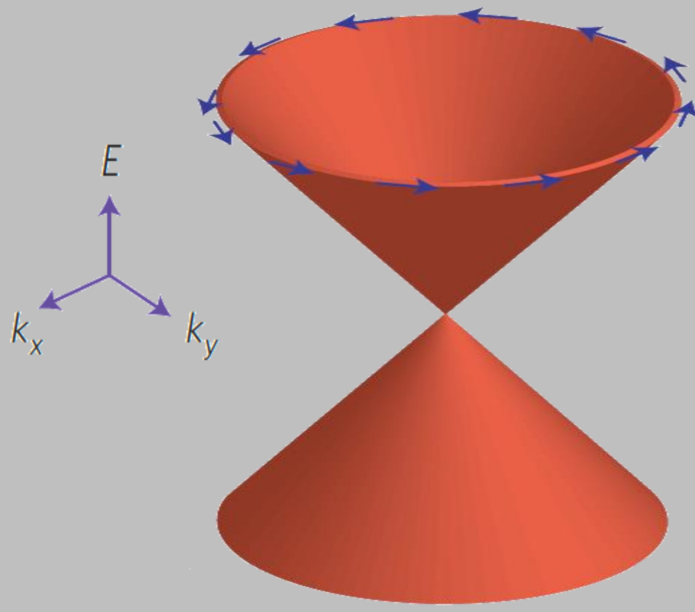


Strained HgTe: A Model 3D-Topological Insulator

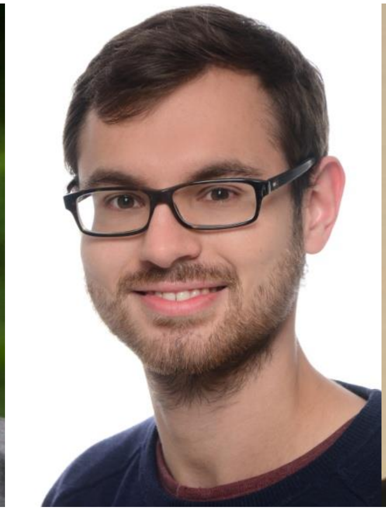
Dieter Weiss

Universität Regensburg

Collaborators

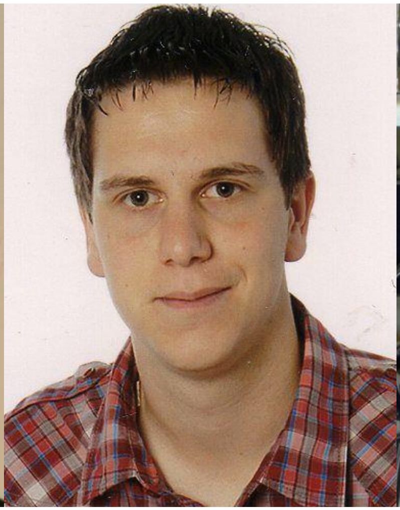
Johannes Ziegler

Raphael Kozlovsky



Hubert Maier

Ralf Fischer



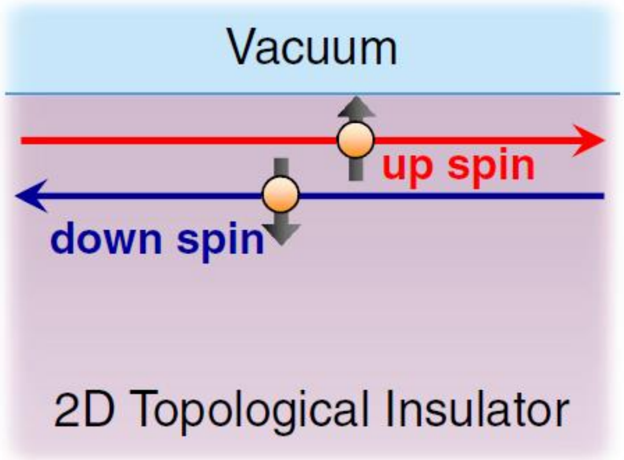
Dimitry Kozlov

A. V. Rzhanov Institute of Semiconductor Physics, Novosibirsk:
D.A. Kozlov, Z.D. Kvon, N. N. Mikhailov, S.A. Dvoretsky

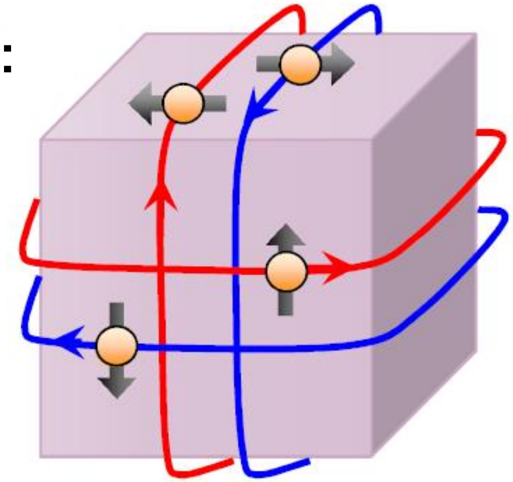
Physics Department, Universität Regensburg:
<u>Experiment:</u> J. Ziegler, H. Maier, R. Fischer, S. Weishäupl, S. Hartl, E. Richter, D. Weiss
<u>Theory:</u> R. Kozlovski, M.-H. Liu, C. Gorini, K. Richter

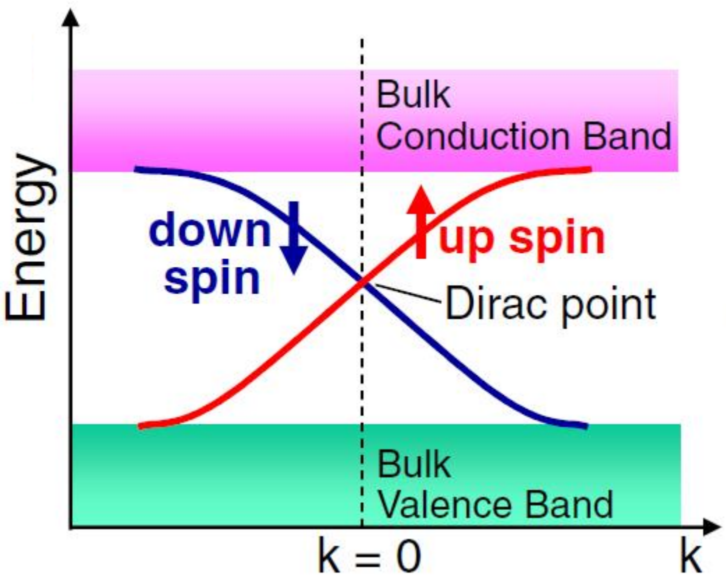
Topological insulators in pictures

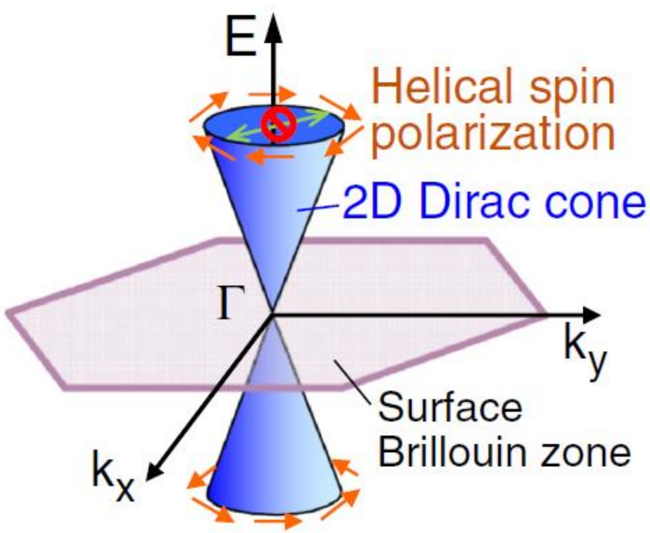
2D:



3D:

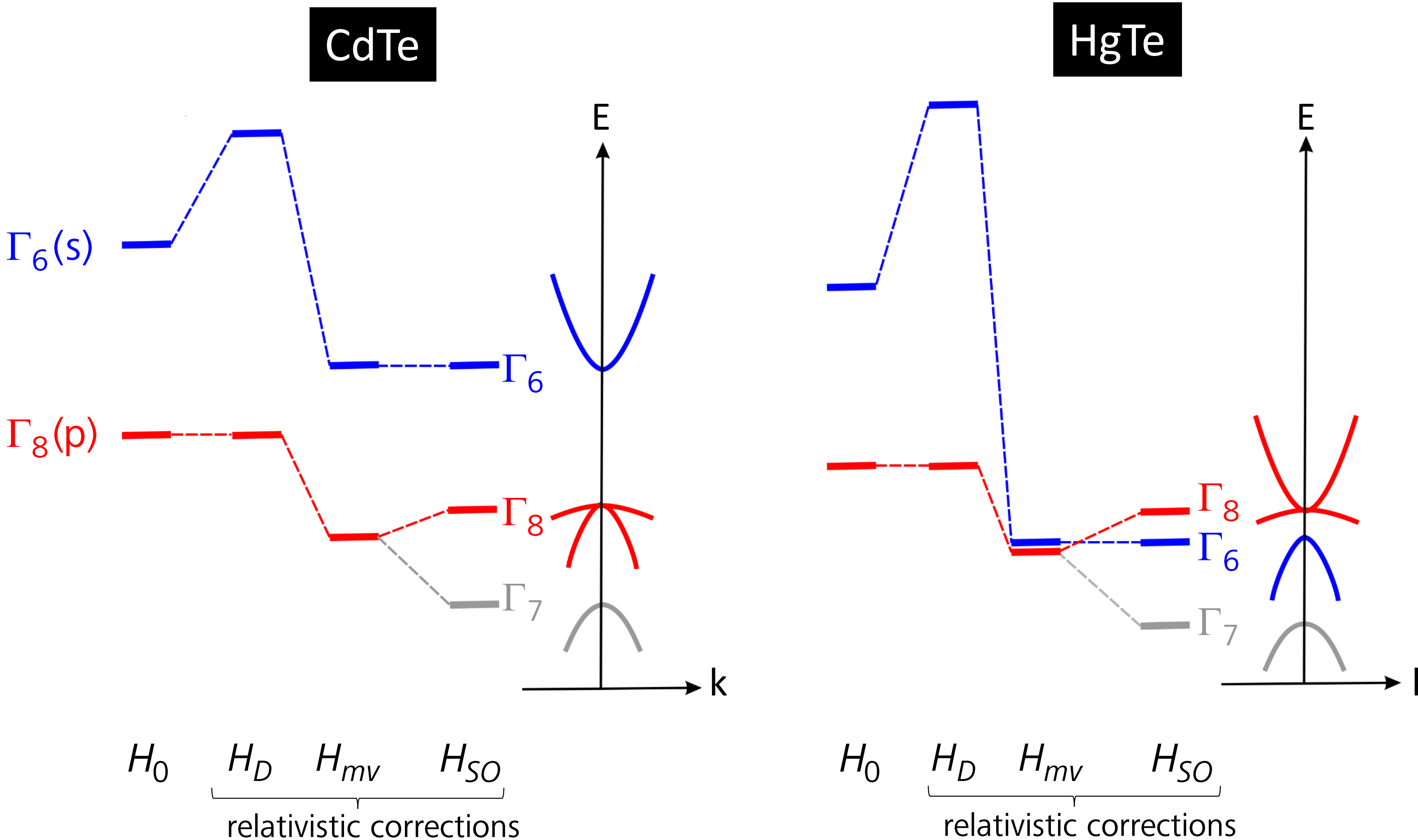






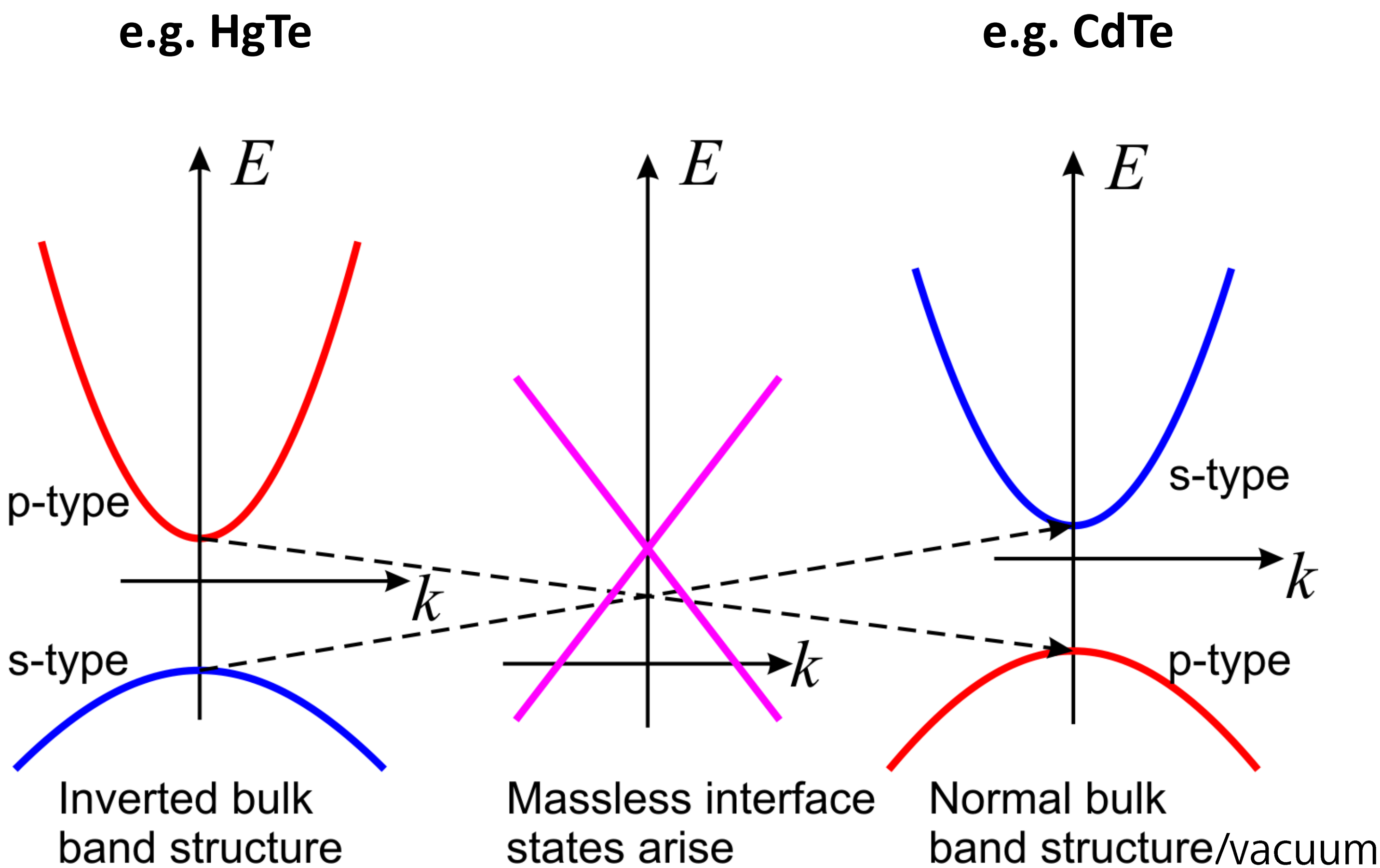
Yoichi Ando, J. Phys. Soc. Jap. **82**, 102001 (2013)

HgTe: Inverted band structure



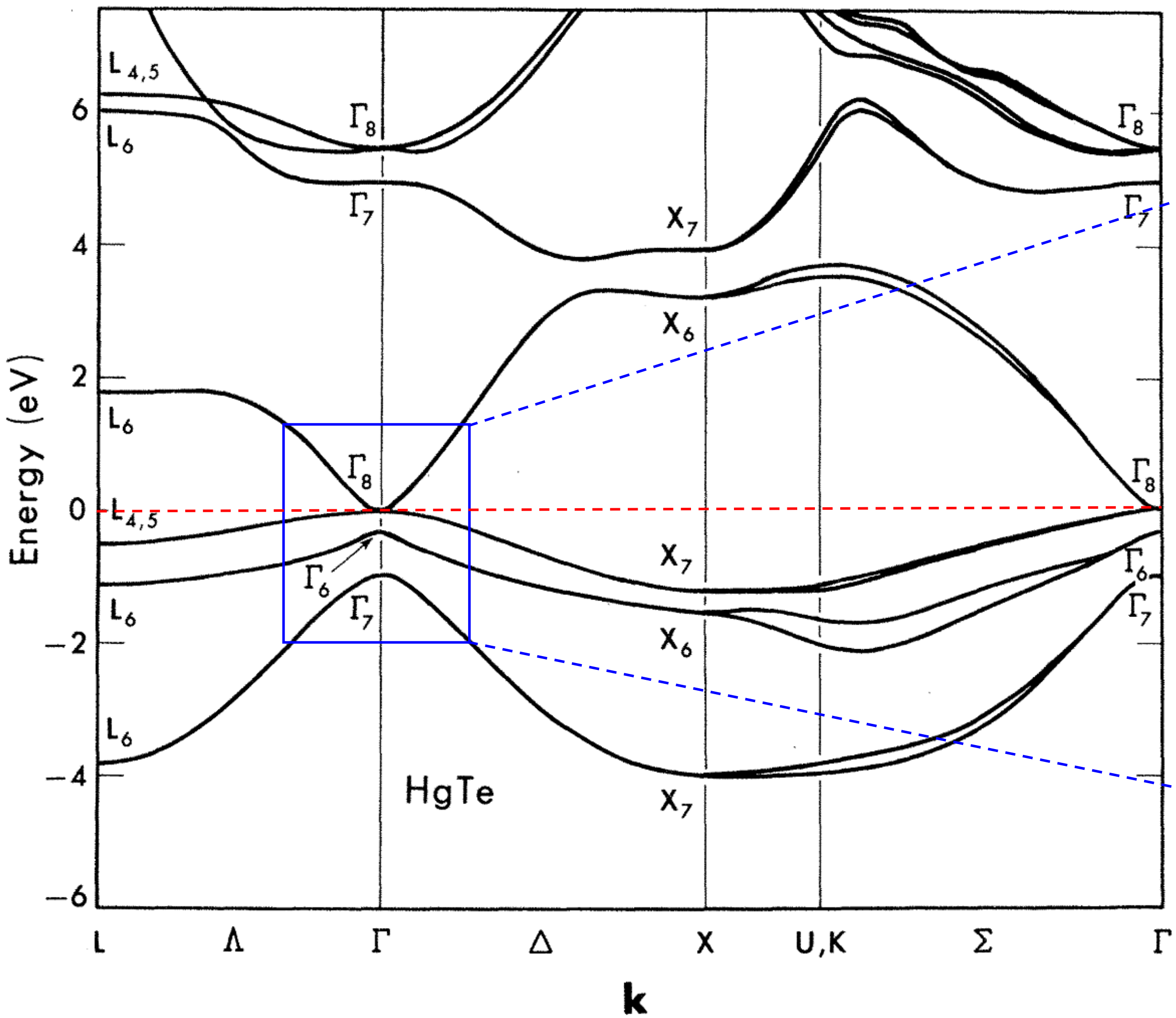
N.N. Berchenko, M.V. Pashkovskii, Usp. Fiz. Nauk. **119**, 223 (1976)

Formation of topological surface states

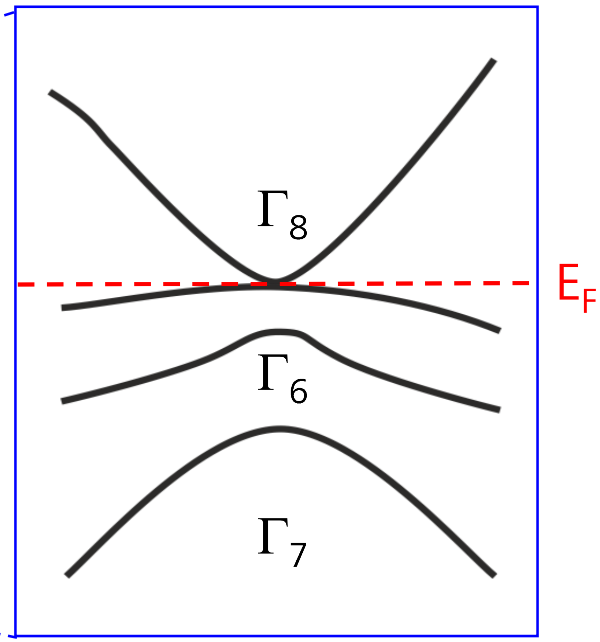


At the interface band gap needs to close → 2D Dirac-like surface states form

HgTe: Inverted band structure



Strain opens small gap

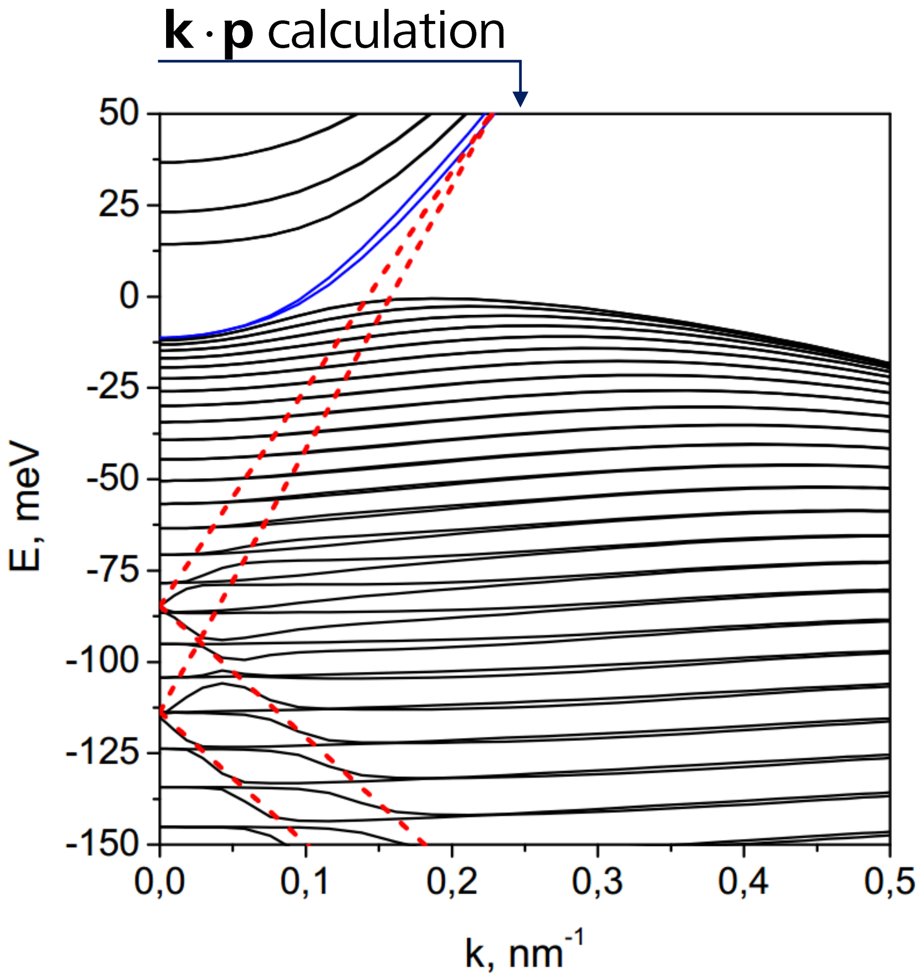


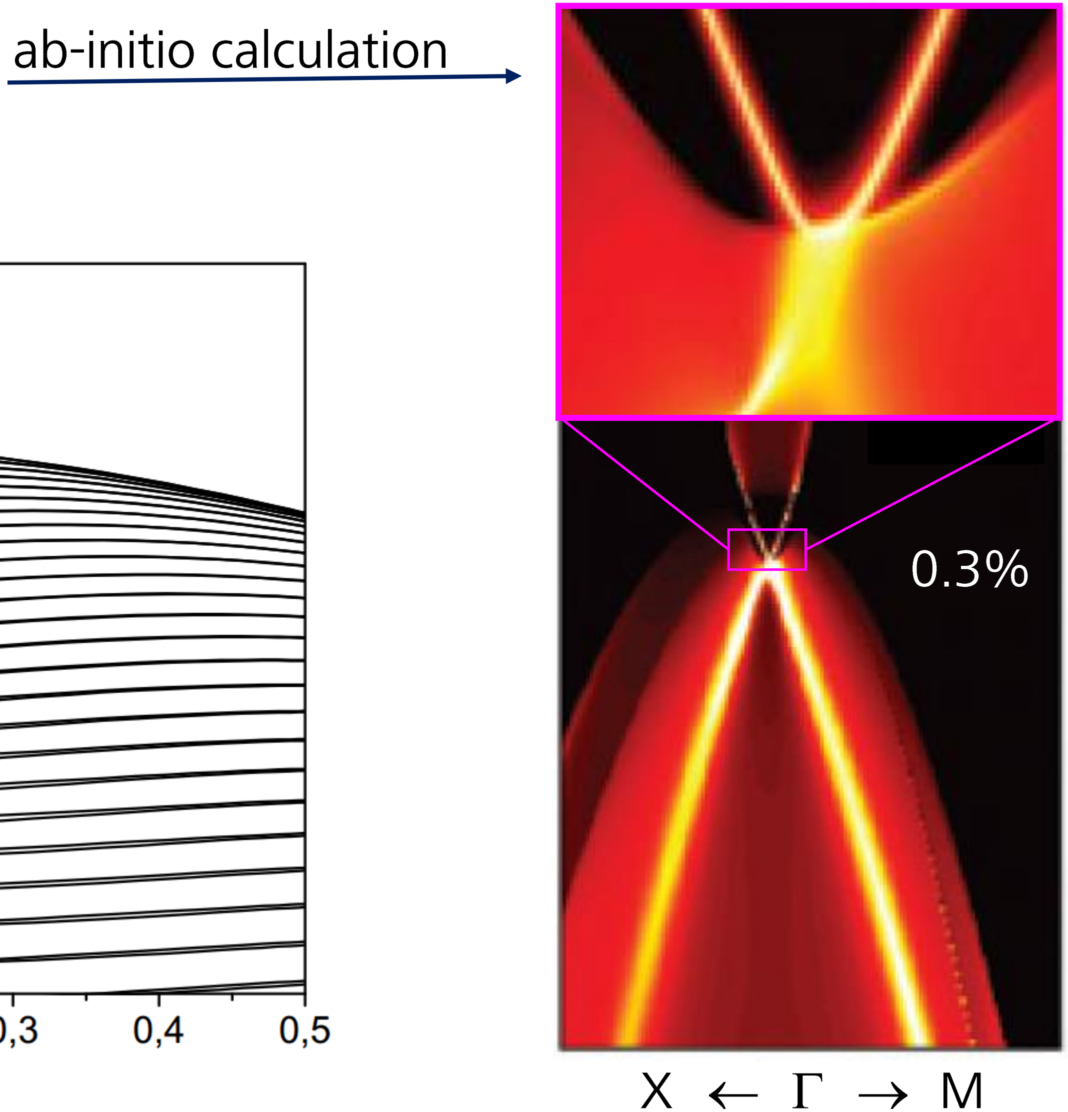
$E_{\Gamma 6} - E_{\Gamma 8} = -300$ meV

Fu & Kane PRB **76**, 045302 (2007):
Strained HgTe = strong TI

D. J. Chadi et al., PRB **5** 3058 (1972)

Band structure of strained HgTe (001)

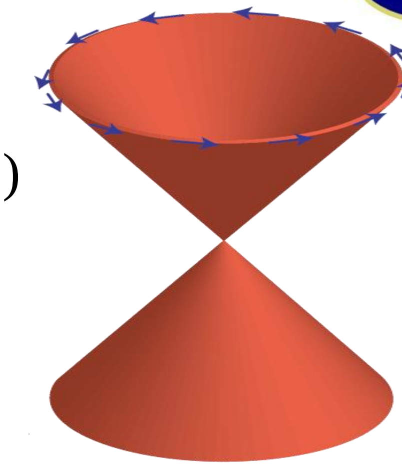




C. Brüne et al., PRL**106**,126803 (2011)

S.-C. Wu et al., EPL**107,** 57006 (2014)

Topological surface states



$$\hat{H}_{xy} = \hbar v_F (k_y \sigma_x - k_x \sigma_y)$$

$$E_{xy} = \pm \hbar v_F \sqrt{k_x^2 + k_y^2}$$

bulk
insulating

surface states
metallic like but with
finite density of states

<u>Signatures of topological surface states:</u>

Spin momentum locking

Phase of quantum oscillations (Berry phase)

States are spin-polarized,

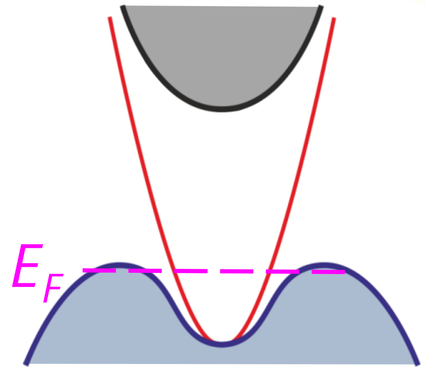
i.e., no spin splitting of LLs, $k_F = \sqrt{4\pi n_s}$

Outline

- Transport

  From Drude to quantum Hall effect: carrier densities

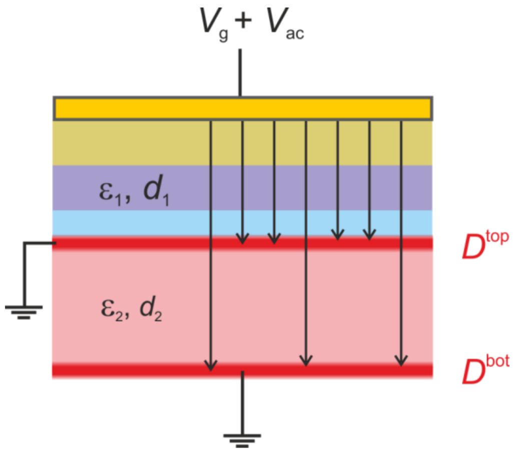
  Landau fan charts



- Quantum capacitance

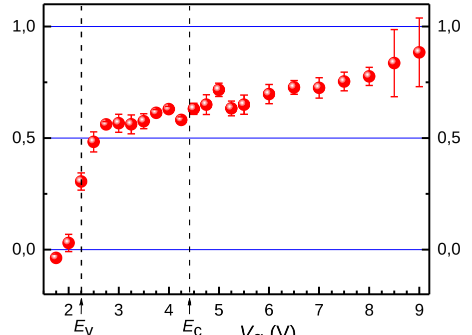
  Some basics

  Probes top surface only

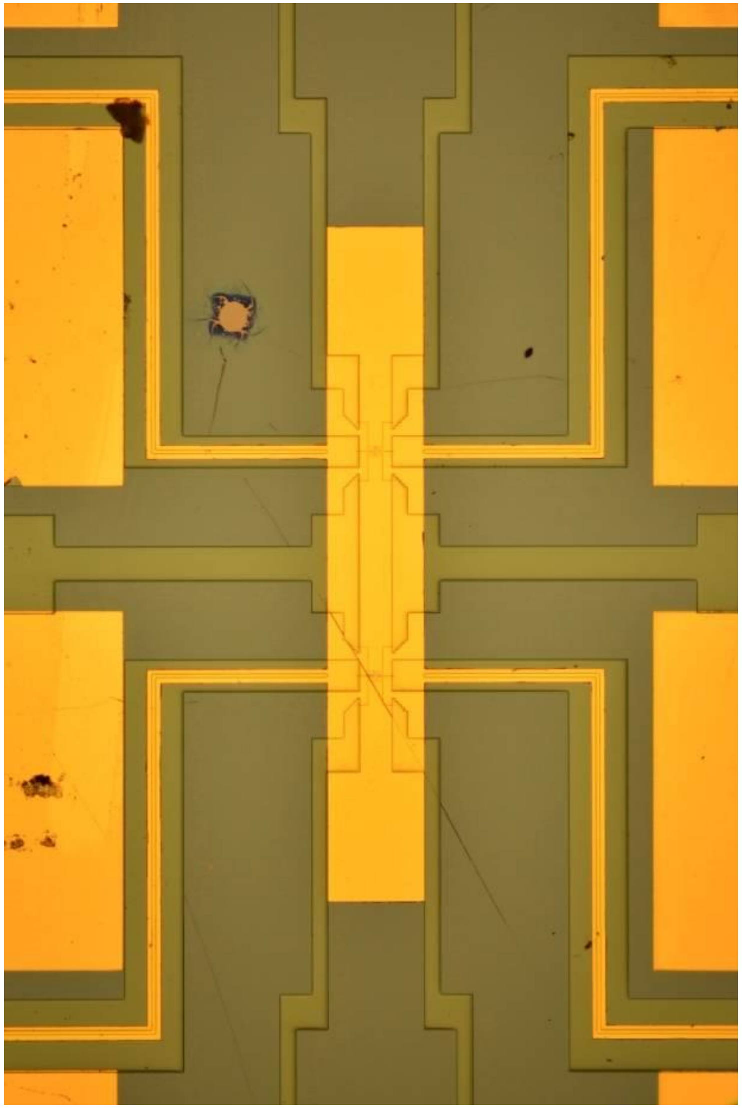


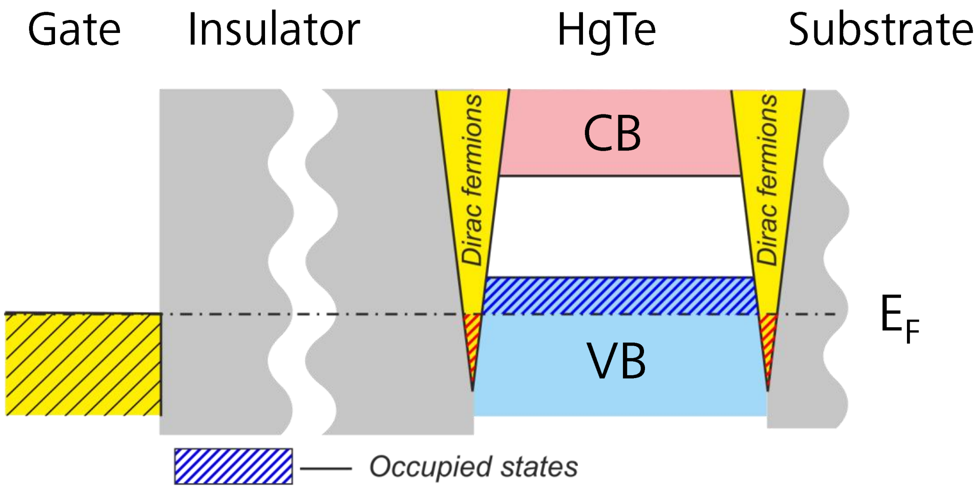
- Phase of quantum oscillations

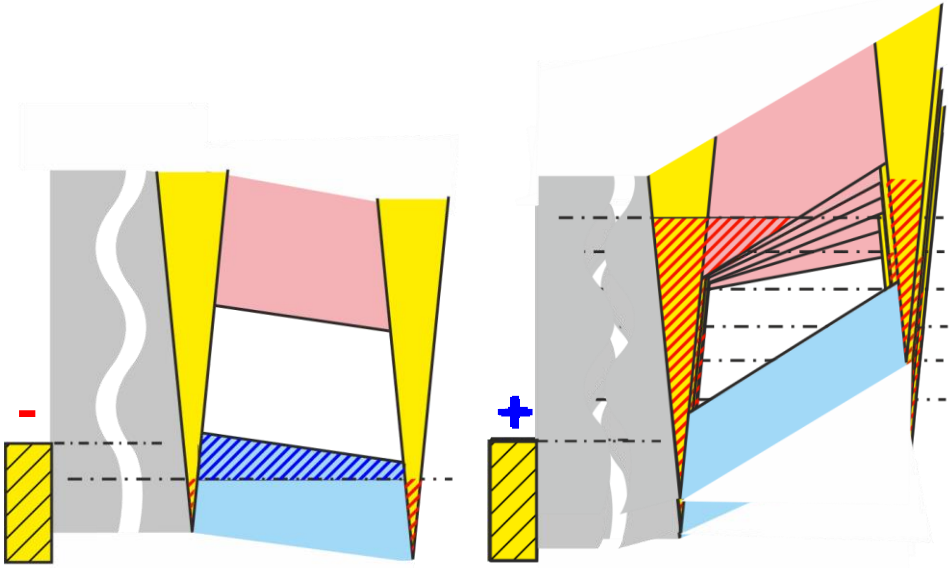
  Confirms topological nature of surface states



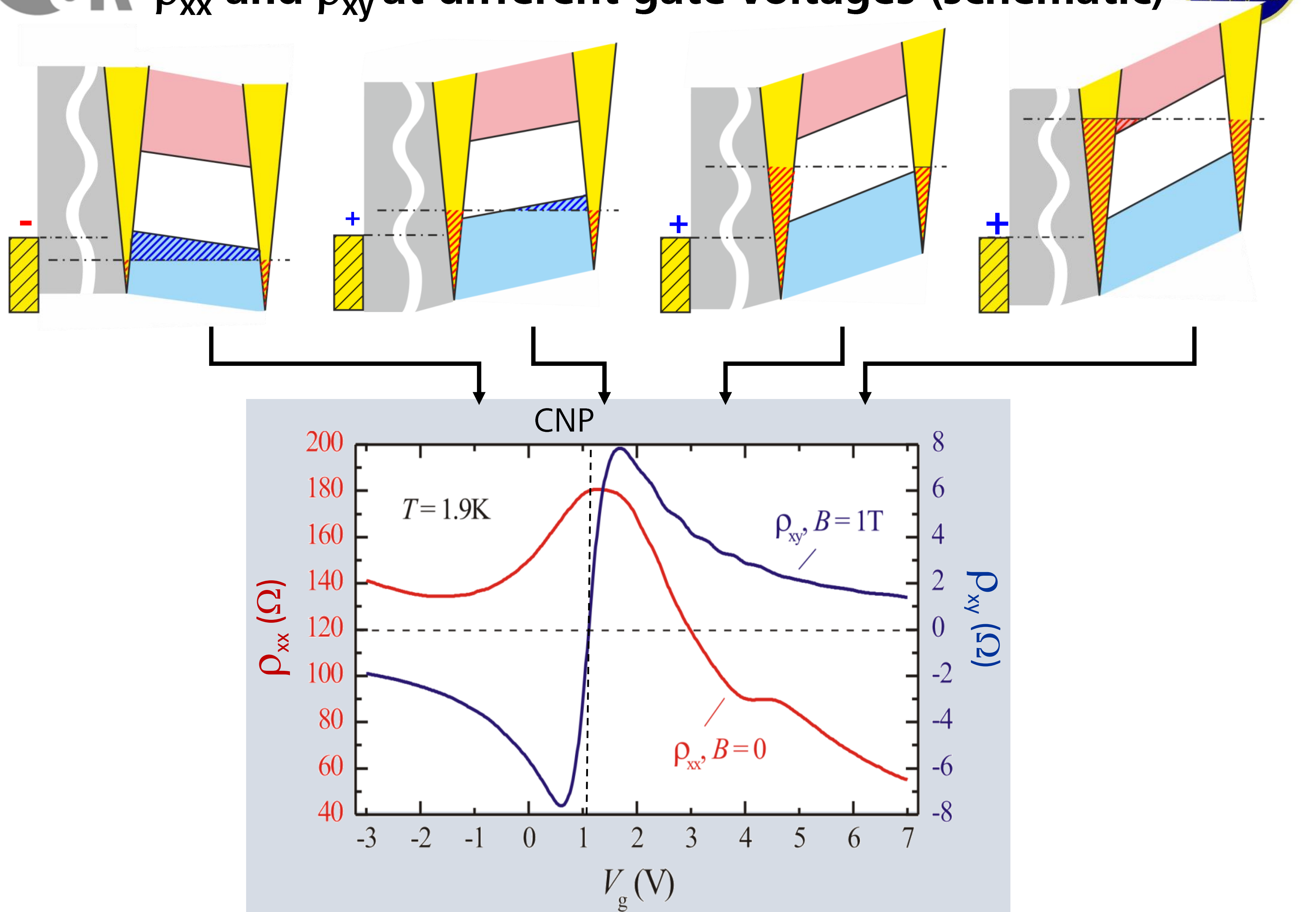
Gating



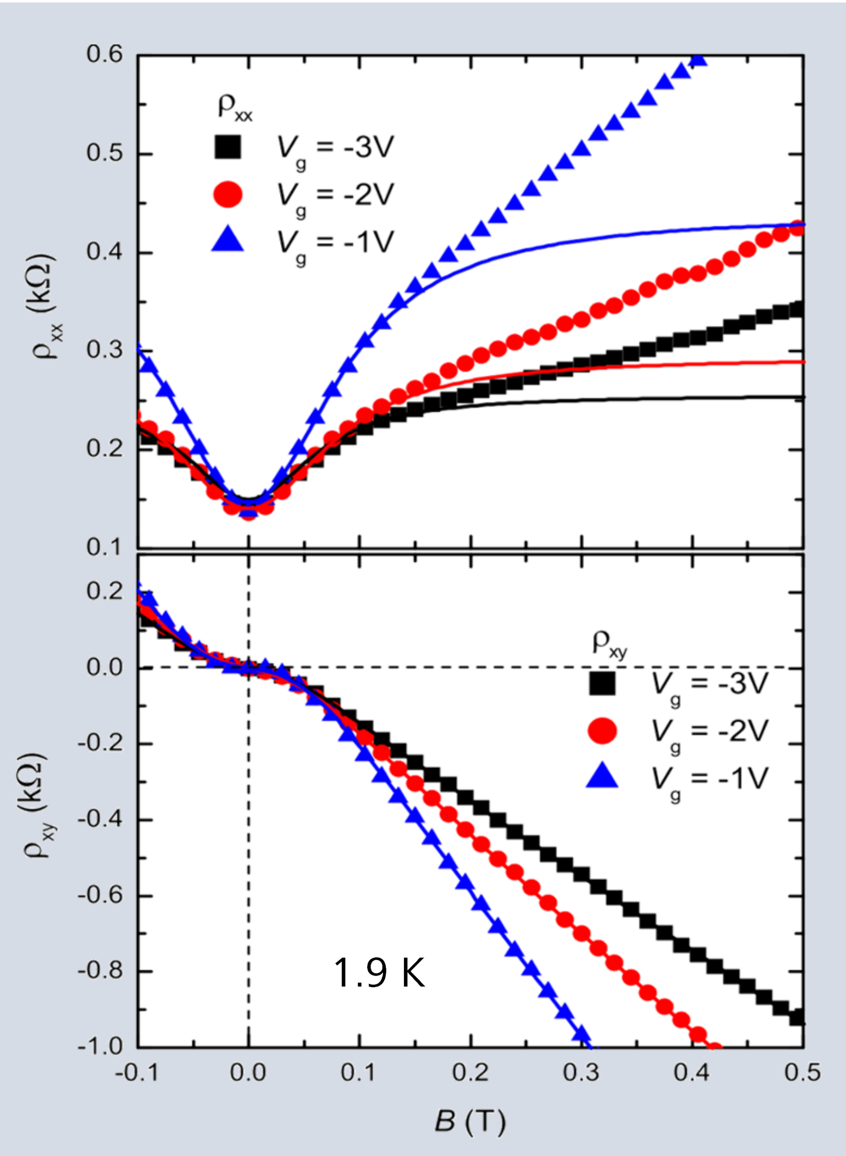

Gate
Insulator
HgTe
Substrate
CB
Dirac fermions
Dirac fermions
E_F
VB
Occupied states


-
+

ρ_{xx} and ρ_{xy} at different gate voltages (schematic)



N and P from 2-carrier Drude model



$$\sigma_{xx} = \sigma_{xx}^{(N)} + \sigma_{xx}^{(P)}$$

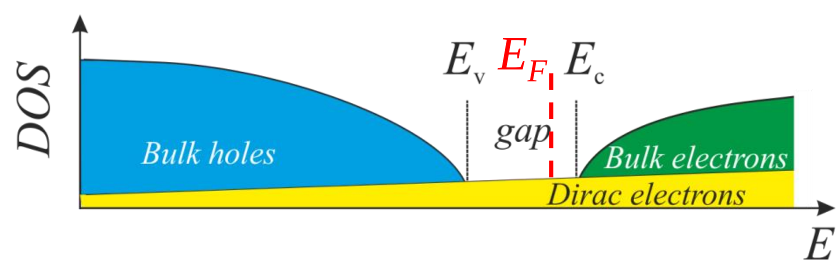
$$\sigma_{xy} = \sigma_{xy}^{(N)} + \sigma_{xy}^{(P)}$$

with

$$\sigma_{xx}^{(N)} = e\frac{N\mu_N}{1+(\mu_N B)^2}; \quad \sigma_{xx}^{(P)} = e\frac{P\mu_P}{1+(\mu_P B)^2};$$

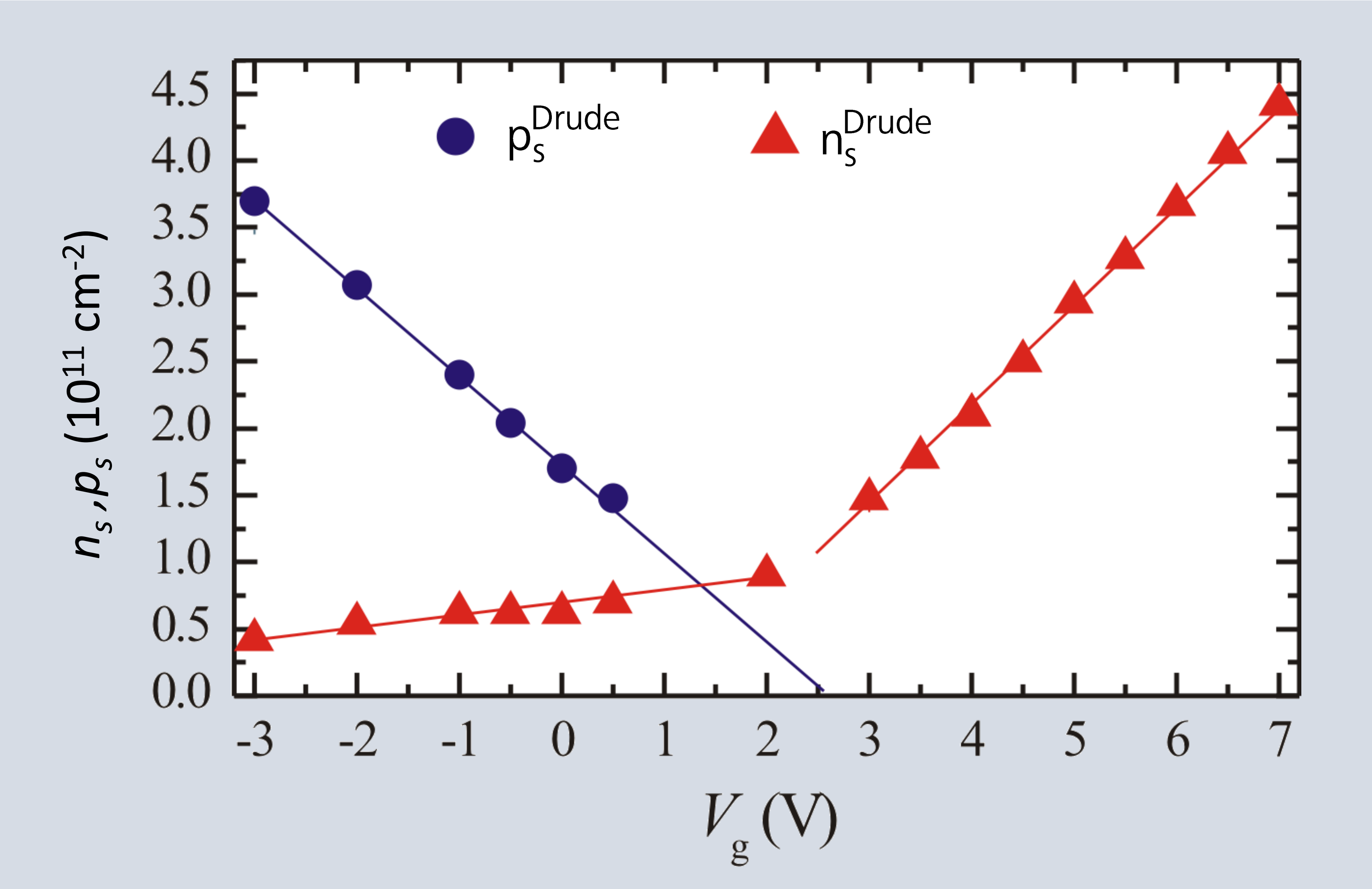
$$\sigma_{xy}^{(N)} = e\frac{N\mu_N^2 B}{1+(\mu_N B)^2}; \quad \sigma_{xy}^{(P)} = e\frac{P\mu_P^2 B}{1+(\mu_P B)^2}$$

ρ_{xx} and ρ_{xy} from tensor inversion



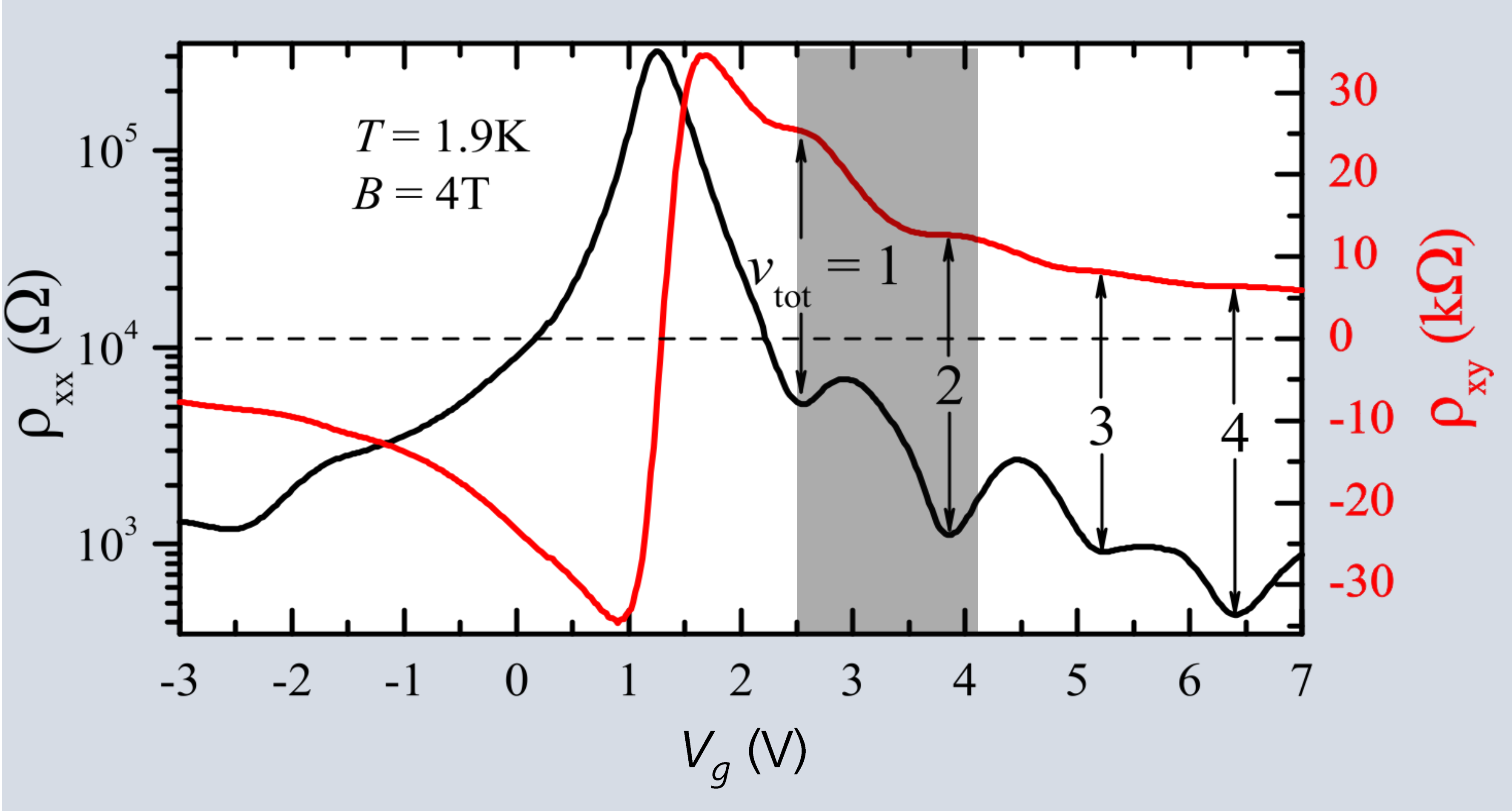
D. Kozlov et al., PRL **112**,196801 (2014)

From Drude model: $P(V_g)$ and $N(V_g)$



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

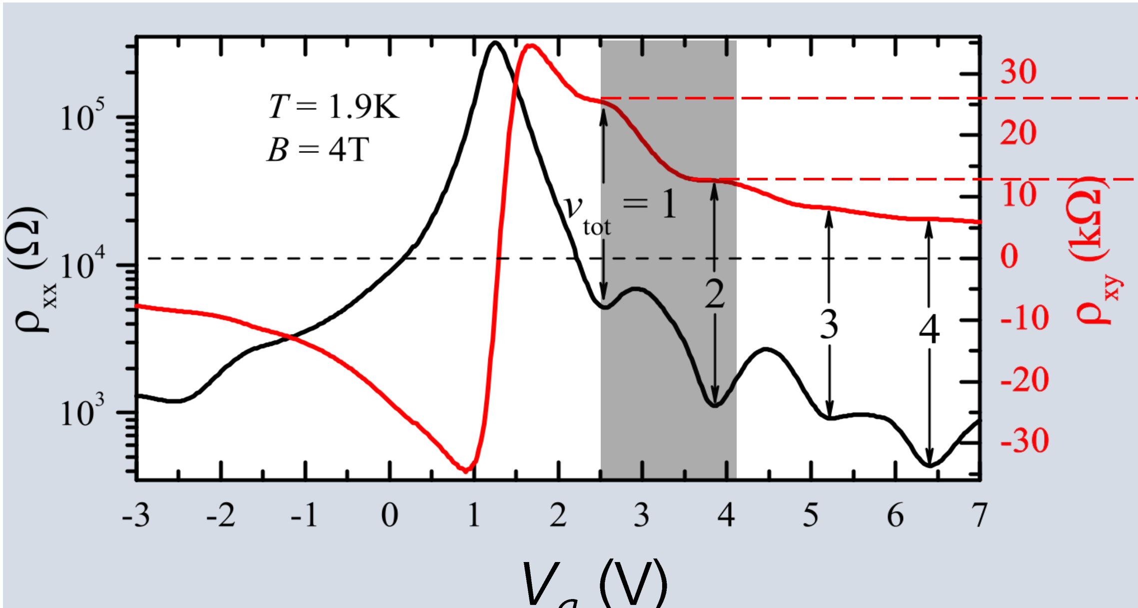
$\rho_{xx}(V_g)$ and $\rho_{xy}(V_g)$ in quantizing B - fields



Quantized ρ_{xx} values and SdH oscillations occur for E_F in the gap **and** in the conduction band

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

Carrier density from Shubnikov de Haas oscillations



$\sim 25.8 k\Omega = h/e^2$

$\sim 12.9 k\Omega = h/2e^2$

Condition for ρ_{xx} (σ_{xx}) Minimum

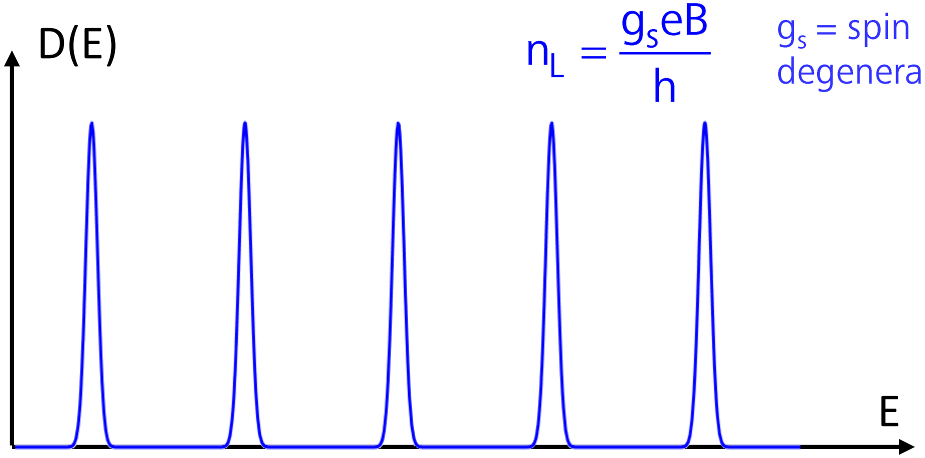
carrier density — filling factor — Landau level degeneracy

$$n_s = \nu \cdot n_L$$

n_s = const. B-sweep	B = const. V_g-sweep
$\Delta\left(\frac{1}{B}\right) = \frac{g_s e}{n_s h}$	$\Delta V_g = \frac{g_s e^2 B}{hC}$

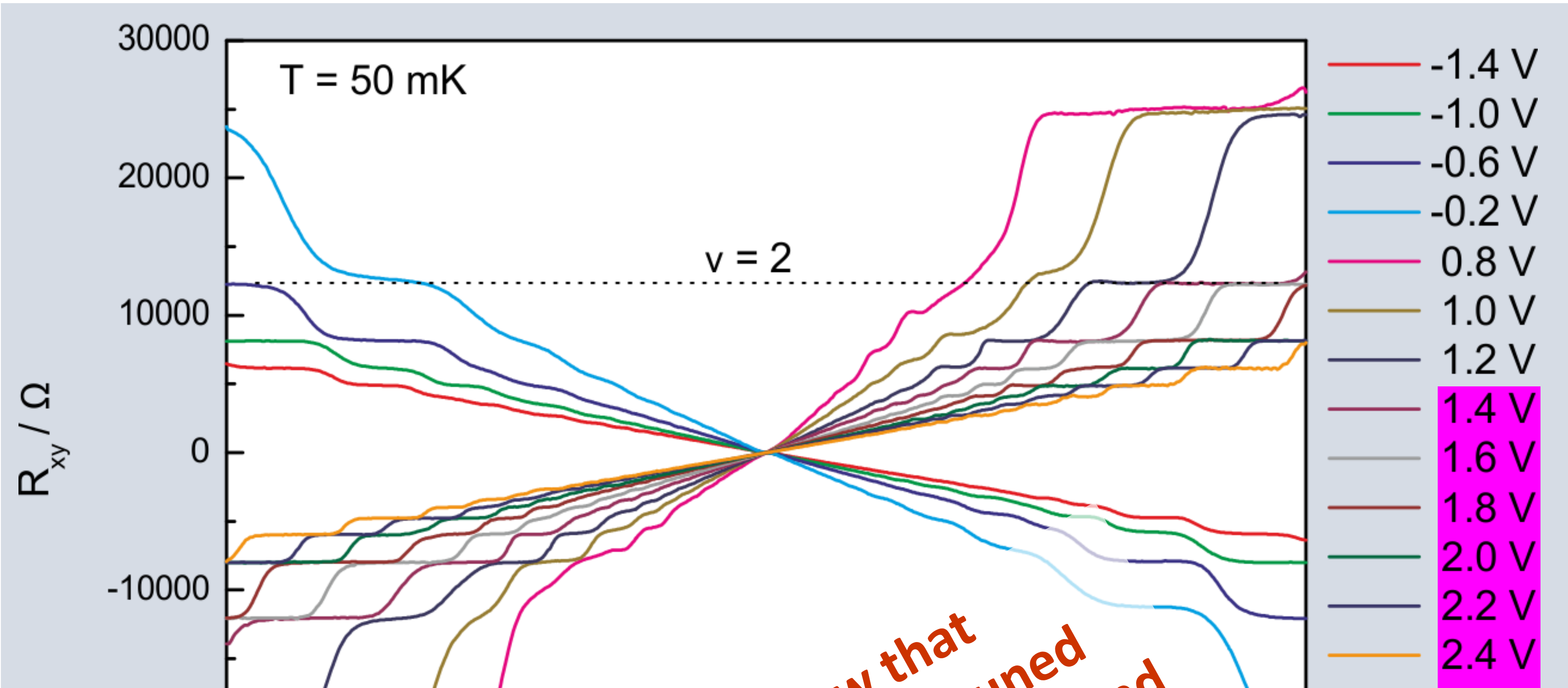
$$n_L = \frac{g_s eB}{h}$$

g_s = spin degeneracy



Quantized Hall resistance at mK temperatures

(different sample)



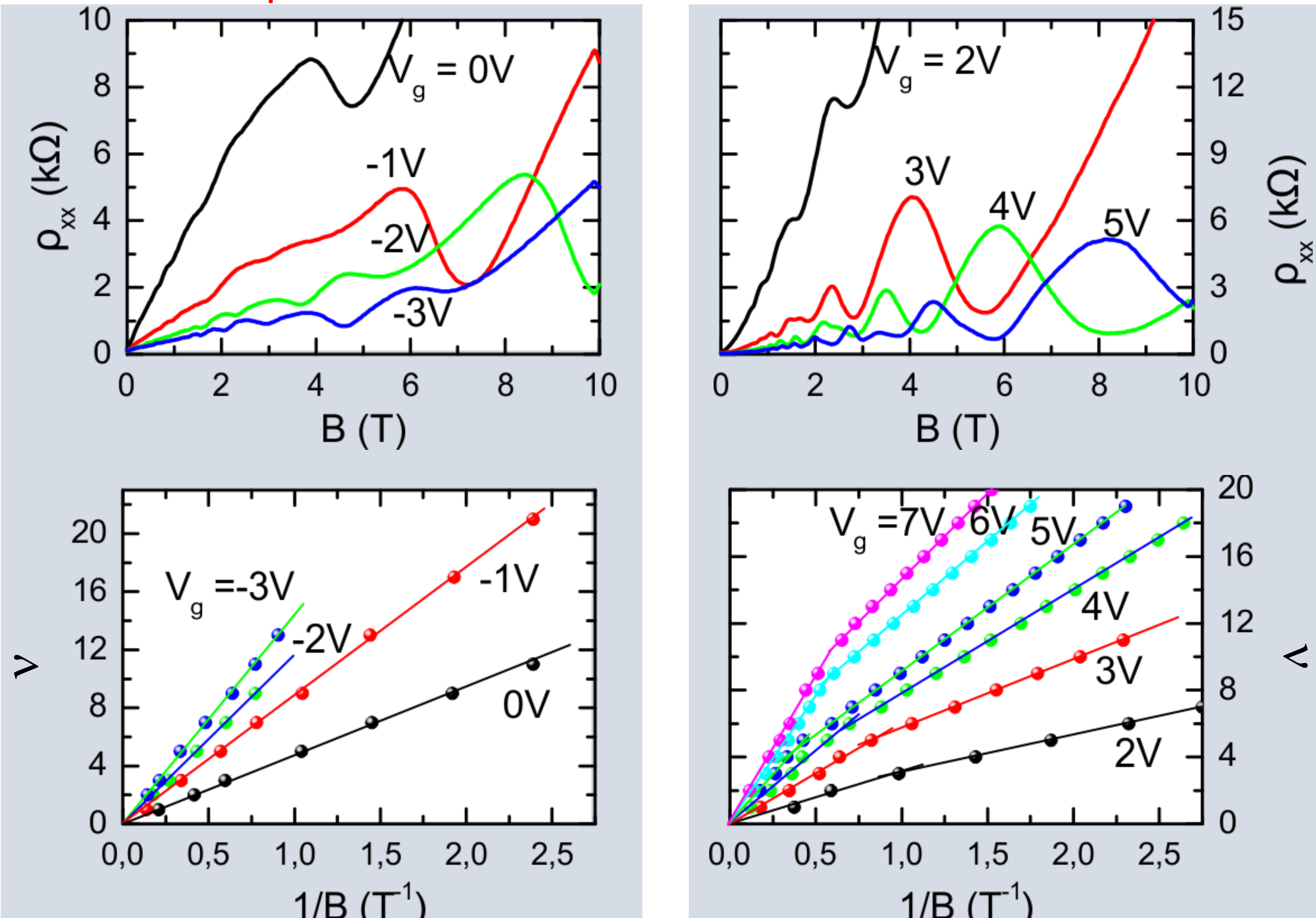
"Within this model, we find that the Fermi energy resides in the band gap for all applied gate voltages, in agreement with our experiments. Additional charge on the gates results mainly in a shift of the position of the Dirac points of the surface states, while the location of the Fermi level is hardly affected."

Molenkamp group PRX **4**, 041045 (2014)

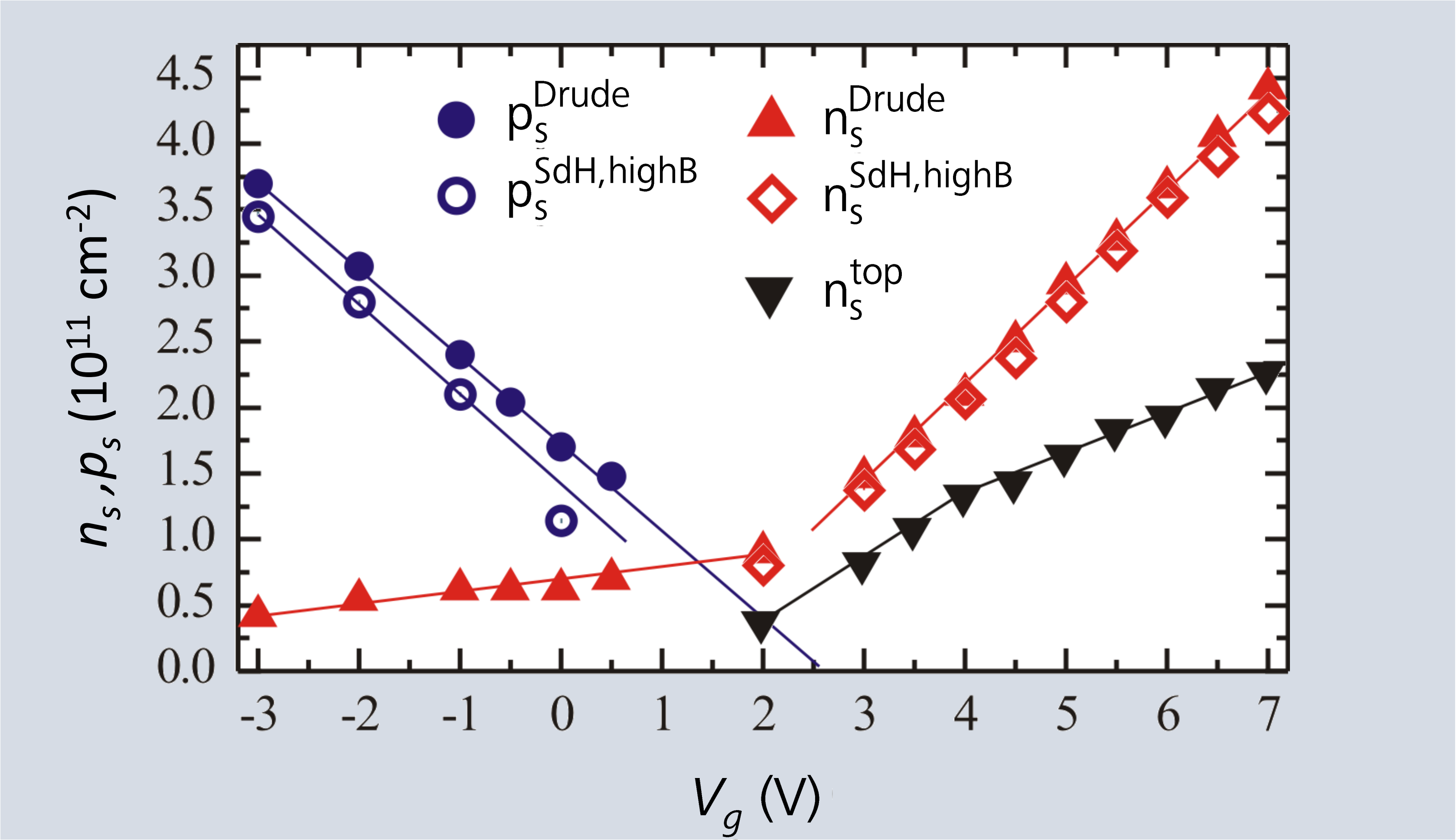
our experiments show that Fermi level can be easily tuned from valence to conduction band

ρ_{xx} at different V_g

p-side n-side



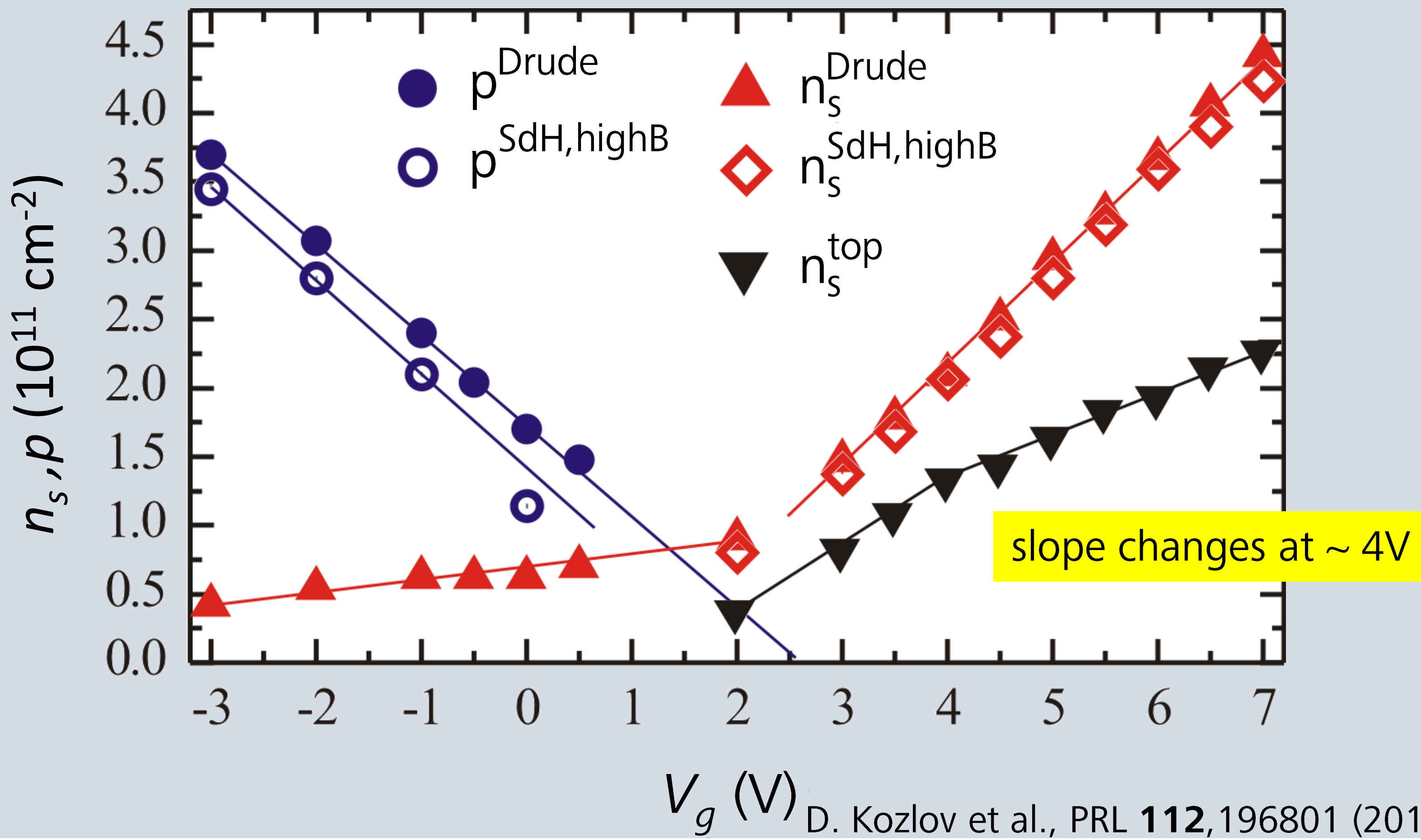
N, P obtained from Drude and SdH (QHE)



$E_F > E_V$: Period of SdH oscillations at high B determined by total electron density

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

Slope change of $n_s^{top}(V_g)$



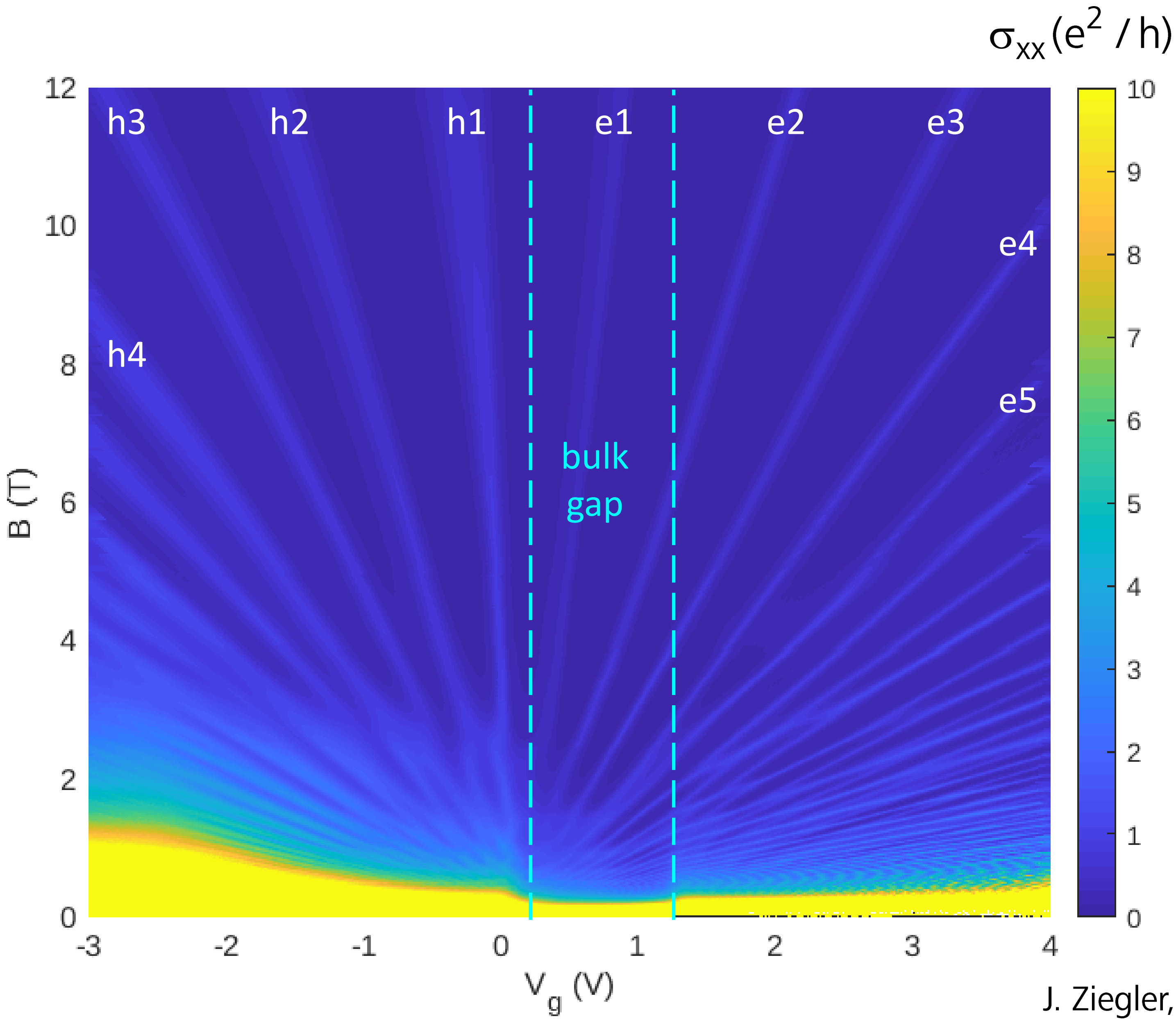
D. Kozlov et al., PRL **112**,196801 (2014)

filling rate :

$$\frac{dn_s}{dV_G} = \frac{dn_s^{top}}{dV_G} + \frac{dn_s^{bulk}}{dV_G} + \frac{dn_s^{bot}}{dV_G} = \frac{C}{e} \sim \text{constant} \Rightarrow$$

Reduced slope dn_s^{top} / dV_g reflects E_F entering the conduction band

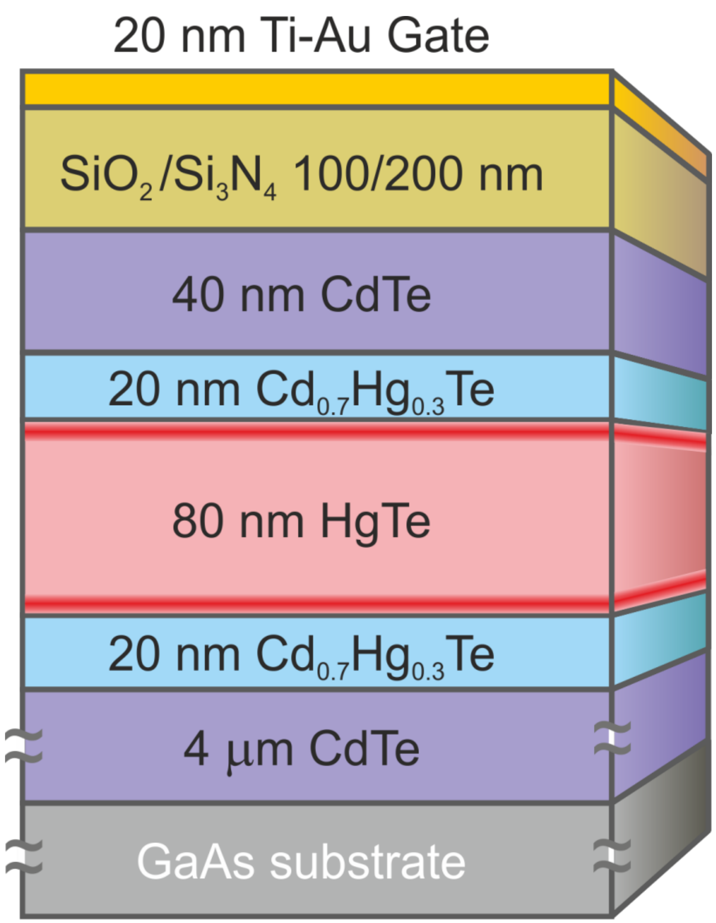
Landau-level fan chart

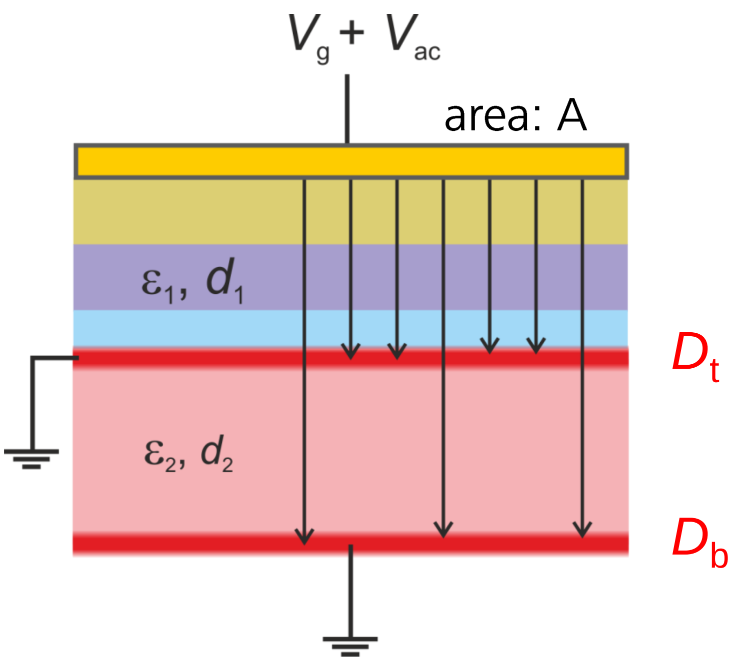


J. Ziegler, unpublished

Magnetocapacitance measurements

reflects density of states, sensitive primarily to top surface

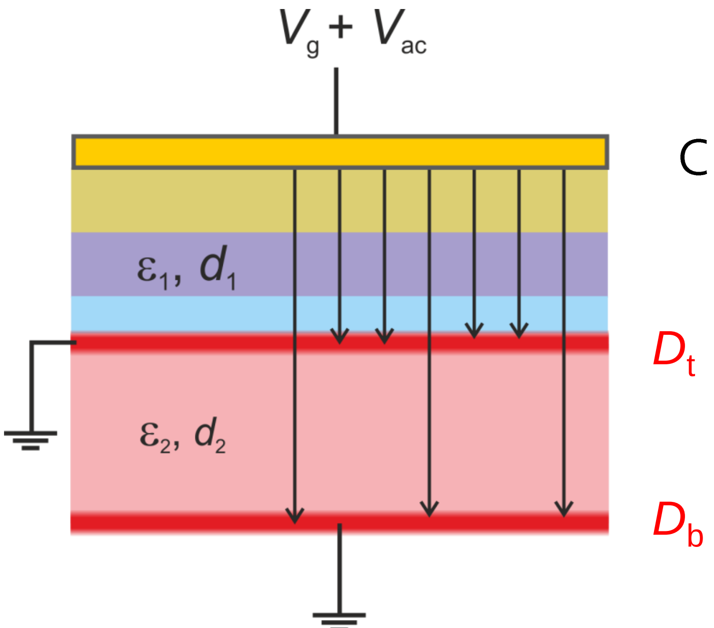


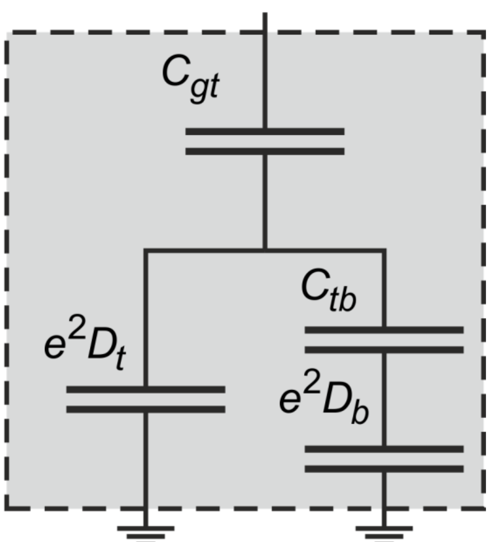


Total capacitance depends also on quantum capacitance Ae^2D in series to the geometrical capacitance $\varepsilon\varepsilon_0 A / d$

S. Luryi, APL **52**, 501 (1988)

Capacitance (equivalent circuit for E_F in gap)





$$C = \frac{C_{gt}e^2(C_{tb}D_b + e^2D_tD_b + D_tC_{tb})}{e^2C_{tb}D_b + e^4D_tD_b + e^2C_{tb}D_t + e^2C_{gt}D_b + C_{gt}C_{tb}}$$

$$\frac{\partial C / \partial D_t}{\partial C / \partial D_b} = \frac{(e^2D_b + C_{tb})^2}{C_{tb}^2}$$

measured capacitance most sensitive to top layer

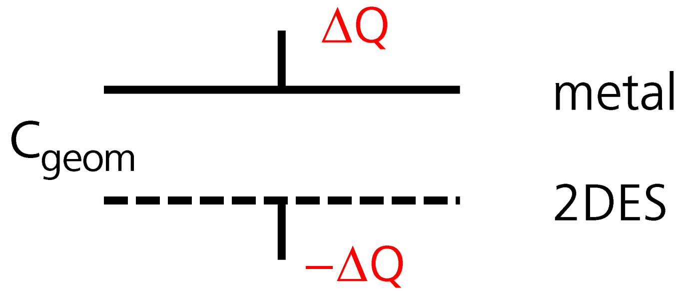
For $C_{tb} \to 0$ or $D_b \to 0$

$$\frac{1}{C} = \frac{1}{C_{gt}} + \frac{1}{e^2D_t}$$

usual result for conventional 2DES

T.P. Smith III et al, PRB **32**, 2696 (1985)

The quantum capacitance



Quantum capacitance = $e^2D(E)$

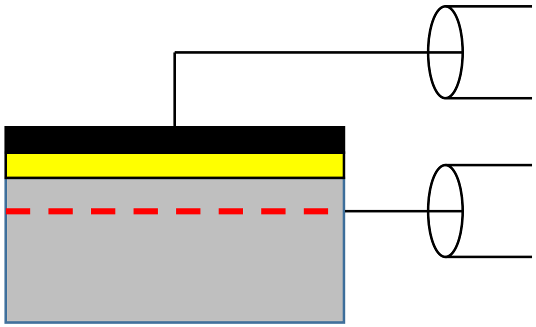
Voltage change connected to addition of charge ΔQ: $\Delta V_{galv} = \dfrac{\Delta Q}{C_{geom}} = \dfrac{Ne}{C_{geom}}$

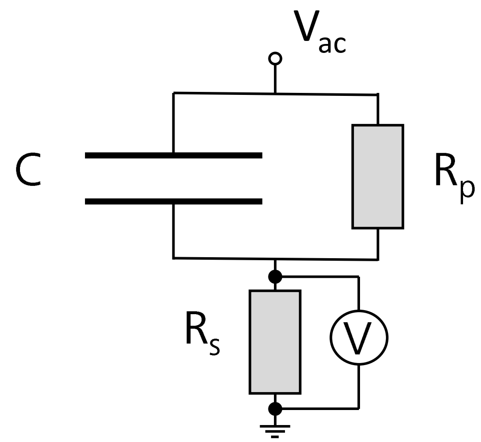
Adding, e.g., N electrons to 2DES changes chemical potential by: $\Delta\mu = \dfrac{N}{D(E)} = \dfrac{\Delta Q}{eD(E)}$

The change by $\Delta\mu$ is connected to a change in voltage: $\Delta V_q = \dfrac{\Delta\mu}{e} = \dfrac{\Delta Q}{e^2 D(E)}$

Total voltage change $\Delta V = \Delta V_{galv} + \Delta V_q = \dfrac{\Delta Q}{C_{geom}} + \dfrac{\Delta Q}{e^2 D(E)} \Rightarrow \dfrac{1}{C} = \dfrac{1}{C_{geom}} + \dfrac{1}{e^2 D(E)}$

Capacitance measurements





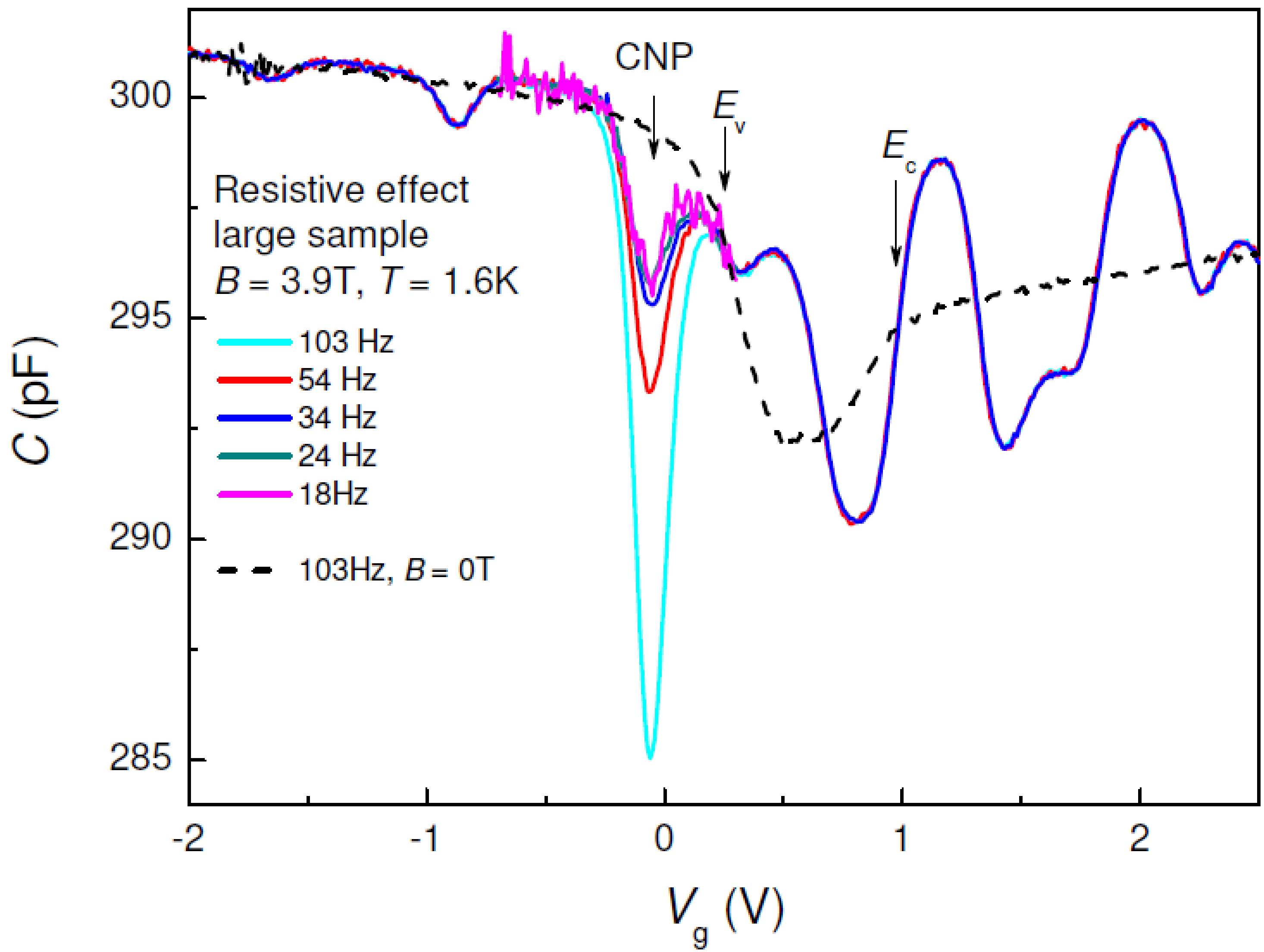
$$Z = \left(\frac{1}{i\omega C} + \frac{1}{R_p} \right)^{-1} + R_s$$

Imaginary part of voltage signal (= out-of-phase signal of Lock-in amplifier) reflects capacitance, real part ohmic contribution

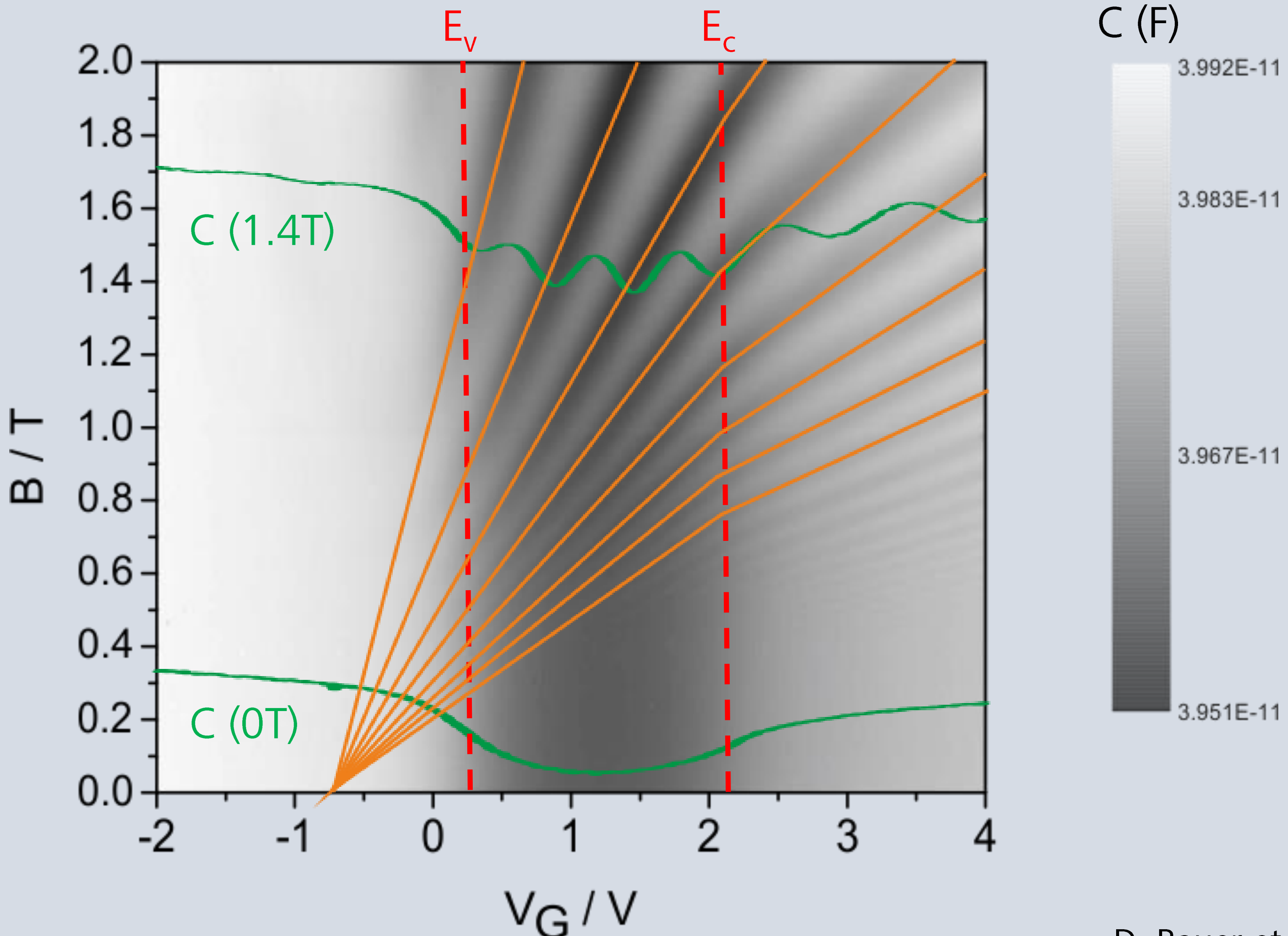
Signal is only proportional to capacitance if $\omega R_s C << 1$

Typical capacitances: ~5 – 50 pF

Only low frequencies reflect DOS…..



Magnetocapacitance



D. Bauer et al.

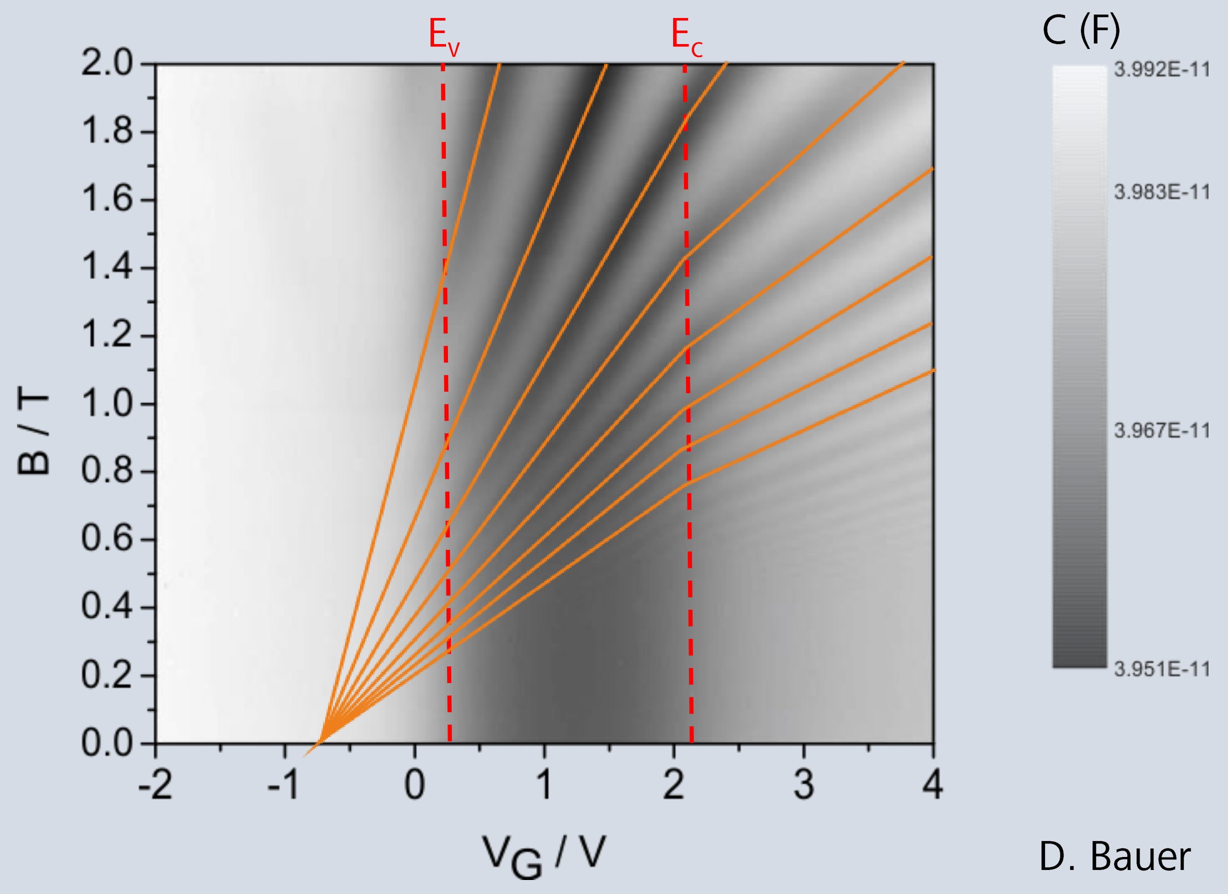
Magnetocapacitance

Meaning of slope:

Lines mark LL minima→

$$n_s = \nu n_L = \nu \frac{eB_\nu}{h} \rightarrow$$

$$B_\nu = \frac{1}{\nu}\frac{h}{e} n_s \rightarrow \frac{dB_\nu}{dV_g} = \frac{1}{\nu}\frac{h}{e}\underbrace{\frac{dn_s}{dV_g}}_{\text{filling rate}}$$



D. Bauer

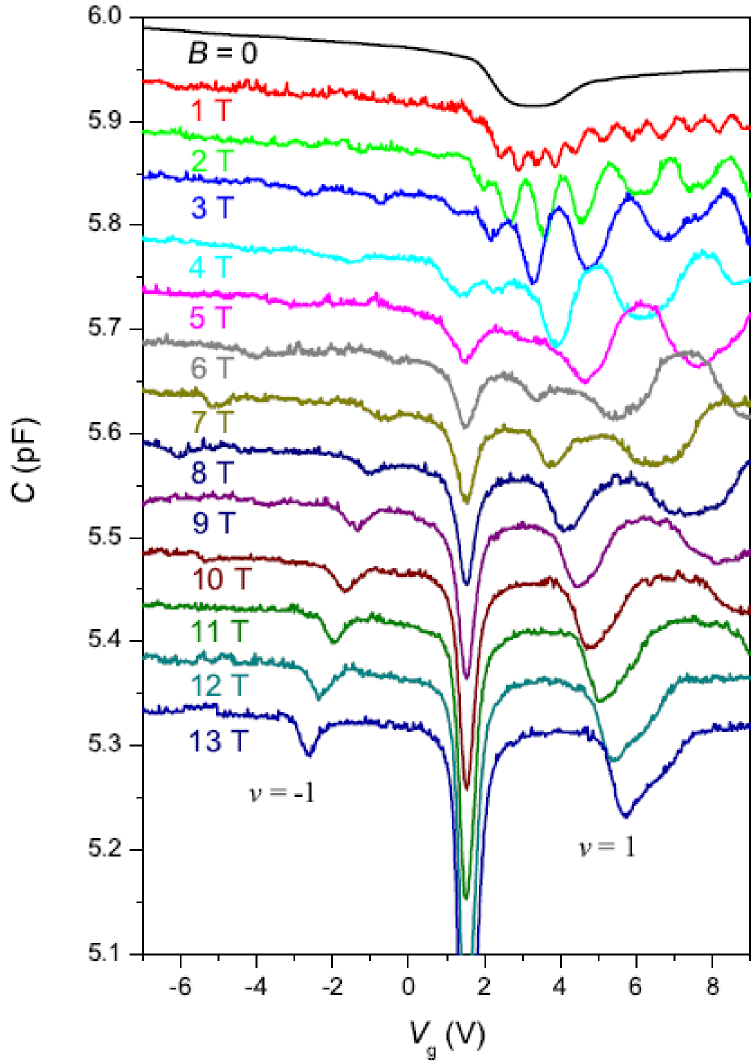
$$\frac{dn_s}{dV_G} = \frac{dn_s^{top}}{dV_G} + \frac{dn_s^{bulk}}{dV_G} + \frac{dn_s^{bottom}}{dV_G} \propto C \approx \text{constant} \Rightarrow$$

Reduced slope dB_ν/dV_G reflects E_F entering the conduction band

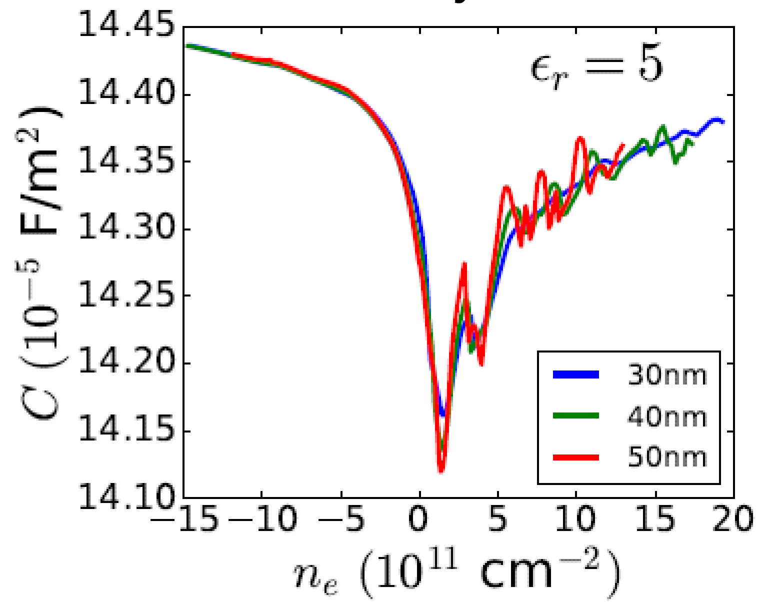
D. Kozlov, et al., PRL **116** 166802 (2016)

Capacitance: Comparison Theory-Experiment

Experiment



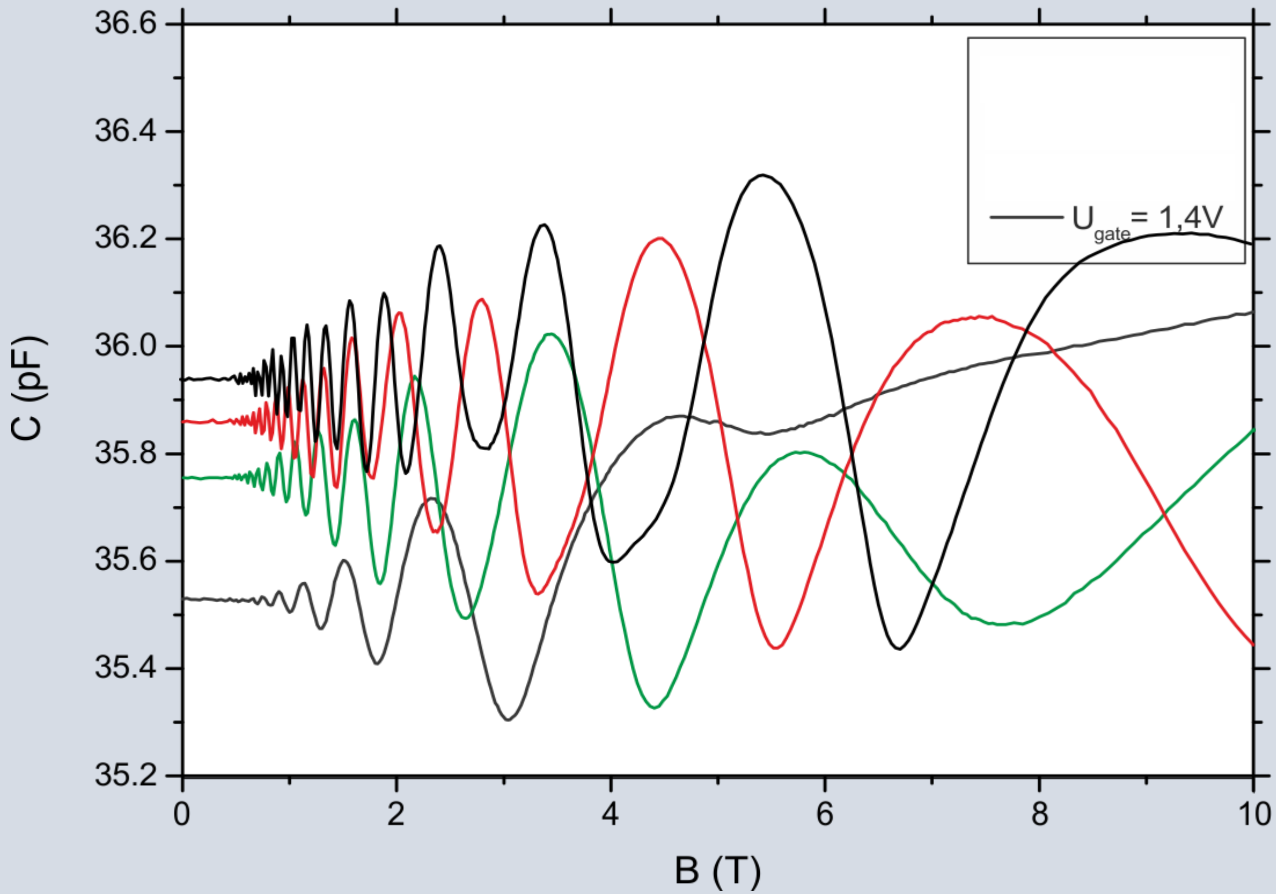
Theory



..the Fermi level can be easily tuned into the quasi-2D conduction and valence bands…
The phenomenological effective potential for the sake of keeping the Fermi level within the bulk gap is not proper.

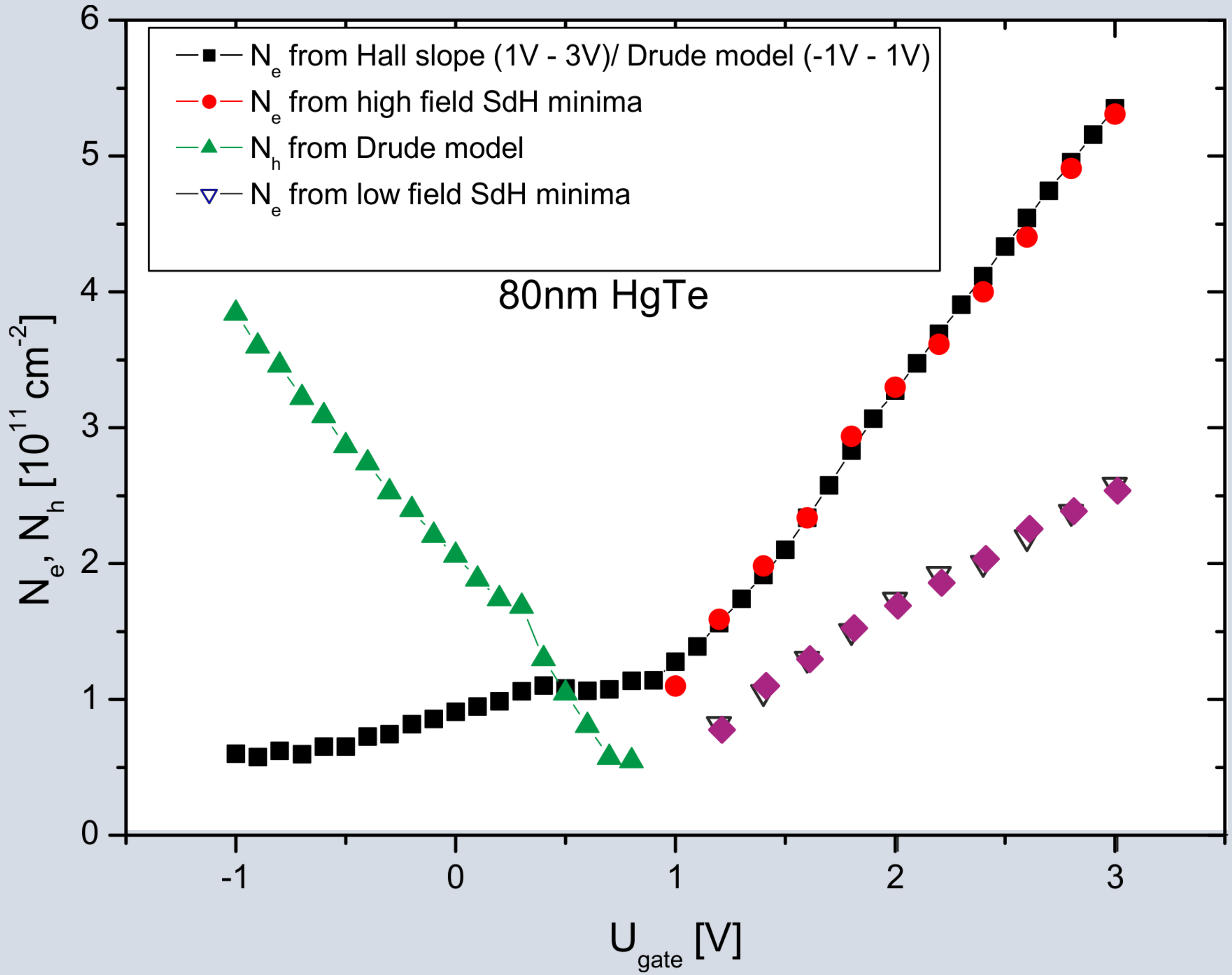
J. Zhu, C. Lei, A. H. MacDonald, arXiv:1804.01662 (2018)

Magnetocapacitance oscillations



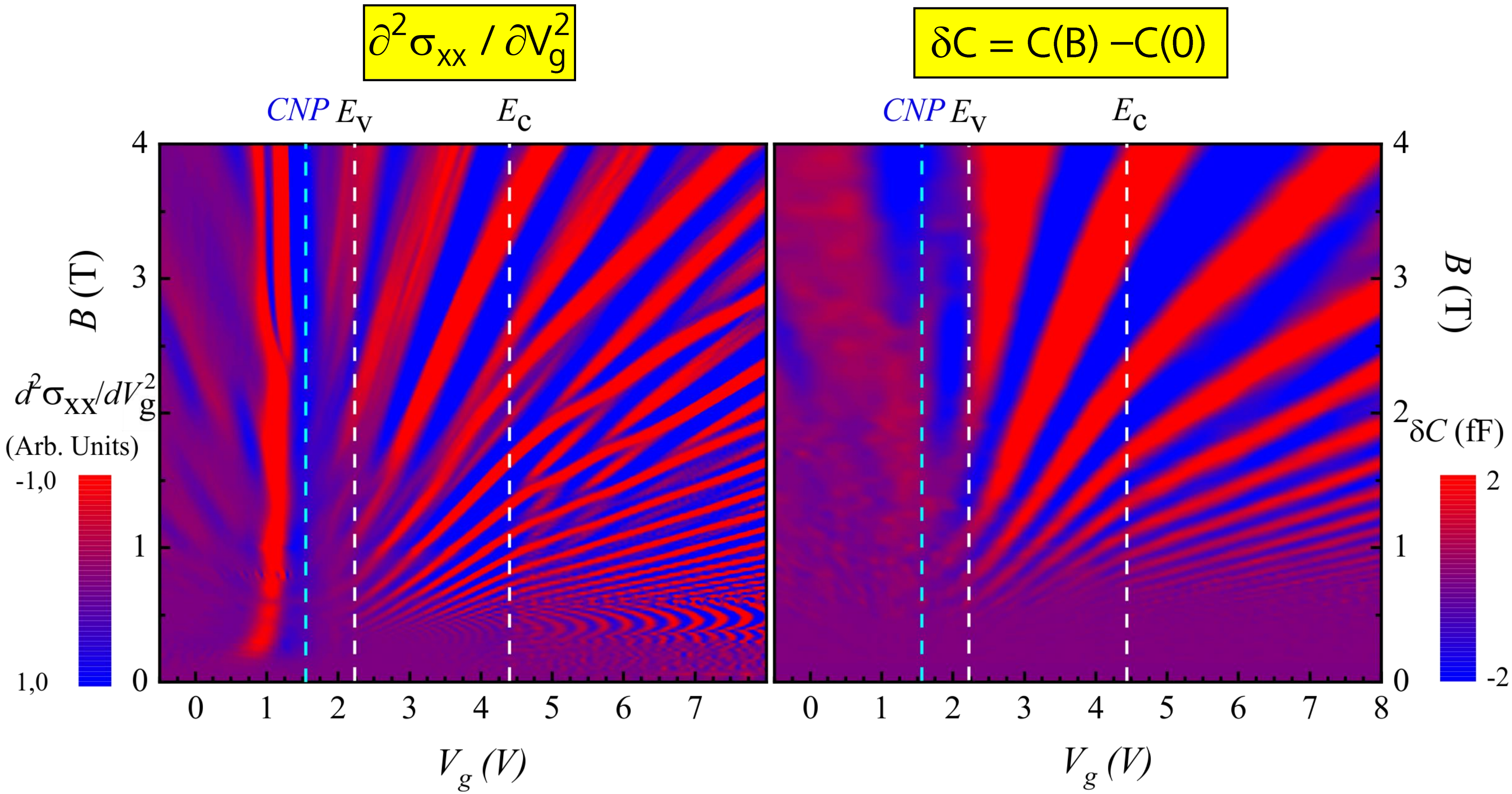
D. Kozlov, et al., PRL **116** 166802 (2016)

Comparison: Density from SdH and C(B)



R. Fischer, J. Ziegler et al

Comparison of transport and capacitance



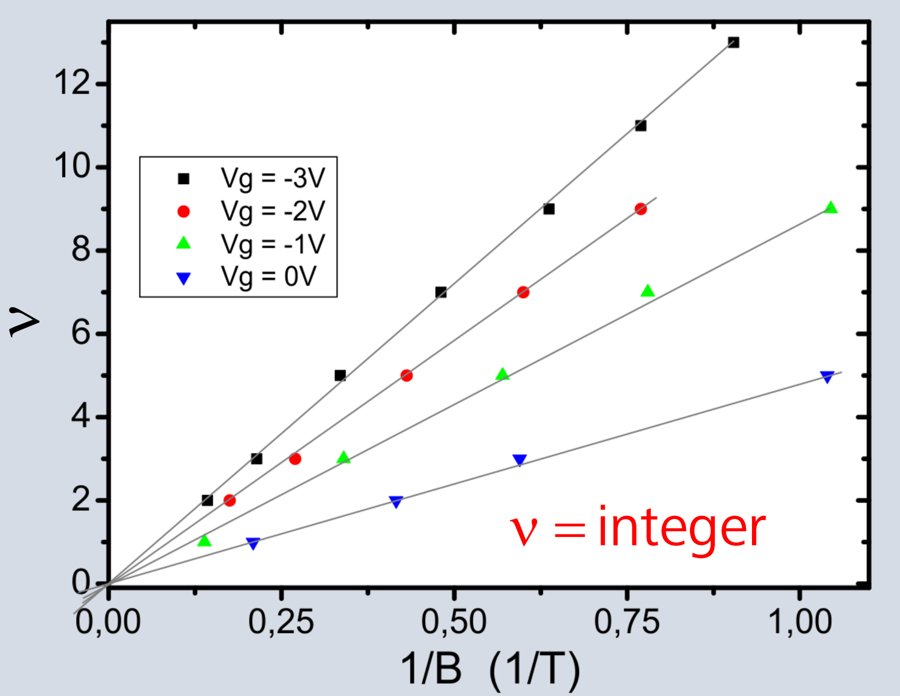
σ_{xx} displays for E_F in the conduction band more complex behavior

Capacitance probes predominatly top surface

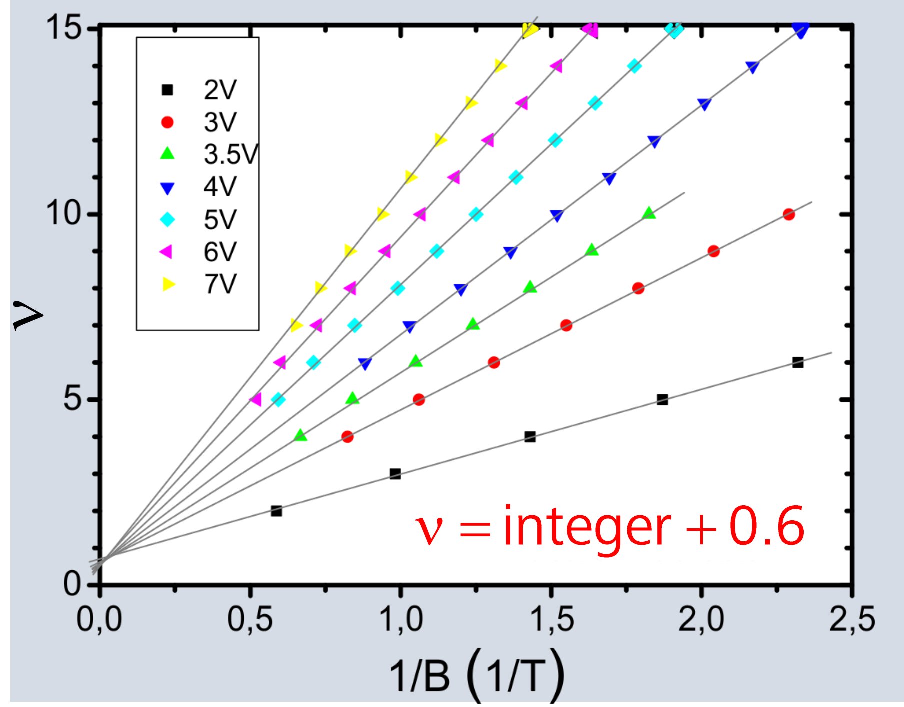
D. Kozlov, et al., PRL **116** 166802 (2016)

Phase of SdH oscillations

SdH (valence band)



Low-B SdH (gap and conduction band)



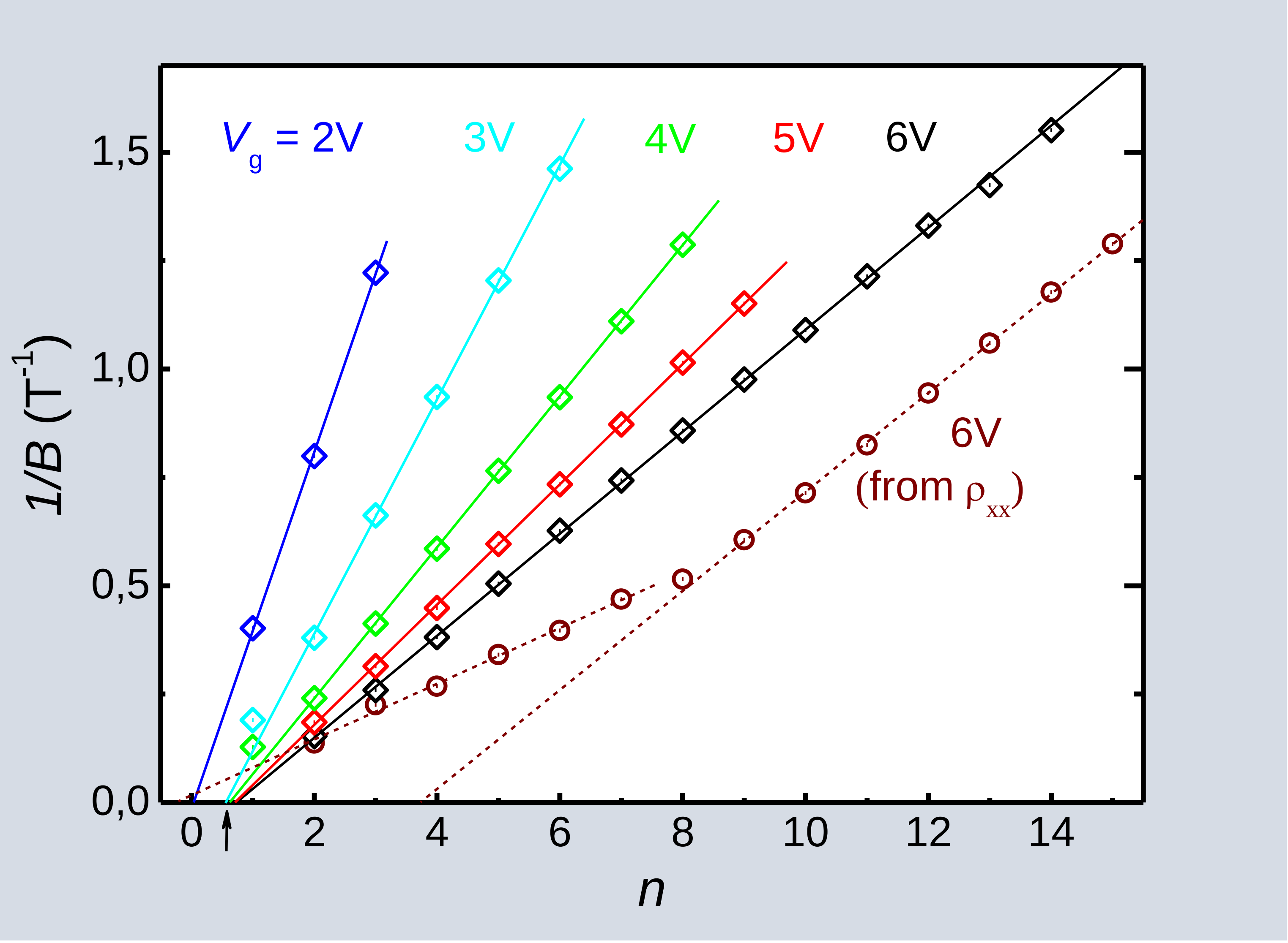
SdH-oscillations: $\Delta\rho_{xx} \propto \cos\left(2\pi\left[\frac{hn_s}{eB} - \gamma\right]\right)$; $\gamma - \frac{1}{2} = -\frac{1}{2\pi}\oint \mathbf{\Omega} d\mathbf{k}$ [*]

($\frac{hn_s}{eB}$: ν; $\oint \mathbf{\Omega} d\mathbf{k}$: Berry phase)

Dirac: $\oint \mathbf{\Omega} d\mathbf{k} = \pi$; 2DEG: $\oint \mathbf{\Omega} d\mathbf{k} = 0 \Rightarrow$ SdH minima for ν=integer (2DEG)
SdH minima for ν=half-integer (Dirac)

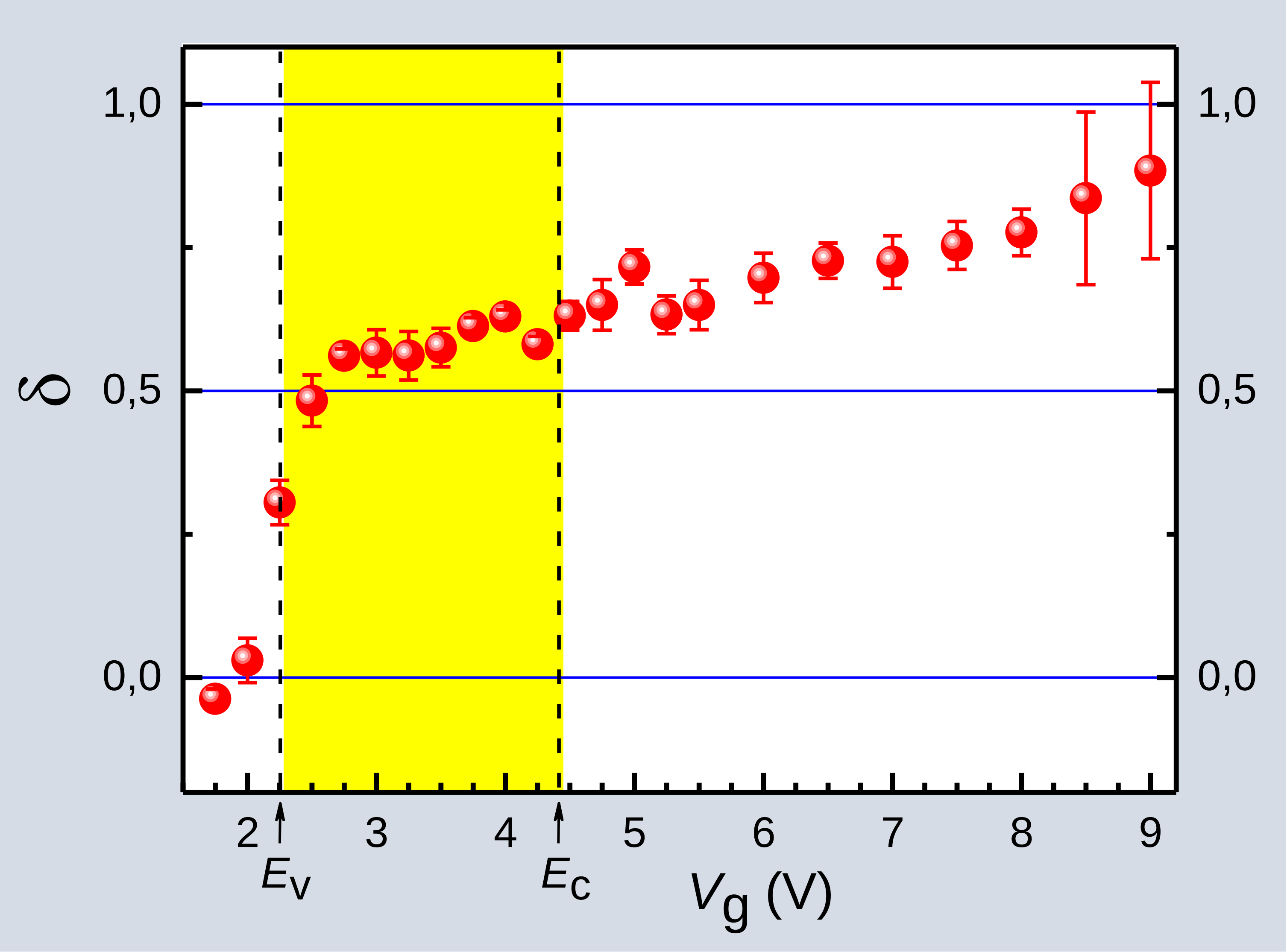
[*] see, e.g., A. A. Taskin and Y. Ando, Phys. Rev. B **84**, 035301 (2011)

Phase of quantum capacitance oscillations



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

Phase of quantum capacitance oscillations



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