# Electrically Controlled Topological States in Bilayer Graphene

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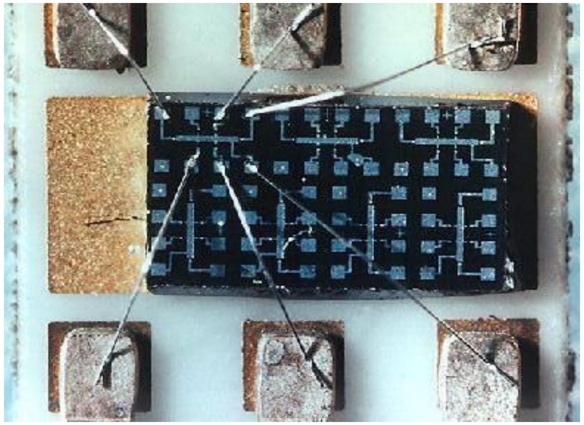
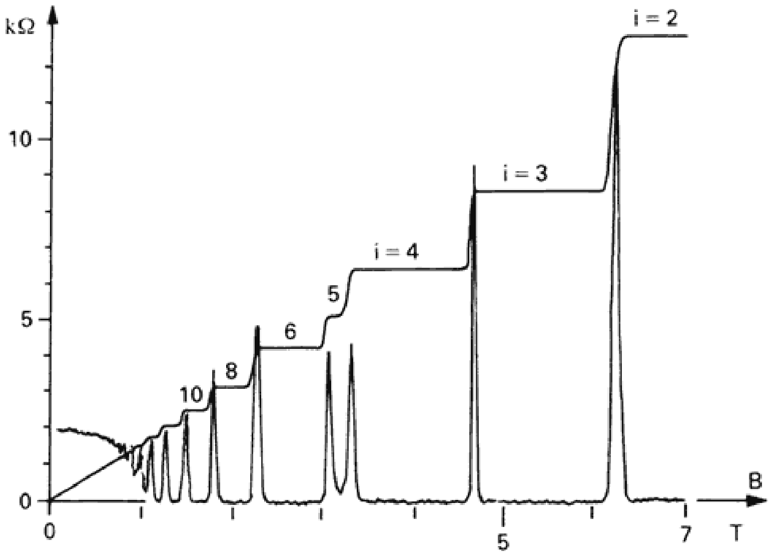
Dec. 5, 2019

# Quantum Hall Effect

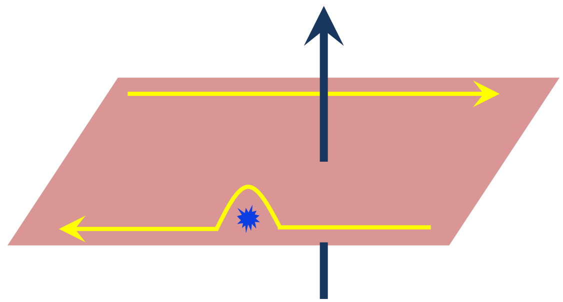
In the 2D limit, Landau-level quantization from strong magnetic field leads to ***quantized Hall conductance*** --- zero longitudinal resistance.





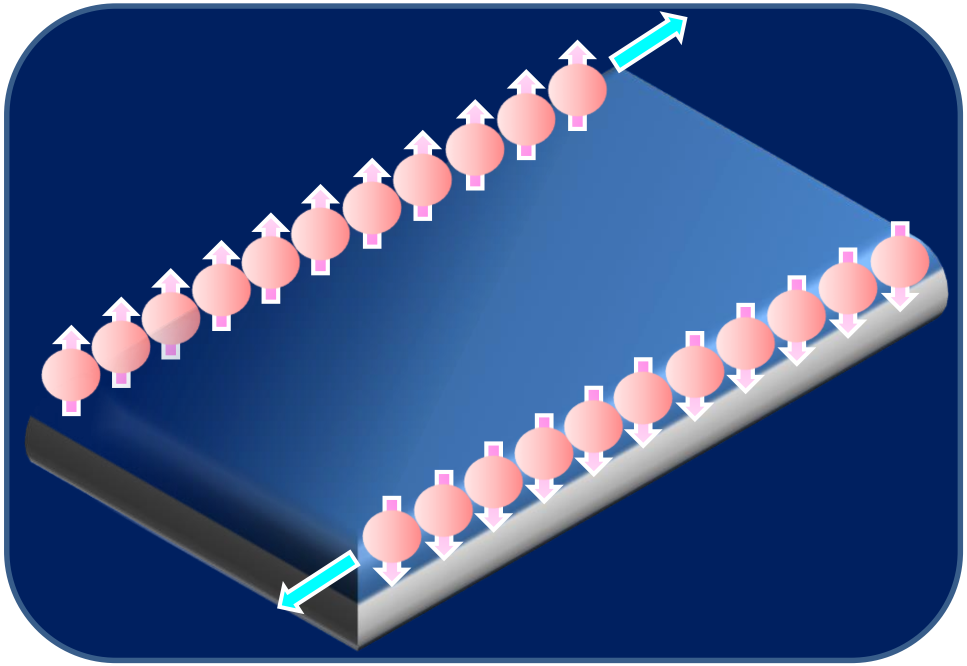
# Edge States of Quantum Hall Effect (QHE)

**Back-scattering is forbidden!**



Real topological state: Robust against any disorders

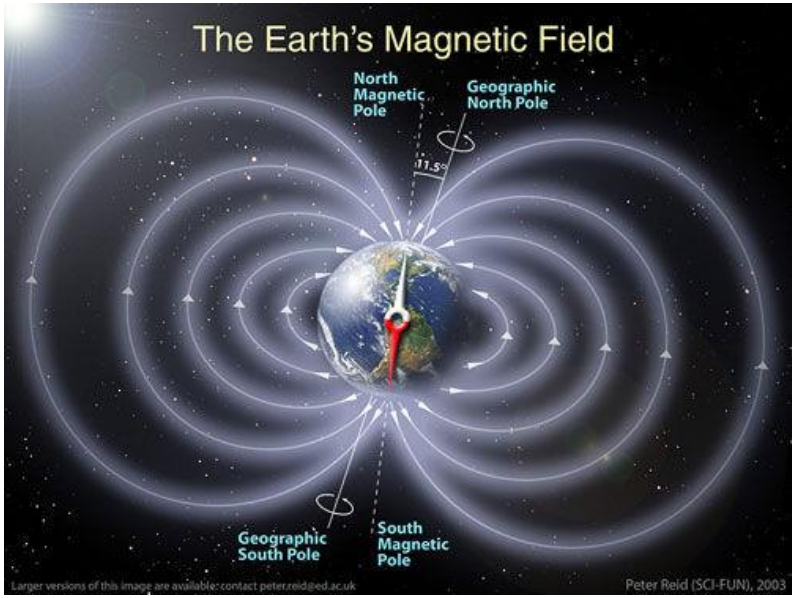
Potential application: Zero/low power electronics

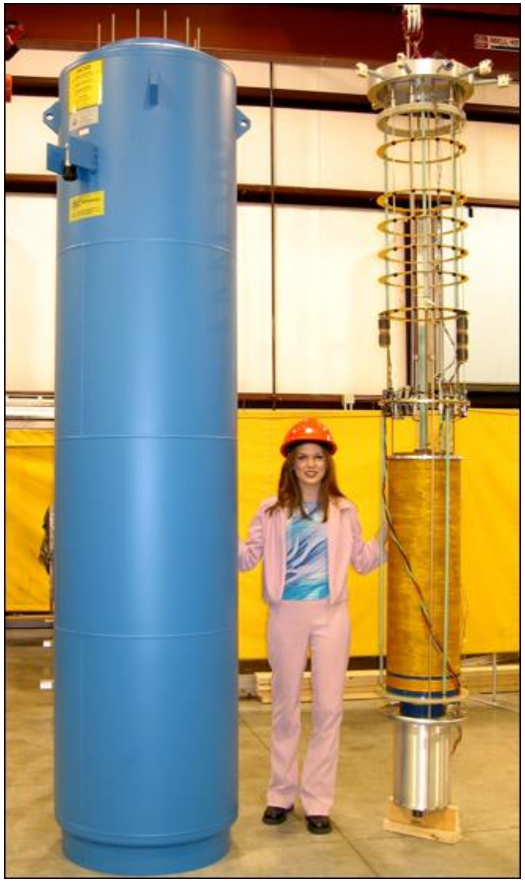


# The Disadvantage of QHE: Strong B field

**QHE: 10000 Gauss**

**Earth: 0.5 Gauss**



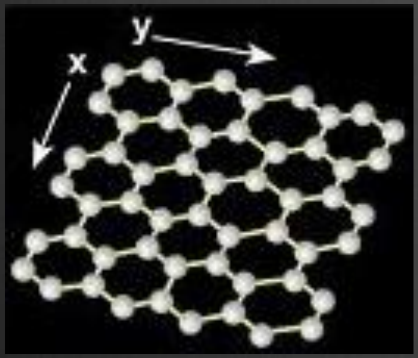
# Quantum Hall Effect without Magnetic Field

**Goal of both condensed matter physics and materials physics:**

Quantum Hall effect ***without magnetic field***

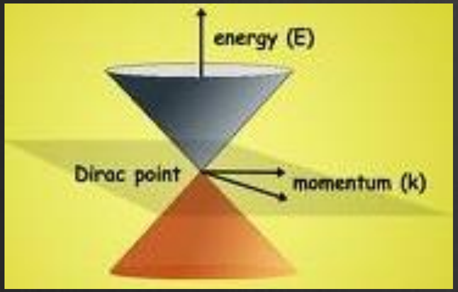
**Quantum anomalous Hall Effect**
**Quantum spin Hall Effect**
**Quantum valley Hall Effect**
**…**

# Graphene



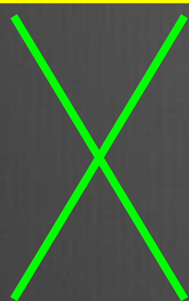

- thinnest
- mechanical property
- low resistivity
- room temperature QHE

Silicon terminator?

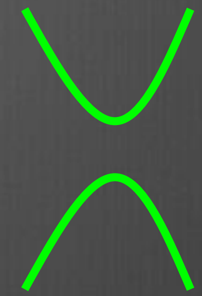



- linear dispersion
- zero gap

# Engineering band gaps

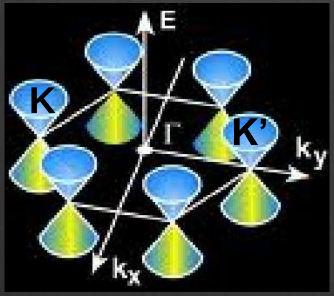


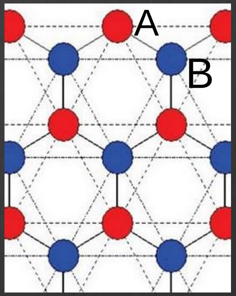
How?

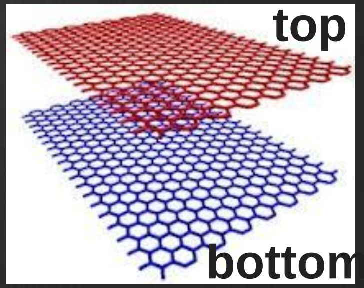


**Degrees of freedom**

- Real spin
- Valleys
- Sublattices
- Layers



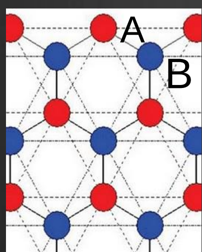



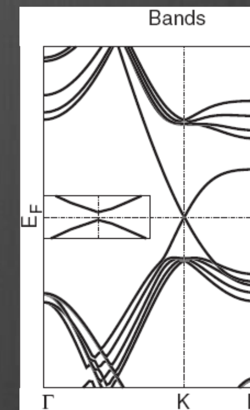
# Gap opening mechanism (1)

- Breaking inversion symmetry.

(a) Placing graphene on top of hexagonal boron nitride:

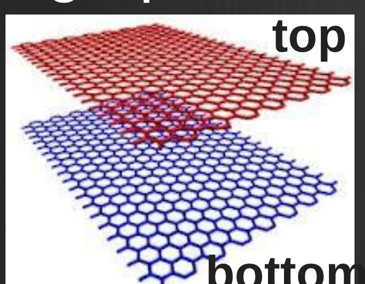



G. Giovannetti et al.,
PRB 76, 073103 (2007)

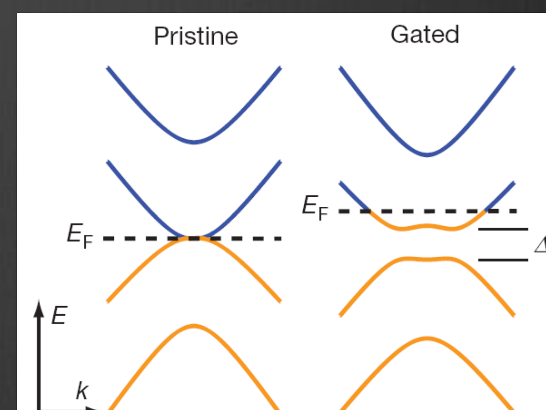



53 meV

(b) Applying an interlayer potential difference in AB-stacking bilayer graphene:




Y. Zhang et al.,
Nature 459, 820 (2008)



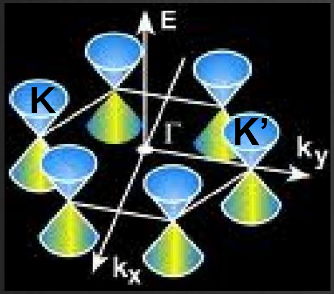

Tunable band gap

**Supporting quantum valley-Hall state**

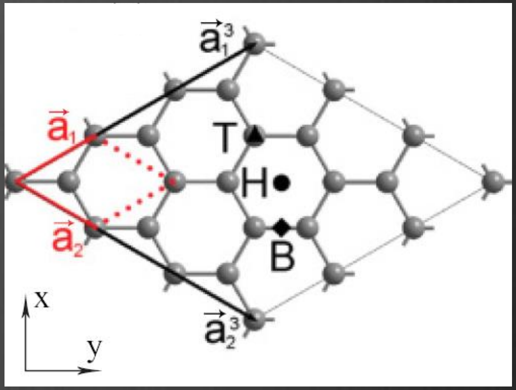
# Gap opening mechanism (2)

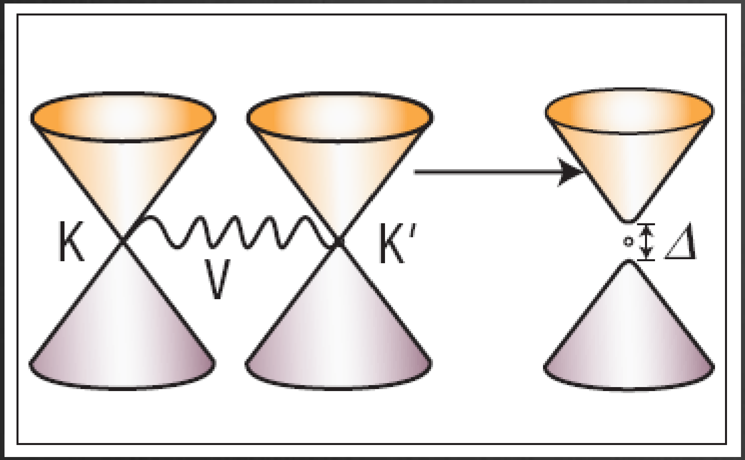
- Intervalley scattering.

Doping in 3N*3N supercell of graphene.

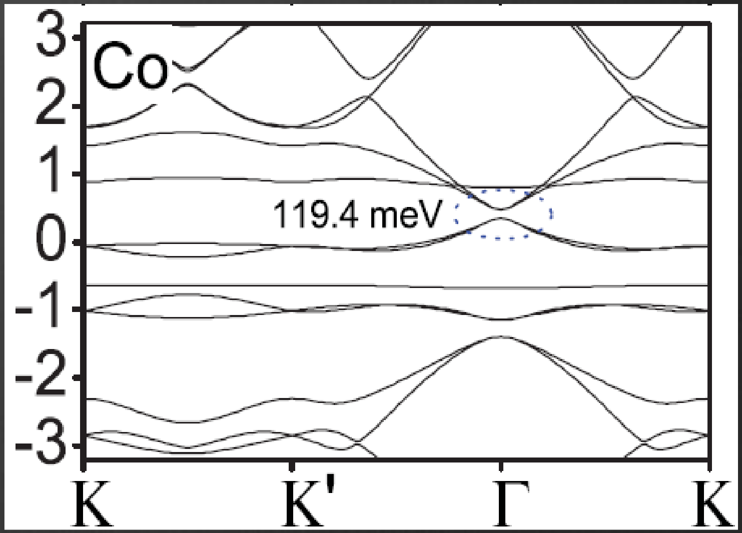



J. Ding et al., PRB 84,195444 (2011)
Z. Qiao, et al., PRB 85,115439 (2012)
Y. Ren et al, PRB 91,245415 (2015)




**Co doping**



# Gap opening mechanism (3)

- Intrinsic spin-orbit coupling

Kane-Mele model

$\mathbf{V_{SO} >> V_r}$

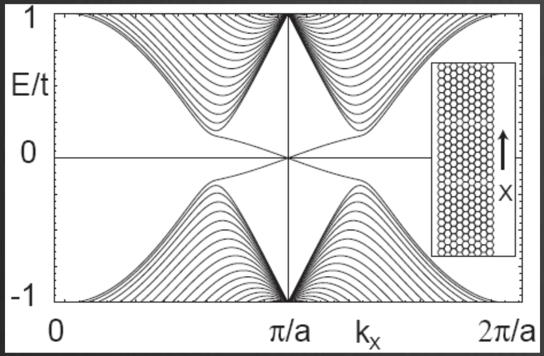
$$H = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_{SO} \sum_{\langle\langle ij \rangle\rangle} c_i^\dagger \sigma \cdot (\mathbf{d}_{kj} \times \mathbf{d}_{ik}) c_j$$

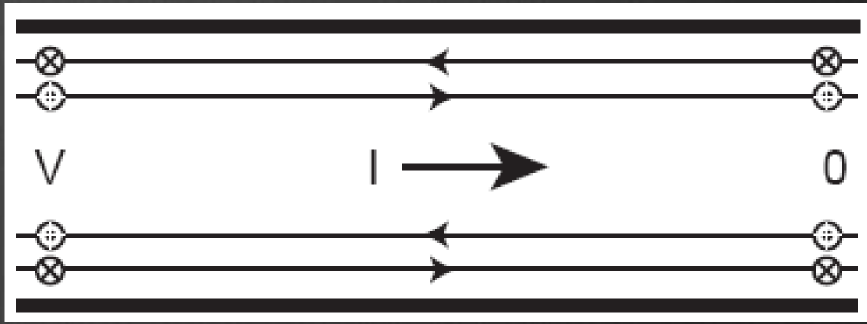
Intrinsic SOC

$$+ i V_r \sum_{\langle ij \rangle} c_i^\dagger \hat{\mathbf{e}}_z \cdot (\sigma \times \mathbf{d}_{ij}) c_j$$

Rashba SOC

Quantum spin-Hall effect




C. Kane et al., PRL 95, 146802 (2005)

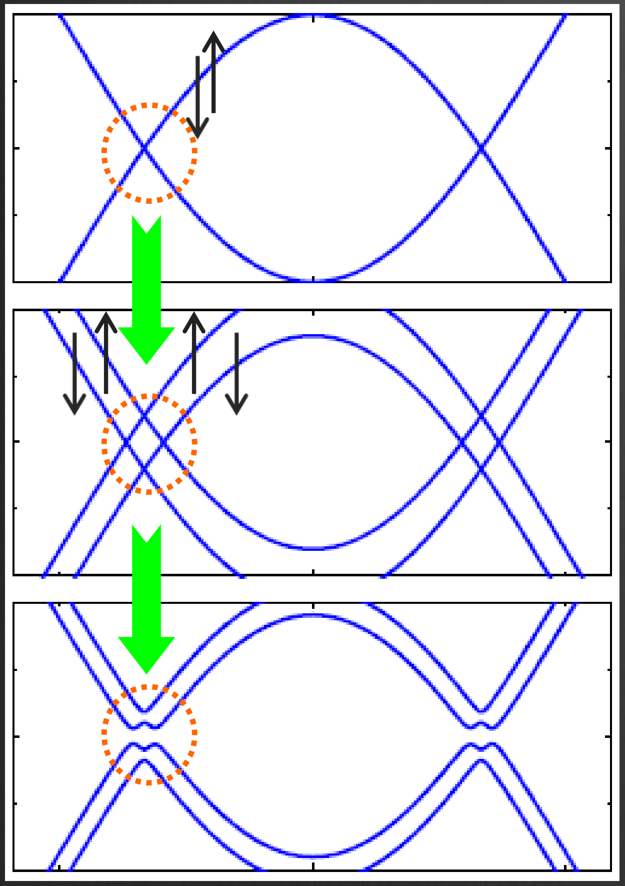
**Extremely weak intrinsic SOC!**

Y. Yao et al., PRB 75, 041401 (2007)
H. Min et al., PRB 74, 165310 (2006)

# Gap opening mechanism (4)

Modified

Kane-Mele model



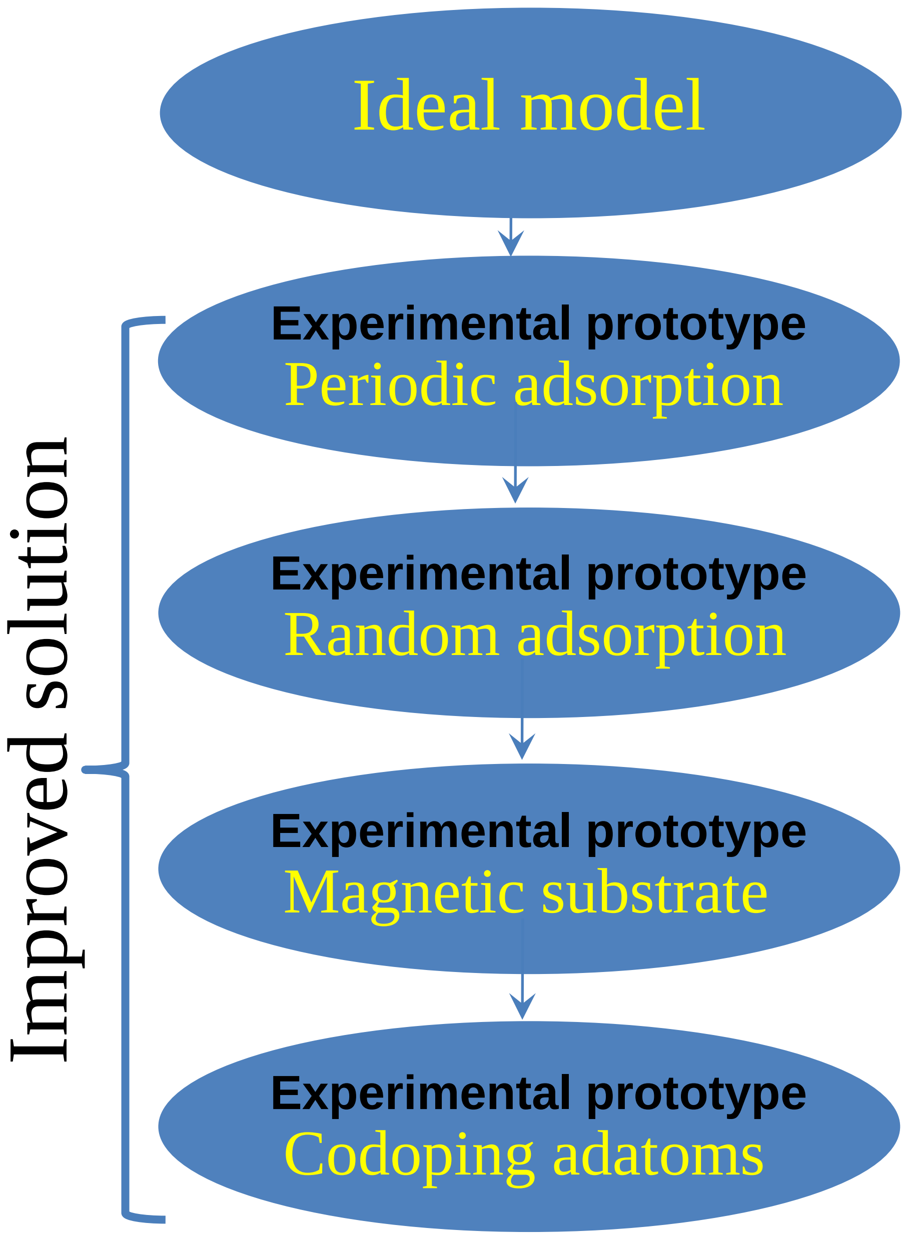

$$H = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_{SO} \sum_{\langle\langle ij \rangle\rangle} c_i^\dagger \sigma \cdot (\mathbf{d}_{kj} \times \mathbf{d}_{ik}) c_j$$

$$+ i V_r \sum_{\langle ij \rangle} c_i^\dagger \hat{\mathbf{e}}_z \cdot (\sigma \times \mathbf{d}_{ij}) c_j + \lambda \sum_{i\alpha} c_{i\alpha}^\dagger \sigma_z c_{i\alpha}$$

Zeeman field

Quantum anomalous-Hall effect

# Roadmap of QAHE in graphene




Qiao, Yang *et al*,
*PRB* 82, 161414 (2010)

Ding, Qiao *et al.*,
*PRB* 84,195444 (2011)

Jiang, Qiao *et al.*,
*PRL* 109,116803 (2012)

Qiao, Ren *et al.*,
*PRL* 112,116404 (2014)

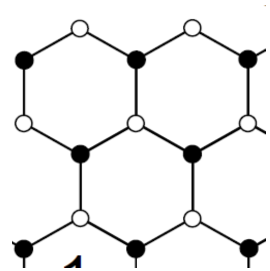
Ren, Qiao, Niu,
*Rep. Prog. Phys.* 112,116404 (2014)

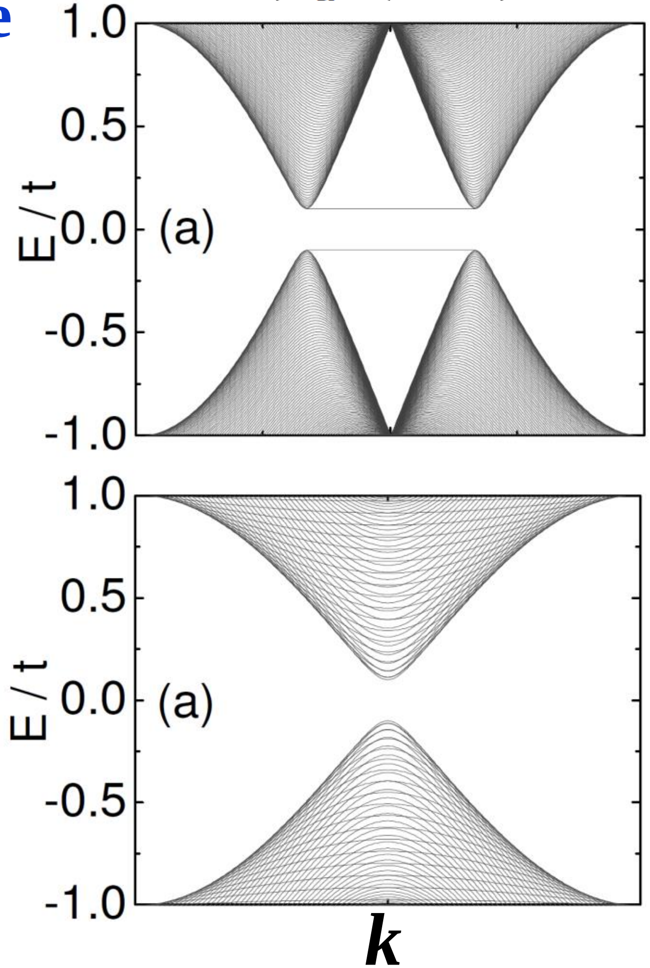
Deng, Qi, Xu, and Qiao,
*PRB* *95*, *121410* (2017)

# Engineering topological states using electric means but not spin-related elements

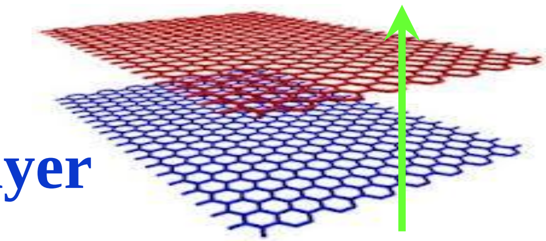
# Quantum valley-Hall effect

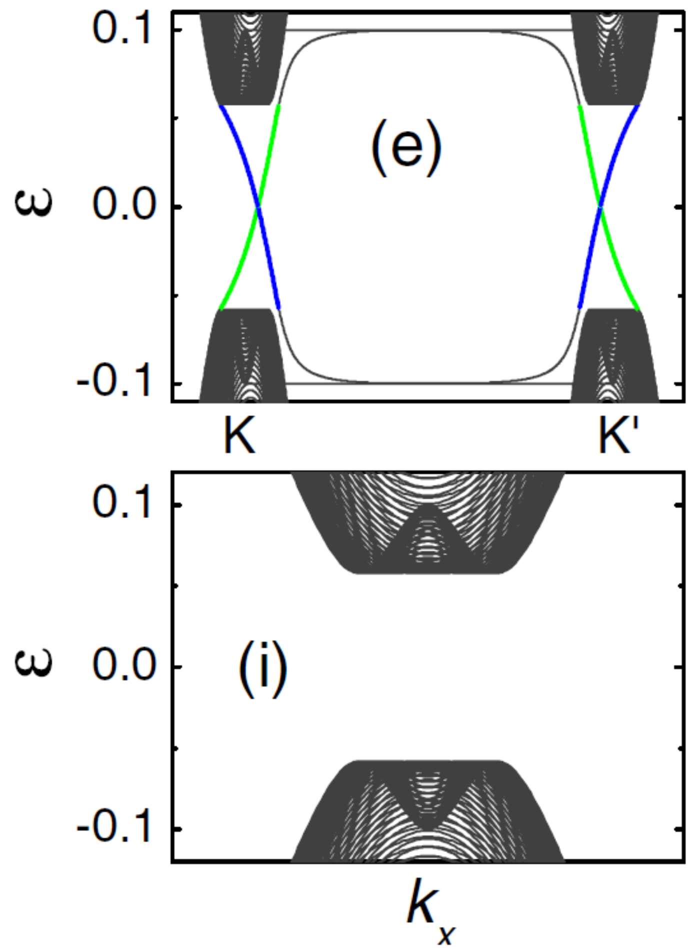
**Monolayer graphene with sublattice potential**





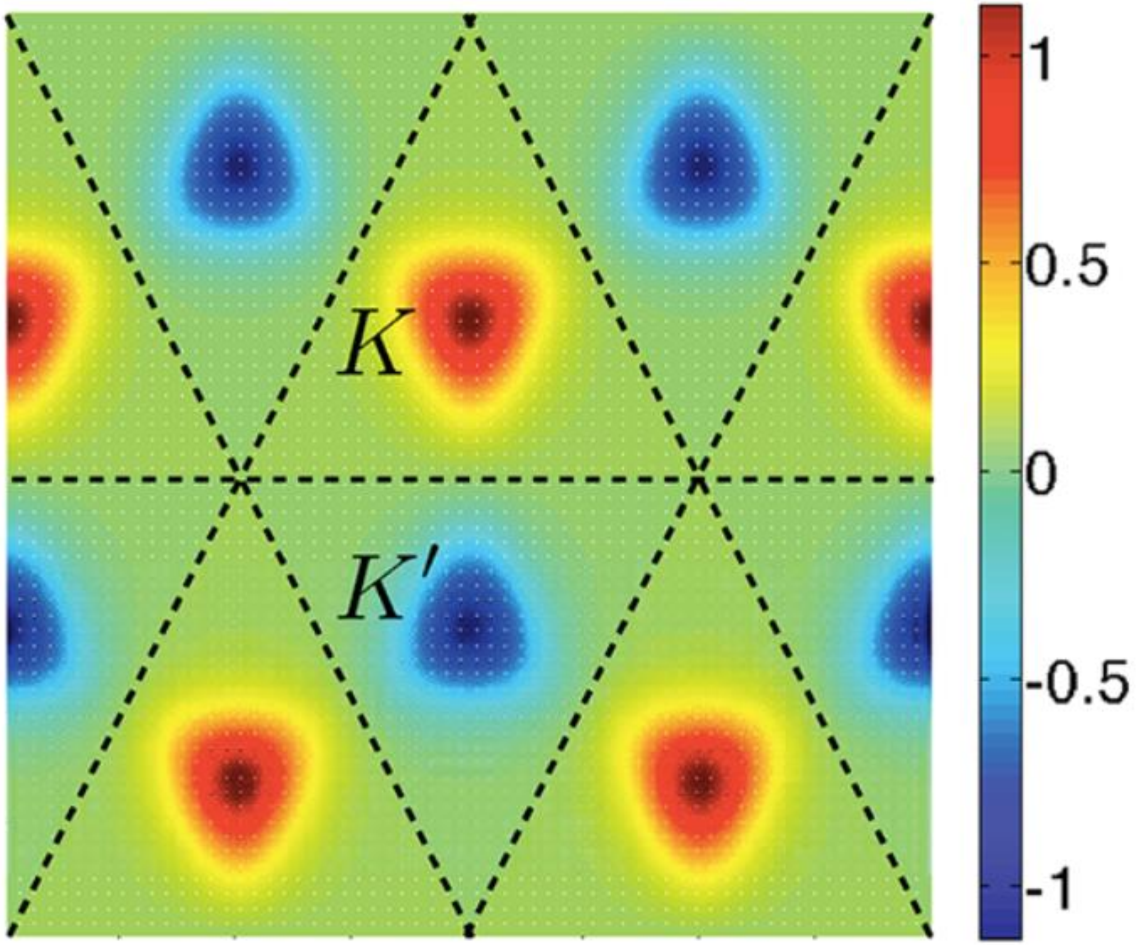

**Gated bilayer graphene**



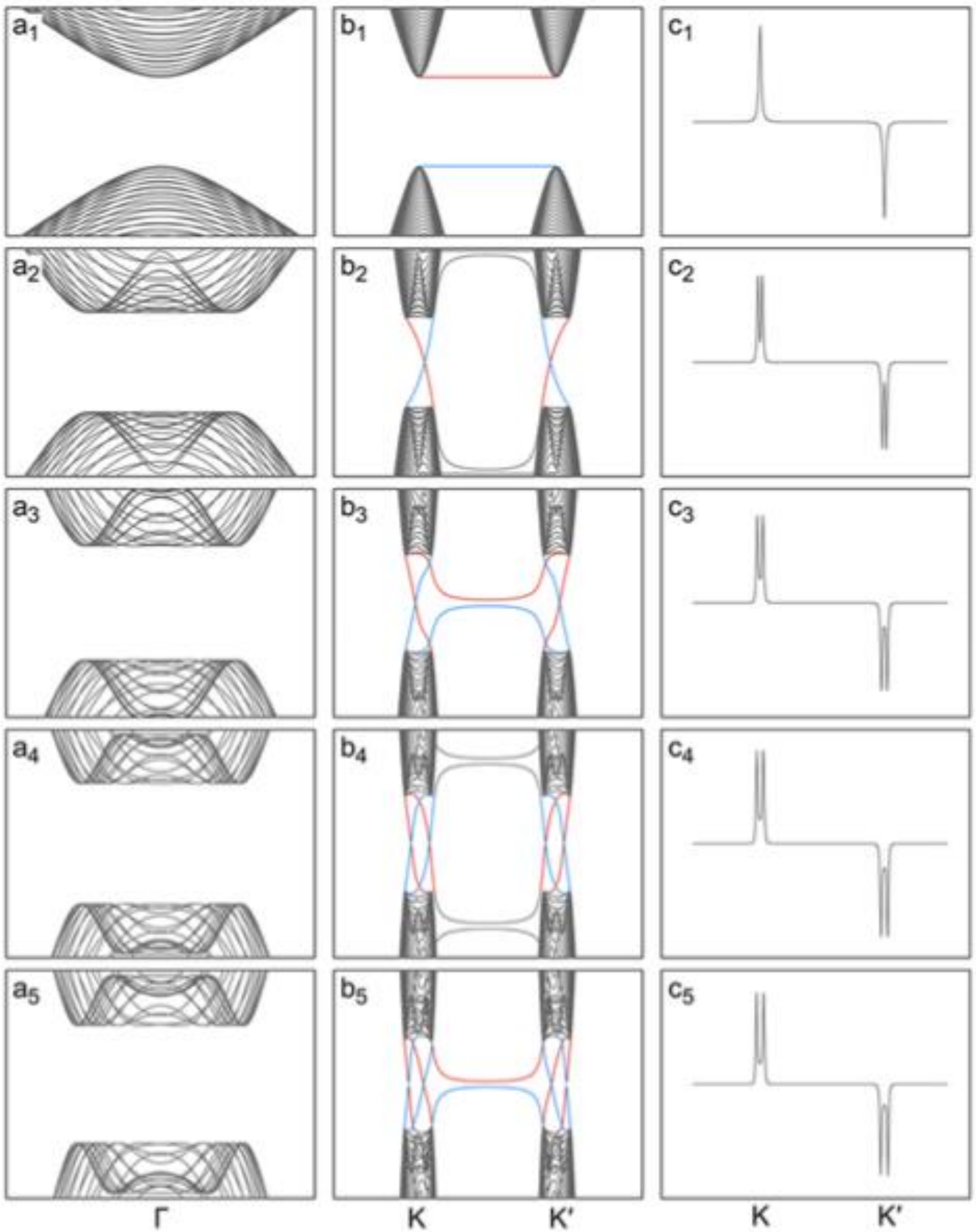


# Quantum valley-Hall effect

**Topological order：** $C_V = C_K - C_{K'}$



# Quantum valley-Hall effect




1-layer $C_V=1/2$

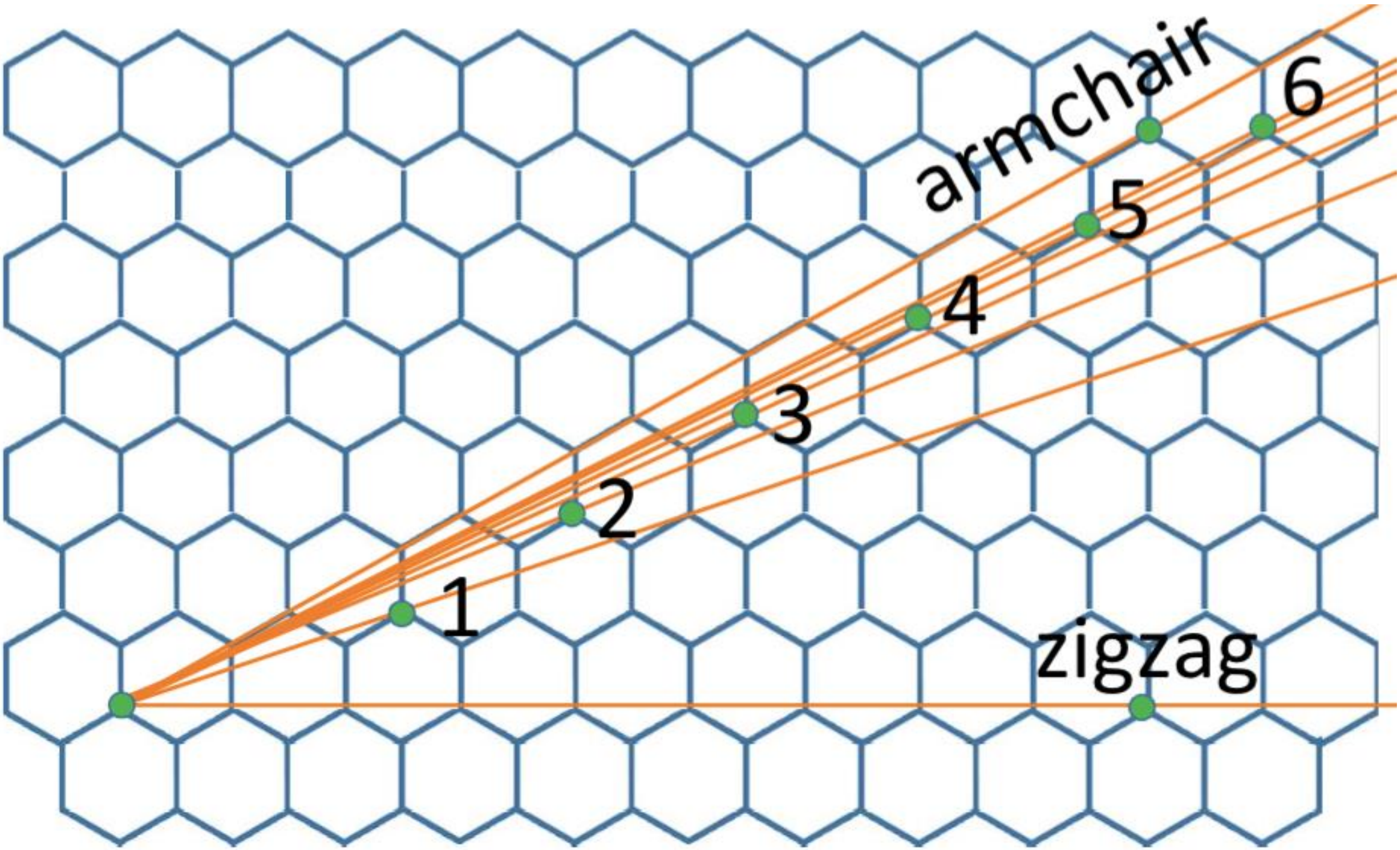
2-layer $C_V=1$

3-layer $C_V=3/2$

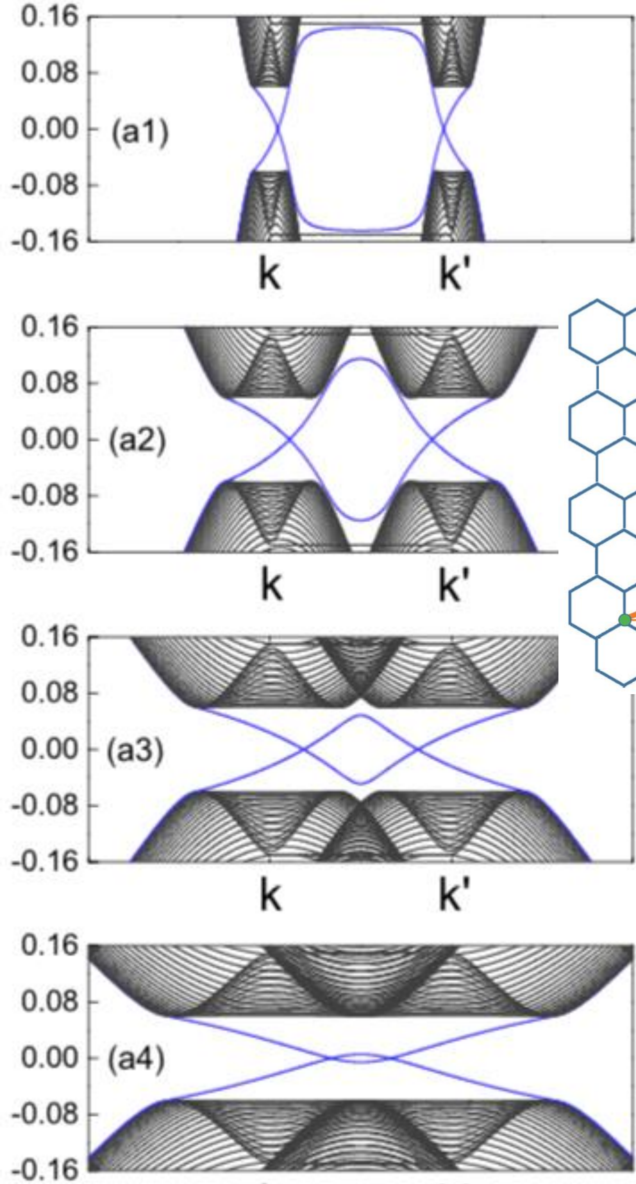
4-layer $C_V=2$

5-layer $C_V=5/2$

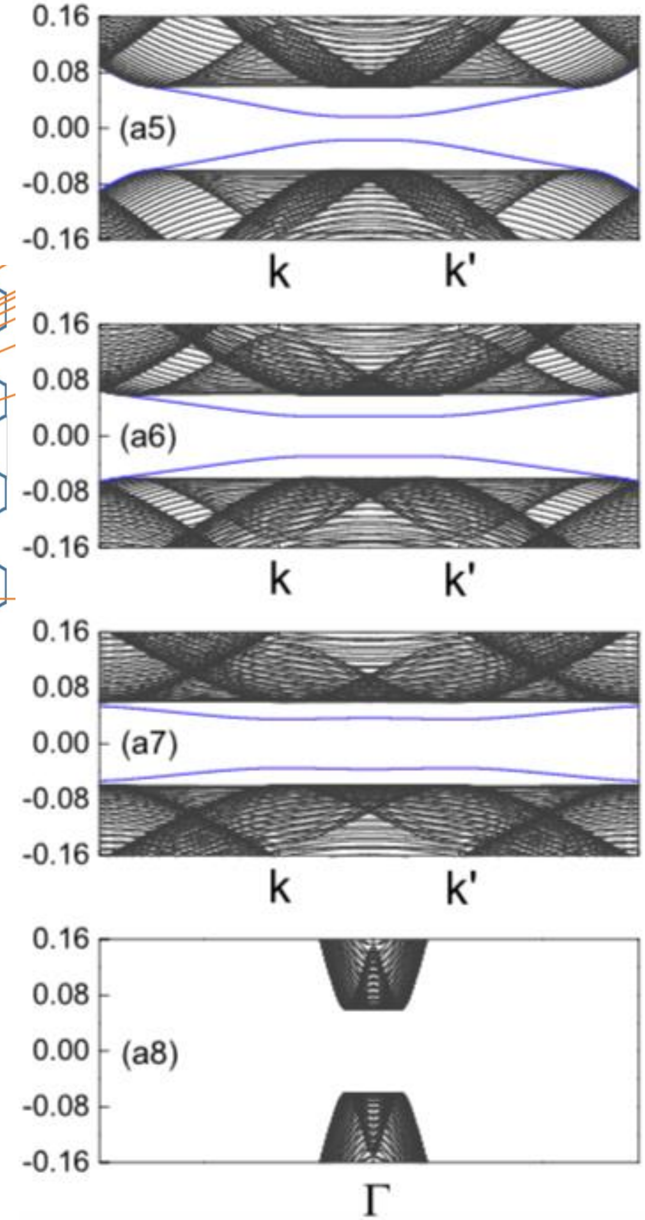
# Quantum valley-Hall effect



# Quantum valley-Hall effect




**Various bilayer graphene ribbons**

# Quantum valley-Hall effect

## Comparison with QHE and Z2 Topological insulator

| | QHE | Z2 TI | QVHE |
|---|---|---|---|
| **Topological state** | Strong | weak | Weak |
| **Topological number** | Chern number | Z2 number | Valley Chern number |
| **Robustness** | Any kind of disorder | Time-reversal invariance | Without inter-valley mixing |

# Quantum valley-Hall effect

**Advantage:**

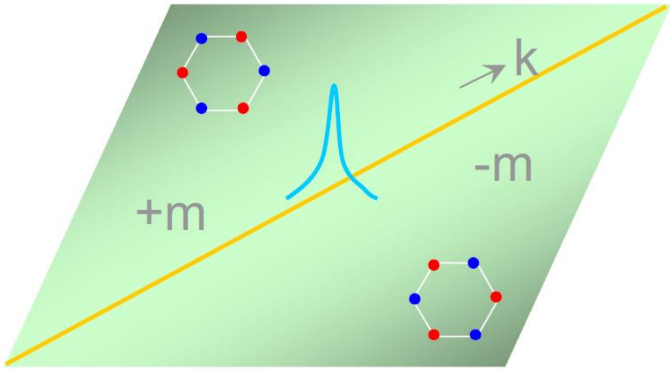
Robust against long-range disorders

**Disadvantages:**

1. Difficult to grow or cut some specific ribbons with gapless edge modes
2. Easy to be destroyed by short-range disorders

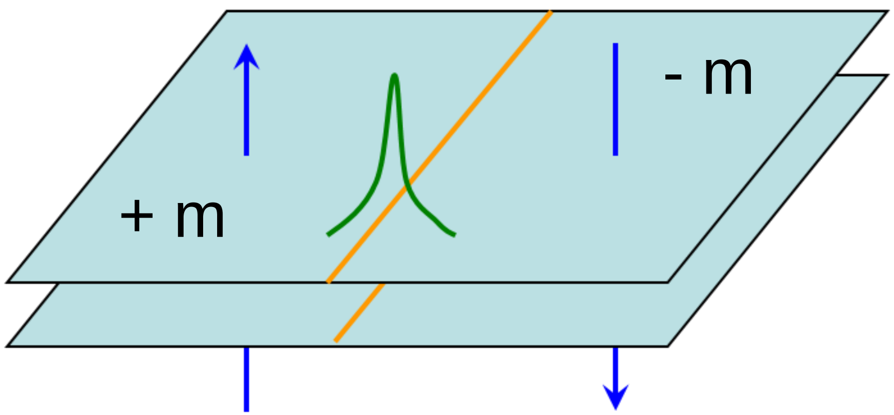
# From
# quantum valley-Hall effect
# to
# Topological 1D zero-line mode

# Topological 1D zero-line mode




Monolayer graphene with alternating sublattice potentials

Semenoff et al., PRL 101, 087204 (2008)
Yao et al., PRL 102, 096801 (2009).




AB stacking bilayer graphene with alternating electric fields

Martin et al., PRL 100, 036804 (2008)

**Energy dispersion**

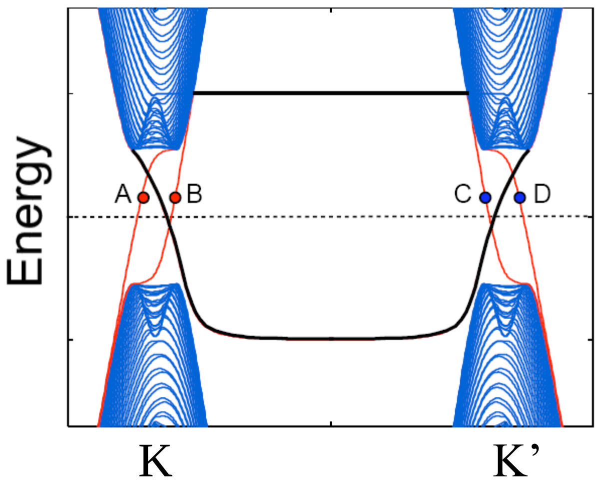
**K : E=+k**
**K’: E=-k**

**Other names: topological confinement state, kink state, topological zero mode, domain-wall state**

# Topological 1D zero-line mode

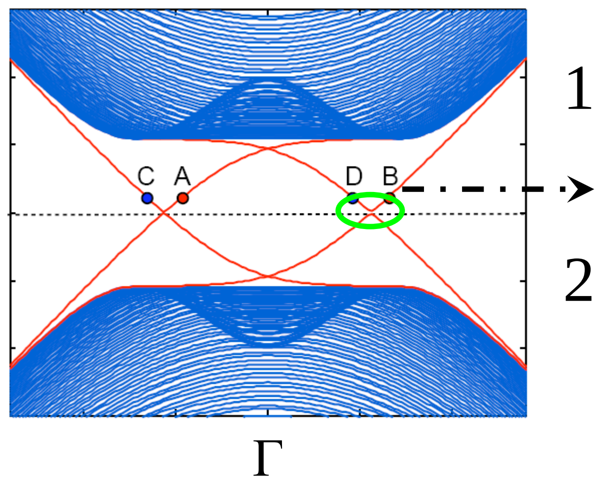
Two representative zero lines (bilayer graphene with varying potential differences):

**Zigzag zero line**




**Gapless mode!**

**Armchair zero line**



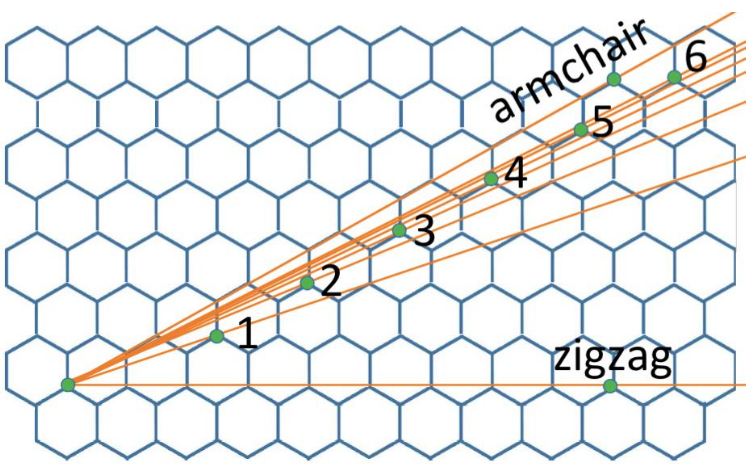

1. Small avoided crossing band gap
2. Easy to be scattered

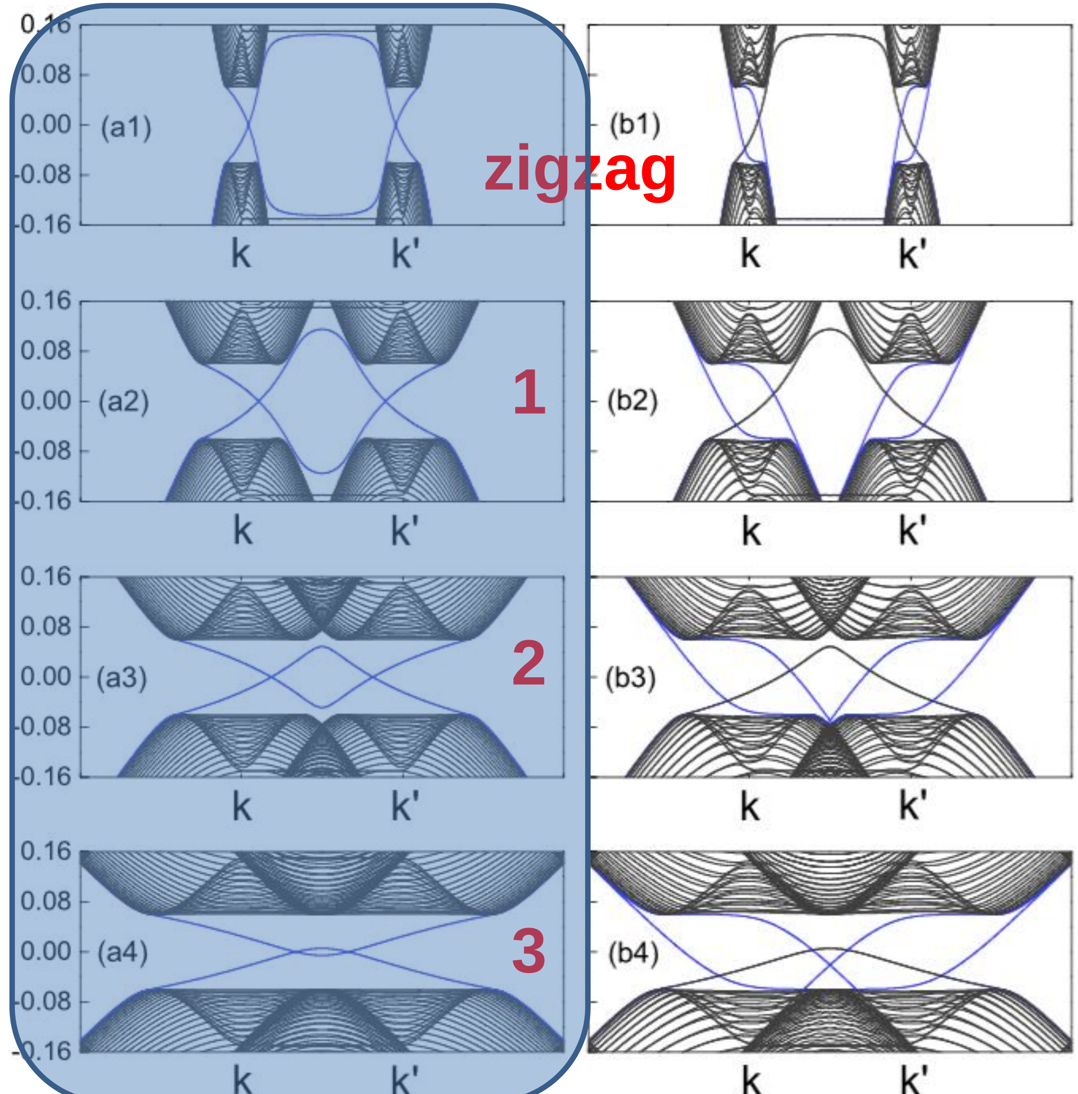
**Gapped mode!**

Qiao, Jung, Niu, MacDonald, Nano Lett. 11, 3453 (2011)

# Topological 1D zero line mode

**Evolution of band structure from zigzag to armchair zero lines**:

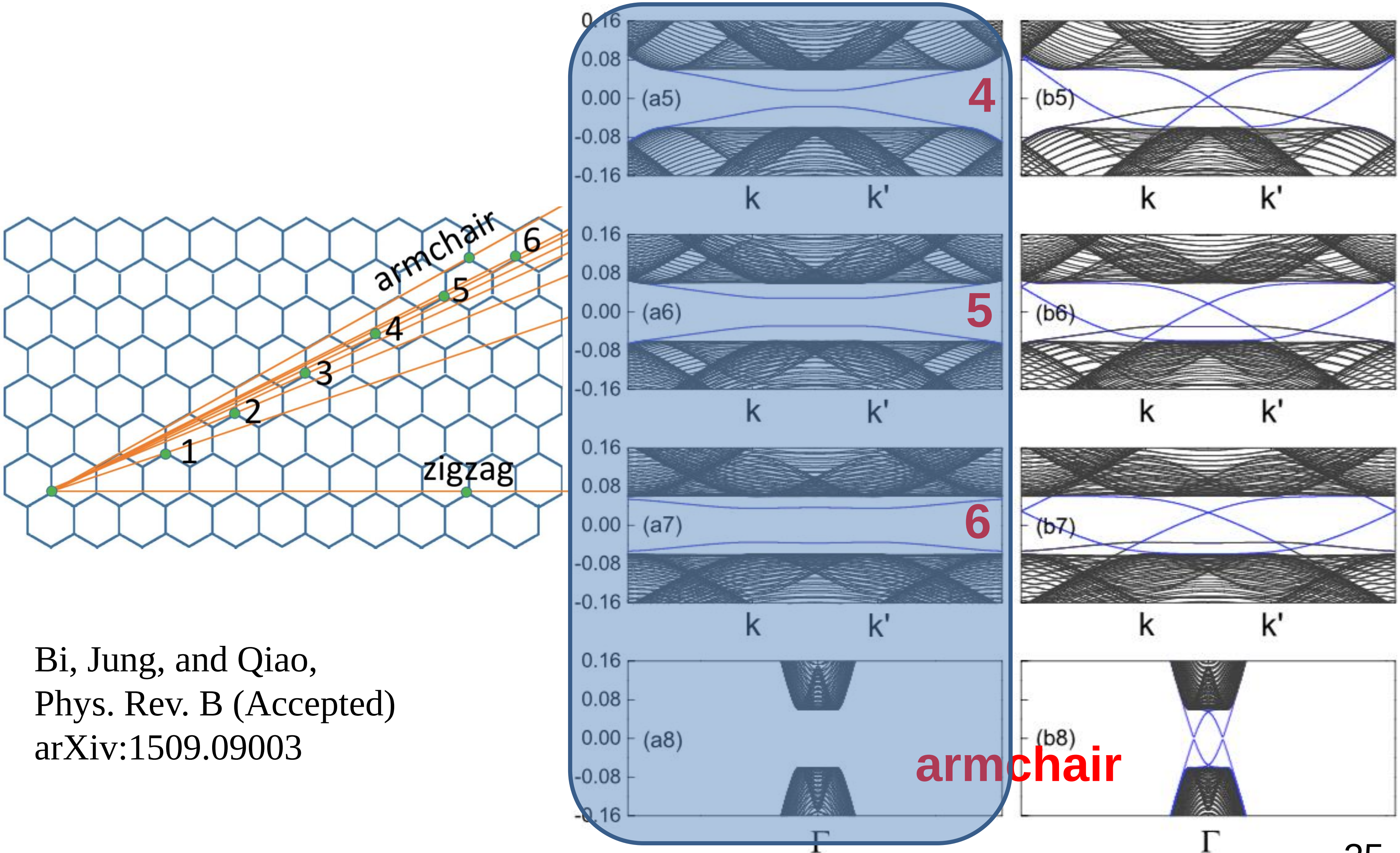



Bi, Jung, and Qiao,
Phys. Rev. B (Accepted)
arXiv:1509.09003

# Topological 1D zero line mode

**Evolution of band structure from zigzag to armchair zero lines**:




Bi, Jung, and Qiao,
Phys. Rev. B (Accepted)
arXiv:1509.09003

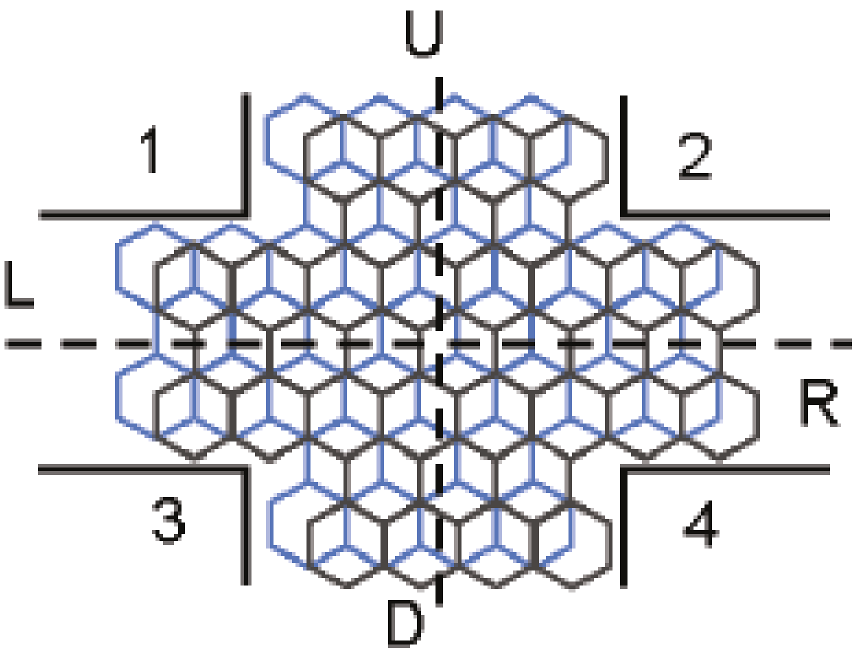
# Topological 1D zero line mode

Zero line modes are gapless with distinguishable valleys in any ribbons except armchair ribbon.

Whether such a mode is useful in realistic systems?

# Schematic of a 4-terminal device

In a bilayer graphene:




Single 1D zero line can be created by considering different potential profiles:

(+, +, -, -)

(+, -, +, -)

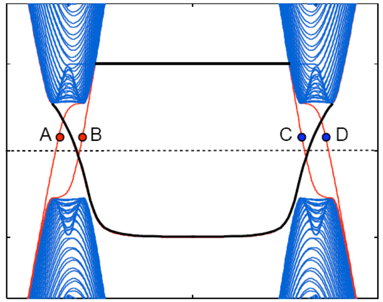
(+, +, +, -)

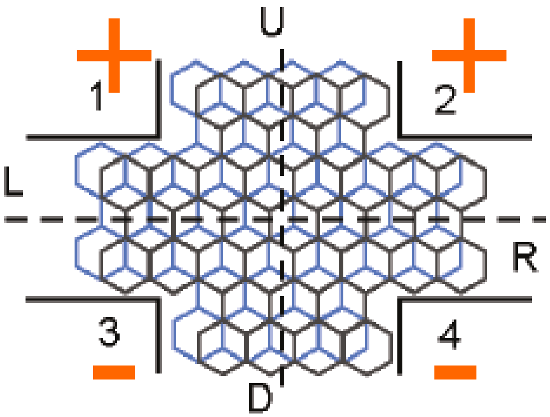
(+, -, +, +)

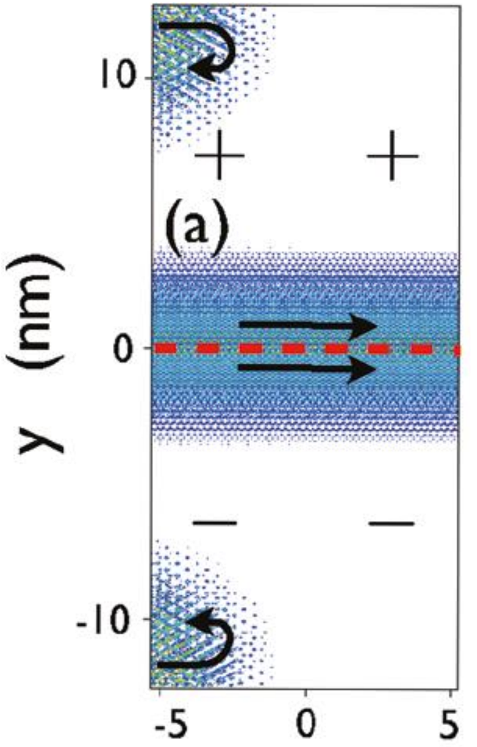
(-, +, +, +)

(+, +, -, +)

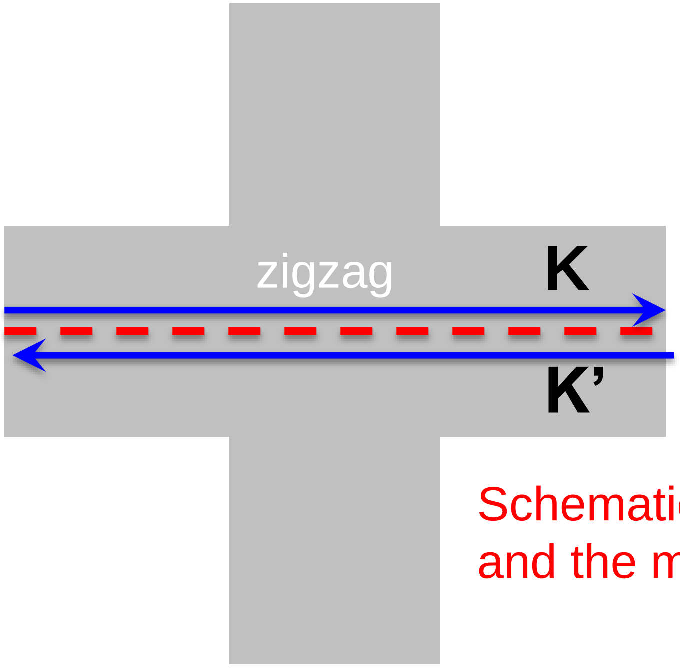
# Transport of single zero line



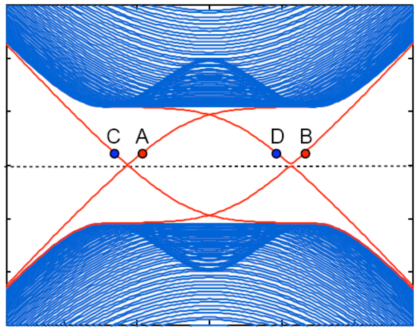

Conductance from L to R is quantized to $2e^2/h$.

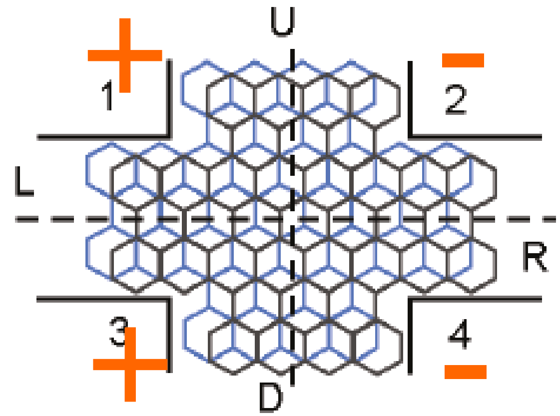


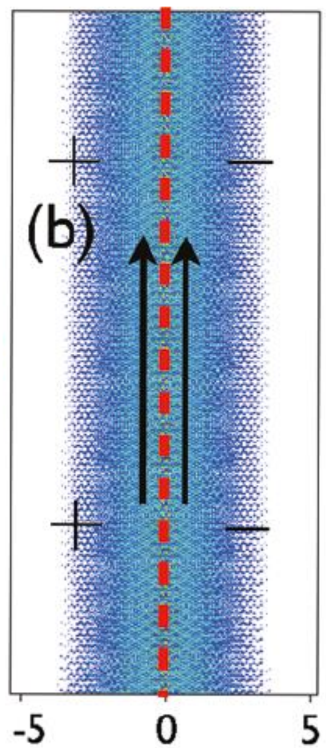

Schematic of zero-line and the mode.

Qiao, Jung, Niu, MacDonald, Nano Lett. 11, 3453 (2011)

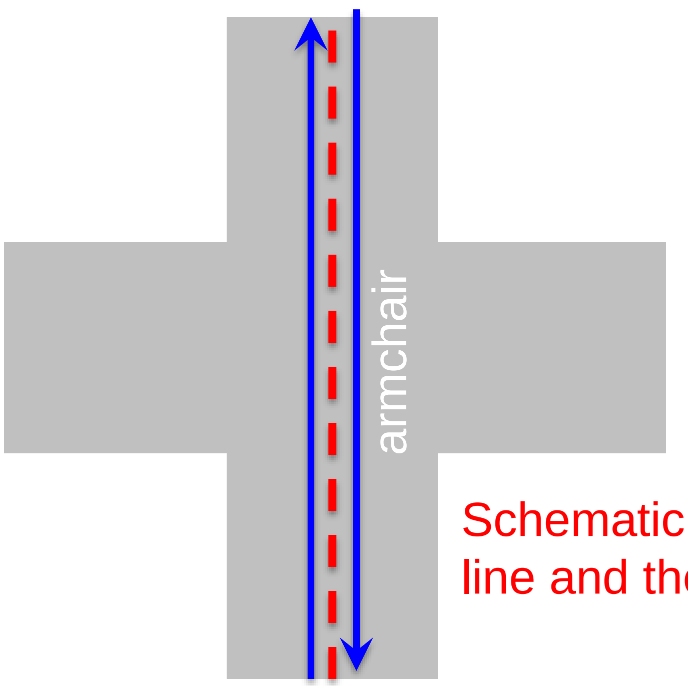
# Transport of single zero line



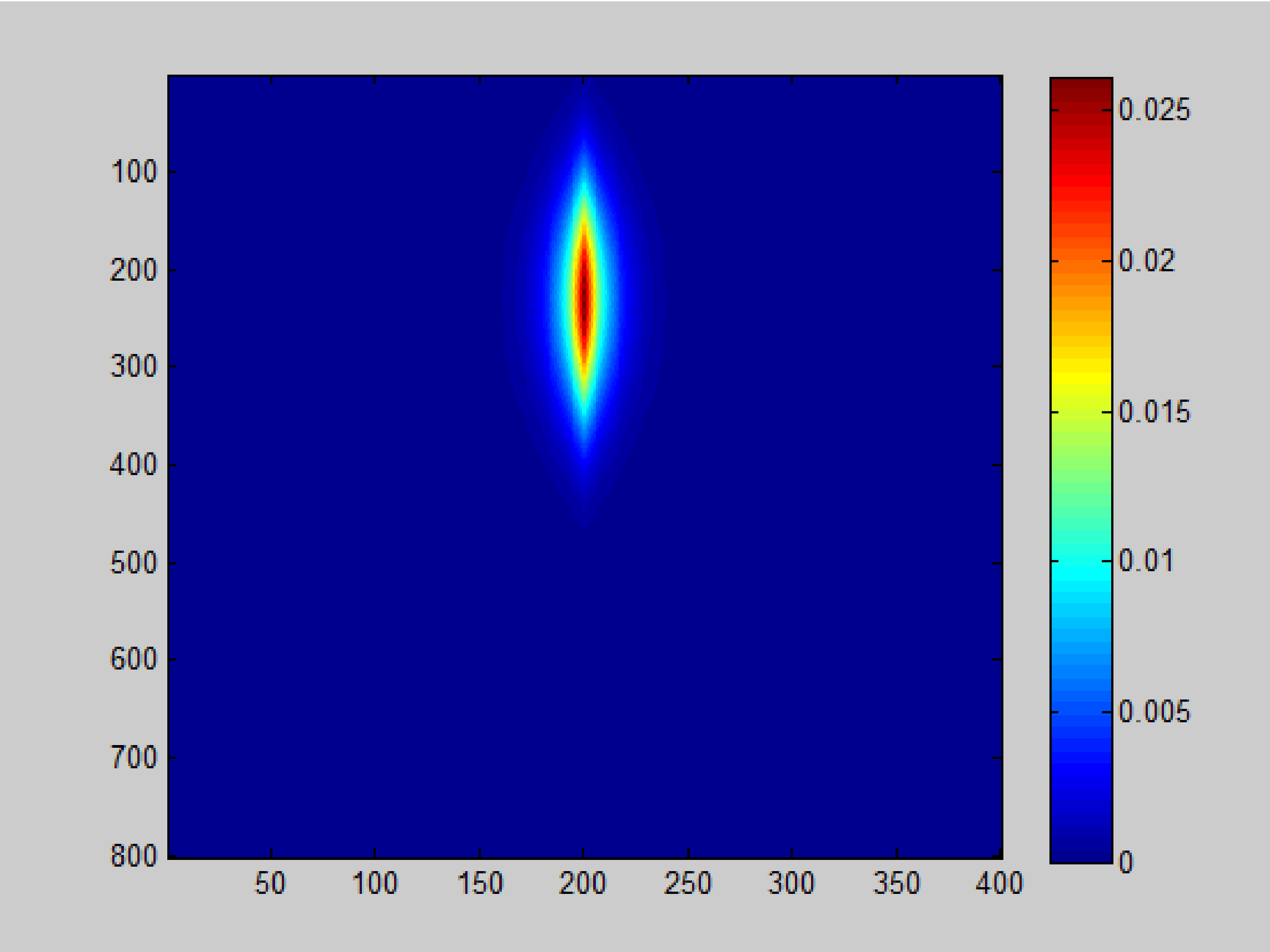

Conductance from D to U is quantized to $2e^2/h$.

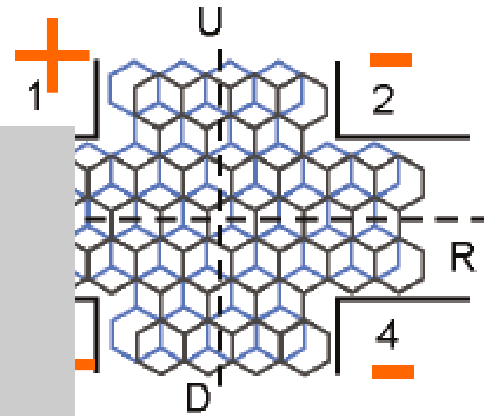



Schematic of zero-line and the mode.

Qiao, Jung, Niu, MacDonald, Nano Lett. 11, 3453 (2011)

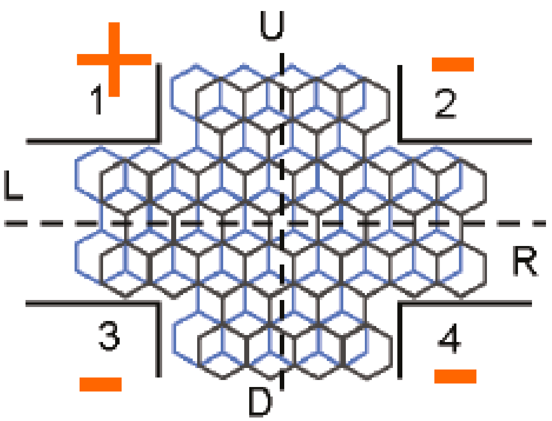
# Transport of single zero line



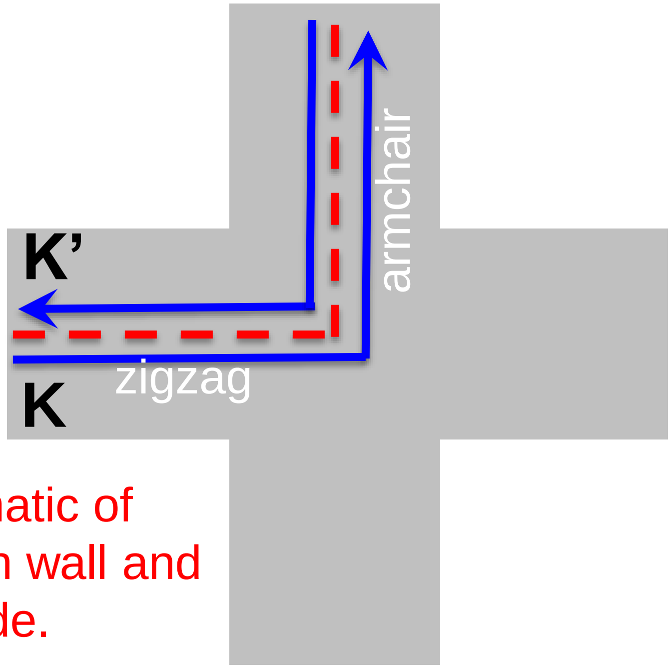

Sanyi You, and Zhenhua Qiao, *in preparation* (2019)

# Transport of single zero line

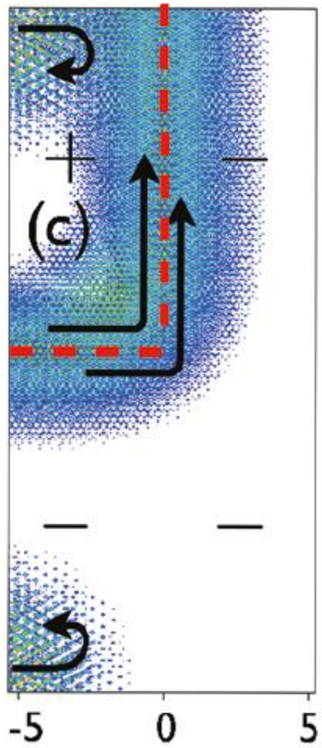



Numerically obtained local DOS distribution in real space:

## Mixed valleys



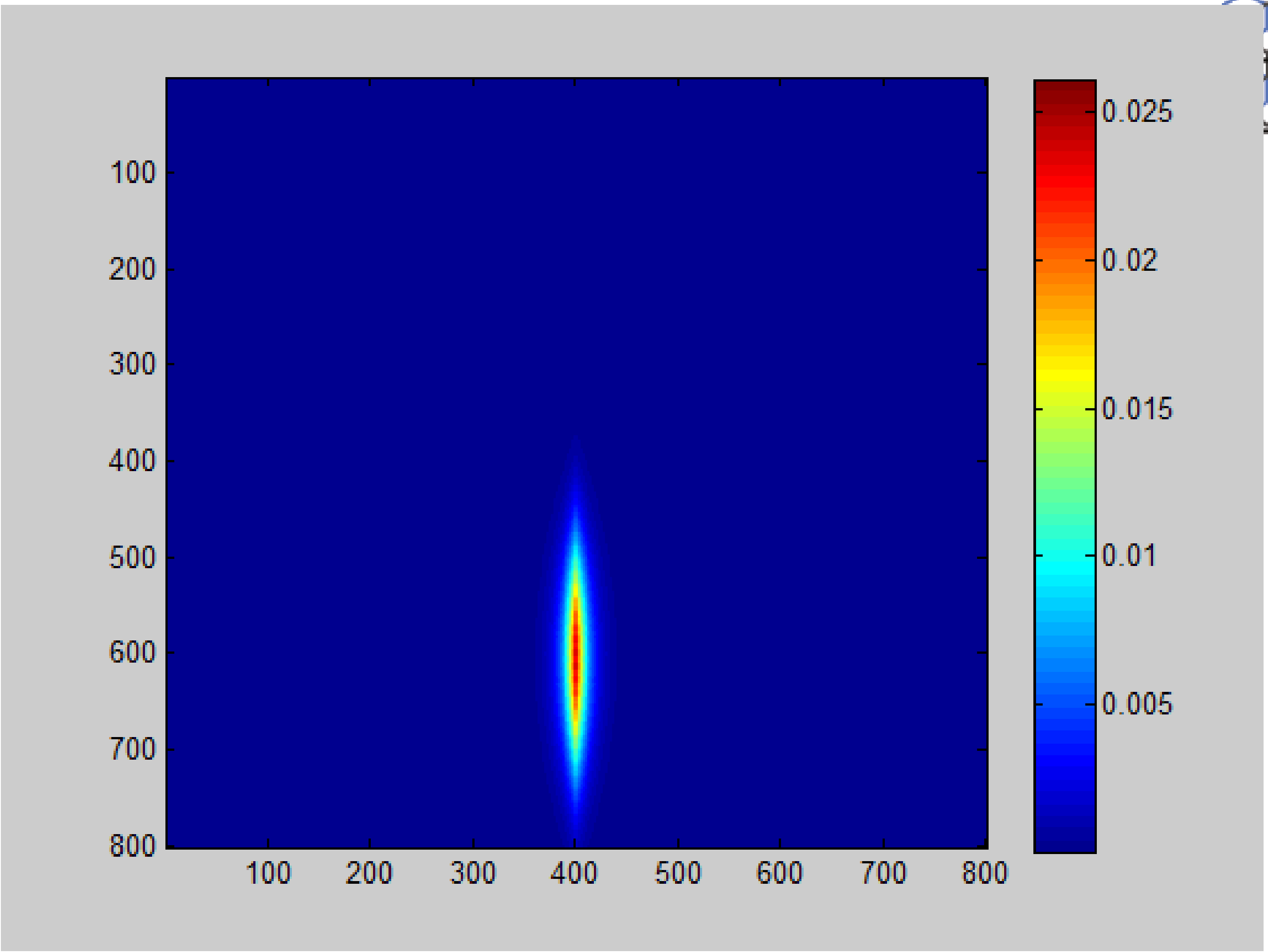

Schematic of domain wall and its mode.

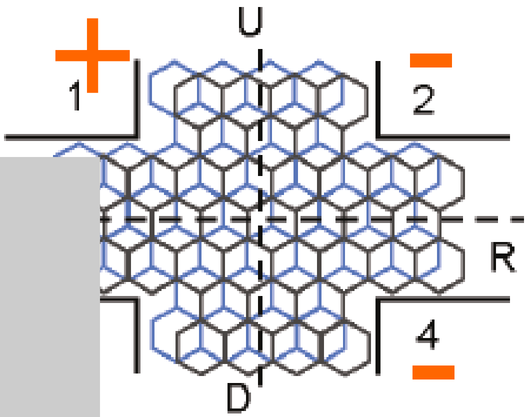



Conductance from L to U is quantized to $2e^2/h$.

Qiao, Jung, Niu, MacDonald, Nano Lett. 11, 3453 (2011)

# Transport of single zero line

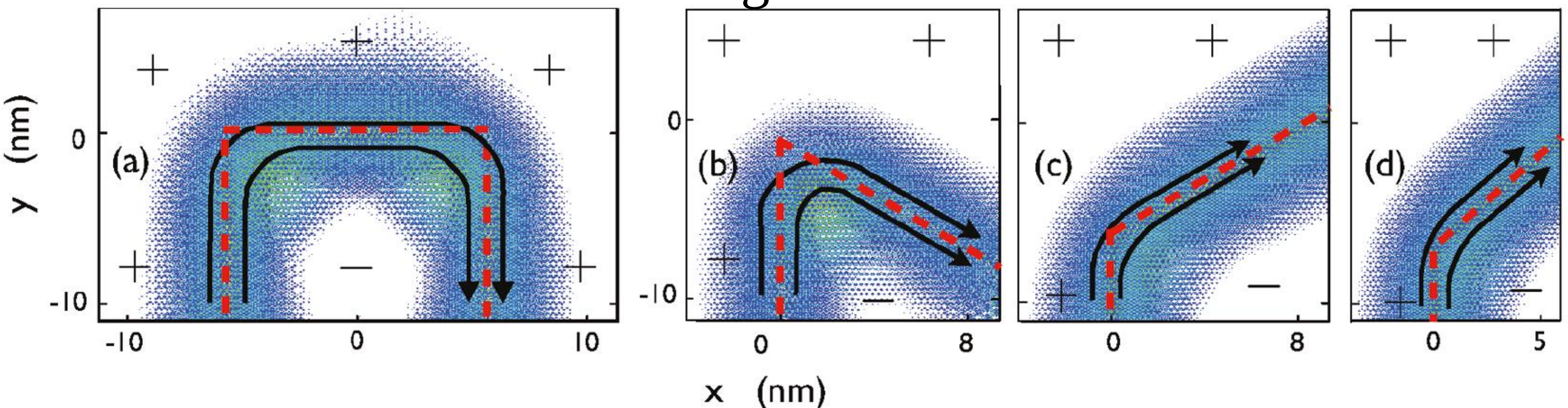


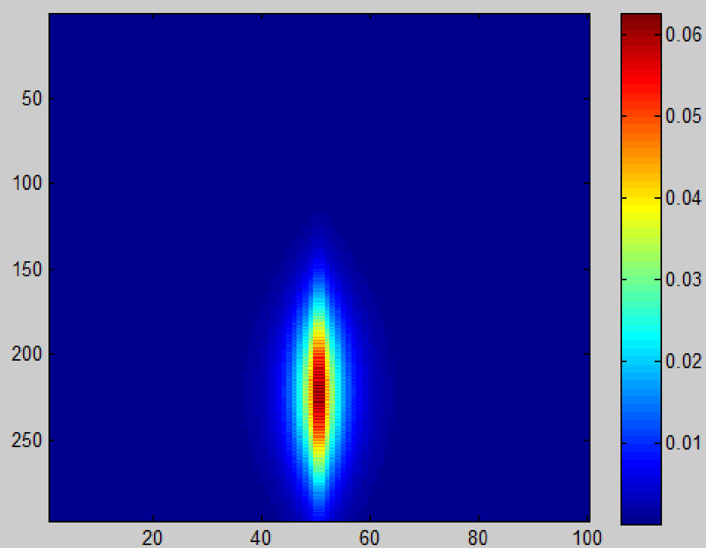

Sanyi You, and Zhenhua Qiao, *in preparation* (2019)

# Transport of single zero line

LDOS distribution for other single zero-lines:




$180^0$ turn $60^0$ turn $120^0$ turn $131^0$ turn




The conductance along any zero-line is quantized to $2e^2/h$.

Qiao, Jung, Niu, MacDonald, *Nano Lett.* **11**, 3453 (2011)

Sanyi You, and Zhenhua Qiao, *in preparation*, (2019)

# Transport of single zero line

1D zero-line state **chirally propagates**;

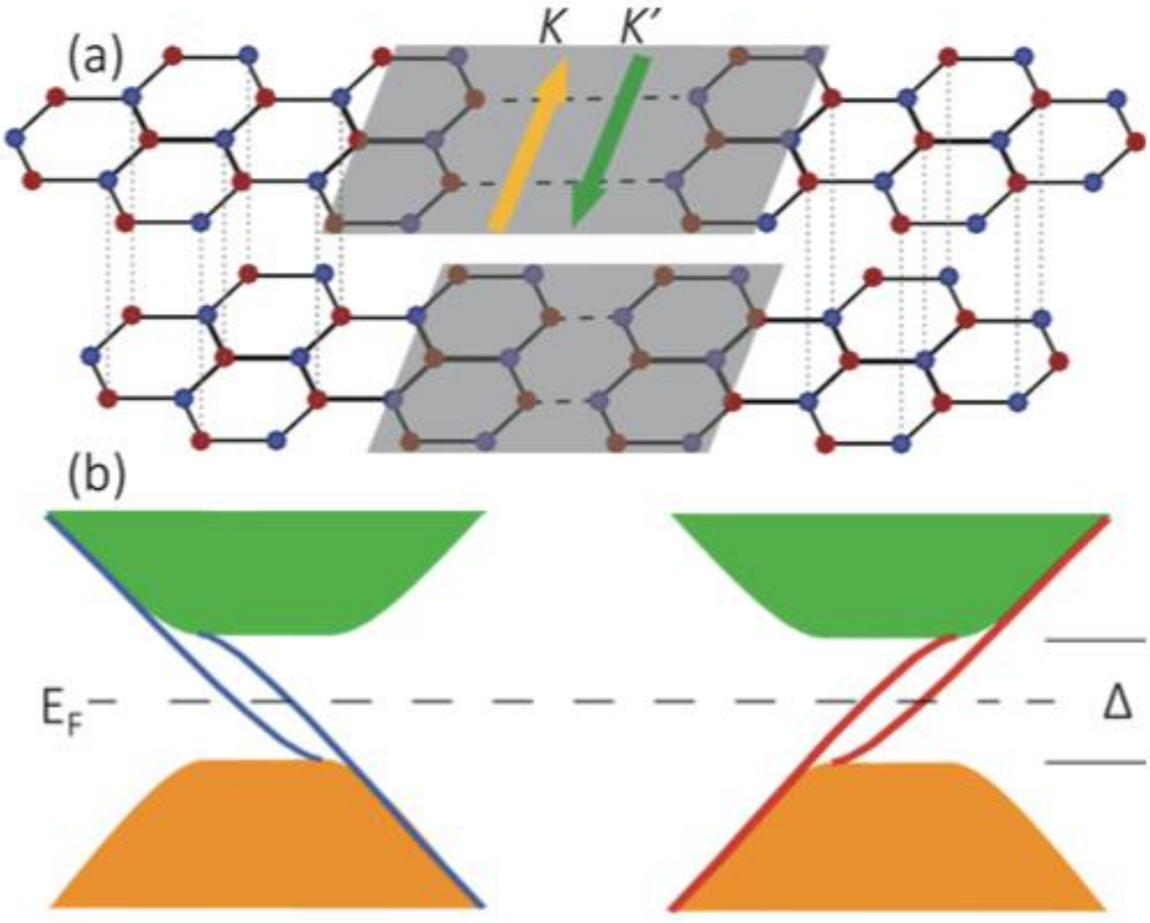
1D zero-line state exhibits a **zero bend resistance**.

**Similar to the quantum Hall effect, except the spatial overlap between the counter-propagating chiral edge modes**

# Experimental realization of the topological 1D mode

# Experimental Realization (1)

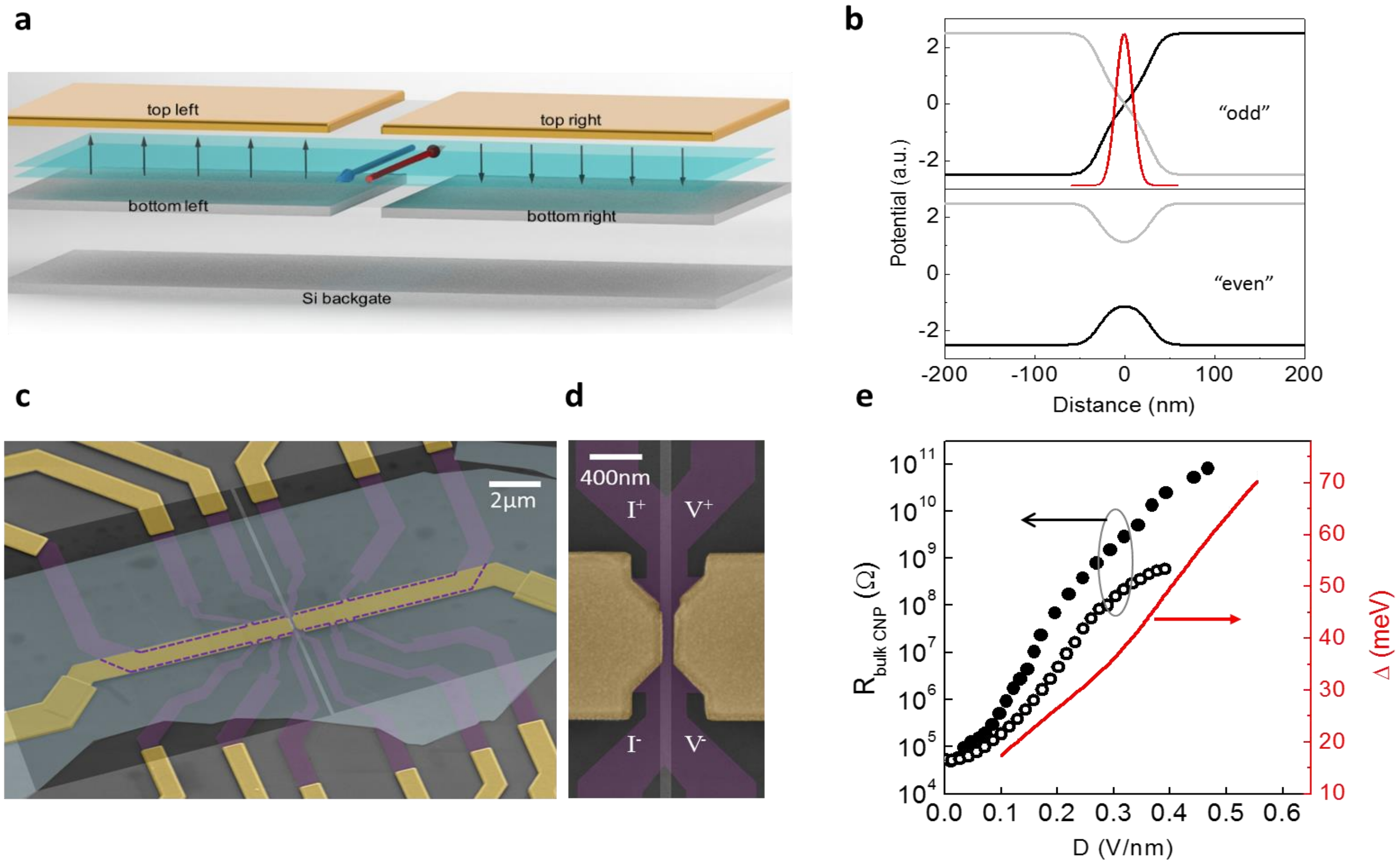
**Recent observation of the topological zero-line mode**




**Feng Wang's group, Nature 520, 650 (2014)**

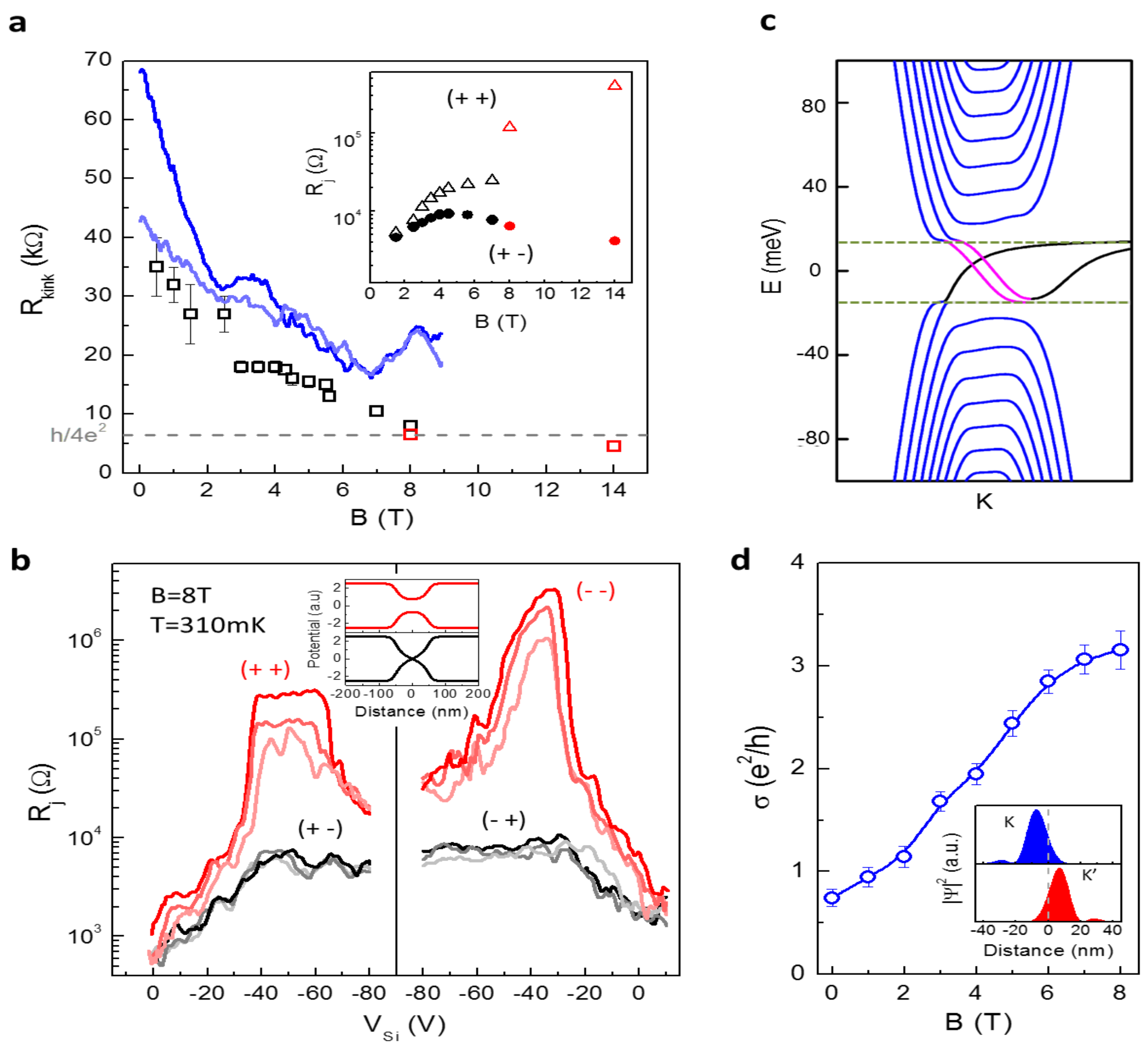
# Experimental Realization (2)

**Real bilayer graphene with opposite biases**




J. Li et al., *Nature Nanotech.* **11**, 1060 (2016)

# Experimental Realization (2)




J. Li et al., *Nature Nanotech.* **11**, 1060 (2016)

# Zero line mode in folded bilayer graphene

PHYSICAL REVIEW B **98**, 245417 (2018)

Editors' Suggestion

## Topological zero-line modes in folded bilayer graphene

Tao Hou,[1,2] Guanghui Cheng,[1,3] Wang-Kong Tse,[4] Changgan Zeng,[1,2,*] and Zhenhua Qiao[1,2,†]
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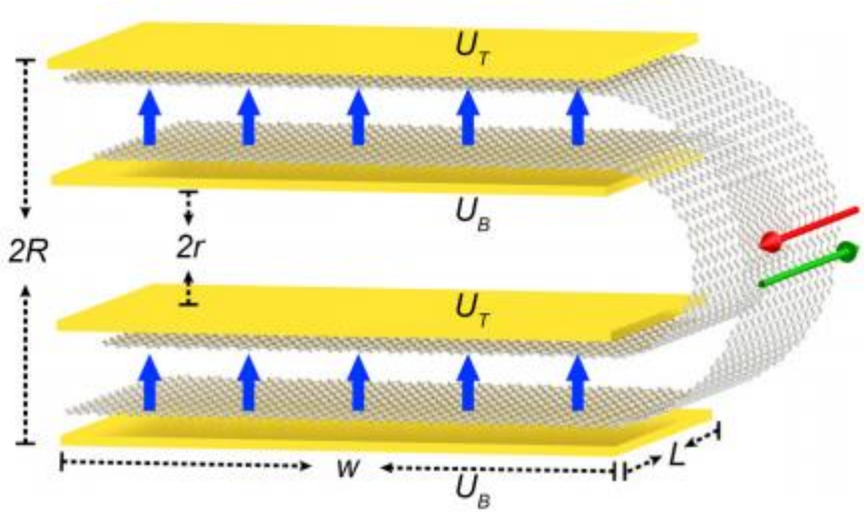
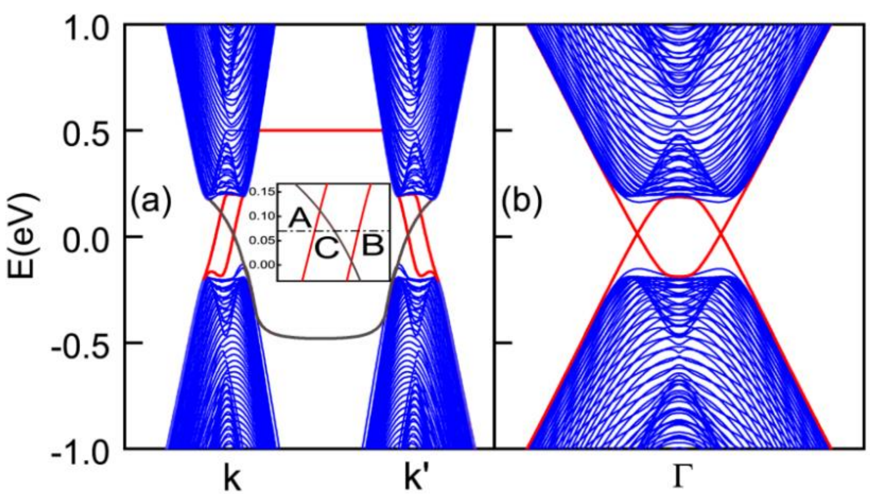
[2]*CAS Key Laboratory of Strongly-Coupled Quantum Matter Physics and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*
[3]*Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China*
[4]*Department of Physics and Astronomy and Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama 35487, USA*

(Received 25 September 2018; published 19 December 2018)

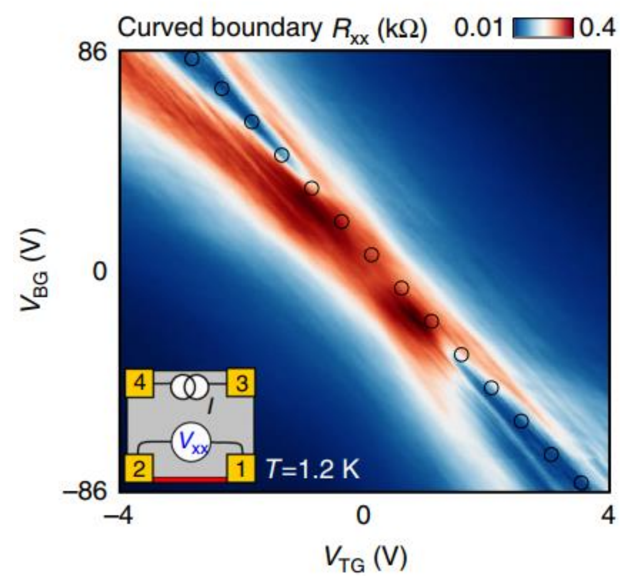


# Zero line mode in folded bilayer graphene

COMMUNICATIONS PHYSICS

**Experimental Realization**

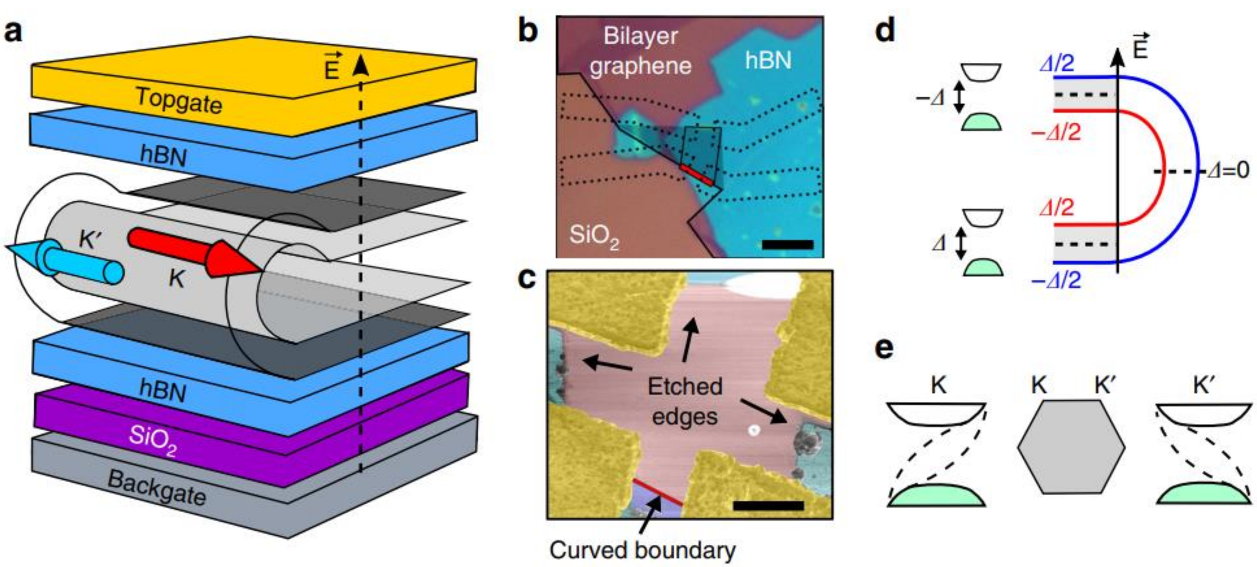


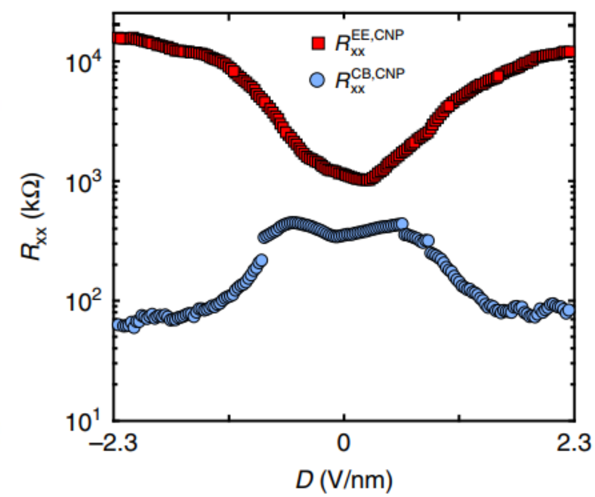

ARTICLE


https://doi.org/10.1038/s42005-018-0106-4 OPEN

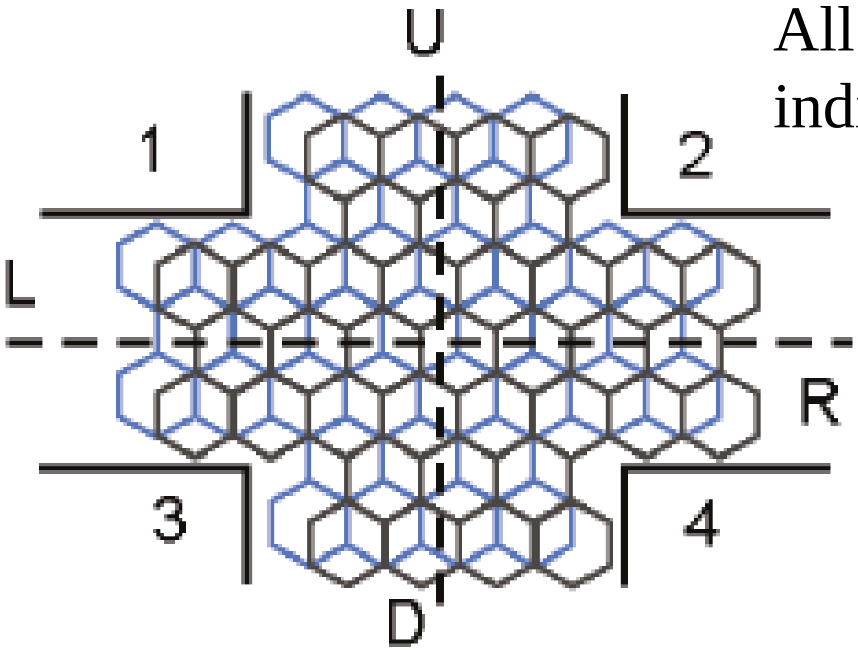

## Topological valley transport at the curved boundary of a folded bilayer graphene


E. Mania[1,2], A.R. Cadore[1], T. Taniguchi[3], K. Watanabe[3] & L.C. Campos[1]

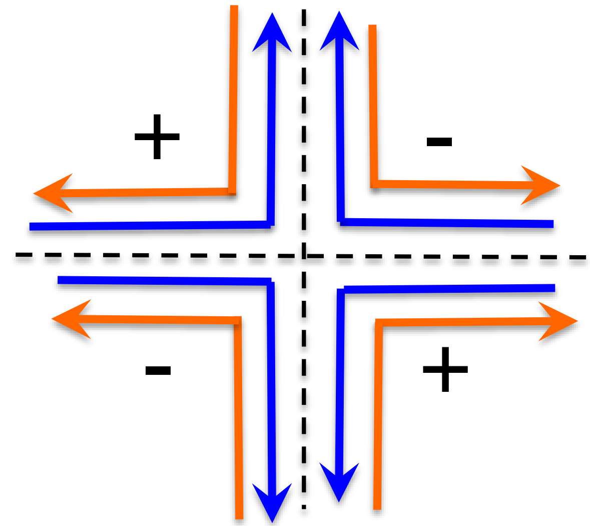



# Current partition at a topological intersection




All permitting electronic ways (colors indicate different chiral properties):

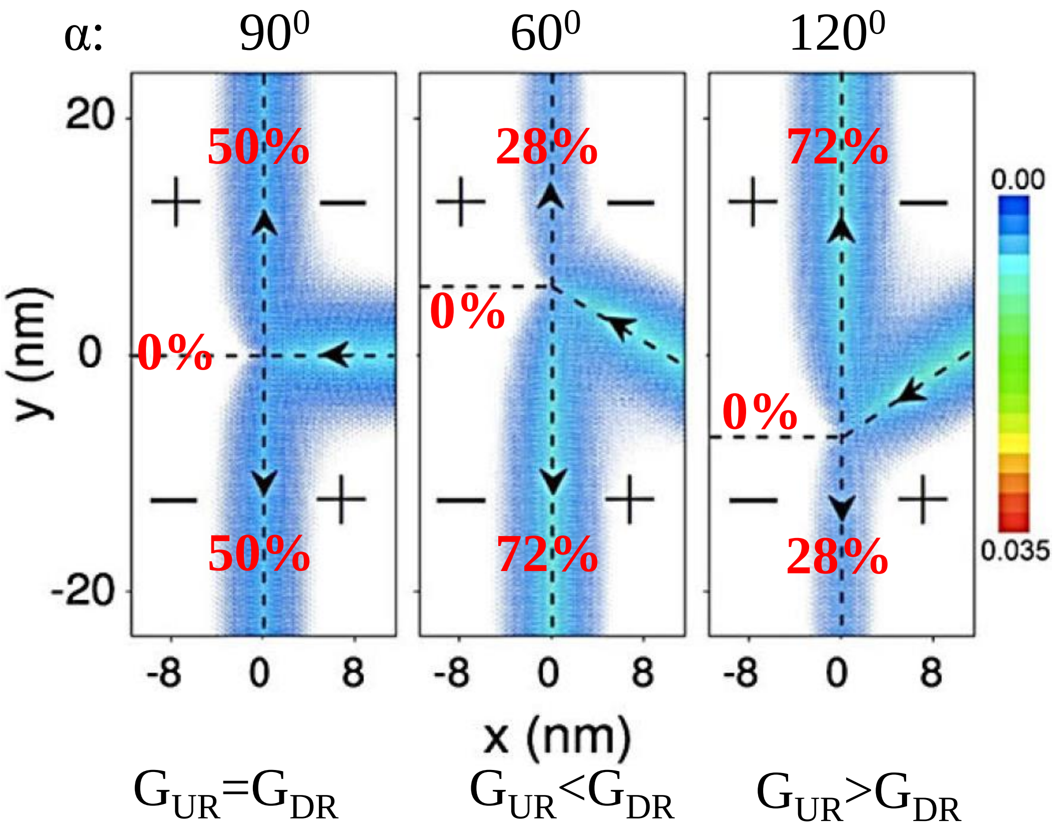


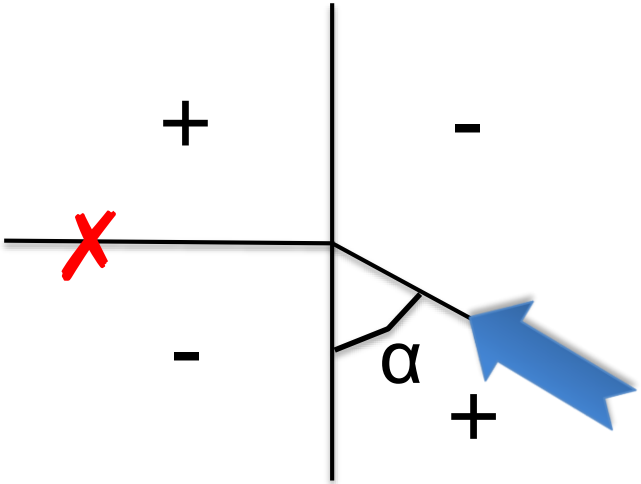

Time reversal invariance and zero bend resistance give the relations:

$$G_{RL} = G_{UD} = 0$$
$$G_{UL} + G_{DL} = G_0$$
$$G_{UR} + G_{DR} = G_0$$
$$G_{UL} = G_{DR}$$
$$G_{DL} = \boxed{G_{UR}}$$

There is only one independent variable.

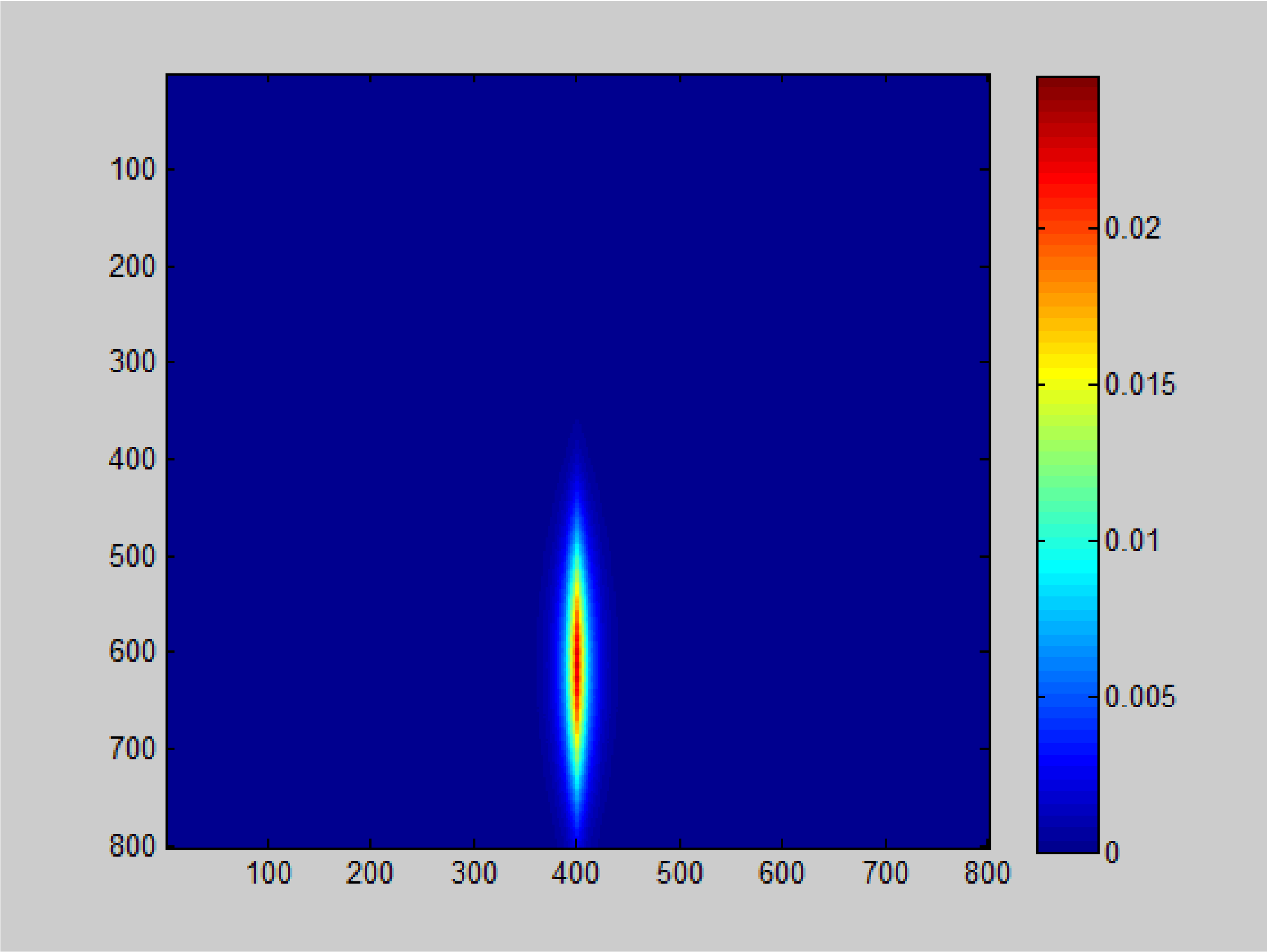
# Current partition at a topological intersection



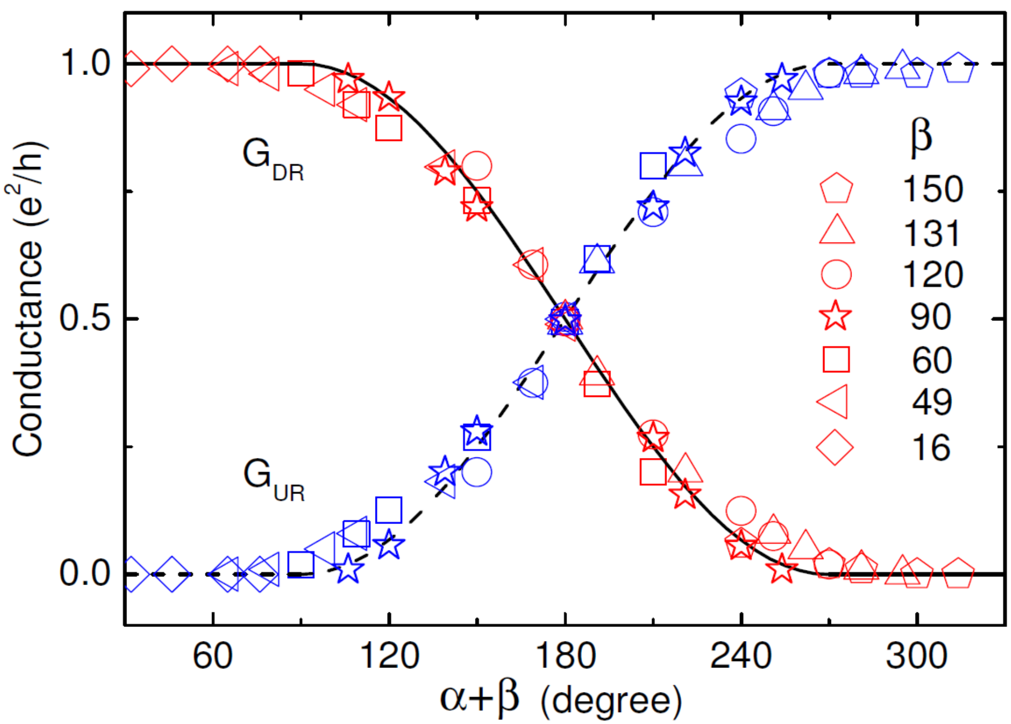

**Counter-intuitive current partition**

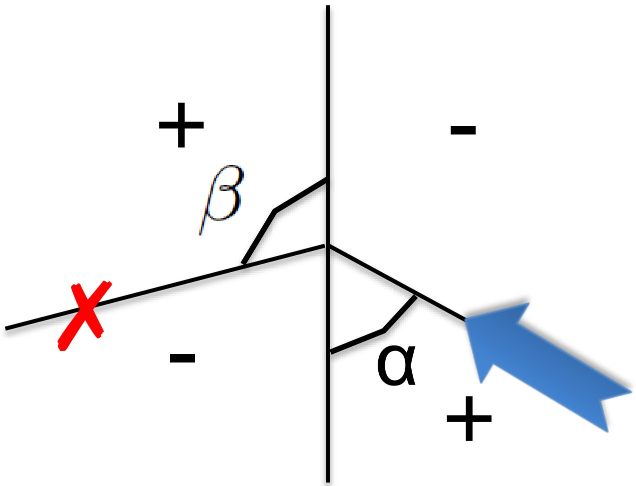
# Current partition at a topological intersection




Sanyi You and Zhenhua Qiao, *in preparation* (2019)

# Current partition at a topological intersection




$$G_{UR} = \frac{G_0}{2}\left[1 - \sin(\alpha + \beta)\right]$$

$$G_{DR} = \frac{G_0}{2}\left[1 + \sin(\alpha + \beta)\right]$$

**Counterintuitive current partition laws**

Qiao, Jung, Lin, Ren, MacDonald, and Niu, *Phys. Rev. Lett.* **112**, 206601 (2014)

# External tunability of current partition

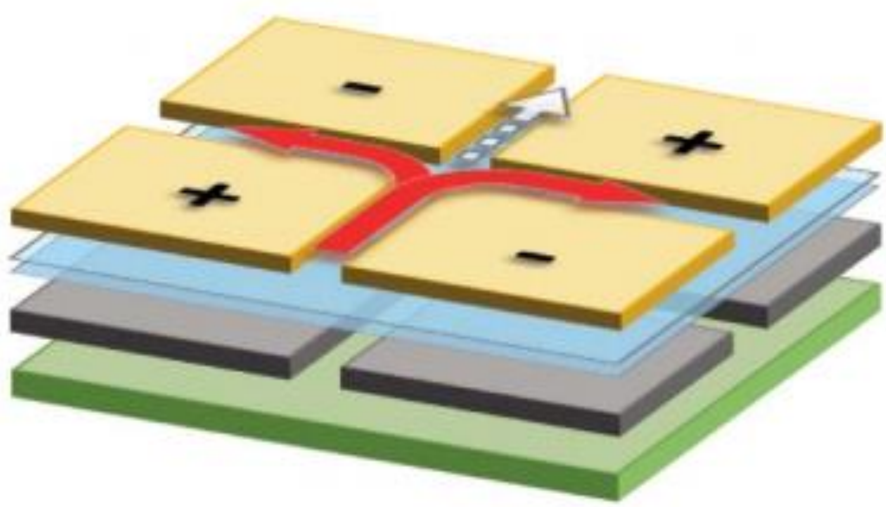
In experiment, the precise control of top/back gates is very difficult. Therefore, it is impossible to design a controllable current splitter by rotating the zero-line angles.

Some possible external manipulating methods:

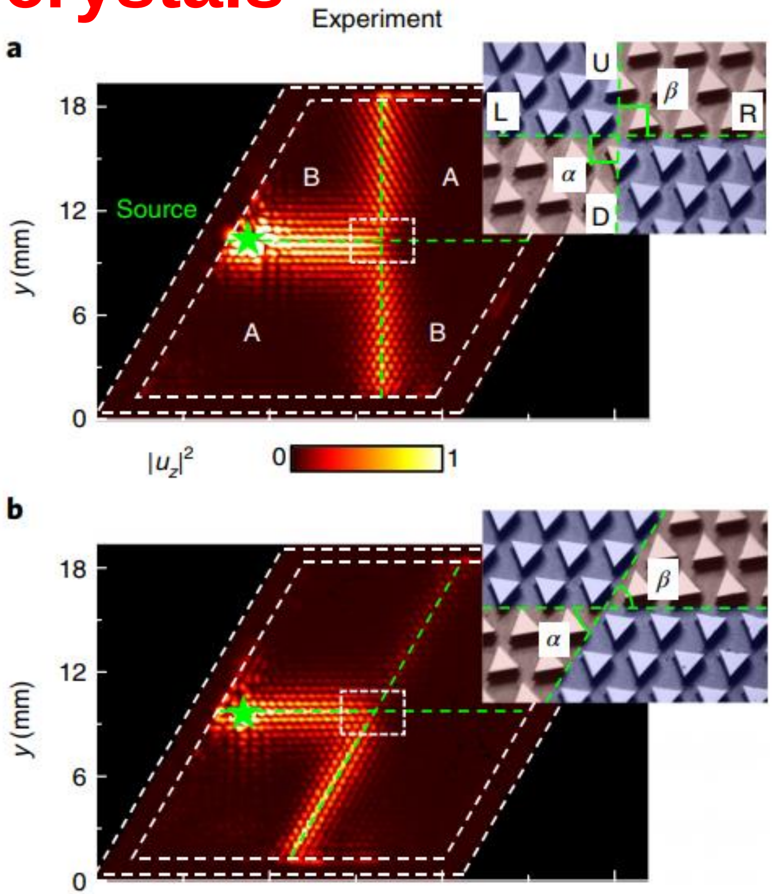
1. The Fermi level;
2. The relative electric field strengths;
3. Weak magnetic field;
4. ......

# Two zero line topological intersection

**A-B stacked bilayer graphene**



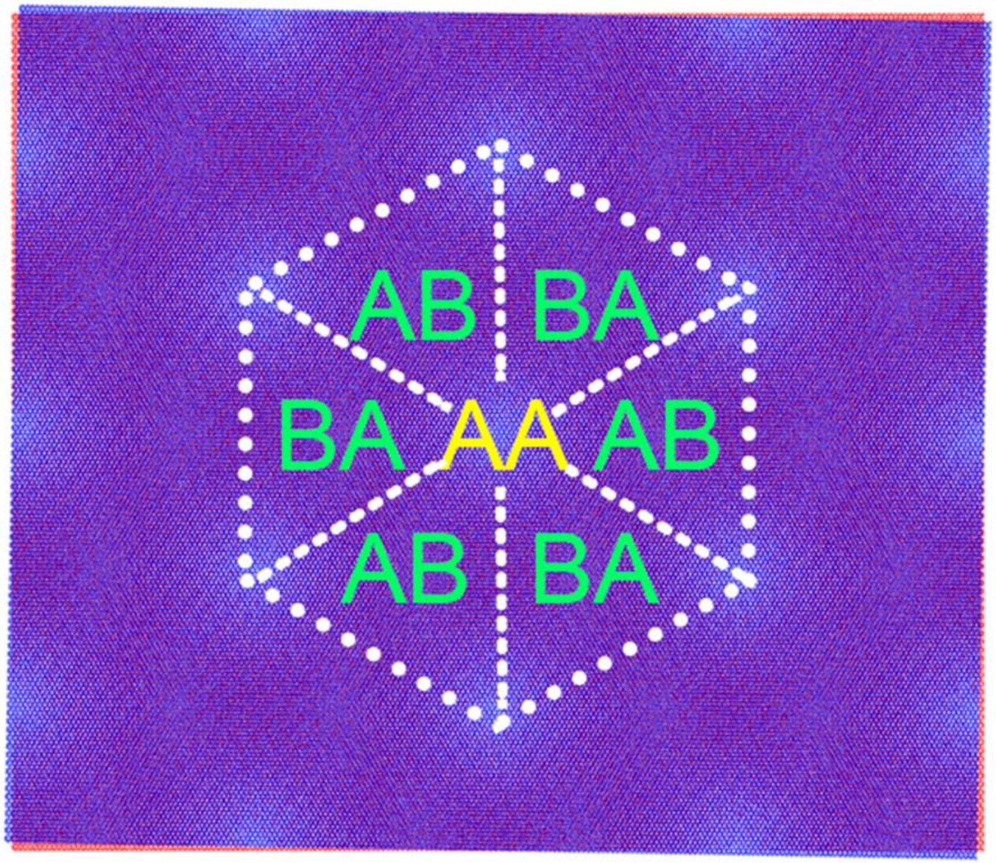
**phononic crystals**




J. Zhu Group,
Science 362, 11491152 (2018)

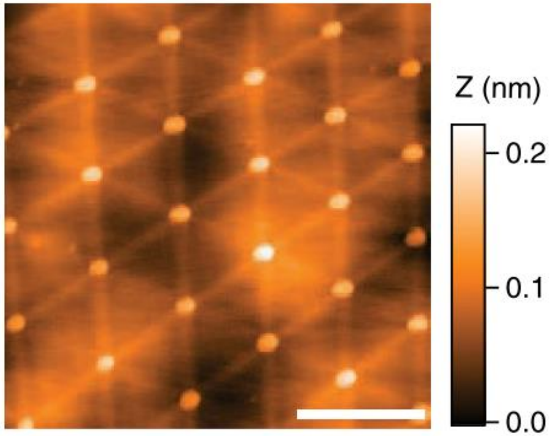
Z. Liu Group,
Nat. Material. 17, 993 (2018)

# Zero line modes in twisted graphene bilayer

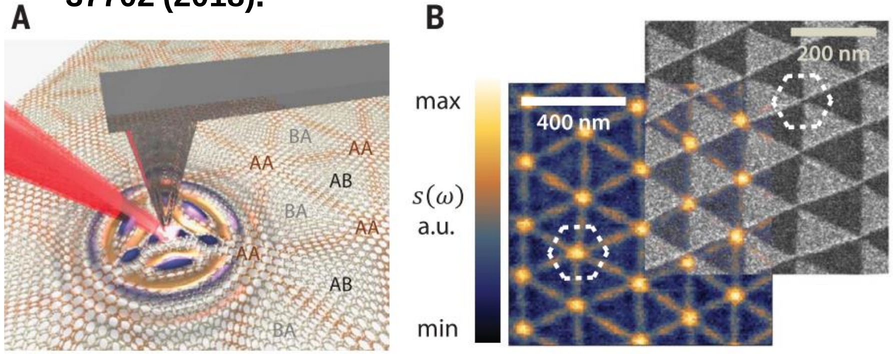



**θ~1°**

**Moir éis different**

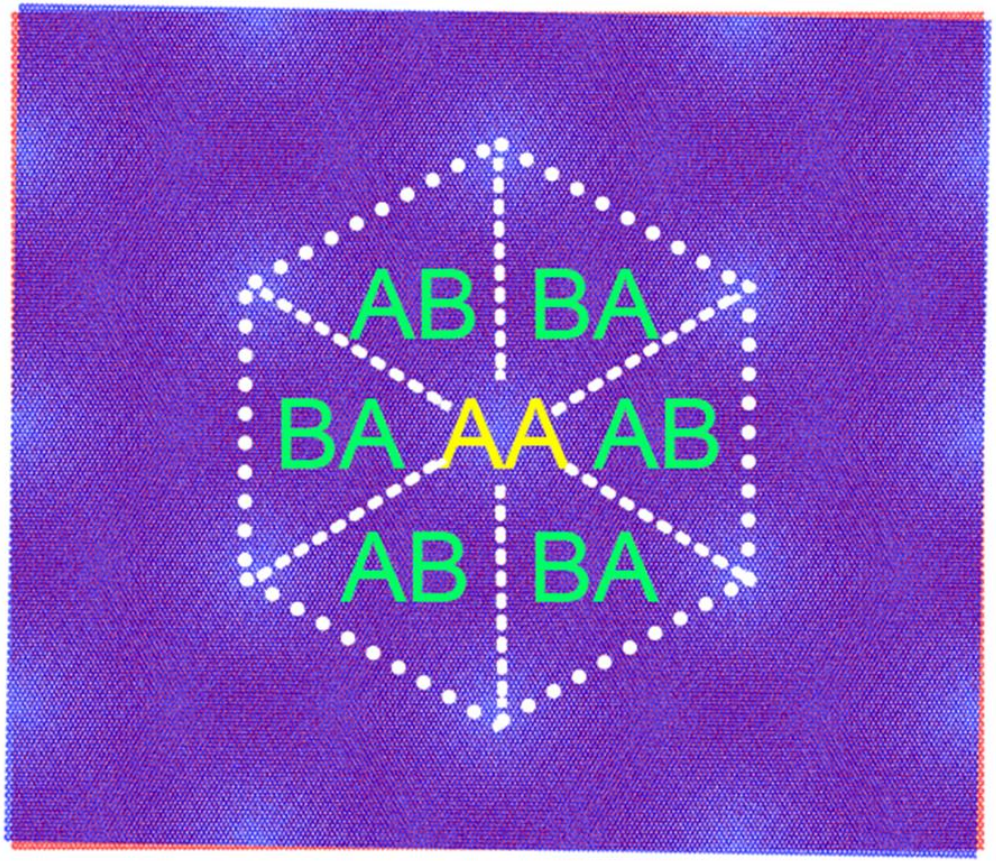


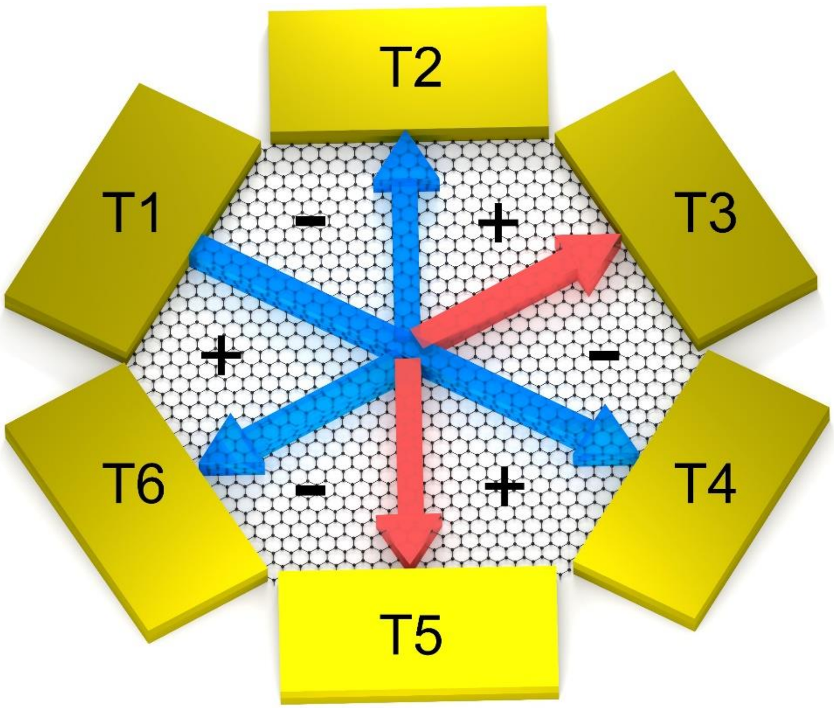

S. Huang, K. Kim, D. K. Emkin, T. Lovorn, T. Taniguchi, K. Watanabe, A. H. MacDonald, E. Tutuc, and B. J. LeRoy, Phys. Rev. Lett. 121, 37702 (2018).




S. S. Sunku, G. X. Ni, B. Y. Jiang, H. Yoo, A. Sternbach, A. S. McLeod, T. Stauber, L. Xiong, T. Taniguchi, K. Watanabe, P. Kim, M. M. Fogler, D. N. Basov Science 362, 1153-1156 (2018)

# Three zero line topological intersection

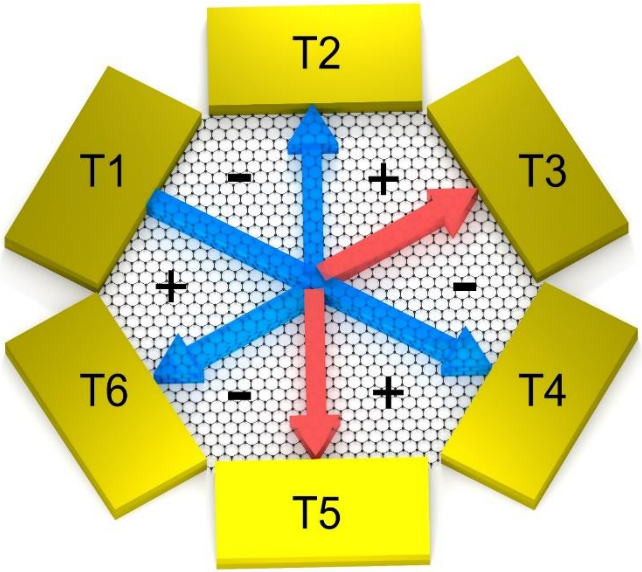


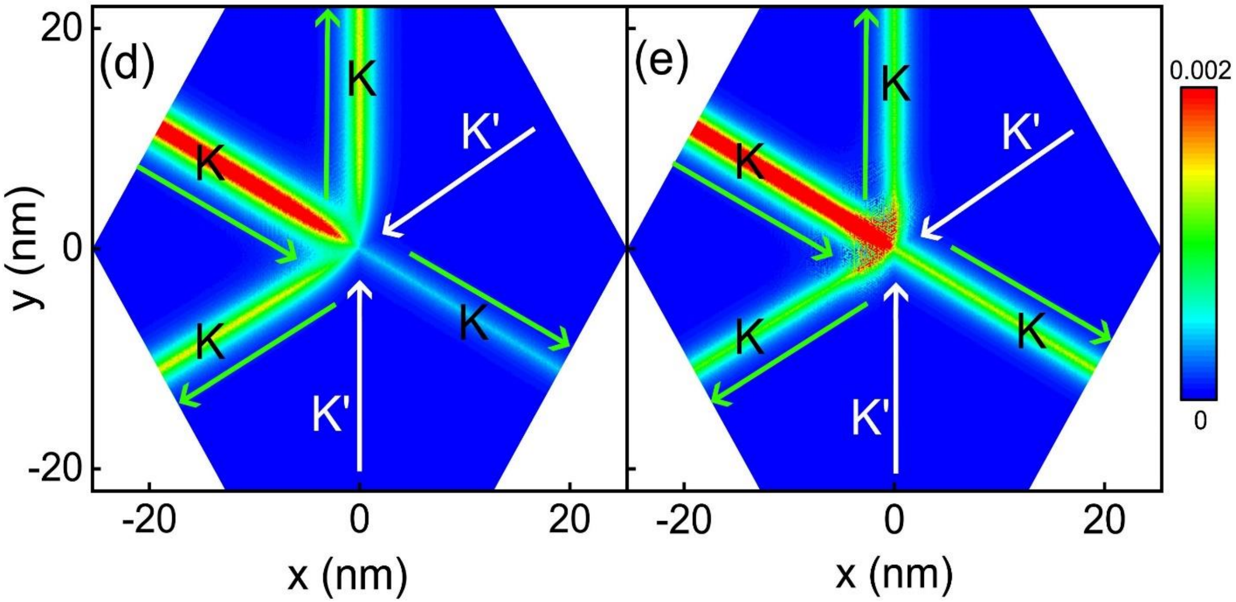




**Diameter: 50 nm**

[T. Hou, Yafei Ren, et al., arXiv: 1904.12826]

# Three zero line topological intersection



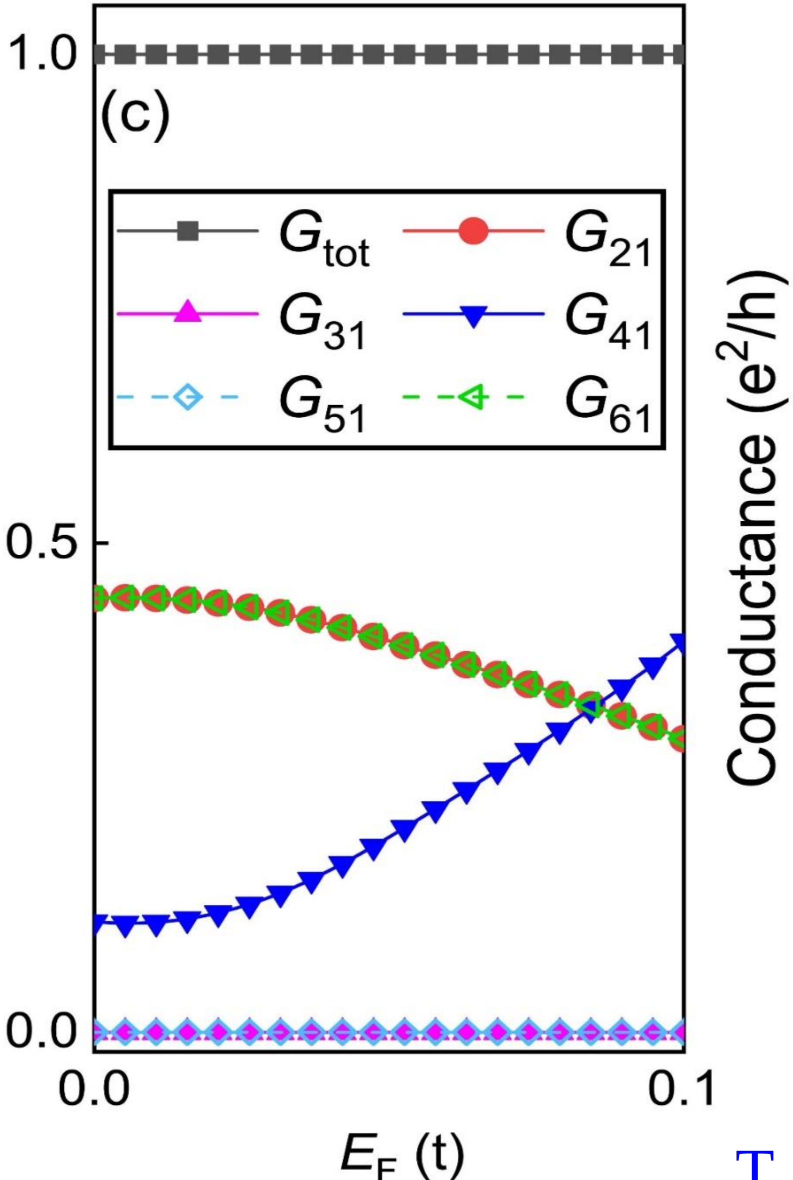




**Fermi energy close to the charge-neutrality point**

**Fermi energy close to band edge**

[T. Hou, Yafei Ren et al., arXiv: 1904.12826]

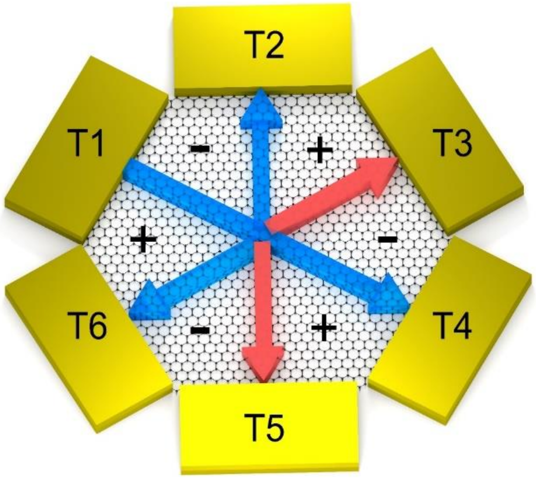
# Three zero line topological intersection




$$G_{31} = G_{51} = 0,$$ **Opposite chirality**

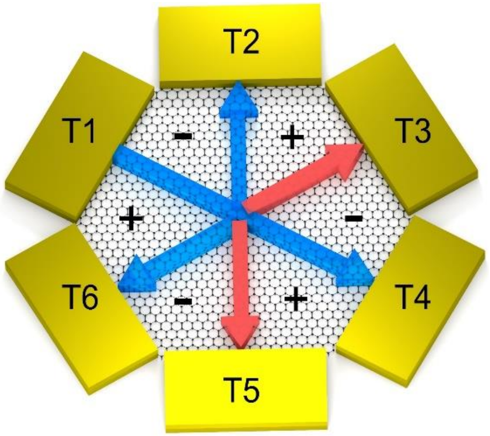
$$G_{21} = G_{61},$$ **Mirror reflection symmetry**

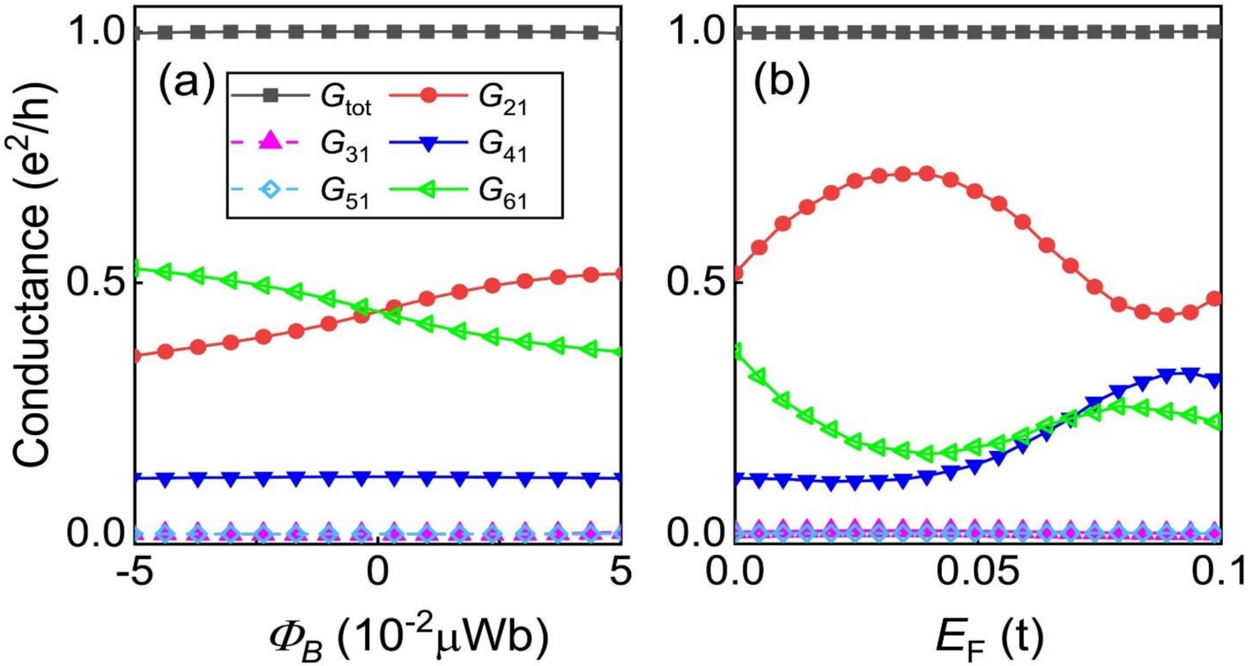
$$G_{tot} = G_{21} + G_{41} + G_{61} = e^2/h.$$




T. Hou, Yafei Ren et al., arXiv: 1904.12826

# Three zero line topological intersection



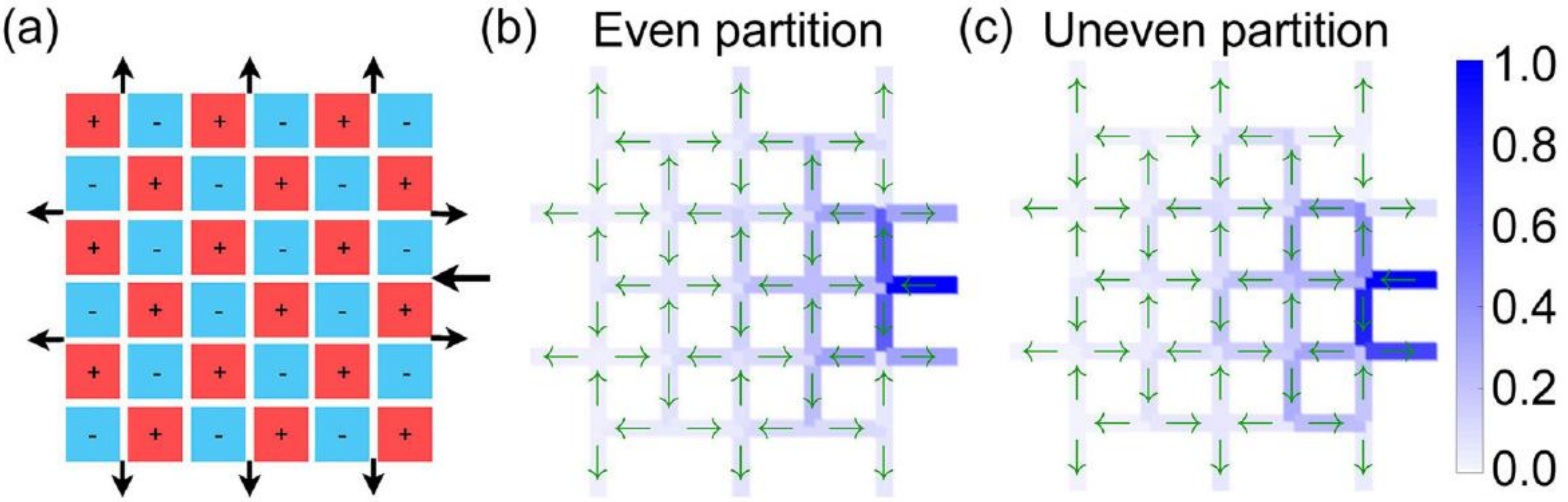

T. Hou, Yafei Ren et al., arXiv: 1904.12826

# Topological network

**For each node, it tends to be back, with a tiny part.**
**For a series of nodes, what happen?**

**Insulating?**

# Current routing--- network systems




Phys. Rev. B **95**, 245420 (2017)

# Topological network

**Atomic and electronic reconstruction at van der Waals interface in twisted bilayer graphene**

**P. Kim group**
**arXiv:1804.03806**

Hyobin Yoo[1], Rebecca Engelke[1], Stephen Carr[1], Shiang Fang[1], Kuan Zhang[2], Paul Cazeaux[3], Suk Hyun Sung[4], Robert Hovden[4], Adam W. Tsen[5], Takashi Taniguchi[6], Kenji Watanabe[6], Gyu-Chul Yi[7], Miyoung Kim[8], Mitchell Luskin[9], Ellad B. Tadmor[2], Efthimios Kaxiras[1,10], Philip Kim[1*]

[1] Department of Physics, Harvard University, Cambridge, MA 02138, USA

[2] Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, MN 55455, USA

[3] Department of Mathematics, University of Kansas, Lawrence, KS 66045, USA

[4] Department of Materials Science and Engineering, University of Michigan, Ann Arbor, MI 48109, USA

[5] Institute for Quantum Computing and Department of Chemistry, University of Waterloo, Waterloo, ON N2L 3G1, Canada

[6] National Institute for Materials Science, Namiki 1-1, Ibaraki 305-0044, Japan

[7] Department of Physics and Astronomy, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea

[8] Department of Materi... Gwanak-gu, Seoul 0882...

[9] School of Mathematic...

[10] John A. Paulson Scho...

**crossover angle, $\theta_c$ ~1°. In the twist regime smaller than $\theta_c$ where the atomic and electronic reconstruction become significant, a simple moiré band description breaks down. Upon applying a transverse electric field, we observe electronic transport along the network of one-dimensional (1D) topological channels that surround the alternating triangular gapped domains, providing a new pathway to engineer the system with continuous tunability.**

LETTERS
https://doi.org/10.1038/s41563-019-0346-z
nature materials

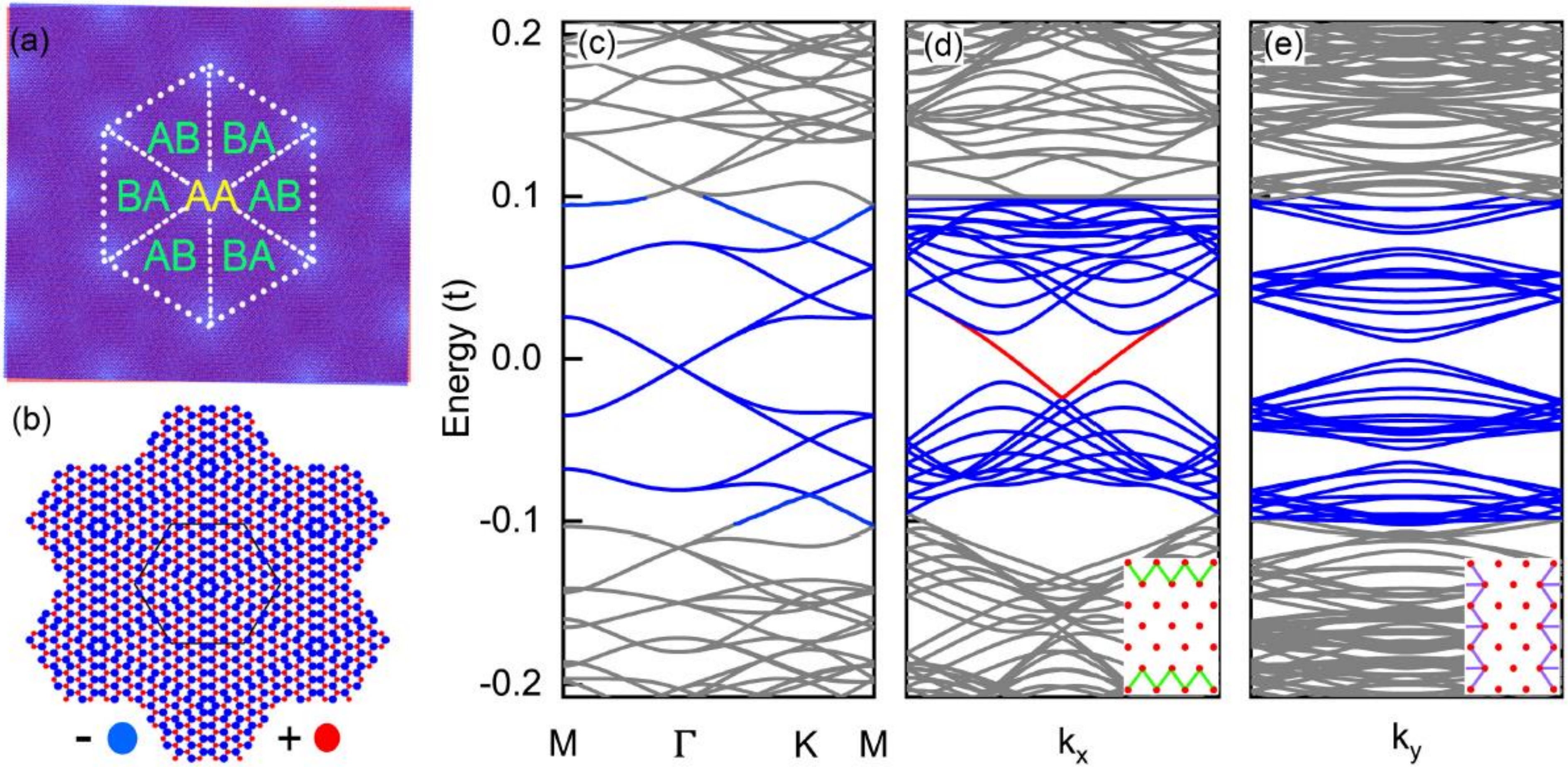
# Atomic and electronic reconstruction at the van der Waals interface in twisted bilayer graphene

Hyobin Yoo[1], Rebecca Engelke[1], Stephen Carr[1], Shiang Fang[1], Kuan Zhang[2], Paul Cazeaux[3], Suk Hyun Sung[4], Robert Hovden[4], Adam W. Tsen[5], Takashi Taniguchi[6], Kenji Watanabe[6], Gyu-Chul Yi[7], Miyoung Kim[8], Mitchell Luskin[9], Ellad B. Tadmor[2], Efthimios Kaxiras[1,10] and Philip Kim[1*]

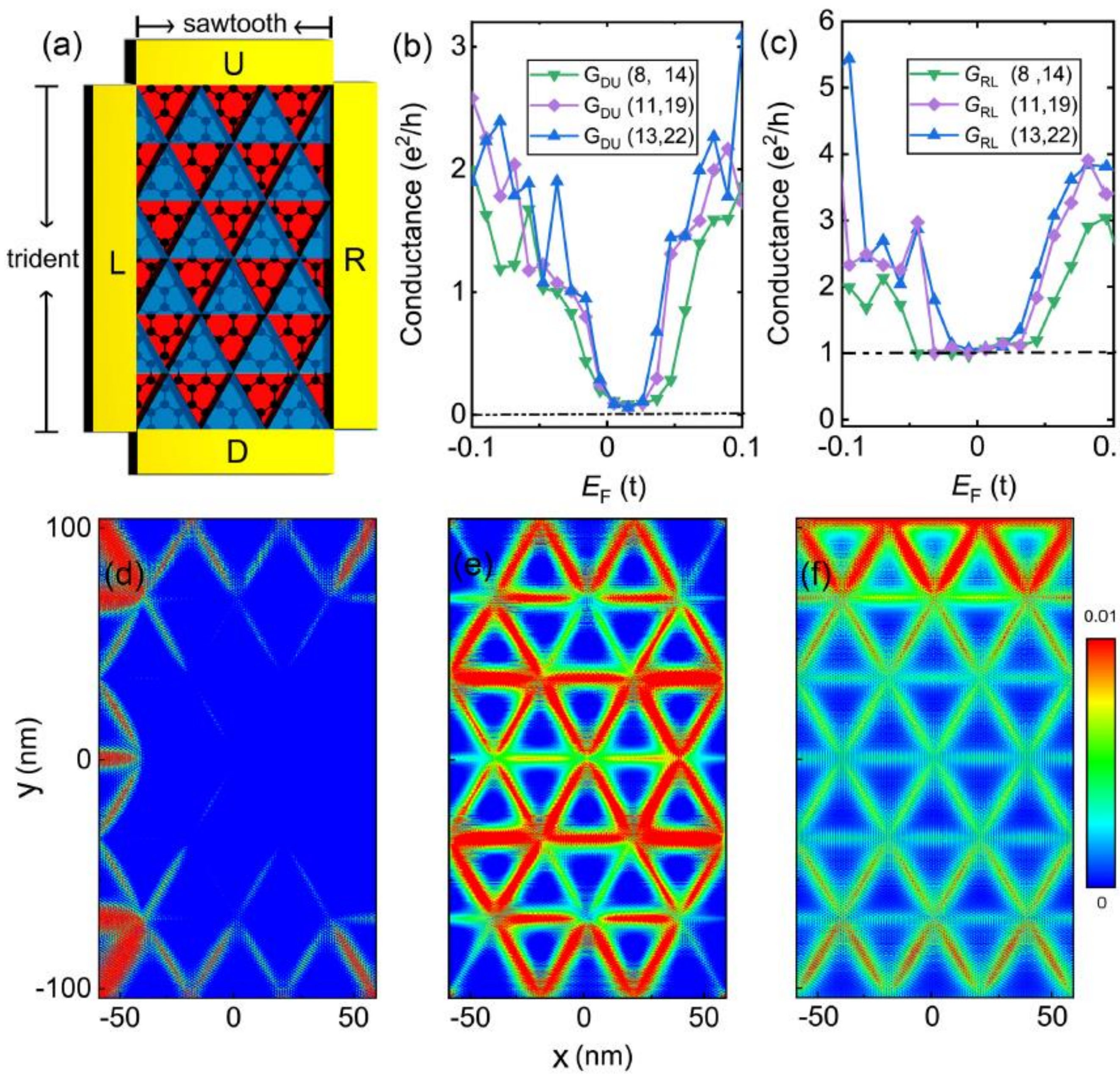
In the small twist angle regime ($\theta < \theta_c$), the triangular network of 1D topological channels can be developed by applying a transverse electric field. Figure S10i shows the plot of longitudinal resistance $R_{xx}$ at CNP as a function of transverse electric displacement field. S1-4 show that the channel resistances exhibit an increase and saturate to a value ranging from 1.6 kΩ to 13 kΩ. The value of channel resistances at the saturated regime at high displacement field is of similar order of magnitude to $R_q = \frac{h}{4e^2} \cong 6.4$ kΩ, suggesting electronic transport across the triangular network of 1-D channels. The details of the displacement field dependence on the Dirac peak resistance $R(D)$ of each device can be attributed to many parameters such as device geometry, sample inhomogeneity and different amount of interlayer biasing that is required to create a 1-D conduction channel depending on the twist angle.

**Conductance at CNP is quantized.**

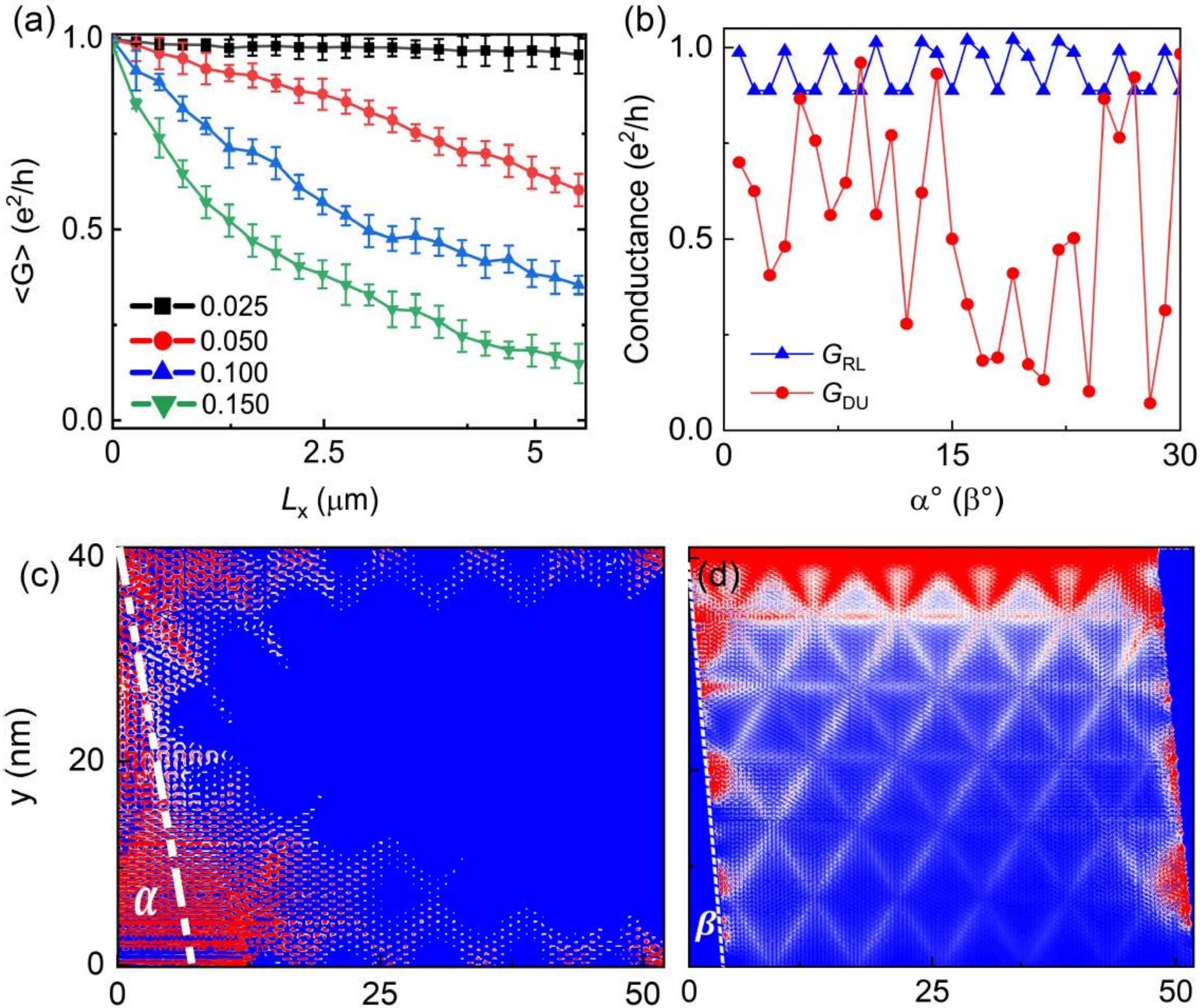
# Topological network



# Topological network



# Topological network



# Summary

**1、Brief review of topological zero line mode in graphene systems.**

**2、Recent progress on electronic transport in twisted bilayer graphene systems.**