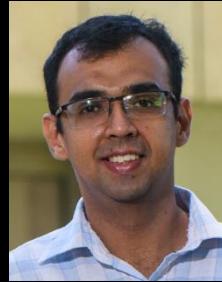
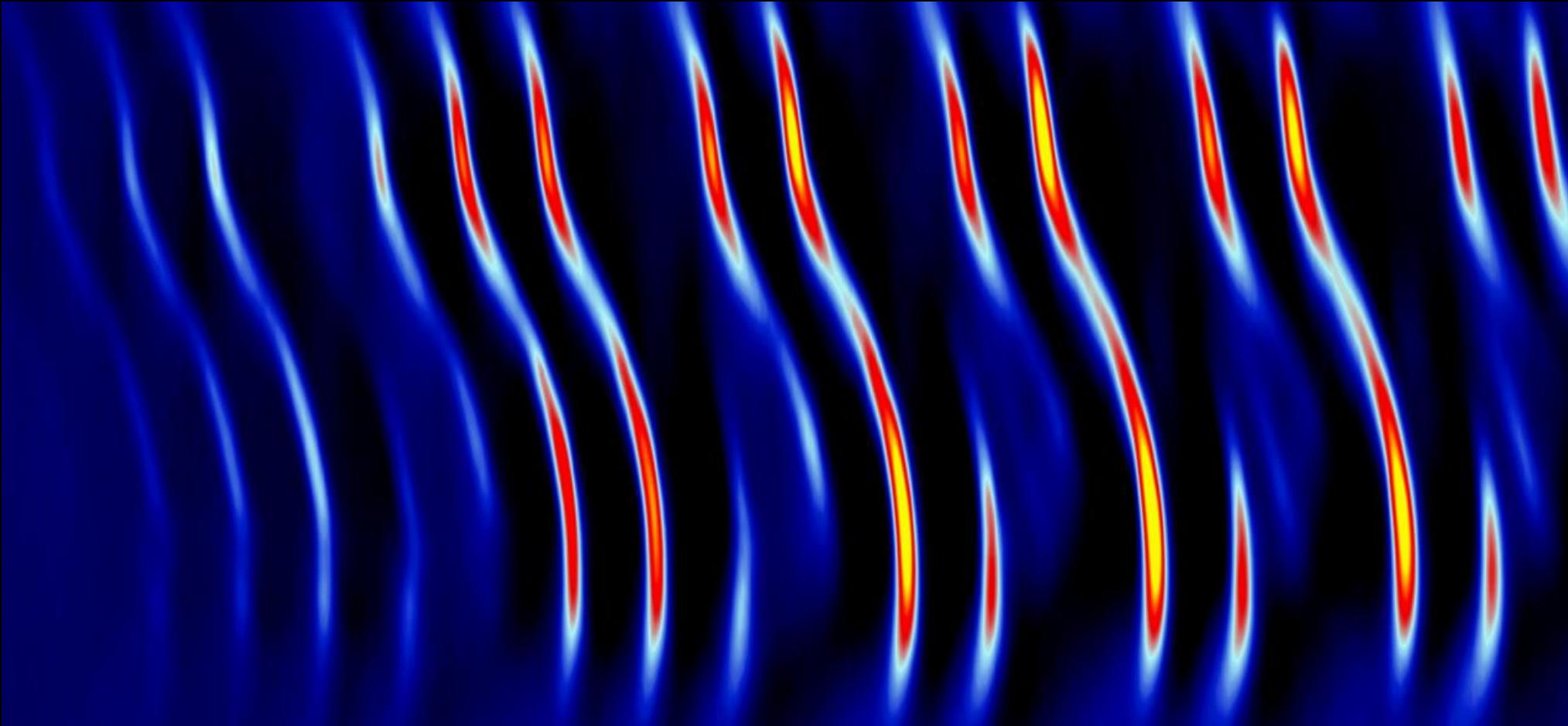


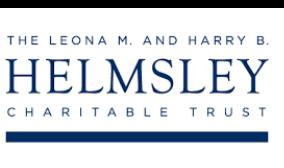
Topological currents, twist-angle disorder and unconventional Landau levels in MA graphene



Aviram
Uri



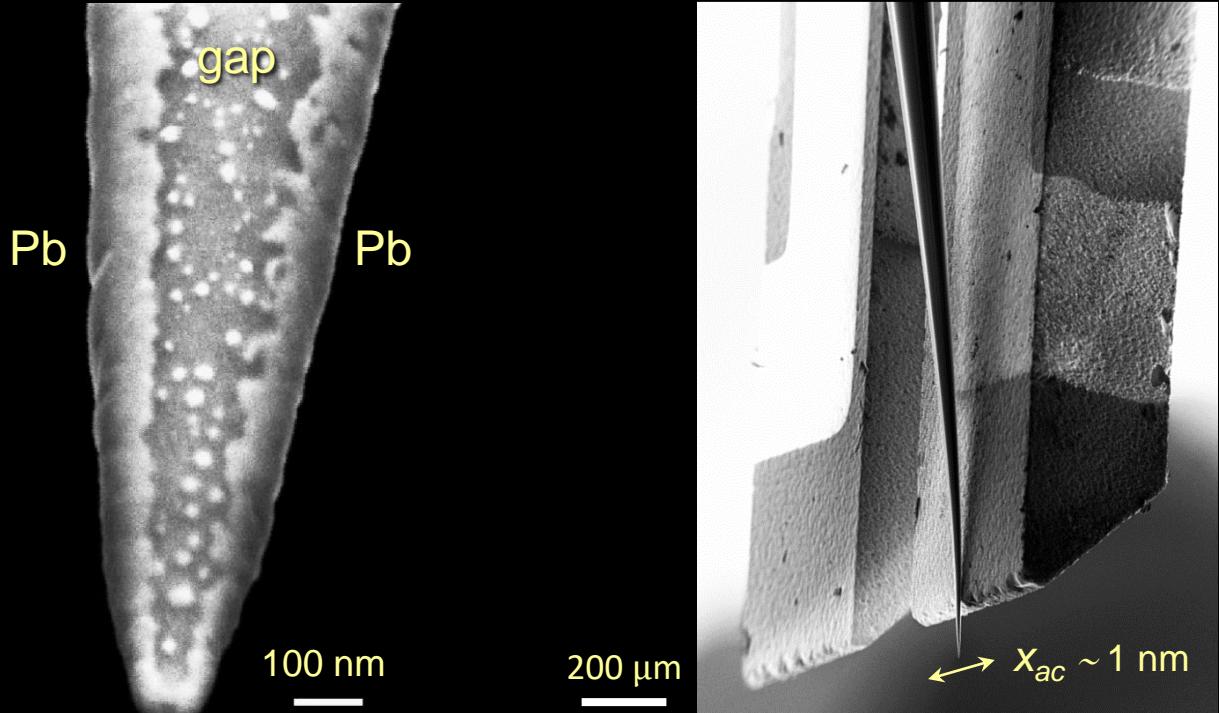
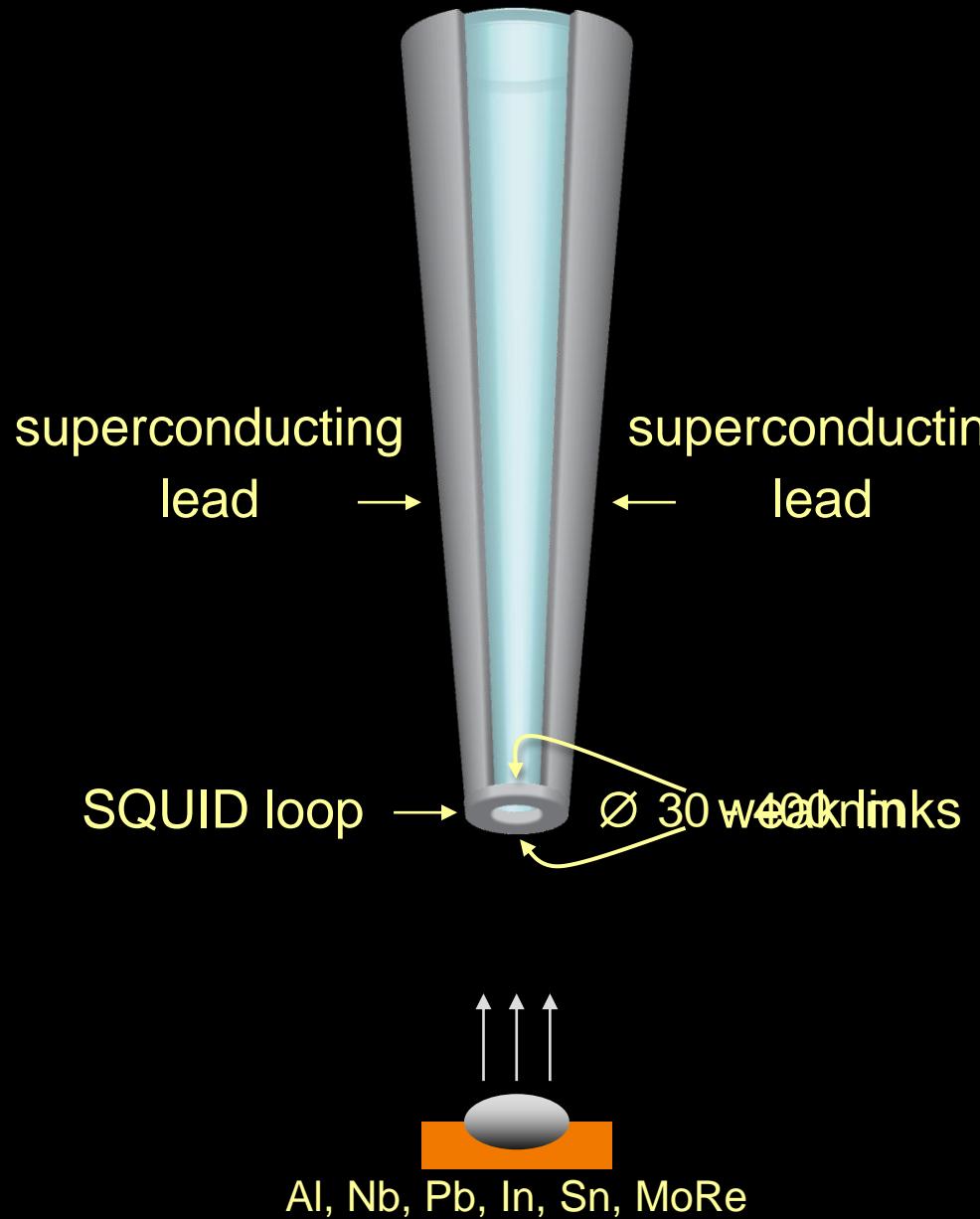
Sameer
Grover



Eli Zeldov
Weizmann Institute of Science
Israel



SQUID on tip



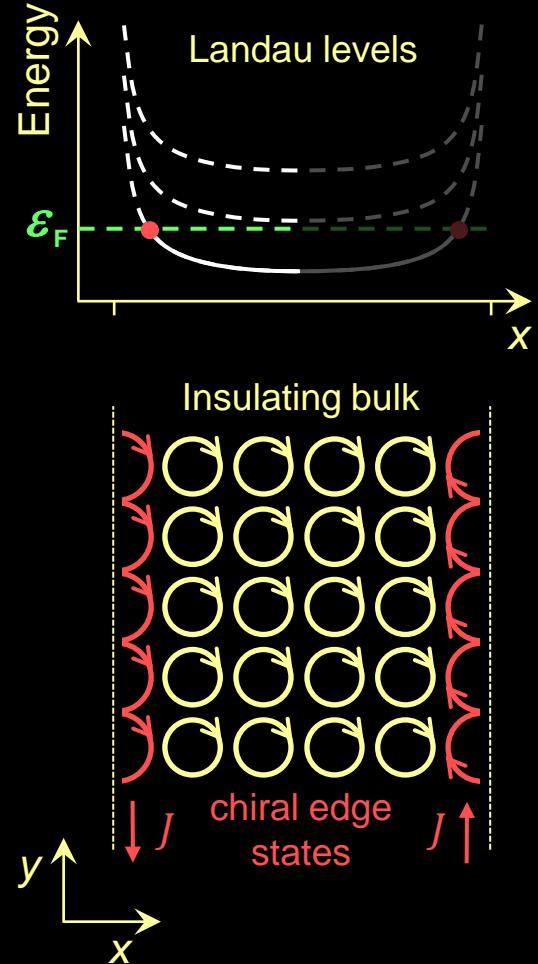
Loop diameter $< 40 \text{ nm}$
Operating field $> 1 \text{ T}$
Flux noise: $S_\Phi^{1/2} = 50 \text{ n}\Phi_0/\text{Hz}^{1/2}$
Spin noise: $S_n^{1/2} = 0.3 \text{ } \mu\text{B}/\text{Hz}^{1/2}$
Thermal noise: $S_T^{1/2} < 1 \text{ } \mu\text{K}/\text{Hz}^{1/2}$

SQUID-on-tip attached to
tuning fork for force sensing
Scan height: $\sim 10 \text{ nm}$

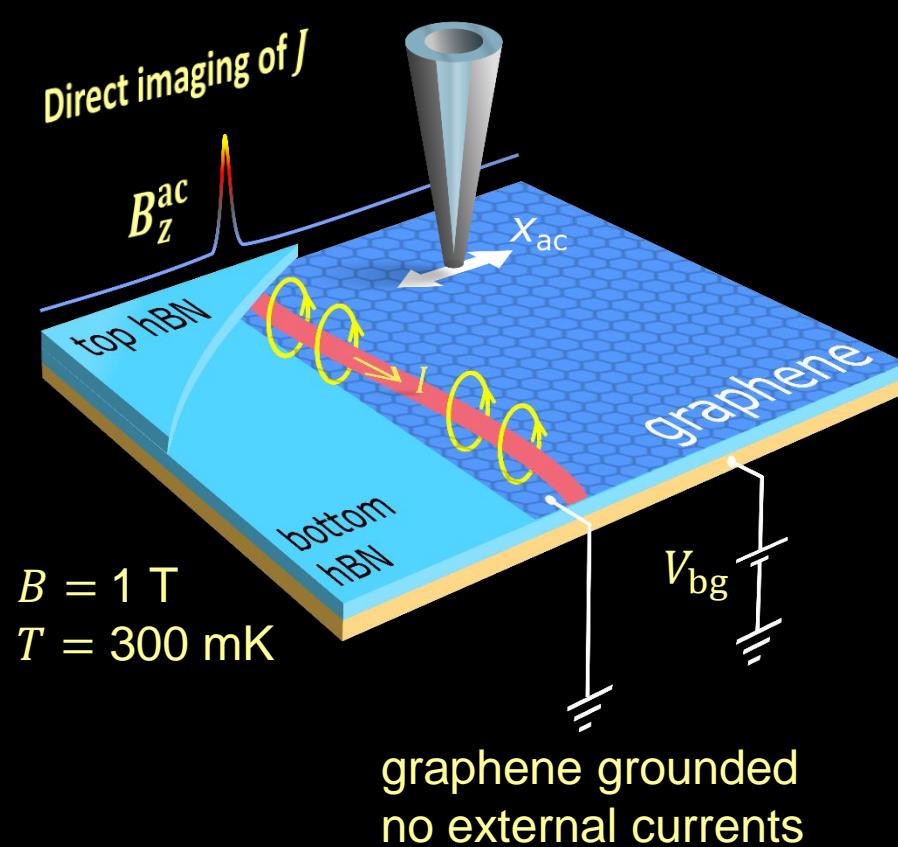
- K. Bagani, PR Applied **12**, 044062 (2019)
D. Vasyukov *et al.*, Nature Nanotech. **8**, 639 (2013)
D. Halbertal *et al.*, Nature **539**, 407 (2016)

Imaging equilibrium currents in QH edge states in graphene

Quantum Hall effect



SQUID on tip



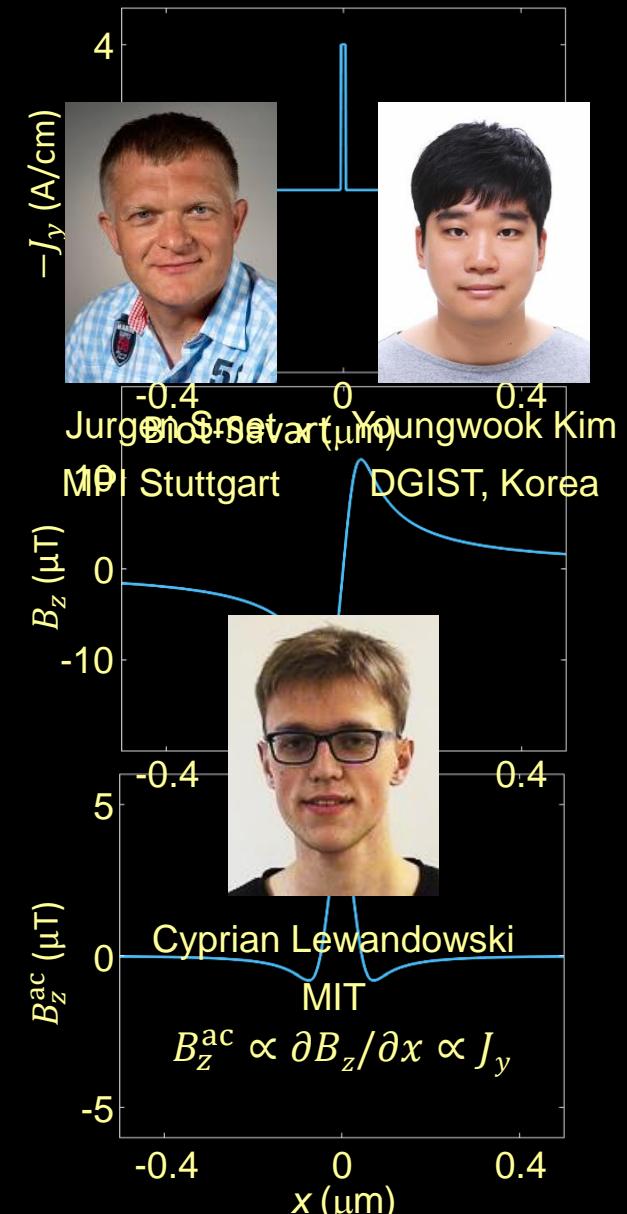
Weis, von Klitzing, Phil. Trans. **369**, 3954 (2011)

Lai *et al.*, PRL **107**, 176809 (2011)

Feldman, Krauss, Smet, Yacoby, Science **337**, 1196 (2012)

Suddards, Baumgartner, Henini, Mellor, New J. Phys. **14**, 083015 (2012)

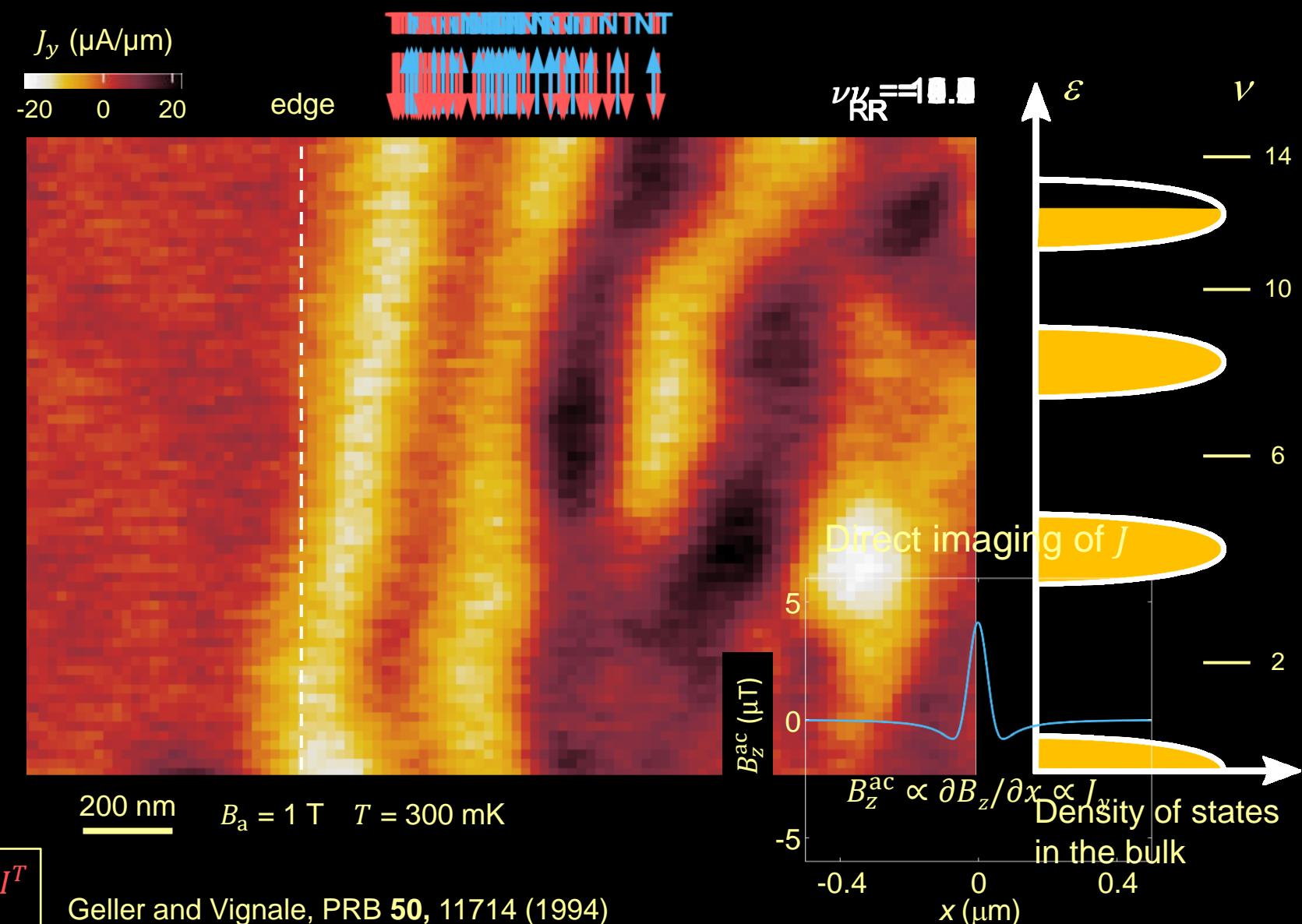
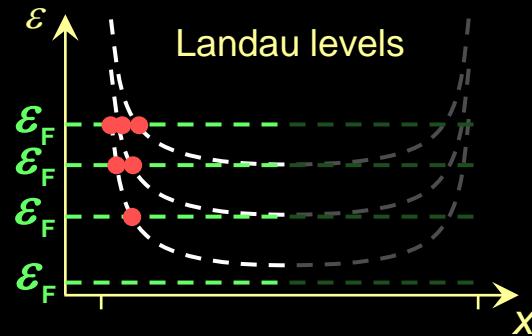
Cui *et al.*, PRL **117**, 186601 (2016)



A. Uri *et al.*, Nature Physics **16**, 164 (2020)

Imaging equilibrium currents in quantum Hall edge states

Quantum Hall effect

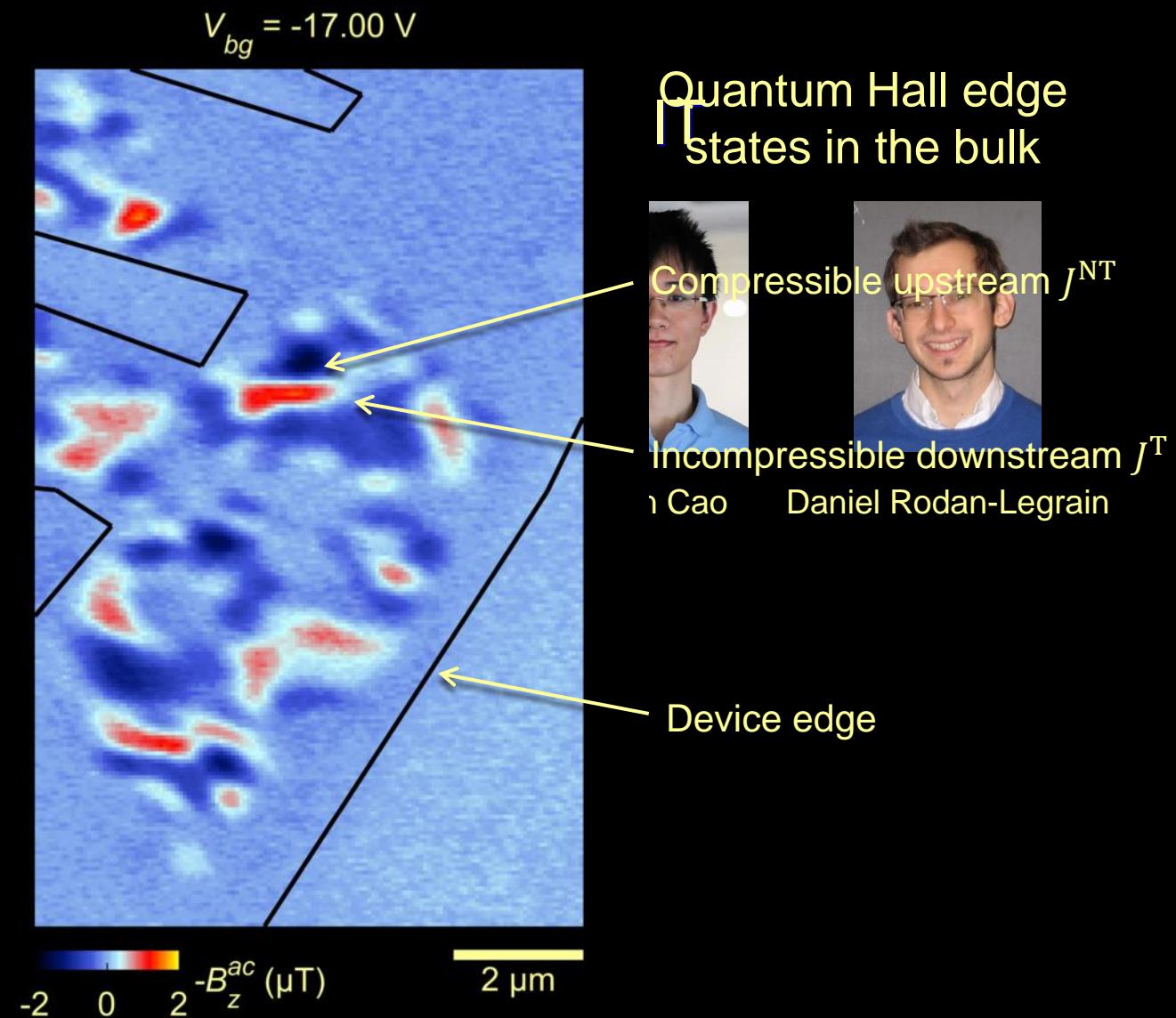
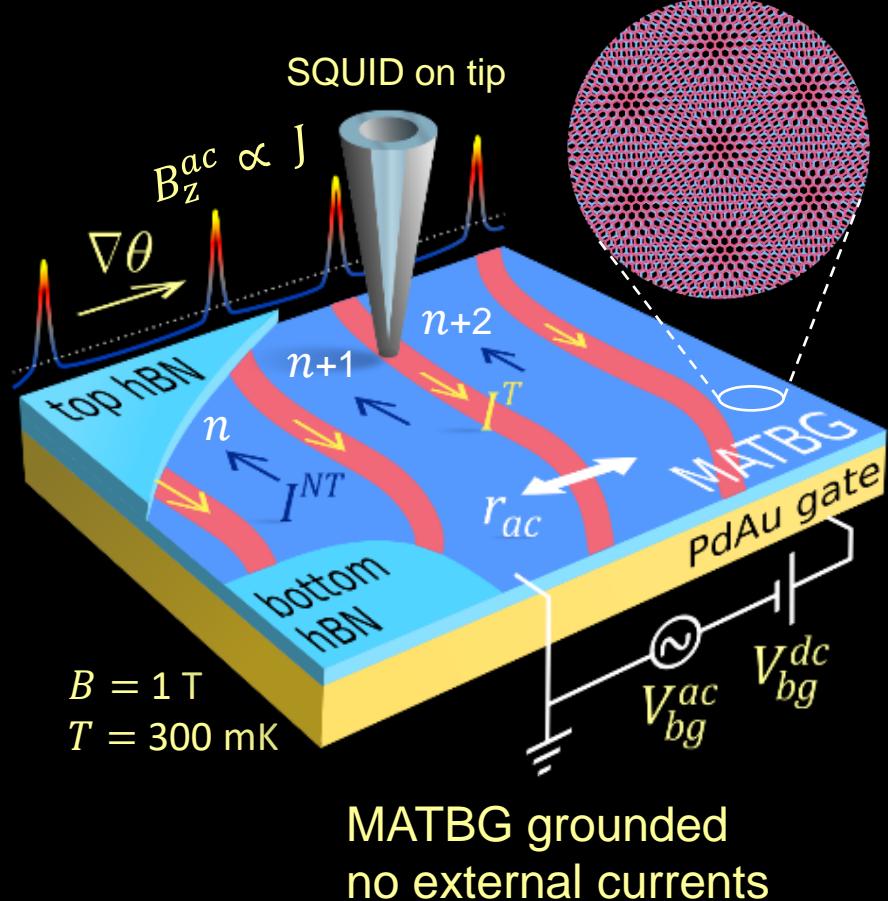


Incompressible strips carry downstream I^T
Compressible strips carry upstream I^{NT}

Geller and Vignale, PRB **50**, 11714 (1994)

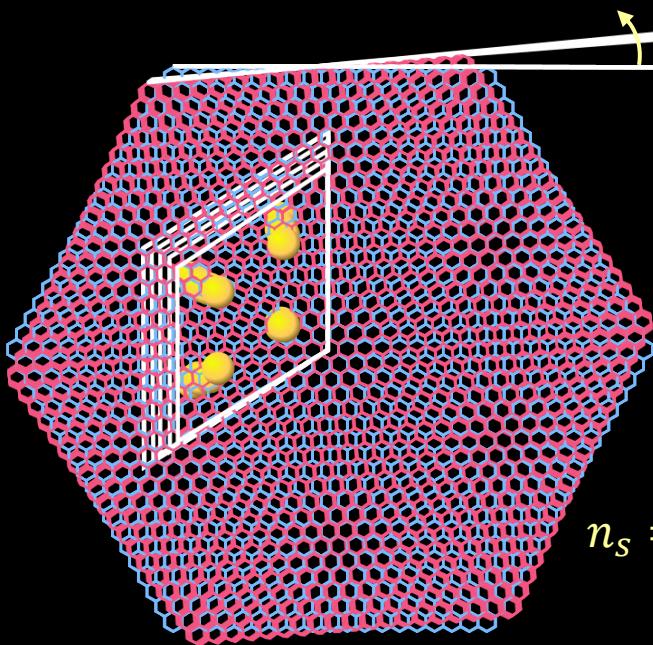
A. Uri *et al.*, Nature Physics **16**, 164 (2020)

Equilibrium currents in magic angle graphene

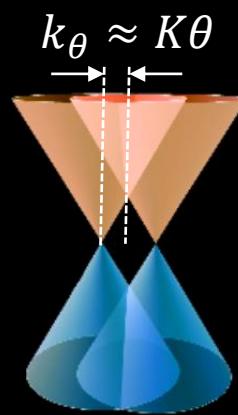


Magic angle physics

Moiré super-lattice

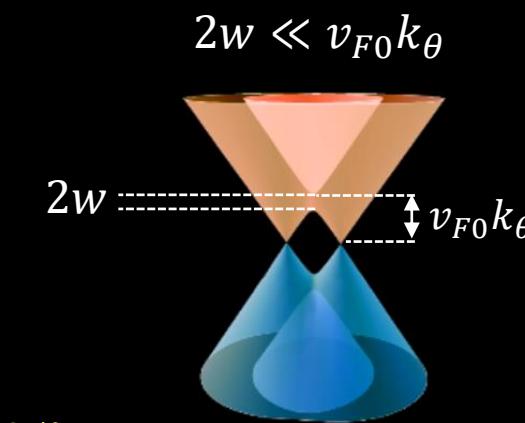


No interlayer interaction



$$n_s = \frac{8\theta^2}{\sqrt{3}a^2}$$

Interlayer interaction w

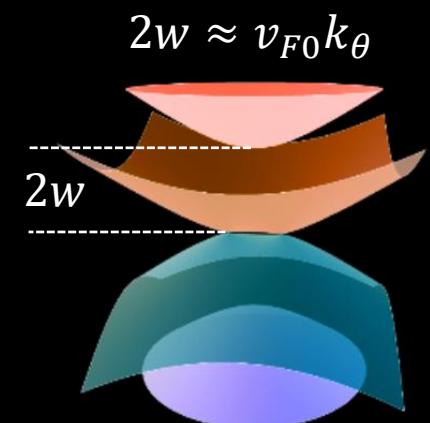


$$2w \ll v_{F0} k_\theta$$

$$v_{F0} k_\theta$$

$$2w \approx v_{F0} k_\theta$$

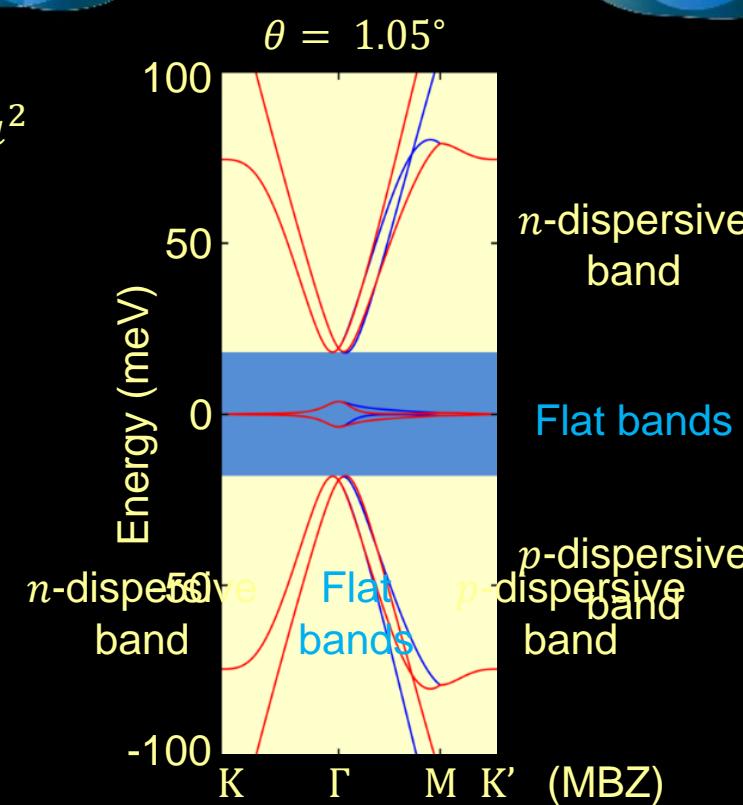
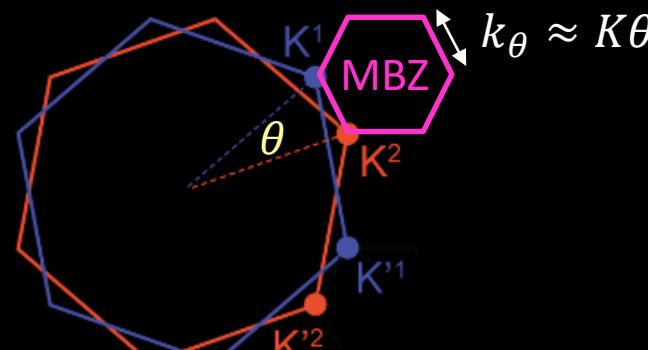
Magic angle $\theta_M \approx 1.1^\circ$



$$2w \approx v_{F0} k_\theta$$

$$2w$$

Mini Brillouin zone (MBZ)



Decreasing Twist Angle

$$v_F \approx 0$$

Coulomb $e-e \gg \epsilon_k$

Correlated states, superconductivity, magnetism, topology, ...

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

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

G. Li *et al.*, Nature Phys. **6**, 109 (2010)

M. Yankowitz *et al.*, Science **363**, 1059 (2019)

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

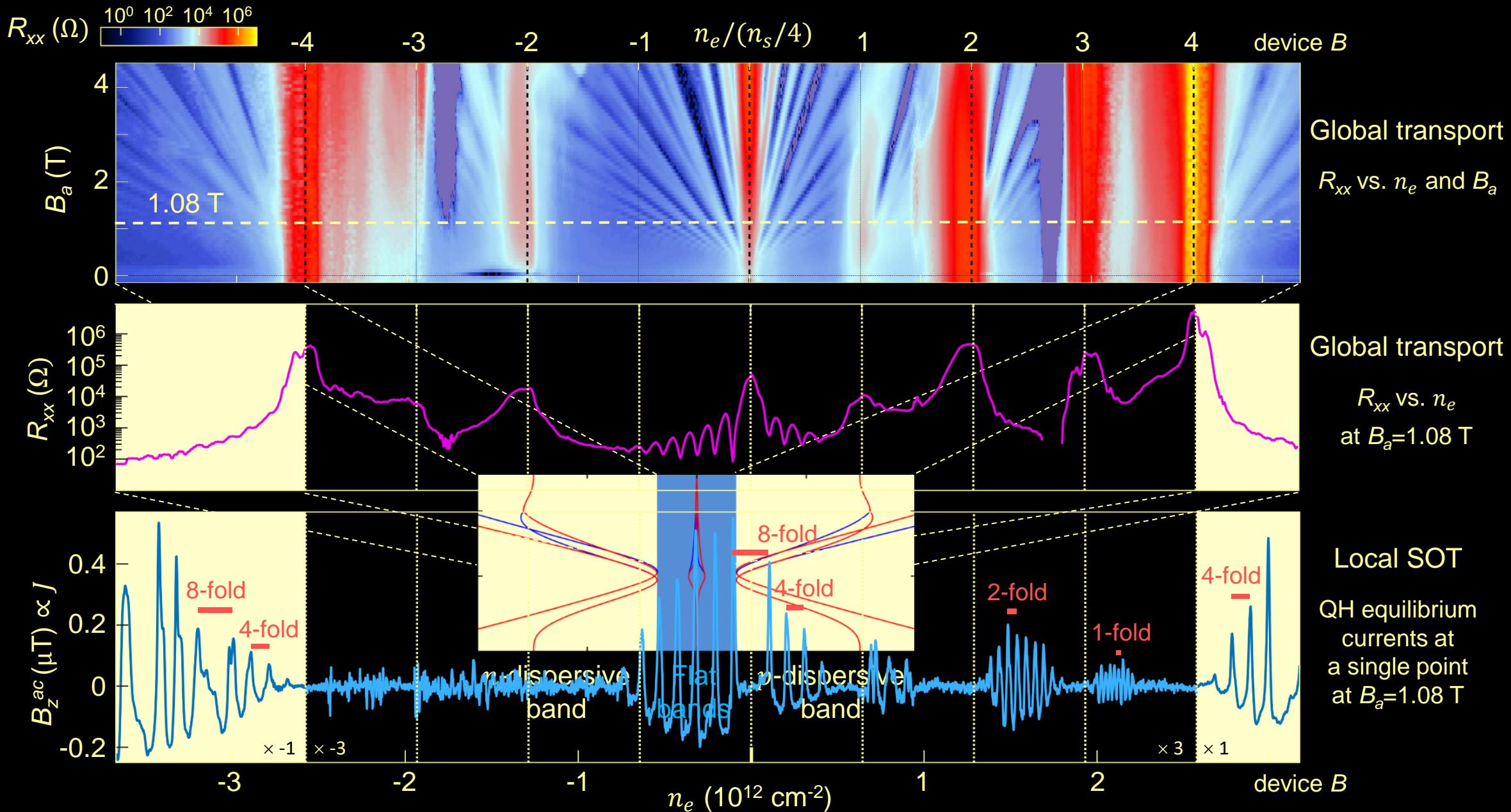
A. L. Sharpe *et al.*, Science **365**, 605 (2019)

E. Suarez Morell *et al.*, PRB **82**, 121407 (2010)

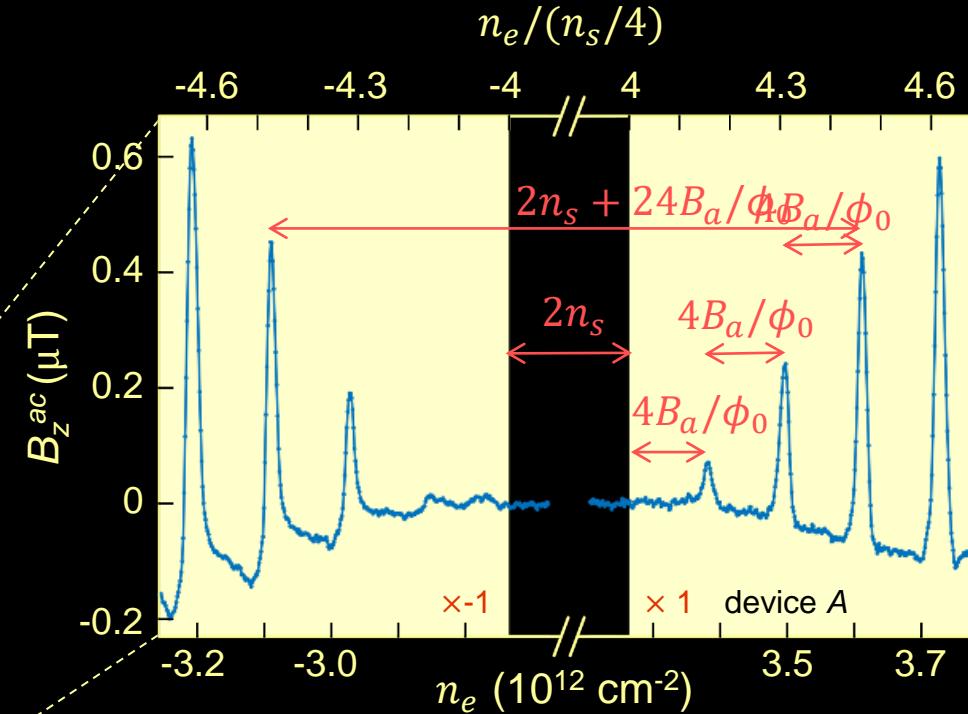
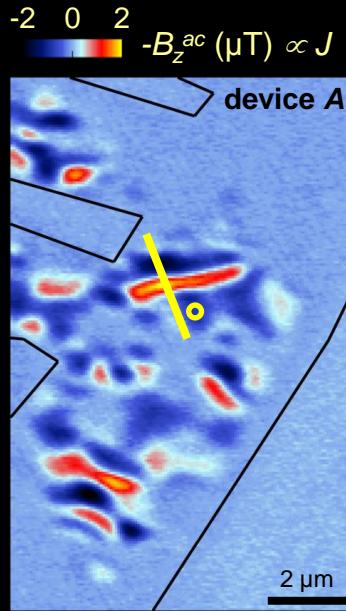
Bistritzer, MacDonald, PNAS **108**, 12233 (2011)

Nam, Koshino, PRB **96**, 075311 (2017)

Global and local Landau levels



Determining the local twist angle

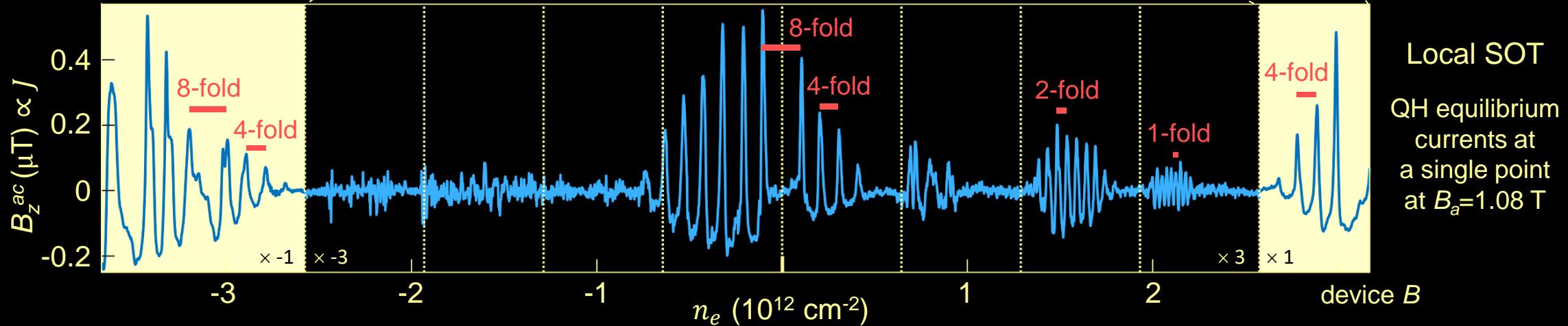


$\theta(r) = a \sqrt{\sqrt{3}n_s(r)/8}$

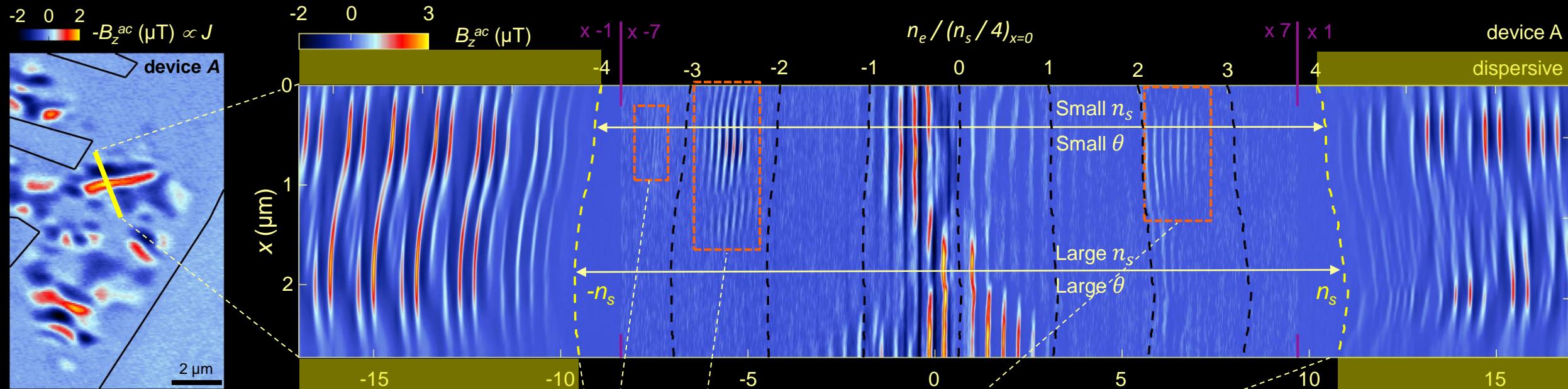
Relative θ accuracy: $\pm 0.0002^\circ$

Spatial resolution: ~ 50 nm

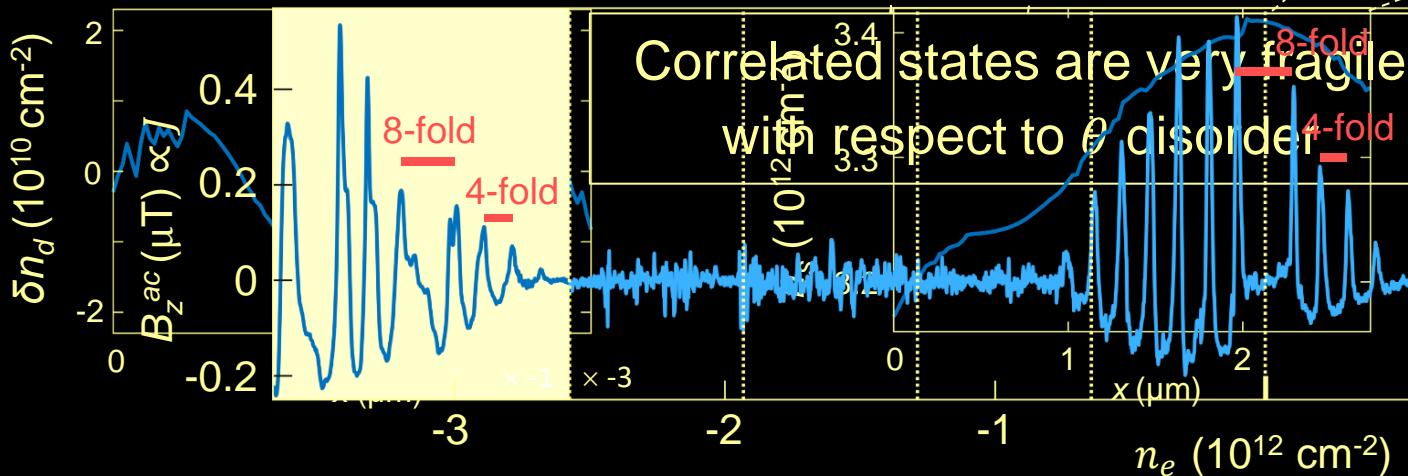
2D maps θ accuracy: $\pm 0.001^\circ$
(absolute global accuracy: $\pm 0.005^\circ$)



Imaging LLs along a line

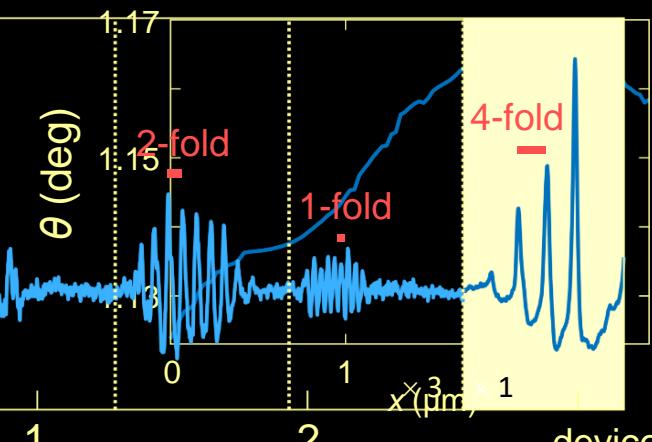


Charge disorder $\delta n_d(x)$



Correlated states are very fragile
with respect to ℓ disorder

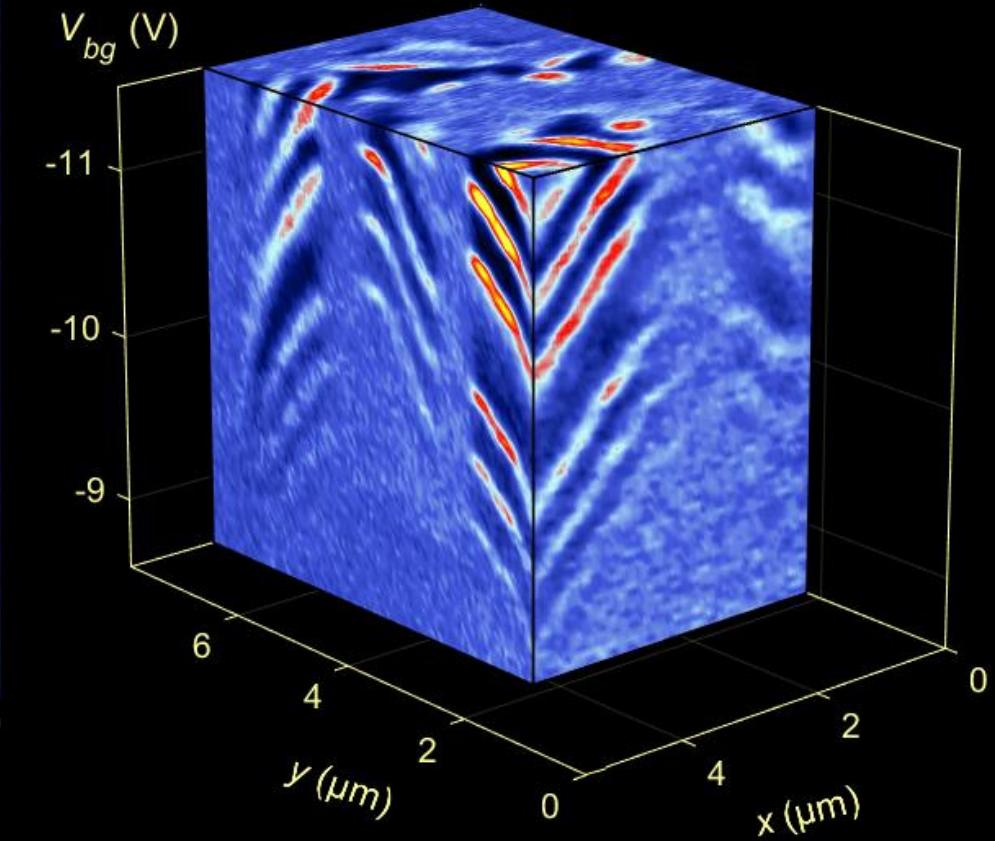
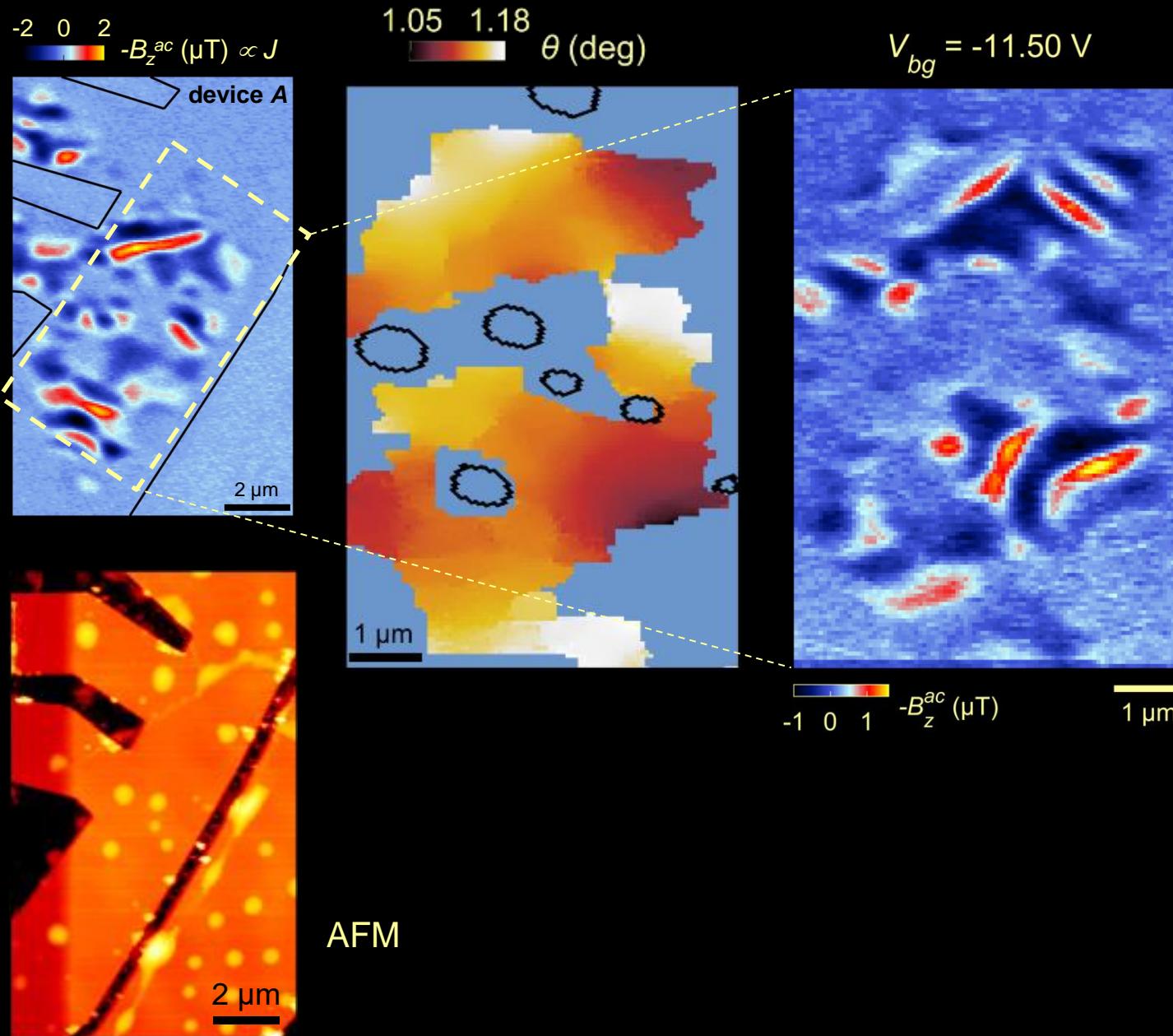
Twist-angle disorder $\theta(x) \propto \sqrt{n_s(x)}$



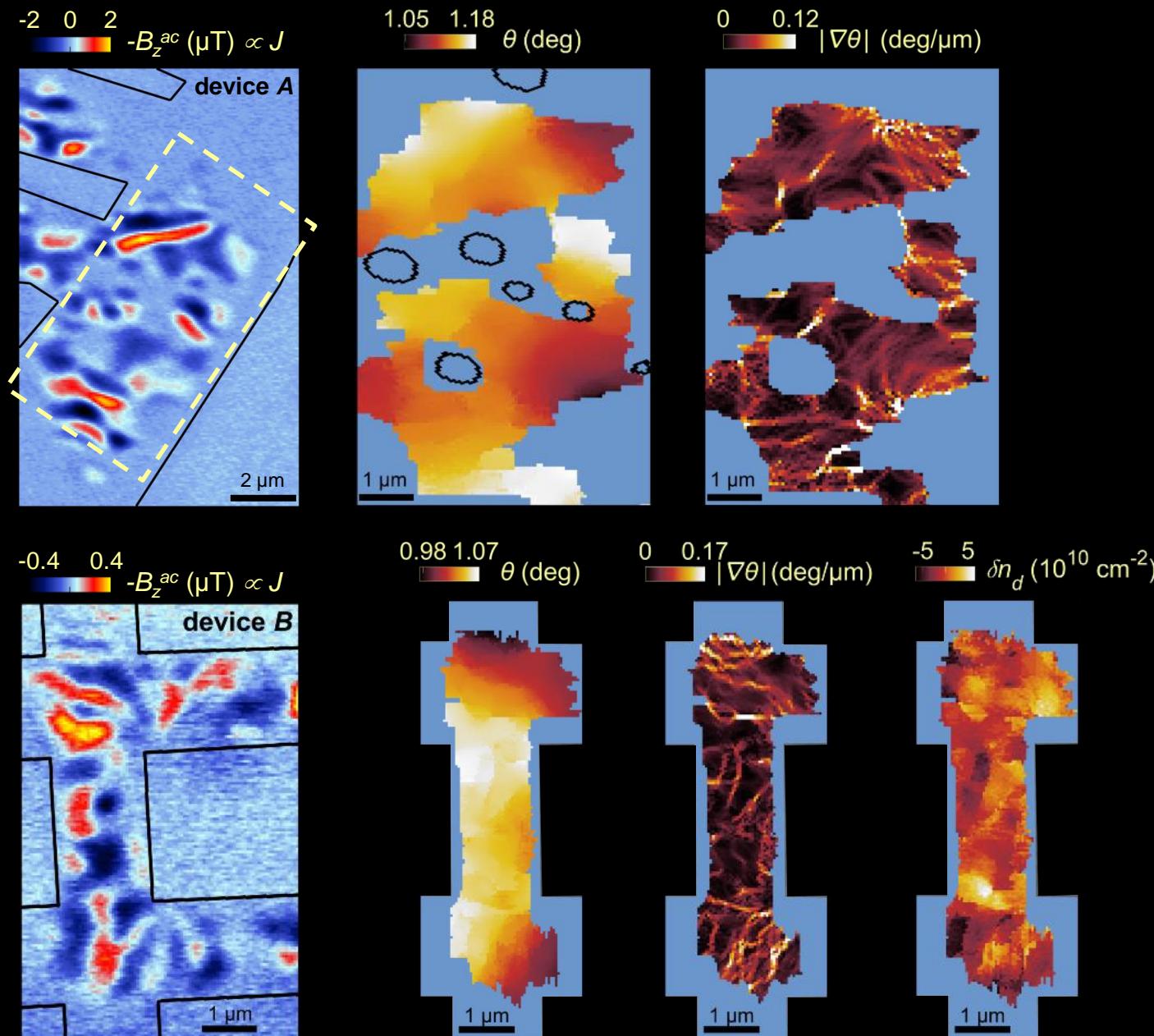
Local SOT

QH equilibrium currents at a single point at $B_a=1.08$ T

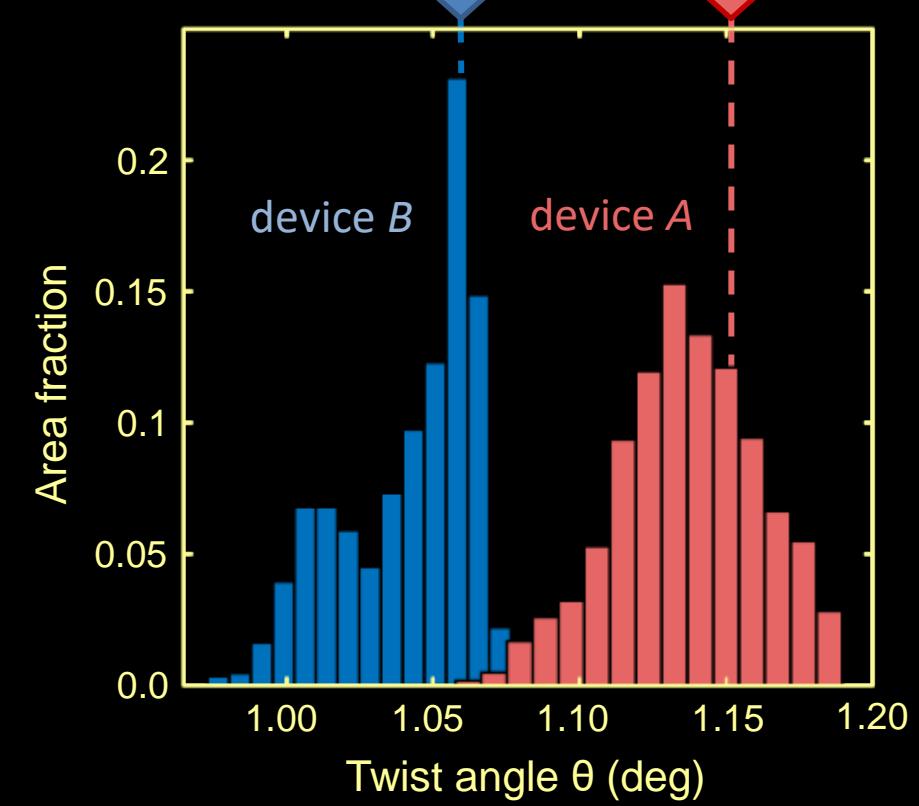
LL tomography and 2D mapping of θ



Twist-angle disorder



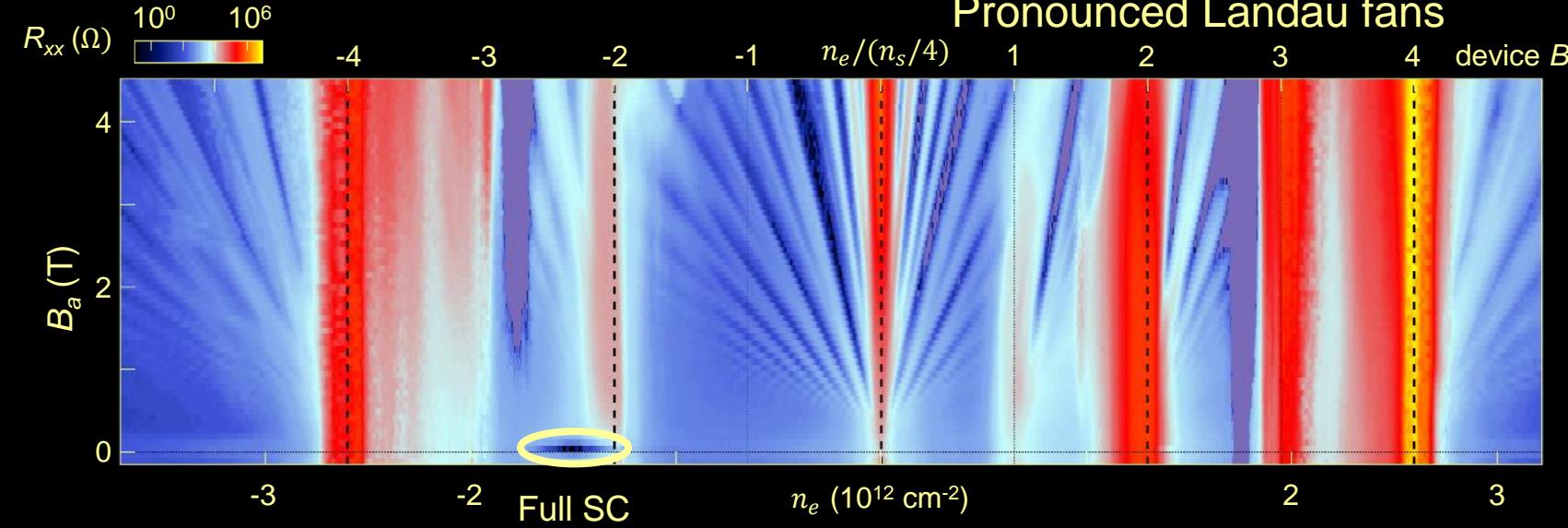
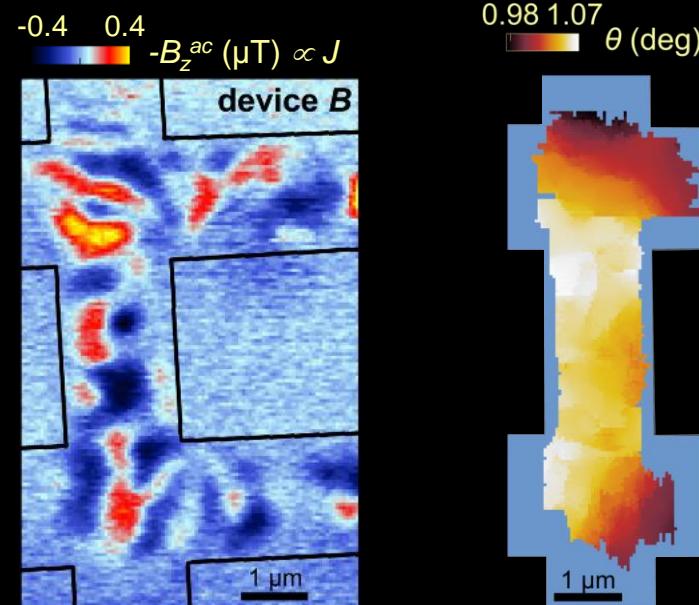
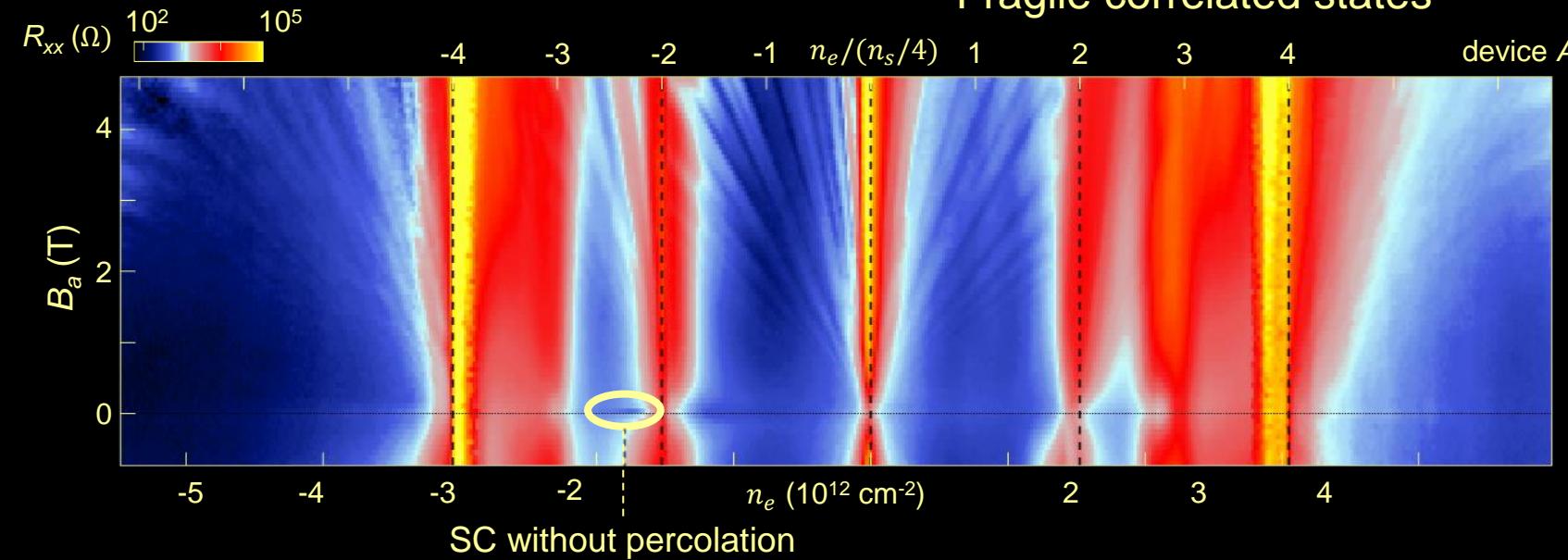
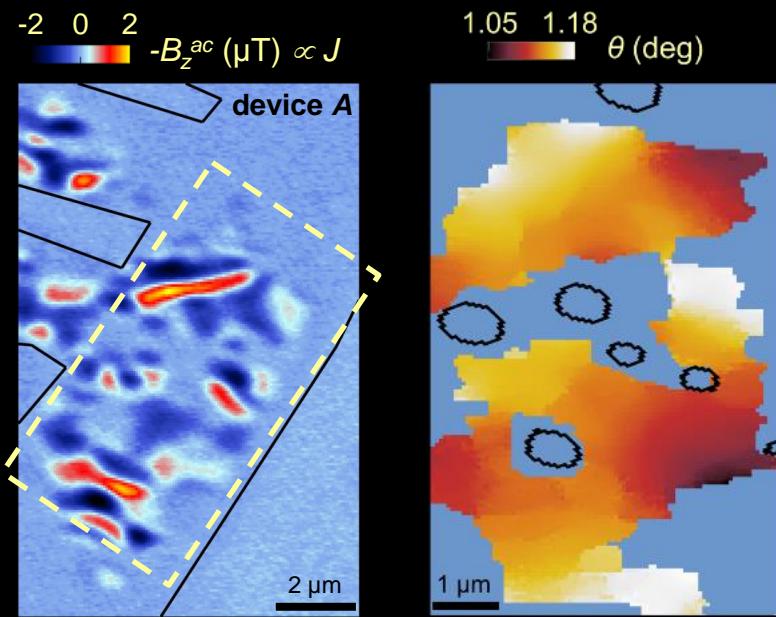
Global transport θ : 1.06° 1.15°



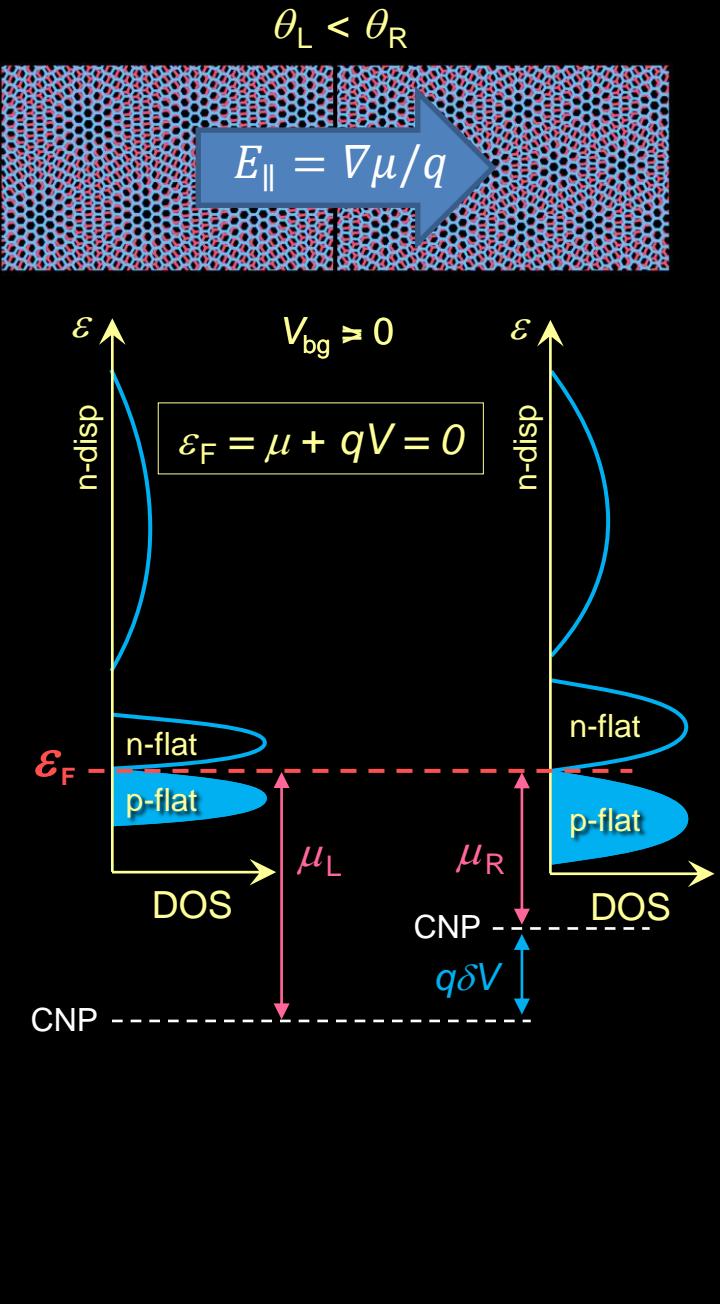
Twist-angle disorder $\approx 10\%$

Percolation physics

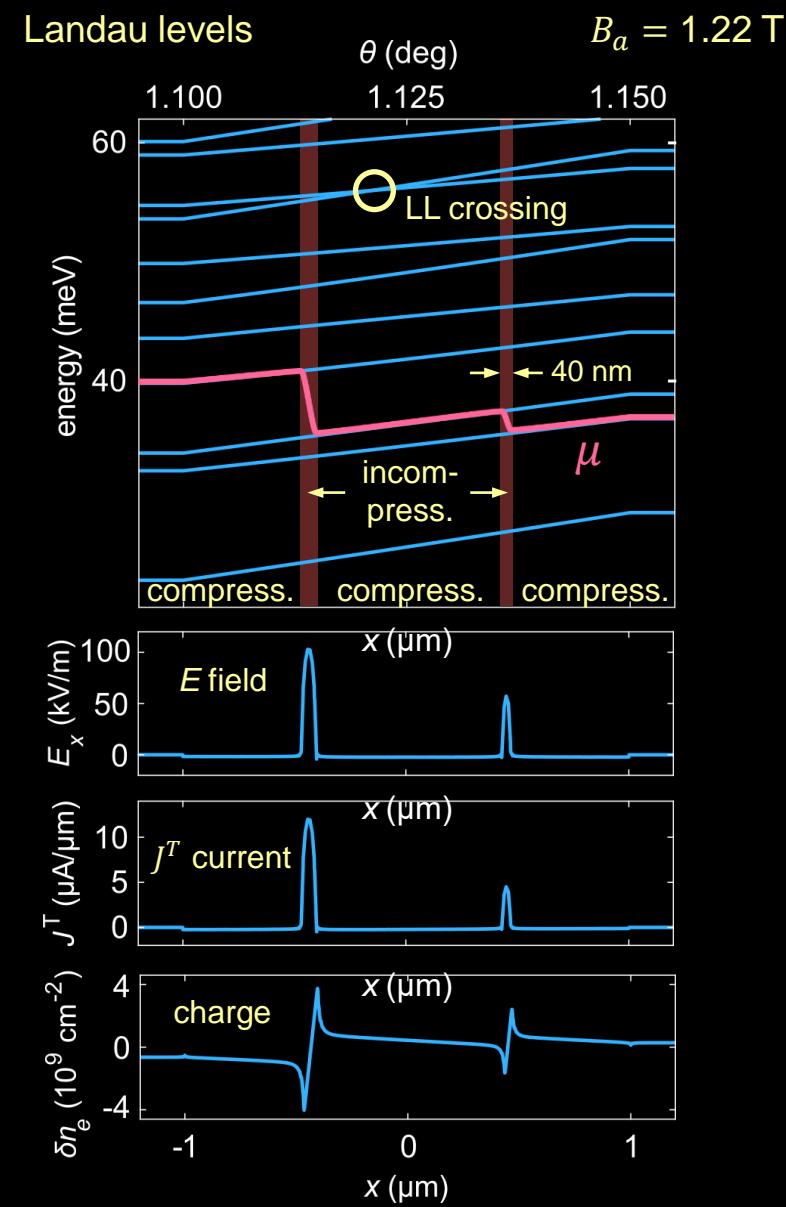
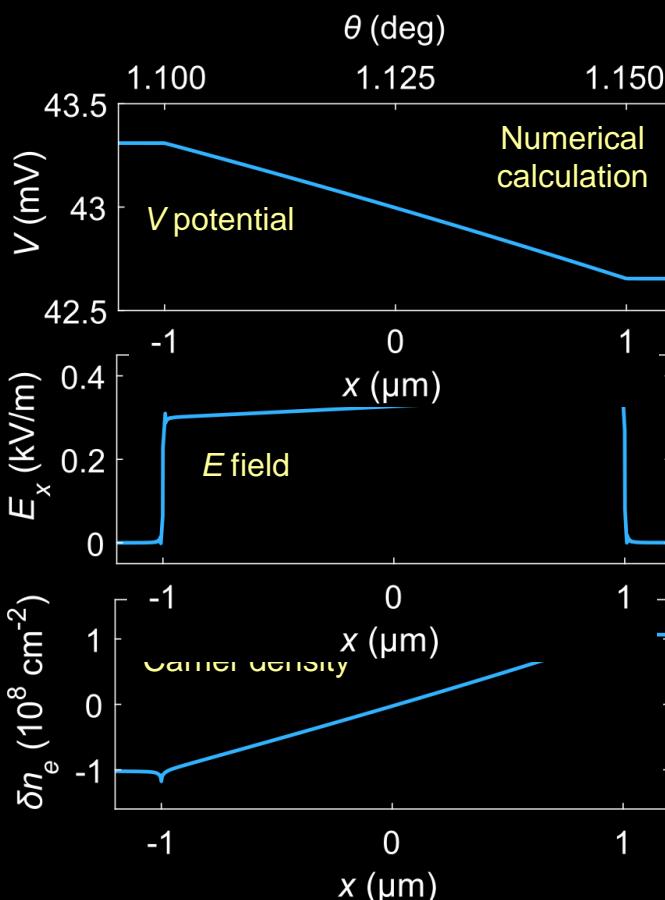
Fragile correlated states



Twist-angle disorder – a new type of disorder



Band structure disorder
Effective mass disorder
Symmetry breaking disorder
Large unscreened electric fields
Gate tunable in-plane electric fields
QH edge states in the bulk



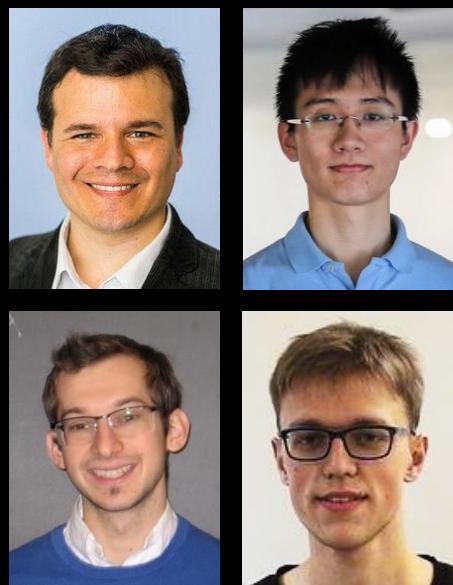
Weizmann

Aviram Uri
Sameer Grover
Kousik Bagani
Nadav Auerbach
Ella O. Lachman
Yuri Myasoedov



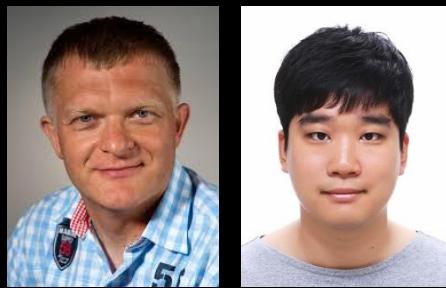
MIT

Pablo Jarillo-Herrero
Yuan Cao
Daniel Rodan-Legrain
Cyprian Lewandowski



MPI Stuttgart

Jurgen Smet
Youngwook Kim



UC Denver

Martin Huber



Osaka

Mikito Koshino



NYU Shanghai

Pilkyung Moon
John Alex Crosse



NIMS

Takashi Taniguchi
Kenji Watanabe



θ -disorder map and LL tomography

