CHERN BANDS AND TOPOLOGICAL CURRENTS IN GRAPHENE SUPERLATTICES

Leonid Levitov (MIT)

- **Topological currents and valley transport**
- **Long-range nonlocal response**
- **Valley transistor**

University of Evora, 6-10 October 2014

Carrier dynamics: anomalous Hall effect & topological valley currents

Electrons in crystals have charge, energy, momentum and Berry's curvature (built-in vorticity)

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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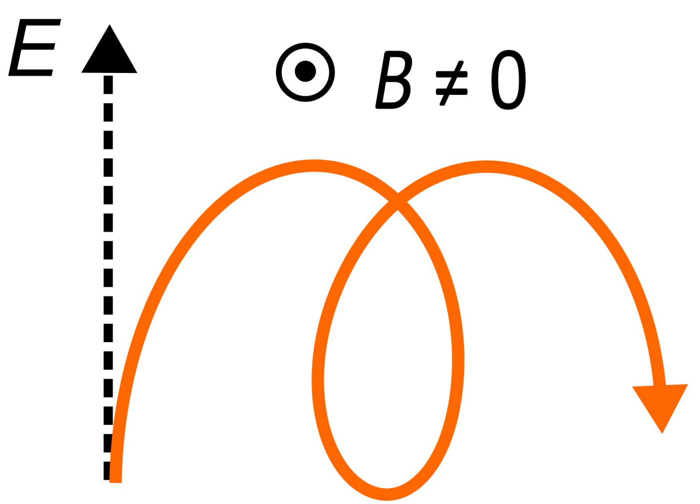
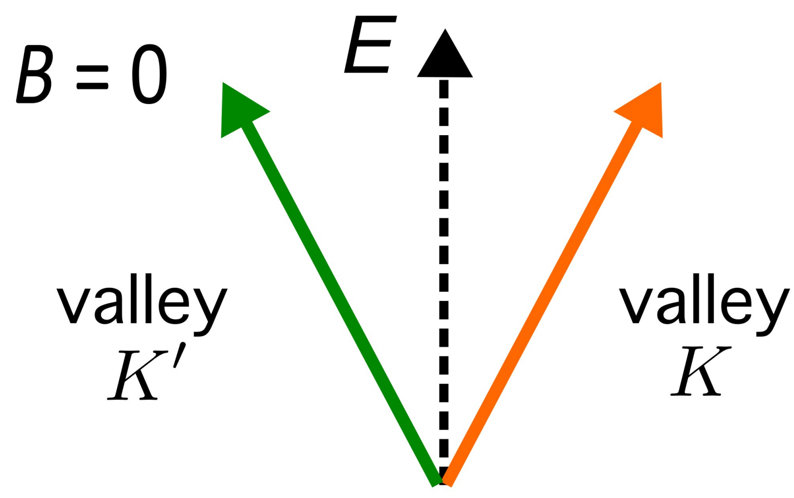
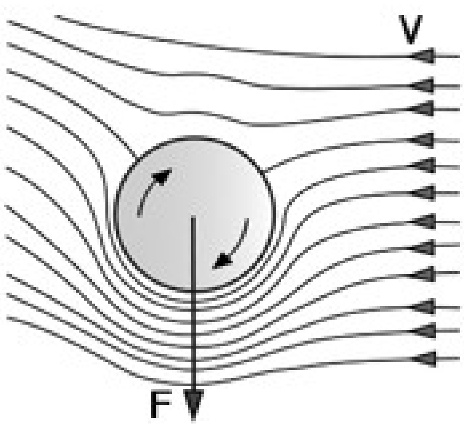
Hall currents at *B*=0

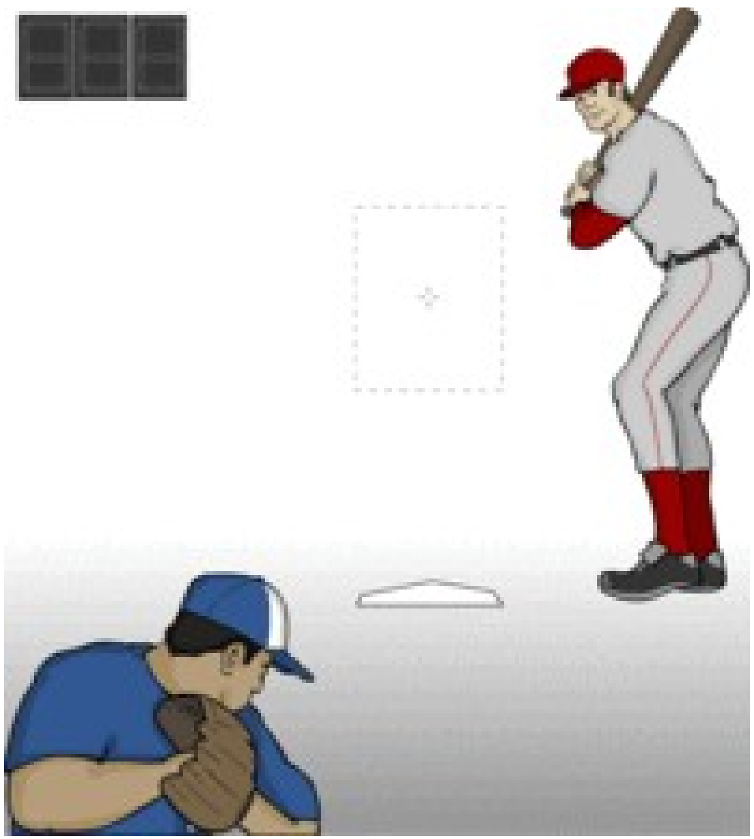




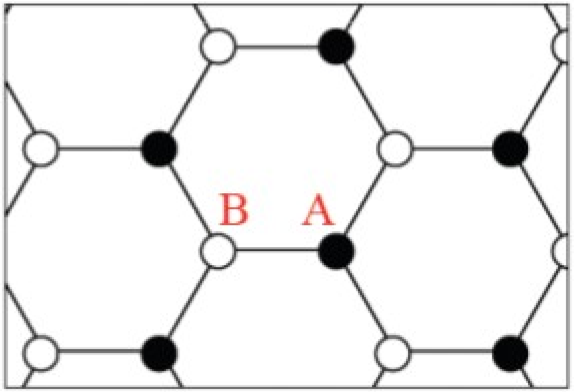
Gorbachev, Song, et. al. , Science (2014)

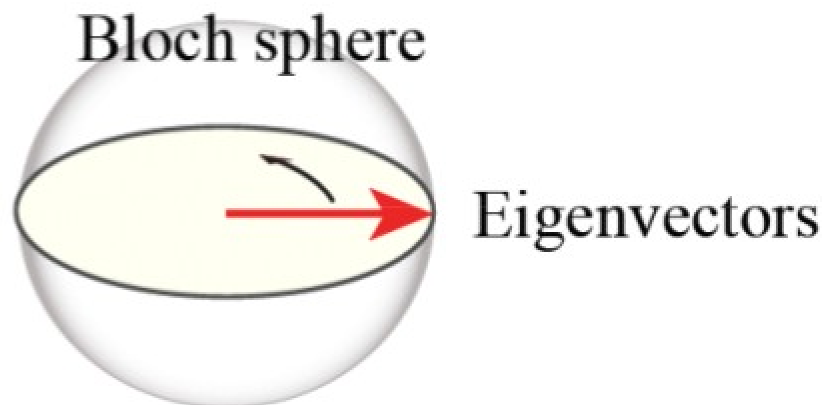
Analogy w/ Magnus effect and curveballs





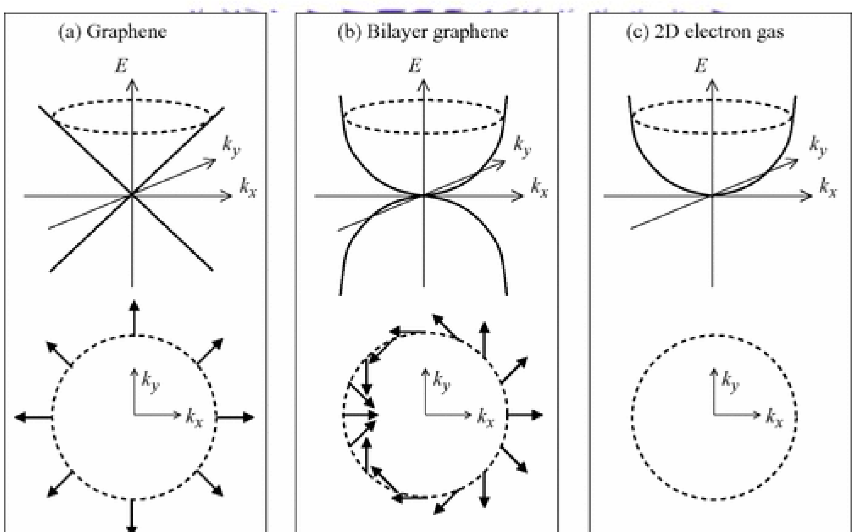
Berry phase in hexagonal lattice





$$H(\mathbf{k}) = -J\begin{pmatrix} 0 & A(\mathbf{k}) \\ A^*(\mathbf{k}) & 0 \end{pmatrix}$$

$$A(\mathbf{k}) = e^{i\mathbf{k}\cdot\mathbf{a}_1} + e^{i\mathbf{k}\cdot\mathbf{a}_2} + e^{-i\mathbf{k}\cdot(\mathbf{a}_1+\mathbf{a}_2)}$$



- Eigenvectors lie in the XY plane
- Around each Dirac point eigenvector makes 2π rotation
- Integral of the Berry phase is π

$$\int_C \langle \psi_k \,|\, \partial_{\vec{k}} \,|\, \psi_k \rangle \, d\vec{k} = \pi$$

Image credit: Park, Marzari (2011)

Massive (gapped) Dirac particles

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

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

Valley Chern invariant
(for closed bands)

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

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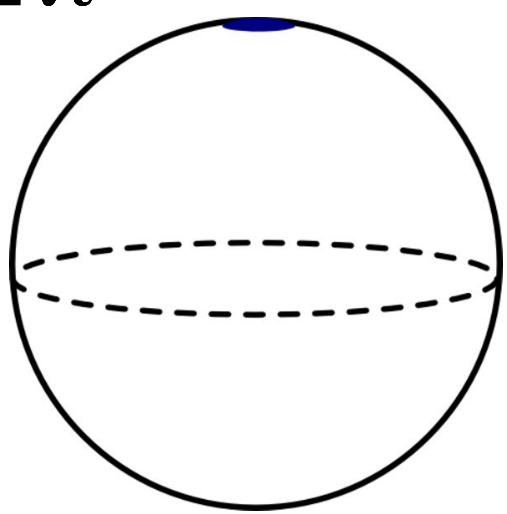
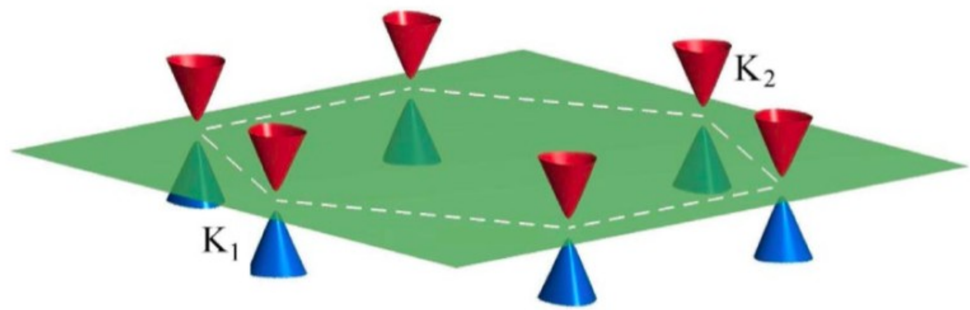
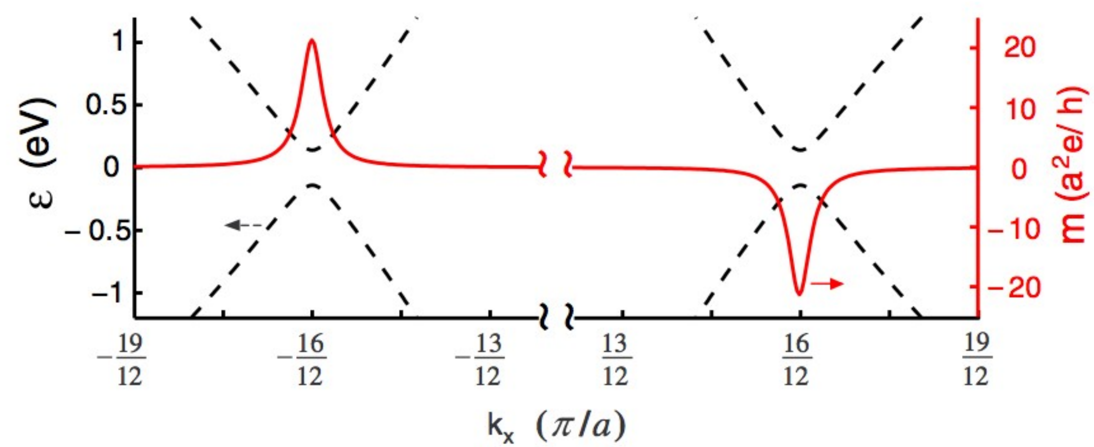


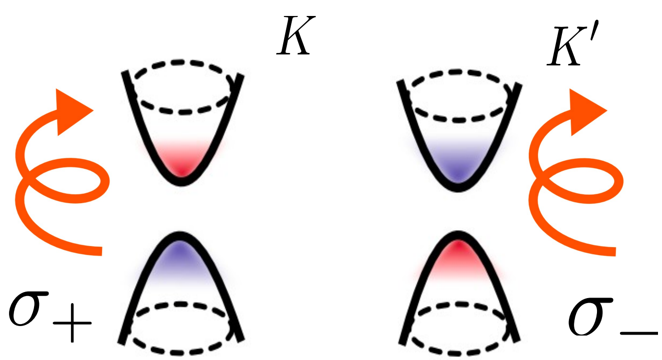




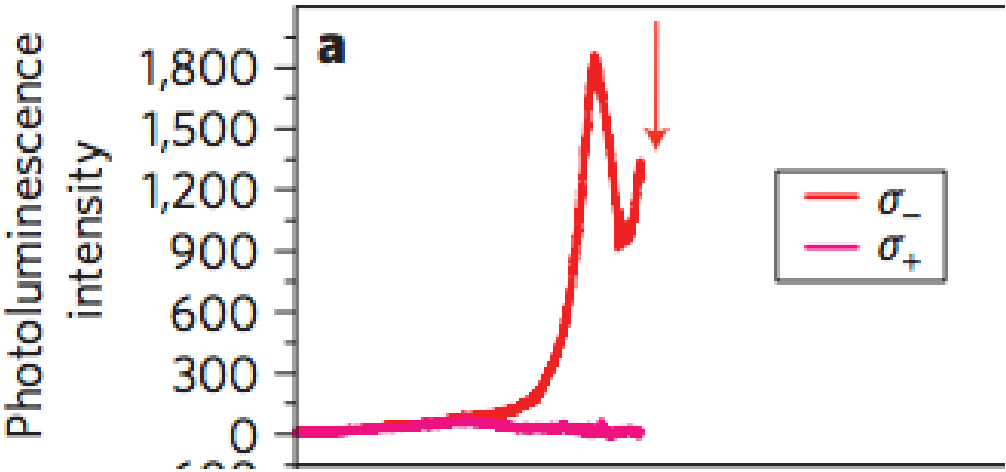
D. Xiao, W. Yao, and Q. Niu, PRL 99, 236809 (2007)

Optical control of valleys

Optical selection rules: individual valley control

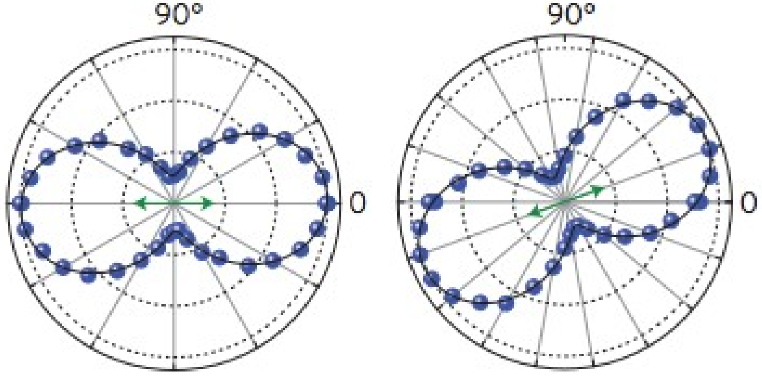


PL (MoS_2) after shining σ-



Long-lived Intervalley coherences (WSe_2)

PL polarization tracks excitation polarizatior



Jones et. al. , Nat. Nano (2013)

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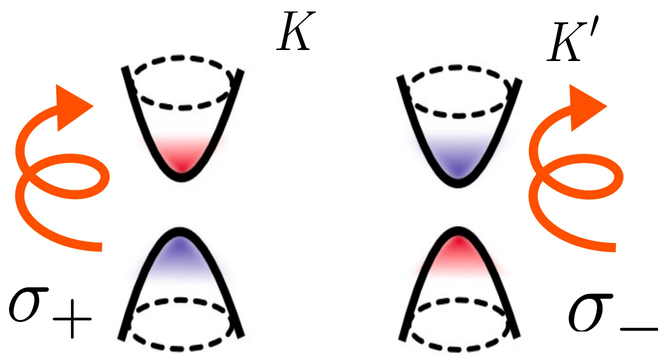

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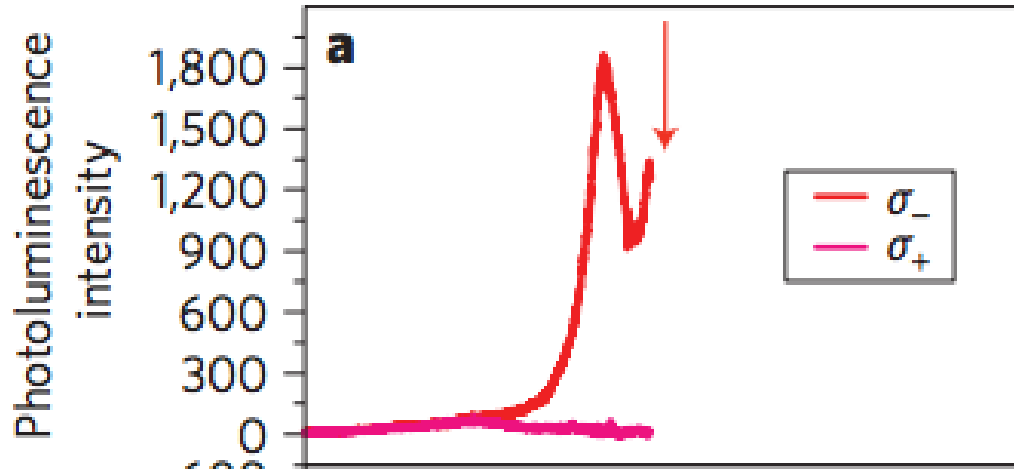


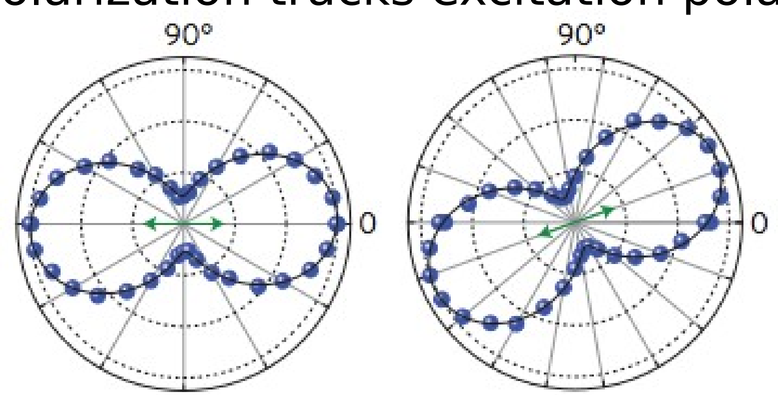
Current research:

*** New magnetooptical effects (photoinduced magnetization and Kerr effect at B=0)**

*** Valley population accumulation (optical probes)**

Long-lived Intervalley coherences (WSe_2)

PL polarization tracks excitation polarization



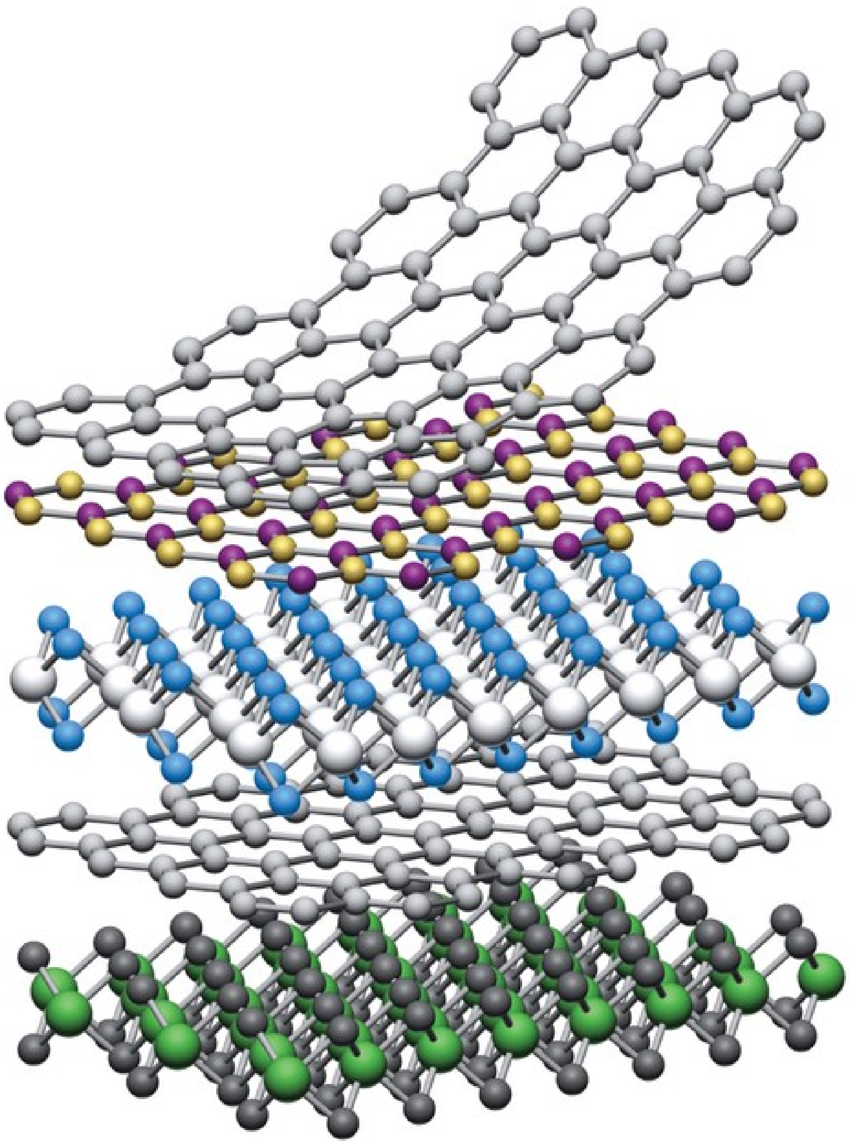
Jones et. al. , Nat. Nano (2013)

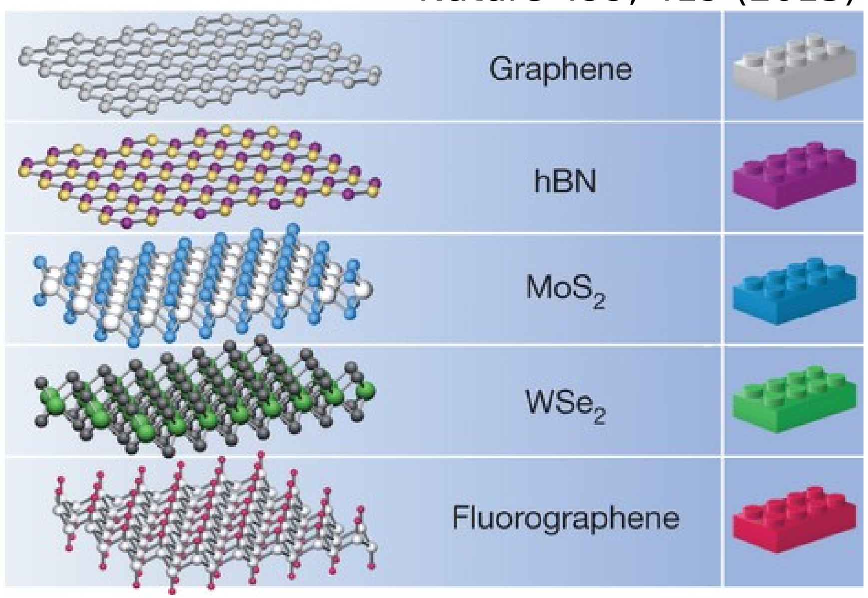
Create topological bands in graphene?
(and play curveball)

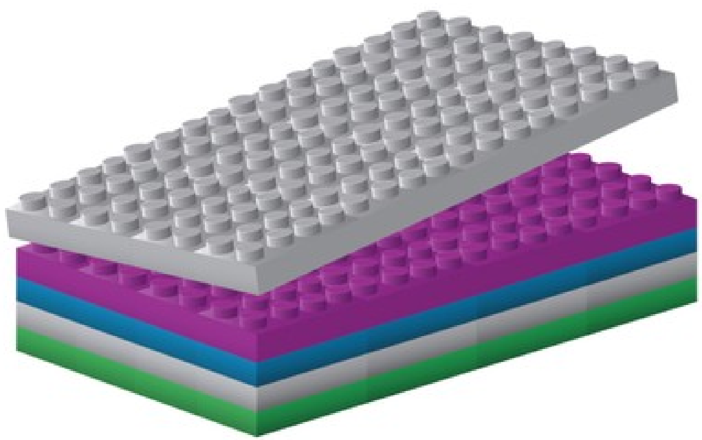
Valley transport in vertical heterostructures

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

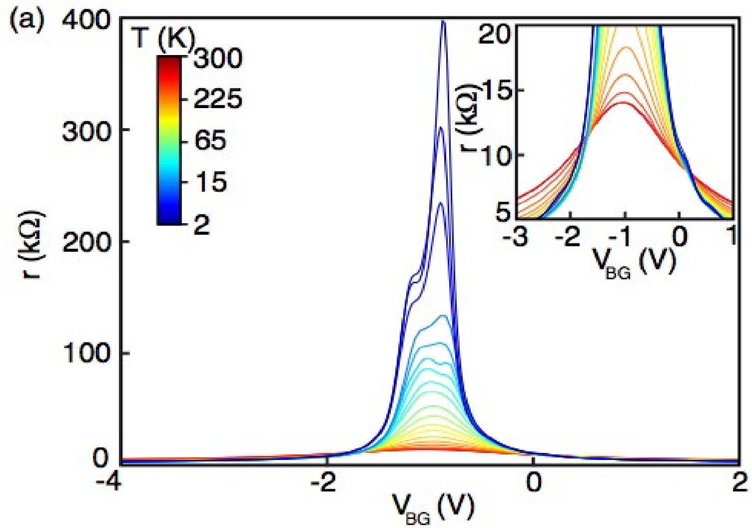
Image from: Geim & Grigorieva, Nature 499, 419 (2013)



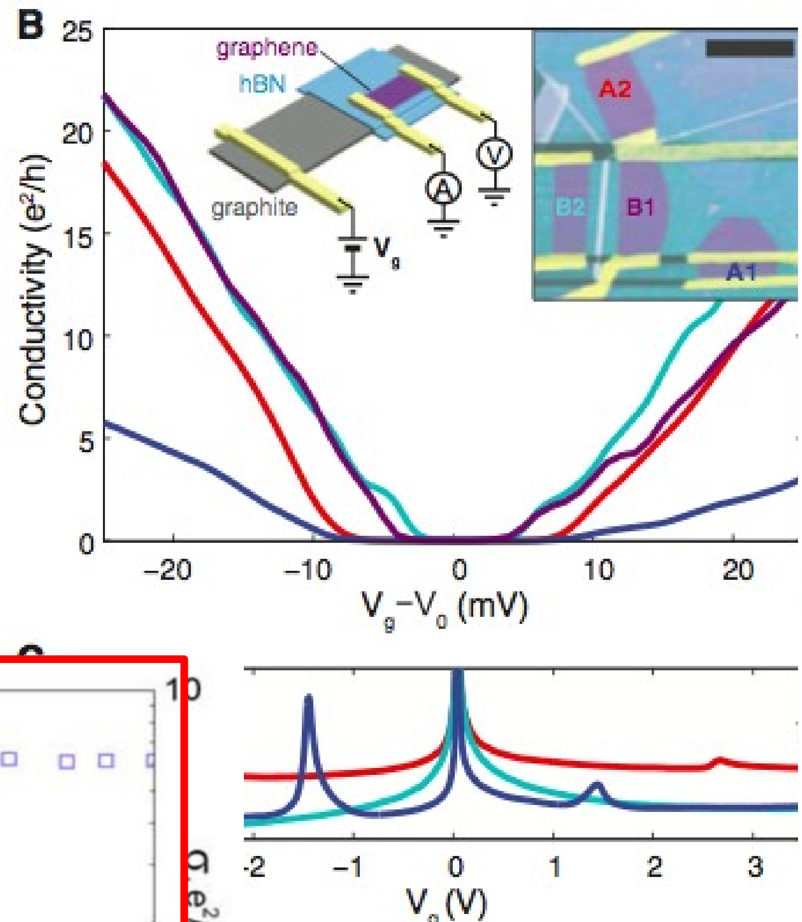


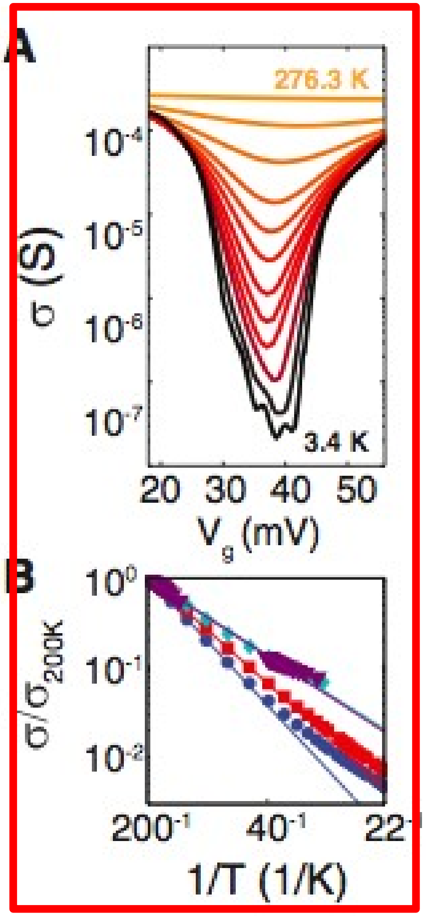


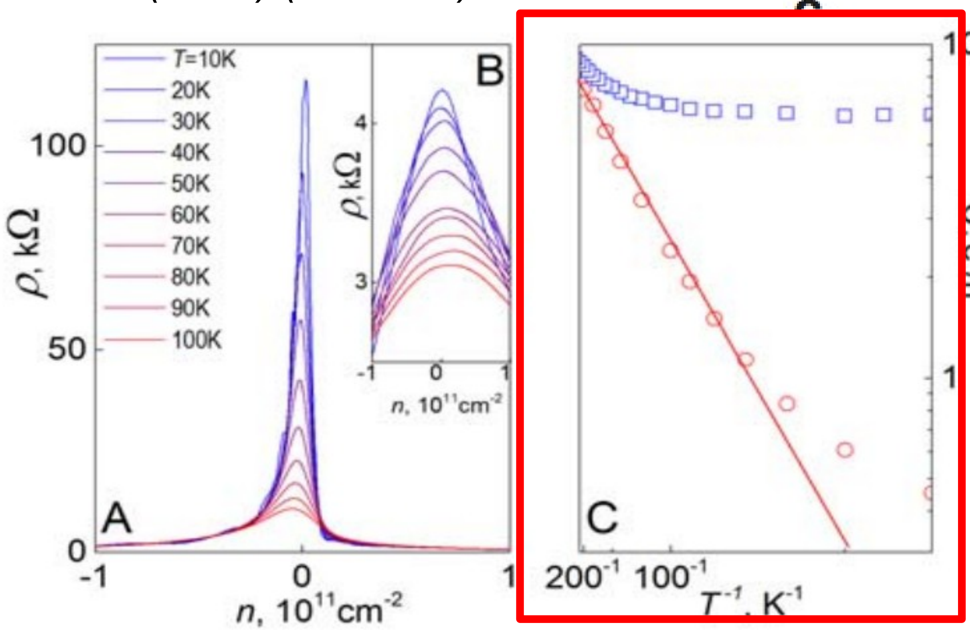
Gap opening in graphene on hBN



F. Amet, et. al., Phys. Rev. Lett., 110, 216601 (2013) (Stanford)







B. Hunt, et. al., Science, 340, 1430 (2013) (MIT Group)

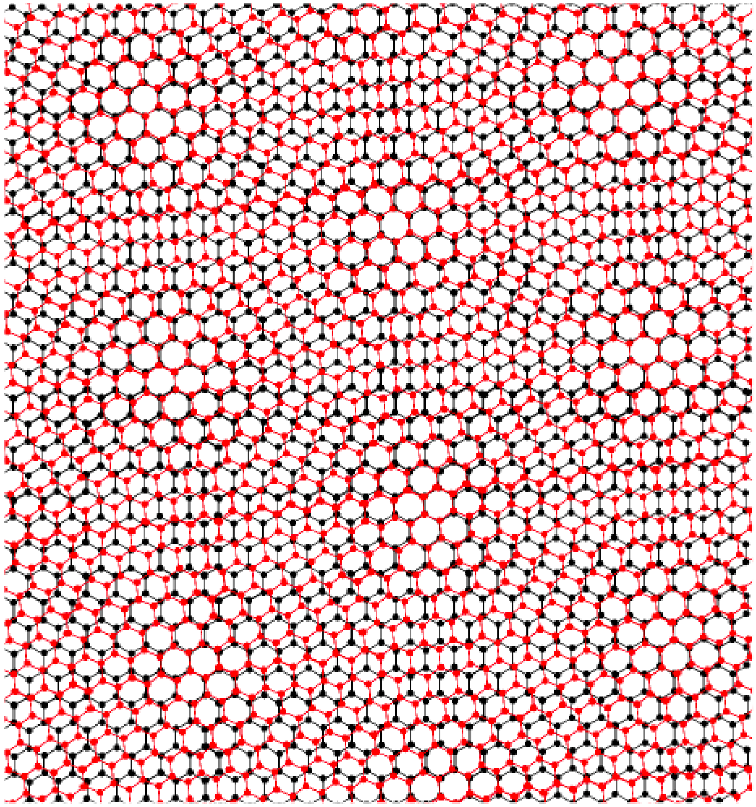
Activated behavior gap Δ~200-400 K

CR Woods, et.al. arXiv: (2013) (Manchester Group)

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)
Ponomarenko et al Nature 497, 594 (2013)

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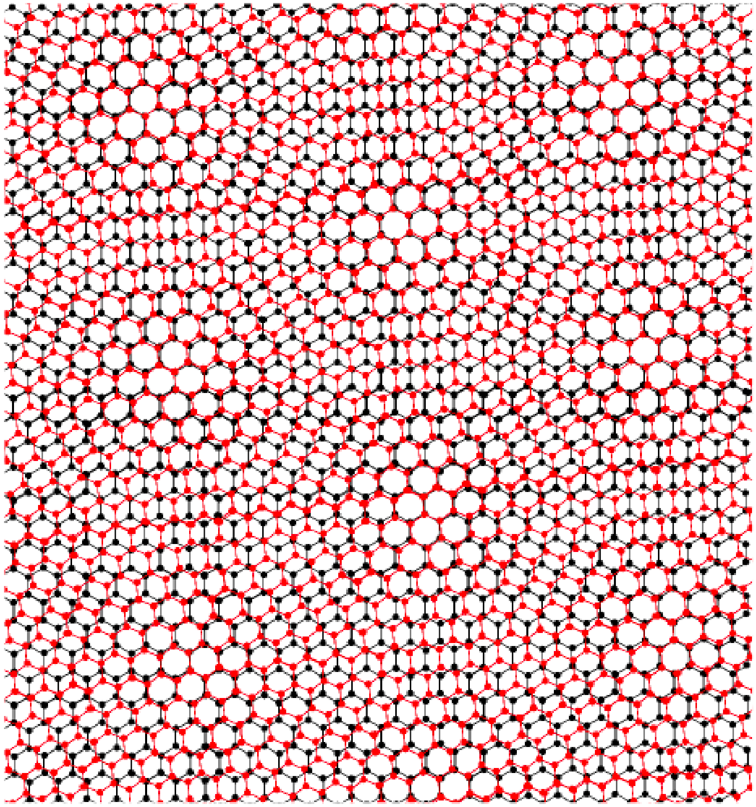
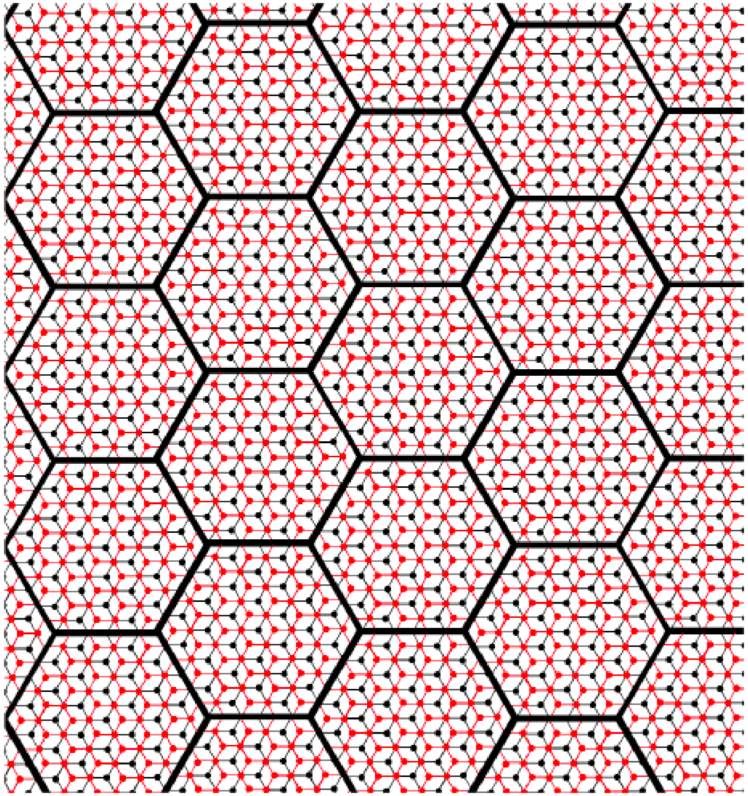


Dean et.al. Nature 497, 213 (2013)
Ponomarenko et al Nature 497, 594 (2013)

Commensurate stacking
global A/B asymmetry
global gap



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

Low-energy Hamiltonian

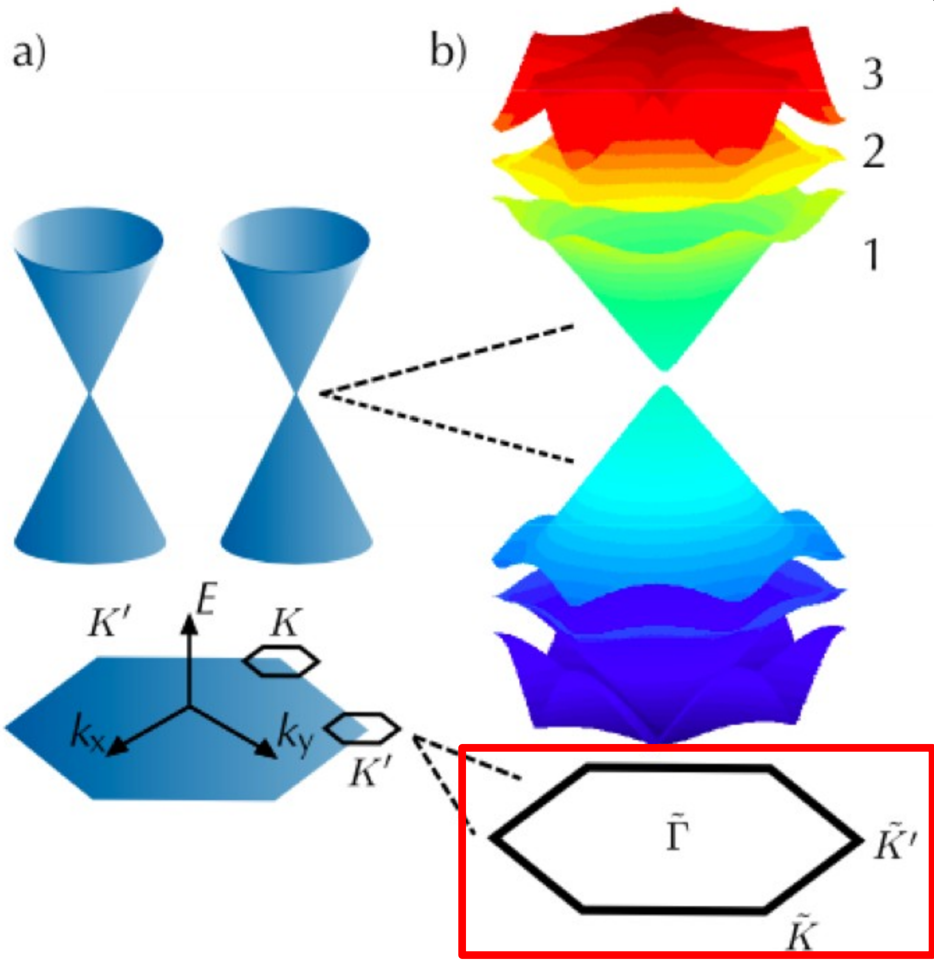
San-Jose et al. arXiv:1404.7777, Jung et al arXiv:1403.0496, Song, Shytov LL PRL (2013), Kindermann PRB (2012) Sachs, et. al. PRB (2011)

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

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

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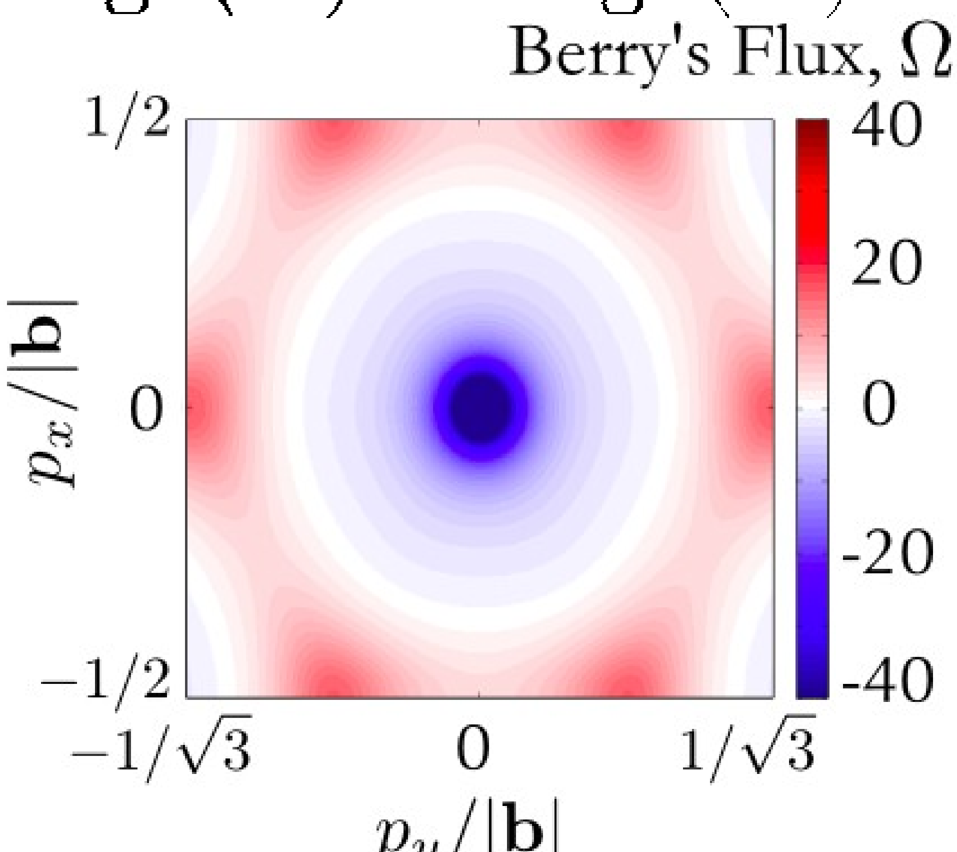
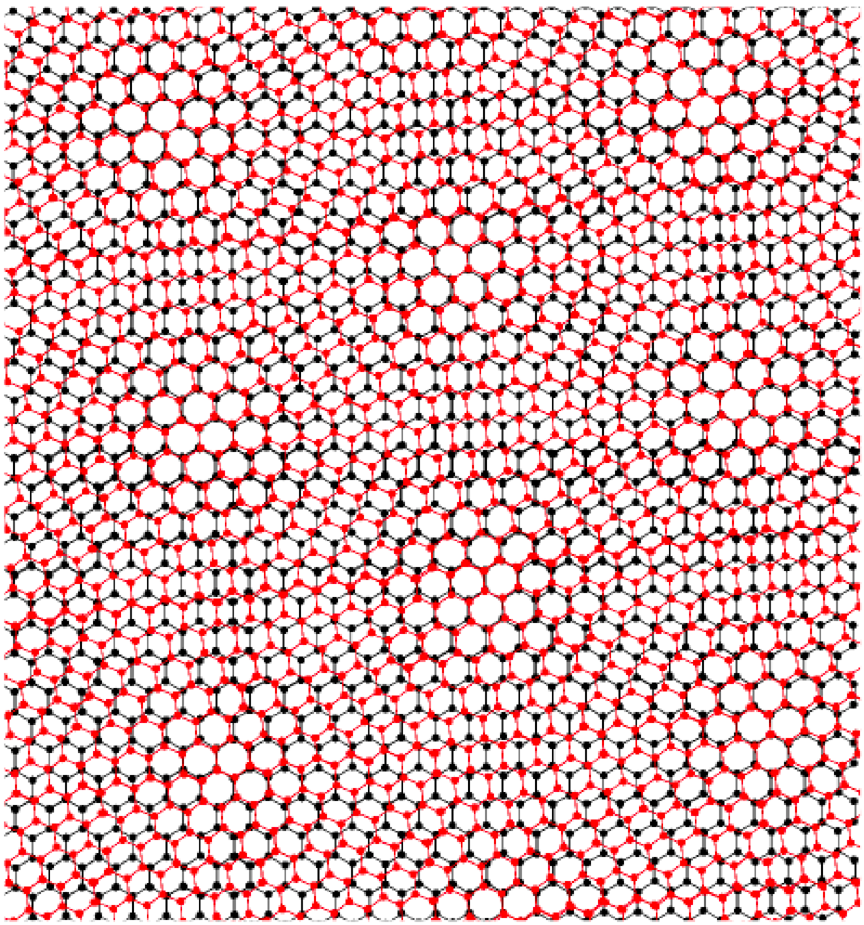
$$\mathrm{sgn}(\Delta) = -\mathrm{sgn}(m)$$





Commensurate case

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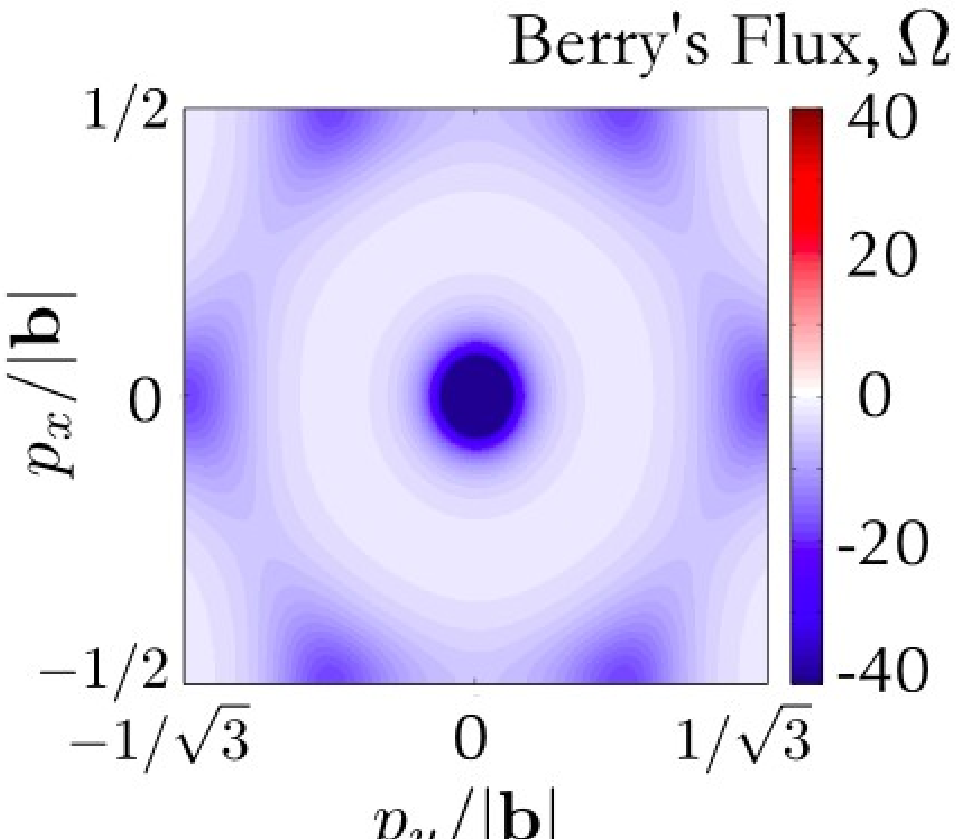
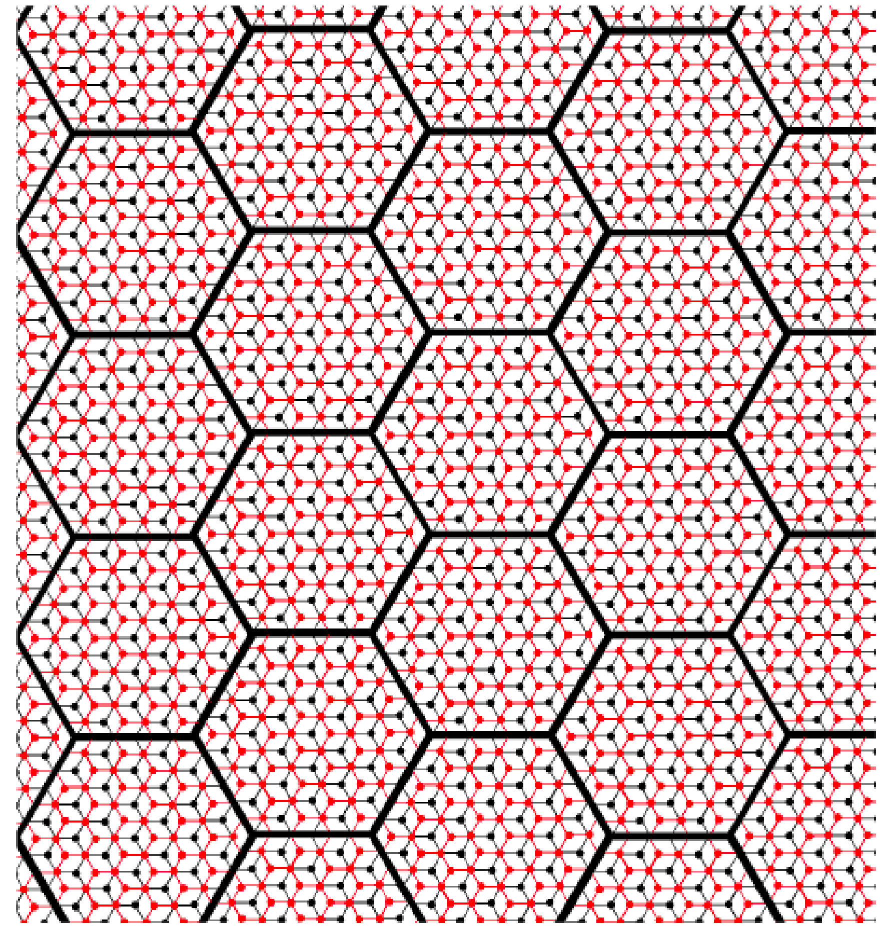
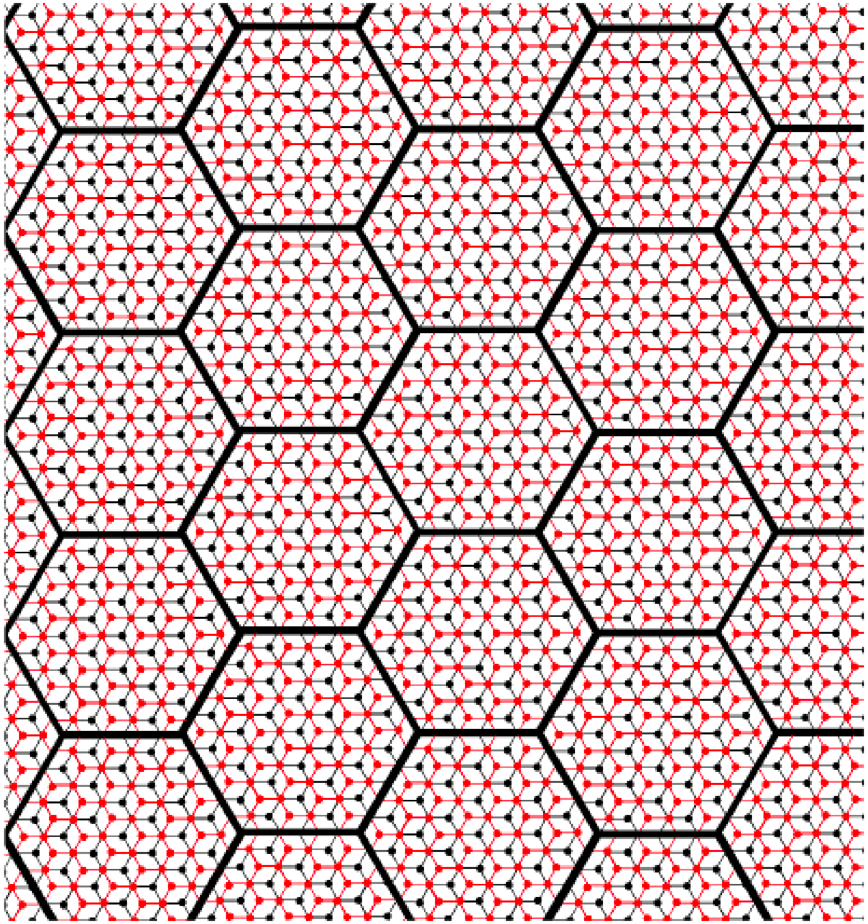


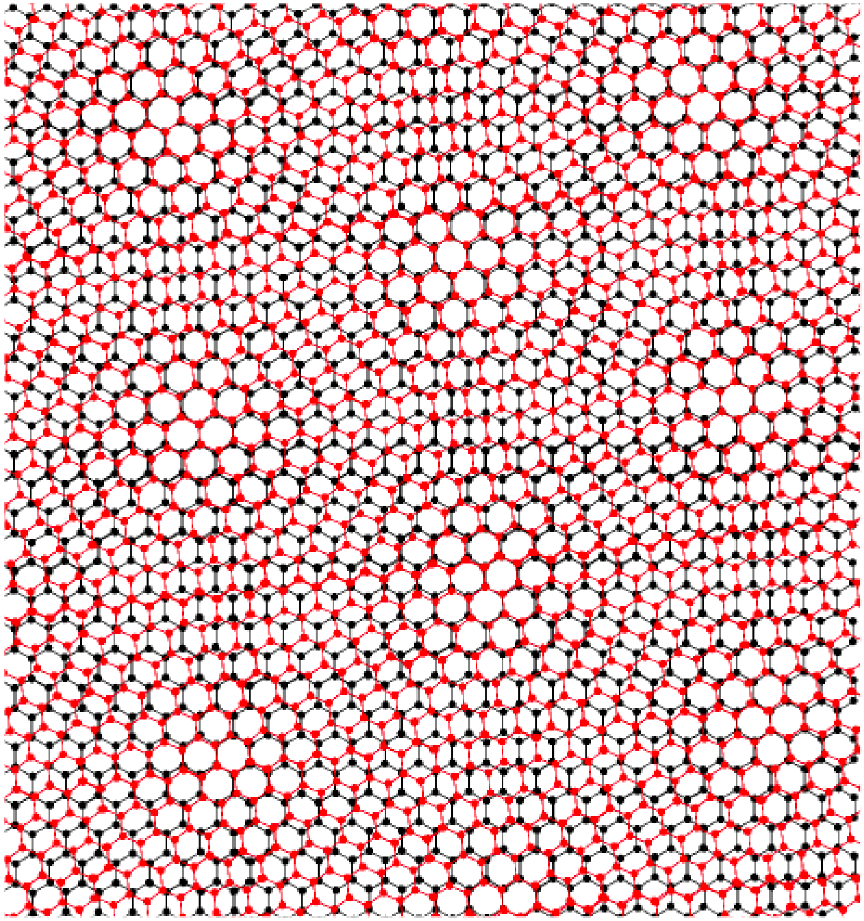


Band topology tunable by crystal axes alignment

Topological bands C=1

Trivial bands C=0





Berry curvature and valley transport

MIT

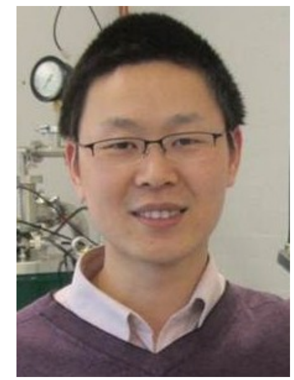
Manchester

Exeter

Justin Song

Polnop Samutraphoot

Andre Geim



Geliang Yu

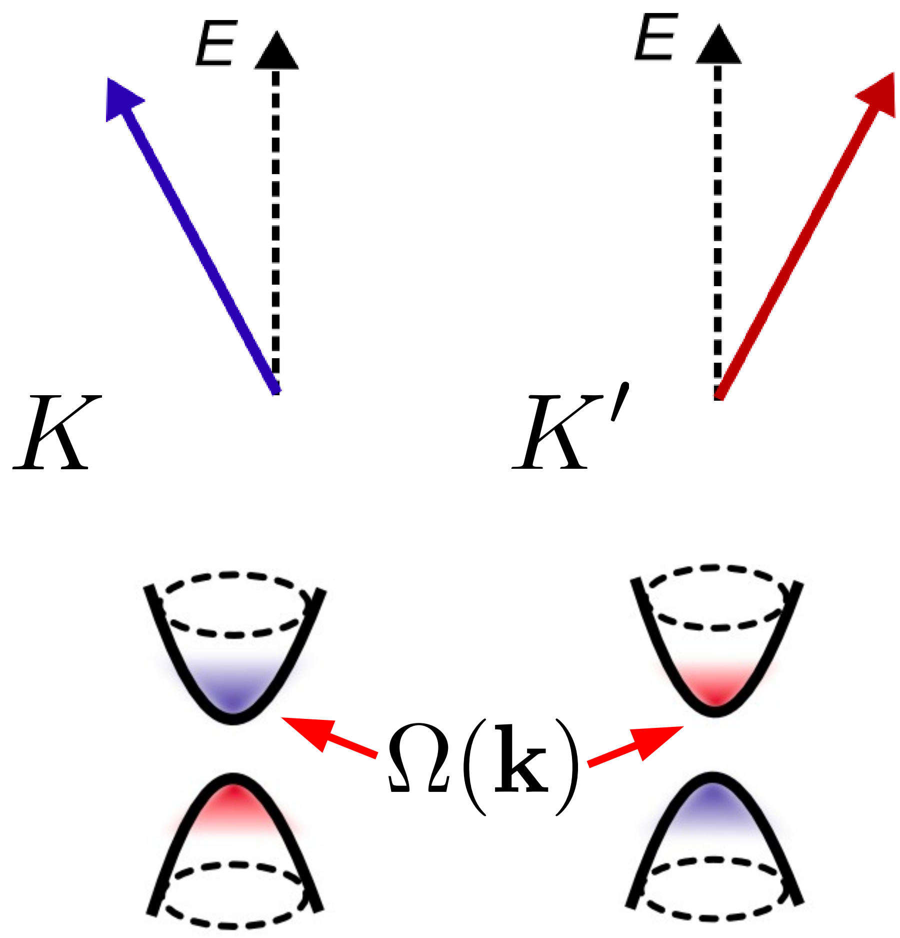
Andrey Shytov

Song, Shytov, LL Phys. Rev. Lett. 111, 266801 (2013)

Song, Samutpraphoot, LL arXiv:1404.4019 (2014)

Gorbachev, Song et al arXiv:1409.0113 (2014)

Use Berry curvature to electrically manipulate valleys



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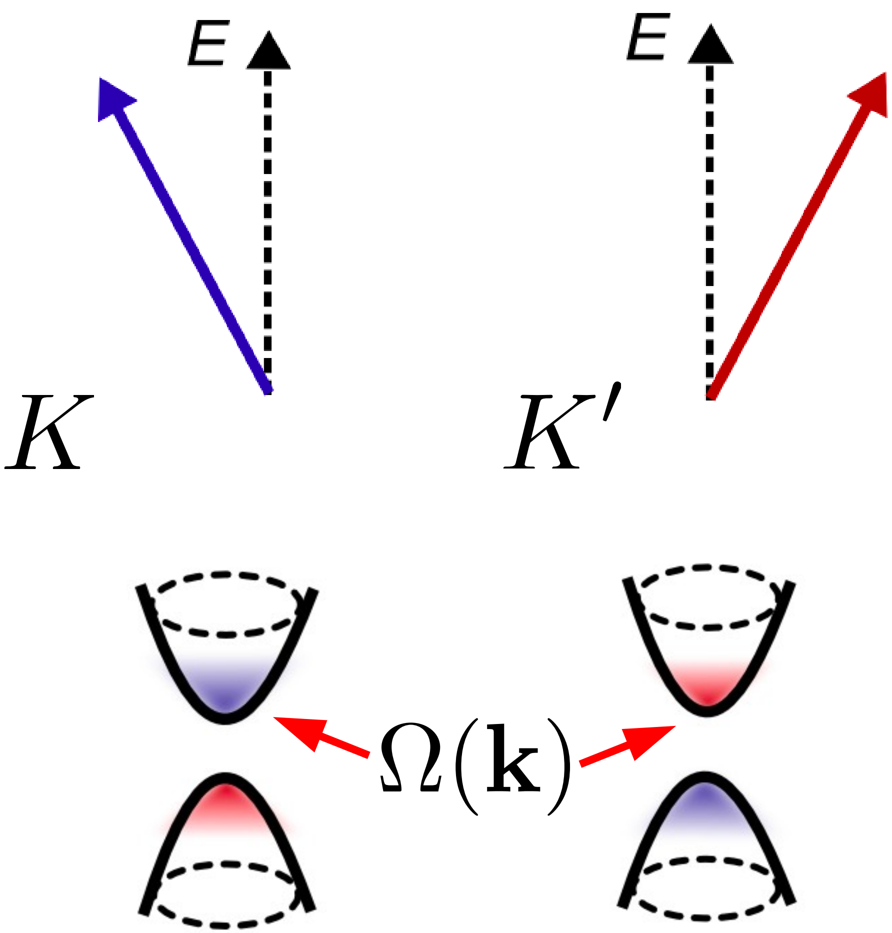

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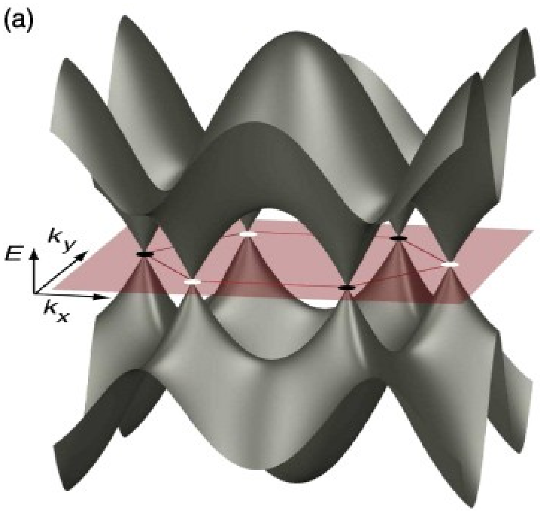
Valley Hall effect:
Transverse charge-neutral currents

$$\vec{J}_v = \vec{J}_K - \vec{J}_{K'}$$

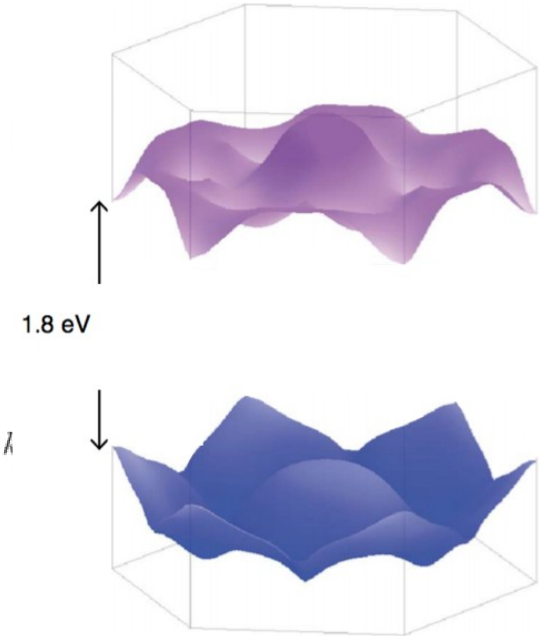
$$\vec{J}_v = \sigma_{xy}^v \vec{z} \times \vec{E}$$

Valley currents

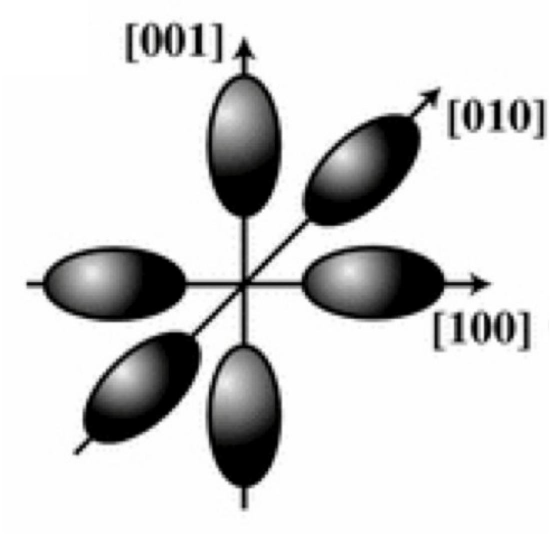
Valleys in Graphene



Valleys in MoS2



Valleys in Bulk Si



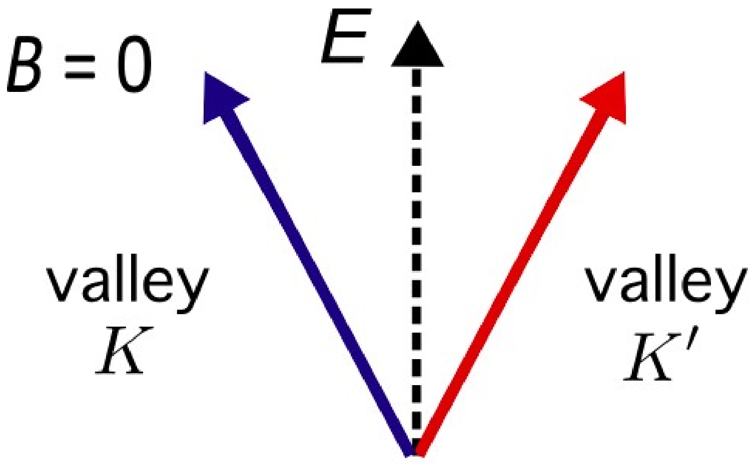
Berry curvature

$$\sigma_{xy}^{v} \neq 0$$

No Berry curvature

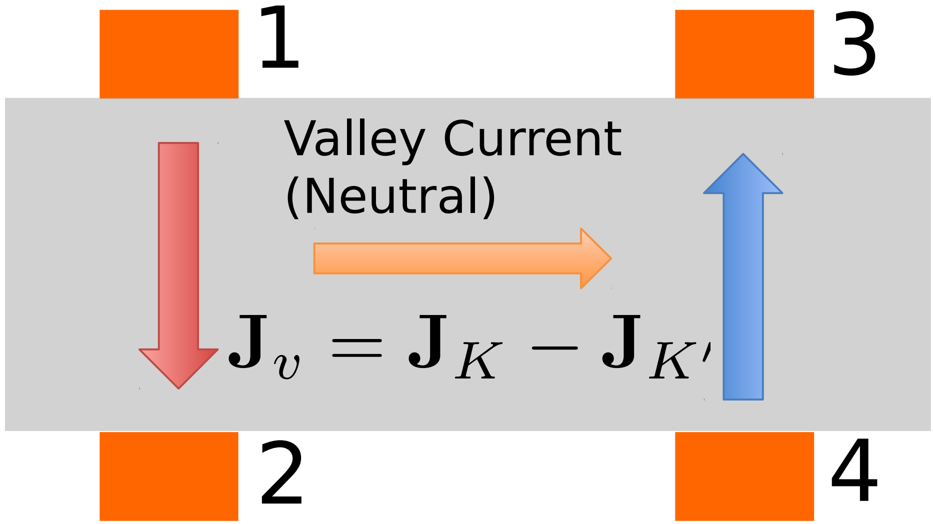
$$\sigma_{xy}^{v} = 0$$

Detecting valley currents

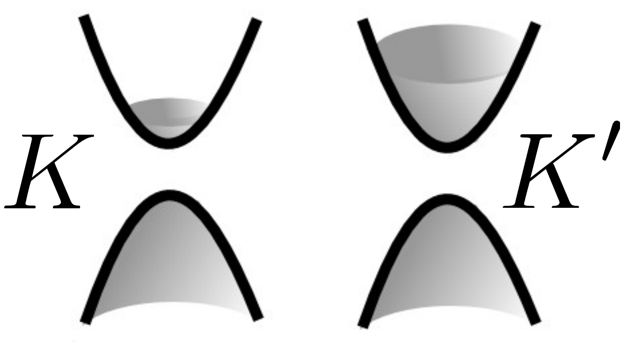


$$\sigma^{v}_{xy} = N\frac{e^2}{h}\int d^2k\,\Omega(k)f(k)$$

$$V_{34} = R_{\rm NL} I_{12}$$



Pump valley imbalance



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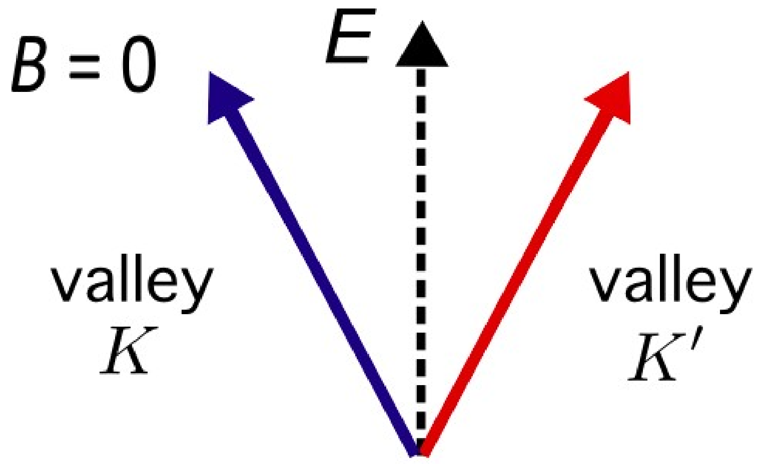

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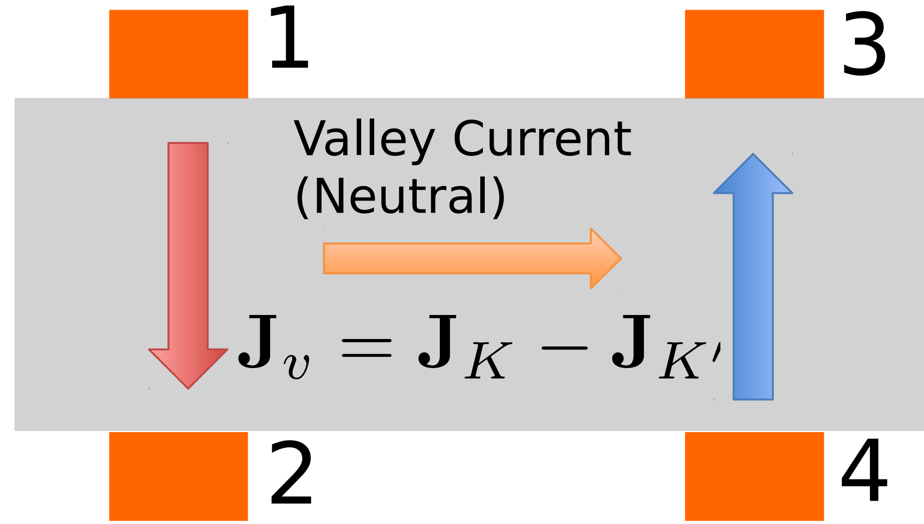

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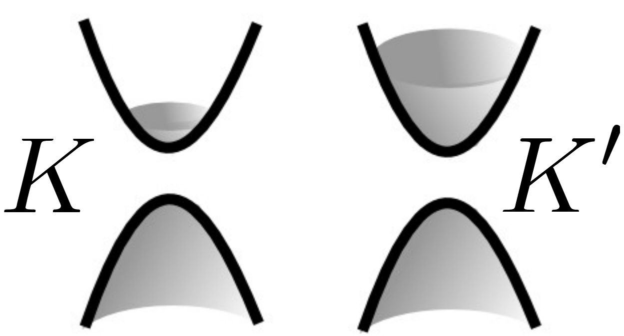


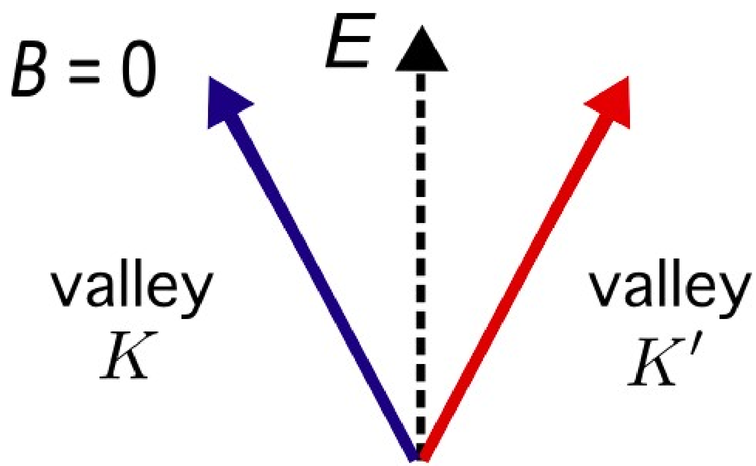
Valley Hall Effect (VHE):

$$\mathbf{J}_v = \frac{\sigma_{xy}^{v}}{\sigma}\mathbf{j}\times\hat{\mathbf{z}}$$

Reverse Valley Hall Effect (RVHE):

$$\mathbf{E} = -\frac{\sigma_{xy}^{v}}{\sigma^2}\mathbf{J}_v\times\hat{\mathbf{z}}$$

Detecting valley currents



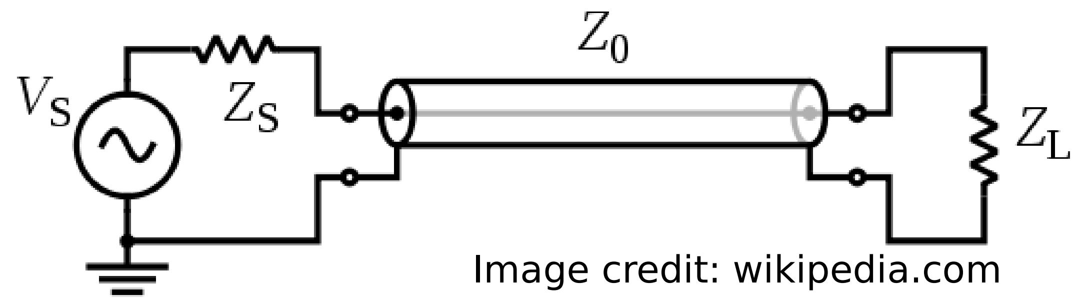


Image credit: wikipedia.com

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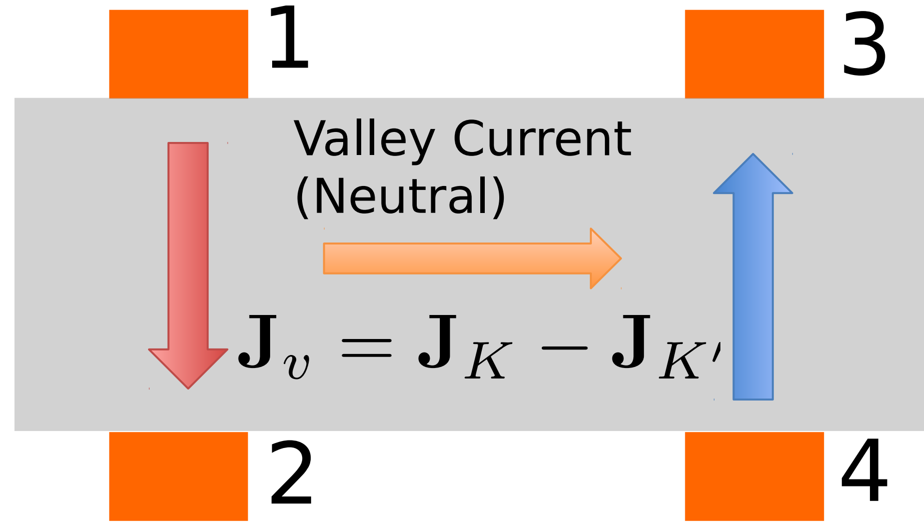

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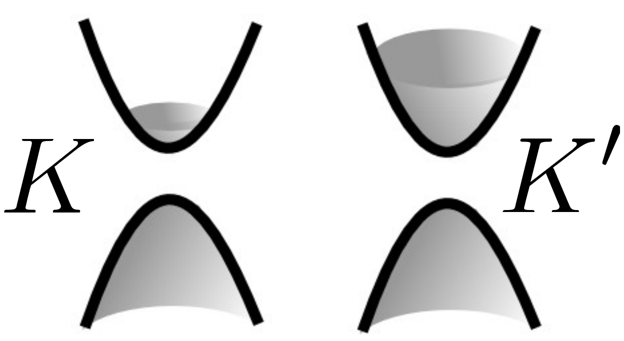

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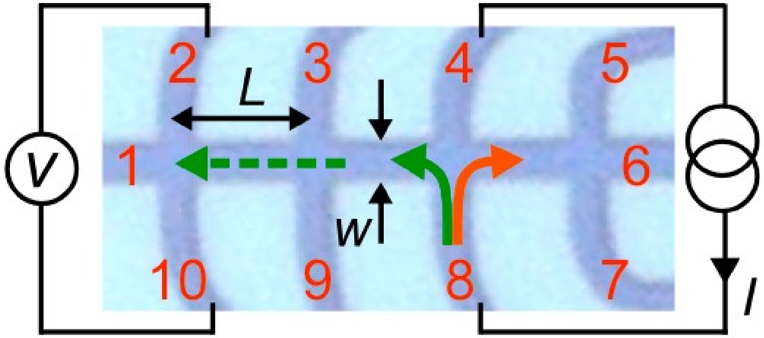
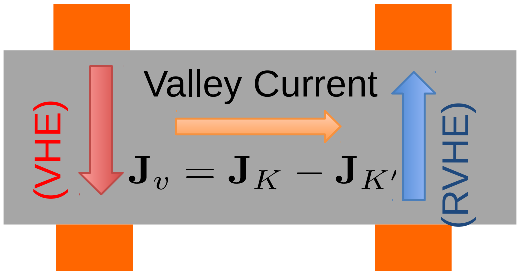
Nonlocal response in aligned G/hBN



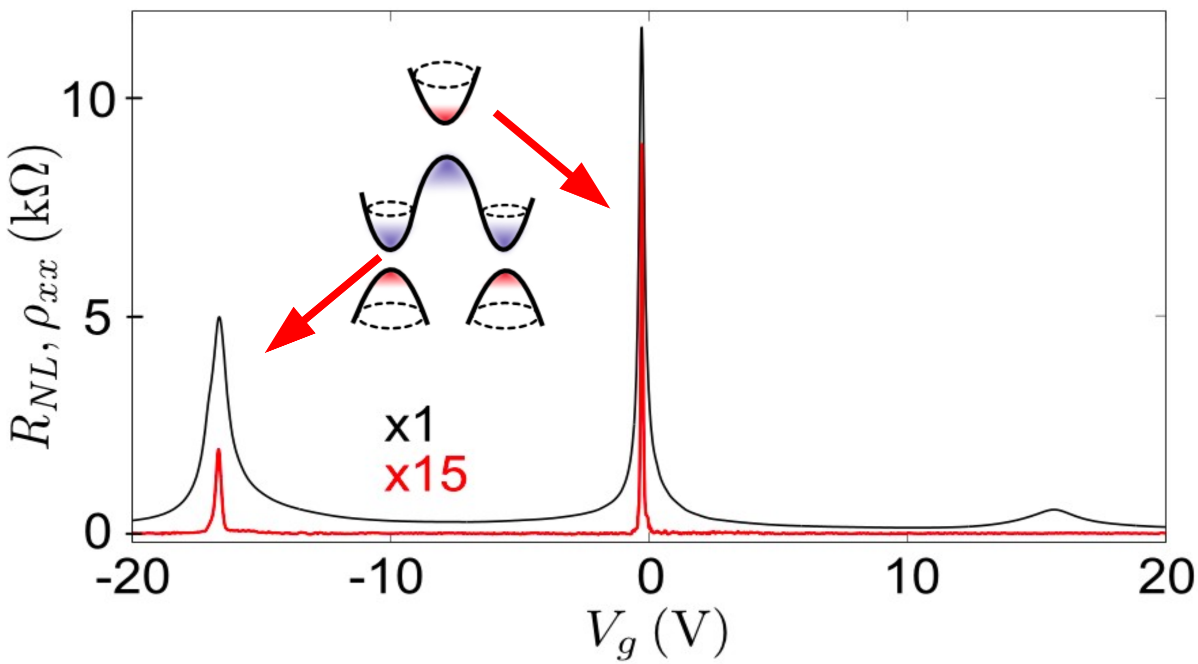
Collaboration:
U Manchester



$$V_{2,10} = R_{\rm NL} I_{4,8}$$

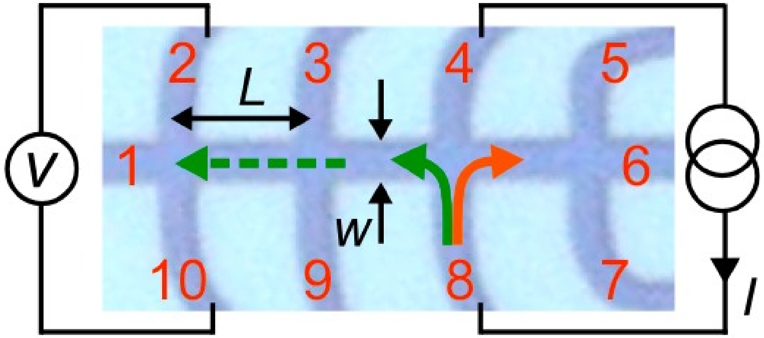
Van der Pauw bound: $R_{\rm NL}^{VdP} \approx \rho_{xx} e^{-\pi L/w}$

Berry hot spots

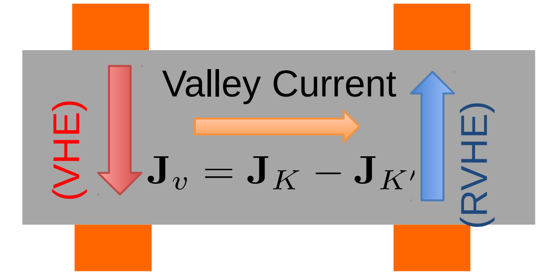


Gorbachev, Song, et. al. , Science (2014)

Nonlocal response in aligned G/hBN



Collaboration:
U Manchester



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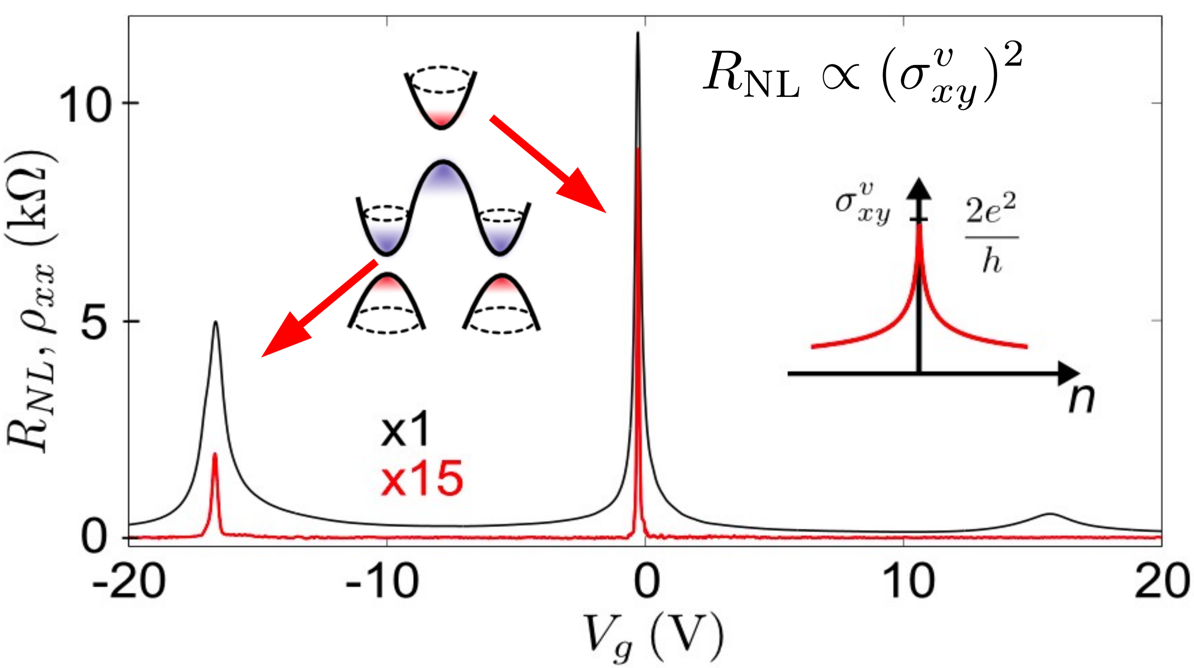
Van der Pauw bound: $R_{\mathrm{NL}}^{VdP} \approx \rho_{xx} e^{-\pi L/w}$

Berry hot spots



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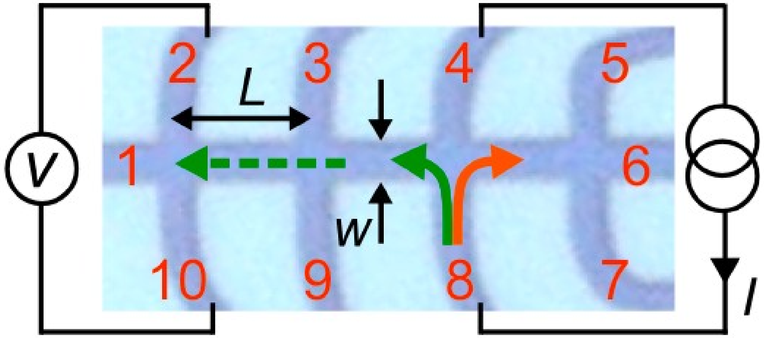

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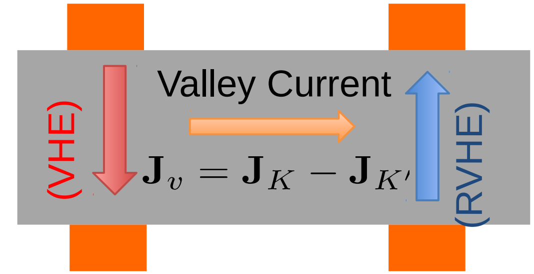

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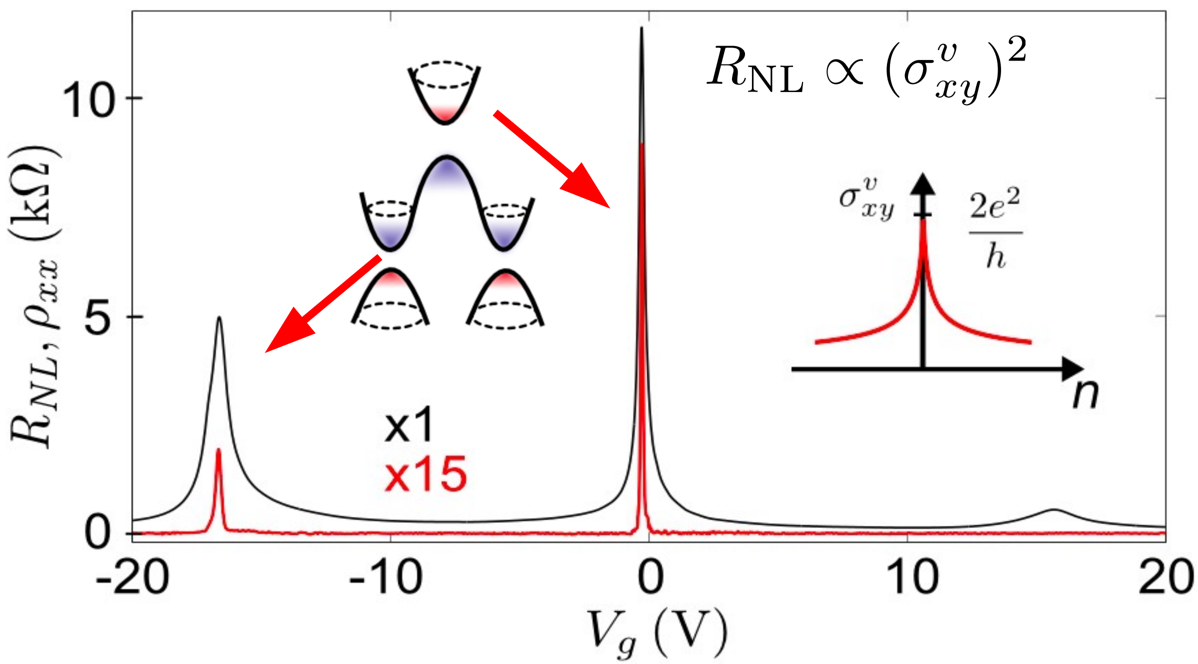
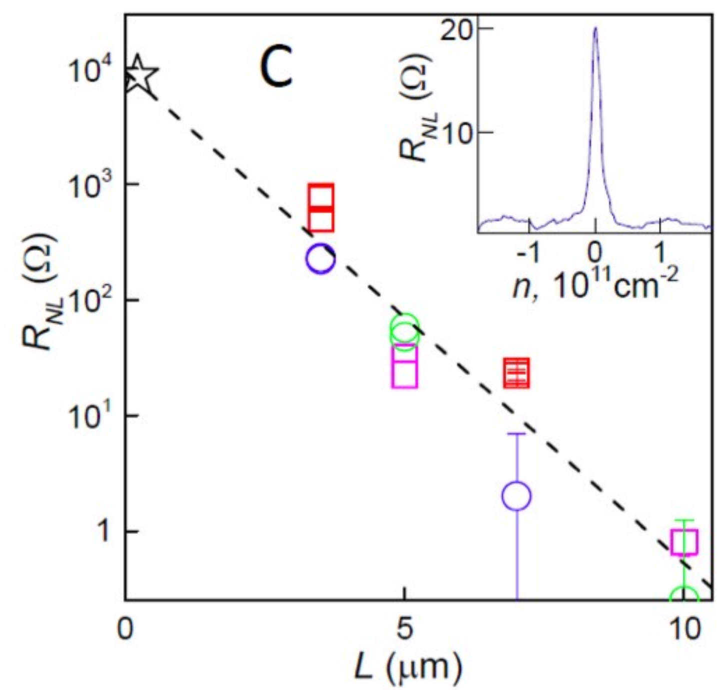


Gorbachev, Song, et. al. , Science (2014)

Distance dependence



Checklist

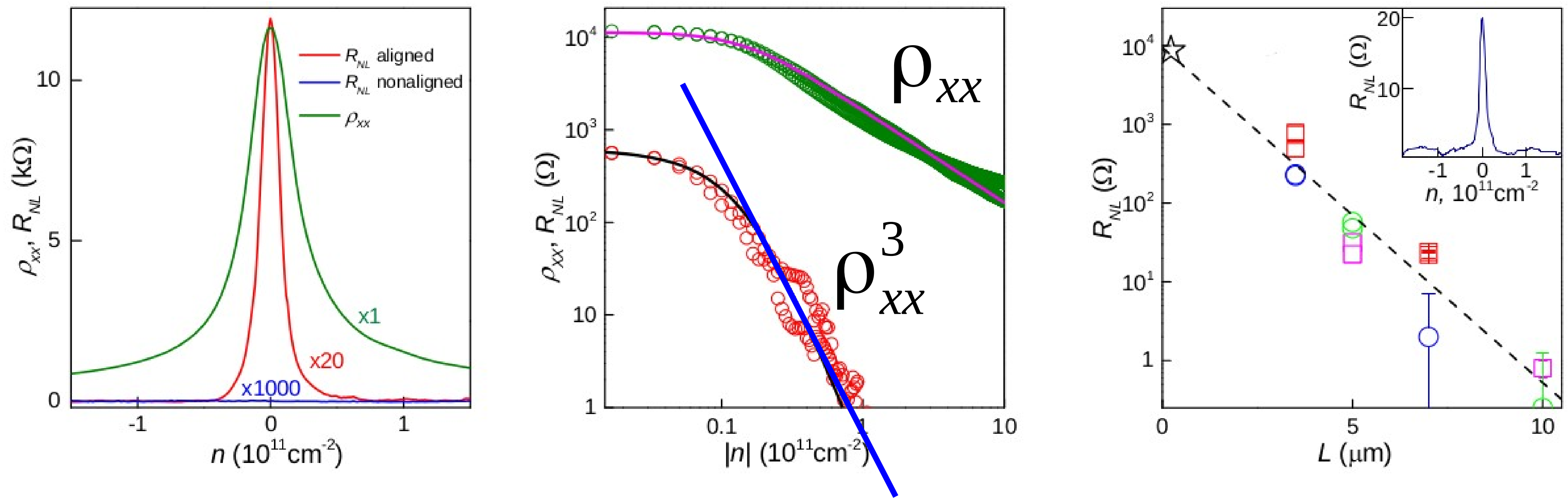
☑ 1) Non-ohmic: stray charge currents too small, super-sharp density dependence; mediated by long-range neutral currents

2) Observed at B=0, excludes energy and spin (prev work)

3) Good quantitative agreement w/ topo valley currents for Berry curvature induced by gap opening

4) Seen in aligned G/hBN devices, never in nonaligned devices

5) Scales as cube of ρxx as expected for valley currents



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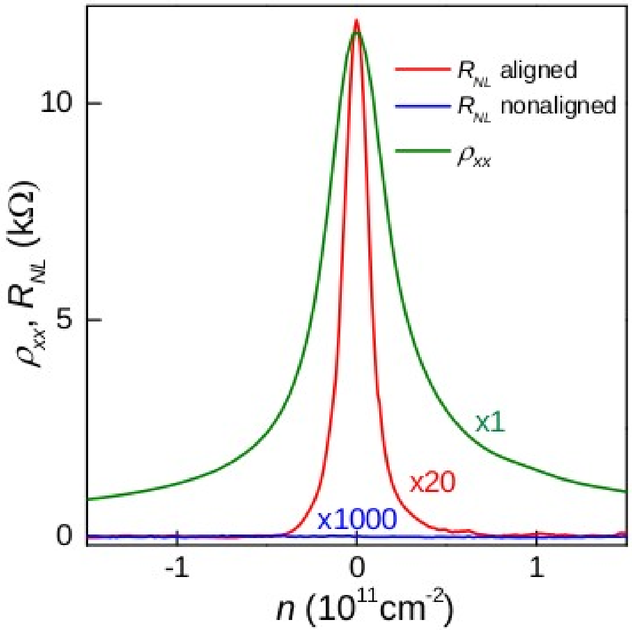

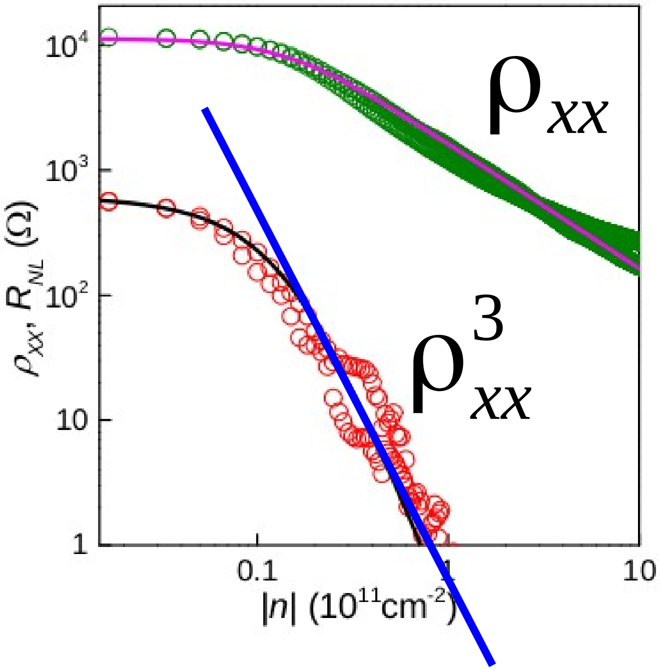

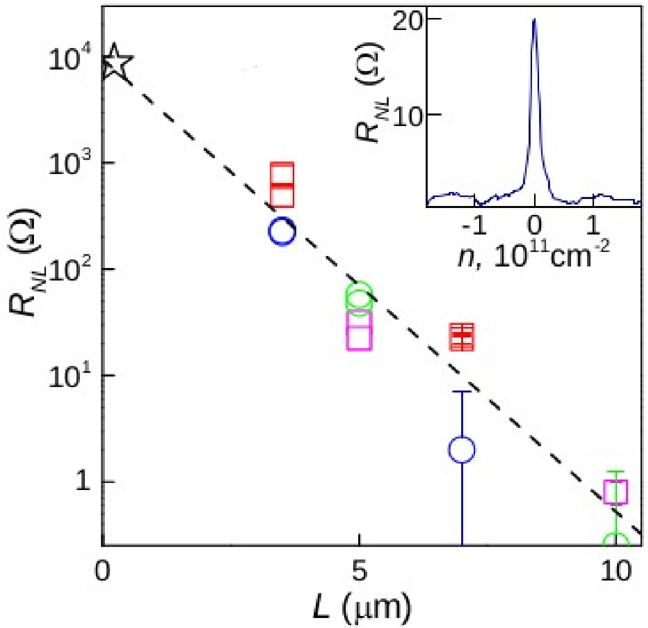

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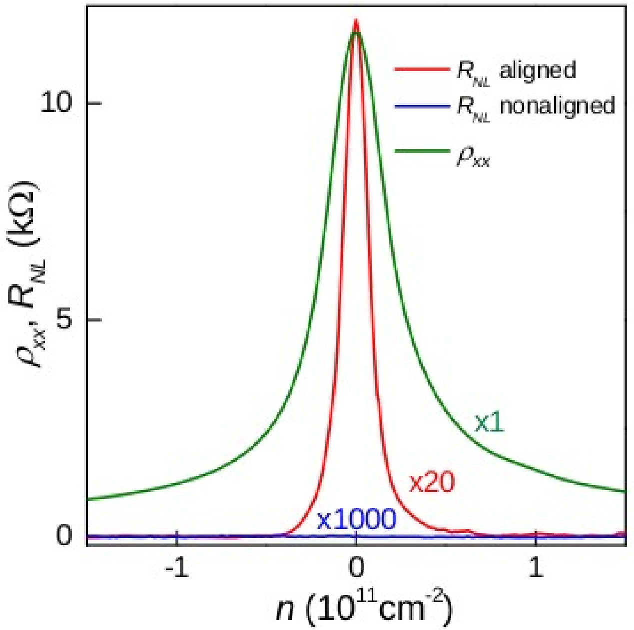
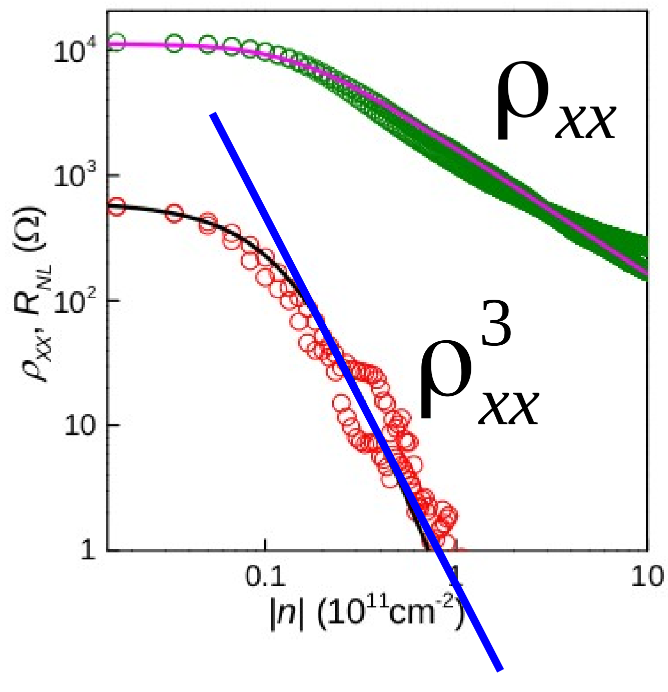
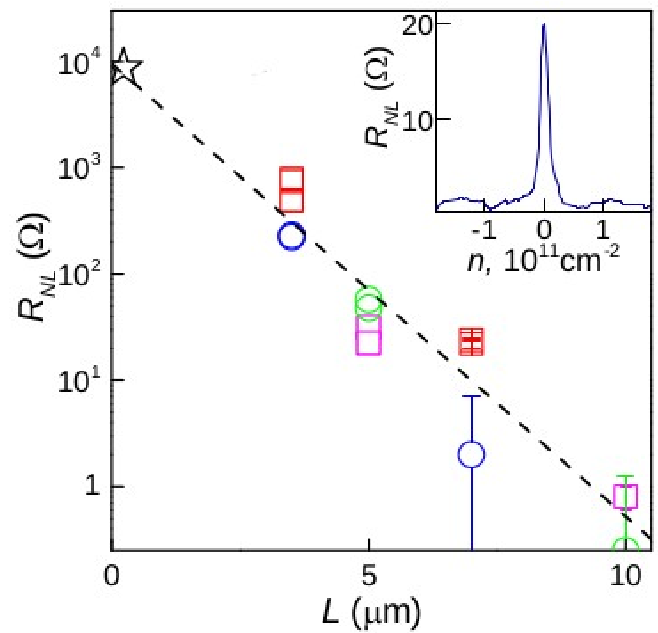


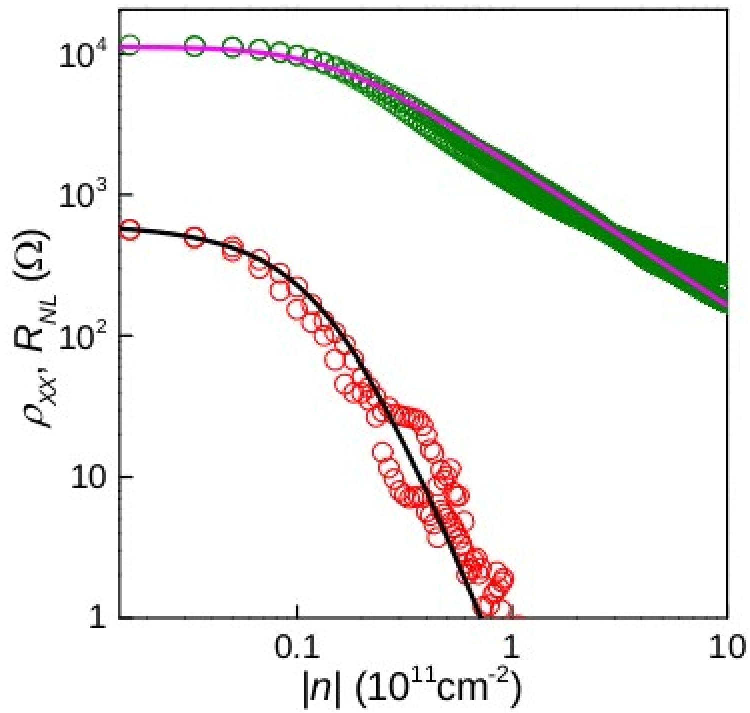


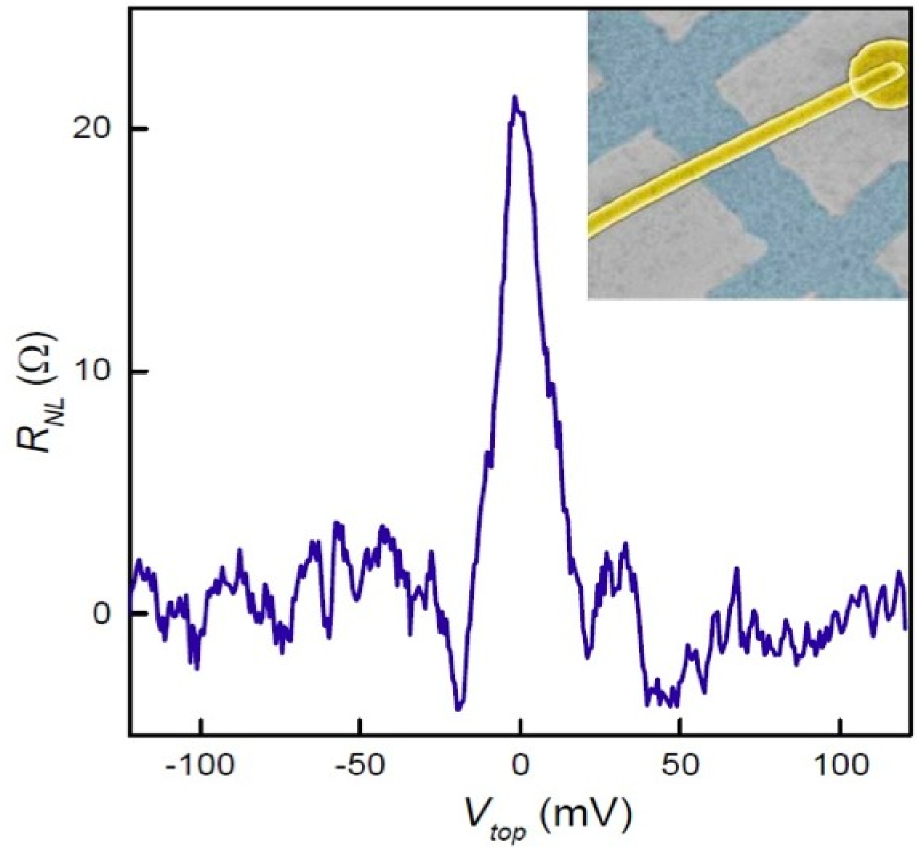


Valley transistor: proof of concept

1) Full separation of valley and charge current
2) ~140 mV/decade
3) Gate-tunable valley current

Modulation > 100 fold





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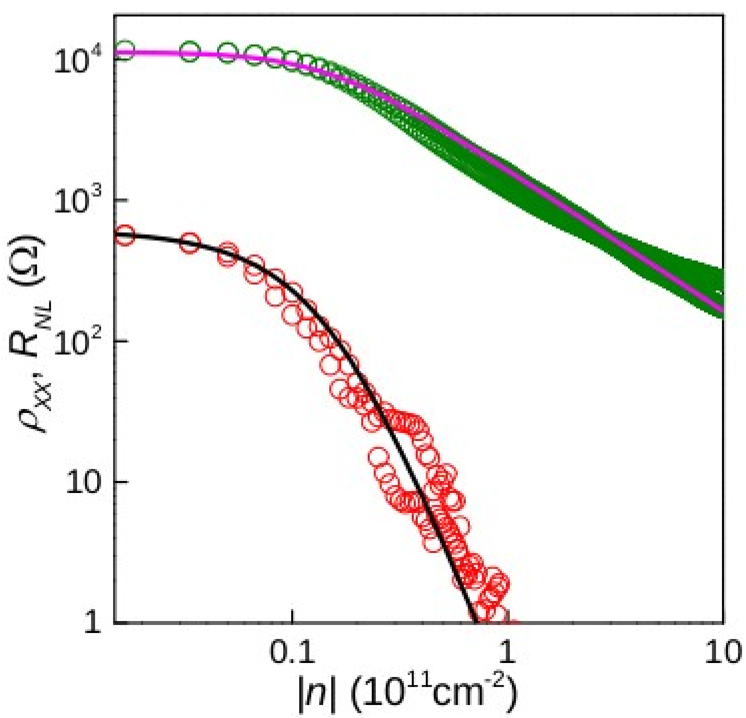
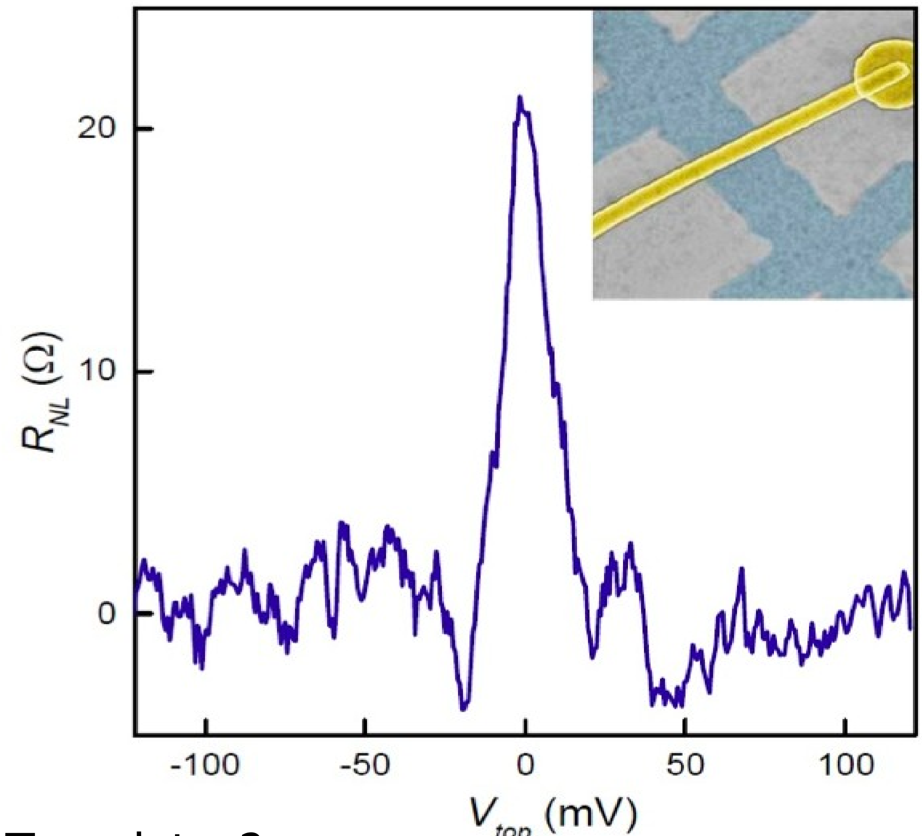
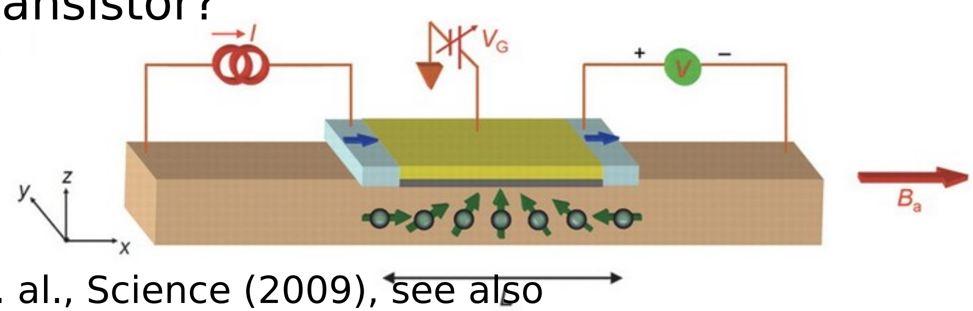


Gorbachev, Song, et. al. , Science (2014)



Spin Transistor?



Koo, et. al., Science (2009), see also Wunderlich, et. al. , Science (2010)
Original Proposal: Datta, Das, APL (1990)

Future

- **Chargeless long-range currents: Dissipationless transport?**
- **Berry curvature spectroscopy (signs, Chern numbers)**
- **Waveguides for valley currents**
- **Valley currents in 1D channels (graphene edge, BLG domain walls, p-n junctions)**