MANCHESTER 1824

The University of Manchester

# GRAPHENE: magic of flat carbon

Andre Geim

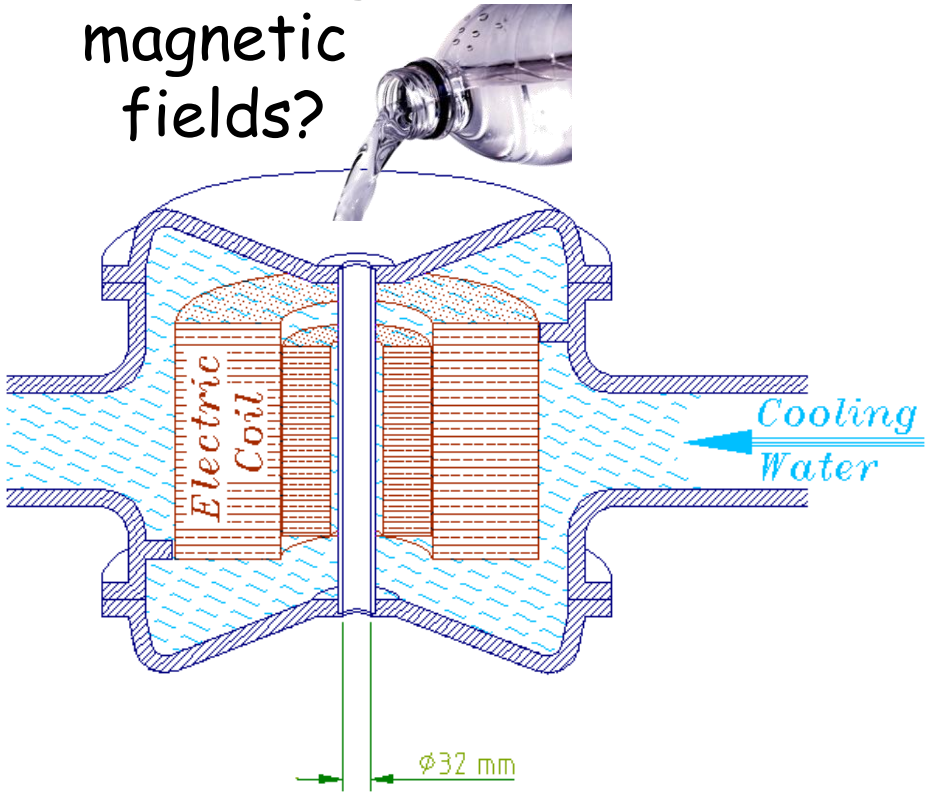
January 14, 2012, KITP Teachers' Conference

# ON THE IMPORTANCE OF CURIOSITY

# "FRIDAY NIGHT EXPERIMENTS"

magnetic water descaler

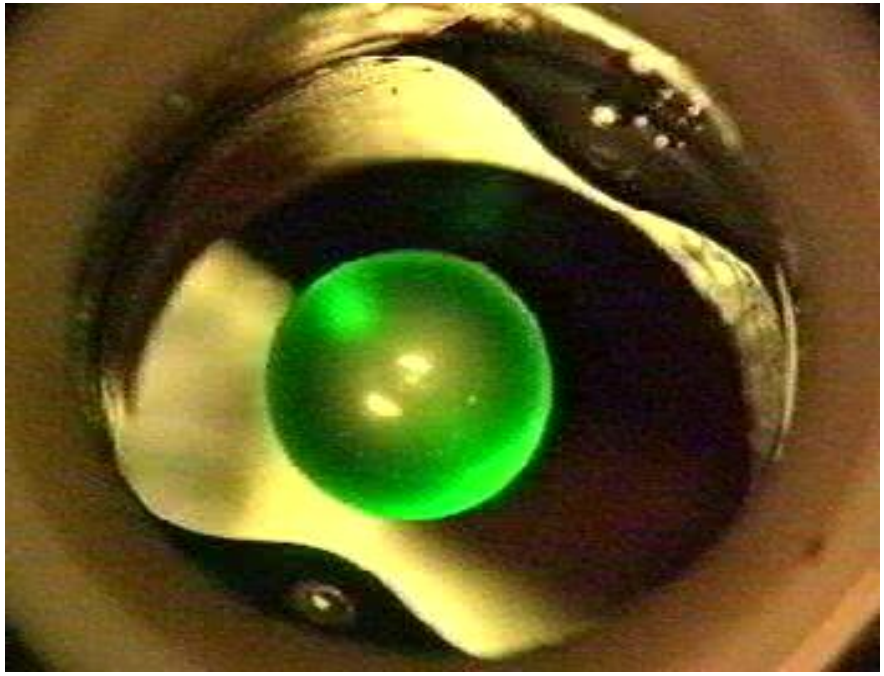
water in high magnetic fields?



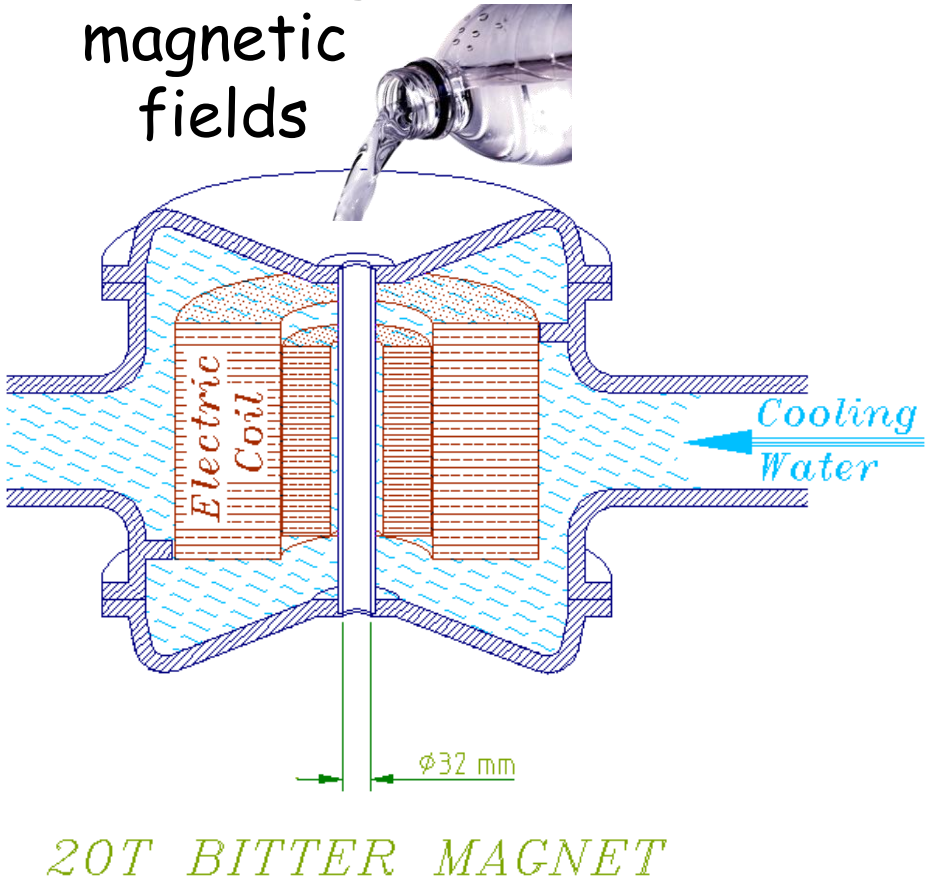

20T BITTER MAGNET

ancient magnets:
consume a lot of energy
require extra cryostats

# A BIT OF LEVITY

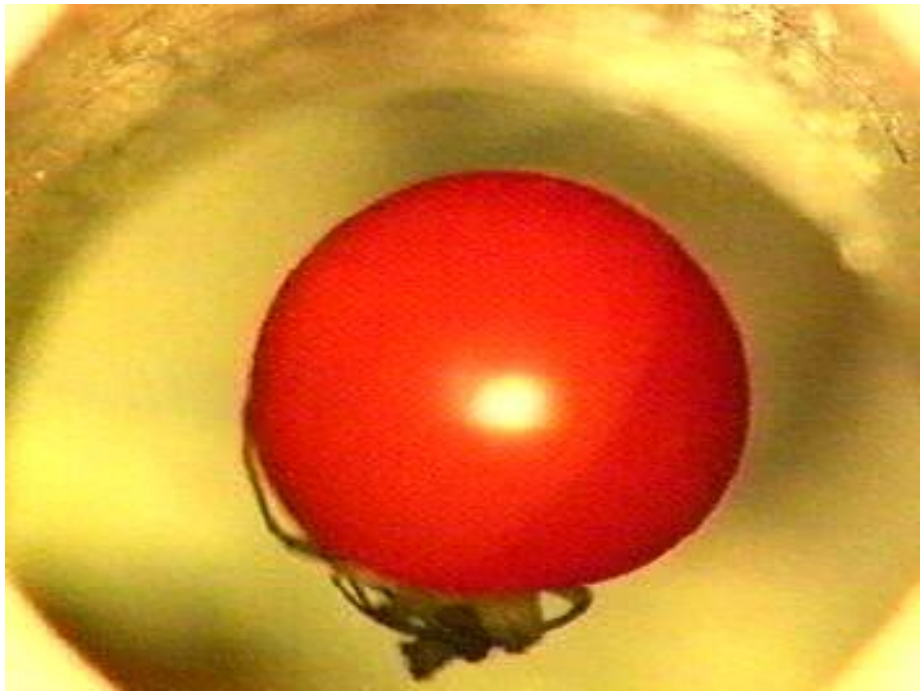


water in high magnetic fields




ever present diamagnetism
NOT as negligible as commonly believed

# KNOWLEDGE IS FUN



# KNOWLEDGE IS FUN

ELSEVIER

Physica B 294–295 (2001) 736–739

PHYSICA B

www.elsevier.com/locate/physb

## Detection of earth rotation with a diamagnetically levitating gyroscope

A.K. Geim*, H.A.M.S. ter Tisha

official name:
dwarf hamster

nickname: Tisha

job: levitator

# SCIENCE TO THE MASSES

New Scientist, 26 July

# And God said

...let there be levitating strawberries, flying frogs and humans that hover over Seattle. *Mark Buchanan* went forth in search of miracles

9 JUN 97

DAVE BARRY

## Facts About Floating Frogs

MIAMI—Get ready to dance naked in the streets, because scientists have finally done something that humanity has long dreamed about, but most of us thought would never happen within our lifetimes.

That's right: They have levitated a frog.

I swear I am not making this up. According to an Associated Press article in by a number of alert readers, Dutch scientists "have suc- a frog in air." They magnetism, which, as how many times 7 goes into 56; naturally, the child prefers the bed.

Think, parents, how much easier it would be if, at 6:30 A.M. on school mornings, you could simply press a button, thereby activating gigantic magnets under your child's bed that would cause the child to float upward, along with any frogs that happened to be in bed with the child. Then, instead of wasting your time yelling, "YOU'RE GOING TO BE LATE FOR SCHOOL!" you could waste your time yelling, "STOP DRAWING WITH THAT MARKING PEN OF STILLING!" So perhaps this od use for magnetic le

APRIL 12, 1997

It's al up in the air

The Guardian April 12, 1997

Frog floats through

Sue Quinn

HUMANS could soon ready for the ultimate lifting experience, ac to scientists who ha frog levitate six fe British and cists used netic fiel force o the f wa

# Scientists magnetised by levitating frog

The Independent 12/04/97

Charles Arthur
Science Editor

Take one extremely powerful magnet, and one slightly prised but compli one on to what project to build a magnet str enough to levitate 100 metr issue is your sensation, though, being weight- It's not a surface effect, like you

NEWS OF THE WORLD, October 5, 1997

INCREDIBLE!

Animal magnetism machi

frog float in thin

## Gravity is leap-frogged by a magnet

By Aisling Irwin
Science Correspondent

A DUTCH frog may have become the first living creature to experience levitation. Physicists made it rise and hover in the air using a strong magnetic field. They repeated the procedure with a cheese sandwich.

The physicist

Robin Wheeler

THE SECRET FORMULA IS : ab+rat+cad-ab÷rd

LEVITY

floating in the air inside a magnetic cylinder."

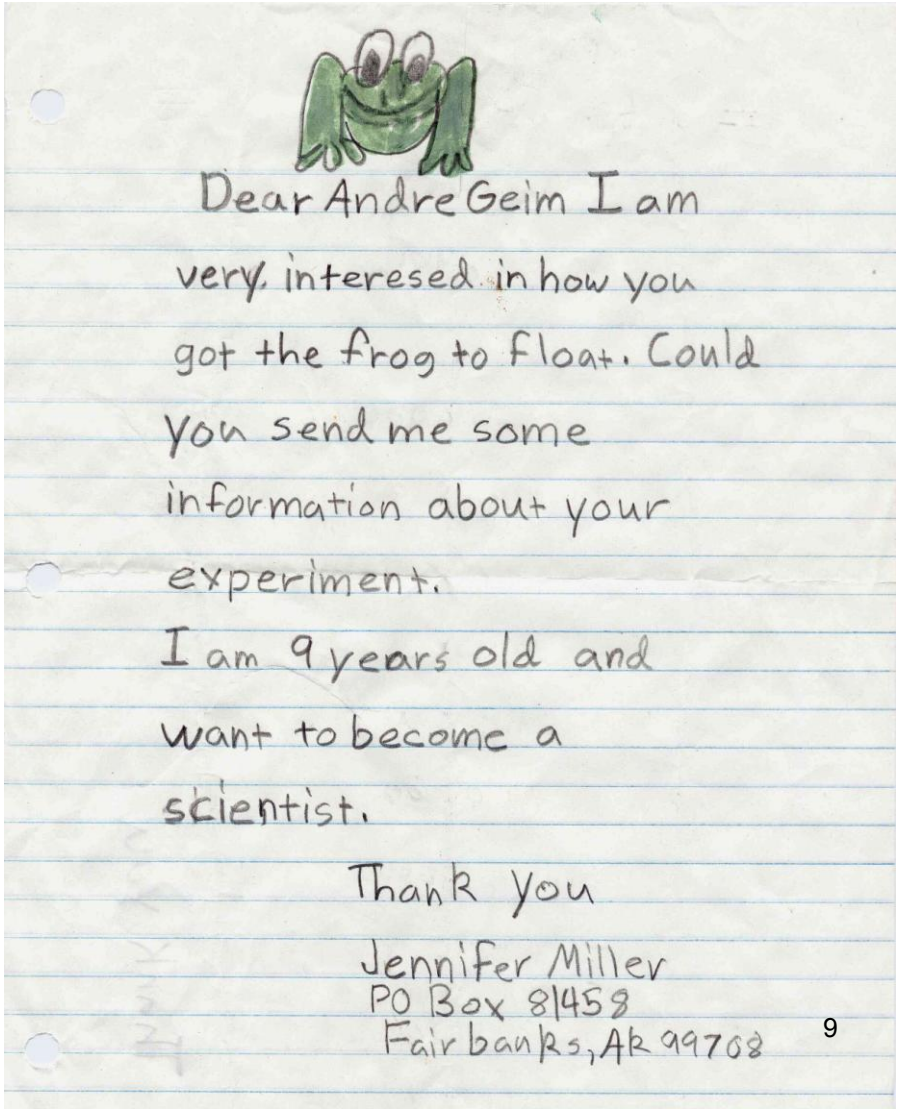
I am not a trained scientist, but my reaction to that last statement is – and I quote – "Duh." Of course the frog "showed no signs of distress": It's a frog. Frogs are not known for showing emotions; they are limited to essentially one facial expression, mu like Jean-Claude Van Damme. What did the ists expect the f Hop arou

ET READY TO dance naked in the streets, be- scientists have done ething that humanity long dreamed about but that most of us thought would never hap- pen. That's right: They levitated a frog. ding to an Asso- British have

# PERCEPTION CHANGE

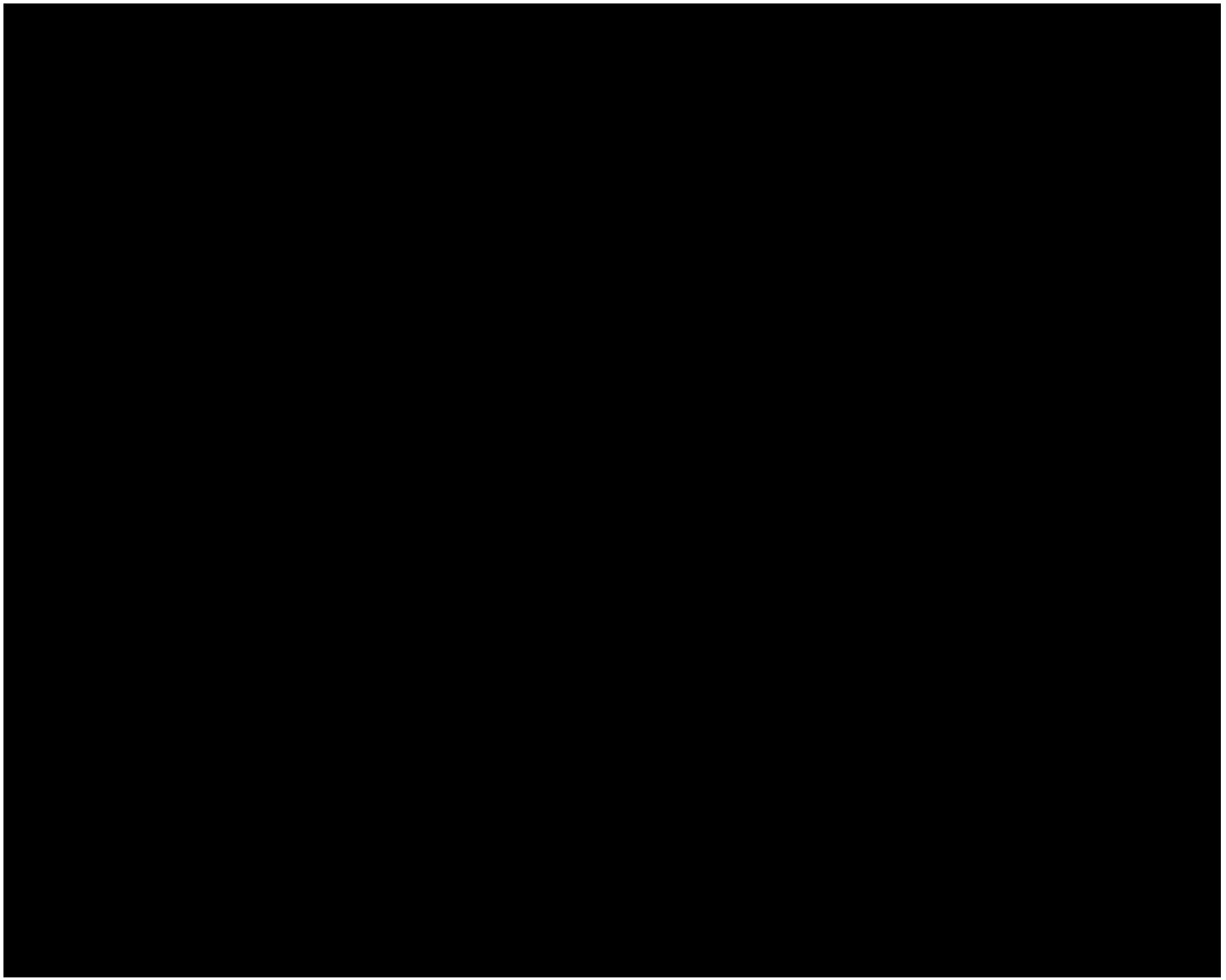
everything and everybody is magnetic;
ever present diamagnetism is NOT negligible

in many textbooks



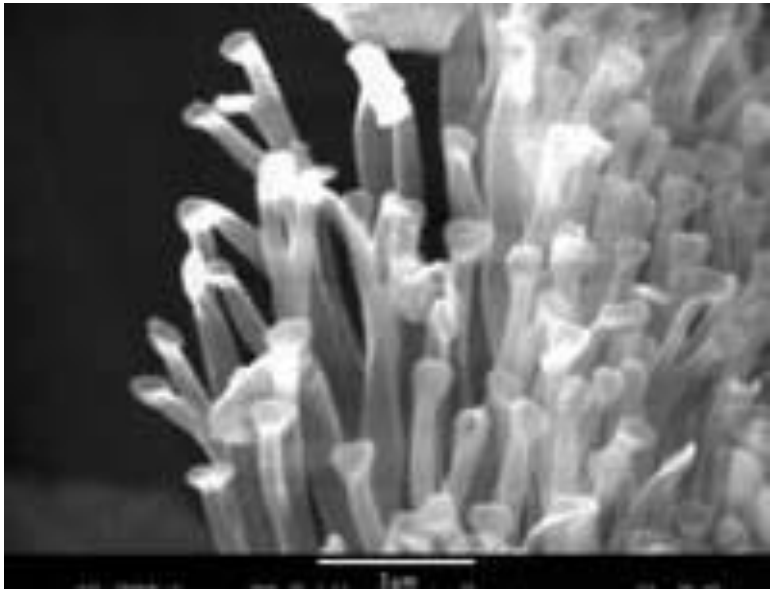
# "FRIDAY NIGHT EXPERIMENTS"

## *HOW COMES THAT GECKO CAN CLIMB WALLS?*



# "FRIDAY NIGHT EXPERIMENTS"

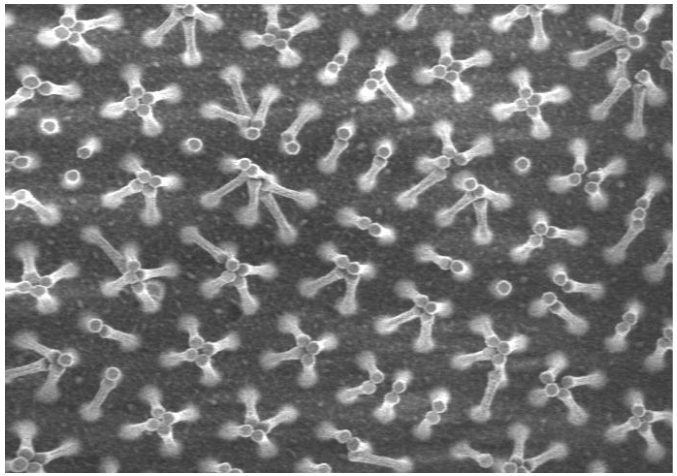
## *sticky feet:*
## *geckos climb due to their hairy toes*

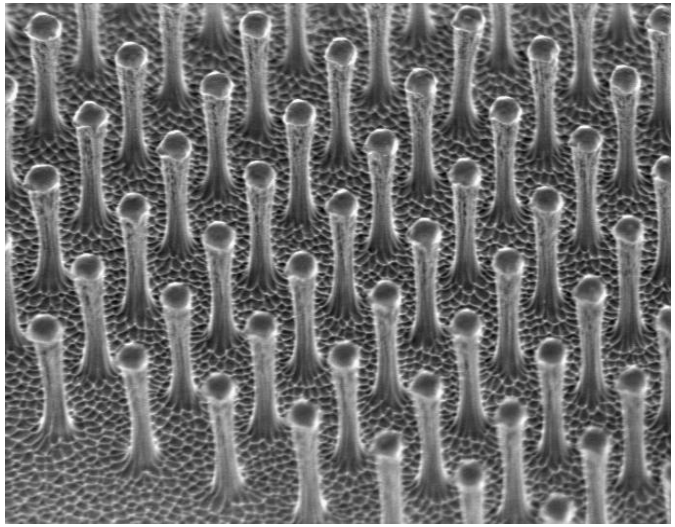



*submicron size* (!) - standard spatial scale in our work

# GECKO TAPE

proof of concept:
biomimetic dry adhesive
based on "gecko principle"





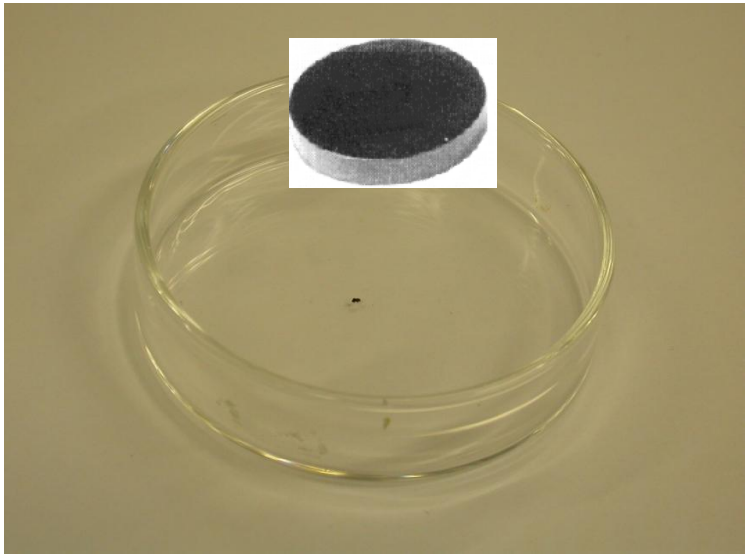
## PLACING EMPHASIS

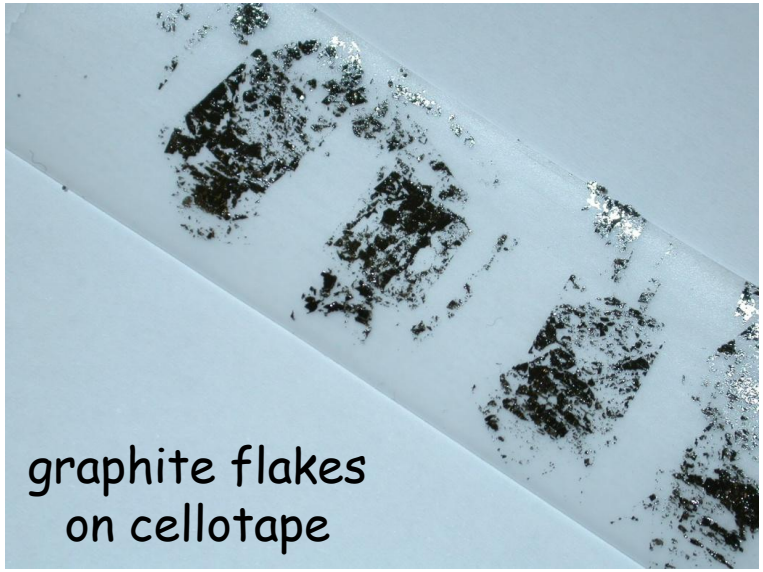
Geim, Sergey Dubonos, Irina Grigorieva *et al*
*Nature Mater* 2003

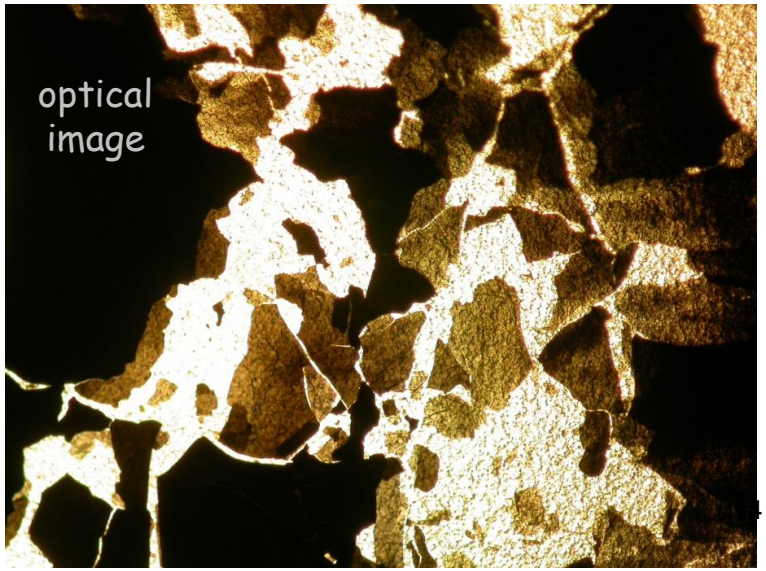
# BRIEF HISTORY OF GRAPHENE

# THE LEGEND OF SCOTCH TAPE

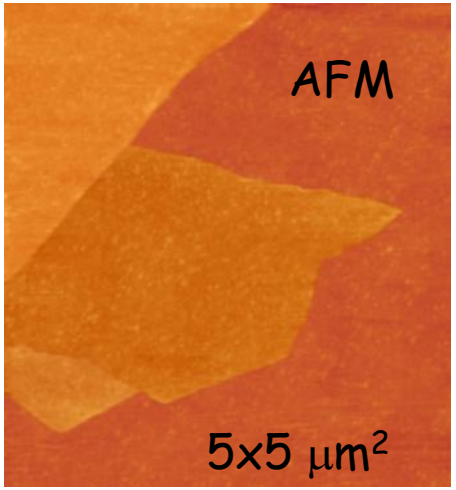
2002 PhD project of Da Jiang:
make films of graphite
as thin as possible
and study
their properties





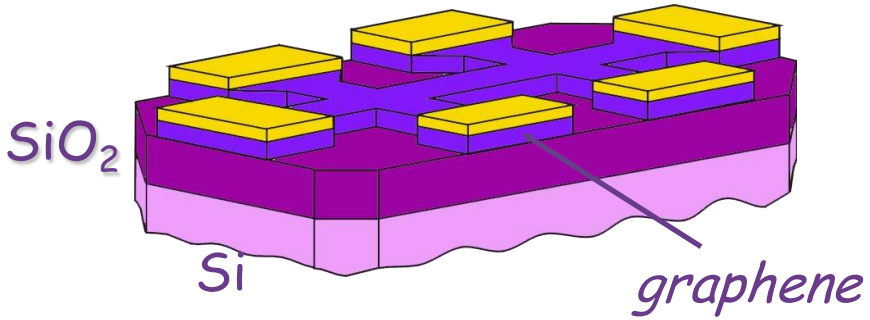



# UNTIL A SINGLE LAYER FOUND

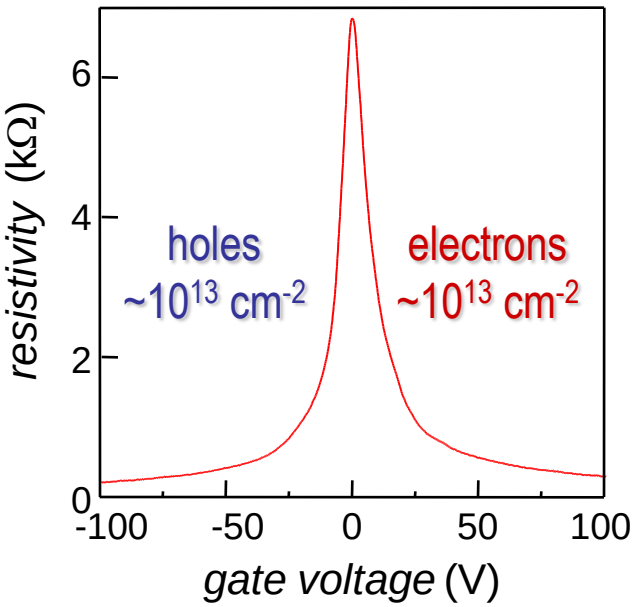



a few months later

make devices




study properties




- CHANGE PROPERTIES
  by voltage from a battery

- ASTONISHING ELECTRONIC QUALITY
  shoot like bullets

# And after a lot of hard work …

22 OCTOBER 2004 VOL 306 SCIENCE www.sciencemag.org

## Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1*] S. V. Morozov,[2] D. Jiang,[1]
Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

N.B. twice rejected by *Nature*

"the paper offers little new insights" - *Nature's referee*

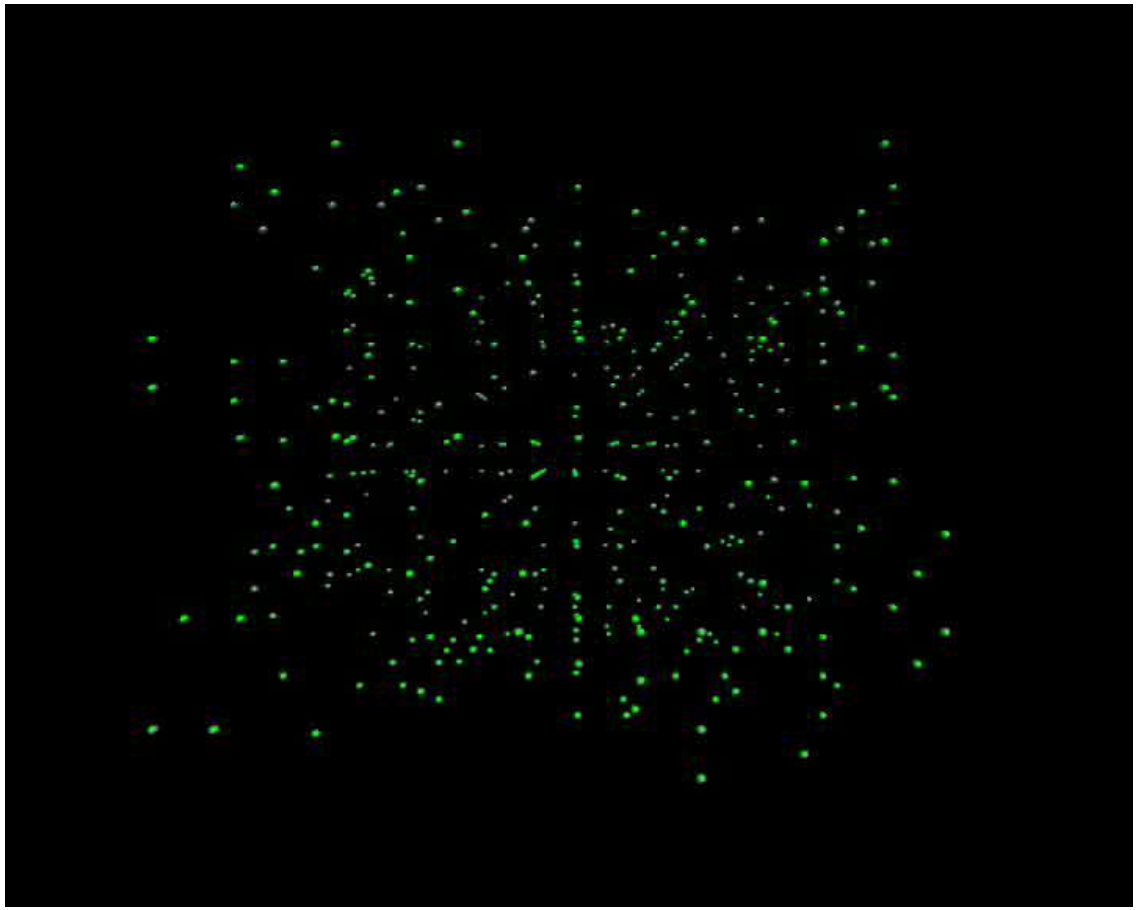
# WHY THE INTEREST?

# Everything Has Three Dimensions





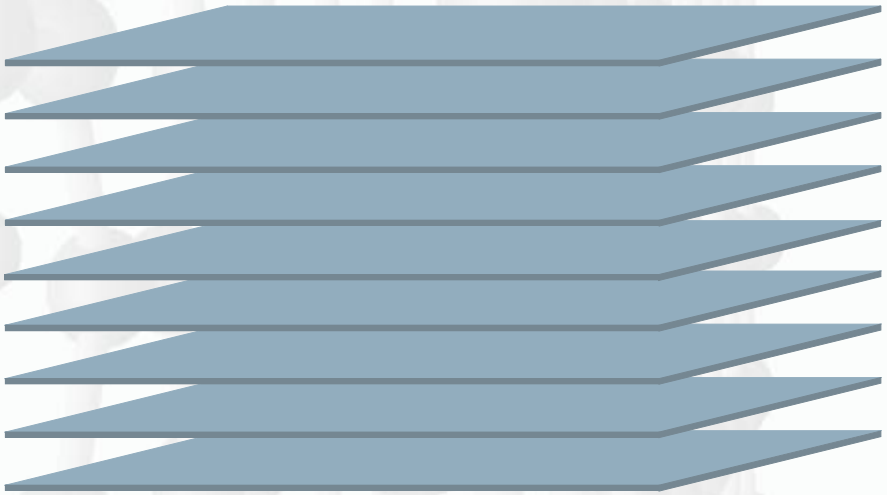

# Nature Hates Low Dimensions



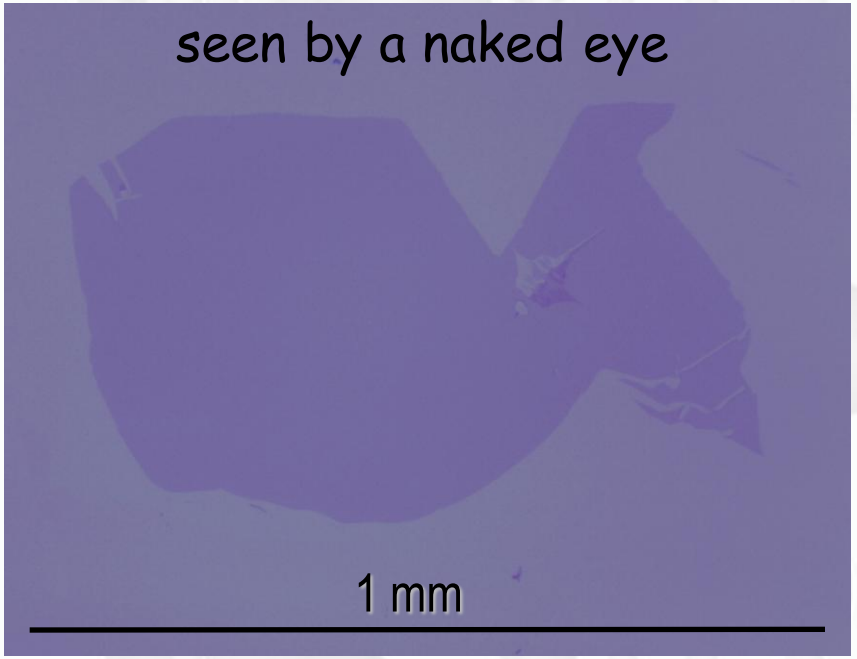
growth of one atom thick materials
is STRICTLY forbidden

# What Can We Do About This?

3D MATERIAL

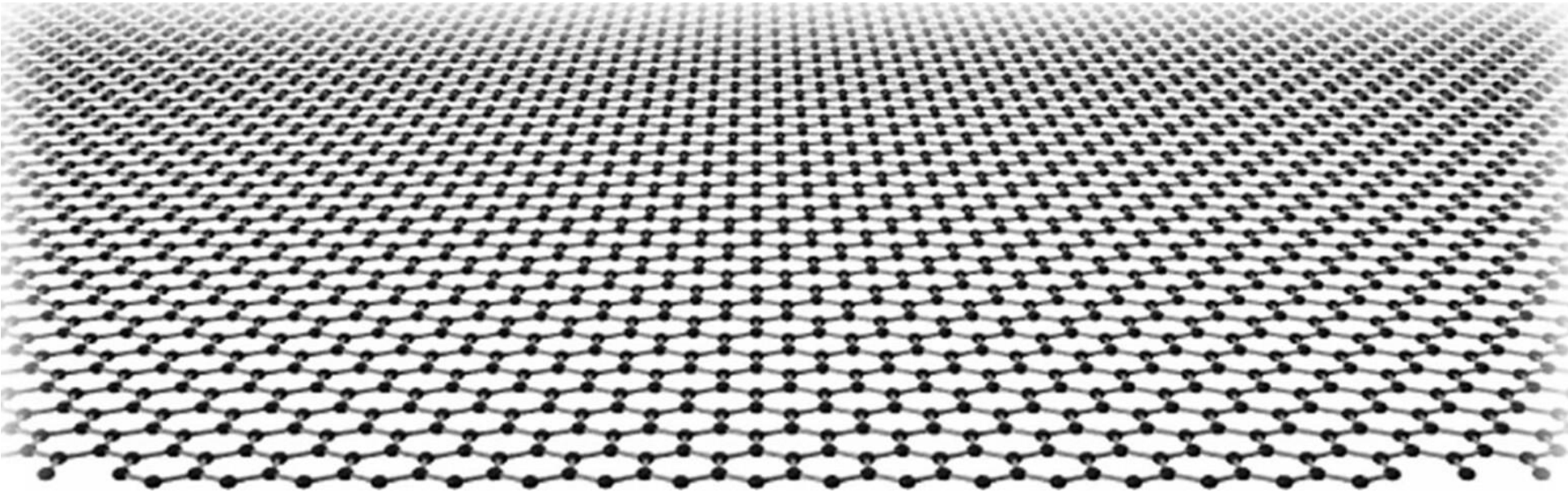


PULL OUT
INDIVIDUAL ATOMIC PLANES




*forbidden in nature*
*does not mean cannot be made artificially*

# WHAT'S SO SPECIAL ABOUT GRAPHENE?



extremely simple structure

# GRAPHENE'S SUPERLATIVES

*thinnest imaginable material*

*largest surface area* (~3,000 $m^2$ per gram)

*strongest material 'ever measured'* (theoretical limit)

*stiffest known material* (stiffer than diamond)

*most stretchable & pliable crystal* (up to 20% elastically)

*record thermal conductivity* (outperforming diamond)

*highest current density at room T* (thousands times of Cu)

*completely impermeable* (even He atoms cannot squeeze through)

*conducts electricity in the limit of no electrons*

*lightest charge carriers* (zero rest mass)

*longest mean free path at room T* (micron range)

*highest ever mobility* (>100 times more than in Si)

… … … … …

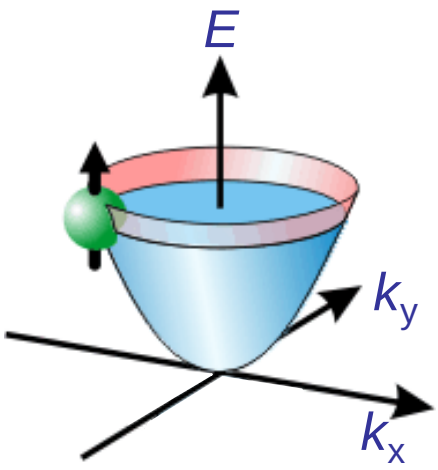
# NEW SCIENCE

# VERY SPECIAL ELECTRONS INSIDE GRAPHENE

# "CERN ON A DESK TOP"

## "Schrödinger fermions"

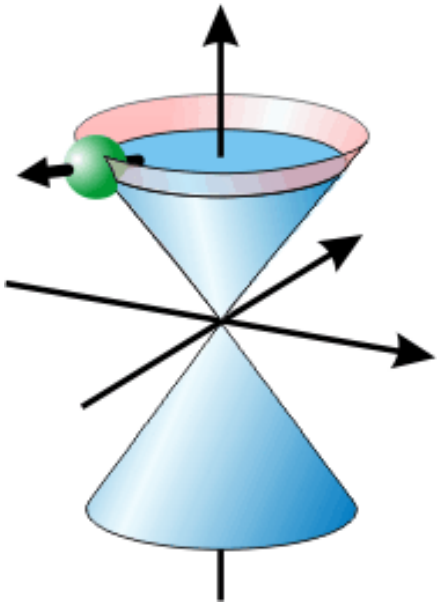
$\hat{H} = \hat{p}^2 / 2m^*$




metals
and
semiconductors

## ultra-relativistic particles

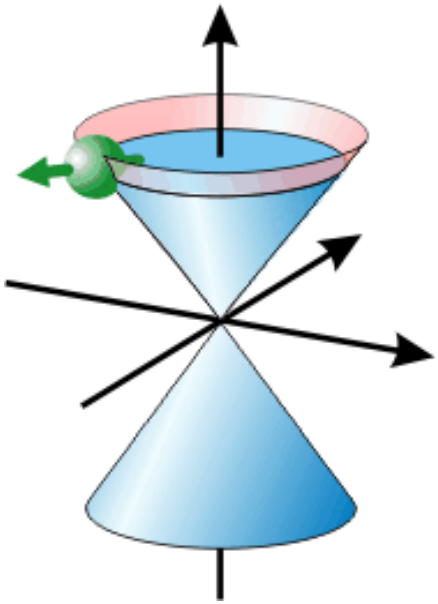
$\hat{H} = c\ \vec{\sigma} \cdot \hat{p}$



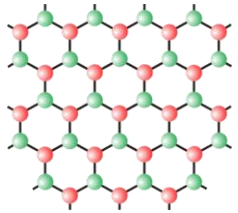
neutron stars
and
accelerators

## massless Dirac fermions

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

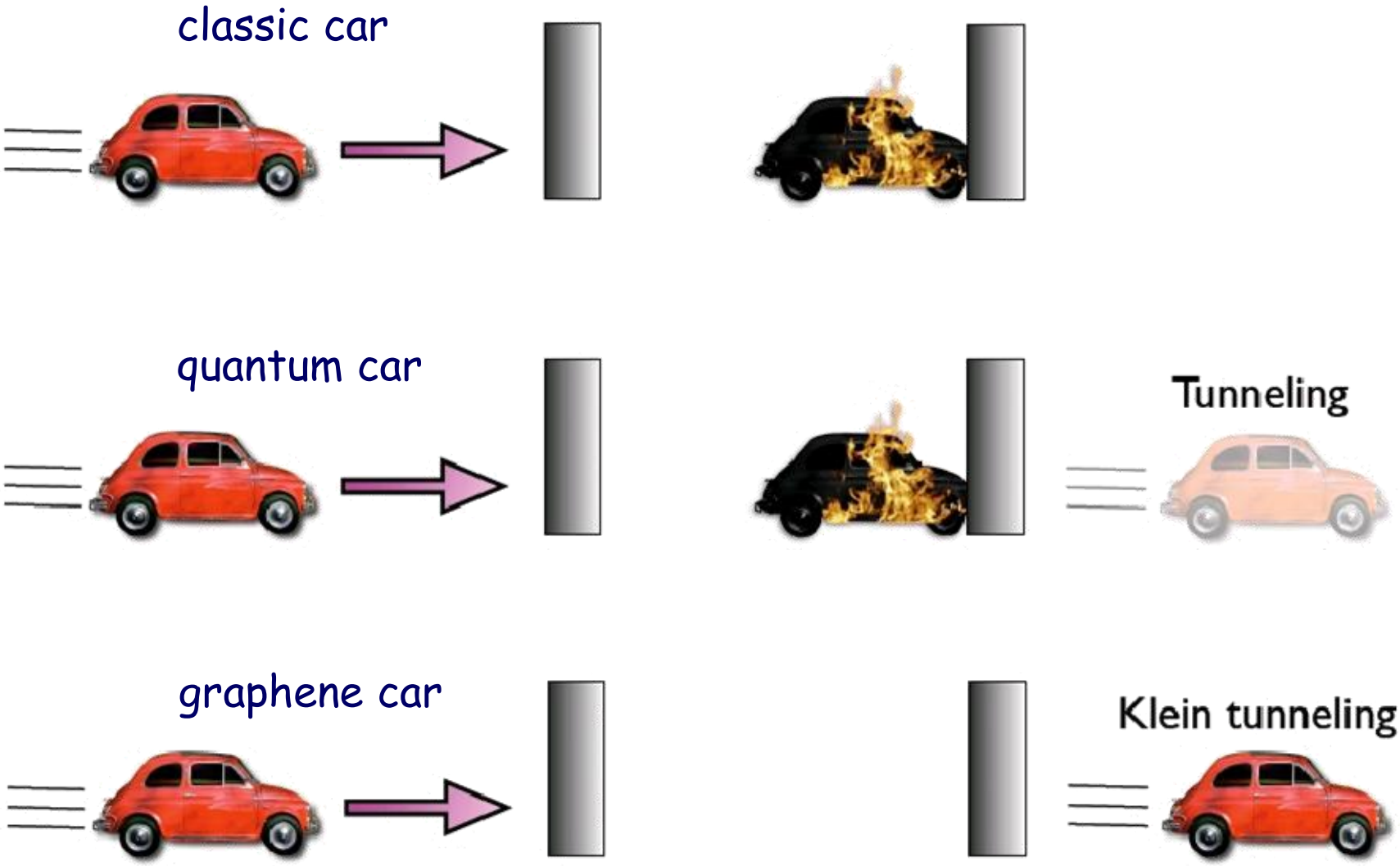


monolayer graphene



# EXAMPLE #1:
# *'WHAT CERN CANNOT DO'*

# Klein Tunnelling

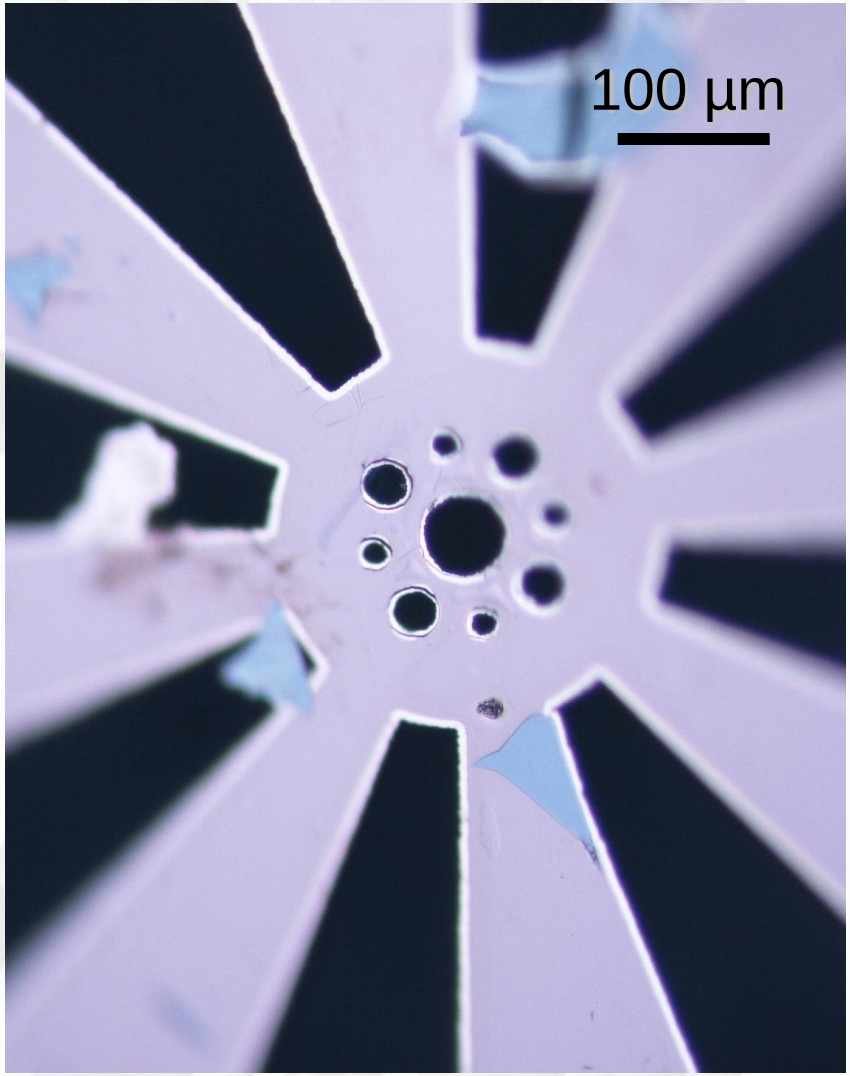


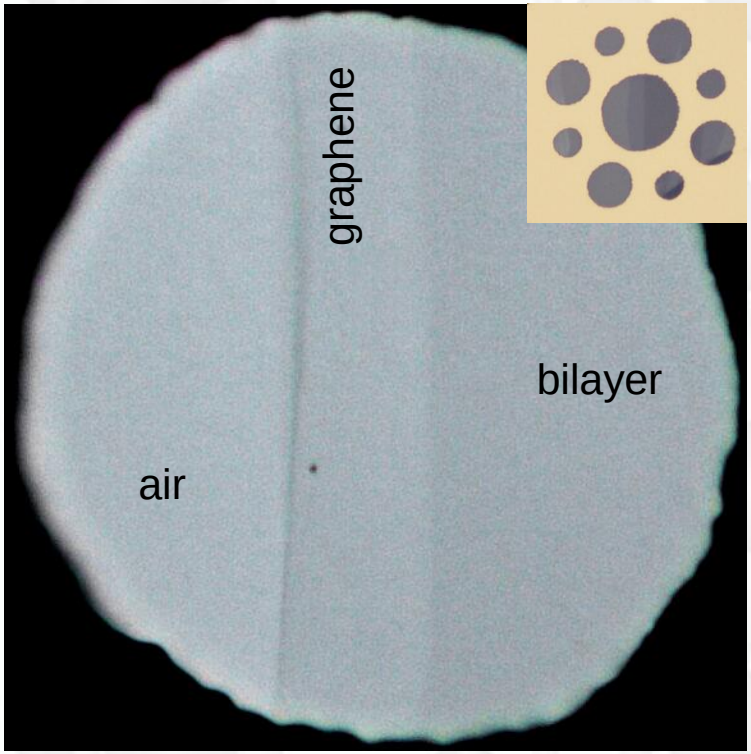
# EXAMPLE #2:

## *visualization of fine structure constant*

# GRAPHENE OPTICS

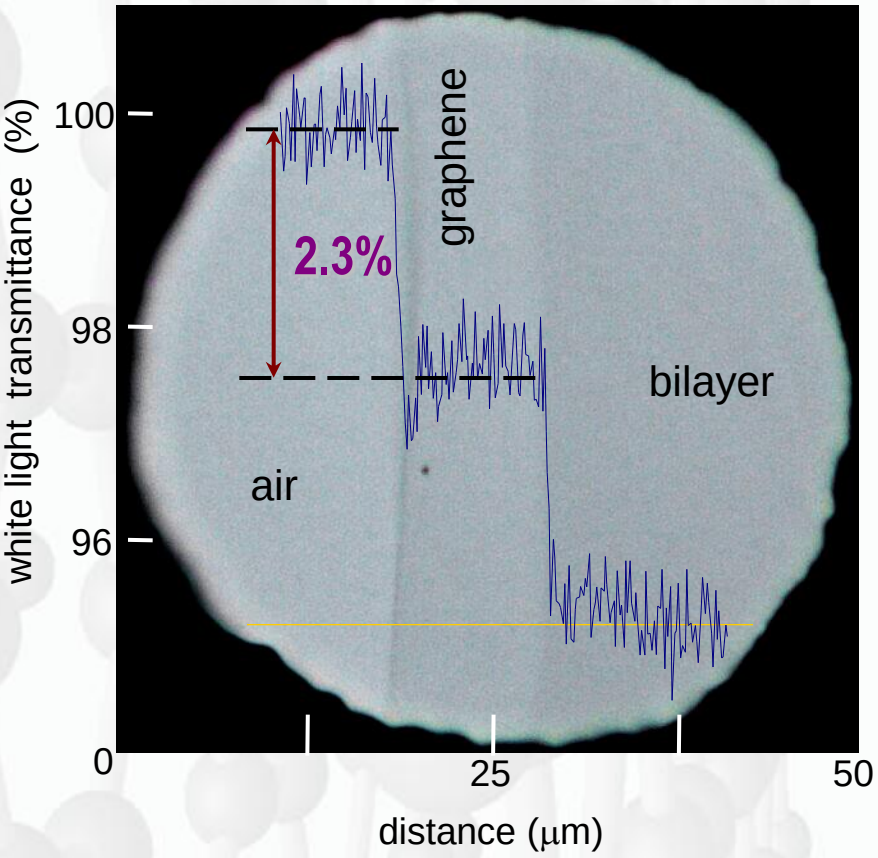
Manchester, *Science* '08



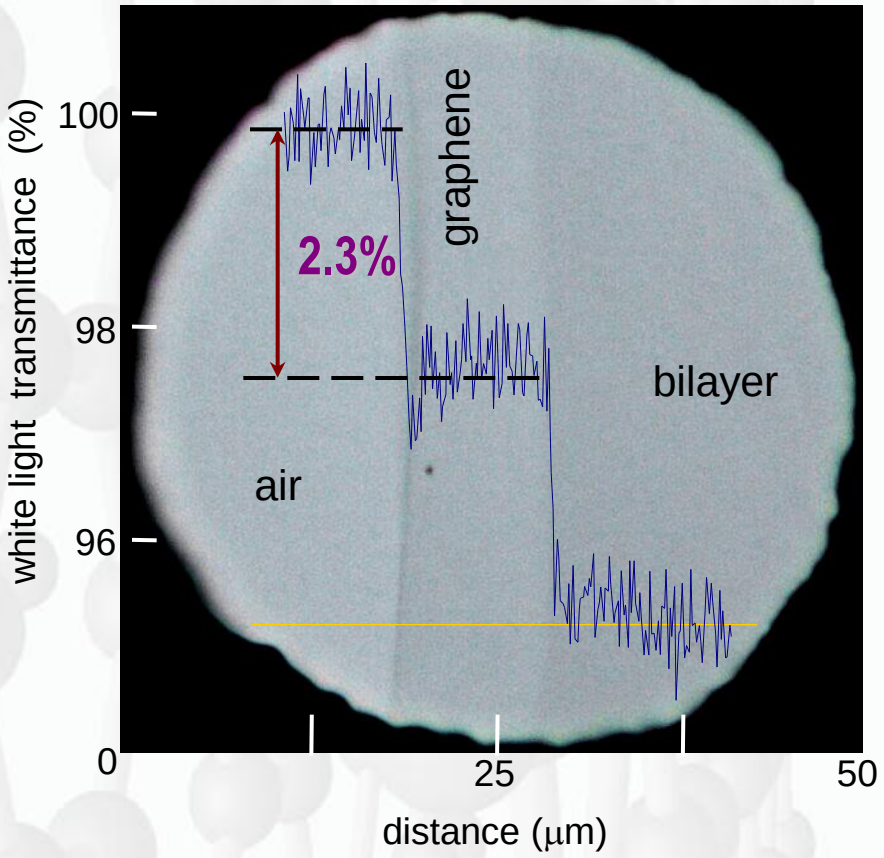

one-atom-thick single crystal
visible by naked eye

# GRAPHENE OPTICS

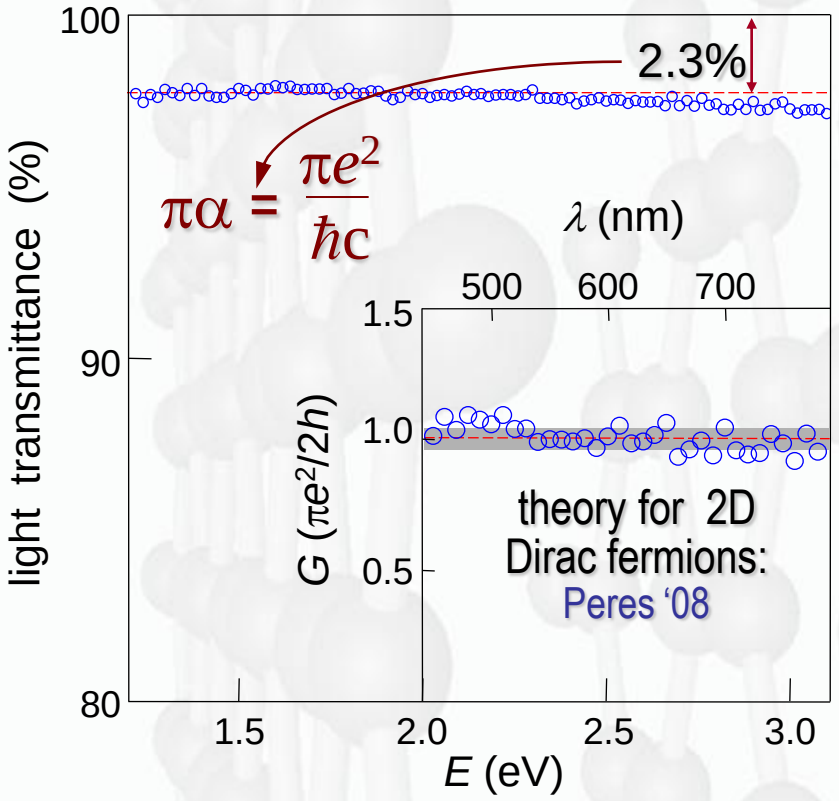



one-atom-thick
single crystal
visible by naked eye

# GRAPHENE OPTICS




one-atom-thick
single crystal
visible by naked eye

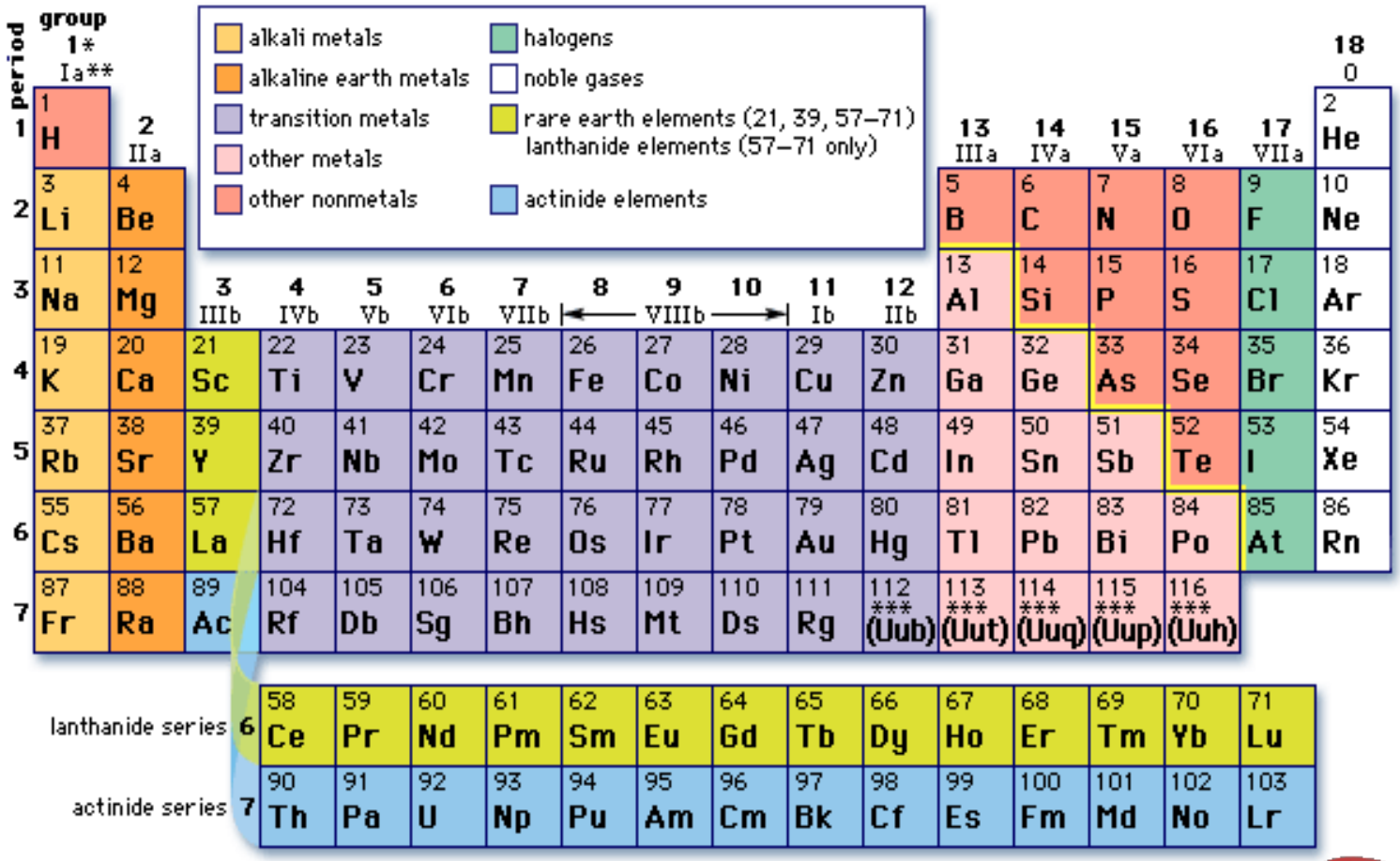



coupling of light with
relativistic-like charges
should be described by
coupling constant $\alpha$ =1/137
a.k.a. fine structure constant

# EXAMPLE #3:

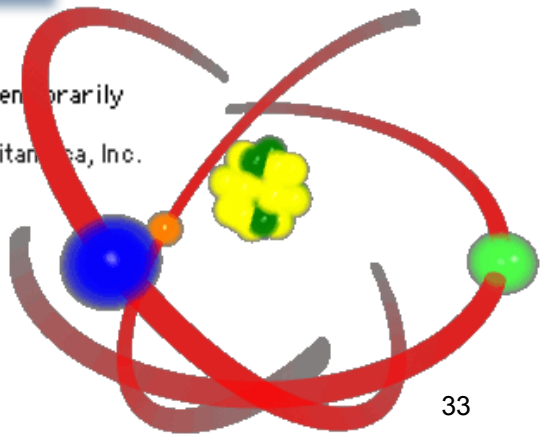
## *fundamental limits of the periodic table*

# Periodic table of the elements




* Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).
** Numbering system widely used, especially in the U.S., from the mid-20th century.
*** Discoveries of elements 112–116 are claimed but not confirmed. Element names and symbols in parentheses are temporarily assigned by IUPAC.





# Atomic Physics

$$Z < \frac{1}{\alpha} \approx 137$$


supercritical regime


$$Z > \frac{1}{\alpha} \approx 137$$

Positron emission

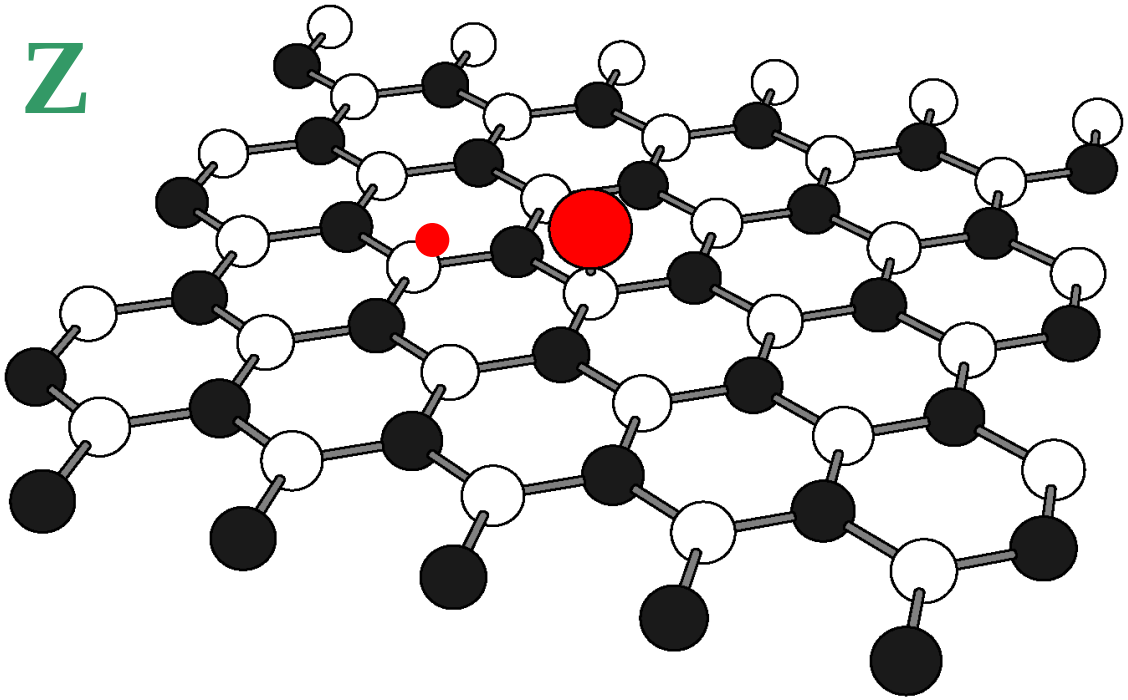
# Graphene Physics

"artificial atoms" easily become overcritical

$$\alpha_G = \frac{e^2}{\hbar v_F} \approx 1$$

$$Z > \frac{1}{\alpha_G} \approx 1$$

Z

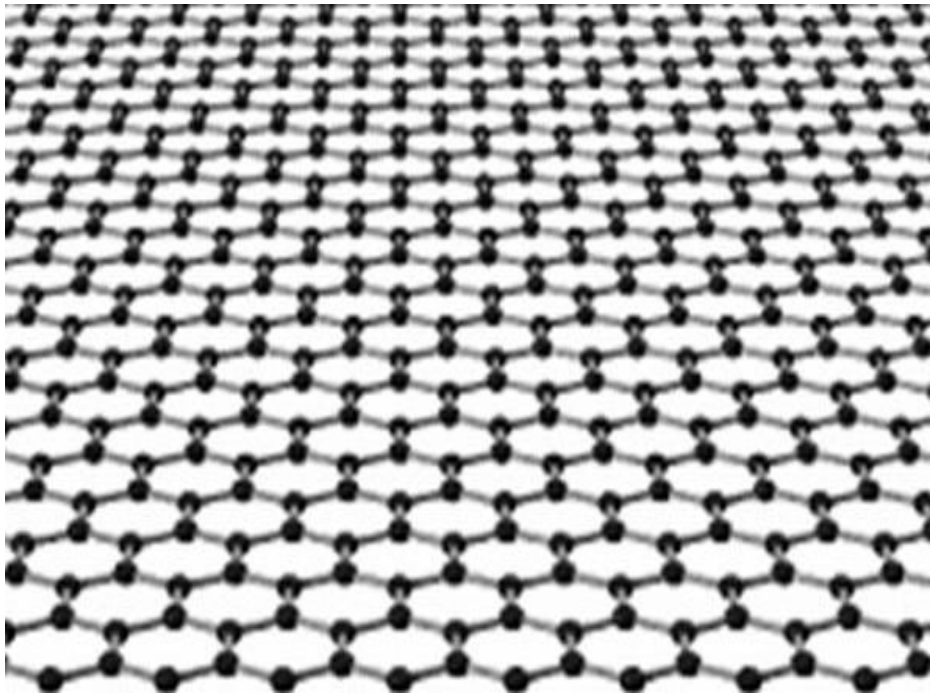


# EXAMPLE #4

## *Chemistry of Individual Giga-Molecules*

# Graphene as GigaMolecule

GRAPHENE

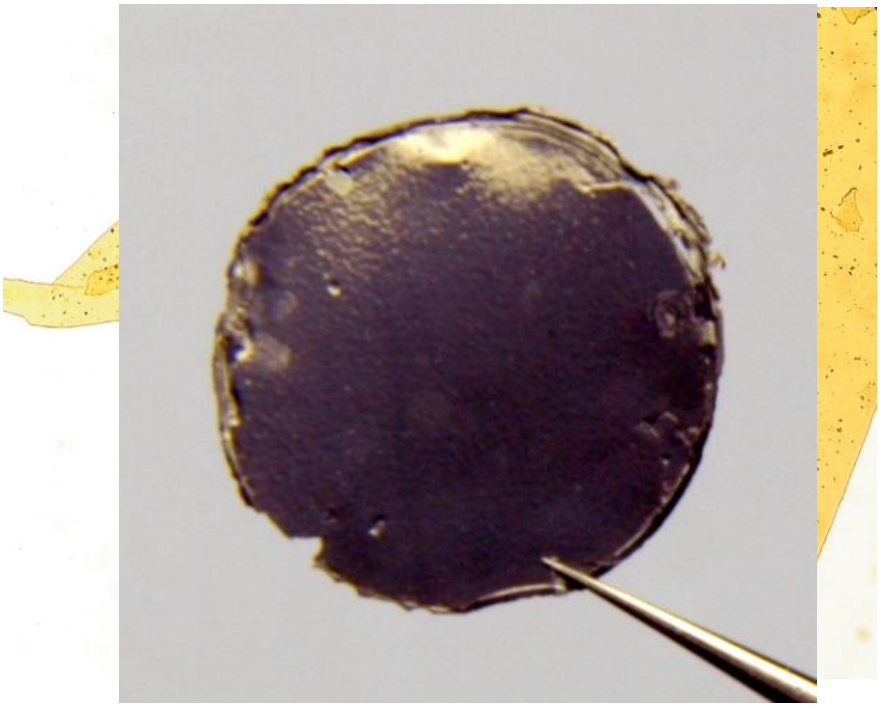


chemical reactions:

$C^{\infty} + \infty X \Rightarrow CX^{\infty}$

# Stoichiometric Derivative

wide-gap semiconductor

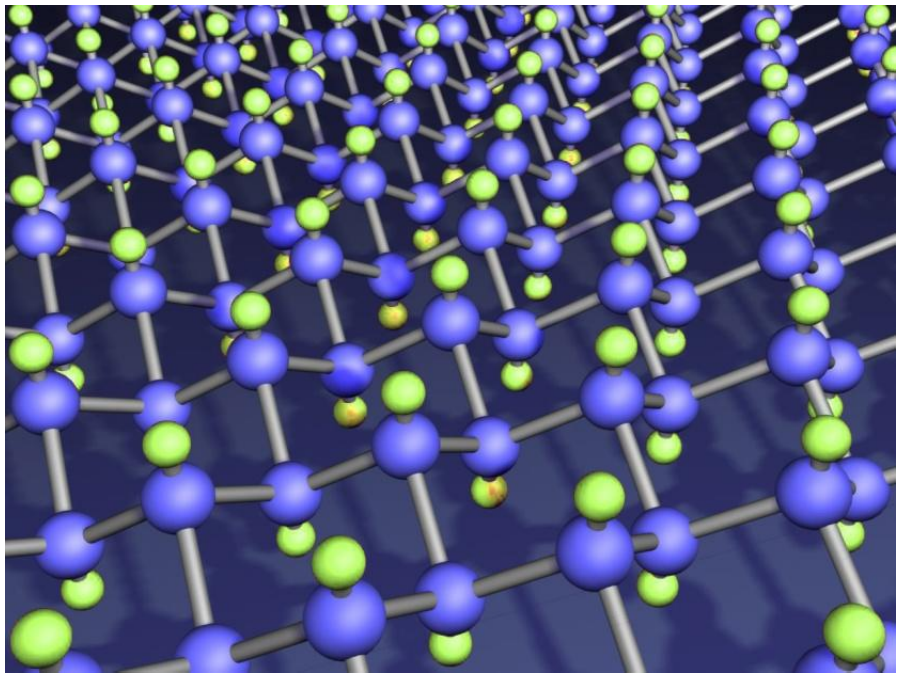


chemical reactions:

$C_{\infty} + \infty F \Rightarrow (CF)_{\infty}$

exposure to
atomic fluorine, using $XeF_2$

fluorographene (*"2D Teflon"*)



- *chemically & thermally stable*
  (similar to Teflon)
- *as strong as graphene*

# MESSAGE TO TAKE AWAY

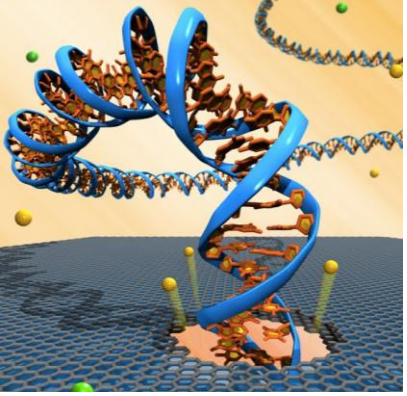
## CORNUCOPIA OF NEW SCIENCE

*already found and*
*far from being exhausted*

# APPLICATIONS

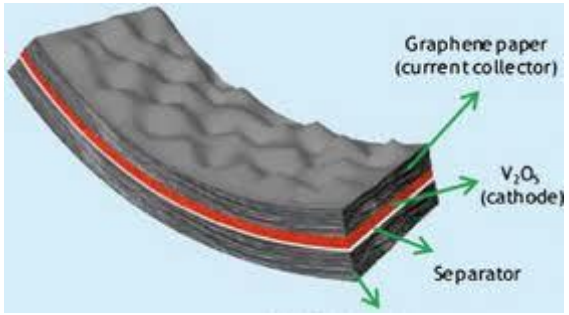
## EACH SUPERLATIVE OFFERS SOMETHING NEW & COMPETITIVE

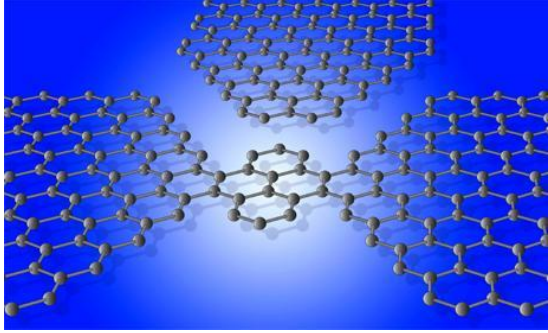
# graphene applications



medical applications: drug delivery; lab-on-chip; DNA sequencing

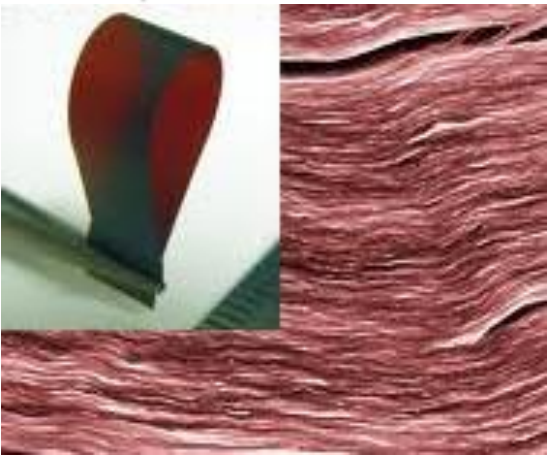
batteries; supercapacitors
conductive inks; etc.

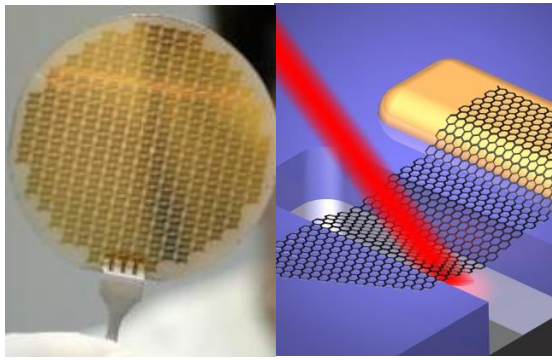


graphene as next Si

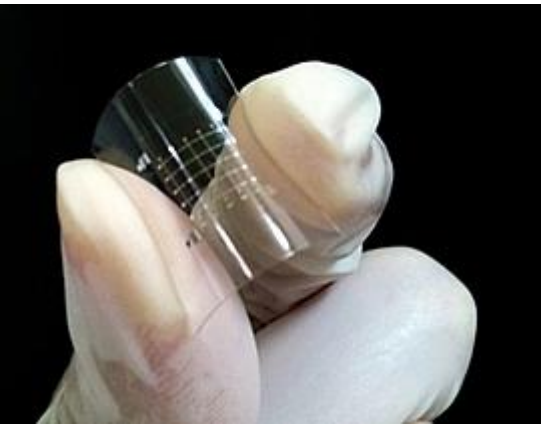
composites; 2D Teflon

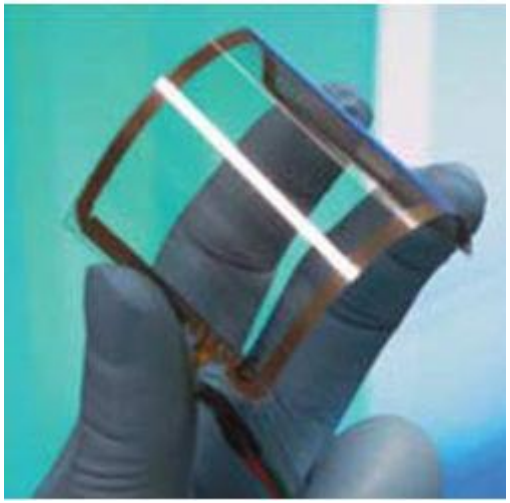




ultra-high frequency electronics; optoelectronics

MEMS; various sensors





touch screens & similar

# MESSAGE TO TAKE AWAY

## APPLICATIONS ARE COMING

only their extent remains unclear

# MAIN MESSAGE TO TAKE AWAY

HOW LITTLE WE KNOW
ABOUT THE WORLD AROUND US

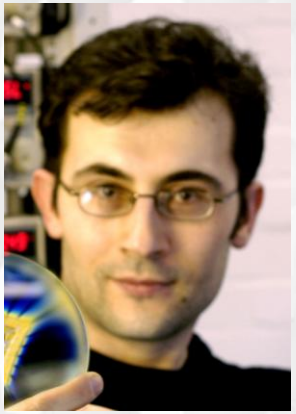
Kostya Novoselov

Sergey Morozov
(Chernogolovka)

Rahul Nair

Misha Katsnelson
(Nijmegen)

Irina Grigorieva



L.Ponomarenko

D. Elias

P. Blake

A. Castro Neto
(Singapore)

F. Schedin

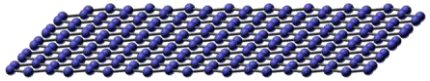
Nuno Peres
(Braga)

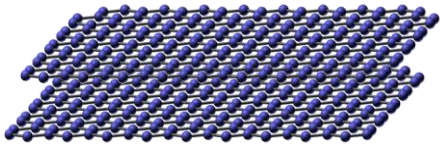
*Andrea Ferrari (Cambridge), Paco Guinea (Madrid), Leonid Levitov (MIT), Ernie Hill, Roman Gorbachev, Alex Kuzmenko (Geneva), Sasha Zhukov, Sasha Grigorenko*

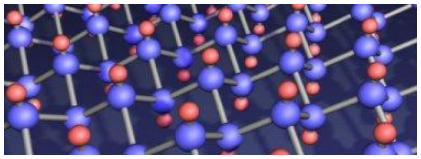
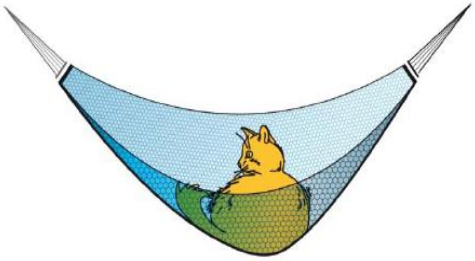
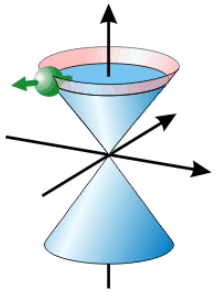
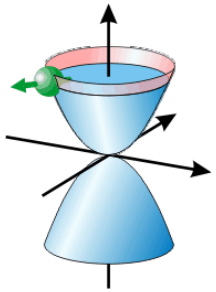
*for graphene reviews, see: Nature Mat* '07; *RMP* '09; *Science* '09

# GRAPHENE
# IS JUST ONE PLANE
# OF GRAPHITE

# NOT JUST ULTRA-THIN GRAPHITE



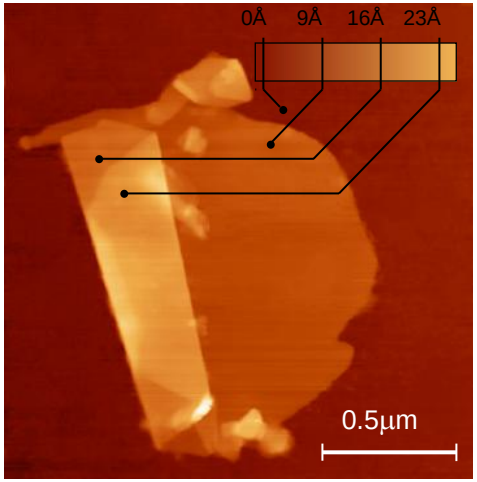


| | | |
|---|---|---|
| CHEMISTRY |  new materials: *graphAne* *fluorographene* | chemically less reactive |
| MECHANICAL PROPERTIES |  ultimate strength | cleaves easily |
| ELECTRONIC PROPERTIES |  massless charges |  massive chiral quasiparticles |
| | ELECTRIC FIELD GOES THRU | STRONG SCREENING |

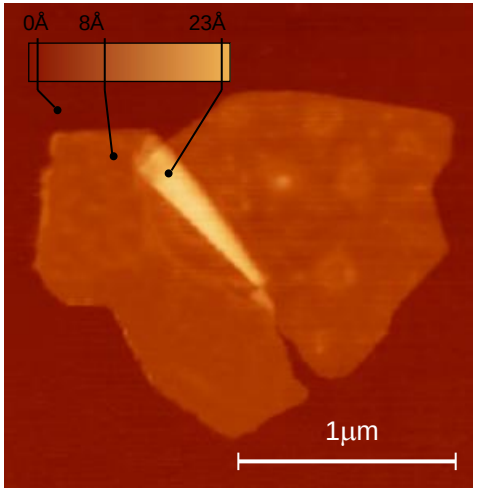
# WHITHER GRAPHENE?

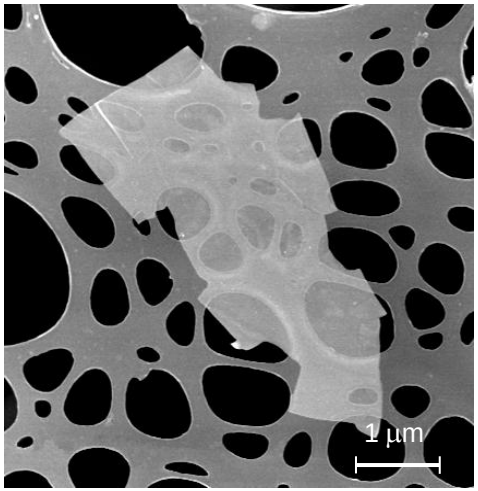
# ...any Other 2D Materials Possib...

2D boron nitride in AFM

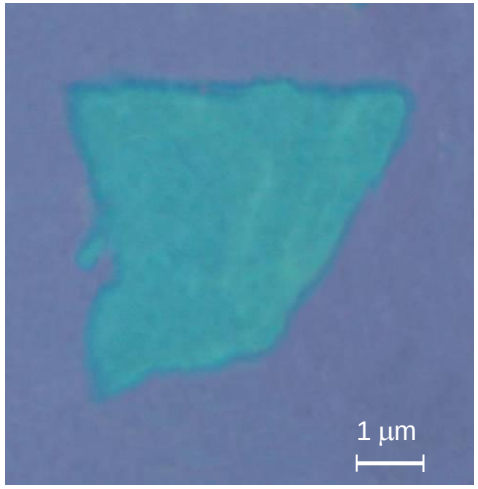



2D $NbSe_2$ in AFM




2D $Bi_2Sr_2CaCu_2O_x$ in SEM



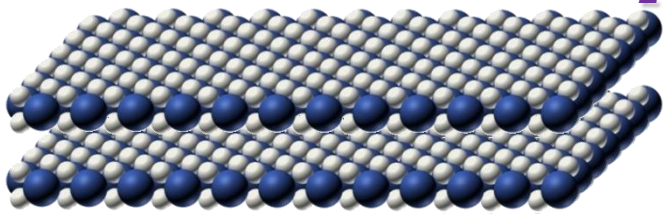

2D $MoS_2$ in optics

some are insulators, some are metals, semiconductors, superconductors, ferromagnets, etc.

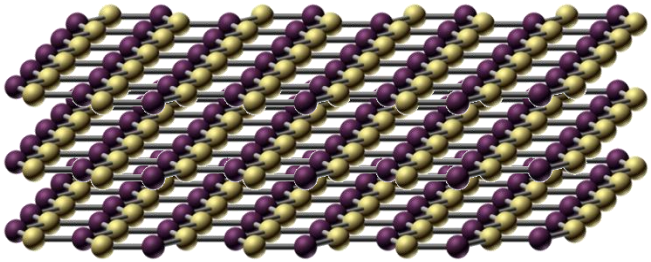
Manchester, *PNAS* 2005

# ew Layered Materials on Dema

$MoS_2$

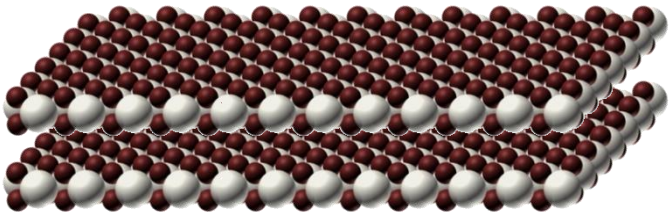


Graphene



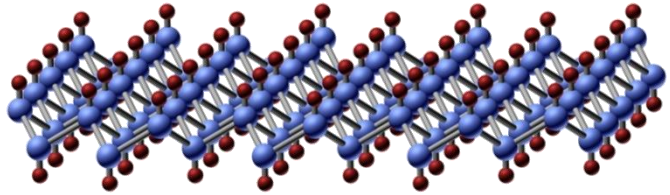
Boron-Nitride

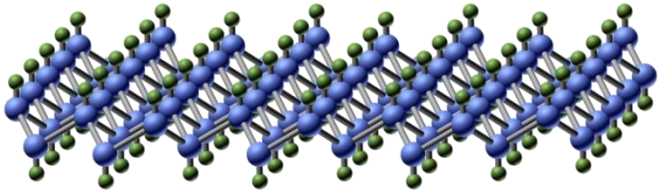
what their properties would be?



$NbSe_2$

*some other layered material*





*mica*

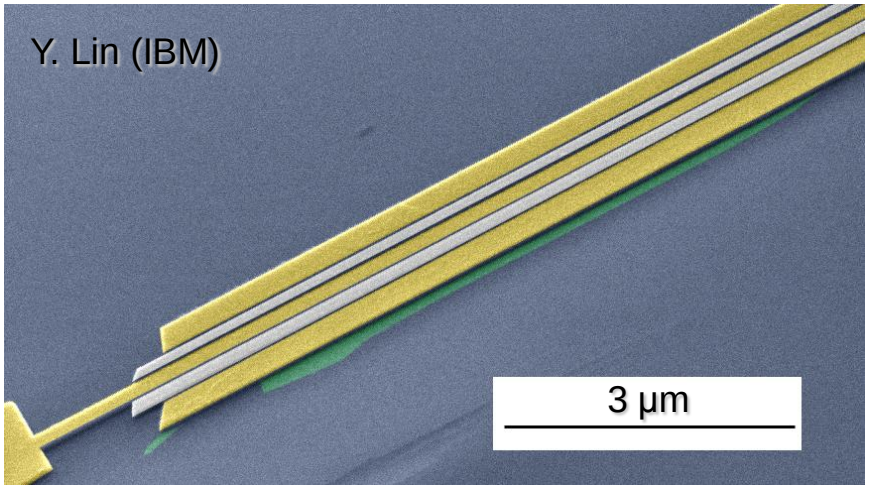


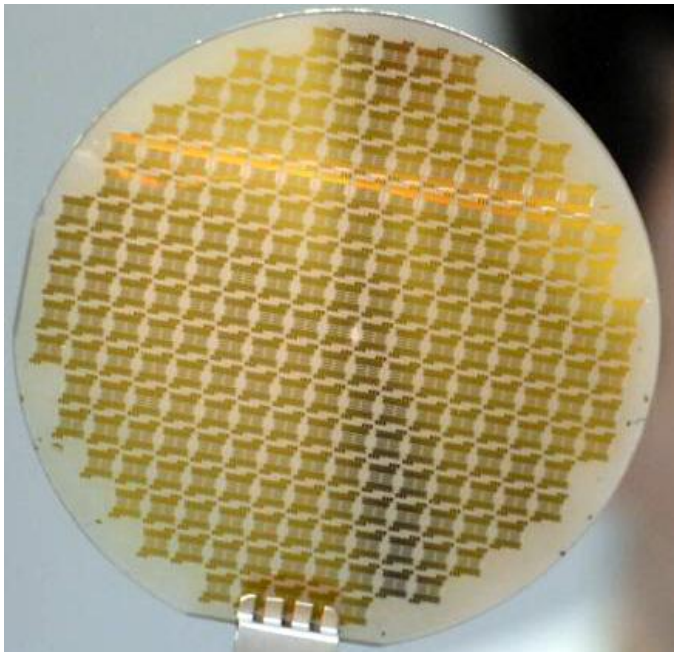
*movie by Kostya Novoselov*

# EXAMPLE #1

# *Ultra High Frequency Transistors*

# "BALLISTIC" TRANSISTORS



- ballistic transport
- high velocity
- great electrostatics
- scales to nm sizes

Manchester, *Science '04*

2008:
>$30M US military programs:
500 GHz transistors
on sale by 2013 years

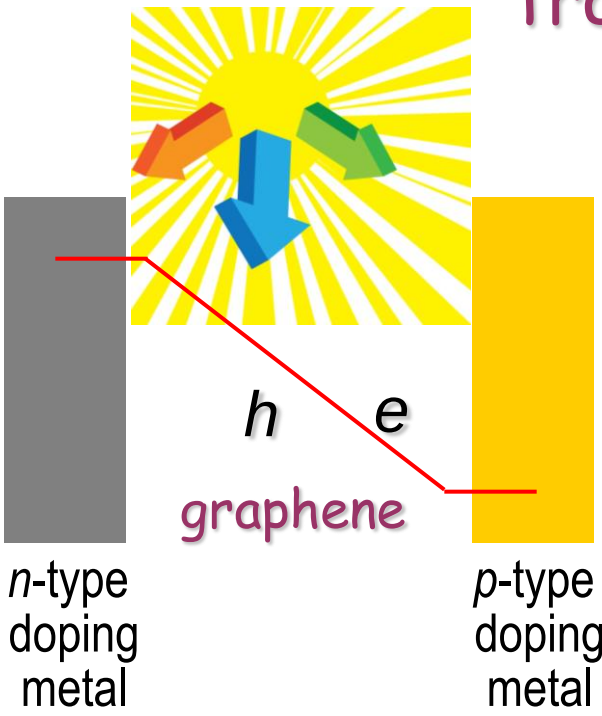
2009: 100 GHz (IBM & HRL)

2010: 300 GHz (UCLA & Samsung)
scaling >1THz

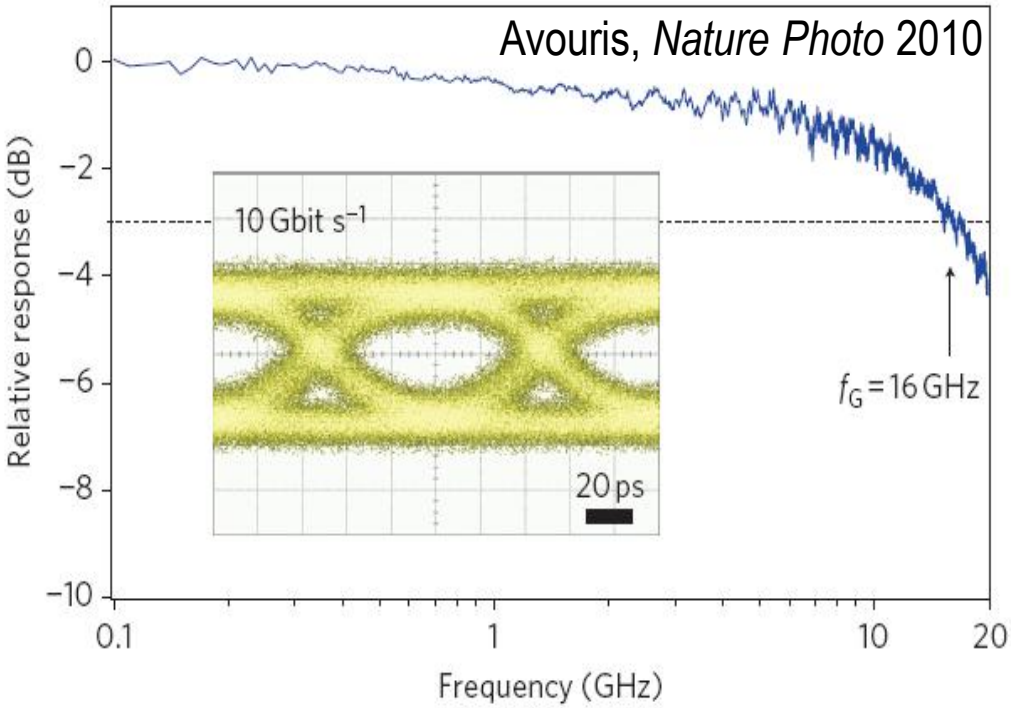
# EXAMPLE #2:
# *OPTOELECTRONICS*

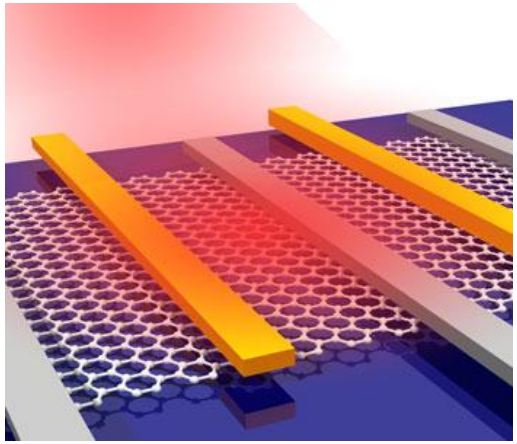
# ULTRAFAST PHOTODETECTORS

## transparent metal




ballistic transport
of photo-generated carriers
in built-in electric field



# EXAMPLE #3:

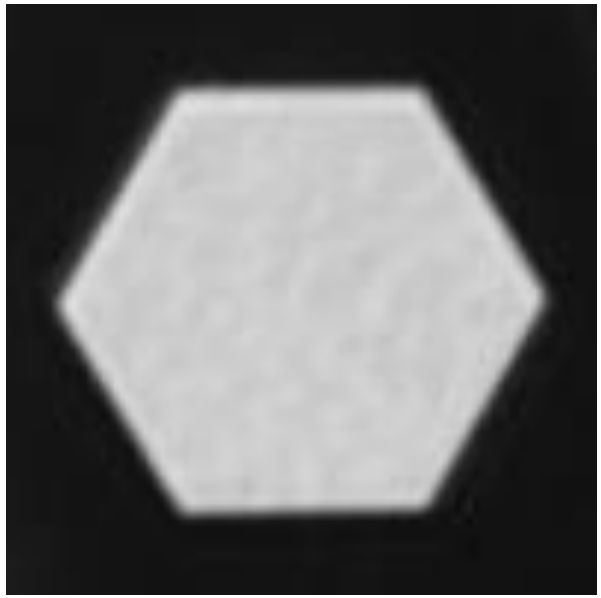
# *Graphene instead of ITO*

# GRAPHENE AS SUBSTITUTE FOR ITO

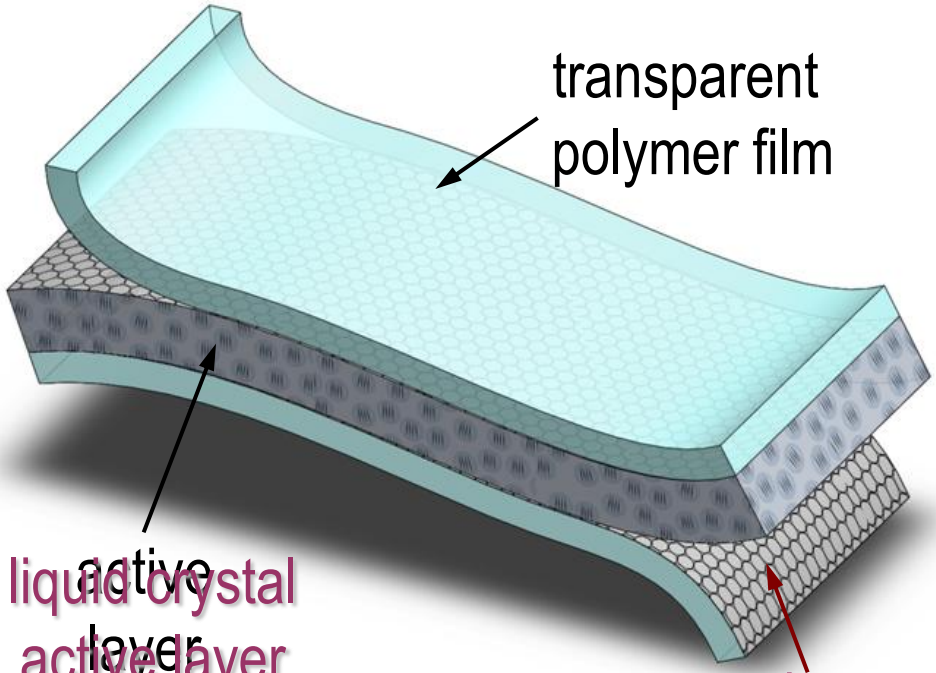
transparent: ~97%

conductive: $\rho$ <10$\Omega/\square$

Manchester, *NanoLett* 2008



WORKING 10 $\mu$m
LCD-GRAPHENE PIXEL



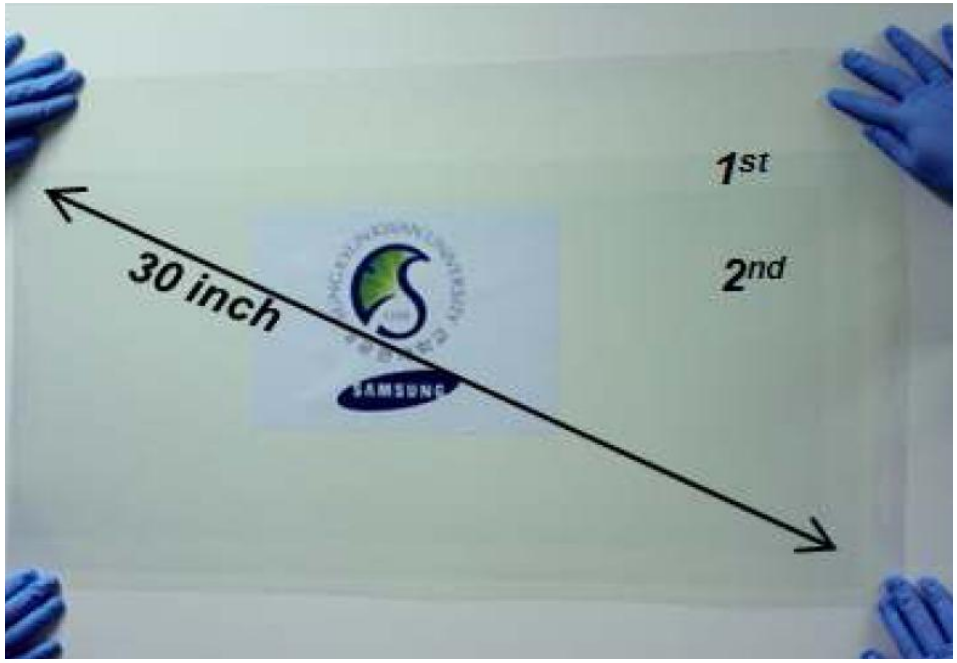
# GRAPHENE AS SUBSTITUTE FOR ITO

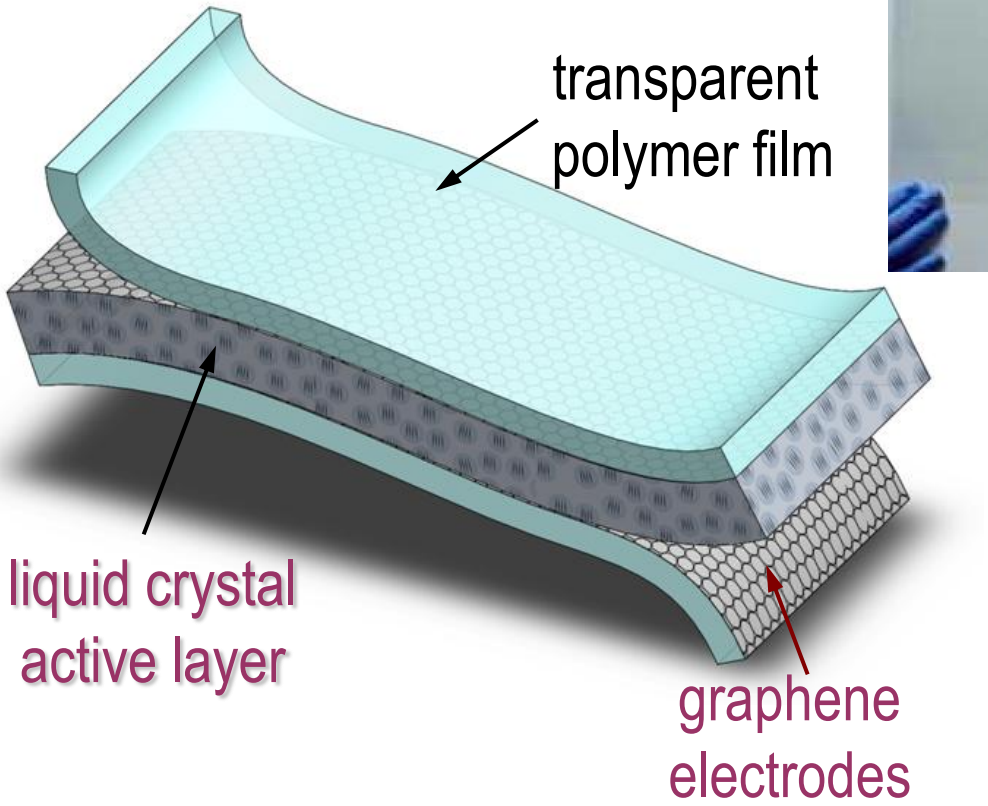
transparent: ~97%

conductive: ρ <10Ω/□

flexible: strain >15%

chemically inert




ρ down to 40Ω/□

transparency ~90%

μ ~5,000 cm²/Vs

Hong+Ahn, Nature Nano 2010

reasonably cheap:
~$50/m²

# TOUCH SCREENS & OTHERS

## bendable & wearable gadgets

Samsung's Advert


Samsung's Graphene Road Map:
first consumer products in 2012