Quantum Hall effects at oxide heterointerfaces

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Quantum Hall effect ⟷ Superconductivity

Generality

- **GaAs/AlGaAs**
- Si MOSFET, Si/SiGe
- InSb, CdTe
- Graphene
- Topological insulator HgTe, $(Bi,Sb)_2Te_3$
- **ZnO**

Diversity

- Metal (Al, Nb, In)
- Alloy (NbTi, Nb_3Sn)
- High T_c ($(La,Sr)_2CuO_4$, YBCO)
- Iron-based (*Ln*FeAs(O,F), FeSe)
- Organic (Cs_3C_{60})

Collaborators

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University of Tokyo

Denis Maryenko
RIKEN

Atsushi Tuskazaki
Tohoku University

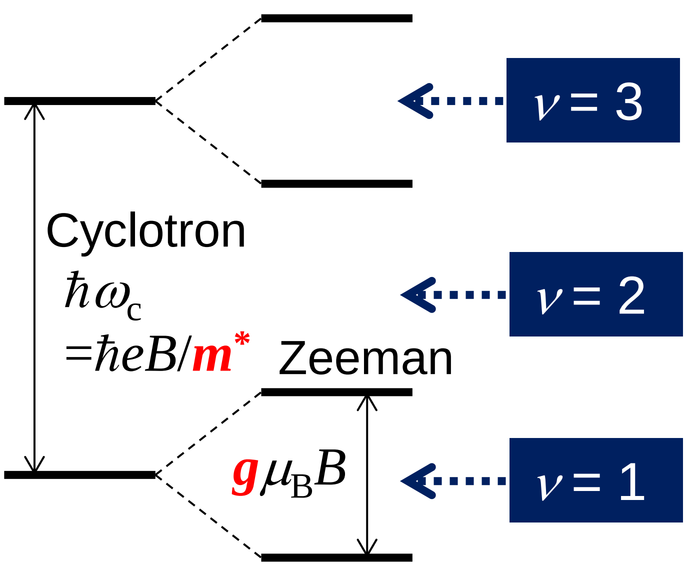
Benedikt Friess
Ding Zhang
Jurgen Smet
Max-Planck Institute

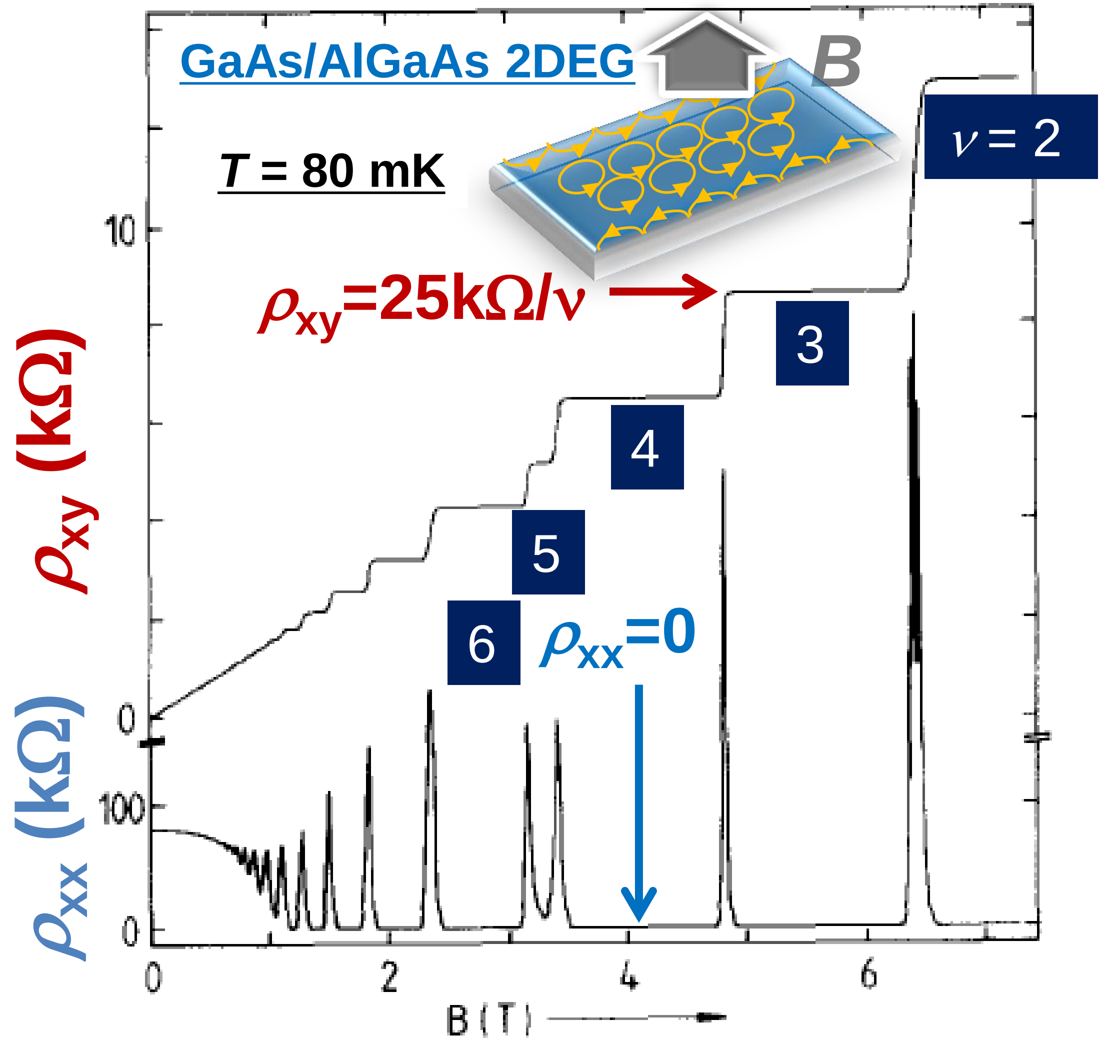
Quantum Hall Effect

$$\nu = \frac{(\text{\# of electrons})}{(\text{\# of magnetic flux quanta})} = \frac{hn}{eB}$$

- $\hbar\omega_c > k_B T$
- $\omega_c \tau > 1$

μ > 10,000 cm^2/Vs



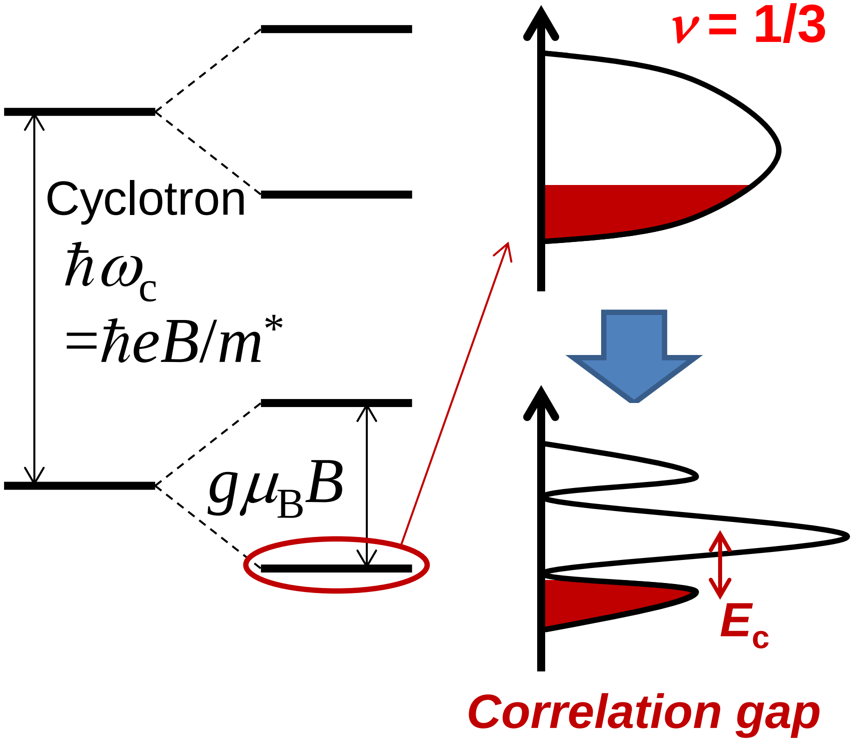


K. v. Klitzing, Physica **126B**, 242 (1984)

$$\Psi = \frac{C}{lm} z^m \exp\left[-\frac{|z|^2}{4l^2}\right]$$

($z = x + iy$: complex coordinate)

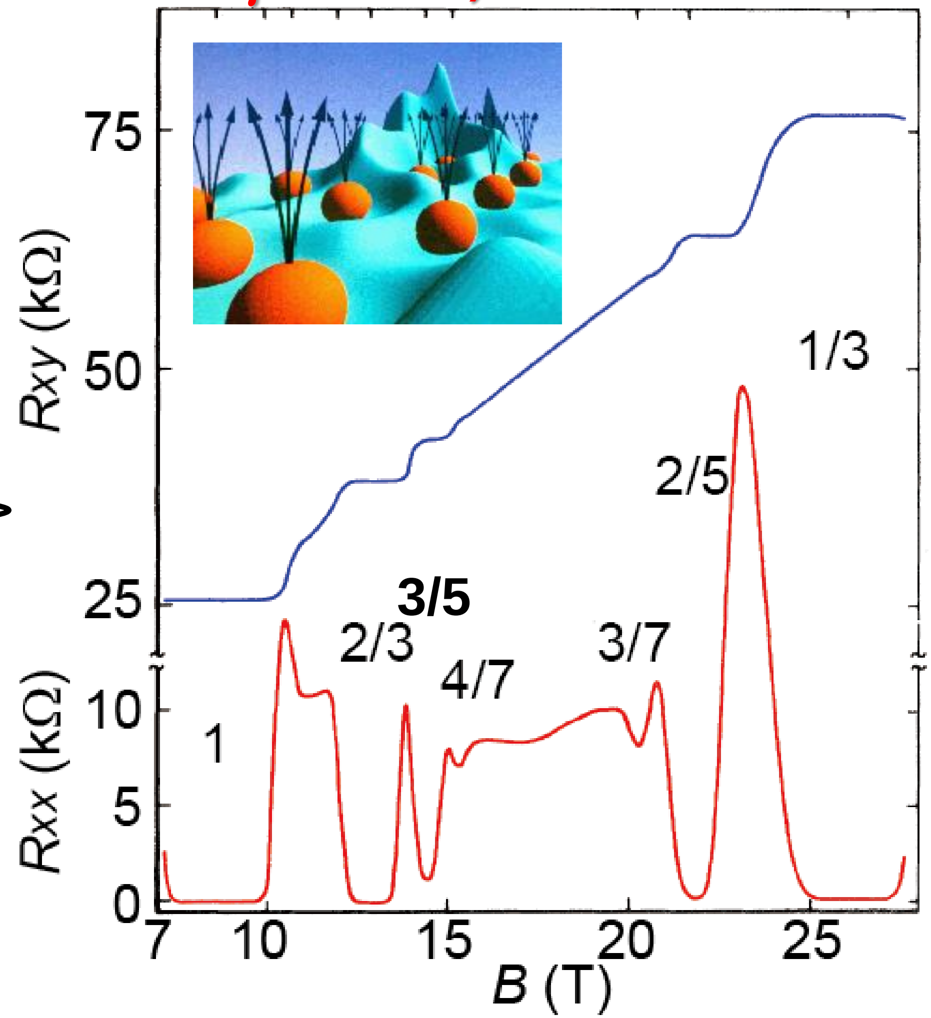
Fractional quantum Hall effect



$$\Psi = \prod_{i<j} (z_i - z_j)^m \exp\left[-\sum_k |z_k|^2 / 4l^2 \right]$$

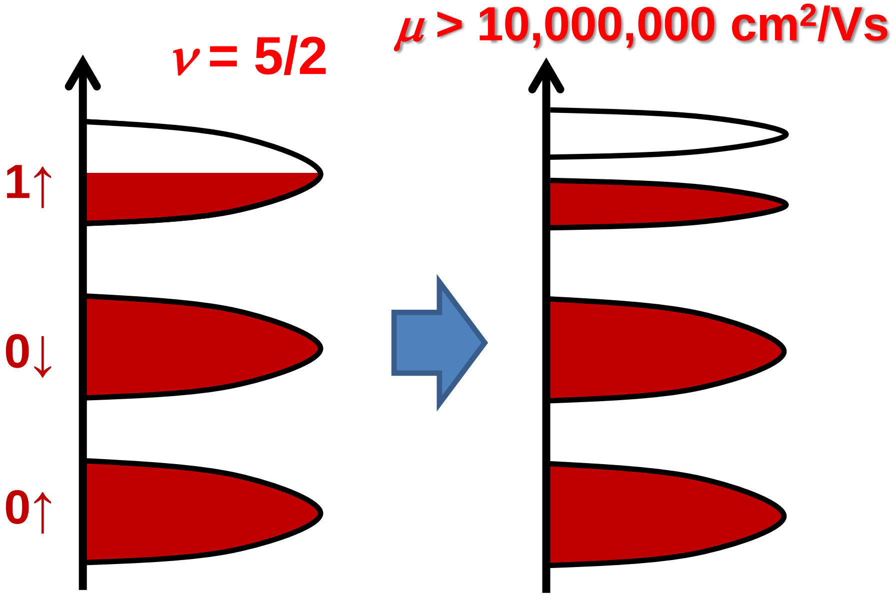
$$(\nu = 1/m)$$

μ > 100,000 cm^2/Vs



A. M. Chang *et al.*, Phys. Rev. Lett. **53**, 997 (1984)

Even-denominator fractional quantum Hall effect

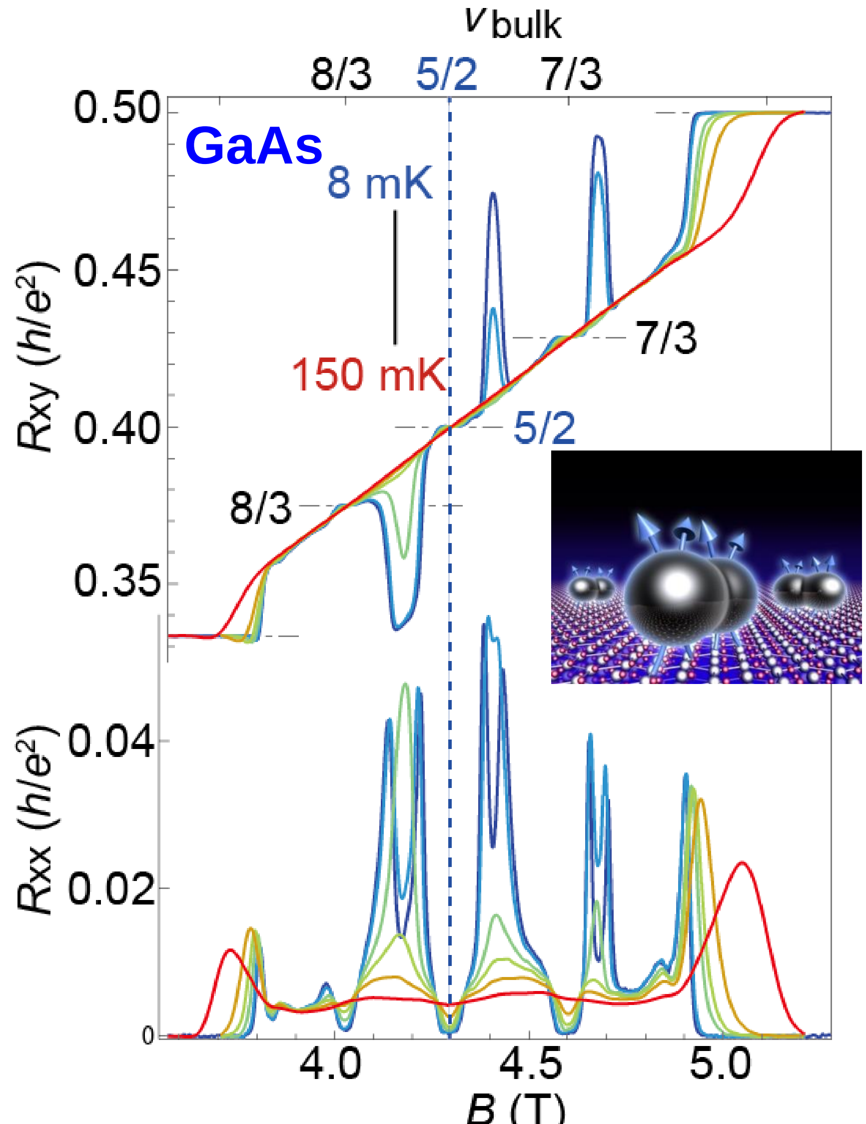


Phaffian state

$$\Psi = \prod_{i<j}\left(z_i - z_j\right)^2 \mathrm{Pf}\,\frac{1}{\left(z_i - z_j\right)} \exp\left[-\sum_k \left|z_k\right|^2 / 4l^2\right]$$

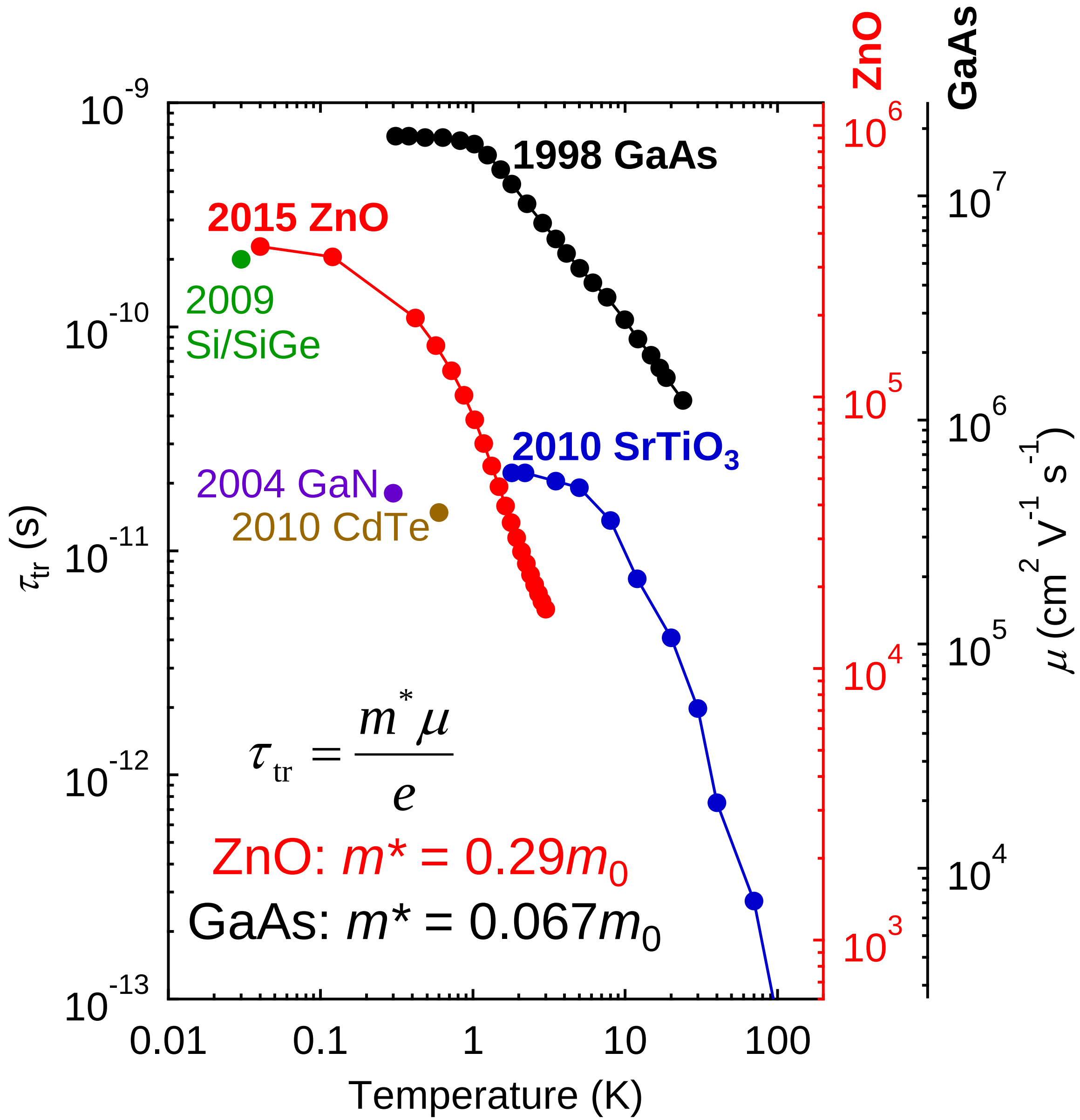
$$\left(\mathrm{Pf}\,\frac{1}{\left(z_i - z_j\right)} = \frac{1}{z_1 - z_2}\frac{1}{z_3 - z_4}\frac{1}{z_5 - z_6}\cdots - \frac{1}{z_1 - z_3}\frac{1}{z_2 - z_4}\frac{1}{z_5 - z_6}\cdots + \cdots - \right)$$

Fragile and competing with other phases

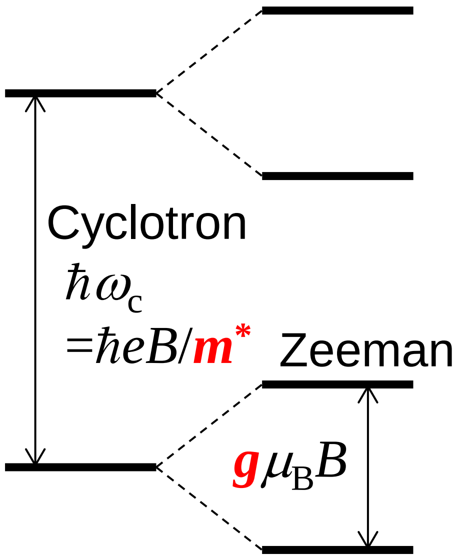


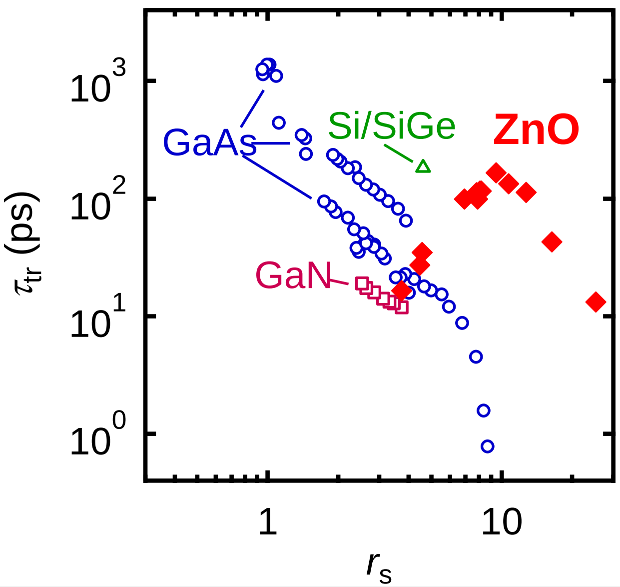
J. B. Miller *et al.*, Nat. Phys. **3**, 561 (2007)

High mobility electrons in oxides



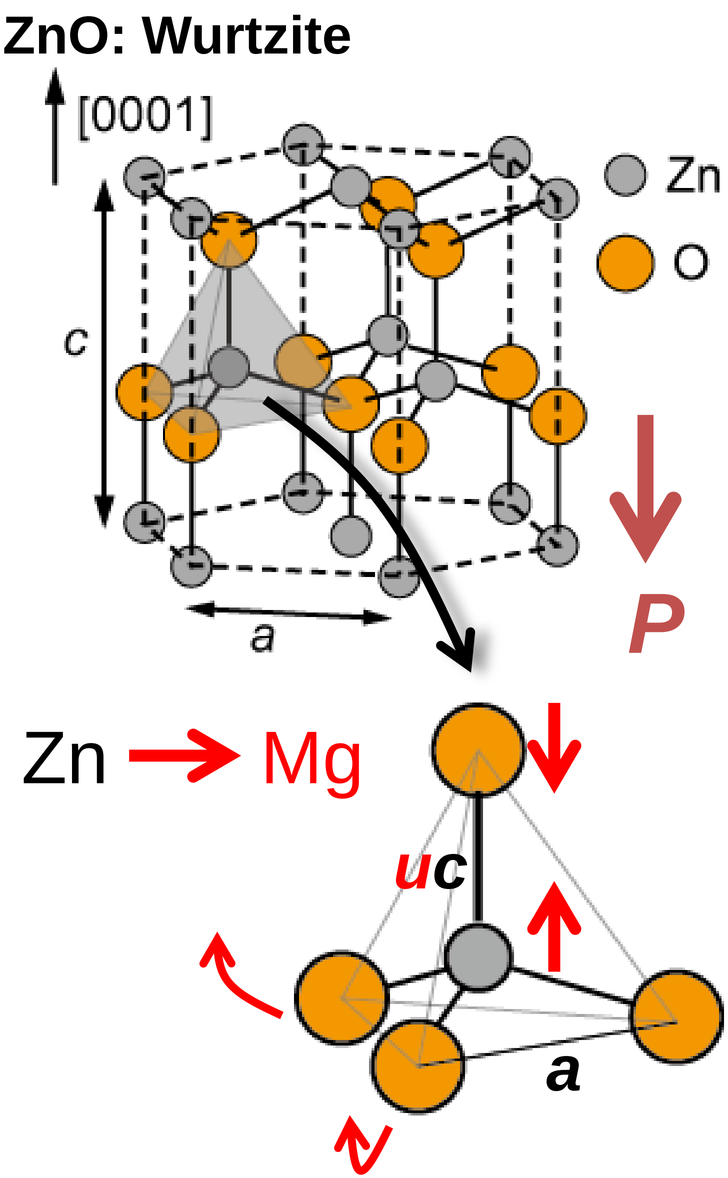
Comparison of materials parameters

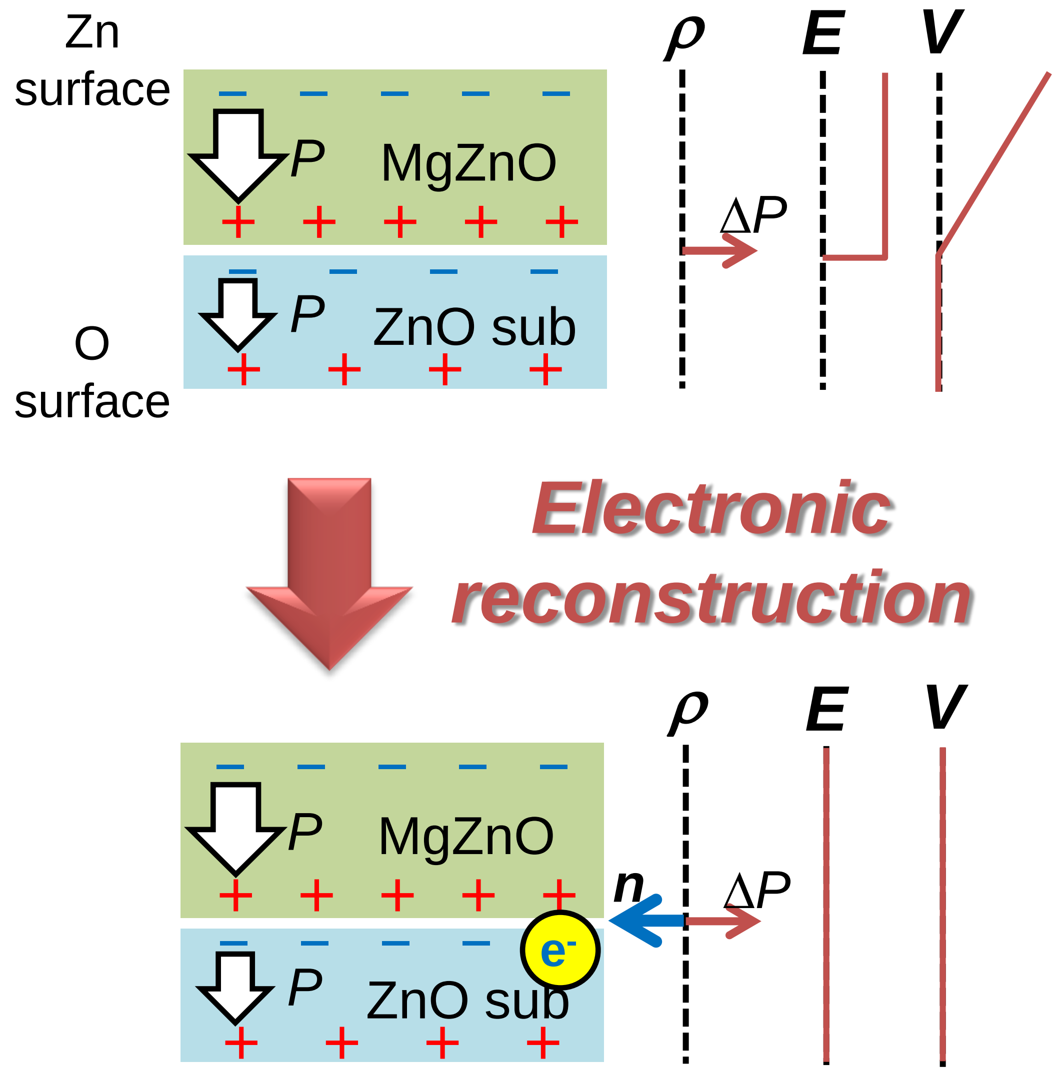




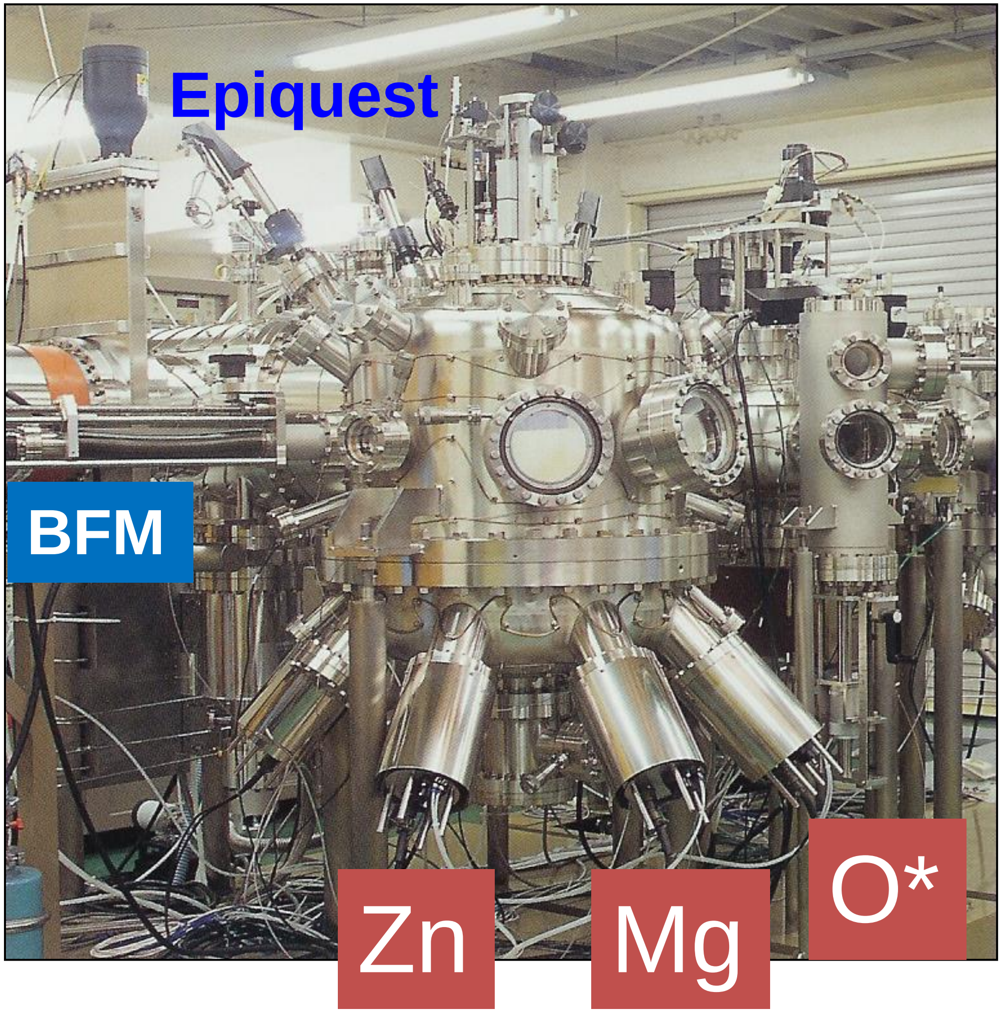
	GaAs	ZnO	
m^*/m_0	0.069	0.29	
g-factor	-0.44	2	
ε (dielectric constant)	13	8.5	
(Zeeman)/(Cyclotron)	**0.015**	**0.29**	
r_s (Coulomb/Fermi energy)	**1.8/√n**	**11.9/√n**	n (10^{11} cm^{-2})
Landau level mixing (Coulomb/Cyclotron)	**2.6/√B**	**17.2/√B**	B (T)

Polarization-induced 2DEG





Molecular beam epitaxy



▪**Sources Zn : 7N Mg : 6N**

▪**ZnO single crystal substrate**

Tokyo Denpa

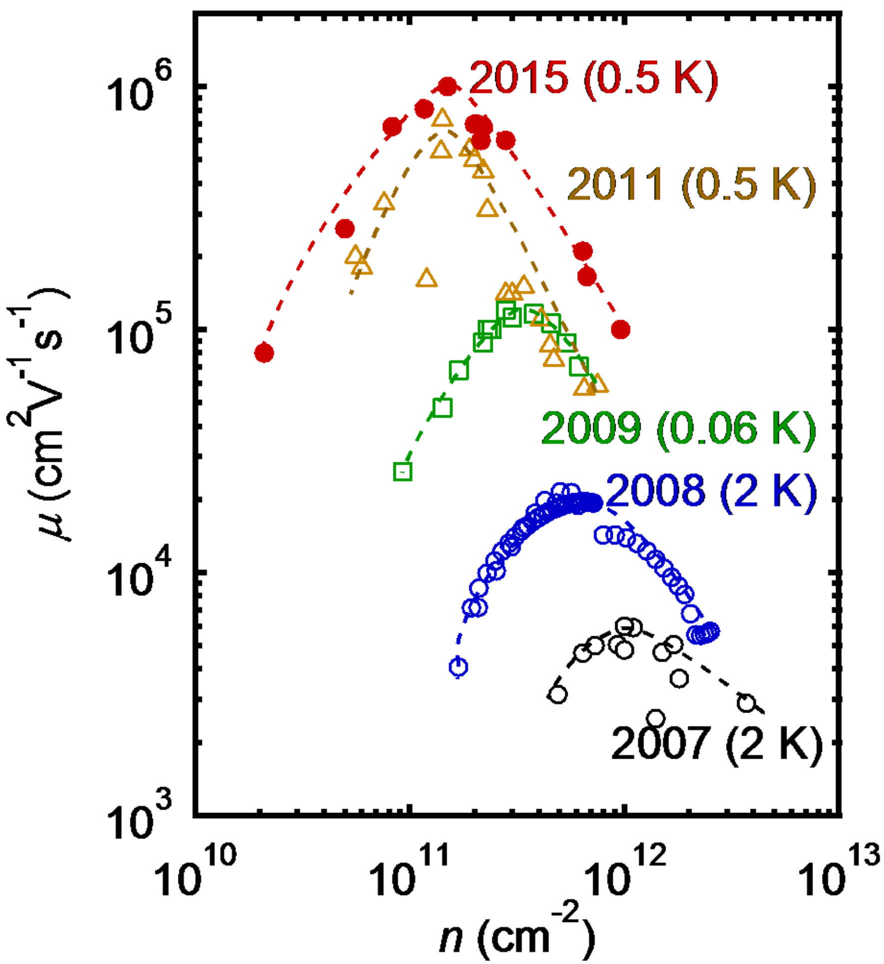
K. Maeda *et al*., Semicond. Sci. Technol. **20**, S49 (2005)

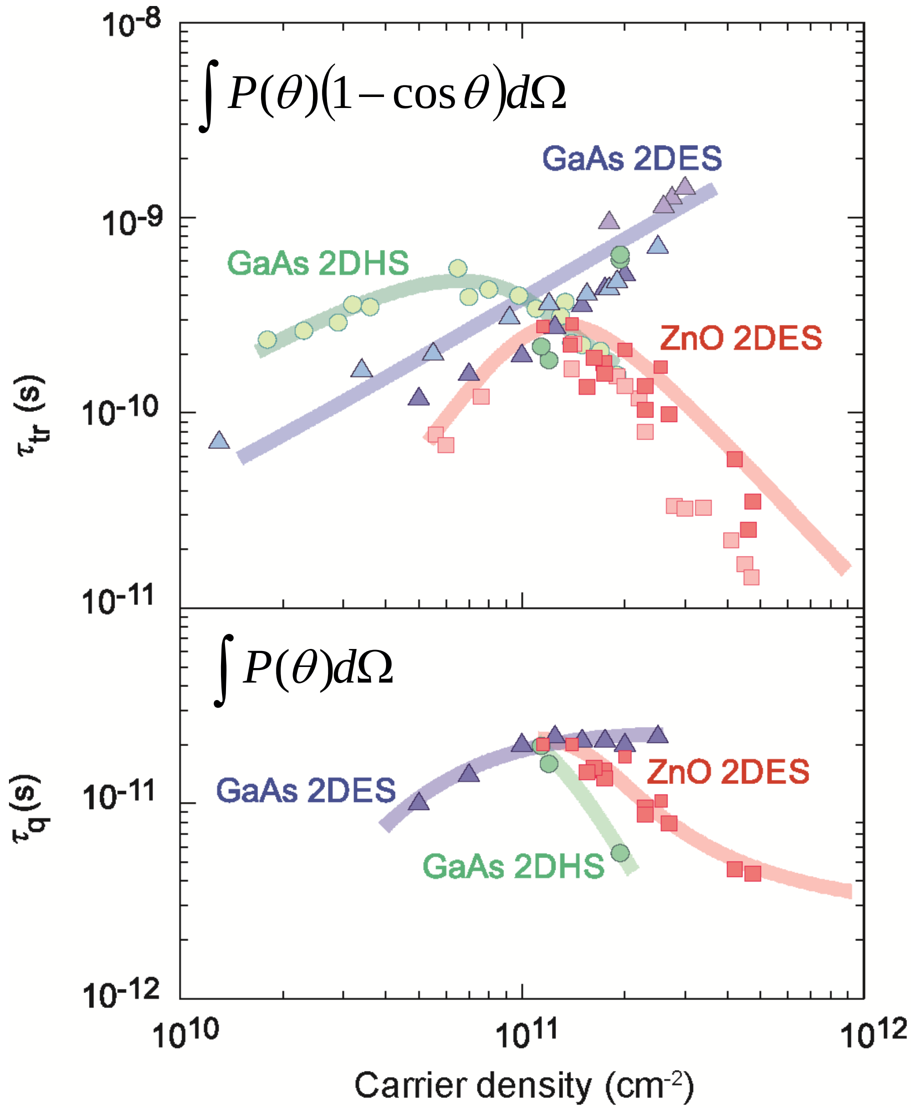
▪**Pure Ozone**

Meidensha Co.

High-mobility electrons in ZnO heterostructures

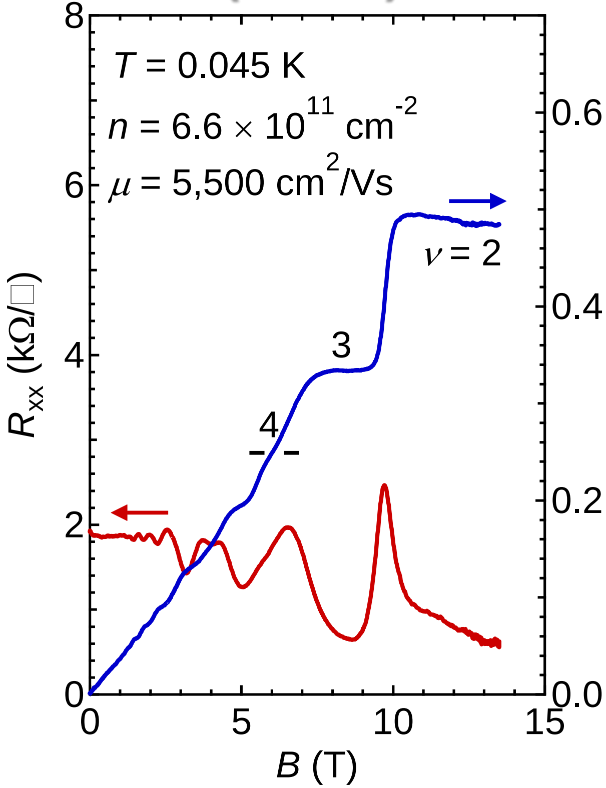
μ > 1,000,000 cm²/Vs





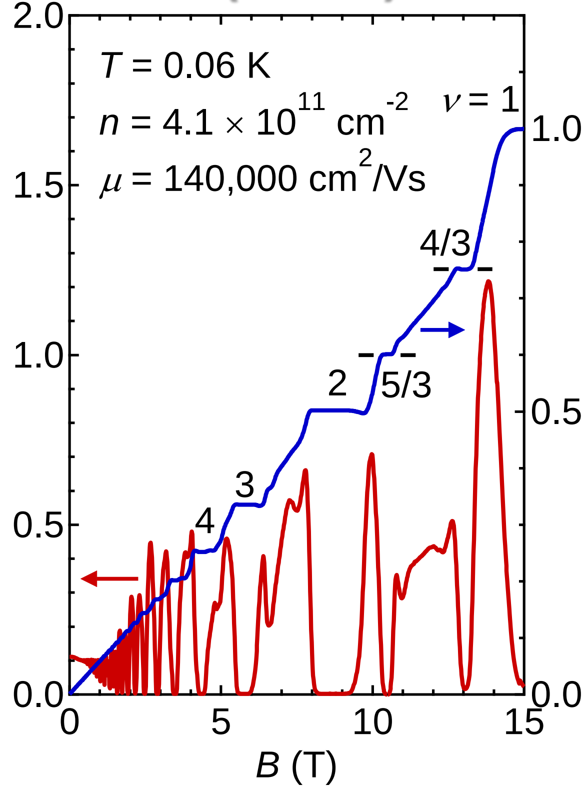
Quantum Hall Effects in ZnO

Integer QHE (2007)



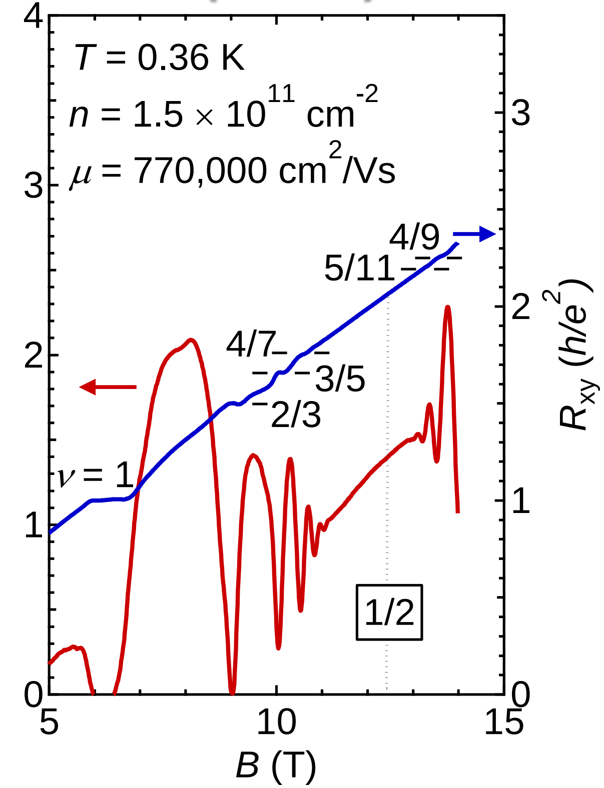
A. Tsukazaki *et al.*,
Science **315**, 1388 (2007)

Fractional QHE (2010)



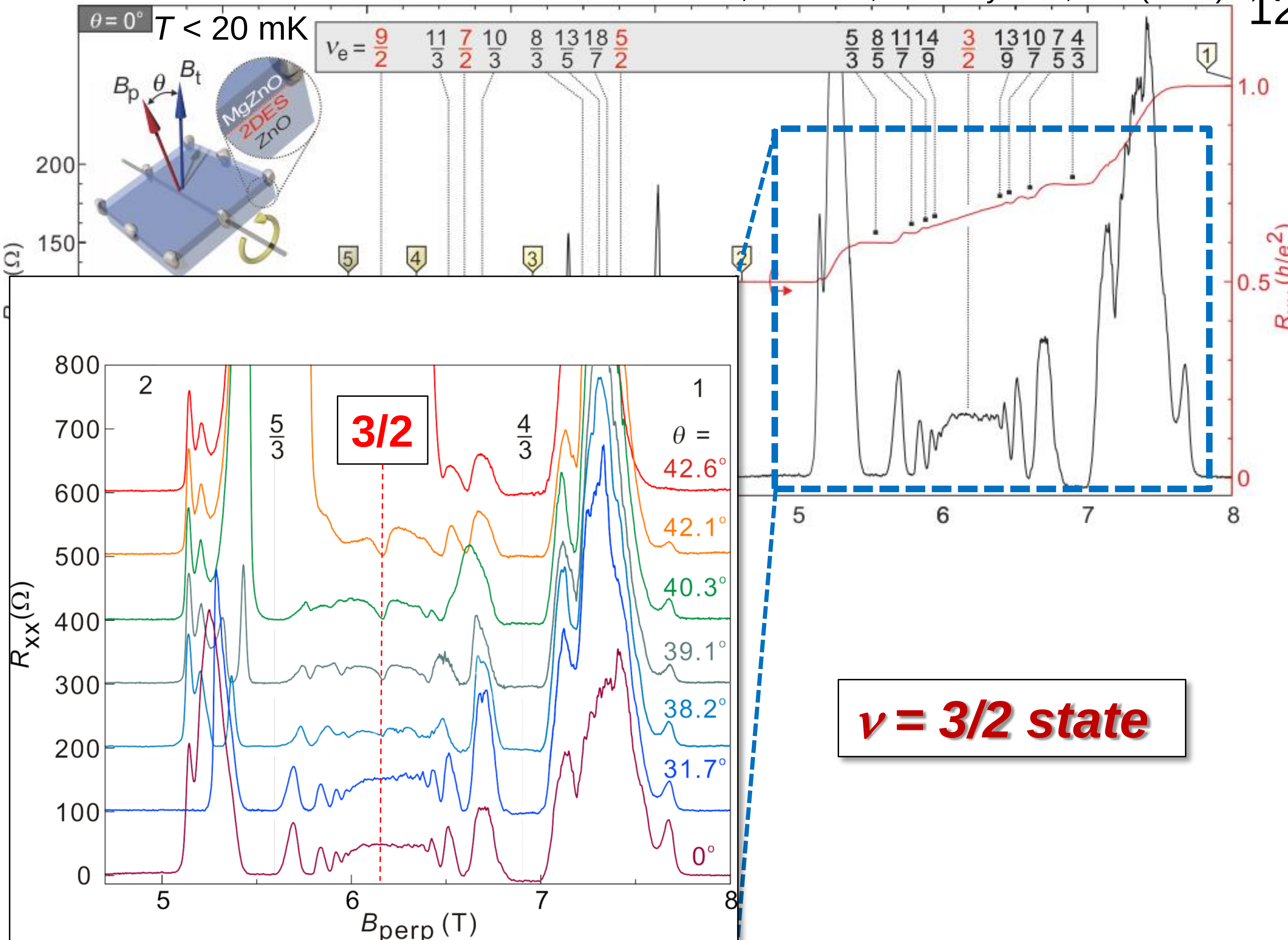
A. Tsukazaki *et al.*,
Nature Mater. **9**, 889 (2010)

Fractional QHE (ν<1) (2012)



D. Maryenko & YK *et al.*,
Phys. Rev. Lett. **108**, 186803 (2012)

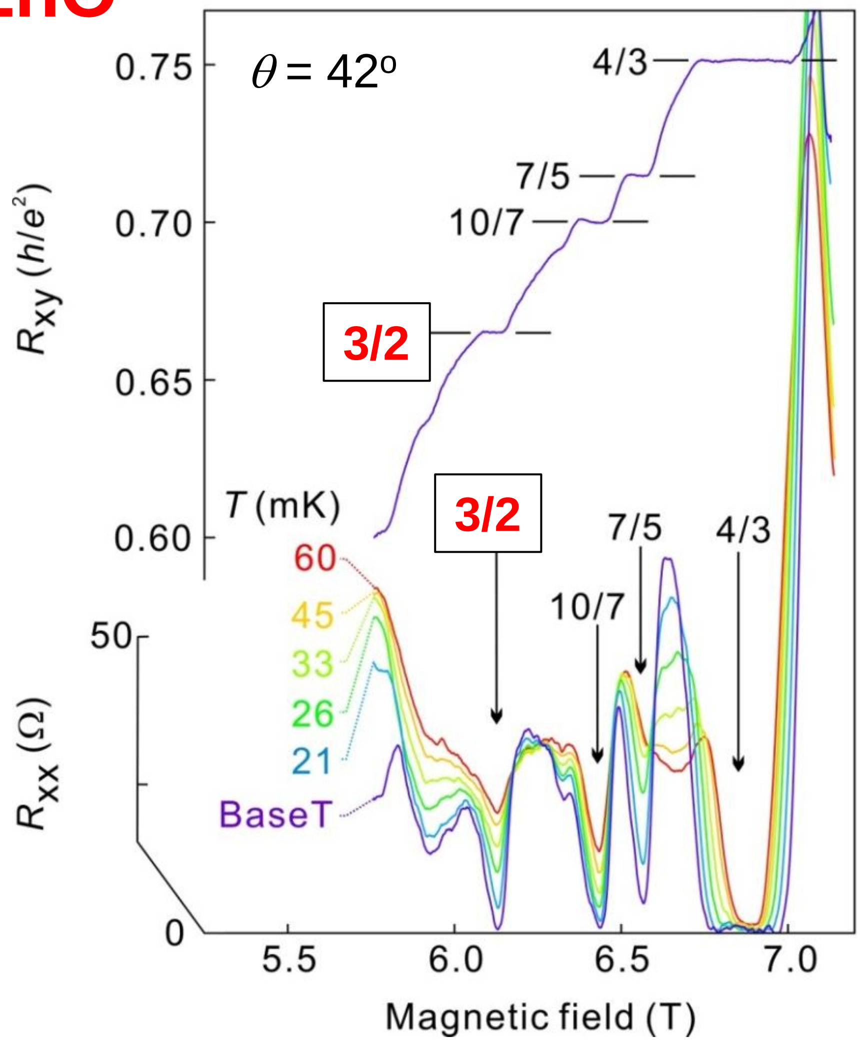
J. Falson, YK *et al.*, Nat. Phys. **11**, 347 (2015)



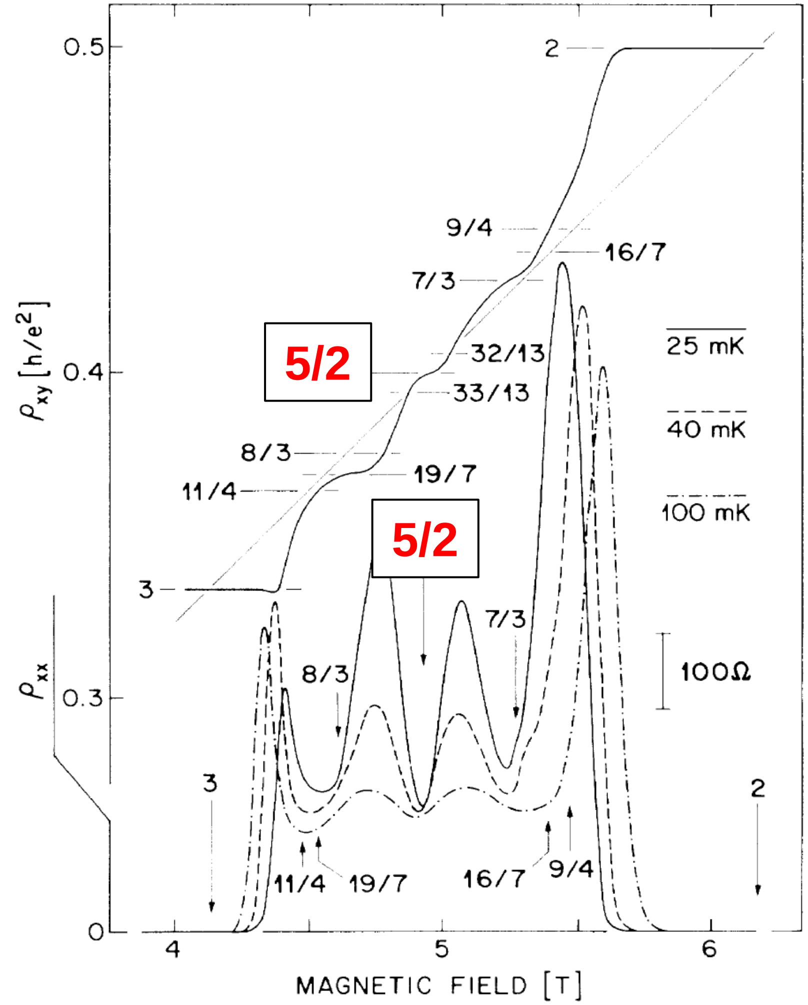
$\nu = 3/2$ state

Even-denominator fractional QHE in ZnO

ZnO



GaAs



R. Willet *et al.*, *Phys. Rev. Lett.* **59**, 1776 (1987)

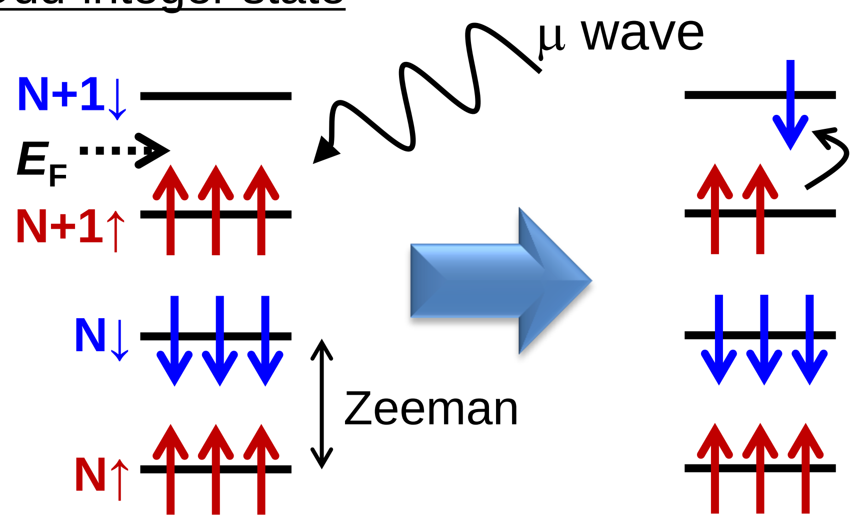
Large electron correlation

Spin degree of freedom

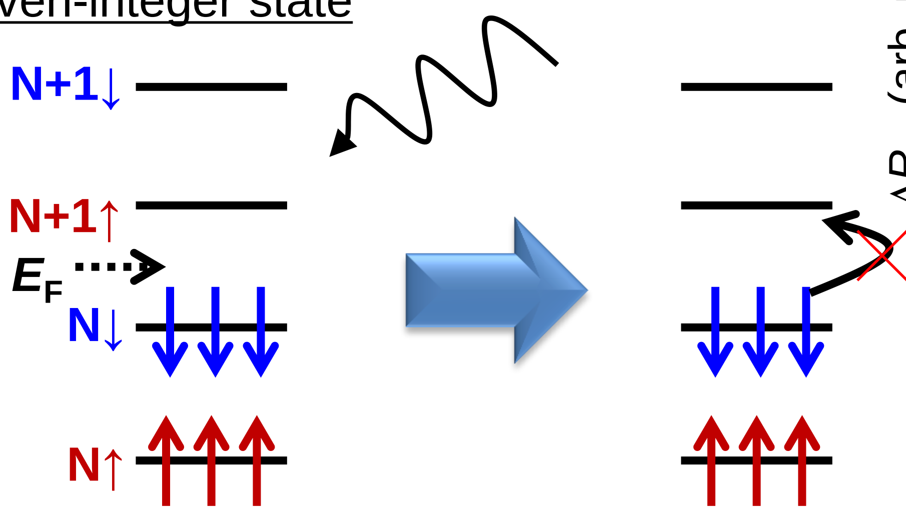
Electron spin resonance in integer QHE

Acknowledgement:
S. Teraoka, A. Oiwa, S. Tarucha

Odd-integer state



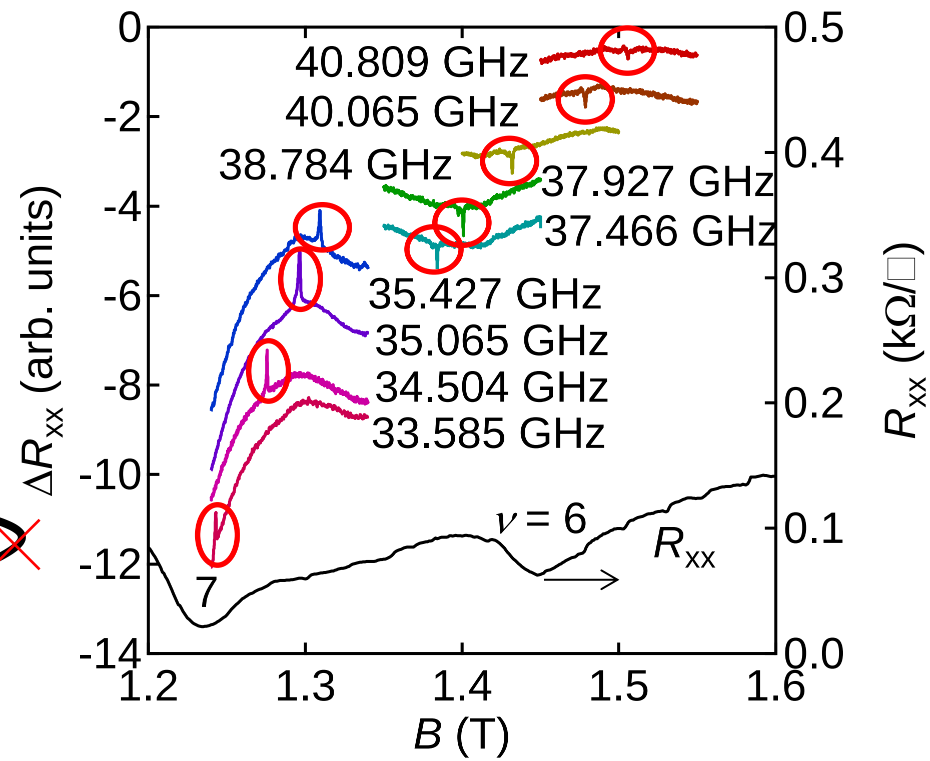
Even-integer state



Y. Kozuka *et al*., PRB **87**, 205411 (2013)

Under μ wave

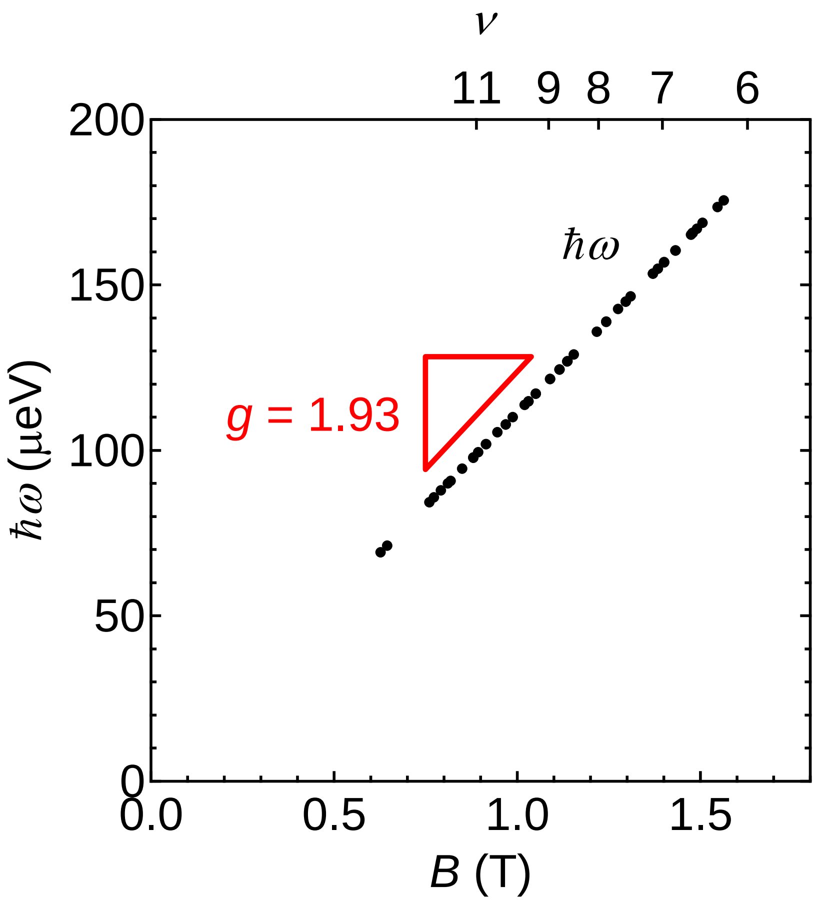
ZnO 2DEG



ESR in even-integer QHE

ZnO

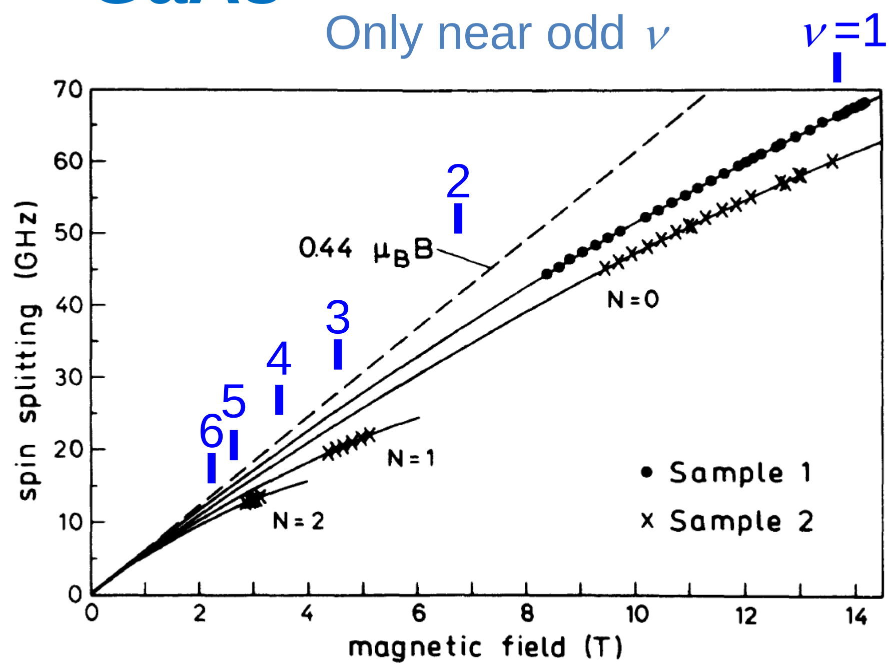
ESR appears independent of ν



Y. Kozuka *et al*., PRB **87**, 205411 (2013)

GaAs

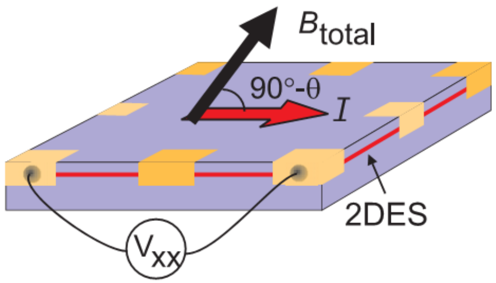
Only near odd ν



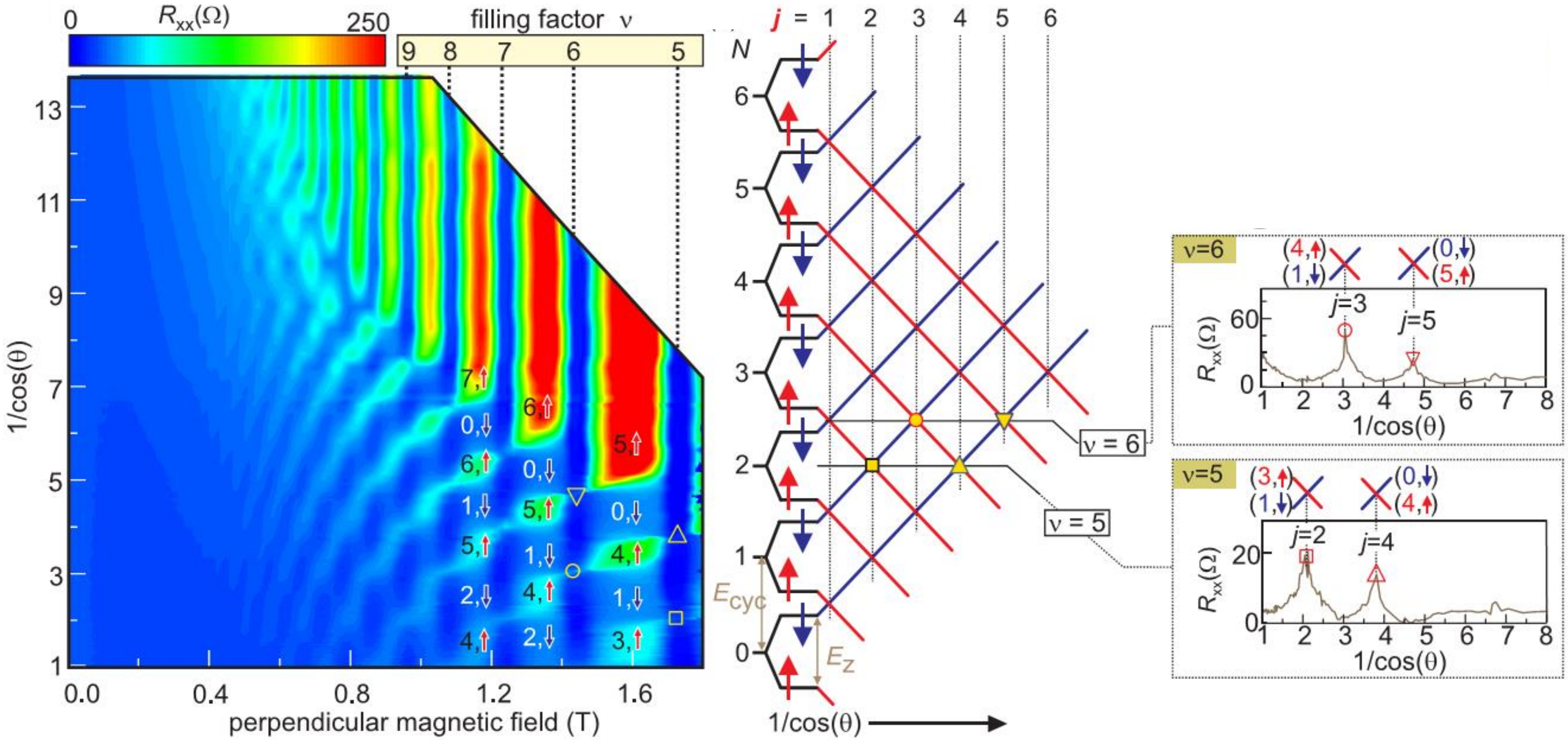
M. Dobers *et al.*, Phys. Rev. B **38**, 5453 (1988)

Partial spin polarization even for even-integer states

Detecting spin susceptibility g^*m^*

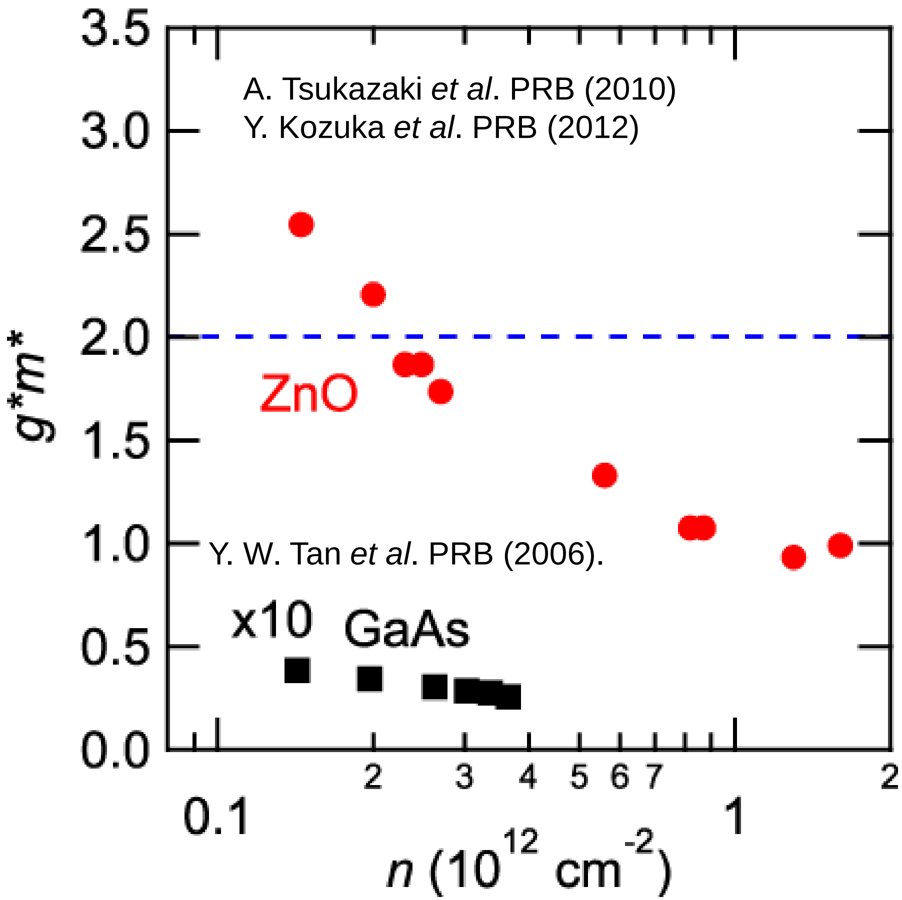


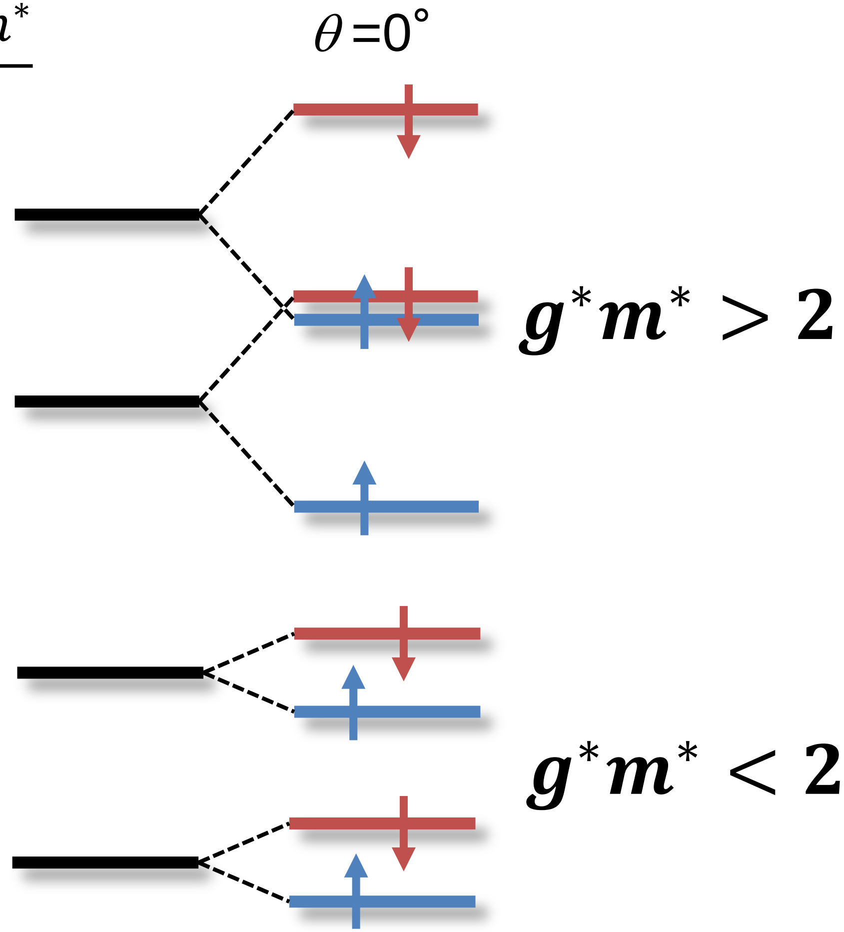
Coincidence: $\frac{g^* m^*}{2} = j\cos(\theta)$



Spin transition in integer QHE

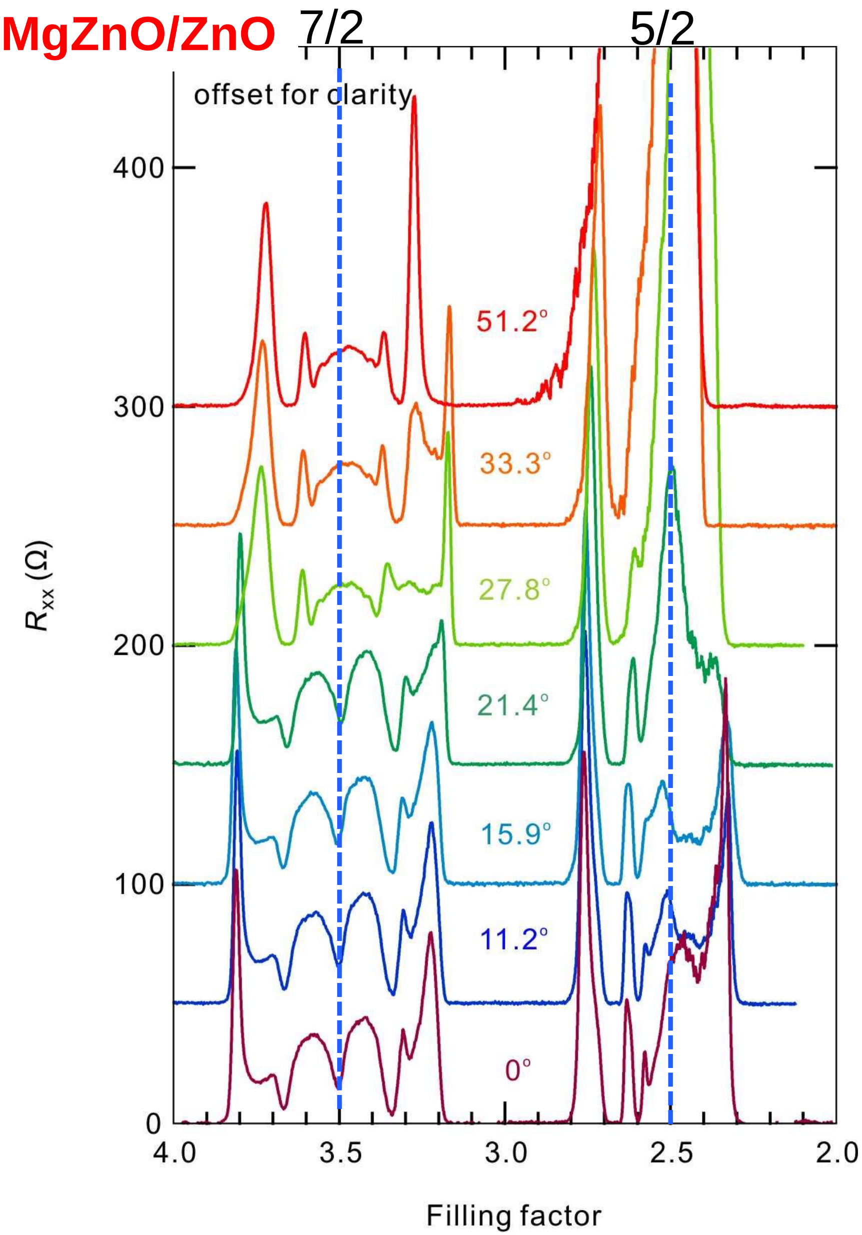
Zeeman/Cyclotron ratio $\frac{\Delta E_z}{\Delta E_{\mathrm{cyc}}} = \frac{g^* m^*}{2}$



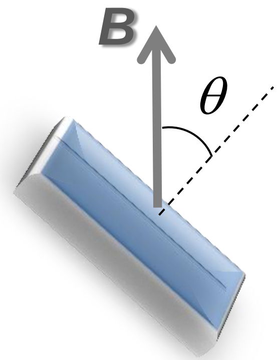


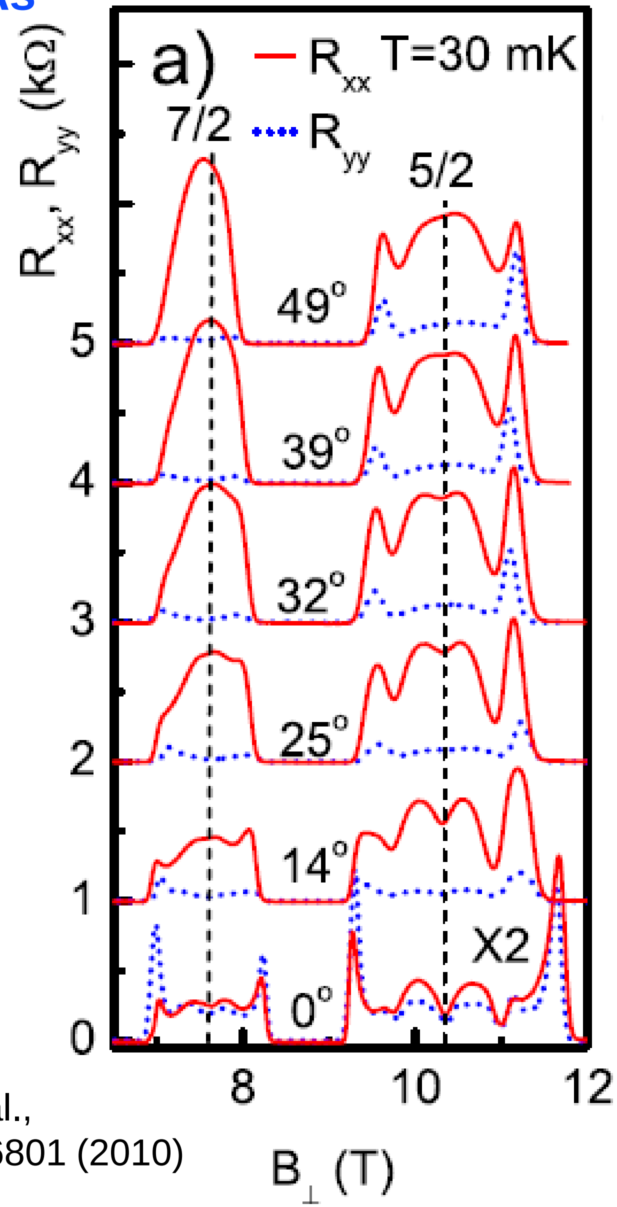
Vanishing $\nu = 7/2$ at high angles

MgZnO/ZnO



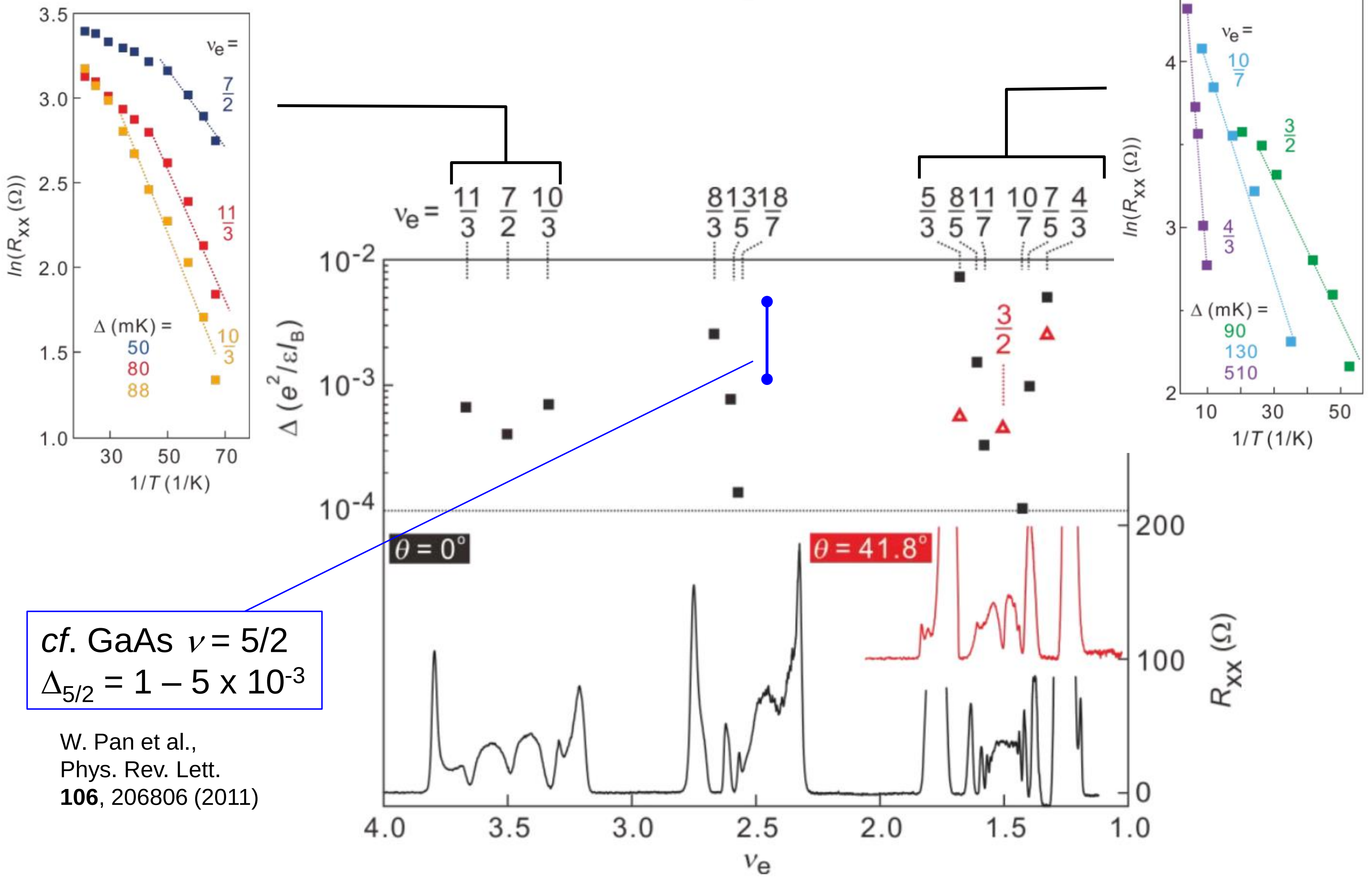
AlGaAs/GaAs





C. Zhang et al.,
PRL **104**, 166801 (2010)

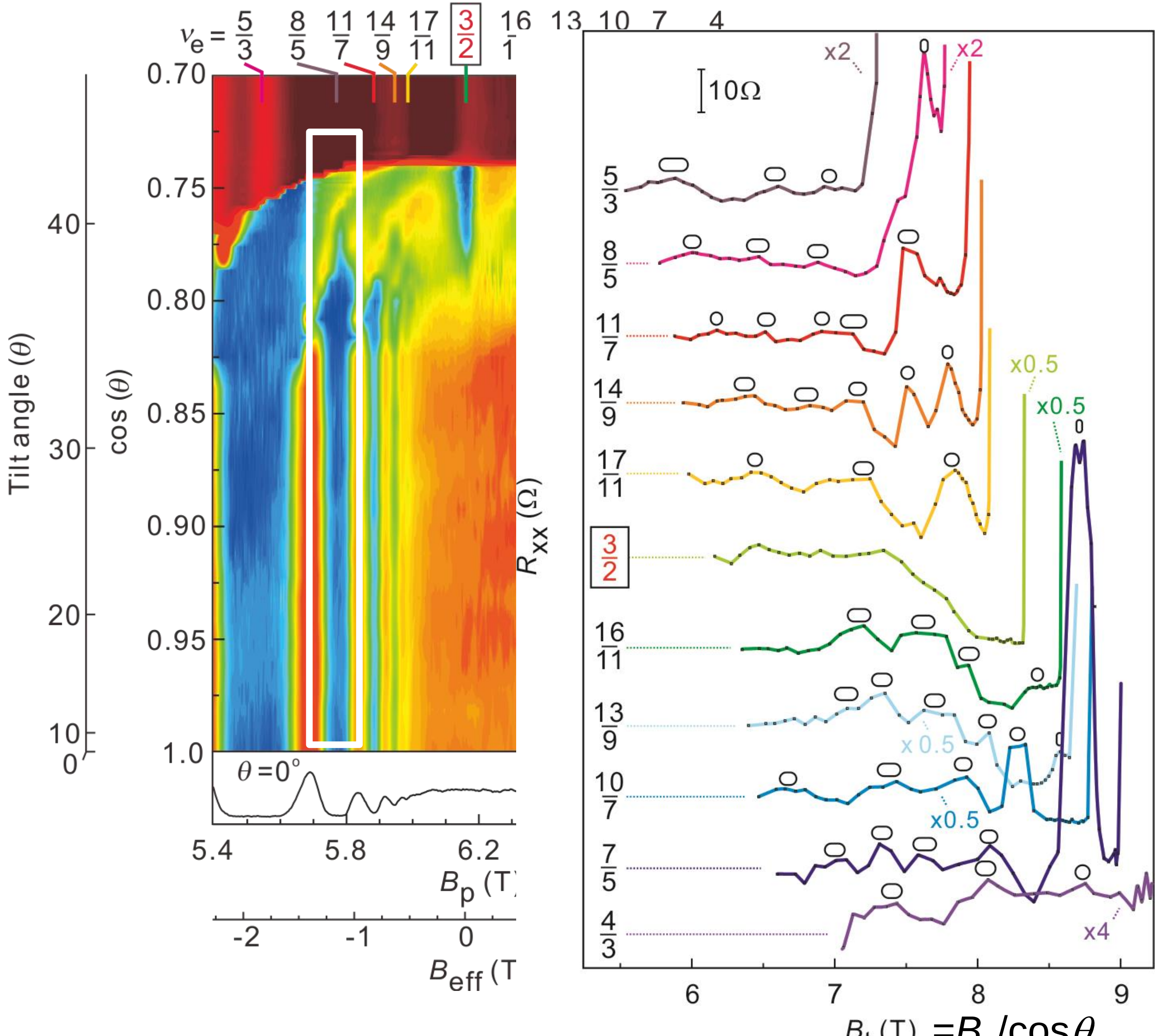
Activation energies of FQHE



cf. GaAs $\nu = 5/2$
$\Delta_{5/2} = 1 - 5 \times 10^{-3}$

W. Pan et al.,
Phys. Rev. Lett.
106, 206806 (2011)

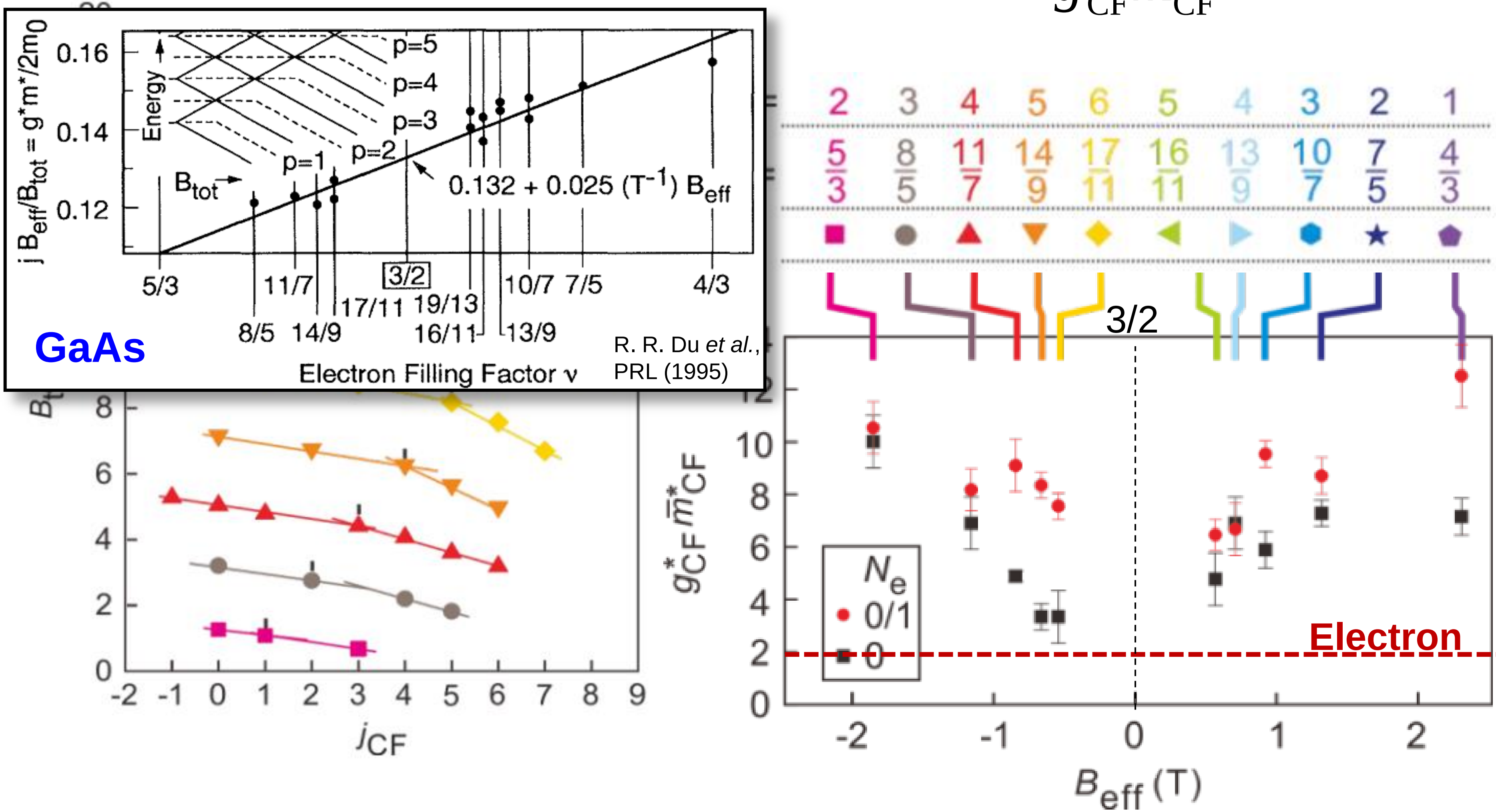
Spin susceptibility of composite Fermion



$=B_p/\cos\theta$

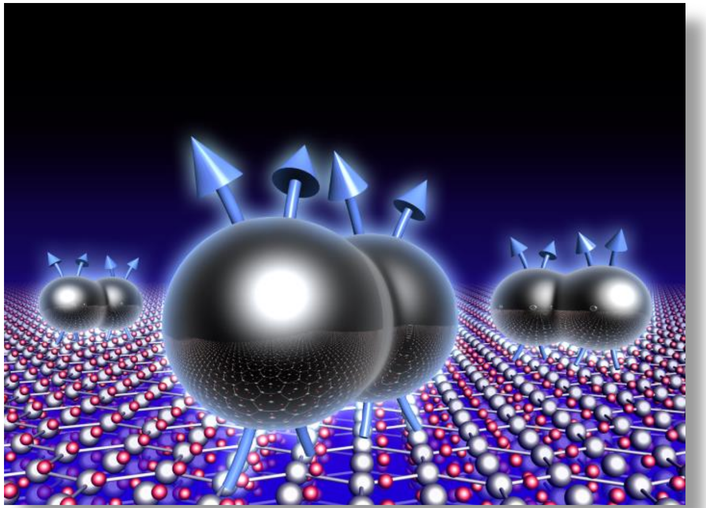
Spin susceptibility of composite Fermion

$$g^*_{\mathrm{CF}}\mu_{\mathrm{B}}B_{\mathrm{t}} = j_{\mathrm{CF}}\hbar\omega_{\mathrm{CF}} \quad \Rightarrow \quad B_{\mathrm{t}}/B_{\mathrm{eff}} = j_{\mathrm{CF}}\frac{2m_0}{g^*_{\mathrm{CF}}m^*_{\mathrm{CF}}}$$



Conclusion

- **Electron mobility ~ 1,200,000 cm^2/Vs**
- **Even denominator fractional quantum Hall state ν = 3/2**



- **Strong electron correlation**
- **Large spin polarization**
- **Landau level mixing**

Qualitatively different composite Fermion properties