Designer Spin-Orbit Interaction in graphene on TMDs
&
Electron-hole scattering in charge neutral bilayer graphene

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Spin-orbit: ***Z. Wang, D.-K. Ki, D. Mauro***
Electron-hole scattering: ***Y. Nam, D.-K. Ki, D. Soler***

Collaborations
Theory: ***A. MacDonald, H. Chen*** *(UTexas)*
L. Levitov, J. Khoo *(MIT)*
Materials: ***H. Berger*** *(EPFL)*

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

QSIT Quantum Science and Technology
National Centre of Competence in Research

GRAPHENE FLAGSHIP

Outline

- ***Very strong spin-orbit interaction in graphene-on-TMDs***

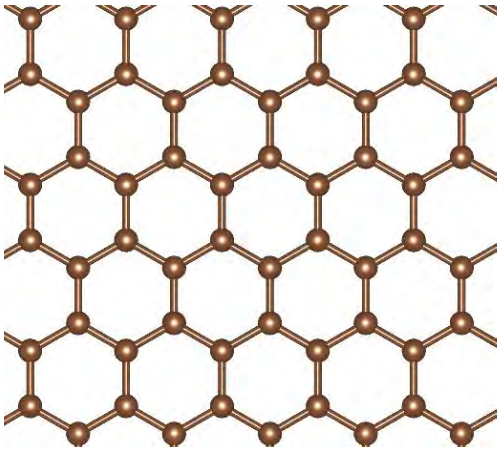
  Spin-dependent band-structure modification
  due to interfacial interactions

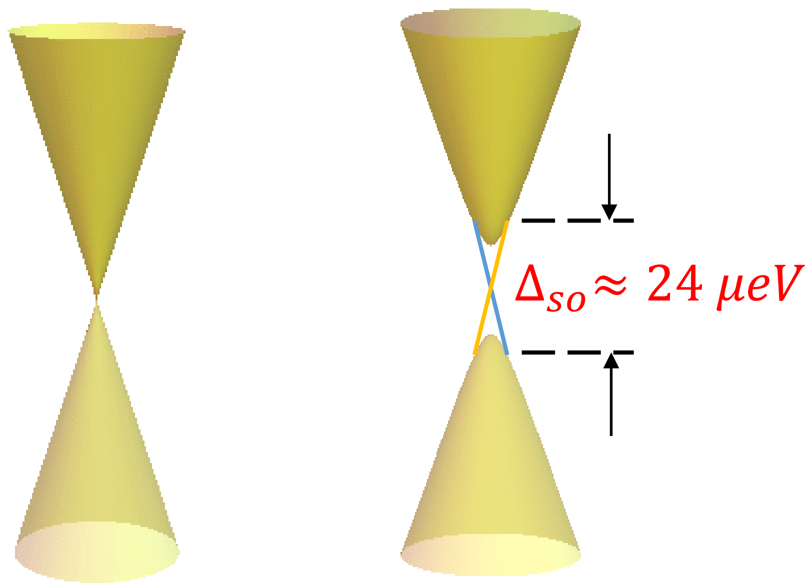
- ***Ballistic transport in charge neutral graphene***
  is prevented by electron-hole collisions

  e-e scattering is does not normally limit the conductivity
  of a material; e-h scattering is drastically different

Spin-orbit interaction in graphene

Kane,C.L. & Mele,E.J. *Phys. Rev. Lett.* **95** 226801 (2005)





$$\mathcal{H} = -i\hbar v_F \psi^\dagger(\sigma_x \tau_z \partial_x + \sigma_y \partial_y)\psi + \Delta_{SO}\psi^\dagger \sigma_z \tau_z s_z \psi$$

- Graphene is a topological insulator due to intrinsic spin-orbit interaction (SOI)
- Intrinsic SOI is too small to experimentally observe topological properties

Can we induce strong SOI in graphene while preserving Dirac nature of electrons and material quality?

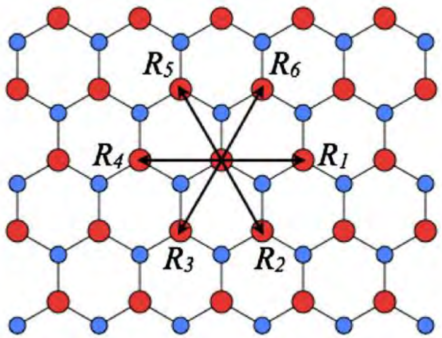
Idea: exploit interfacial interactions on semiconducting TMD substrates

Coupled Spin and Valley Physics in Monolayers of MoS_2 and Other Group-VI Dichalcogenides

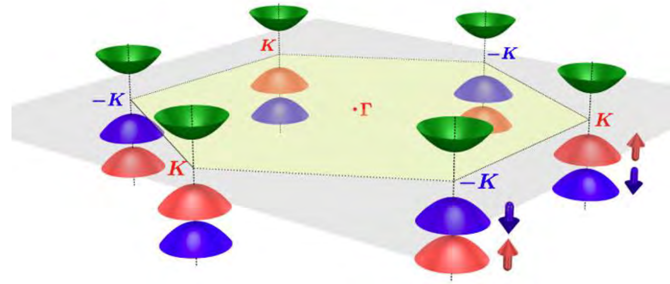
PRL 108, 196802 (2012)

Di Xiao,[1,*] Gui-Bin Liu,[2] Wanxiang Feng,[1,3,4] Xiaodong Xu,[5,6] and Wang Yao[2,†]

Hexagonal lattice without inversion symmetry



Spin-valley coupling



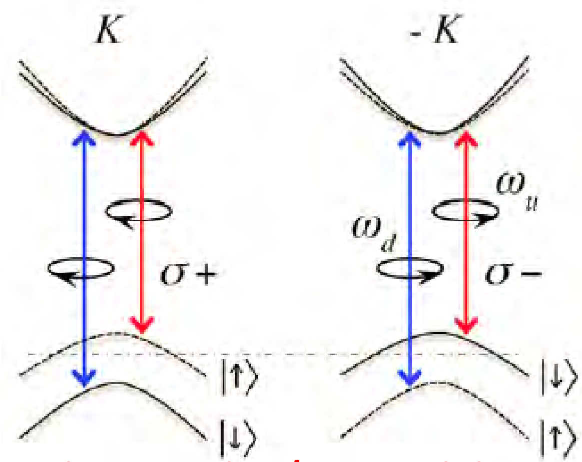
Close to K, K' point = massive Dirac fermions with huge SOI

$$\hat{H} = at(\tau k_x \hat{\sigma}_x + k_y \hat{\sigma}_y) + \frac{\Delta}{2}\hat{\sigma}_z - \lambda\tau\frac{\hat{\sigma}_z - 1}{2}\hat{s}_z$$

Finite Berry curvature close to K,K' points

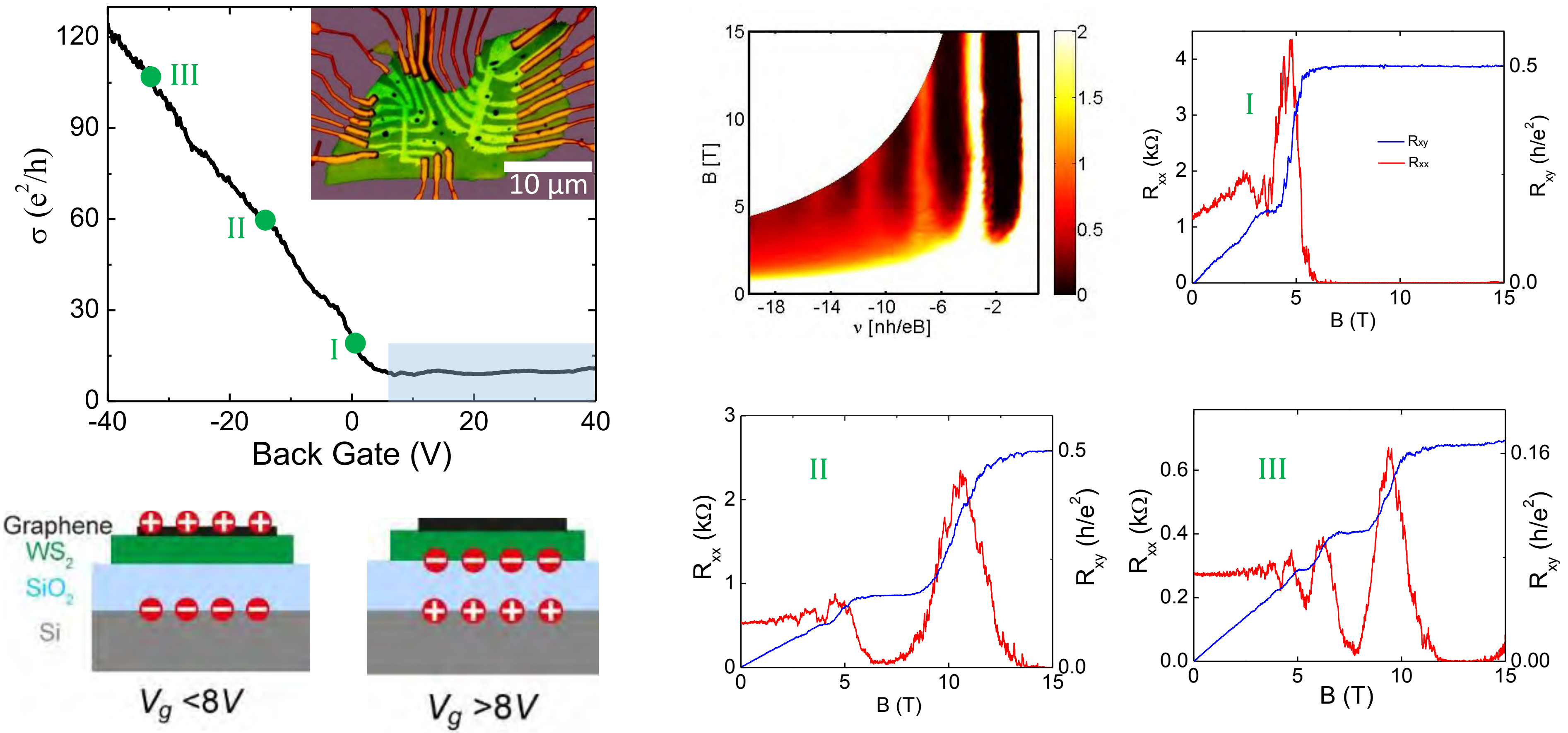
$$\Omega_n(\boldsymbol{k}) \equiv \hat{z}\cdot\boldsymbol{\nabla}_{\boldsymbol{k}} \times \langle u_n(\boldsymbol{k})|i\boldsymbol{\nabla}_k|u_n(\boldsymbol{k})\rangle$$

$$\Omega_c(\boldsymbol{k}) = -\tau\frac{2a^2t^2\Delta'}{[\Delta'^2 + 4a^2t^2k^2]^{3/2}}.$$



Valley-selective optical transitions with circularly polarized light

Graphene-on-WS_2: first generation devices



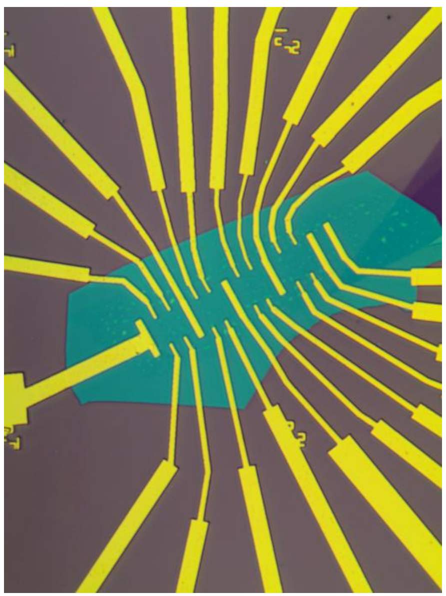
- For V_g>8V, conductance saturates because charges are accumulated in WS_2
- For V_g<8V, device shows typical behavior of high quality graphene: half-integer quantum Hall effect with mobility of 13 000 cm²/VS

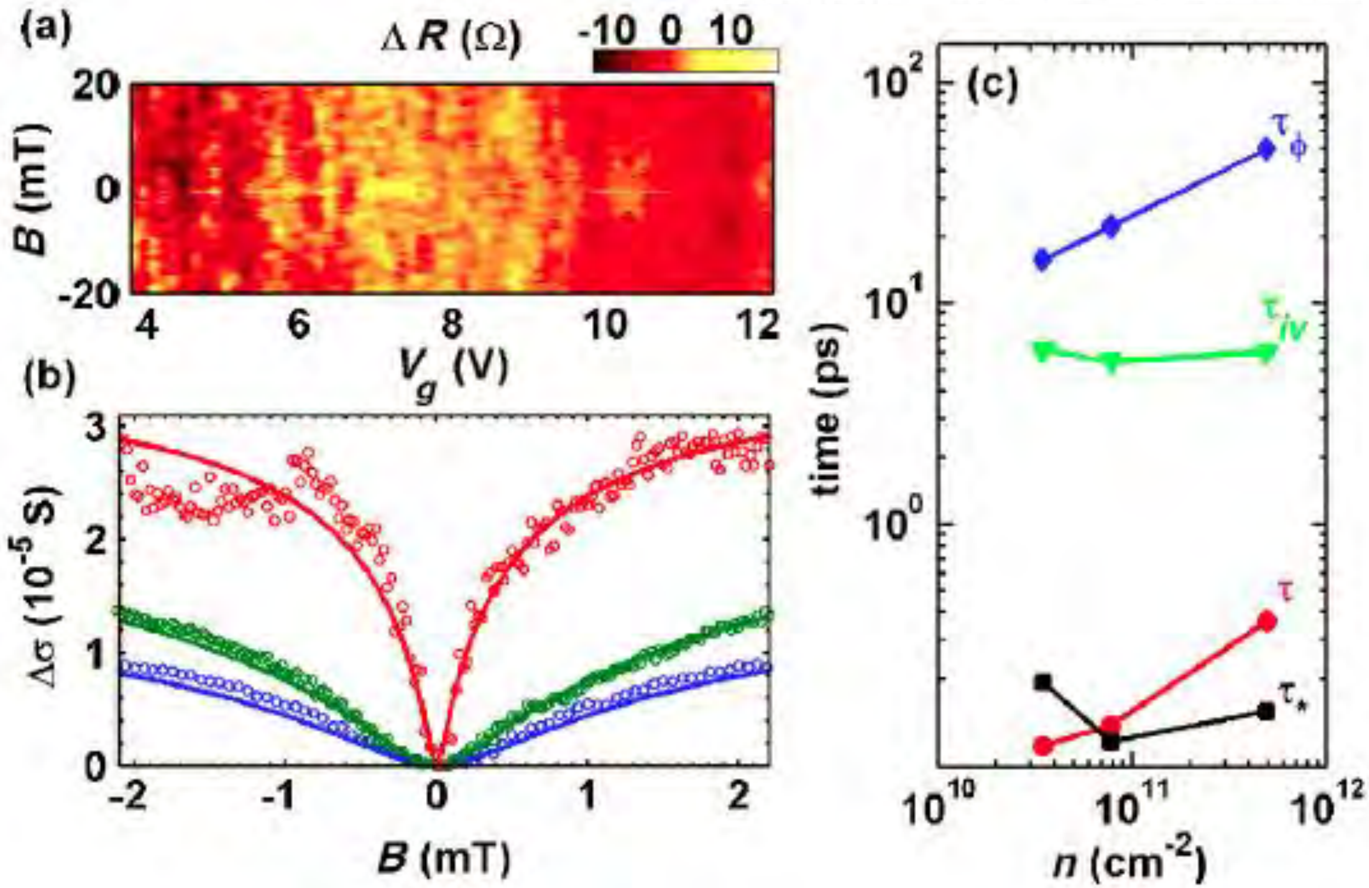
Weak localization in graphene on hBN

Random Strain Fluctuations as Dominant Disorder Source for High-Quality On-Substrate Graphene Devices

Nuno J. G. Couto,[1] Davide Costanzo,[1] Stephan Engels,[2] Dong-Keun Ki,[1] Kenji Watanabe,[3] Takashi Taniguchi,[3] Christoph Stampfer,[2] Francisco Guinea,[4] and Alberto F. Morpurgo[1,*]

PHYSICAL REVIEW X **4**, 041019 (2014)

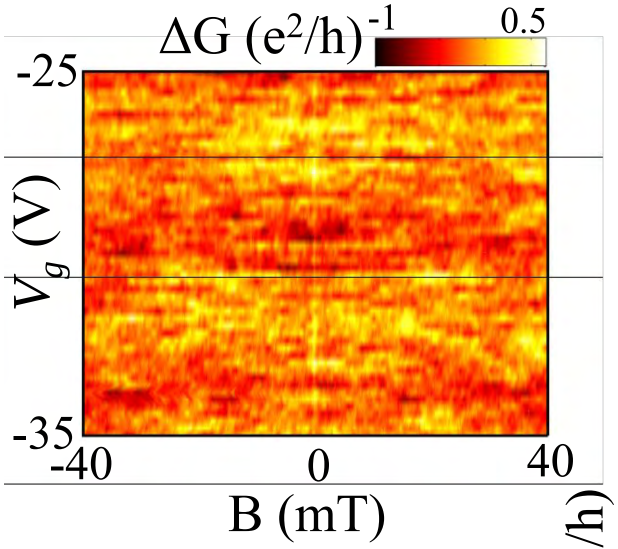




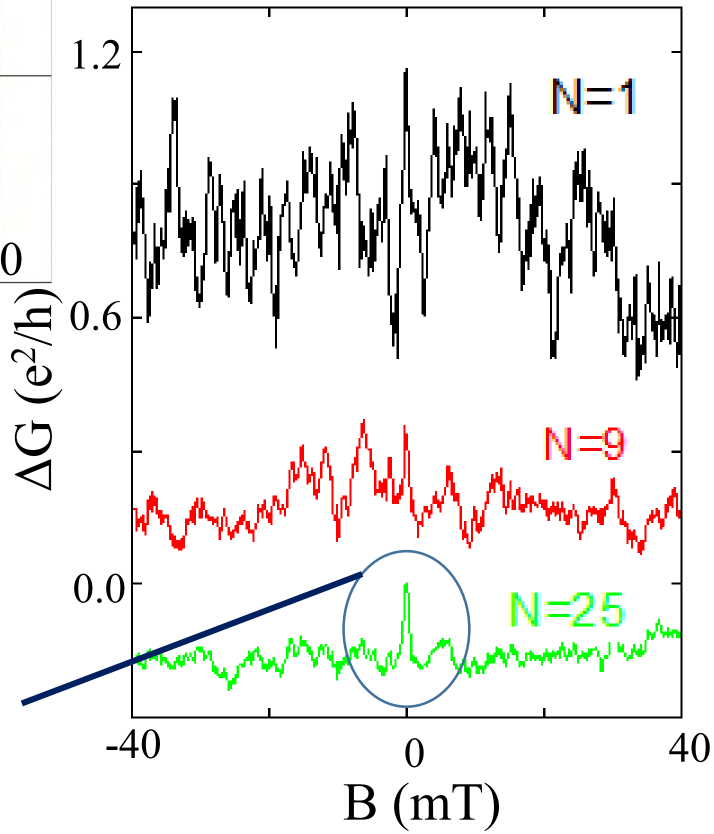
Same behavior seen earlier for graphene on SiO_2 by several groups

Graphene on WS_2: Weak antilocalization

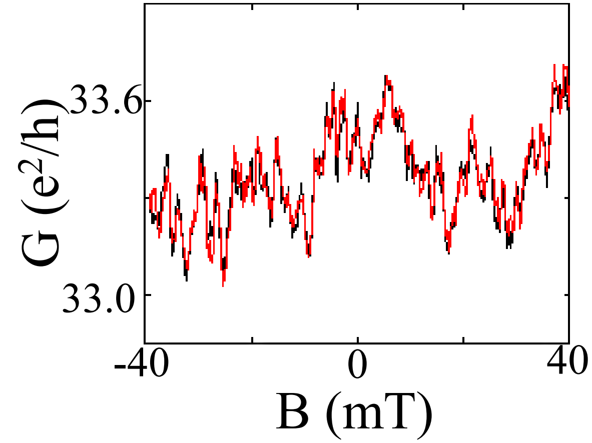
WAL eclipsed by UCF



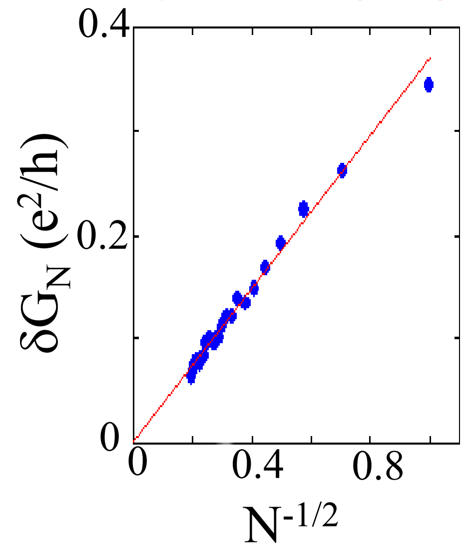
Ensemble-averaged magnetoresistance



Reproducibility



UCF suppressed by averaging

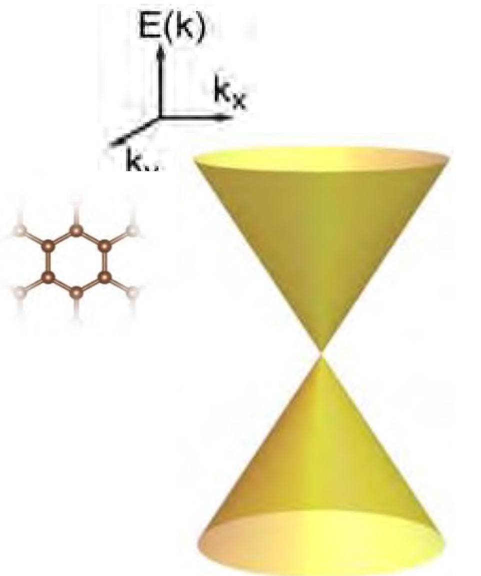


WAL emerges after ensemble averaging

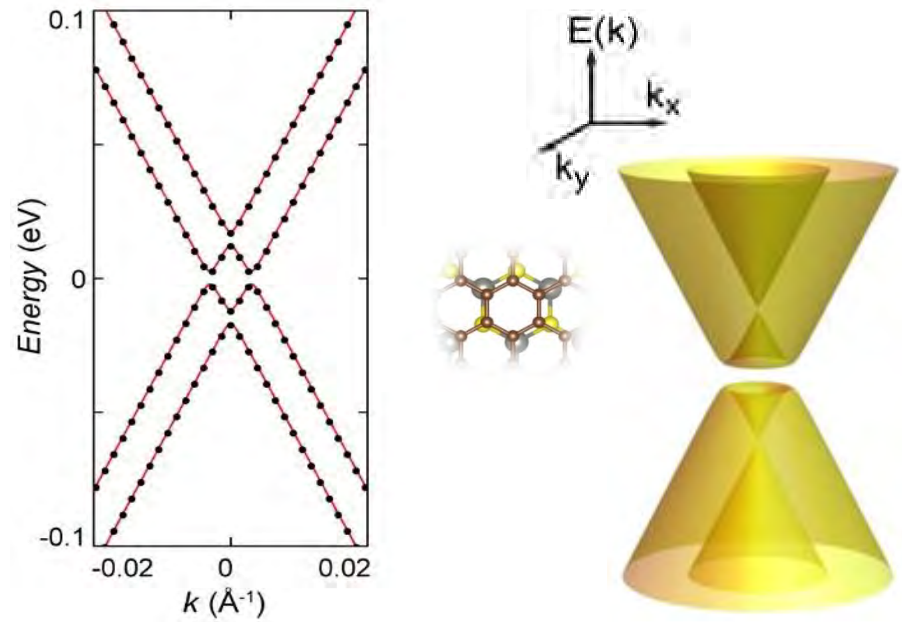
Z. Wang, AM, et al. Nat Comms (2015)

Low-energy band structure from DFT calculations

Pristine graphene



Graphene-on-WS_2

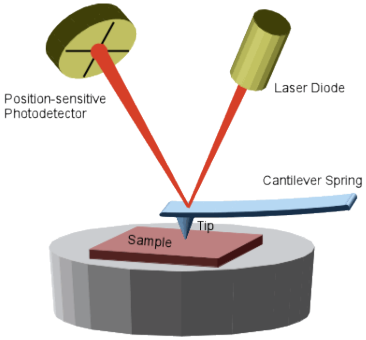


Z. Wang, AM et al Nat Comms (2015)

Ab-initio band structure maps onto the continuum Hamiltonian (close to K)

$$H = H_{Dirac} + \frac{\lambda}{2}\tau_z s_z + \frac{\lambda_R}{2}\left(\tau_z \sigma_x s_y - \sigma_y s_x\right) \quad \text{with } \lambda, \lambda_R \approx \text{few meV}$$

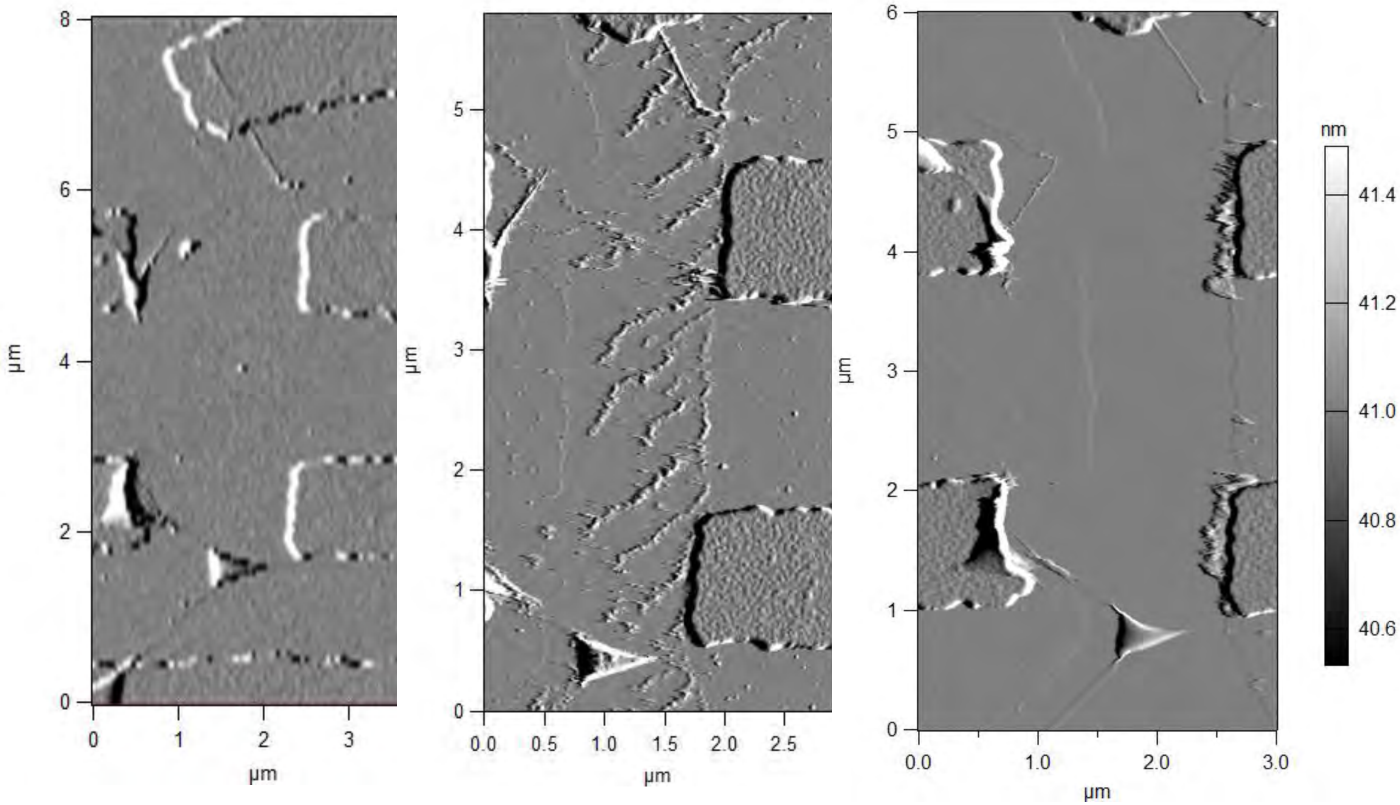
- *λ, λ_R approximately 100 x the strength of SOI in graphene on SiO_2*
- *If $\lambda > \lambda_R$ a gap opens at charge neutrality (~ λ_R) graphene-on-WS_2 is a topological insulator (different from the Kane&Mele one)*



How to remove atomic crumbs: "Floor sweeping" with an atomic force broom….microscope

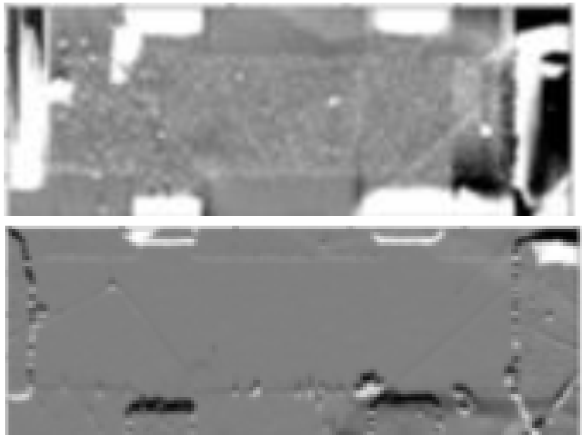
Optical image

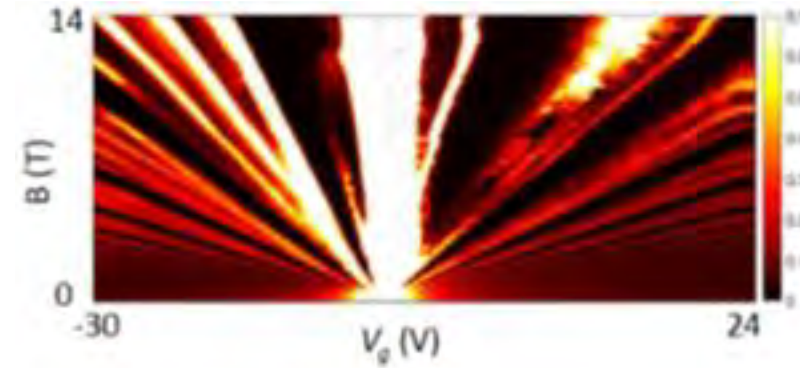
Before → During → After



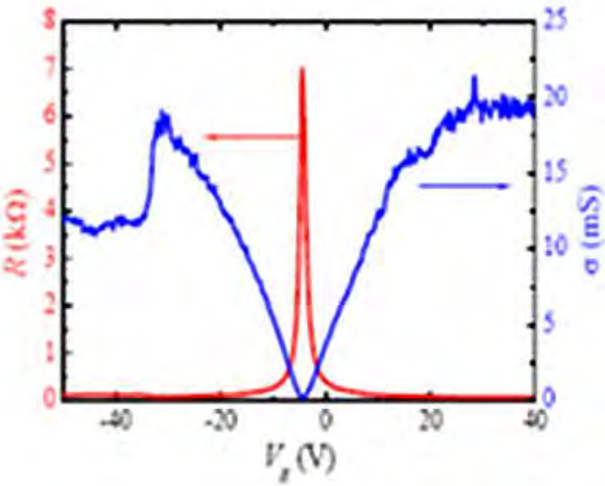
Second generation devices: Graphene-on-WSe_2, MoS_2, WS_2

From top quality “AFM” annealed (μ up to 200.000 cm^2/Vs)
To large area with “bubbles” (μ ~ 3.000 cm2/Vs)

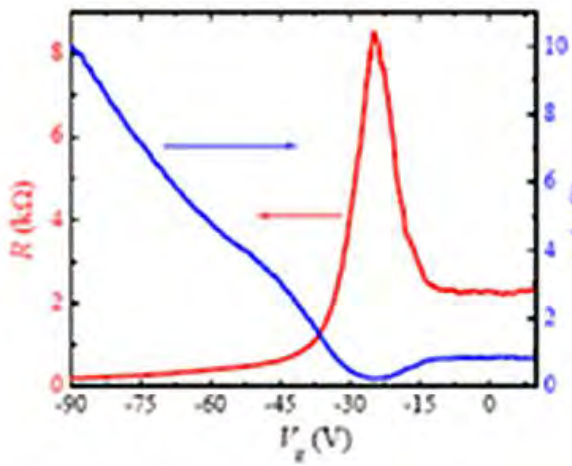




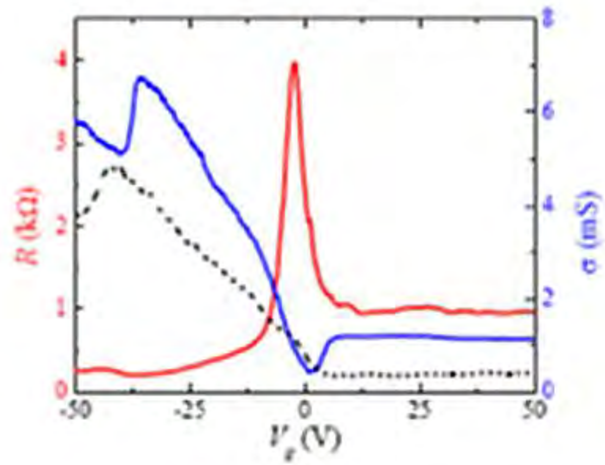
G/WSe_2-A



G/MoS_2

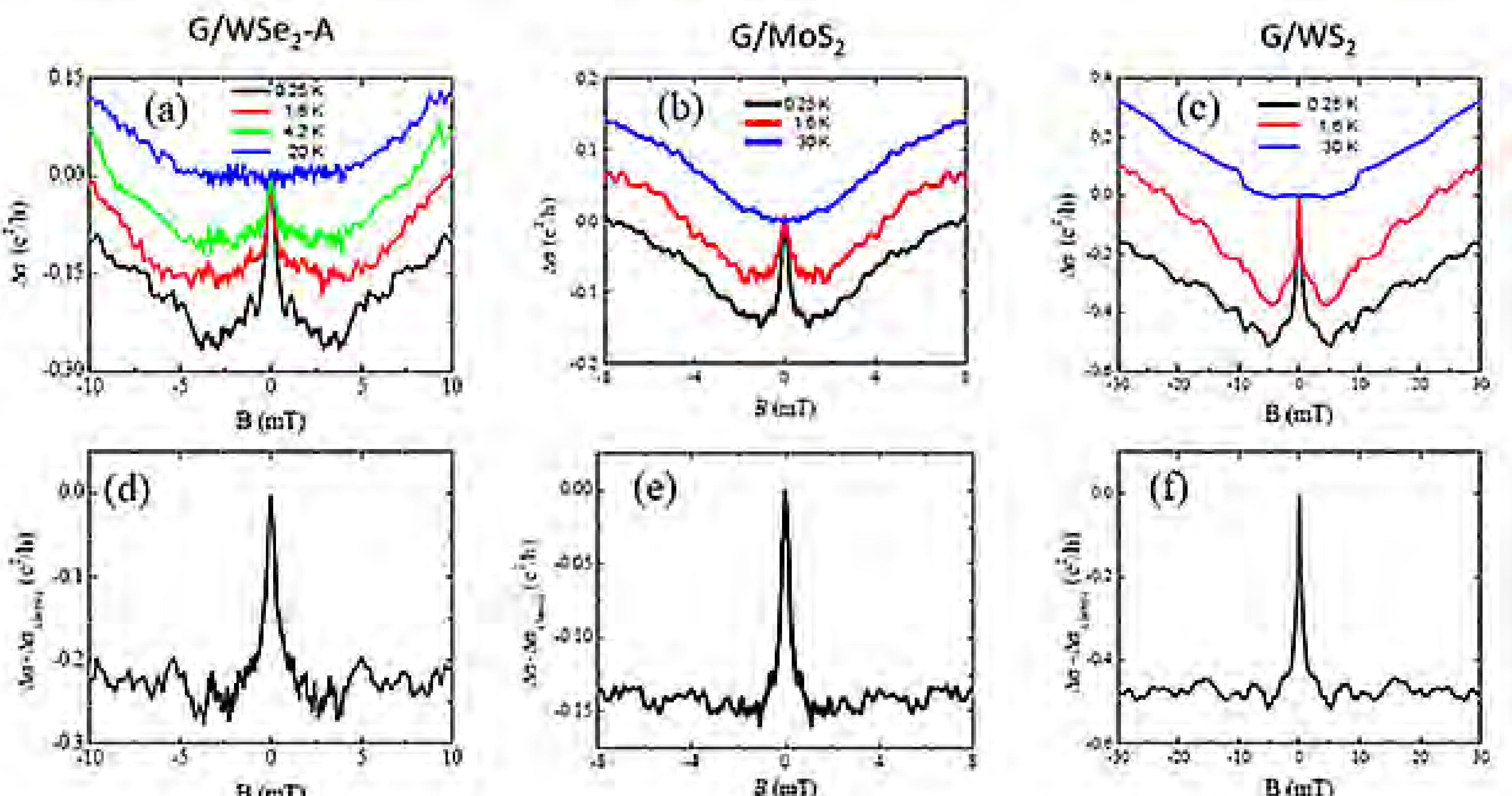


G/WS_2



New +: Graphene on WSe2 has Dirac point fully exposed

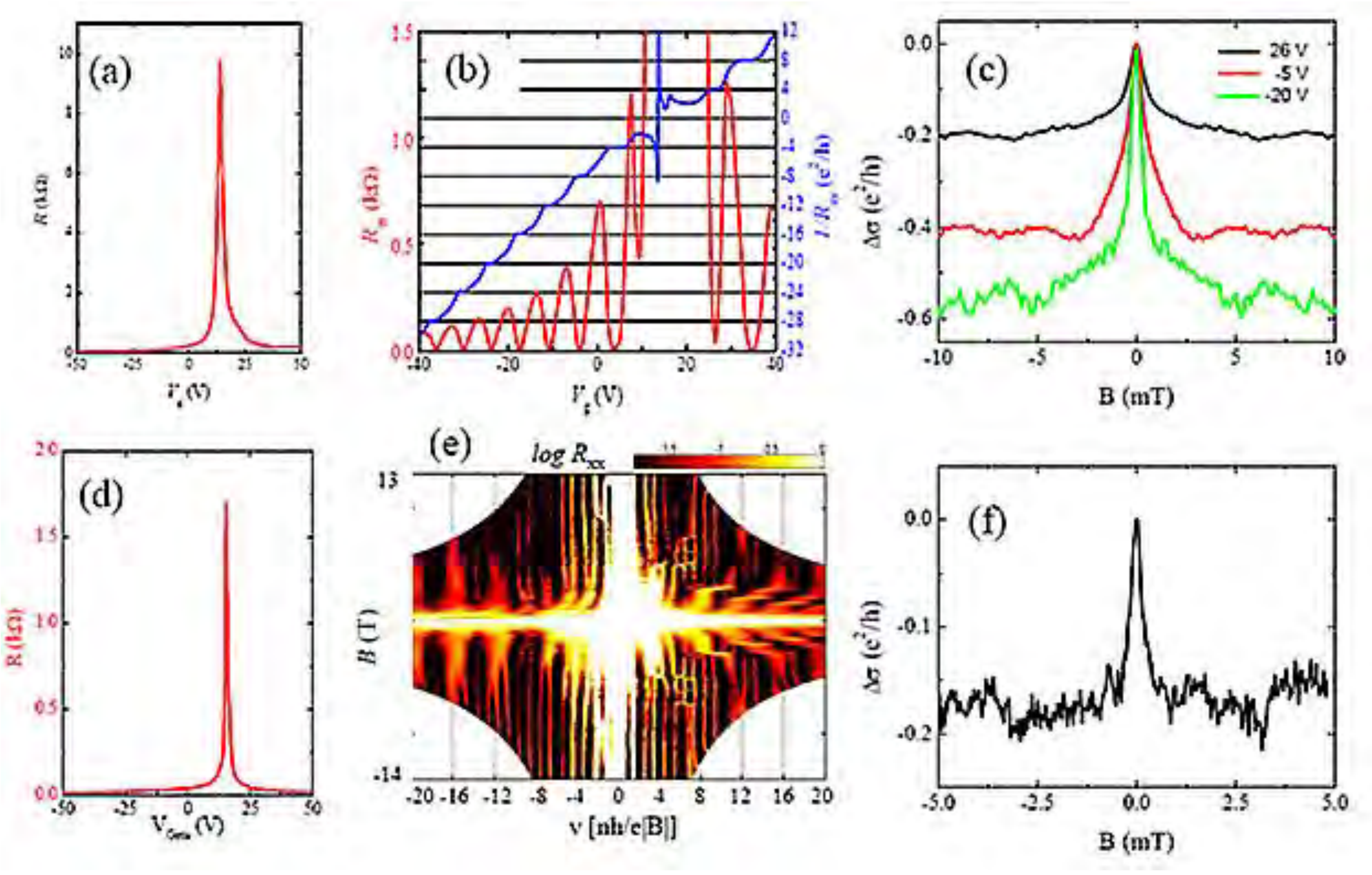
On TMD substrated: In all cases only WAL and never WL



*On all TMDs, for all μ values, and for 1L, 2L, 3L…**only WAL is observed***

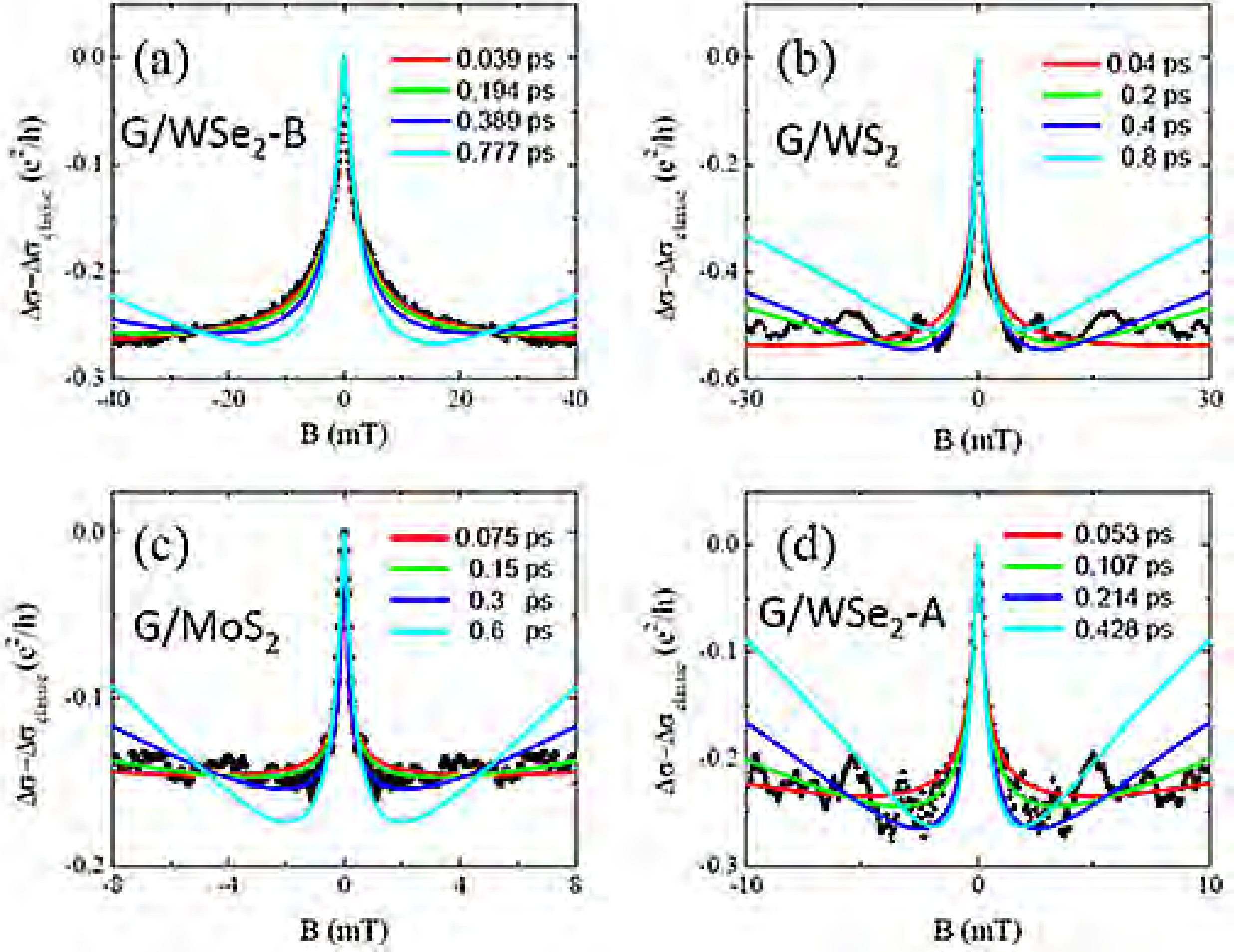
Remove "classical background" to estimate τ_{so}

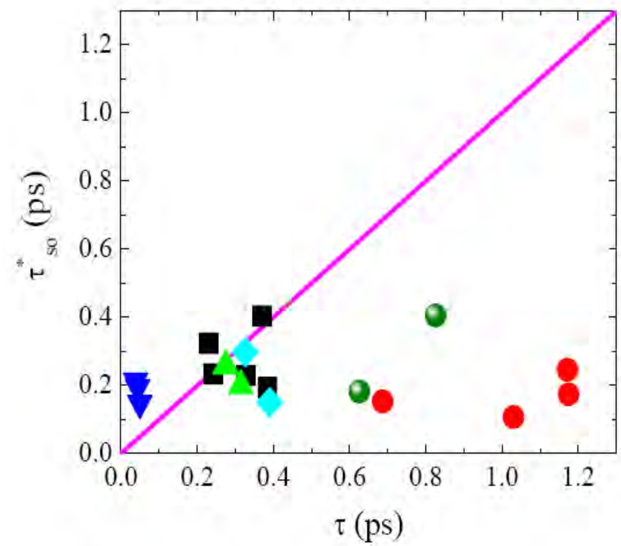
WAL in high-quality bilayers and trilayers



Fitting WAL gives an upper limit for τ_{so} ~ 0.2 ps

Uppper bound to τ_{so} independent of TMD, gate voltage, mobility, etc.





τ_{so} < 0.2 ps
extremely short

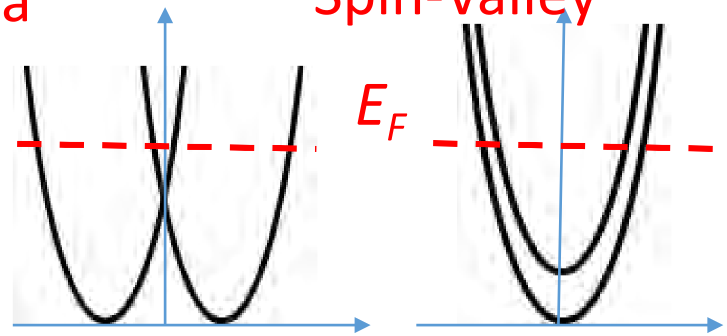
Seems compatible only with SOI modifying the band structure of G

How can we prove it?

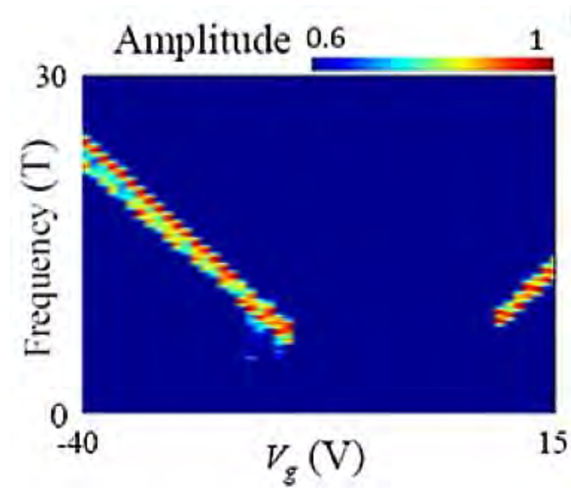
Spin splitting in bilayer Graphene on Wse_2

Rashba

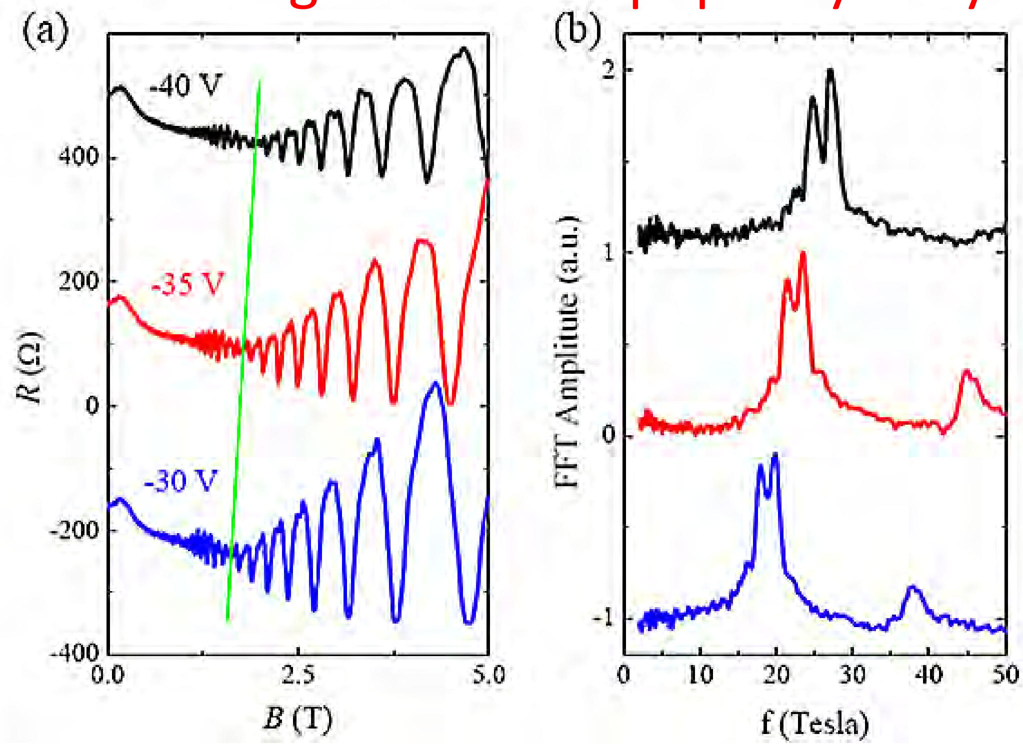
Spin-Valley

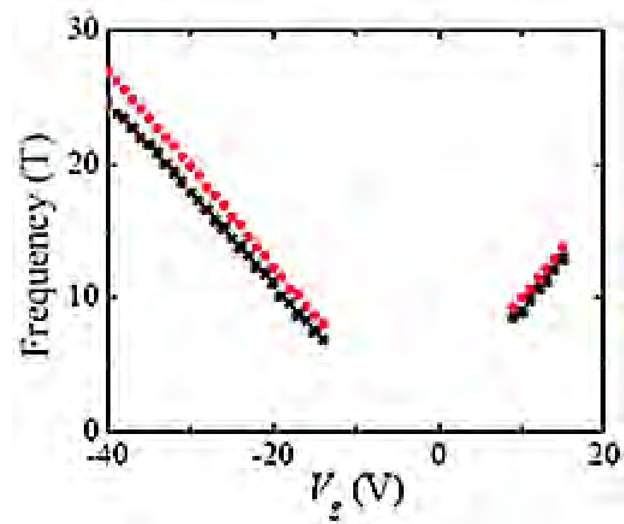


V_G dependence: Beating gives splitting of SdH frequency



Beating visible in top quality bilayers

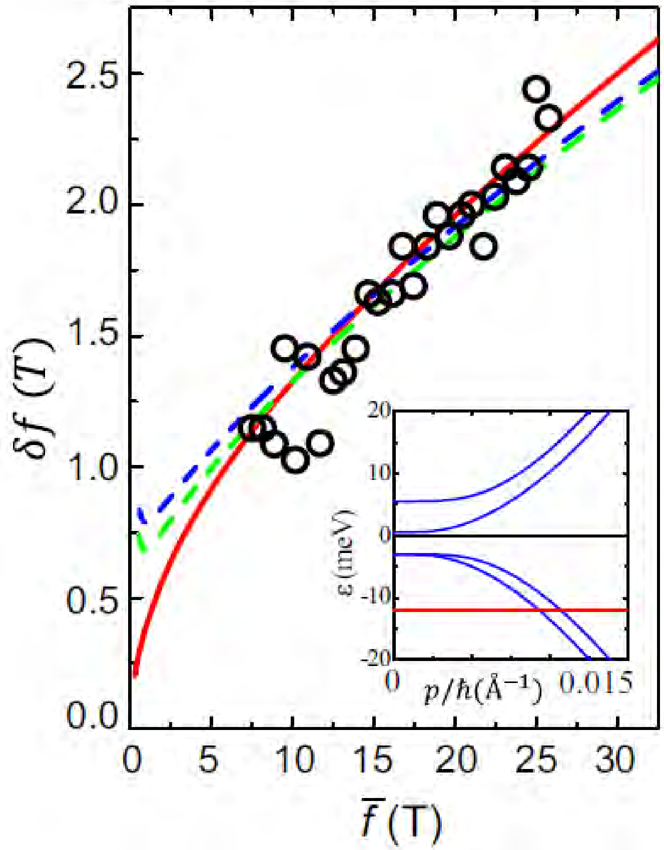


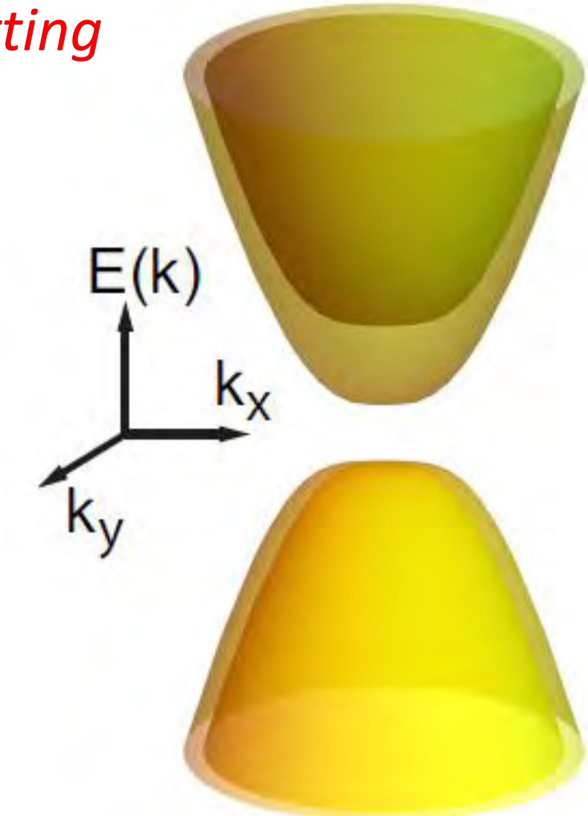


SOI modifies band-structure: How?

Quantitative determination of type and magnitude of SOI

Theory reproduces the V_g dependence of splitting





Resulting band structure

$$H = H_{Dirac} + \frac{\lambda}{2}\tau_z s_z + \frac{\lambda_R}{2}\left(\tau_z\sigma_x s_y - \sigma_y s_x\right)$$

with $\lambda_R \approx$ **10 - 15 meV** $\lambda <$ **6 - 7 meV**

Z. Wang et al PRX 2016

Ballistic transport limited by e-h collisions in charge neutral suspended bilayer graphene

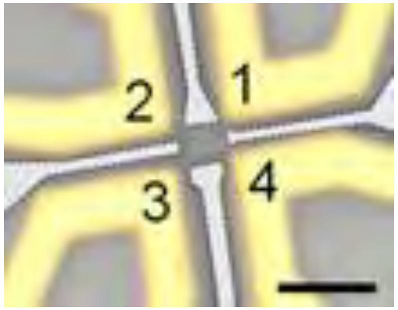
What limits ballistic transport in suspended bilayers?

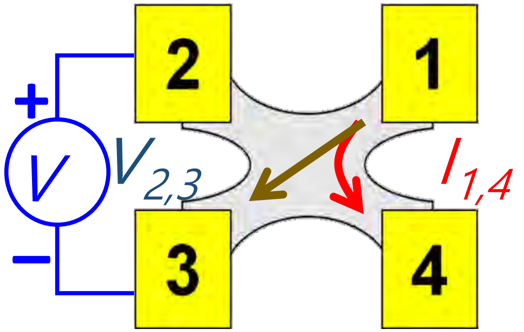
Suspended bilayer devices of very high quality

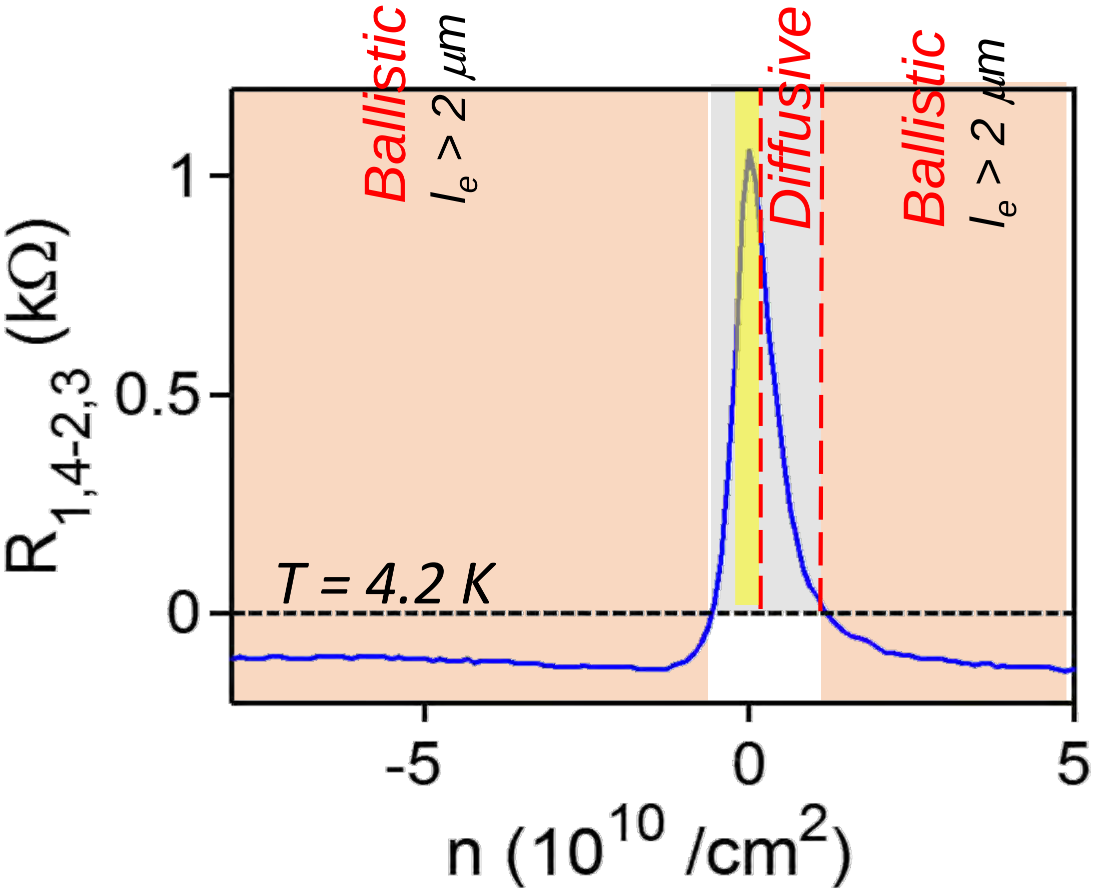
- *Charge fluctuations* *< 10^9 cm^{-2}*

- *Quantum Hall plateaus* *starting from 300 Gauss*

- *Observed* *even-denominator FQHE*

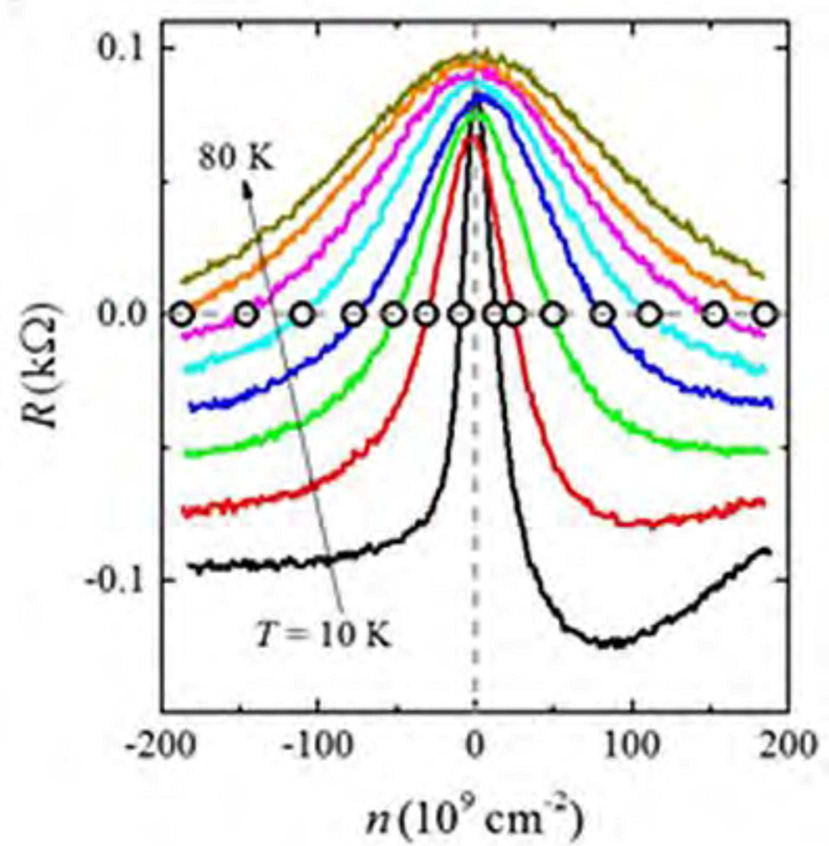


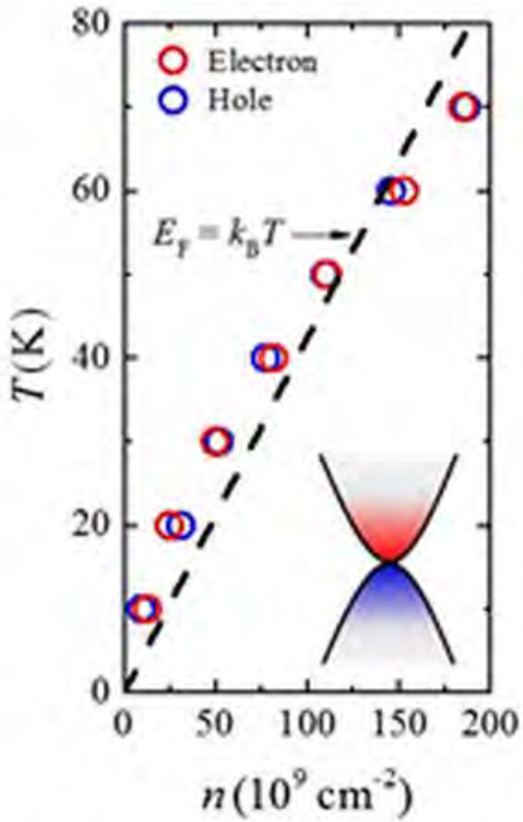




Strongly T & n dependent scattering mechanism

Onset of negative resistance (=ballistic transport)
depends strongly on temperature and carrier density





- *Onset of negative resistance transport at E_F ~ kT*
- *Ballistic transport for $E_F > kT$*

Hint for the role of e-h collisions

Can e-h collisions explain transport in the diffusive regime?

At charge neutrality *(= kT > E_F)* *we have electron and holes*

(1) $\sigma = n_e e \mu_e + n_h e \mu_h$ $\mu_{e/h} = \frac{e\tau_{e/h}}{m}$

Assume: *e-h collision determine velocity relaxation*

(2) $\frac{1}{\tau_e} = \Gamma \frac{n_h}{n_e + n_h}$ $\frac{1}{\tau_h} = \Gamma \frac{n_e}{n_e + n_h}$ $\Gamma = C \frac{kT}{\hbar}$ $C \sim 1$

We obtain:

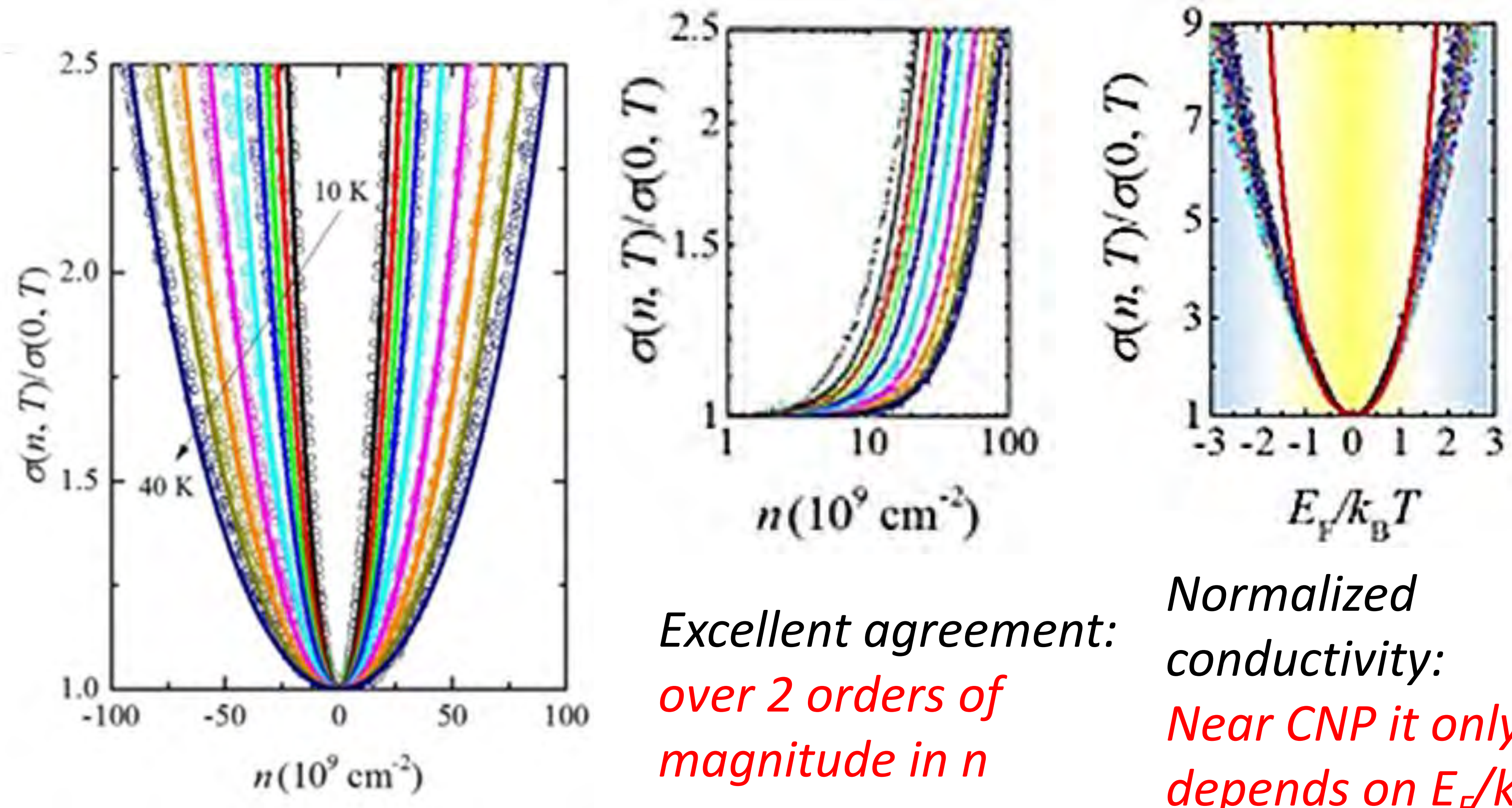
(1) + (2) $$\sigma(n, T) = C^{-1} \frac{\hbar}{kT} \frac{e^2}{m^*} (n_e + n_h) \frac{{n_e}^2 + {n_h}^2}{n_e n_h}$$

$$\frac{\sigma(n, T)}{\sigma(0, T)} = \frac{\pi \hbar^2}{8kTm^* \ln(2)} \frac{(n_e + n_h)({n_e}^2 + {n_h}^2)}{n_e n_h}$$

$m^* = 0.033\ m_o$

No free parameters: either it reproduces the data or it does not

Perfect agreement with no free parameters when $kT > E_F$



Excellent agreement: *over 2 orders of magnitude in n*

Normalized conductivity: *Near CNP it only depends on E_F/kT*

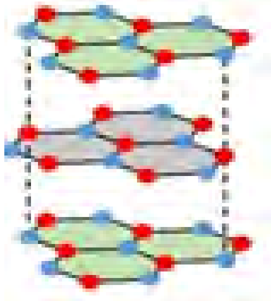
Observed in 4 out of 4 samples investigated in detail

- between 10 and 100 K,

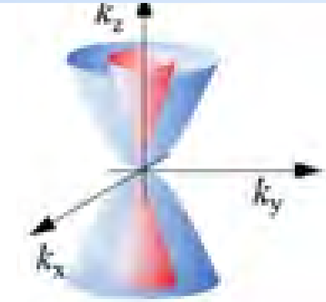
- with $m^* = 0.031\text{-}0.034\ m_o$

It also works on Bernal-stacked trilayer graphene

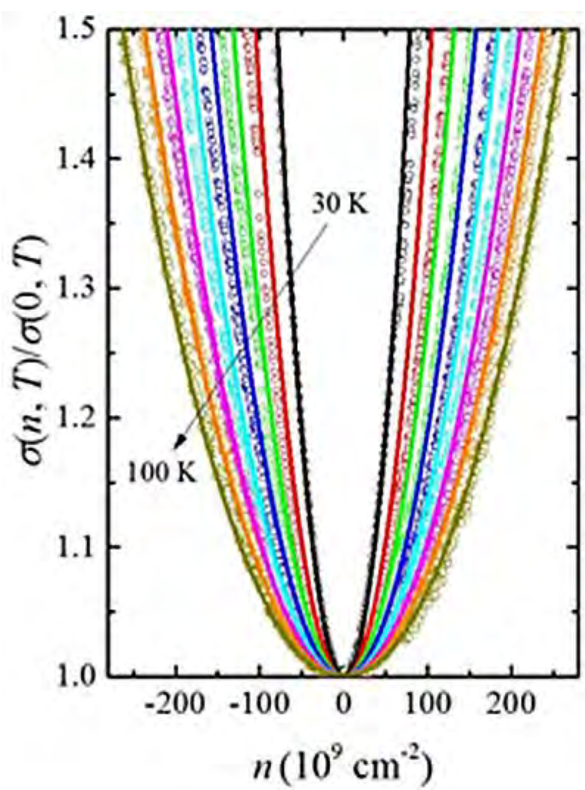
Bernal stacked trilayer

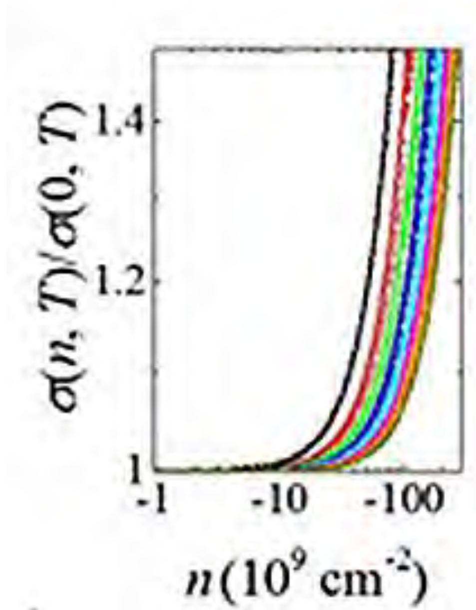


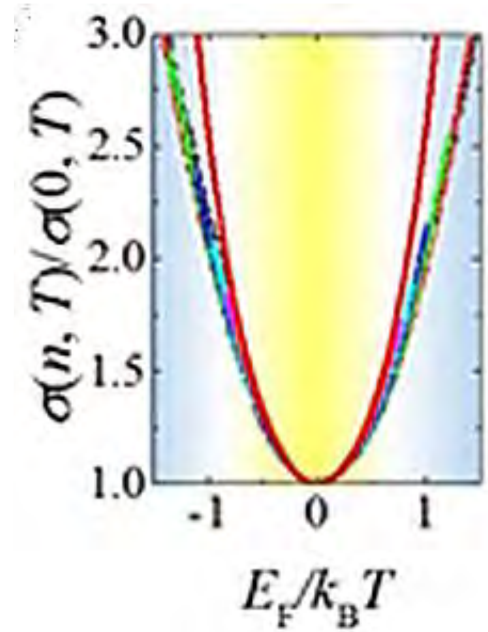
Bands:
1 x linear
1 x quadratic



- *For $E \sim kT > E_F$ quadratic band DOS > 100 x linear band DOS*
- *Quadratic band dominates transport*







Perfect agreement with $m^* = 0.06\ m_o$

(expected $m^* = 0.05\ m_o$)

Also quantitative agreement with no free parameters

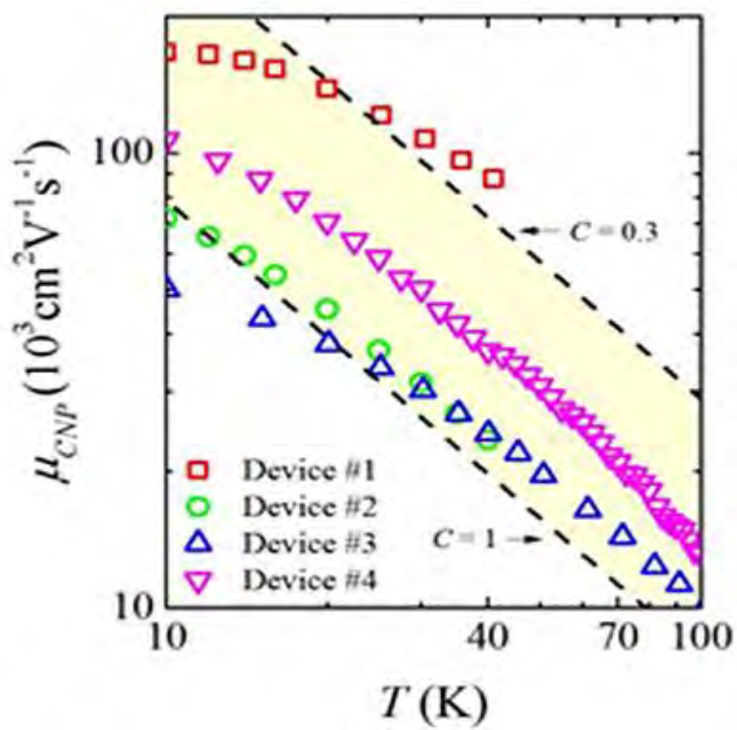
$$\sigma(n,T) = C^{-1}\frac{\hbar}{kT}\frac{e^2}{m^*}(n_e+n_h)\frac{{n_e}^2+{n_h}^2}{n_e n_h}$$

C ~ 1

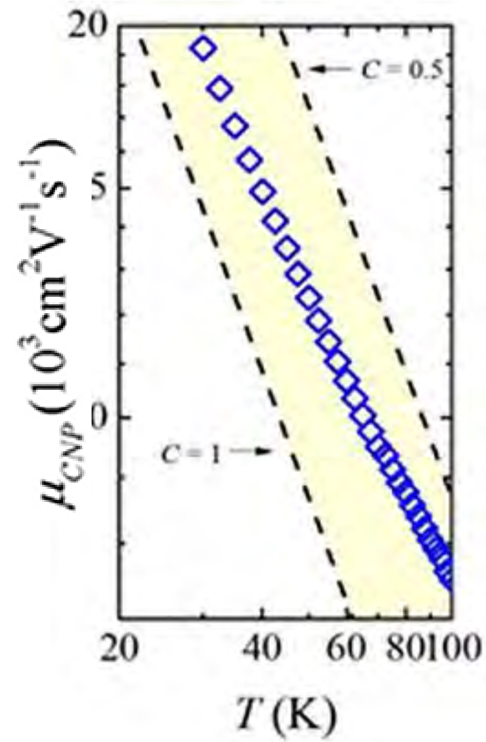
T-dependent mobility at CNP

$$\mu(T) = \frac{\sigma(n=0,T)}{n_e(n=0,T)+n_h(n=0,T)}$$

Bilayer

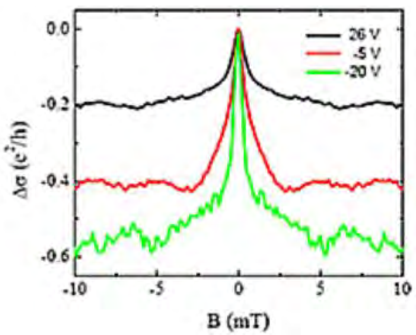


Trilayer

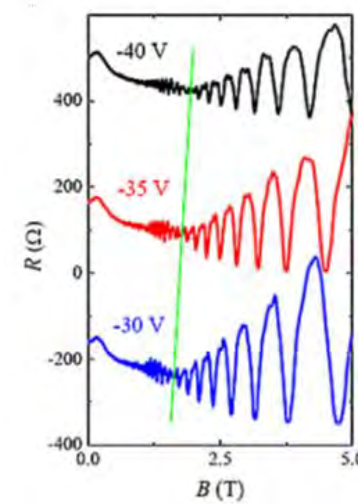


- *Quantiative agrement within a factor of 2-3 or better*
- *Expected due to indtermination on C and precise geometry*

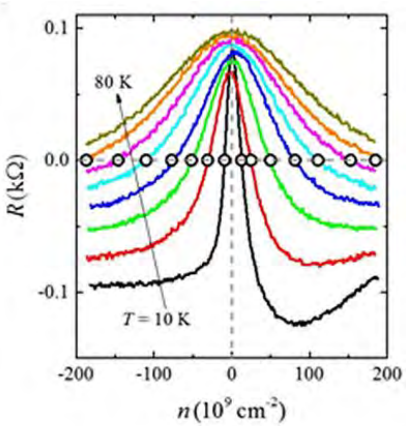
Conclusions



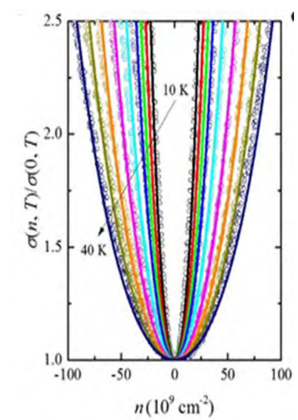
Very strong spin-orbit interaction from weak antilocalization



Band-structure of graphene-on-TMD contains a ~10 meV Rashba term



Ballistic motion near charge neutrality ($kT > E_F$) is limited by e-h collisions



e-h scattering of thermally activated carriers accounts for transport in 2LG and 3LG near the CNP