Title: Observation of Fractional Quantum Anomalous Hall Effect

Speakers: Xiaodong Xu

Series: Quantum Matter

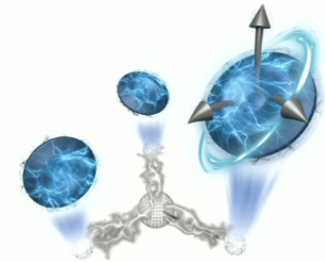
Date: April 08, 2024 - 11:00 AM

URL: https://pirsa.org/24040085

Abstract: The interplay between spontaneous symmetry breaking and topology can result in exotic quantum states of matter. A celebrated example is the quantum anomalous Hall (QAH) effect, which exhibits an integer quantum Hall effect at zero magnetic field due to topologically nontrivial bands and intrinsic magnetism. In the presence of strong electron-electron interactions, fractional-QAH (FQAH) effect at zero magnetic field can emerge, which is a lattice analog of fractional quantum Hall effect without Landau level formation. In this talk, I will present experimental observation of FQAH effect in twisted MoTe 2 bilayer, using combined magneto- optical and -transport measurements. In addition, we find an anomalous Hall state near the filling factor -1/2, whose behavior resembles that of the composite Fermi liquid phase in the half-filled lowest Landau level of a two-dimensional electron gas at high magnetic field. Direct observation of the FQAH and associated effects paves the way for researching charge fractionalization and anyonic statistics at zero magnetic field.

Reference 1. Observation of Fractionally Quantized Anomalous Hall Effect, Heonjoon Park et al., Nature, https://www.nature.com/articles/s41586-023-06536-0 (2023);
2. Signatures of Fractional Quantum Anomalous Hall States in Twisted MoTe2 Bilayer, Jiaqi Cai et al., Nature, https://www.nature.com/articles/s41586-023-06289-w (2023);
3. Programming Correlated Magnetic States via Gate Controlled Moiré Geometry, Eric Anderson et al., Science, https://www.science.org/doi/full/10.1126/science.adg4268 (2023)

Zoom link



Observation of Fractional Quantum Anomalous Hall Effect

Xiaodong Xu
Department of Physics
Department of Materials Science and Engineering
University of Washington, Seattle WA

SEMINAR, PERIMETER INSTITUTE, APRIL 8, 2024

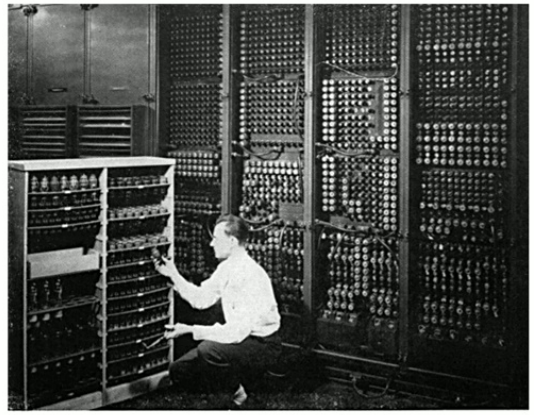
Discovery of transistor

- **Revolution of micro electronics**

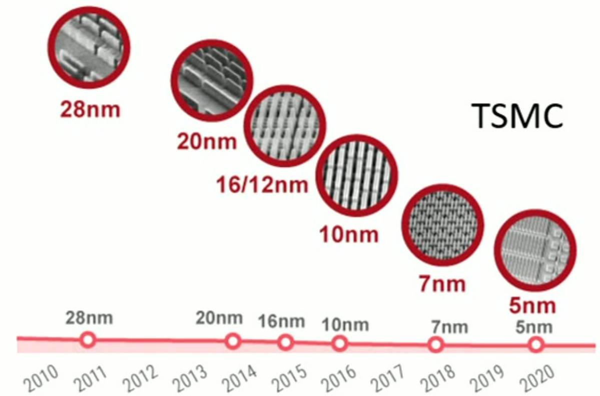
John Bardeen, William Shockley and Walter Brattain at Bell Labs, 1948

Nobel Prize in Physics, 1956 "for their researches on semiconductors and their discovery of the transistor effect".

https://en.wikipedia.org/wiki/History_of_the_transistor



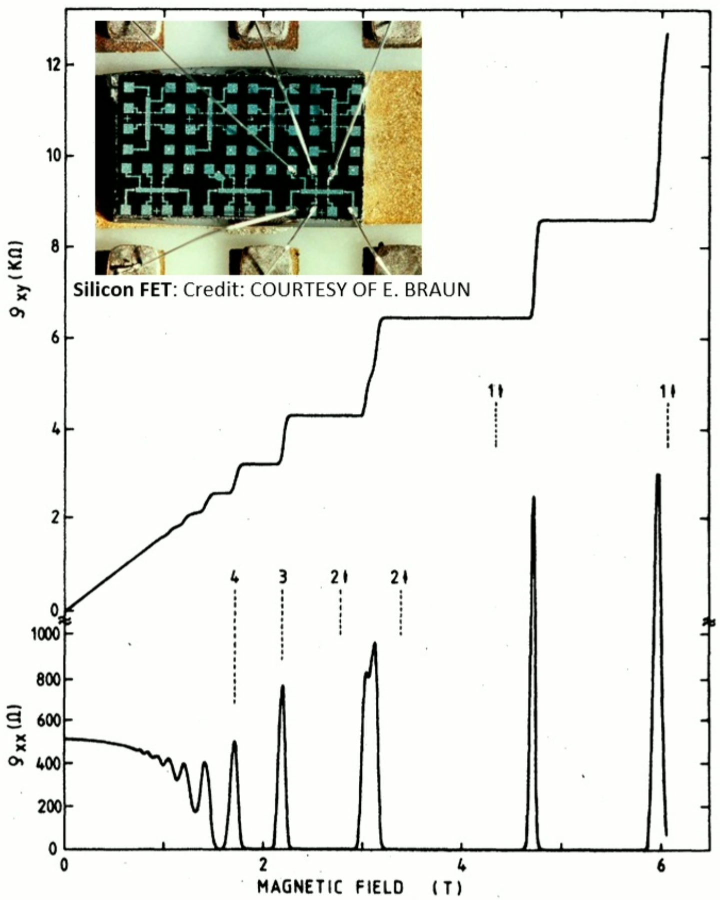
Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.



Apple MacIntosh (1984)

https://homepage.cs.uri.edu/faculty/wolfe/book/Readings/Reading03.htm

Integer quantum Hall effect



Silicon FET: Credit: COURTESY OF E. BRAUN

2D electron gas subject to strong magnetic field

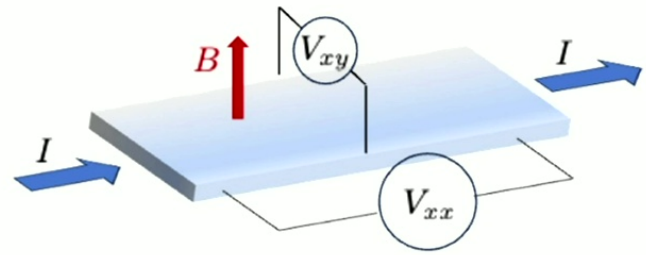


Image from http://nanoscale.blogspot.com/2023/08/

Quantized Hall conductance

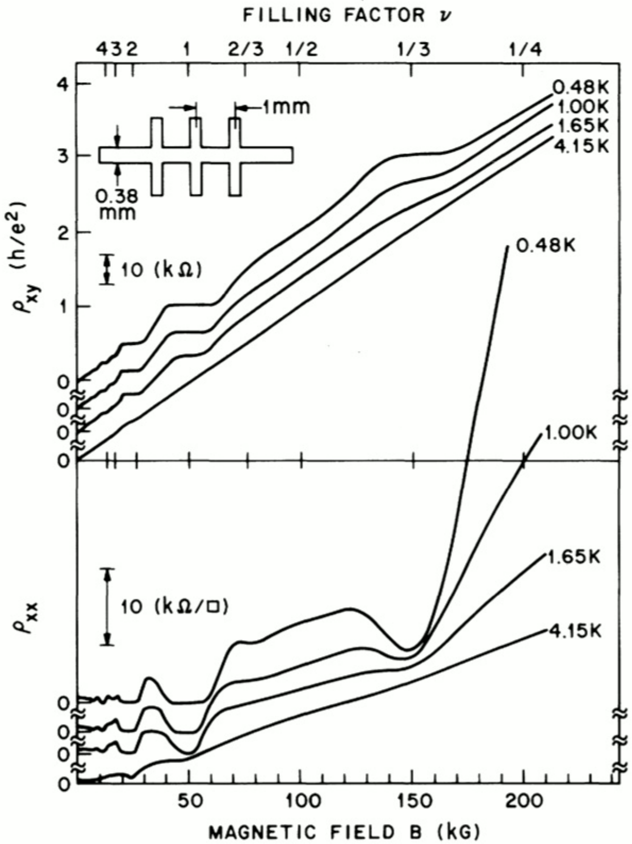
$$\sigma_{xy} = C\,\frac{e^2}{h}$$

K. v. Klitzing, G. Dorda, and M. Pepper PRL **45**, 494 (1980)

Nobel Prize 1985

Fractional quantum Hall effect – high mobility electron gas

Electron-electron interactions become important



Fractionally quantized Hall conductance

$$\sigma_{xy} = C\,\frac{e^2}{h}$$

C is a *fractional* number: $\frac{p}{q}$ *(p and q are integers)*

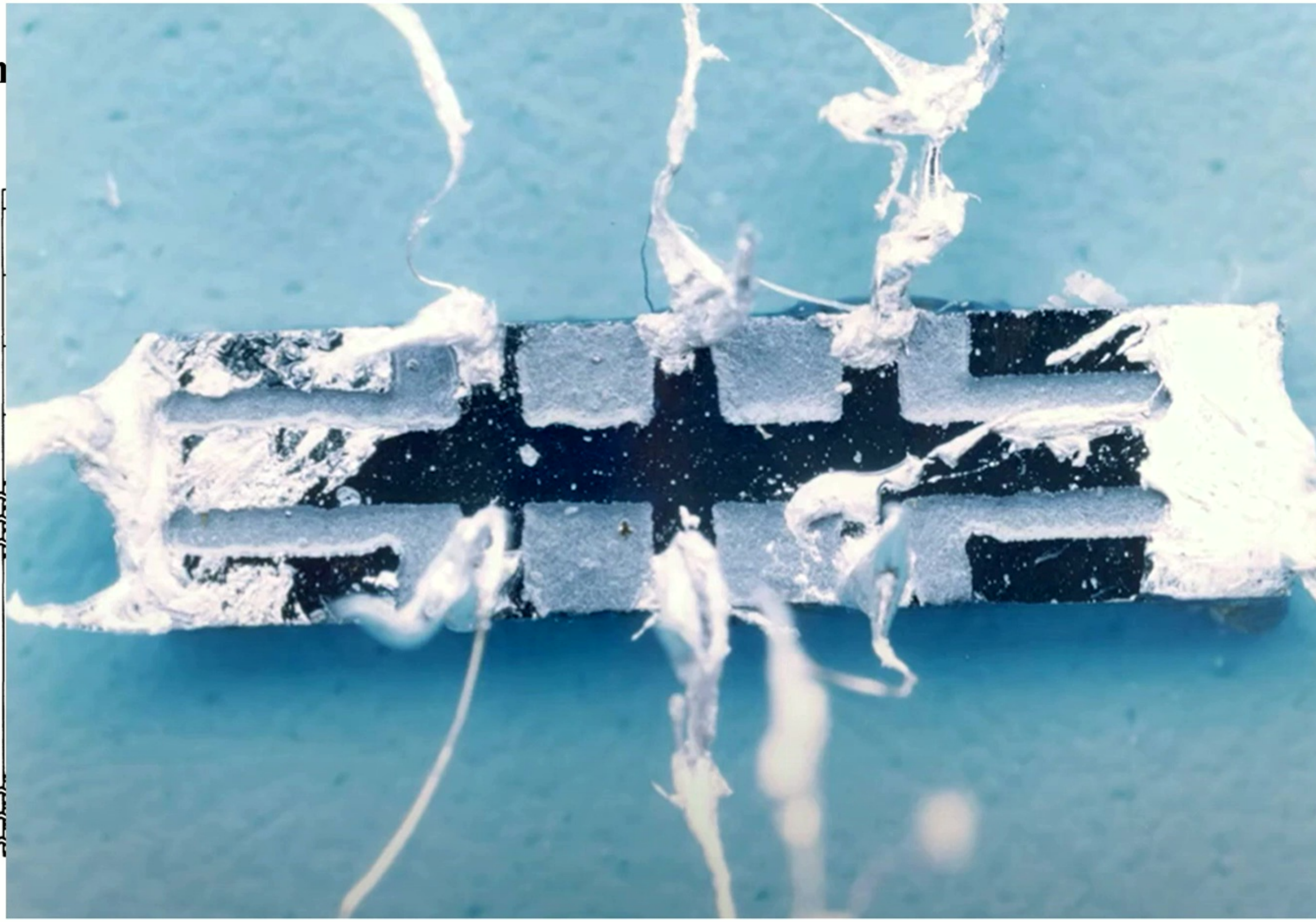
D.C. Tsui; H.L. Stormer; A.C. Gossard (1982). "Two-Dimensional Magnetotransport in the Extreme Quantum Limit". Physical Review Letters. 48 (22)

R.B. Laughlin (1983). "Anomalous Quantum Hall Effect: An Incompressible Quantum Fluid with Fractionally Charged Excitations". Physical Review Letters. 50 (18): 1395–1398.

Nobel Prize 1998

Fractional quantum Hall effect – high mobility electron gas

Electron ... ed Hall



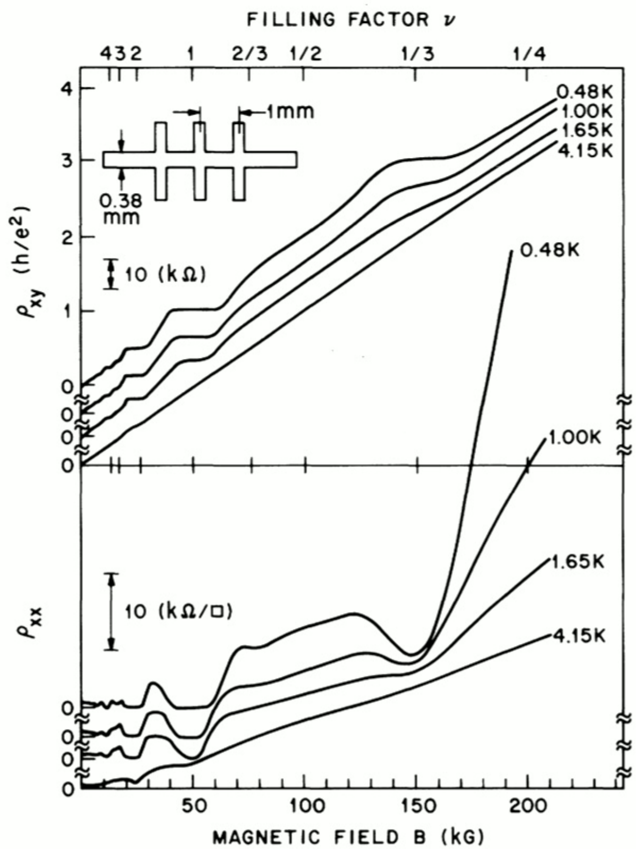
...er: $\frac{p}{q}$ (p
...rs)

...(1982). "Two-
...xtreme Quantum
...)

...ntum Hall Effect:
... Fractionally
... Letters. 50 (18):

Fractional quantum Hall effect – high mobility electron gas

Electron-electron interactions become important



Fractionally quantized Hall conductance

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D.C. Tsui; H.L. Stormer; A.C. Gossard (1982). "Two-Dimensional Magnetotransport in the Extreme Quantum Limit". Physical Review Letters. 48 (22)

R.B. Laughlin (1983). "Anomalous Quantum Hall Effect: An Incompressible Quantum Fluid with Fractionally Charged Excitations". Physical Review Letters. 50 (18): 1395–1398.

Nobel Prize 1998

Quantum Hall effect – Topology

Quantized Hall Conductance in a Two-Dimensional Periodic Potential

D. J. Thouless, M. Kohmoto,[a] M. P. Nightingale, and M. den Nijs
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 30 April 1982)

The Hall conductance of a two-dimensional electron gas has been studied in a uniform magnetic field and a periodic substrate potential U. The Kubo formula is written in a form that makes apparent the quantization when the Fermi energy lies in a gap. Explicit expressions have been obtained for the Hall conductance for both large and small $U/\hbar\omega_c$.

Quantized Hall conductance as a topological invariant

Qian Niu, D. J. Thouless,* and Yong-Shi Wu†
Department of Physics FM-15, University of Washington, Seattle, Washington 98195
(Received 21 September 1984)

Whenever the Fermi level lies in a gap (or mobility gap) the bulk Hall conductance can be expressed in a topologically invariant form showing the quantization explicitly. The new formulation generalizes the earlier result by Thouless, Kohmoto, Nightingale, and den Nijs to the situation where many-body interaction and substrate disorder are also present. When applying to the fractional quantized Hall effect, we draw the conclusion that there must be a symmetry breaking in the many-body ground state. The possibility of writing the fractionally quantized Hall conductance as a topological invariant is also discussed.

Quantized Hall conductance

$$\sigma_{xy} = C\frac{e^2}{h}$$

$$C = \frac{1}{2\pi}\int_S \mathcal{B}\, ds$$

Integer quantum Hall effect without Landau level – Haldane model

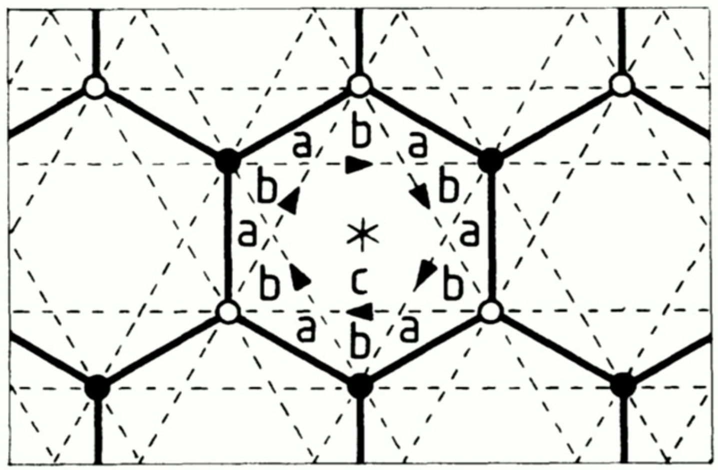
VOLUME 61, NUMBER 18 PHYSICAL REVIEW LETTERS 31 OCTOBER 1988

Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly"

F. D. M. Haldane

Department of Physics, University of California, San Diego, La Jolla, California 92093

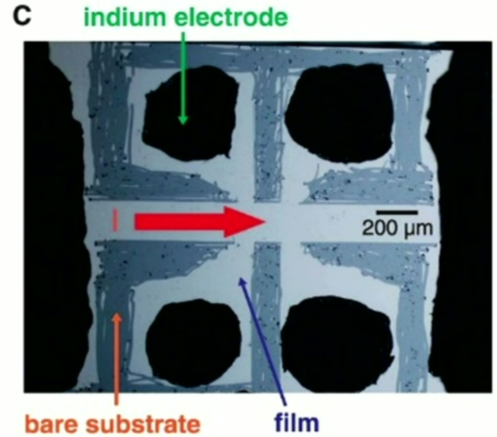
(Received 16 September 1987)

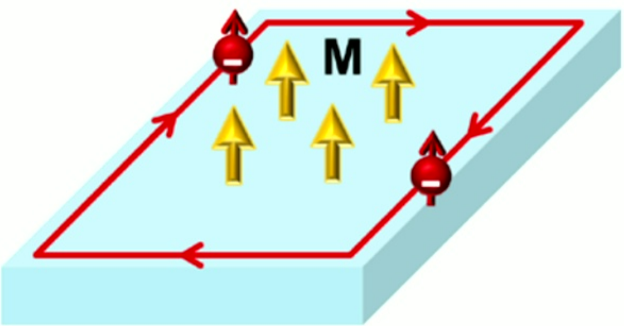


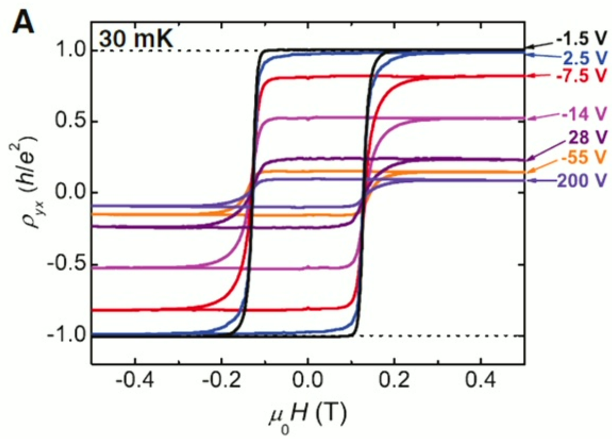
Experimental realization of quantum anomalous Hall effect

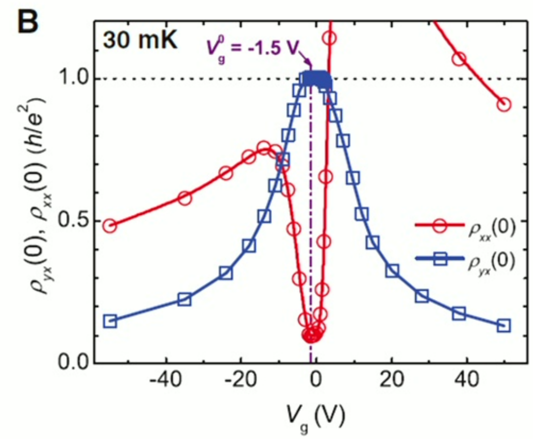
Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator

Cui-Zu Chang,[1,2*] Jinsong Zhang,[1*] Xiao Feng,[1,2*] Jie Shen,[2*] Zuocheng Zhang,[1] Minghua Guo,[1] Kang Li,[2] Yunbo Ou,[2] Pang Wei,[2] Li-Li Wang,[2] Zhong-Qing Ji,[2] Yang Feng,[1] Shuaihua Ji,[1] Xi Chen,[1] Jinfeng Jia,[1] Xi Dai,[2] Zhong Fang,[2] Shou-Cheng Zhang,[3] Ke He,[2†] Yayu Wang,[1†] Li Lu,[2] Xu-Cun Ma,[2] Qi-Kun Xue[1†]









Theory - fractional quantum Hall effect in lattice

FQHE + Spin lattice

PHYSICAL REVIEW B VOLUME 39, NUMBER 16 1 JUNE 1989

Theory of the spin liquid state of the Heisenberg antiferromagnet

Vadim Kalmeyer
Department of Physics, Stanford University, Stanford, California 94305

R. B. Laughlin
Department of Physics, Stanford University, Stanford, California 94305
and Lawrence Livermore Laboratory, University of California, Livermore, California 94550
(Received 5 December 1988)

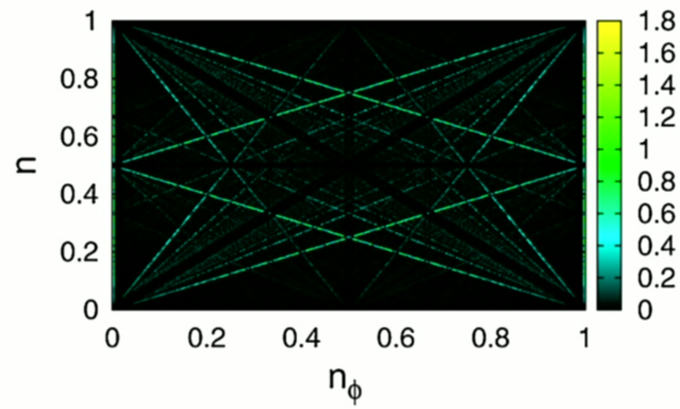
FQHE + Lattice

PHYSICAL REVIEW B VOLUME 48, NUMBER 12 15 SEPTEMBER 1993-II

Fractional quantum Hall effect in a periodic potential

A. Kol and N. Read*
Departments of Physics and Applied Physics, P. O. Box 2157, Yale University, New Haven, Connecticut 06520
(Received 28 May 1993)

FQHE + optical lattices (cold atoms)



- •Sørensen, Demler, Lukin, *FQH States in Optical Lattices*, 2005 (+Hafezi, PRA 2007)
- •Palmer, Jaksch, *High Field FQHE in Optical Lattices*, 2006 (+Klein, PRA 2008)
- •Moller, Cooper, *CF Theory for Bosonic Quantum Hall States on Lattices*, 2009
- •Kapit, Mueller, *Parent Hamiltonian for Quantum Hall States in a Optical Lattice*, 2010

Theory - zero-magnetic field fractional quantum Hall effect

PRL 106, 236802 (2011) Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS week ending 10 JUNE 2011

High-Temperature Fractional Quantum Hall States

Evelyn Tang,[1] Jia-Wei Mei,[1,2] and Xiao-Gang Wen[1]
[1]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Institute for Advanced Study, Tsinghua University, Beijing, 100084, People's Republic of China*
(Received 14 December 2010; published 6 June 2011)

PRL 106, 236804 (2011) Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS week ending 10 JUNE 2011

Fractional Quantum Hall States at Zero Magnetic Field

Titus Neupert,[1] Luiz Santos,[2] Claudio Chamon,[3] and Christopher Mudry[1]
[1]*Condensed Matter Theory Group, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland*
[2]*Department of Physics, Harvard University, 17 Oxford Street, Cambridge, Massachusetts 02138, USA*
[3]*Physics Department, Boston University, Boston, Massachusetts 02215, USA*
(Received 22 December 2010; published 6 June 2011)

PRL 106, 236803 (2011) Selected for PHYSICAL I

Nearly Flatbands

Kai Sun,[1] Zhengcheng Gu,[2]
[1]*Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[2]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[3]*Department of Physics, Gakushuin University, Mejiro, Toshima-ku, Tokyo 171-8588, Japan*
(Received 28 December 2010; revised manuscript received 19 March 2011; published 6 June 2011)

Key: Flat Chern band!

l 2011 DOI: 10.1038/ncomms1380

ll effect in the absence of Landau levels

D.N. Sheng[1], Zheng-Cheng Gu[2], Kai Sun[3] & L. Sheng[4]

ARTICLE

Received 20 Jun 2011 | Accepted 18 Nov 2011 | Published 20 Dec 2011 DOI: 10.1038/ncomms1602

Interface engineering of quantum Hall effects in digital transition metal oxide heterostructures

Di Xiao[1], Wenguang Zhu[1,2], Ying Ran[3], Naoto Nagaosa[4,5] & Satoshi Okamoto[1]

PHYSICAL REVIEW X 1, 021014 (2011)

Fractional Chern Insulator

N. Regnault[1] and B. Andrei Bernevig[2]
[1]*Laboratoire Pierre Aigrain, ENS and CNRS, 24 rue Lhomond, 75005 Paris, France*
[2]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
(Received 16 June 2011; published 2 December 2011)

Experimental evidence of high-temperature zero-field integer (C= -1) and fractional Chern (C= -2/3, -3/5, -4/7) insulator states.

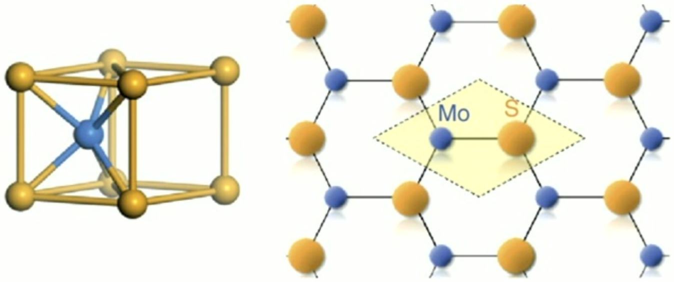
Gate tunable ferromagnetism:
Science DOI: 10.1126/science.adg4268 (2023)

Trion sensing of FQAHE:
Nature, www.nature.com/articles/s41586-023-06289-w (2023)

Transport measurements of FQAHE,
Nature, https://doi.org/10.1038/s41586-023-06536-0 (2023)

Also See Zeng, Mak, Shan et al *Nature* (2023) for thermal dynamic evidence of the -1 and -2/3 CI states;
F. Xu, T. Li et al, Transport evidence of the -1 and -2/3 CI states, Phys. Rev. X (2023)
FQAHE in pentalayer graphene moire superlattices, Z. Lu, L. Ju et al, Nature (2024).

Monolayer transition metal dichalcogenides



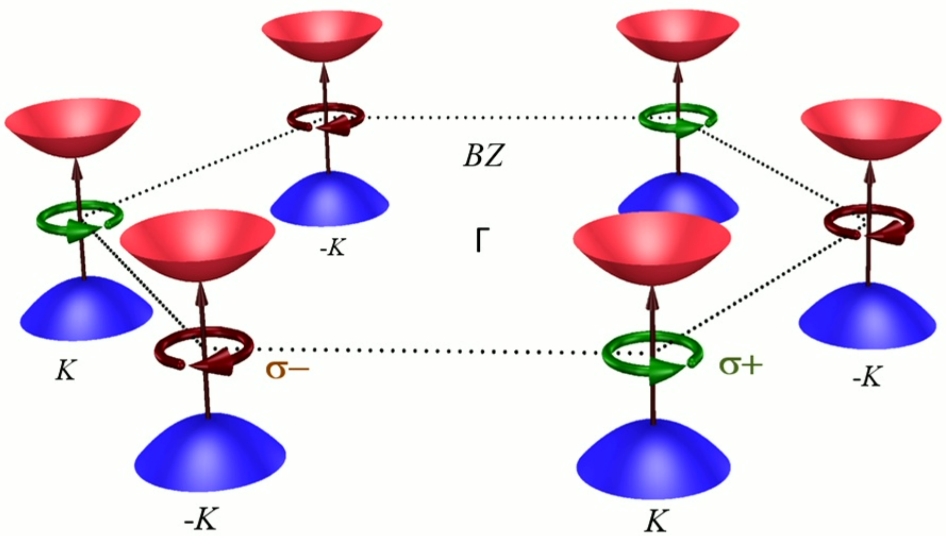
Monolayer

D_{3h}^{1}

without inversion symmetry

$\Omega(\boldsymbol{k}) \neq 0 \quad m(\boldsymbol{k}) \neq 0$

Xiao, Xu, Yao *et al*, PRL 108, 196802 (2012)



Dr. D Xiao

Dr. W Yao

Theory progress: TMD homobilayer for QAHE, QSHE, and FCI

PHYSICAL REVIEW LETTERS **122,** 086402 (2019)

Layer Pseudospin skyrmion

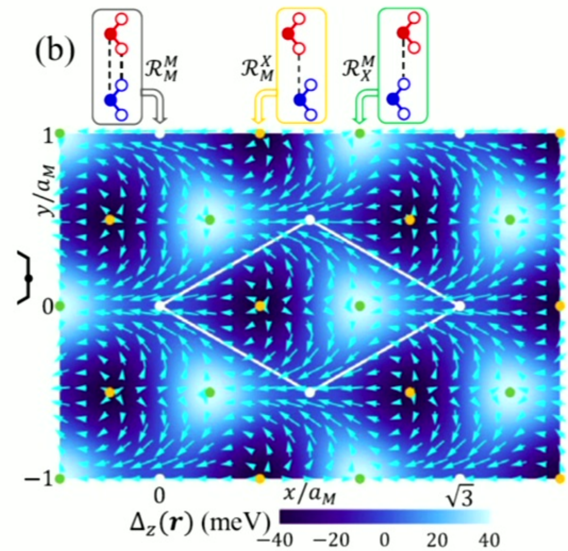
Topological Insulators in Twisted Transition Metal Dichalcogenide Homobilayers

Fengcheng Wu,[1,2] Timothy Lovorn,[3] Emanuel Tutuc,[4] Ivar Martin,[1] and A. H. MacDonald[3]
[1]*Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[3]*Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA*
[4]*Department of Electrical and Computer Engineering, Microelectronics Research Center, The University of Texas at Austin, Austin, Texas 78758, USA*

(Received 9 July 2018; published 28 February 2019)

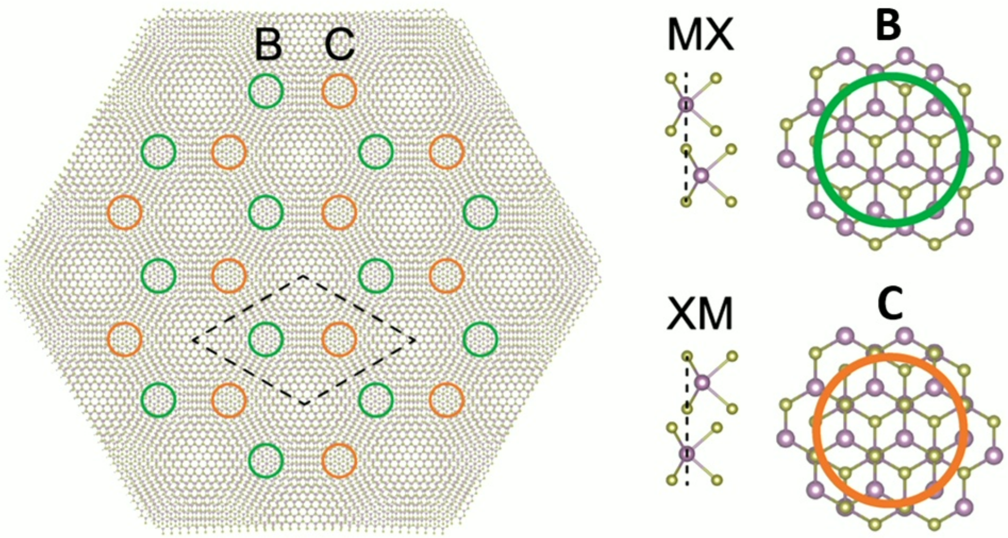
We show that moiré bands of twisted homobilayers can be topologically nontrivial, and illustrate the tendency by studying valence band states in $\pm K$ valleys of twisted bilayer transition metal dichalcogenides, in particular, bilayer $MoTe_2$. Because of the large spin-orbit splitting at the monolayer valence band maxima, the low energy valence states of the twisted bilayer $MoTe_2$ at the $+K$ $(-K)$ valley can be described using a two-band model with a layer-pseudospin magnetic field $\mathbf{\Delta}(\boldsymbol{r})$ that has the moiré period. We show that $\mathbf{\Delta}(\boldsymbol{r})$ has a topologically nontrivial skyrmion lattice texture in real space, and that the topmost moiré valence bands provide a realization of the Kane-Mele quantum spin-Hall model, i.e., the two-dimensional time-reversal-invariant topological insulator. Because the bands narrow at small twist angles, a rich set of broken symmetry insulating states can occur at integer numbers of electrons per moiré cell.

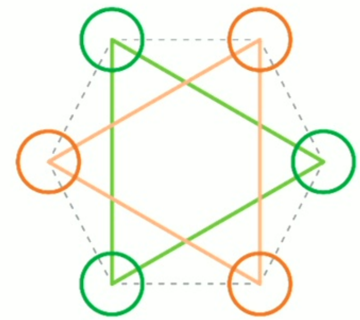
DOI: 10.1103/PhysRevLett.122.086402



Yu, Chen & WY, Natl. Sci. Rev. 7, 12 (2019).
Zhai & WY, Phys. Rev. Mat. 4, 094002 (2020).
H. Li, U. Kumar, K. Sun, S. Z. Lin,. *Phys. Rev. Res*. **3**, L032070 (2021).
T. Devakul, V. Crépel, Y. Zhang, L. Fu, *Nat. Commun.* **12**, 1–9 (2021);
Valentin Crépel and Liang Fu, Phys. Rev. B **107**, 201109 (2023)

Twisted bilayer TMD in rhombohedral stacking





Honeycomb

Flat bands: M. H. Naik, M. Jain, *Phys. Rev. Lett.* **121**, 266401 (2018).

Z. Zhang et a, *Nature Physics* **16**, 1093–1096 (2020).

Moiré induced Berry phase effect

Electron's equations of motion

$$\dot{R} = \frac{\partial E}{\partial k} - \dot{k} \times \Omega^k$$

$$\dot{k} = \frac{\partial E}{\partial R} - \dot{R} \times \Omega^R$$

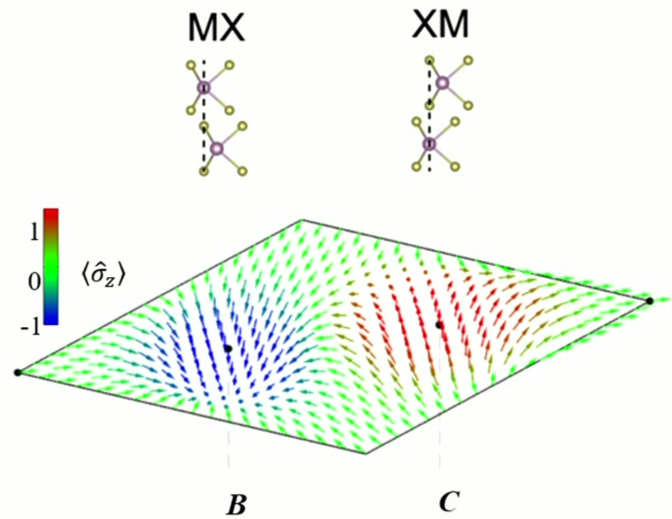
$$\mathbf{\Omega}^R \equiv i \langle \frac{\partial u}{\partial \mathbf{R}} | \times | \frac{\partial u}{\partial \mathbf{R}} \rangle$$

Berry curvature from real space texture: emergent magnetic field

Yu, Chen & WY, Natl. Sci. Rev. 7, 12 (2019).

Zhai & WY, Phys. Rev. Mat. 4, 094002 (2020).

N. Morales-Durán, N. Wei, A. H. MacDonald arXiv:2308.03143 (2023)



Layer pseudospin Skyrmion

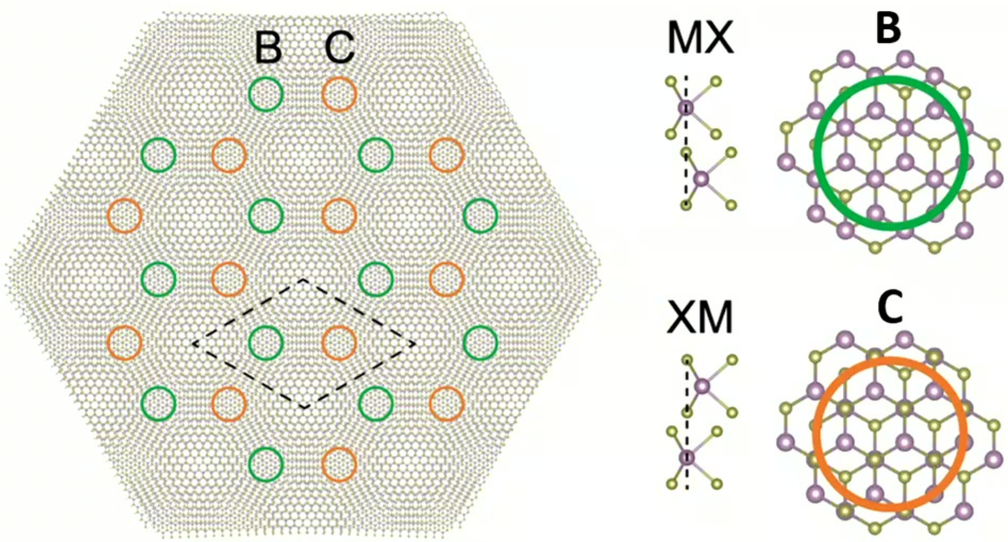
Moire Atomic texture:

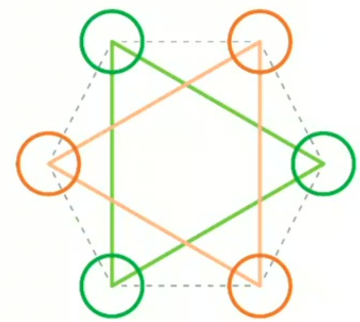
Layer-pseudospin texture $|u(\mathbf{R})\rangle$

Wu, MacDonald et al., PRL (2019)

Yu, Chen & WY, Natl. Sci. Rev. 7, 12 (2019).

Twisted bilayer TMD in rhombohedral stacking





Honeycomb

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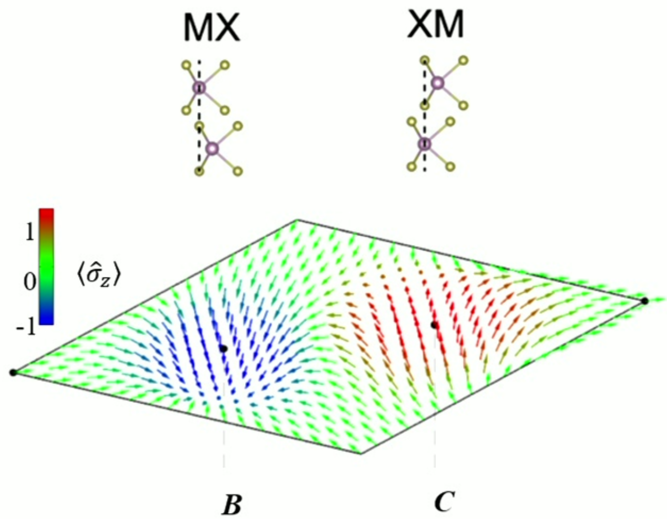
Zhai & WY, Phys. Rev. Mat. 4, 094002 (2020).

N. Morales-Durán, N. Wei, A. H. MacDonald arXiv:2308.03143 (2023)



Layer pseudospin Skyrmion

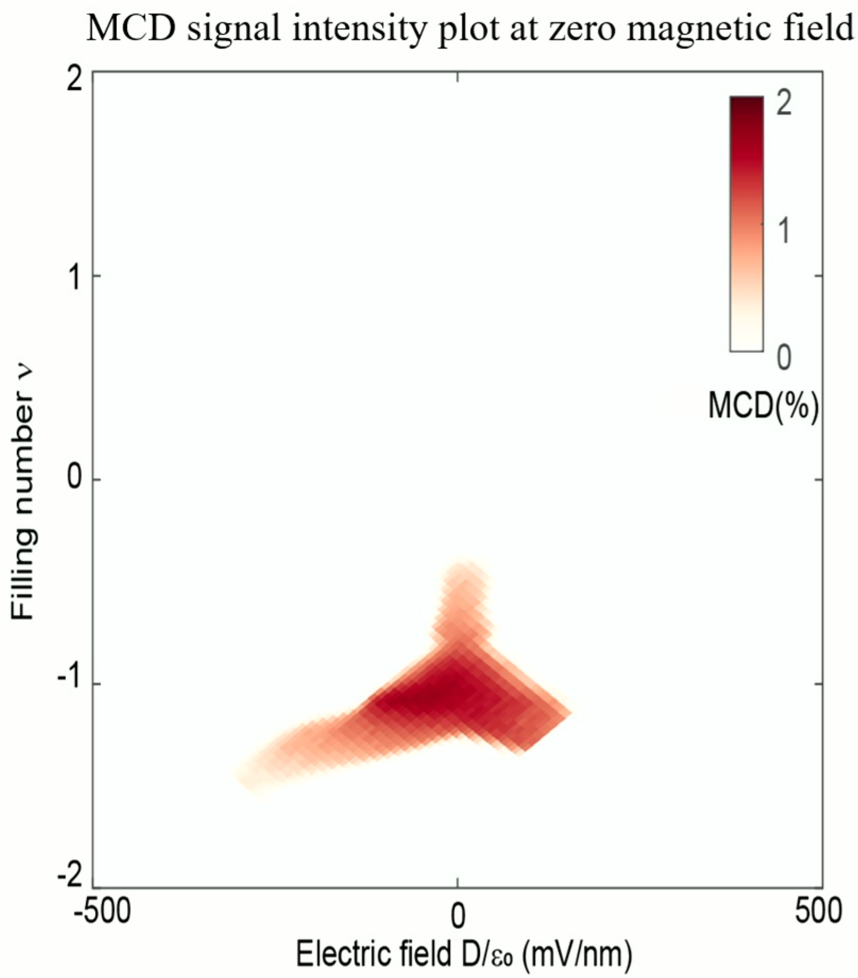
Moire Atomic texture:

Layer-pseudospin texture $|u(\mathbf{R})\rangle$

Wu, MacDonald et al., PRL (2019)

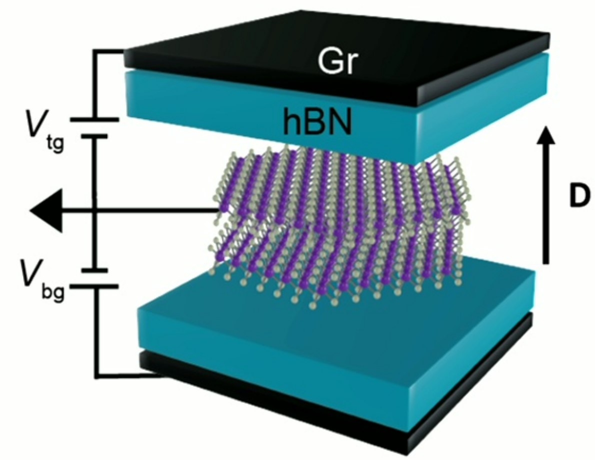
Yu, Chen & WY, Natl. Sci. Rev. 7, 12 (2019).

MCD measurements of 3.9-degree twisted $MoTe_2$ bilayer



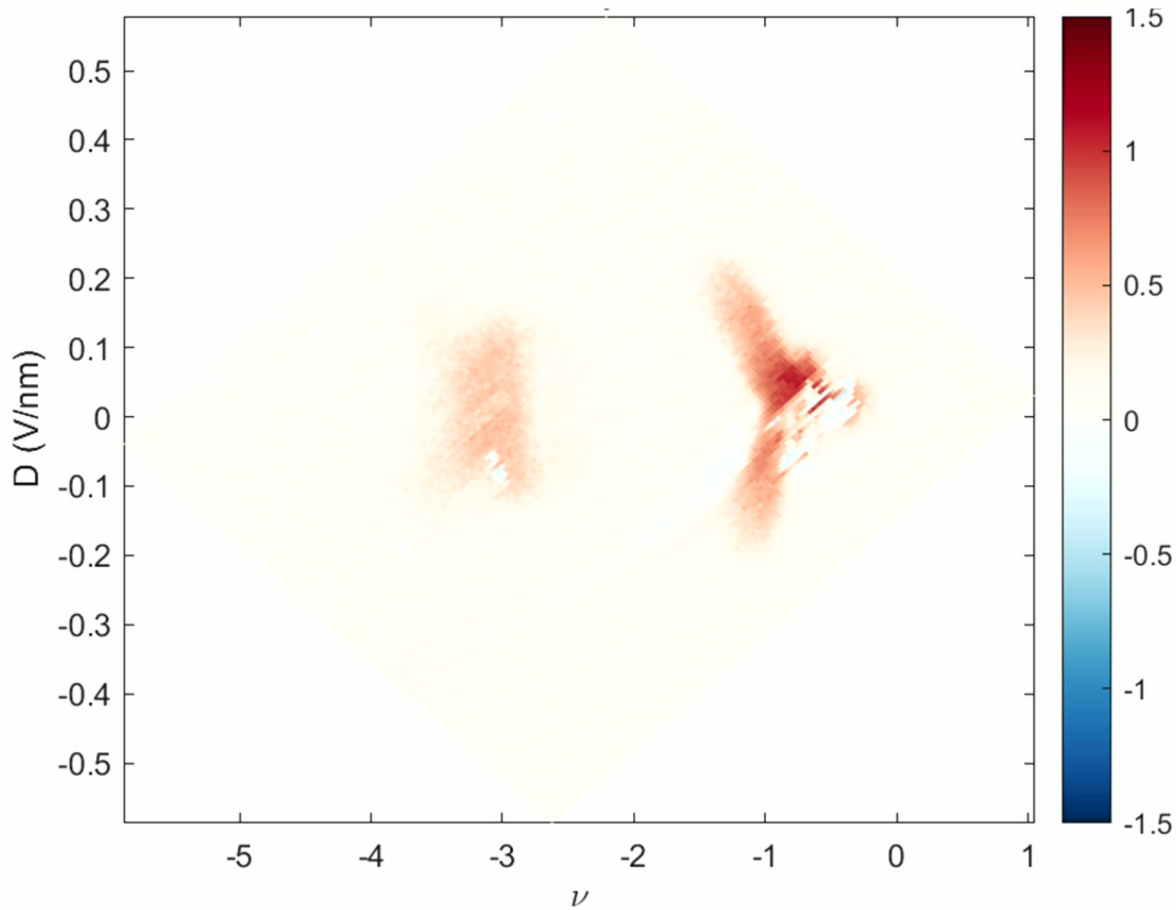
Magnetic circular dichroism (MCD): optical absorption difference between left and right circular polarized light ----> measurement of Hall conductivity at optical frequency

Filling number ***v***:
number of
carriers/moiré unit cell



Ferromagnetism in remote moire Chern band

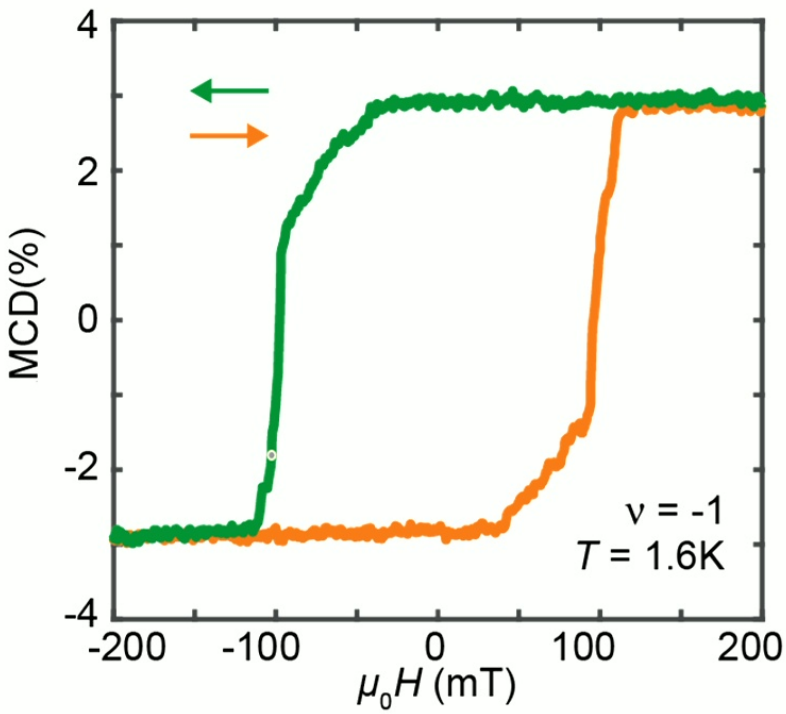
Magnetic circular dichroism of a **2.7** degree twisted at B=0 (T=1.6K)

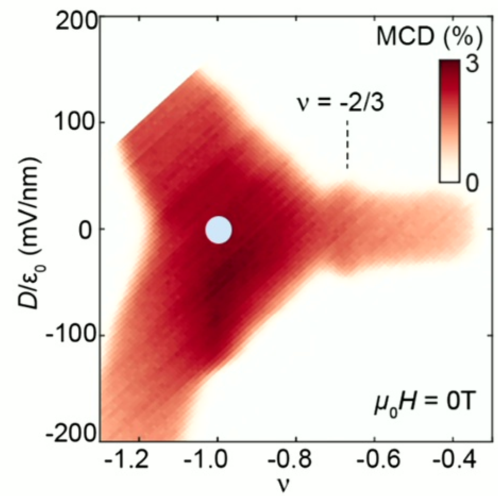


17

Observation of interaction induced ferromagnetic state at ν=-1

ν=-1, D=0 V/nm, T=1.6K

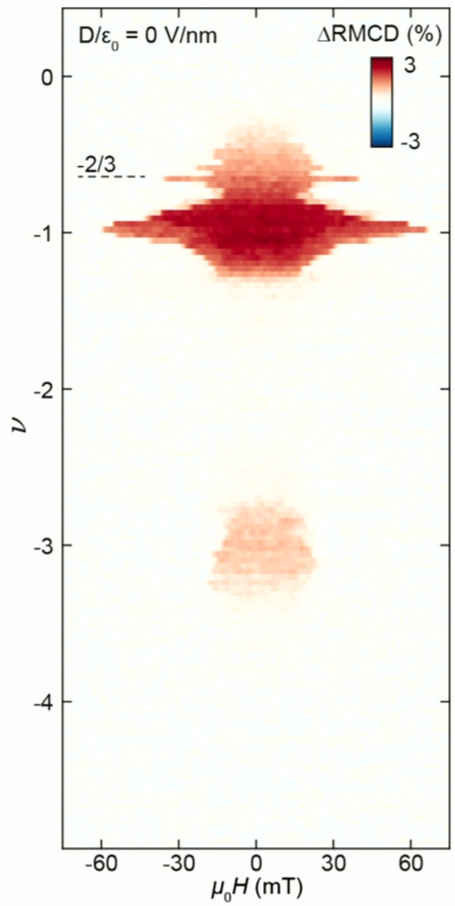




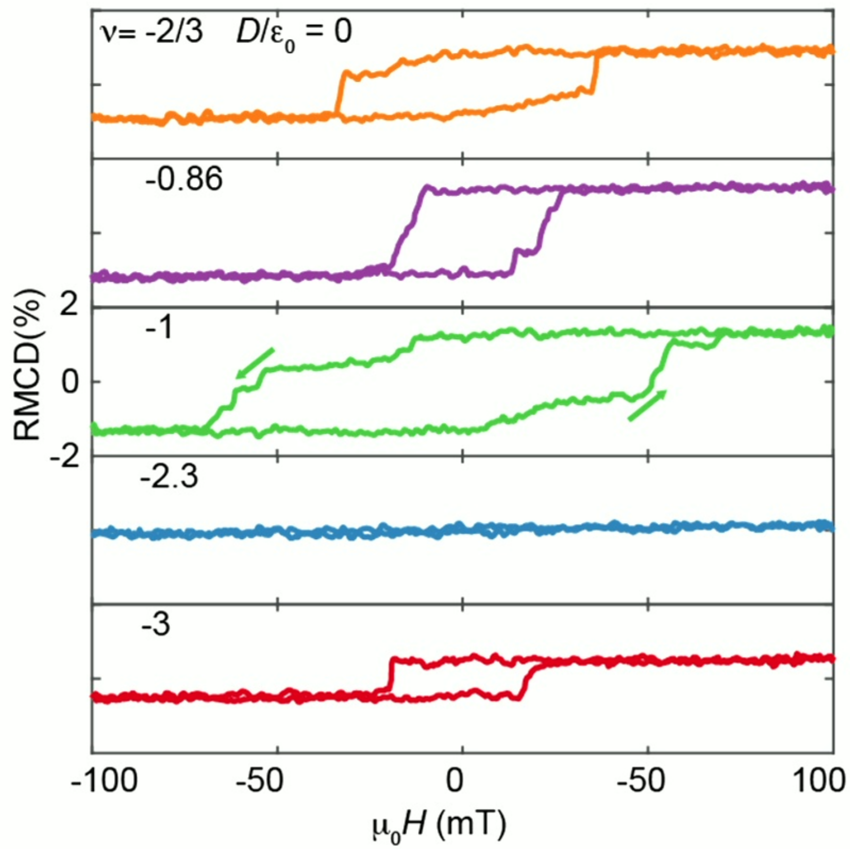
16

Ferromagnetic phase diagram of a 2.7-degree twisted MoTe2 bilayer

Δ(MCD)



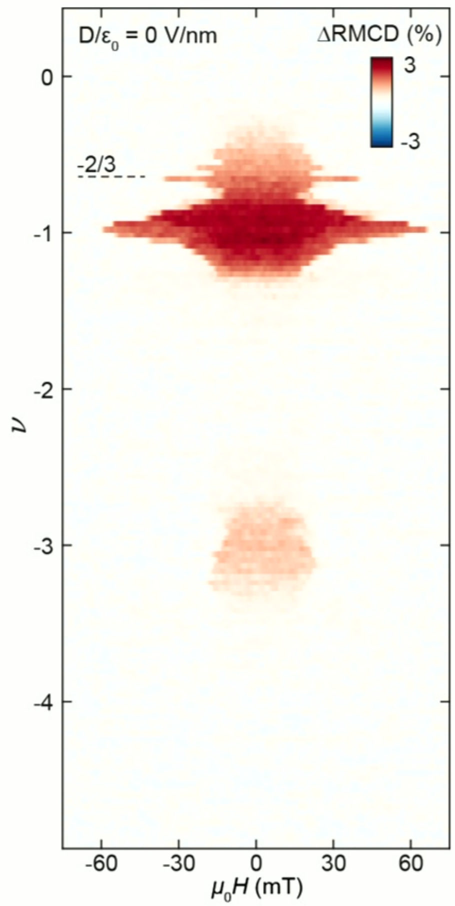
MCD vs B field



18

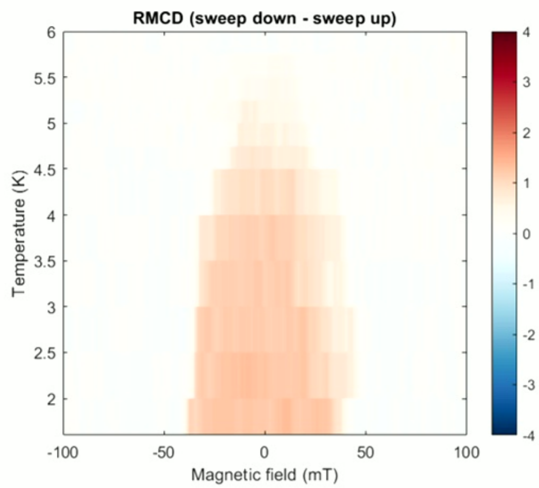
Ferromagnetic phase diagram of a 2.7-degree twisted MoTe2 bilayer

Δ(MCD)

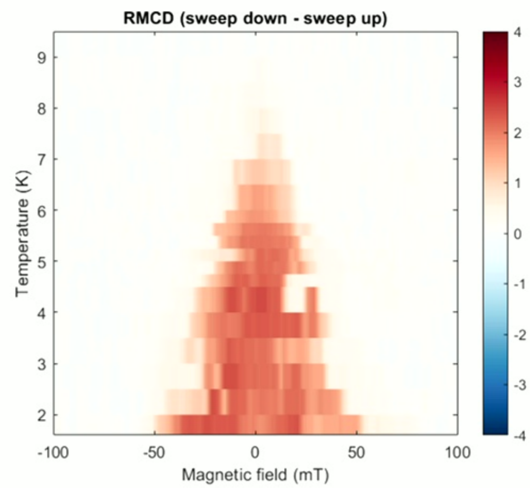


Temperature dependent Δ(MCD)

V=-3 Tc ~ 5.5K



V=-1 Tc ~ 9K



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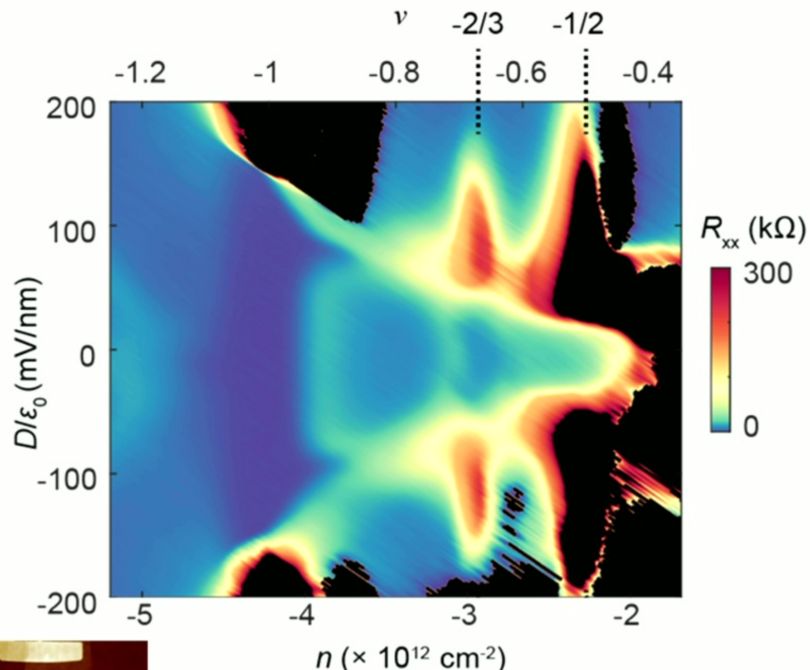
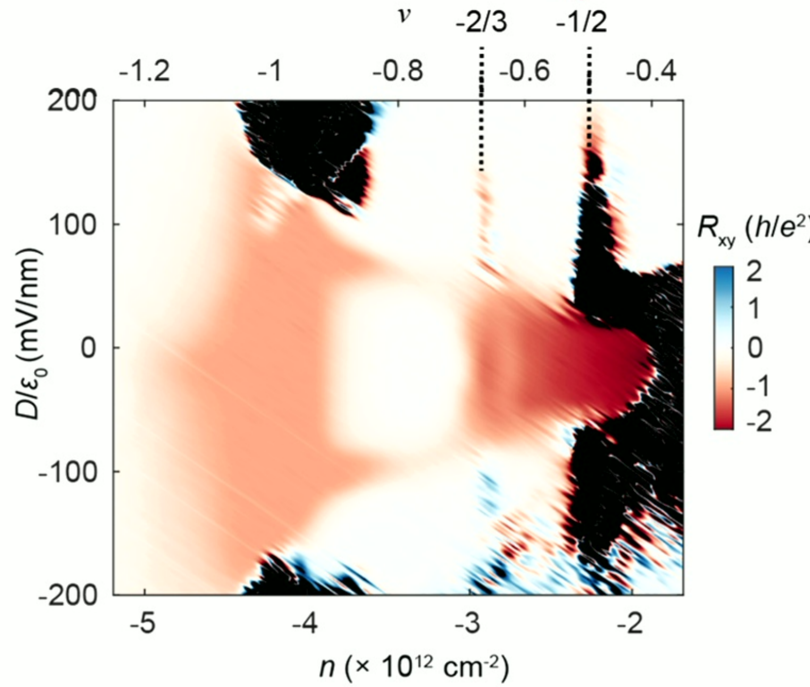
Transport measurements of zero-field fractiona Chern Insulator

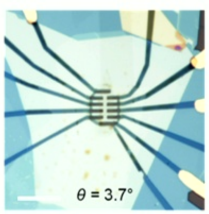
Device 3.7° twist, T=100 mK

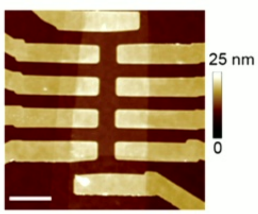
Longitudinal Resistance (R_{xx})



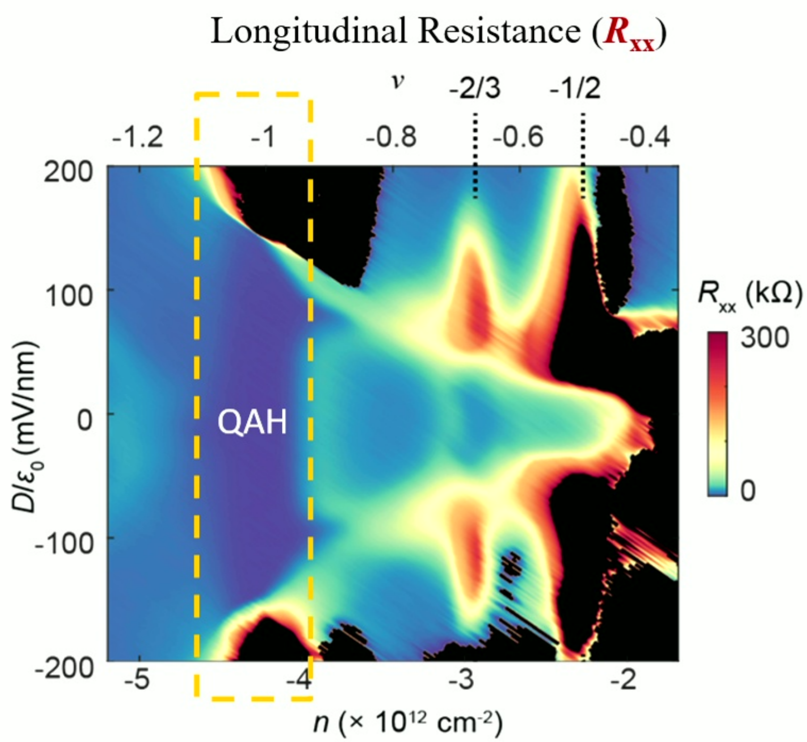
Hall Resistance (R_{xy})

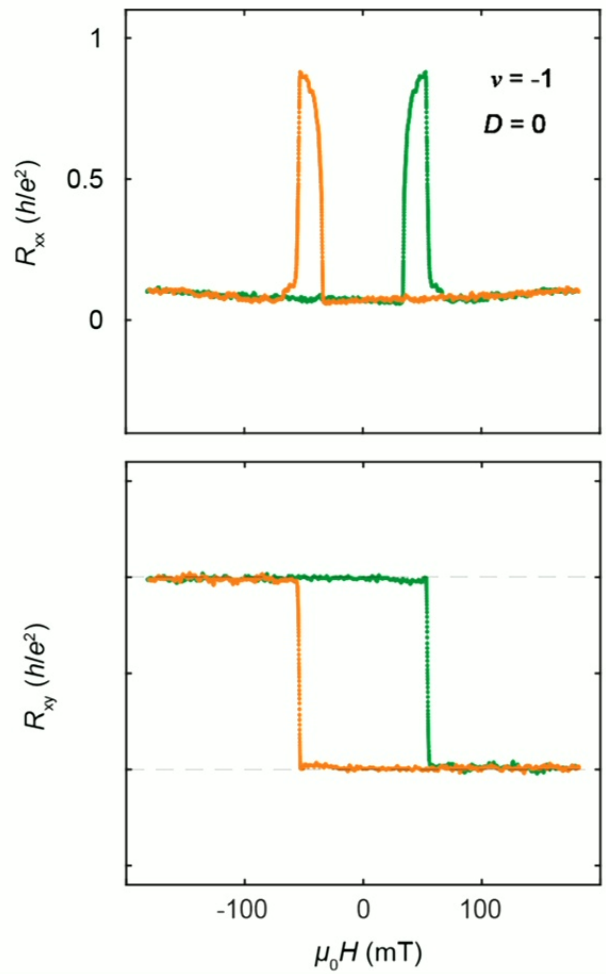






Quantized anomalous Hall effect at ν=-1





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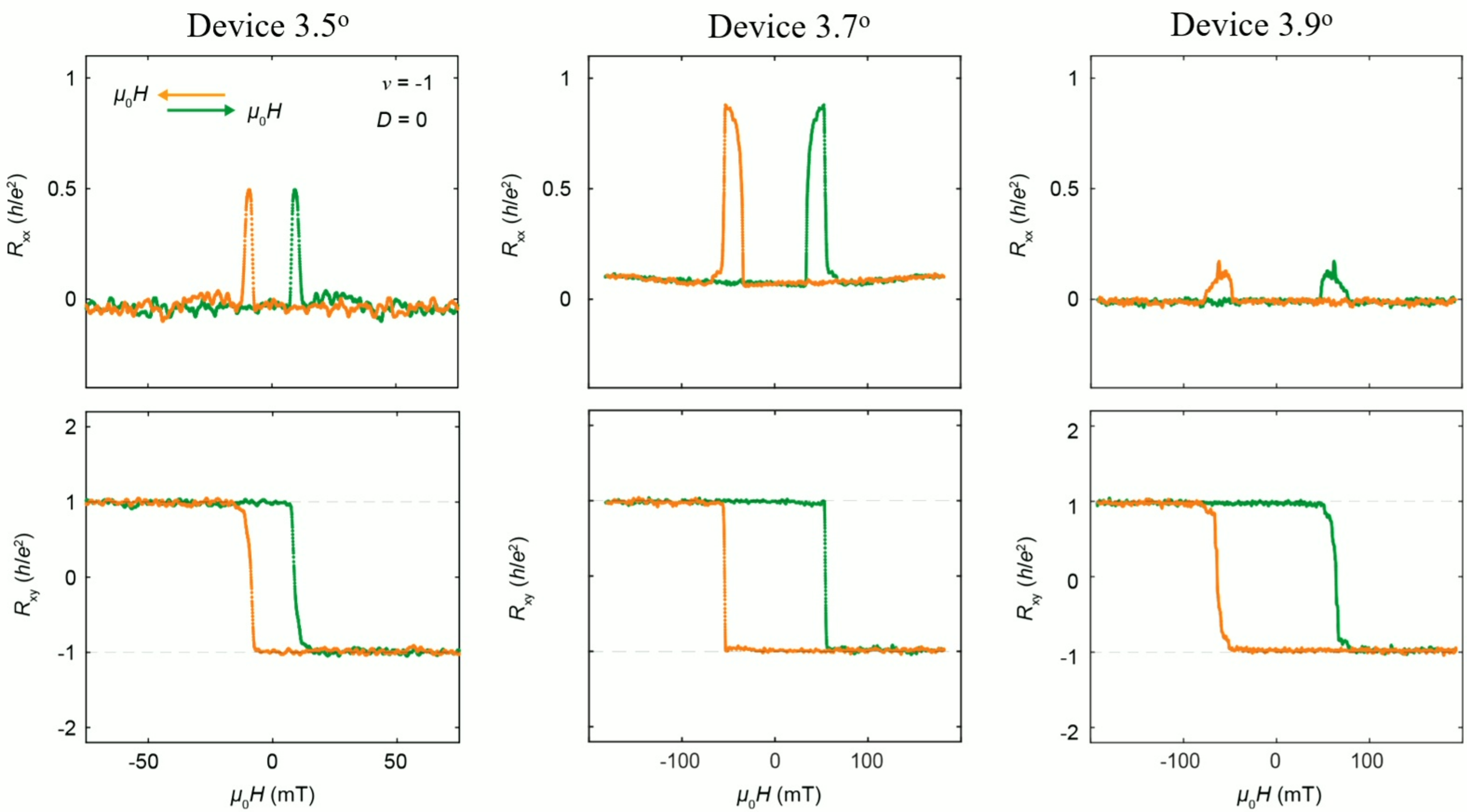
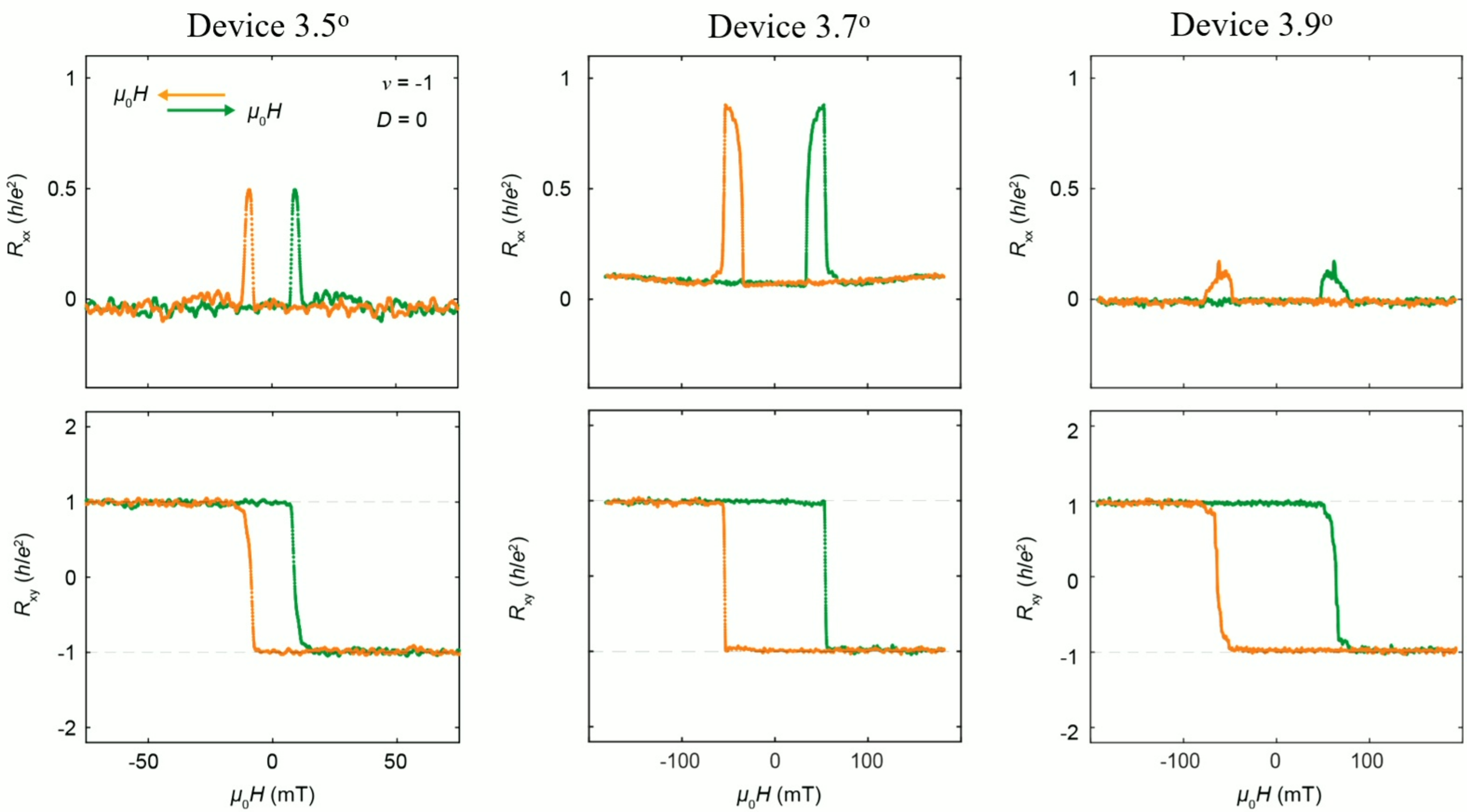
Reproducible quantized anomalous Hall effect in a broad range of twist angles



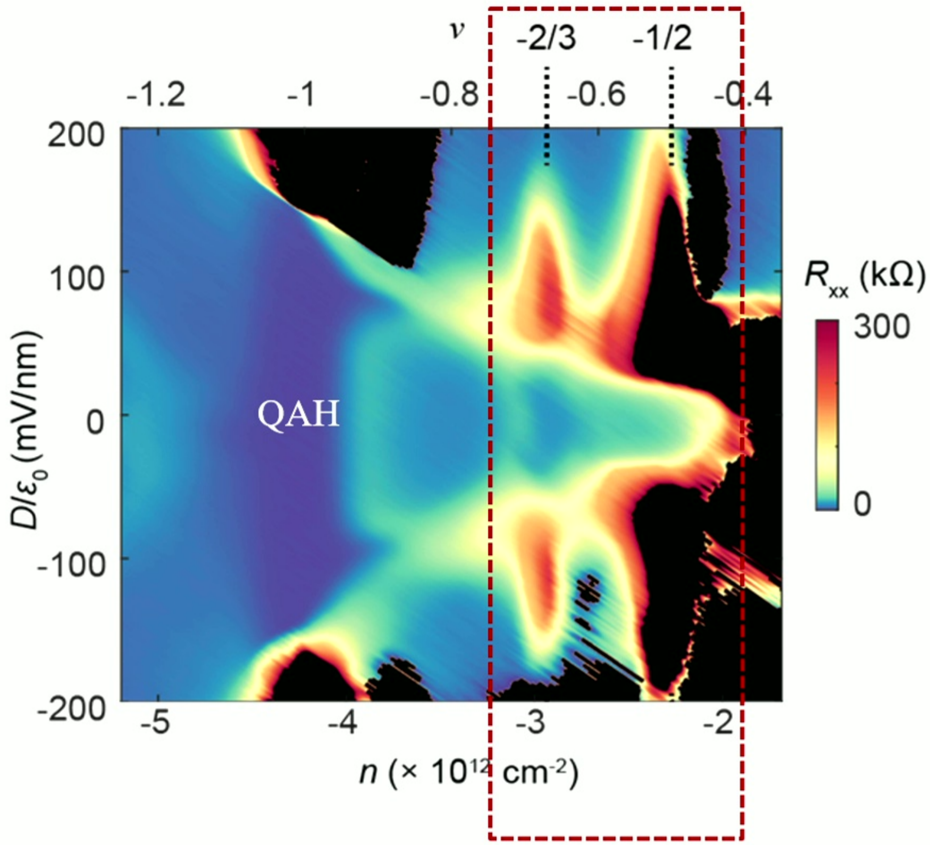
Reproducible quantized anomalous Hall effect in a broad range of twist angles

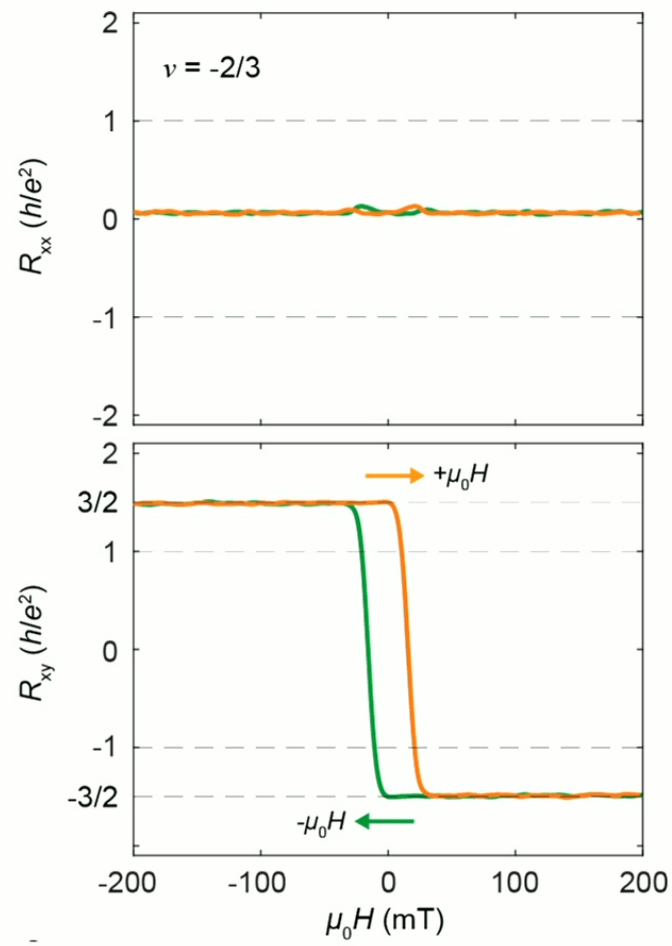


Fractional quantum anomalous Hall effect at fractional fillings

Device 3.7° twist

Longitude resistance R_{xx}





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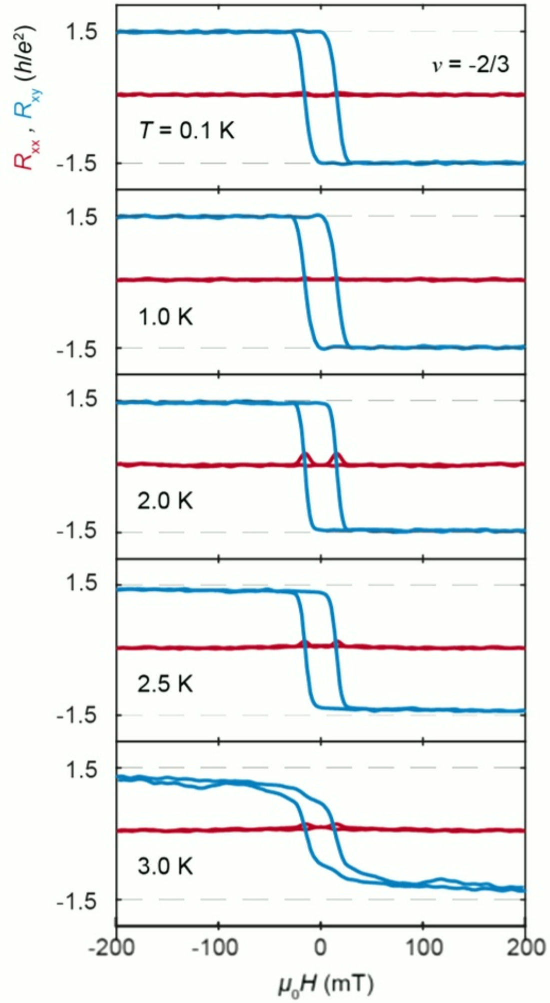
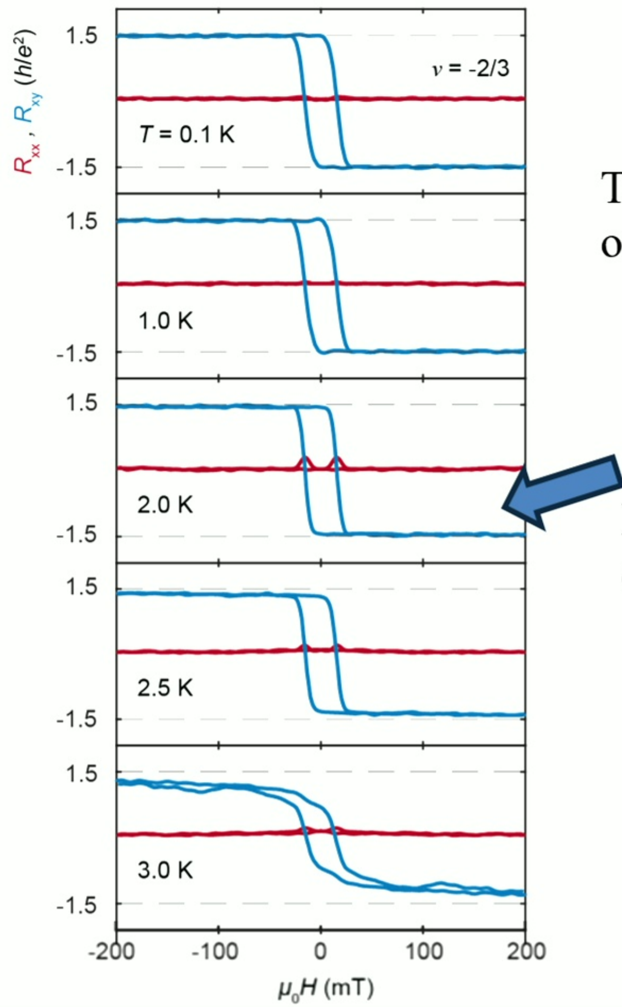
High temperature fractional quantum anomalous Hall effect



Temperature dependence of -2/3 FCI state

High temperature fractional quantum anomalous Hall effect

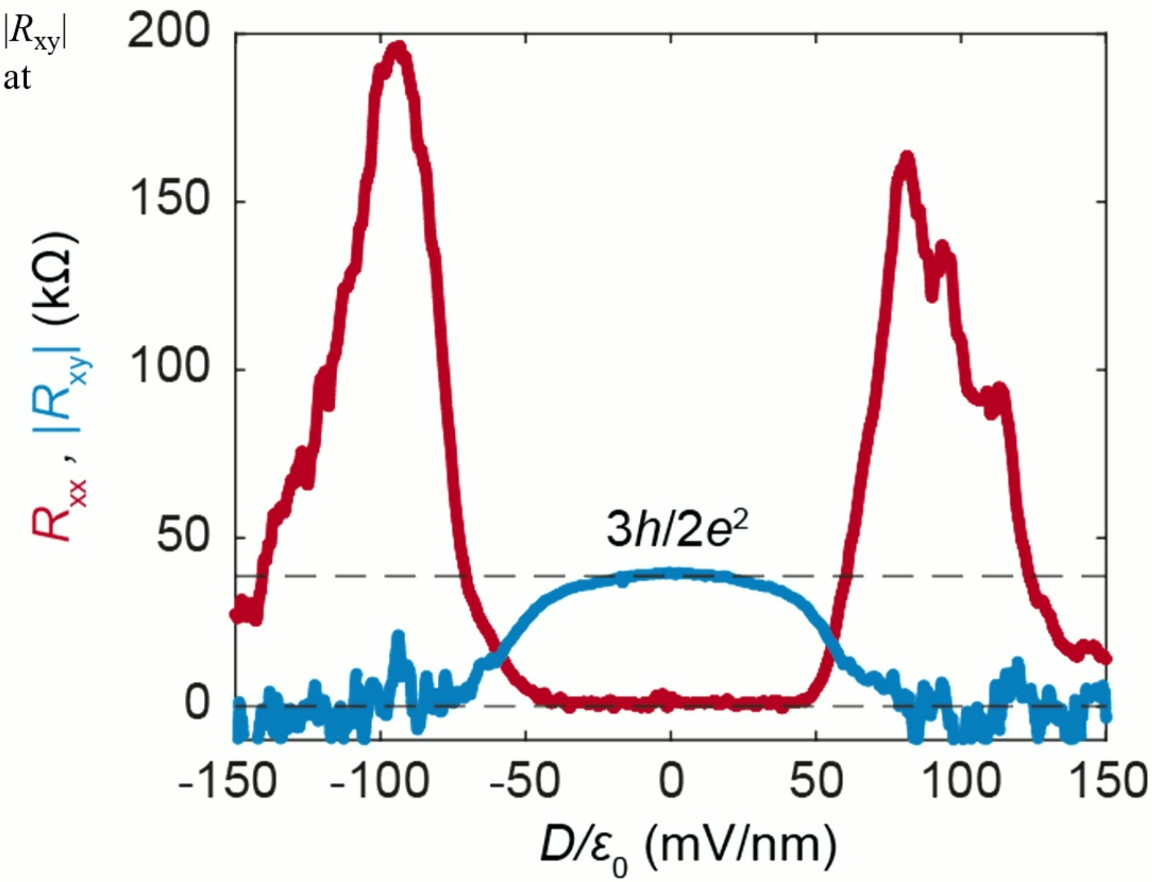


Temperature dependence of -2/3 FCI state

R_{xy} is nearly quantized even at 2K!

Electric field tuning -2/3 FCI state

T=100 mK
antisymmetrized $|R_{xy}|$
symmetrized R_{xx} at
$|\mu_o H| = 50$ mT



Pressing questions

- Intrinsic property of FCI - Bulk-edge correspondence (insulating in the bulk but conducting at edge).
- Moiré disorder effect
- Nature of the electrical field tuned topological phase transition

Local probe of bulk state conductivity

Measurement

Device

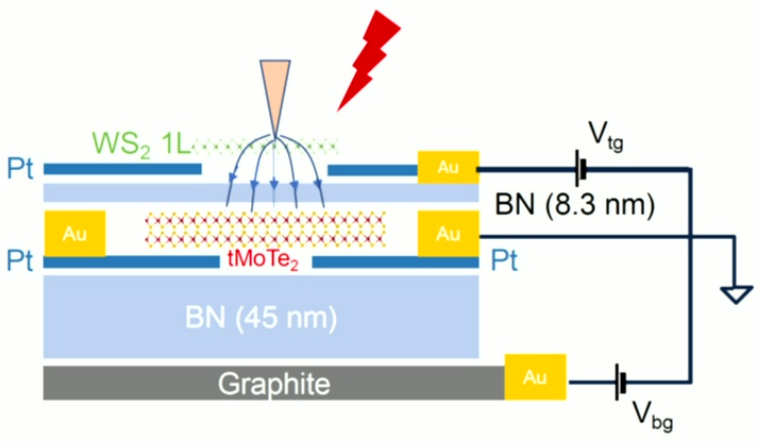
ZX Shen

Zhurun (Judy) Ji

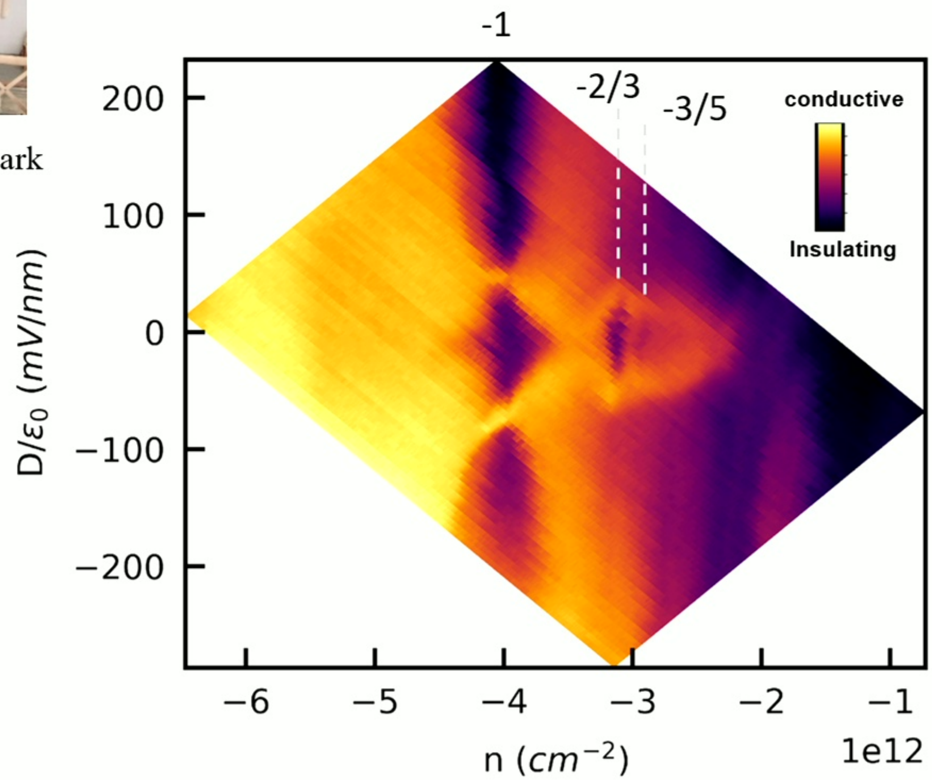
Mark Barber

Heonjoon Park

Microwave impedance microscopy (MIM)



MIM signal map (T=500 mK)



Local probe of bulk state conductivity

Measurement

Device

ZX Shen

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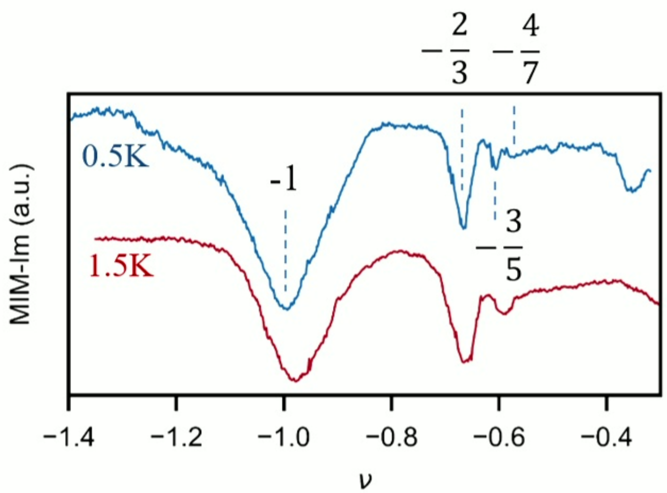
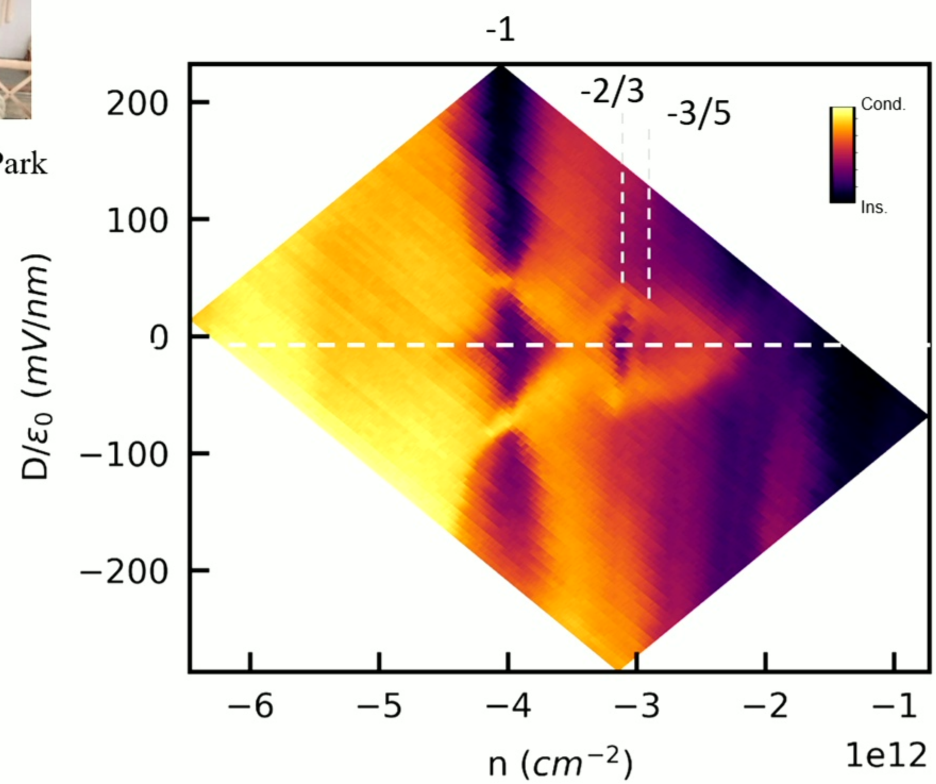
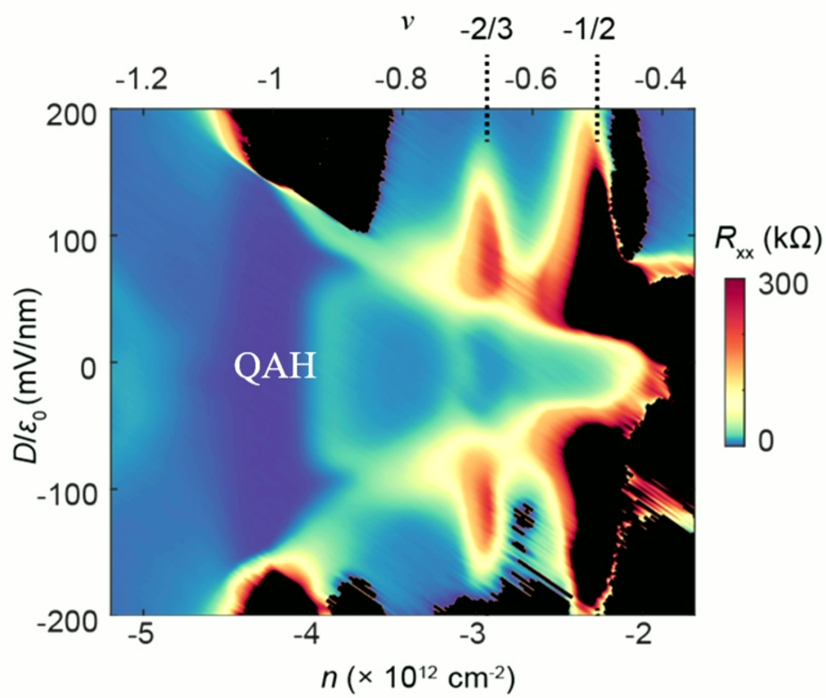


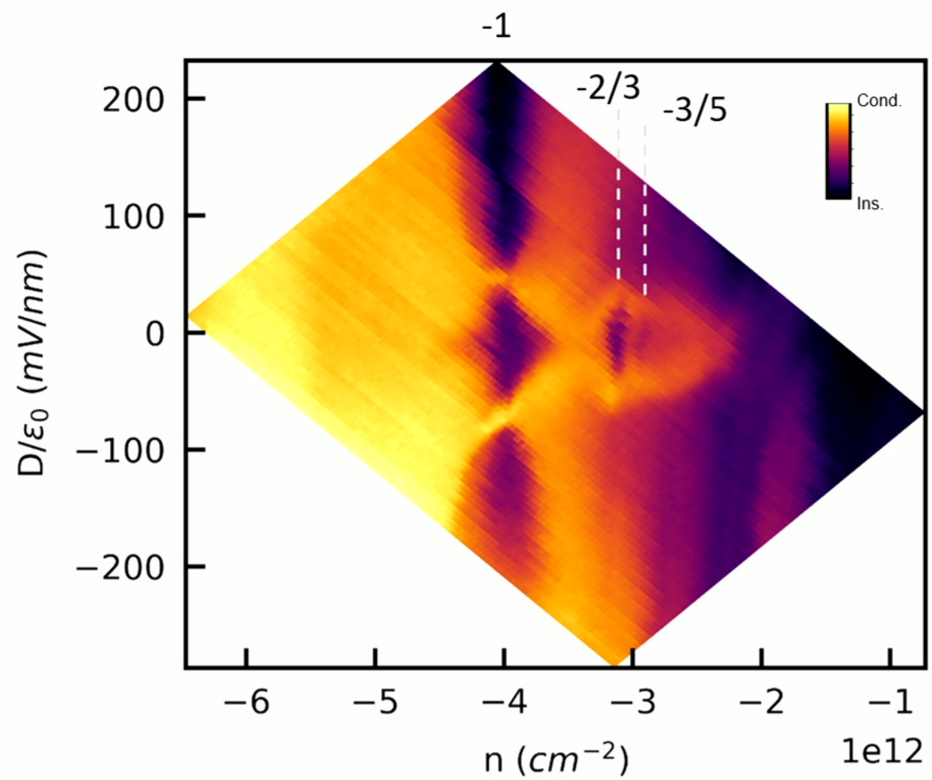
MIM signal linecut

MIM signal map (T=500 mK)



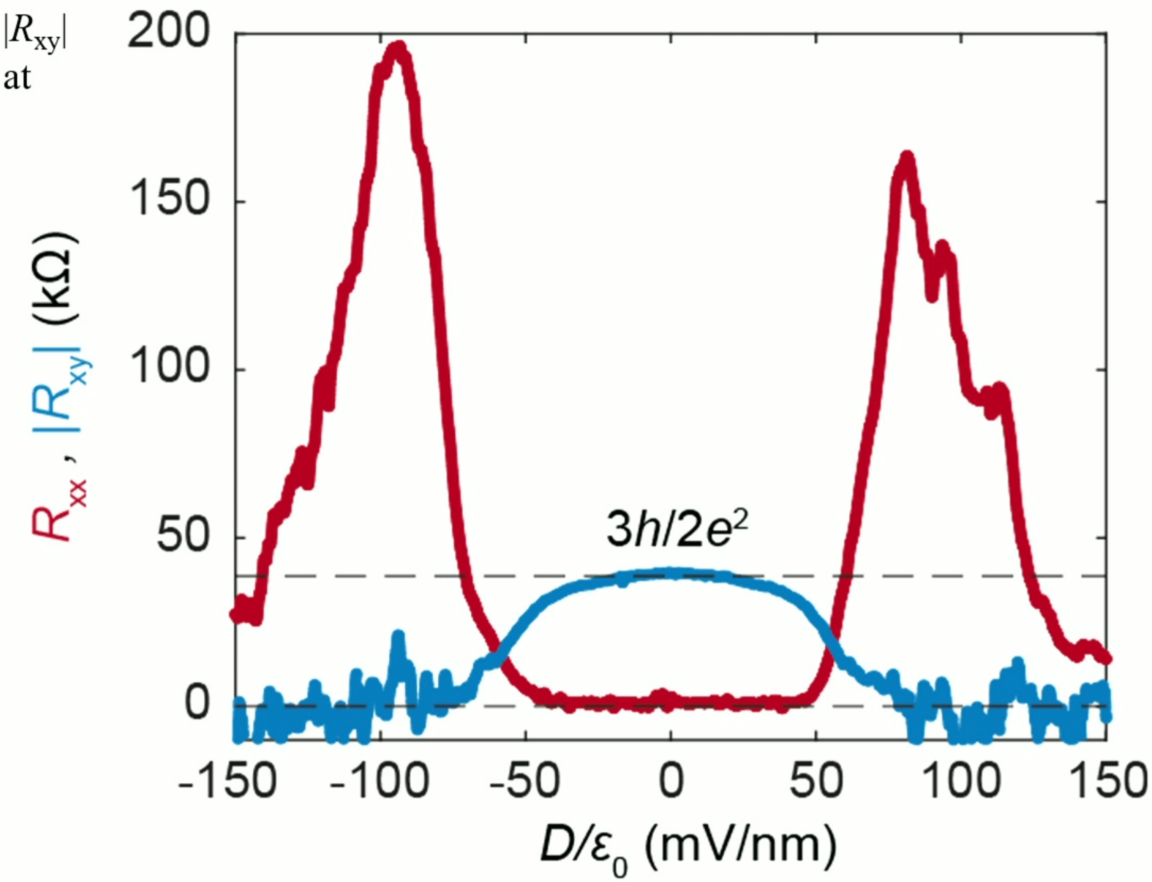
Comparison between MIM and transport results





Electric field tuning -2/3 FCI state

T=100 mK
antisymmetrized $|R_{xy}|$
symmetrized R_{xx} at
$|\mu_o H| = 50$ mT



Imaging quantum anomalous Hall edge conduction channel

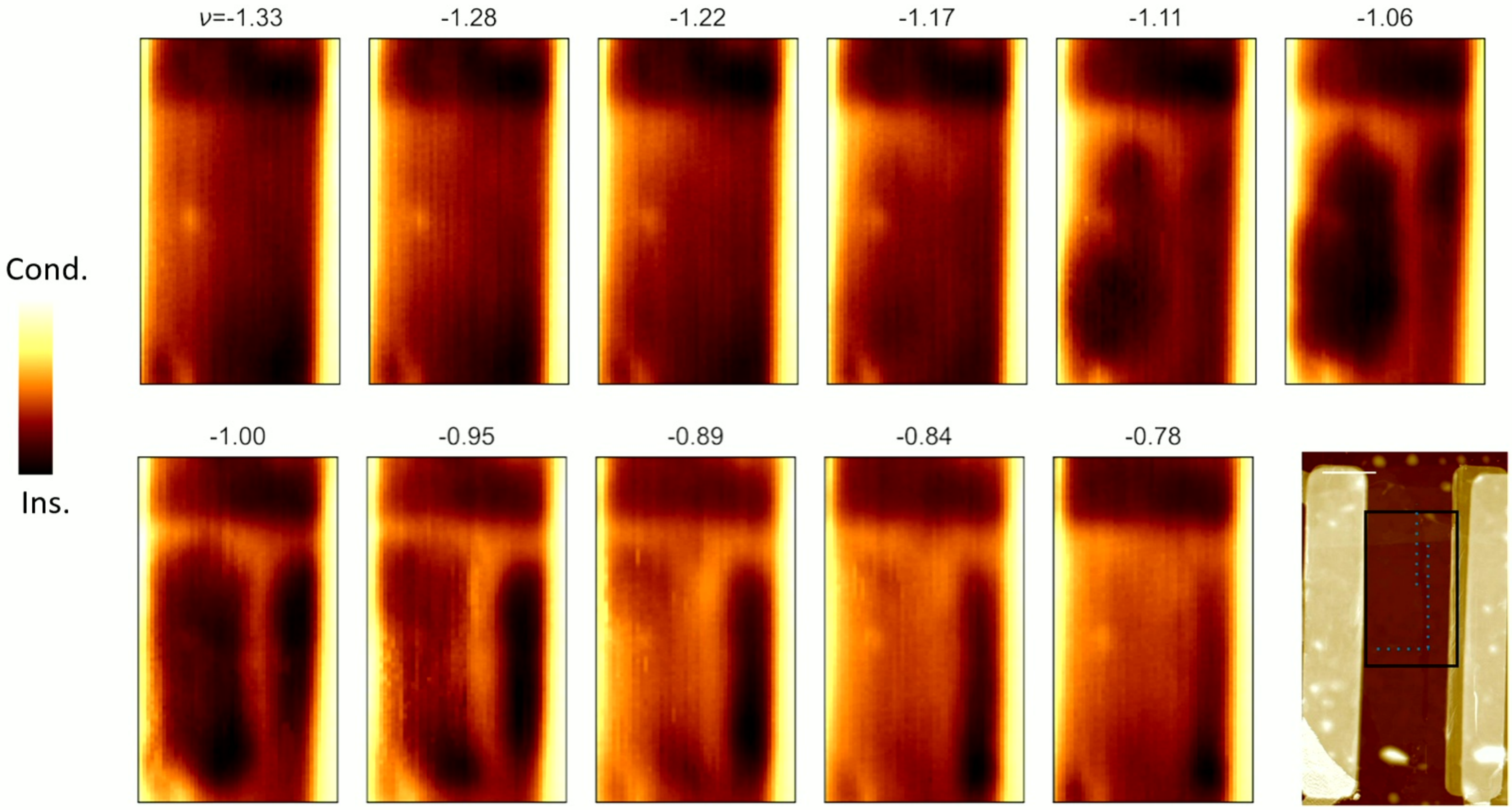
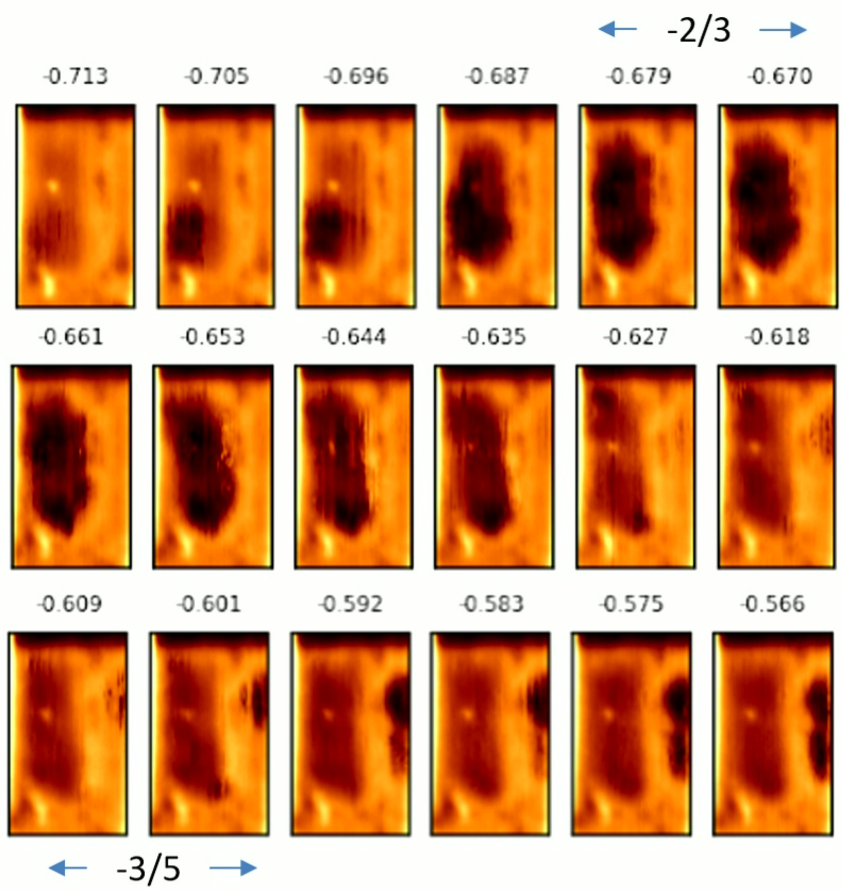
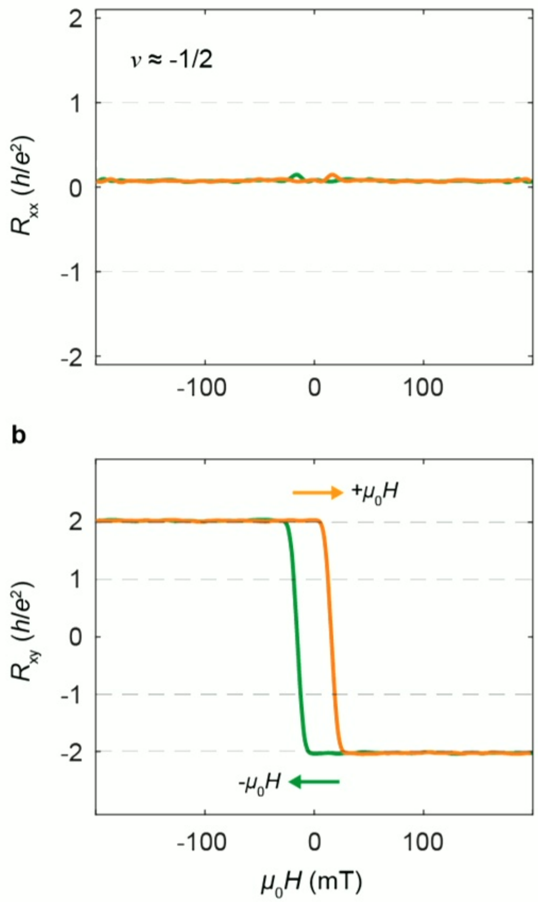
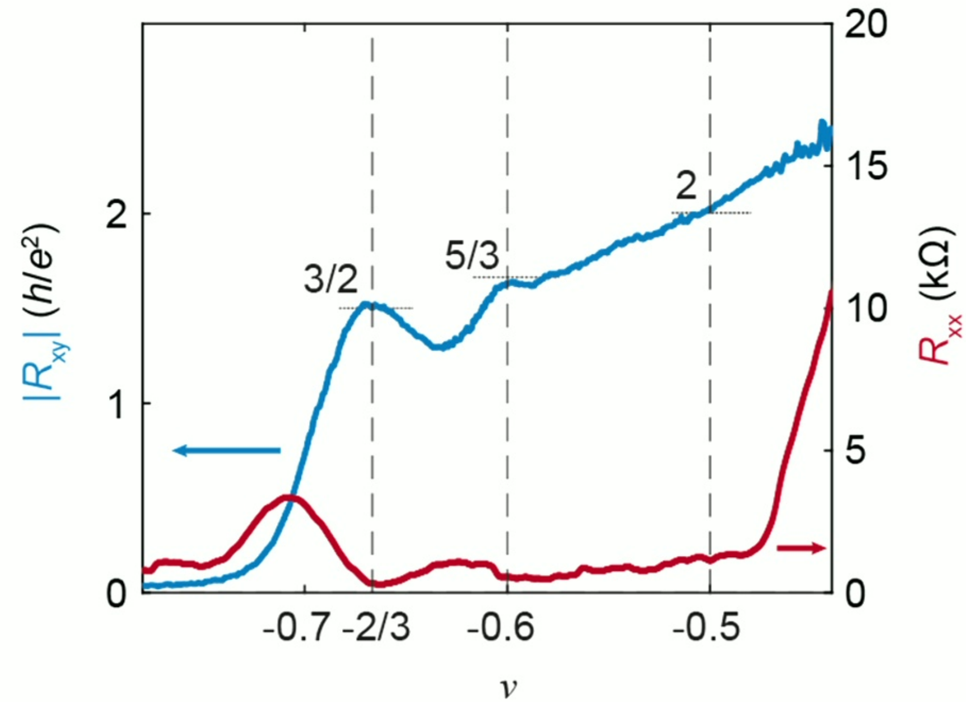


Image fractional quantum anomalous Hall edge conduction channel



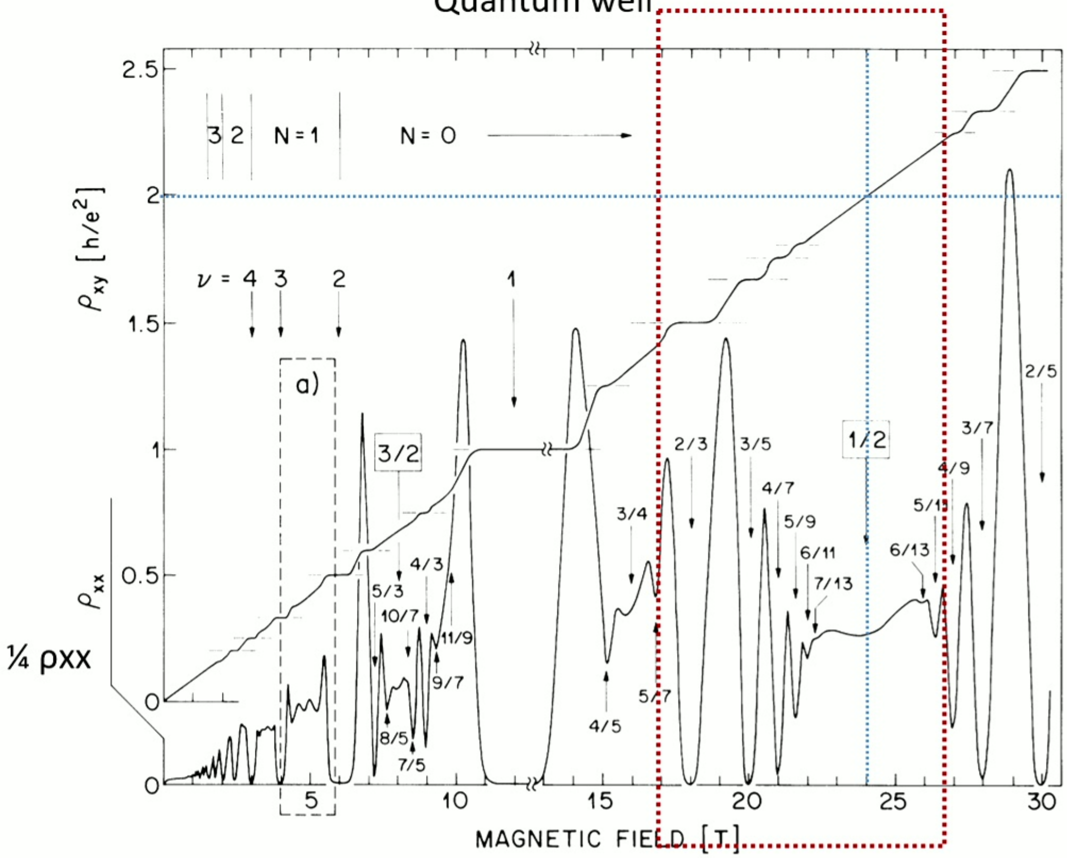
Anomalous Hall effect at half filling



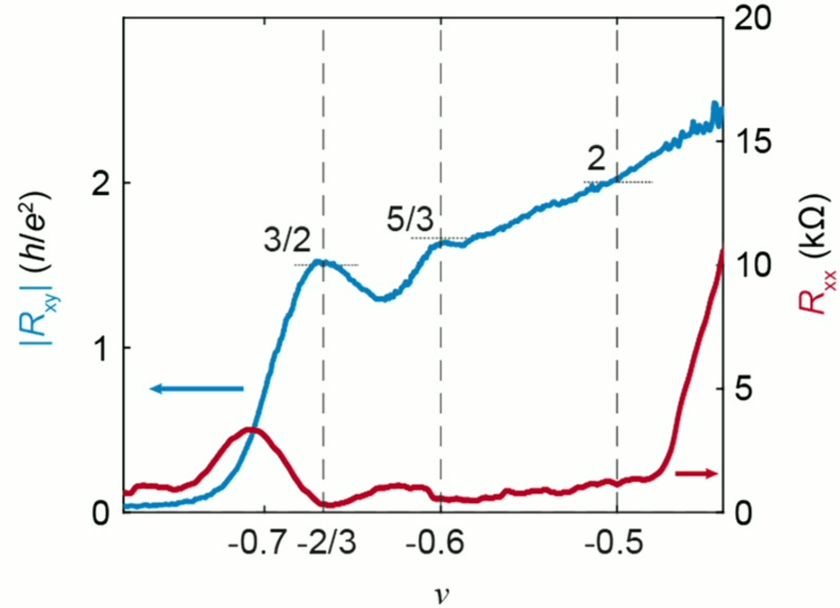


Comparison to ½ quantum Hall state in 2D electron gas

Quantum well



Twisted MoTe2 bilayer



Theory of zero-field composite fermi liquid in twisted $MoTe_2$

PHYSICAL REVIEW LETTERS **131,** 136501 (2023)

Editors' Suggestion | Featured in Physics

Zero-Field Composite Fermi Liquid in Twisted Semiconductor Bilayers

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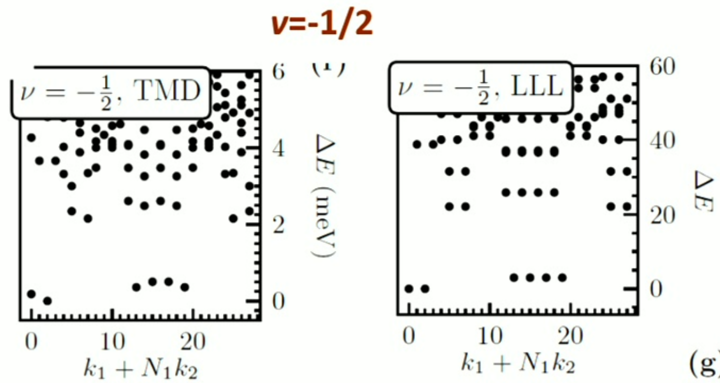
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 14 June 2023; accepted 19 July 2023; published 27 September 2023)



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PHYSICAL REVIEW LETTERS **131,** 136502 (2023)

Editors' Suggestion | Featured in Physics

Composite Fermi Liquid at Zero Magnetic Field in Twisted $MoTe_2$

Junkai Dong,[1,*] Jie Wang,[1,2,†] Patrick J. Ledwith,[1,‡] Ashvin Vishwanath,[1,§] and Daniel E. Parker[1,∥]

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Comparison between MIM and transport results