Topology and quantum geometry in 2D moiré materials*

*Berry curvature dipole senses topological transitions

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Sinha and Adak et al. Nature Physics 18, 765 (2022)
Sinha and Adak et al. Nature Communications, 11, 5548 (2020).
Adak et al. submitted

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Lammi, Finland
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www.tifr.res.in/~nano

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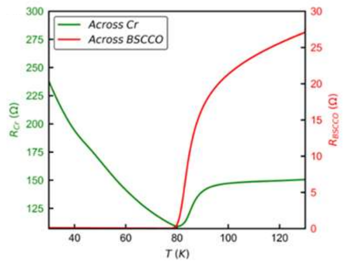
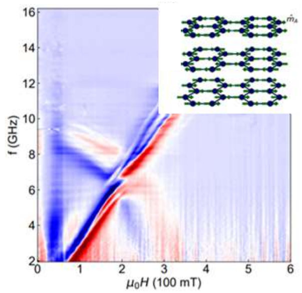
Kenji Watanabe (NIMS, Japan), Takashi Taniguchi (NIMS Japan)

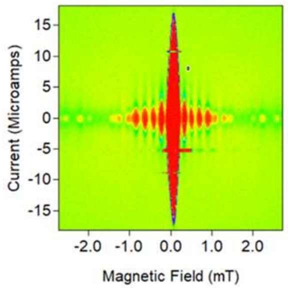
What do we do?



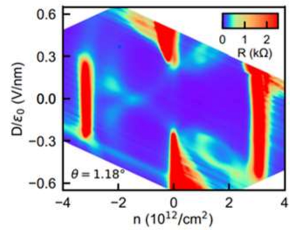
2D high temperature superconductor detector



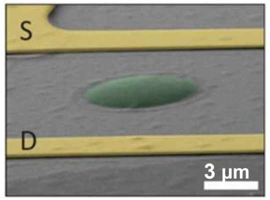
2D Magnonics



Graphene Josephson junctions



Twistronics and quantum transport

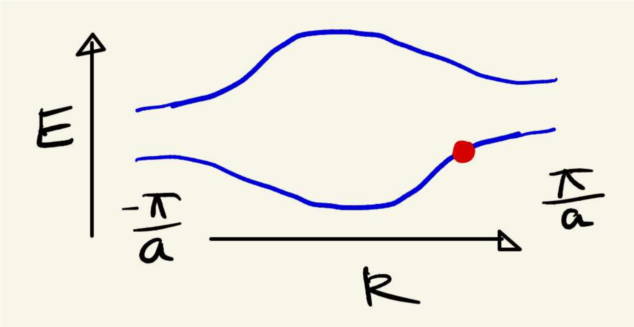


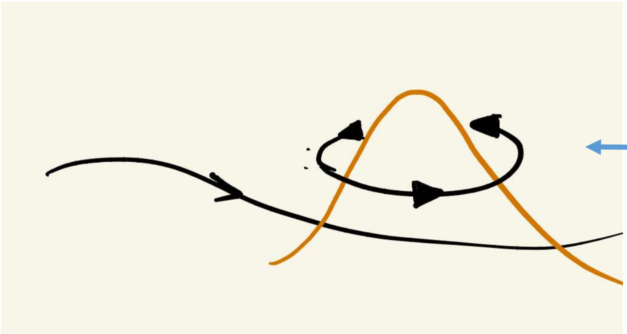
Nanomechanics

Outline

- Berry physics and topology in condensed matter
- Twisted layers – a new way to designer materials
- Valley transport in flat bands
- Berry curvature dipole senses a topological transition
- Magneto-electric coupling in flat bands

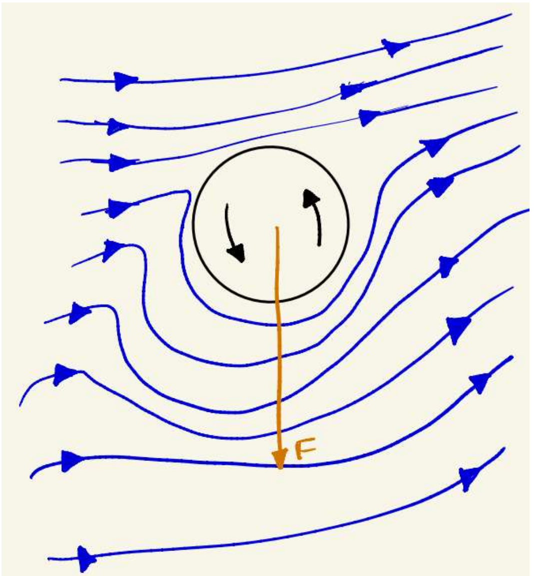
Electronic bands and self rotation of wave packets





Self rotation in some bands

Motion of wave packets in bands



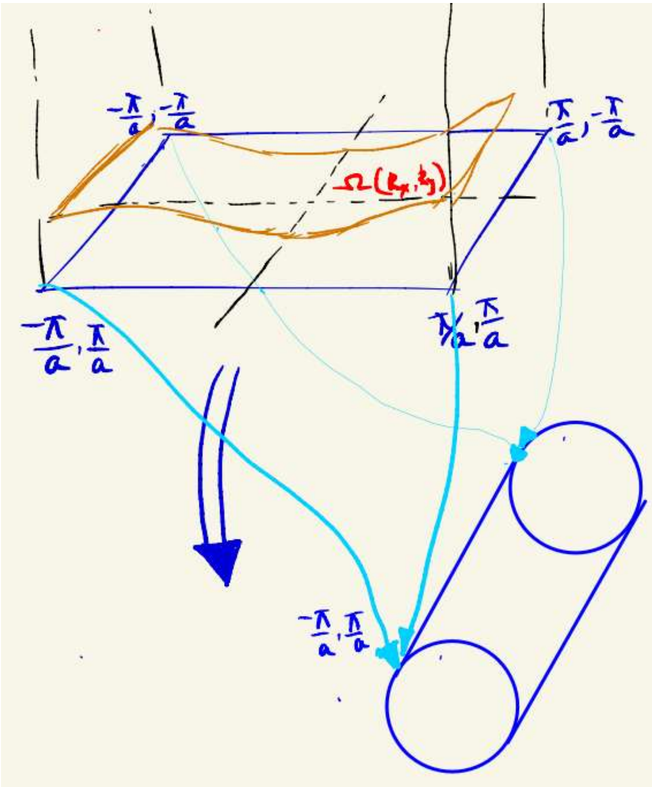
Magnus like effect

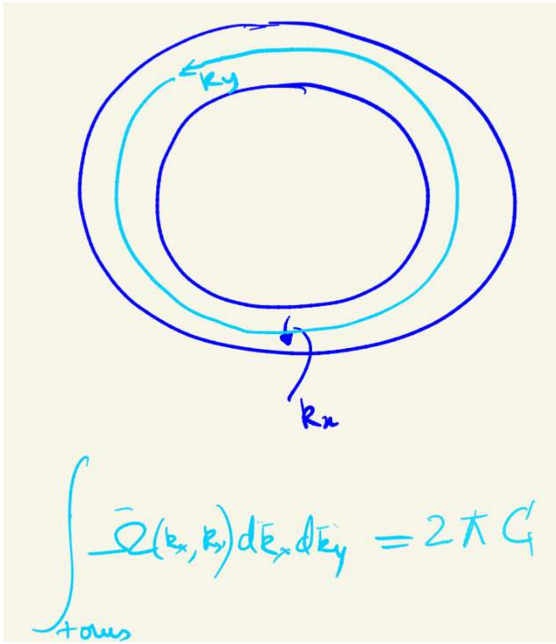
$$\dot{\boldsymbol{r}} = \frac{1}{\hbar}\frac{\partial E_{n.\boldsymbol{k}}}{\partial \boldsymbol{k}} - \dot{\boldsymbol{k}} \times \boldsymbol{\Omega}_n(\boldsymbol{k})$$ anomalous velocity !

$$\hbar\dot{\boldsymbol{k}} = -e\boldsymbol{E} - e\dot{\boldsymbol{r}} \times \boldsymbol{B}$$

Berry curvature non-zero if inversion, or time reversal, symmetry is broken

Chern number -- a topological invariant



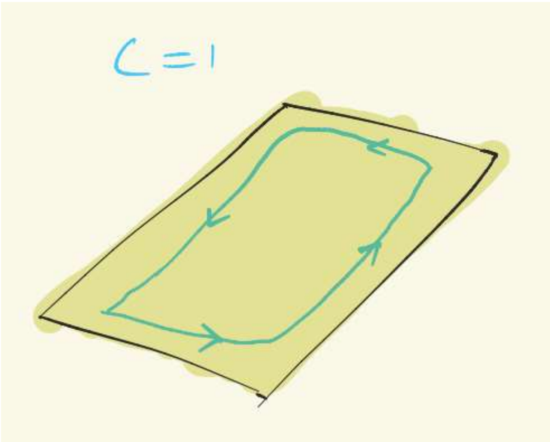


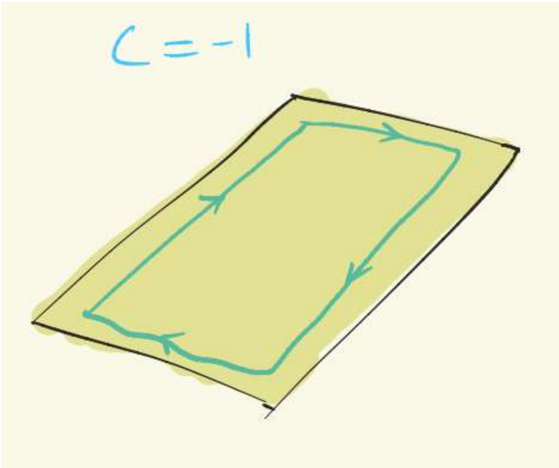
Chern number non-zero if time reversal symmetry is broken

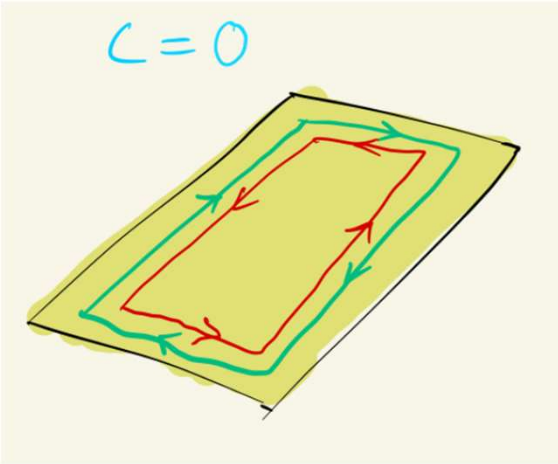
For time reversal symmetric system $C_K = -C_{K'}$

 Related work: Berry phase physics, Datta et al. Science Advances 5, eaax6550 (2019).

Boundary modes for non-zero Chern number system







Connection with topology

$$\int_S \bar{B}\cdot ds = \frac{c\hbar}{2q_e}\, n$$

n – integer

magnetic charge

$$\int_{BZ} \bar{\Omega}\cdot d\bar{k} = 2\pi C$$

C – integer

Chern number

TKNN invariant

$$\int_S \bar{K}\cdot ds = 2\pi \chi_M$$

χ_M – even integer

Euler characteristic

magnetic field, the Berry curvature, and the Gaussian curvature
all of them are described by the same mathematical structure: fiber bundles

Quantum geometry

$$ds^2 = |\langle u_n(\mathbf{k})|u_n(\mathbf{k} + d\mathbf{k})\rangle|^2.$$

$$ds^2 = g_{ij}dk_idk_j$$

$$\mathcal{Q}_{ij,n} = g_{ij,n} + i\Omega_{ij,n}/2$$

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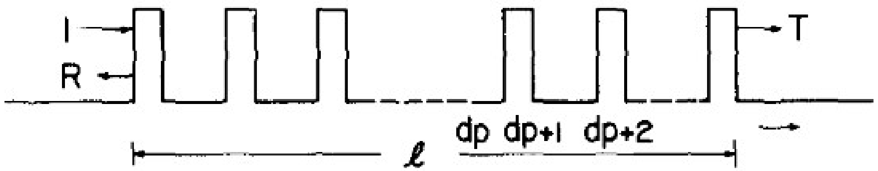
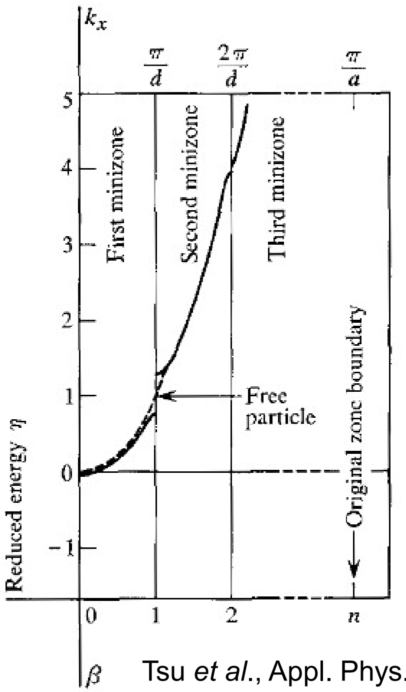
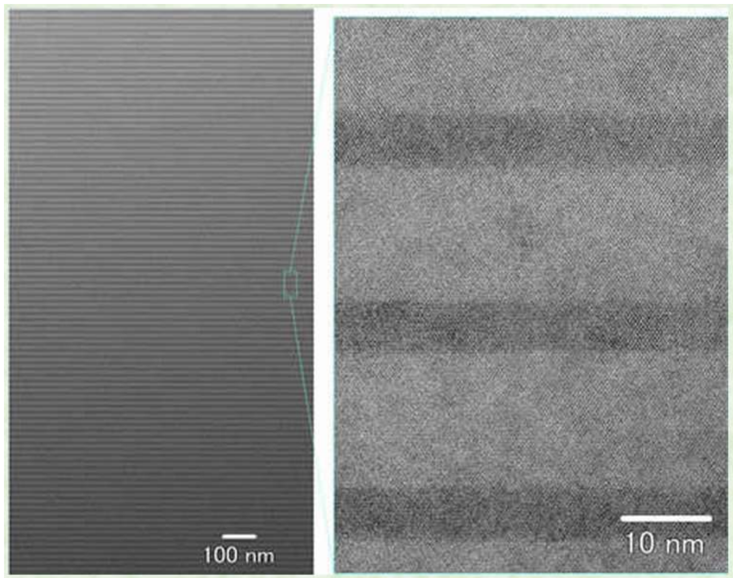
Superlattice – a way to tune band structure

Superlattice - Any long range periodicity larger than the atomic spacing





- Band structure engineering (Kronig-Penny model)
- High efficiency solar cells

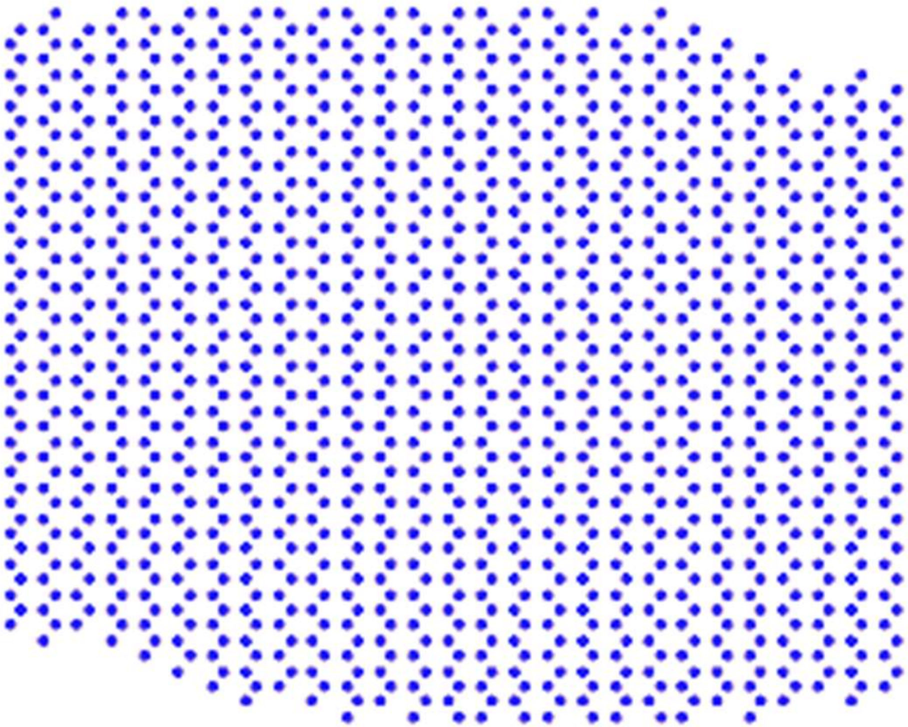


Tsu *et al*., Appl. Phys. Lett. **22**, 562 (1973)

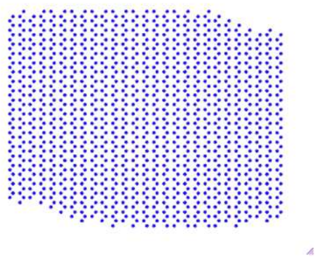
Esaki *et al*., IBM J. Res. Develop. **14**, 61 (1970)

www.ee.t.u-tokyo.ac.jp/~sugiyama/research/index-e.html

2D superlattice -- tuning periodicity of superlattice with twist



Rise of *twistronics*: Twisted bilayer graphene (TBG)

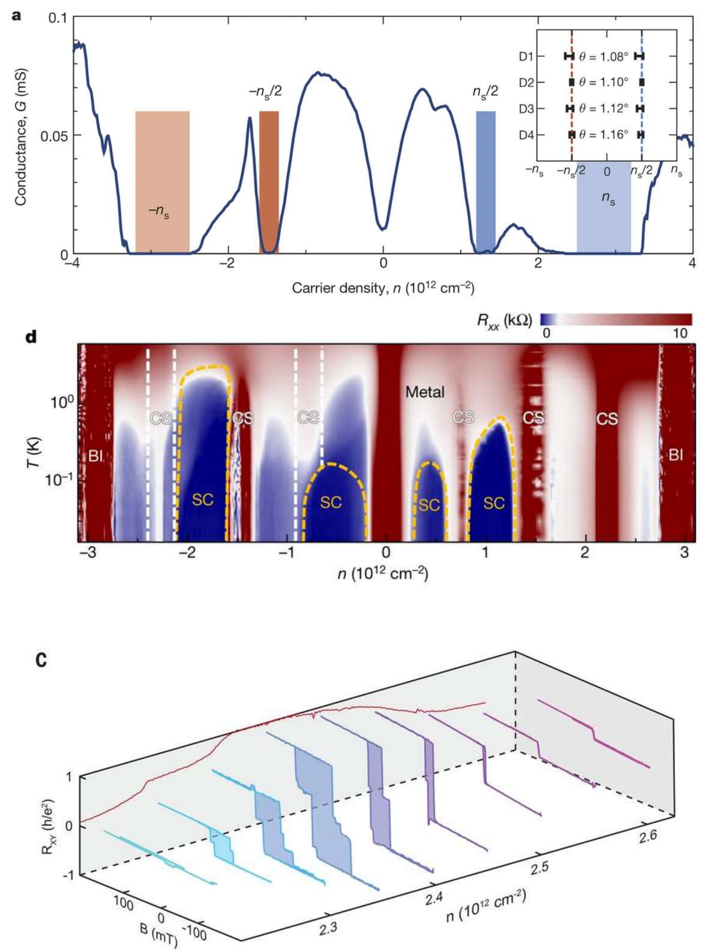


R. Bistritzer and A. H. MacDonald,
Proc. Natl. Acad. Sci. USA **108**, 12233 (2011).

Very flat band for twist angle ~ 1.1°

Electron correlations effect

Mott insulator, superconductivity, Ferromagnetism,…



✔ Correlated insulator

Y Cao et al.
Nature **556**, 80 (2018)

✔ Superconductivity

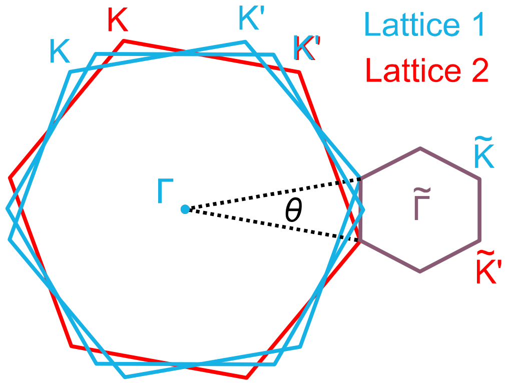
Y Cao et al.
Nature **556**, 43 (2018)

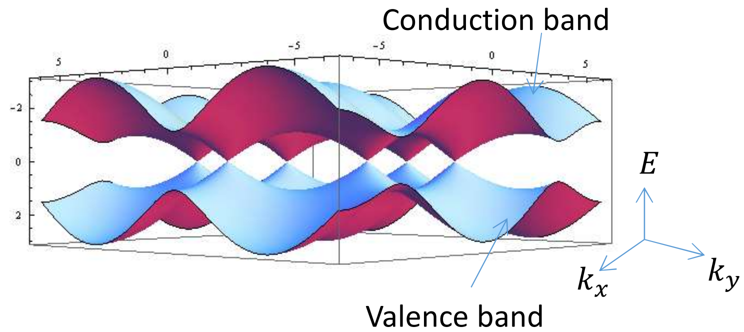
X Lu, et al.
Nature **574**, 653 (2019)

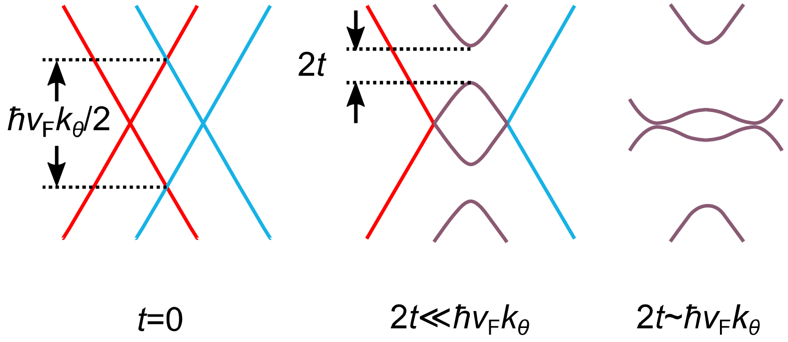
✔ Ferromagnetism

A L Sharpe et al.
Science **365**, 605 (2019)

M Serlin, et al.
Science **367**, 900 (2020)

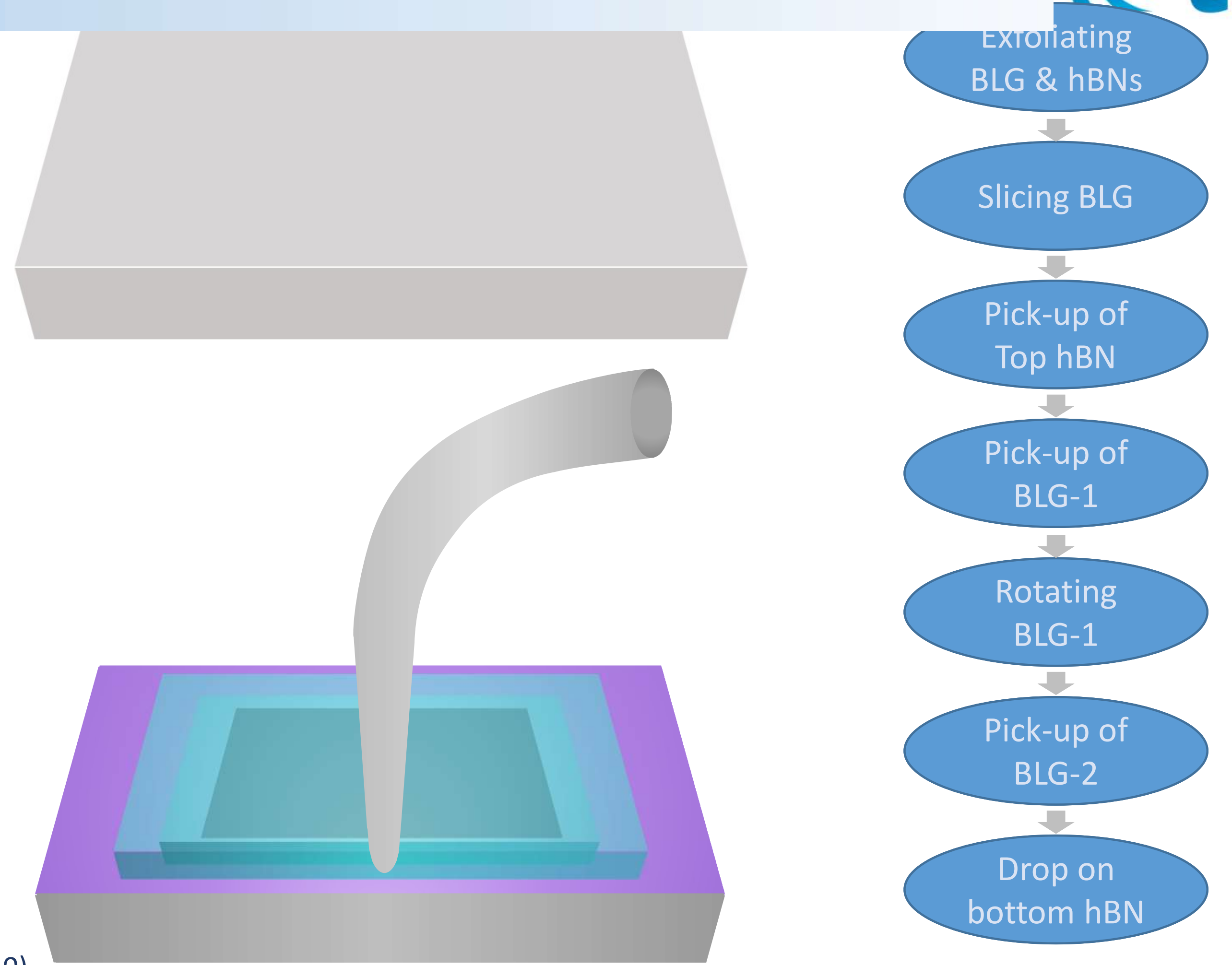






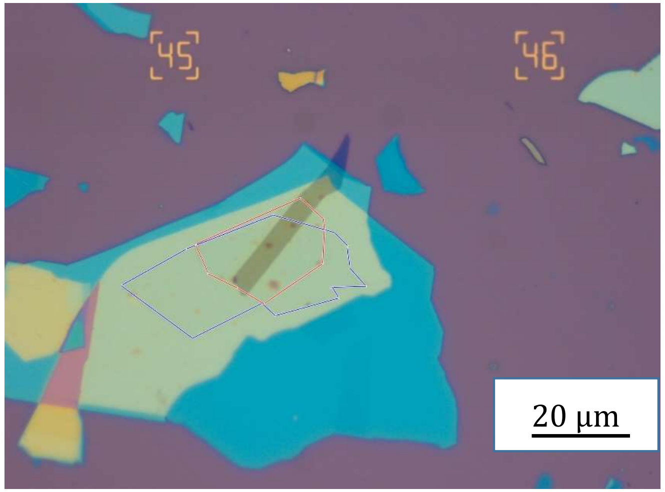
Flat bands in other twisted 2D systems as well

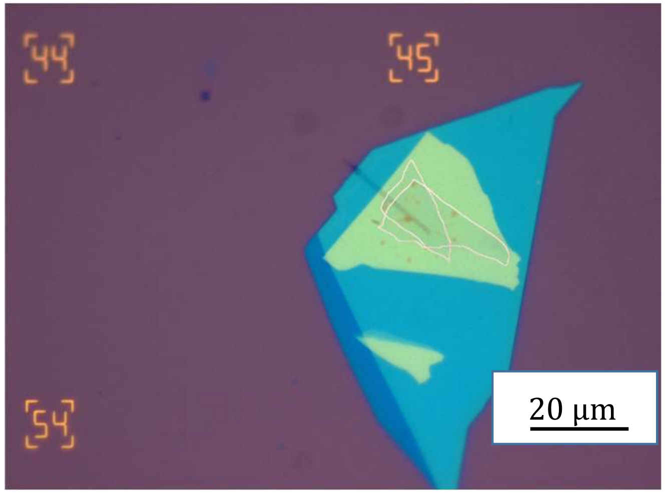
Stacking van der Waals heterostructure for twisted devices



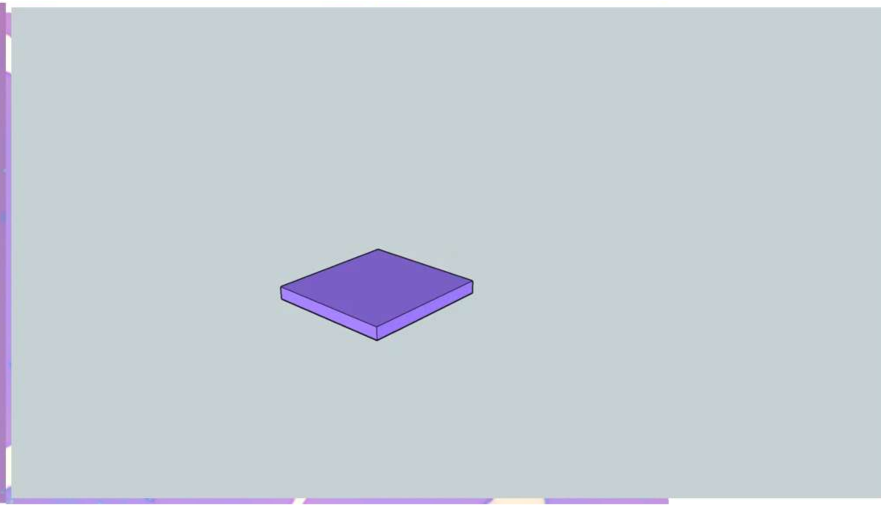
L D Varma Sangani, et al. *Nanotechnology* **31**, 32LT02 (2020)

Examples of “stacks”





Making electrical connections



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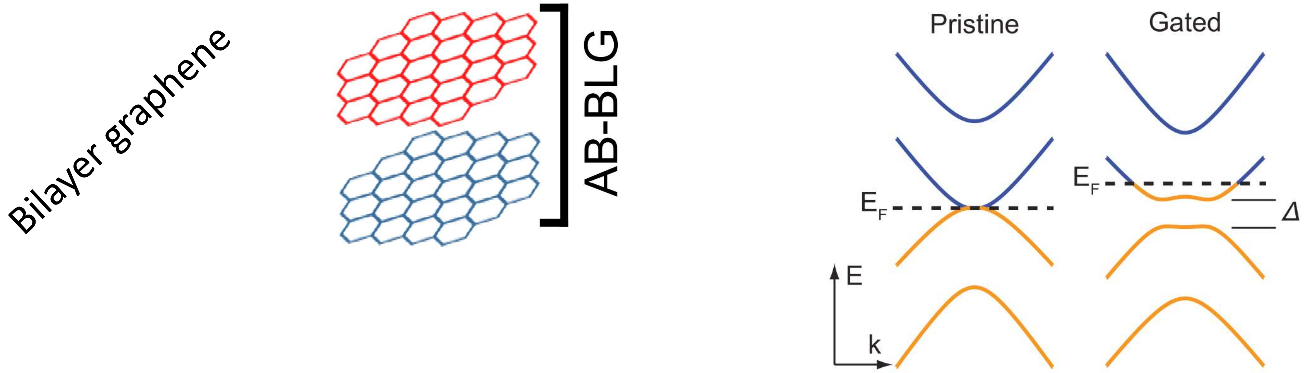
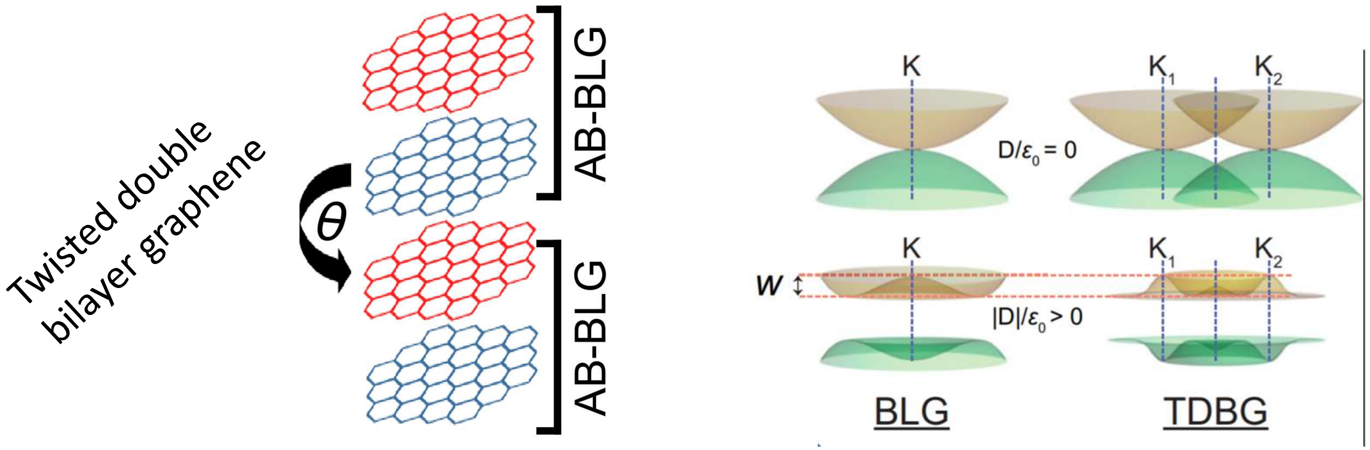
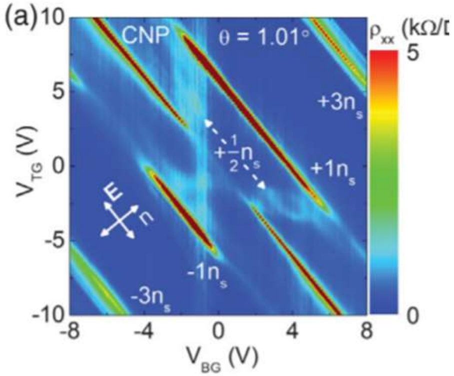
Twisted **double** bilayer: material with *in situ* tunable bandstructure



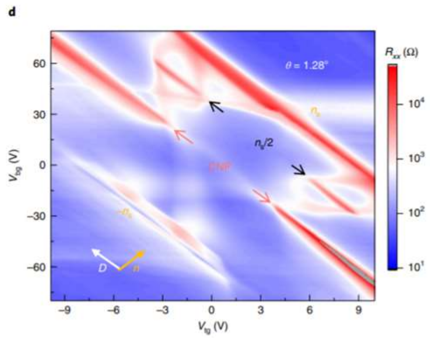
Electric field tunable band structure



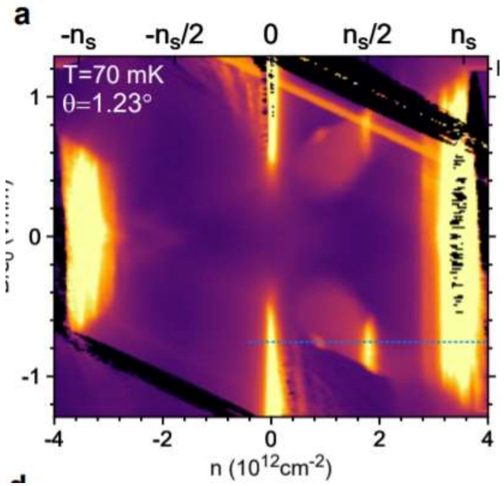
Correlated insulating states in twisted double bi-layer



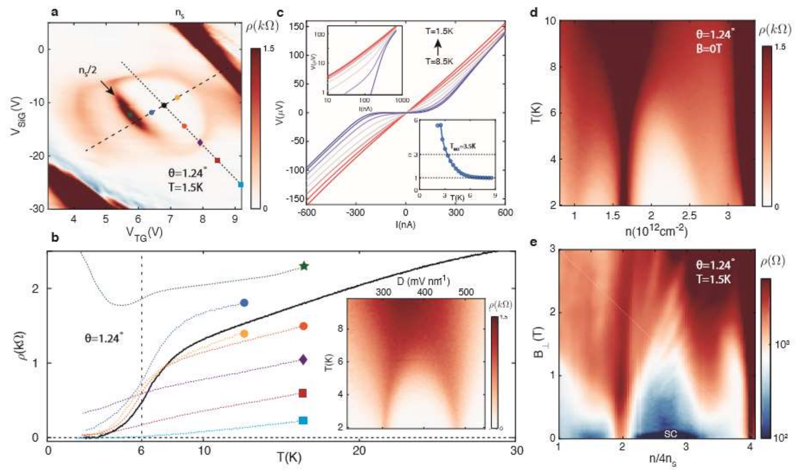
Burg et al. Physical Review Letters 123, 197702 (2019).



Shen et al. Nature Physics, 16, 520 (2020).

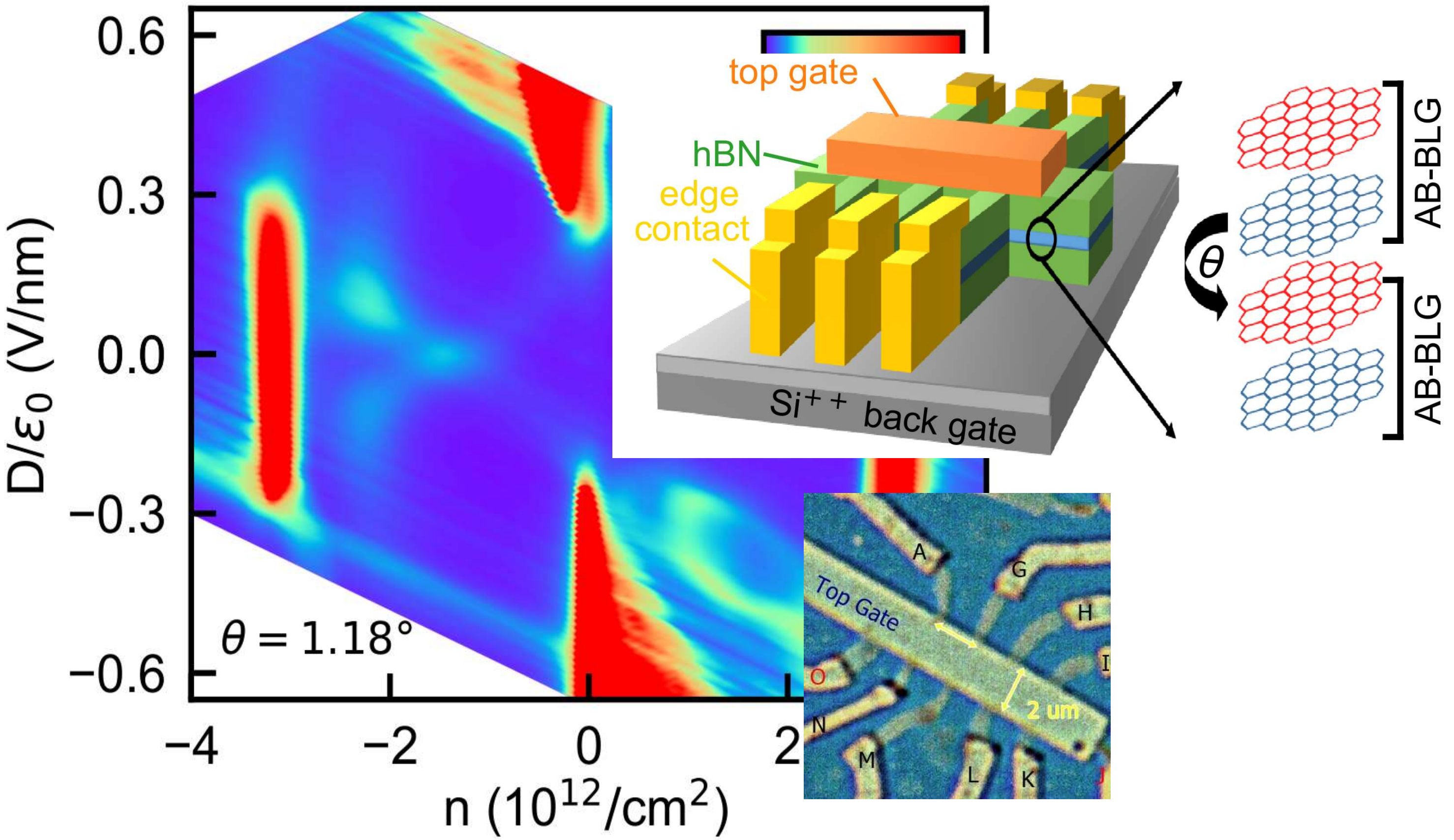


Cao et al. Nature 583, 215 (2020).

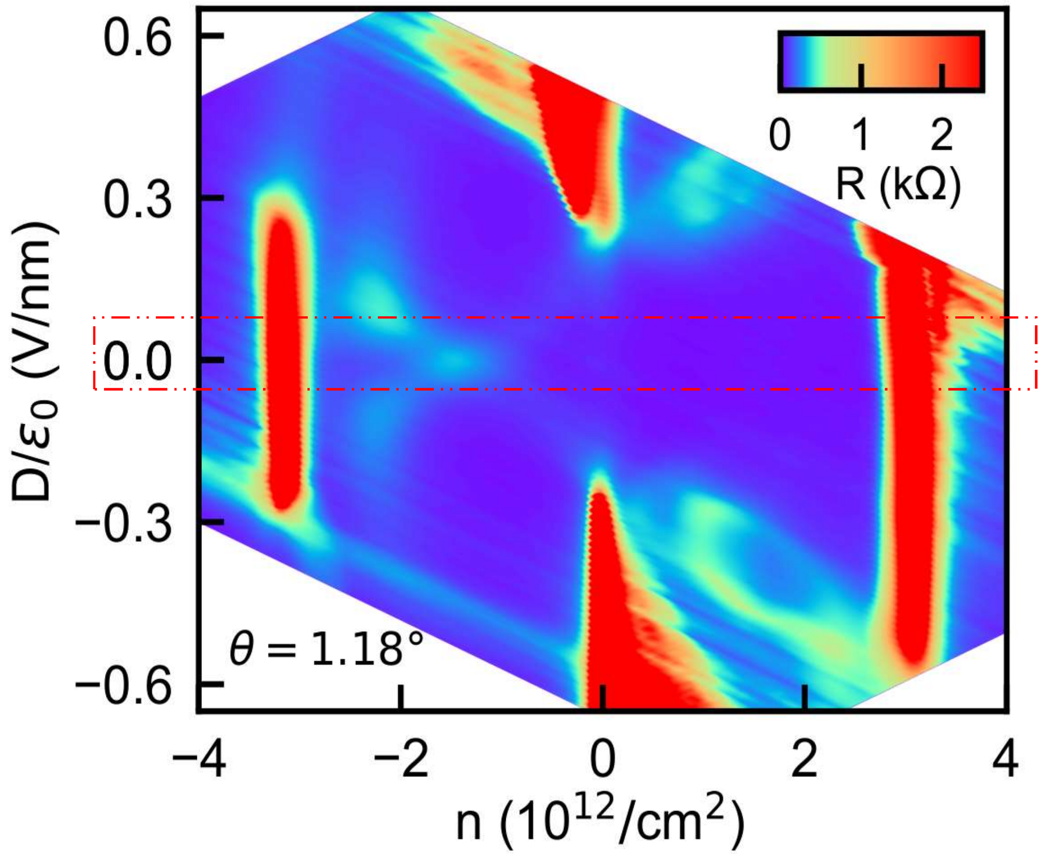


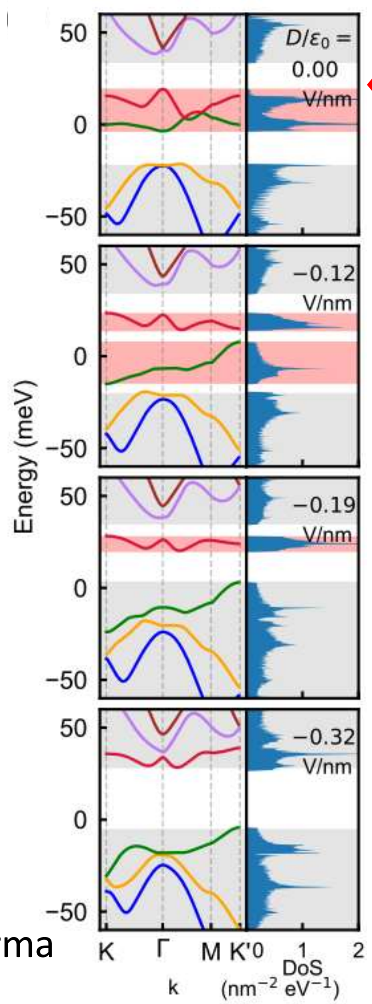
Liu et al. Nature 583, 221 (2020).

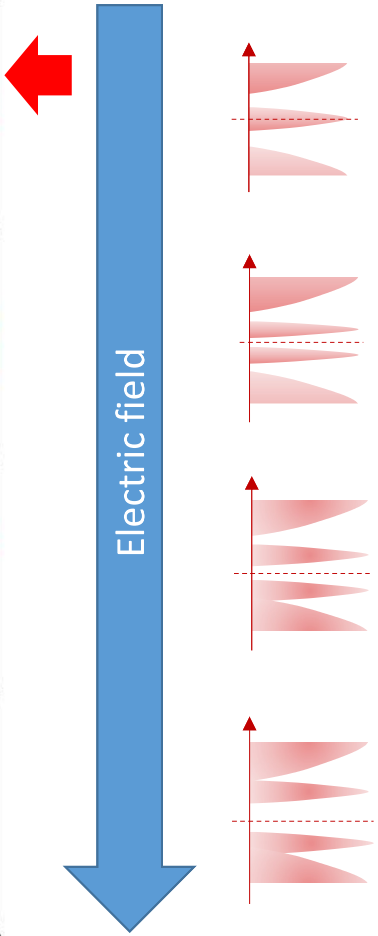
Electrical response at low temperature



Resistance at low temperature and band structure







One flat band

Splits into two

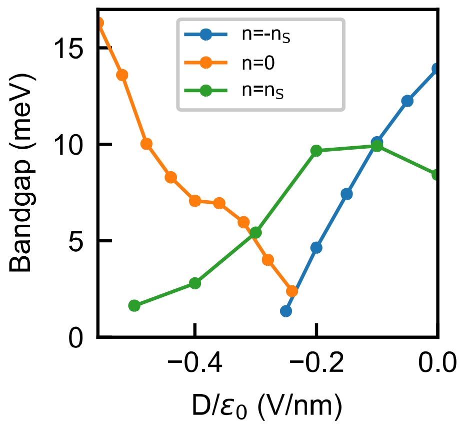
And then merges with higher bands

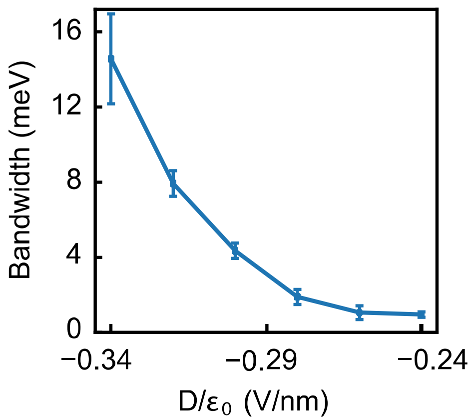
Theory collaboration with Unmesh Ghorai, Rajdeep Sensarma (TIFR)

Adak, Sinha, Ghorai, Sensarma, et al.Phys. Rev. B 101, 125428 (2020)

Key properties of twisted double bilayer graphene

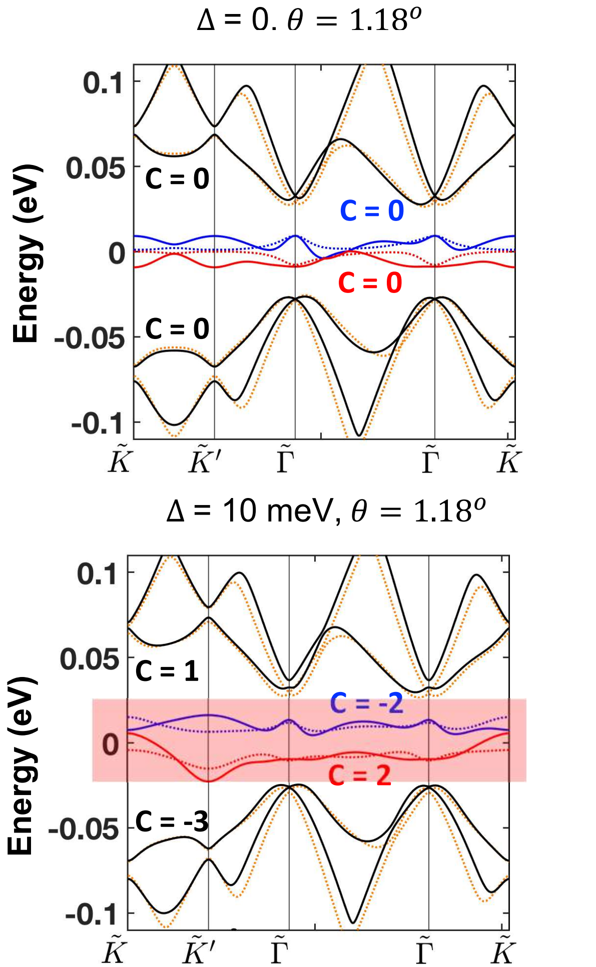
- TDBG has an electric field-tunable band structure
- Estimation of bandwidth from electron transport measurement



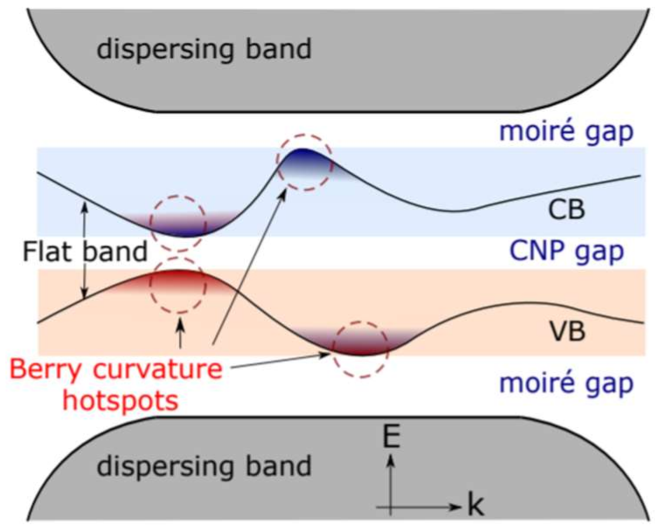


P C Adak, S Sinha, et al. *Phys. Rev. B* **101,** 125428 (2020).

Berry curvature hotspots in twisted double bilayer graphene



Jeil Jung et al., PRB 99, 235417 (2019)

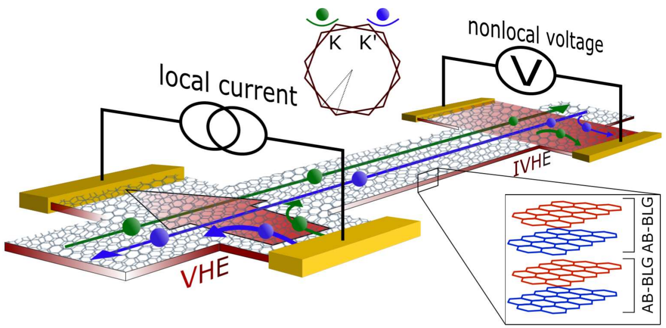


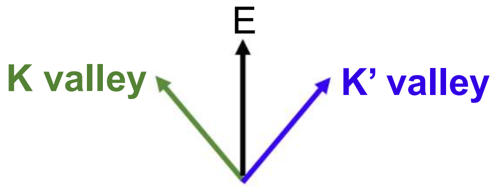
Electrical control of Berry curvature

collaboration with Bheema Lingam Chittari and Jeil Jung (University of Seoul)

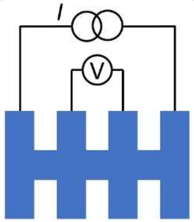
Berry curvature and Valley Hall Effect (VHE)

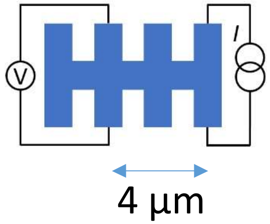
$$\dot{\boldsymbol{r}} = \frac{1}{\hbar}\frac{\partial E_{n.\boldsymbol{k}}}{\partial \boldsymbol{k}} - \dot{\boldsymbol{k}} \times \boldsymbol{\Omega}_n(\boldsymbol{k})$$

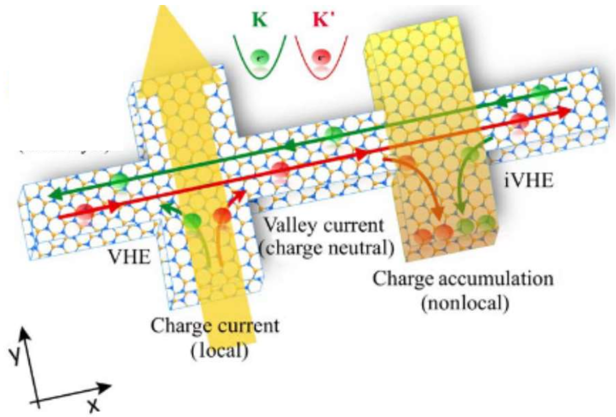




Large nonlocal signal -- signature of bulk valley transport







Sinha and Adak et al. Nature Communications, 11, 5548 (2020).

related work: Wang et al. Nature Physics 18, 48–53 (2022).

Signature of bulk transport: Scaling between R_L and R_{NL}

Diffusive valley transport via bulk:

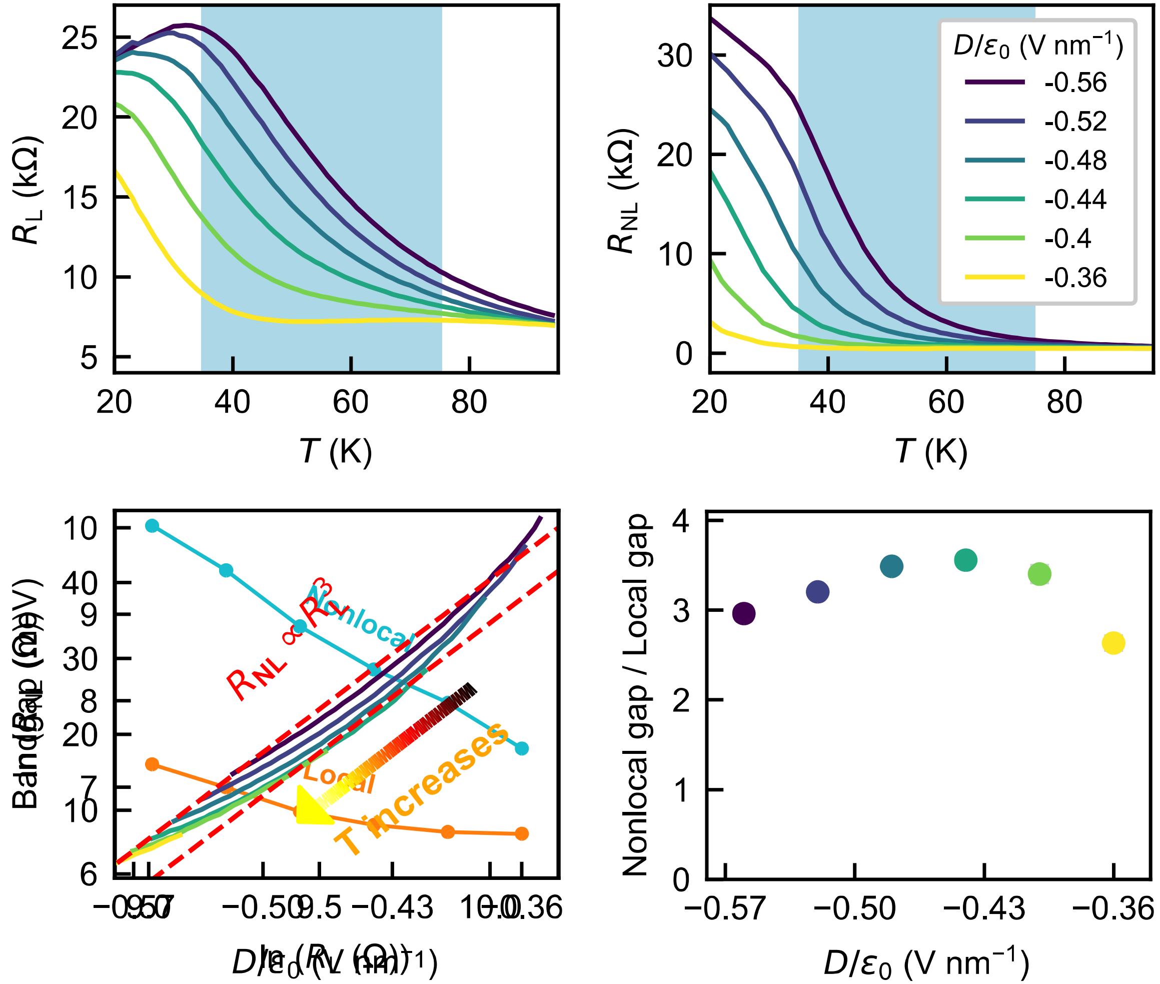
$$R_{\mathrm{NL}} = \frac{1}{2}\left(\frac{\sigma_{xy}^{\mathrm{VH}}}{\sigma_{xx}}\right)^2 \left(\frac{W}{\sigma_{xx} l_v}\right) \exp\left(-\frac{L}{l_v}\right)$$

(when $\sigma_{xy}^{\mathrm{VH}} \ll \sigma_{xx}$)

$$R_{\mathrm{NL}} \sim R_{\mathrm{L}}^3$$

The nonlocal resistance we observe is due to bulk valley current

$l_v \sim 1 - 2\ \mu\mathrm{m}$



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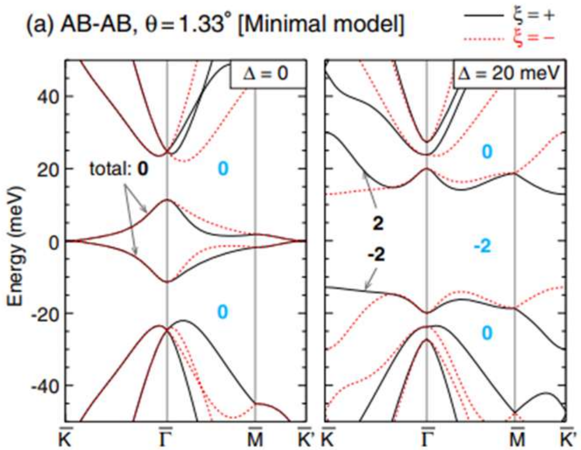
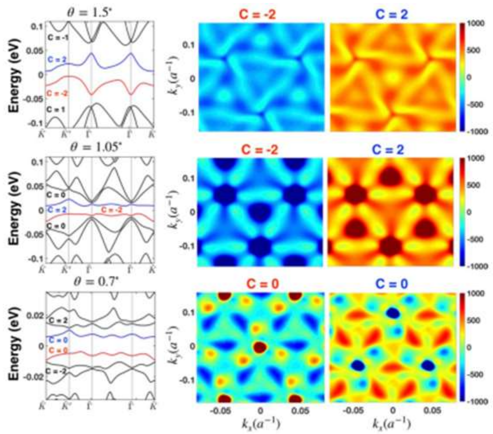
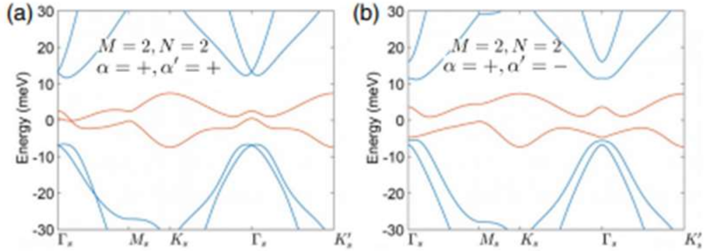
Topological bands in twisted double bilayer graphene



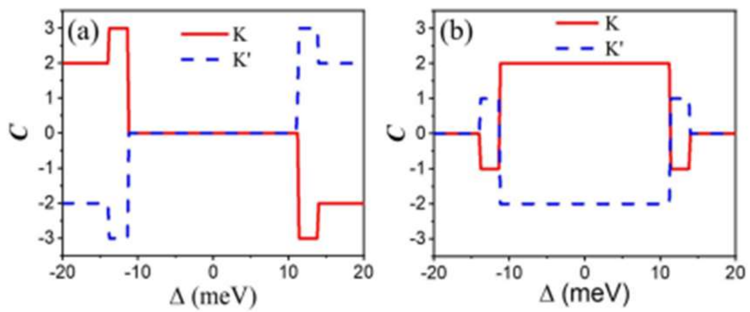
Koshino, Phys. Rev. B 99, 235406 (2019).



Chebrolu, Chittari, and Jung Phys. Rev. B 99, 235417 (2019).



Liu, Ma, Gao and Dai, Phys. Rev. X 9, 031021 (2019).



Mohan, Ghorai, Sensarma Phys. Rev. B 103, 155149 (2021).

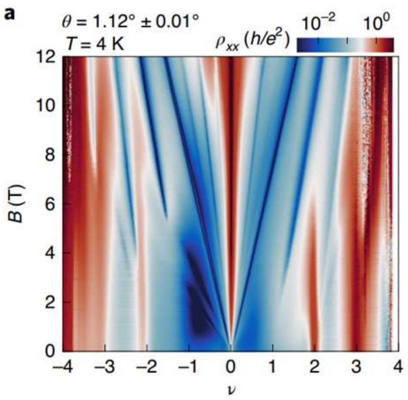
Other related works:
Zhang, Dai, Liu arXiv:2101.04711

Lin, Zhu, and Ni Phys. Rev. B 101, 155405 (2020)

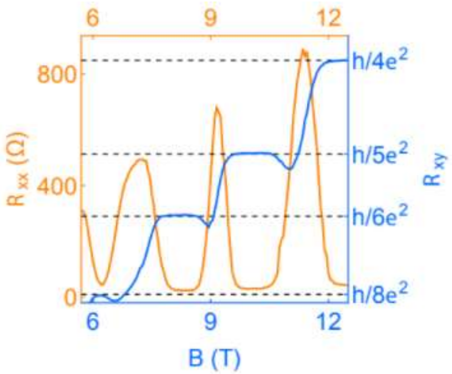
Wang, Li, and Zhang, Phys. Rev. B 103, 115201 (2021)

Studying topological states and transitions

- Tuning with Fermi energy in time reversal broken system



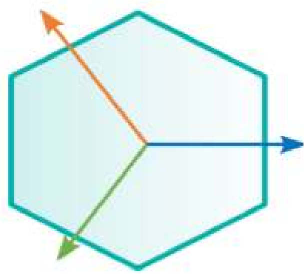
Saito et al Nature Physics (2021)



- Very hard to detect when time reversal symmetry intact

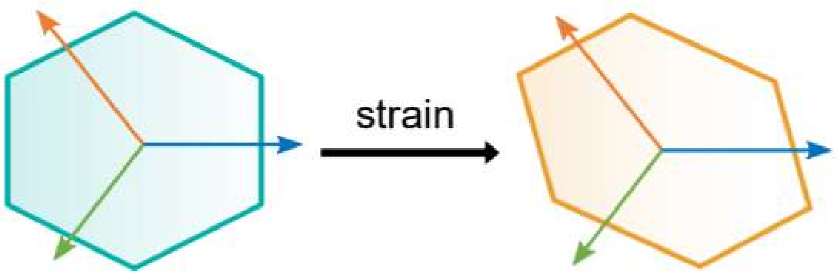
-We demonstrate a way to detect topological transitions using first moment of Berry curvature

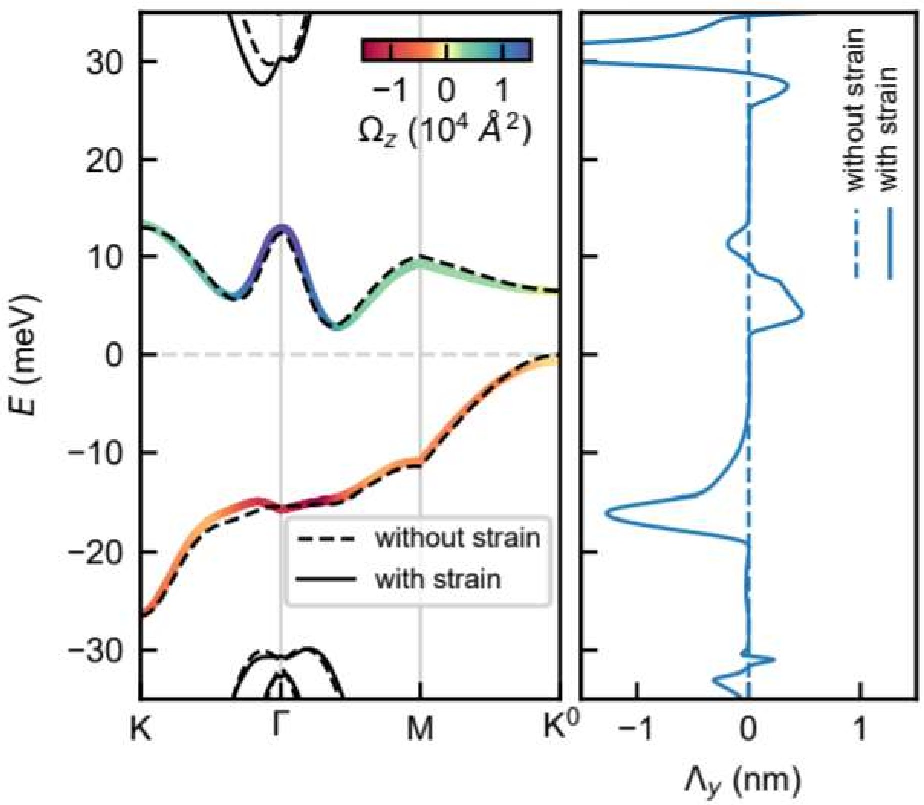
Breaking of discrete rotational symmetry (C_3) leads to distortion of Berry curvature



Emergence of Berry curvature dipole – the first moment of Berry curvature

$$\Lambda_\alpha = \sum_n \int_{\mathrm{mBZ}} \frac{d\mathbf{k}}{(2\pi)^2} \Omega_z^n \frac{\partial \epsilon_{\mathbf{k}}^n}{\hbar \partial k_\alpha} \frac{\partial f(\epsilon_{\mathbf{k}}^n)}{\partial \epsilon_{\mathbf{k}}^n}$$

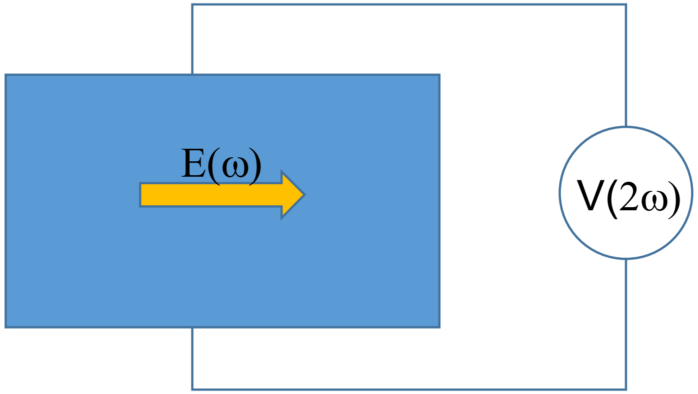




Sodemann and Fu, Phys. Rev. Lett. **115**, 216806 (2015)

Consequence of Berry curvature dipole with time reversal symmetry intact

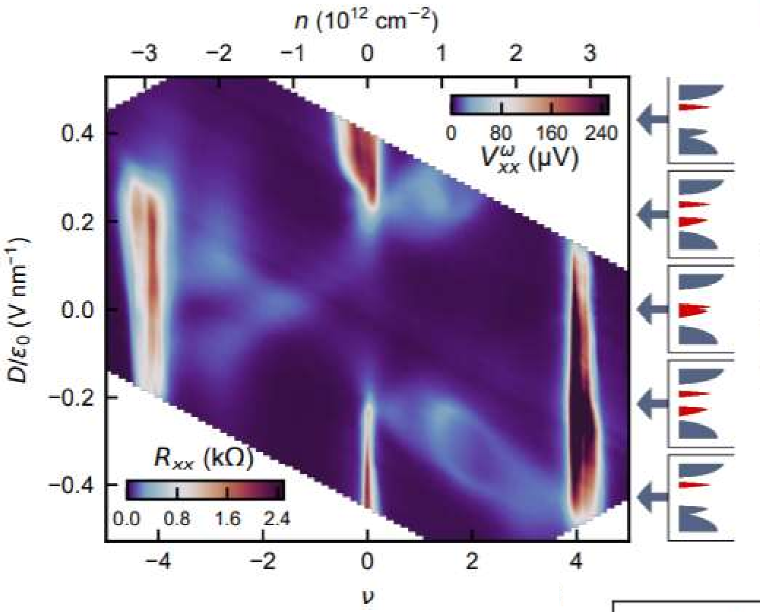
$$\vec{j}^{2\omega} \propto \hat{z} \times \vec{E}^{\omega}(\vec{\Lambda} \cdot \vec{E}^{\omega})$$

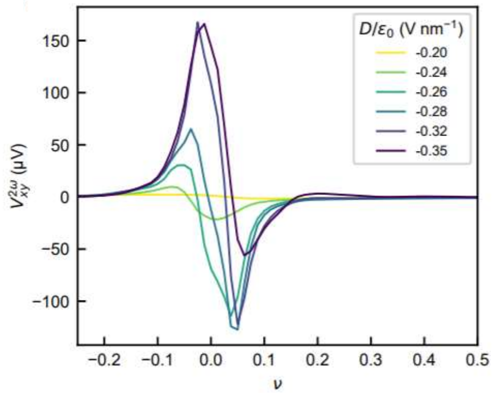


Theory: Sodemann and Fu, Phys. Rev. Lett. **115**, 216806 (2015)

Experiment First observation in WTe2 Ma, et al. Nature 565, 337–342 (2019).

Berry curvature dipole near hot spots of Berry curvature





Tunable non-linear Hall signal with transverse electric field as Band structure changes

Measuring BCD with non-linear Hall signal

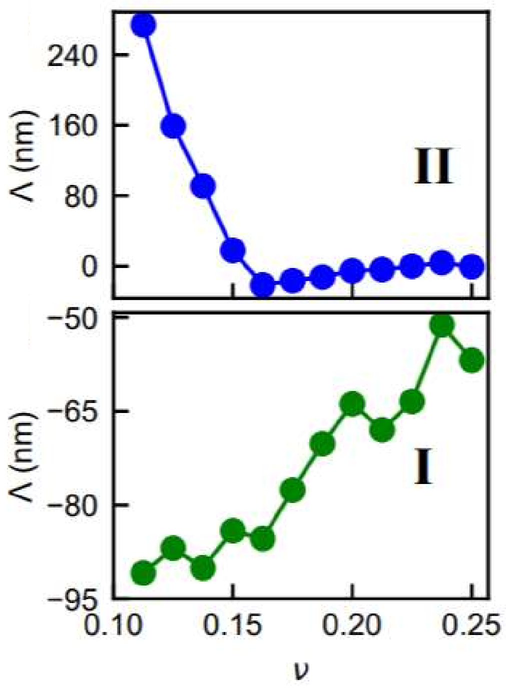
$$V_{xy}^{2\omega}/(V_{xx}^{\omega})^2 = A\sigma_{xx}^2 + B$$

Du et al. Nature Communications 10, 3047 (2019).

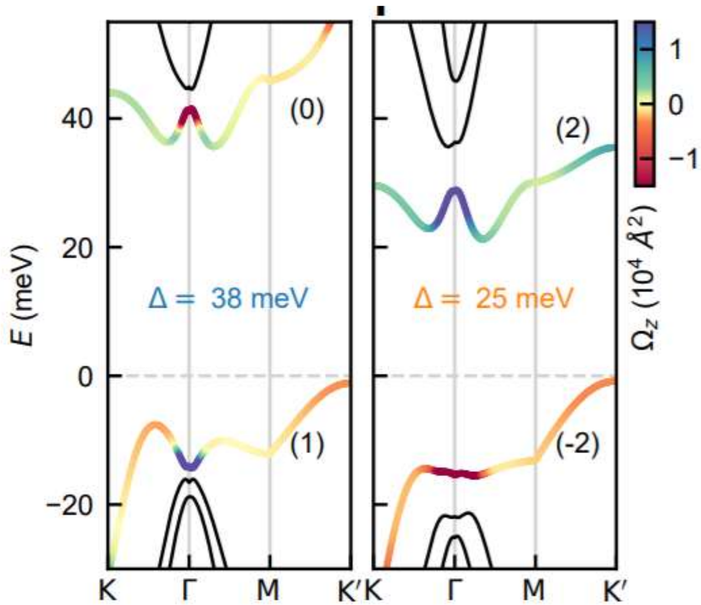
Berry curvature dipole changes sign!

 Sinha and Adak et al. Nature Physics 18, 765 (2022)

Variation of BCD with doping

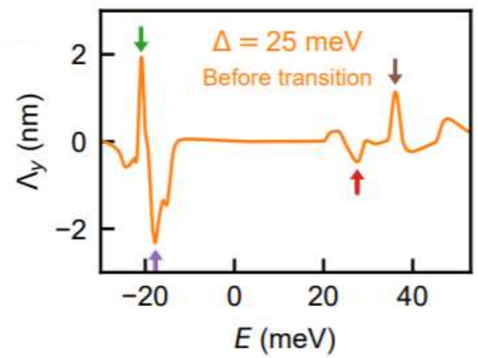


What is happening?



A topological transition with valley Chern number change!

Berry curvature dipole senses a topological transition



Berry curvature dipole will change sign even in a time reversal symmetric system

Summary

- Berry physics and topology in condensed matter
- Twisted layers – a new way to designer materials
- Valley transport in flat bands
- Berry curvature dipole senses a topological transition
- Magneto-electric coupling in flat bands

Sinha and Adak et al. Nature Physics 18, 765 (2022).
Sinha and Adak et al. Nature Communications, 11, 5548 (2020).