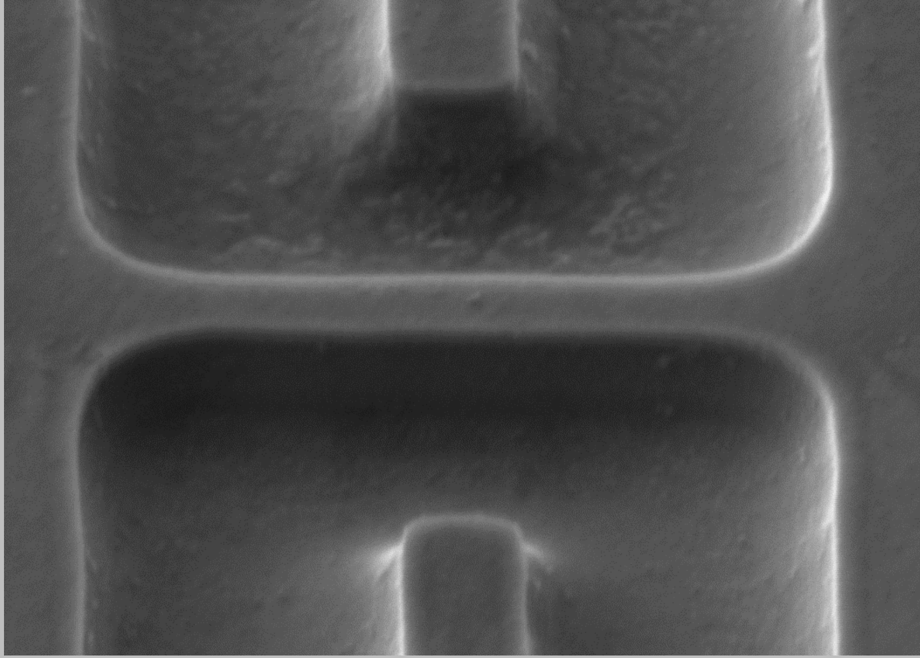


Transport in mesoscopic topological insulators: Antidot lattices and nanowires made from strained 3D HgTe

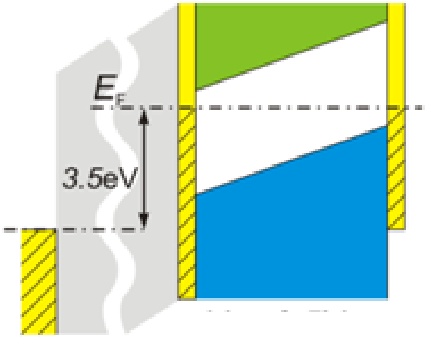
Dieter Weiss

Universität Regensburg

Outline

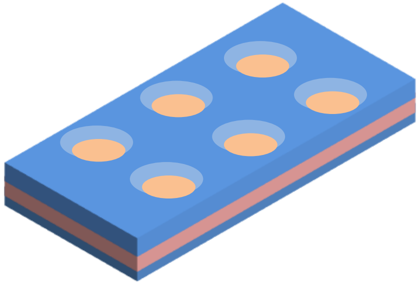
- Brief reminder

  Transport and capacitance measurements



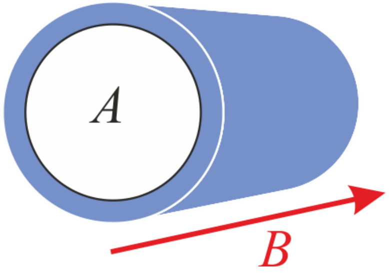
- Transport in antidot arrays

  Resonances probe directly k_F and confirm topological nature of surface states

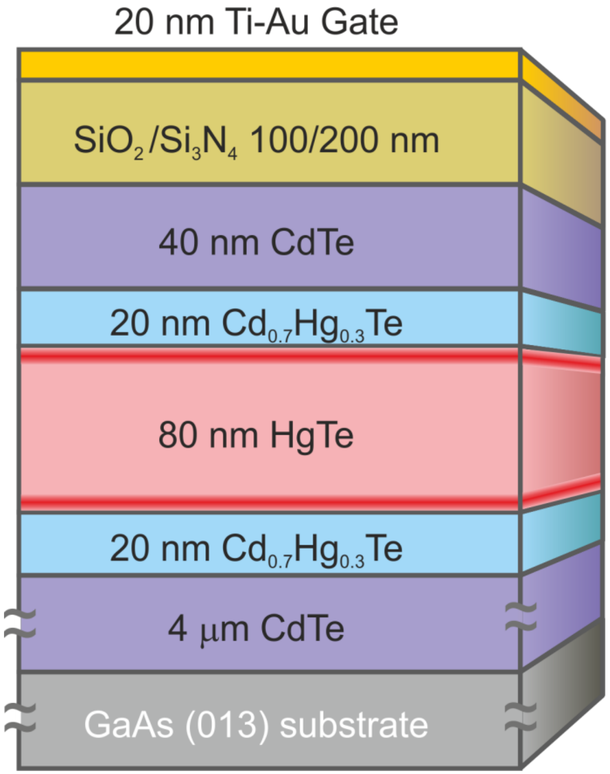


- TI nanowires

  Confirmation of topological surface states ⇨ Promising system to search for Majorana bound states

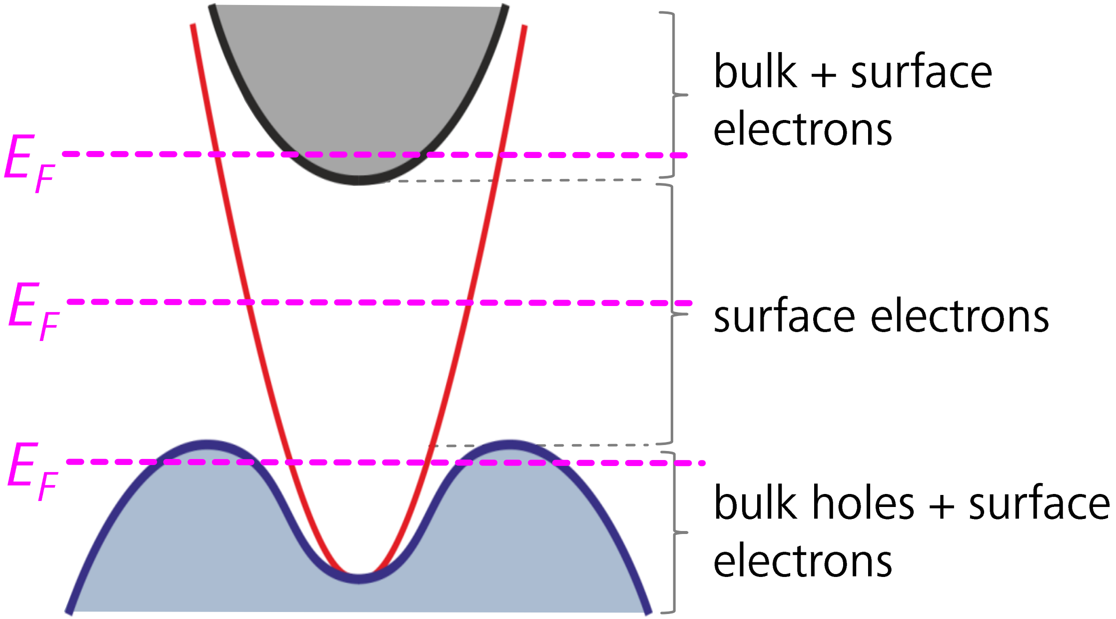


Devices



HgTe tensile strained

schematic band structure



high mobility: up to $4\cdot10^5$ cm^2/Vs

HgTe material:

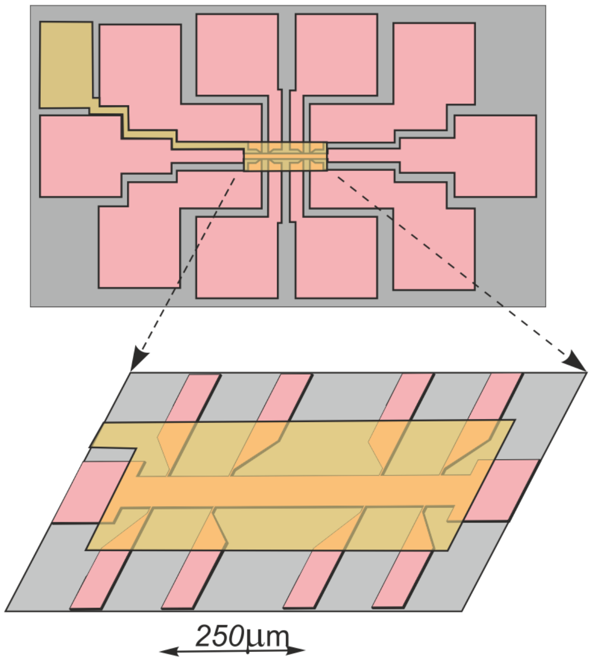
Nikolai Mikhailov, Sergey Dvoretsky, Novosibirsk

See Supplemental Material to Kozlov et al. I

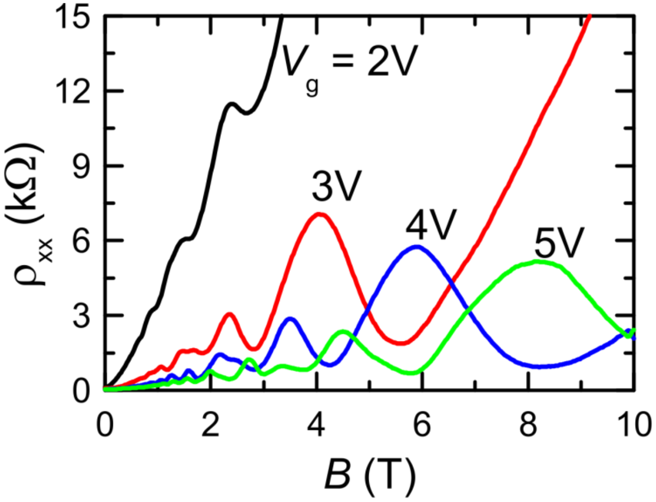
Transport and (magneto-)capacitance experiments

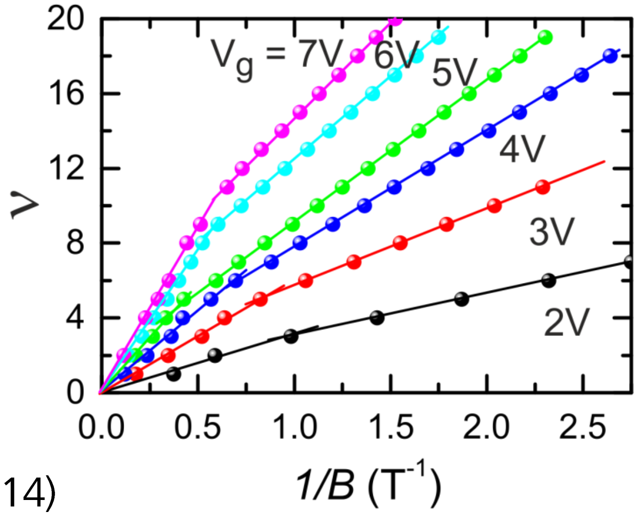
Sample Layout

Top view

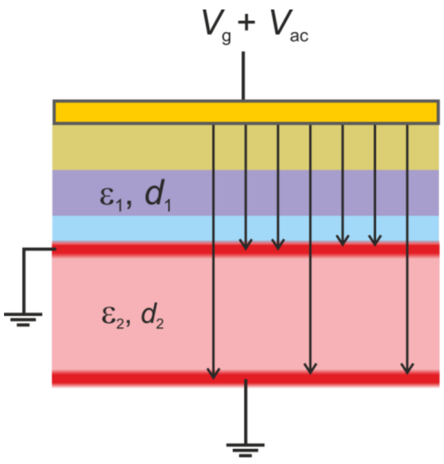


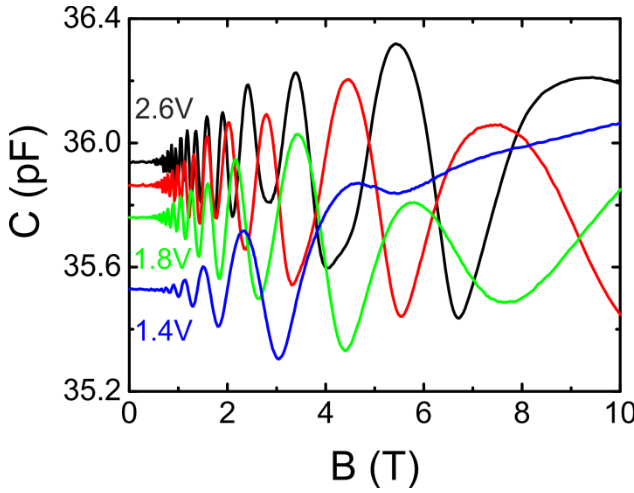
Transport





Capacitance



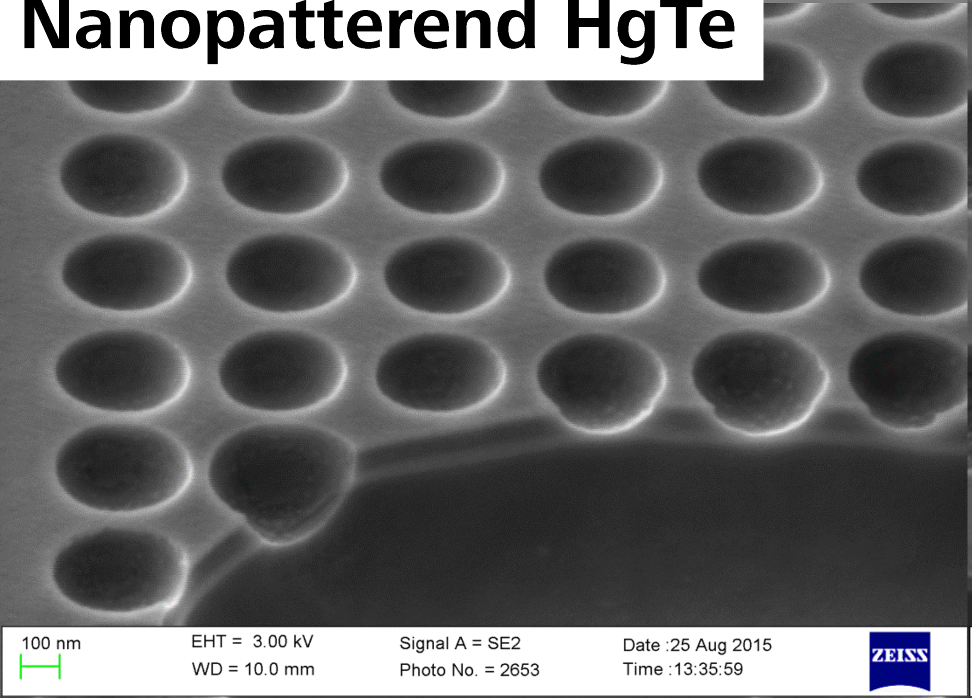


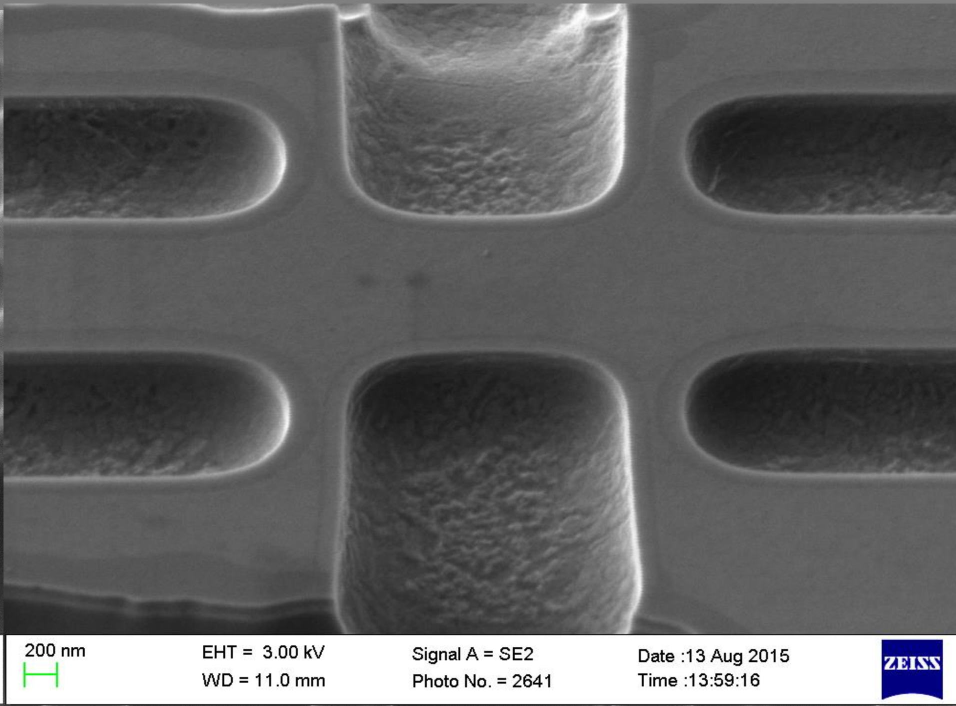
More:

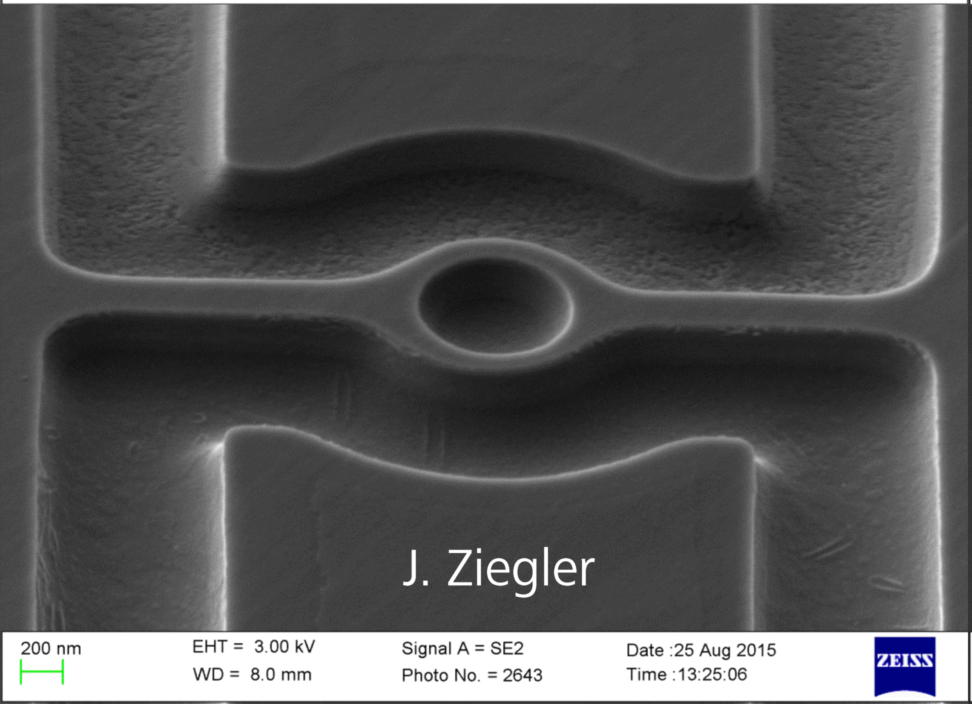
Kozlov et al. PRL **112**,196801 (2014)

Kozlov et al. PRL **116**, 166802 (2016)

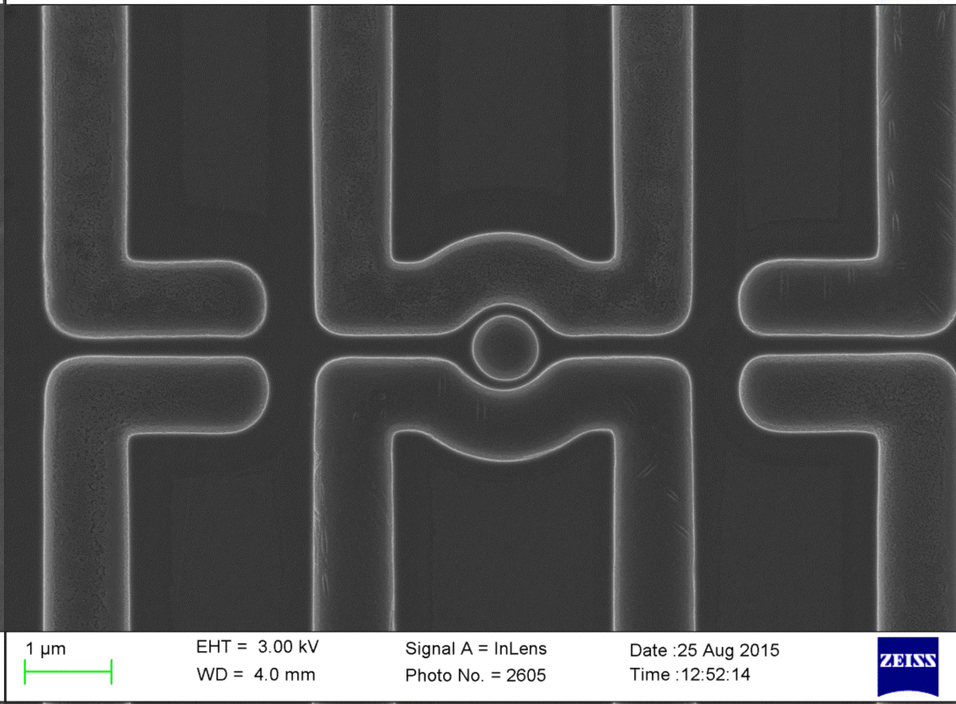
Nanopatterend HgTe



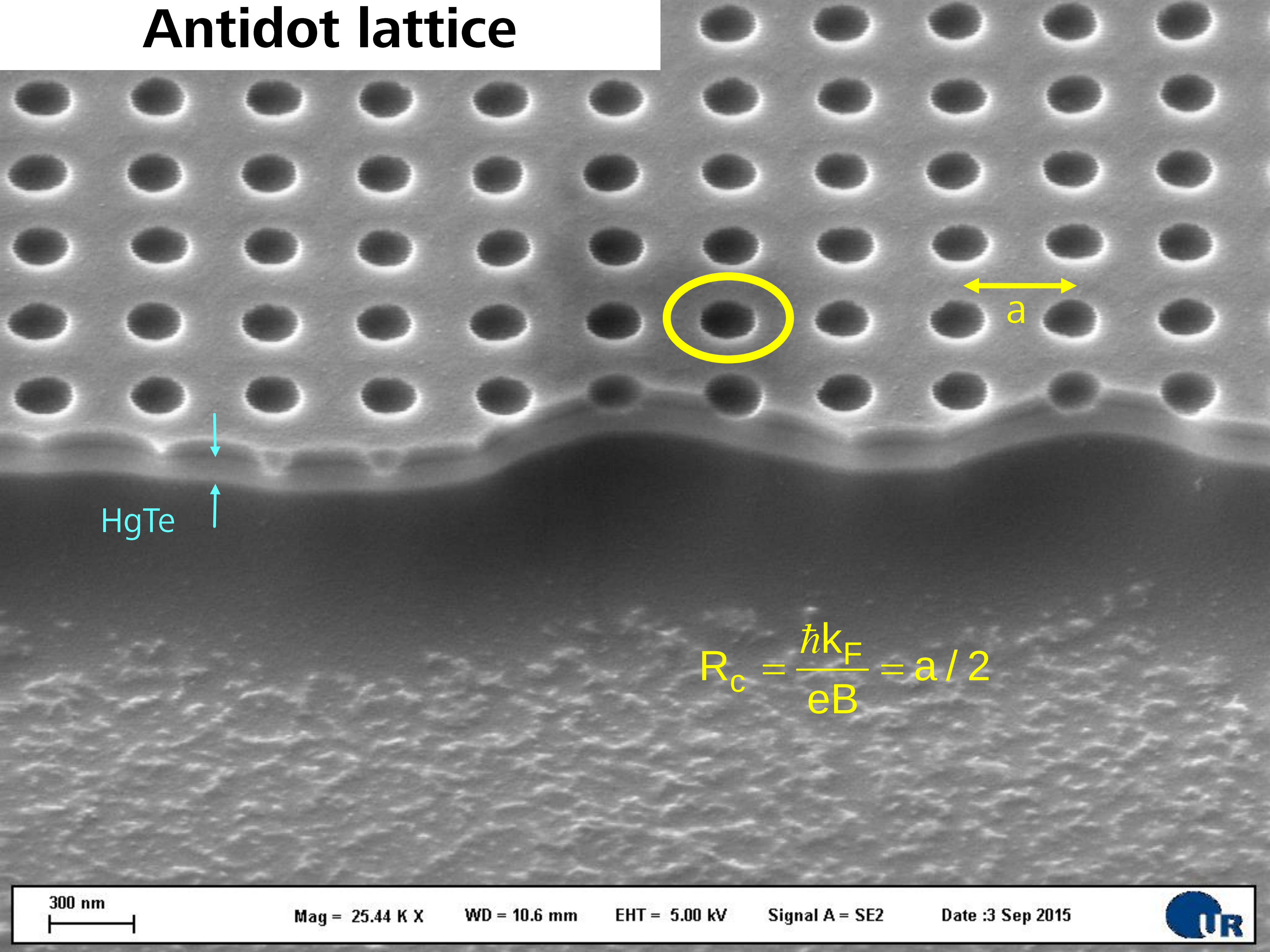




J. Ziegler



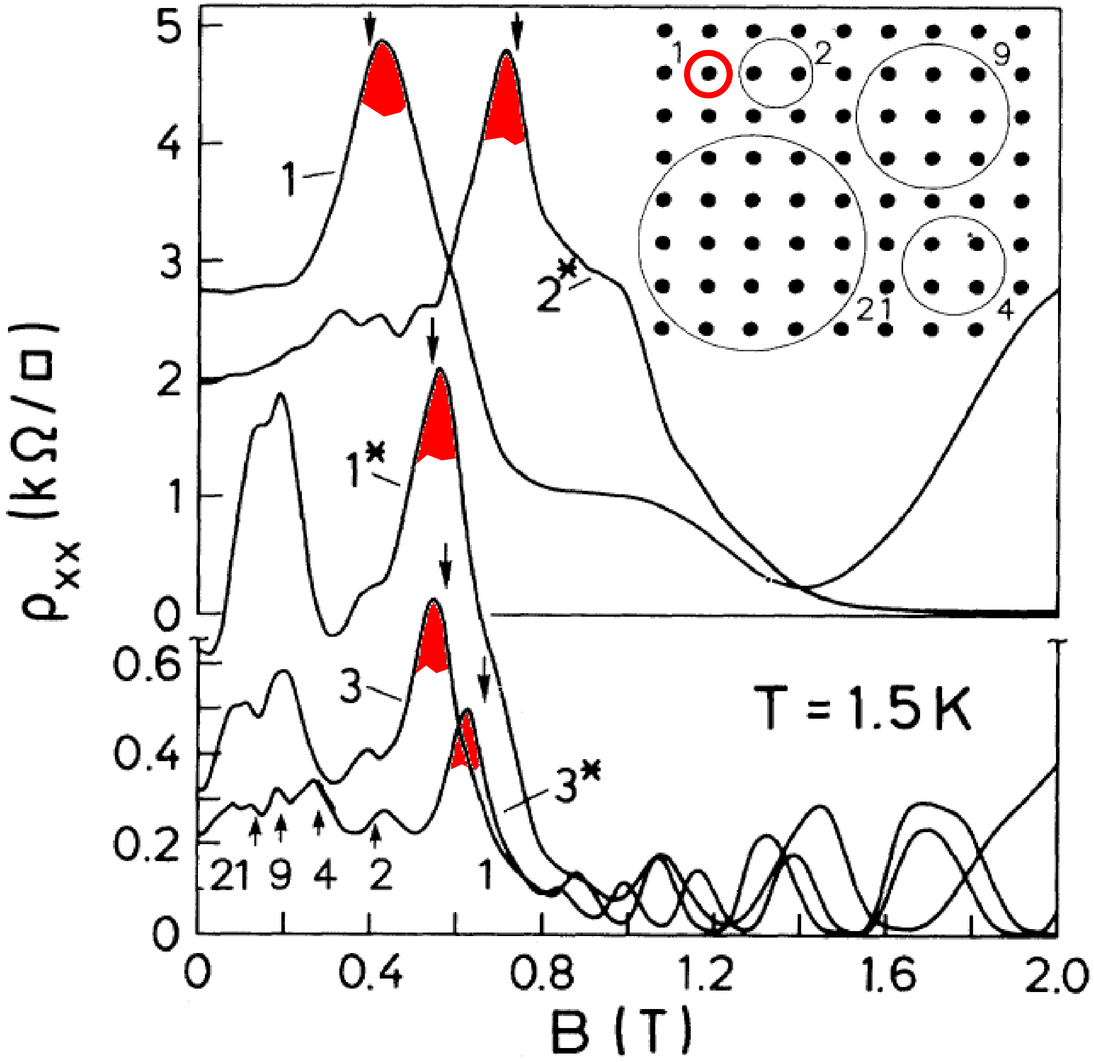
Antidot lattice



$$R_c = \frac{\hbar k_F}{eB} = a/2$$

Geometric resonances in an antidot lattice *

*periodic array of holes punched through 2DES



Mean free path >> a

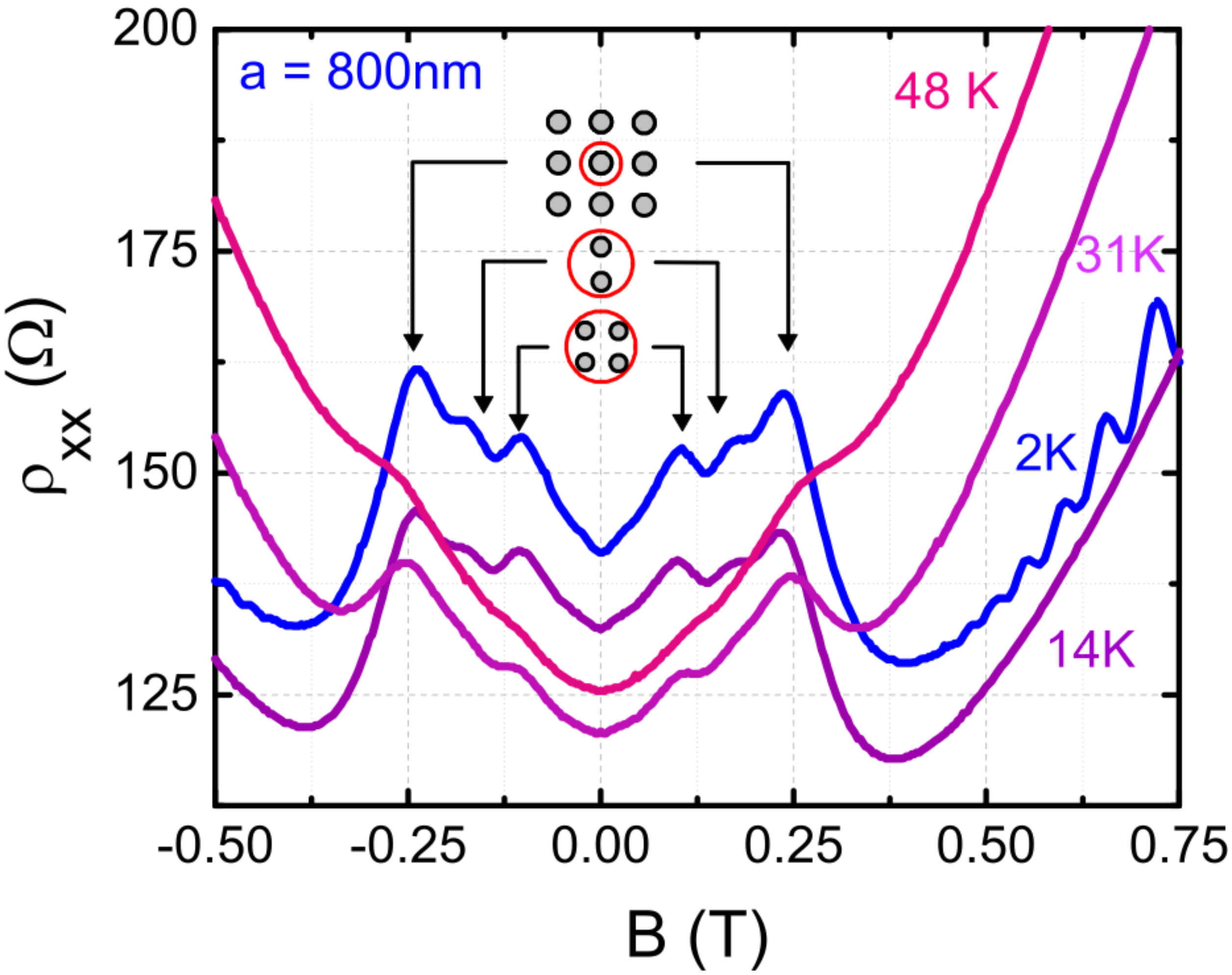
Resistance peaks whenever cyclotron orbit R_C can orbit around group of antidots

Fundamental peak at $2R_c = a$

$$R_c = \frac{\hbar\sqrt{2\pi n_s}}{eB}$$

D. Weiss, M.L. Roukes et al., Phys. Rev. Lett. **66**, 2790 (1991)

Antidot resonances in HgTe – T dependence

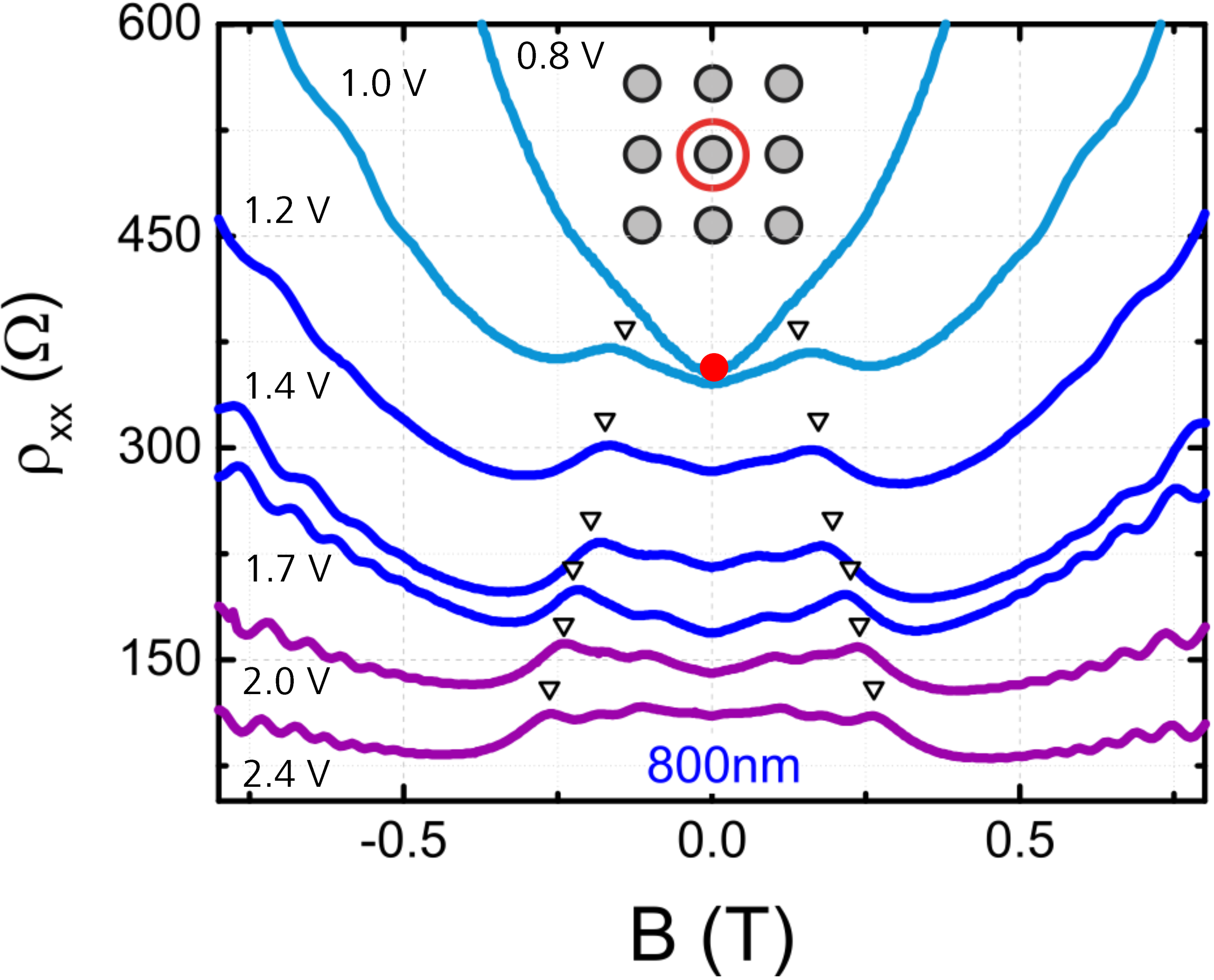


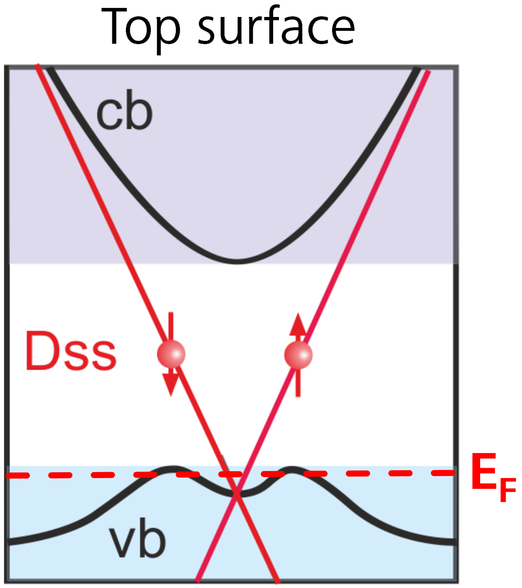
H. Maier et al.
Nature Commun. **8**, 2023 (2017)

Peak positions calculated from: $R_c = 0.5a$ ◎ 0.8a ⦂ 1.14a ⸬ ; $R_c = \frac{\hbar\sqrt{4\pi n_s}}{eB}$

Antidot resonances – n_s dependence

from capacitance oscillations





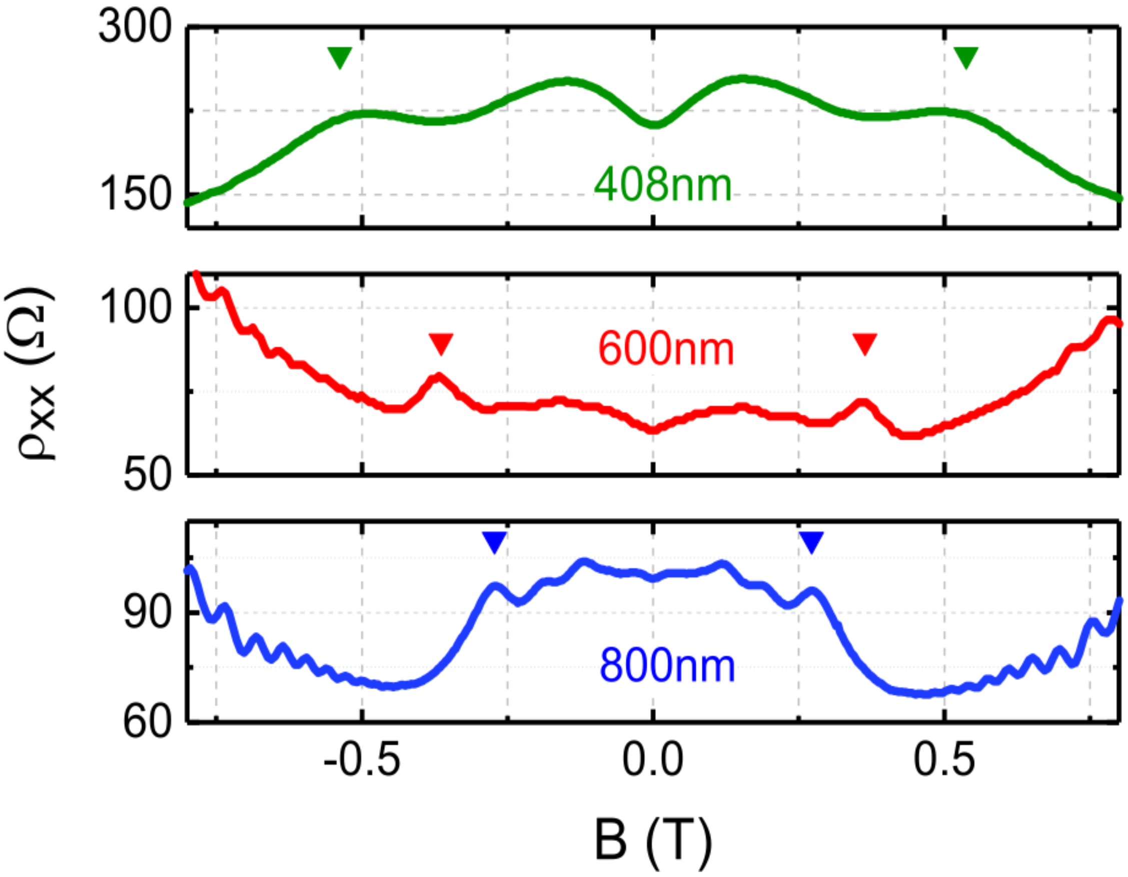
▽ $2R_c = a$
(calculated)

H. Maier et al., *Nature Commun.* **8**, 2023 (2017)

Antidot resonances – ‘a’ dependence

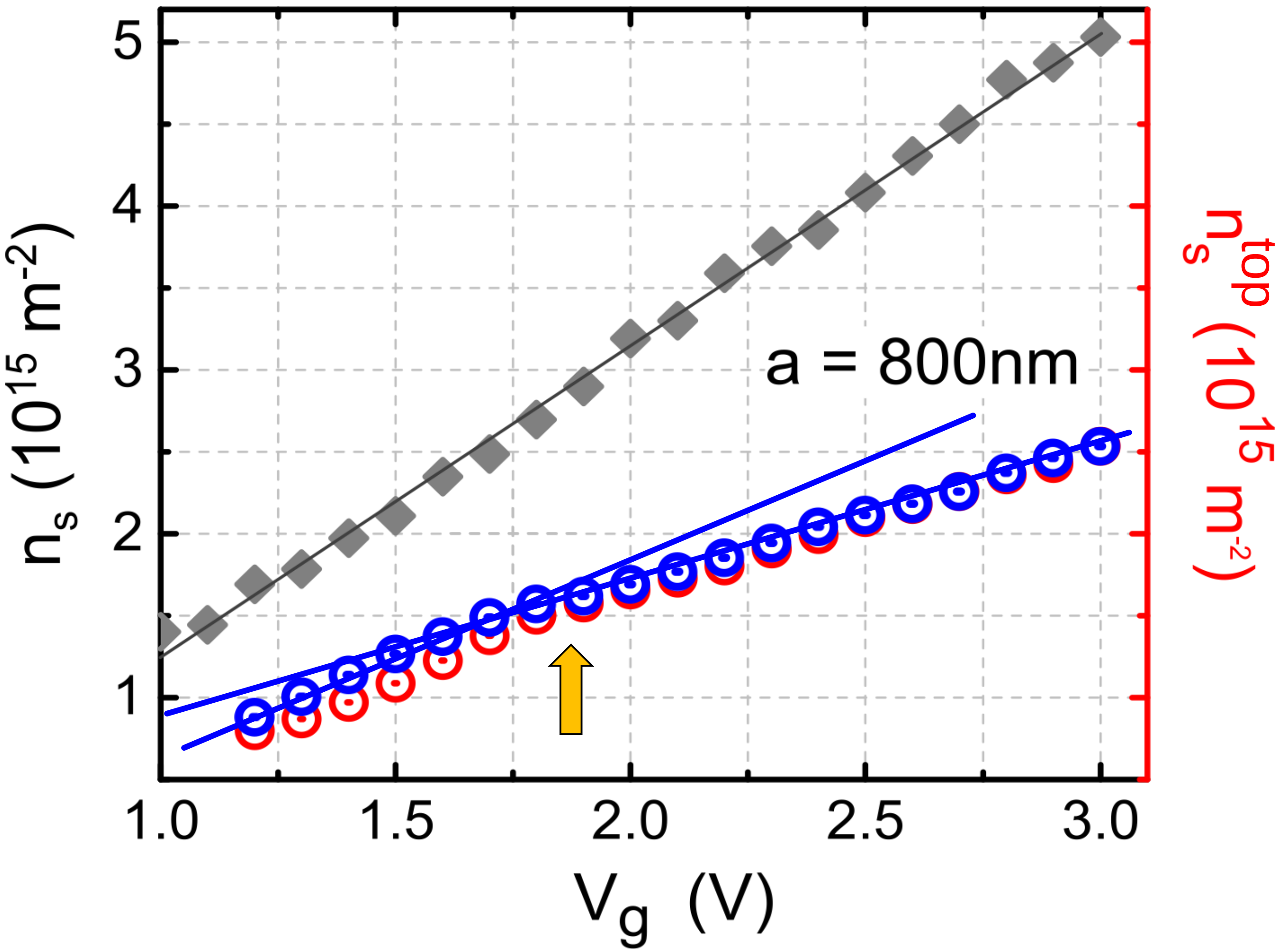
Arrow positions calculated from: $R_c = 0.5a$ ◉ ; $R_c = \frac{\hbar\sqrt{4\pi n_s}}{eB}$

from capacitance oscillations



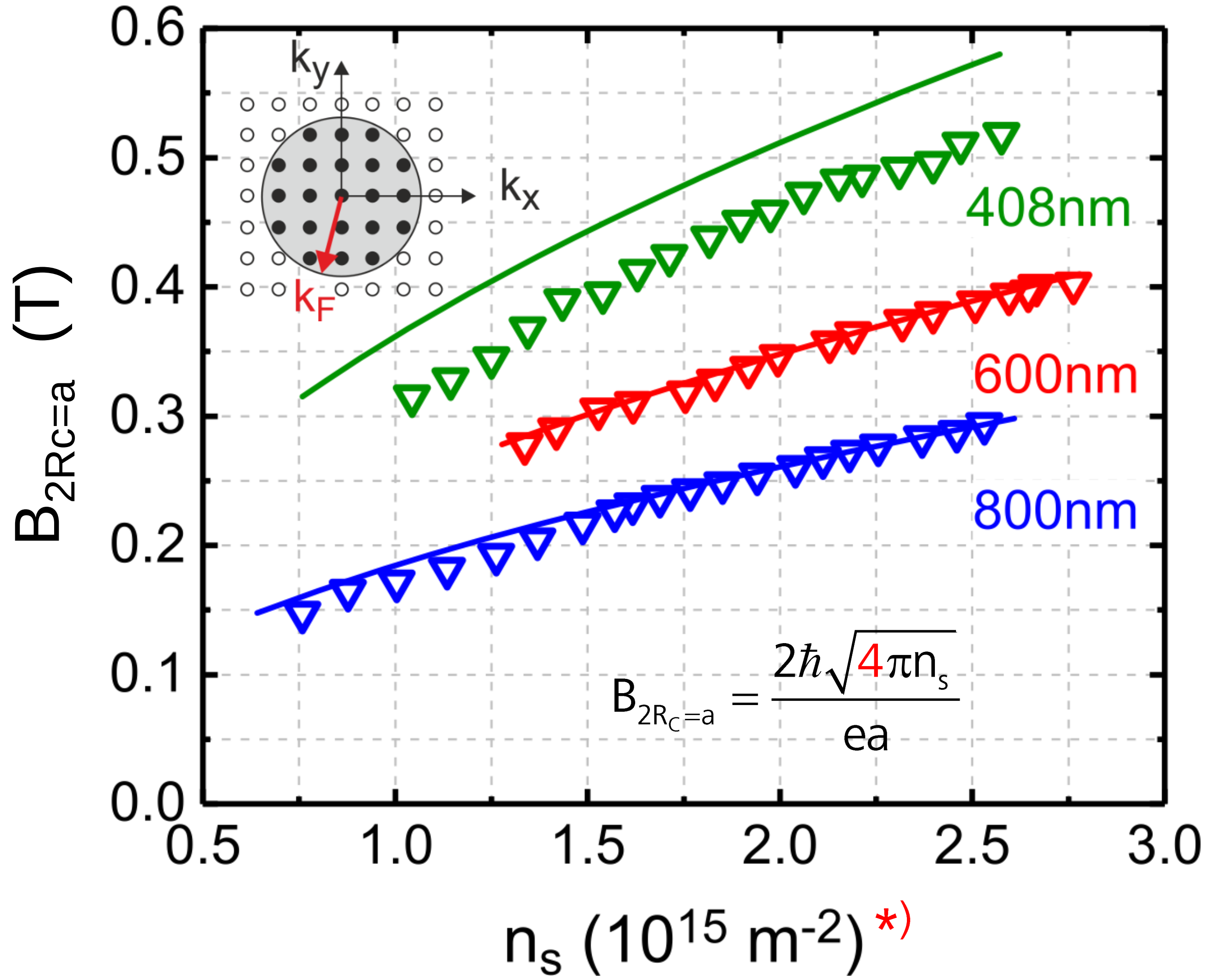
H. Maier et al., *Nature Commun.* **8**, 2023 (2017)

Carrier density: from QHE ◆, antidot resonance ⊙ and capacitance ⊙



Both, antidot resonances and capacitance oscillations probe **single** TI surface

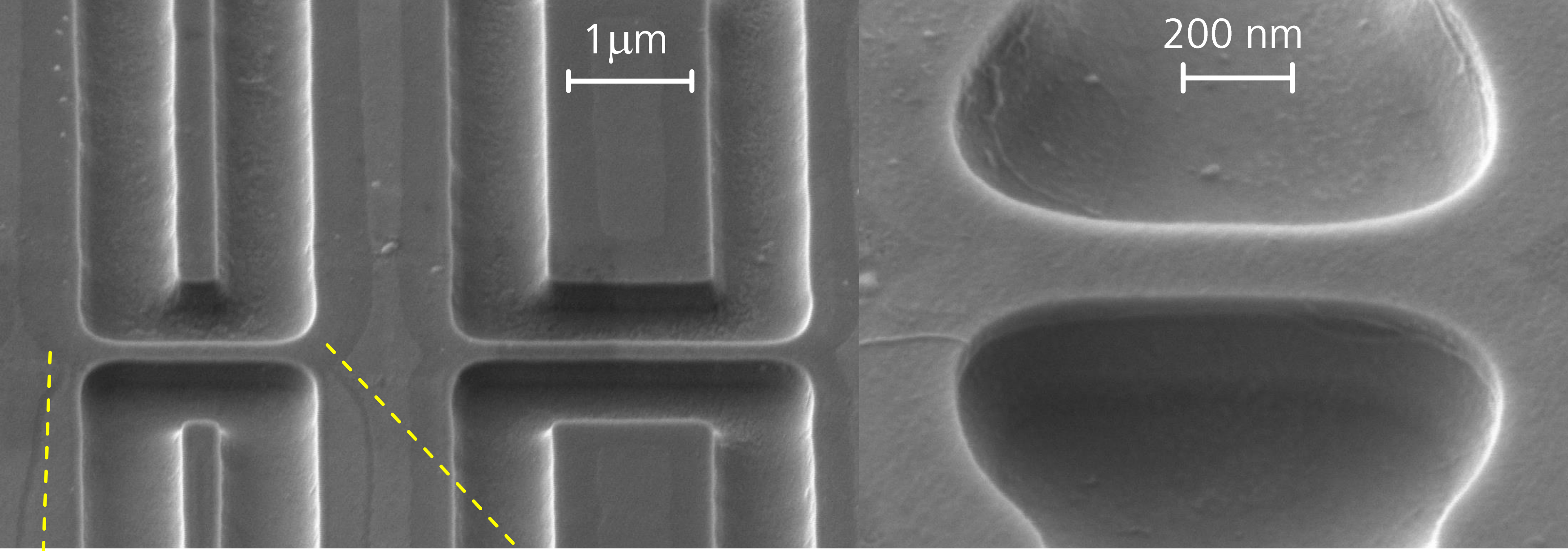
Position of fundamental antidot resonance



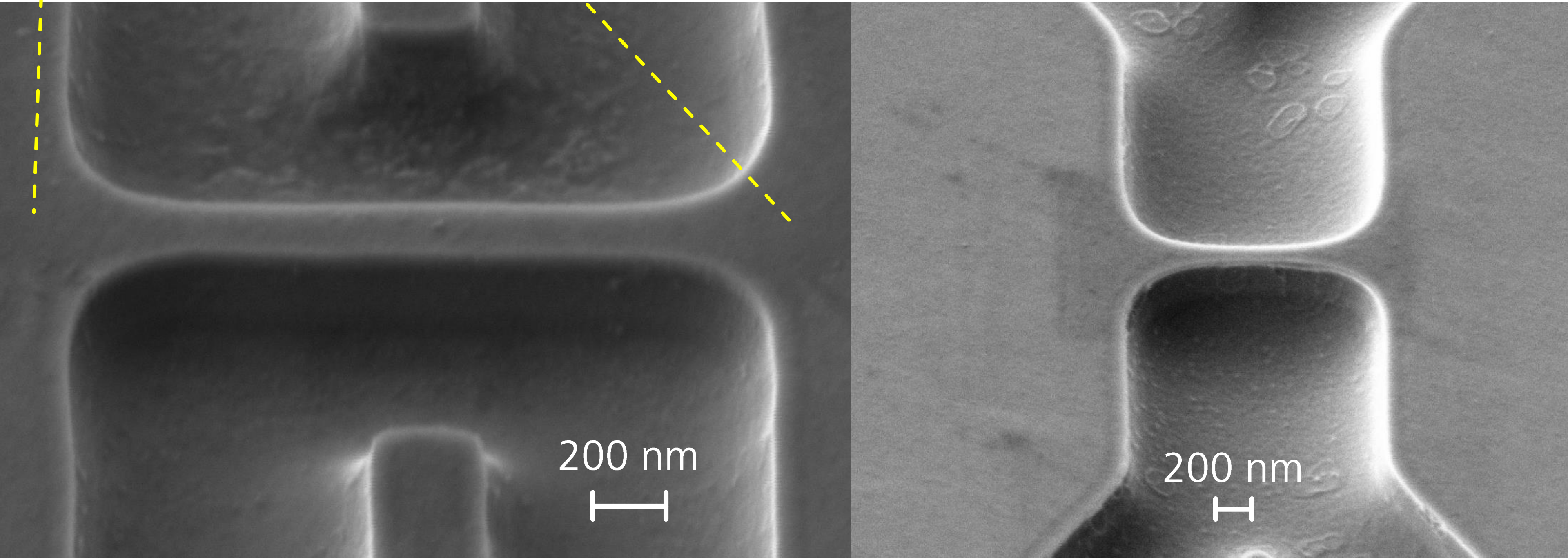
$$B_{2R_C=a} = \frac{2\hbar\sqrt{4\pi n_s}}{ea}$$

*) from C(B) oscillations

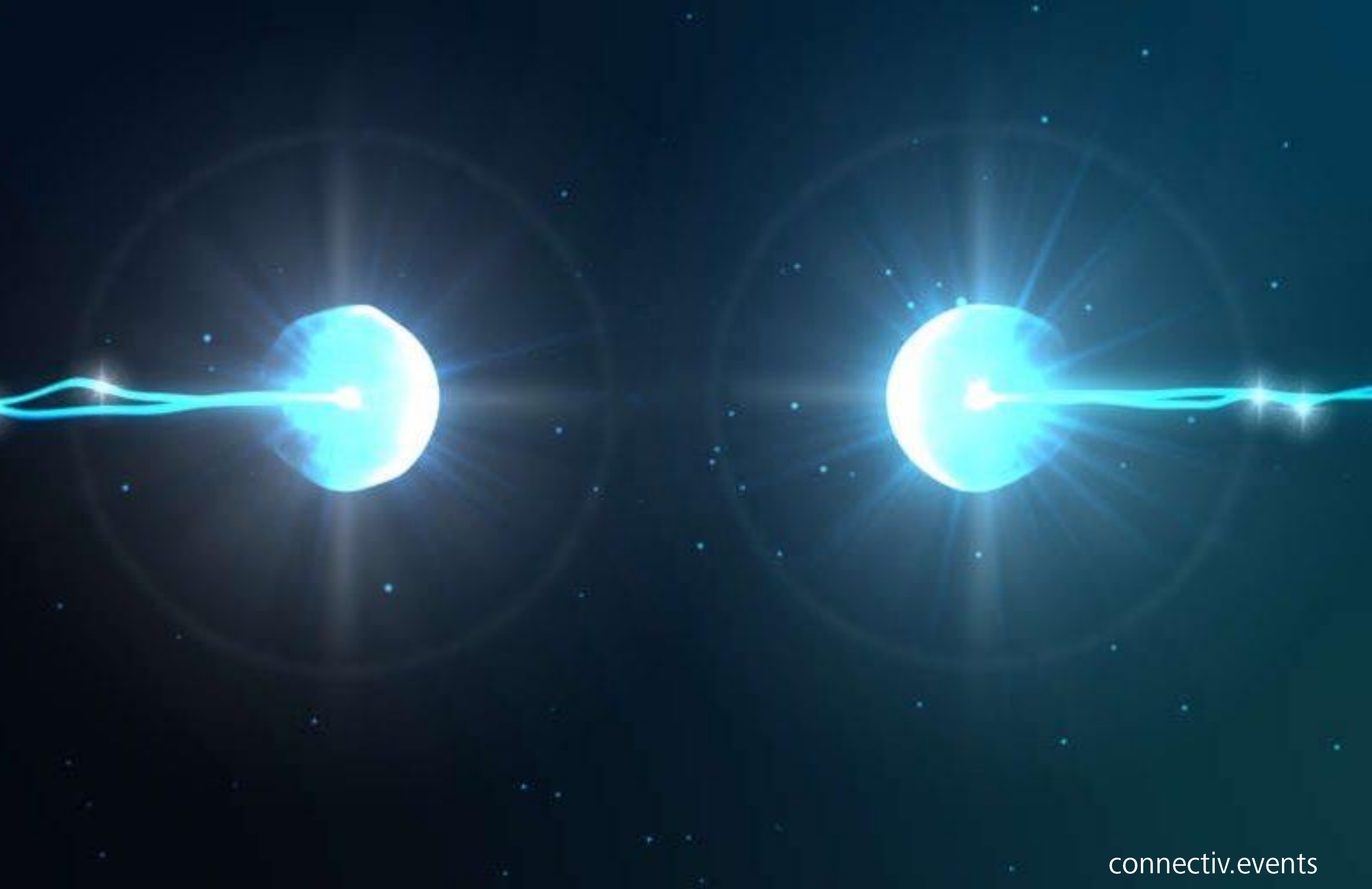
H. Maier et al., *Nature Commun.* **8**, 2023 (2017)



wires



Majorana fermions (artists view)

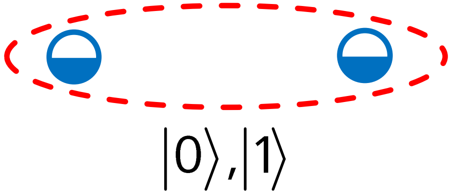


Majorana bound states (MBS)

A Majorana quasi-particle is a superposition of an electron (particle) and a hole (antiparticle)

Two majorana bound states form one fermion (electron, hole)

Majorana bound states come in pairs – if spatially separated they are topologically protected → qubit



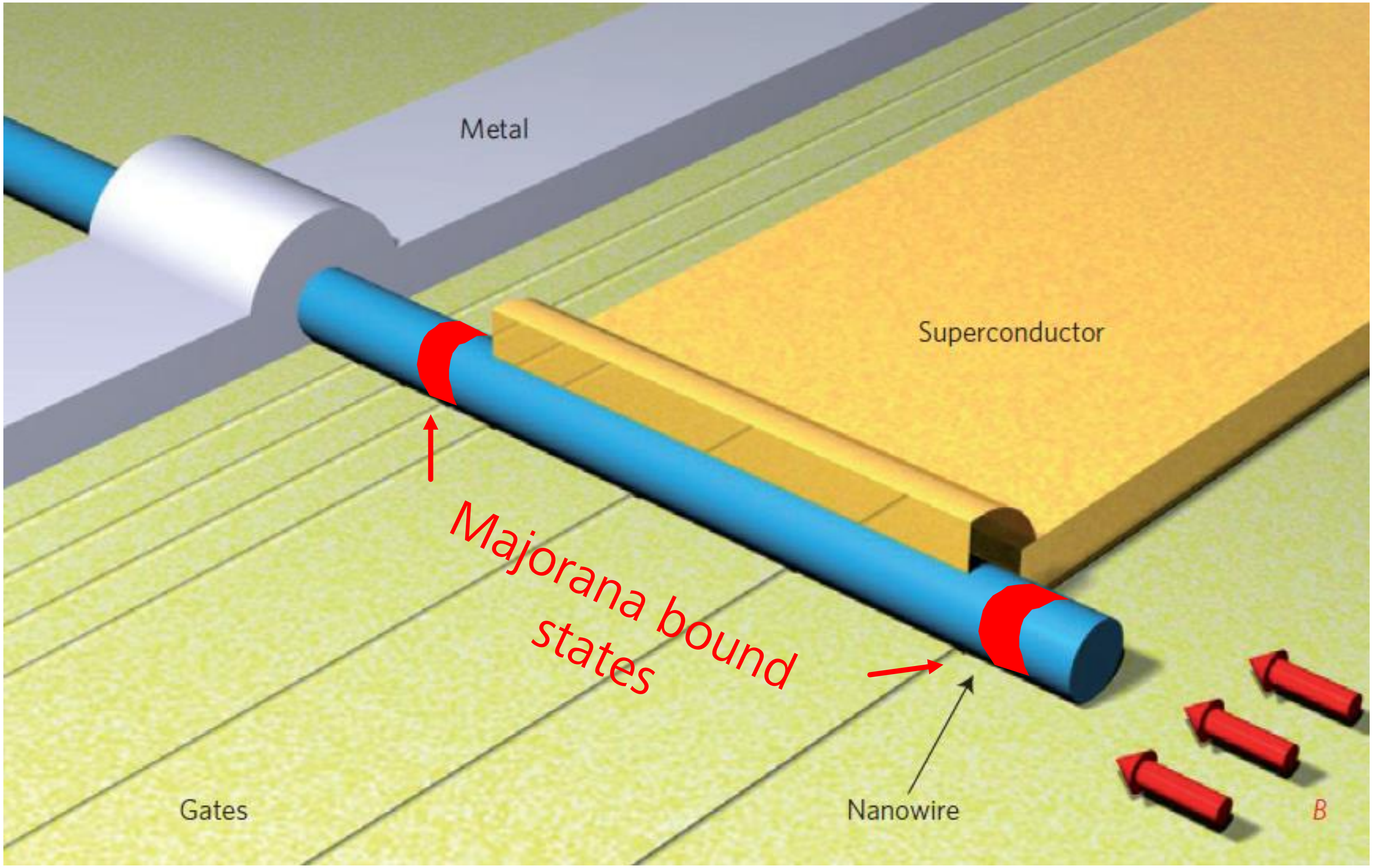
$|0\rangle, |1\rangle$

Fermion encoded in a *non-local* way: protected from local perturbation

Suitable system to look for MBS: proximity induced superconductors in semiconductors and TI wires.

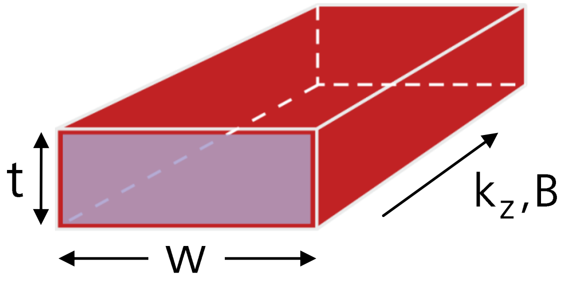
So far signatures of MBS in semiconductor nanowires but existence of MBS not yet unambiguously shown.

TI wires for probing Majorana bound states

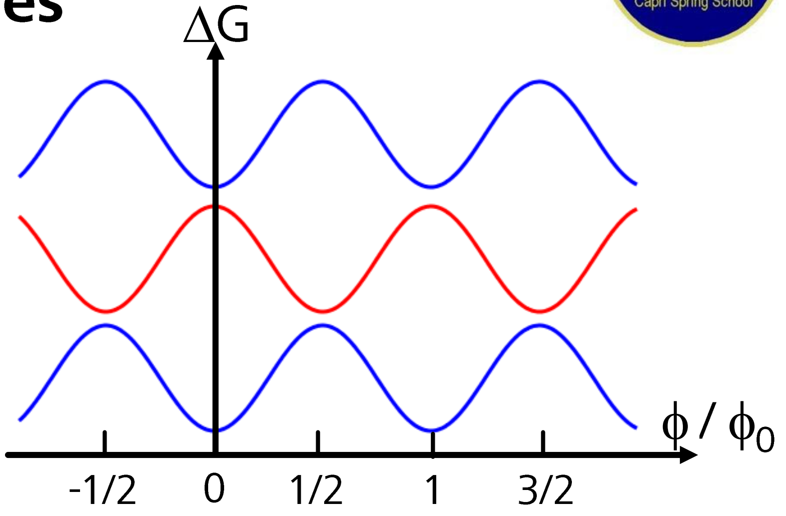


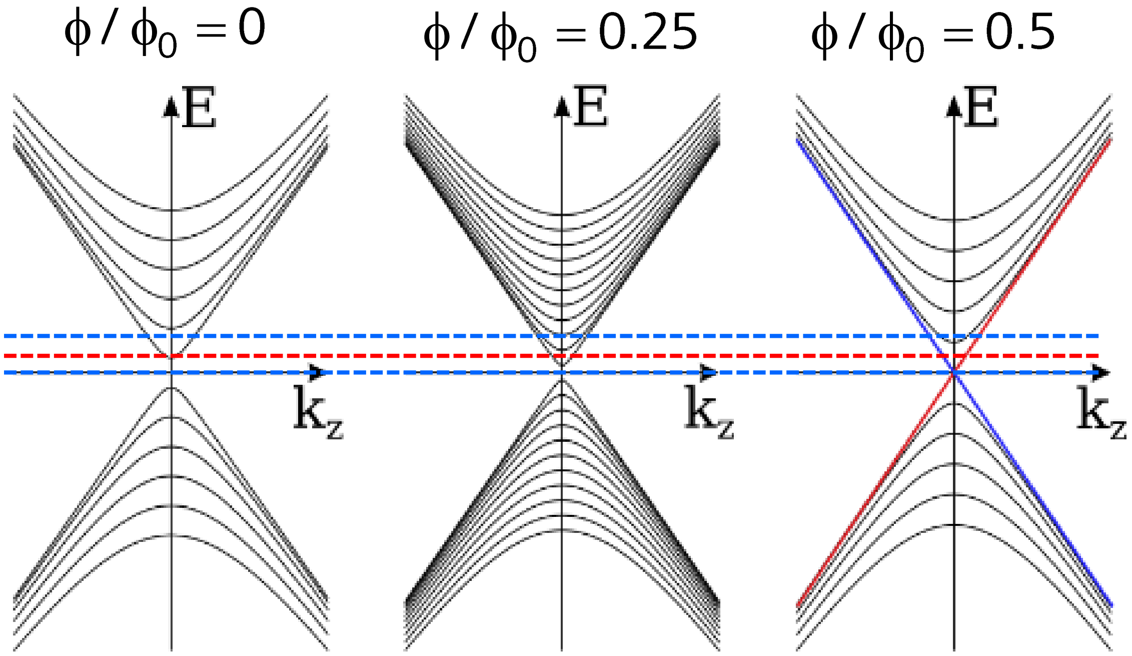
M. Franz, Nature Nano. **8**, 149 (2013)
A. Cook, M. Franz, PRB **84**, 201105(R) (2011)

Bandstructure of TI nanowires



$$\phi = B \cdot w \cdot t$$





S. Cho et al., Nat. Commun. **6**, 7634 (2015)
L.A. Jauregui et al., Nat. Nanotech. **11**, 345 (2016)

Energy spectrum:

$$E = \pm \hbar v_F \sqrt{k_z^2 + k_\ell^2} \text{ with}$$

$$k_\ell = \Delta k_\ell \left(\overset{\in \mathbb{Z}}{\ell} + \overset{\text{Berry-phase}}{\frac{1}{2}} - \overset{\text{magnetic flux}}{\frac{\phi}{\phi_0}} \right)$$

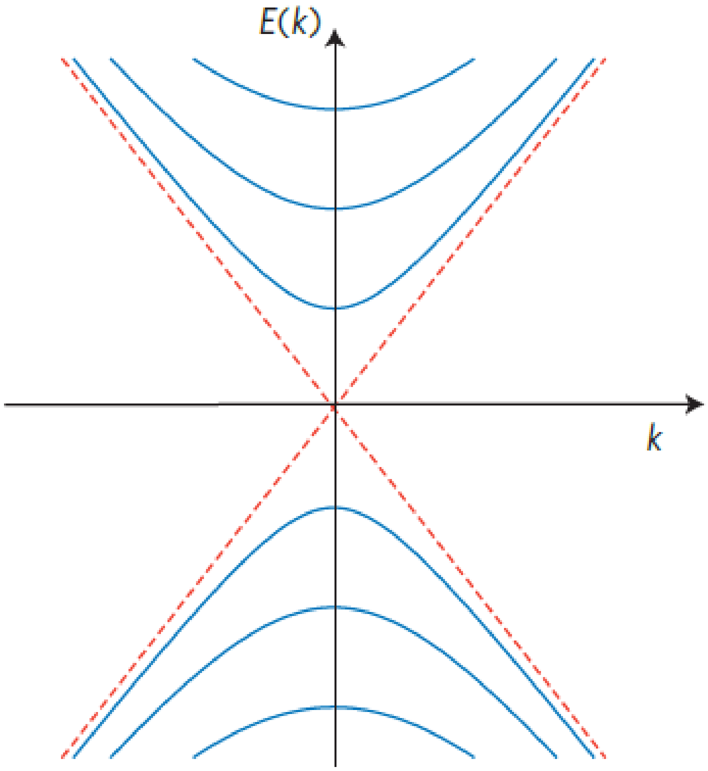
$$\Delta k_\ell = 2\pi / P$$

$$P = \text{perimeter}$$

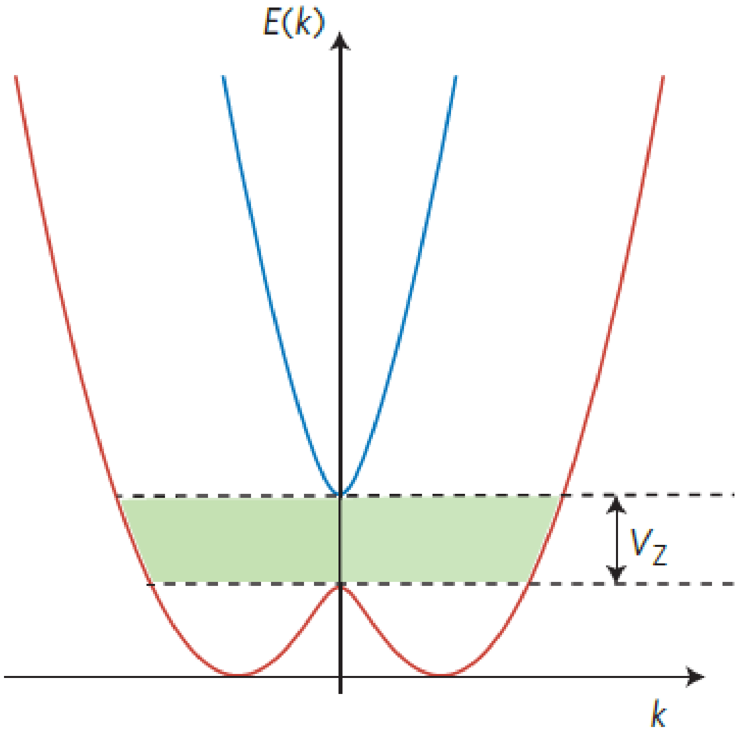
Bardarson & Moore, PRL **105**, 156803 (2010)

Advantage of TI wires

TI wire: $\phi / \phi_0 = 0.5$



Wire with SO interaction: V_z tuned by **B**-field



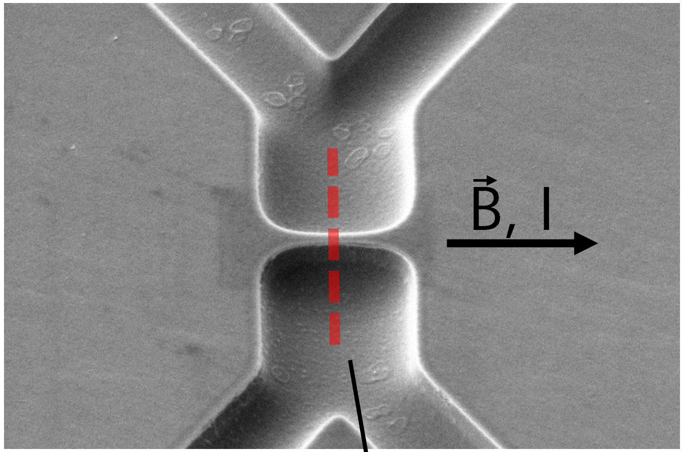
Odd number of Fermi points in the right half of the Brillouin zone everywhere in the bulk gap

Condition for topological phase only fulfilled in gap (green)

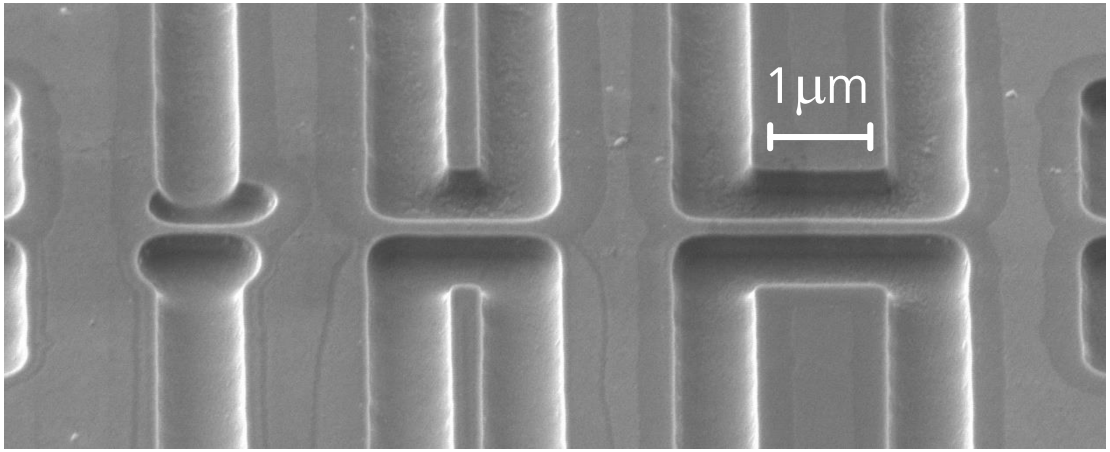
M. Franz, Nature Nano. **8**, 149 (2013)

Nanowire devices

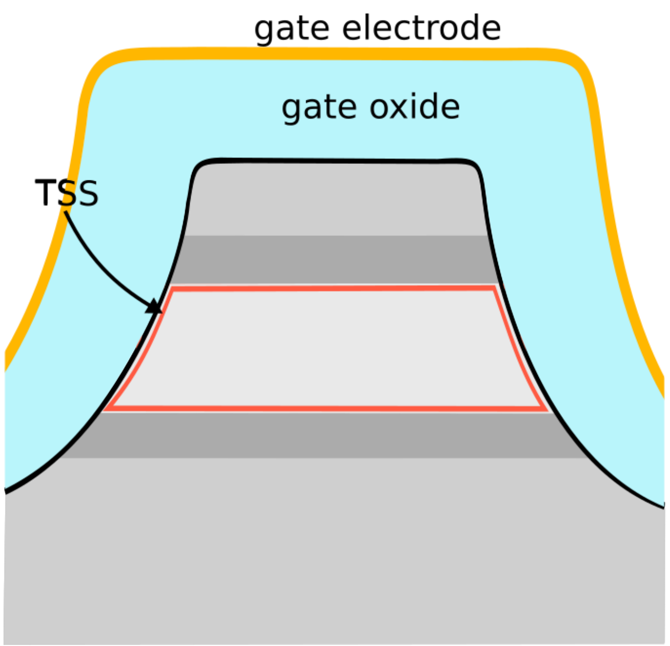
quasi 2-point



4-point



tilted view (50°)



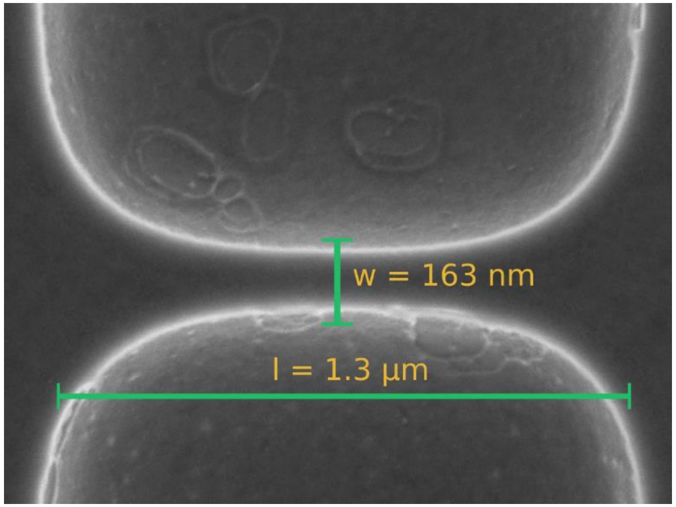
CdTe (40 nm)

$Hg_{0.7}Cd_{0.3}Te$ (20 nm)

HgTe (80 nm)

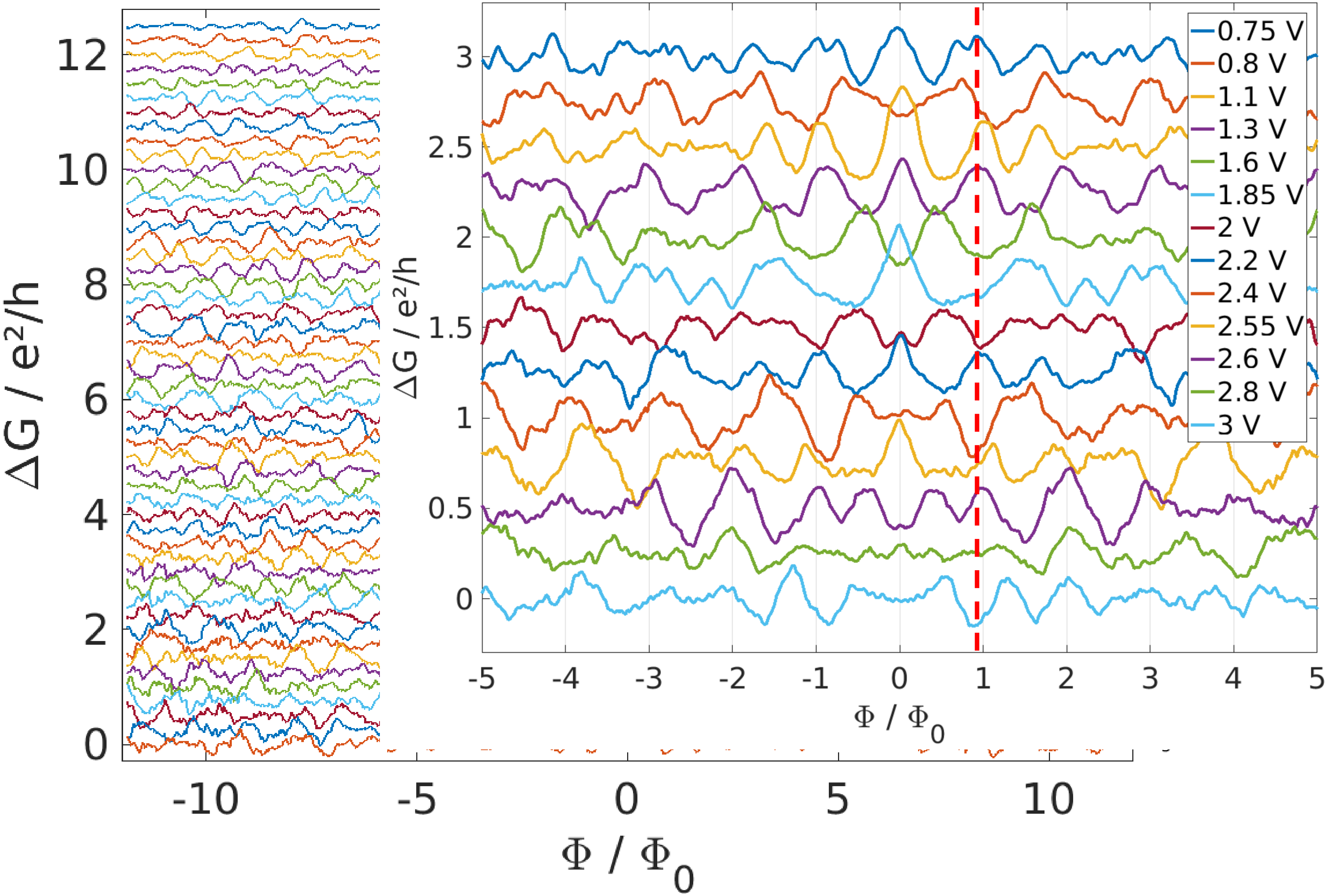
$Hg_{0.7}Cd_{0.3}Te$ (20 nm)

CdTe (4 µm)
(on (013) GaAs)

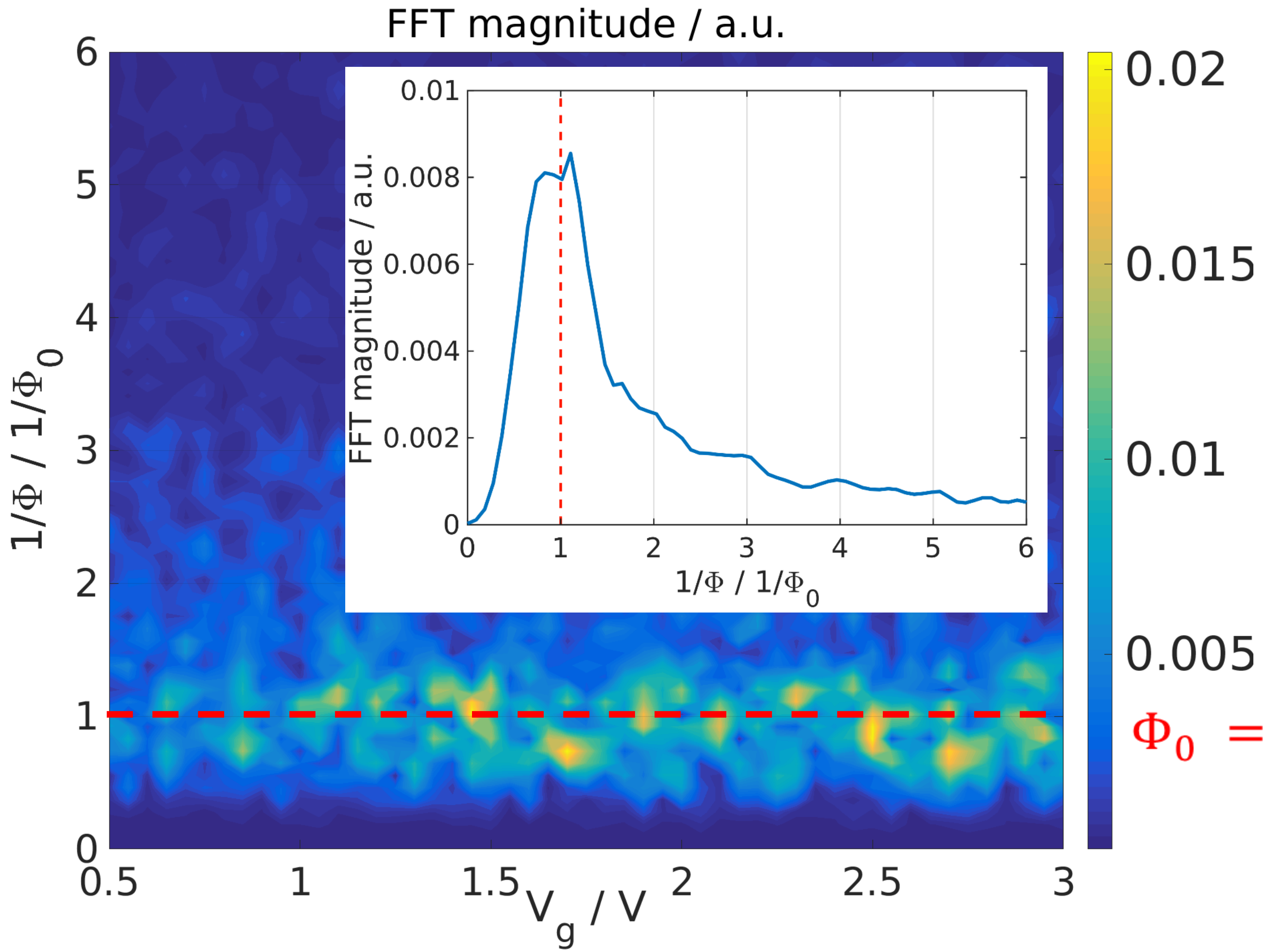


top view

Aharonov Bohm-type oscillations

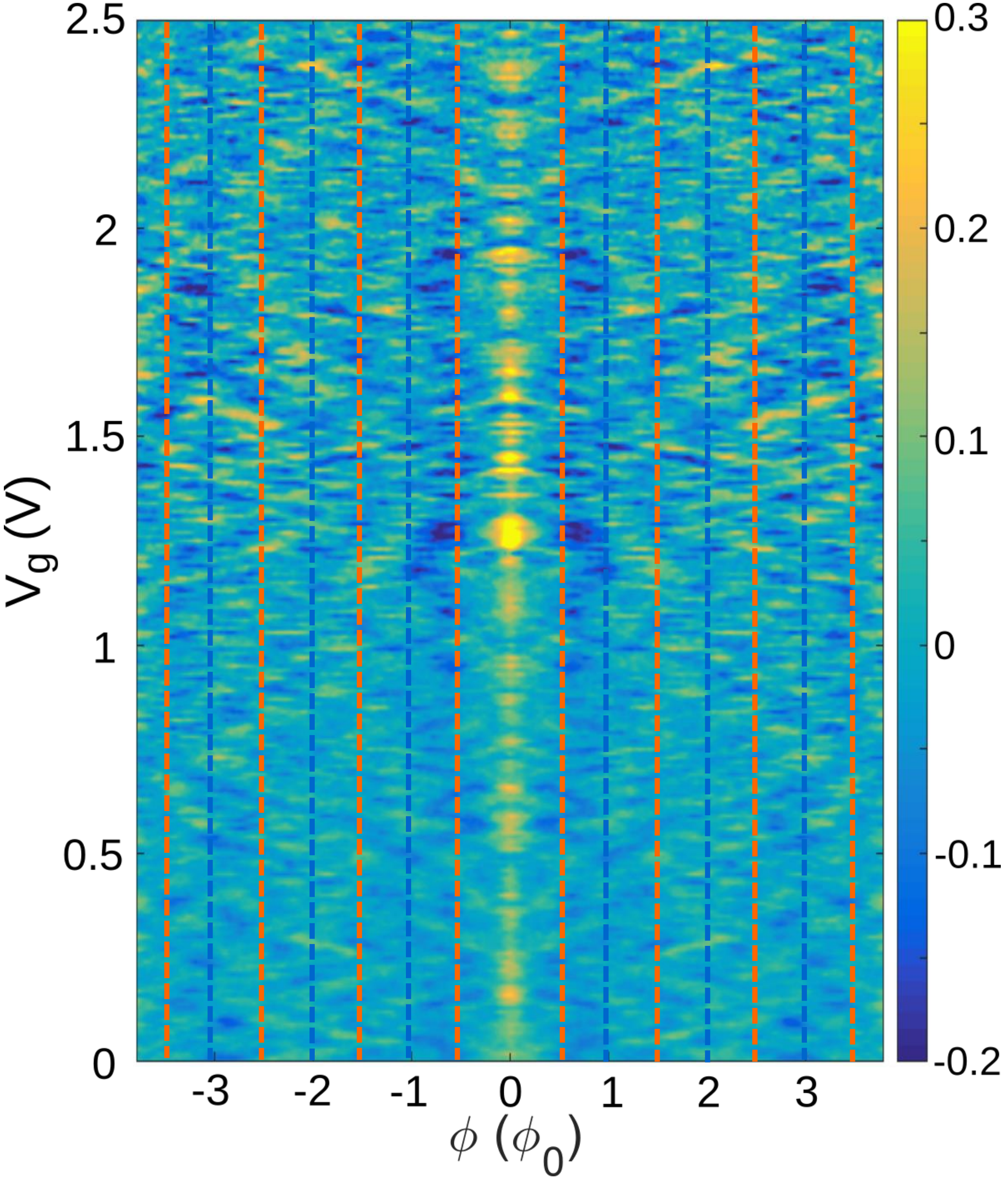


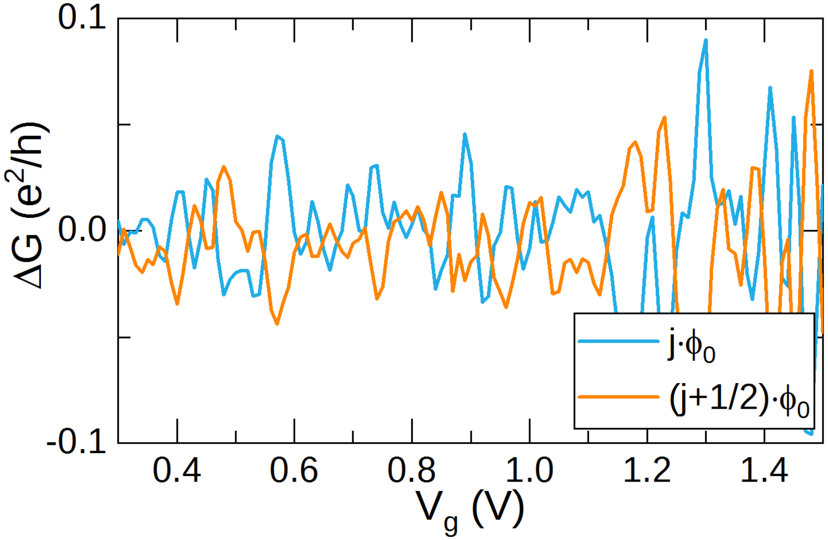
Aharonov Bohm-type oscillations



$\Phi_0 = h/e$

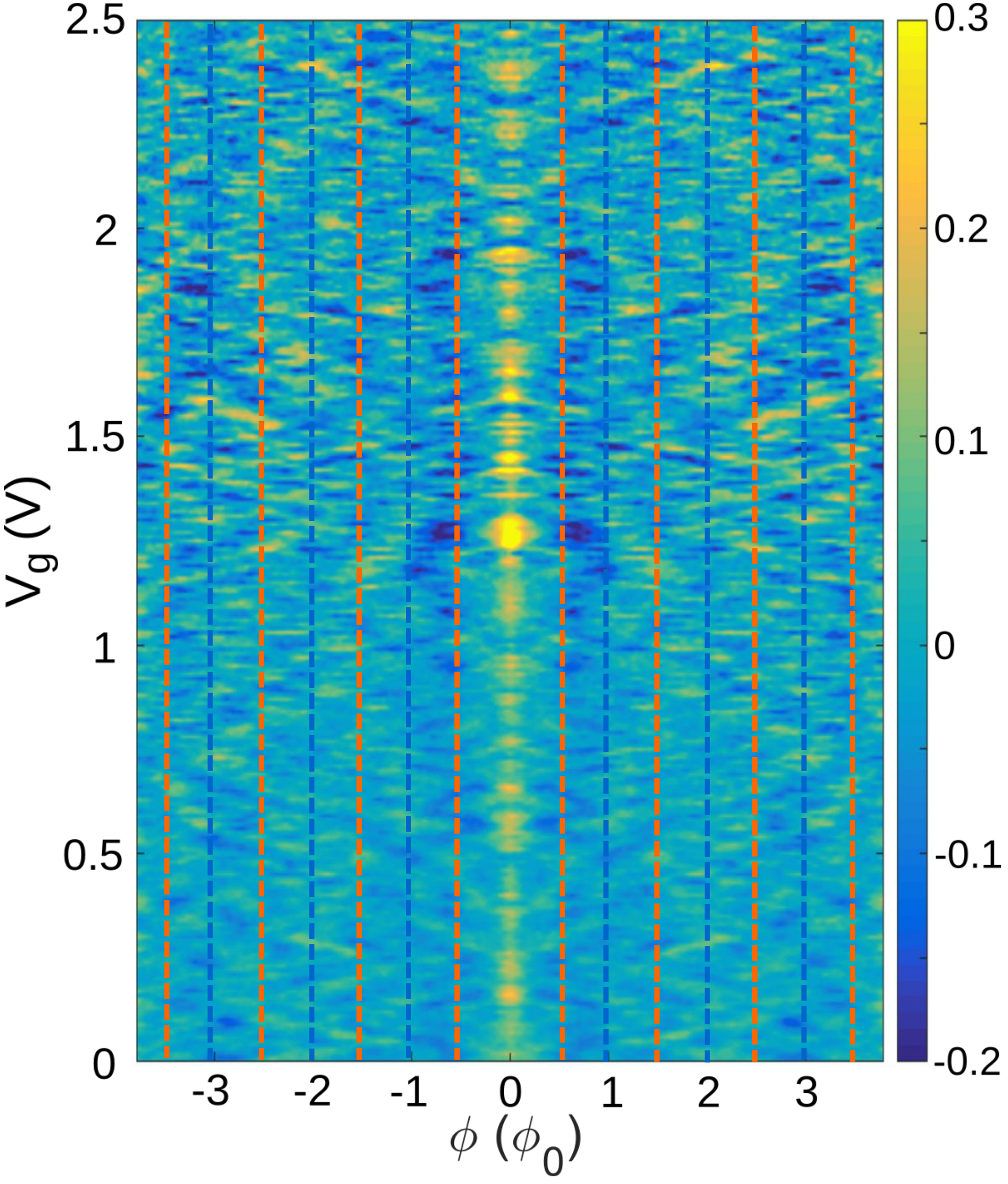
Counting subbands

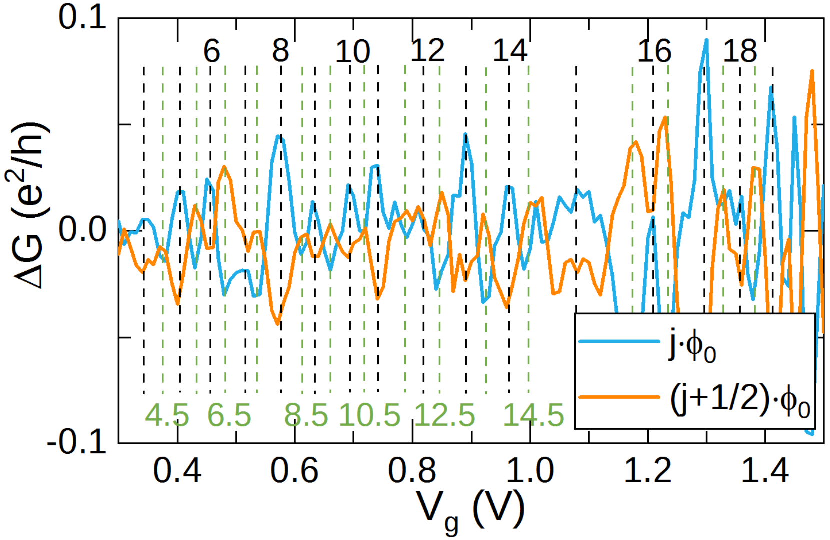


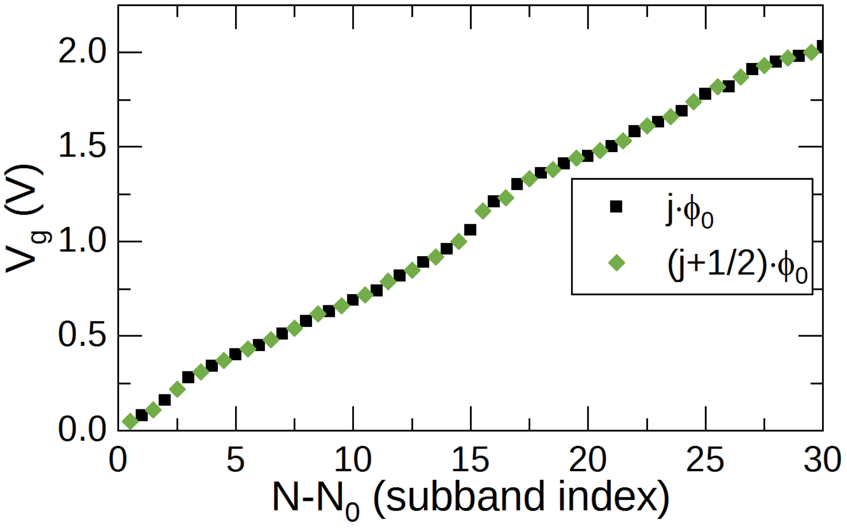


J. Ziegler, R. Kozlovsky *et al.*, PRB **97**, 035157 (2018)

Counting subbands

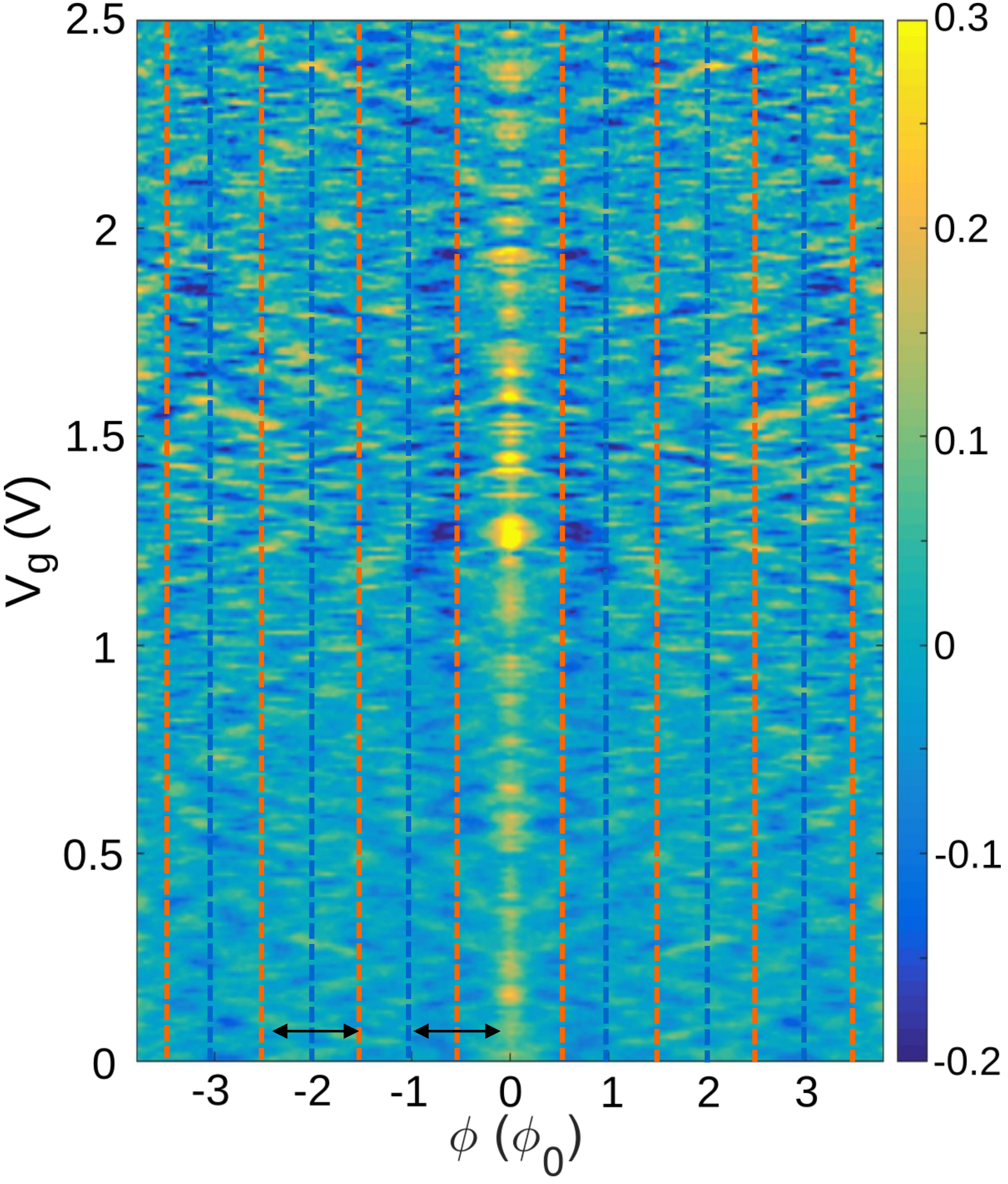


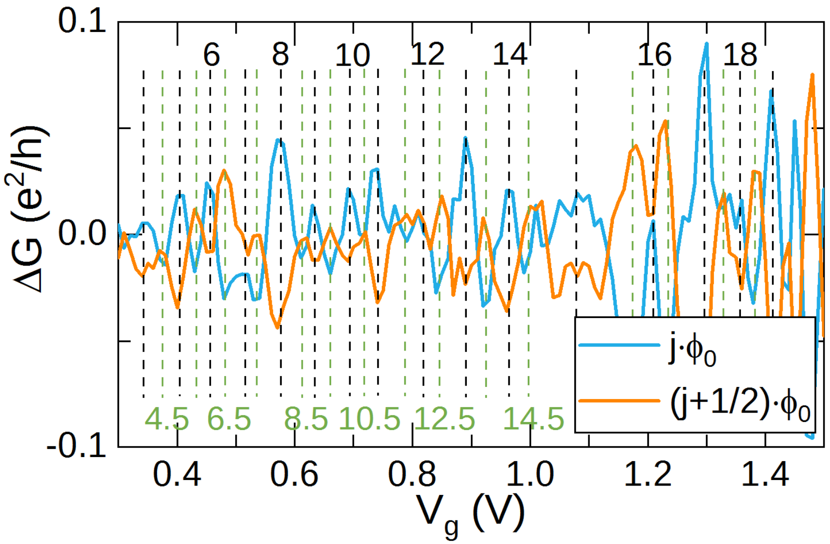


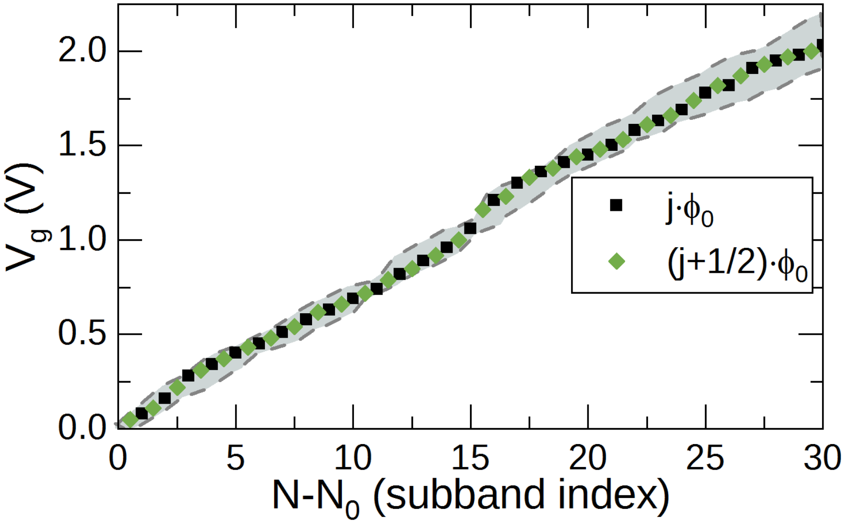


J. Ziegler, R. Kozlovsky *et al.*, PRB **97**, 035157 (2018)

Counting subbands

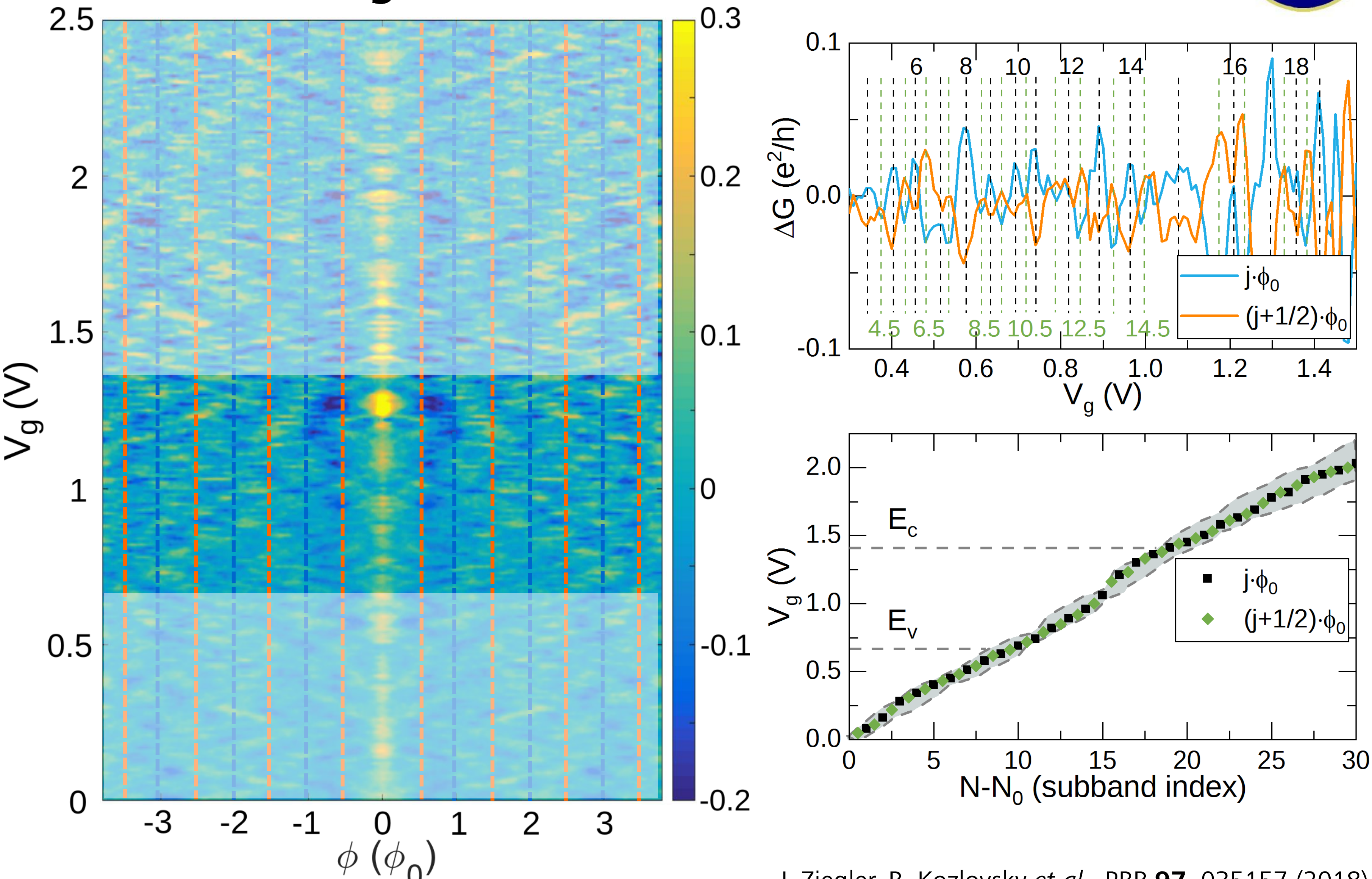






J. Ziegler, R. Kozlovsky *et al.*, PRB **97**, 035157 (2018)

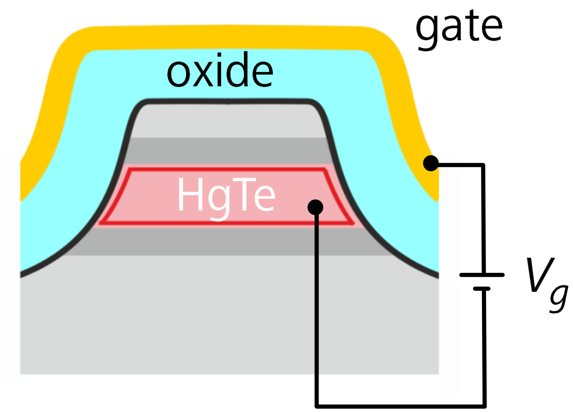
Counting subbands



J. Ziegler, R. Kozlovsky *et al.*, PRB **97**, 035157 (2018)

Subband spacing: simple model

…relation between Δk and ΔV



$$n_s = \frac{k^2}{4\pi}\ ; \qquad n_s = \frac{C}{e}(V_g - V_0) + n_0\ ;$$

$$n_0 = \frac{k_0^2}{4\pi} = \text{electron density at } V_g = V_0$$

helical Dirac electrons

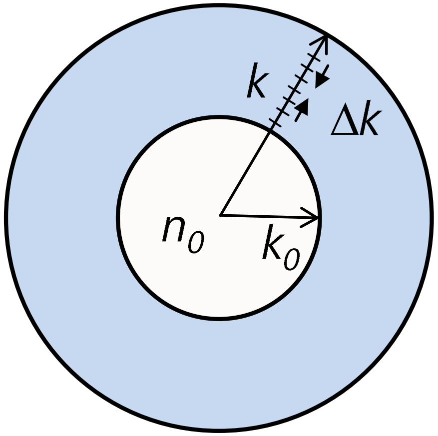
Fermi wave vector at conductance minimum (= subband opening):

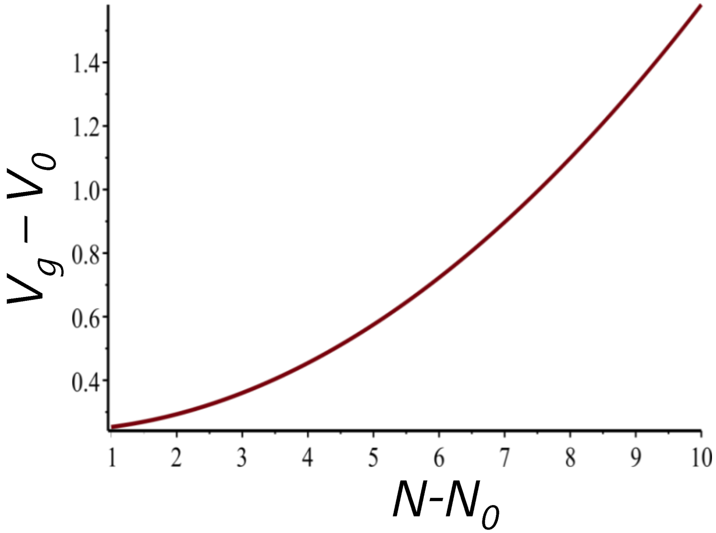
$$k_F = k_0 + (N - N_0)\Delta k$$

$$N - N_0 = 1,2,3\ldots$$

$$V_g - V_0 = \frac{e}{4\pi C}\left(2k_0(N-N_0)\Delta k_\ell + (N-N_0)^2\,\Delta k_\ell^2\right)$$

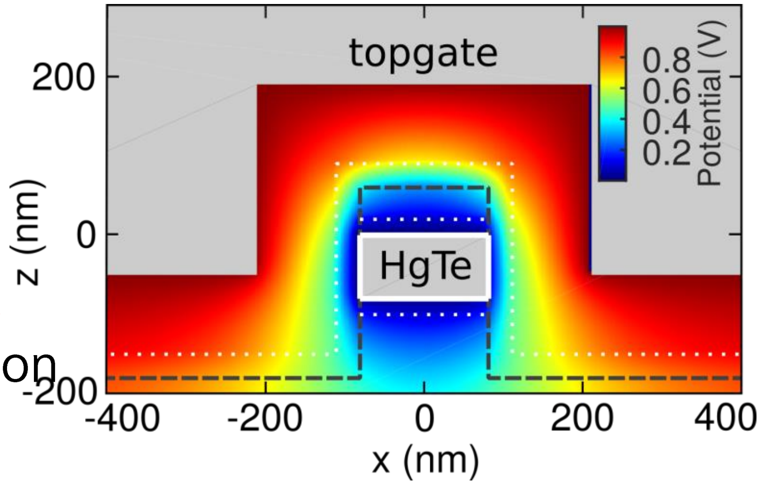
determined by C and $\Delta k_\ell = 2\pi / P$





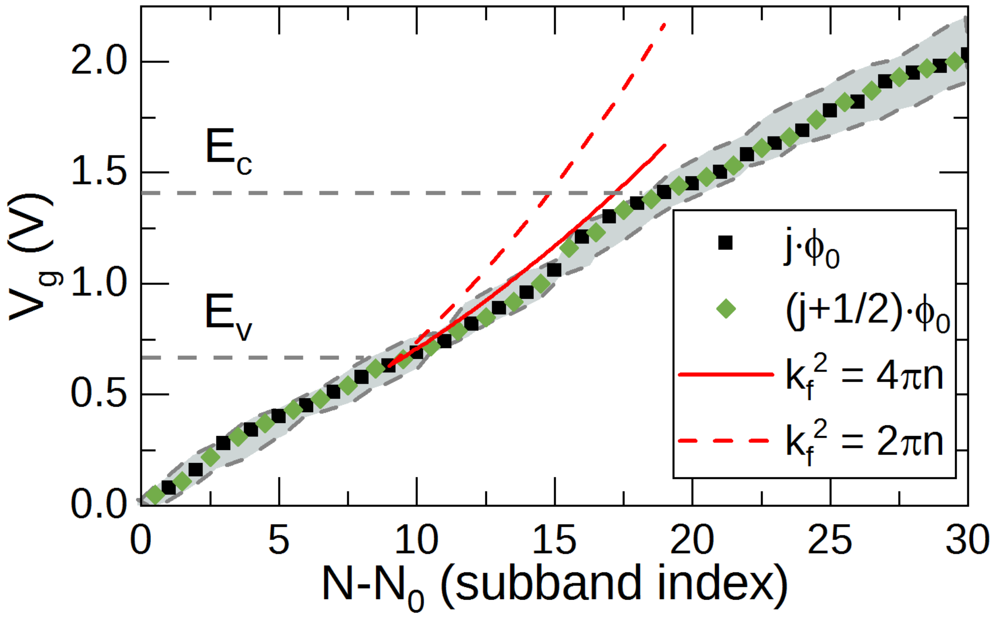
Electrostatic model

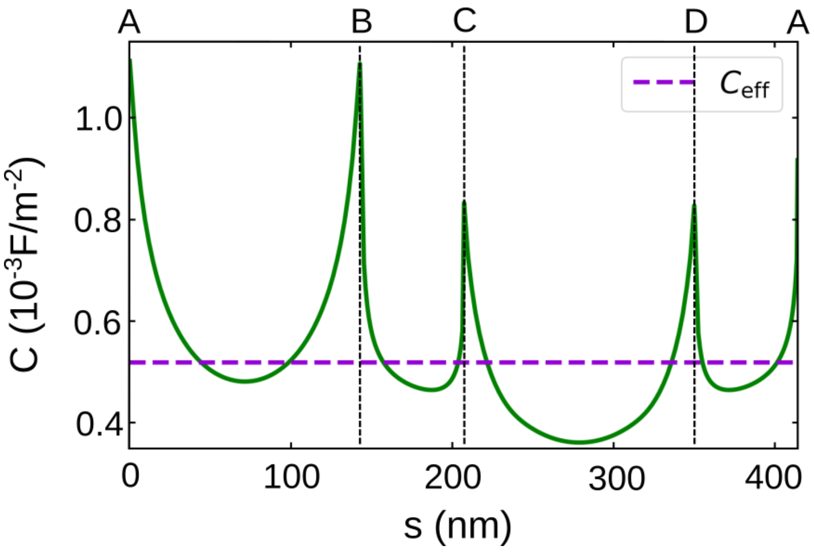
$$n(y) = \frac{C(s)}{e} V_g$$



$$V_g - V_0 = \frac{e}{4\pi C}\left(2k_0(N-N_0)\Delta k + (N-N_0)^2 \Delta k^2\right)$$

Numeric solution of Laplace equation

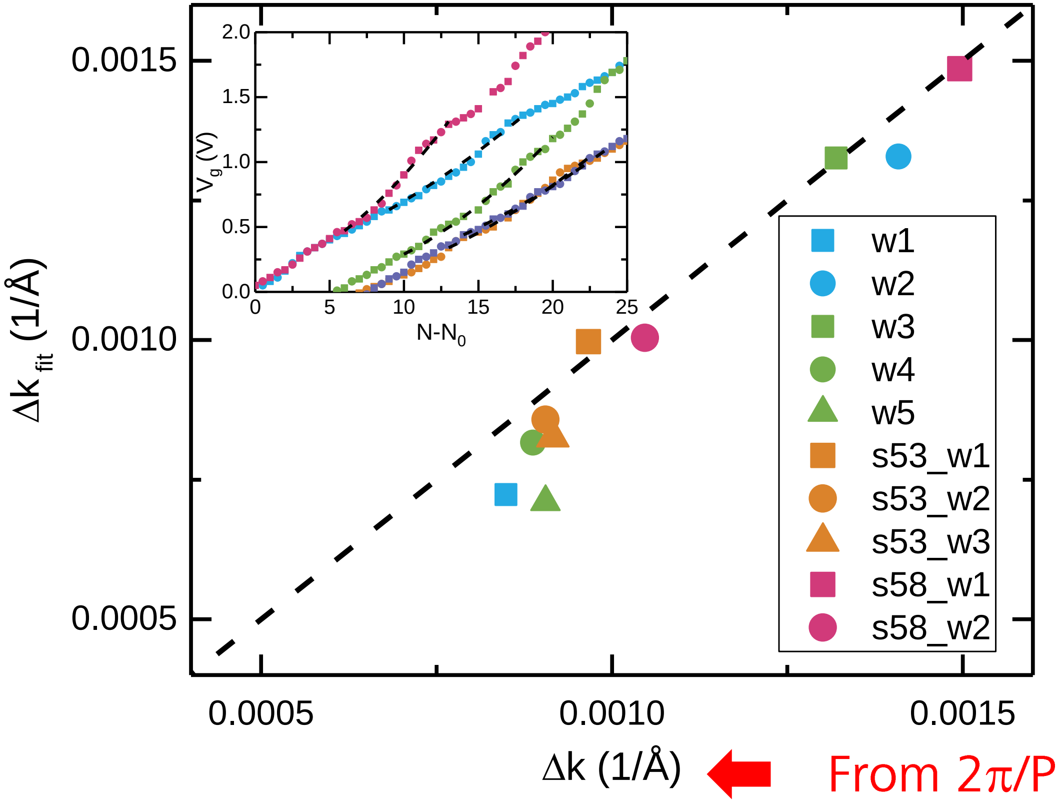




J. Ziegler, R. Kozlovsky *et al.*, PRB **97**, 035157 (2018)

Validity check (with 10 nanowires)

$$V_g - V_0 = \frac{e}{4\pi C}\left(2k_0(N-N_0)\Delta k + (N-N_0)^2 \Delta k^2\right)$$



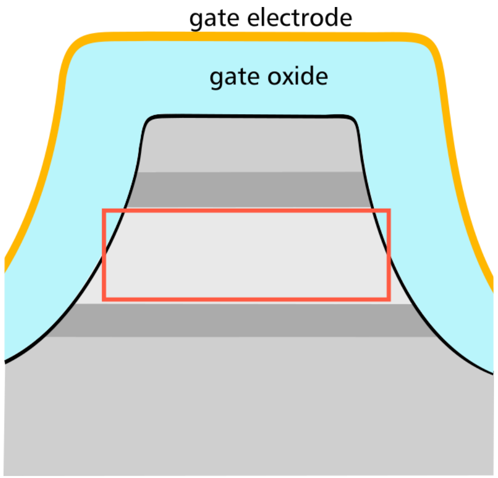
From 2π/P

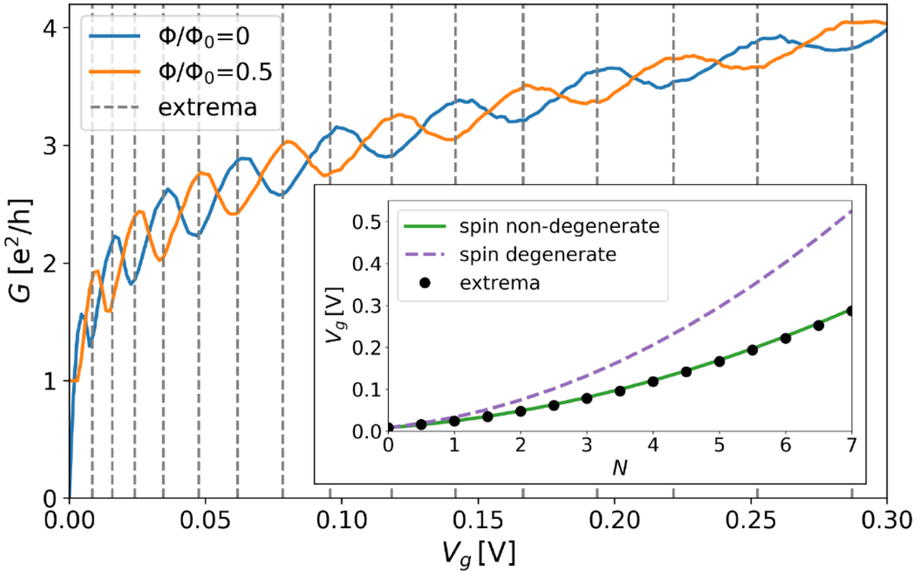
Subband structure: experimentally confimed ✓

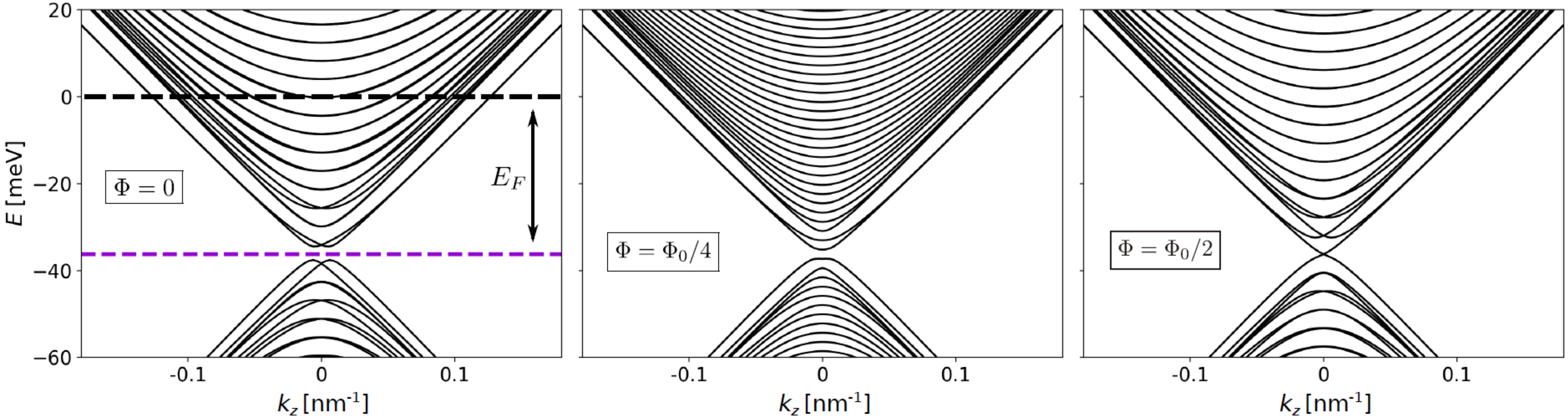
Topological nature of surface states confirmed ✓

Existence of perfectly transmitted mode ✓

Full capacitance model (transport calculation using Kwant)







J. Ziegler, R. Kozlovsky et al., PRB **97**, 035157 (2018)

Summary

- Antidot peak position probes k_F of top surface and confirms topological nature of surface states
- HgTe nanowires show *h/e* periodic quantum oscillations
- Anti-phase oscillations observed as function of V_g– but only quantitative correct description of V_g-N relation confirms topological origin
- Indirect proof that perfectly transmitted mode can be switched on and off by half flux quantum

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