Graphene: Worlds oldest and newest material Properties and Current Research

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Graphene

Graphene – very old new material

Panoply of interesting physics

Measuring strain with light scattering

Friction – What happens when you pull it?

Discovery of graphene

APS NEWS

This Month in Physics History

October 22, 2004: Discovery of Graphene

Scientists often find ingenious ways to attain their research objectives, even if that objective is a truly two-dimensional material that many physicists felt could not be grown. In 2003, one ingenious physicist took a block of graphite, some Scotch tape and a lot of patience and persistence and produced a magnificent new wonder material that is a million times thinner than paper, stronger than diamond, more conductive than copper. It is called graphene, and it took the physics community by storm when the first paper appeared the following year.

The man who first discovered graphene, along with his colleague, Kostya Novoselov, is Andre Geim. Geim studied at the Moscow Physical-technical University and earned his PhD from the Institute of Solid State Physics in Chernogolovka, Russia. He spent two years at the Institute for Microelectronics Tech-

nature by first making a three-dimensional material, which is graphite, and then pulling an individual layer out of it," said Geim.

In October 2004, Geim published a paper announcing the achievement of graphene sheets in *Science* magazine, entitled "Electric field effect in atomically thin carbon films." It is now one of the most highly cited papers in materials physics, and by 2005, researchers had succeeded in isolating graphene sheets. Graphene is a mere one atom thick– perhaps the thinnest material in the universe–and forms a high-quality crystal lattice, with no vacancies or dislocations in the structure. This structure gives it intriguing properties, and yielded surprising new physics.

From a fundamental standpoint, graphene's most exciting capability is the fact that its conducting electrons arrange

Graphene: most popular search word in ***Nature***

Graphene beats cancer, HIV, and obesity

<< Back to previous results list

Citation Report Topic=(graphene)

Timespan=1995-2009. Databases=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH.

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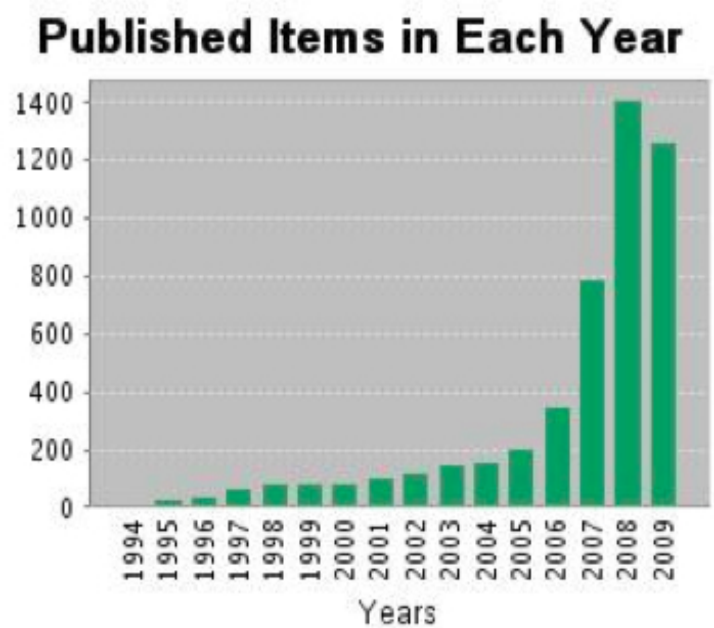

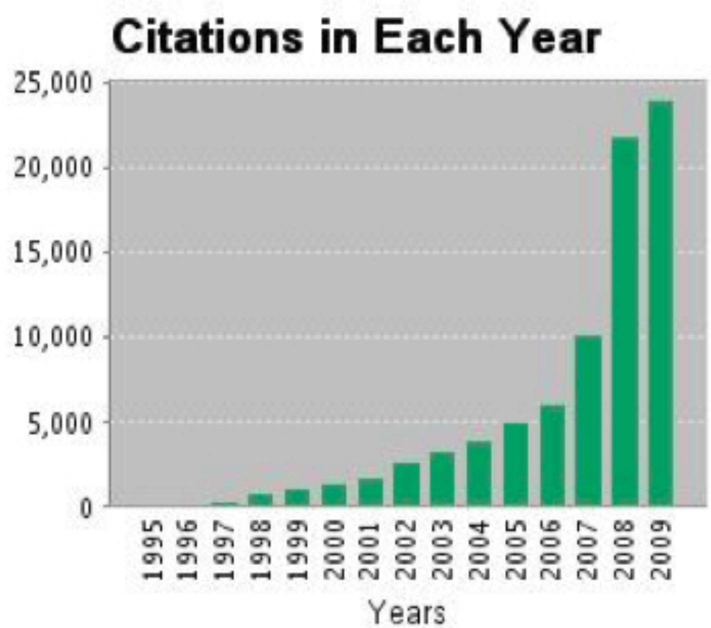

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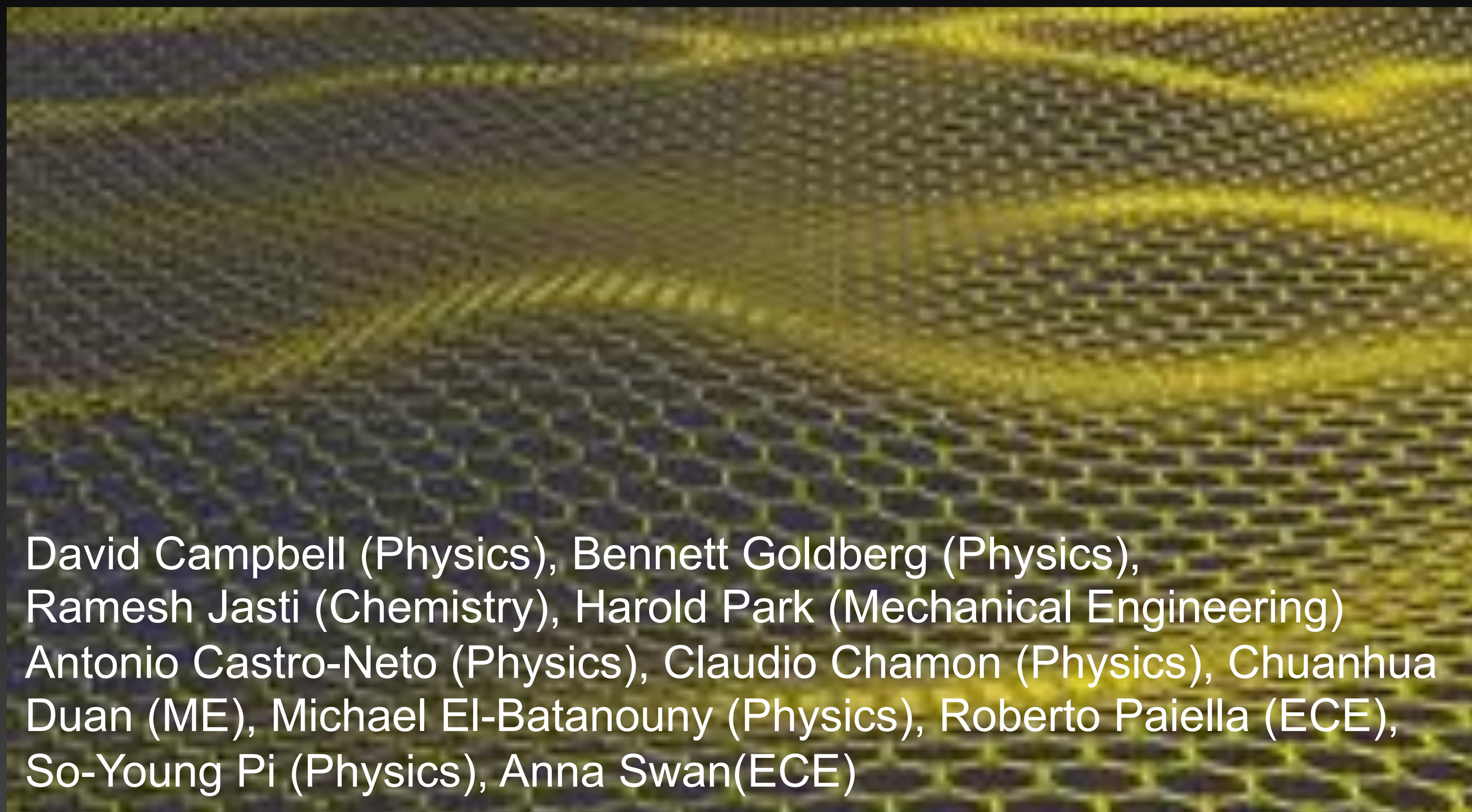
Graphene Research at Boston University



David Campbell (Physics), Bennett Goldberg (Physics),
Ramesh Jasti (Chemistry), Harold Park (Mechanical Engineering)
Antonio Castro-Neto (Physics), Claudio Chamon (Physics), Chuanhua Duan (ME), Michael El-Batanouny (Physics), Roberto Paiella (ECE),
So-Young Pi (Physics), Anna Swan(ECE)

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DEPARTMENT OF DEFENSE · UNITED STATES OF AMERICA

DEPARTMENT OF THE NAVY · ONR · Science & Technology

SCIENCE TO SHAPE THE FUTURE OF THE ARMY · ARMY RESEARCH OFFICE · 1951

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NATIONAL SCIENCE FOUNDATION · NSF

EPSRC

Engineering and Physical Sciences Research Council

JST Japan Science and Technology Agency

CREST

Competitive Funding for Team-based Basic Researches

GRApheneND

Graphene-based Nanoelectronic Devices

intel

SAMSUNG

FUJITSU

IBM

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What do you know or think about Graphene?

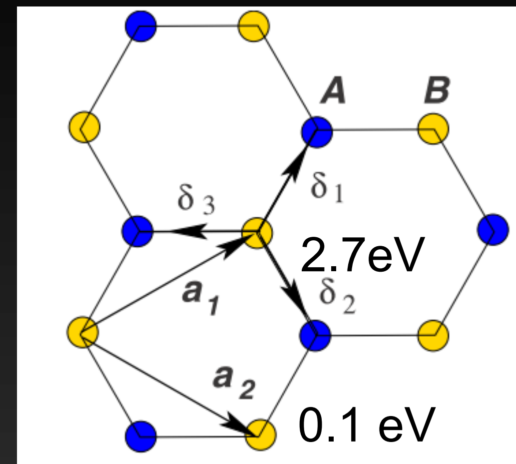
- Worksheet, 1st page
- Draw lattice structure
- 10 minutes or so

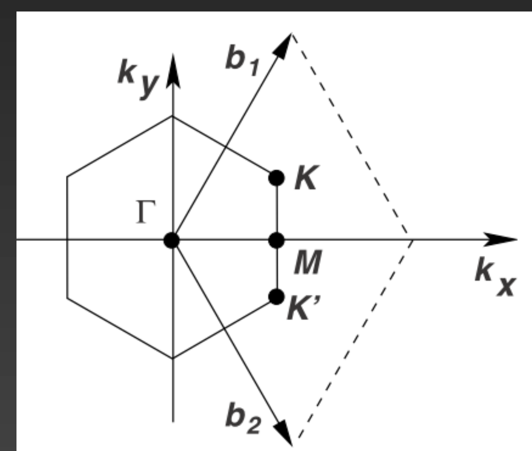
Graphene lattice

A. Šiber, 2003.

- Single layer of graphite; sp2 bonding
  - interlayer spacing ≈ 3.4 Å
- Triangular Bravais lattice with 2 atom basis
  - a ≈ 1.42 Å
- 1 electron per orbital
  - Half filled
- Hexagonal reciprocal lattice
  - High symmetry points: Γ, K, K'

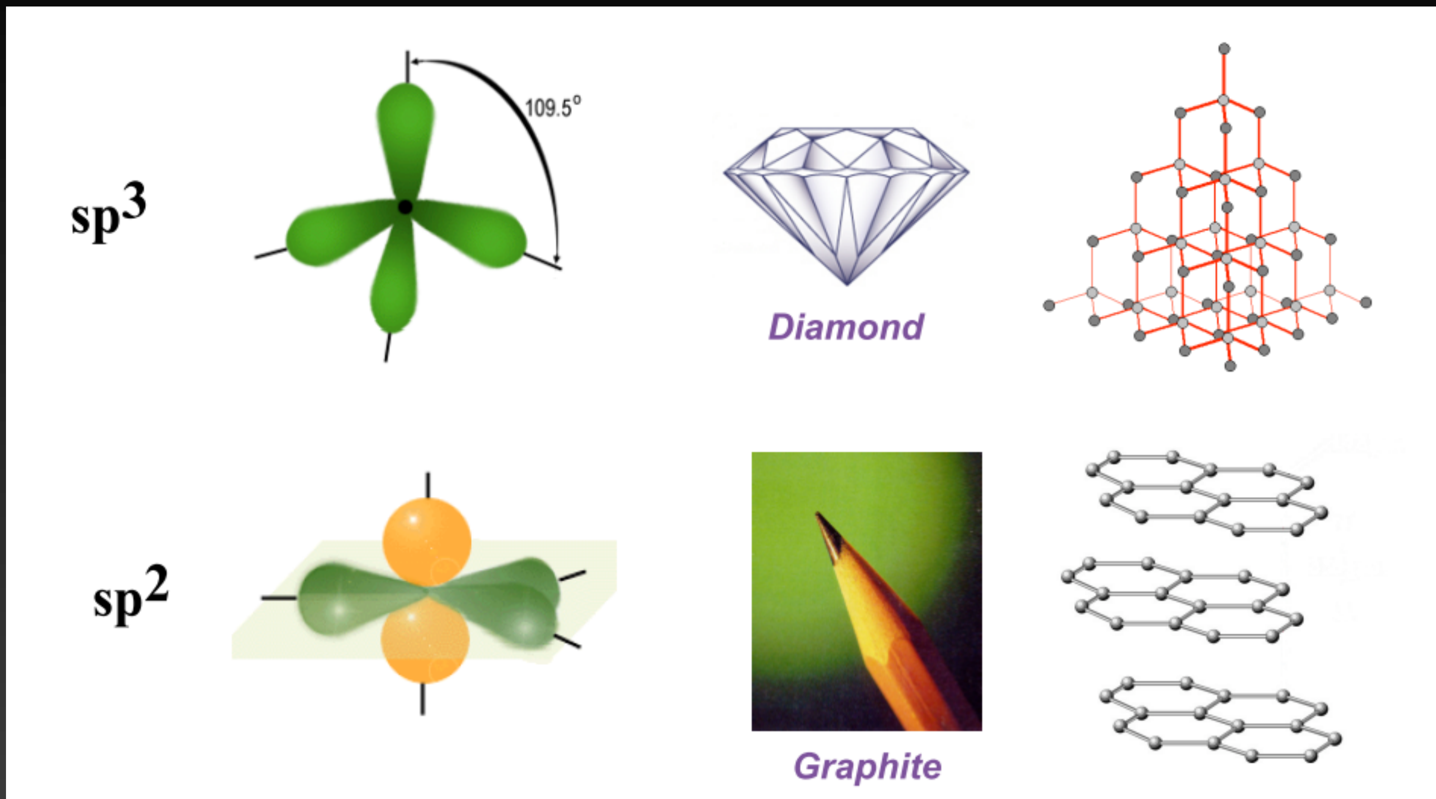
nanoatlas.ifs.hr





Castro Neto et al, Rev Mod Phys (2009)

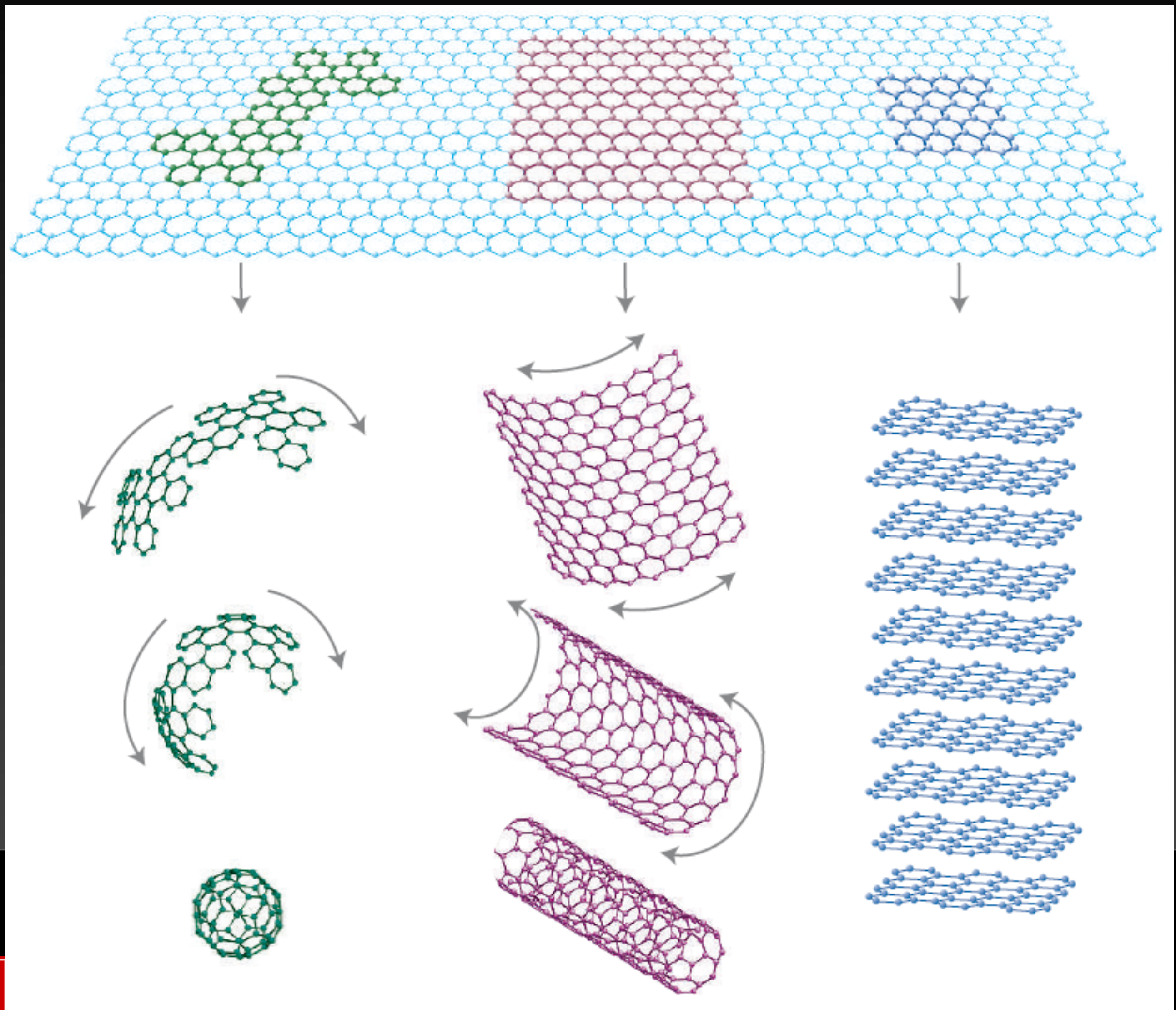
Bonding in Carbon



What does it mean when we say something is 0, 1, 2 or 3 Dimensional?

- Worksheet, 2nd page
- Define what you think dimensionality means to a physicist

0D, 1D, and 2D Carbon



Graphene - Mother of all graphitic forms

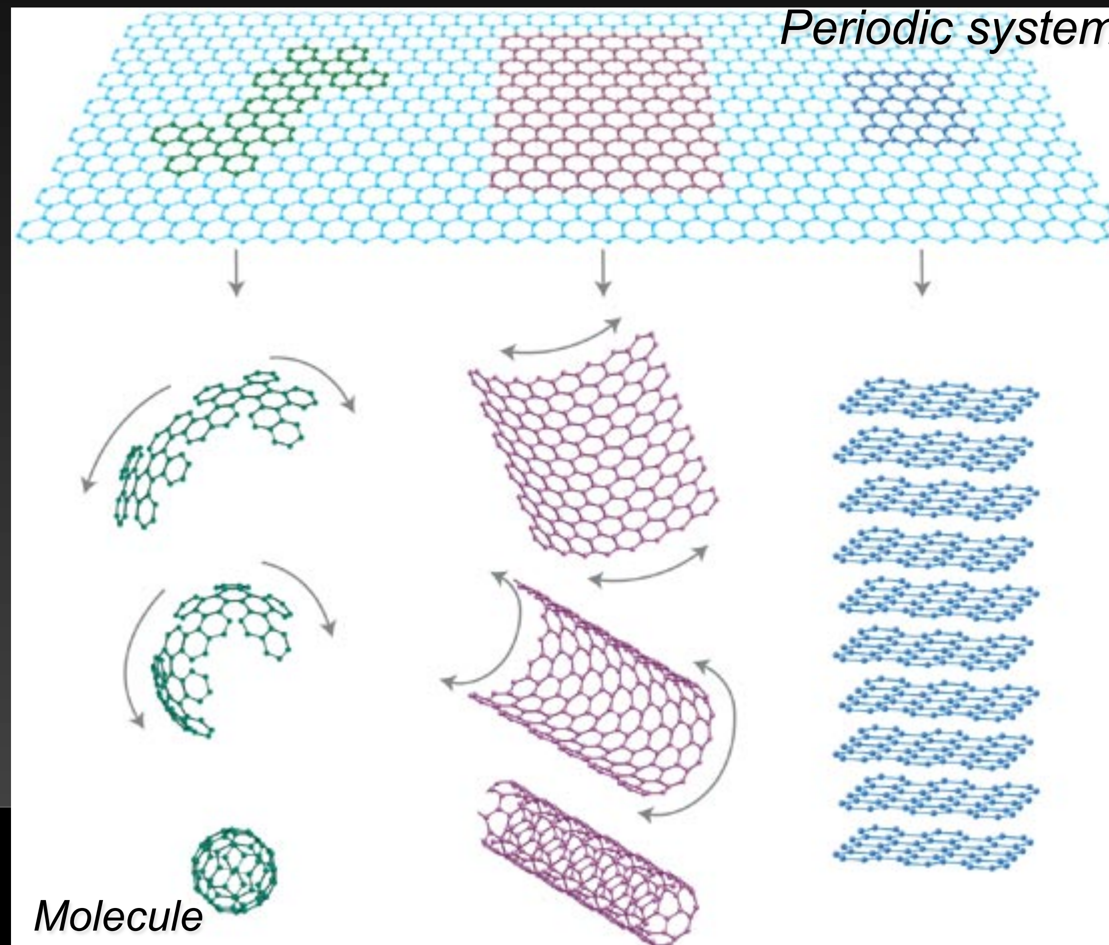
2004 –Graphene 2D

1991 -Carbon nanotubes 1D

1985 –Buckyballs - 0D

The rise of graphene
Geim and Novoselov
Nature Mat. 6 2007

Nobelprize.org
The Official Web Site of the Nobel Prize



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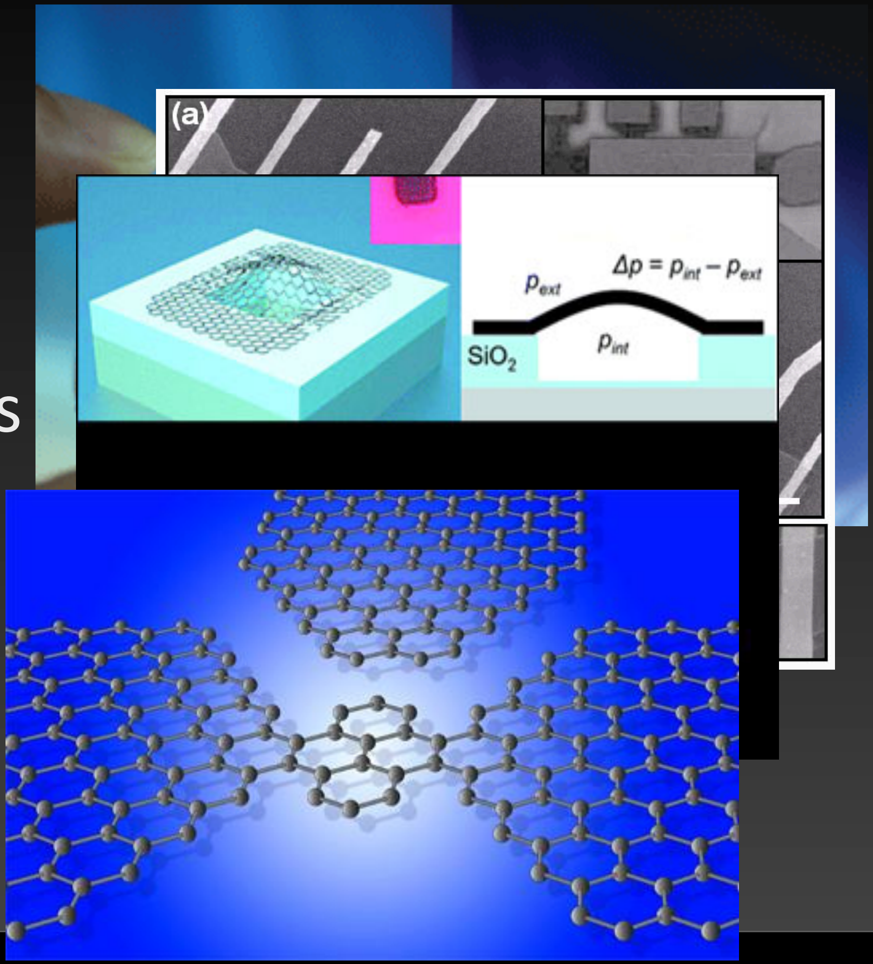
?

Unusual material

- Strictly 2-dimensional material
- High mobility, $\mu \approx 2x10^5 cm^2/Vs$ *Bolotin et al, Solid State Comm(2008)*
- Thermal conductivity, $\kappa \approx 5x10^3$ W/mK *Balandin et al, Nano Lett(2008)*
  - Comparison to diamond $\kappa \approx 3x10^3$ W/mK
- Resilience to strain, $\sigma_{intrinsic} \approx 130$ GPa *Changgu et al, Science(2008)*
- New physical effects
- Recommended reading:
  - Andre Geim, "Graphene: Status and Prospects, Science **324**, 1530 (2009)

Wide ranging applications

- Stretchable displays
- High frequency devices
- Sensors (e.g. pressure)
- Energy storage; ultracaps
- CMOS electronics
- Non volatile memory
- Biotechnology
- Coatings



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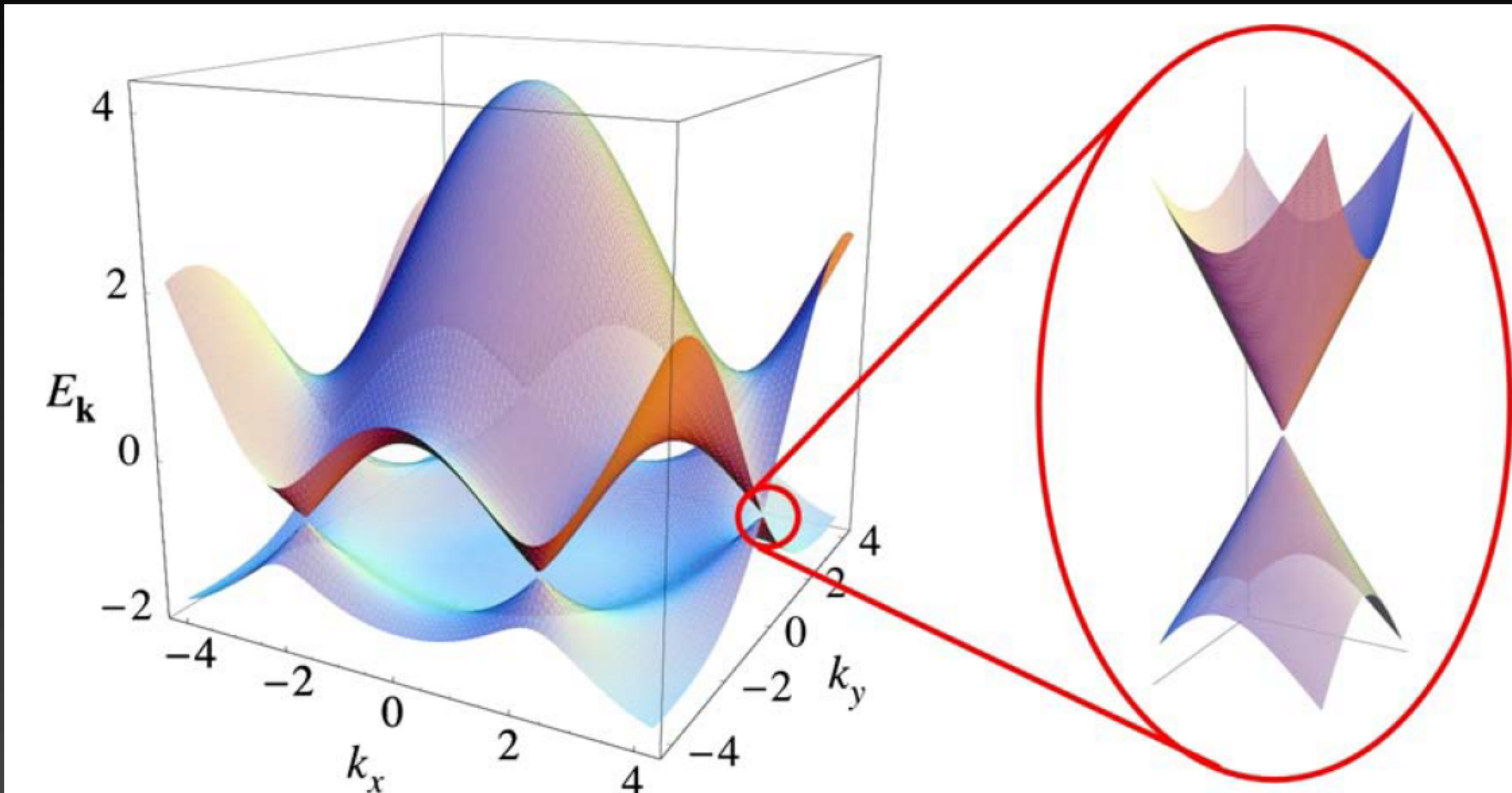
Electronic structure



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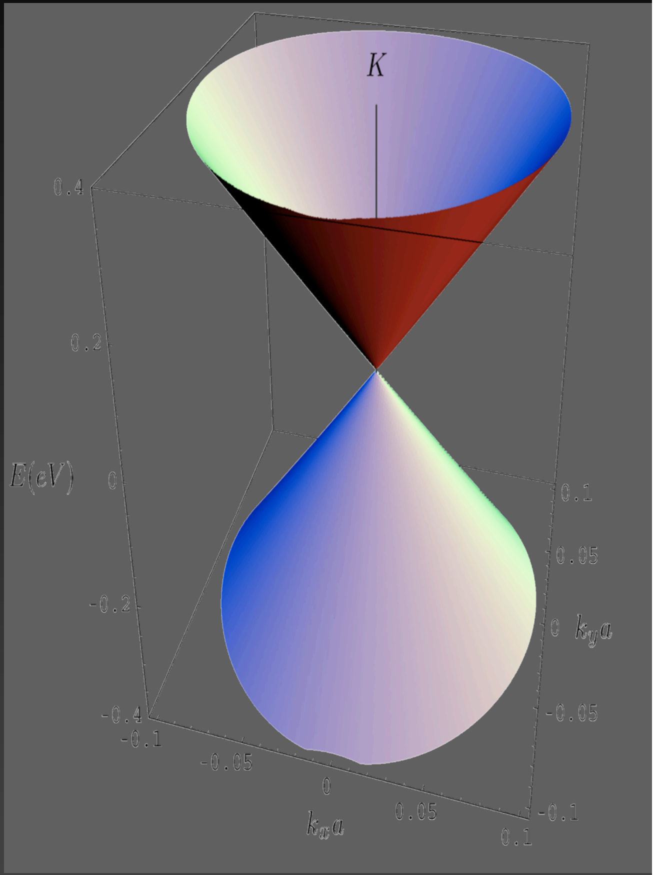
Electronic structure

- Conduction & valence band touch in K,K', "Dirac-Points", making a semimetal
- $E_k \approx \pm \mathbf{v_F k}$ + higher order terms
  - Dispersion of massless particles
  - Analogy to relativistic physics
  - $v_F \approx 10^6$ m/s ≈ c/300

$$E_\pm(p) = \pm v_F \sqrt{p_x^2 + p_y^2} = \pm v_F p$$

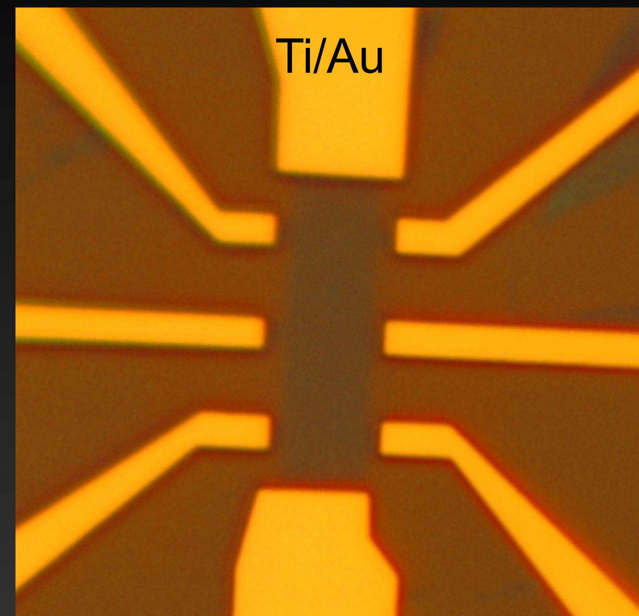
$$E_\pm(p,m) = \pm\sqrt{m^2 {v_F}^4 + {v_F}^2 p^2} \quad \text{with} \quad m = 0$$

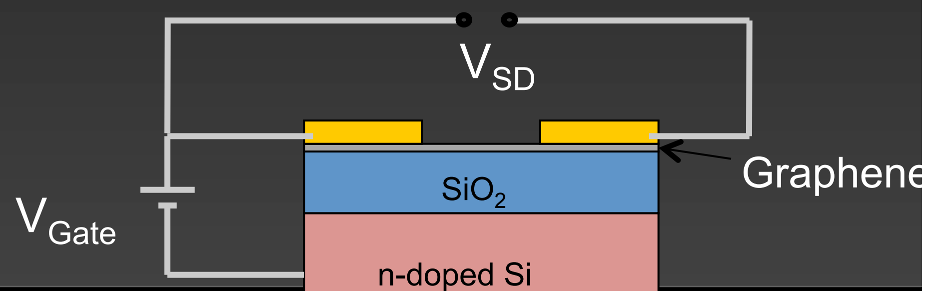
$$v_F = \frac{3ta}{2} \approx c/300$$



Graphene Field Effect Transistor

- Optical or ebeam lithography
- Standard semiconductor processing
- Field effect devices
- Control amount of charge in the system
- For 300nm oxide
  - $n \approx 0.7x1011 cm^{-2}V^{-1}$





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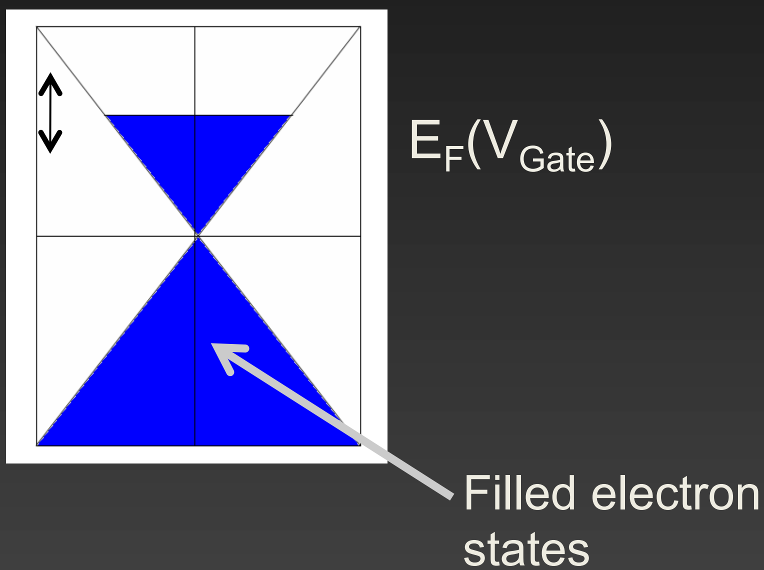
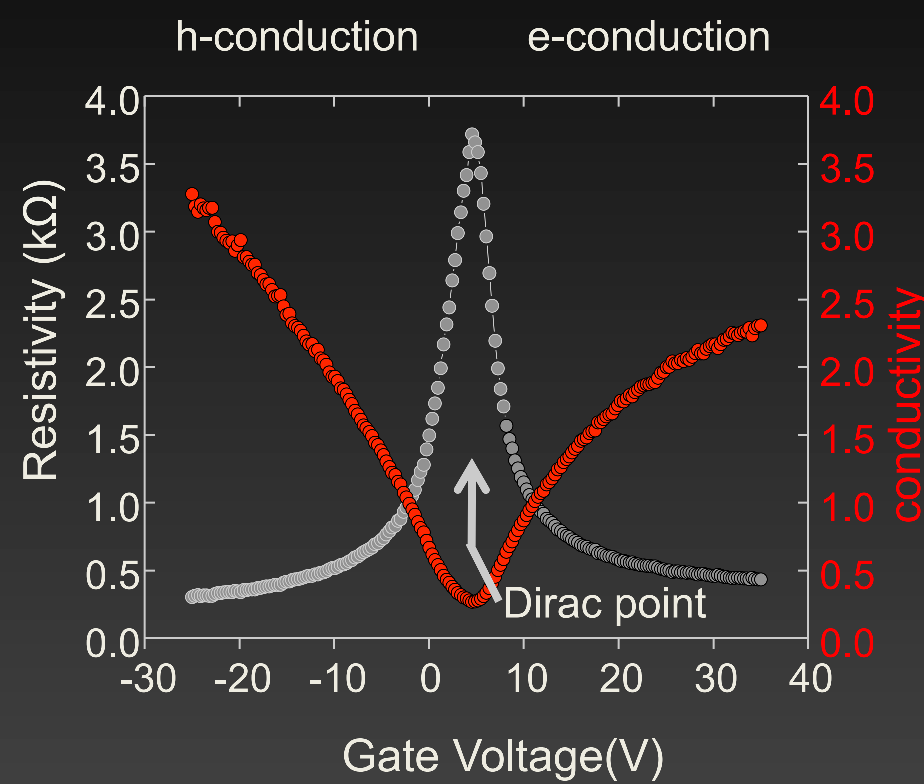
Transport

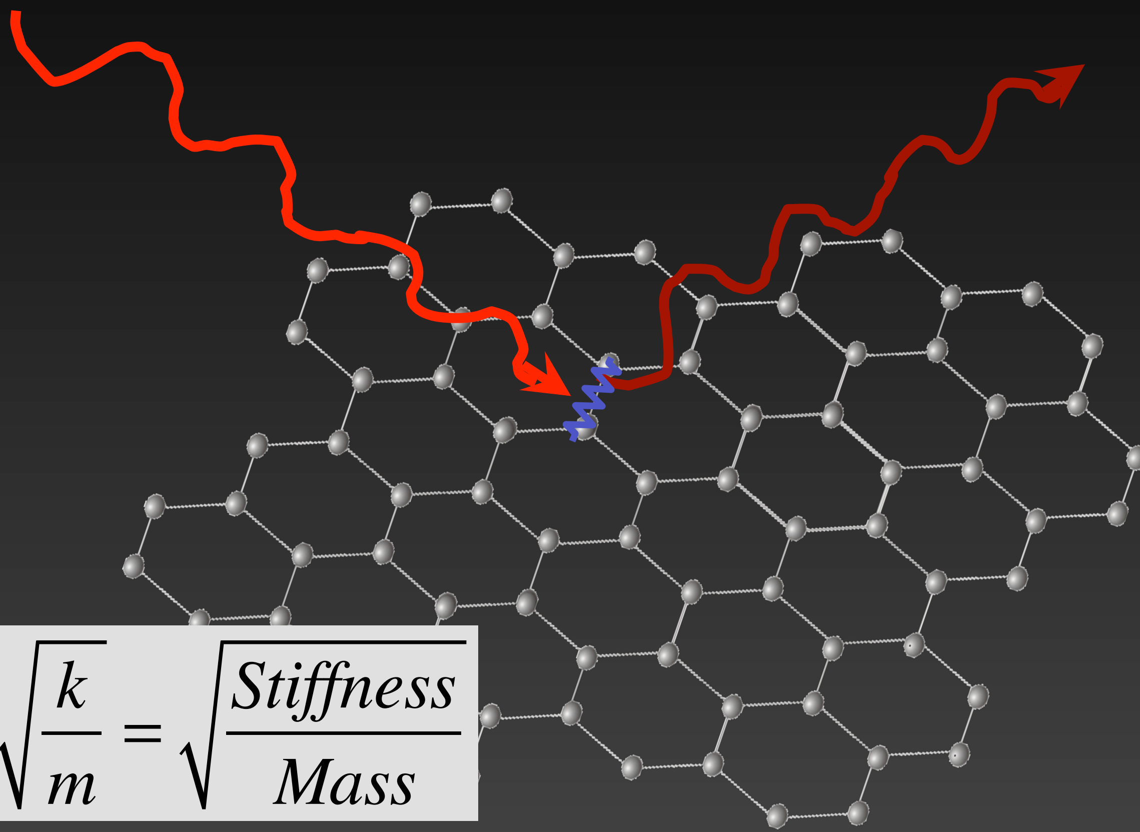
- V_{gate} determines Fermi energy E_F
- Change type of charge carrier





How we use light to study materials

Raman Scattering in Graphene



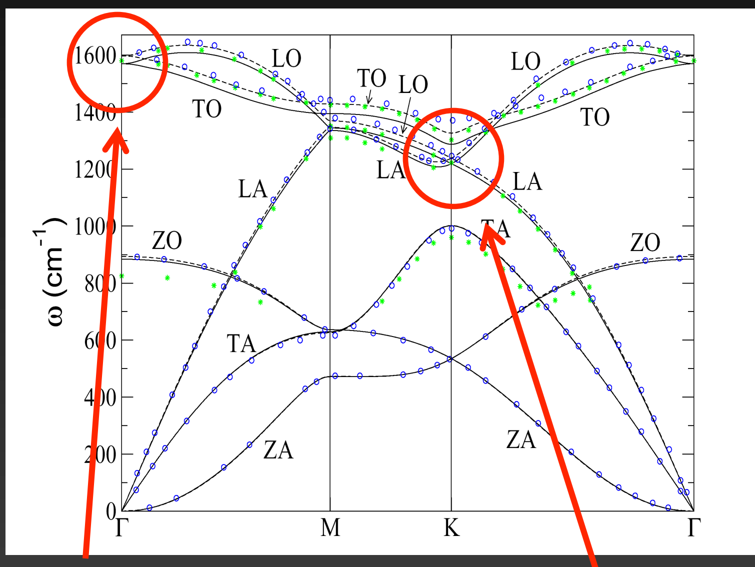
$$\lambda_{out} = \lambda_{in} \pm \lambda_{ph}$$

- Lattice structure
- Non-invasive, local probe
- Elastic properties
- Electron-phonon coupling
- . . .

$$\omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{Stiffness}{Mass}}$$

Phonons in Graphene

Phonon band structure of graphene

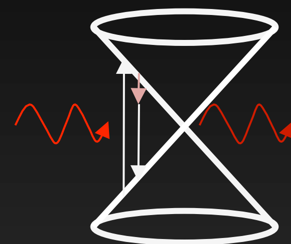


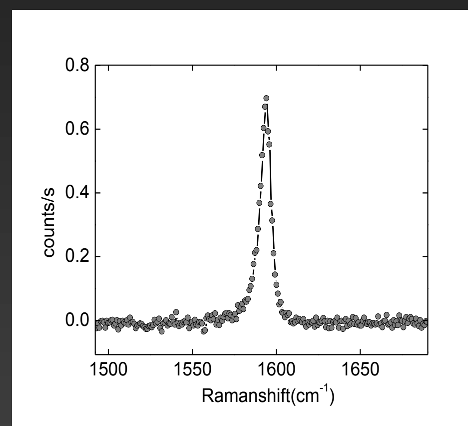
0 momentum phonons, G-Band

2D Band
G' Band
D* Band

G Band

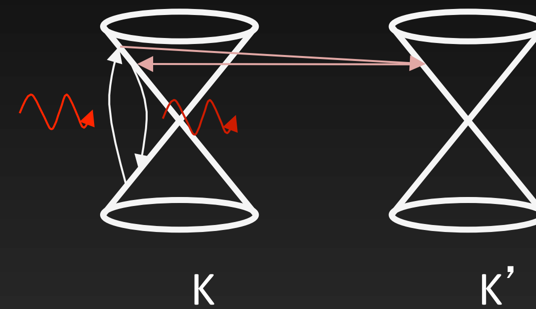
1st order process

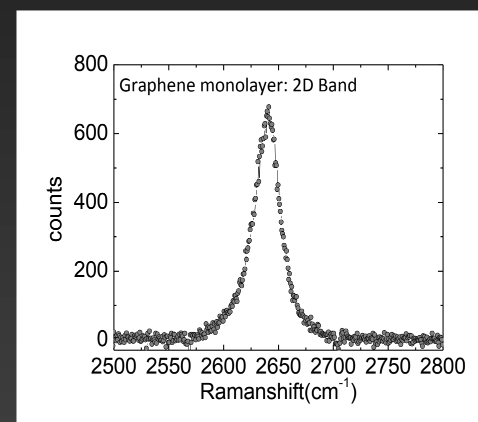




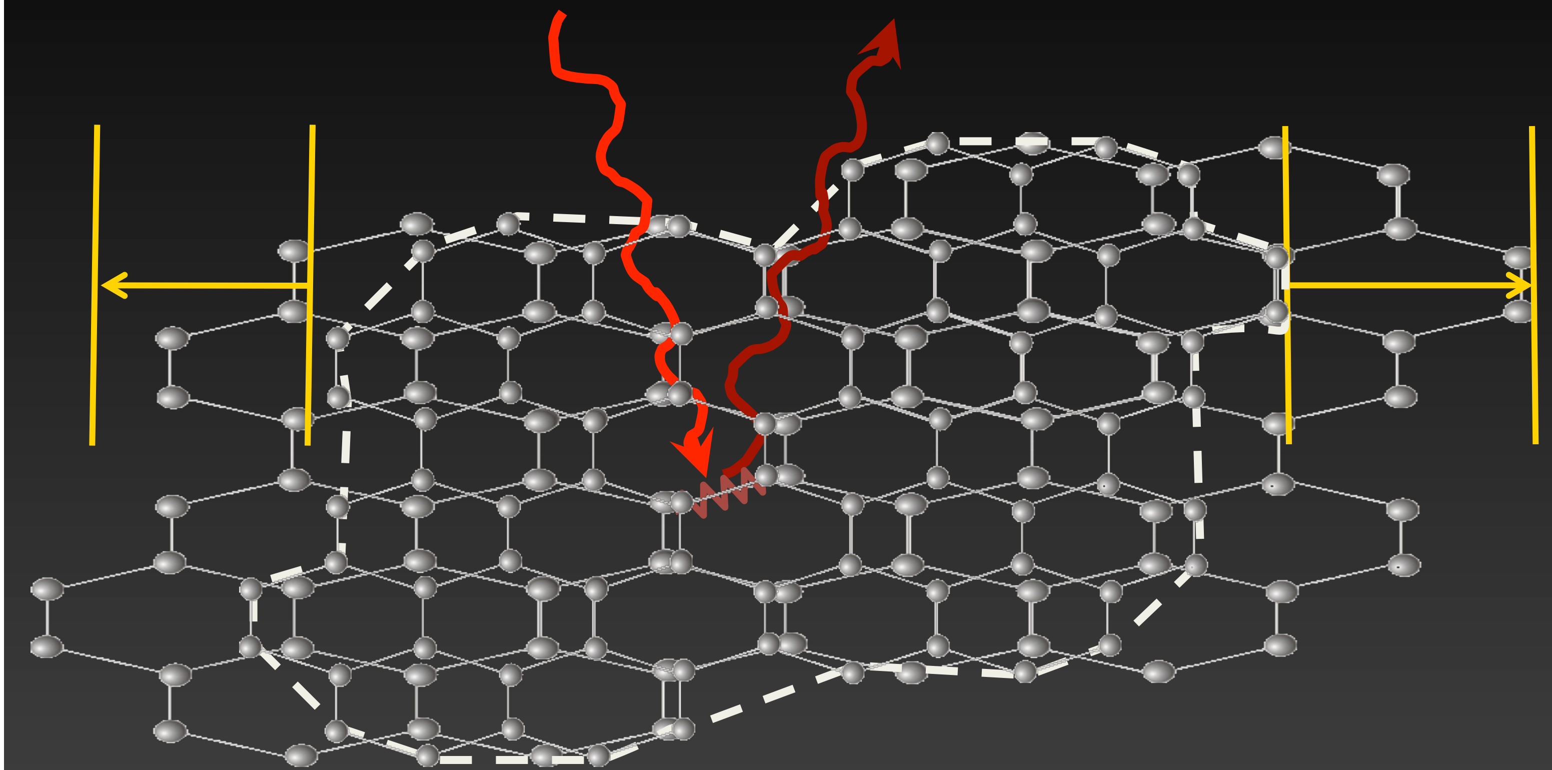
2D Band

2nd order process, E_{2g}





Raman scattering and strain response of graphene



- Place uniaxial strain on graphene: symmetry of lattice broken
- Raman is sensitive tool to monitor strain!

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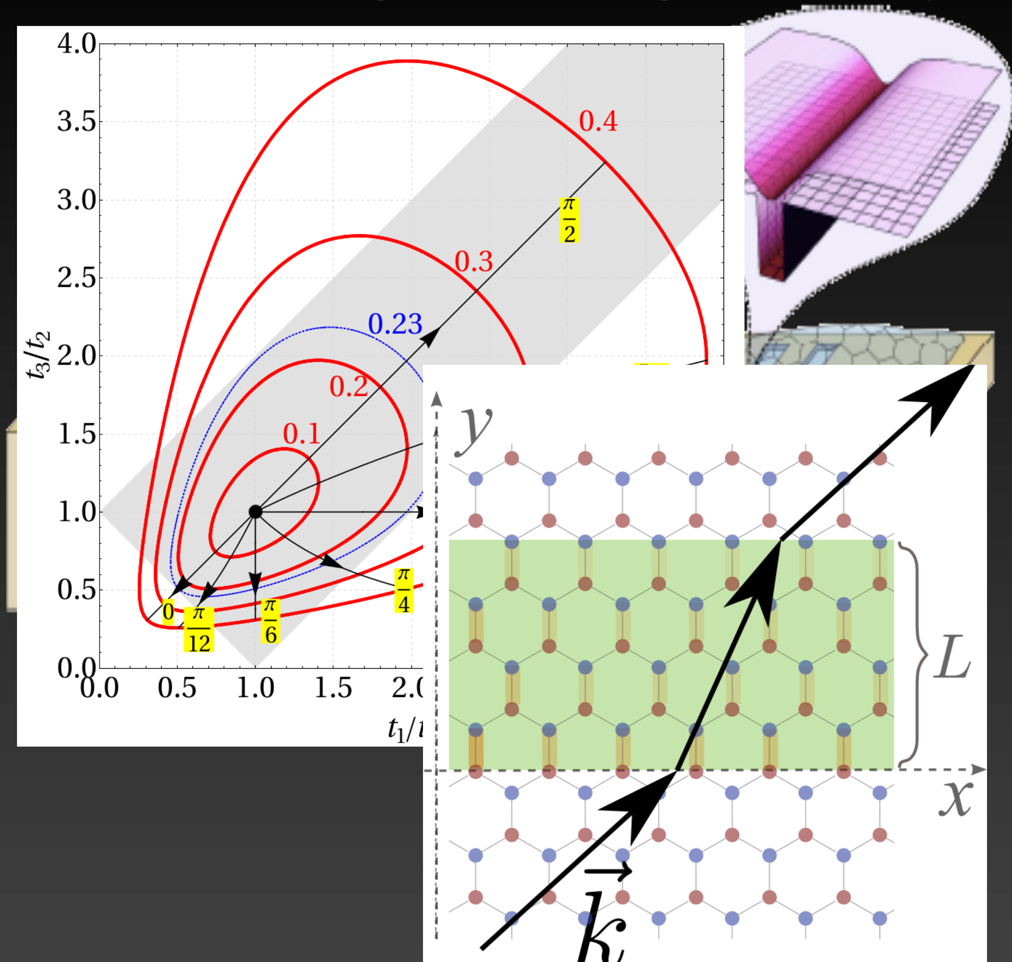
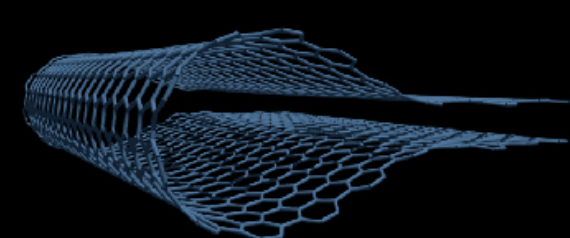
Strain Engineering of Graphene – a New Toolset



- Strain! Confinement, 1D channels, collimation,…
- Substrate patterned, not graphene
- Anisotropic in-plane hopping
- But…Challenges…
- Require high strain
- But.. Opportunities… transport



"All-graphene integrate circuits via strain engineering" by Vitor M. Pereira and A. H. Castro Neto, *Phys. Rev. Lett.* 103, 046801 (2009).

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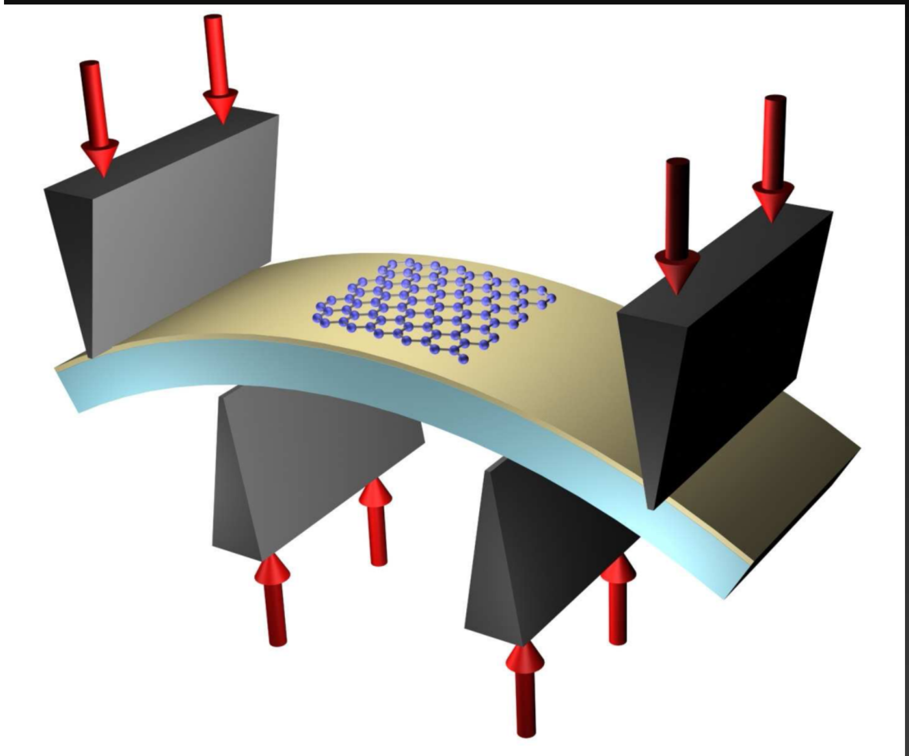
Strain measurements in graphene

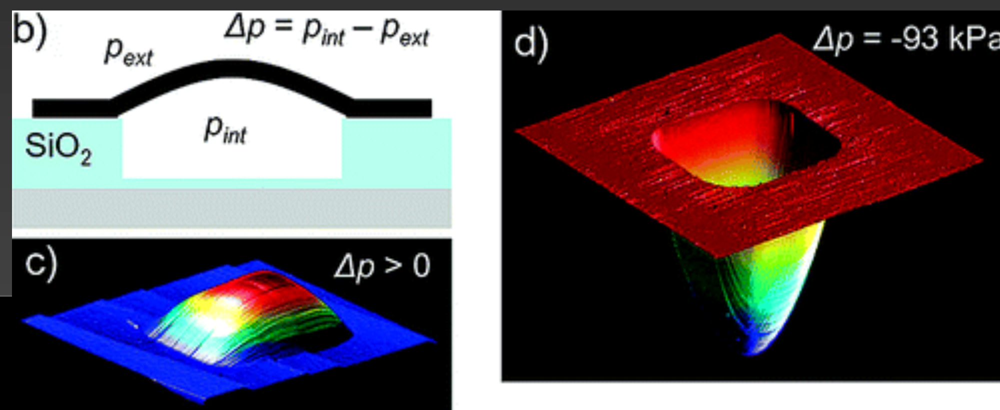


Mohiuddin, Ferrari

- Uniaxial strain in single layer on SU8, PDMS
- G, 2D soften with strain
- Degenerate G phonon splits into polarization dependent lines

Graphene as impermeable membrane

- Graphene sealed micro chamber
  - Impermeability to gases
  - Confirmed even for He
- Pressure difference causes graphene membrane to bend
- Measurement of deflection
  - Direct detection (optical)
  - Measure capacitive change in the graphene – Si system



Bunch et al, Nano Lett. 2008

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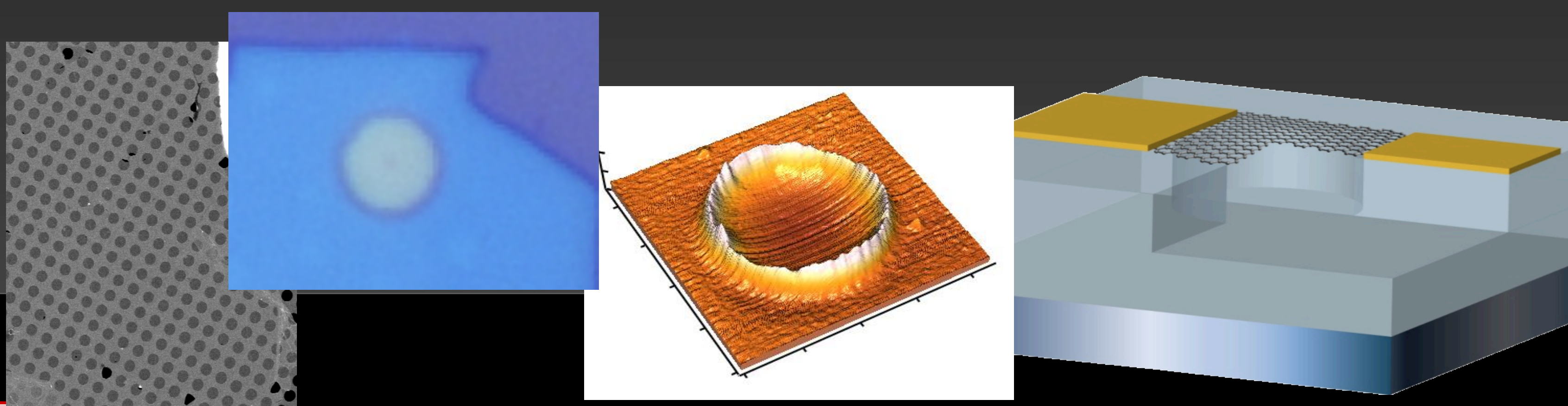
Graphene membranes as micro- and nano- pressure sensors

- Environmental testing of graphene material, membranes and devices
- Graphene membrane fabrication
- Measurement of fundamental mechanical properties of graphene membranes
- Demonstration of capacitance pressure sensing



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How graphene slides: Measurement and theory of frictional forces between graphene and SiO_2

Alex Kitt, Zenan Qi, Sebastian Remi, Harold Park, Anna Swan, Bennett Goldberg

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How graphene slides: Measurement and theory of **frictional forces** between graphene and SiO_2

Alex Kitt, Zenan Qi, Sebastian Remi, Harold Park, Anna Swan, Bennett Goldberg

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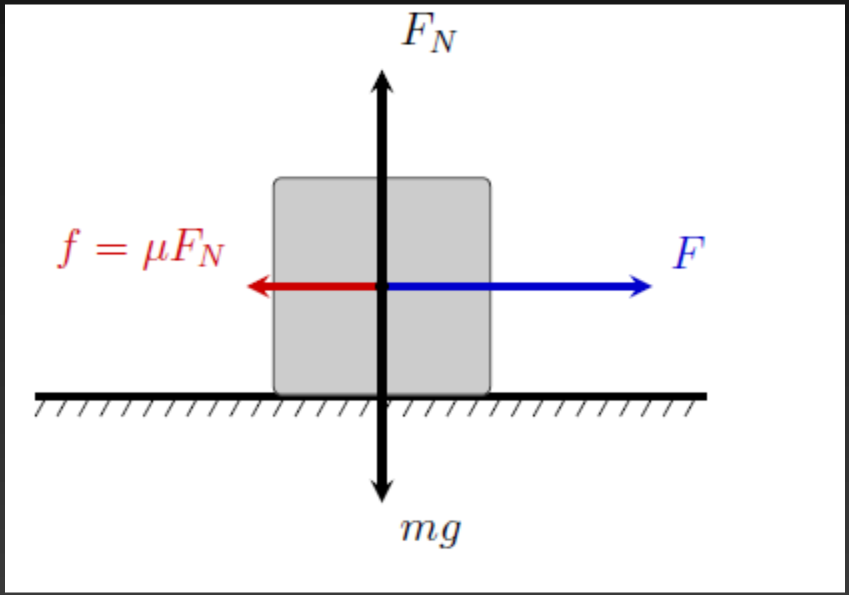
Friction 101



Amontons' (macroscopic) Laws:

Friction is…

1. Proportional to applied load, F_N
2. Independent of contact area

Friction 801

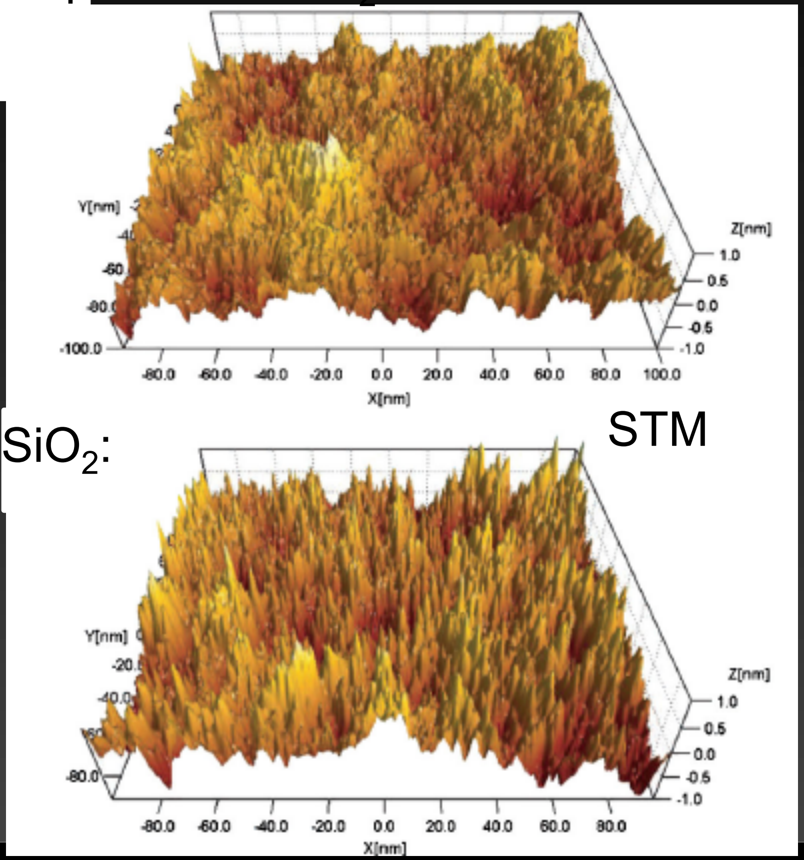
$$F = \mu F_N$$ Macroscopic

$$F_N \sim A_c$$

$$F = \eta \upsilon A_c$$ Microscopic

Krim *Langmuir* **12**, 4654 (1996)

Graphene on SiO_2:



SiO_2:

STM

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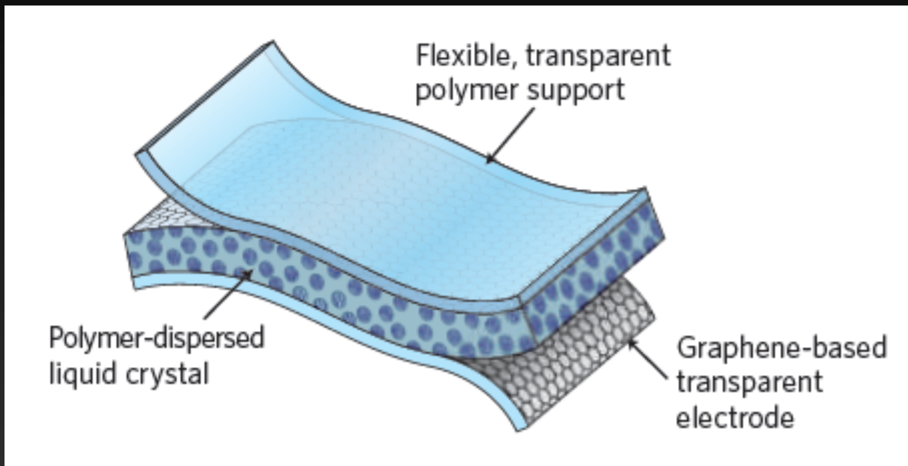
What happens when load isn't needed for perfect conformation?

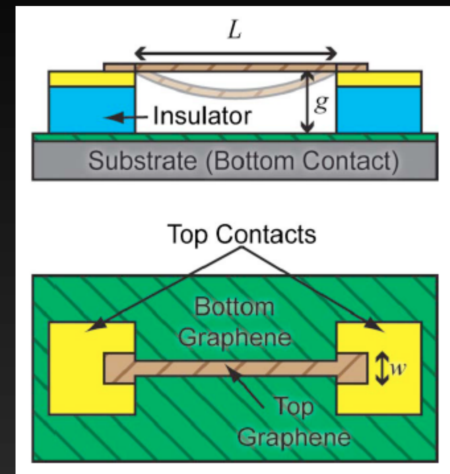
Frictions role in graphene devices

Flexible polymer dispersed liquid crystal device:



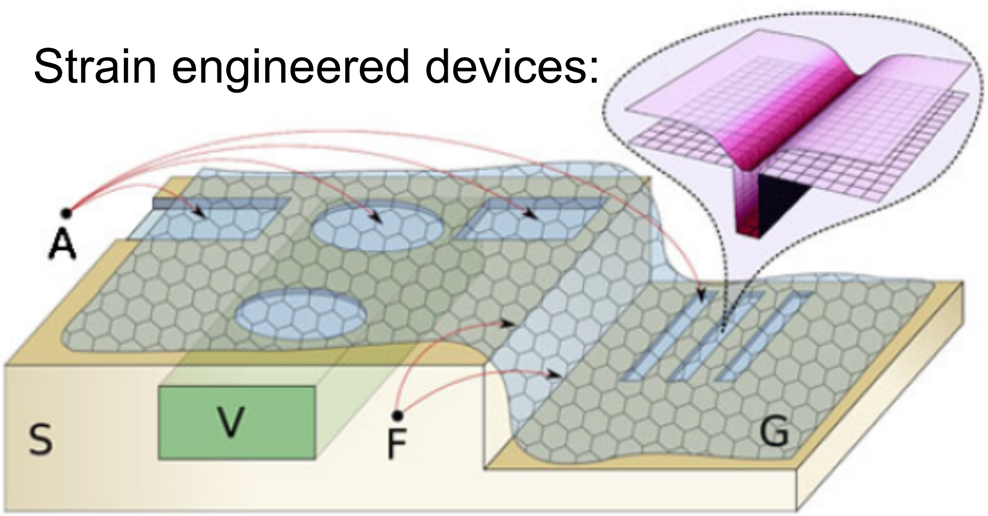
Bonaccorso et al. *Nature Photon.* **4**, 611 (2010)

Graphene mechanical switch:



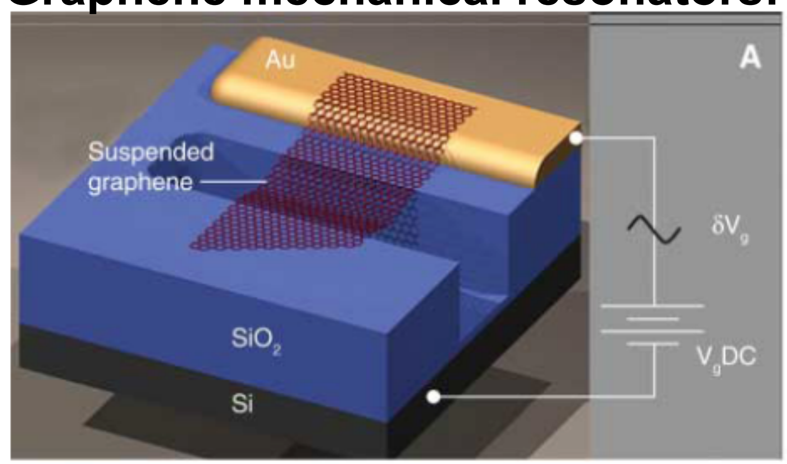
Milaninia et al. APL **95**, 183105 (2009)

Strain engineered devices:



Pereira an

Graphene mechanical resonators:



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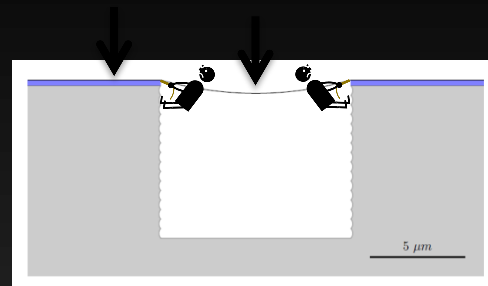
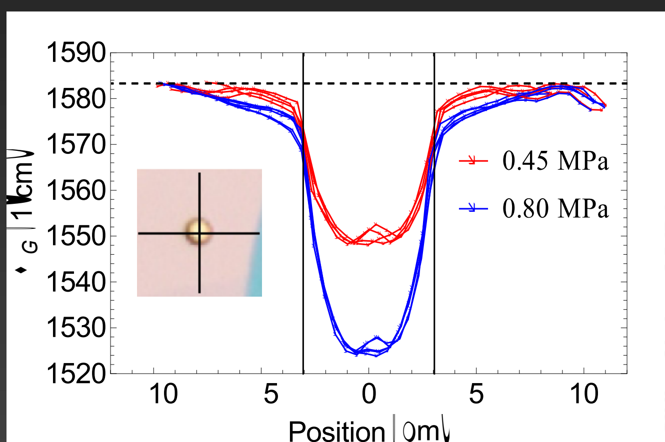
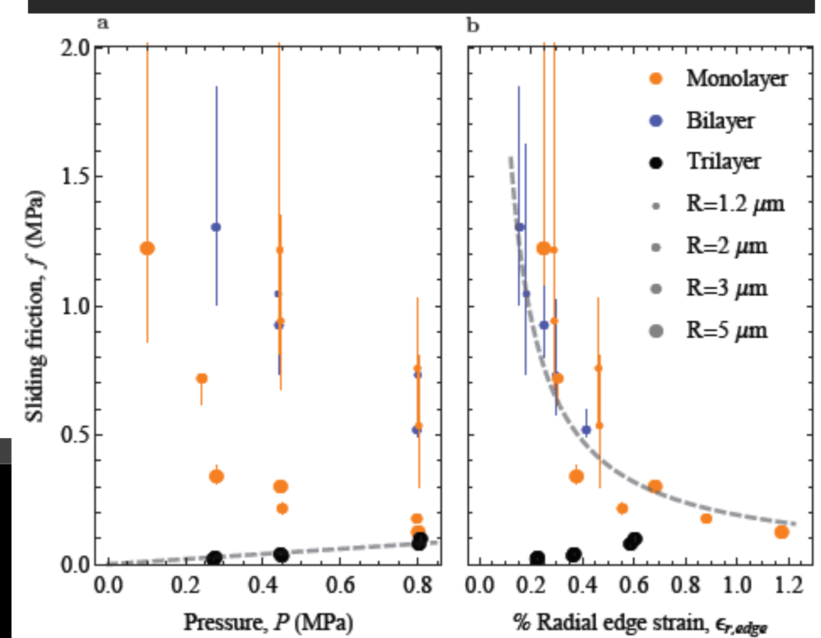
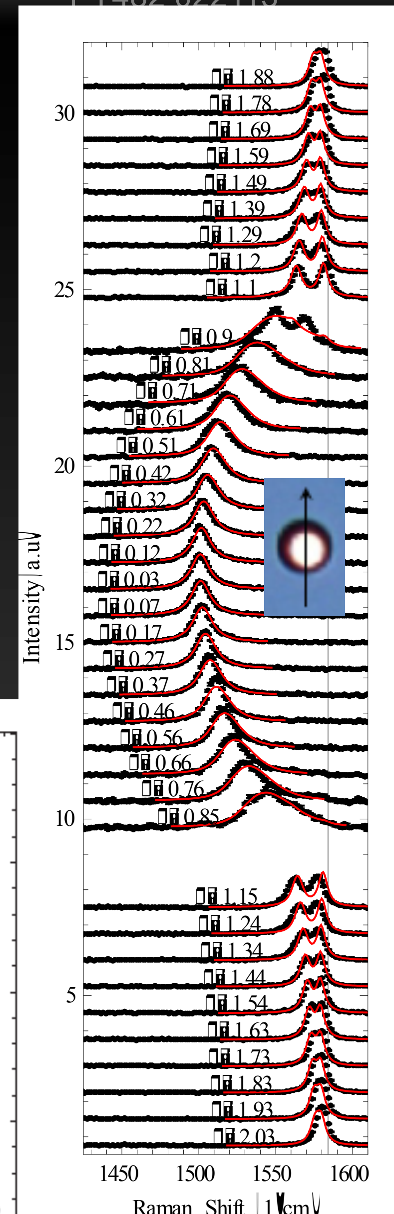
Outline

1. Experiment
2. Qualitative observations
3. Modeling
4. Pressure and strain dependence of friction









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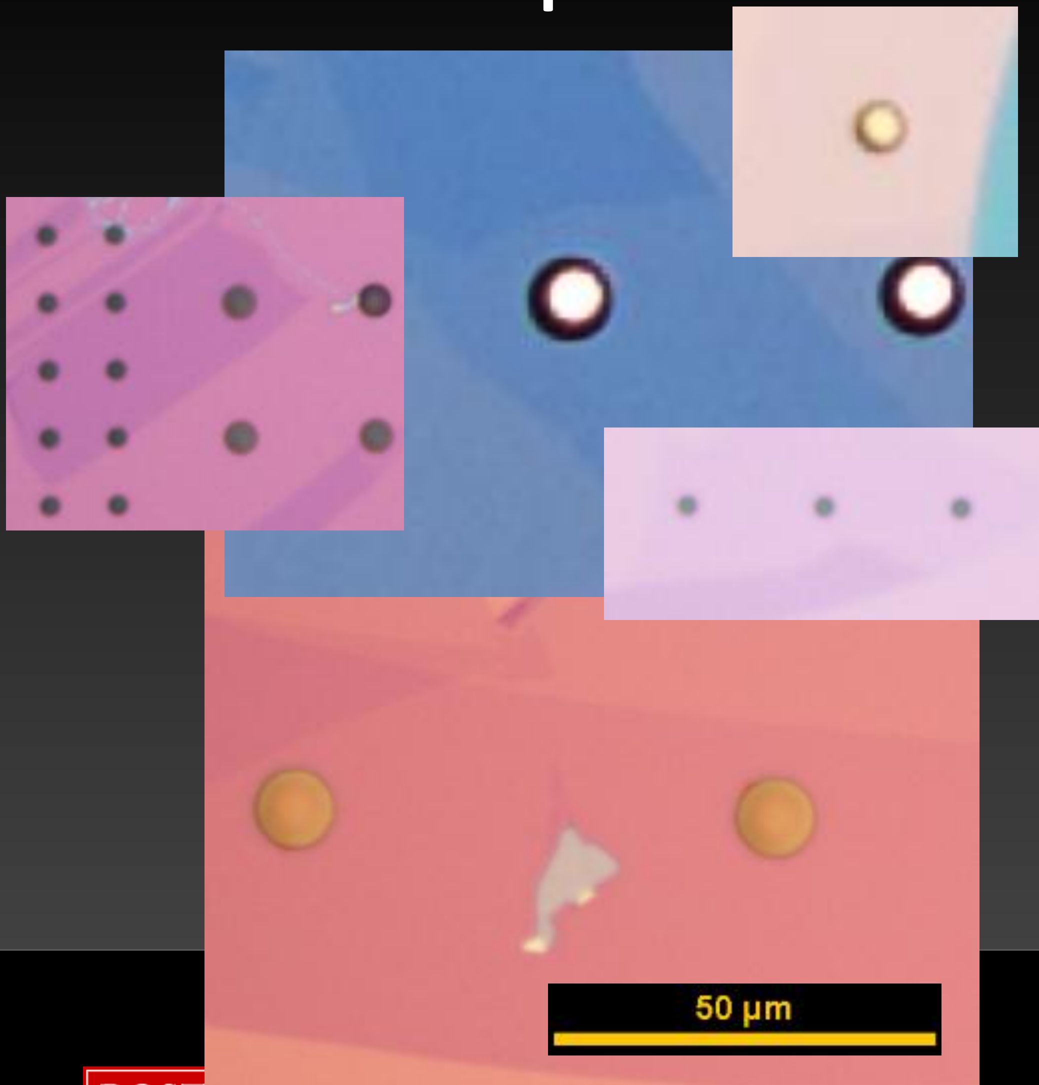
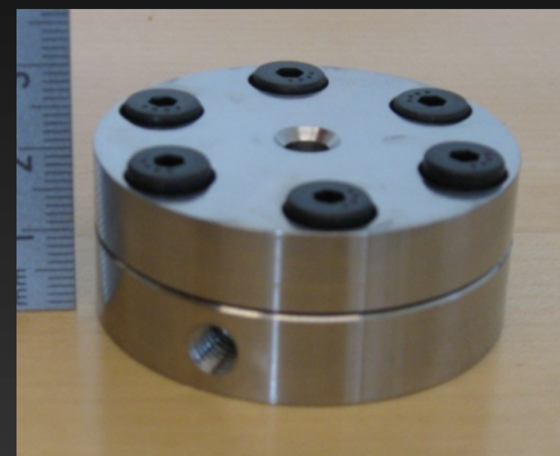
Experimental Design



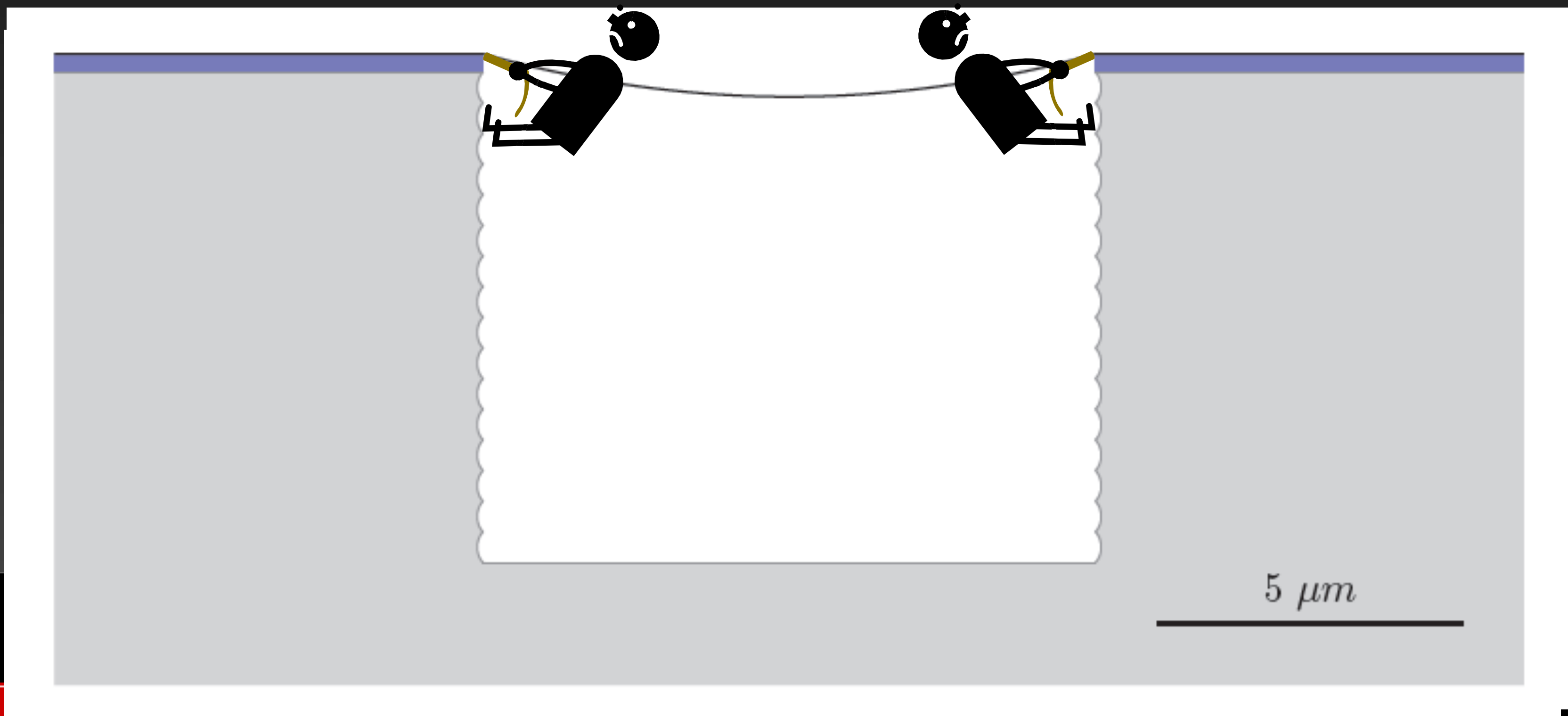


0.1-0.8 MPa
15-100 psi
N_2 gas

Dual role or pressure

Pressure acts as a load

Pressure pulls graphene

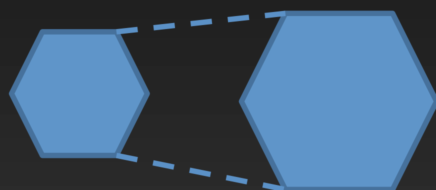


Raman G band strain response

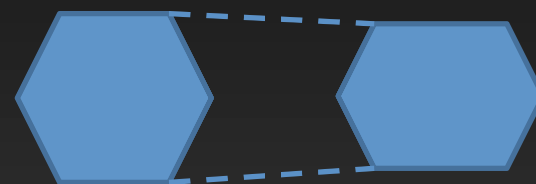
Perturbing the inter-ionic forces with strain:

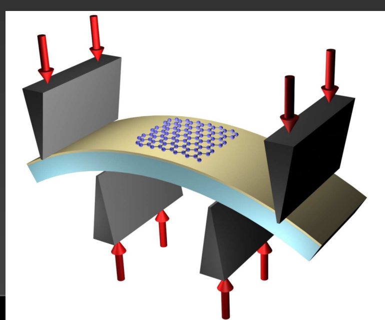
$$\Delta\omega_G = -\omega_0\gamma(\epsilon_{xx}+\epsilon_{yy}) \pm \frac{1}{2}\beta\sqrt{(\epsilon_{xx}-\epsilon_{yy})^2+4\epsilon_{xy}^2}$$

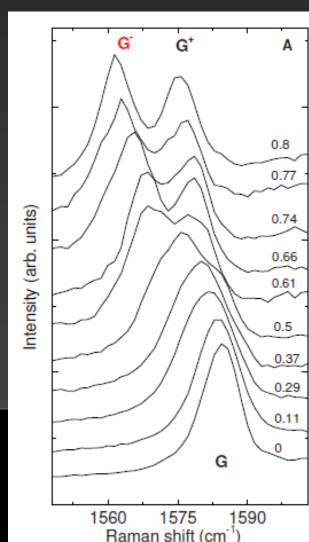
Biaxial strain



Shear strain



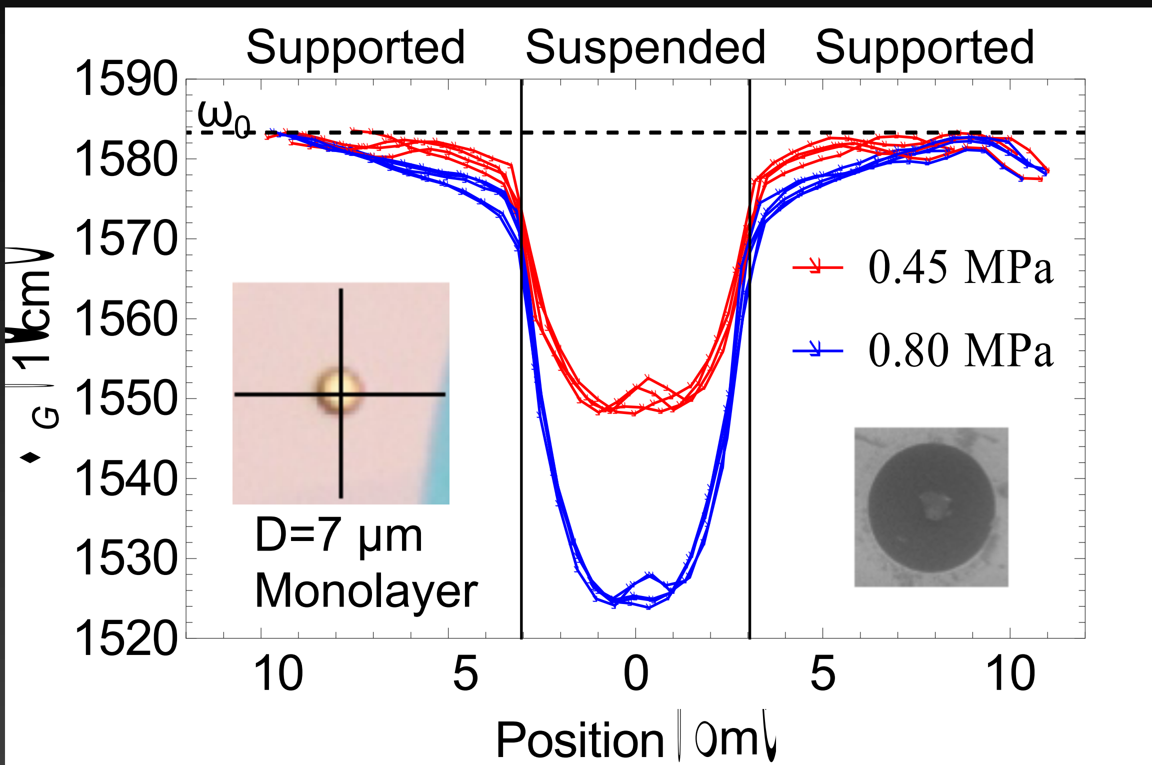




	γ	β
Huang *et al.* 2009	.69	.38
Mohiuddin *et al.* 2009	1.99	.99
Metzger *et al.* 2010	2.4	
Frank *et al.* 2010	2.01	1.01
Yoon *et al.* 2011	2.2	.93
Zabel *et al.* 2012	1.8	
Cheng *et al.* 2011	1.86	.96

Mohiuddin

Qualitative results: Sliding!



1. Supported graphene strained
2. Strain further distributed at higher pressure
3. Reproducible
   - Spatially
   - Temporally
   - 8 devices
     - 1,2, and 3 layers
     - R=1.2 to 5 μm

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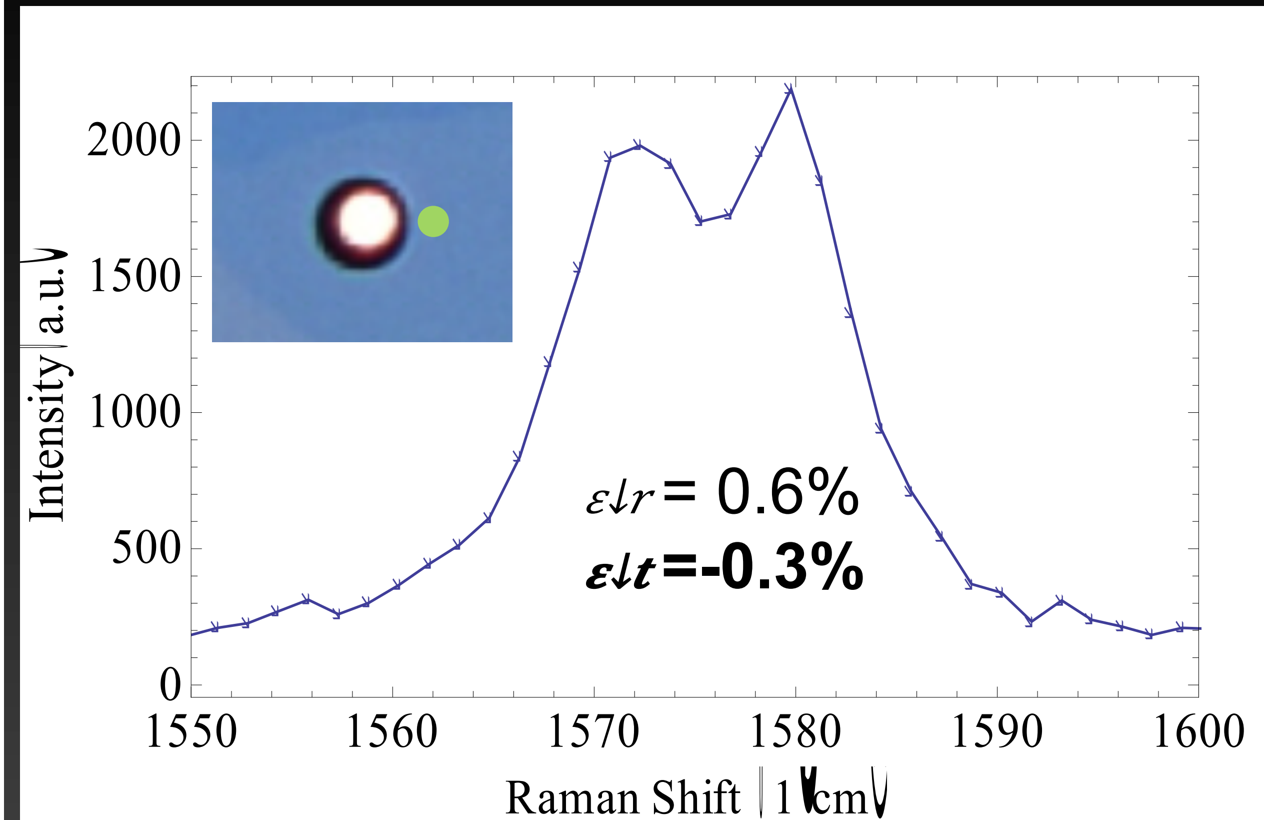
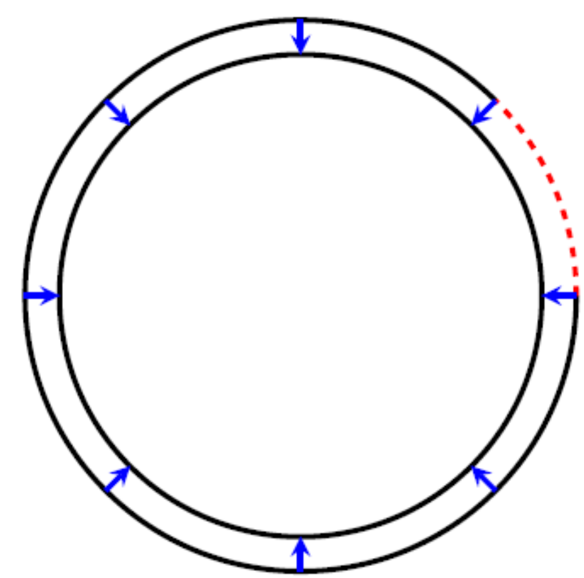
Compressive tangential strain

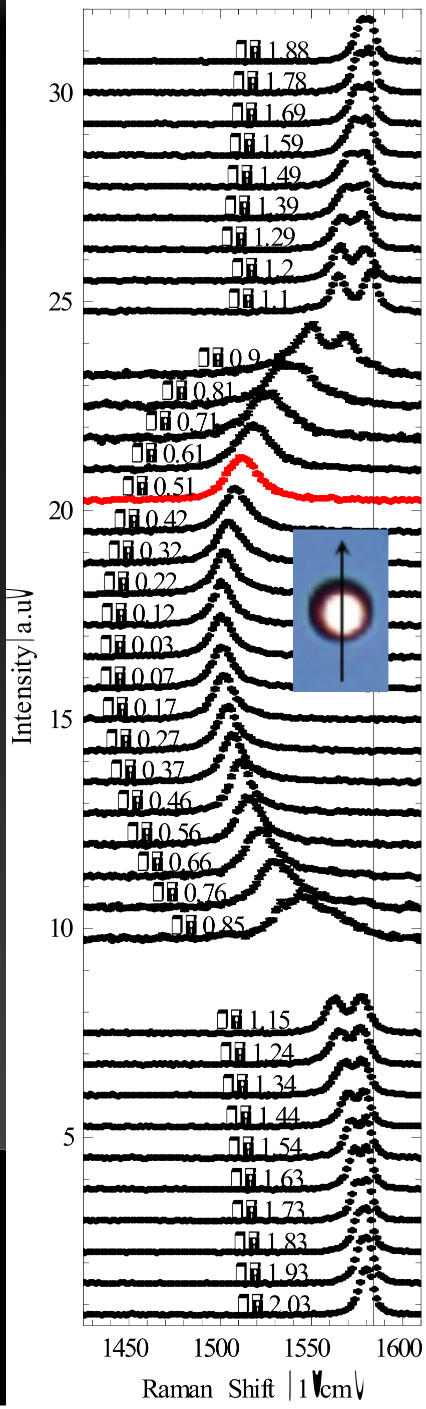




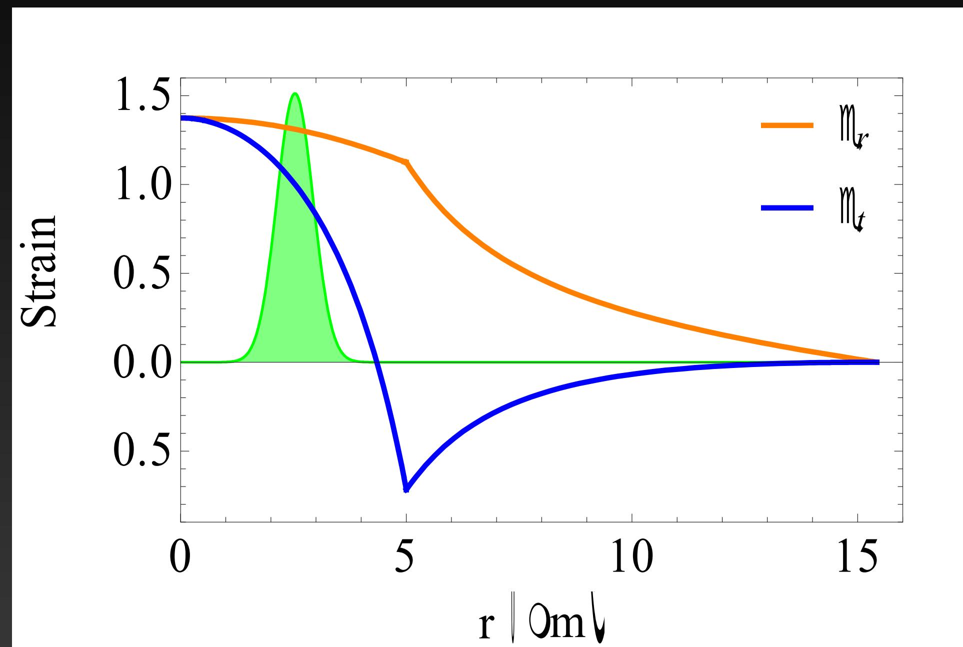
D=10 µm monolayer
P=.08 MPa=115 psi

Data

Supported



Suspended



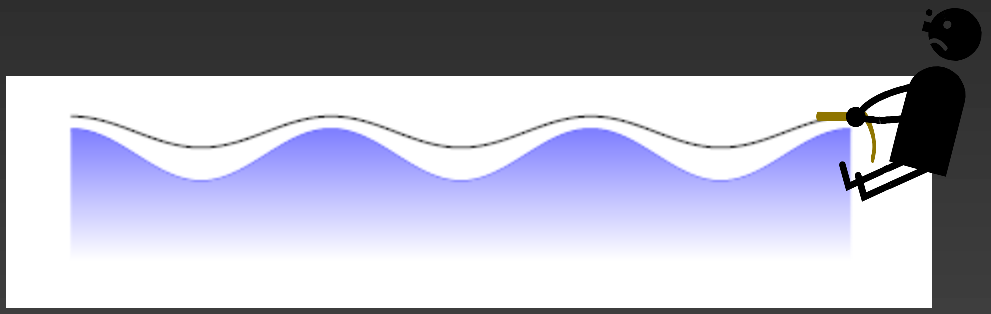
Supported

Can't simply invert spectra to get strains

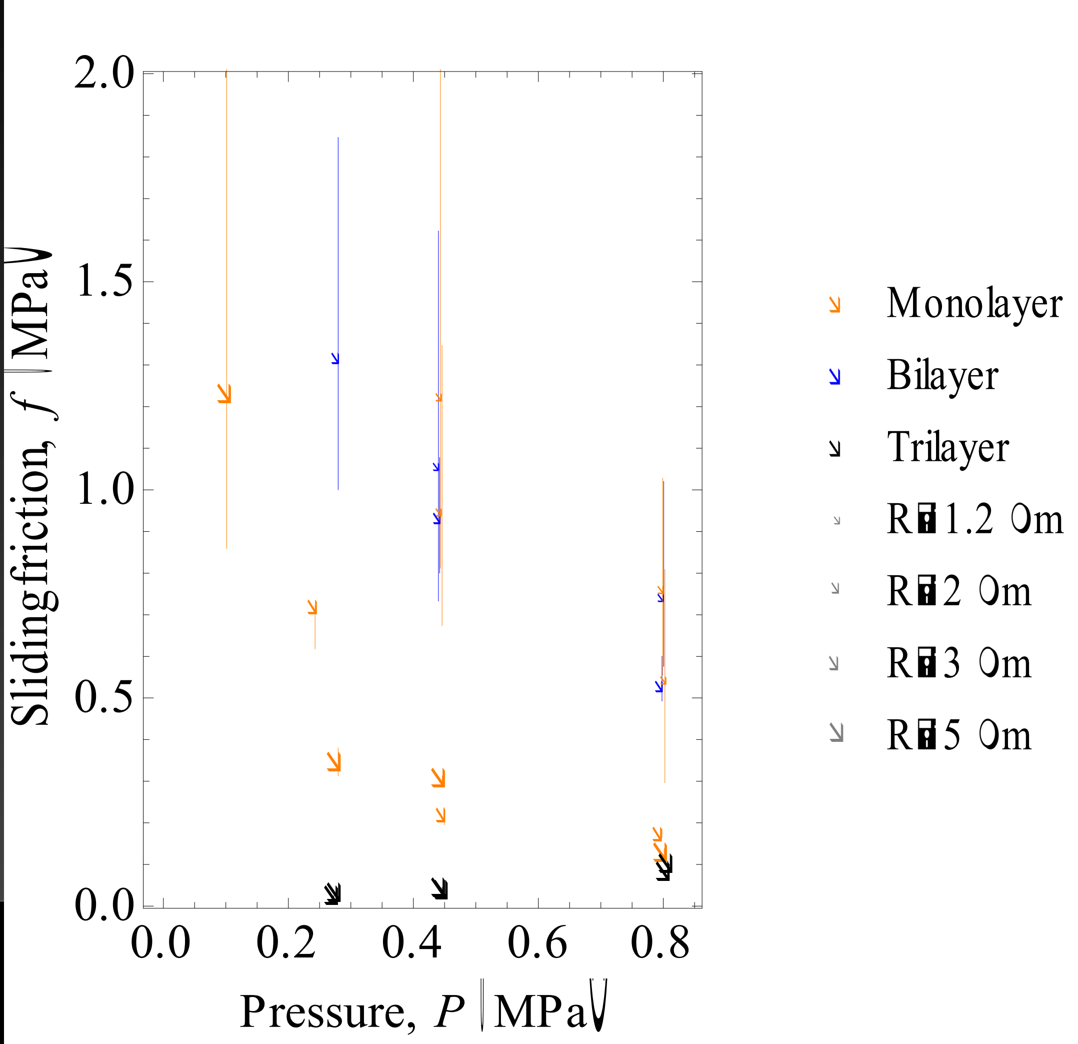
D=10 μm monolayer
P=.08 MPa=115 psi

Pressure dependence of friction

1. Trilayer graphene
2. Monolayer and bilayer graphene
3. Microscopic explanation



Pressure dependence



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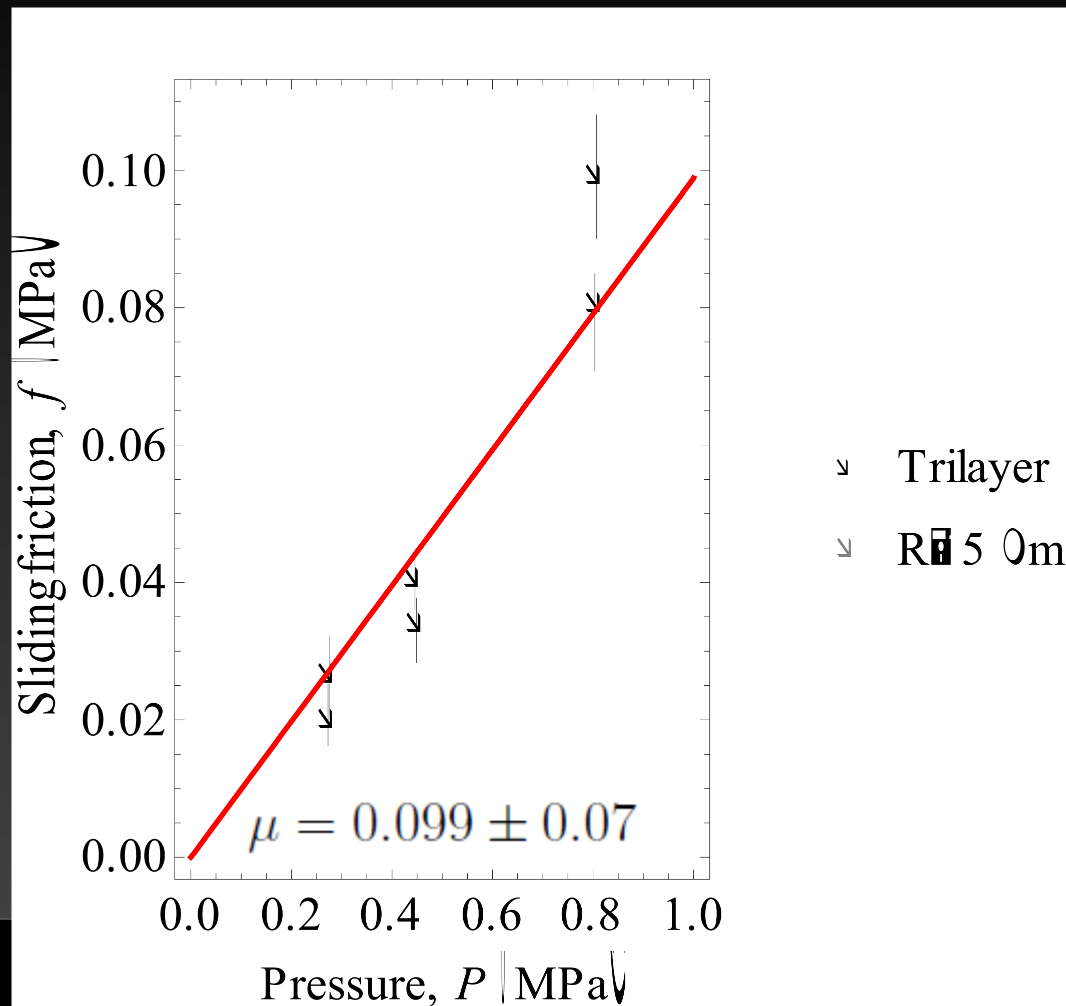
Trilayer graphene

Amontons' law:

$$F_f = \mu F_N$$

$$f = \mu P$$

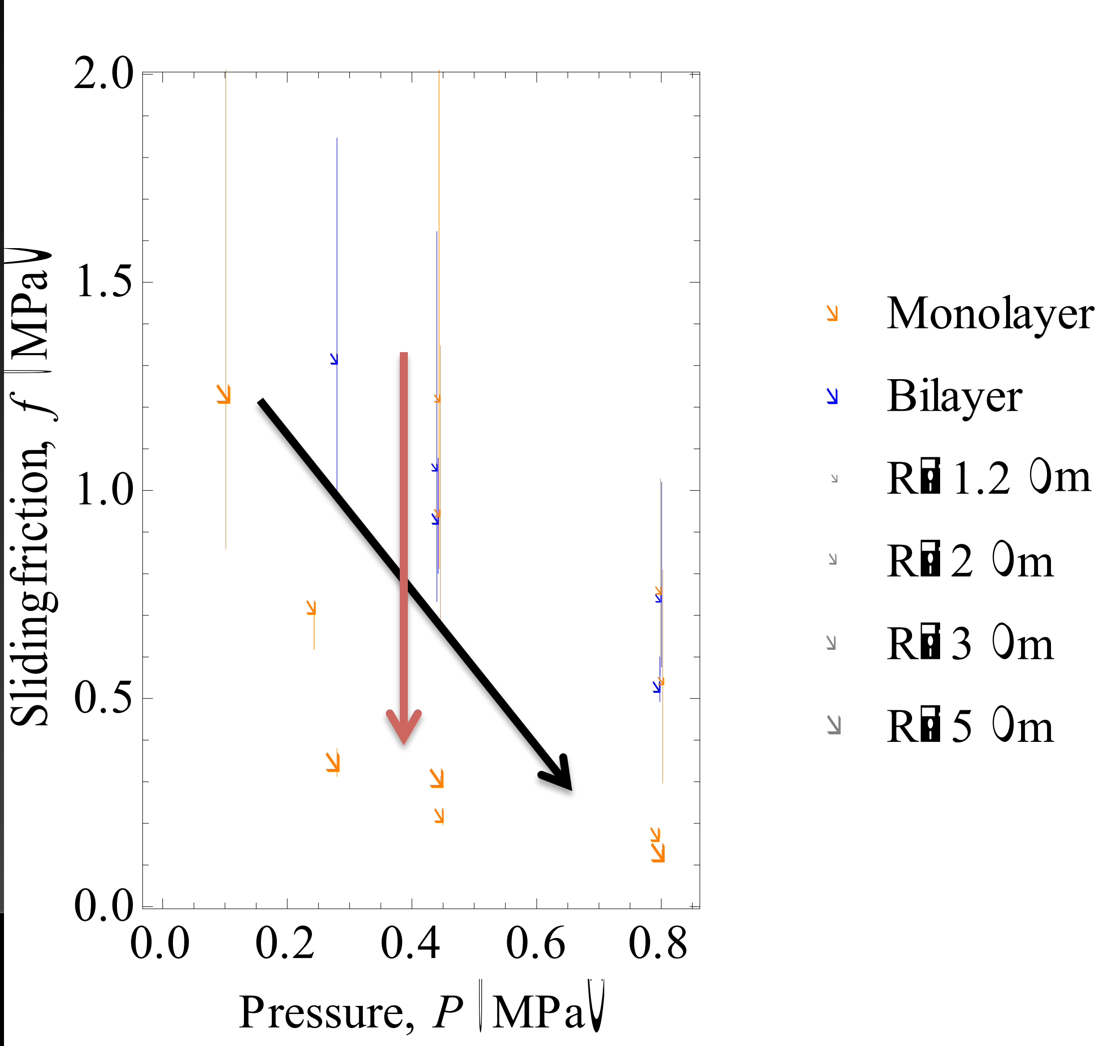
	μ
Teflon on Teflon	0.04
Trilayer on SiO2	0.1
Metal on Wood	0.2-0.6



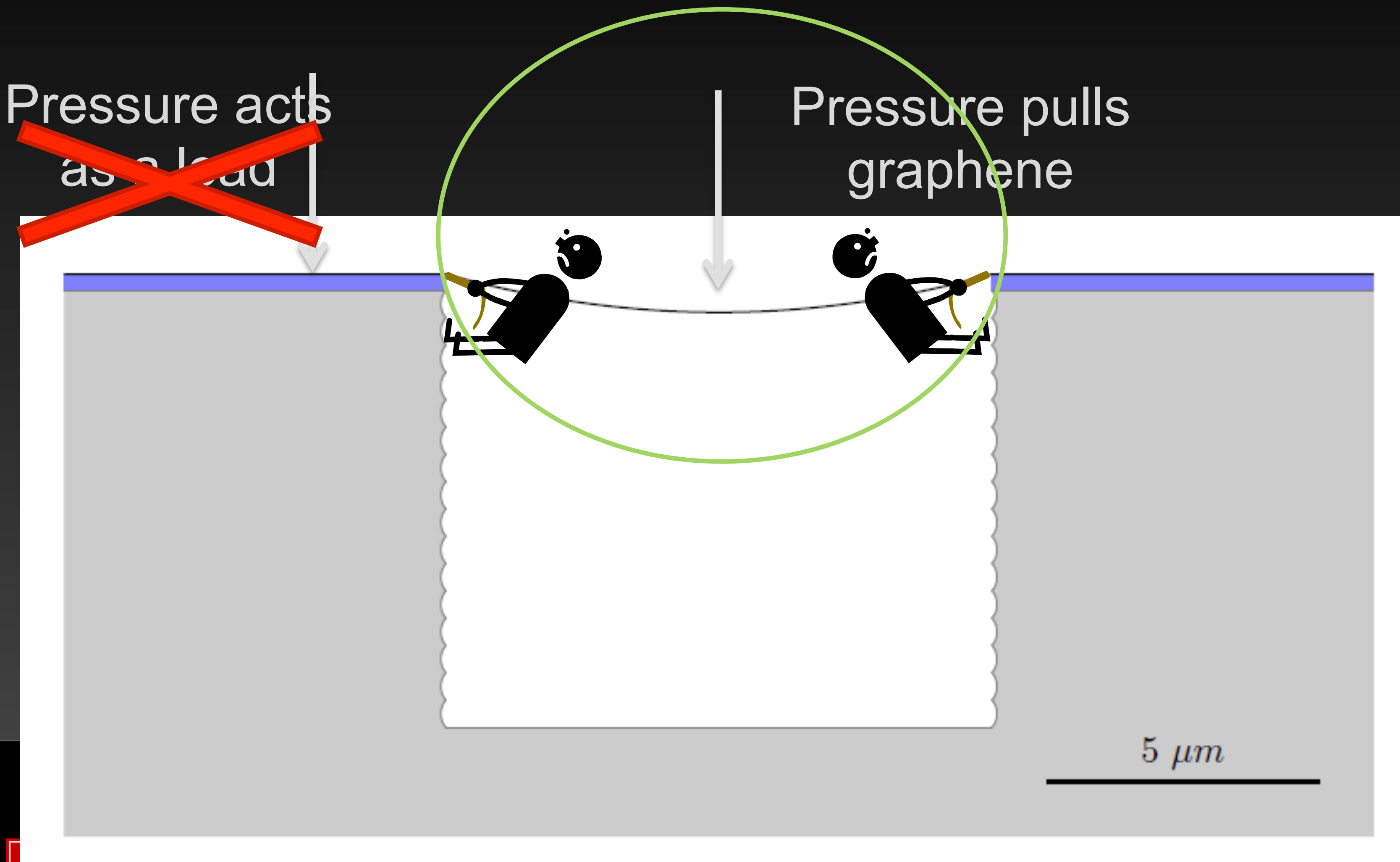
Monolayer and bilayer?

Sliding friction:

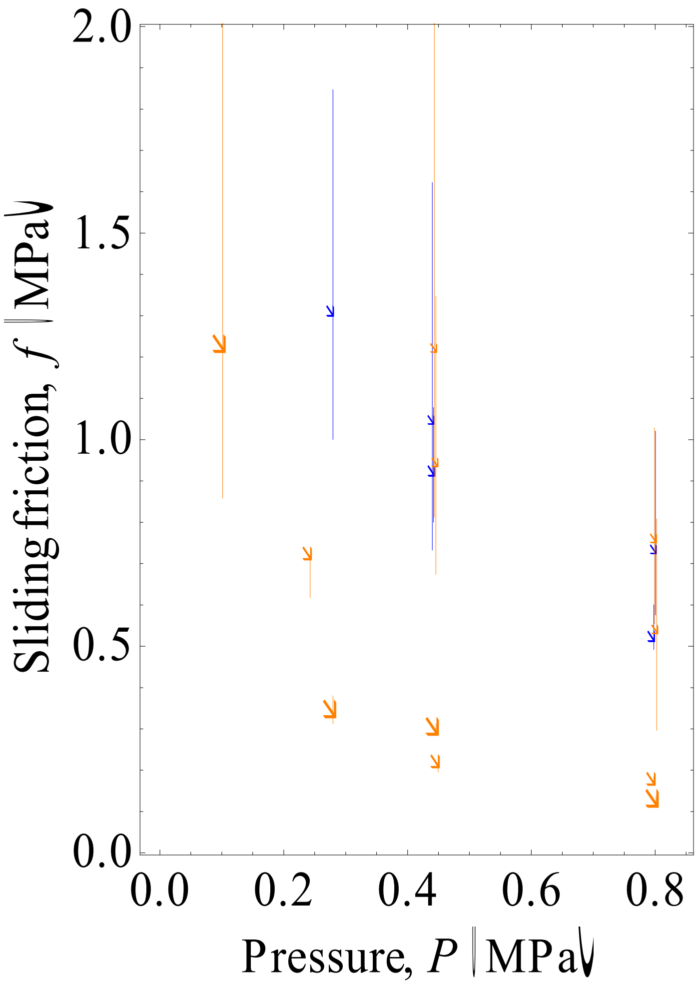
1. **Decreases** with pressure?
2. Decreases with **radius**?



Dual role or pressure



Friction as a function of strain



Microscopic explanation

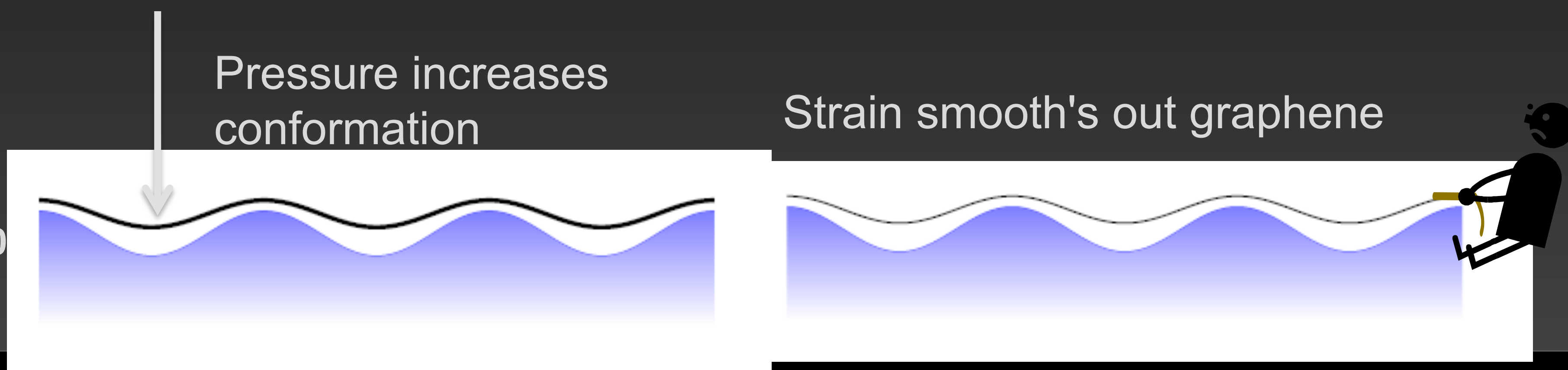
Trilayer | **Mono and bilayer**

P=0

Pressure increases conformation

Strain smooth's out graphene

P>0



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Cullen et al. PRL **105**, 215504 (2010)