Edge states in 2D-TI HgTe Quantum Wells studied by **Scanning Gate Microscopy**

Reyes Calvo

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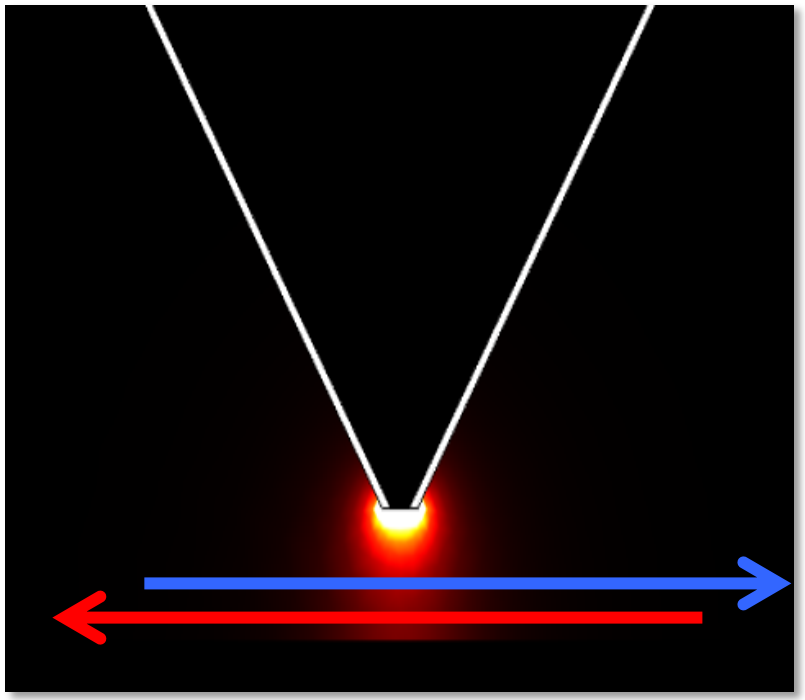

Universitat d'Alacant
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LELAND STANFORD JUNIOR UNIVERSITY
DIE LUFT DER FREIHEIT WEHT
1891

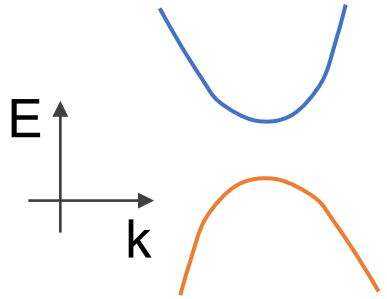
CIC nanoGUNE
nanoscience cooperative research center

2D - Topological insulators

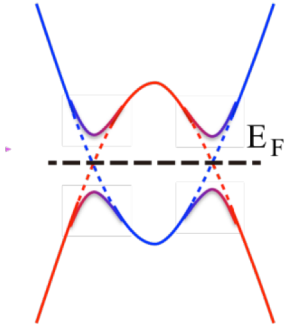
g=0

g=1

Trivial semiconductor

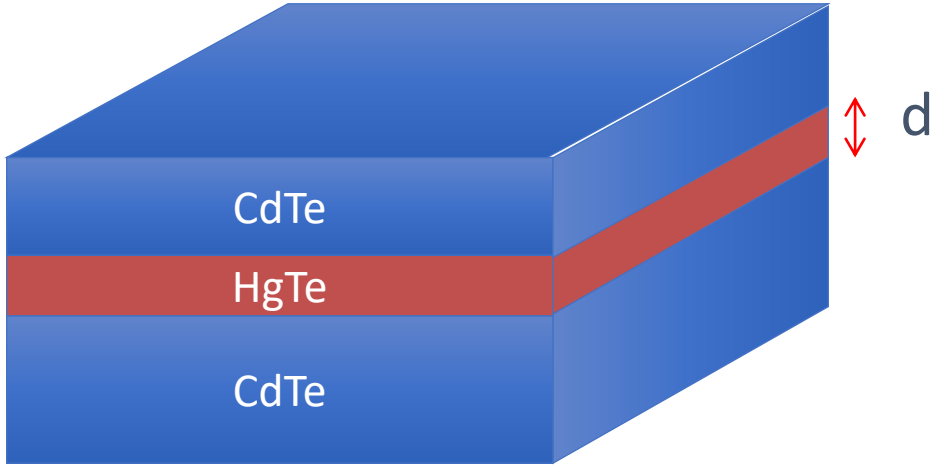


Topological Insulator



- Topological classification of insulators: trivial and ”*topological*”
- Topological insulators present band inversion, and QSH states at the edge

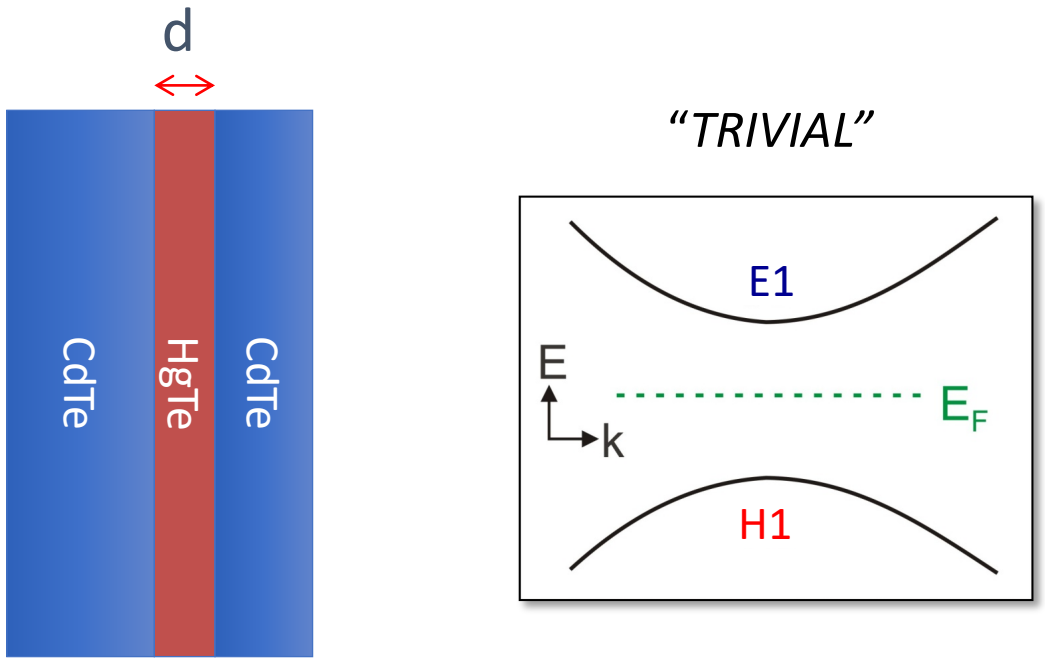
2D-TI HgTe quantum wells



Bernevig et al. *Science*, 314, (2006)

- Predicted for HgTe epitaxial quantum wells

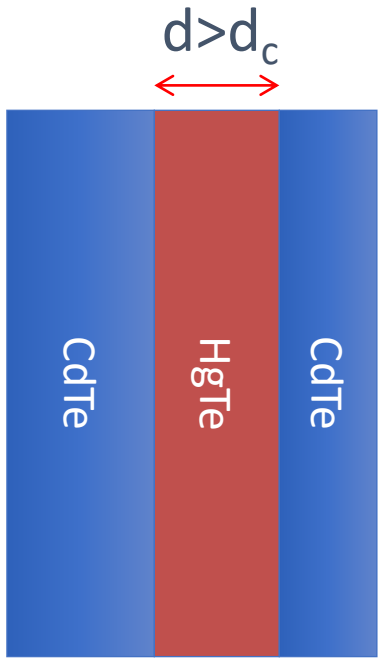
QSHE in HgTe quantum wells

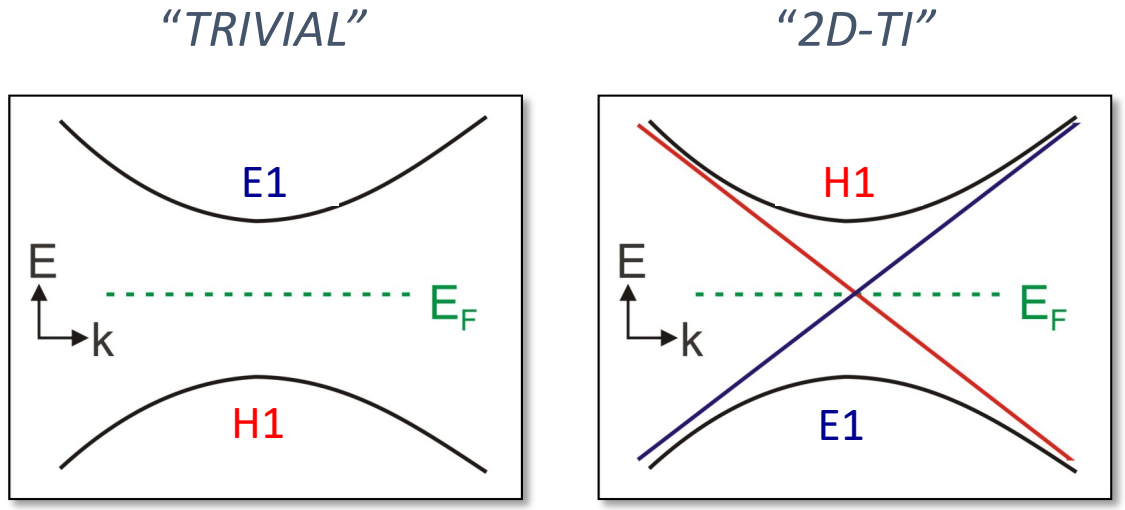


Bernevig et al. *Science*, 314, (2006)

- Below critical thickness: trivial semiconductor

QSHE in HgTe quantum wells



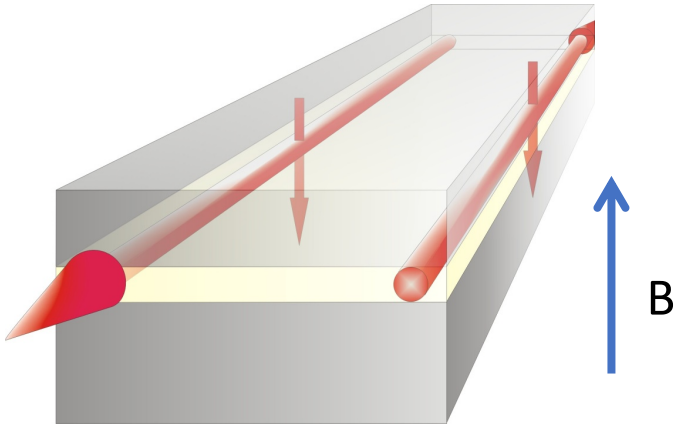


Bernevig et al. *Science*, 314, (2006)

- Below critical thickness: trivial semiconductor
- Above critical thickness: band inversion, topologically insulator

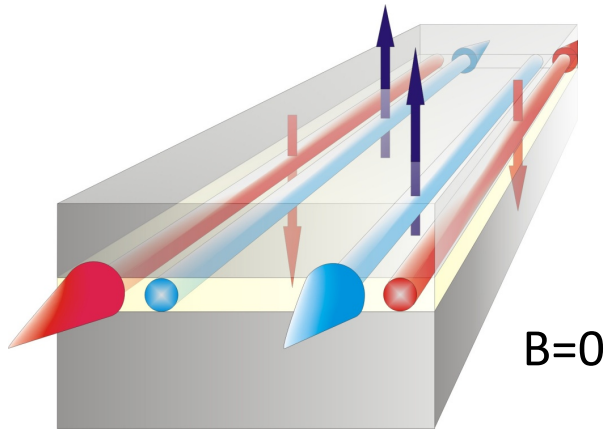
Quantum Hall vs Quantum Spin Hall Effect

QHE



M. Koenig Phd thesis (2008)

QSHE



- Chiral states

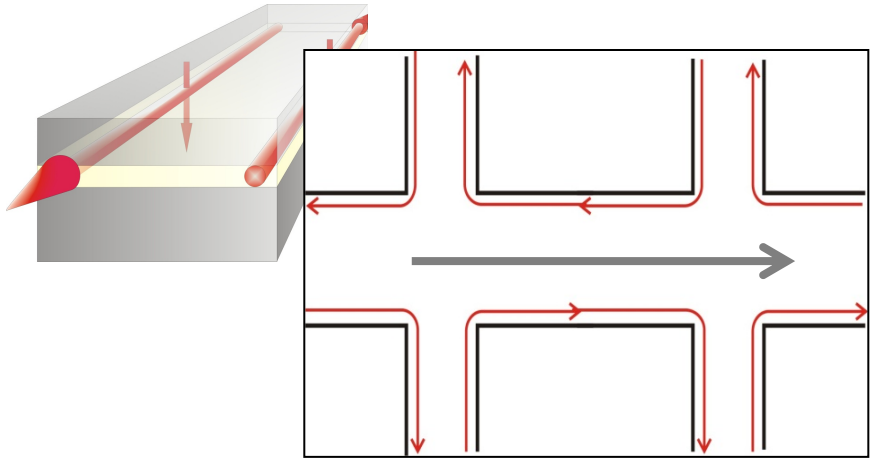
Propagating opposite edges
N modes
Same spin polarization

- Helical states:

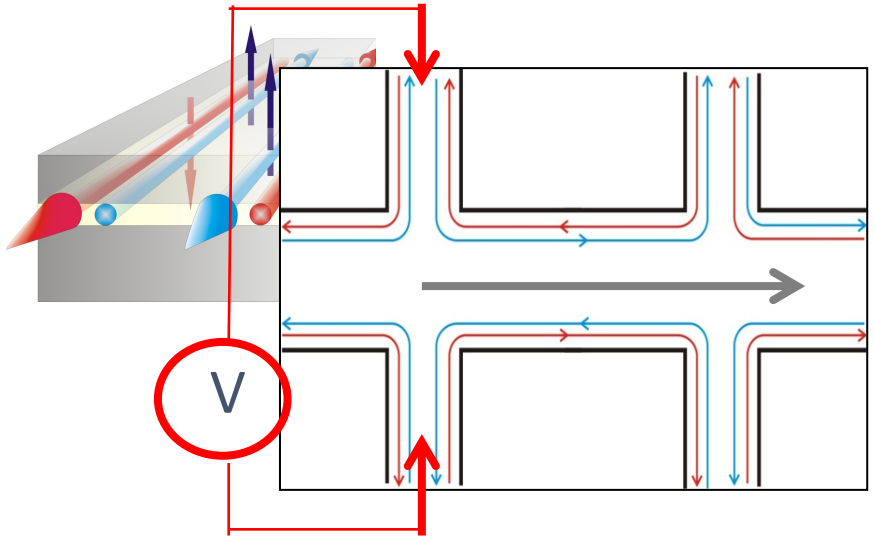
2 counter-propagating modes
Spin-momentum locked
“Time reversal symmetry protection”

Quantum Hall vs Quantum Spin Hall Effect

QHE



QSHE



M. Koenig Phd thesis (2008)

$$R_{xx} = 0$$

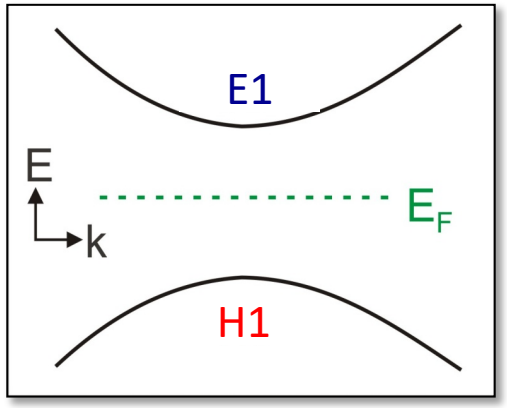
$$R_{xy} = \frac{h}{Ne^2}$$

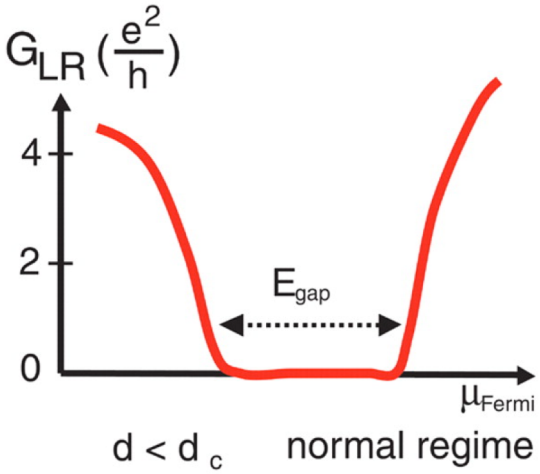
$$R_{xx} = \frac{h}{2e^2}$$

$$R_{xy} = 0$$

Backscattering in 2D-TI quantum wells

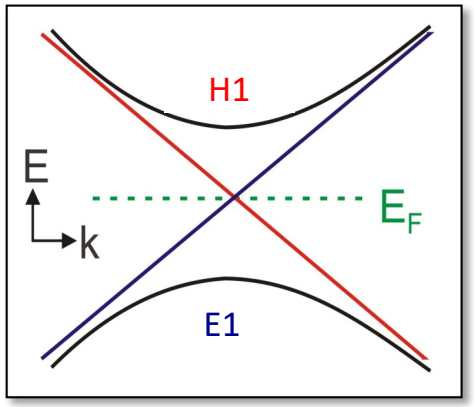
Trivial Insulator

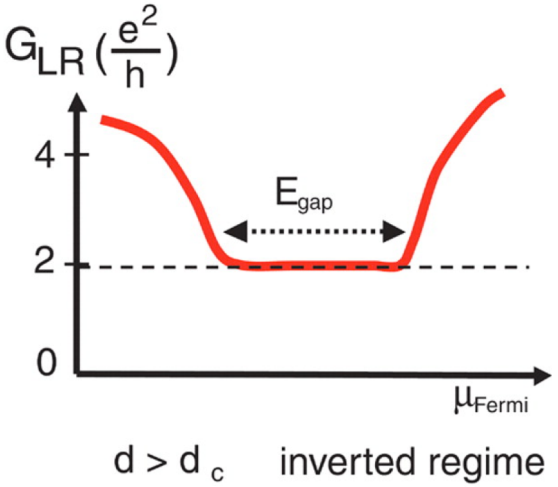




Bernevig et al. *Science*, 314, (2006)

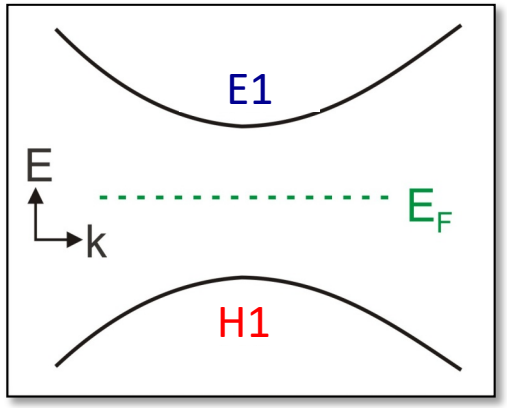
2D Topological Insulator

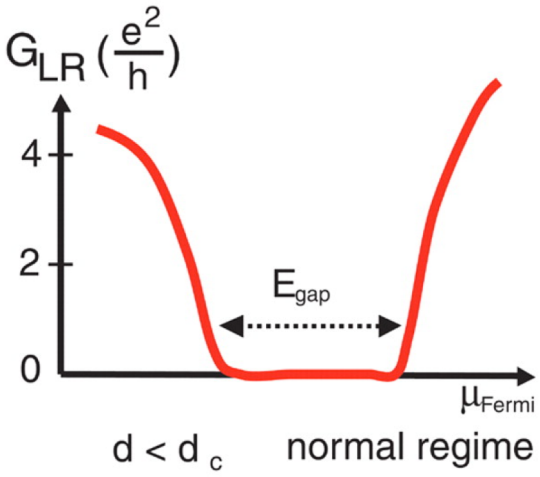




Backscattering in 2D-TI quantum wells

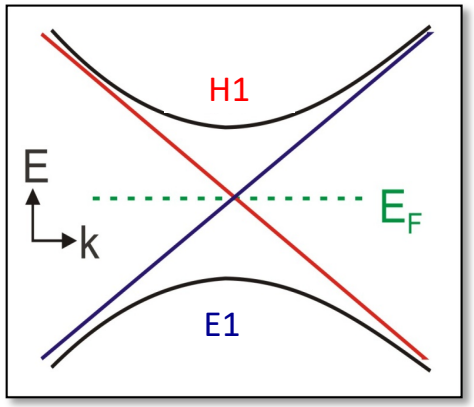
Trivial Insulator

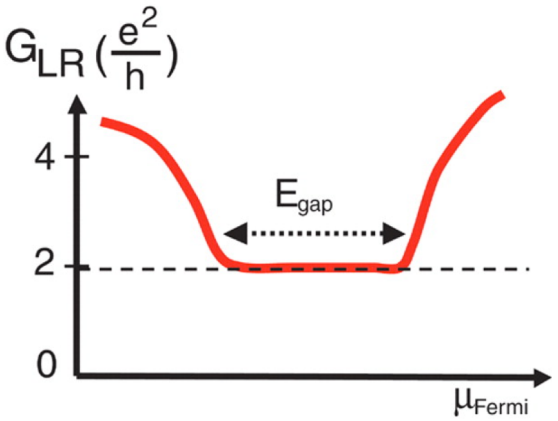




d < d c normal regime

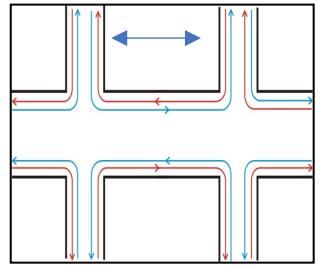
2D Topological Insulator

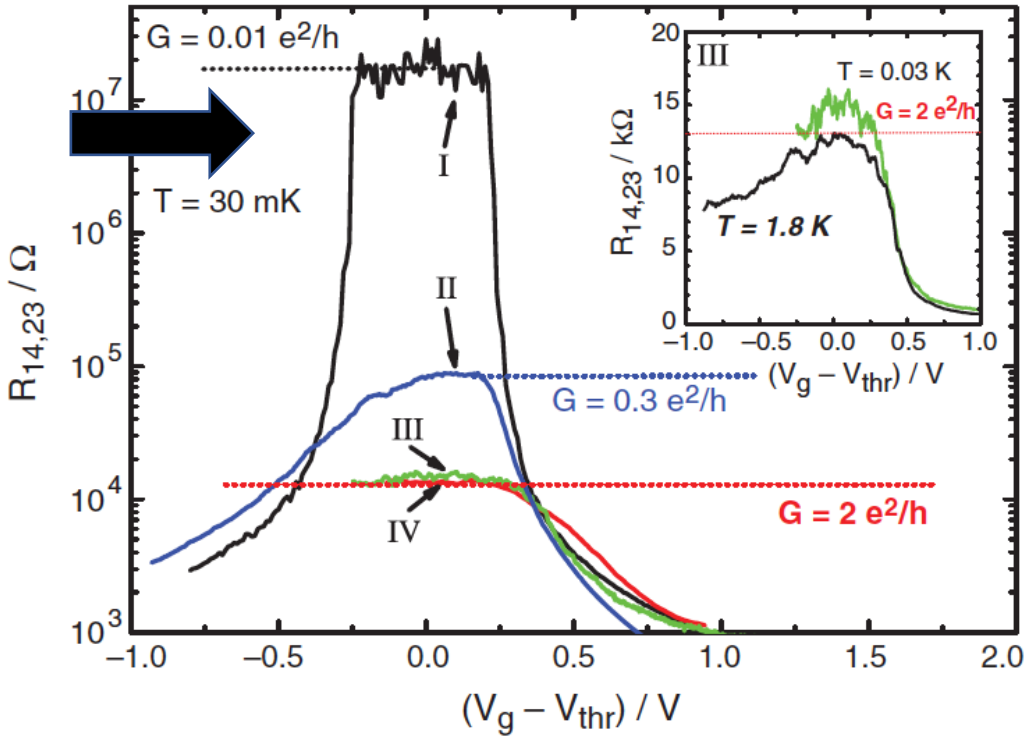




d > d c inverted regime

$d<d_c$

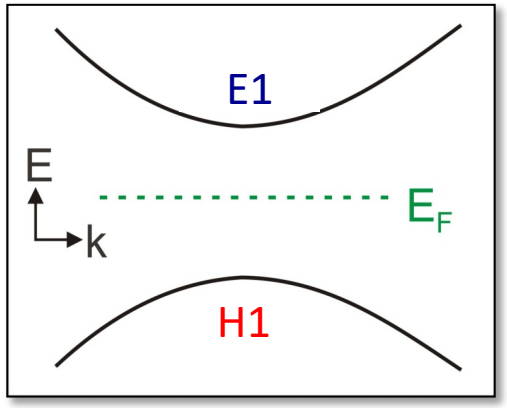


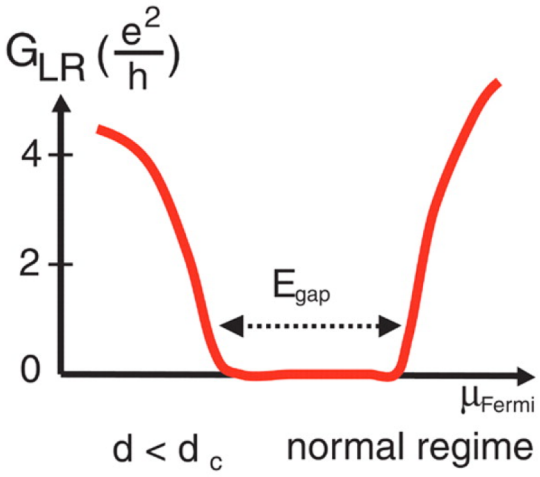


Koenig et al. *Science*, 318, 2007

Backscattering in 2D-TI quantum wells

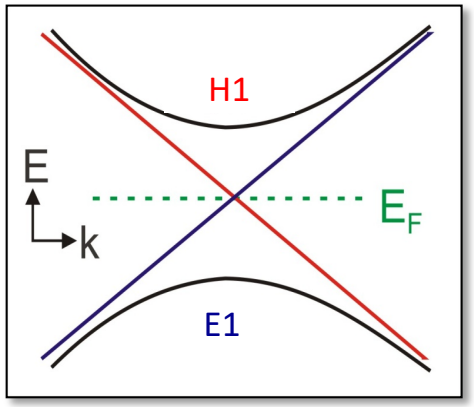
Trivial Insulator

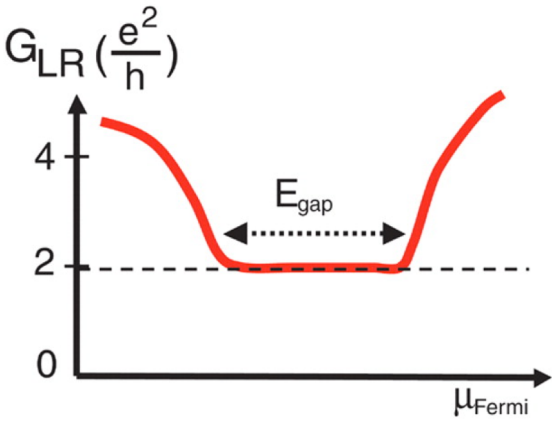




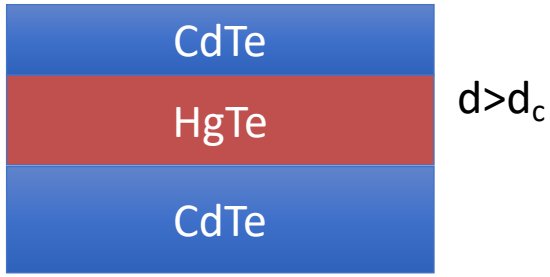
d < d c normal regime

2D Topological Insulator

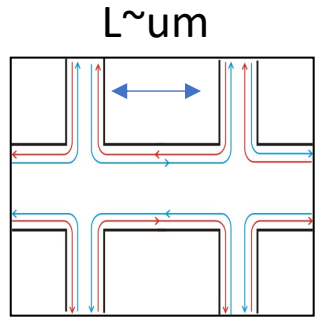


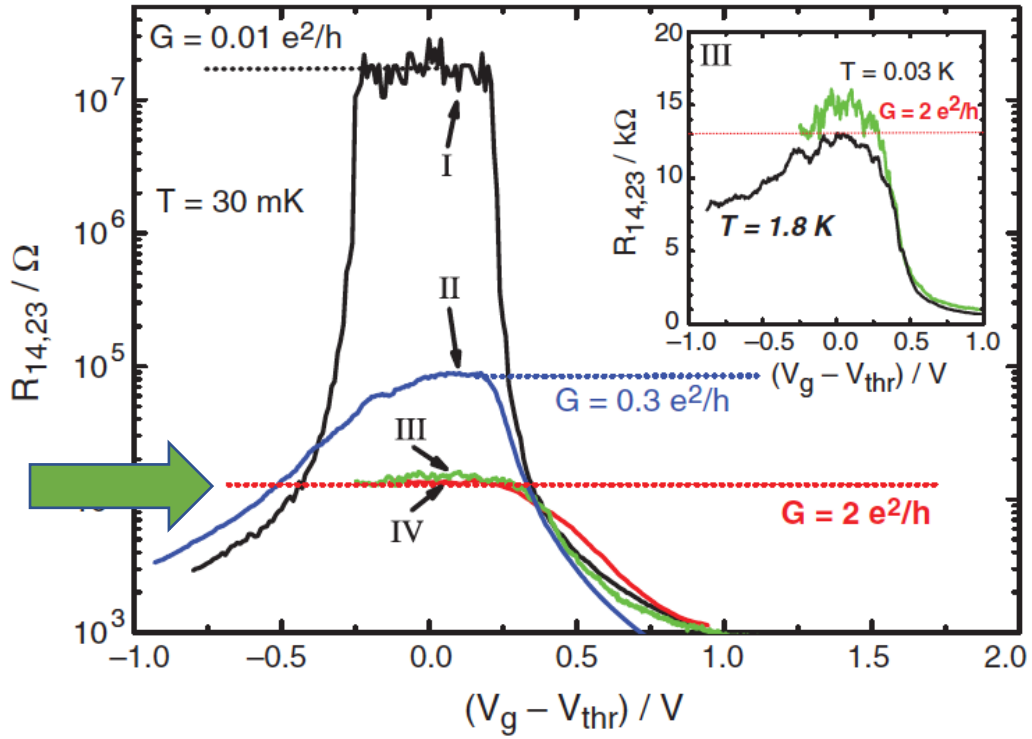


d > d c inverted regime



$d>d_c$

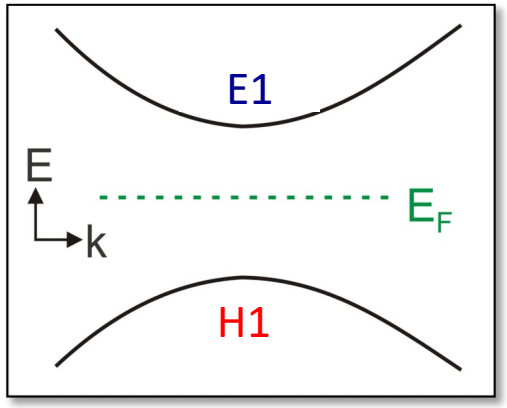


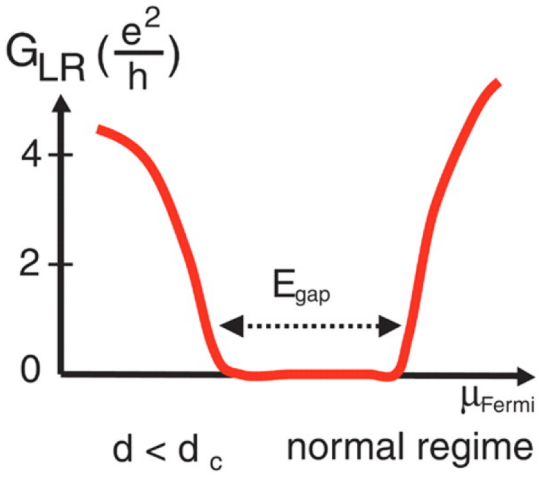


Koenig et al. *Science*, 318, 2007

Backscattering in 2D-TI quantum wells

Trivial Insulator





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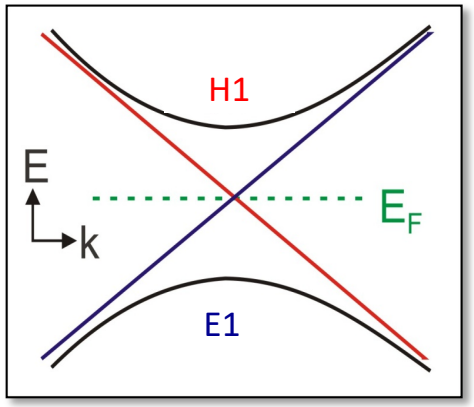
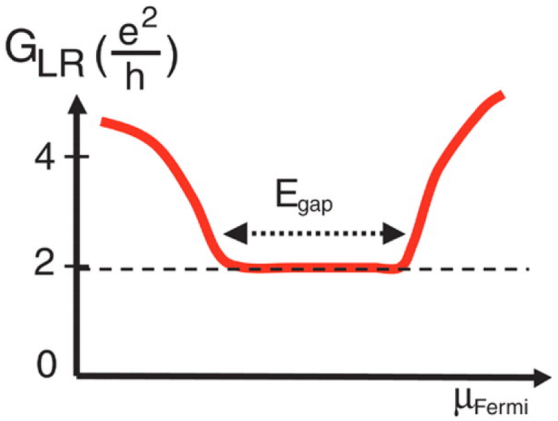
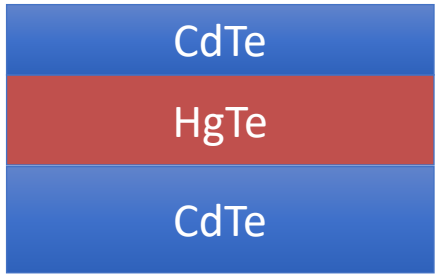
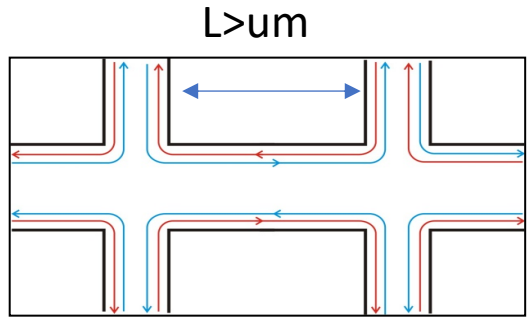


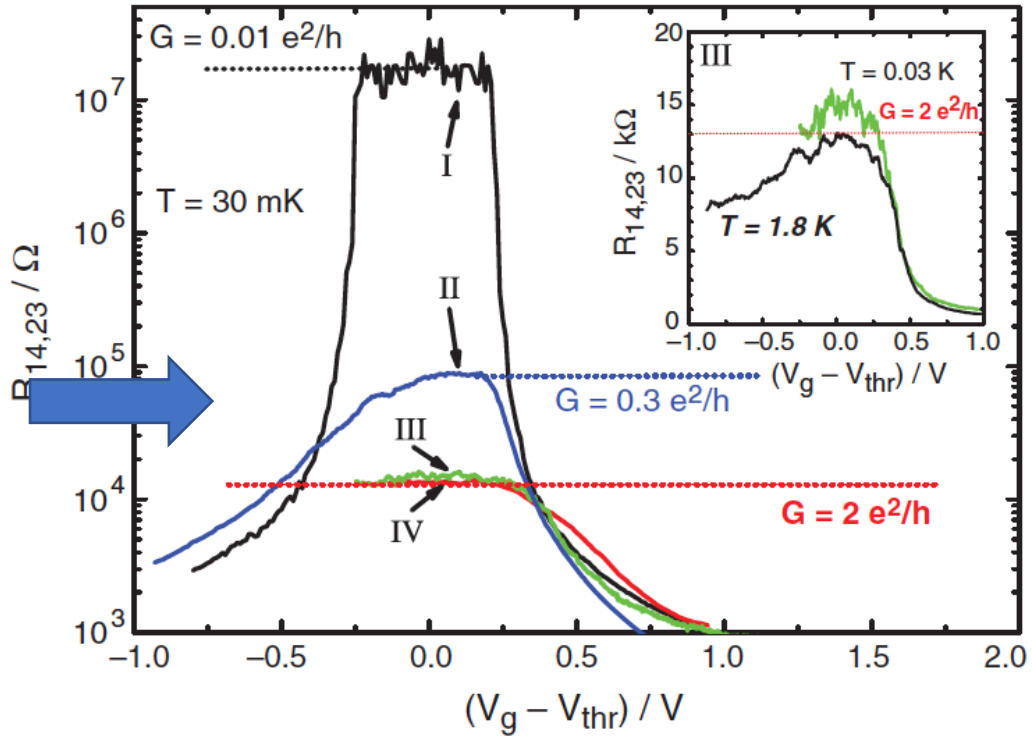


d > d c inverted regime



d>d$_c$





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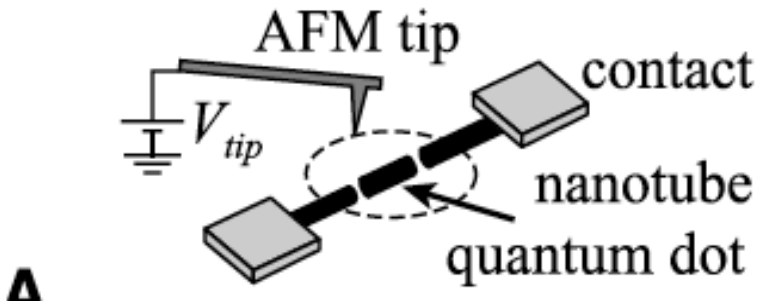
Scanning Gate Microscopy

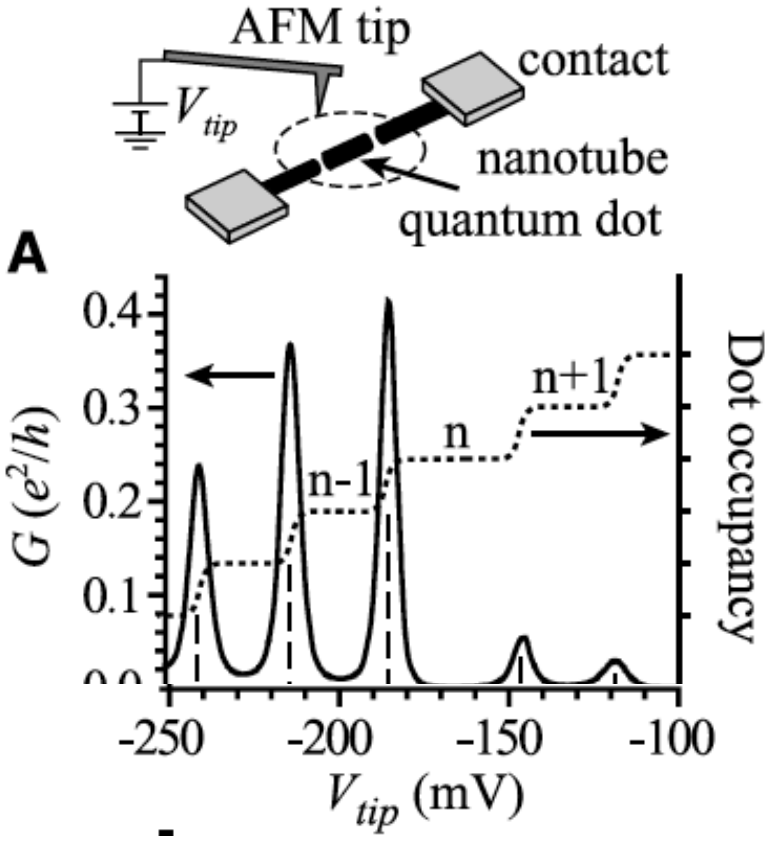


A

Woodside et al. *Science* **296**, 1098 (2002).

- Conductive AFM tip acts as a local gate

Scanning Gate Microscopy



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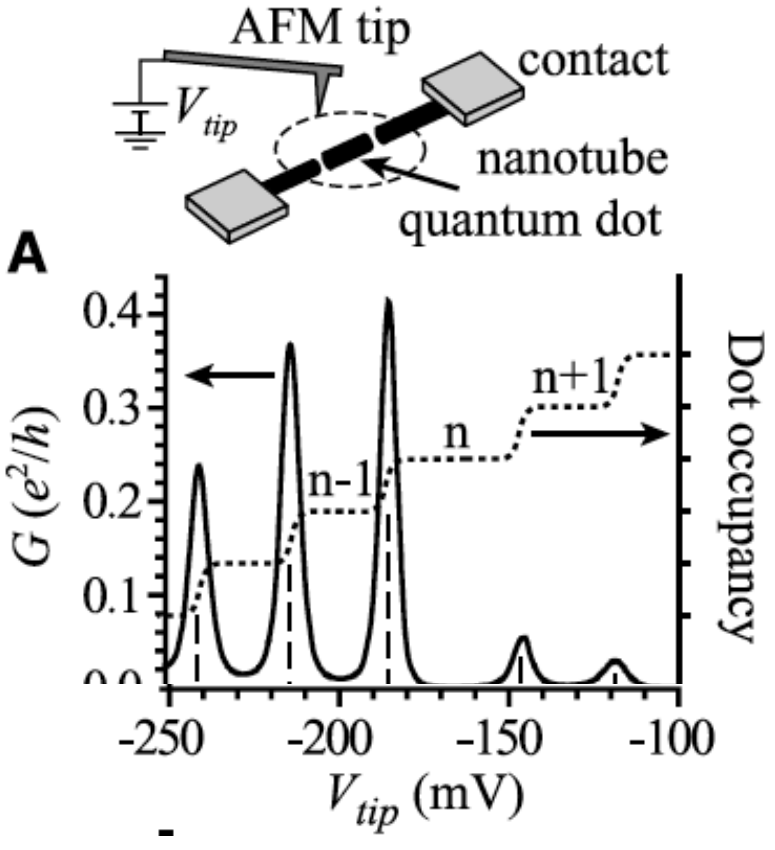
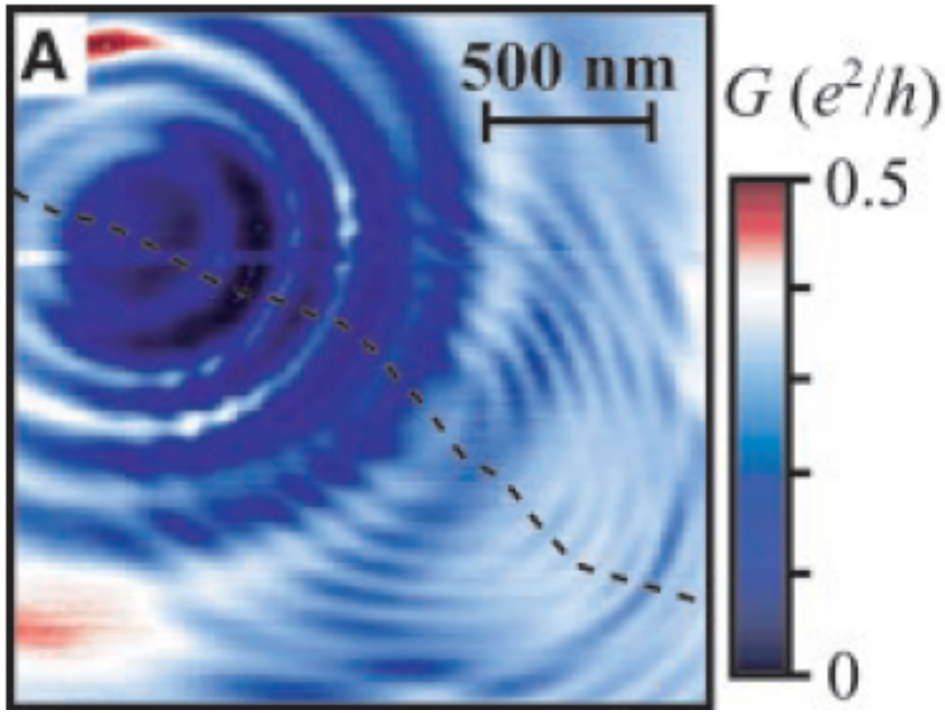
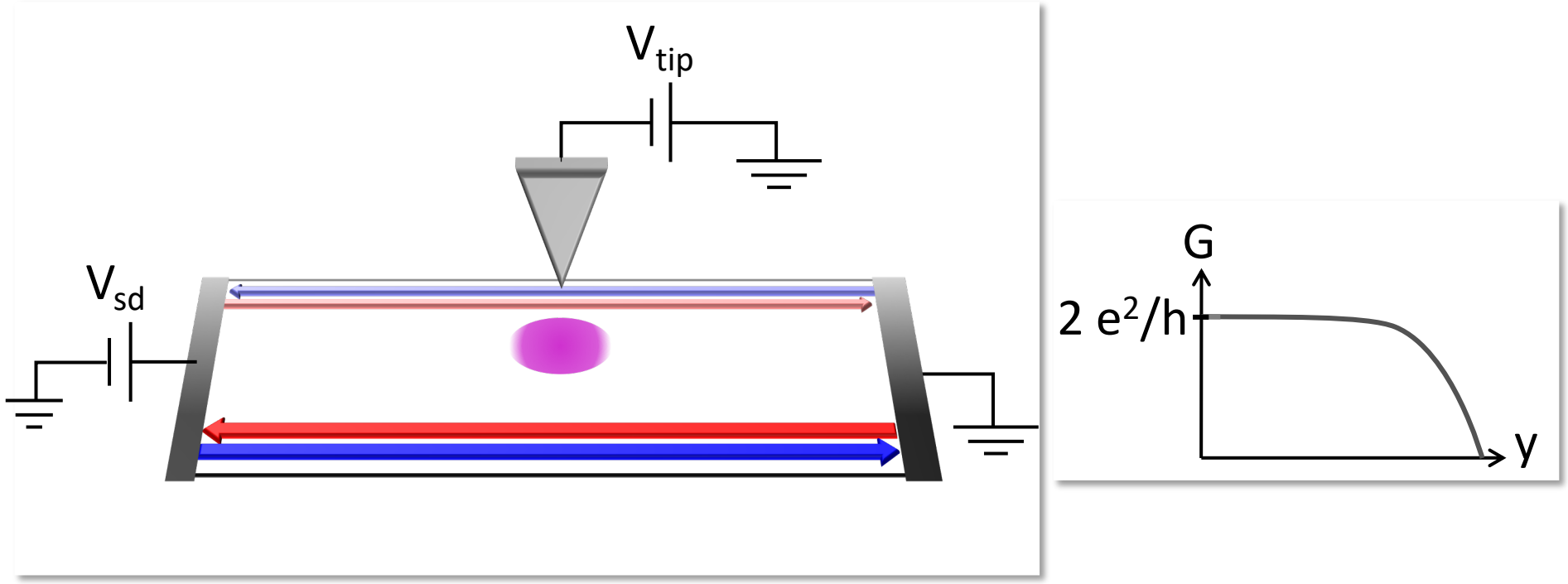




Woodside et al. *Science* **296**, 1098 (2002).

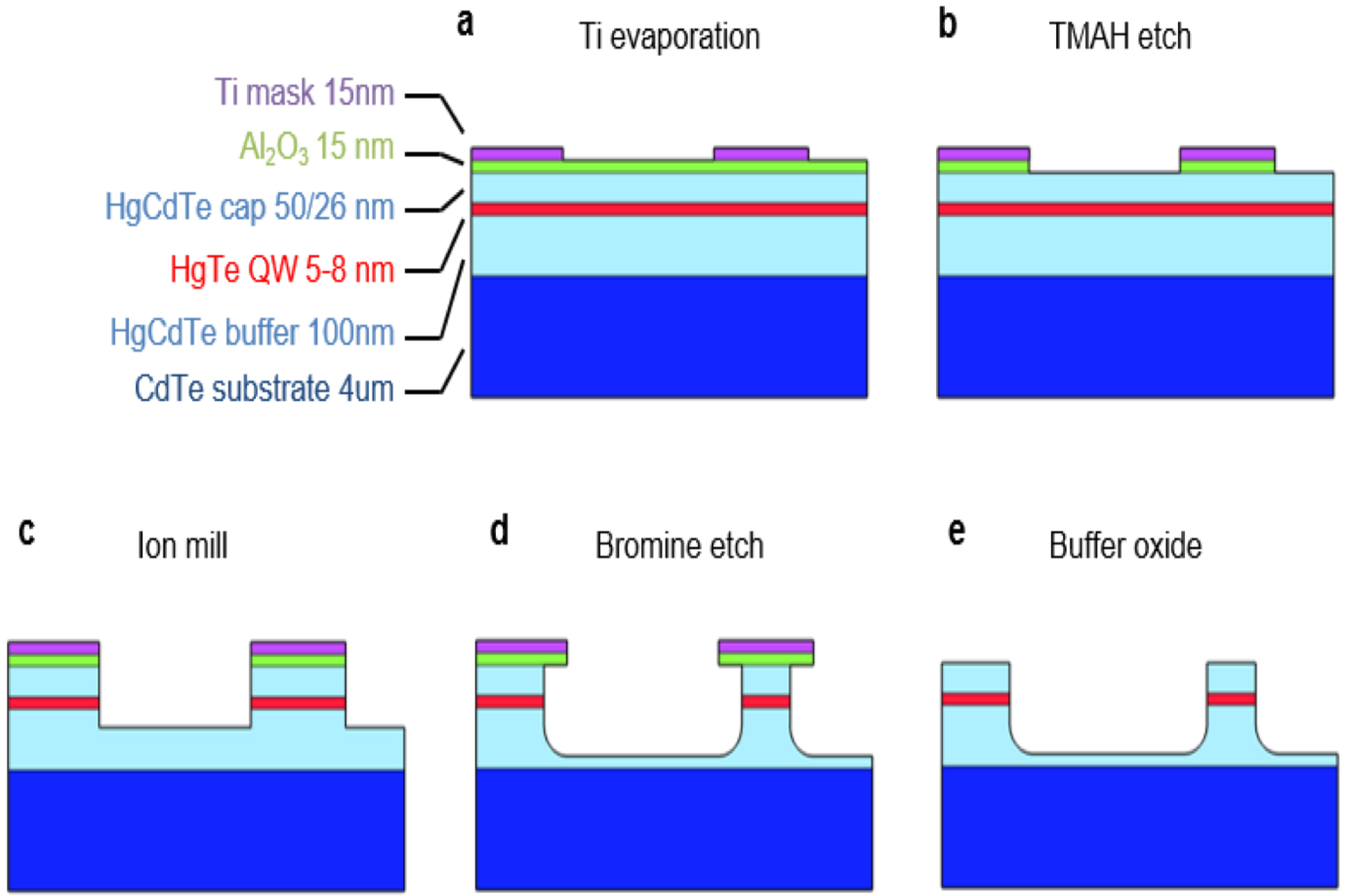
- Conductive AFM tip acts as a local gate
- Peaks in conductance appear in the SGM maps as sets of concentric rings
- SGM provides spatial information on scattering

SGM on QSH edge states



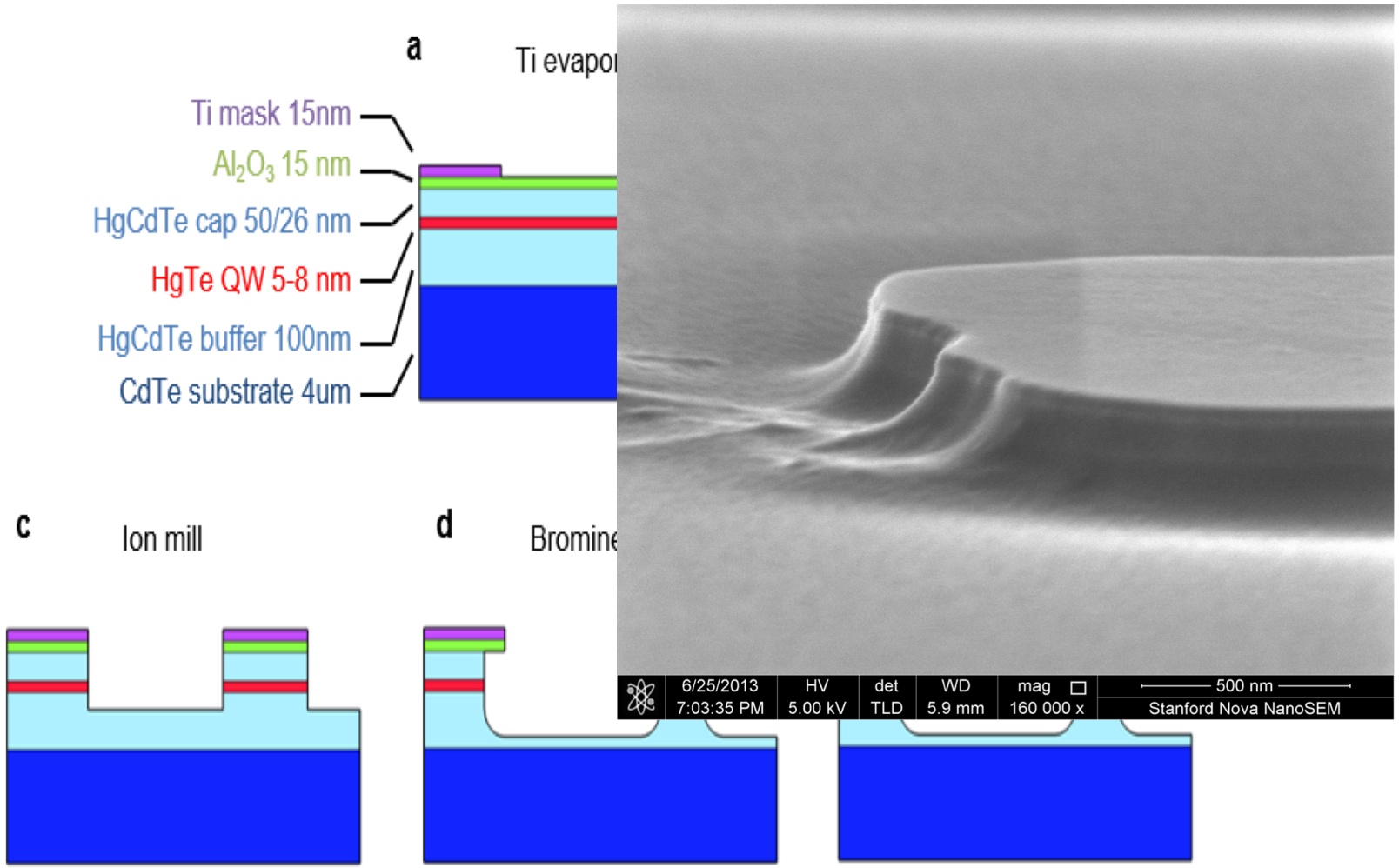
Koenig et al. *Phys. Rev. X* 3, 021003 (2013)

HgTe device fabrication for SPMs

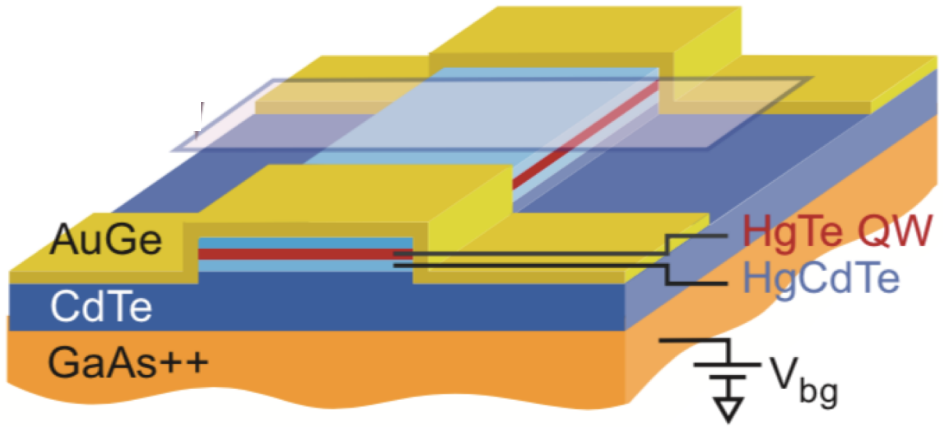


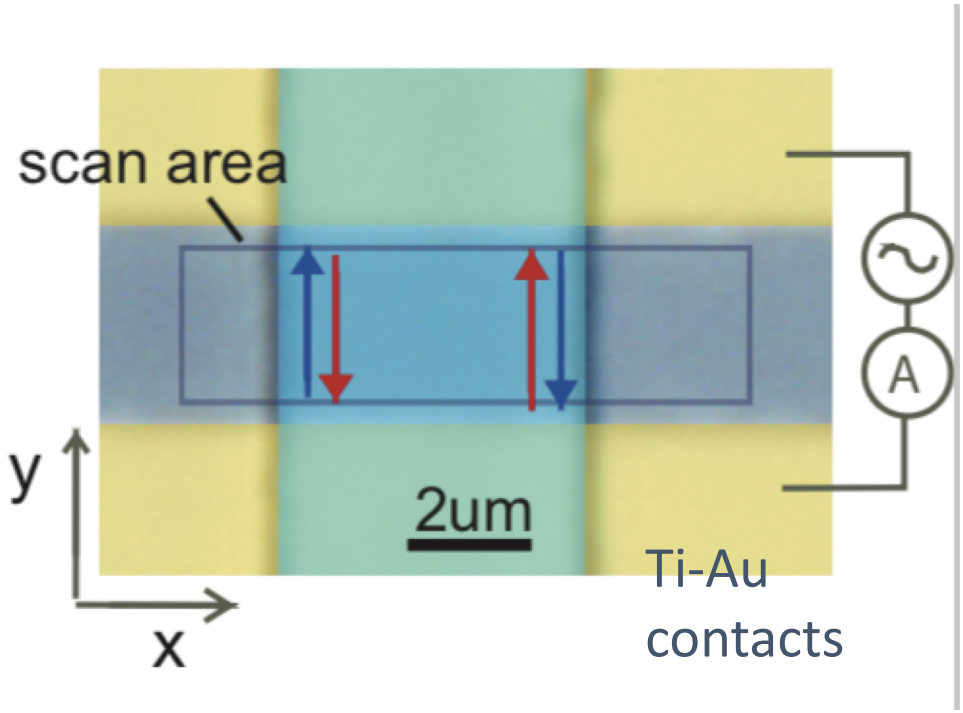
- Layered structure grown on GaAs wafer: backgate
- 2 step etching process for mesa definition

HgTe device fabrication for SPMs



SGM on 2D-TI HgTe quantum wells





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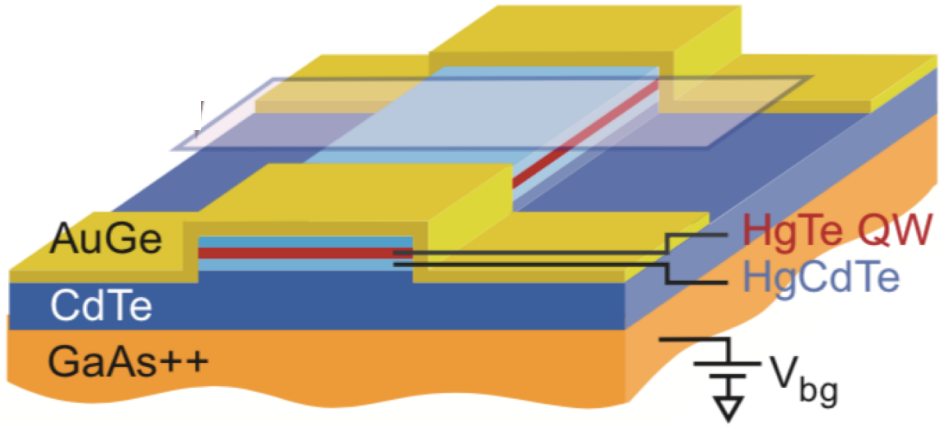
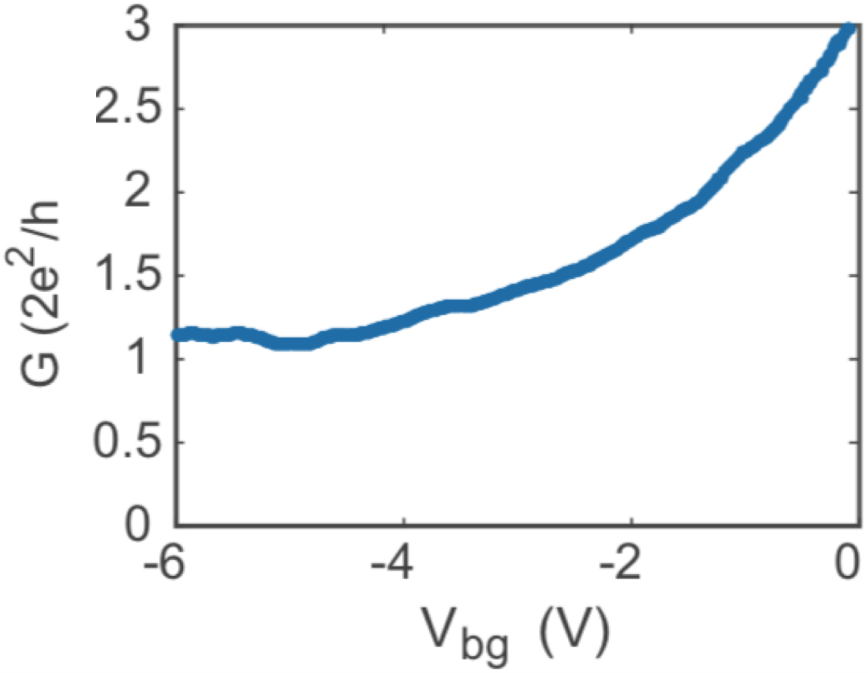
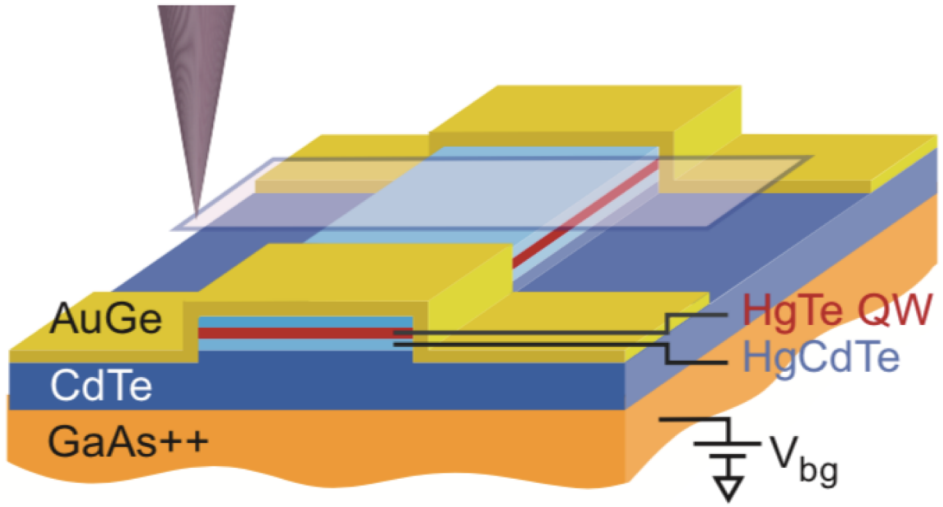
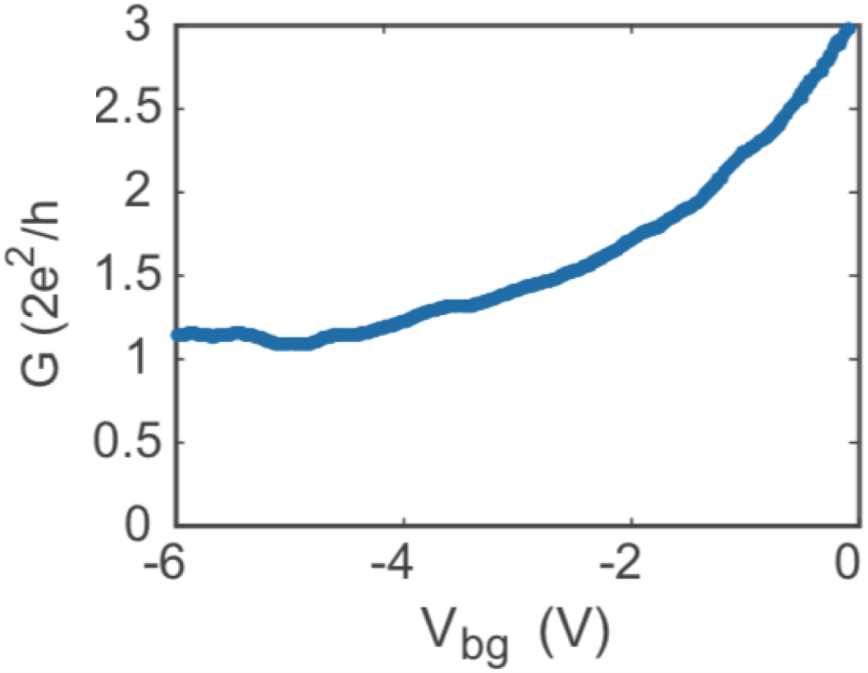




- Backgate voltage tunes the Fermi energy across the bandgap
- Set to a slightly p-doped device

SGM on 2D-TI HgTe quantum wells





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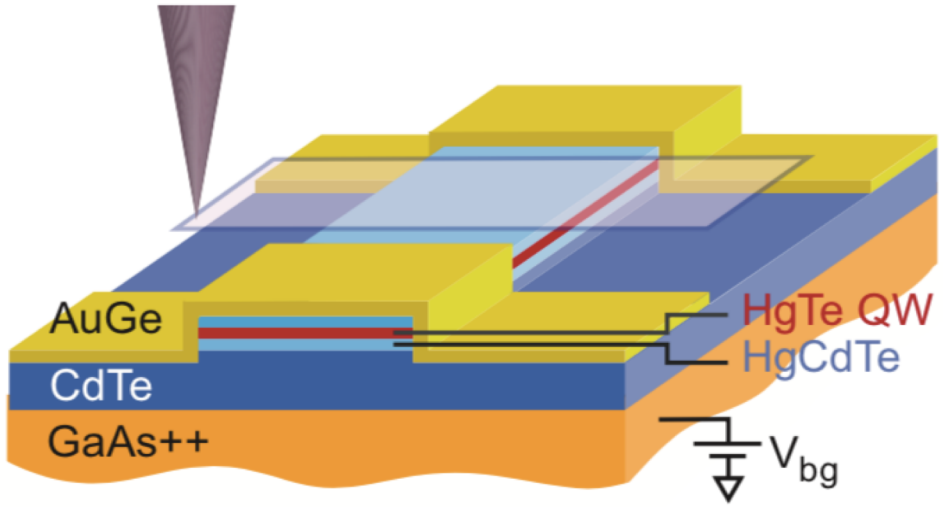

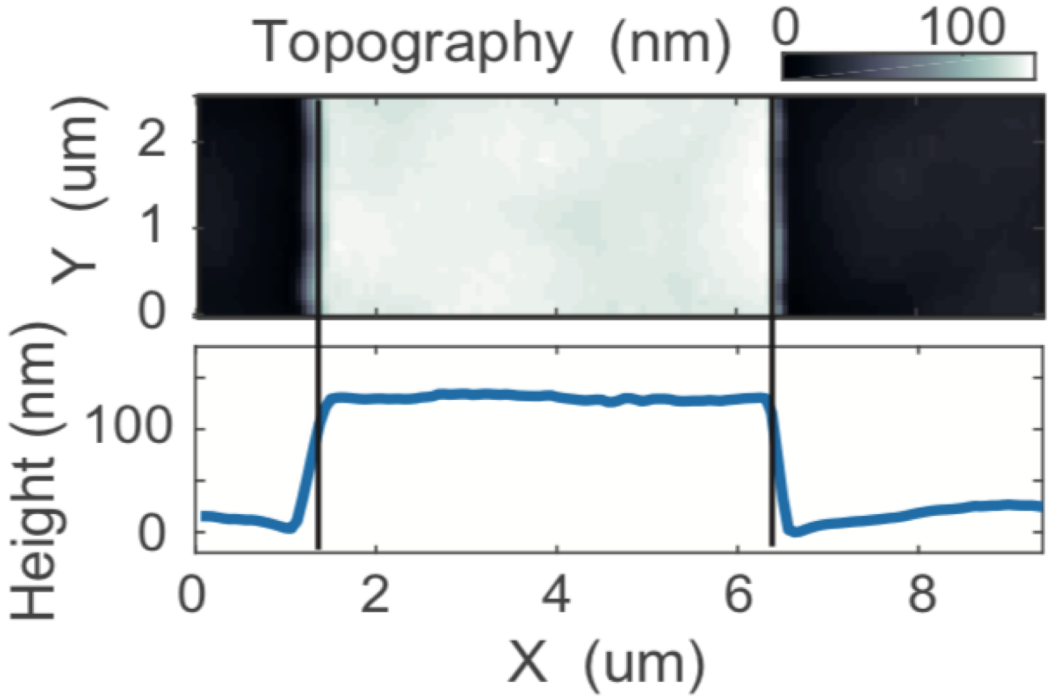

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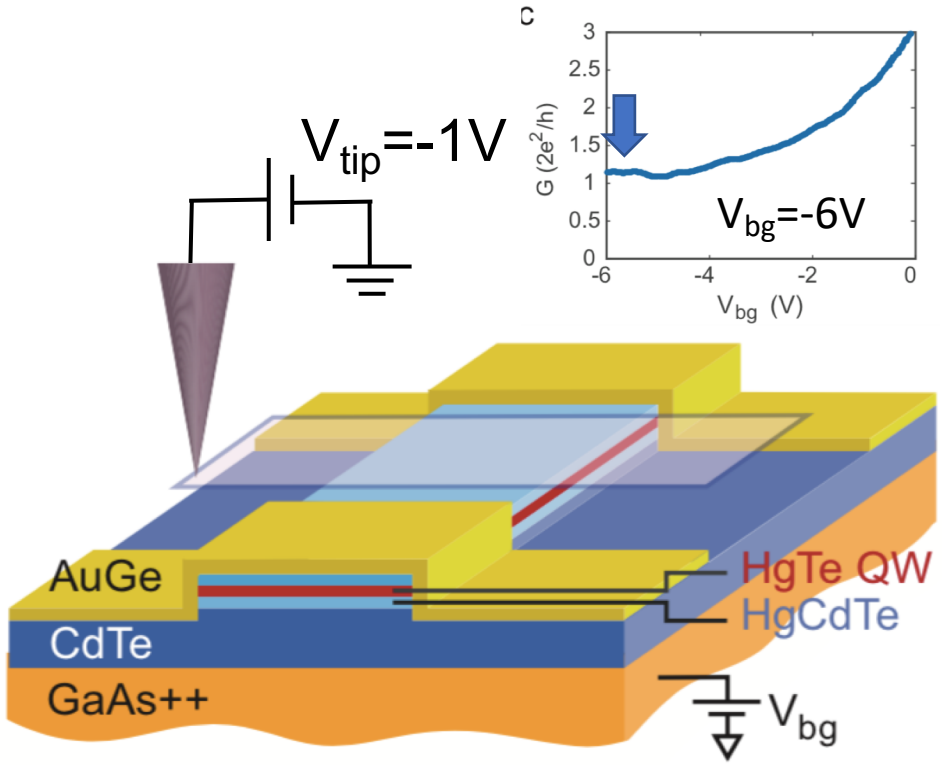
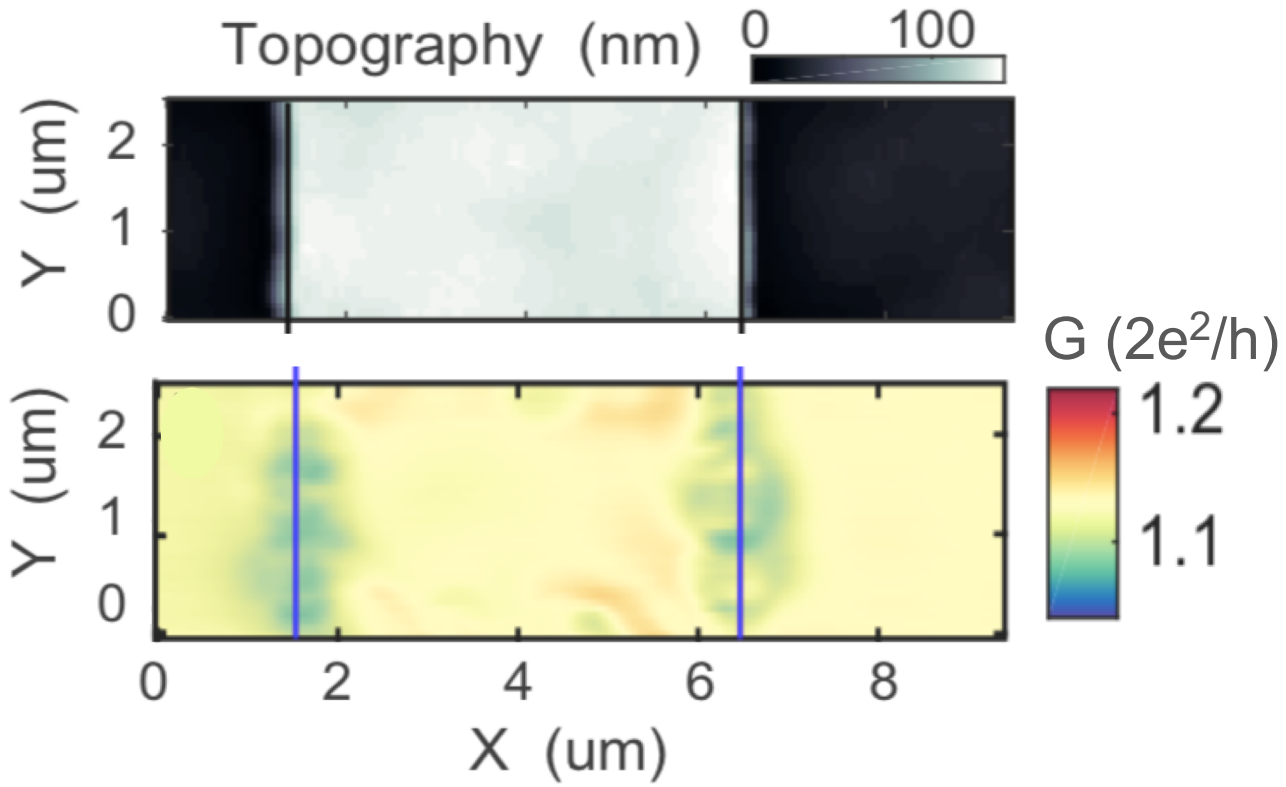
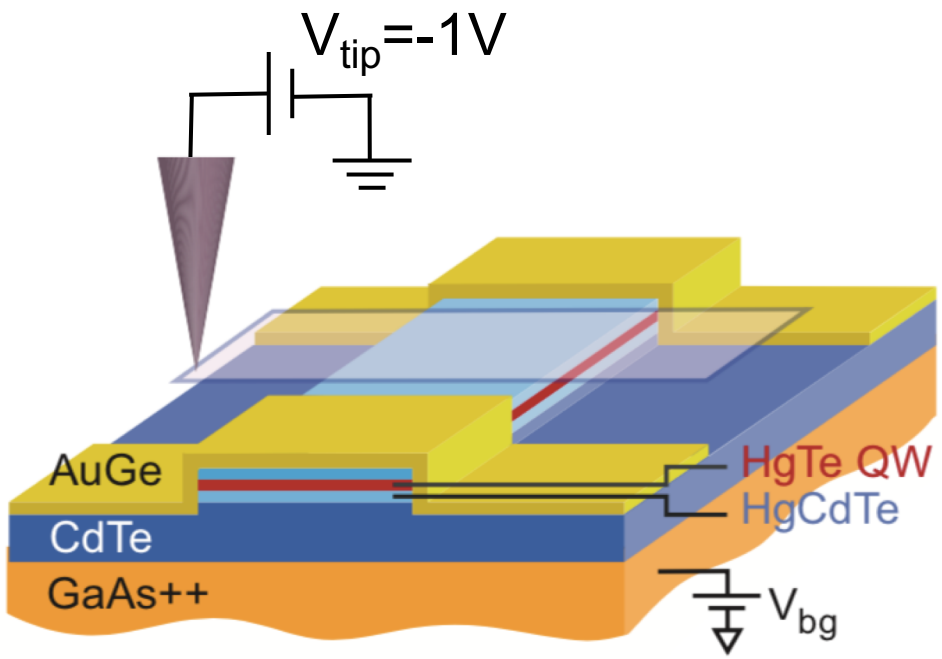
SGM on 2D-TI HgTe quantum wells

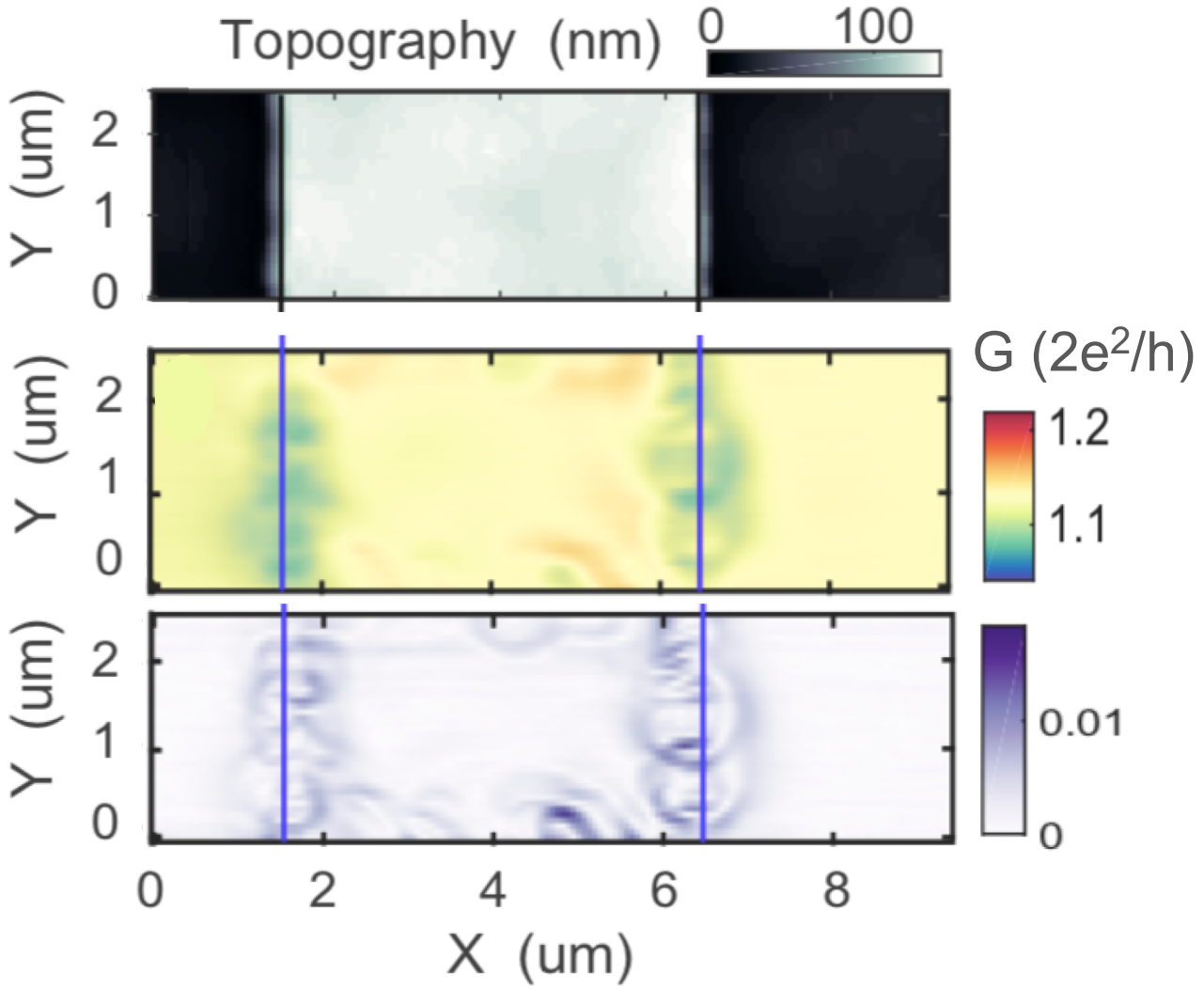




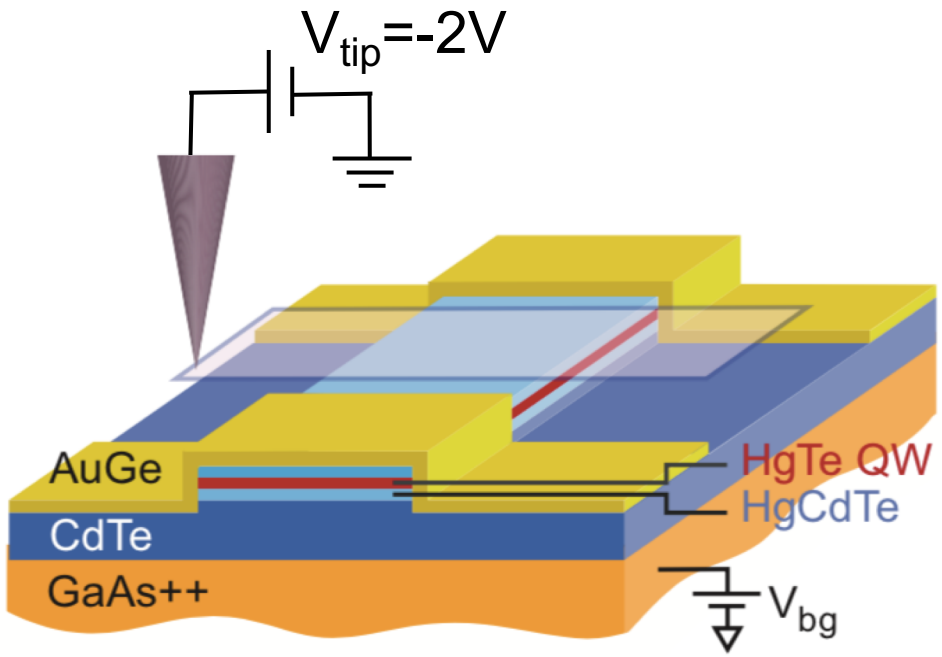
- Backgate voltage set to tune the device into the bulk gap
- The SPM metallic tip acts as a local top-gate electrode
- By monitoring the conductance as a function of tip position: conductance maps

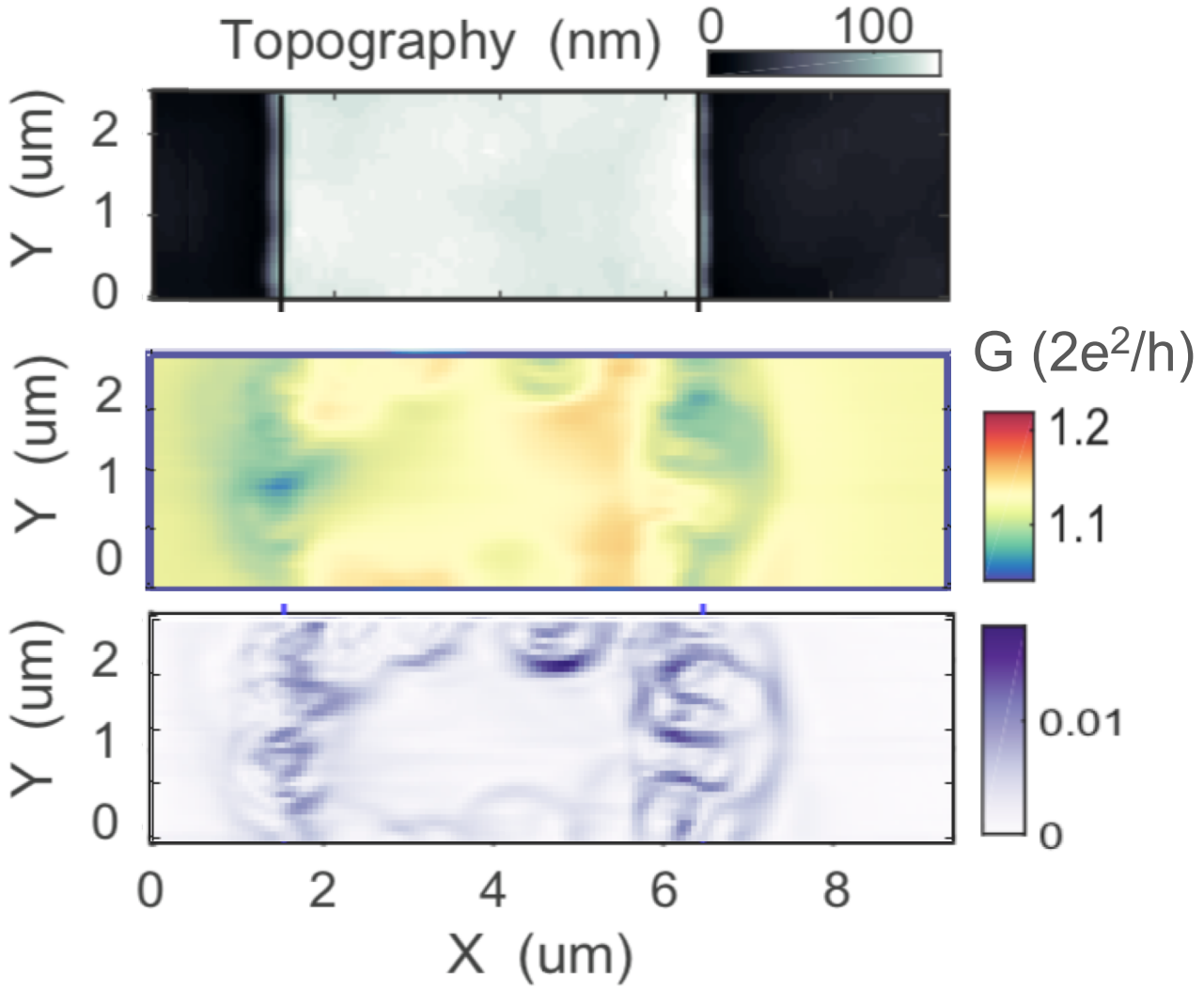
SGM on 2D-TI HgTe quantum wells



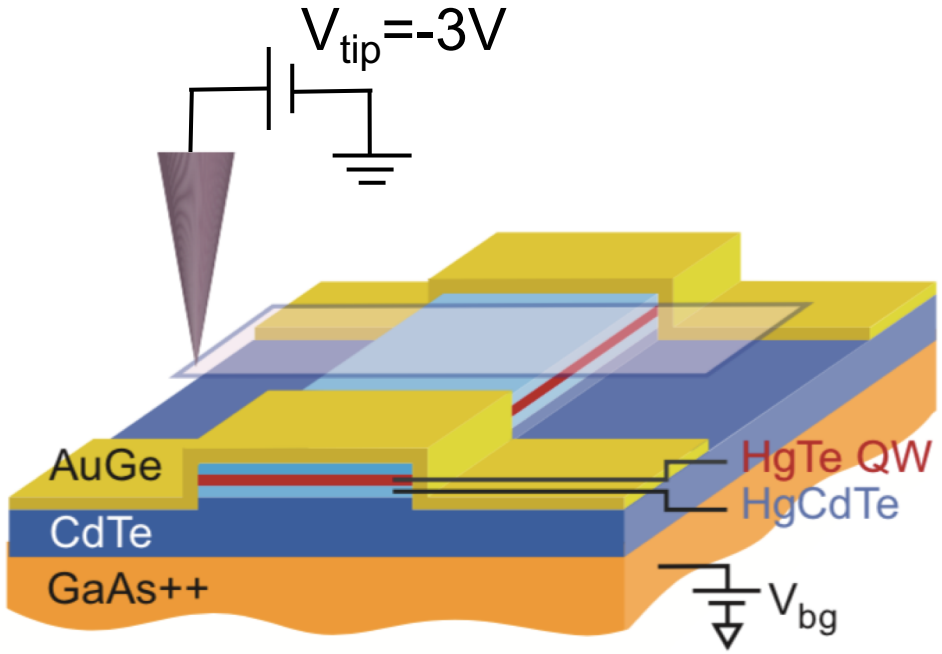


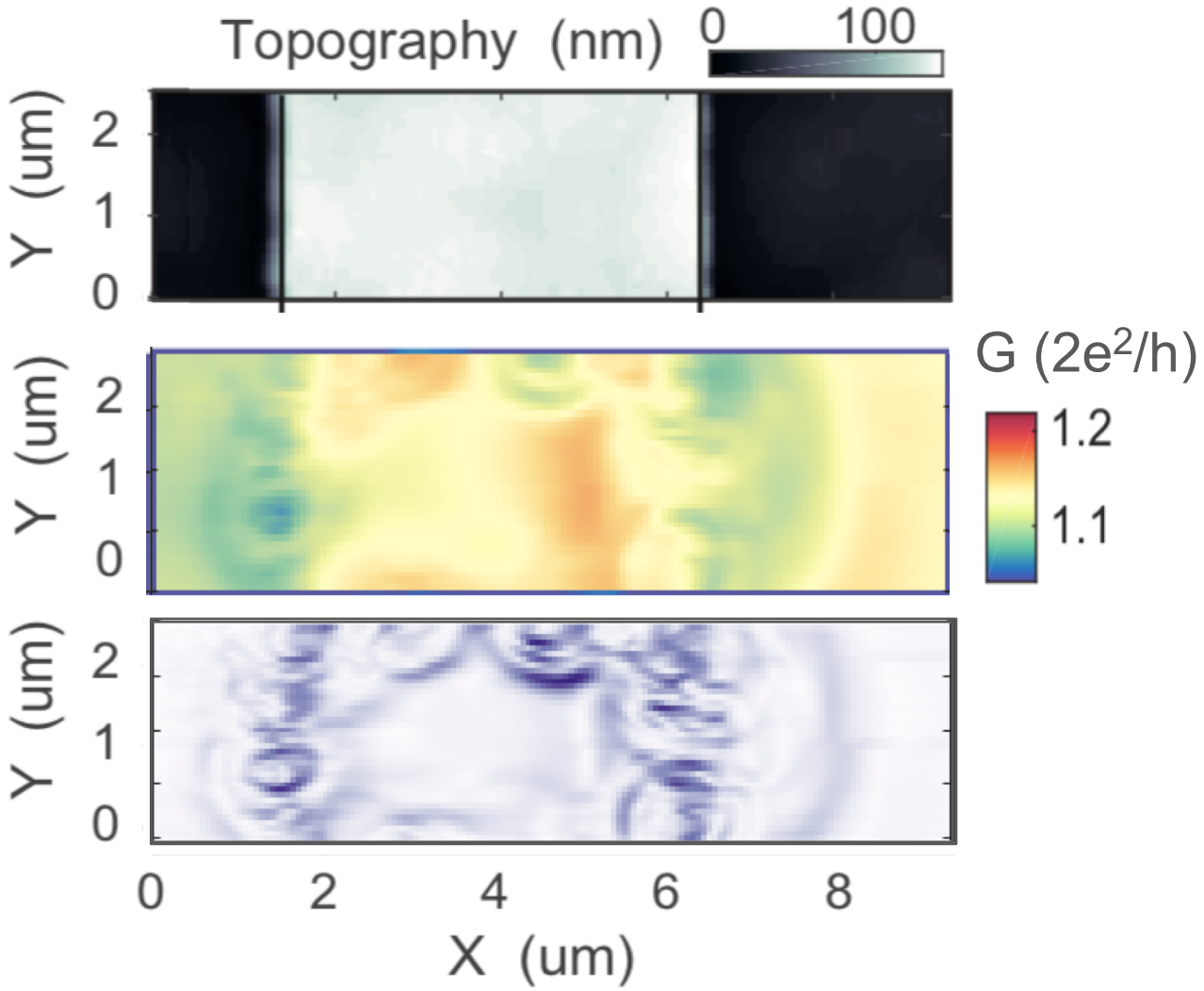
SGM on 2D-TI HgTe quantum wells



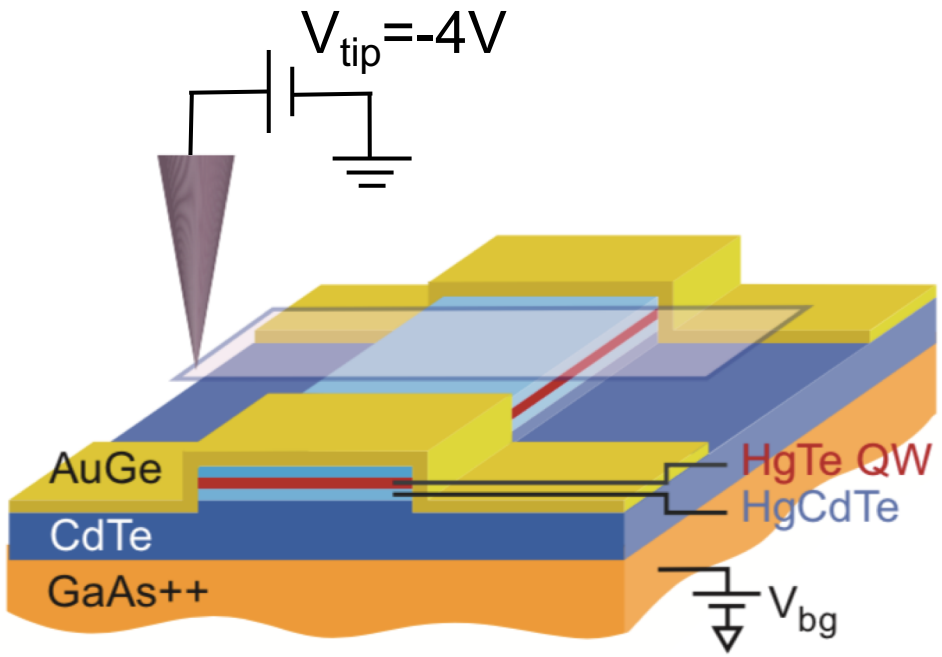


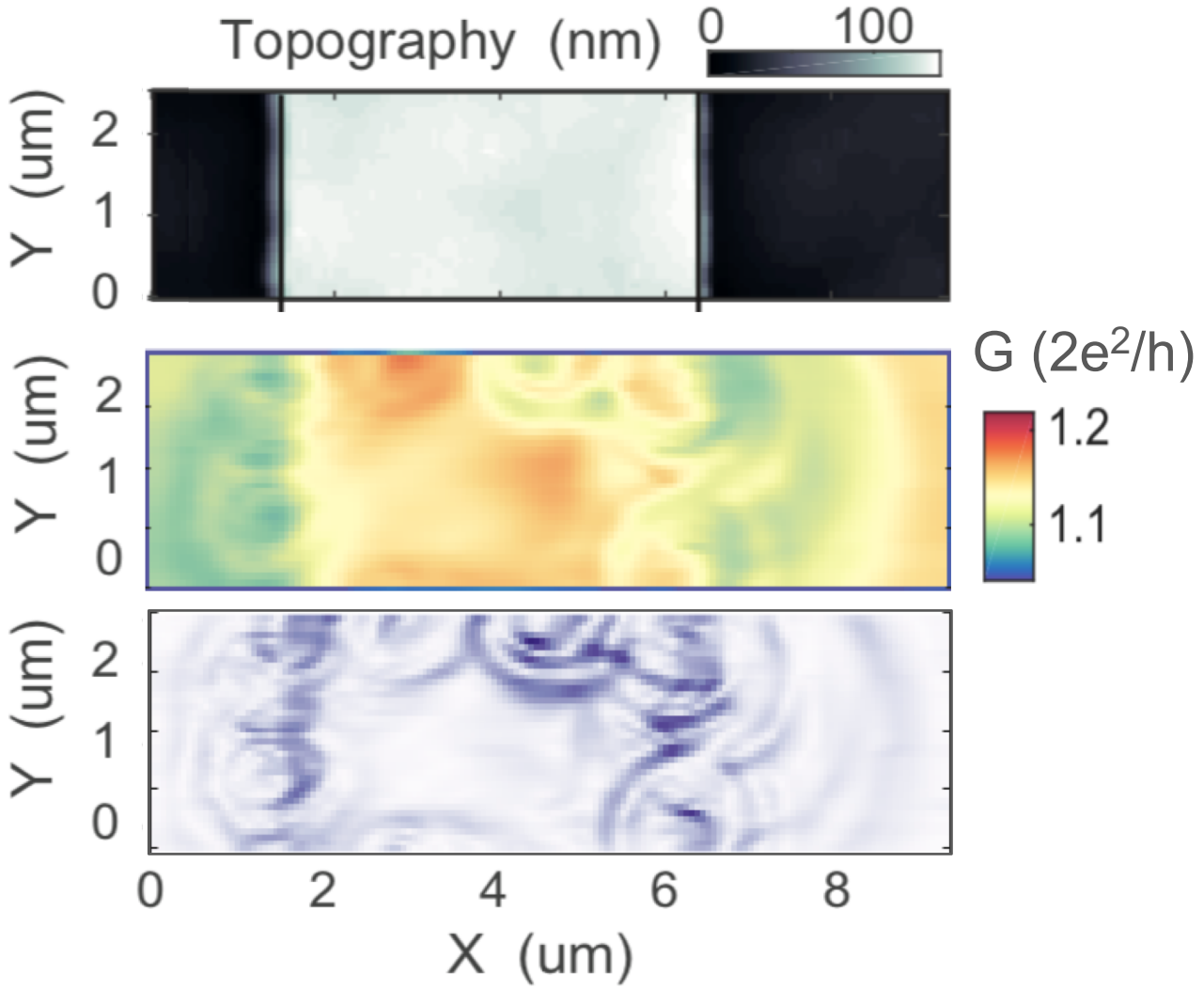
SGM on 2D-TI HgTe quantum wells





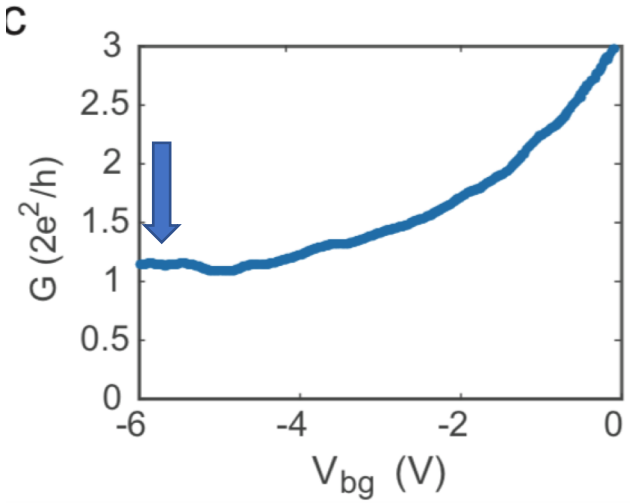
SGM on 2D-TI HgTe quantum wells

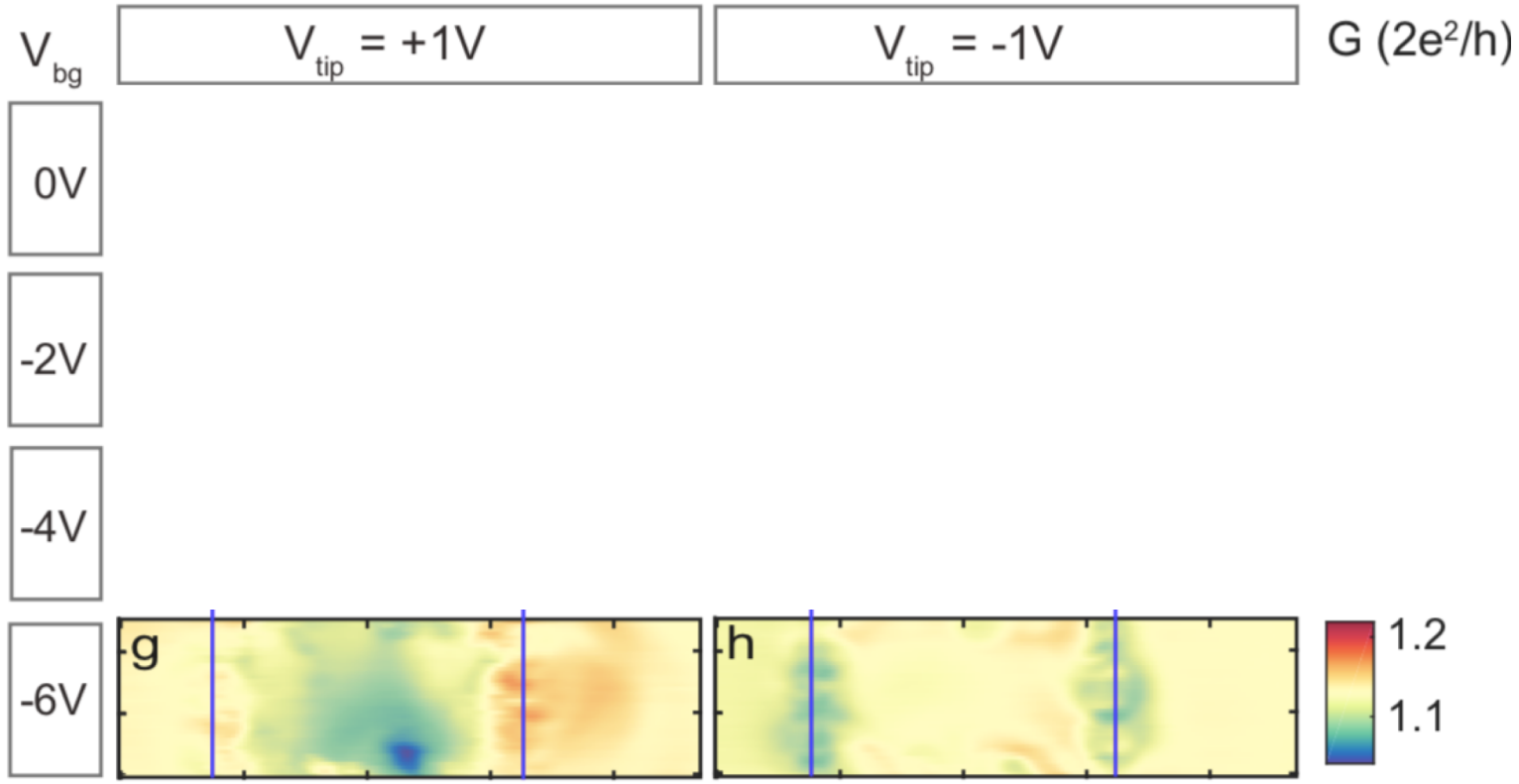




In agreement with results by Koenig et al. PRX 2013

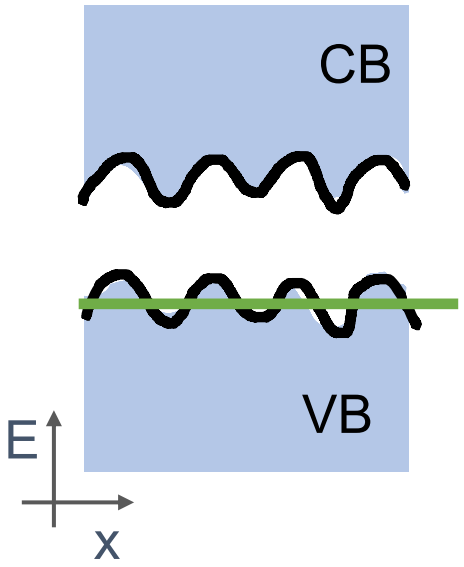
SGM on 2D-TI HgTe quantum wells





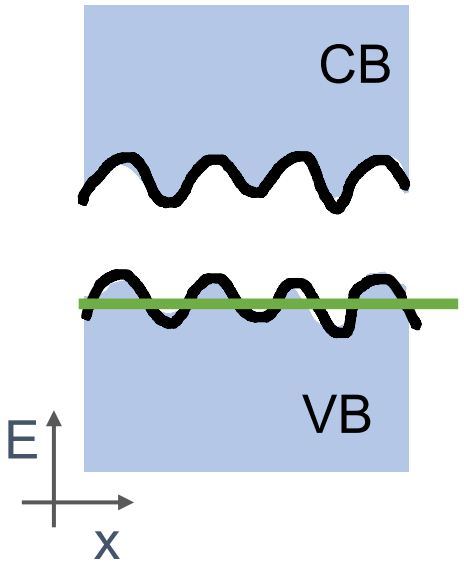
- Rings features that increase in size with tip voltaje
- Slight decrease of conductance when tip is above the edge with Vtip<0
- Slight increase of conductance when tip is above the edge with Vtip>0

Backscattering sources



- Charge puddles Inelastic scattering
- Metallic regions intercalated with QSH edges.
- p-doped puddles size increases for $V_{tip}<0$, increasing backscattering

Backscattering sources



Vayrynen et al. PRB 90, 2014

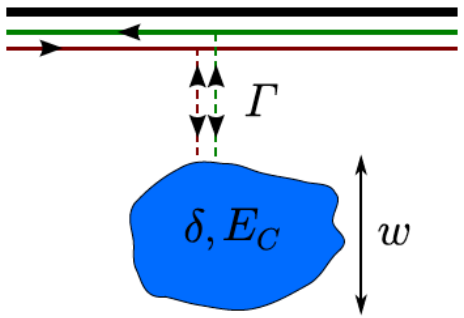


FIG. 1. (Color online) A quantum dot of linear size w (bottom) tunnel-coupled to a helical edge (top). The mean level spacing of the puddle is denoted by δ and its charging energy by E_C. The typical tunneling-induced level width is Γ.

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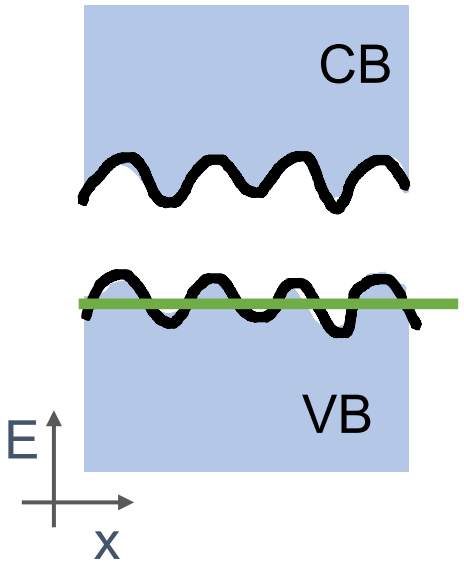
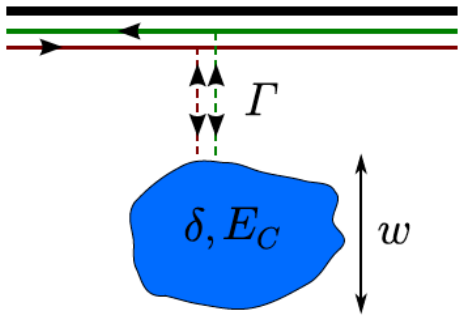


Vayrynen et al. PRB 90, 2014



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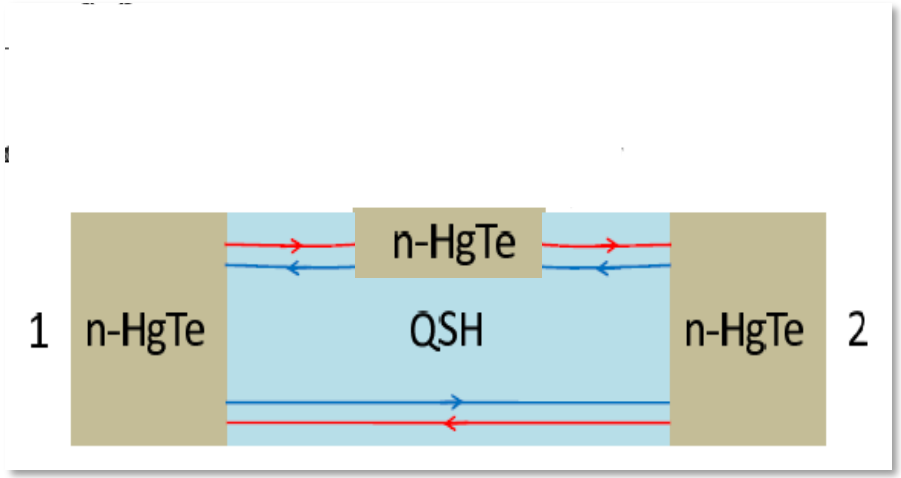

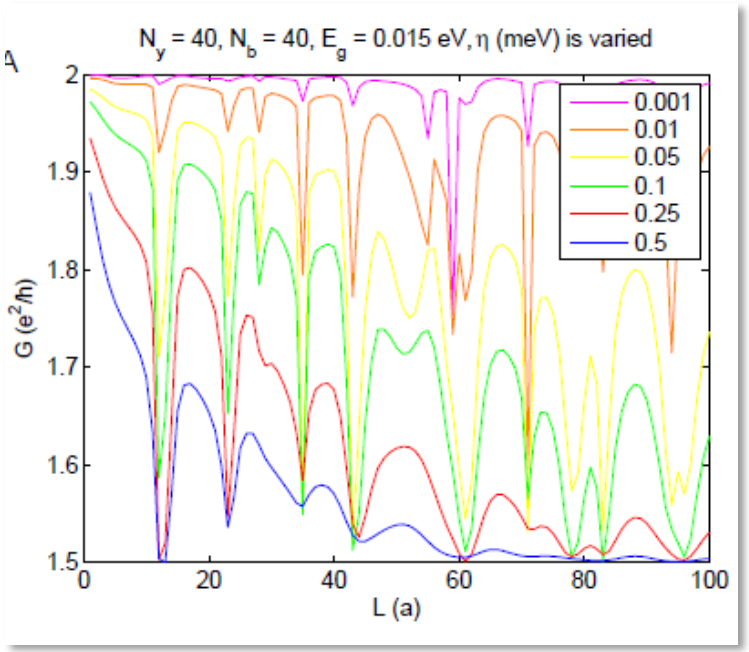

- Charge puddles Inelastic scattering
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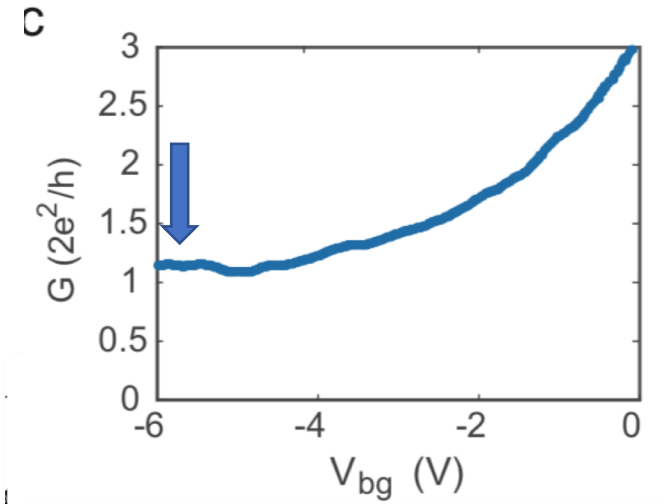
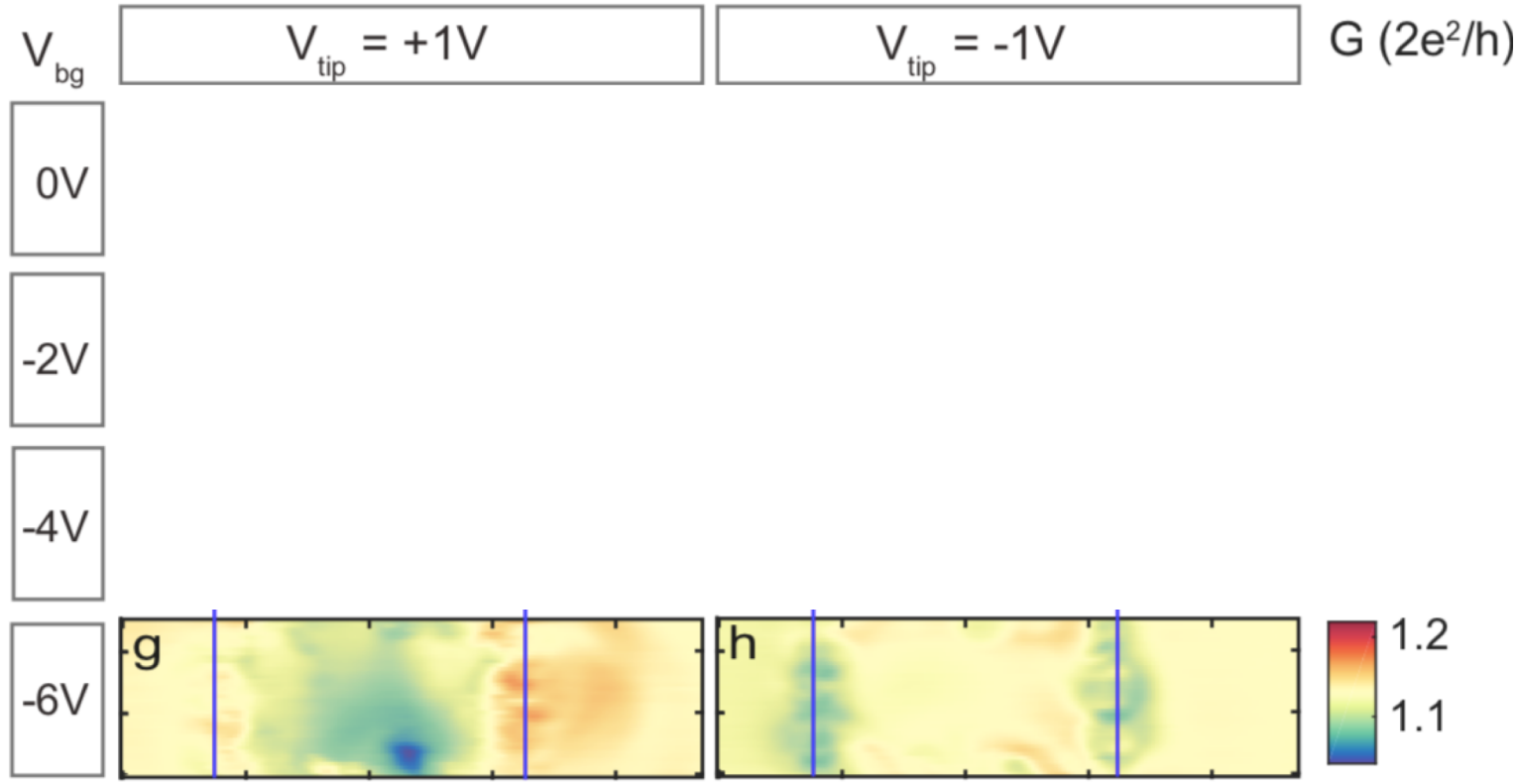
Roth et al., Science **325**, 294 (2009)

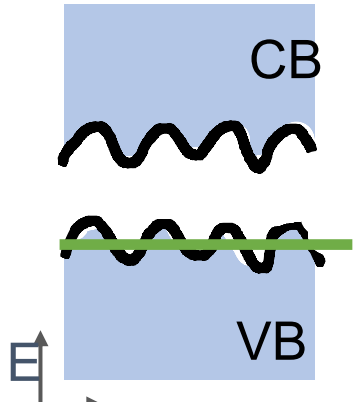
Koenig et al. *PRX* 3, 021003 (2013)

Calvo, Bercioux et al. *In preparation*

SGM on 2D-TI HgTe quantum wells

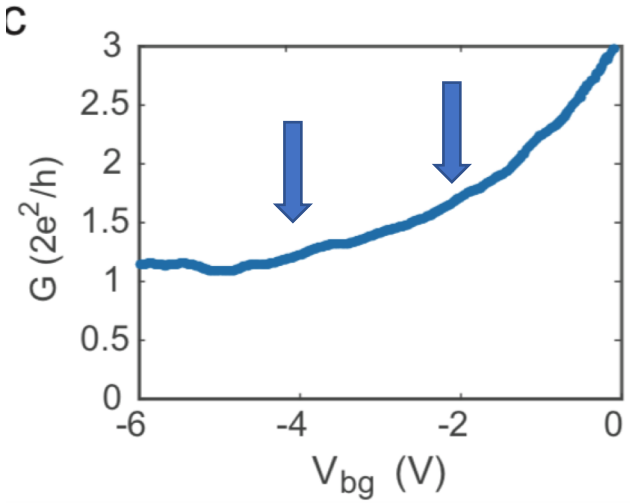


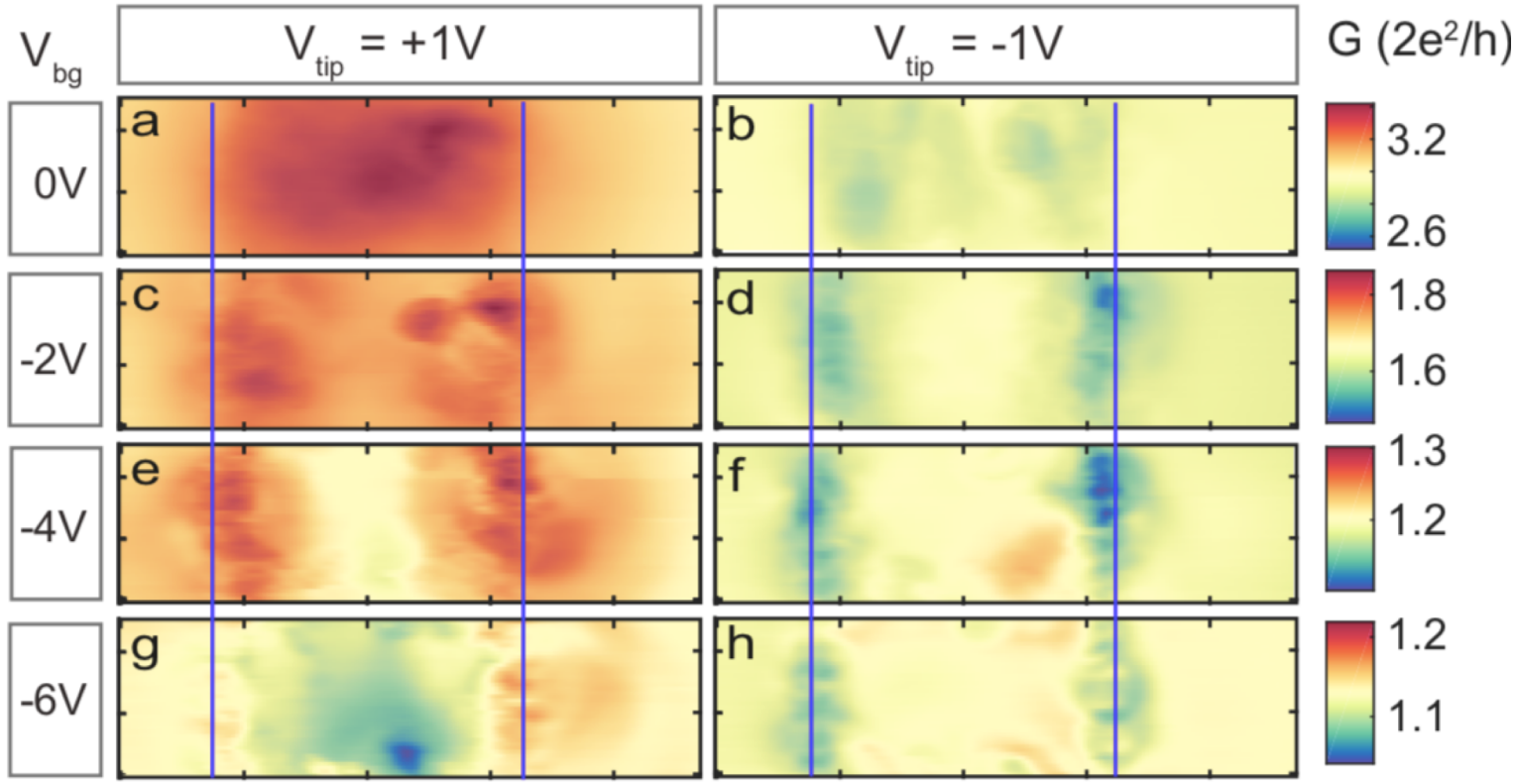




- p-doped puddles size increases for $V_{tip}<0$, increasing backscattering
  Decreases for $V_{tip}>0$, decreasing backscattering

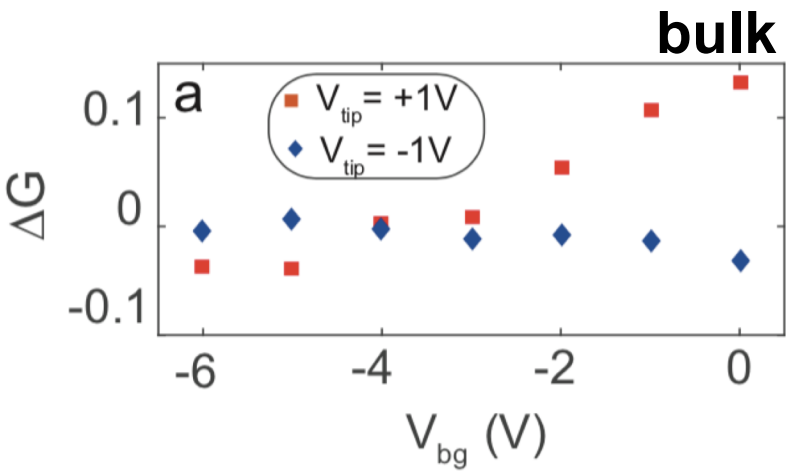
SGM on 2D-TI HgTe quantum wells

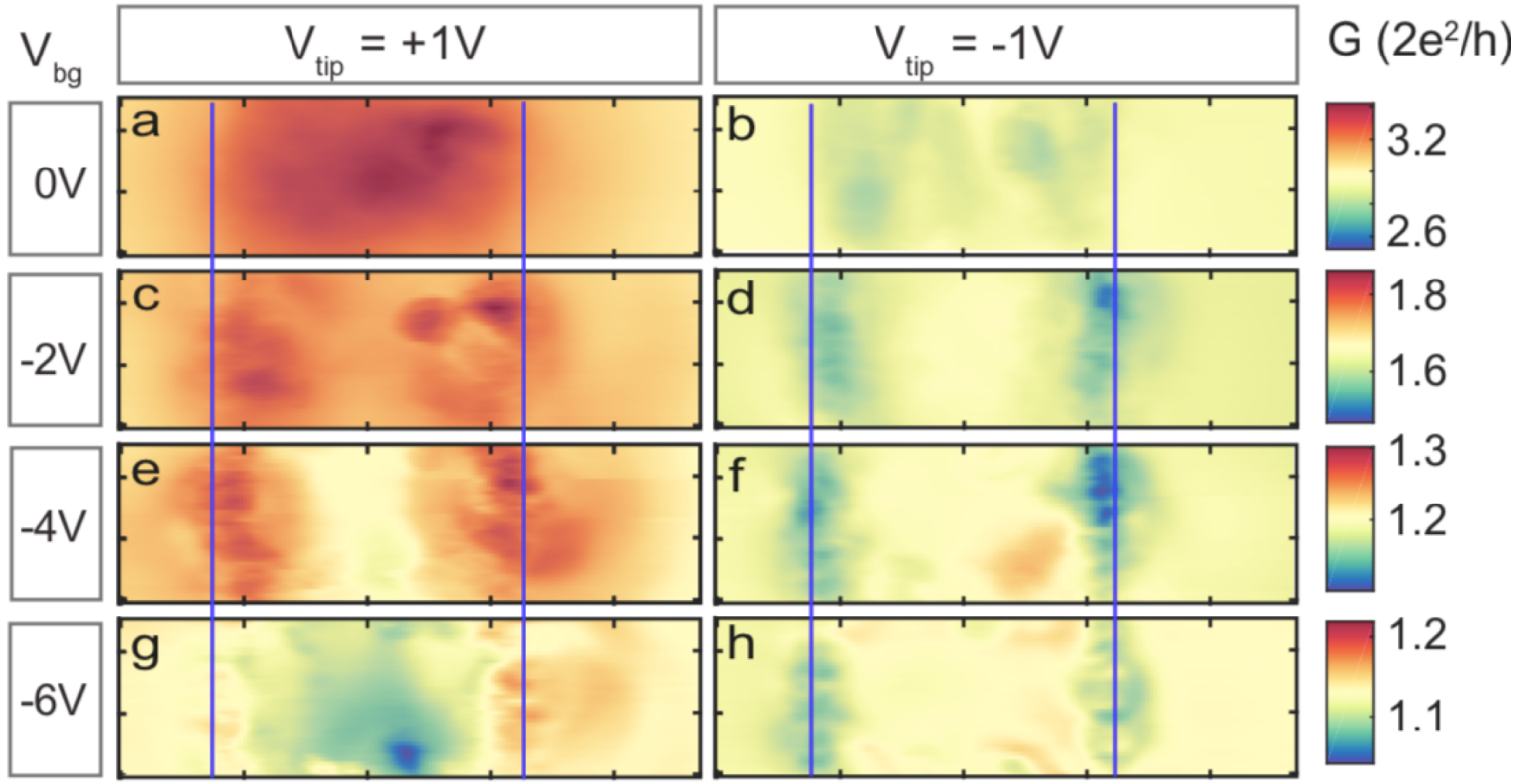




- Similar behavior at the edge for other gate voltage configurations

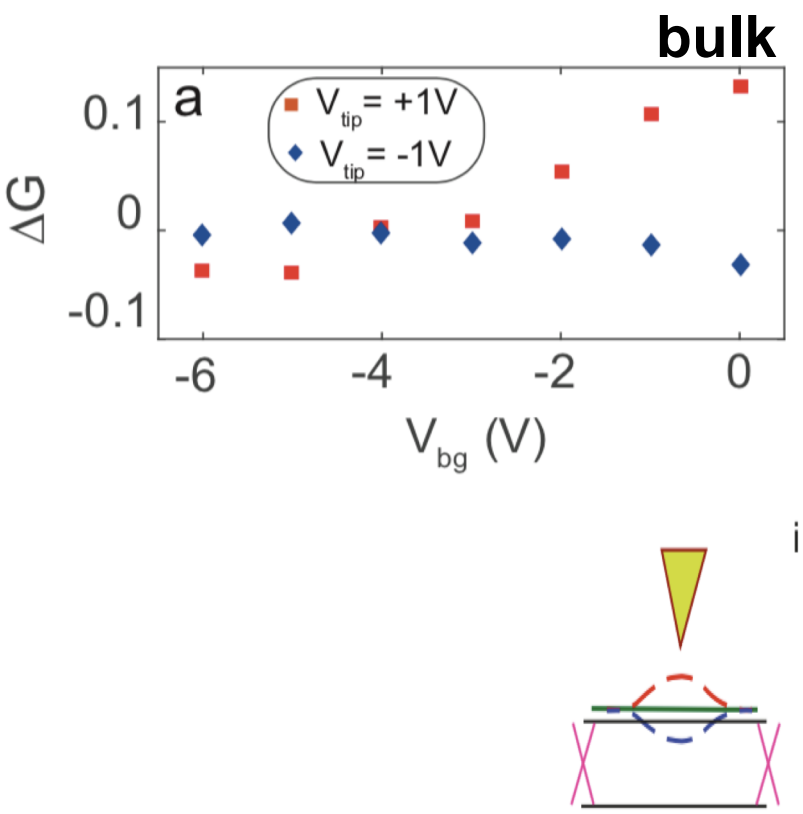
SGM on 2D-TI HgTe quantum wells

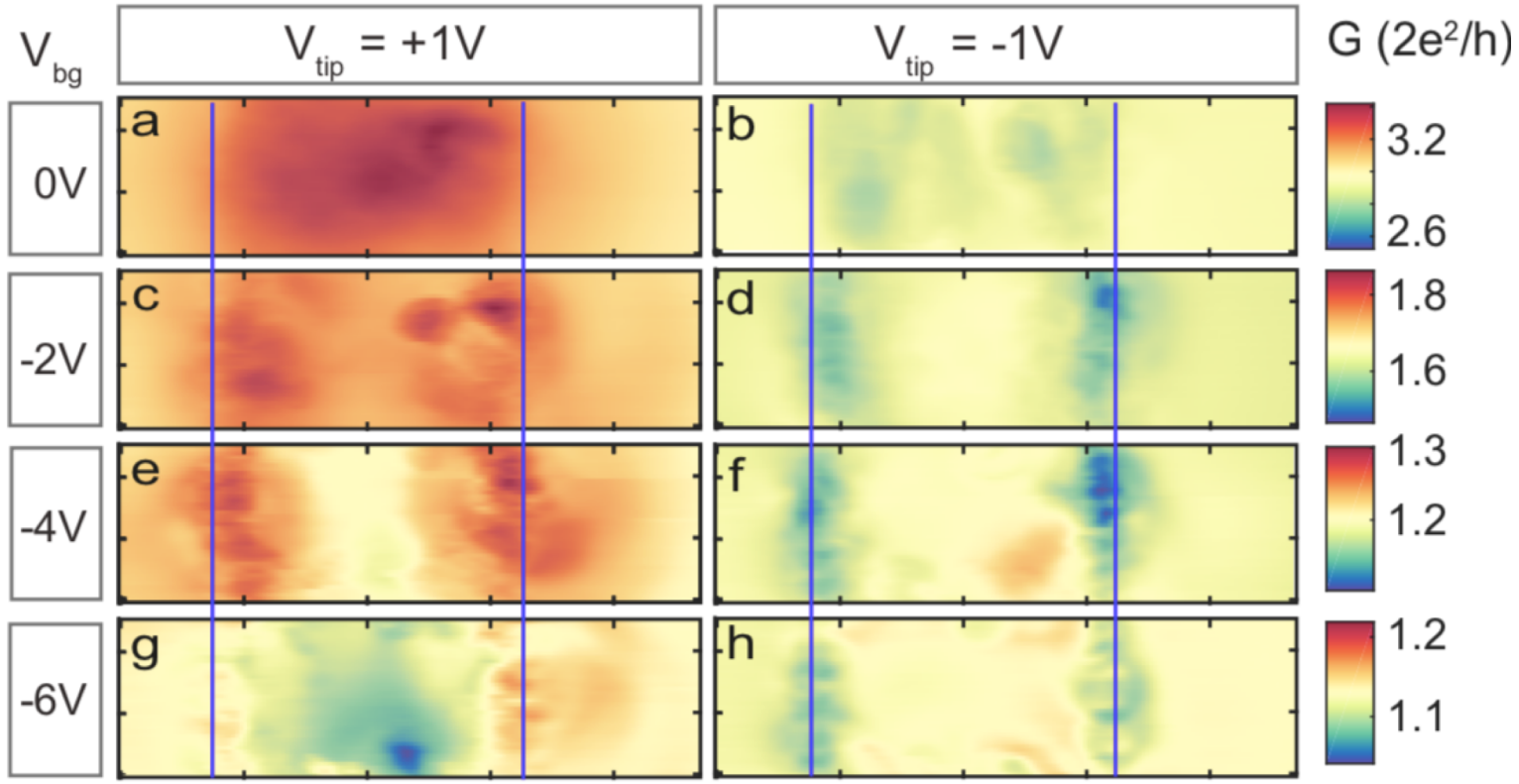




- We observe how the action of a positive tip voltage on conductance changes sign across the gap

SGM on 2D-TI HgTe quantum wells





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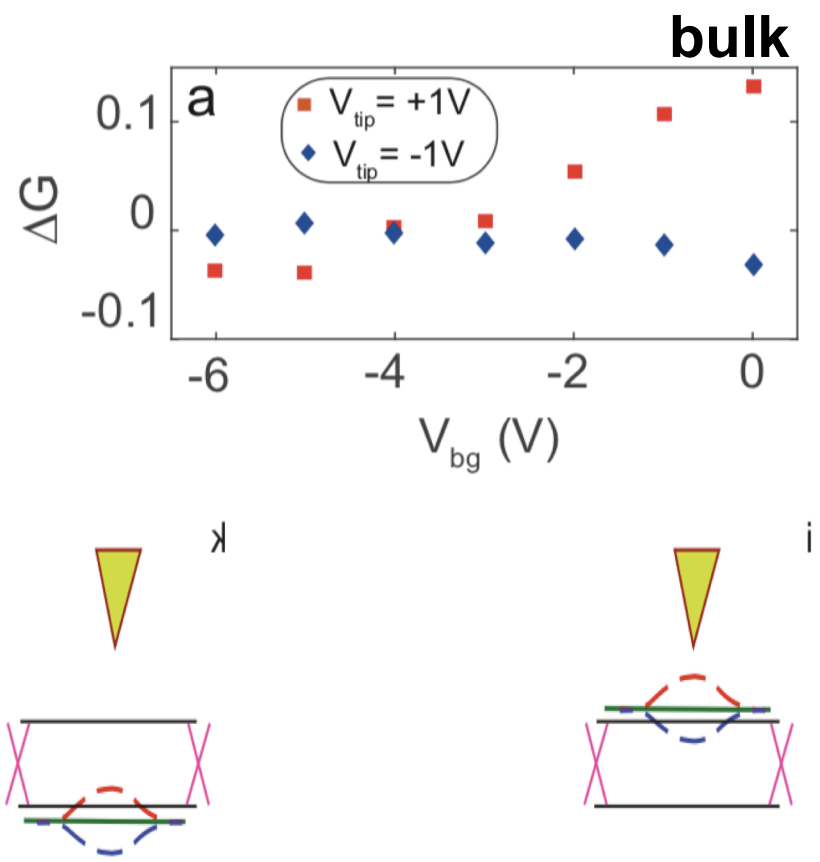

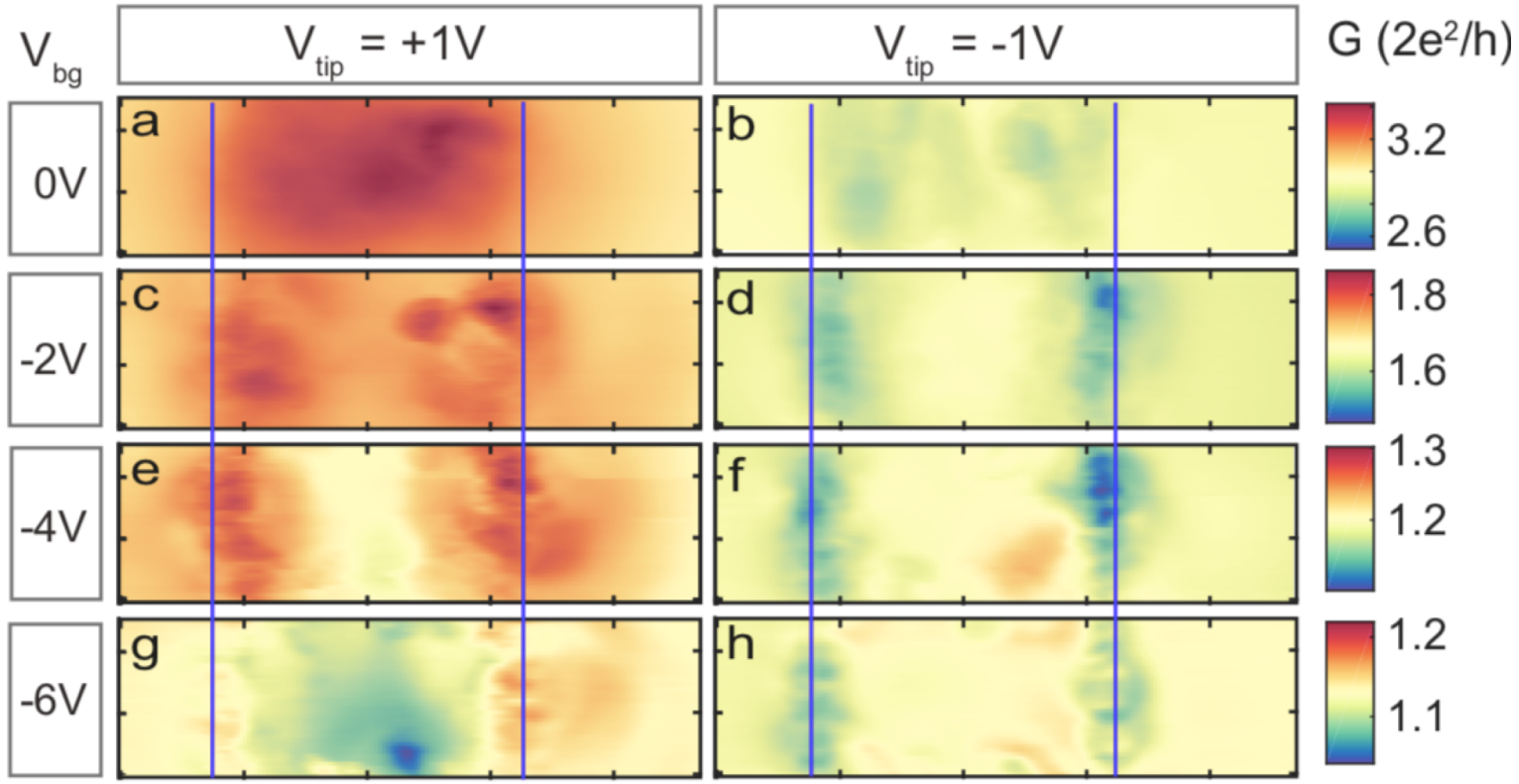

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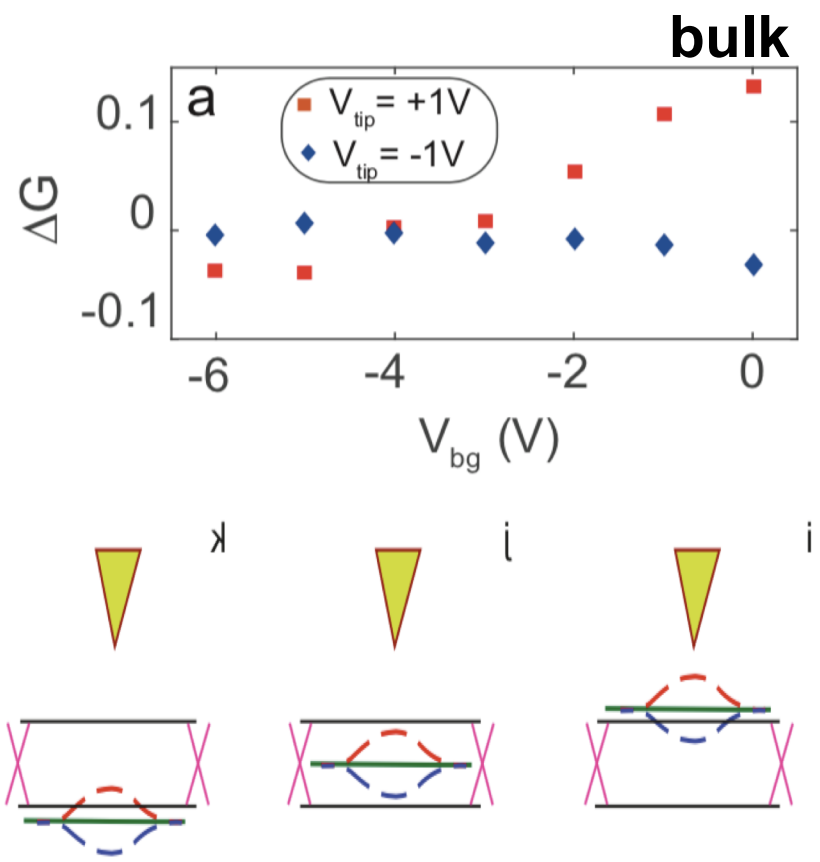
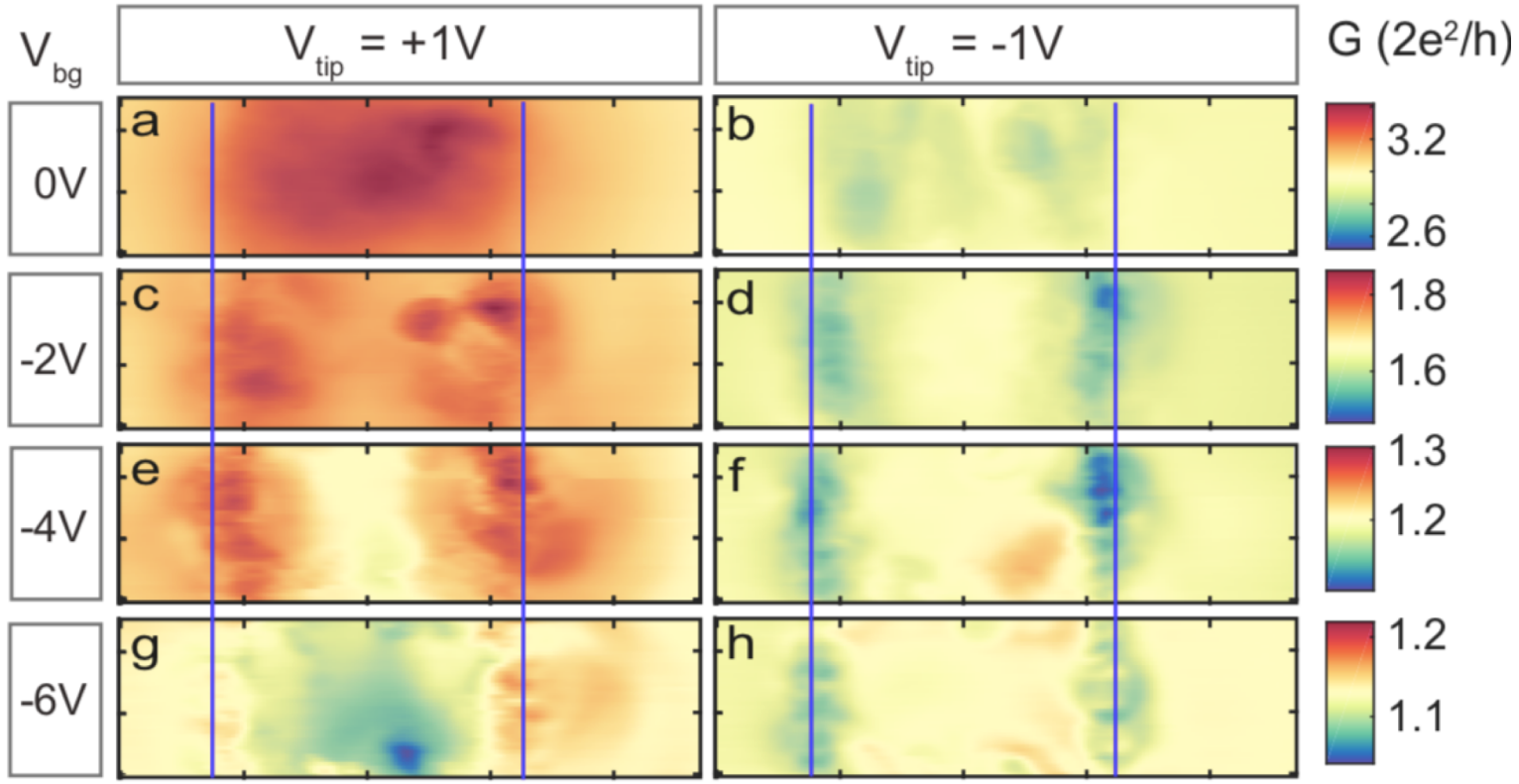
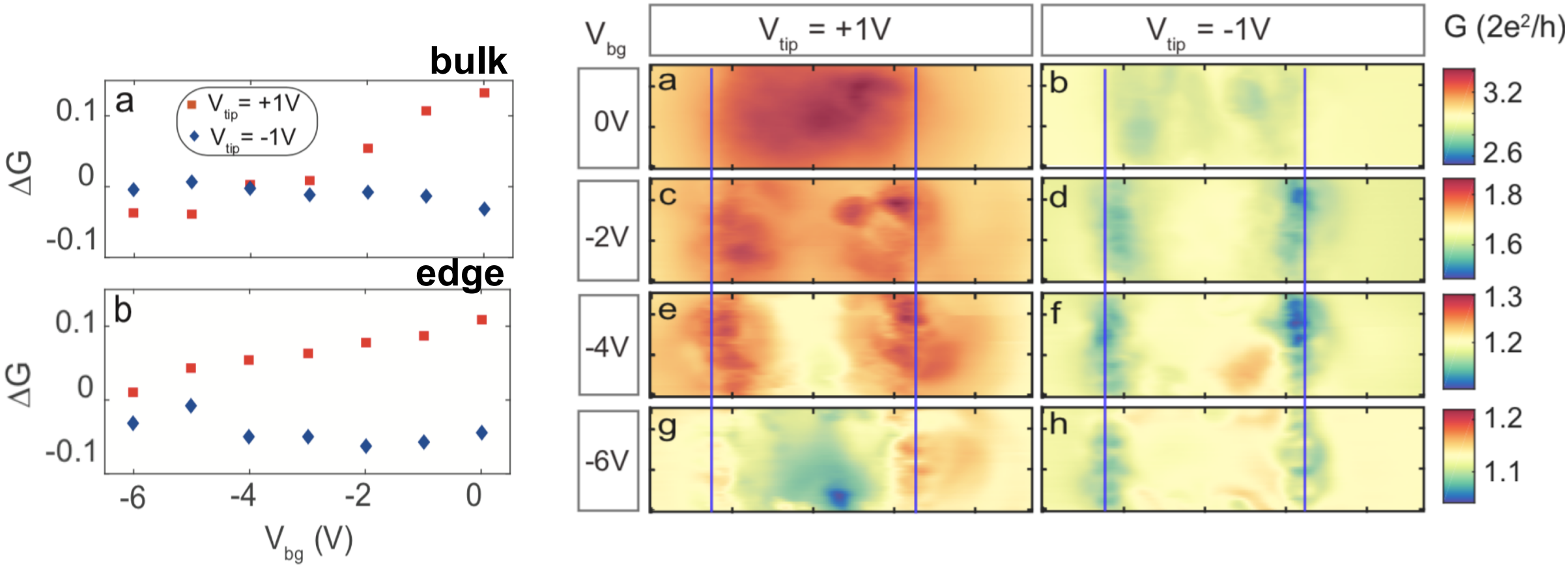




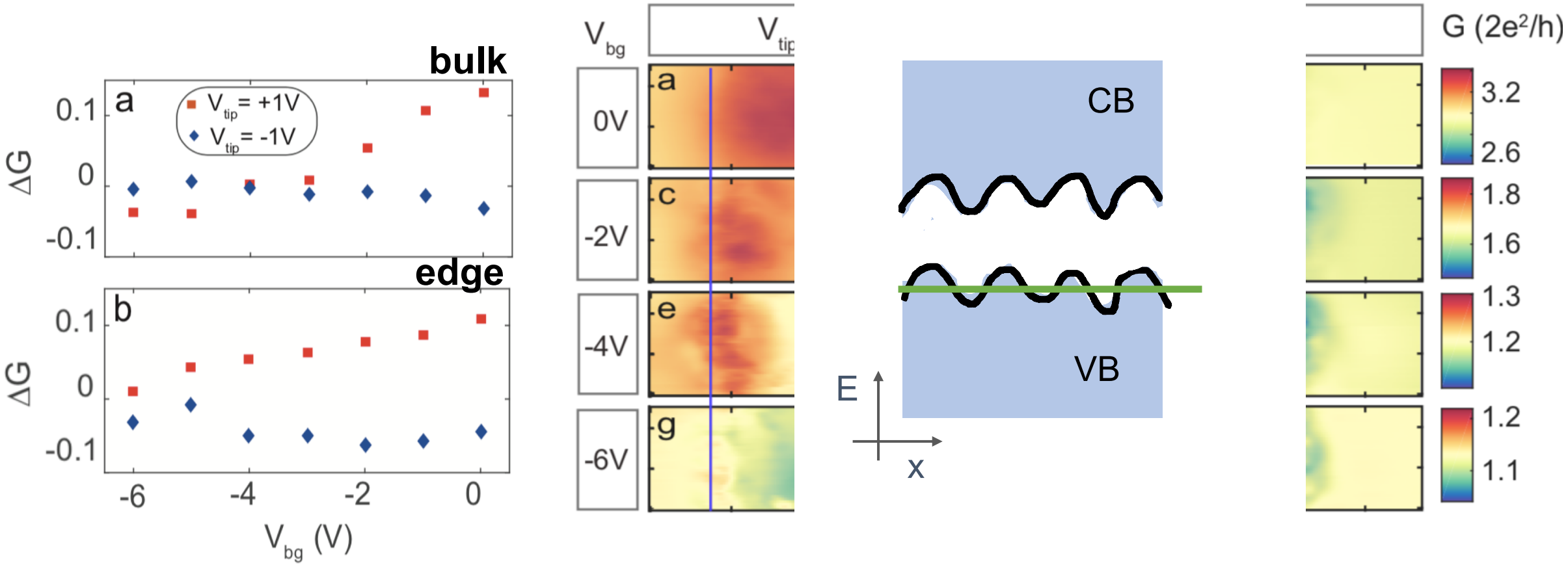
- We observe how the action of a positive tip voltage on conductance changes sign across the gap
- We identify the bulk charge neutrality point
- Conductance > 2e2/h and no sign of bulk conduction

SGM on 2D-TI HgTe quantum wells



- We observe how the action of a positive tip voltage on conductance changes sign across the gap
- A similar change of polarity does not occur for the edges and effect of the tip in conductance when at the edge is larger for V_{bg}>-6V

SGM on 2D-TI HgTe quantum wells



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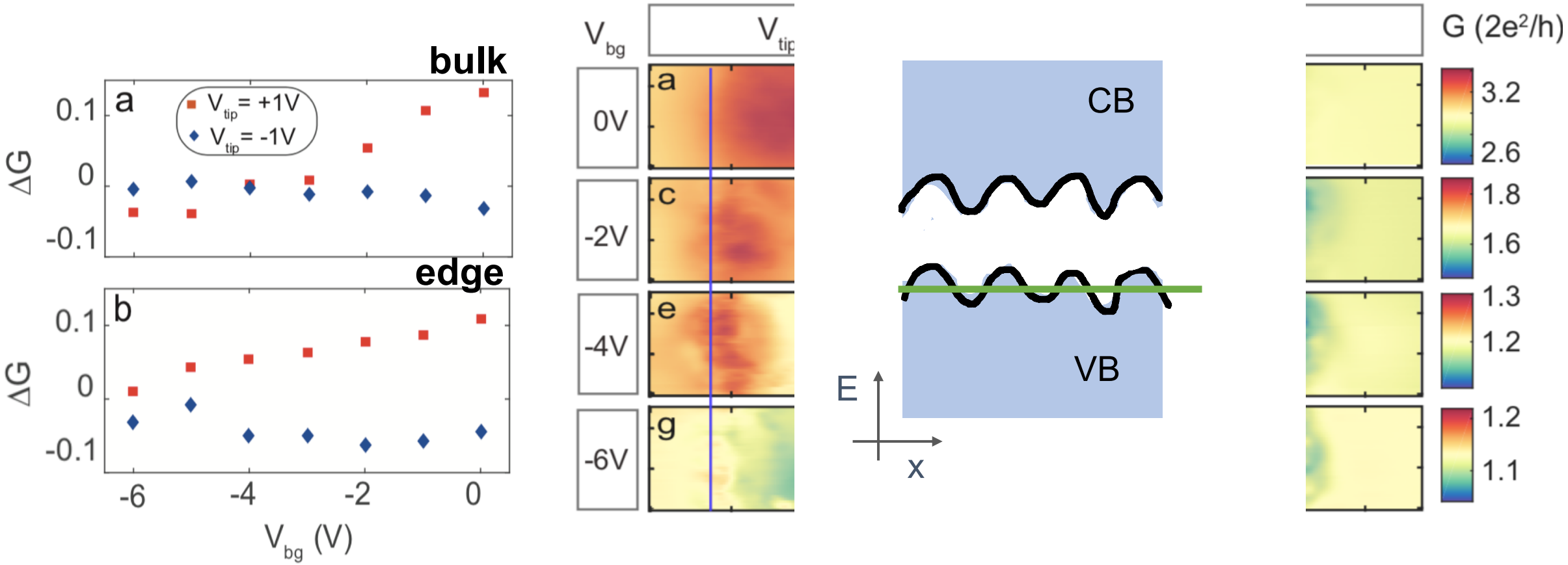
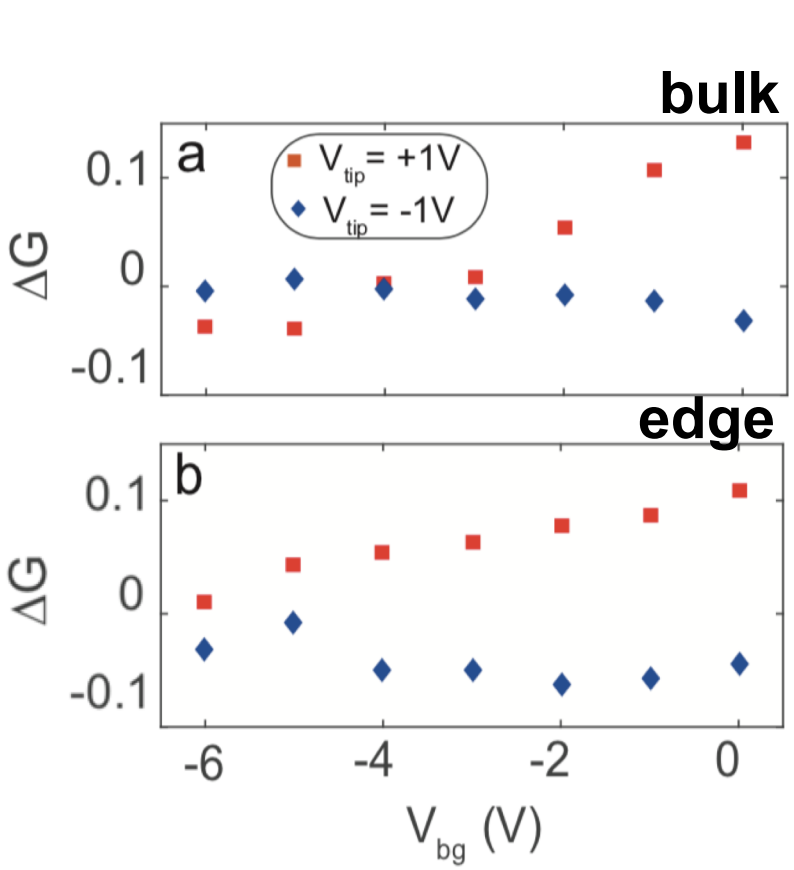
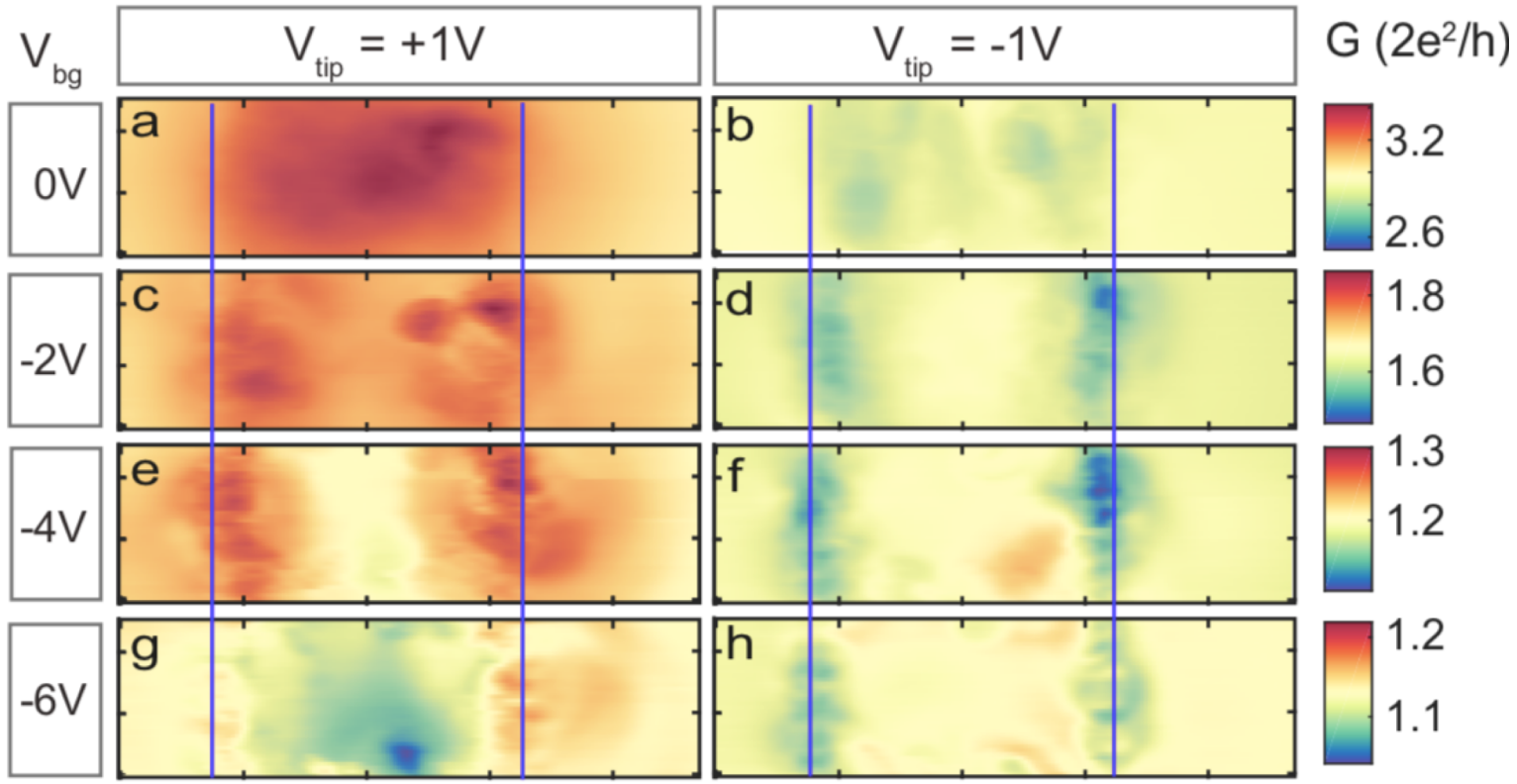


- We observe how the action of a positive tip voltage on conductance changes sign across the gap

- A similar change of polarity does not occur for the edges.
- We cant explain just with a puddle picture, **we need to invoke electrostatics**

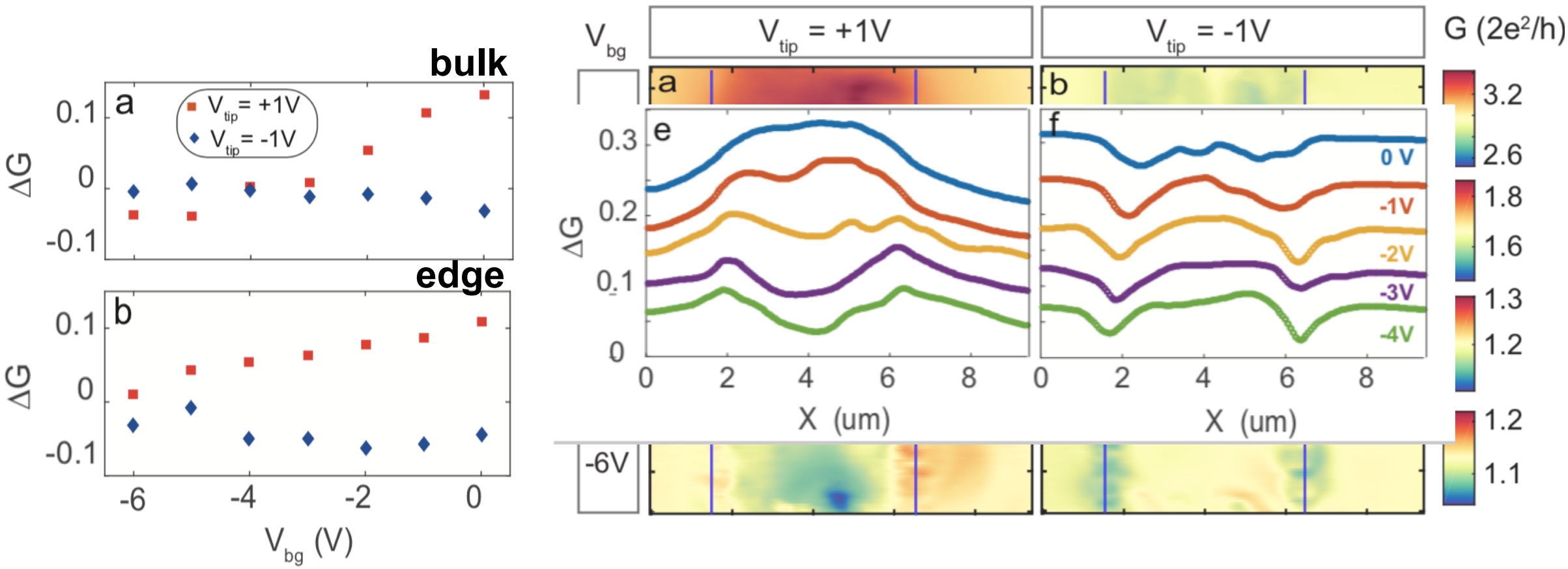
SGM on 2D-TI HgTe quantum wells





- We observe how the action of a positive tip voltage on conductance changes sign across the gap
- A similar change of polarity does not occur for the edges, which we cant explain just with a puddle picture
- We observe an inwards shift of the tunable áreas as n-doping the device

SGM on 2D-TI HgTe quantum wells



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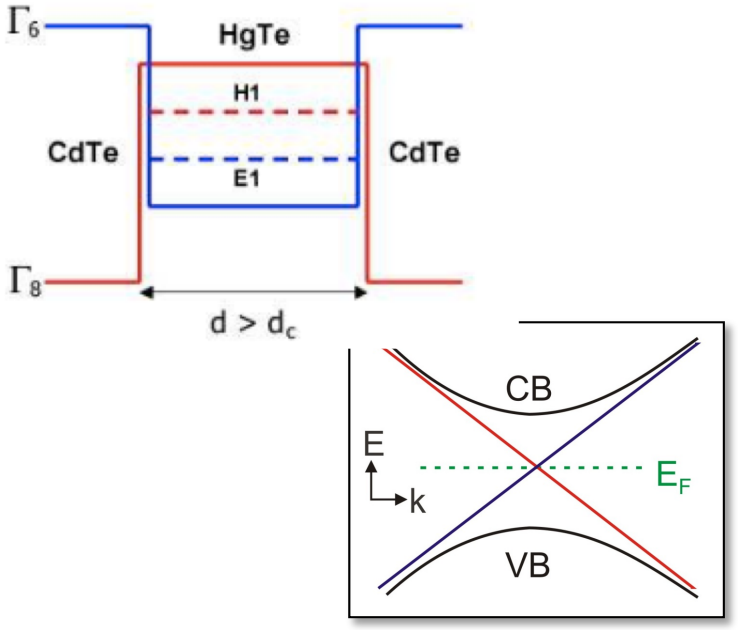
BHZ model

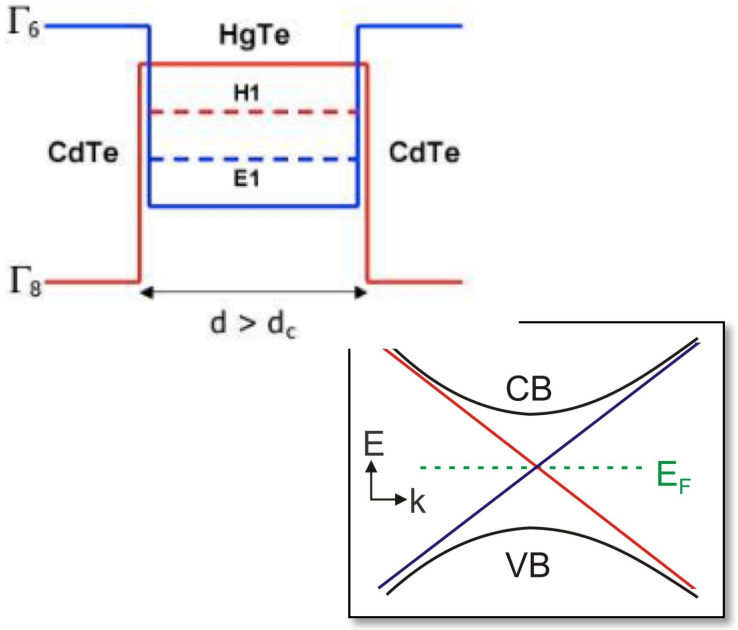
Bernevig et al. *Science*, 314, (2006)



- Dirac crossing center of the gap
- Abrupt topological to trivial transition

BHZ model

Bernevig et al. *Science*, 314, (2006)



- Dirac crossing center of the gap
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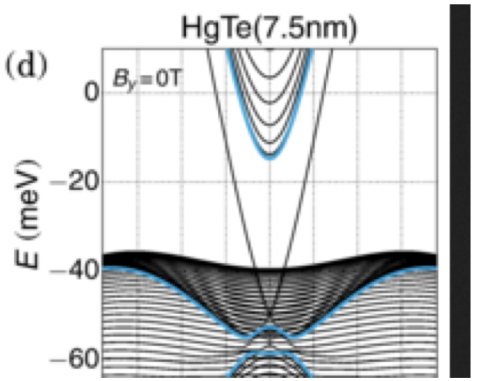
k.p model

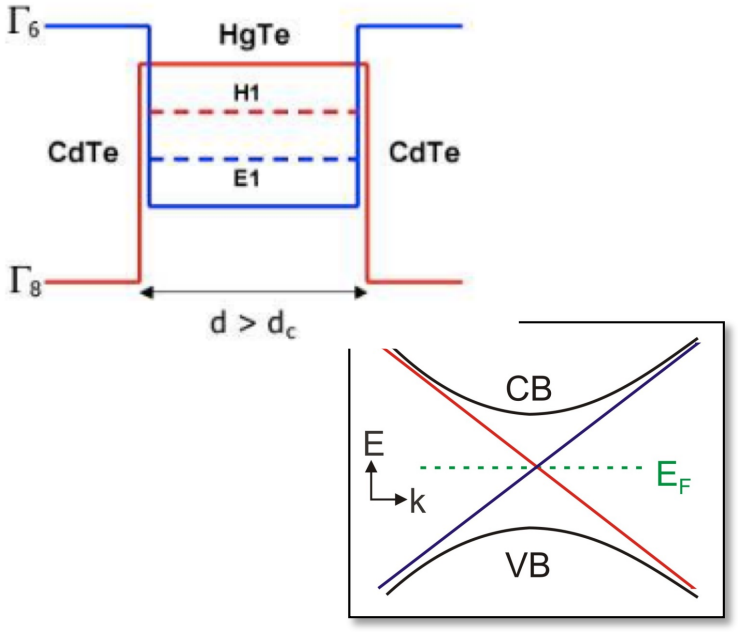
Skolasinski et al. Phys. Rev. B 98 (2018)



- Finite size effects
- Burial of Dirac point
- High DOS, flat valence band

BHZ model

Bernevig et al. *Science*, 314, (2006)



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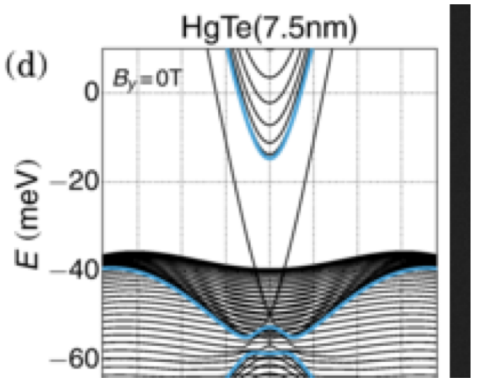
k.p model

Skolasinski et al. Phys. Rev. B 98 (2018)



- Finite size effects
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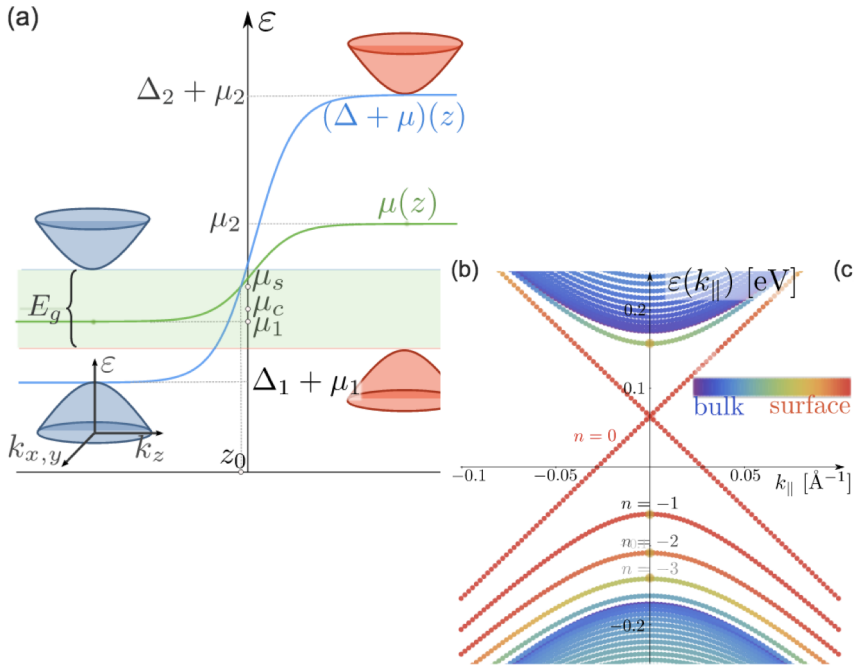
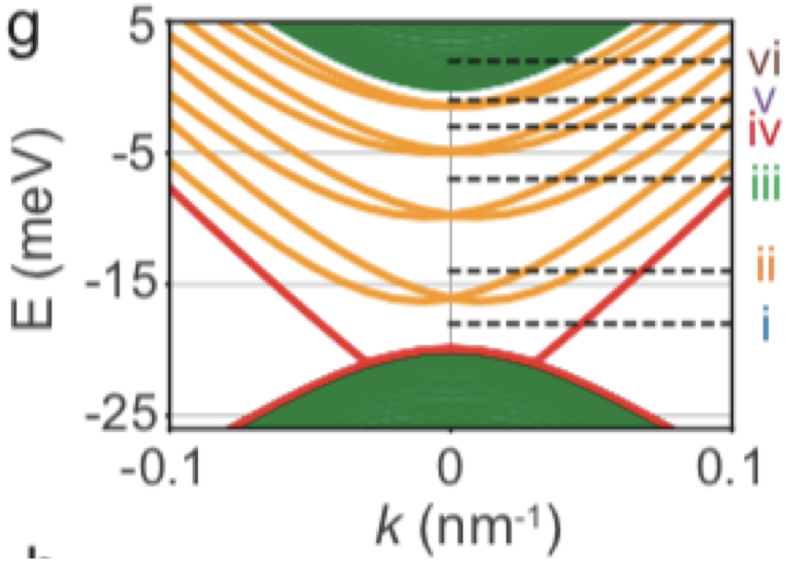
Volkov-Pankratov model

Tchoumakov et al. Phys. Rev. B 96 (2017)

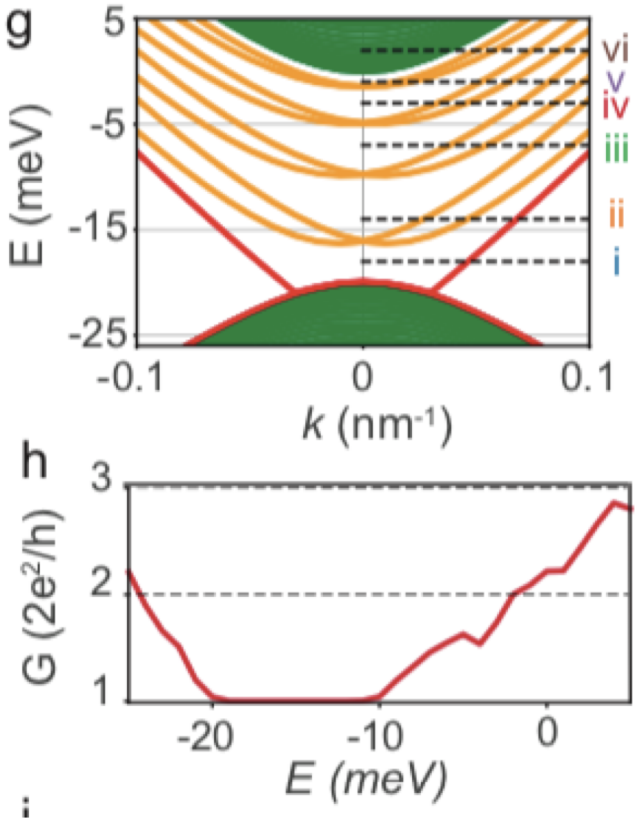


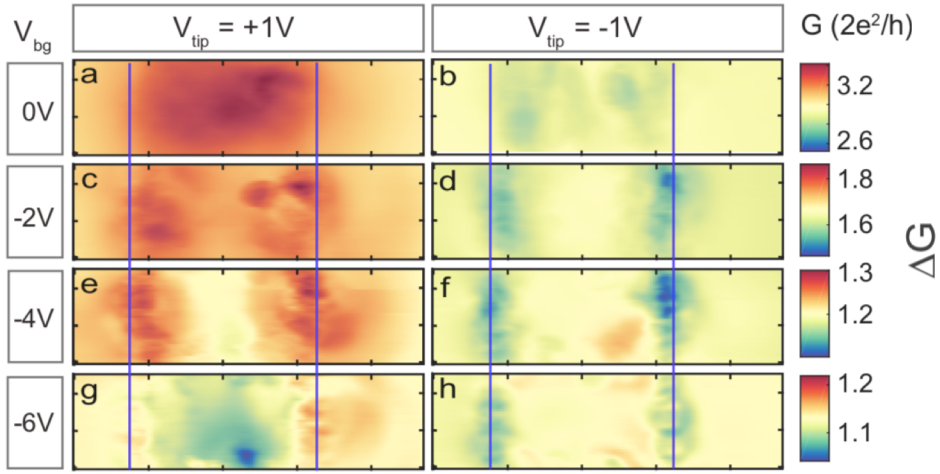
- Smooth topological to trivial transition
- QSH linear + extra V-P parabollic states

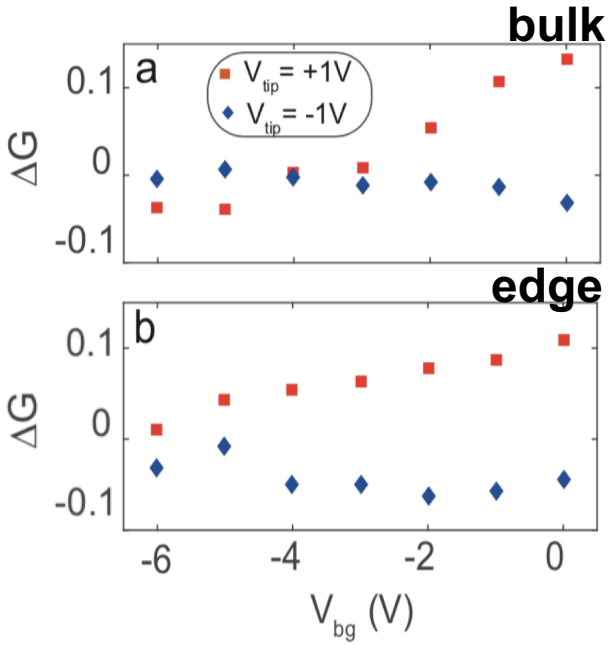
Extra edge states in HgTe quantum wells



Dressed edge states in HgTe quantum wells



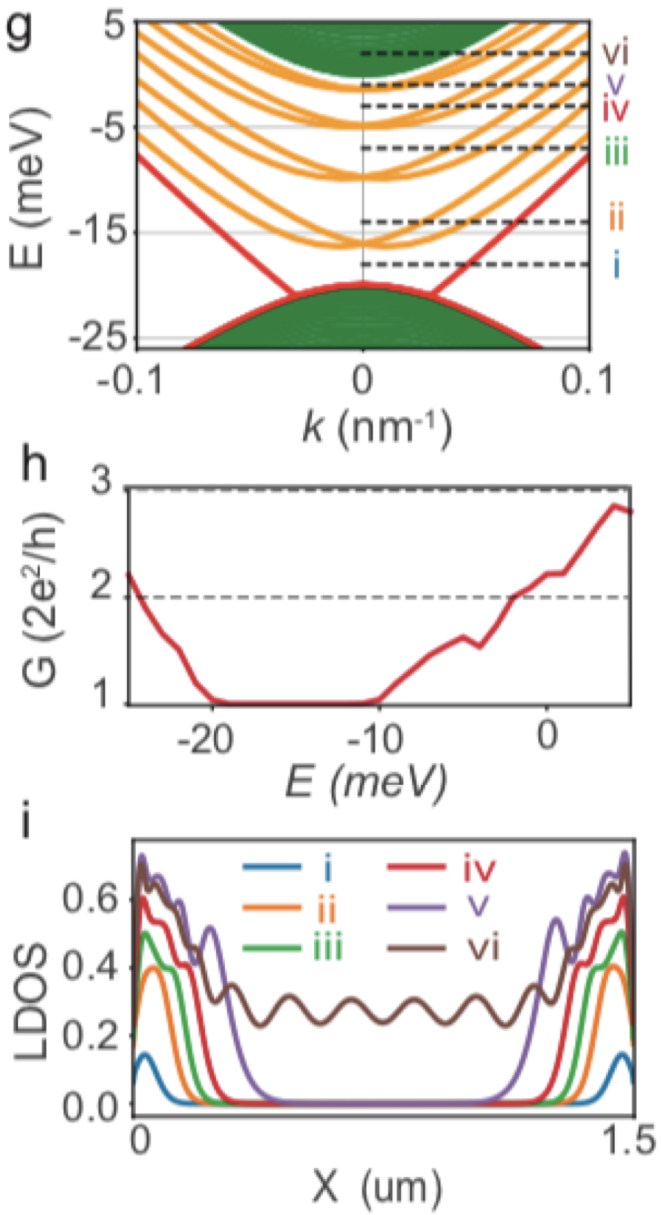


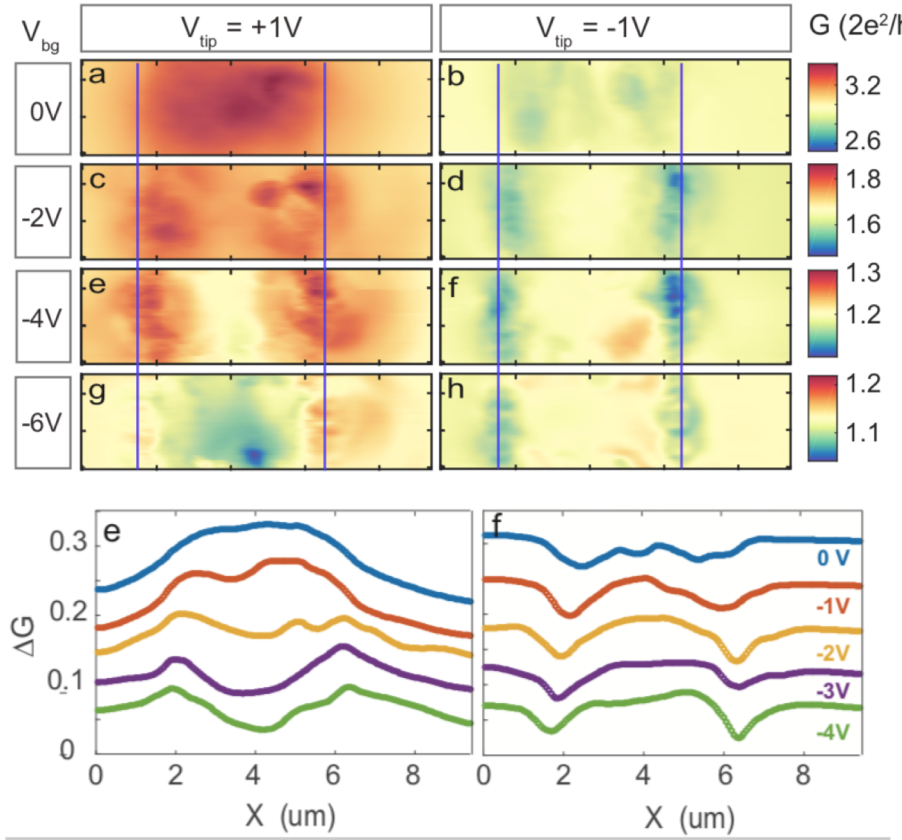


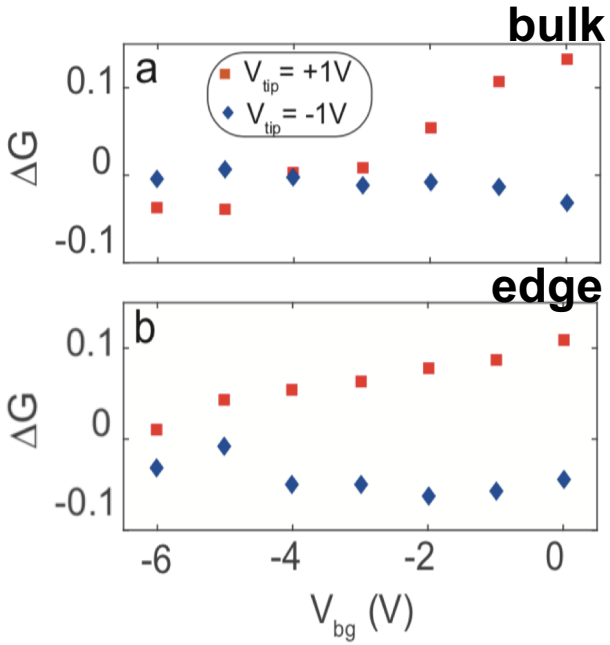
Extra states explain:

- A Higher conductance than 2e2/h due to only edge contributions
- N-doped like behavior of the edges, and stronger effect of the tip for V_{bg}>-6V

Dressed edge states in HgTe quantum wells

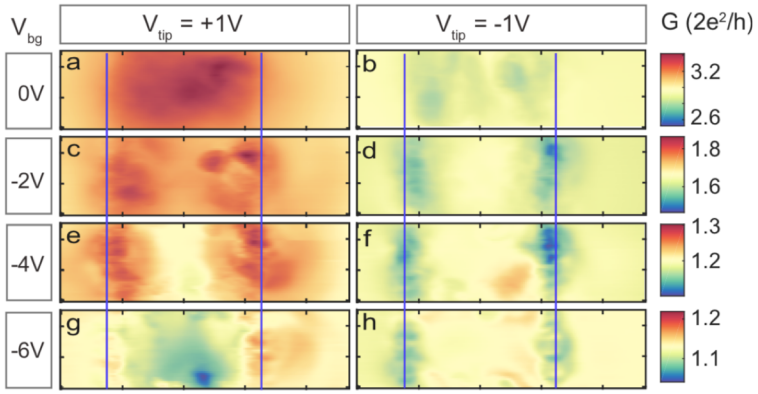


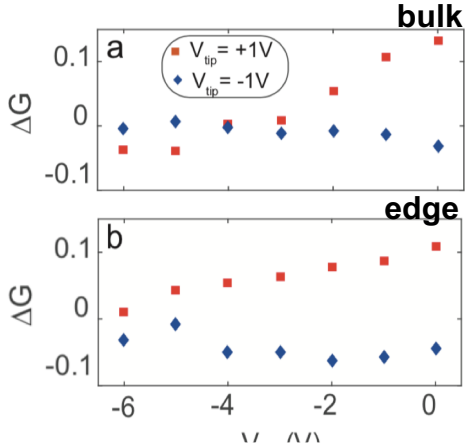


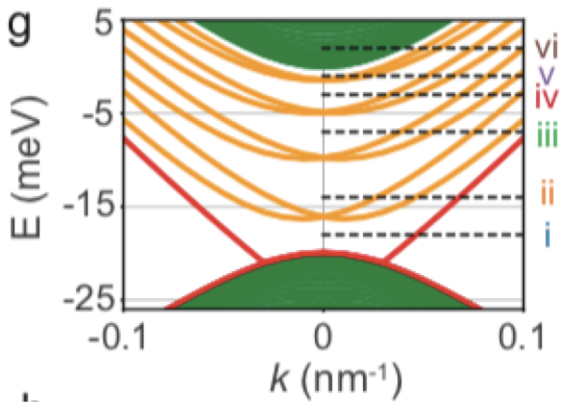


Extra states explain:

- A Higher conductance than 2e2/h due to only edge contributions
- N-doped like behavior of the edges, and stronger effect of the tip for V_{bg}>-6V
- Inwards evolution of the tunable areas







- SGM maps reveal a distinct behavior of edge versus bulk response to the action of the tip. Edge behavior resembles the n-doped bulk.

- Our results can be explained by a minimal model accounting for both disorder and <u>electrostatics on the QSH picture</u>.

- A modulation of the electrostatic landscape towards the egde results in extra states at the edge that justifies our observations and could lie behind other observed phenomenology:

  - Unexpected edge conduction under strong magnetic field (Ma et al. Nat Comms. 2017)
  - Unexpected behavior of edge resistance with temperature (P. Leubner thesis, unpublished)
  - Higher conductance for short devices usually atributed to bulk states? (Calvo et al. PRL 2018)
  - **RF Capacitance measurements: dressed edge states.**
    See next talk by Alexandre Gourmelon!
    Dartiailh et al. arXiv:1903.12391

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