Detecting and quantifying orbital magnetism in moiré quantum matter

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SuperQmap ESSM24, 4/24/2024

National Institute of Standards and Technology
U.S. Department of Commerce

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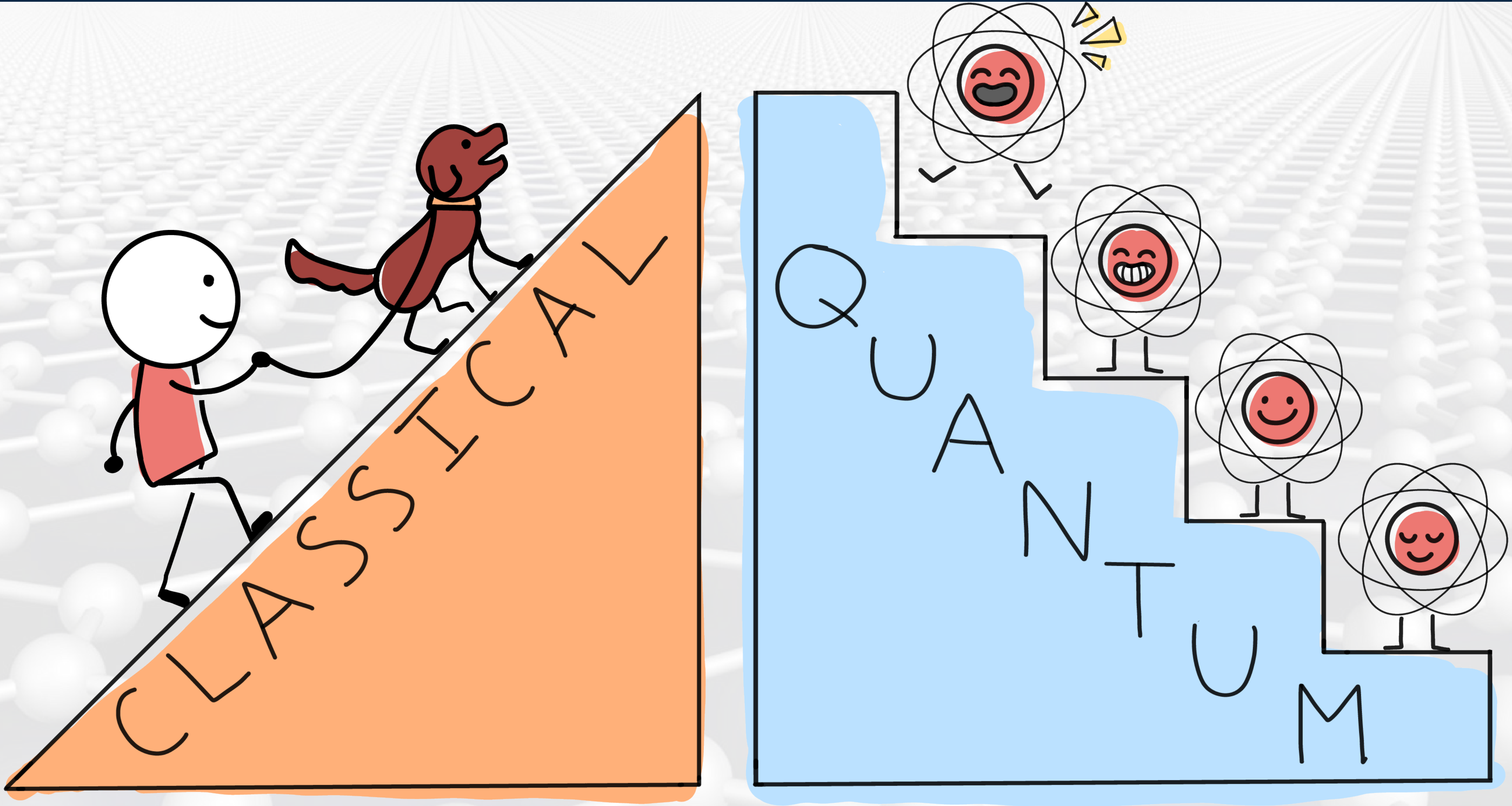
Science & Technology

PML
PHYSICAL MEASUREMENT LABORATORY

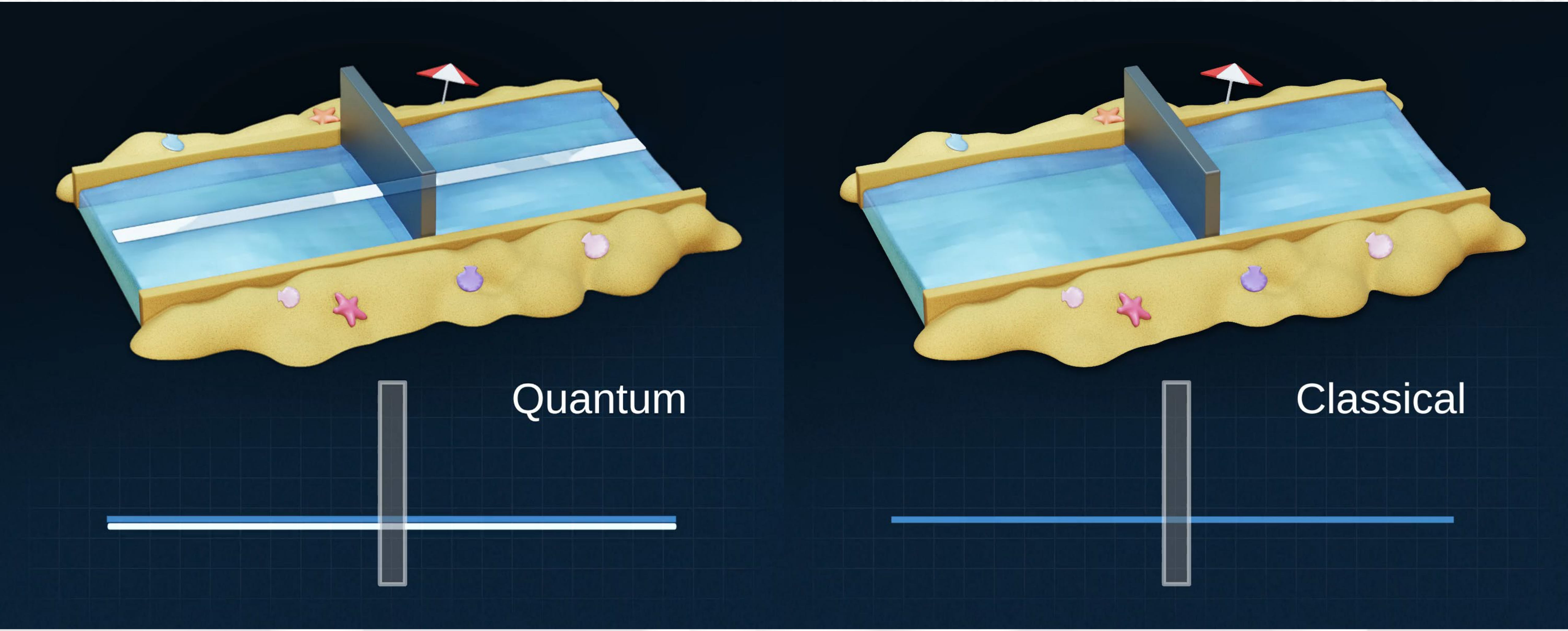
Scanning tunneling microscopy

Classical vs Quantum?



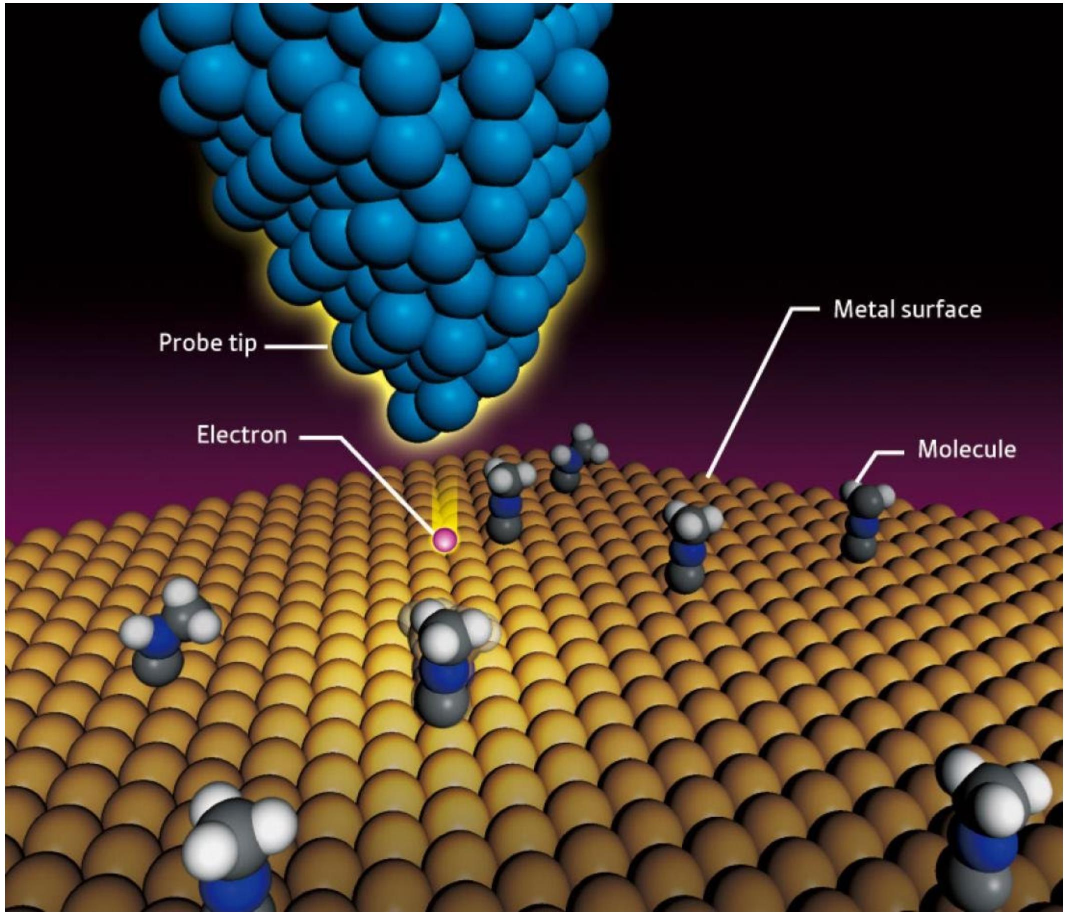
Eileen Stauffer/The Quantum Atlas: NSF grant, UMD/NIST, IQUIST

Quantum tunneling



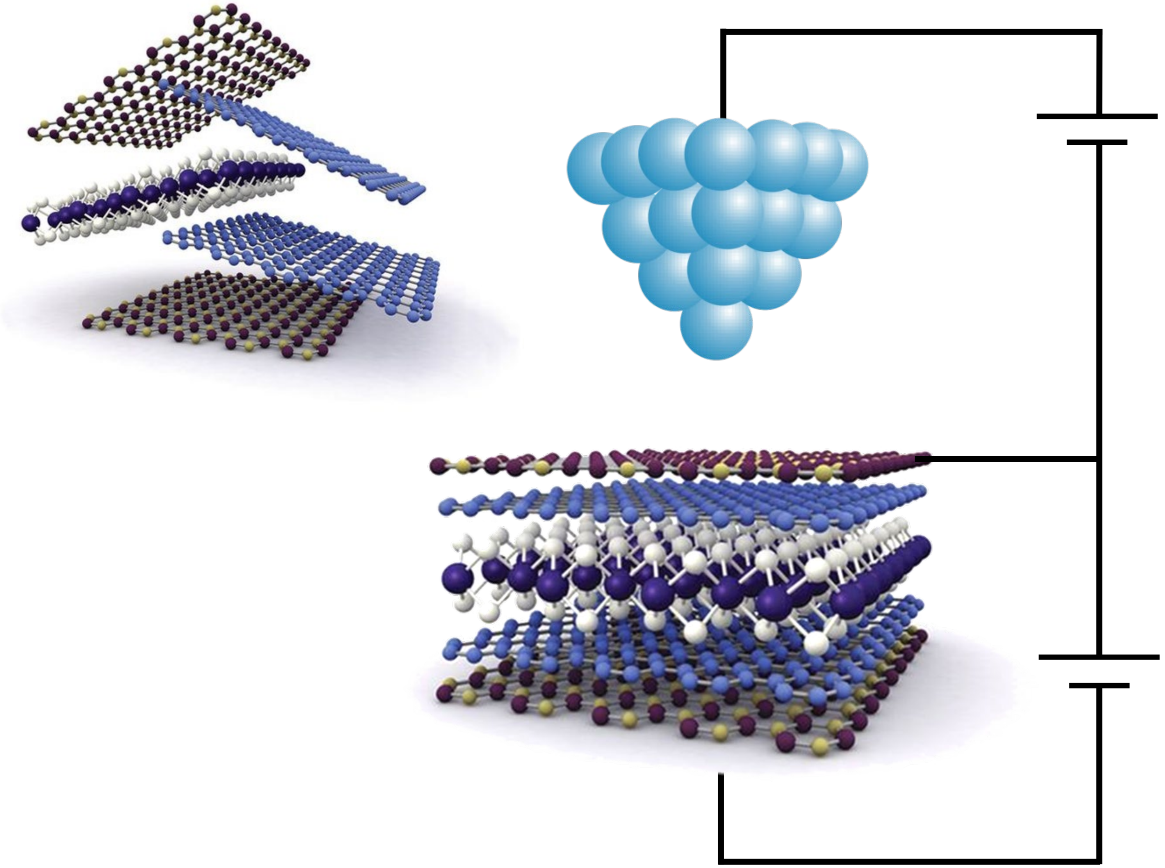
Scanning tunneling microscopy

Single atoms and molecules



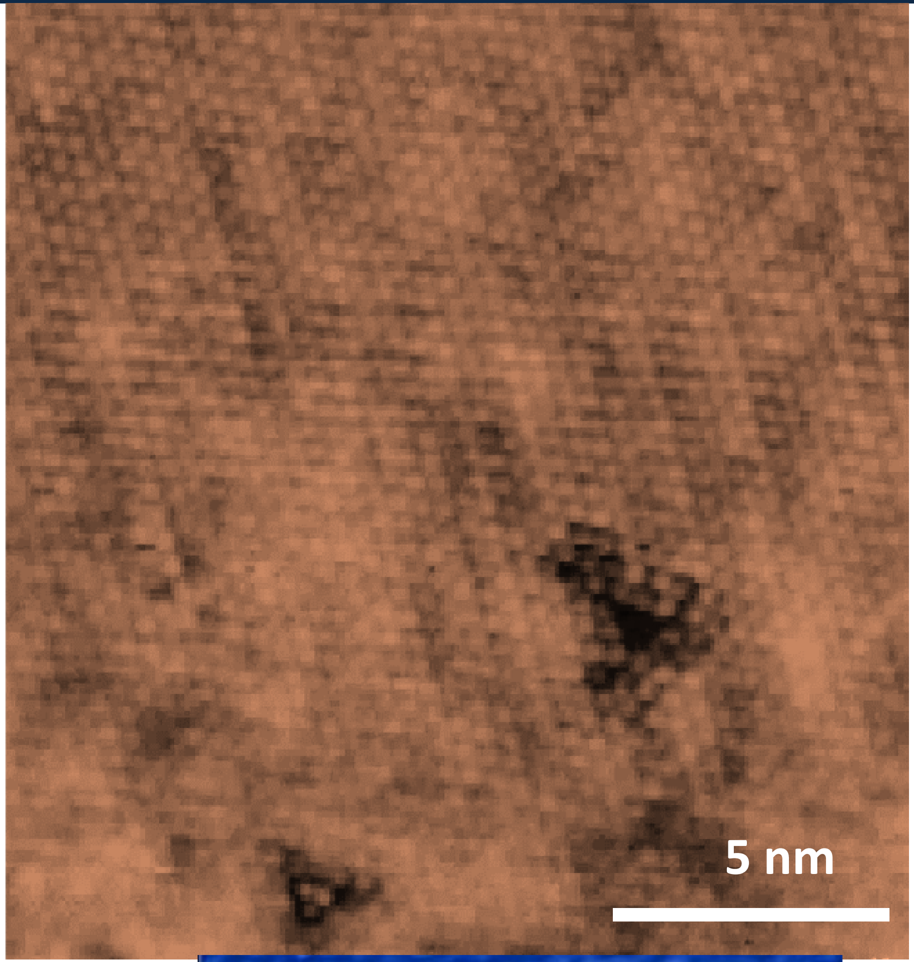
RIKEN research

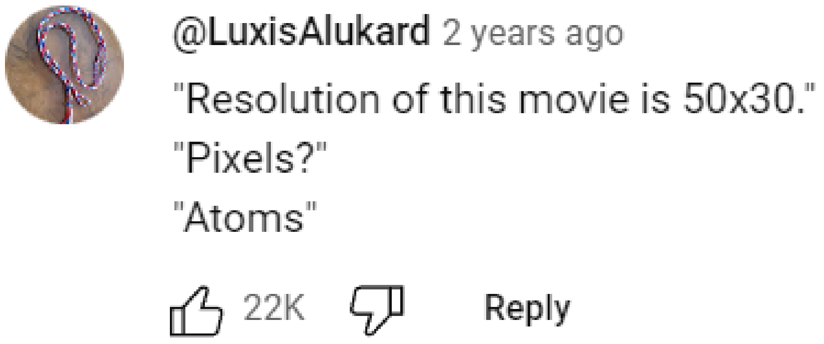
Devices



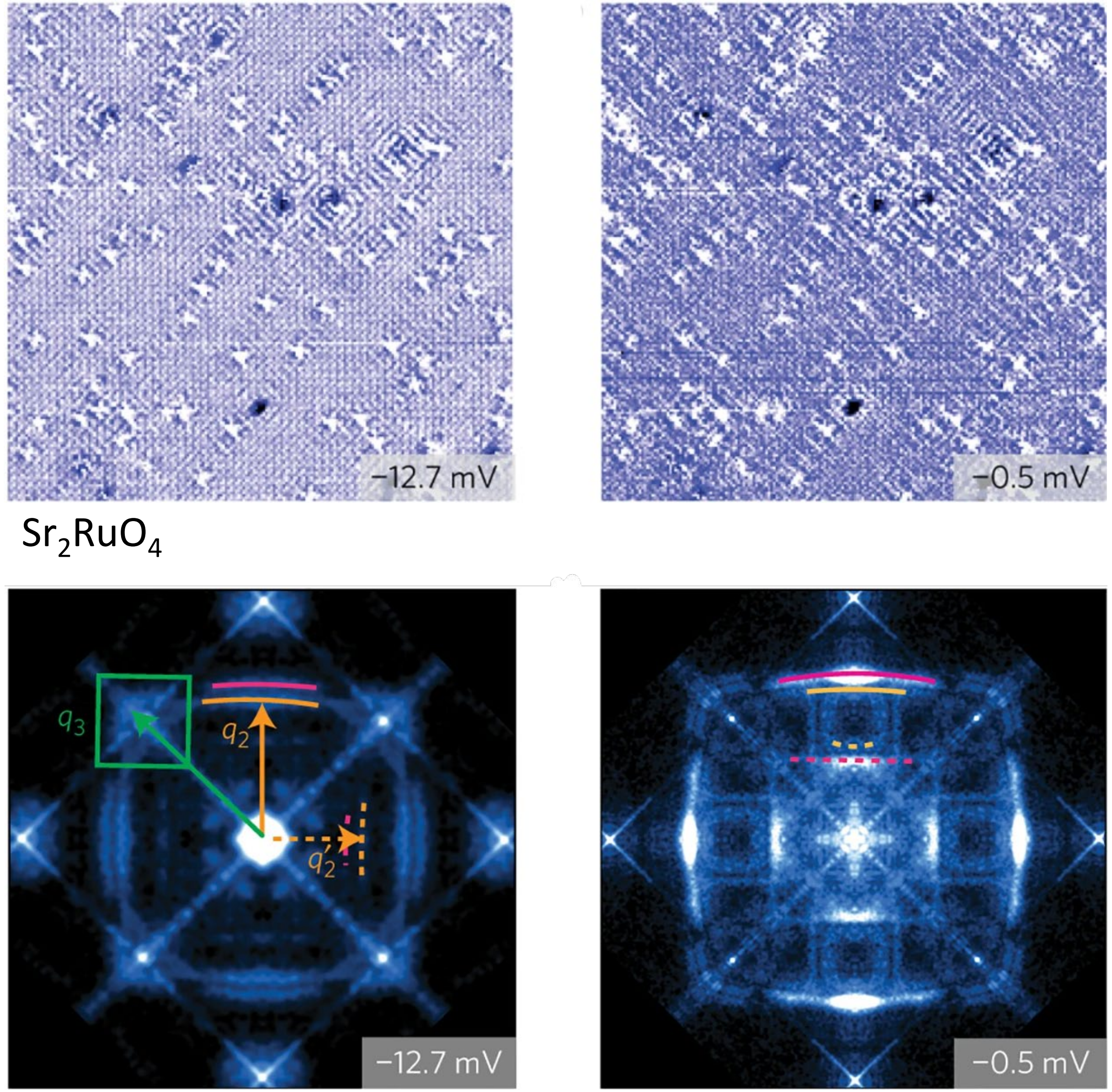
K. S. Novoselov et al. Science **353**, 6298 (2016)

Quantum properties with atomic resolution

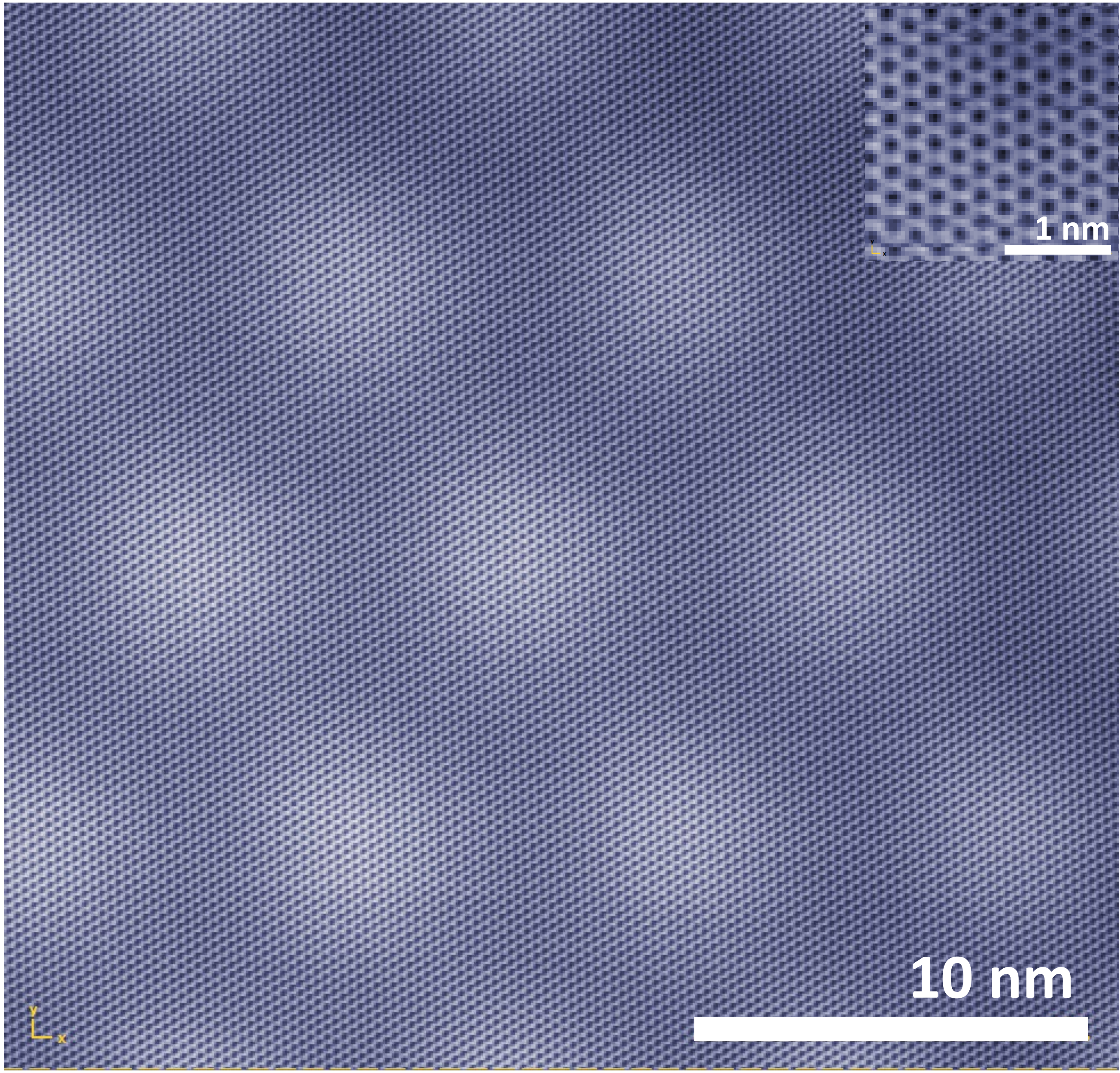




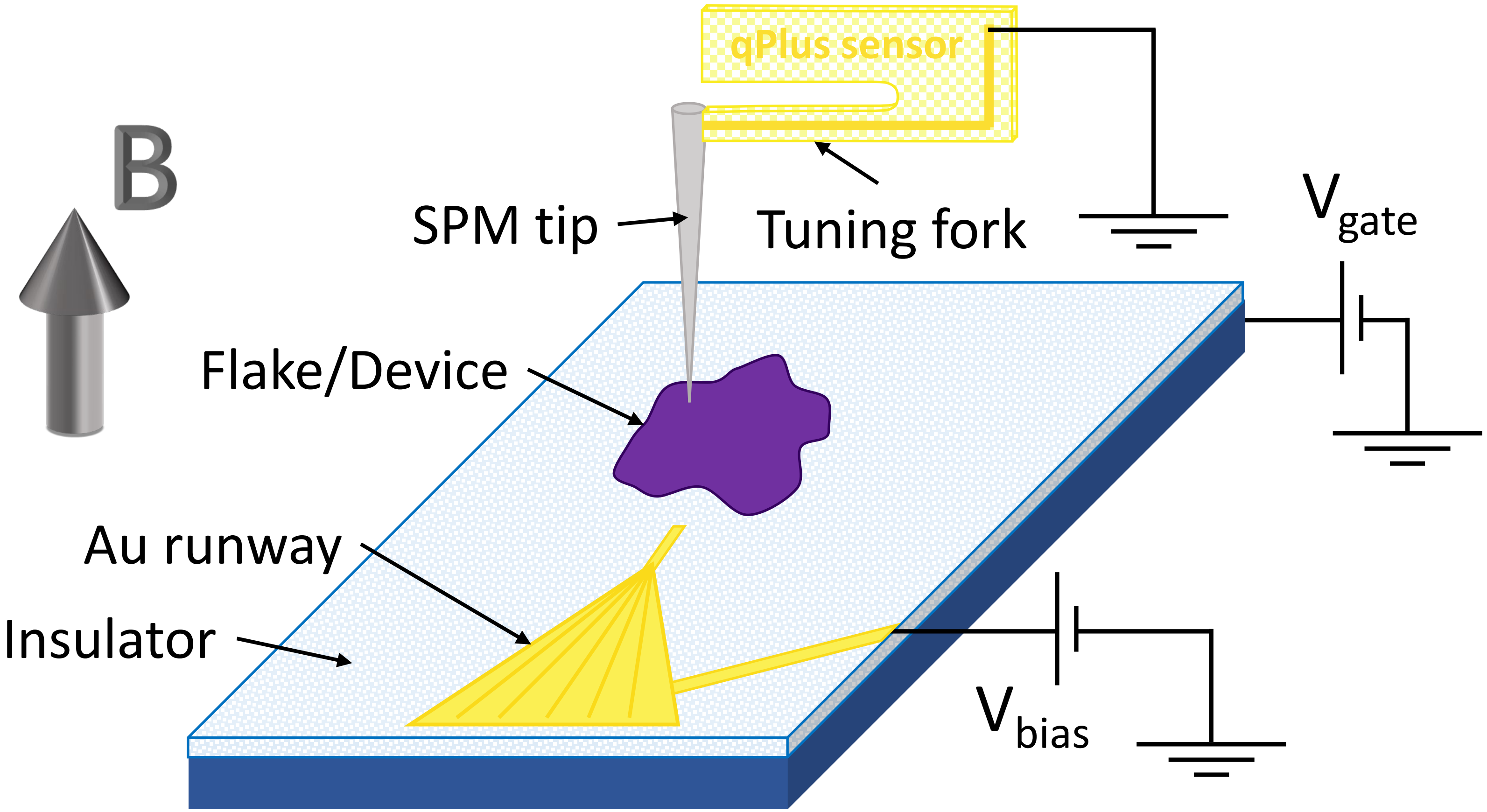
Quantum properties with atomic resolution



Wang, Z., Walkup, D. *et al.* *Nature Phys* **13**, 799–805 (2017).

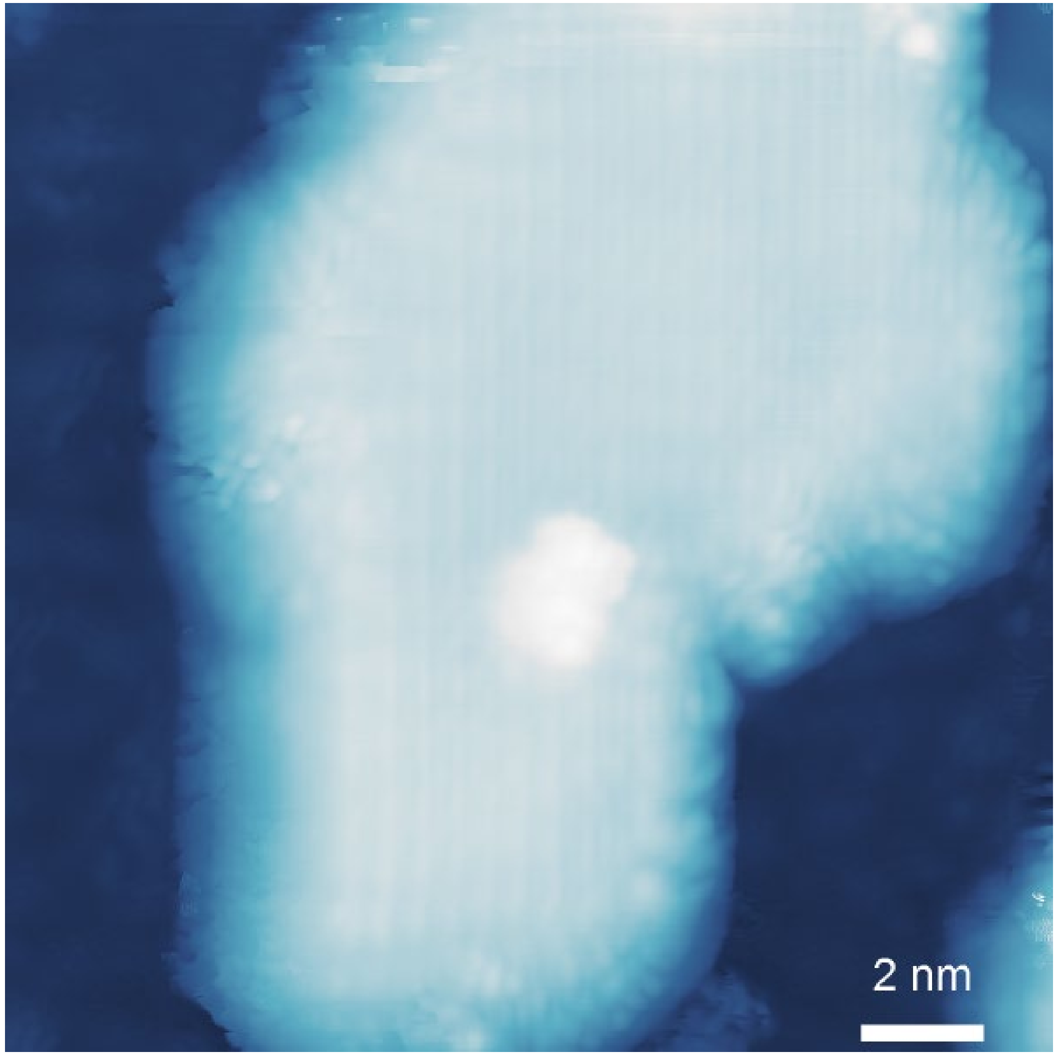


STM of devices

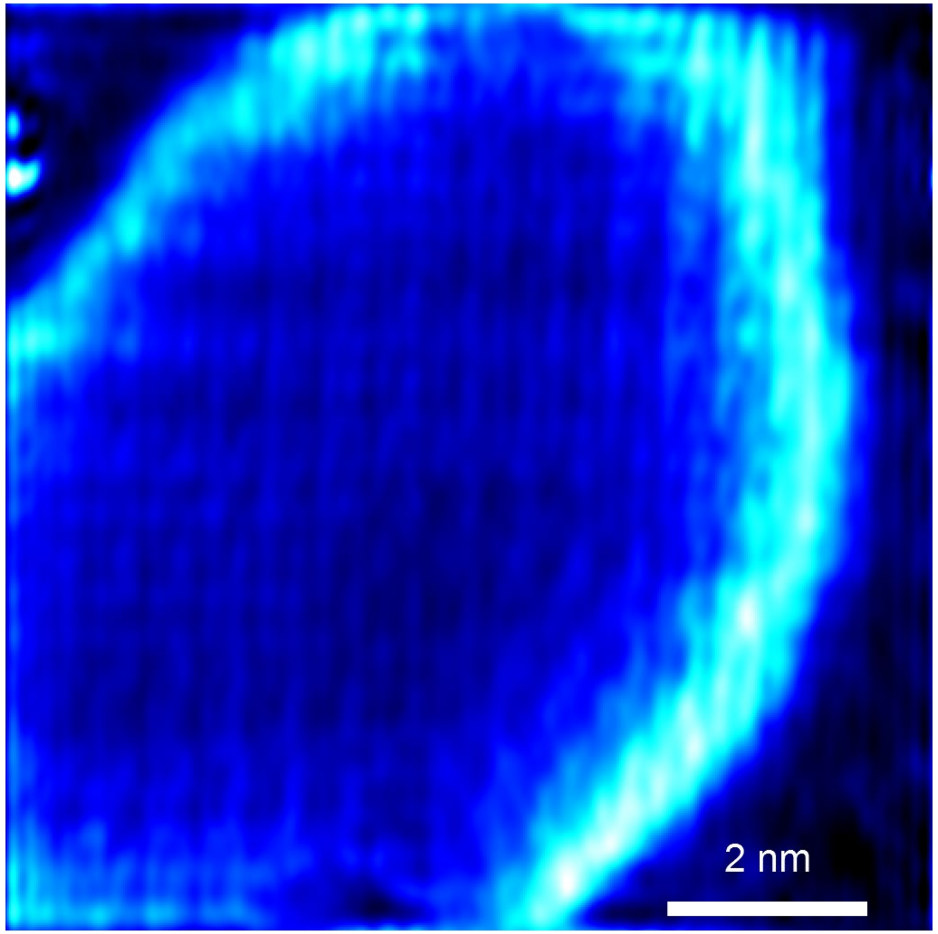


- Controlling carriers
- Controlling *D/E* and *B*
- Mixing&matching 2D materials
- Atomically resolved local studies
- Measure LDOS, probe quantum states

LDOS a.k.a. dI/dV

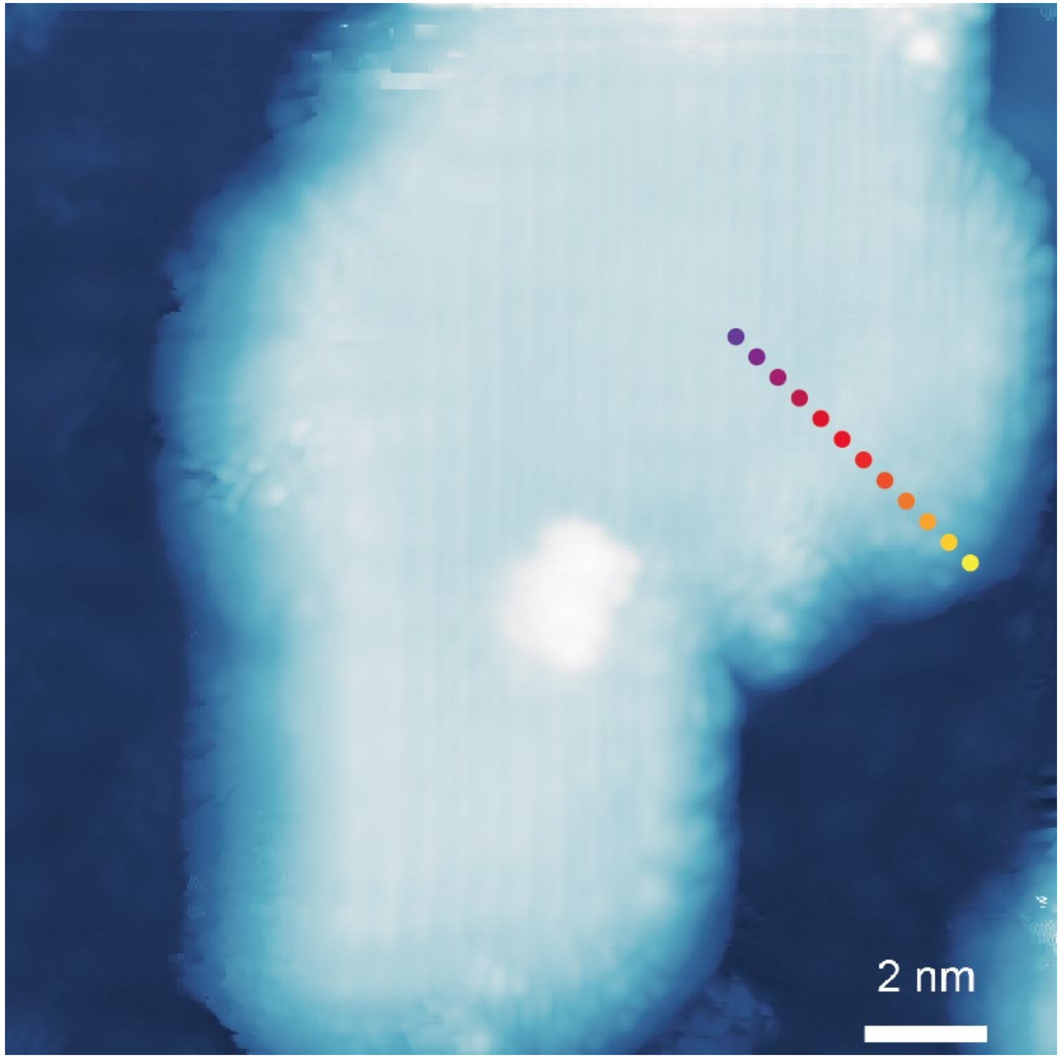


Topographical image of WTe_2

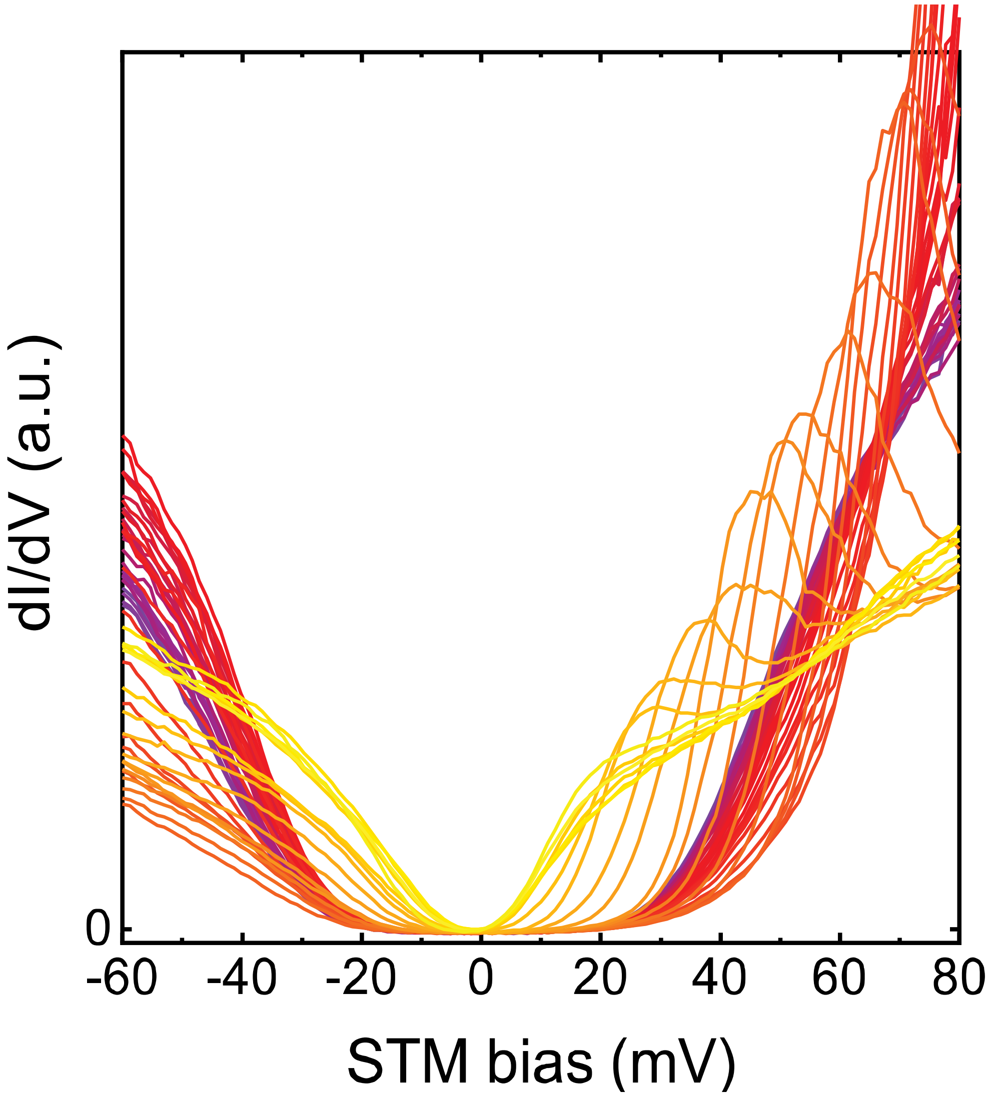


dI/dV image

LDOS a.k.a. dI/dV

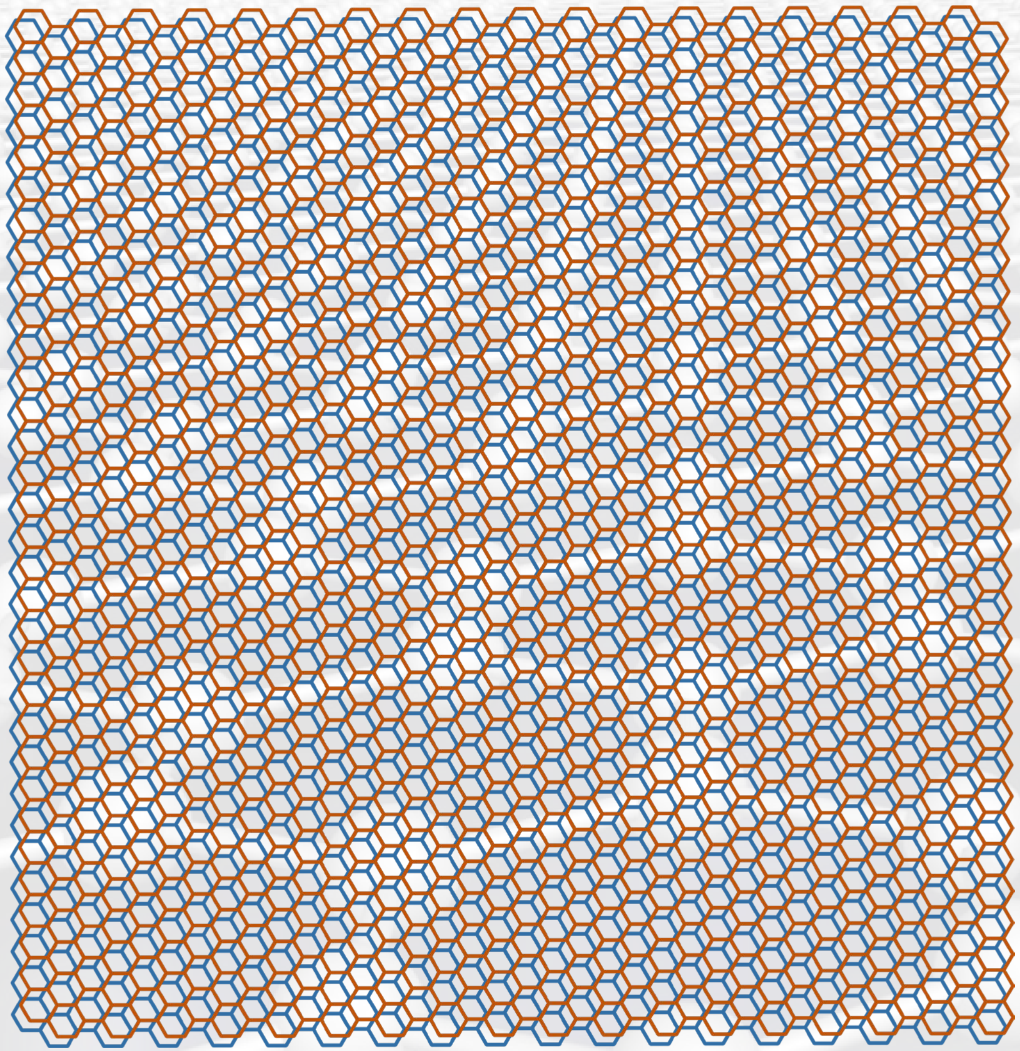


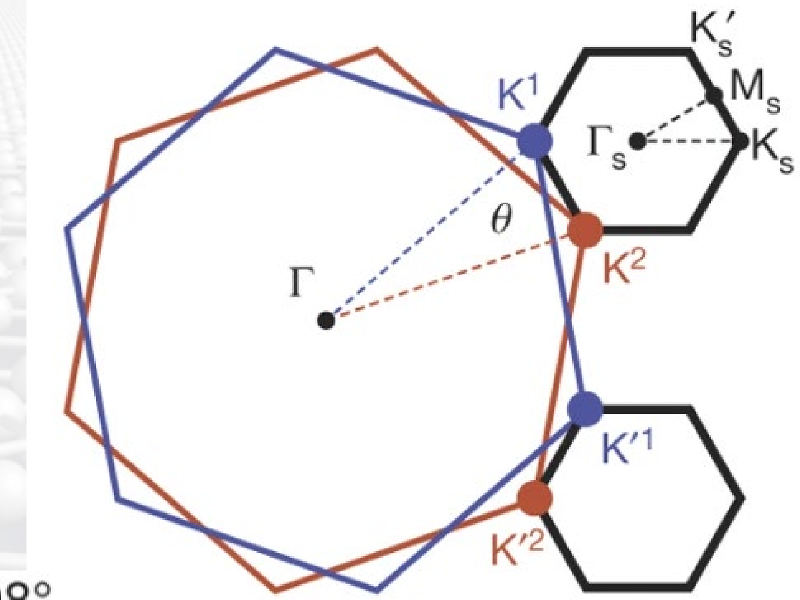
Topographical image of WTe_2

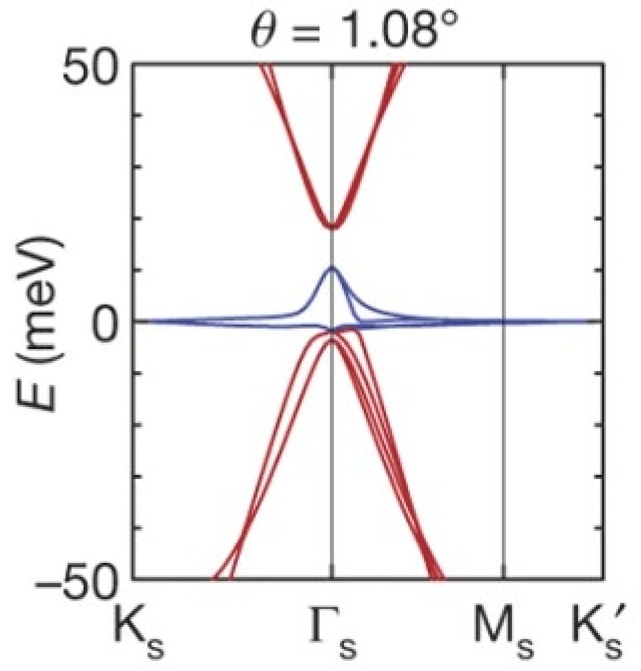


Twisted (moiré) materials

Flat bands in moiré materials



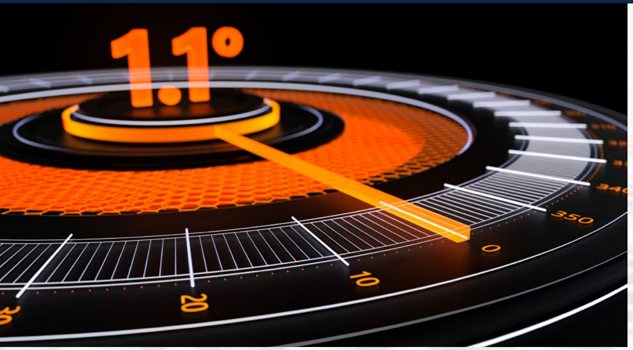


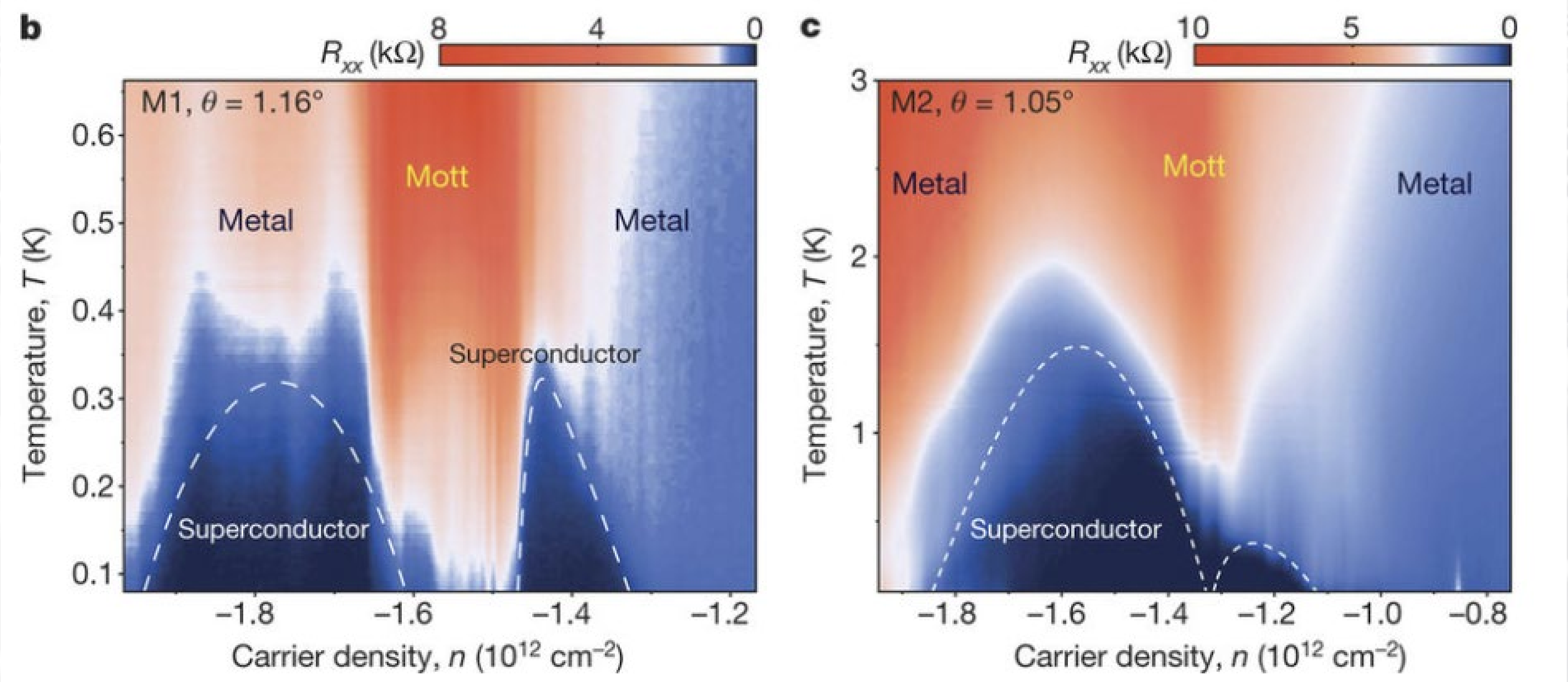


Cao *et al.*, Nature **556,** 80 (2018)

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

Magic angle twisted graphene

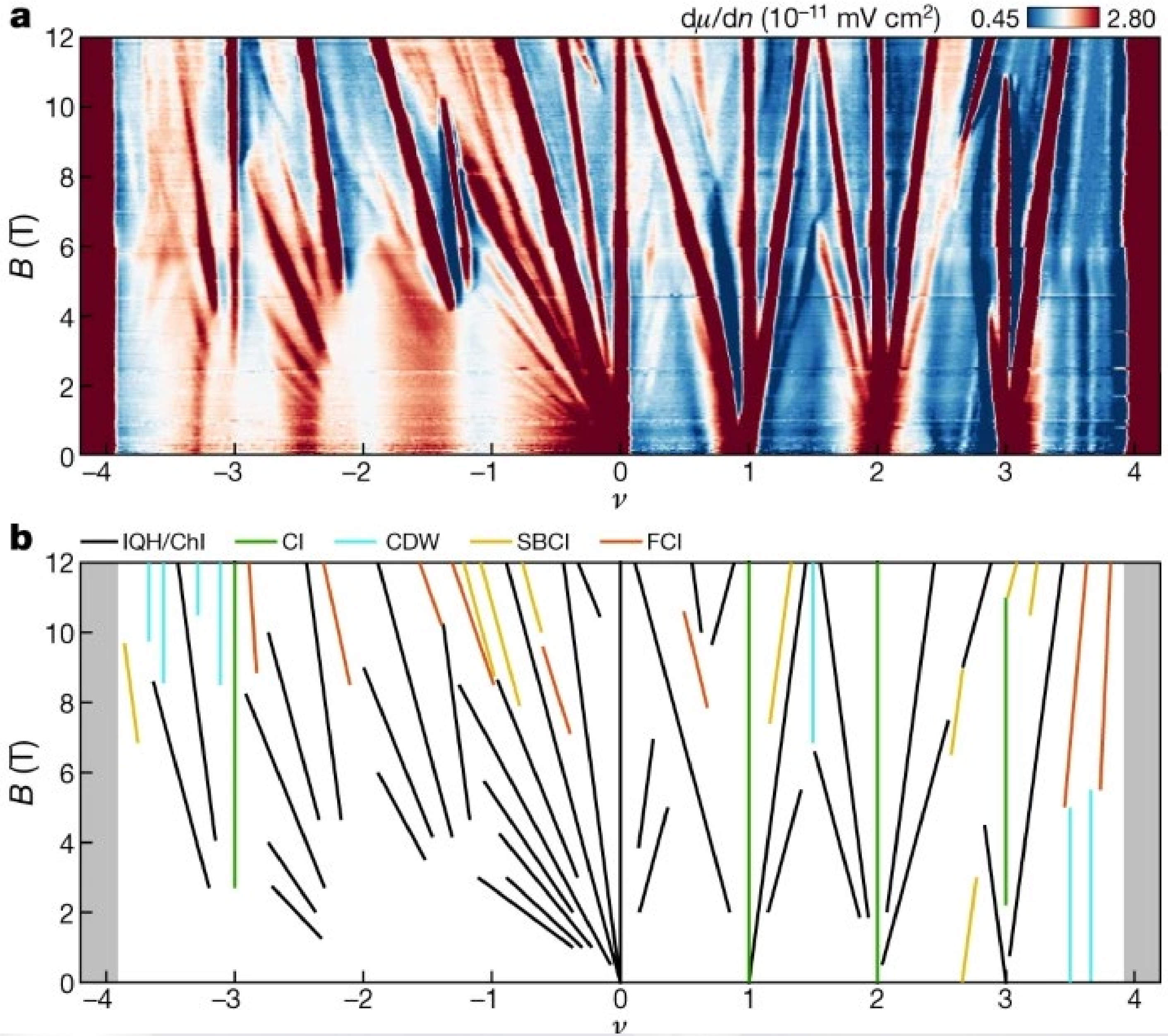




Cao *et al.*, Nature **556,** 80 (2018)

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

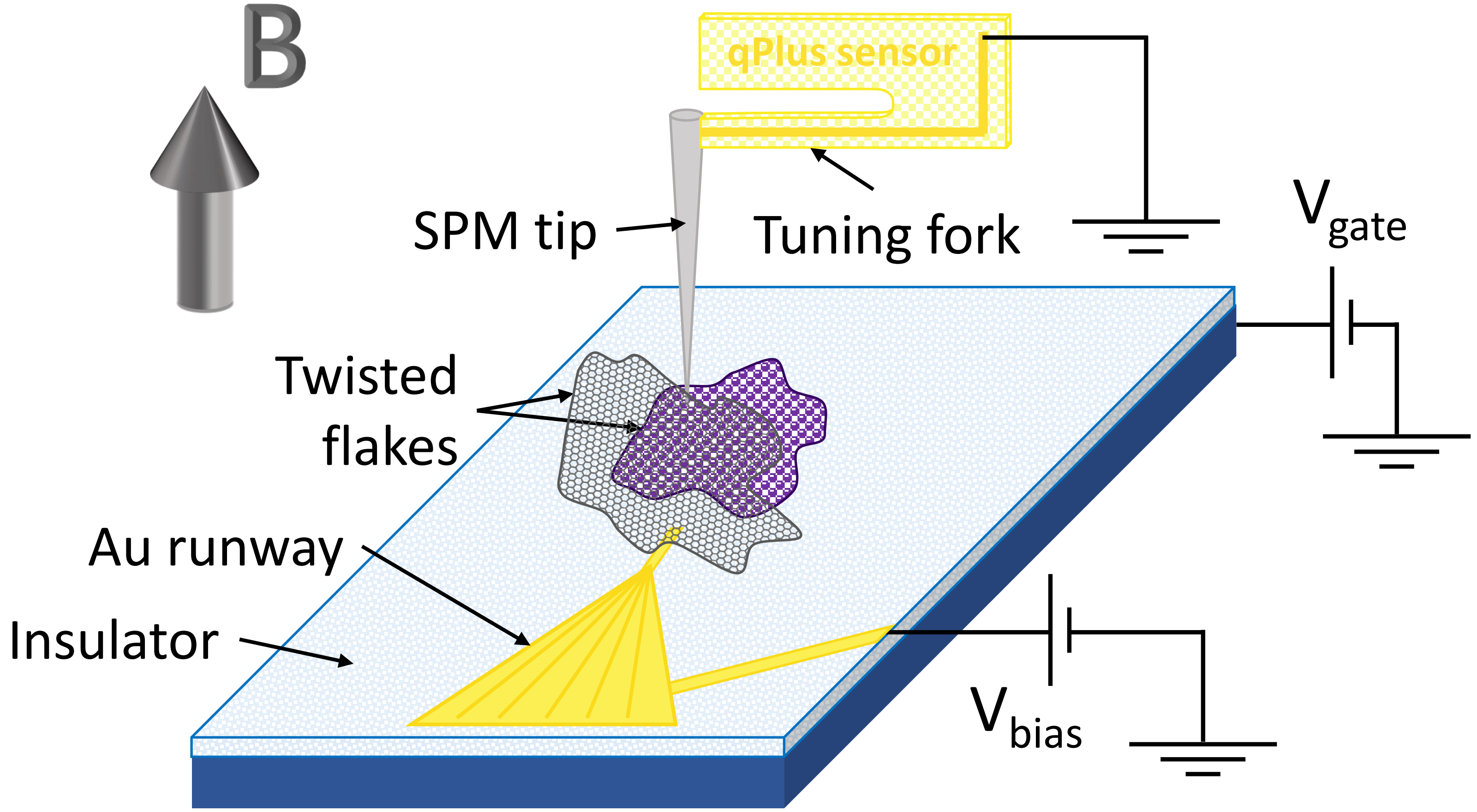
Quantum phases in twisted layers



- Unconventional superconductivity
- Correlated insulators
- Orbital magnetism and QAH
- Density waves
- Strange metal states
- Fractional Chern insulator

Nature **600**, 439–443 (2021)

STM of twisted devices

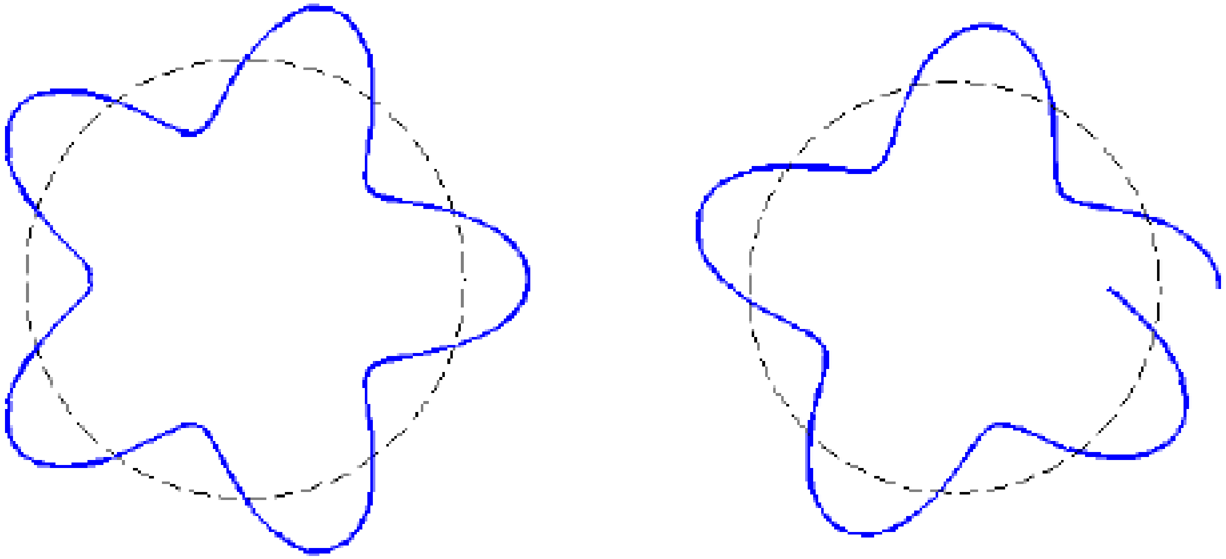


- Local angle/moiré wavelength
- Local strain
- Local response to tunable parameters

Probing *B*=0 properties with Landau levels

Semiclassical theory of magnetic response

- Electrons in a magnetic field



Real space orbits enclose an integer multiple of φ_0

Bohr-Sommerfeld Quantization

$$\oint (\boldsymbol{p} - e\boldsymbol{A}) \cdot d\boldsymbol{l} = 2\pi\hbar(n + 1/2)$$

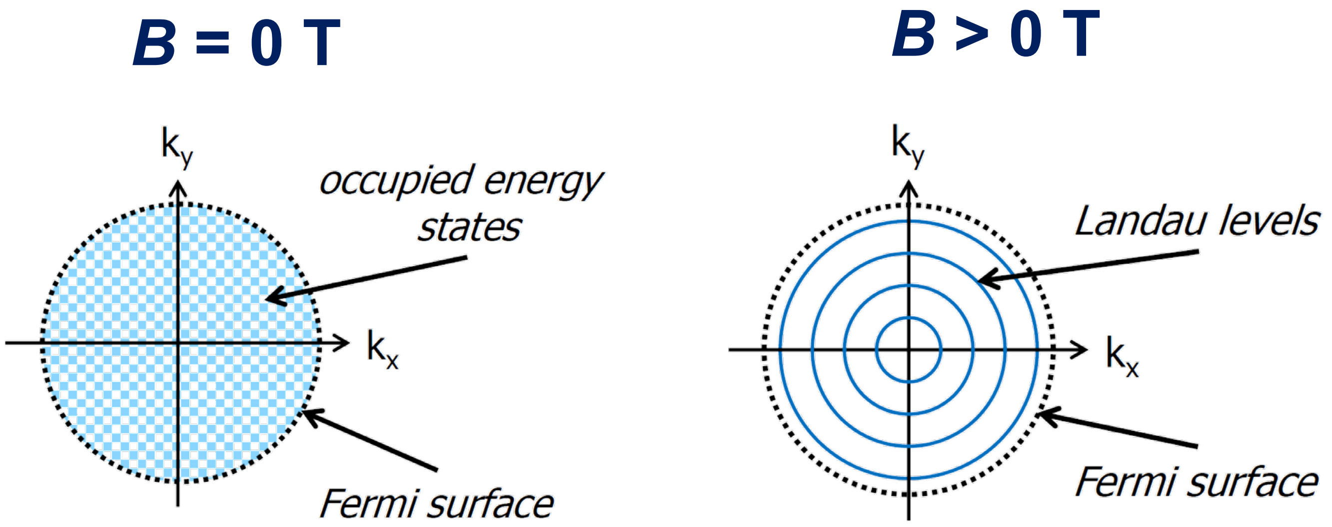
Onsager Relation

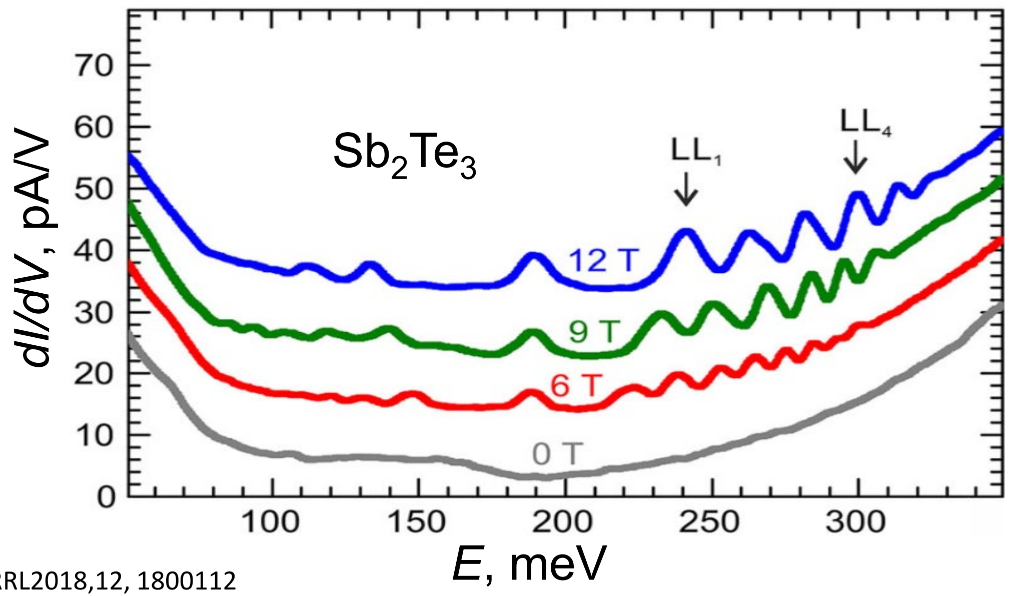
$$S(E_n)/4\pi^2 = \frac{B_n}{\varphi_0}\left(n + \frac{1}{2}\right)$$

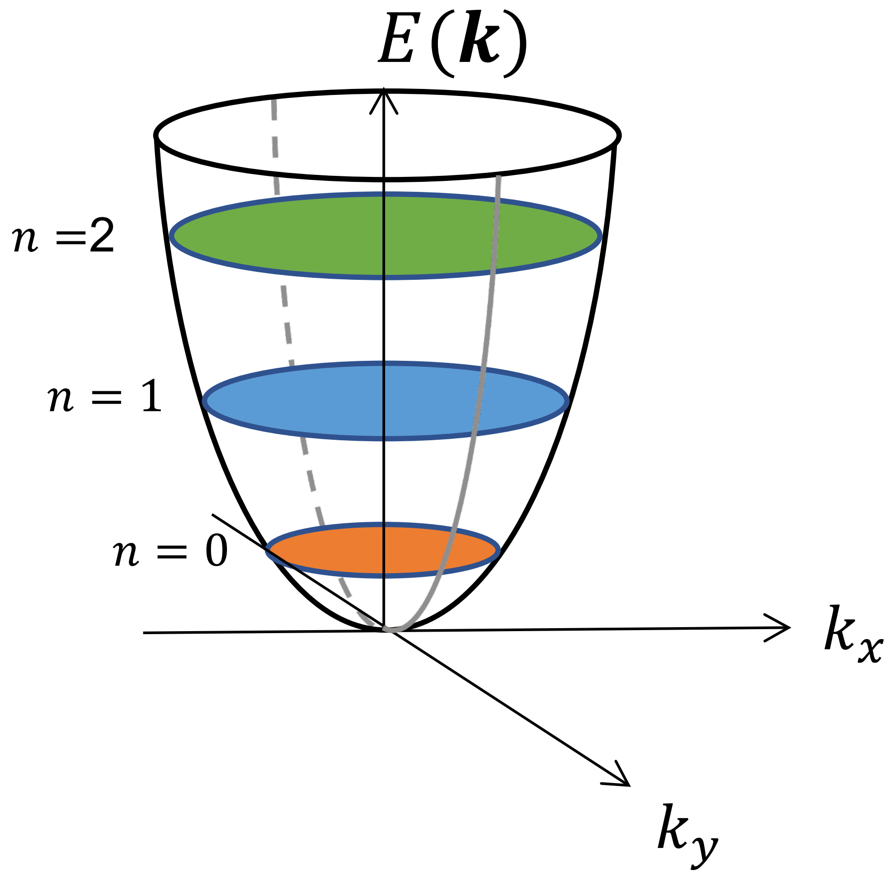
Integrated density of states

$$N(E_n) = S(E_n)/4\pi^2$$

Landau quantization as a probe of $E(k)$



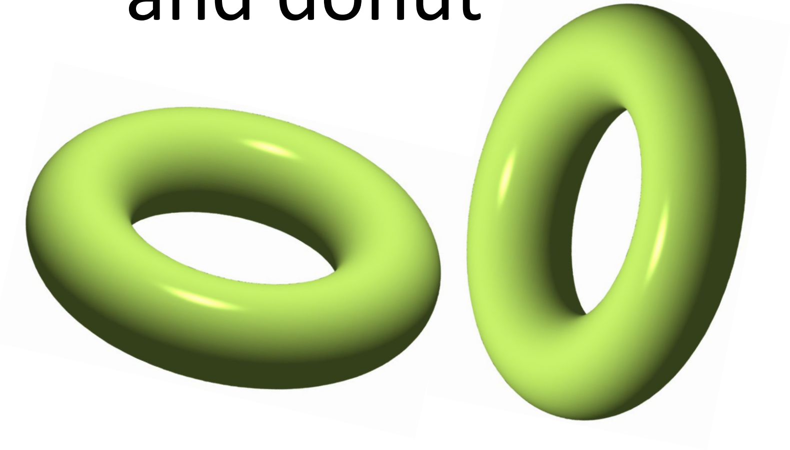




Phys. Status Solidi RRL2018,12, 1800112

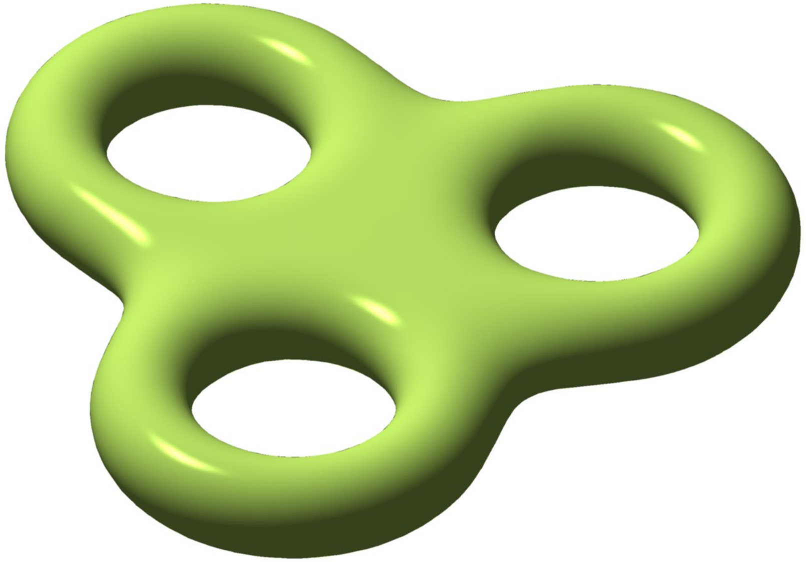
Topology

Cup of coffee
and donut



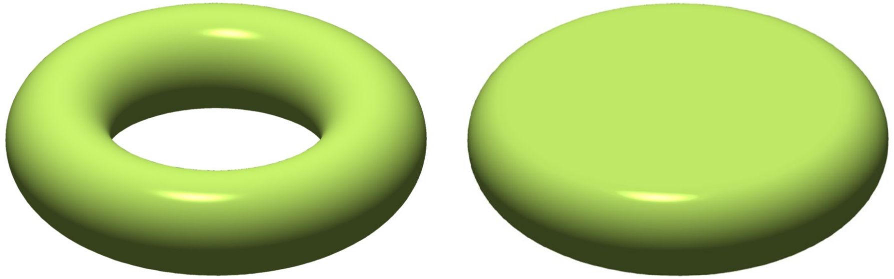
Pants

T-shirt



Morning of a topologist

Socks



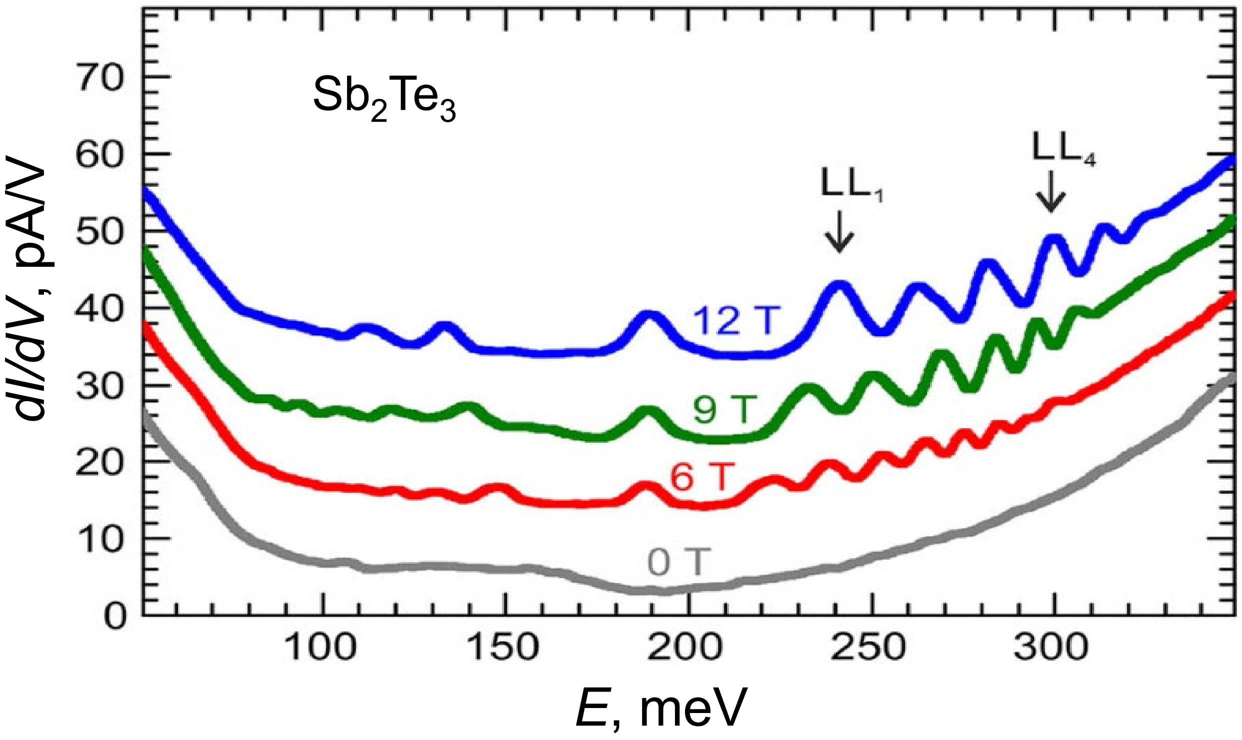
Quantum geometry and magnetism

Berry curvature	$\Omega(\boldsymbol{k})$	Magnetic field	$B(\boldsymbol{r})$
Berry connection	$\left\langle \psi \middle\| i\frac{\partial}{\partial k} \middle\| \psi \right\rangle$	Vector potential	$A(\boldsymbol{r})$
Geometric phase	$\oint dk \left\langle \psi \middle\| i\frac{\partial}{\partial k} \middle\| \psi \right\rangle$	AB phase	$\oint dr\, A(\boldsymbol{r})$

Q. geometry contribution to magnetic response

NIST

$$B_n\left(n+\frac{1}{2}\right)\frac{2\pi e}{\hbar} = S(E_n) + 4\pi^2 m'(E_n)B_n + 2\pi^2\chi'(E_n)B_n^2 + \cdots$$



First order: orbital magnetic moment

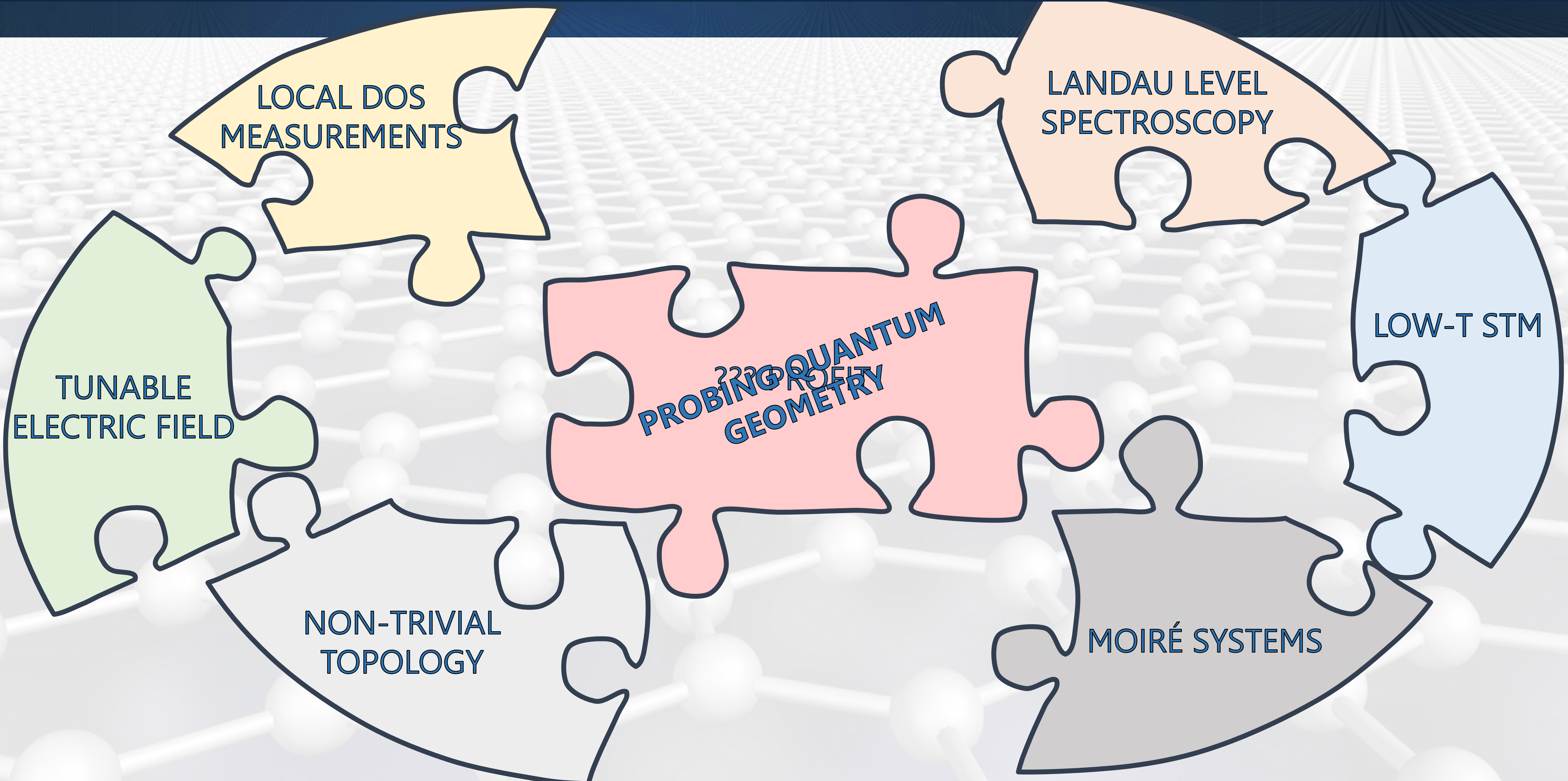
Second order: orbital magnetic susceptibility

Geometry dependent terms

Y. Gao, S.A. Yang, Q. Niu. PRB **91**, 214405 (2015)

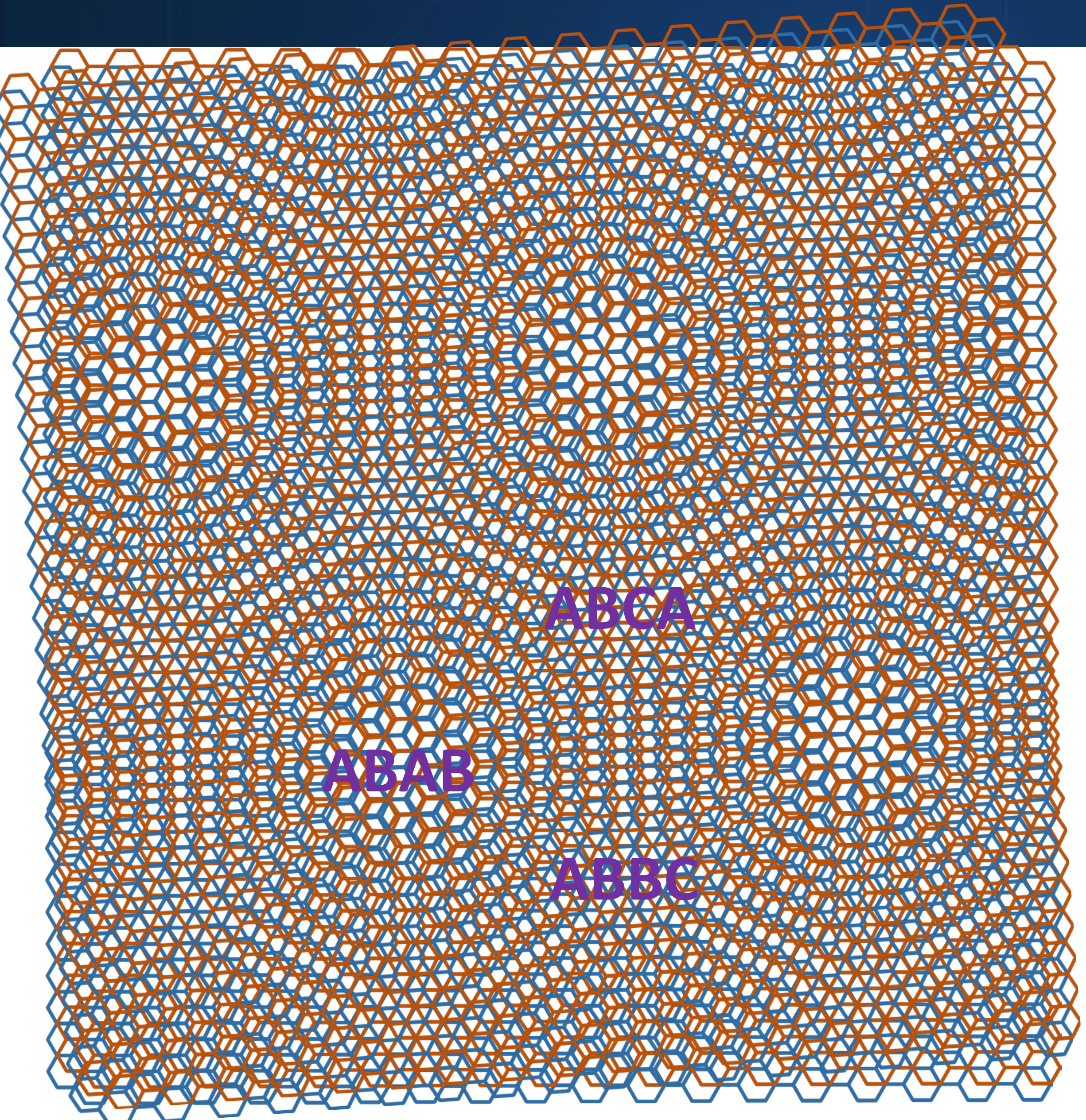
Phys. Status Solidi RRL2018,12, 1800112

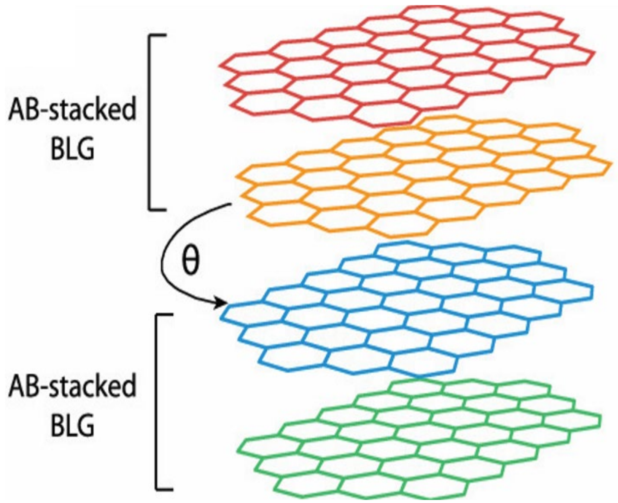
All pieces come together

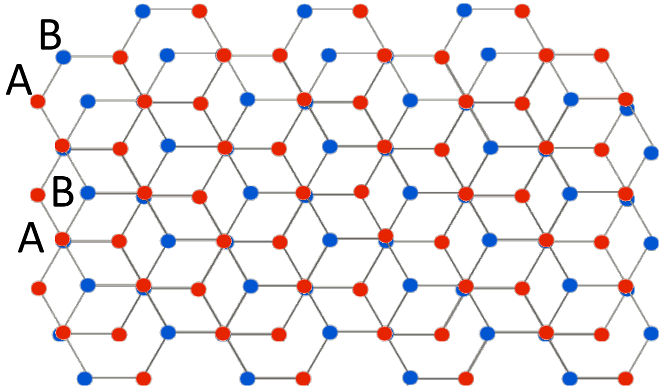


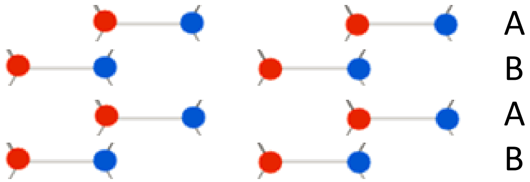
Twisted double bilayer graphene

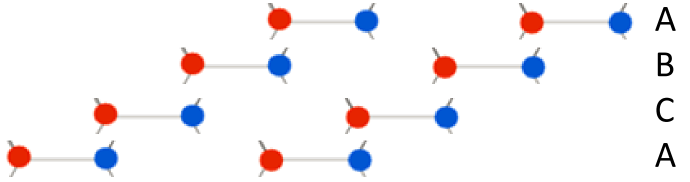
Twisted double bilayer graphene

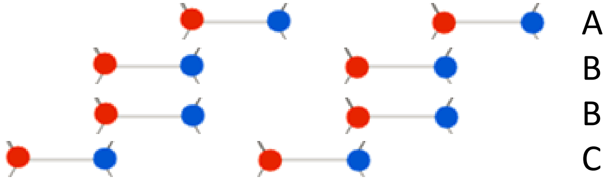




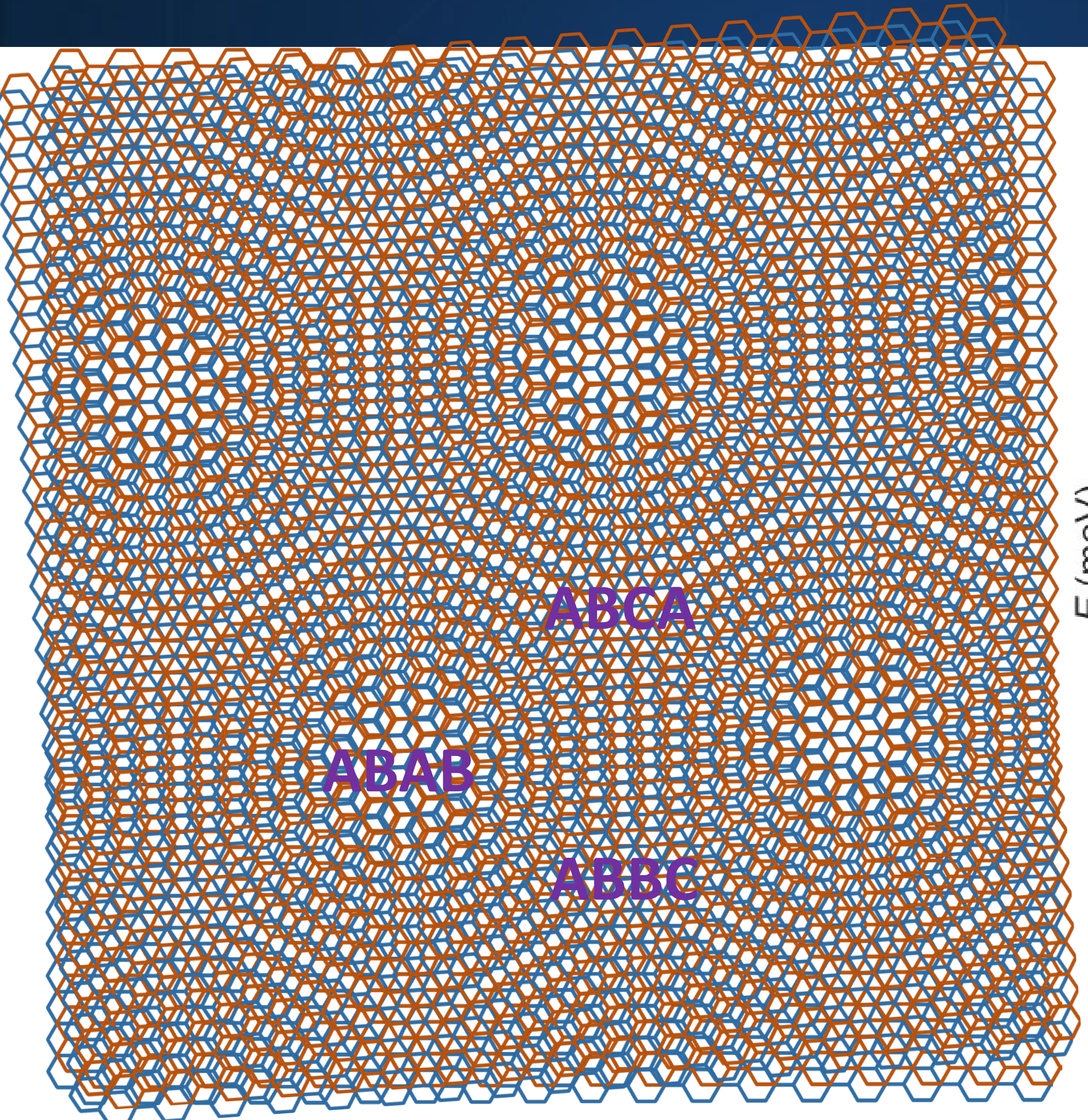


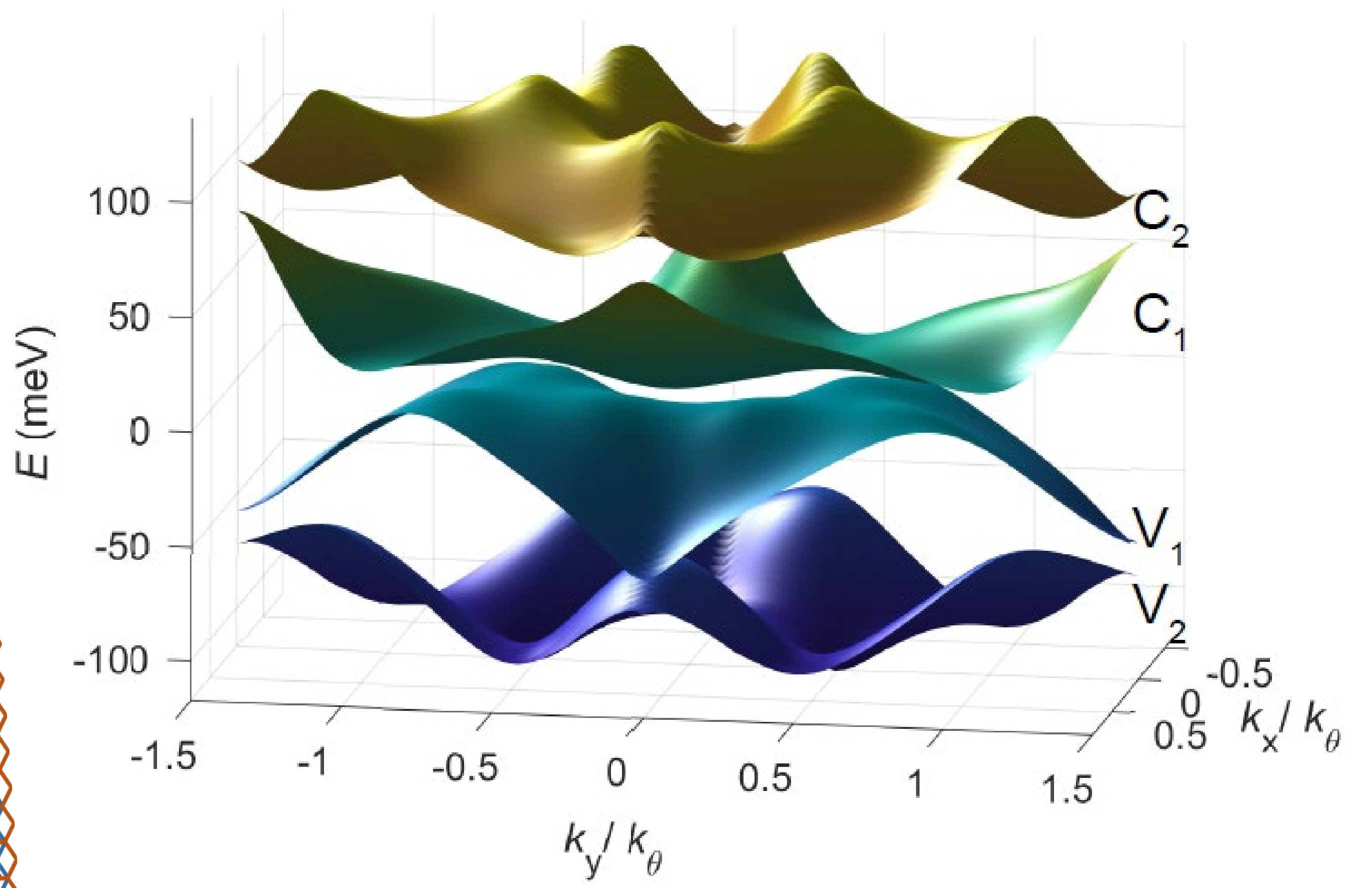






Electrostatically tunable bands



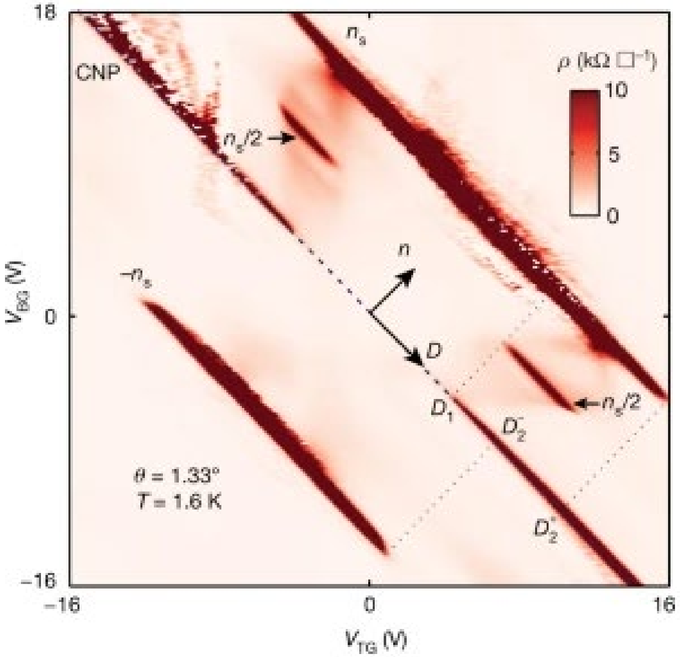


Tuning the twist angle

Our angle:

θ ≈ 0.8° … 1.4° → **θ = 1.75°** → **θ ≈ 2.37°**

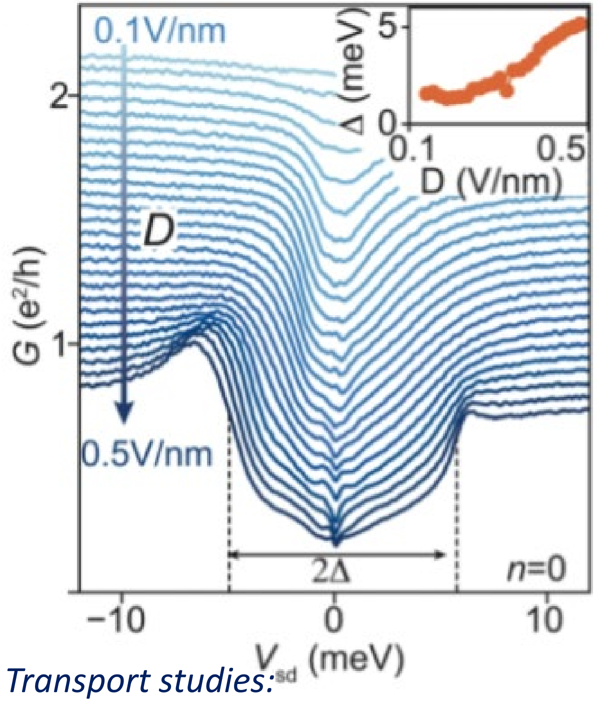
Gate-tuned correlated insulator



Transport studies:
Shen *et al.*, Nat. Phys. **16,** 520 (2020)
Burg *et al.*, Phys. Rev. Lett. **123**, 197702 (2019)
Liu *et al.*, Nature **583,** 221 (2020)
Cao *et al.*, Nature **583**, 215 (2020)
He *et al.*, Nat. Phys. **17,** 26 (2021)

Very rich system!

Gate-tuned density-wave state



Transport studies:
Rickhaus *et al.*, Science **373**, 1257 (2021)
De Vries *et al.*, Phys. Rev. Lett. **125**, 176801 (2020)
STM:
Liu *et al.*, Nat. Commun. **12**, 2732 (2021)
Zhang *et al.*, Nat. Commun. **12**, 2516 (2021)
Rubio-Verdú *et al.*, Nat. Phys. **18**, 196 (2022)

Ultra-low temperature scanning tunneling microscope

NIST

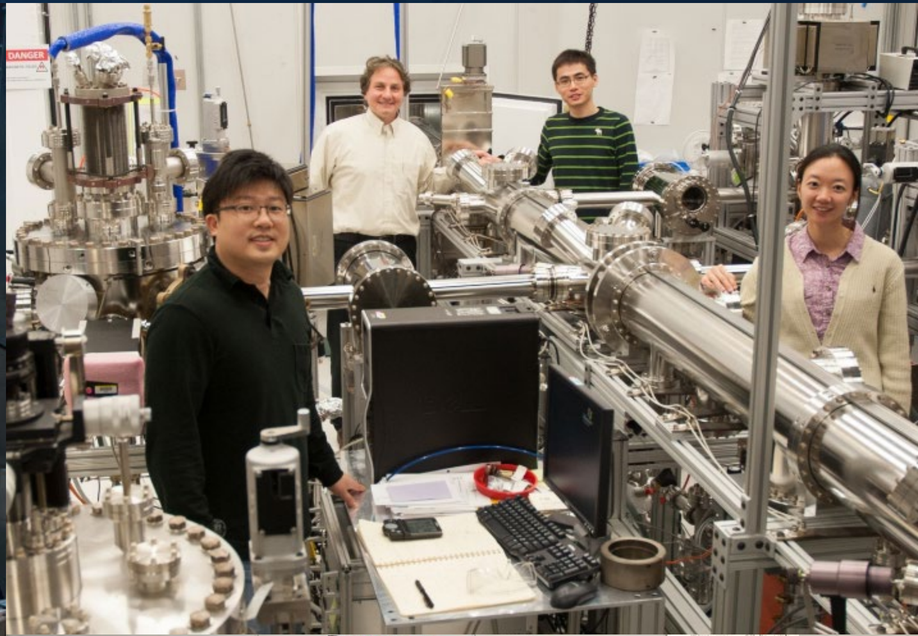
- **Combined STM/AFM/Transport**

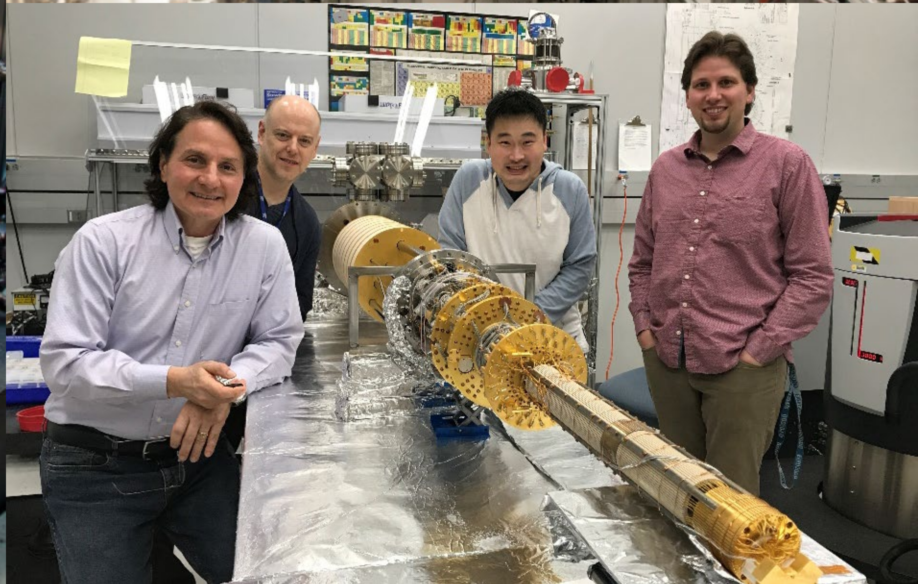
T = 10 mK

$B_{\perp}$ = 15 T

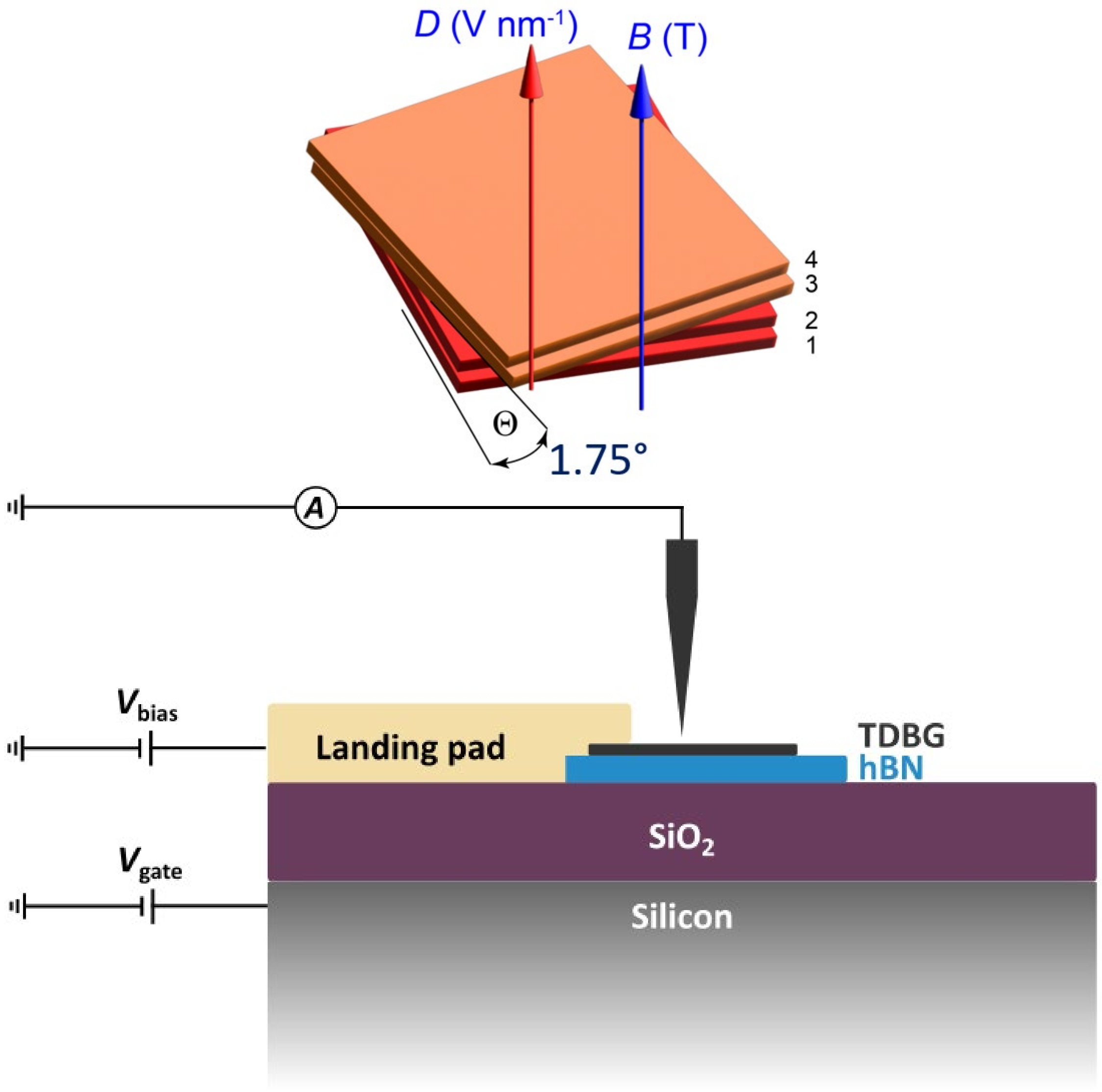
ΔE < 8 μeV

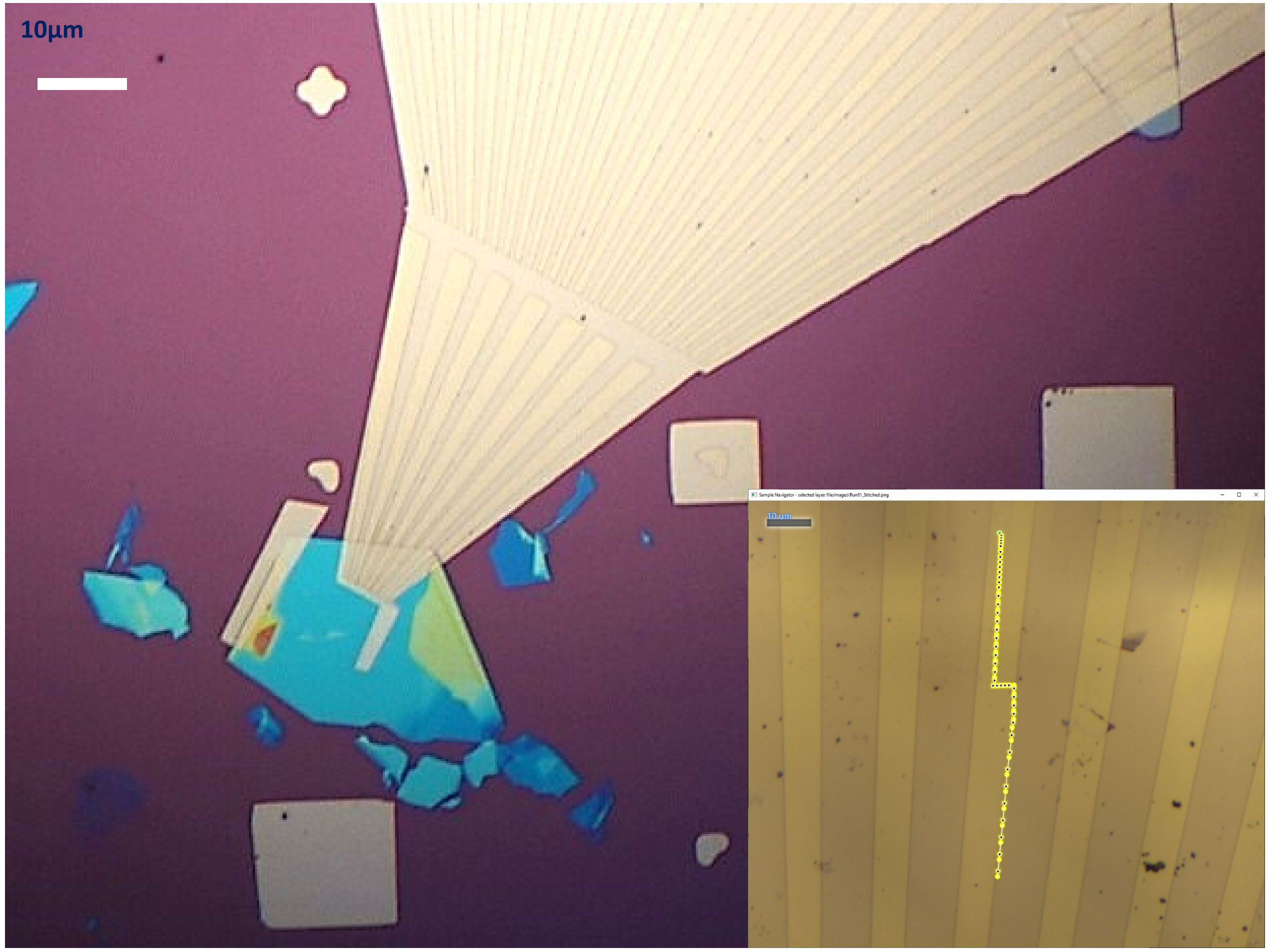
Schwenk *et al.*, Review of Scientific Instruments 91, 071101 (2020)



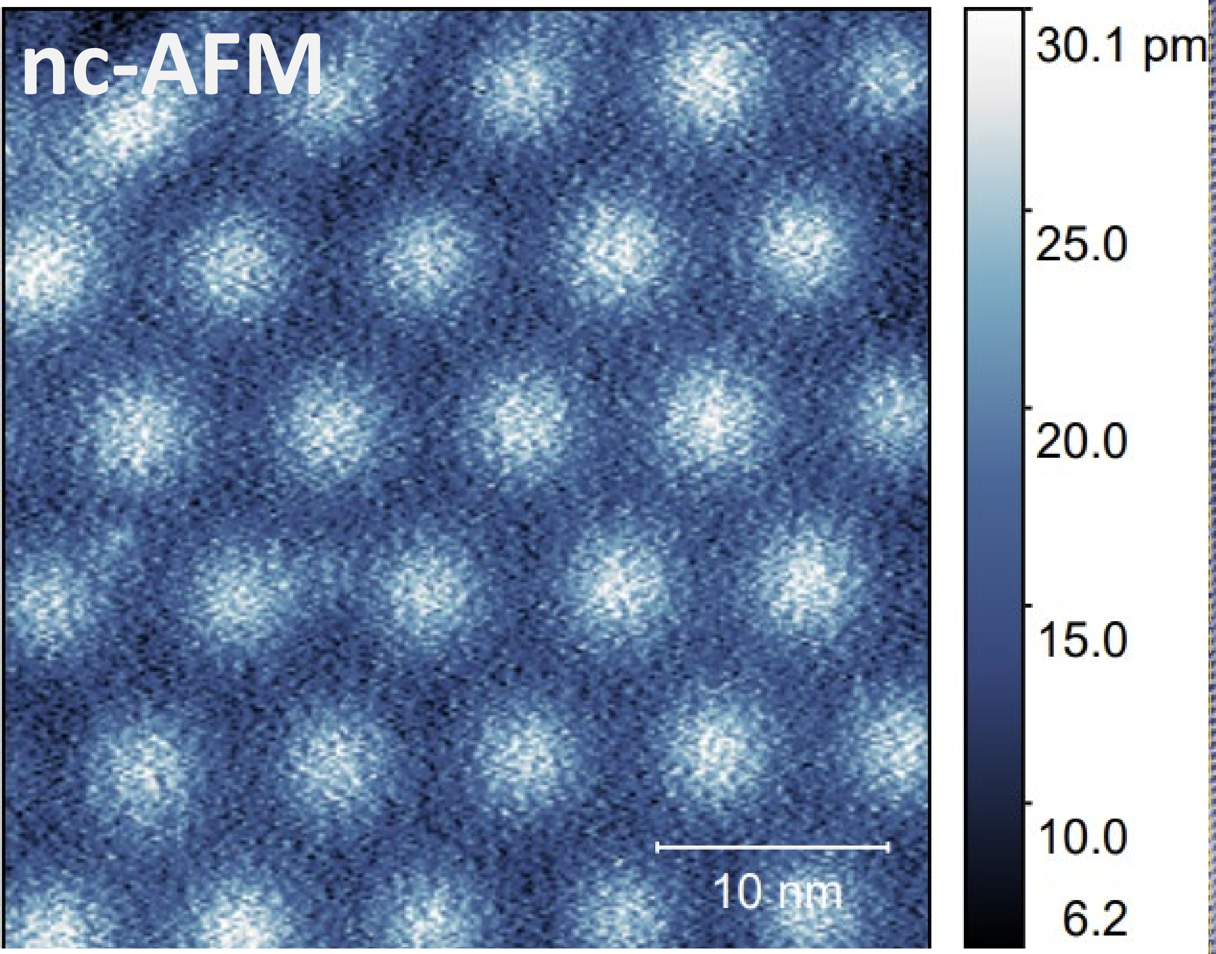


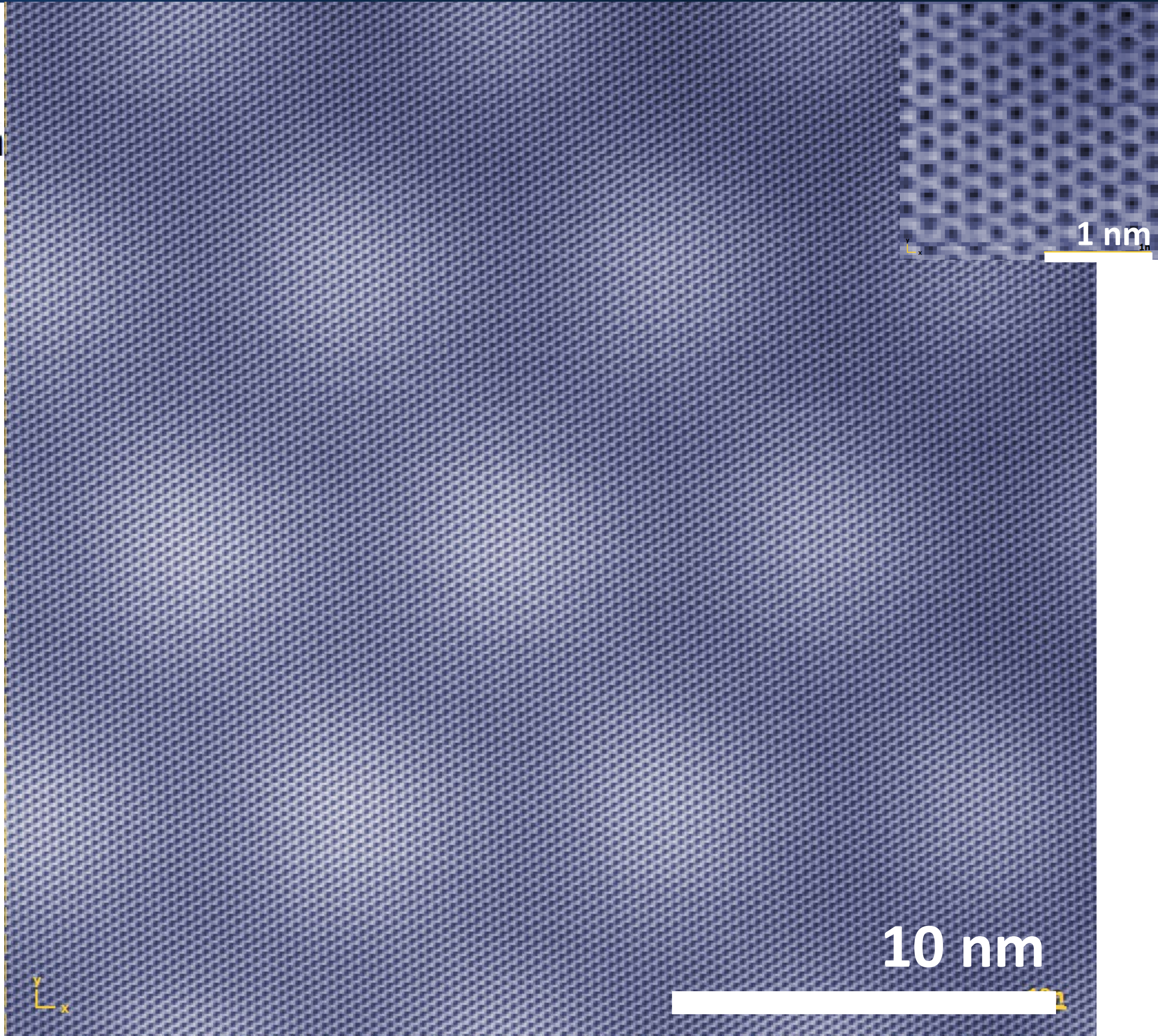
TDBG at 1.75° probed locally





STM imaging of TDBG moiré





Applying a displacement field

STM:

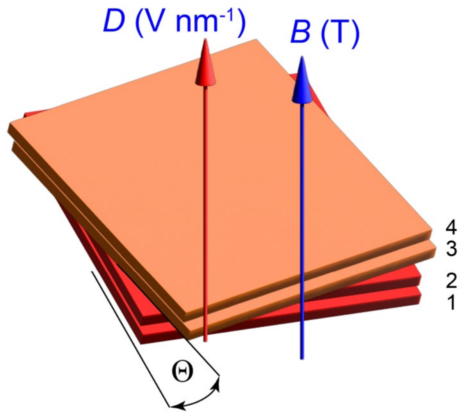
Carrier density:

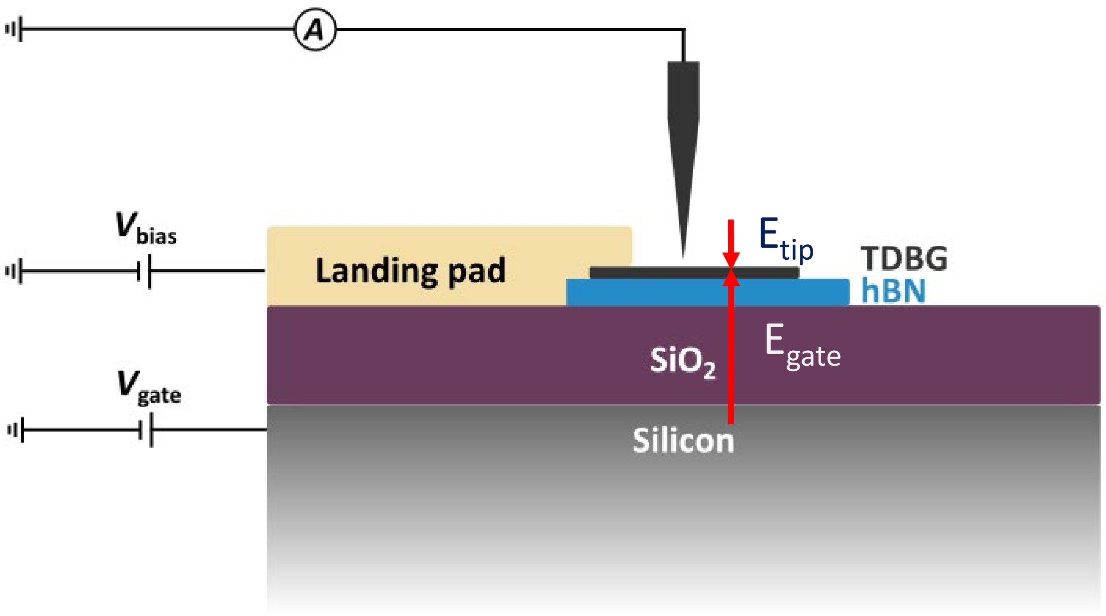
$$n \sim C_g V_g + C_t V_t$$

Displacement field

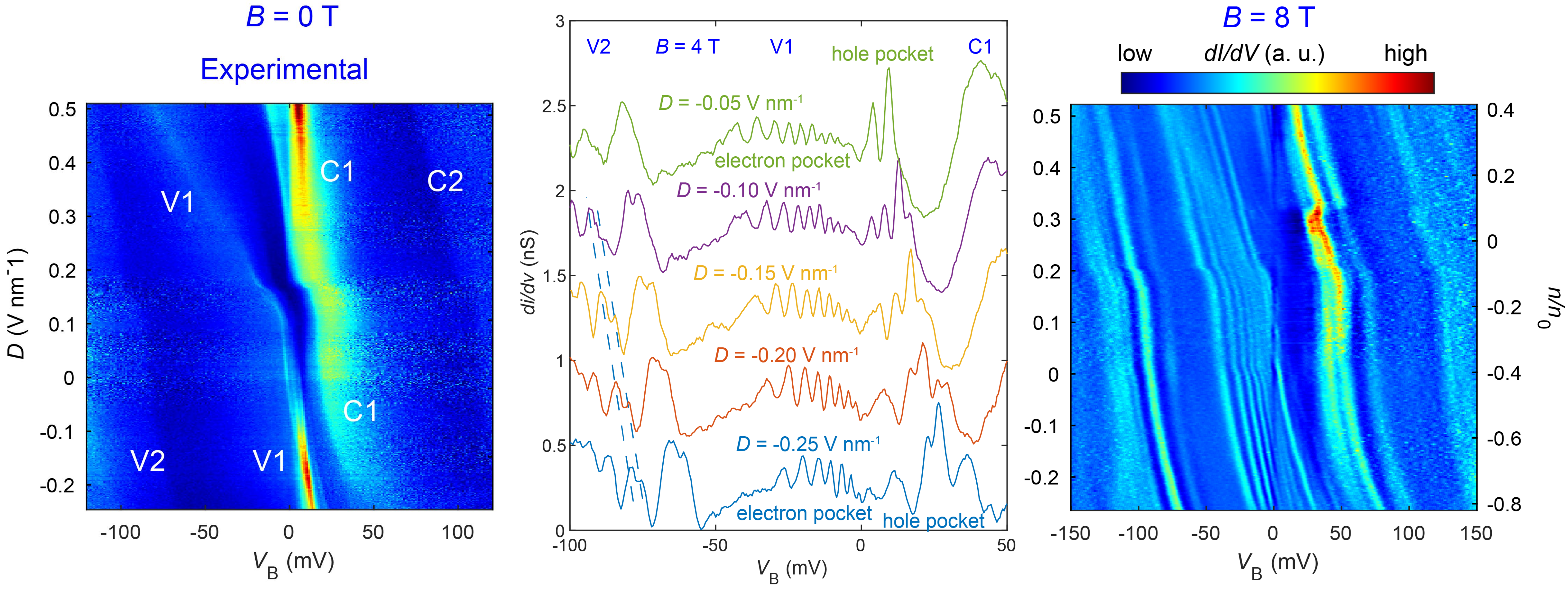
$$D \sim C_g V_g - C_t V_t$$

V_t obtained from AFM CPD measurements

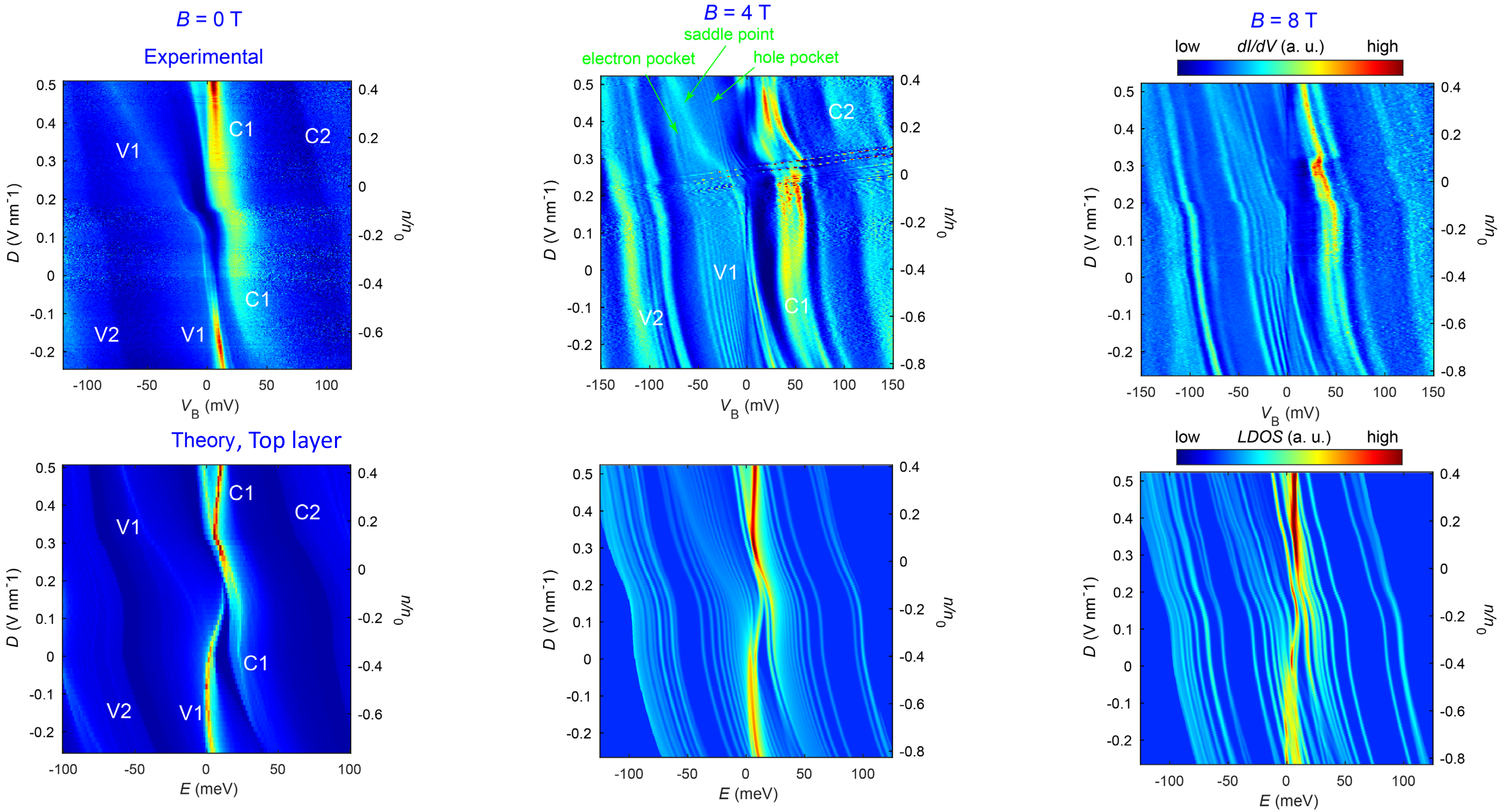




STM "gate maps"

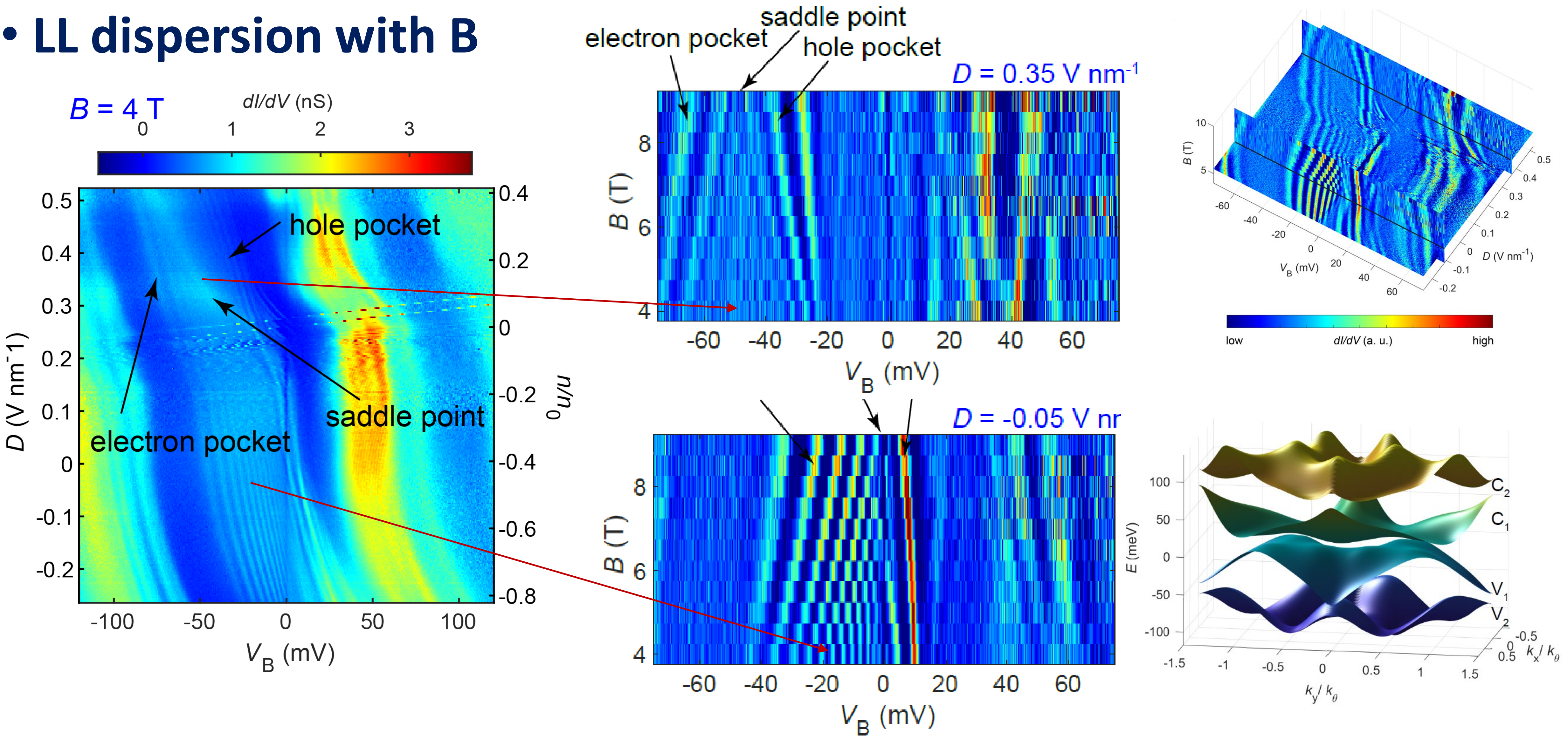


Comparison to (single-particle) theory



Electron and hole pockets in magnetic fields

- **LL dispersion with B**



Electron and hole pockets in magnetic fields

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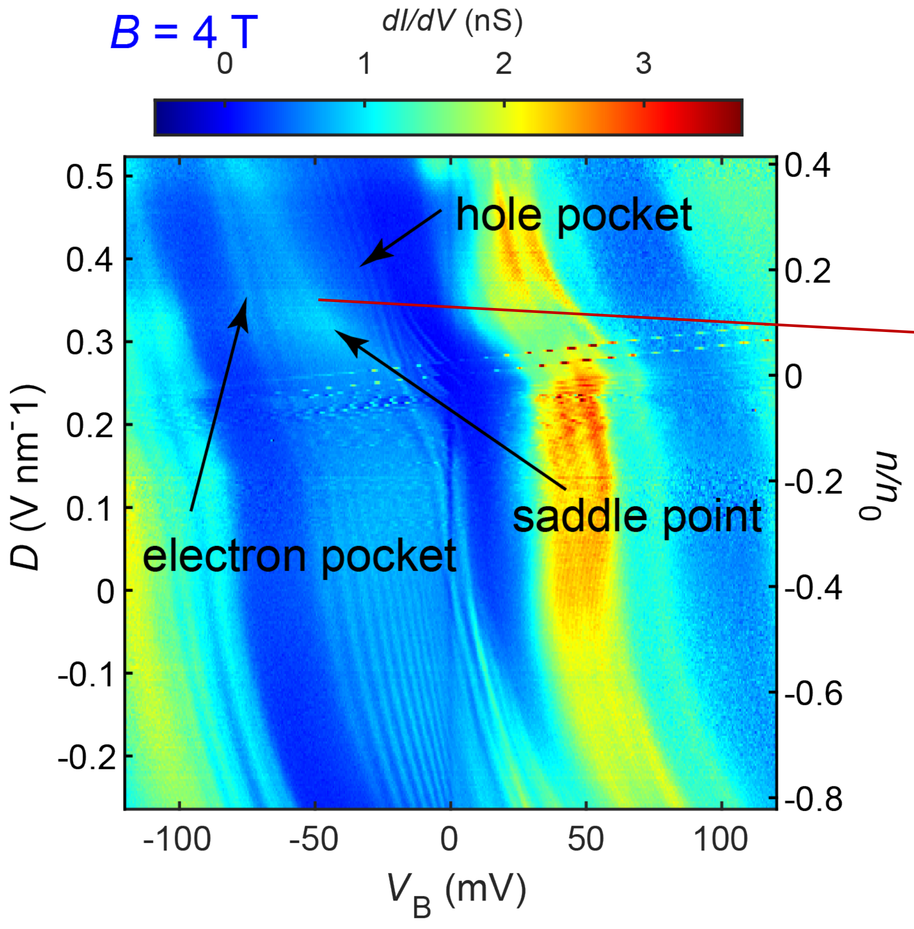
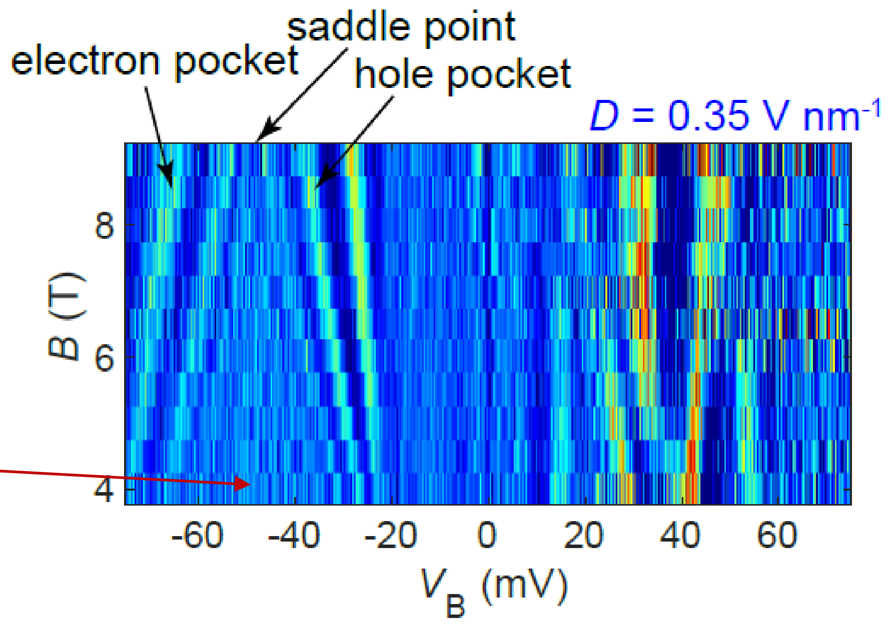
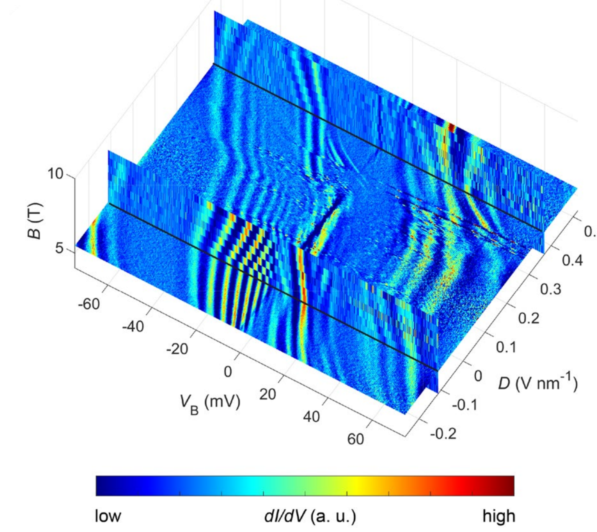
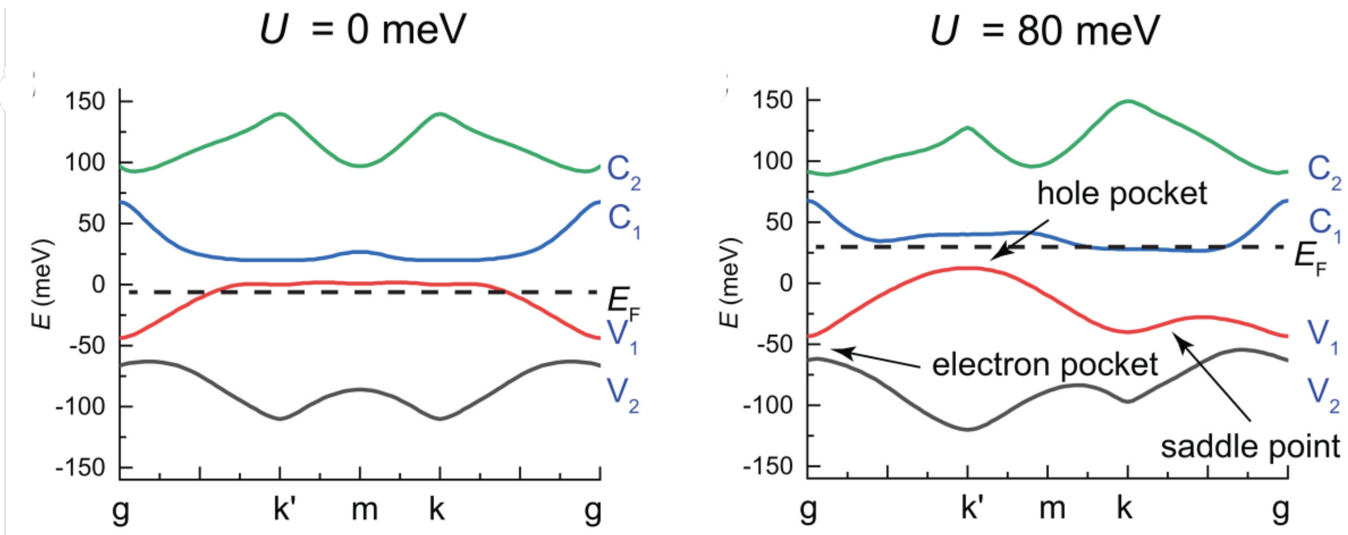
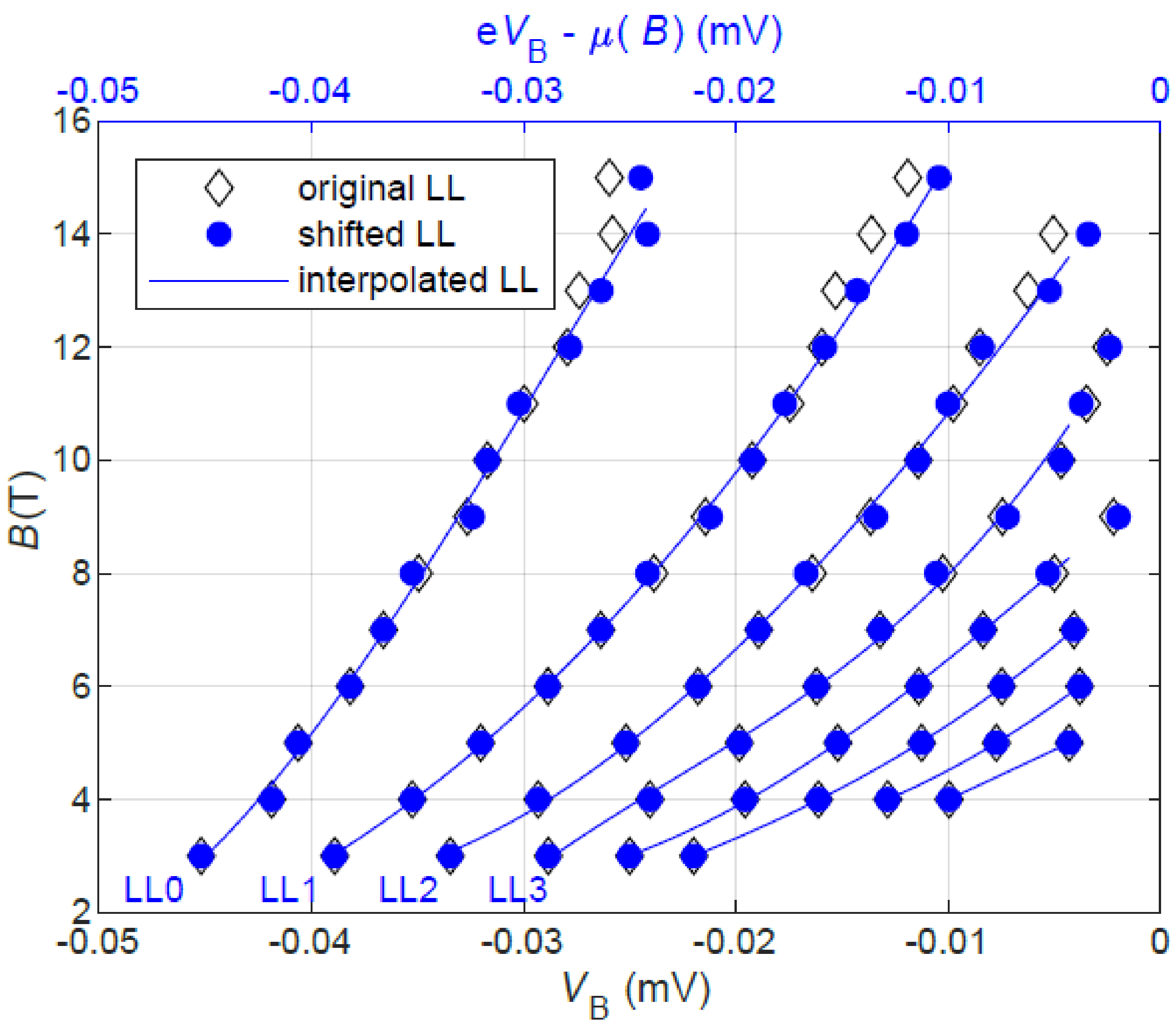




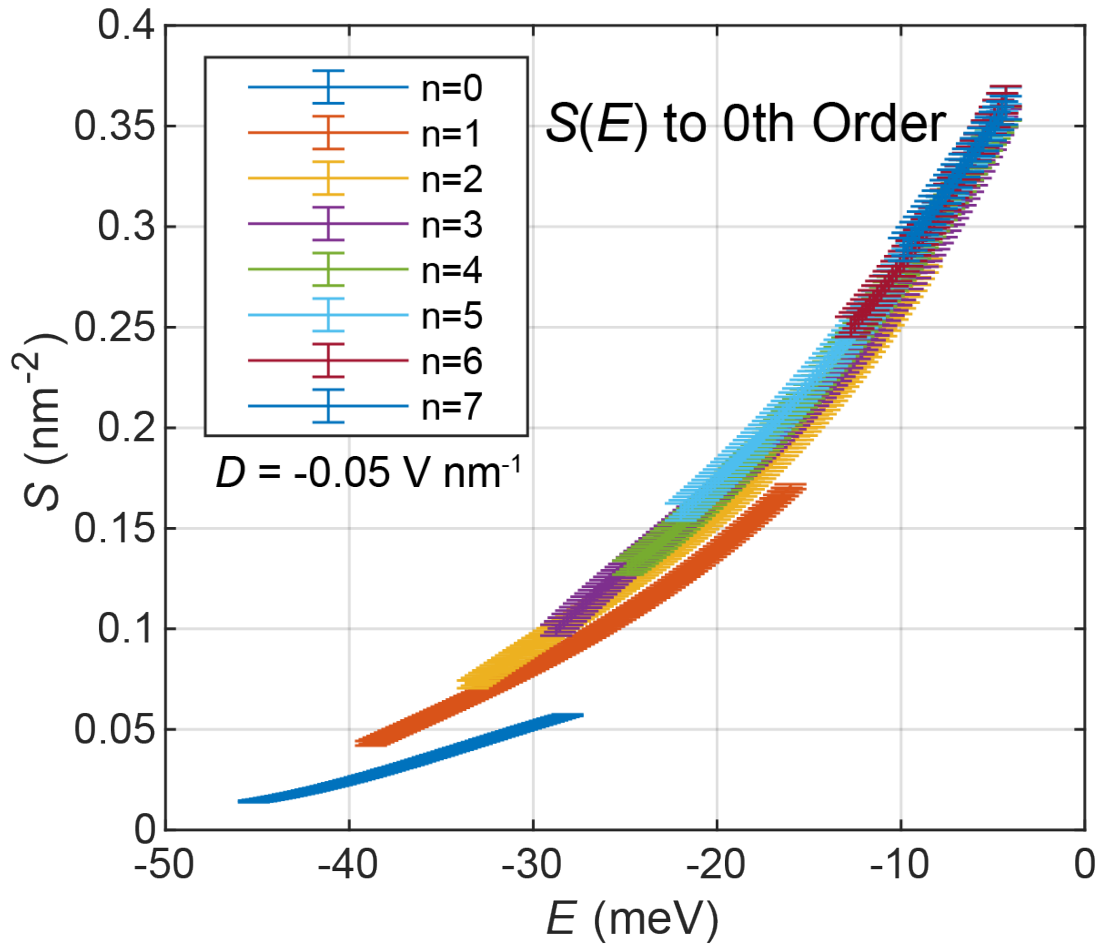




Extracting magnetic response functions



$$S(E_n) = \frac{qB}{\hbar} \cdot 2\pi \left(n + \frac{1}{2}\right)$$



Paul Haney, NIST

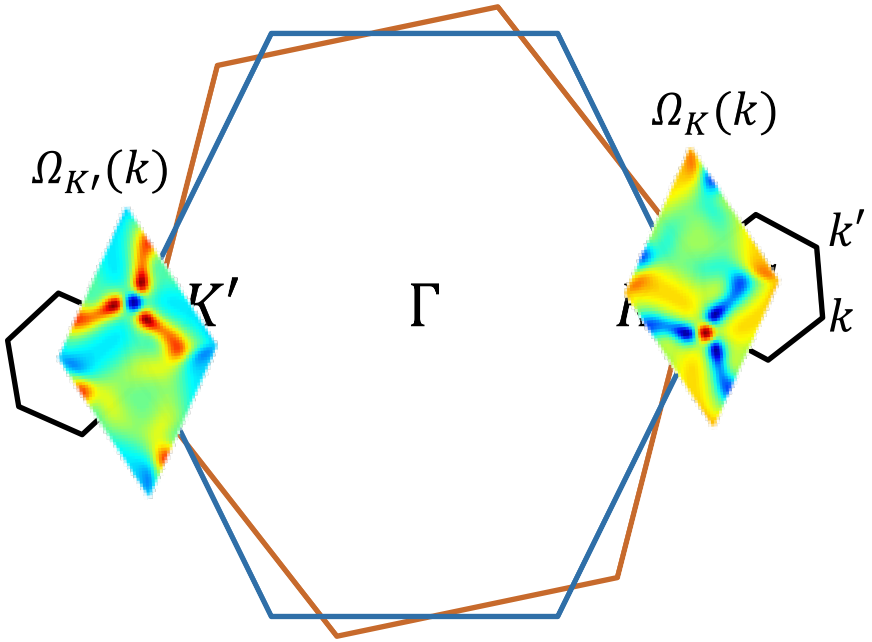
Geometric contributions

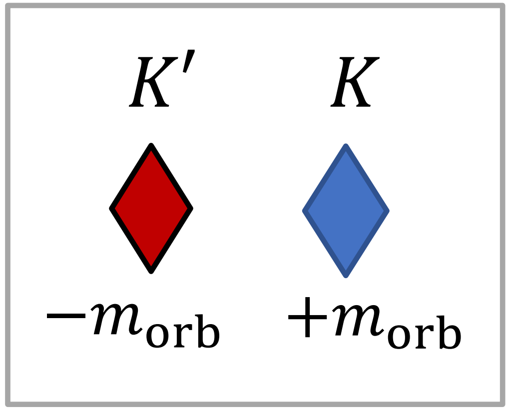
- Extended Onsager relation

Depends on Berry curvature

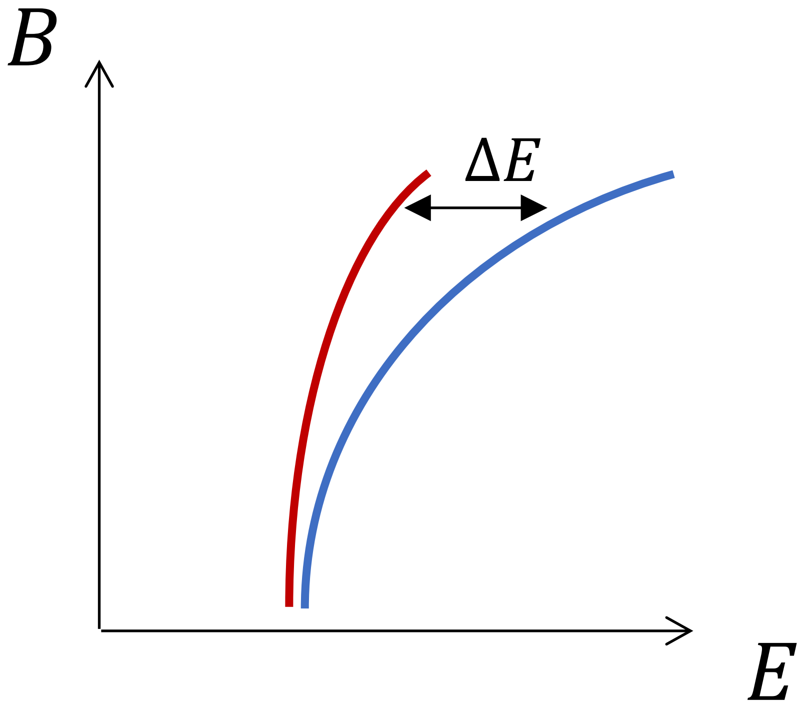
Depends on quantum metric and other wave packet properties

$$B_n(n+1/2)/\phi_0 = S(E_n)/4\pi^2 + m'(E_n)B_n + \chi'(E_n)B_n^2/2$$



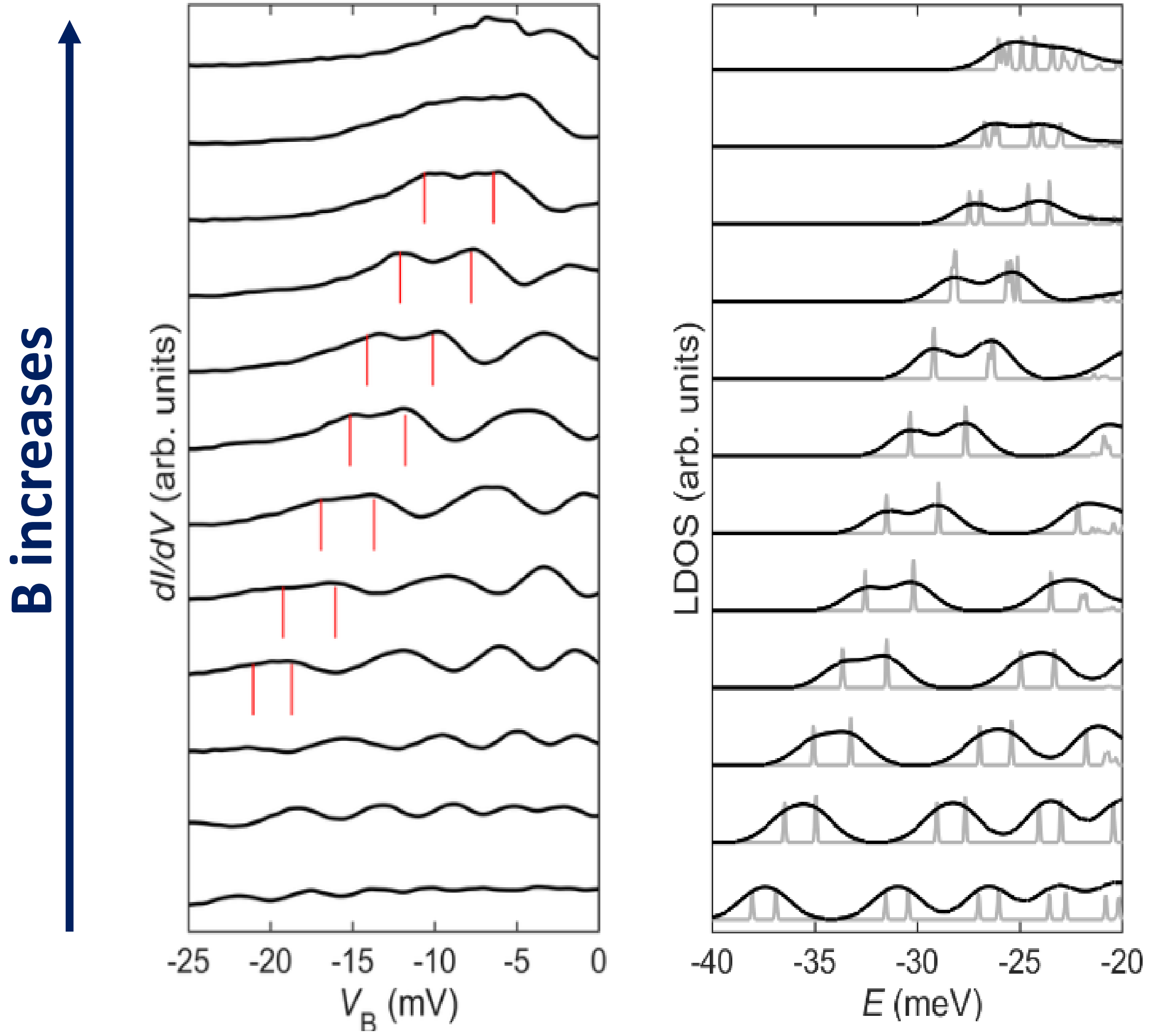


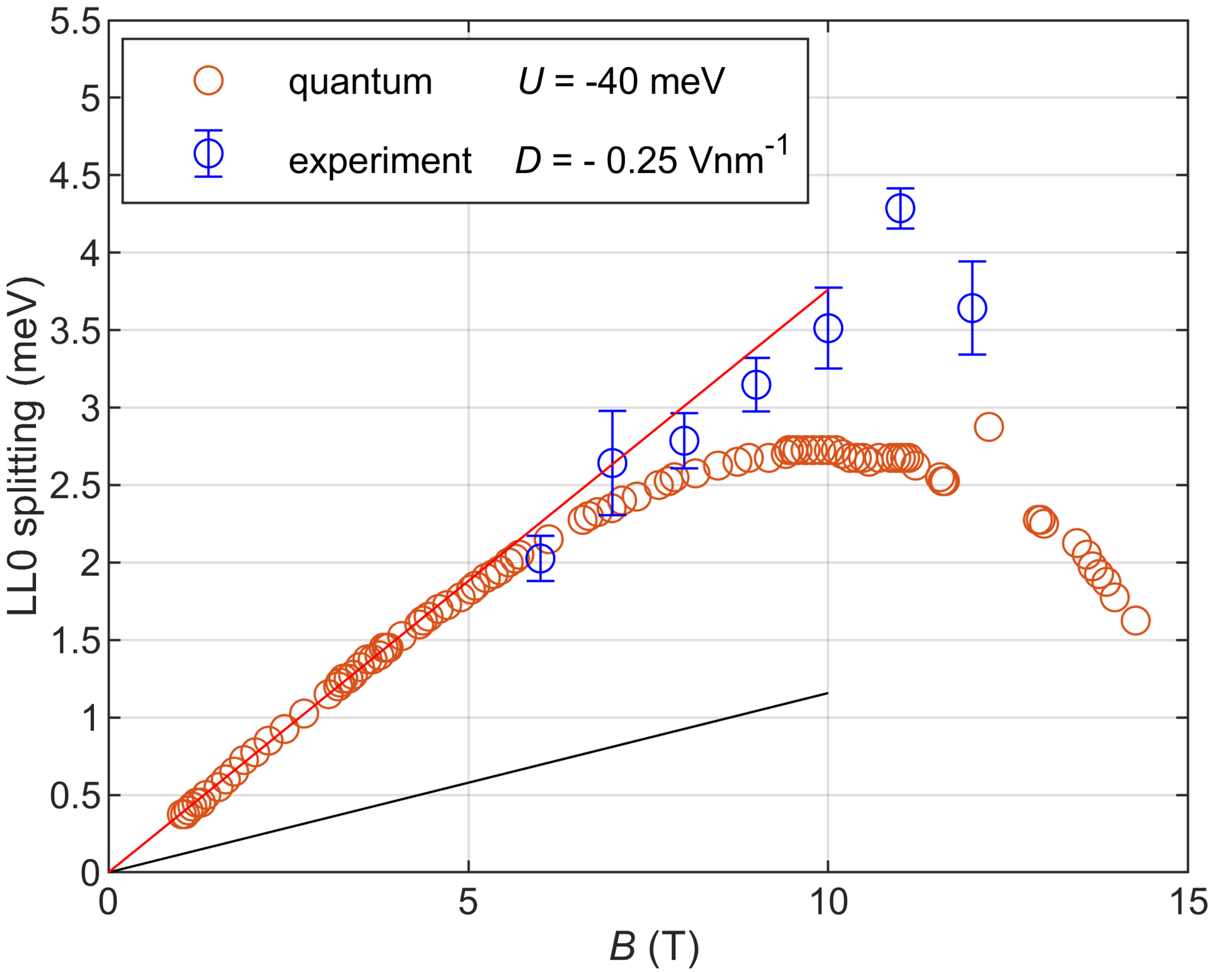
Note that total $\boldsymbol{m}_{\mathrm{orb}}$= 0.



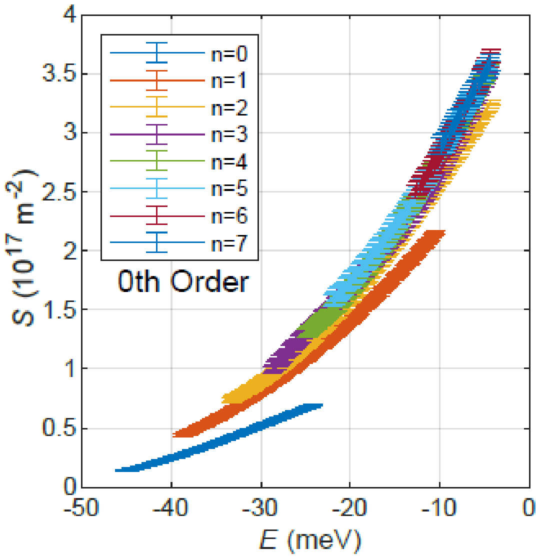
$$\Delta E = g(E)\mu_B B$$

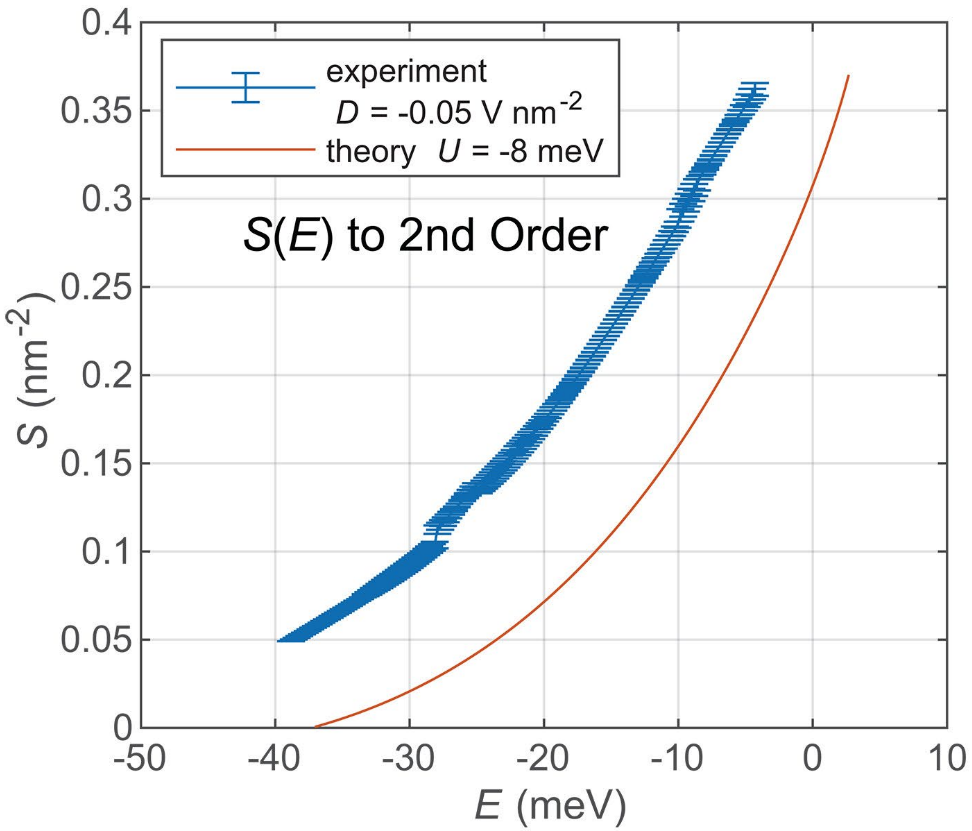
First order: orbital magnetic moment

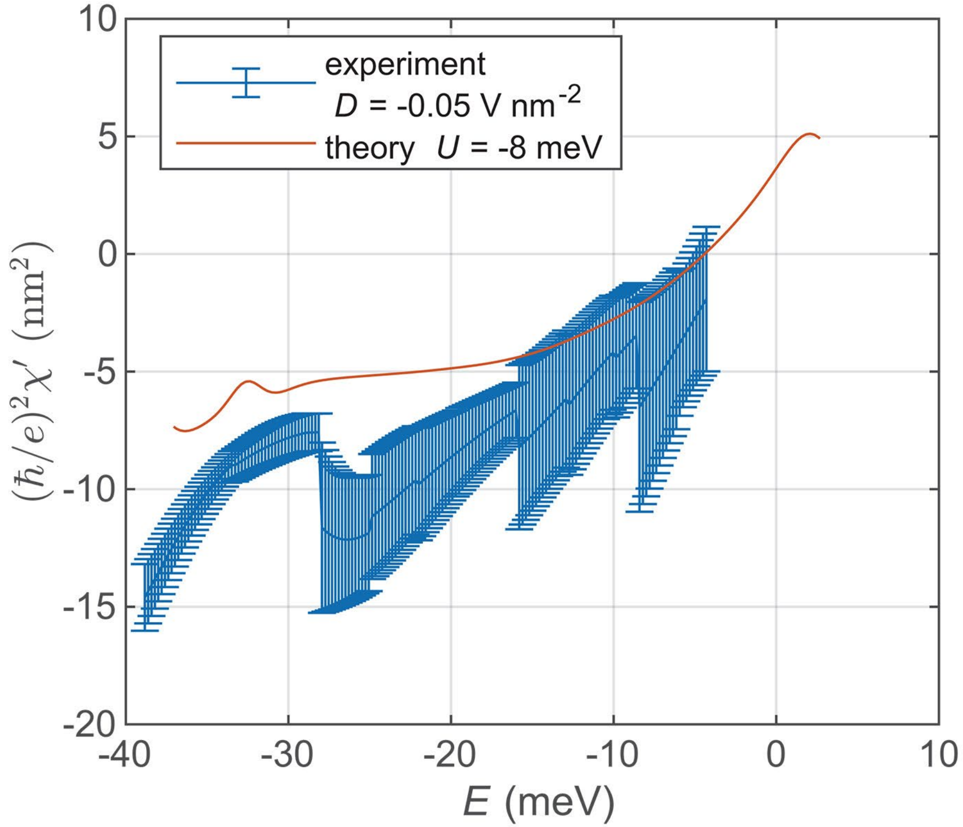




2^{d} order correction – susceptibility







$$B_n(n+1/2)/\phi_0 = S(E_n)/4\pi^2 + m'(E_n)B_n + \chi'(E_n)B_n^2/2$$

Average $m'(E_n)$ ~ 5 μA/eV, m ~ 3μ_B

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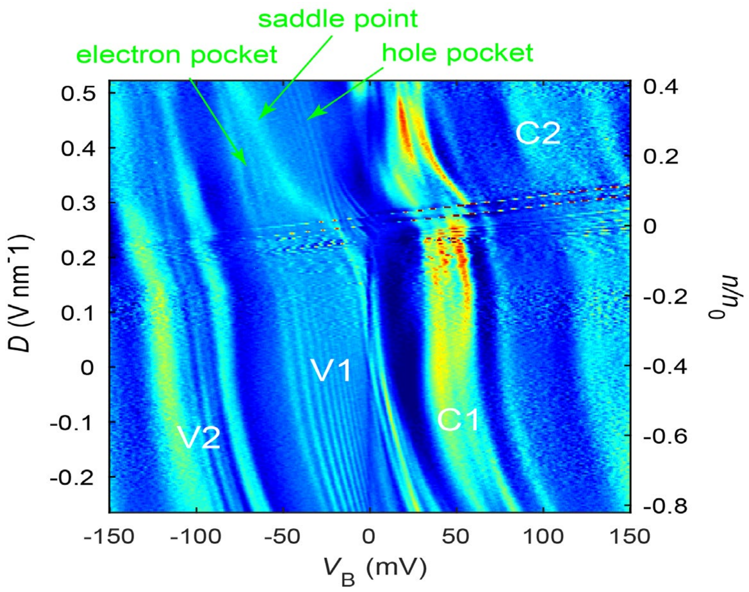
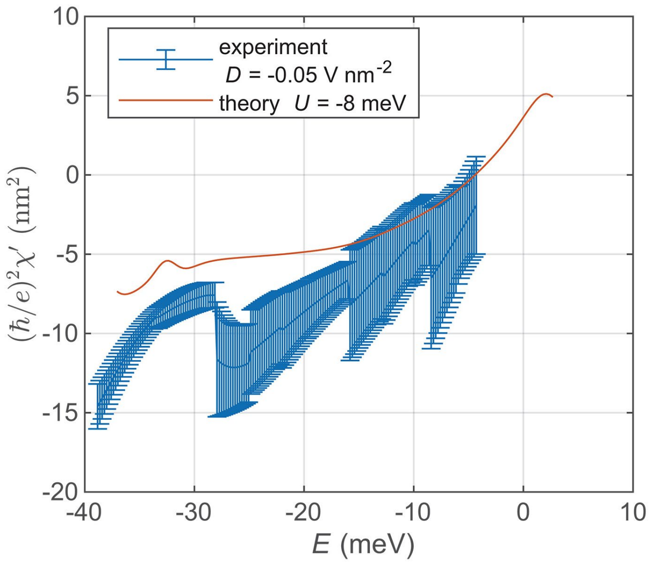
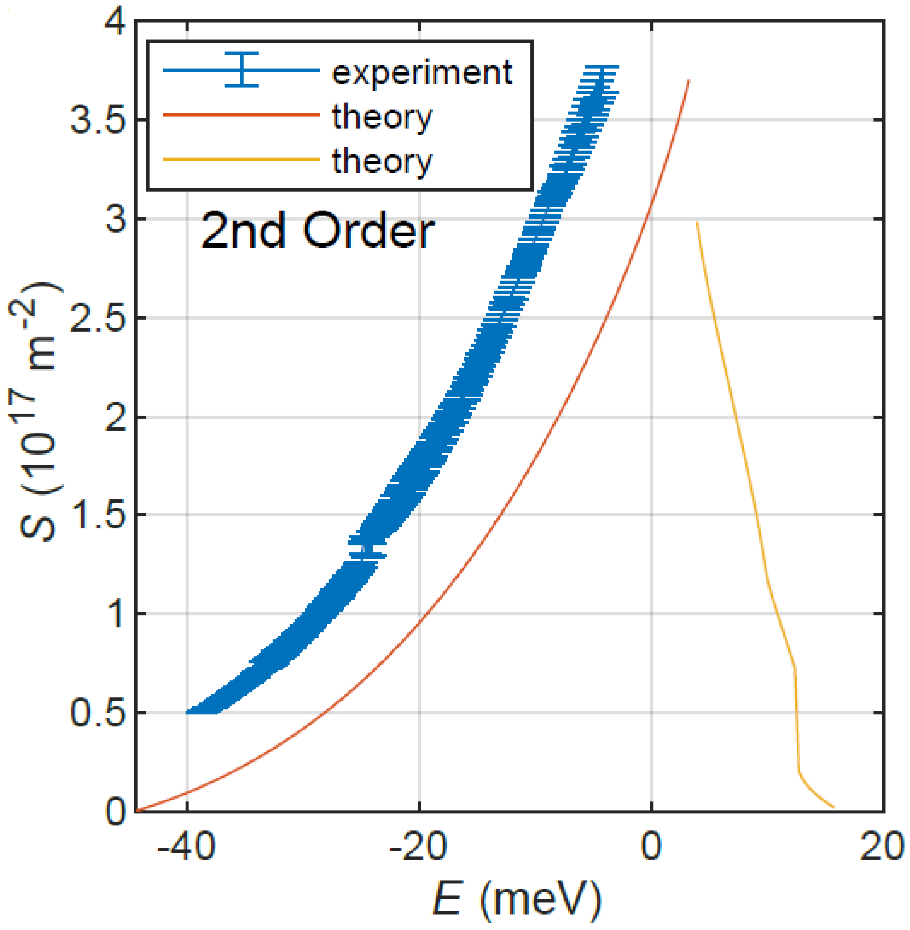
Main points

- **Landau level spectroscopy of narrow bands**
- **Tunable band structure in TDBG changes character from electron-like to hole-like**
- **Orbital magnetism and magnetic susceptibility detected and quantified**



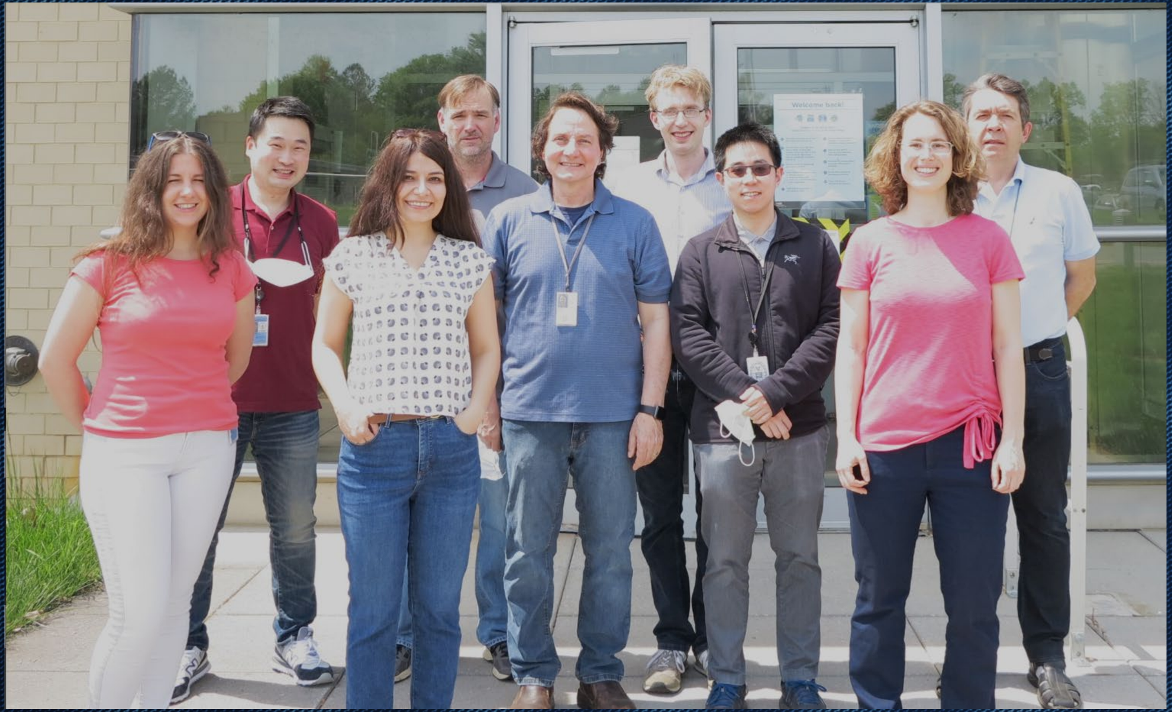




Thank you for your attention!

NIST

NIST team



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