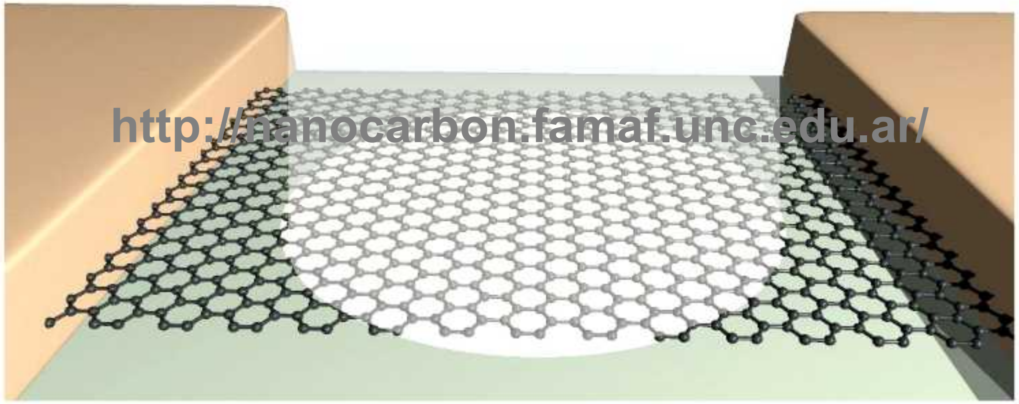
UNC Universidad Nacional de Córdoba

400 años 1613-2013
FORMÁ PARTE DE ESTA HISTORIA

CONICET



http://nanocarbon.famaf.unc.edu.ar/

Tuning the transport properties of graphene through AC fields

Hernán L. Calvo (RWTH – Aachen)
Claudia G. Rocha (University of Jyväskylä, Finland)
Lucas Ingaramo (UNC - Córdoba)
Pablo Pérez Piskunow (UNC – Córdoba)
G. Cuniberti (TU Dresden)
Horacio M. Pastawski (UNC - Córdoba)
Stephan Roche (ICN - Barcelona)

Luis E. F. FOA TORRES

Graphene 2012, Brussels
April 2012

Our vision : AC fields for novel, low dissipation, active nanodevices

Why ac fields?

control	novel phenomena	applications
conductance	quantum pumping	
noise	laser-induced gaps	
	Floquet topological insulators	
	...	

LFT, PRB 72, 245339 (2005).
LFT and Cuniberti, APL 94, 222103 (2009).
Rocha, LFT and Cuniberti, PRB 81, 115435 (2010);
Rocha, Pacheco et al. EPL (2011)
LFT, Calvo, Rocha, and Cuniberti, APL 99, 092102 (2011).
Ingaramo and LFT, to be published.

Calvo, Pastawski, Roche and LFT, APL 98, 232103 (2011).
Calvo, Pastawski, Roche and LFT, to appear (2012).
Suárez-Morell and LFT, to be published.

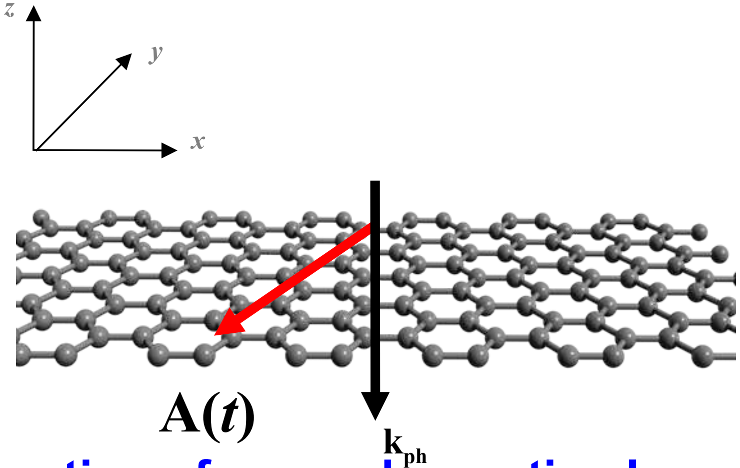
S. V. Syzranov, M. V. Fistul, and K. B. Efetov, PRB 78, 045407 (2008). *microwaves*
T. Oka and H. Aoki, PRB 79, 081406(R) (2009) “*Photovoltaic Hall effect in graphene*” *visible light*

Could a laser induce a measurable gap in graphene?

How and for which frequencies / intensities / polarization?

Idea: Exploit the low dimensionality and the peculiar electronic structure of graphene.

Overview of the simulation scheme




Hernán Calvo

Semi-classical propagation of monochromatic plane waves:

$$\mathbf{A} = \mathrm{Re}\,\mathbf{A}_0 \exp[\mathrm{i}(\mathbf{k}\cdot\mathbf{r} - \Omega t)]$$

$$A_0 = \frac{E}{\Omega}\left(1, e^{i\varphi}\right)$$

Intensity and polarization

Hamiltonian model for the electronic structure: k.p, tight-binding

$$\hat{\boldsymbol{k}}' \to \hat{\boldsymbol{k}} - \frac{e}{\hbar}\boldsymbol{A}$$

Floquet theory for the solutions

Contents not available for the online version.
For more info please check
http://nanocarbon.famaf.unc.edu.ar/

Brief Summary of Floquet Theory

$$\boxed{\left[\underbrace{\hat{H}(x,t) - i\hbar\frac{\partial}{\partial t}}_{\hat{H}_F(x,t)}\right]\phi_\alpha(x,t) = \varepsilon_\alpha\phi_\alpha(x,t)}$$

Floquet Hamiltonian

Floquet (Sambe) space

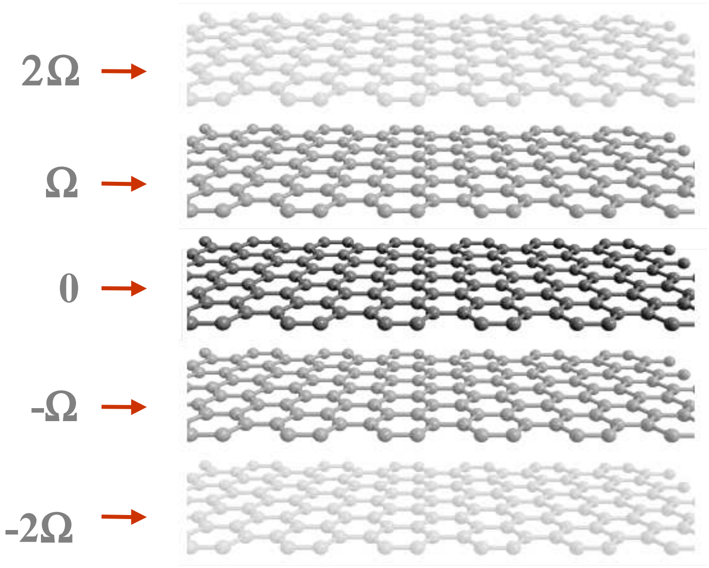
Usual Hilbert space → $\mathbf{R} \otimes \mathbf{T}$ ← **Space of T-periodic functions**

Then use Floquet theory approach for driven transport:

S. Camalet *et al.*, PRB 70, 155326 (2004);

S. Kohler, J. Lehmann and P. Hänggi, Phys. Rep. 406, 379 (2005).

L. Foa Torres, PRB 72 245339 (2005)



Laser-induced gaps in the Floquet spectra

$$N(\varepsilon) = -\frac{1}{\pi} Im \left\{ Tr \left(\mathbf{G}_F(\varepsilon) \right)_{0,0} \right\}$$

For visible light: effects are too small,
the required gate voltages as too large...

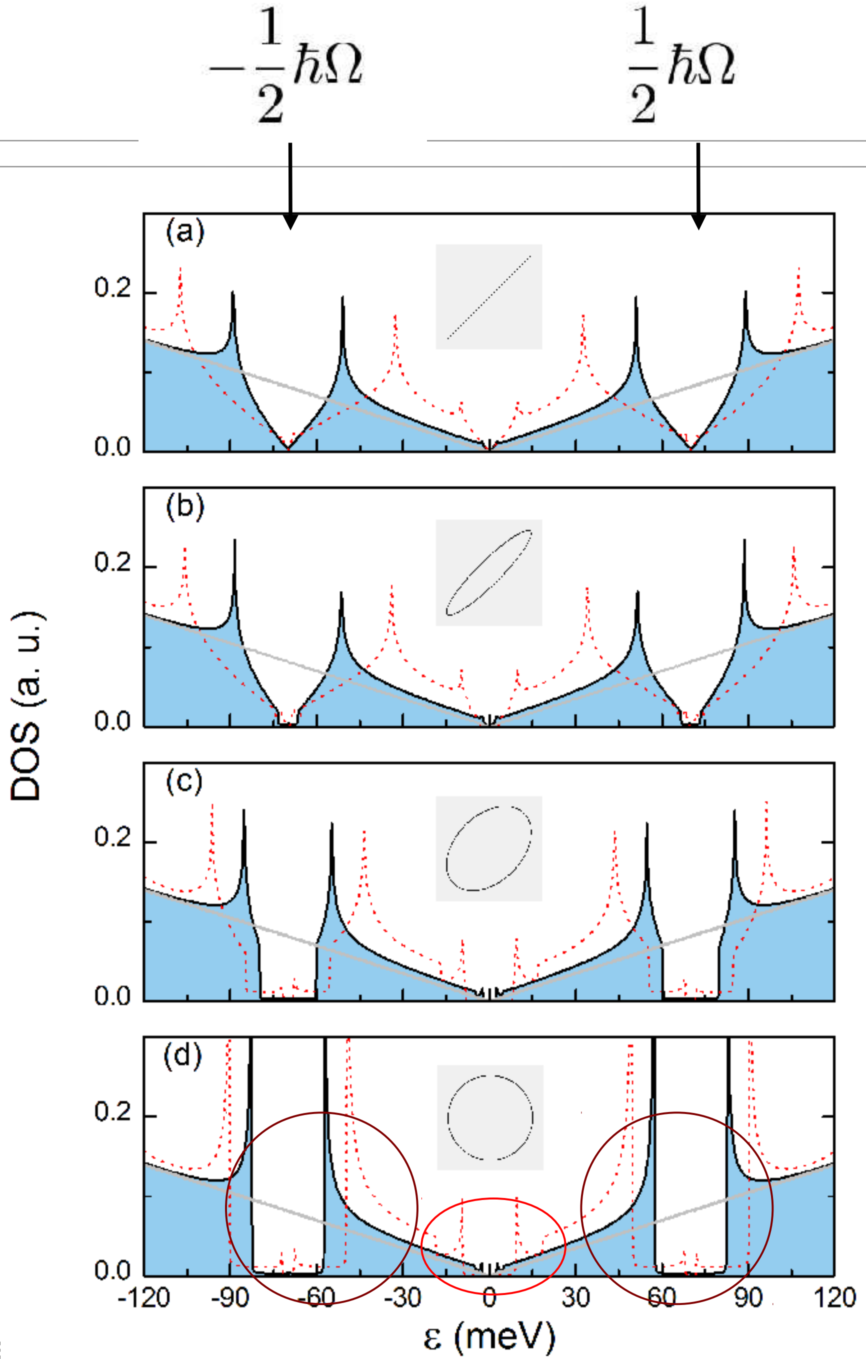
Mid-infrared laser, λ = 8 μm

Laser-induced gaps

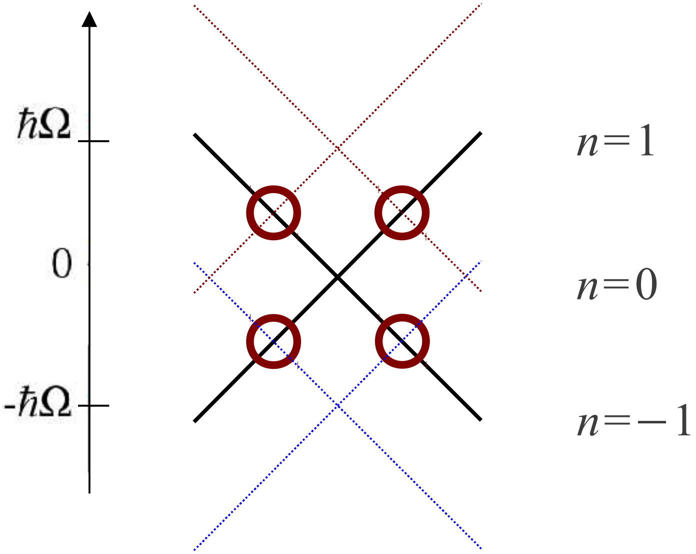
$$N(\varepsilon) = -\frac{1}{\pi} Im \left\{ Tr \left(\mathbf{G}_F(\varepsilon) \right)_{0,0} \right\}$$

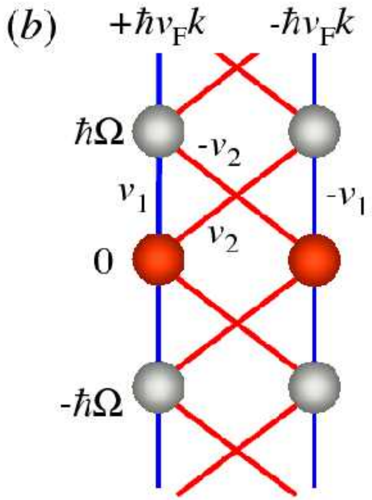
Gaps evolve with polarization

They appear at ± ħΩ/2
and at the Dirac point (pseudogap)



Simple picture for laser-induced gaps





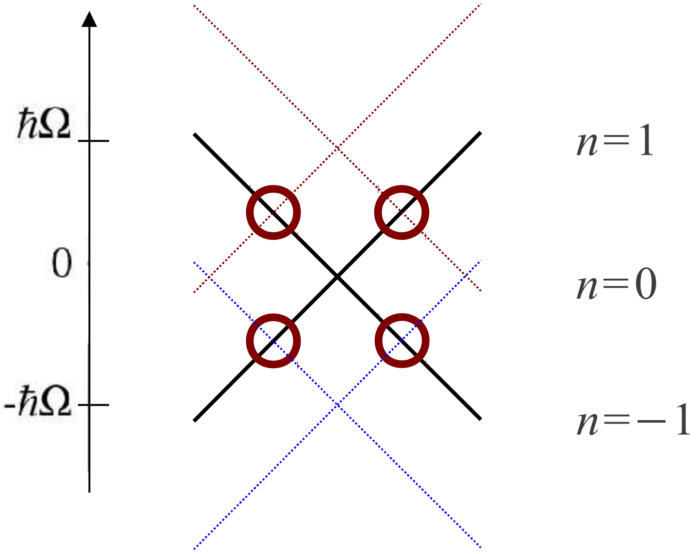
***Inelastic* Bragg reflection /**
Lifting of degeneracies in Floquet space

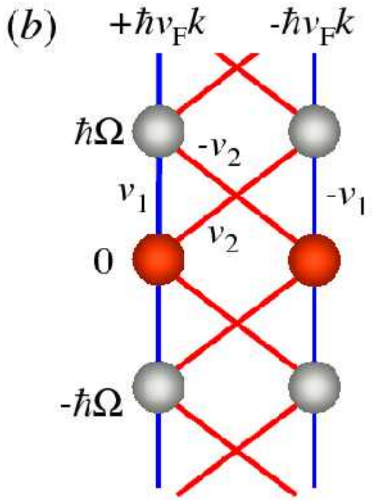
$$v_1 = \frac{eA_0 v_F}{2}\left(\cos\alpha + e^{-i\varphi}\sin\alpha\right)$$

$$v_2 = i\frac{eA_0 v_F}{2}\left(e^{-i\varphi}\cos\alpha - \sin\alpha\right)$$

$$\alpha = \tan^{-1}(k_y/k_x)$$

Simple picture for laser-induced gaps





$$v_1 = \frac{eA_0 v_F}{2}(\cos\alpha + e^{-i\varphi}\sin\alpha)$$

$$v_2 = i\frac{eA_0 v_F}{2}(e^{-i\varphi}\cos\alpha - \sin\alpha)$$

$$\alpha = \tan^{-1}(k_y/k_x)$$

Inelastic Bragg reflection / Lifting of degeneracies in Floquet space

Similar to mechanism in :
LFT and S. Roche, PRL 97, 076804 (2006);
LFT, R. Avriller, S. Roche, PRB 2008

Laser-induced gaps

$$N(\varepsilon) = -\frac{1}{\pi} Im\left\{Tr\left(\mathbf{G}_F(\varepsilon)\right)_{0,0}\right\}$$

Dynamical Gap

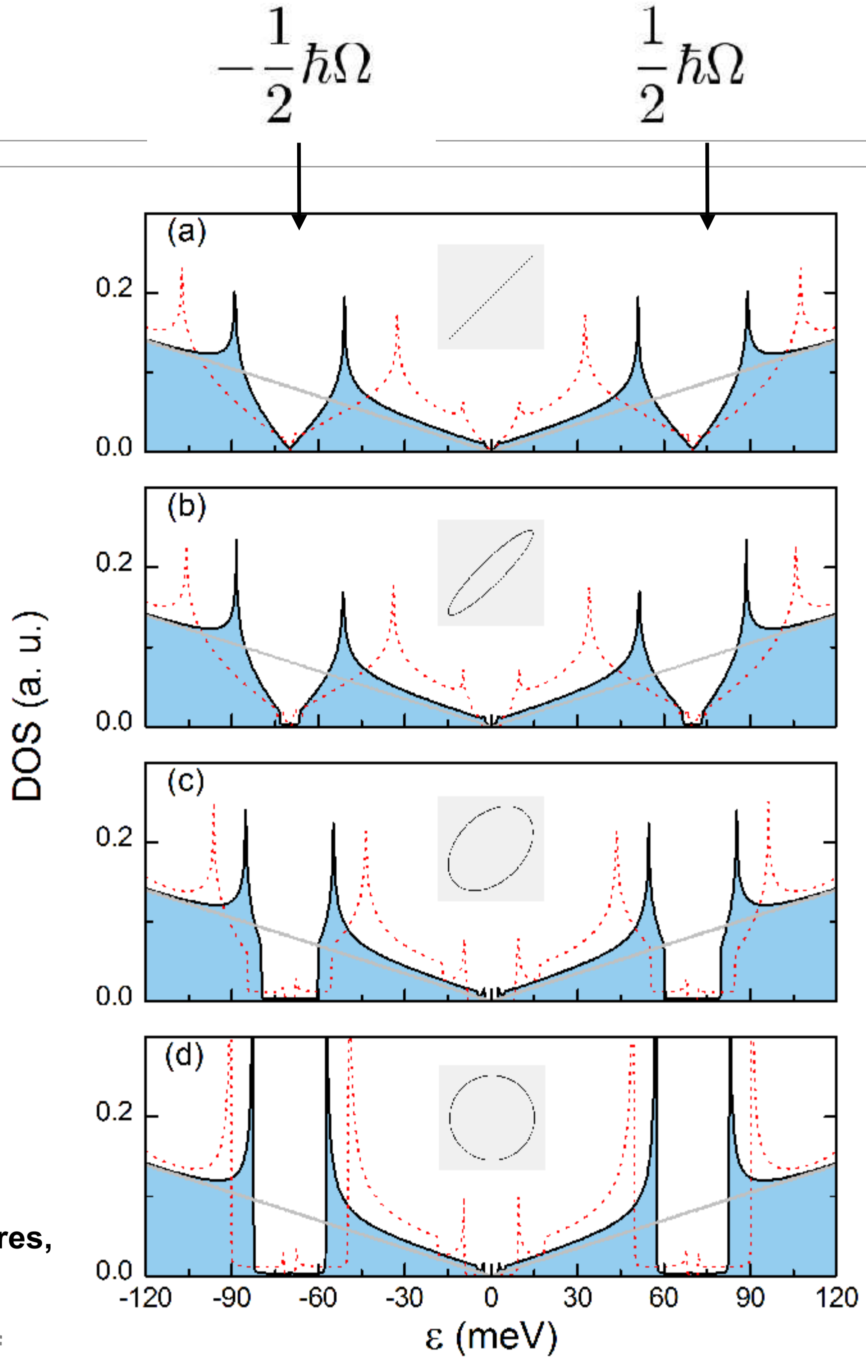
$$\Delta_{k=\Omega/2v_F} \simeq eA_0v_F\sqrt{1-\cos(\varphi)\sin(2\alpha)}$$

Dirac Gap

$$\Delta_{k=0} \simeq \frac{8}{\hbar\Omega}\mathrm{Re}\left\{\gamma_1\gamma_2^*\right\} = 2\frac{(eA_0v_F)^2}{\hbar\Omega}\sin\varphi$$

Circ. Pol. Oka and Aoki PRB 2009

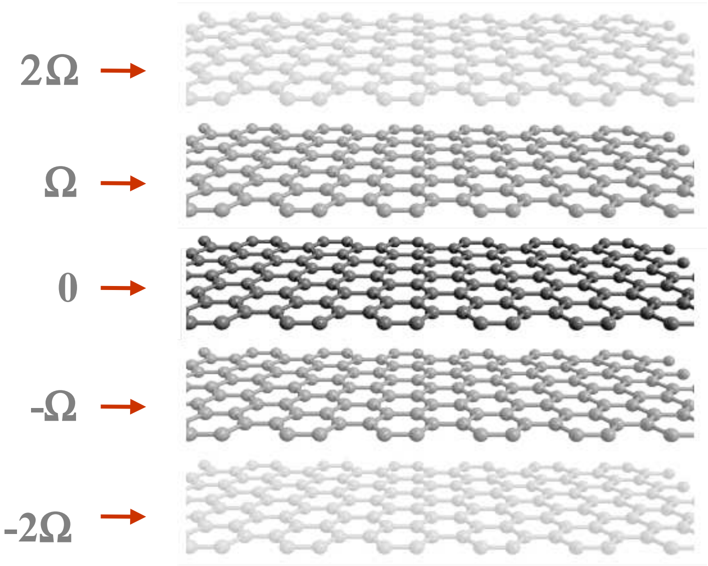
H. L . Calvo, H. M. Pastawski, S. Roche and L. E. F. Foa Torres, Appl. Phys. Lett. 98, 232103 (2011)



What about the influence on transport?

Observable effects of these gaps in the Floquet spectra ?

Tight-binding model and Floquet space (R x T)



The *ac* field is included through the Peierls substitution

$$v_{ij}(t) = \gamma_0 \exp\left[\mathrm{i}\frac{2\pi}{\phi_0}\int_{\mathbf{r}_i}^{\mathbf{r}_j} \mathbf{A}(t)\cdot \mathrm{d}\mathbf{r}\right]$$

We use the Anger-Jacobi expansion

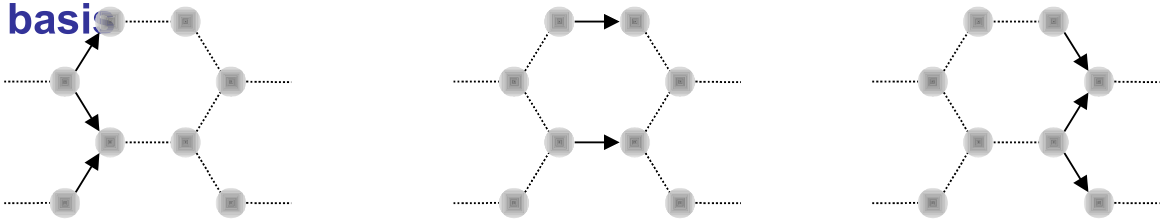
- ***m* – Absorbed or emitted photons**

$$t^{m}_{\pm\,\pm} = \gamma_0 \sum_k \mathrm{i}^k J_k(\pm z_x) J_{m-k}(\pm z_y)$$

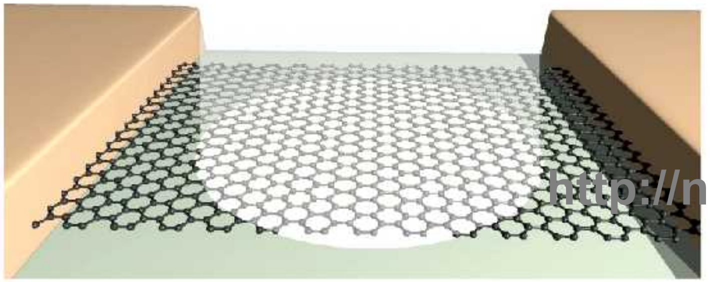
$$z_x = \frac{\pi a A_x}{\phi_0}$$

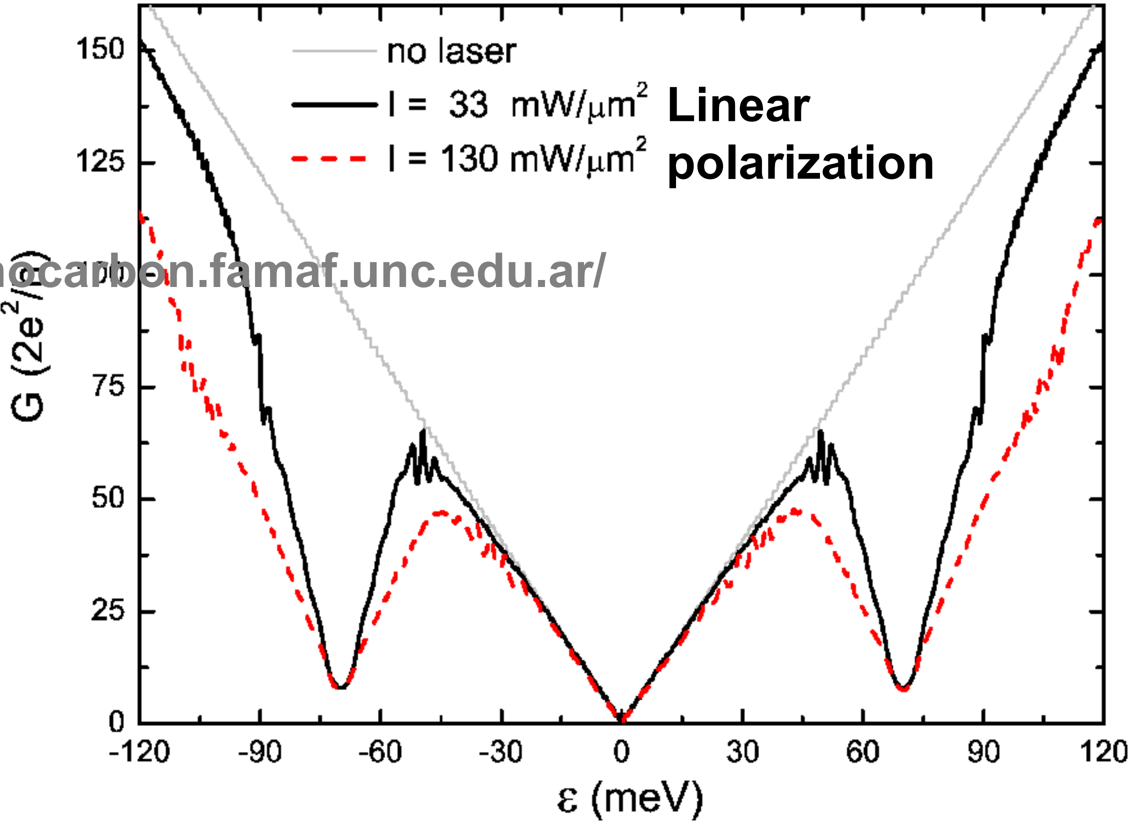
$$z_y = \frac{\sqrt{3}\pi a A_y}{\phi_0}$$

We choose $A_x = A_0$ y $A_y = 0$, in order to decompose H_F in the transversal momentum basis



Radiation effects on the dc Conductance





Linear polarization

- armchair
- 1μm x 1μm size (!)
- no dissipation in the sample
- no radiation in the leads

Mid-infrared laser (λ=8μm)

Depletion areas mimic what we showed for the DOS.

H. L . Calvo, H. M. Pastawski, S. Roche and L. E. F. Foa Torres, Appl. Phys. Lett. 98, 232103 (2011)

What about nanoribbons?

Contents not available for the online version.
For more info please check
http://nanocarbon.famaf.unc.edu.ar/

Power and Temperature dependence

Contents not available for the online version.
For more info please check
http://nanocarbon.famaf.unc.edu.ar/

A laser-induced Topological Insulator?

"Floquet topological insulator in semiconductor quantum wells"
Netanel H. Lindner, Gil Refael and Victor Galitski
Nature Physics 7, 490 (June 2011).

"Transport properties of nonequilibrium systems under the application of light: Photoinduced quantum Hall insulators without Landau levels"
T. Kitagawa, T. Oka, A. Brataas, L. Fu, E. Demler,
PRB 84 235108 (Dec. 2011).

Can be verified as well by:

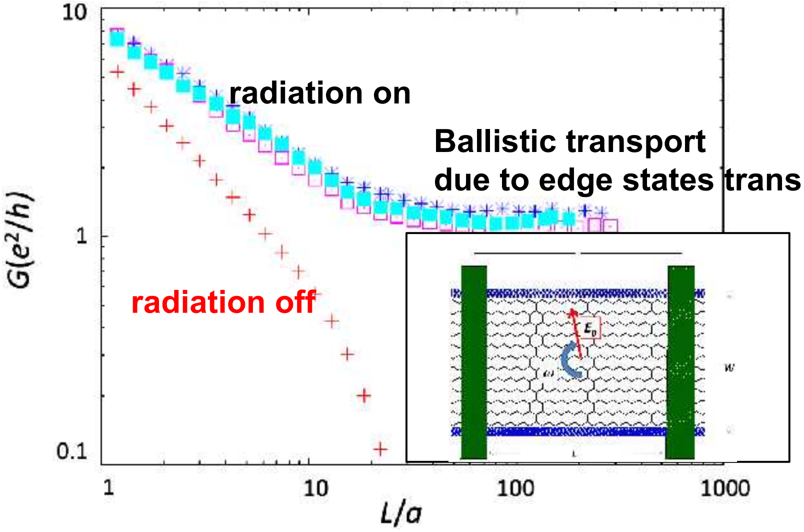
- Calculation of effective Hamiltonian.

+

- Calculation of the associated Chern number, which gives 1 for circular polarization.

Eric Suárez Morell and LFT, to be published.

Evanescent transmission in irradiated system.



radiation on

Ballistic transport
due to edge states transport

radiation off

Zhenghao Gu, H.A. Fertig, Daniel P. Arovas, Assa Auerbach
PRL 107, 216601 (Nov. 2011)

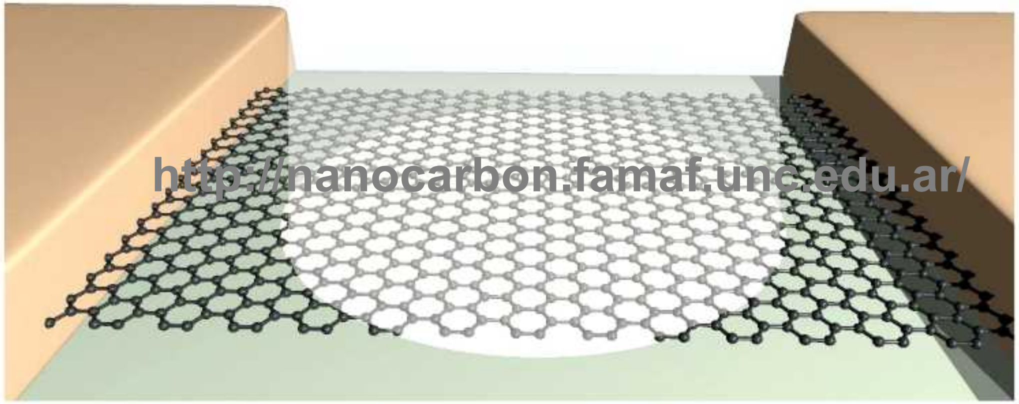
Contents not available for the online version.
For more info please check
http://nanocarbon.famaf.unc.edu.ar/

Conclusions

Our simulations show that laser fields in the *mid-infrared* can be used to induce tunable gaps in the electrical response of graphene.
First atomistic simulations of the transport response.

Key ingredients: low dimensionality, peculiar electronic structure,
» non adiabaticity

Possibility of inducing a topological insulator.



Related publications available at :
http://nanocarbon.famaf.unc.edu.ar/

FaMAF
Facultad de Matemática,
Astronomía y Física
Universidad Nacional de Córdoba

Thank you!
Gracias!

Hernán Calvo

Horacio Pastawski

Stephan Roche

Alexander von Humboldt
Stiftung/Foundation

AGENCIA

G. Cuniberti

Claudia Rocha

Lucas Ingaramo

Pablo Pérez Piskunow

ICTP

http://nanocarbon.famaf.unc.edu.ar/