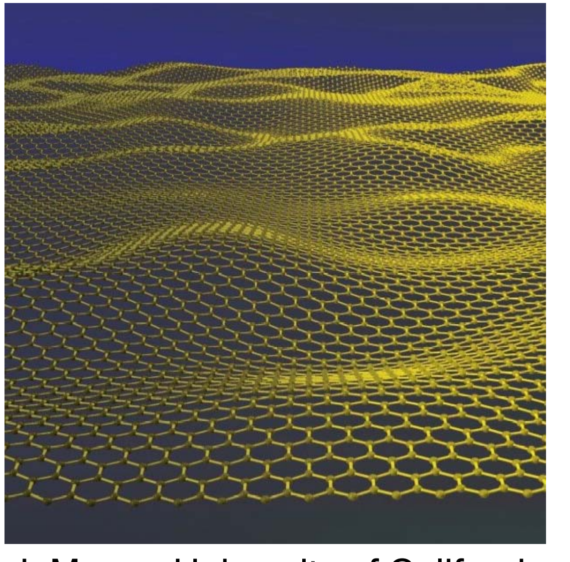
# Nanodispositivos en el límite cuántico: Domando electrones en un mundo de carbono

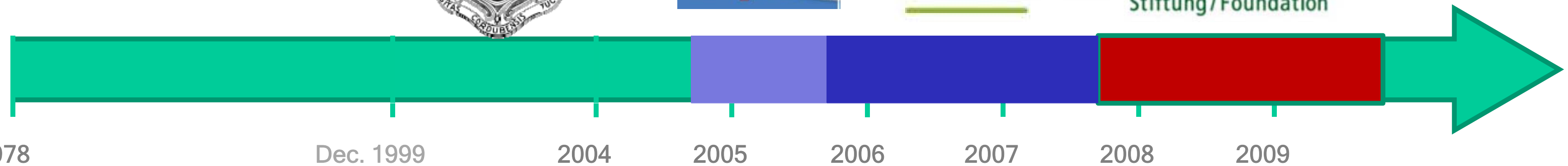
**Luis Foà Torres**

**FaMAF – Universidad Nacional de Córdoba**

**GTMC, Córdoba, 2 de Marzo de 2010**



J. Meyer, University of California

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**TU Dresden, chair of Prof. G. Cuniberti**

**FaMAF, PRH Nanociencias, CONICET**

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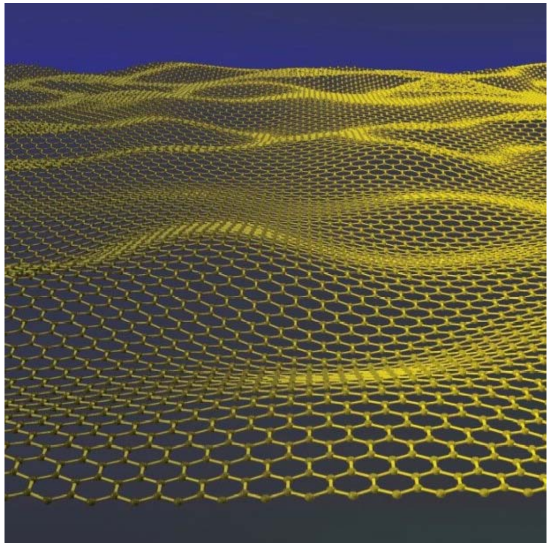
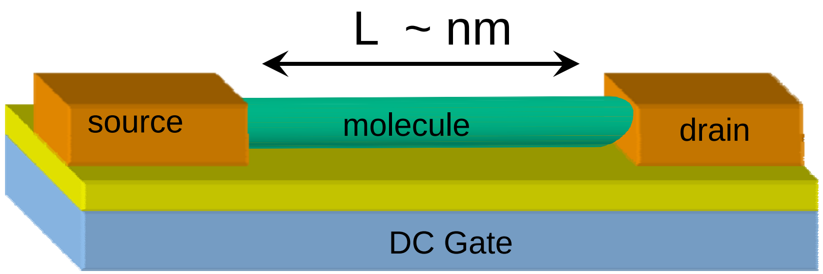
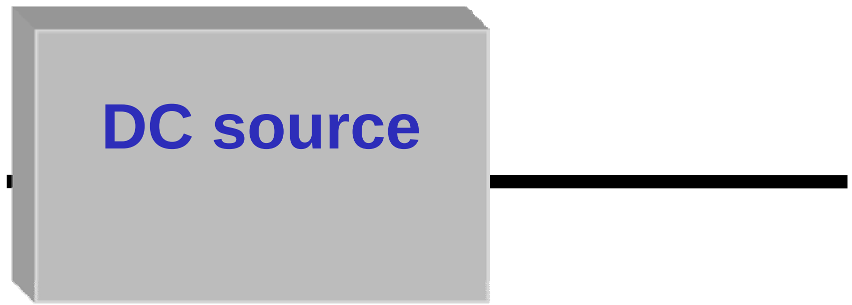


J. Meyer, University of California

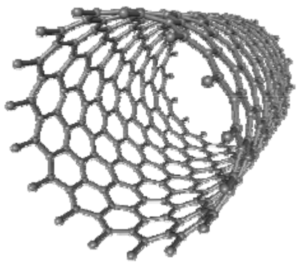
# Single-molecule electronics



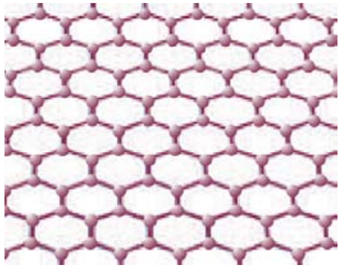




# Carbon-based devices

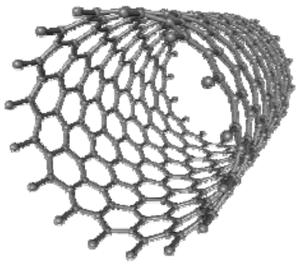


carbon nanotubes

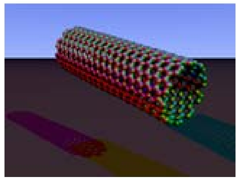


graphene

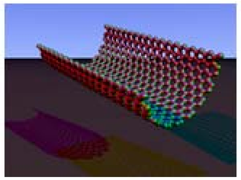
# Carbon-based devices: carbon nanotubes



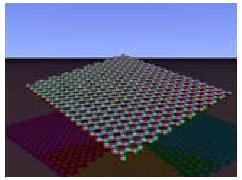
Metallic or semiconducting!



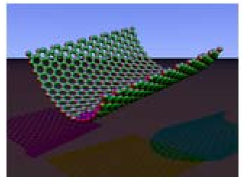
Armchair (*n*,*n*)



The chiral vector is bent, while the translation vector stays straight



Graphene nanoribbon



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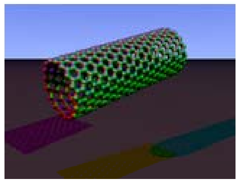
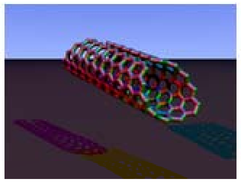
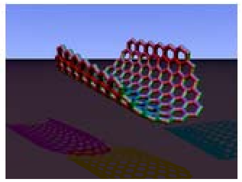


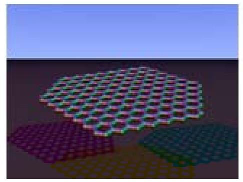
Zigzag (*n*,0)



Chiral (*n*,*m*)

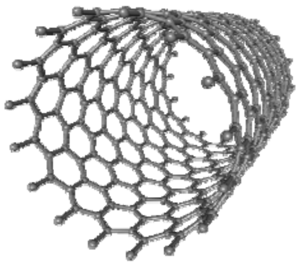


*n* and *m* can be counted at the end of the tube



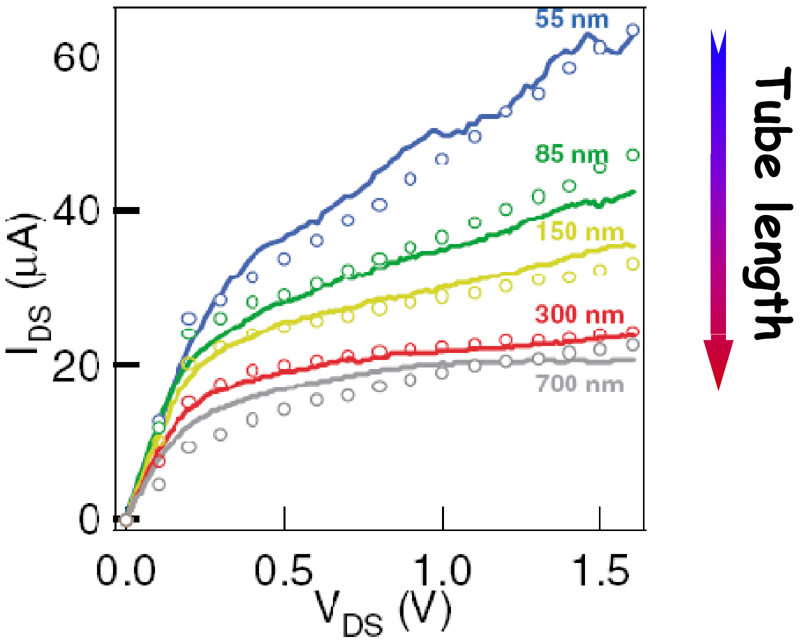
Graphene nanoribbon

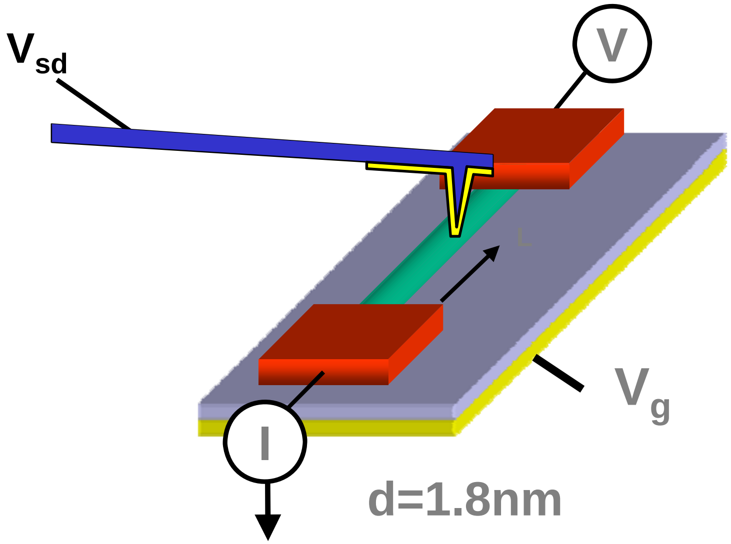
# Carbon-based devices: carbon nanotubes



Metallic or semiconducting!

Extraordinary conduction at low bias, good contacts

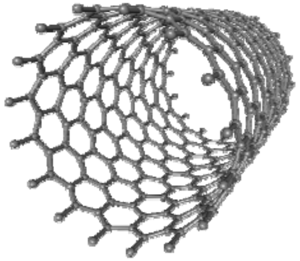



A. Javey et al PRL 92, 106804 (2004),

see also Park et al., Nano Lett. 2004.

# Carbon-based devices: carbon nanotubes



Metallic or semiconducting!

Extraordinary conduction at low bias, good contacts

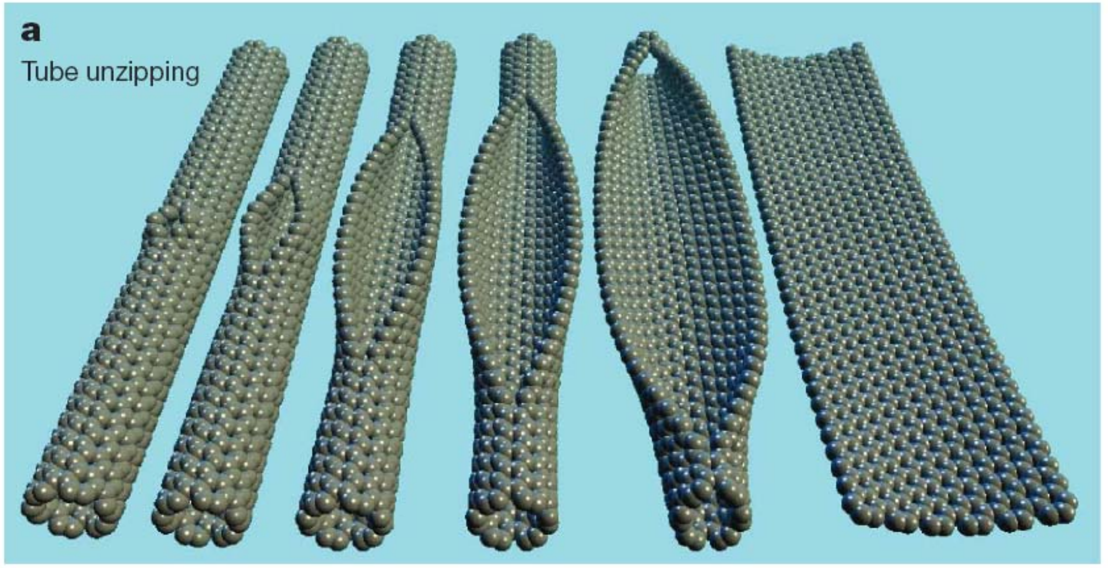
Extraordinary mechanical properties

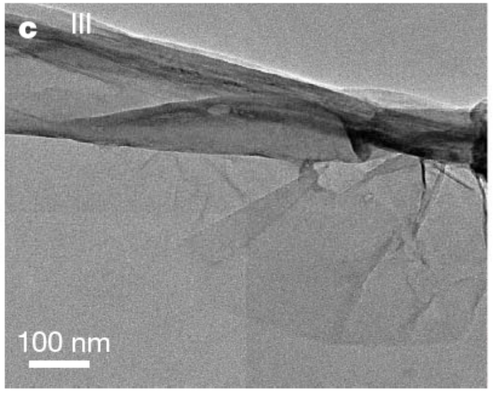
**Comparison of mechanical properties**[13][14][15][16][17][12][18][19]

| Material | Young's Modulus (TPa) | Tensile strength (GPa) | Elongation at break (%) |
|---|---|---|---|
| SWNT | ~1 (from 1 to 5) | 13–53$^{E}$ | 16 |
| Armchair SWNT | 0.94$^{T}$ | 126.2$^{T}$ | 23.1 |
| Zigzag SWNT | 0.94$^{T}$ | 94.5$^{T}$ | 15.6–17.5 |
| Chiral SWNT | 0.92 | | |
| MWNT | 0.8–0.9$^{E}$ | 11–150$^{E}$ | |
| Stainless Steel | ~0.2 | ~0.65–3 | 15–50 |
| Kevlar | ~0.15 | ~3.5 | ~2 |
| Kevlar$^{T}$ | 0.25 | 29.6 | |

$^{E}$Experimental observation; $^{T}$Theoretical prediction

# Carbon-based devices: unzipping carbon nanotubes



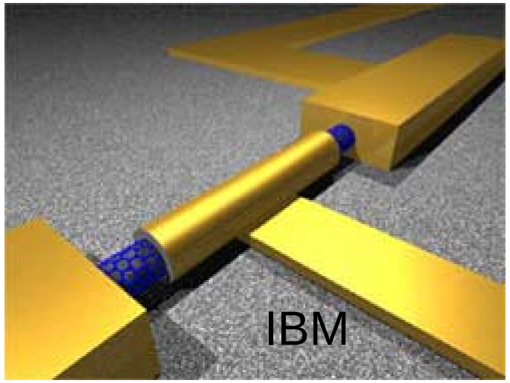



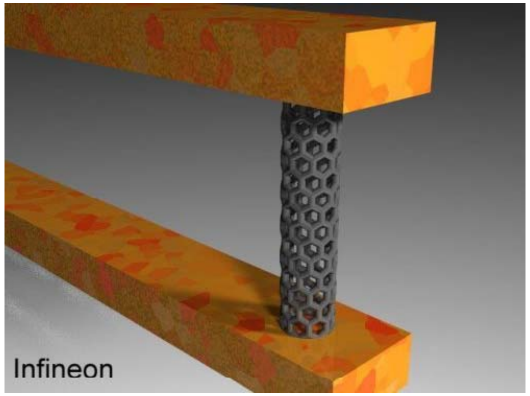

nature
Vol 458 | 16 April 2009 | **doi:10.1038/nature07872**

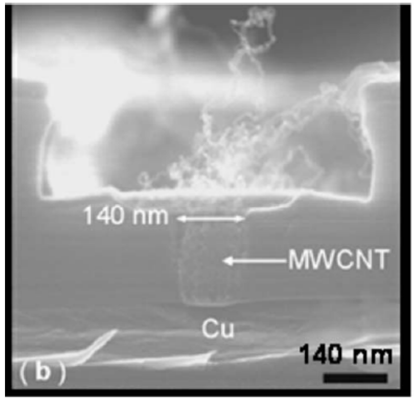
# Carbon-based devices: graphene


A. K. Geim, *et al.*
*Science* **324**, 1530 (2009)

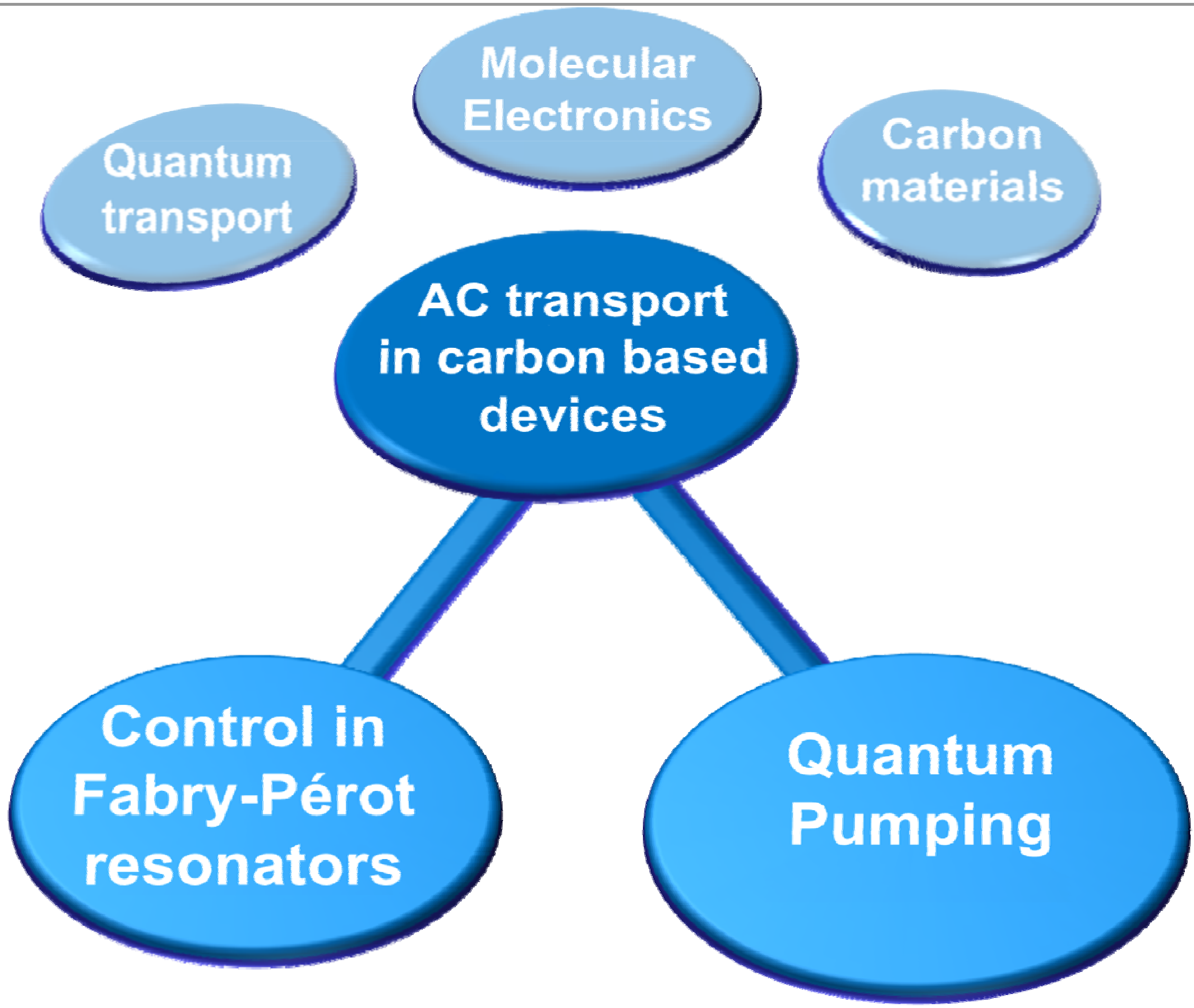
# Carbon-based devices: applications



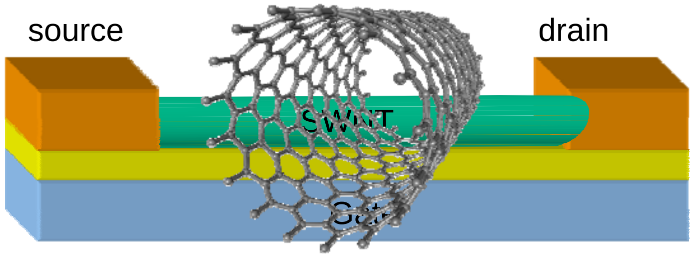




Coiffic et al. Appl. Phys. Lett. **91**, 252107 (2007)


Molecular Electronics
Quantum transport
Carbon materials
AC transport in carbon based devices
Control in Fabry-Pérot resonators
Quantum Pumping

# Fabry-Pérot interference in nanotubes

Good quality contacts,
(almost) ballistic transport!




Fabry-Pérot interfere
in nanotube device

?

Conductance Oscillations

**Effect of ac fields…**
**Control?**

**Recent experiments on noise**

F. Wu *et al.*, PRL **99**, 156803 (2007).

L. G. Herrmann *et al.* PRL **99**, 156804 (2007).

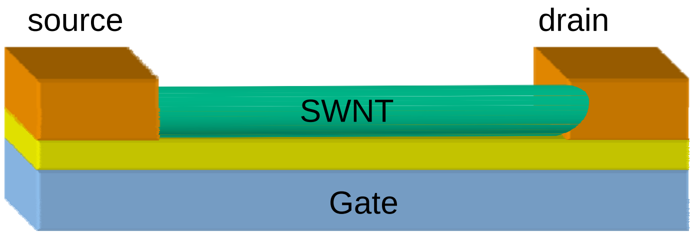
Na Young Kim *et al.*, PRL **99**, 036802 (2007).

Conductance
stability diagram
controlled by level spacing
not charging energy

gate

# Fabry-Pérot interference in nanotubes

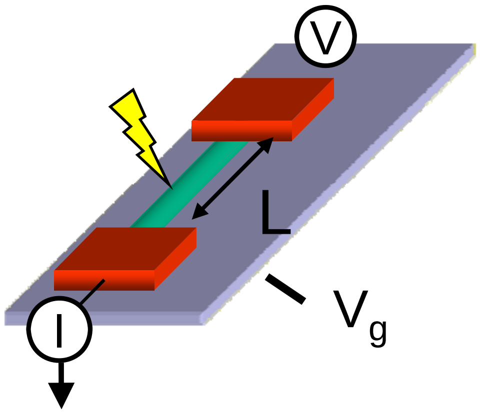
Good quality contacts,
(almost) ballistic transport!




## Why AC potentials?

**control** **novel phenomena** **applications**

# Floquet Theory approach for transport




$$H(t) = H_{\mathrm{CNT}}(t) + H_{\mathrm{leads}}(t) + H_{\mathrm{CNT/leads}}(t)$$

pi-orbitals model

$$E_i(t) = V_{ac}\cos(\Omega t)$$

## Average current

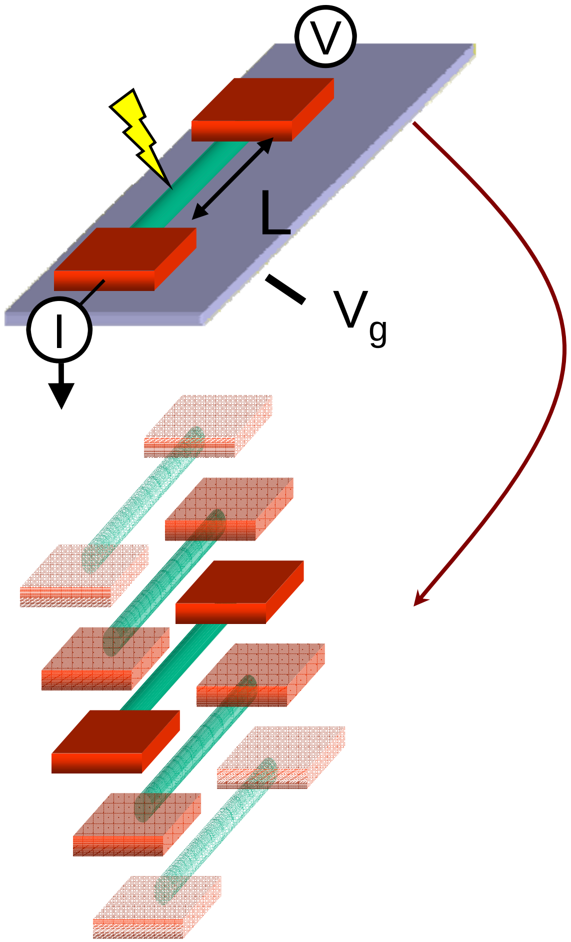
M. Moskalets and M. Büttiker, PRB **66**, 205320 (2002).
Camalet *et al.*, PRL **90**, 210602 (2003).
Foa Torres, PRB **72**, 245339 (2005).

## Current noise

$$S(t,t') = \frac{1}{2}\langle[\Delta I(t), \Delta I(t')]_+\rangle$$

M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).
S. Kohler *et al.,* Phys. Rep. **406**, 379 (2005).

# CNT Floquet Hamiltonian




$$H(t) = H_{\rm CNT}(t) + H_{\rm leads}(t) + H_{\rm CNT/leads}(t)$$

pi-orbitals model

$$E_i(t) = V_{ac}\cos(\Omega t)$$

Floquet Theorem leads to time-independent replica picture

$$H_F = H(t) - i\hbar\frac{\partial}{\partial t}$$

Floquet space

$$\mathbf{R} \otimes \mathbf{T}$$

**Floquet replica**

$$|\, j, n\rangle$$

one electron at site $j$

# Floquet Theory approach for transport

## Average current

$$\bar{I} = \frac{e}{h} \sum_{n=-\infty}^{\infty} \int d\varepsilon \left[ T_{LR}^{(n)}(\varepsilon) f_R(\varepsilon) - T_{RL}^{(n)}(\varepsilon) f_L(\varepsilon) \right]$$

M. Moskalets and M. Büttiker, PRB **66**, 205320 (2002).
Camalet *et al.*, PRL **90**, 210602 (2003).

$$G = d\bar{I} / dV_{bias}$$ dc conductance

## Current noise

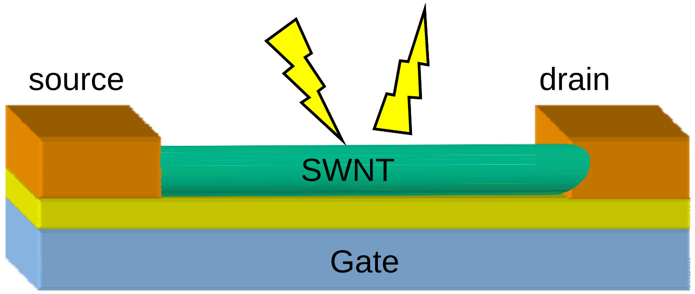
$$S(t,t') = \frac{1}{2} \langle [\Delta I(t), \Delta I(t')]_{+} \rangle$$

$$\bar{S} = \frac{1}{\mathcal{T}} \int_0^{\mathcal{T}} dt \int_{-\infty}^{+\infty} d\tau S(t, t-\tau)$$

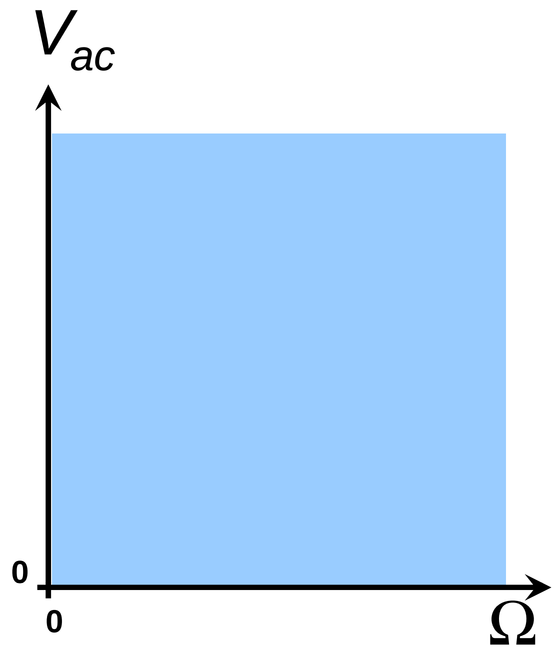
## Signal to noise ratio

$$F = \bar{S}/(e\bar{I})$$ dimensionless Fano factor

# Modifications of the FP pattern under AC gating




$$E(t) = V_{ac}\cos(\Omega t)$$



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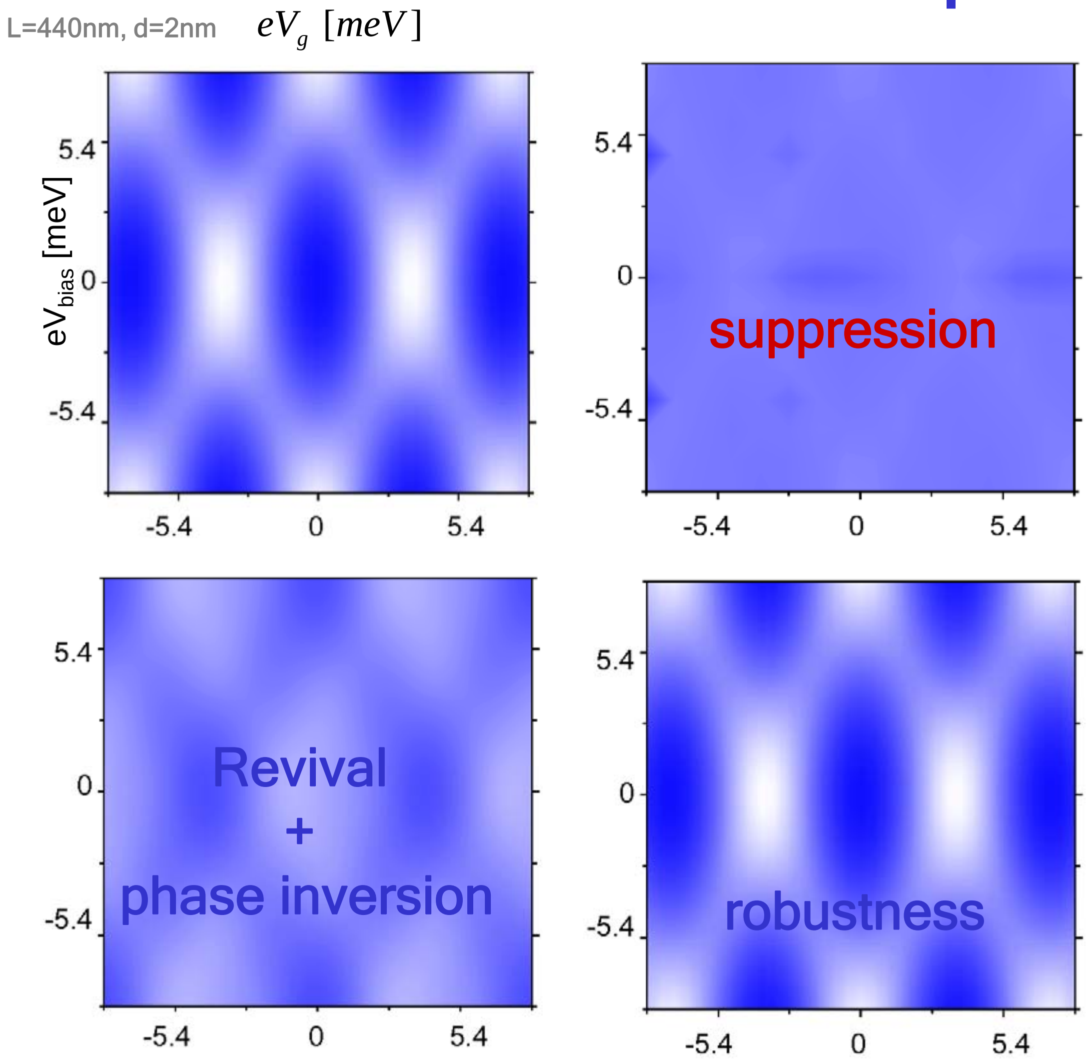
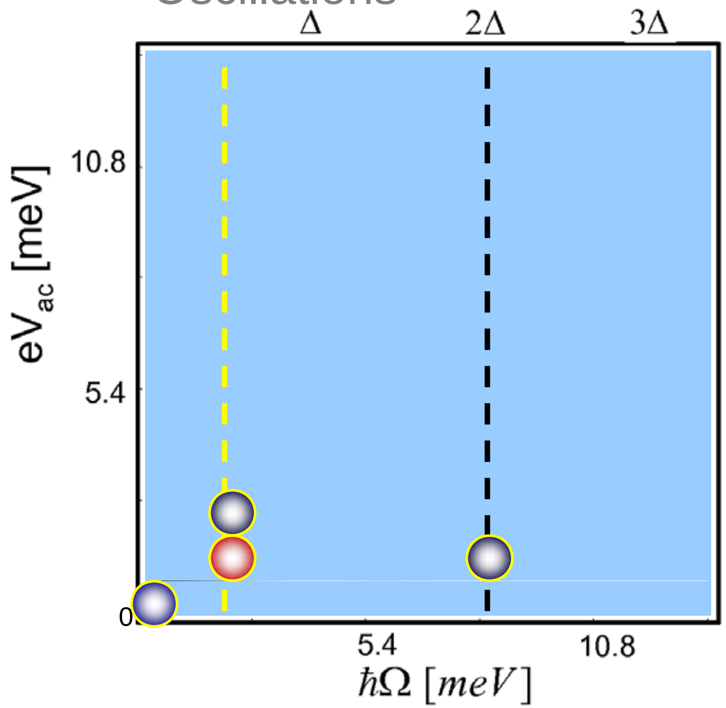



Half Amplitude of Conductance Oscillations

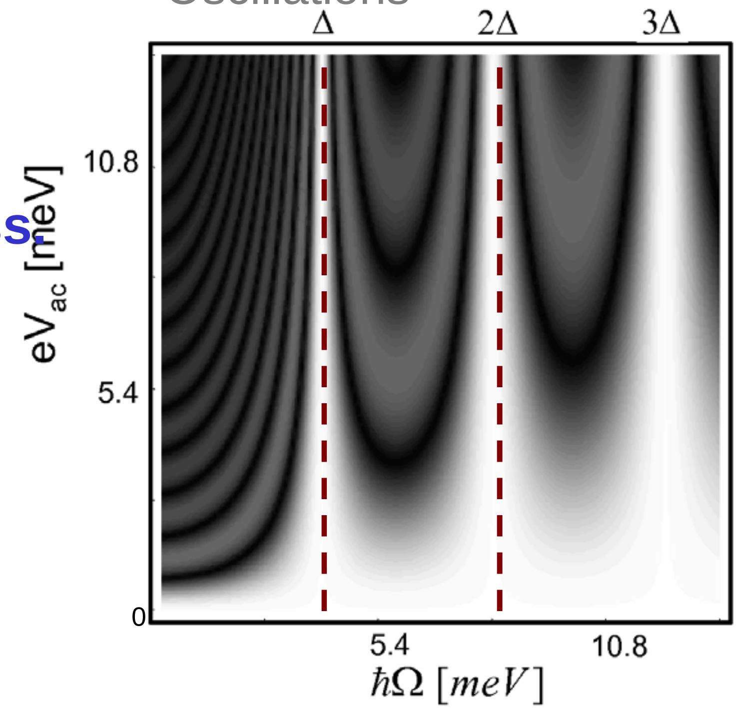


# Modifications of the FP pattern under AC gating

**Oscillations even in the adiabatic limit.**

**Wagon-wheel condition: Robustness.**

Half Amplitude of Conductance Oscillations

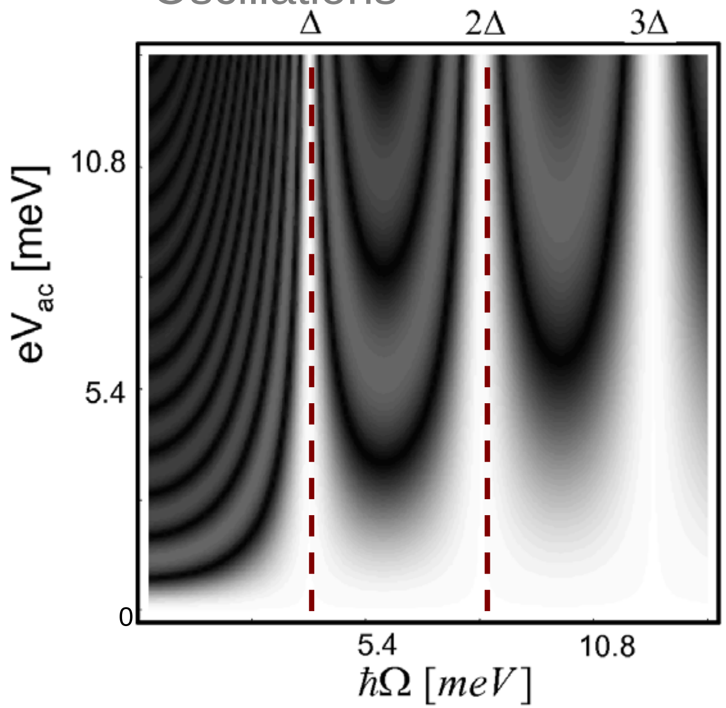



LFT and G. Cuniberti, Appl. Phys. Lett. 2009

**LITE Project, Boston University, http://lite.bu.edu/**

# Modifications of the FP pattern under AC gating: Wagon-wheel effect

Half Amplitude of Conductance Oscillations




For the noise this picture requires modifications…

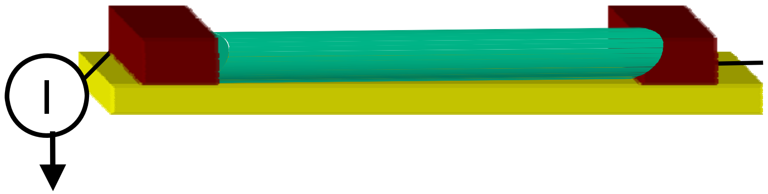
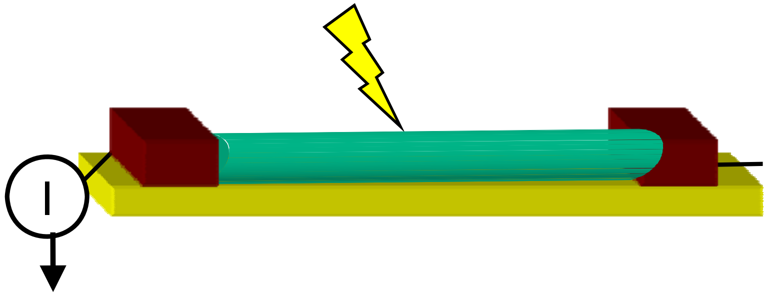
LFT and G. Cuniberti, Appl. Phys.Lett. 2009

**LITE Project, Boston University, http://lite.bu.edu/**

# Dynamically induced Noise

Noise at zero bias?

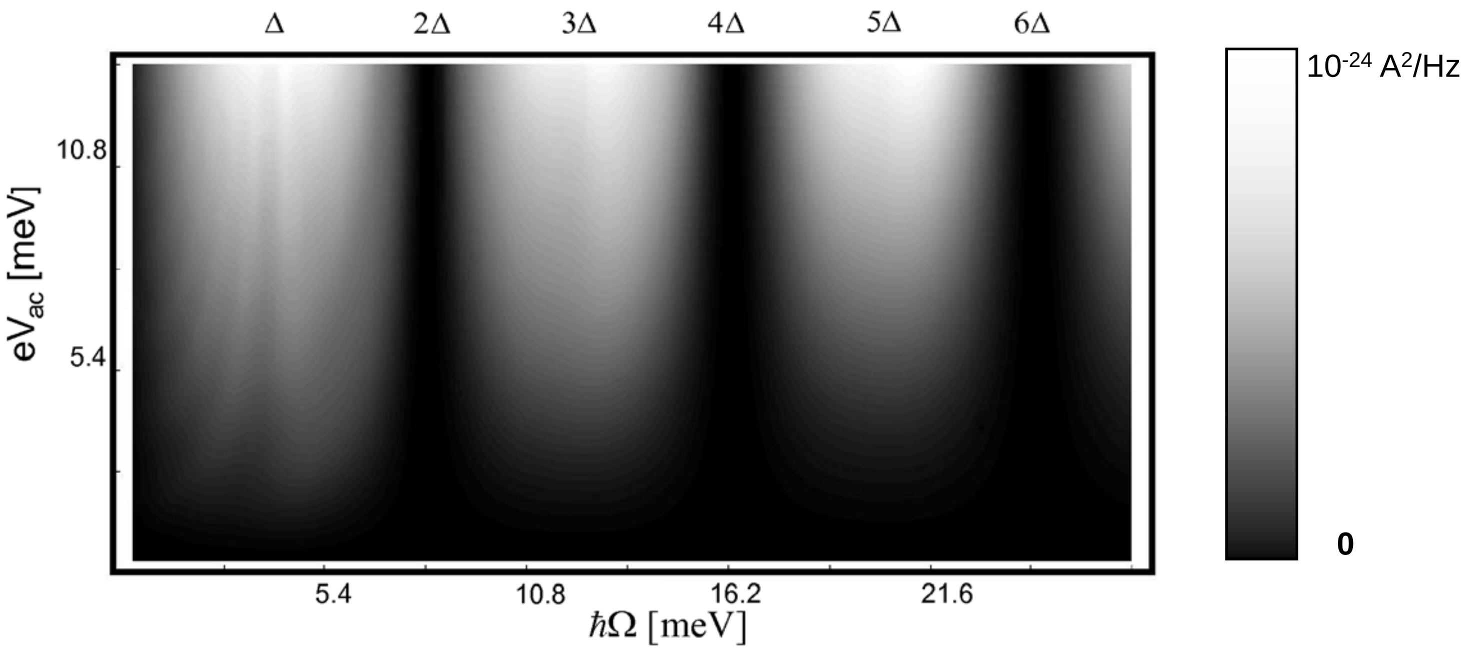
$$kT \to 0, V_{bias} \to 0$$

| dc | ac |
|---|---|
|   |   |
| $\bar{S} = 0$ | $\bar{S} \neq 0$ |

**Adiabatic approximation fails completely in this parameter regime!**

# Dynamical suppression of Noise

Noise Power




**Noise vanishes for even multiples of the mean level spacing:**

**Phase sensitivity!**

LFT and G. Cuniberti, Appl. Phys. Lett. **94**, 222103 (2009); C.R. Phys.**10**, 297 (2009).

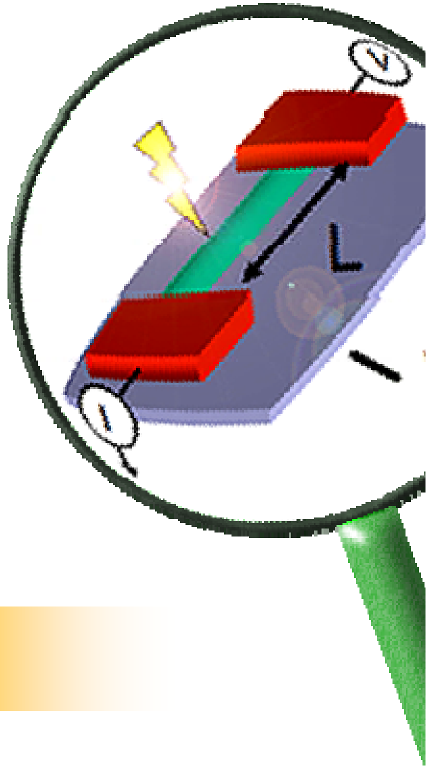
# Partial Conclusions

**AC Control** of a nanotube Fabry-Perot resonator.

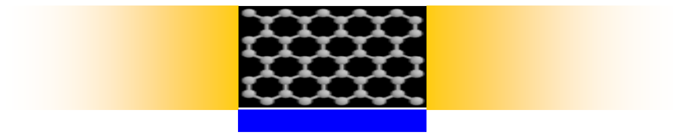
Wagon-wheel effect in the quantum domain.

Phase sensitivity of the noise.

LFT and G. Cuniberti, Appl. Phys. Lett. **94**, 222103 (2009);
C. R. Phys.**10**, 297 (2009).



C. G. Rocha, LFT and G. Cuniberti,
Phys. Rev. B in press (2010).



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CARBON NANOTUBE DEVICES AT THE QUANTUM LIMIT
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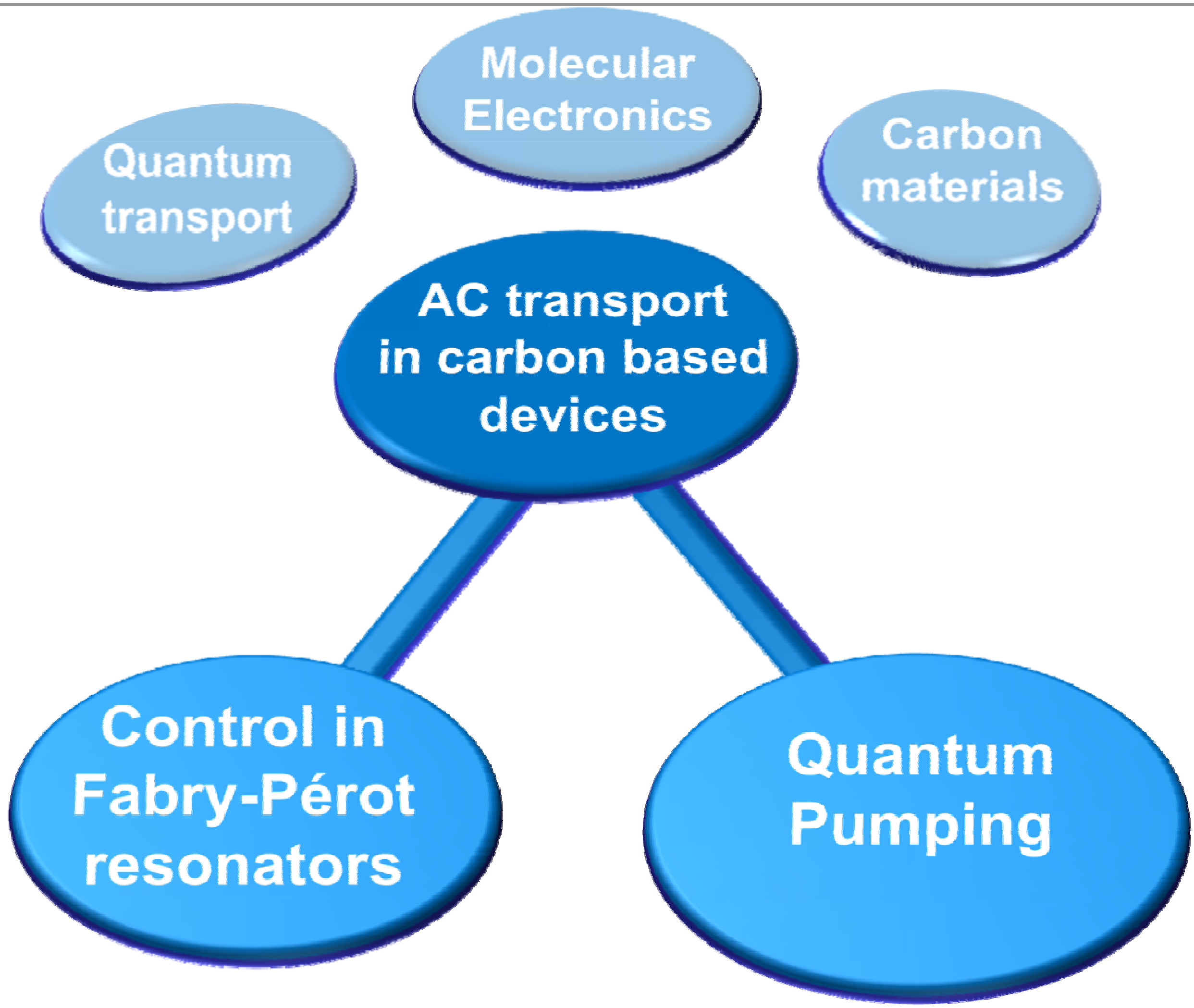
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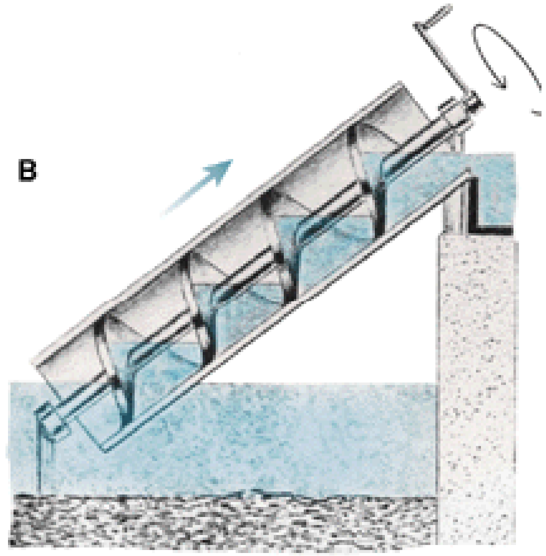
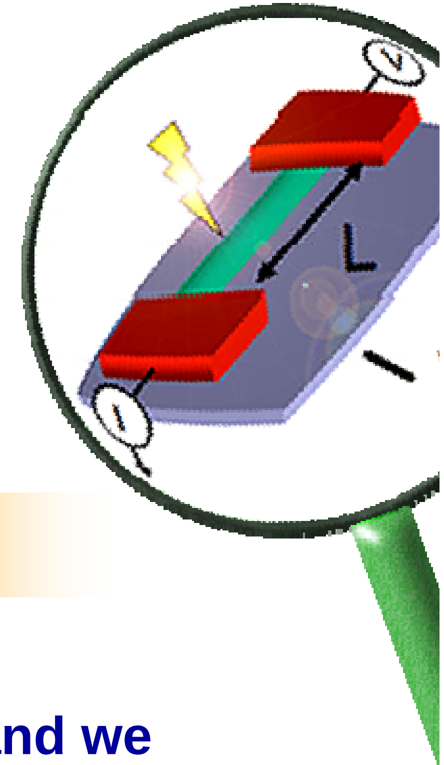



Altshuler and Glazman, Science 283, 1864 (1999)

# Conclusions



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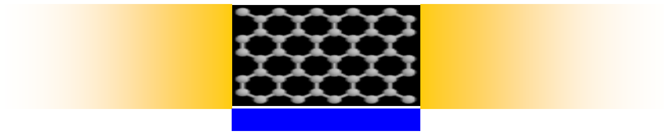

**Quantum Pumping with a single parameter is possible and we can exploit the electronic structure of carbon devices to tune it**

LFT et al., unpublished (2010)

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