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LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

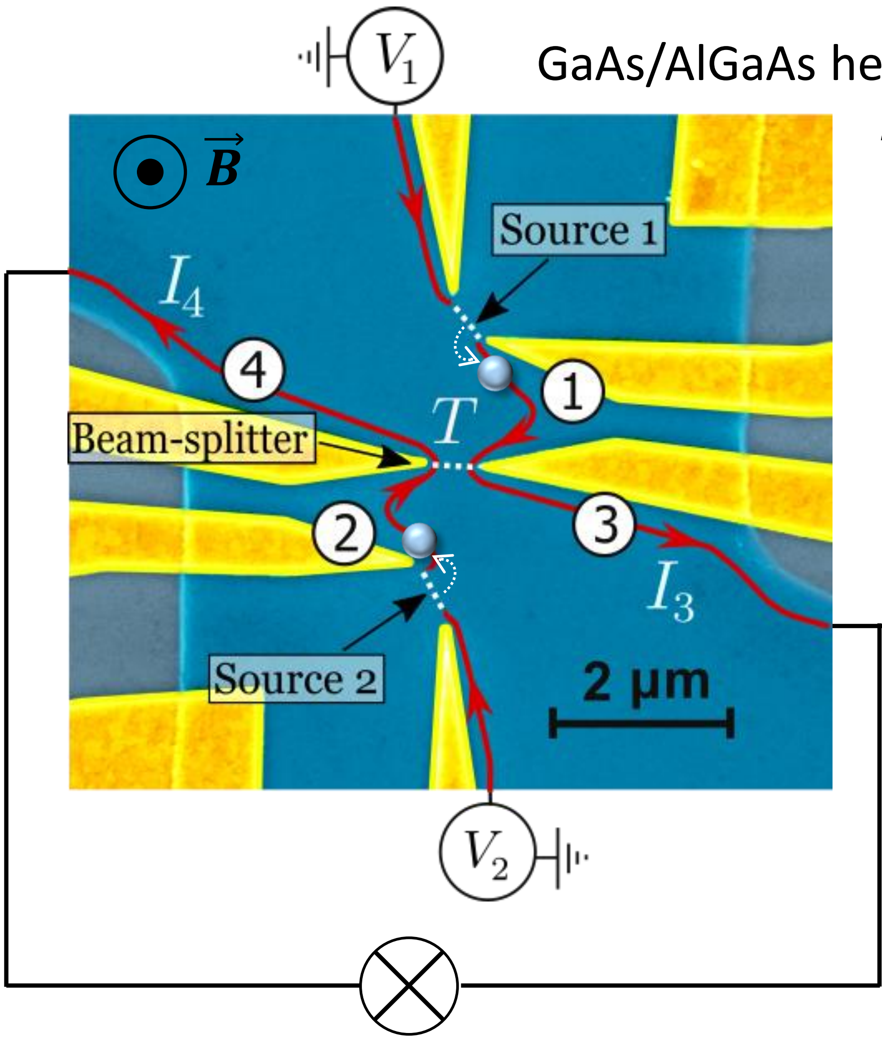
Noise measurements for the characterization of anyons in the fractional quantum Hall effect (1)

G. Fève, Laboratoire de Physique de l'ENS

Electron optics experiments in quantum Hall conductors

GaAs/AlGaAs heterostructure

$T_{el} = 30mK$



Current correlations $\langle I_3 I_4 \rangle$

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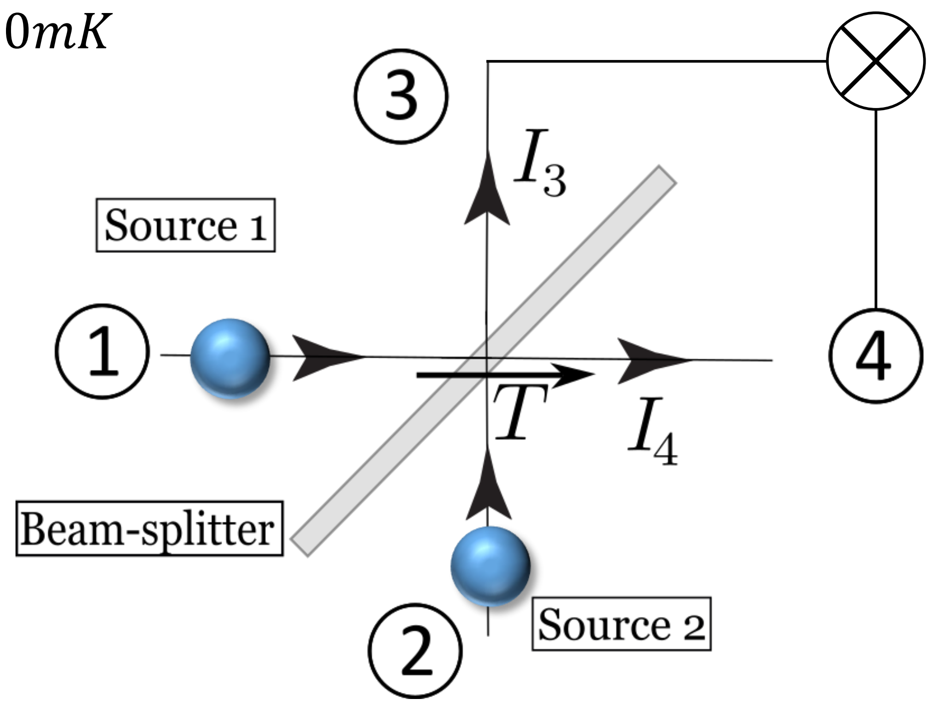
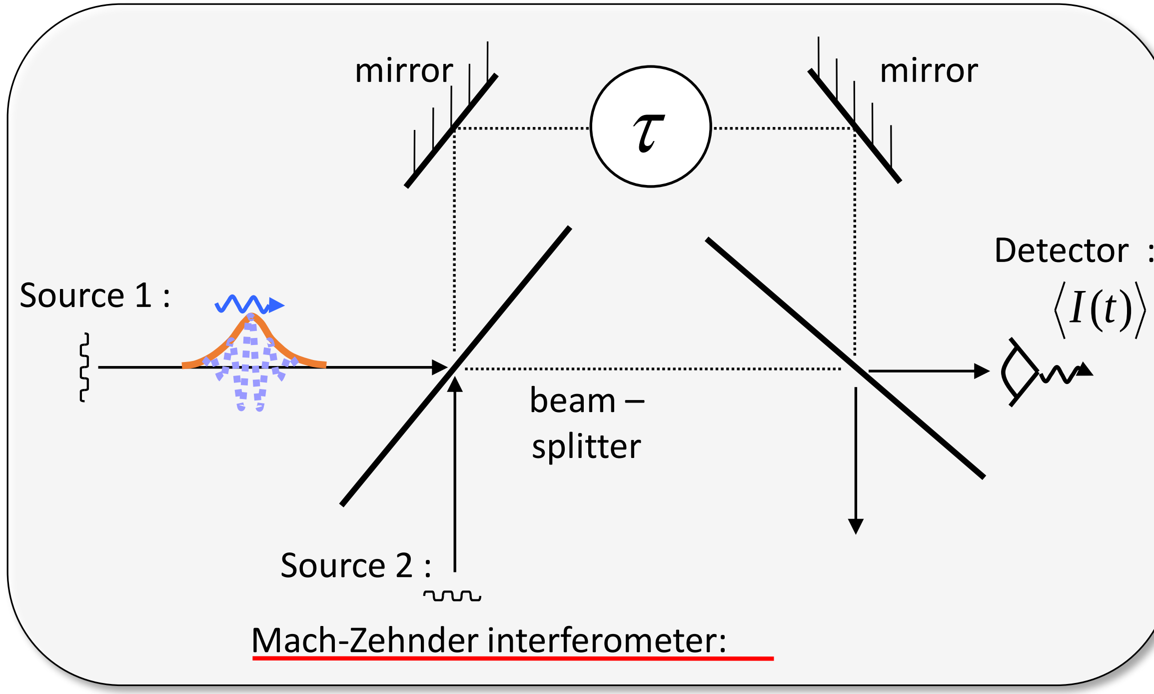


Single-particle vs two-particle interferometry

Optics: $\begin{cases} E(t) & \text{Electric field} \\ I(t) & \text{light intensity} \end{cases}$



Single particle interferometer

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

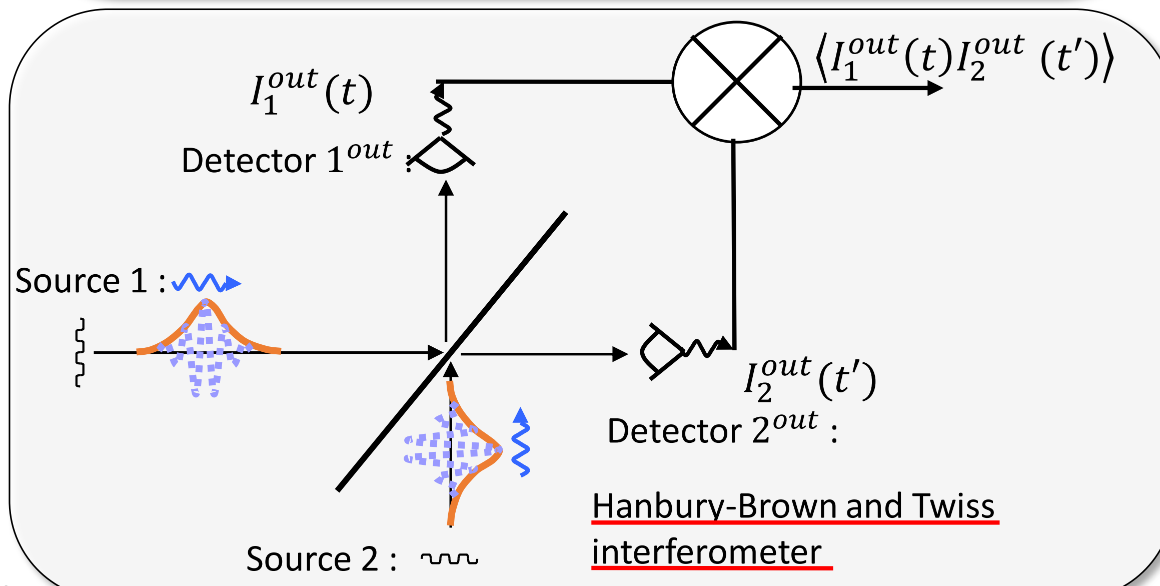
Coherence of electric field

Two-particle interferometer

$$\langle I_1^{out}(t) I_2^{out}(t') \rangle$$

$$\propto \langle E_1^{in}(t) E_1^{in}(t') \rangle \langle E_2^{in}(t) E_2^{in}(t') \rangle$$

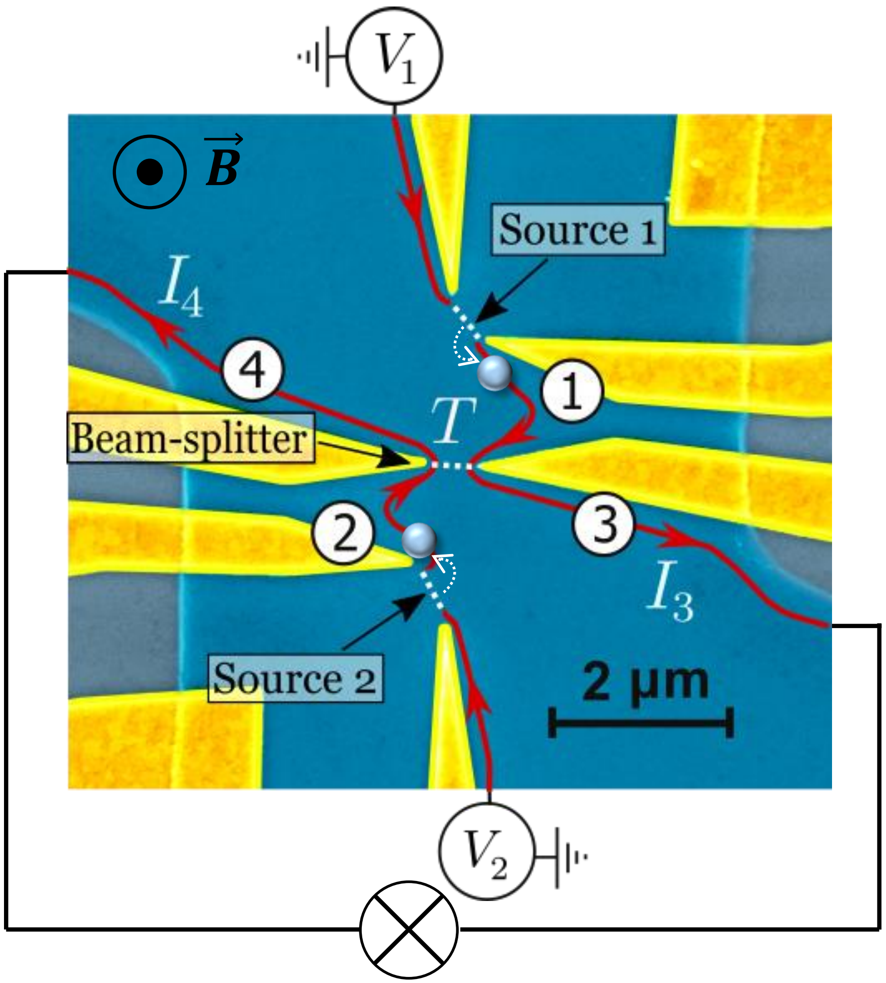
Product of coherences
HBT interferometry



Electronics: $\begin{cases} \psi(t) & \text{Fermion field} \\ I(t) & \text{Electrical current} \end{cases}$

Single and two particle interferometers in quantum Hall conductors

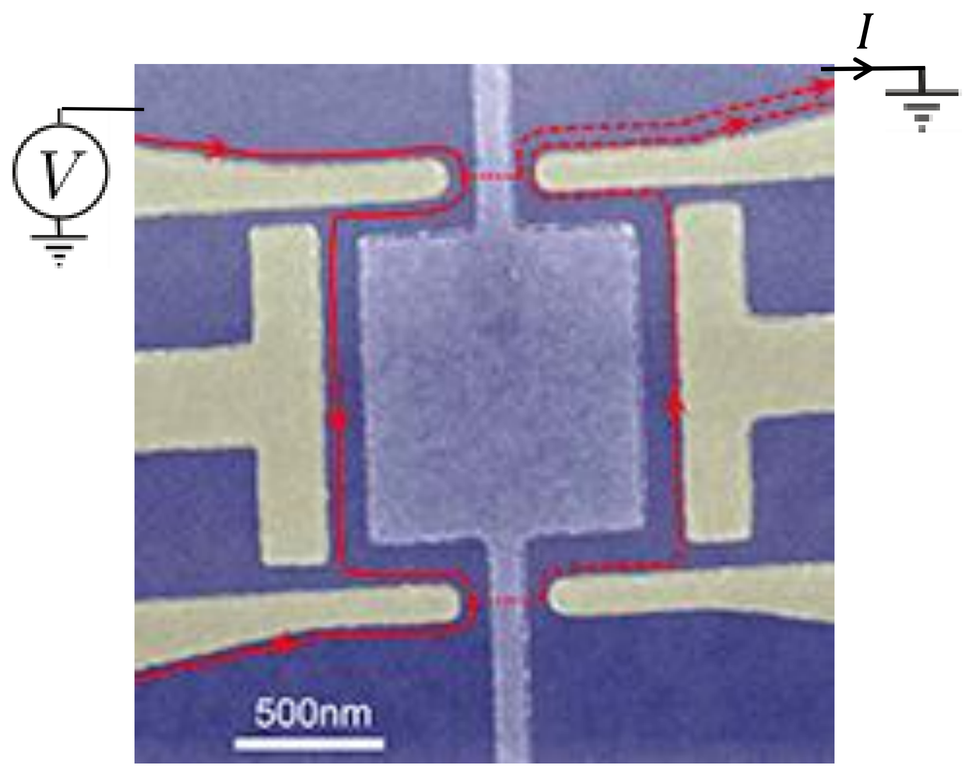
Electron optics experiments in quantum Hall conductors



Current correlations $\langle \delta I_3(t) \delta I_4(t') \rangle$

Two-particle interferometry

H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)



Electrical current $\langle I\ (t)\ \rangle$

Single-particle interferometry

J. Nakamura, S. Liang, G.C. Gardner, M.J. Manfra, Nature Physics **16** 931 (2020).

Outline

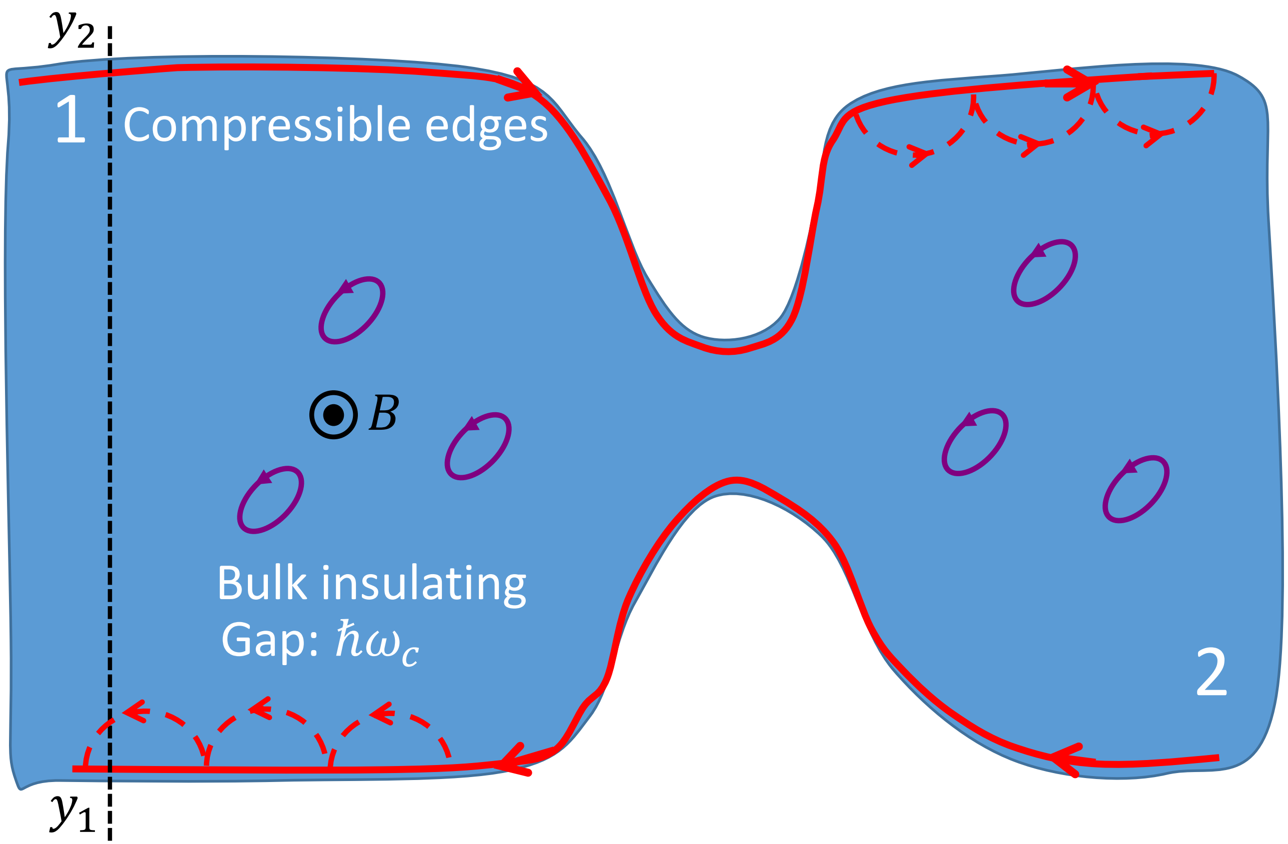
Course 1: Noise and fractional charge

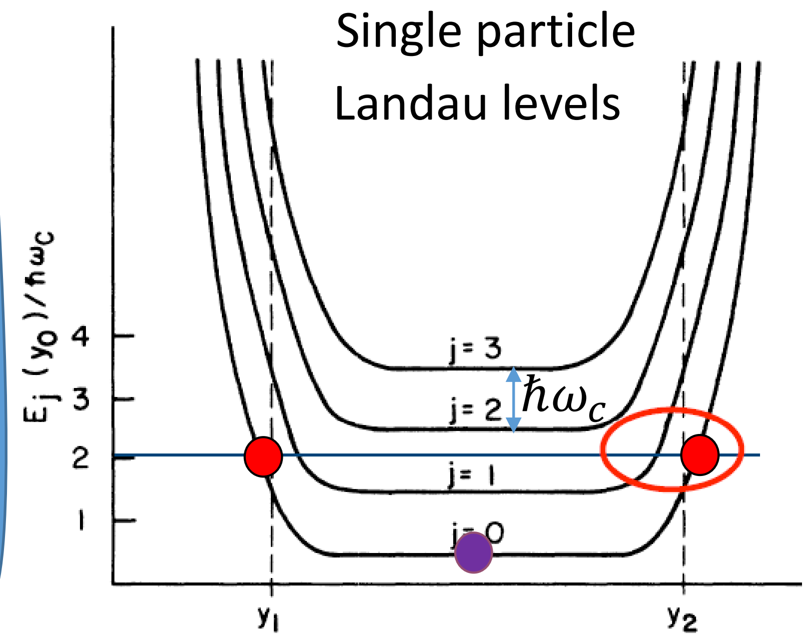
- 1) Electron optics toolbox
- 2) Two particle interferometry, noise and tunneling rates
- 3) Voltage biased quantum point contact: electron and anyon charges

Course 2: noise and fractional statistics

- 1) Electronic/Photonic Hong-Ou-Mandel experiments
- 2) Collider: fermion case
- 3) Collider: anyon case

Integer quantum Hall effect: insulating bulk and transport at the edges





Filling factor: ν (integer) filled Landau levels $\nu = \frac{N_e}{N_s} = \frac{N_e}{\phi/\phi_0} = \frac{N_e}{BSe/h}$ ↘ when B ↗

Protection from backscattering

ν 1D wires carrying the current without backscattering $I = \nu \frac{e^2}{h} V$

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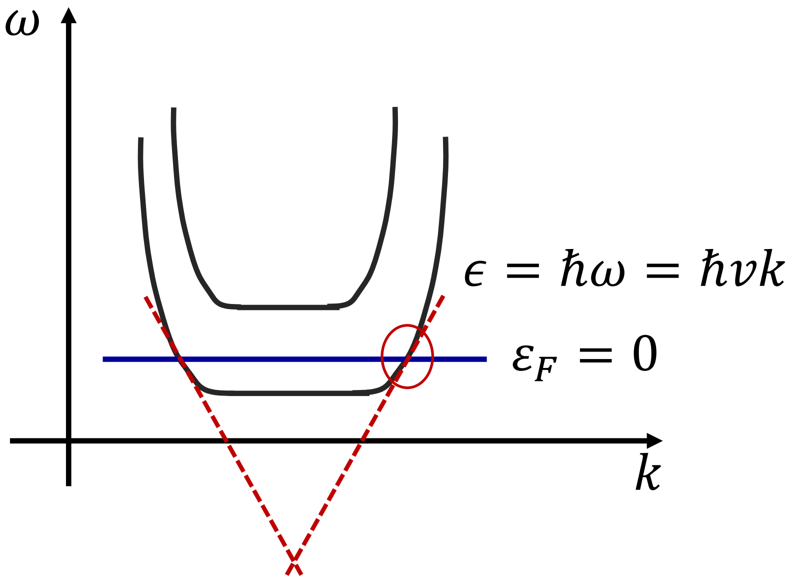
Electron optics toolbox (Integer case)
Fermion field

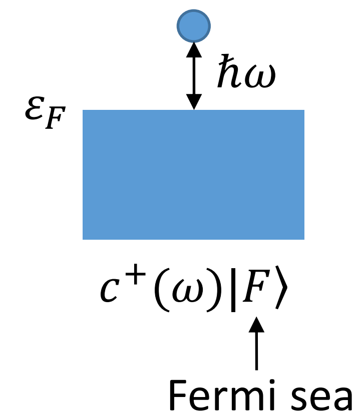
Linearization of energy spectrum



- Creation/annihilation operator:

$$\{c(\omega), c^+(\omega')\} = \delta(\omega - \omega')$$

$$H = \int d\omega\ \hbar\omega\ c^+(\omega)c(\omega)$$



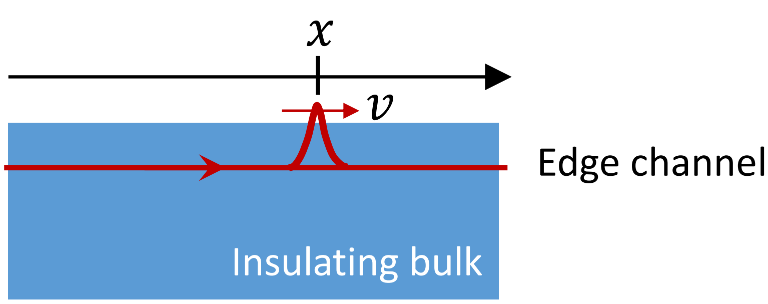
- Fermion field operator

$$\psi(x) = \int \frac{d\omega}{\sqrt{2\pi v}}\ e^{i\omega x/v}\ c(\omega)$$

$$\{\psi(x), \psi^+(x')\} = \delta(x - x')$$

- Dynamics of the field: Chiral propagation

$$\psi(x,t) = \int \frac{d\omega}{\sqrt{2\pi v}}\ e^{i\omega(\frac{x}{v} - t)}\ c(\omega) = \psi(x - vt)$$



- Current $\frac{\partial\rho}{\partial t} + \frac{\partial I}{\partial x} = 0$ ⇒ $\mathrm{I}(x,t) = -ev\psi^+(x,t)\psi\ (x,t)$

In the following
$v = 1$

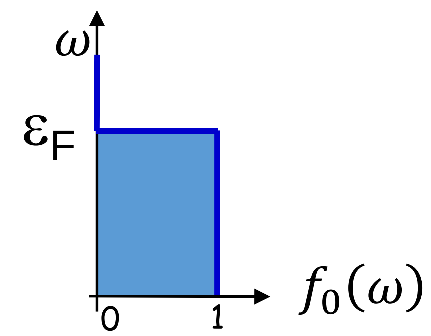
Electron optics toolbox (Integer case)
First order coherence, equilibrium

- First order coherence/ correlation function of the field

$$G(t,t') = \langle \psi^{+}(x,t)\psi(x,t')\rangle$$

G. Haack et al., Phys. Rev. B **84**, 081303 (2011).
C. Grenier et al., New J. Phys. **13**, 093007 (2011)

Equilibrium correlation function: Fermi sea :



$$G_{eq}(t-t') = \langle F|\psi^{+}(t)\psi(t')|F\rangle \neq 0$$

$$G_{eq}(t-t') = \int \frac{d\omega}{2\pi} f_0(\omega) e^{i\omega[t-t'-i\tau_c]} = \frac{i/(2\tau_{th})}{\sinh\left[i\frac{\pi\tau_c}{\tau_{th}} - \frac{\pi(t-t')}{\tau_{th}}\right]}$$

$$\tau_{th} = \frac{\hbar}{k_B T_{el}}$$

$$T_{el} = 25mK$$

$$\tau_{th} \approx 300ps$$

$$t-t' \ll \tau_{th}, G_{eq} \approx \frac{1}{2i\pi(t-t'-i\tau_c)}$$

$$t-t' \gg \tau_{th}, G_{eq} \approx e^{-\frac{\pi(t-t')}{\tau_{th}}}$$

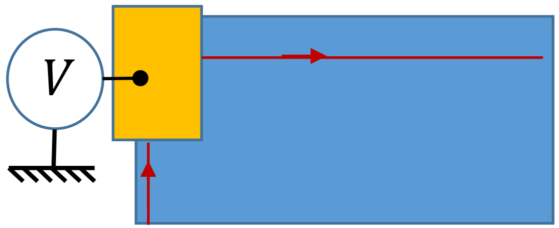
Electron optics toolbox (IQHE)
First order coherence, DC bias

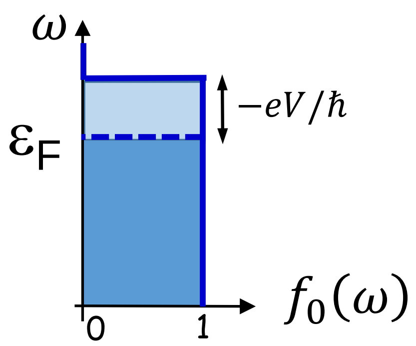
- First order coherence/ correlation function of the field

$$G(t,t') = \langle \psi^+(t)\psi(t')\rangle$$

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

C. Grenier et al., New J. Phys. **13**, 093007 (2011)





$$G_V(t-t') = \int \frac{d\omega}{2\pi} f_0(\omega + eV/\hbar) e^{i\omega[t-t'-i\tau_c]} = e^{-i\frac{eV(t-t')}{\hbar}} G_{eq}(t-t')$$

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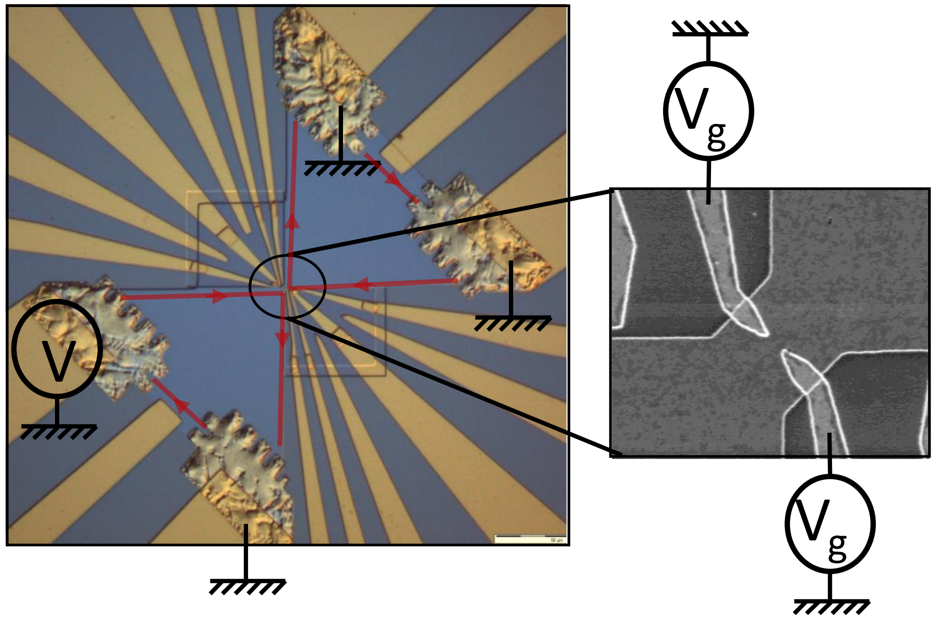
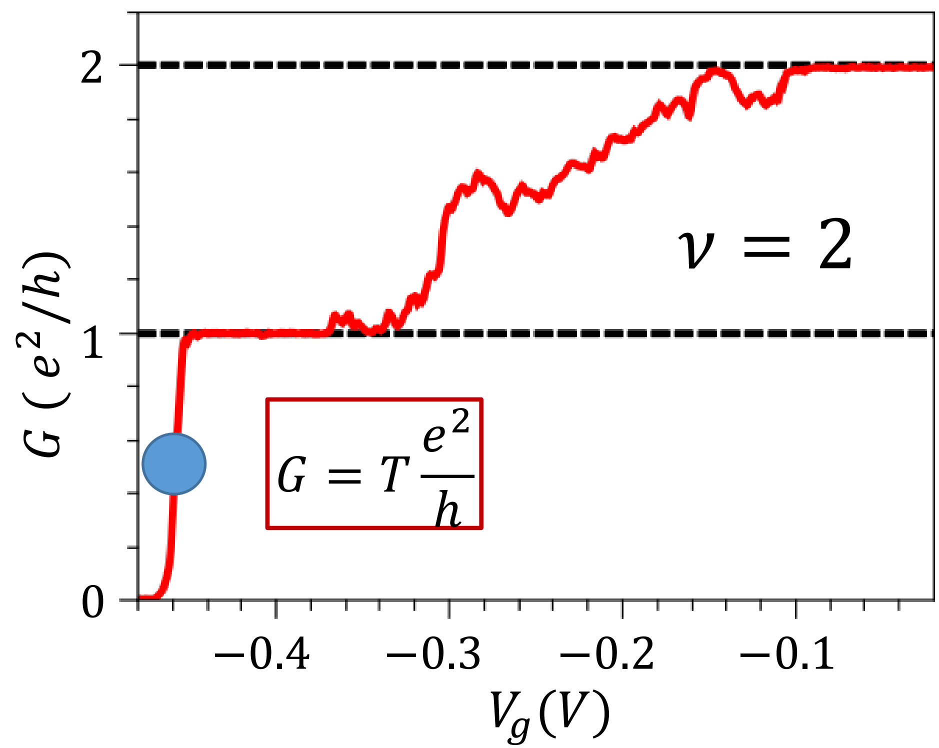
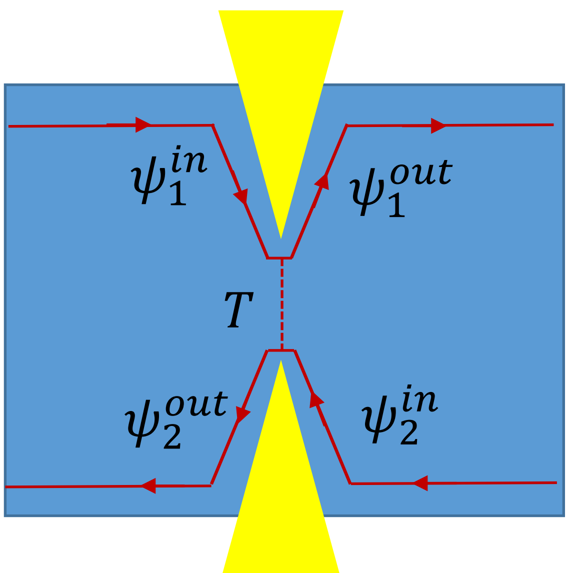
Electron optics toolbox (IQHE)
The quantum point contact (QPC)





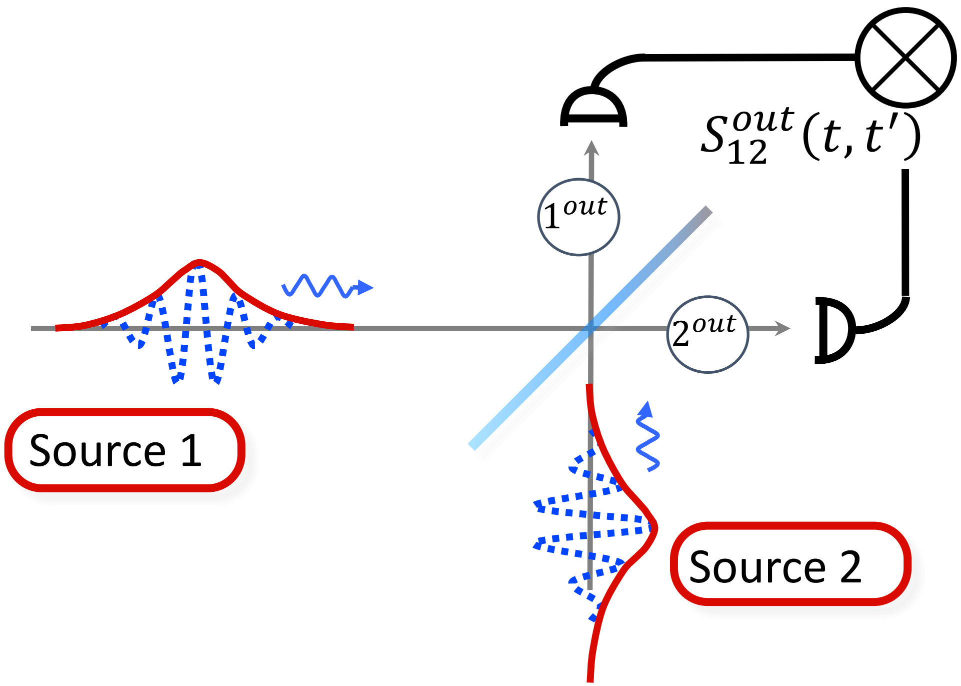


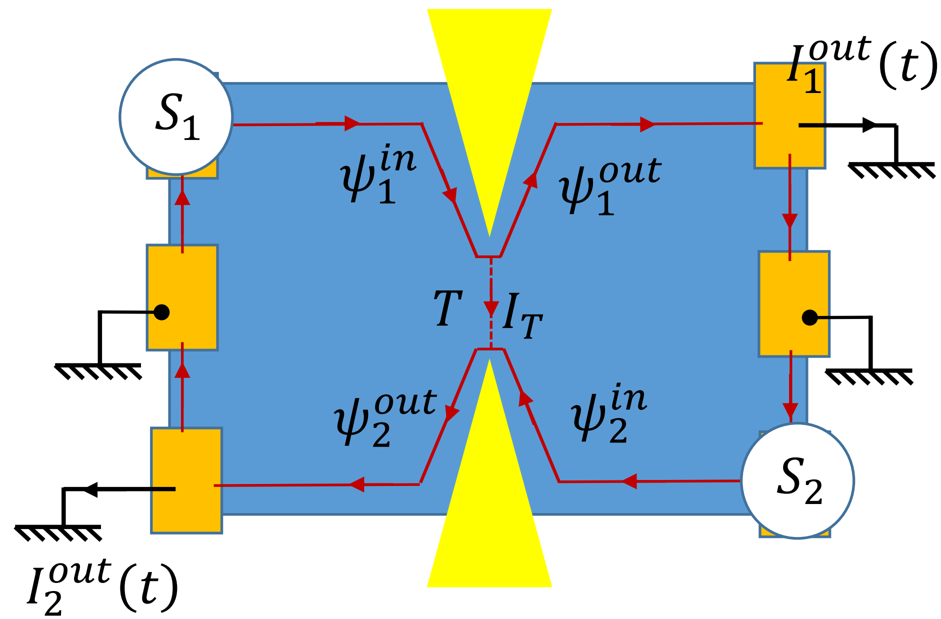
$$\begin{pmatrix} \psi_1^{out} \\ \psi_2^{out} \end{pmatrix} = \underbrace{\begin{pmatrix} r & it \\ it & r \end{pmatrix}}_{S} \begin{pmatrix} \psi_1^{in} \\ \psi_2^{in} \end{pmatrix}$$

Scattering matrix

$T = |it|^2$: tunneling probability

The electronic Hanbury Brown and Twiss experiment





$$S_{12}^{out}(t,t') = \langle \delta I_1^{out}(t) \delta I_2^{out}(t') \rangle = \langle I_1^{out}(t) I_2^{out}(t') \rangle - \langle I_1^{out}(t) \rangle \langle I_2^{out}(t') \rangle$$

$$I_1^{out}(t) = -e \psi_1^{+,out}(t) \psi_1^{out}(t)$$

$$I_2^{out}(t') = -e \psi_2^{+,out}(t') \psi_2^{out}(t')$$

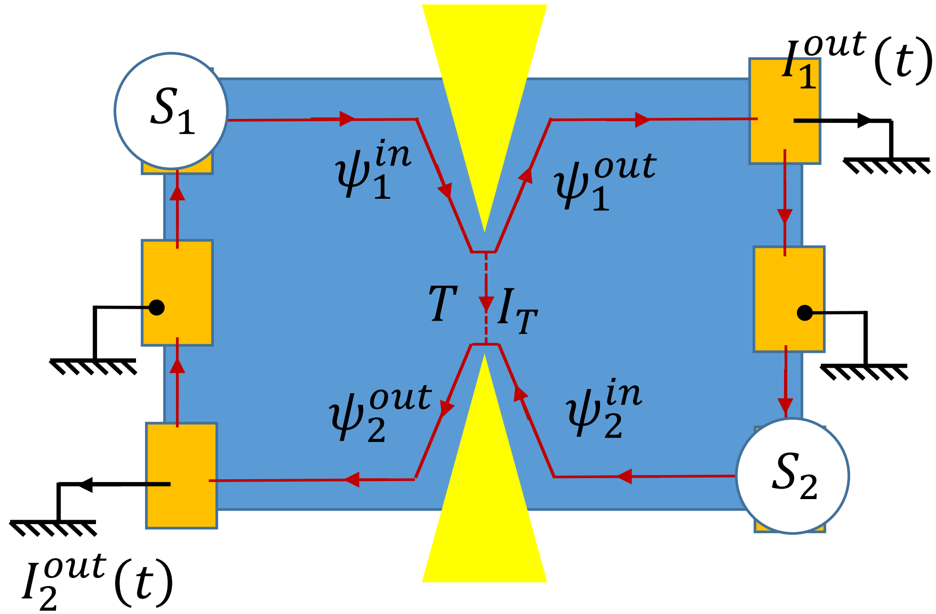
$$\frac{S_{12}^{out}(t,t')}{e^2} = \langle \psi_1^{+,out}(t) \psi_1^{out}(t) \psi_2^{+,out}(t') \psi_2^{out}(t') \rangle - \langle \psi_1^{+,out}(t) \psi_1^{out}(t) \rangle \langle \psi_2^{+,out}(t') \psi_2^{out}(t') \rangle$$

The electronic Hanbury Brown and Twiss experiment

$$\begin{pmatrix}\psi_1^{out}\\ \psi_2^{out}\end{pmatrix} = \begin{pmatrix} r & it \\ it & r\end{pmatrix}\begin{pmatrix}\psi_1^{in}\\ \psi_2^{in}\end{pmatrix}$$

$$R = r^2$$

$$T = t^2$$



$$S_{12}^{out}(t,t') = \langle \delta I_1^{out}(t)\delta I_2^{out}(t')\rangle = \langle I_1^{out}(t) I_2^{out}(t')\rangle - \langle I_1^{out}(t)\rangle\langle I_2^{out}(t')\rangle$$

$$\frac{S_{12}^{out}(t,t')}{e^2} = \langle \psi_1^{+,out}(t)\psi_1^{out}(t)\psi_2^{+,out}(t')\psi_2^{out}(t')\rangle - \langle \psi_1^{+,out}(t)\psi_1^{out}(t)\rangle\langle \psi_2^{+,out}(t')\psi_2^{out}(t')\rangle$$

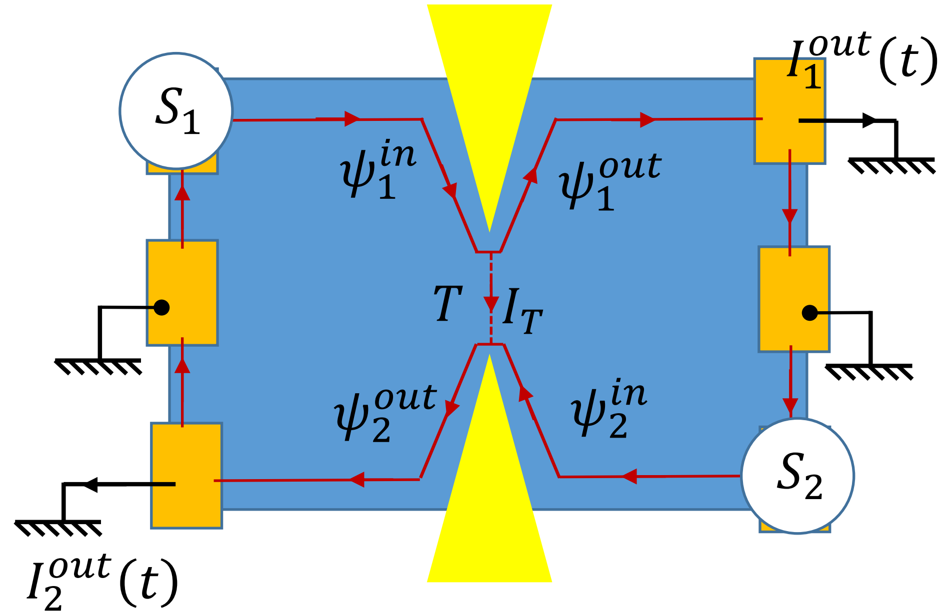
$$\frac{S_{12}^{out}(t,t')}{e^2} = RT\left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_1^{in}(t')\right\rangle + RT\left\langle \psi_2^{+,in}(t)\psi_2(t)\psi_2^{+,in}(t')\psi_2^{in}(t')\right\rangle$$
$$+T^2\left\langle \psi_2^{+,in}(t)\psi_2^{in}(t)\psi_1^{+,in}(t')\psi_1^{in}(t')\right\rangle + R^2\left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\psi_2^{+,in}(t')\psi_2^{in}(t')\right\rangle$$
$$-RT\left\langle \psi_2^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_2^{in}(t')\right\rangle - RT\left\langle \psi_1^{+,in}(t)\psi_2^{in}(t)\psi_2^{+,in}(t')\psi_1^{in}(t')\right\rangle - \sum\langle\quad\rangle\langle\quad\rangle$$

The electronic Hanbury Brown and Twiss experiment

$$\begin{pmatrix}\psi_1^{out}\\ \psi_2^{out}\end{pmatrix} = \begin{pmatrix} r & it \\ it & r\end{pmatrix}\begin{pmatrix}\psi_1^{in}\\ \psi_2^{in}\end{pmatrix}$$

$$R = r^2$$

$$T = t^2$$



$$S_{12}^{out}(t,t') = \langle \delta I_1^{out}(t)\delta I_2^{out}(t')\rangle = \langle I_1^{out}(t) I_2^{out}(t')\rangle - \langle I_1^{out}(t)\rangle\langle I_2^{out}(t')\rangle$$

$$\frac{S_{12}^{out}(t,t')}{e^2} = \langle \psi_1^{+,out}(t)\psi_1^{out}(t)\psi_2^{+,out}(t')\psi_2^{out}(t')\rangle - \langle \psi_1^{+,out}(t)\psi_1^{out}(t)\rangle\langle \psi_2^{+,out}(t')\psi_2^{out}(t')\rangle$$

$$\frac{S_{12}^{out}(t,t')}{e^2} = RT\left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_1^{in}(t')\right\rangle + RT\left\langle \psi_2^{+,in}(t)\psi_2(t)\psi_2^{+,in}(t')\psi_2^{in}(t')\right\rangle$$
$$+T^2\left\langle \psi_2^{+,in}(t)\psi_2^{in}(t)\psi_1^{+,in}(t')\psi_1^{in}(t')\right\rangle + R^2\left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\psi_2^{+,in}(t')\psi_2^{in}(t')\right\rangle$$
$$-RT\left\langle \psi_2^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_2^{in}(t')\right\rangle - RT\left\langle \psi_1^{+,in}(t)\psi_2^{in}(t)\psi_2^{+,in}(t')\psi_1^{in}(t')\right\rangle - \sum\langle\ \rangle\langle\ \rangle$$

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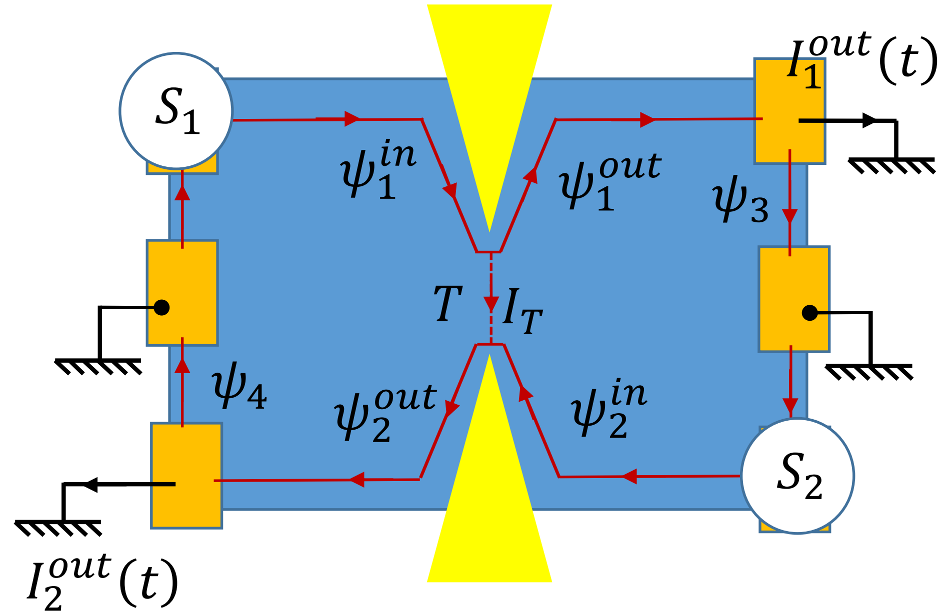
The electronic Hanbury Brown and Twiss experiment

$$\begin{pmatrix} \psi_1^{out} \\ \psi_2^{out} \end{pmatrix} = \begin{pmatrix} r & it \\ it & r \end{pmatrix} \begin{pmatrix} \psi_1^{in} \\ \psi_2^{in} \end{pmatrix}$$

$$R = r^2$$

$$T = t^2$$



$$S_{12}^{out}(t,t') = \langle \delta I_1^{out}(t) \delta I_2^{out}(t') \rangle = \langle I_1^{out}(t) I_2^{out}(t') \rangle - \langle I_1^{out}(t) \rangle \langle I_2^{out}(t') \rangle$$

$$\frac{S_{12}^{out}(t,t')}{e^2} = RT \left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_1^{in}(t') \right\rangle - RT \left\langle \psi_1^{+,in}(t)\psi_1^{in}(t) \right\rangle \left\langle \psi_1^{+,in}(t')\psi_1^{in}(t') \right\rangle$$

$$+RT \left\langle \psi_2^{+,in}(t)\psi_2(t)\psi_2^{+,in}(t')\psi_2^{in}(t') \right\rangle - RT \left\langle \psi_2^{+,in}(t)\psi_2^{in}(t) \right\rangle \left\langle \psi_2^{+,in}(t')\psi_2^{in}(t') \right\rangle$$

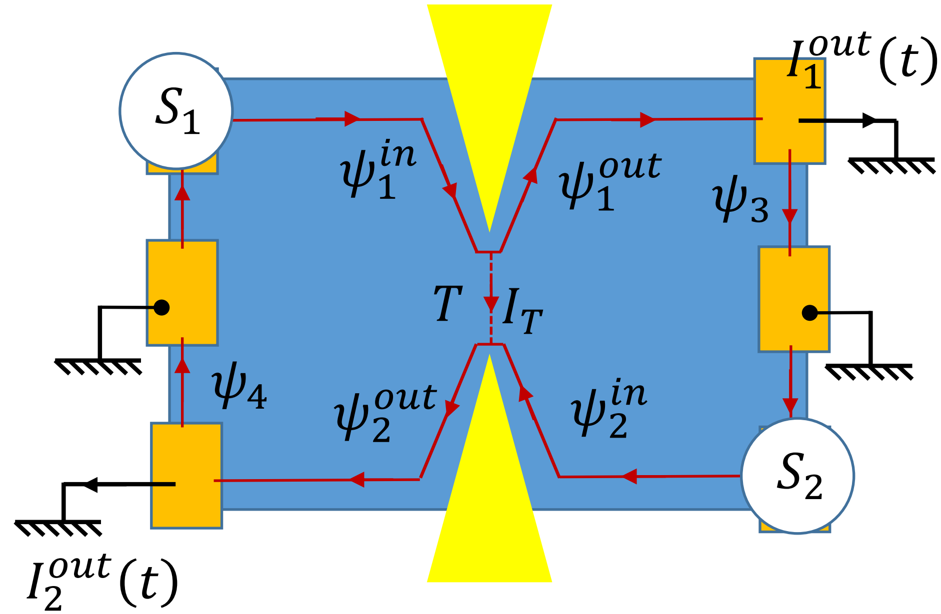
$$-RT \left[\left\langle \psi_2^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_2^{in}(t') \right\rangle + \left\langle \psi_1^{+,in}(t)\psi_2^{in}(t)\psi_2^{+,in}(t')\psi_1^{in}(t') \right\rangle \right]$$

The electronic Hanbury Brown and Twiss experiment

$$\begin{pmatrix}\psi_1^{out}\\ \psi_2^{out}\end{pmatrix} = \begin{pmatrix} r & it \\ it & r\end{pmatrix}\begin{pmatrix}\psi_1^{in}\\ \psi_2^{in}\end{pmatrix}$$

$$R = r^2$$

$$T = t^2$$



$$S_{12}^{out}(t,t') = \langle \delta I_1^{out}(t)\delta I_2^{out}(t')\rangle = \langle I_1^{out}(t) I_2^{out}(t')\rangle - \langle I_1^{out}(t)\rangle\langle I_2^{out}(t')\rangle$$

$$RTS_{11}^{in}$$

$$\frac{S_{12}^{out}(t,t')}{e^2} = RT\left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_1^{in}(t')\right\rangle - RT\left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\right\rangle\left\langle \psi_1^{+,in}(t')\psi_1^{in}(t')\right\rangle$$

$$+RT\left\langle \psi_2^{+,in}(t)\psi_2(t)\psi_2^{+,in}(t')\psi_2^{in}(t')\right\rangle - RT\left\langle \psi_2^{+,in}(t)\psi_2^{in}(t)\right\rangle\left\langle \psi_2^{+,in}(t')\psi_2^{in}(t')\right\rangle \quad RTS_{22}^{in}$$

$$-RT\left[\left\langle \psi_2^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_2^{in}(t')\right\rangle + \left\langle \psi_1^{+,in}(t)\psi_2^{in}(t)\psi_2^{+,in}(t')\psi_1^{in}(t')\right\rangle\right]$$

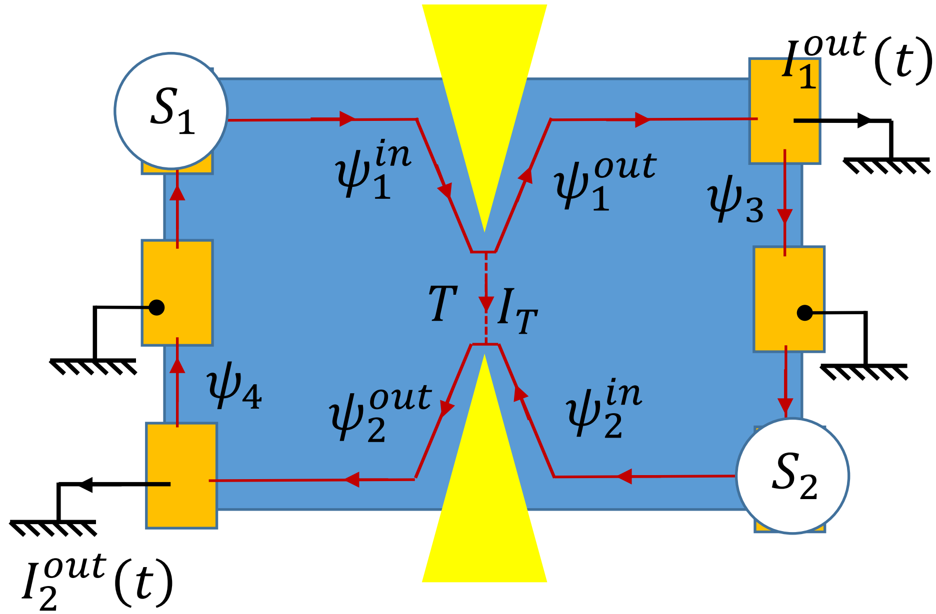
$$-S_{I_T}$$

The electronic Hanbury Brown and Twiss experiment, weak backscattering $T \ll 1$

$$\begin{pmatrix} \psi_1^{out} \\ \psi_2^{out} \end{pmatrix} = \begin{pmatrix} r & it \\ it & r \end{pmatrix} \begin{pmatrix} \psi_1^{in} \\ \psi_2^{in} \end{pmatrix}$$

$$R = r^2$$

$$T = t^2$$



$$S_{12}^{out}(t,t') = \langle \delta I_1^{out}(t) \delta I_2^{out}(t') \rangle = \langle I_1^{out}(t) I_2^{out}(t') \rangle - \langle I_1^{out}(t) \rangle \langle I_2^{out}(t') \rangle$$

$RTS_{11}^{in} \approx TS_{11}^{in}$ $(T \ll 1)$

$$\frac{S_{12}^{out}(t,t')}{e^2} = T \left\langle \psi_1^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_1^{in}(t') \right\rangle - RT \left\langle \psi_1^{+,in}(t)\psi_1^{in}(t) \right\rangle \left\langle \psi_1^{+,in}(t')\psi_1^{in}(t') \right\rangle$$

$$+ T \left\langle \psi_2^{+,in}(t)\psi_2(t)\psi_2^{+,in}(t')\psi_2^{in}(t') \right\rangle - RT \left\langle \psi_2^{+,in}(t)\psi_2^{in}(t) \right\rangle \left\langle \psi_2^{+,in}(t')\psi_2^{in}(t') \right\rangle$$

$RTS_{22}^{in} \approx TS_{22}^{in}$

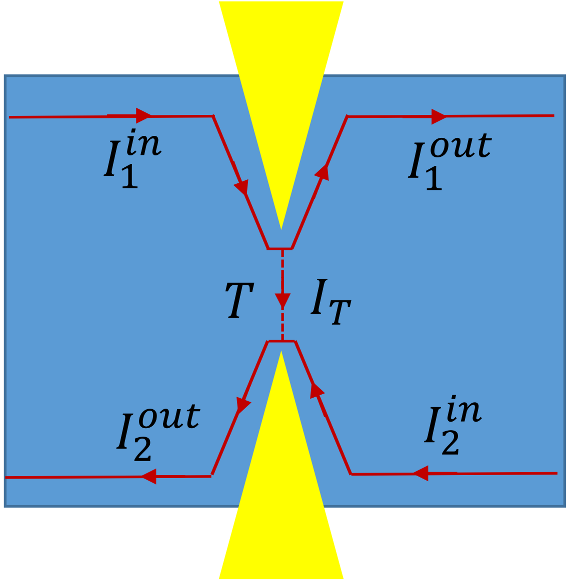
$$-T \left[\left\langle \psi_2^{+,in}(t)\psi_1^{in}(t)\psi_1^{+,in}(t')\psi_2^{in}(t') \right\rangle + \left\langle \psi_1^{+,in}(t)\psi_2^{in}(t)\psi_2^{+,in}(t')\psi_1^{in}(t') \right\rangle \right]$$

$-S_{I_T}$

Cross-correlations S_{12}^{out} and noise of the tunneling current S_{I_T}

$$I_1^{out} = I_1^{in} - I_T$$

$$I_2^{out} = I_2^{in} + I_T$$



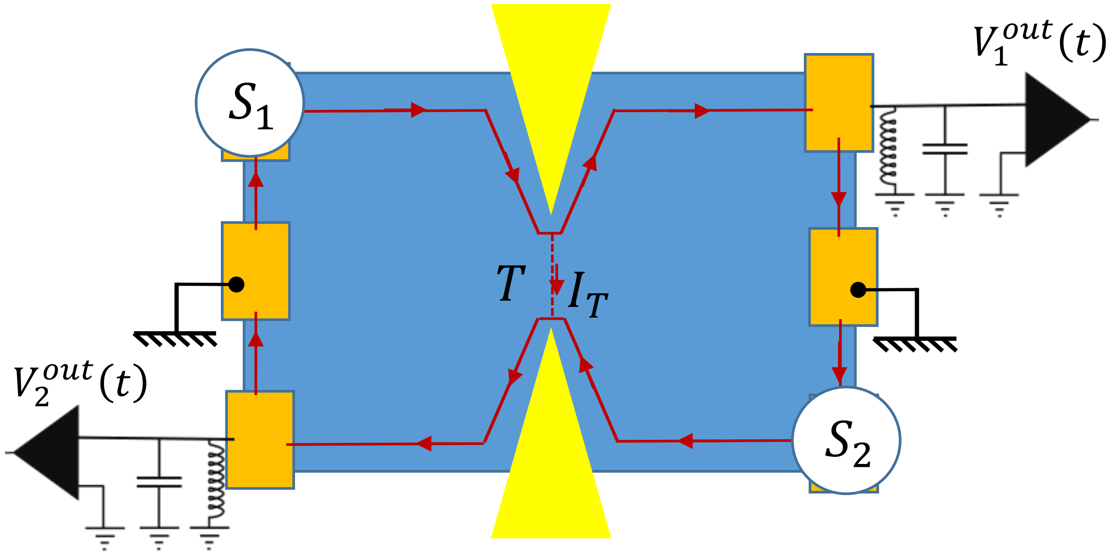
$$\langle \delta I_1^{out} \delta I_2^{out} \rangle = \langle \delta I_1^{in} \delta I_2^{in} \rangle + \langle \delta I_1^{in} \delta I_T \rangle - \langle \delta I_T \delta I_2^{in} \rangle - \langle \delta I_T \delta I_T \rangle$$

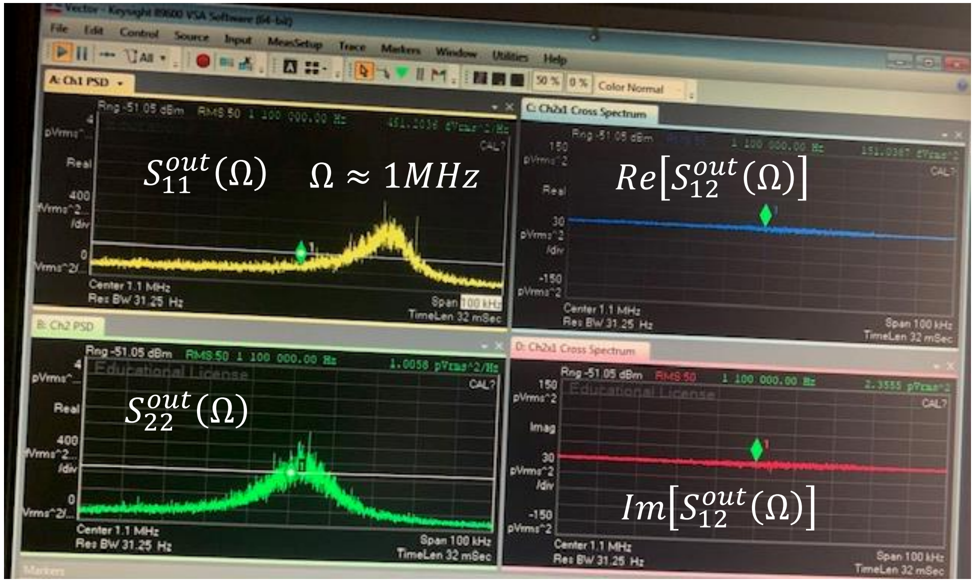
$$\delta I_T \approx T\left[\delta I_1^{in} - \delta I_2^{in}\right]$$

$$\langle \delta I_1^{out} \delta I_2^{out} \rangle = T\langle \delta I_1^{in} \delta I_1^{in} \rangle + \mathrm{T}\langle \delta I_2^{in} \delta I_2^{in} \rangle - \langle \delta I_T \delta I_T \rangle$$

$$S_{12}^{out} = T\left[S_{11}^{in} + S_{22}^{in}\right] - S_{I_T}$$

Power spectral density of current fluctuations





$$S_{12}^{out}(\Omega) = 2 \lim_{T_{meas}\to\infty} \frac{1}{T_{meas}} \int d\bar{t}\, d\tau\, S_{12}^{out}\left(\bar{t}+\frac{\tau}{2}, \bar{t}-\frac{\tau}{2}\right) e^{i\Omega\tau} = \frac{2\langle \delta I_1^{out}(\Omega)\delta I_2^{out}(-\Omega)\rangle}{T_{meas}}$$

Low frequency noise: $S_{12}^{out}(\Omega = 0) = 2 \lim_{T_{meas}\to\infty} \frac{1}{T_{meas}} \int d\bar{t}\, d\tau\, S_{12}^{out}\left(\bar{t}+\frac{\tau}{2}, \bar{t}-\frac{\tau}{2}\right)$

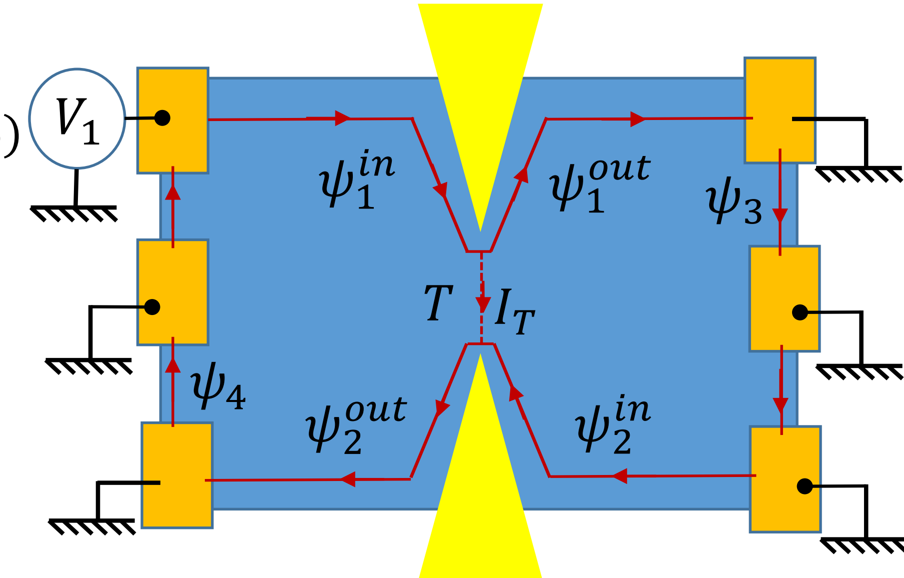
Stationary case: no dependence on $\bar{t}$:

$$S_{I_T}(\Omega = 0) = 2e^2 \Bigg[\underbrace{T \int d\tau \left\langle \psi_1^{+,in}(\tau)\psi_1^{in}(0)\right\rangle \left\langle \psi_2^{in}(\tau)\psi_2^{+,in}(0)\right\rangle}_{\Gamma_{1\rightarrow 2}} + \underbrace{T \int d\tau \left\langle \psi_1^{in}(\tau)\psi_1^{+,in}(0)\right\rangle \left\langle \psi_2^{+,in}(\tau)\psi_2^{in}(0)\right\rangle}_{\Gamma_{2\rightarrow 1}} \Bigg]$$

Example: voltage biased QPC

$$\left\langle \psi_1^{+,in}(\tau)\psi_1^{in}(0)\right\rangle = e^{-i\frac{eV_1\tau}{\hbar}} G_{eq}(\tau) = \int \frac{d\omega}{2\pi} e^{i(\omega - eV_1/\hbar)\tau} f_0(\omega)$$

$$\left\langle \psi_1^{in}(\tau)\psi_1^{+,in}(0)\right\rangle = e^{i\frac{eV_1\tau}{\hbar}} G_{eq}(\tau) = \int \frac{d\omega}{2\pi} e^{i(\omega + eV_1/\hbar)\tau} f_0(\omega)$$



$$\Gamma_{1\to 2} = T\int \frac{d\omega d\omega'}{2\pi}\delta(\omega + \omega' - eV_1/\hbar) f_0(\omega) f_0(\omega')$$

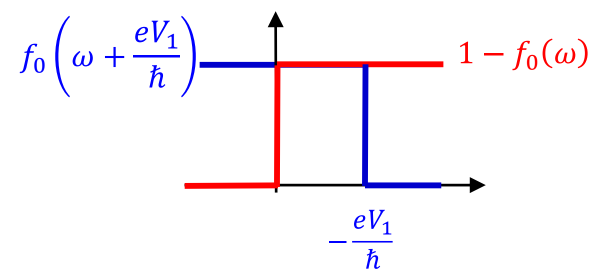
$$\Gamma_{1\to 2} = T\int \frac{d\omega}{2\pi} f_0(\omega + eV_1/\hbar)[1 - f_0(\omega)] \qquad \Gamma_{2\to 1} = T\int \frac{d\omega}{2\pi}[1 - f_0(\omega + eV_1/\hbar)] f_0(\omega)$$

Classical picture: $\frac{eV_1\tau_{th}}{h} \gg 1$ (zero temperature limit)

$V_1 < 0$ $\quad \Gamma_{1\to 2} = -T\frac{eV_1}{h}$ $\quad \Gamma_{2\to 1} = 0$

$\Gamma_{1\to 2} = T\Gamma_1^{in}$ Tunelling rate for electrons from $1 \longrightarrow 2$

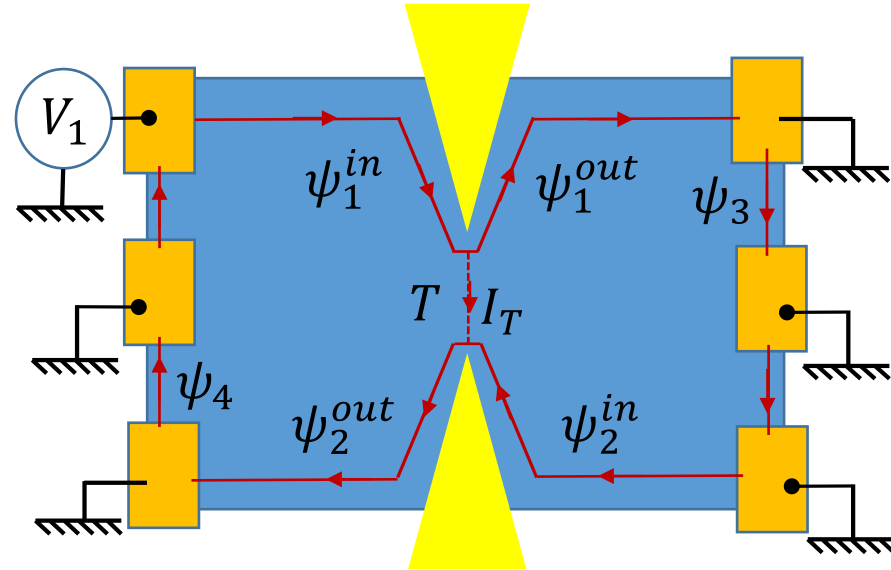
$V_1 > 0$ $\quad \Gamma_{1\to 2} = 0$ $\quad \Gamma_{2\to 1} = T\Gamma_2^{in}$ Tunelling rate for e- from $2 \longrightarrow 1$



Example: voltage biased QPC, exact results

$$\Gamma_{1\to 2} = T \int \frac{d\omega}{2\pi} f_0(\omega + eV_1/\hbar)[1 - f_0(\omega)]$$

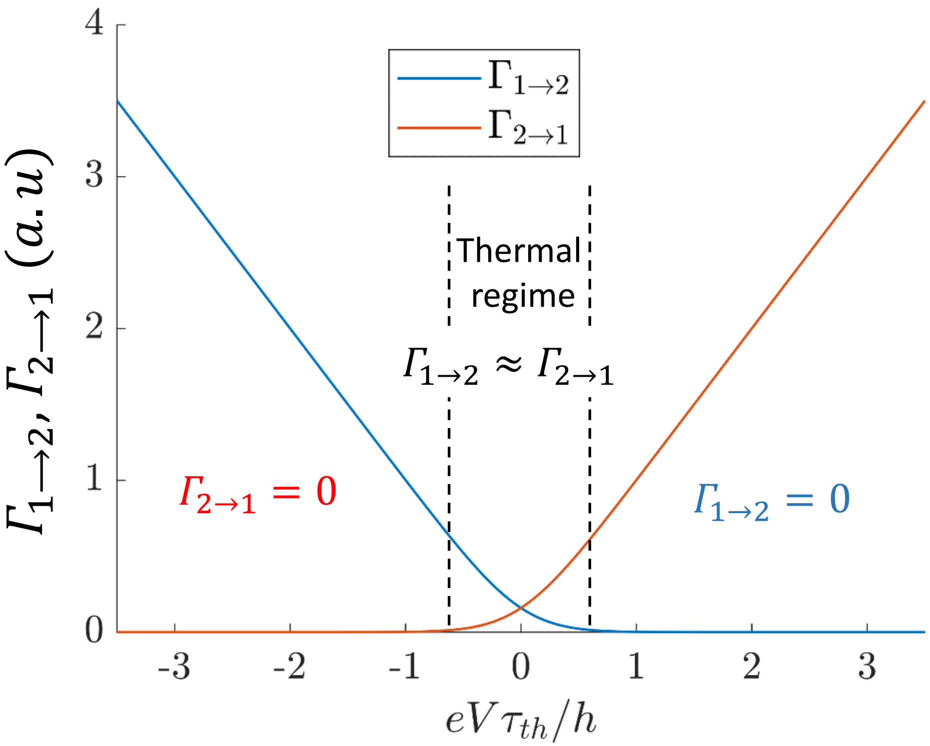
$$\Gamma_{2\to 1} = T \int \frac{d\omega}{2\pi} [1 - f_0(\omega + eV_1/\hbar)] f_0(\omega)$$



$$z = \frac{eV\tau_{th}}{h}$$

$$\Gamma_{1\to 2} = -\frac{T}{\tau_{th}} z \frac{e^{-2\pi z}}{e^{-2\pi z} - 1}$$

$$\Gamma_{2\to 1} = \frac{T}{\tau_{th}} z \frac{e^{2\pi z}}{e^{2\pi z} - 1}$$

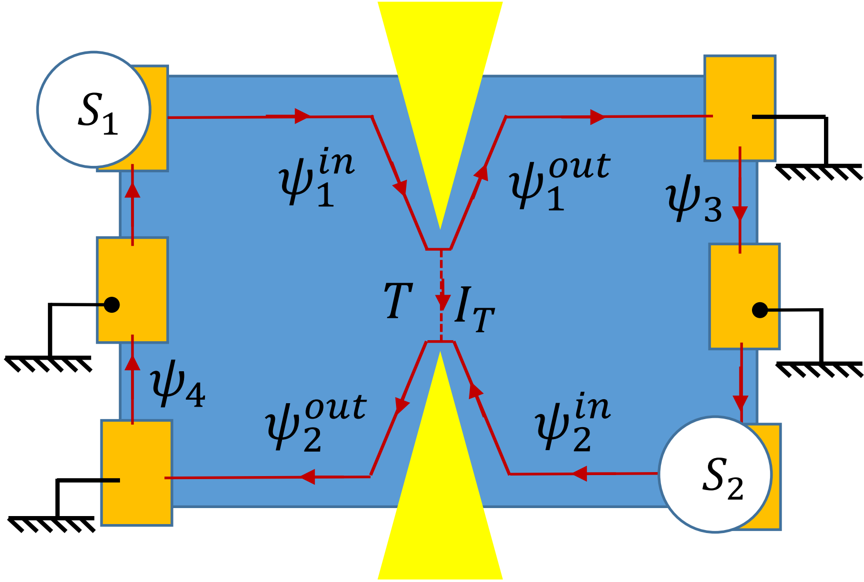


Cross-correlations and noise of the tunneling current in two-particle interferometry

Result for out of equilibrium tunneling at the beam-splitter at first order in the tunneling Hamitlonian H_T:

$$H_T = \zeta \psi_1^+ \psi_2 + \zeta^* \psi_2^+ \psi_1$$

Valid in the integer and fractional quantum Hall regime



Observable quantities:

$$\langle I_T \rangle = e(\Gamma_{2\to1} - \Gamma_{1\to2})$$

$$S_{I_T} = 2e^2(\Gamma_{2\to1} + \Gamma_{1\to2})$$

$$S_{12}^{out} = T\left[S_{11}^{in} + S_{22}^{in}\right] - S_{I_T}$$

$$\Gamma_{1\to2} = T\int d\tau \left\langle \psi_1^{+,in}(\tau)\psi_1^{in}(0)\right\rangle \left\langle \psi_2^{in}(\tau)\psi_2^{+,in}(0)\right\rangle$$

$$\Gamma_{2\to1} = T\int d\tau \left\langle \psi_2^{+,in}(\tau)\psi_2^{in}(0)\right\rangle \left\langle \psi_1^{in}(\tau)\psi_1^{+,in}(0)\right\rangle$$

Fano factors:

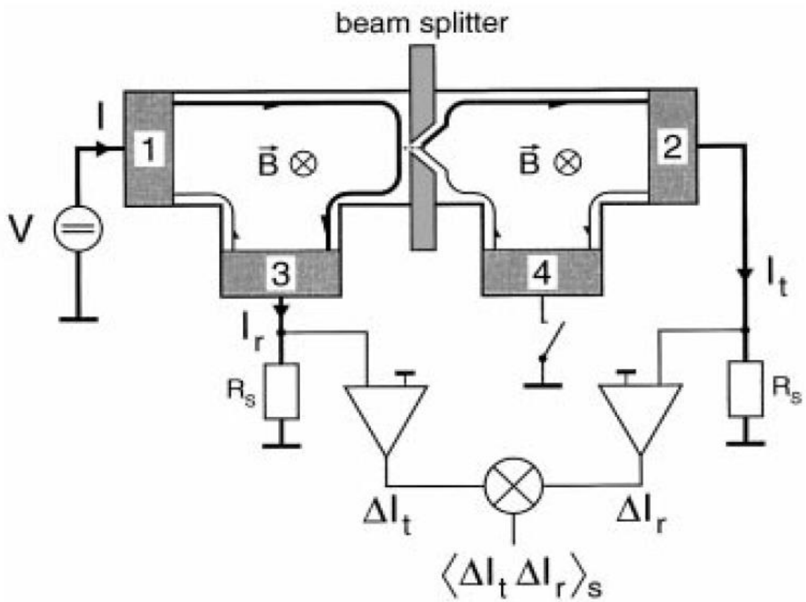
$$F = \frac{S_{I_T}}{2eI_T} = \frac{\Gamma_{2\to1} + \Gamma_{1\to2}}{\Gamma_{2\to1} - \Gamma_{1\to2}}$$

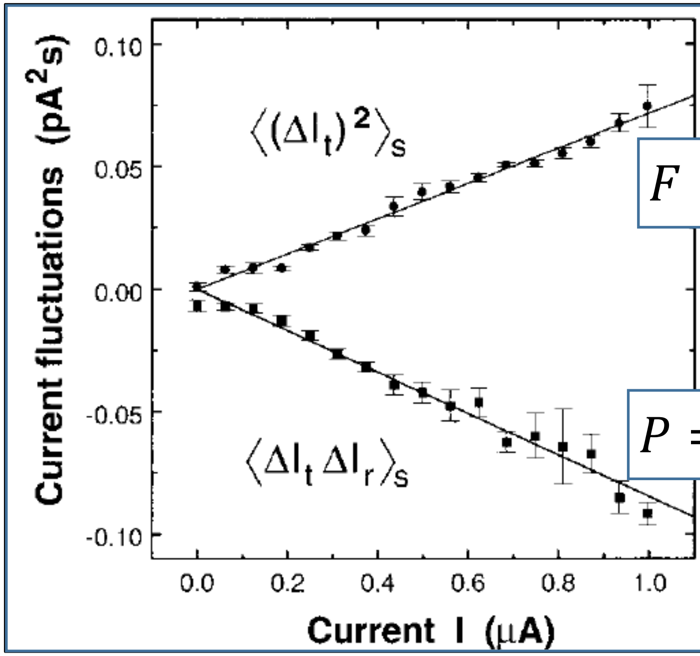
DC biased QPC: $F = 1$

$$P = \frac{S_{12}^{out}}{2eT(I_1 + I_2)} = \frac{S_{12}^{out}}{2eTI_+}$$

DC biased QPC: $P = -1$

Experiments





M. Henny et al., Science **284** 296 (1999)

$$S_{11}^{in} = S_{22}^{in} = 0 \quad \Rightarrow \quad S_{11}^{out} = S_{22}^{out} = -S_{12}^{out} = S_{I_T}$$

Single source dc case:

$$F = \frac{S_{I_T}}{2e^* I_T}$$

$T \ll 1$

Weak-backscattering

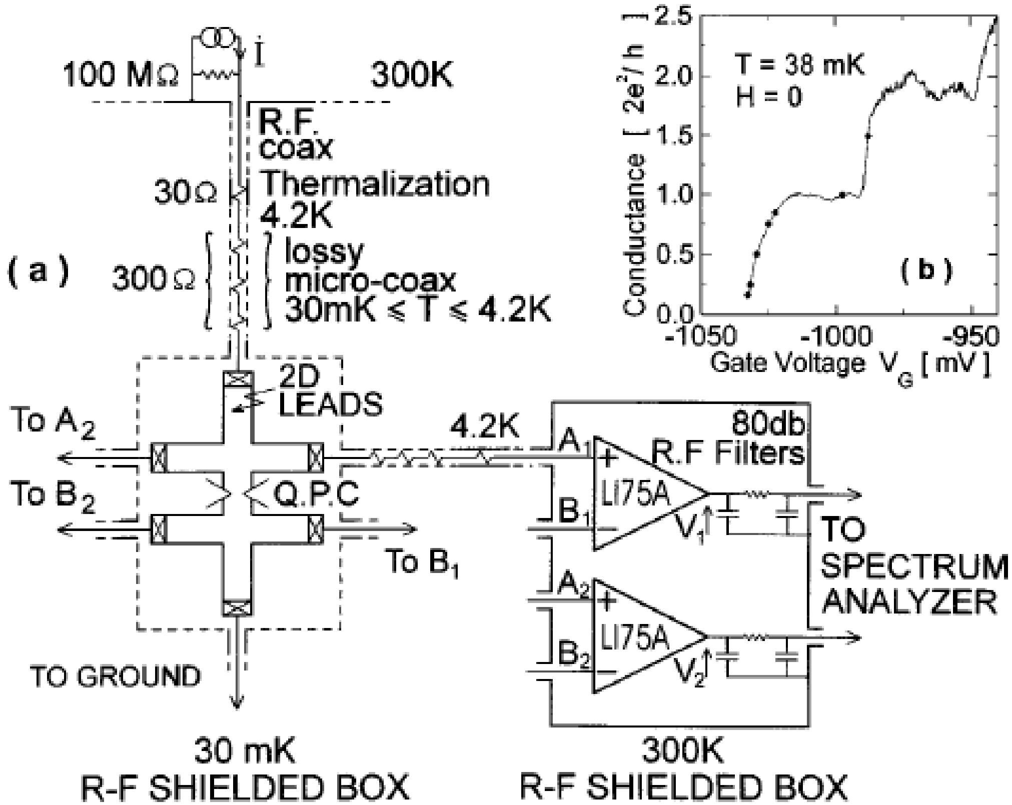
$$P = \frac{S_{12}^{out}}{2eTI_1} \qquad I_T = TI_1 \qquad P = -F = -1$$

Orders of magnitude: $V \leq 100\mu V \qquad \frac{eV}{k_B} \leq 1K$

$$S_I \leq 2eT\frac{e^2}{h}V \approx qq\ 10^{-28}A^2.Hz^{-1} \quad (T = 0.1) \longrightarrow T_N \approx 20mK$$

Cold amplifiers: $T_{N,a} \approx 100mK$ 100µK resolution in ~minute

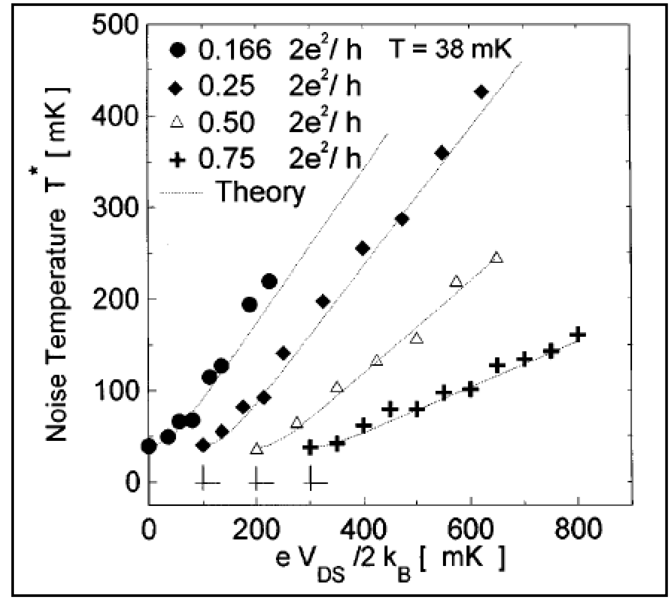
First measurements of partition noise in quantum point contact

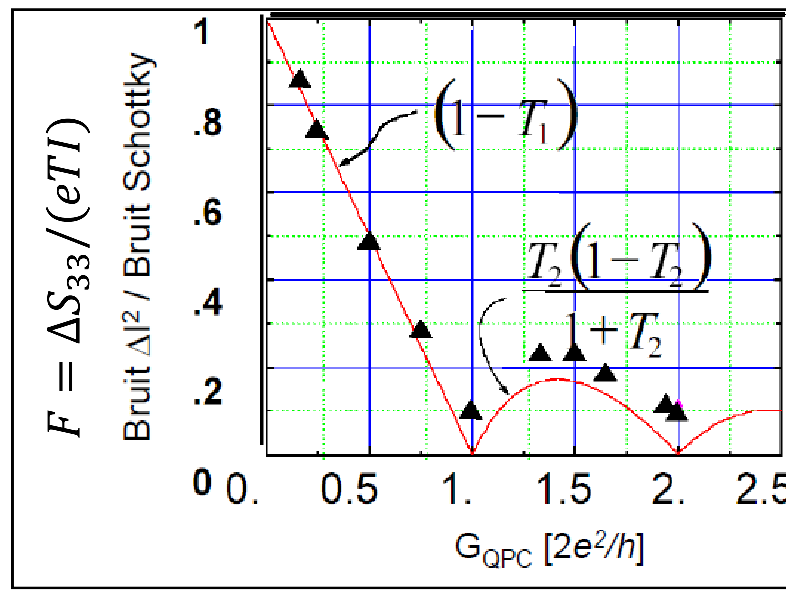


Deviations from weak-backsctering regime:

$$S_{I_T} \propto RT.. = T(1-T) \ldots$$

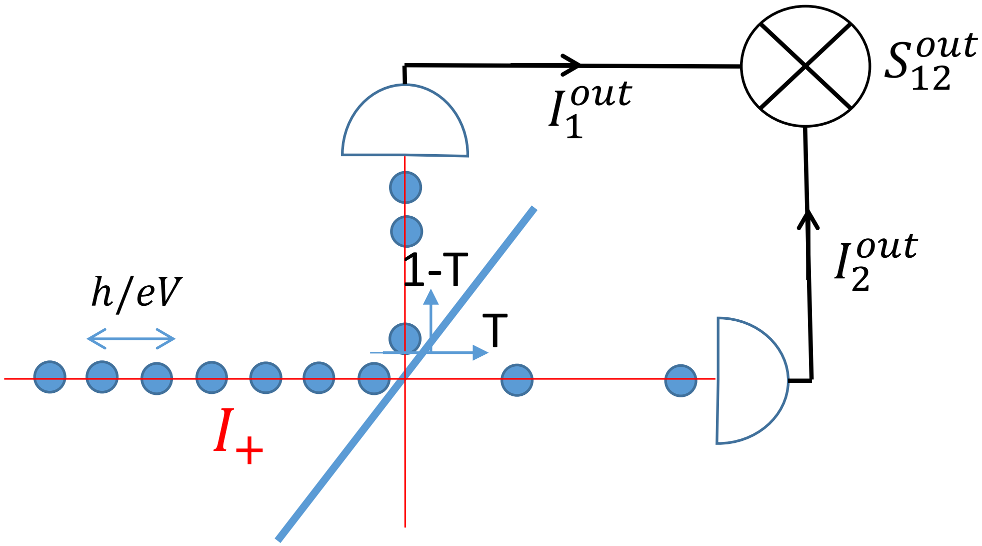
$$F = -P = (1-T)$$





A. Kumar et al.,
Phys. Rev. Lett. **76** 2778 (1996)

Single quantum point contact in the dc regime: electron charge

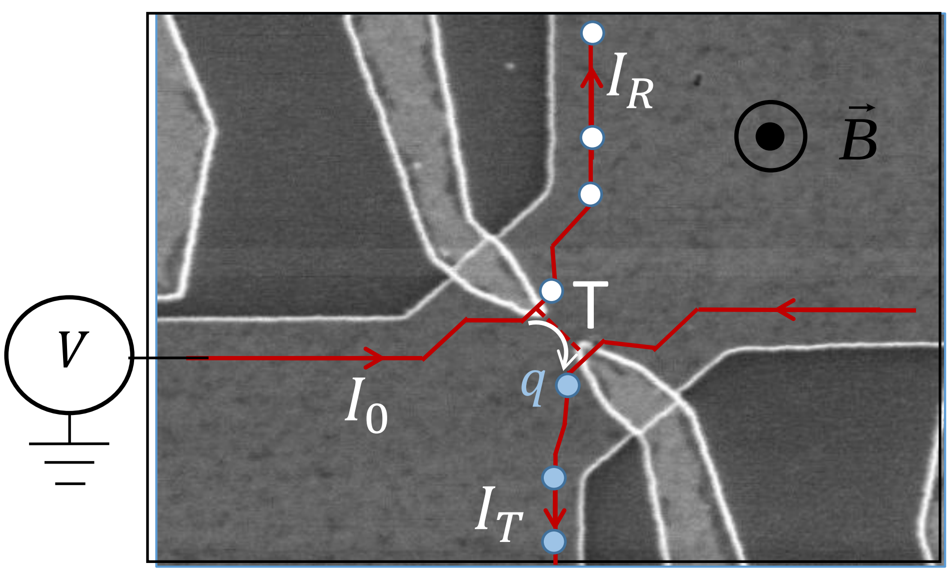


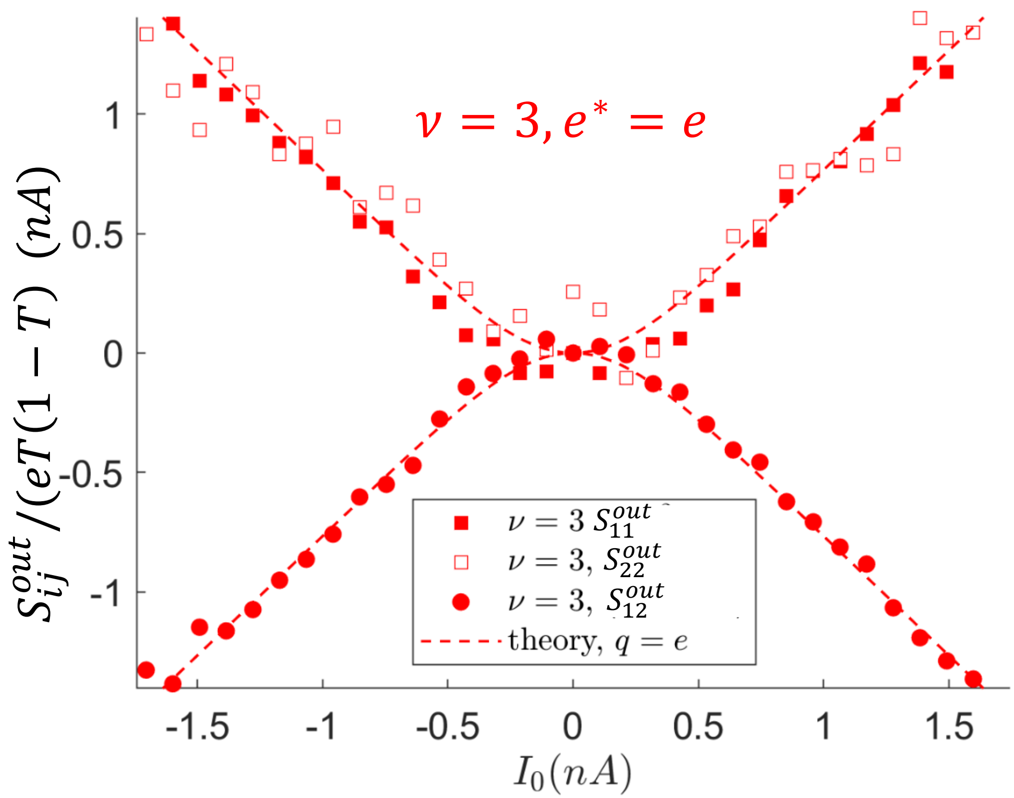
Binomial law: $\langle \Delta N_T^2 \rangle = T(1-T)\, N_+$

$$S_{rp} = 2eT(1-T)I_+$$

$$S_{rp} \approx 2eTI_+ \quad (T \ll 1)$$

$$S_{12}^{out} = -S_{11}^{out} = -S_{22}^{out} = S_{rp}$$

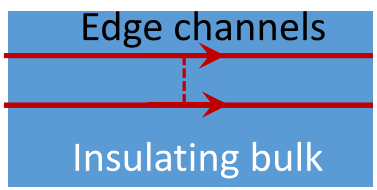




Anyons and the Fractional Quantum Hall Effect (FQHE)

$T_{el} \approx 30\ mK$

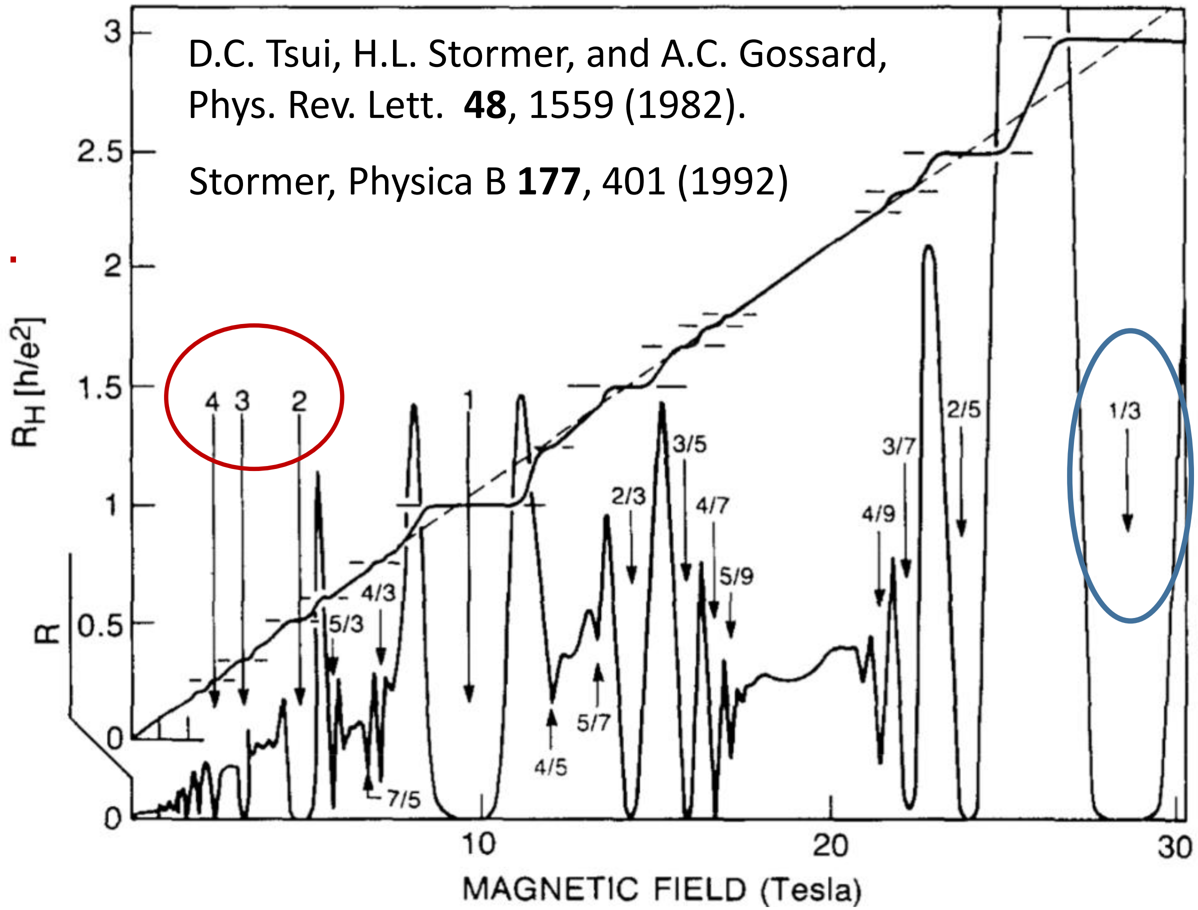
IQHE, $\nu = 1, 2, 3..$



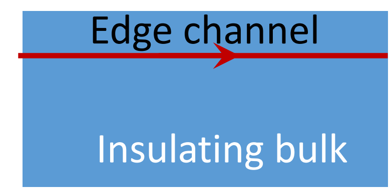
$$G_0 = N\frac{e^2}{h}$$

$$e^* = e$$

$$\varphi = \pi$$



FQHE, $\nu = 1/3$



$$G_0 = \frac{1}{3}\frac{e^2}{h}$$

$$e^* = e/3$$

$$\varphi = \pi/3$$

Each FQHE phase hosts a specific variety of anyons characterized by their fractional charge q and their fractional statistics φ

Halperin, PRL **52** 1583 (1984)

Arovas, Schrieffer, Wilczek PRL **53** 722 (1984)

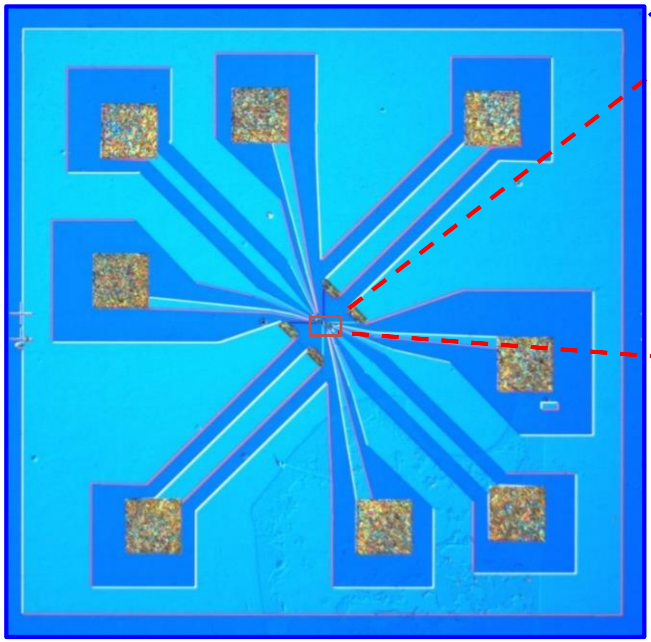
Review: Stern, Annals of Physics **323** 204 (2008)

LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

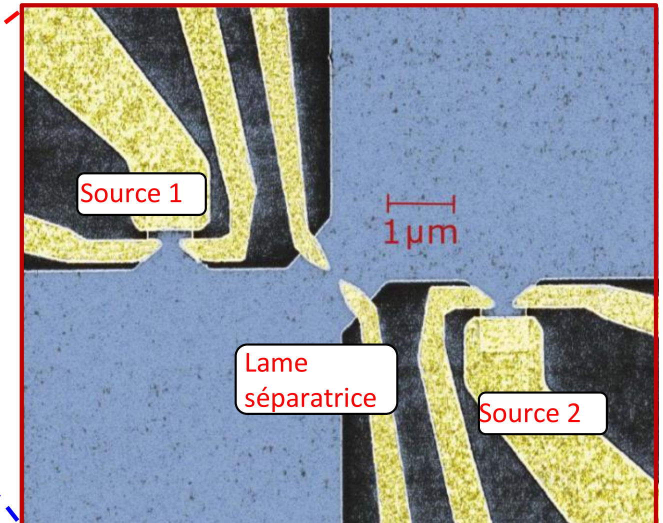
Experimental setup: sample and printed circuit board

Sample (optical microscope)

2 mm

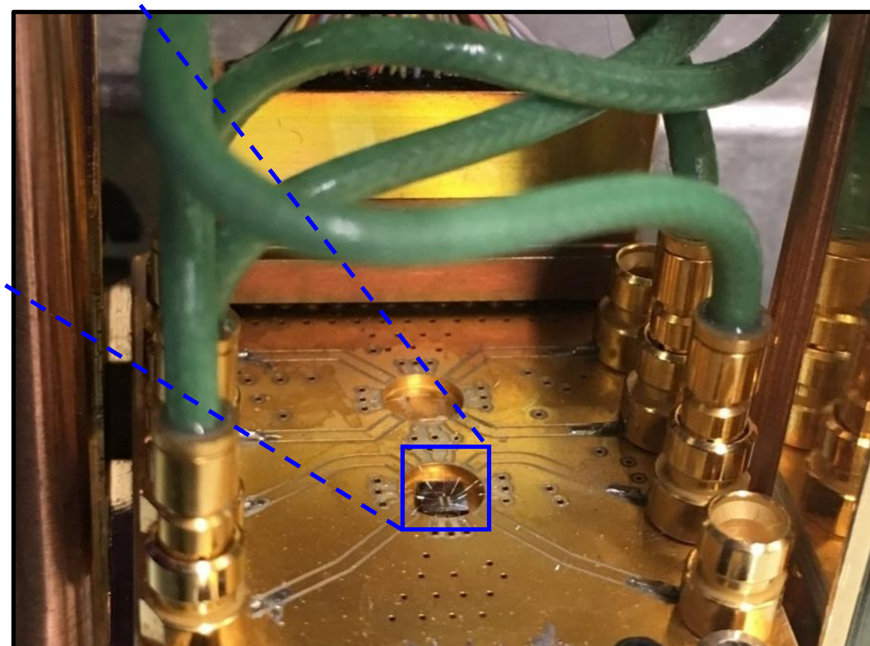


Sample (electronic microscope)



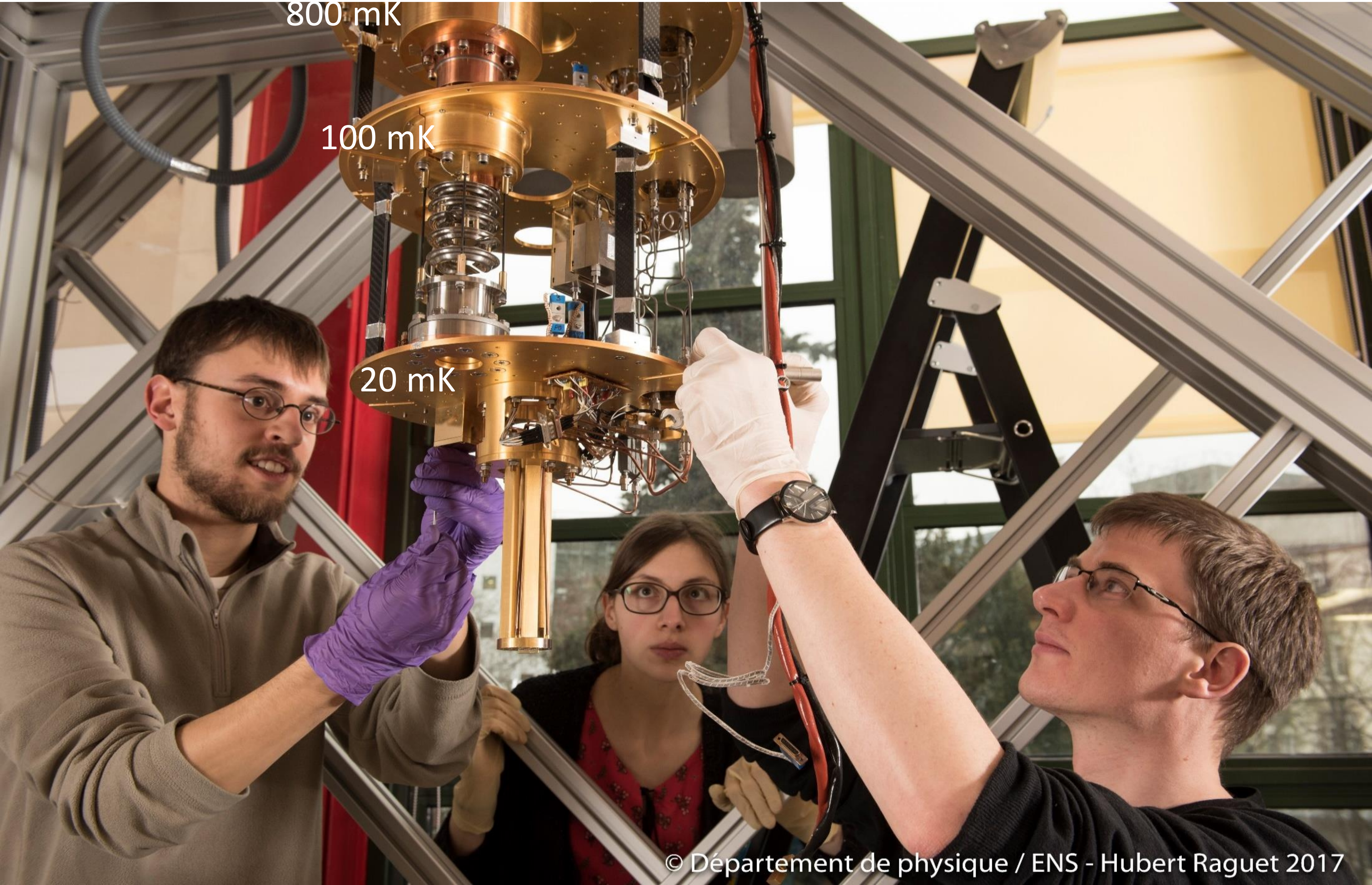
Sample holder and printed circuit board with RF coaxial cables

2 cm

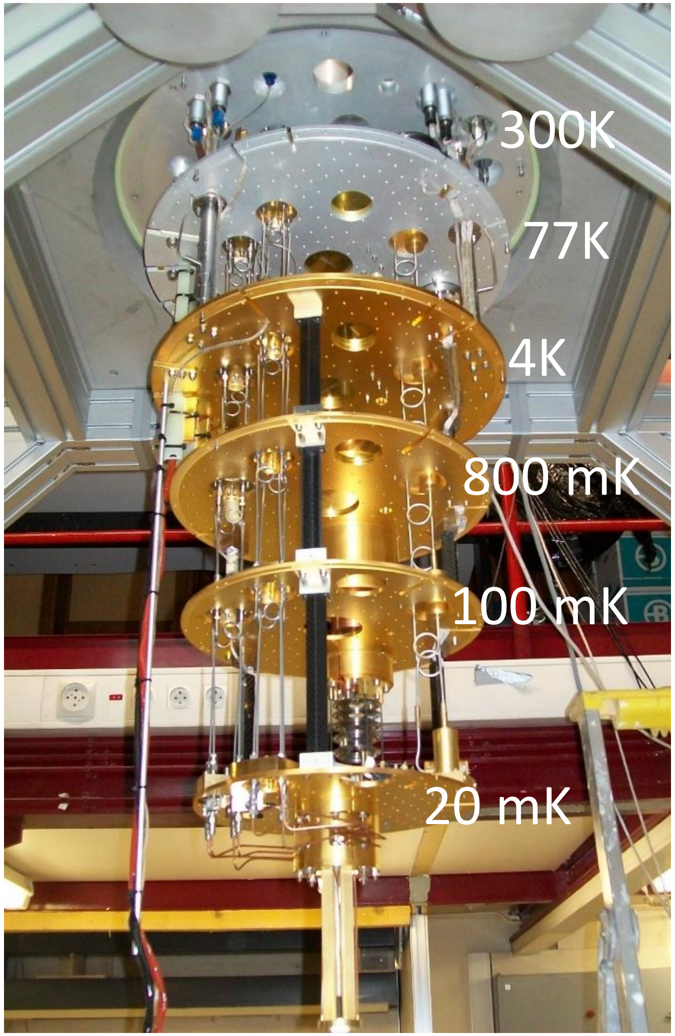


Sample fabricated at the Centre of Nanosciences and Nanotechnologies (C2N), CNRS, by U. Gennser, A. Cavanna and Y. Jin

Experimental setup: dilution fridge



Experimental setup: dilution fridge



Conclusion course 1

Two particle interferometry and noise:

$$S_{I_T}(\Omega=0) = 2q^2\left[\underbrace{T\int d\tau\left\langle\psi_1^{+,in}(\tau)\psi_1^{in}(0)\right\rangle\left\langle\psi_2^{in}(\tau)\psi_2^{+,in}(0)\right\rangle}_{\Gamma_{1\longrightarrow 2}} + \underbrace{T\int d\tau\left\langle\psi_1^{in}(\tau)\psi_1^{+,in}(0)\right\rangle\left\langle\psi_2^{+,in}(\tau)\psi_2^{in}(0)\right\rangle}_{\Gamma_{2\longrightarrow 1}}\right]$$

Some (important) technicalities: $S_{12}^{out} = T\left[S_{11}^{in} + S_{22}^{in}\right] - S_{I_T}$

$$I_T = e^*(\Gamma_{2\rightarrow 1} - \Gamma_{1\rightarrow 2}) \qquad S_{I_T} = 2e^{*2}(\Gamma_{2\rightarrow 1} + \Gamma_{1\rightarrow 2})$$

Voltage biased QPC, integer and fractional case (see next course for fractional)

$$e^*V \gg k_B T_{el} \qquad \Gamma_{1\rightarrow 2} \neq 0 \qquad \Gamma_{2\rightarrow 1} = 0 \qquad S_{I_T} = 2e^* I_T \qquad S_{12}^{out} = -S_{I_T}$$

Voltage biased QPC is a random poissonian source of electrons/anyons