Scanning Single Electron Transistor Microscopy on Graphene

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outline

Motivation: why graphene?

Problem: Disorder !

Measurement technique:

Scanning Single Electron Transistor

typical graphene sample

Disorder at B=0T

Disorder in the QH regime

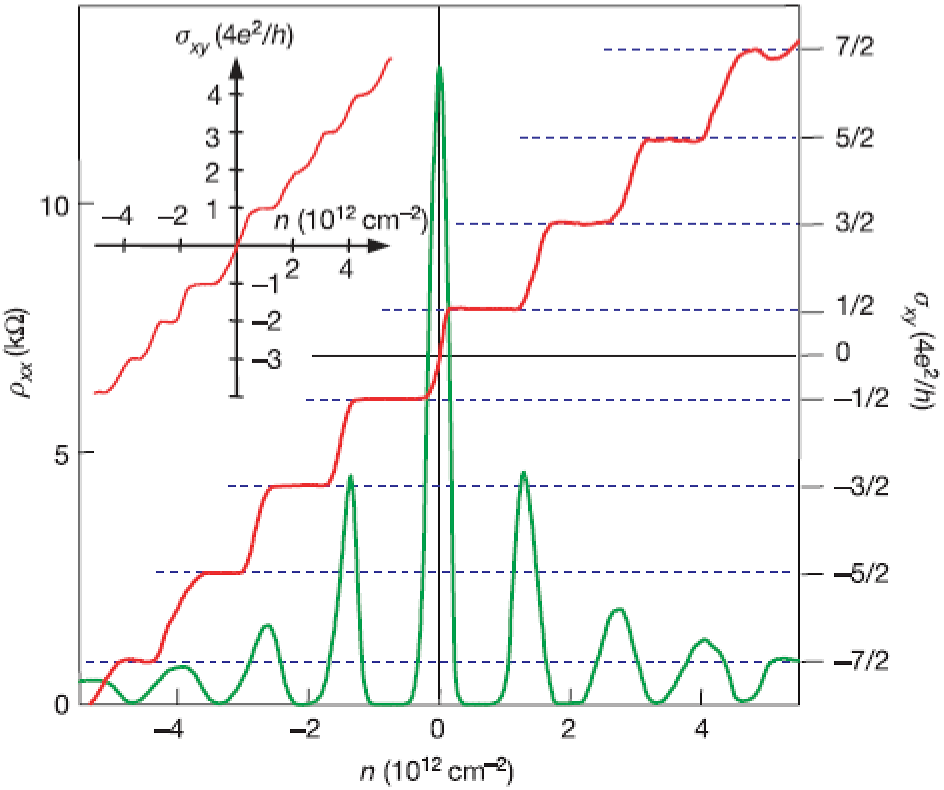
Transport through suspended Bilayers

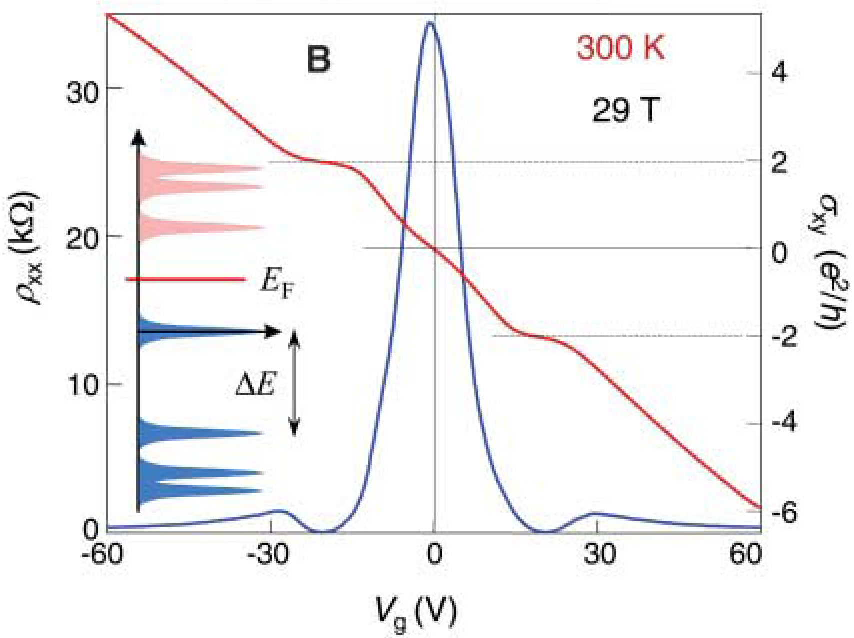
Conclusions

Motivation: why graphene?

unusual QHE

K. Novoselov *et al.* Nature **438** 197 (2005)
Y. Zhang *et al.* Nature **438** 201 (2005)



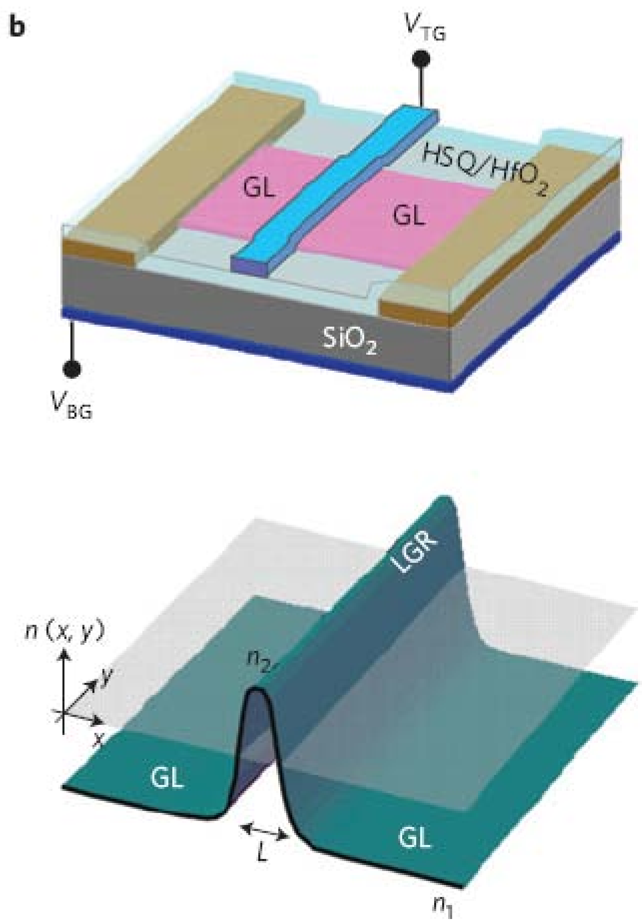


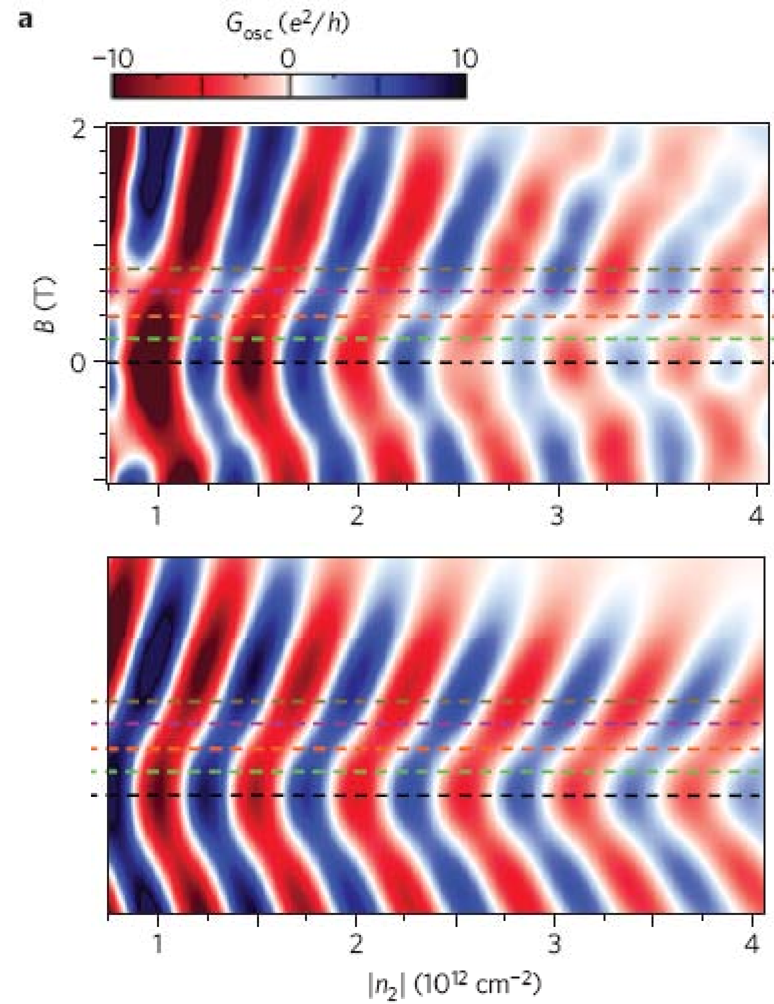
K. Novoselov *et al.* Science **315** 1379 (2007)

Motivation: why graphene?

Klein-tunneling

A. Young *et al.* Nature **315** 1379 (2007)

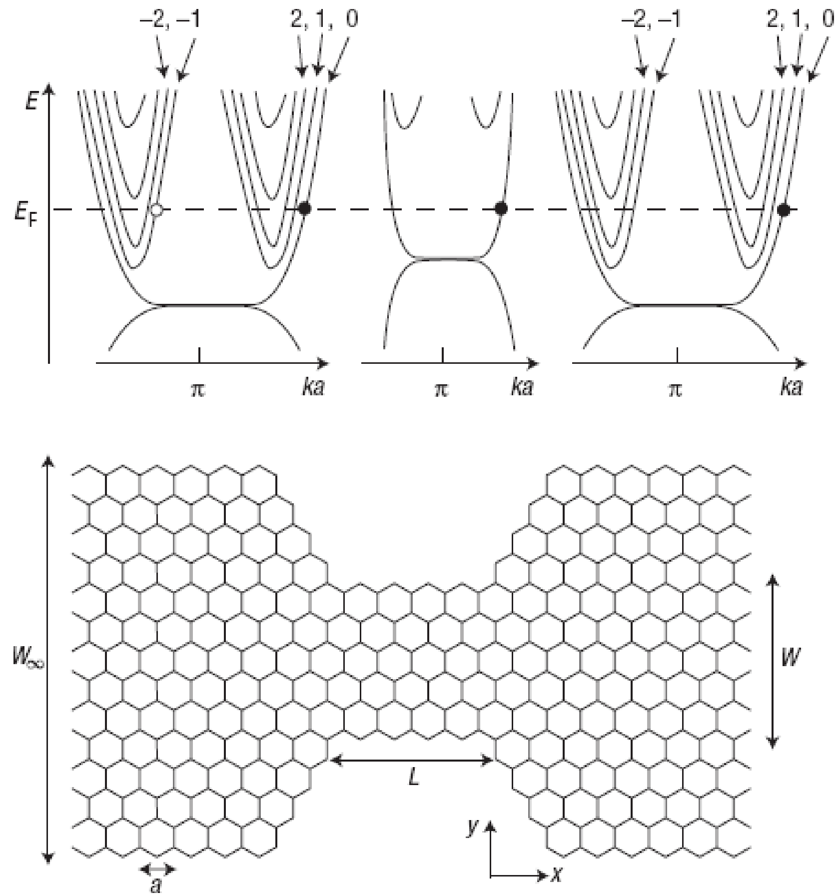




Motivation: why graphene?

‘Valleytronics’

A. Rycerz *et al.*
Nature physics **3** 172 (2007)



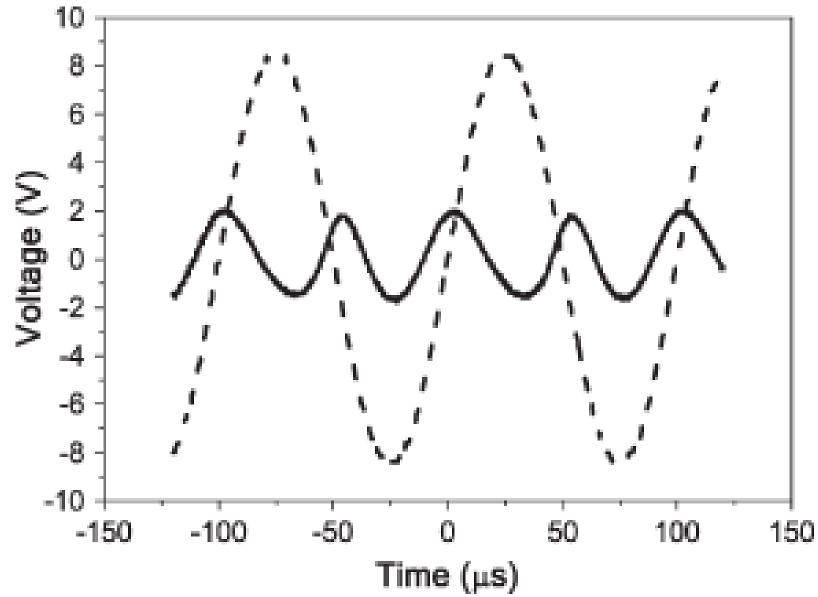
Topological confinement in bilayer graphene, I.Martin *et al.* cond-mat 01009.3522

Carbon nanoelectronics:
unzipping tubes into graphene ribbons, H.Santos *et al.* cond-mat 0904.3676

Motivation: why graphene?

bipolar: frequency mixers

H. Wang *et al.* IEEE electronic device letters **30**, 5, 547 (2009)



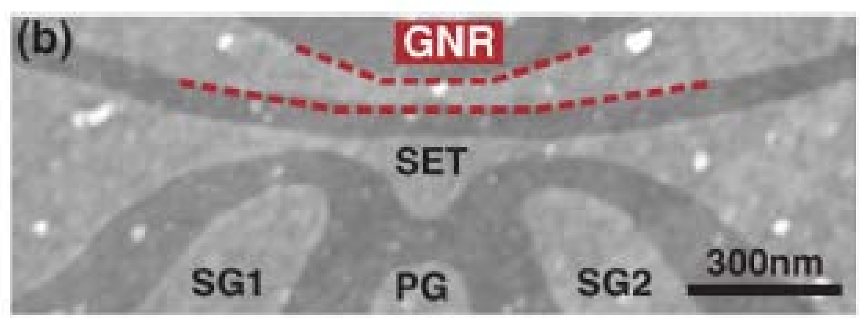
bandgap engineering:

spatial confinement, nano-ribbons

C. Stampfer *et al.* PRL **102** 056403 (2009)

electrical field (bi-layers)

E.V. Castro *et al.* PRL **99**, 216802 (2007)



Motivation: why graphene?

high mobility: up to 200.000 $cm^2/Vsec$

X. Du *et al.* Nature nanotechnology **3** 491 (2008)
K.I. Bolotin *et al.* Solid State Comm. **146** 351 (2008)

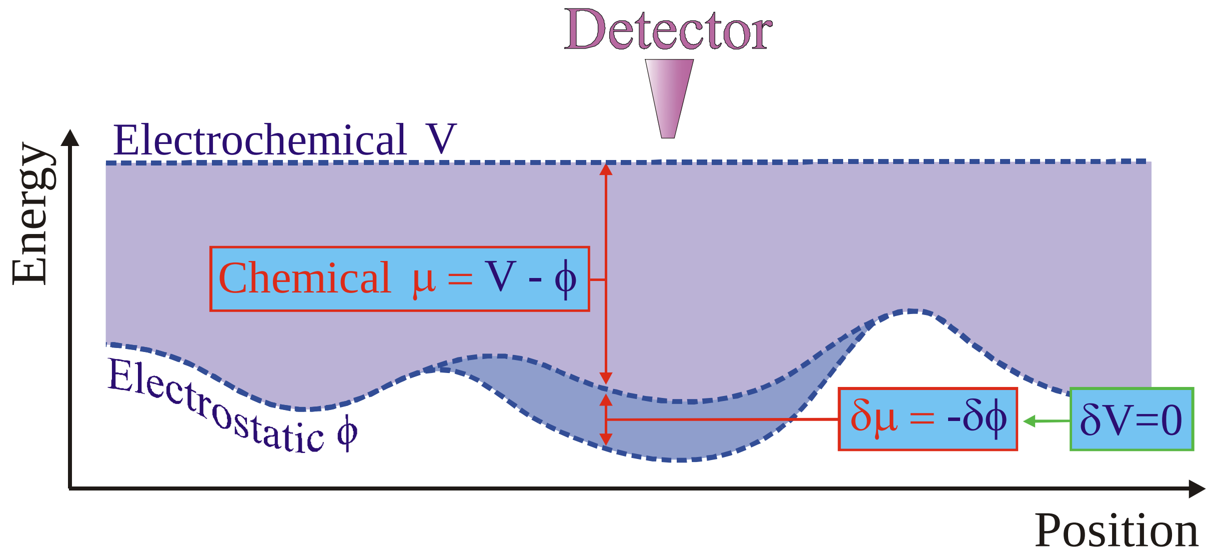
Disorder:
- What are the dominant contributions?
- What are the effects on graphene?
- How can we improve sample quality?

Local measurements necessary:
- compressibility / many body density of states
- electrostatic disorder potential

➔ Scanning Single Electron Transistor

How to Measure Compressibility Locally ?

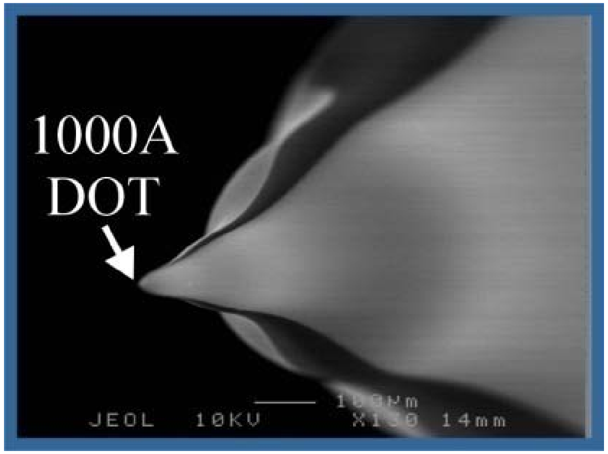
Compressibility: $\sim \left[\frac{\delta\mu}{\delta n}\right]^{-1}$ ➡ Need to measure $\delta\mu$

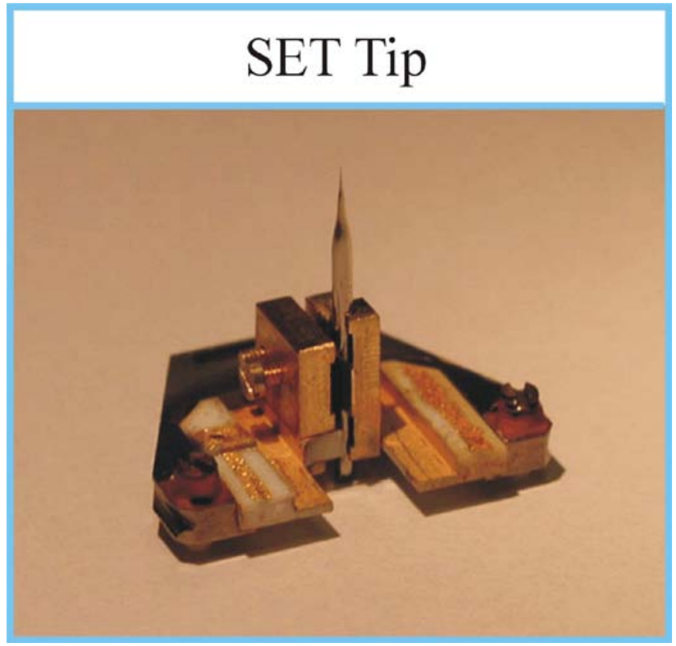


Thermodynamic equilibrium ➡ V is constant in space ➡ $\boxed{\delta\mu = -\delta\phi}$

> If we can measure the local $\delta\phi$
>
> we will immediately get the local $\delta\mu$

Single Electron Transistor:
100nm, ≈5 μV





SET:
100nm, ≈5 μV

Simultaneous Transport & Local Potential

T=350mK, UHV, B=12 T

S. Ilani et al, *Nature* 328 (2004), J. Martin et al,*Science* (2004)

T=350mK, UHV, B=12 T

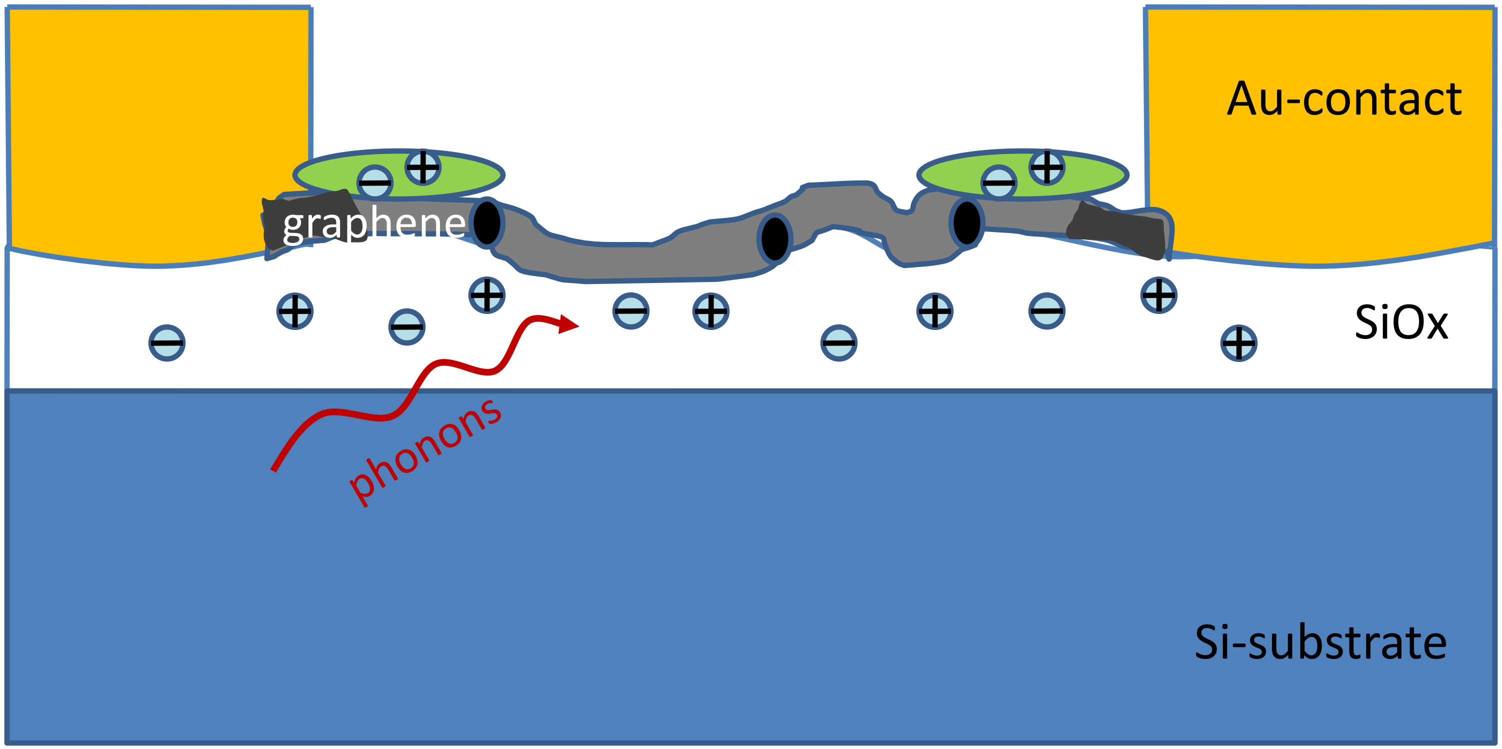
disorder in a typical graphene device

Novoseloy *et. al.* Nature 438, 197 (2005), Zhang *et. al.* Nature 438, 201 (2005)

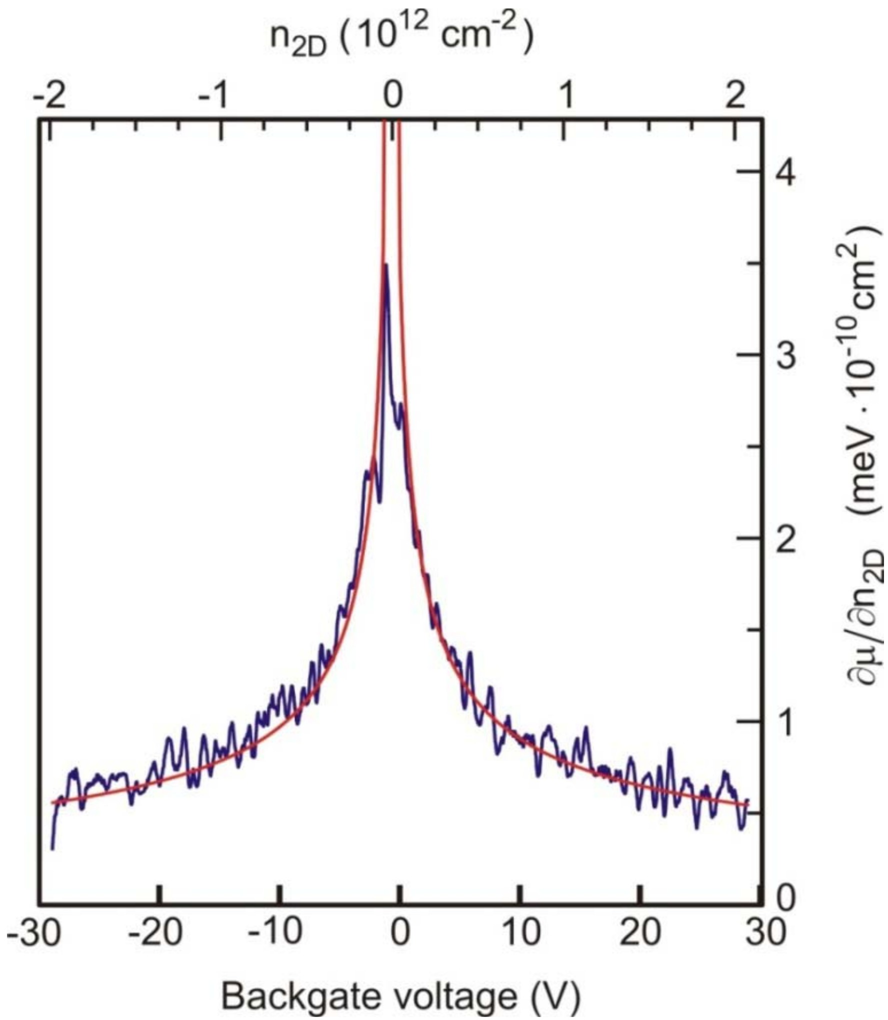
other techniques: epitaxial graphene (SiC): Joseph A. Stroscio, NIST

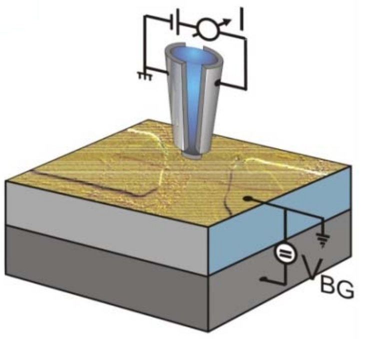
...

disorder in a typical graphene device



Local inverse compressibility, B=0T





Inverse density of states:

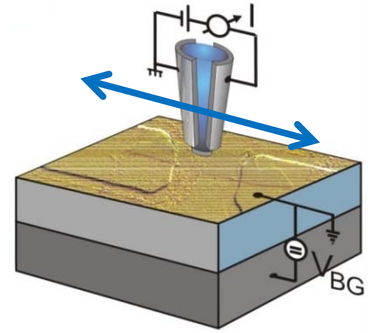
v_F= 1.1 10^6 m/s

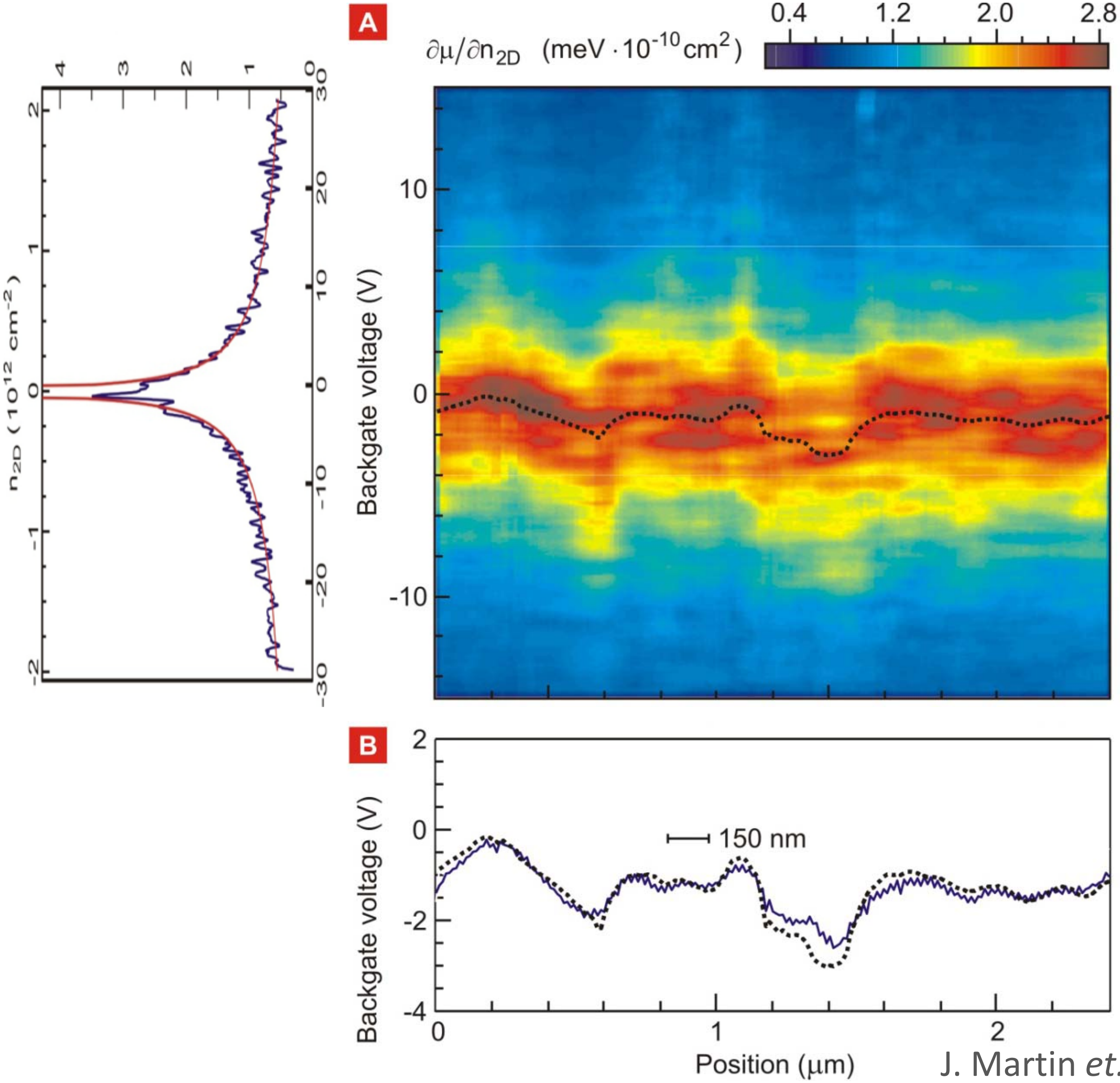
electron-electron interactions in the range of 10%

theory: E. H. Hwang *et al.* PRL 99 (2007)

J. Martin *et. al* Nature Physics **4** 144(2008)

Local inverse compressibility, B=0T



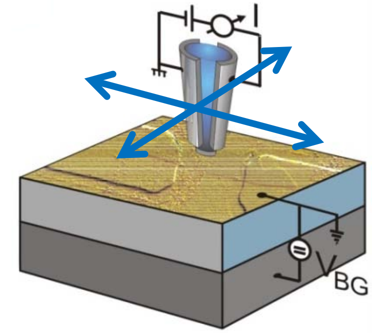


Inverse Compressibility

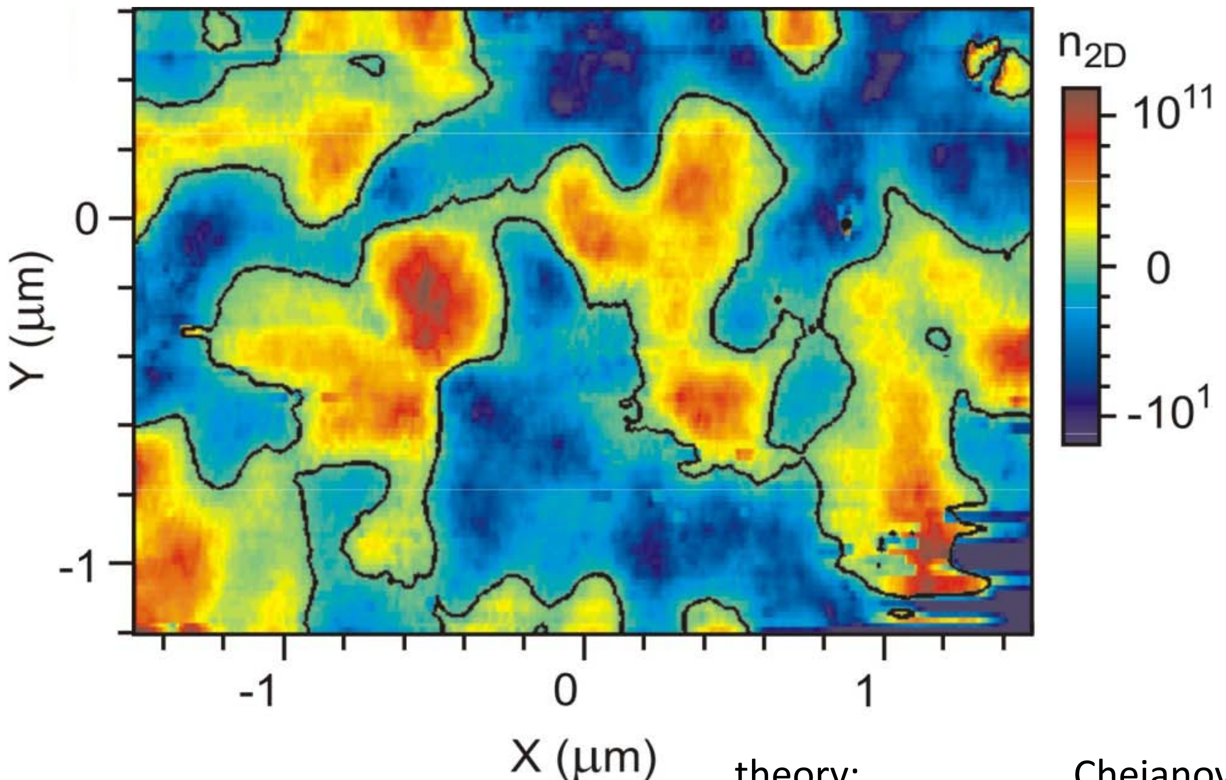
electrostatic disorder potential

J. Martin *et. al* Nature Physics **4** 144(2008)

Local inverse compressibility, B=0T



Density variations near charge neutrality



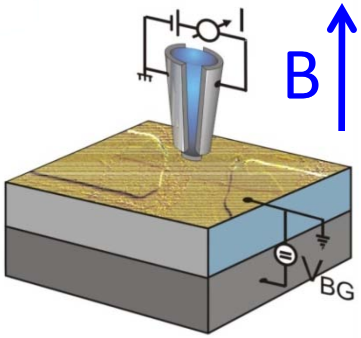
Electron-hole puddles:

finite density at 'Dirac point' : $\Delta n \approx 10^{11} cm^{-2}$

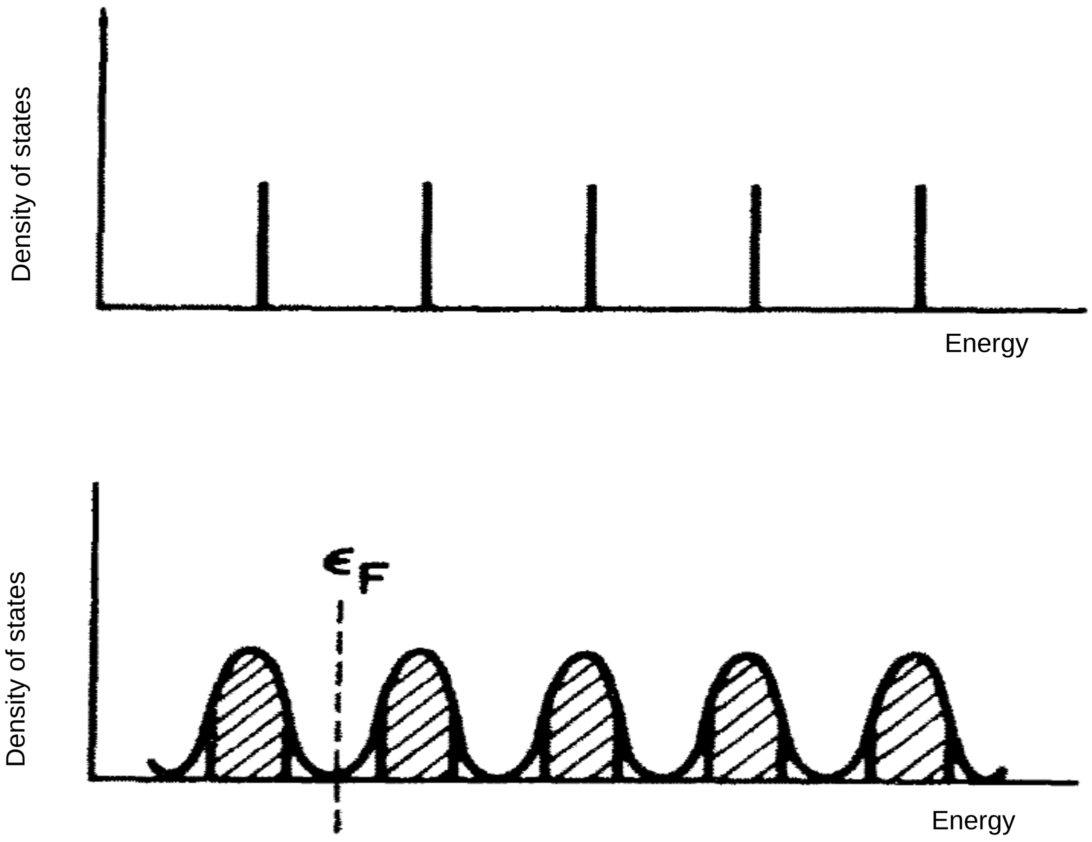
theory: Cheianov *et al.* PRL 99 (2007)
Katsnelson et al. Nature Physics 2 (2006)
STM: A. Deshpande *et. al.* cond-mat 0812.1073
Y. Zhang *et. al.* cond-mat 0902.4793
Kelvin Probe: Fuhrer (Maryland)…

J. Martin *et. al* Nature Physics **4** 144(2008)

Local inverse compressibility, QH-regime



QHE, Landau Level, localized states



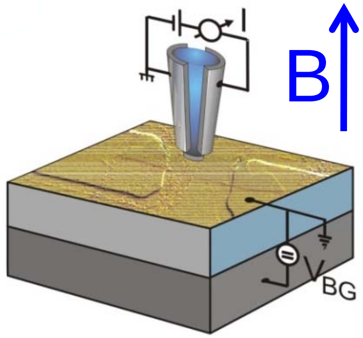
Laughlin, Phys. Rev. B. 23 (1991)

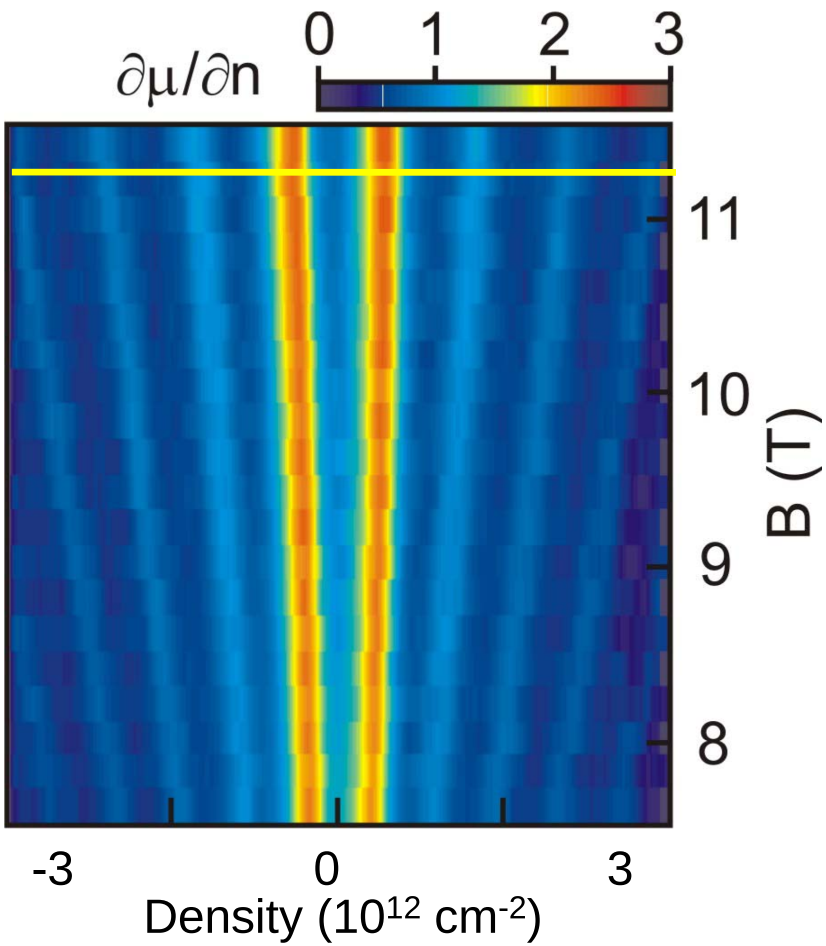
Disorder !!

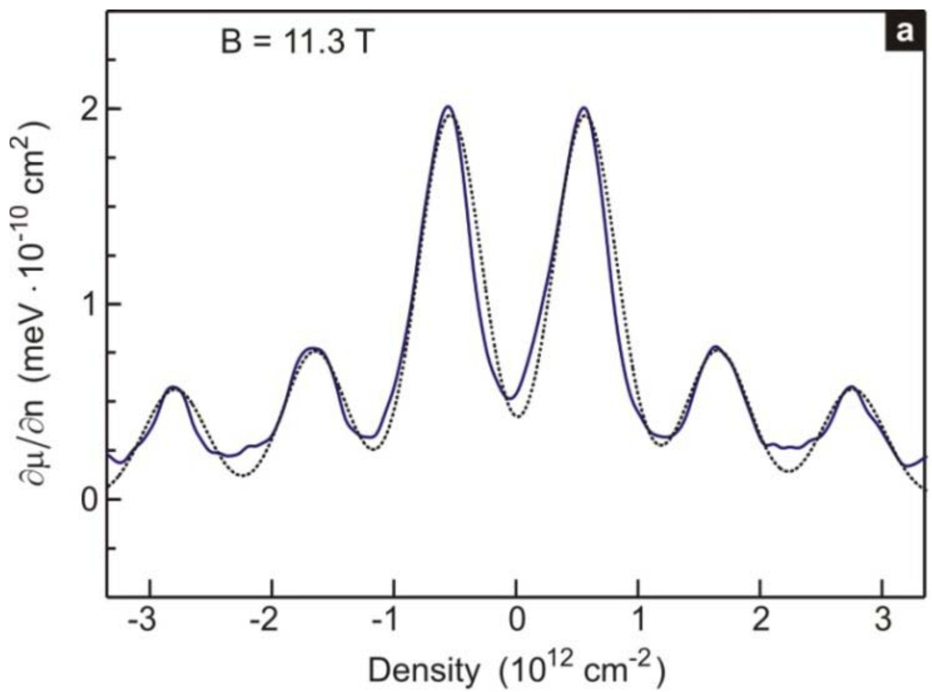
Landau Level DOS ?
Imaging of localized states ?

→ local Compressibility

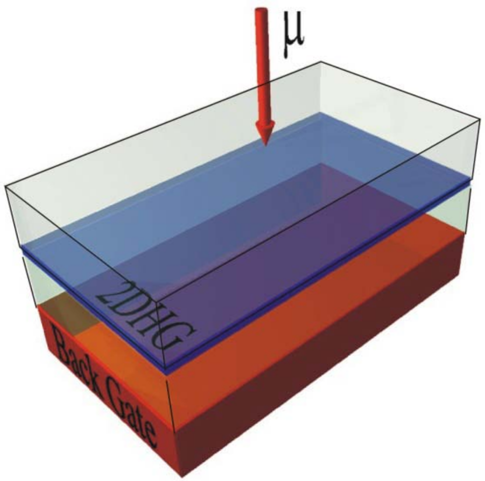
Local inverse compressibility, QH-regime

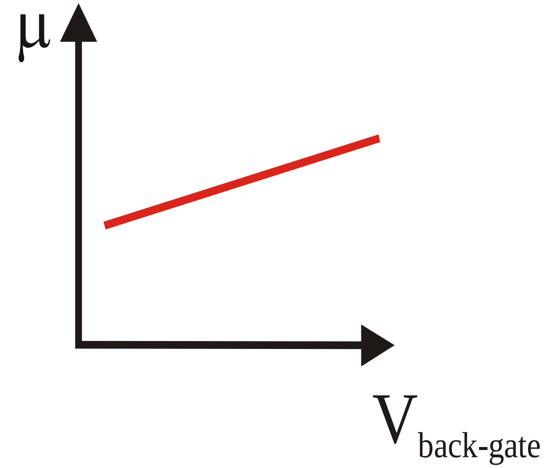




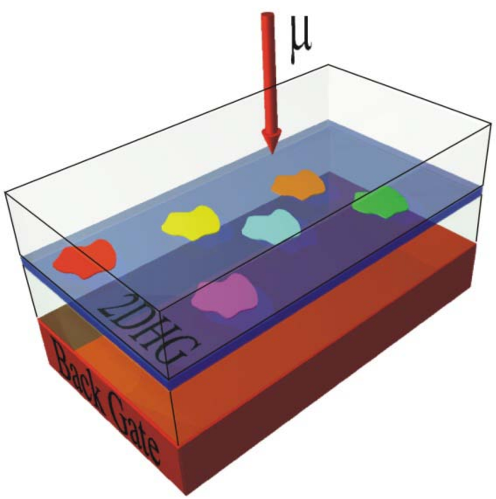


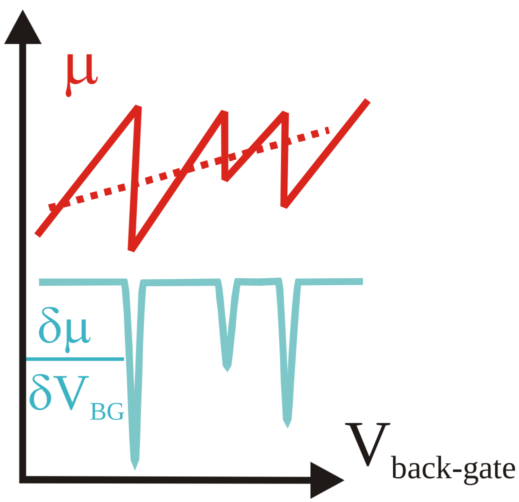
Compressibility – measures localized states





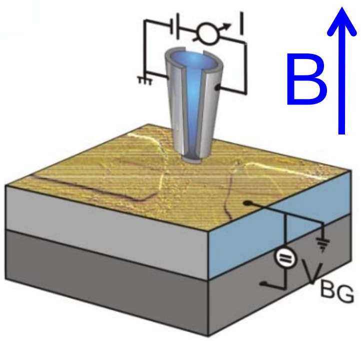
$$e \cdot \Delta n_{\min} = \frac{e}{A}$$

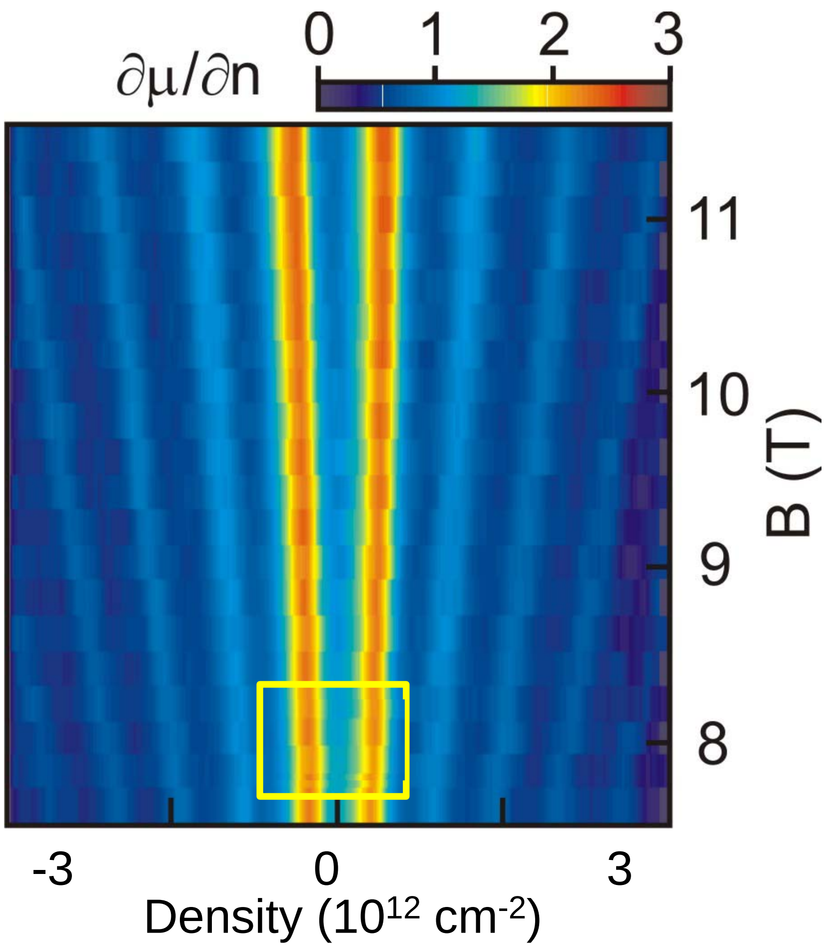




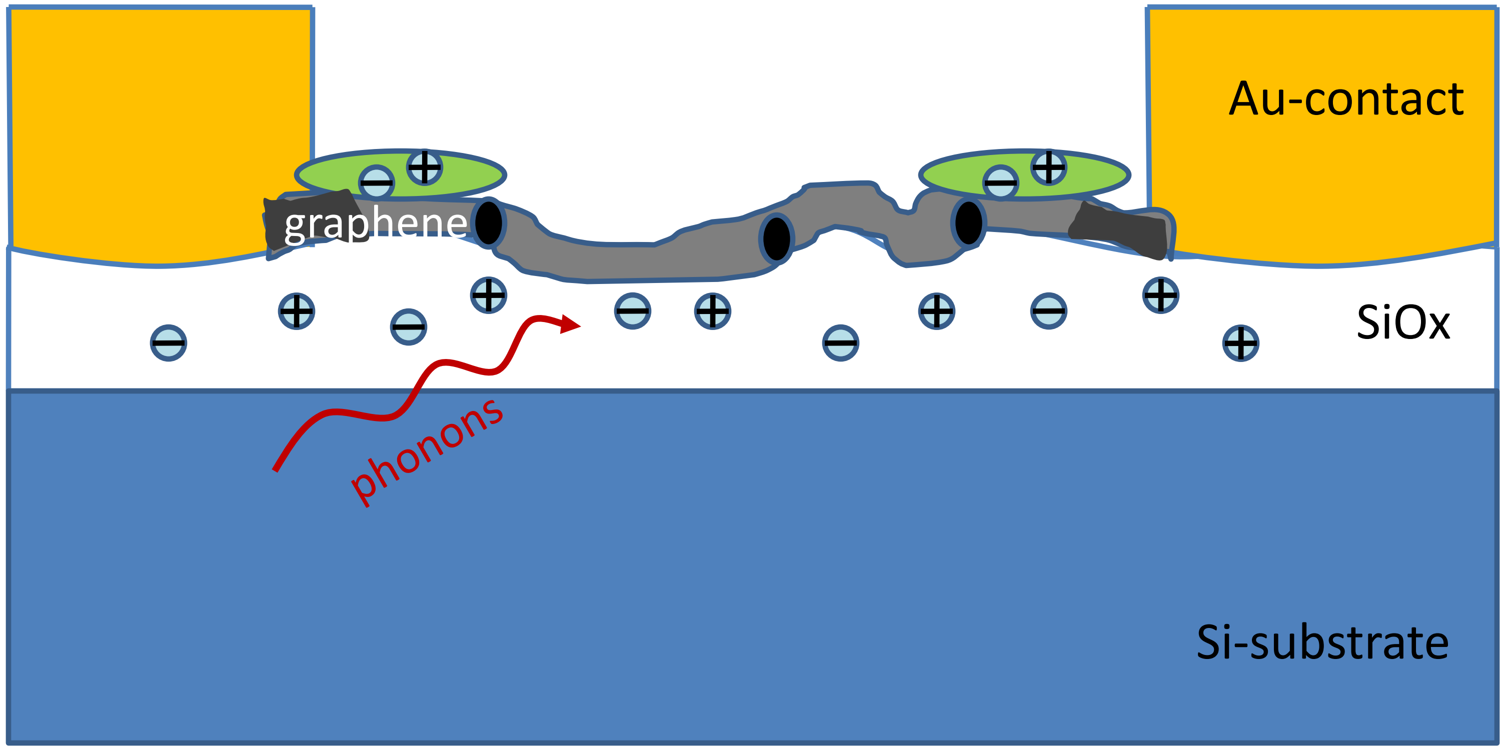
$$e \cdot \Delta n_{\min} = \frac{e}{\xi^2}$$

Local inverse compressibility, QH-regime





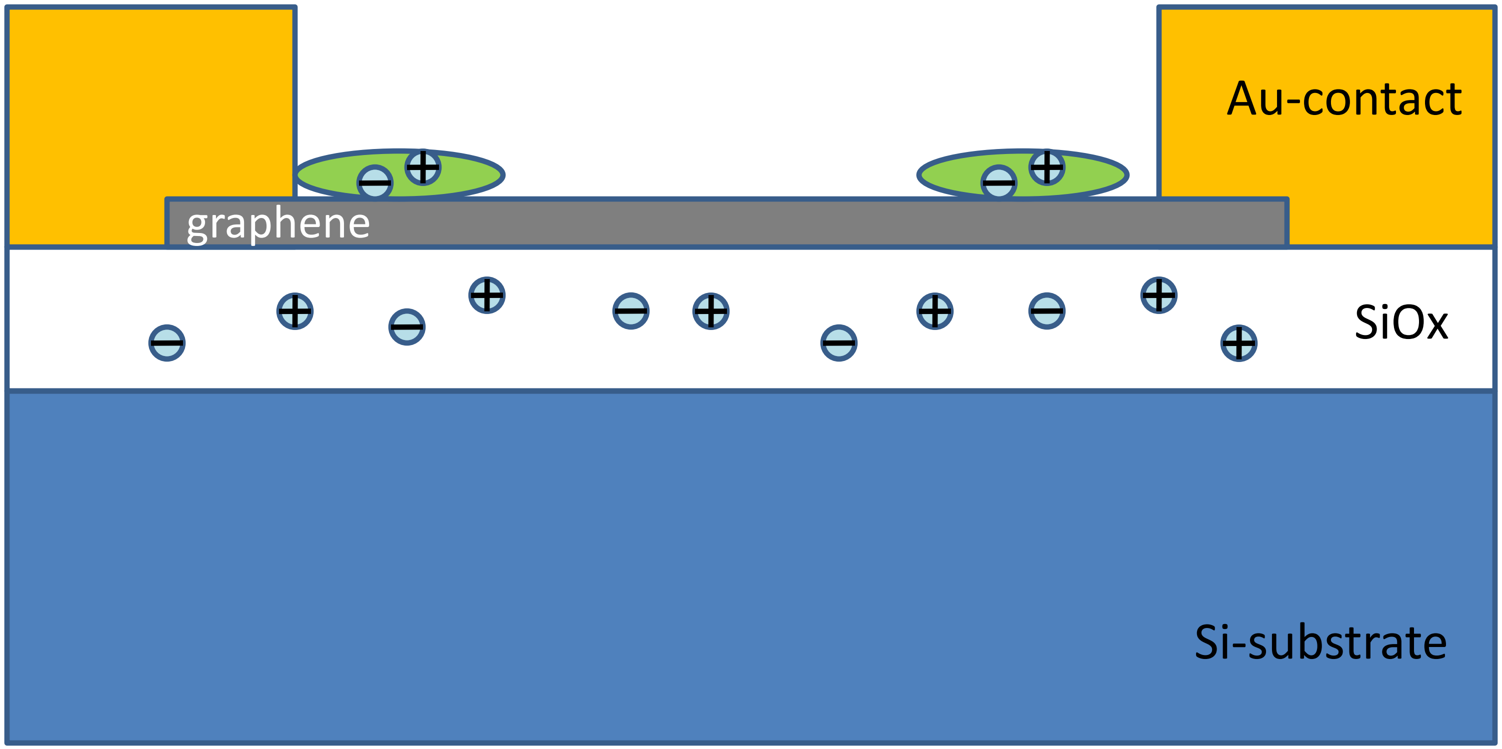
disorder in a typical graphene device



disorder in a typical graphene device

Charge impurities

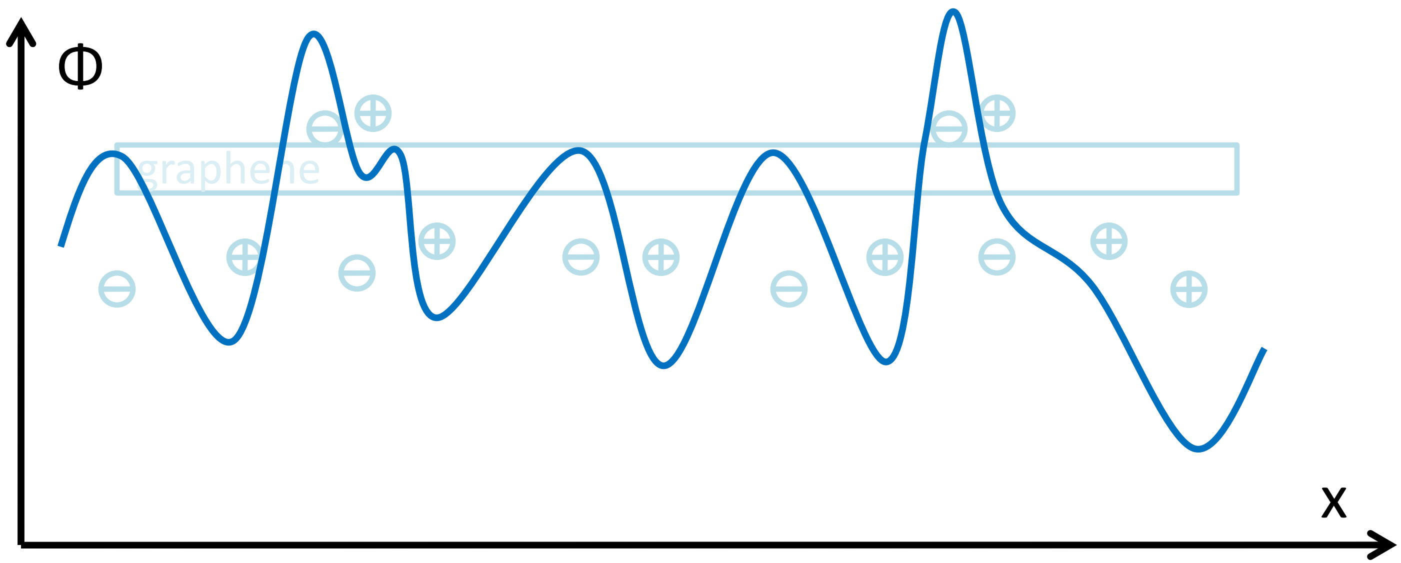
J.H. Chen *et. al.*, cond-mat 0812.2504
S. Adam et al. cond-mat 0705.1540



disorder in a typical graphene device

Charge impurities

long range potential fluctuations, <u>extrinisic</u>



How can we improve sample quality?

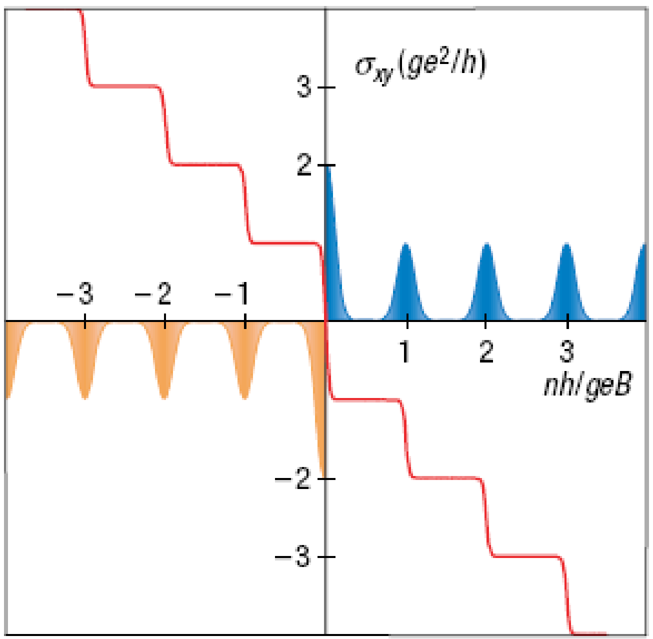
Will we observe new physics in cleaner samples?

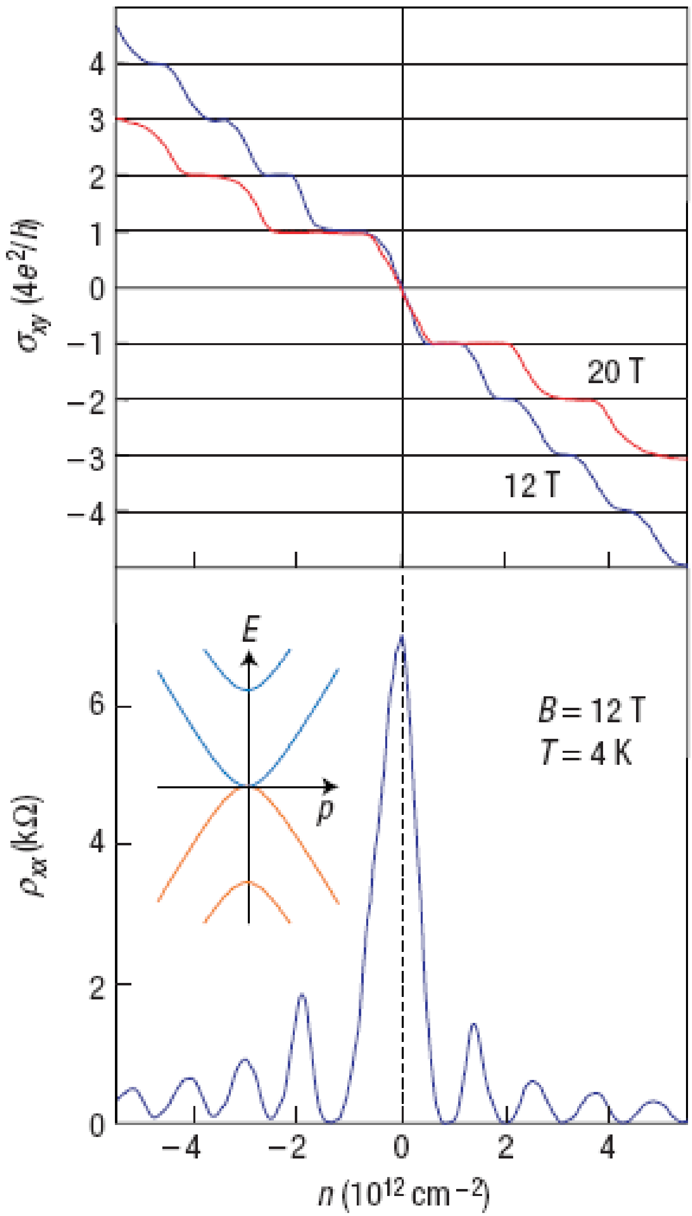
QHE in suspended bilayers

QHE in suspended bilayers

suspended monolayers with high mobility:
K.I. Bolotin *et al.* Solid State Communication 146, 351 (2008)
Du, X. *et al.* Nat. Nano 2008, **3**, 491-495

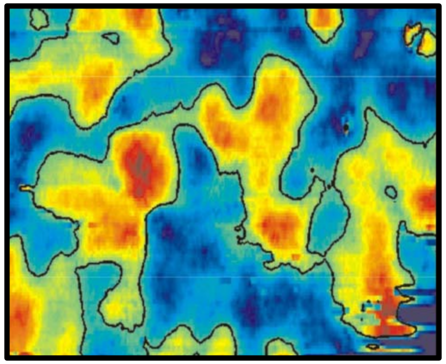
QHE in suspended bilayers





Figures from: K. S. Novoselov, et. al., Nature Physics. **2**, 177 - 180 (2006)

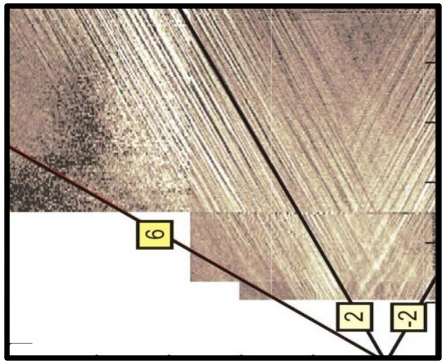
Conclusions



Scanning SET measures local compressibility

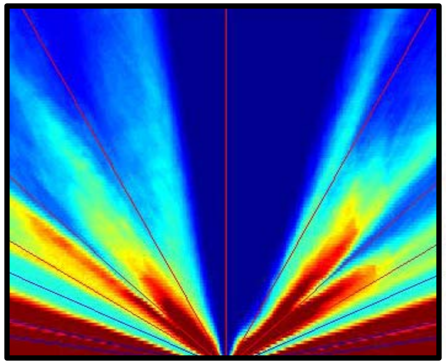
<u>B=0T</u>

- electrostatic disorder potential
- electron/hole puddles
- non-interacting electrons



<u>QHE</u>

- electrostatic disorder potential
- localized states
- non-linear screening



<u>Suspended Bilayers</u>

- Splitting of 8-fold degeneracy