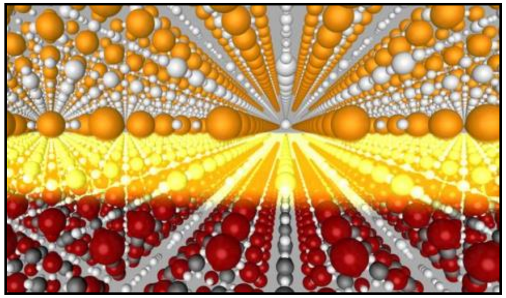
A unique exploration

Hans Boschker

Department Mannhart
Max Planck Institute for Solid State Research
Stuttgart, Germany



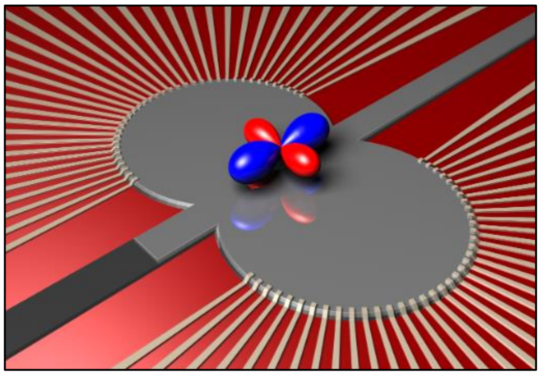
Why do science?

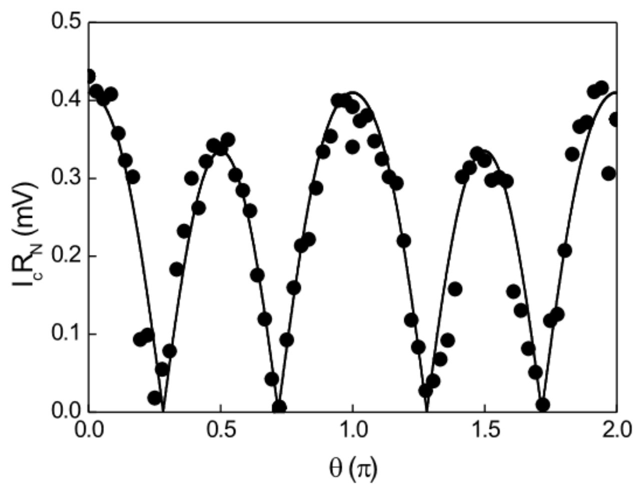
Intrinsic curiosity

Technology development

Condensed matter physics

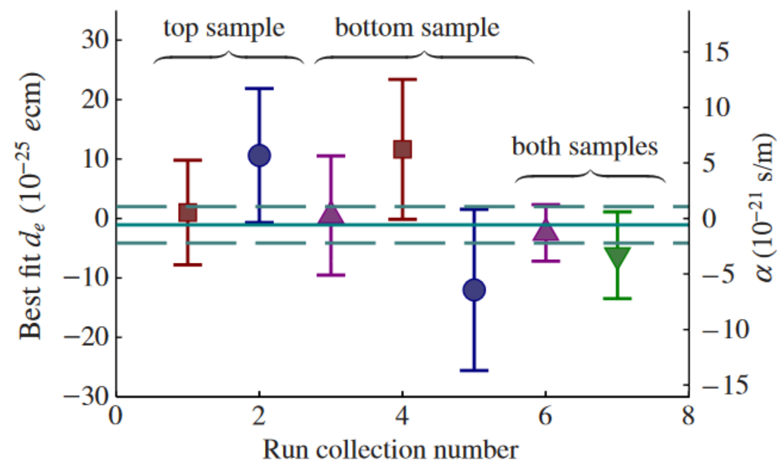
$YBa_2Cu_3O_7$





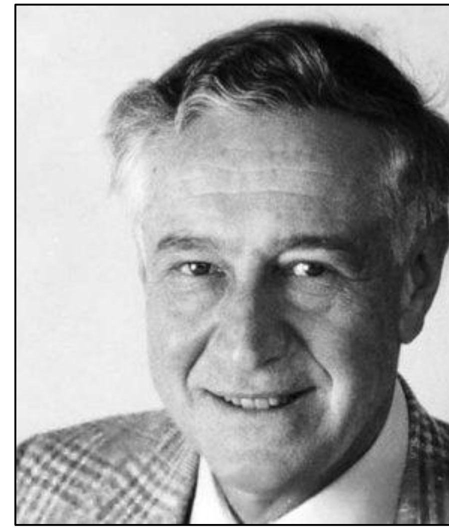
H.J.H. Smilde, *et al.*, Phys. Rev. Lett. **91**, 257001 (2005)

$Eu_{0.5}Ba_{0.5}TiO_3$



S. Eckel, *et al.*, Phys. Rev. Lett. **109**, 193003 (2012)

A sobering publication



ADVANCED TECHNOLOGY AND TRUTH IN ADVERTISING

Rolf LANDAUER

IBM Research Division, Thomas J. Watson Research Center, Yorktown Heights, USA

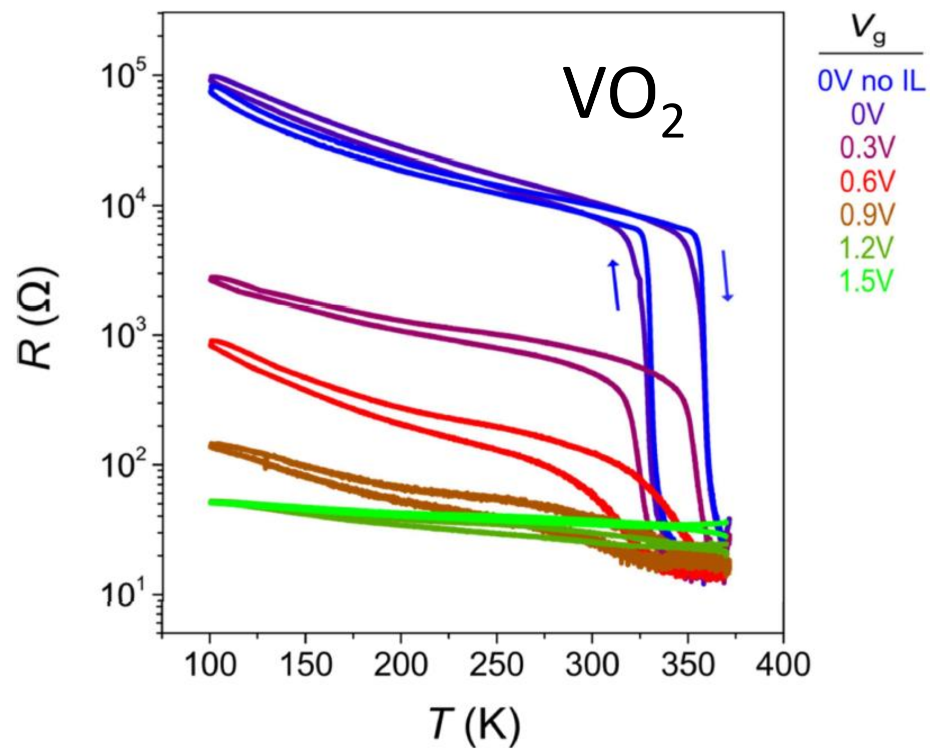
Most proposals for new technological approaches fail, and that is reasonable. Despite that, most of the technological proposals arising from basic science are promoted unhesitantly, with little attention to critical appraisal, even little opportunity for the presentation of criticism.

R. Landauer, Physica A **168**, 75 (1990)

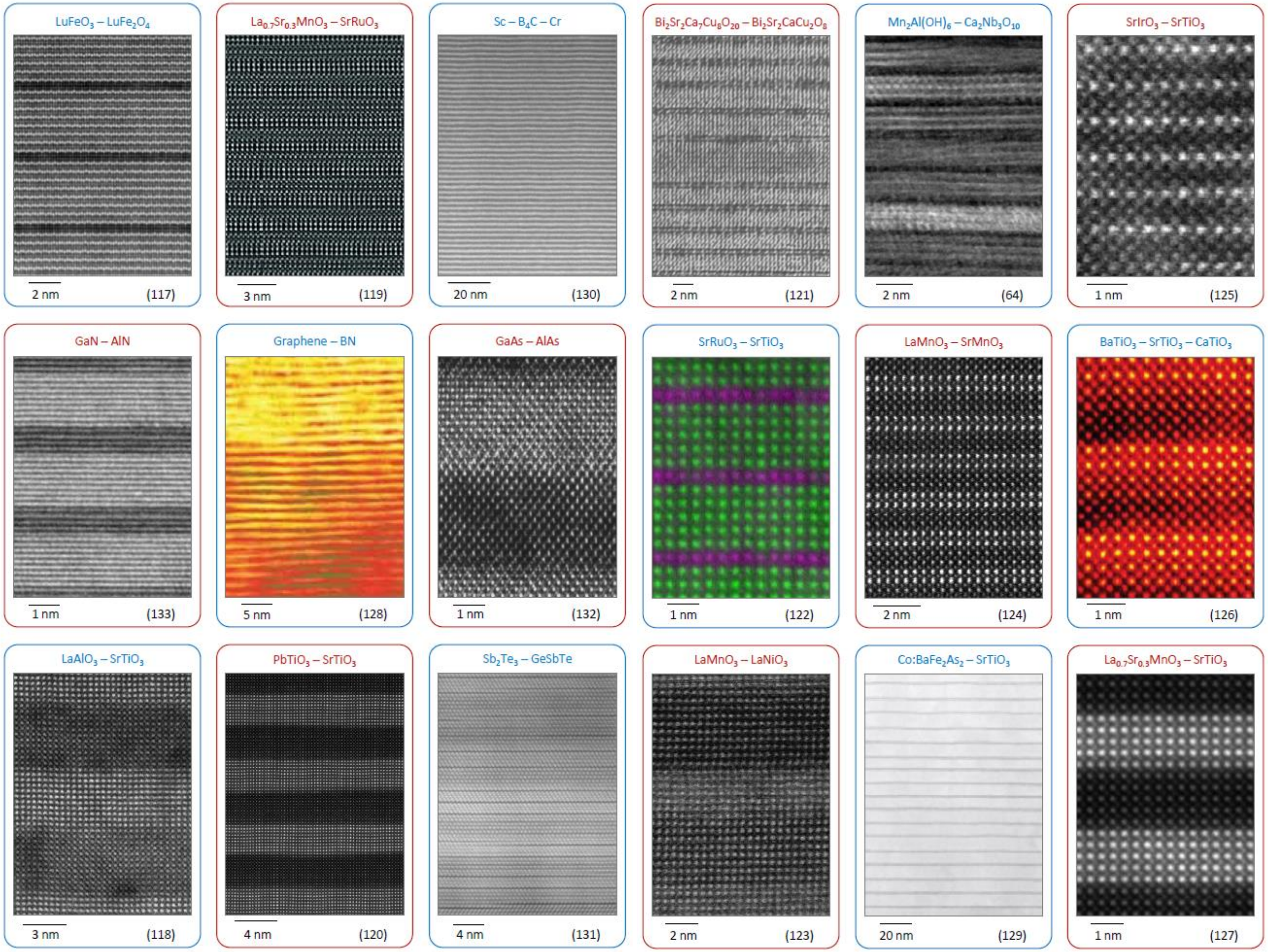
Quantum matter

Matter defined by quantum effects that generate phenomena that surpass incoherent or mean-field behavior, and often are collective and emergent.

- Competing ground states
- Complex phase diagrams
- Electronic and ionic degrees of freedom
- Phase transitions
- Sensitive to external parameters

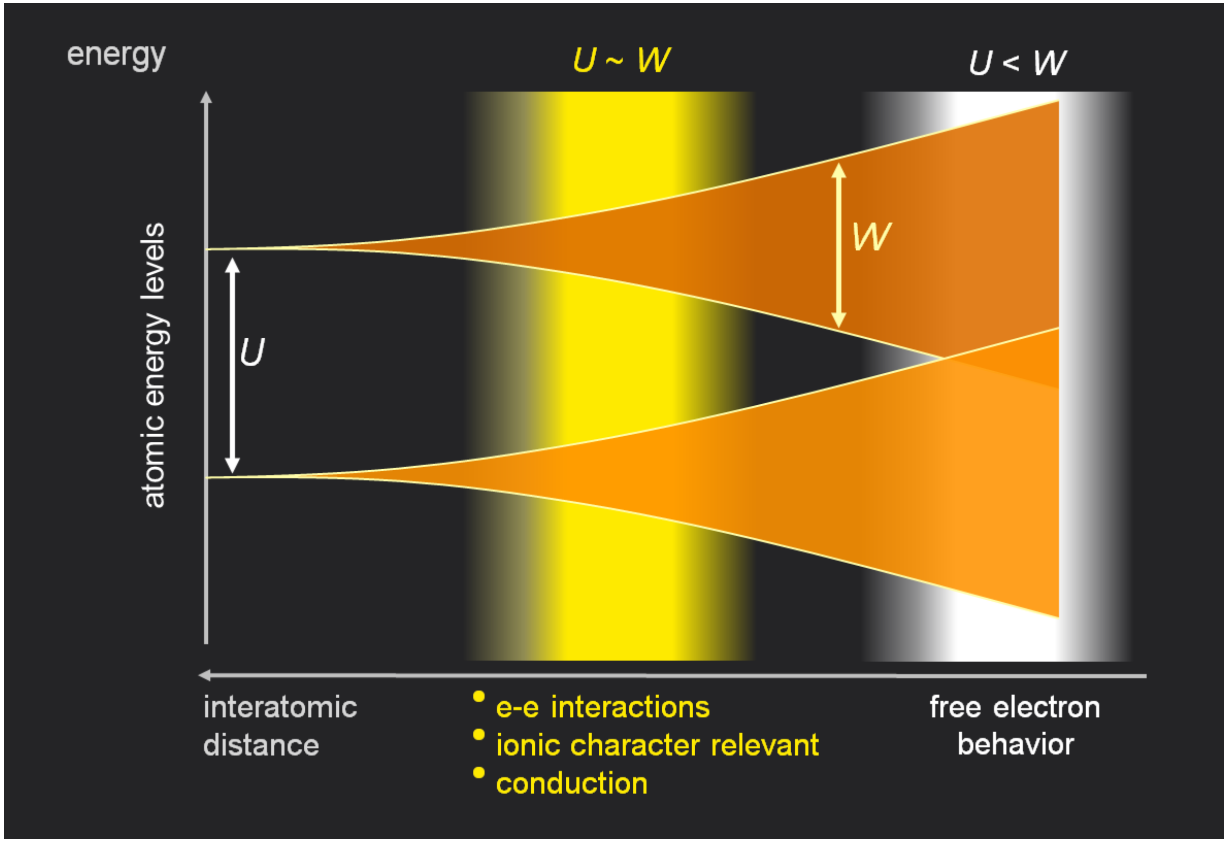


Quantum-matter heterostructures

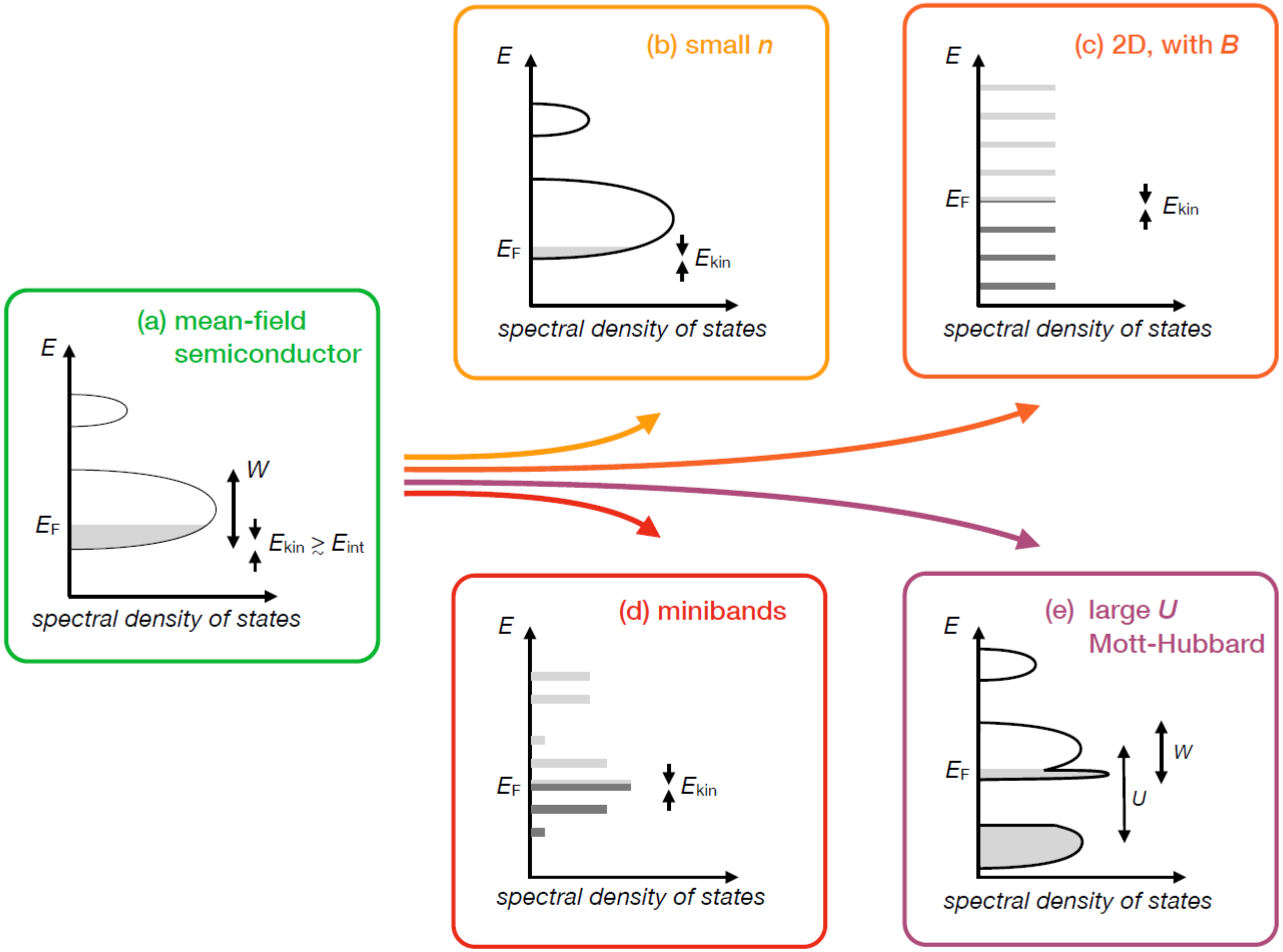


H.B., J. Mannhart, Annu. Rev. Condens. Matter Phys. **8**, 154 (2017)

Electronic Correlation



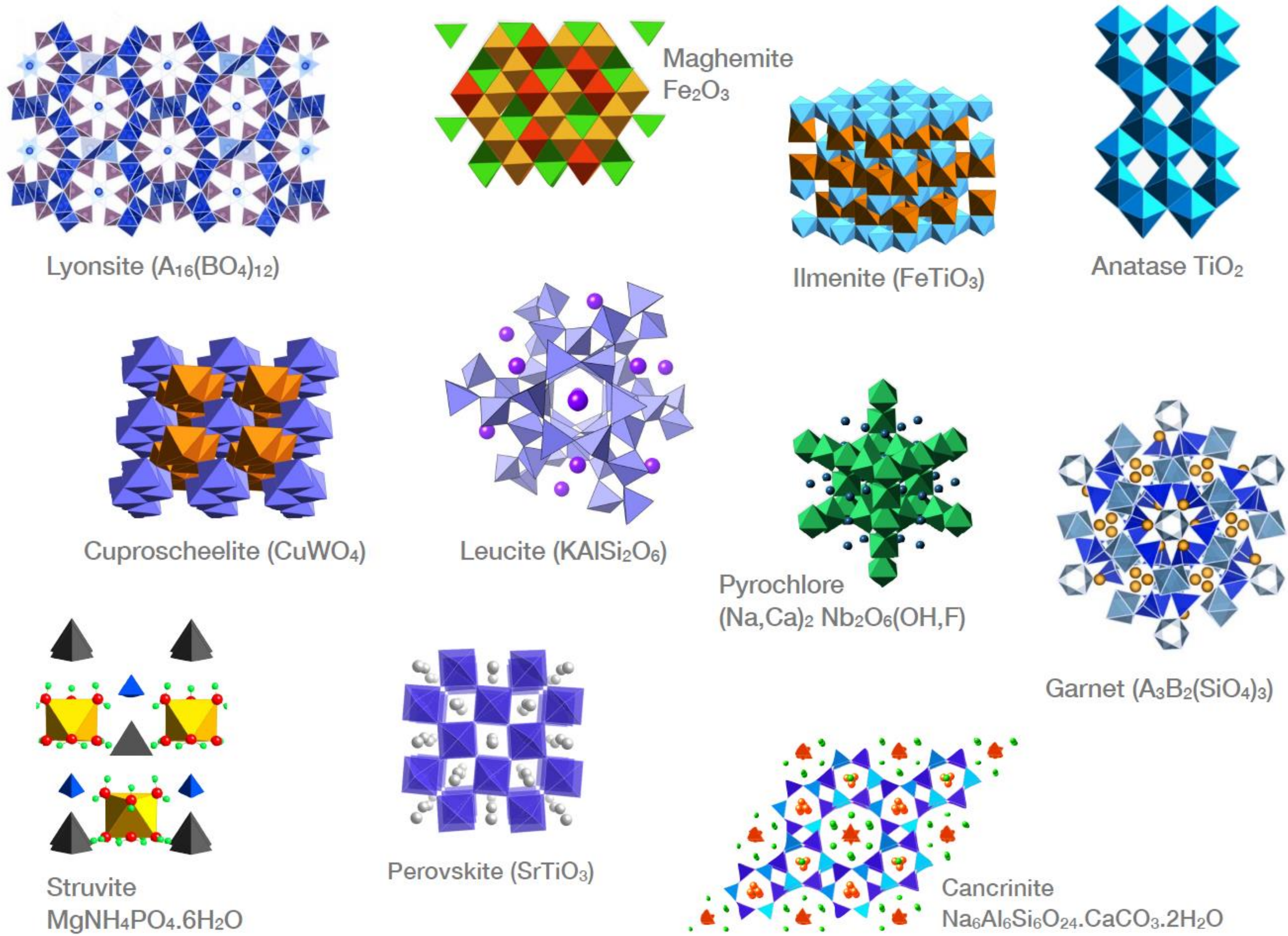
Fourfold way to electronic correlations



J. Mannhart, *et al.*, RPP **79**, 084508 (2016)

Why oxides?

- ✓ Highly electronegative
- ✓ Small ion
- ✓ Diverse chemical bonding
- ✓ Large stability range

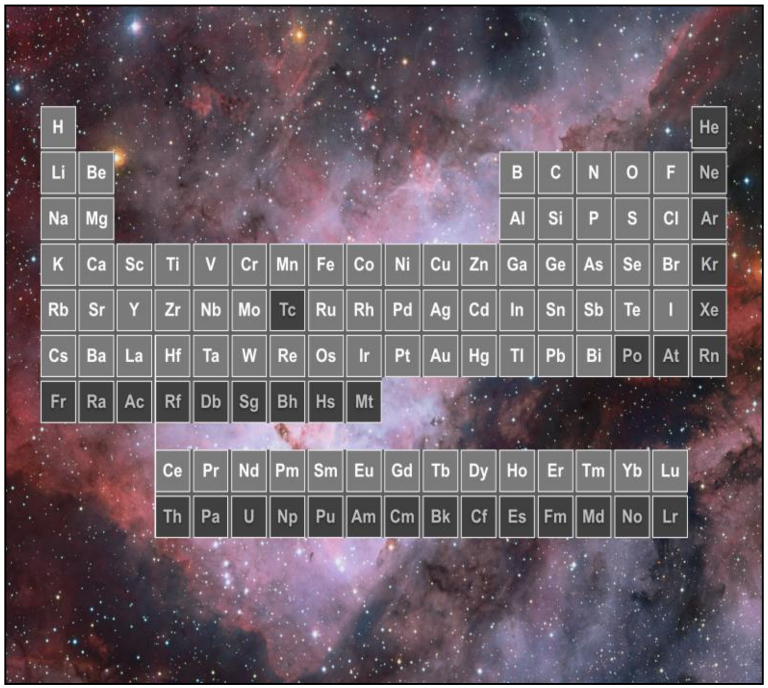


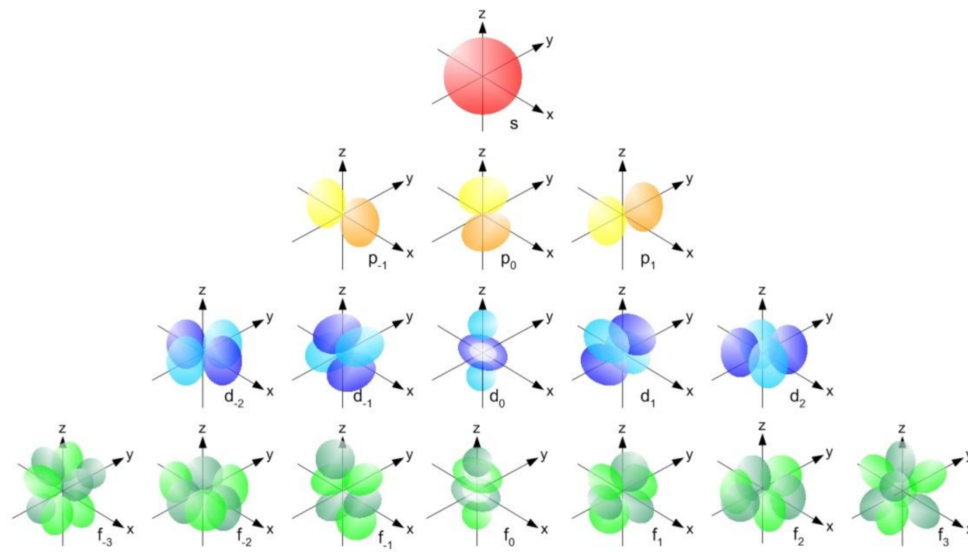
Lyonsite ($A_{16}(BO_4)_{12}$)
Maghemite
Fe_2O_3
Ilmenite ($FeTiO_3$)
Anatase TiO_2
Cuproscheelite ($CuWO_4$)
Leucite ($KAlSi_2O_6$)
Pyrochlore
$(Na,Ca)_2$ $Nb_2O_6(OH,F)$
Garnet ($A_3B_2(SiO_4)_3$)
Struvite
$MgNH_4PO_4.6H_2O$
Perovskite ($SrTiO_3$)
Cancrinite
$Na_6Al_6Si_6O_{24}.CaCO_3.2H_2O$

Challenges of Quantum Matter

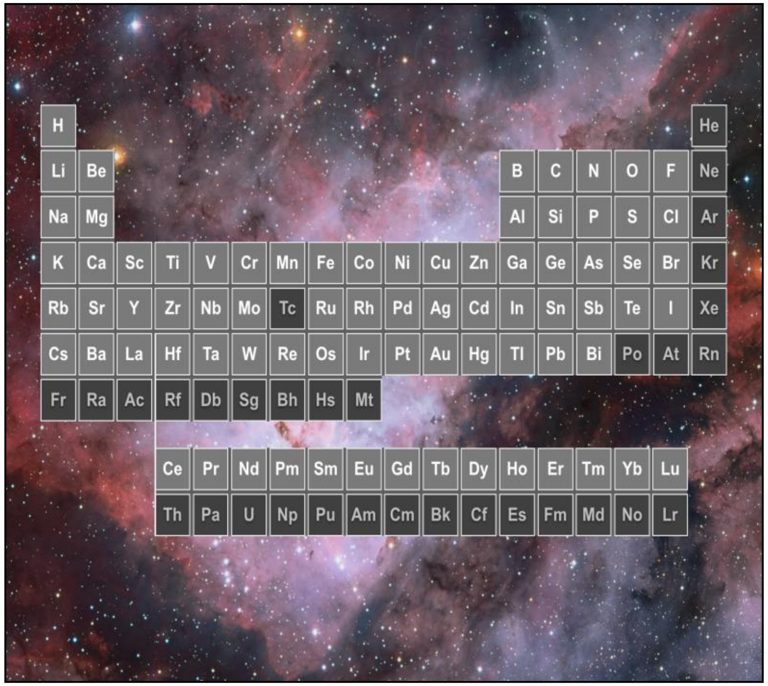
- ✓ The choice problem
- ✓ Defects

Exploration of the periodic table





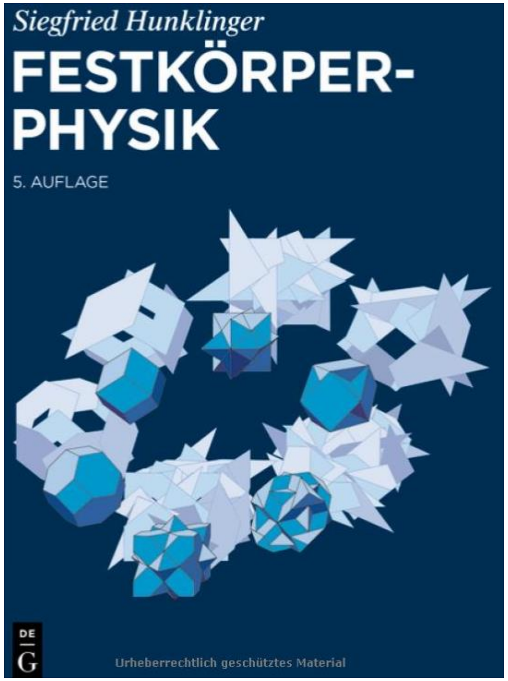
Long-term perspective

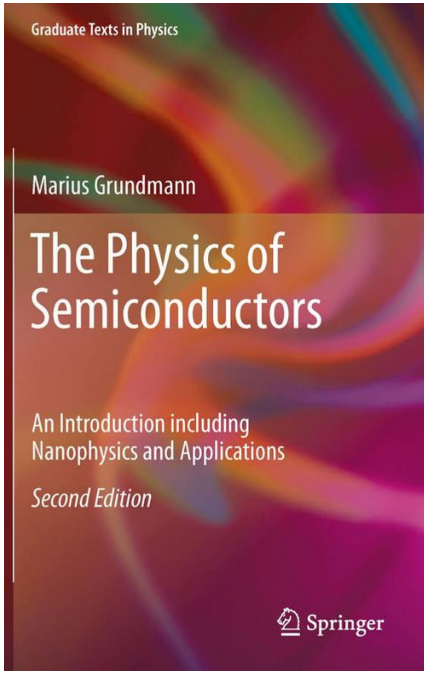


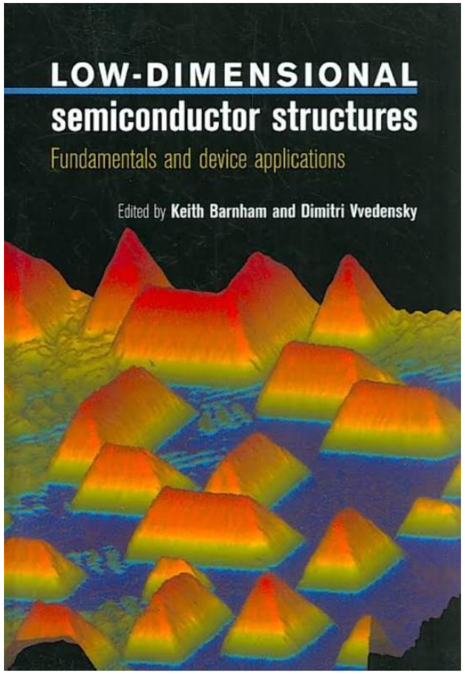
- ✓ Only one periodic table
- ✓ Complicated materials
- ✓ Metastable phases
- ✓ Smaller energy scales

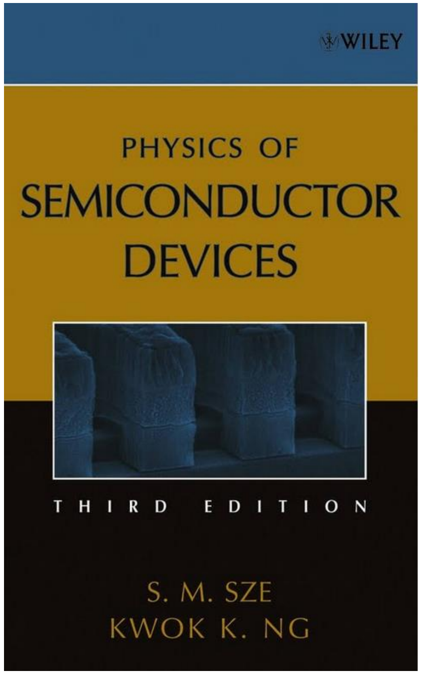
J. Mannhart, H.B., *A unique exploration,*
in *Towards Oxide Electronics: a Roadmap*, Appl. Surf. Sci. **482**, 4-6 (2019)

Semiconductor Heterostructures









Basics of Transport in Semiconductors

✓ Fermi gas

$$\sigma = \frac{ne^2\tau}{m^*}$$

✓ Band bending

$$\lambda_D = \sqrt{\frac{\epsilon_0 \epsilon_r kT}{q^2 N_D}}$$

Applications of Semi-conductor Heterostructures

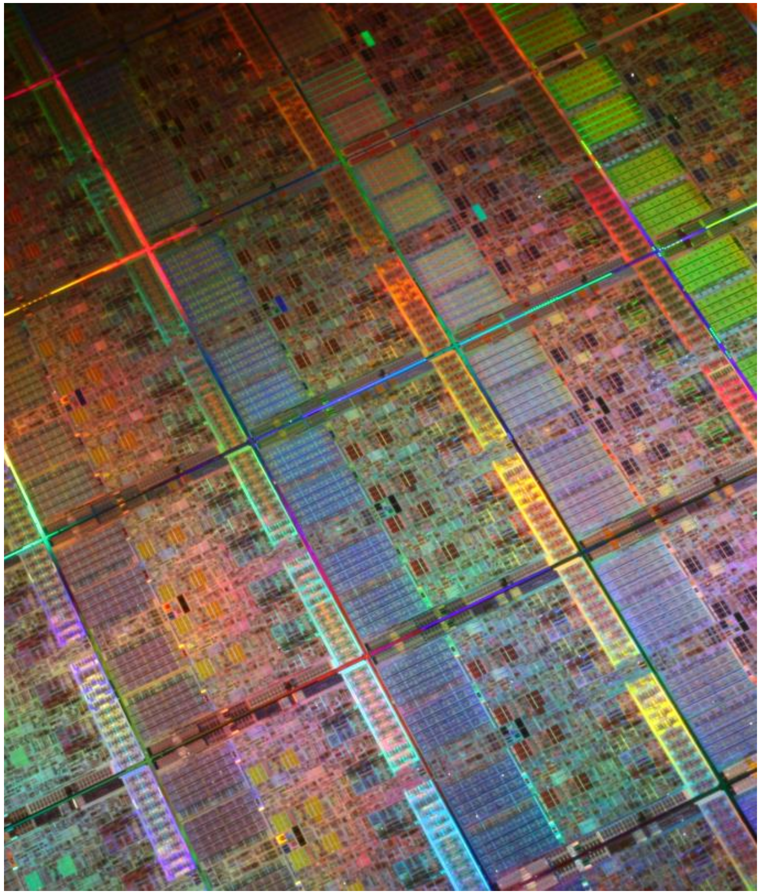
- ✓ Electronic devices
- ✓ Optics
- ✓ Electrical transport experiments
- ✓ Quantum hall effect

Semiconductor epitaxy

10 nm

J. Gowers, Philips research laboratory, 1980s

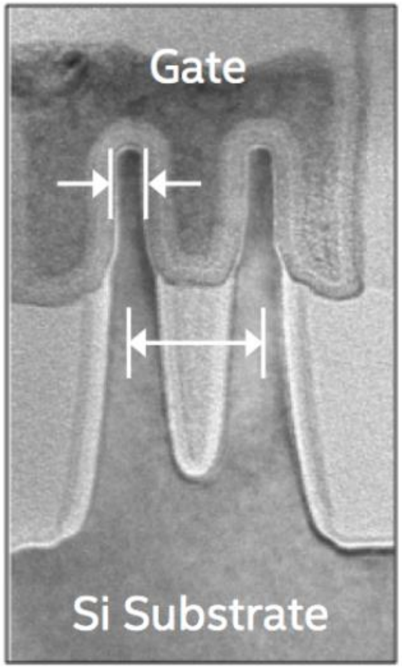
Semiconductor processing



14 nm Tri-gate Transistor Fins

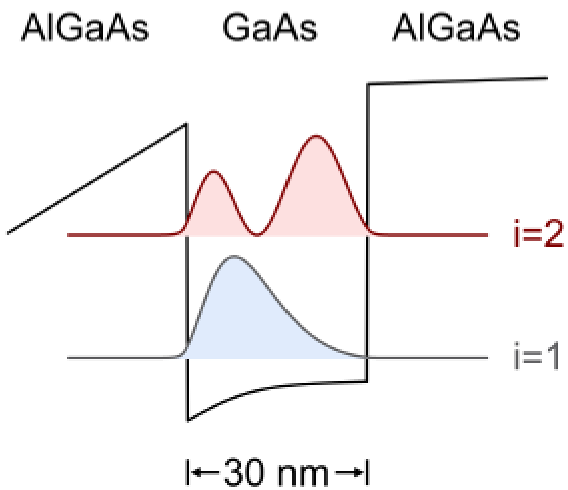
8 nm Fin Width

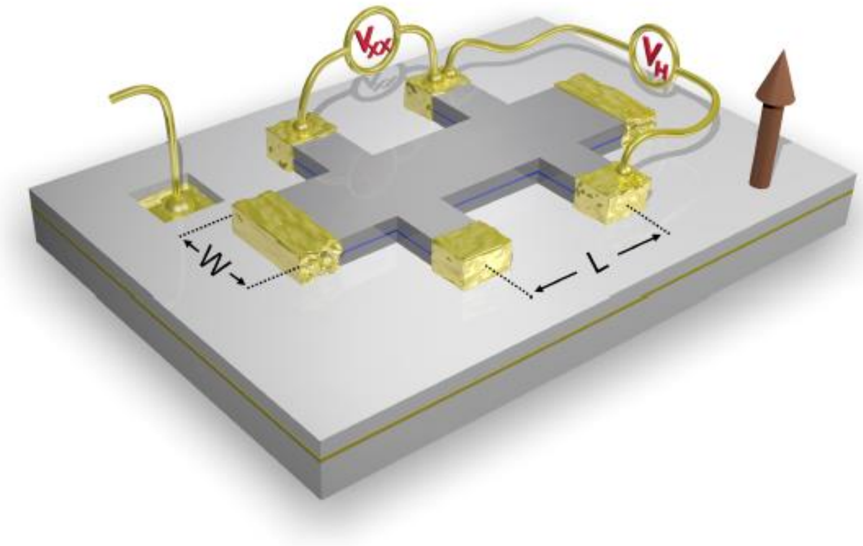
42 nm Fin Pitch



Intel

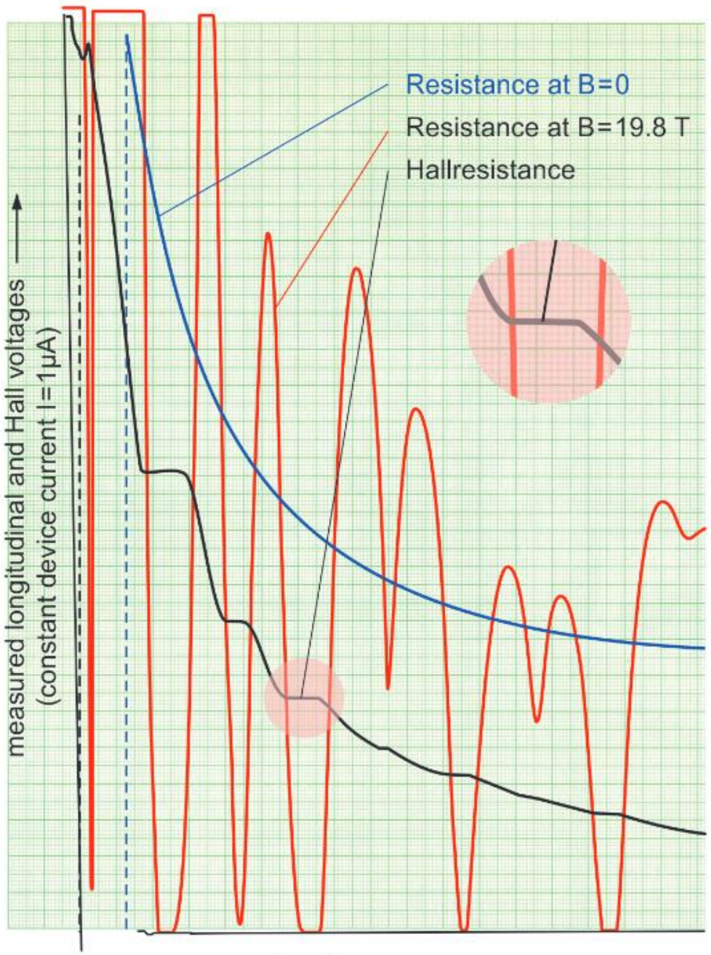
GaAs quantum well

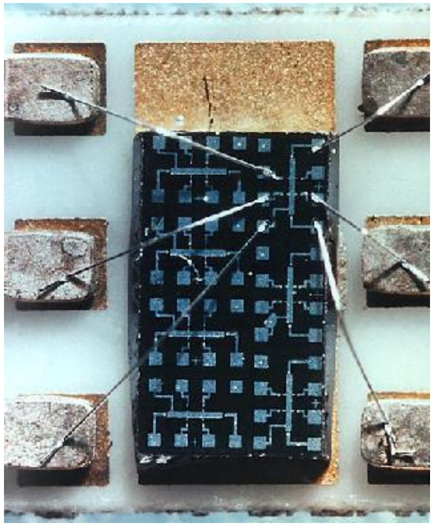


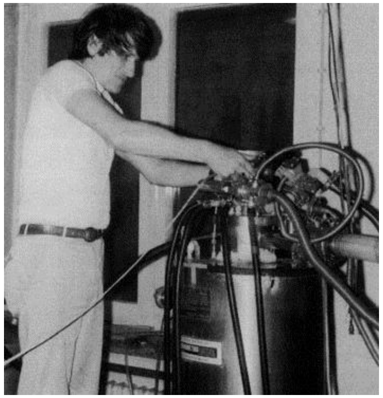


B. Friess, PhD Thesis, TU München & MPI FKF

Discovery of the Quantum Hall Effect

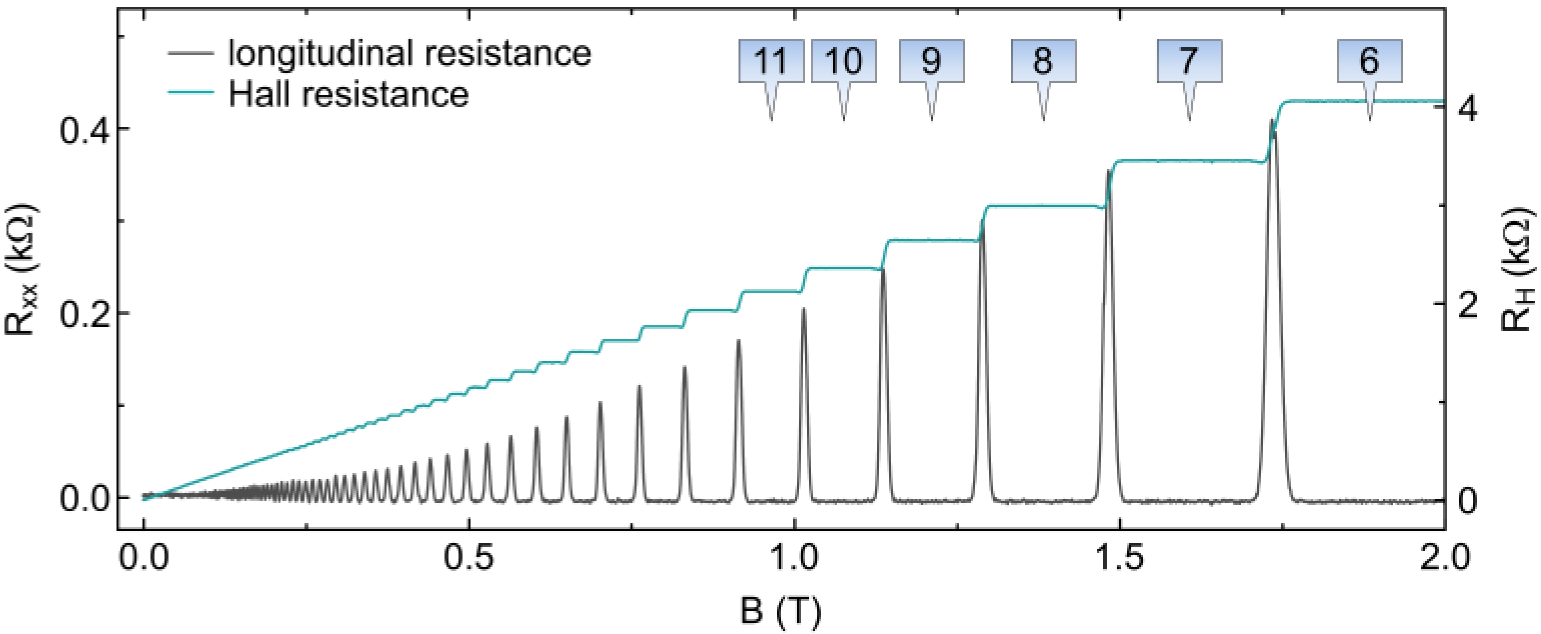






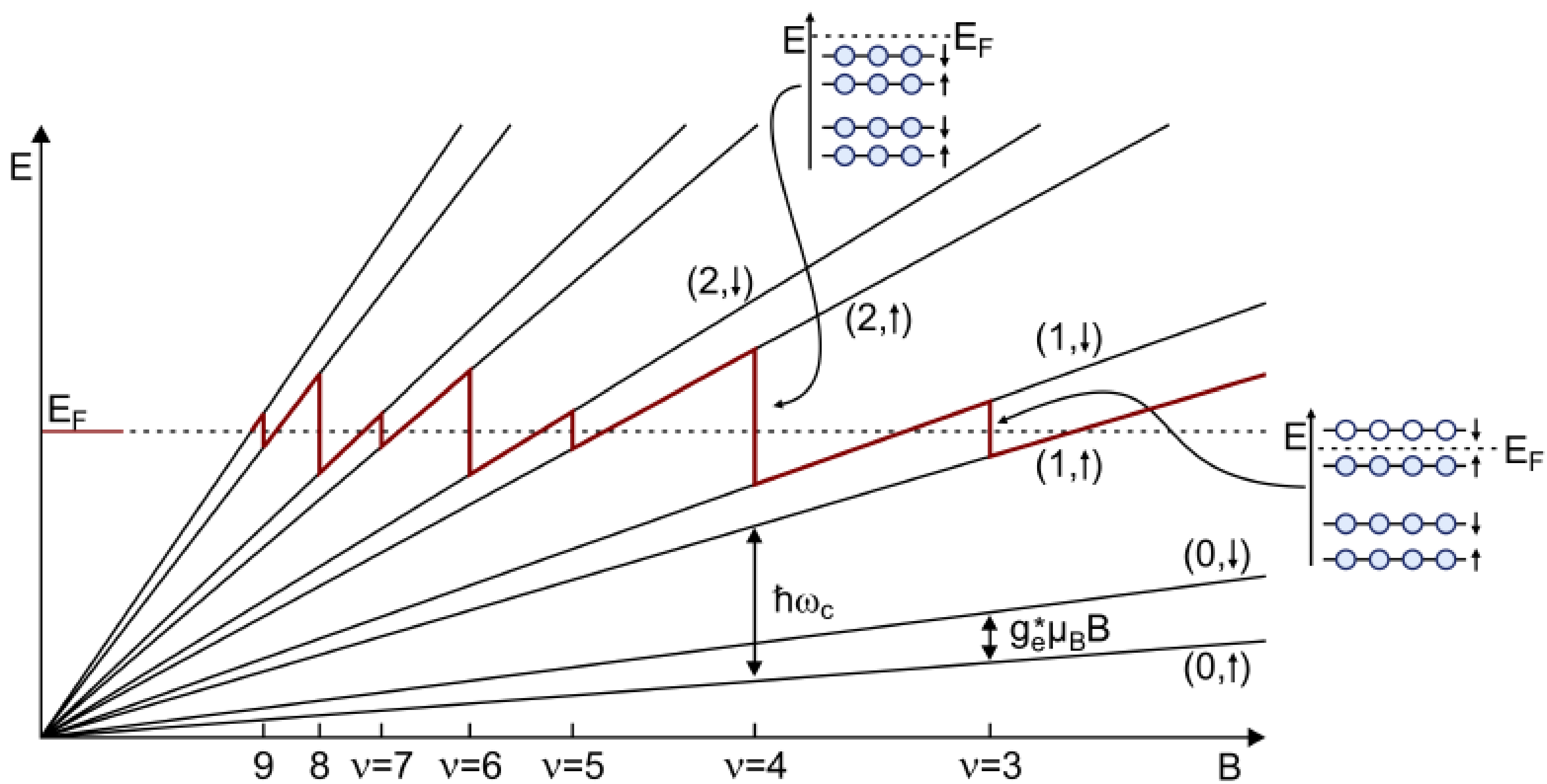
K. Von Klitzing, Ann. Rev. Condens. Matter Phys. **8**, 13 (2017).

Quantum Hall Effect in all its beauty



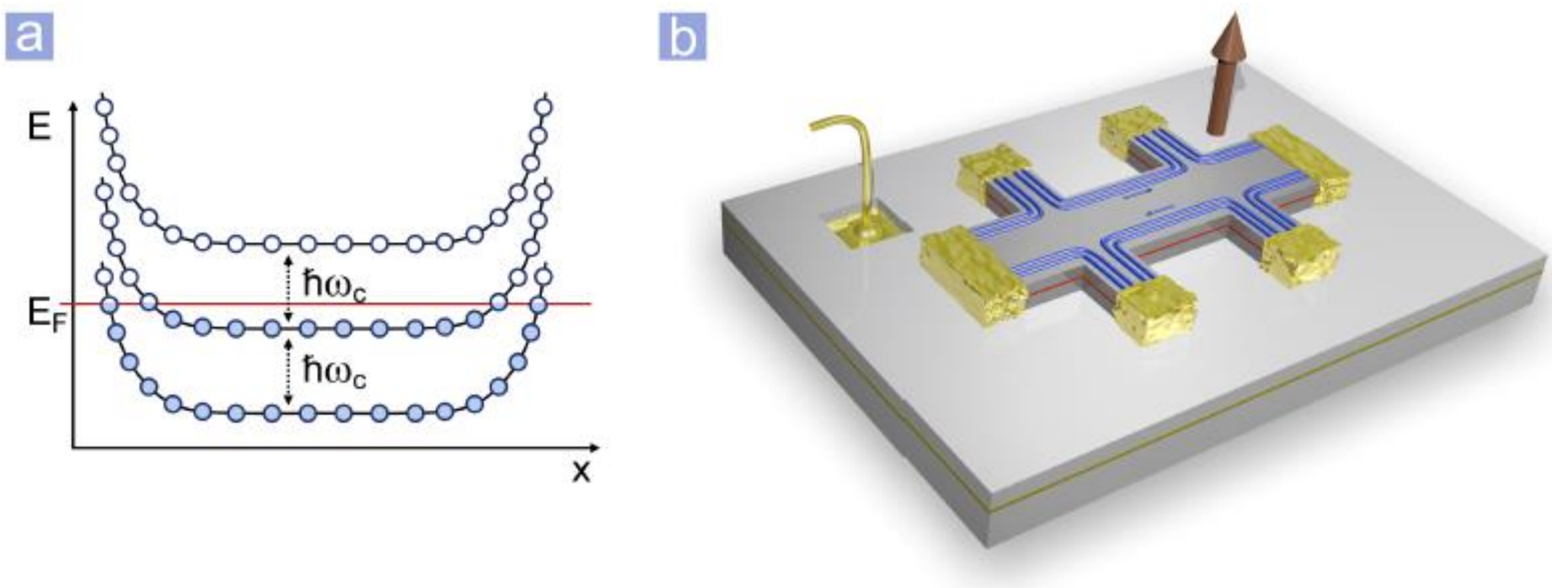
B. Friess, PhD Thesis, TU München & MPI FKF

Landau Level Energies



B. Friess, PhD Thesis, TU München & MPI FKF

Landauer-Büttiker Edge Channel Picture

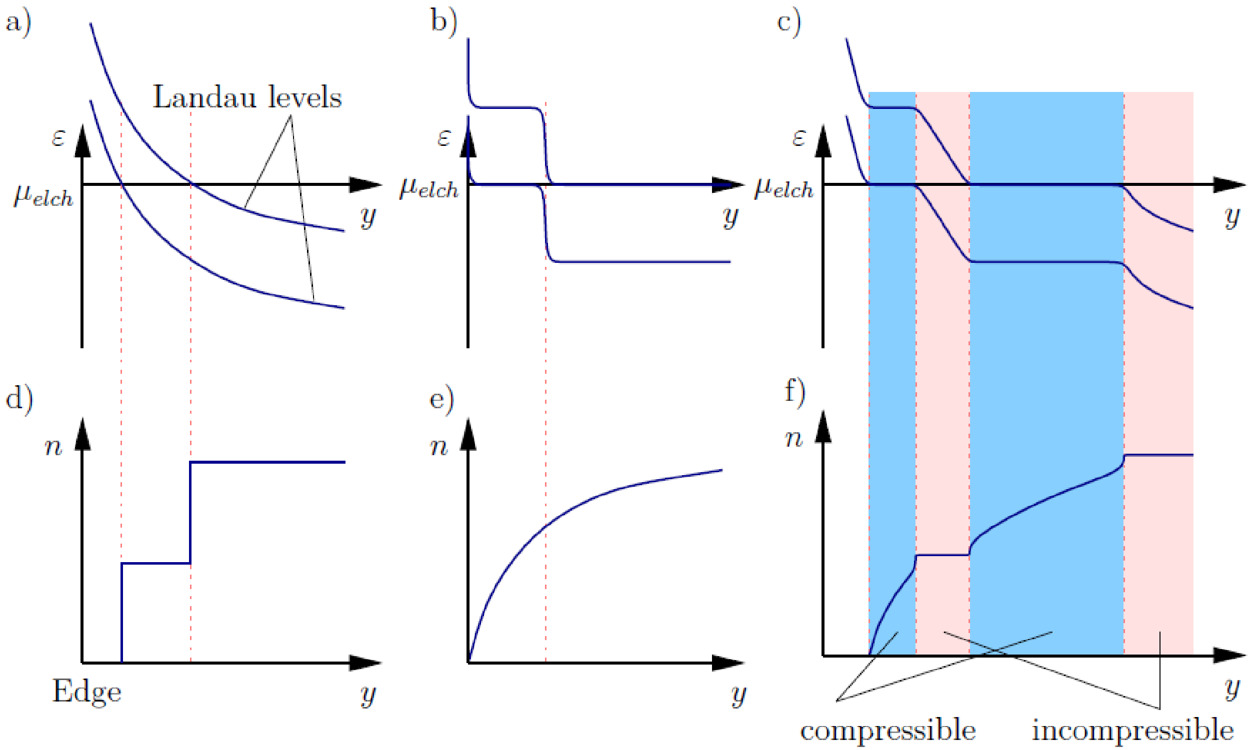


- ✓ Disorder pins chemical potential in the LL gap

- ✓ Transport along edge channels

B. Friess, PhD Thesis, TU München & MPI FKF

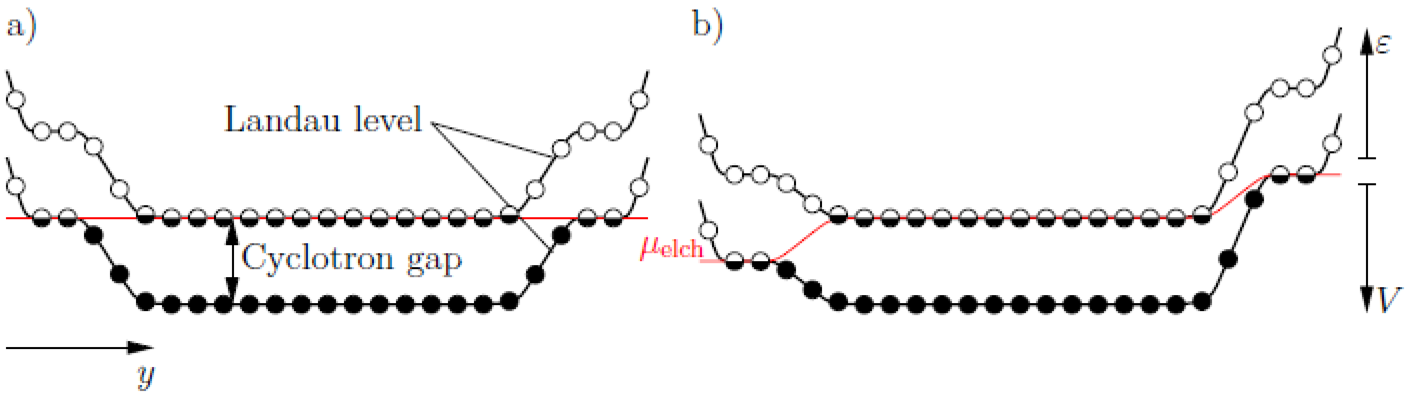
Compressible and incompressible stripes



K. Panos, PhD Thesis, Uni Stuttgart & MPI FKF

D. B. Chklovskii, B. I. Shklovskii, and L. I. Glazman., Electrostatics of edge channels. Phys. Rev. B, **46**, 4026 (1992).

Quantum Hall Effect

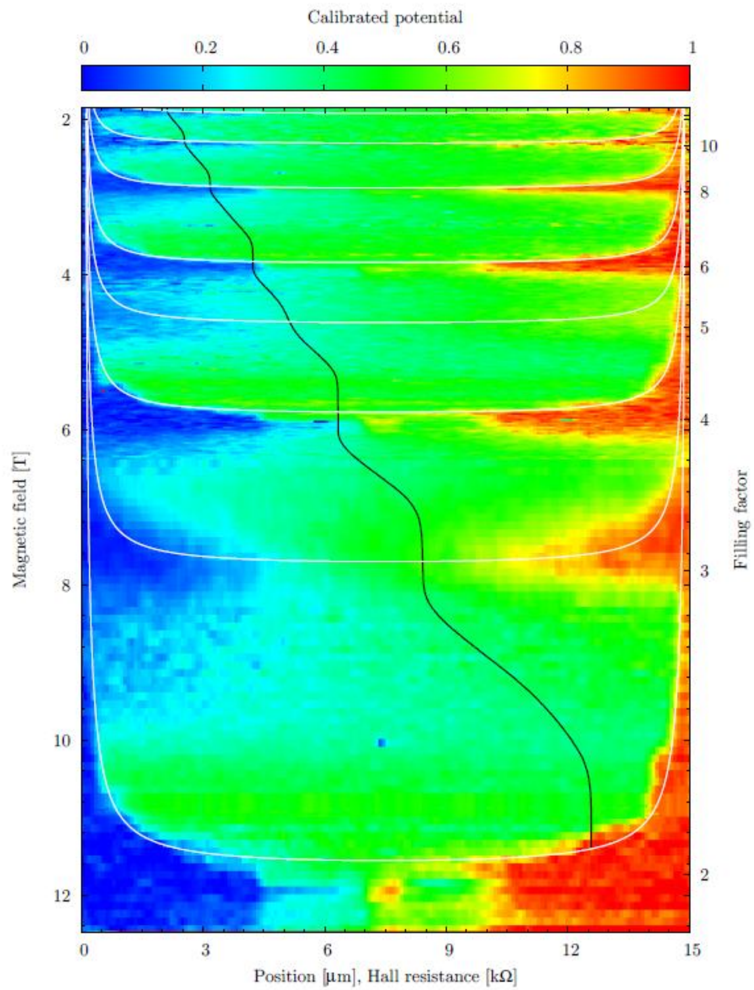


- ✓ Current flows in the innermost incompressible stripe.

- ✓ Because of the LL gap, the filling is exact, => QHE.

K. Panos, PhD Thesis, Uni Stuttgart & MPI FKF

Measurements of the Hall Potential

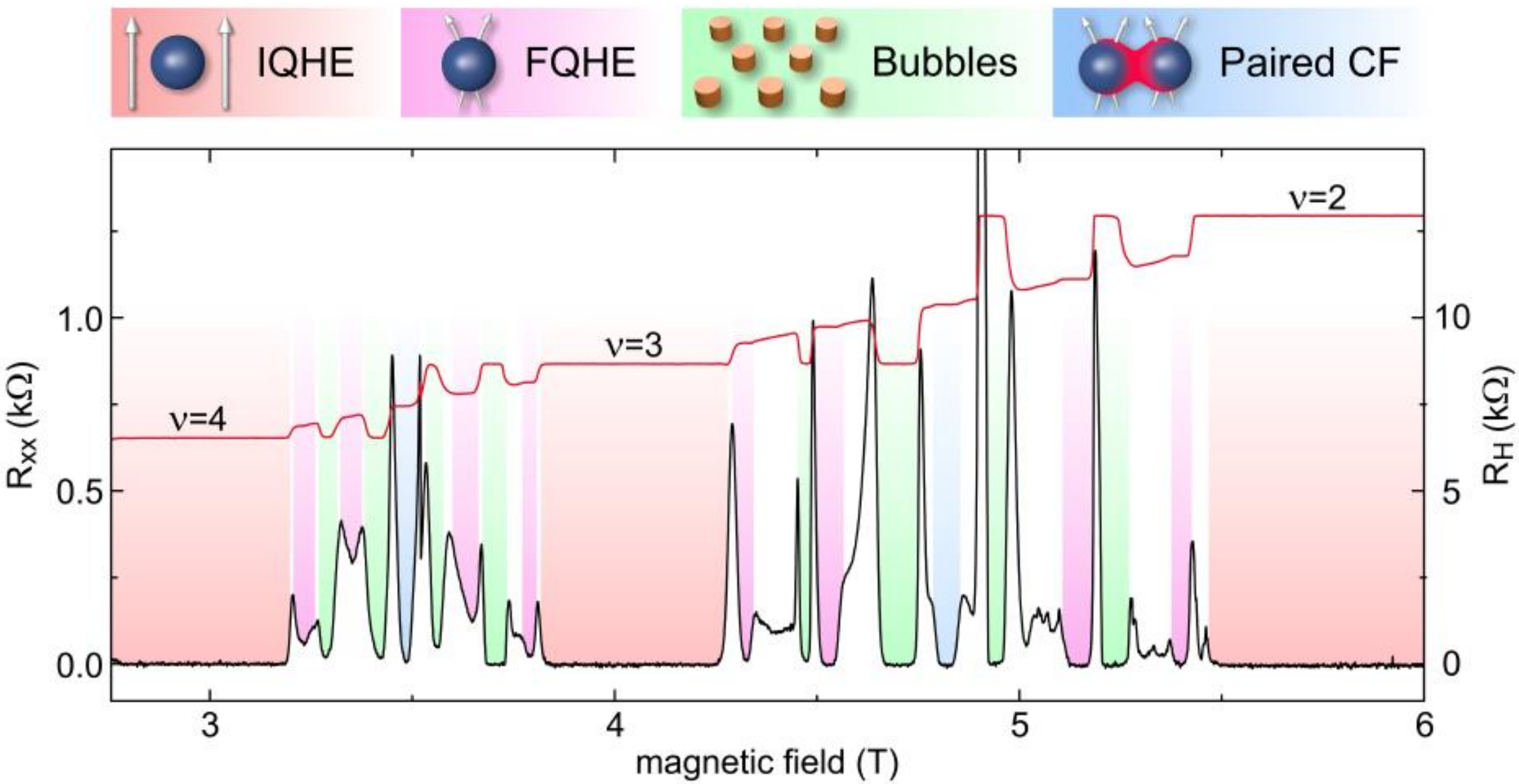


K. Panos, PhD Thesis, Uni Stuttgart & MPI FKF

Conclusion

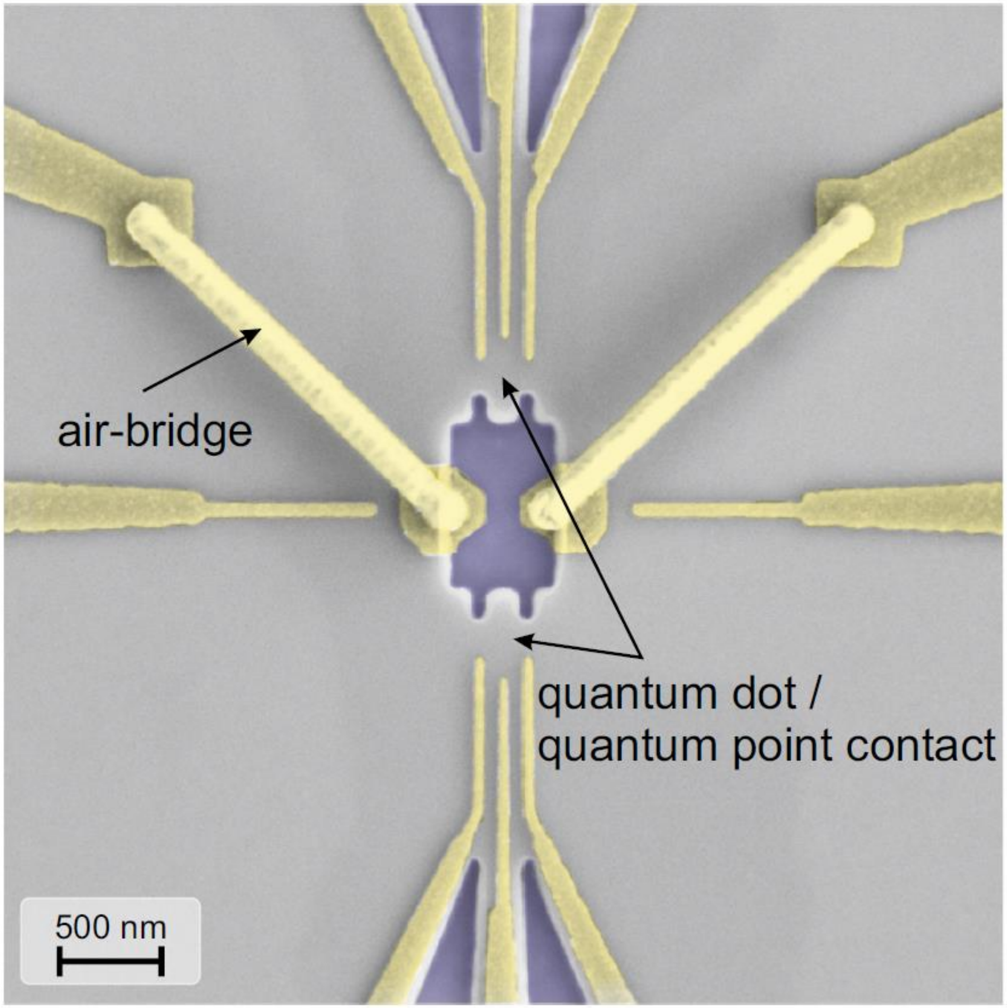
- ✓ The measurements indicate that all the current flows in the innermost incompressible stripe
- ✓ All completely filled Landau levels in this stripe participate in the transport
- ✓ This is not consistent with the edge channel picture

Physics in the Second Landau Level



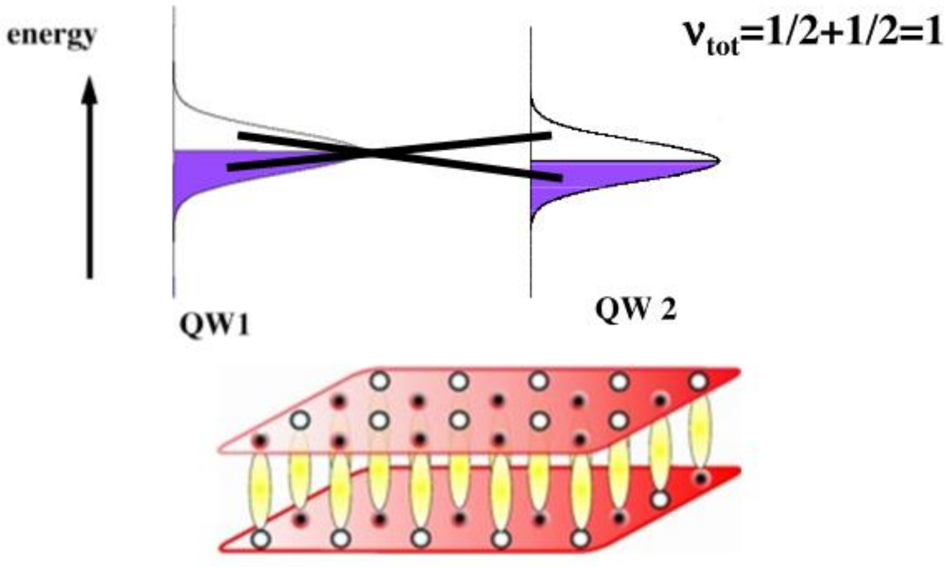
B. Friess, PhD Thesis, TU München & MPI FKF

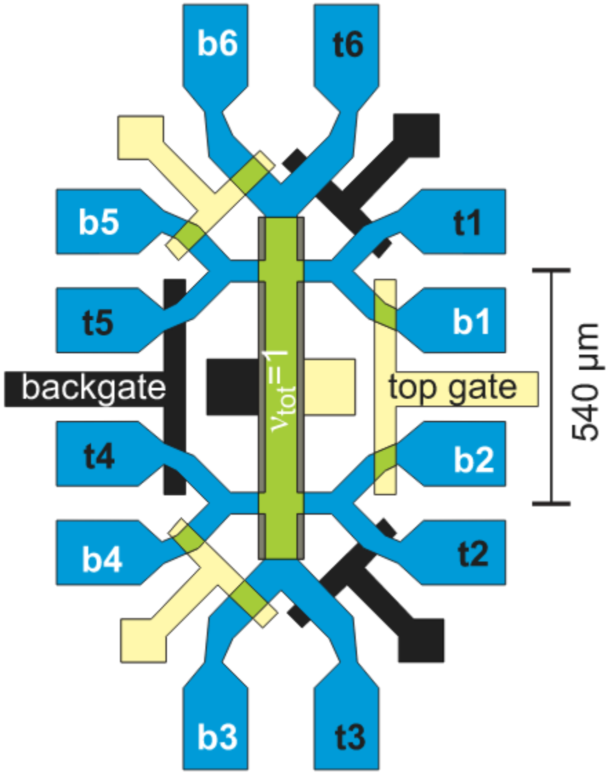
Advanced gating



L. Schulz, *Dissertation,* Universität Stuttgart (2014)

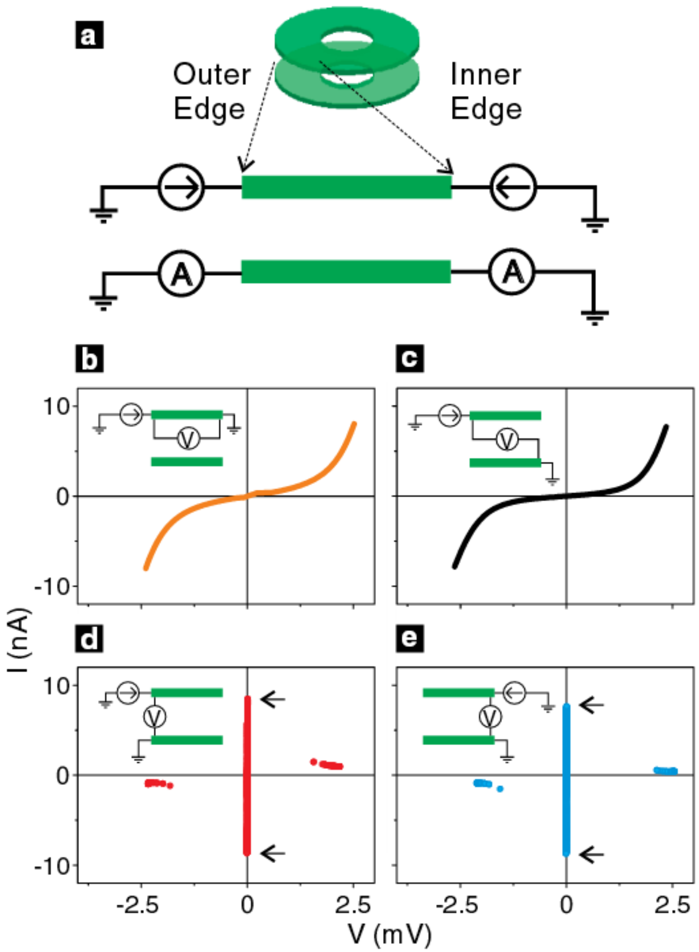
Double well GaAs

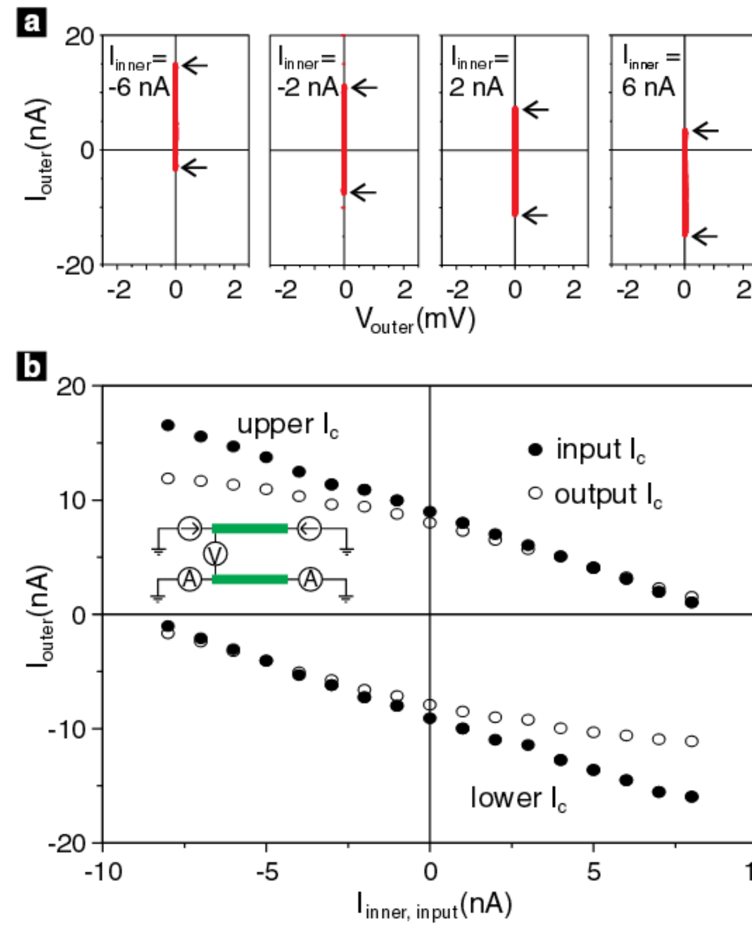




D. Zhang, *et al.*, PRL **116**, 186801 (2016)

Beautiful experiment





X. Huang, *et al.*, PRL **109**, 156802 (2012)

For further reading

- Overview of experiments:
  Metrology and microscopic picture of the integer quantum Hall effect, J. Weis, K. von Klitzing, Philosophical Transactions of the Royal Society A **369**, 3954 (2011).

- Evidence for the stripes:
  Edge strips in the quantum Hall regime imaged by a single-electron transistor, Y.Y. Wei, J. Weis, K. von Klitzing, K. Eberl, Physical Review Letters **81**, 1674 (1998).

- Self consistent solutions:
  Incompressible strips in dissipative Hall bars as origin of quantized Hall plateaus, A. Siddiki, R.R. Gerhardts, Physical Review B **70**, 195335 (2004).

- Breakdown of the QHE:
  Current distribution and Hall potential landscape towards breakdown of the quantum Hall effect: a scanning force microscopy investigation, K. Panos, R. R. Gerhardts, J. Weis, K. von Klitzing, New Journal of Physics **16**, 113071 (2014).