Spin-dependent electron scattering in 2D electron systems

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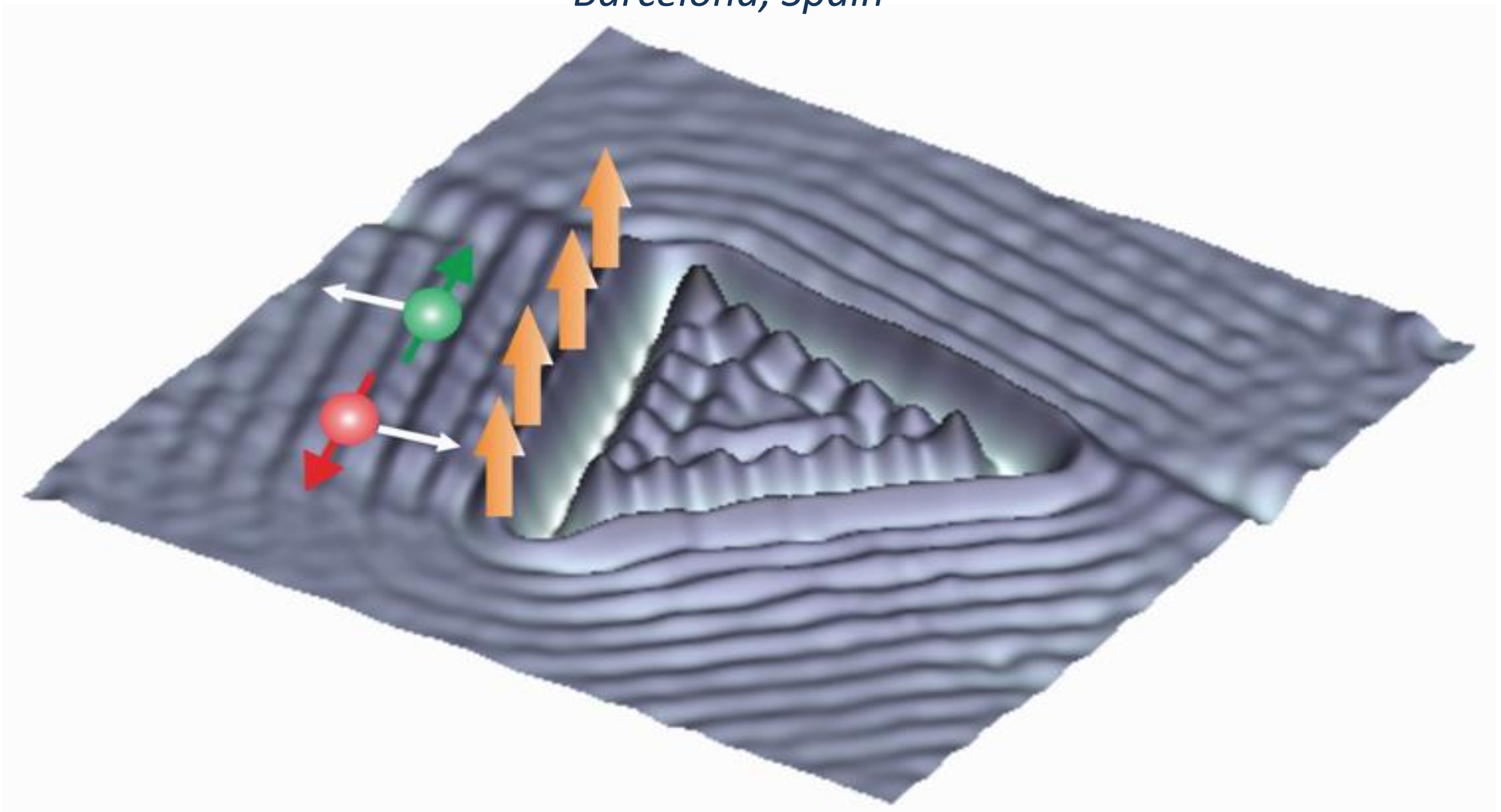


Generalitat de Catalunya
Departament d'Economia i Coneixement

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

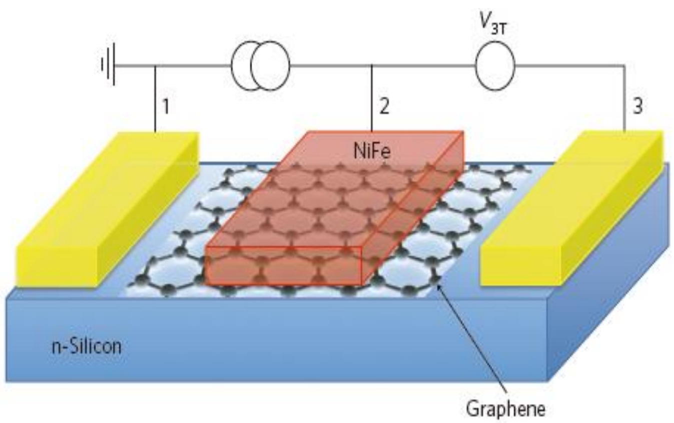
ICREA

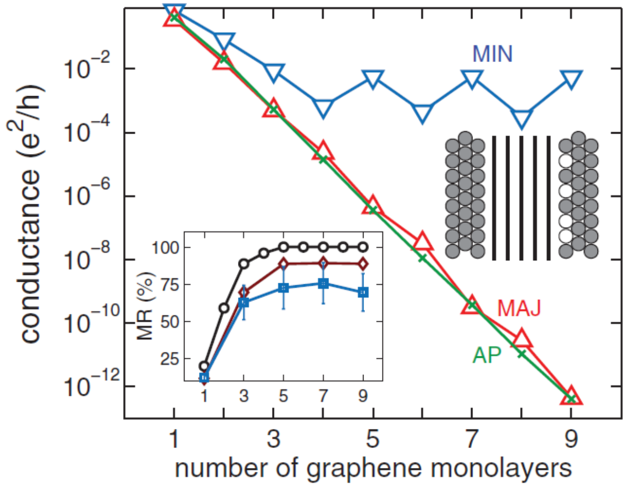
ICN2 Institut Català de Nanociència i Nanotecnologia

EXCELENCIA SEVERO OCHOA

Nanospain, Donostia, March 9th 2017

Spin filtering at the G/Ni(111) interface





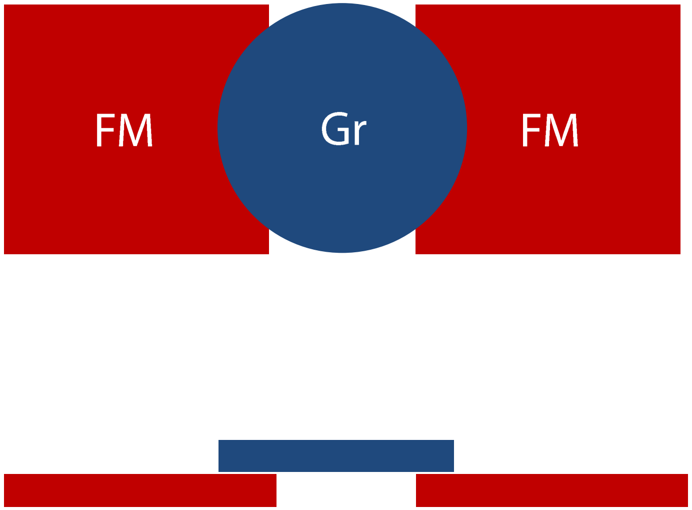
In FM/semiconductor junctions:
- ❑ High injection efficiency
- ❑ Low barrier resistance

van t'Erve et al. Nat. Nanotech. 7 (2012)

Spin filtering in G/Ni interfaces:
- ❑ Magnetoresistance close to 100%

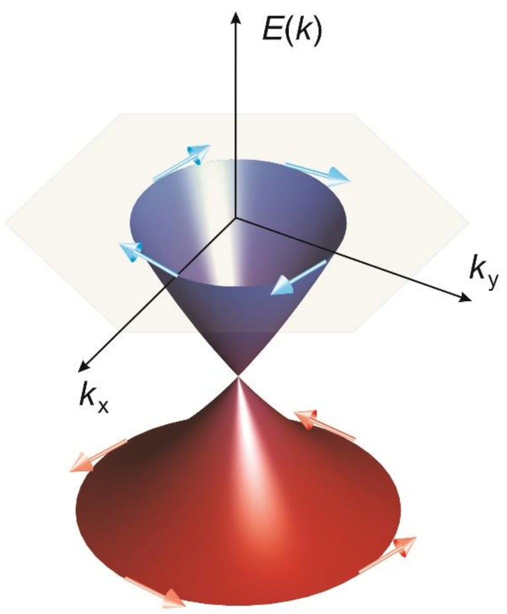
V. M. Karpan et al. PRL 99 (2007)

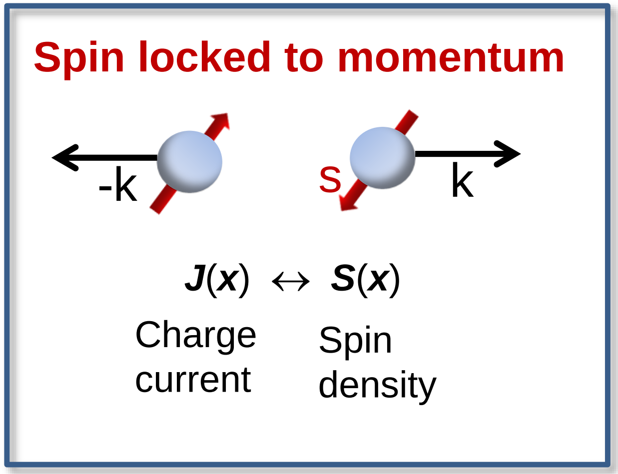
Spin in scattering: Exchange split states



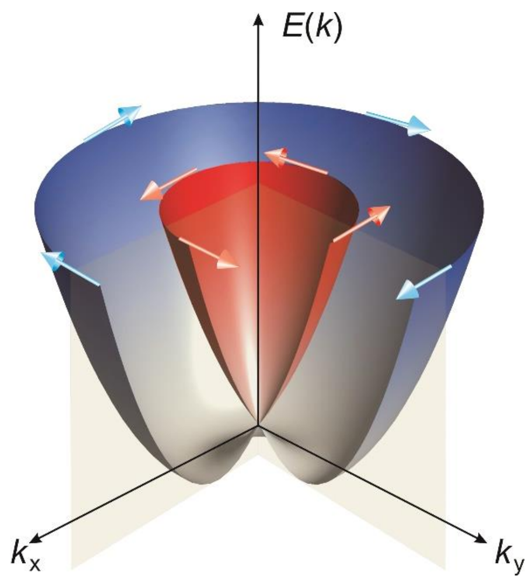
Spin in scattering: spin-orbit coupling

Topological states



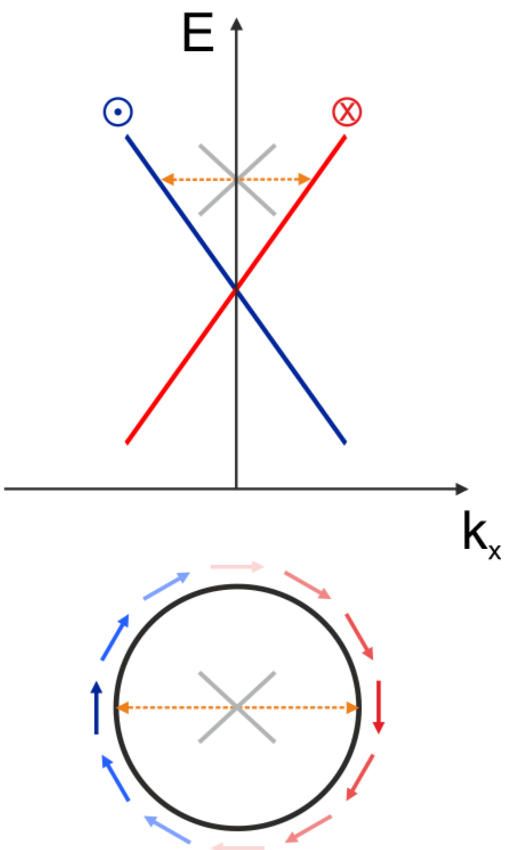


Rashba states



Spin in scattering: spin-orbit coupling

Topological states

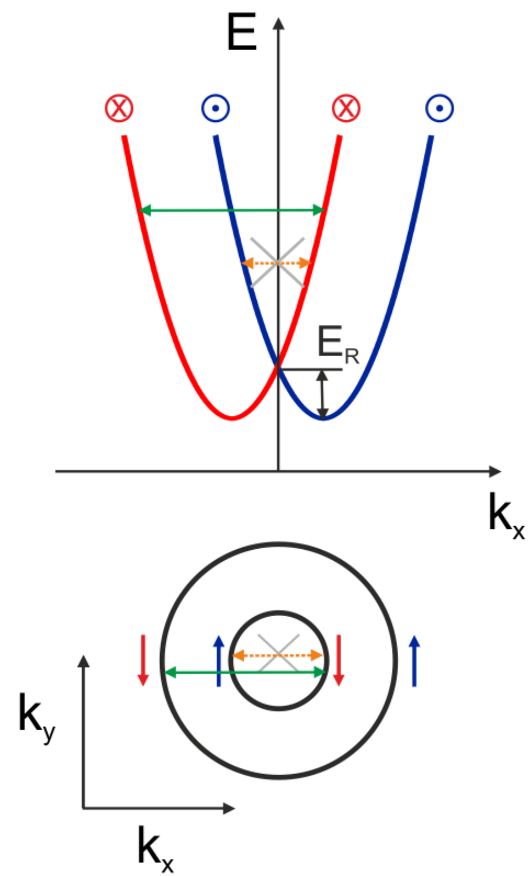


Spin locked to momentum

$\boldsymbol{J}(\boldsymbol{x}) \leftrightarrow \boldsymbol{S}(\boldsymbol{x})$

Charge current | Spin density

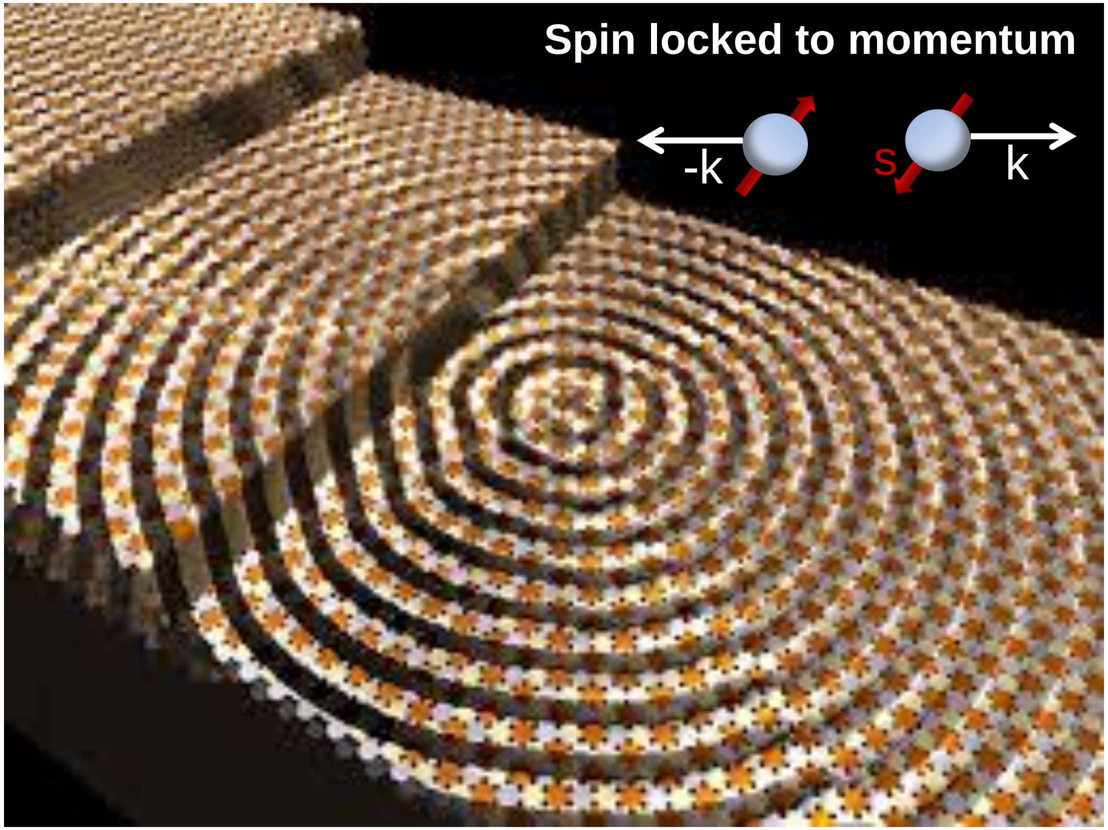
Rashba states



Quenching of backscattering

Non-dissipative currents?

Quenching of backscattering in topological insulators



J. Seo et al. Nature **466** , 343 (2010)

$\boldsymbol{J}(\boldsymbol{x}) \leftrightarrow \boldsymbol{S}(\boldsymbol{x})$

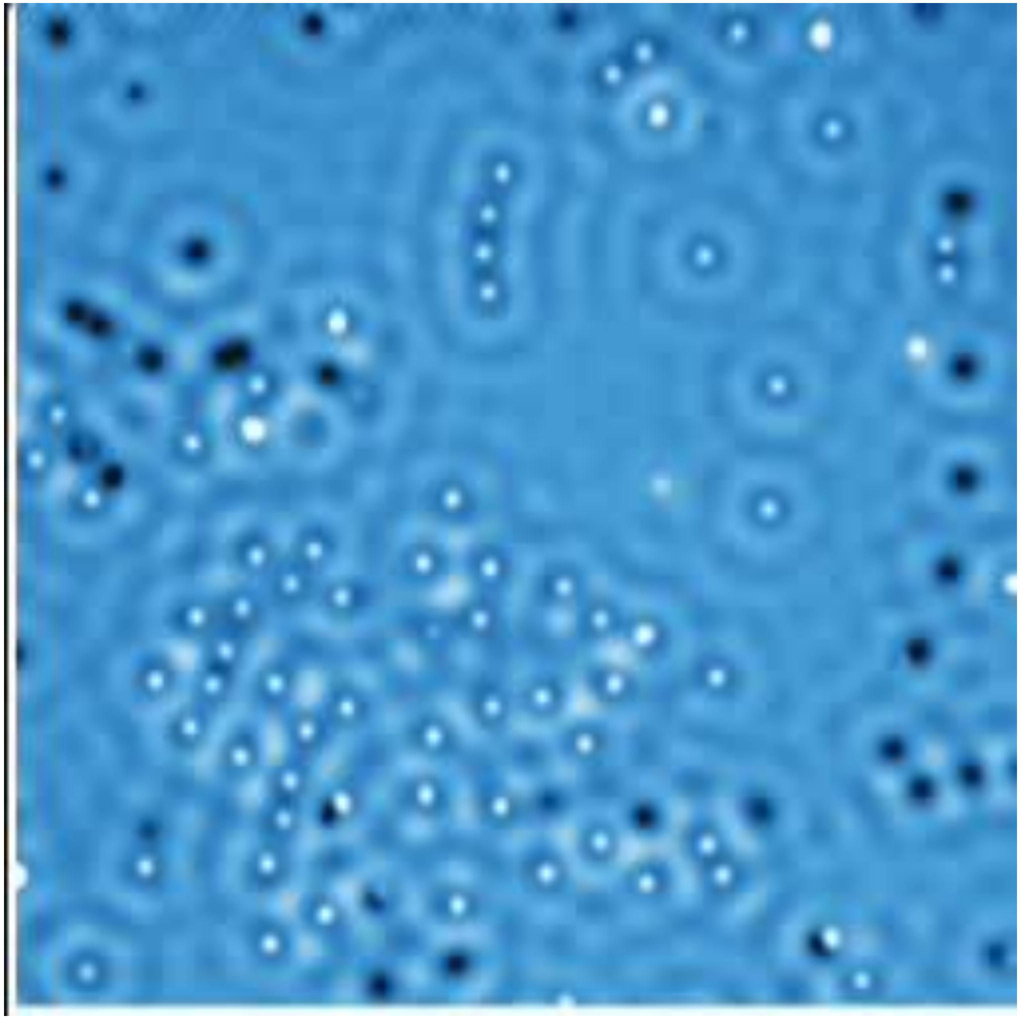
Charge current

Spin density

Non-dissipative spin polarized currents?

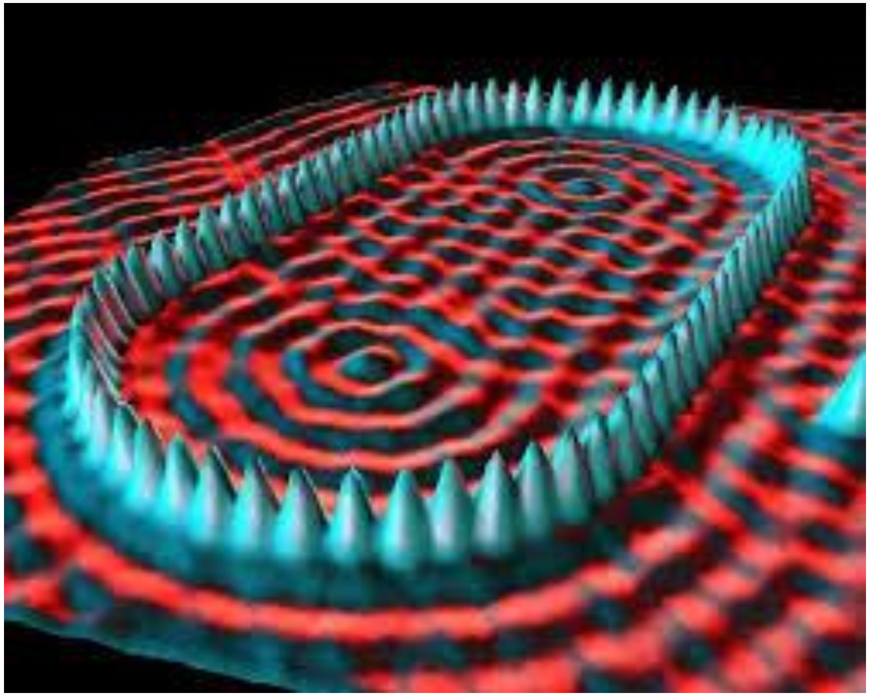
Standing waves: a way to “see” and measure electrons

Ag atoms on Ag(111)



R. Berndt, Uni Kiel

Standing waves: a way to "see" and measure electrons

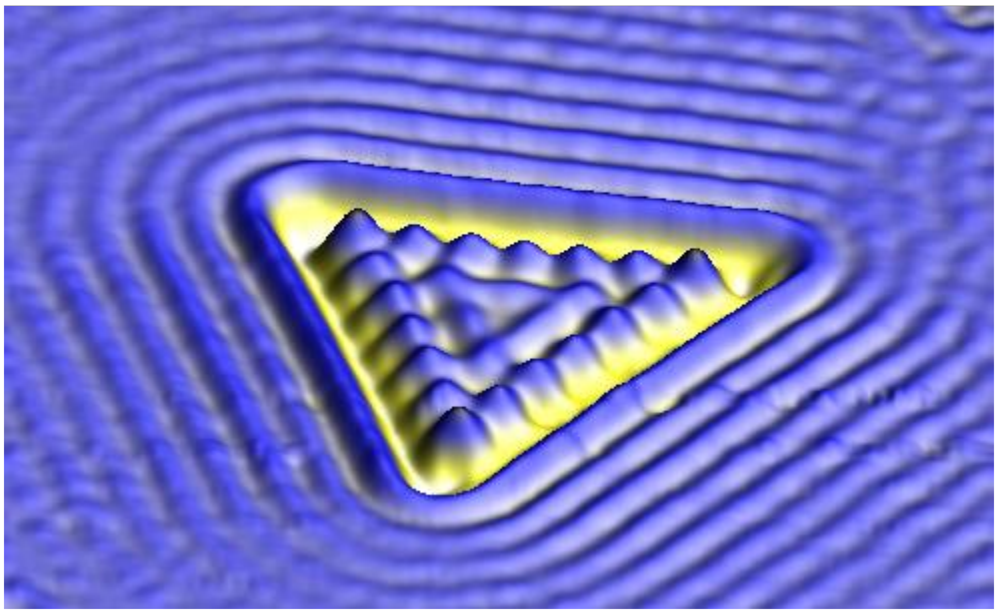


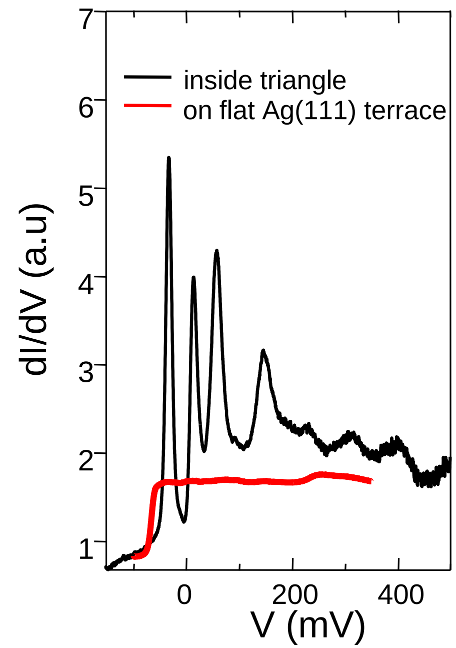
Scattering coefficients	Heller Nature **369**, 464 (1994)
Quantum mirage	Manoharan Nature **403**, 512 (2000)
Quantum invisibility	Fransson Nano Lett. **10**, 1600 (2010).

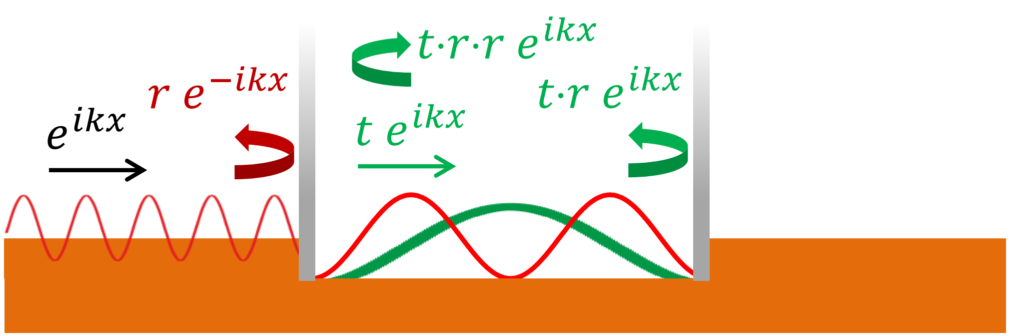
Standing waves: a way to "see" and measure electrons

Vacancy island on Ag(111)

Topo
STS

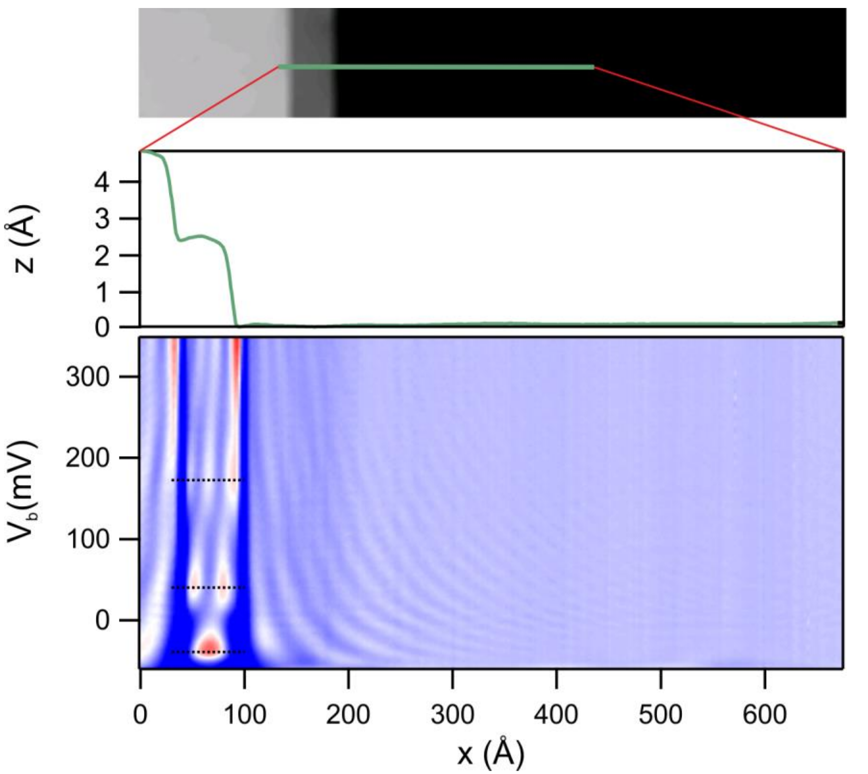






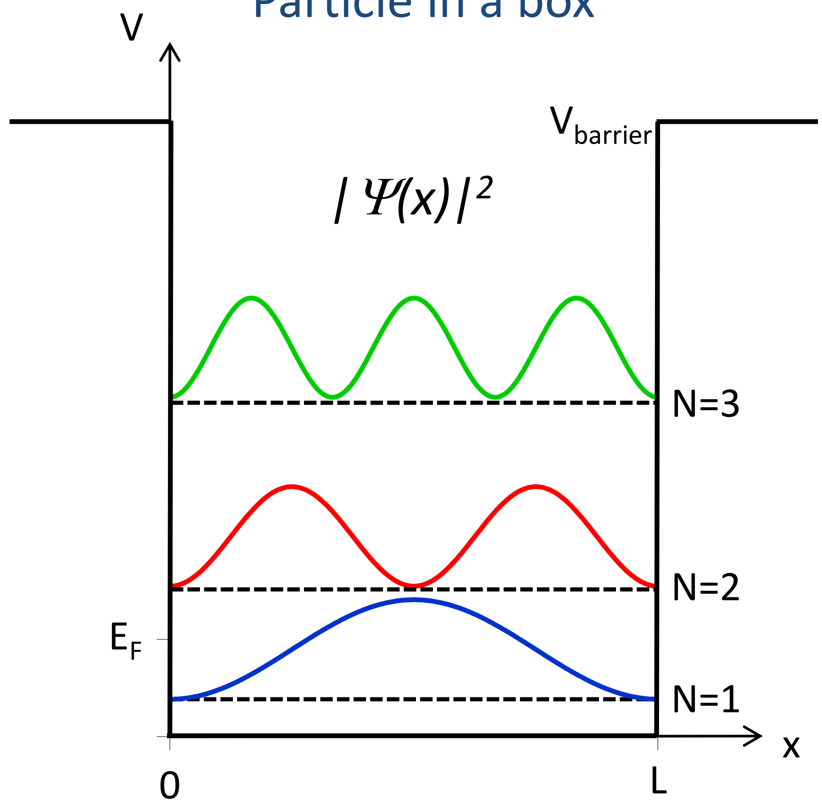
Electron scattering and confinement in 1D: monoatomic steps

Monoatomic steps on Ag(111)



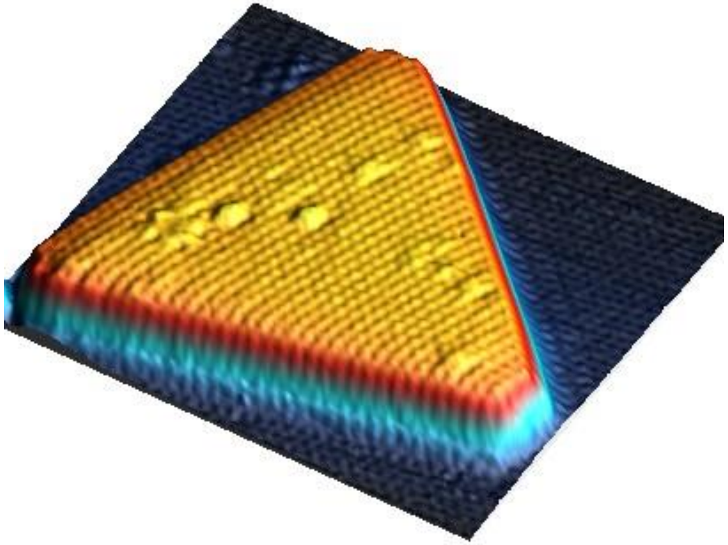
A. Mugarza et al. PRL ***87****, 3 (2001)*
F. Schiller et al., NJP ***16****, 123025 (2014)*
J. E. Ortega et al. PRB ***87****, 115425 (2013)*
J. E. Ortega et al., Handbook of Surface Science (Springer, coming son!)

Particle in a box

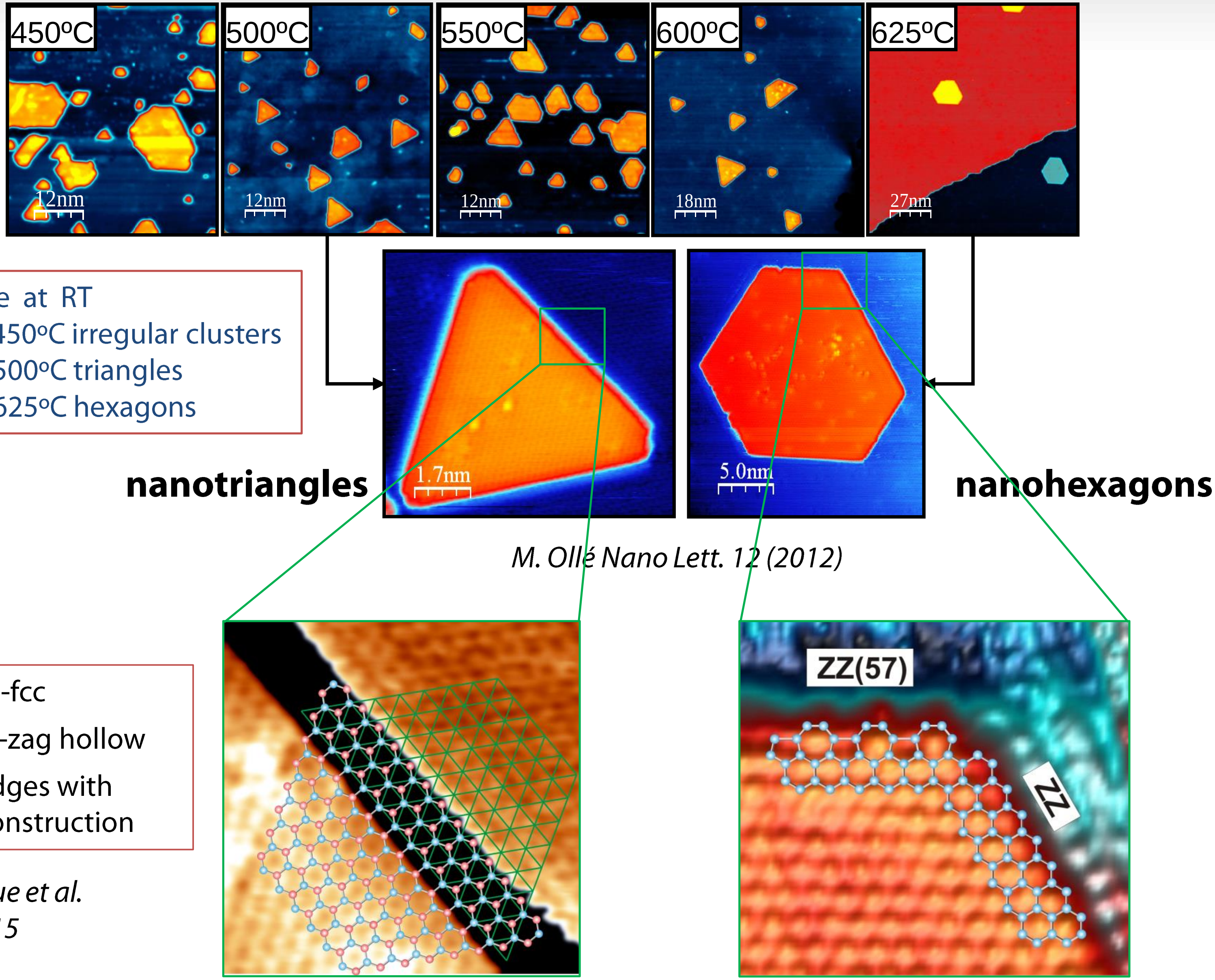


Quantum interference effects in a potential well: standing waves and discrete energy levels

Graphene nanoislands



Synthesis of nanographene on Ni(111)



Propene dose at RT
Anneal to: 450ºC irregular clusters
500ºC triangles
625ºC hexagons

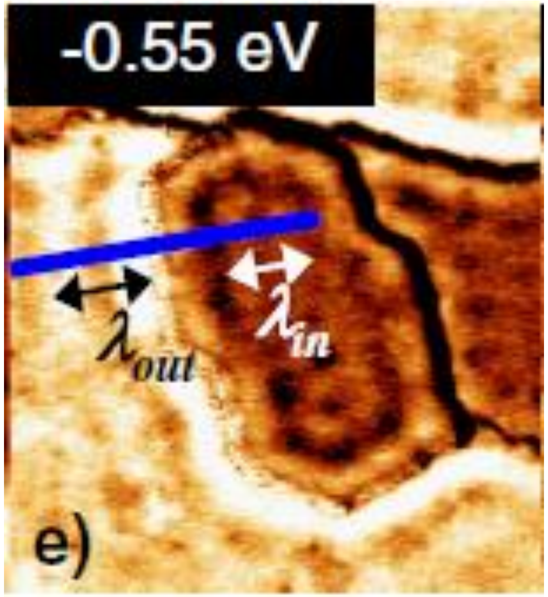
M. Ollé Nano Lett. 12 (2012)

- ❑ Stacking: top-fcc
- ❑ Triangles: zig-zag hollow
- ❑ Hexagons: edges with different reconstruction

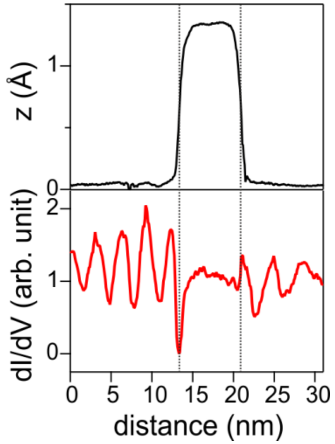
A. Garcia-Lekue et al.
JPC C 119, 2015

Surface state scattering at graphene

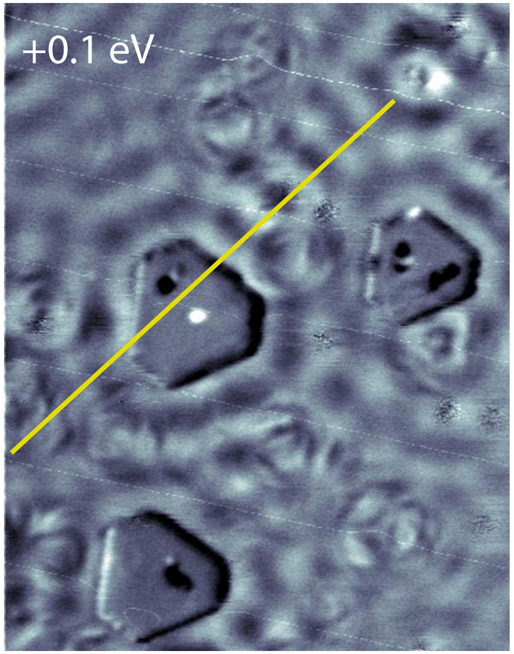
G/Ir(111)



S. J. Altenburg et al., PRL 108 (2012)
D. Subramaniam et al., PRL 108 (2012)
S. K. Hämäläinen et al., PRL 107 (2011)



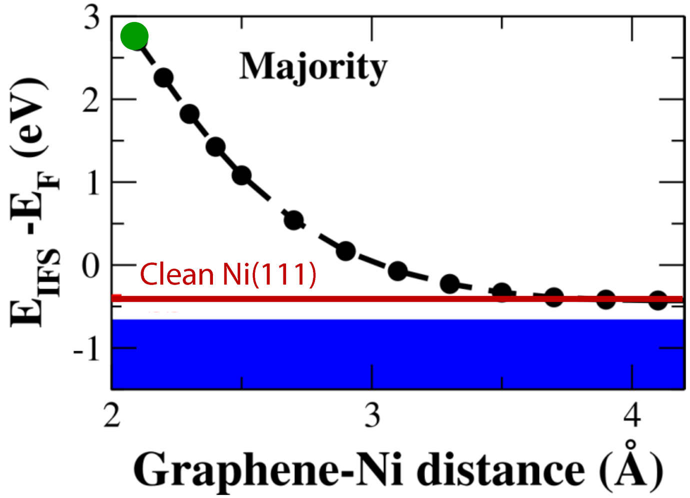
G/Ni(111)

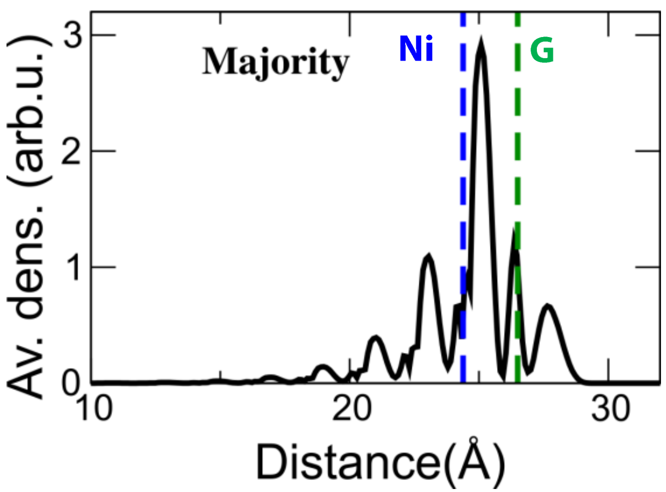


A. Garcia-Lekue et al., PRL 112, 066802 (2014)

Surface state scattering at graphene

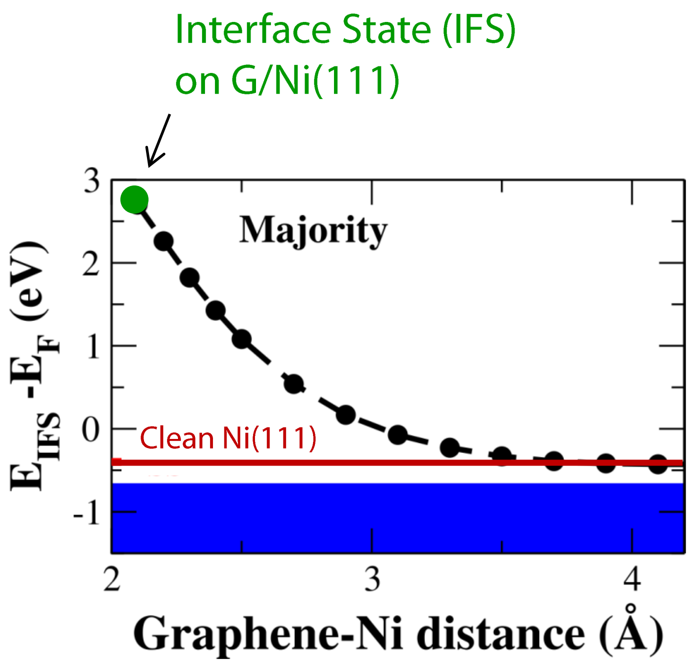
Interface State (IFS)
on G/Ni(111)

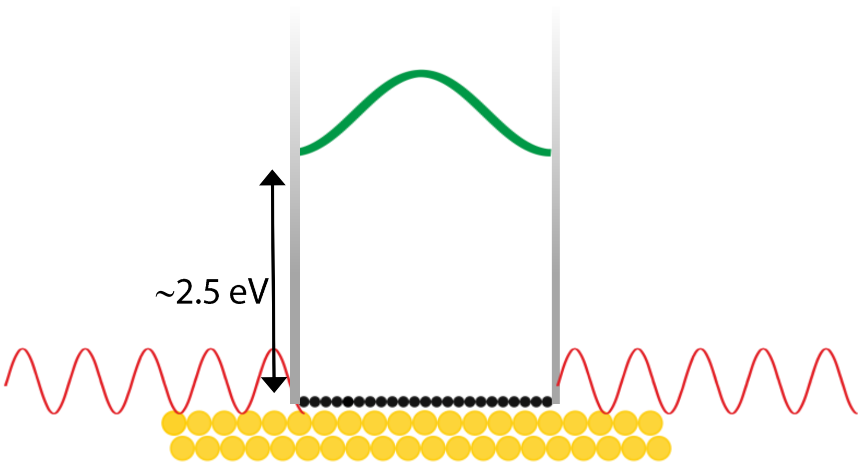




A. Garcia-Lekue et al., PRL 112, 066802 (2014)

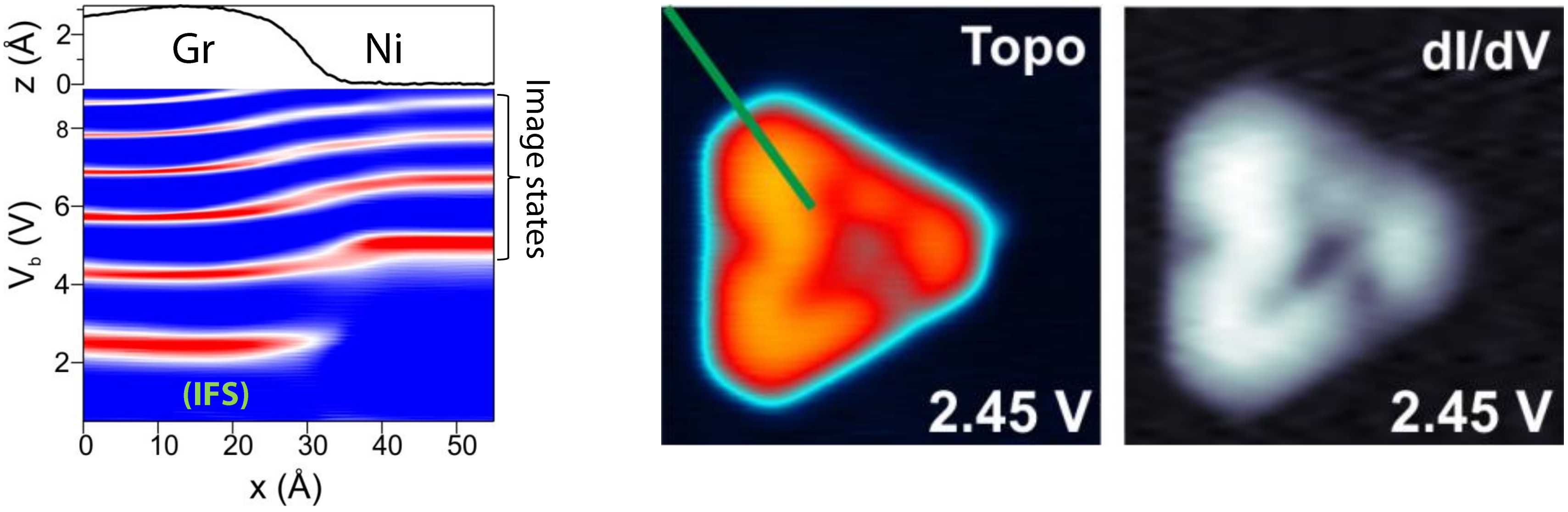
Surface state scattering at graphene





A. Garcia-Lekue et al., PRL 112, 066802 (2014)

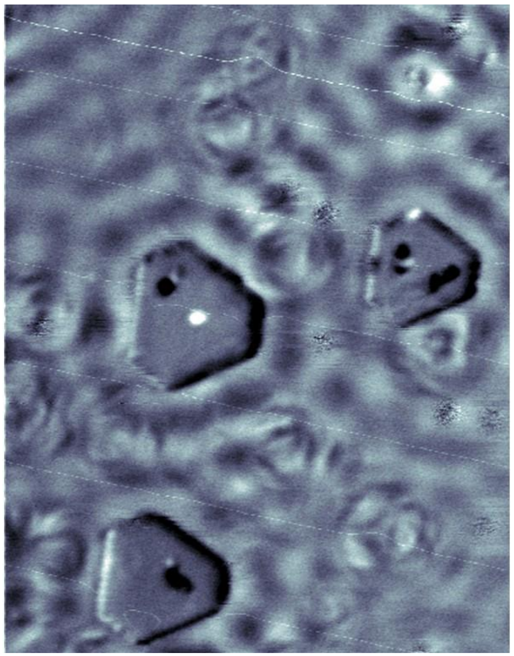
Surface state scattering at graphene



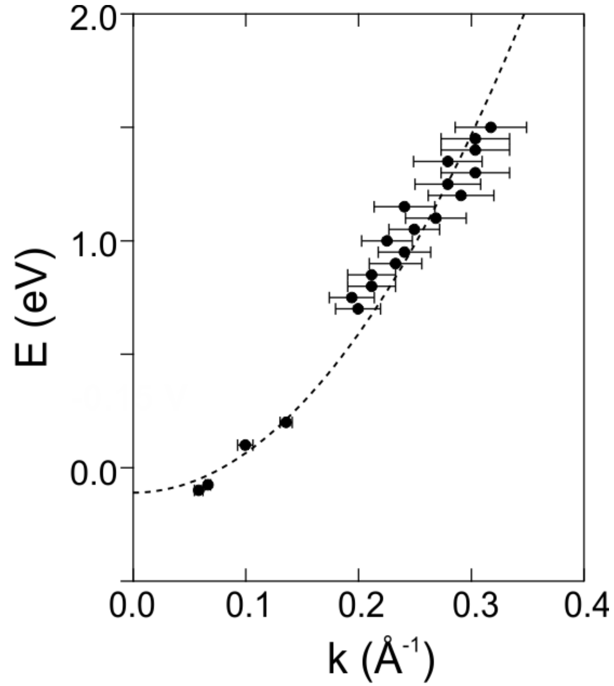
A. Garcia-Lekue et al., PRL 112, 066802 (2014)

Lateral spin filter

dI/dV map



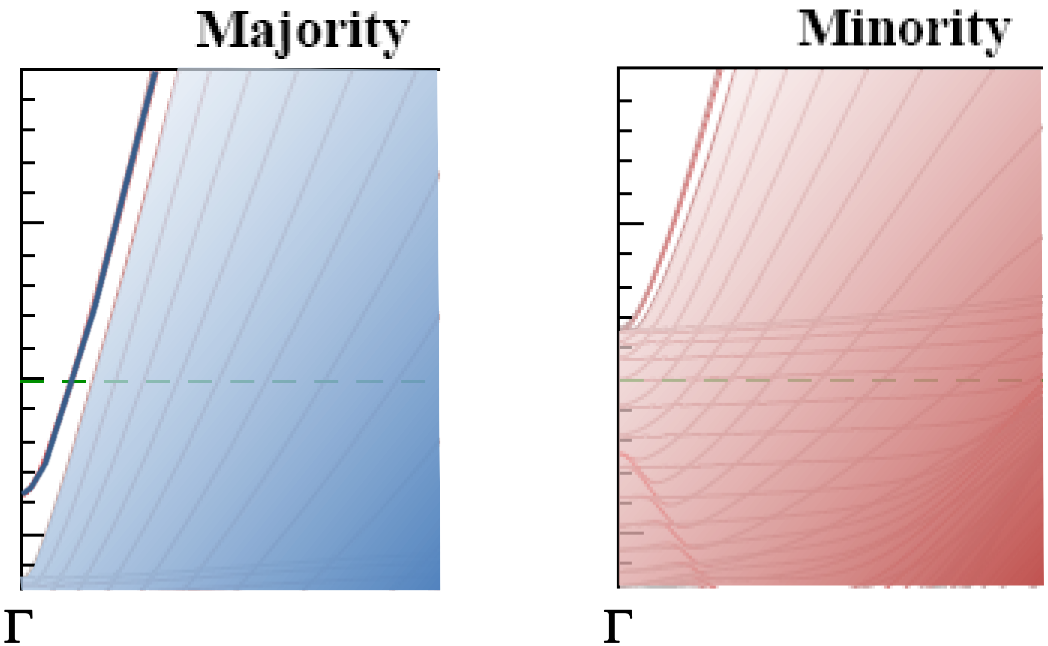
Dispersion obtained from periodicity of standing waves



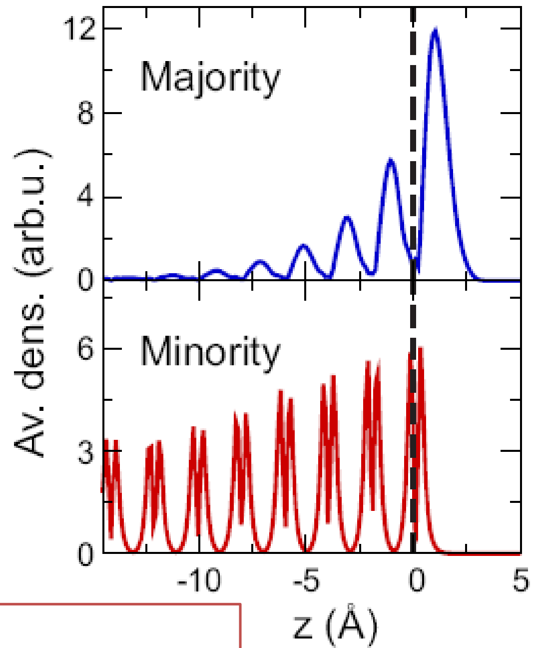
Graphene: perfect reflector for Ni surface states

…for both spins?

Coupling to bulk states



Planar average of density of states of S_1 at Γ

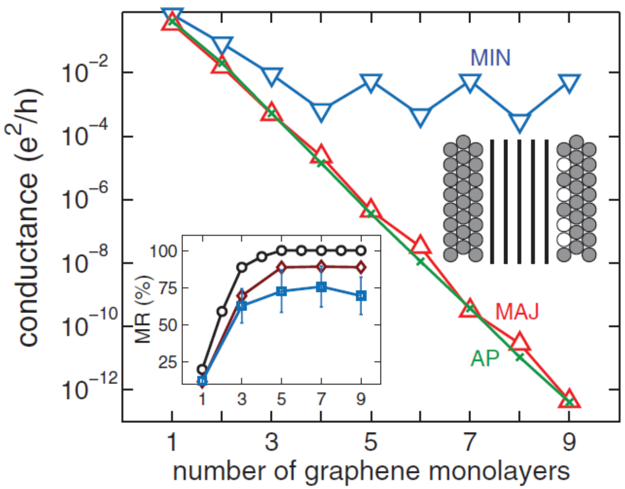


Minority band:
- ❑ Closer to bulk states → larger absorption to bulk
- ❑ Larger bulk penetration→ less sensitivity to surface potentials

⇓

Spin-dependent scattering

Coupling to bulk states



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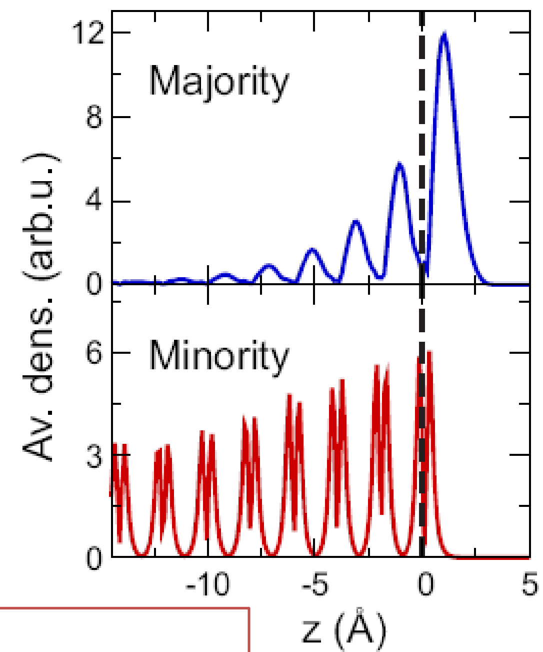

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V. M. Karpan et al. PRL 99 (2007)

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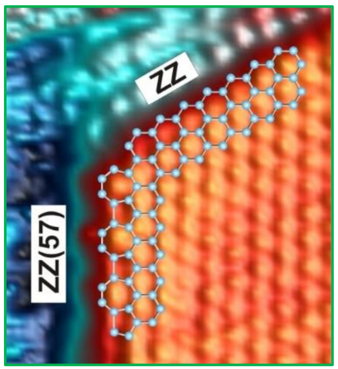
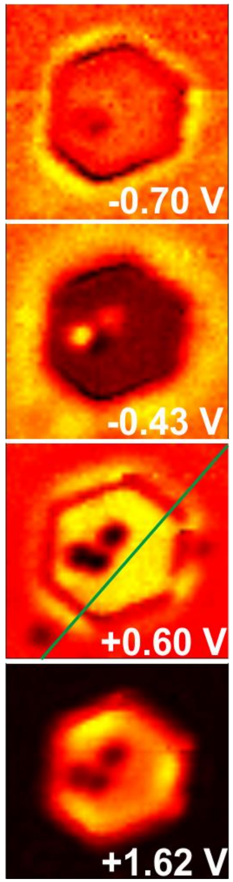
Spin-dependent scattering

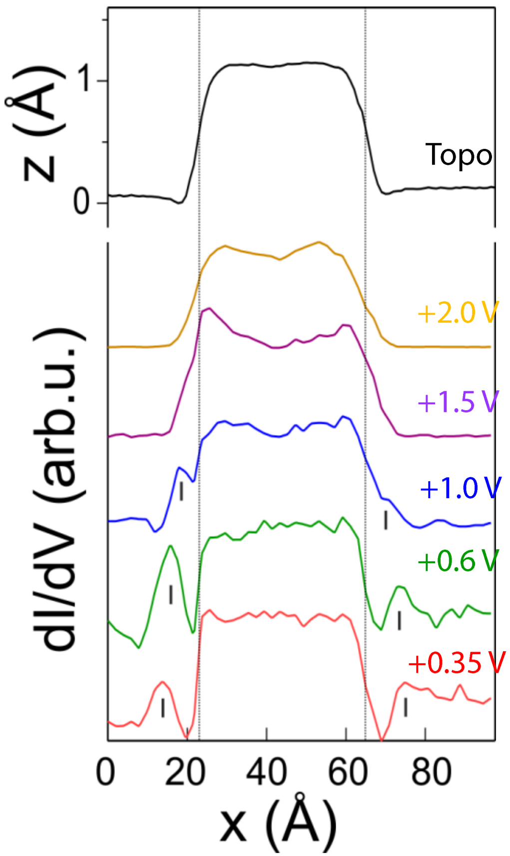
Effect of graphene edge on scattering



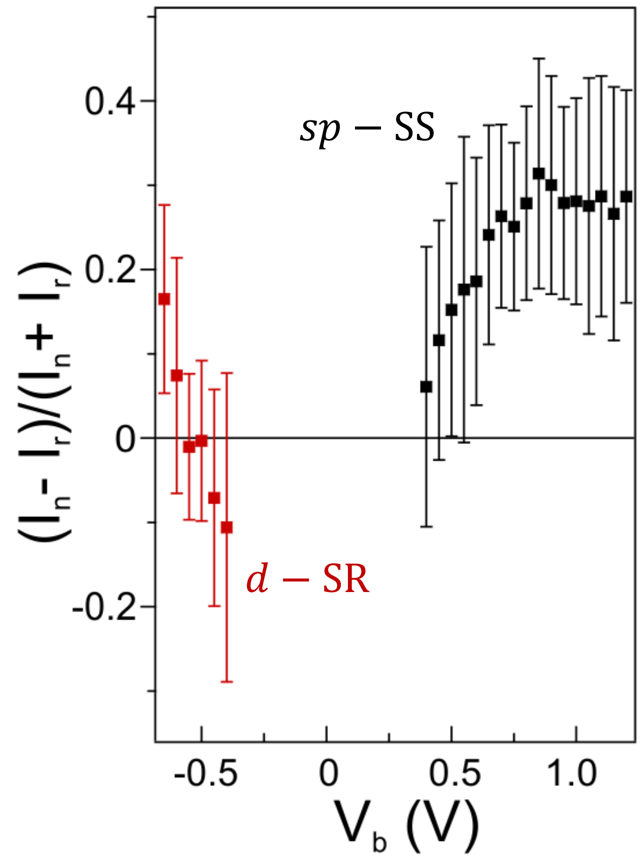
dI/dV maps



dI/dV profiles at different energy

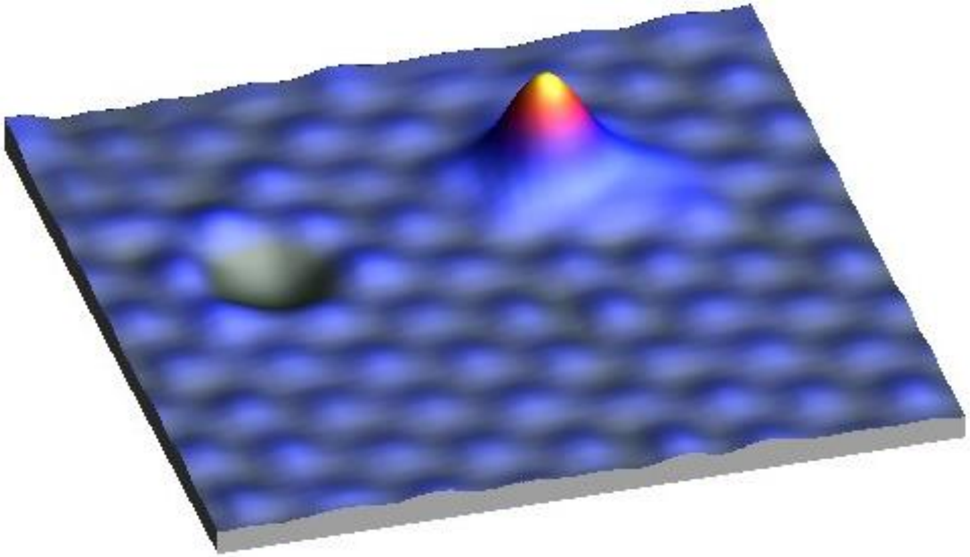


Asymmetry of scattering amplitude

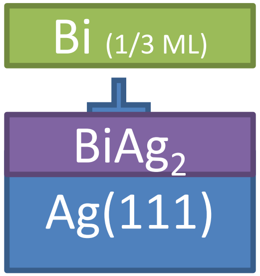


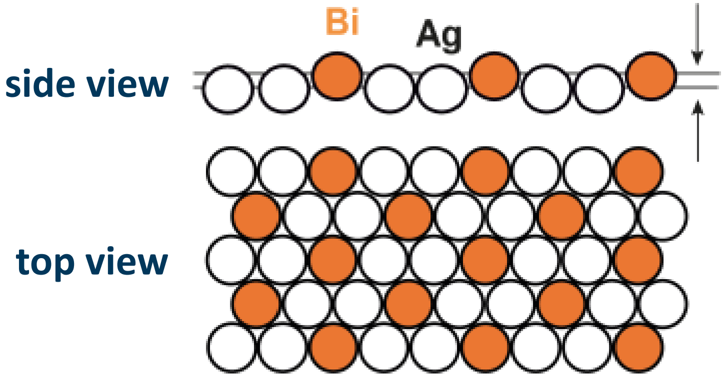
- Scattering stronger in zig-zag edges
- Asymmetry depens on energy and type of surface state

Heavy metal alloys



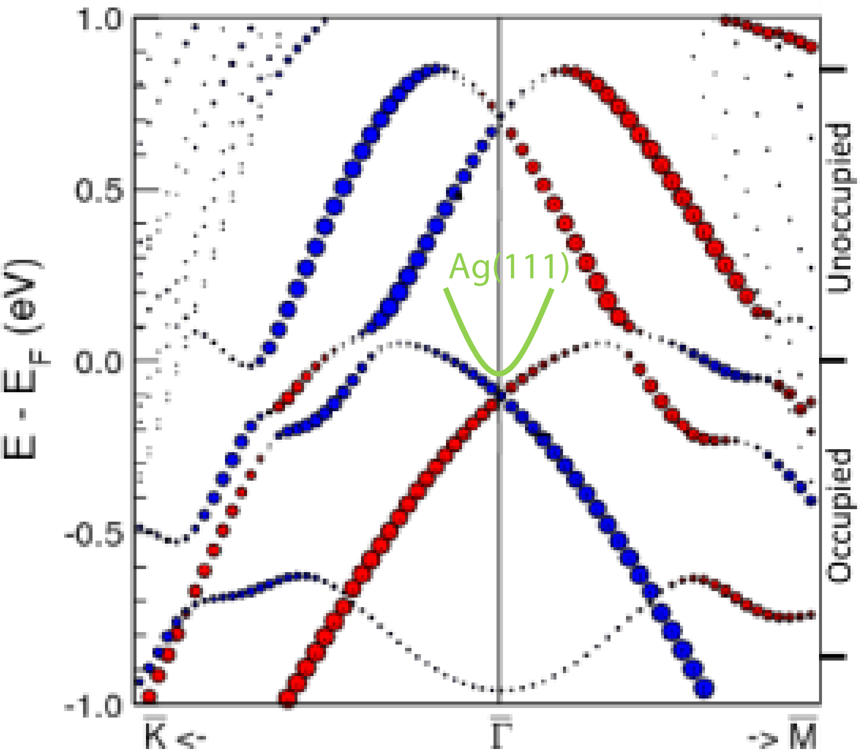
BiAg$_2$ surface alloy





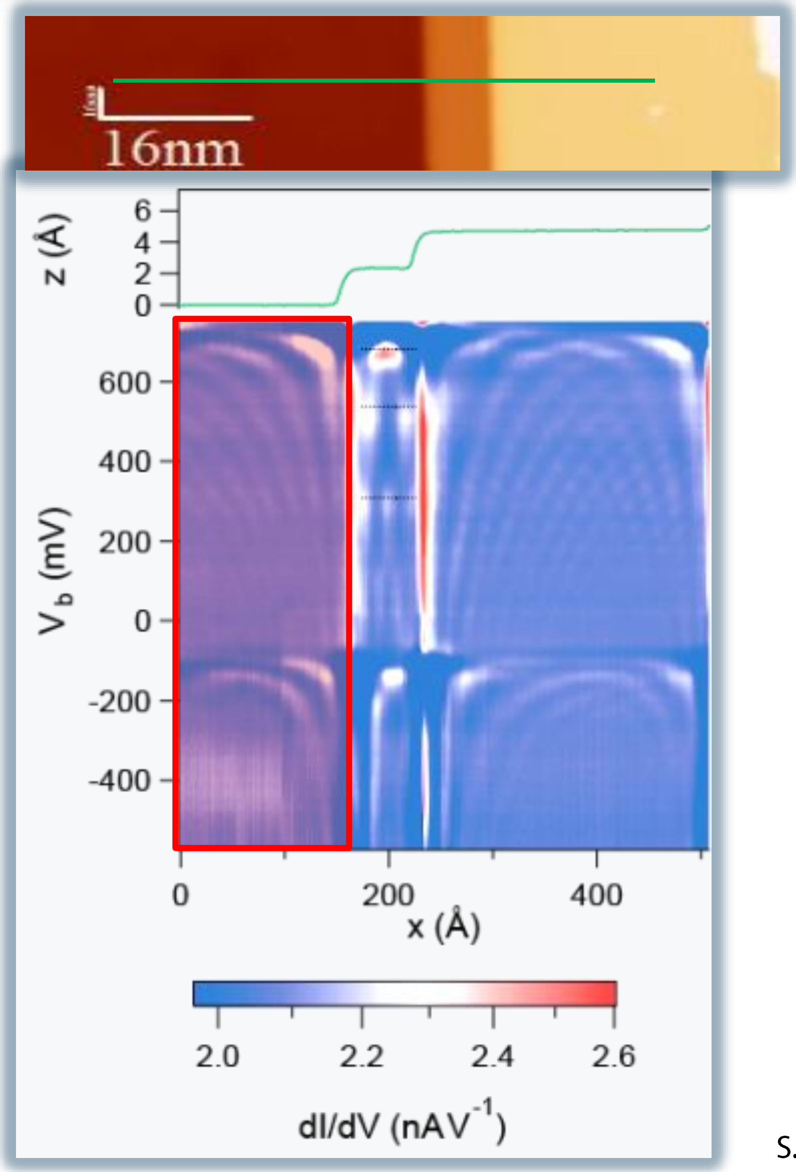
$(\sqrt{3} \times \sqrt{3})\ R30^{\circ}$

Band structure



S. Schirone et al. PRL 114, 166801 (2015)

Scattering at semi-infinite terraces



S. Schirone et al. PRL 114, 166801 (2015)

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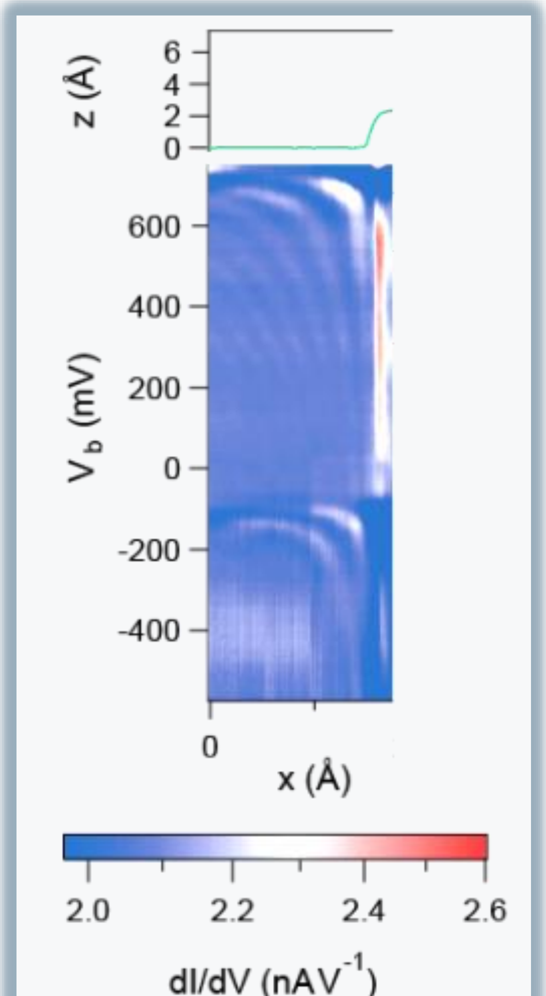
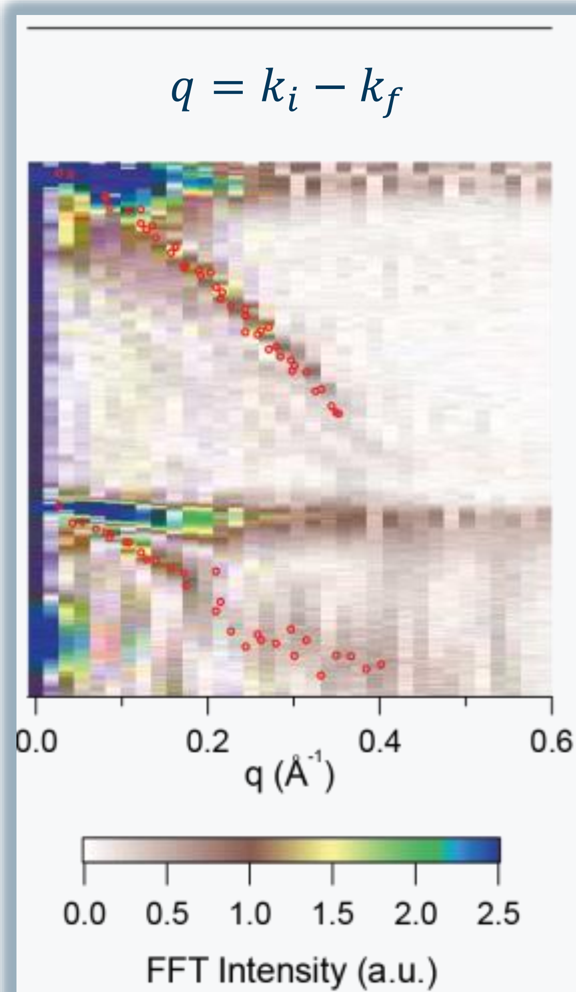
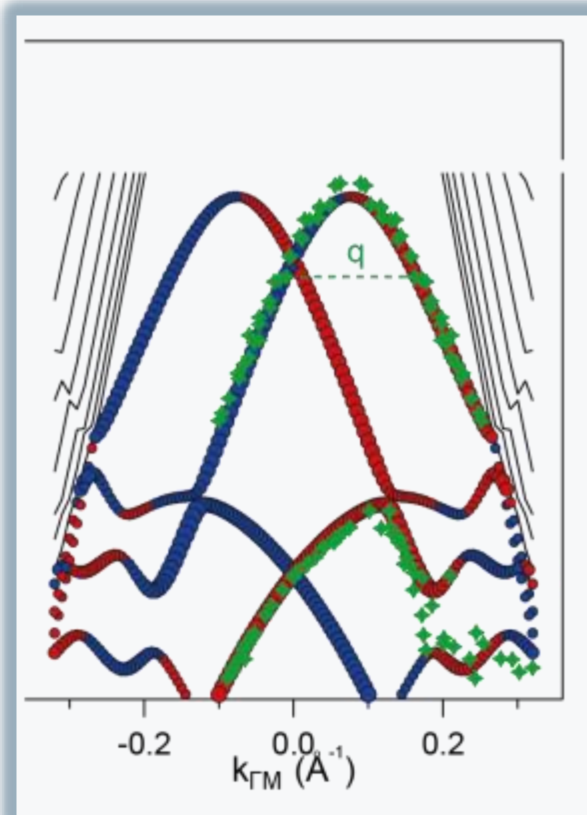




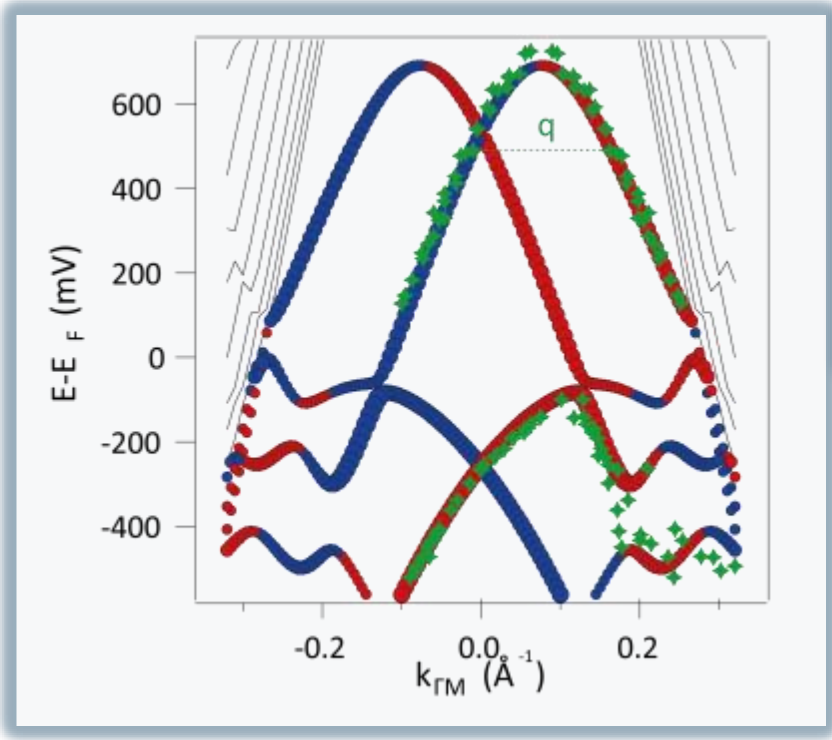


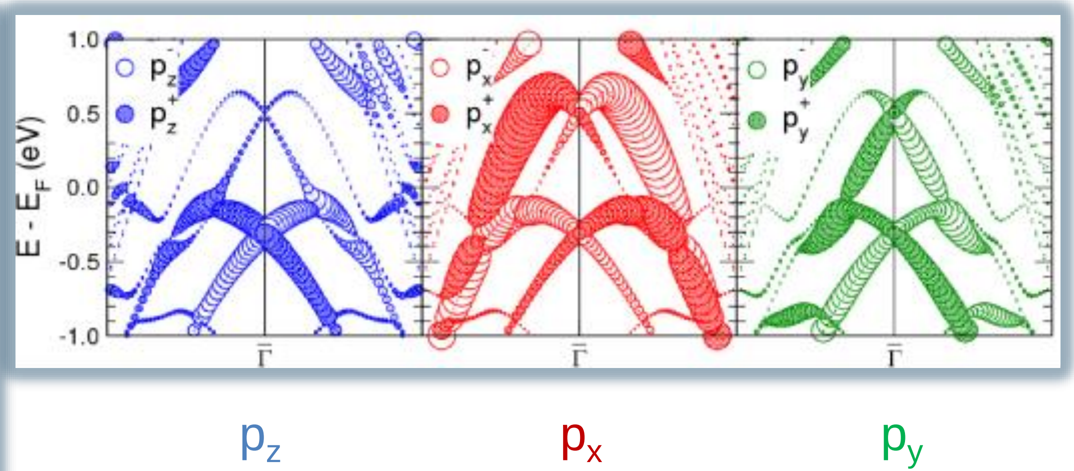
Only intraband transitions!

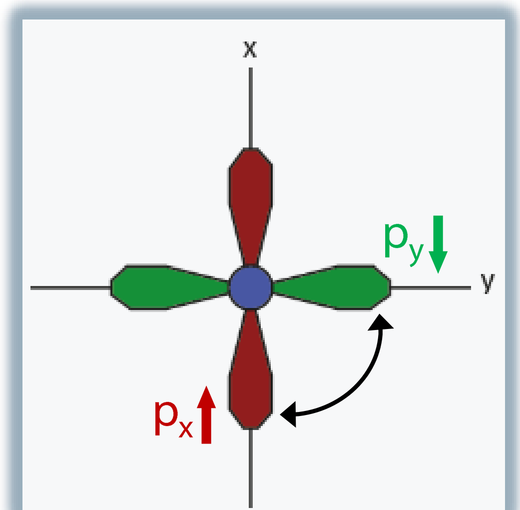
FFT → q(E) → vs Theory

S. Schirone et al. PRL 114, 166801 (2015)

Spin-orbital flip scattering





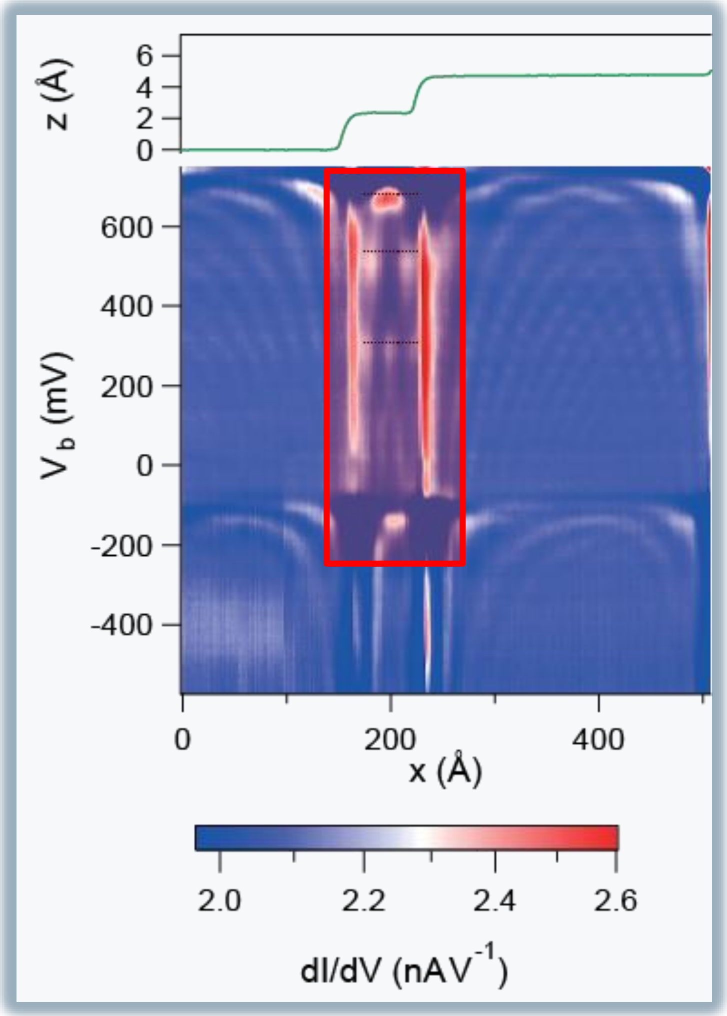


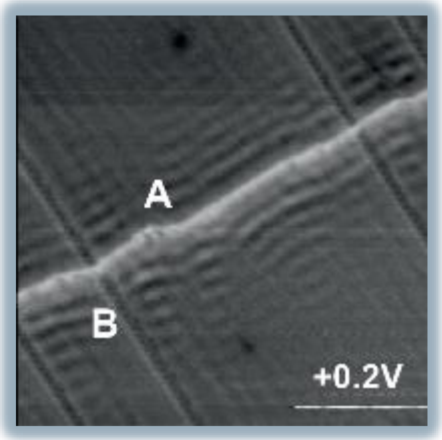
$$\langle p_y, \downarrow |\mathbf{L} \cdot \mathbf{S}| p_x, \uparrow \rangle \neq 0$$

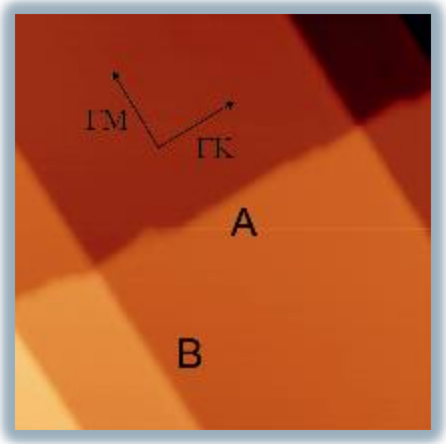
$$\Delta \mathbf{J} = \Delta \mathbf{L} + \frac{1}{2} \Delta \mathbf{S} = 0$$

S. Schirone et al. PRL 114, 166801 (2015)

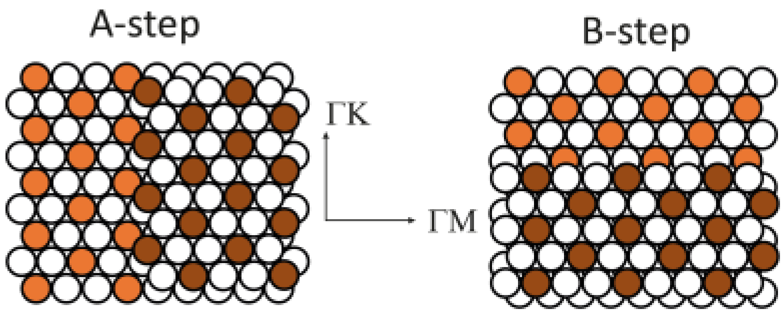
Scattering in resonators





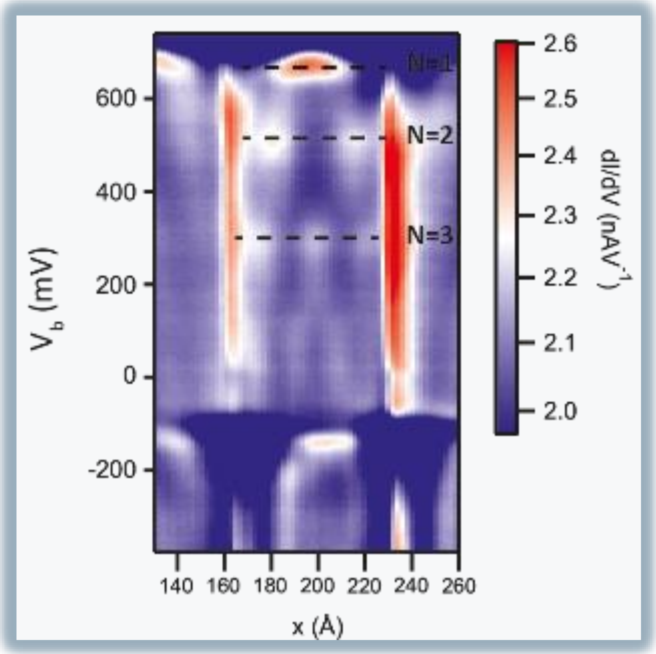


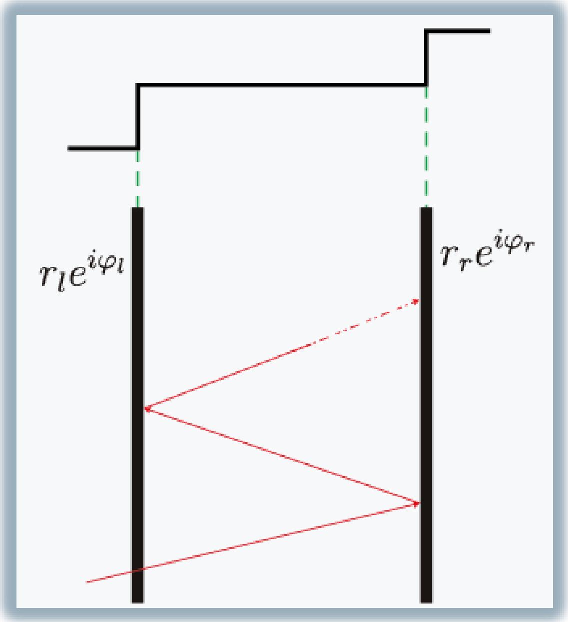
Different intensity

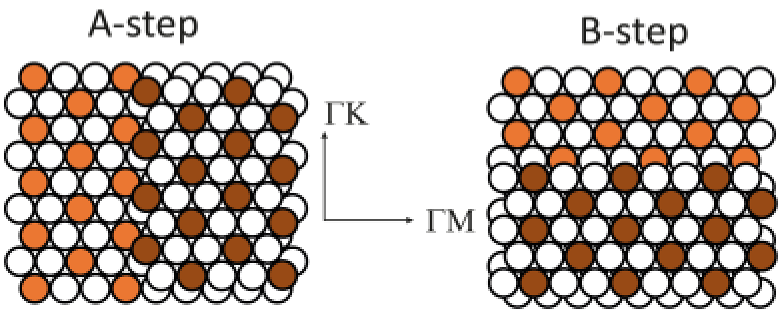


S. Schirone et al. PRL 114, 166801 (2015)

Scattering in resonators

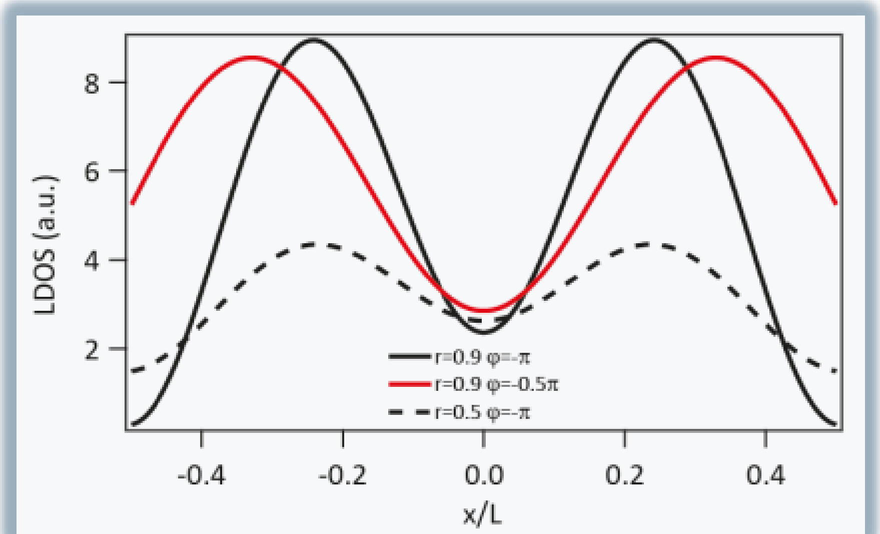






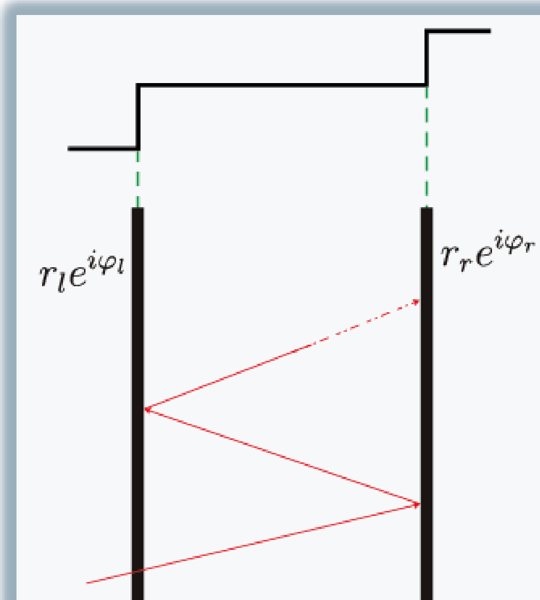
S. Schirone et al. PRL 114, 166801 (2015)

Fabry Perot resonator



Infinite barrier → $\varphi = -\pi$

L. Bürgi et al., Phys. Rev. Lett. 81, 5370 (1998).



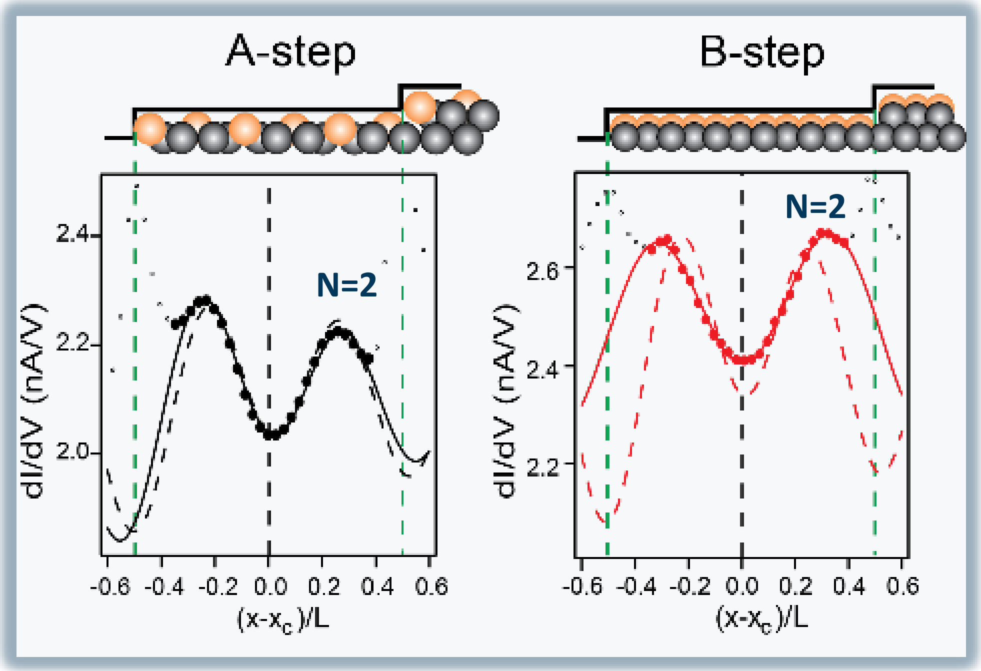
$$\frac{dI}{dV}(E,x) \propto \rho_b + \frac{\rho_s}{\pi}\int_{k_R}^{k_E} dk_x \frac{1}{\sqrt{k_E^2-(q/2)^2}}$$
$$\times \left\{ \frac{(1-r_l^2)\left[1+r_r^2+2r_r\cos\left(qL\left(x-\frac{1}{2}\right)-\varphi_r\right)\right]}{1+r_l^2r_r^2-2r_rr_l\cos\left(qL+\varphi_r+\varphi_l\right)} + \frac{(1-r_r^2)\left[1+r_l^2+2r_l\cos\left(qL\left(x+\frac{1}{2}\right)+\varphi_l\right)\right]}{1+r_l^2r_r^2-2r_rr_l\cos\left(qL+\varphi_r+\varphi_l\right)}\right\}$$

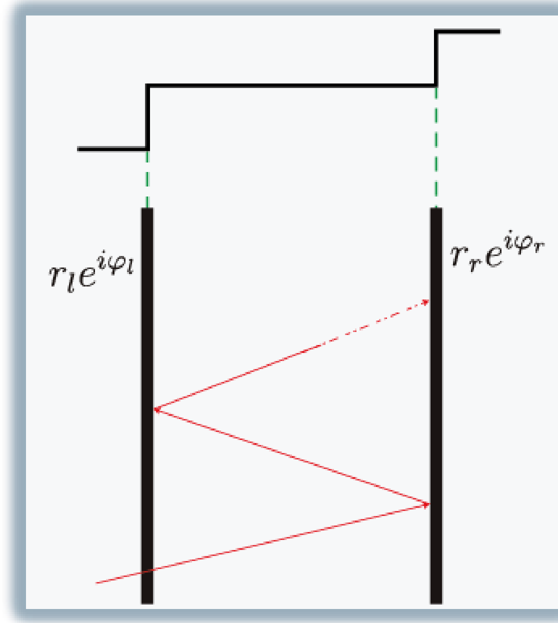
$$k_E = k - k_R = \sqrt{2m_{\text{eff}}/\hbar^2(E-E_0)}$$

$$q = 2(k_x - k_R)$$

S. Schirone et al. PRL 114, 166801 (2015)

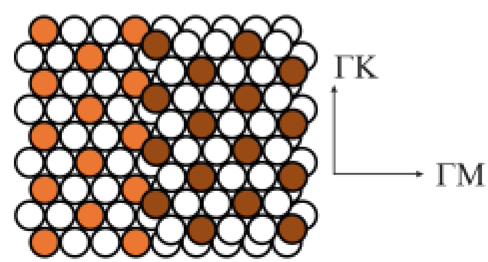
Effect of resonator edge structure





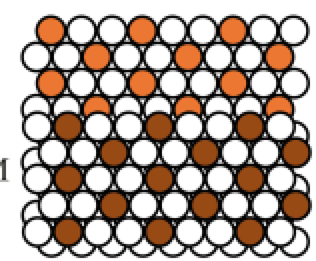
strong resonator

A-step



weak resonator

B-step

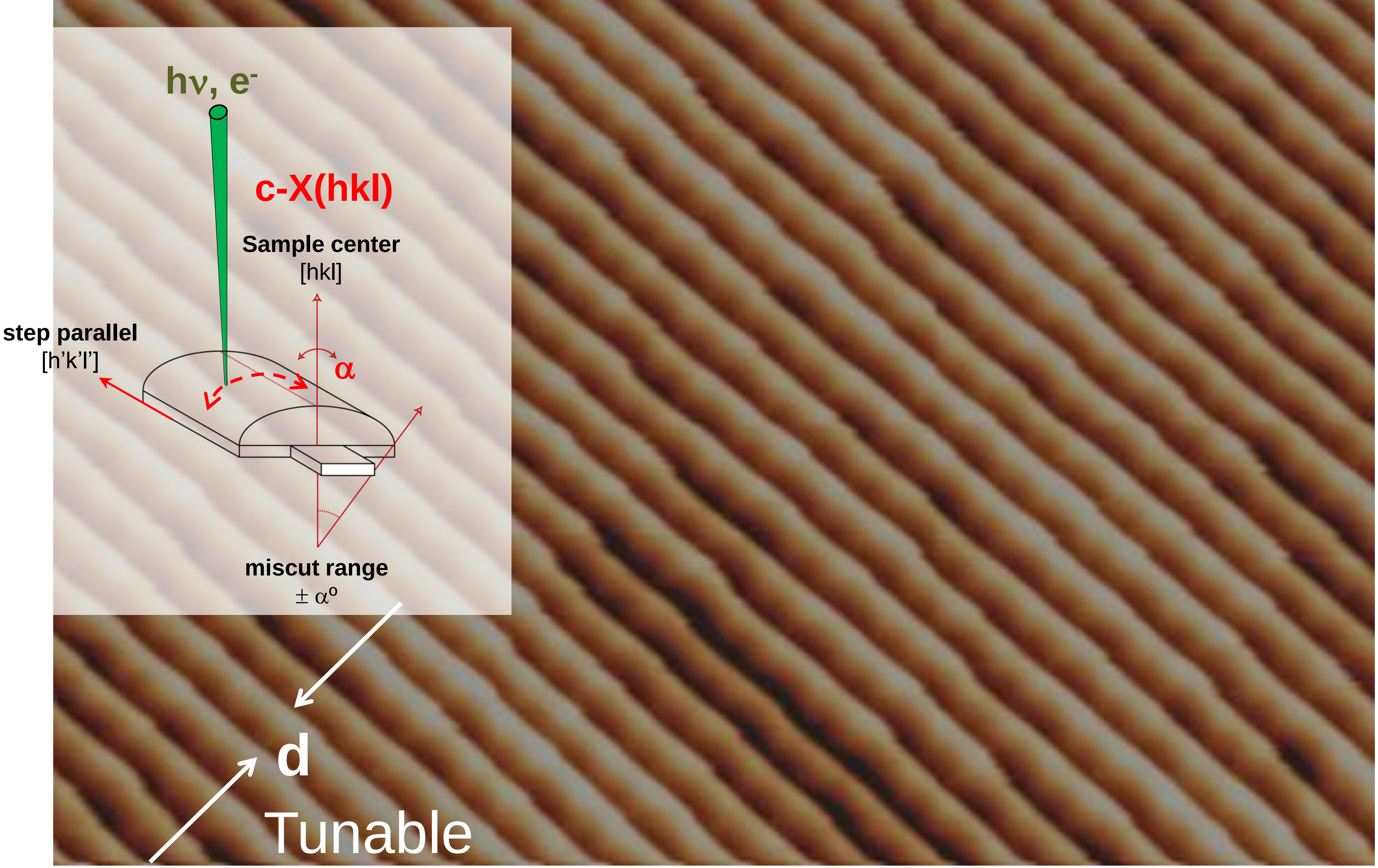


	r_l	r_r	φ_l/π	φ_r/π
A-step	0.70±0.30	0.21±0.07	-0.83±0.02	-0.95±0.02
B-step	0.40±0.18	0.36±0.15	-0.56±0.02	-0.51±0.02

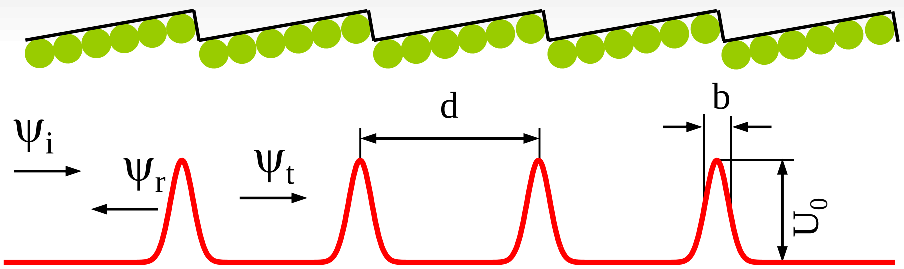
S. Schirone et al. PRL 114, 166801 (2015)

The Curved Surface Approach

Curved surfaces allows to **<u>tune</u>** and achieve **atomic scale control** over **physical-chemical** processes related to **<u>atomic steps</u>**

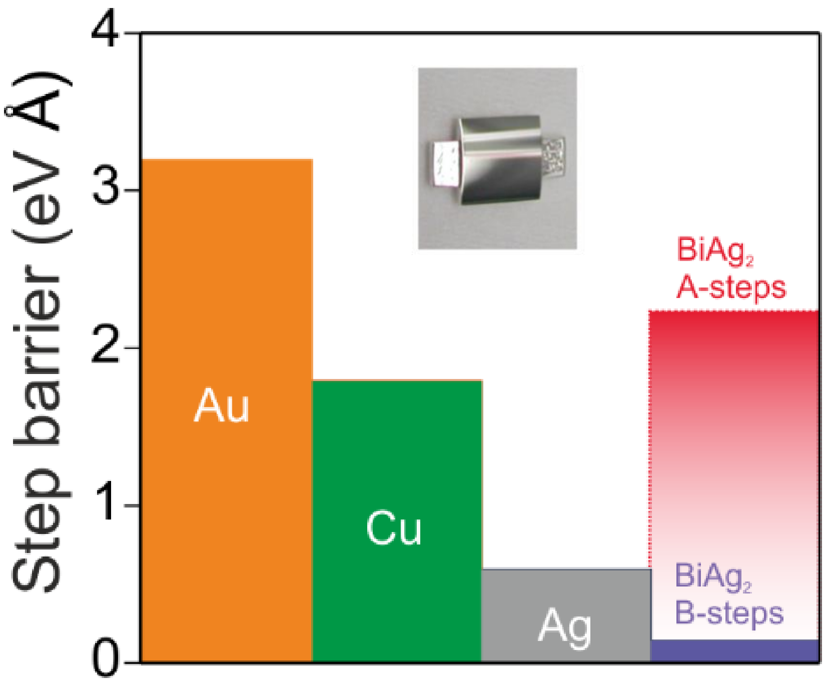


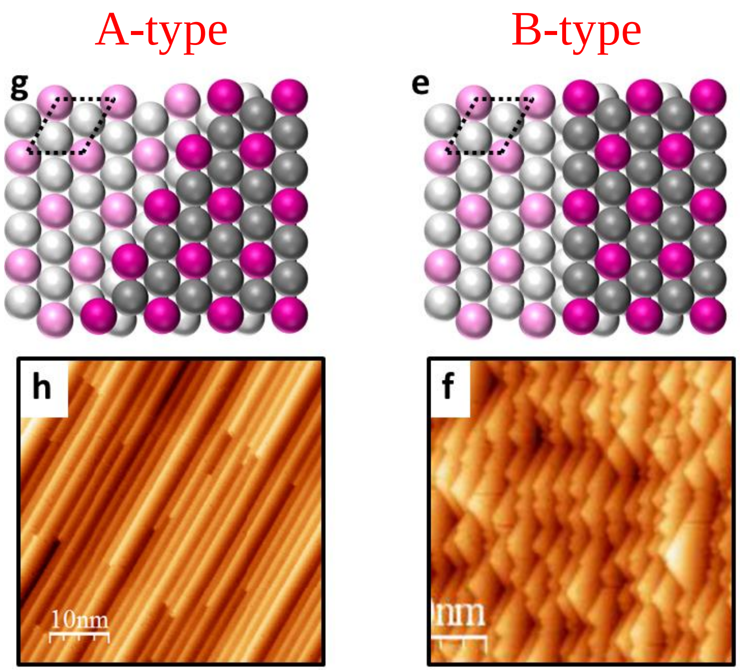
Scattering analysis framework: 1D Kronig-Penney model



$$\Delta E = \frac{2\hbar^2}{m^*}\frac{1}{d^2}\left(tg^{-1}\left(\frac{U_0 b}{\sqrt{\frac{2\hbar^2}{m^*}\Delta E}}\right)\right)^2$$

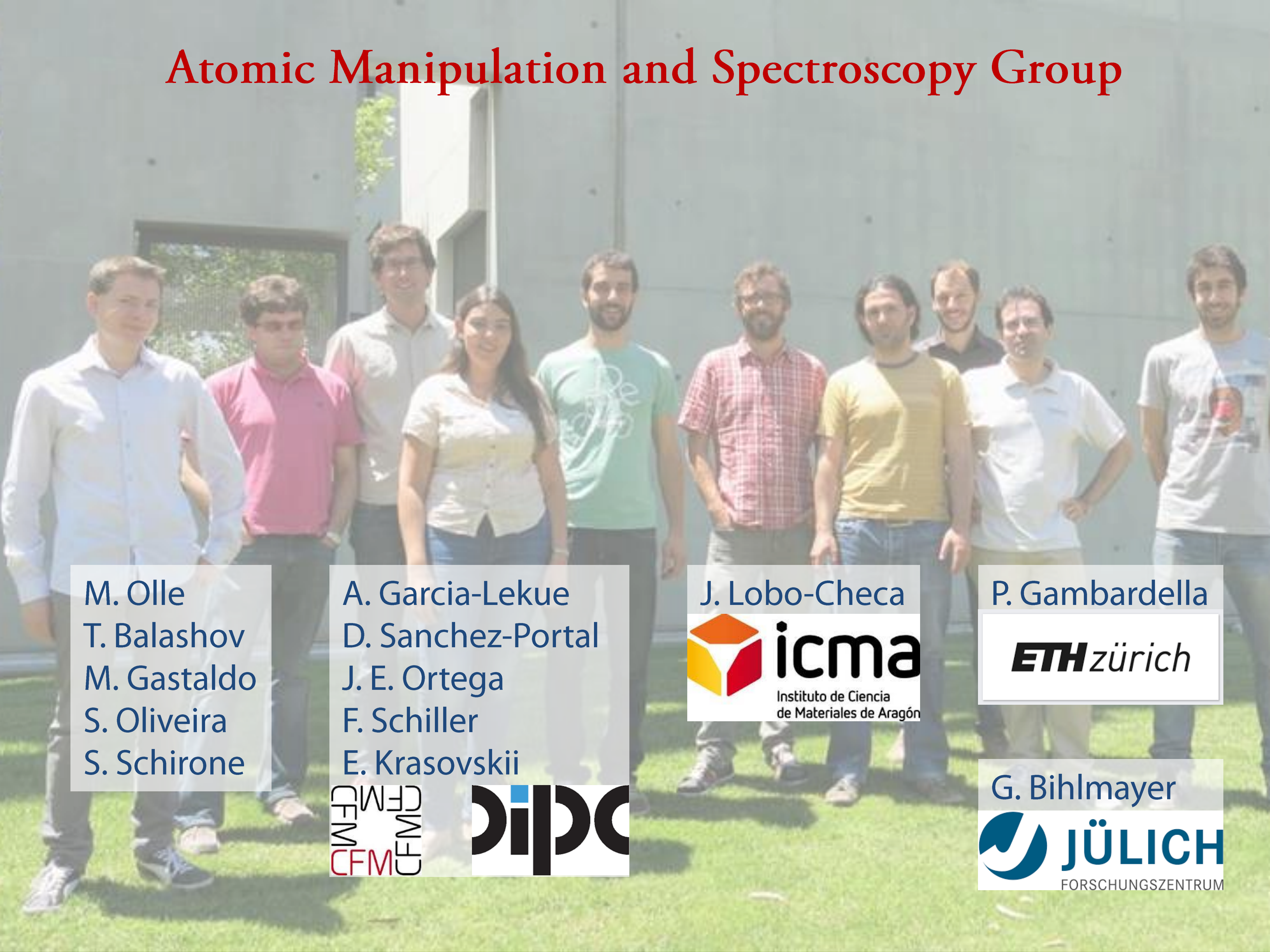
1D Kronig-Penney model





J. Lobo-Checa *et al.*, *unpublished*

Atomic Manipulation and Spectroscopy Group



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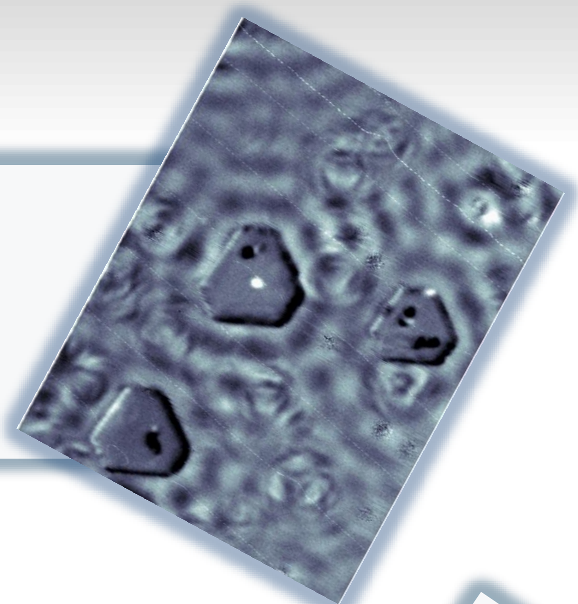
- Lateral spin-filtering
- Efficiency depends on edge structure



- New scattering mechanism in spin-orbitronic materials
- Controlled by chemical composition of steps