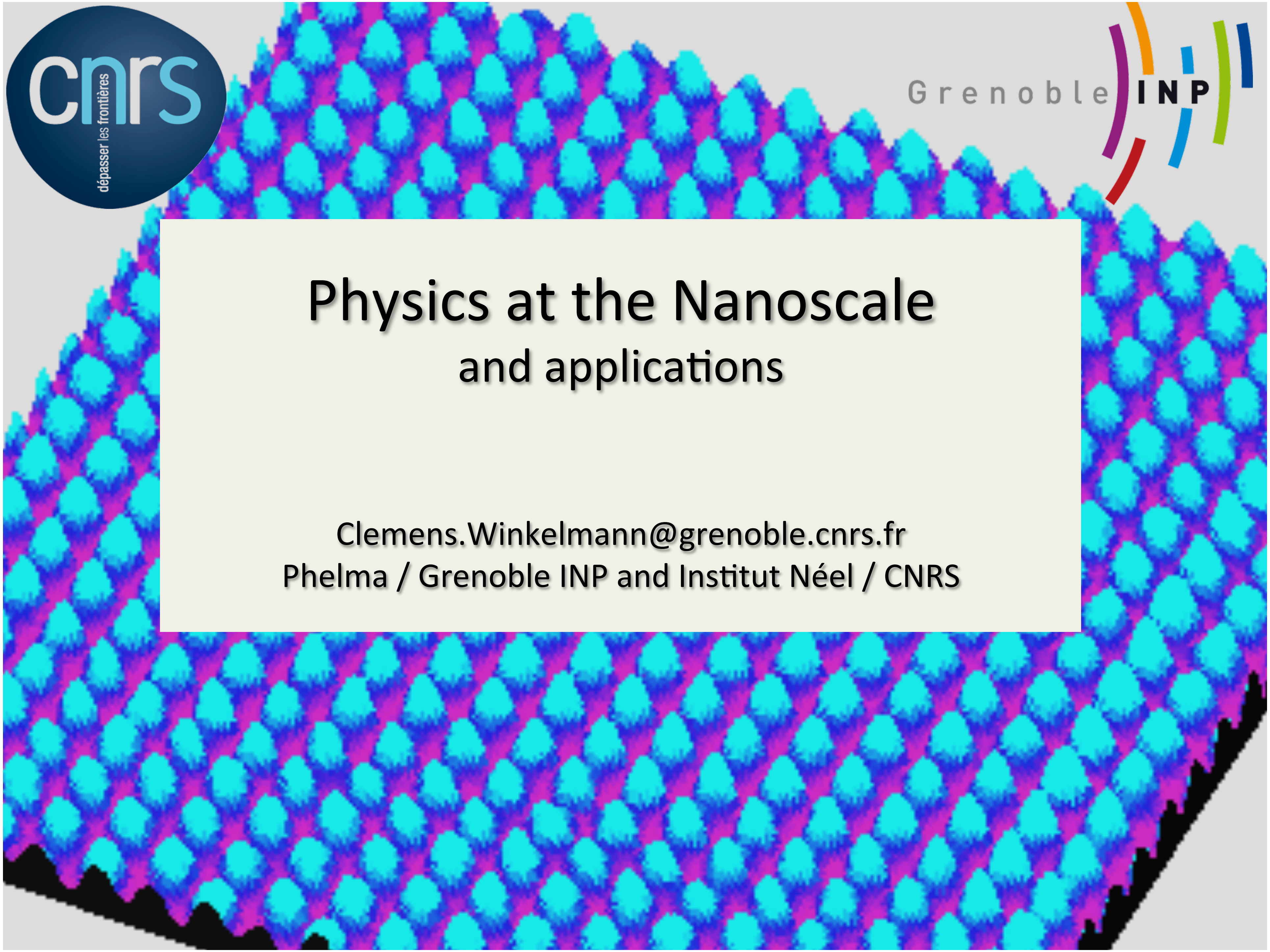

Physics at the Nanoscale

and applications

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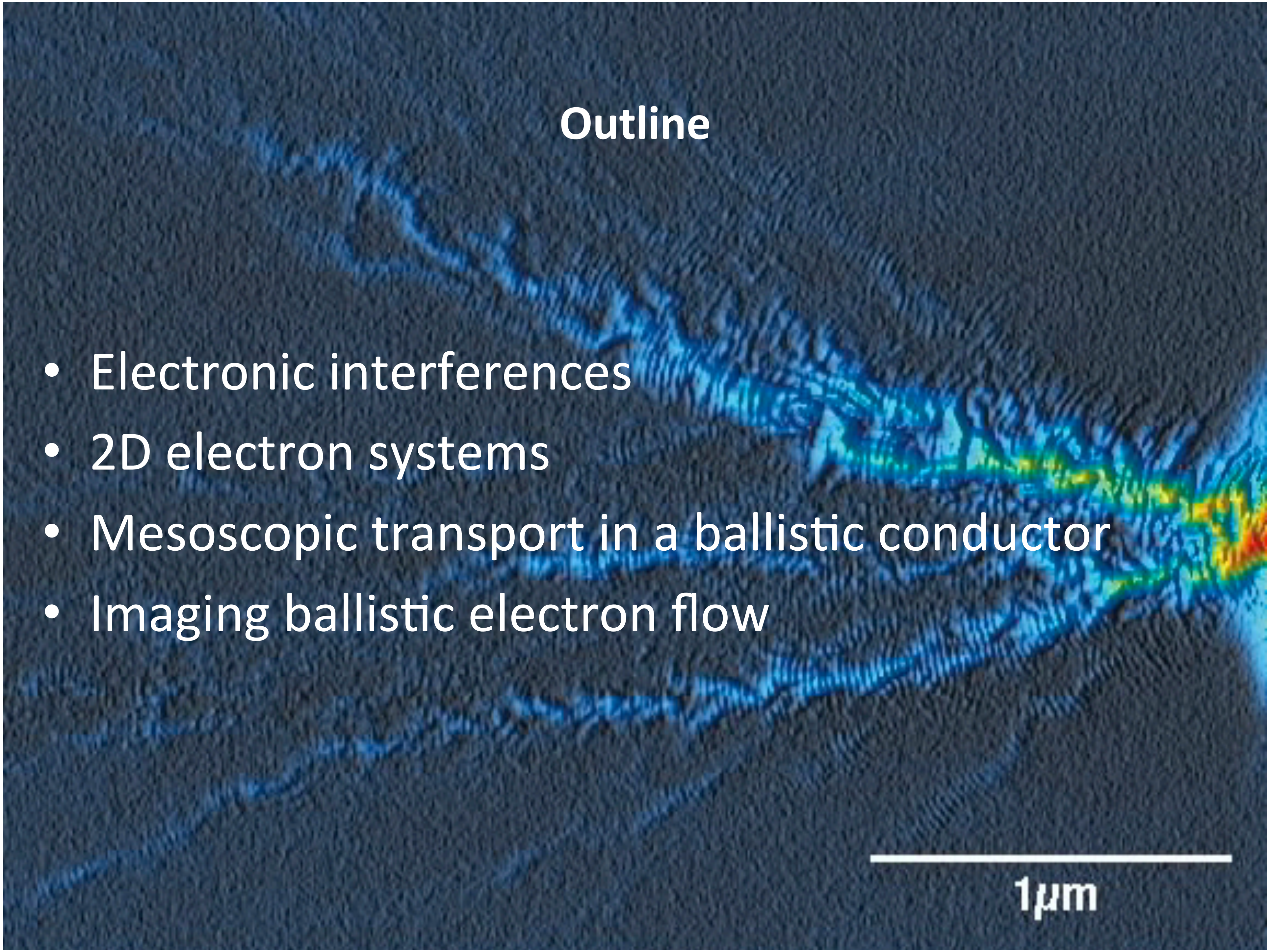
Physics at the Nanoscale

- I Basics of quantum mechanics
- II Statistical Physics
- III Forces at the nanoscale
- IV Electron tunneling and applications
- V Quantum electronic transport

Outline

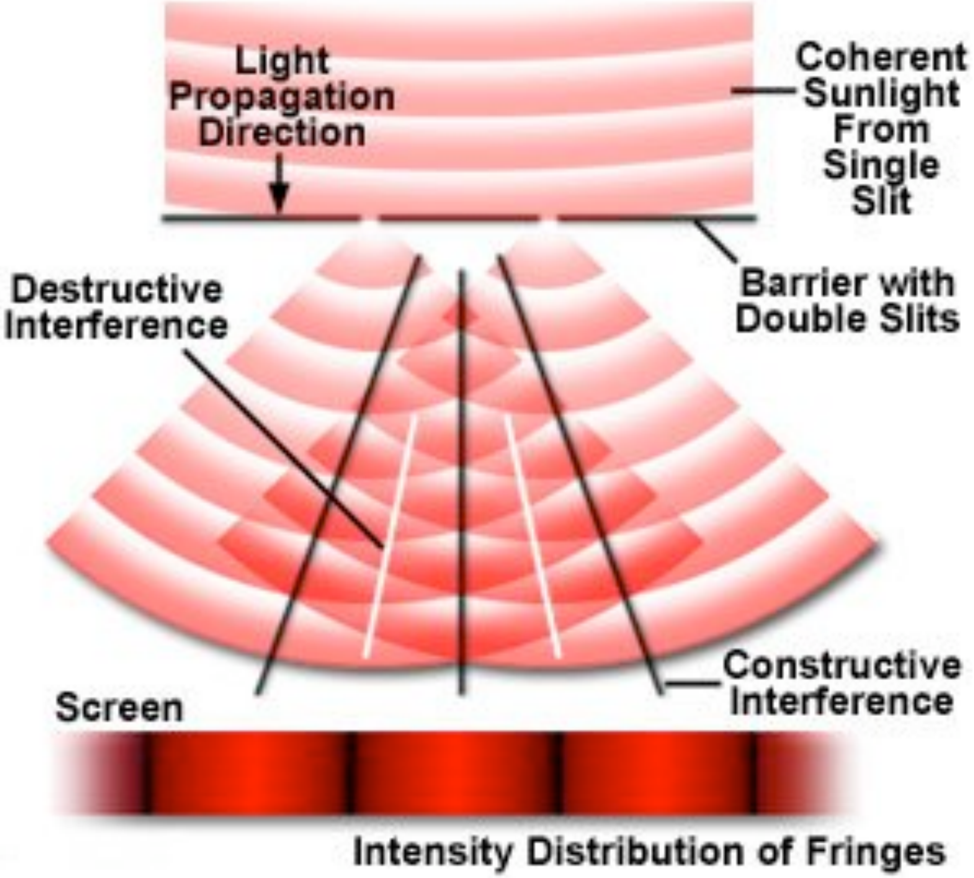


- Electronic interferences
- 2D electron systems
- Mesoscopic transport in a ballistic conductor
- Imaging ballistic electron flow

Quantum Electronic Transport

Interference of propagating waves

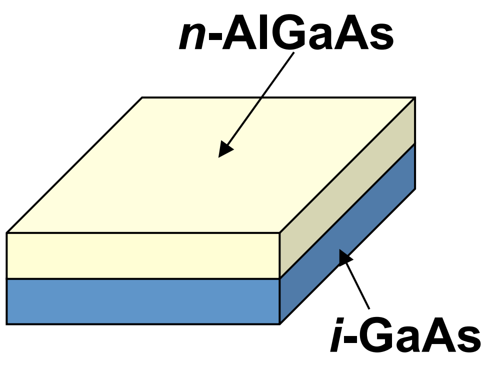
Young's double
slit experiment
for photons

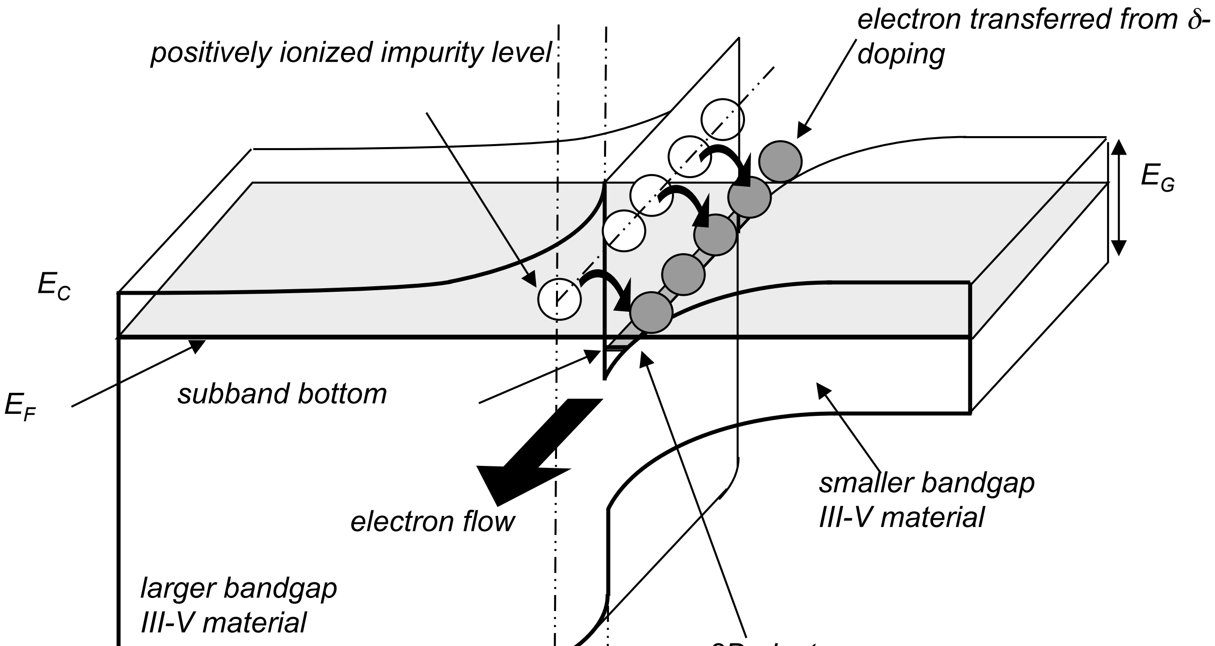


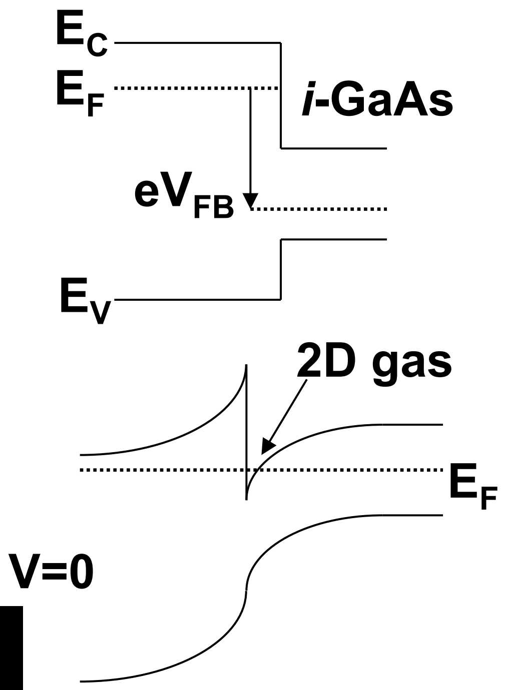
Quantum Electronic Transport

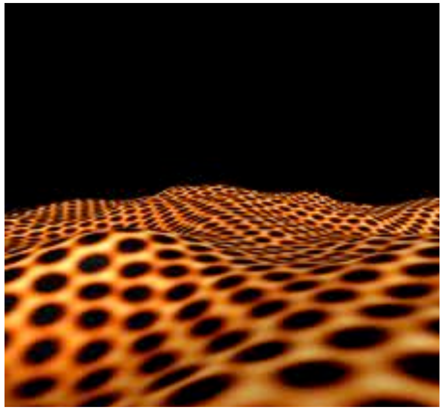
2D Electron Gases

Mobilities higher than 10^7cm^2/v/s at 4K in modulation-doped GaAs; 2D concentrations in the 10^{11}cm^{-2} range.









… and more recently: graphene

Quantum Electronic Transport

Mesoscopic transport in a ballistic conductor

In a macroscopic conductor and at low electric field, the conductance is *ohmic*:

$$\boxed{G = \sigma \frac{W}{L}}$$

A conductor is ohmic if its dimensions are much larger than

1/ the Fermi wavelength λ_F.
2/ the momentum mean free path λ_m.
3/ the phase relaxation length λ_Φ.

When the device dimensions get small enough for this law to break down, the device is called mesoscopic.

→ *Depending on the device materials and conditions (temperature), from a few nanometers up to mm!*

Characteristics physical lengths

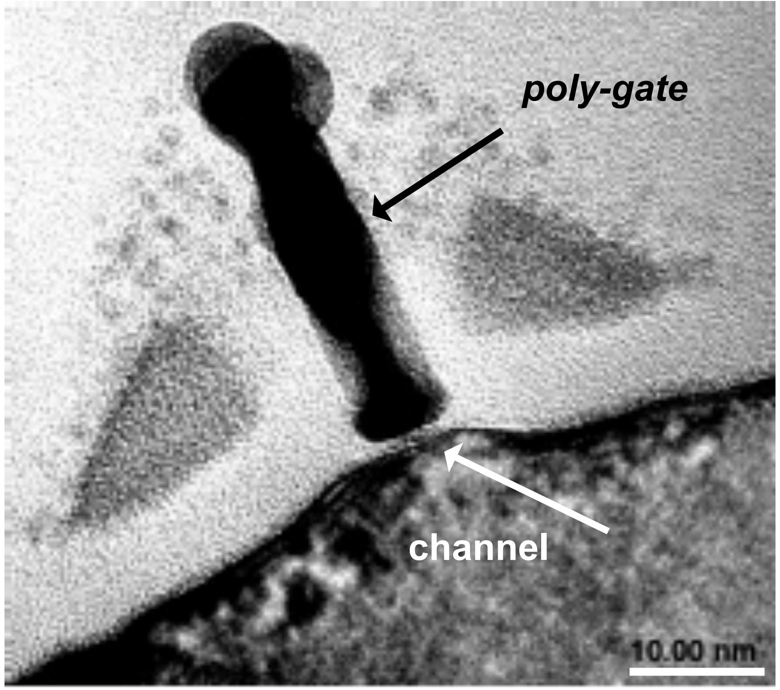
- Fermi wavelength λ_F: electron wavelength at the Fermi energy:
- Mean free path λ_M: distance that an electron travels before loosing its initial momentum

Degenerate electron gas: $\lambda_m = v_F \tau_m$

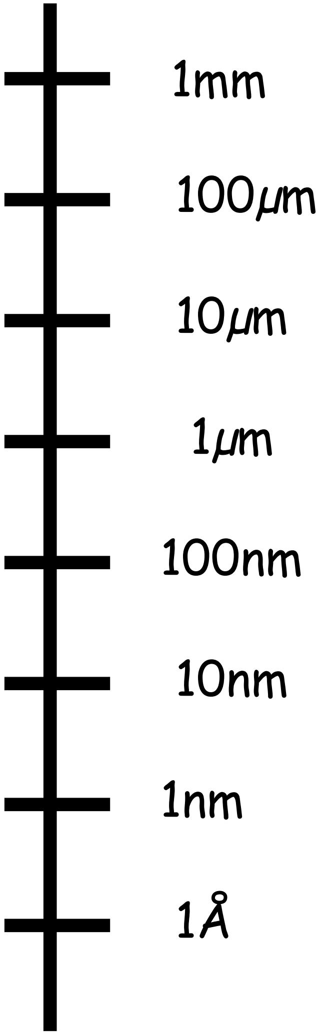
- Phase-relaxation length $\lambda\varphi$: distance that an electron travels before loosing its initial phase.

Example

- Today MOS transistors actually get close to the ballistic regime



Typical length scales



Mean free path in the quantum Hall effect

Mean free path, phase-relaxation length
in a high mobility semiconductor, low T

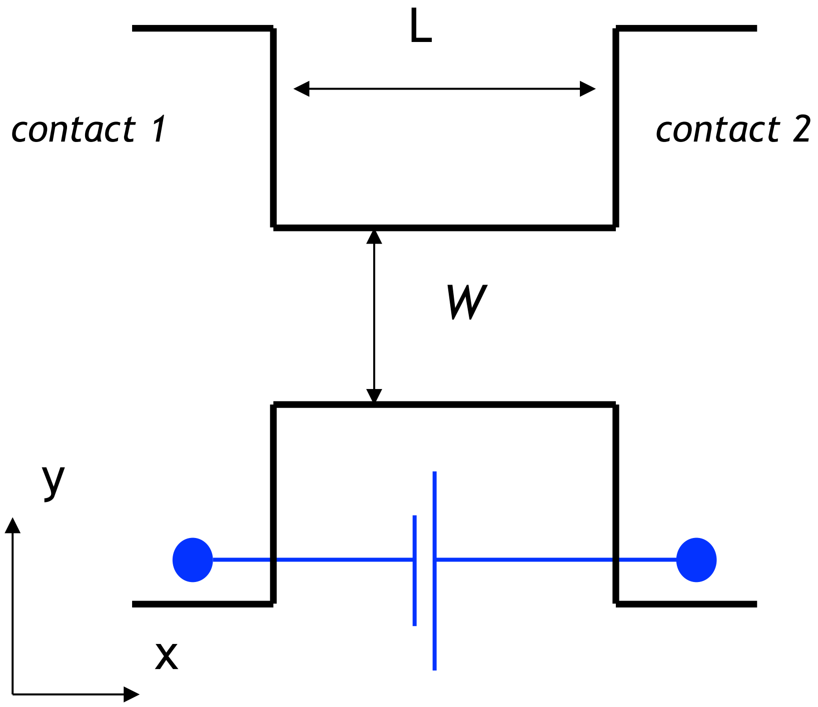
Commercial MOSFET channel length (2005)

Fermi wavelength in semiconductors

Fermi wavelength in metals

Distance between atoms

Resistance of a narrow ballistic channel : towards the quantum of resistance

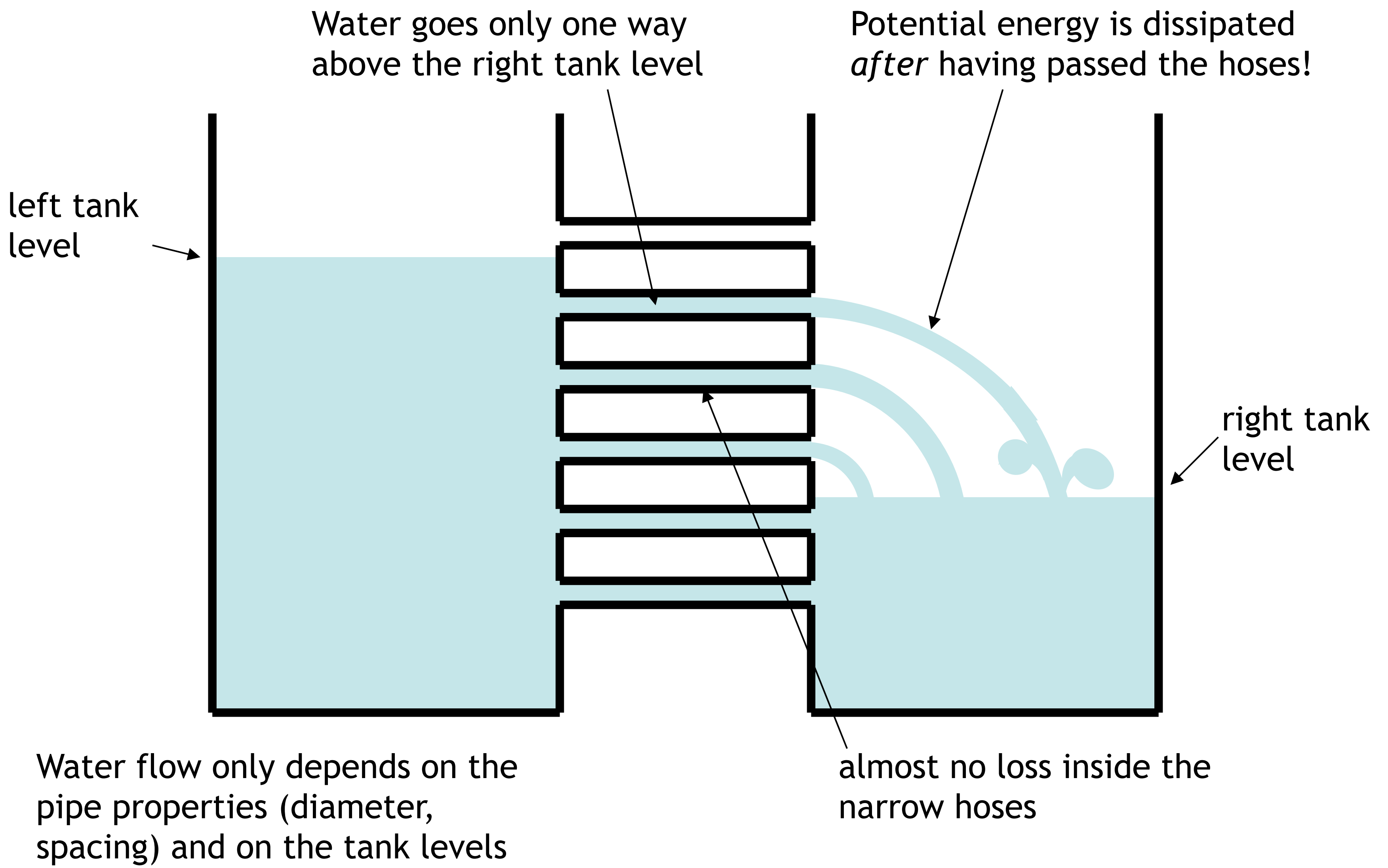


$$k_y = k_n = n\frac{2\pi}{W}$$

$$E = \frac{\hbar^2 k_x^2}{2m} + E_n = \frac{\hbar^2 k_x^2}{2m} + \frac{\hbar^2 k_n^2}{2m}$$

$$M = \frac{k_F W}{2\pi} = \frac{W}{\lambda_F}$$

Ballistic conductors : a classical analogy



Water goes only one way above the right tank level

Potential energy is dissipated *after* having passed the hoses!

left tank level

right tank level

Water flow only depends on the pipe properties (diameter, spacing) and on the tank levels

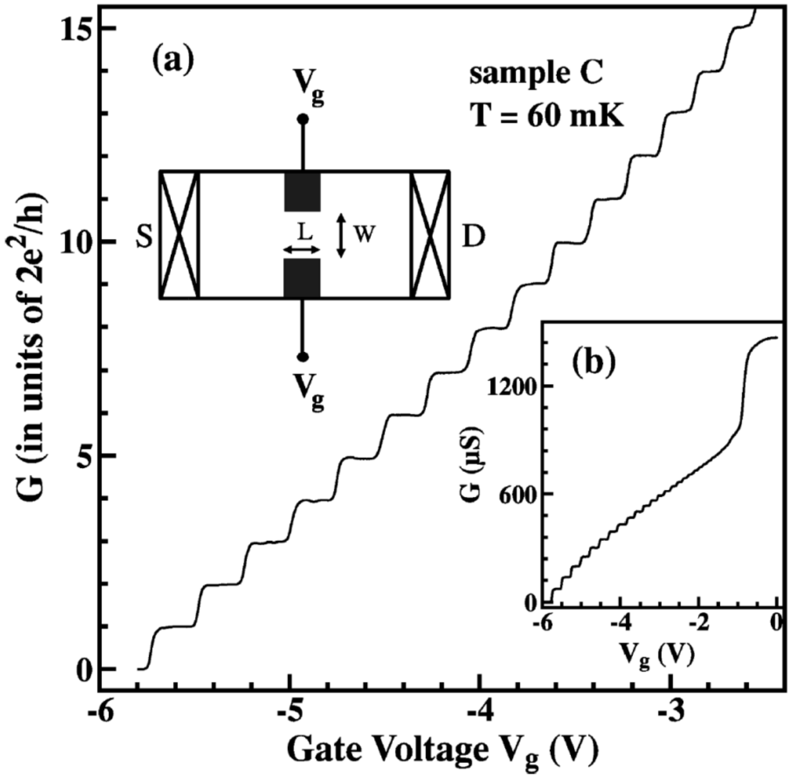
almost no loss inside the narrow hoses

Contact resistance: quantum of resistance

If T=0K and the number of open channels is constant in the range $\mu_1 < E < \mu_2$:

$$I = \frac{2e^2}{h} M \frac{\mu_1 - \mu_2}{e}$$

$$\boxed{G_C = M \frac{2e^2}{h}} \qquad \boxed{R_C = \frac{h}{2e^2 M} = \frac{12.9k\Omega}{M}}$$

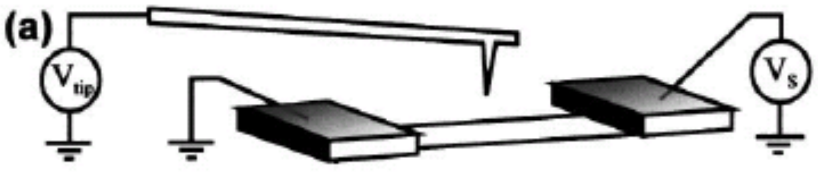


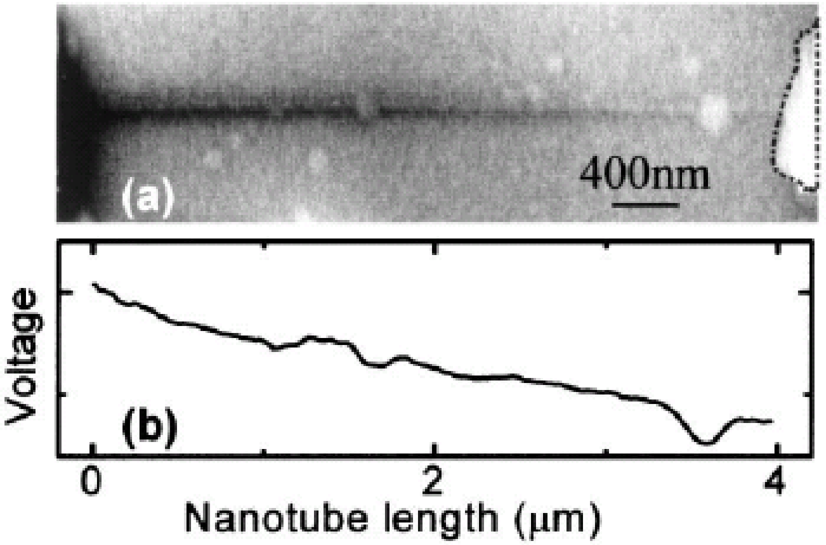
K. J. Thomas *et al*.
Phys. Rev. B 58, 4846 (1998)

First observation in 1988

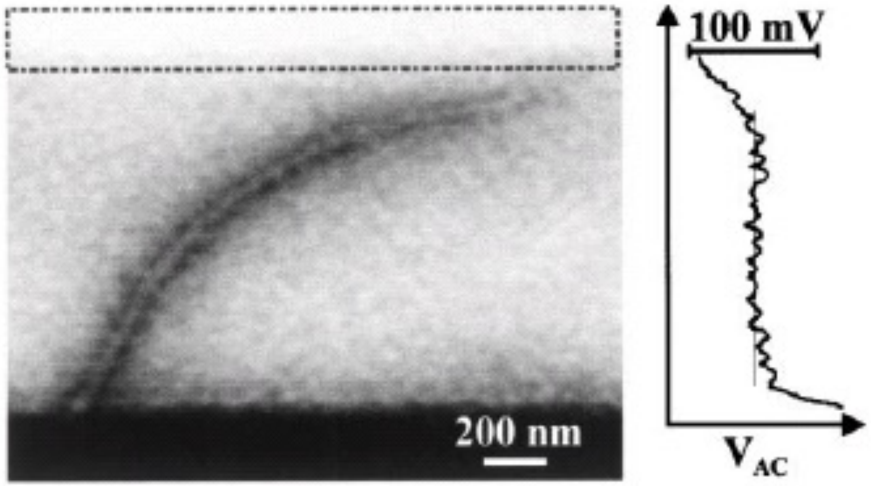
Absence of voltage drop in a ballistic conductor: Experimental verification with carbon nanotubes

After Bachtold et al. (2000)





non –ballistic multi-wall nanotube

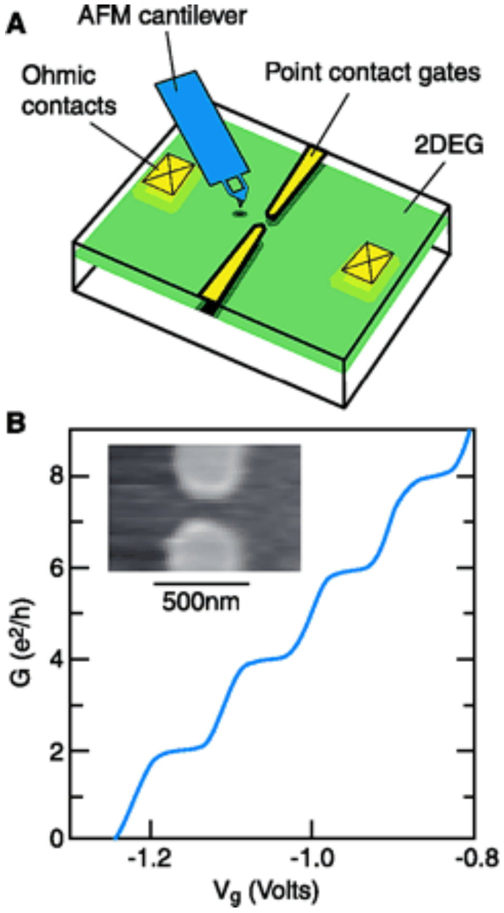


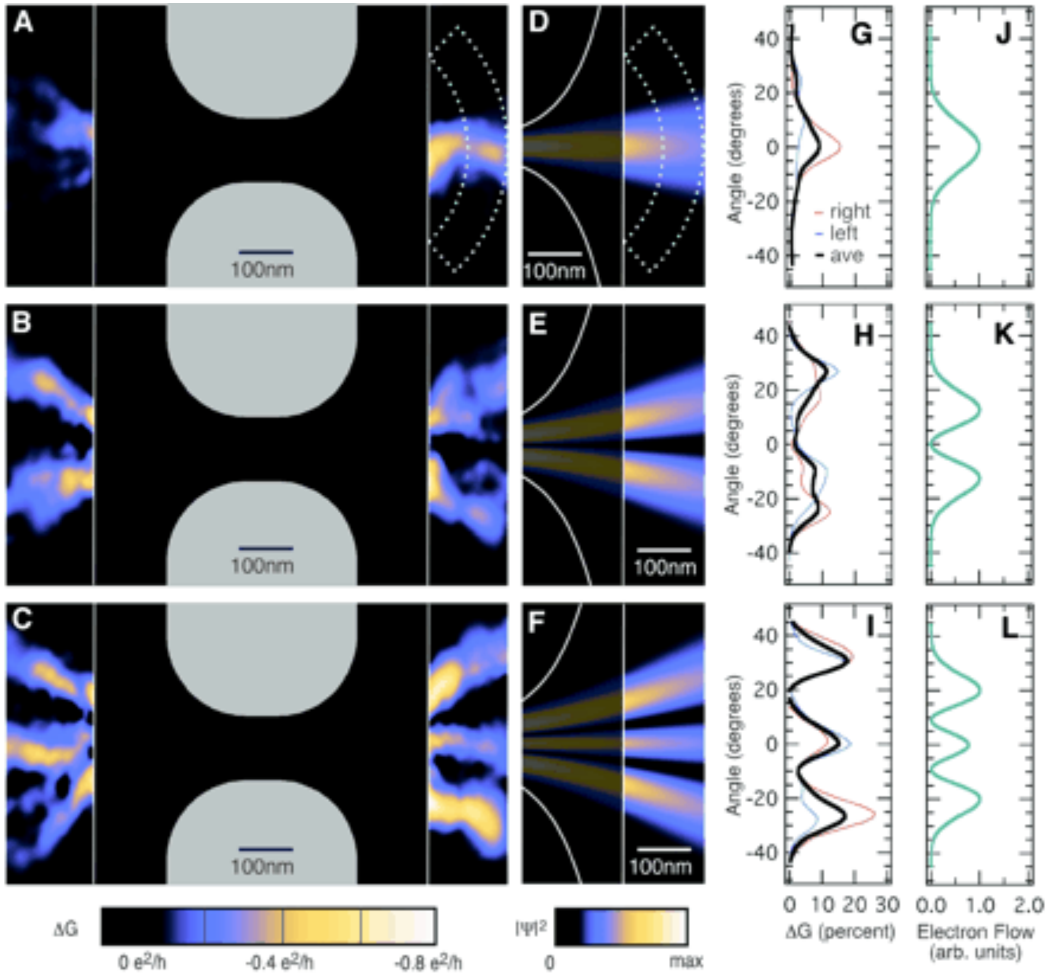
ballistic single wall nanotube: potential is constant inside the nanotube.

Quantum Electronic Transport

Imaging ballistic electron flow

Scanning Gate Microscopy close to a Quantum Point Contact





Experiment: Topinka et al. Science (2000)

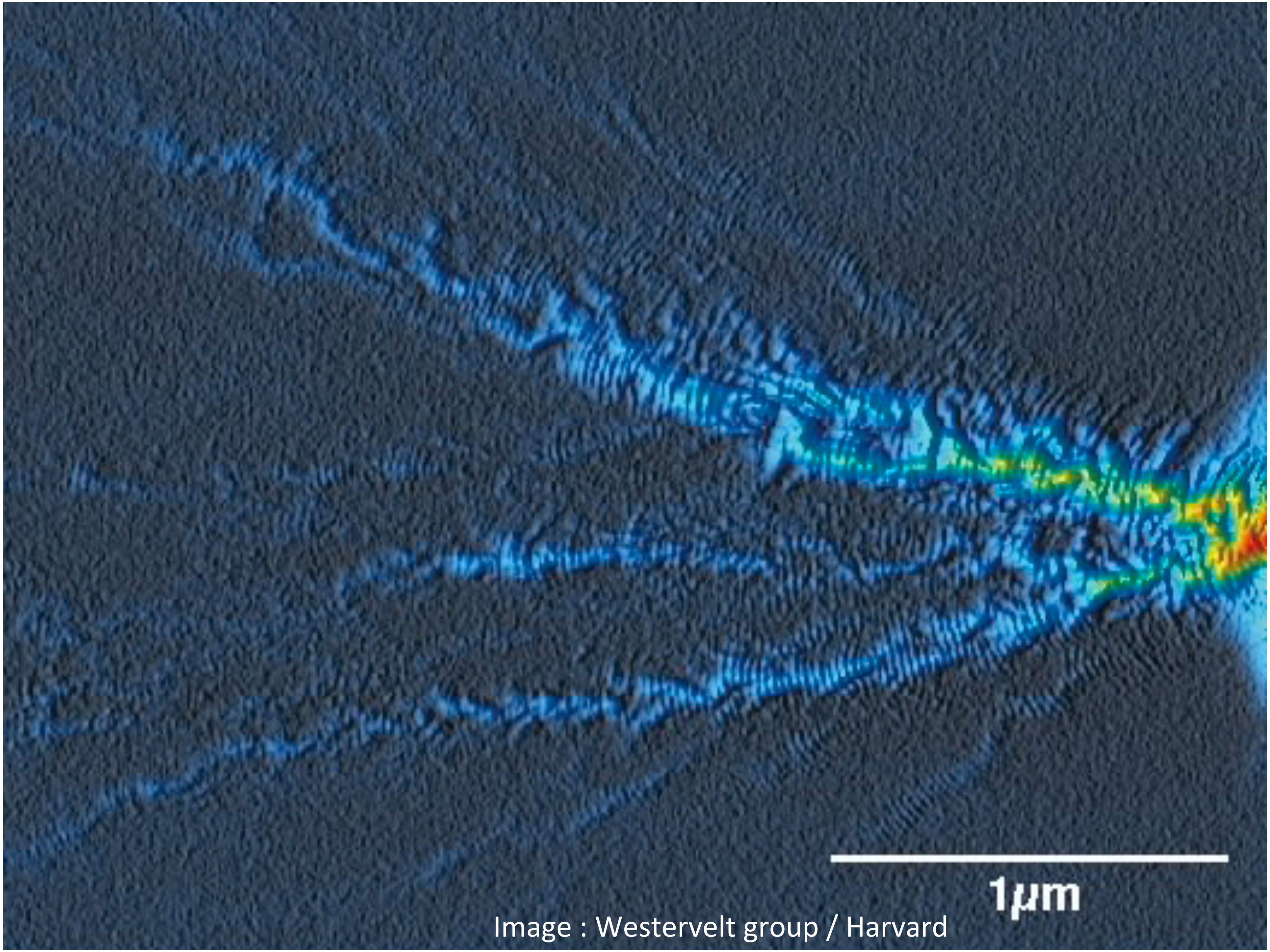
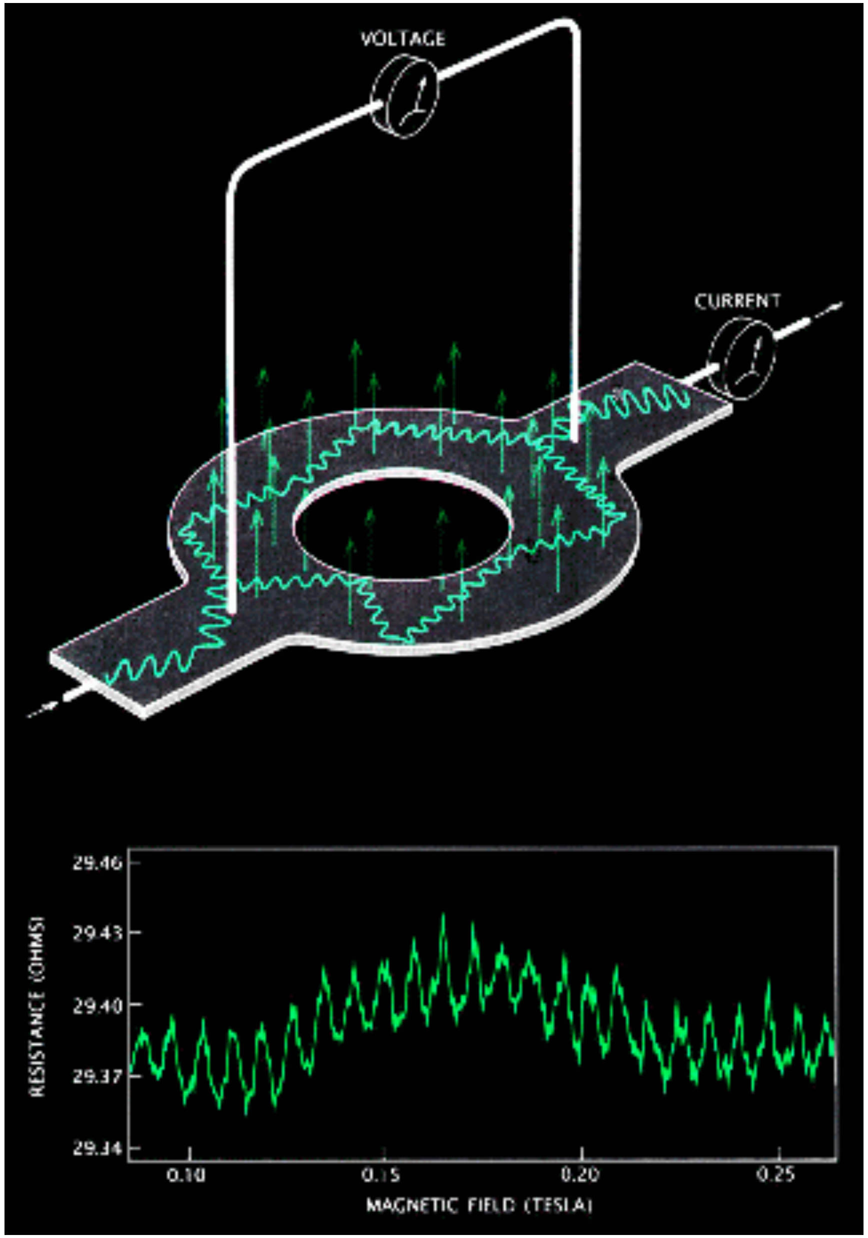


Image : Westervelt group / Harvard

Double slit experiment with electrons : The Aharonov-Bohm effect

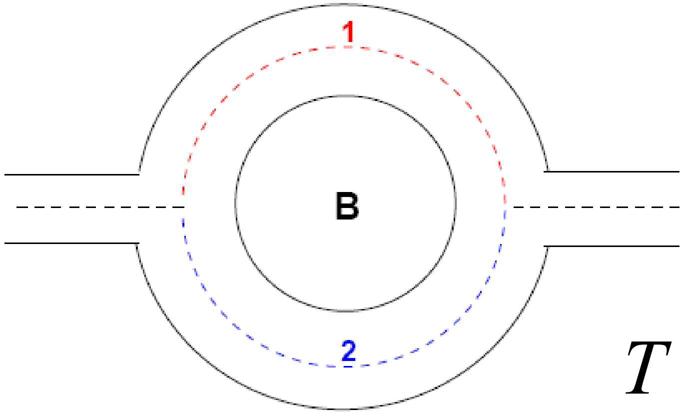


Electrons are waves !

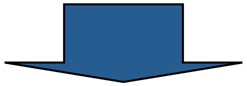
3 length scales:

1/ the Fermi wavelength λF.
2/ the momentum mean free path λm.
3/ the phase relaxation length $\lambda \Phi$.

Interference between two paths under magnetic field



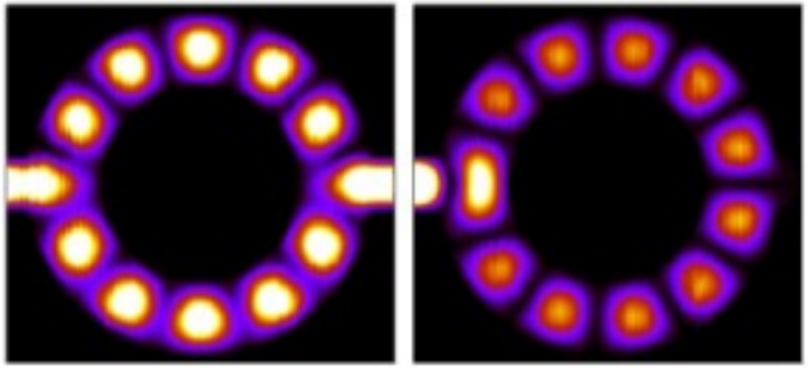
$$\varphi = \pm\frac{e}{\hbar}\int\vec{A}\cdot d\vec{r}$$



$$T = |t_1 + t_2|^2 = 2T_0\left[1 + \cos\left(eBS/\hbar\right) + \varphi_0\right]$$

$$S \times \Delta B = \frac{h}{e} = \Phi_0$$

Partial Local DOS

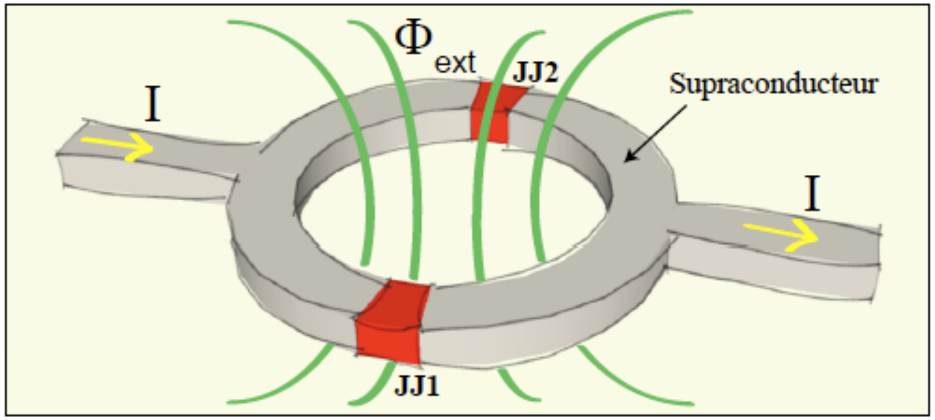


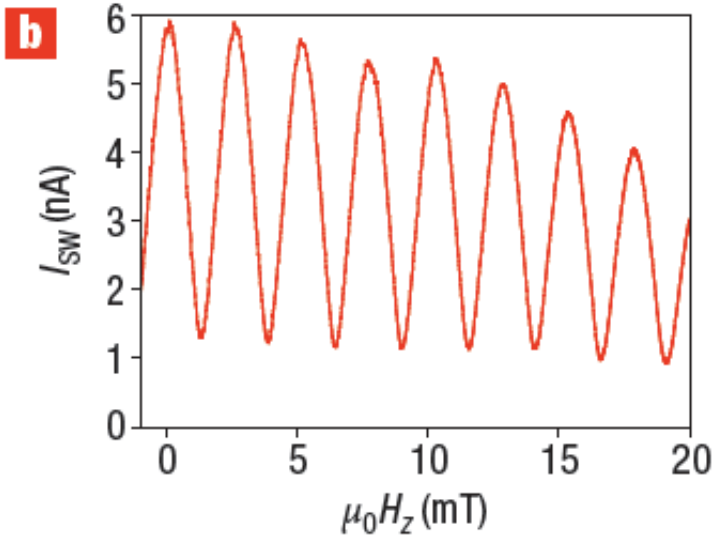
MAX MIN

SQUID

Superconducting quantum interference device

Superconductivity (celebrating 100 years) : coherent macroscopic quantum state





Very sensitive magnetometers

Scanning µ-squid
Force Microscope