MANCHESTER
1824

The University of Manchester

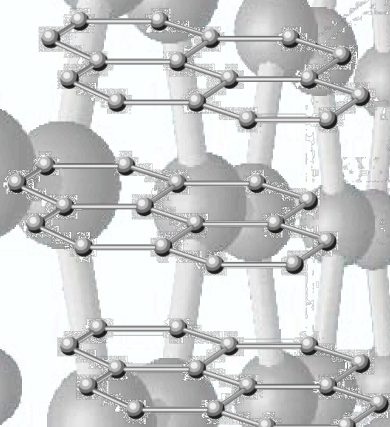
Introduction to Graphene

Andre Geim

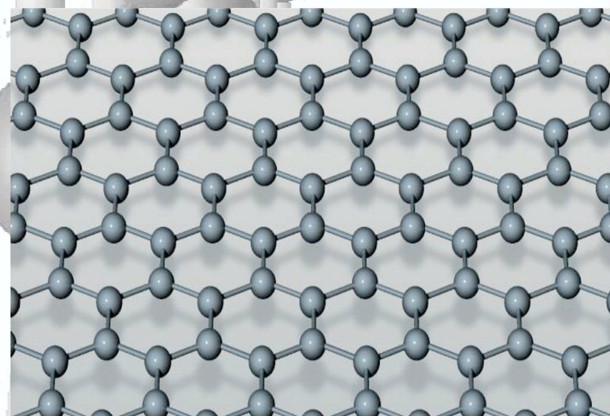
in collaboration with
K. Novoselov, S. Morozov, F. Schedin
P. Blake & M. Katsnelson

MOTHER OF ALL GRAPHITIC FORMS

3D	2D	1D	0D



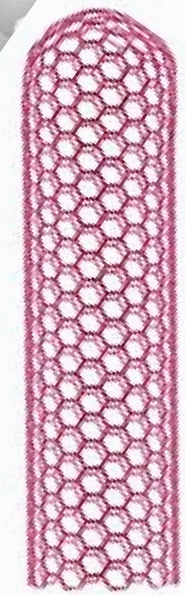
Graphite



graphene

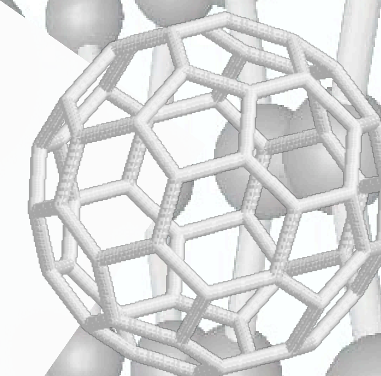
PRESUMED NOT TO EXIST IN THE FREE STATE

Manchester 2004



Carbon Nanotube

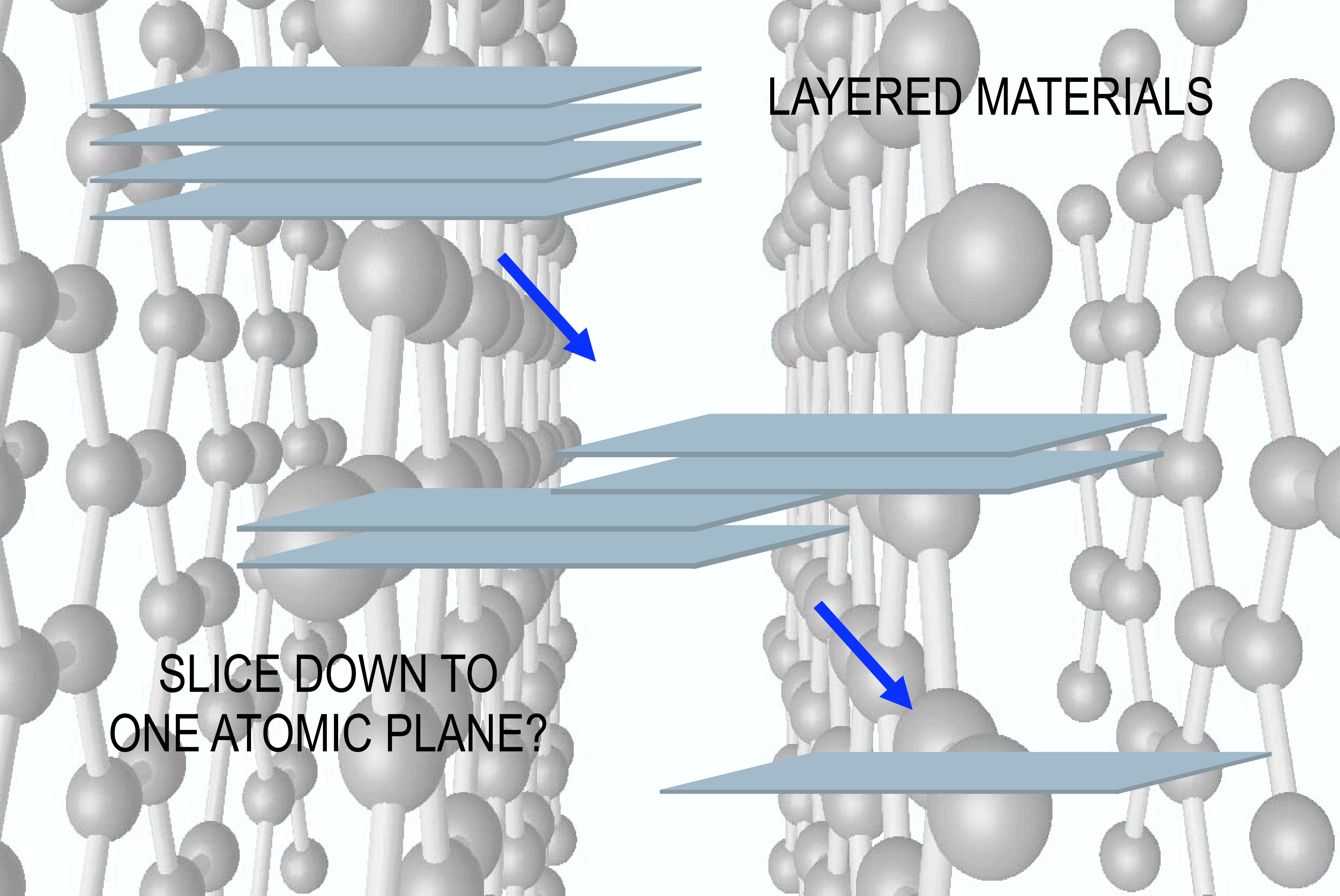
from 1952 to Iijima 1991



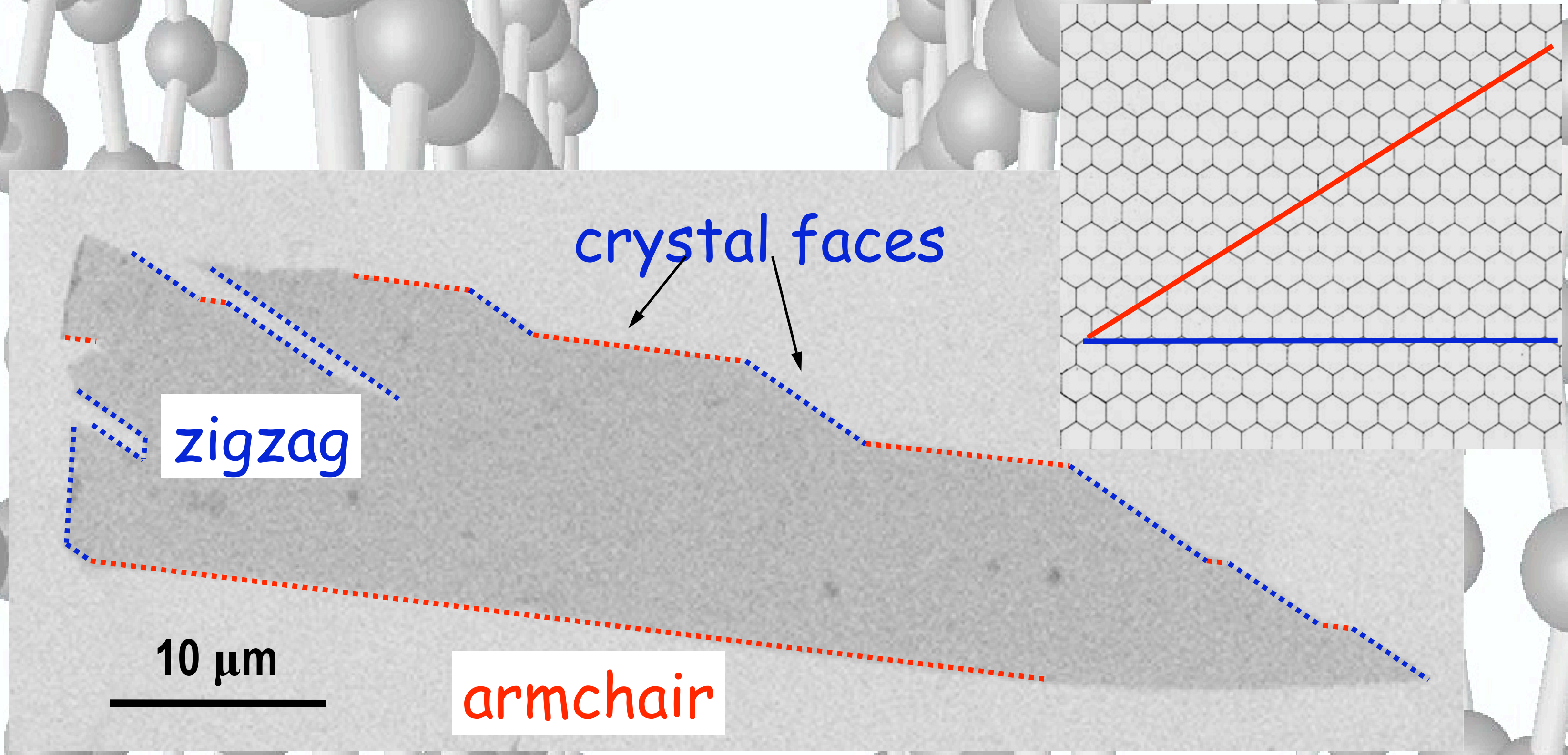
Buckyballs

Kroto et al 1985

Extracting a Single Plane

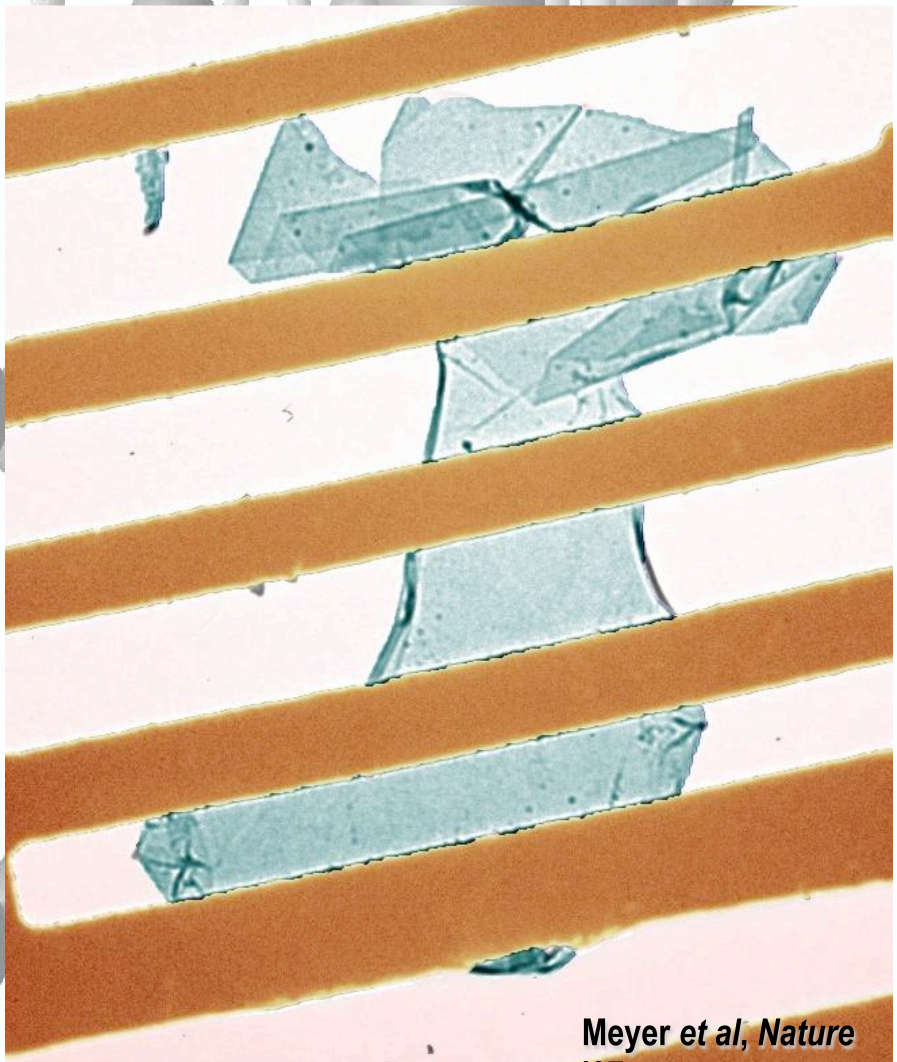


Two Dimensional Crystallites



not just flakes
but graphene crystallites

Two Dimensional Crystallites



Meyer *et al*, *Nature* '07

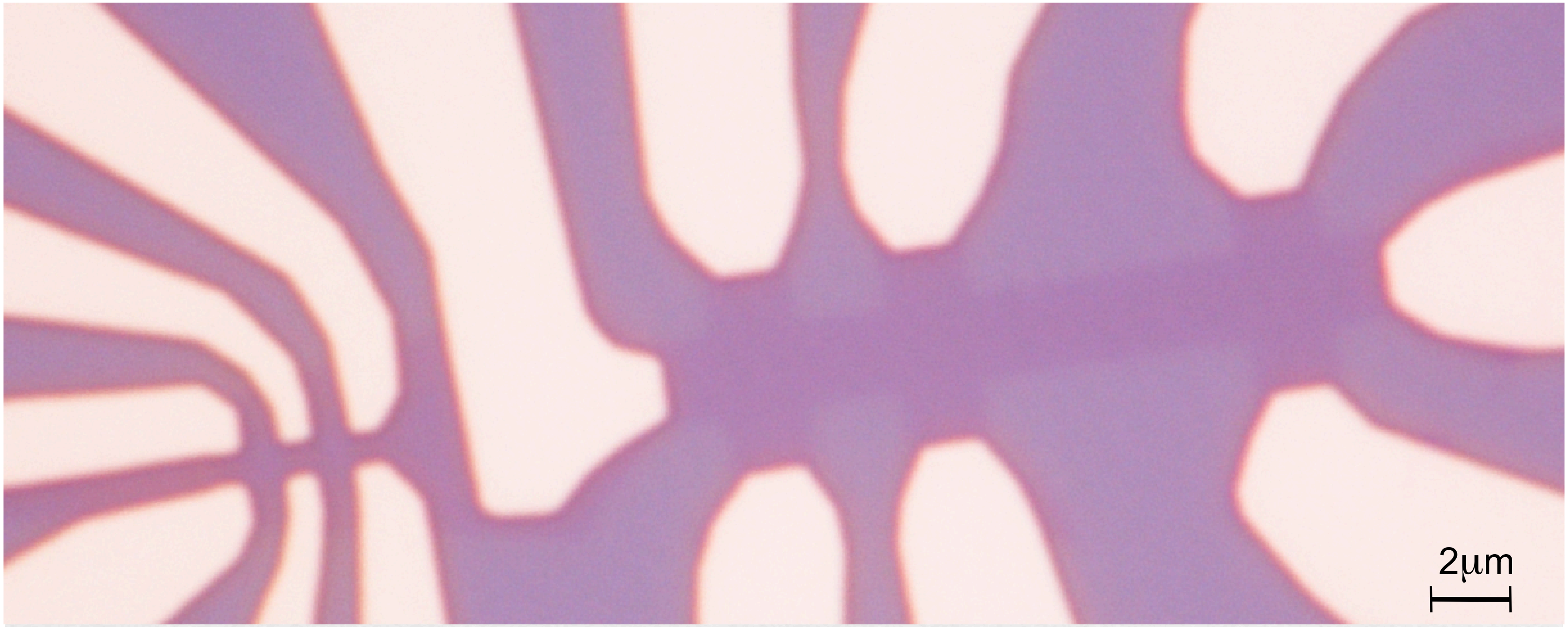
one-atom-thick single-crystals

graphene lattice in SuperSTEM

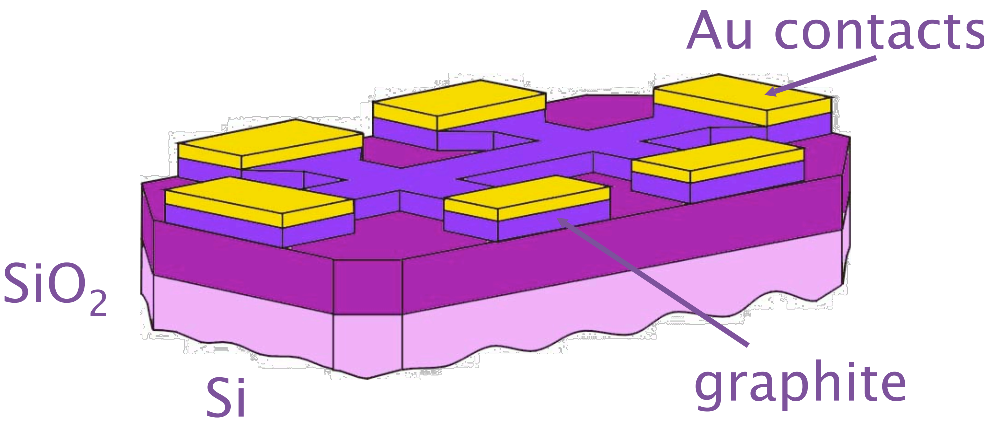
2D crystals first demonstrated
- Manchester, *Science* '04


REASON # 1
EXCEPTIONAL
QUALITY

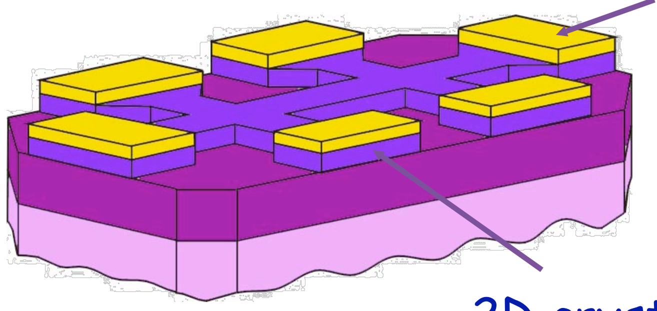
Graphene Devices



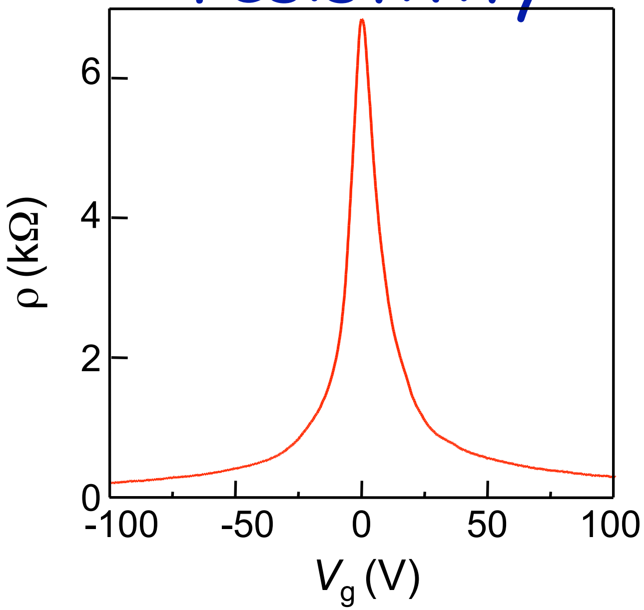
- optical image
- SEM image
- design
- contacts and mesa



Exceptional Quality



resistivity



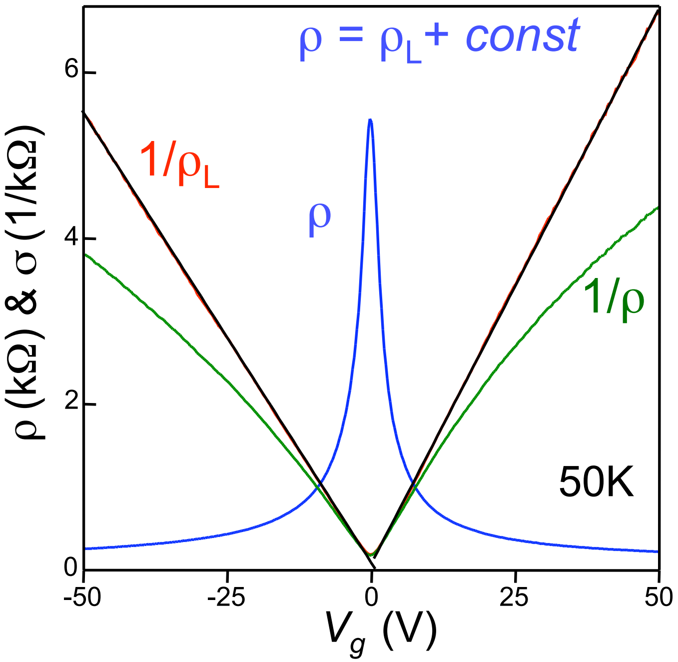
ballistic transport on submicron scale under ambient conditions

graphene: carrier mobility at 300K

<u>currently</u>: up to 15,000 $cm^2/V\cdot s$

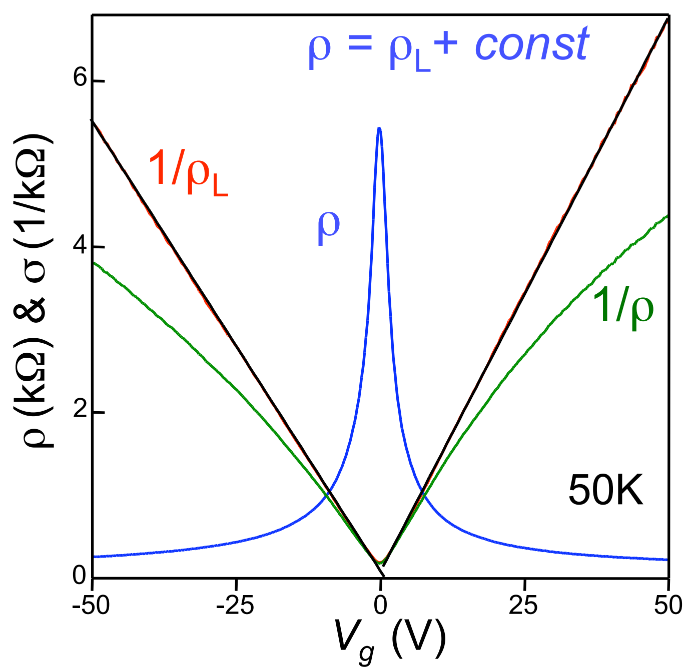
<u>intrinsic</u>: >200,000 $cm^2/V\cdot s$

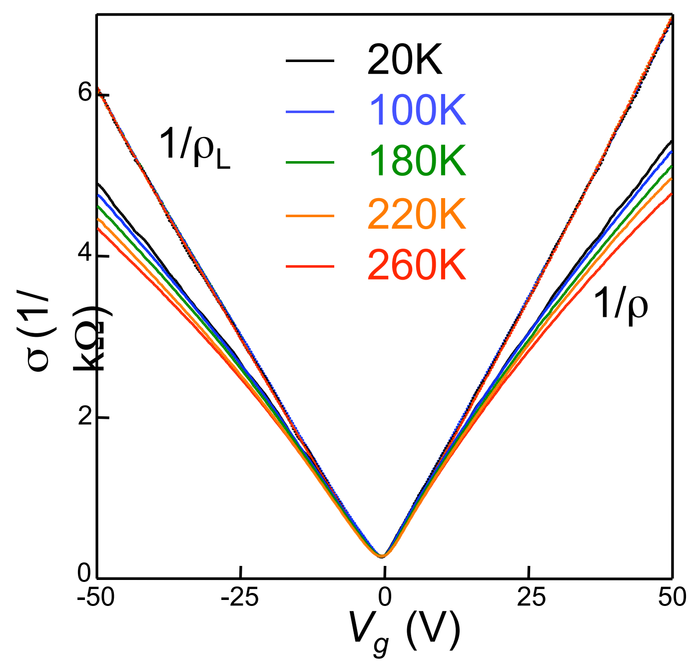
Intrinsic Mobility



resistivity consists of
long ($\sigma \propto n$) and short (const ρ)
range contributions

Intrinsic Mobility





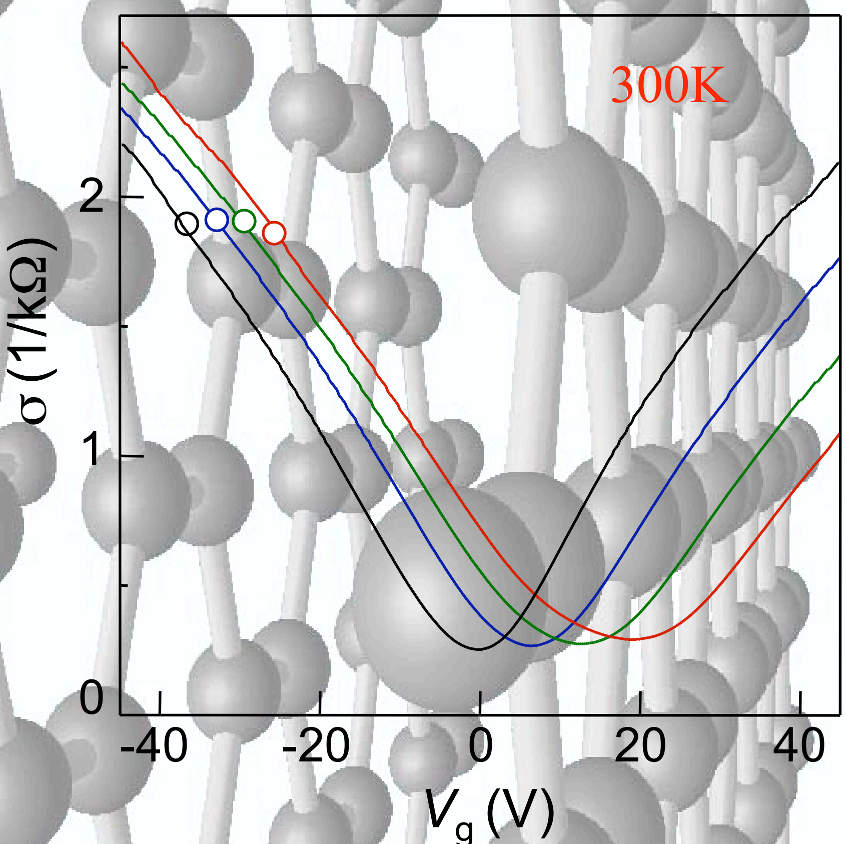
resistivity consists of long ($\sigma \propto n$) and short (const $\delta\rho$) range contributions

phonons are short-range scatterers contributing $\delta\rho$ <50Ω at 300 K (maybe, "extrinsic" phonons)

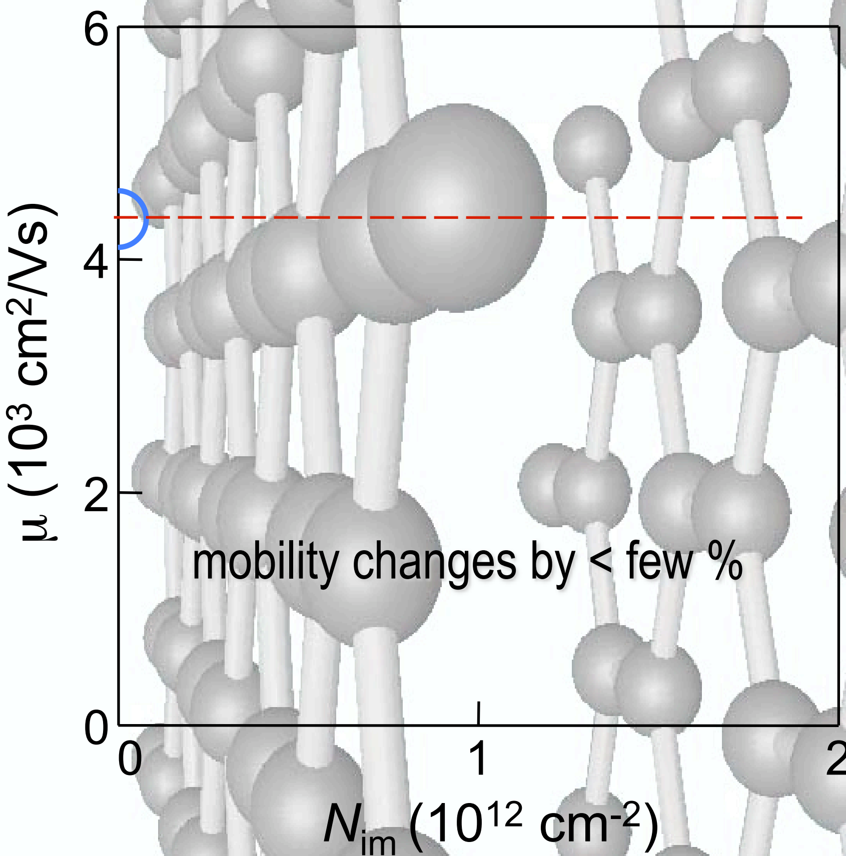
phonon-limited mobility >200,000 $cm^2/V{\cdot}s$ at 300K

Doping Does Not Reduce Carrier Mobility

conductivity with increasing doping by NO_2



changes in mobility with increasing acceptor concentration

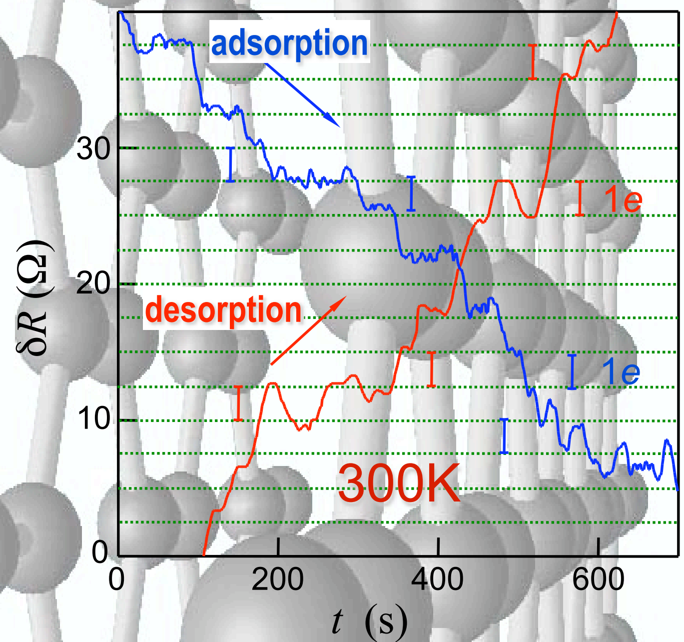


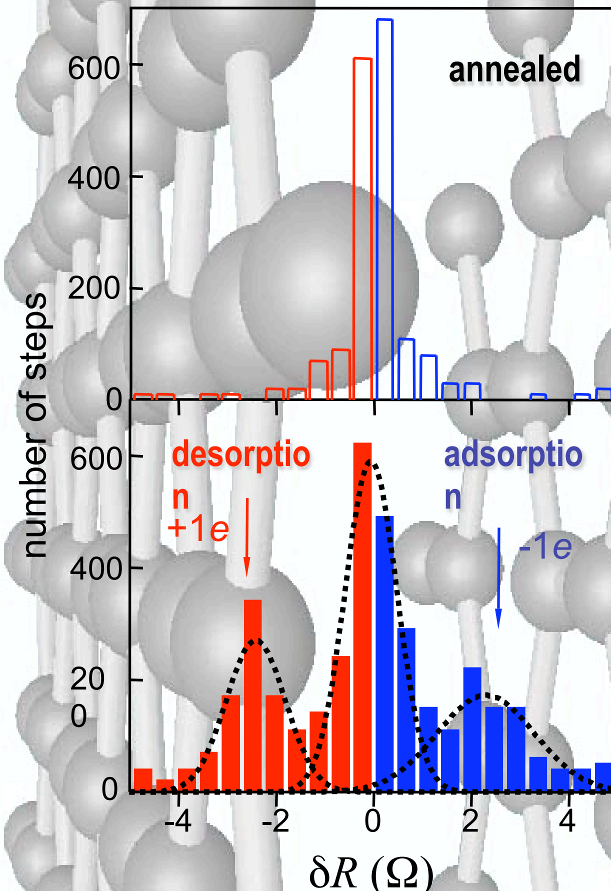
ballistic transport on 1μm scale

with charged impurities at <10nm spacing

Manchester, *Nature* Mat '07

Single-Molecule Detection

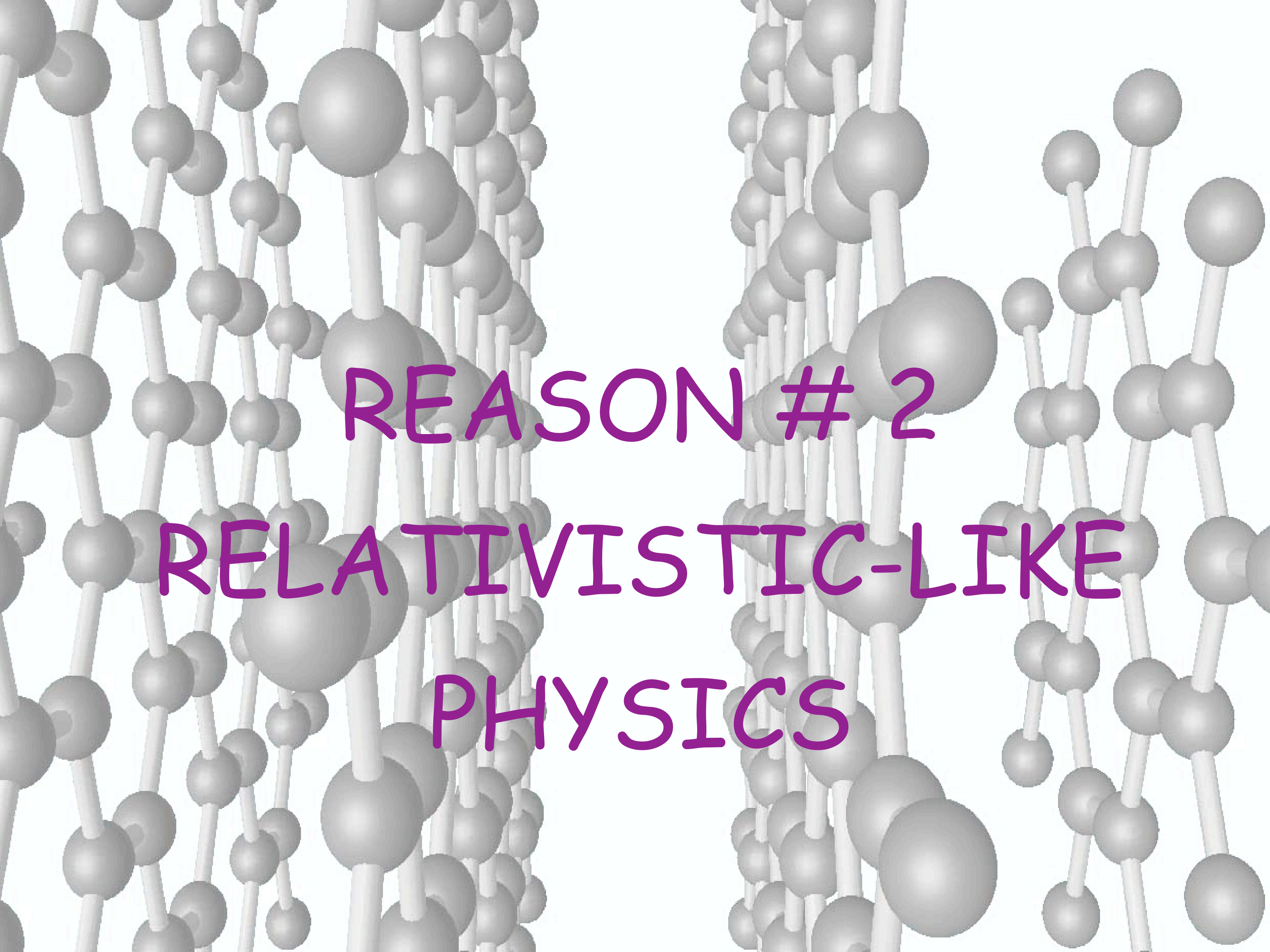




step-like changes near zero concentration

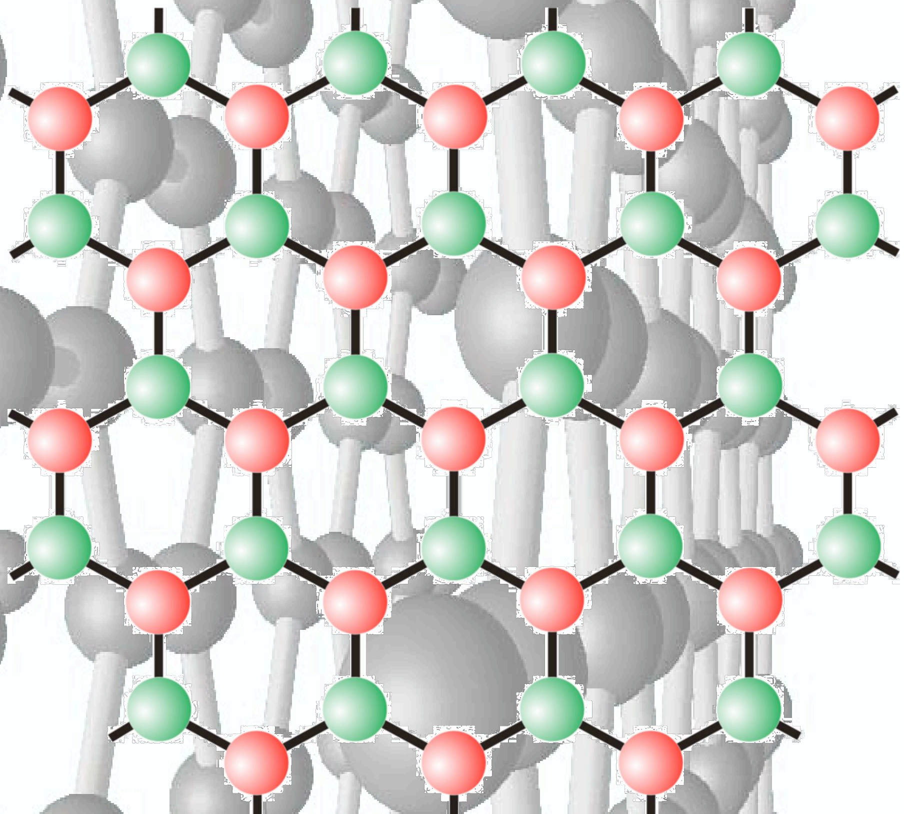
Manchester, *Nature* Mat '07

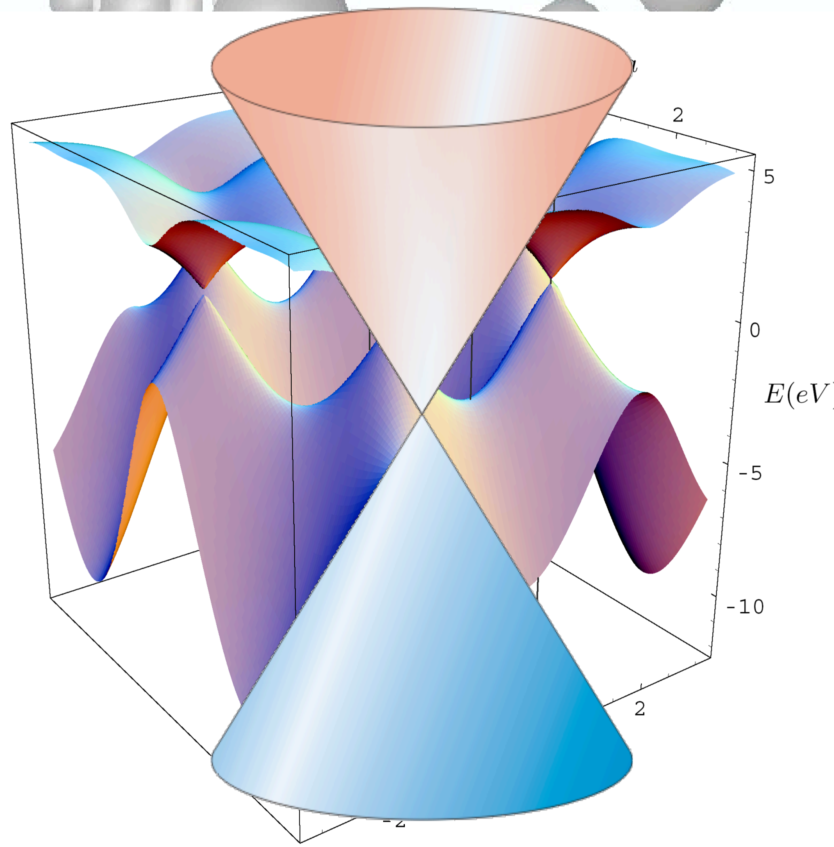
EXTREMELY ELECTRONICALLY QUIET: FEW UNSTABLE DEFECTS



REASON # 2
RELATIVISTIC-LIKE PHYSICS

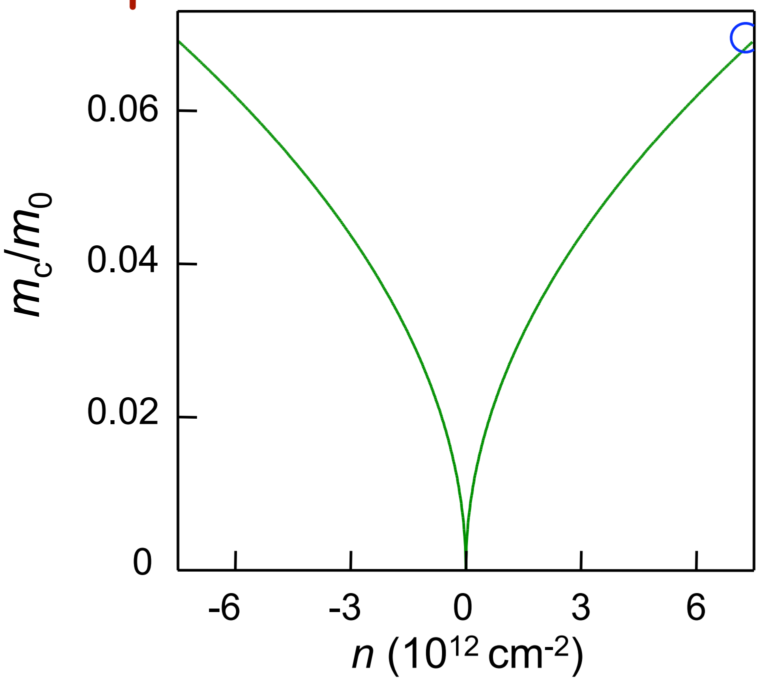
Chiral Fermions in Graphene



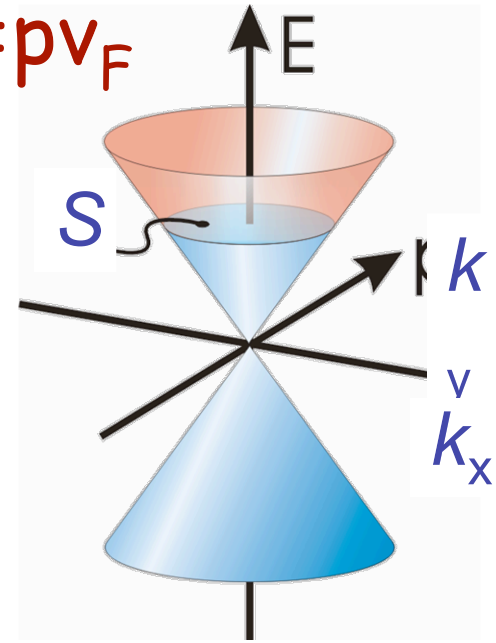


Band Structure of Graphene

cyclotron mass strongly depends on concentration



$E = pv_F$



$B_F = (\hbar/2\pi e)S$ and $m_c = (\hbar^2/2\pi)\partial S/\partial E$

experimental dependences

$B_F \sim n$ and $m_c \sim n^{1/2}$

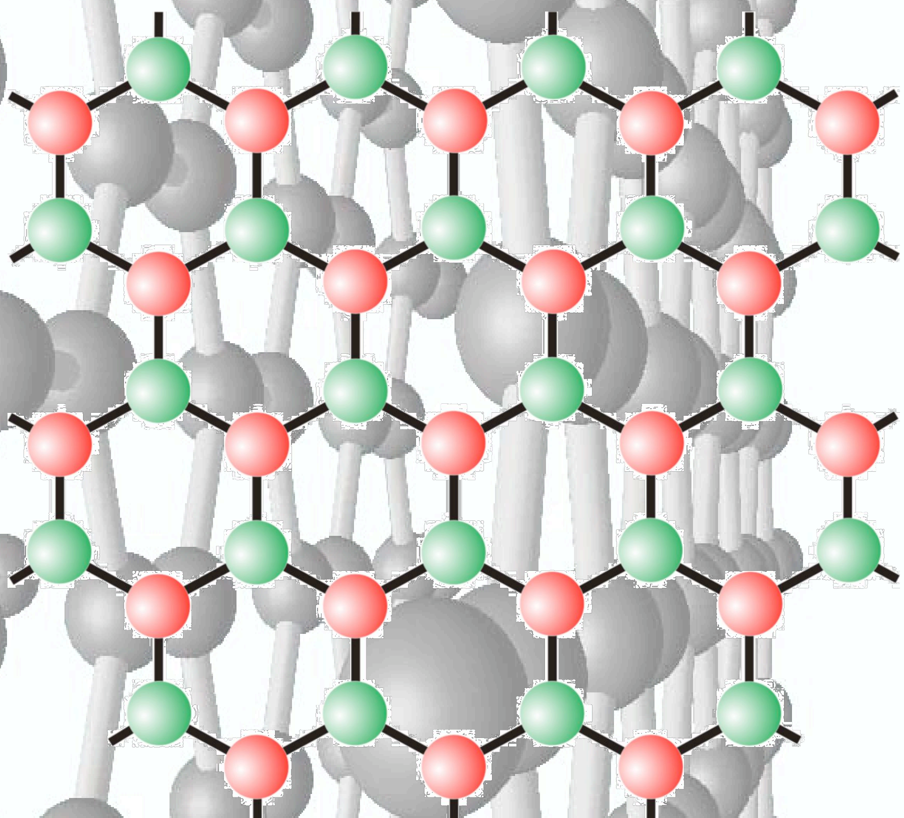
necessitates $S \sim E(k)^2$ or $E \sim k$

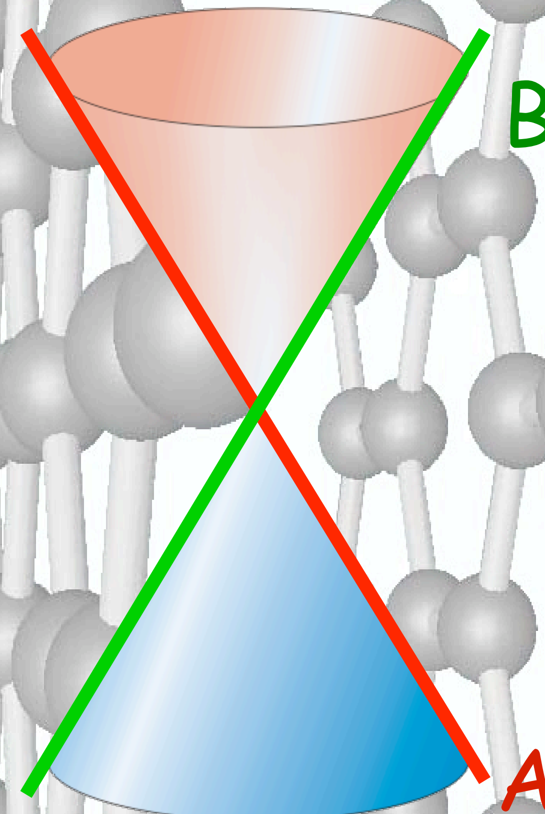
effective mass

$E = m_c v_F^2$

$v_F = 10^6$ m/s ±5%

Chiral Fermions in Graphene



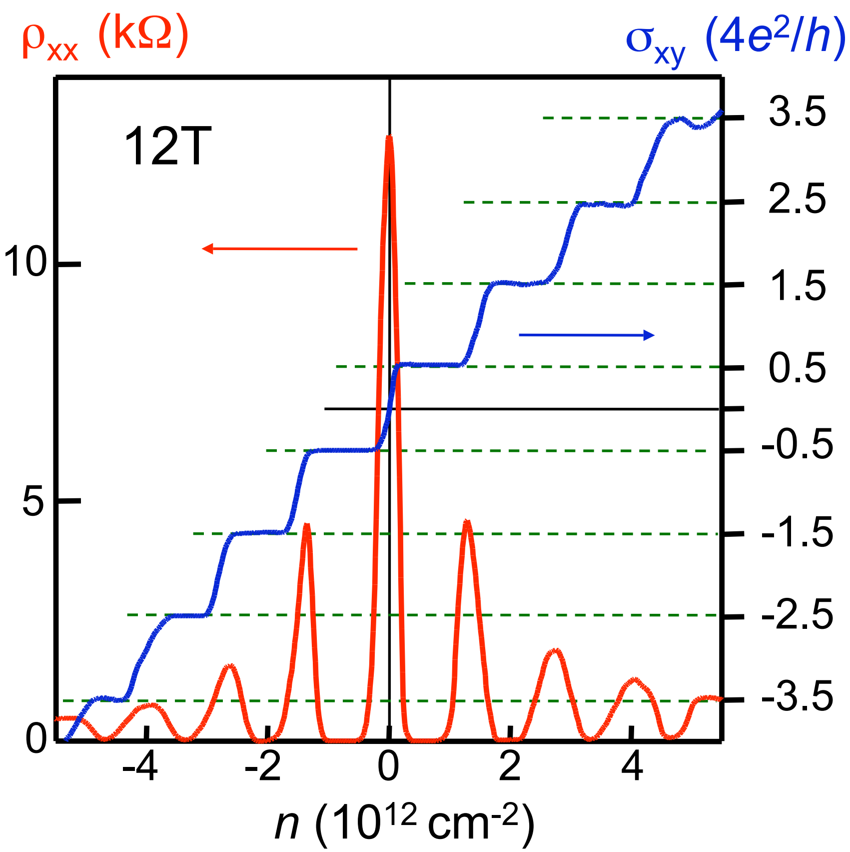


Dirac-like equation:

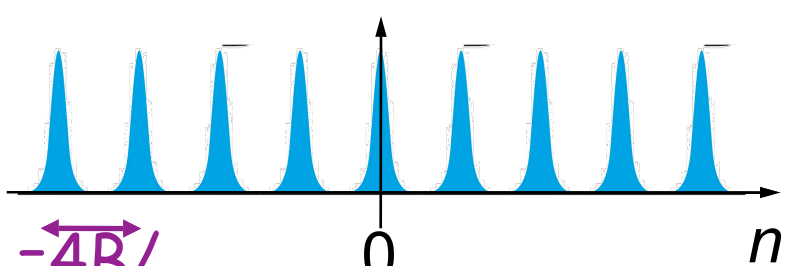
$$\hat{H} = v_F \begin{pmatrix} 0 & \hat{p}_x + i\hat{p}_y \\ \hat{p}_x - i\hat{p}_y & 0 \end{pmatrix} = v_F \vec{\sigma} \times \vec{p}$$

McClure 56; Semenoff 84

half-integer quantum Hall effect



relativistic analogue of the integer QHE

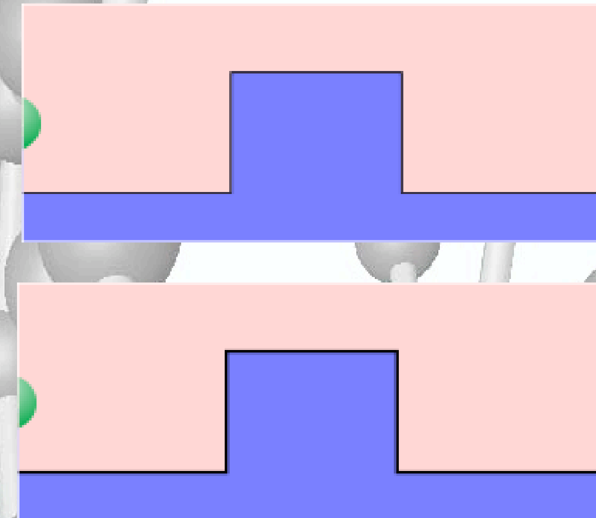


$\Delta n = 4B/\varphi_0$

Manchester, Nature **438**, 197 ('05)

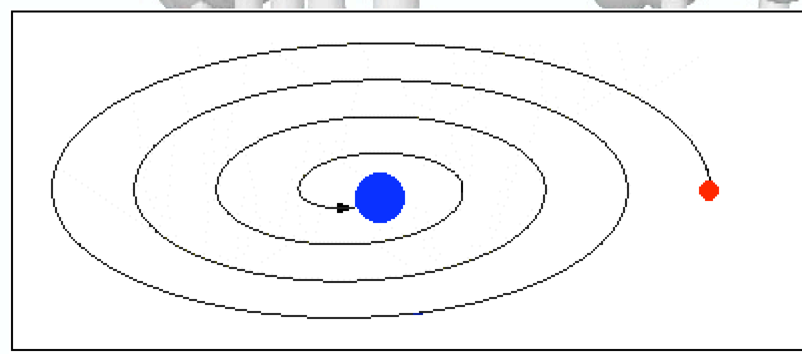
also, Philip Kim's group ibid 201 ('05)

ACCESS TO QED-LIKE PHYSICS IN CONDENSED MATTER EXPERIMENT



Klein "Paradox"

relativistic fall-down on the centre



$Z > \hbar c / e^2 \approx 137$

The End of Periodic Table

Zitterbewegung

responsible for the finite conductivity of $\approx e^2/h$ (?)

major observations
(... at these very early days)

conductivity 'without' charge carriers

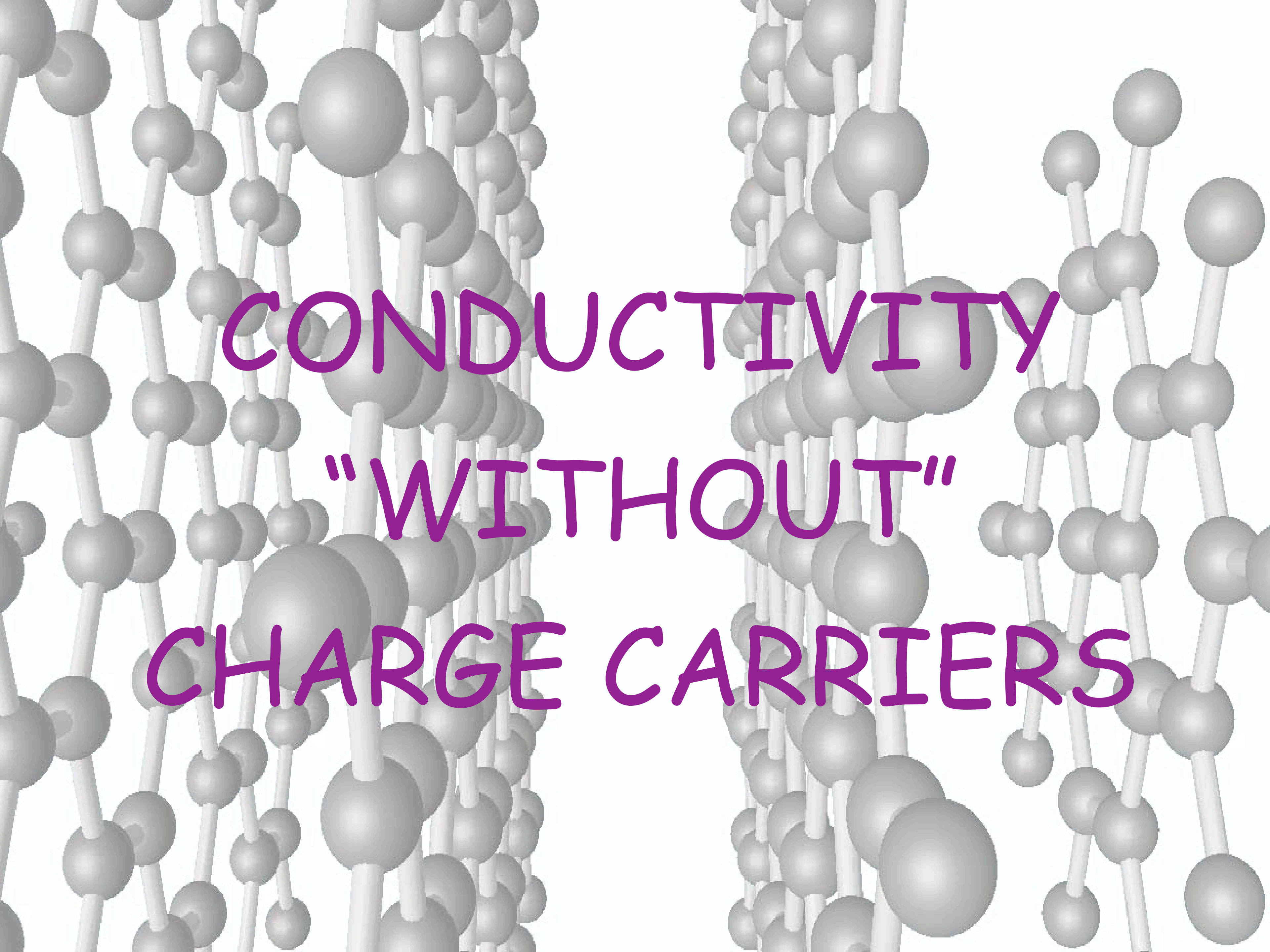
chiral QHE in its bilayer

random vector & scalar fields
microscopic corrugations

suppression of weak localization

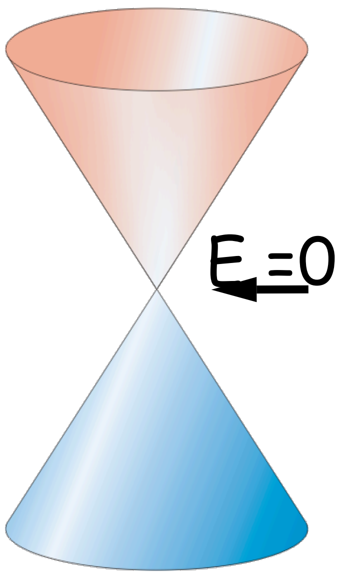
long-range spin transport at room T

quantum chaos in graphene dots

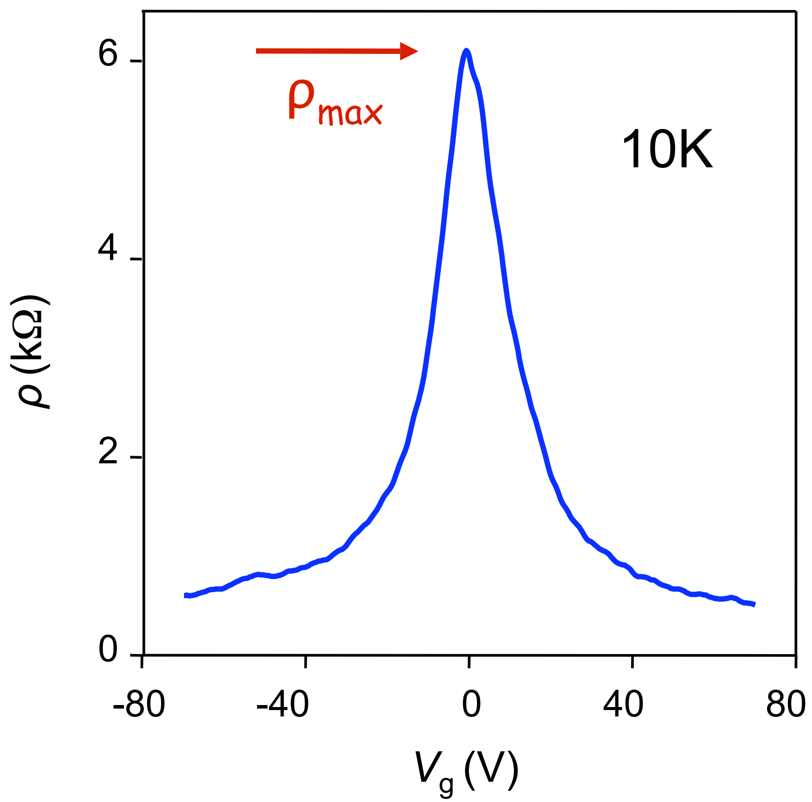


CONDUCTIVITY "WITHOUT" CHARGE CARRIERS

Minimum Quantum Conductivity



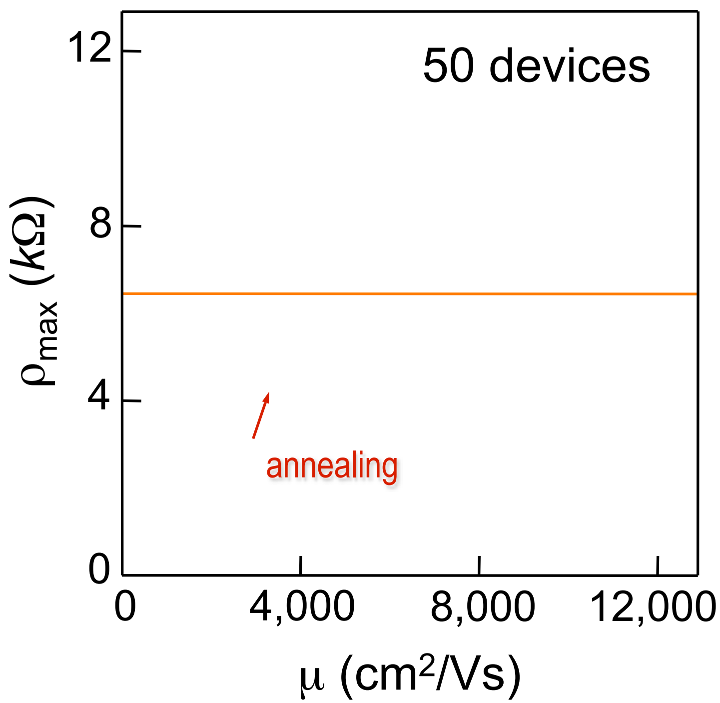
zero-gap
semiconductor



no temperature
dependence
in the peak
from 3 to 300K

NO
metal-insulator
transition

Minimum Quantum Conductivity



$h/4e^2$

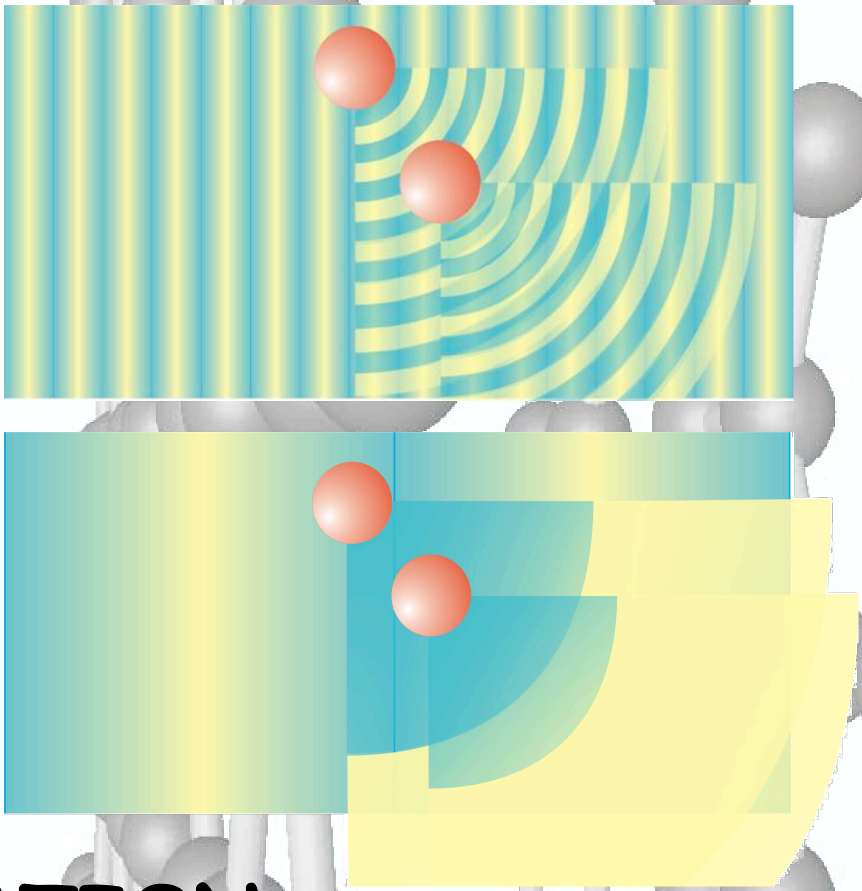
most theories predict π-times larger value

Fradkin 1986
Lee 1993
Ludwig 1994
Morita 1997
Ziegler 1998
Peres 2005
Gusynin 2005
Katsnelson 2006
Tworzydlo 2006
Cserti 2006
Ostrovsky 2006
.....
.....

quantized resistivity NOT resistance

(h/e^2 per spin and valley)

Minimum Quantum Conductivity



Mott's argument: $l \geq \lambda_F$

$$\sigma = ne\mu = \frac{e^2}{h} k_F l \geq \frac{e^2}{h}$$

<u>NO LOCALIZATION</u>

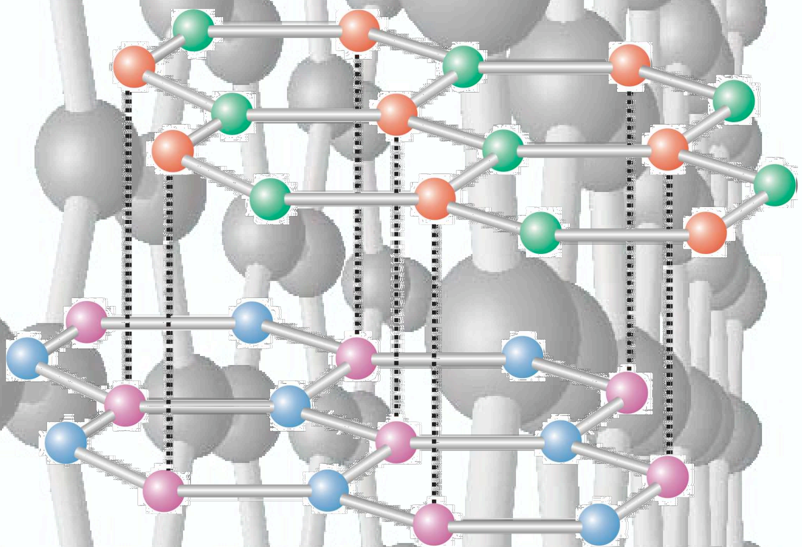
<u>NO METAL-INSULATOR TRANSITION</u>

Geim & MacDonald Phys.Today 07

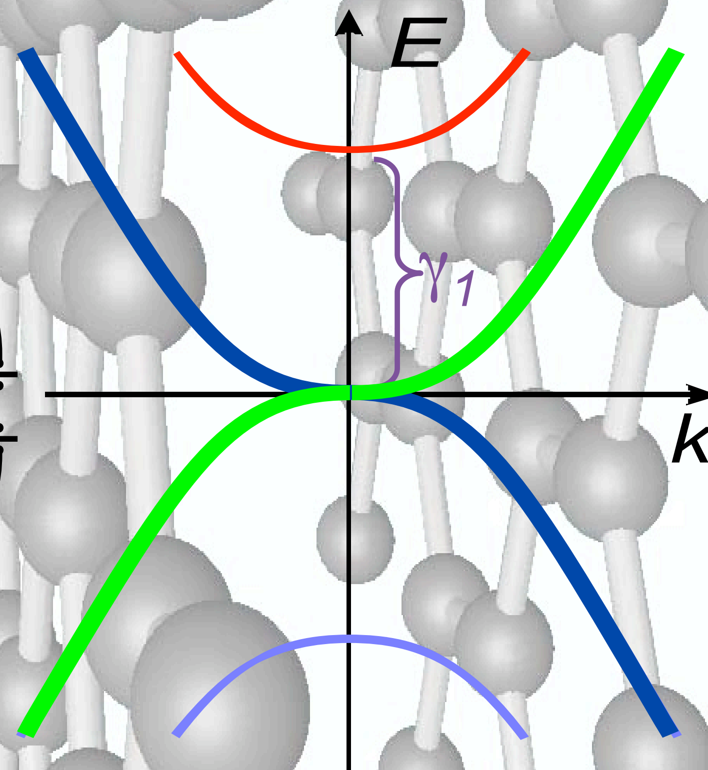
CHIRAL Quantum Hall Effect

(massive Dirac fermions)

massive Dirac fermions



$$E(p) = \pm \tfrac{1}{2}\gamma_1 \pm \sqrt{\tfrac{1}{4}\gamma_1^{\,2} + v_F^2 p^2}$$

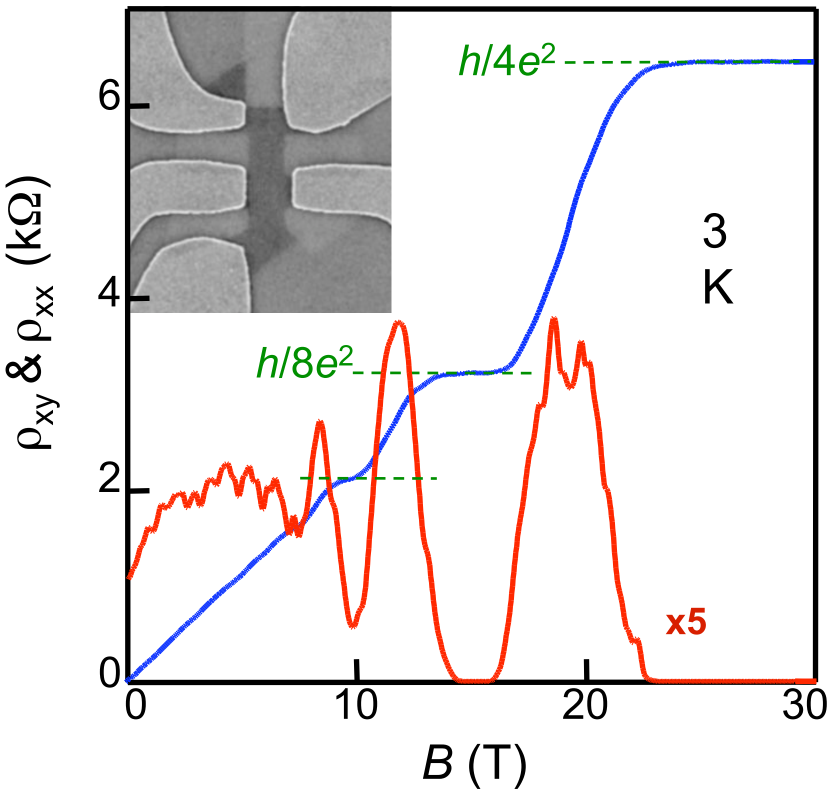


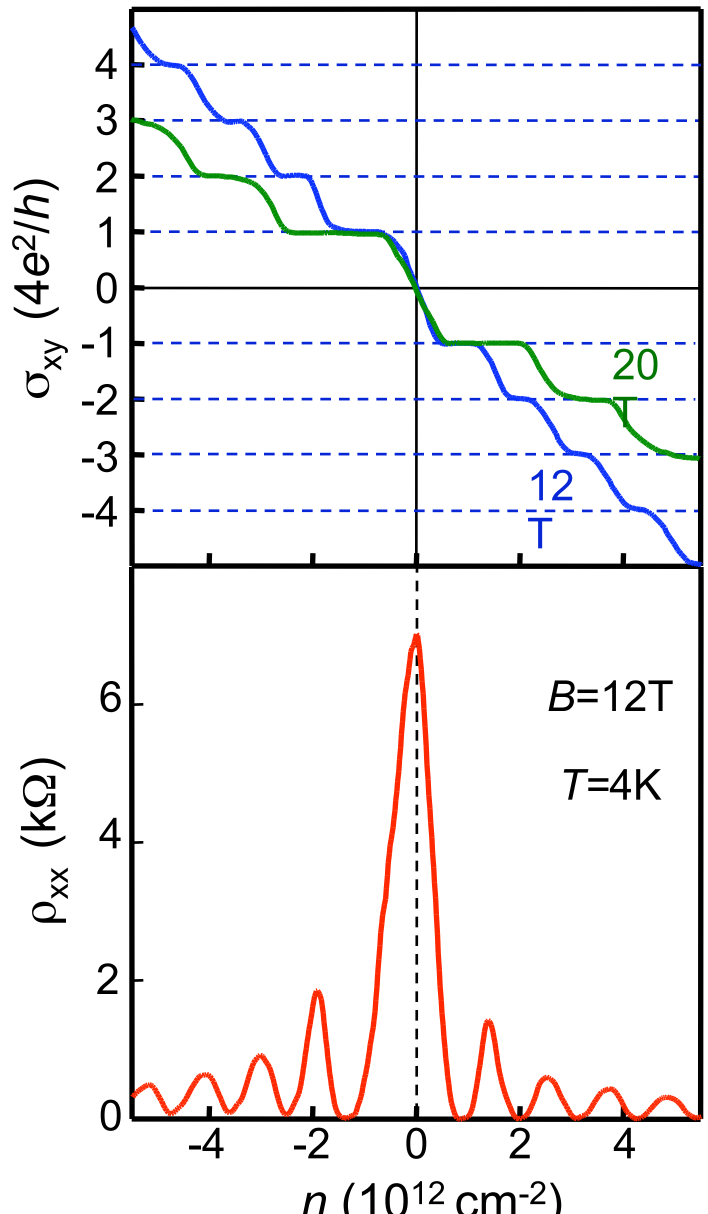
$$\hat{H} = -\frac{1}{2m}\begin{pmatrix} 0 & (\hat{p}_x + i\hat{p}_y)^2 \\ (\hat{p}_x - i\hat{p}_y)^2 & 0 \end{pmatrix}$$

$$E_N = \pm\hbar\omega_c\sqrt{N(N-1)}$$

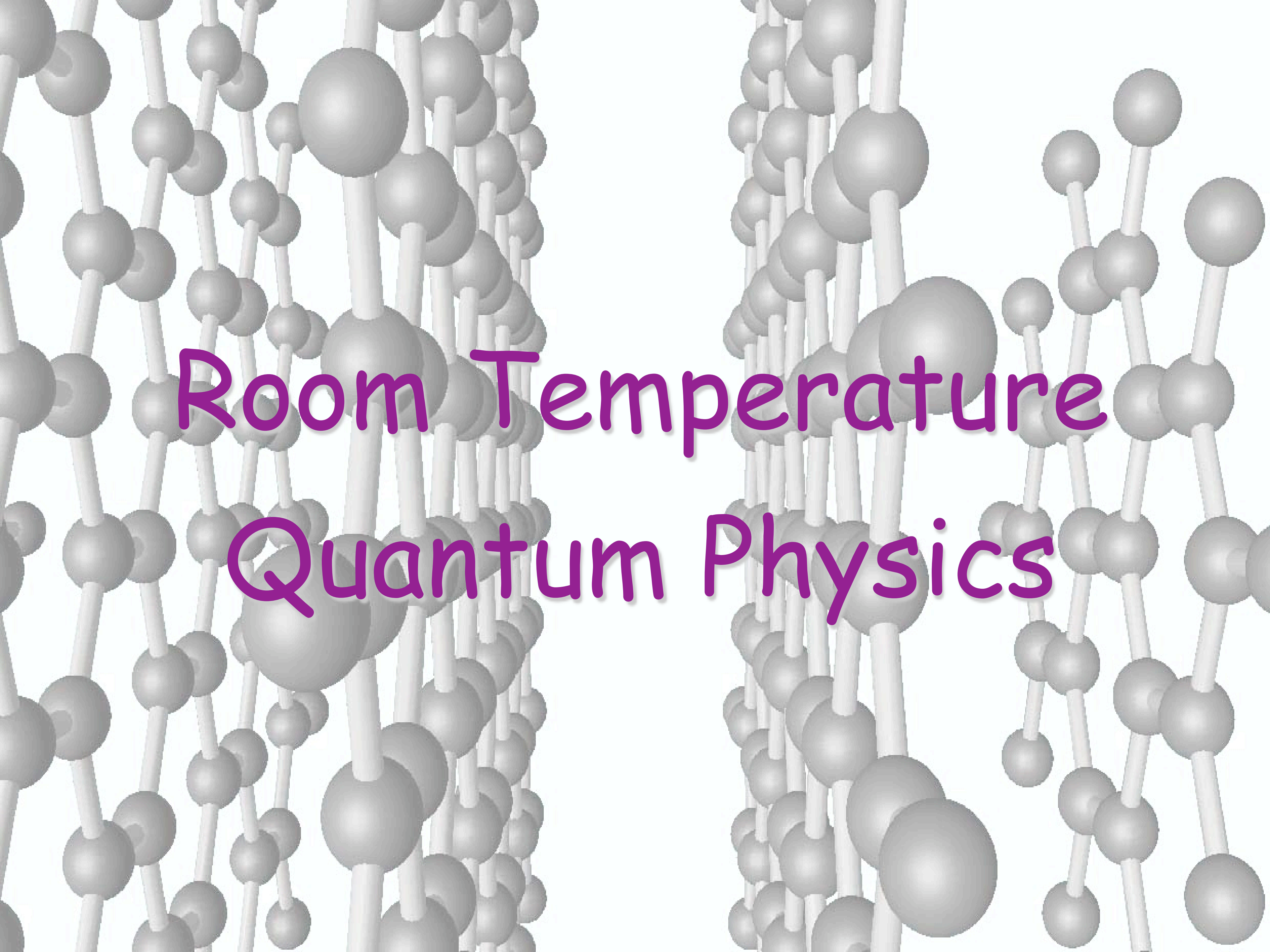
McCann & Falko 2006

QHE in bilayer graphene



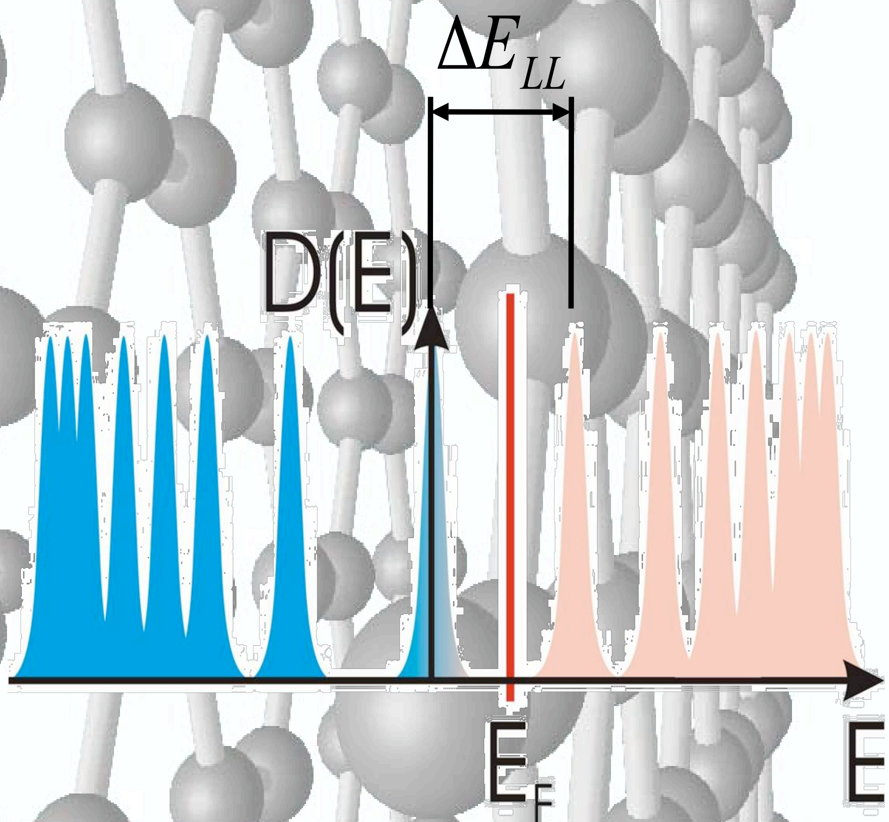


Nature Phys **2**, 177 (2006)



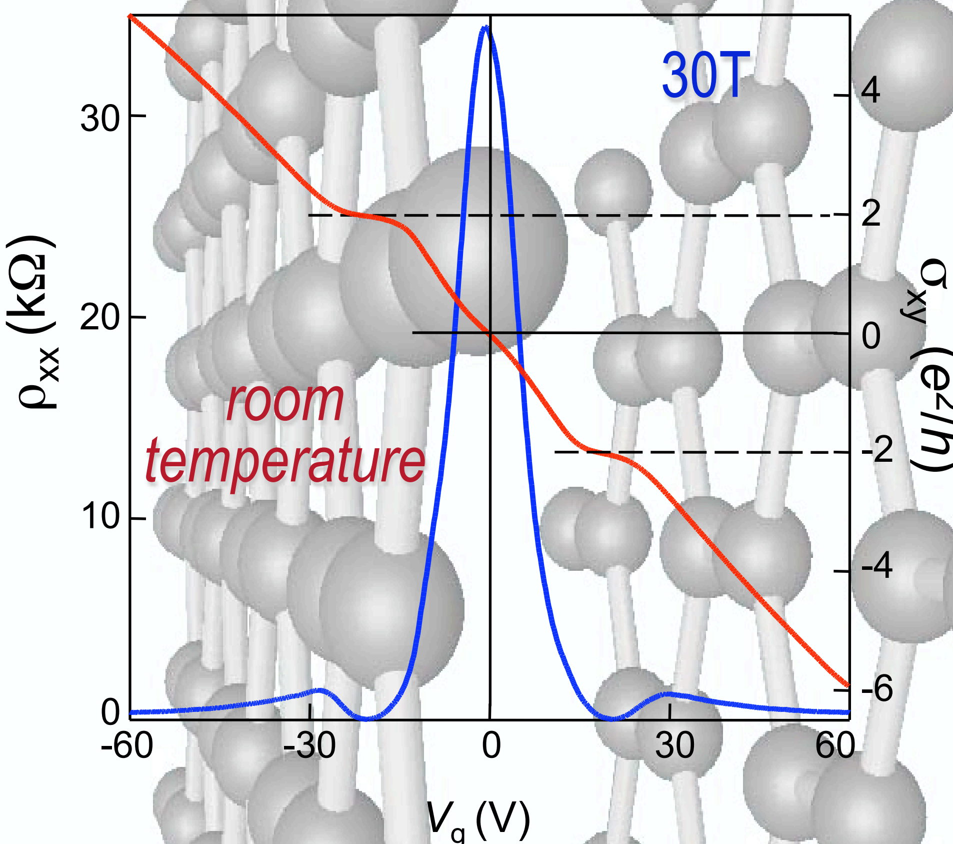
Room Temperature Quantum Physics

room-temperature QHE



$$\Delta E_{LL} = v_F \sqrt{2e\hbar B}$$

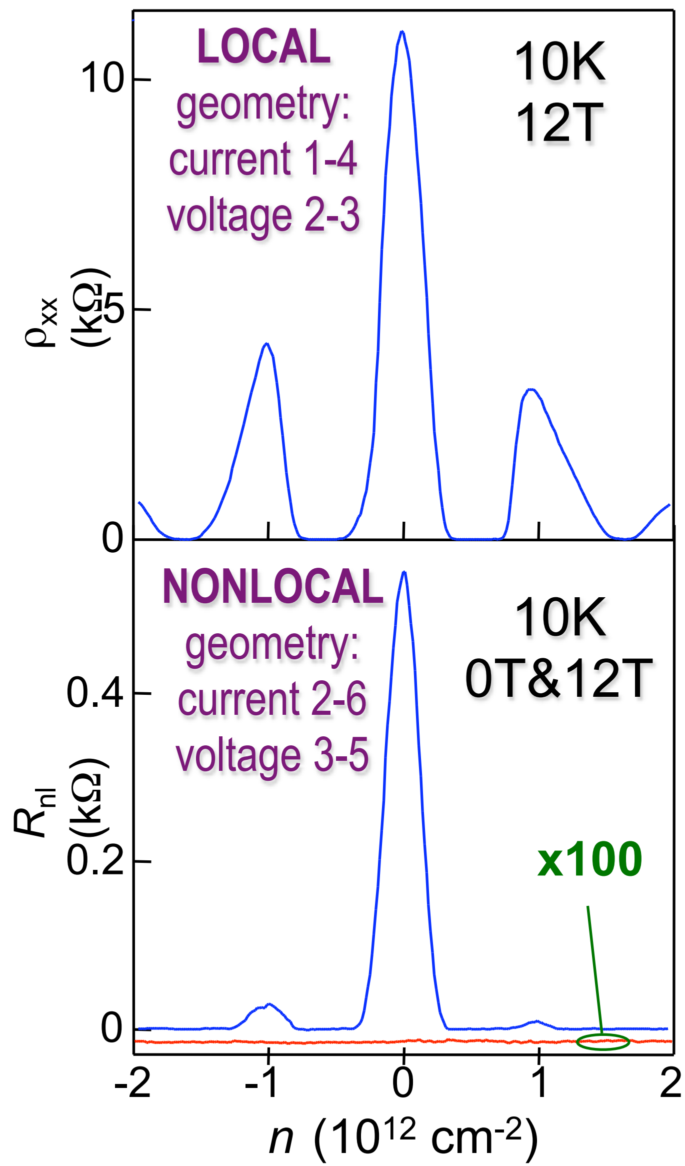
$$\Delta E_{LL}(K) = 420\sqrt{B(T)}$$

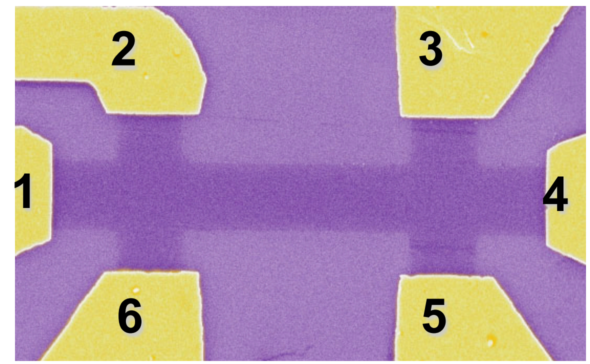


previously, QHE only below 30K

Novoselov *et al*, *Science* '07

Nonlocal Edge-State Transport

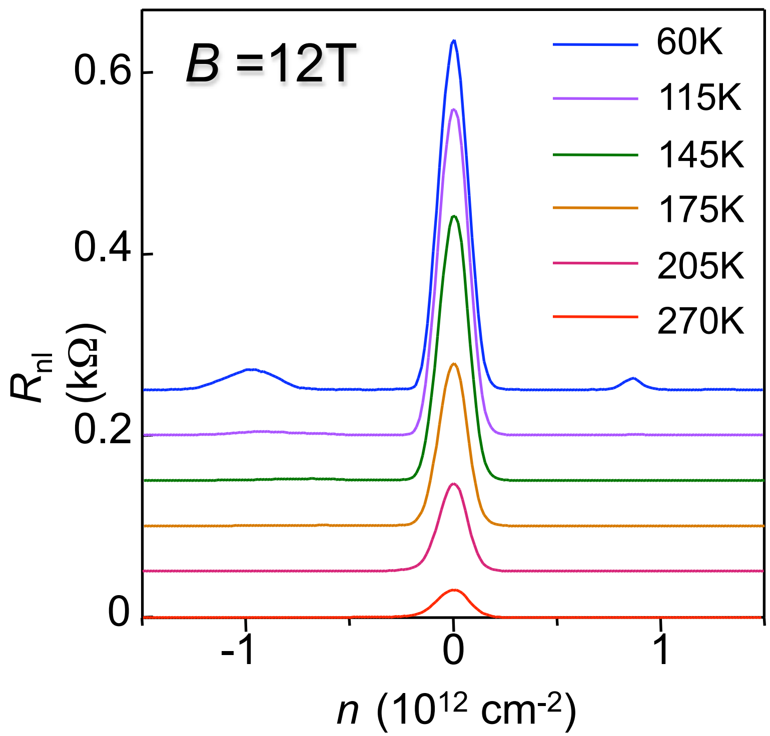




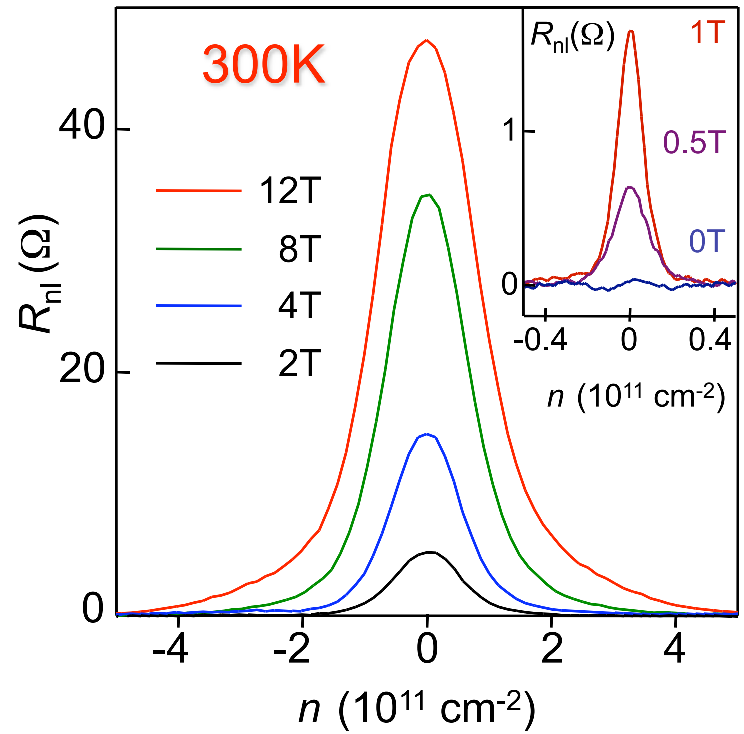
in magnetic field, current starts flowing in classically inaccessible regions

Room-T Nonlocal Transport

slow decay with T

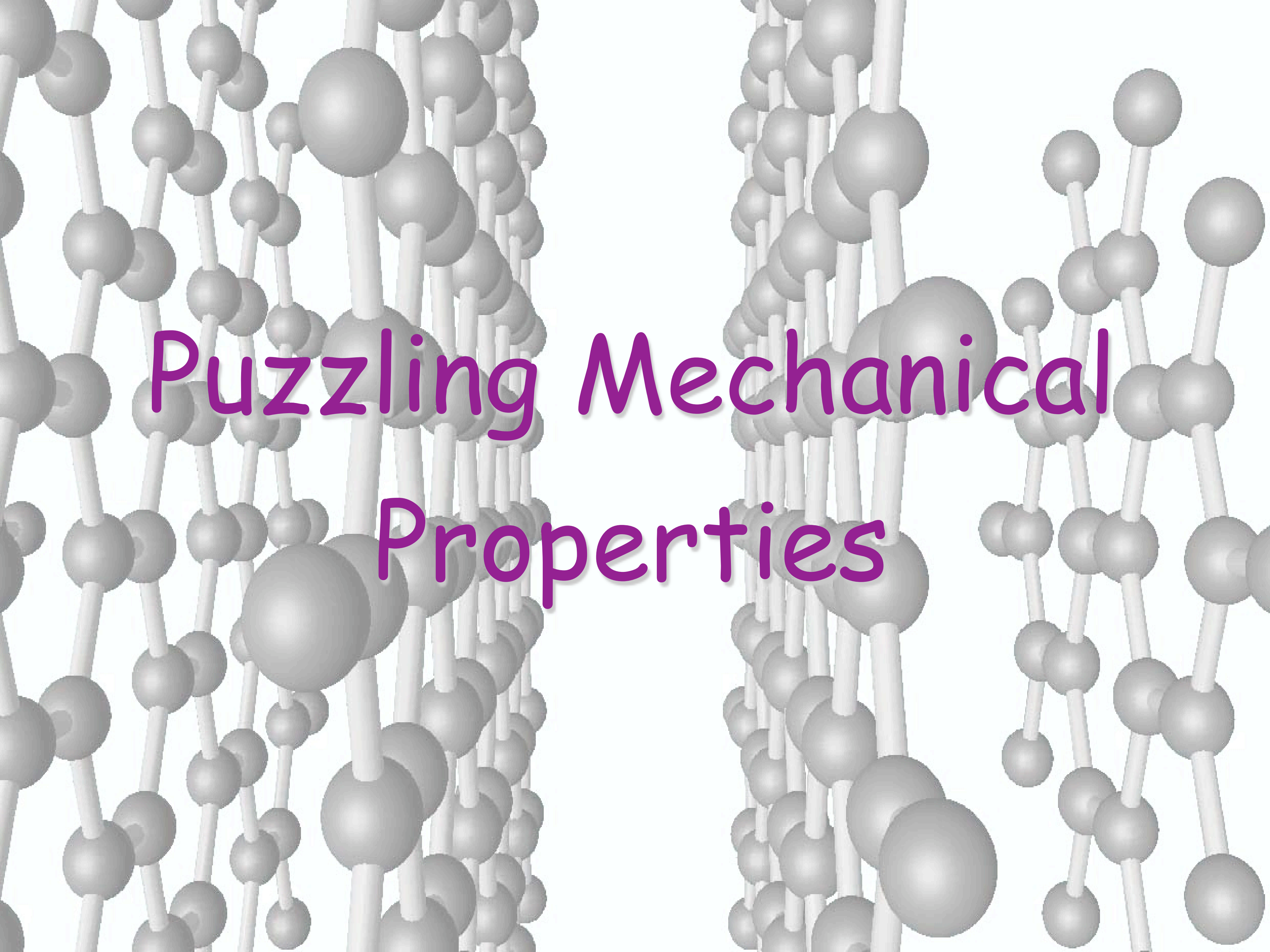


slow decrease with B

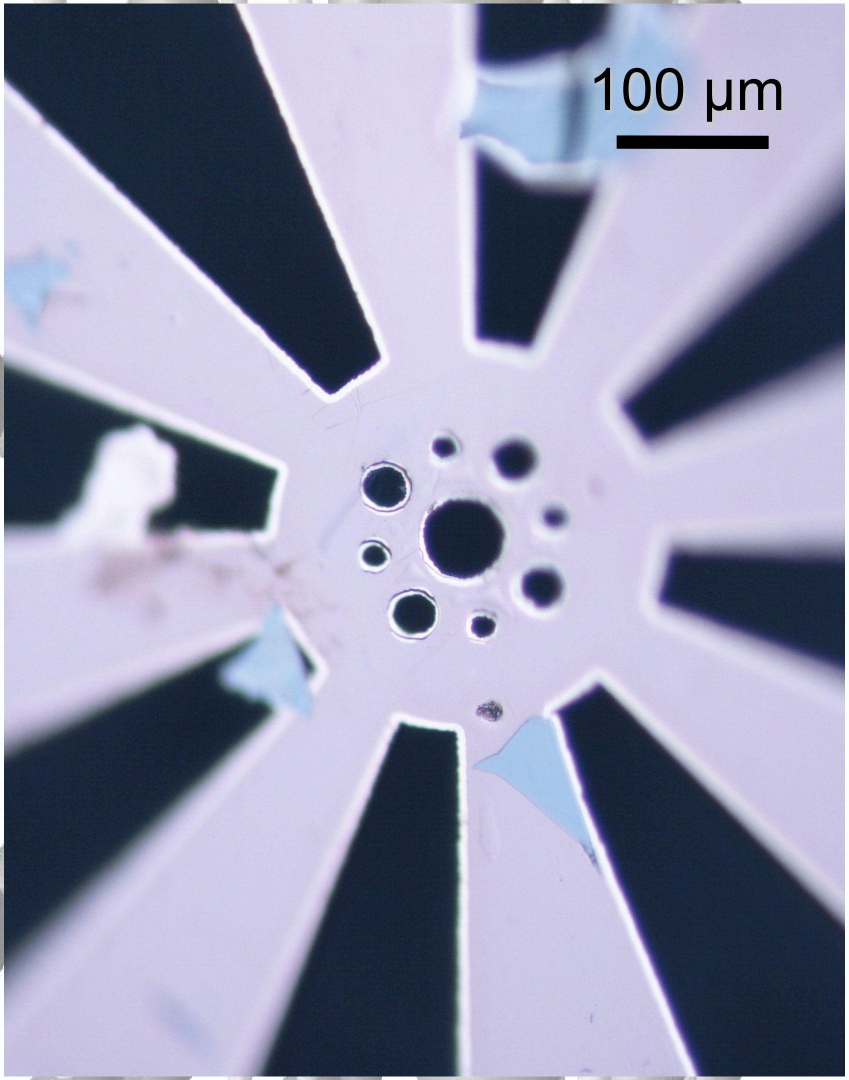


macroscopic-scale quantum effect
at 300K in fields < 1 Tesla
valley- or spin- polarized boundary states ?

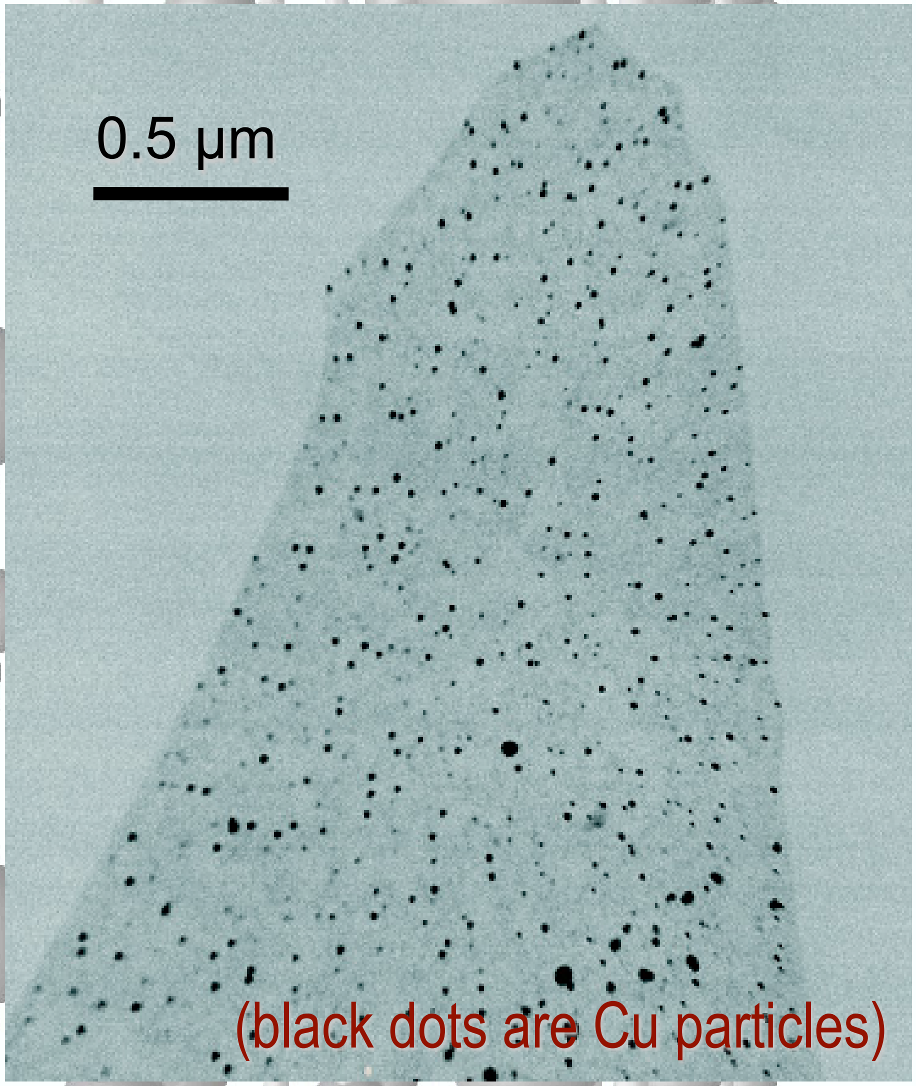
Puzzling Mechanical Properties

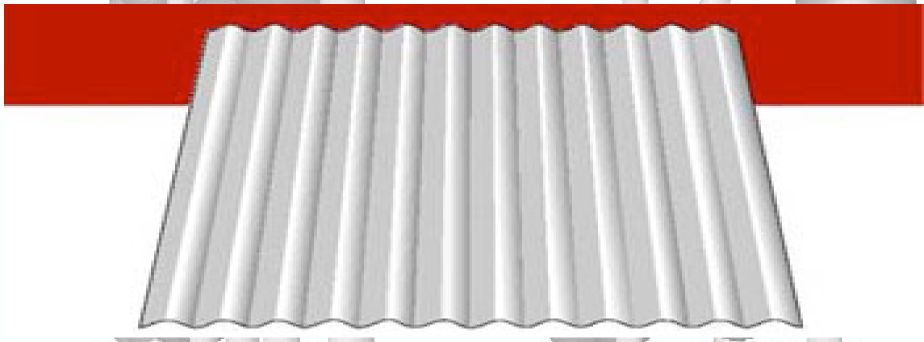


Graphene Membranes



Free-Standing Graphene



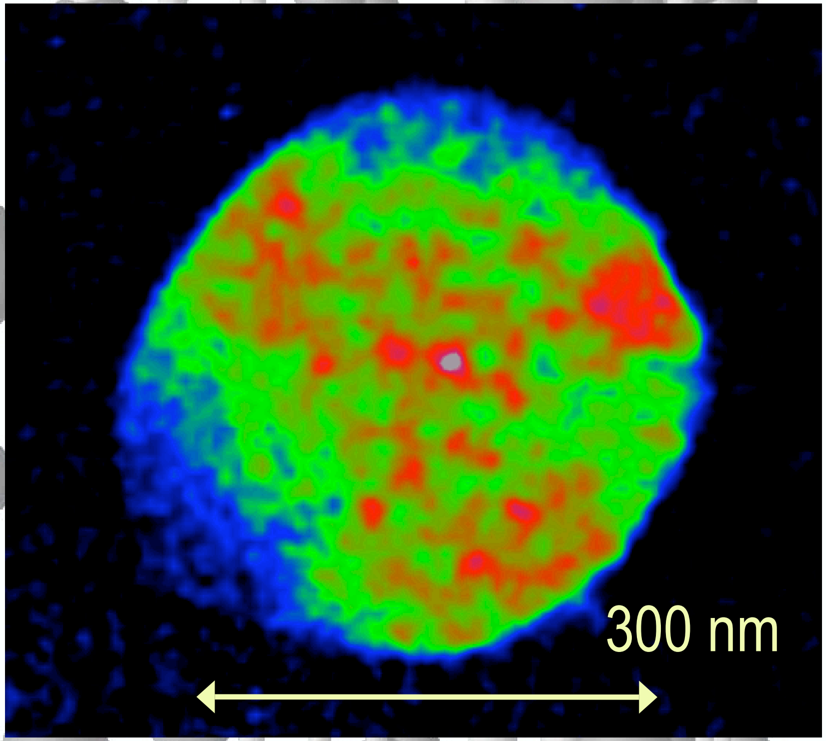


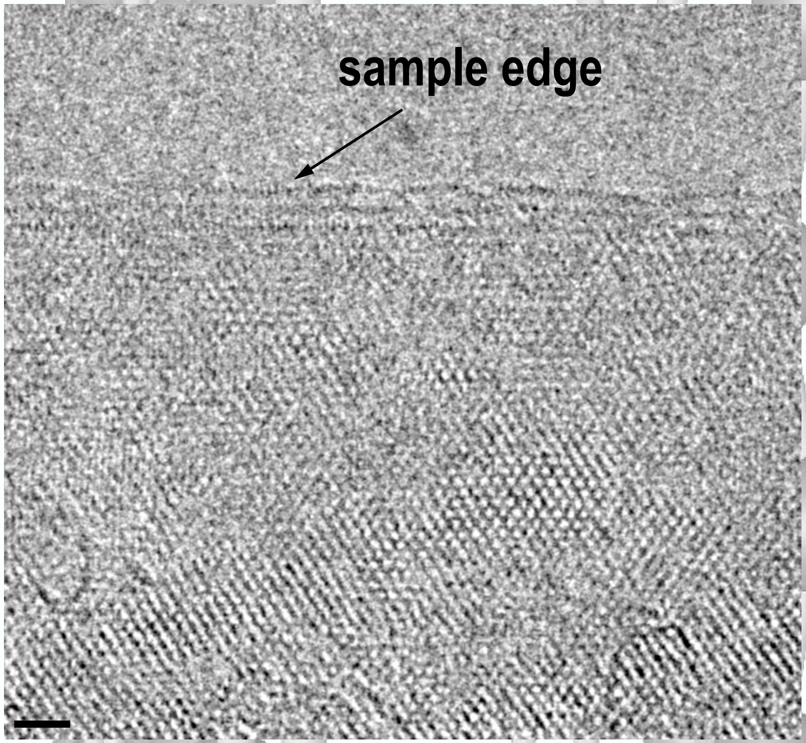
TEM image:
graphene crystals
supported by one side
DO NOT BEND !

atomic sheets are extremely stiff

Graphene Is Not Flat

microscopic ripples visualized in TEM



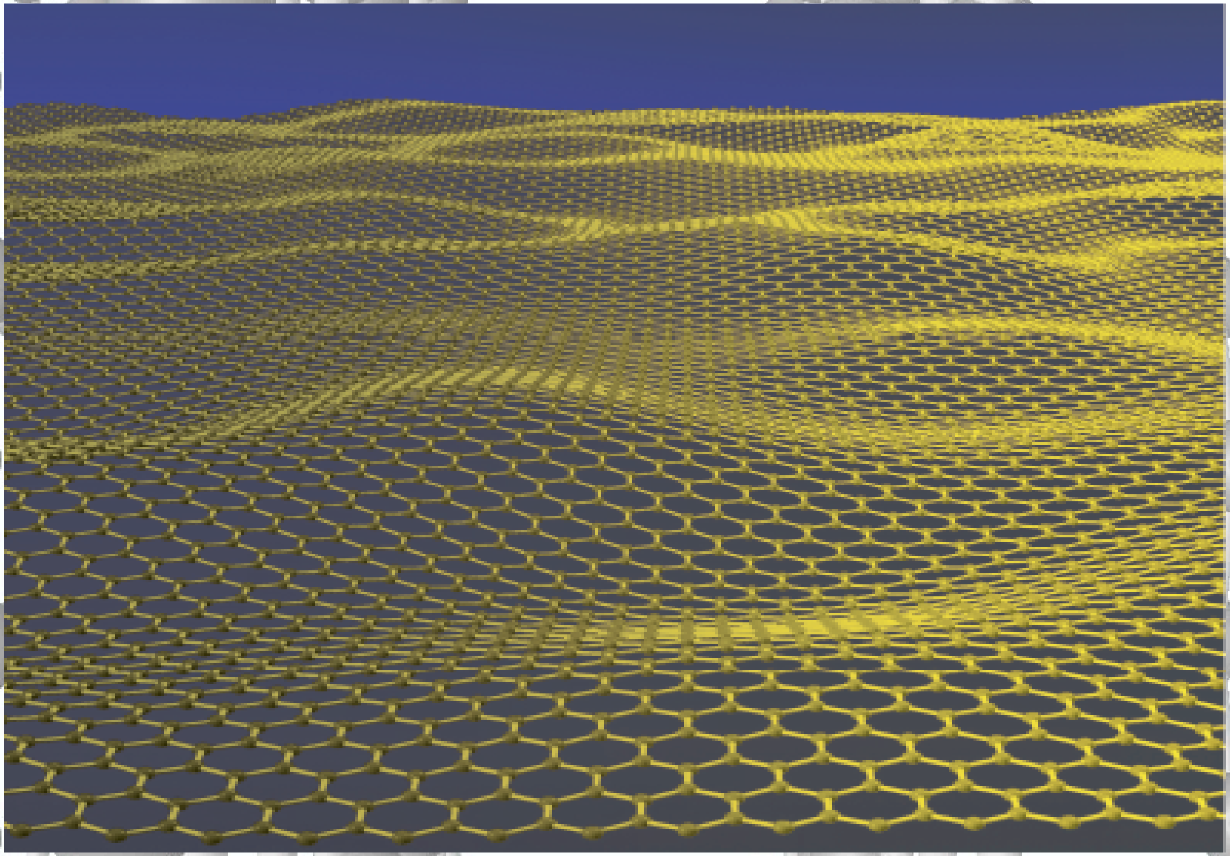


diffraction contrast:
visible ripples > 10 nm

atomic resolution TEM
ripples visible in a bilayer;
down to 5 nm in size

Meyer, AKG, et al, Nature 2007

Puzzling Micro-Mechanics



all scales present

but typical size ≈10 nm with height ≈1 nm

induced elastic strain ≈1%

Intrinsic Property (?)

CONCLUSIONS

new class of materials: individual atomic planes

graphene: high-quality system

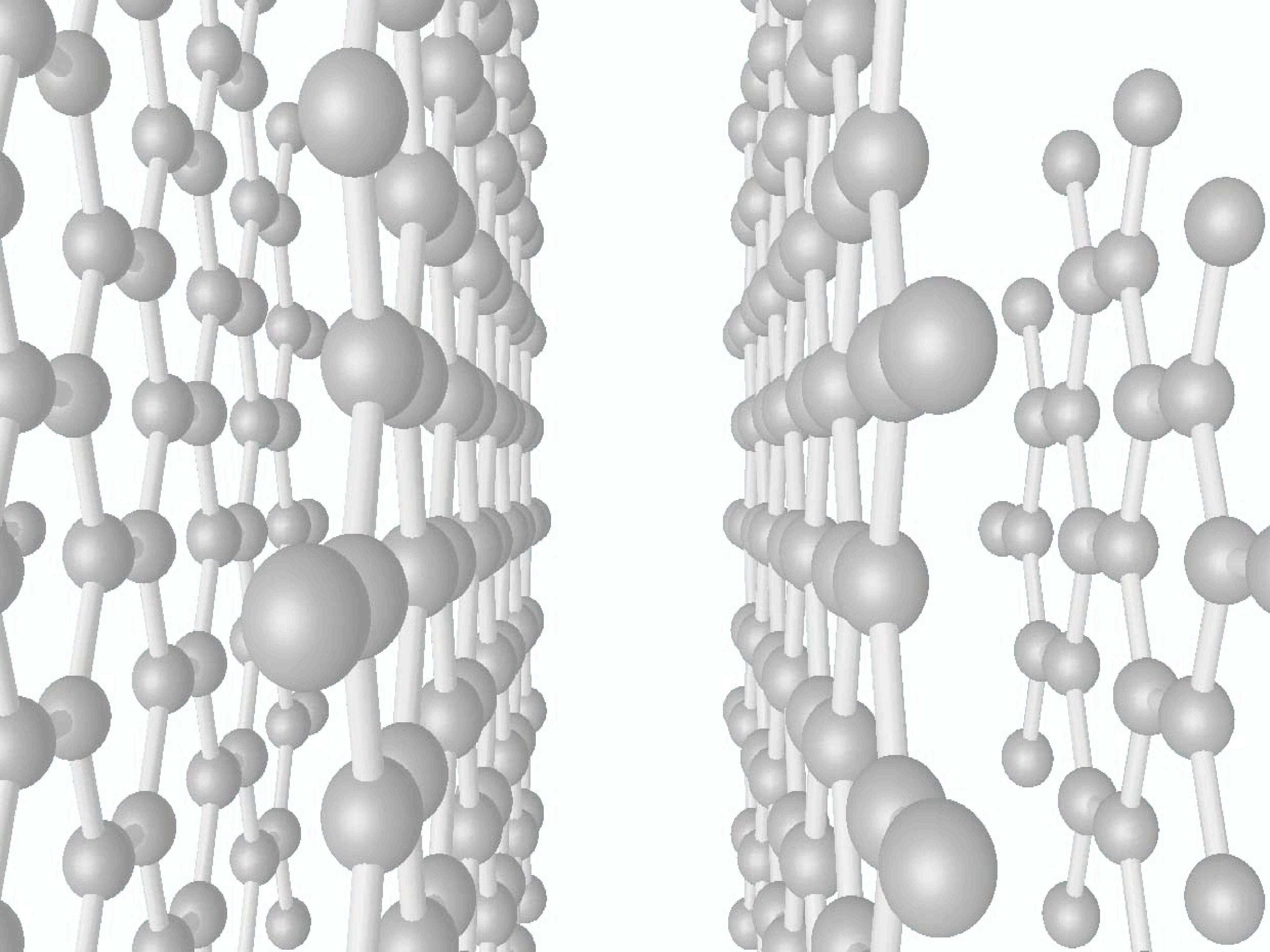
"relativistic"
condensed matter physics

APPLICATIONS:
carbon nanotubes serve as excellent guide

THANK YOU VERY MUCH FOR LISTENING

for review, see

Nature Materials **6**, 183 (2007)

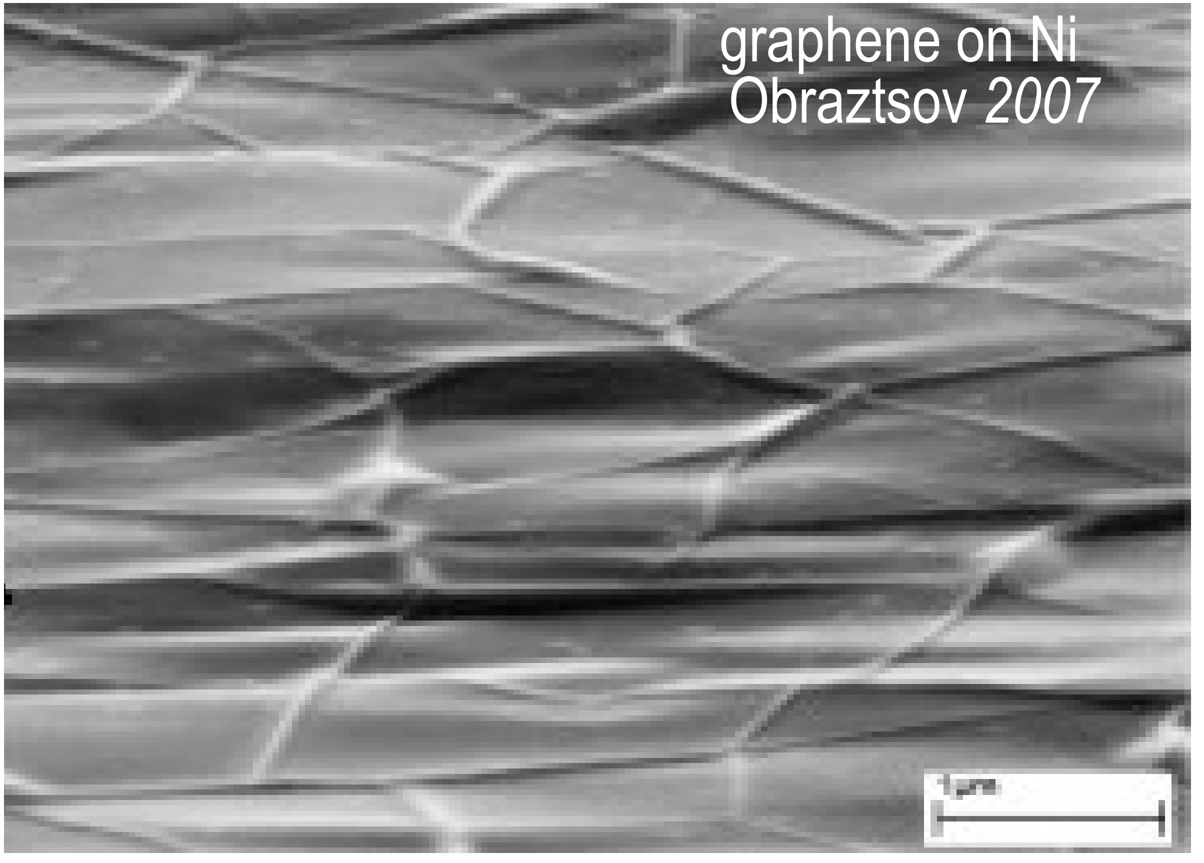


POTENTIAL APPLICATIONS

("but can we eat them?")

imagine graphene in large wafers

Graphene Wafers?



epitaxial growth on top of bulk crystals

GRAPHENE-BASED ELECTRONICS

- ✓ ballistic field-effect transistor

(large <u>but</u> still low on-off ratio ~100 at room T; Science '04)

- ⌖ THz-frequency operation

- ✓ chemical sensors

(detection of a single gas molecule!)

- ✓ micromechanical devices (McEuen's group)

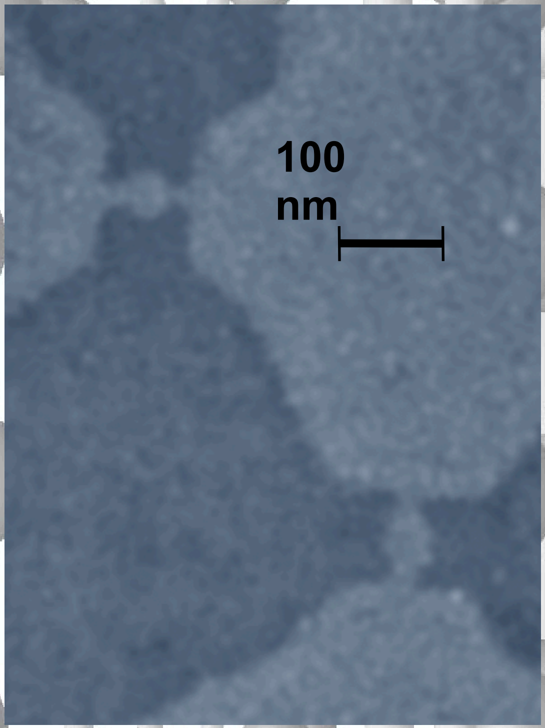
- ✓ superconducting FETs (Morpurgo's group)

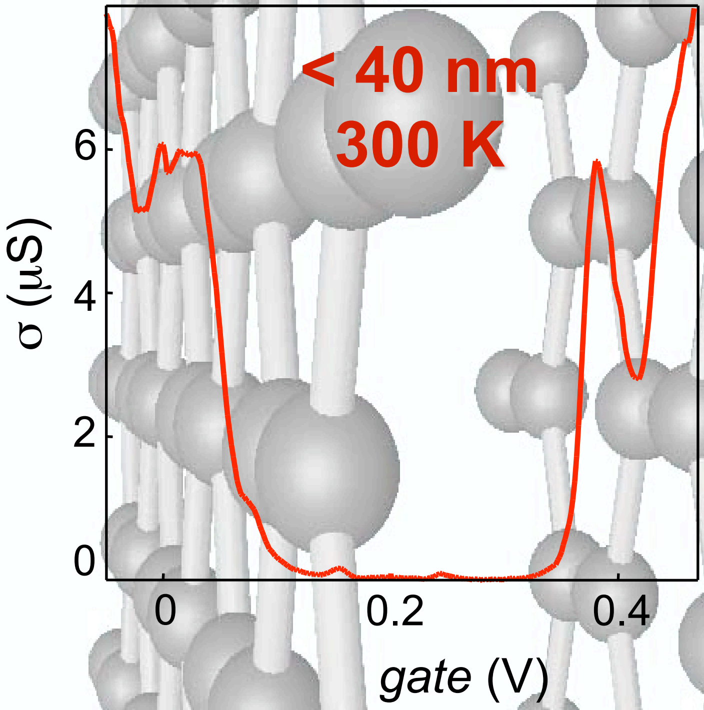
- ✓ room-T graphene spintronics

- ⌖ gate control

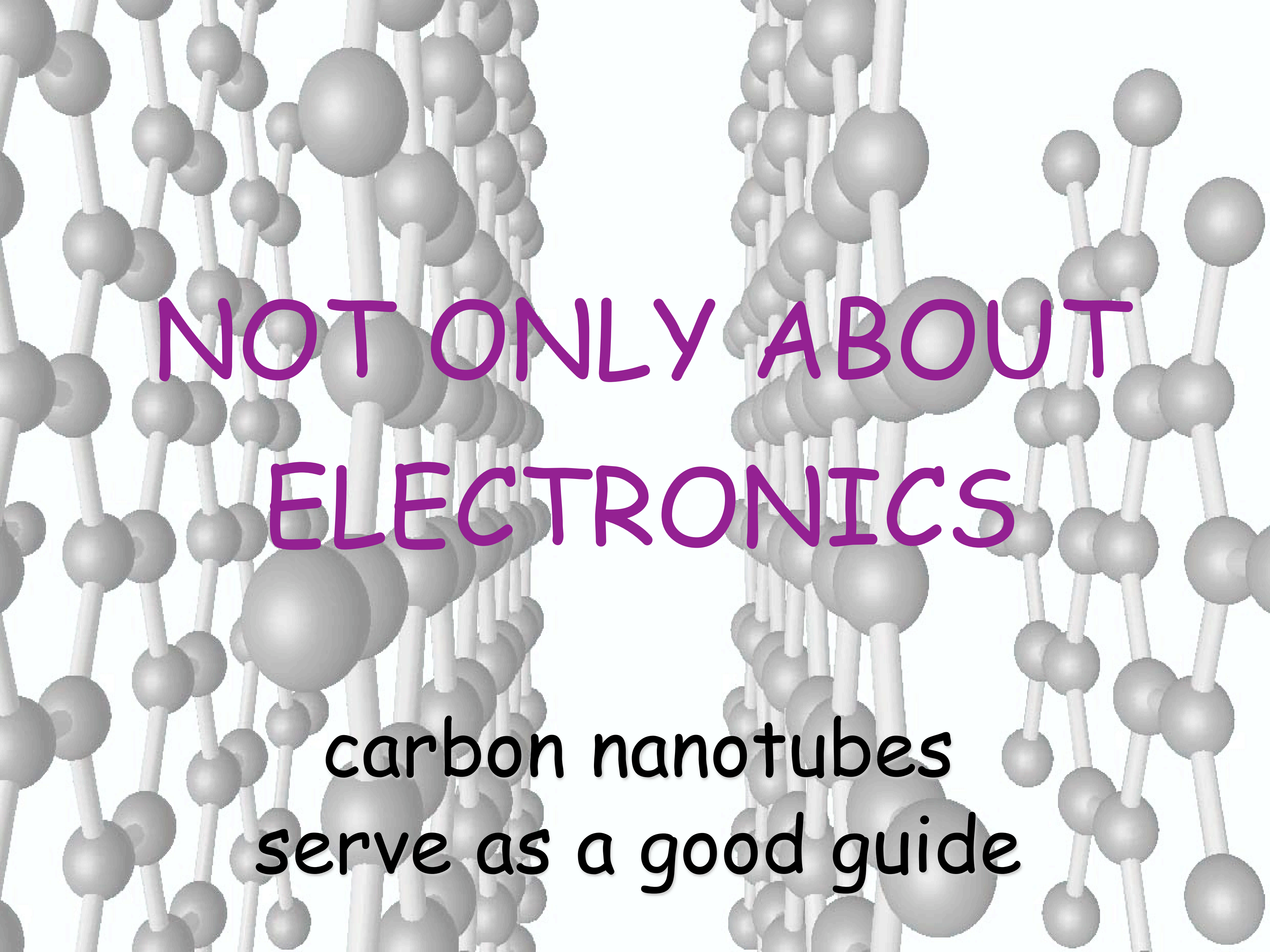
GRAPHENE DREAMS

entire circuitry carved in graphene





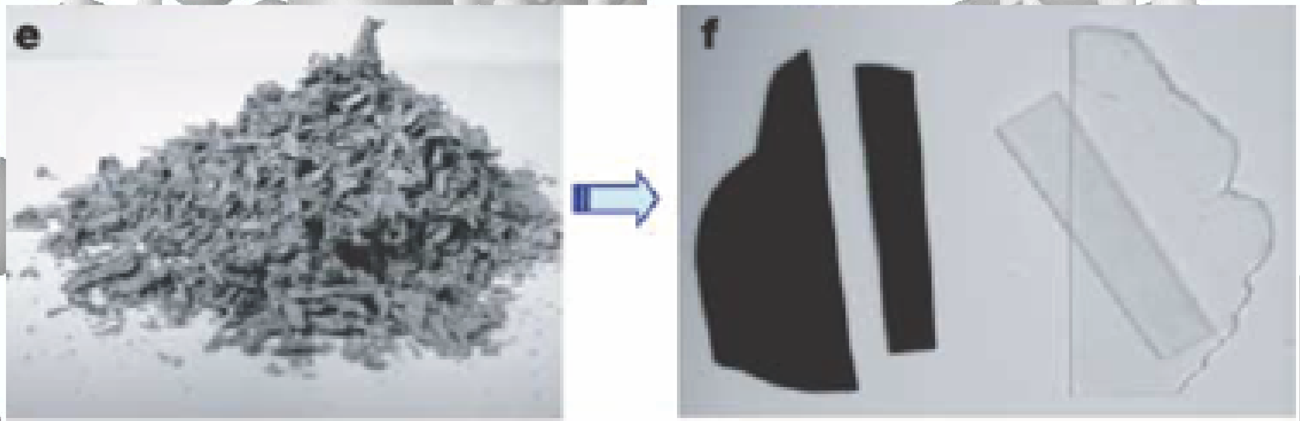
combines several proposed "beyond-Si" technologies:
single electronics plus carbon nanotubes
plus molecular electronics (but top-down approach)



NOT ONLY ABOUT ELECTRONICS

carbon nanotubes serve as a good guide

composite materials

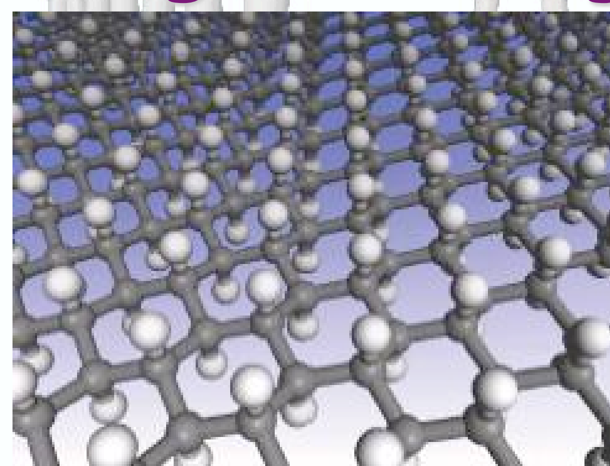


graphene-based composite Ruoff 2006

field-emitters

very thin graphite flakes (already used; PFE Ltd)

hydrogen storage



"GRAPHANE"

electrical batteries

“Applied” Conclusions

SPOILING CHOICE OF DIRECTIONS

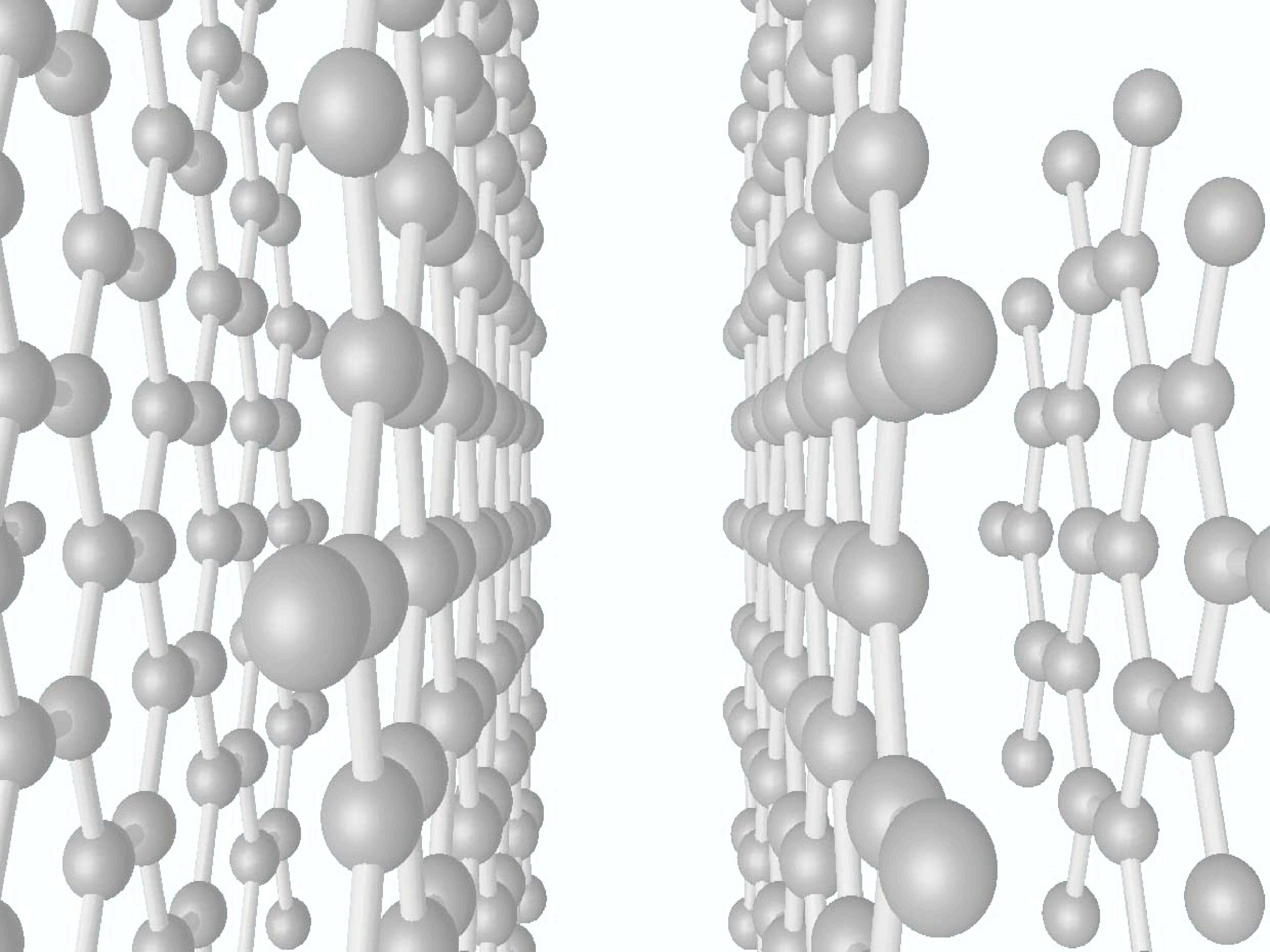
(no choice: all must be investigated)

TOO EARLY DAYS TO JUDGE

(if you are not a nanotube believer)

HOPEFULLY, NOT ANOTHER

MUCH-ADO-ABOUT NANOTHING



mechanical cleavage in retrospect

Ohashi (1997, 2000)

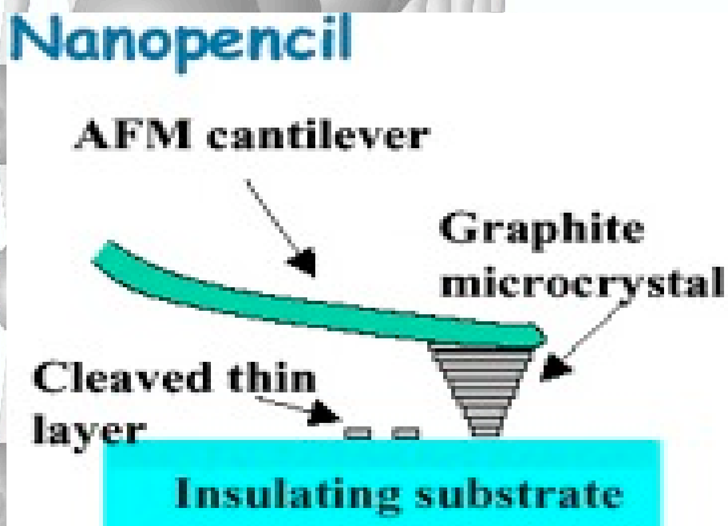
from 1000 down to 50 layers

single layer demonstrated

(Novoselov et al, Science 2004)

Philip Kim's & Paul McEuen's groups

(PRL 2005 & Nanoletters 2005) down to 30 layers



for >10 layers,

electronic structure

of bulk graphite

(Partoens 2006, Guinea 2006)