Phase transition from composite fermion liquid to Wigner solid in the lowest landau level of MgZnO/ZnO.

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ICAM Annual Meeting
Hsinchu City, Taiwan.
Friday 18th January, 2019

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ZnO electronic properties

Wide gap semiconductor (II-VI)

Direct band gap ~ 3.37 eV.

e$^-$ mobility ~ 2000 cm^2 V^{-1} s^{-1}

Bonding is mainly ionic: Zn^{2+}, O^{2-}.

(0001) surfaces are polar.

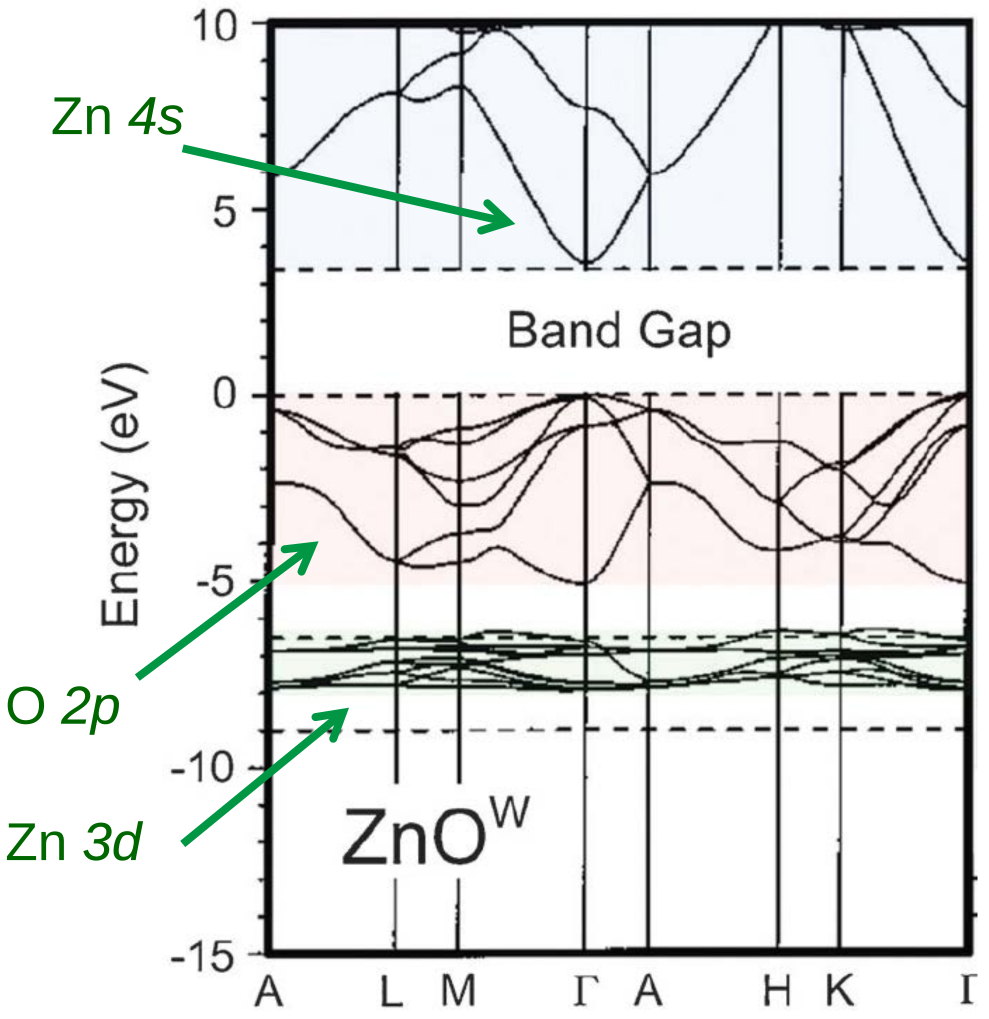
MgO bandgap ~ 7.8 eV

Oxide heterostructure : ~ 1% Mg doping of ZnO

2D electron gas at interface.

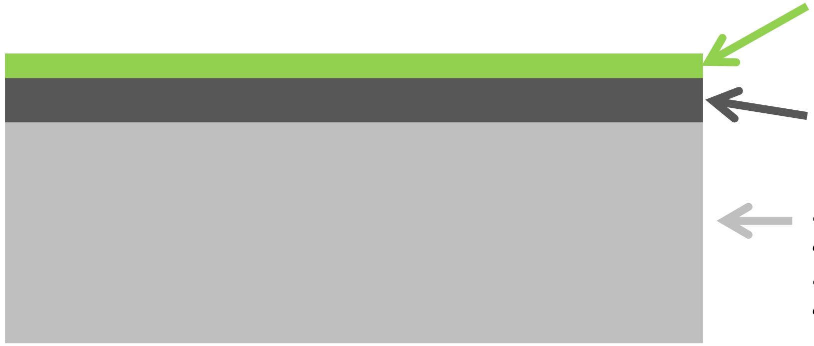
Very high mobility system : μ ~ 500 000 cm^2 V^{-1} s^{-1}

Low carrier density: n ~ 1.7 x 10^{11} cm^{-2}



$Mg_xZn_{(1-x)}O/ZnO$ heterostructure

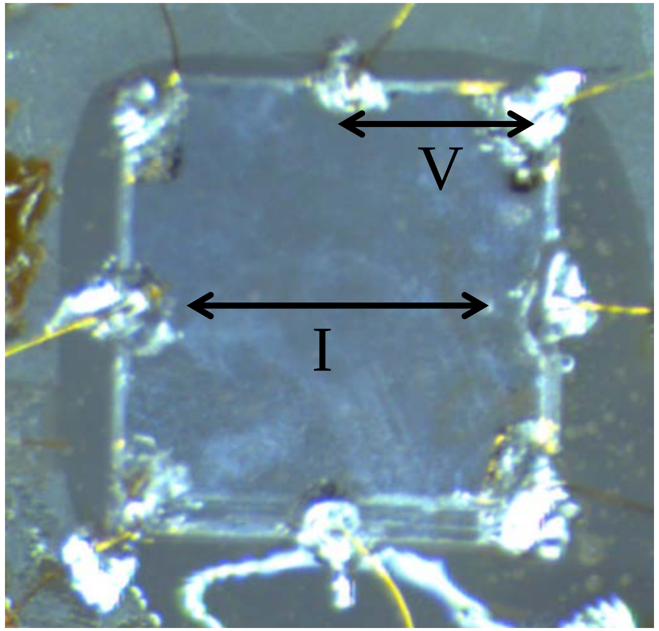
$Mg_xZn_{(1-x)}O$ grown on ZnO (0001) surface.



$Mg_xZn_{(1-x)}O$ (200 nm)

ZnO buffer layer (400 nm)

ZnO substrate (400 μm)
Zn terminated after etching with HCl



Sample mounted on dilution refrigerator rotating stage (x ~ 0.01).

3mm x 3mm

van der Pauw contact geometry

Indium contacts, gold bonding wires

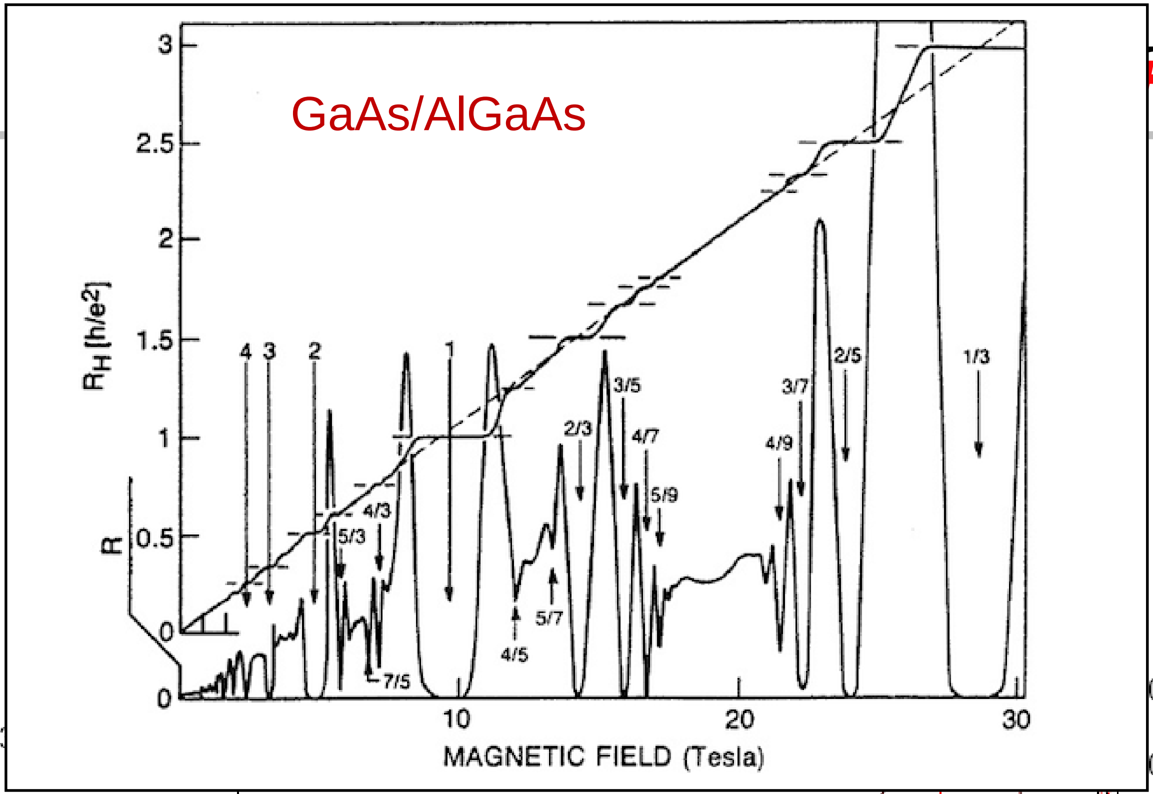
~1% Mg doping of ZnO

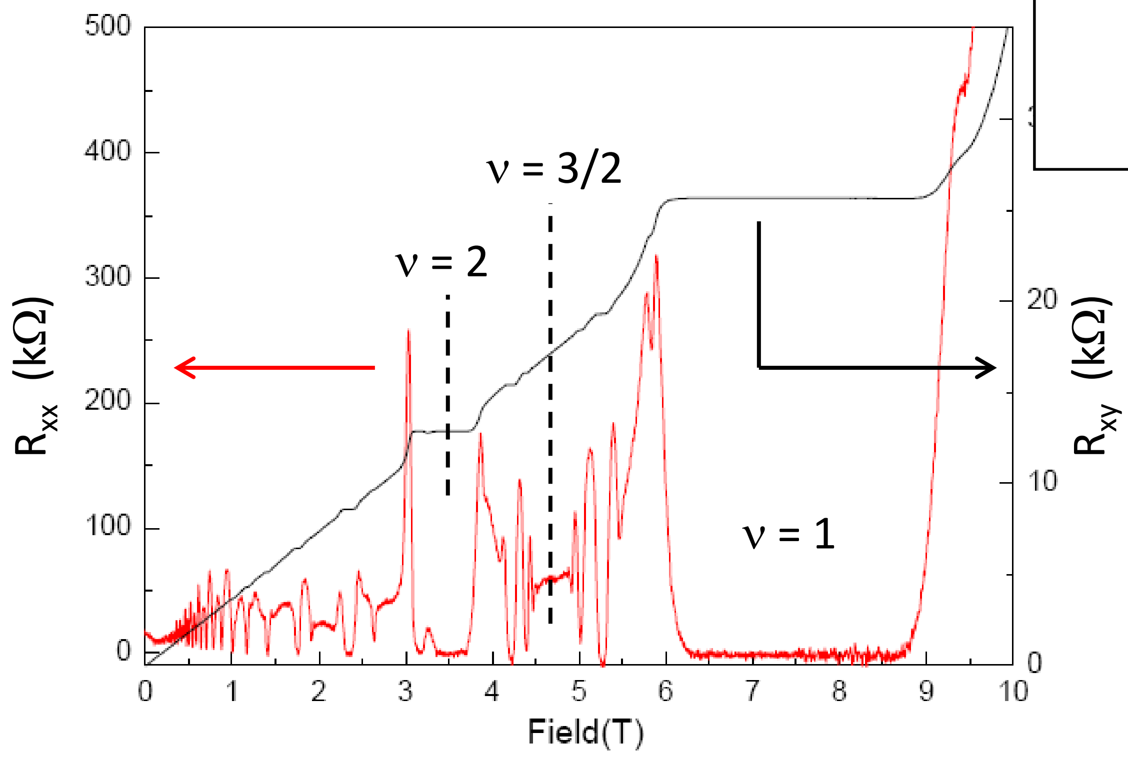
2D electron gas at interface

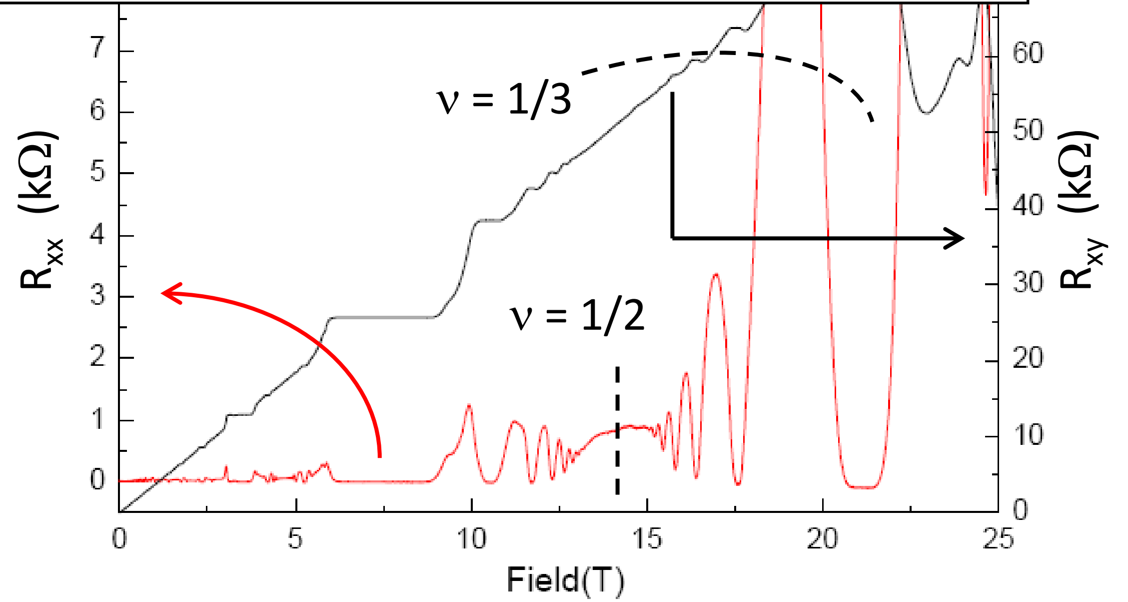
High mobility: $\mu \sim 500\,000\ \mathrm{cm^2\ V^{-1}\ s^{-1}}$

Low carrier density: $n \sim 1.7 \times 10^{11}\ \mathrm{cm^{-2}}$

Eisenstein and Störmer, Science **248**, 1510 (1990)

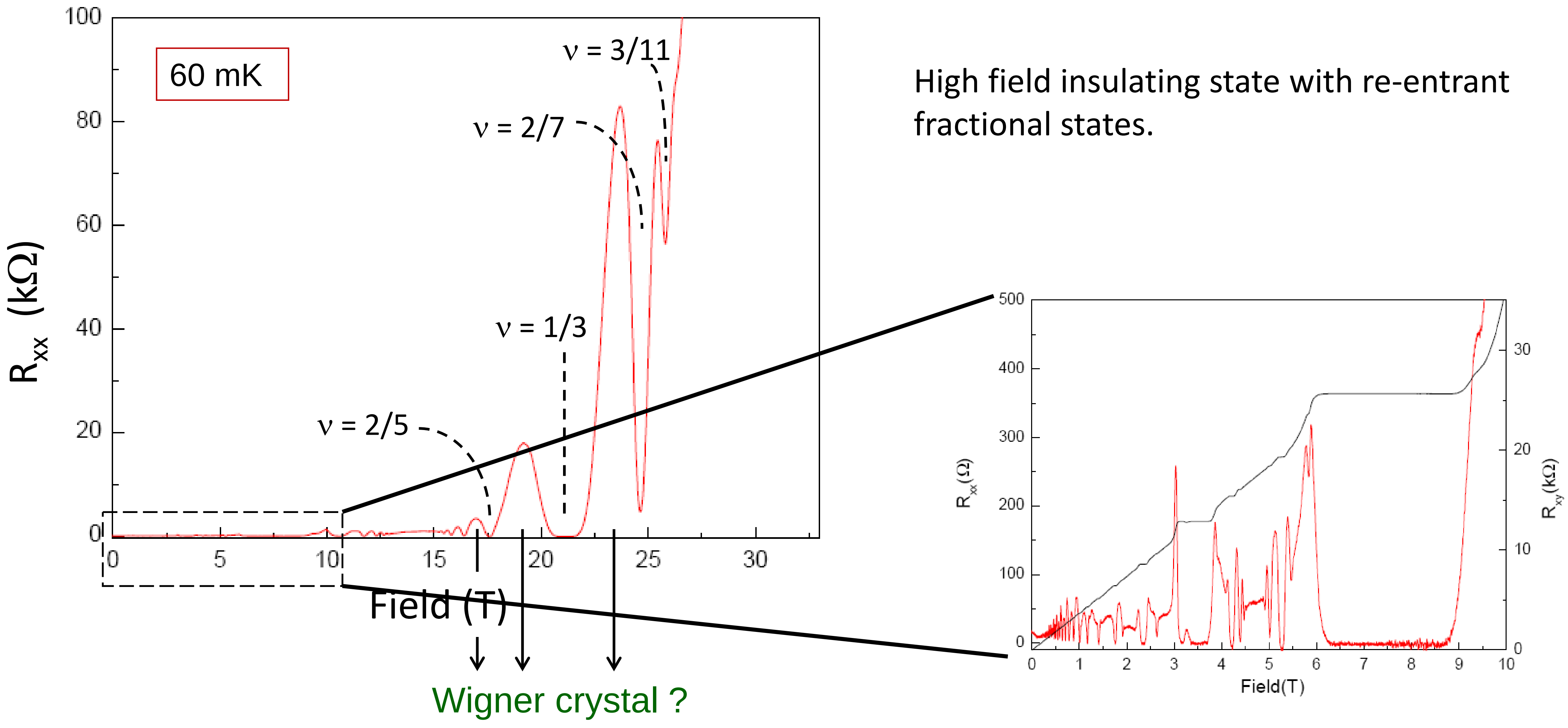




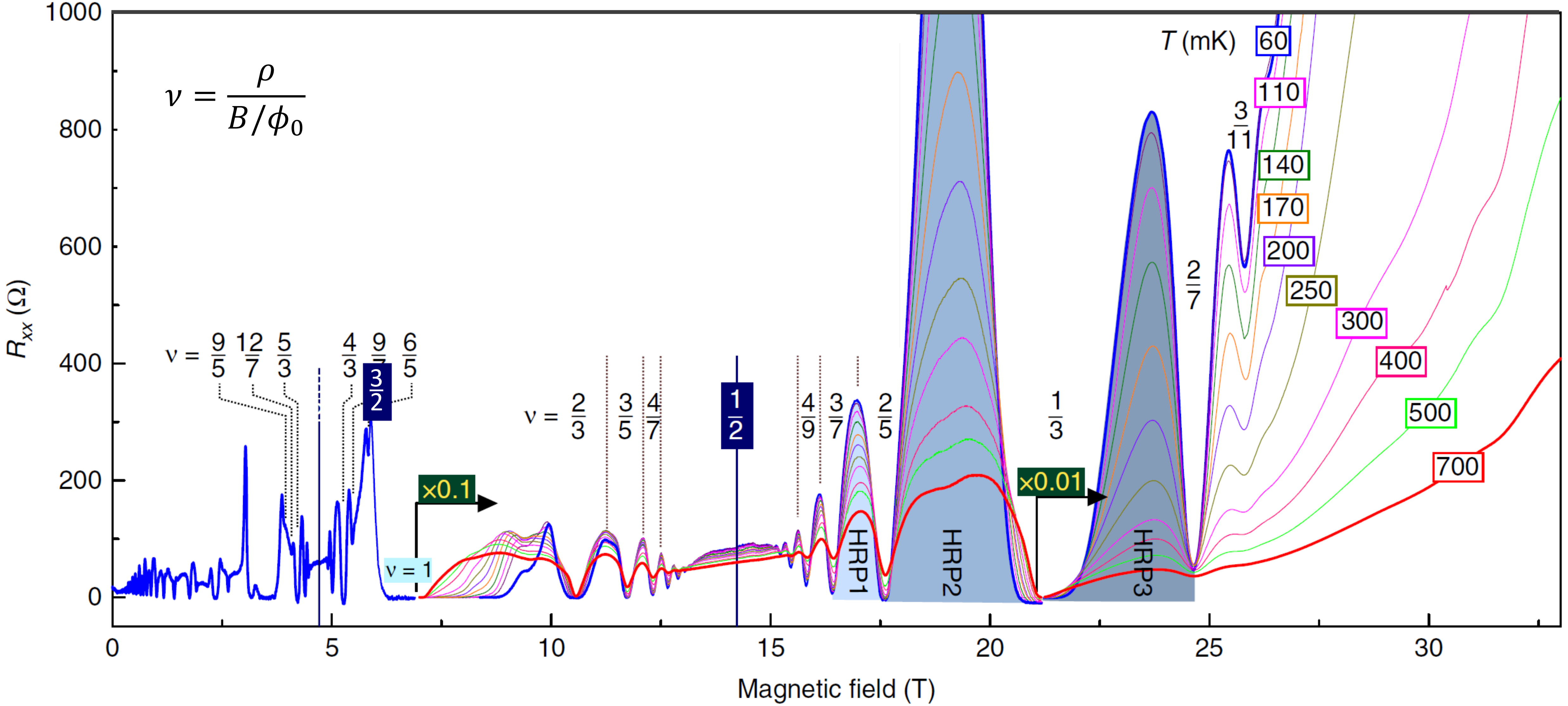


High field data – Wigner crystal

High field insulating state with re-entrant fractional states.



Temperature dependence



HFML

Solid crystalline phase formed when electron interactions (PE) dominate kinetic energy.

Crystal will form when carrier density is less than a certain value.

Can also be induced in a 2d system by high magnetic field – localization within a magnetic length:

$$l = \left(\frac{\hbar c}{eB}\right)^{1/2} \approx \frac{25}{\sqrt{B}} \quad [\mathrm{nm}]$$

$$V_C = \frac{e^2}{\epsilon l} \approx 50\sqrt{B} \quad [\mathrm{K}]$$

$$\hbar\omega_c \approx 20\, B \quad [\mathrm{K}]$$

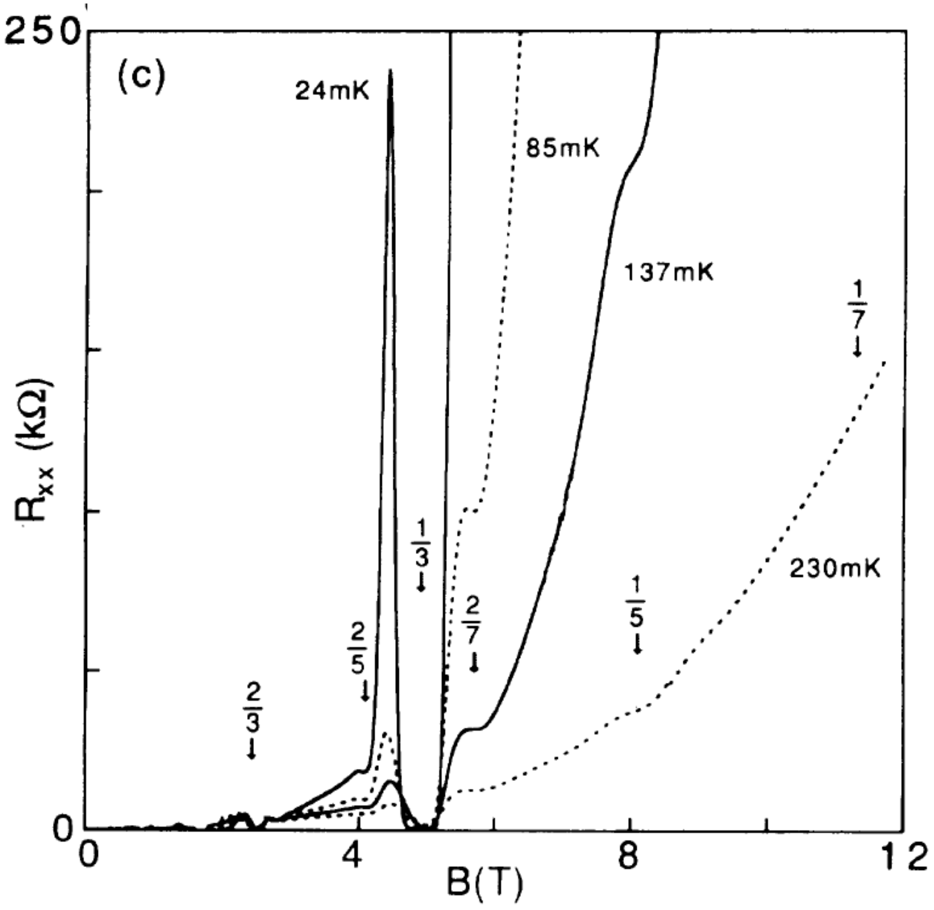
$$\kappa = \frac{e^2}{\hbar\omega_c \epsilon l} = \frac{\sqrt{\nu}}{2 r_s}$$

GaAs electron	$\kappa = 2.6\sqrt{B}$
GaAs hole	$\kappa = 14.6\sqrt{B}$
ZnO electron	$\kappa = 16.7\sqrt{B}$
AlAs electron	$\kappa = 22.5\sqrt{B}$

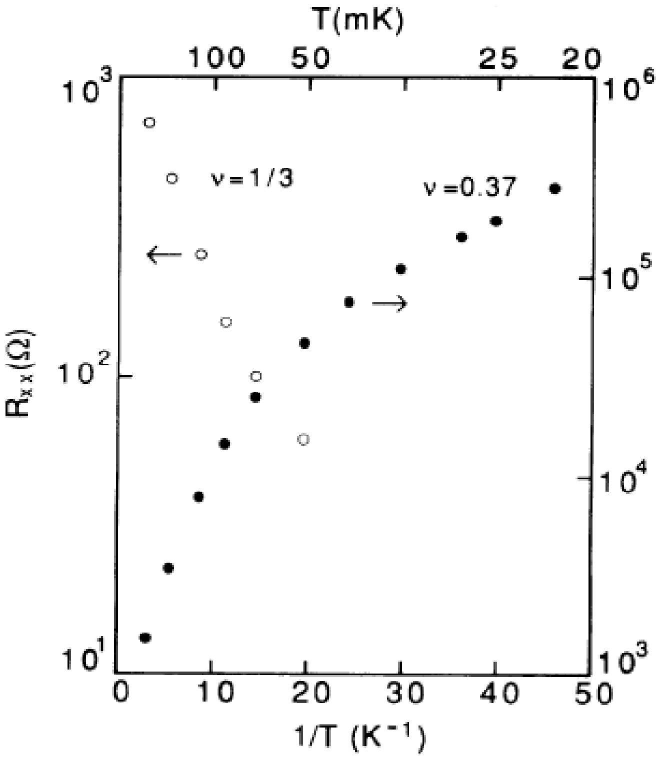
$\nu < 1/5$ GaAs 2deg
$\nu < 1/3$ GaAs 2dhg

Sodemann and MacDonald, PRB **87**, 245425 (2013)

Example of GaAs/AlGaAs hole system



$p_s \sim 4 \times 10^{10}$ cm^{-2}

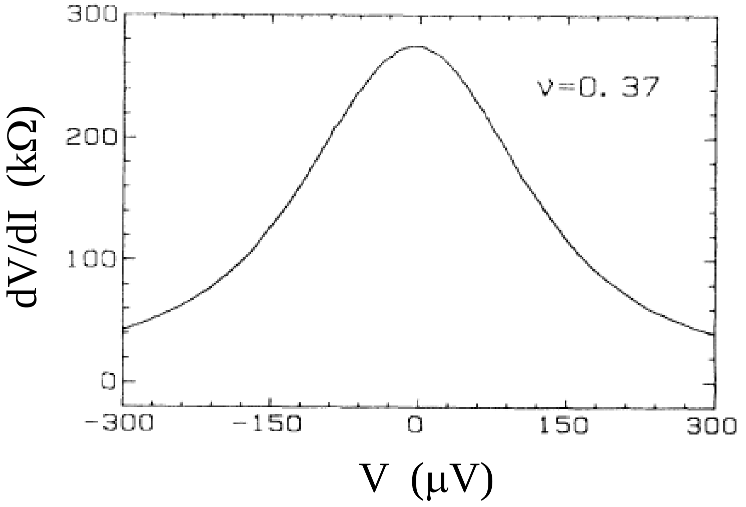


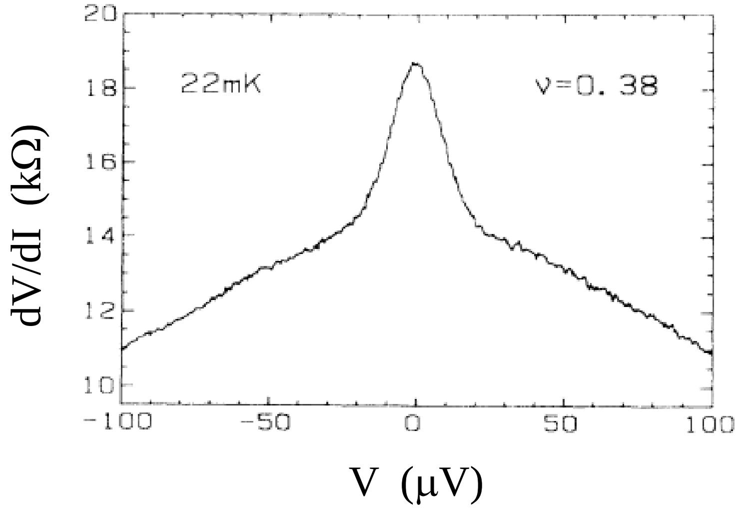
I –V curves for

1/3 < ν < 2/5

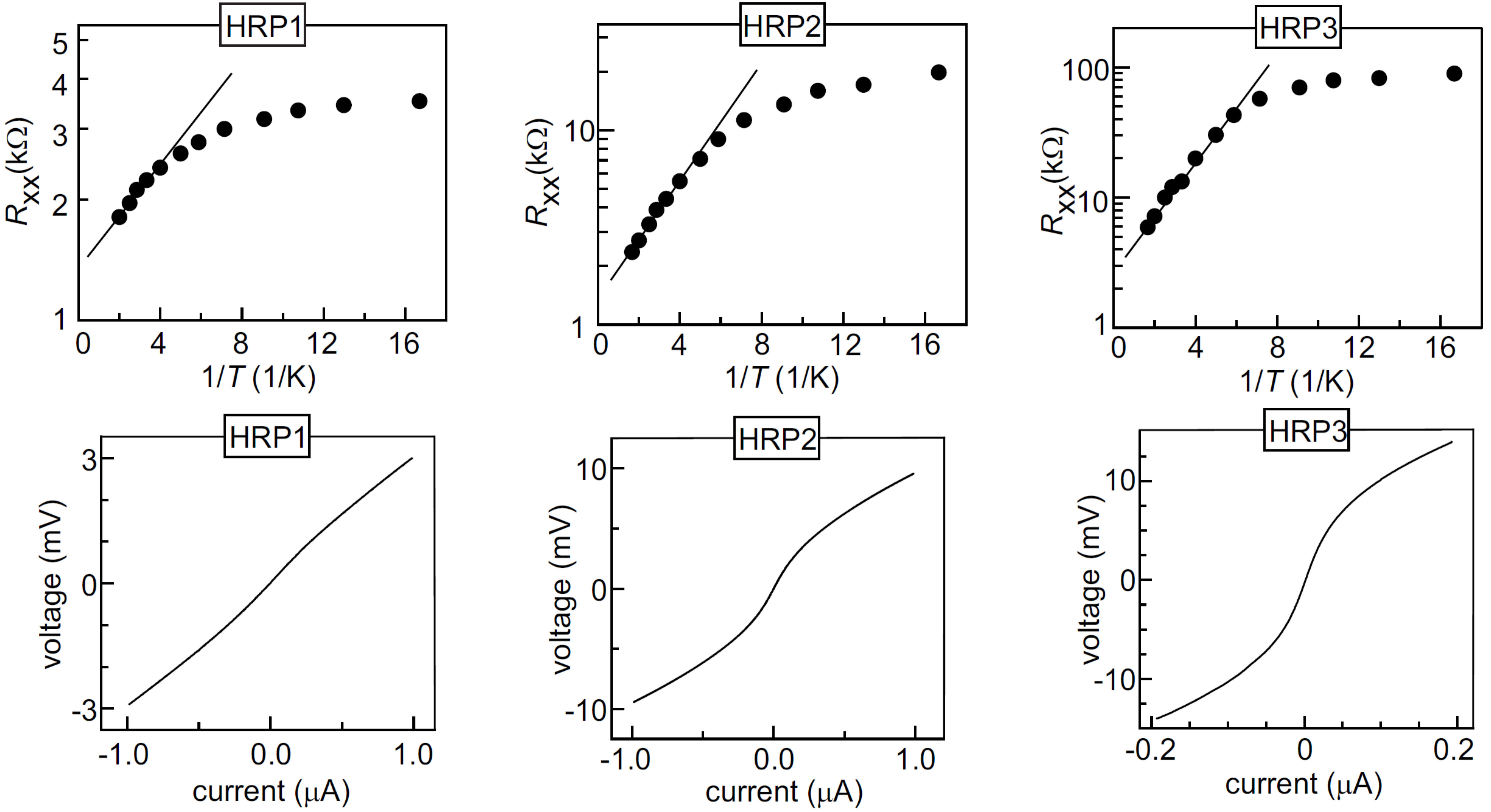
Santos *et al*, PRL **68**, 1188 (1992)

Crystal is pinned to the lattice.

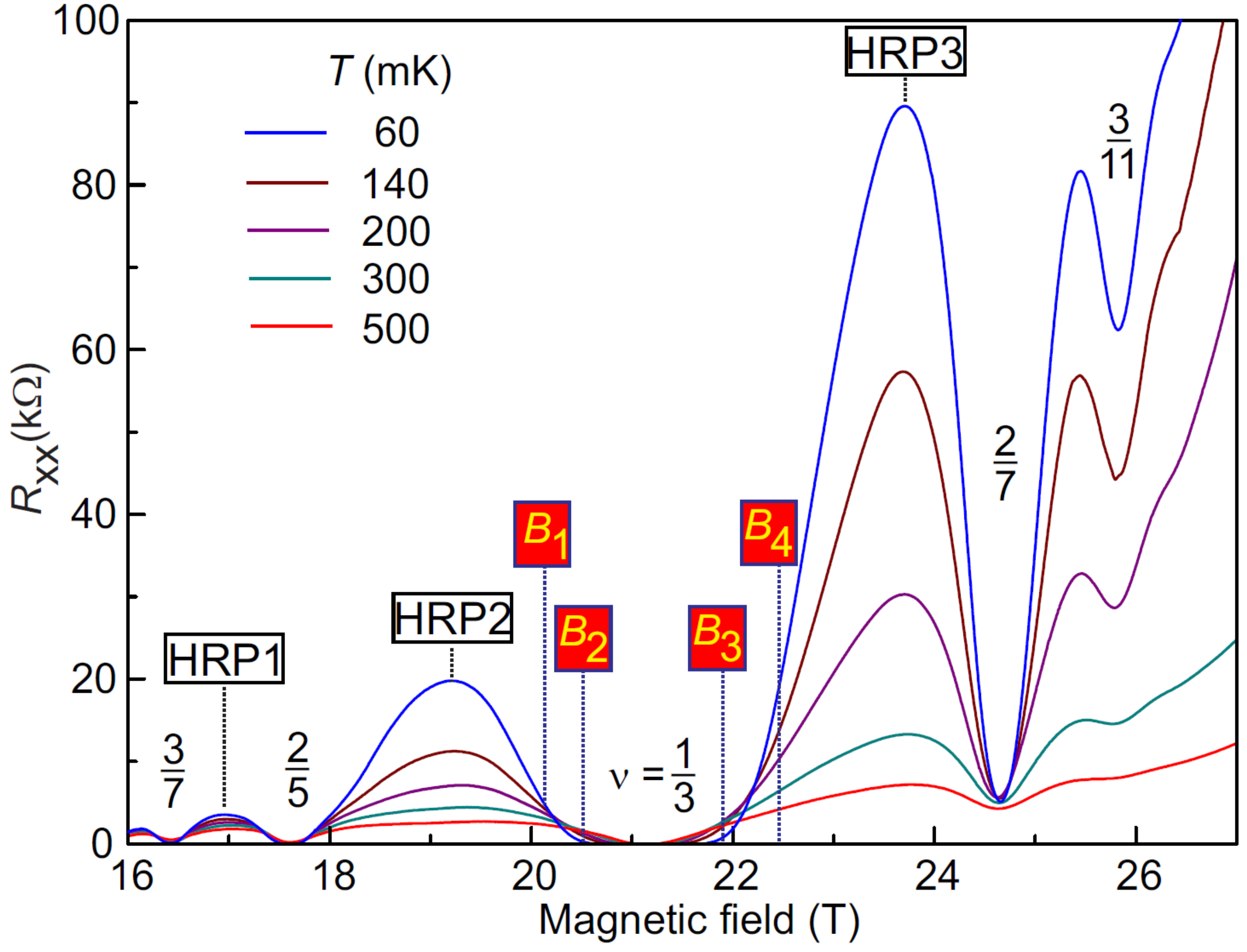


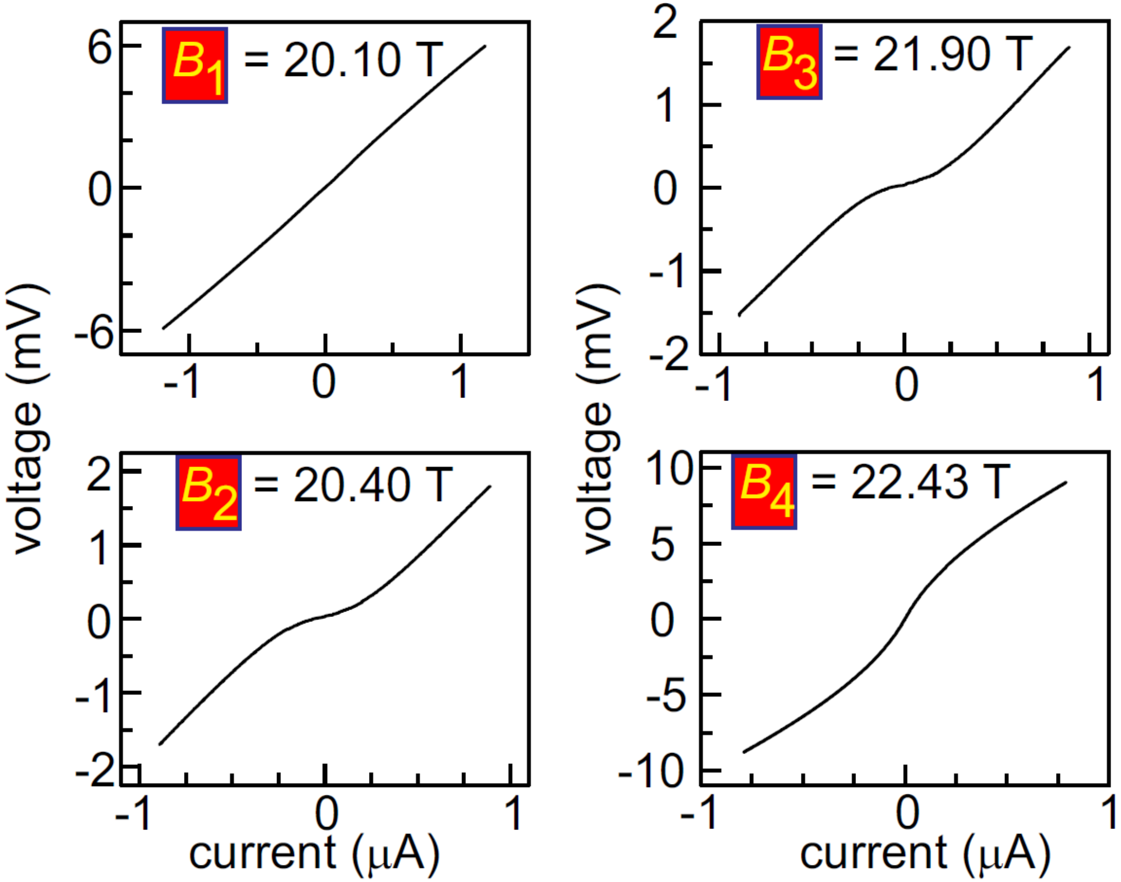


Properties of the high field insulating phases of MgZnO/ZnO



Metal–insulator transition

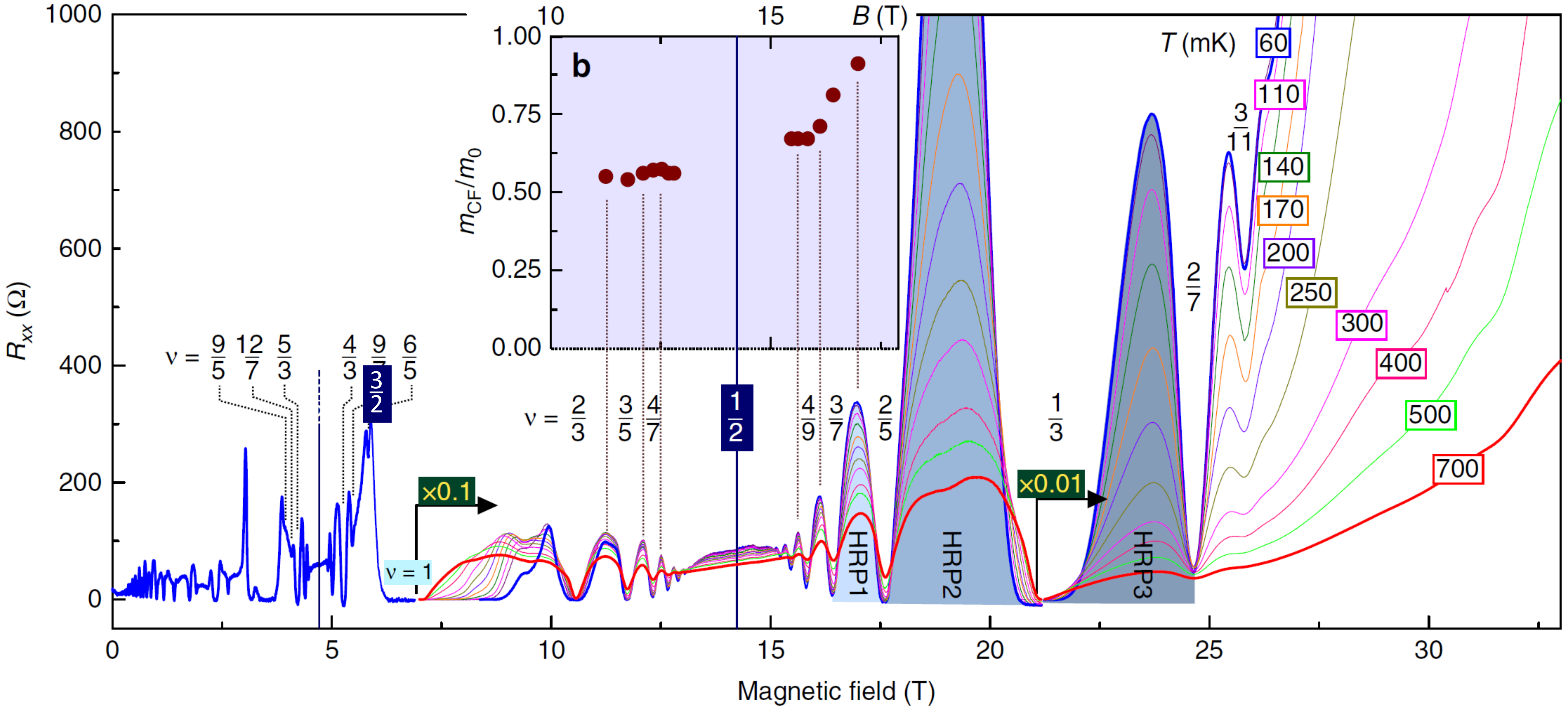




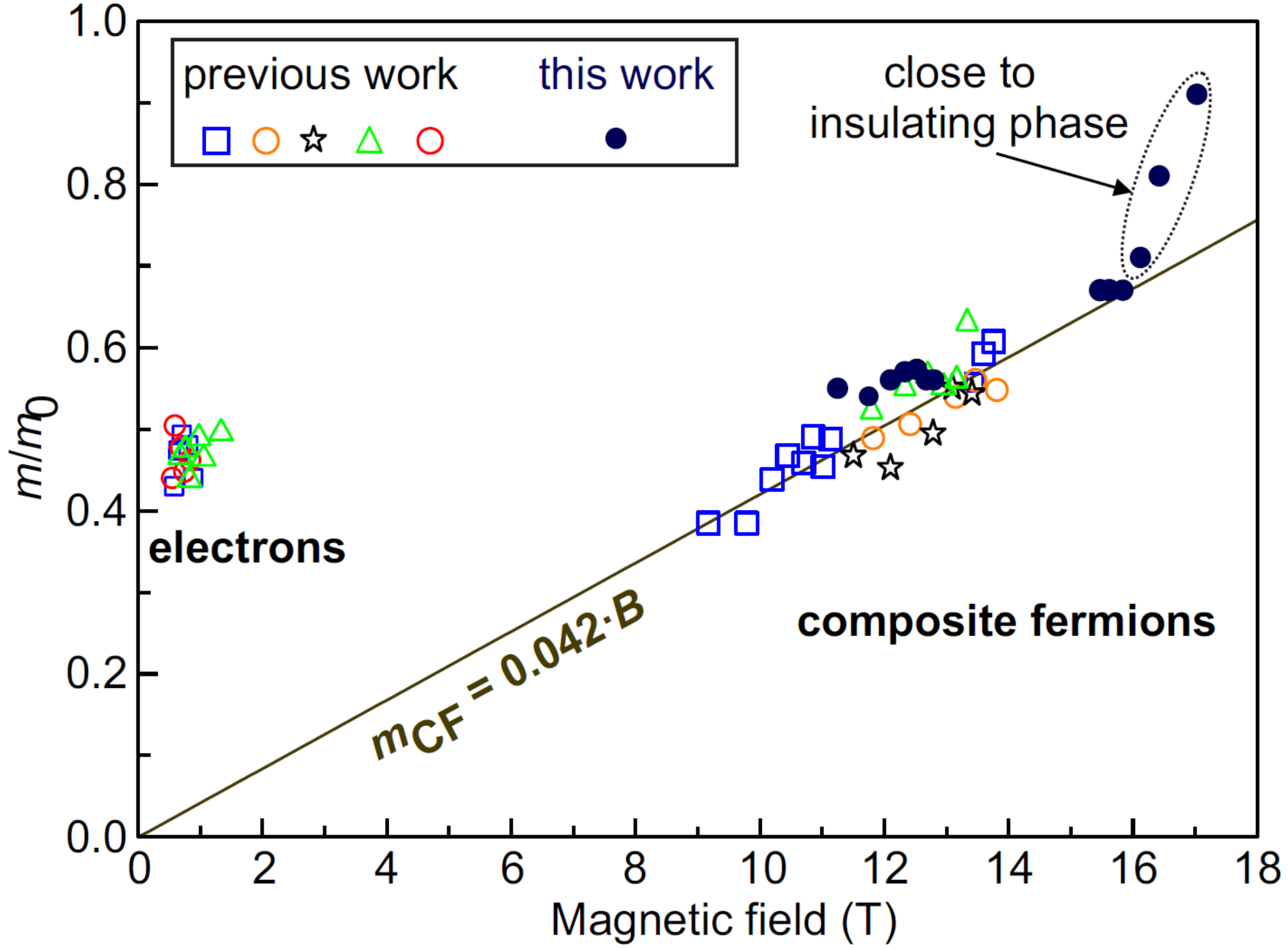
$\partial R_{xx}/_{\partial T} < 0$ in insulating (solid) phase

$\partial R_{xx}/_{\partial T} > 0$ in conducting (liquid) phase

Effective mass (of composite fermions)



Effective mass (of composite fermions)



$$B_{\mathrm{eff}} = B - B_{\nu=1/2}$$

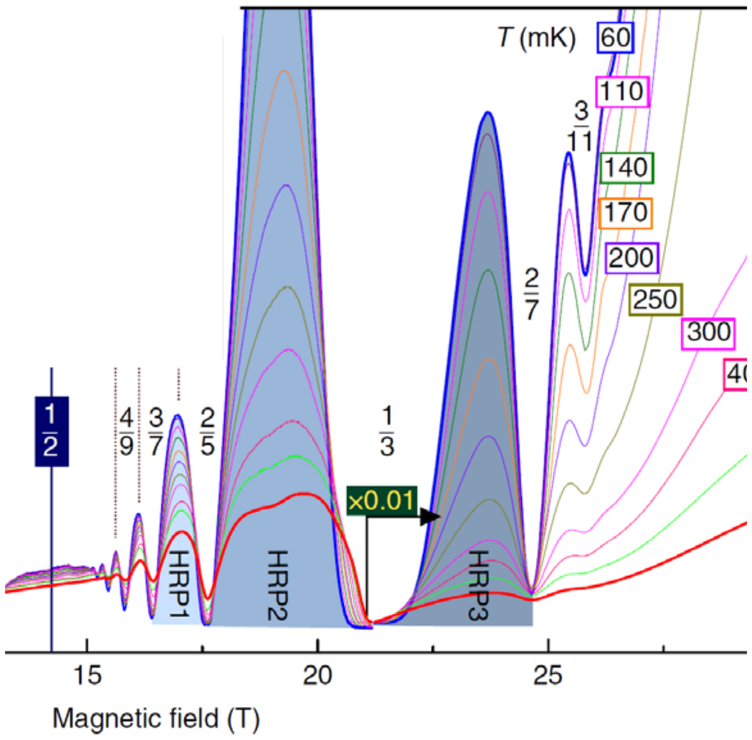
$$\Delta R_{xx} = R_0 \frac{XT}{\sinh(XT)} \exp\left(-\frac{\pi}{\omega_{\mathrm{CF}}\tau_{\mathrm{q}}}\right)$$

$$X = \frac{2\pi^2 k_{\mathrm{B}}}{\hbar} \frac{m_{\mathrm{CF}}}{e B_{\mathrm{eff}}}$$

What are the insulating phases?

Wigner crystal of electrons?
Wigner crystal of composite fermions?

Narevich *et al.*, PRB 64, 245326 (2001)
Archer, Park and Jain, PRL **111**, 146804 (2013)
Zhiao, Zhang and Jain, PRL **121**, 116802 (2018)
Liu *et al.*, PRL **113**, 246803 (2014)

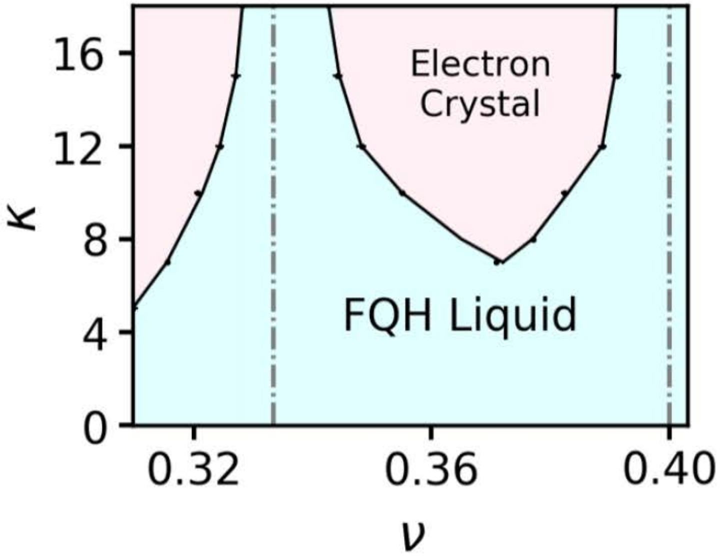


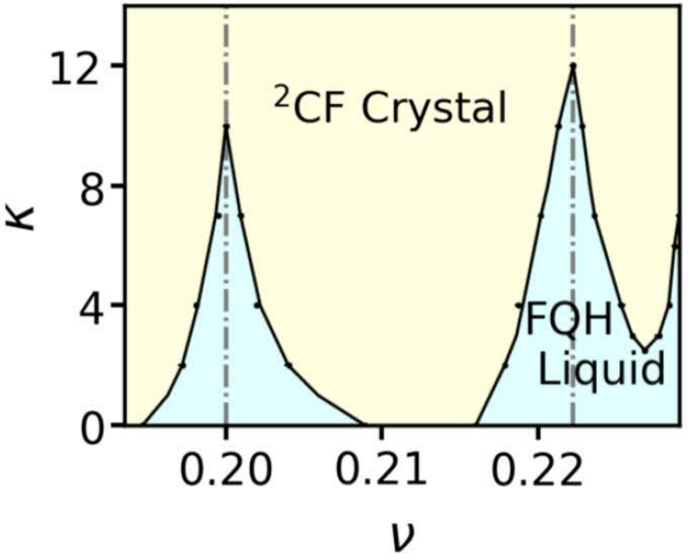
Strong ν (or κ) dependence of the boundary between FQH and WC phases

For $\kappa \geq 7$: electron crystal for ν between 1/3 and 2/5,
CF crystal in region of 1/5 and 2/9

(ZnO $\kappa = 16.7\sqrt{B}$)

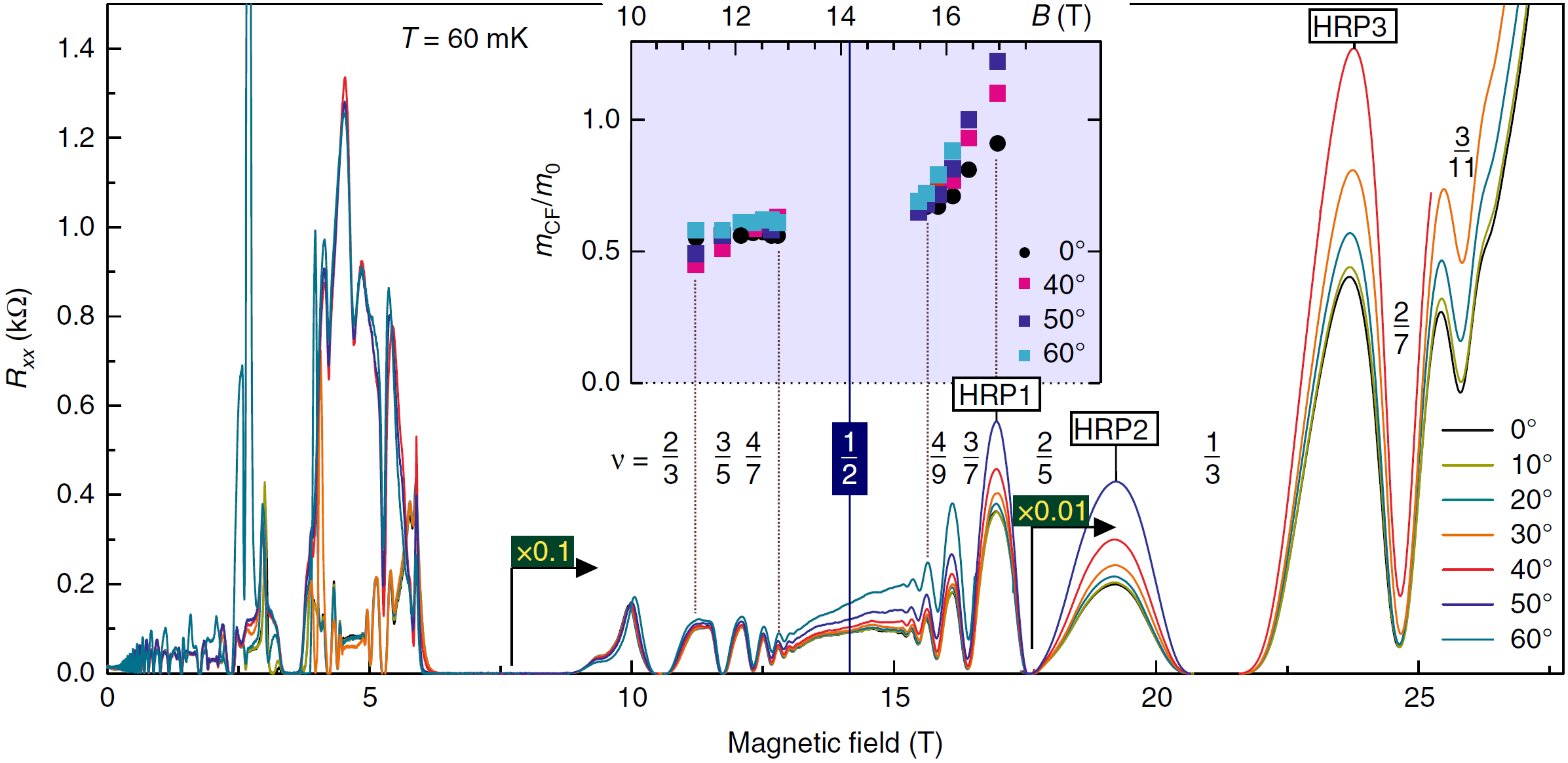
HRP3 is candidate for CF crystal.



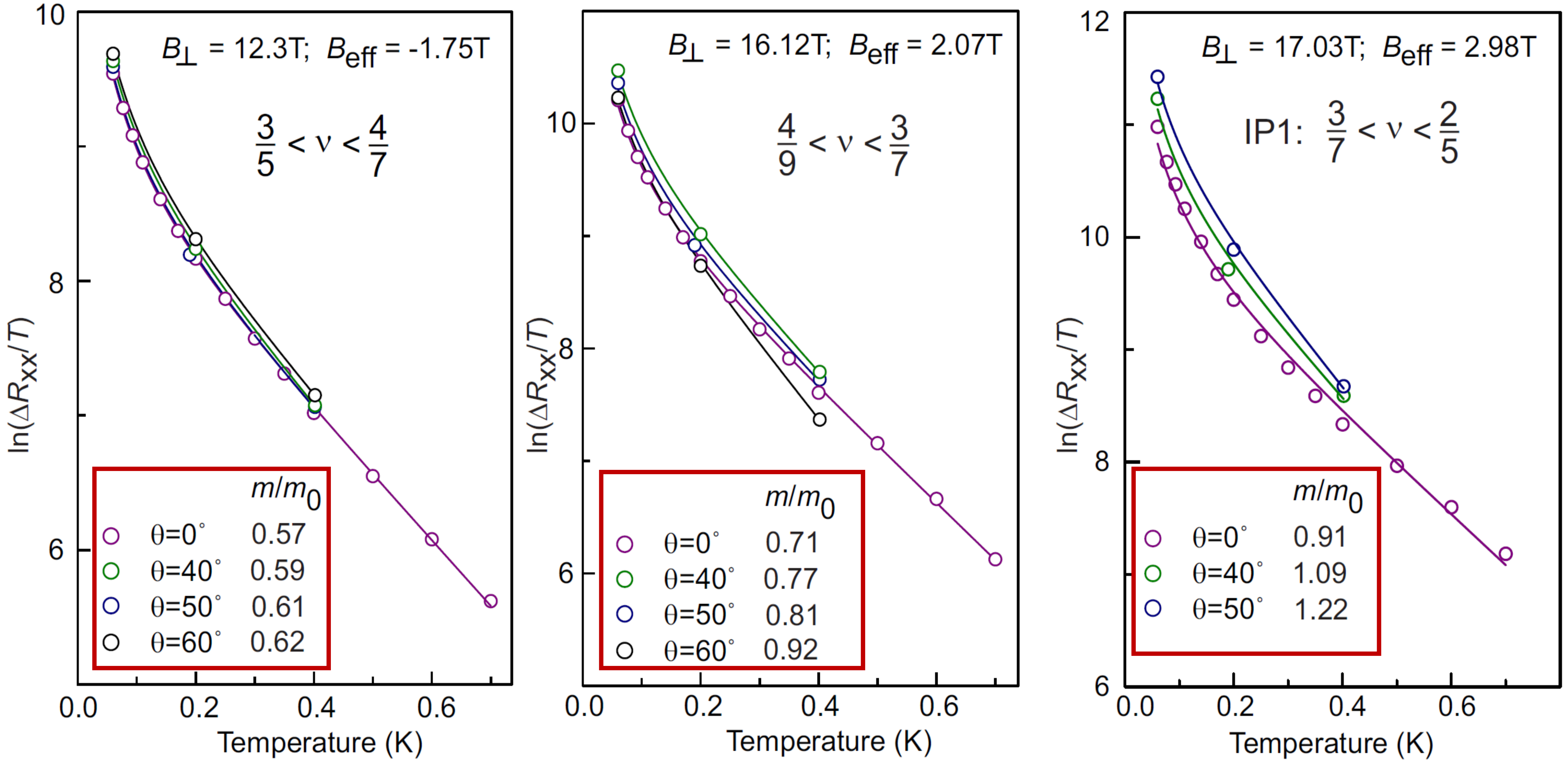


Zhiao, Zhang and Jain, PRL **121**, 116802 (2018)

Tilted magnetic field



CF effective mass



Not much effect for $\nu > 1/2$

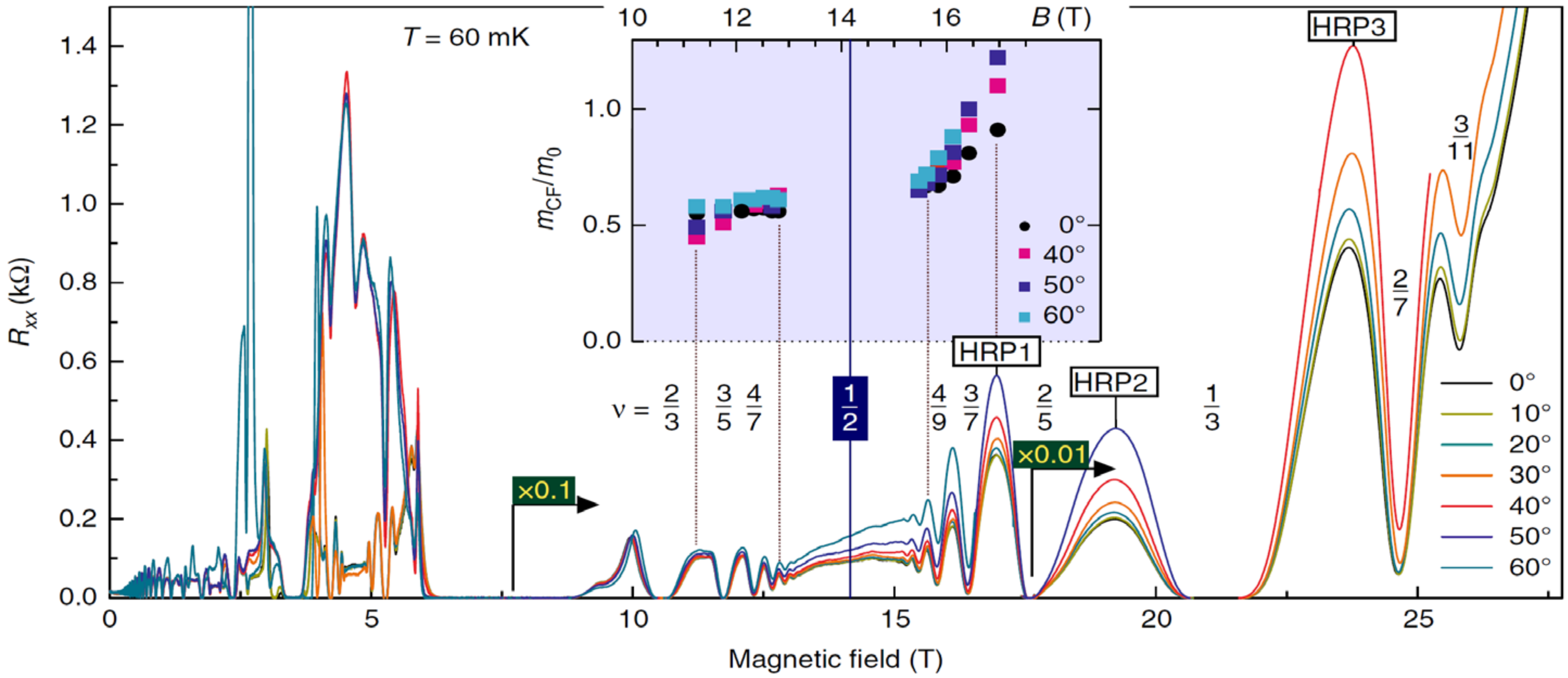
CF mass enhanced by in-plane magnetic field in insulating regions.

Effect of tilted field

Effect of in-plane magnetic field ($B_{//}$) is asymmetric above and below $\nu = 1/2$.

Insulating phases enhanced by ($B_{//}$).
Minima at $\nu = 1/2, 2/7, 1/3$, largely unaffected.

Insulating phase extends towards $\nu = 1/2$ region.



Summary

High magnetic field reveals unusual features of FQH effect in MgZnO/ZnO.

Several insulating phases with character of Wigner crystal form below ν=3/7.

Composite fermion effective mass is enhanced approaching insulating phase.

Properties of ZnO mean that HRP3 is candidate for a composite fermion crystal.

In-plane magnetic field enhances the insulating phase and leads to coexistence of FQH and insulating phases as high as ν = 1/2.

From an emergence perspective, MgZnO/ZnO is rich in topological phases and phase transitions, perhaps we can learn a lot…

D. Maryenko, A. McCollam, J. Falson, Y. Kozuka, J. Bruin, U. Zeitler and M. Kawasaki,
Nature Communications DOI: 10.1038/s41467-018-06834-6