TOPOLOGICAL VALLEY CURRENTS IN GAPPED GRAPHENE

Leonid Levitov (MIT)

- **Berry phase in gapped graphene**
- **Valley Hall effect without edge states**
- **Detecting valley currents in G/hBN superlattices: an all-electrical approach**

NPSMP2015 symposium, ISSP, Tokyo University

Berry curvature and topological currents

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

Semiclassical eqs of motion:

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

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

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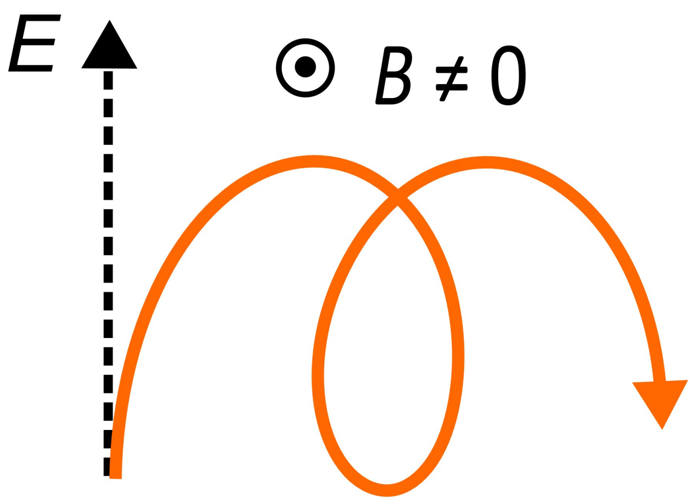
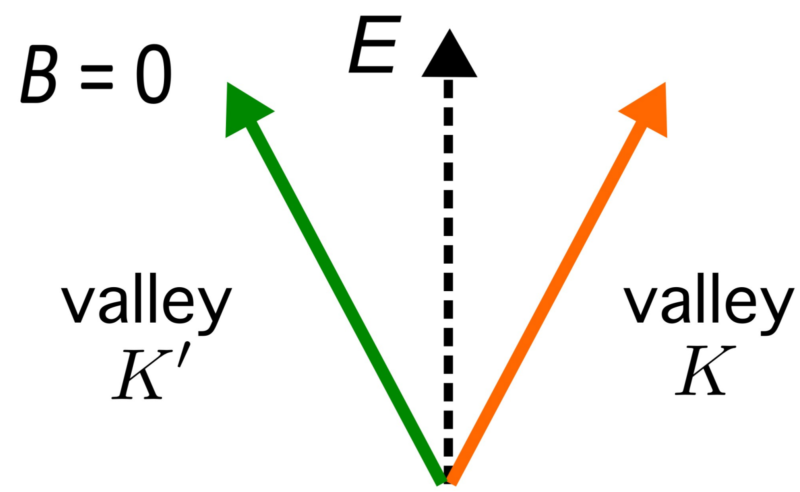
Hall currents at *B*=0





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

History and context

Karplus and Luttinger (1954), Blount (1955):
"anomalous velocity"

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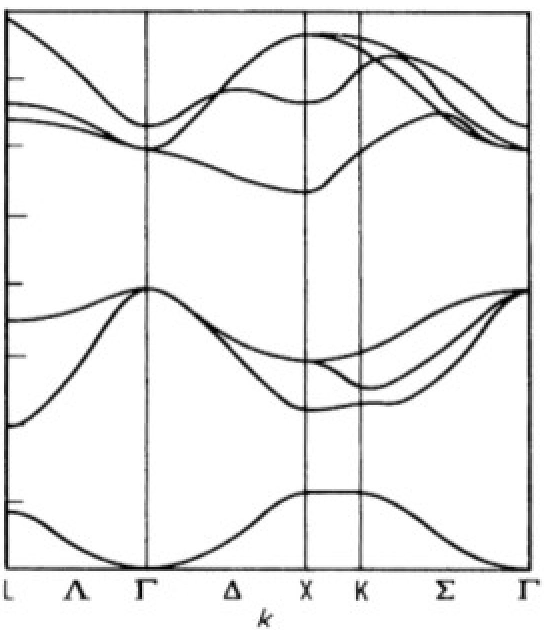

Confine particle to single band (no interband transitions)

Price of projection (constraint):
Anomalous Velocity and Berry phase

Modern Theory: Chang & Niu (1996), Sundaram & Niu (1999), Haldane (2002), Jungworth, Niu, MacDonald (2002), see also review by Nagaosa (2009) and references therein

Berry connection/Berry's vector potential

$$\Omega_n(\mathbf{k}) = \nabla_\mathbf{k} \times \mathbf{A}_n(\mathbf{k}), \quad \mathbf{A}_n(\mathbf{k}) = i\langle u_n(\mathbf{k})|\nabla_\mathbf{k}|u_n(\mathbf{k})\rangle.$$

Berry curvature

Bloch wavefunction

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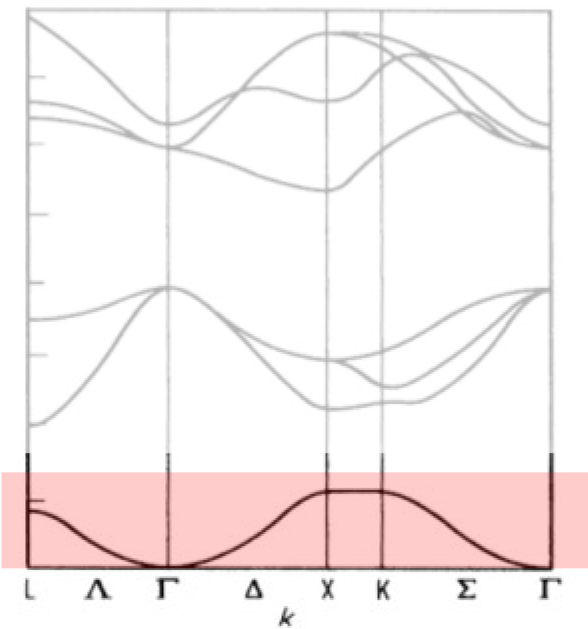

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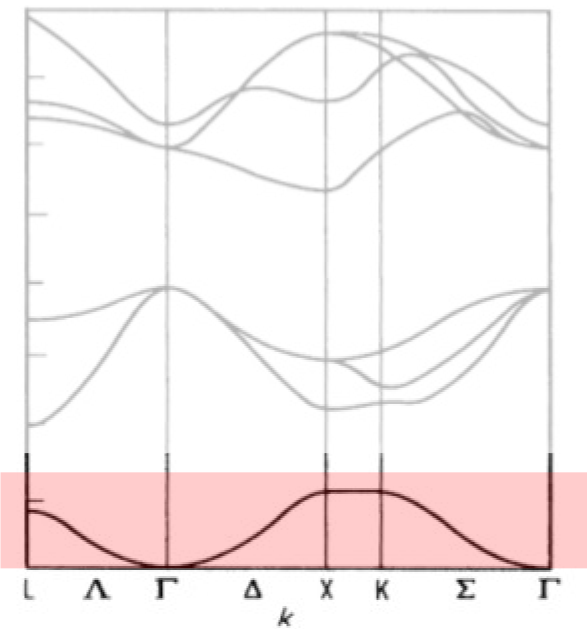

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Berry curvature

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Schematic derivation of anomalous velocity

$$H = V(\mathbf{R}) + \epsilon_n(\mathbf{k}),$$

Evolution of wavefunction picks up a Berry phase

Berry connection

$$\langle \mathbf{r}|\psi\rangle = u_{n\mathbf{k}}(\mathbf{r})e^{-i\chi(\mathbf{k})}$$ with $$\chi(\mathbf{k}) = -\int_C^{\mathbf{k}} d\mathbf{k}' \cdot A(\mathbf{k}')$$

Gauge this phase away: $\mathbf{x} = \mathbf{R} + A(\mathbf{k})$

$$H' = V(i\nabla_{\mathbf{k}} + A) + \epsilon_n(\mathbf{k})$$

$$[x_i,\ x_j] = i\epsilon^{ijk}\Omega_k.$$

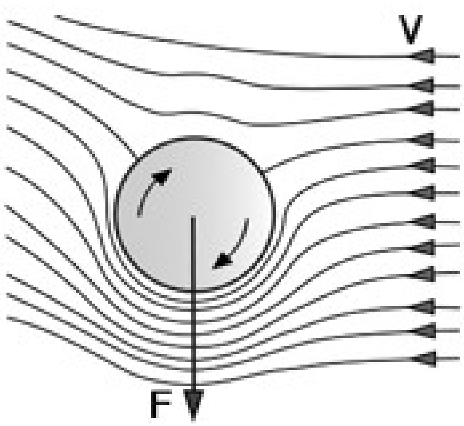
Equation of motion:

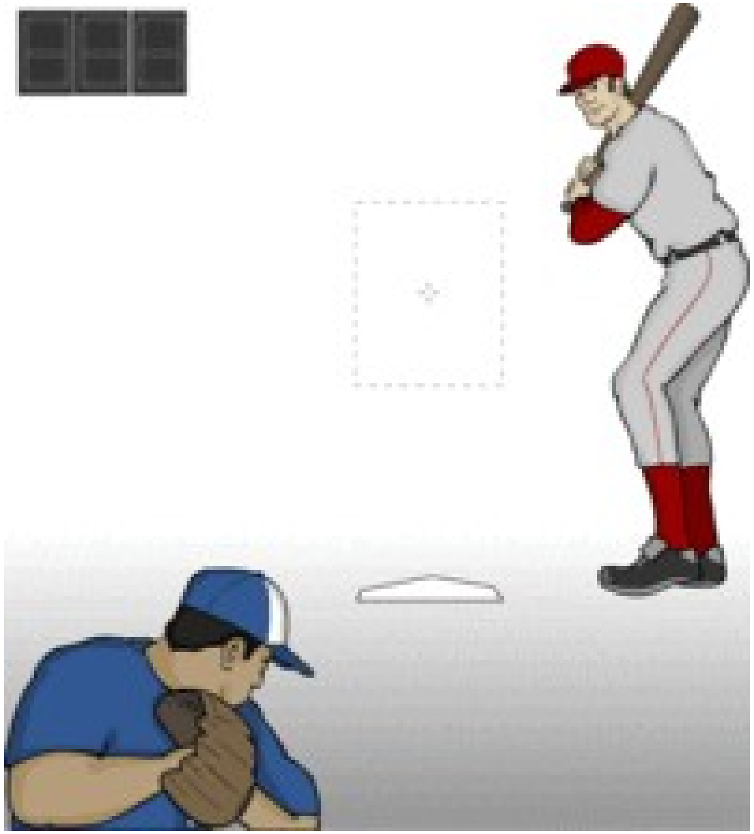
$$\hbar\mathbf{v} = -i[\mathbf{x}, H'] = \nabla_{\mathbf{k}}\epsilon_n(\mathbf{k}) + \left(\frac{\partial V}{\partial \mathbf{x}}\right) \times \mathbf{\Omega}(\mathbf{k}).$$

$$\Omega_n(\mathbf{k}) = \nabla_{\mathbf{k}} \times \mathbf{A}_n(\mathbf{k}),$$

Berry curvature

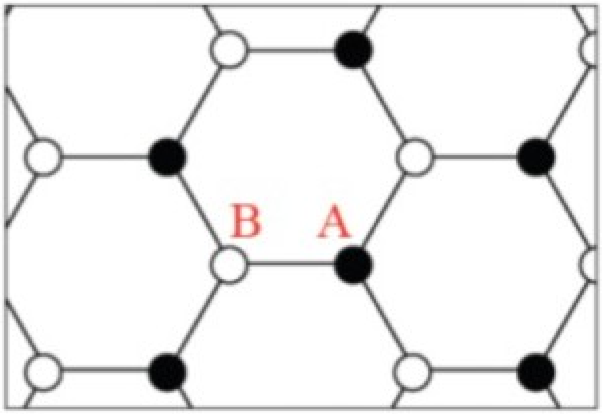
Analogy w/ Magnus effect





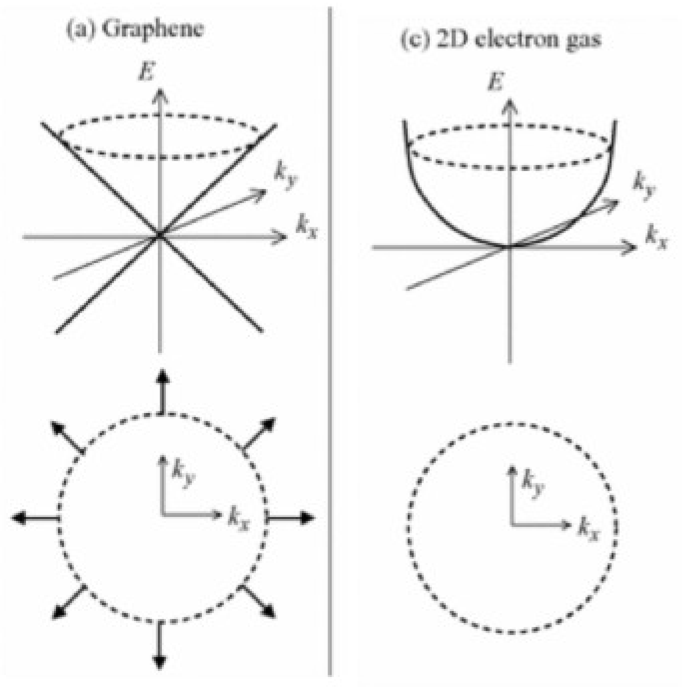
Berry phase, Berry curvature and gap opening in graphene

Berry phase in hexagonal lattice

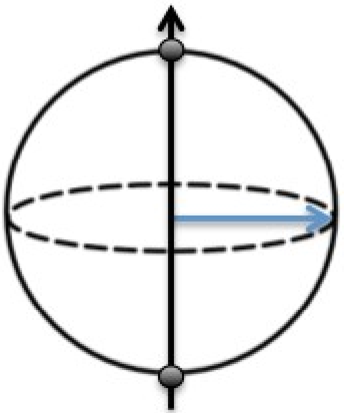


Spinor-type wavefuntion:

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



Map onto Bloch Sphere:

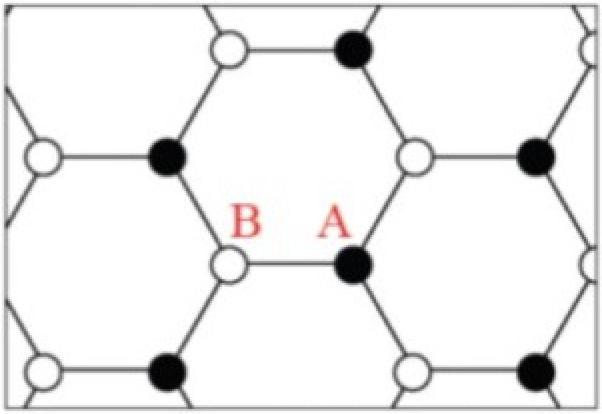


- Eigenvectors in x-y plane
- Berry's phase (full rotation)

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

Image Credit: Park and Mazari (2011)

Massive/gapped Dirac particles



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Finite $\Omega_n(\mathbf{k})$ can occur when either is broken

Time-reversal symmetry
$$\Omega_n(-\mathbf{k}) = -\Omega_n(\mathbf{k})$$

Inversion symmetry
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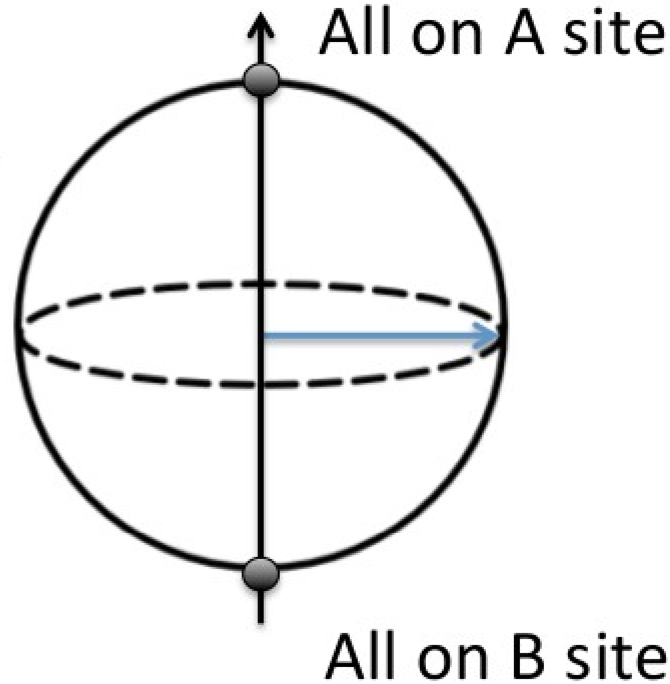

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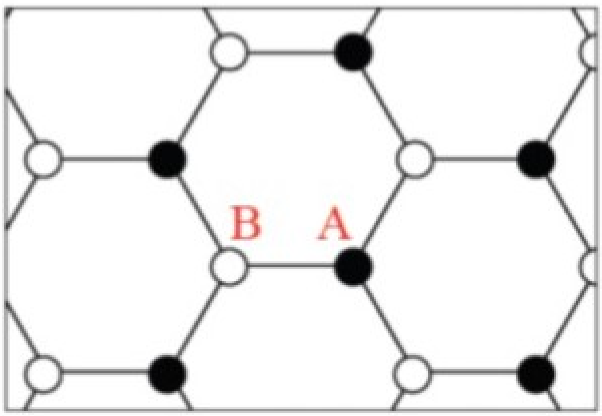

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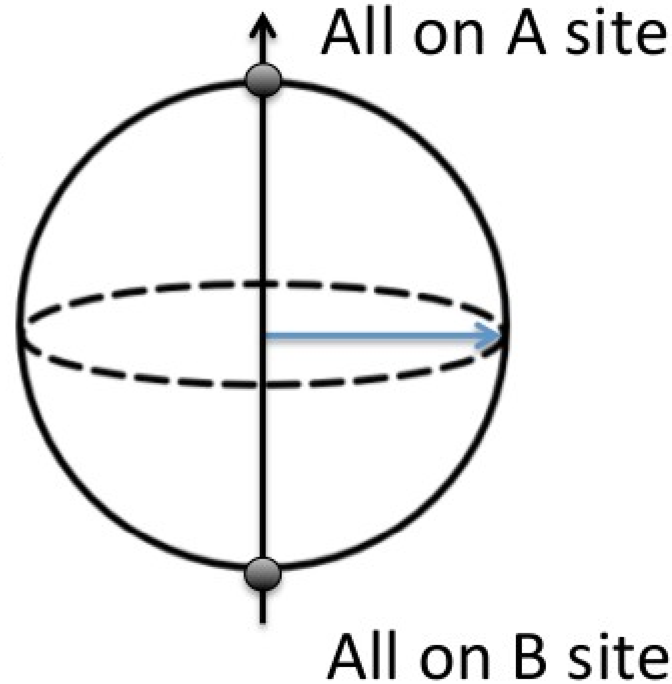

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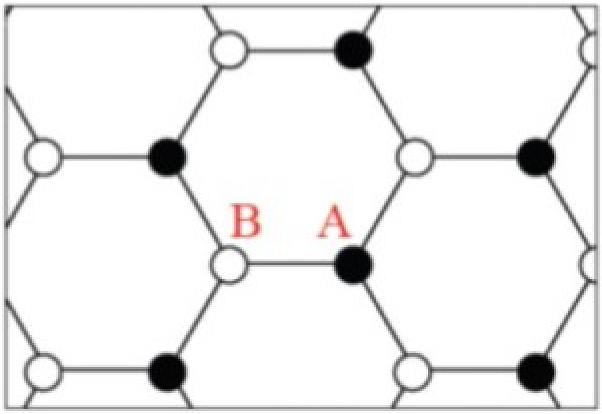

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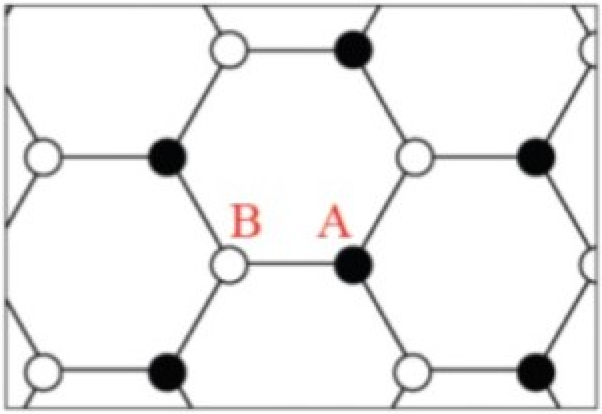
Magnetic AHE

Massive/gapped Dirac particles



A/B sublattice asymmetry a gap-opening perturbation

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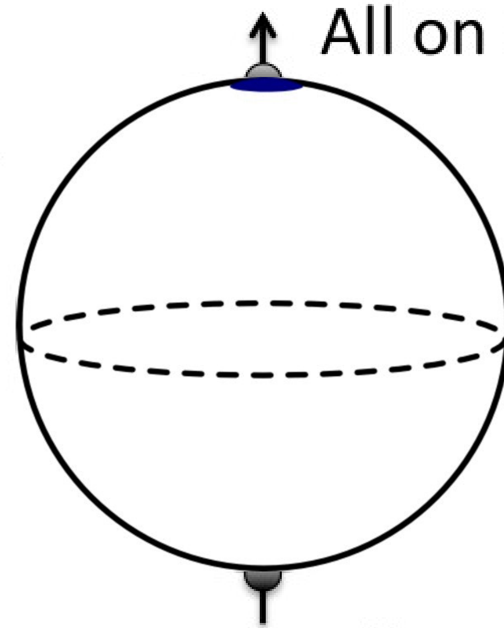
Valley or spin AHE



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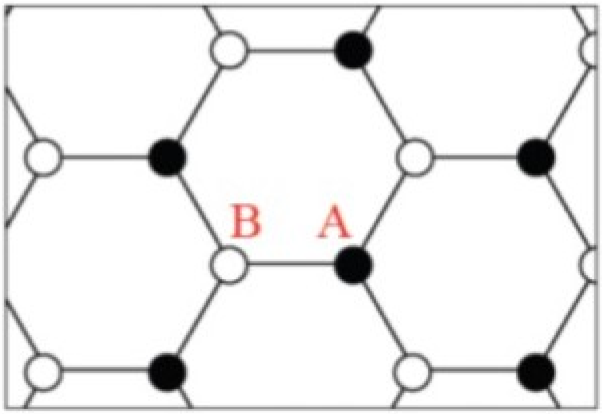
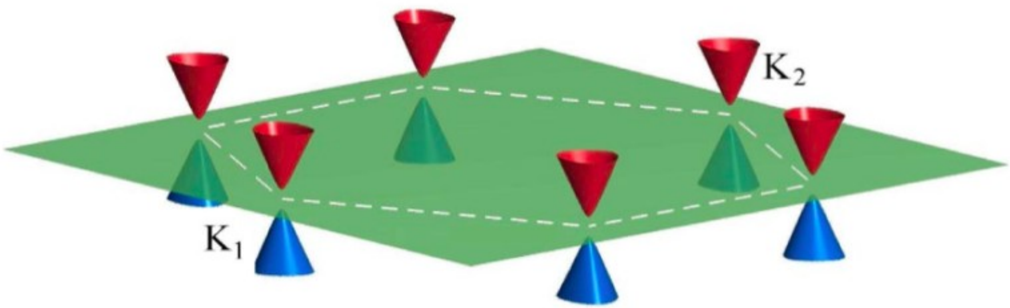
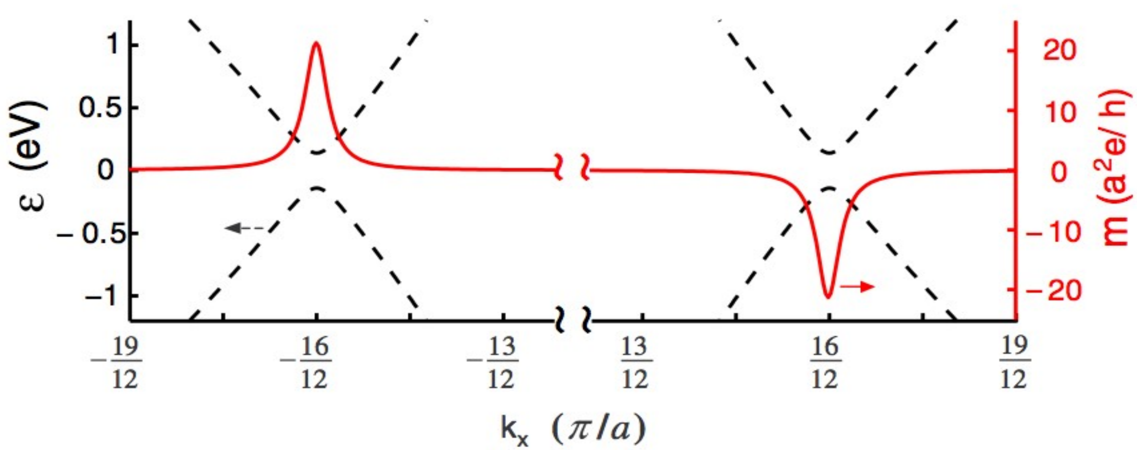
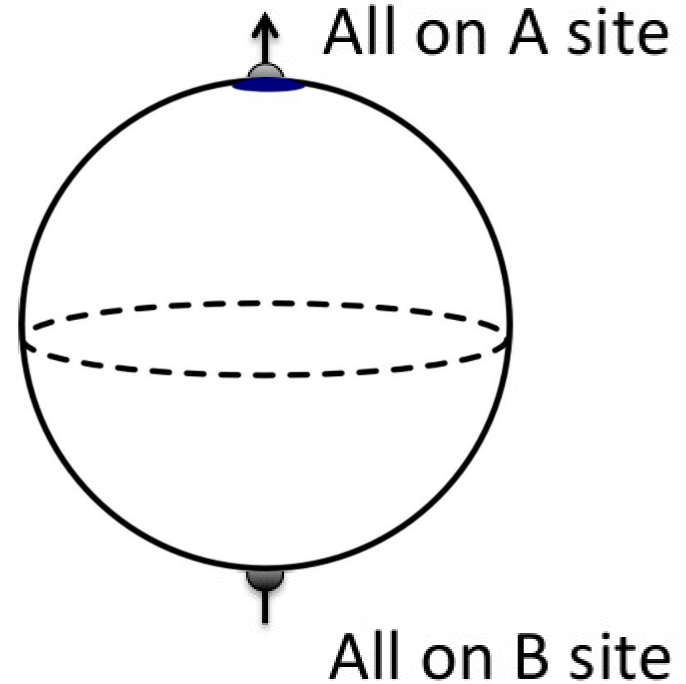
Berry curvature hot spots above and below the gap



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







Bloch Sphere

Create topological bands in graphene? (and play curveball)

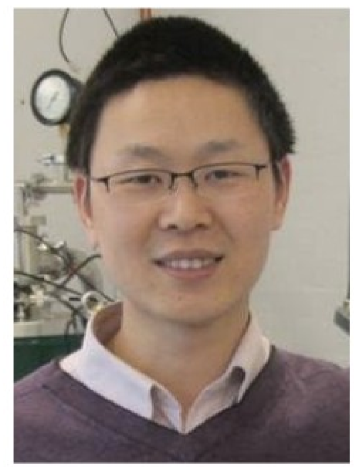
Justin Song

Polnop Samutpraphoot

Yuri Lensky

Andrey Shytov

Andre Geim



Geliang Yu

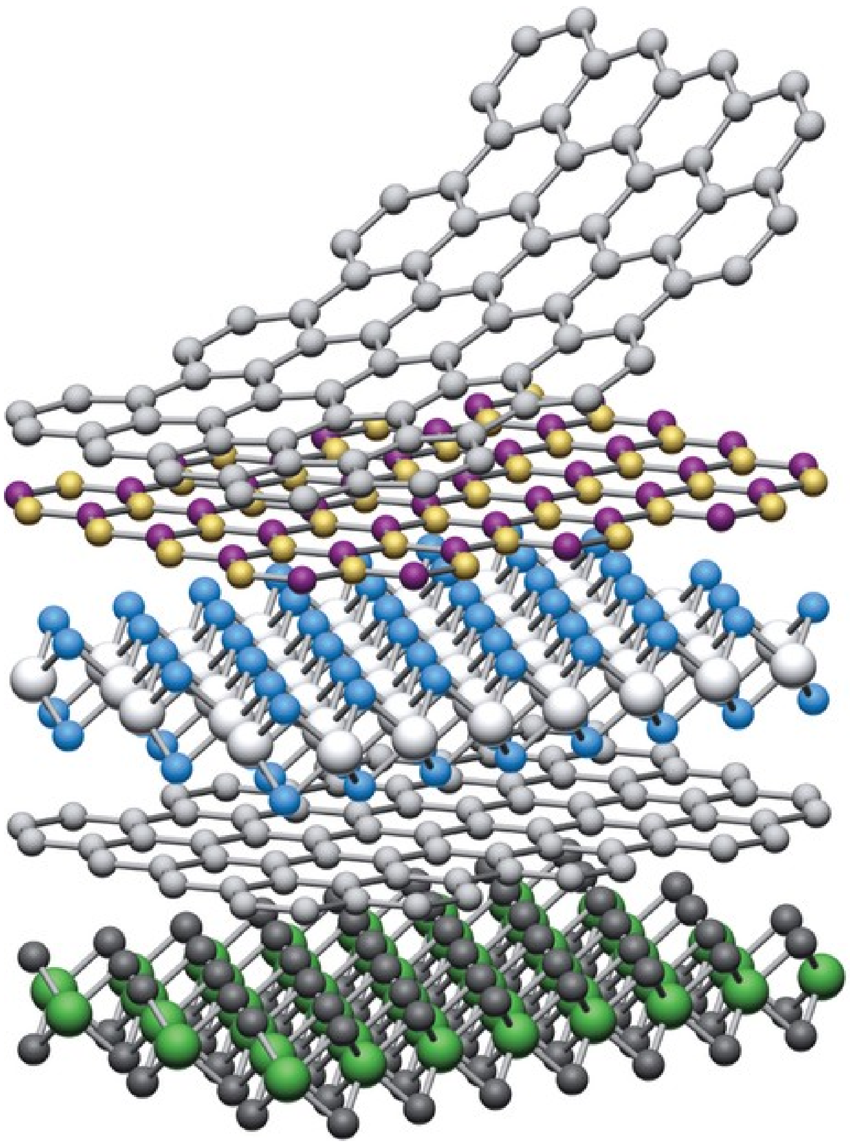
Roman Gorbachev

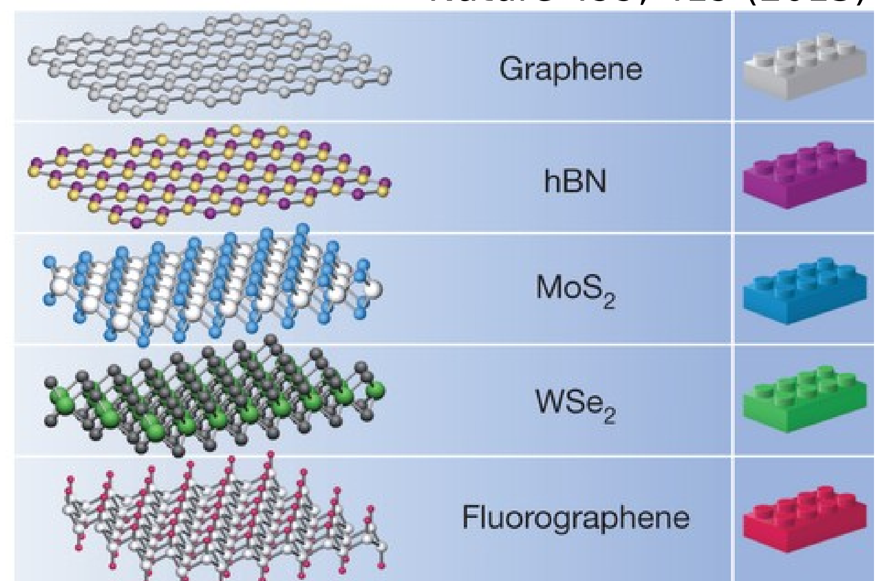
Song, Shytov, LL PRL 111, 266801 (2013)
Song, Samutpraphoot, LL arXiv:1404.4019 (2014)
Gorbachev, Song et al arXiv:1409.0113 (2014)
Lensky, Song, Samuthrapoot, LL, arXiv:1412.1808 (2014)

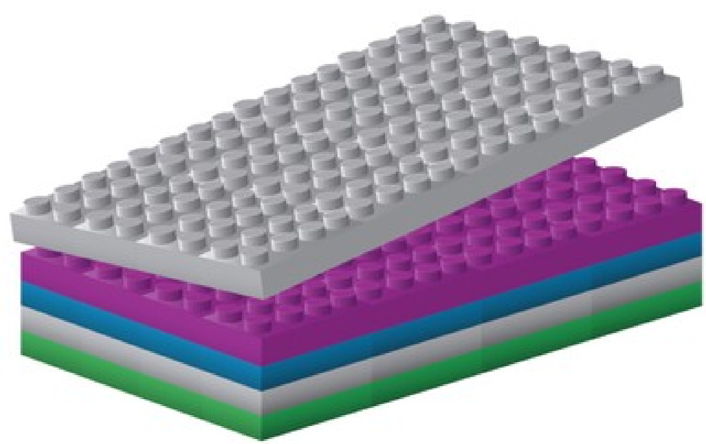
Stacked Van der Waals heterostructures

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

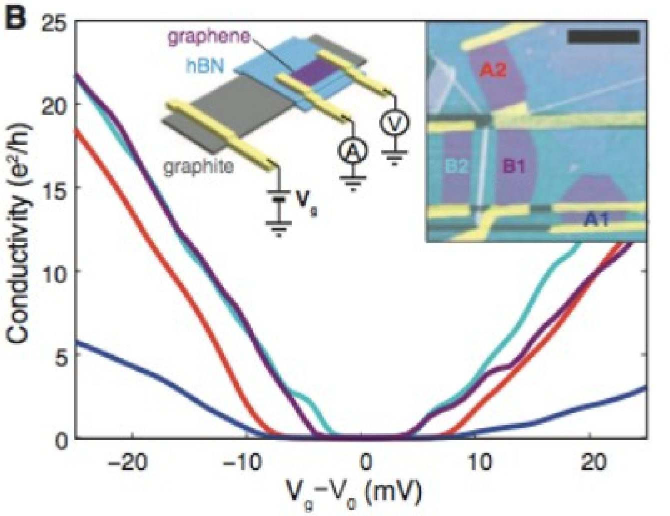
Image from: Geim & Grigorieva, Nature 499, 419 (2013)

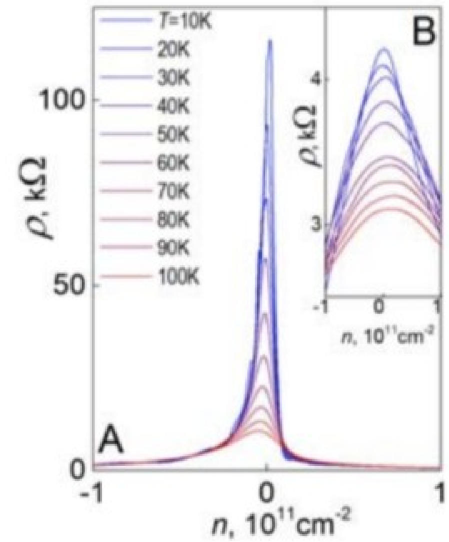






Gap opening for G/hBN



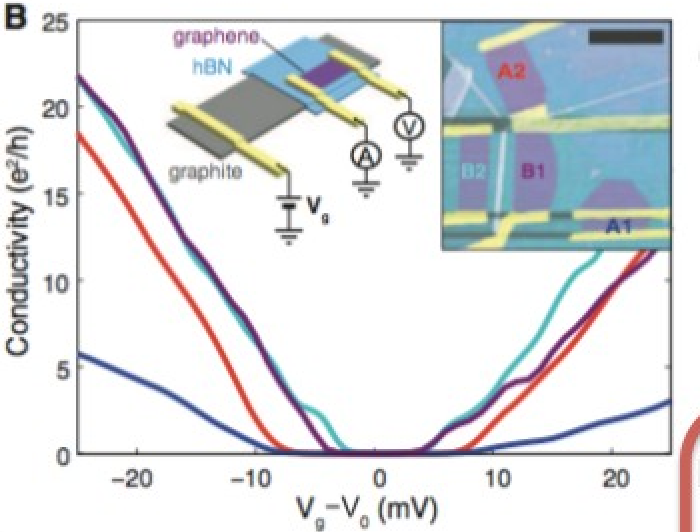


B. Hunt, et. al., Science, 340, 1430 (2013) (MIT Group)
See also stanford and columbia groups

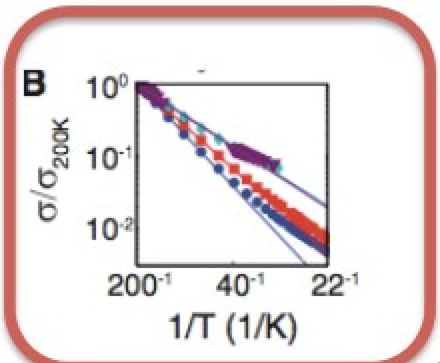
CR Woods, et.al. Nat. Phys (2014) (Manchester Group)

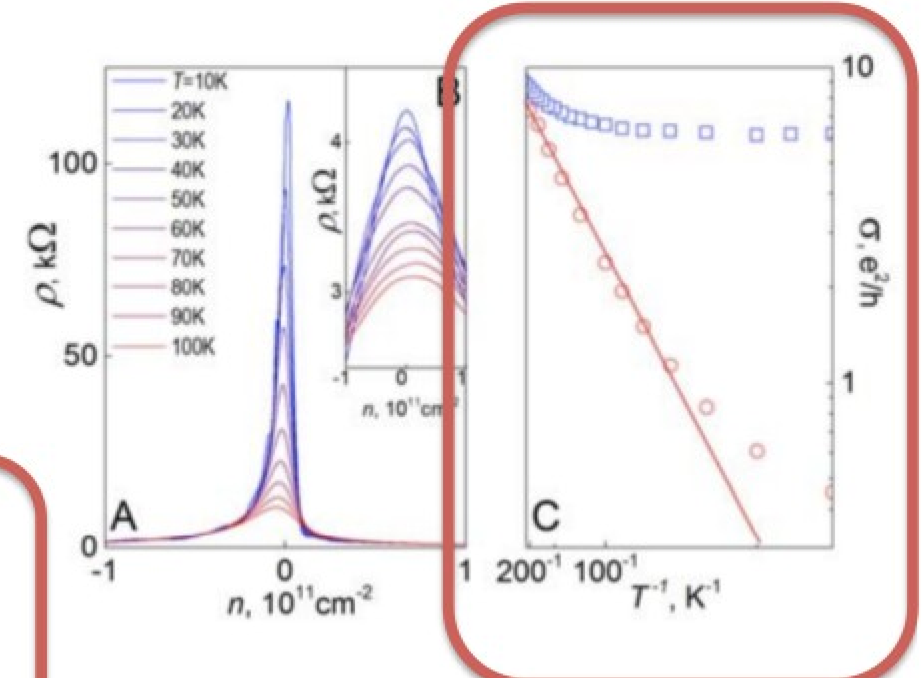
Gap opening for G/hBN

Activated behaviour



Arhenius plot





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

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Activated behavior: gap Δ~200-400 K

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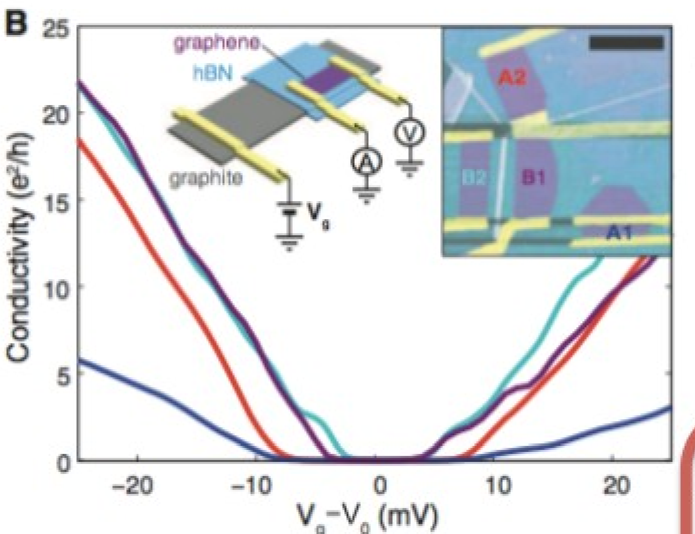

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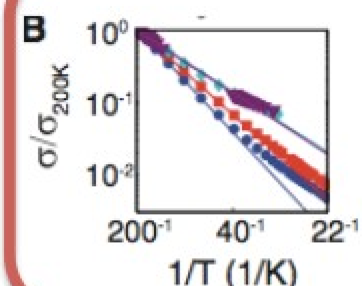

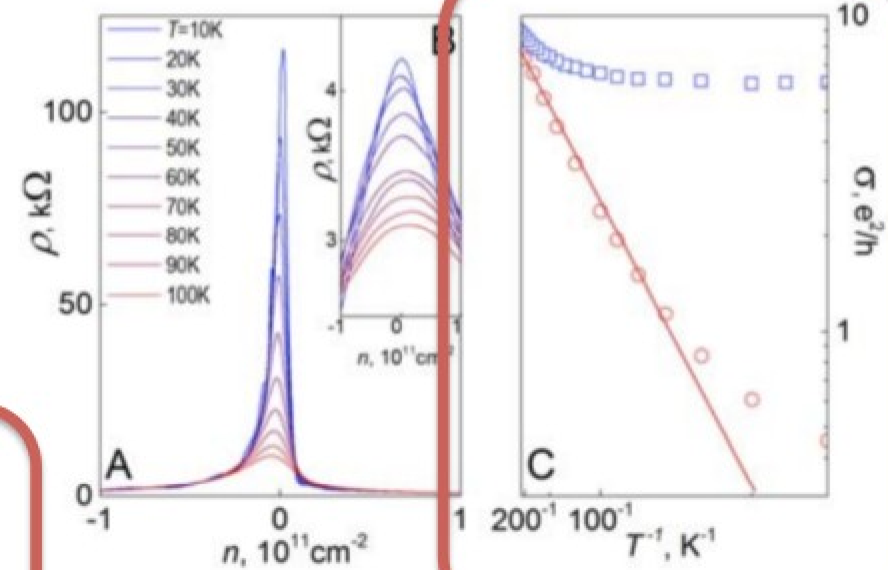

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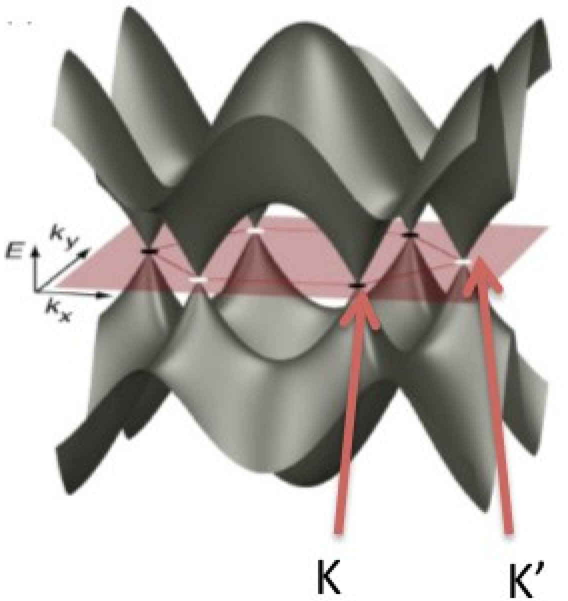
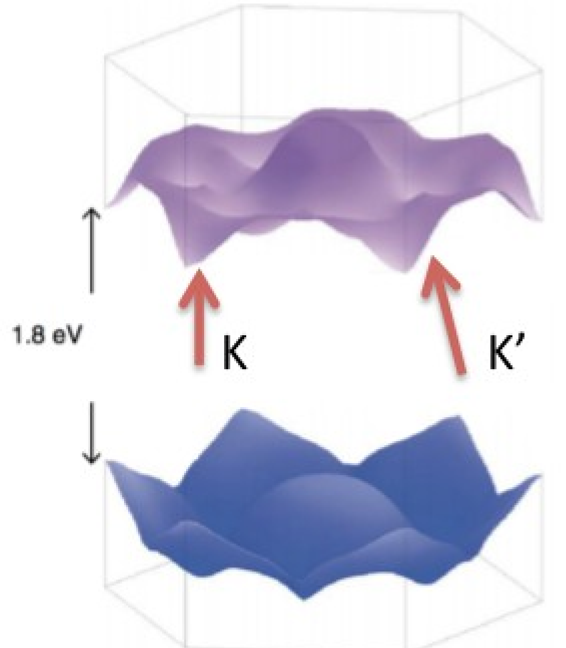
Valley currents: Gorbachev, Song, et. al. , Science (2014)

Valley index

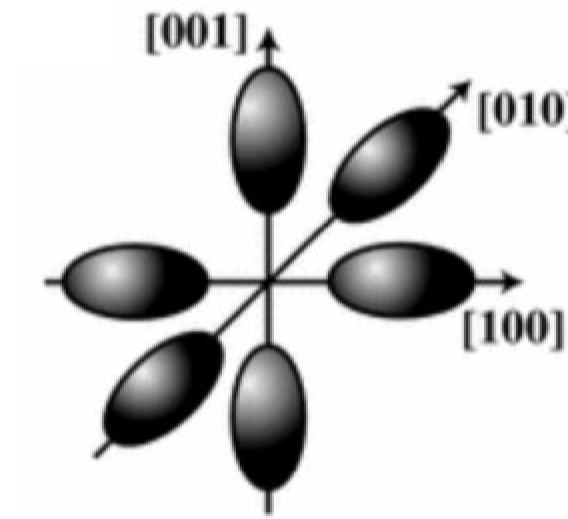
Valleys in Graphene



Valleys in MoS_2



Valleys in Bulk Si

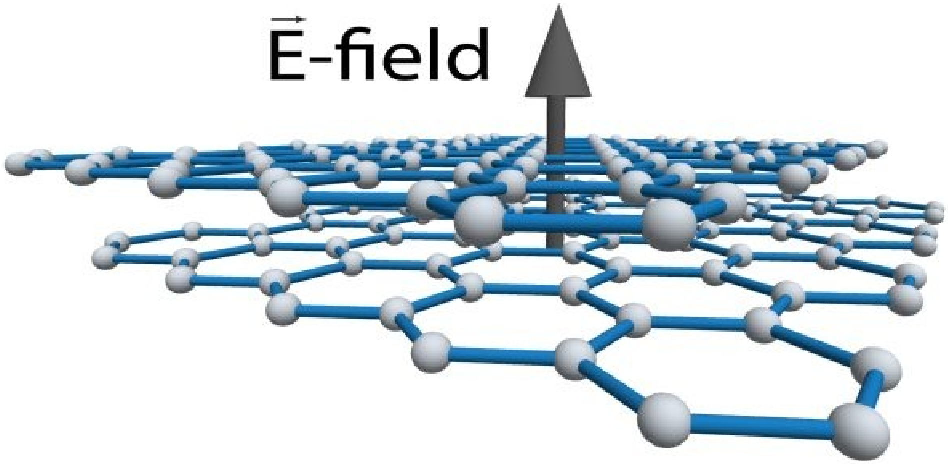


Internal degree of freedom

Long-lived, inter valley scattering ≈ Hundreds of ps

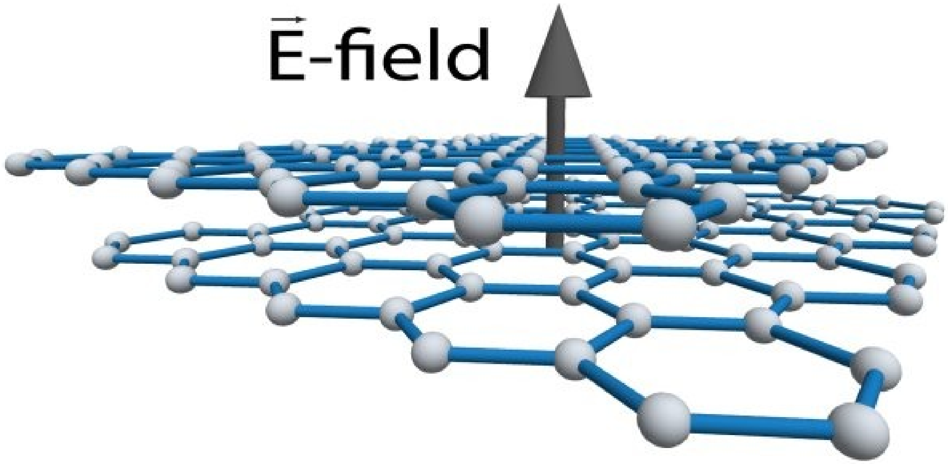
Valley current, $J_K - J_{K'}$

Dual gated bilayer graphene: field-tunable gap and Berry curvature



Broken A/B sublattice symmetry

Dual gated bilayer graphene: field-tunable gap and Berry curvature



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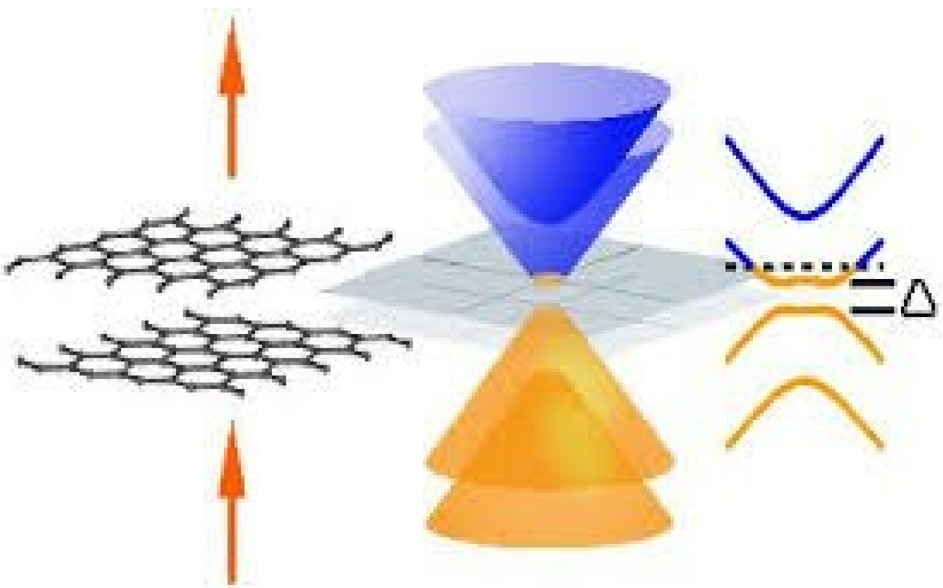
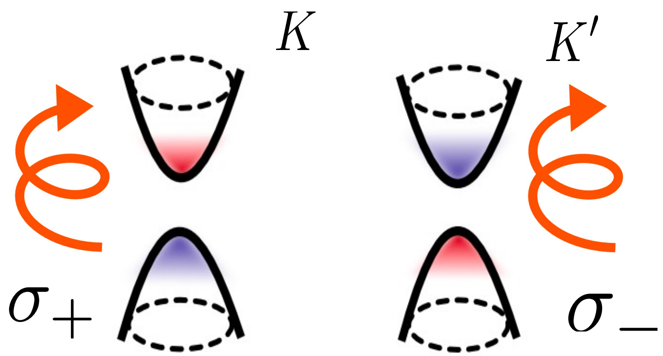


Valley currents:

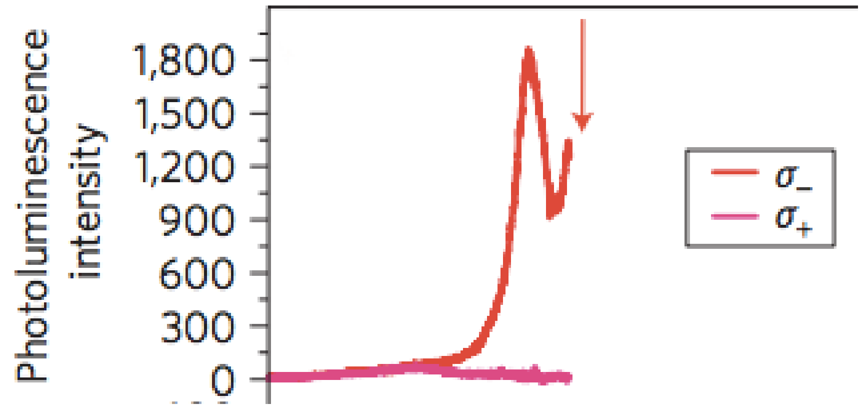
Shimazaki et al. arxiv:1501.04776 (2015)

Optical control of valleys

Optical selection rules: addressing valleys individually



PL (MoS_2) after shining σ-



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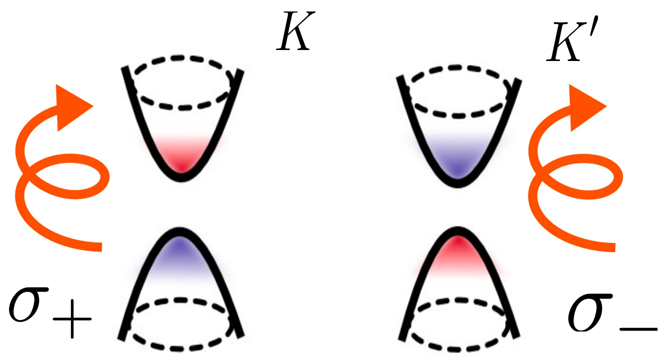

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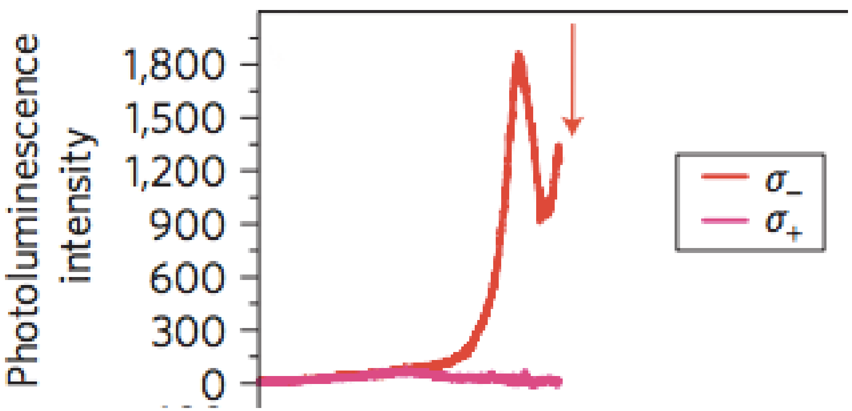
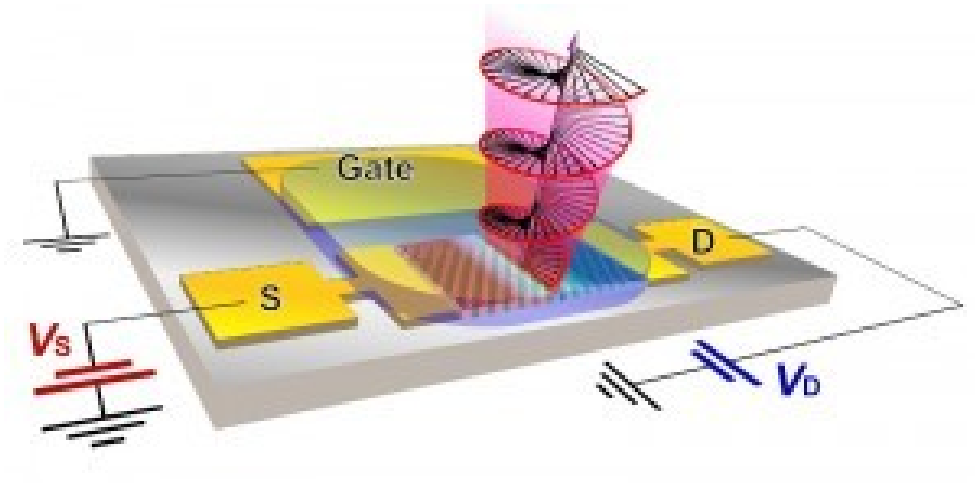


Electrically switchable chiral light-emitting transistor



Zhang et. al. , Science (2014)

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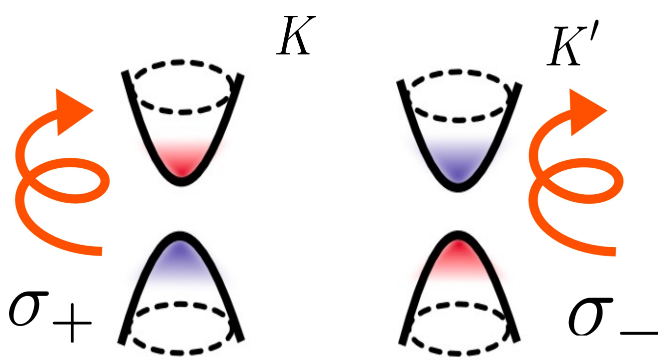

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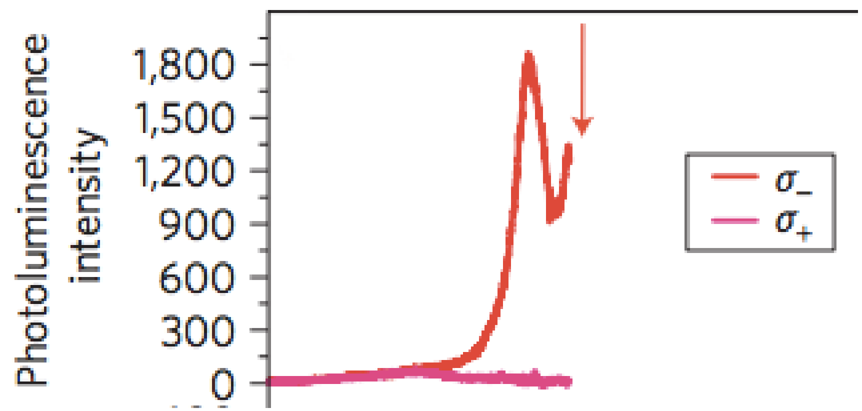

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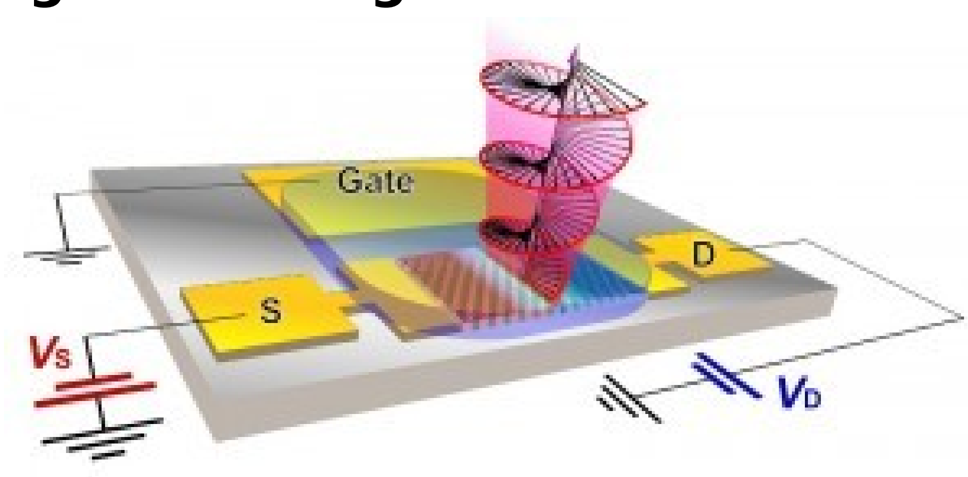
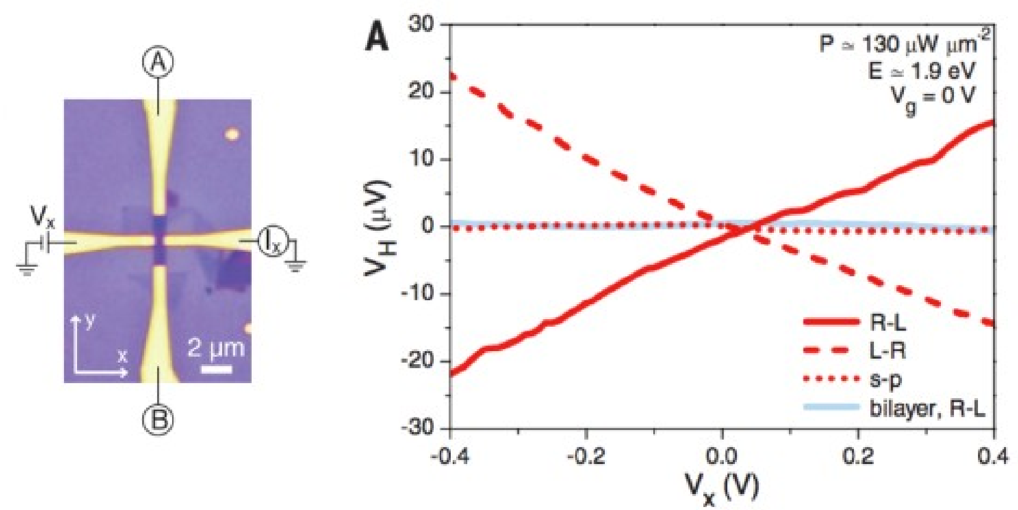


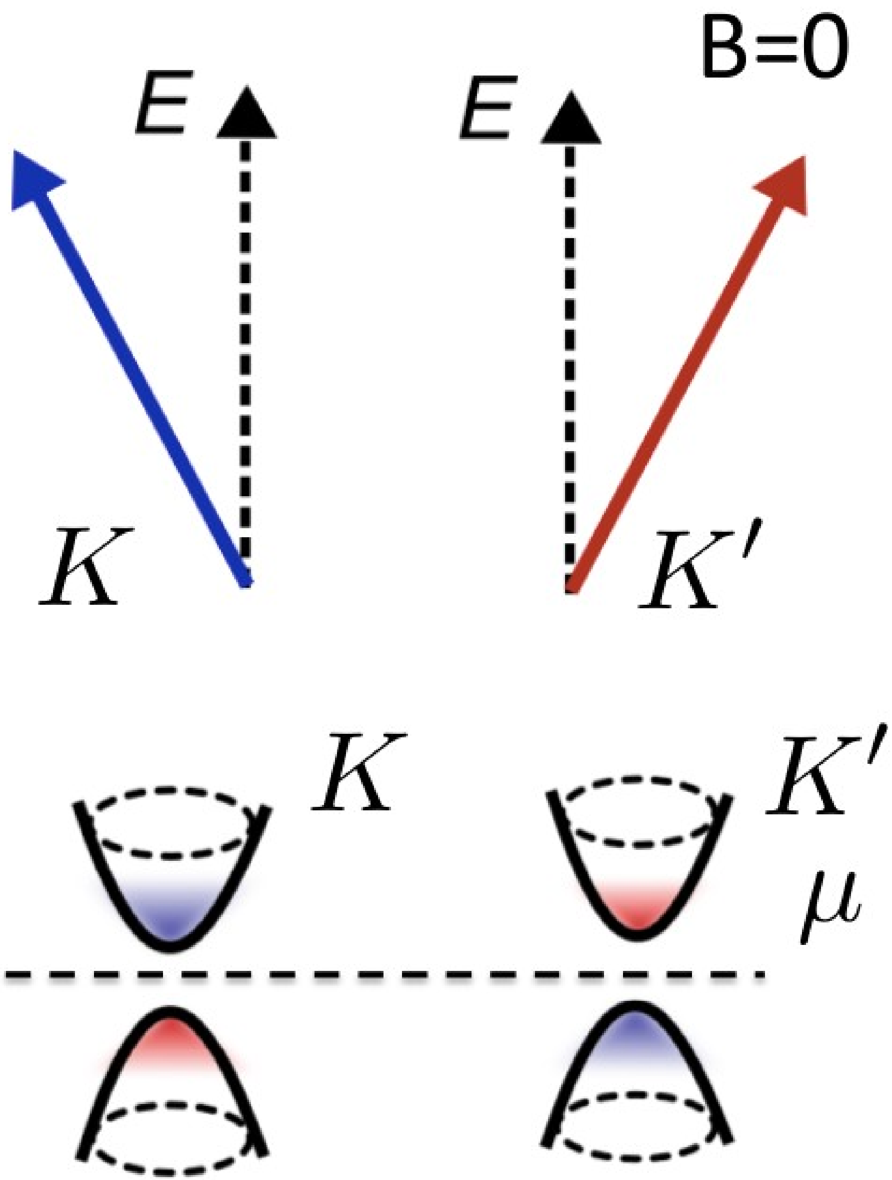
Zhang et. al. , Science (2014)

Valley Selective Hall Effect in MoS_2



Mak, McGill, Park, McEuen, Science (2014)

Valley transport in the gap?



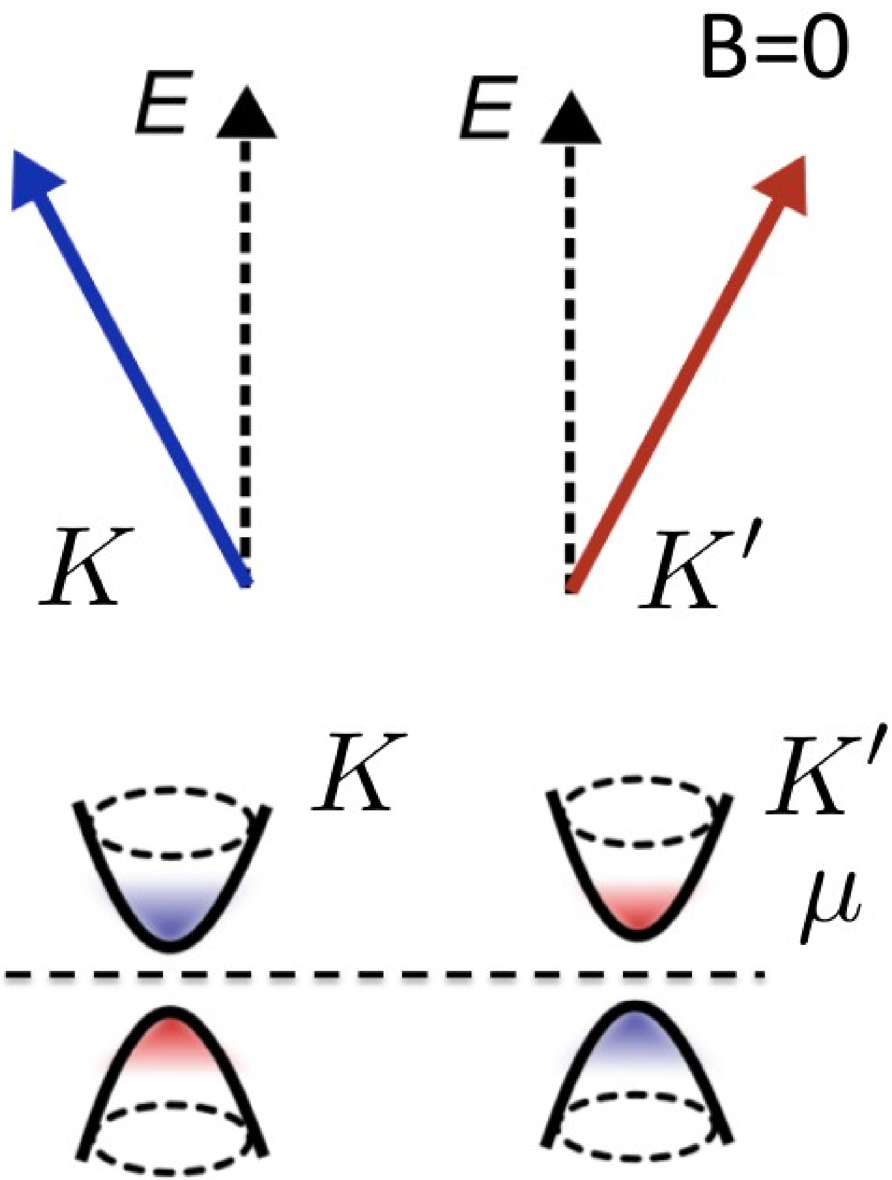
- **No edge states** demanded by symmetry or topology + rough boundaries will scatter between valleys

No valley current?

$$\mathbf{J}_v = 0?$$

Conventional wisdom:
Valley Hall Conductivity vanishes in the gap
Xiao, Yao, Niu, PRL 2007, PRL 2012

Valley transport in the gap?



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No valley current?

$$\mathbf{J}_v = 0?$$

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Valley Hall Conductivity vanishes in the gap
Xiao, Yao, Niu, PRL 2007, PRL 2012

revisit

Claim:
$\mathbf{J}_v \neq 0$ **even when in the gap**

Currents for an edgeless setting

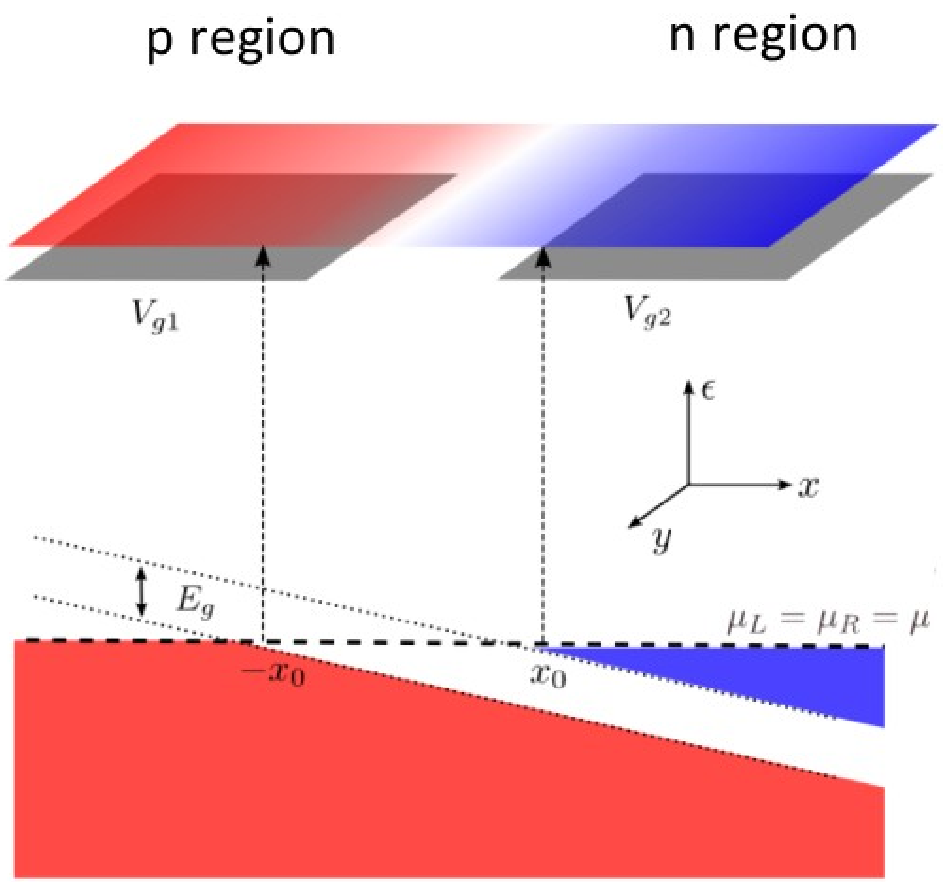
*Lensky, **JS**, Samutpraphoot, Levitov, arxiv: 1412:1808 (2014)*

$$H = \begin{pmatrix} \Delta & vp_- \\ vp_+ & -\Delta \end{pmatrix} - eEx, \quad p_\pm = p_1 \pm ip_2,$$

Berry curvature

$$\mathbf{v} = \frac{\partial \epsilon}{\partial \mathbf{p}} + \dot{\mathbf{p}} \times \Omega(\mathbf{k})$$

$$\dot{\mathbf{p}} = e\mathbf{E}, \quad \mathbf{p} = \hbar \mathbf{k}$$



Solving for velocity in y-direction:

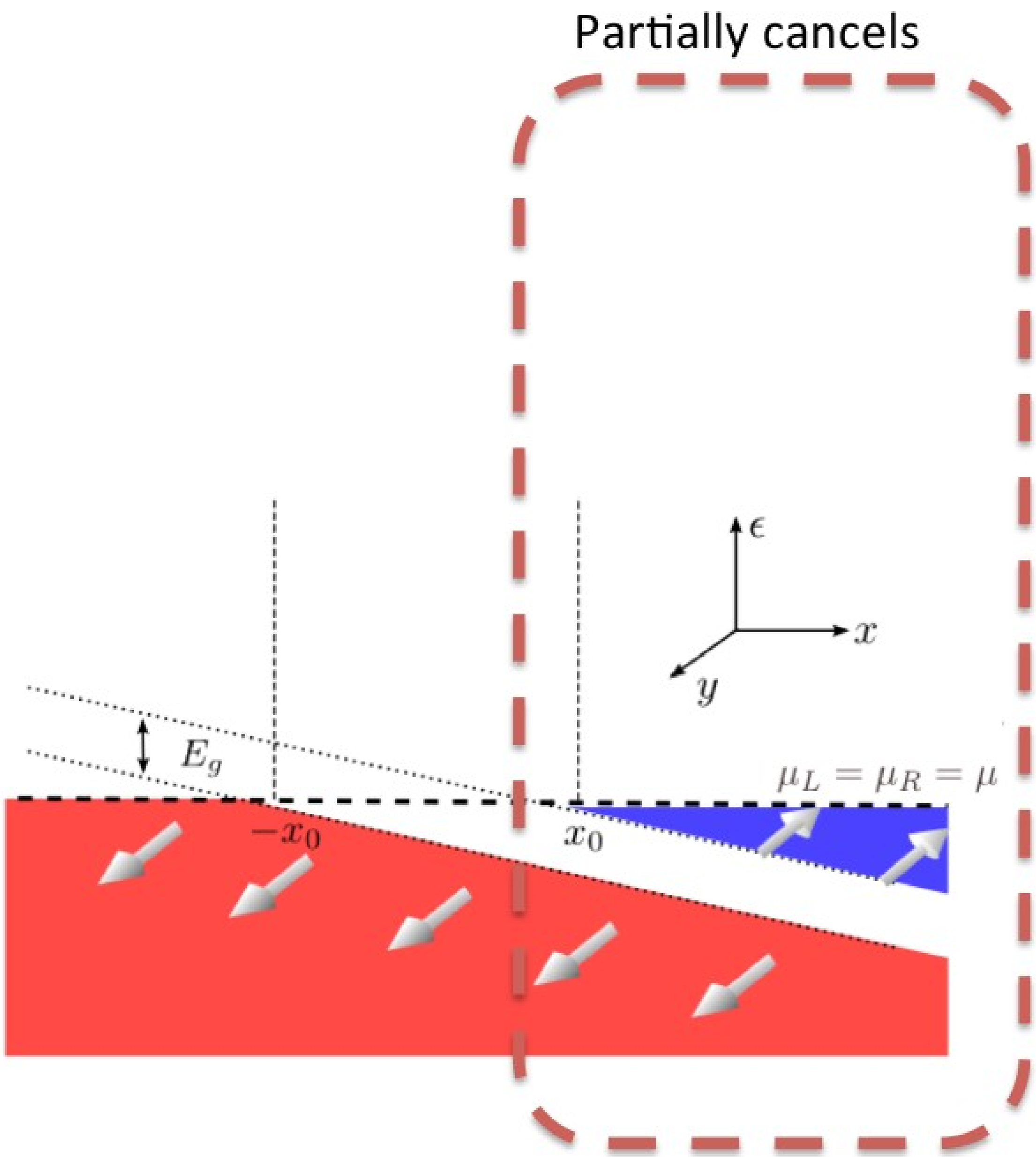
Group vel: *Anomalous vel:*

$$\dot{y} = \frac{vp_y}{\sqrt{v^2|\mathbf{p}|^2 + \Delta^2}} + \Omega(\mathbf{p})eE$$

Summing to get currents:

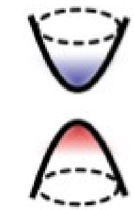
$$\mathbf{j} = \sum_{\mathbf{p},\pm} e\dot{\mathbf{r}} f(\mathbf{p})$$

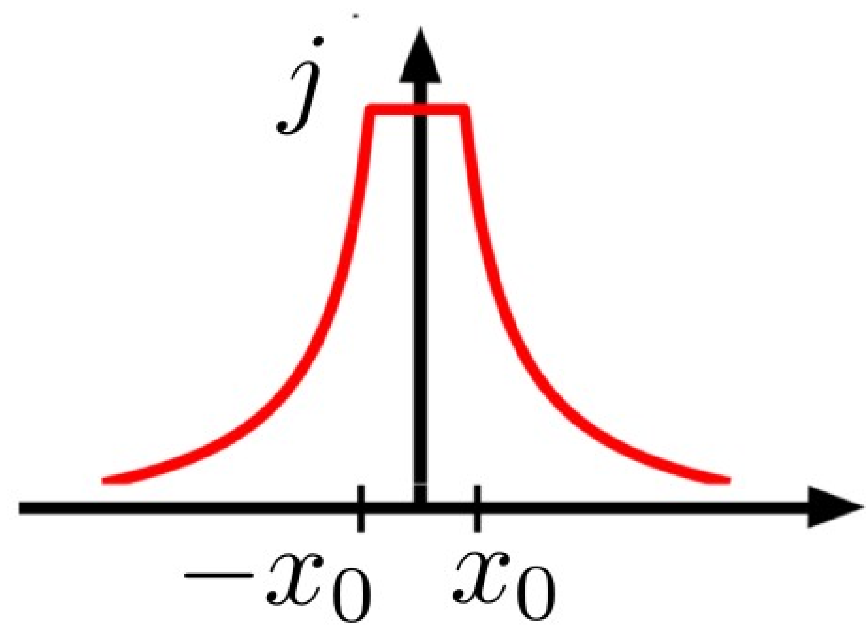
Currents peak in the gap



Berry curvature in ± bands:

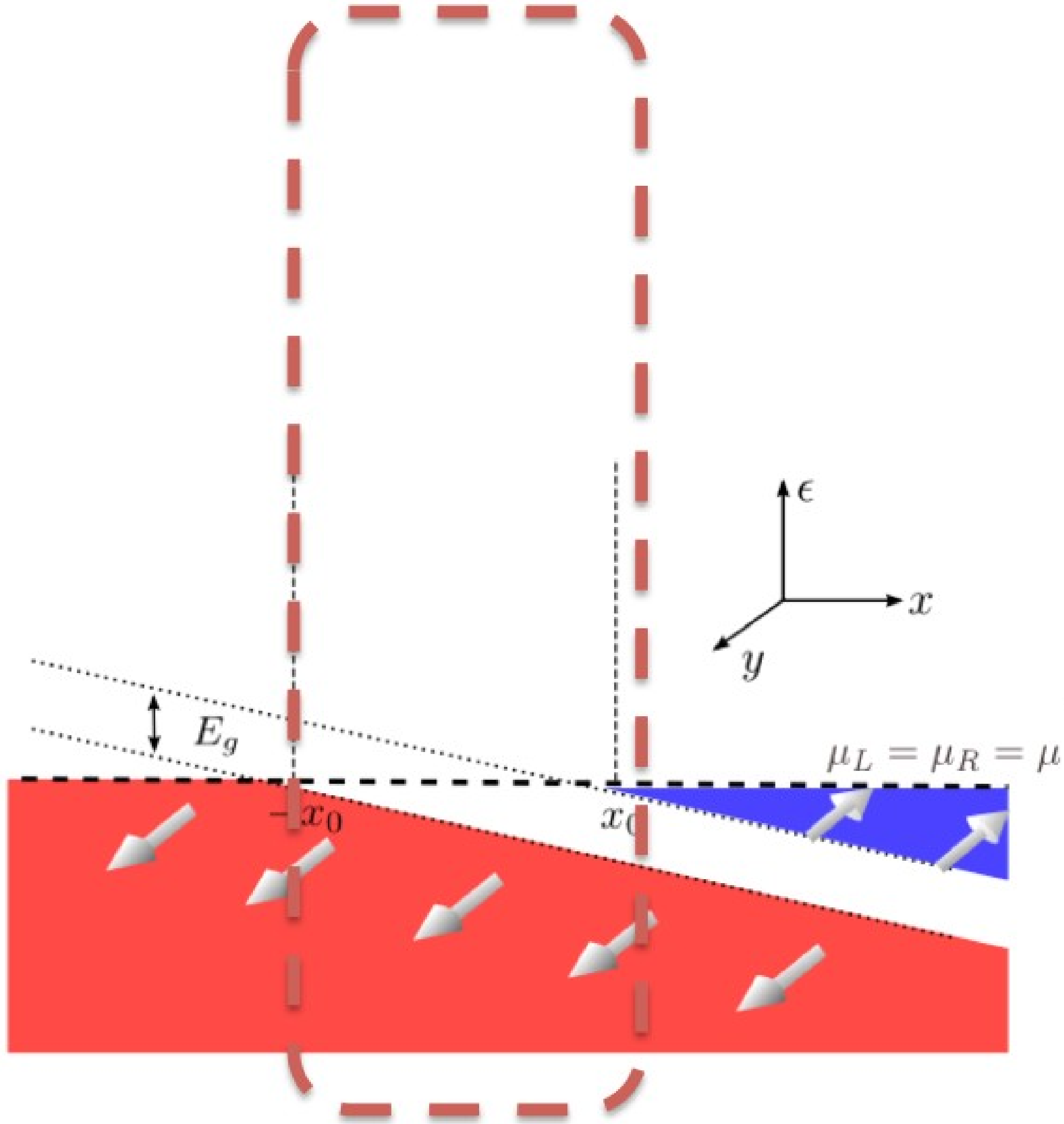
$$\Omega_{\pm}(\mathbf{p}) = \frac{v^2\Delta}{\pm 2(v^2|\mathbf{p}|^2 + \Delta^2)^{3/2}}$$





Currents peak in the gap

Maximum valley current



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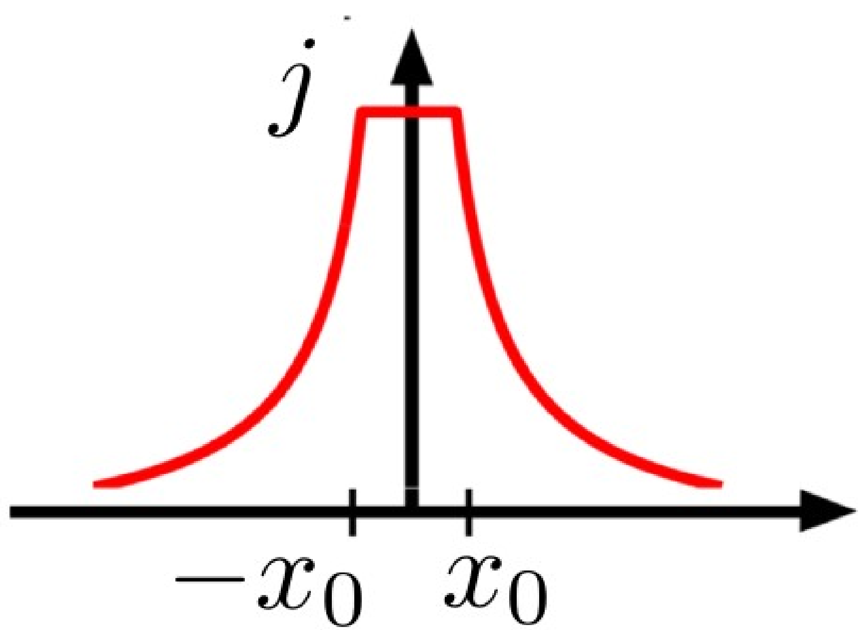
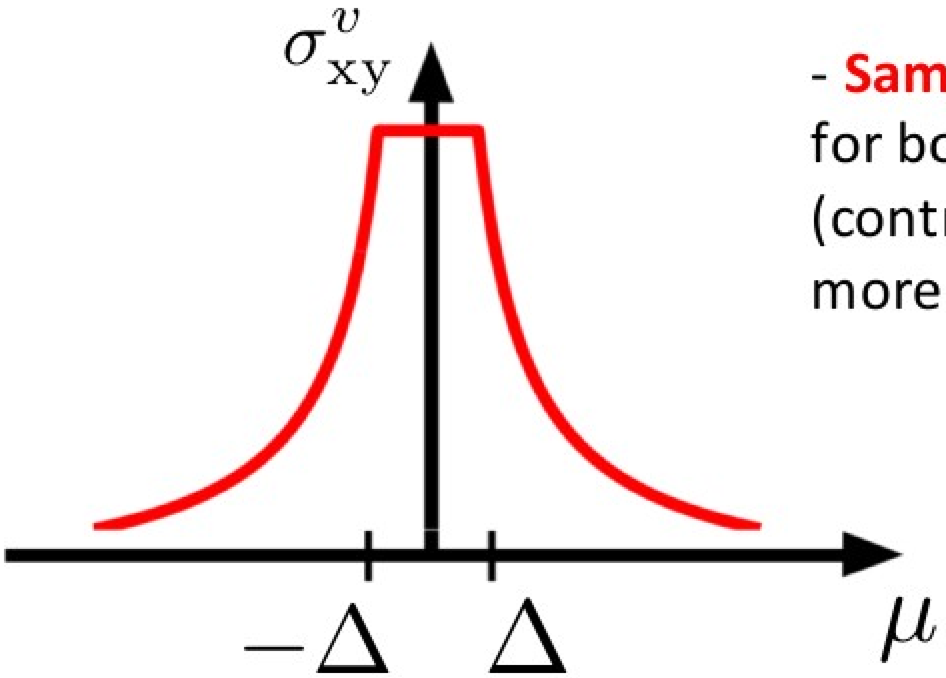


Valley Hall conductivity



- Peaks in the gapped region

- **Same sign** of valley hall conductivity
for both p and n doping
(contrast with ordinary hall effect;
more robust against density inhomogeneity)

Microscopic particle trajectories

$$\mathbf{v} = \frac{\partial \epsilon}{\partial \mathbf{p}} + \dot{\mathbf{p}} \times \Omega(\mathbf{k})$$

$$\dot{\mathbf{p}} = e\mathbf{E}, \quad \mathbf{p} = \hbar \mathbf{k}$$

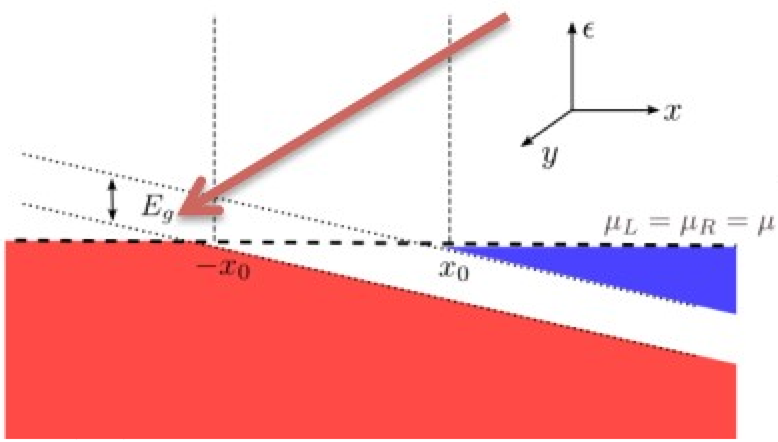
Trajectories close to gap region

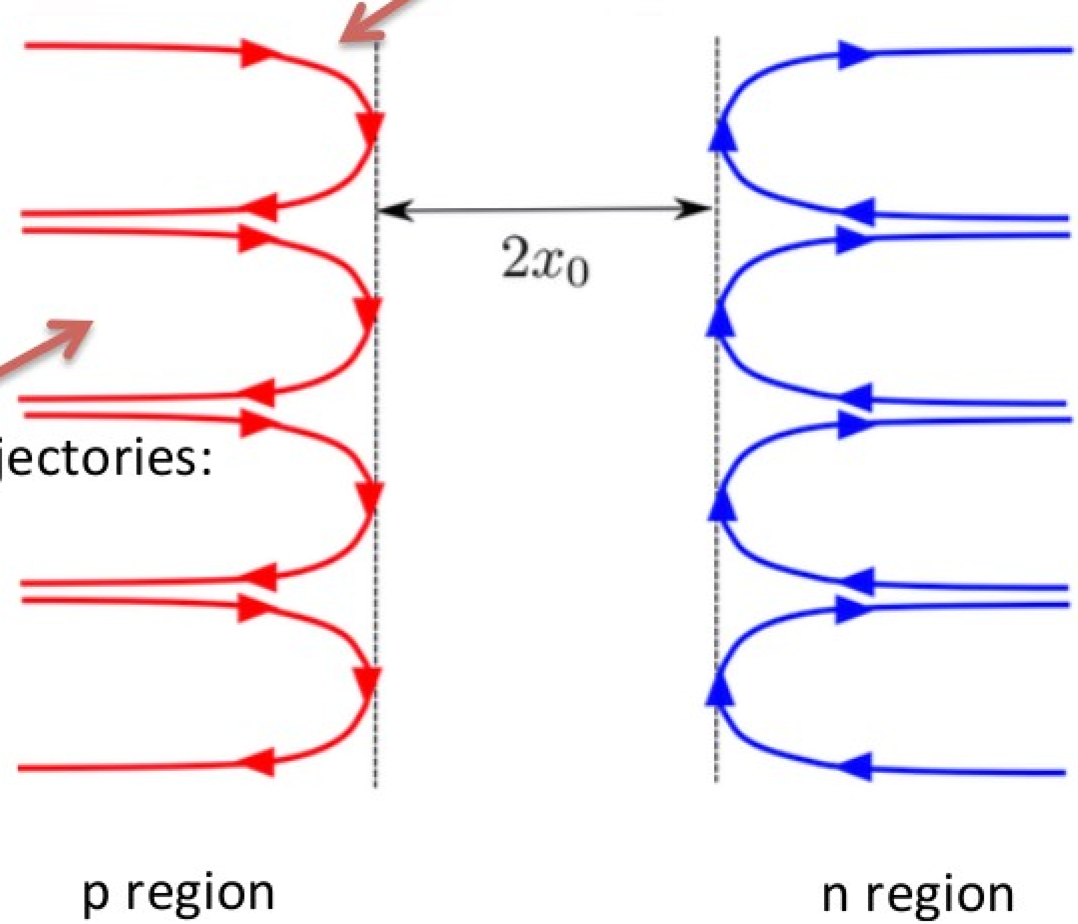
Side jump, $\ell = \hbar v / \Delta$

Particle trajectory for $p_y = 0$:

$$\left(\frac{2(y-y_0)}{\ell}\right) + \left(\frac{x_0}{x}\right)^2 = 1$$

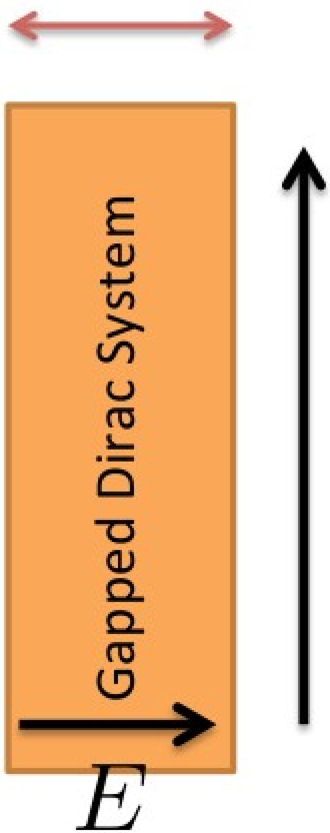
Focus on $\epsilon = 0$ trajectories:





Fully gapped system under bias

$$L < 2x_0 = 2\Delta/eE$$



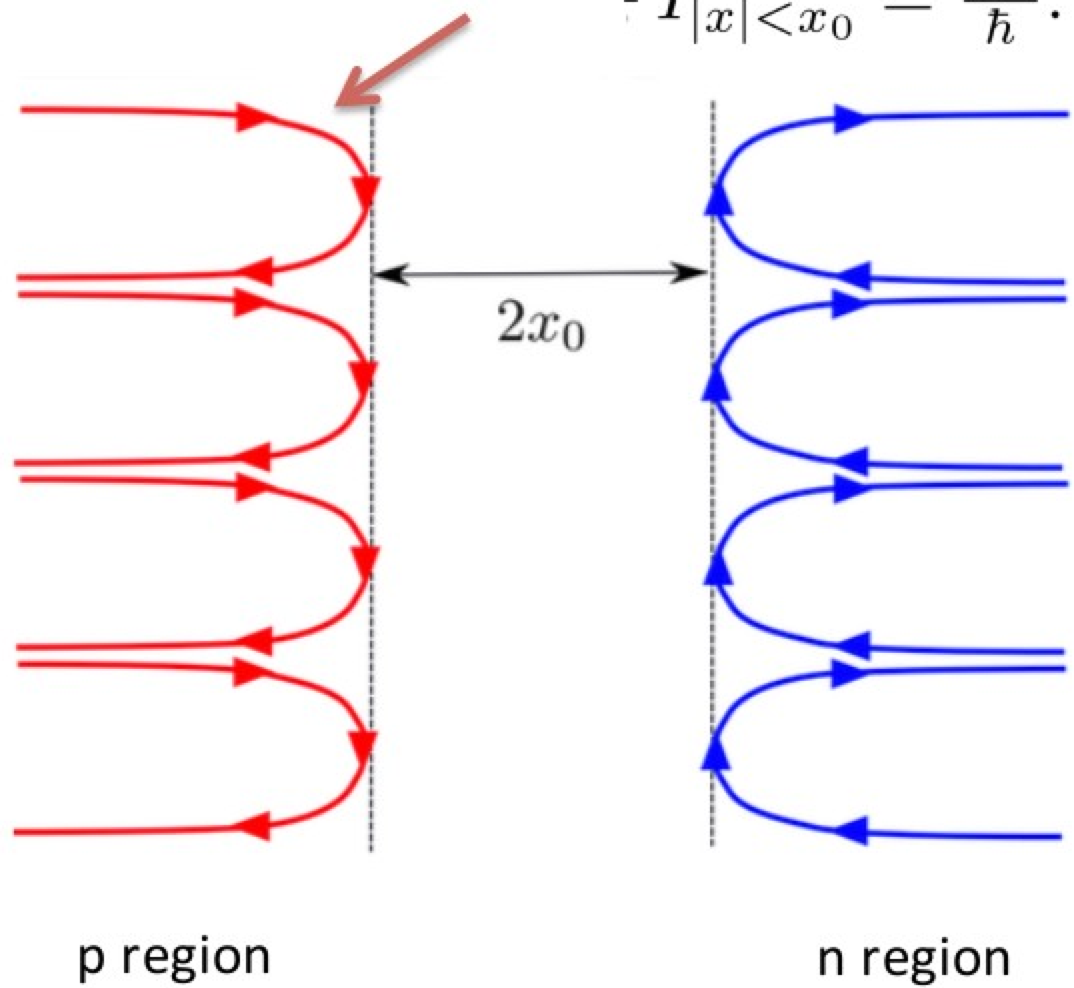
$$j = \sigma^v_{\rm xy} E$$

Universal valley hall conductivity:

$$\sigma^v_{\rm xy} = \frac{e^2}{2h}$$ per valley/flavor

Side jump, $\ell = \hbar v/\Delta$

- Side jump is small
- E independent
- $I_{|x|<x_0} = \frac{e\Delta}{\hbar}$.



Valley transport in a fully gapped system

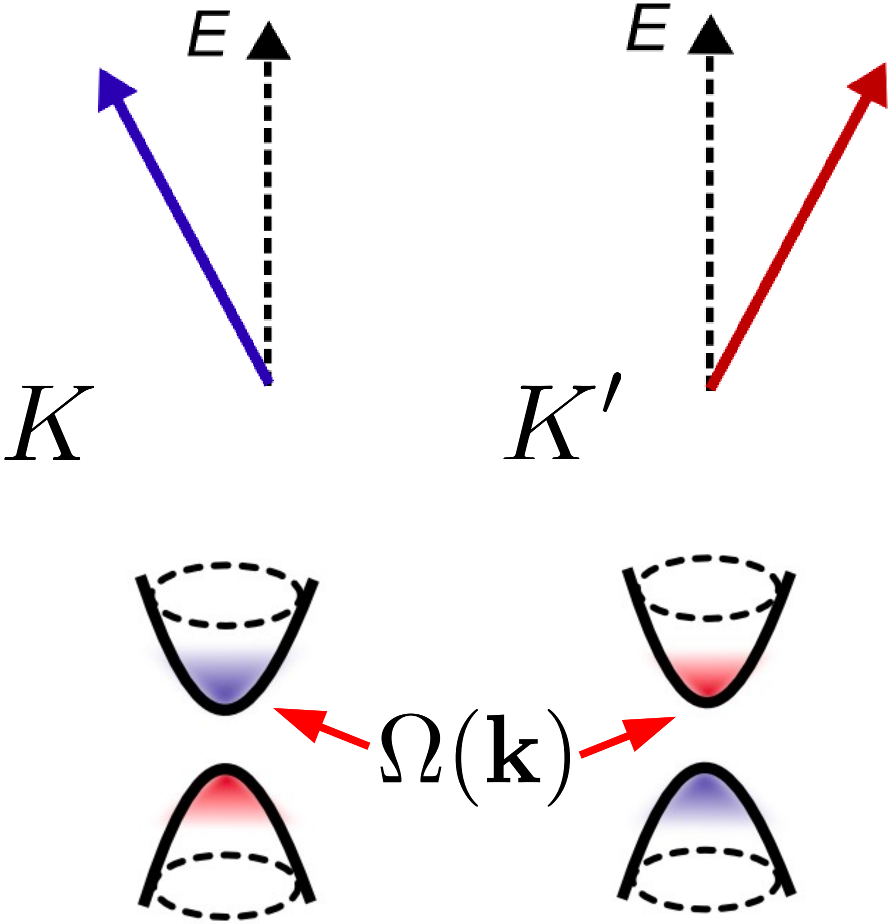
$\mathbf{J}_v \neq 0$ **even when in the gap without edge states (current flows in system bulk);**

Valley current peaks in the gap region; outside gap region partial cancellation; σ_{xy}^{v} has same sign for p & n regions

In fully gapped samples, valley currents transmitted by under gap states: "dissipationless".

Systems: graphene/hBN and bilayer graphene:
Gorbachev, Song, et. al. , Science (2014)
Shimazaki et al. Arxiv:1501.04776 (2015)

Use Berry curvature to electrically manipulate valleys



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

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

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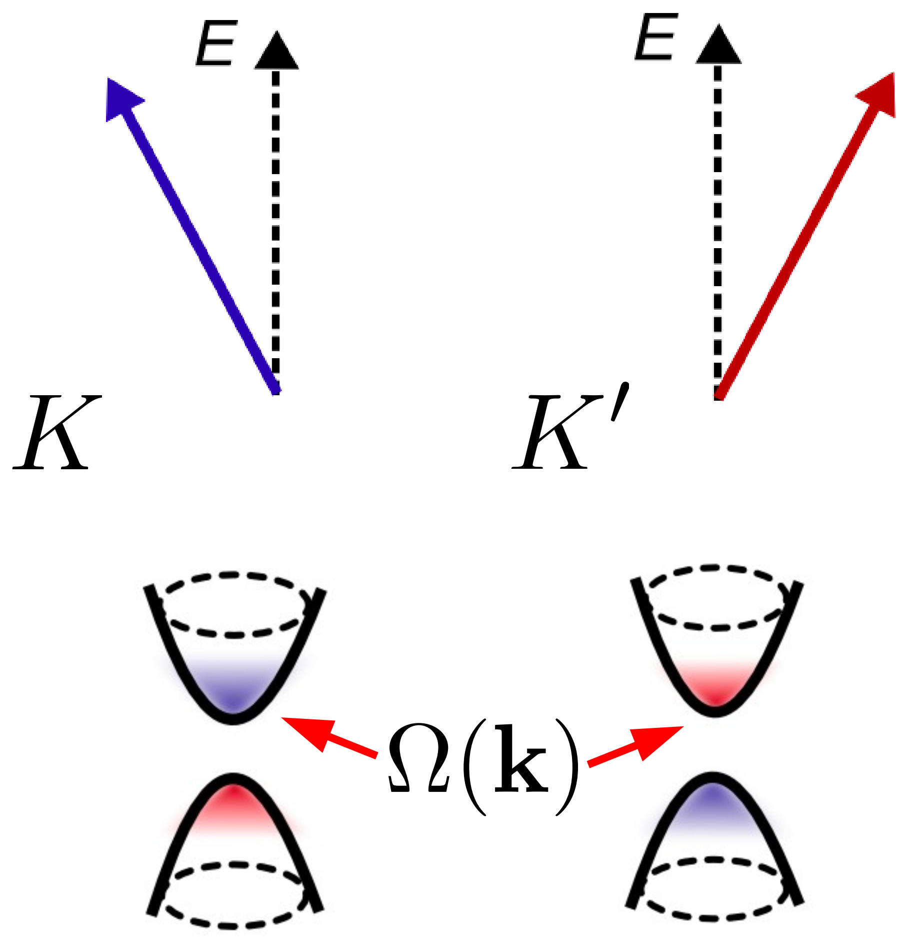

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$$\dot{\mathbf{k}} = e\mathbf{E} + e\mathbf{v}_{\mathbf{k}} \times \mathbf{B}$$

Valley Hall effect:

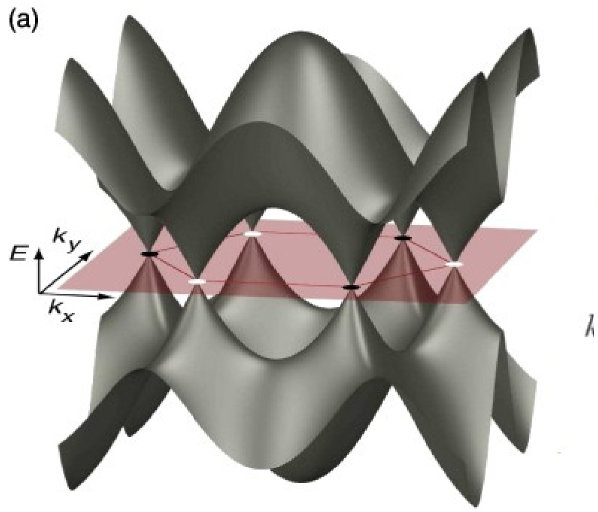
Transverse charge-neutral currents

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

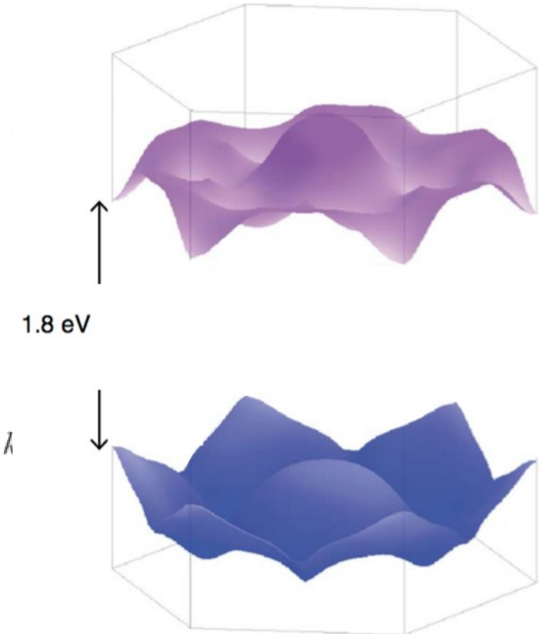
$$\vec{J}_v = \sigma_{xy}^{v}\, \vec{z} \times \vec{E}$$

Valley currents

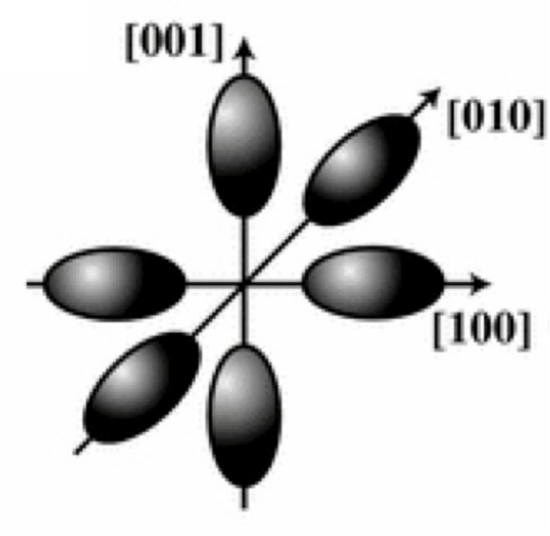
Valleys in Graphene



Valleys in MoS2



Valleys in Bulk Si



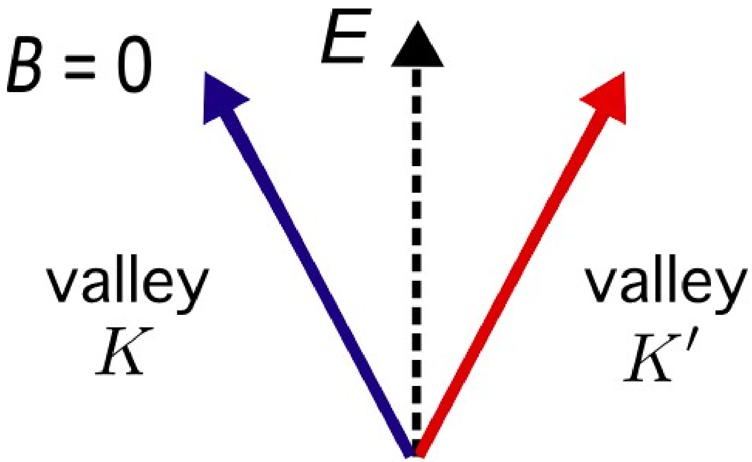
Berry curvature

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

No Berry curvature

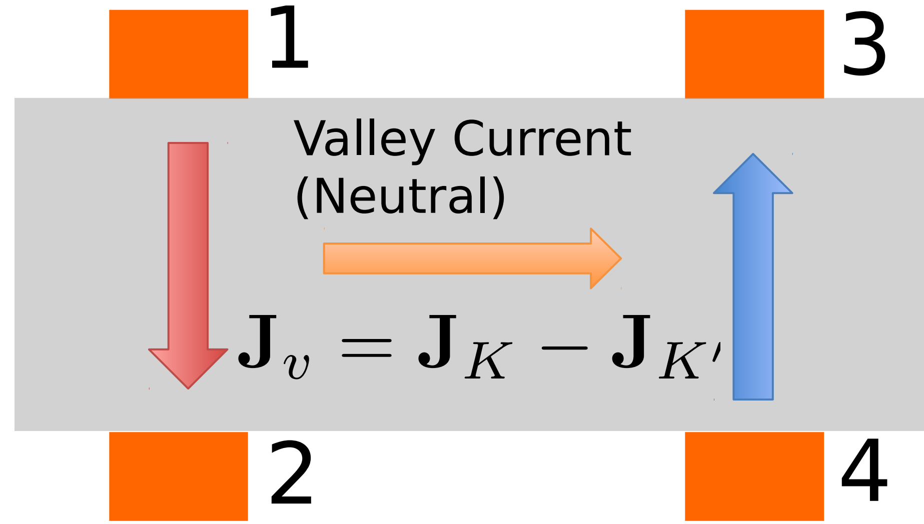
$$\sigma_{xy}^{v} = 0$$

Detecting valley currents

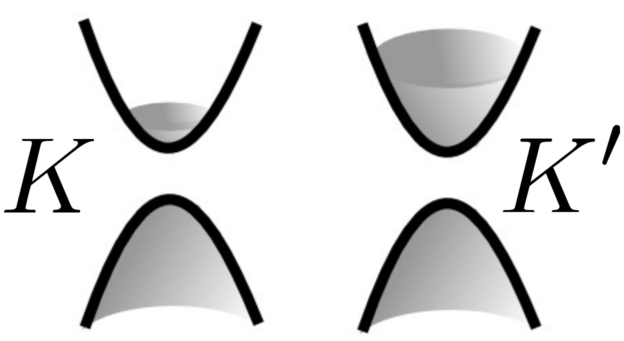


$$V_{34} = R_{\mathrm{NL}} I_{12}$$

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



Pump valley imbalance



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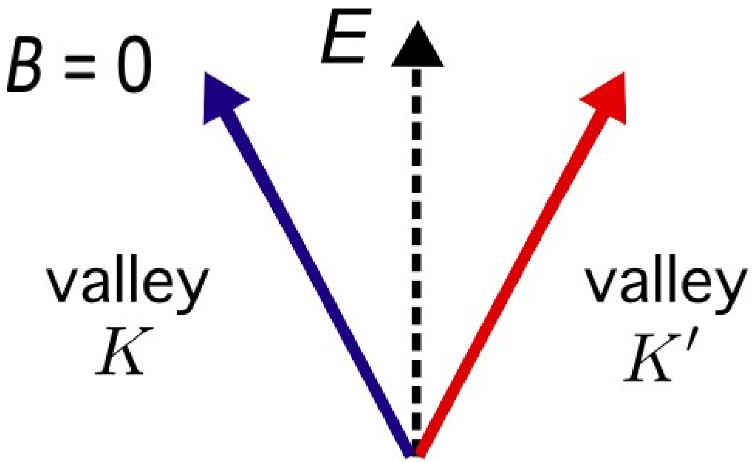

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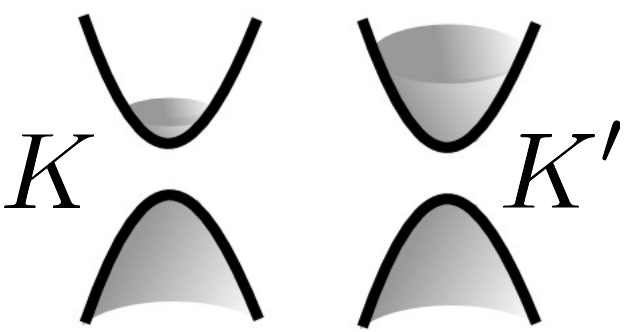

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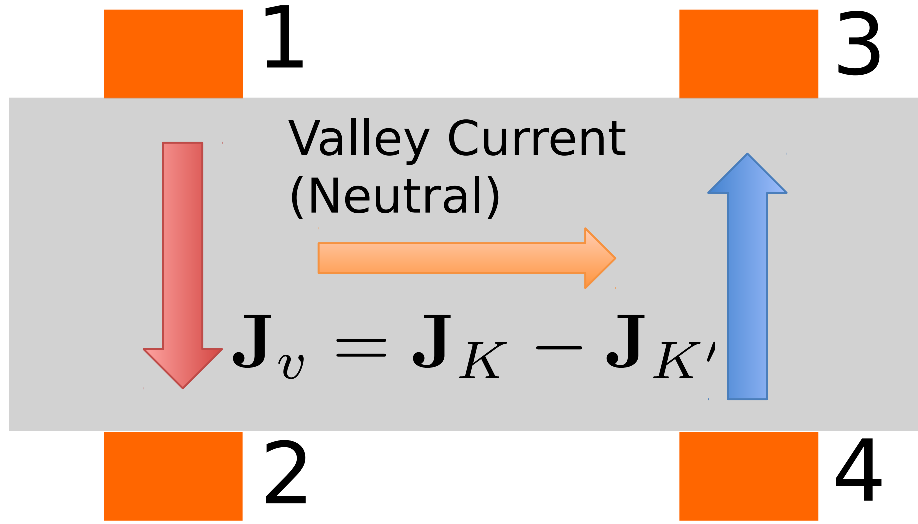


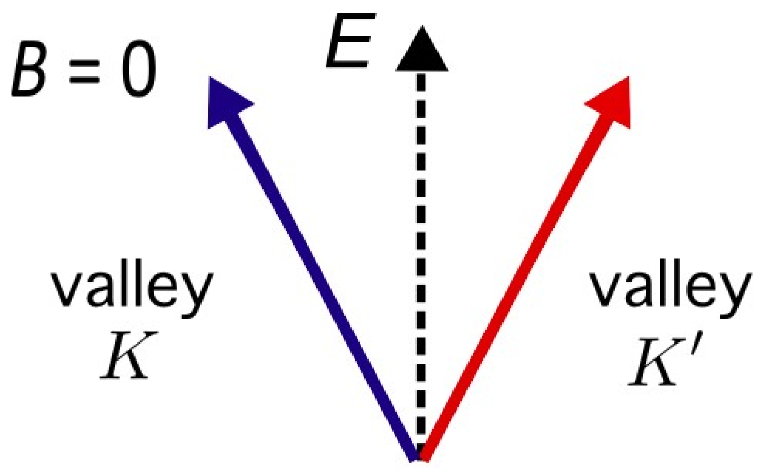
Valley Hall Effect (VHE):

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

Reverse Valley Hall Effect (RVHE):

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

Detecting valley currents



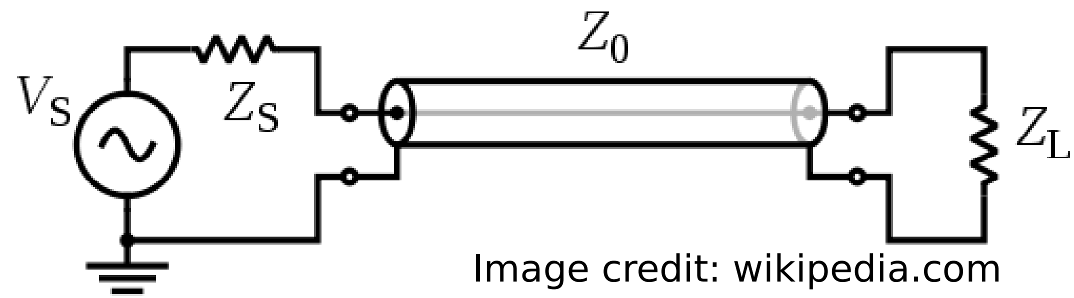


Image credit: wikipedia.com

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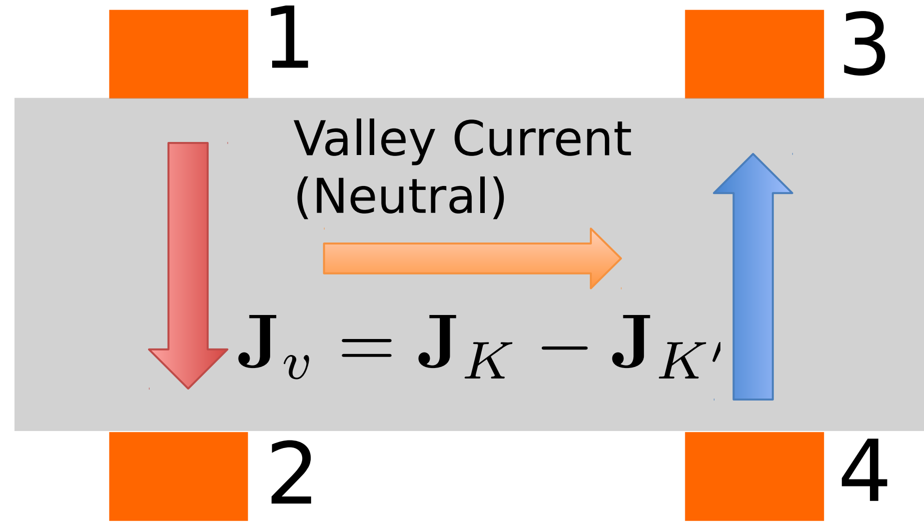

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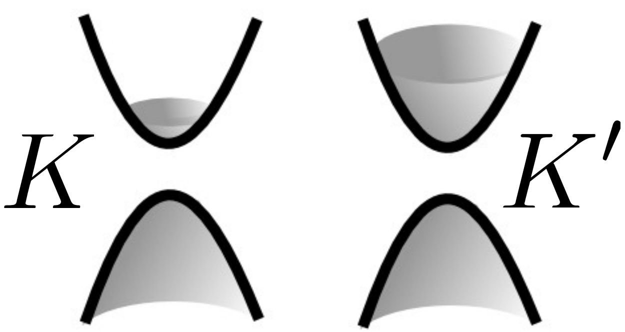

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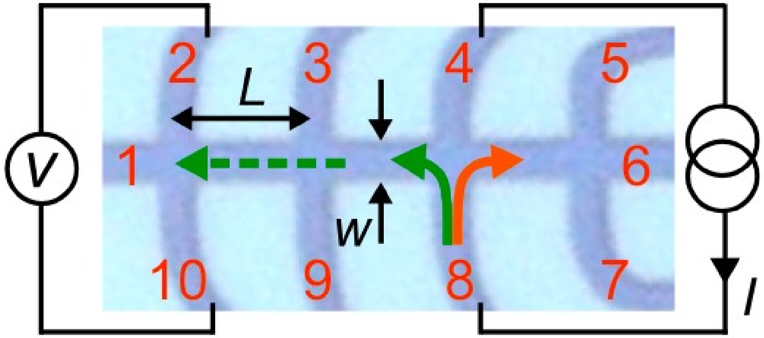
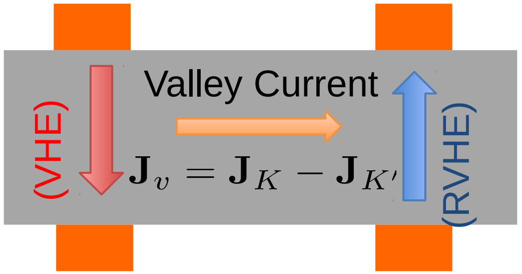
Nonlocal response in aligned G/hBN



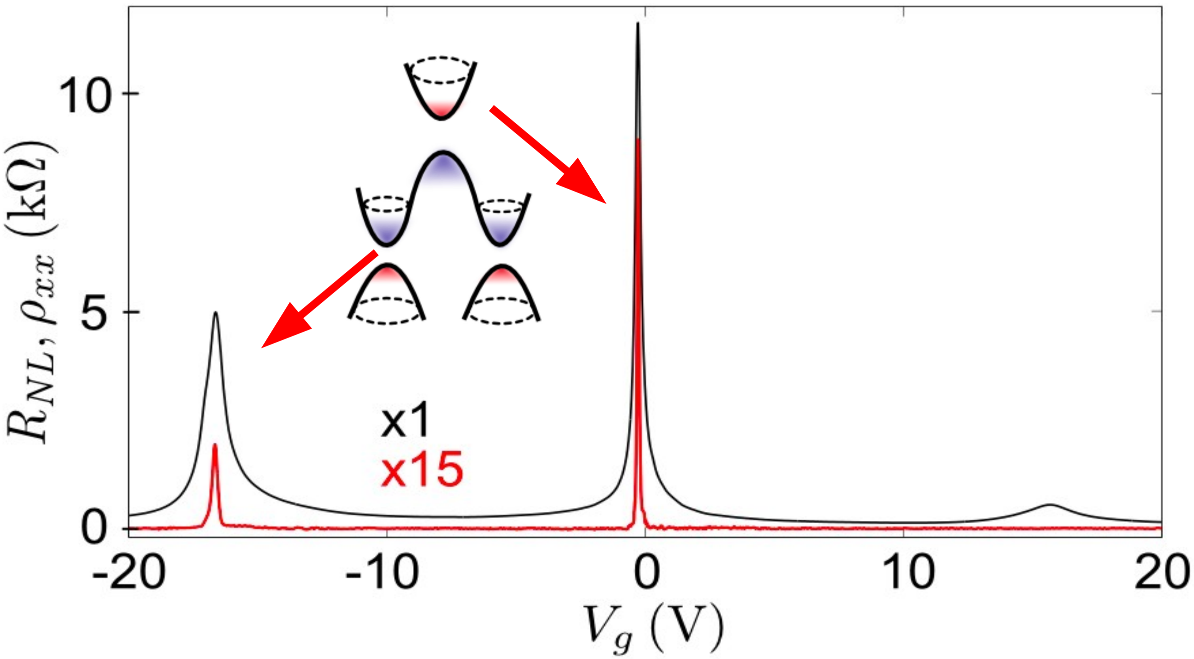
Collaboration:
U Manchester



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

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

Berry hot spots



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

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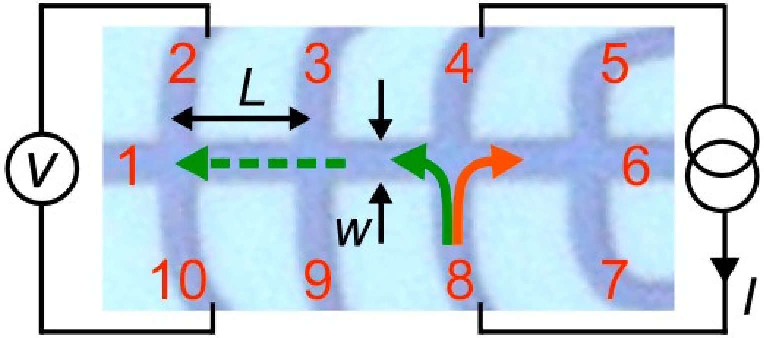

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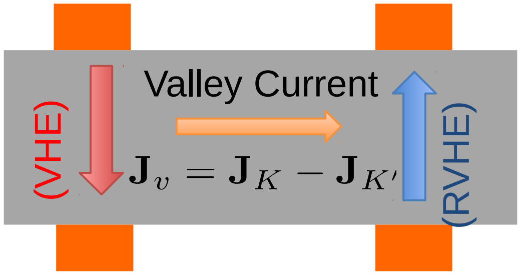

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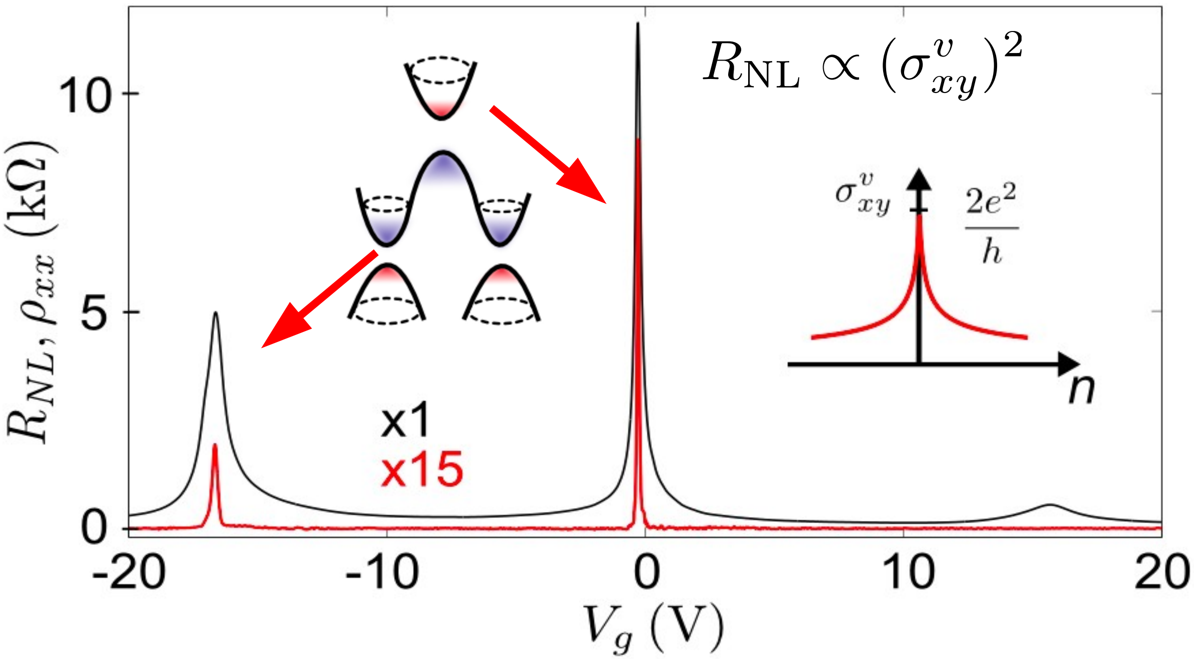

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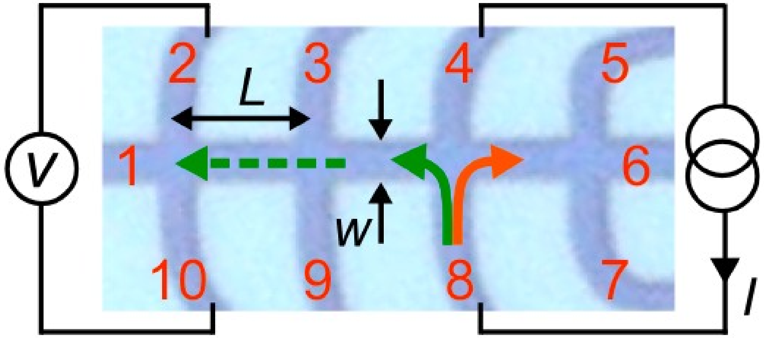

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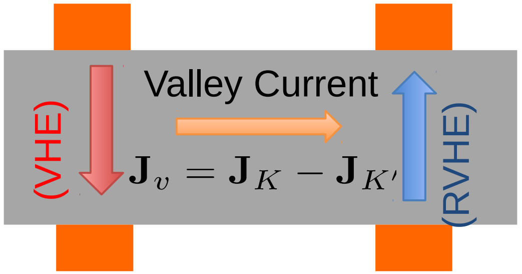

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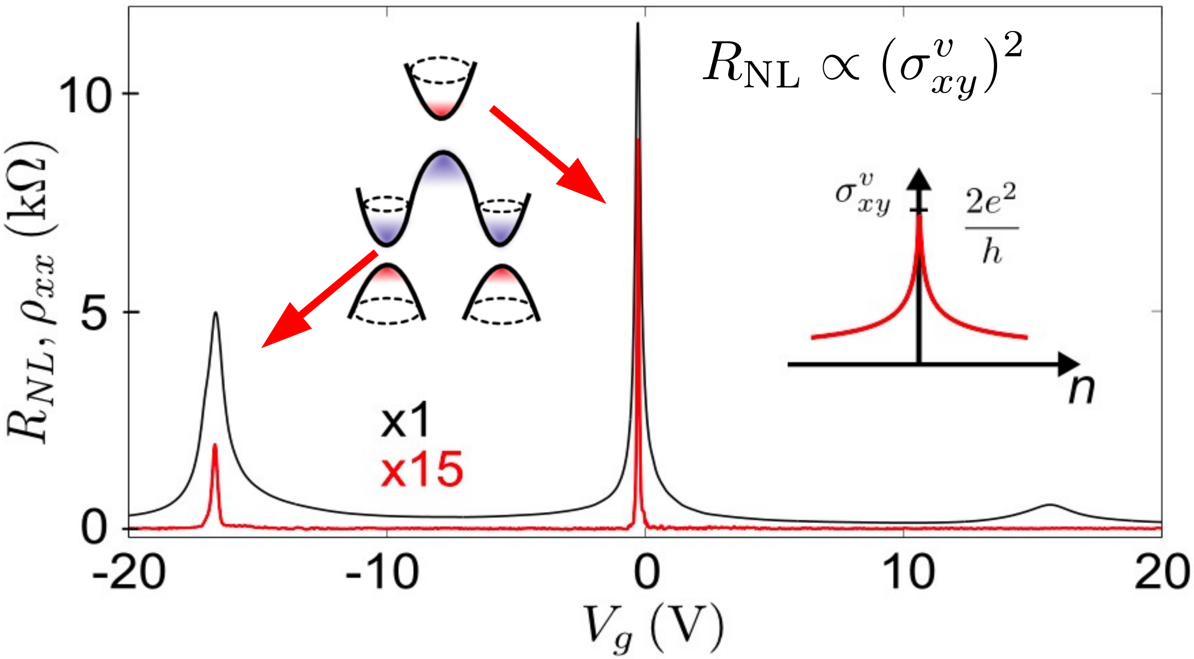
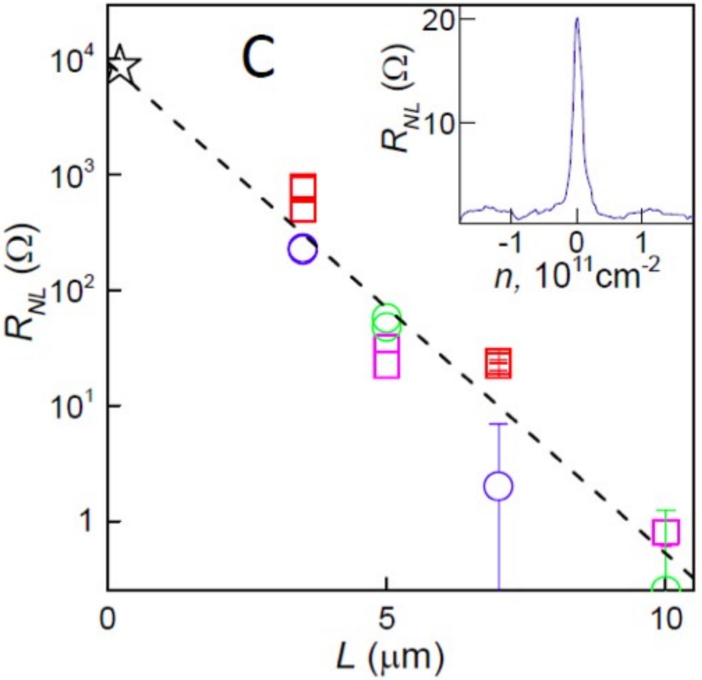


Distance dependence



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

Valley currents in BLG: Shimazaki et al. arxiv:1501.04776

Checklist

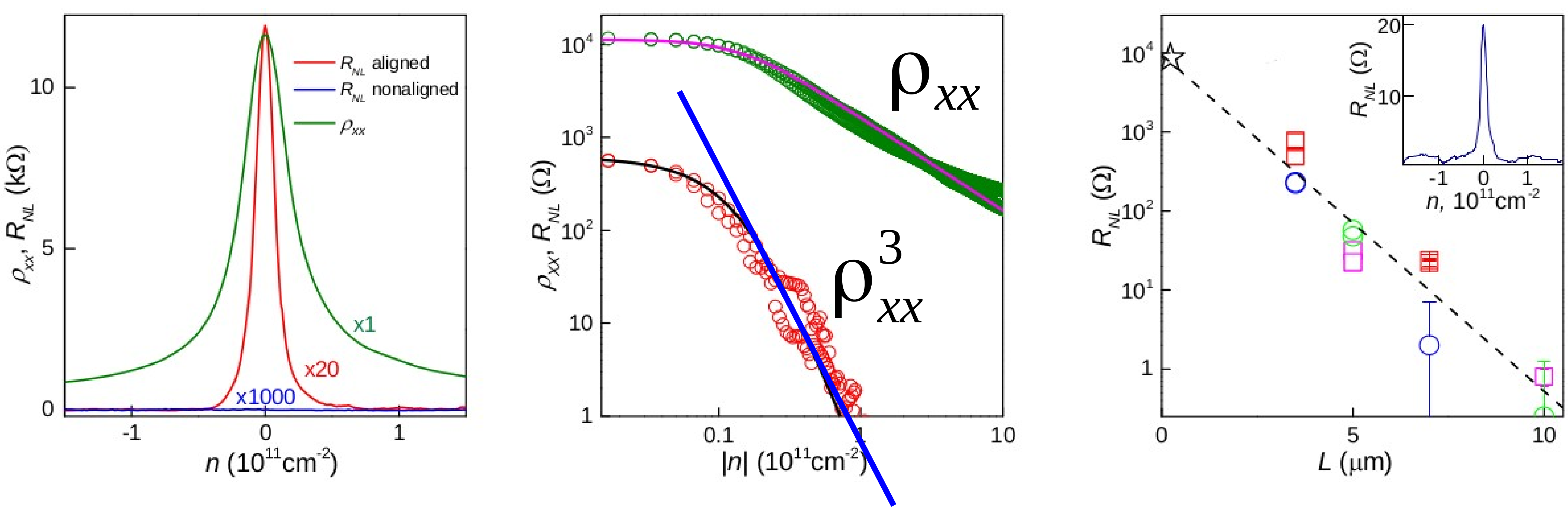
☑ 1) Non-ohmic: stray charge currents too small, super-sharp density dependence; mediated by long-range neutral currents

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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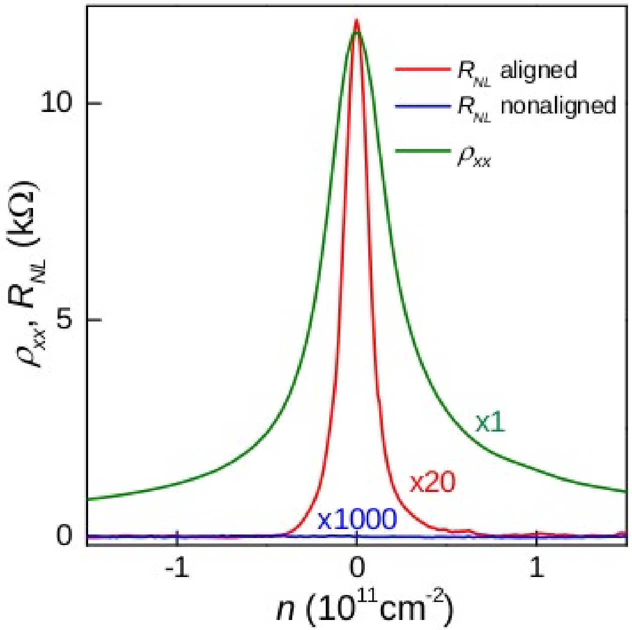

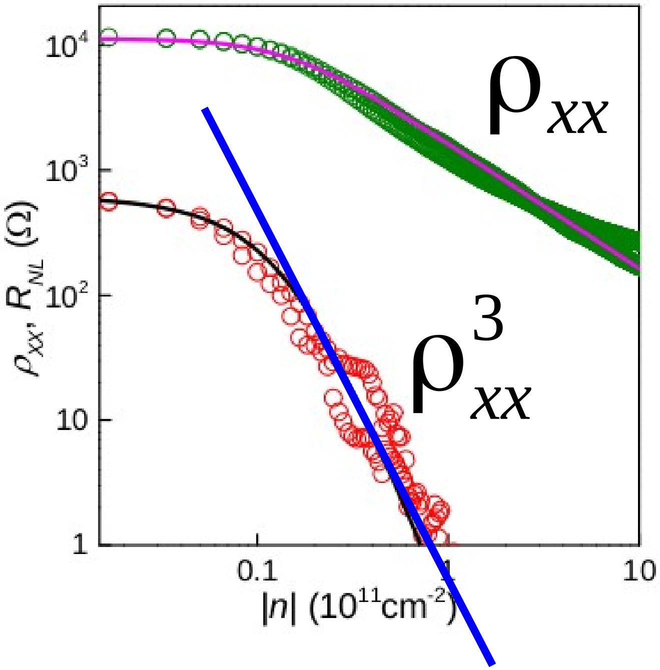

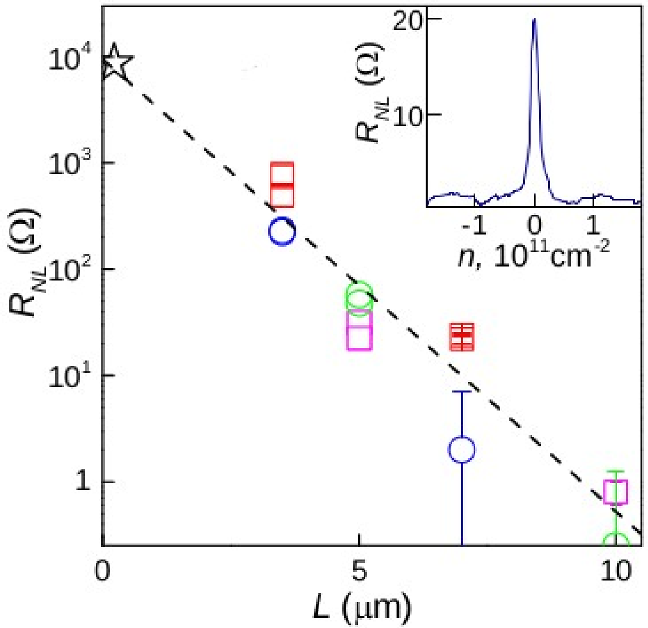

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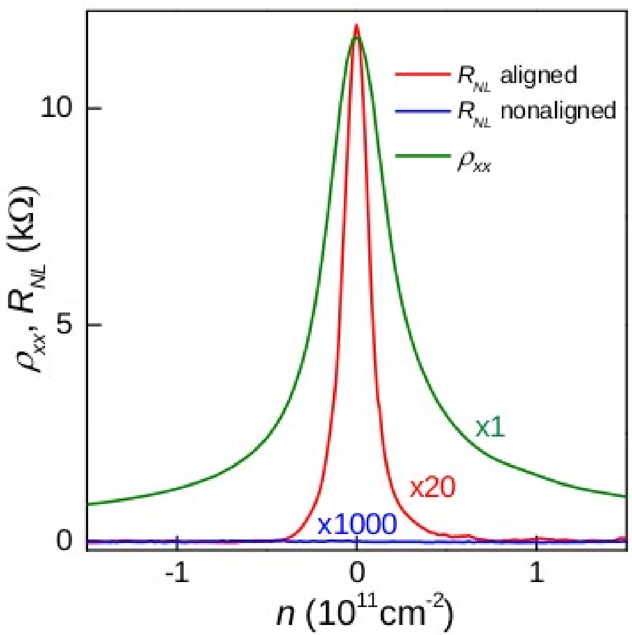
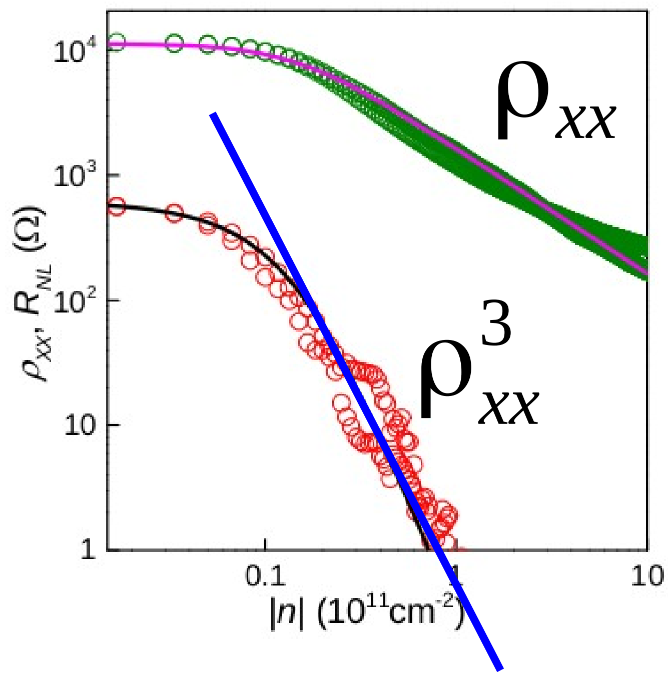
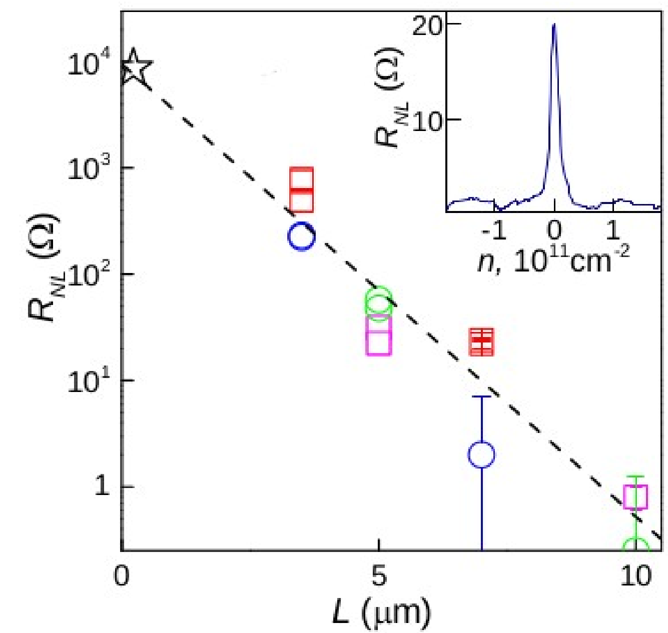


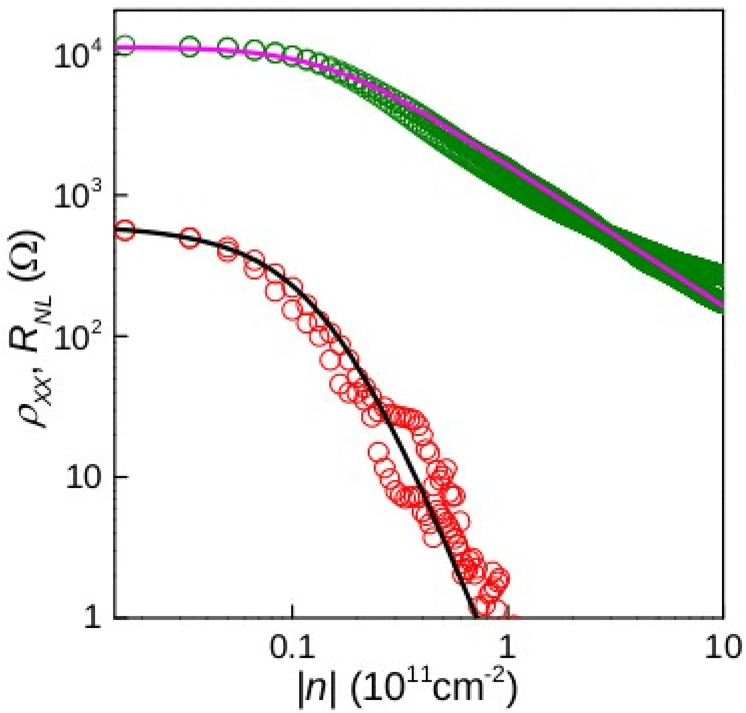


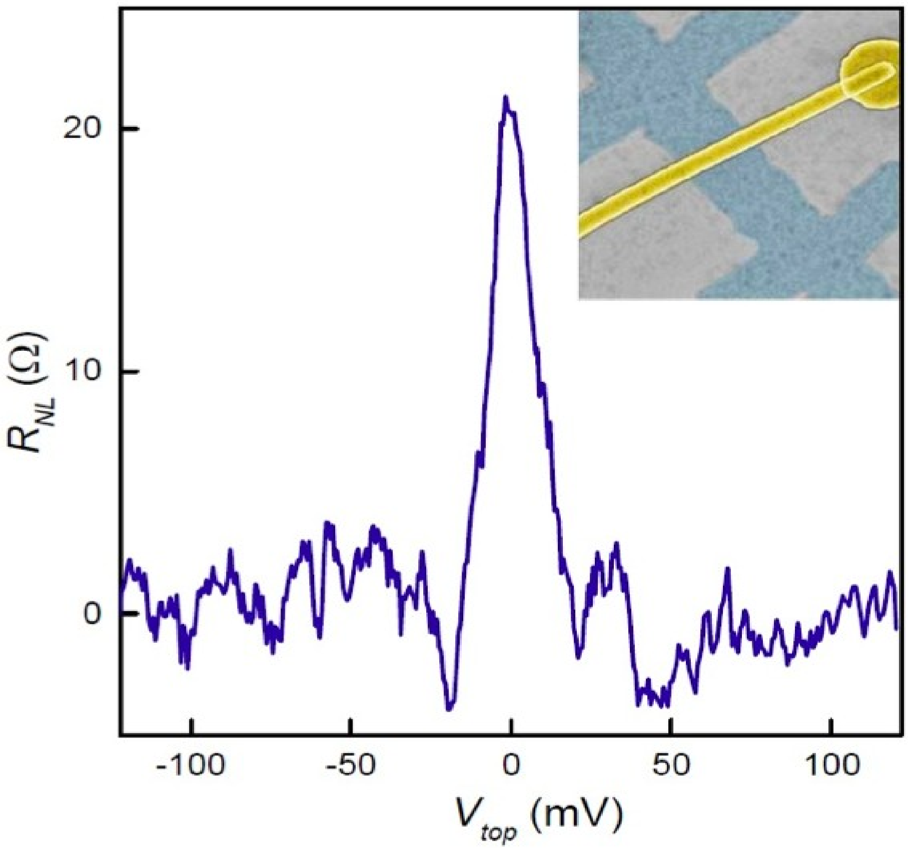


Valley transistor: proof of concept

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

Modulation > 100 fold





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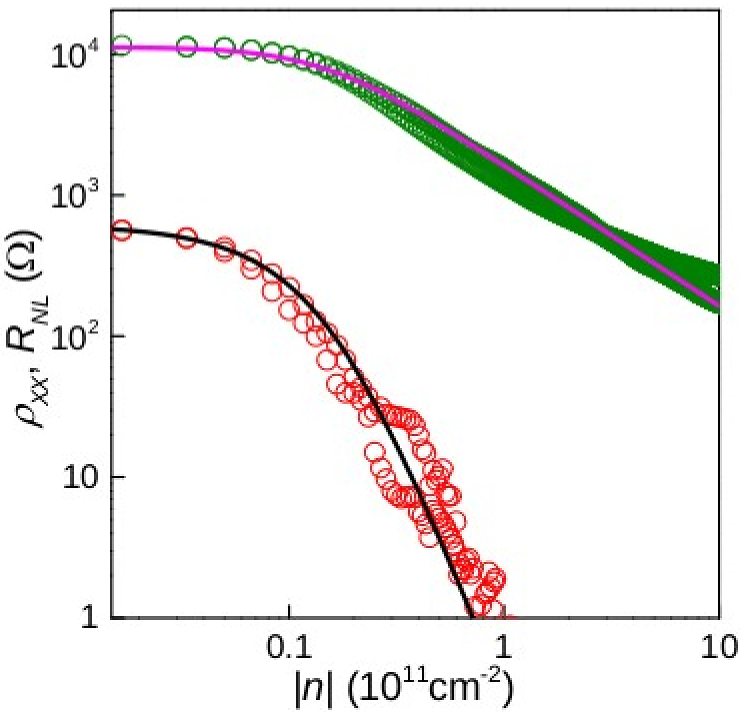
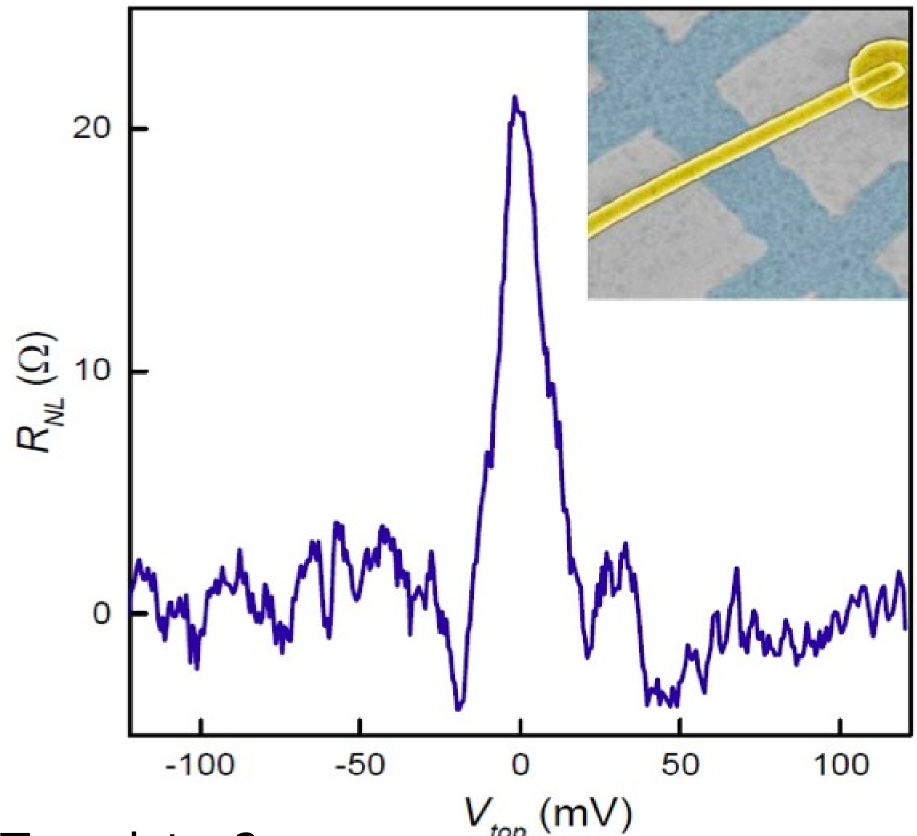
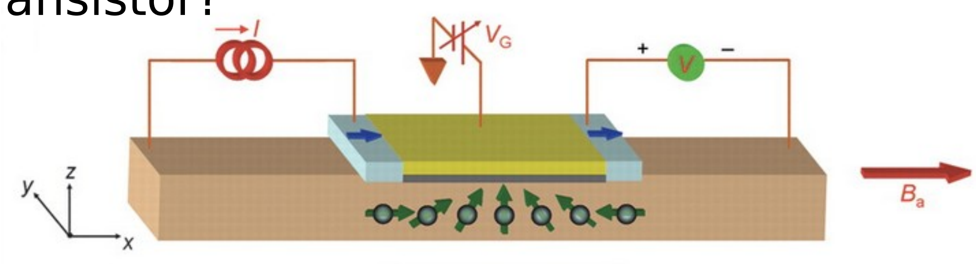




Spin Transistor?



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

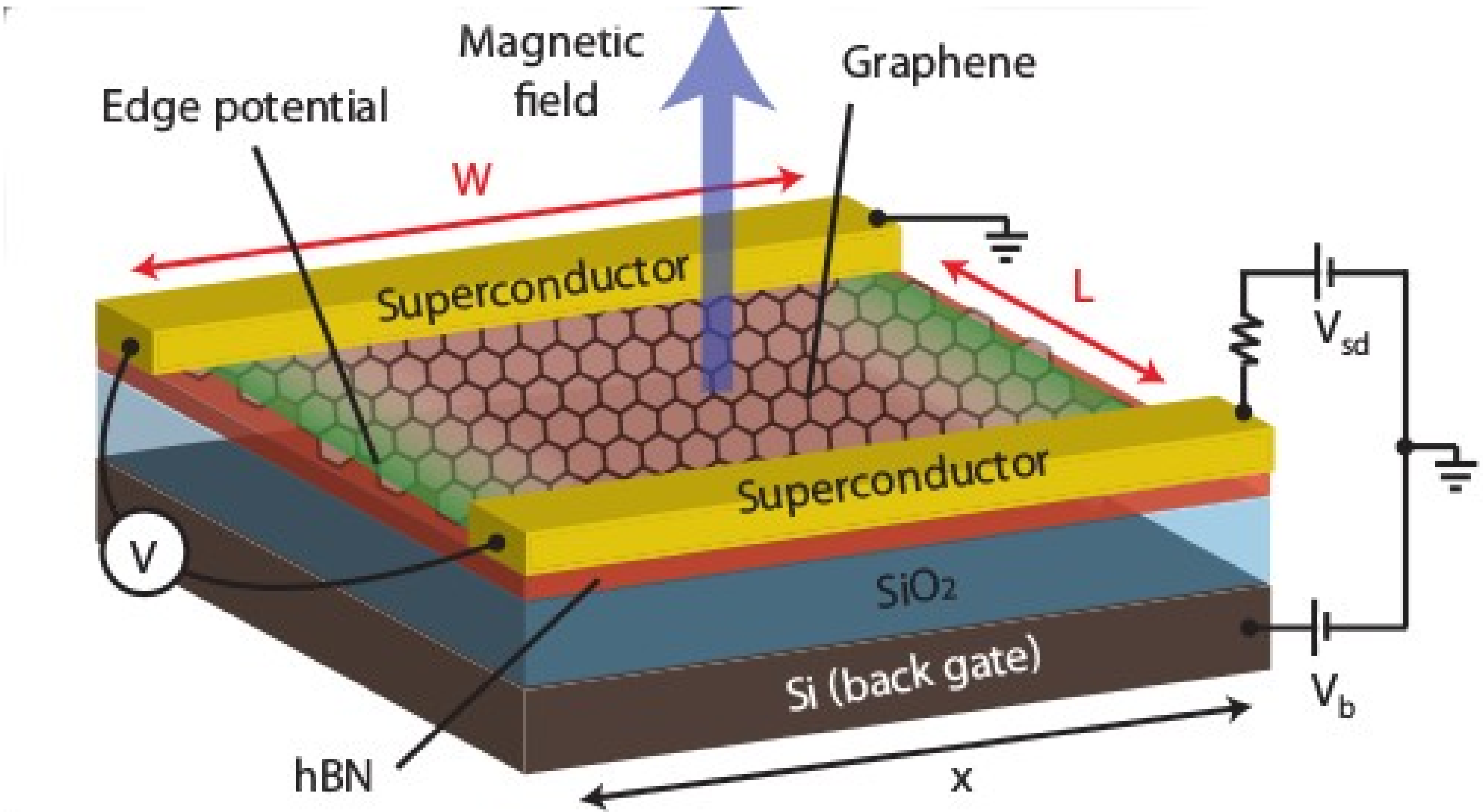
Koo, et. al., Science (2009), see also
Wunderlich, et. al. , Science (2010)

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)**

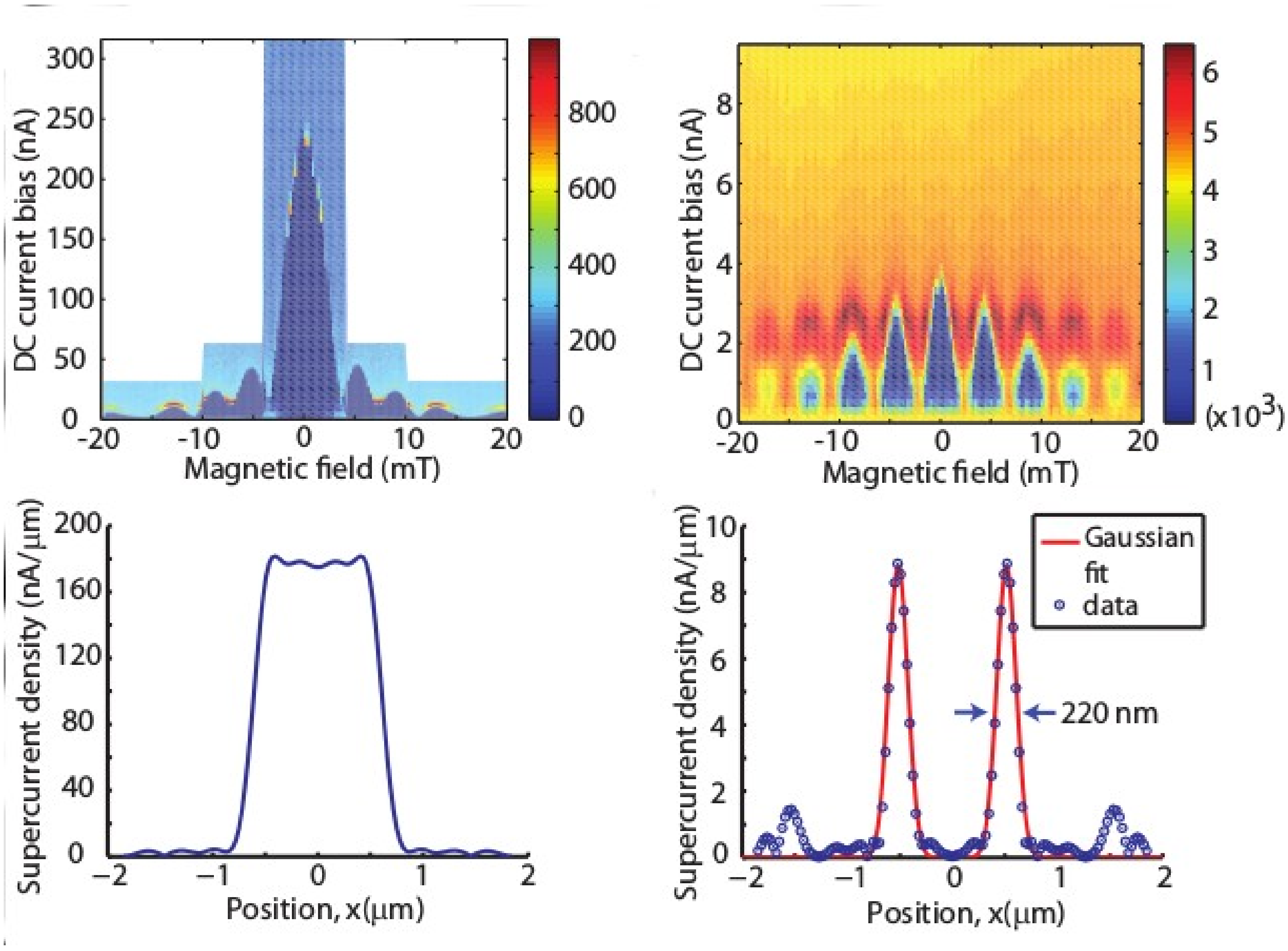
Edge currents from Josephson interferometry (Yacoby group 2015)



Edge currents from Josephson interferometry (Yacoby group 2015)

Away from DP

Near DP



Edge currents from Josephson interferometry (Yacoby group 2015)

Evidence for guided-wave states at the edge