# Local probing of Quantum Spin Hall edge states

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# Acknowledgements

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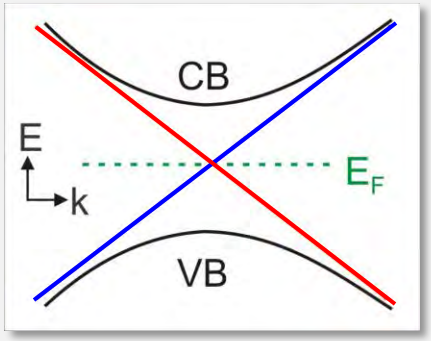
Yue Ma, Worasom Kundhikanjana, ZX Shen

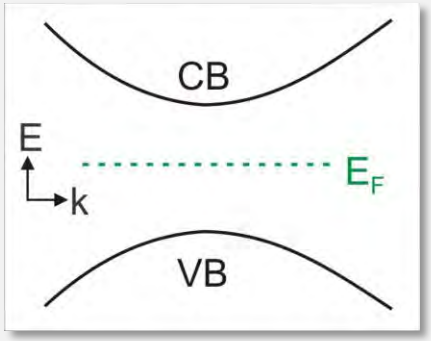
Katja Nowack, Eric Spanton, Kathryn Moler

# A special “insulator”




„Electrical insulators are usually appreciated for their ability to do nothing.“

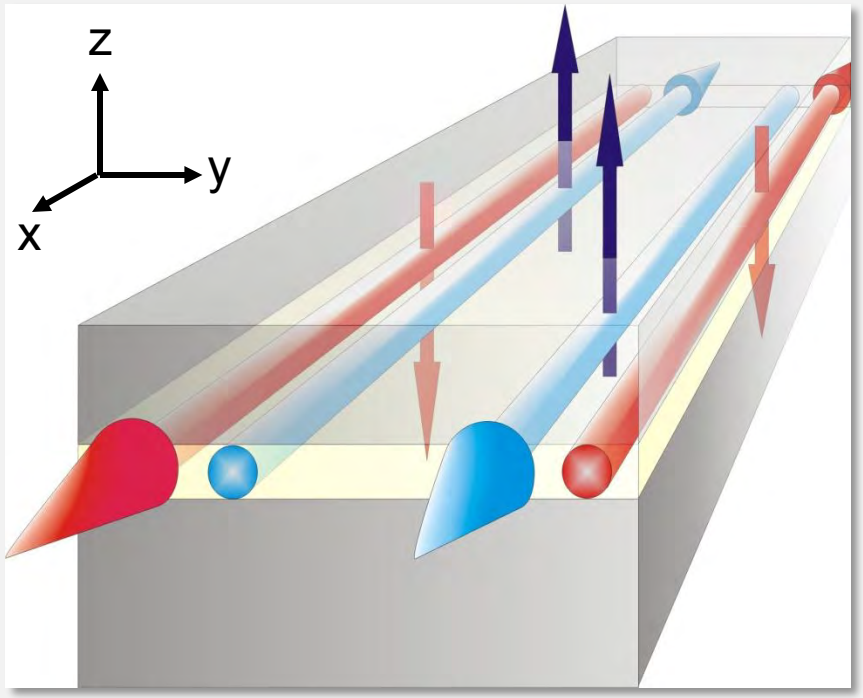
C. Kane and E. Mele, Science **314**, 1692 (2006)




## Topological Insulators

- Insulating bulk
- Surface states topologically protected
- Spin-momentum locking
- Suppression of backscattering

# The Quantum Spin Hall Effect

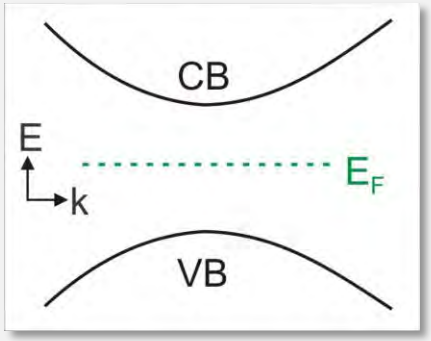


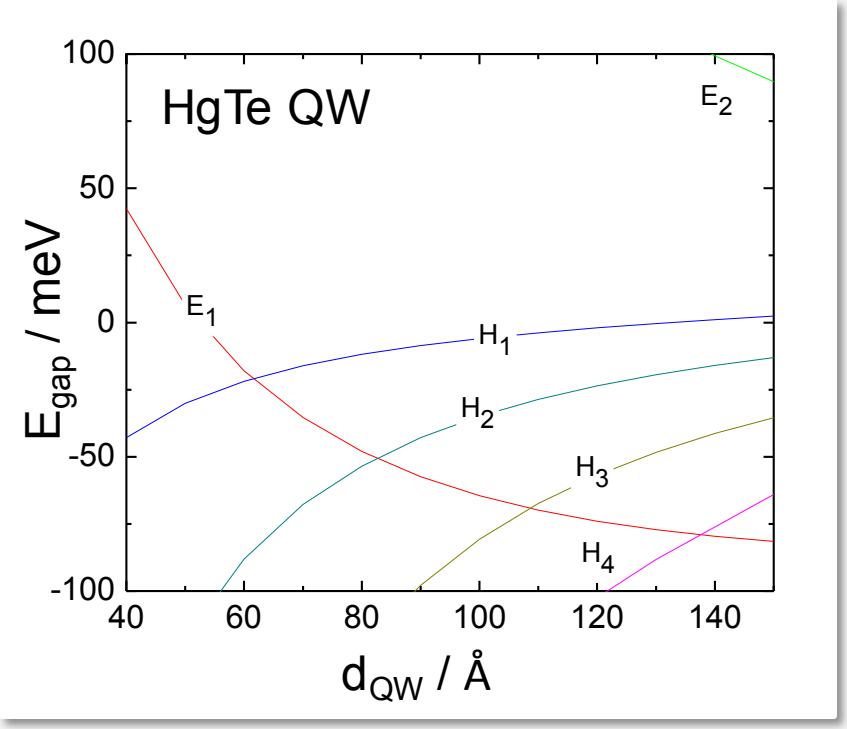

Quantum Spin Hall state is 2D manifestation of a topological insulator

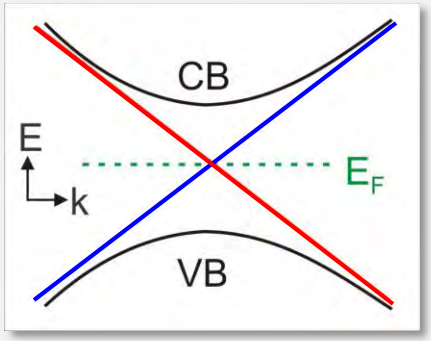
- spin-polarized edge states
- backscattering suppressed by time-reversal symmetry
- dissipationless transport along sample edge

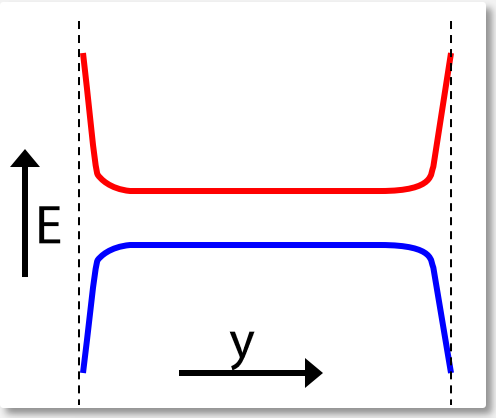
C.L. Kane and E.J. Mele, PRL **95**, 226801 (2005)
B.A. Bernevig and S.C. Zhang, PRL **96**, 106802 (2006)

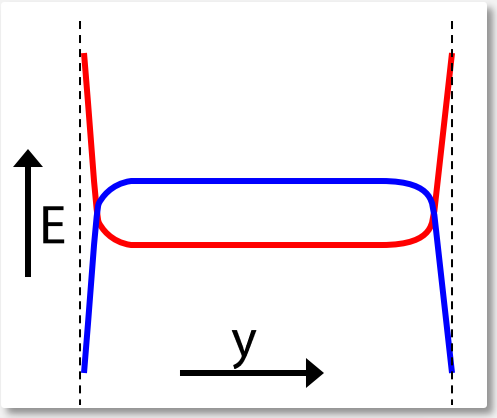
# HgTe quantum wells



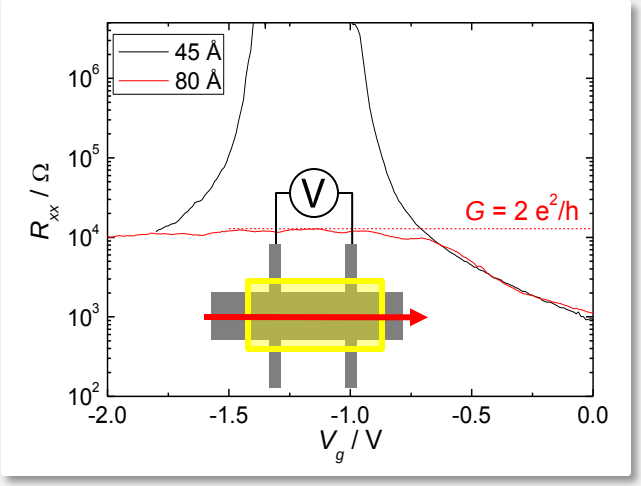



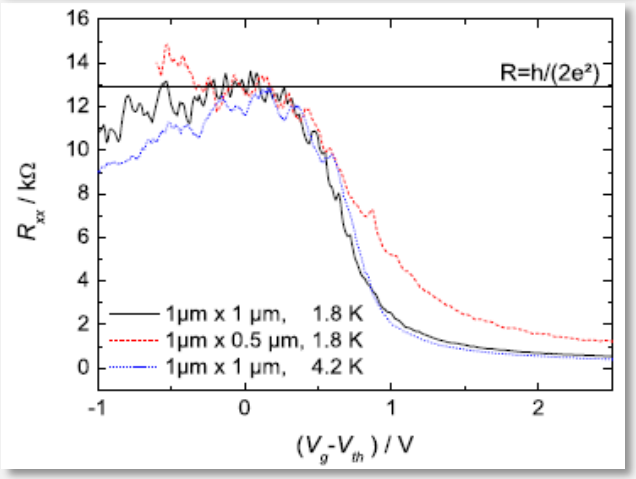



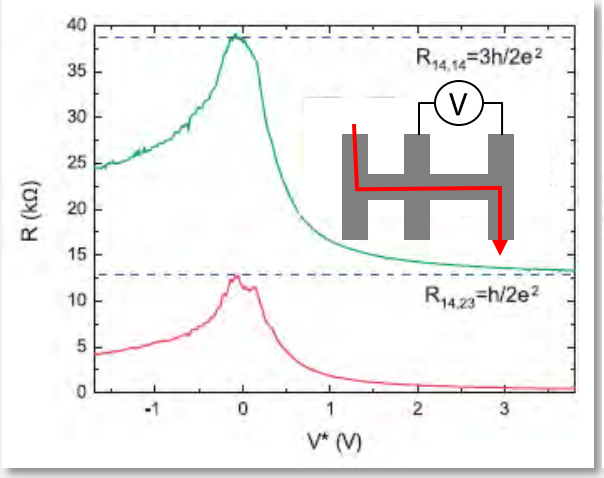

B.A. Bernevig, T. L. Hughes, and S. C. Zhang, Science **314**, 1757 (2006)

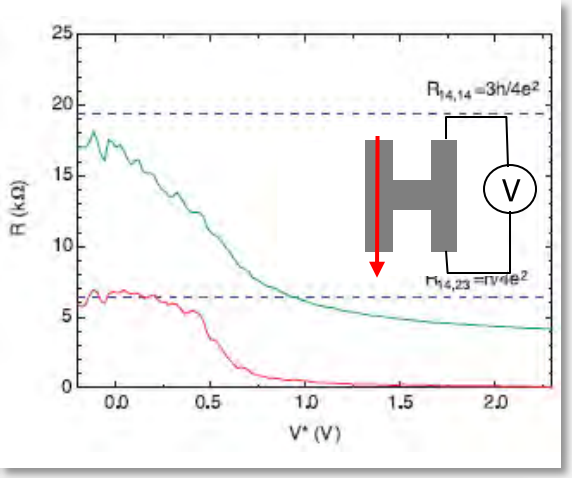
# Experimental observations




- QSHE observed for $d_{QW}$ > 63 Å, thinner QWs show insulating behavior
- $G \approx 2e^2/h$ not depending on aspect ratio
- non-local measurements in agreement with LB formalism
  → edge state transport



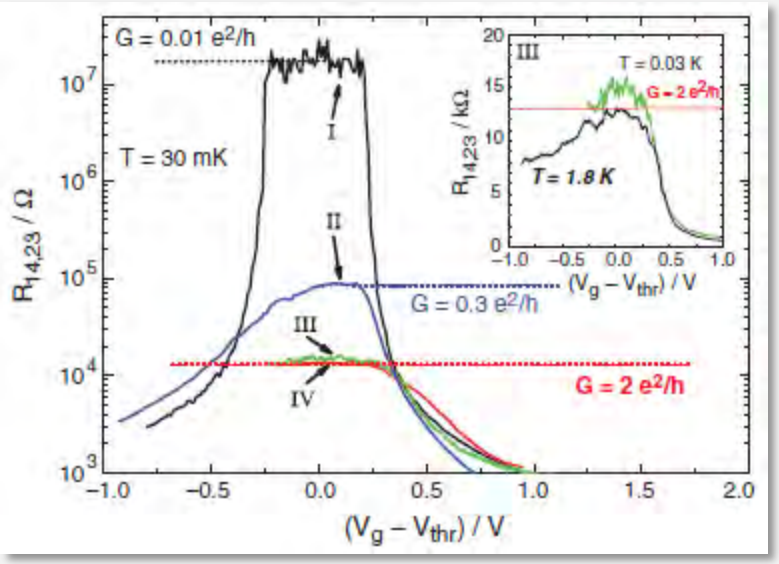



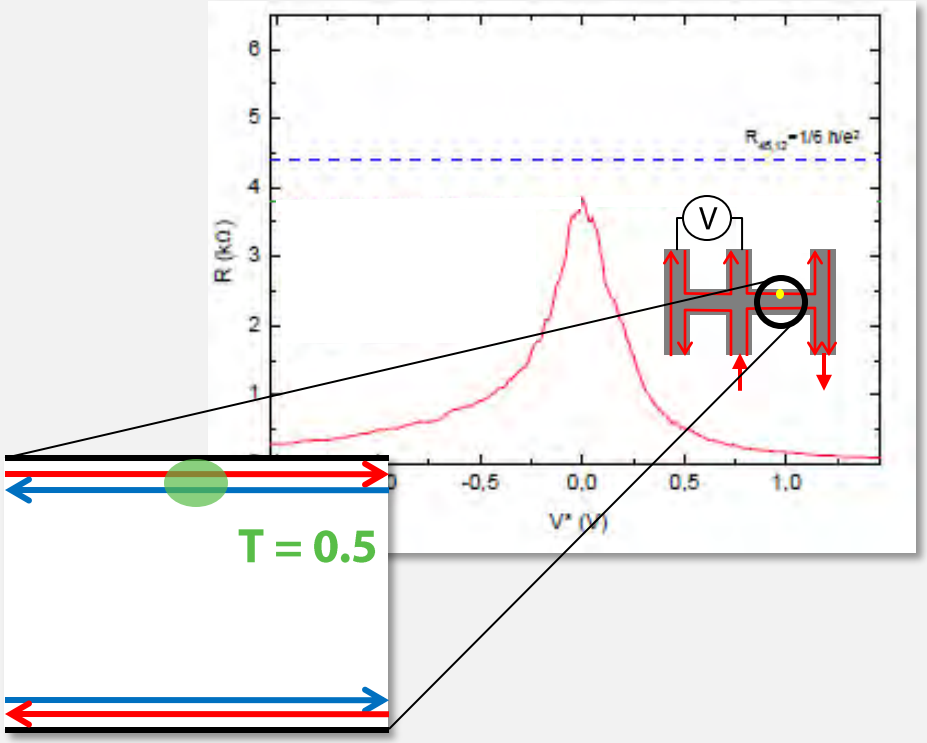




M. König *et al.*, Science **318**, 766 (2007); M. König *et al.*, JPSJ 77, 031007 (2008); A. Roth *et al.*, Science **325**, 294 (2009)

# Scattering of QSH edge channels

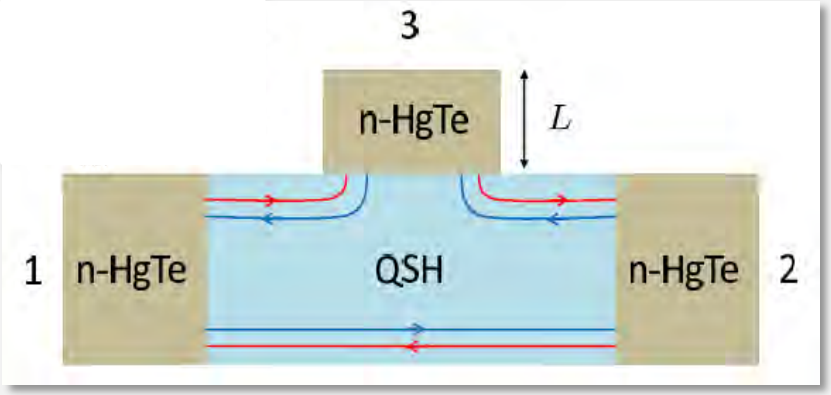
- mean free path ~ 1 µm
- single scattering site sufficient for full equilibration

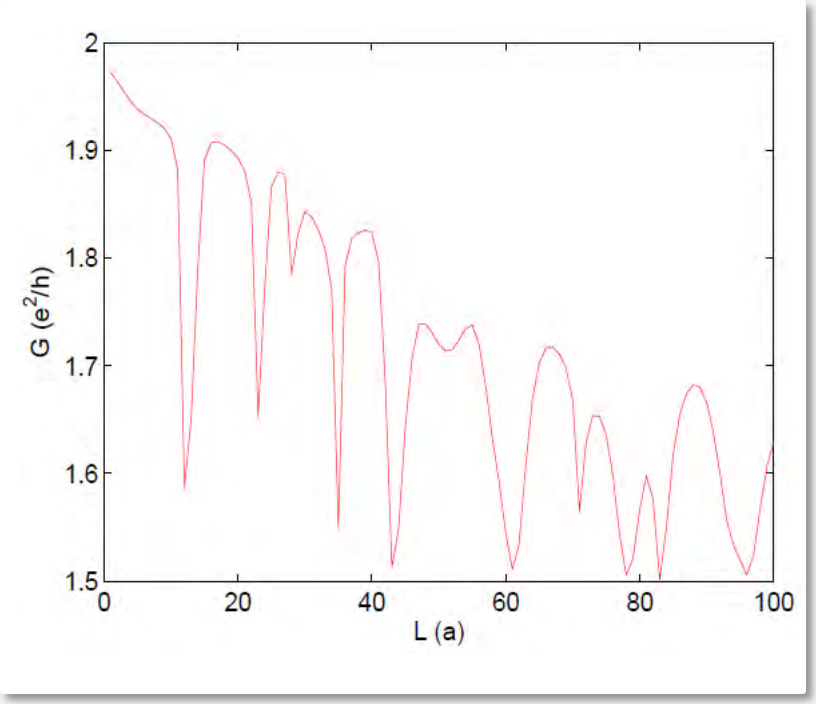



M. König *et al.*, Science **318**, 766 (2007);
A. Roth *et al.*, Science **325**, 294 (2009)

# Dephasing in a metallic region




Metallic region leads to dephasing:

- electron-electron interaction
- electron-phonon interaction
- ...

Roth *et al.*, Science **325**, 294 (2009)

# QSH state in transport

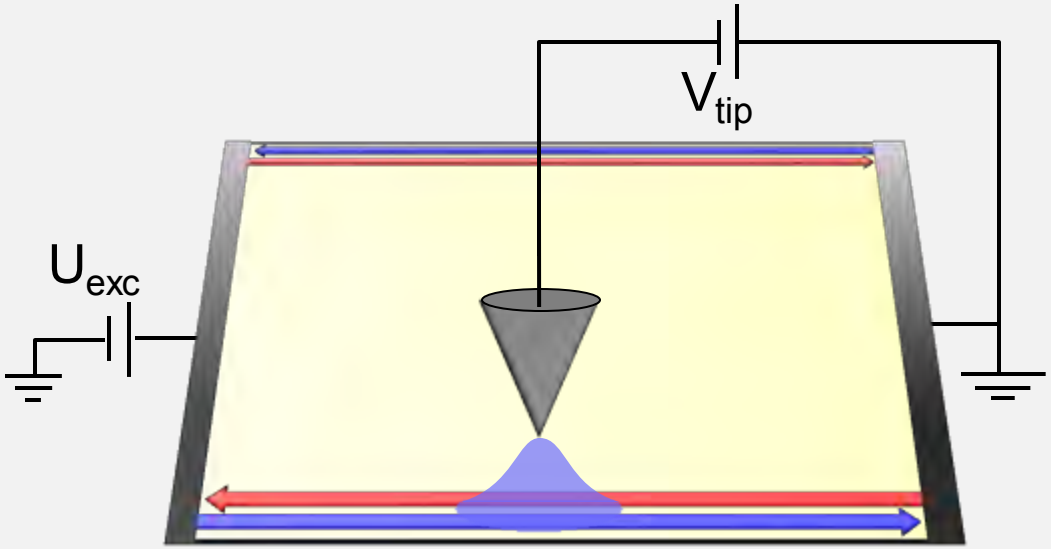
- QSH state in HgTe QW structures with $d_{QW} > 63$ Å
- Width of edge states around 100 nm
- Demonstration of spin polarization

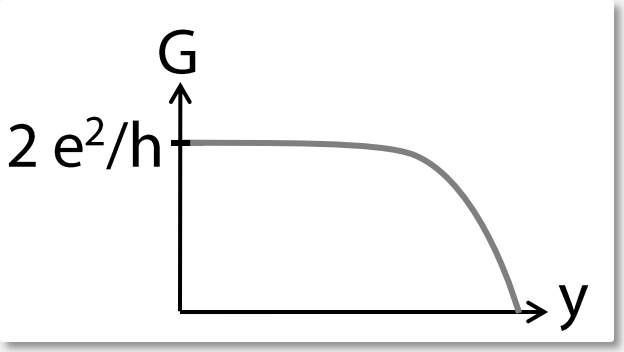
- Backscattering for $L > 1$ µm
  - source of backscattering?
  - sensitivity to potential fluctuations?

M. König *et al.*, Science **318**, 766 (2007); A. Roth *et al.*, Science **325**, 294 (2009); C. Brüne *et al.*, Nat. Phys. 6, 449 (2010); C. Brüne *et al.*, Nat. Phys. 8, 485 (2012)

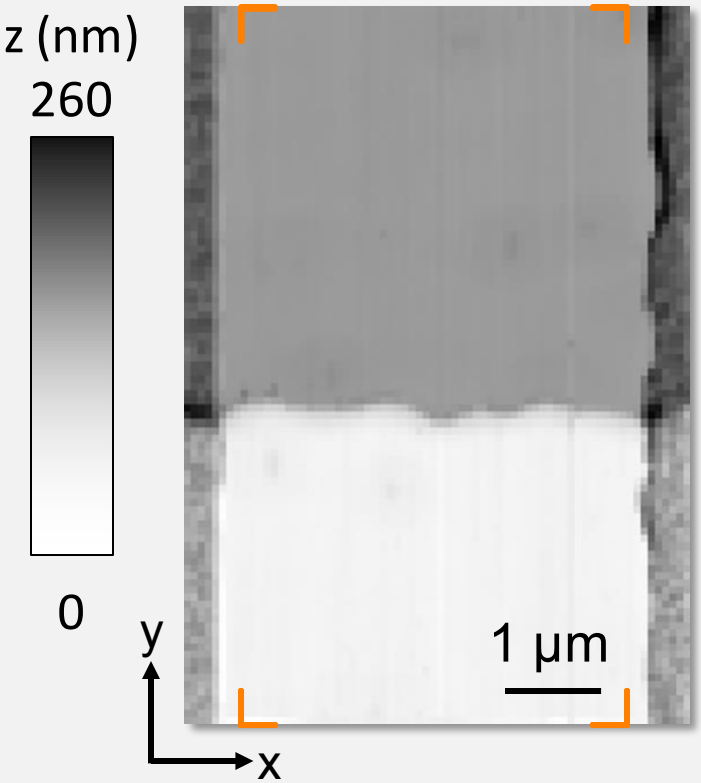
# Scanning Gate Microscopy (SGM)

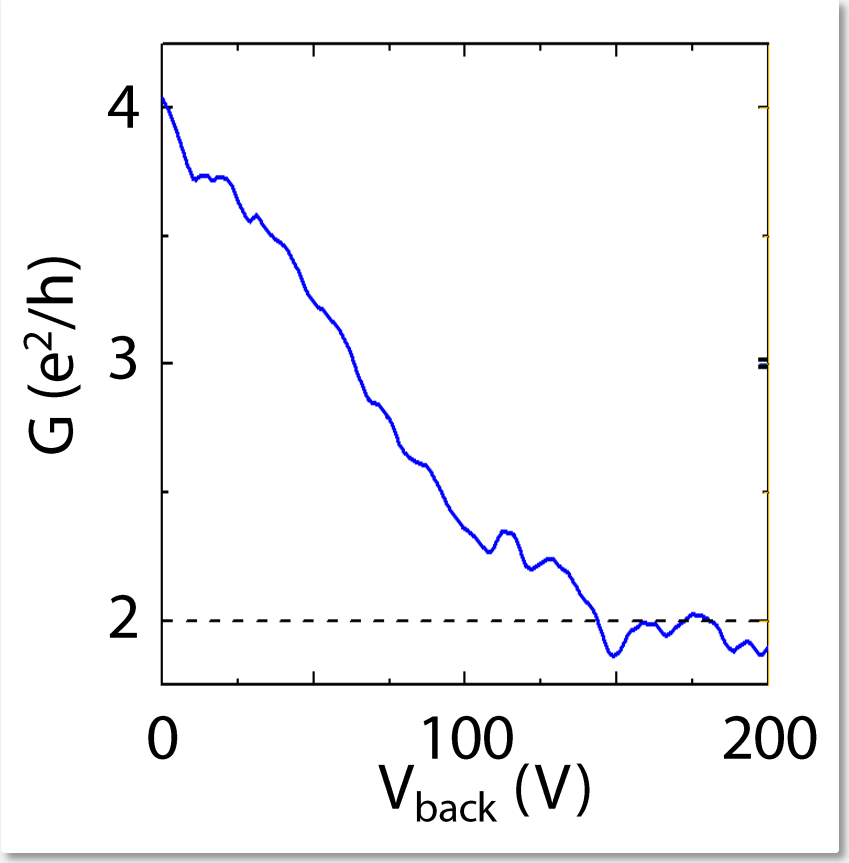
- effect of a local potential modulation on transport properties
- charged AFM tip is scanned over surface
- correlation of tip position and conductance



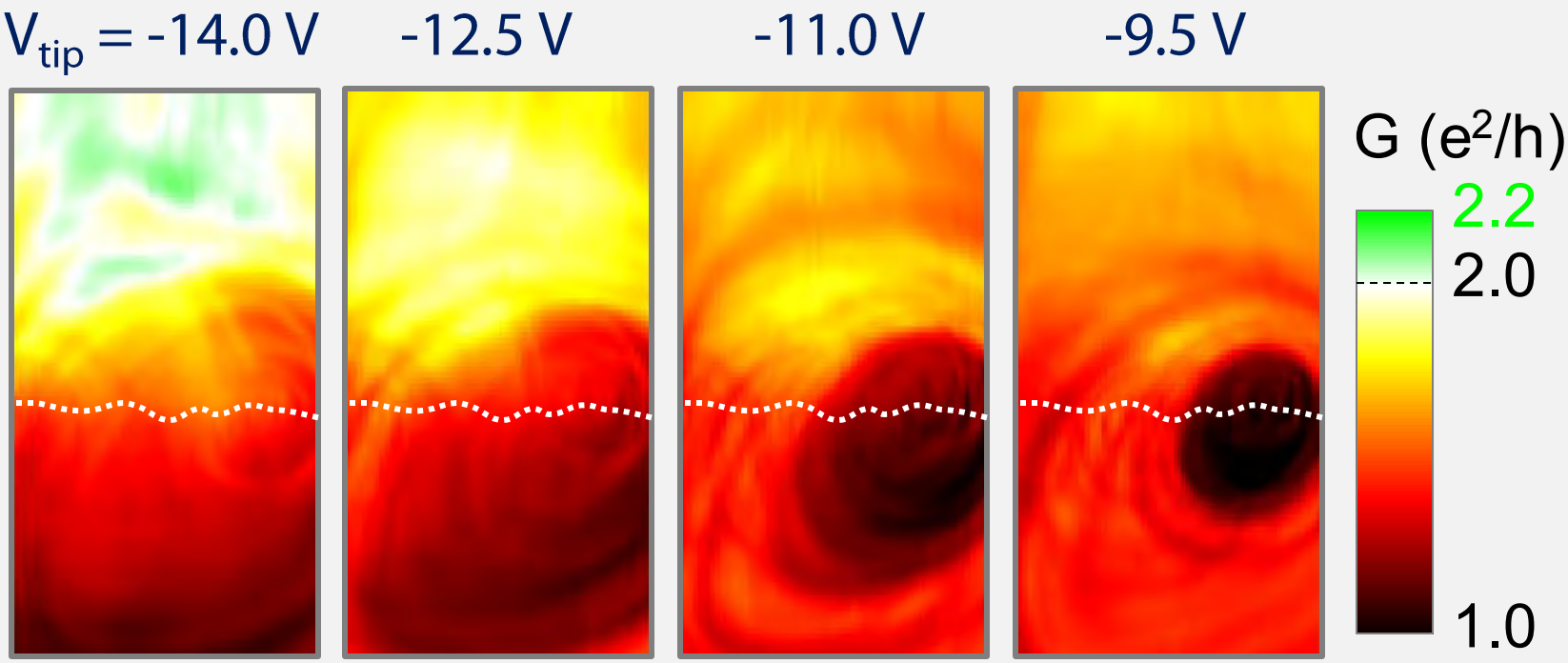



# Sample characterization



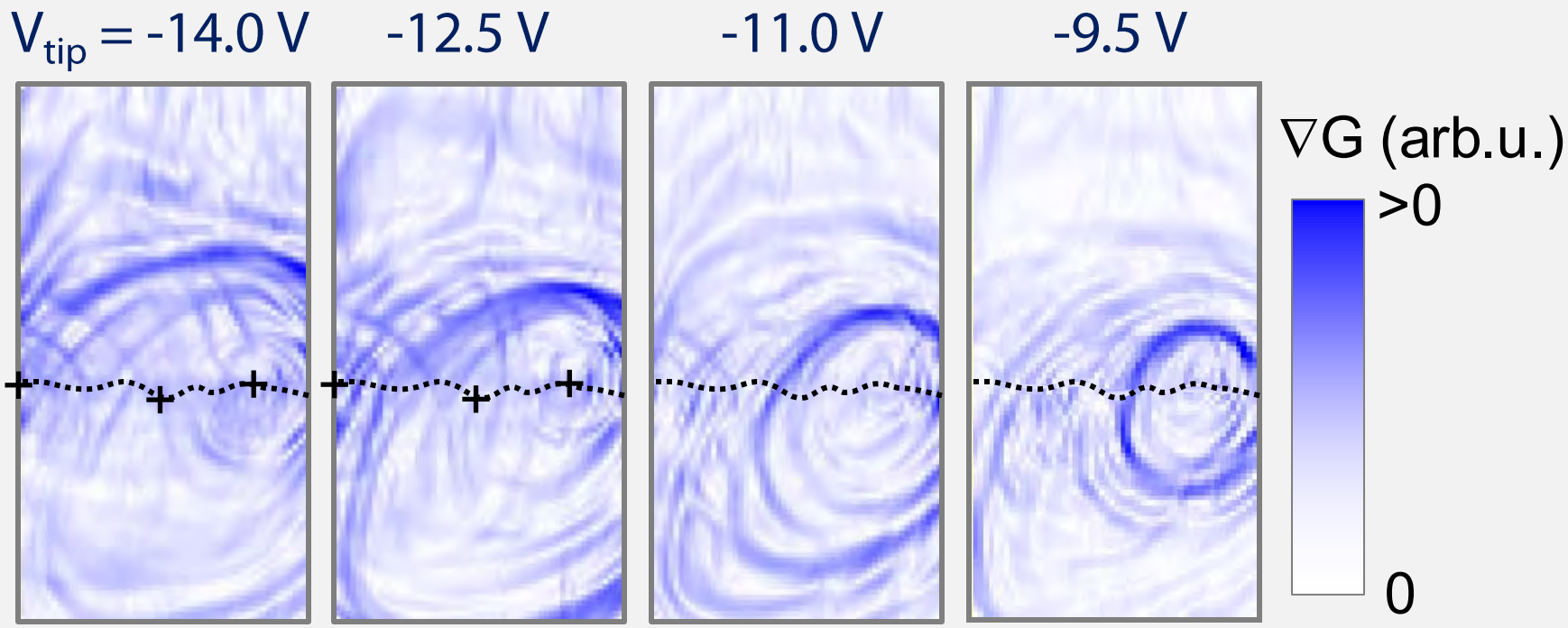



# Strong conductance modulation




- local gating causes decrease of G to ~1$e^2/h$
- full suppression of edge state transport

# Rings of conductance suppression

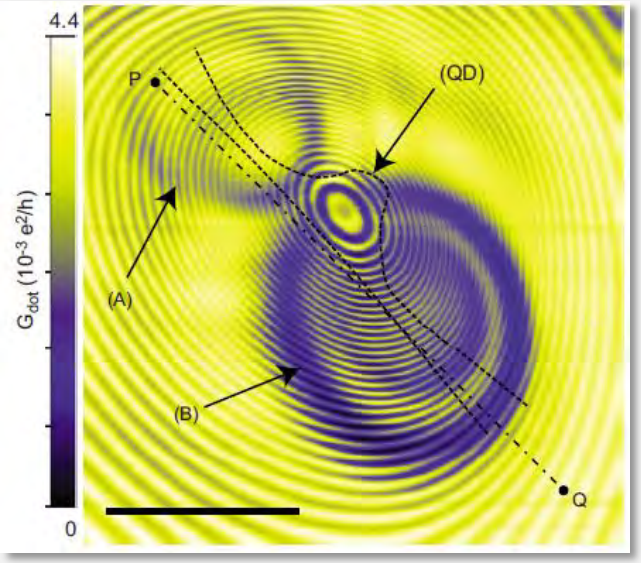



- multiple sets of concentric rings: $\Delta G \approx 0.1\ e^2/h$

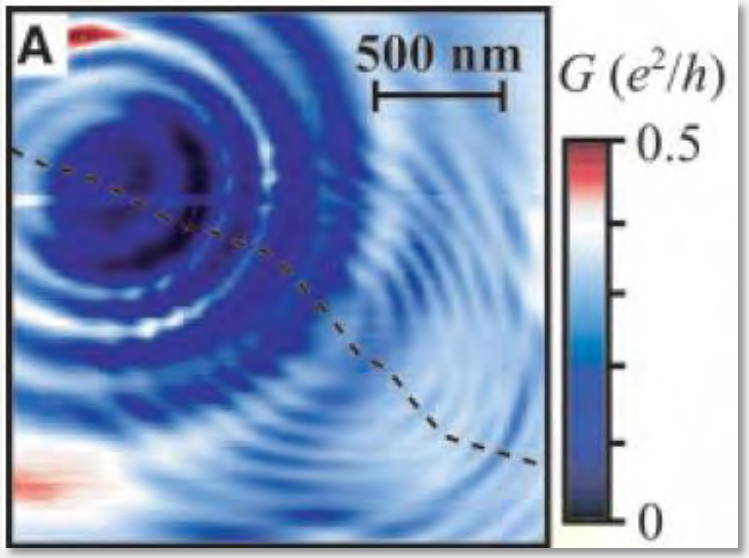
# Rings in SGM experiments

- Concentric rings:
  transport is function of potential at a sensitive site
- Rings correspond to equicapacitance lines

Graphene nanostructure



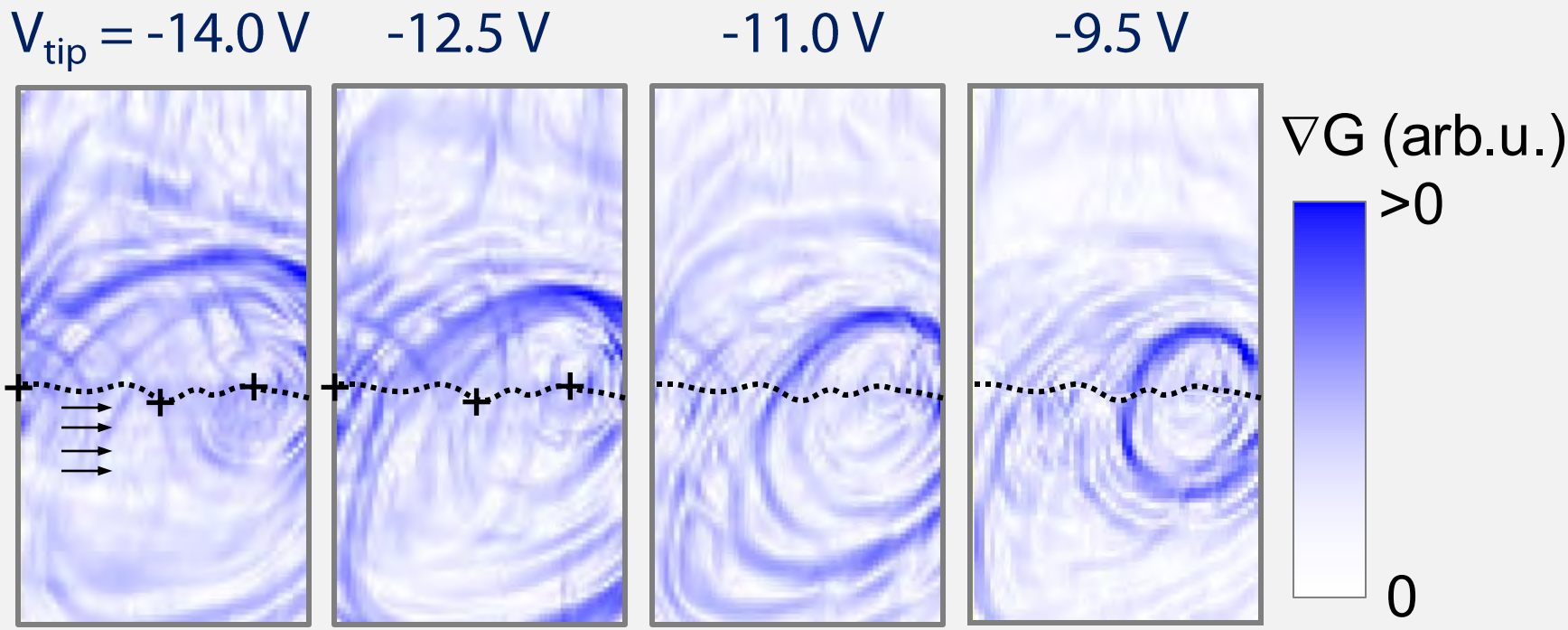

Carbon nanotube



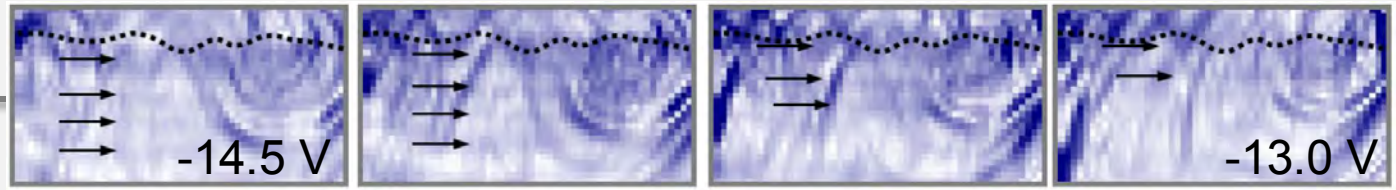

Schnez *et al.* (Ensslin lab),
PRB **82**, 165445 (2010)

Woodside and McEuen,
Science **296**, 1098 (2002).

# Rings of conductance suppression

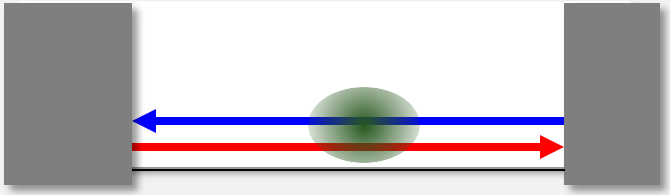


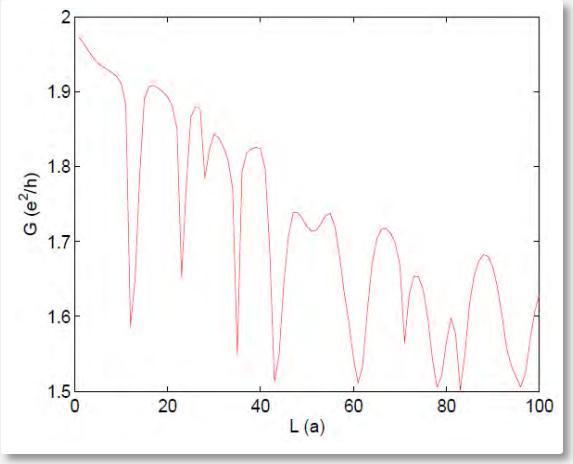

- multiple sets of concentric rings: $\Delta G \approx 0.1\ e^2/h$
- lines parallel to mesa edge: $\Delta G < 0.05\ e^2/h$



# Tuning a dephasing region

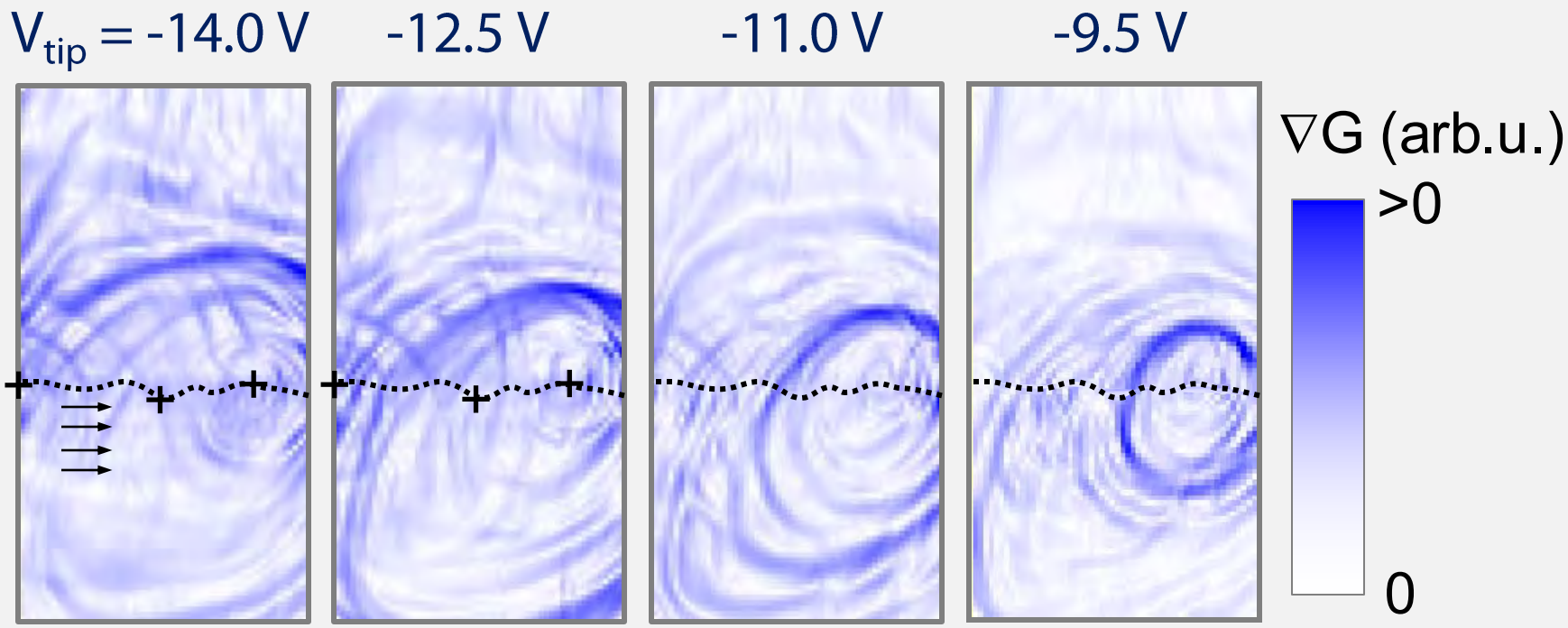
- unperturbed edge transport:
  backscattering is possible if perturbation is sufficiently strong
  → homogeneous behavior along edge
  → lines parallel to edge in SGM maps





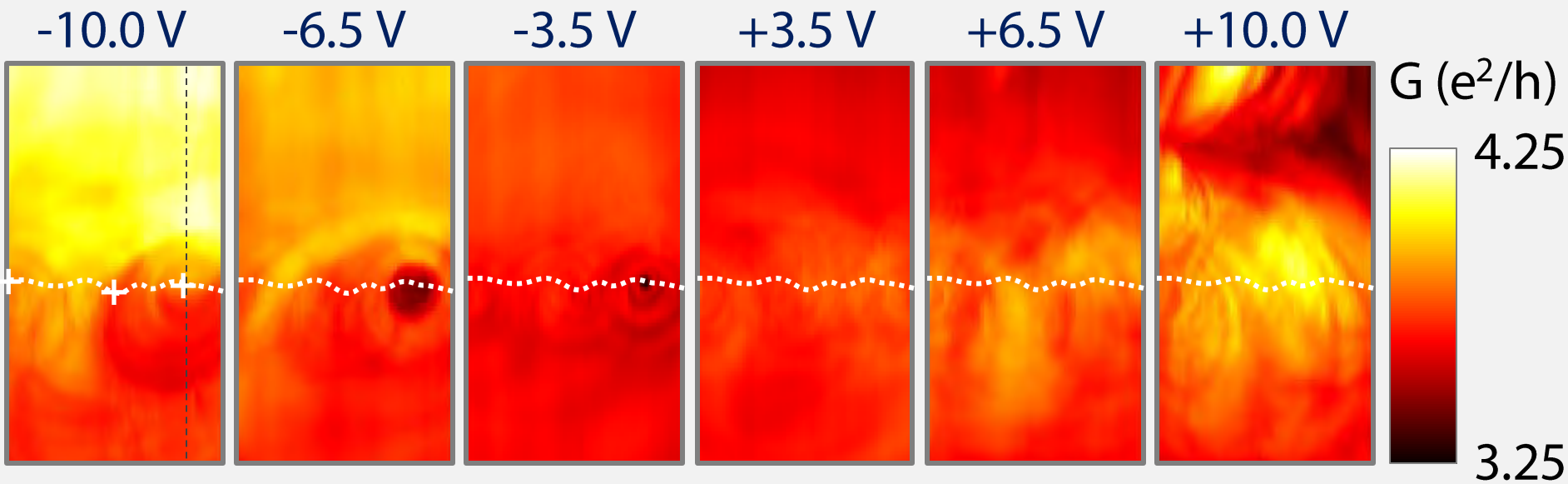

- scattering sites are sensitive to local potential
  → ring patterns in conductance modulation

# Patterns of conductance suppression



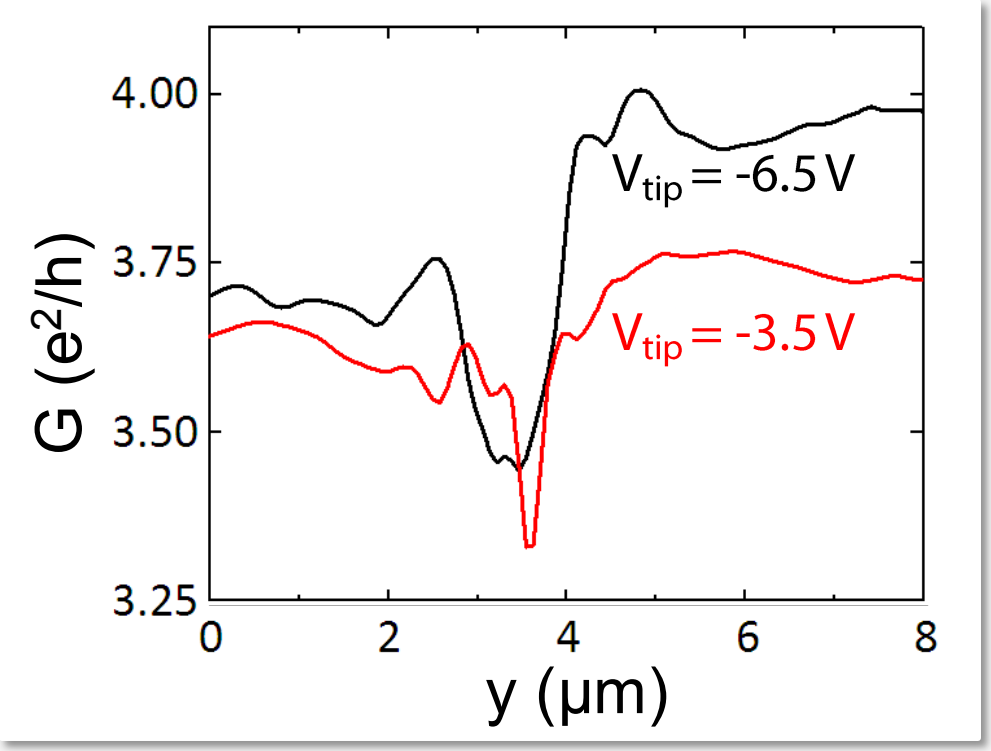

- concentric rings: distinct scattering sites
- parallel lines: tip-induced scattering in “clean” regions

# Coexistence of edge and bulk transport



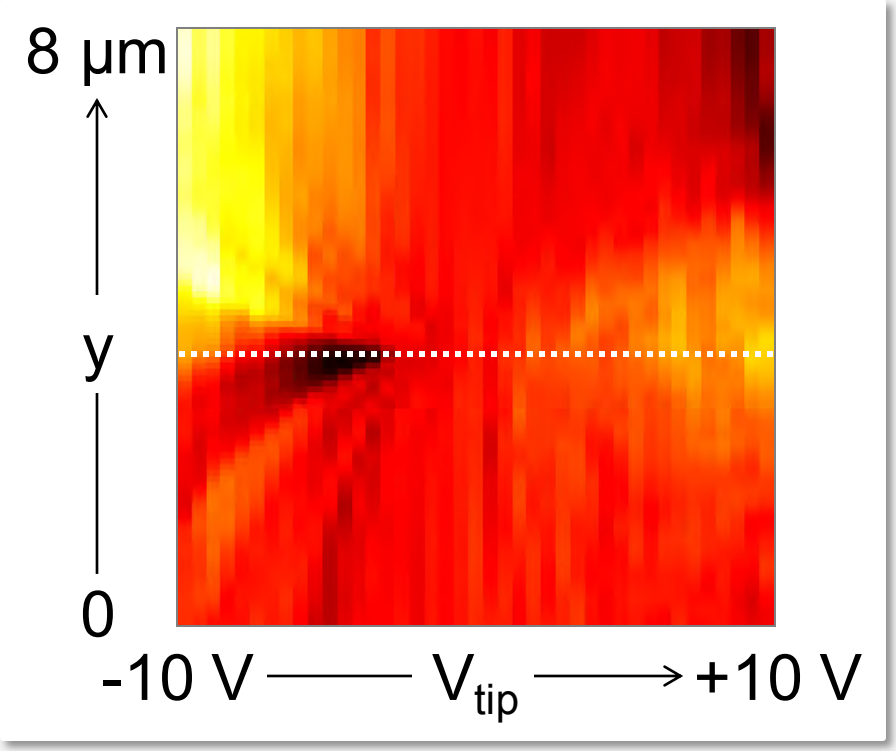

- $G > 2e^2/h$ → contribution of bulk transport ($p \approx 2 \cdot 10^{10}$ $cm^{-2}$)
- strong local gating along edge → edge transport
- sets of rings around same locations

# Tip voltage dependence




- significant edge state contribution: $\Delta G \approx 0.5\ e^2/h$
- strong gating effect within 250 nm (FWHM) from edge

# Tip voltage dependence




- traces indicative of resonant dephasing at identified sites visible up to $V_{tip} \approx -1$ V
- no signs of tip-induced backscattering in adjacent regions

→ carrier density in metallic regions: $p \sim 10^{11}$ cm$^{-2}$

# Summary

Local study of backscattering in the QSH state:

- identification of pre-existing scattering sites:
  - p-type metallic puddles resulting in dephasing
  - separation ~ 1.5 μm → limit for ballistic transport
  - caused by potential fluctuations in QW structure
- much larger tip- induced potential required to perturb "clean" QSH edge
- mechanism for full suppression unclear

Physical Review X **3**, 021003 (2013)

# Acknowledgements

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