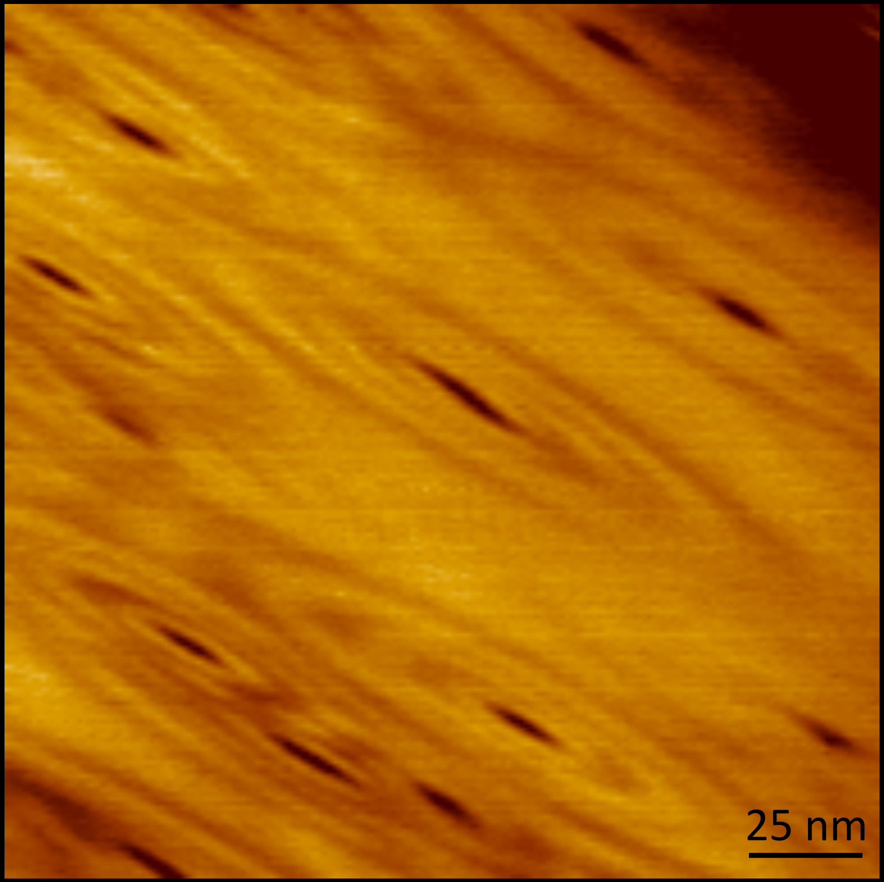
Imaging Landau orbits to observe a nematic quantum Hall phase



Mallika Randeria

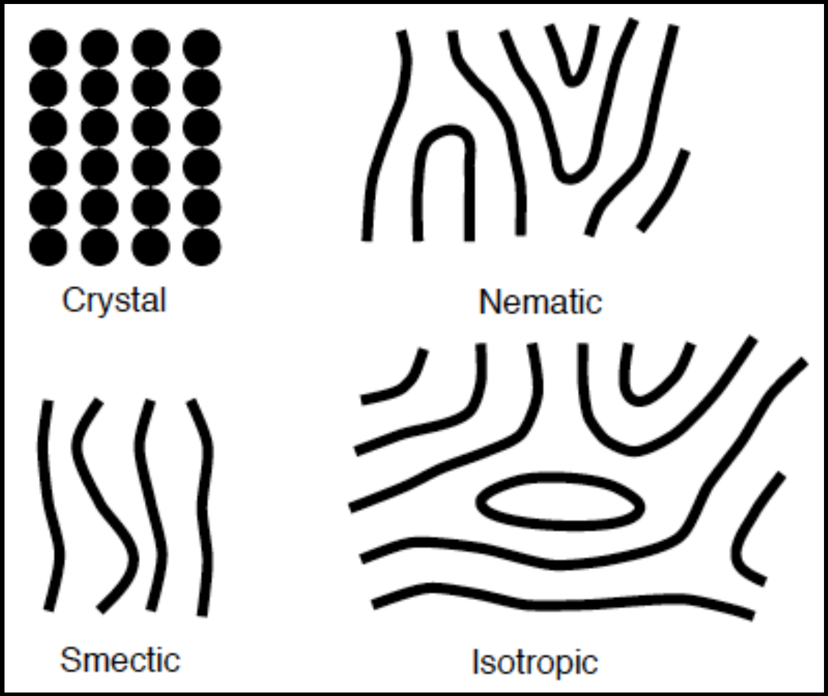
PRINCETON UNIVERSITY

KITP Intertwined order

August 1, 2017

Nematic electronic phases

- Break the rotational symmetry of the underlying crystal lattice
- Spontaneously form, *e.g.* as a result of electron-electron interactions

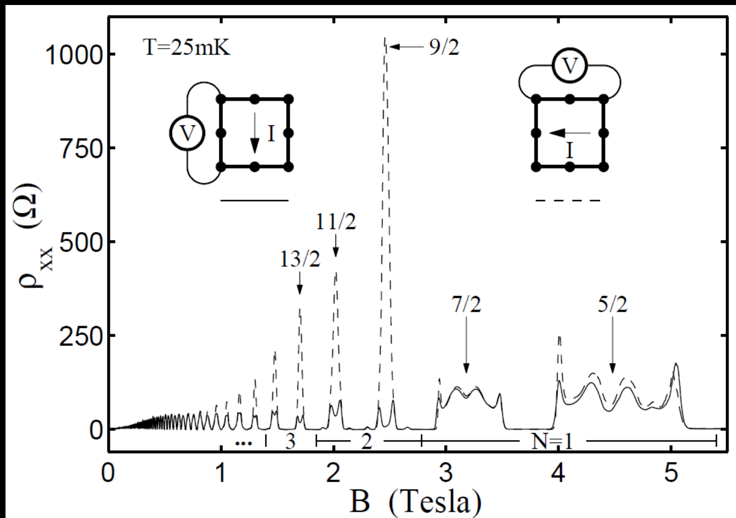


Kivelson, Fradkin & Emery, *Nature* **393**, 550-553 (1998)

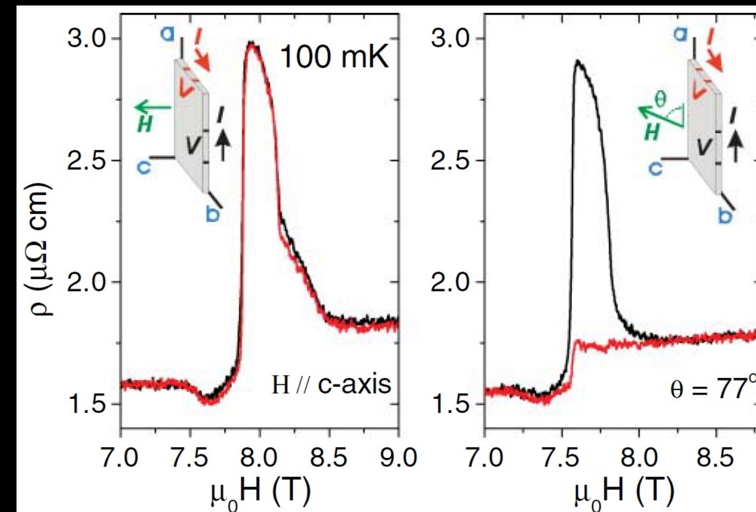
See also: M. M. Fogler *et al.*, *Phys. Rev. B.* **54**, 1853 (1996)

Previous evidence for nematic electronic states

2D electron systems: GaAs, AlAs, graphene

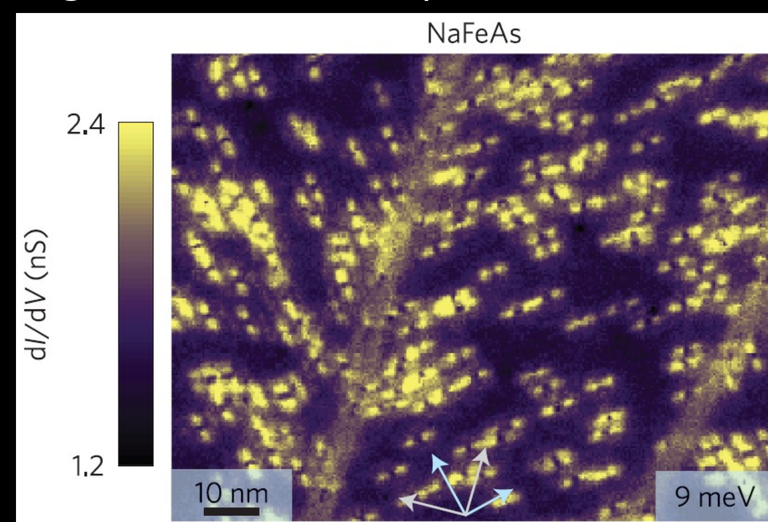


$Sr_3Ru_2O_7$



“Vestigial order” – Strain or external fields needed to align domains to enable detection

High-Tc, Fe-based superconductors

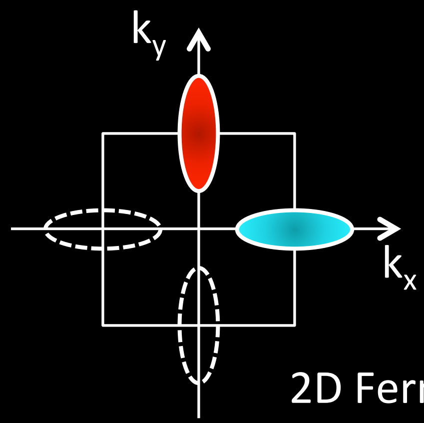


Lilly, M. P. *et al., Phys. Rev. Lett.* **82**, 394-397 (1999)
Borzi, R. A. *et al., Science* **315**, 214-217 (2007)
Rosenthal, E. P. *et al., Nat. Phys.* **10**, 225-232 (2014)

See also work from: Seamus Davis, Ian Fisher groups & many others

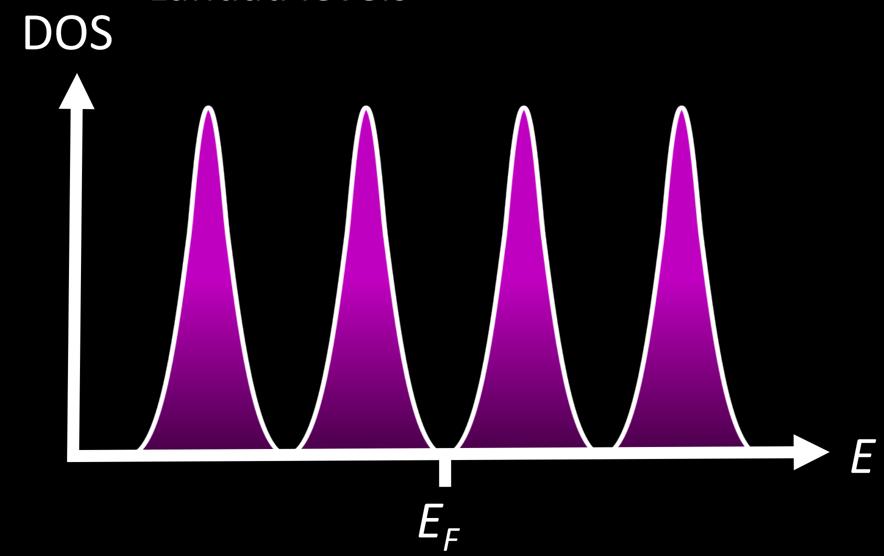
A nematic quantum Hall state

Anisotropic valley degree of freedom



2D Fermi pockets (schematic for AlAs)

Landau levels

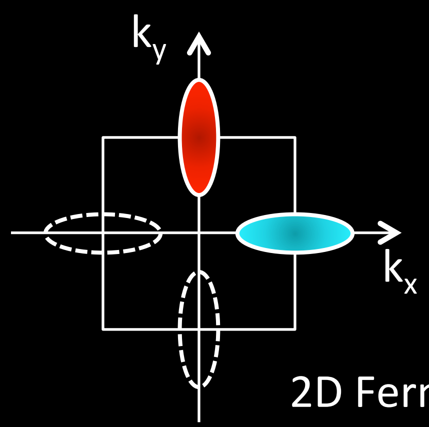


D. Abanin *et al., Phys. Rev. B* **82**, 035428 (2010)
A. Kumar *et al., Phys. Rev. B* **88**, 045133 (2013)

See also AlAs work from Shayegan group

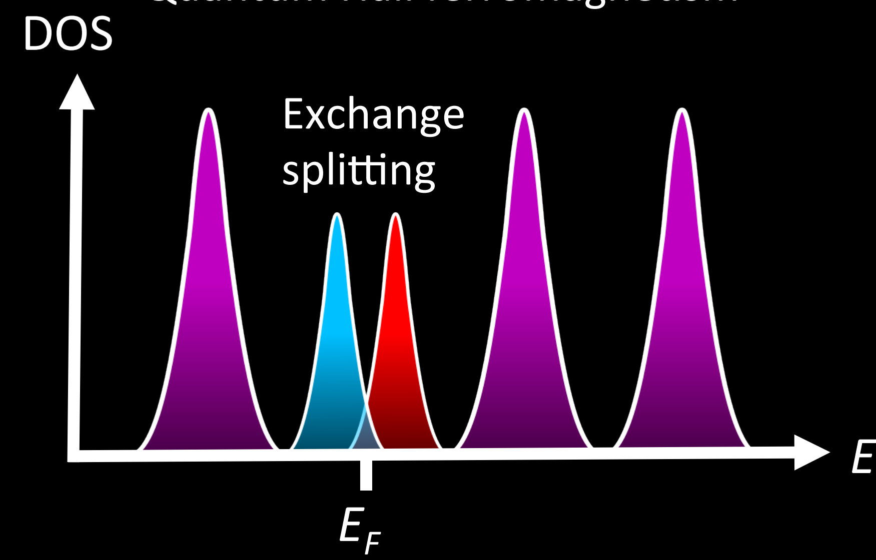
A nematic quantum Hall state

Anisotropic valley degree of freedom



2D Fermi pockets
(schematic for AlAs)

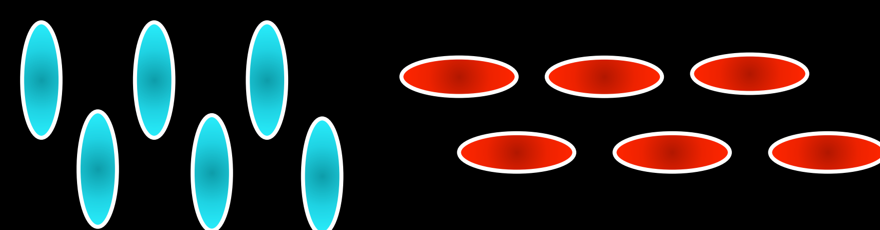
Quantum Hall ferromagnetism



Model nematic system

- Quantify role of interactions
- resulting Landau orbit anisotropy
- Locally probe individual domains

Resulting cyclotron orbit anisotropy

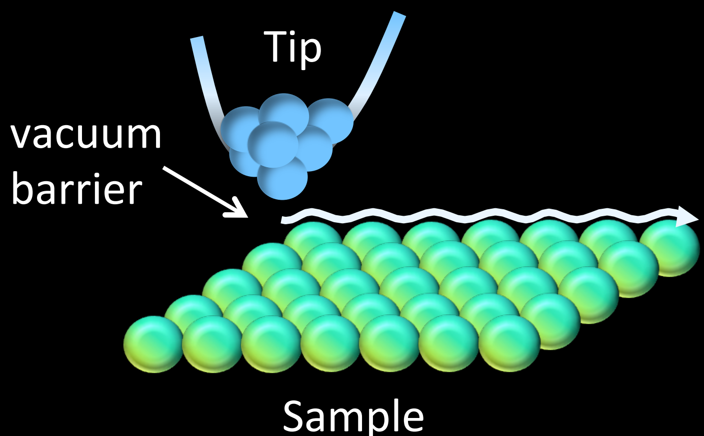


D. Abanin *et al., Phys. Rev. B* **82**, 035428 (2010)
A. Kumar *et al., Phys. Rev. B* **88**, 045133 (2013)

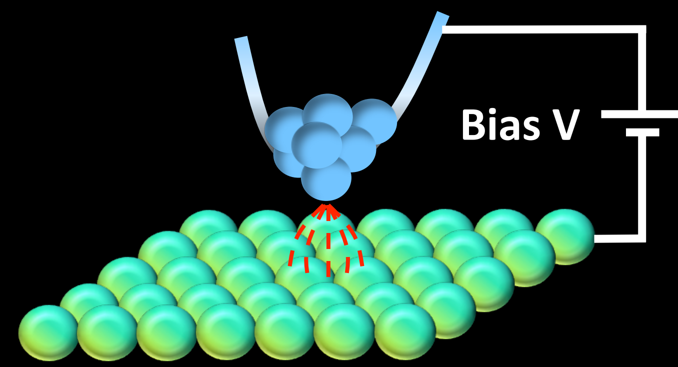
See also AlAs work from Shayegan group

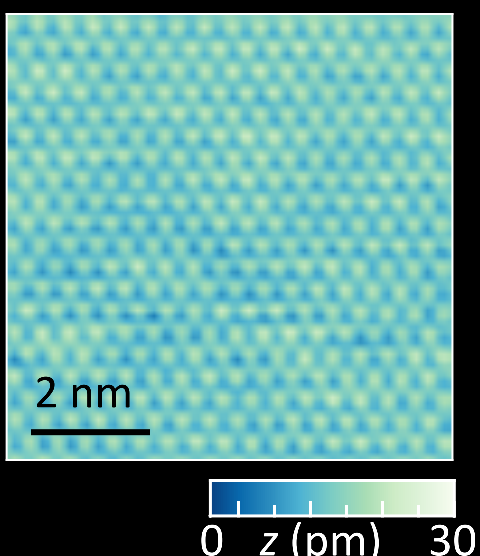
Scanning tunneling microscope (STM)

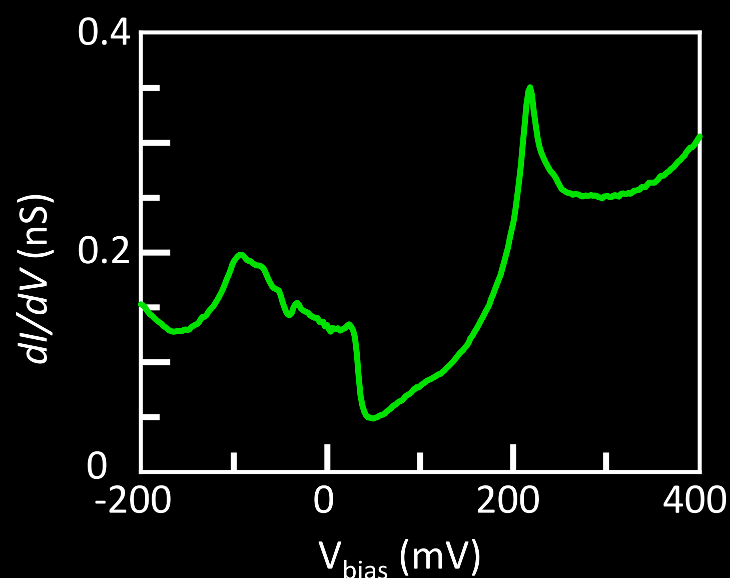
Atomic resolution imaging

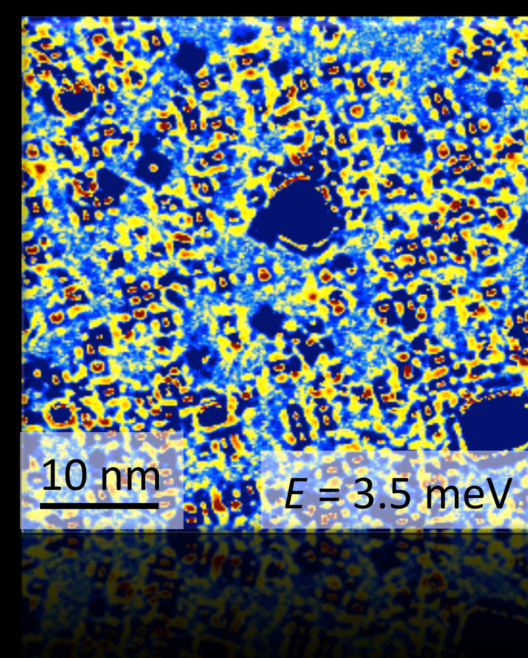


Spectroscopic mapping: dI/dV ∝ ρ(r, V)





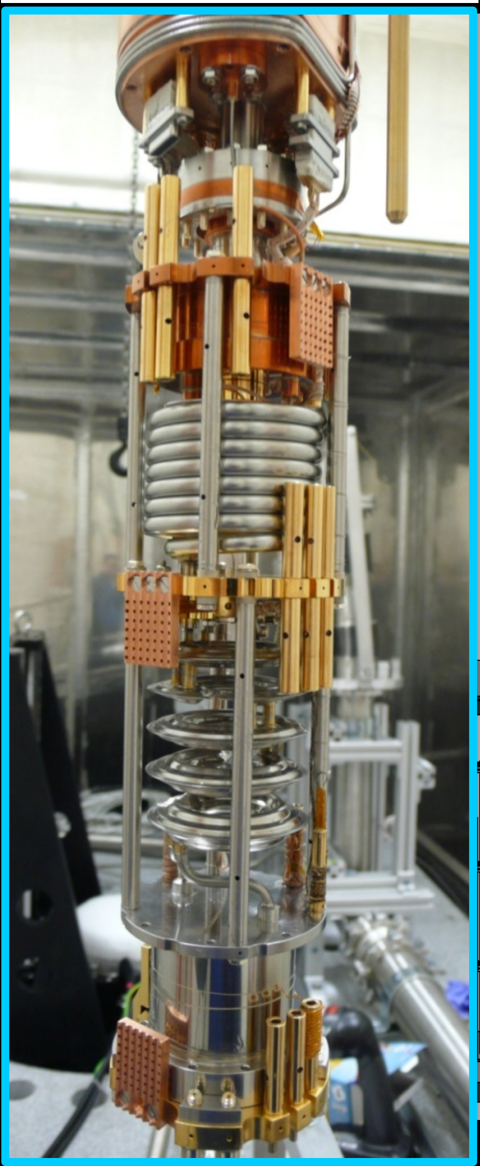


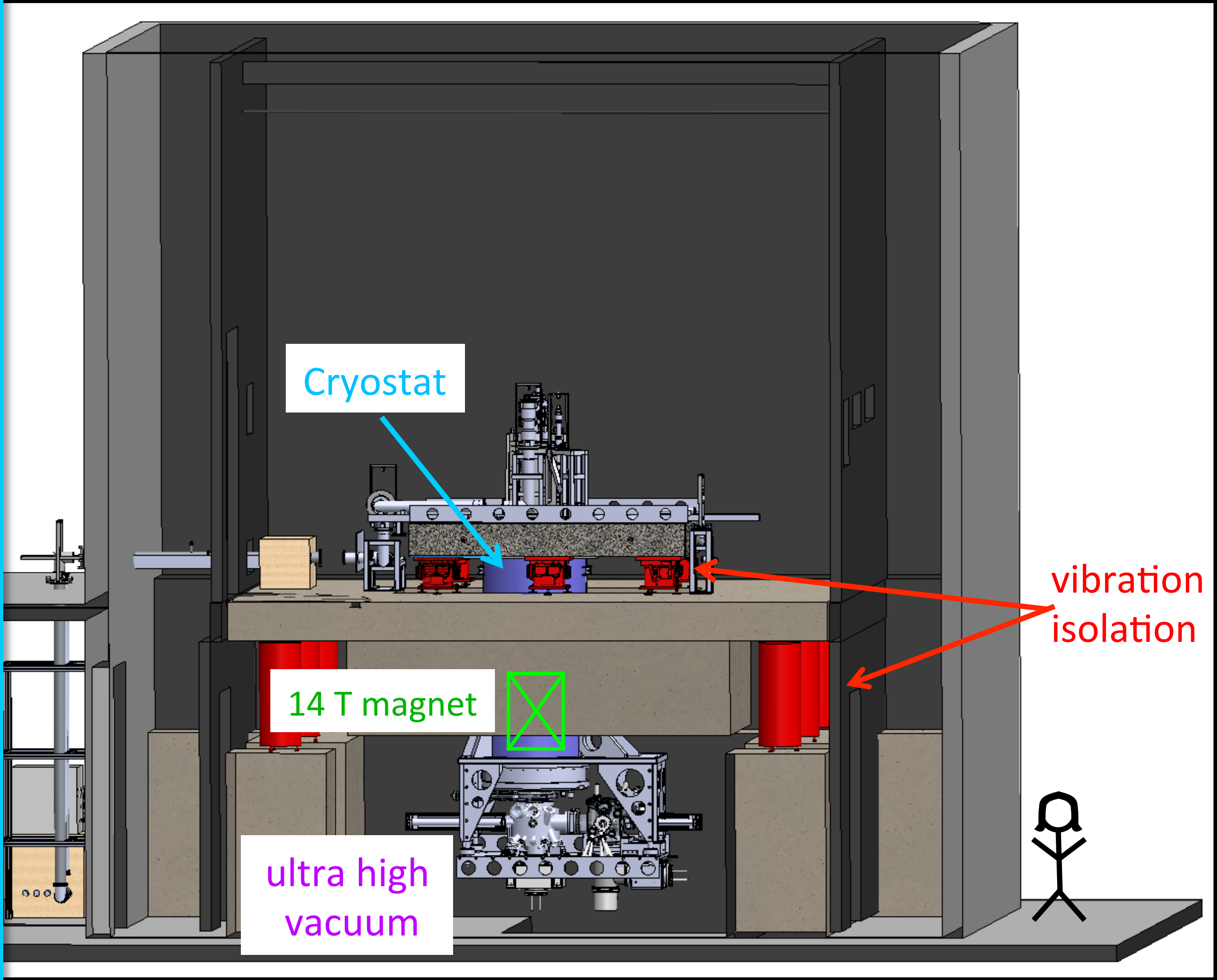


Dilution refrigerator
T_{phonon} = 20 mK
$T_{electron}$ = 250 mK

Our STM in the lab

Ultra-low temperature high magnetic field STM



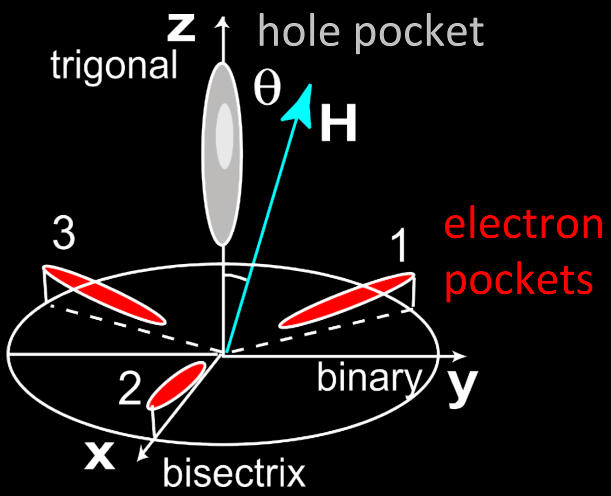


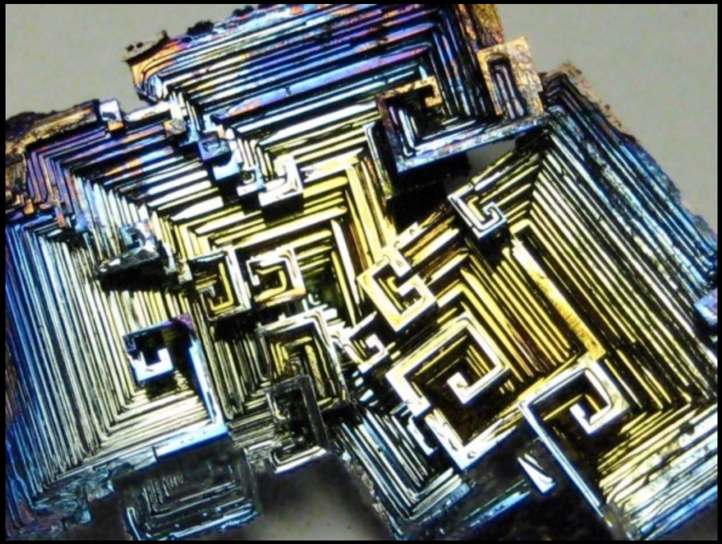
S. Misra *et al.*, ***Rev. Sci. Inst.*** **84, 103903 (2013)**

Bismuth: the pioneering quantum material

- Compensated semimetal
- Extremely clean (high mobility)
- Strong spin-orbit coupling
- Multiple degenerate Fermi pockets in the bulk

Bulk Bi Fermi surface





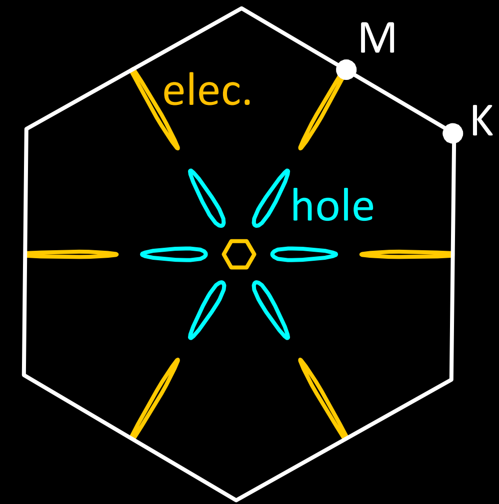
Bi single crystal

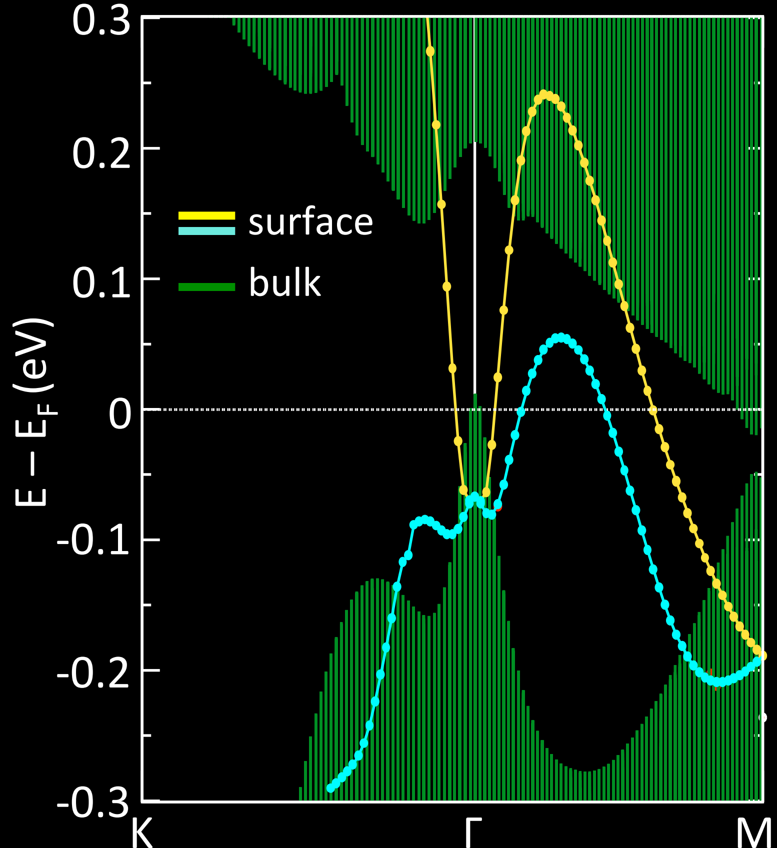
Valley polarization in bulk bismuth at high B, low T:

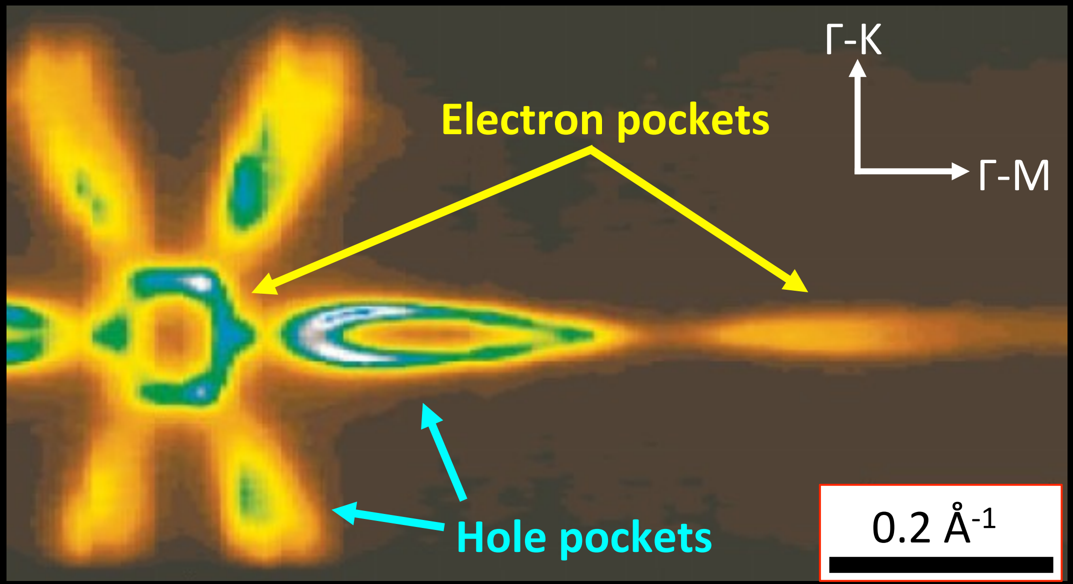
Torque magnetometry: Li, L. *et al., Science* **321**, 547-550 (2008)
Magnetoresistance: Zhu, Z. *et al., Nat. Phys*. **8**, 89-94 (2012)
Magnetostriction: Kuchler, R. *et al., Nat. Mater*. **13**, 461-465 (2014)

Bi(111) surface states

Large spin-orbit coupling – lifts spin degree of freedom
Multiple degenerate valleys



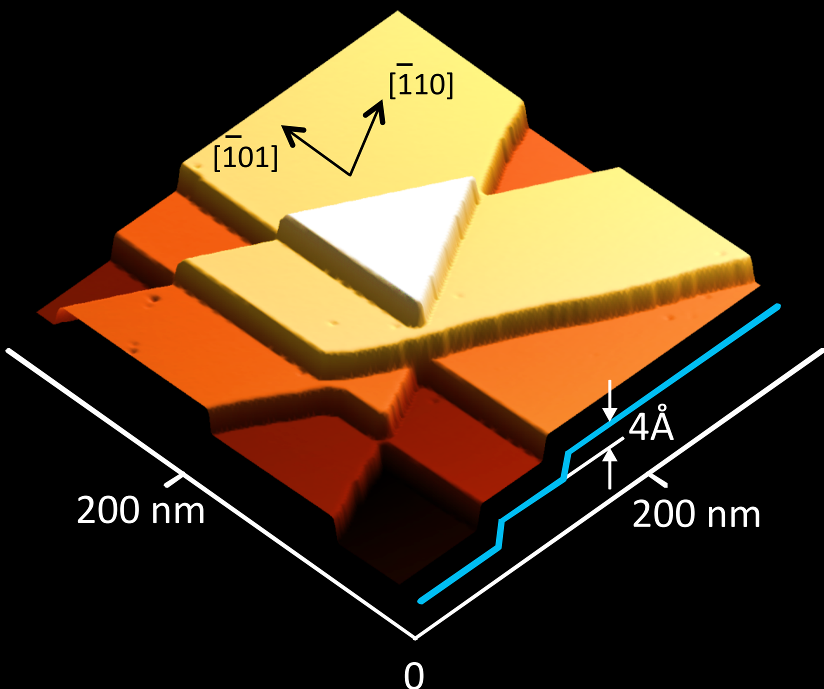




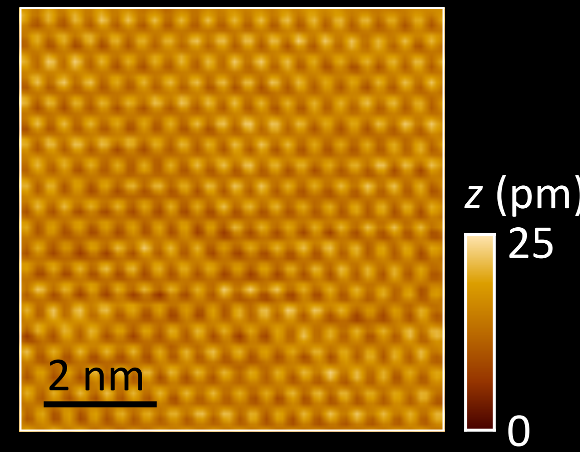
Ast, C. R. and Höchst, H., *Phys. Rev. Lett.* **87**, 177602 (2001)
Koroteev, Yu. M. *et al.*, *Phys. Rev. Lett.* **93**, 046403 (2004)
Hirahara, T. *et al.*, *Phys. Rev. Lett.* **97**, 146803 (2006)

Bi(111) surface

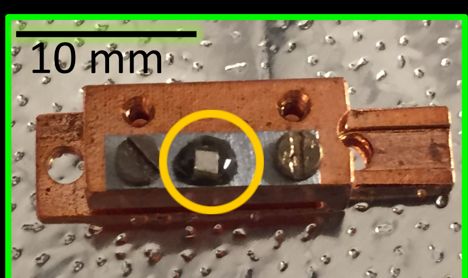
A typical cleaved surface

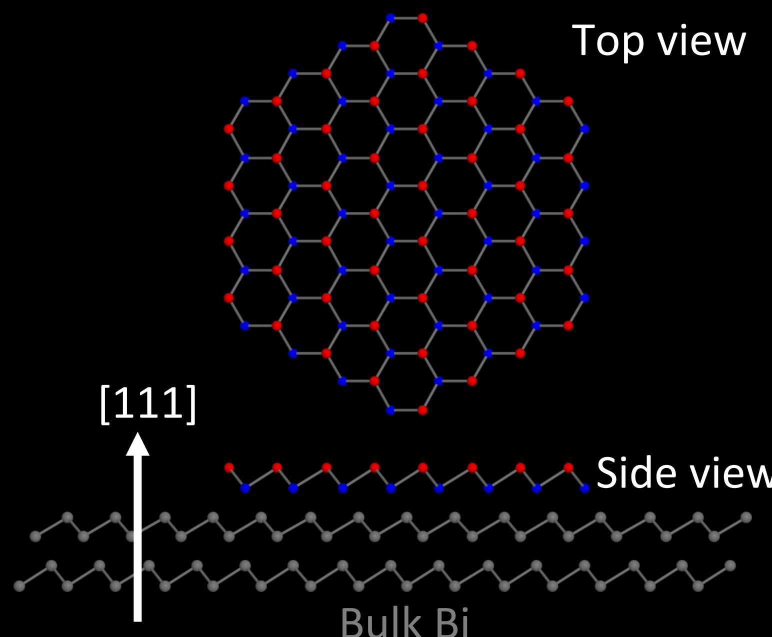


Hexagonal atomic lattice



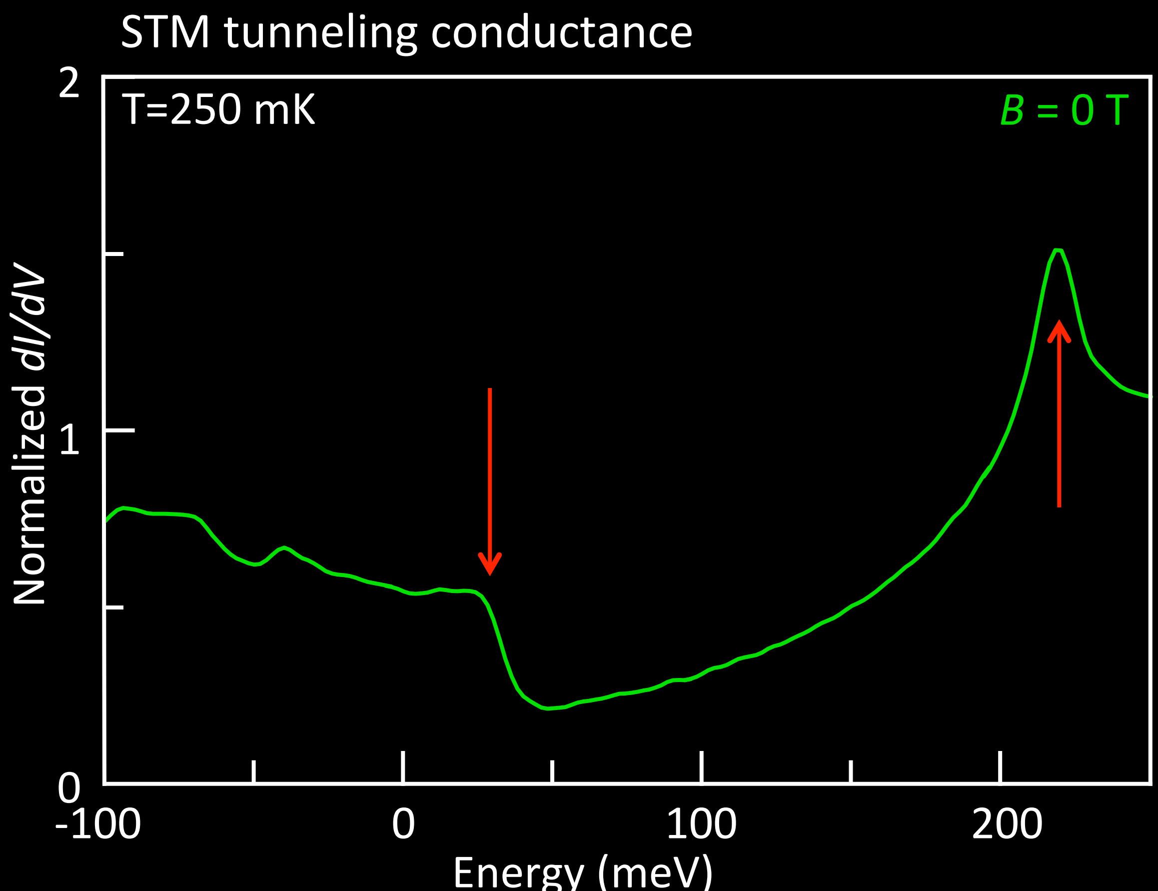
Bi crystal on sample holder

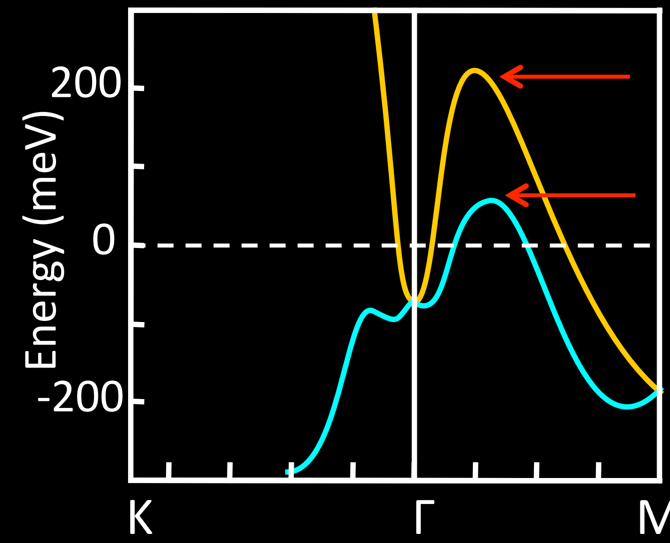




I. K. Drozdov *et al., Nat. Phys.* **10**, 664 (2014)

Quantized energy levels of the bismuth surface

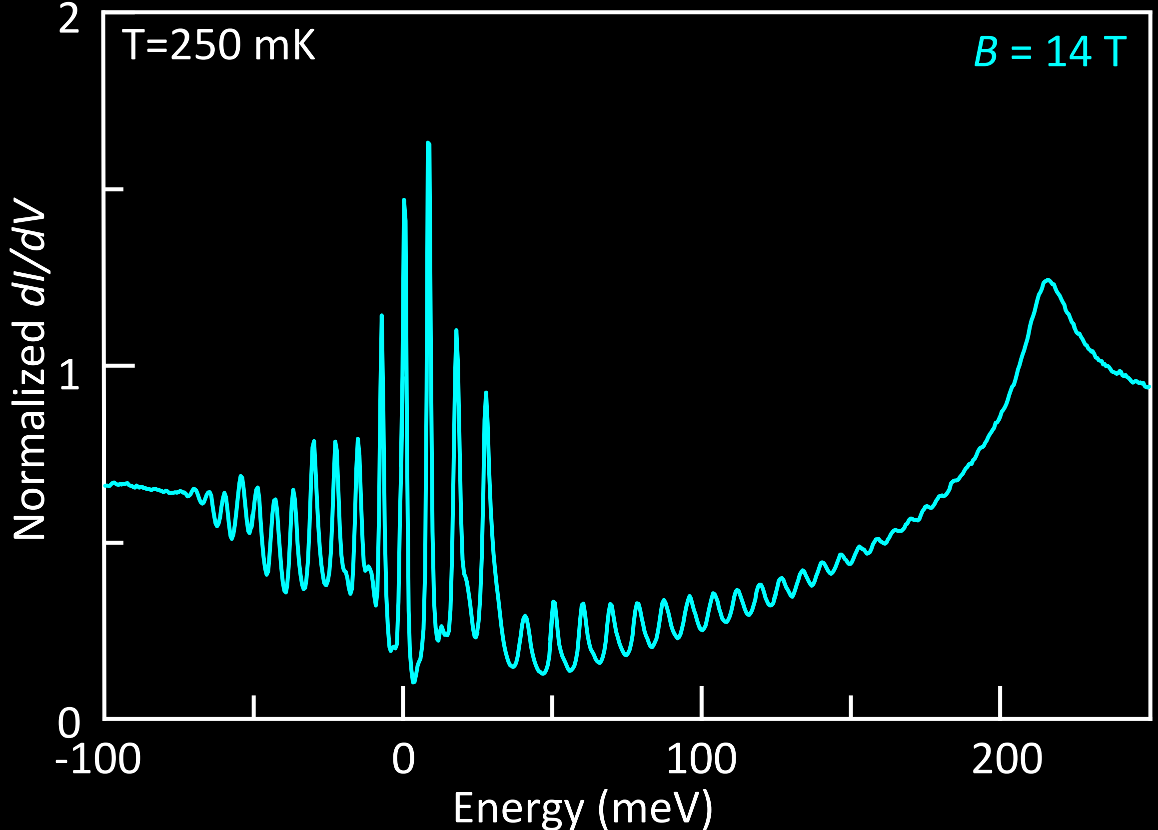




B. E. Feldman*, MTR* *et al., Science* **354,** 316 (2016)

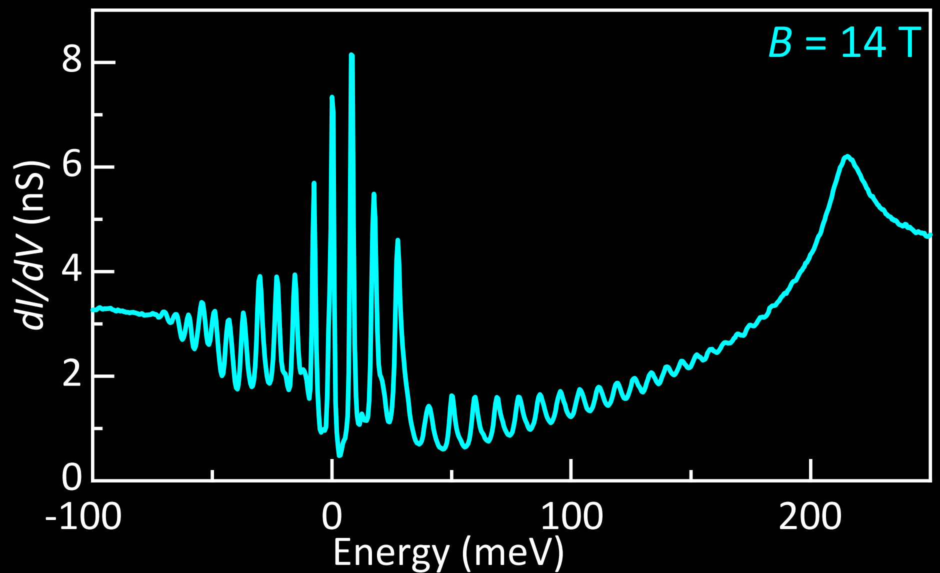
Quantized energy levels of the bismuth surface

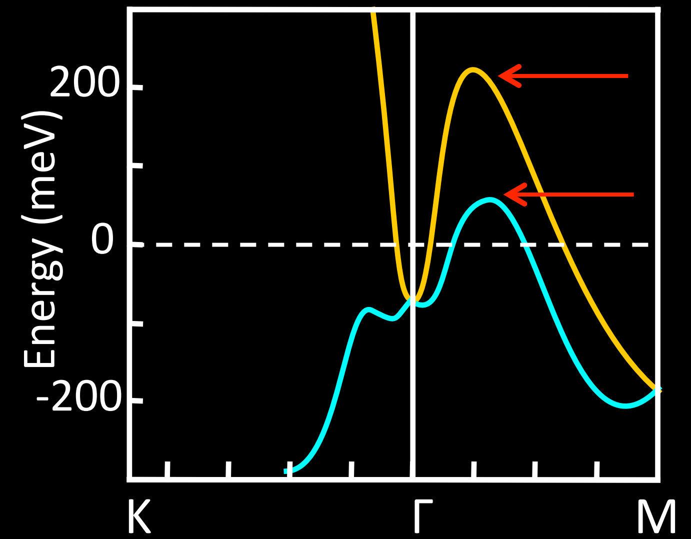
Landau levels!



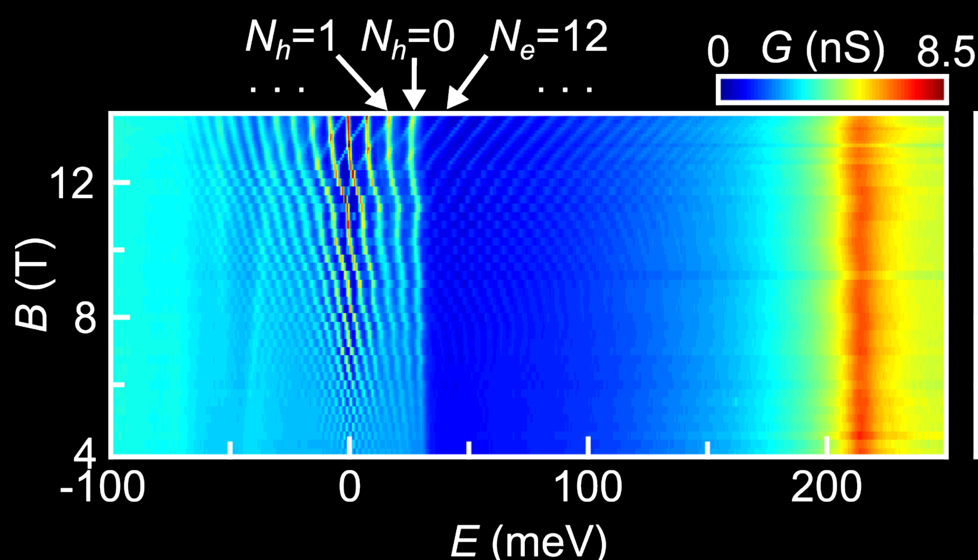
B. E. Feldman*, MTR* *et al., Science* **354,** 316 (2016)

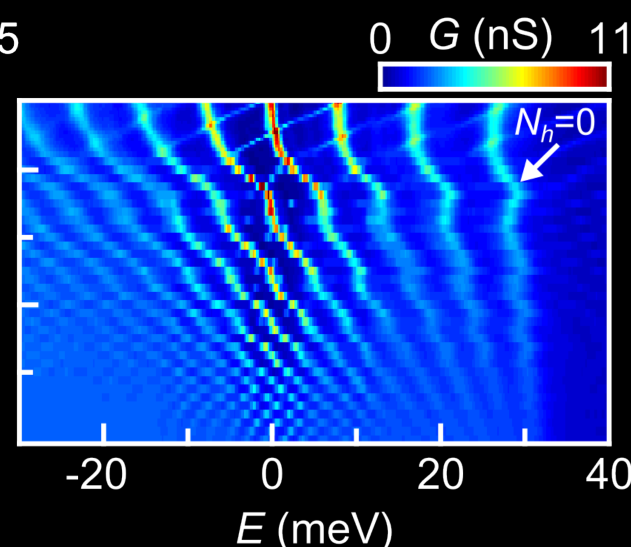
Surface state Landau levels (LLs)





Fixed hole density: $p \approx 7e12\ cm^{-2}$

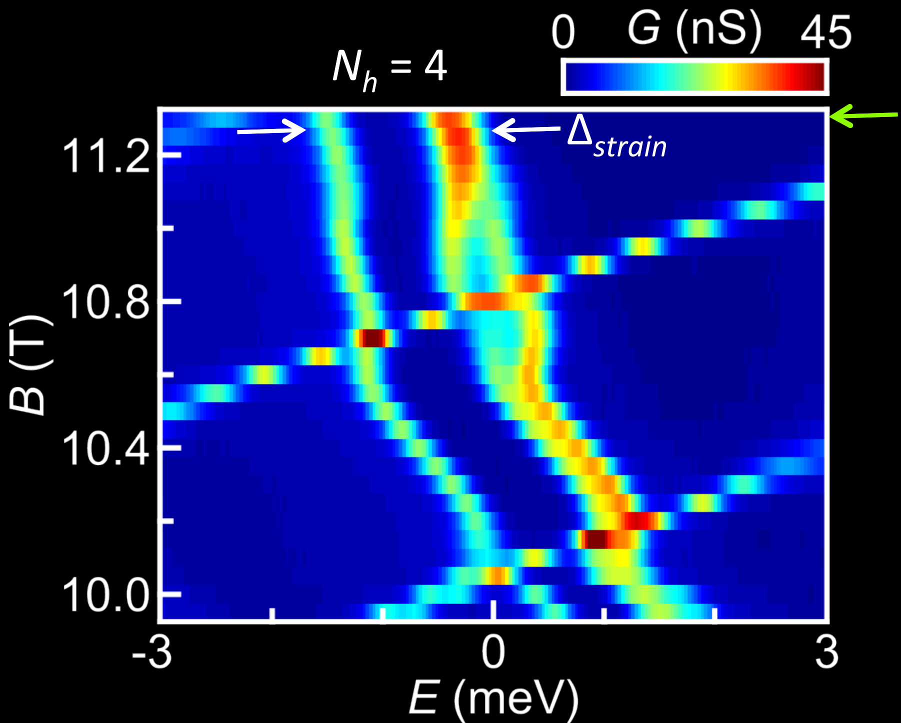


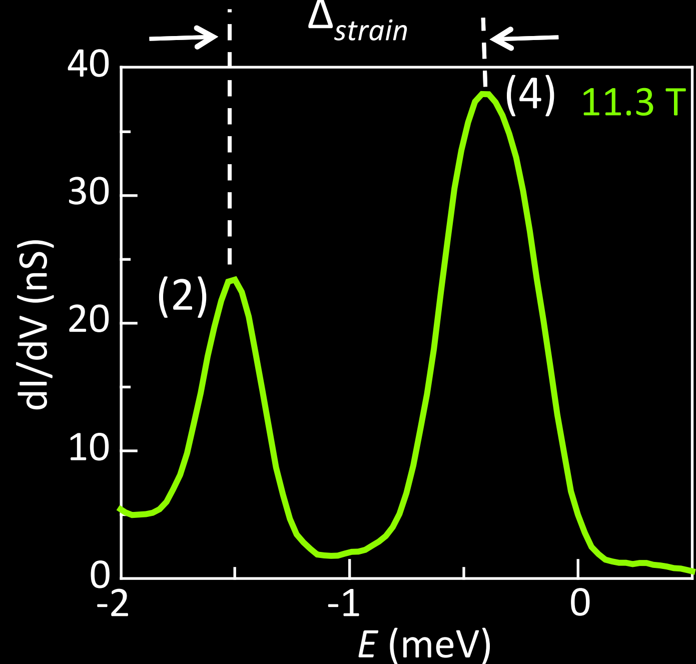


B. E. Feldman*, MTR* *et al., Science* **354,** 316 (2016)

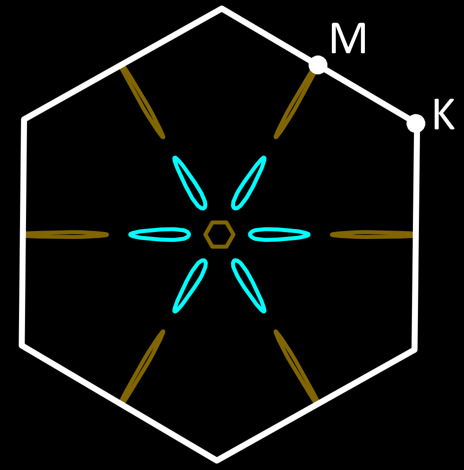
see also: Du, H. *et al., Nat. Comms.* **7**, 10814 (2016)

Lifting of the six-fold valley degeneracy



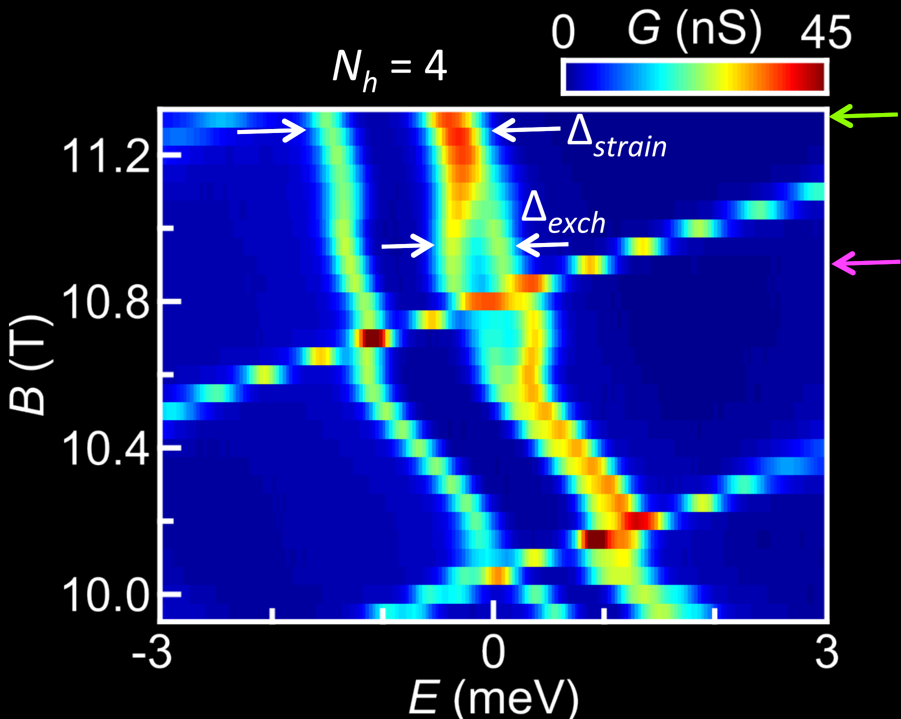


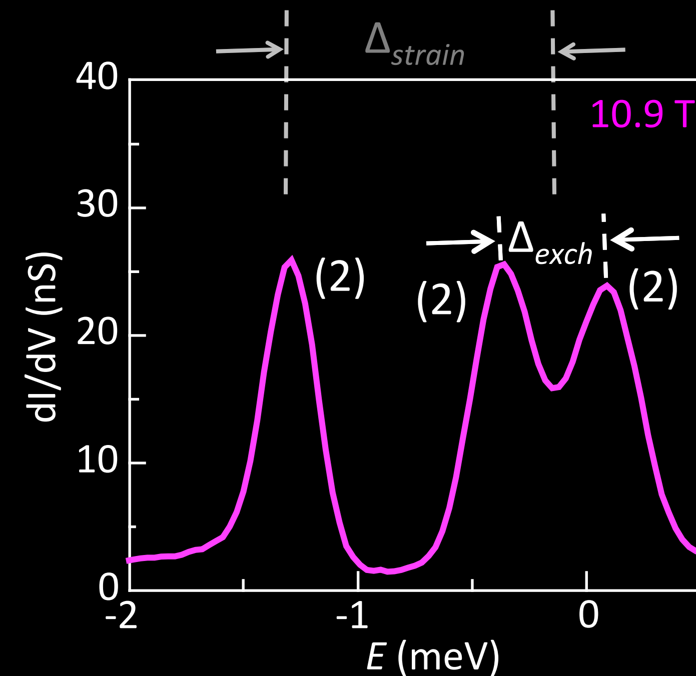
Local strain: independent of Fermi level and orbital index, but depends on position



B. E. Feldman*, MTR* *et al., Science* **354,** 316 (2016)

Lifting of the six-fold valley degeneracy

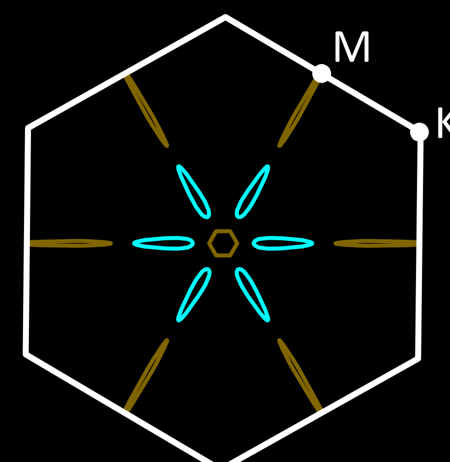




Local strain: independent of Fermi level and orbital index, but depends on position

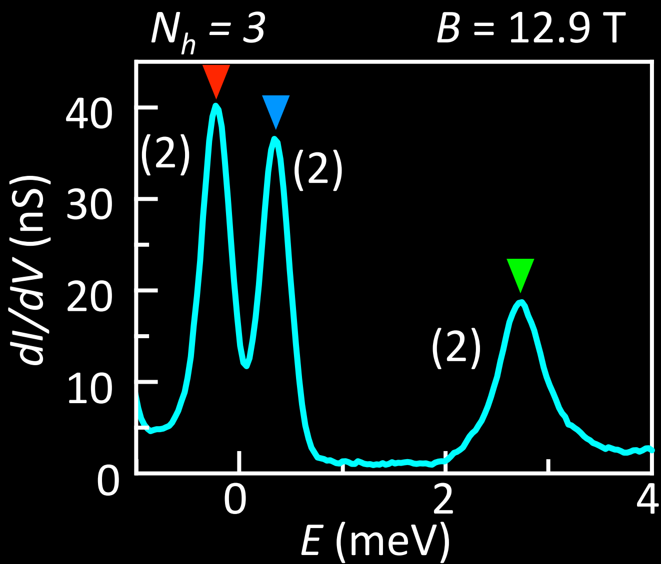
Exchange interactions: opens gap *only* at Fermi level

Spectroscopy: quantitative probe of single-particle vs. many-body effects in the formation of these broken symmetry states

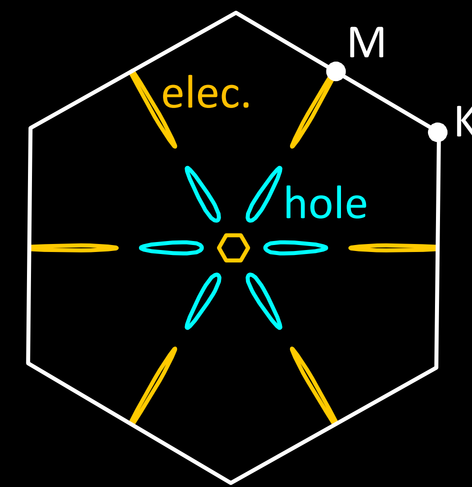


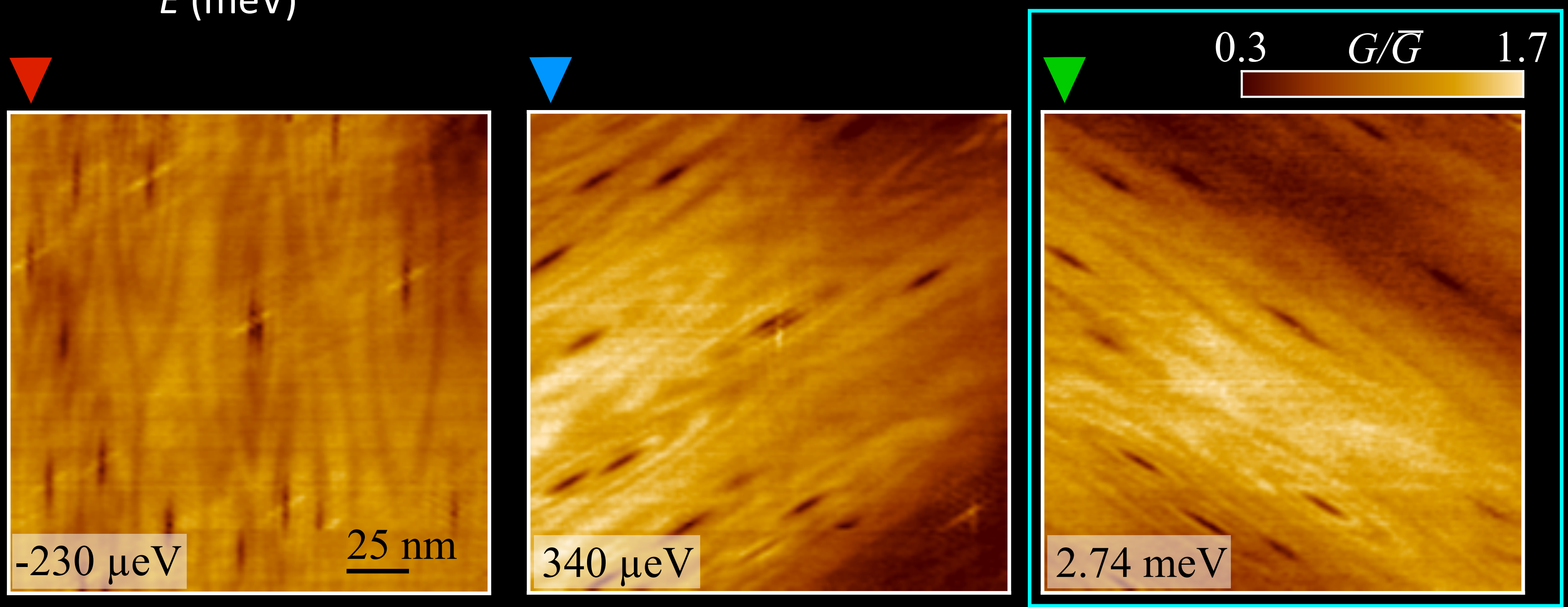
B. E. Feldman*, MTR* *et al., Science* **354,** 316 (2016)

Real-space imaging of broken symmetry states



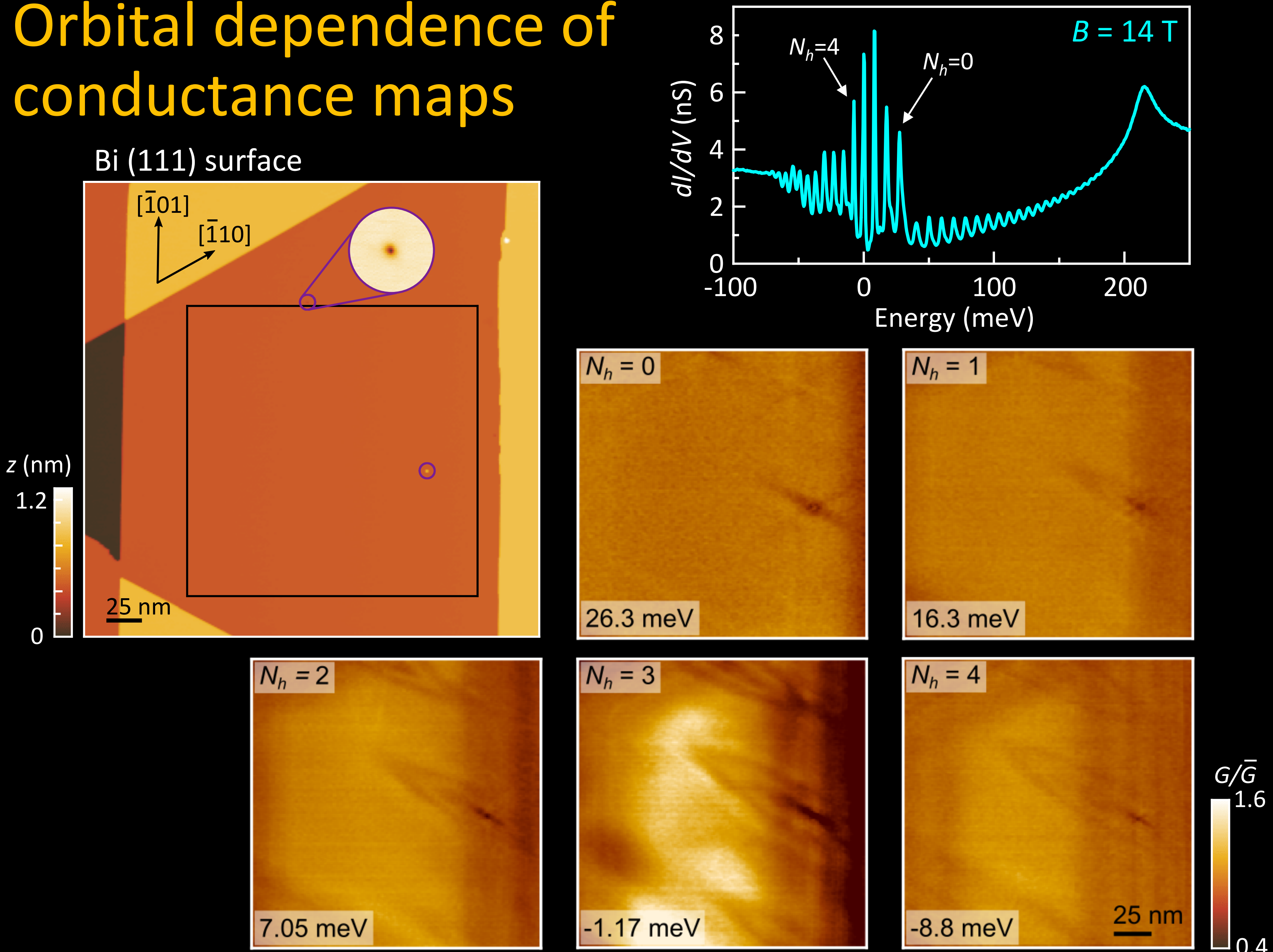
Remainder of talk:
- Imaging individual Landau level wavefunctions
- Observing nematic domains





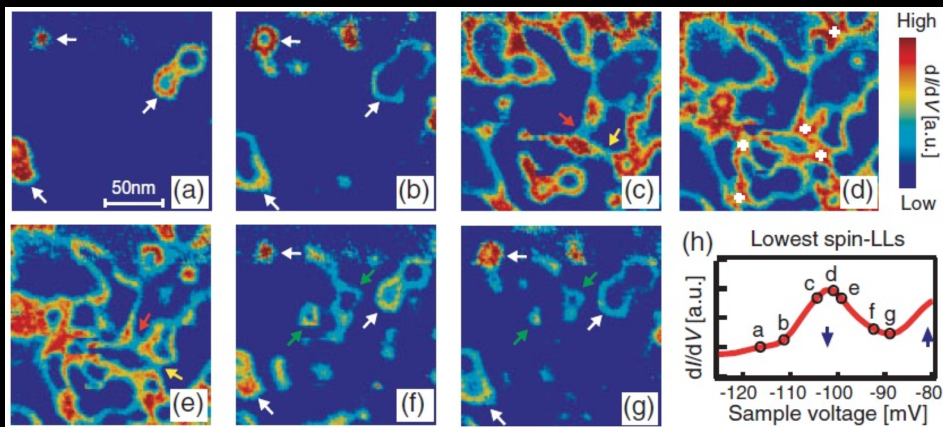
B. E. Feldman*, MTR* *et al.*, *Science* **354,** 316 (2016)

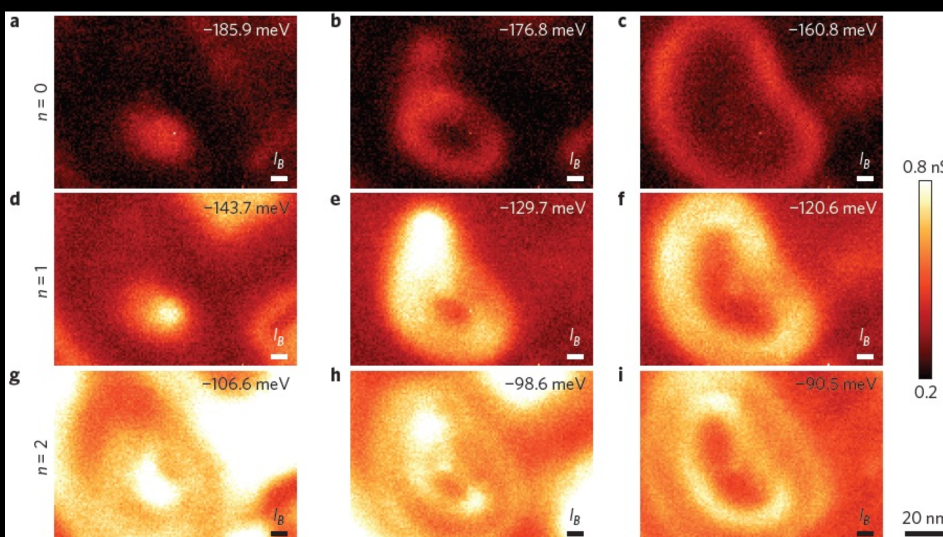
Orbital dependence of conductance maps



Previous STM imaging in the quantum Hall regime

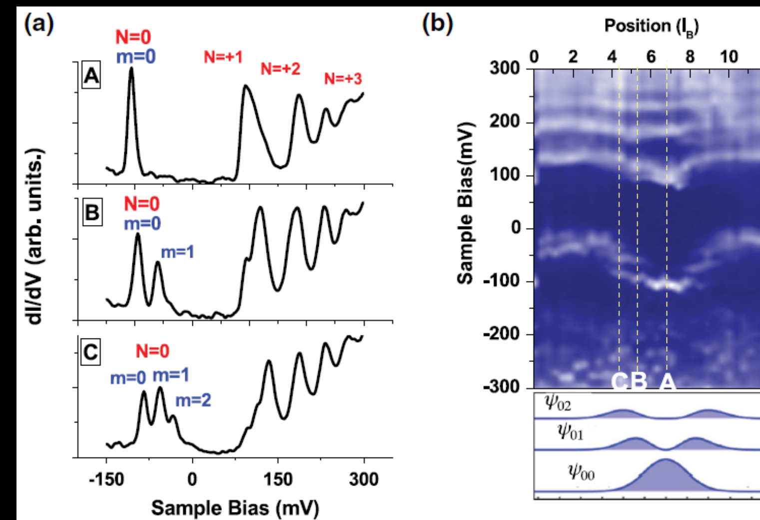
More disordered samples: drift states

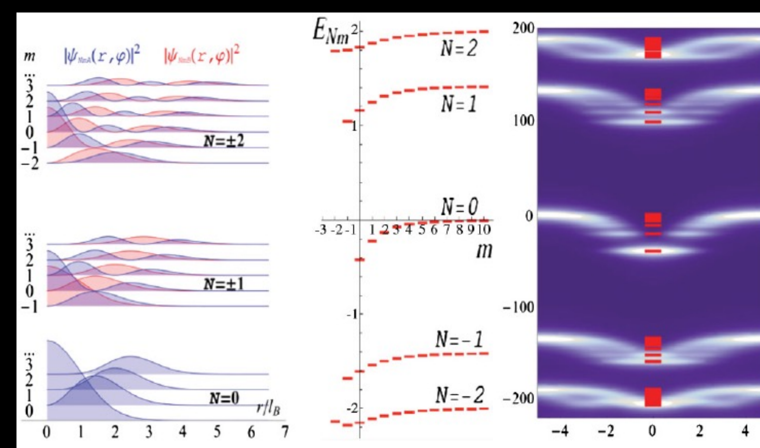




K. Hashimoto *et al.*, *Phys. Rev. Lett.* **101**, 256802 (2008)
Y.-S. Fu *et al.*, *Nat. Phys.* **10**, 815-819 (2014)

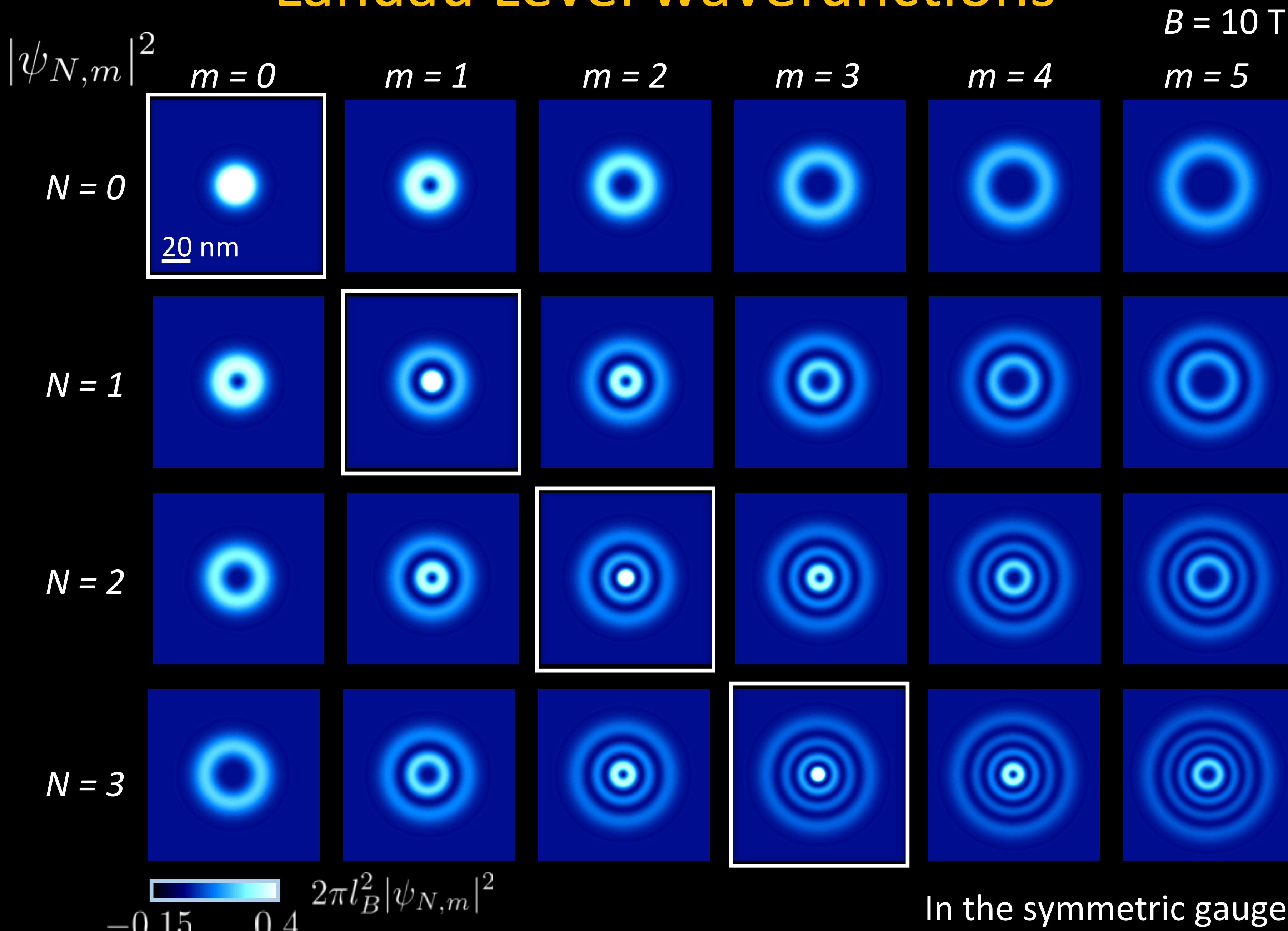
Evidence of impurity-shifted Landau orbits





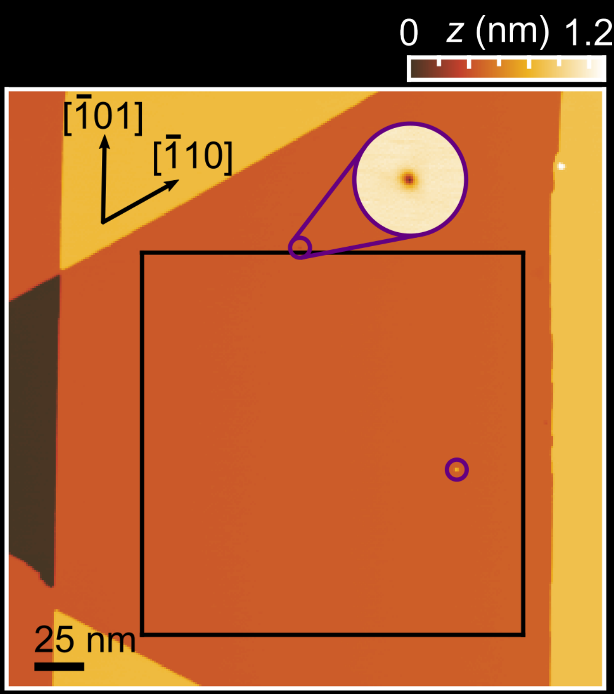
A. Luican-Mayer *et al.*, *Phys Rev. Lett.* **112**, 036804 (2014)
see also: Y. Okada *et al.*, *Phys. Rev. Lett.* **109**, 166407 (2012)

Landau Level wavefunctions



In the symmetric gauge

Effect of a defect

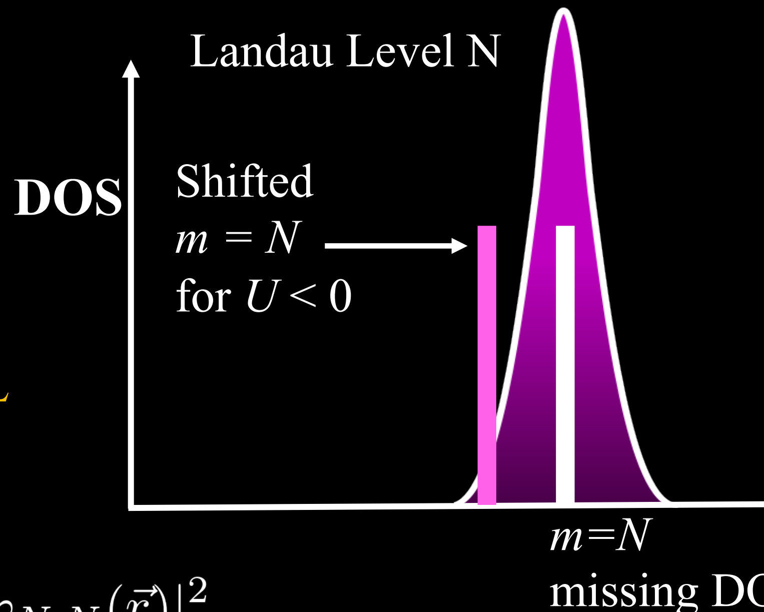


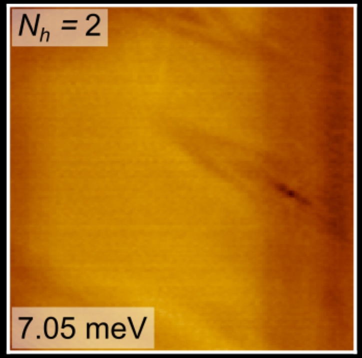
Model atomic-scale defect as a delta function potential

$$U = \alpha\delta(\vec{r})$$

Only $m = N$ cyclotron orbit is shifted in energy

$$E_{N,N} - E_{N,m\neq N} = \alpha|\varphi_{N,N}(0)|^2 = \frac{\alpha}{2\pi l_B^2}$$



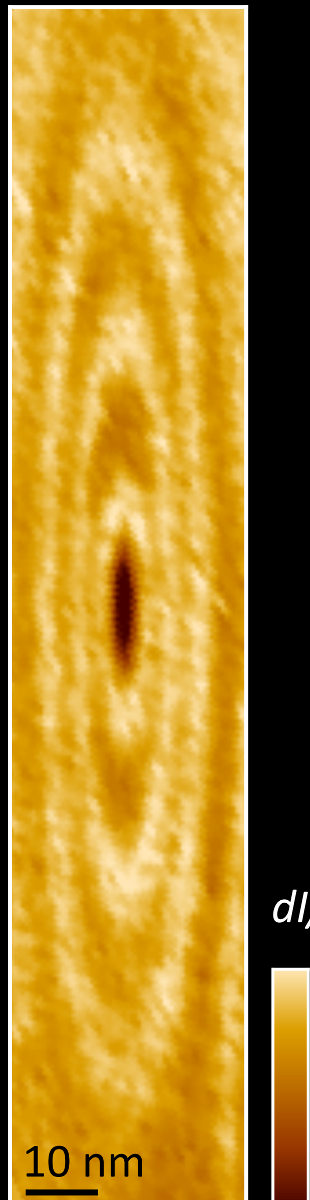


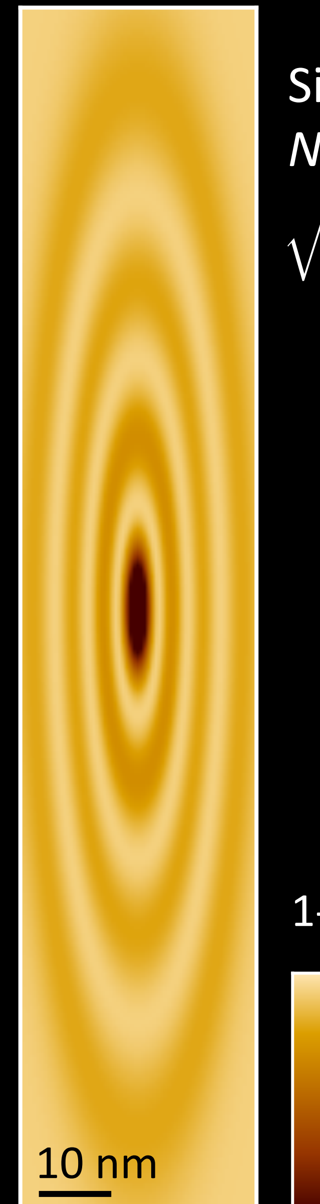
Conductance map measured at LL peak has decreased signal due to shifted cyclotron orbit.

$$\sum_{m\neq N} |\varphi_{N,m}(\vec{r})|^2 = \frac{1}{2\pi l_B^2} - |\varphi_{N,N}(\vec{r})|^2$$

Imaging an individual Landau orbit

Experiment
B = 12.75 T
E = 770 μeV

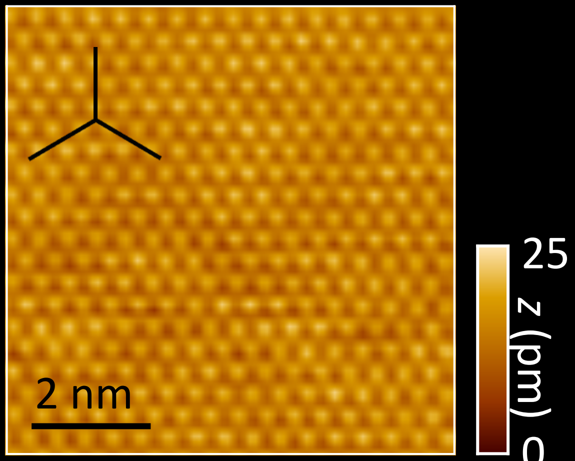




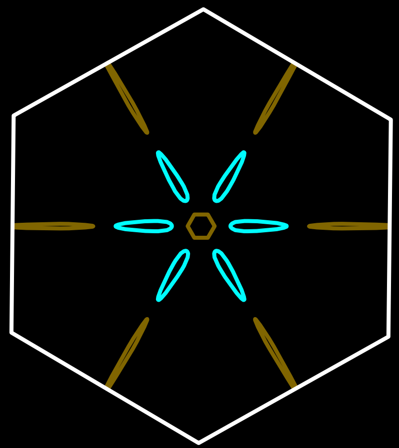
Simulation for
N=3 Landau level
$\sqrt{m_x/m_y} = 5$

Symmetry of the Bi(111) surface

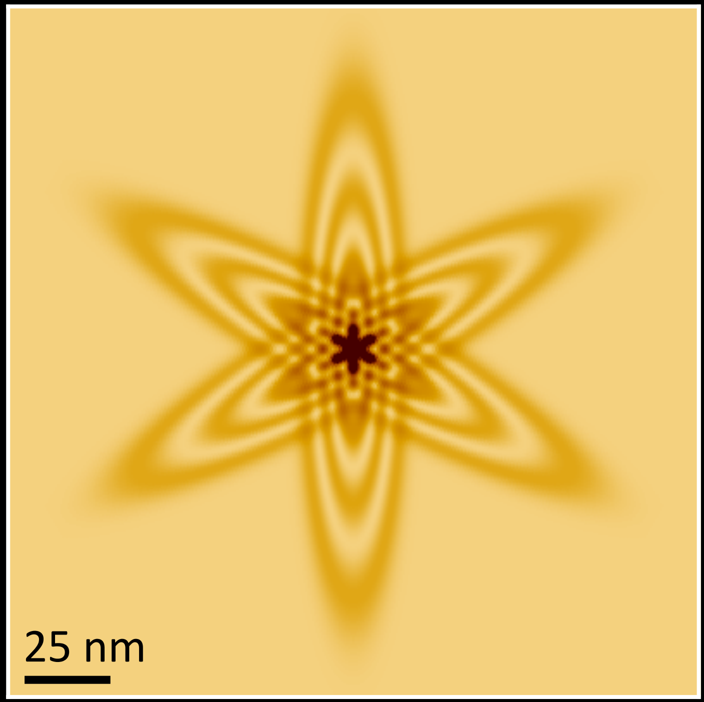
atomic lattice



Fermi surface

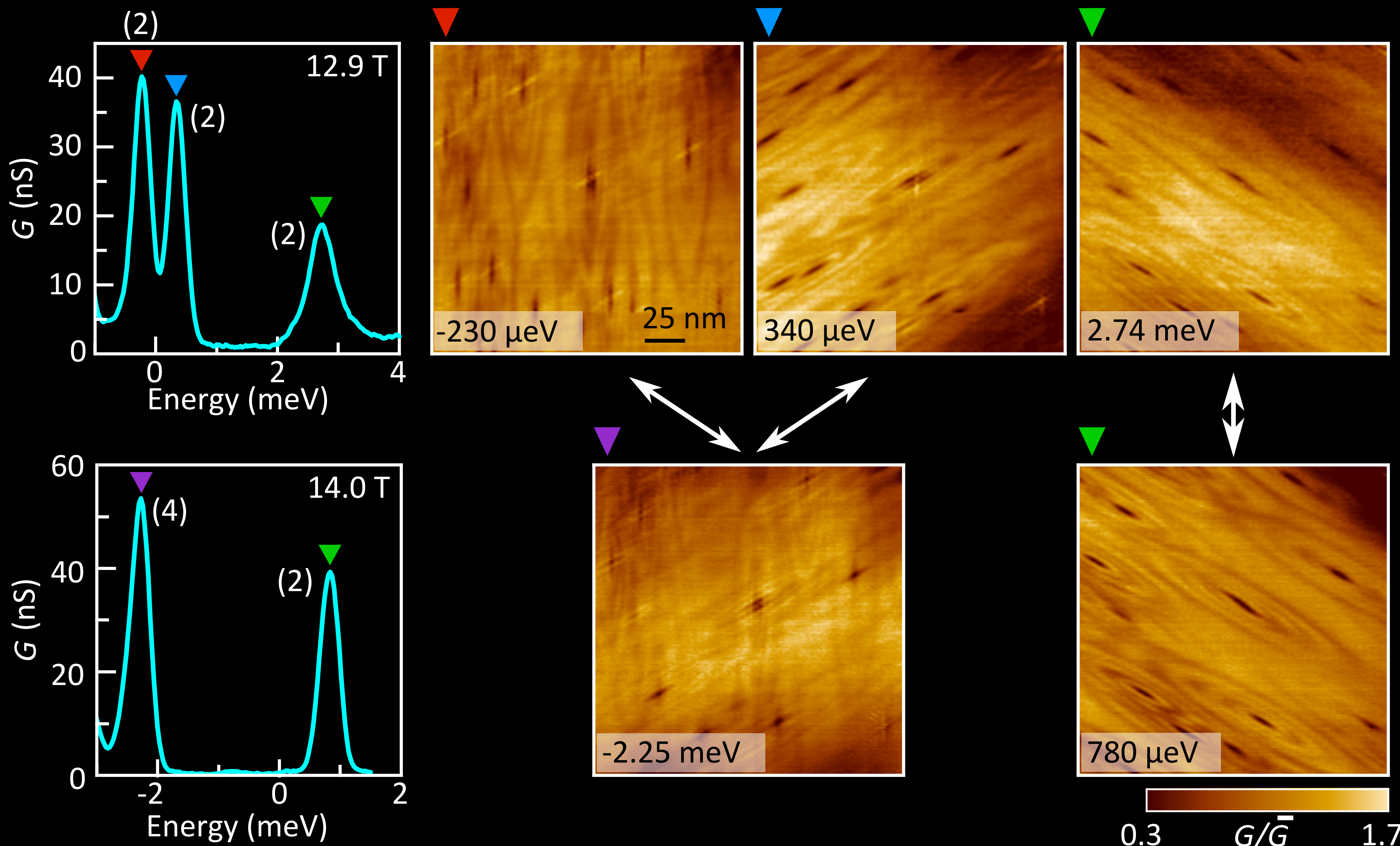


Expected electron wavefunction in the absence of symmetry breaking



Interaction driven nematic quantum phase

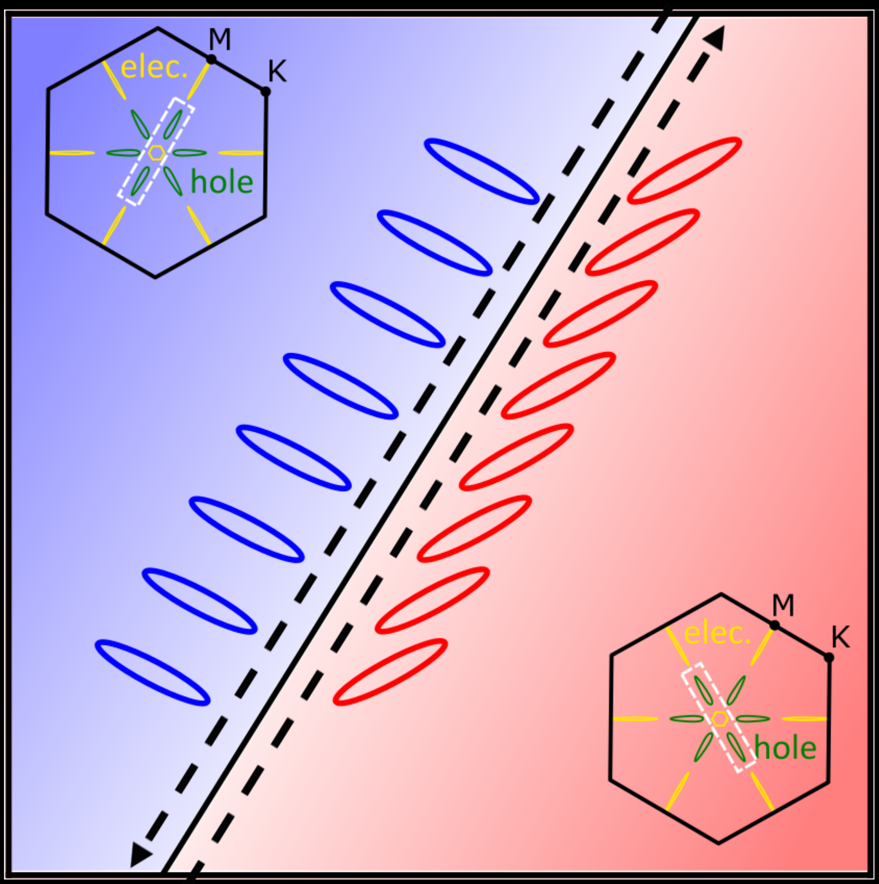
Spontaneous valley-symmetry breaking: image unidirectionality of wavefunctions
Quantify roles of single-particle and many-body effects

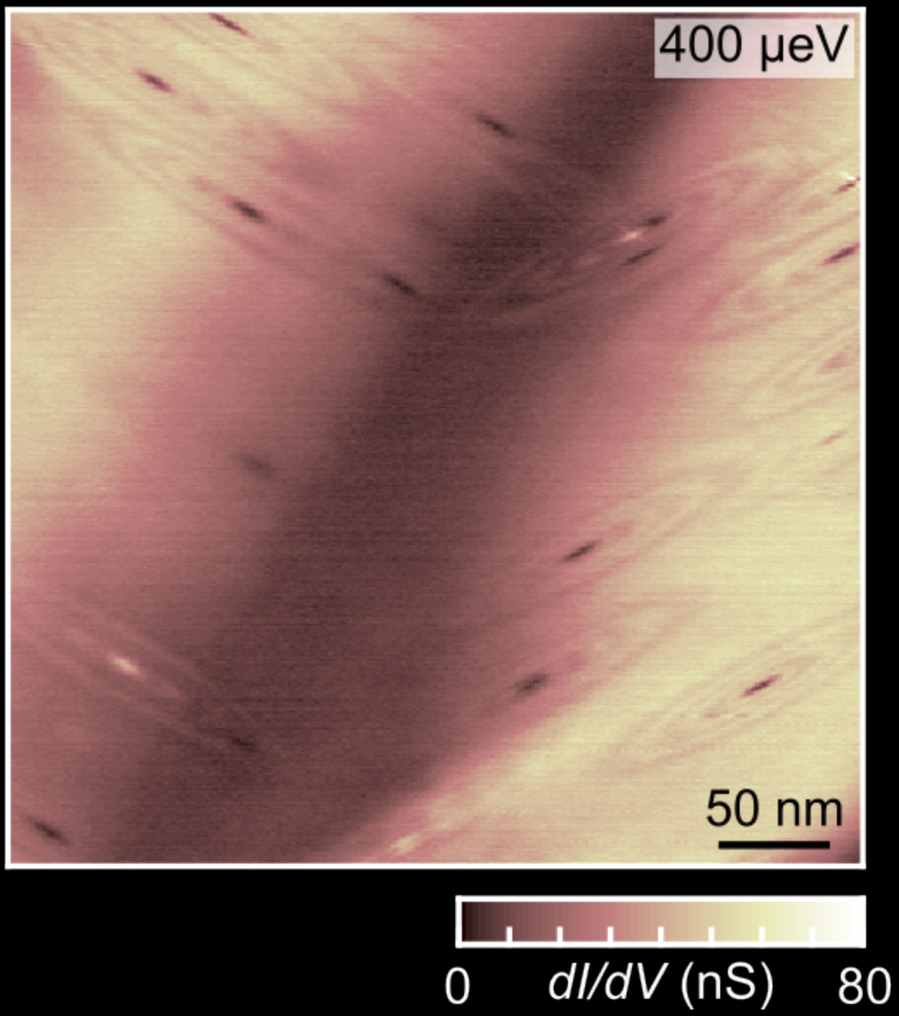


B. E. Feldman*, MTR*, *et. al.*, *Science* **354,** 316 (2016)

The boundary between nematic domains

- 1D counter-propagating chiral edge modes, Luttinger liquid behavior

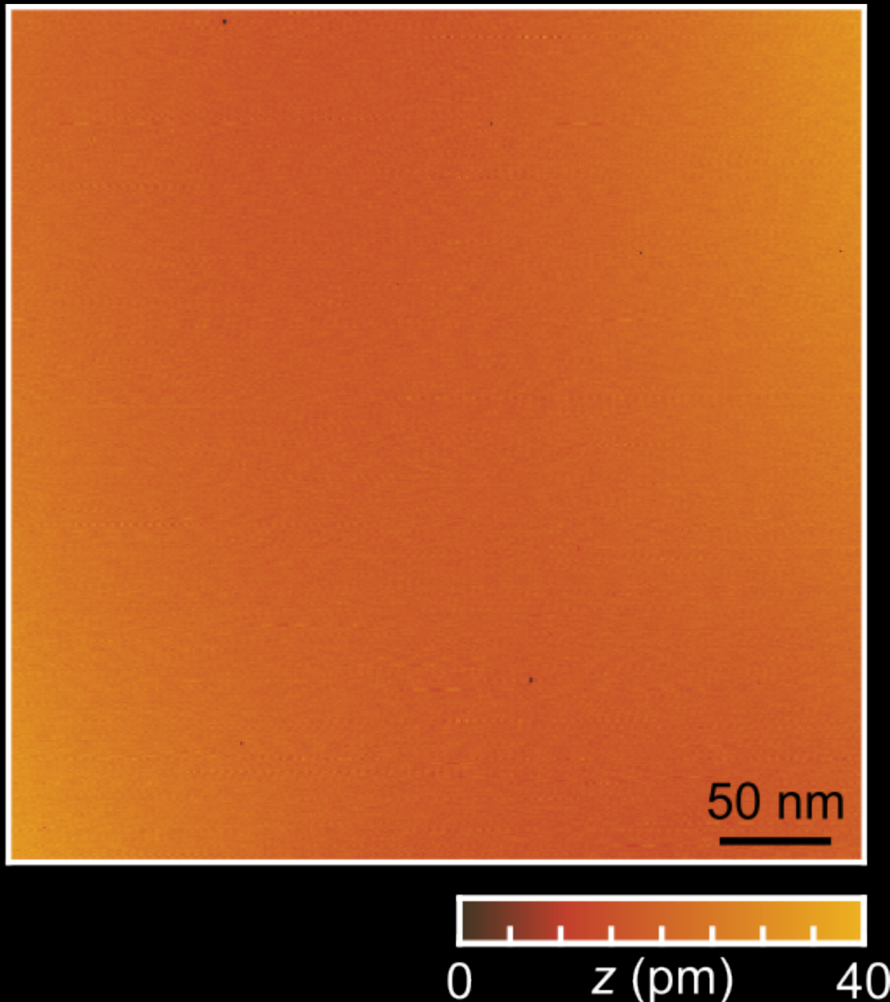




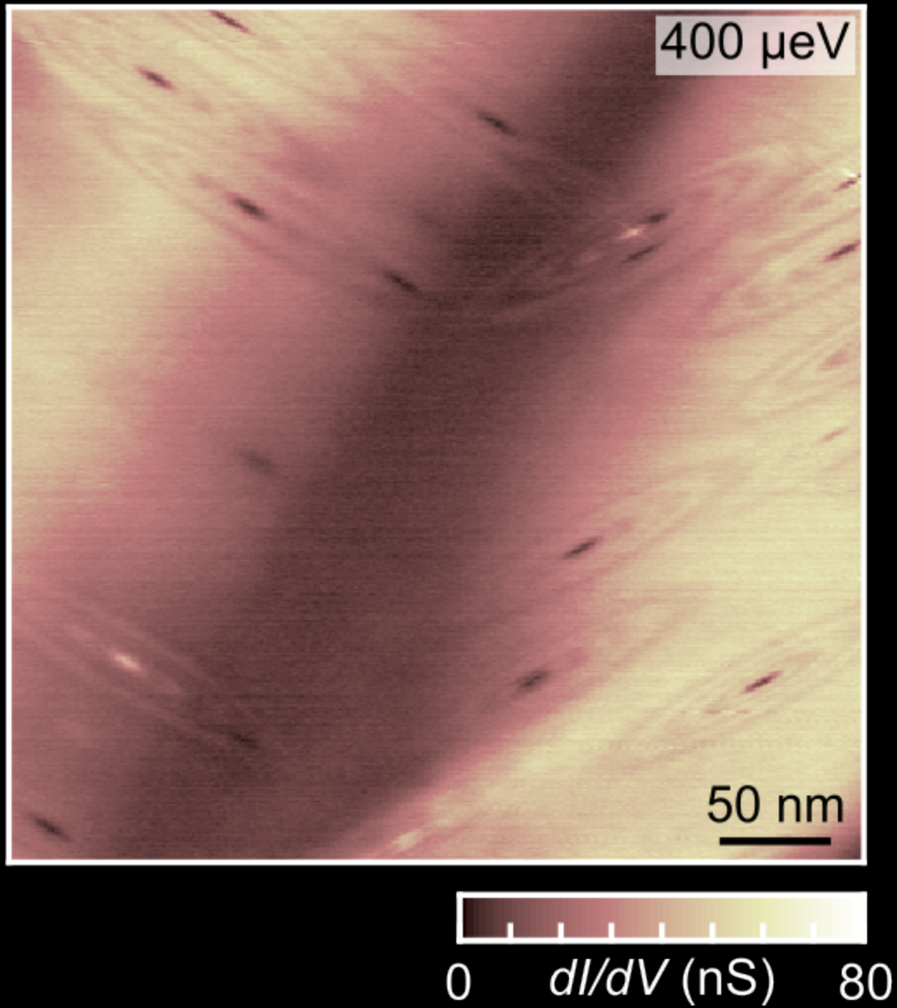
D. A. Abanin *et al.,* PRB 82, 035428 (2010)
A. Kumar *et al.,* PRB 88, 045133 (2013*)*

A pristine domain wall

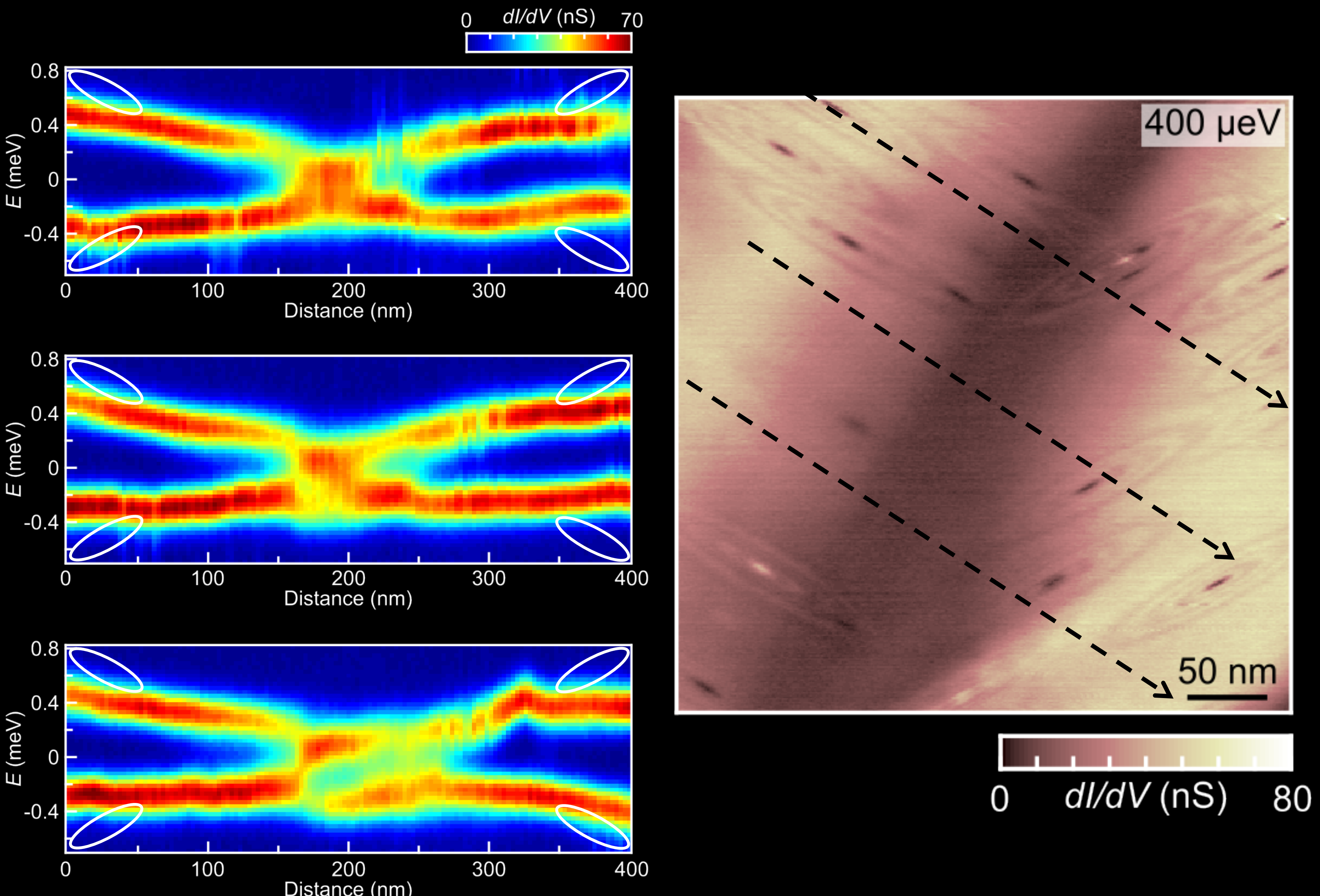
Featureless topography



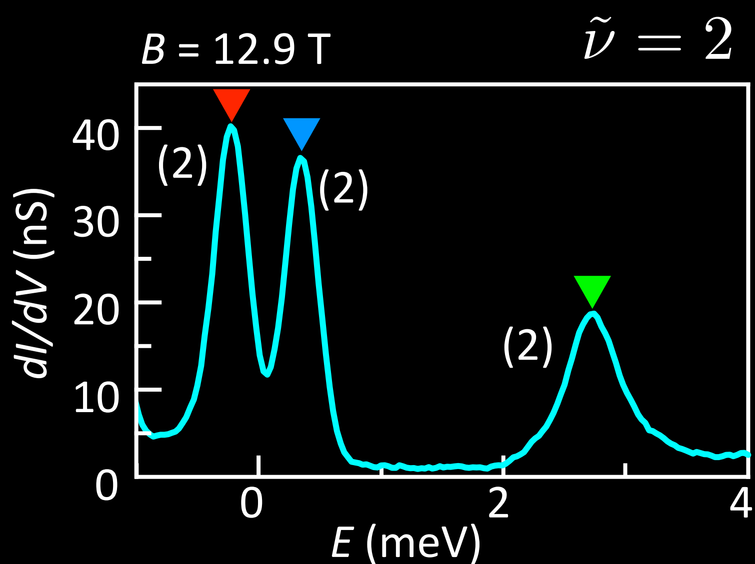
Nematic domains in conductance maps

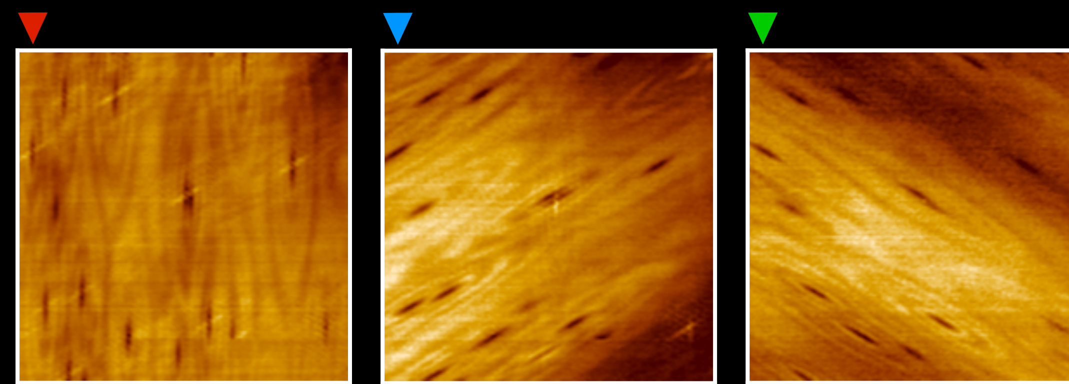


Linecuts across nematic domain wall



Imaging additional broken symmetry states





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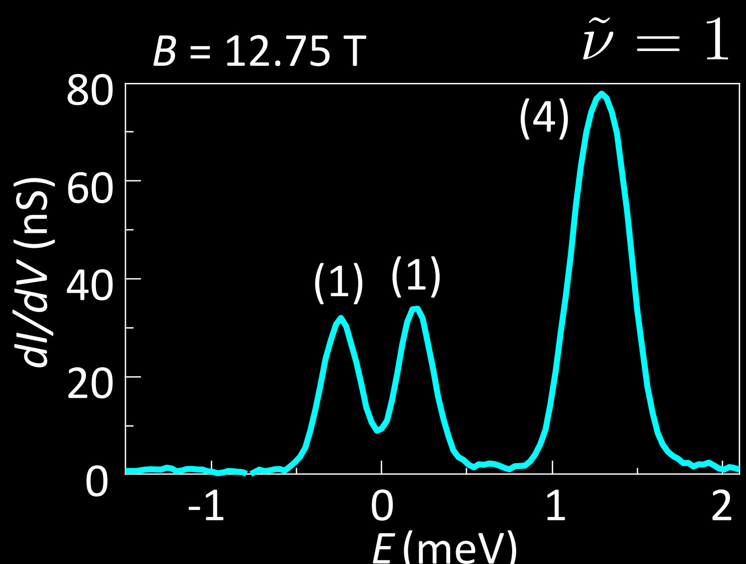
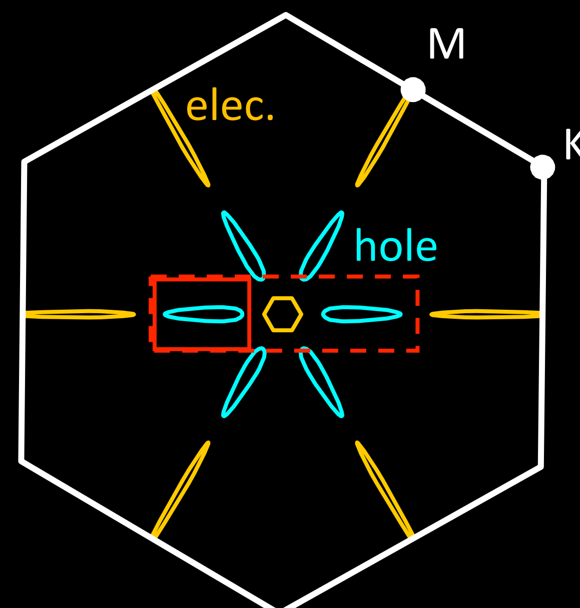
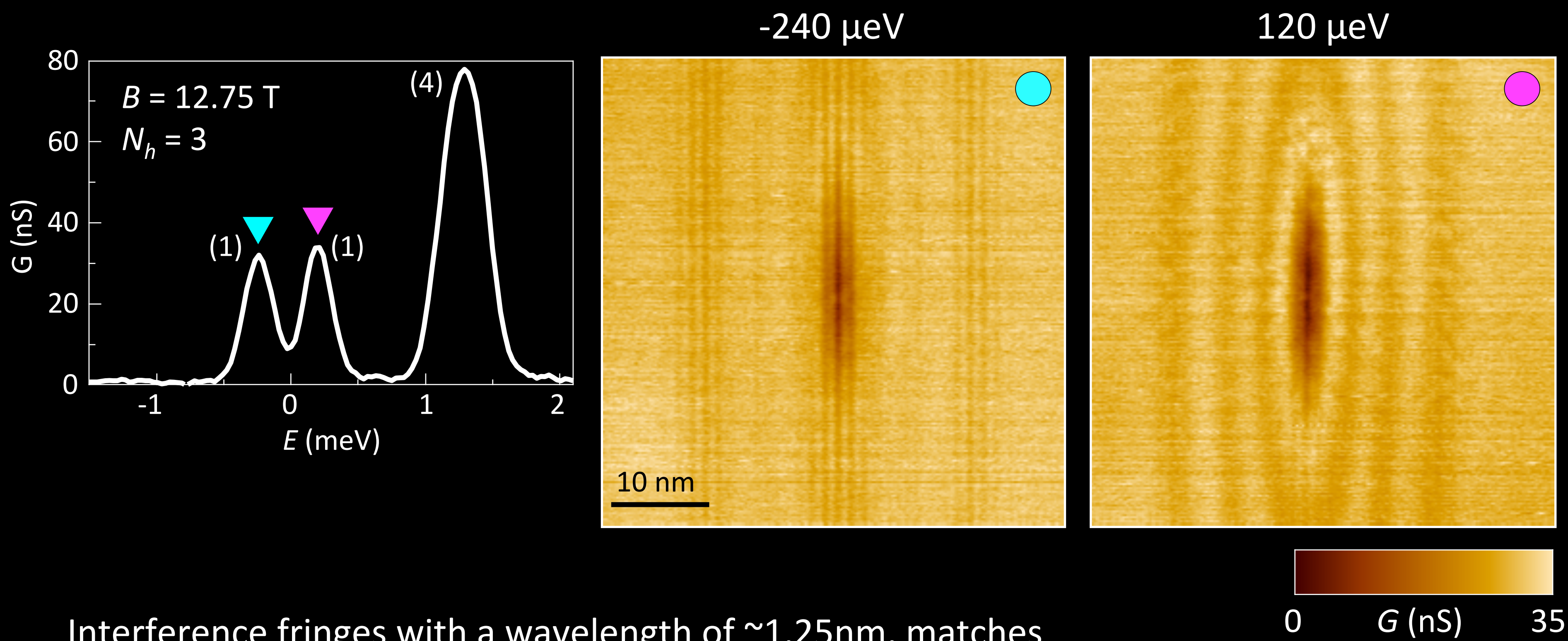
Driven by electron-electron interactions



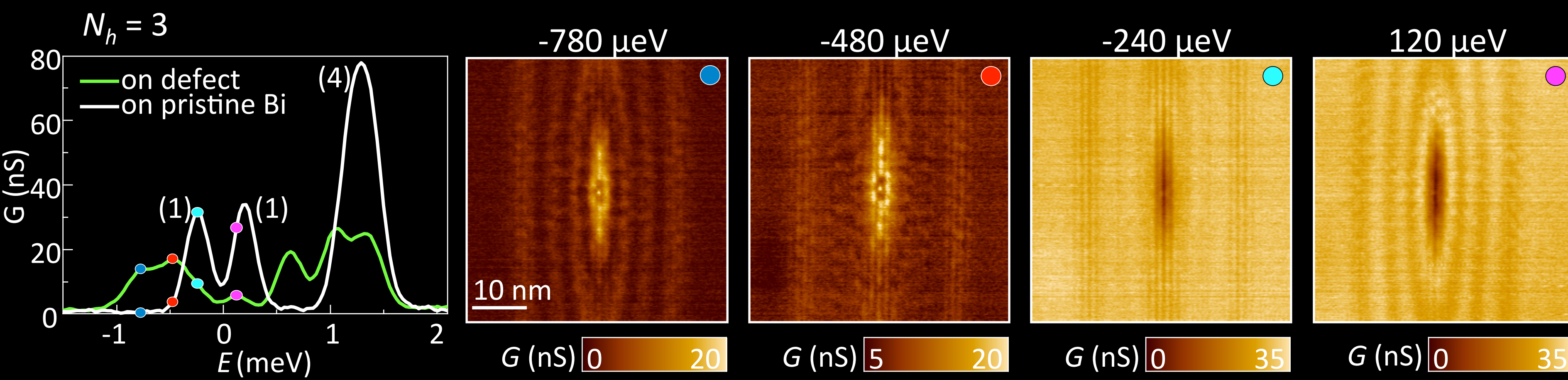


Higher resolution wavefunction mapping

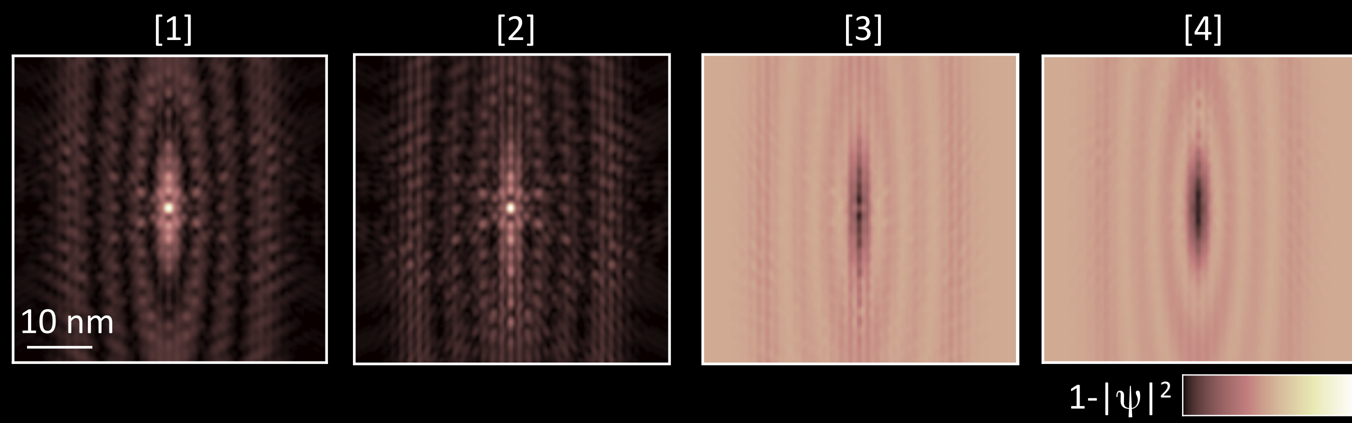


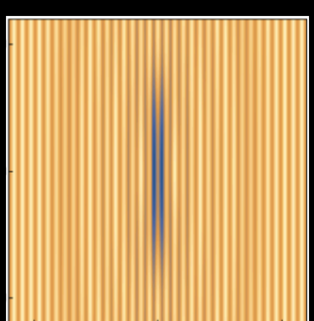
Interference fringes with a wavelength of ~1.25nm, matches well to corresponding valley separation in momentum space

Valley-polarized ferroelectric ground state



Theoretical simulations for a *valley-polarized* ground state, including defect induced mixing of LL wavefunctions from different valleys





Valley-coherent simulation

Acknowledgements

Experiment

Ben Feldman

Andras Gyenis

Hao Ding

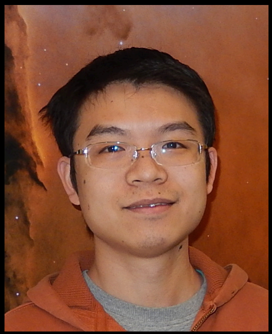
Ali Yazdani

Sample growth

Huiwen Ji

Bob Cava

Theoretical support



Fengcheng Wu

Allan MacDonald

UT Austin

Kartiek Agarwal

Sid Parameswaran

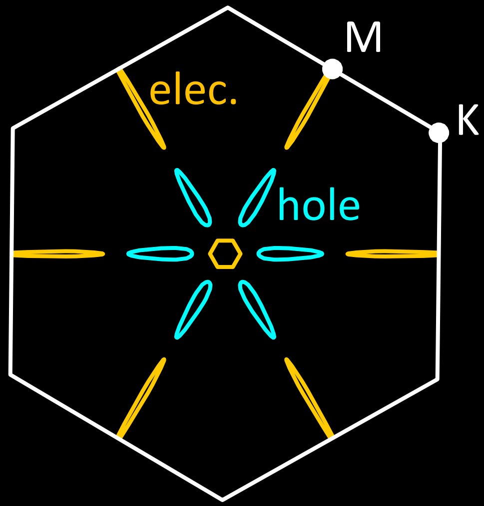
UC Irvine

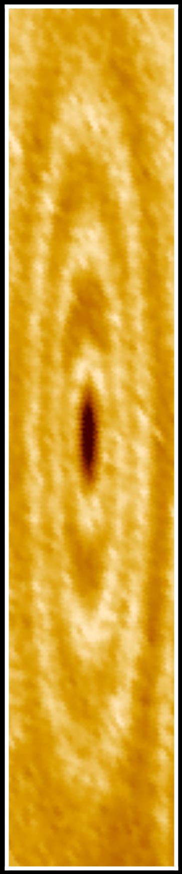
Shivaji Sondhi

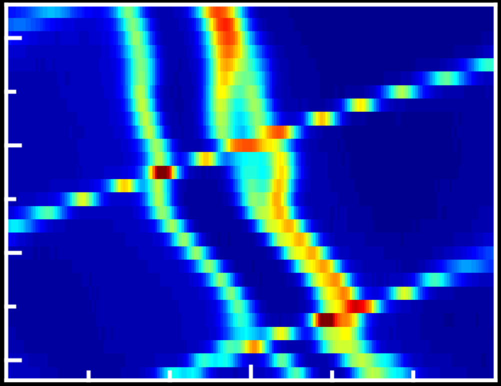
Summary & Outlook

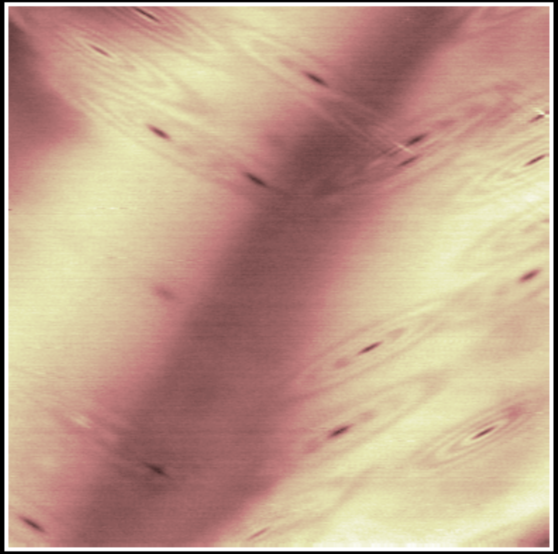
- Bi(111) surface - unique platform to explore interaction driven nematic quantum Hall phase

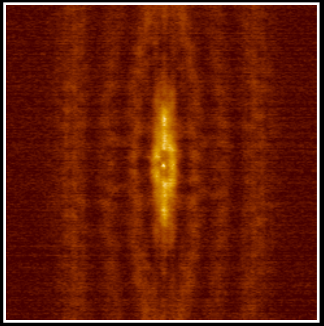
- Real-space imaging of Landau orbits: domains of local nematic order

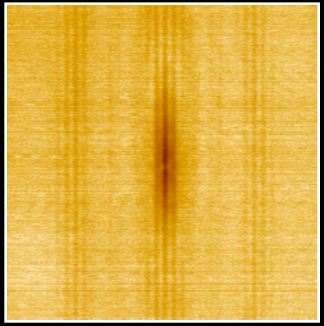












Thank you!