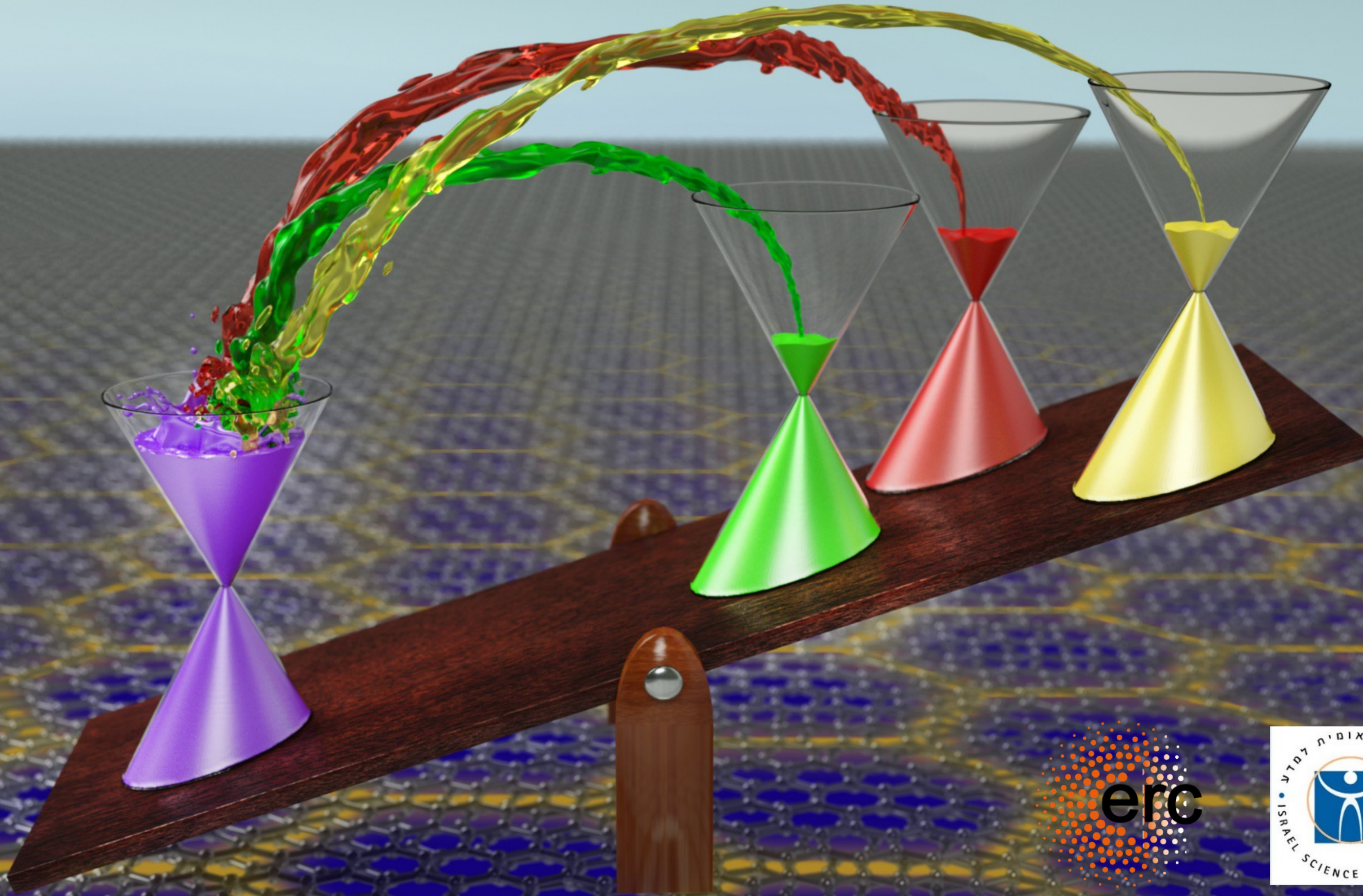
Visualizing the Quantum Phases of Magic Angle Graphene

Shahal Ilani

Department of Condensed Matter Physics
Weizmann Institute of Science

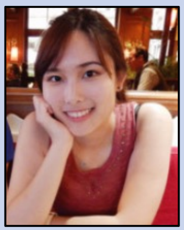


Acknowledgements

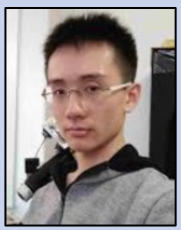
MIT

Pablo Jarillo-Herrero

Daniel Rodan-Legrain



Jane Park



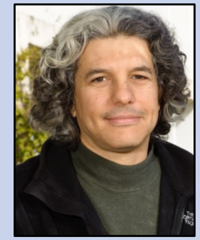
Yuan Cao

Weizmann
Experiments

Uri Zondiner

Asaf Rozen

Weizmann
Theory



Yuval Oreg

Erez Berg

Ady Stern

Raquel Queiroz

NIMS
h-BN

Takashi Taniguchi

Kenji Watanabe

Weizmann
ebeam

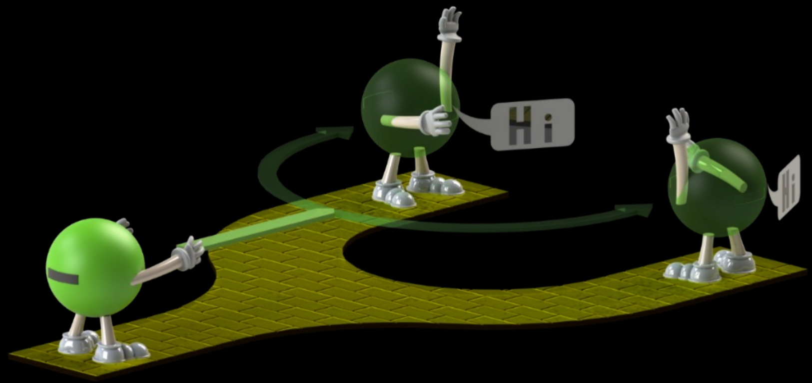
Diana Mahalu

Berlin

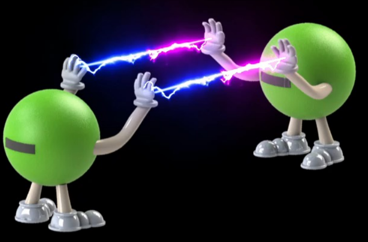
Felix von Oppen

Quantum mechanics and Interactions

Quantum mechanics



Interactions

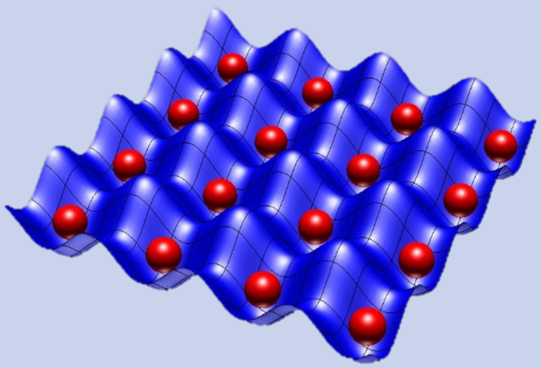


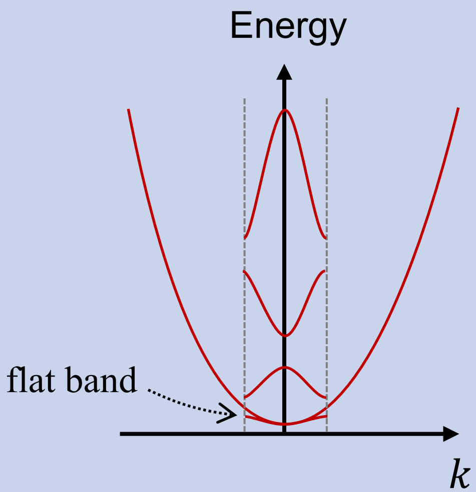
electrons are too light

To make quantum effects and interactions on equal footing
need flat energy bands

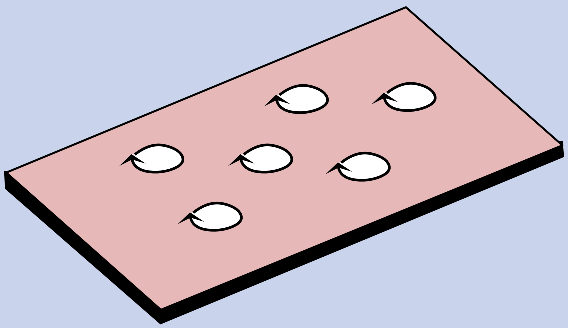
Two ways to make flat bands

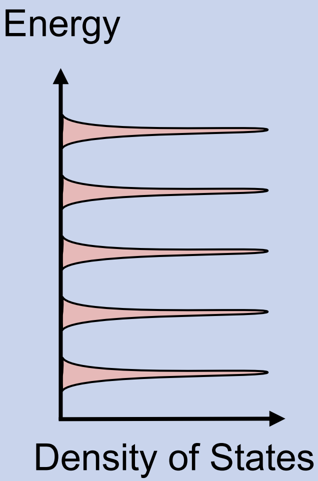
Electrons on a Lattice



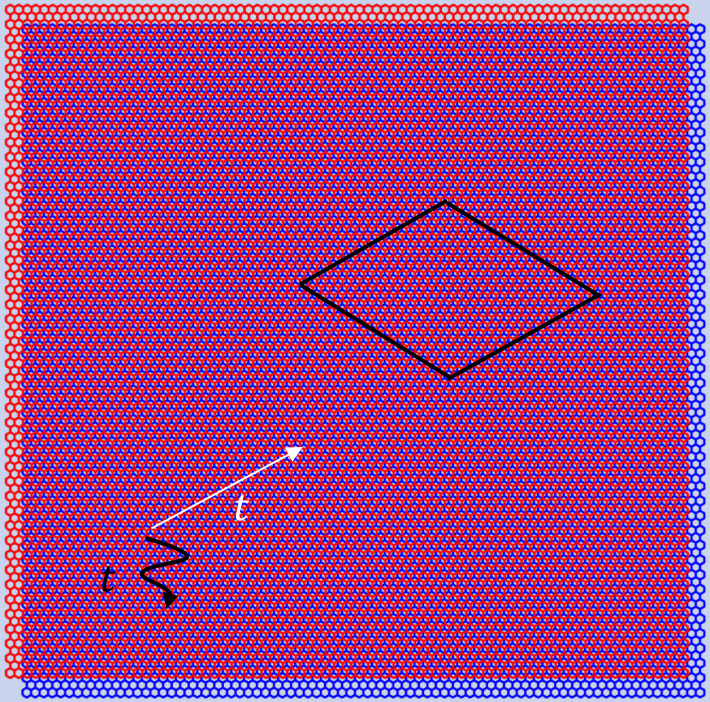


Landau levels





A new approach to flat bands: magic angle graphene

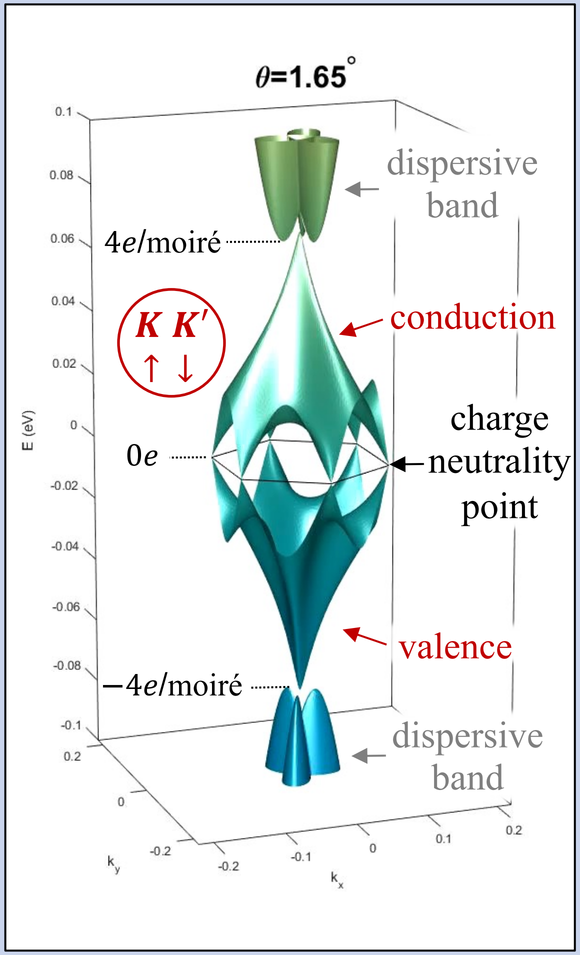


Rafi Bistritzer

Allan Macdonald

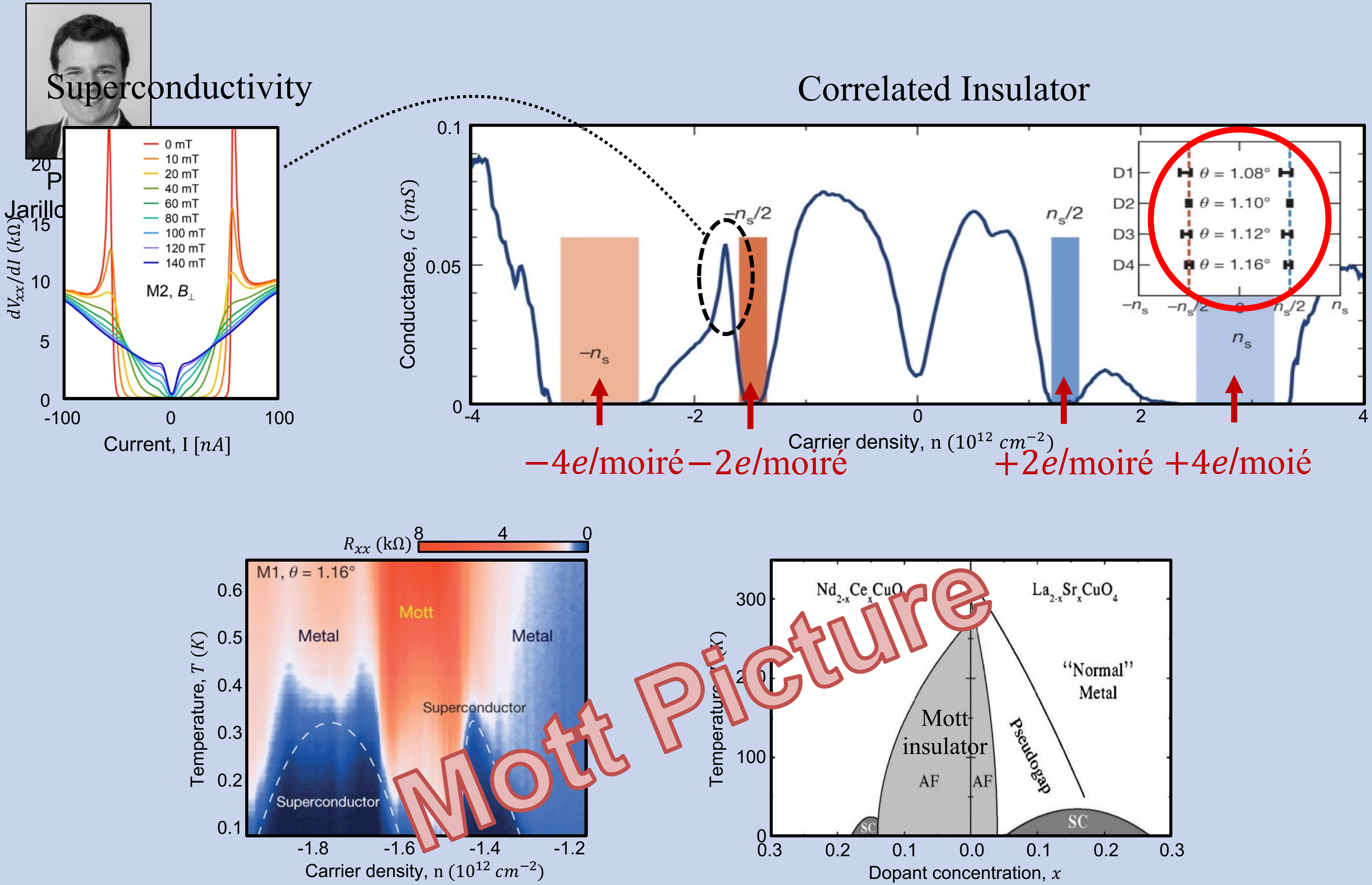
a magic twist angle

$\theta \approx 1.1°$



Bistritzer and Macdonald **PNAS** (2011), M. Suarez *et al.*, **PRB** (2010). G. Li, *et. al*, **Nature Physics** (2010)

Transport at the Magic Angle



Y. Cao *et. al*, **Nature** + **Nature** (2018)

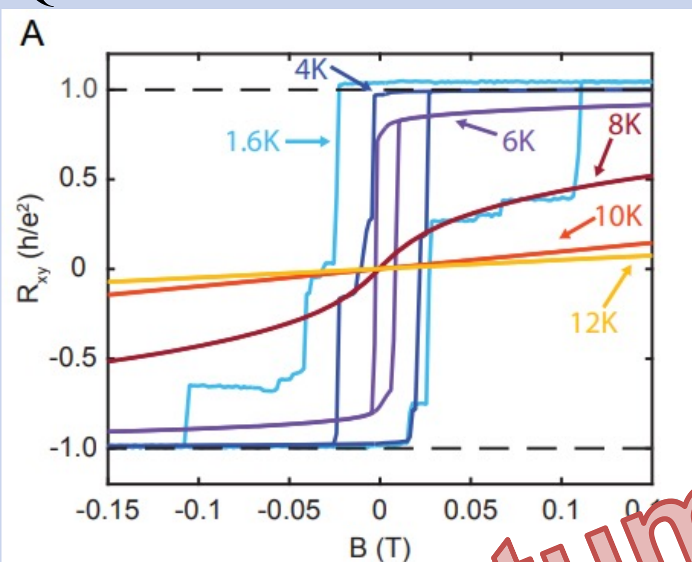
But also topological

Breaking a symmetry

inversion symmetry E

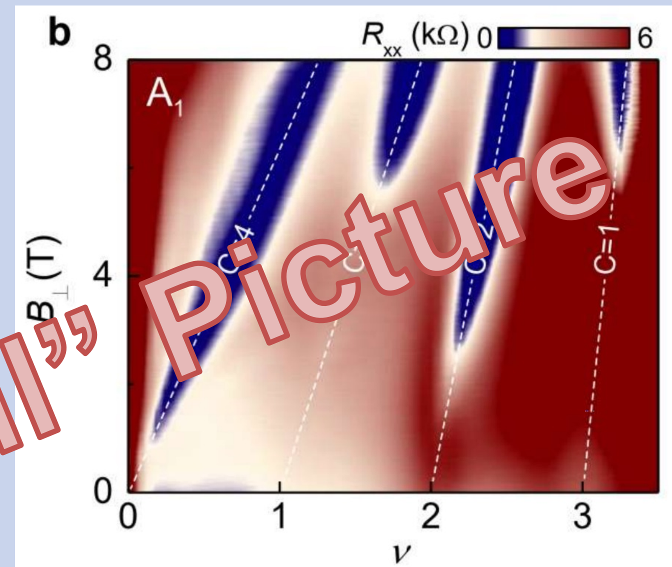
B time reversal symmetry

Quantum Anomalous Hall Effect



A.L Sharpe *et. al*, **Science** (2019)
M. Serlin *et. al*, **Science** (2020)

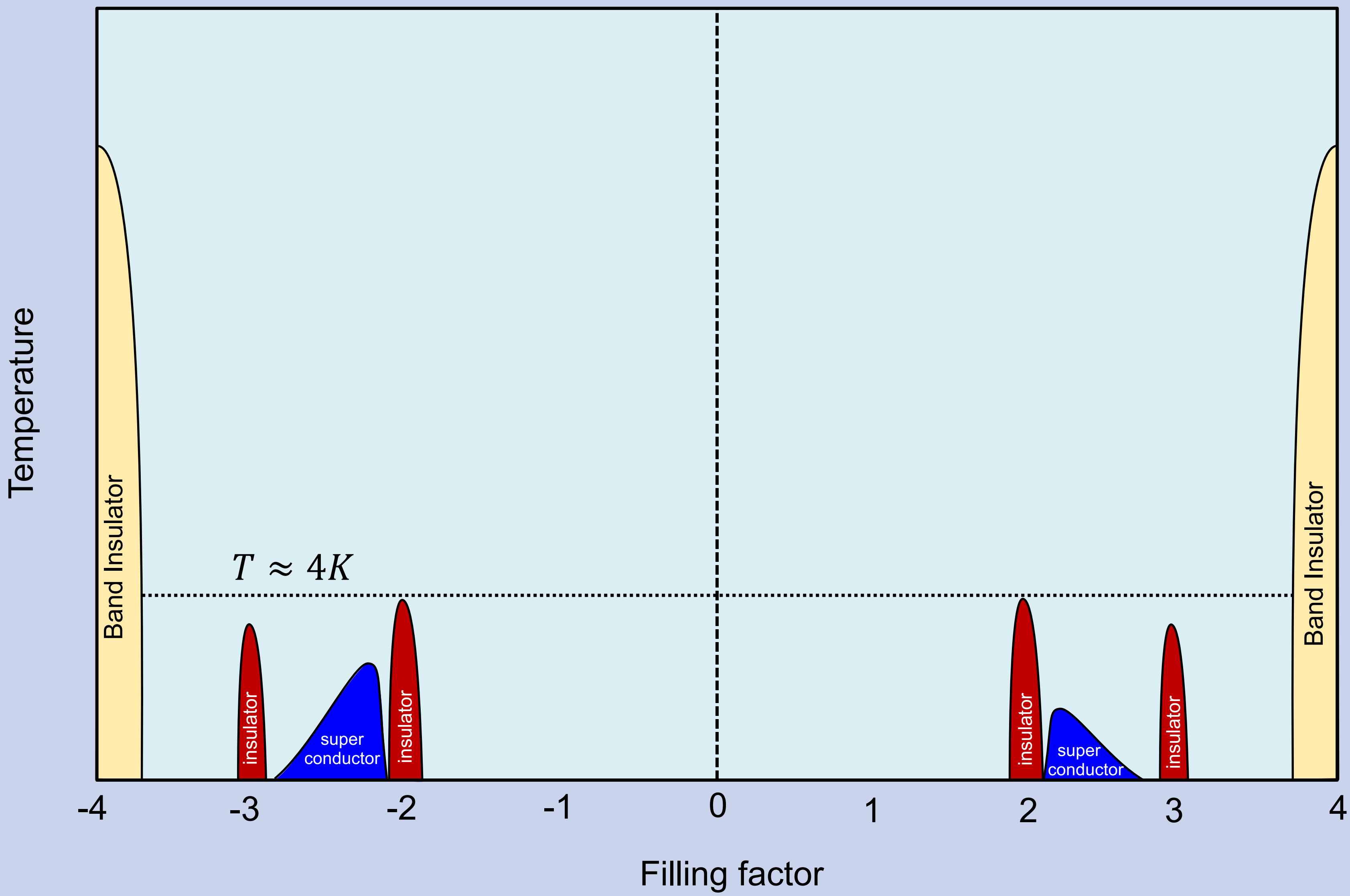
Chern Insulators



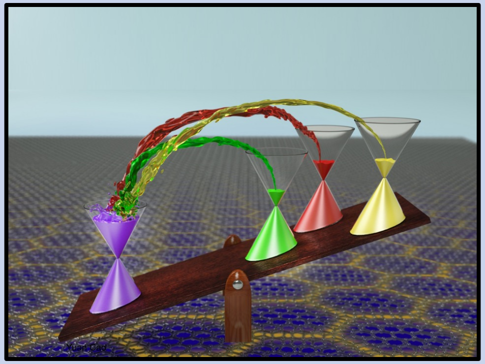
I. Das *et. al*, **arXiv:**2007.13390
K.P. Nuckolls *et. al*, **arXiv:**2007.03810
S. Wu *et. al*, **arXiv:**2007.03735
Y. Choi *et. al*, **arXiv:**2008.11746

"Quantum Hall" Picture

Early physical picture



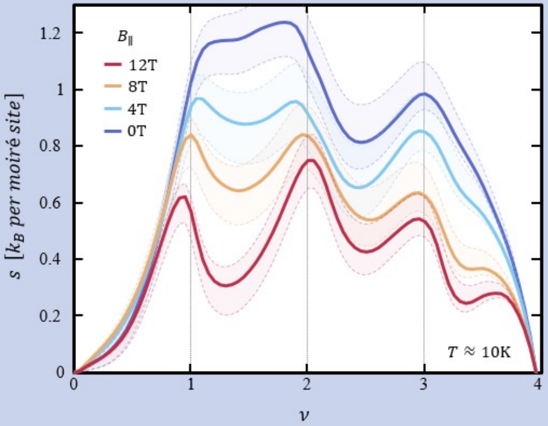
Outline



Electronic compressibility

Cascade of phase transitions and Dirac revivals

broken-symmetry parent state



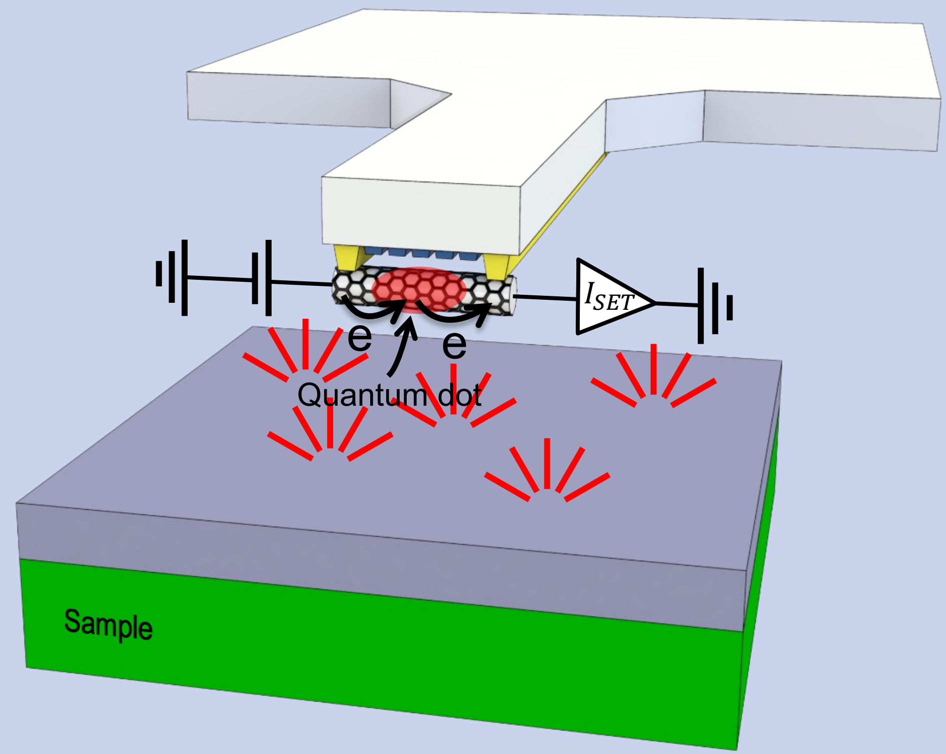
Electronic entropy

direct evidence for Pomeranchuk effect

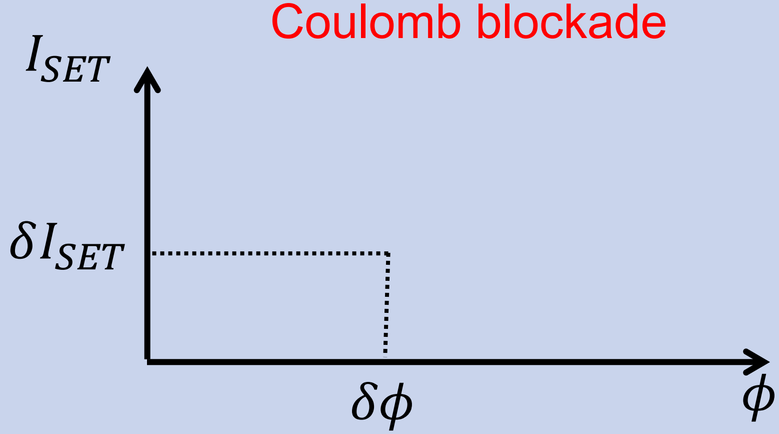
puzzling new state

A scanning nanotube single electron transistor (SET)

M. Honig, SI *et. al*, **Nature Materials** (2013)



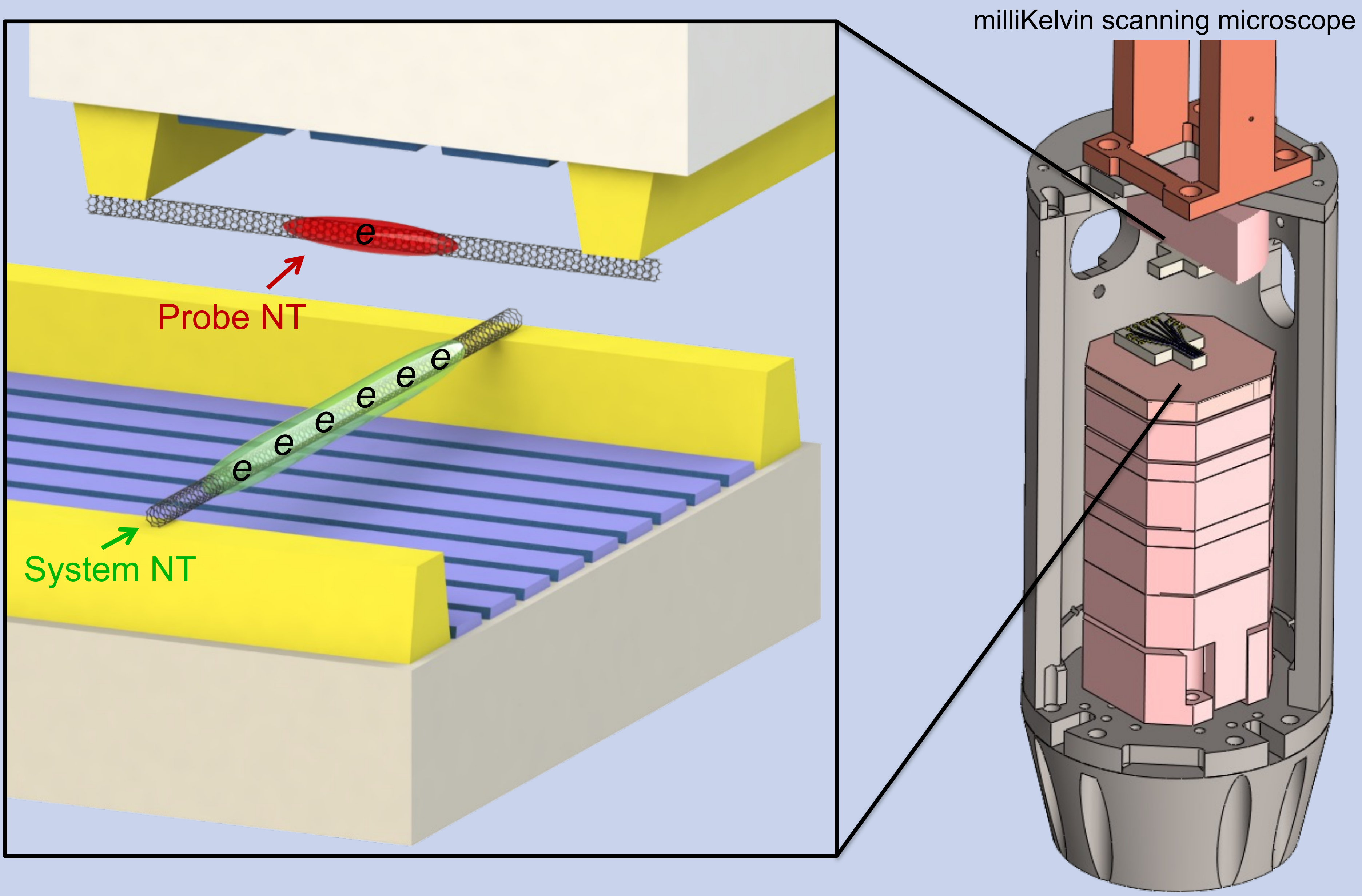
Coulomb blockade



can measure:

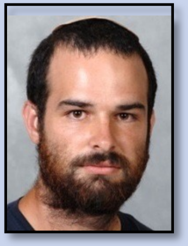
$$10^{-5} - 10^{-6}\ electron\ charge/\sqrt{Hz}$$

Imaging single electrons

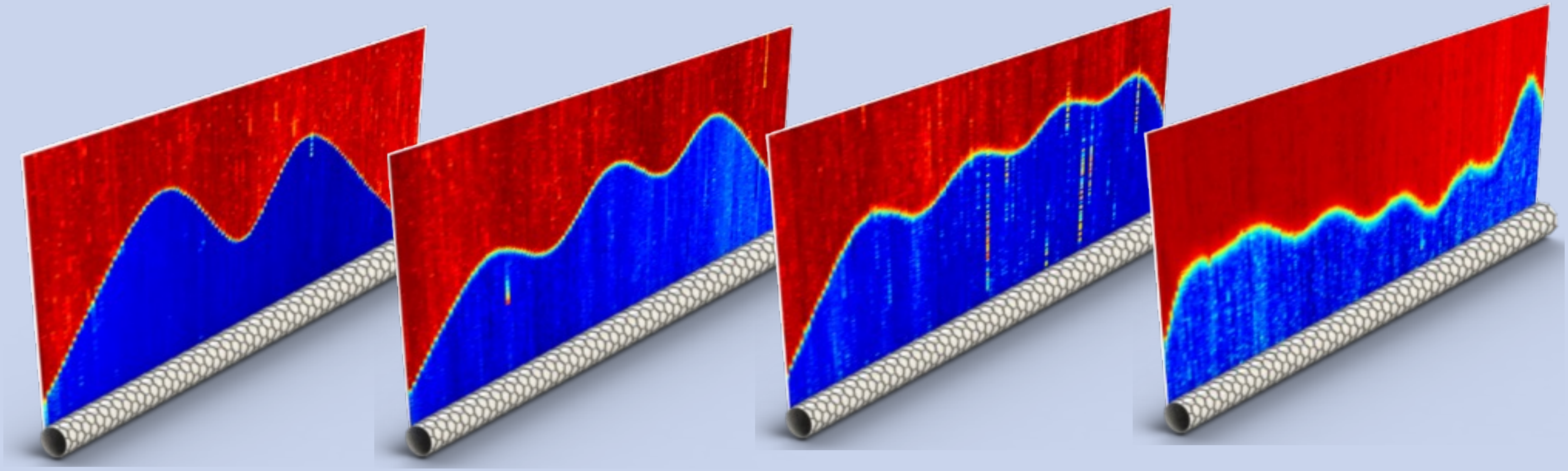


First images of the quantum electronic crystal

Ilanit Shapir

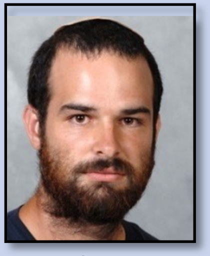


Assaf Hamo



I. Shapir, A. Hamo, S. Pecker, C.P. Moca, O, Legeza, G. Zarand and SI, **Science** 365, 870 (2019)

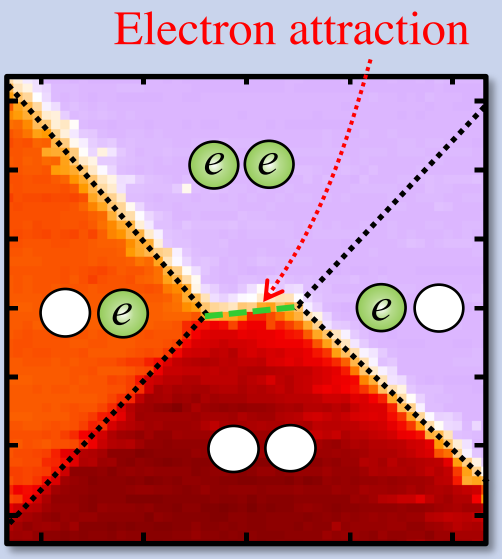
Attractive electrons via Coulomb repulsion

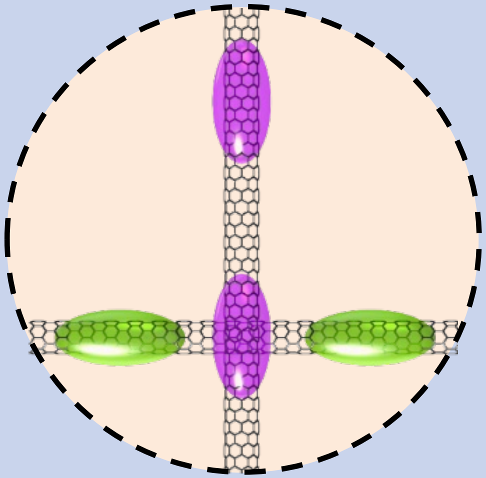


Assaf Hamo

Avishai Benyamini

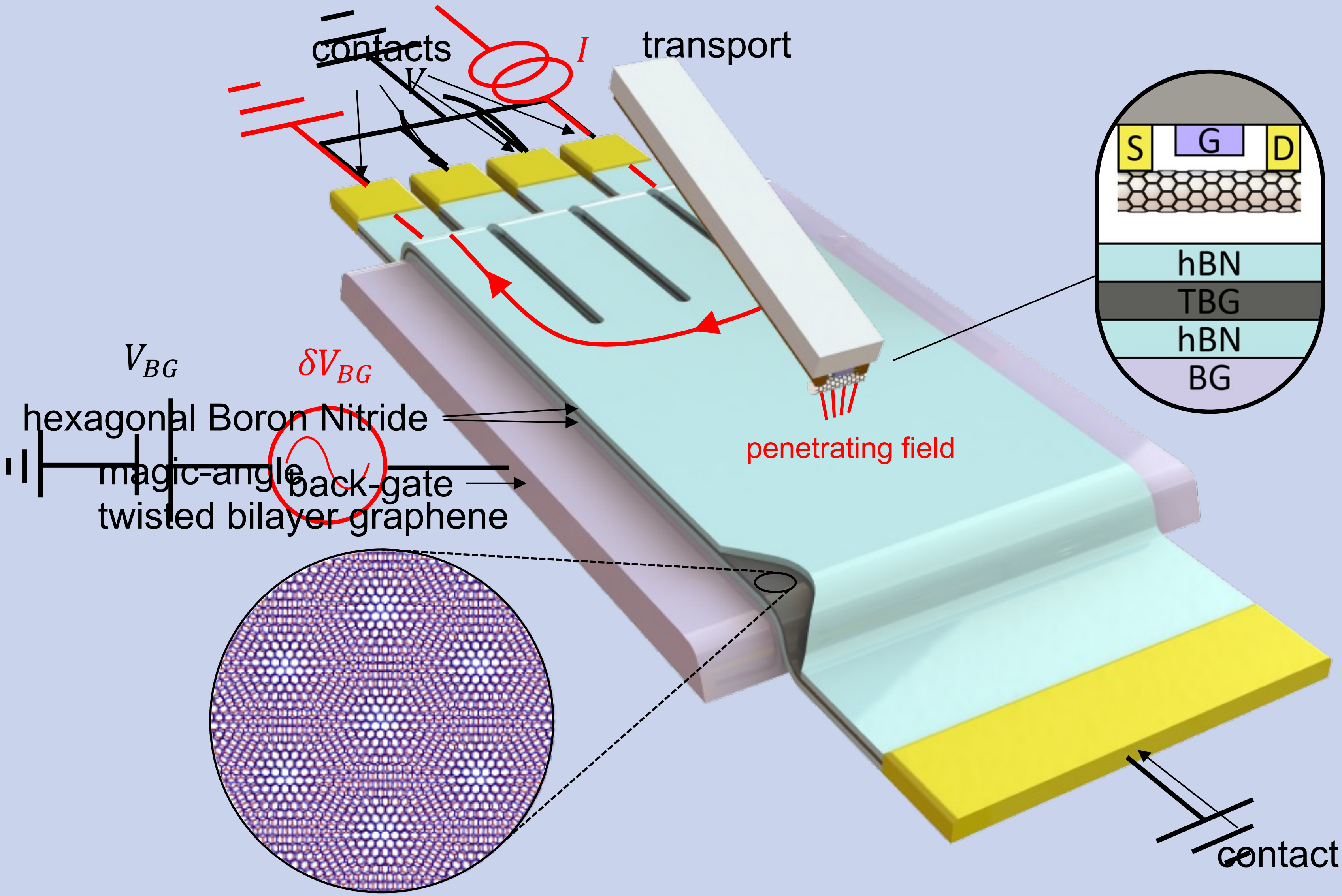
Ilanit Shapir





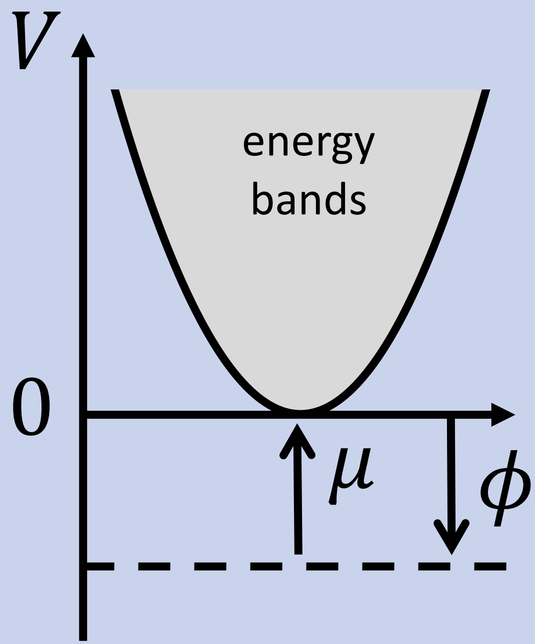
A. Hamo, A. Benyamini, I. Shapir, I. Khivrich, J. Waissman, K. Kaasbjerg, Y. Oreg, F. von Oppen and SI, **Nature** 535, 395 (2016)

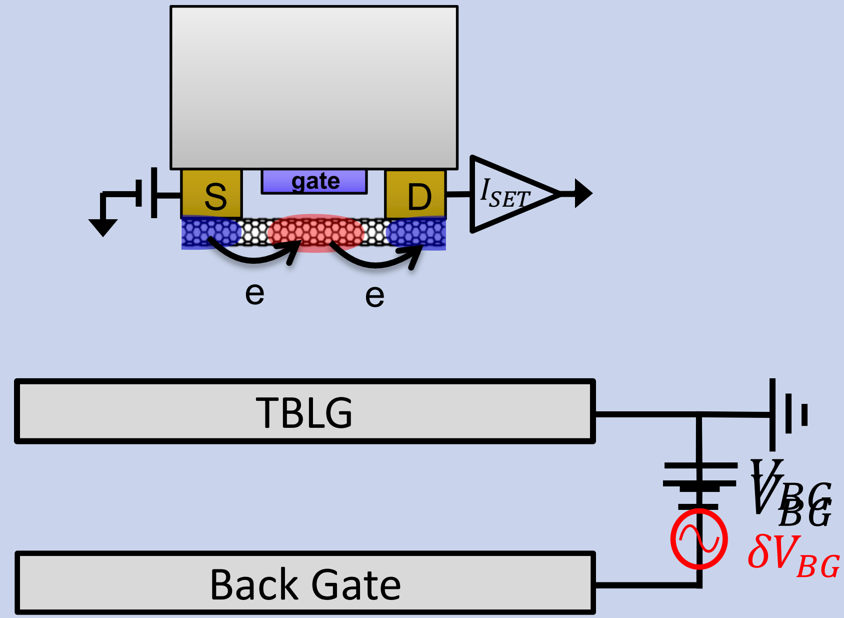
Electrostatic measurements of magic-angle graphene



U. Zondiner, SI, *et. al*, **Nature** (2020)

Measurement of the electronic compressibility



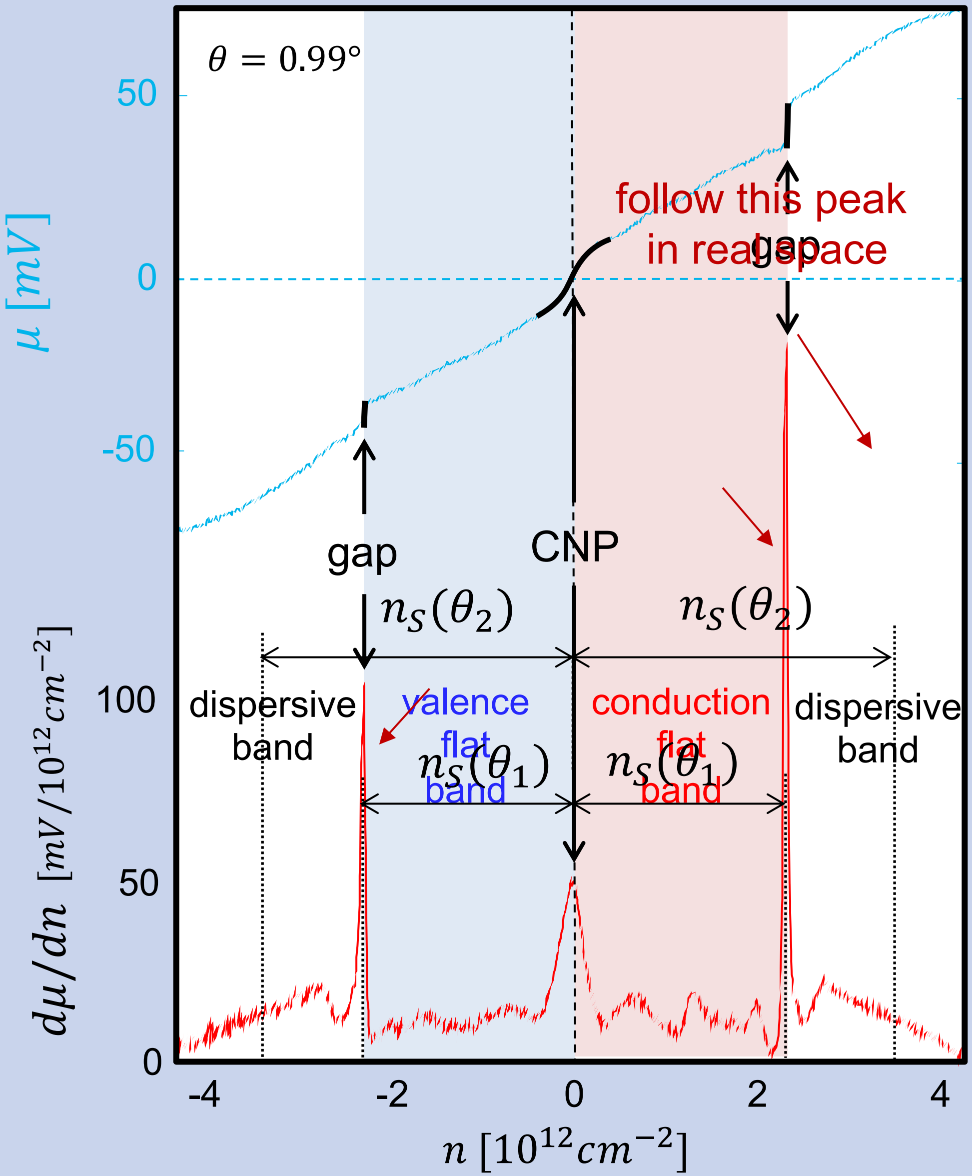


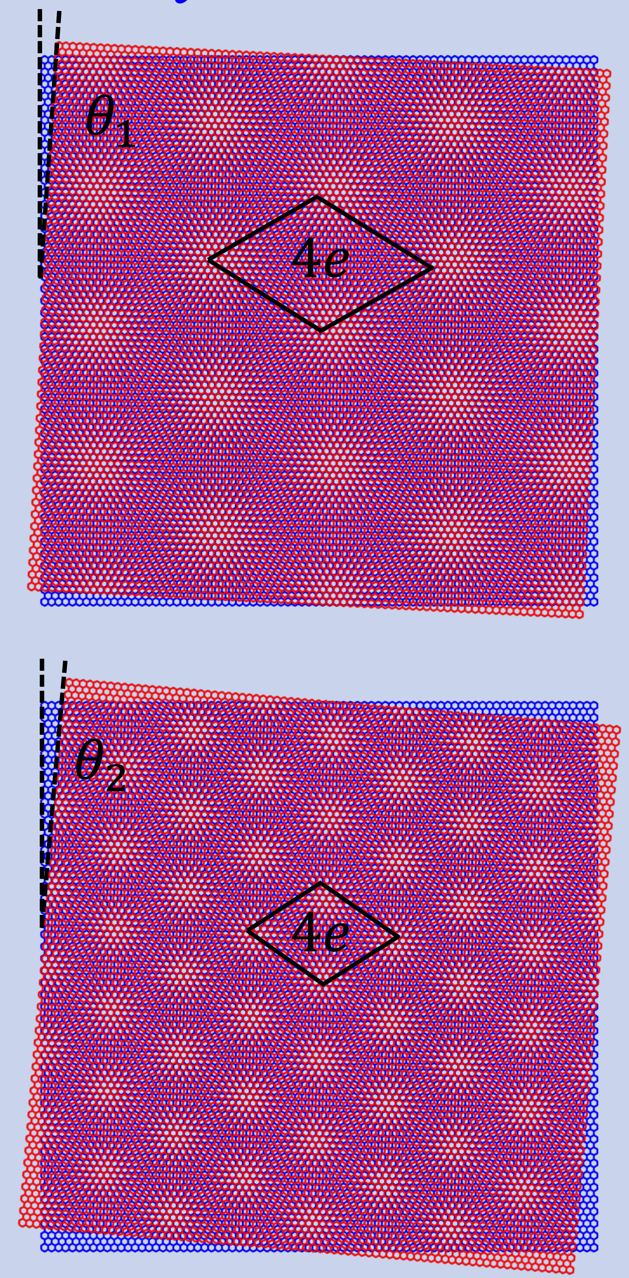
$$\phi = -\mu$$

$$\frac{d\phi}{dV_{BG}} \sim \frac{d\mu}{dn}$$ ⇨ inverse electronic compressibility $$\sim \frac{1}{D.O.S.}$$

See also:
Capacitance measurements Ashoori group (**PRL** 2019)

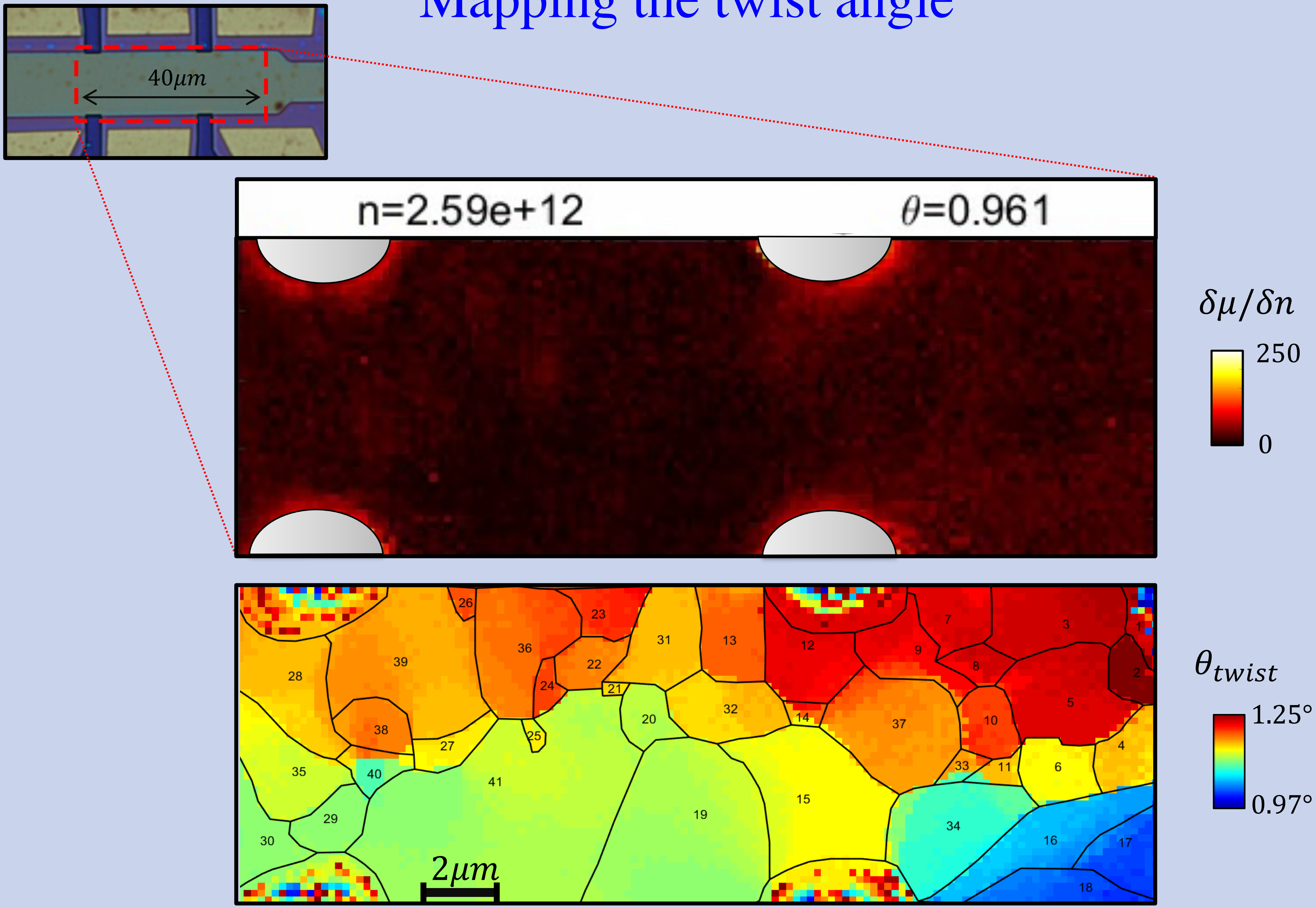
Measured inverse compressibility





U. Zondiner, SI, *et. al*, **Nature** (2020)

Mapping the twist angle

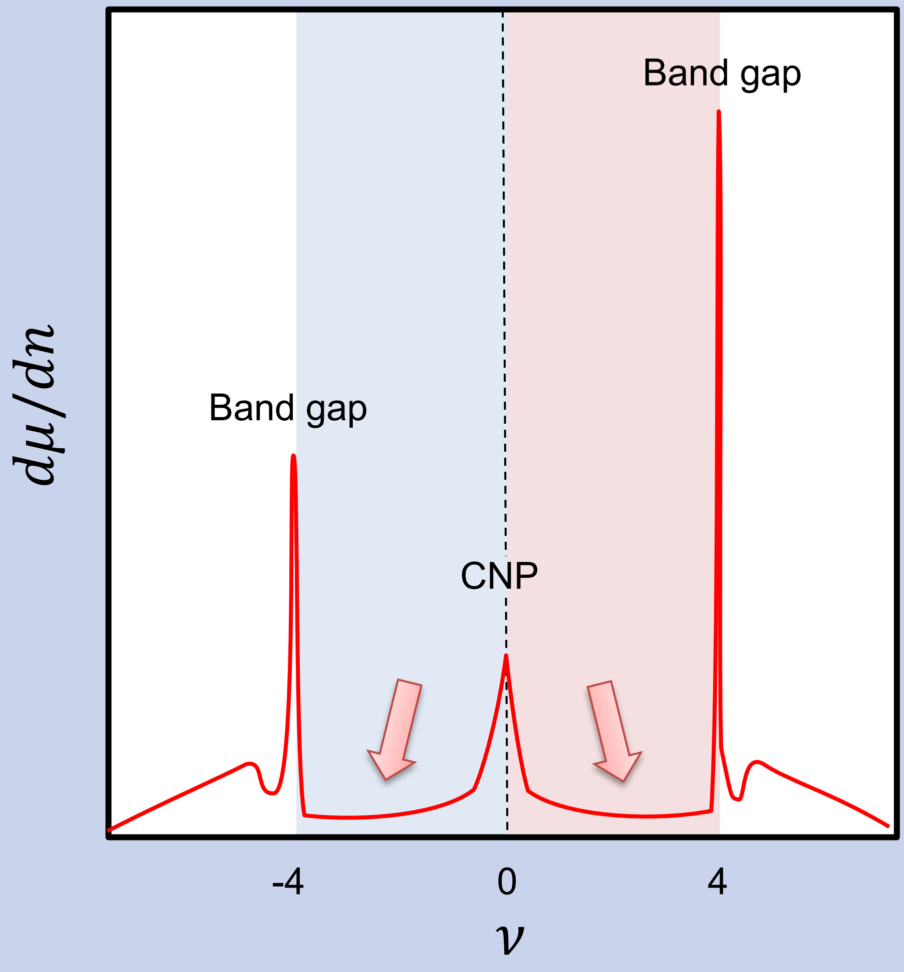


Angle mapping using scanning SQUID: U. Aviram, E. Zeldov et al. ***Nature*** (2020)

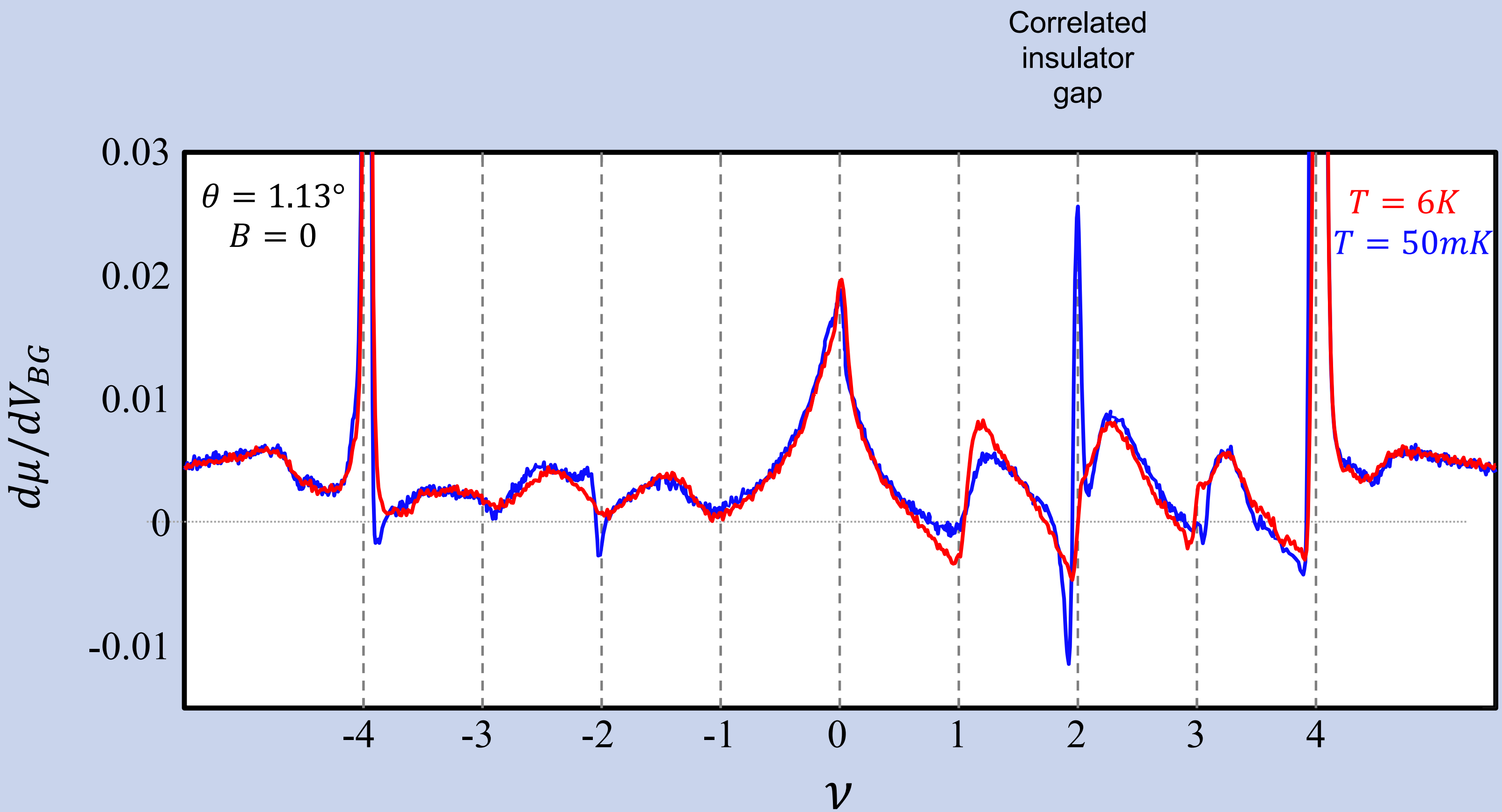
U. Zondiner, SI, *et. al*, **Nature** (2020)

The question

What are the correlated states
that are formed within the flat bands?

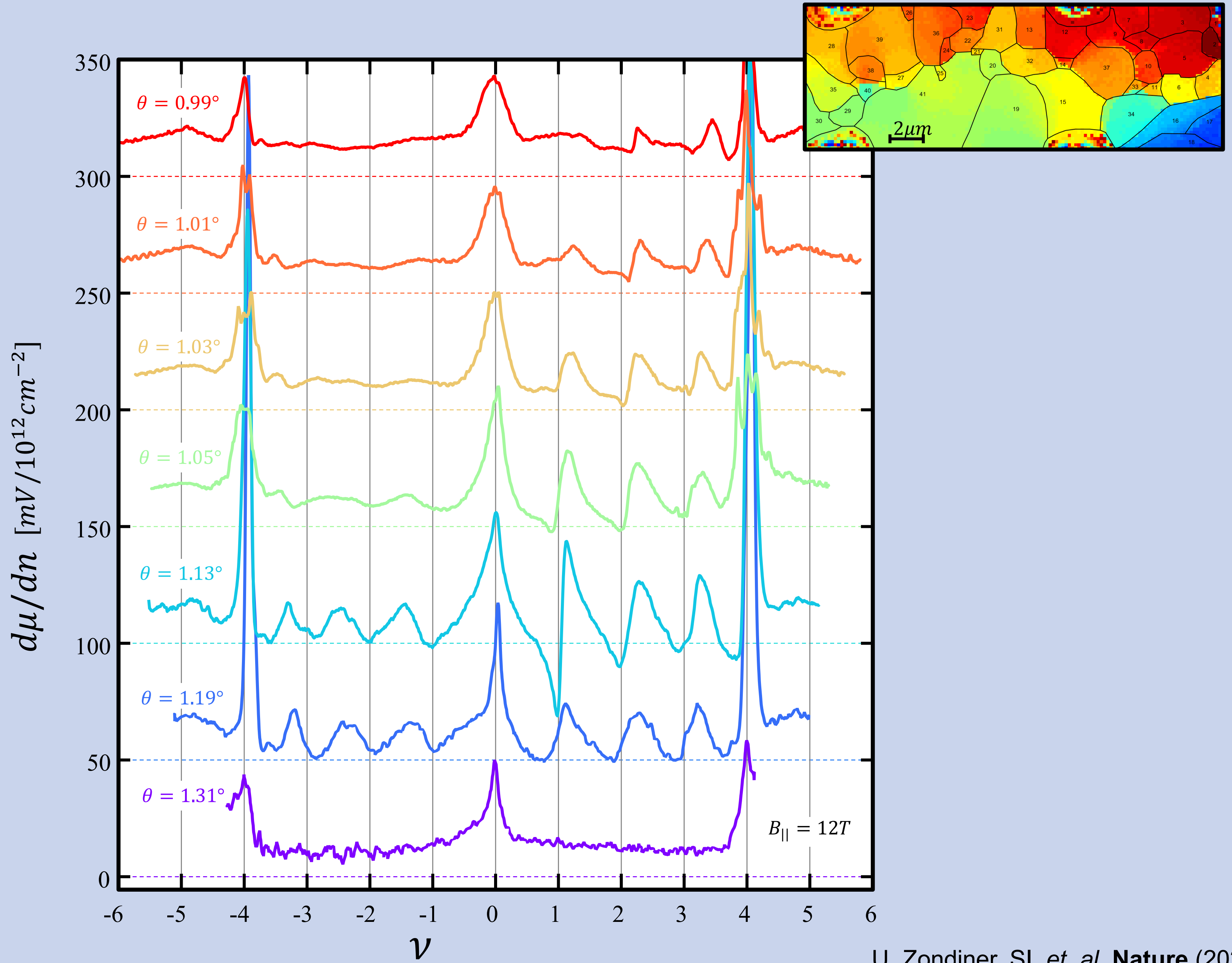


Sharp asymmetric compressibility features



U. Zondiner, SI, *et. al*, **Nature** (2020)

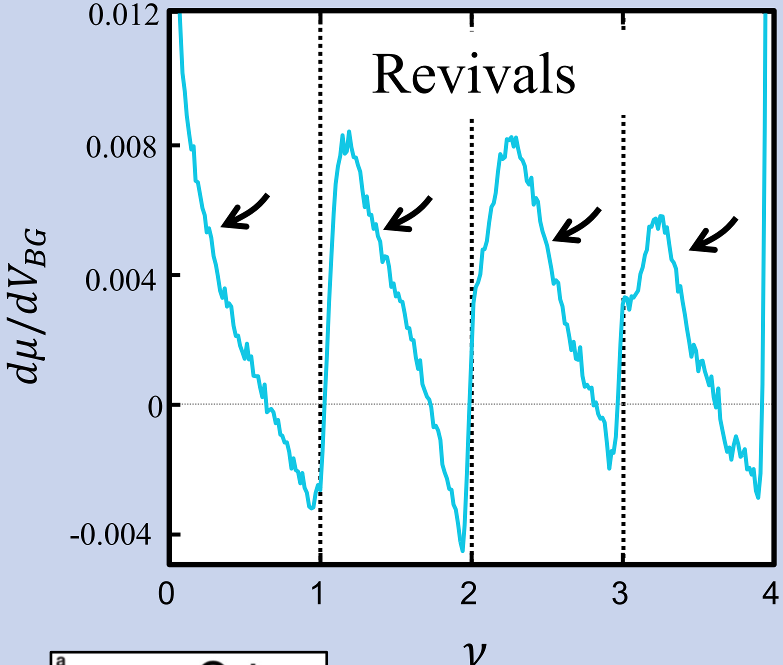
Appear in a narrow angle window around the magic angle

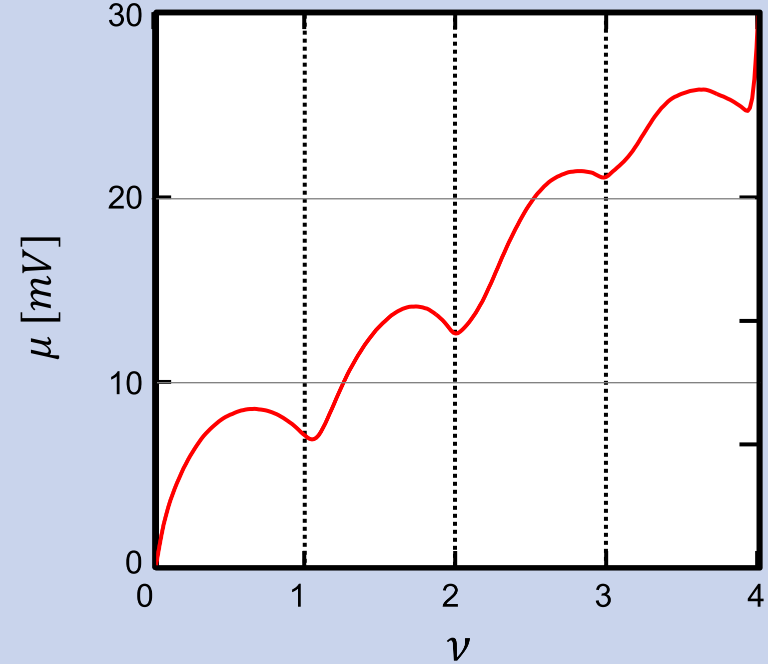


U. Zondiner, SI, *et. al*, **Nature** (2020)

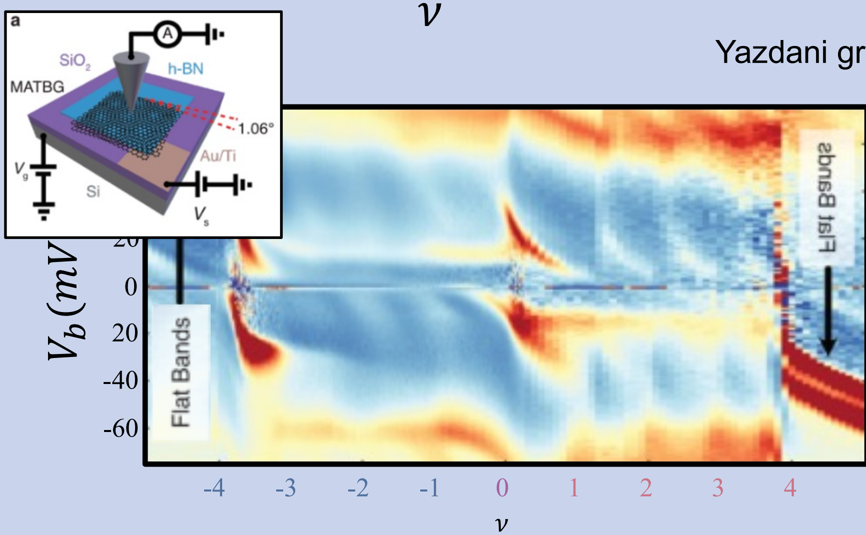
Physics in the conduction flat band

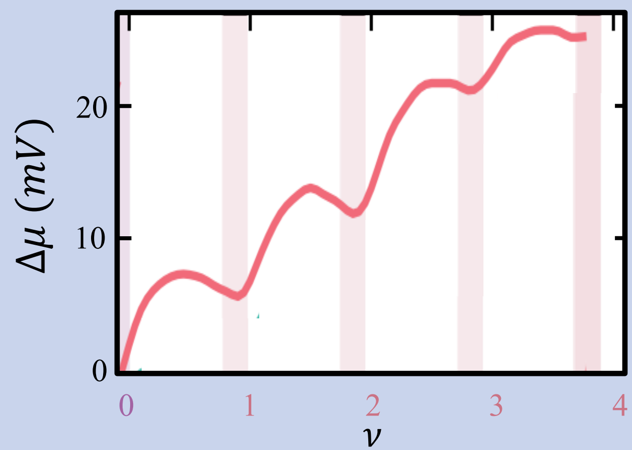
U. Zondiner, SI *et al.*, **Nature** (2020)





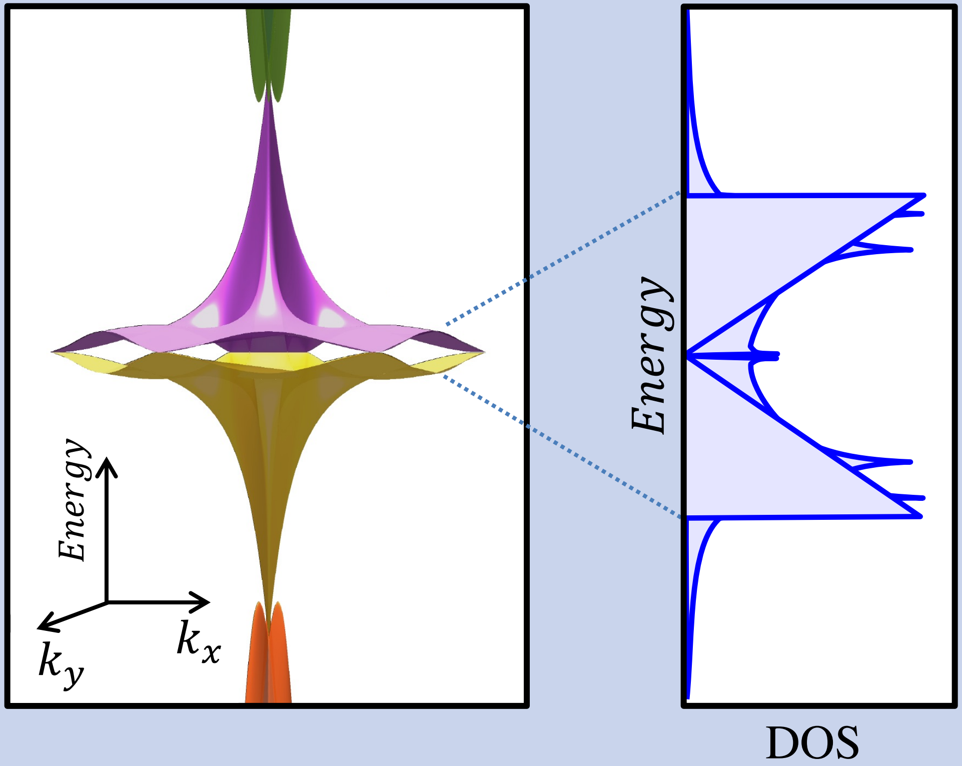
Yazdani group, **Nature** (2020)





See also: J.M. Park, P. Jarillo-Herrero *et al.*, **arXiv** 2008.12296, S. Wu, E.Y. Andrei **Nature Mat.** (2021), Y. Choi, S. Nadge-Perge *et al.*, **arXiv** 2102.02209, Y. Saito, A.F. Young *et al.*, **arXiv** 2008.10830, A.T. Pierce, A. Yacoby *et al.*, **arXiv** 2101.04123

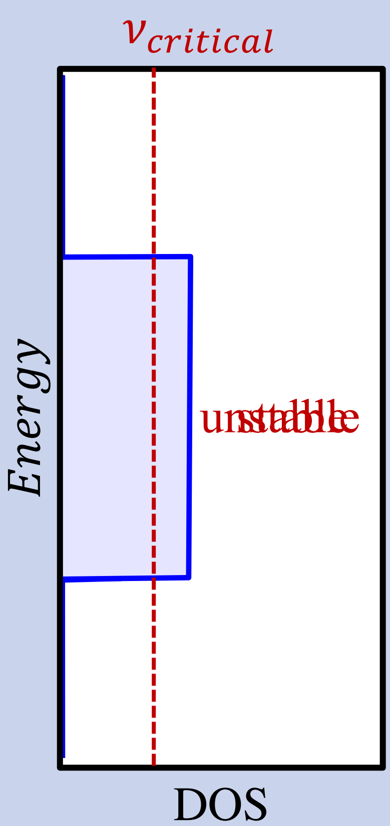
A simple model

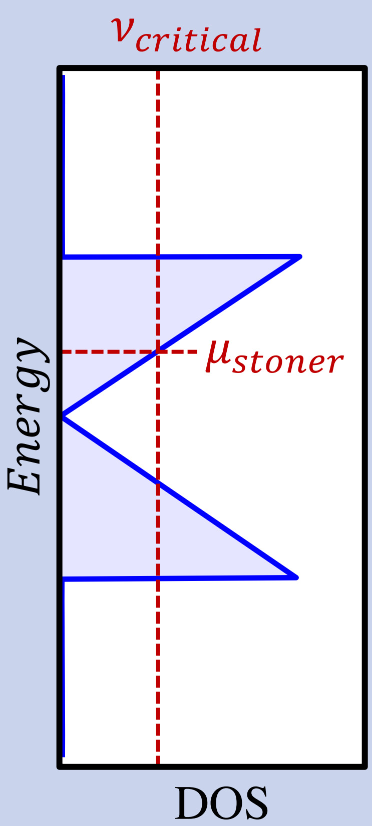


U. Zondiner, SI *et al.*, **Nature** (2020)

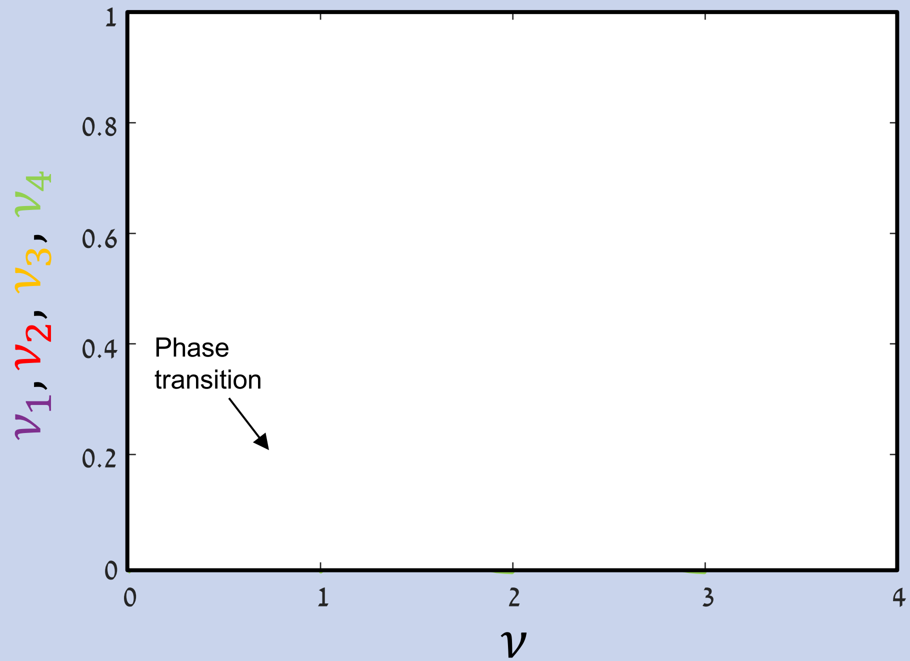
Stoner instability: Flavor symmetry breaking

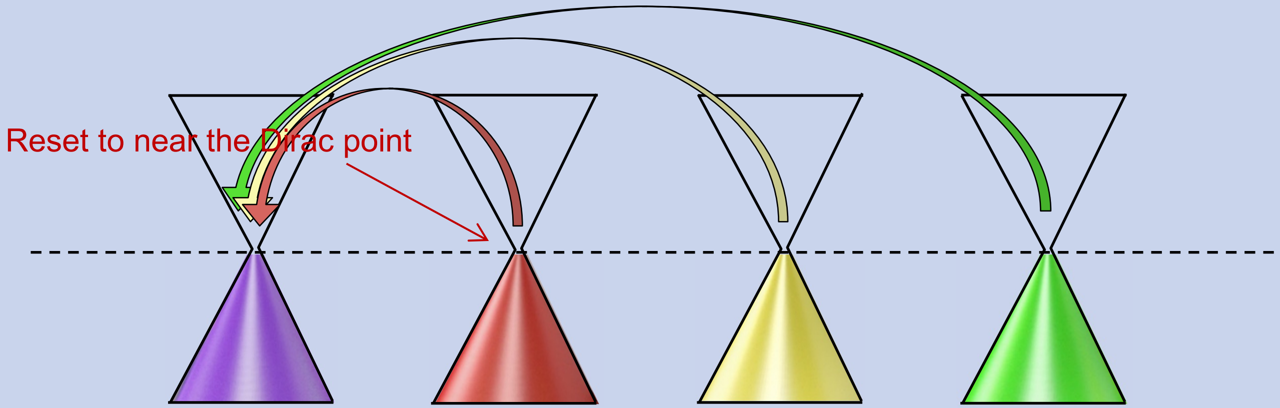
Stoner instability: $U \cdot DOS > const$





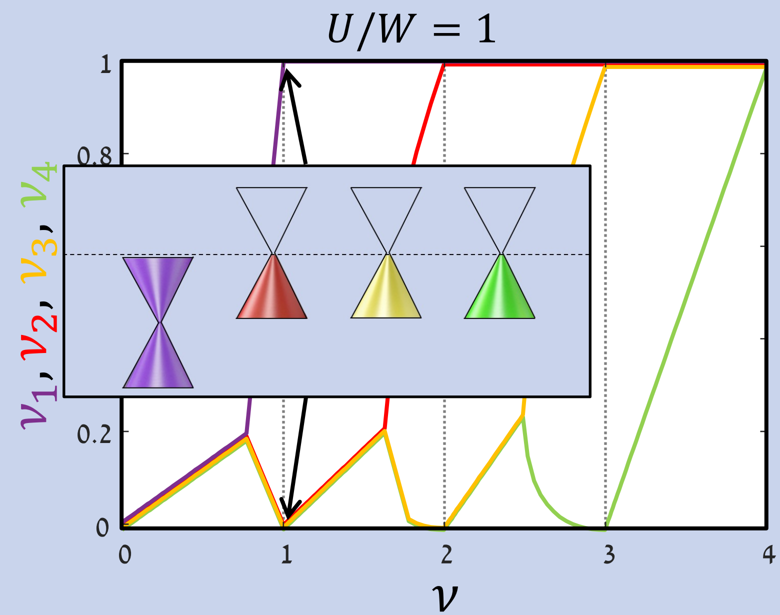
The Dirac revivals model (mean field theory)

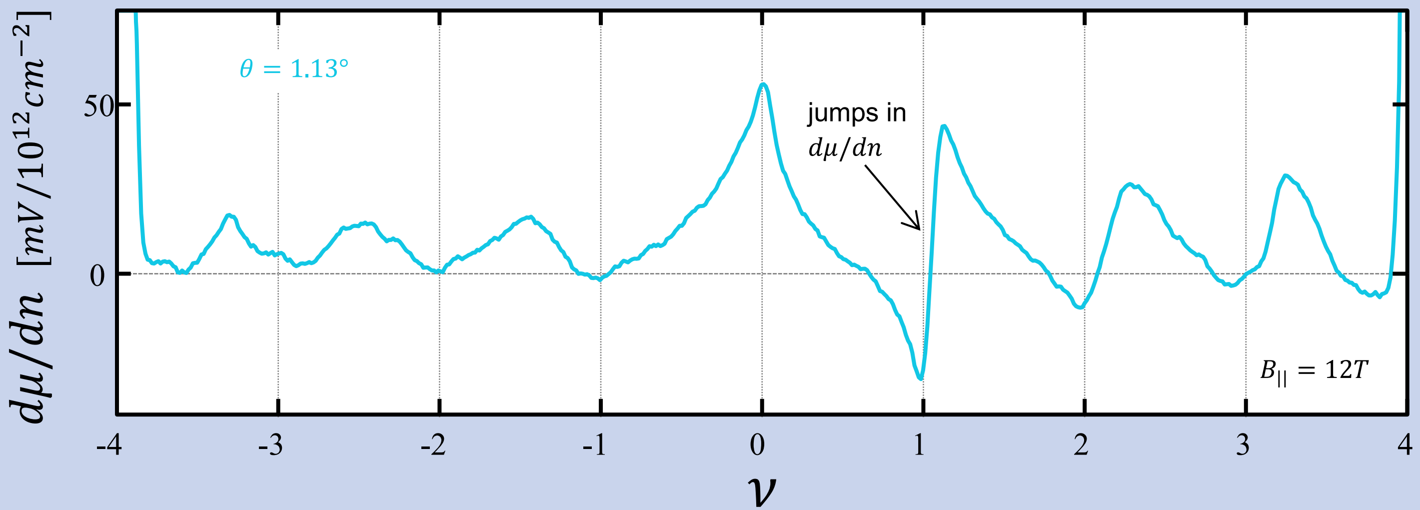




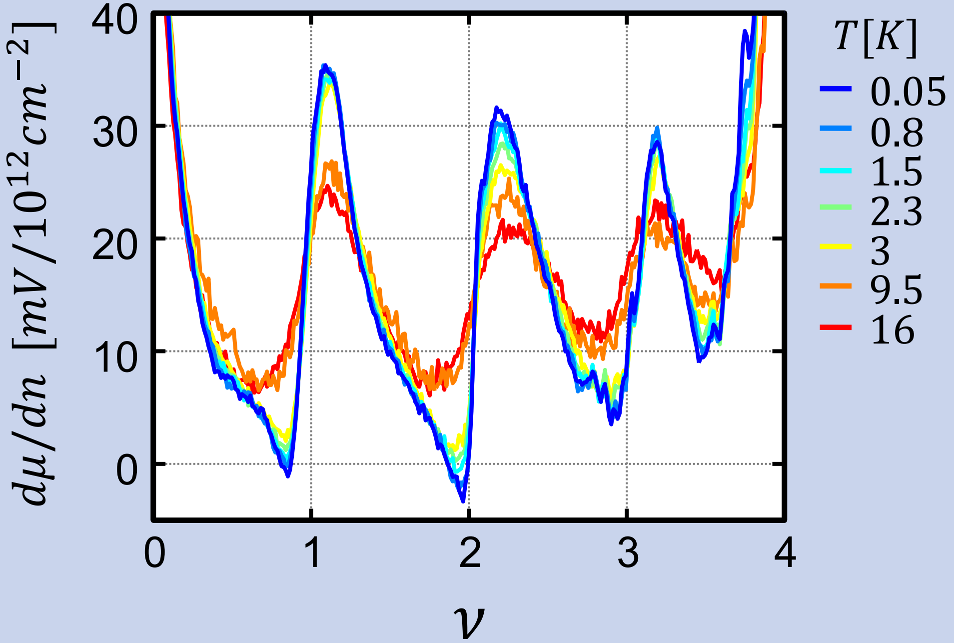
U. Zondiner, SI *et al.*, **Nature** (2020)

Explain the asymmetric jumps in $d\mu/dn$





Temperature dependence



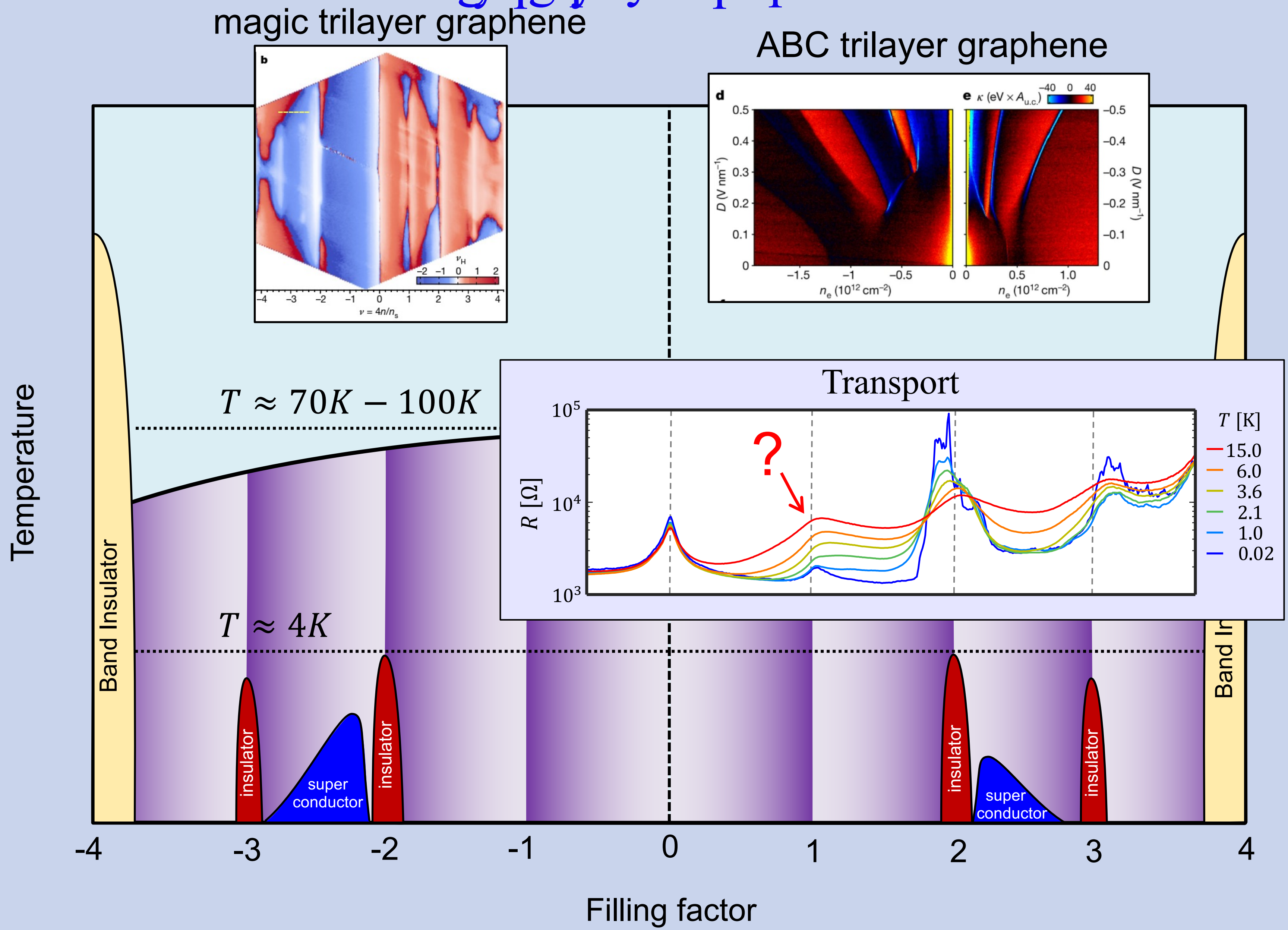
$T_{revivals} \approx 70-100K$

$T_{Correlated\ Insulator} \approx 4K$

$T_{superconductivity} \lesssim 3K$

U. Zondiner, SI *et al.*, **Nature** (2020), J.M. Park, P. Jarillo-Herrero *et al.*, **arXiv** 2008.12296, Y. Saito, A.F. Young *et al.*, **arXiv** 2008.10830

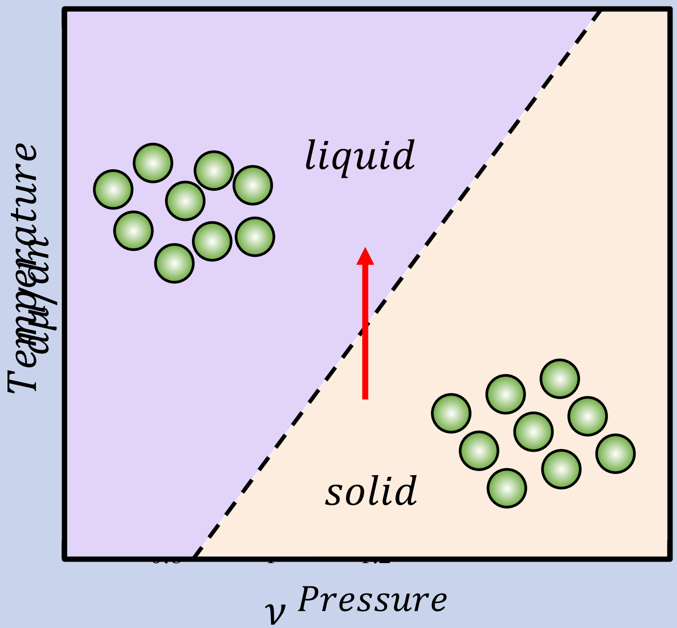
Emerging physical picture



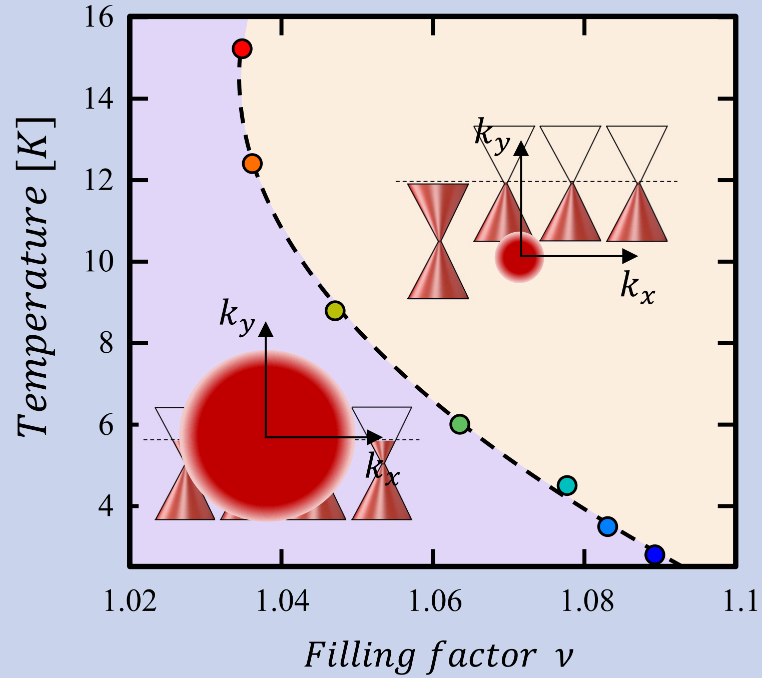
U. Zondiner, SI *et al.*, **Nature** (2020)

A surprising phase boundary

$$G = U + pV - TS$$



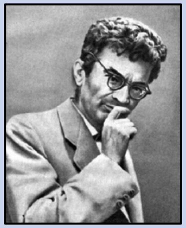
?



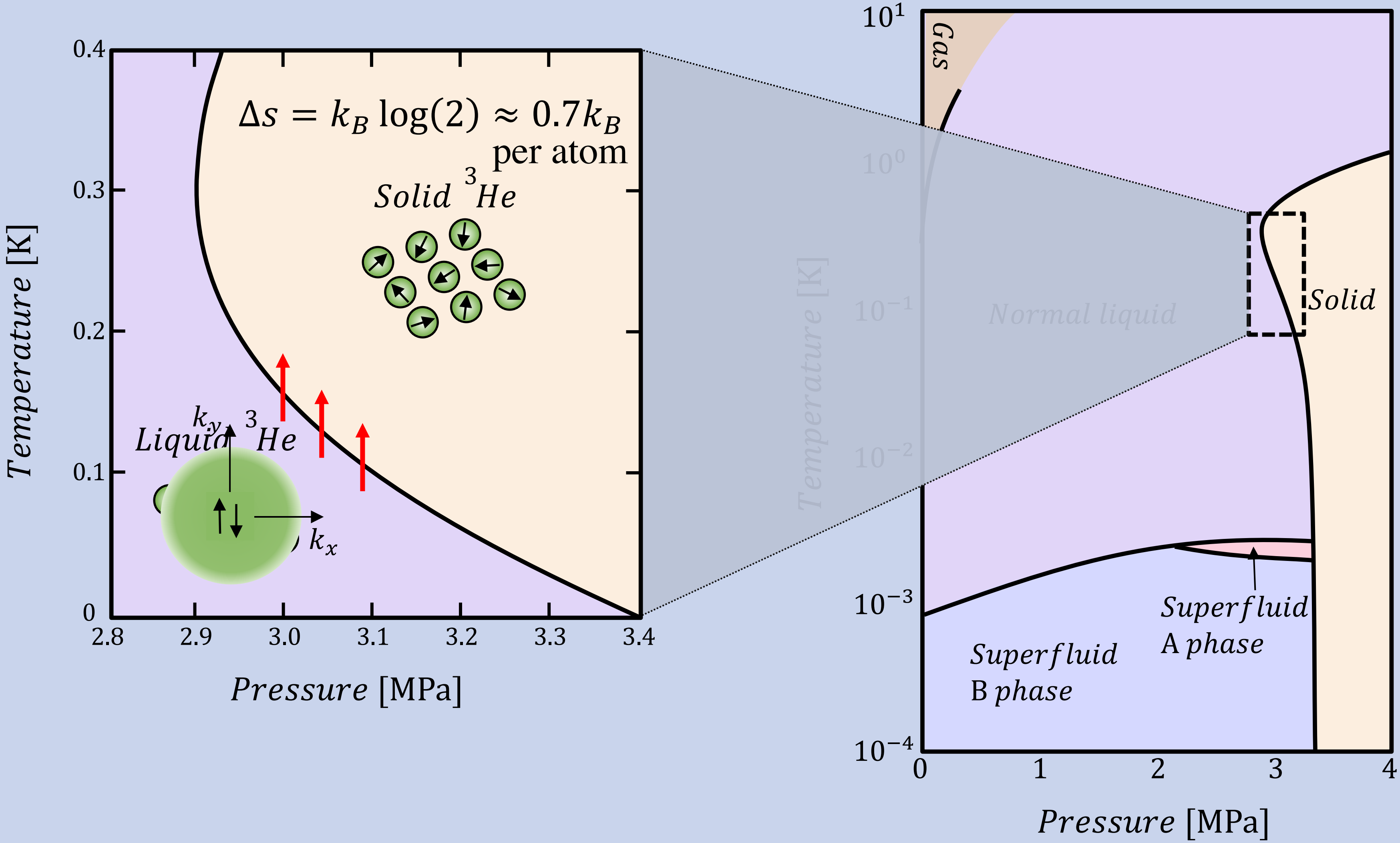
See also: Y. Saito, A.F. Young *et. al*, **arXiv**:2008.010830

A. Rozen, SI *et. al*, **Nature** (2021)

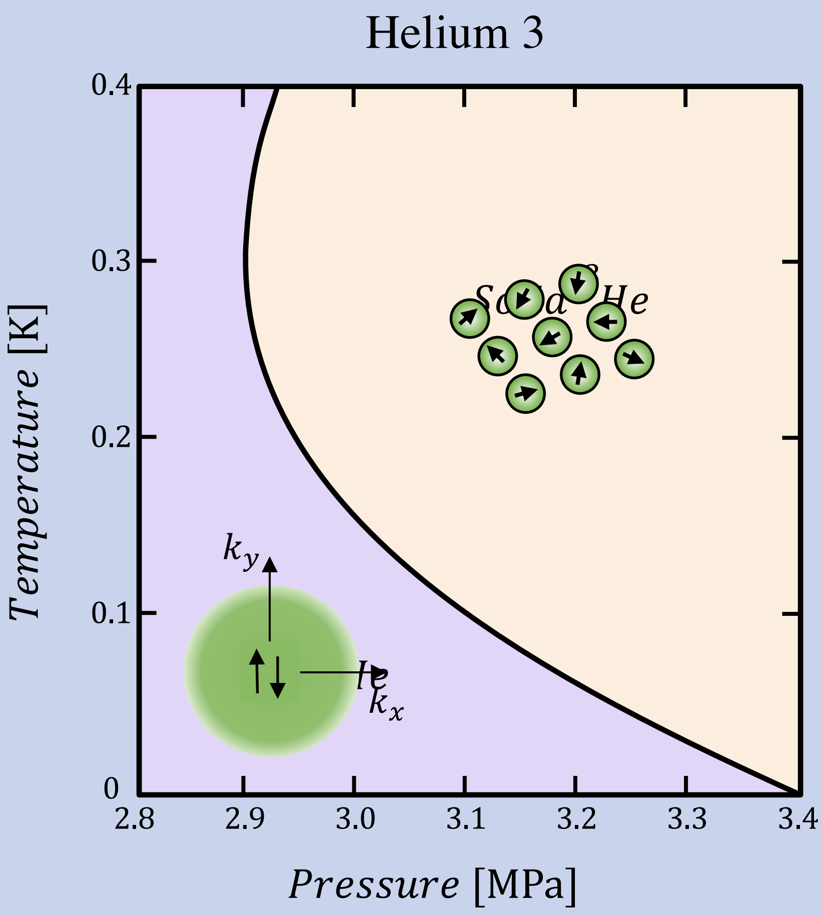
Pomeranchuk Effect in Helium 3

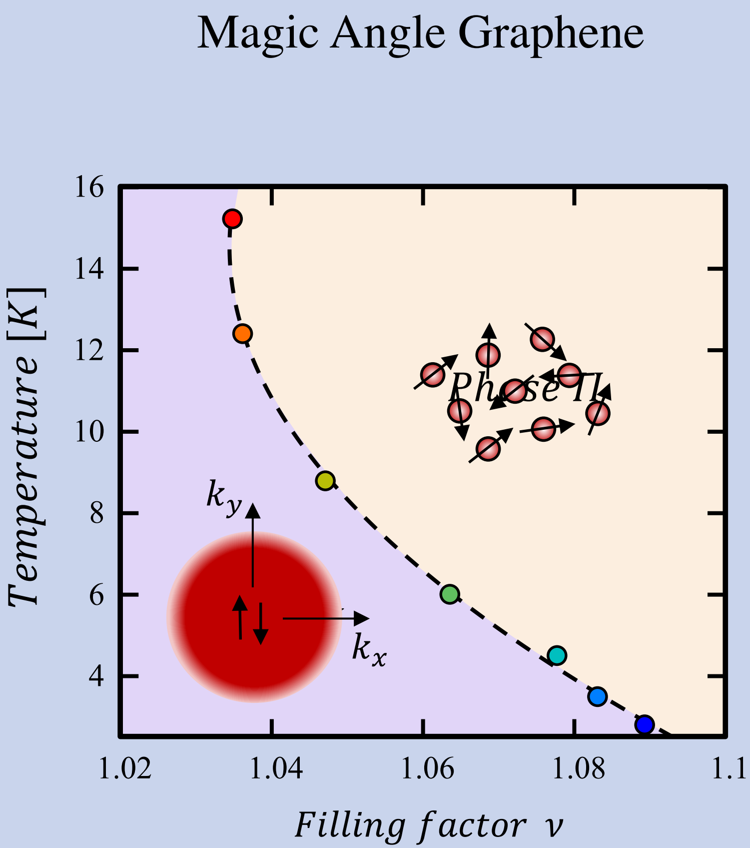


Isaak Pomeranchuk



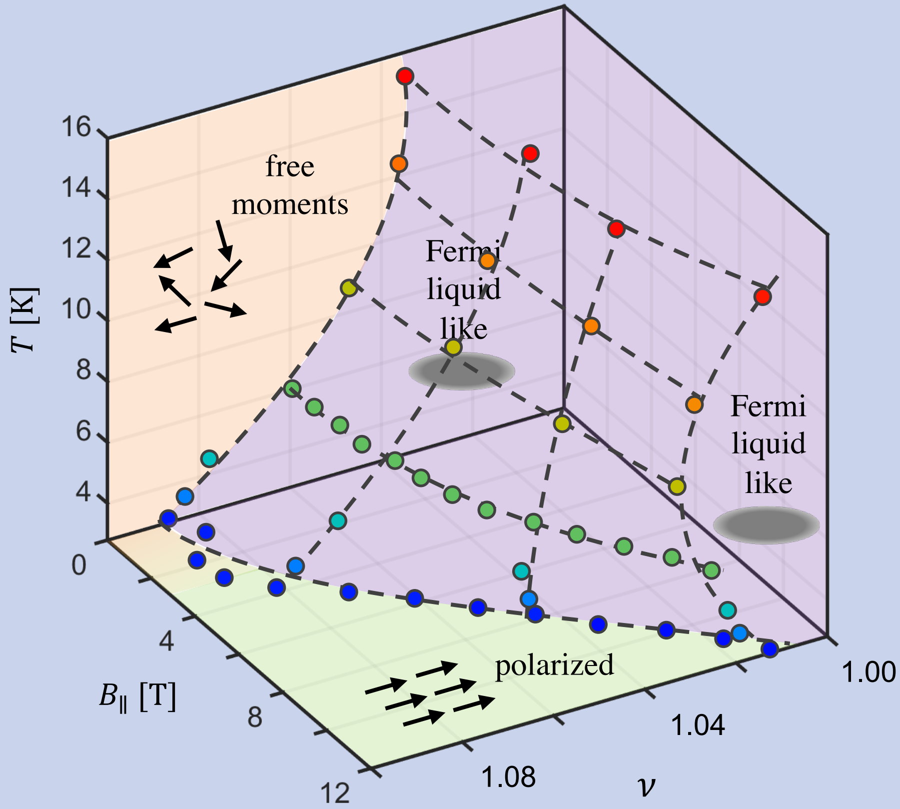
The similarity between magic angle graphene and ^{3}He





A. Rozen, SI *et. al*, **Nature** (2021)

The full phase diagram



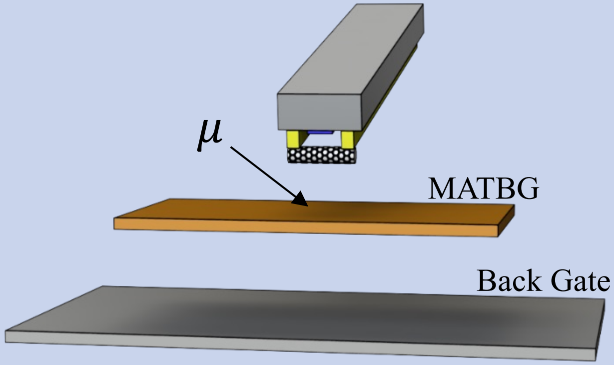
A. Rozen, SI *et. al*, **Nature** (2021)

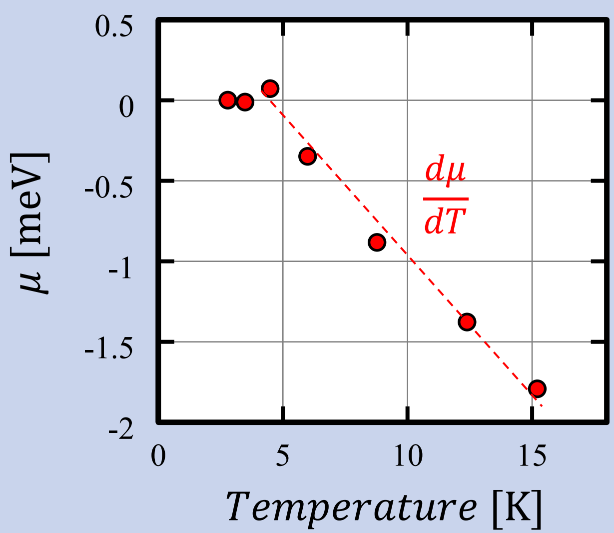
Measuring the local electronic entropy

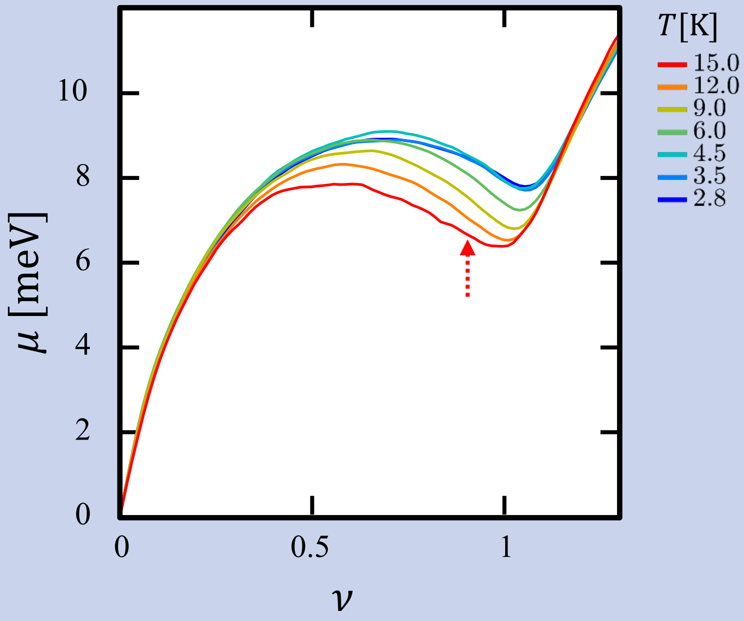
Maxwell's relation

$$\frac{d\mu}{dT} = -\frac{ds}{d\nu}$$

s is the entropy per moiré unit cell

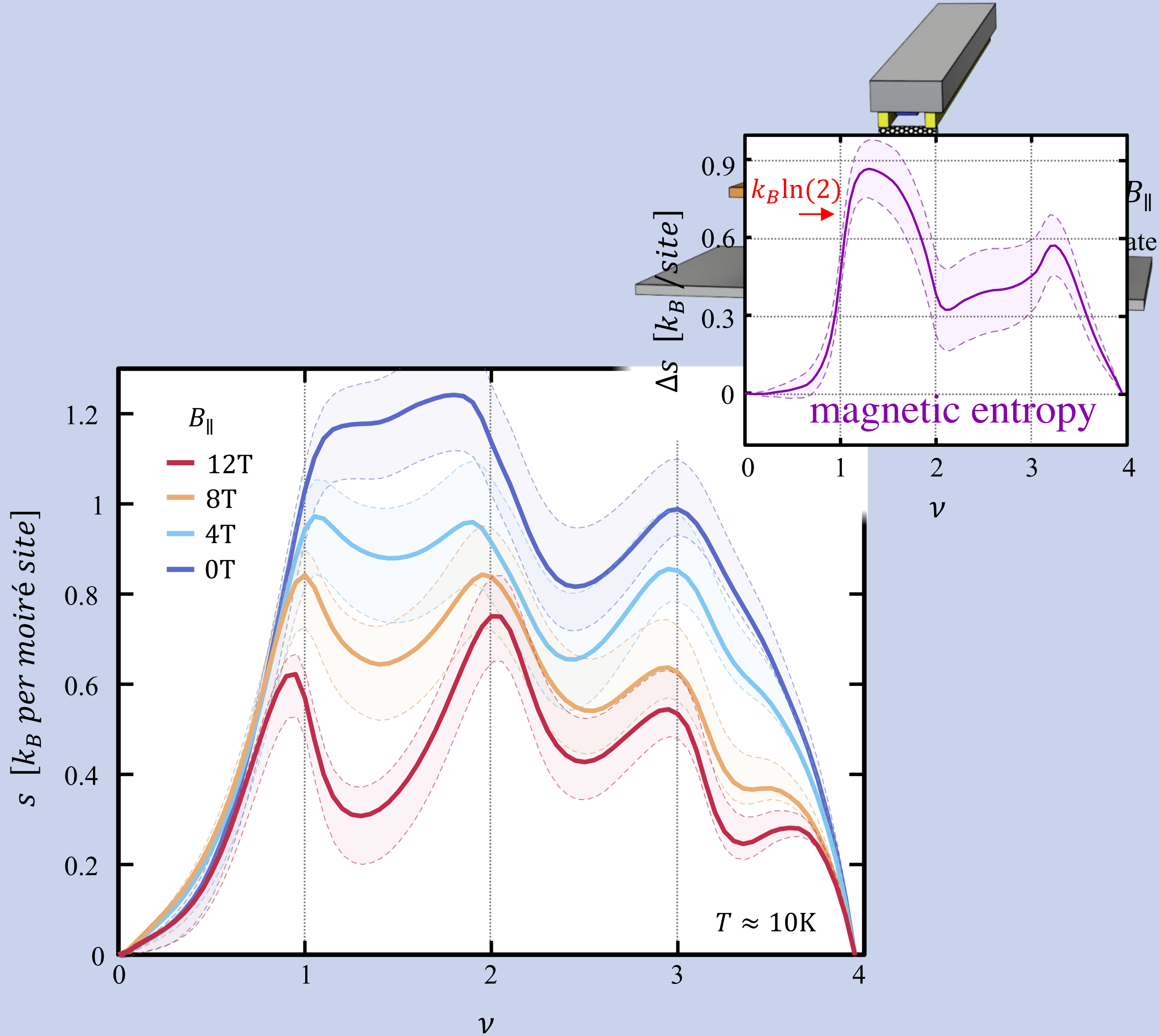






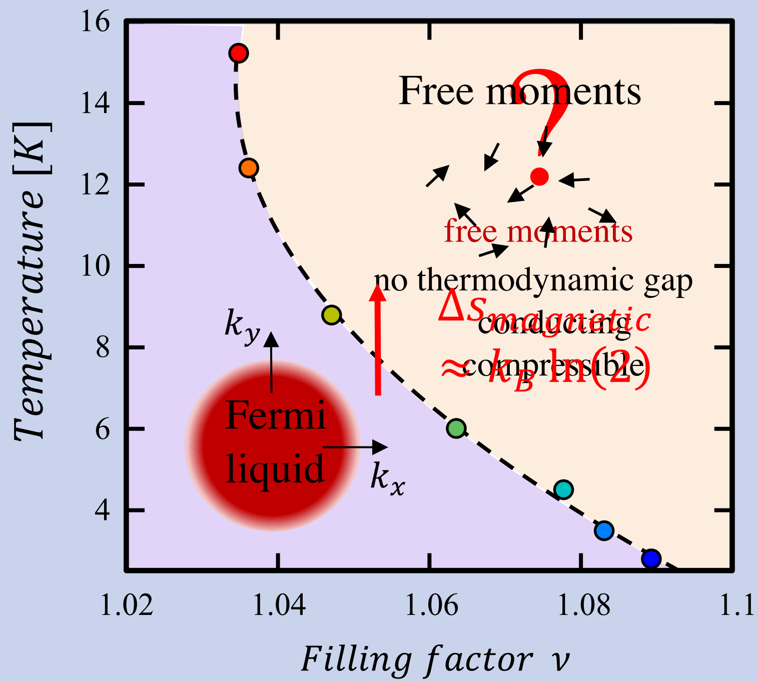
A. Rozen, SI *et. al*, **Nature** (2021)

The measured entropy



A. Rozen, SI *et. al*, **Nature** (2021)

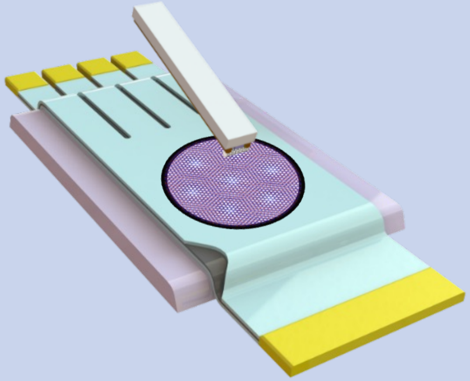
Pomeranchuk effect in magic angle graphene

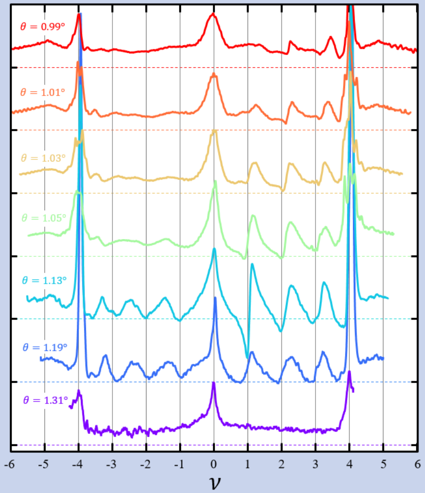


A. Rozen, SI *et. al*, **Nature** (2021)

Summary

Scanning nanotube
single-electron transistor

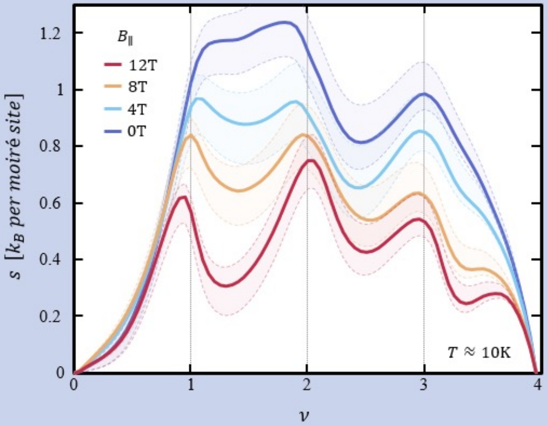




Electronic compressibility

Cascade of phase transitions and Dirac revivals

broken-symmetry parent state



Electronic entropy

direct evidence for Pomeranchuk effect

puzzling new state