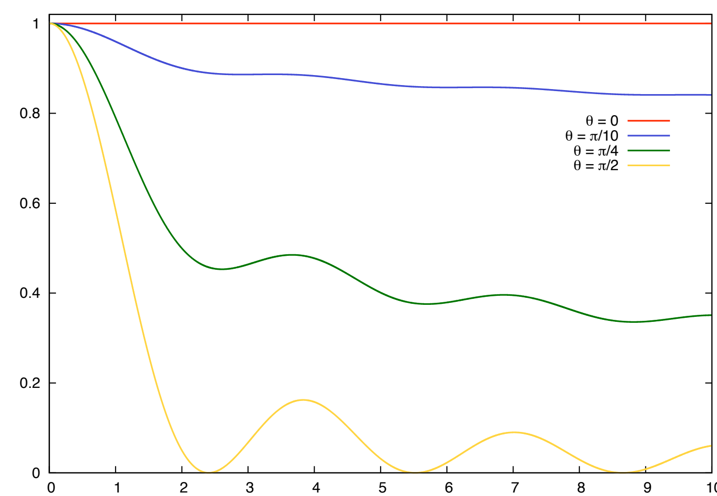






Characteristic decaying length $l(\varepsilon_0) \sim \hbar v/\varepsilon_0$

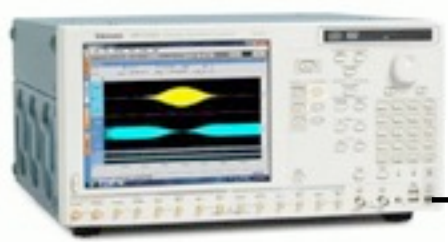
No well defined quasi particle!



P. Degiovanni, Ch. Grenier, G. Fève, Phys. Rev. B **80**, 241307(R) (2009)

Fractionalization of Lorentzian pulses

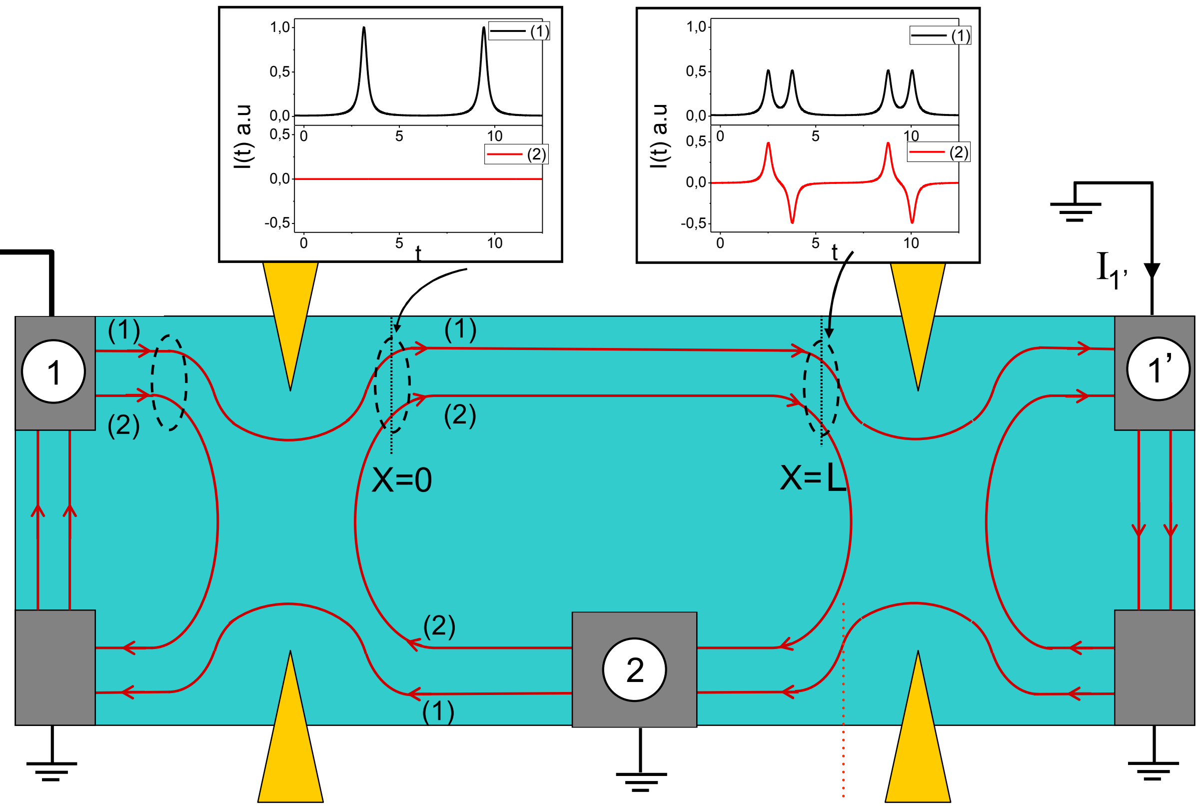
Lorentzian voltage pulse



Periodic train of quantized pulses

$$\int eV_d(t)\,dt = h$$

Ch. Glattli, *ERC project*



Stroboscopic coherence revivals: dispersionless magnetoplasmon eigenmodes

Fractionalization: e/h pair production *vs* charge...

Ch. Grenier, G. Fève et P. Degiovanni, *in preparation*

Conclusion…

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Electron quantum optics

Coherence properties of the single electron source

Single electron quantum tomography protocol

New Journal of Physics **13**, 093007 (2011)

Plasmon scattering role in electric and energy transport along chiral edges

Applications to energy relaxation in edge channels at $\nu=2$.

Phys. Rev. B **81**, 121302(R) (2010)

Non perturbative solution to the Laudau problem in chiral edge channels (*relaxation of a single electron excitation above the Fermi level*).

Phys. Rev. B **80**, 241307(R) (2009)

Quantum detection of electronic flying qubits

Phys. Rev. B **77**, 035308 (2008)

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Case of $n=0$ harmonics

Control parameters: μ_2 (DC bias)

$$\frac{\partial(\Delta\mathcal{Q}_0)}{\partial\mu_2}[\omega=0,\mu_2,V_{\rm ac}(t)=0]=-\frac{2e^2}{h}\,v_F\Delta\mathcal{G}^{(e)}_{1,n=0}(\mu_2/\hbar)$$

Higher harmonics

Control parameters: μ_2 and ϕ, the phase of the AC drive $V_{\rm ac}(t)=V\cos{(2\pi nft+\phi)}$

Susceptibility: $$\bar{\chi}_n(\mu_2,\phi)=\left(\frac{\partial(\Delta\mathcal{Q}_0)}{\partial(eV/nhf)}\right)_{\omega=0,V=0}$$

$$\frac{\partial\bar{\chi}_n}{\partial\mu_2}(\mu_2,\phi)=\frac{e^2}{h}\,\Re\Big[e^{i\phi}\left(v_F\Delta\mathcal{G}^{(e)}_{1,n}(\frac{\mu_2}{\hbar}+\pi nf)-v_F\Delta\mathcal{G}^{(e)}_{1,n}(\frac{\mu_2}{\hbar}-\pi nf)\right)\Big]$$