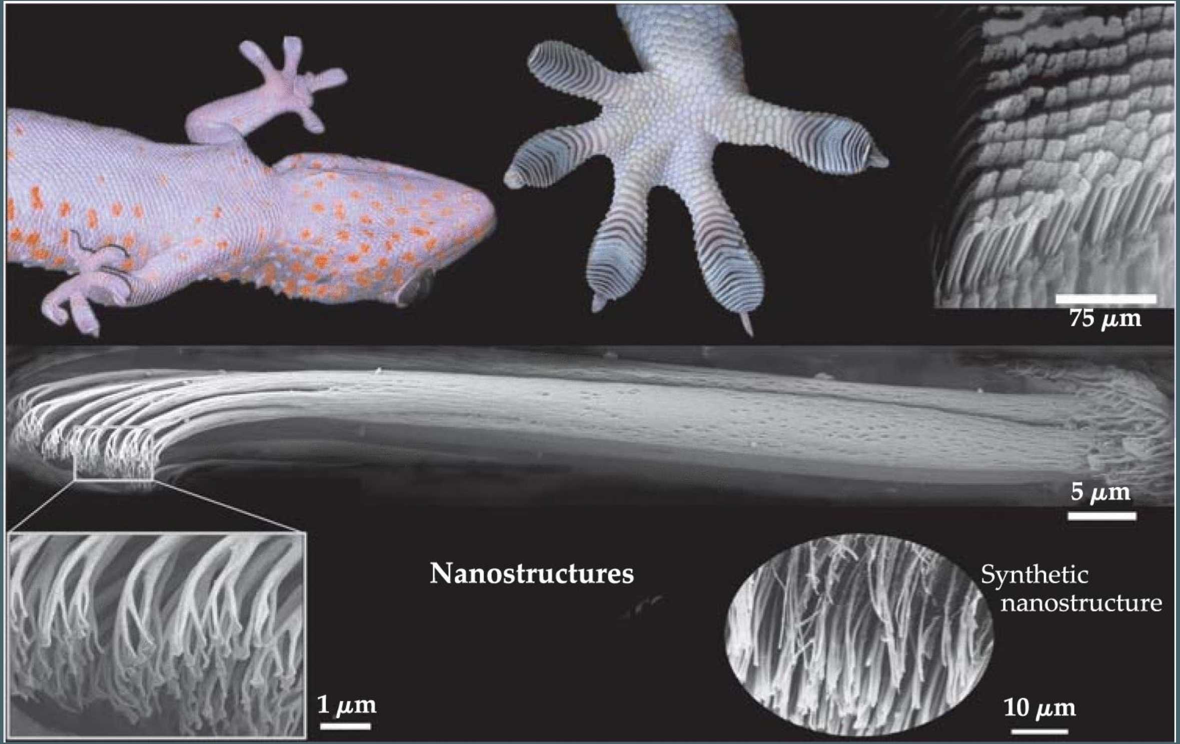
Casimir-Polder effect and Quantum Reflection in 2D-materials

Speaker: Tarik P. Cysne (UFF)

e-mail: (tarik.cysne@gmail.com)

e-mail: (ppabrantes91@gmail.com)



Collaborators

UFRJ- BR

Prof. C. Farina

UFRJ- BR

Prof. F. S. S. Rosa

UFRJ- BR

Prof. F. A. Pinheiro

UFRJ- BR

Profa. D. Szilard

UFSCar - BR

P. P. Abrantes
(PostDoc)

UFF - BR

T. P. Cysne
(PostDoc)

Los Al. Nat. Lab. (USA)

W. Kort-Kamp
(Staff researcher)

Scope of presentation

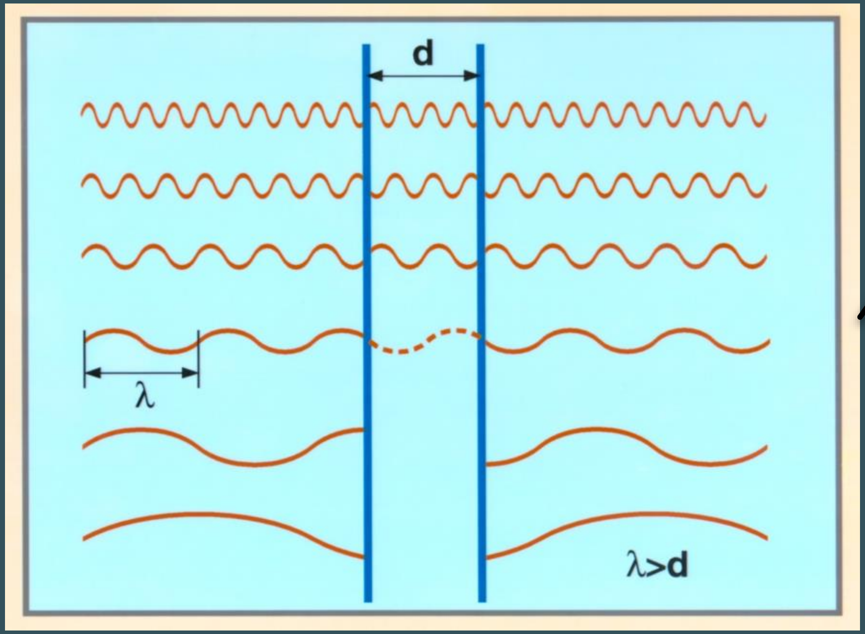
I - Casimir-Polder effect and Quantum Reflection

II - A brief review of graphene and graphene-family materials

III - Casimir-Polder and Quantum Reflection in 2D-Materials

I - Casimir-Polder effect and Quantum Reflection

(Hendrik Casimir)
Proc. K. Ned. Akad. Wet. 51, 793 (1948).



The attraction between two metals plates is related to **zero-point energy** fluctuations of the quantized electromagnetic field.

$$E_{Vac} = \sum_k \frac{1}{2} \hbar \omega_k$$

signal"−" for attraction

Casimir formula for attraction (**perfect** metal plates):

$$P_{Casimir} = -\hbar c \frac{\pi^2}{240} \frac{1}{d^4} = -0{,}013 \frac{1}{d^4} \text{ dyne}/cm^2$$

$1 \text{ dyne} = 10^{-5}$ Newtons

I - Casimir-Polder effect and Quantum Reflection

Experimental demonstration of Casimir force on long-distance regime (1997) by S. K. Lamoreaux.

PHYSICAL REVIEW LETTERS

Demonstration of the Casimir Force in the 0.6 to 6 μm Range

S. K. Lamoreaux*

Physics Department, University of Washington, Box 35160, Seattle, Washington 98195-1560

(Received 28 August 1996)

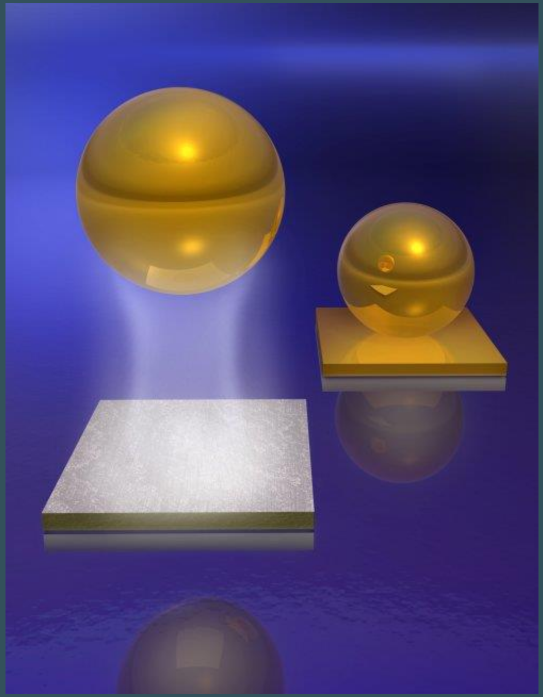
The vacuum stress between closely spaced conducting surfaces, due to the modification of the zero-point fluctuations of the electromagnetic field, has been conclusively demonstrated. The measurement employed an electromechanical system based on a torsion pendulum. Agreement with theory at the level of 5% is obtained. [S0031-9007(96)02025-X]

S. K. Lamoreaux

I - Casimir-Polder effect and Quantum Reflection

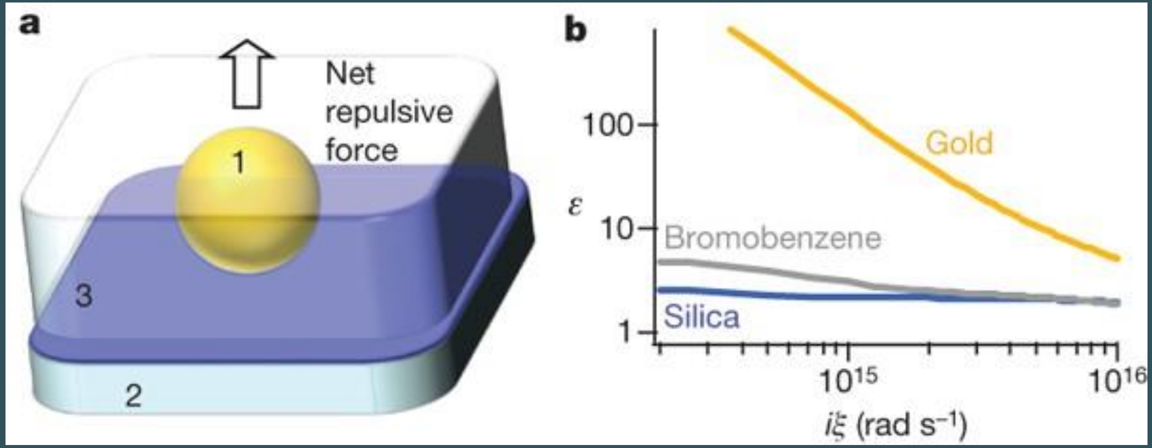
- **Casimir effect:** interaction between neutral (but polarizable) macroscopic bodies mediated by vacuum fluctuations.

-Usually, it is an **attractive** interaction.



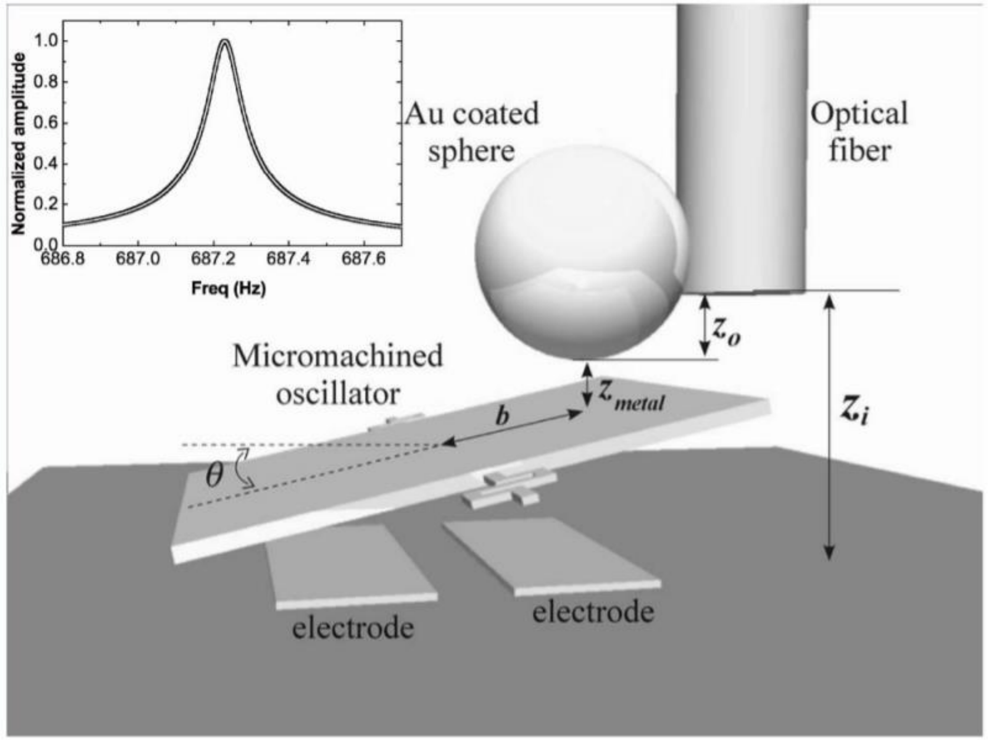
-In some particular situations, the Casimir interaction can be repulsive.

Ex: Nature **volume 457**, pages170–173 (2009)



I - Casimir-Polder effect and Quantum Reflection

Technological application: **NEMs** and **MEMs** (Nano/Micro electro mechanical machines)

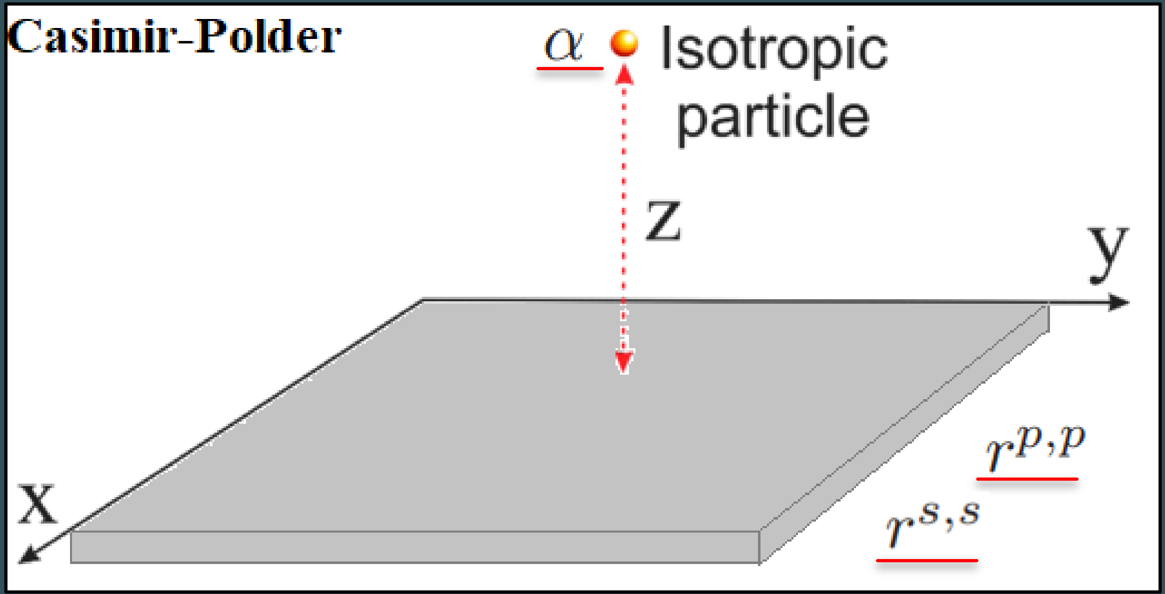


R. S. Decca, et al. Phys. Rev. D **68**, 116003 (2011).

-Casimir (dispersive) forces are dominant at microscale and nanoscale.

-These forces are important in understanding the operation of **NEMs** and **MEMs**.

I - Casimir-Polder effect and Quantum Reflection



- **Casimir-Polder interaction**: Interaction between a microscopic particle (atom) and a macroscopic body (neutral planar surface) mediated by vacuum fluctuations.

Lifshitz formula for **planar geometry** [JETP **2**, 73 (1956)]:

$$U_T(z) = \frac{k_B T}{\varepsilon_0 c^2} \sum_{l=0}^{\infty}{}' \xi_l^2 \, \alpha(i\xi_l) \int \frac{d^2\mathbf{k}}{(2\pi)^2} \frac{e^{-2\kappa_l z}}{2\kappa_l} \times \left[r^{s,s}(\mathbf{k}, i\xi_l) - \left(1 + \frac{2c^2k^2}{\xi_l^2}\right) r^{p,p}(\mathbf{k}, i\xi_l) \right]$$

$\alpha(i\xi)$ "optical polarizability of the particle"

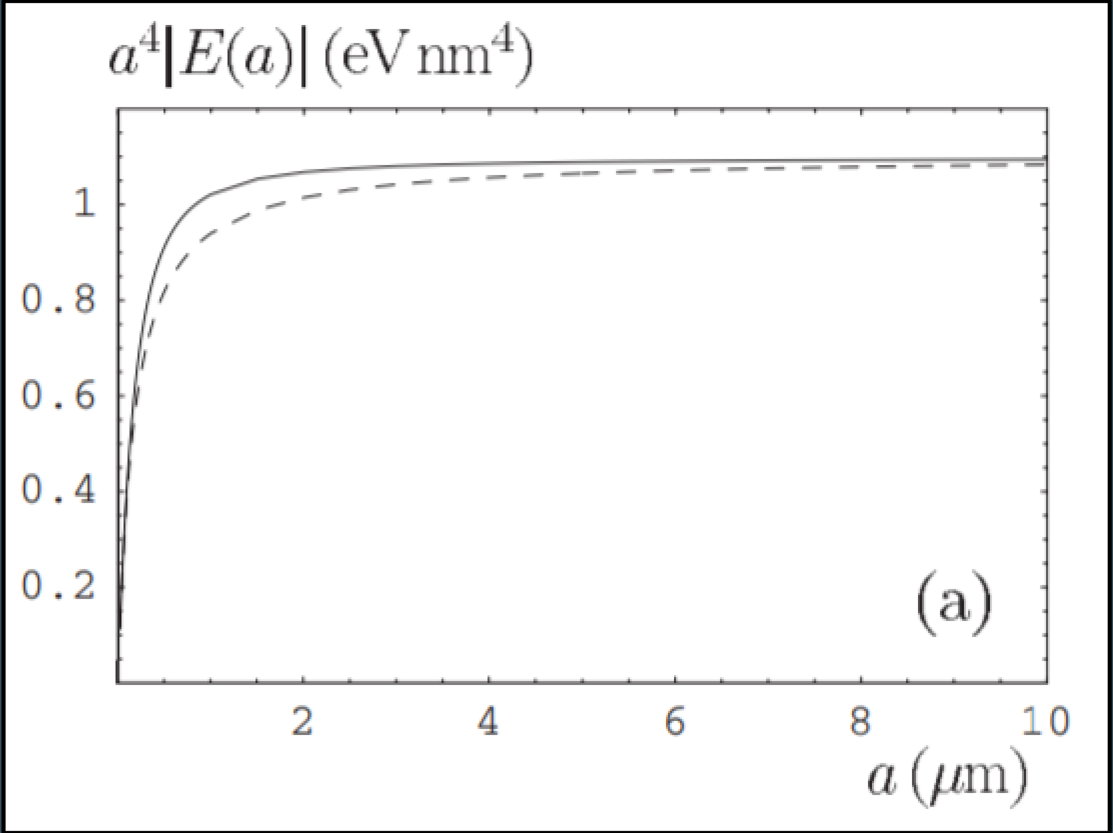
Lorentz Model: $\alpha_l(i\xi) = \frac{\alpha_l(0)}{1 + \frac{\xi^2}{\xi_l^2}}$

$r^{s,s}(\mathbf{k}, i\xi)$: "TE Fresnel coeficiente"

$r^{p,p}(\mathbf{k}, i\xi)$: "TM Fresnel coeficiente"

I - Casimir-Polder effect and Quantum Reflection

Example: Casimir-Polder energy between He atom and a gold plate.



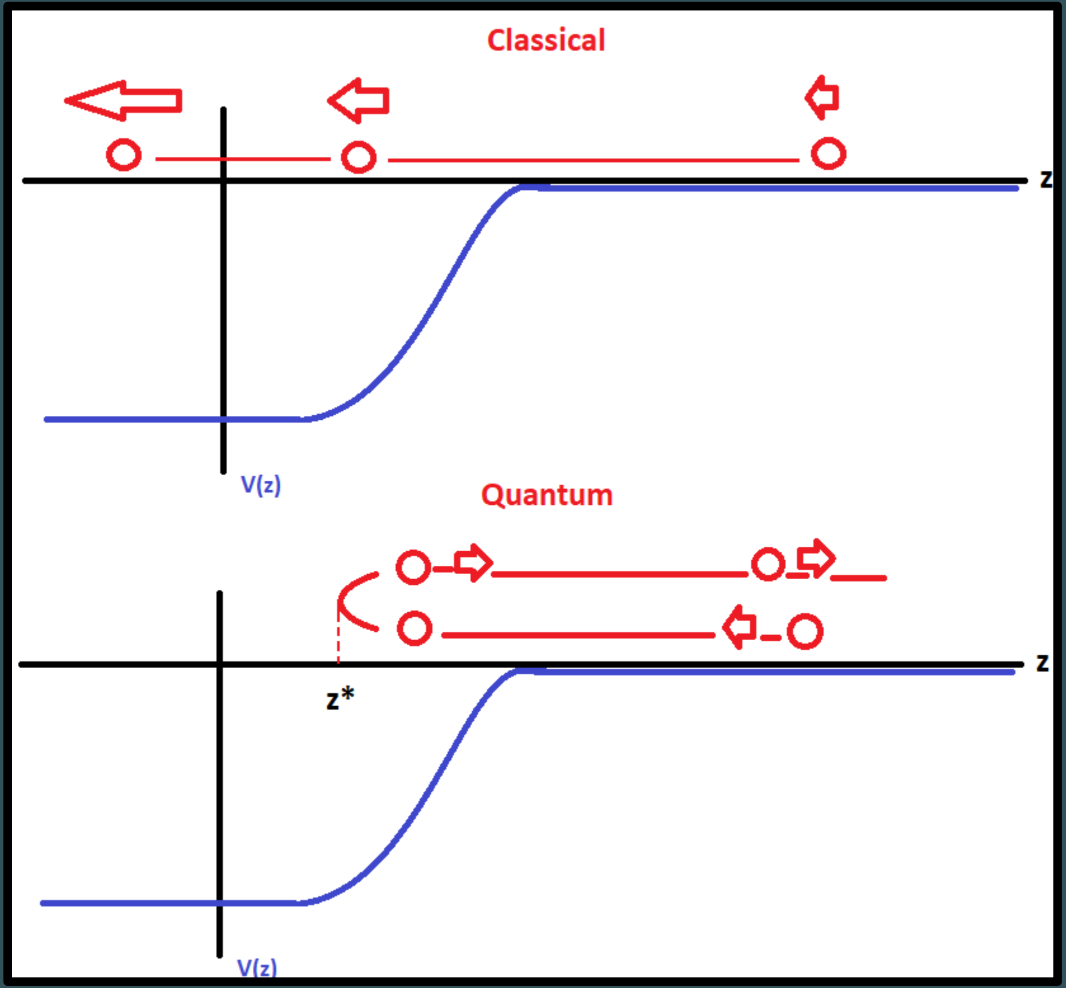
V. Bezerra, et. al. Phys. Rev. A 78, 042901 (2001).

The Casimir-Polder interaction between an atom and a translational invariant surface is **attractive**:

$$U(z) < 0$$

I - Casimir-Polder effect and Quantum Reflection

Quantum Reflection (QR) is the reflection of a quantum particle by an attractive potential.
Ex: The reflection of a **low-energetic atom** by the **attractive Casimir-Polder potential U(z)**.



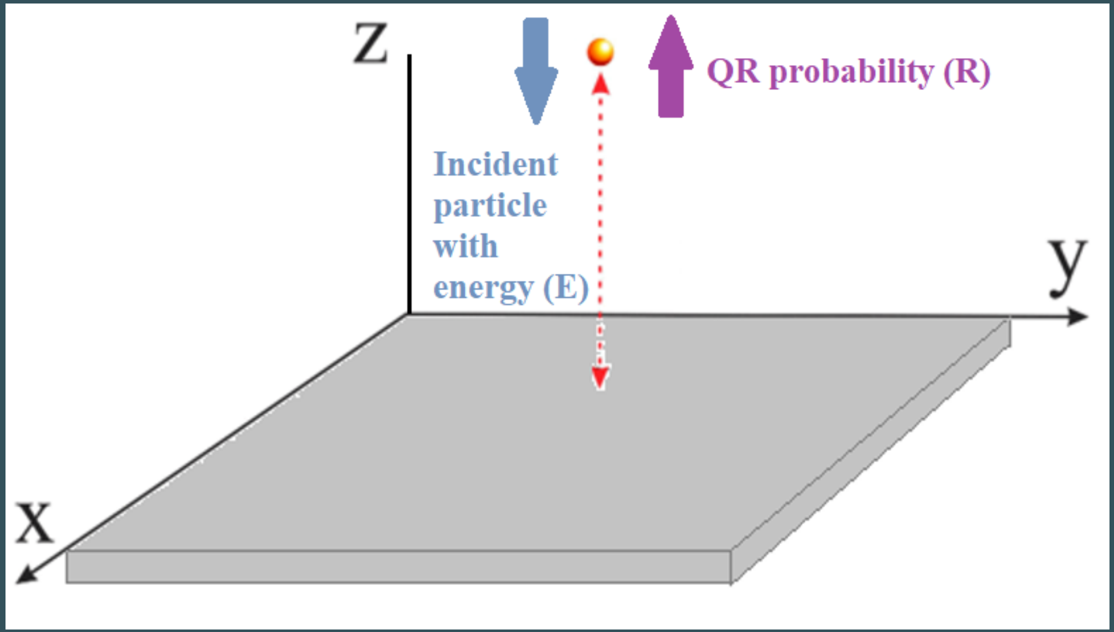
Applications of QR:

1- "Atom-optics" Ex: (i) atomic mirrors, (ii) wave matter diffraction gratings, (iii) atomic traps, etc…
See: "*Optics and interferometry with atoms and molecules*", Rev. Mod. Phys. **81**, 1051 (2009).

2- Action of gravity field in antimatter
(GBAR experiment - CERN):
See: "*The GBAR antimatter gravity experiment*", Hyperfine Interact. 233, 21 (2015).

I - Casimir-Polder effect and Quantum Reflection

For details: M. Silvestre et. al., Phys. Rev. A **100**, 033605 (2019)
P. P. Abrantes et. al., Phys. Rev. B **104**, 075409 (2021)



Atom-Surface (CP) interaction: Lifshitz formula

$$U_T(z) = \frac{k_B T}{\varepsilon_0 c^2} \sum_{l=0}^{\infty}{}' \xi_l^2 \, \alpha(i\xi_l) \int \frac{d^2\mathbf{k}}{(2\pi)^2} \frac{e^{-2\kappa_l z}}{2\kappa_l} \times \left[r^{s,s}(\mathbf{k}, i\xi_l) - \left(1 + \frac{2c^2k^2}{\xi_l^2}\right) r^{p,p}(\mathbf{k}, i\xi_l) \right]$$

Wave equation of incident particle with energy (E):

$$\frac{\partial^2 \psi(z)}{\partial z^2} + \frac{p^2(z)}{\hbar^2}\psi(z) = 0, \qquad p(z) = \sqrt{2m[E - U(z)]}.$$

Assuming a WKB-like wave-function

$$\psi(z) = \frac{c_+(z)}{|\sqrt{p(z)}|} e^{i\phi(z)} + \frac{c_-(z)}{\sqrt{|p(z)|}} e^{-i\phi(z)}$$

$$\phi(z) = \int_{z_0}^{z} \frac{p(z')}{\hbar} dz'$$

$$\frac{\partial c_+(z)}{\partial z} = e^{-2i\phi(z)} \frac{c_-(z)}{2p(z)} \frac{\partial p(z)}{\partial z}$$

$$\frac{\partial c_-(z)}{\partial z} = e^{+2i\phi(z)} \frac{c_+(z)}{2p(z)} \frac{\partial p(z)}{\partial z}$$

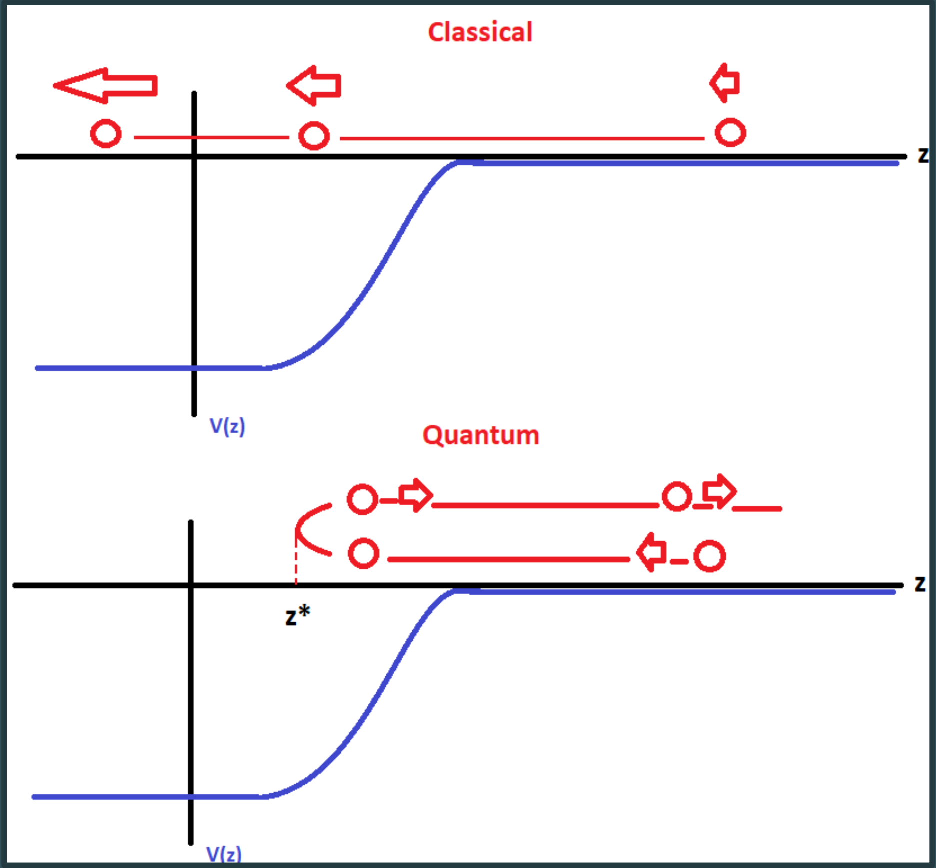
$$c_+(0) = 0 \text{ and } c_-(0) = 1$$

QR Probability!

$$R = \lim_{z \to \infty} \left| \frac{c_+(z)}{c_-(z)} \right|^2$$

I - Casimir-Polder effect and Quantum Reflection

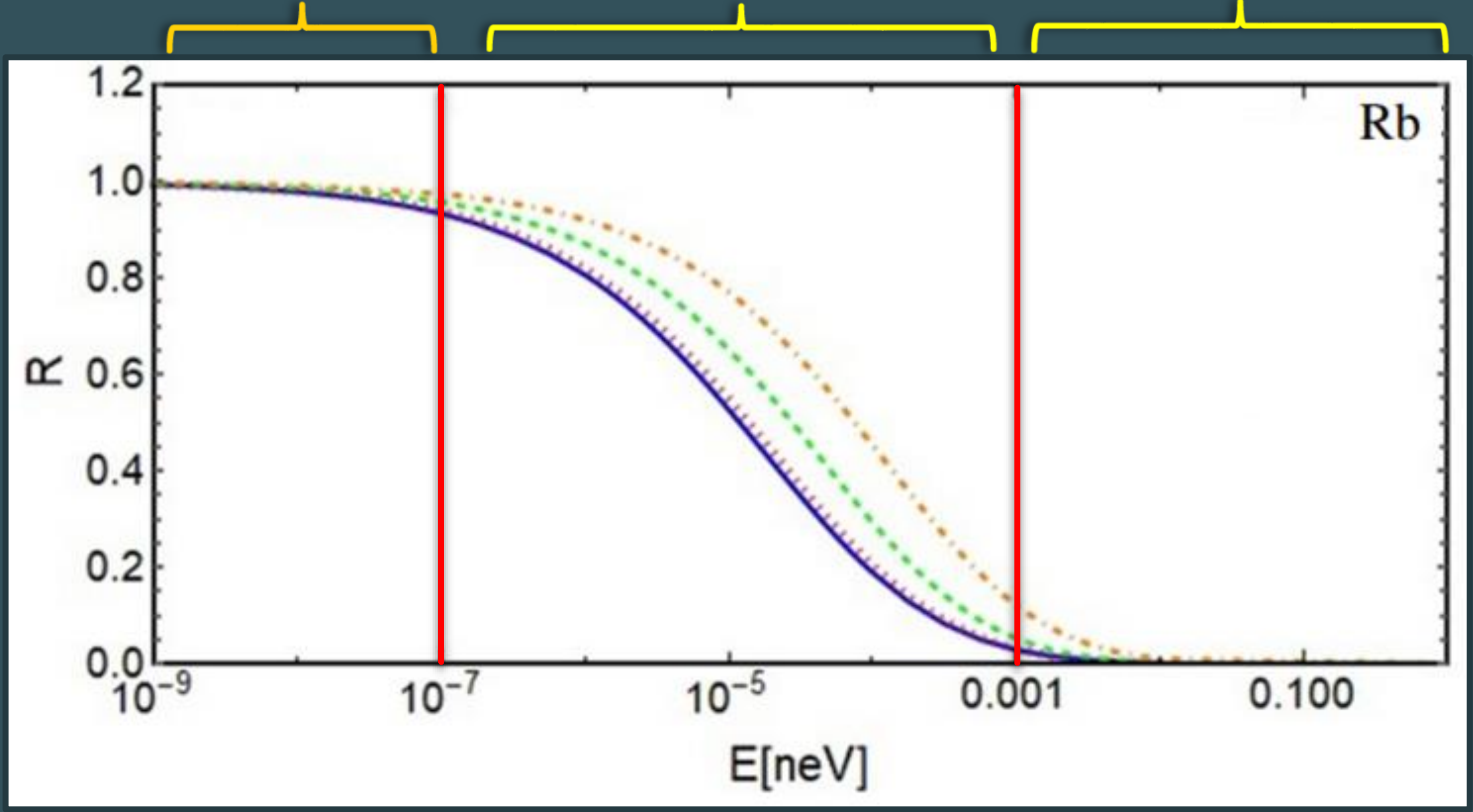
Typical curve of QR probability as a function of the energy of the incident atom



Quantum Regime (Wave)

Transient Regime (Wave + Particle)

Classical Regime (Particle)



Energy of incident particle

I - Casimir-Polder effect and Quantum Reflection

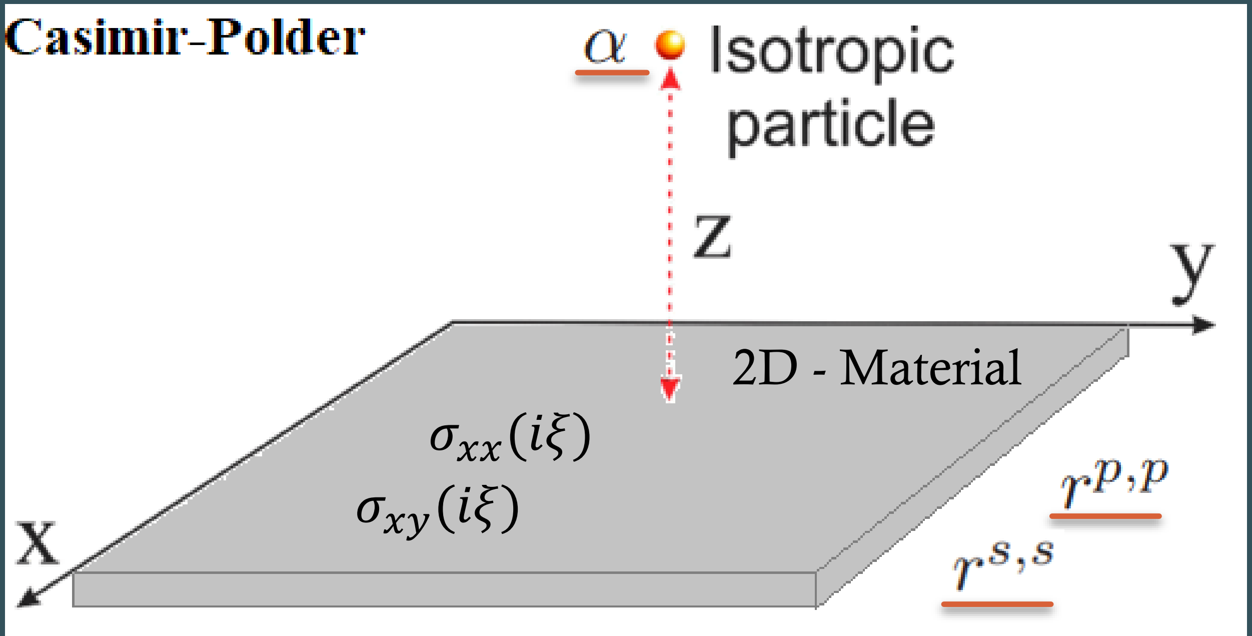
- The surface may be a 2D material !
- If we know the Fresnel coefficients of the material $r^{s,s}$ and $r^{p,p}$ we can compute the CP interaction and the QR probability.

- The Fresnel coefficients of a 2D material can be straightforwardly computed:

$\sigma_{xx}(i\xi)$ Longitudinal Conductivity

$\sigma_{xy}(i\xi)$ Hall Conductivity

} 2D - Material



Fresnel coefficients

$$r^{ss}(\boldsymbol{k}, i\xi) = \frac{2\sigma_{xx}(i\xi)Z^{\mathrm{H}} + \eta_0^2[\sigma_{xx}^2(i\xi) + \sigma_{xy}^2(i\xi)]}{-\Phi(\boldsymbol{k}, i\xi)}$$

$$r^{pp}(\boldsymbol{k}, i\xi) = \frac{2\sigma_{xx}(i\xi)Z^{\mathrm{E}} + \eta_0^2[\sigma_{xx}^2(i\xi) + \sigma_{xy}^2(i\xi)]}{\Phi(\boldsymbol{k}, i\xi)}$$

Where:

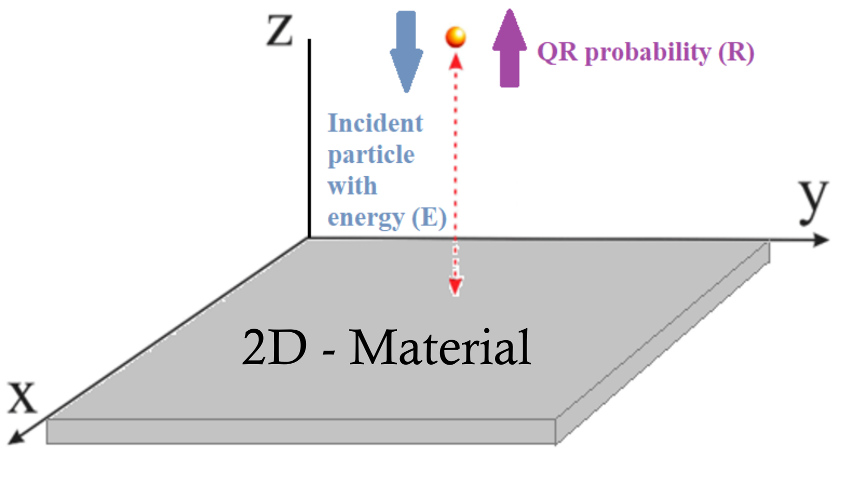
$$\Phi(\boldsymbol{k}, i\xi) = [2 + Z^{\mathrm{H}}\sigma_{xx}(i\xi)][2 + Z^{\mathrm{E}}\sigma_{xx}(i\xi)] + [\eta_0\sigma_{xy}(i\xi)]^2$$

$$Z^{\mathrm{H}} = \xi\mu_0/\kappa,\ Z^{\mathrm{E}} = \kappa/(\xi\epsilon_0),\ \eta_0^2 = \mu_0/\epsilon_0$$

I - Casimir-Polder effect and Quantum Reflection

- In 2D materials, the **electronic structure is highly tunable by external agents**: Electric field, Magnetic Field, Strain, Stacking, etc.

-The modifications of **electronic structure** translate into a modification of **optical conductivities** $\sigma_{xx}(i\xi)$ and $\sigma_{xy}(i\xi)$.



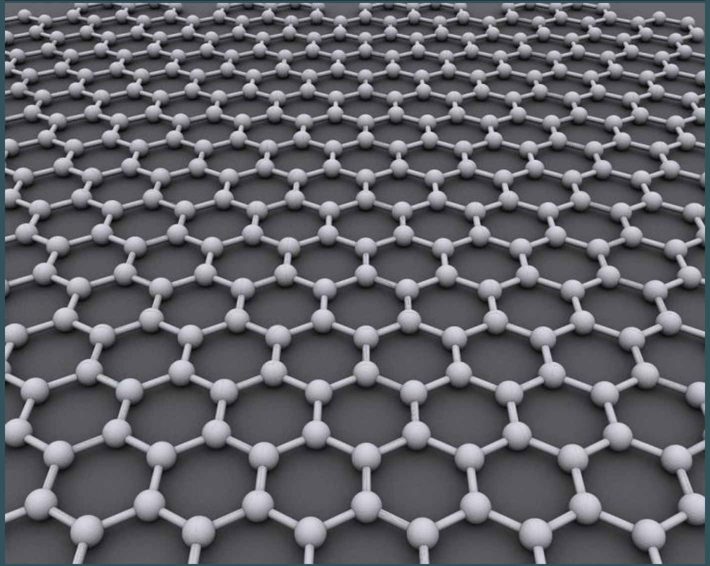
In 2D-Materials:

(External Parameter) → (Optical Conductivities) → (Fresnel Coefficients) → (Casimir-Polder Interaction) → (Quantum Reflection Probability)

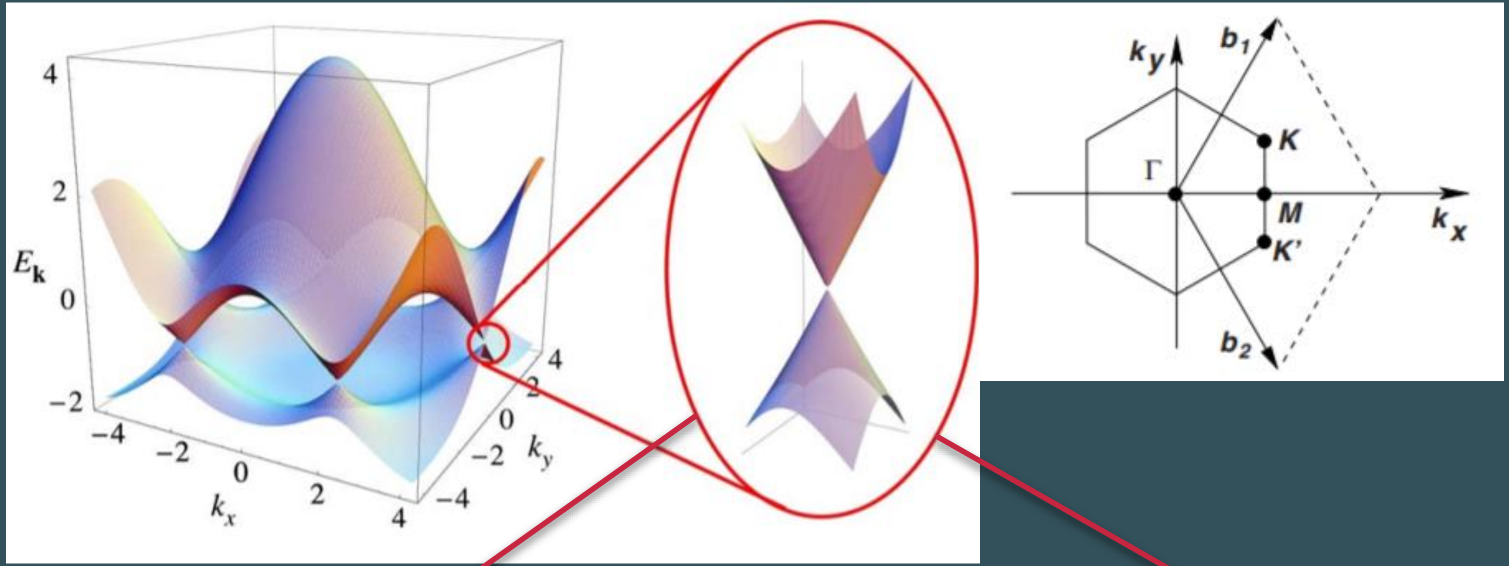
E_z, B_z, Λ, … Affect → $\sigma_{xx}(i\xi)$, $\sigma_{xy}(i\xi)$ Affect → $r^{ss}(\boldsymbol{k}, i\xi)$, $r^{pp}(\boldsymbol{k}, i\xi)$ Affect → $U(z)$ Affect → R

II - A brief review of graphene and graphene-family materials

Graphene (Highly tunable electronic structure):



Near the valleys, we can model graphene using the Dirac model.



$$H_g = \hbar v_f\left(\eta\tau_x k_x + \tau_y k_y\right)$$

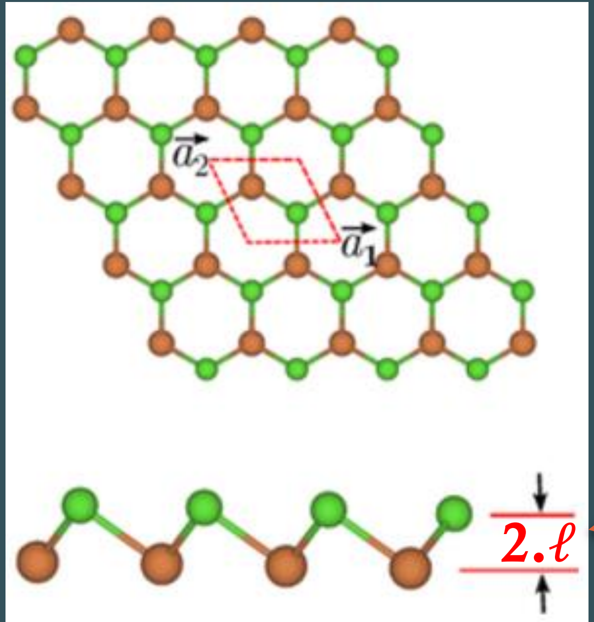
Two “problems” of graphene:

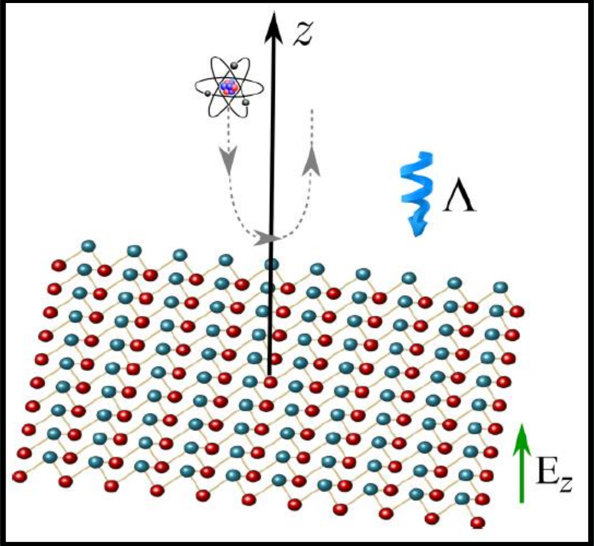
1 - Small spin-orbit coupling (~μeV) → No topological phase transitions

2 - Flat material → Does not respond to the external electric fields. (No controllable band-gap.)

II - A brief review of graphene and graphene-family materials

Graphene Family Materials





Material	λ_{SO} (meV)	t (eV)	ℓ (Å)	a (Å)
Silicene	2	1.6	0.11	3.86
Germanene	20	1.3	0.16	4.02
Stanene	50	1.3	0.20	4.70

P. P. Abrantes et al., PRB 104, 075409 (2021).

1 - The graphene Family materials have a high intrinsic spin-orbit coupling (λ_{SO}):

2 - The buckled lattice (ℓ) of graphene-family materials makes that it respond to perpendicular electric fields:

3 – We may also expose graphene family material to a circular polarized optical field (Λ):

Hamiltonian of Graphene Family Materials

$$H_{GF} = \hbar v_f\left(\eta\tau_x k_x + \tau_y k_y\right) + \frac{1}{2}\eta s\lambda_{SO} - \frac{1}{2}e\ell E_z - \frac{1}{2}\eta\Lambda$$

II - A brief review of graphene and graphene-family materials

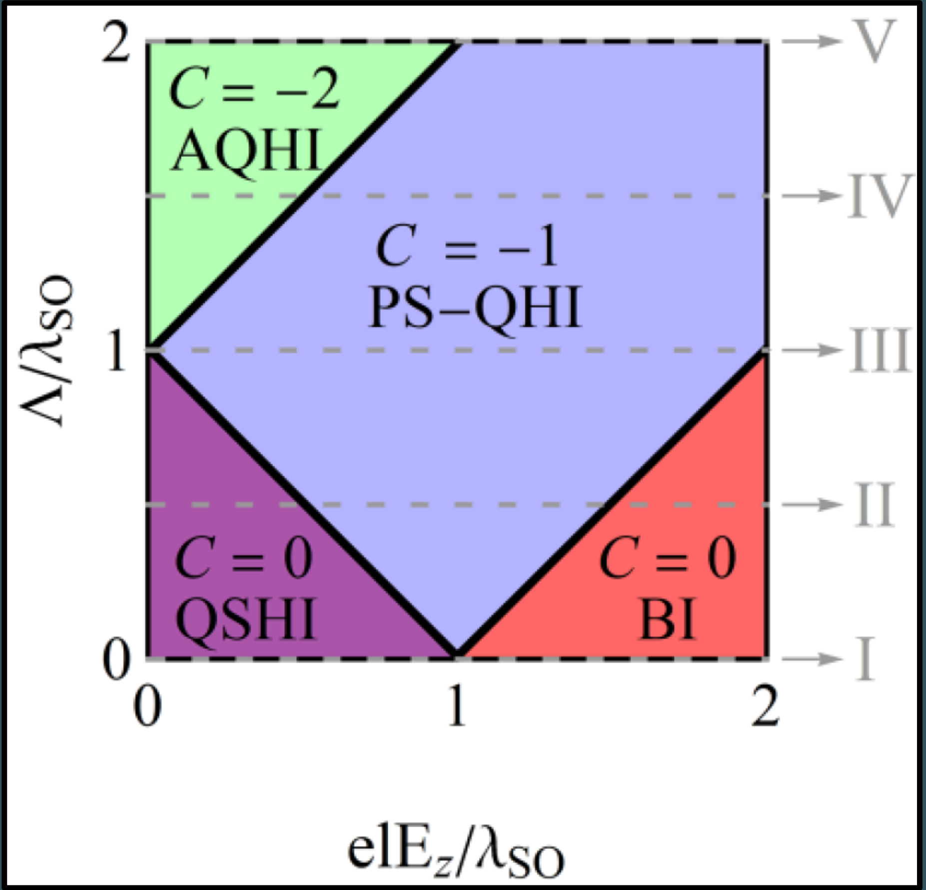
$$H_{GF} = \hbar v_f\left(\eta\tau_x k_x + \tau_y k_y\right) + \frac{1}{2}\eta s\lambda_{SO} - \frac{1}{2}e\ell E_z - \frac{1}{2}\eta\Lambda$$

graphene-family low-energy Hamiltonian

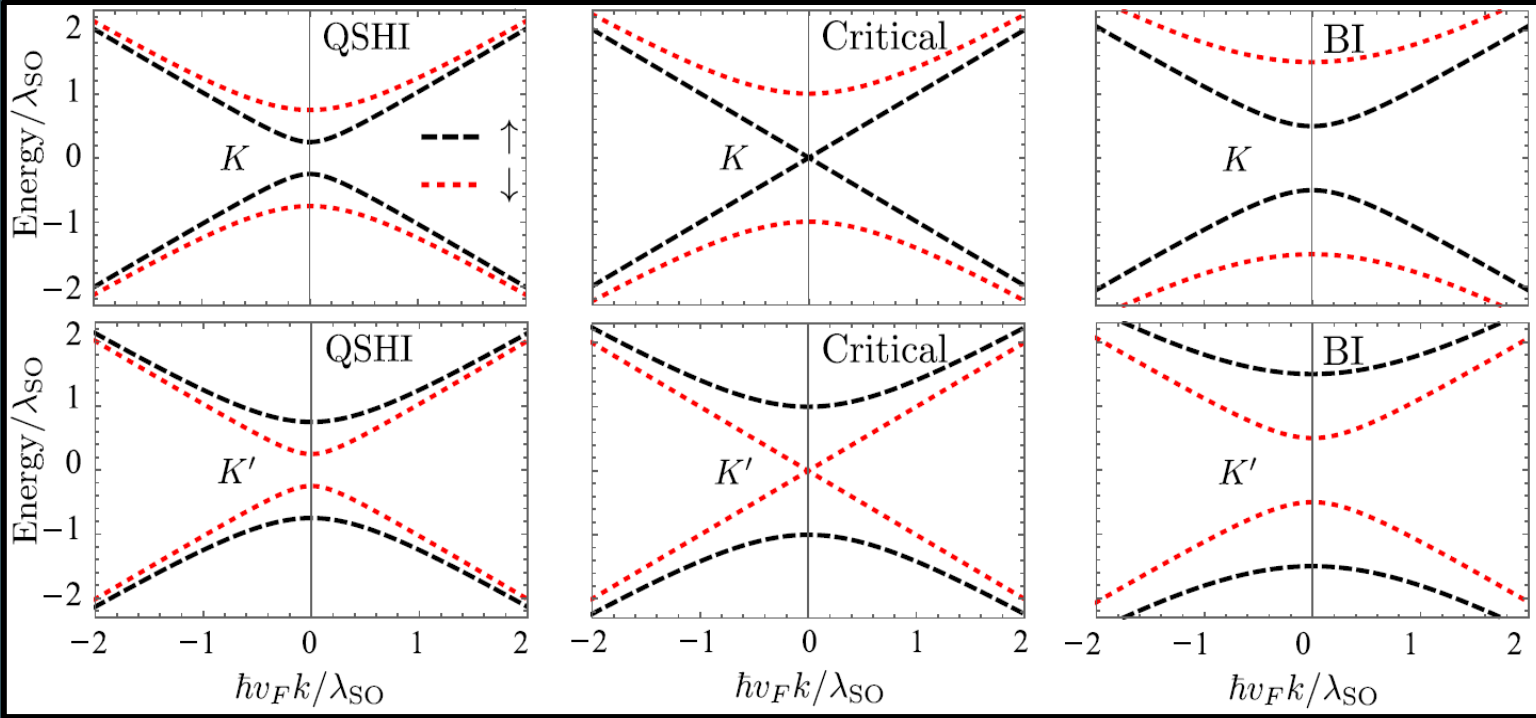
$$H_s^\eta = \hbar v_F(\eta k_x\tau_x + k_y\tau_y) + \frac{\Delta_s^\eta}{2}\tau_z - \mu$$

$$\Delta_s^\eta = \eta s\lambda_{SO} - e\ell E_z - \eta\Lambda$$

Topological Phase Diagram



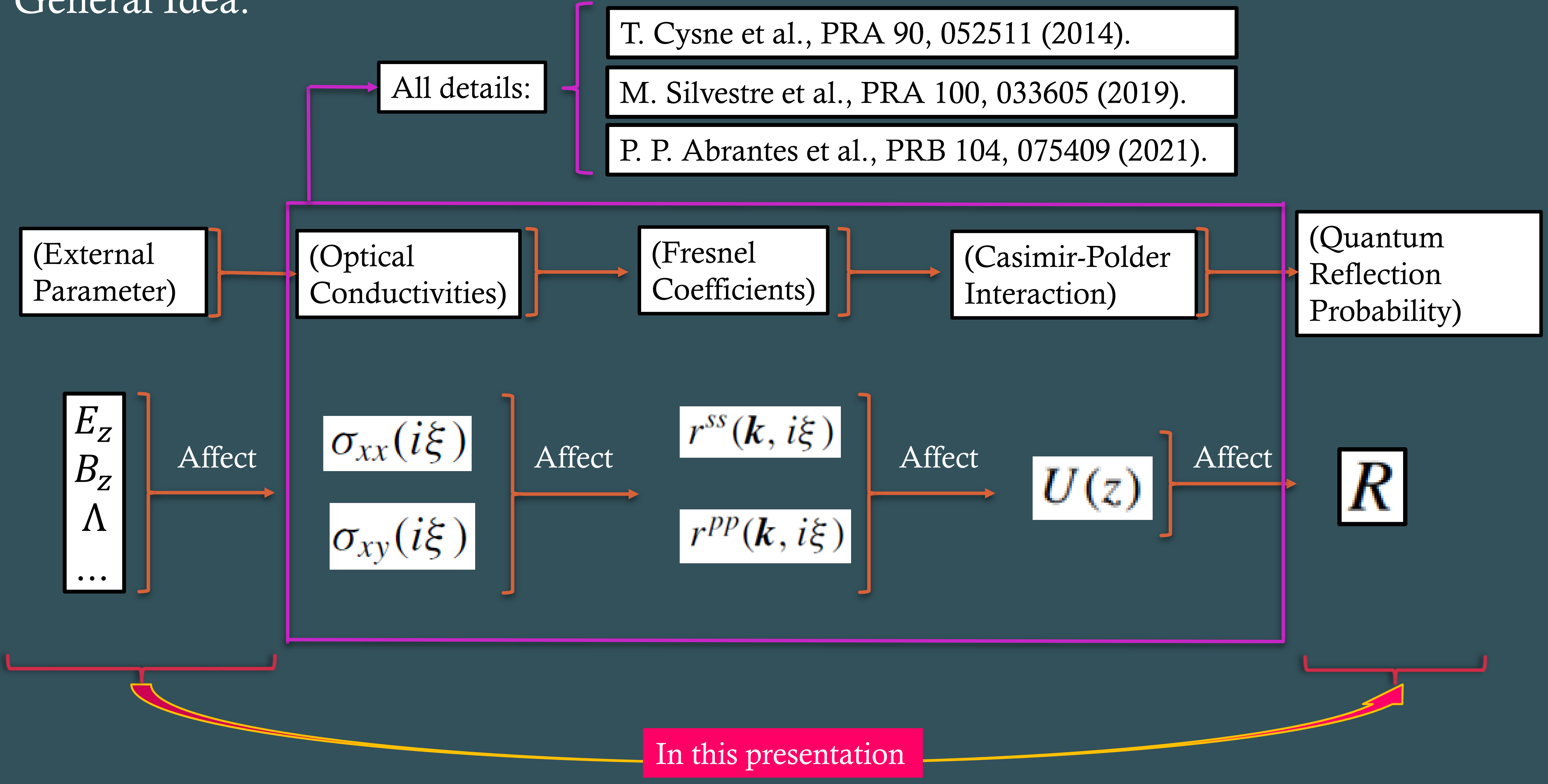
P. P. Abrantes et al., PRB 104, 075409 (2021).



Electronic Spectra - Path I: $\Lambda = 0$

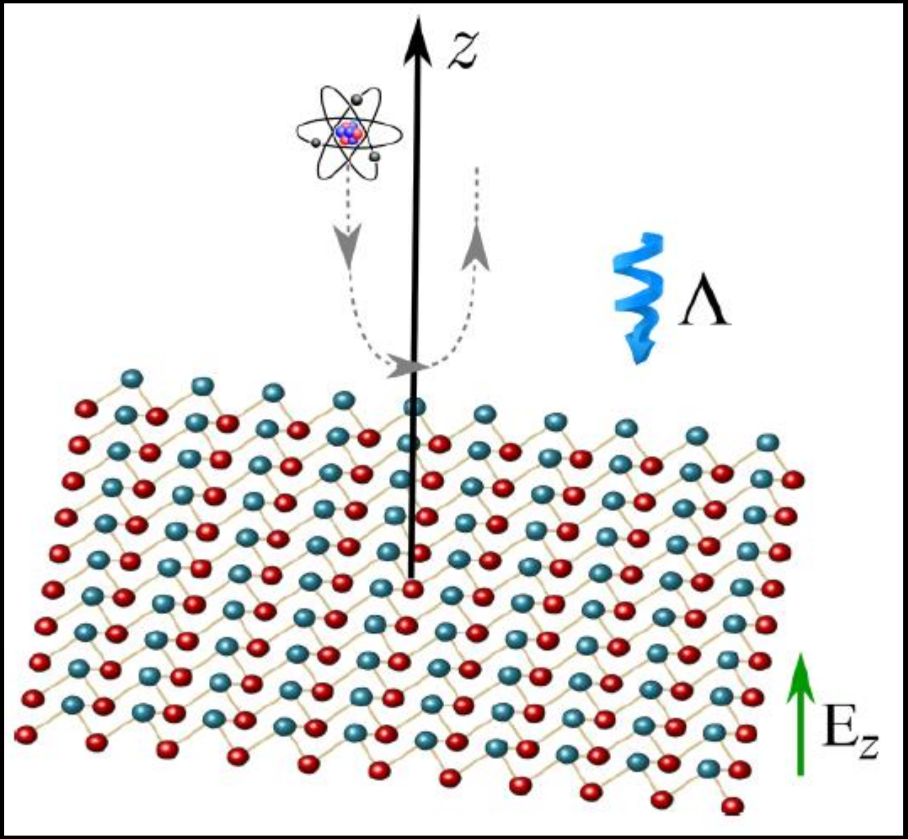
III - Casimir-Polder and Quantum Reflection in 2D-Materials

General Idea:



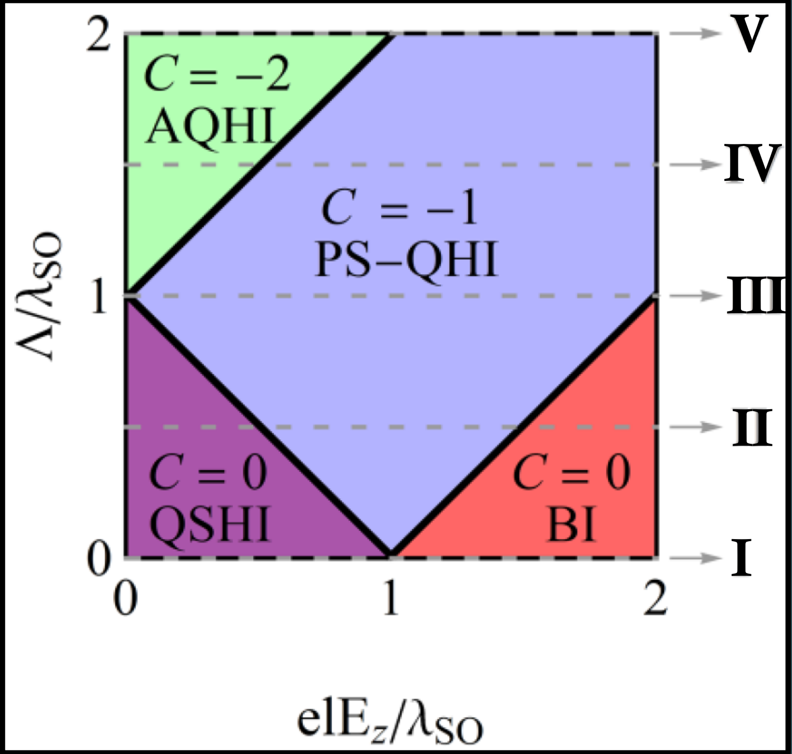
III - Casimir-Polder and Quantum Reflection in 2D-Materials

P. P. Abrantes et al., PRB 104, 075409 (2021).



(Quantum Reflection of atoms by graphene Family materials)

(Topological Phase diagram of Graphene Family materials)



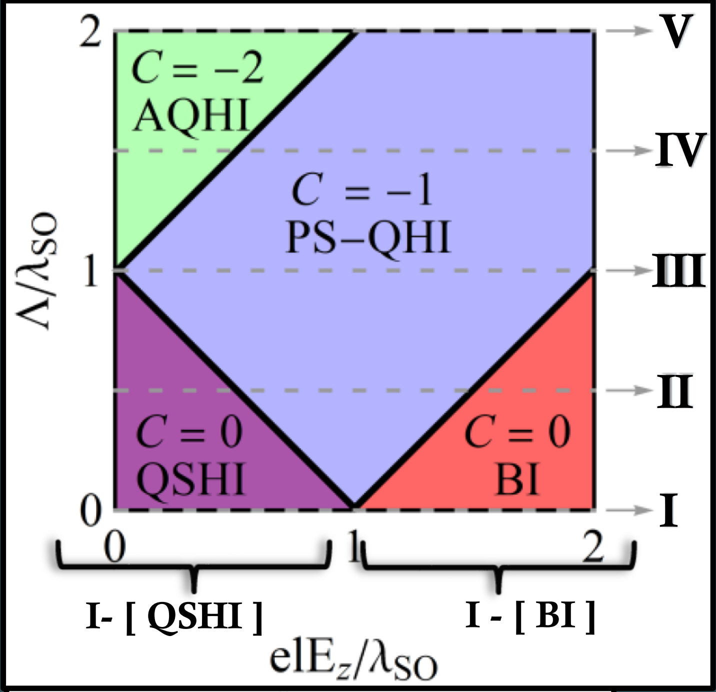
$$H_s^\eta = \hbar v_F(\eta k_x \tau_x + k_y \tau_y) + \frac{\Delta_s^\eta}{2}\tau_z - \mu$$

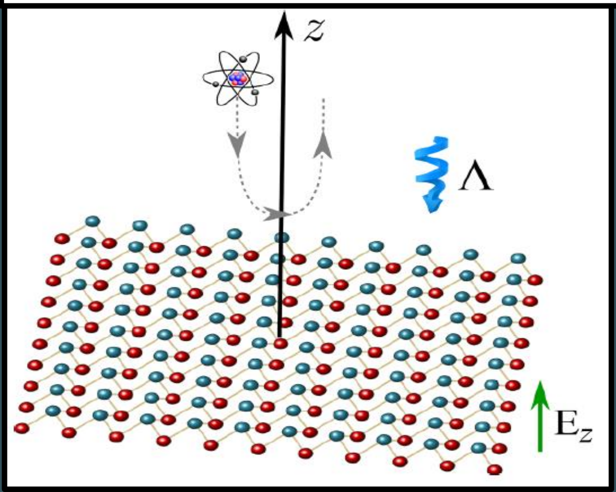
$$\Delta_s^\eta = \eta s \lambda_{SO} - e\ell E_z - \eta \Lambda$$

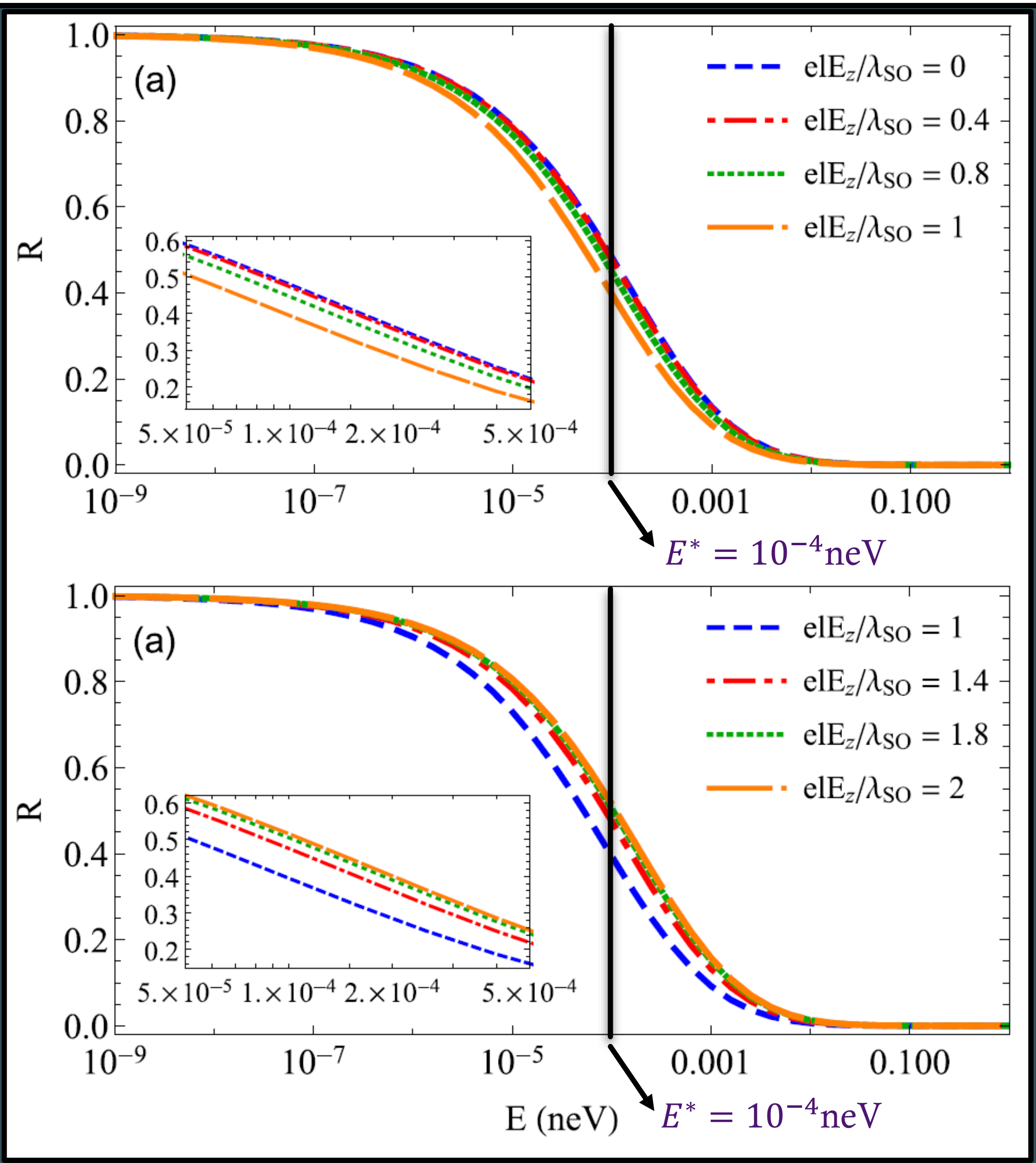
III - Casimir-Polder and Quantum Reflection in 2D-Materials

P. P. Abrantes et al., PRB 104, 075409 (2021).

(Atom: Rb / 2D Material: Stanene/ Neutrality $\mu = 0$/ **Path I:** $\boldsymbol{\Lambda = 0}$)







I- [QSHI]

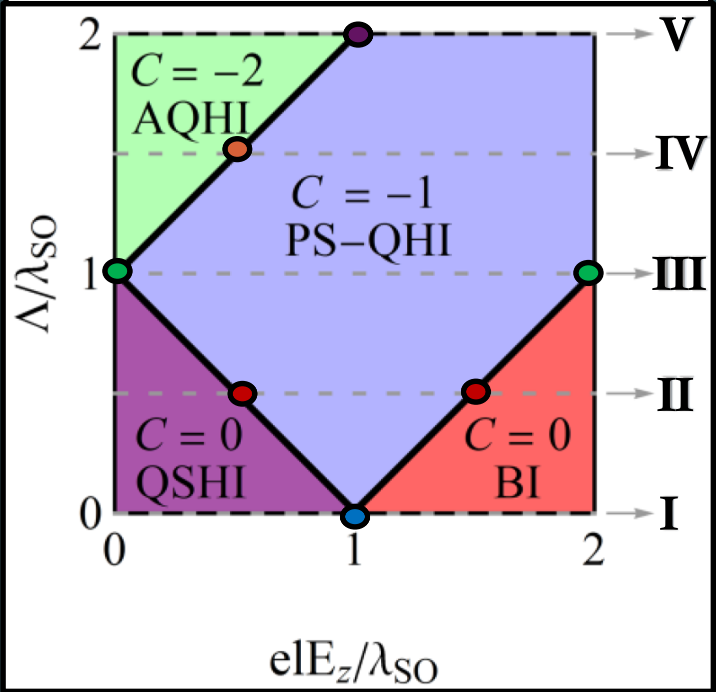
I- [BI]

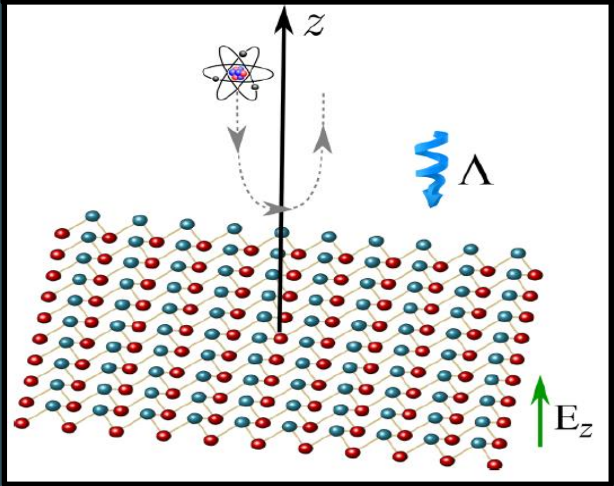
III - Casimir-Polder and Quantum Reflection in 2D-Materials

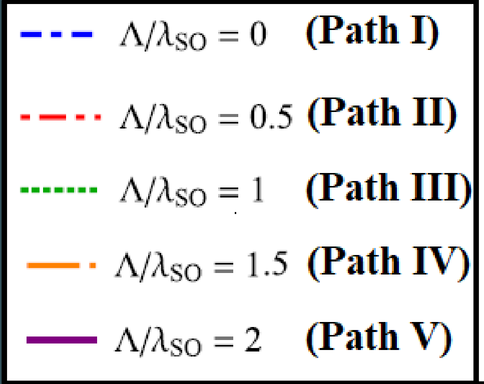
P. P. Abrantes et al., PRB 104, 075409 (2021).

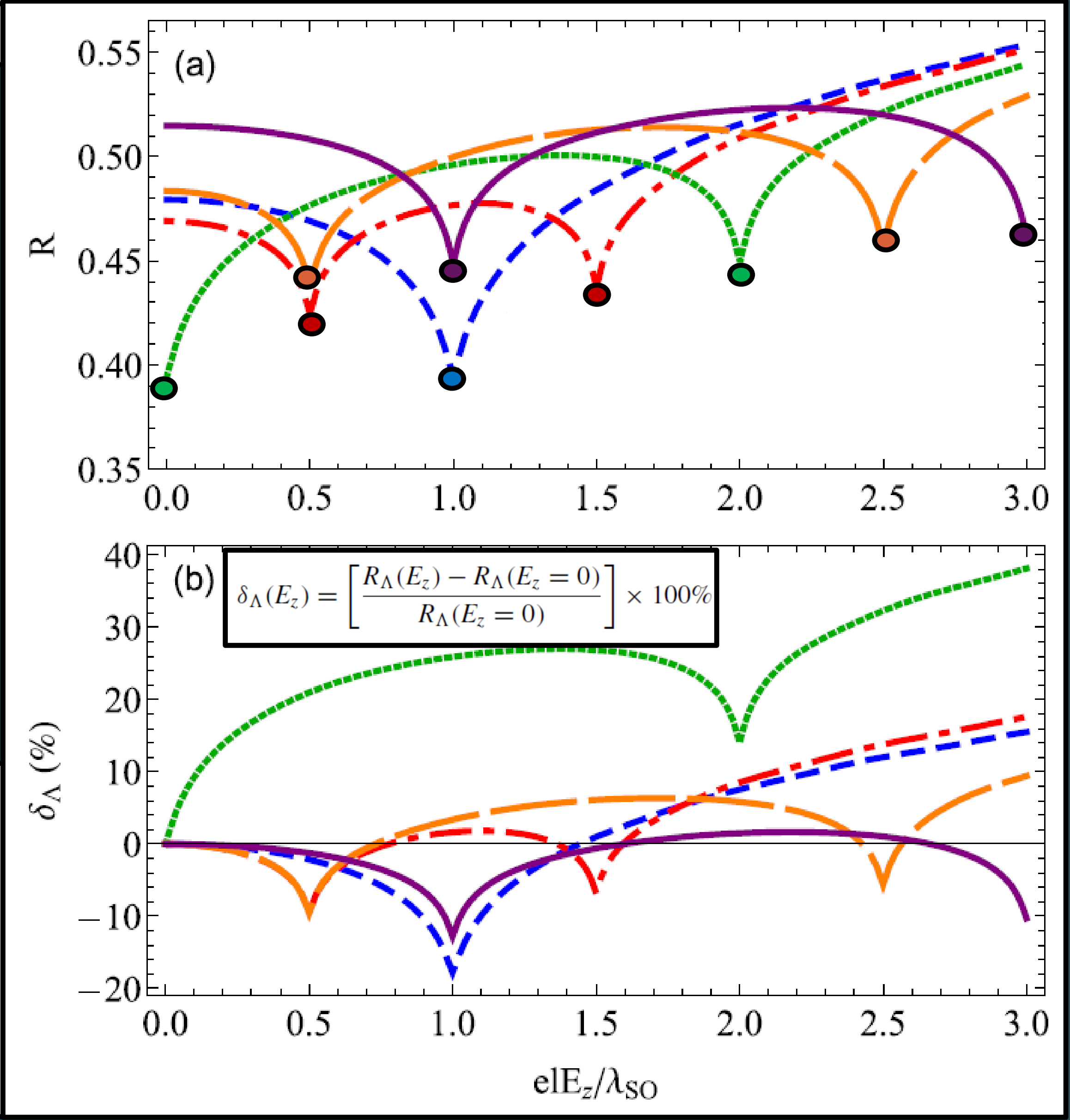
(Atom: Rb / 2D Material: Stanene/ Neutrality $\mu = 0$)

$E^* = 10^{-4}$**neV**



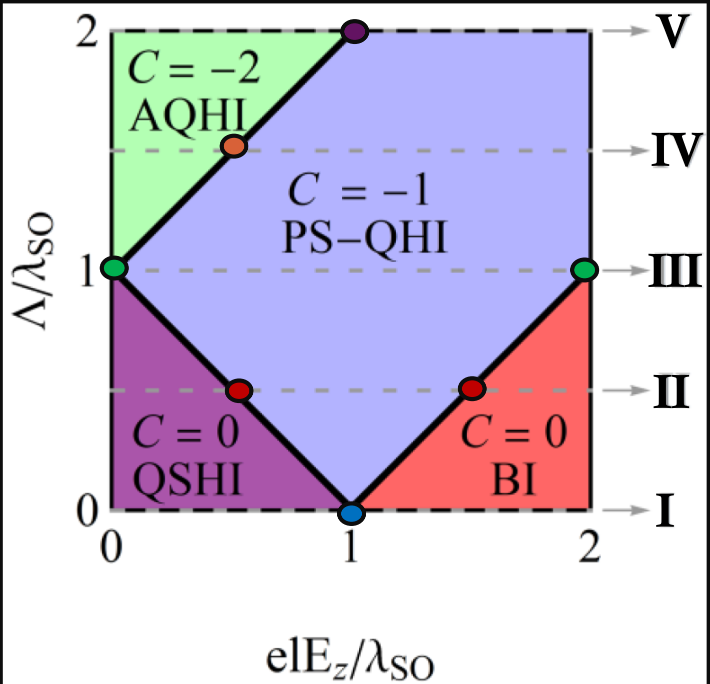


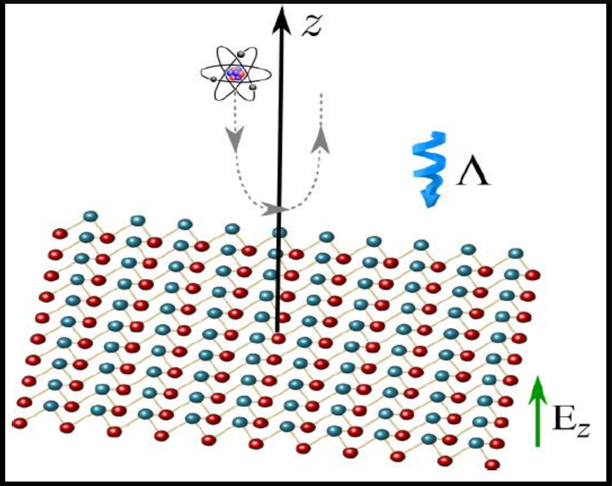




III - Casimir-Polder and Quantum Reflection in 2D-Materials

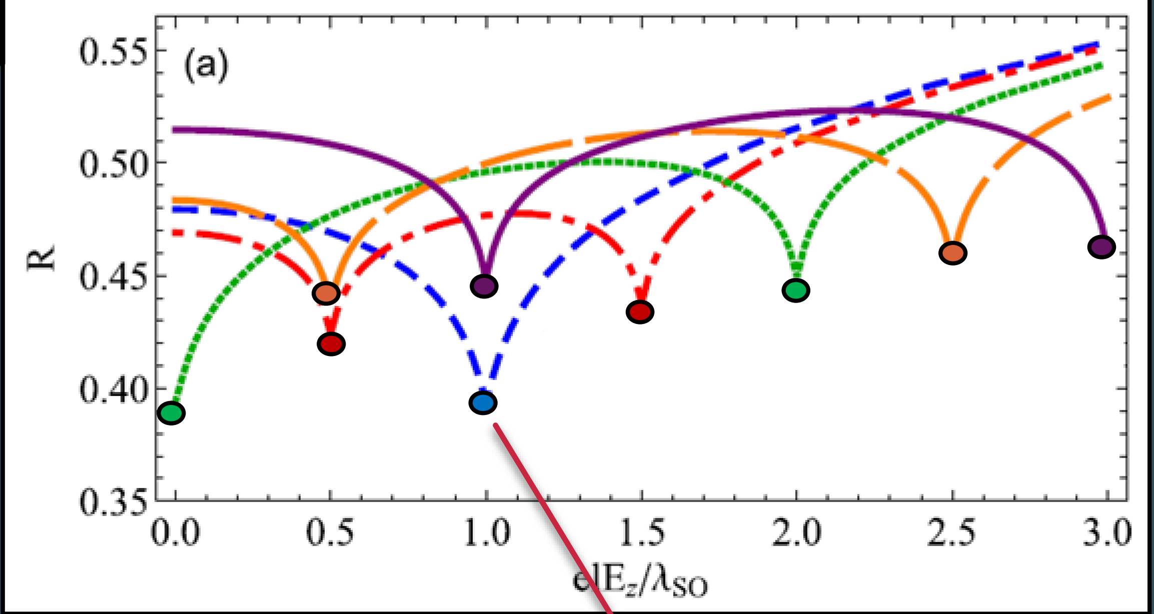
P. P. Abrantes et al., PRB 104, 075409 (2021).





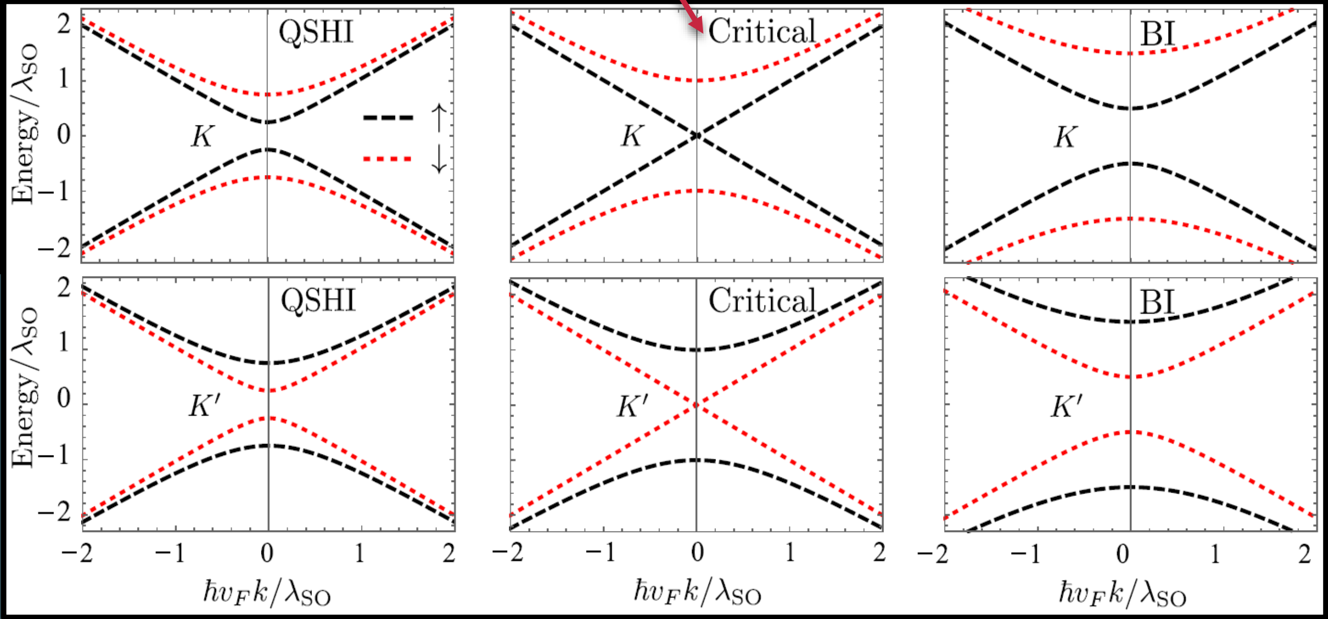
(Atom: Rb / 2D Material: Stanene/ Neutrality $\mu = 0$)

$E^* = 10^{-4}$neV



Electronic Spectra

Path I: $\Lambda = 0$

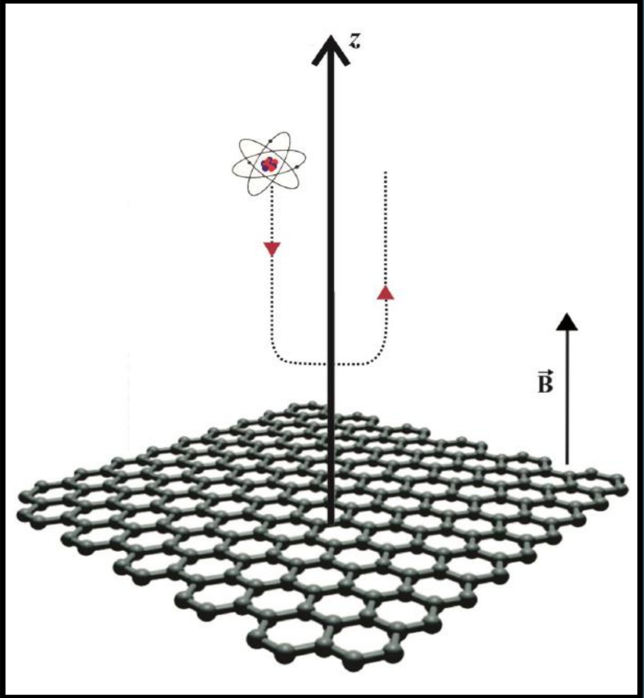


III - Casimir-Polder and Quantum Reflection in 2D-Materials

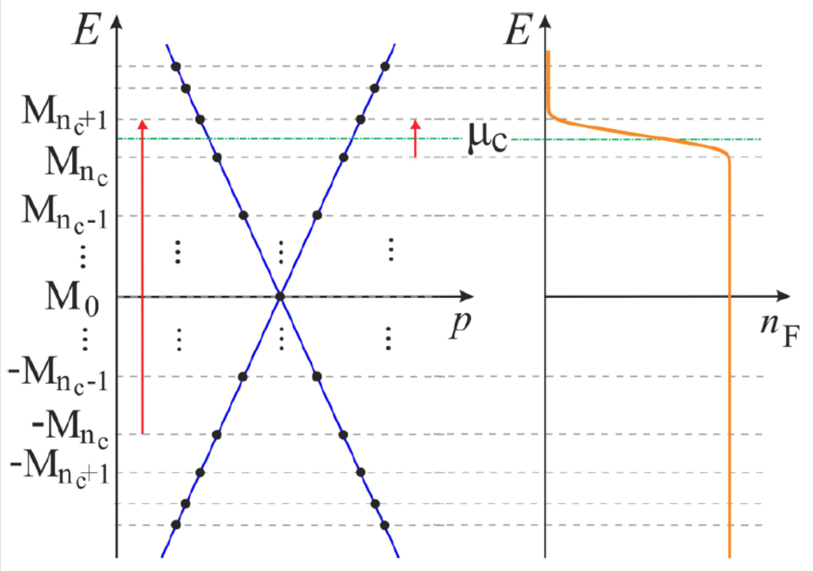
T. Cysne et al., PRA 90, 052511 (2014).
M. Silvestre et al., PRA 100, 033605 (2019).

- Graphene has no spin-orbit coupling ($\lambda_{SO} \sim 0$) and is flat ($\ell = 0$).
- There are no topological phase transitions and, the material does not respond to the external electric fields (E_z).

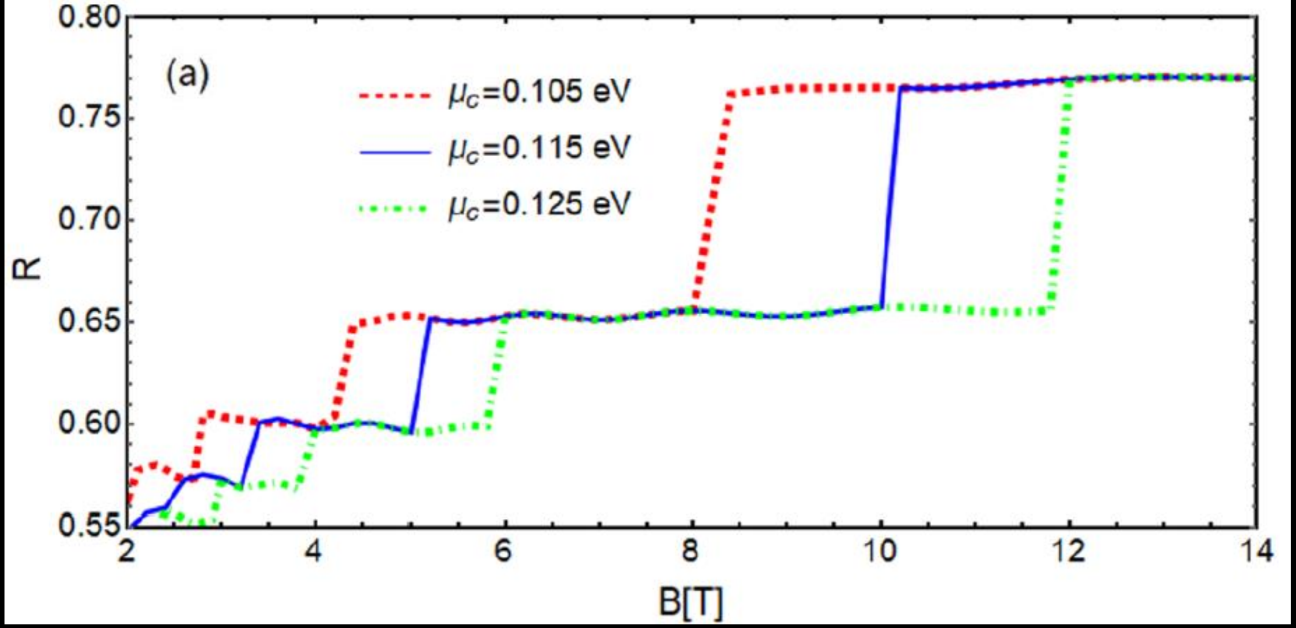
- On the other hand, graphene responds to external magnetic fields (B_z).



The magnetic field (B_z) generates a Landau quantization of electronic levels in graphene.

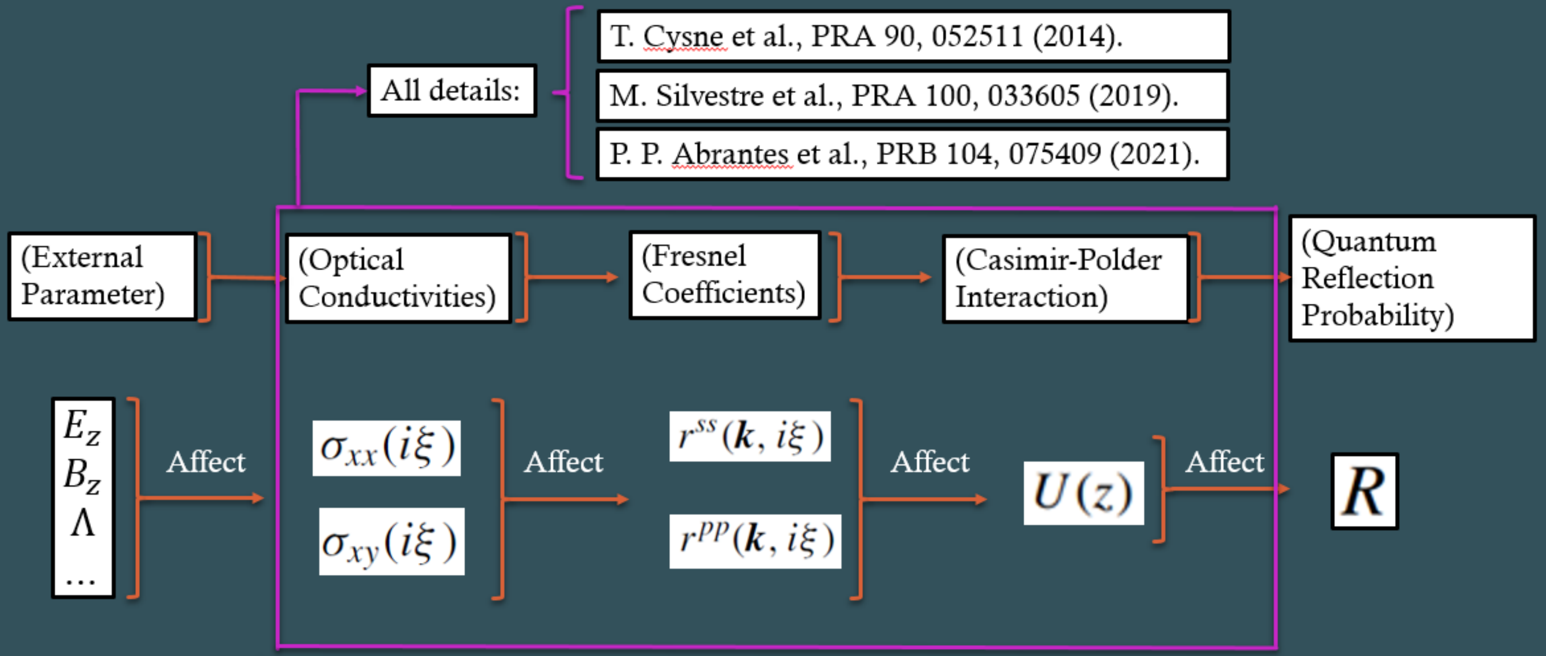


(Atom: Rb / 2D Material: Graphene/ elec. doped $\mu = \mu_c$)



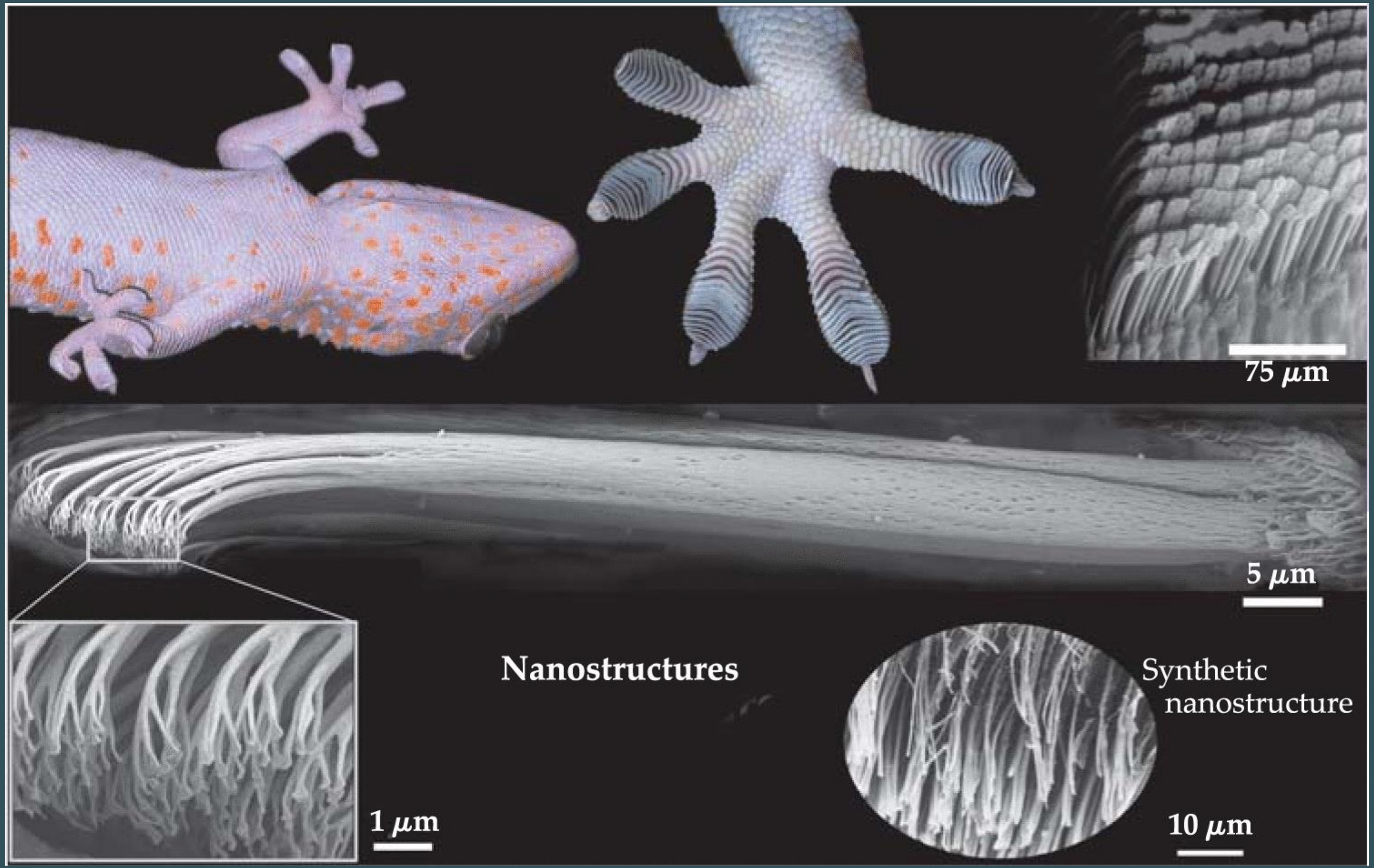
IV - Main conclusions of the presentation

A. The high tunable electronic structure of 2D materials can be explored to control quantum vacuum fluctuations effects (Casimir/Casimir-Polder/ quantum reflection).



B. Our theoretical results can be used to design novel nano/micro-mechanical devices and atom-optical systems based on two-dimensional materials.

Thank you for your attention!



e-mail: (tarik.cysne@gmail.com)
e-mail: (ppabrantes91@gmail.com)