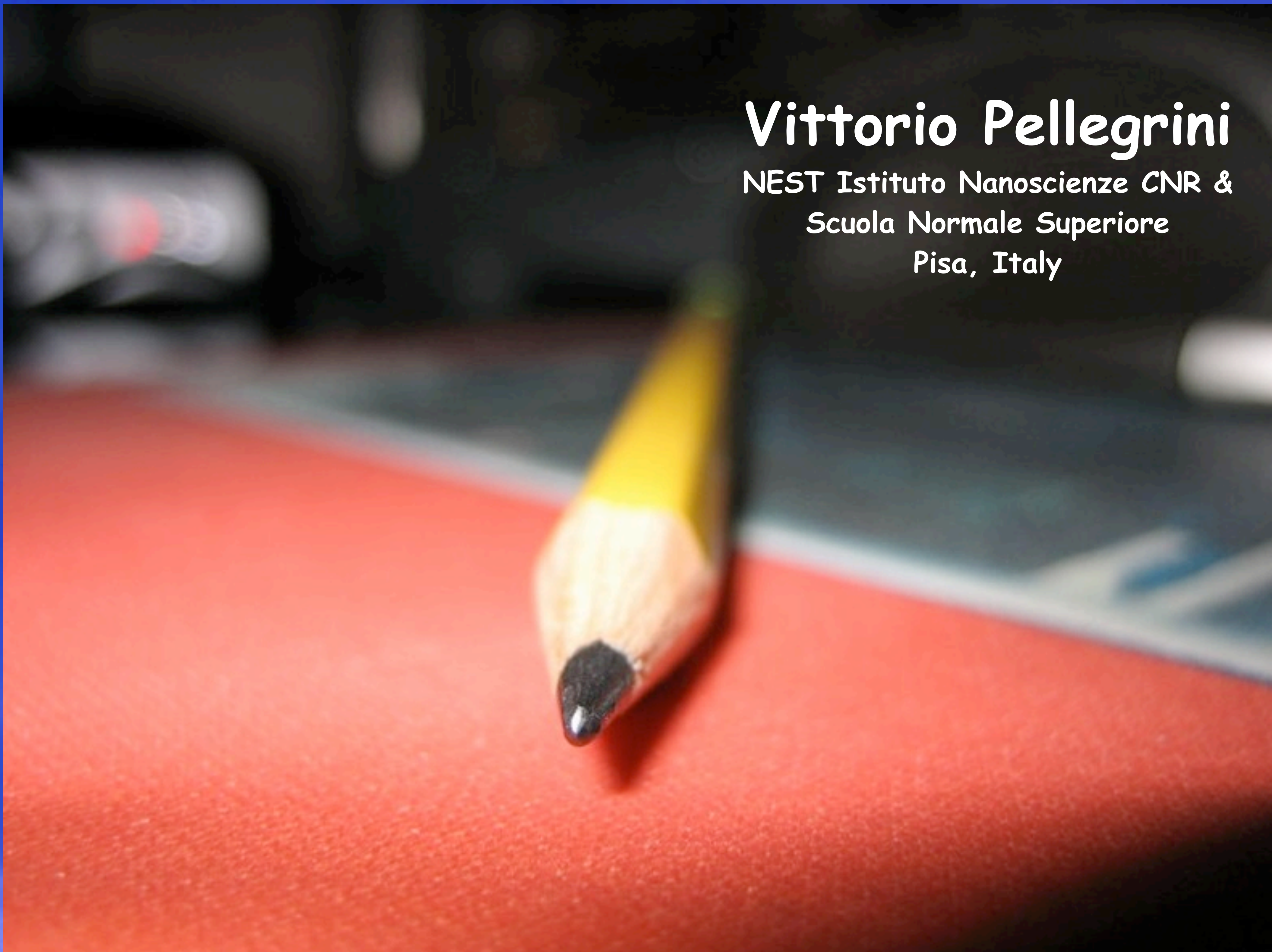
Graphene: An electron wonderland



Vittorio Pellegrini
NEST Istituto Nanoscienze CNR &
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Experimental

Achintya Singha - Bose Institute India

Sarah Goler - NEST & SNS, Pisa

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Aron Pinczuk - Columbia U. USA

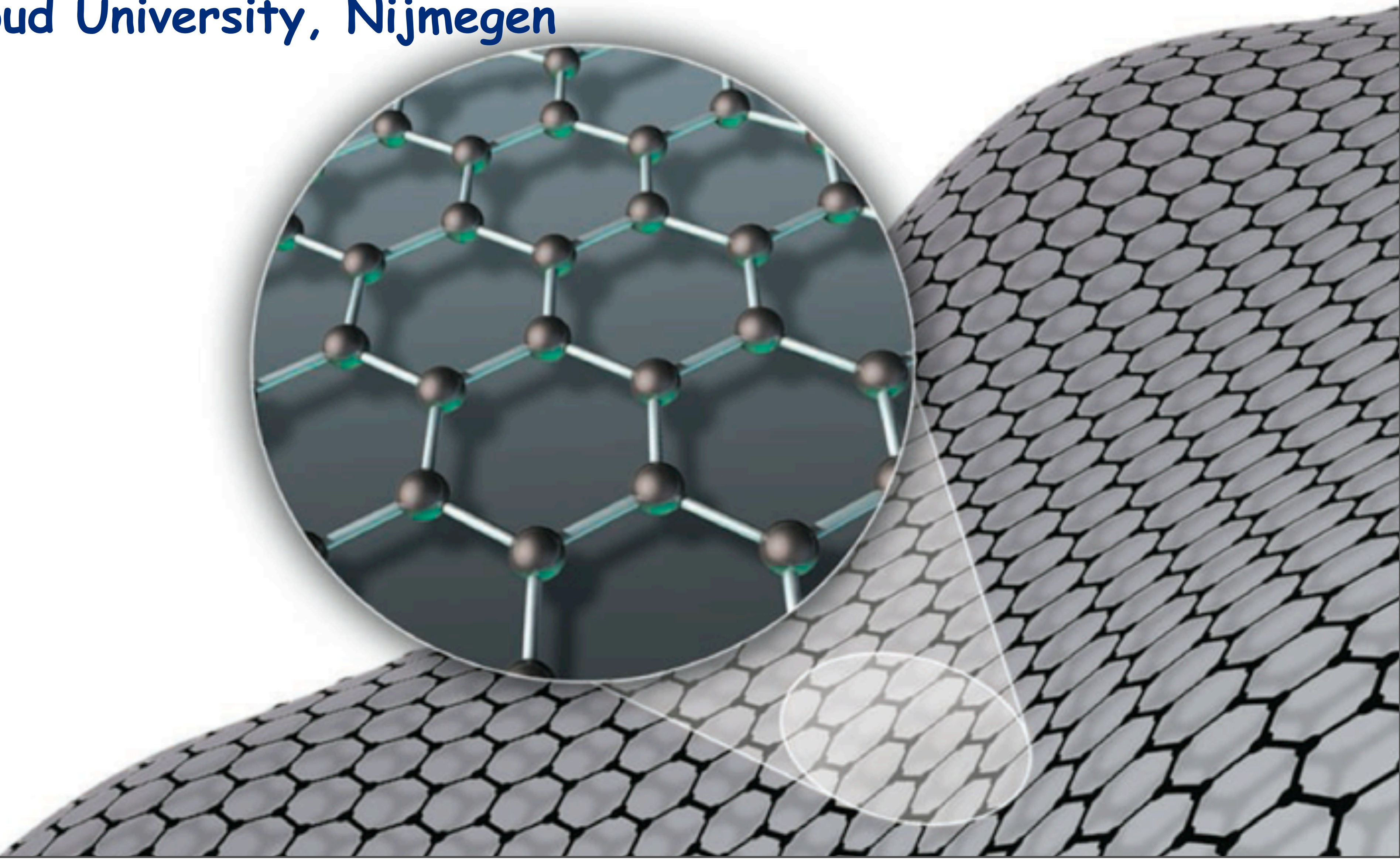
Philip Kim - Columbia U. USA

Theoretical

Marco Polini - NEST & SNS, Pisa

Giovanni Vignale - U. Missouri, USA

Misha Kastnelson - Radboud University, Nijmegen



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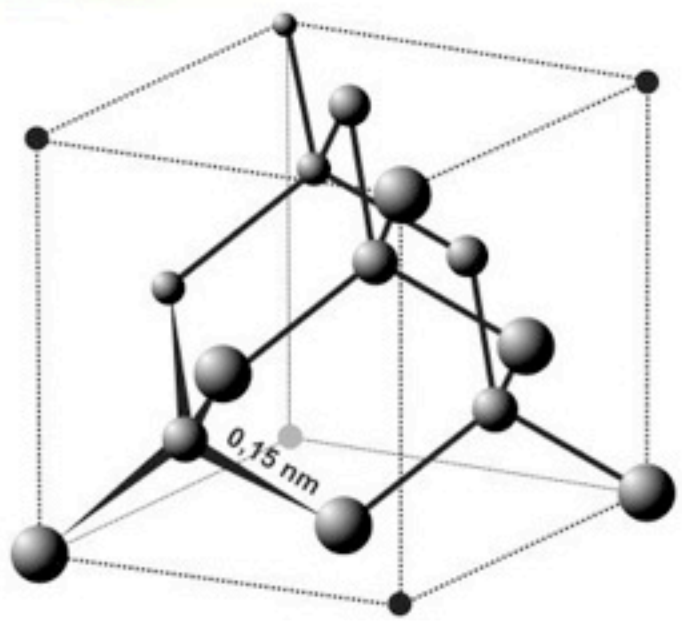
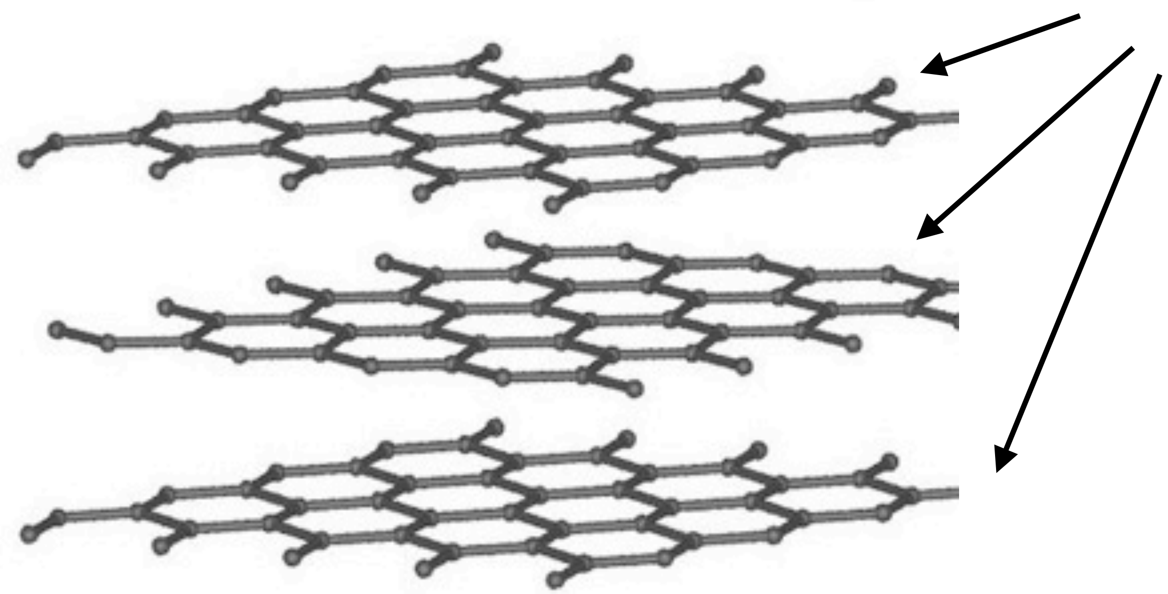
Common Carbon-based materials

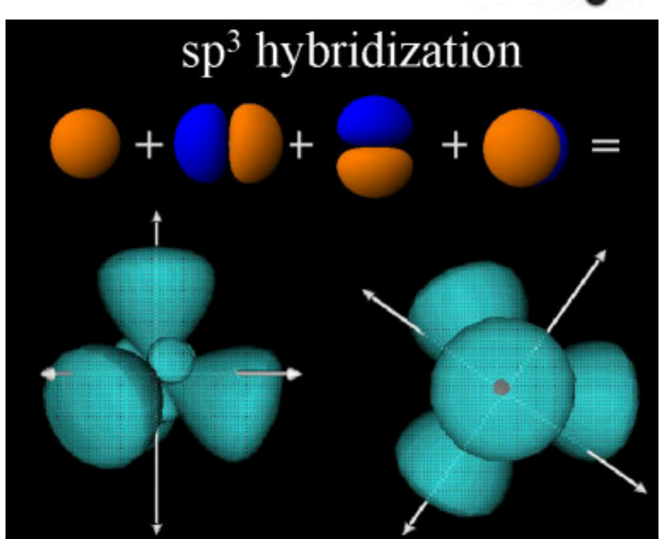
Diamond

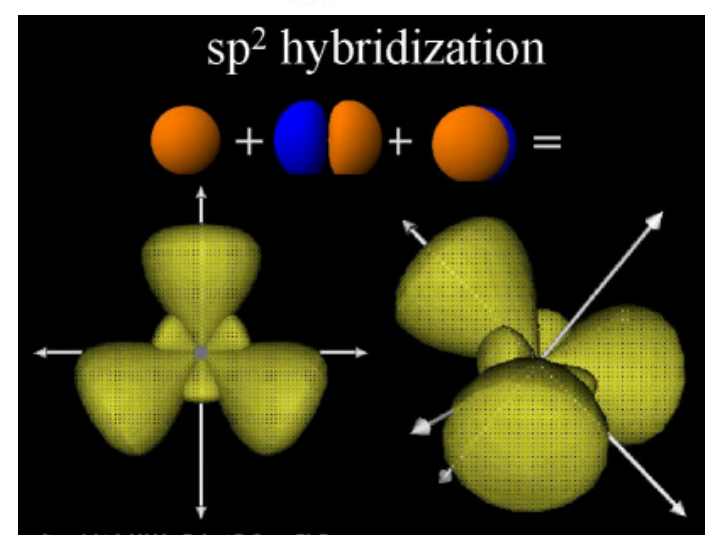
Graphite



Graphene layers







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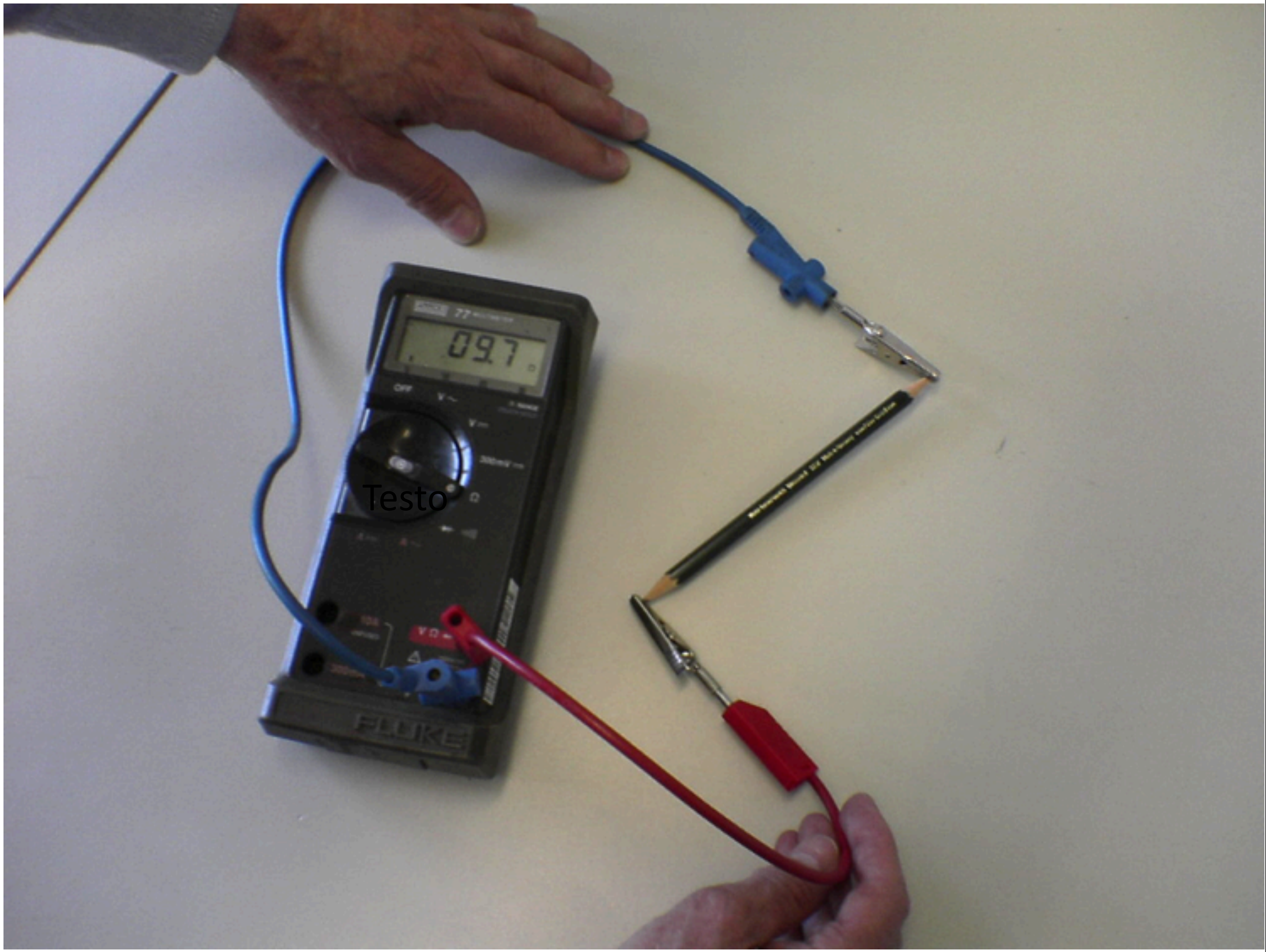
Graphite is a semi-metal and a very good conductor



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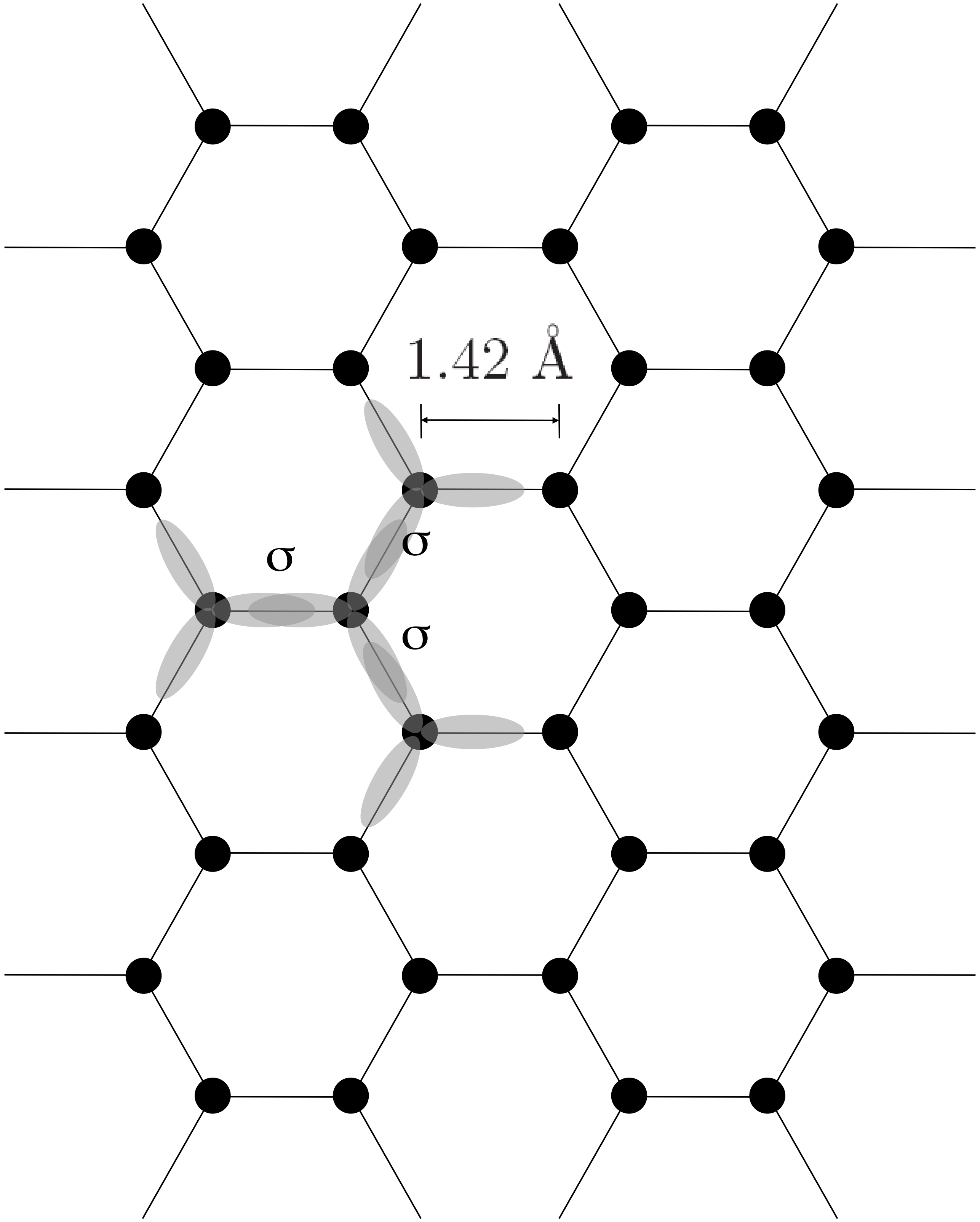
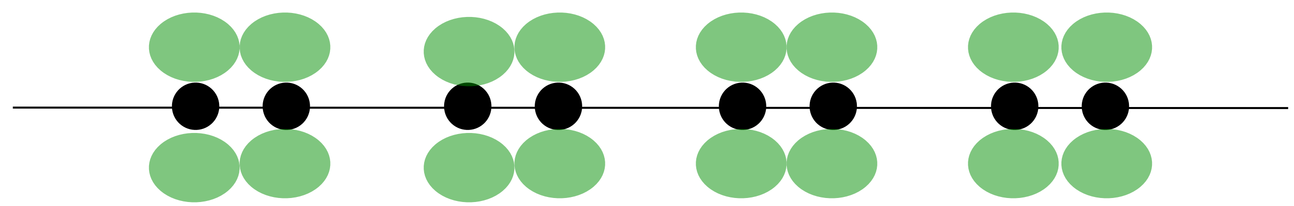
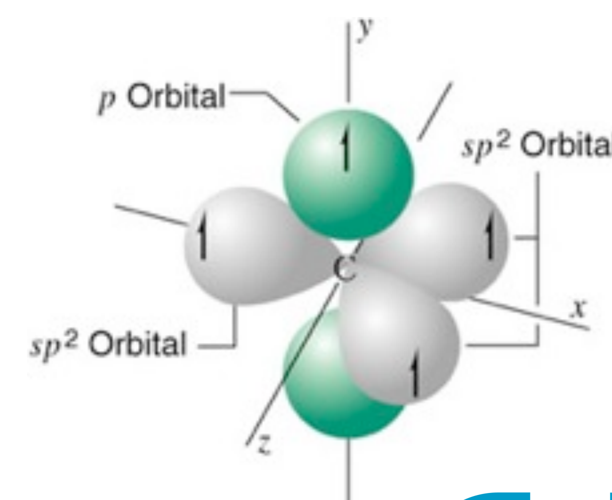
Graphene (one atomic layer of graphite)







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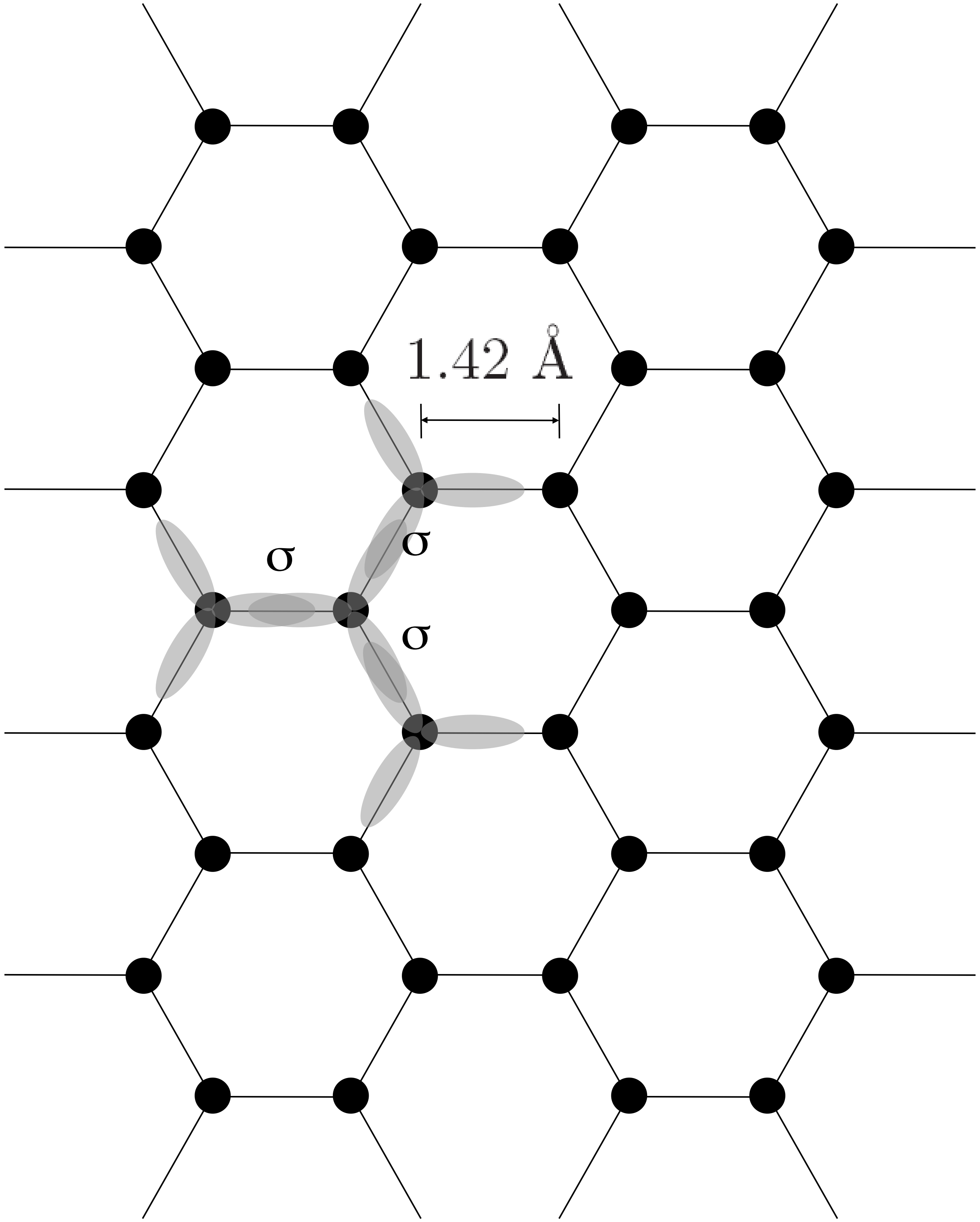
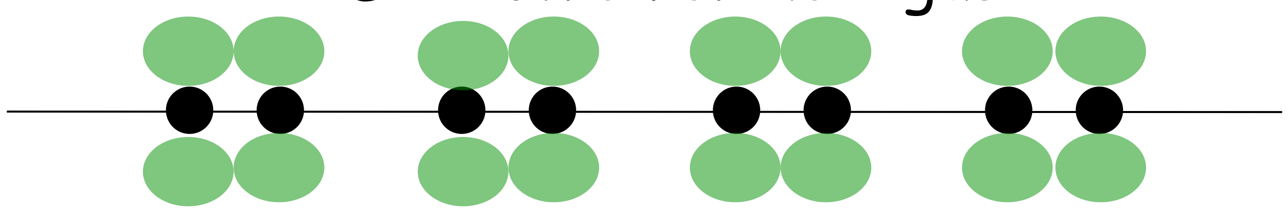
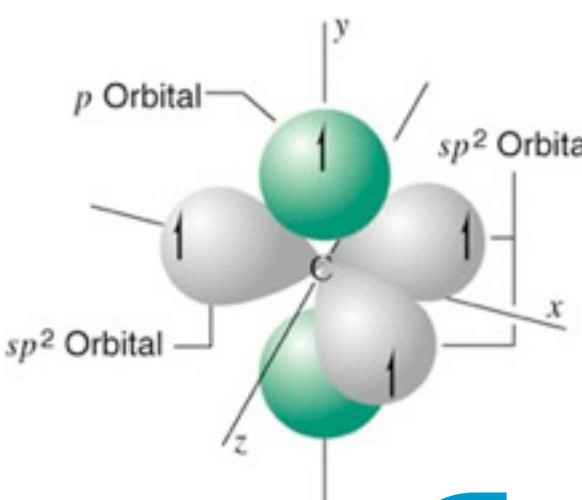
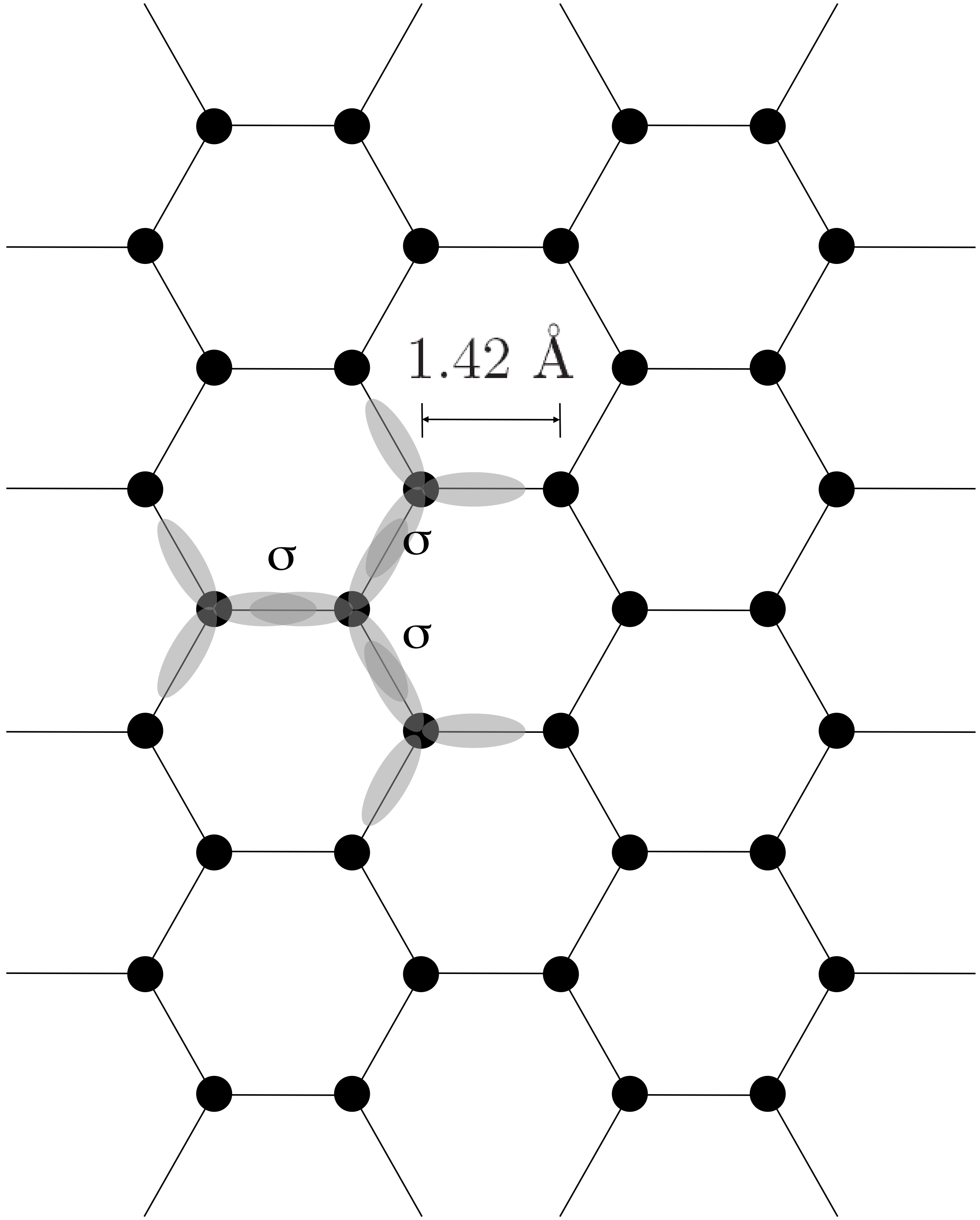


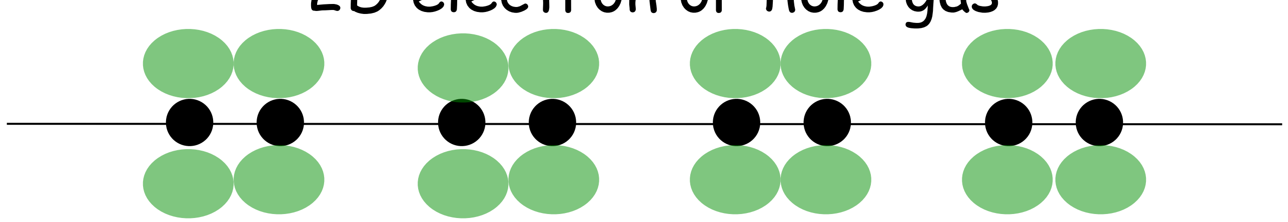
2D electron or hole gas

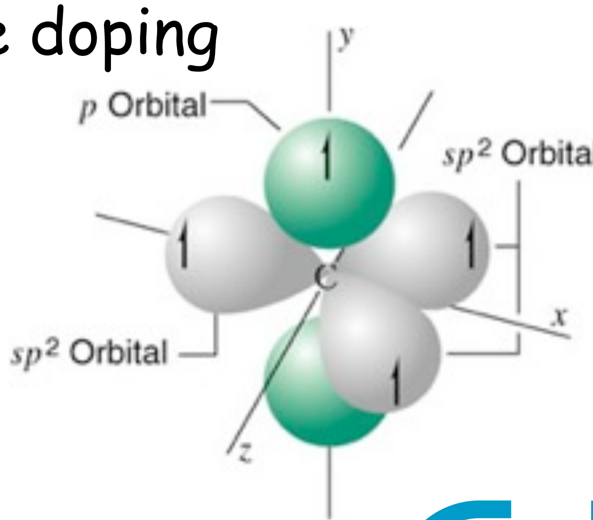




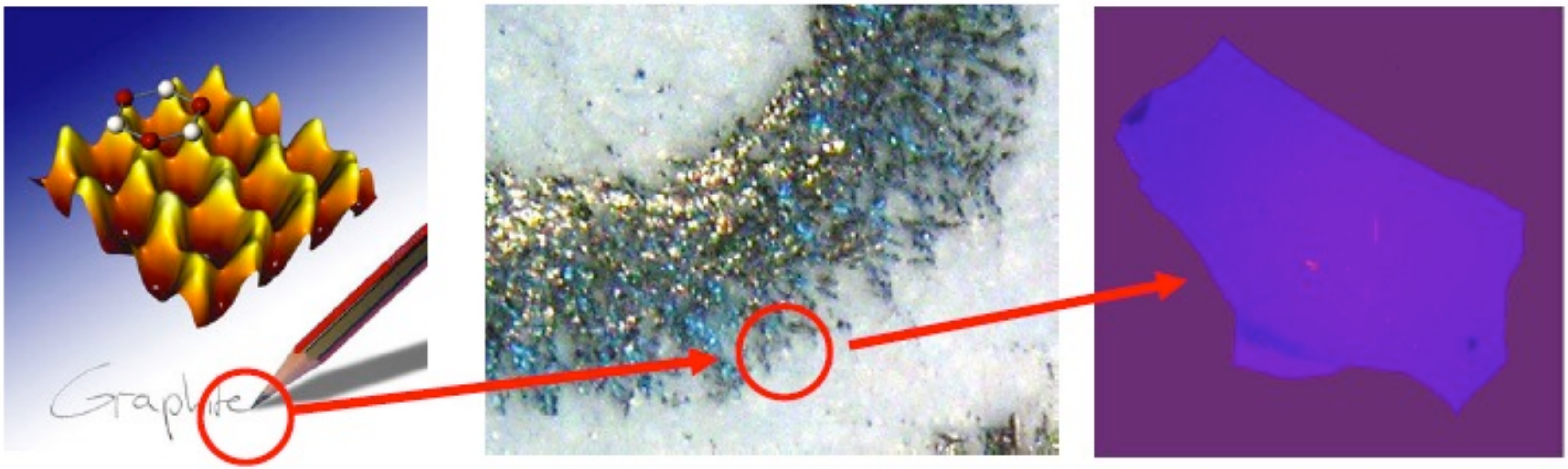
Graphene (one atomic layer of graphite)



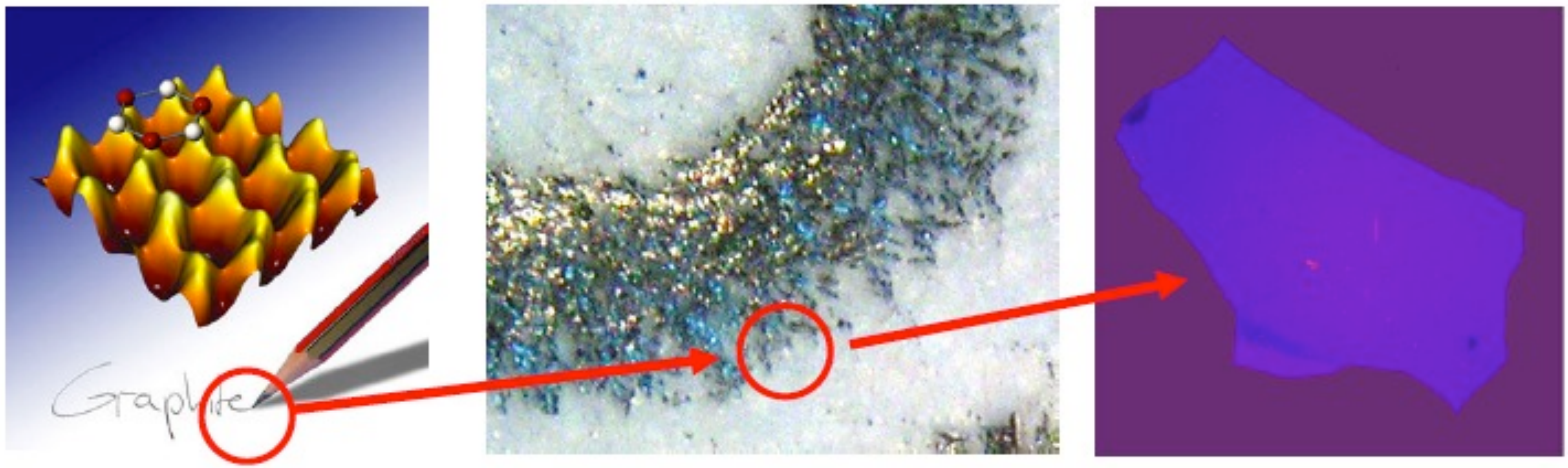




Methods of fabrication



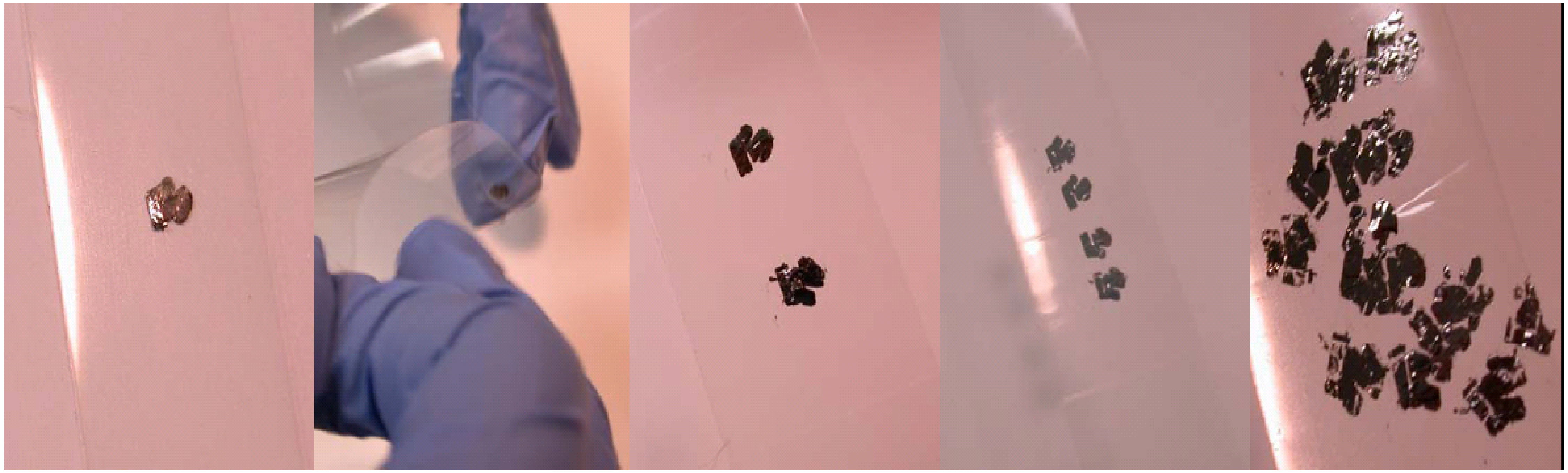
Methods of fabrication



First application of exfoliated graphite
1928

Giuseppe Biagi

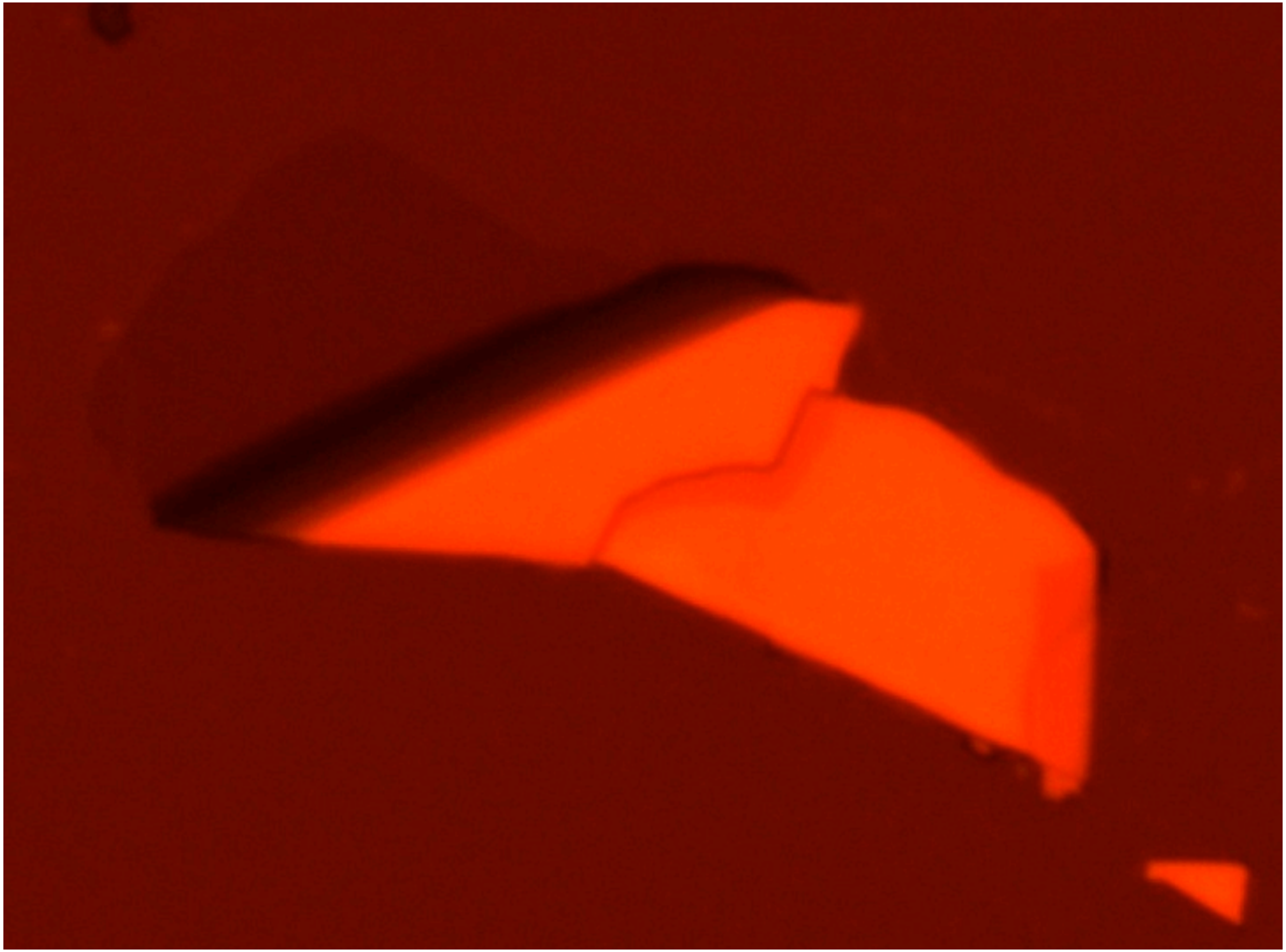
Mechanical Exfoliation (scotch tape)



Novoselov, Geim et al Science (2004)
Zhang, Tan, Stormer & Kim – Nature (2005)

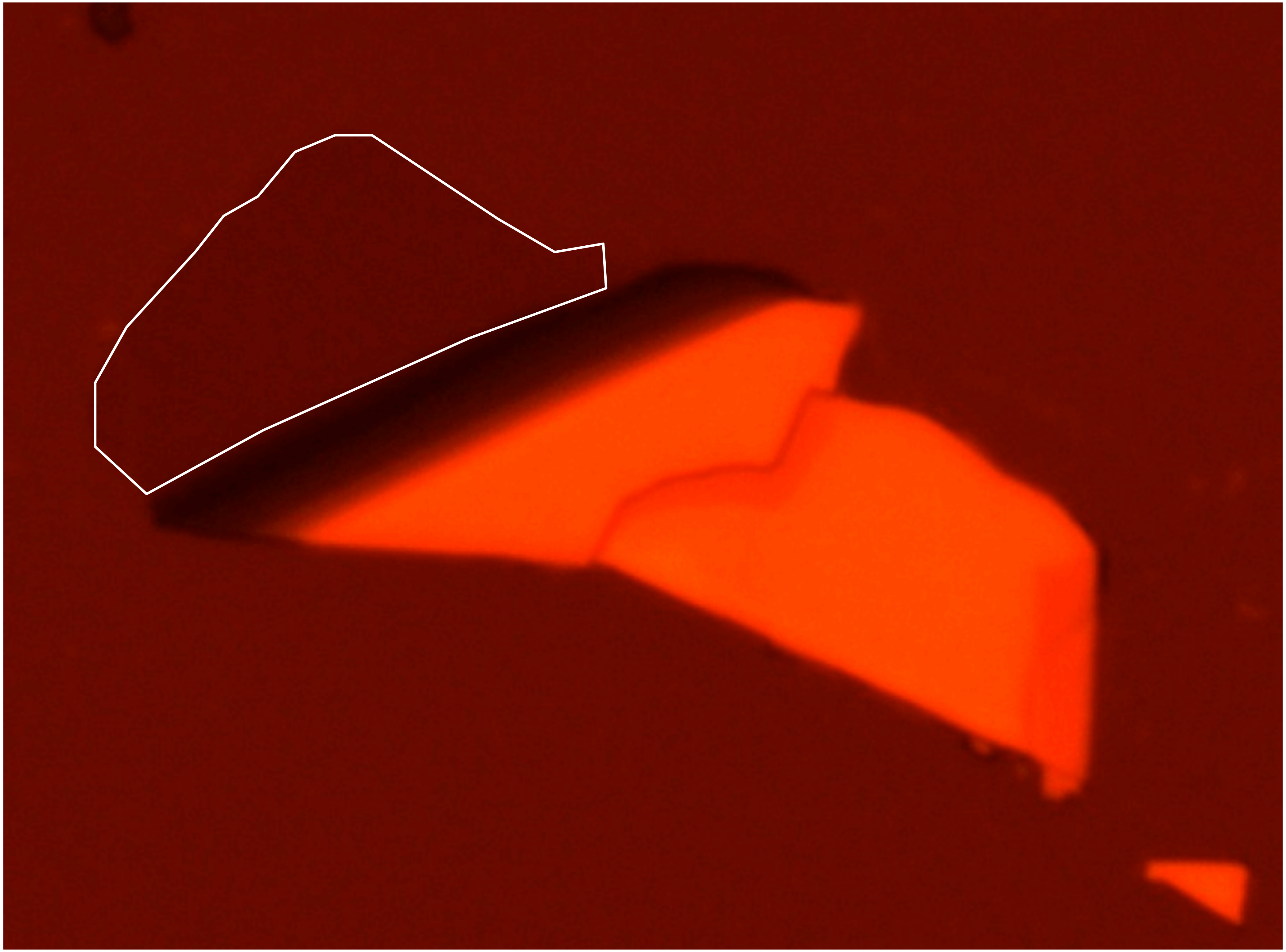
1. Graphene flakes are exfoliated with scotch tape!
2. Tape is dissolved in acetone
3. The solution is deposited on $n^+Si:SiO_2$

Graphene monolayers are visible under the optical microscope



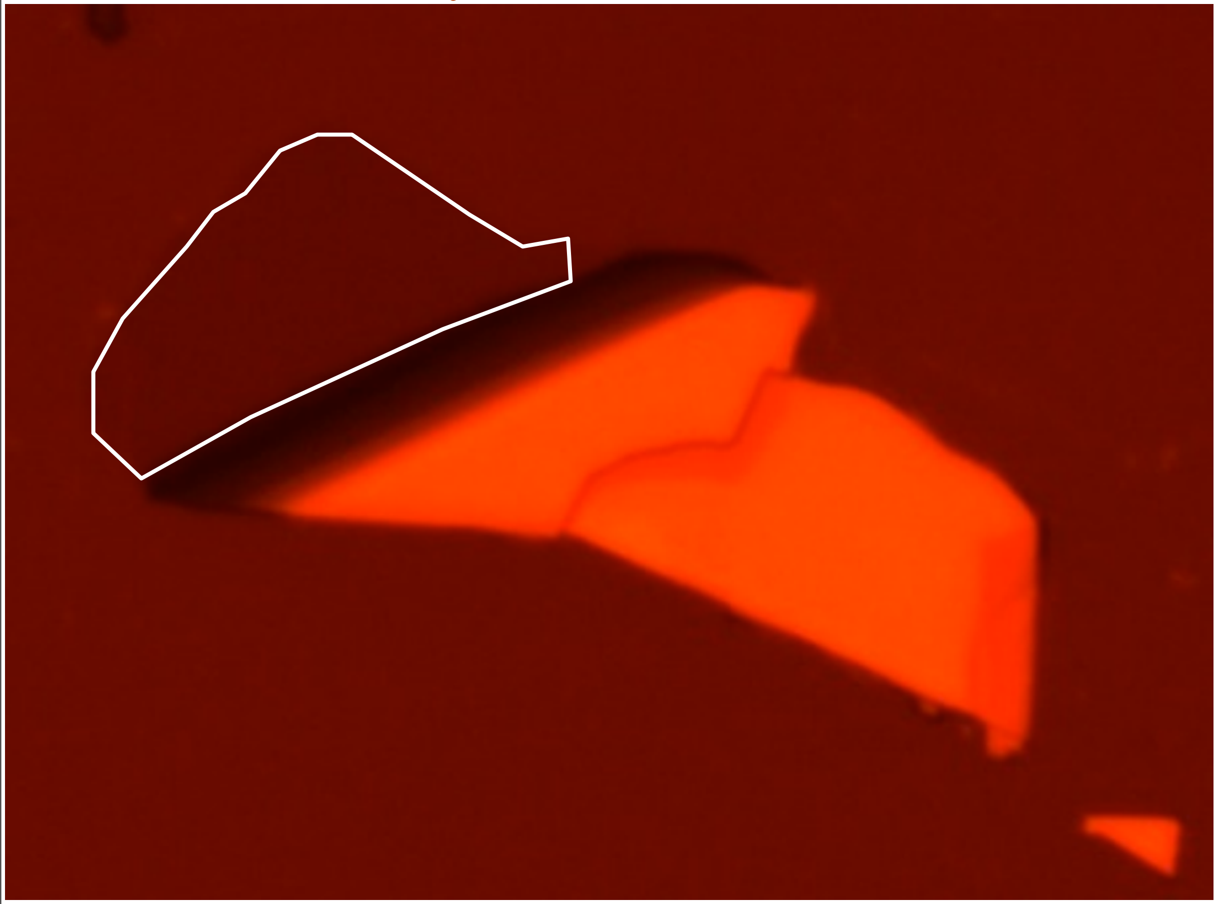
Optical imaging on SiO_2

Graphene monolayers are visible under the optical microscope

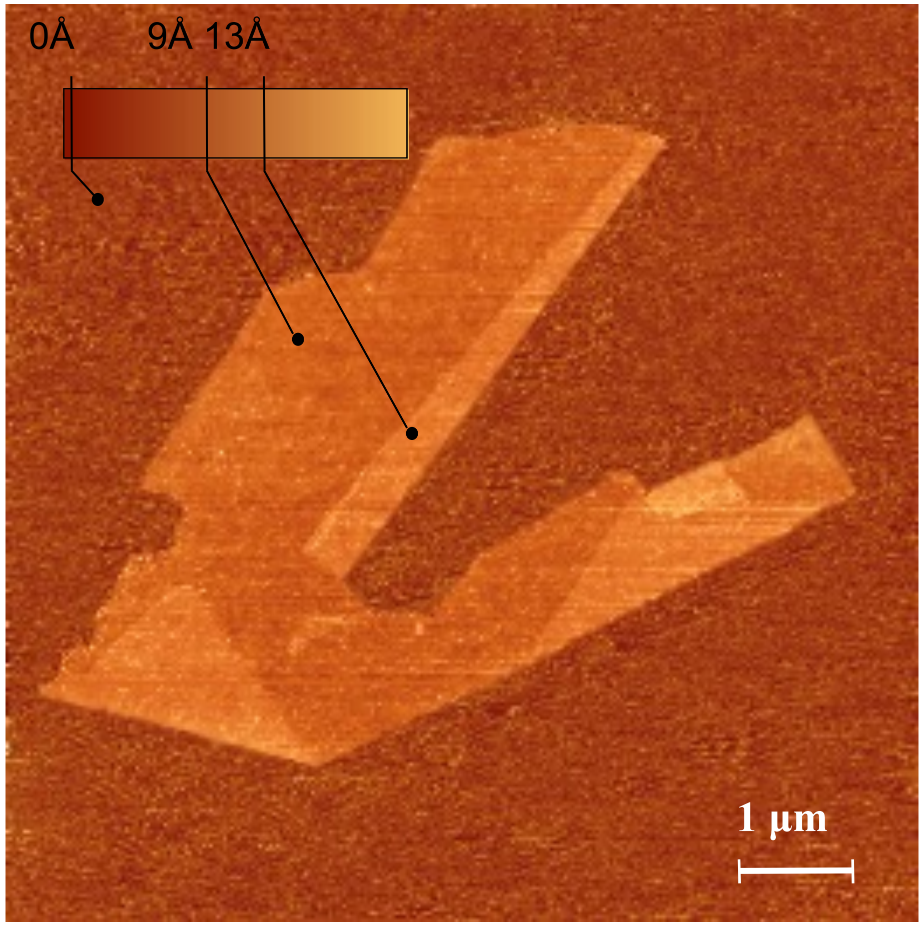


Optical imaging on SiO_2

Graphene monolayers are visible under the optical microscope

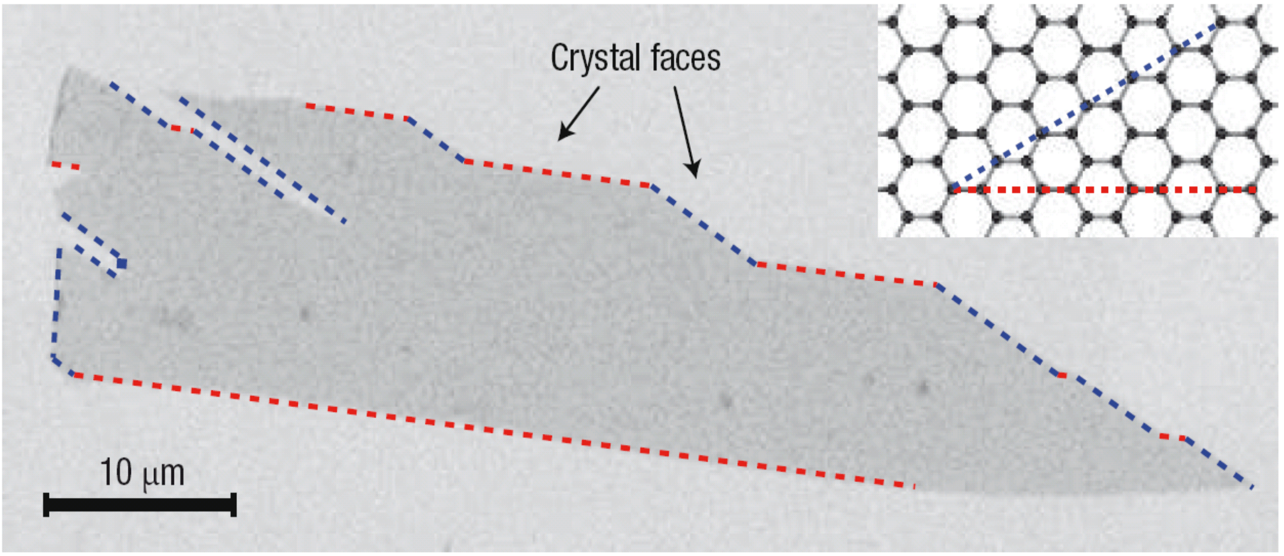


Optical imaging on SiO_2



AFM

- graph monolayer ~ 4Å
- "Dead space" ~ 5Å



SEM imaging

A. Geim et al - Nature Materials (2007)

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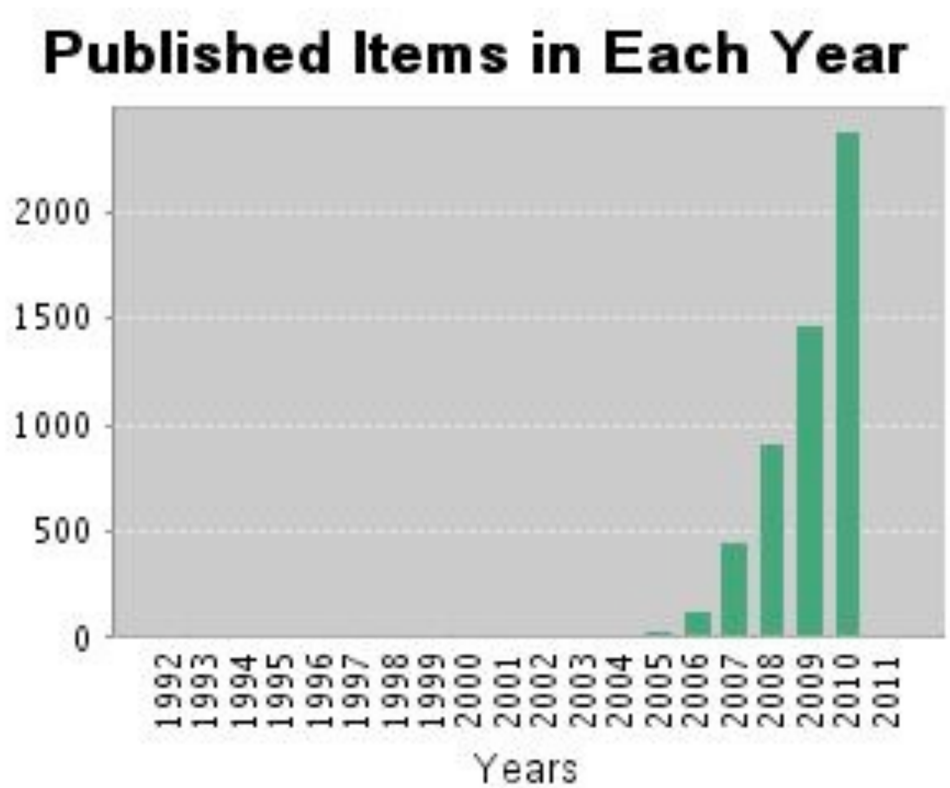
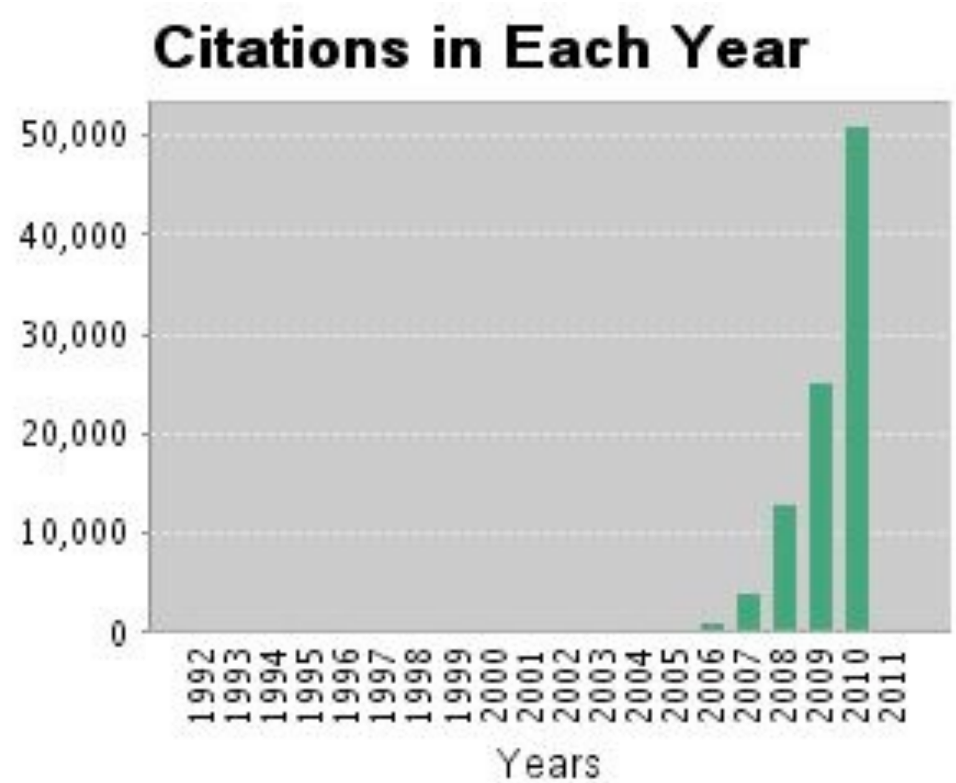
Discovery and fabrication

Graphite: invention of the pencil in 1564. Writing process probably already produces monolayers...

Graphene monolayers: for the first time fabricated and prepared by mechanical exfoliation in 2004

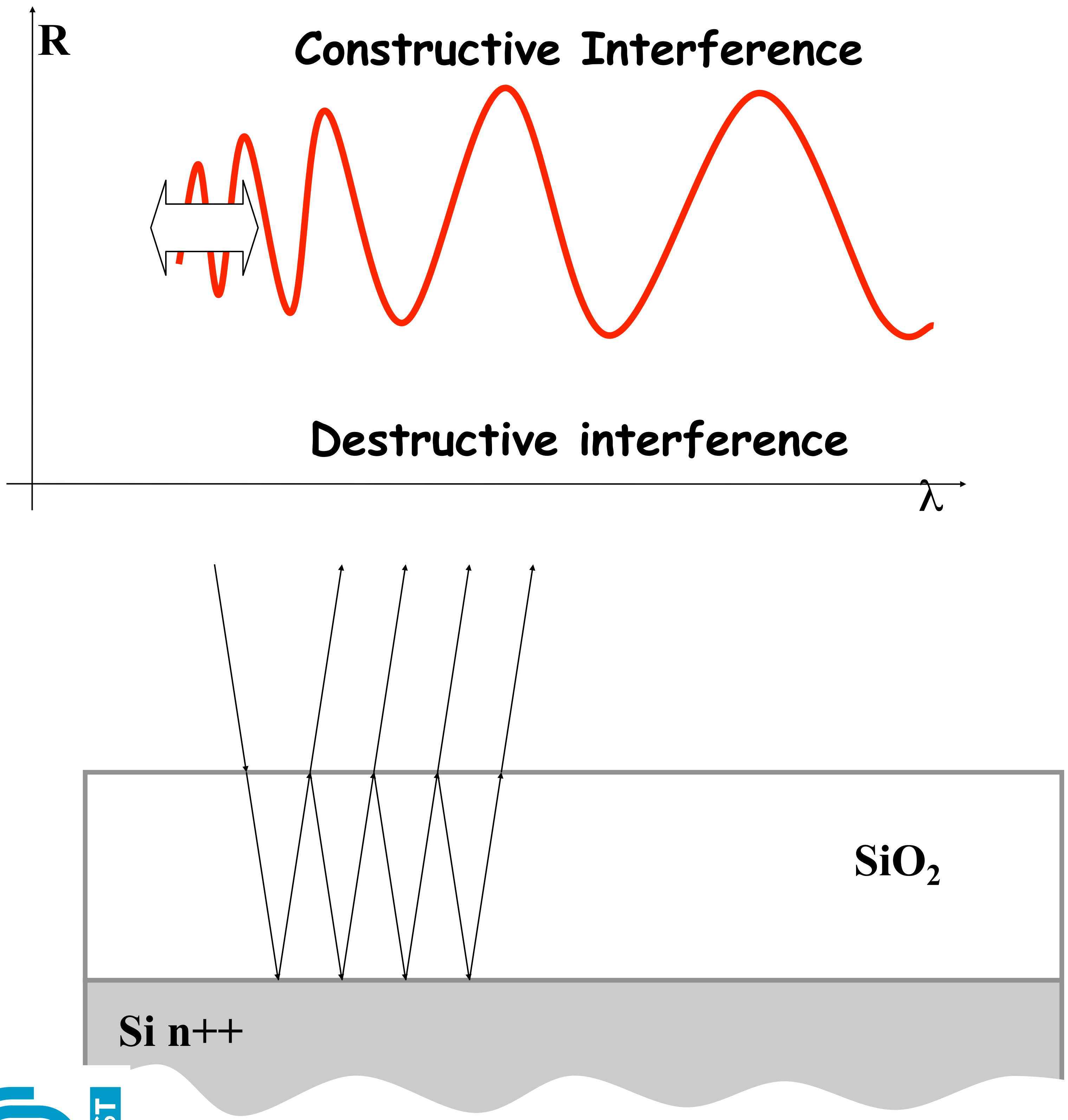
Novoselov et al., Science 2004

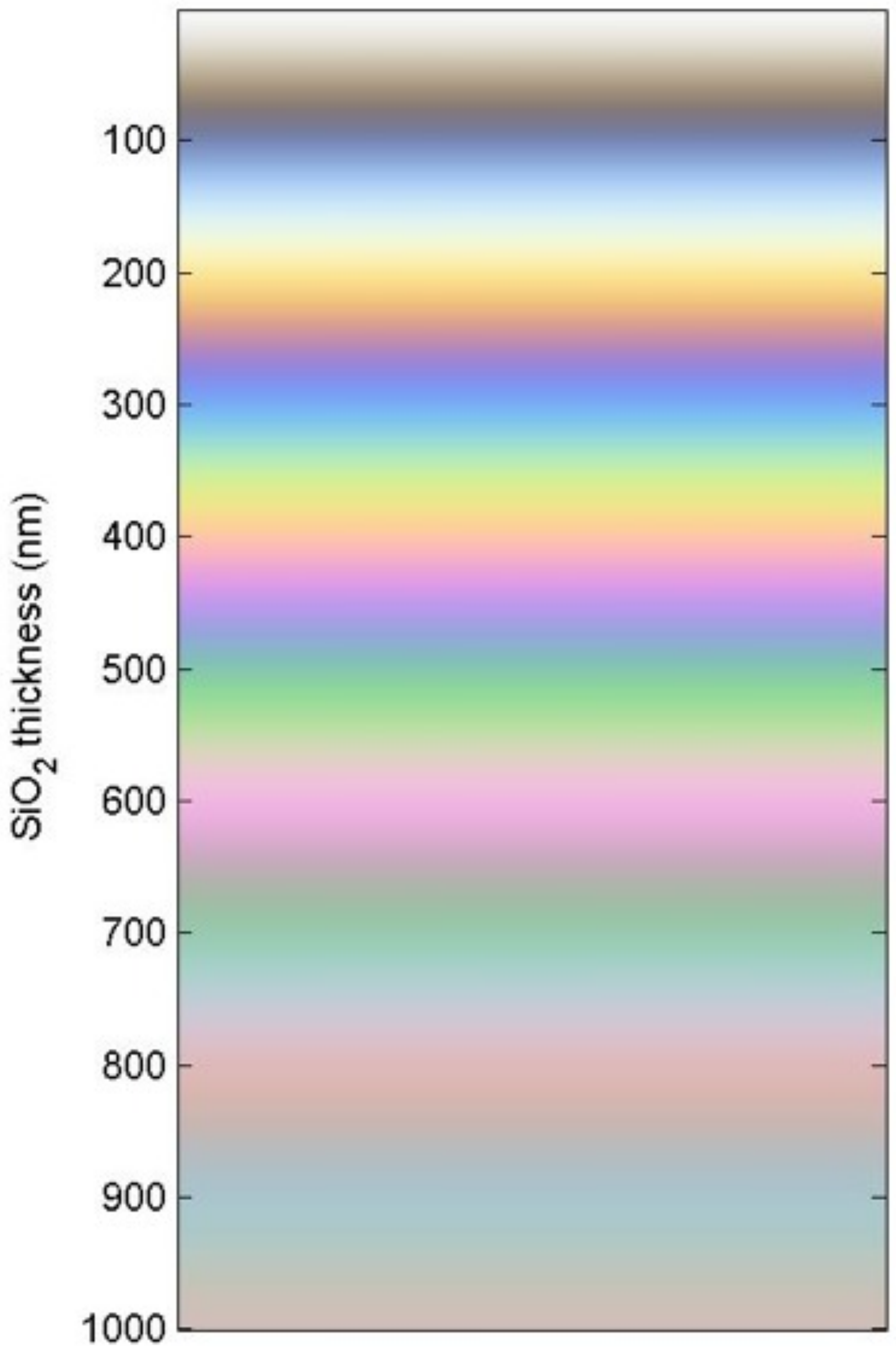




Papers with "graphene" in title

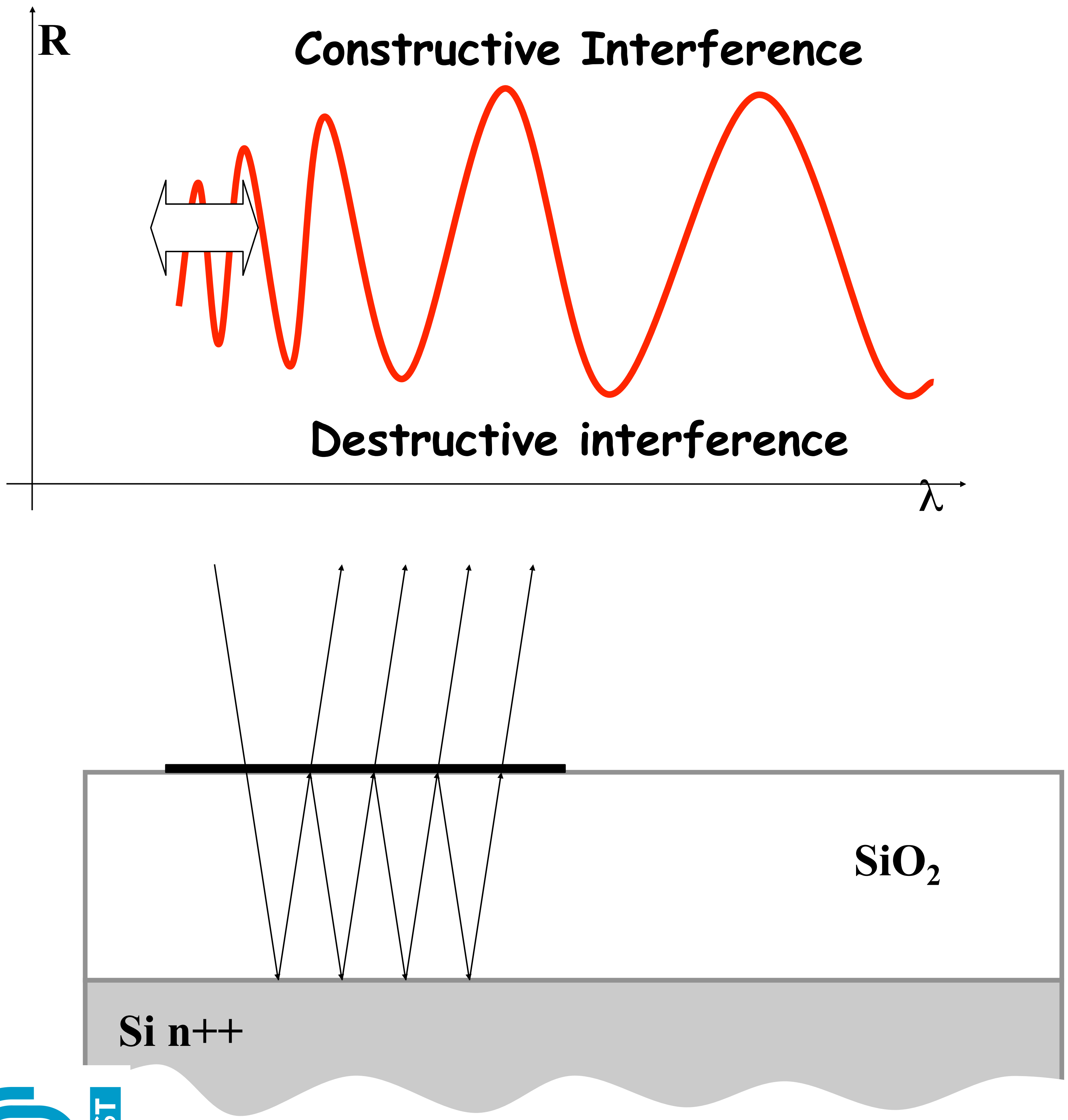
Optical visibility

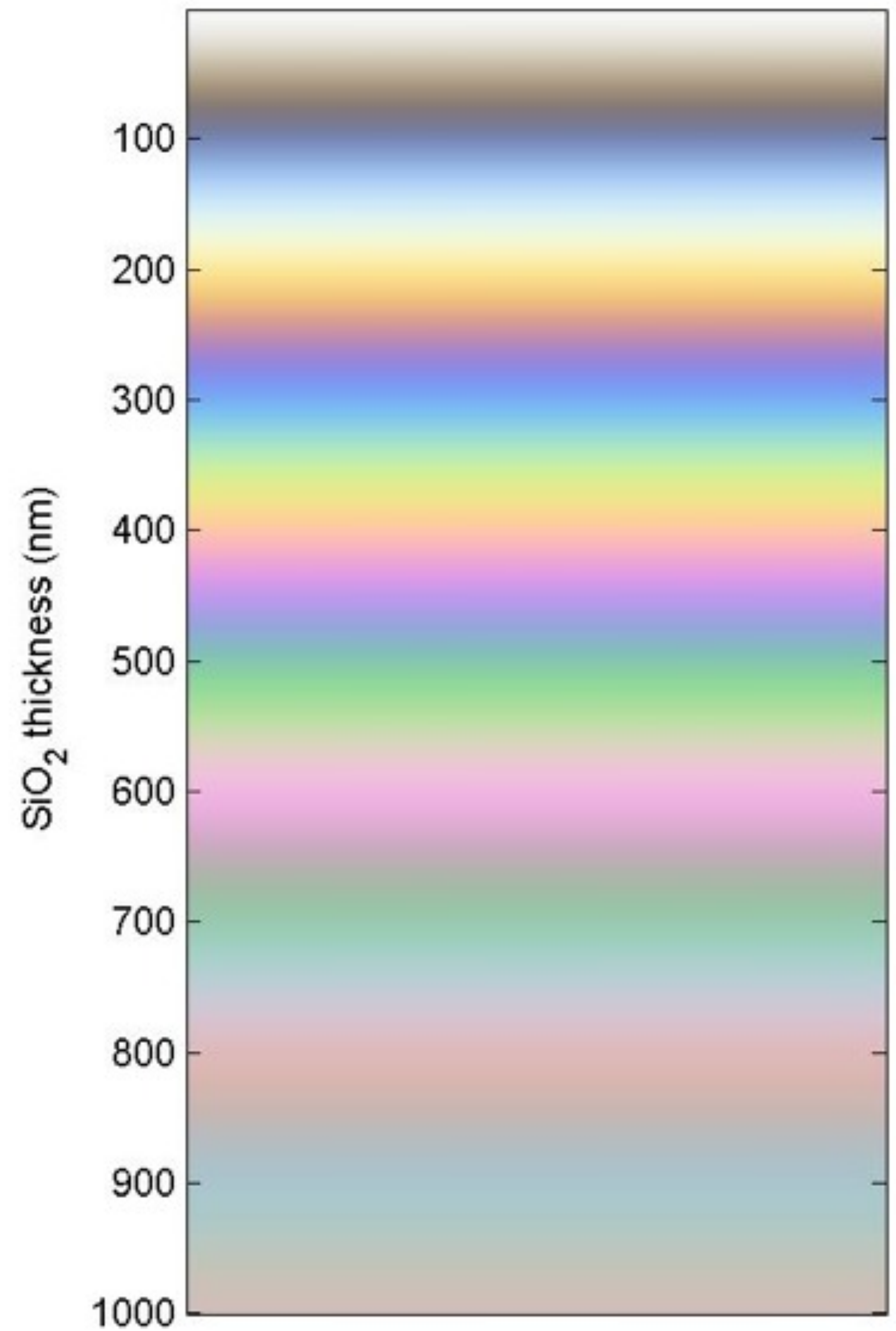




S. Roddaro, VP et al. NanoLetters (2007)

Optical visibility





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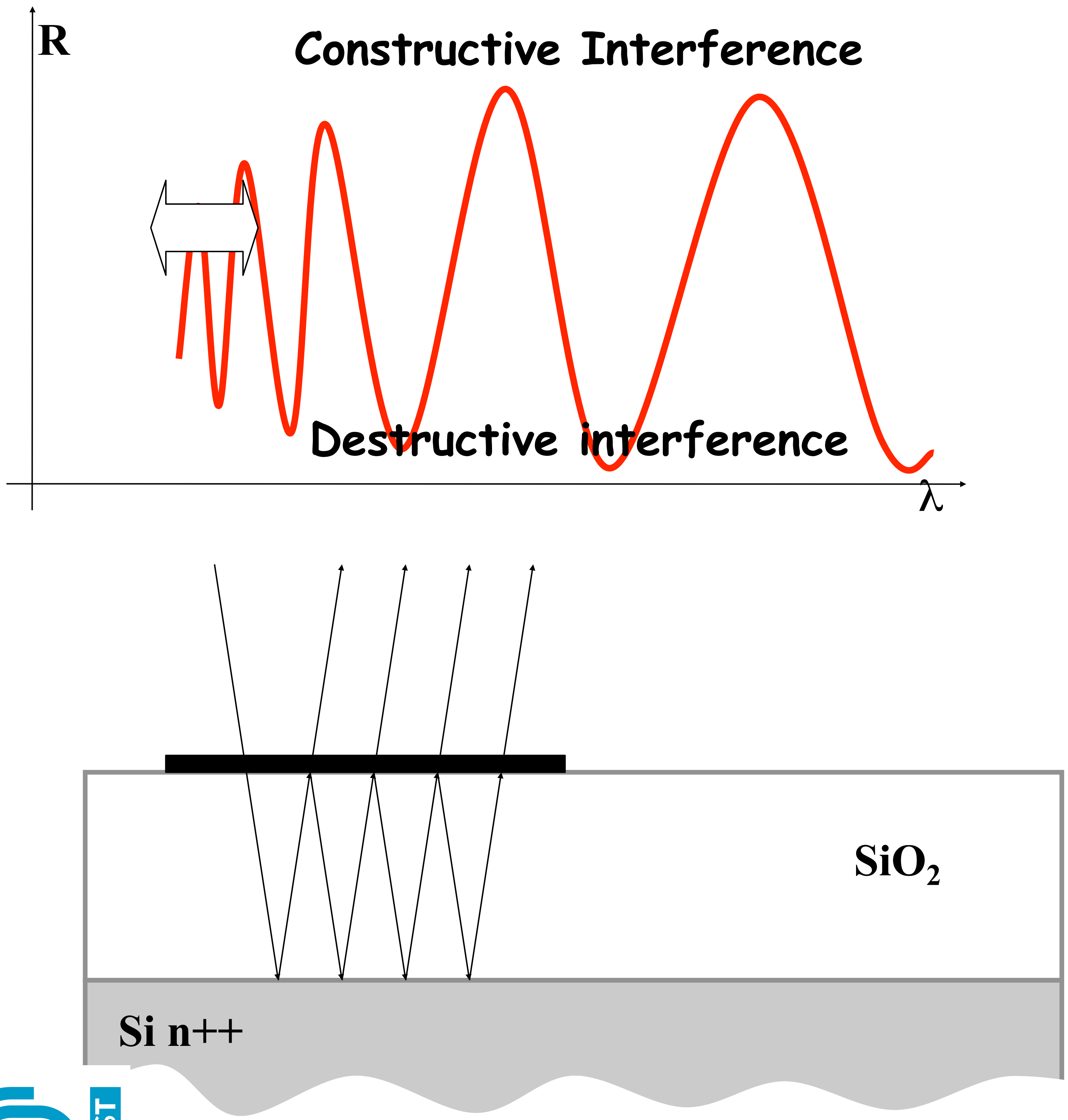
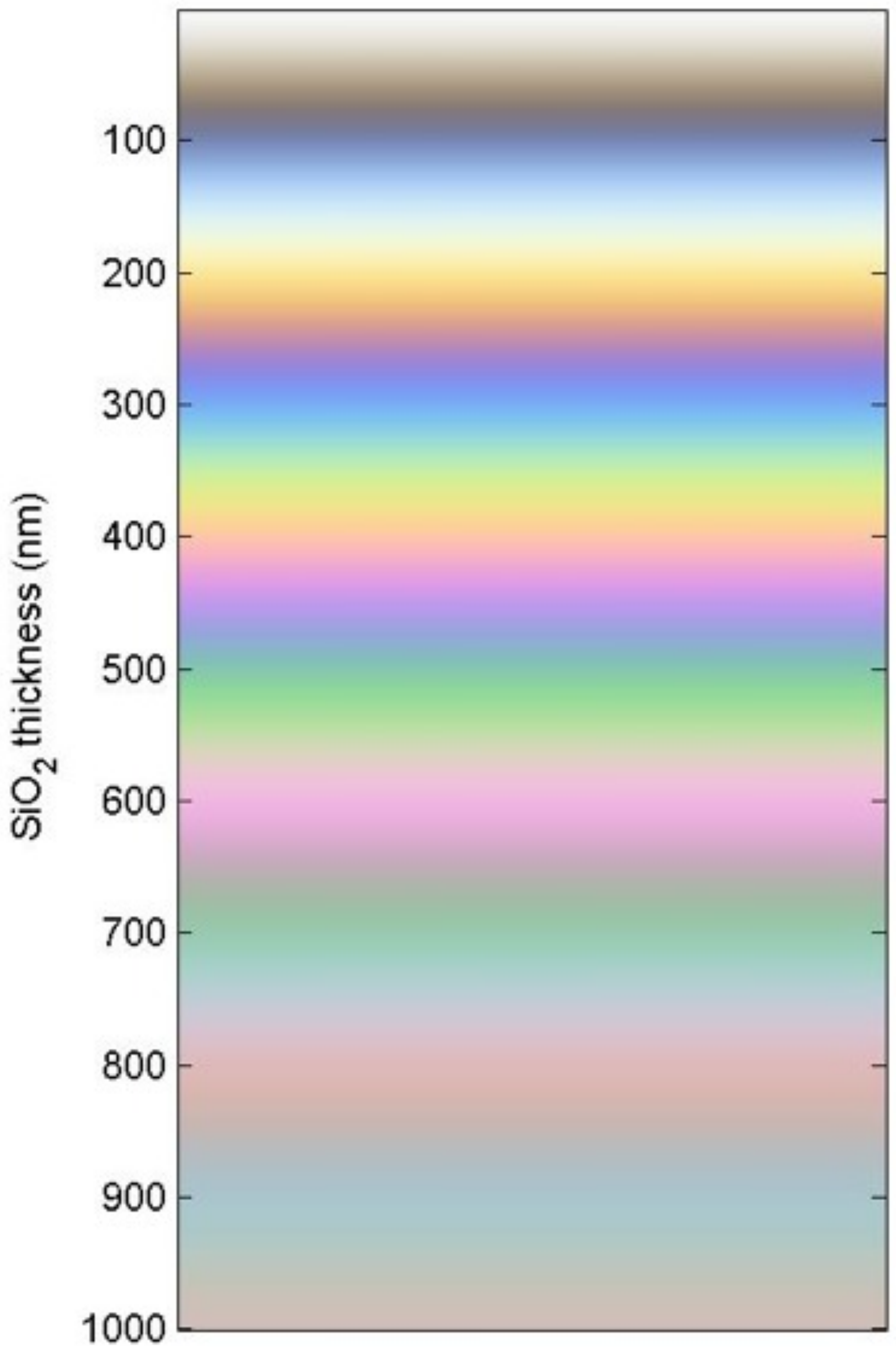
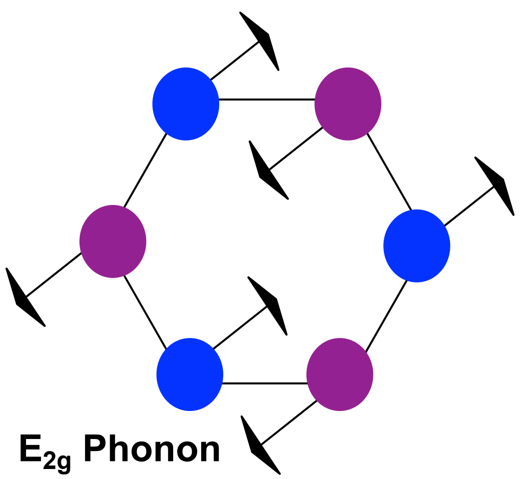
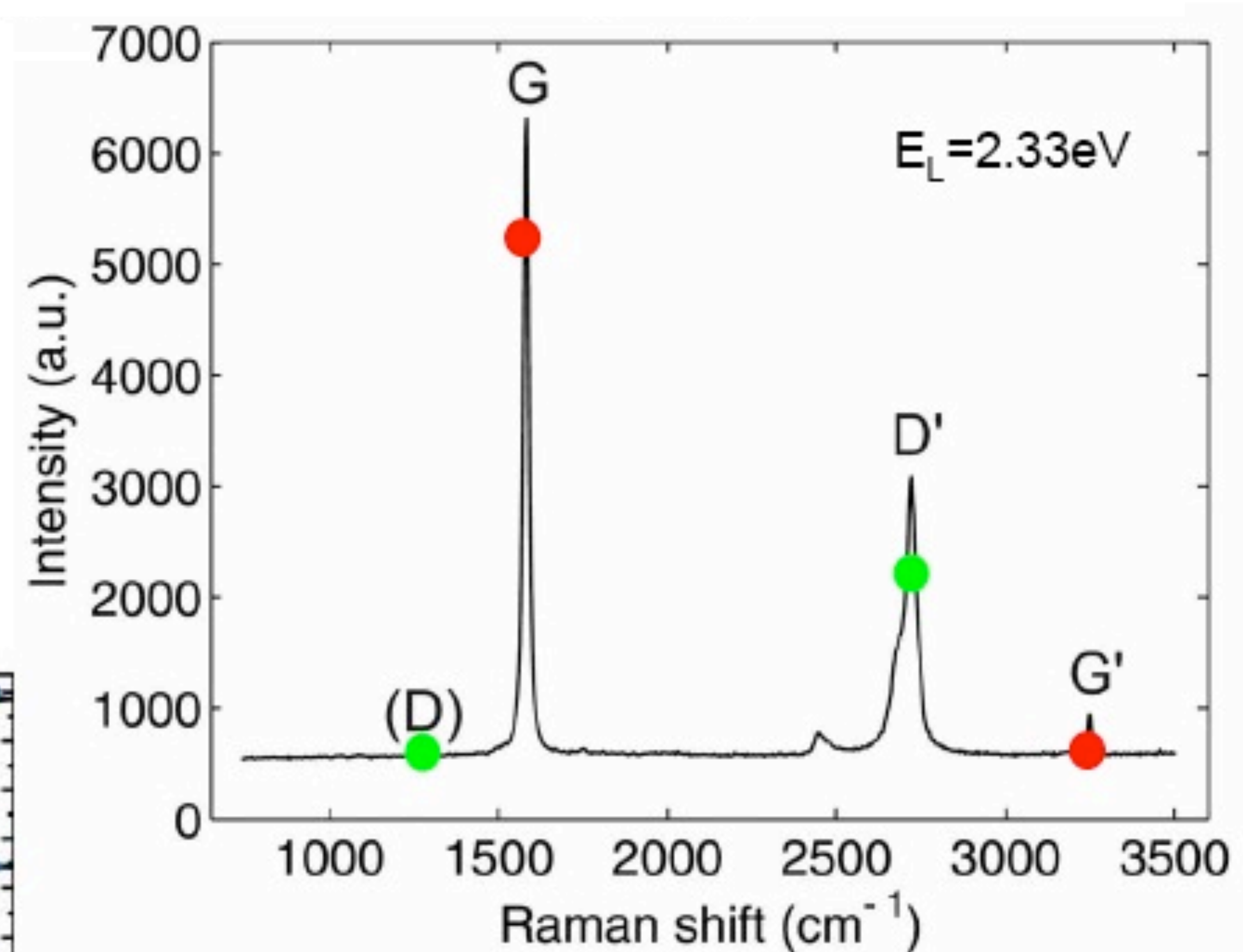


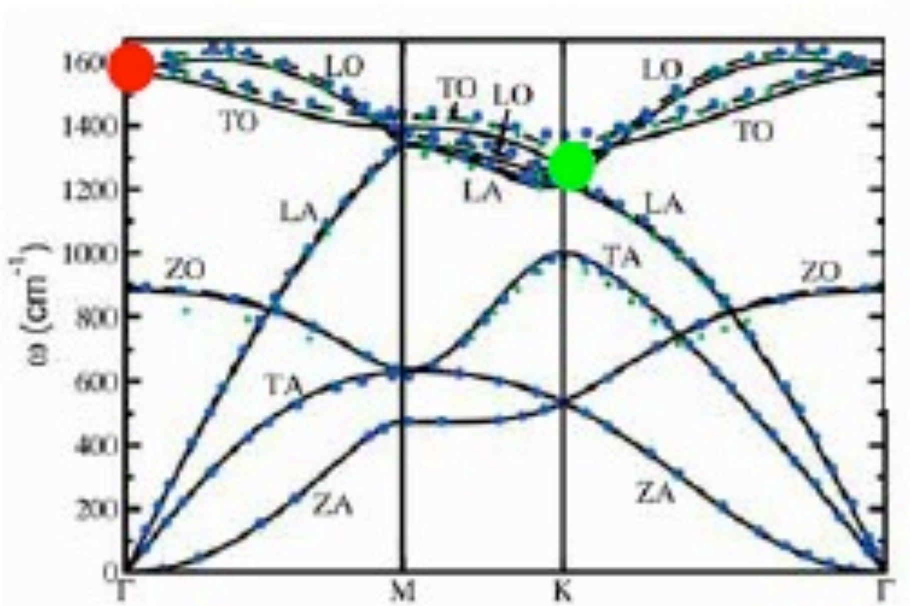


S. Roddaro, VP et al. NanoLetters (2007)

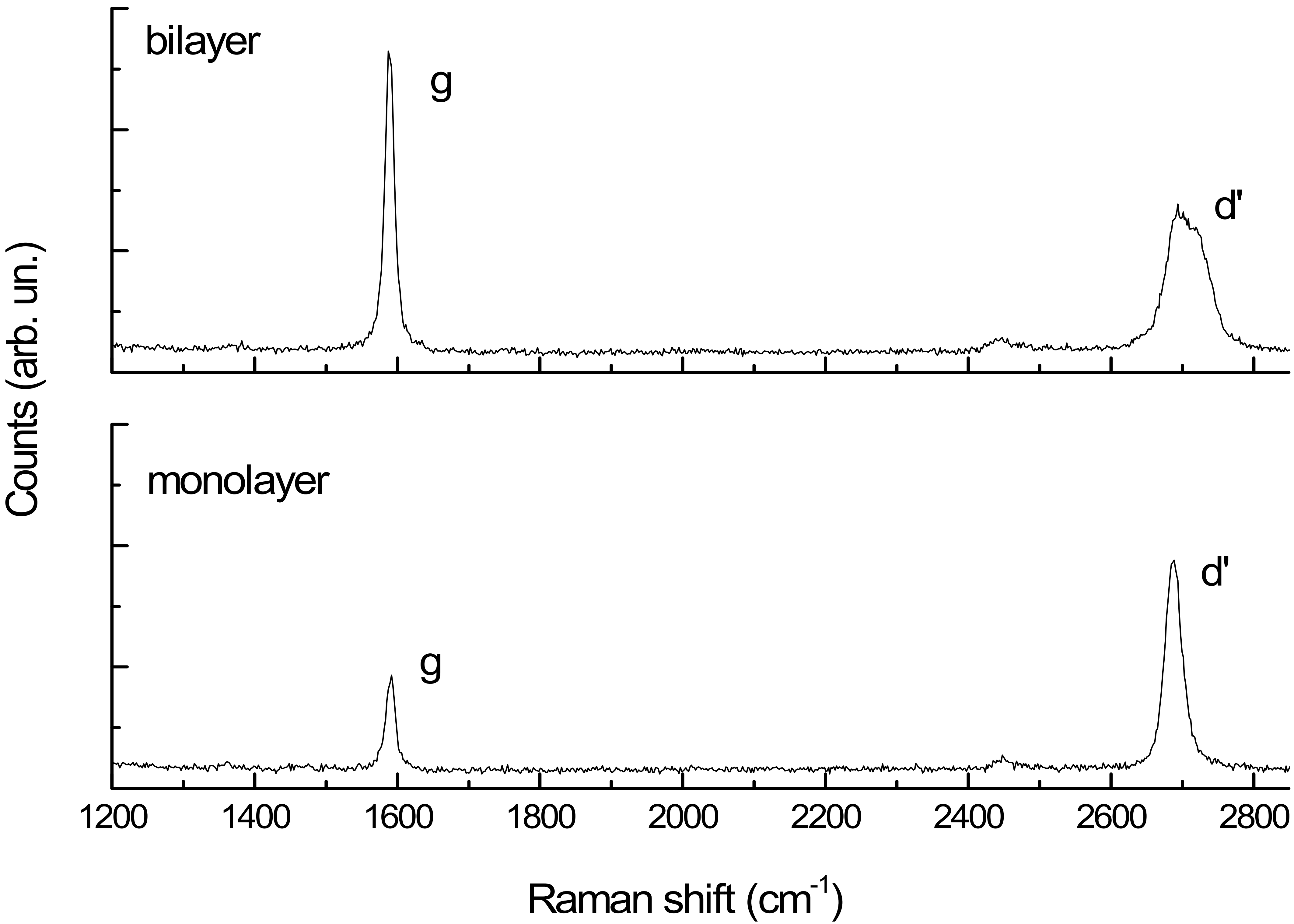
Raman spectrum of graphite







Raman spectrum depends on the number of layers



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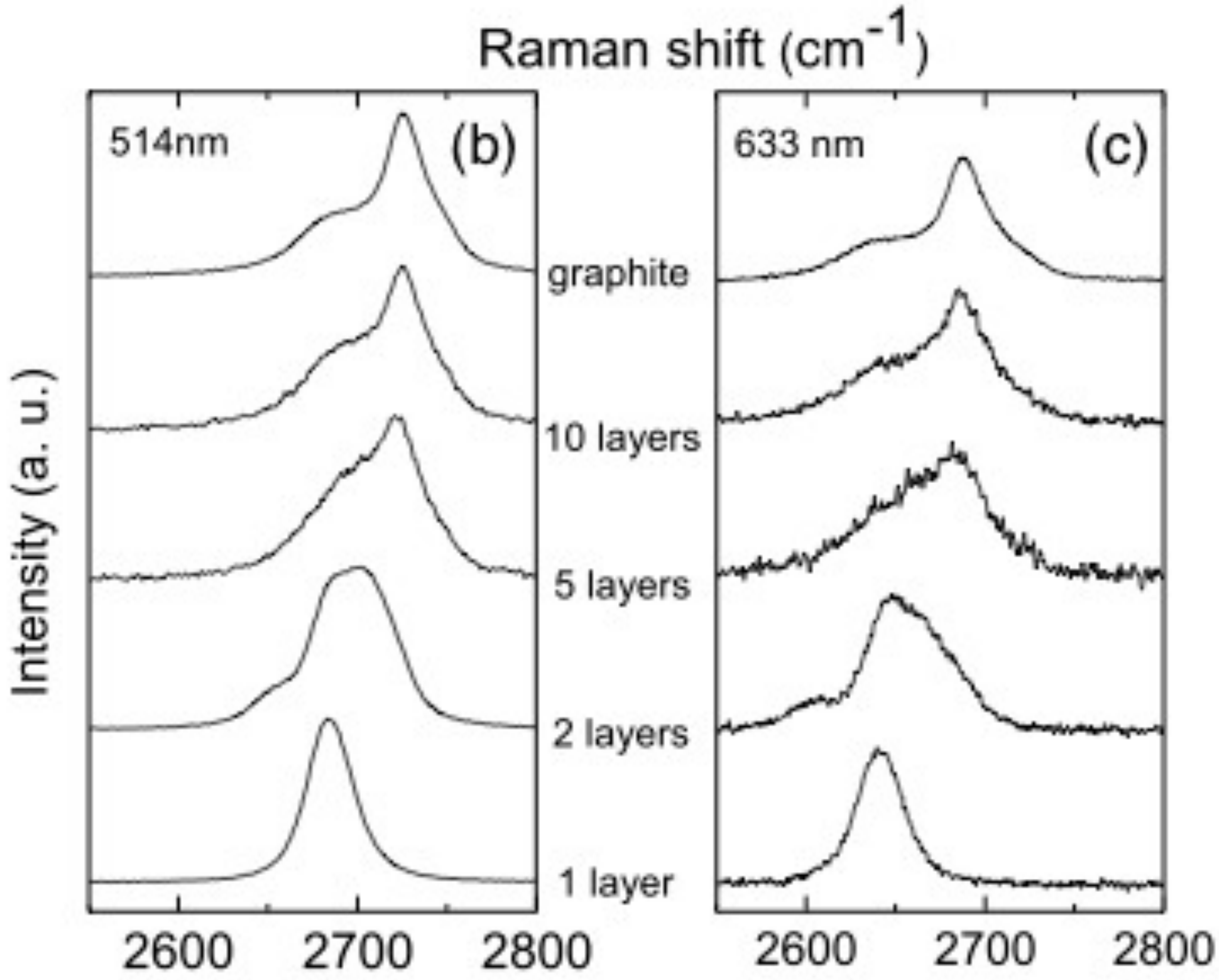
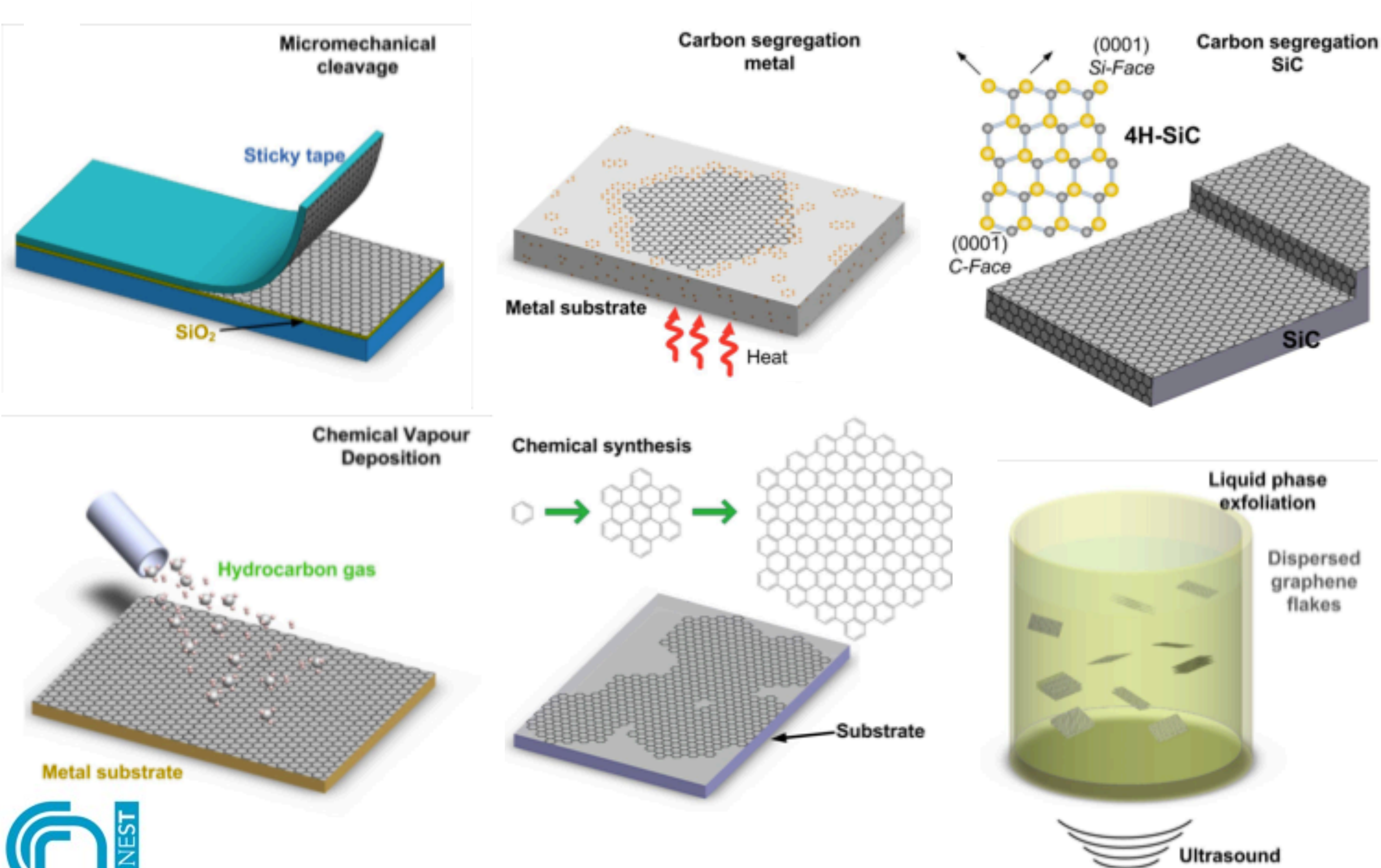


A. Ferrari et al. Phys. Rev. Lett. 97, 187401 (2006)

Graphene production in 2010



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Courtesy of A. Ferrari

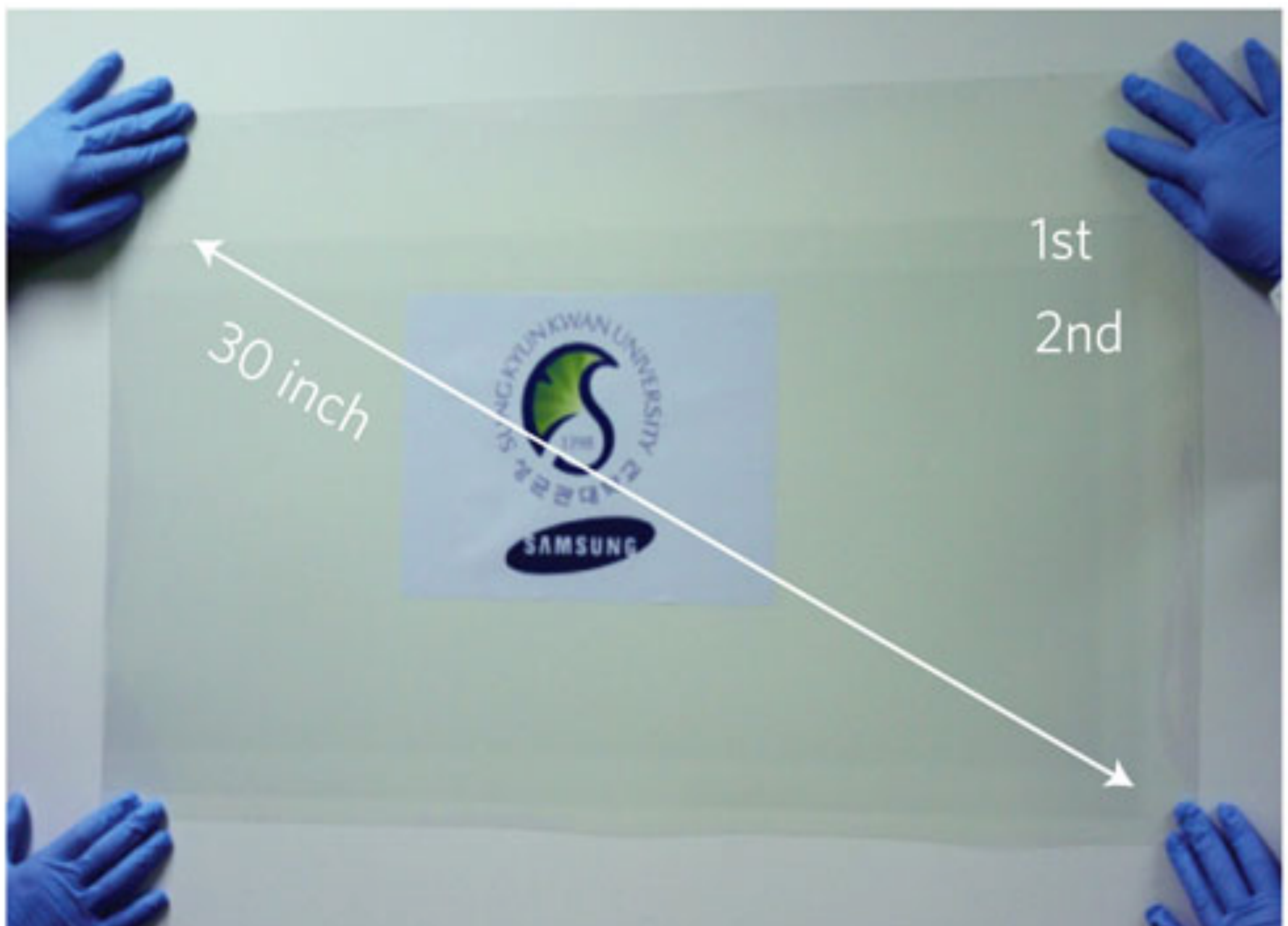
Graphene: a novel platform for applied physics

Photonics and optoelectronics
broadband tunability, ultrafast lasers, smart windows, transparent conductors, Terahertz plasmon-based photodetectors, etc

2) Energy
hydrogen storage, supercapacitors

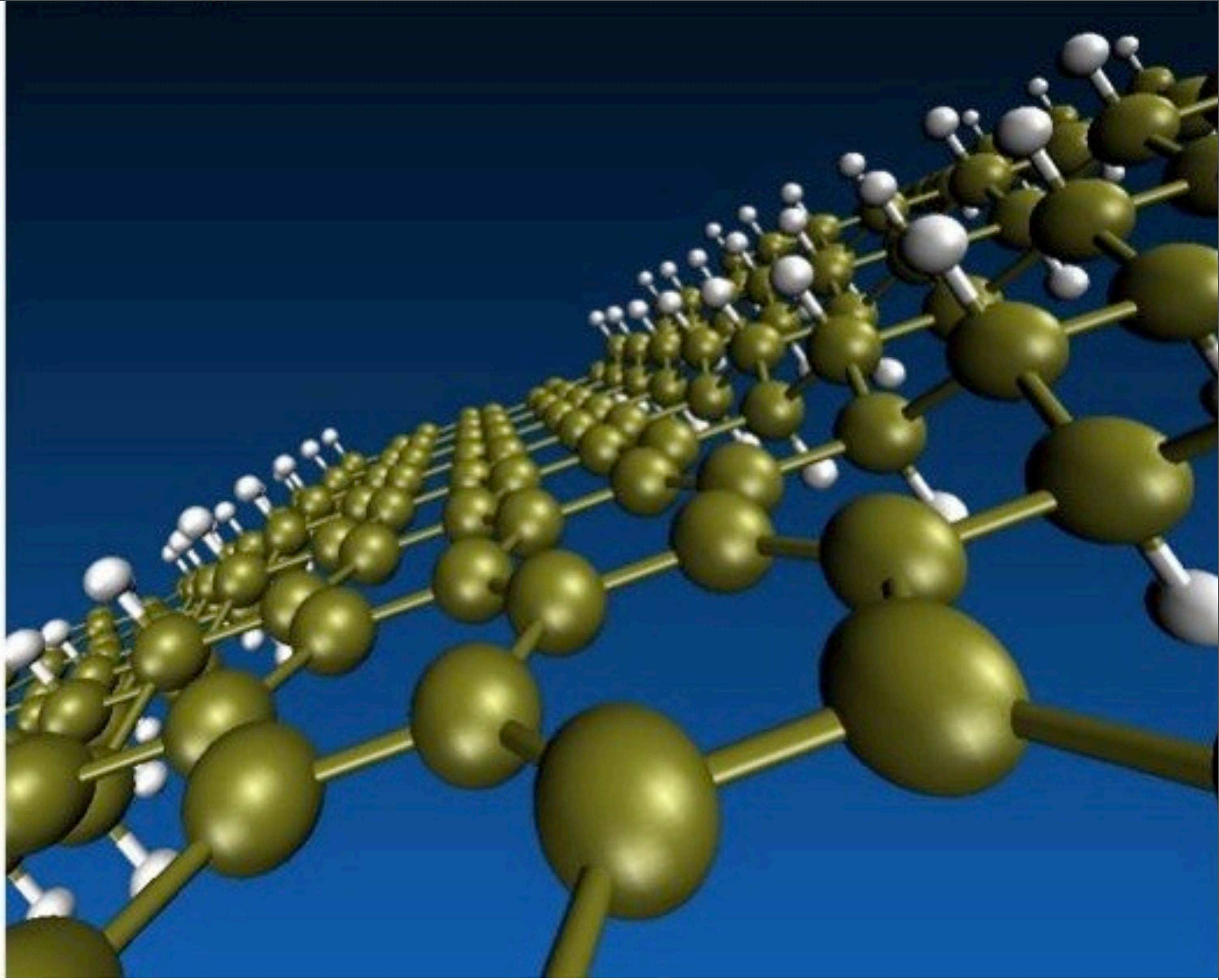
3) Electronics and sensors
ultrafast transistors, electronic properties are very sensitive to atoms and molecules deposited on it, etc

4) **Nanomechanics**
ultrastiff one-atom-thick membrane

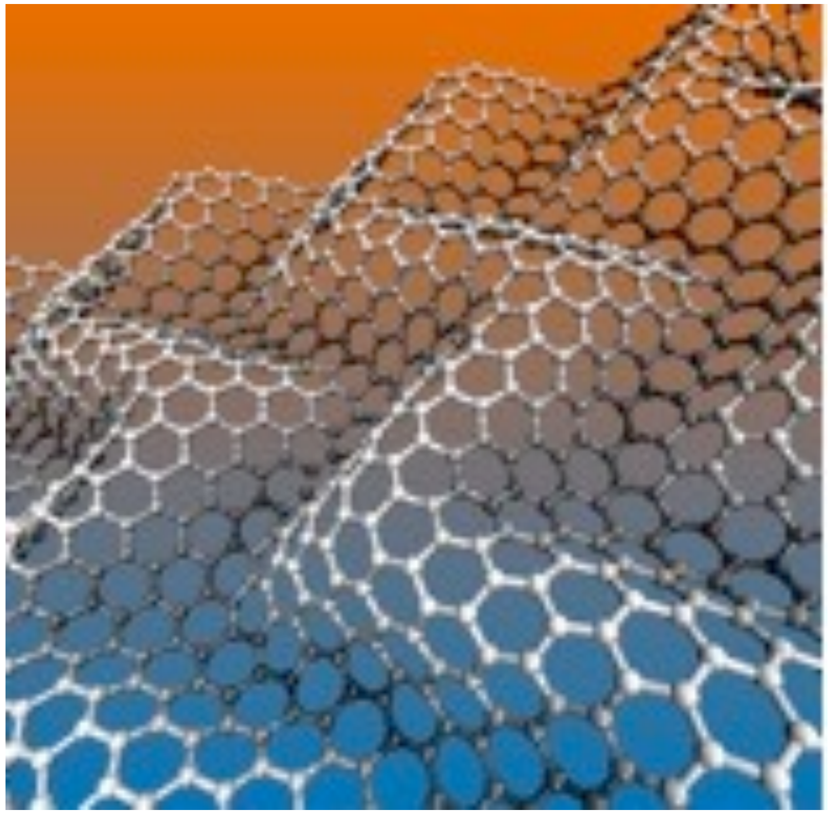


S. Bae et al., Nature. Nanotech. (2010)

Graphene and Hydrogen



Stable and disorder-free nanoribbons can be sculpted in graphane



Corrugation favours hydrogen adsorption

V. Tozzini and VP Phys. Rev. B (2010)
V. Tozzini and VP, submitted

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Graphene: a novel platform for fundamental physics

Fundamentals:

High-energy physics on a table top: massless Dirac fermions akin to neutrinos

Klein tunneling, Zitterbewegung, Atomic collapse, Supercritical charges, etc

2) Elastic one-atom thick membrane
Statistical mechanics in 2D, ripples, corrugations, synthetic gauge fields, gravity in curved space, etc

3) A new-type of many-body problem
Fractional quantum Hall states, non-Galileian-protected plasmons, spontaneous pseudospin magnetism and pseudospin-based quantum technology, high-T_c exciton condensation, etc

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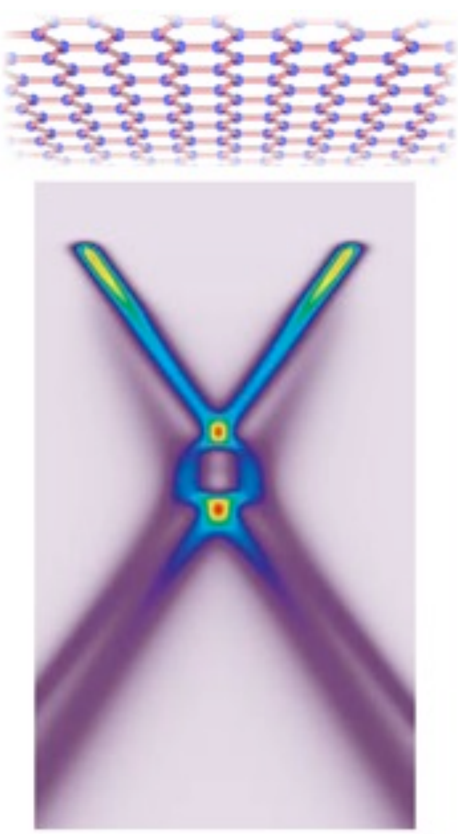
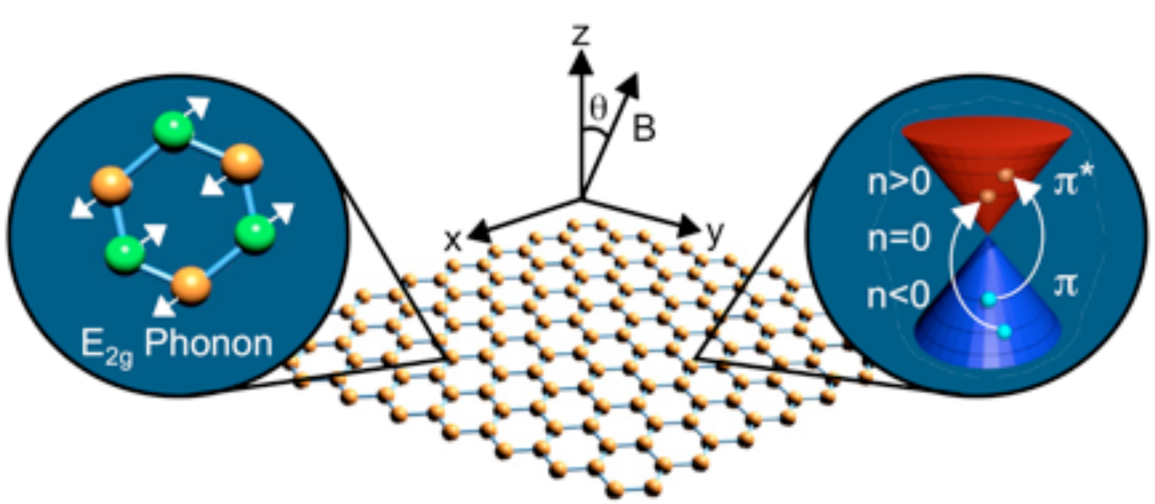
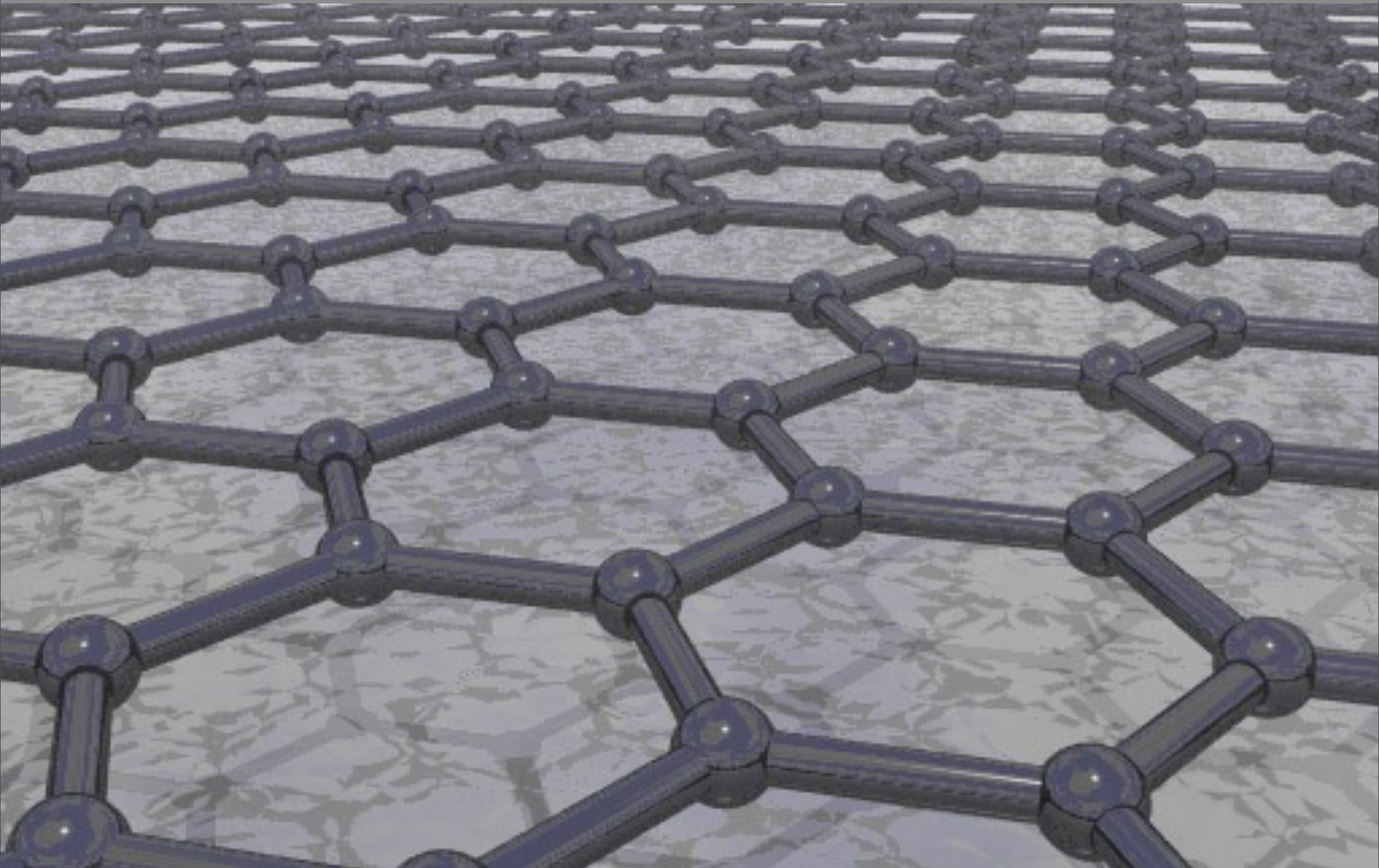


Plasmarons. Science 2010
NANO-NEST & LBN,
Texas U. Erlagen



Magneto-polarons.
PRL 2010
NANO-NEST & Columbia

Tight - binding model



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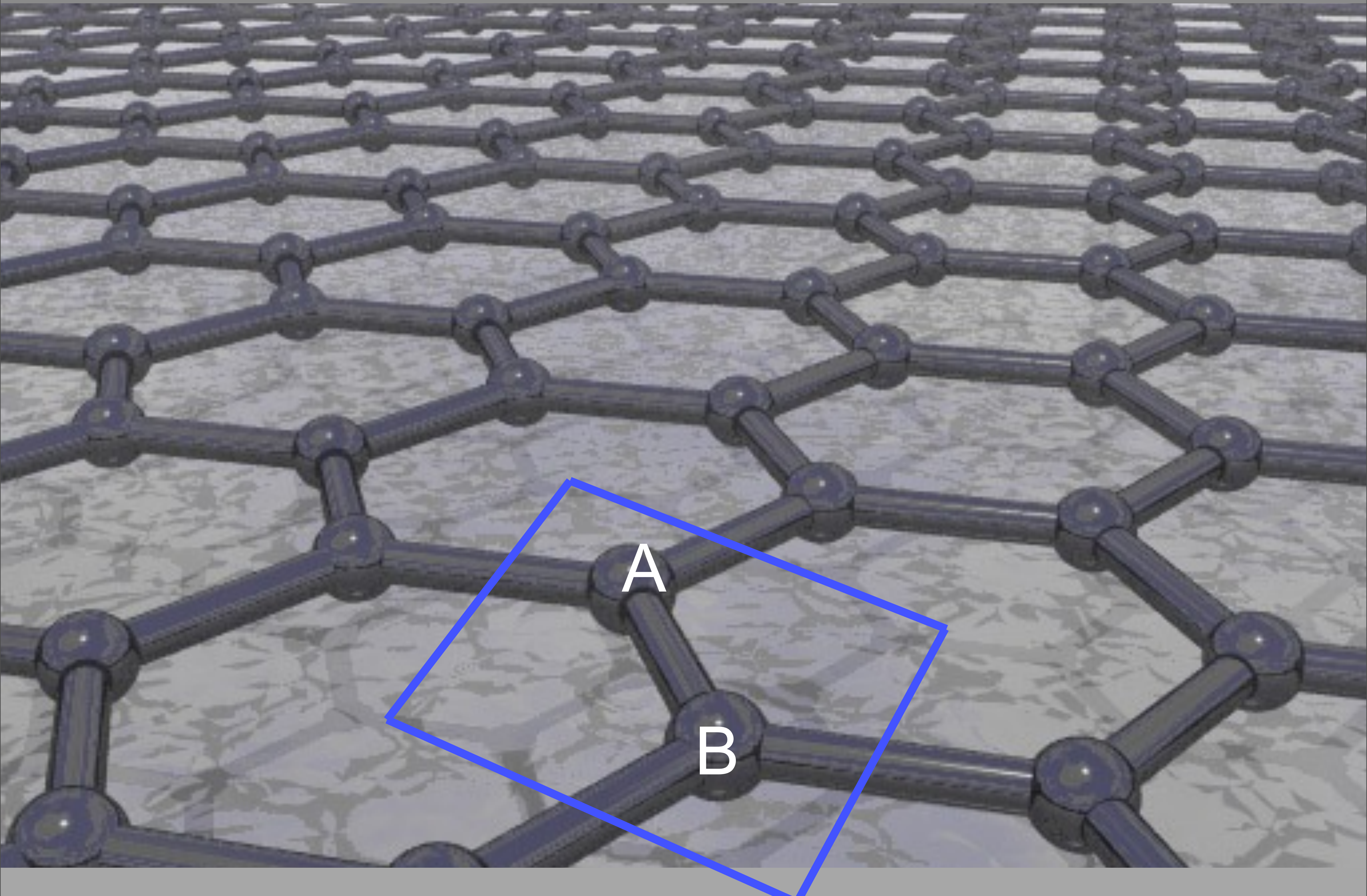
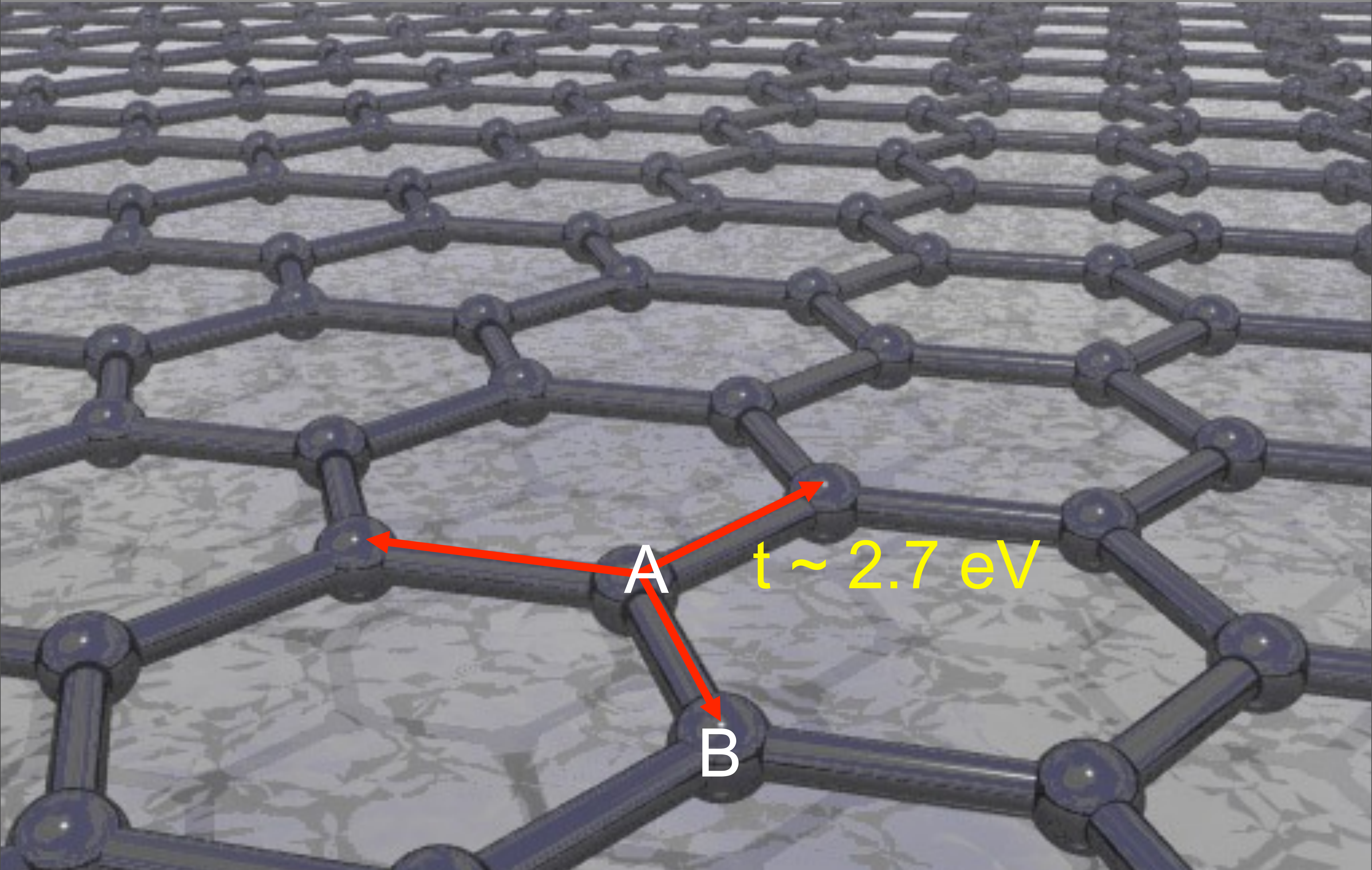


Unit cell

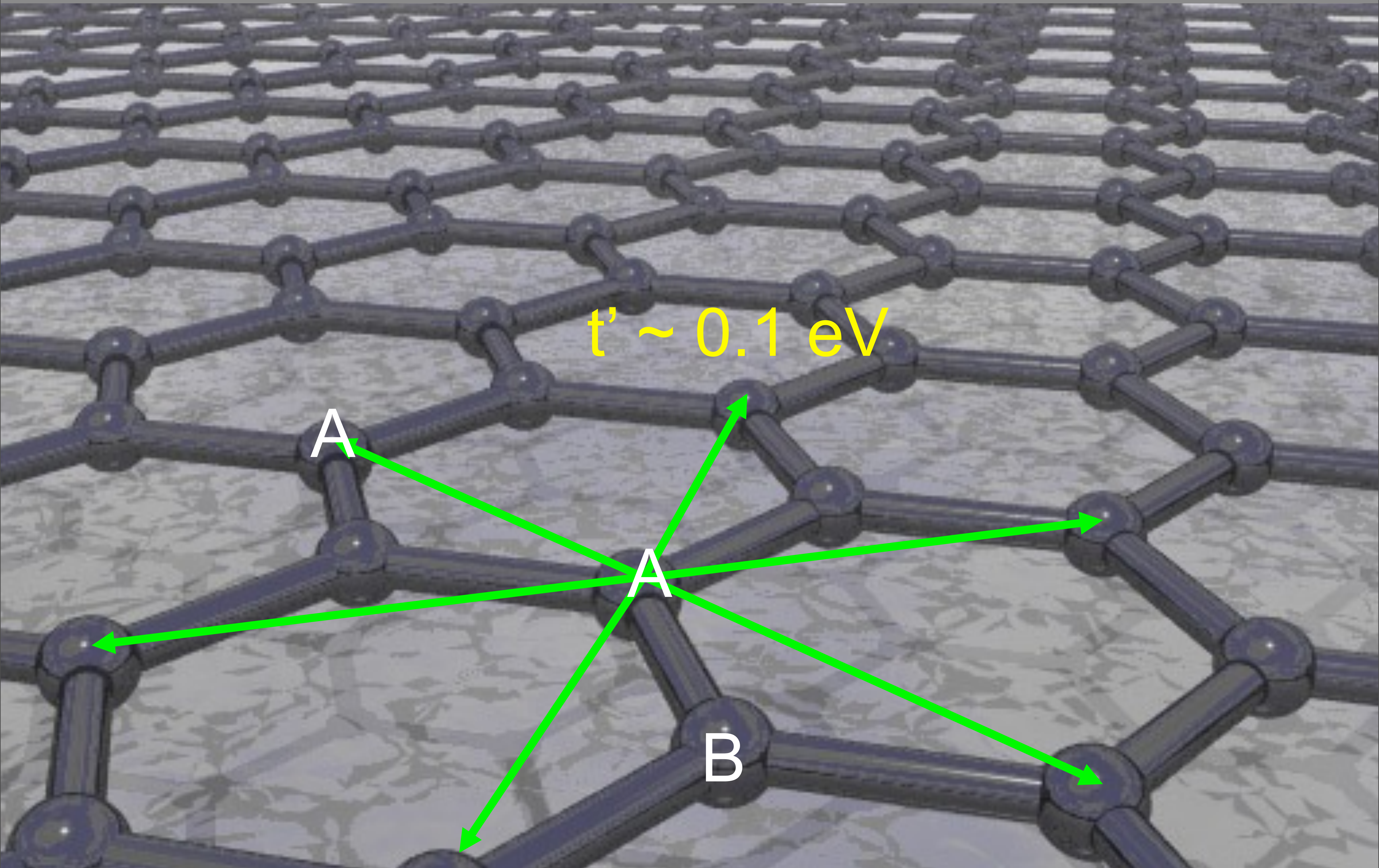
Tight - binding model



Unit cell

Nearest neighbors

Tight - binding model

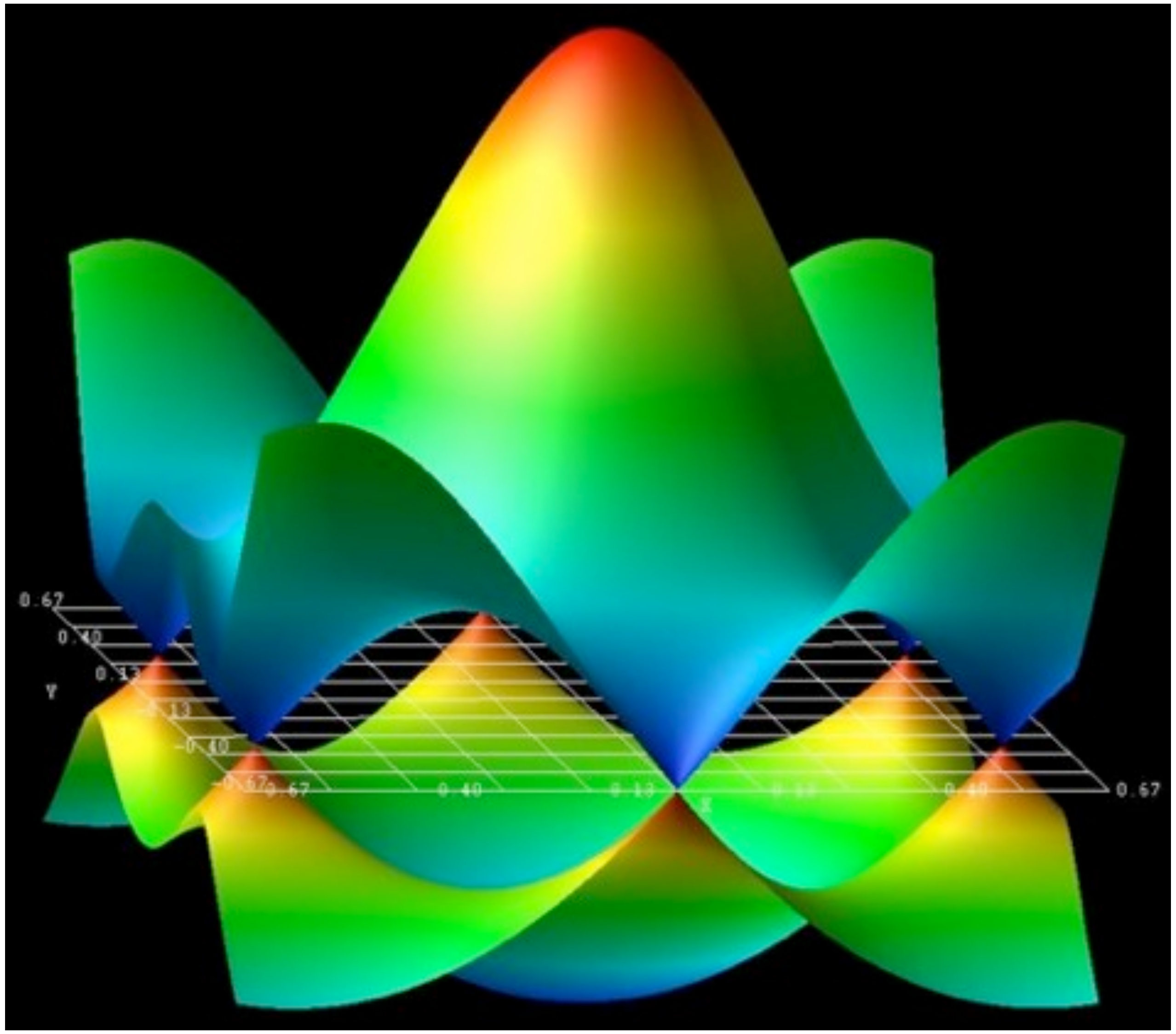


Next Nearest neighbors

Energy bands in Graphene

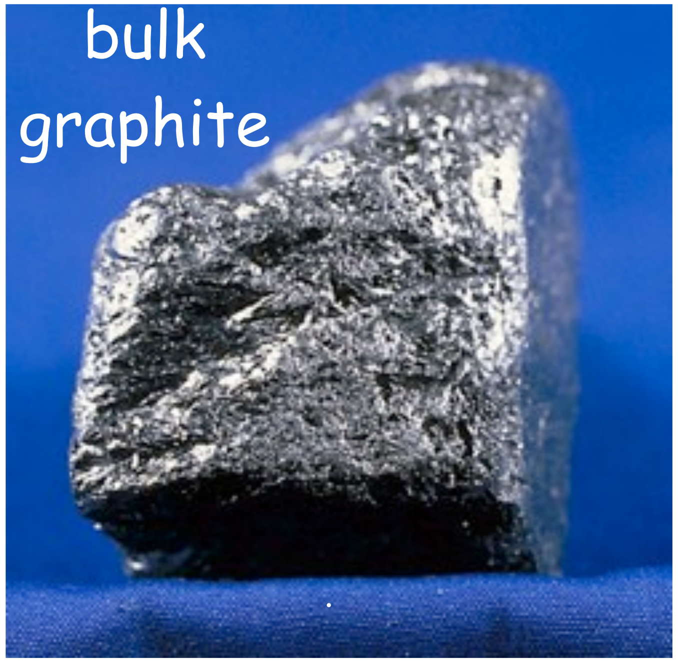
$$H_0 = -t \sum_{i \in A} \sum_{j=1}^{3} \left(b^{\dagger}_{\mathbf{R}_i + \mathbf{e}_j} a_{\mathbf{R}_i} + \mathrm{H.c.} \right)$$

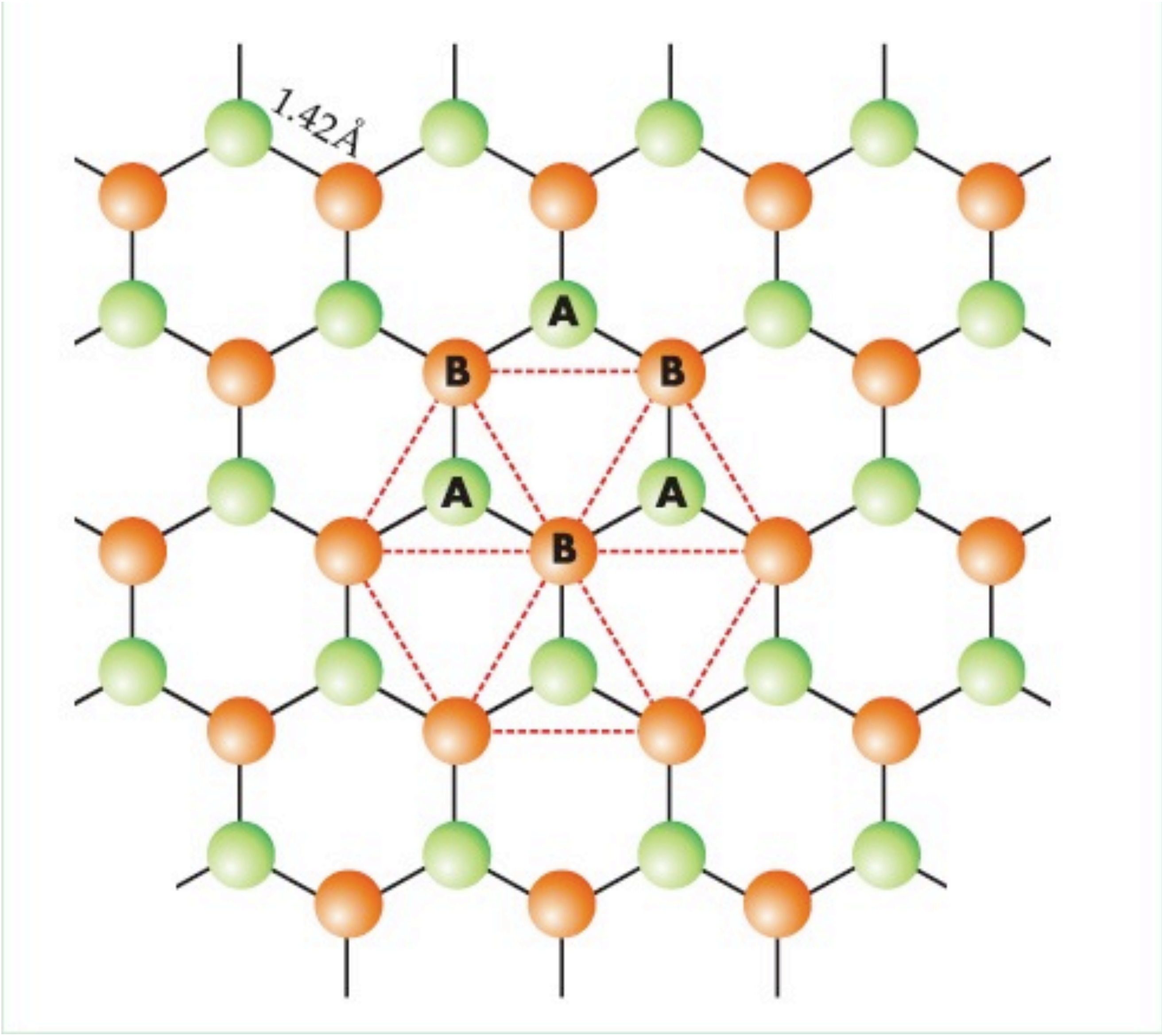
$$\varepsilon_{\mathbf{k}} = \pm t \sqrt{\left[\sum_{j=1}^{3} \cos(\mathbf{k} \cdot \mathbf{e}_j) \right]^2 + \left[\sum_{j=1}^{3} \sin(\mathbf{k} \cdot \mathbf{e}_j) \right]^2}$$



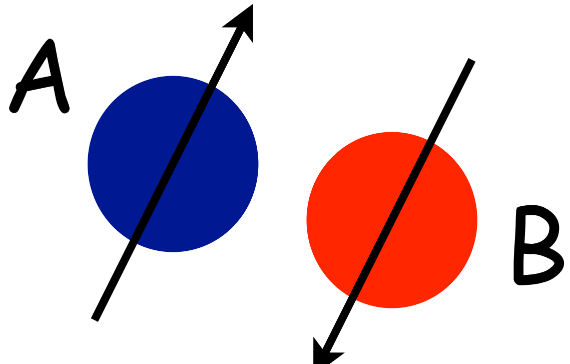
+ upper π band
- lower π* band

Pseudospin degrees of freedom in graphene





pseudospin
and real spin!



A.K. Geim and A.H. MacDonald, Physics Today (2007)

2 valleys — 2 spin states

emergent SU(4) symmetry

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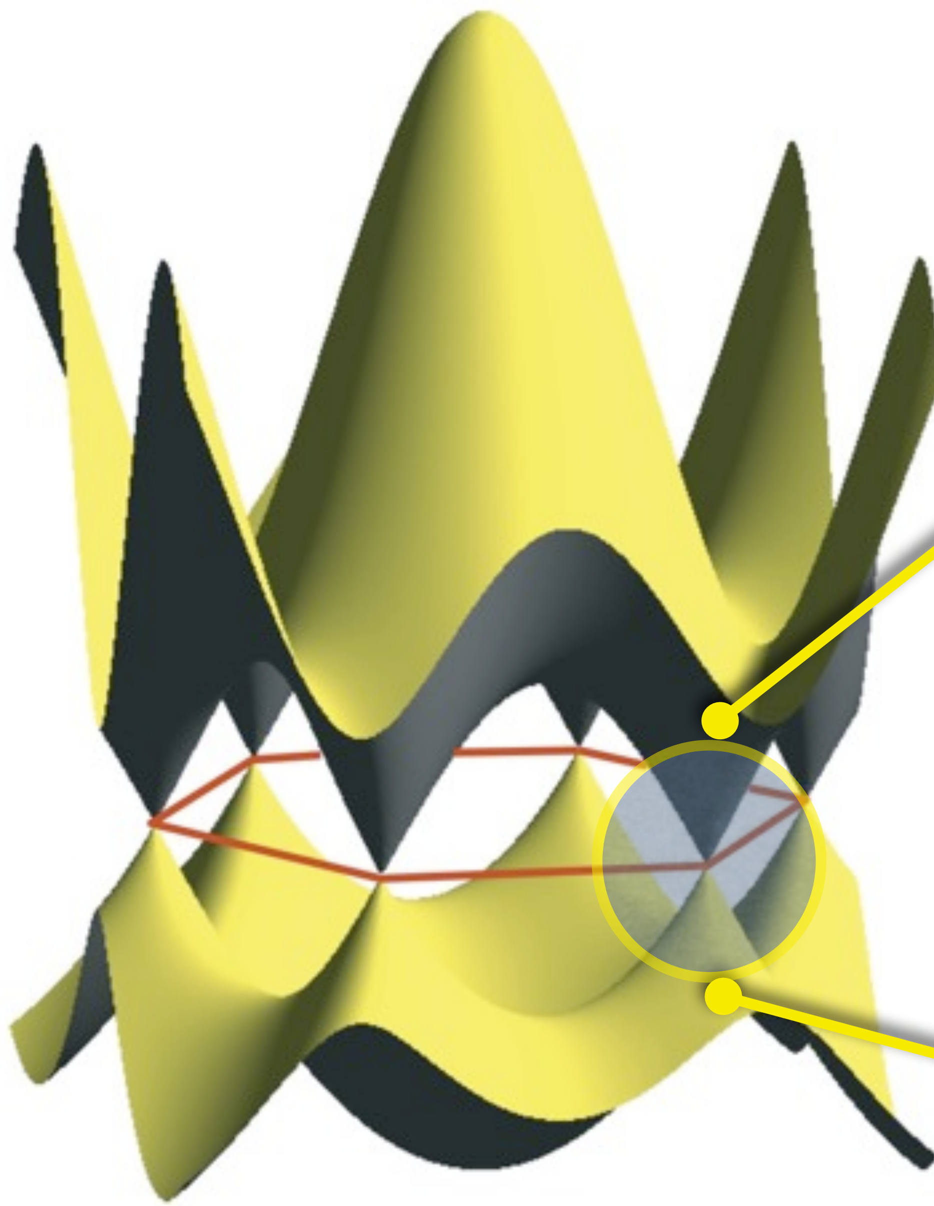
Graphene's band structure



Dirac cones....

Continuum limit near the points
K and K' (valley pseudospin $\pm$ 1)

$$\mathcal{H}^{\pm}(\boldsymbol{\kappa}) = \frac{3}{2} ta \begin{pmatrix} 0 & \kappa_1 \mp i\kappa_2 \\ \kappa_1 \pm i\kappa_2 & 0 \end{pmatrix}$$

$$H = v_F(\sigma \cdot \mathbf{p})$$

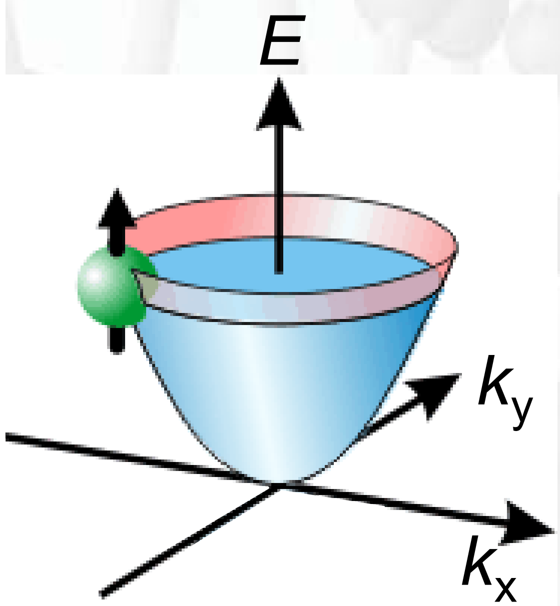
$$v_F = 3ta/2 = c/300$$

massless Dirac fermions!

QED on the pencil trace

"Schrödinger fermions"

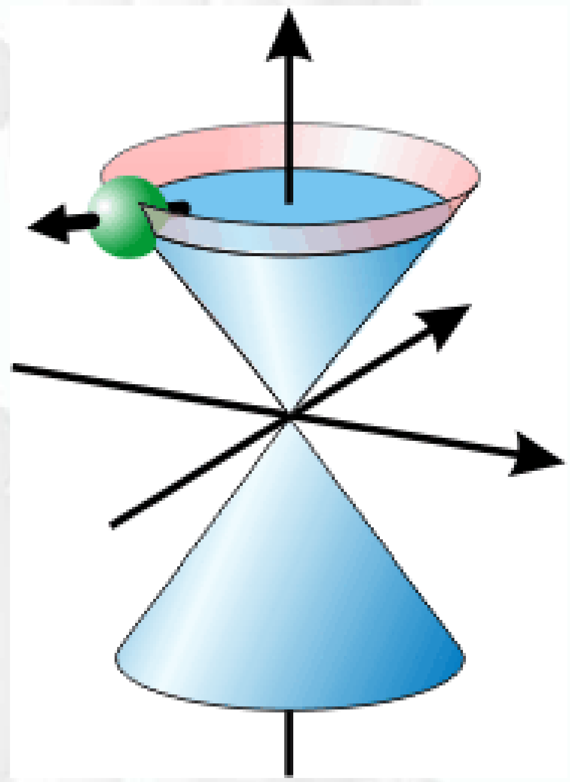
$$\hat{H} = \hat{p}^2 / 2m^*$$



metals and semiconductors

real Dirac fermions

$$\hat{H} = c\,\vec{\sigma} \cdot \hat{p}$$

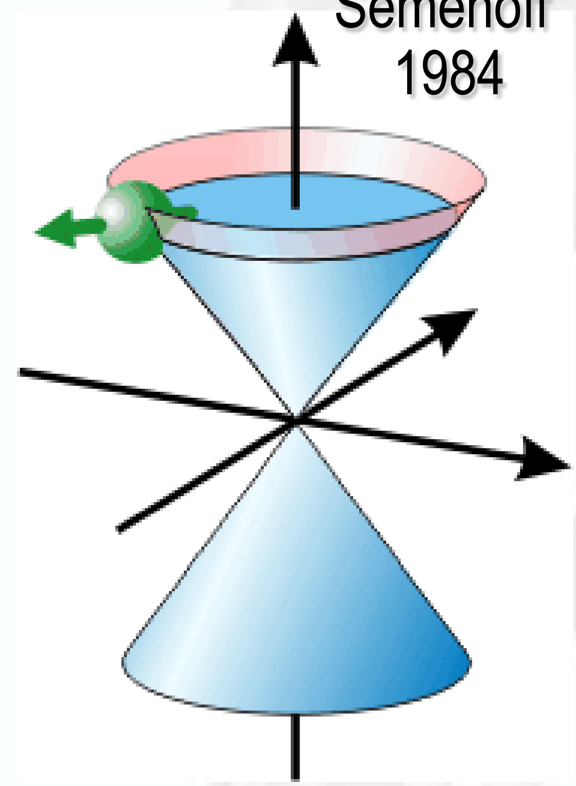


neutron stars and accelerators

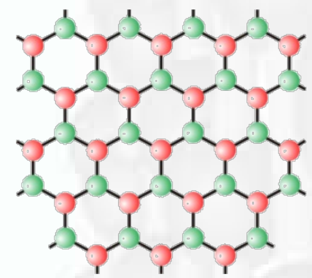
massless Dirac fermions

$$\hat{H} = v_F \vec{\sigma} \cdot \hat{p}$$

Semenoff 1984



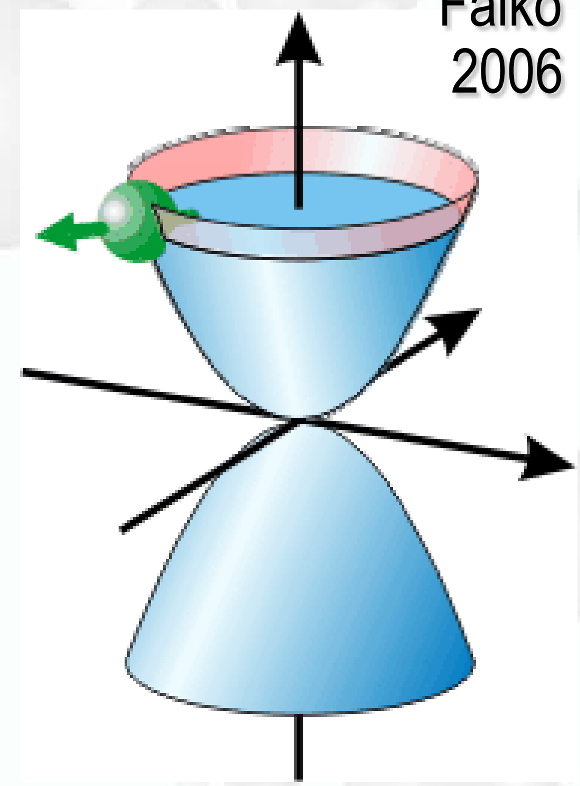
monolayer graphene



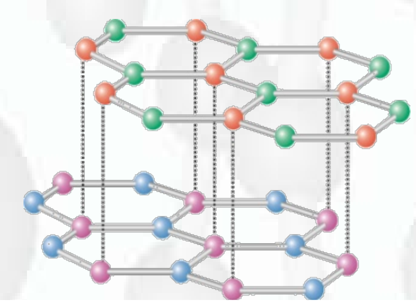
massive chiral fermions

$$\hat{H} = \vec{\sigma} \cdot \hat{p}^2 / 2m^*$$

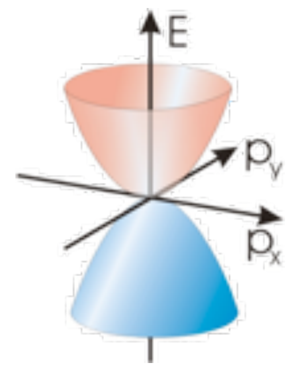
Falko 2006

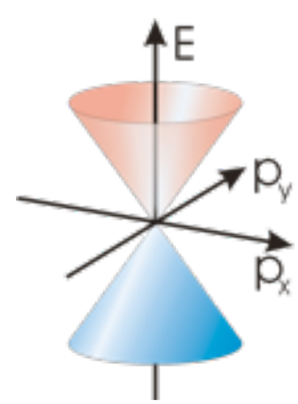


bilayer graphene

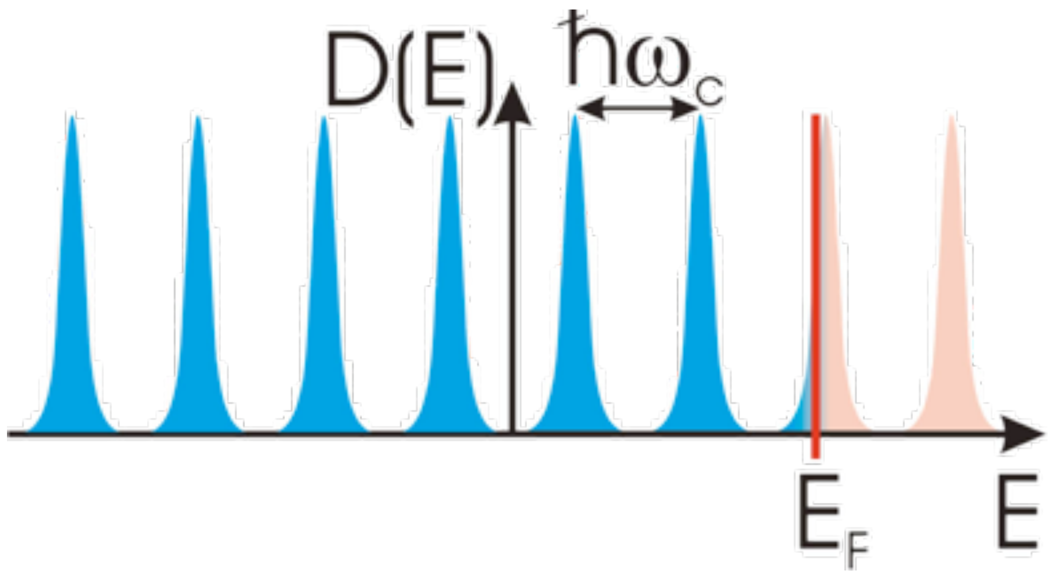


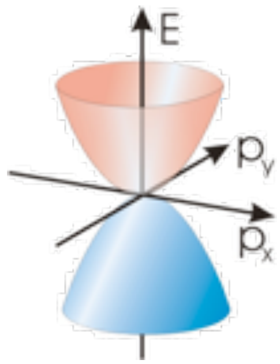
Manifestations of Dirac fermions: Landau levels

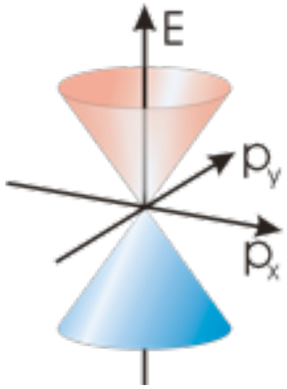




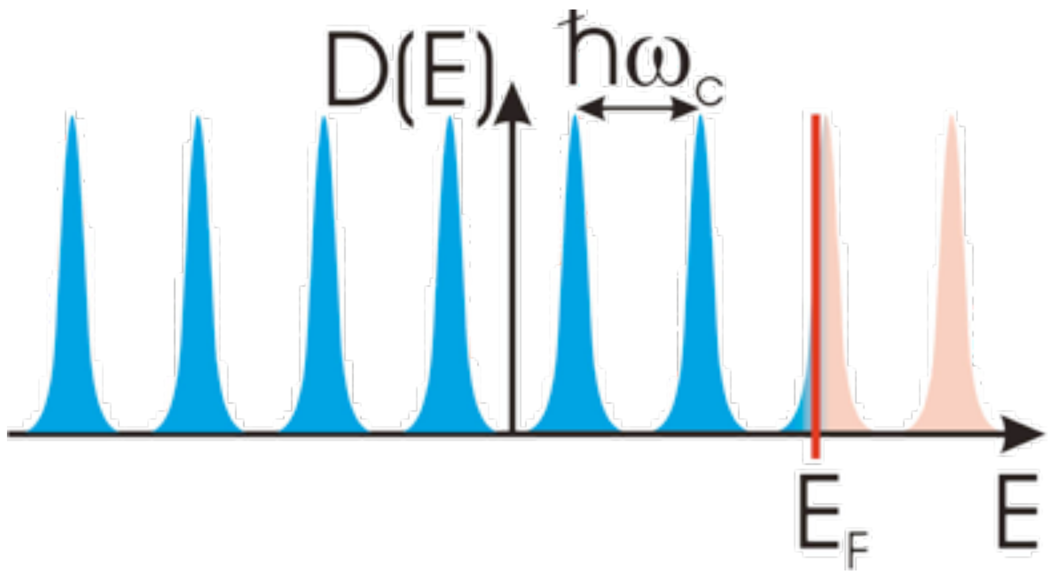
Manifestations of Dirac fermions: Landau levels

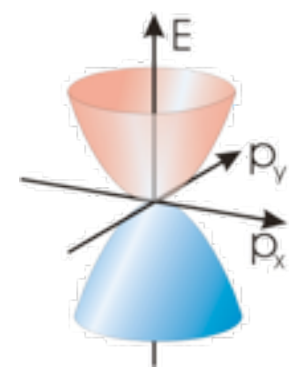






Manifestations of Dirac fermions: Landau levels



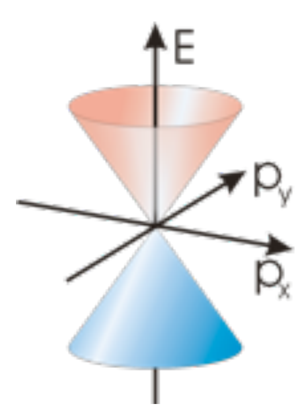


$$\varepsilon_{j,\pm} = \pm\hbar\omega_c\left(j + \tfrac{1}{2}\right)$$

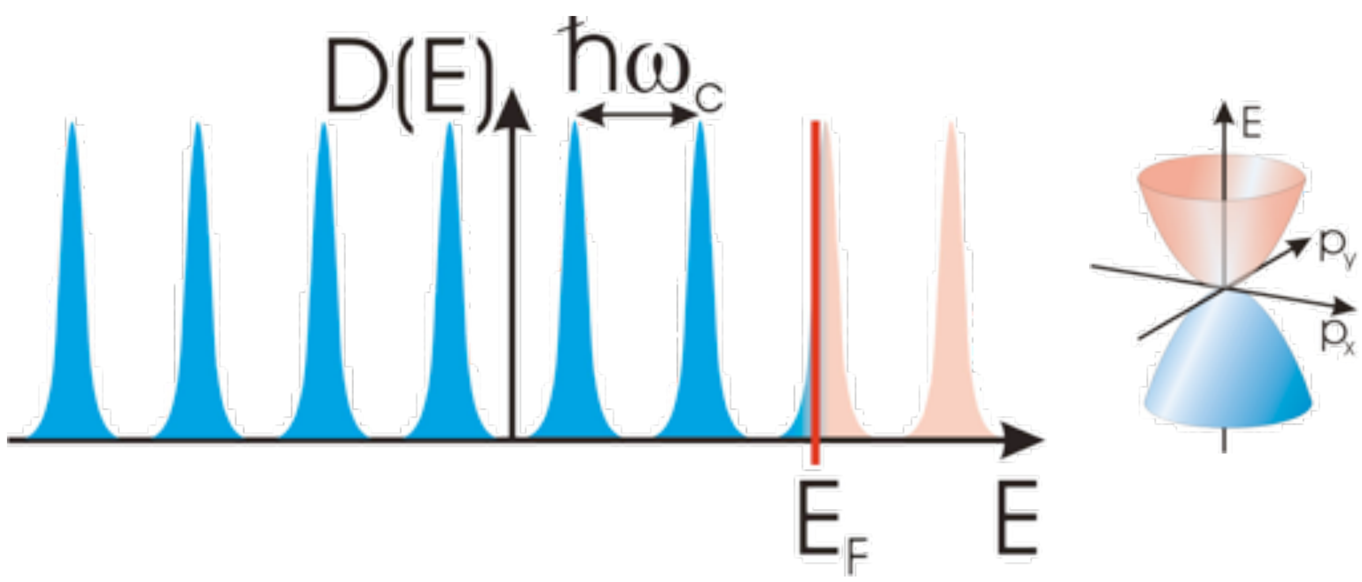
$$\omega_c = eB/(mc) = \hbar/(ml_B^2)$$

$$l_B = \sqrt{\hbar c/(eB)}$$

$$B = 10T \qquad \hbar\omega_c \approx 1K$$



Manifestations of Dirac fermions: Landau levels



$$\varepsilon_{j,\pm} = \pm\hbar\omega_c(j + \tfrac{1}{2})$$

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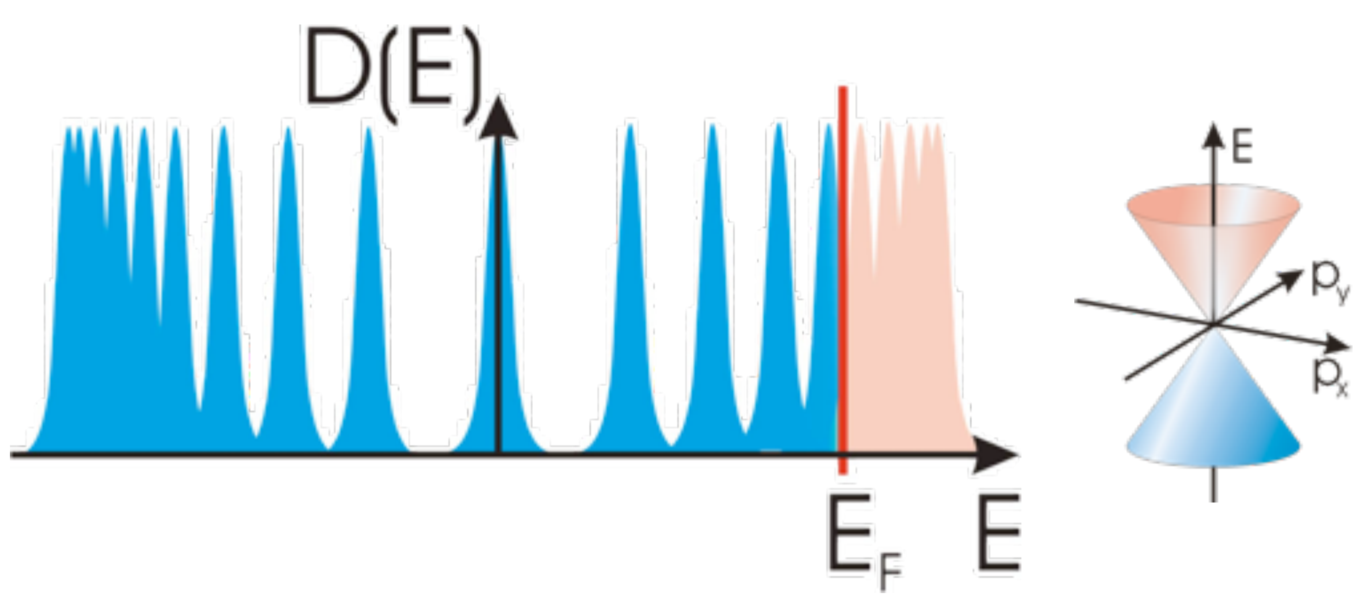
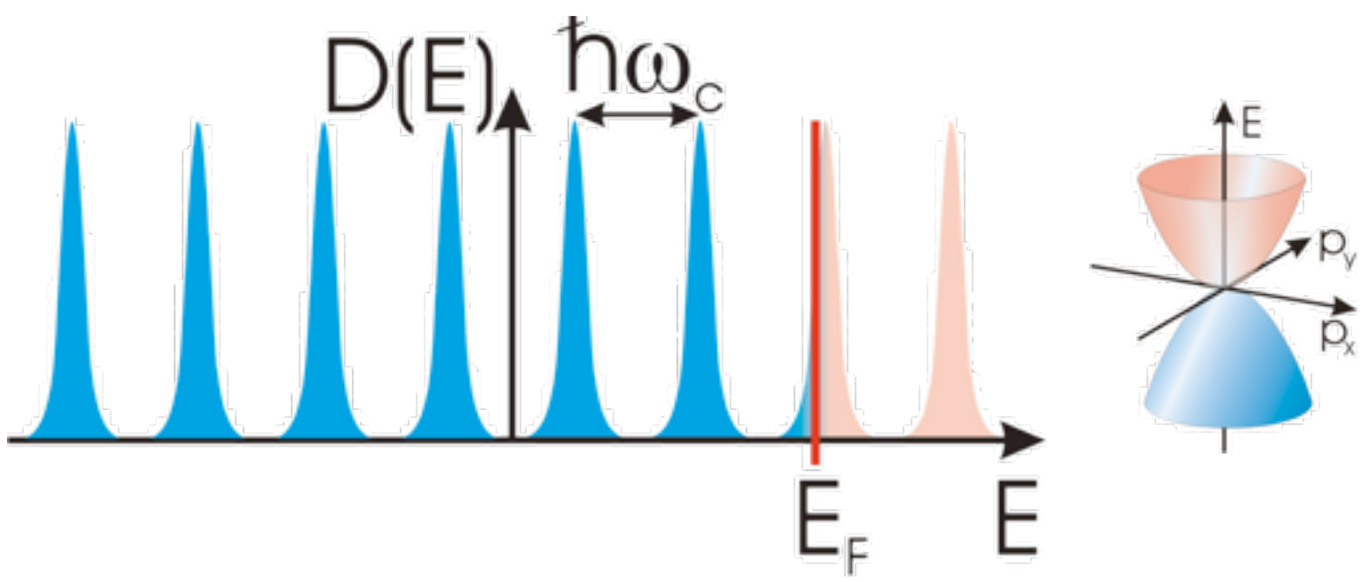


Manifestations of Dirac fermions: Landau levels

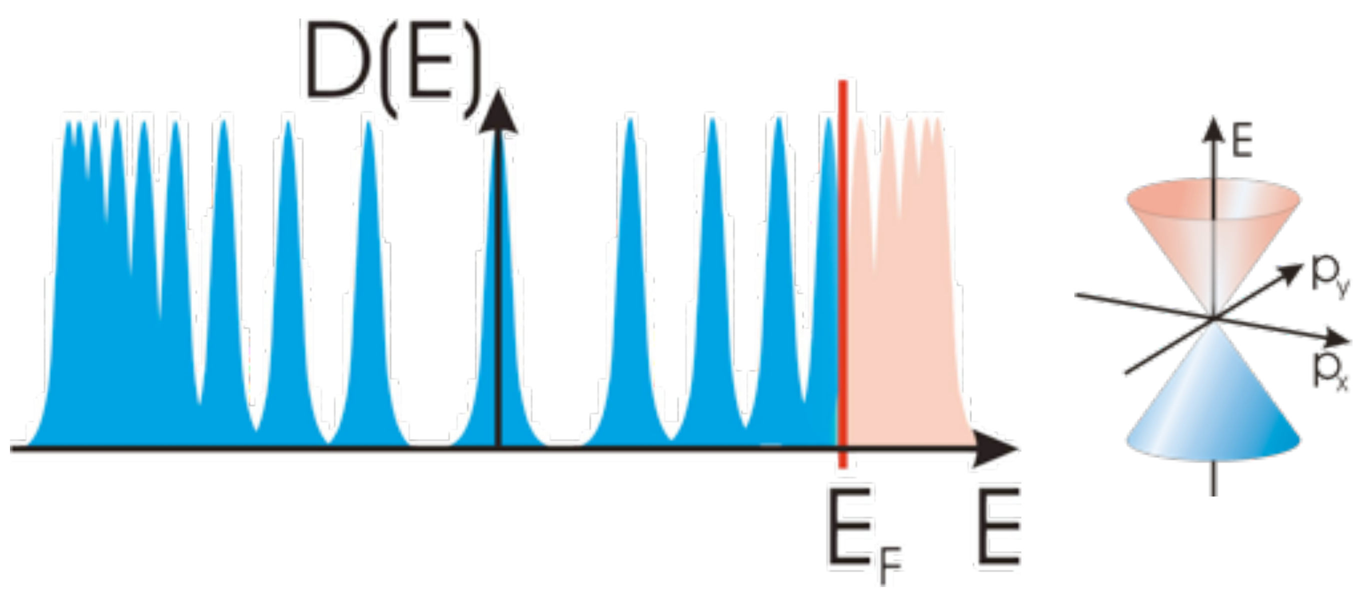


$$\varepsilon_{j,\pm} = \pm\hbar\omega_c\left(j + \tfrac{1}{2}\right)$$

$$\omega_c = eB/(mc) = \hbar/(ml_B^2)$$

$$l_B = \sqrt{\hbar c/(eB)}$$

$$B = 10T \qquad \hbar\omega_c \approx 1K$$

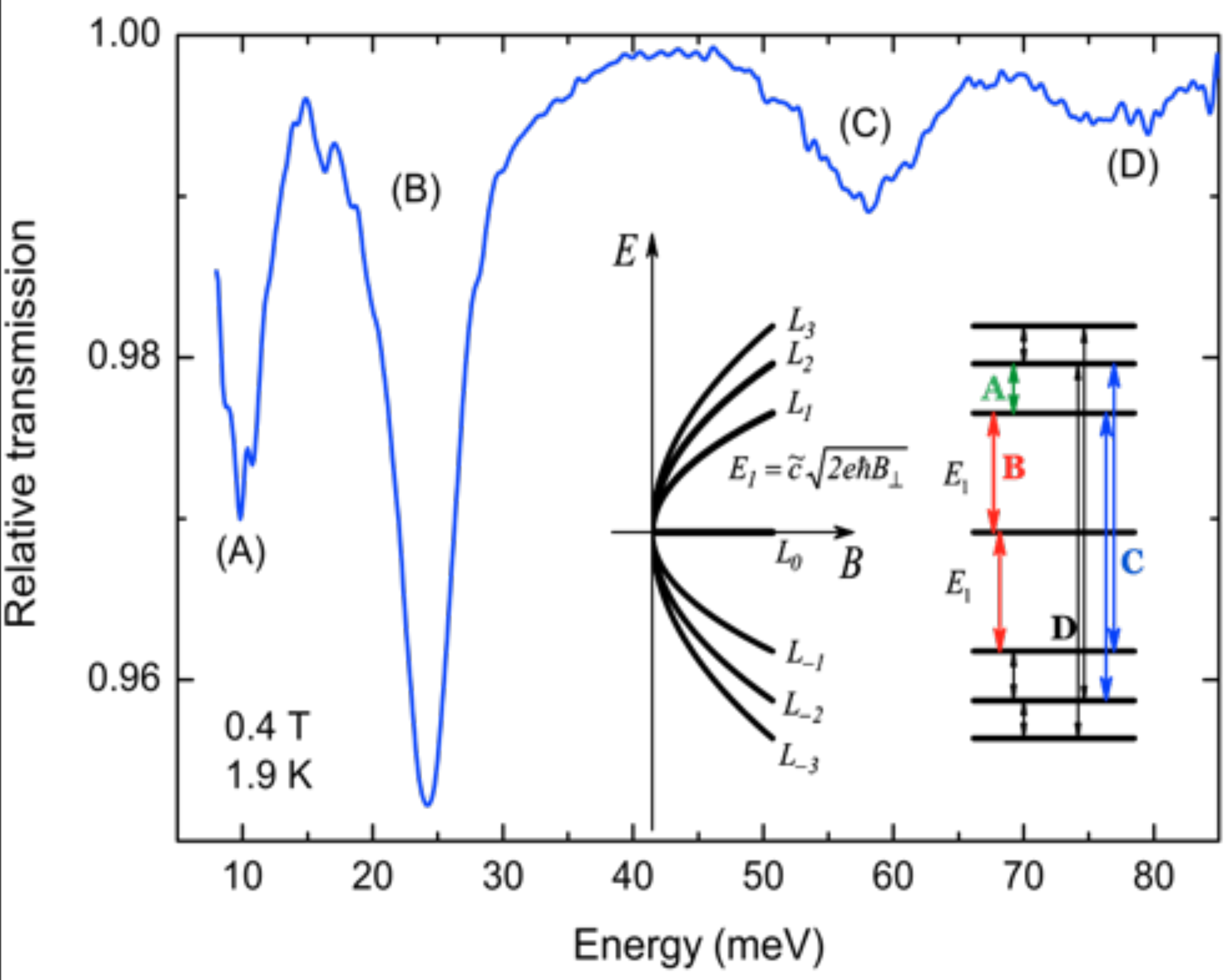


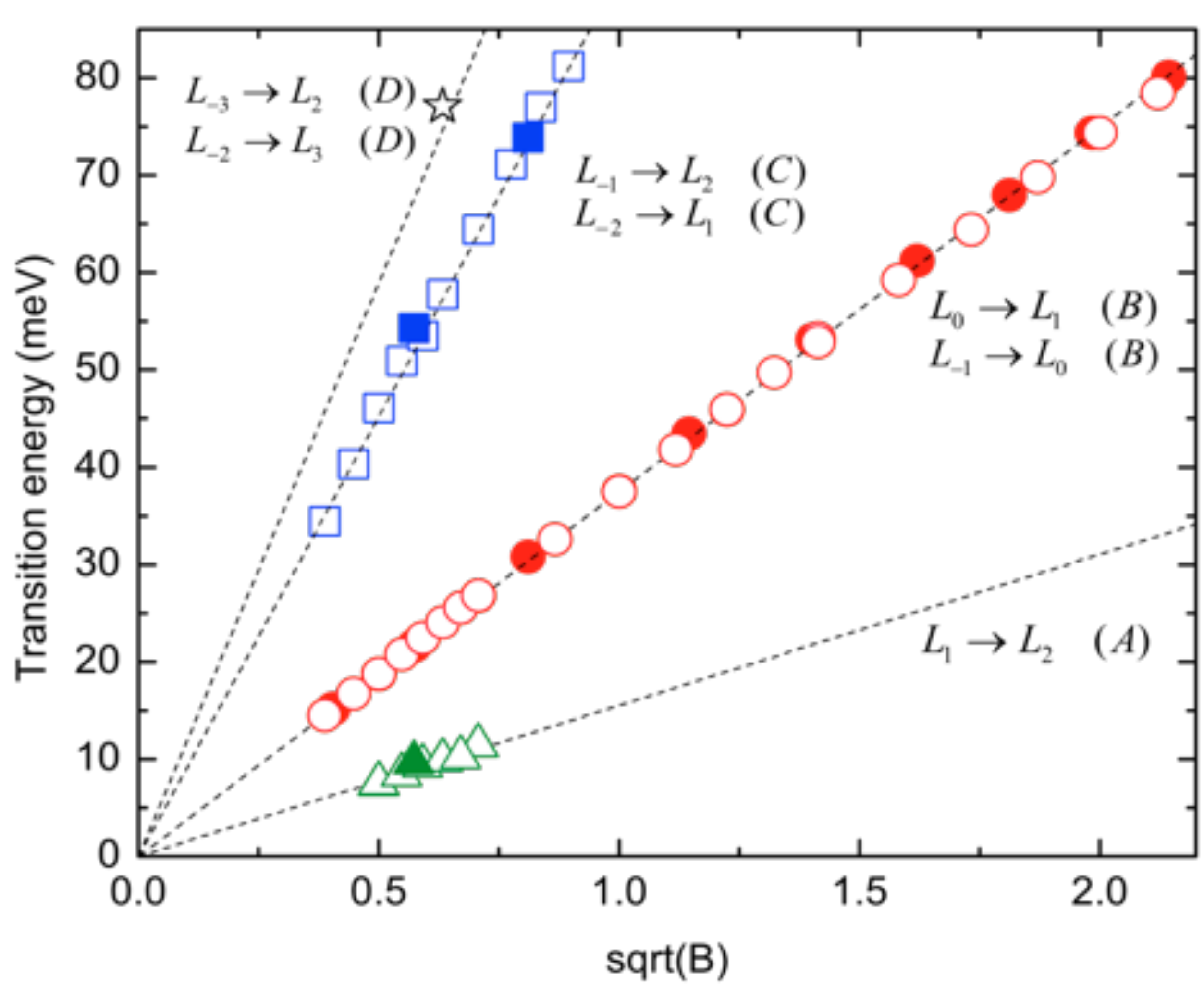
$$\varepsilon_{j,\pm} = \pm\hbar\omega_c\sqrt{n}$$

$$\omega_c = v_F / l_B = v_F\sqrt{eB/\hbar c}$$

$$B = 10T \qquad \hbar\omega_c \approx 1500K$$

Manifestations of Dirac fermions: Landau levels





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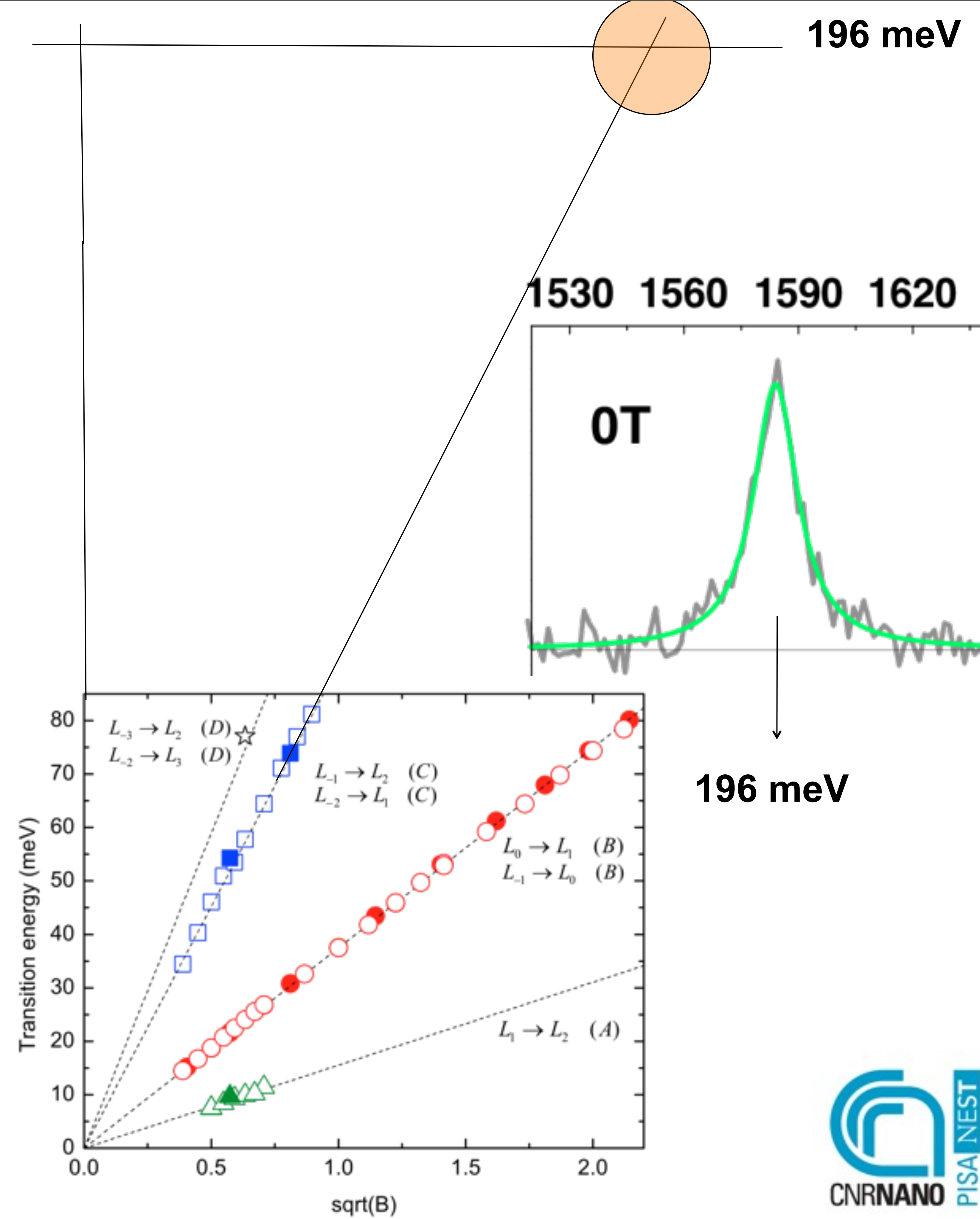
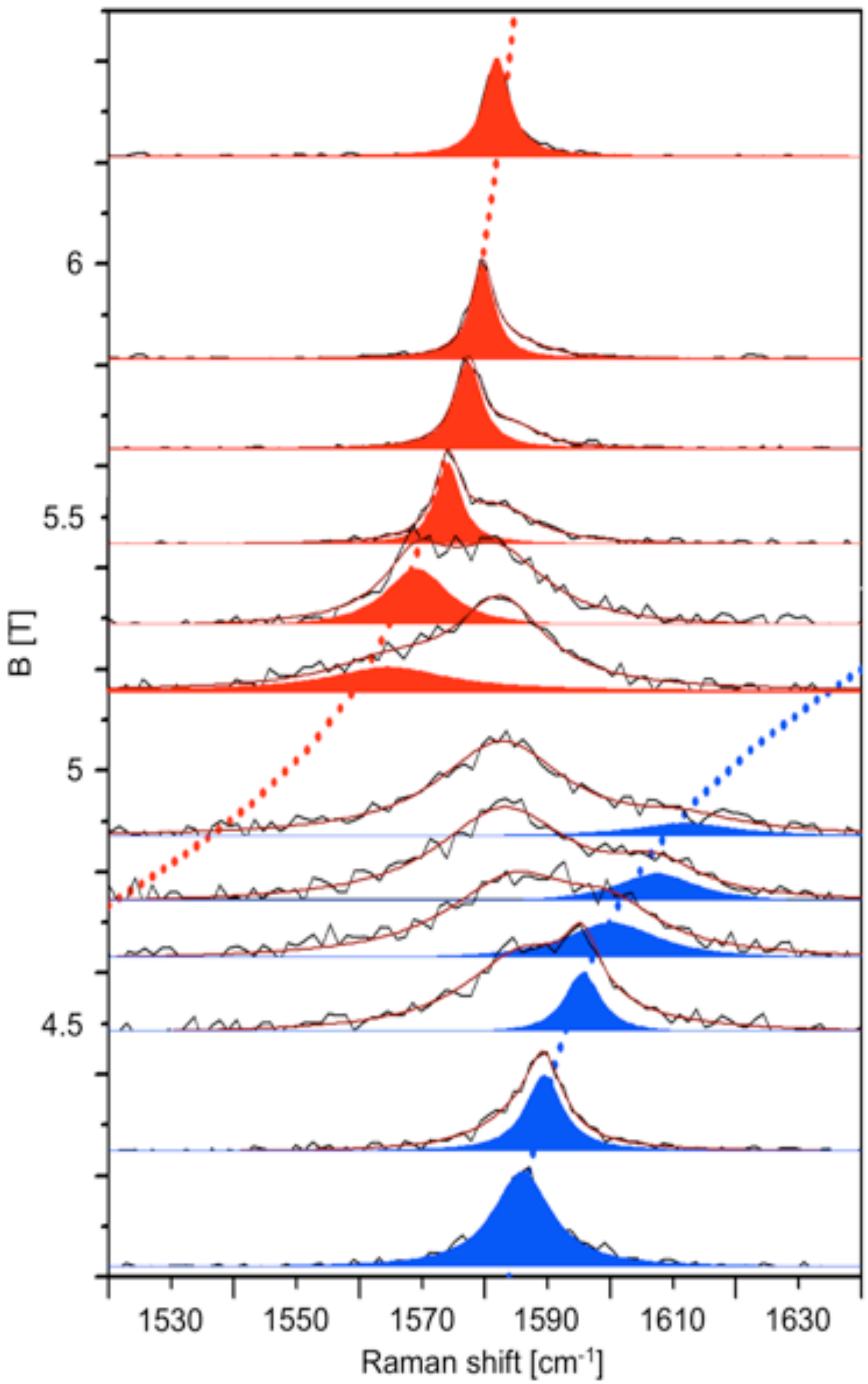
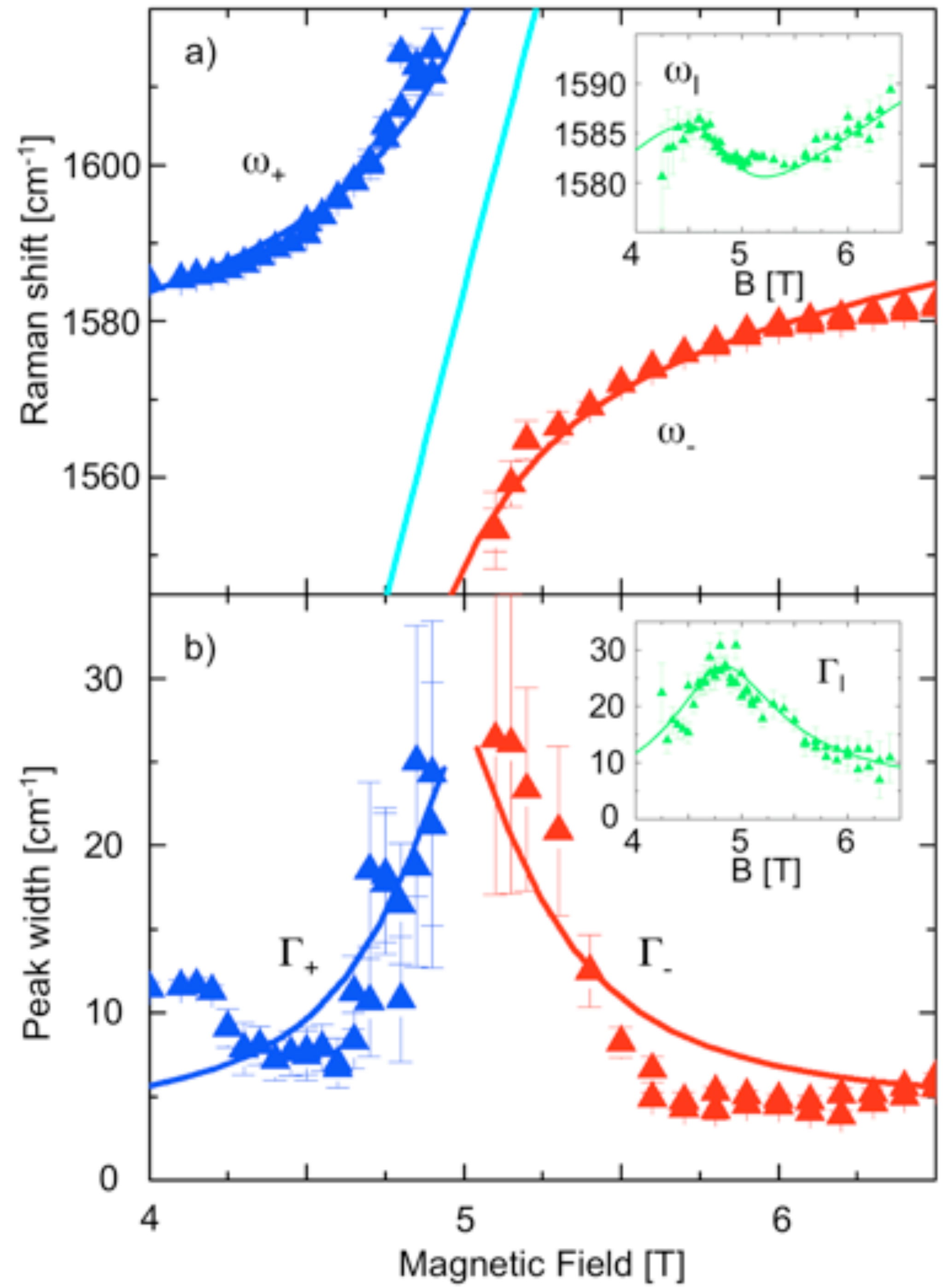
Manifestations of Dirac fermions: Magneto-phonon resonance



Manifestations of Dirac fermions:
Magneto-phonon resonance





J. Yan, VP et al. Phys. Rev. Lett. (2010)

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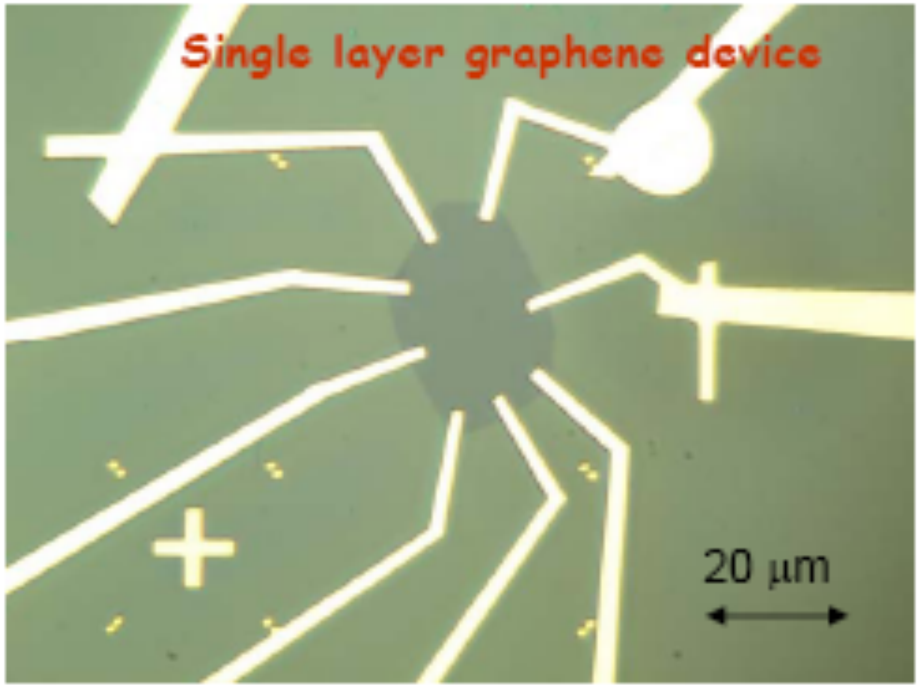
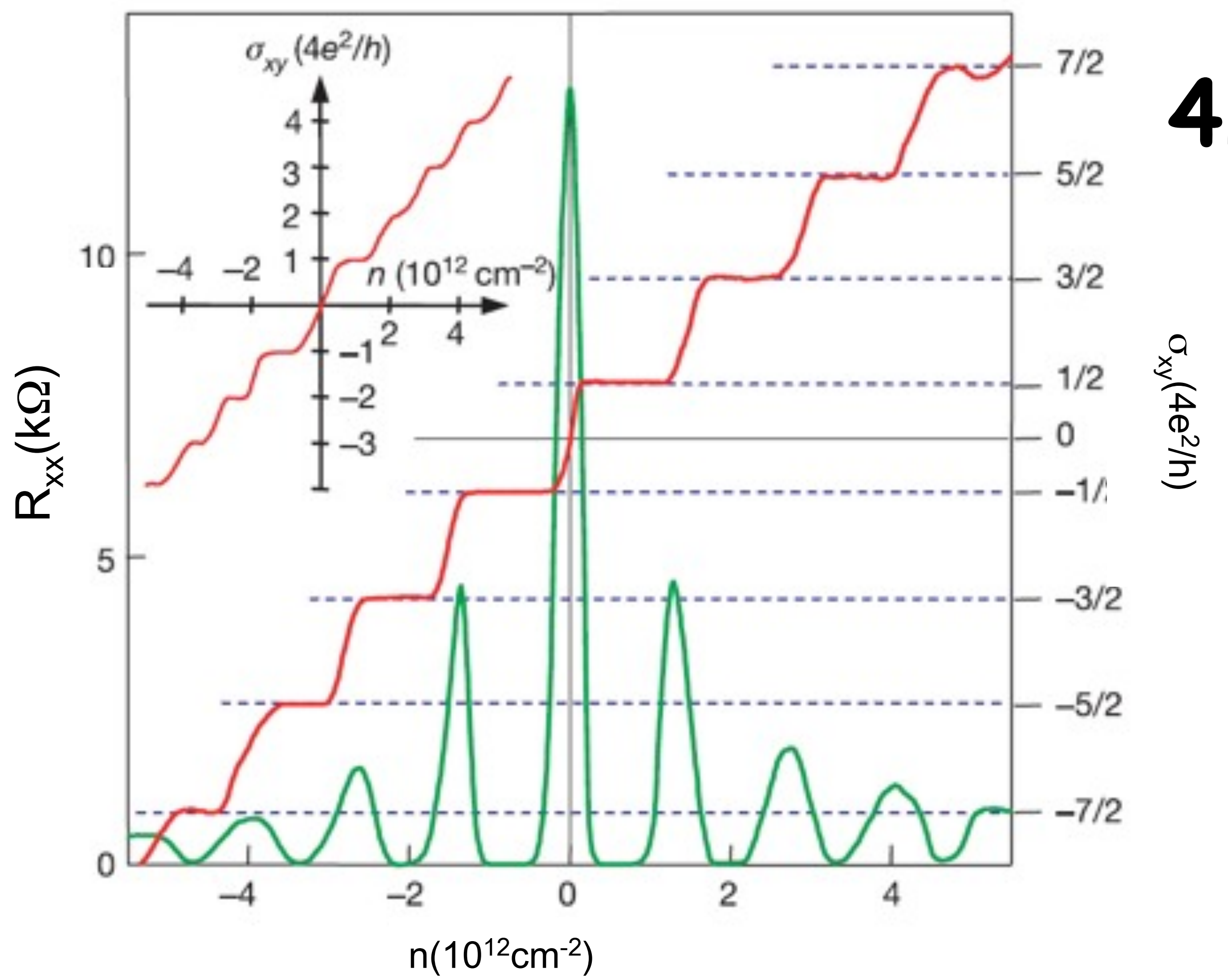
Manifestations of Dirac fermions: Half-integer QHE



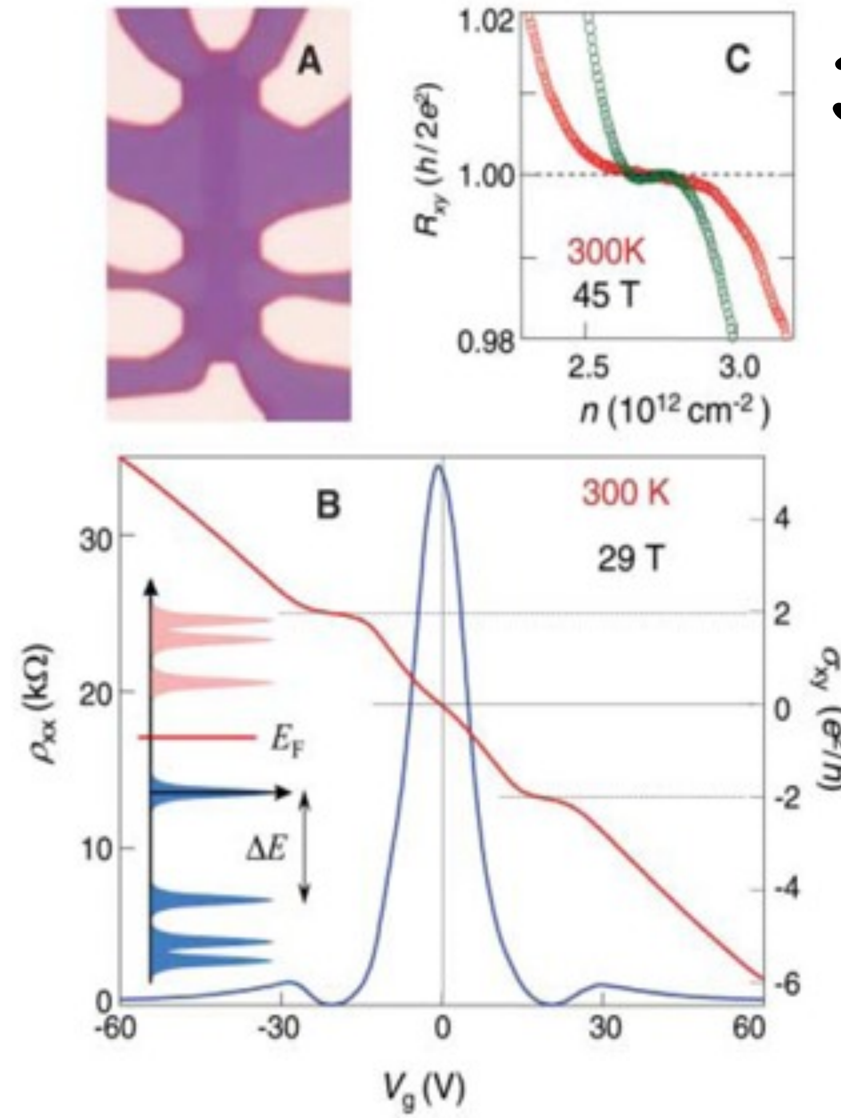
Novoselov, et al – Nature **438**, 197 (2005)

Zhang, et al – Nature **438**, 201 (2005)



4K

$V_g>0$

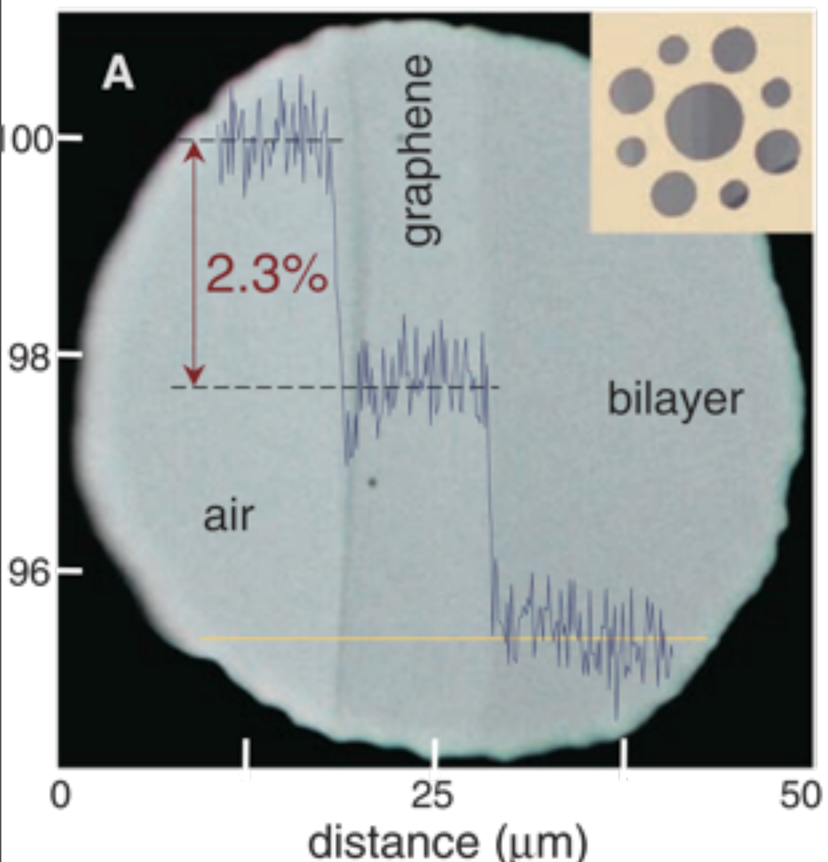


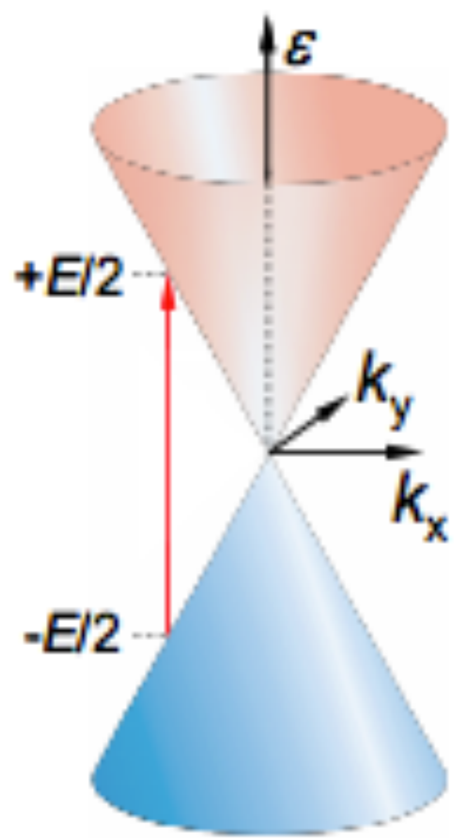
300K

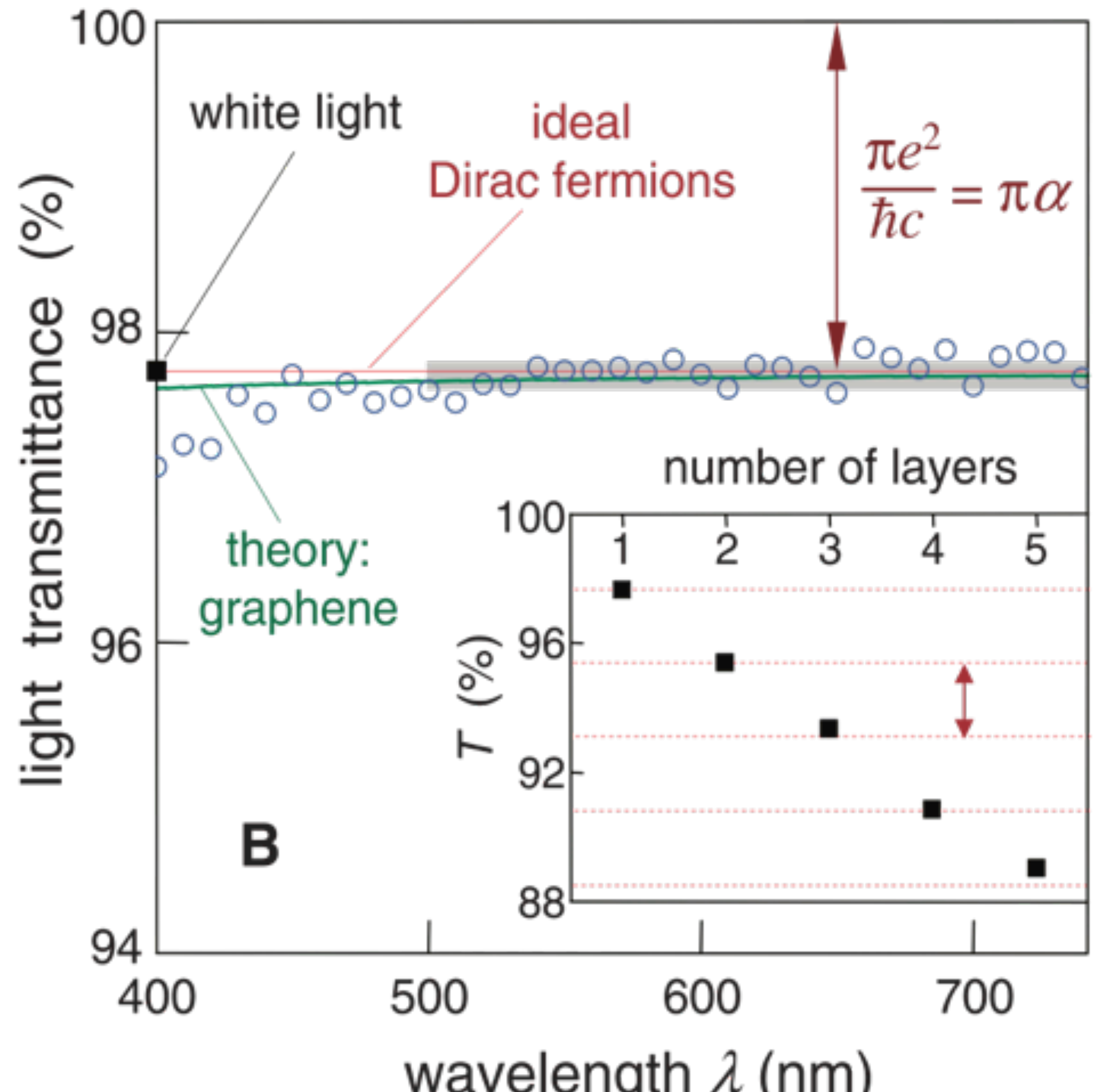
Novoselov, et al – Science **315**, 1379 (2007)

Manifestations of Dirac fermions: absorption determined by fine structure constant

Nair, et al – Science (2008)







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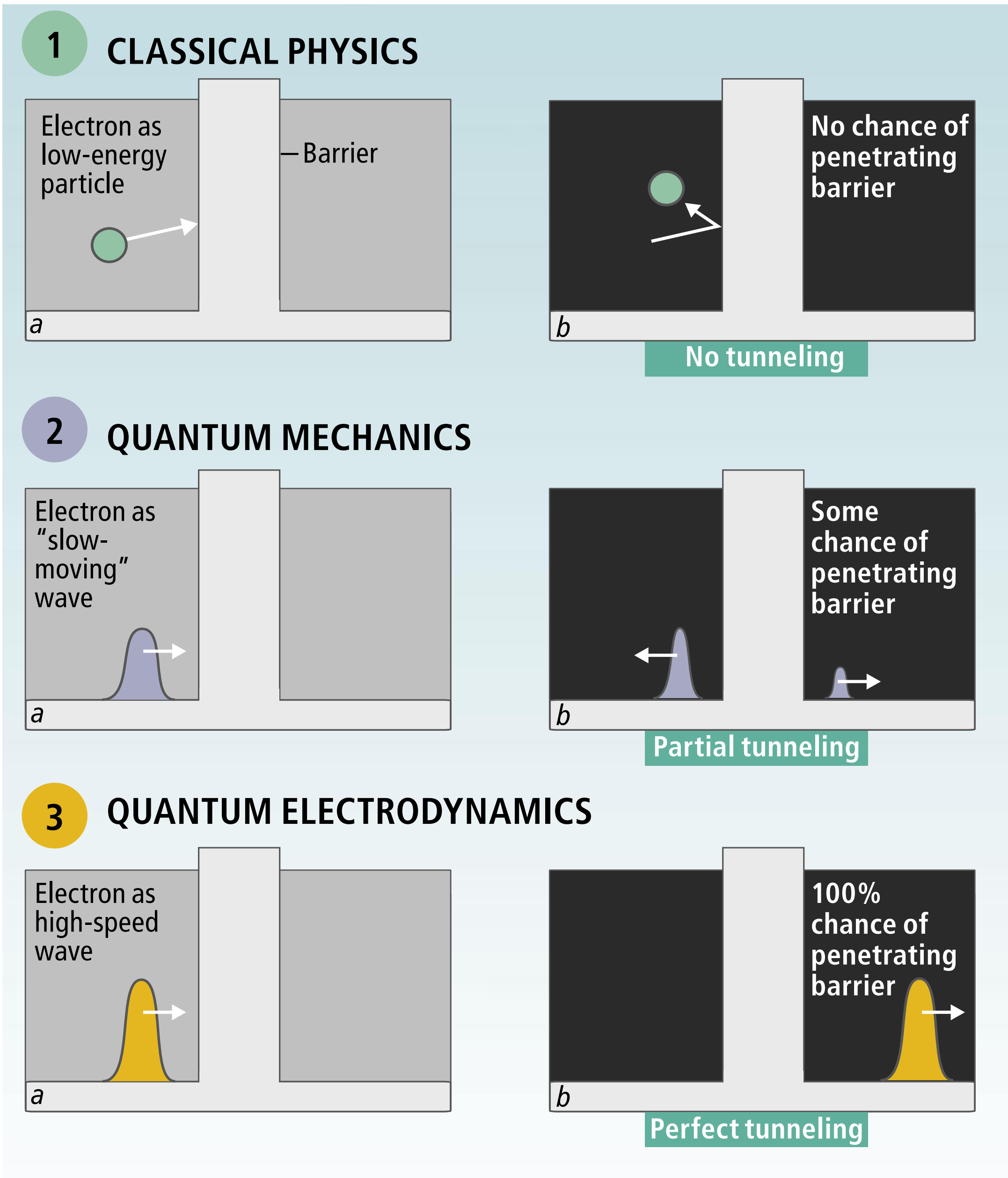
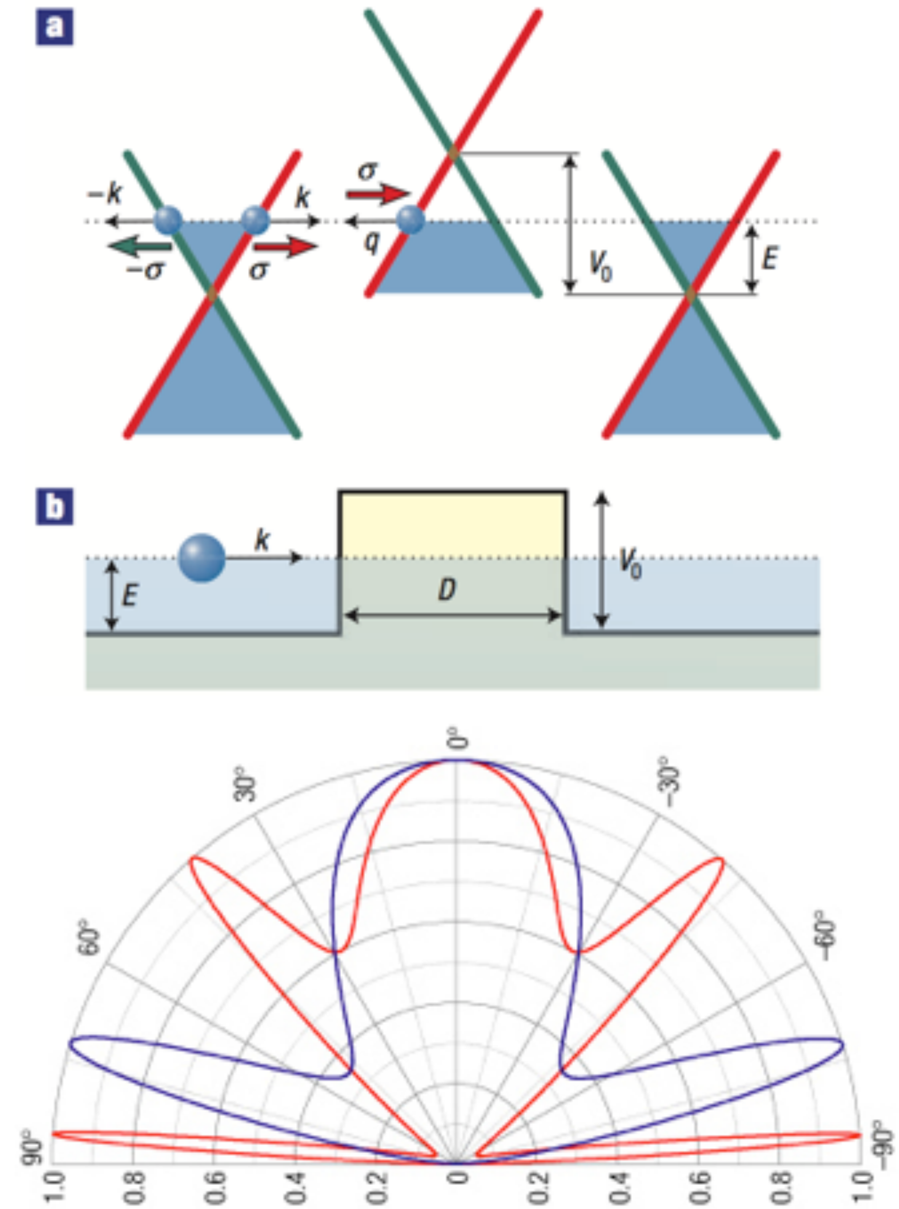
Manifestations of Dirac fermions: Klein paradox





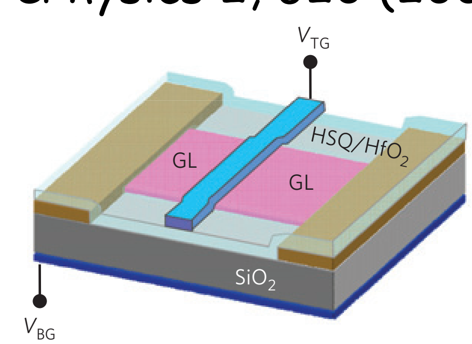
Transmission rate T against incident angle; E = 80 meV, D = 100 nm, V0 = 200 meV (red curve), V0 = 285 meV (blue curve)

M.I.Katsnelson,K.S.Novoselov,A.K.Geim, NaturePhysics 2, 620 (2006)

Observed in 2009:

A.F. Young, P. Kim Nature Physics (2009)

N. Stadler et al., PRL (2009)



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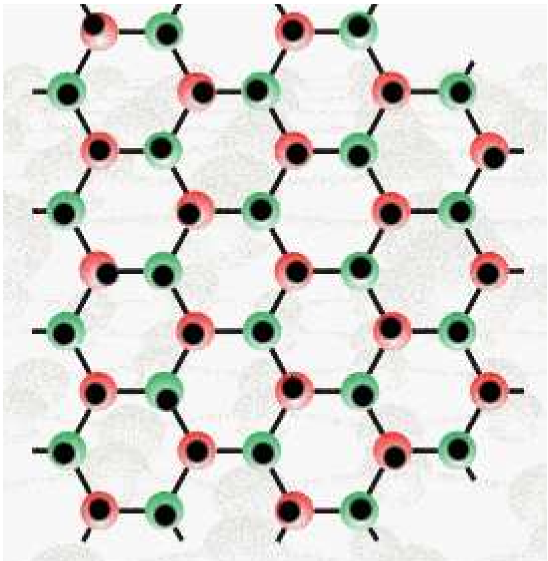
Role of Coulomb interactions

Chiral Symmetry breaking

In particle physics, strong nuclear interactions (QCD):

- break approximate chiral symmetry
- Quarks get mass,
- Pions are the (pseudo-) Goldstone bosons.
- Could this happen in graphene?

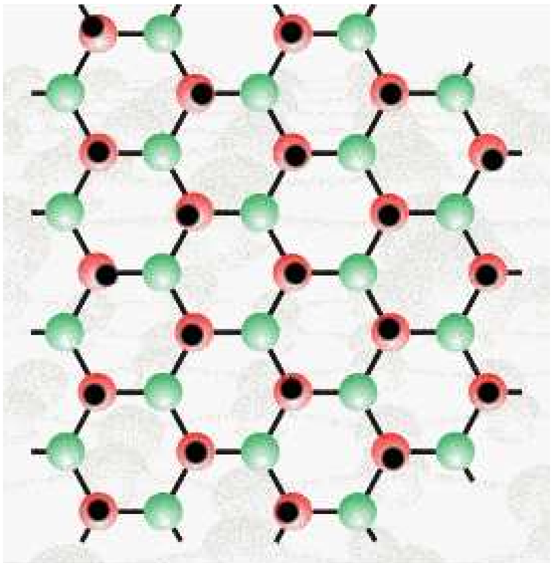


Hubbard model with 1/2 filling

$$H = t\sum_{A,b_i}\left(\psi^\dagger_{A+b_i}\psi_A + \psi^\dagger_A\psi_{A+b_i}\right) + U\sum_{n\in A,B}\left(\sum_{\sigma=\uparrow\downarrow}\psi^\dagger_{\sigma n}\psi_{\sigma n} - 1\right)^2$$

$$U \approx 10ev$$

$$H_{\rm Coul} = \frac{1}{2}\sum_{xy}\left(\psi^\dagger(x)\psi(x) - \frac{1}{2}\right)\frac{e^2}{4\pi|x-y|}\left(\psi^\dagger(y)\psi(y) - \frac{1}{2}\right)$$



Gusynin et.al. PRL., 73 (1994) 3499; Phys.Rev..D, 52 (1995) 4718; Phys.Rev.B, 74 (2006) 195429

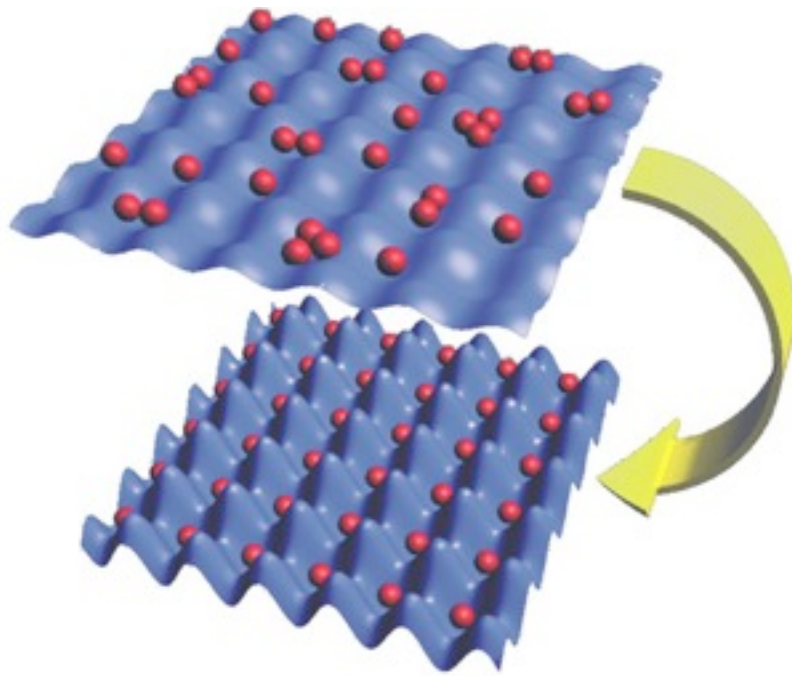
Khveshchenko PRL., 87 (2001) 206401; 87 (2001) 246802;

Khveshchenko and Leal , Nuc.Phys. 687 (2004) 323.

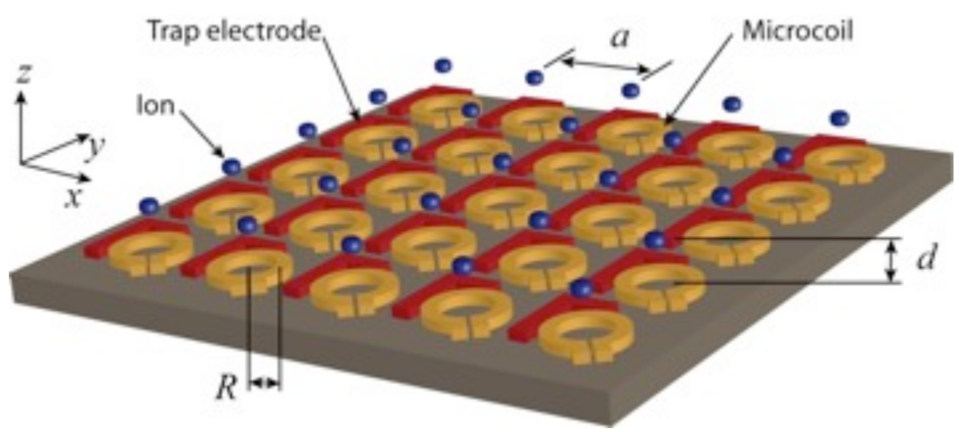
Herbut, PRL., 97 (2006) 146401; Phys.Rev.B, 75 (2007) 165411; 76 (2007) 085432

Proposals and experiments of quantum simulations

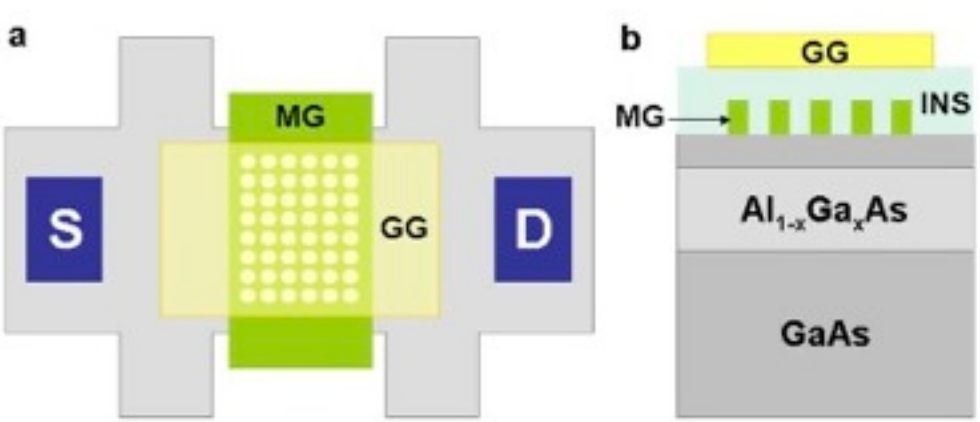
Quantum phase transitions with cold atoms
M. Greiner et al. Nature. 4, 757 (2002)
G-B Jo et al, Science 325 1521 (2009)
LENS Firenze



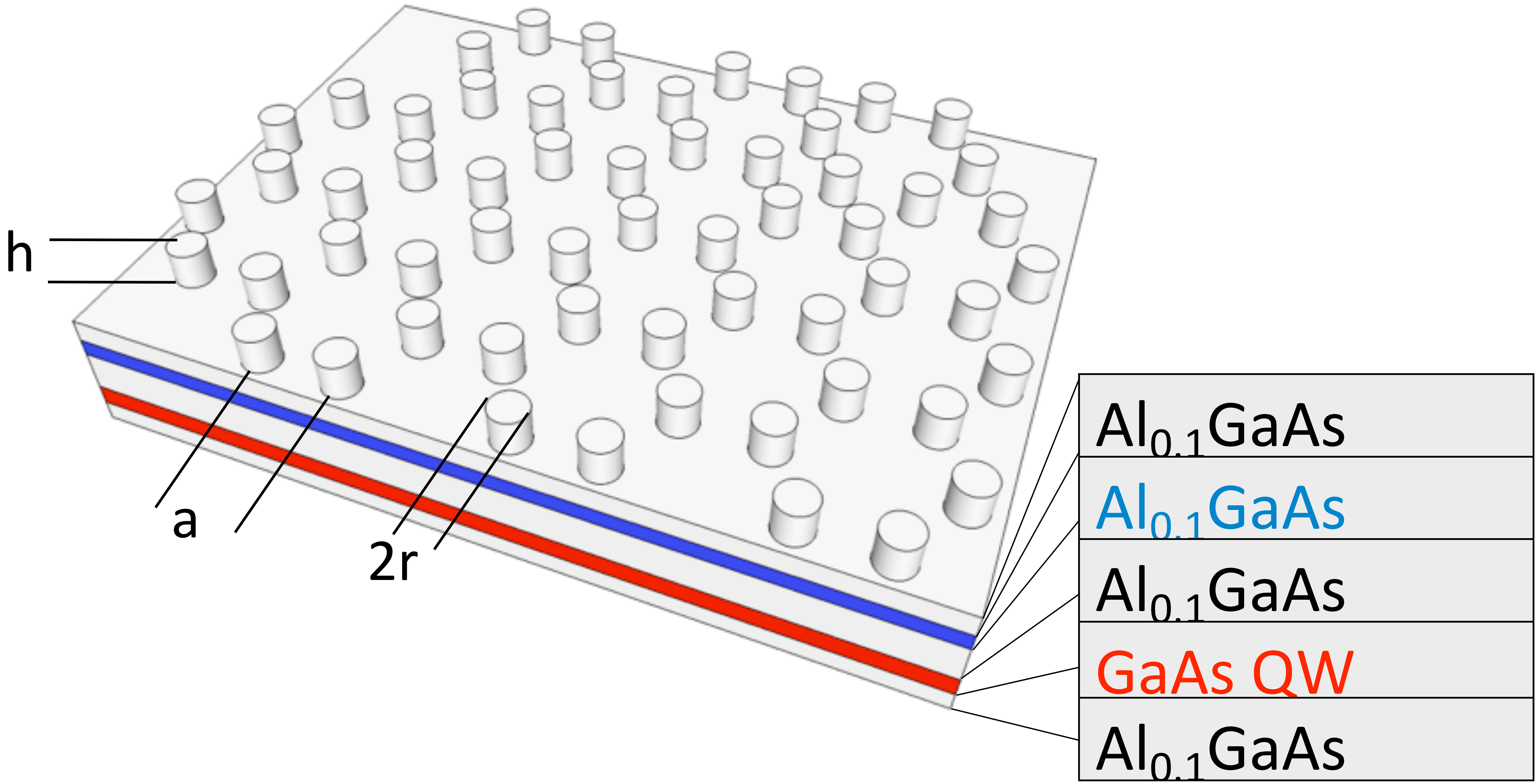
Quantum magnetisms with trapped ions
A. Friedenauer et al. Nat. Phys. 4, 757 (2008)

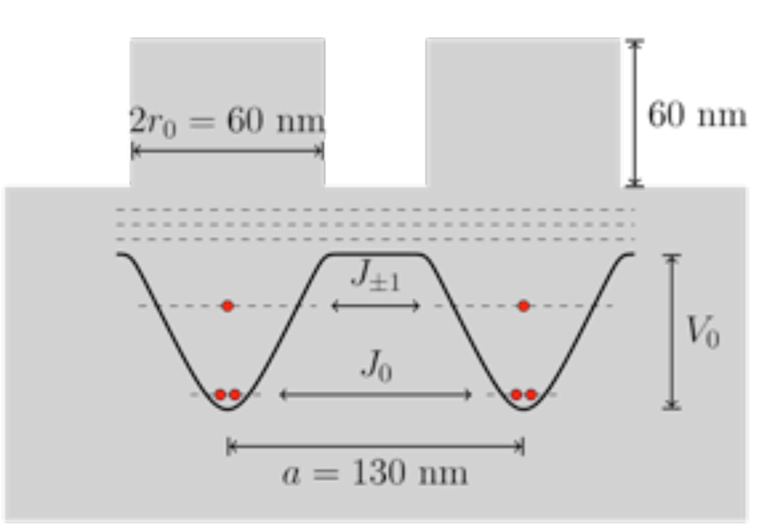


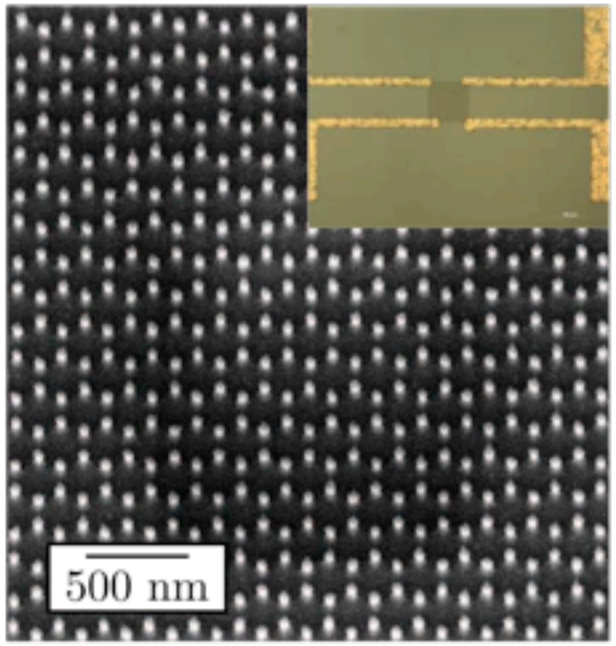
Hubbard models in quantum-dot arrays
T. Byrnes et al., Phys. Rev. Lett. 99, 016405 (2007)
T. Byrnes et al., Phys. Rev. B 78, 075320 (2008)



Artificial lattices in quantum semiconductor structures

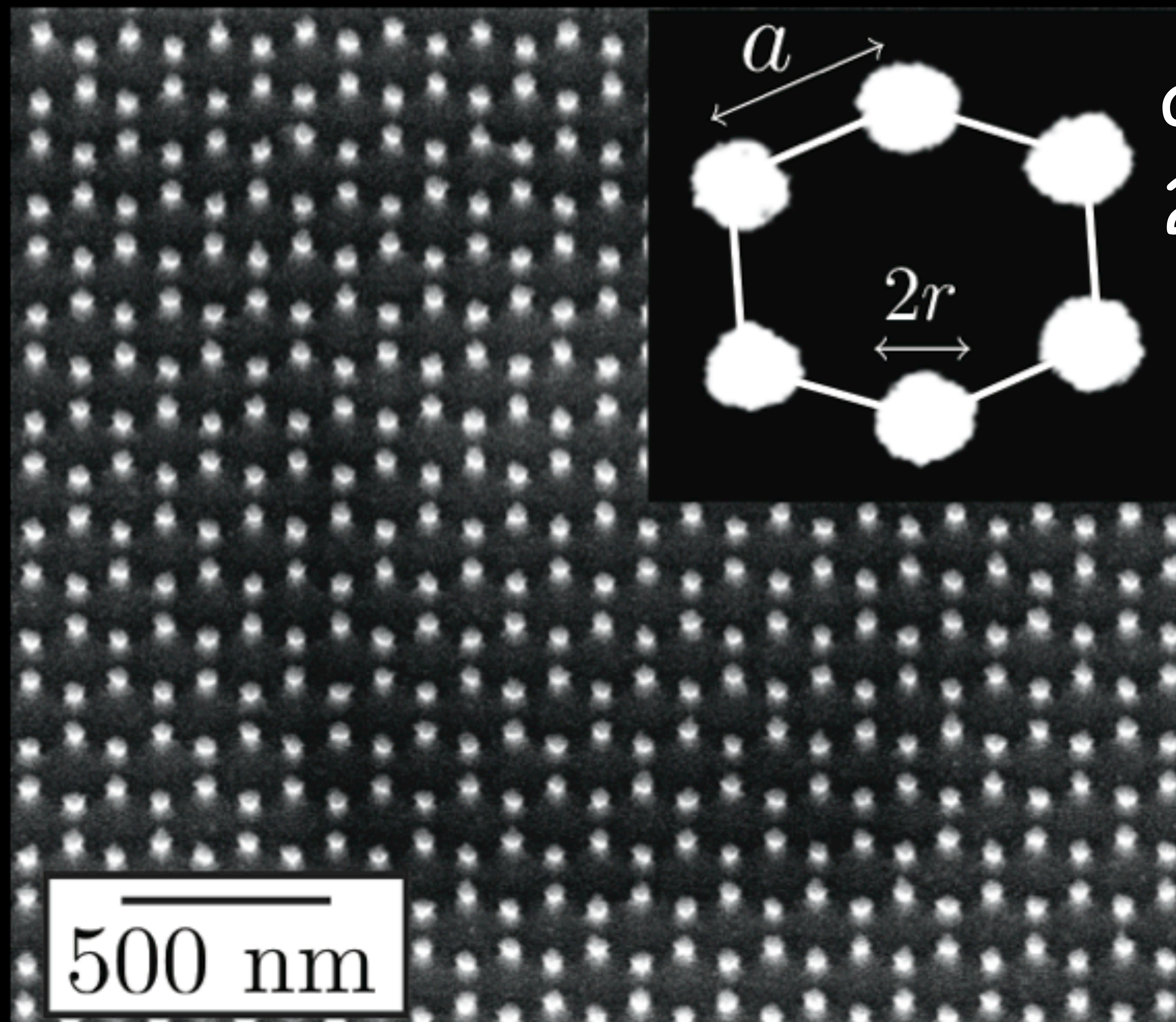






M. Gibertini, VP et al
Phys Rev B RC (2009)
Appl. Phys.Lett. (2010)

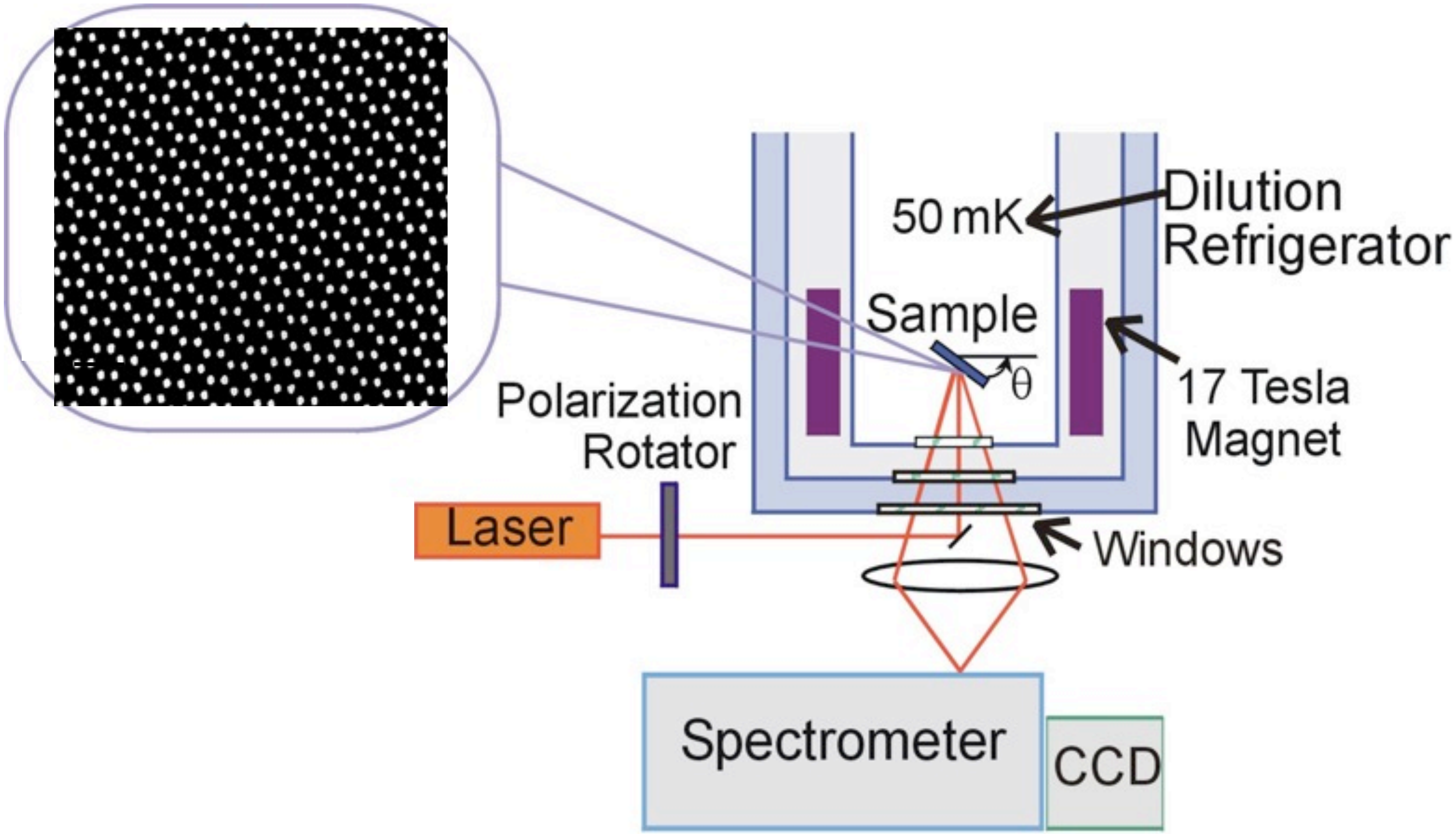
Honeycomb lattice: a quantum simulator for flavor-spin order



a = 130 nm
2r = 60 nm

M. Gibertini et al., PRB 79, 241406(R) (2009)

Resonant inelastic light scattering

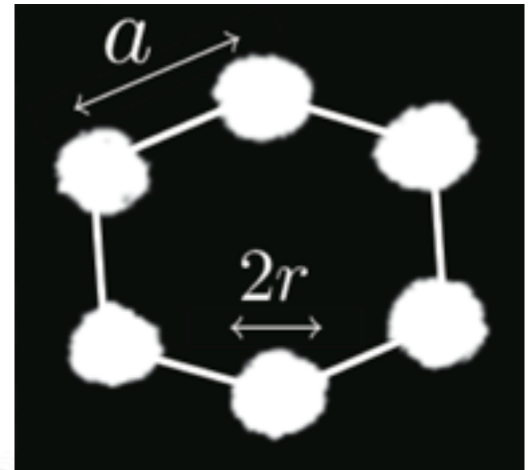


$$\omega_L - \omega_S = \pm\omega(q) \qquad q = |\mathbf{k}_{//}|$$

Translational invariance $\qquad \mathbf{q} = \mathbf{k}_{L//} - \mathbf{k}_{S//} = (k_L - k_S)\sin\theta < \sim 10^5 \mathrm{cm}^{-1}$

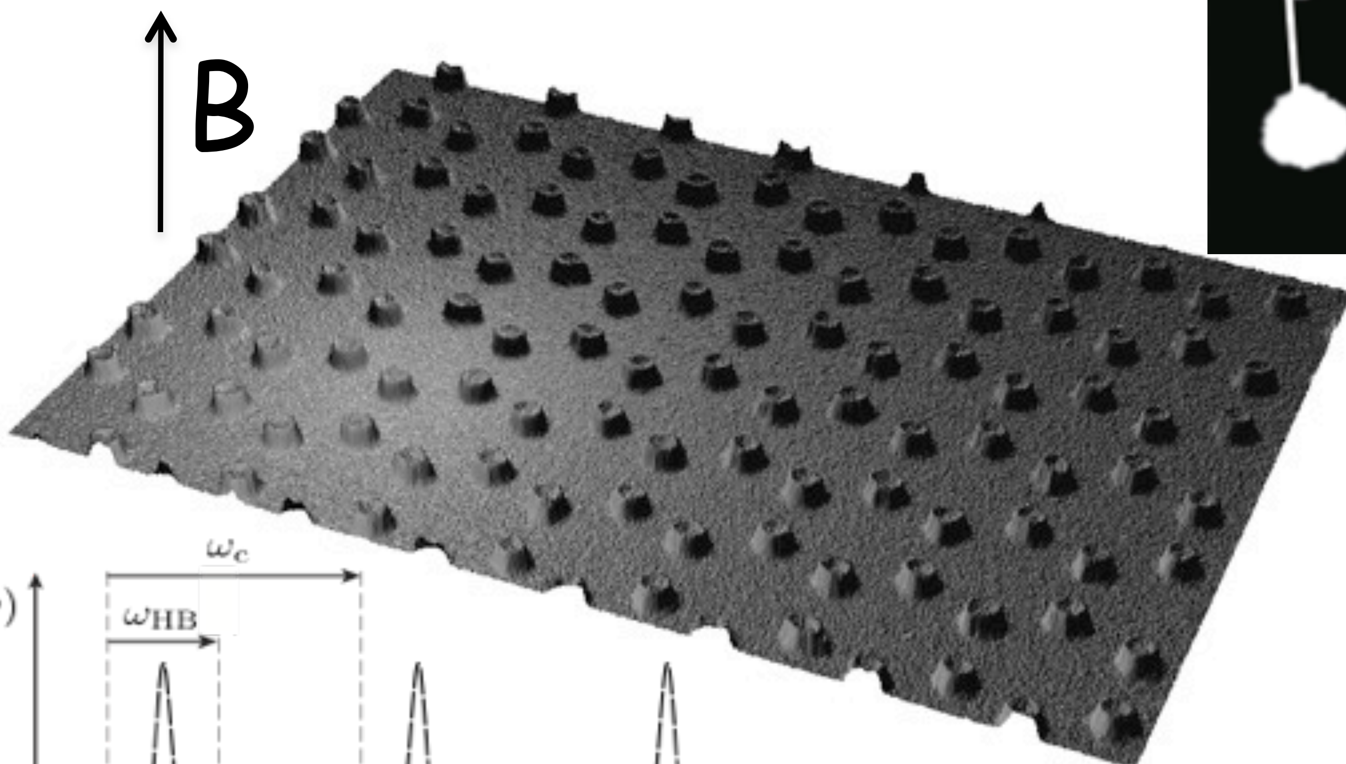
V. Pellegrini, A. Pinczuk Phys. Stat. Sol. (b) **243**, 3617 (2006)

Electrons in Artificial lattices

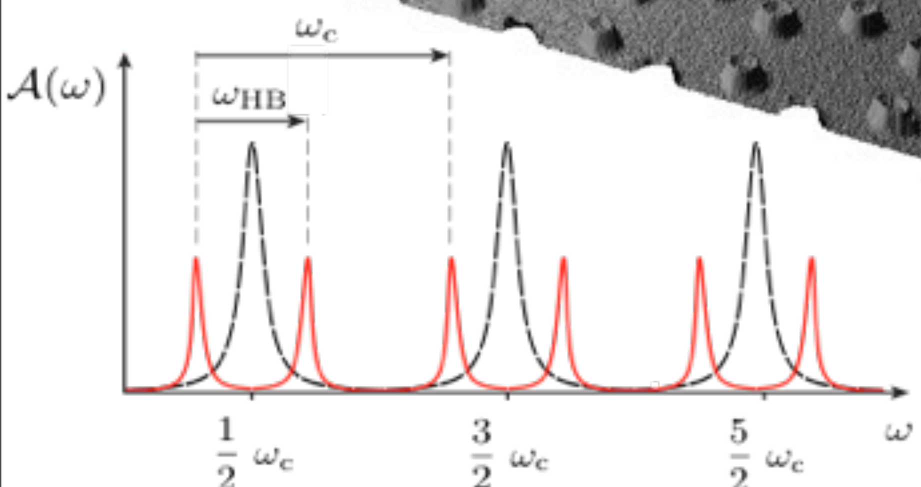


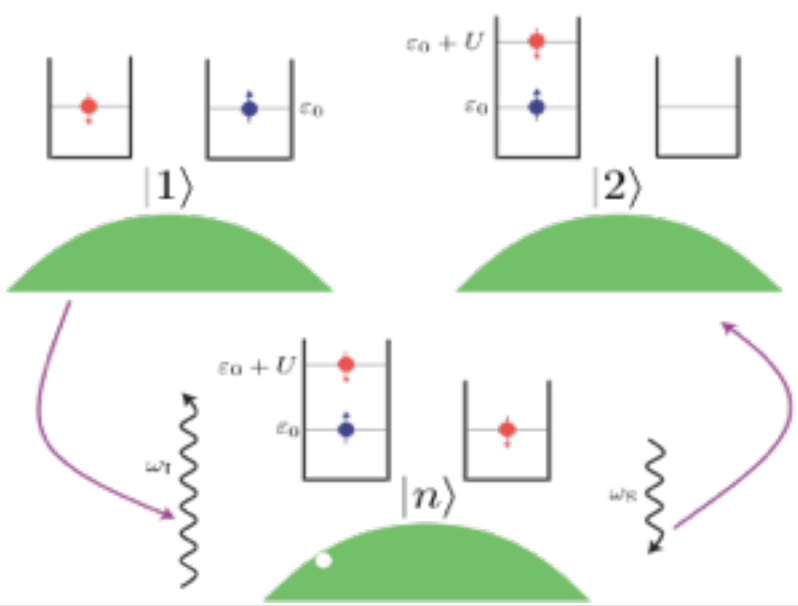
a= 130nm

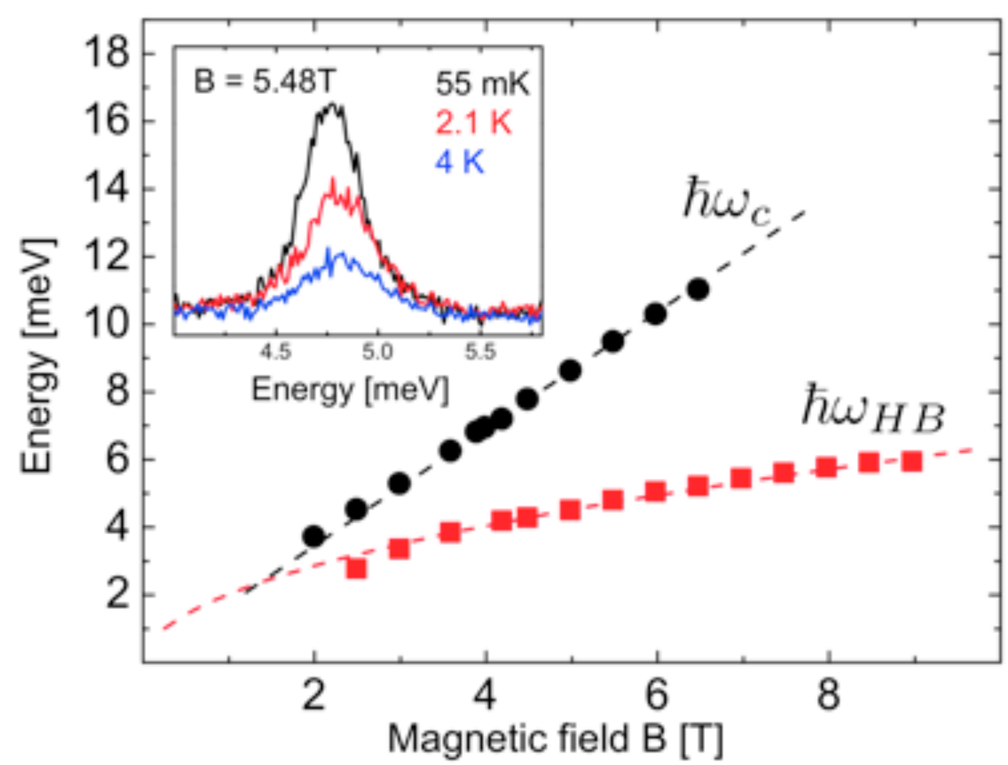
Hubbard Physics



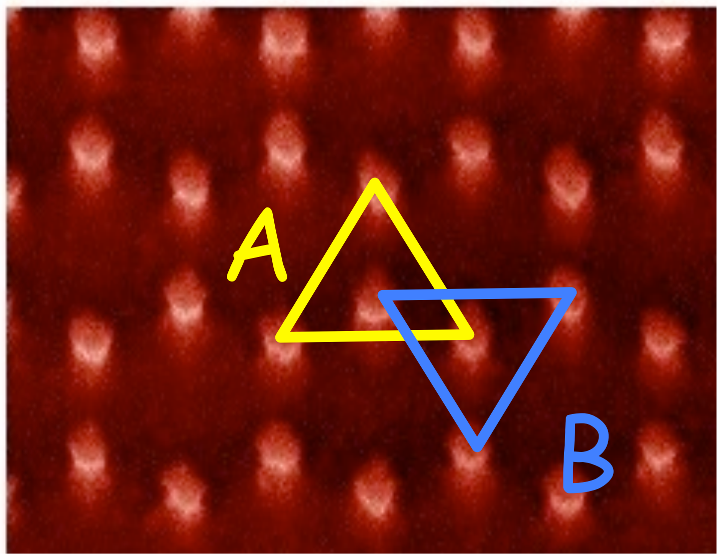
A. Singha, VP et al
submitted







Sub-lattice degeneracy → Flavor degree of freedom

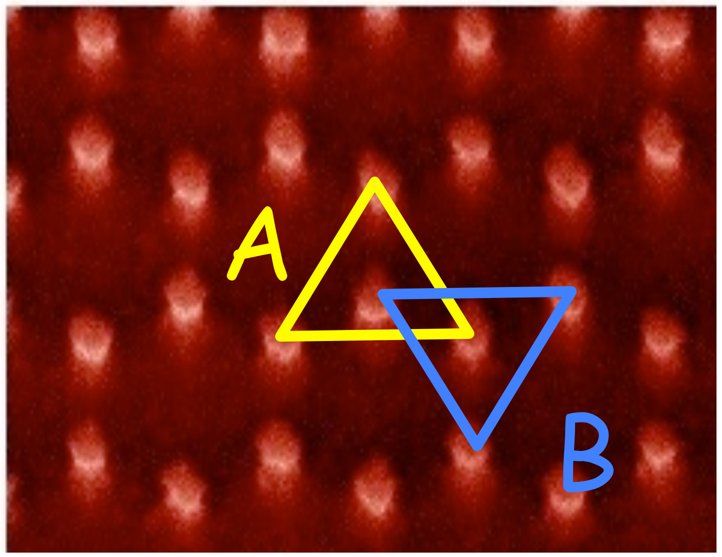


$$E_{SW} = g\mu_B B$$

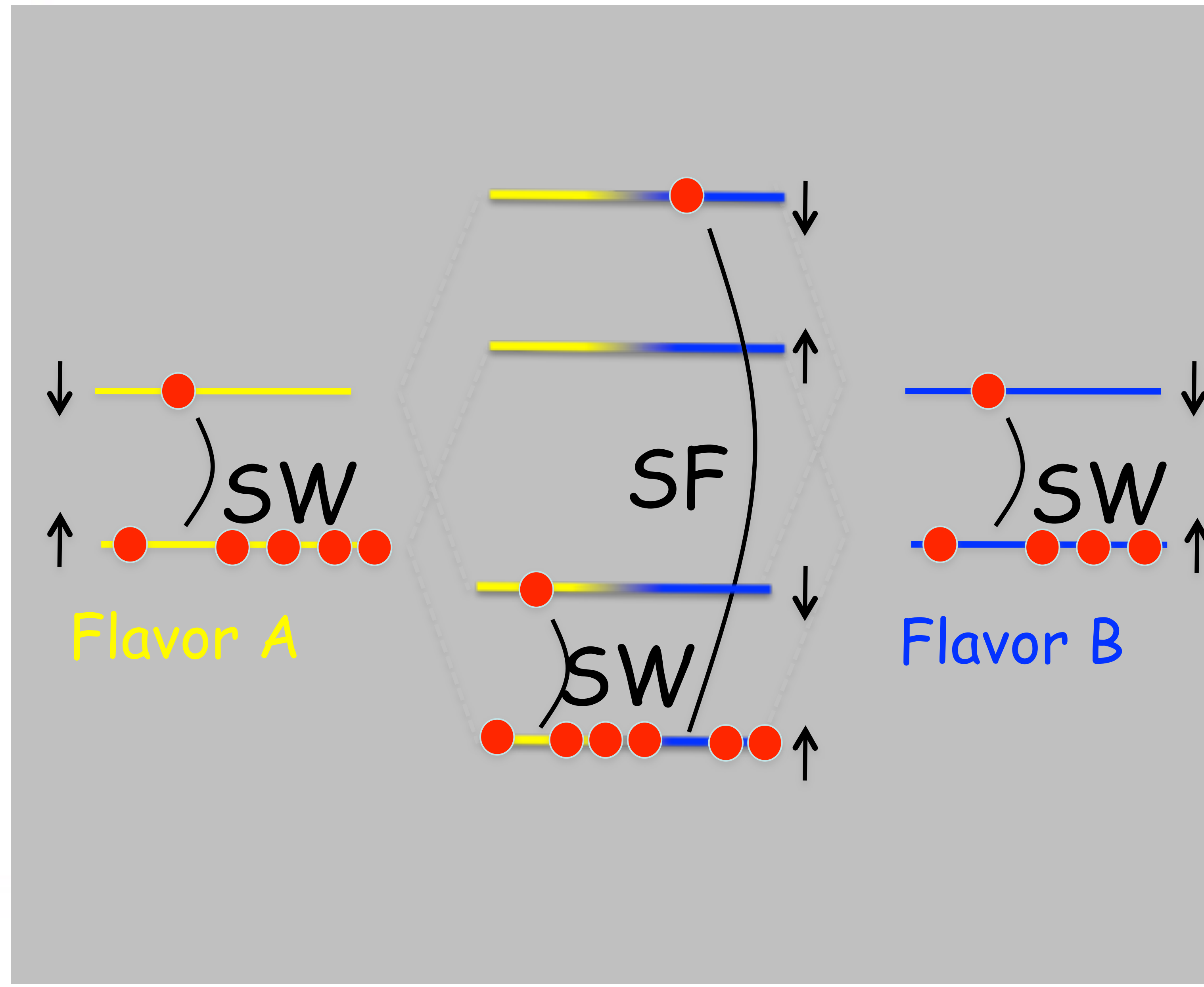
Similar phenomena predicted for graphene at high fields

J. Alicea, M.P. Fisher Physical Review B 74, 075422 (2006)

Sub-lattice degeneracy → Flavor degree of freedom



$E_{SW} = g\mu_B B$ $E_{SF} = g\mu_B B + \Delta$



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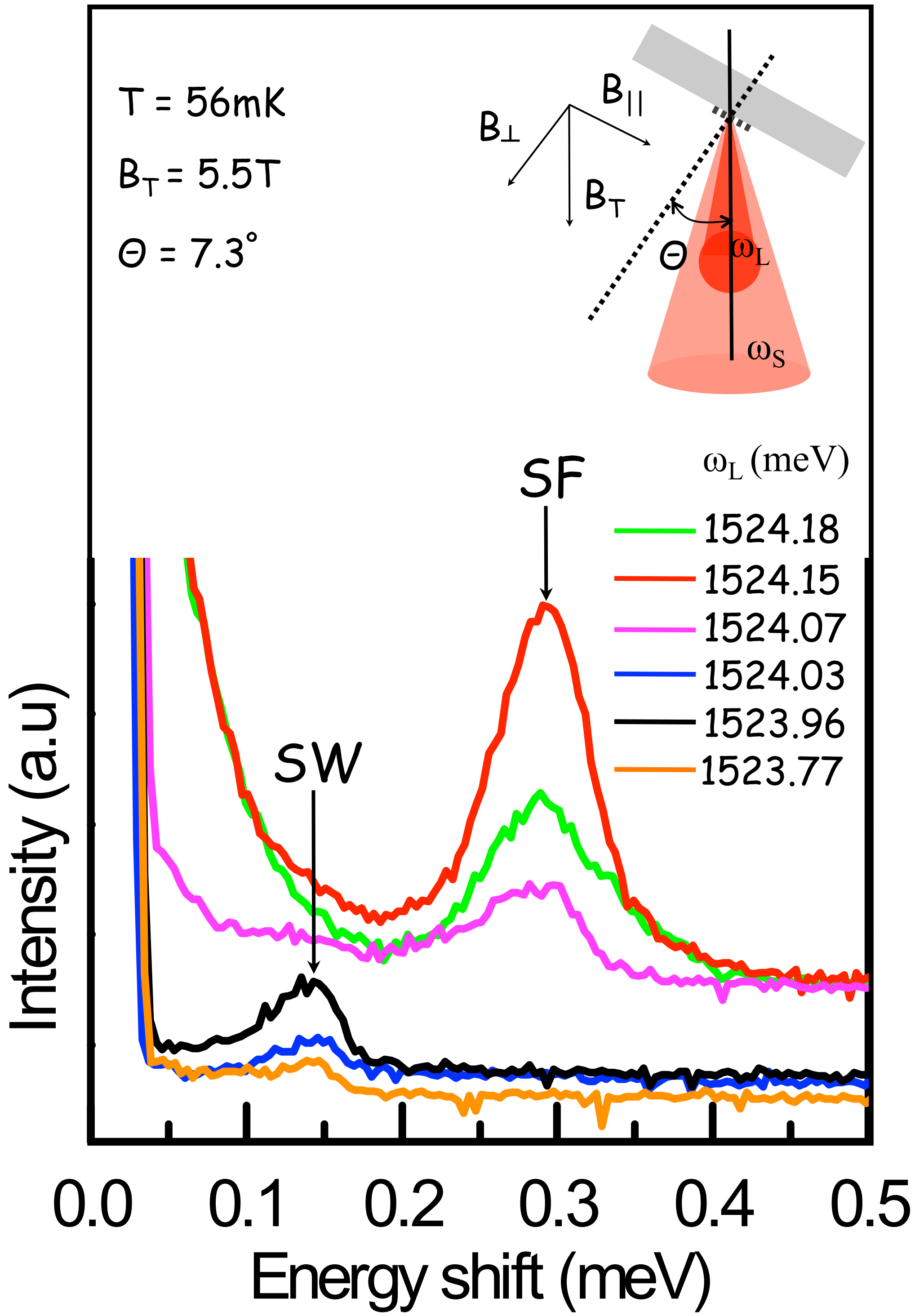
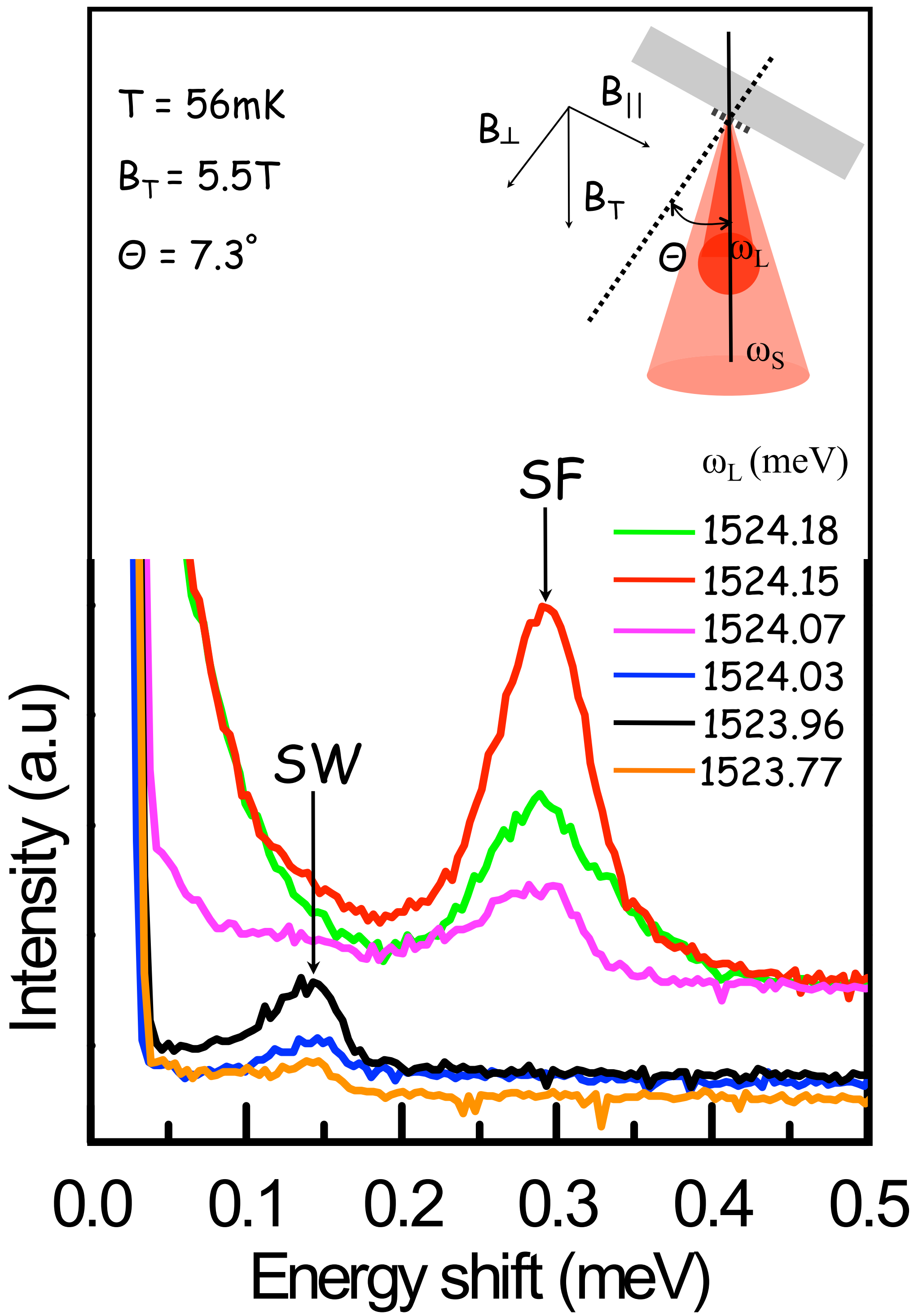
Spin-flavor modes



$$E_{SW} = g\mu_B B$$

In-phase spin mode
between the two sublattices

Spin-flavor modes



$E_{SW} = g\mu_B B$

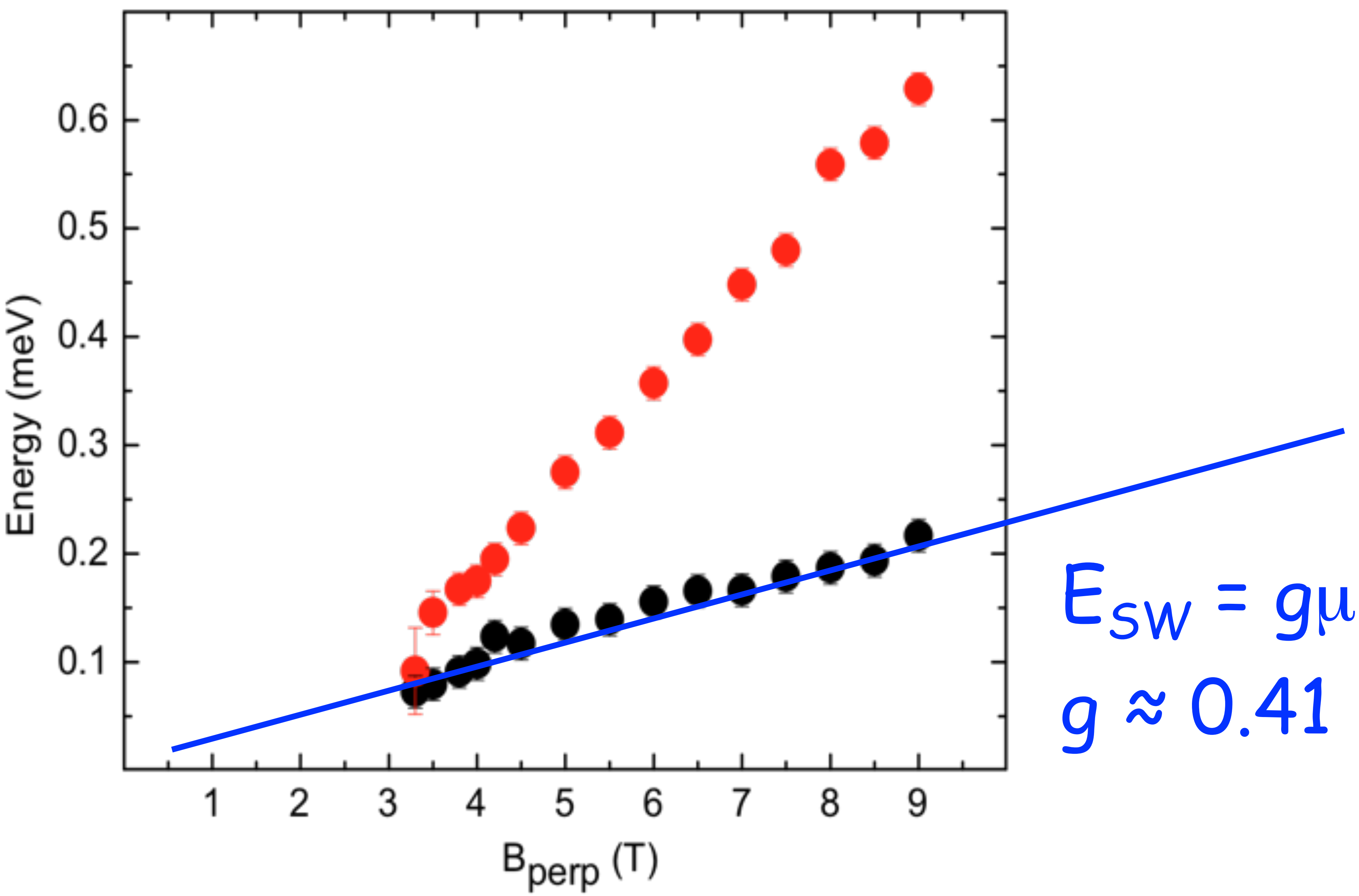
In-phase spin mode
between the two sublattices

$E_{SF} = g\mu_B B + \Delta$

Out-of-phase spin mode
between the two sublattices

Spin-flavor modes

T= 50mK



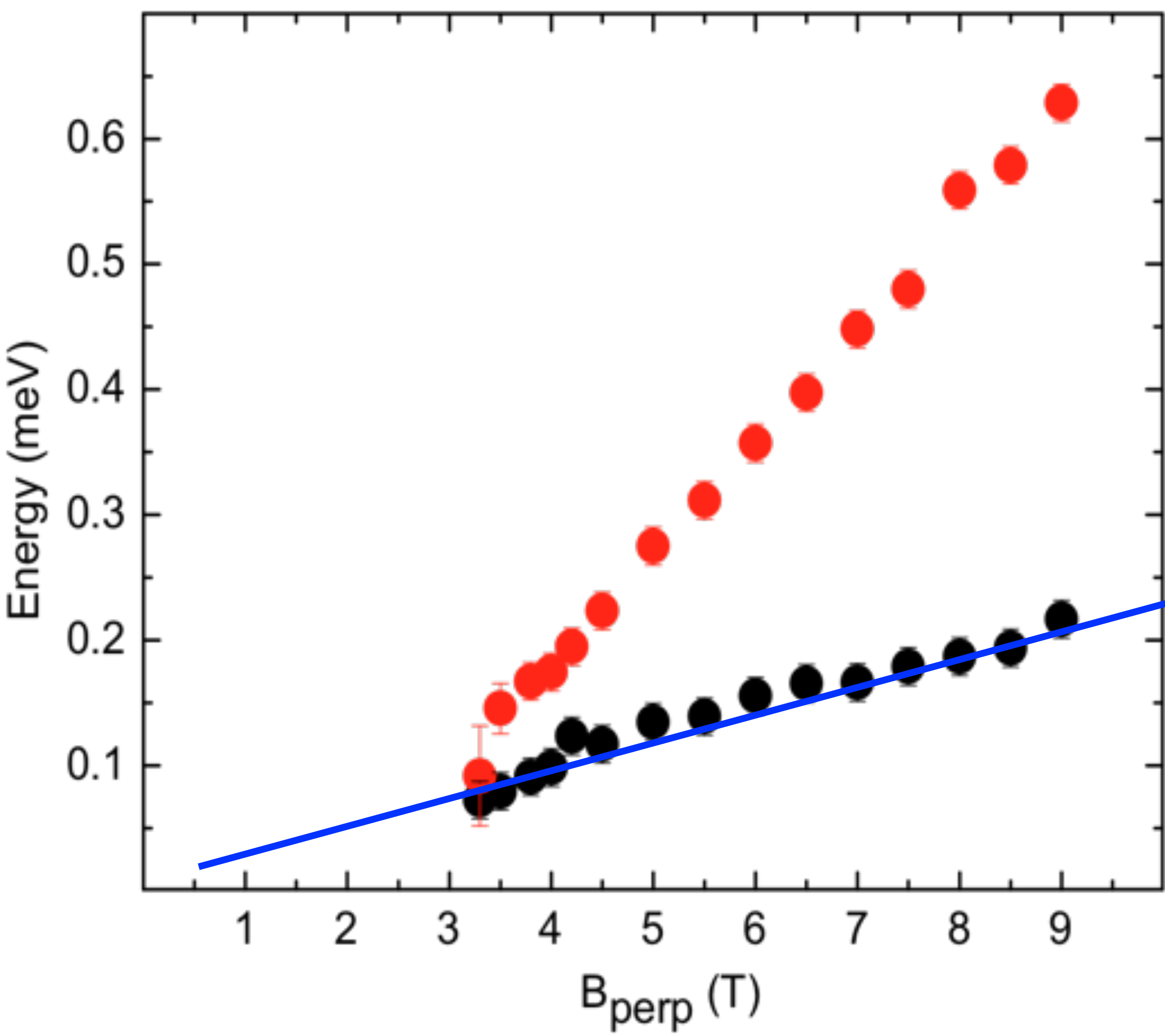
$E_{SW} = g\mu_B B$

$g \approx 0.41$

Spin-flavor modes

T= 50mK

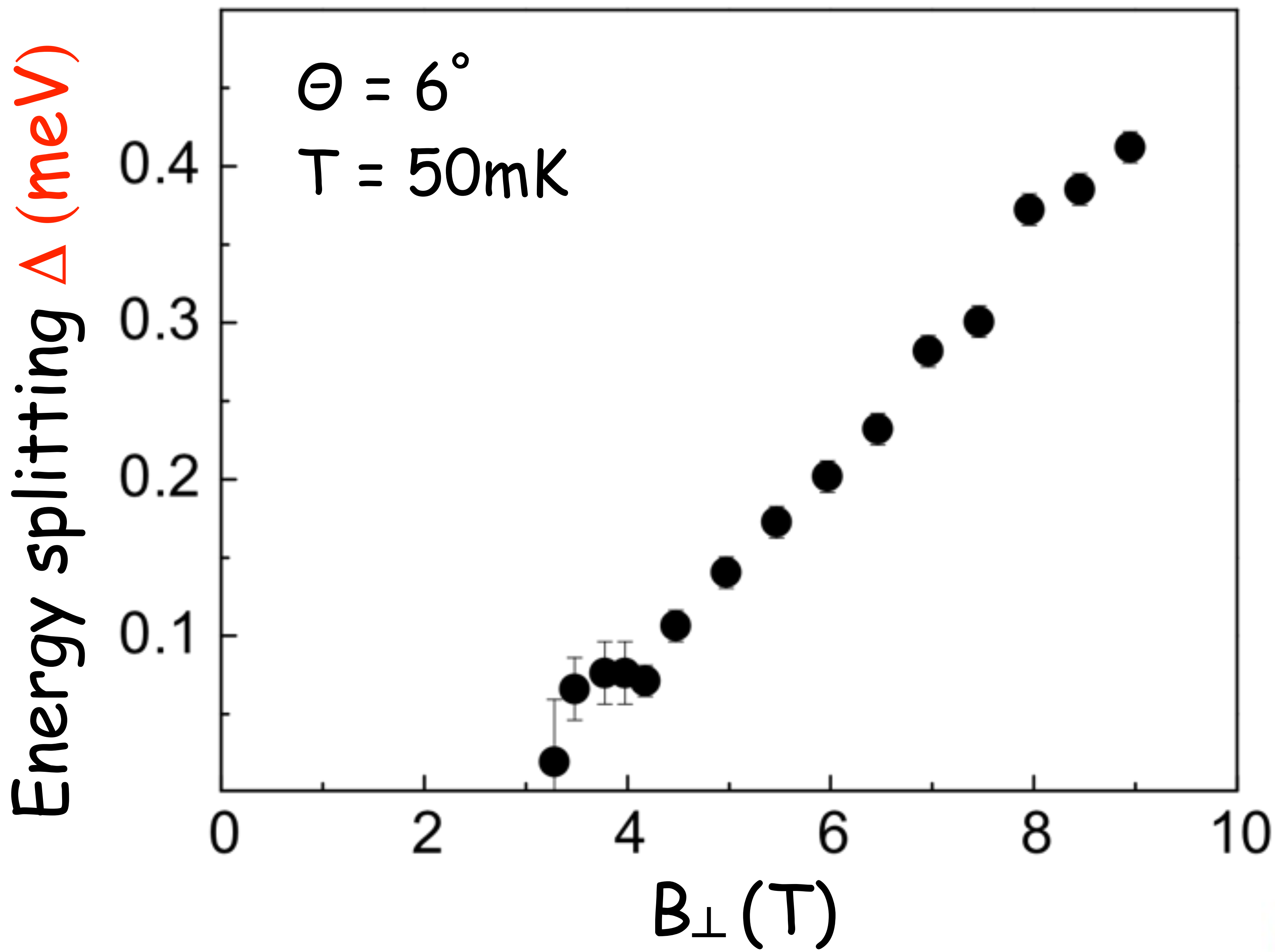
$E_{SF} = g\mu_B B + \Delta$



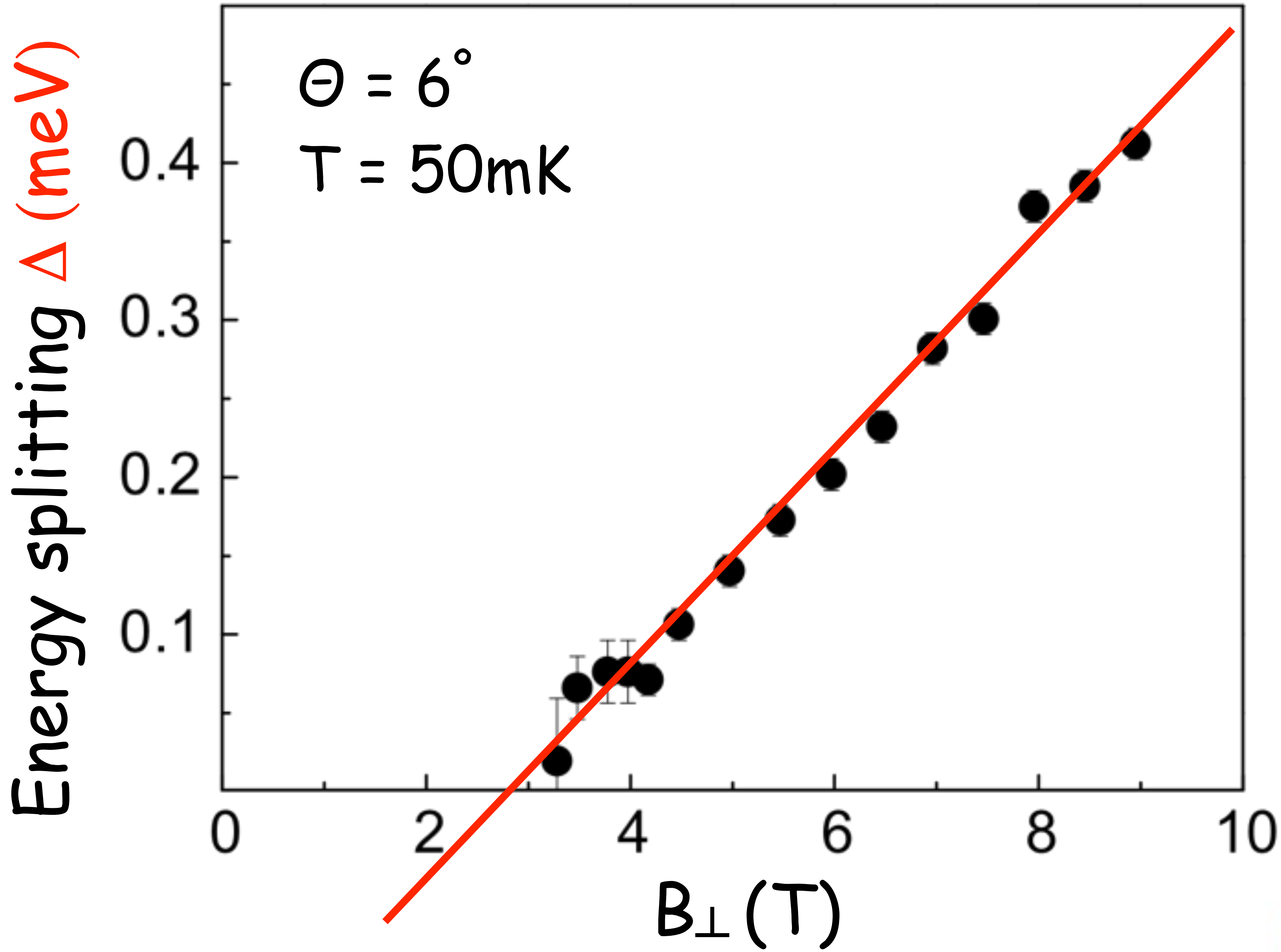
$E_{SW} = g\mu_B B$

$g \approx 0.41$

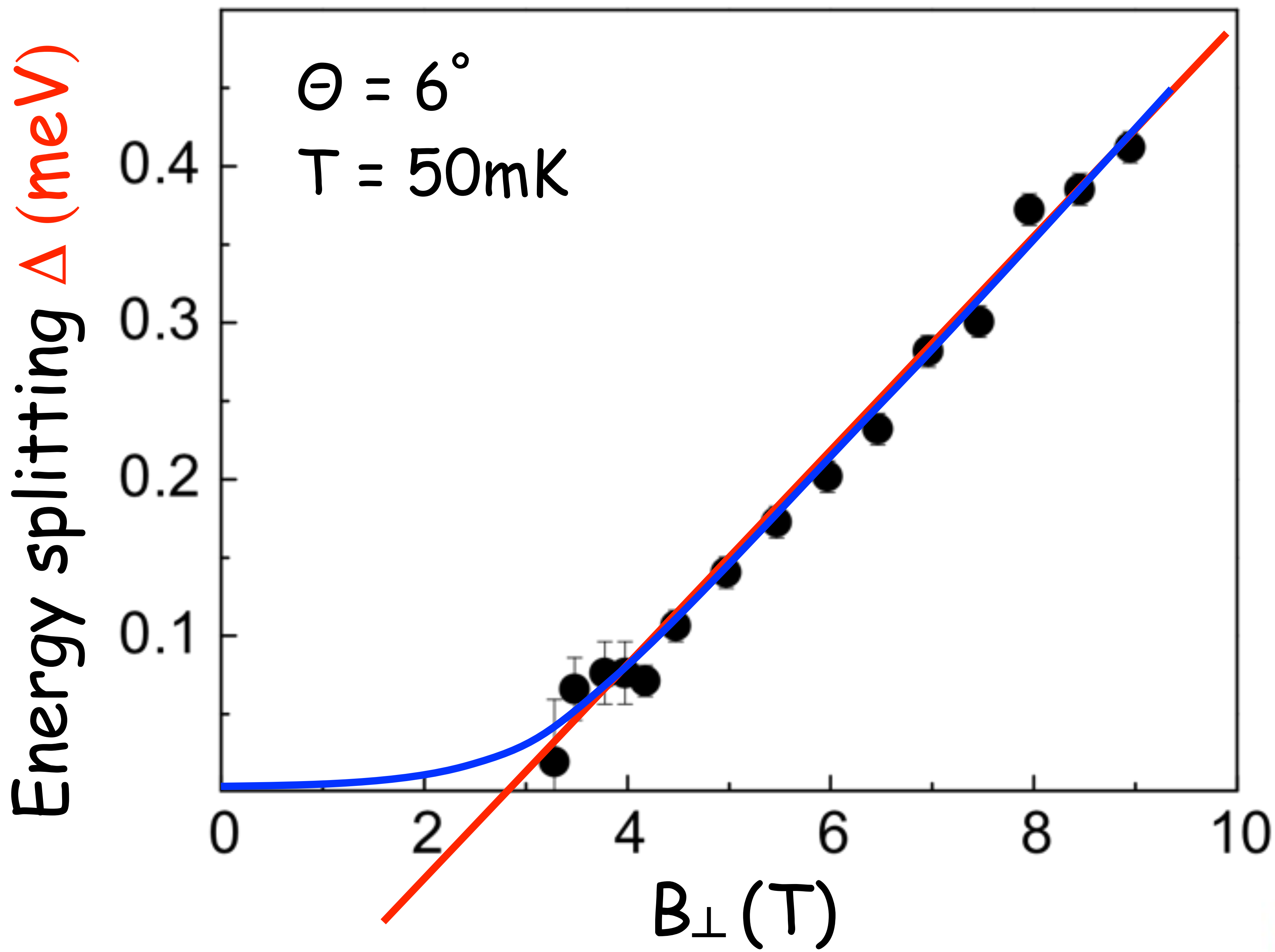
Spontaneous symmetry breaking → lattice scale order (CDW) ?



Spontaneous symmetry breaking → lattice scale order (CDW) ?

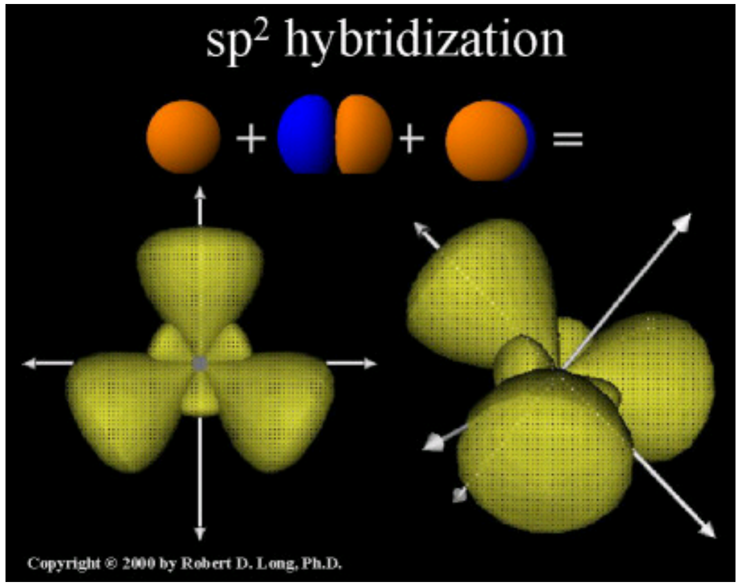


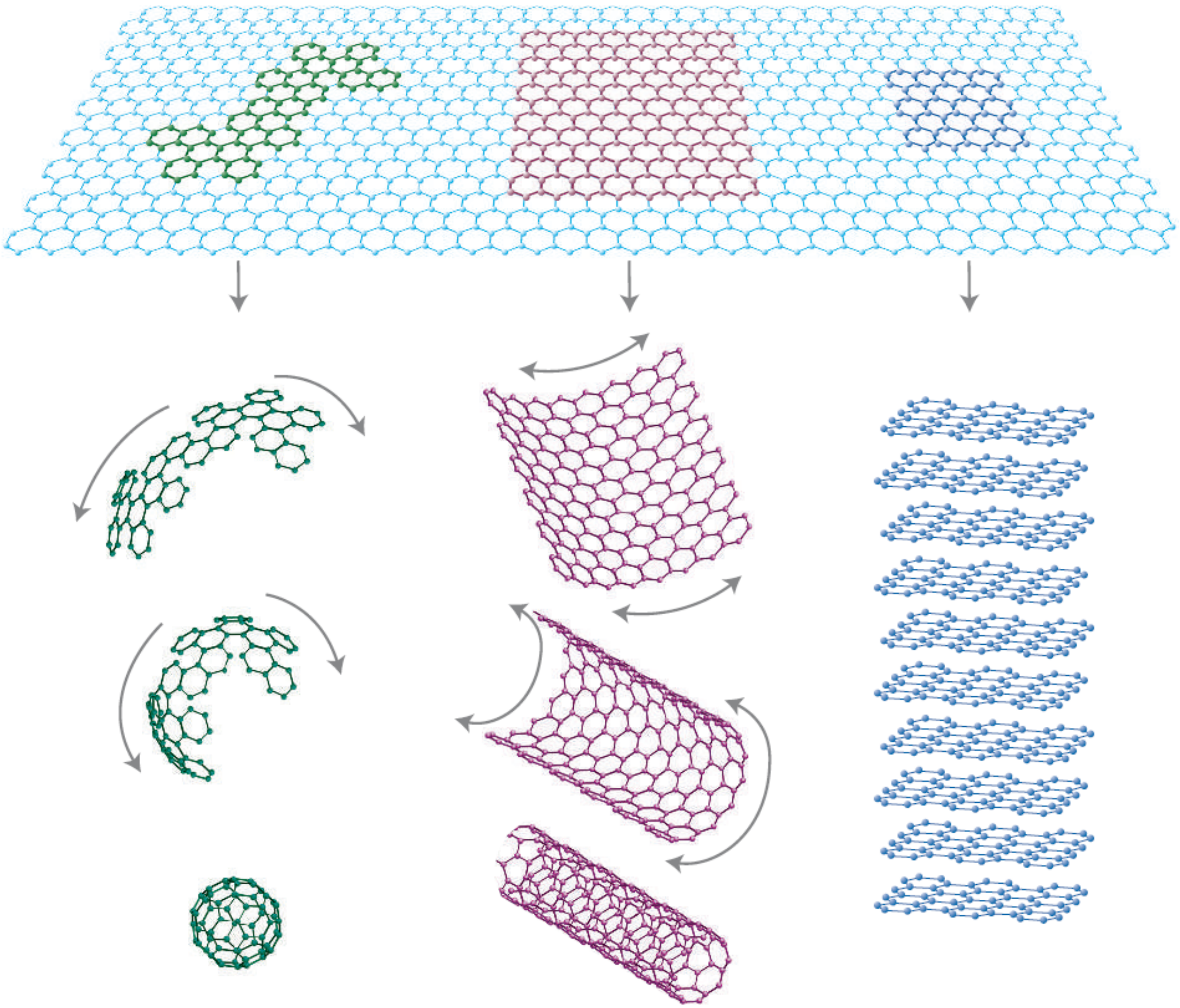
Spontaneous symmetry breaking → lattice scale order (CDW) ?

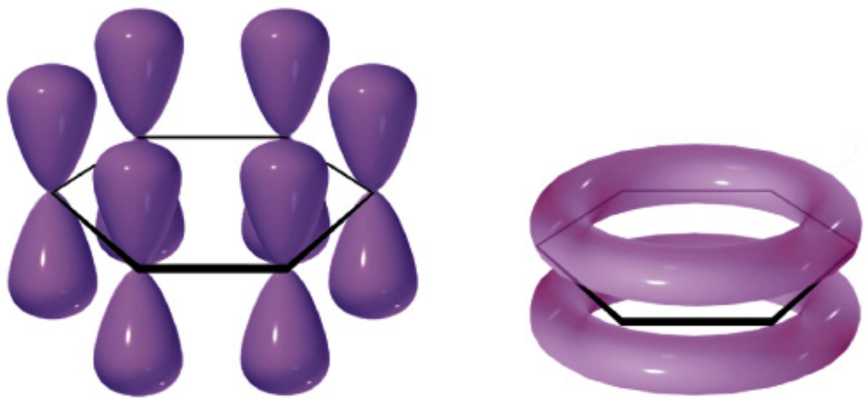


Graphene single layer

Mother of all-carbon materials (fullerenes, nanotubes, graphite): made of benzene rings stripped of H atoms







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