GRAPHENE: BERRY PHASE, TOPOLOGICAL CURRENTS, VALLEY TRANSPORT

Leonid Levitov (MIT)
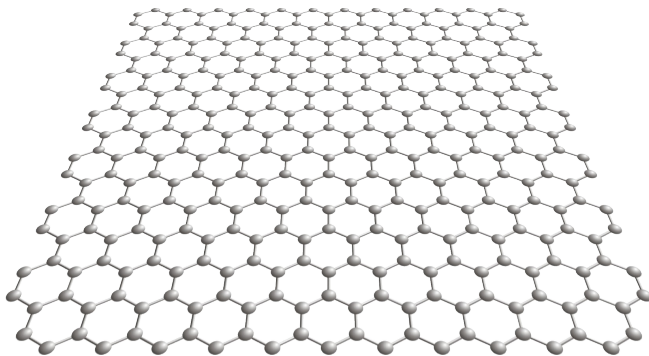
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2D materials

Graphene family

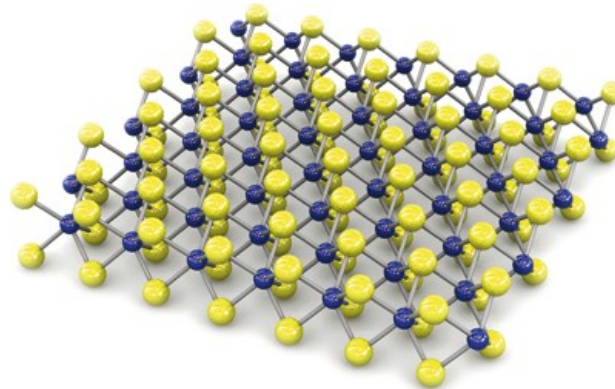Graphene, Bilayer Graphene, Twisted structures

Hexagonal Boron Nitride

Graphene Oxide ...

Novoselov, et. al., Science (2005)

Single layer dichalcognides

MoS2, WS2, WSe2, MoSe2 ...

NbSe2, NbS2 ...

Topological insulators

Bi2Se3, Bi2Te3, BixSb1-x, ..

Topological Crystalline Insulators: SnTe, ..

HgxCd1-xTe Quantum Wells, InAs/GaSb QW
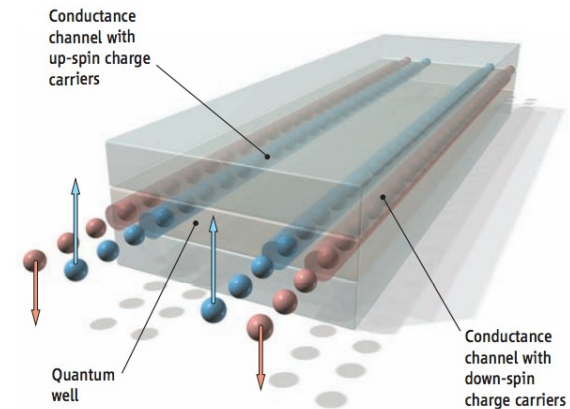
Koing, et. al., Science (2007)

Unique properties

Atomically thin   Topological Currents
Transparent   Valley Degree of Freedom
Flexible   Topologically Protected Transport
Optically Active   Valley Coherent Excitons
Broadband Absorption Bulk Insulating, Surface Metallic
Exposed States   Spin-momentum locking
Proximal Gates   Magneto-electric Effect
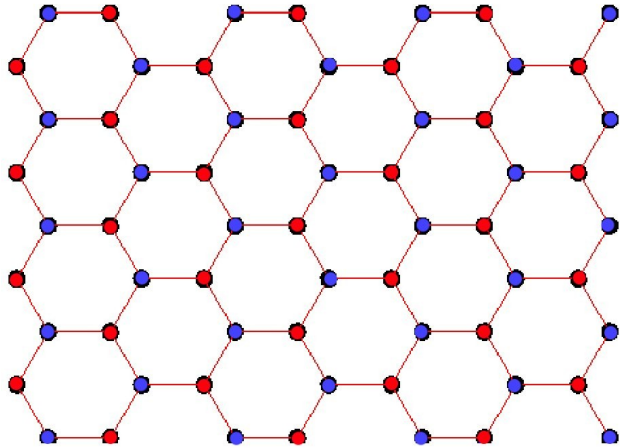**High Mobility**   1D Chiral Edge States

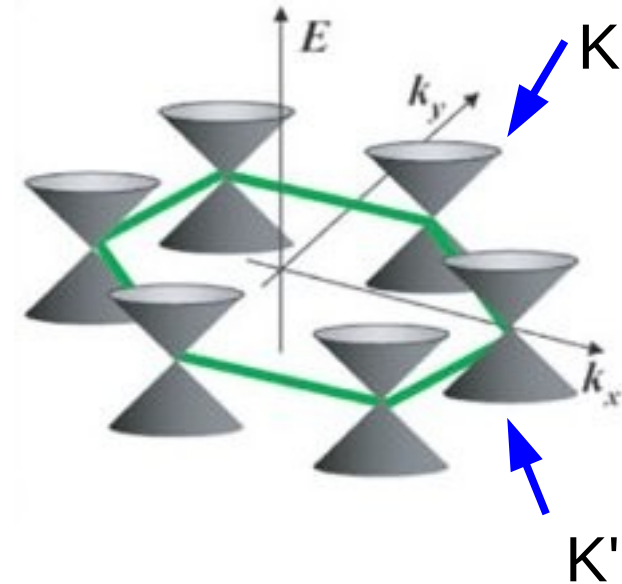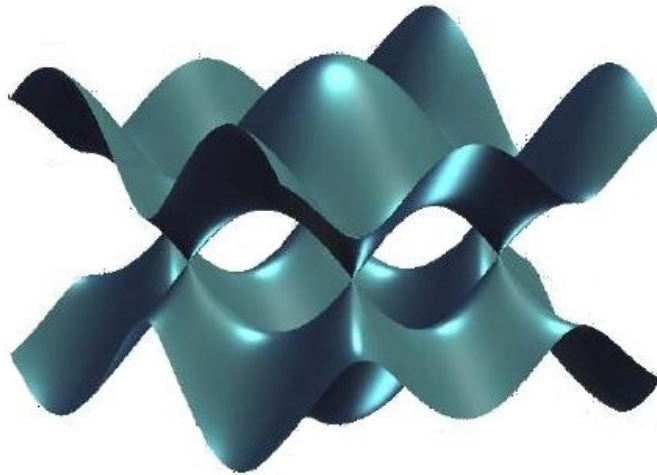**Attractive systems:
New interesting Physics
New toolbox for technology**
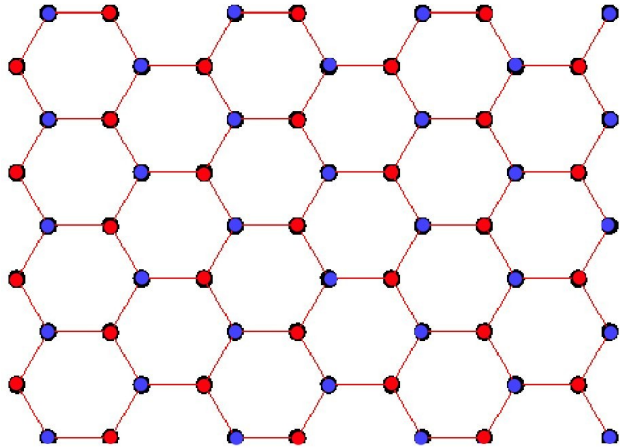
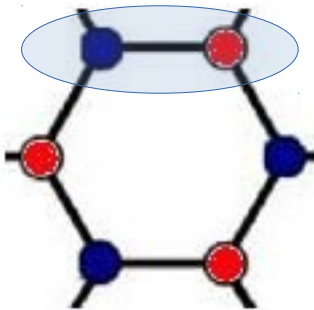# Relativistic particles in graphene

position space

momentum space

K

K'

Relativistic particles in graphene
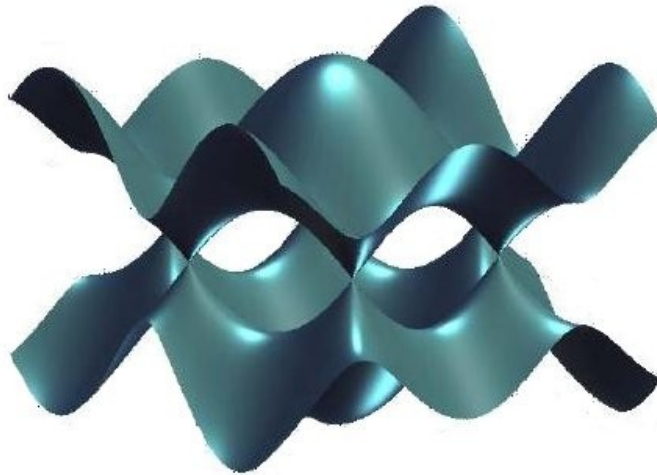
position space

momentum space

pseudo-spin (sublattice)

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

unit cell

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Relativistic particles in graphene

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momentum space

unit cell

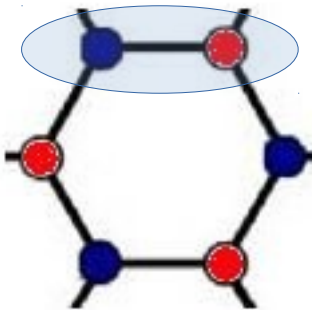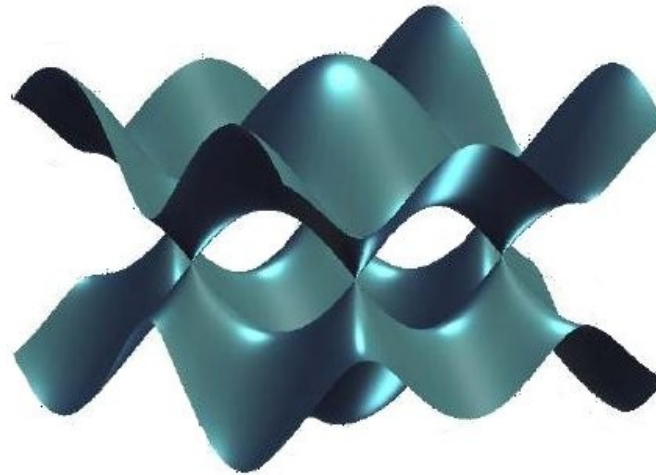pseudo-spin (sublattice)

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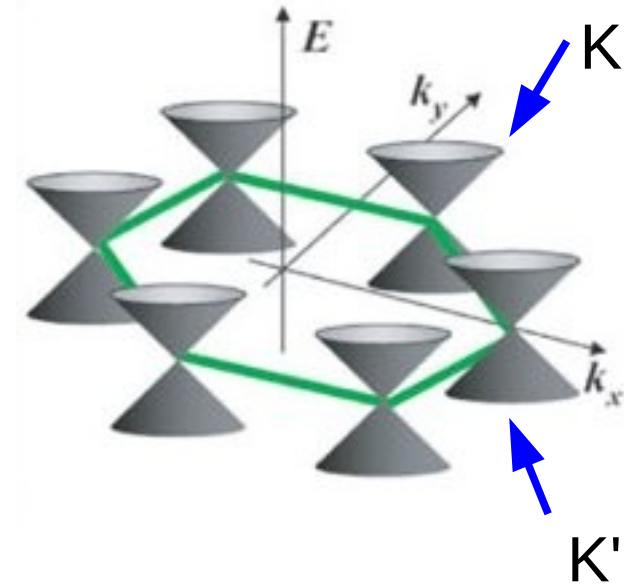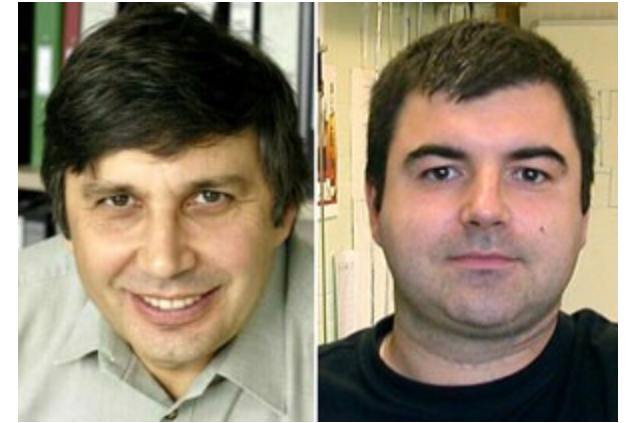
Low-E states: massless Dirac electrons

$$H = v\,\sigma_i\left(p_i - eA_i(r)\right) + e\,\Phi(r)$$

Semimetal (zero band gap); electrons and holes coexist

Some consequences of relativistic QM in graphene

Steep dispersion, $E=v|p|$: electron properties gate-tunable, slow electron-lattice cooling, strong hot carrier effects

Chirality, pseudospin-velocity locking, $H=v\sigma p$: suppression of backscattering, immunity to disorder, high mobility

Berry phase: graphene as a prototype topological material, topological bands and topological currents

Strong interactions: QED at strong coupling, $\alpha \sim 1$, new collective modes, spontaneous ordering

Exploiting New Materials v1.0

Integrated Circuits with MoS2
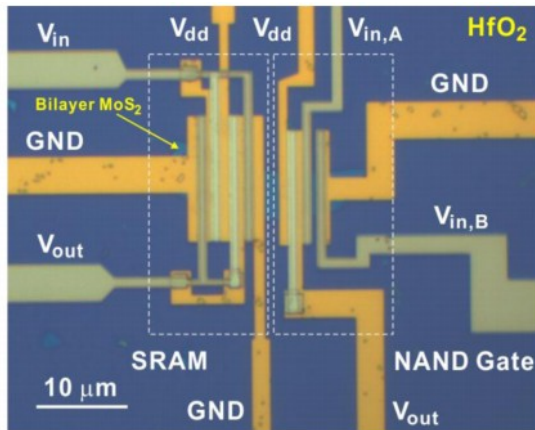
Wang, Nano Lett. (2012)
See also Radisavljevic Nat. Nano (2011)

Atomically Thin Photodetectors & LEDs
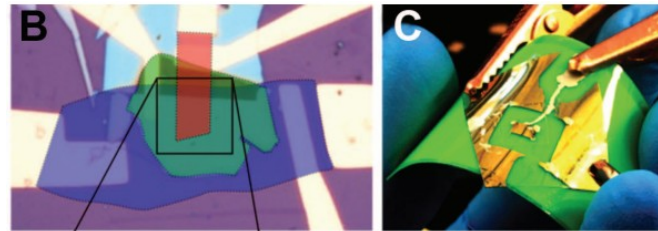
Britnell et al, Science (2013)
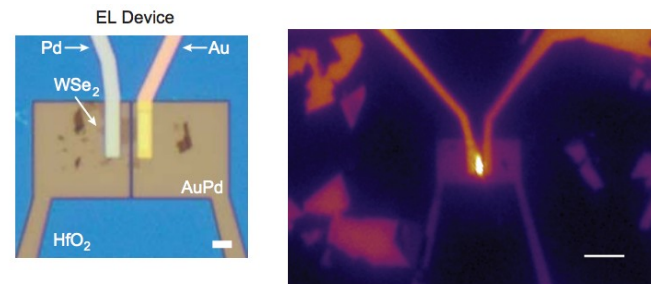
Baugher, et al, Nat. Nano (2014)

Broadband Optical Modulators

(1.3-1.6 µm)

Clock speed: 1GHz
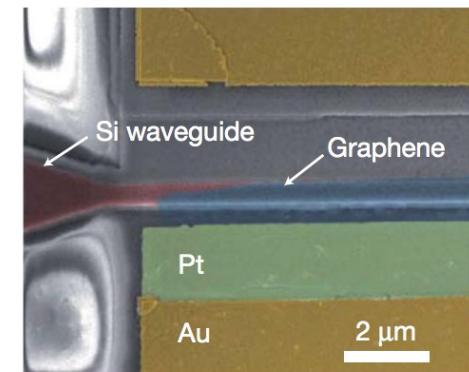
Liu, et. al. Nature (2011)

Unique properties

Atomically thin
Transparent
Flexible
Optically Active
Broadband Absorption
Exposed States
Proximal Gates
High Mobility

Topological Currents
Valley Degree of Freedom
Topologically Protected Transport
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Bulk Insulating, Surface Metallic
Spin-momentum locking
Magneto-electric Effect
1D Chiral Edge States

Valley index: new degree of freedom to encode information

Valleytronics: Beenaker, Nat. Phys. (2007) and others

Valleys in Graphene
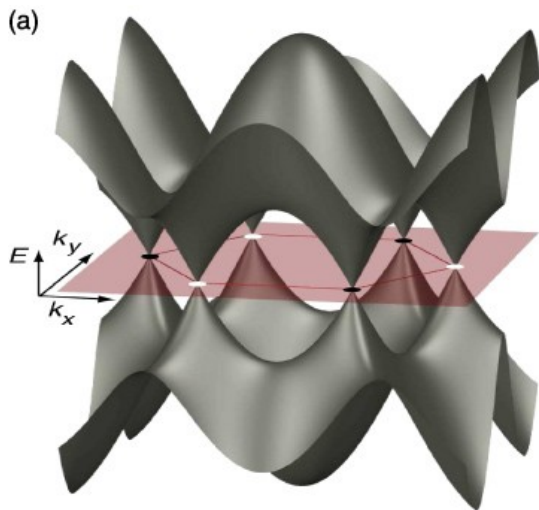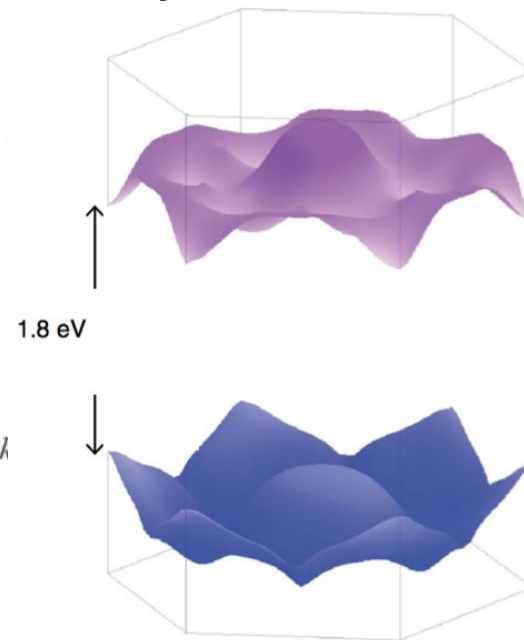
Valleys in MoS2

Valleys in Bulk Si
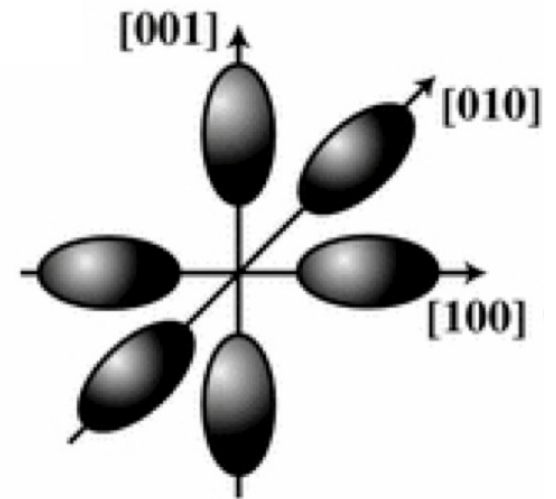
Charge-neutral currents, low dissipation, long-lived, slow intervalley scattering (hundreds of ps)

Use Berry curvature to electrically manipulate valleys

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

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

E E

K K'

$\Omega(\mathbf{k})$

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Valley Hall effect:
Transverse charge-neutral currents

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

$$\vec{J}_v = \sigma^v_{xy}\, \vec{z} \times \vec{E}$$

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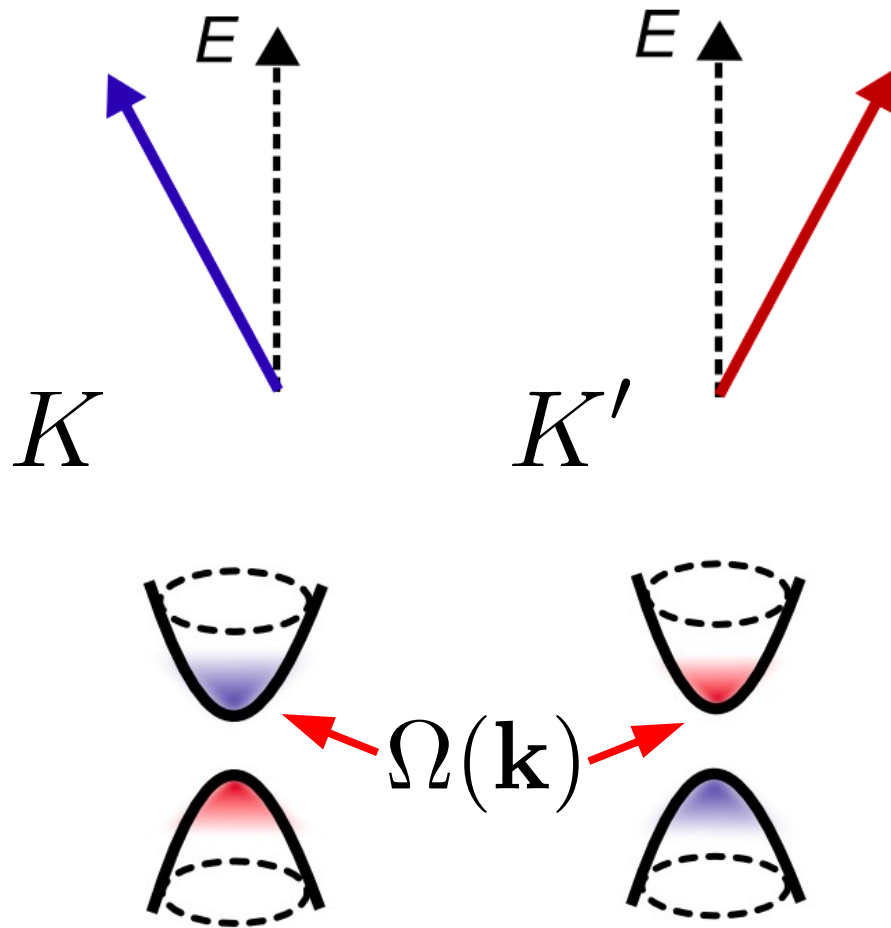
Berry phase primer

The adiabatic theorem (Born&Fock 1928): a QM system remains in its instantaneous eigenstate if the Hamiltonian *H(t)* is changing slowly enough and if there's a gap between the eigenvalue and the rest of *H(t)* spectrum

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This is correct but incomplete (Berry)

For *H(t)* that goes around a closed loop *k(t)* in parameter space, there is an added phase relative to initial state

$$\varphi = \oint \boldsymbol{A}\, d\boldsymbol{k}, \quad \boldsymbol{A} = i\langle \psi(k)|\nabla_{\boldsymbol{k}}|\psi(k)\rangle$$

Features: geometric, independent of w.f. choice

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Vector potential and curvature

Berry gauge transformation

$$\psi(k) \rightarrow e^{i\chi(k)} \psi(k), \quad A(k) \rightarrow A(k) - \nabla_k \chi(k)$$

Loop integrals of *A* will be gauge invariant as will the *curl* of *A* (called "Berry curvature")

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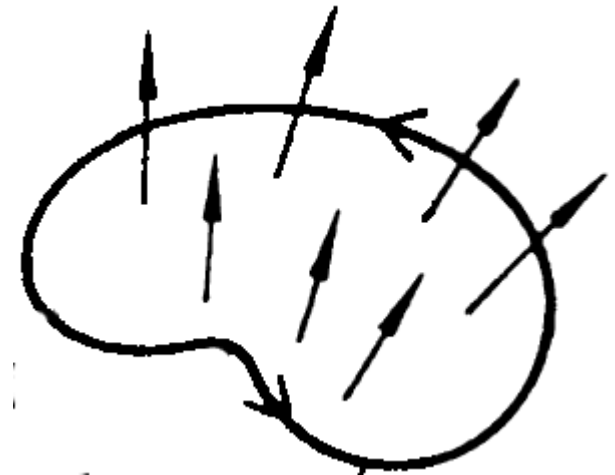$$\varphi = \oint A\, dk, \quad \Omega(k) = \nabla_k \times A(k)$$

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Similar to EM vector potential:
AB phase counts magnetic flux,
Berry phase counts Ω flux

An example: spin ½ particle

Spin ½ in a time-varying B-field tracks the field direction (adiabatic evolution), Berry phase equals the solid angle swept by the field (times ½)

$$H = -\mu\, \boldsymbol{B}\, \boldsymbol{\sigma}$$

A round adiabatic change

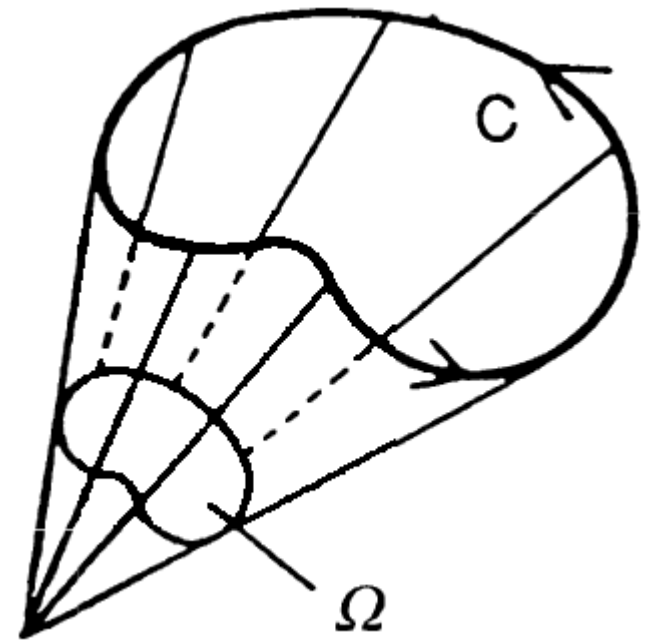$$\varphi(C) = \frac{1}{2} \oiint \frac{\hat{\boldsymbol{B}}}{\boldsymbol{B}^2} d^2 B = \frac{1}{2} \Omega(C)$$
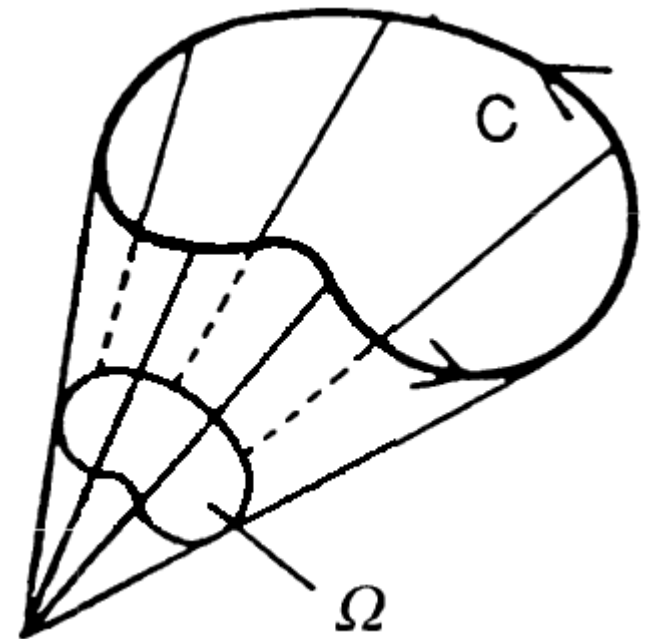
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$$\varphi(C) = \frac{1}{2}\oiint \frac{\hat{\boldsymbol{B}}}{\boldsymbol{B}^2}\,d^2B = \frac{1}{2}\Omega(C)$$

Pristine graphene: massless
Dirac fermions, Berry phase
yet no Berry curvature[1] $\boxed{H = v\,\vec{p}\,\vec{\sigma}}$

Berry phase in solids

In a crystal a natural parameter space is (quasi)momentum for electron Bloch states

$$\psi(r) = e^{ikr} u_k(r)$$

The change in the electron wavefunction within the unit cell yields the Berry connection and Berry curvature

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

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Geometry-inspired physics

Topological invariants (Chern classes)

$$n = \sum_{bands} \oiint \frac{d^2 k}{2\pi} \Omega(k)$$

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Derive quasiclassical e.o.m.

quasiparticle dynamics in band α, an effective action

$$S = \int \left(\boldsymbol{p}\,\dot{\boldsymbol{x}} - H(\boldsymbol{p}(t), \boldsymbol{x}(t)) + \boldsymbol{A}_{Berry}\,\dot{\boldsymbol{p}} + e\,\boldsymbol{A}_{EM}\,\dot{\boldsymbol{x}} \right) dt$$

for adiabatic Hamiltonian $\quad H(\boldsymbol{p}, \boldsymbol{x}) = \epsilon_\alpha(\boldsymbol{p}) + e\,\Phi(\boldsymbol{x})$

$$\delta S = 0: \quad \frac{d}{dt}\frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} = 0 \qquad \boldsymbol{q} = \boldsymbol{x}, \boldsymbol{p}$$

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$$\frac{d\boldsymbol{p}}{dt} = -e\, \nabla_x \Phi + e\, \dot{\boldsymbol{x}} \times \boldsymbol{B} \qquad \text{Q.E.D.}$$

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Analogy w/ Magnus effect and curveballs
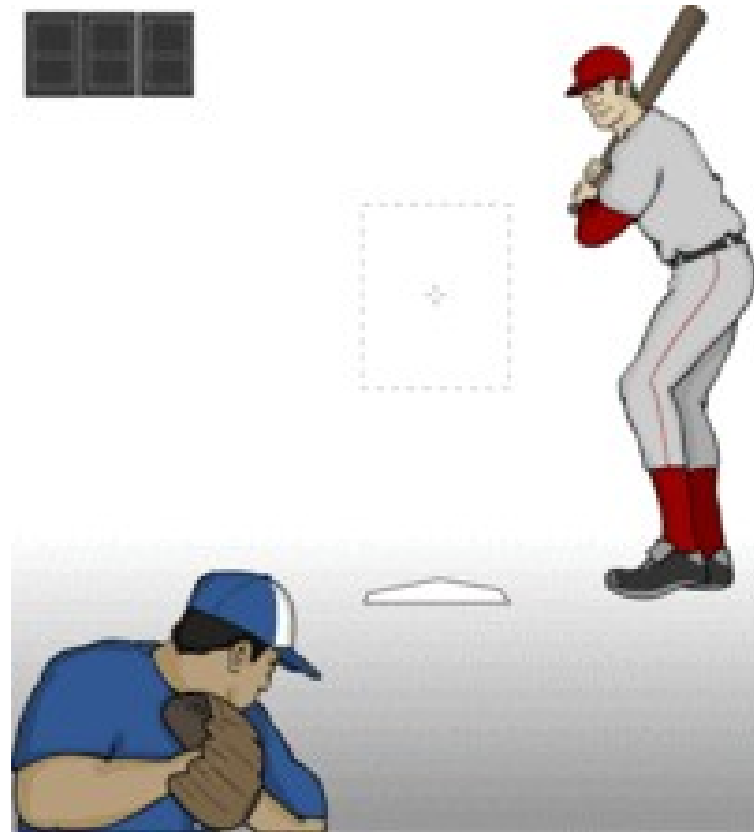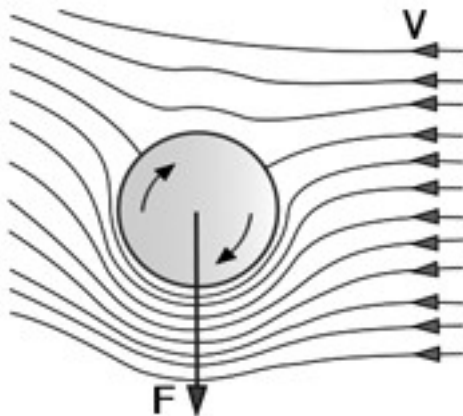
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Many physical properties determined by these geometric quantities

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The 1st one was the Integer Quantum Hall effect (TKNN 1982) "the first Chern number"

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Topological insulators (since 2005)

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Here: valley currents and valley-Hall effect in graphene Kiev 24.10.2015

Graphene-based topological materials

Quantized transport, Quantum Hall effects,
Topological materials, Anomalous Hall effects...

Chern invariant $\quad C = \dfrac{1}{2\pi}\sum_{k}\Omega(k)$

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Pristine graphene: massless Dirac fermions, $H = v\,\vec{\sigma}\,\vec{p}$
Berry phase yet no Berry curvature

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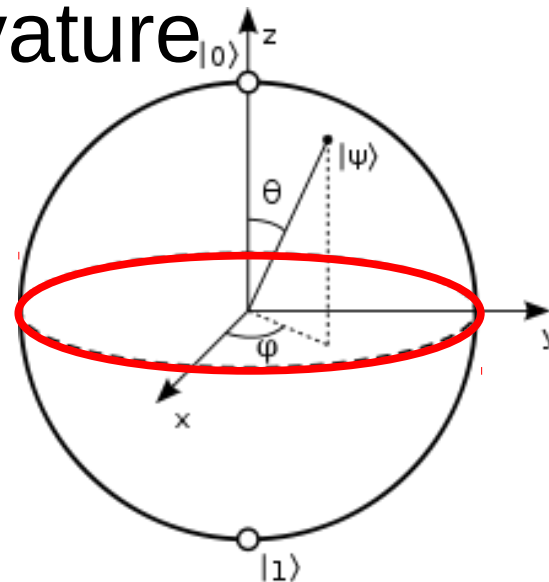
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Massive (gapped) Dirac particles

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

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

Valley Chern invariant
(for closed bands)

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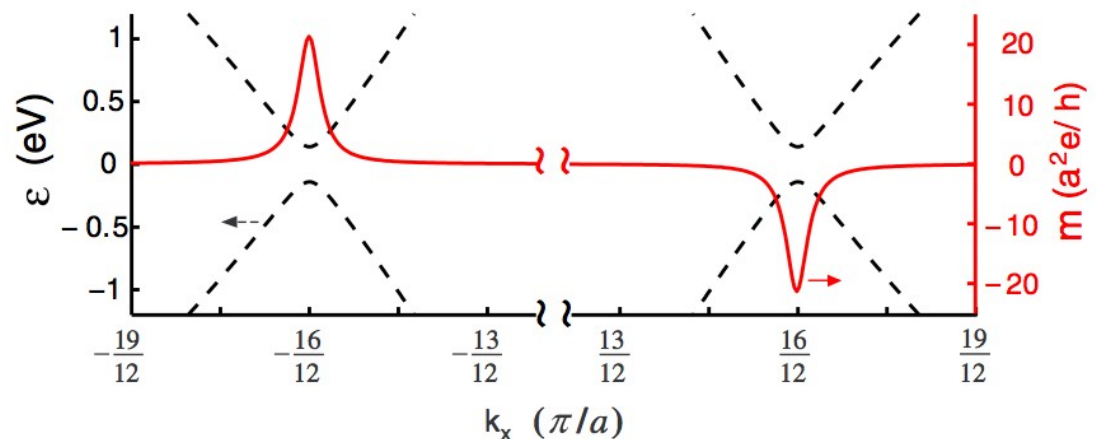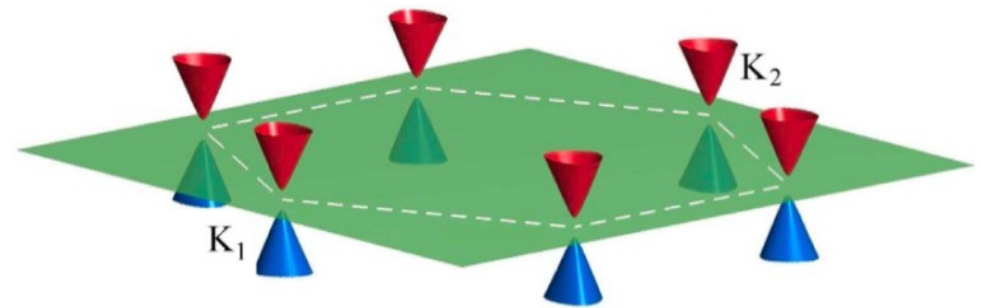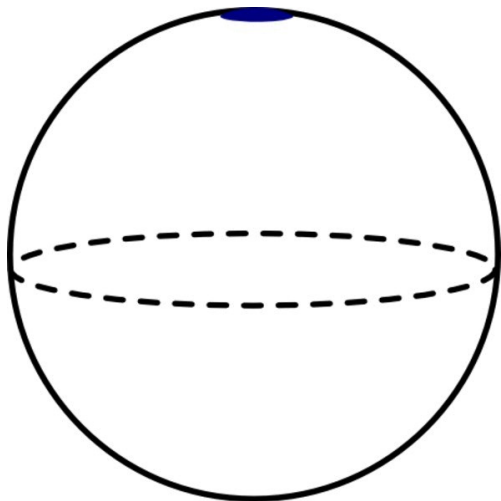
D. Xiao, W. Yao, and Q. Niu, PRL 99, 236809 (2007)

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Create topological bands in graphene?
(and play curveball)

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Collaboration

MIT

Manchester

Exeter

Polnop Samutraphoot   Andre Geim   Geliang Yu   Andrey Shytov
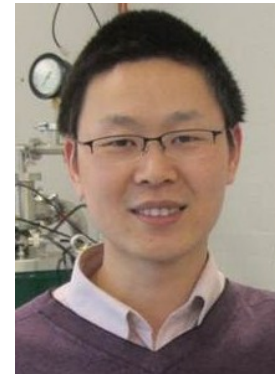
Justin Song

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

Song, Samutpraphoot, LL arXiv:1404.4019 (2014)

Gorbachev, Song et al (submitted, 2014)

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Building quantum cheeseburger

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

Image from: Geim & Grigorieva, Nature 499, 419 (2013)
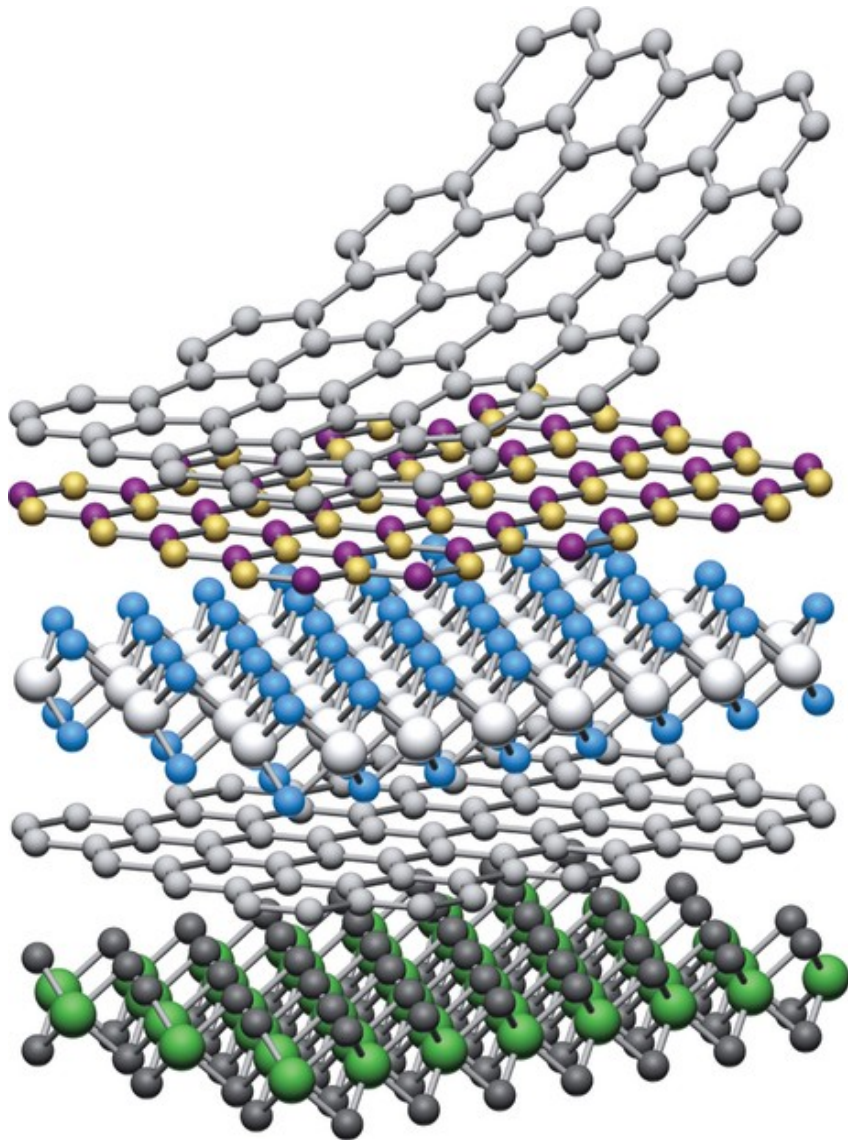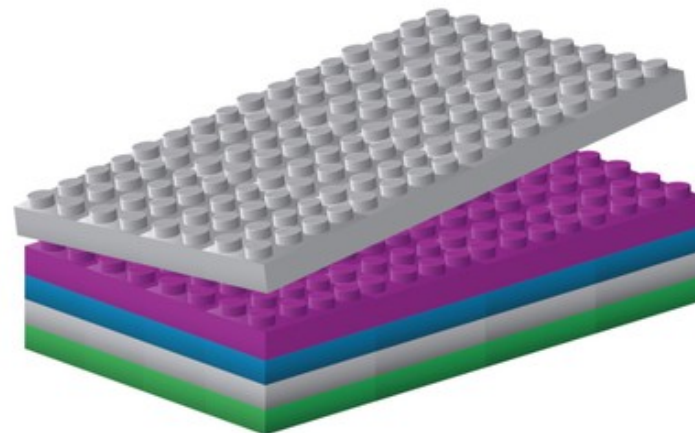
Gap opening in graphene on hBN
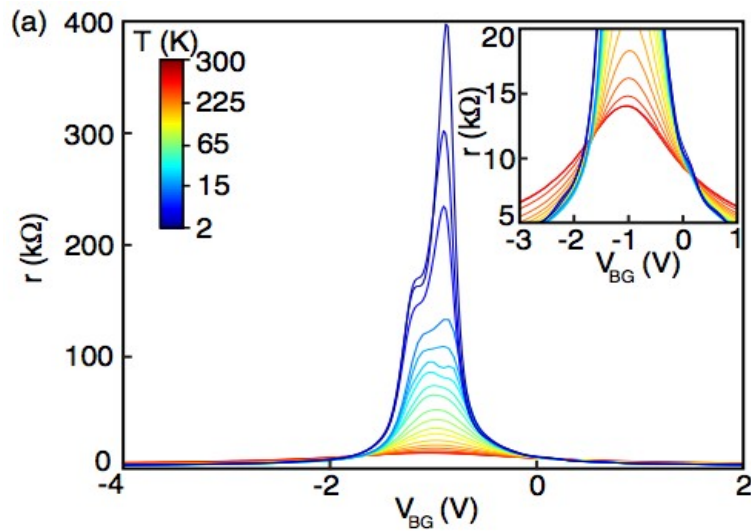
F. Amet, et. al., Phys. Rev. Lett., 110, 216601 (2013) (Stanford)
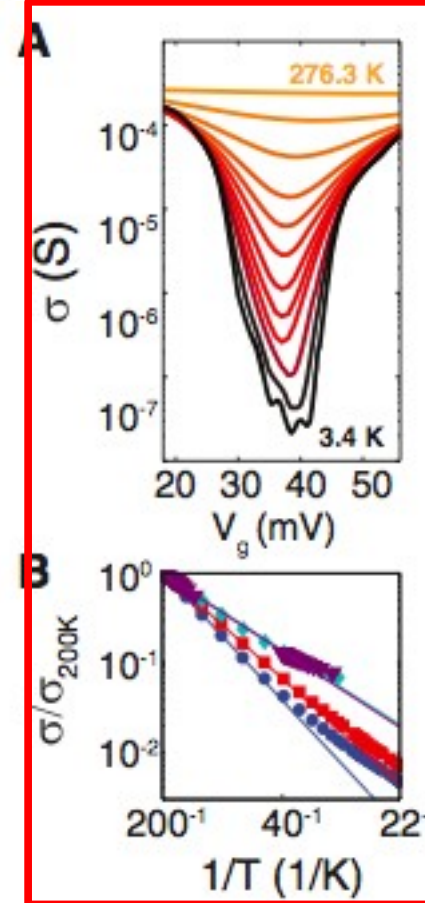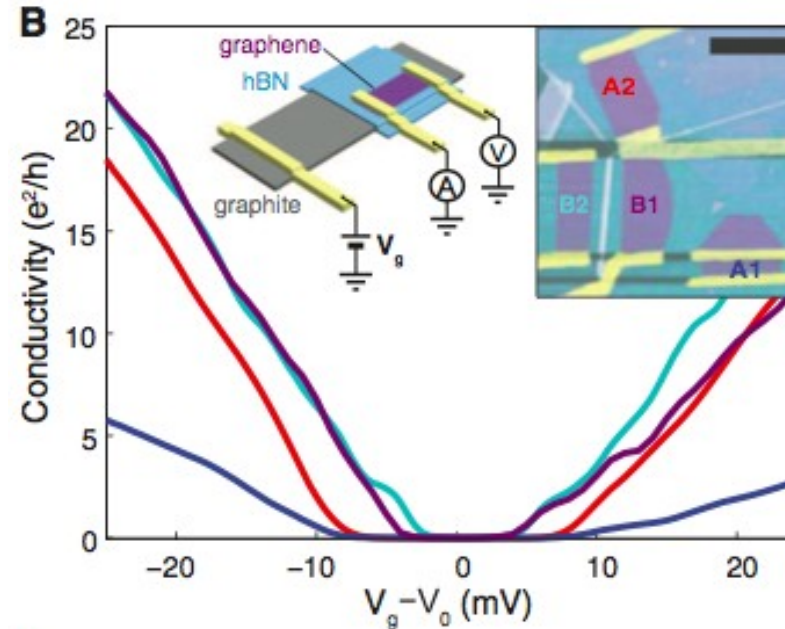
B. Hunt, et. al., Science, 340, 1430 (2013) (MIT Group)

CR Woods, et.al. arXiv: (2013) (Manchester Group)
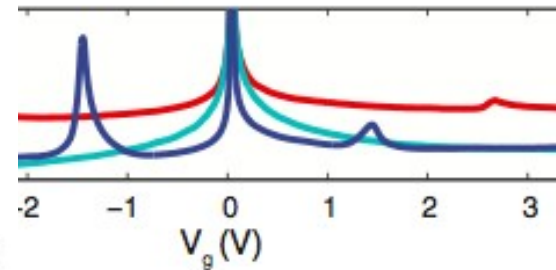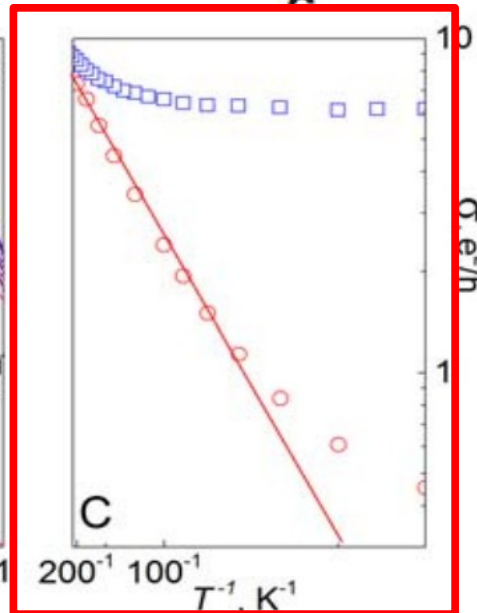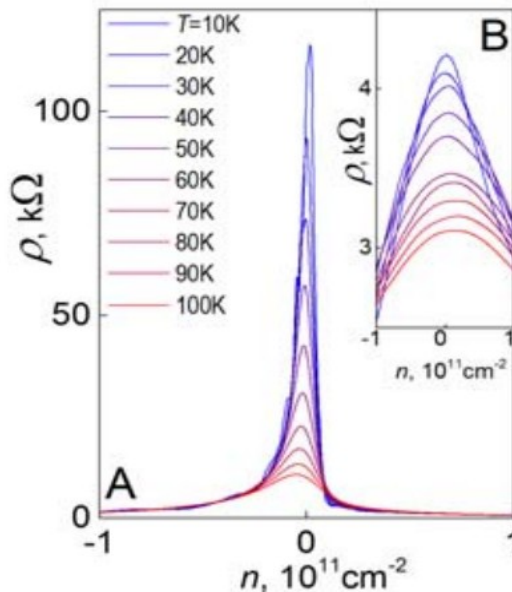
Activated behavior gap Δ~200-400 K

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)
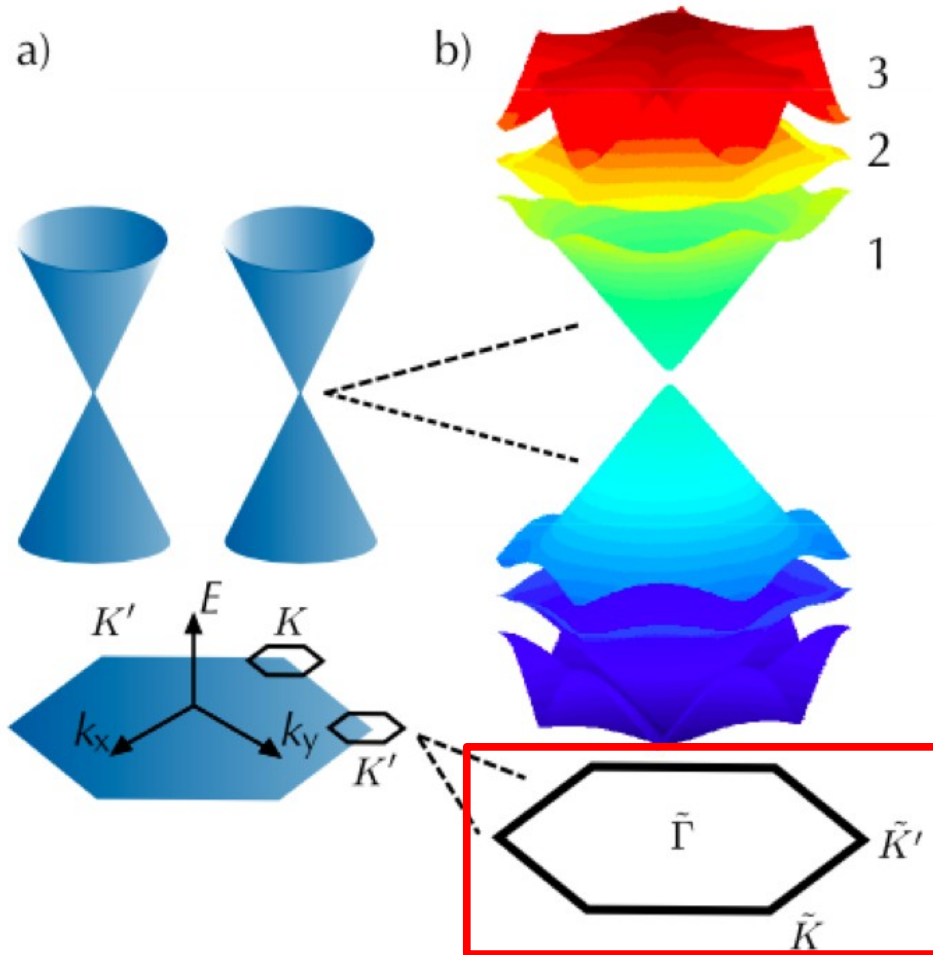
Incommensurate (moire) chirality/mass sign changing
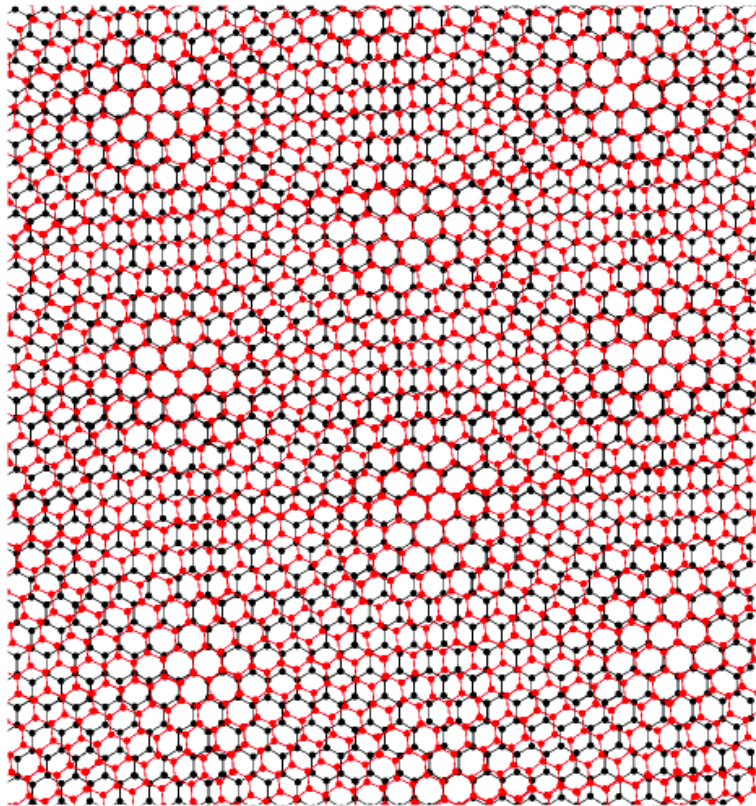
Dean et.al. Nature 497, 213 (2013)
Ponomarenko et al Nature 497, 594 (2013)

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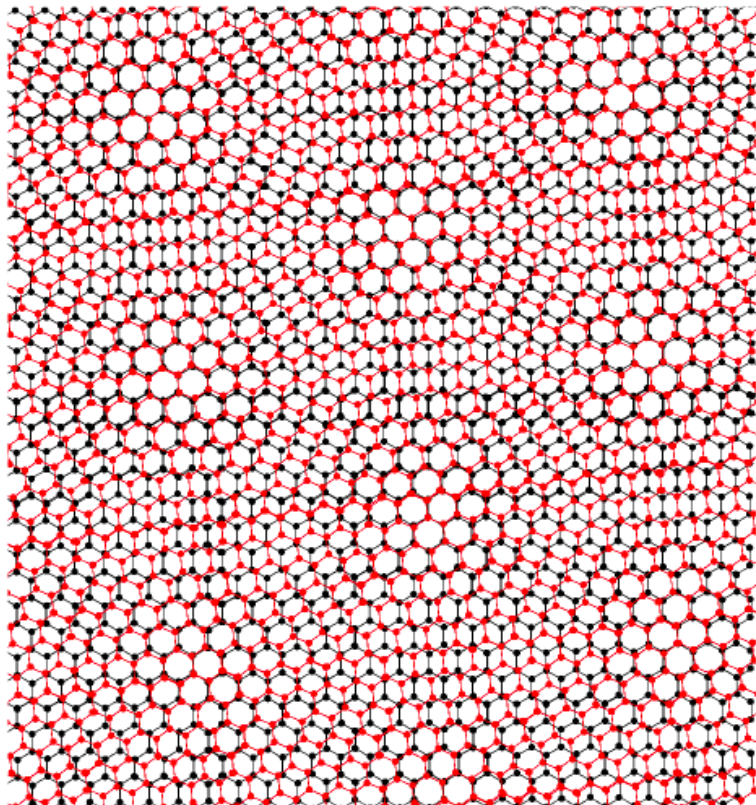
Commensurate stacking global A/B asymmetry global gap

Dean et.al. Nature 497, 213 (2013)
Ponomarenko et al Nature 497, 594 (2013)
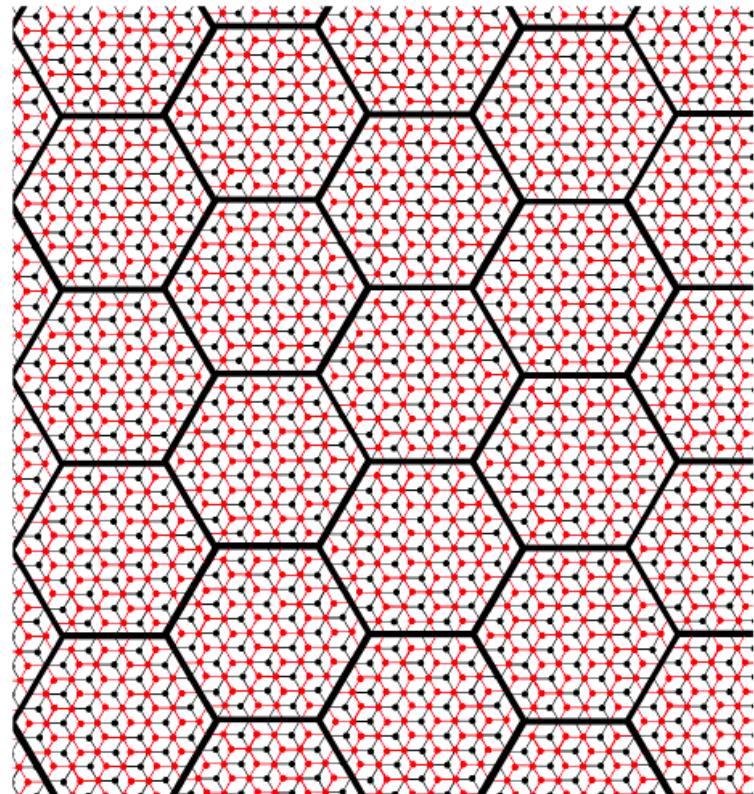
Kiev 24.10.2015
Woods, et.al. Nature Phys 10, 451 (2014)

Low-energy Hamiltonian

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

Constant global gap at DP

$$m(\mathbf{x}) = \Delta + m \sum_{j=1}^{6} e^{i\mathbf{b}_j \cdot \mathbf{x}}$$
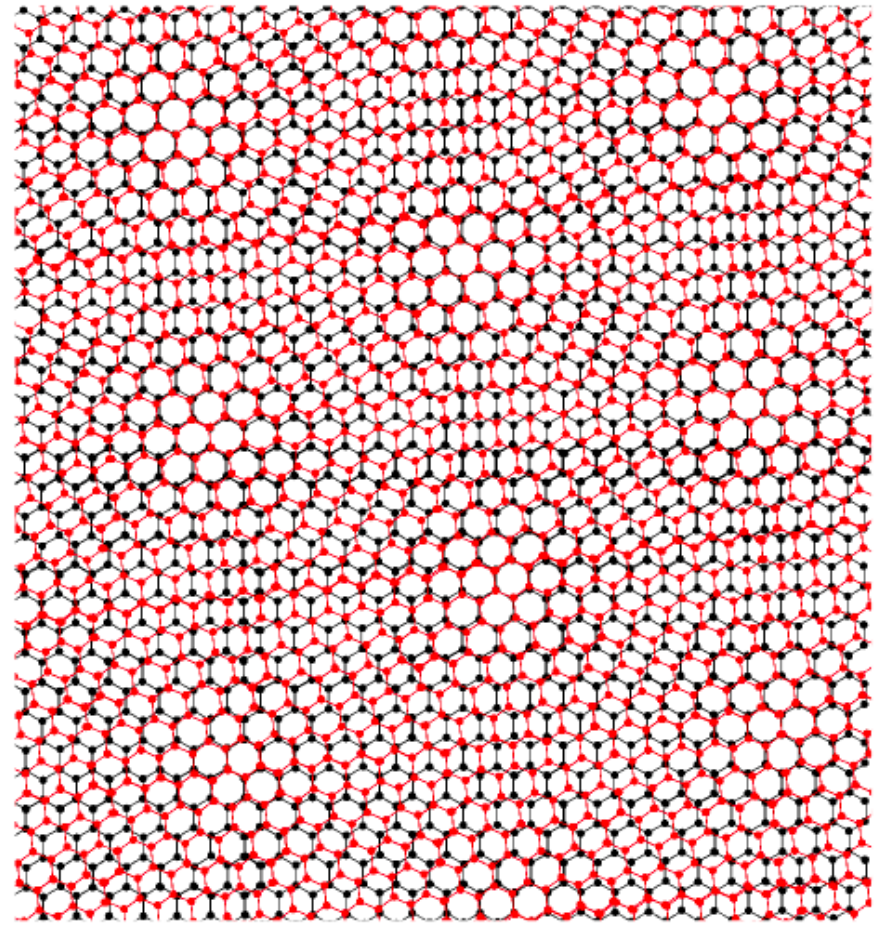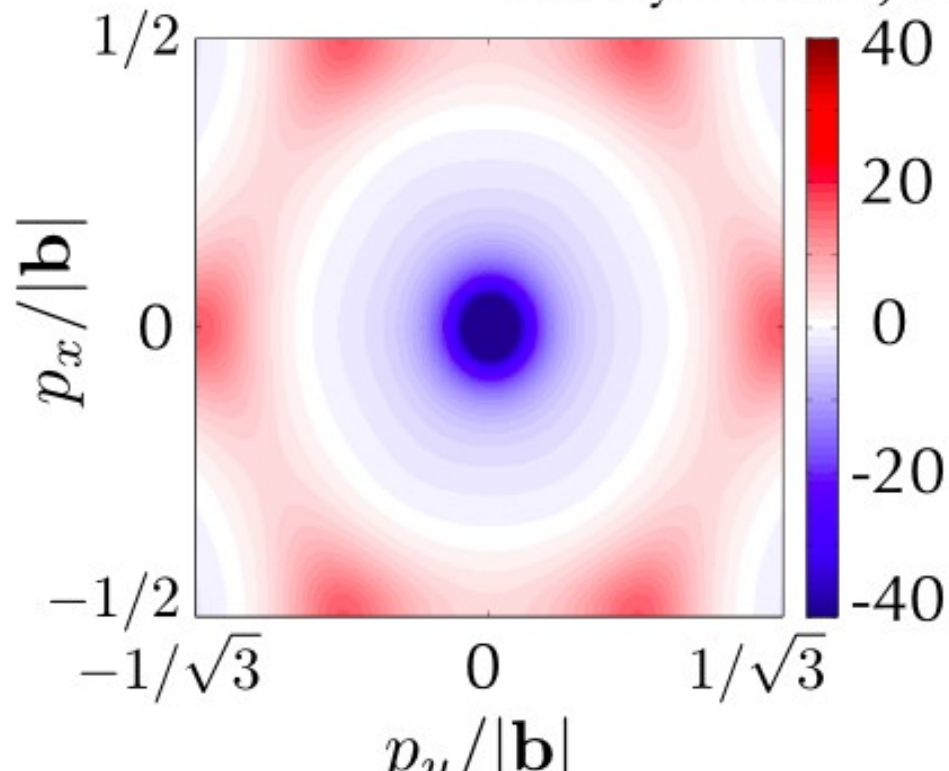
Spatially varying gap, Bragg scattering

Focus on one valley

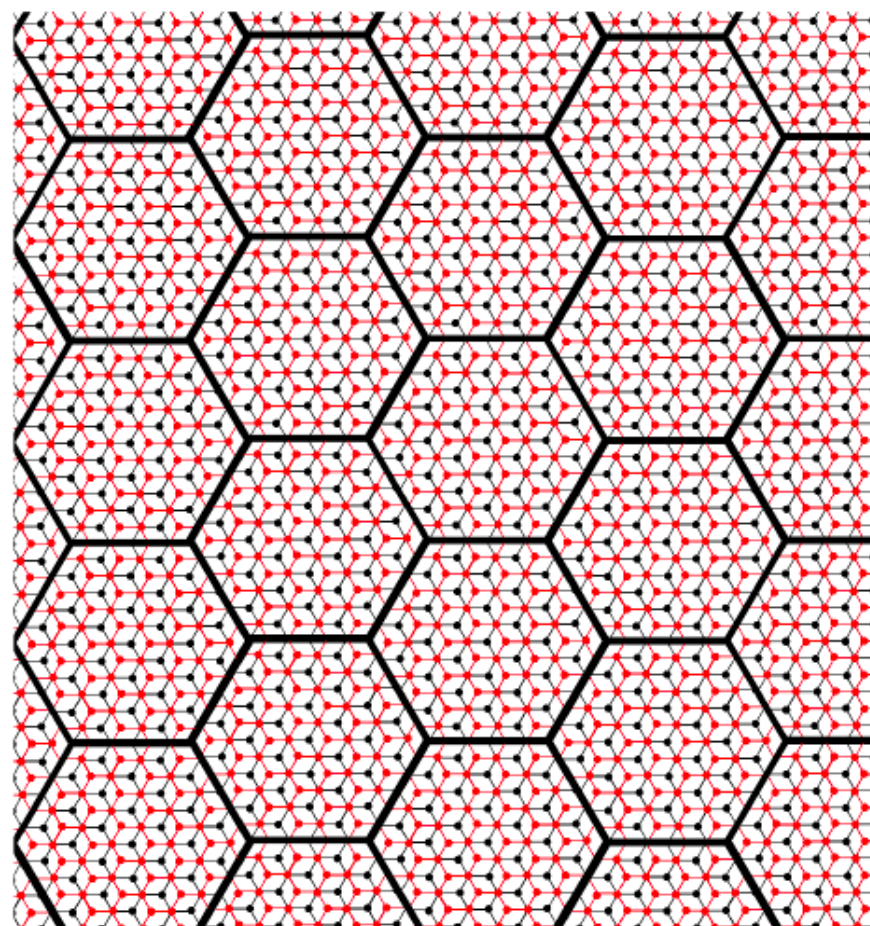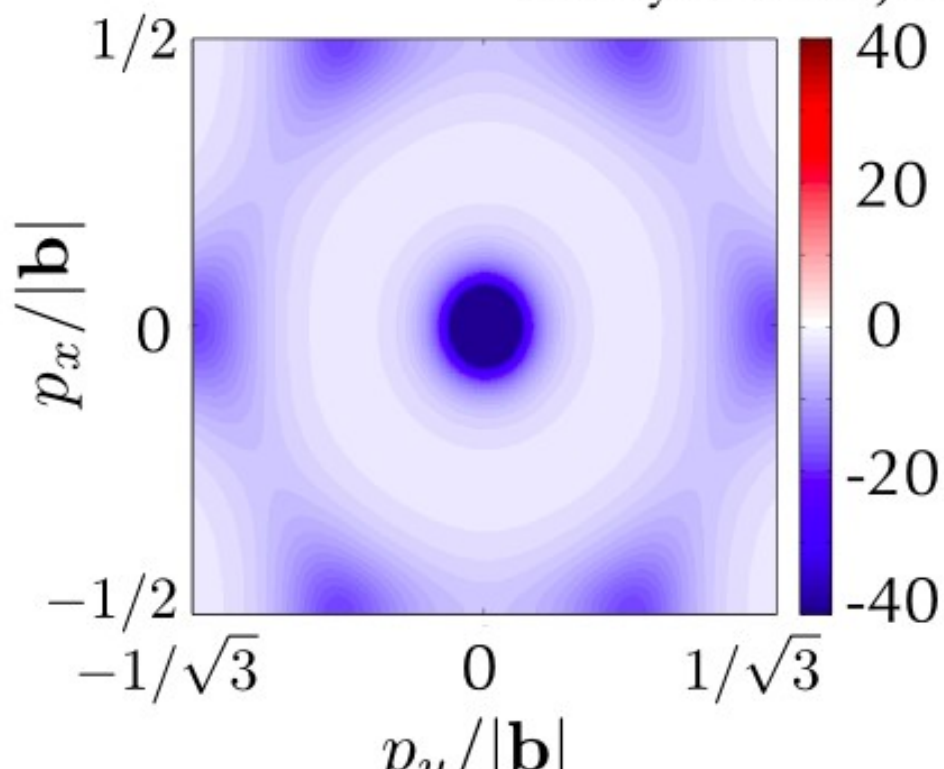a)

b)

Song, Samutpraphoot, LL arXiv (2014)

Incommensurate/Moire case

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

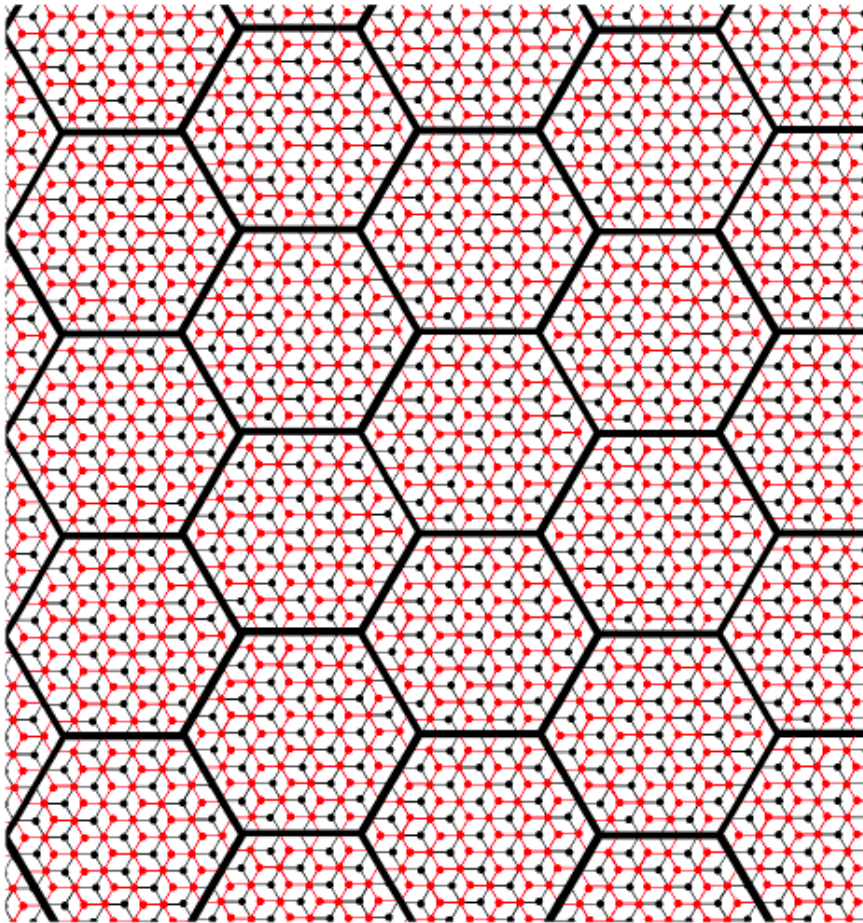$$m(\mathbf{x}) = \Delta + m \sum_{j=1}^{6} e^{i\mathbf{b}_j \cdot \mathbf{x}}$$

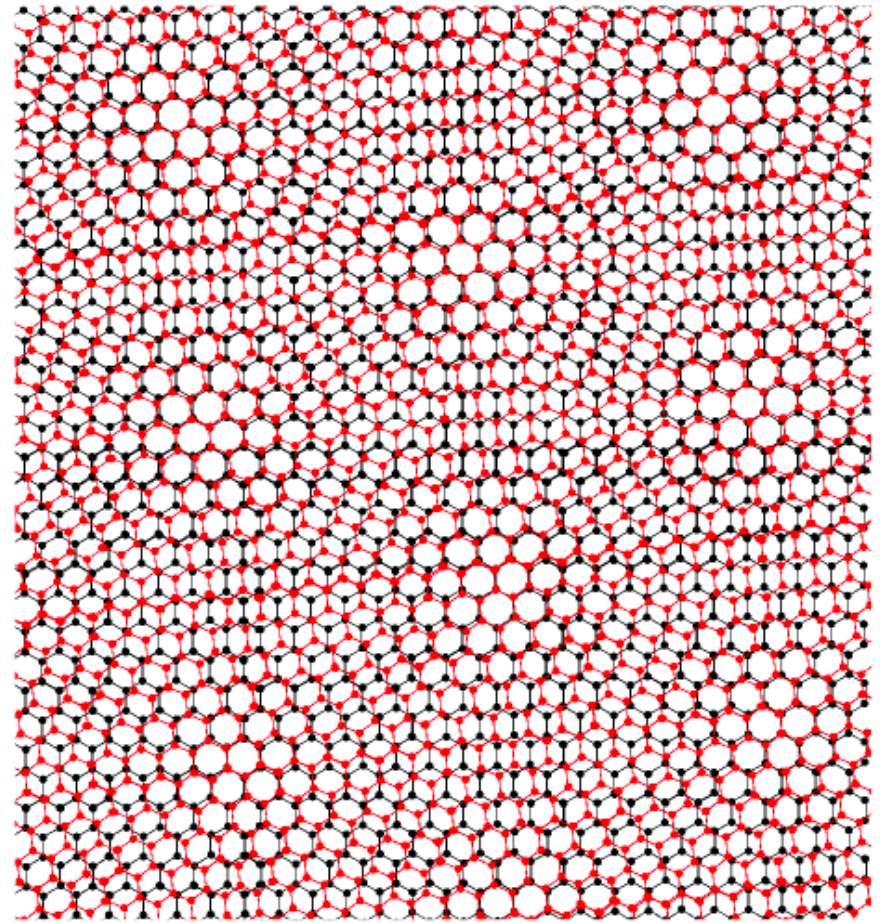$$\mathrm{sgn}(\Delta) = -\mathrm{sgn}(m)$$

Berry's Flux, Ω

4.10.2015

Commensurate case

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

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

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

Berry's Flux, Ω

24.10.2015

Band topology tunable by crystal axes alignment

Topological bands C=1

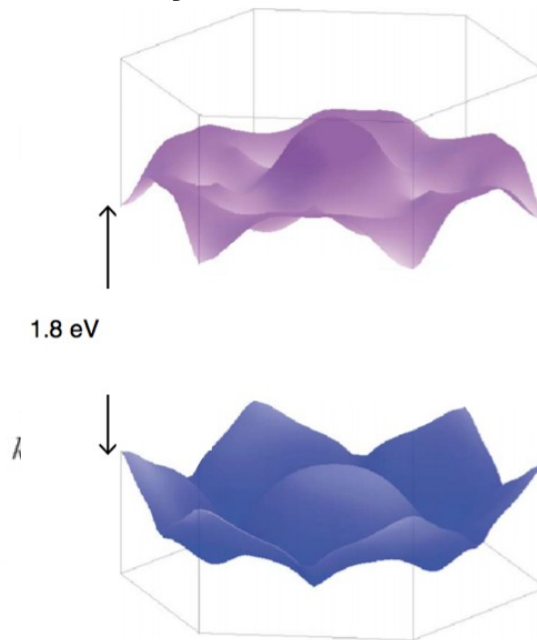## Trivial bands C=0

Kiev 24.10.2015

Berry curvature and Valley transport

Kiev 24.10.2015
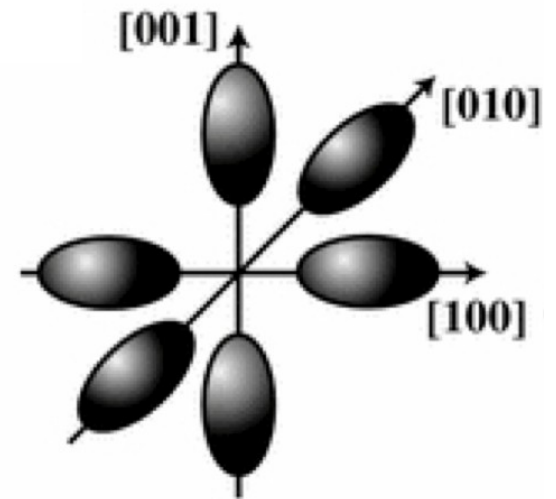
Valley currents

Valleys in Graphene
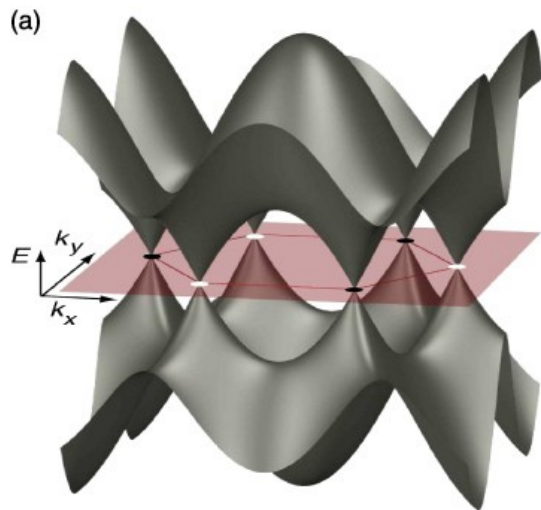
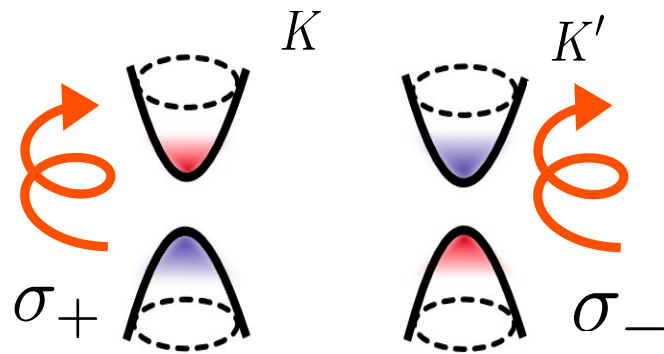Valleys in MoS2

Valleys in Bulk Si

Berry curvature

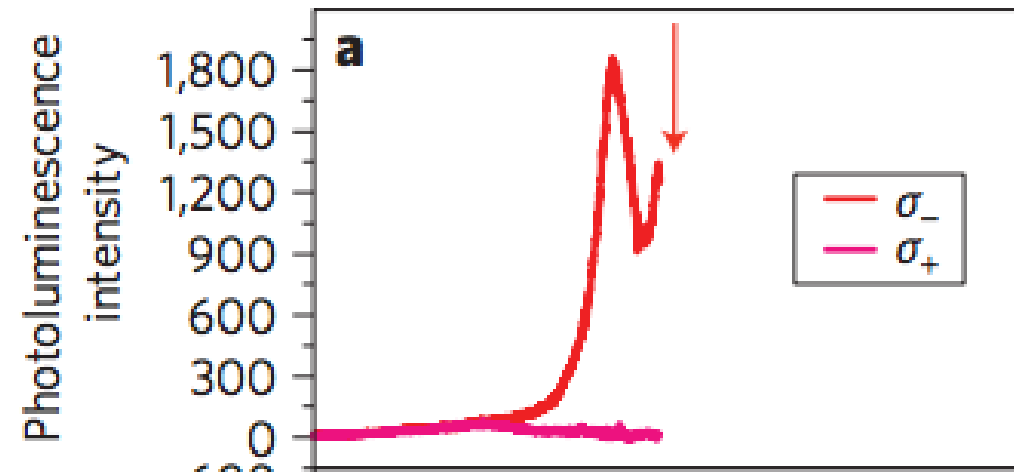$$\sigma^v_{xy} \neq 0$$

No Berry curvature

$$\sigma^v_{xy} = 0$$

Optical control of valleys

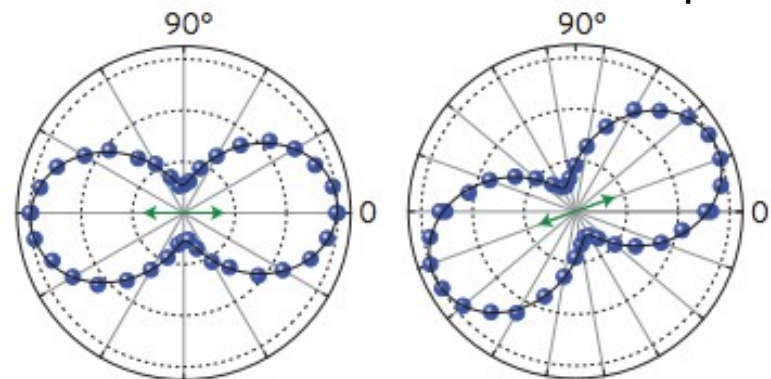## Optical selection rules: individual valley control

PL (MoS2) after shining σ‑

Long-lived Intervalley coherences (WSe2)

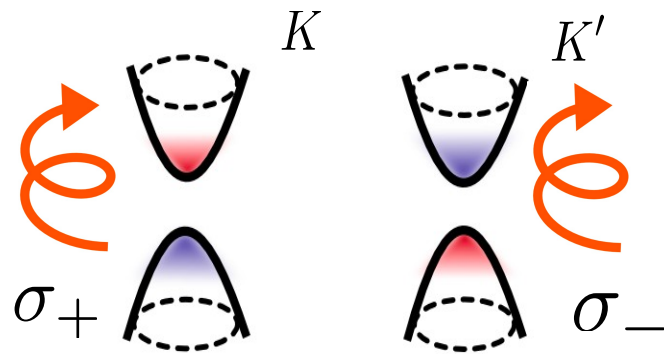PL polarization tracks excitation polarization
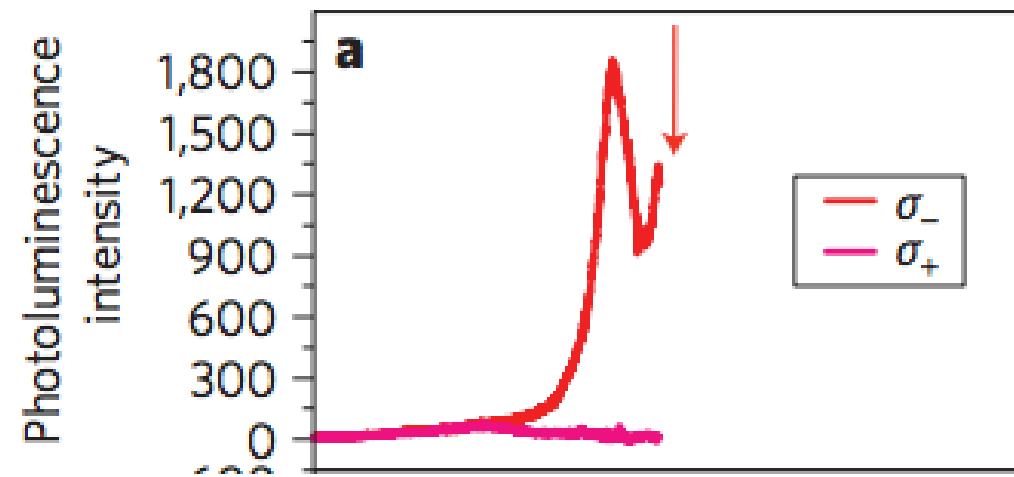

Kiev 24.10.201

Jones et. al. , Nat. Nano (2013)
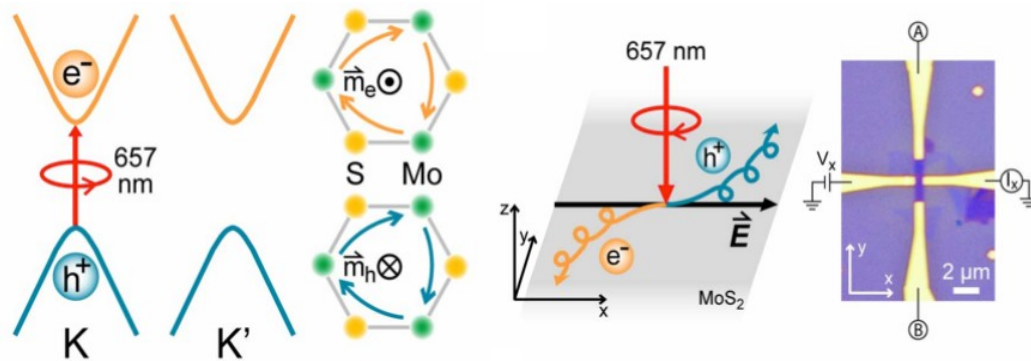
Optical control of valleys

Optical selection rules: individual valley control

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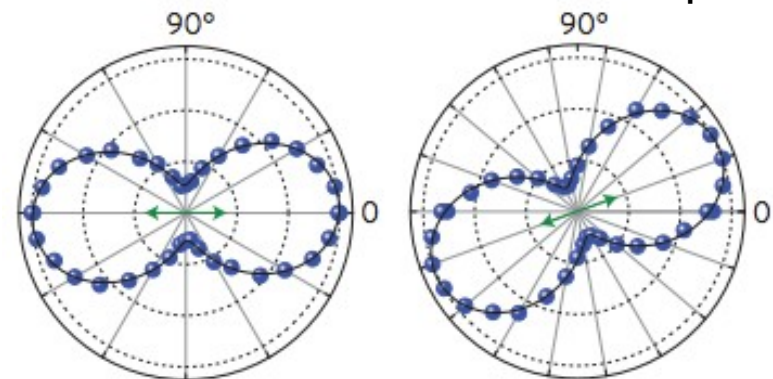

Valley-Hall effect via optically excited photocurrent

Mak *et al* arXiv:1403.5039 (2014)
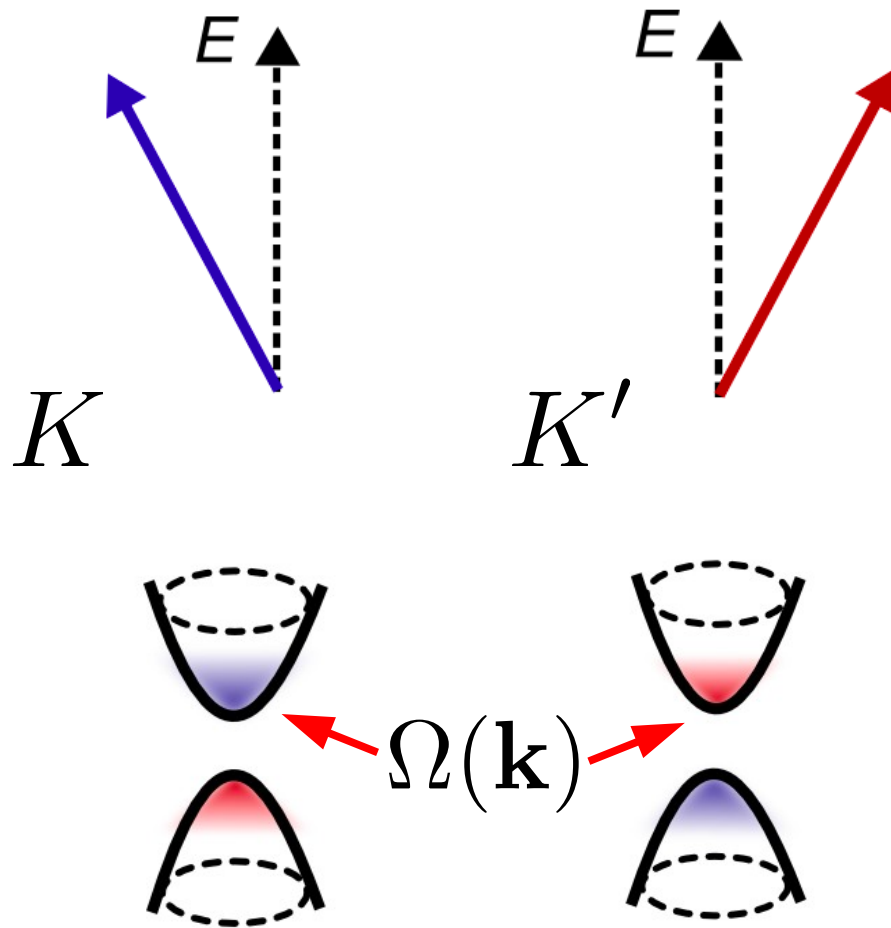
Long-lived Intervalley coherences (WSe2)

PL polarization tracks excitation polarization

Kiev 24.10.201

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

Use Berry curvature to electrically manipulate valleys

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

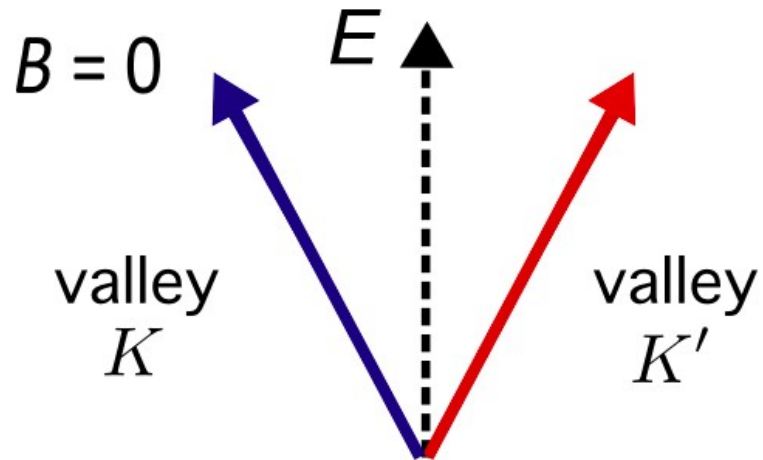$$\dot{\mathbf{k}} = e\mathbf{E} + e\mathbf{v_k} \times \mathbf{B}$$

Valley Hall effect:
Transverse charge-neutral currents

$$\vec{J}_v = \vec{J}_K - \vec{J}_{K'}$$
$$\vec{J}_v = \sigma^v_{xy}\ \vec{z} \times \vec{E}$$

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Detecting valley currents

$B = 0$

valley K

E

valley K'

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

Pump valley imbalance

K K'

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

1 3

Valley Current (Neutral)

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

2 4

Kiev 24.10.2015

Detecting valley currents

$B = 0$

valley K valley K'

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

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1   **3**

Valley Current (Neutral)

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2   **4**

Valley Hall Effect (VHE):

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

Reverse Valley Hall Effect (RVHE):

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

Kiev 24.10.2015

Detecting valley currents

$B = 0$

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Pump valley imbalance

K

K'

Z_0

V_S

Z_S

Z_L

Image credit: wikipedia.com

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

1

3

Valley Current (Neutral)

$$\mathbf{J}_v = \mathbf{J}_K - \mathbf{J}_{K'}$$
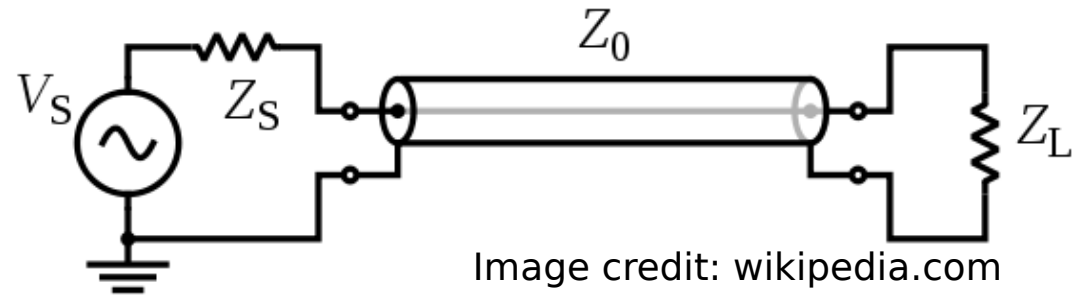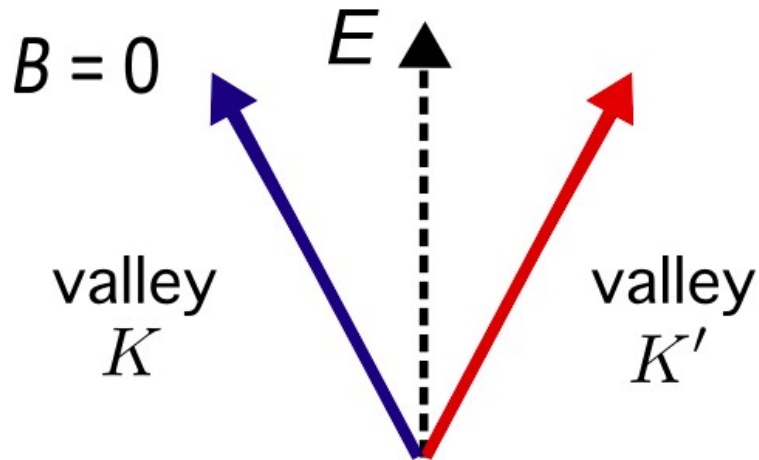
2

4
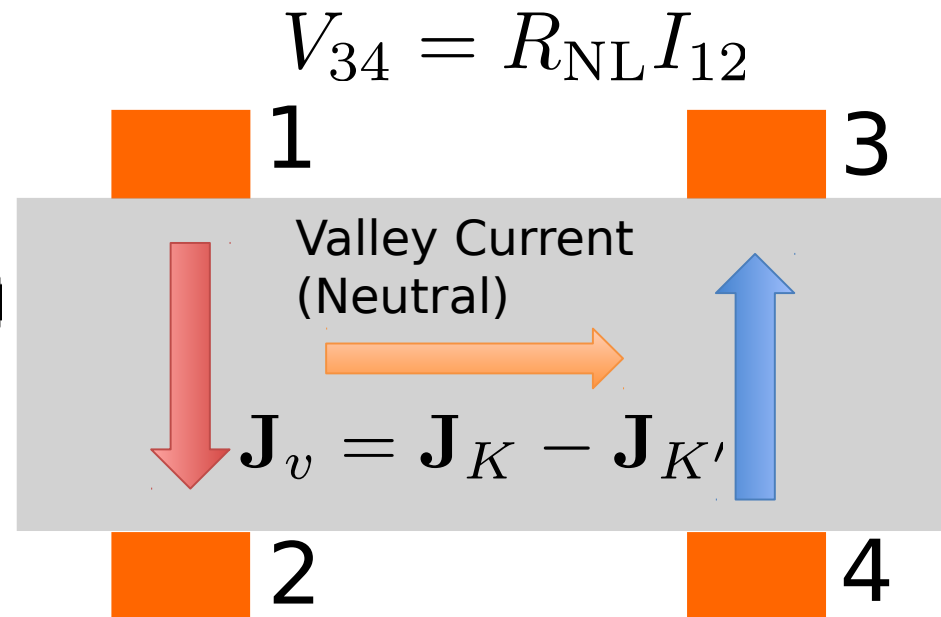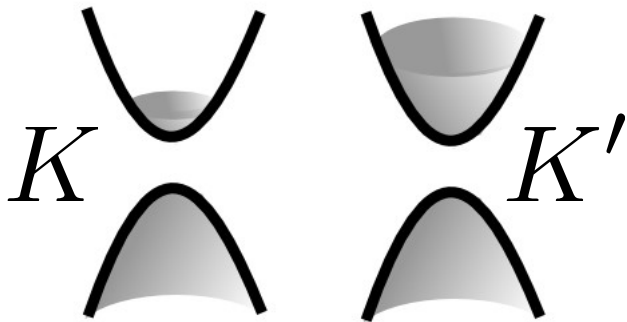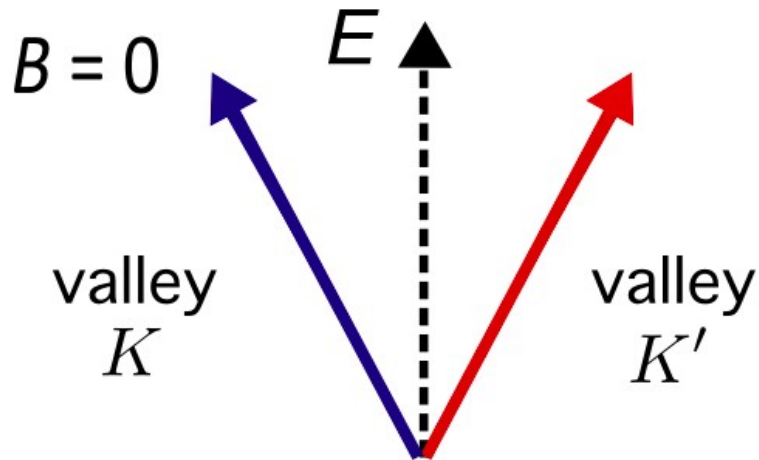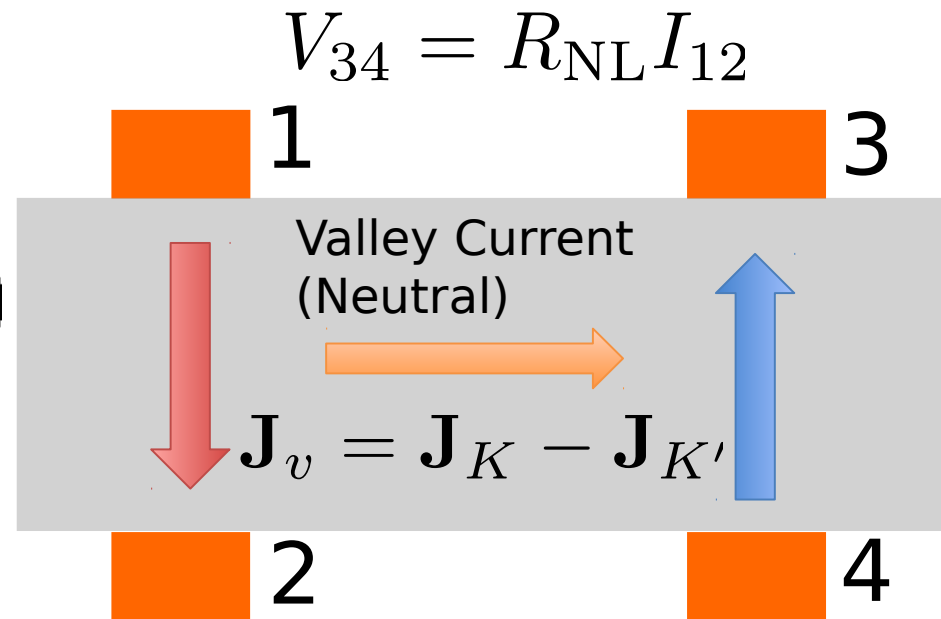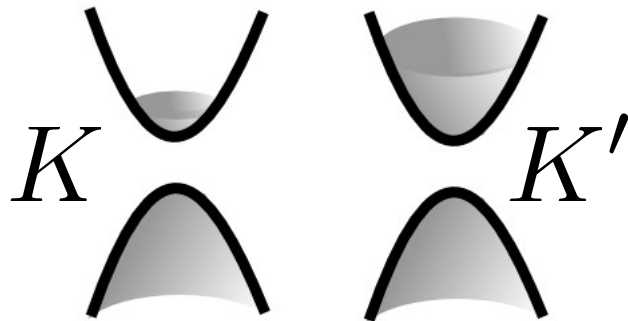
Valley Hall Effect (VHE):

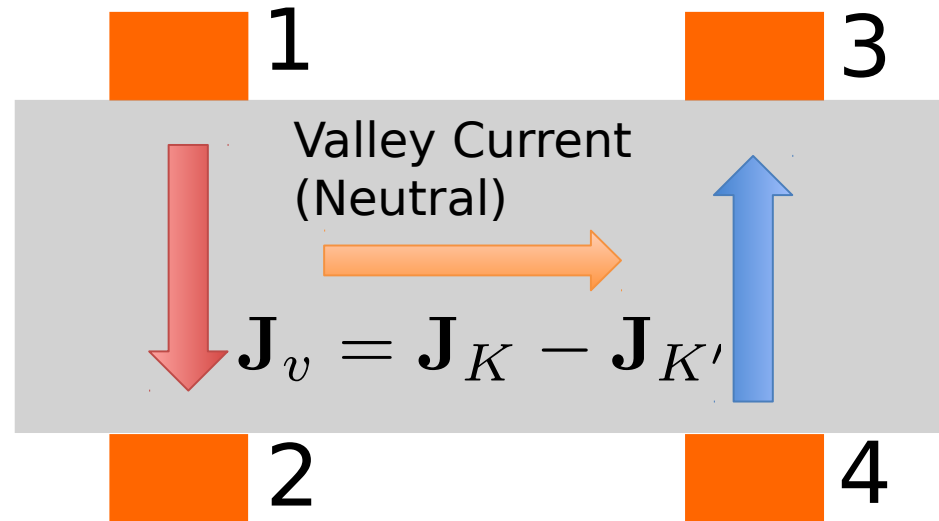$$\mathbf{J}_v = \frac{\sigma_{xy}^{v}}{\sigma}\mathbf{j}\times\hat{\mathbf{z}}$$

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Reverse Valley Hall Effect (RVHE):

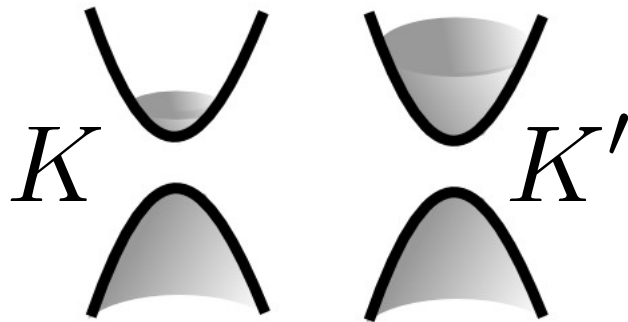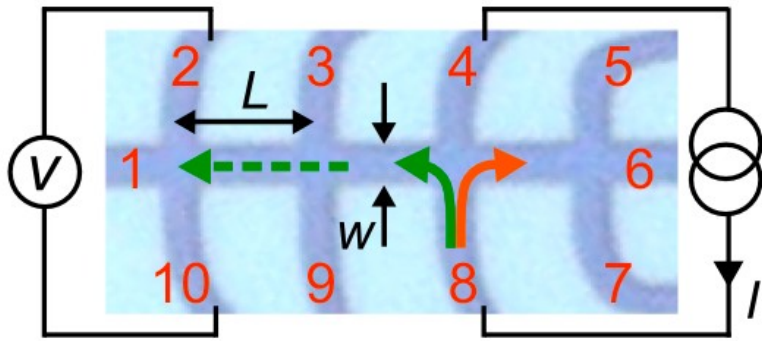$$\mathbf{E} = -\frac{\sigma_{xy}^{v}}{\sigma^2}\mathbf{J}_v\times\hat{\mathbf{z}}$$

Nonlocal response in aligned G/hBN

Manchester
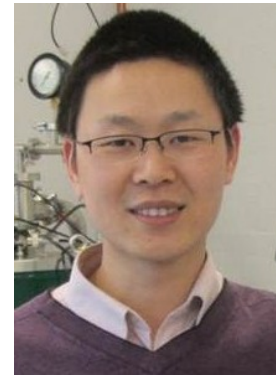
Andre Geim   Geliang Yu

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

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

Berry hot spots

Gorbachev, Song et al (2013) (Manchester & MIT)

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Gorbachev, Song et al (2013) (Manchester & MIT)

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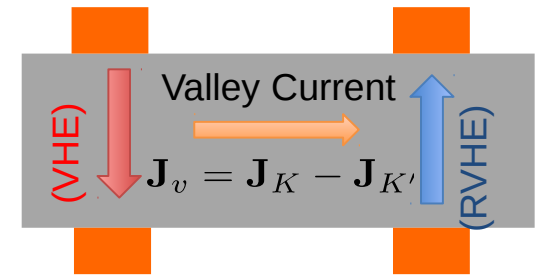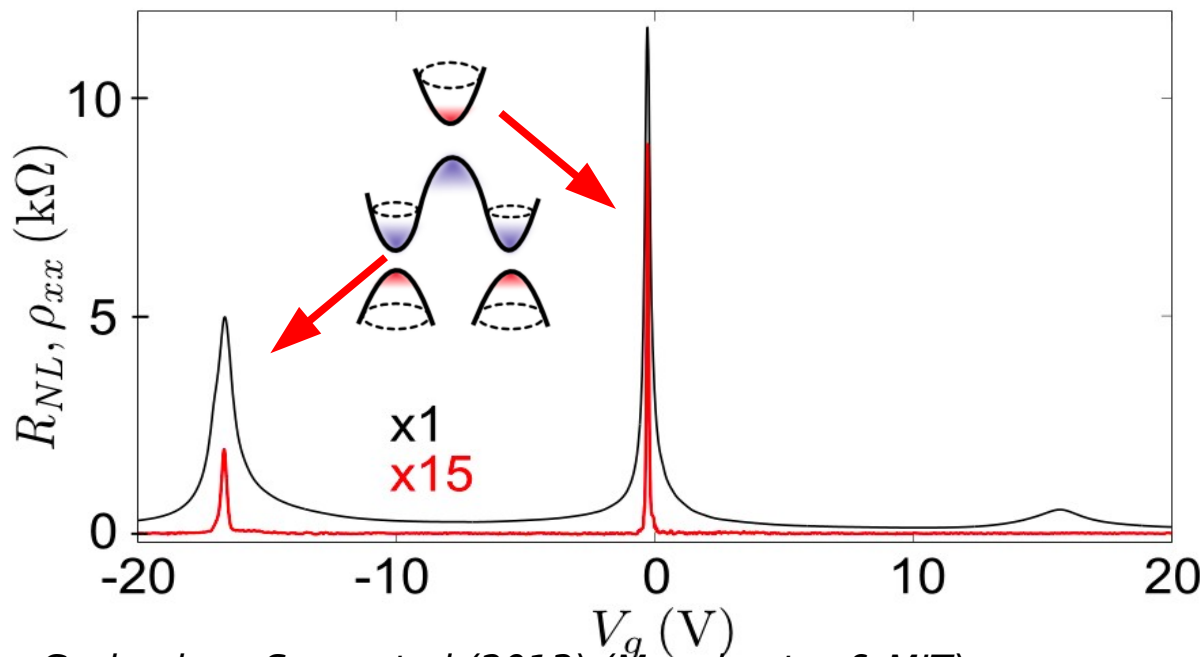
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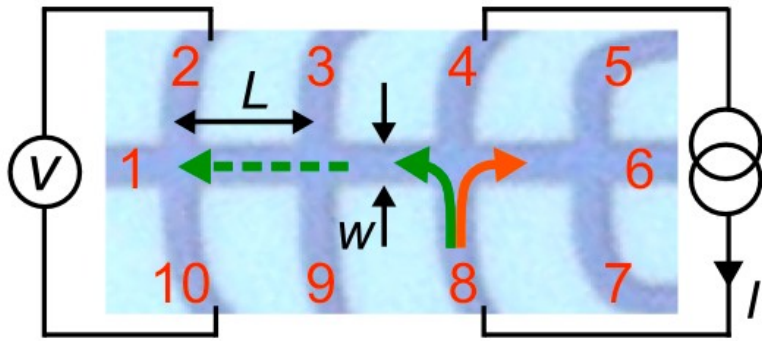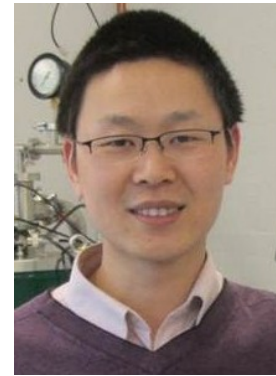Van der Pauw bound: $R_{\mathrm{NL}}^{VdP} \approx \rho_{xx} e^{-\pi L/w}$

Berry hot spots

Distance dependence

$$R_{\mathrm{NL}} \propto (\sigma_{xy}^v)^2$$

Gorbachev, Song et al (2013) (Manchester & MIT)

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 ρ_{xx} as expected for valley currents

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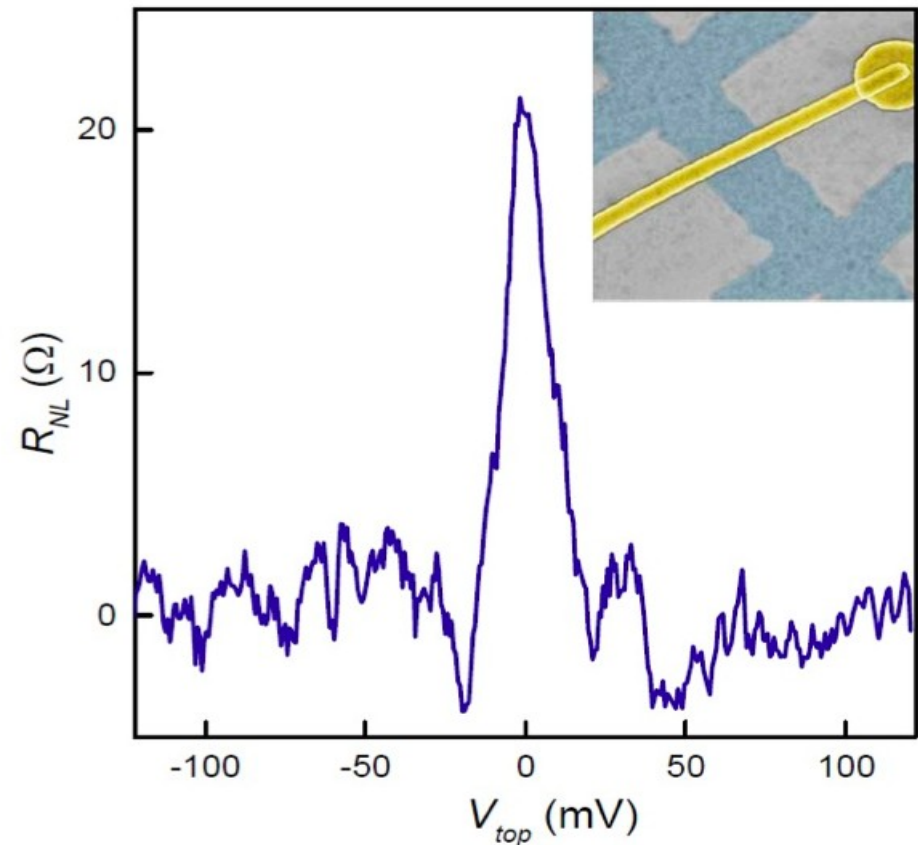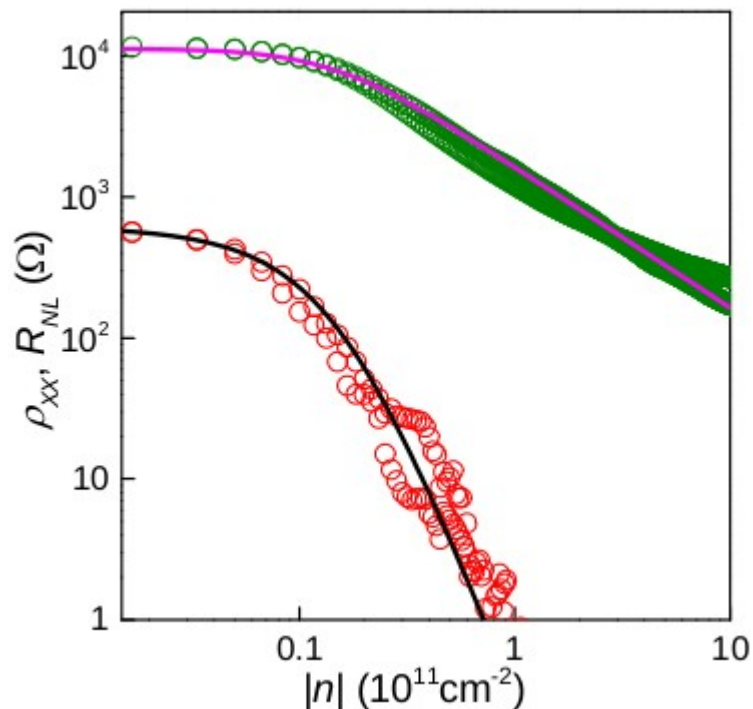
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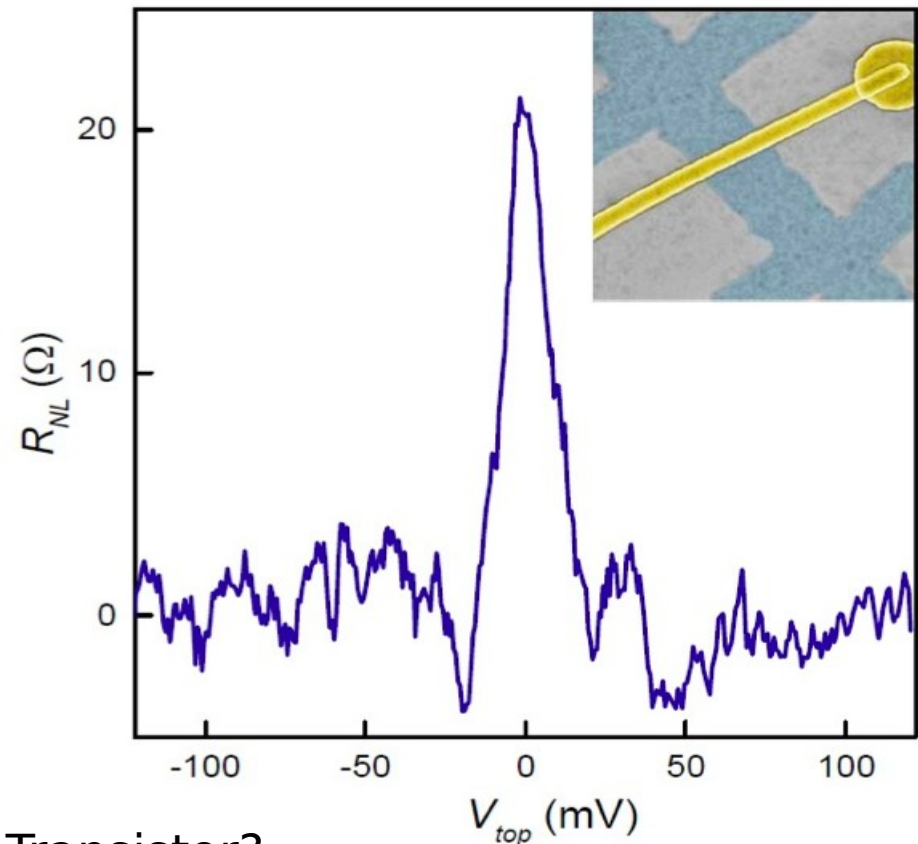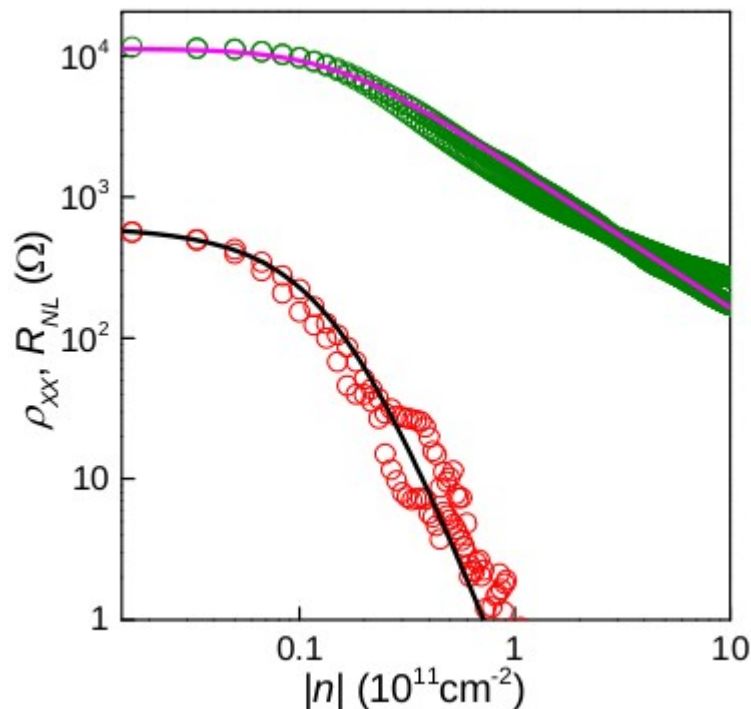
Spin Transistor?
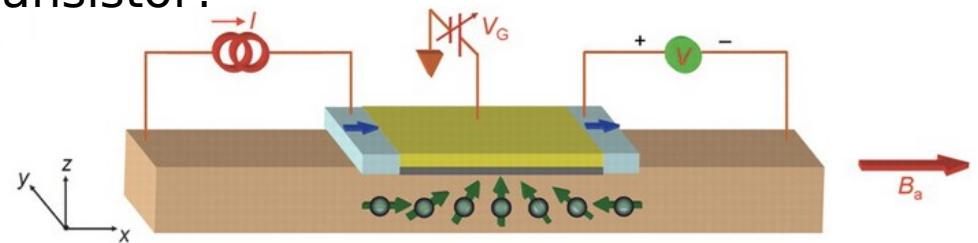
Koo, et. al., Science (2009), see also
Wunderlich, et. al. , Science (2010)
Original Proposal: Datta, Das, APL (1990)

Kiev 24.

Future

1) Measure Chern numbers
(separately gated VHE injection
and detection regions)
2) Waveguides for valley
currents
3) Valley population accumulation (optical
probes)
4) Valley currents in 1D channels (graphene
boundary, BLG domain walls and p-n
junctions)

Valley Current

(VHE)

(RVHE)

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

Kiev 24.10.2015
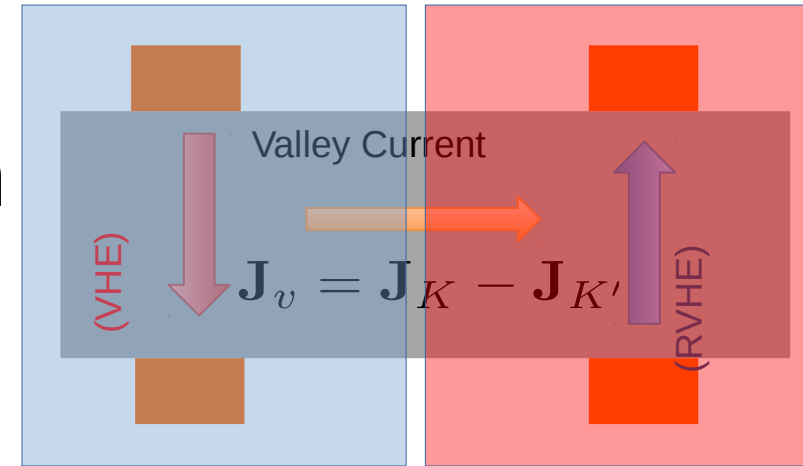
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Enrichment programs for highschool students, bachelor and master students

Leonid Levitov (levitov@mit.edu)

Education & Students & Research as seen from MIT-Physics

- **Research University model: many benefits over traditional models**
- **Research labs on campus, open to ALL students**
- **Research experience is a vital part of education**
- **Toy research morphs into real research**
- **Education and research are integrated (via students)**

Education & Students & Research:
UROP program

- **From a faculty perspective, UROP students are one of the best things about MIT. Undergraduates who spend time in your lab, working on research. Full of creativity and energy. Can be the spark that lights a fire. And they don't cost much**
- **From an undergraduate student perspective, UROP-ing is one of the best things to do at MIT. Real research experience. Jump in and then learn to swim. Sense of accomplishment. And you get paid, too**
- **Guiding UROP students toward careers in nnovation and research, in industry or at universities**
- **Network w/ universities that have UROP e.g. Imperial UK & ETH Zurich; summer exchange of UROP students**
- **Exchange master students (much like UROP)**

MIT Summer programs

MIT does not offer a traditional open-enrollment summer school program where any high school student can come to campus to take courses and live in the dorms. However, several partner organizations run small, specialized programs on campus. If you'd rather study the human genome or build a robot than memorize this year's summer TV reruns, then you might try one of these:

Research Science Institute (RSI) brings together about 70 high school students each summer for six stimulating weeks at MIT. This rigorous academic program stresses advanced theory and research in mathematics, the sciences and engineering. Participants attend college-level classes taught by distinguished faculty members and complete hands-on research, which they often then use to enter science competitions. Open to high school juniors, the program is free of charge for those selected.

Women's Technology Program (WTP) is a four-week summer academic and residential experience where 60 female high school students explore engineering through hands-on classes (taught by female MIT graduate students), labs, and team-based projects in the summer after their junior year. Students attend WTP in either Electrical Engineering and Computer Science (EECS) or Mechanical Engineering (ME).

MIT Launch - a 4-week entrepreneurship program for high school students, teaching the entrepreneurial skills and mindset through starting real companies. Students go through rigorous coursework, collaborate with peers and mentors, and use the multitude of tools surrounding them at MIT to realize what it takes to be successful in the real world – resourcefulness, adaptability, and innovation. Many need-based scholarships are available.

While the Summer Science Program (SSP) is not on campus, MIT-co-sponsored science research program. With locations in New Mexico and Colorado, and many MIT students among the program's alumni/ae, students learn mathematics, physics, astronomy, and programming over the program's 6 weeks. The curriculum is organized around a central research project: to determine the orbit of a near-earth asteroid (minor planet) from direct astronomical observations

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Note:
1) All programs are (highly) competitive but buy your lottery ticket
2) Some are officially `for high school students' but in fact also accept international undergrads;
3) Some require $$ but selection is on merit, never money-based
4) Some are free to all selected students and some even pay you

and innovation. Many need-based scholarships are available.

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Education & Students & Research:
International summer schools

- Boulder Summer School (Master, PhD level)
- MPI Dresden (PhD&Master)
- Les Houches (PhD&Master)
- Weizmann Summer program (international undergrads)
- Windsor Summer School (Master&PhD)
- Also: ICTP Trieste, Dynastia (?)
- Deadlines, $$

Other selective Summer programs

Most summer programs admit all or most students who can pay the (high) tuition. However, a number of competitive-admission summer programs select only the best students on the basis of merit and are often free or comparatively affordable. MIT offers four of our own (above); here are a few more:

Science & Research Programs

BU Research Internship Program

Clark Scholar Program

Garcia Summer Scholars

High School Summer Science Research Program (HSSSRP)

High School Honors Science/Mathematics/Engineering Program (HSHSP)

International Summer School for Young Physicists (ISSYP)

Secondary Student Training Program (SSTP)

Stanford Institutes of Medicine Summer Research Program (SIMR)

Student Science Training Program (SSTP)

QuestBridge College Prep Scholarship

Math Summer programs

AwesomeMath

Canada/USA Mathcamp

Hampshire College Summer Studies in Mathematics (HCSSiM)

Honors Summer Math Camp (HSMC)

MathILy

Program in Mathematics for Young Scientists (PROMYS)

The Ross Program

Stanford University Mathematics Camp (SUMaC)

Prove It! Math Academy