TOPOLOGICAL BANDS IN GRAPHENE SUPERLATTICES

1) Berry curvature in superlattice bands
2) Energy scales for Moire superlattices
3) Spin-Hall effect in graphene

Leonid Levitov (MIT)

NPSMP2015 @ ISSP U Tokyo 15.06.2015

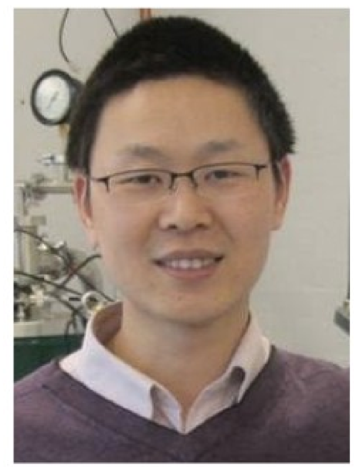
Justin Song

Polnop Samutpraphoot

Yuri Lensky

Andrey Shytov

Andre Geim



Geliang Yu

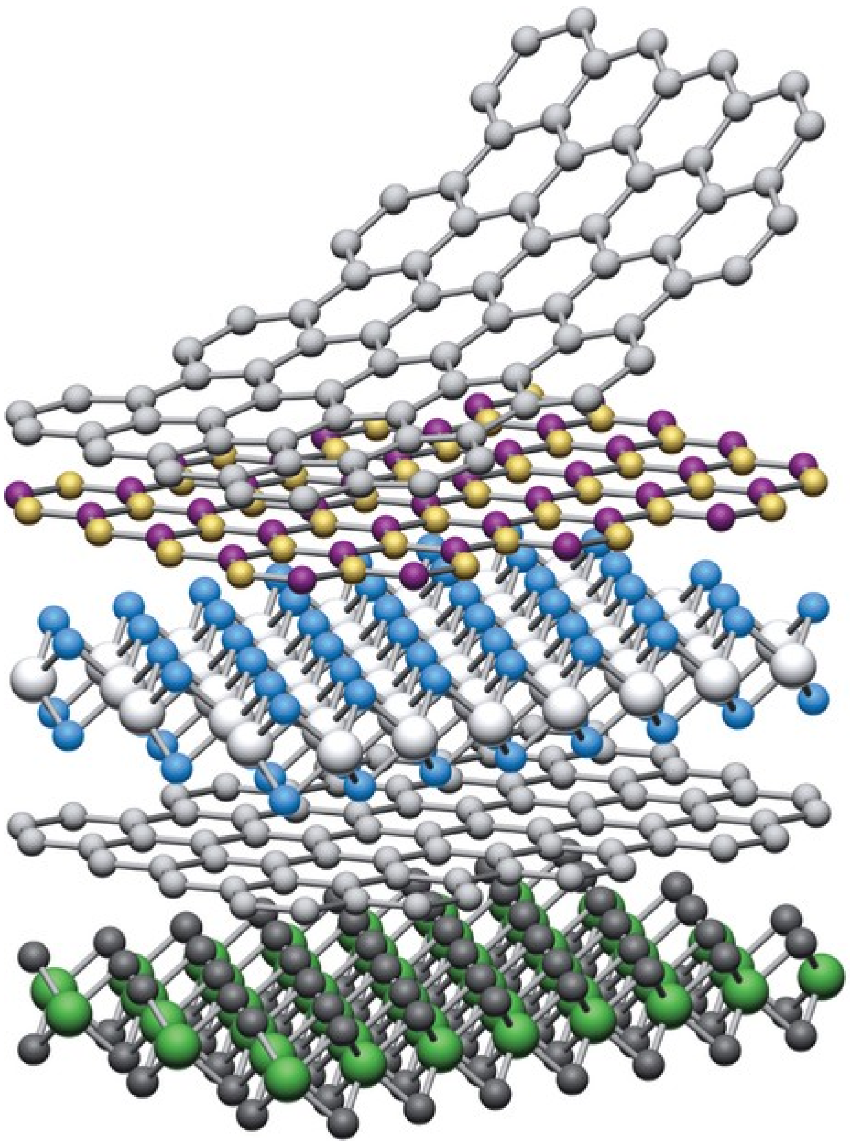
Roman Gorbachev

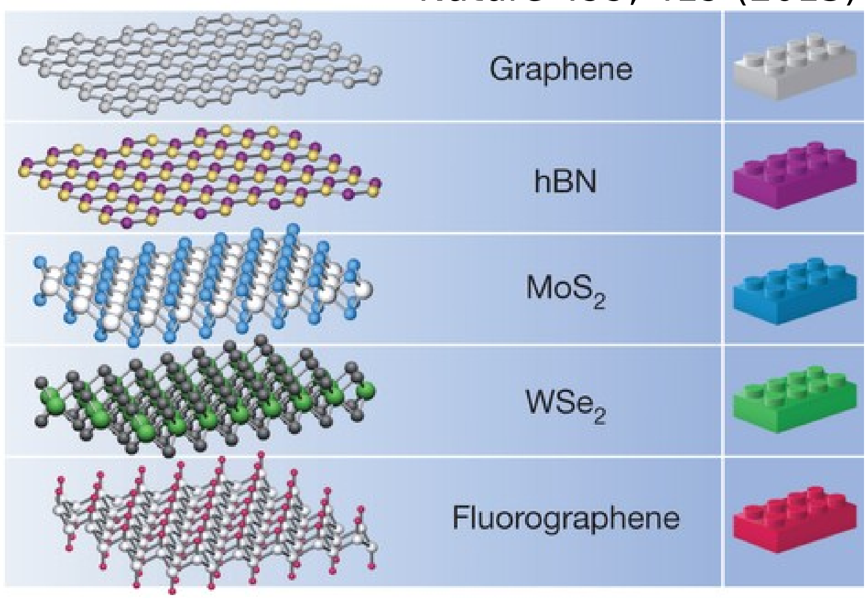
Song, Shytov, LL PRL 111, 266801 (2013)
Song, Samutpraphoot, LL arXiv:1404.4019 (2014)
Gorbachev, Song et al arXiv:1409.0113 (2014)
Lensky, Song, Samuthrapoot, LL, arXiv:1412.1808 (2014)

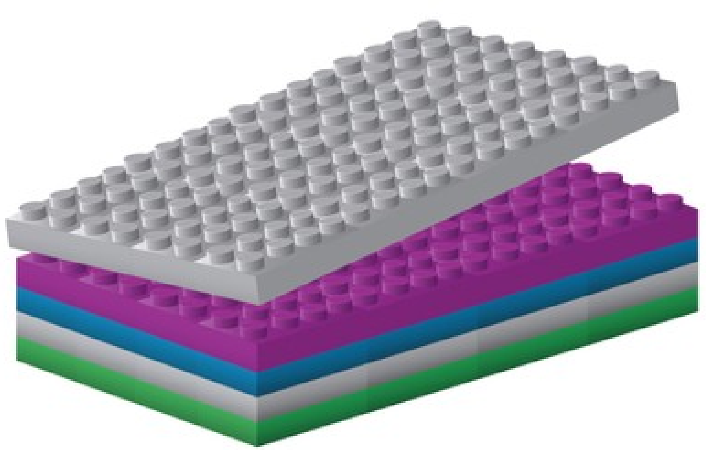
Stacked Van der Waals heterostructures

Stacked atomically thin layers: van der Waals crystals, atomic precision, axes alignment

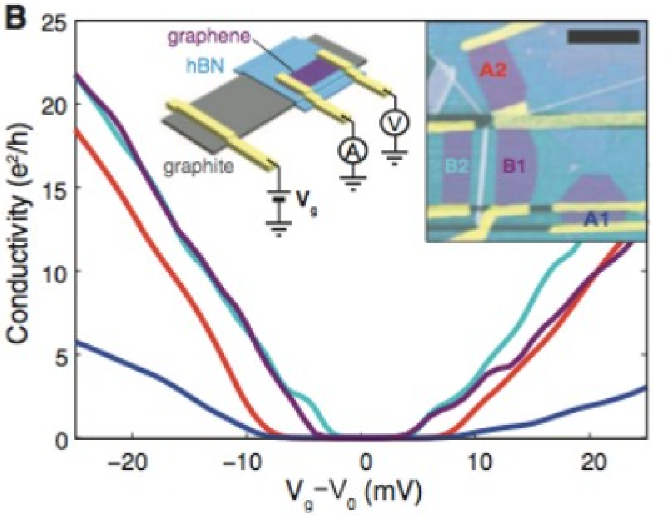
Image from: Geim & Grigorieva, Nature 499, 419 (2013)

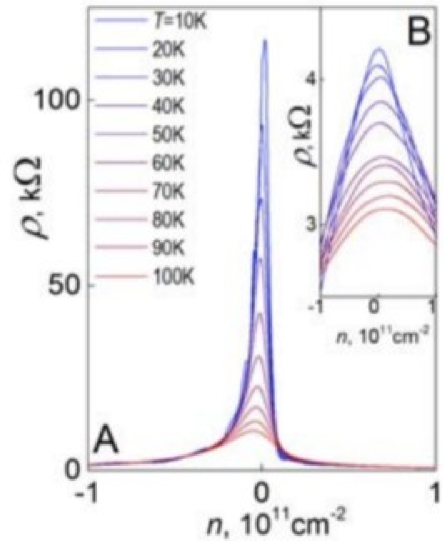






Gap opening for G/hBN





B. Hunt, et. al., Science, 340, 1430 (2013) (MIT Group)
See also stanford and columbia groups

CR Woods, et.al. Nat. Phys (2014) (Manchester Group)

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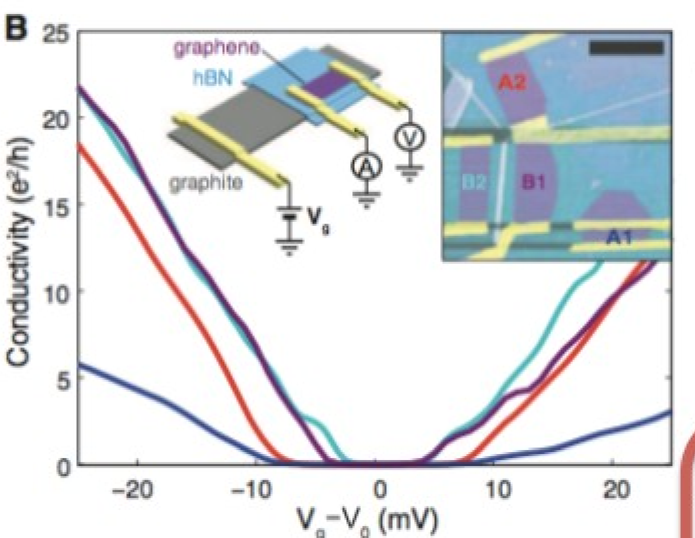
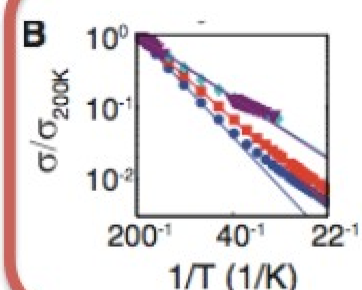


Arhenius plot



Activated behaviour

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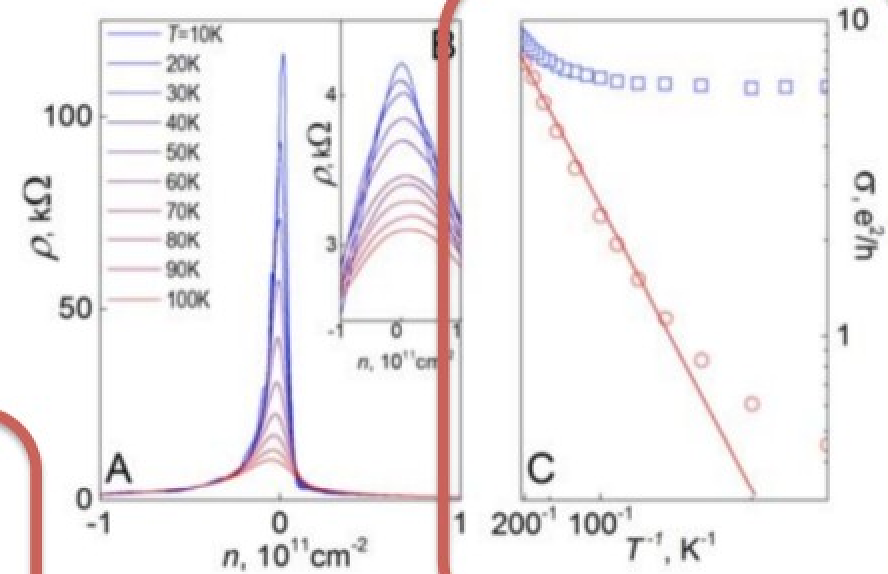

$$\sigma \propto e^{-\Delta/k_B T}$$

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Activated behavior: gap Δ~200-400 K

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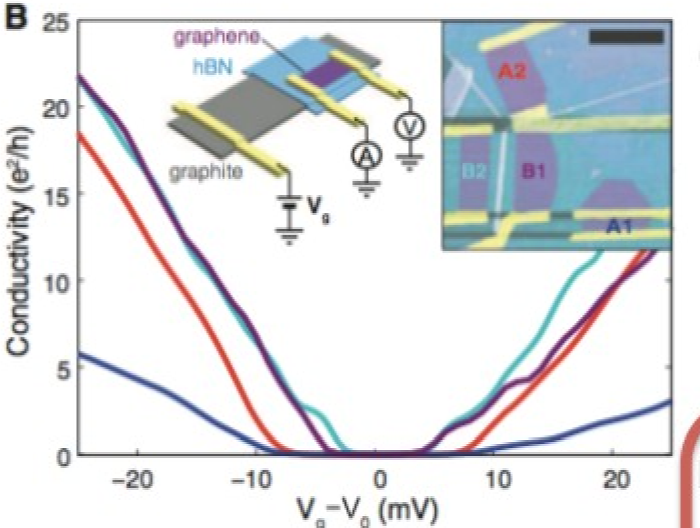

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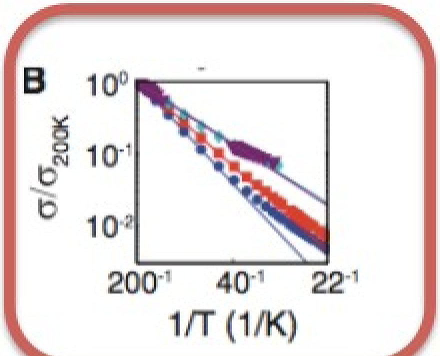

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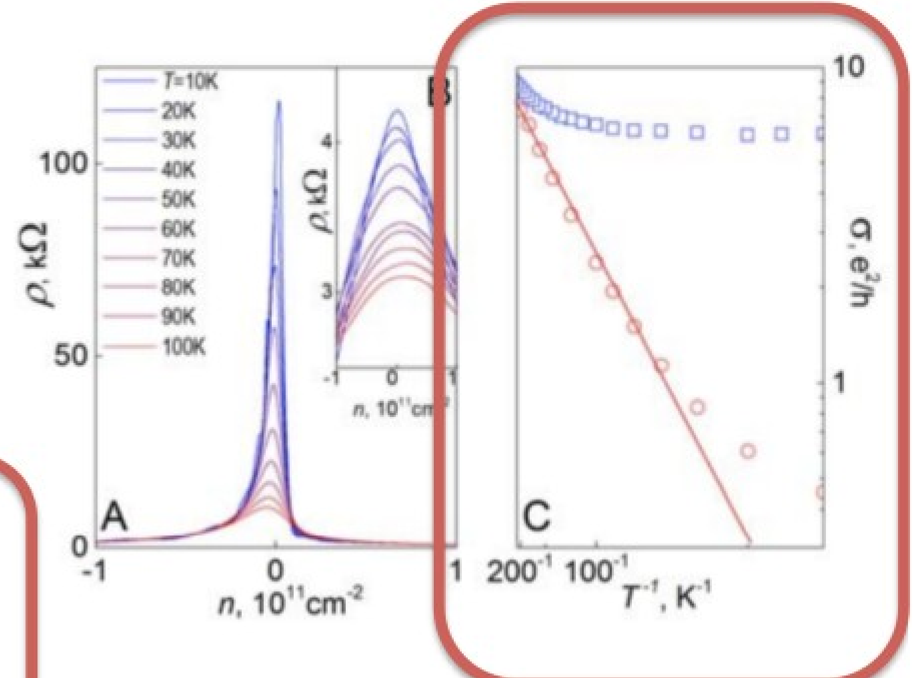

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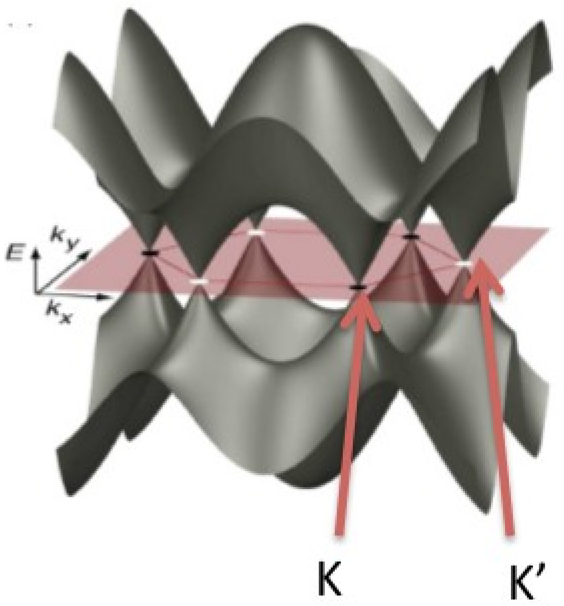
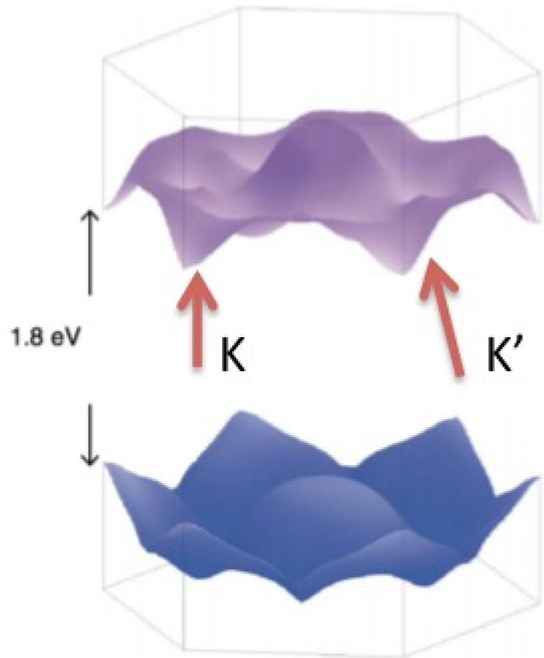
Valley index

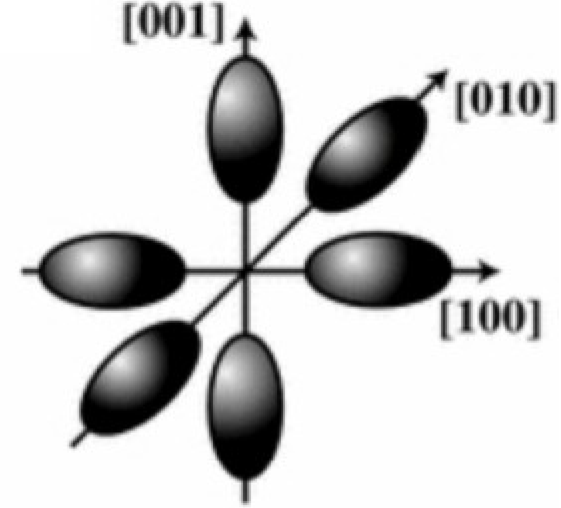
Valleys in Graphene



Valleys in MoS_2



Valleys in Bulk Si



Internal degree of freedom

Long-lived, inter valley scattering ≈ Hundreds of ps

Valley current, $J_K - J_{K'}$

Nonlocal measurements: Gorbachev, Song, et. al. Science (2014)

Topological currents

Electrons in crystals have charge, energy, momentum and Berry's curvature

Semiclassical eqs of motion:

$$\mathbf{v_k} = \frac{1}{\hbar}\frac{\partial \epsilon_\mathbf{k}}{\partial \mathbf{k}} + \dot{\mathbf{k}} \times \Omega(\mathbf{k})$$

$$\dot{\mathbf{k}} = e\mathbf{E} + e\mathbf{v_k} \times \mathbf{B}$$

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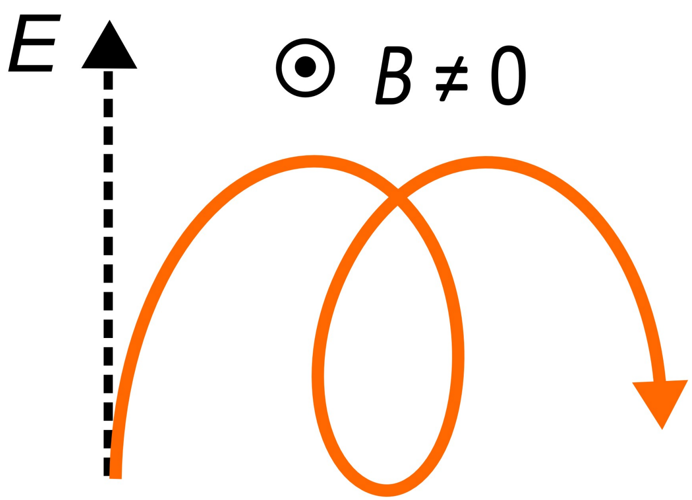
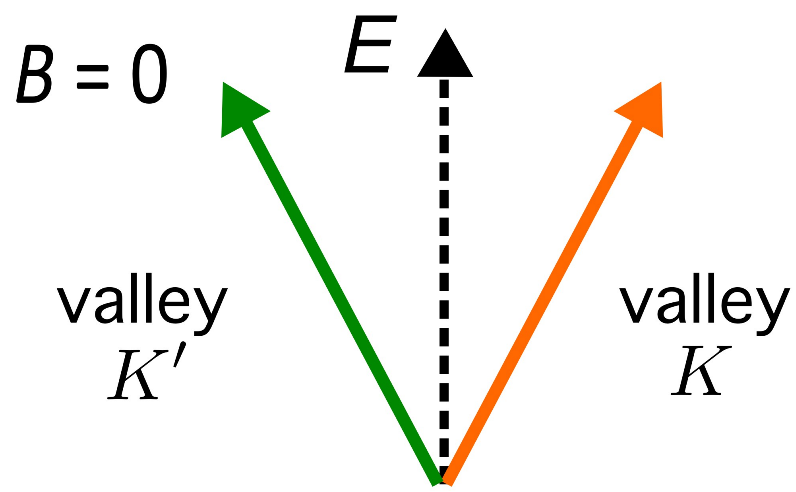
Hall currents at *B*=0





Graphene-based topological materials

Quantized transport, Topological bands, Anomalous Hall effects

Chern invariant $$C=\frac{1}{2\pi}\sum_k \Omega(k)$$

$$\Omega(k)=\nabla_k\times A_k,\quad A_k=i\langle\psi(k)|\nabla_k|\psi(k)\rangle$$

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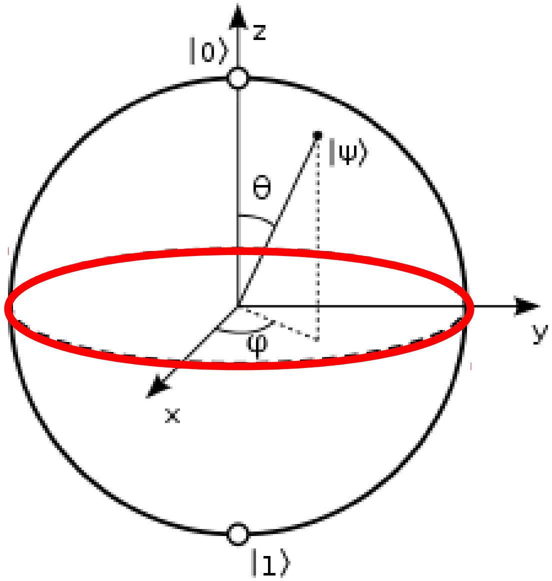
Pristine graphene: massless Dirac fermions, Berry phase yet no Berry curvature

$$\psi_{\pm,\mathbf{K}}(\mathbf{k})=\frac{1}{\sqrt{2}}\begin{pmatrix} e^{-i\theta_{\mathbf{k}}/2} \\ \pm e^{i\theta_{\mathbf{k}}/2}\end{pmatrix}$$



Massive (gapped) Dirac particles

A/B sublattice asymmetry a gap-opening perturbation
Berry curvature hot spots above and below the gap

T-reversal symmetry: $\Omega(-k) = -\Omega(k) \qquad \Omega(k) \neq 0$

Valley Chern invariant
(for closed bands)

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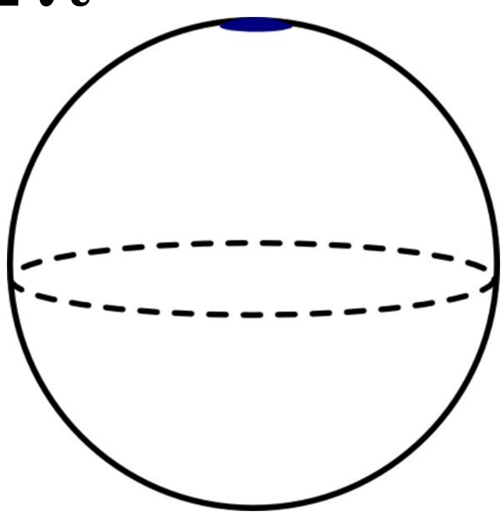
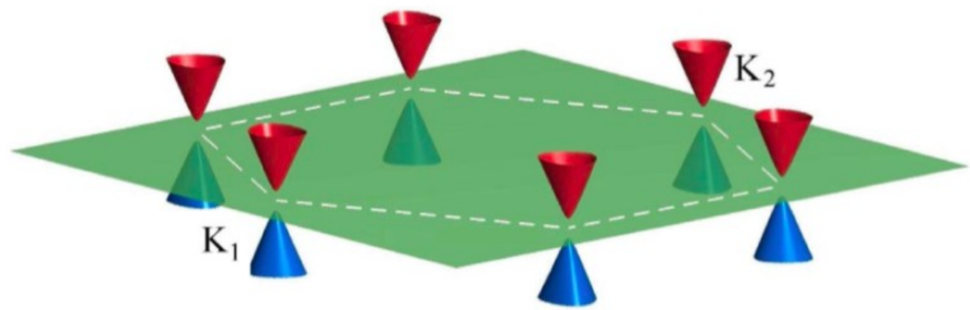
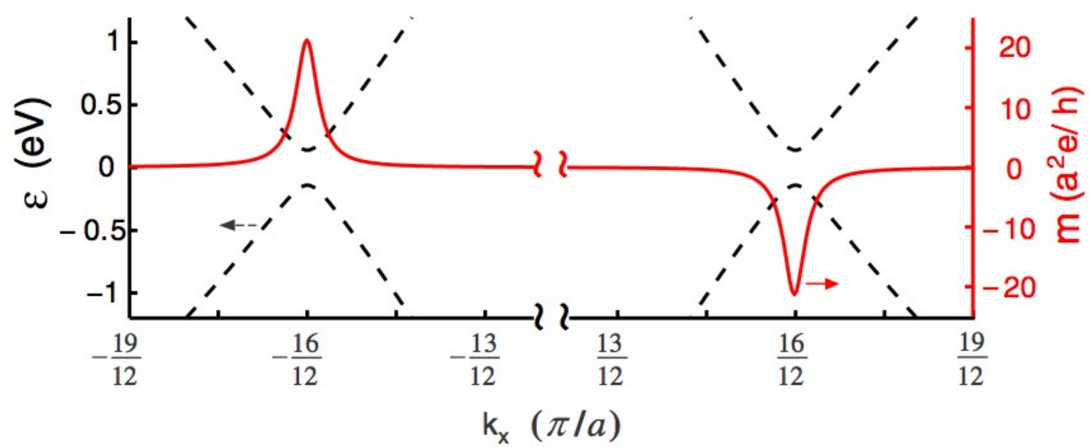




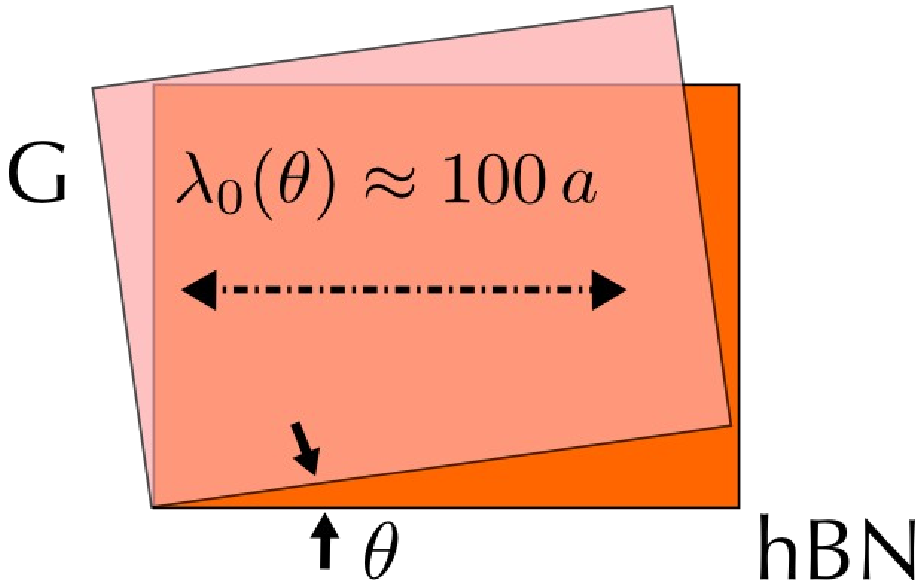


D. Xiao, W. Yao, and Q. Niu, PRL 99, 236809 (2007)

Bloch bands in G/hBN superlattices

Song, Shytov, LL, *PRL **111**, 266801 (2013)*

Song, Samutpraphoot, LL, *PNAS (2015)*



Moiré wavelength λ_0 can as large as 14nm ≈100 times C-C spacing

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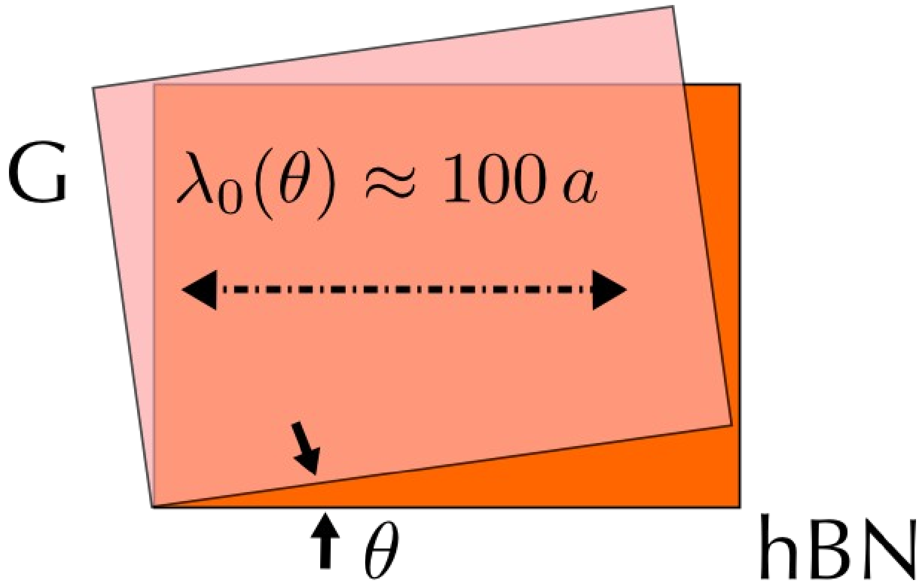


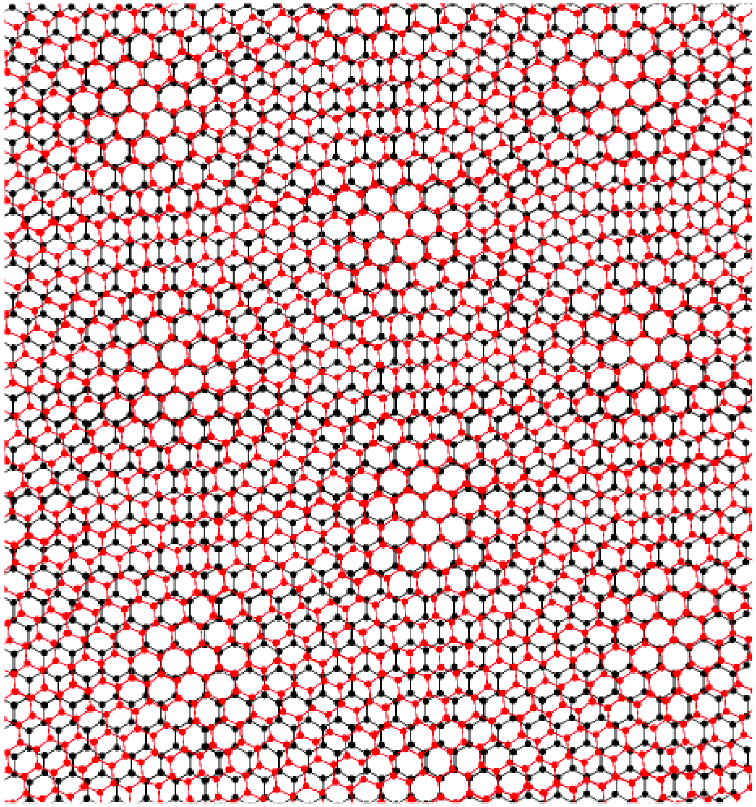
Moiré wavelength λ_0 can as large as 14nm ≈100 times C-C spacing

Focus on one valley, K or K'

The variety of G/hBN superlattices:

San-Jose et al. arXiv:1404.7777, Jung et al arXiv:1403.0496, Song, Shytov LL PRL (2013), Kindermann PRB (2012) Sachs, et. al. PRB (2011)

Incommensurate (moire) chirality/mass sign changing



Dean et.al. Nature 497, 213 (2013)
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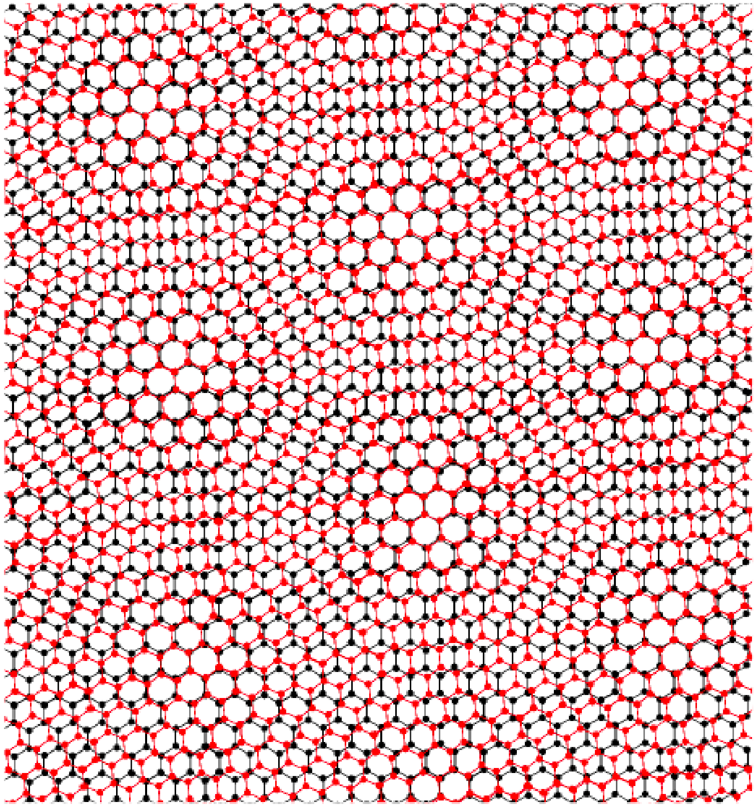

Dean et.al. Nature 497, 213 (2013)
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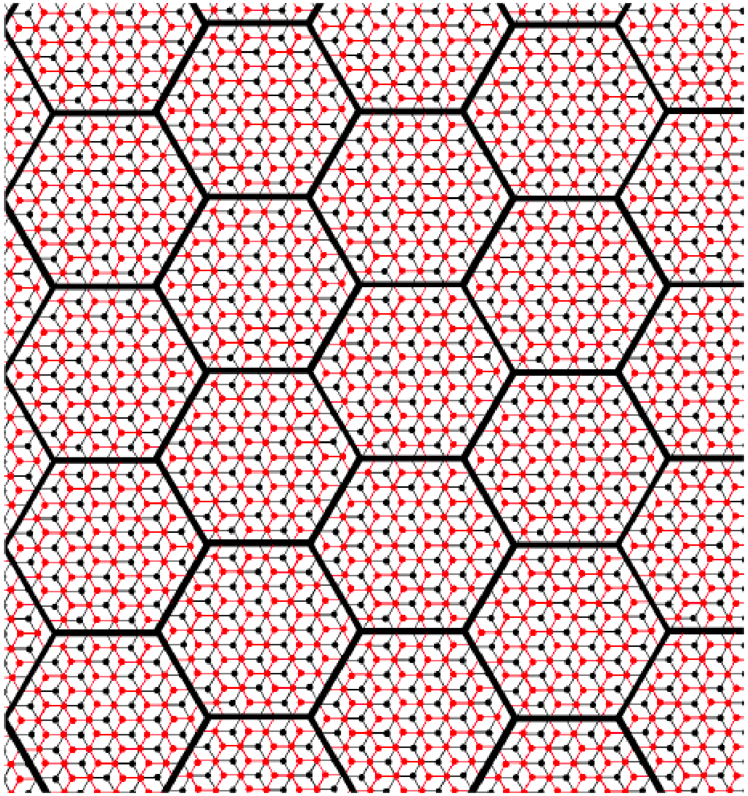
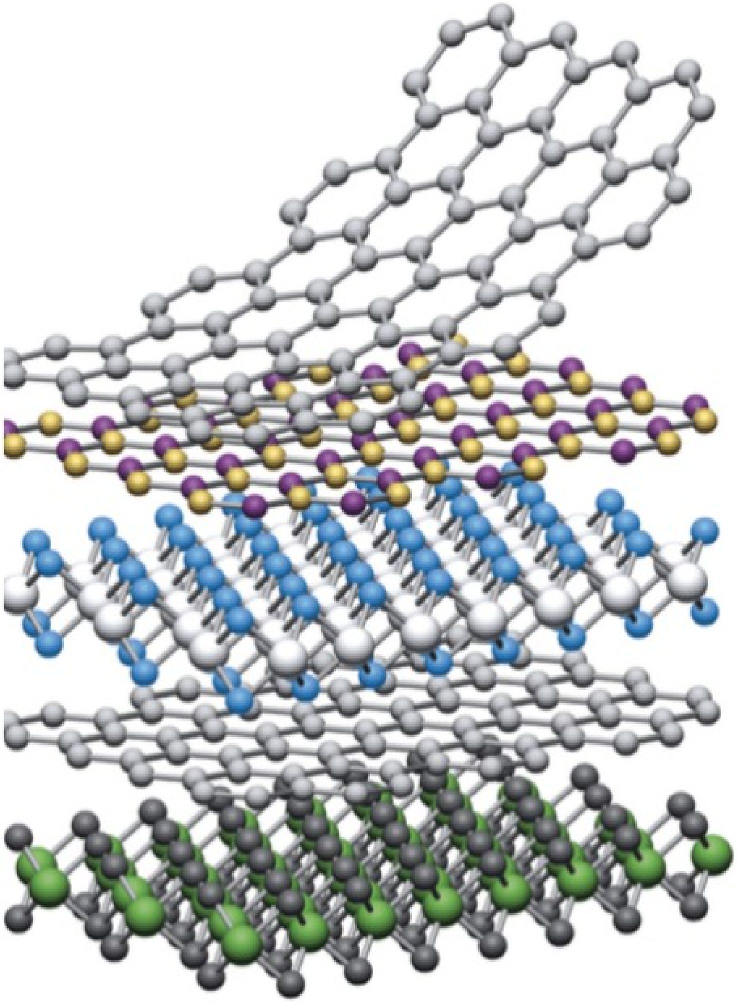
Commensurate stacking global A/B asymmetry global gap



Woods, et.al. Nature Phys 10, 451 (2014)

vdW heterostructures

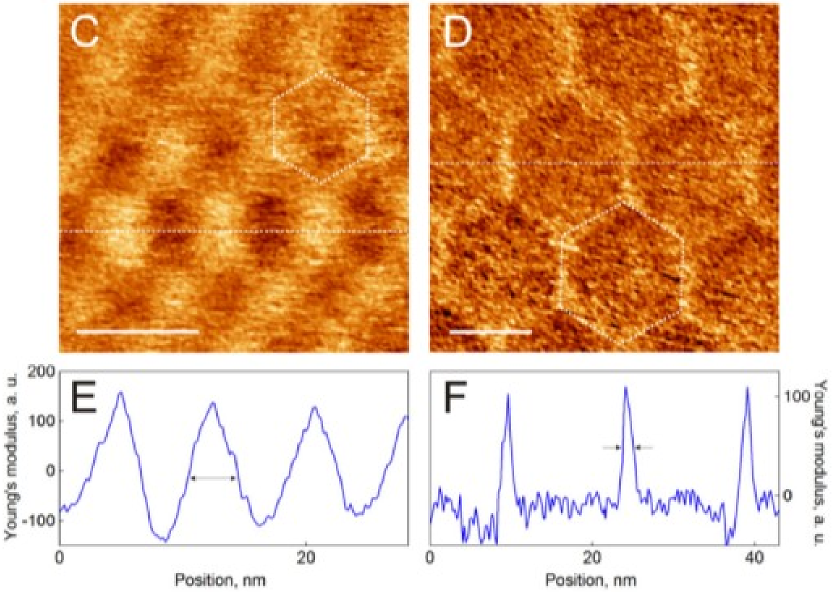
New physics in stacked structures?



Stacked vdW materials exhibit spatial structure

AFM Spatial Map

Large twist angle Small twist angle

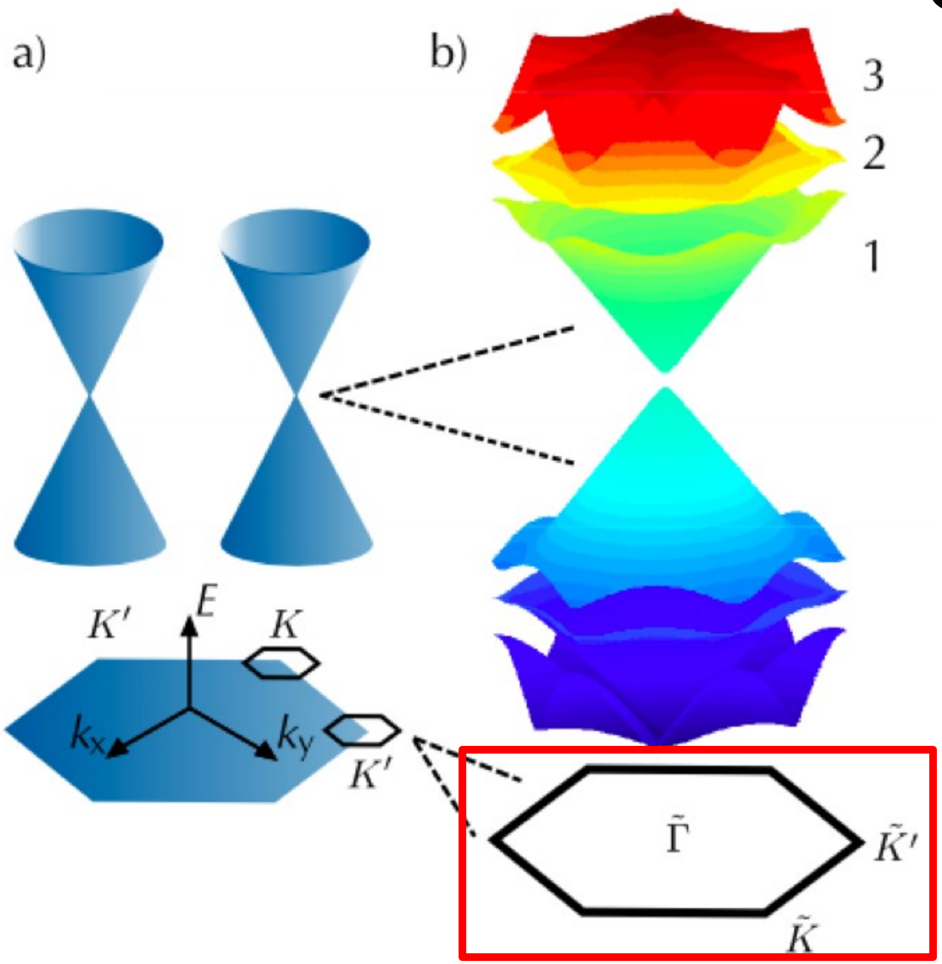


CR Woods, et.al. Nat. Phys (2014)

Low-energy Hamiltonian

San-Jose et al. arXiv:1404.7777, Jung et al arXiv:1403.0496, Song, Shytov LL PRL (2013), Kindermann PRB (2012) Sachs, et. al. PRB (2011)

$$\mathcal{H} = \int d^2x \sum_{i=1}^{N} \psi_i^\dagger(\mathbf{x})[v\sigma\mathbf{p} + m(\mathbf{x})\sigma_3]\psi_i(\mathbf{x})$$



Constant global gap at DP

$$m(\mathbf{x}) = \Delta + m \sum_{j=1}^{6} e^{i\mathbf{b}_j \cdot \mathbf{x}}$$

Spatially varying gap, Bragg scattering

Focus on one valley

Song, Samutpraphoot, LL arXiv (2014)

Incommensurate/Moire case

$$\mathcal{H} = \int d^2x \sum_{i=1}^{N} \psi_i^\dagger(\mathbf{x})[v\sigma\mathbf{p} + m(\mathbf{x})\sigma_3]\psi_i(\mathbf{x})$$

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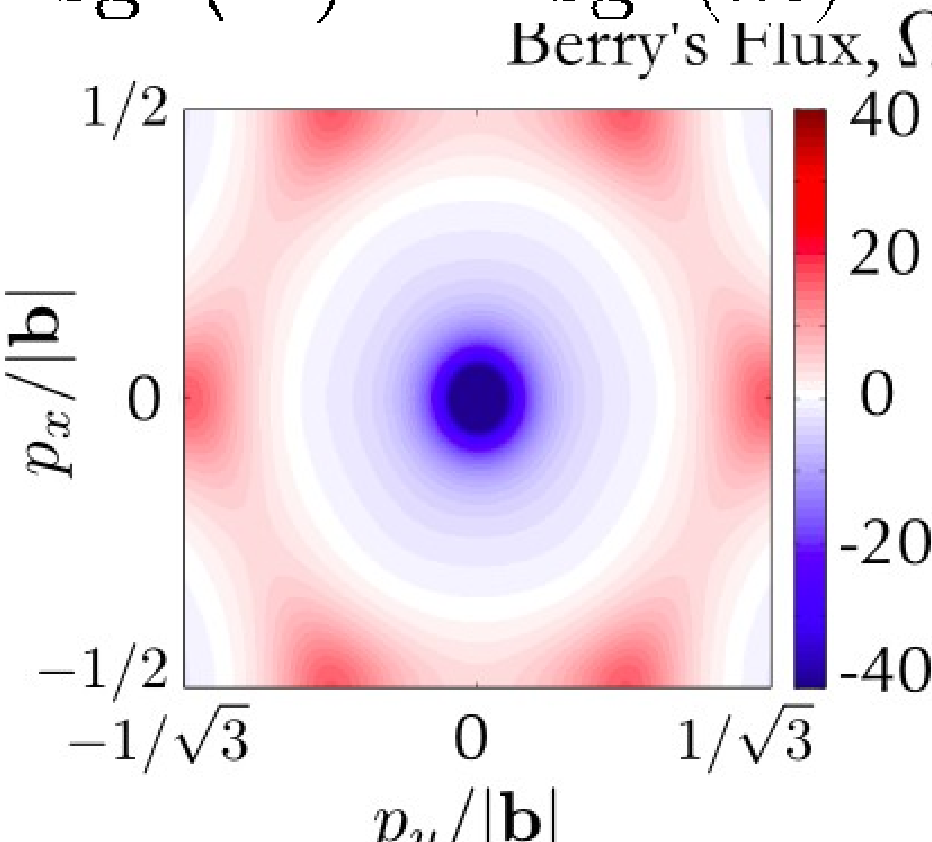

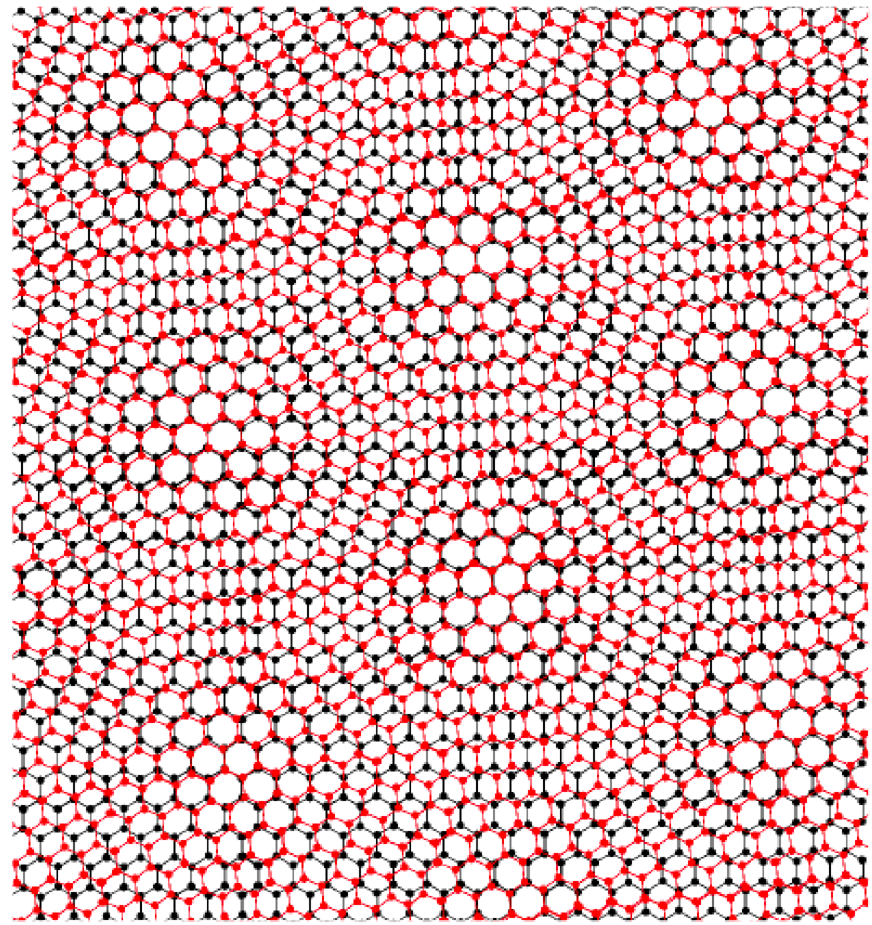

Commensurate case

$$\mathcal{H} = \int d^2x \sum^{N} \psi_i^\dagger(\mathbf{x})[v\sigma\mathbf{p} + m(\mathbf{x})\sigma_3]\psi_i(\mathbf{x})$$

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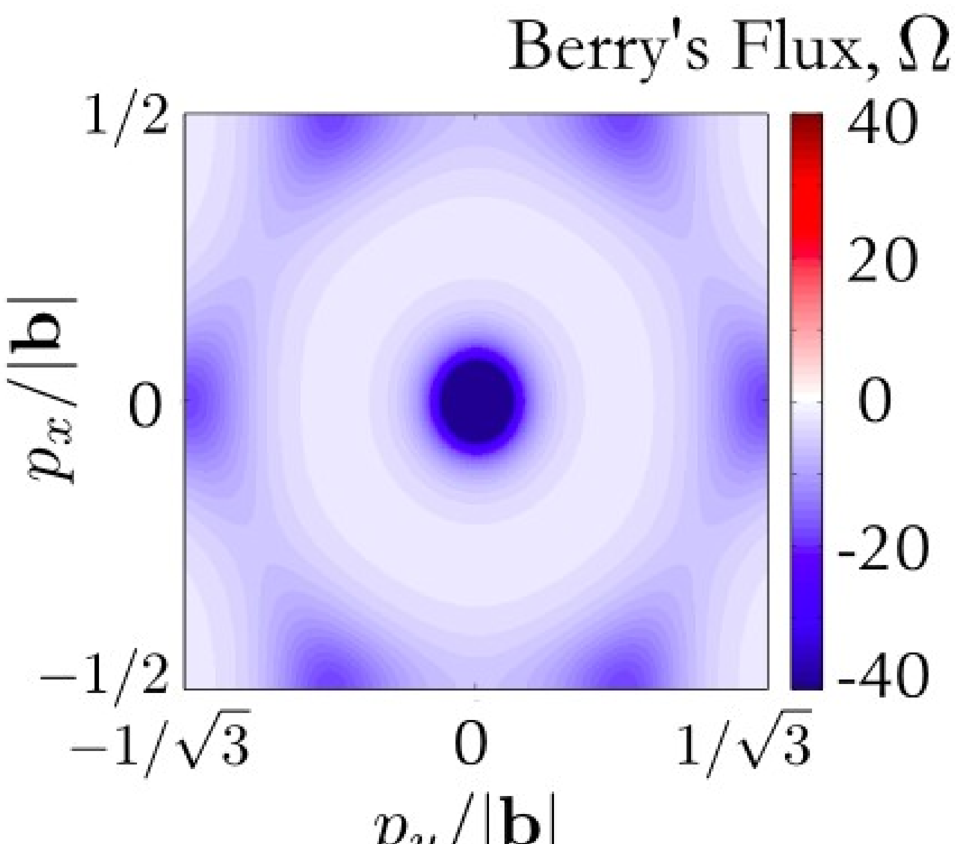
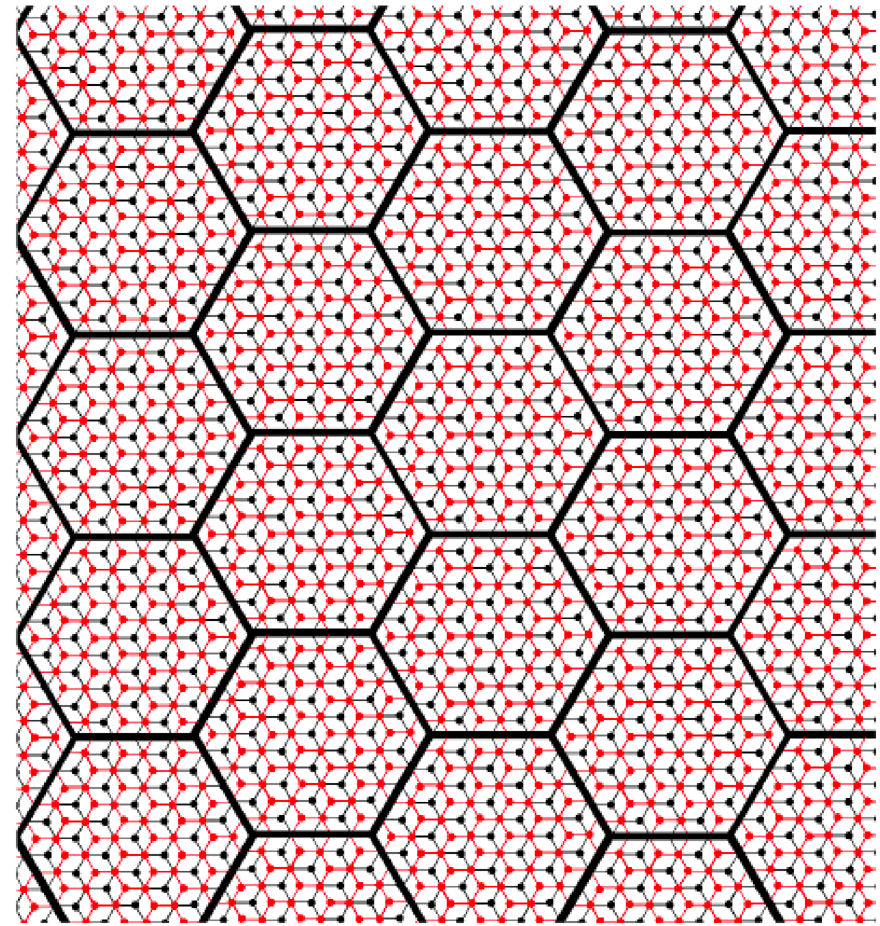
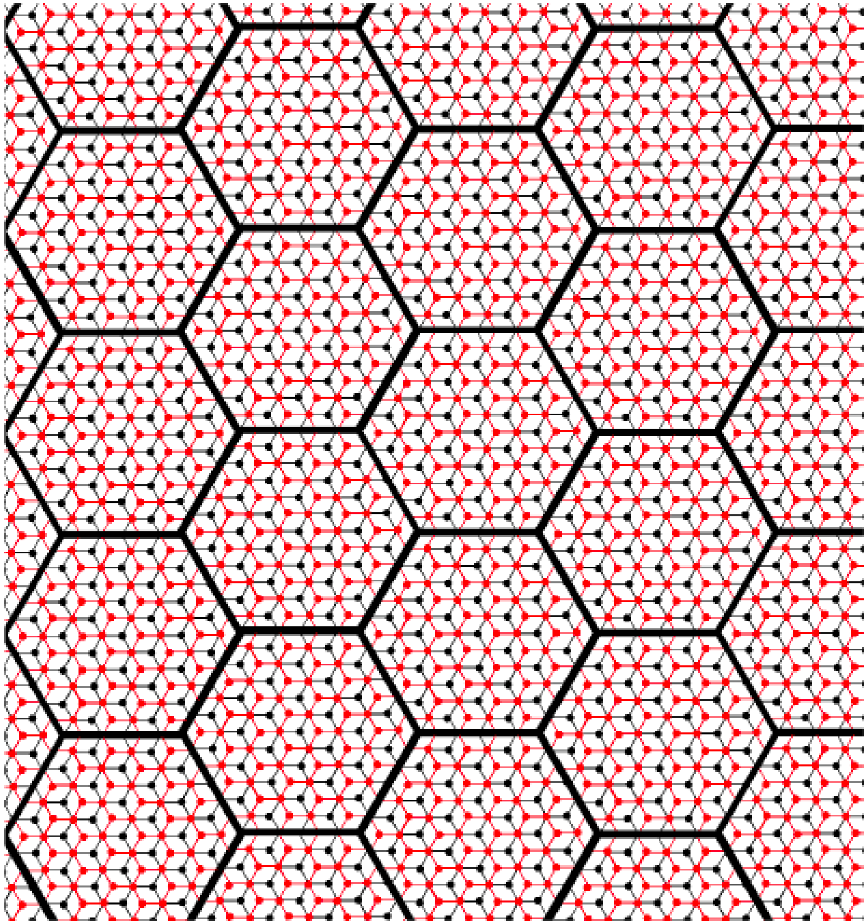


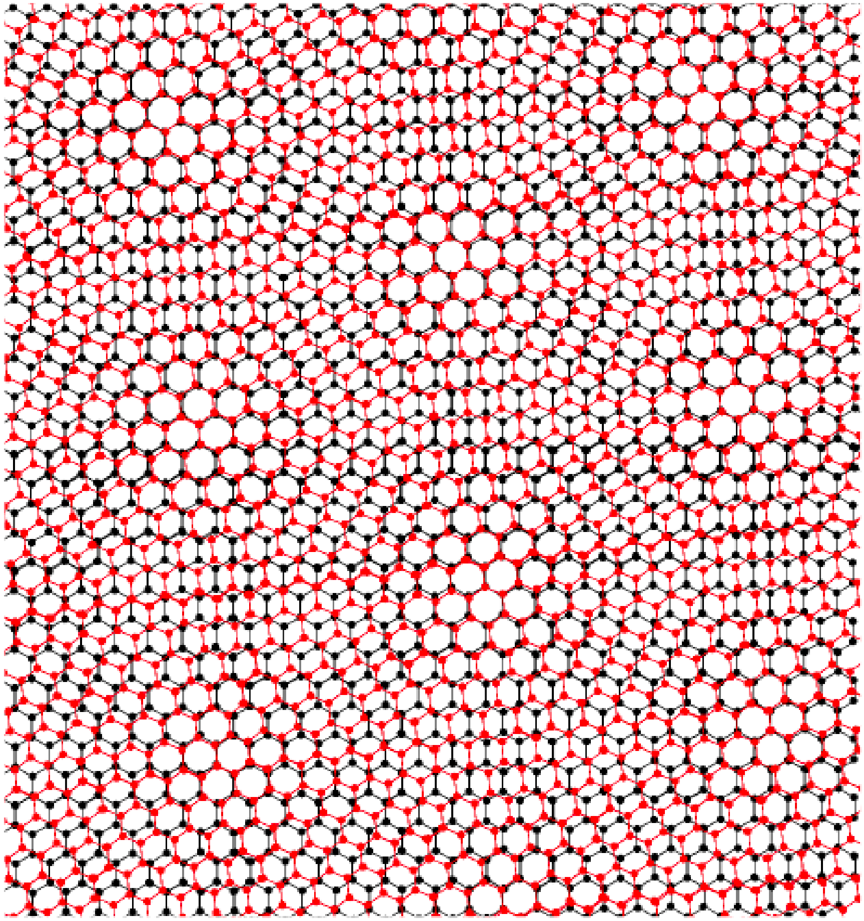


Band topology tunable by crystal axes alignment

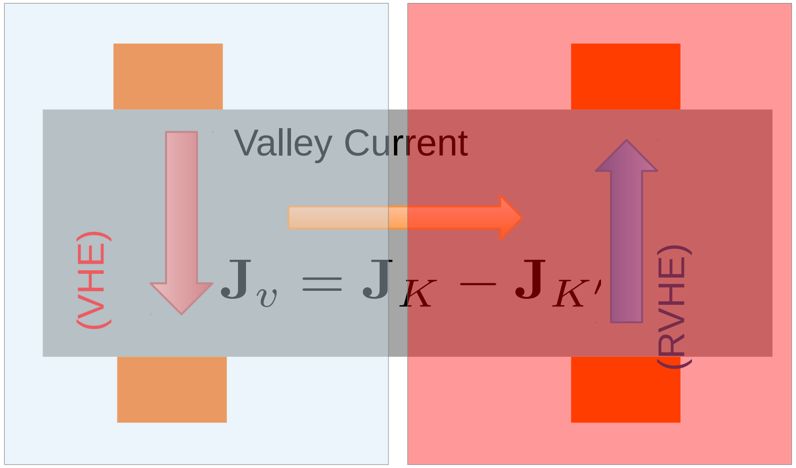
Topological bands C=1



Trivial bands C=0



Future



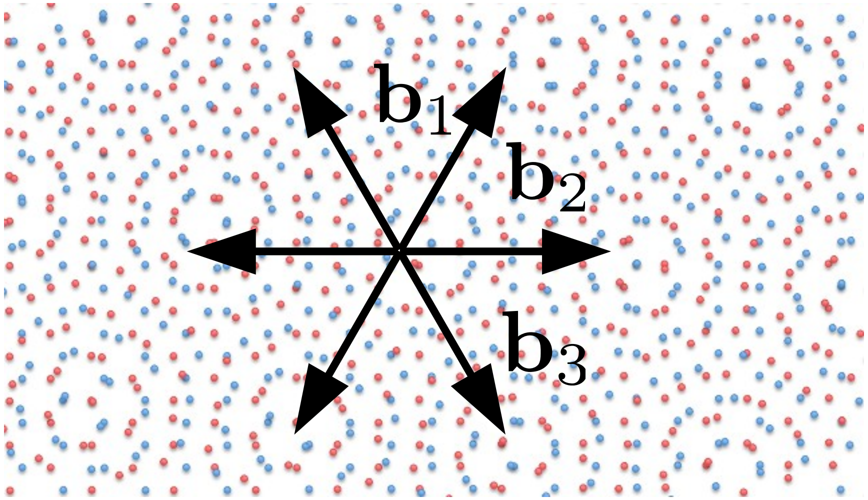
1) Measure Chern numbers (separately gated regions for VHE injection and detection)

2) Waveguides for valley currents

3) Valley population accumulation (optical probes)

Interactions in G/hBN superlattices

Incommensurability from lattice mismatch and twist angle impacts energy scales of superlattice structures



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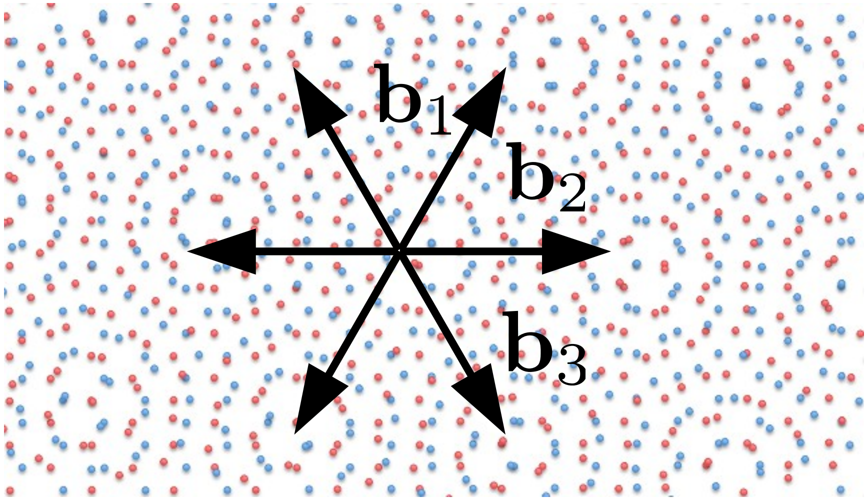

Oscillating gap

$$m_3 \sum_{j=1}^{6} e^{i\mathbf{b}_j\cdot\mathbf{x}}$$

$$\mathcal{H} = \int d^2x \sum_{i=1}^{N} \psi_i^\dagger(\vec{x}) \left[v\sigma\vec{p} + m_3(\vec{x})\sigma_3 + m_0(\vec{x})\right] \psi_i(\vec{x})$$

$$+\frac{1}{2}\int d^2x \int d^2x' \frac{e^2}{\kappa|\vec{x}-\vec{x}'|} n(\vec{x})n(\vec{x}')$$

Interactions

Non-interacting theory

(i) Oscillating $m_3(\mathbf{x})$ gives a first order gap that vanishes, since $\langle e^{i\mathbf{b}\cdot\mathbf{x}}\rangle = 0$

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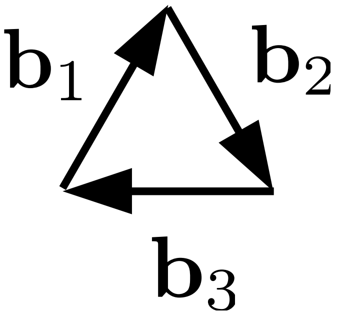
(ii) A large gap at edge of Superlattice Brillouin Zone, $\Delta_1 = 2m_3$

(iii) At 3rd order perturbation theory for

obtain small gap (100 mK)

at Dirac point: $\Delta_0 = \frac{12m_3^3}{(v|\mathbf{b}|)^2}$



Interacting theory

(i) Interactions enhance both velocity and mass terms (σ_3)

(ii) Scalar term $m_0\sigma_0$ not enhanced due to Ward Identity $\Gamma Z = 1$ follows from gauge invariance

Can obtain giant enhancements to 3rd order gap at Dirac point, Δ_0, as large as **three orders of magnitude**.

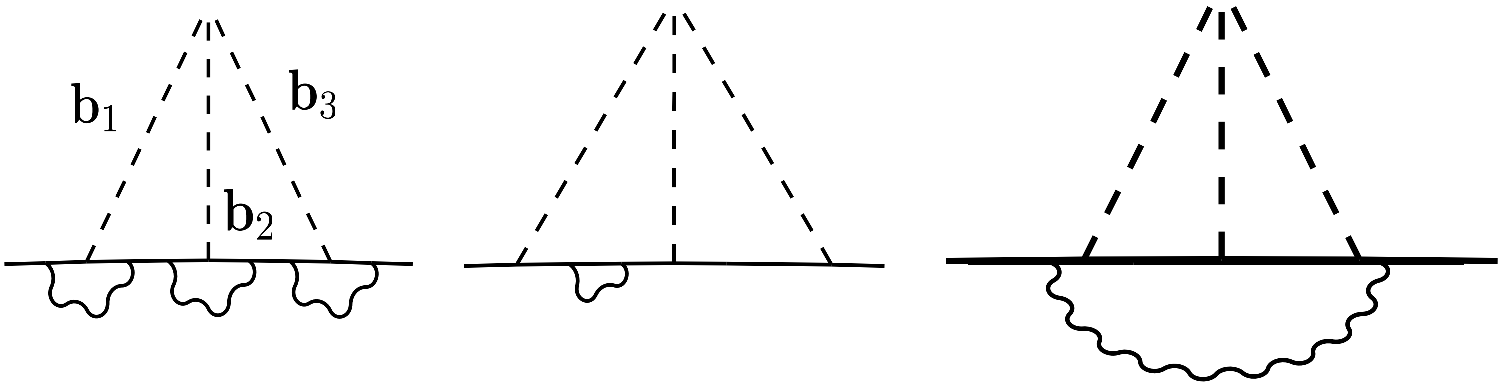
A two-stage RG flow

RG Equations:

$$\frac{dm_3}{d\xi} = \beta m_3$$

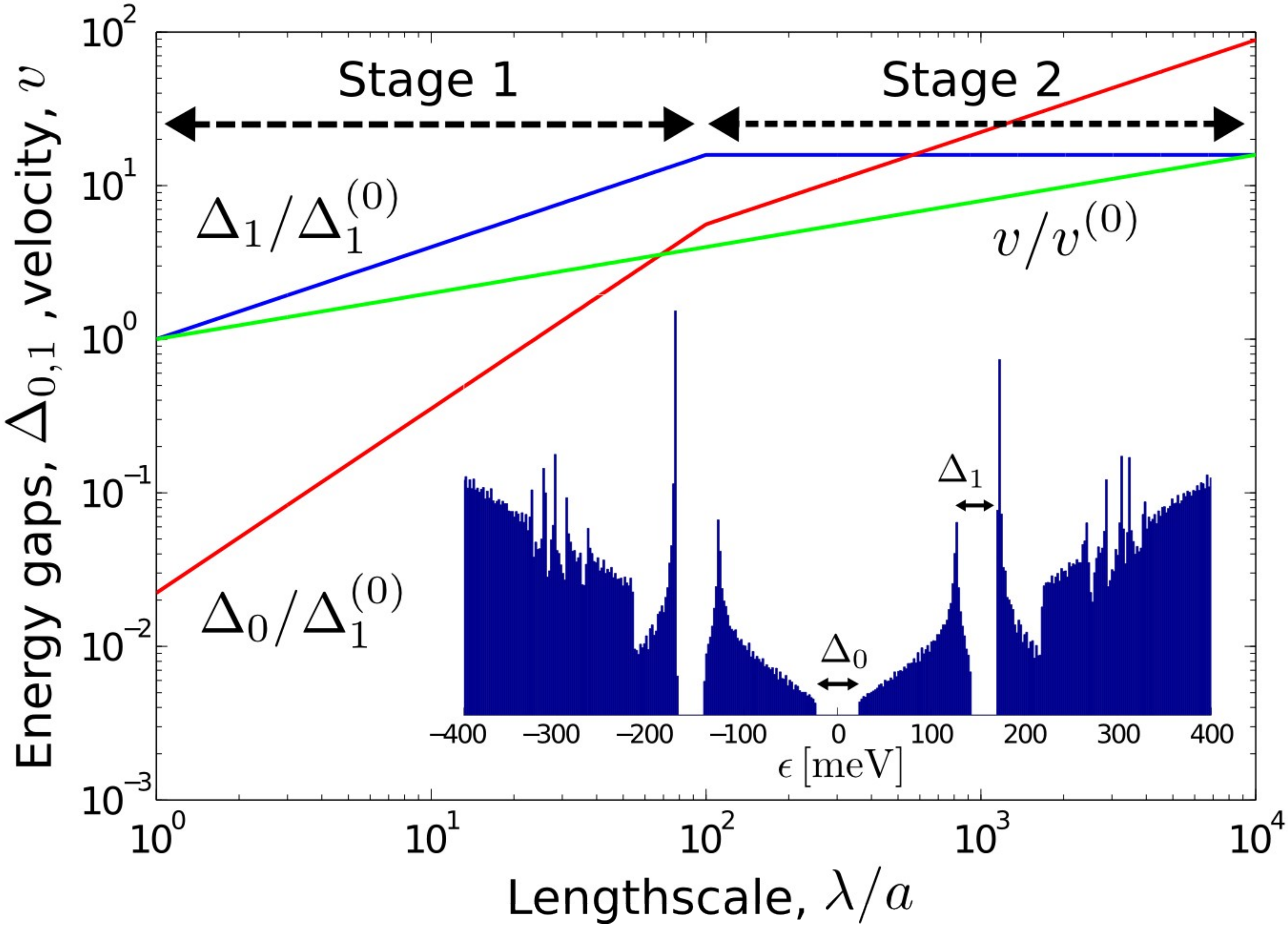
$$\frac{dv}{d\xi} = \beta_v v$$

Stage 1: $a < \lambda \leq \lambda_0$ Stage 2: $\lambda_0 < \lambda$



$$\Delta_0 = (\lambda/a)^{3\beta - 2\beta_v} \Delta_0^{(0)} \qquad \Delta_0 = (\lambda/\lambda_0)^{\beta} \Delta_0(\lambda_0)$$

RG Flow of interaction enhanced couplings to Moiré potential



Interaction enhanced gap features

(I) Sensitivity to λ_0 (controlled by twist angle) and screening (controlled by gates)

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(iv) For self-terminated RG, get gap that scales

$$\Delta_0(\lambda_*) \propto \left(\frac{\lambda_0}{a}\right)^{\gamma} \quad \gamma = 0.27$$ (one loop large-N)

Spintronics in graphene?

Spin manipulation in graphene

Slow spin relaxation due to weak SO in graphene

nature

LETTERS

Electronic spin transport and spin precession in single graphene layers at room temperature

Nikolaos Tombros[1], Csaba Jozsa[1], Mihaita Popinciuc[2], Harry T. Jonkman[2] & Bart J. van Wees[1]

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Young-Woo Son[1,2], Marvin L. Cohen[1,2] & Steven G. Louie[1,2]

LETTERS

Valley filter and valley valve in graphene

A. RYCERZ[1,2], J. TWORZYDŁO[3] AND C. W. J. BEENAKKER[1]*

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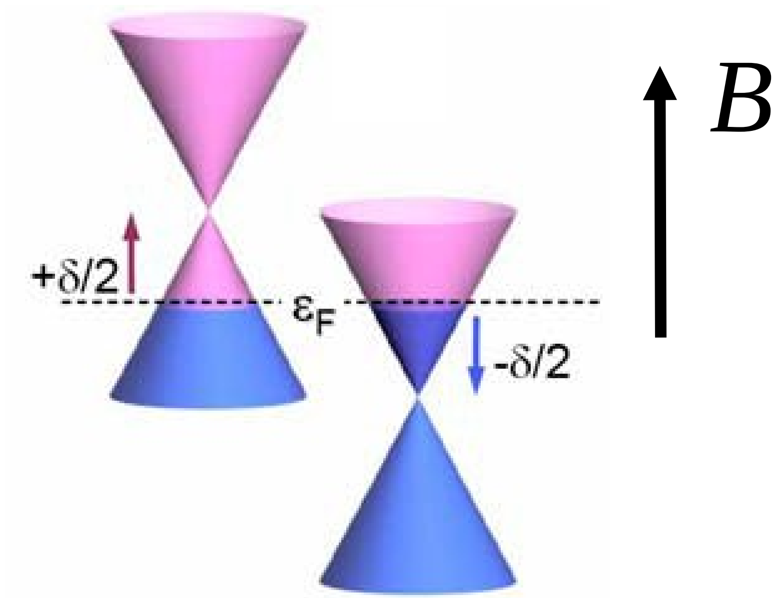
NEW WAYS TO GENERATE & DETECT SPIN/VALLEY CURRENTS?

BUT: impossible to make (edge disorder)

Spin-Hall effect without spin-orbit

-Large value, persists at room *T* and low *B*

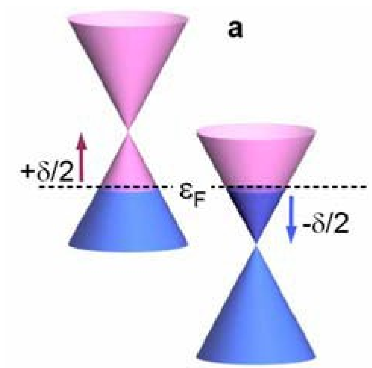
-Stems from Dirac spectrum $\theta_{SH} \approx 0.1$

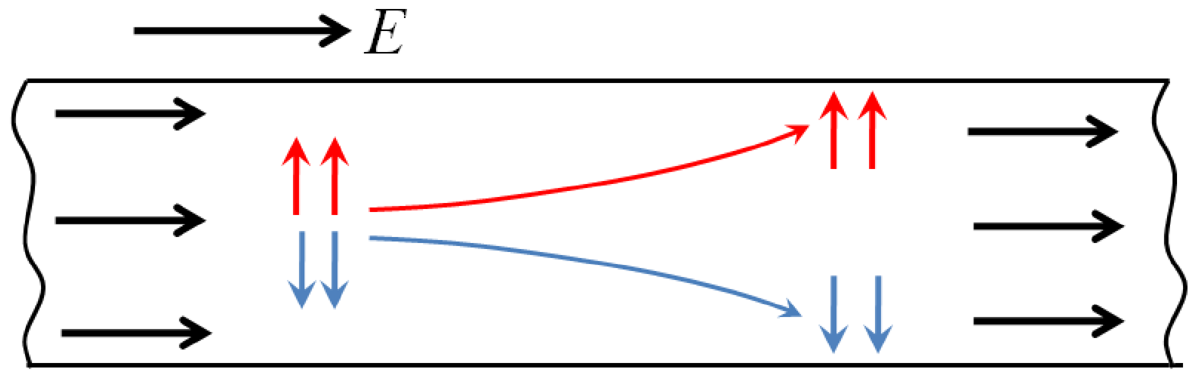


Zeeman-split bands $\varepsilon_{\uparrow(\downarrow)}(k) = vk \pm \delta / 2$

Finite density of electrons and holes

SHE mechanism

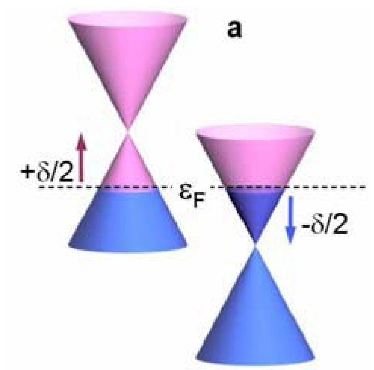


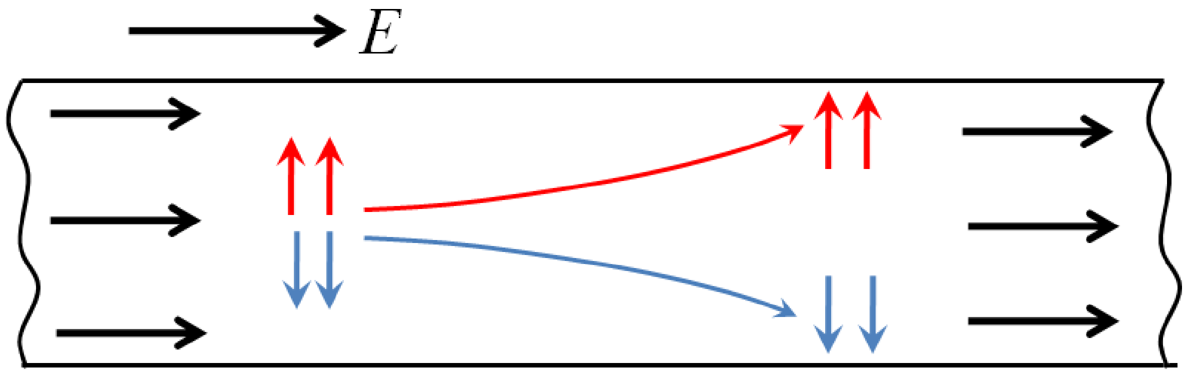


Opposite Lorentz force on the up-spin and down-spin

Spin current in a transverse direction

SHE mechanism



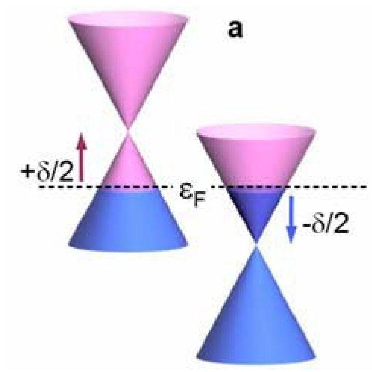


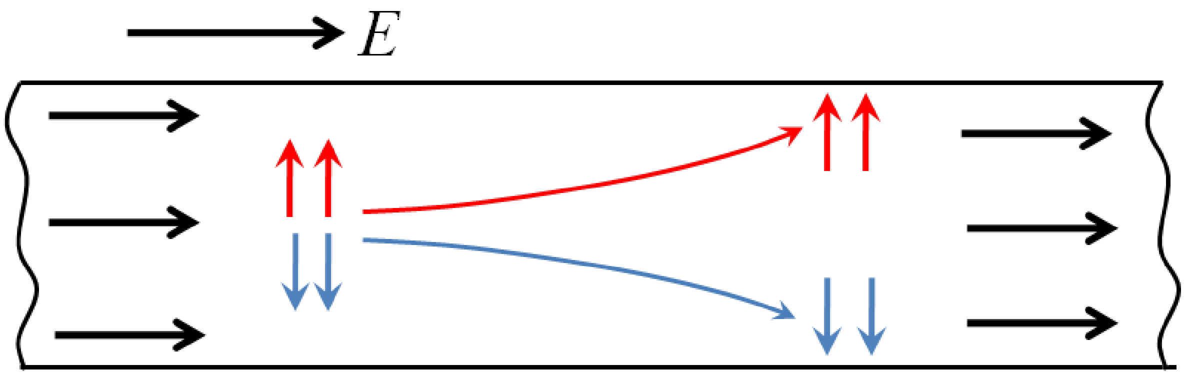
Opposite Lorentz force on the up-spin and down-spin
Spin current in a transverse direction

SHE coefficient $$\theta_{SH} = \frac{\rho_{SH}}{\rho_{xx}} \propto \rho_{xy}^{\uparrow} - \rho_{xy}^{\downarrow} \approx \frac{d\rho_{xy}}{d\mu}\Delta$$

Δ the Zeeman splitting

SHE mechanism





Opposite Lorentz force on the up-spin and down-spin
Spin current in a transverse direction

SHE coefficient $\theta_{SH} = \frac{\rho_{SH}}{\rho_{xx}} \propto \rho_{xy}^{\uparrow} - \rho_{xy}^{\downarrow} \approx \frac{d\rho_{xy}}{d\mu}\Delta$

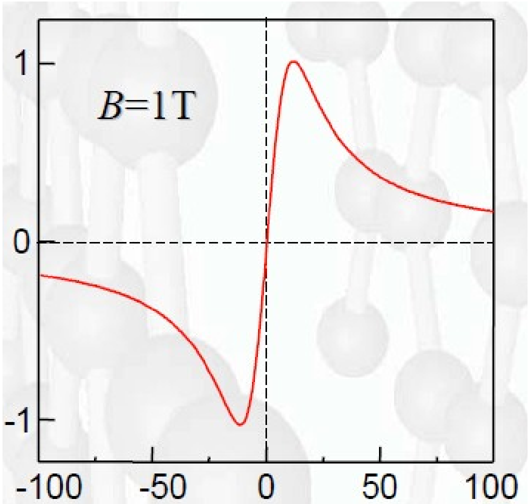
Δ the Zeeman splitting

Need to understand Hall resistivity

Steep ρxy, giant SHE

Abanin et al. PRL 2011

$\rho_{xy}(k\Omega)$



carrier density

Quasiclassical result:

$$\rho_{xy} = -\frac{B}{ne}$$

Diverges at the Dirac point

Singularity smeared by disorder and interactions

Steepening→ large $\frac{d\rho_{xy}}{d\mu}$ → giant SHE at the Dirac point

Predict SHE coefficient

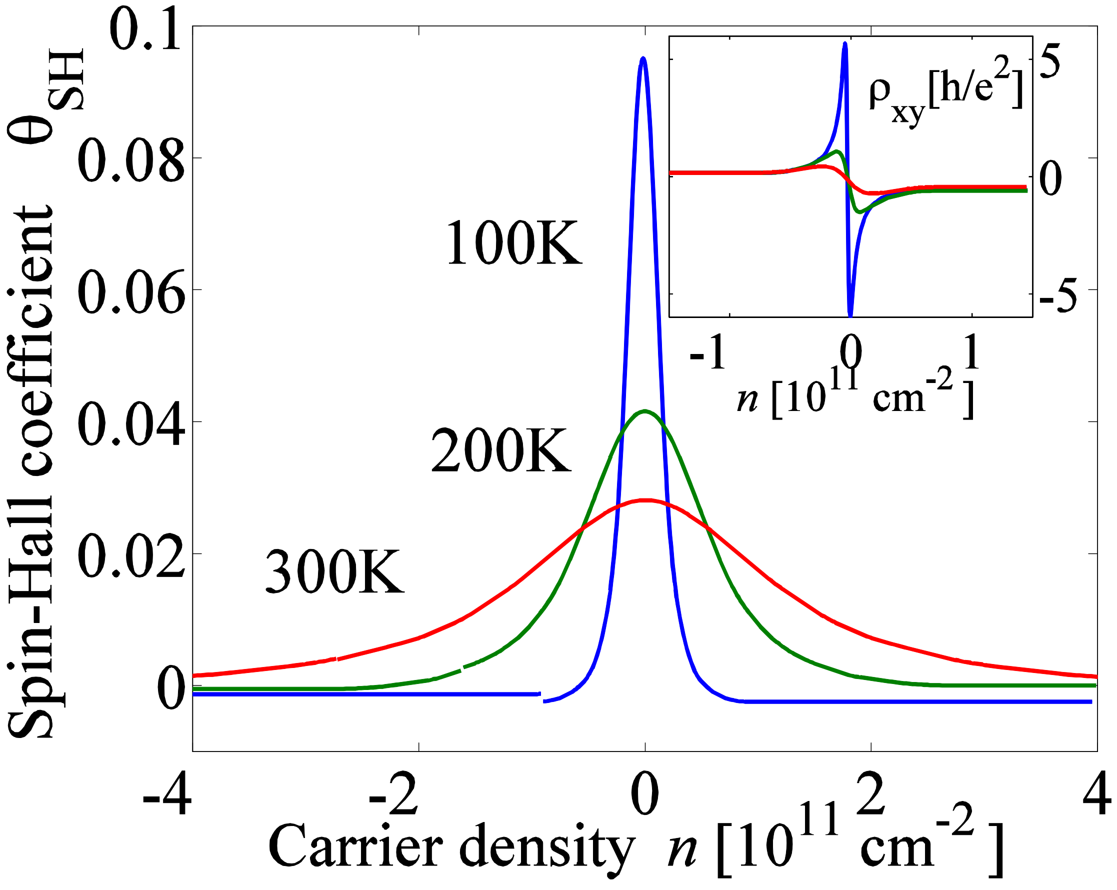
-Grows with *B* and inverse *T*

-Saturates at DP width γ

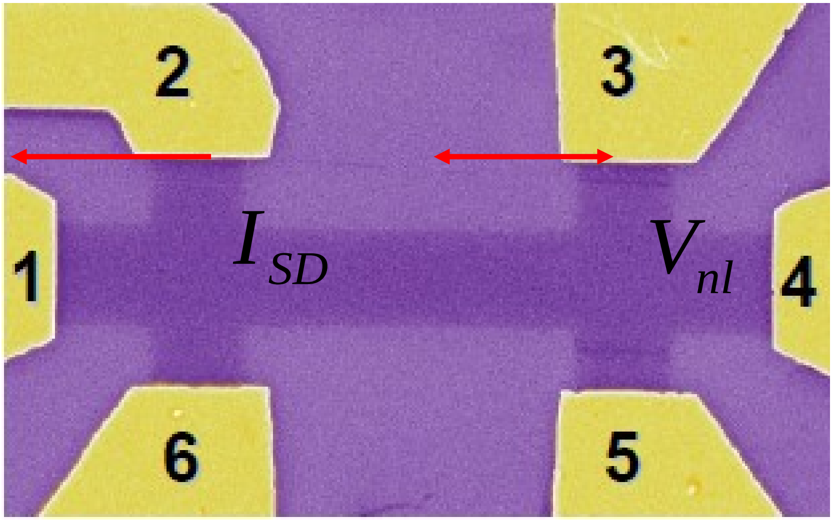
$$T \sim \gamma \qquad \theta_{SH} \propto 1/\gamma^3$$

-Large enhancement in clean samples

$$\theta_{SH} = \begin{cases} C\dfrac{\hbar e B v_0^2}{T\gamma^2}\Delta, T >> \gamma \\ \dfrac{\hbar e B v_0^2}{\gamma^3}\Delta, T \le \gamma \end{cases}$$

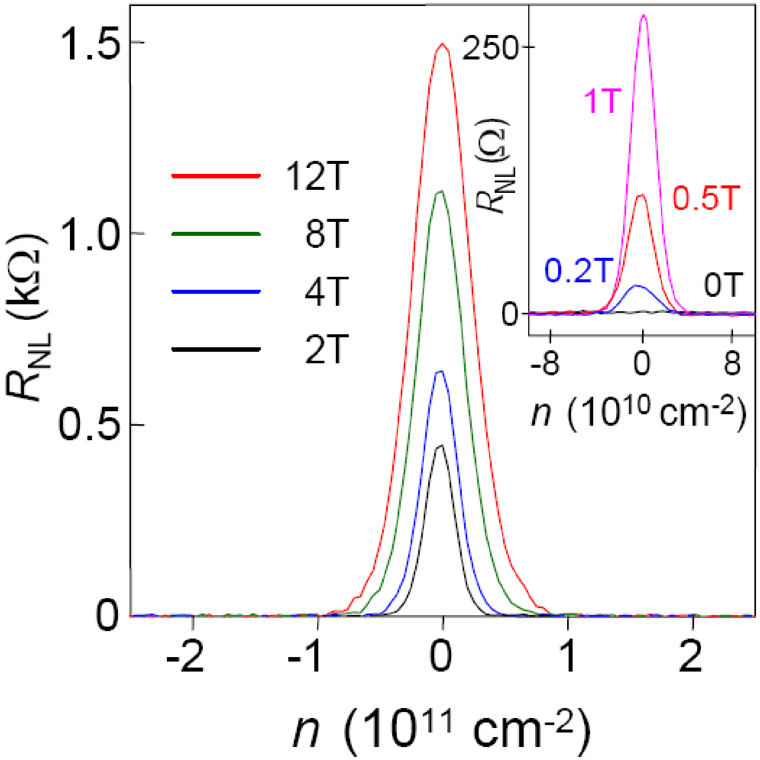


Nonlocal measurement



$$R_{nl} = \frac{V_{35}}{I_{26}}$$

$300K$



Good agreement w theory:

Abanin et al, Science 2012

-Peak at the Dirac point

-Growth as a function of 1/T, B

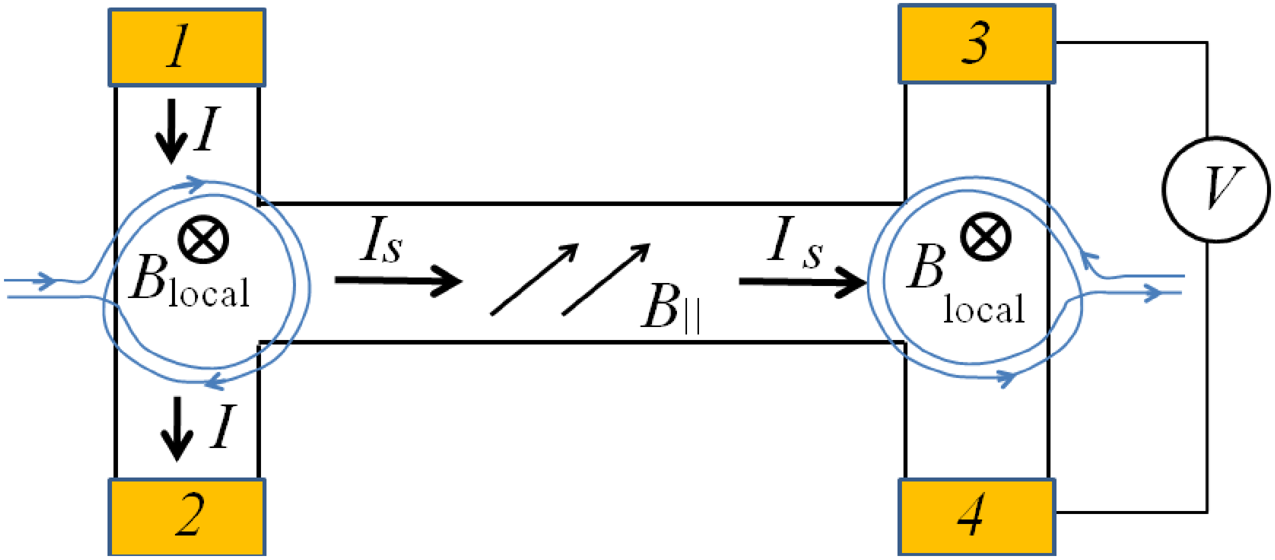
-Magnitude

Future

-Predict large spin accumulation:

$n_s = 1.5 \times 10^{11} cm^{-2}$ 100000 times larger than GaAs

-Generate/detect spin currents using local magnetic fields



-Spin injection into graphene and other materials

Abanin *et al.* PRL (2011), Science (2012)