Clean Answers to Some Dirty Problems in Graphene

Gene Mele
Department of Physics and Astronomy
University of Pennsylvania

PREM Symposium, May 8, 2009

The Neoclassical School

in architecture

e.g. Franklin Institute and Philadelphia Museum of Art

The Neoclassical School

in painting

e.g. Jacques-Louis David: Oath of the Horatii

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The Neoclassical School

and in Condensed Matter Physics

A classical culture in condensed matter physics, with emphasis on phenomena in well ordered, often crystalline forms of matter.

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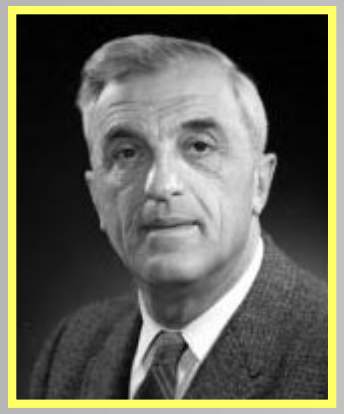
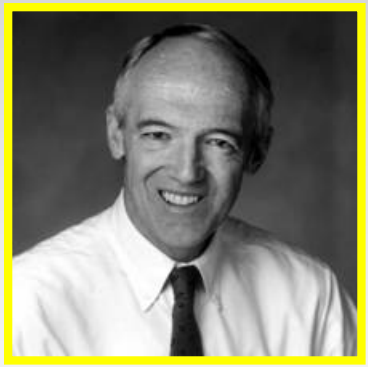
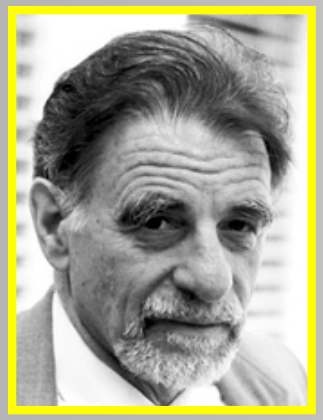
Heroes of Neoclassical Condensed Matter Physics



Felix Bloch: *free propagation of electron waves through a crystalline lattice of ions*

Art Gossard: *fabrication of high quality semiconductor quantum well heterostructures*





K. Alex Muller: *Superconducting Perovskites*

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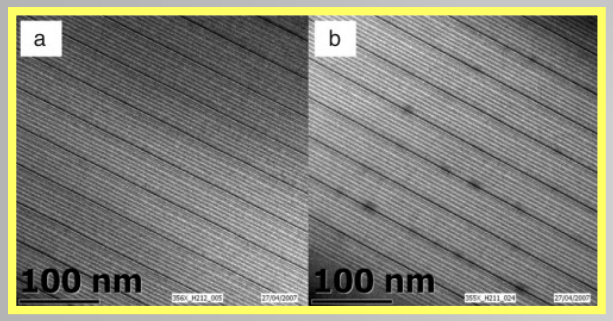
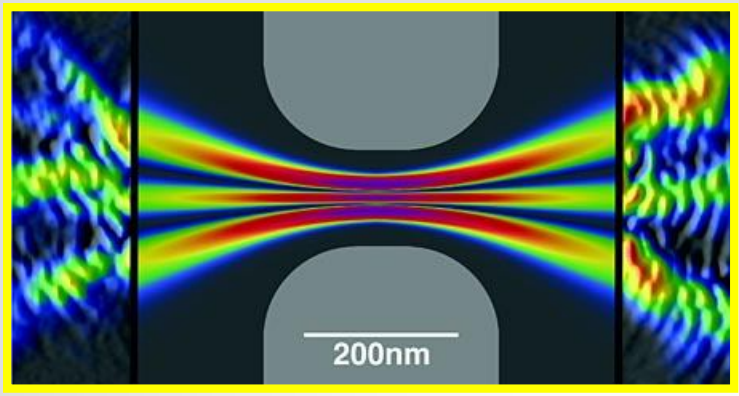
Neoclassical Condensed Matter Physics: Highlights



AlGaAs Heterostructures, with and without Quantum Dots

Imaging Ballistic Channels Through a Quantum Point Contact



(Not a complete list)

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The Avant Garde Movement

in painting

e.g. Dali: Persistence of Memory

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The Avant Garde Movement

in architecture

e.g. Gehry: Dancing House

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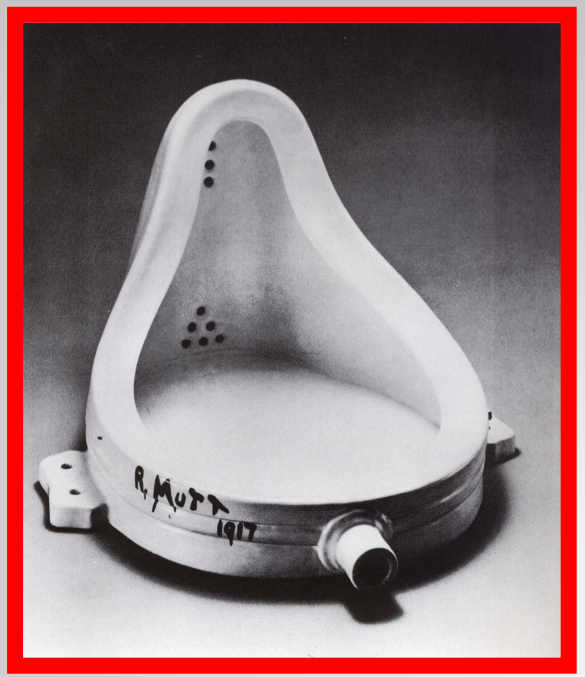
The Avant Garde Movement

in design



Duchamp: Fountain

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The Avant Garde Movement

and in Condensed Matter Physics

Atomically precise control is unnecessary and unnatural;
emphasis on phenomena in poorly ordered,
often heterogeneous forms of matter

"One can see through window glass"

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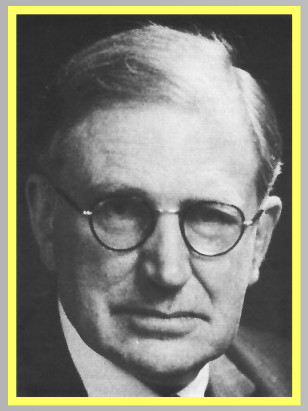
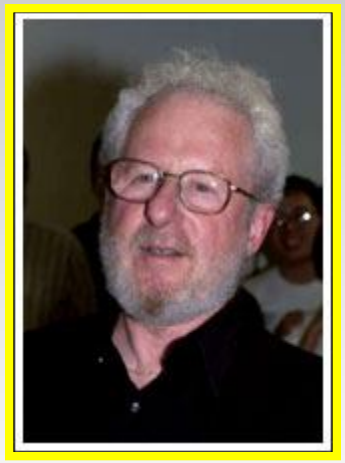
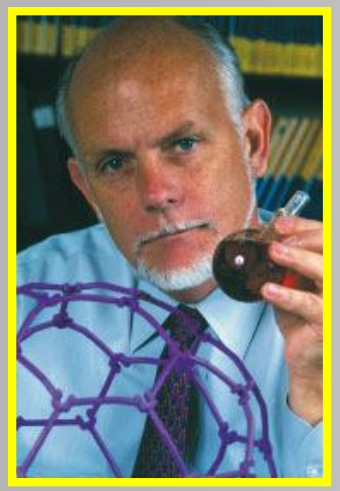
Heroes of Avant Garde Condensed Matter Physics



Neville Mott: *transport in amorphous materials*



Alan Heeger: *Conducting polymers: as the fourth generation of polymeric matter*



Rick Smalley: *Carbon Derived Nanomaterials*

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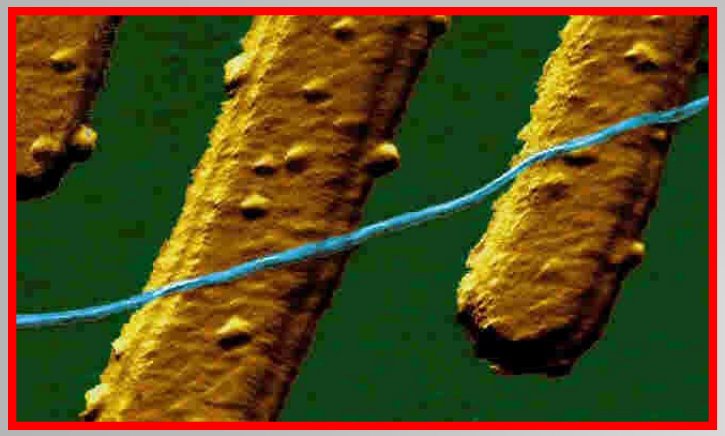
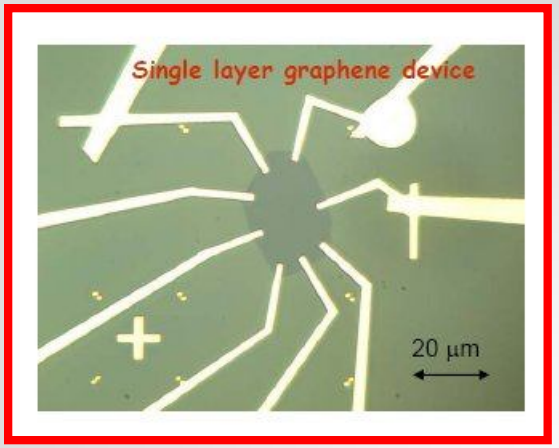
Avant Garde Condensed Matter Physics: Highlights



Nanotube FET



Micromechanical Cleavage Isolates Single Layer Graphene

(Not a complete list)

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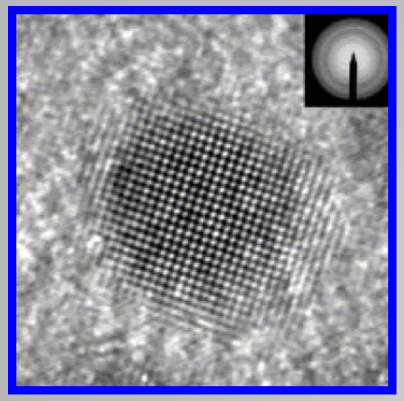
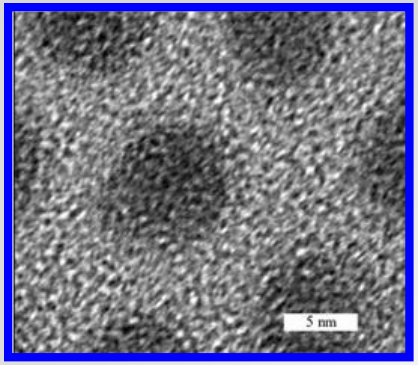
A Post-Impressionist Era in Cond. Matt. Physics



Semiconductor Quantum Dots



And self assembled arrays of QD's

Emphasis on novel mesophases and new metamaterials

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…and in painting

Seurat: Sunday Afternoon on the Island of Grand Jatte

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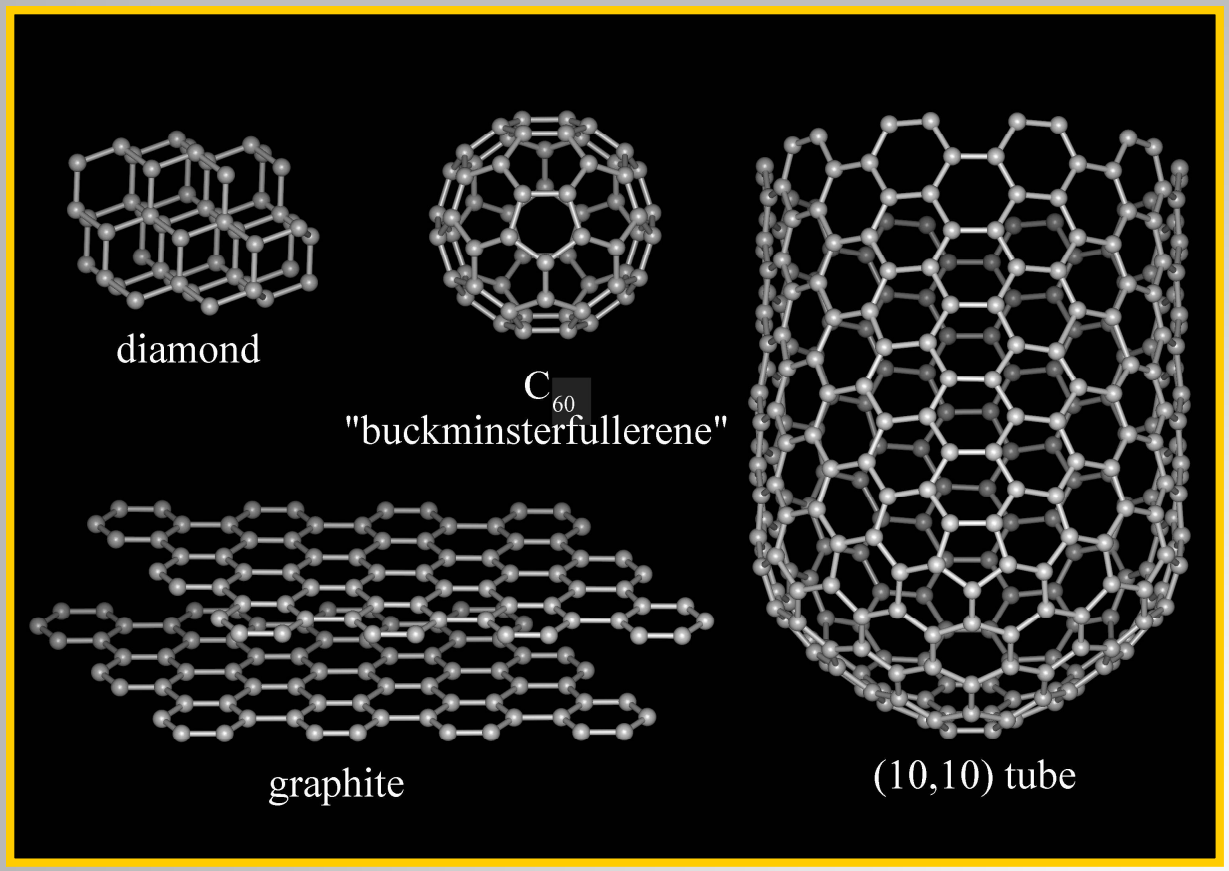
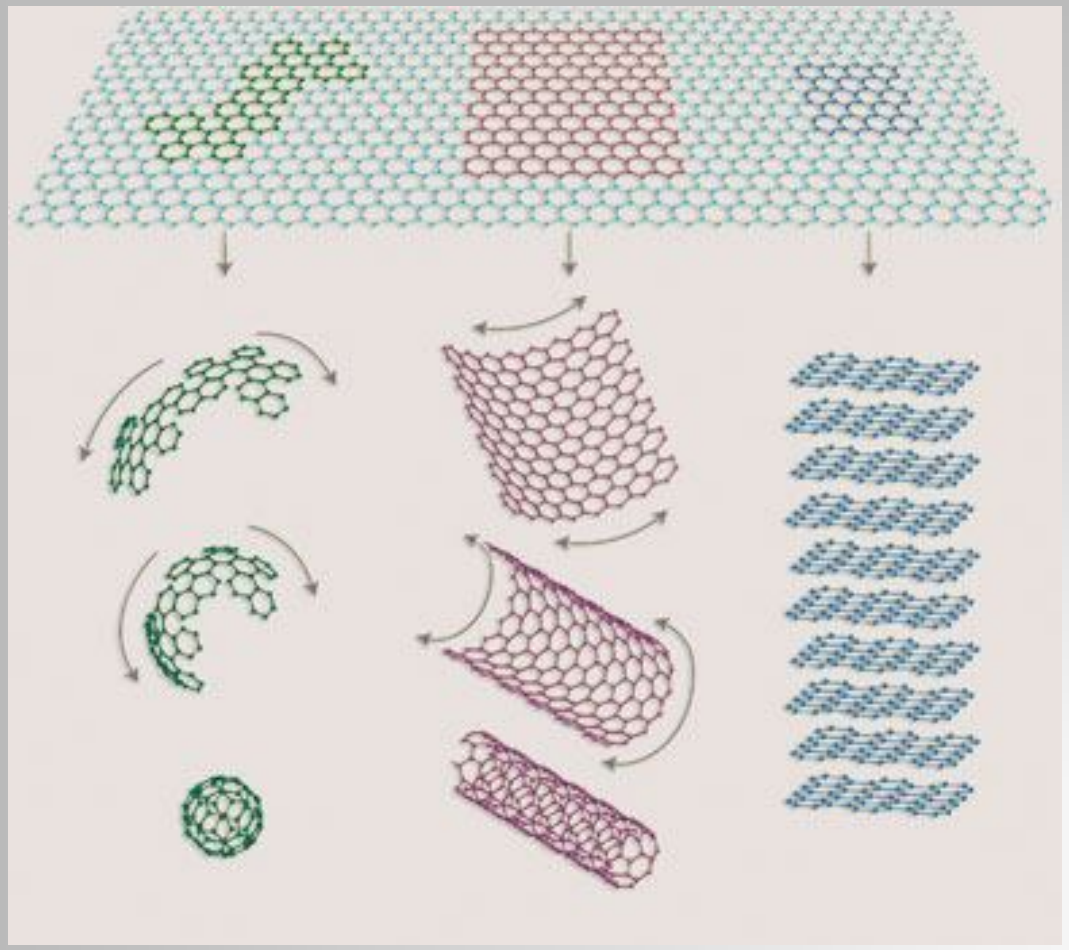
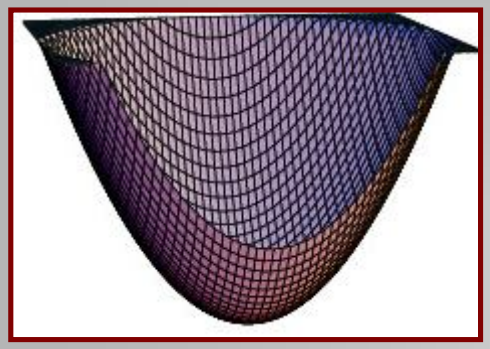
Bonded Structures of Elemental Carbon



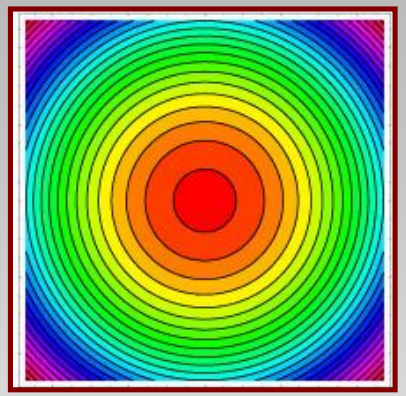
Two Dimensional Graphene is the Parent Phase

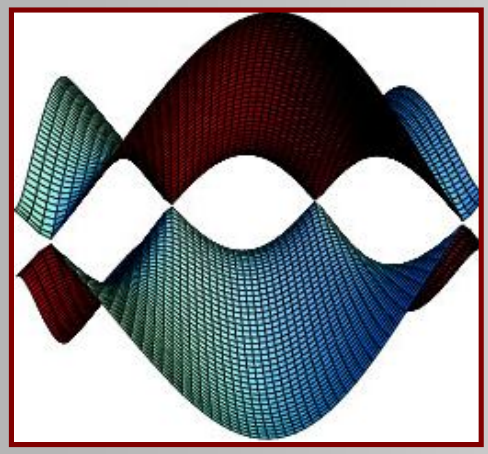


….and it has a critical electronic state

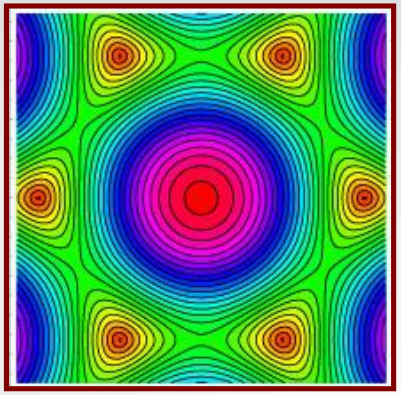


The dispersion of a free particle in 2D..





…is replaced by an unconventional E(k) relation on the graphene lattice



The low energy theory is described by an effective mass theory for massless electrons

$$(Exact\ Wavefunction) = (Wavefunction(s)\ at\ K) \bullet \psi(\vec{r})$$

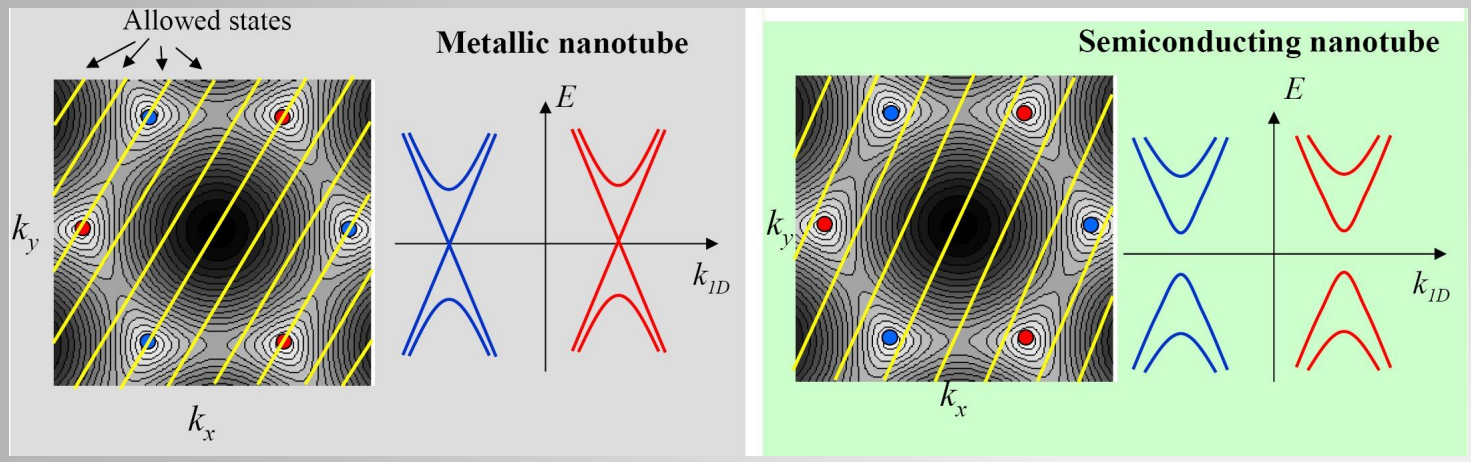
$$H_{eff}\psi(\vec{r}) = iv_F(\vec{\sigma}\bullet\nabla)\psi(\vec{r})$$

It is a massless Dirac Theory in 2+1 Dimensions

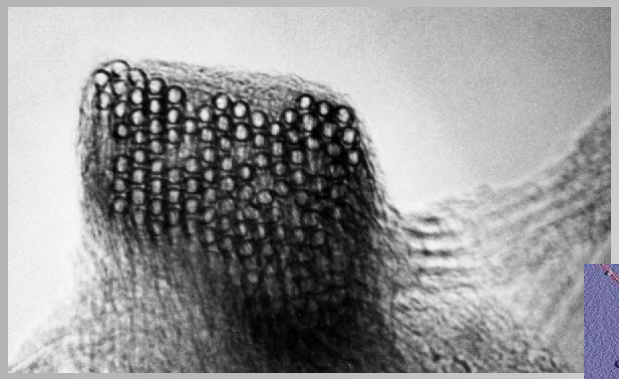
NOTE: Here the "spin" degree of freedom describes the sublattice polarization of the state, called pseudospin. In addition electrons carry a physical spin ½ and an isospin ½ describing the valley degeneracy.

Ref: D.P. DiVincenzo and GM, Phys. Rev. B 29, 1685 (1984)

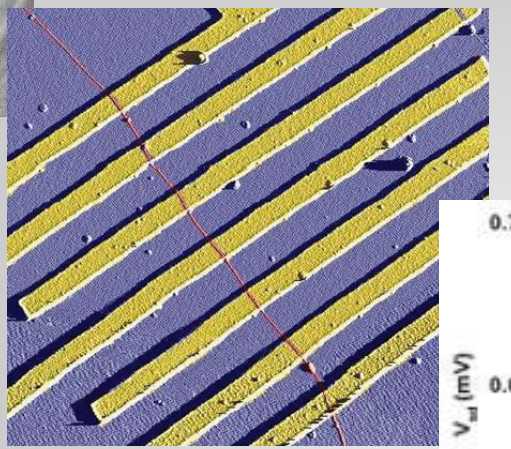
Distinguishing metals from semiconductors



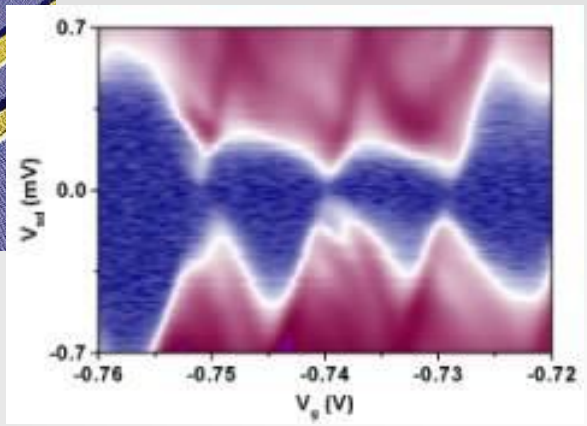
Single Wall Carbon Nanotubes



bundled



contacted



and gated

Some dirty problems

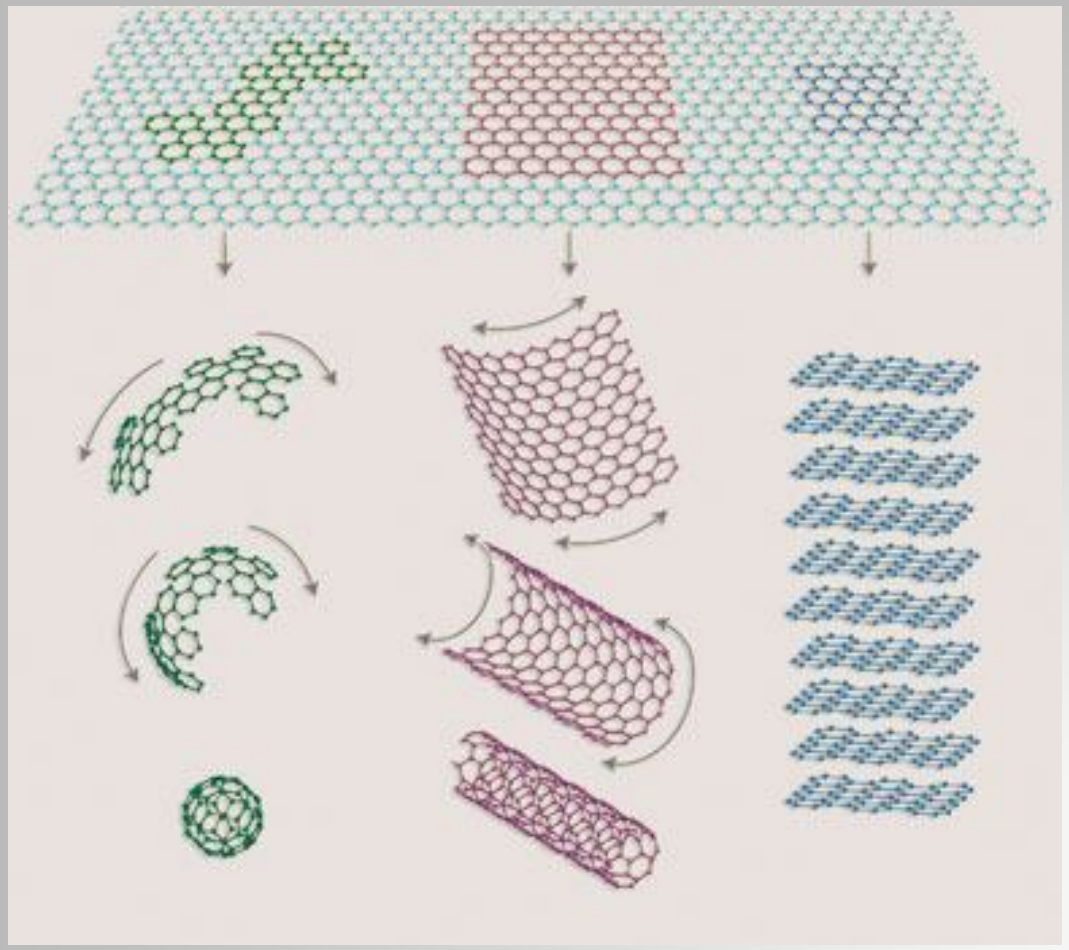
Nanotubes and Graphene(s) have

Surfaces that are curved, buckled and strained

Charge densities that locally break lattice symmetries

Multiple layers

Tube Curvature and Network Topology Modifies H_{eff}



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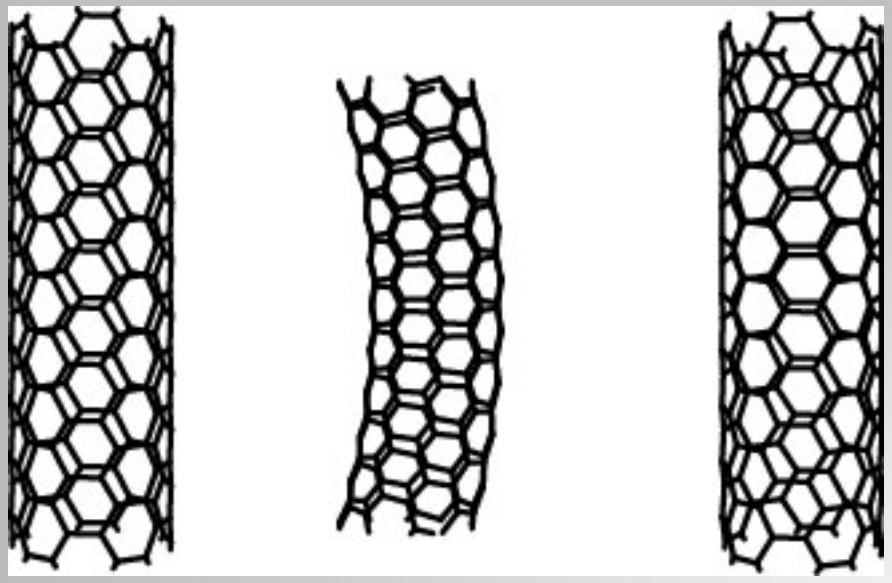
and elastic strain does too



Curvature and strain can be treated as gauge fields, organized as an expansion in a/R.

$$H_{eff}\psi(\vec{r}) = v_F \vec{\sigma} \bullet \left(i\nabla - \vec{a} \right) \psi(\vec{r})$$

(Holds for all perturbations with sublattice symmetry)

Gapless spectrum only for armchair NT's

Backscattering from twist (but not bend)

Three families of gapped tubes

Ref: C.L. Kane and GM, Phys. Rev. Lett. 78, 1932 (1997)

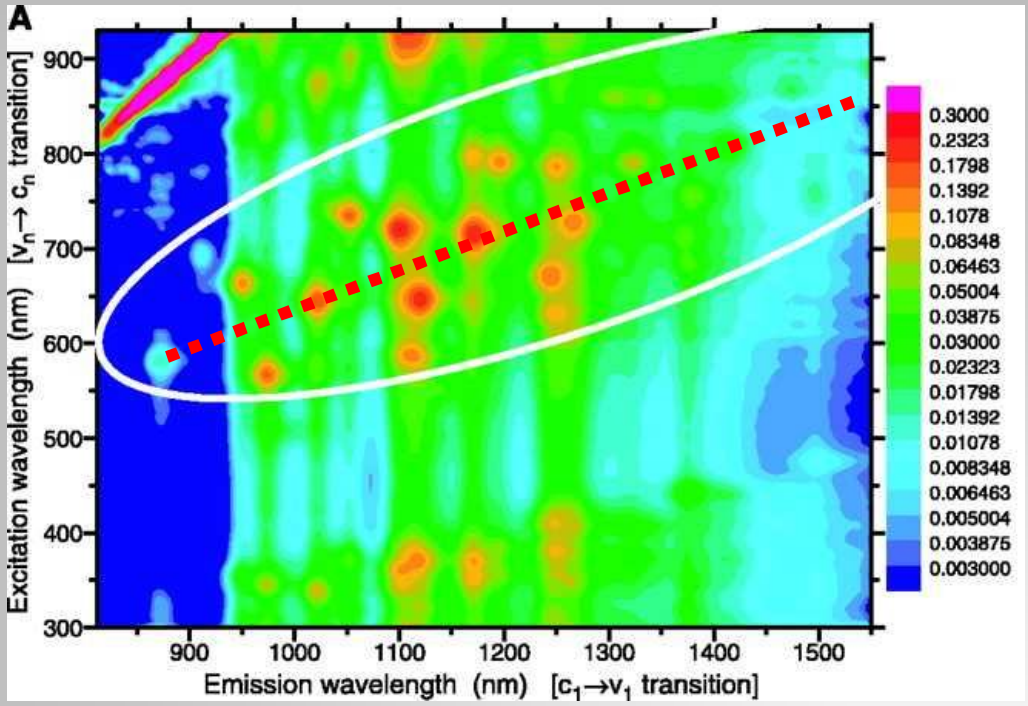
Example: leading corrections to gap from curvature and threefold anisotropy

$$H_{eff}\psi(\vec{r}) = v_F \vec{\sigma} \bullet \left(i\nabla - \vec{a} \right) \psi(\vec{r})$$

$$\vec{a} \propto \nu \frac{a^2}{R^2} \sin 3\theta; \quad \nu = \pm 1 \textbf{ (Chiral Index)}$$

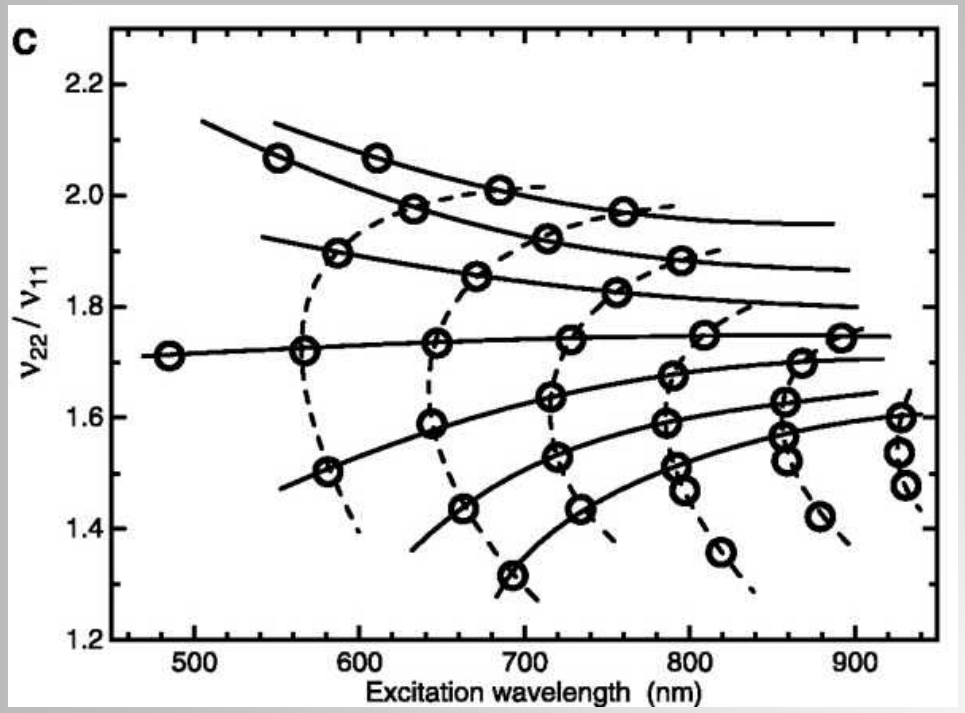
Two Dimensional PLE Spectroscopy

Discrete Peaks in PLE are Excitations of Individual SWNT's



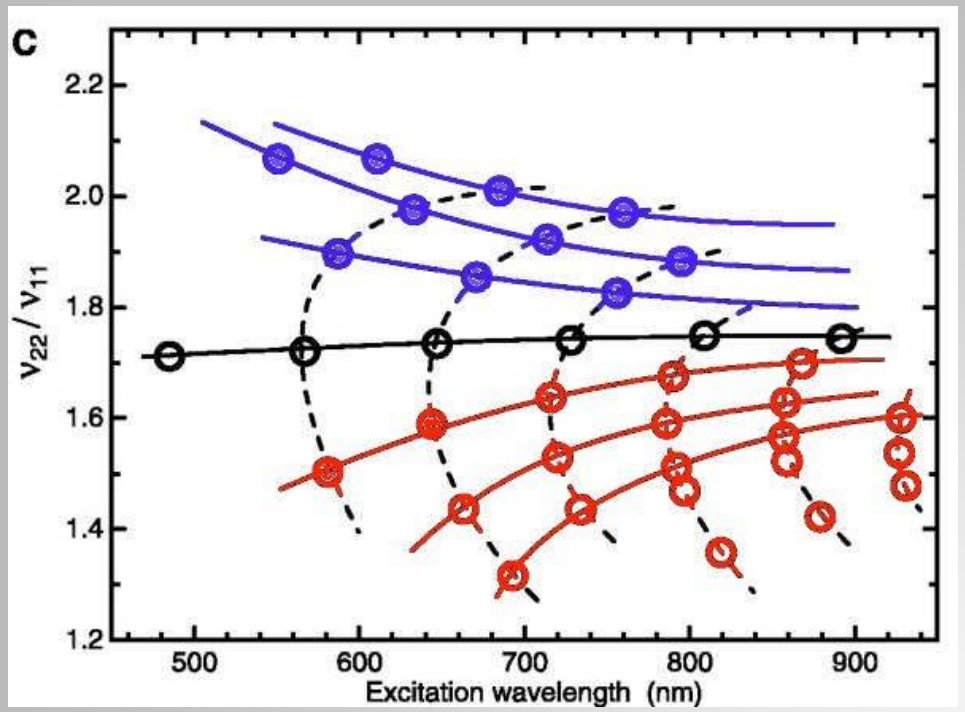
Ref: Structure Assigned Optical Specta of Single Wall Carbon Nanotubes, S. Bachilo et al., Science 298, 2361 (2002)

Systematic scaling of deviations



Data: S.M. Bachilo et al. Science 298, 2361 (2002)

Systematic scaling of deviations



Some dirty problems

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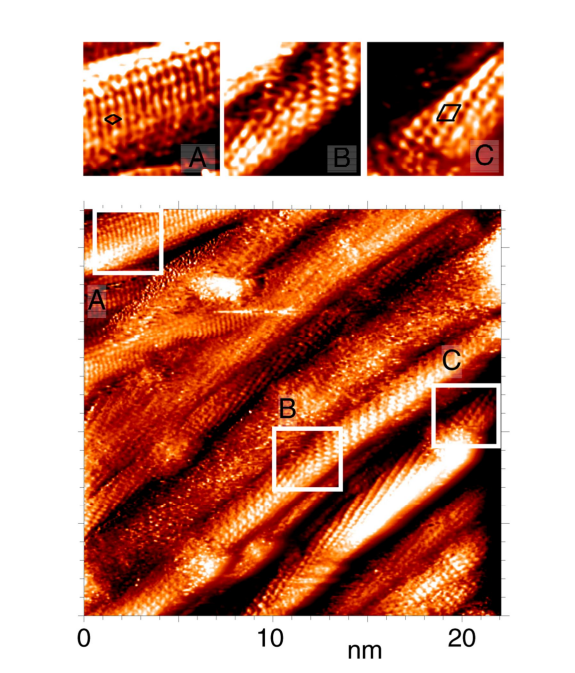
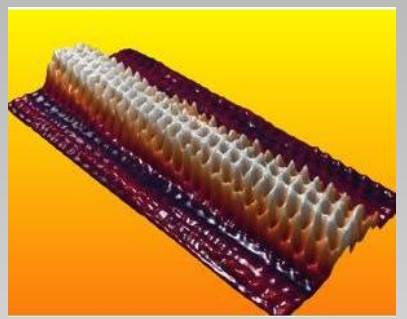
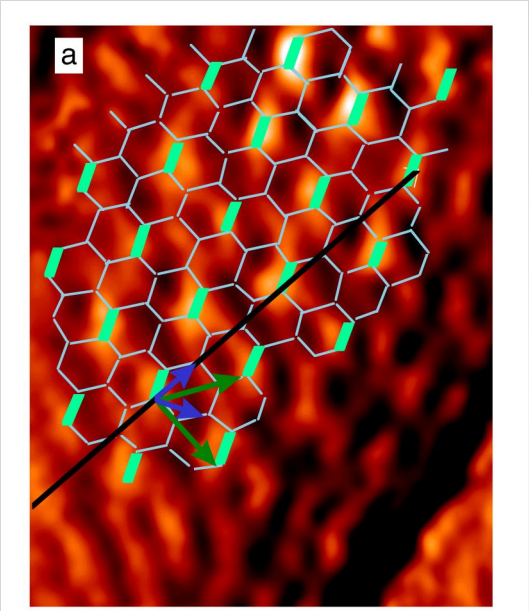
Atomically Resolved STM Images



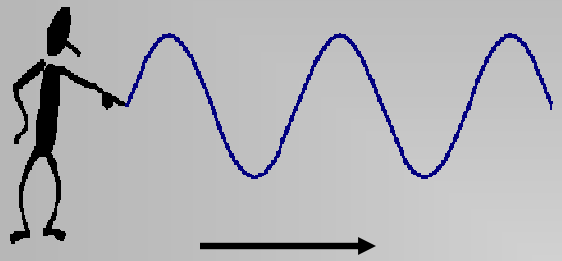
In ropes

And isolated





Waves on a stretched string can backscatter to make a standing wave



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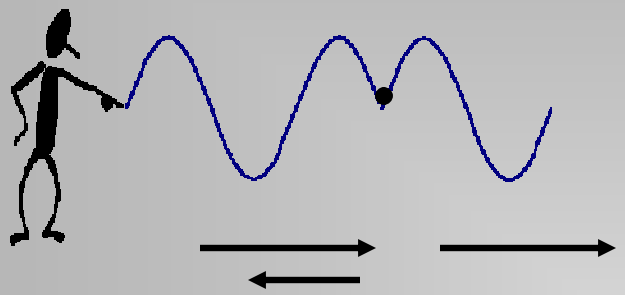

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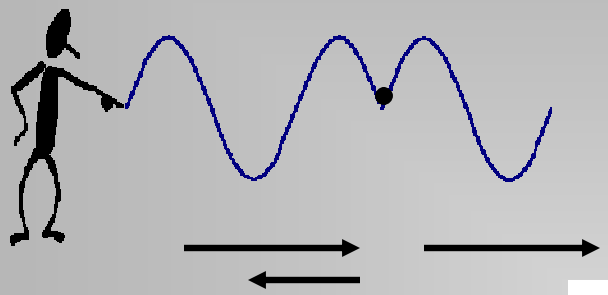
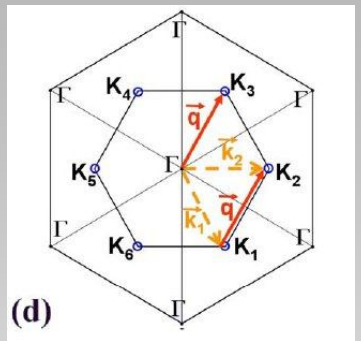
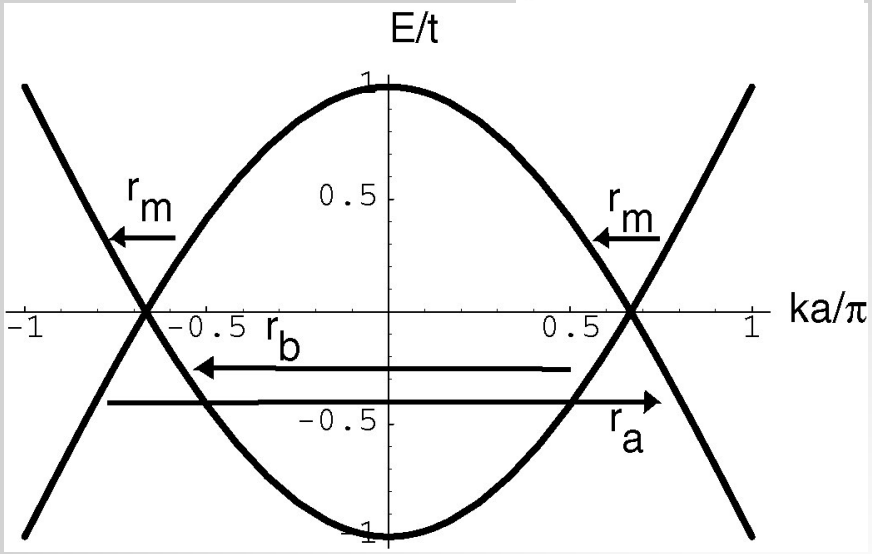


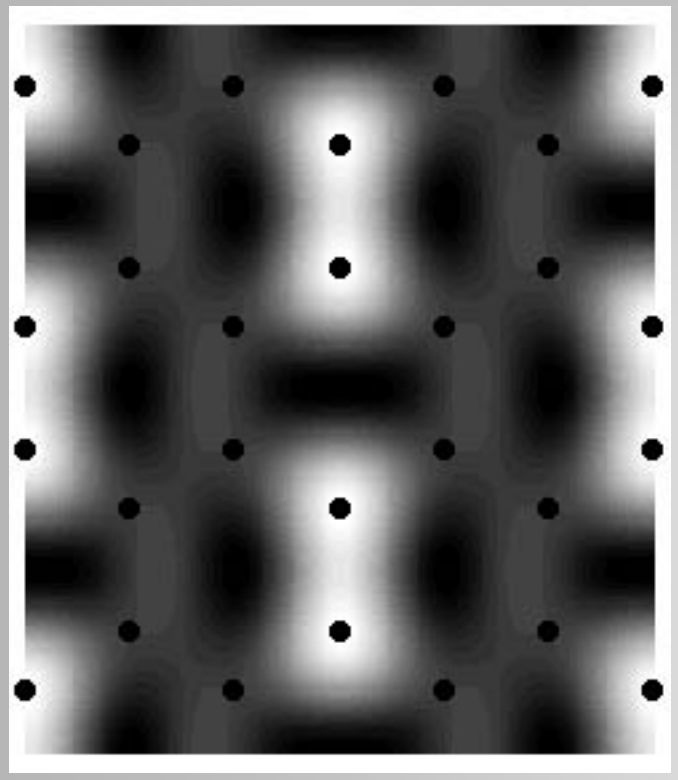


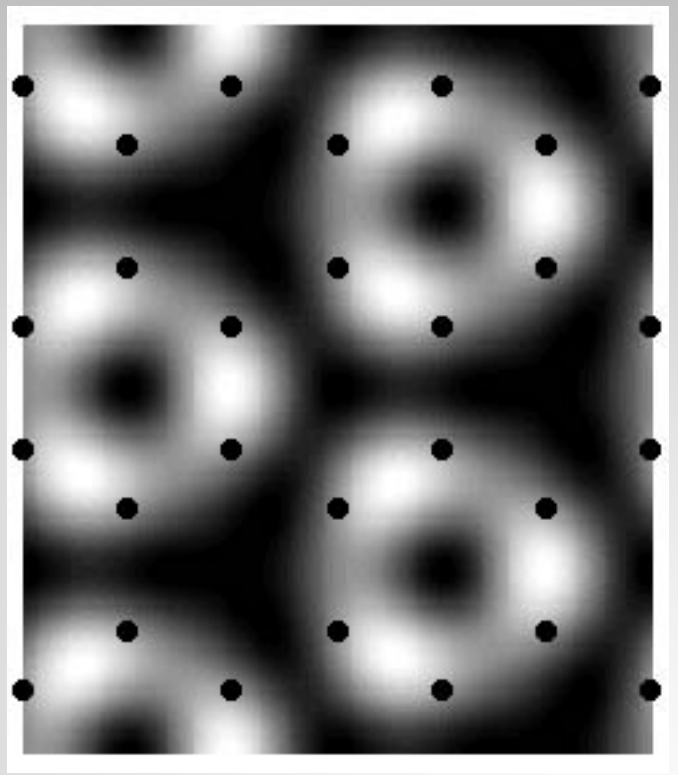
Dirac waves can backscatter with large Q OR small Q



Ref: C.L. Kane and GM, Phys. Rev. B 59, R12759 (1999)

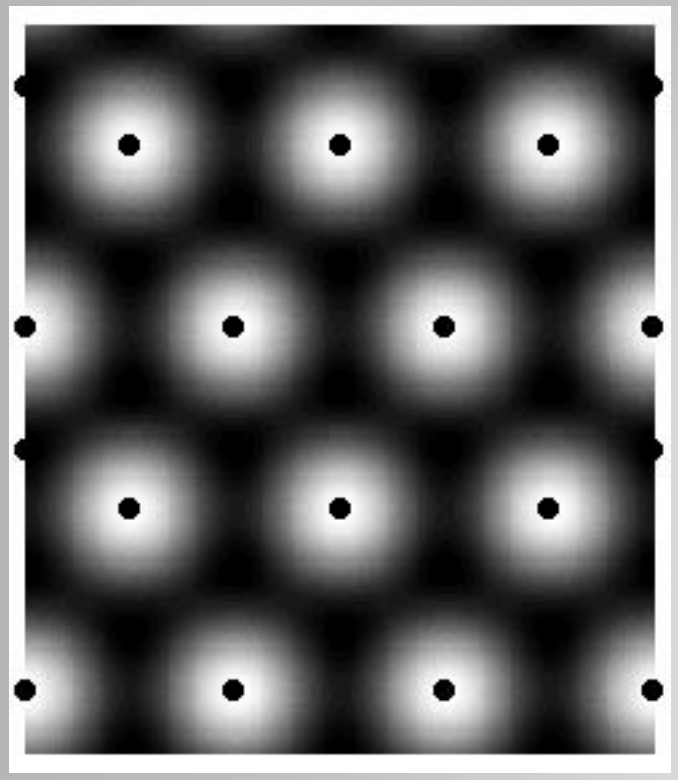
Large Momentum Backscattering: Real and Imaginary Amplitudes

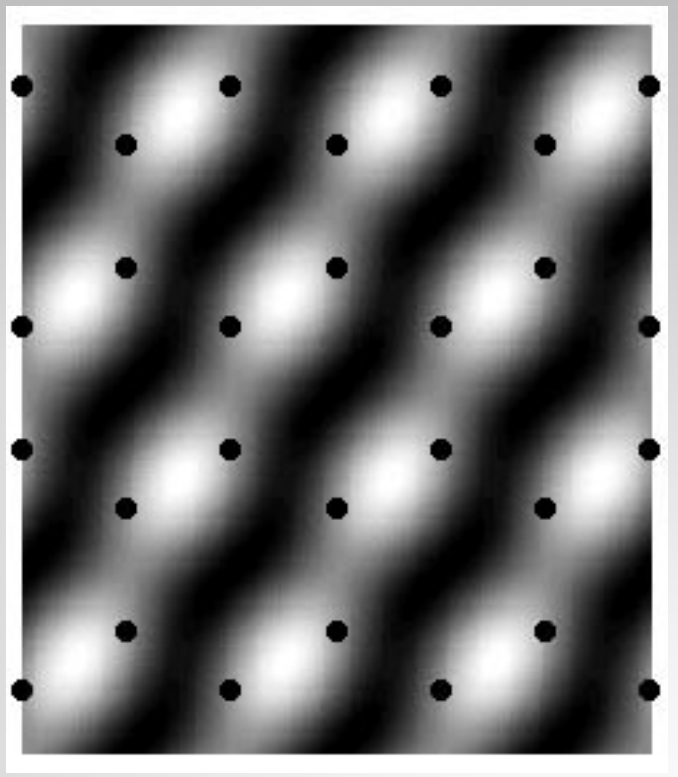




These are the Friedel Oscillations

Small Momentum Backscattering: Real and Imaginary Amplitudes





Cell Periodic Modulation Breaks Point Symmetry

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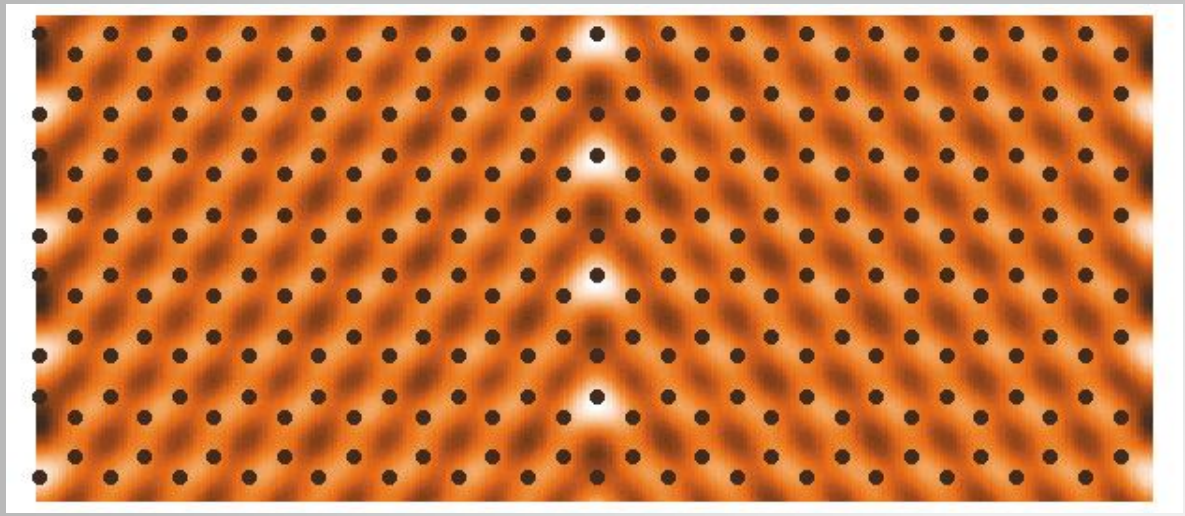
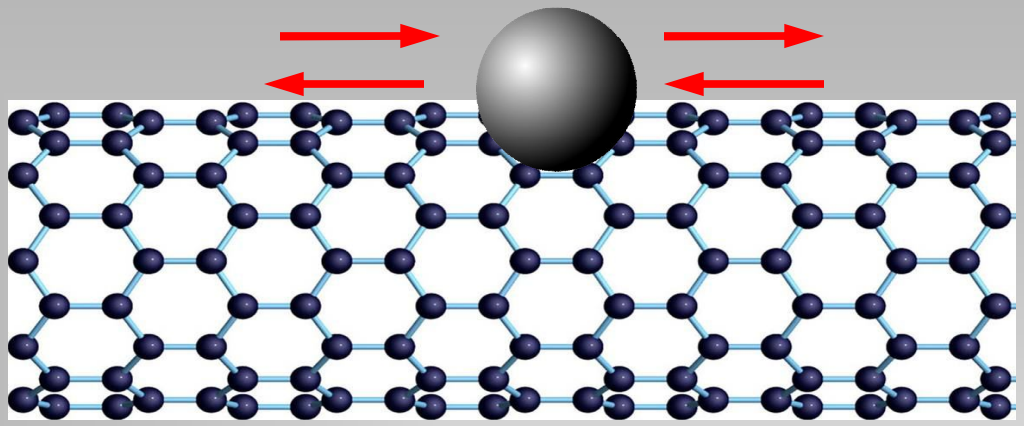
These decay only very weakly* in one dimension



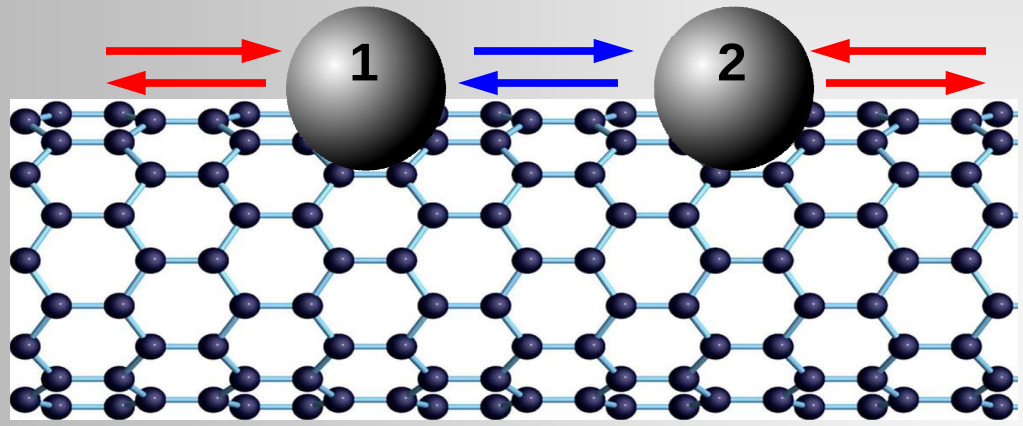
Typically limited by bandwidth set by bias window

Electron States Reflected By Scatterer



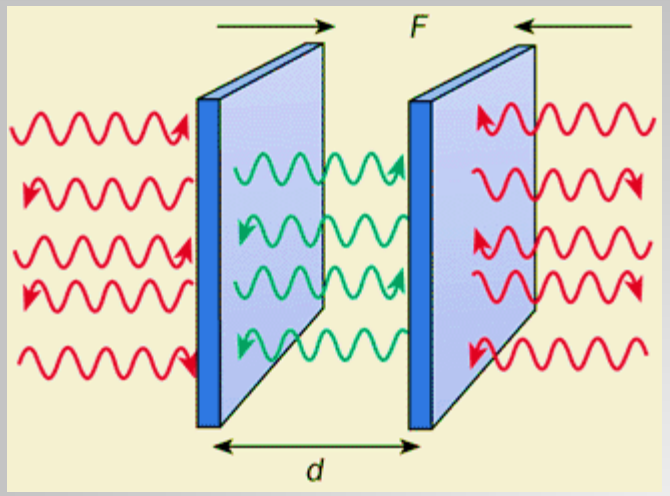
$$F = 0$$

Multiple Reflections



$$F_{1,2} \neq 0$$

This is a new type of Casimir Interaction



Vacuum fluctuations produce an attractive force between conducting plates

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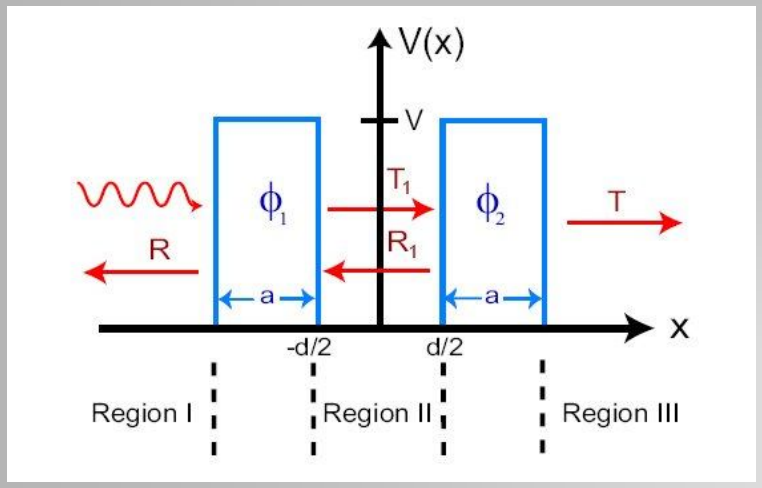
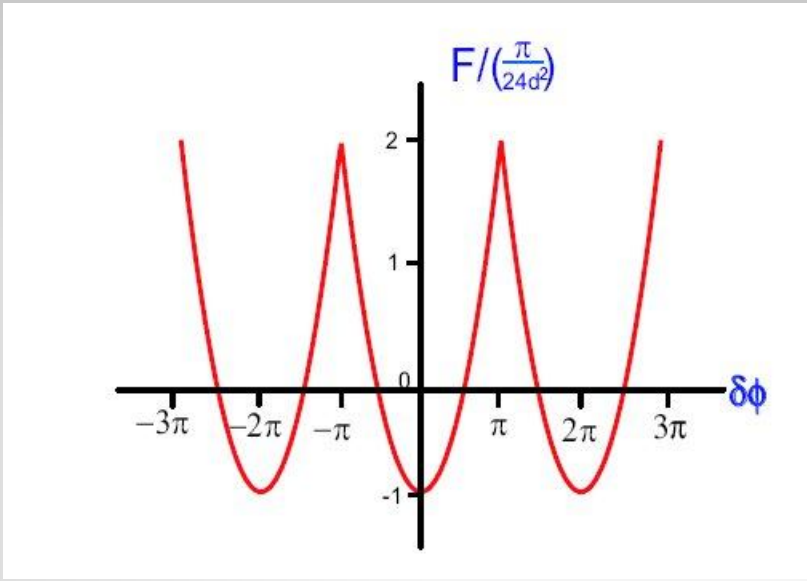
Barriers for Dirac fermions have a pseudospin polarization





D. Zhabinskaya, J.M. Kinder, GM
Phys. Rev. A 78, 060103 (2008)

Sign of long range force depends on relative pseudospin polarization of barriers

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Some dirty problems

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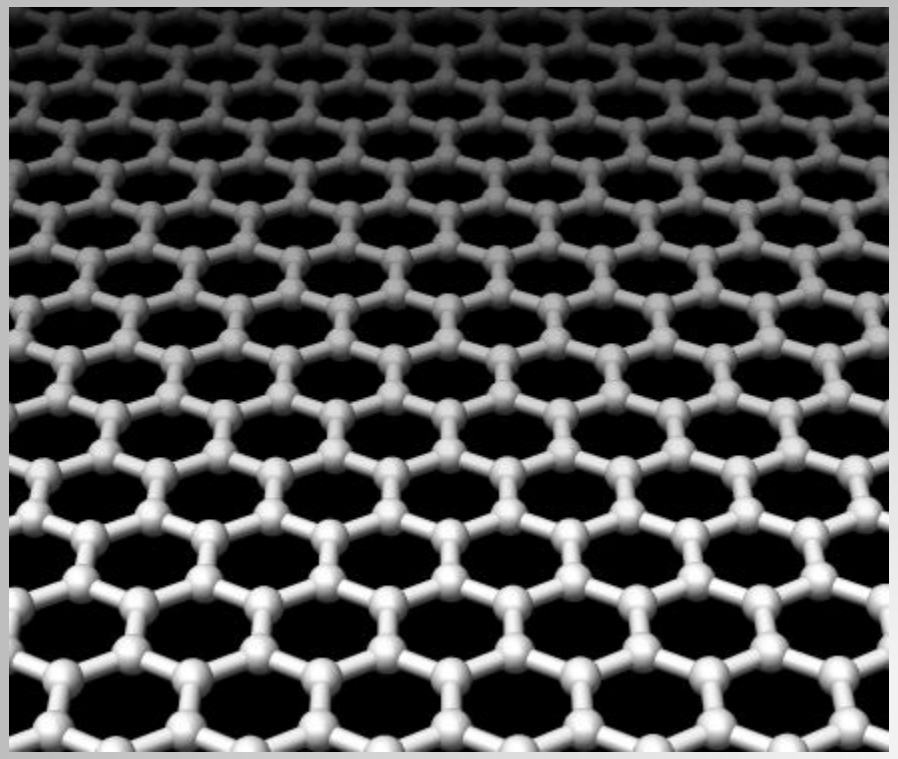
Surfaces that are curved, buckled and strained

Charge densities that locally break lattice symmetries

Multiple layers

Graphene: Return to the Parent Phase



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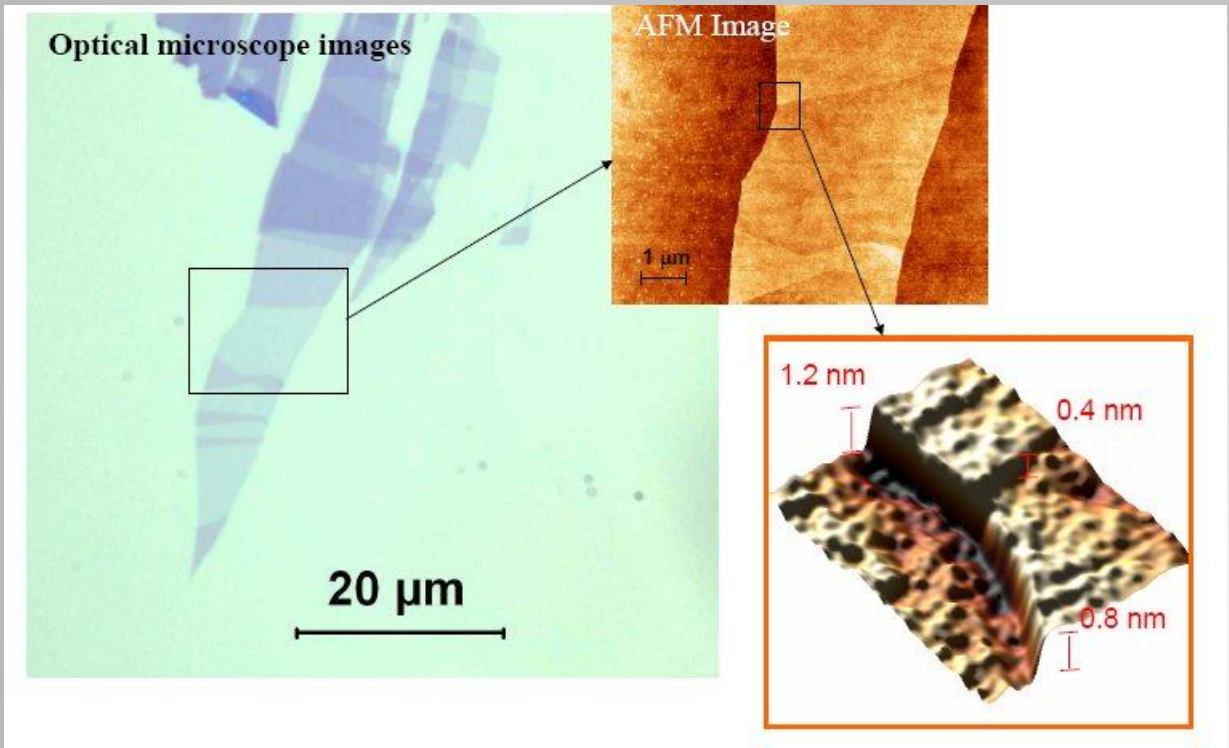
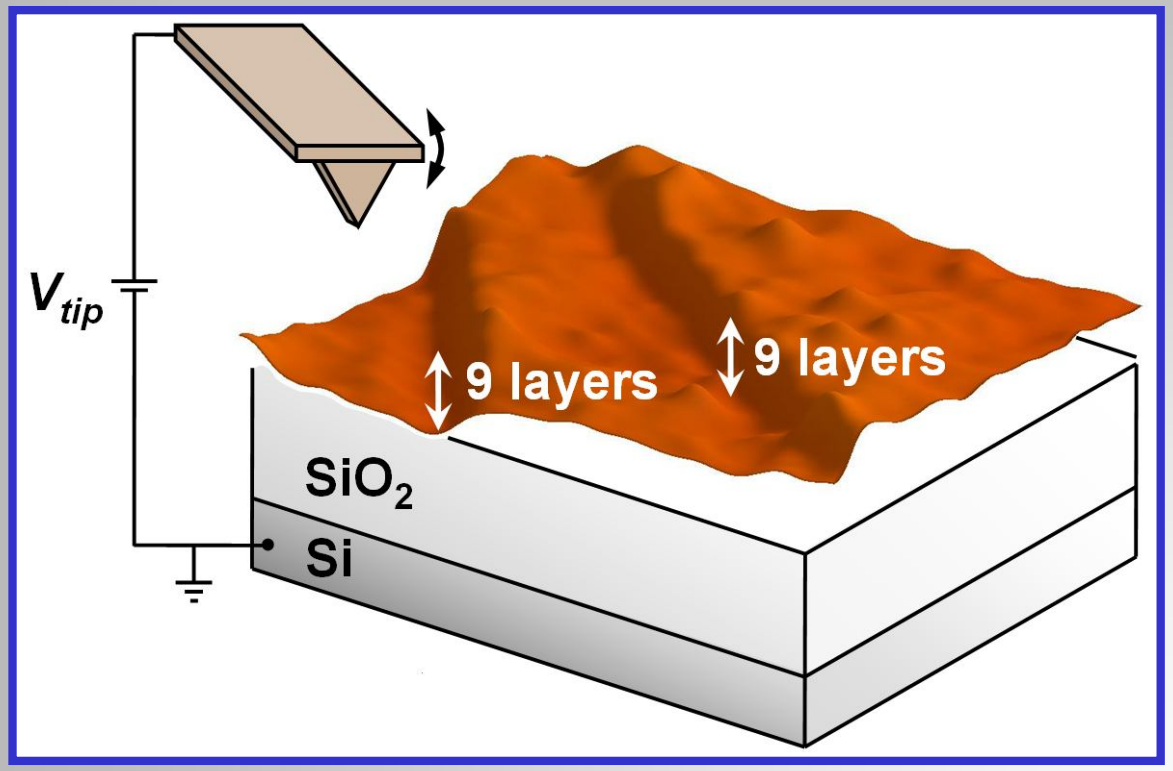
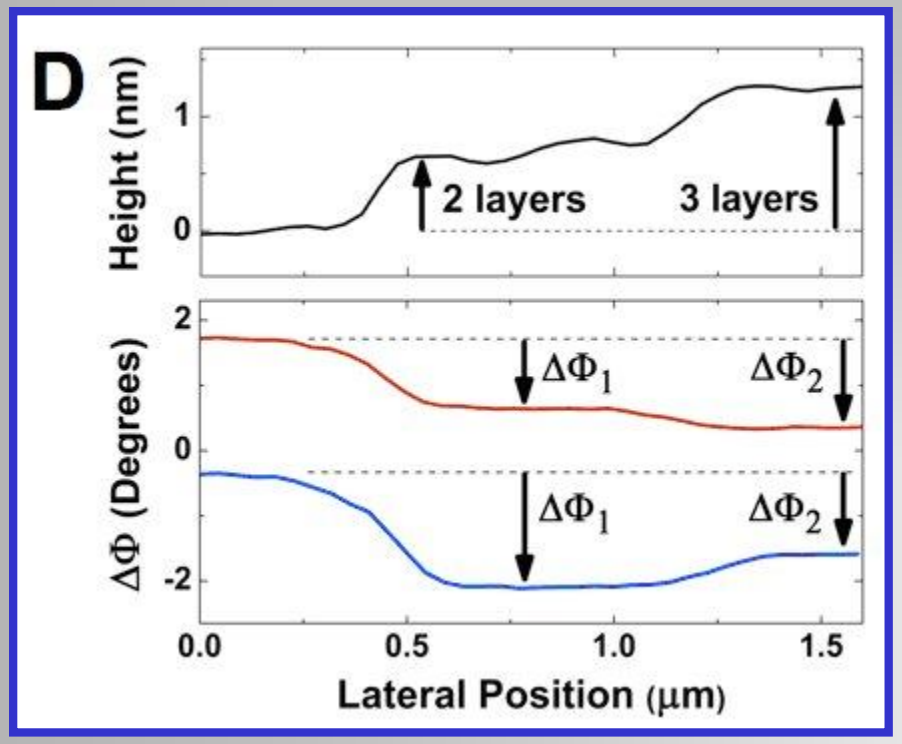
Images of Supported Graphene Samples

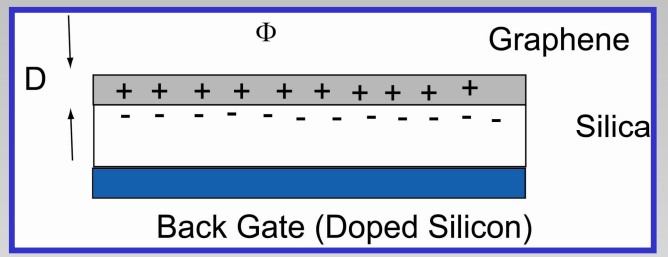


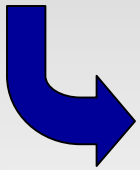
Height and Surface Potential of Few Layer Graphene

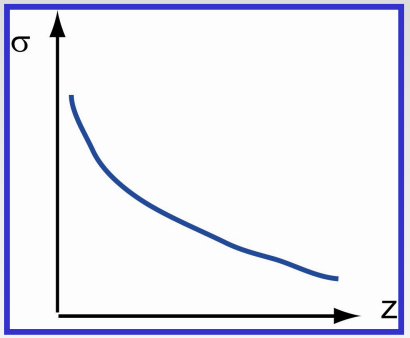


The Surface Potential Depends on Thickness

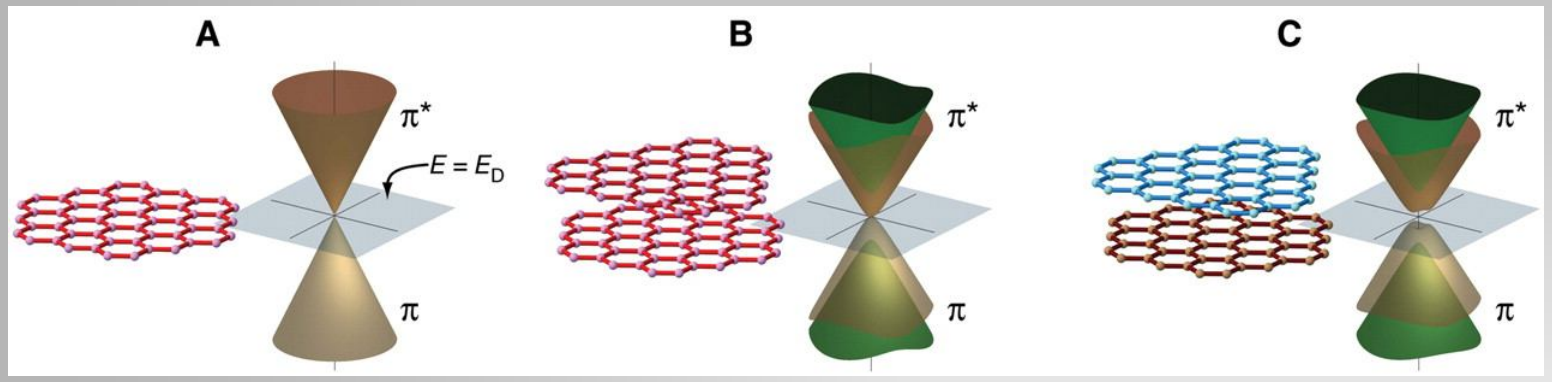








This presents a classic “Dirty Problem”

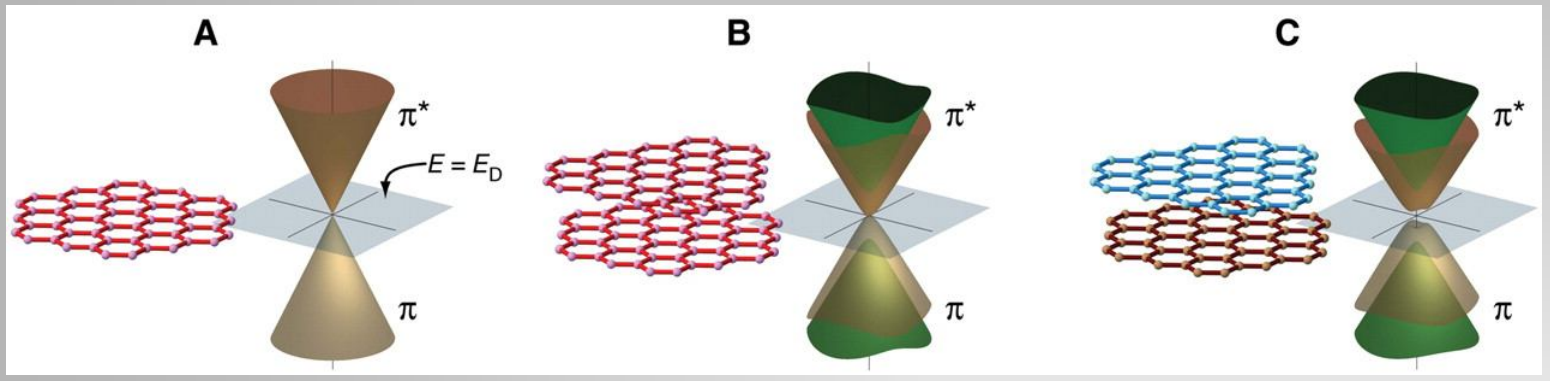


Single layer **Bilayer** **Asymmetric Bilayer**

Trapped Charges
External Fields
Interacting Electrons
Interlayer Tunneling
& Atomic Registry

X 10!

This presents a classic “Dirty Problem”



Single layer **Bilayer** **Asymmetric Bilayer**

~~Trapped Charges~~
External Fields
Interacting Electrons
~~Interlayer Tunneling~~
~~& Atomic Registry~~

} X 10!

Exact solution in the limit of <u>weak</u> interlayer tunneling

$$\Omega = \int_0^D \frac{dz}{a}\left(\gamma\sigma^{3/2}(z) - \mu\sigma(z) - 2\pi e^2 z\sigma_o\sigma(z)\right) - \pi e^2 \int_0^D \frac{dz}{a}\frac{dz}{a'}\sigma(z)\left|z - z'\right|\sigma(z')$$

Nonlinear stiffness **External field** **Interaction**

Minimization of Ω is constrained by conservation law

$$\frac{d}{dz}\left(\frac{1}{2}\left(\frac{df}{dz}\right)^2 - \frac{2\beta}{3a}f^3\right) = 0$$

where

$$f \equiv \sqrt{\sigma(z)\,\mathrm{sgn}(\sigma(z))}$$

Surface Potential Heals with a Power Law Decay

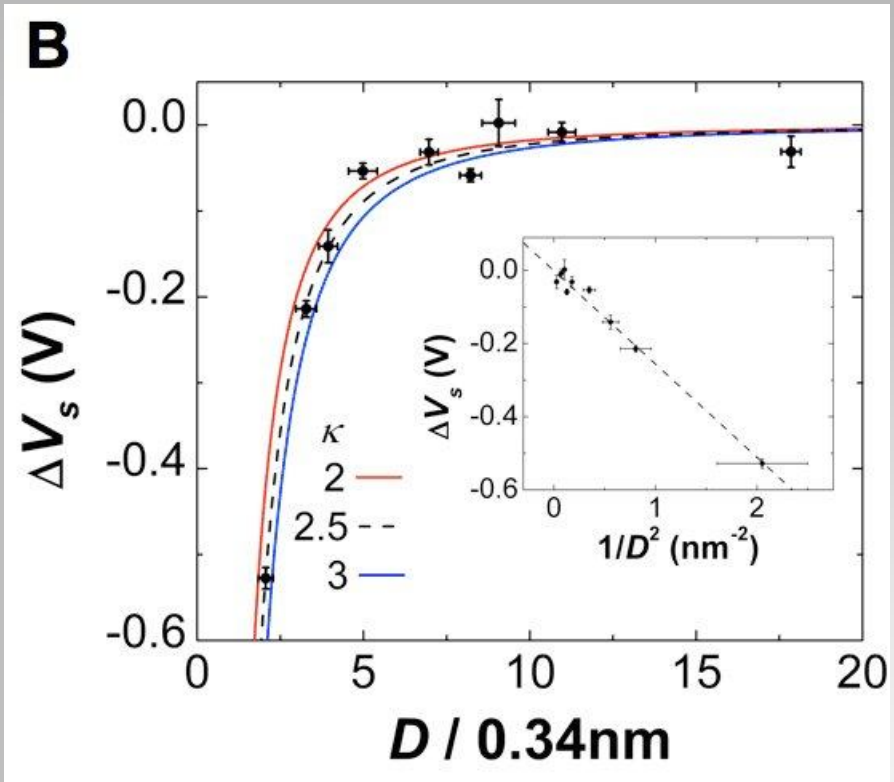
i.e. the screening charge profile follows a power law dependence on film thickness

$$\Delta\Phi = \sqrt{\pi}\hbar v_F \left(\left(3\beta a \sigma_o^2\right)^{1/3} - \frac{3a}{\beta D^2} \right)$$

Although this looks like the zero point energy of a massiveparticle in a box of height D, it arises entirely from the lateral compressibility!

Ref: S.S. Datta, D.R.Strachan, GM, and A.T. Johnson;
"Surface Potentials and Layer Charge Distributions in Few Layer Graphene Films"
Nanoletters 9, 7 (2009) (cover story)

Power Law Decay in Surface Potential



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***Nanoletters* 9, 7 (2009) (cover story)**

Opportunities and Challenges

The promise of graphene and graphene-derived structures for new quantum electronics/electron optics…

… is inevitably controlled (and limited) by various real world materials issues…

and pose problems in search of clean solutions.

Thanks to

Colleagues:

Charlie Kane
Charlie Johnson
Jay Kikkawa

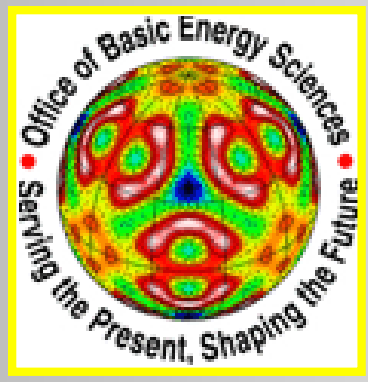
Postdocs:

Na Sai
Doug Strachan

Students:

Jesse Kinder
Paul Michalski
Dina Zhabinskaya
Sujit Datta

Support



LRSM the University of Pennsylvania's Materials Research Science and Engineering Center

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