Magnetotransport in high-mobility Ge/SiGe quantum wells

Qianhui Shi, Michael Zudov
University of Minnesota, Minneapolis, USA

Christopher Morrison, Maksym Myronov
University of Warwick, Coventry, UK

U.S. DEPARTMENT OF ENERGY
Office of Science
Basic Energy Sciences
THE UNIVERSITY OF WARWICK
NATIONAL HIGH MAGNETIC FIELD LABORATORY
UNIVERSITY OF MINNESOTA
Driven to Discover℠

Outline

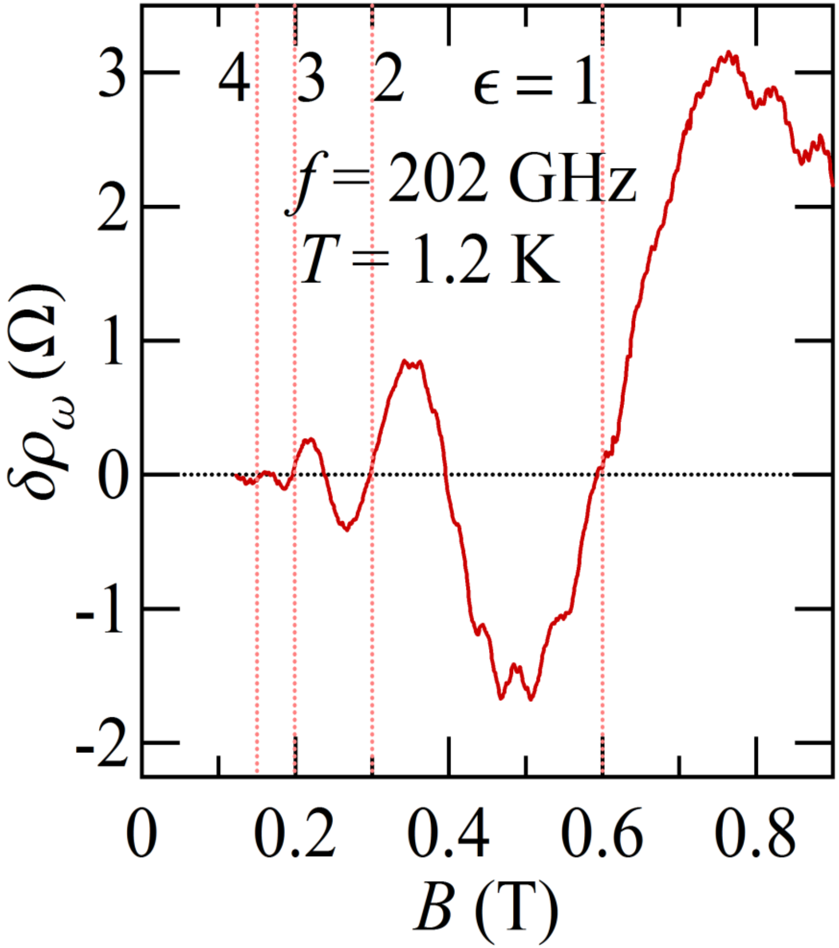
- High-mobility Ge quantum wells:
  - Ge/SiGe 17/20 nm-wide QW (Boron doped)
  - $p \approx 2.8/2.9 \times 10^{11}\ \mathrm{cm}^{-2},\ \mu \approx 1.3 \times 10^{6}\ \mathrm{cm}^{2}/\mathrm{Vs}$
- Noneuilibrium transport
  - First observations of MIRO and HIRO outside GaAs
- Fractional quantum Hall effect
  - First observation of FQHE in Ge
- Tilt-field induced transport anisotropy
  - New class of transport anisotropy

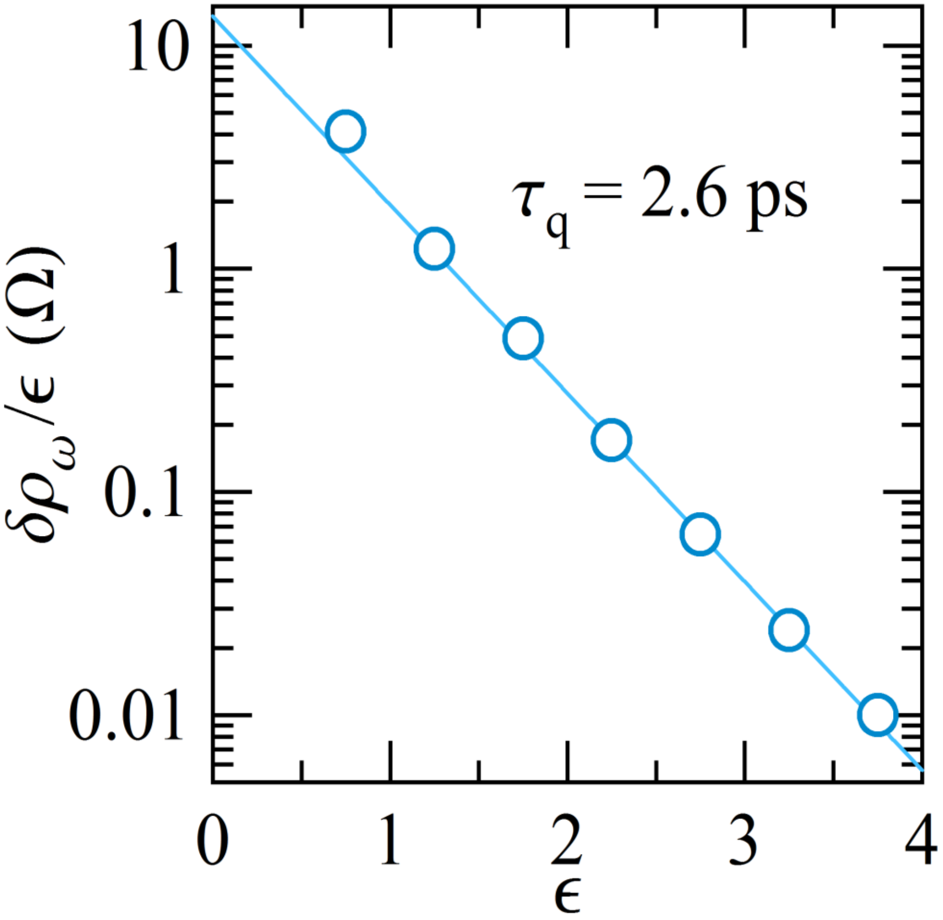
How does Ge compare to GaAs?

- Crystal structure
  - GaAs: zinc blende
  - Ge: diamond, **no** Dresselhaus spin-orbit coupling
- g-factor
  - GaAs: $g_\perp \approx 0.41,\ \ g_\parallel \approx 0.34$
  - Ge: $g_\perp \sim 10,\ \ g_\parallel \approx 0$, 2D spin gas
  - **Ge has larger Zeeman energy, independent of $B_\parallel$**
- Band structure
  - Ge 2DHG: only heavy hole band is populated
  - **Ge 2DHG is more like 2DEG than 2DHG in GaAs**

see, e.g., Drichko *et al.*, PRB **90**, 125436 (2014)

MIRO in Ge

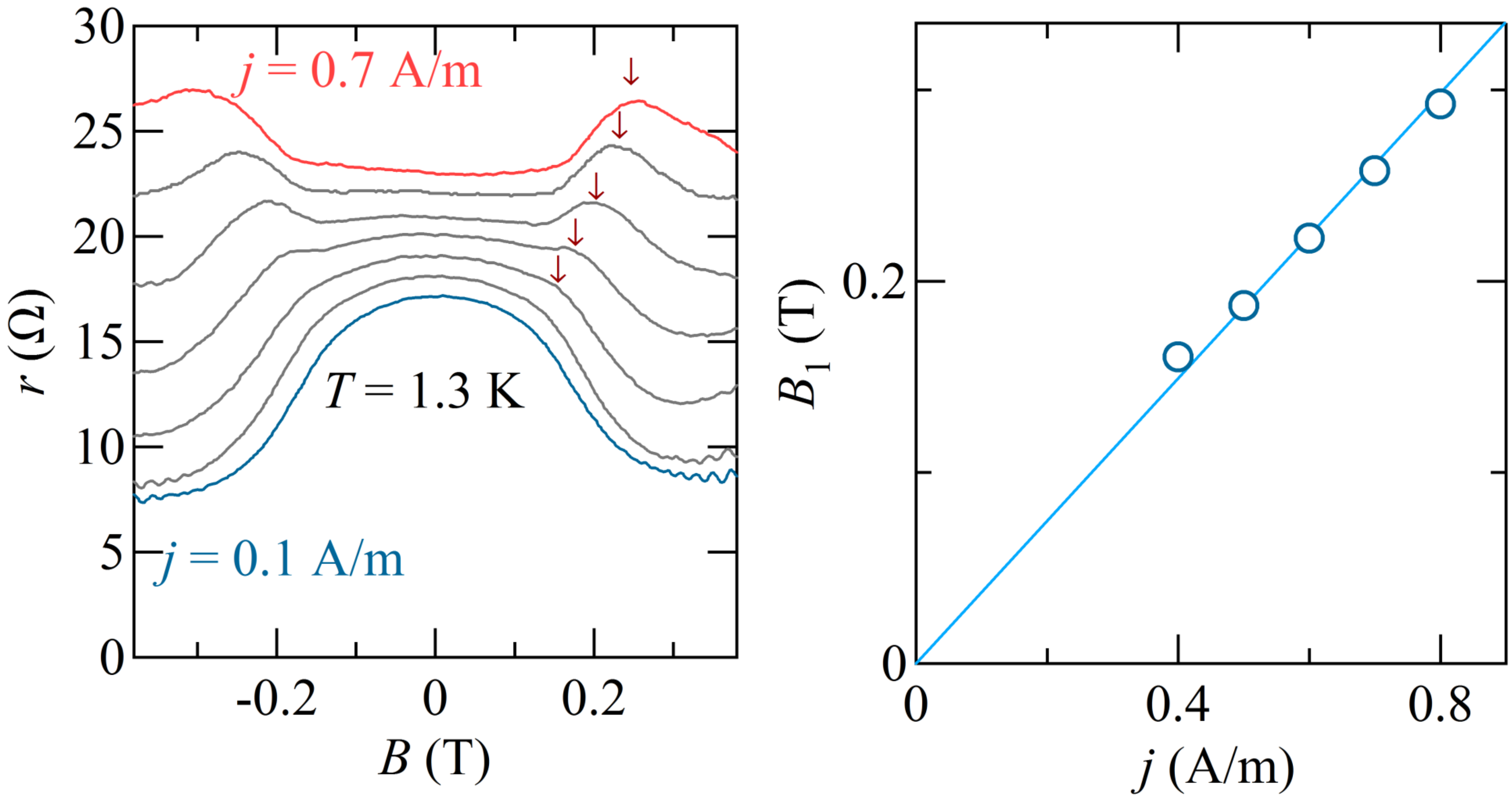




- Effective hole mass from MIRO: $m^* \approx 0.09\, m_e$

Zudov *et al*., PRB **89**, 125401 (2014); Shi *et al*., PRB **90**, 161301(R) (2014)

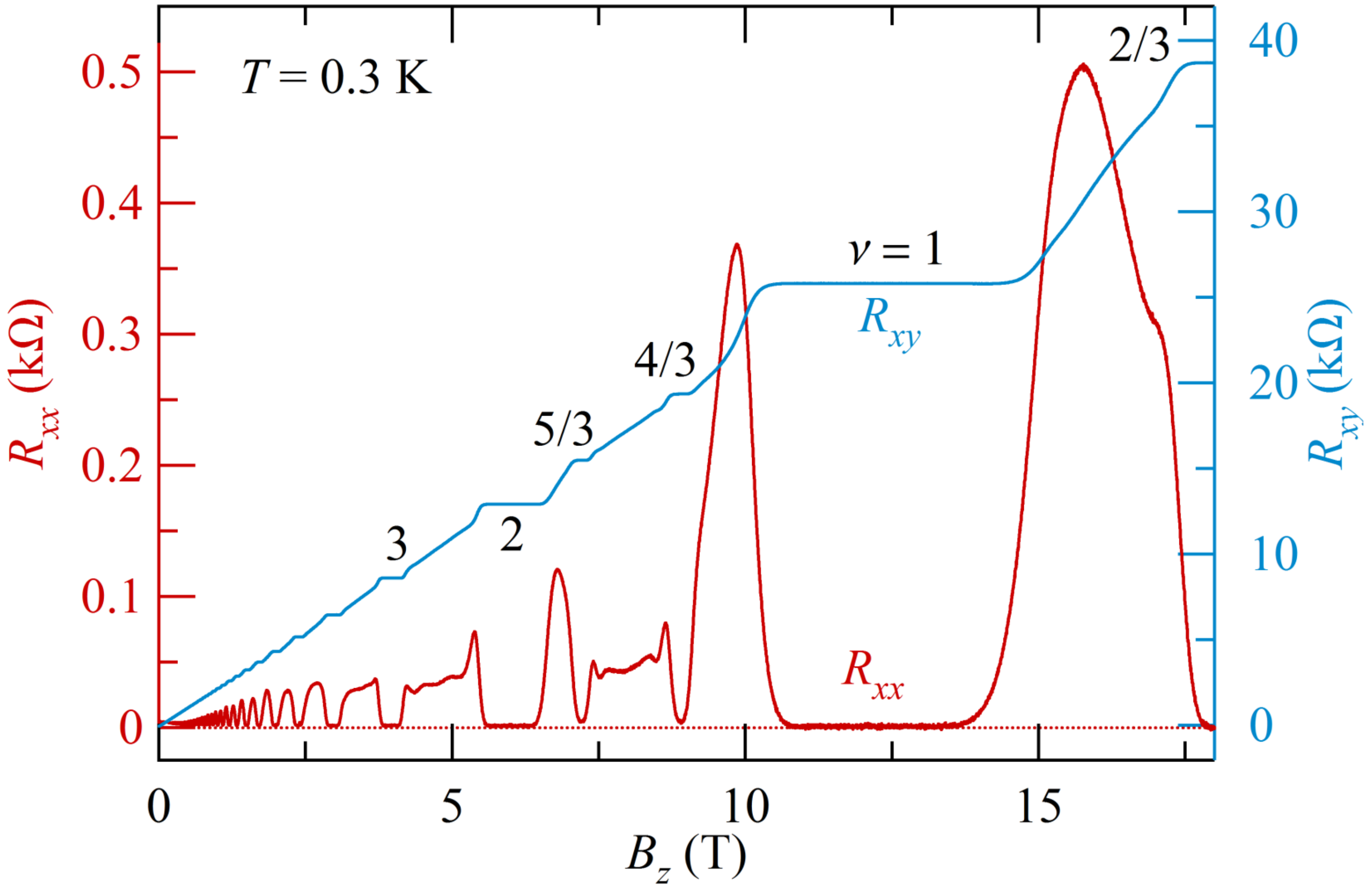
HIRO in Ge



- HIRO are also described by: $m^* \approx 0.09\, m_e$

Shi *et al*., PRB **90**, 161301(R) (2014)

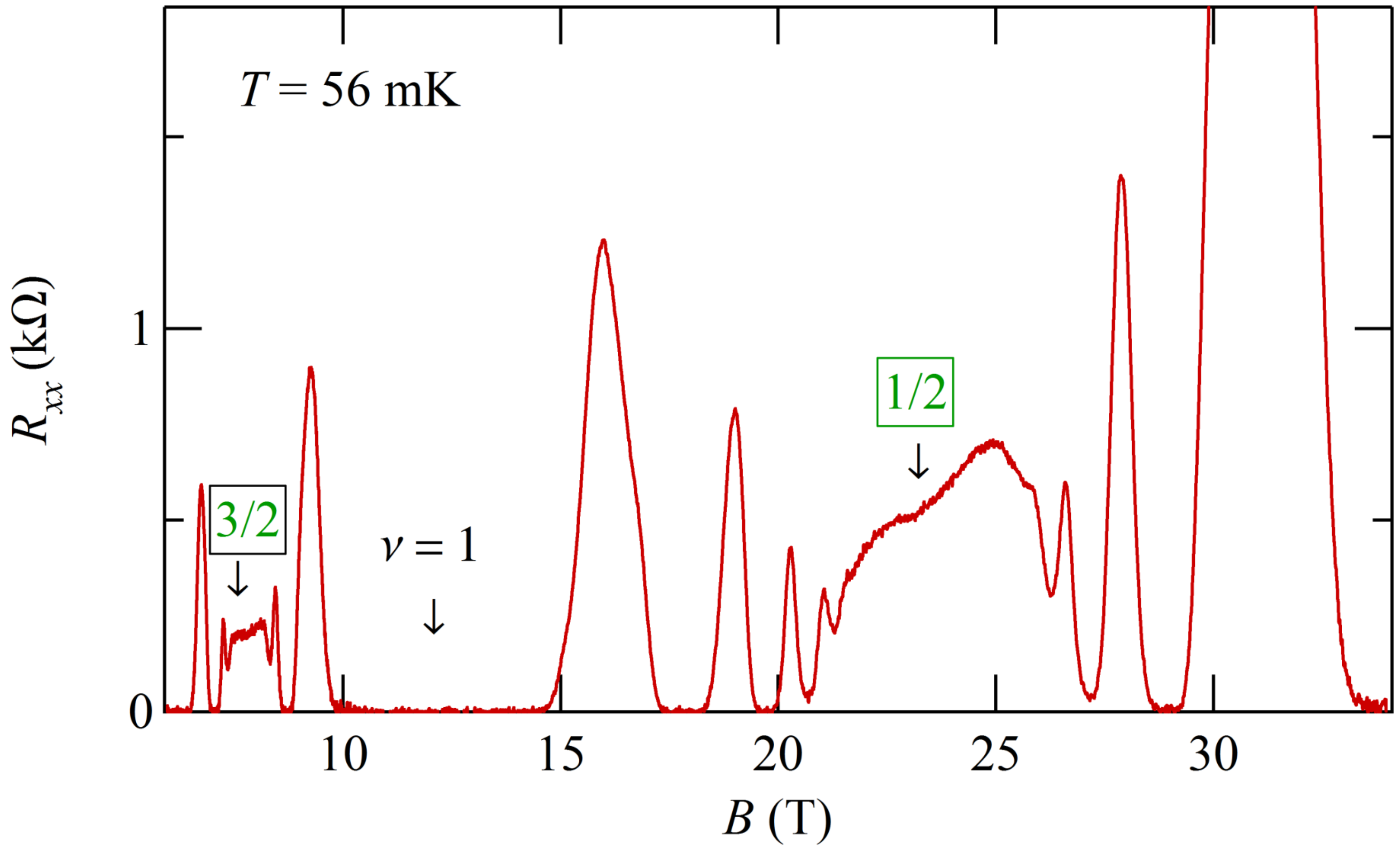
First observation of FQHE in Ge



***T* = 0.3 K: Fully quantized QH states at *ν* = 5/3, 4/3, 2/3**

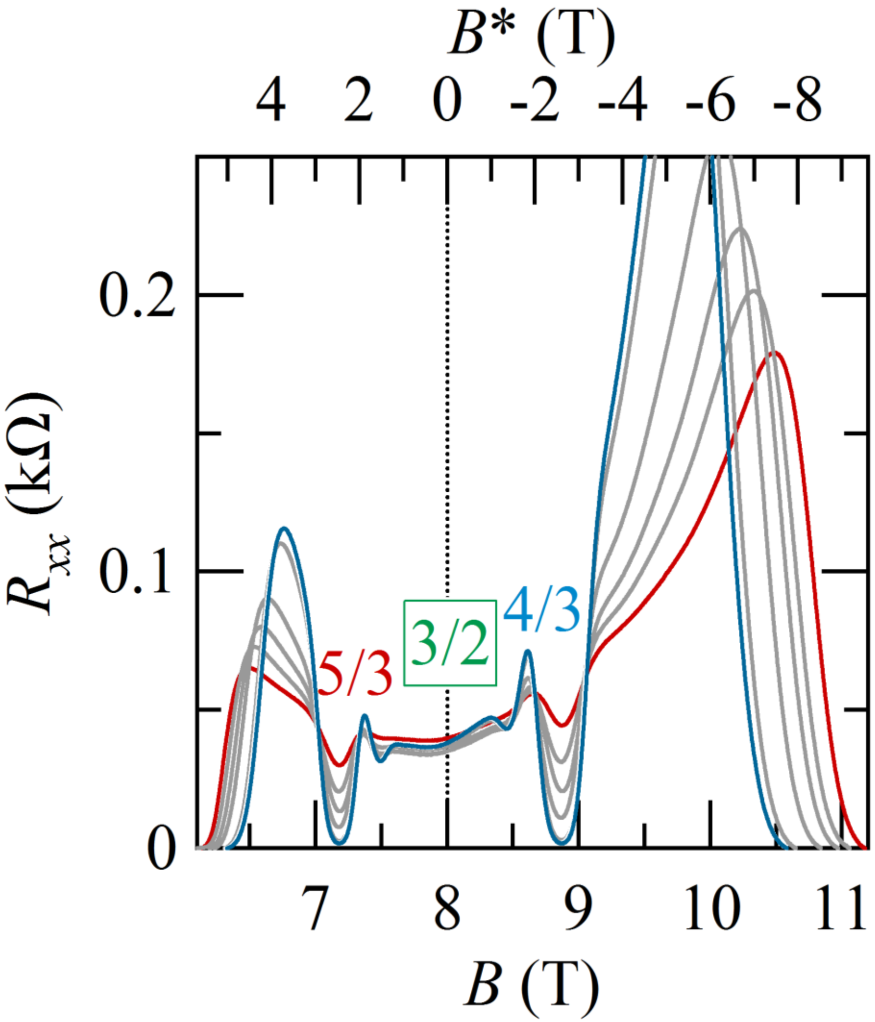
Shi, Zudov, Morrison, Myronov, submitted to PRB (2015)

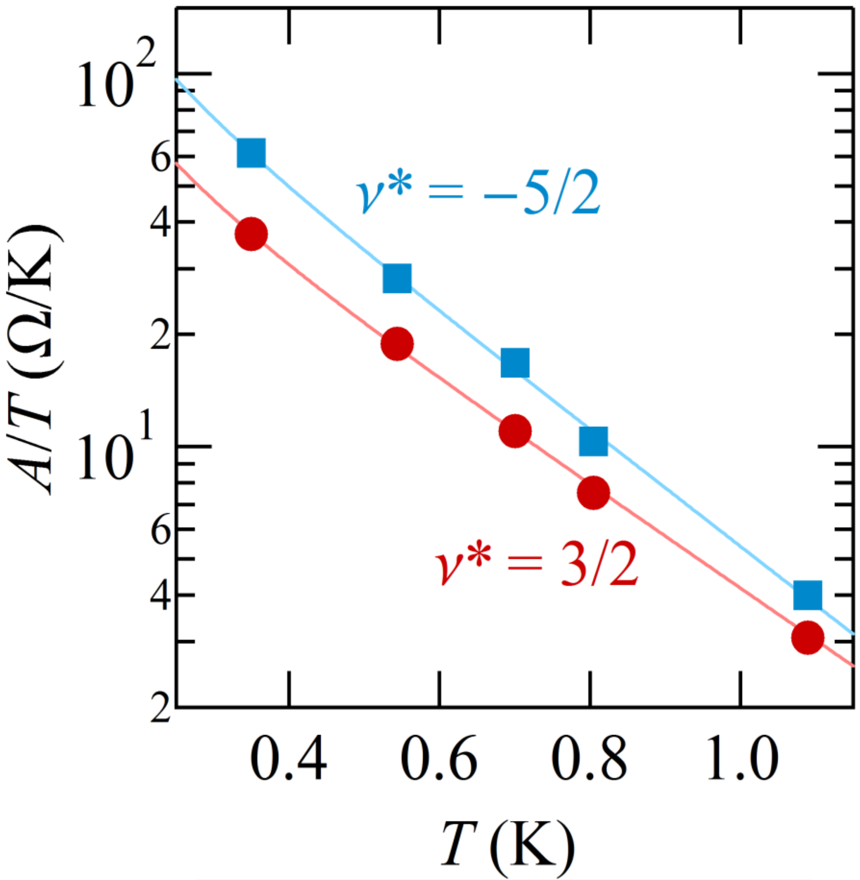
Lower *T*, up to 35 T



$T < 0.06$ K: ν = 8/5, 7/5, 3/5, 4/7, 5/9, 4/9, 3/7, 2/5, 1/3

Spinless CFs around 3/2

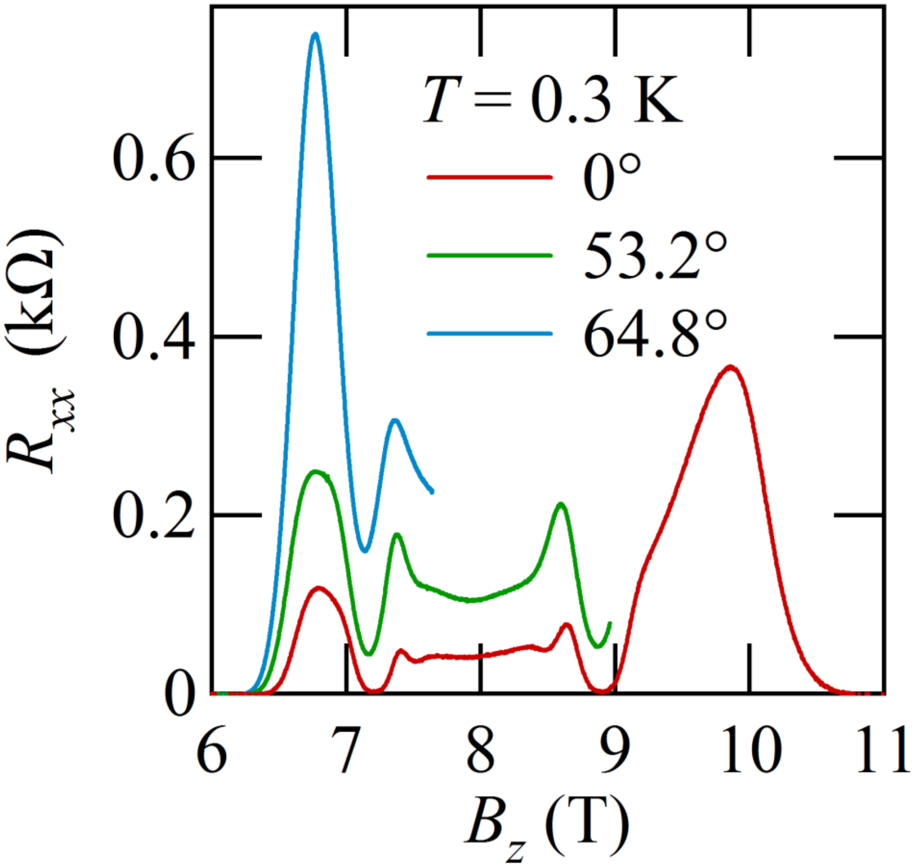


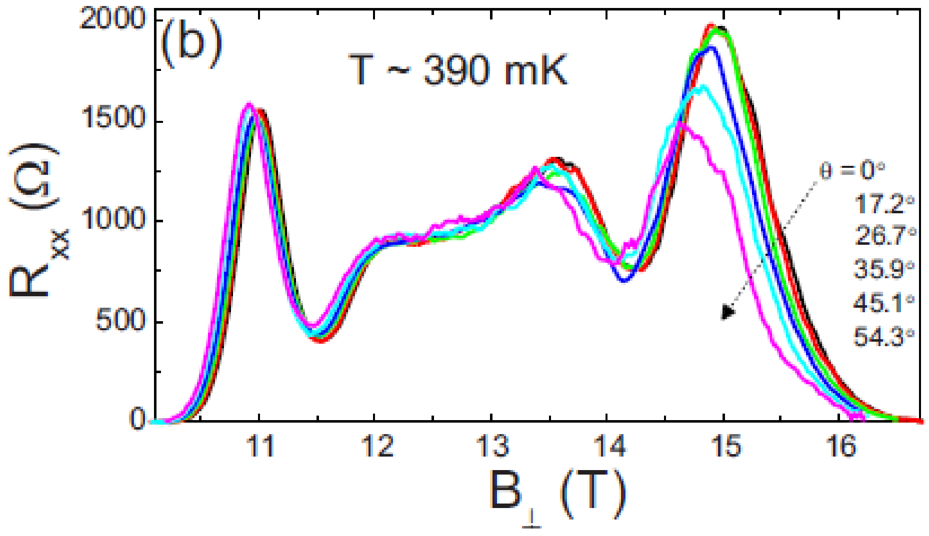


- CF mass from SdHO analysis: $m^*_{\mathrm{CF}} \approx 0.4\, m_e$

Shi, Zudov, Morrison, Myronov, submitted to PRB (2015)

$\nu = 3/2$ in tilted fields ($B_x = B_\parallel$)



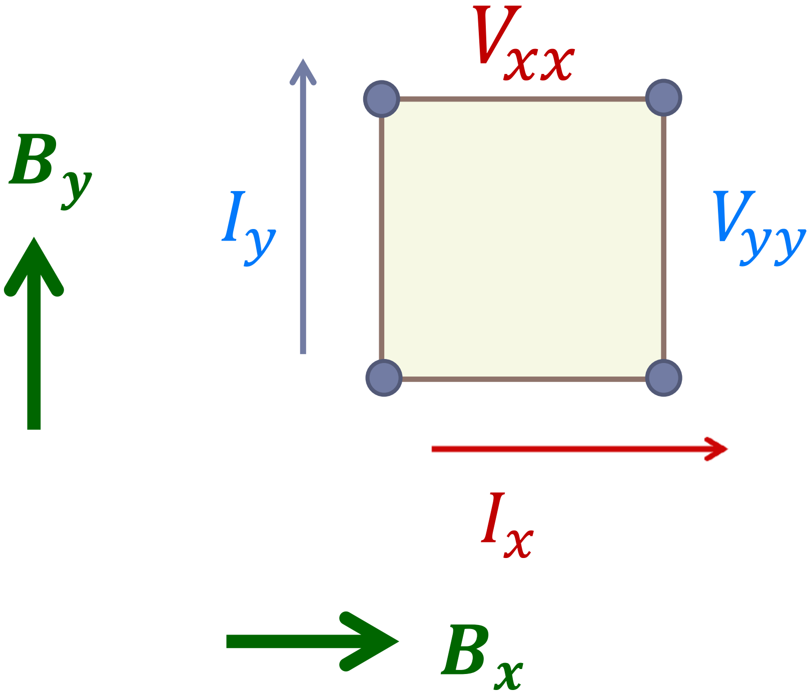


spin-polarized 3/2 in CdTe

Piot *et al.*, PRB **82**, 081307 (2010)

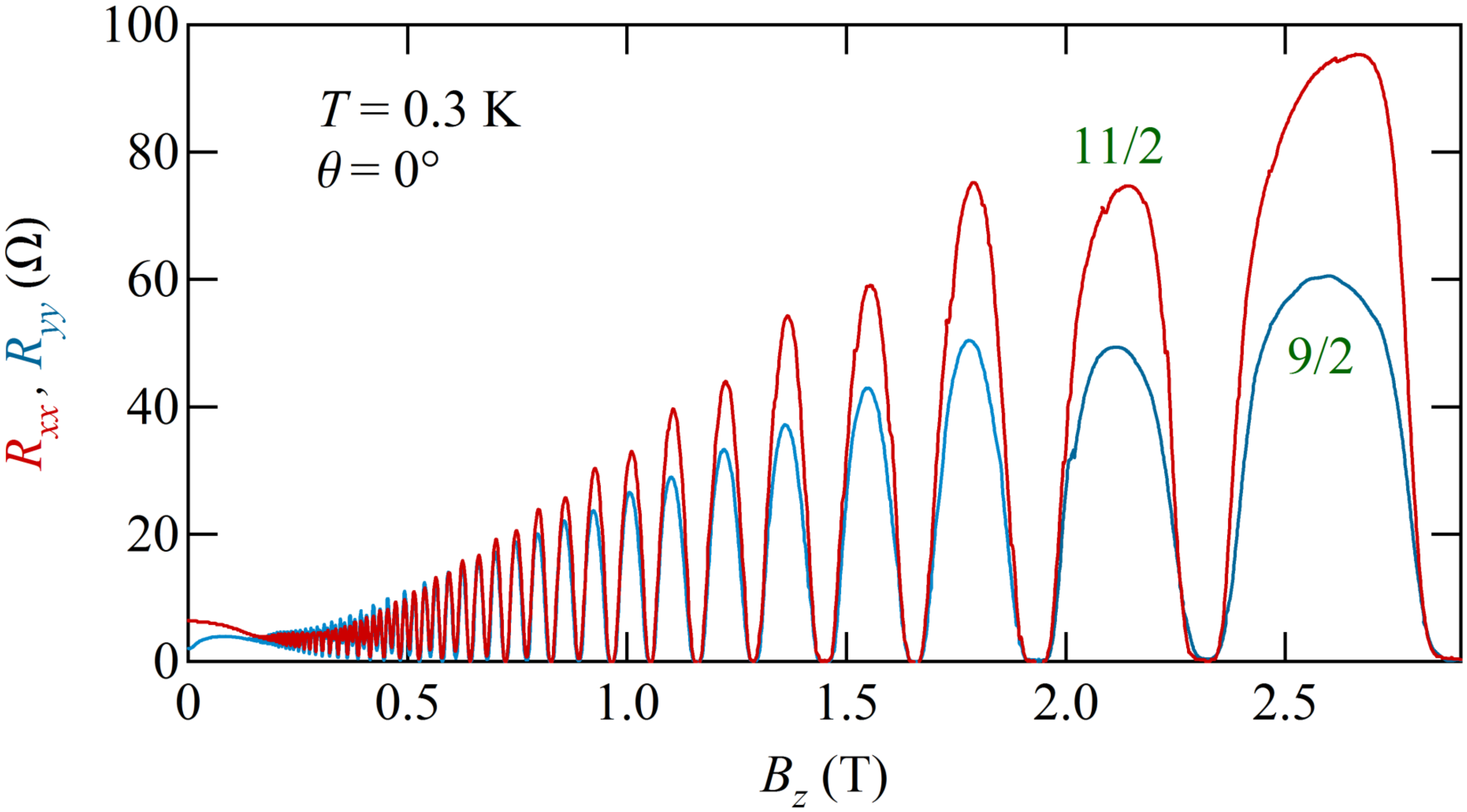
R_{xx} increases with tilt angle when $B_\parallel = B_x$

Magnetotransport in tilted fields



- Resistances R_{xx} and R_{yy} are measured
- B_x (or B_y) is introduced by tilting the sample

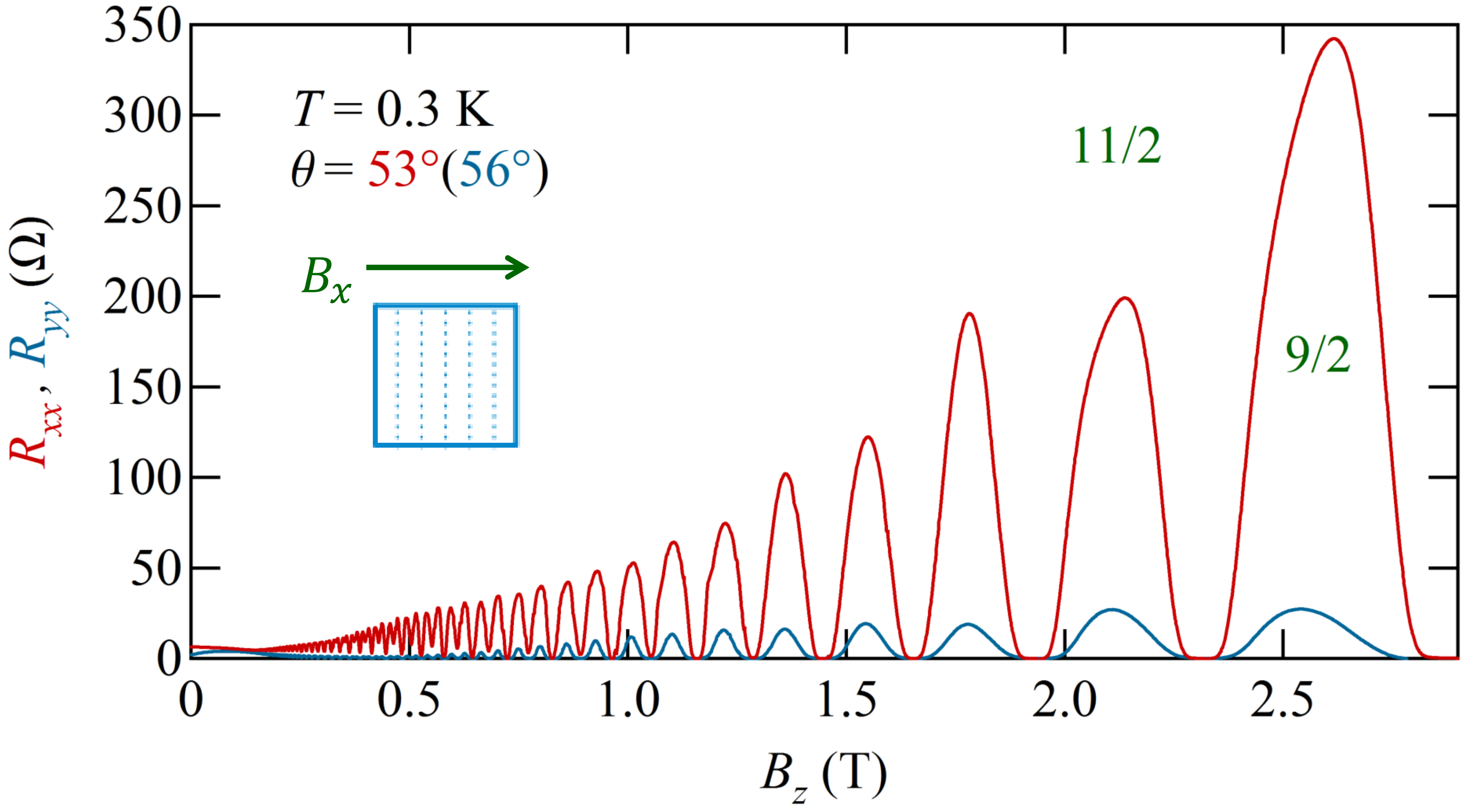
Transport in perpendicular field



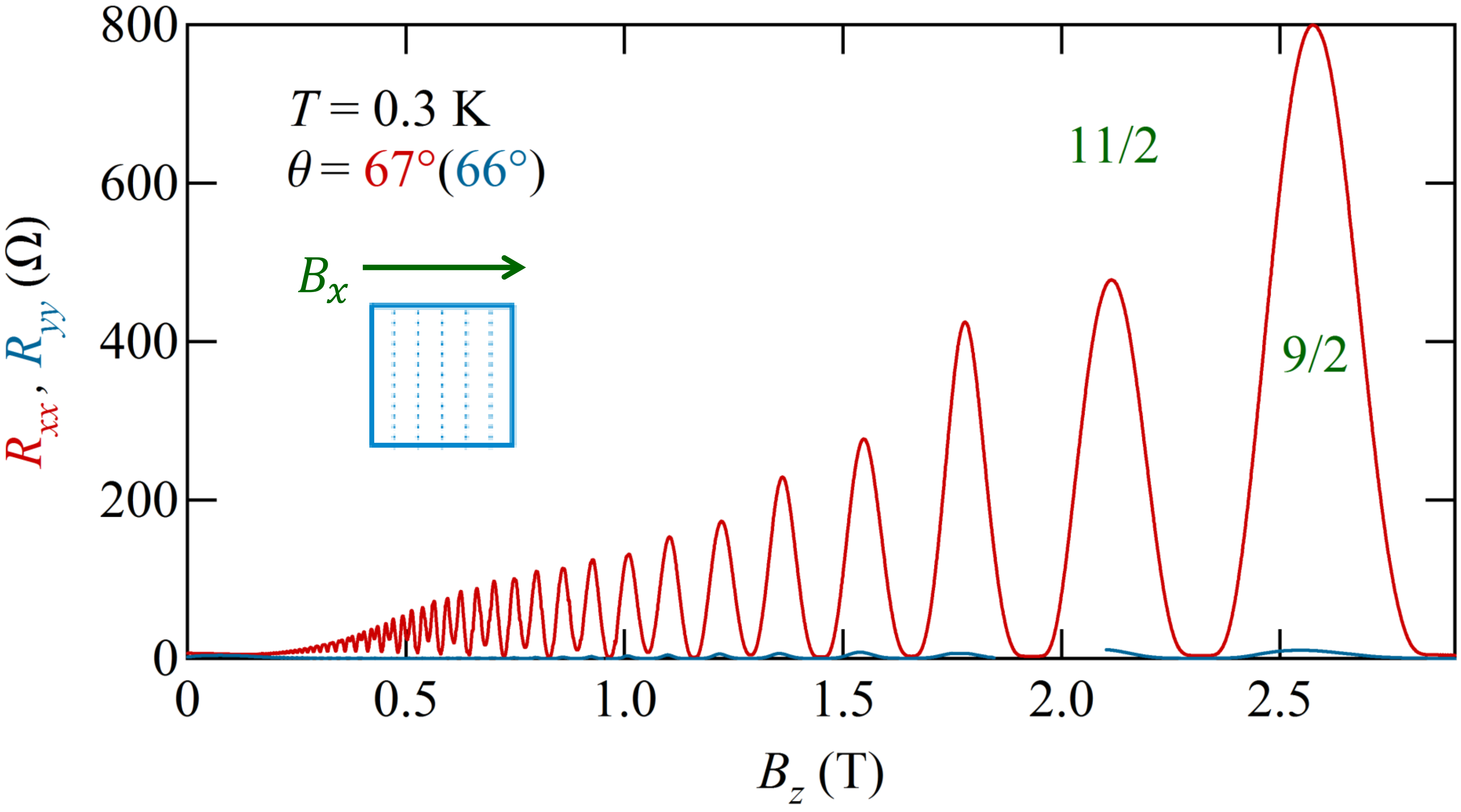
No significant anisotropy at $B_{\|} = 0$

Shi, Zudov, Morrison, Myronov, PRB **91**, 201301(R) (2015)

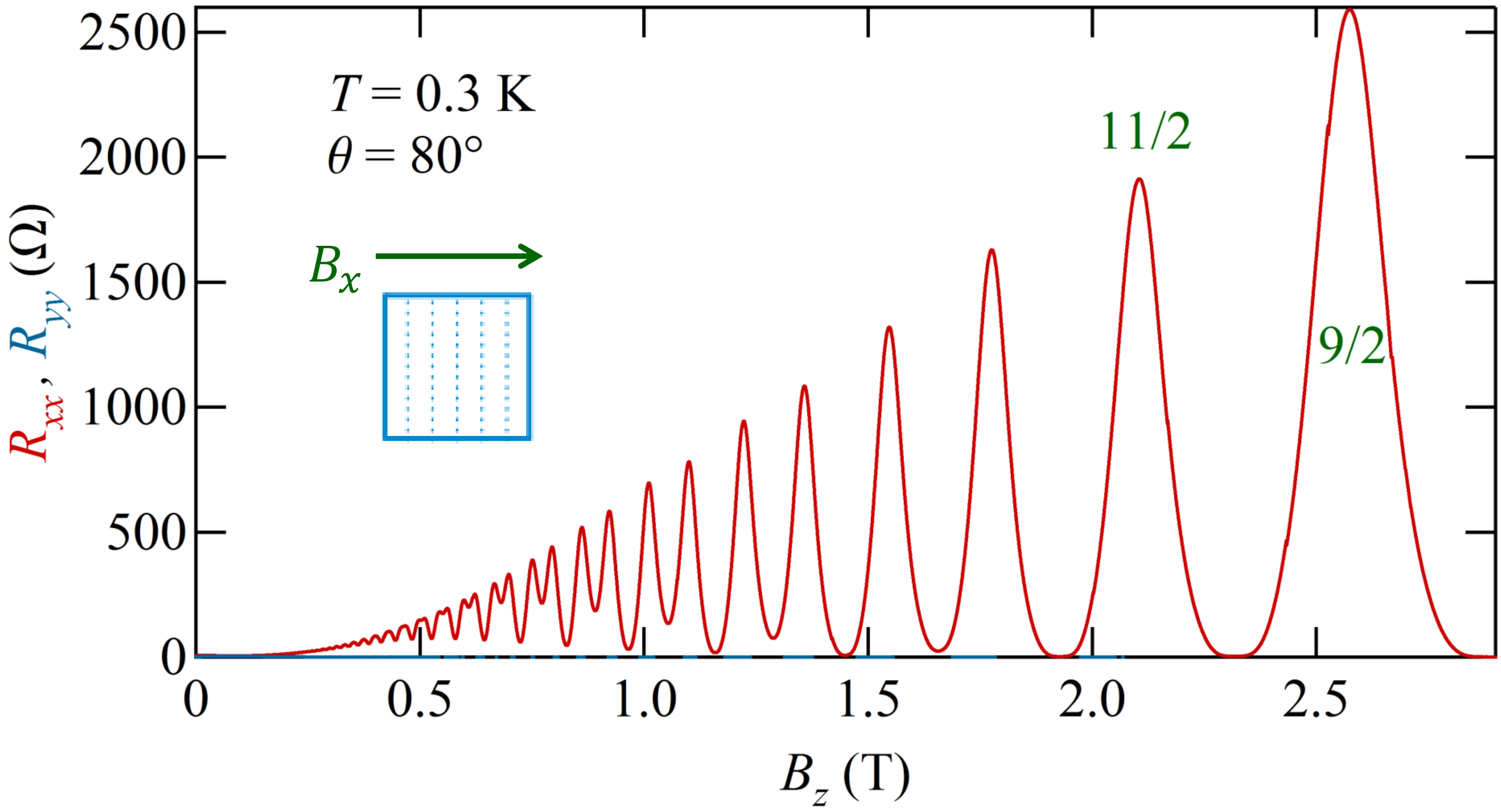
Transport in tilted fields



Transport in tilted fields



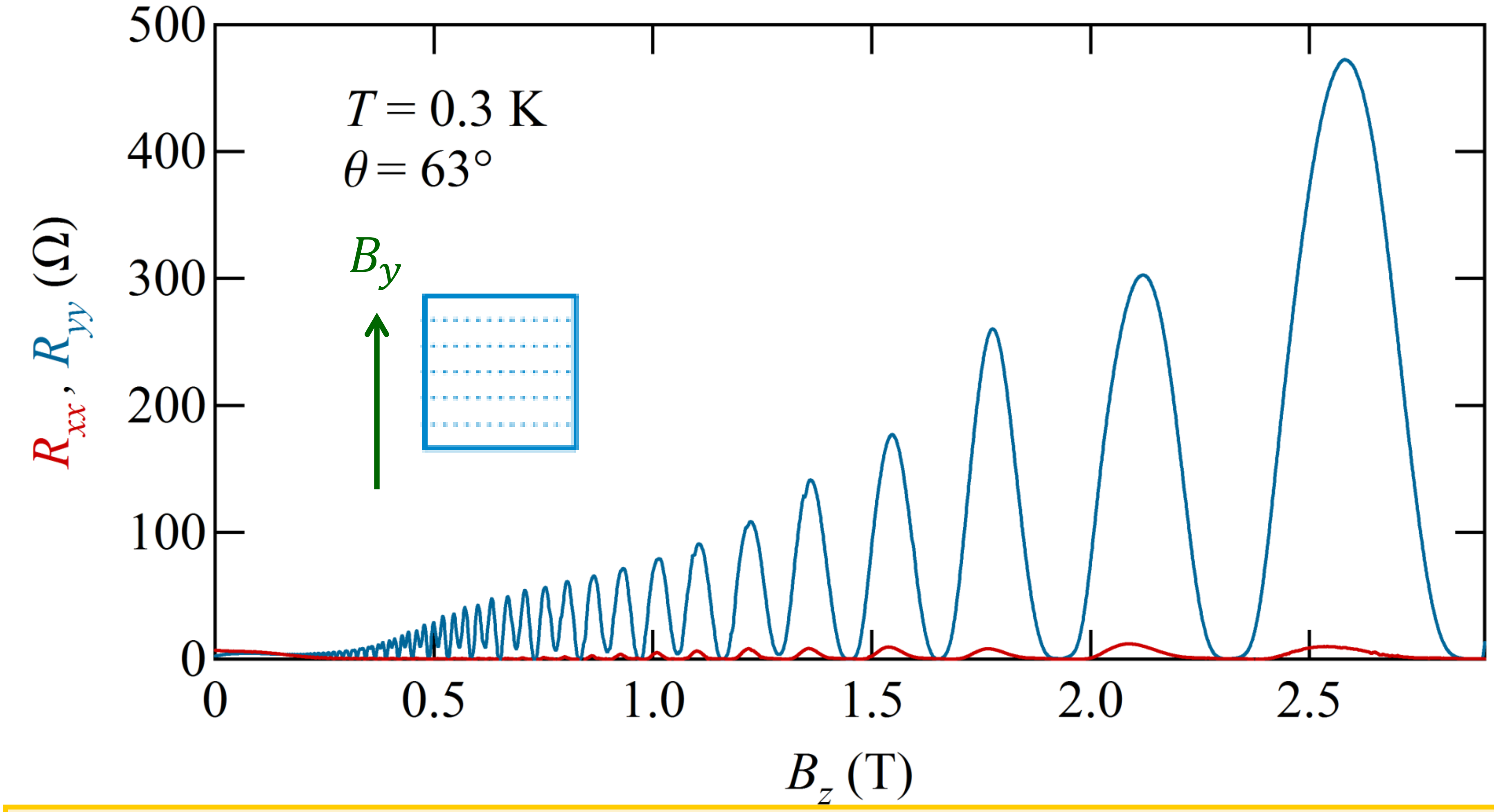
Transport in tilted fields



- At θ = 80 º, ν = 9/2: $R_{xx}/R_{yy} \approx 3\times10^4$, $\rho_{xx}/\rho_{yy} \approx 12$

Huge anisotropy

Transport in tilted fields

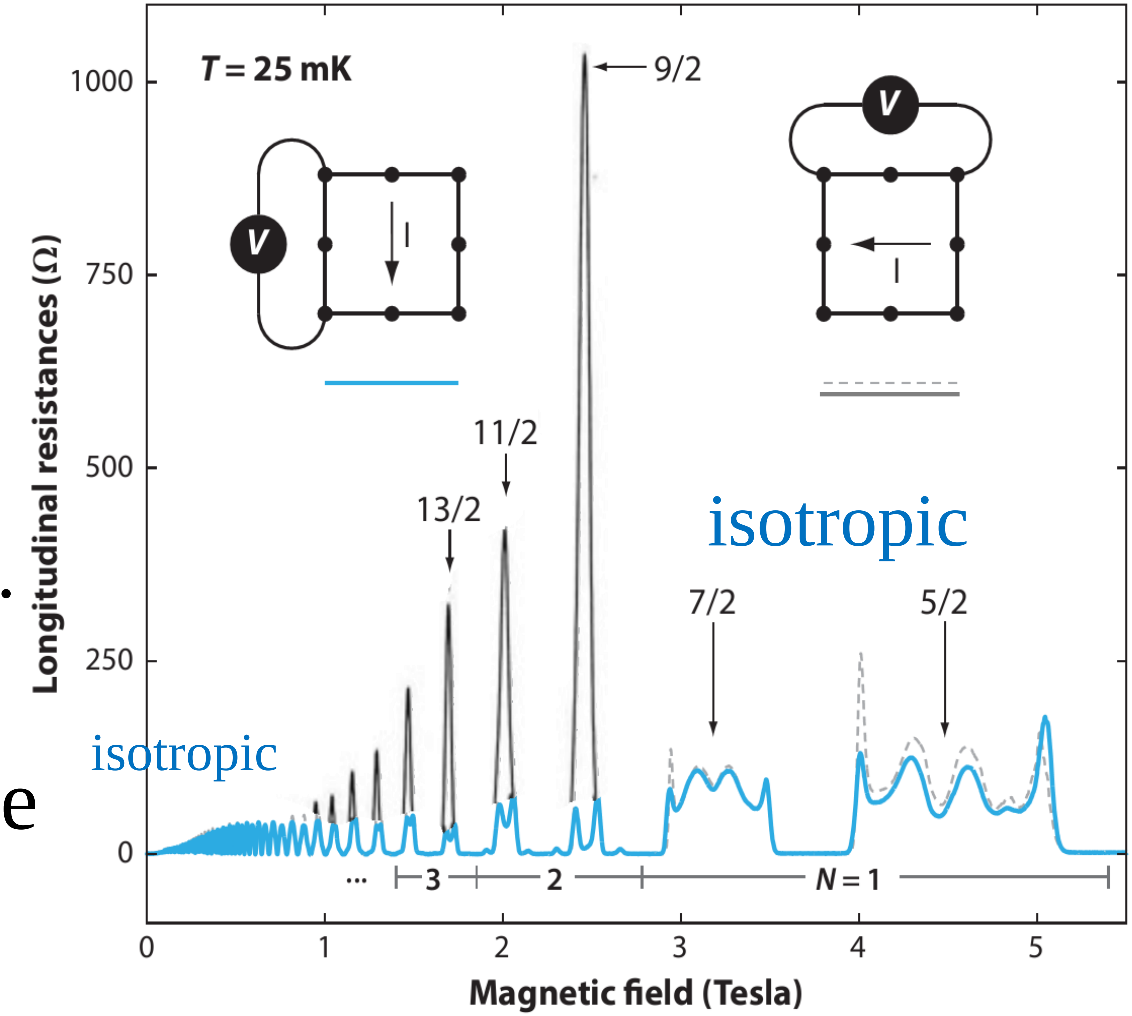


1). Tilt is the only cause of the anisotropy

2). Hard (easy) axis is always parallel (perpendicular) to $B_{\parallel}$

Anisotropy due to stripes in GaAs

- Ultra-high mobility
  $\mu \sim 10^7\ \mathrm{cm}^2/\mathrm{Vs}$
- Low temperatures
  $T < 150\ \mathrm{mK}$
- $\nu \approx 9/2, 11/2, 13/2\ldots$
- Anisotropy appears spontaneously in pure B_z (but can be modified by $B_\parallel$)

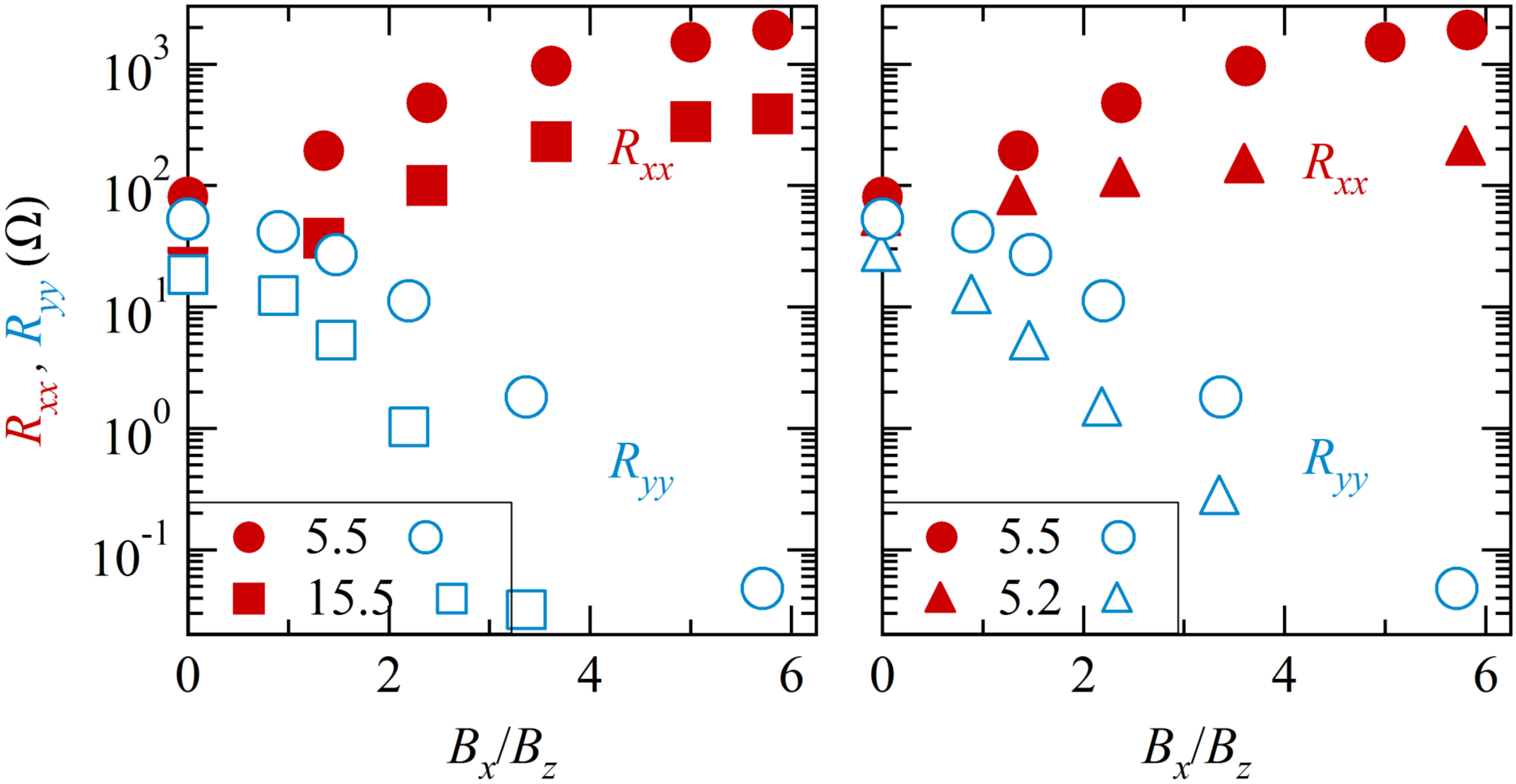


isotropic

isotropic

Lilly *et al.*, Phys. Rev. Lett. **82**, 394 (1999);
Du *et al.*, Solid State Commun. **83**, 389 (1999)

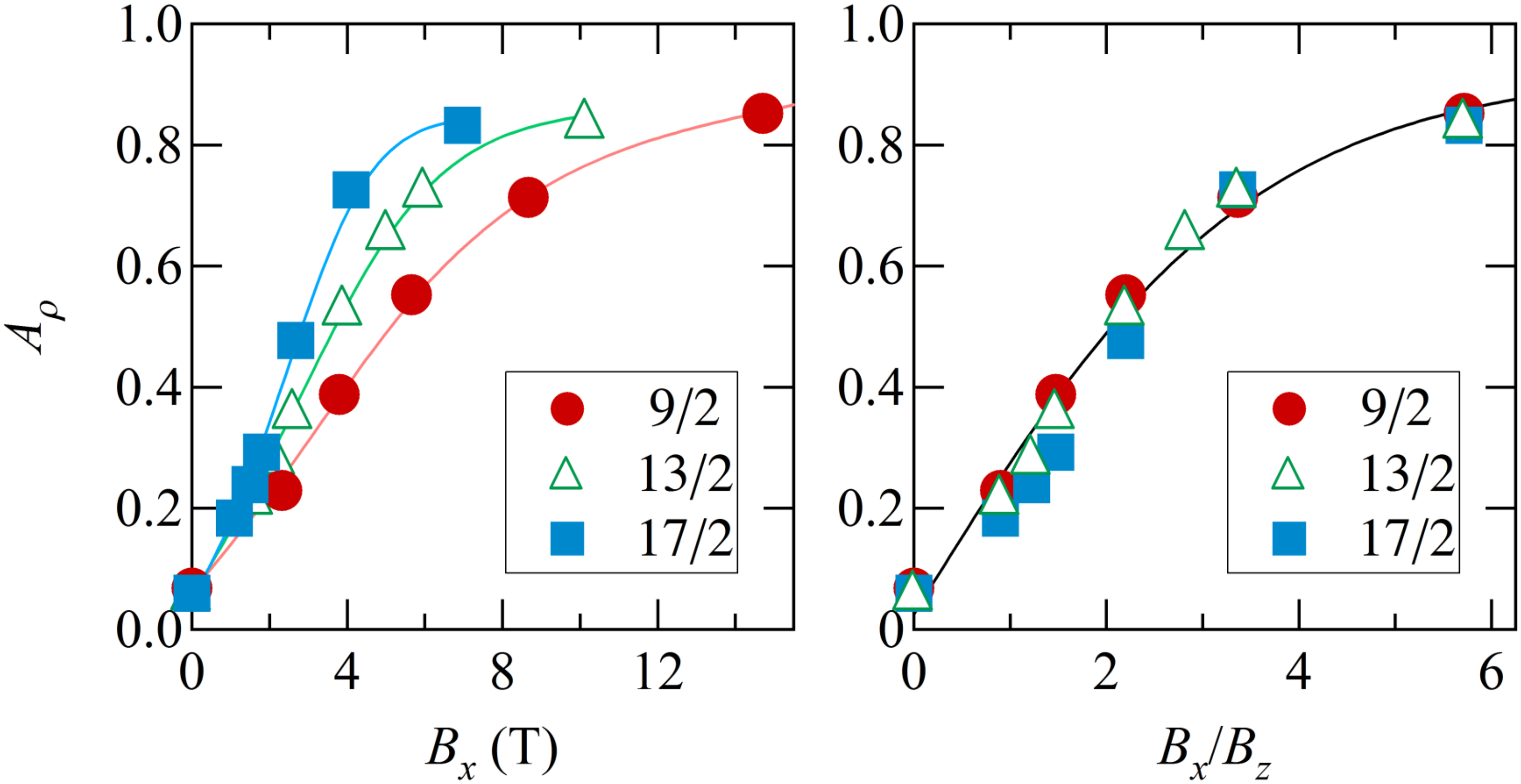
Dependence on the filling factor



Anisotropy persists to very high filling factors (and away from half-filling)

Dependence on B_x and tilt angle

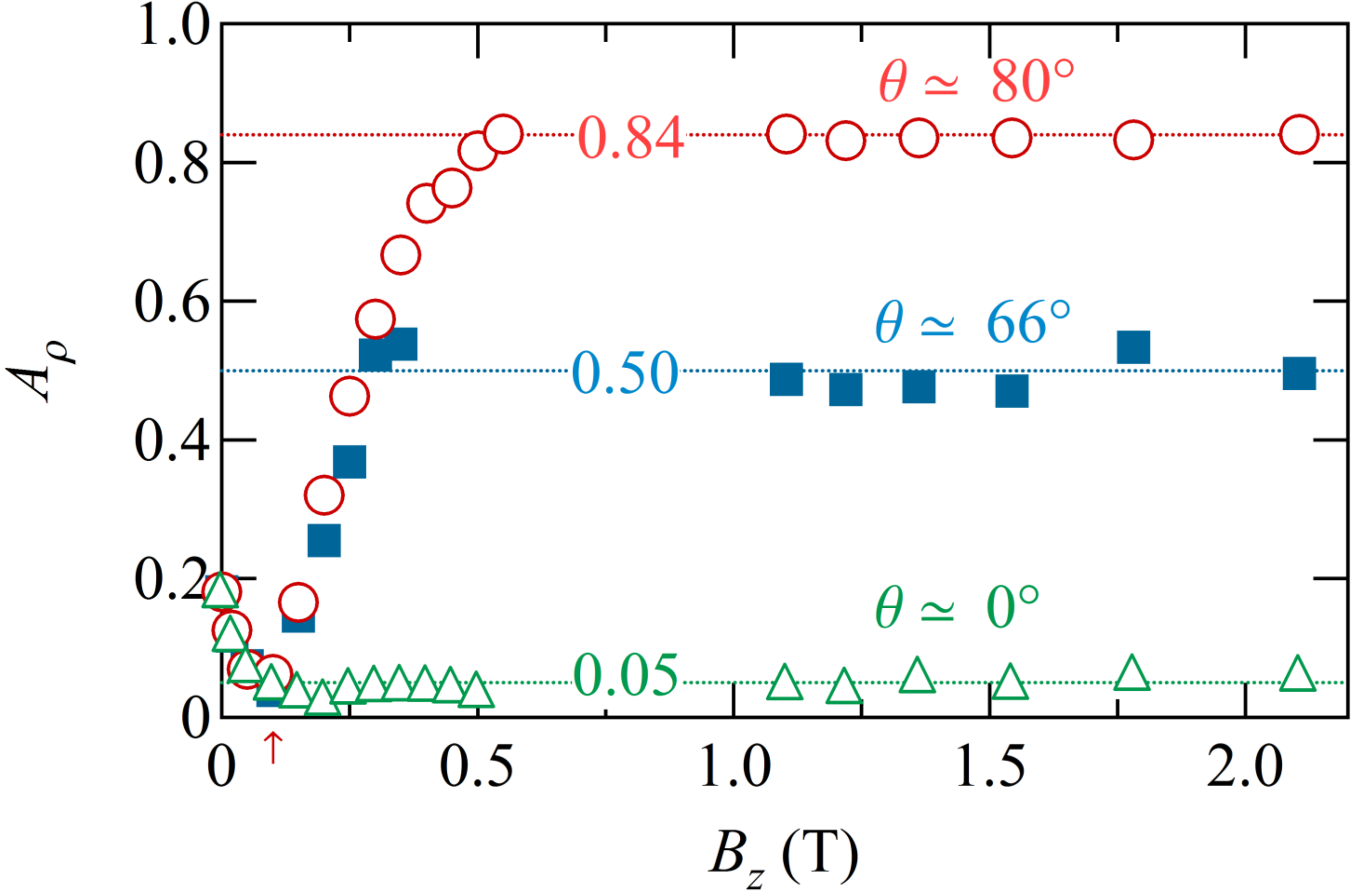
- $(R_{xx}, R_{yy}) \rightarrow (\rho_{xx}, \rho_{yy})$, $A_\rho = \frac{\rho_{xx}-\rho_{yy}}{\rho_{xx}+\rho_{yy}}$



Anisotropy depends only on the tilt angle

Shi, Zudov, Morrison, Myronov, PRB **91**, 201301(R) (2015)

Dependence on B_z at fixed angle

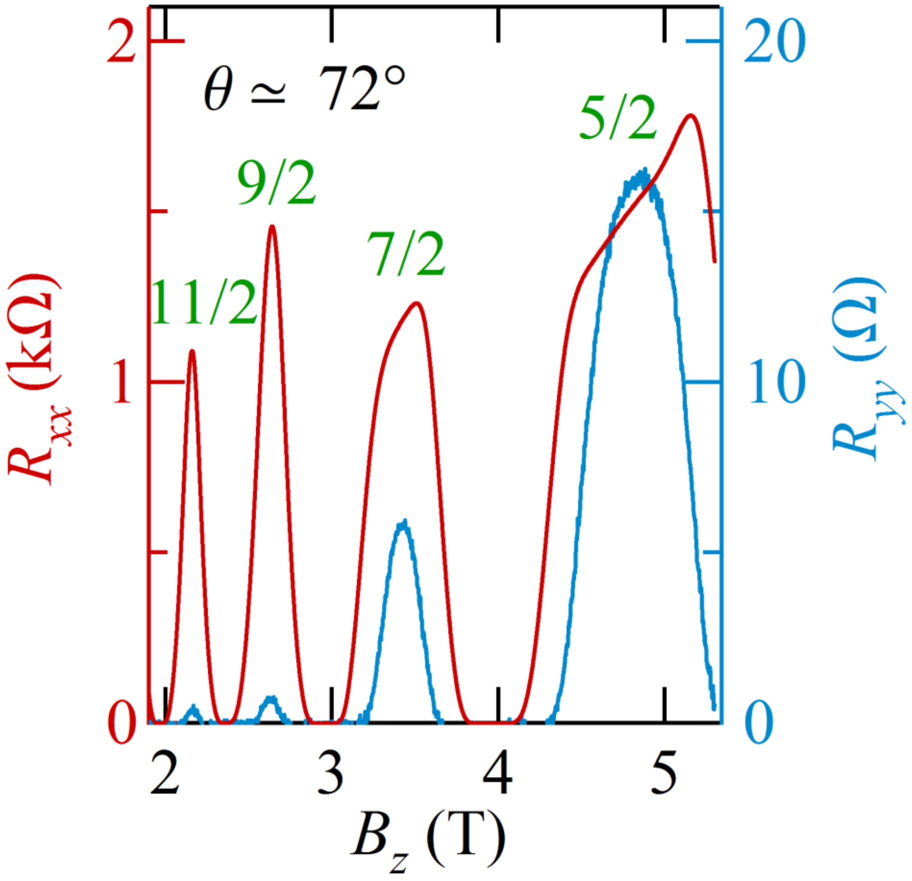


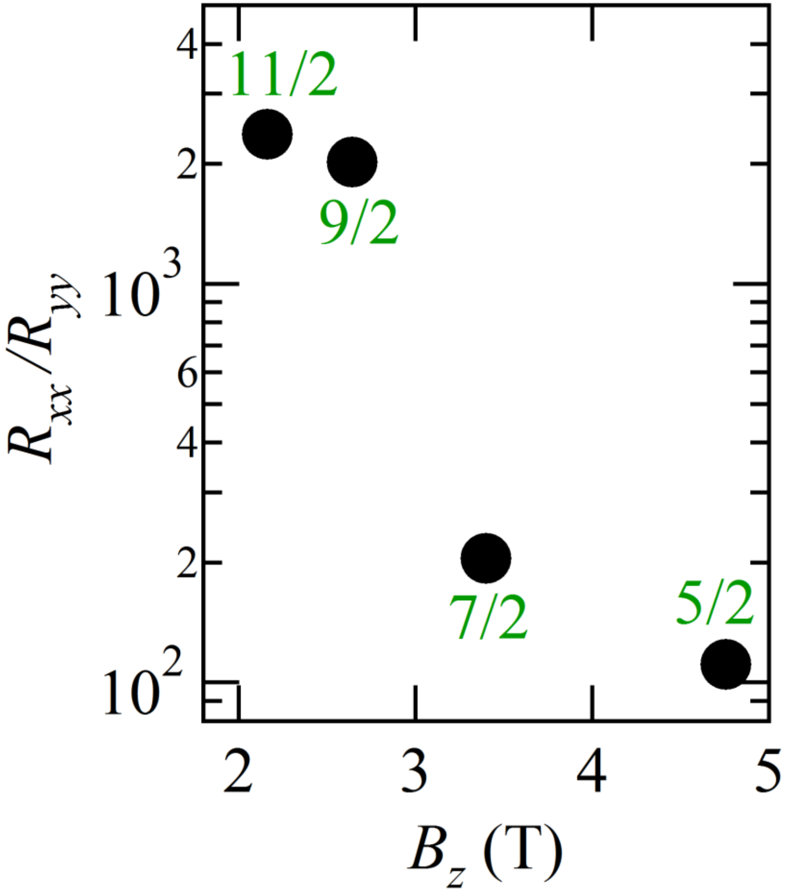
1). Low B_z: Anisotropy increases with B_z

2). High B_z: Anisotropy is independent on the LL index

Shi, Zudov, Morrison, Myronov, PRB **91**, 201301(R) (2015)

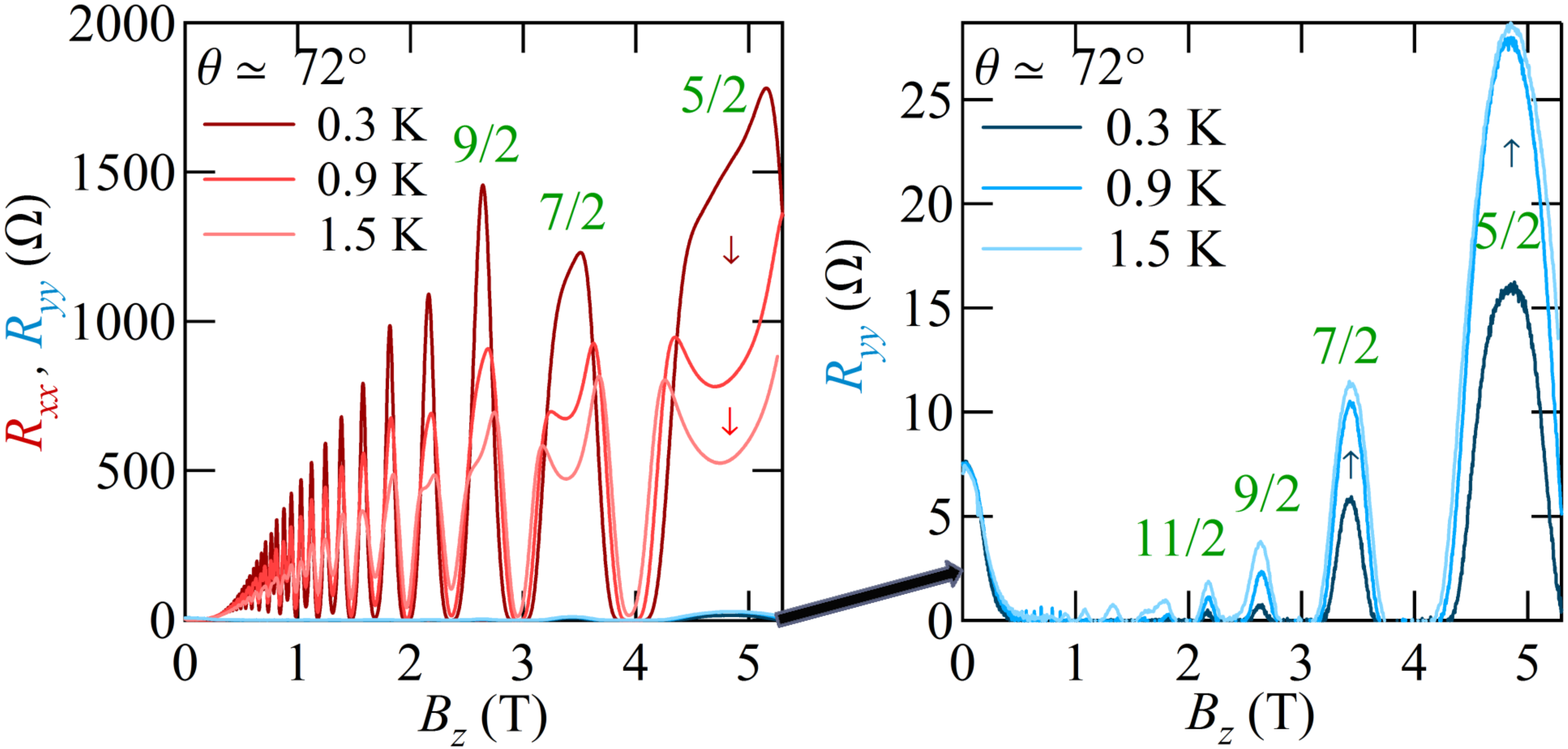
Lower Landau level: $N = 1$





Anisotropy becomes weaker at $\nu = 5/2$ and $7/2$

Temperature dependence at 72°

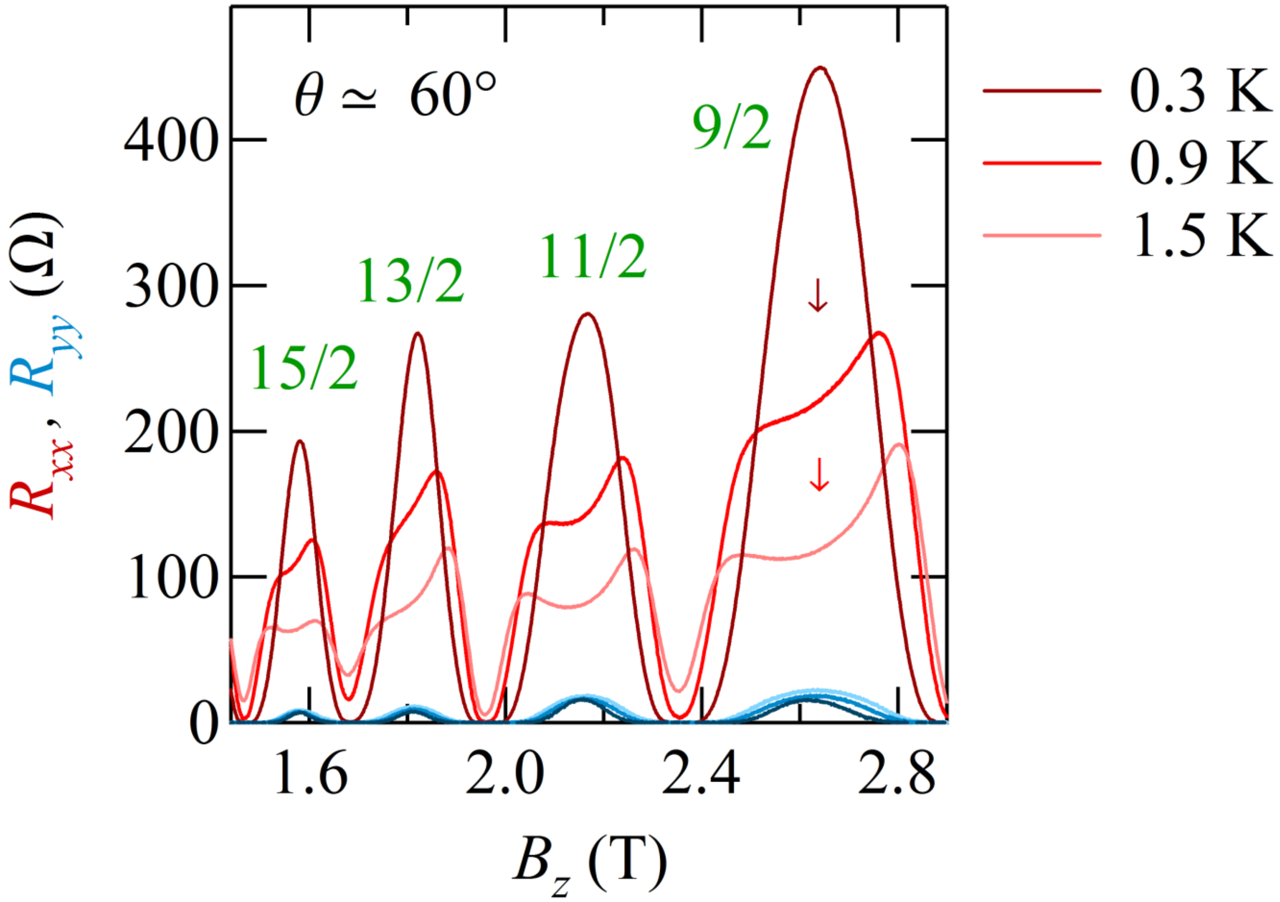


1). With increasing *T*: R_{xx} decreases, R_{yy} increases

2). Anisotropy remains significant up to *T* = 1.5 K

Shi, Zudov, Morrison, Myronov, PRB **91**, 201301(R) (2015)

Temperature dependence at 60°



With increasing T: R_{xx} maxima become minima,

R_{yy} maxima remain maxima

(no minima develop at zero tilt)

Intermediate summary

Tilt field-induced anisotropy in the QHE regime:

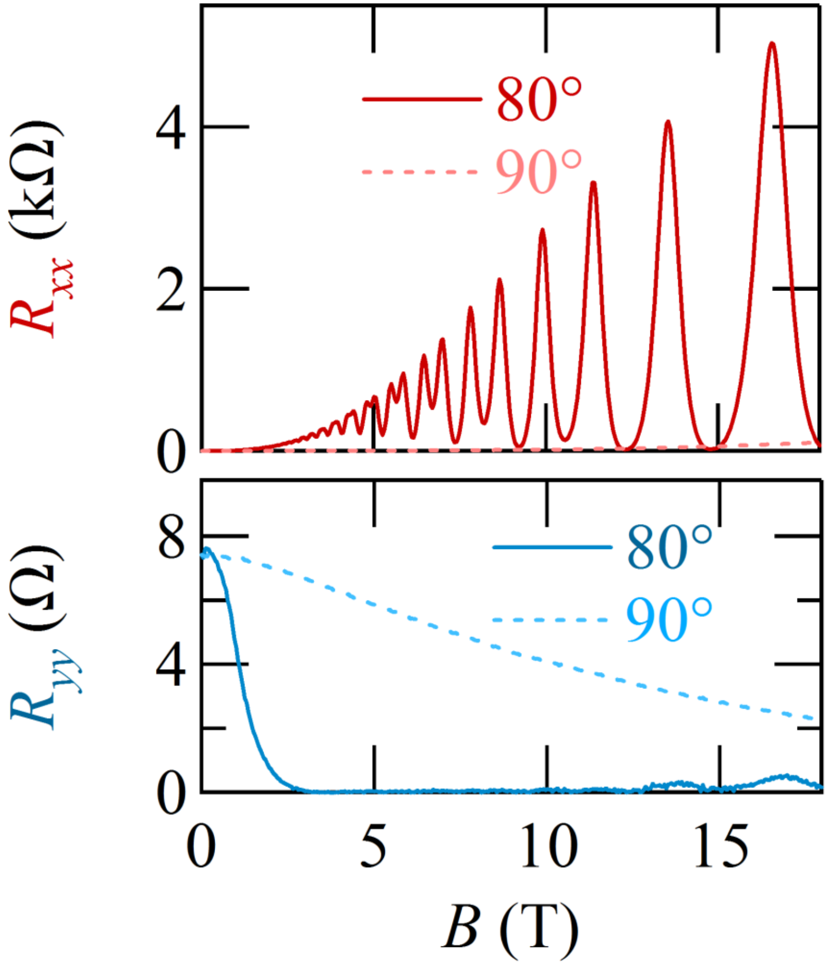
- Has hard transport direction along $B_{||}$
- Depends primarily on the tilt angle
- Decreases with temperature

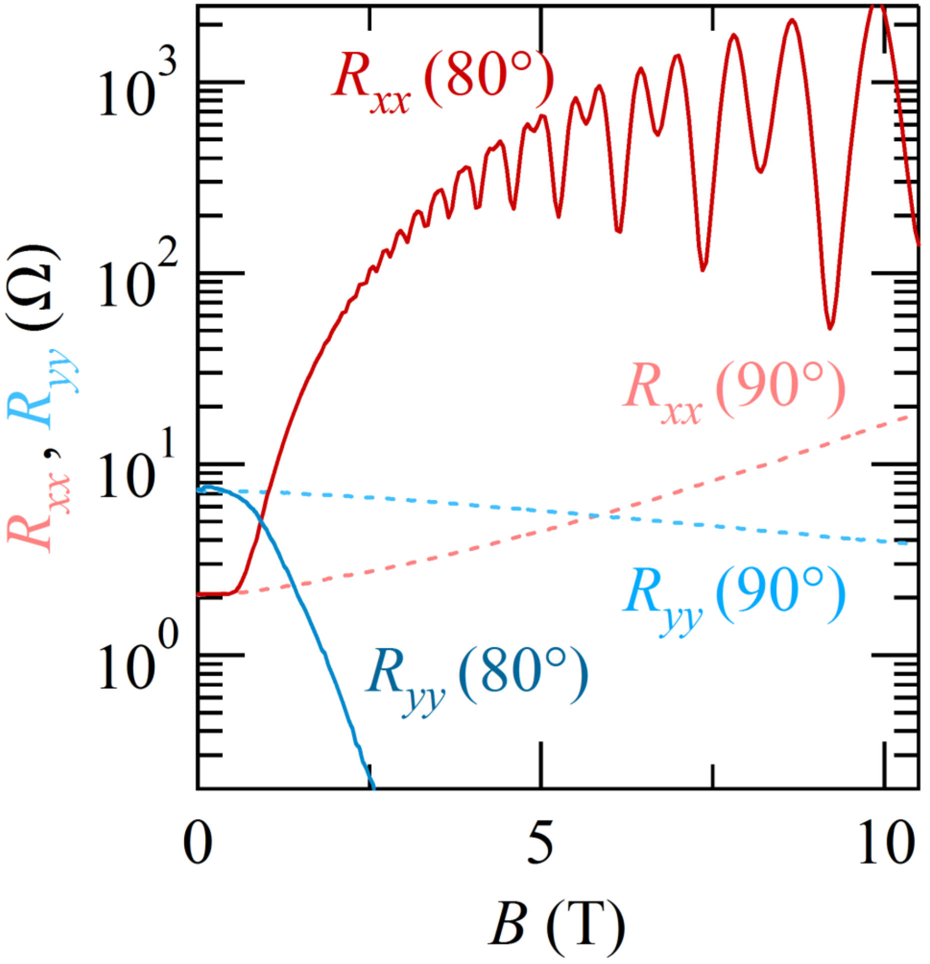
Shi, Zudov, Morrison, Myronov, PRB **91**, 201301(R) (2015)

Can we exclude the possibility of stripes?

- How large B_z is needed?
- How high T can the anisotropy persist to?
- Is quantization necessary?

Pure $B_{\parallel}$ vs. high tilt angle

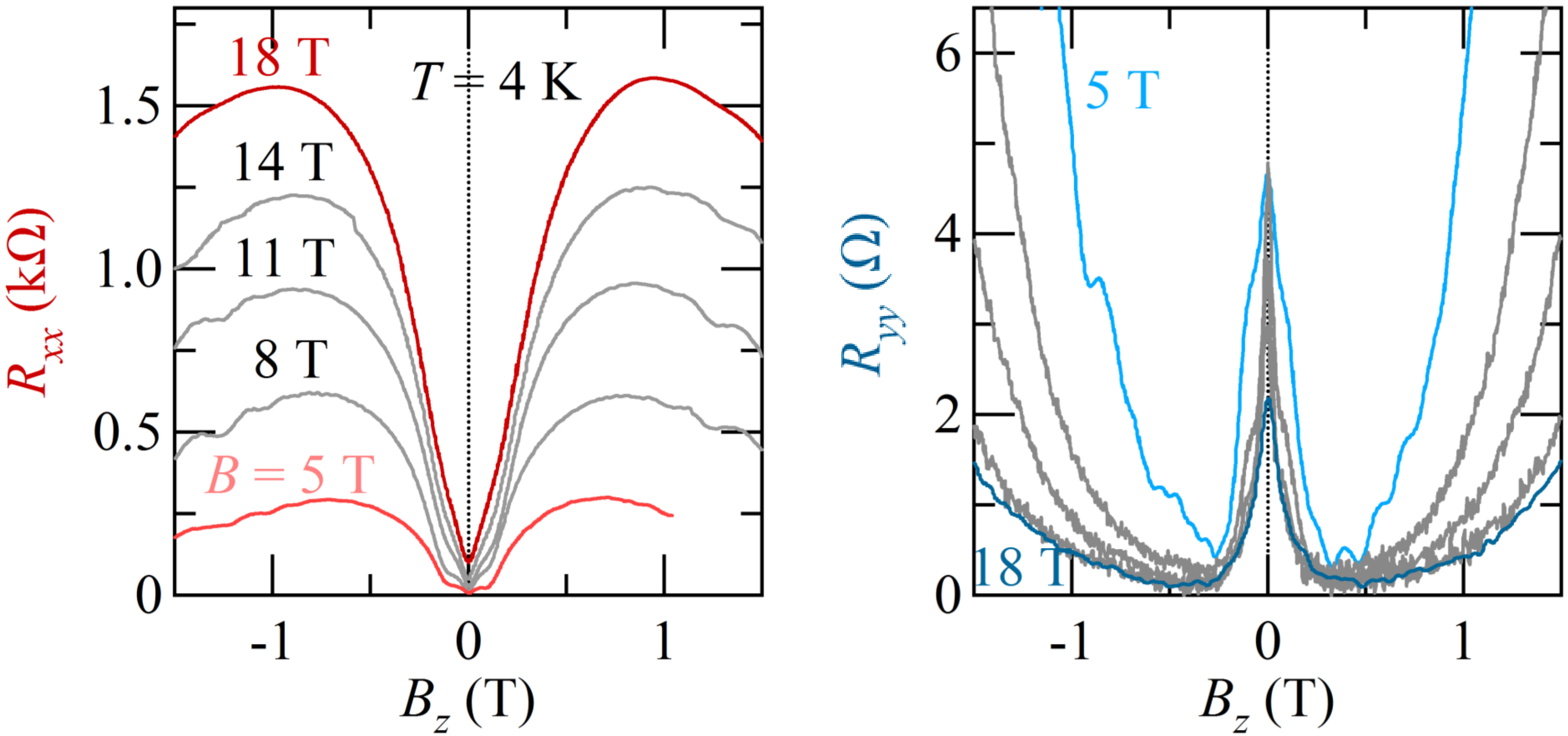




Much weaker anisotropy in pure $B_{\parallel}$

What happens between 80˚ and 90˚ ?

Tilting in fixed fields at *T* = 4 K



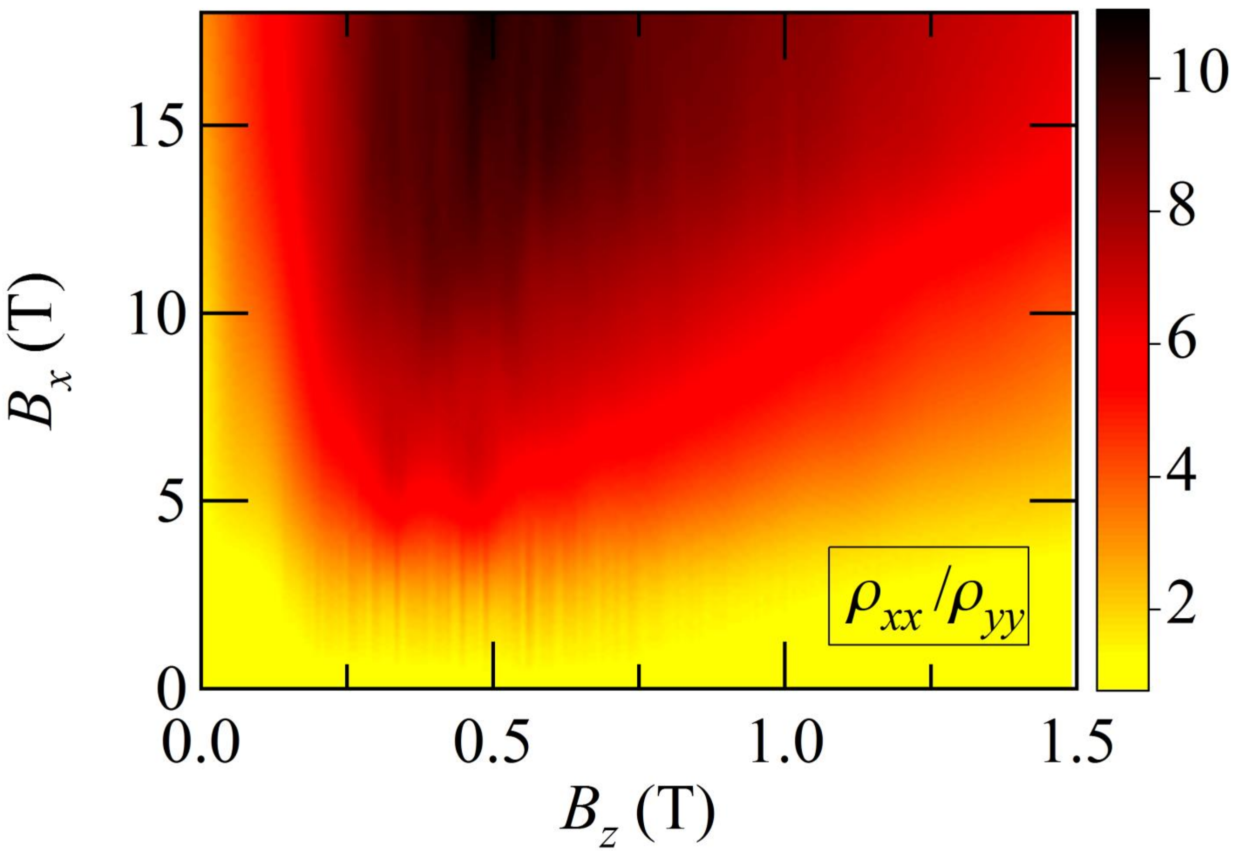
1). Anisotropy sets in as soon as B_z is introduced

2). Anisotropy increases with in-plane field

3). Anisotropy optimized around $B_z \approx 0.5$ T

Shi, Zudov, Morrison, Myronov (2015)

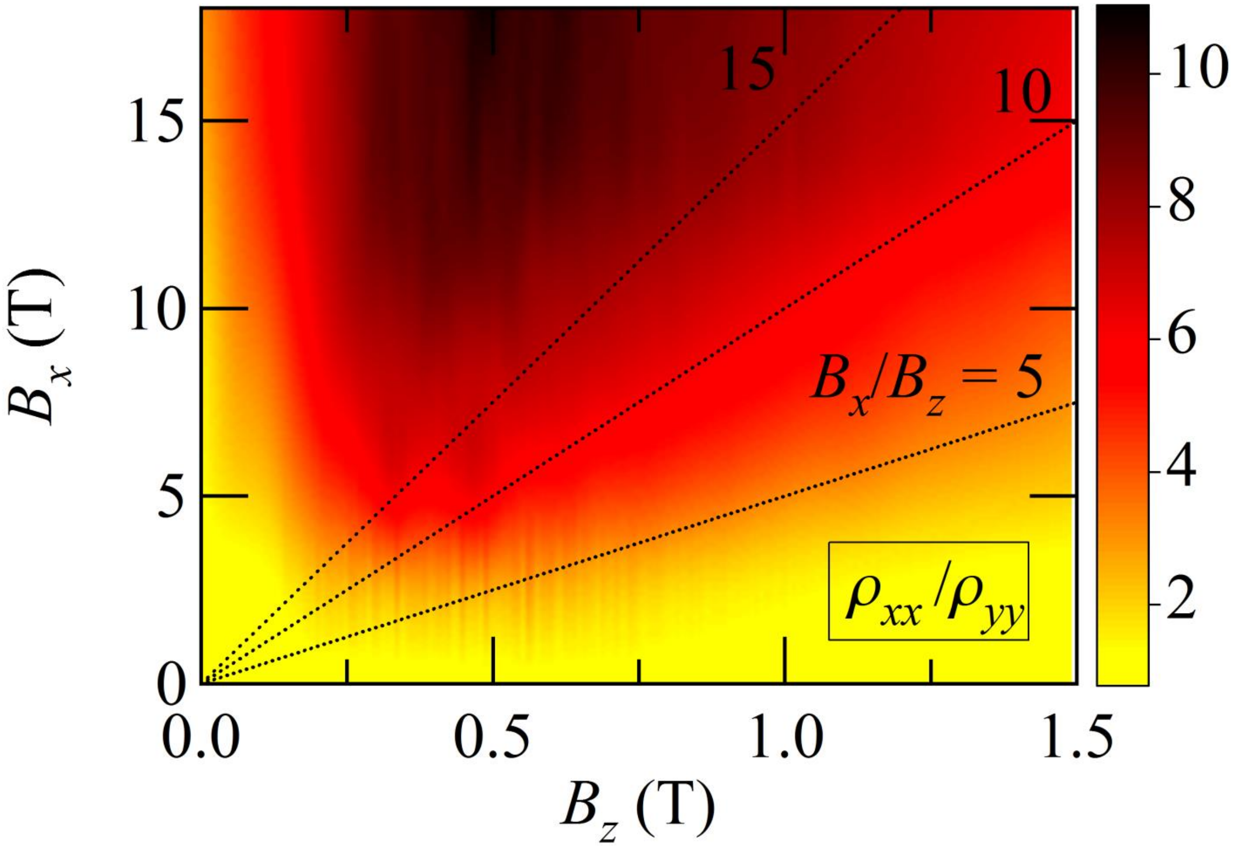
Resistivity ratio vs. B_z and B_x



The anisotropy maximum is domed around $B_z^\star \approx 0.5$ T

Shi, Zudov, Morrison, Myronov (2015)

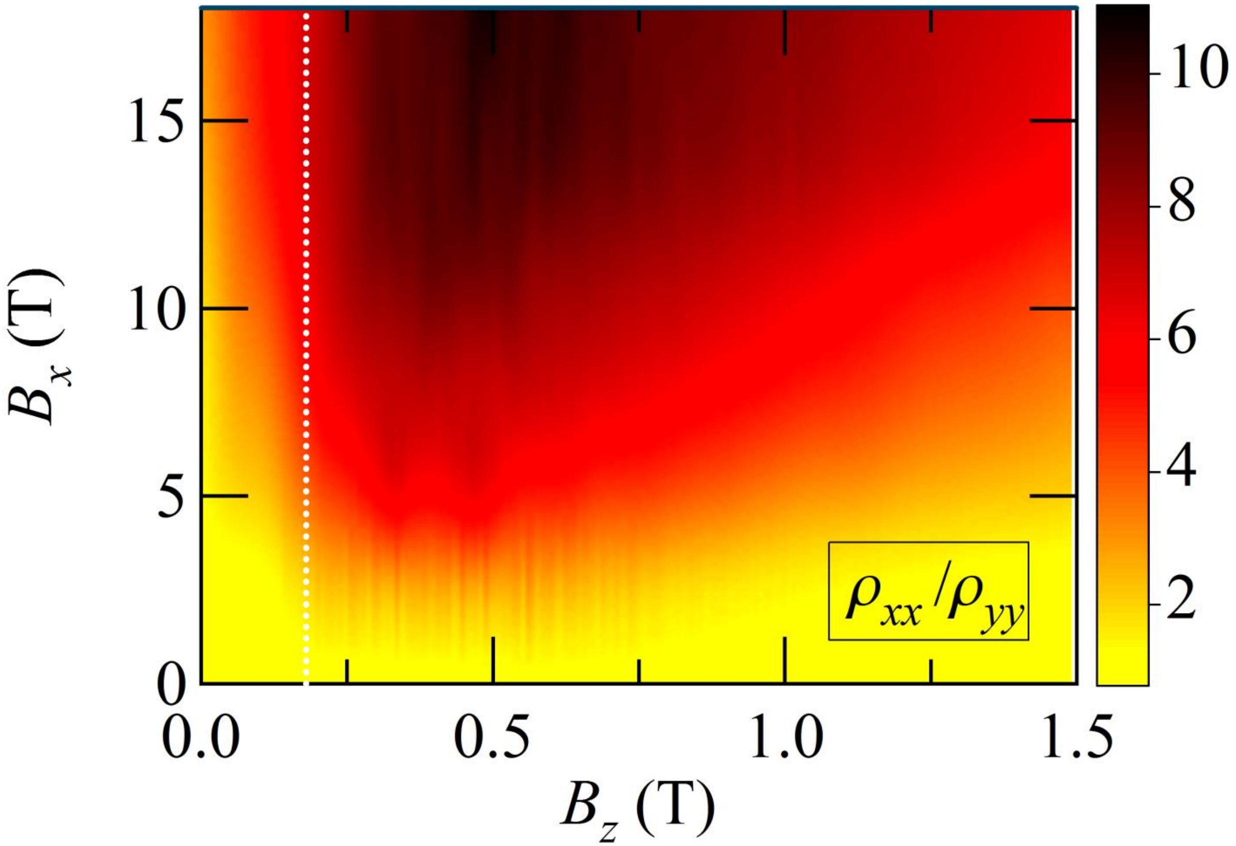
Resistivity ratio vs. B_z and B_x



At $B_z > B_z^\star$, the anisotropy is determined by B_x/B_z

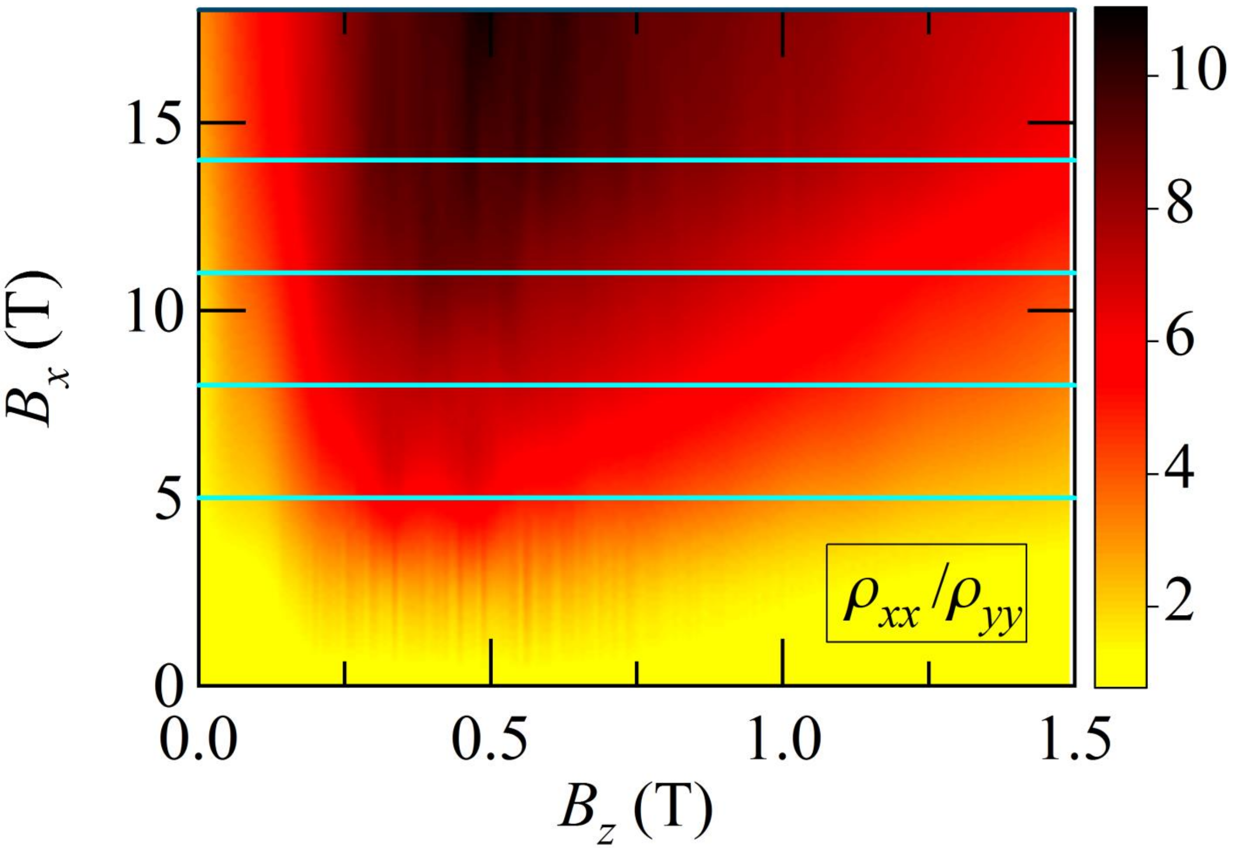
Shi, Zudov, Morrison, Myronov (2015)

Resistivity ratio vs. B_z and B_x

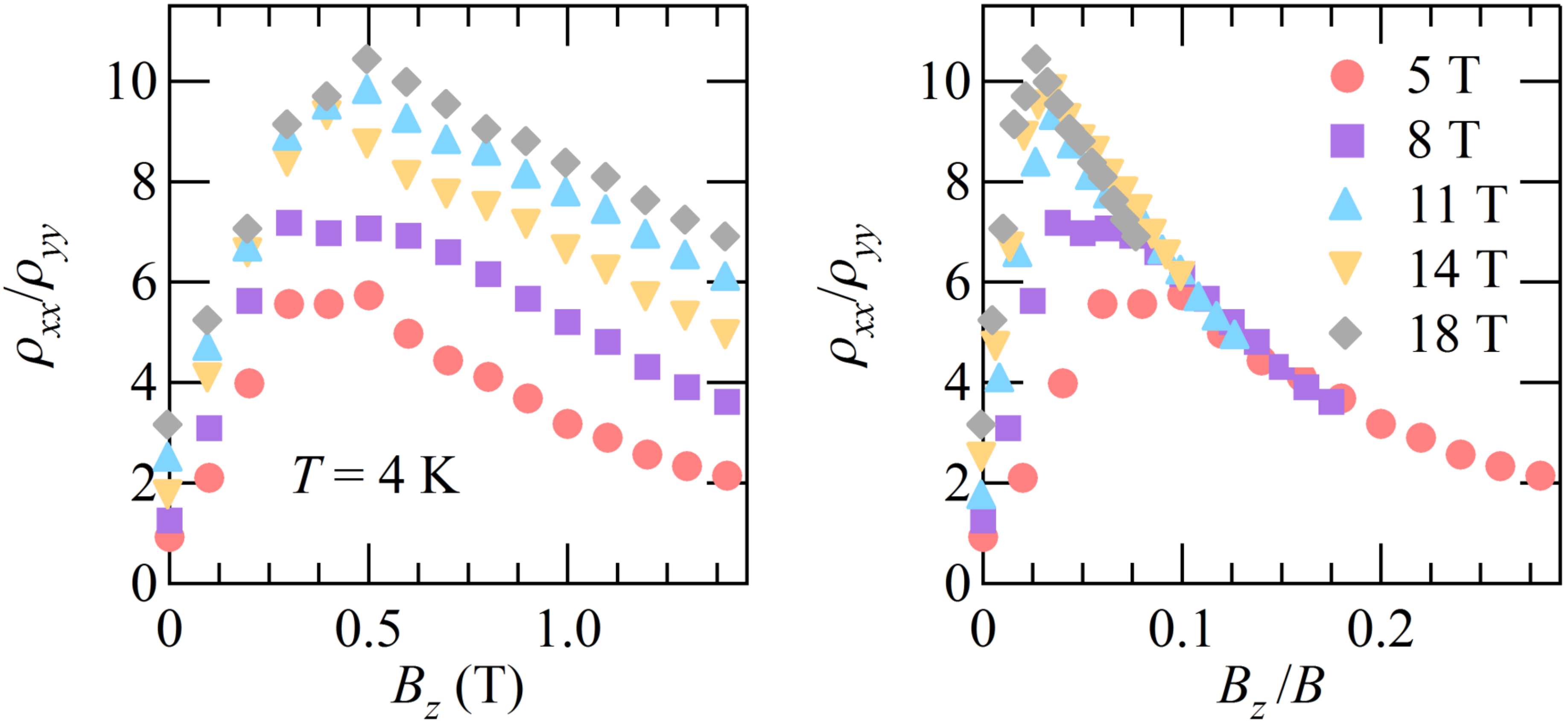


At $B_z < B_z^{\star}$, the anisotropy is controlled (mostly) by B_z

Resistivity ratio vs. B_z and B_x



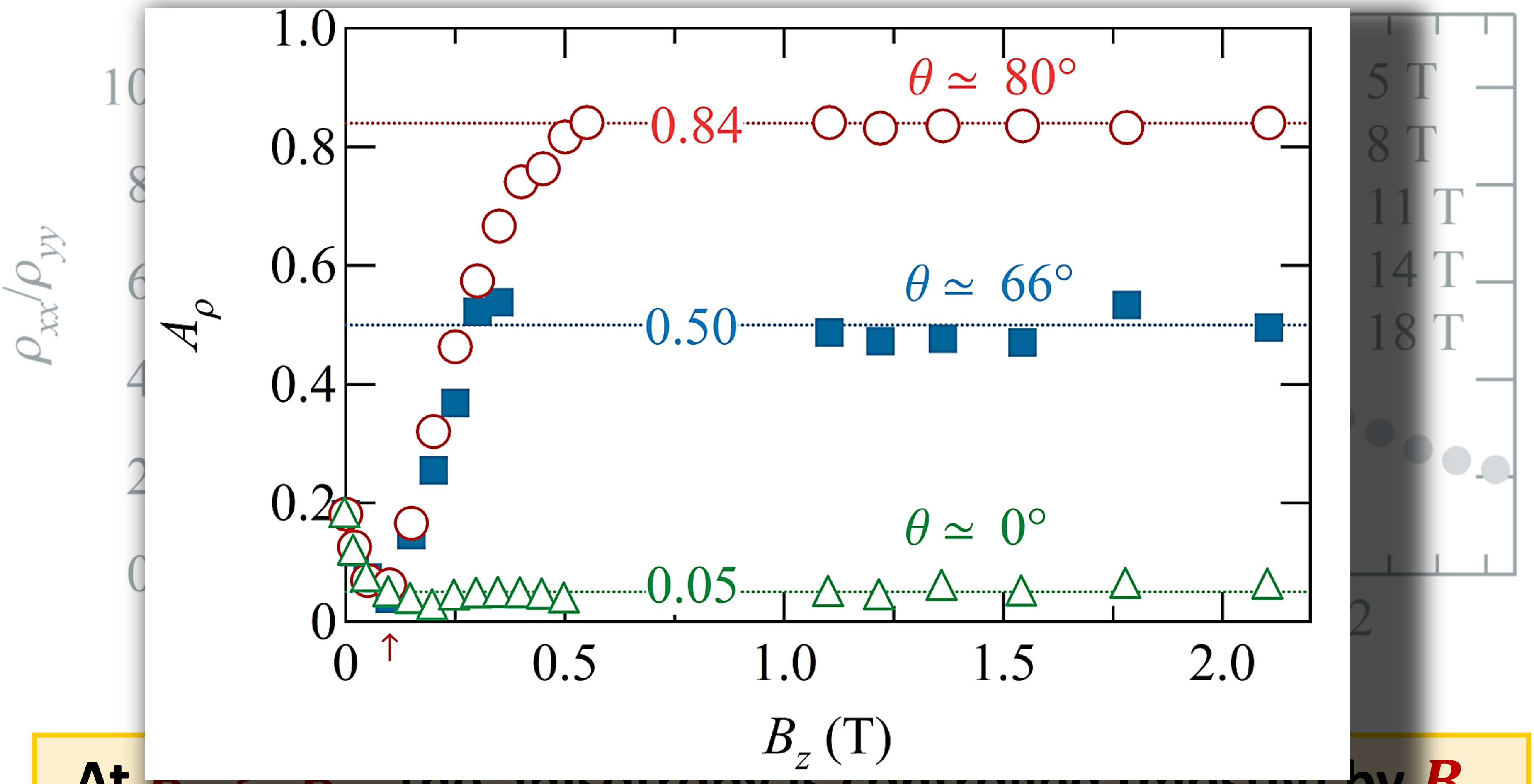
Two regimes separated by $B_z = B_z^\star$



At $B_z < B_z^\star$, the anisotropy is controlled (mostly) by B_z

At $B_z > B_z^\star$, the anisotropy is determined by B_x/B_z

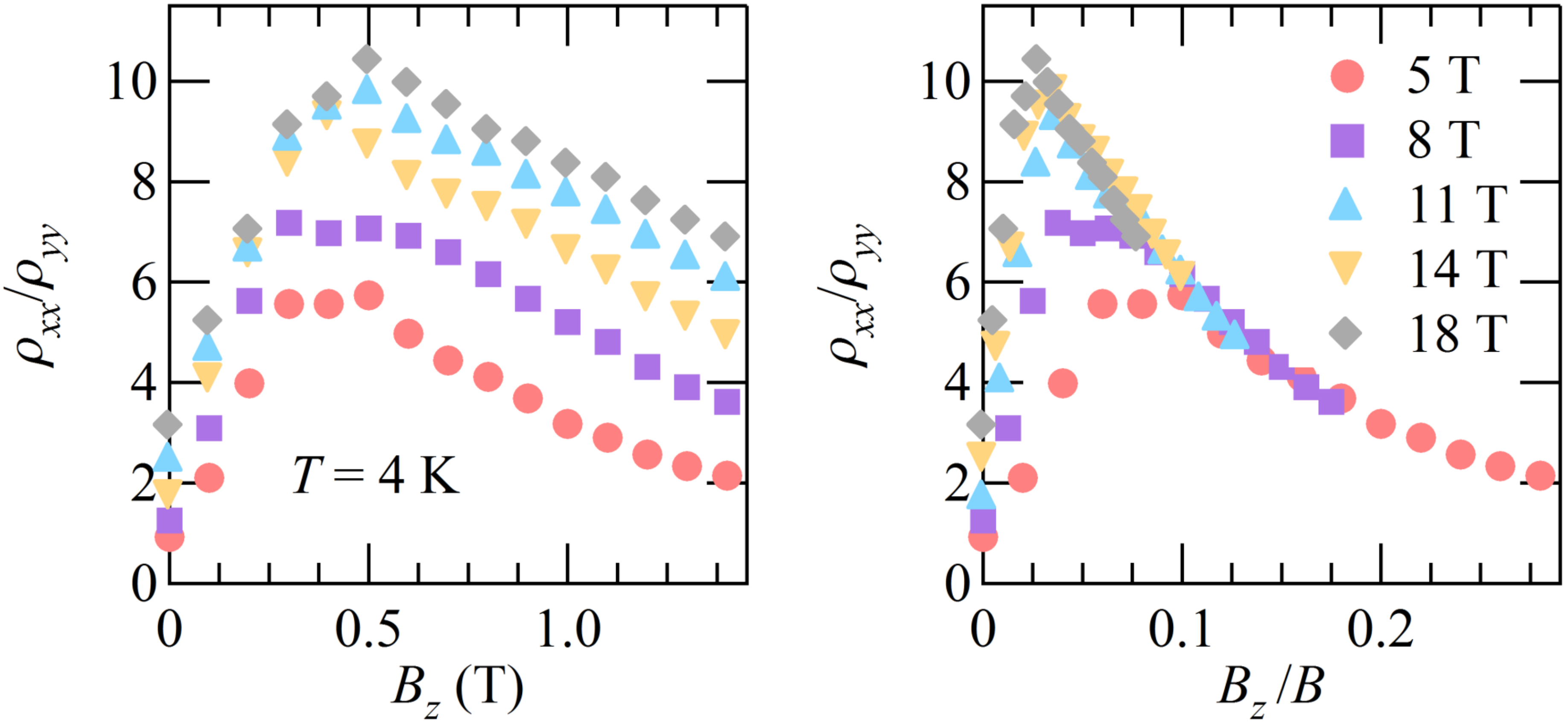
Two regimes separated by $B_z = B_z^\star$



At $B_z < B_z^\star$, the anisotropy is controlled (mostly) by B_z

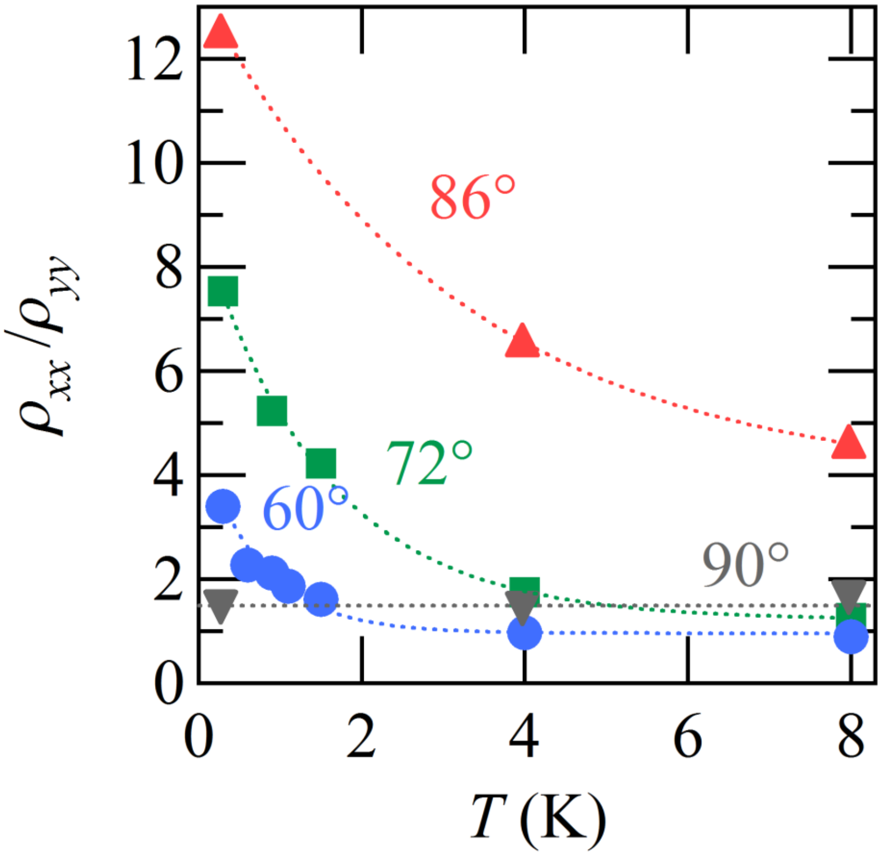
At $B_z > B_z^\star$, the anisotropy is determined by B_x/B_z

Two regimes separated by $B_z = B_z^\star$



At $B_z < B_z^\star$, the anisotropy is controlled (mostly) by B_z
At $B_z > B_z^\star$, the anisotropy is determined by B_x/B_z

Temperature dependence at $B_z > B_z^\star$



1). There is **no** temperature dependence in **pure $B_\parallel$**

2). Anisotropy decreases with T but can **persists to T = 8 K**

3). Anisotropy persists to **higher T** at **larger angle**

Possible origin

- Stripes?
  - Requires neither low T or quantizing field
- Finite thickness effects?
  - Opposite anisotropy axes
- Surface roughness?
  - Unclear how it leads to the anisotropy in the QH regime
- Other mechanism?

Fogler et al., PRB **54**, 1853 (1996)
Das Sarma et al., PRL **84**, 5596 (2000)
Goran et al., Semicond. Sci. Technol. **23**,105017 (2008)
Mirlin et al., PRL **83**, 2801 (1999)

Summary

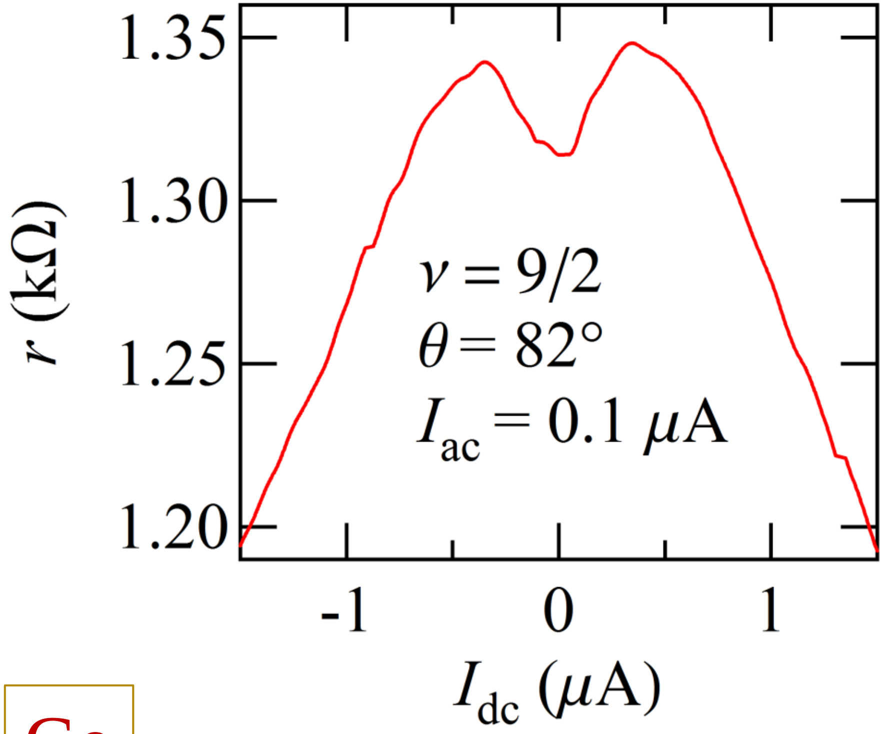
High quality Ge 2DHG reveals:

- MIRO, HIRO, and FQHE
- Mysterious tilt field-induced anisotropy that
  - has hard transport direction along $B_{\parallel}$
  - can have the resistivity ratio of more than 10
  - is determined by B_z at low B_z and by B_x/B_z at high B_z
  - persists to high T (higher T at higher tilt angle)

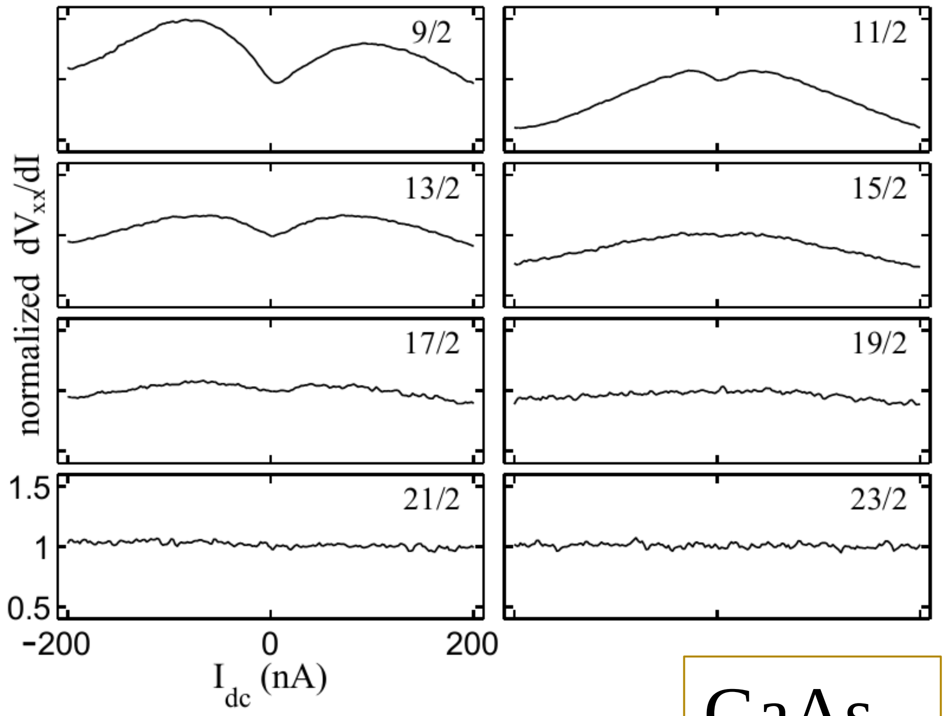
Thanks!

PRB **89**, 125401 (2014); PRB **90**, 161301(R) (2014); PRB **91**, 201301(R) (2015)

Nonlinear transport (sample C)



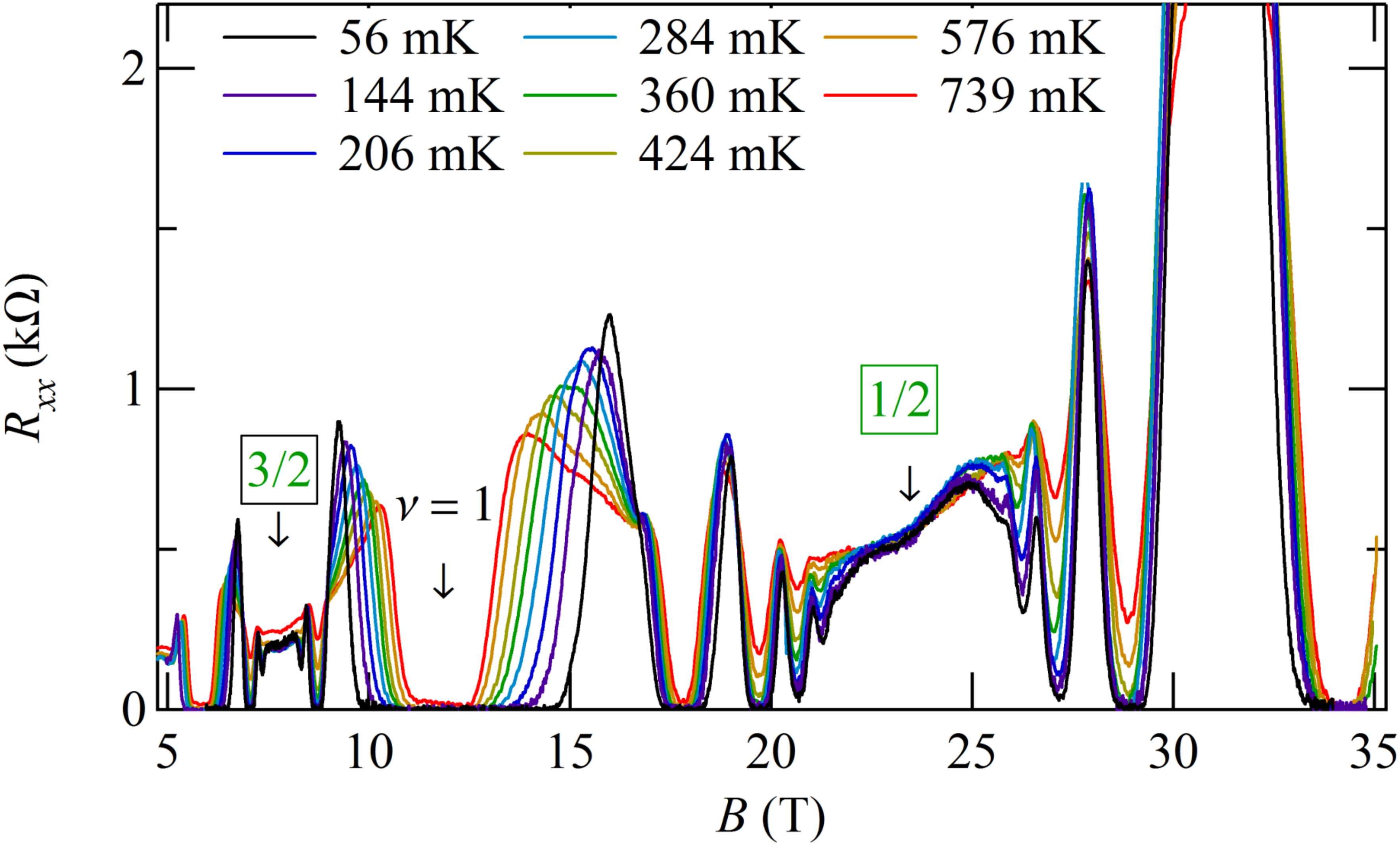
Ge



GaAs

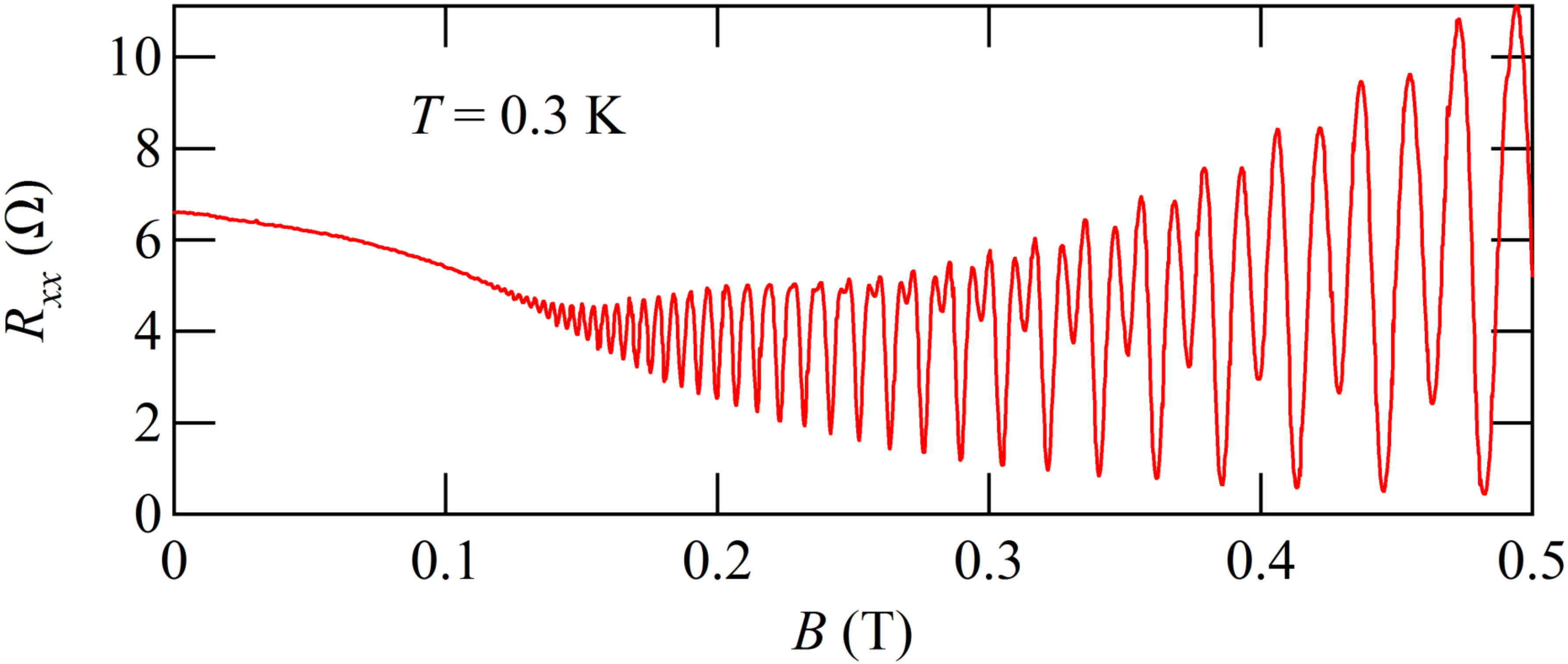
Nonlinear response to direct current

M. Lilly *et al*., Phys. Rev. Lett. **82**, 394 (1999)

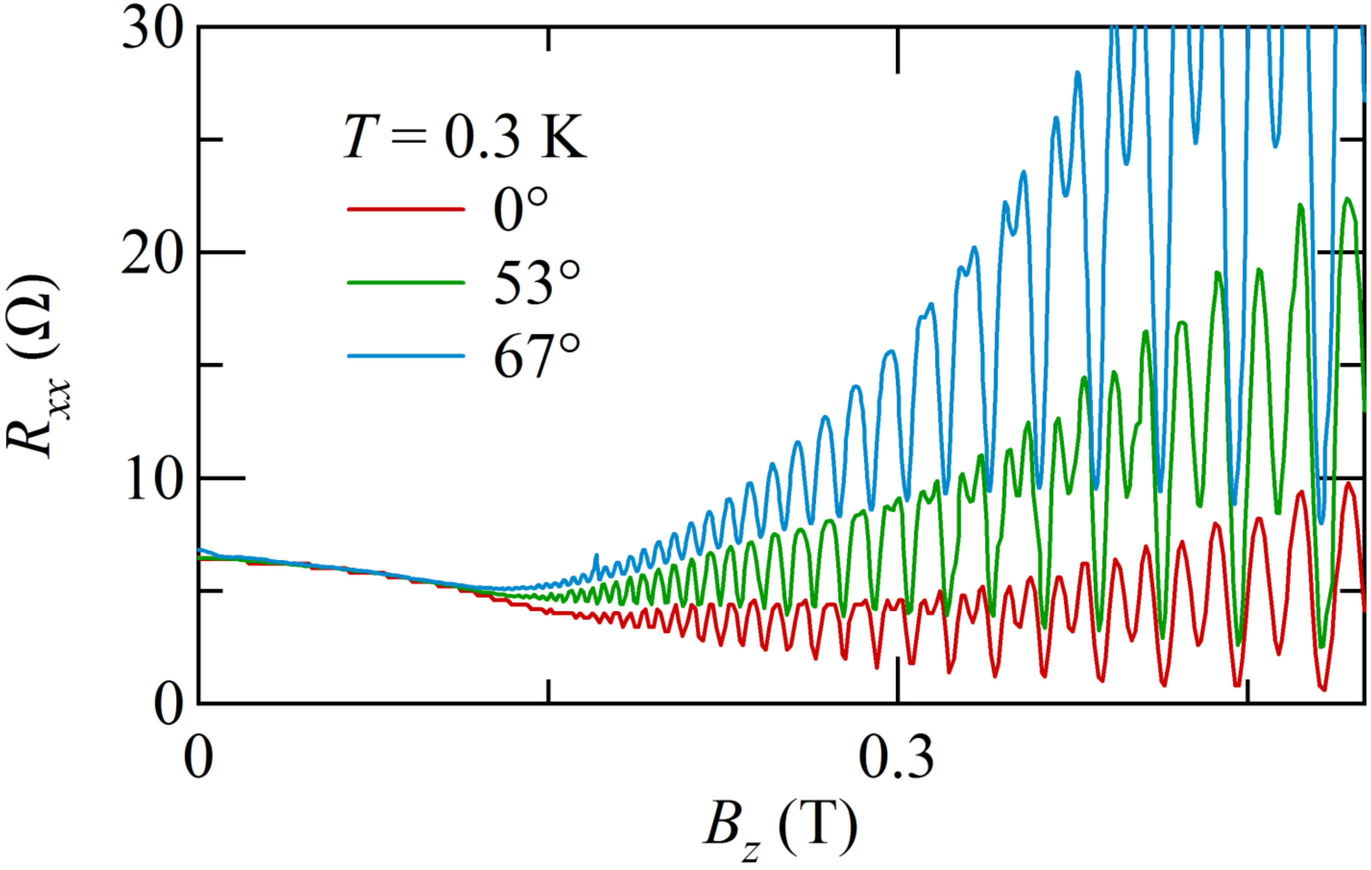

56 mK
144 mK
206 mK
284 mK
360 mK
424 mK
576 mK
739 mK
3/2
ν = 1
1/2
R_{xx} (kΩ)
0
1
2
5
10
15
20
25
30
35
B (T)

Samples studied

- Ge/SiGe 17/20 nm-wide QW (Boron doped)
- Only heavy hole band is populated
- $p \approx 3 \times 10^{11}\ \mathrm{cm}^{-2},\ \mu \approx 1 \times 10^{6}\ \mathrm{cm}^{2}/\mathrm{Vs}$

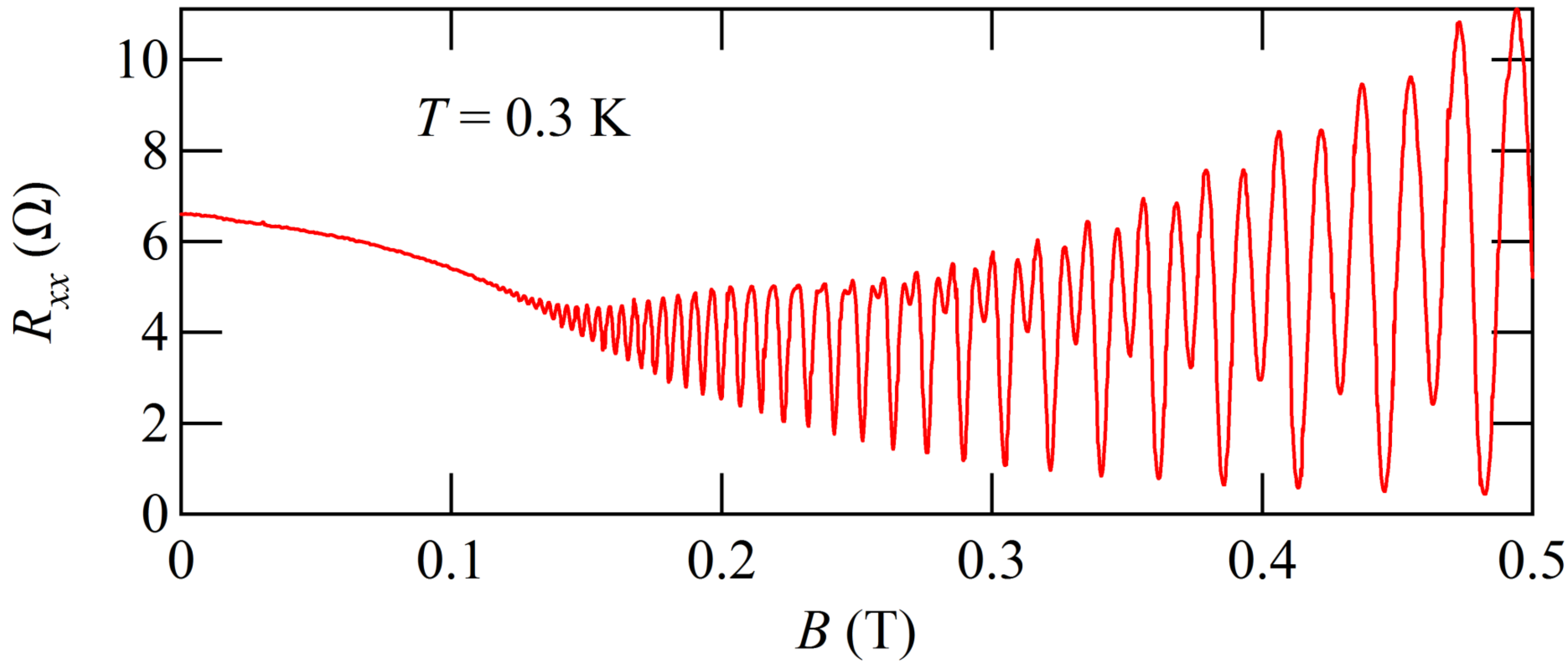


Spin-splitting under tilt ($B_x = B_\parallel$)?



$B_\parallel$ does not enhance the spin gap

Low field transport



$$B_{\mathrm{SdHO}} \approx 0.11\ \mathrm{T},\ B_{\mathrm{spin-spliting}} \approx 0.23\ \mathrm{T}$$

$$[\hbar\omega_c - g\mu_B B]_{B_{\mathrm{SdHO}}} \sim [g\mu_B B]_{B_{\mathrm{spin-spliting}}} \sim \Gamma$$

$$\Rightarrow g \sim 7$$