HUMBOLDT-UNIVERSITÄT ZU BERLIN

Low-dimensional transport in semiconductor nanostructures

Here:
- No ferromagnets (no magnons)
- two-, one-, zero-dimensional regions connect without material interfaces
- negligible lattice contribution at low temperature

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Low-dimensional transport

Quantum wires / Quantum point contacts

- **Open issues**

Spin-related phenomena

- **e.g. "0.7-conductance anomaly"**

Towards (sub-)single-mode interferometry

- **Non-local current heating: de/-coherence**

Thermopower in quasi-1D conductors

Charge transport regimes:

Diffusive

Nanowires
Charge-carriers with lmean-free path << diameter and length,
High temperatures (RT)

Ballistic

Ballistic wires:
- Oscillations of TP as a function of E_F.
- Phonon- drag dominant

e.g. Theory:
Tsaousidou and Butcher,
PRB R10044 (1997).

Quantum

Quantum wires &

Quantum point contacts
-> electron thermometers

e.g. Exp:
L.W. Molenkamp, *et al.*,
PRL 68 (1992) 3765.

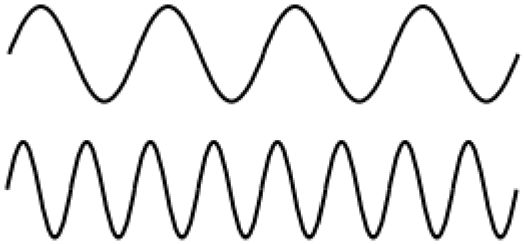
Open issues:

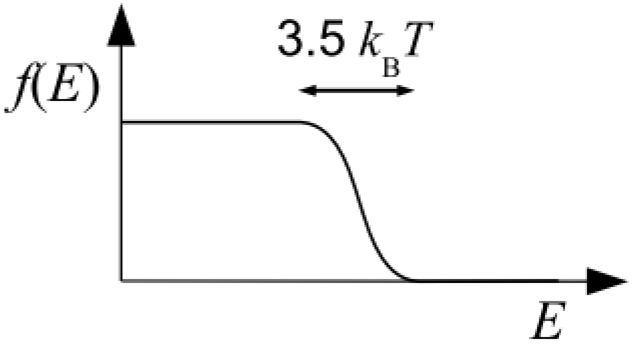
- Thermopower in the presence of strong e-e and **spin-dep. interactions**?
- Effect of **current induced heating on quantum coherence**?

Decoherence

- Phase breaking events [6]
  - inelastic scattering (e-e-interaction)

- Averaging effects [5]
  - Thermal averaging





[6] J.J. Lin, J.P. Bird, *J. Phys.: Condens. Matter* **14**, R501 (2002)

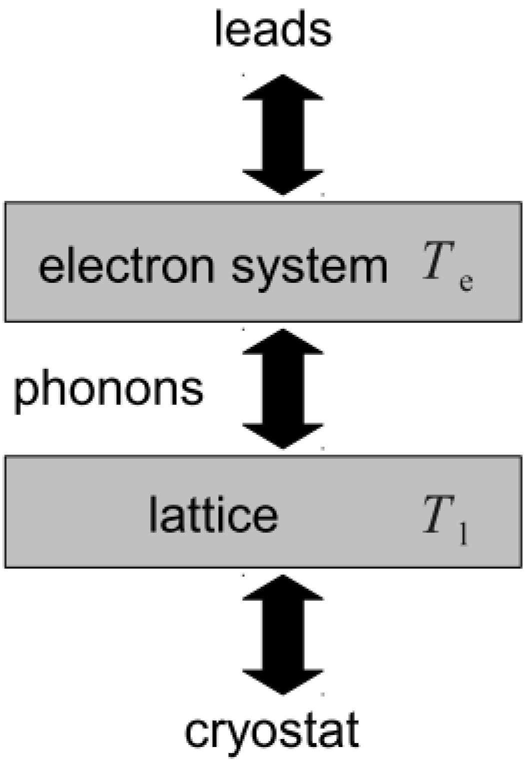
[5] S.S. Buchholz *et al.*, *Phys. Rev. B* **82**, 045432 (2010)

Electron Temperature

- Coupling of electron system and lattice by phonons decreases with temperature

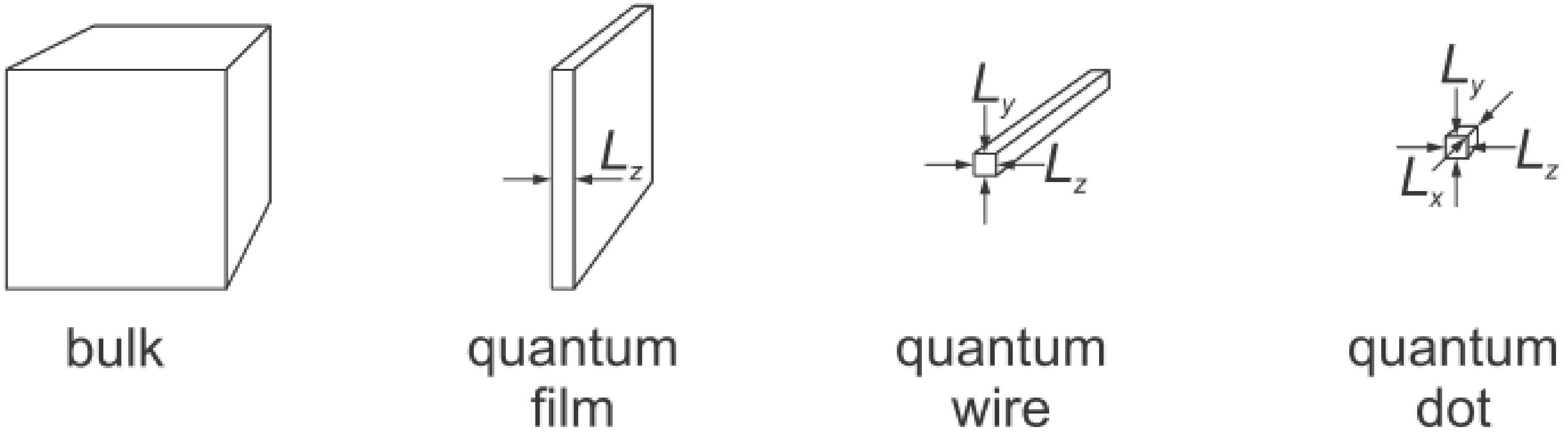
  ▶ Significant deviation between T_l and T_e at low temperatures (few K) possible

  ▶ Control of electron temperature by heating current I_H

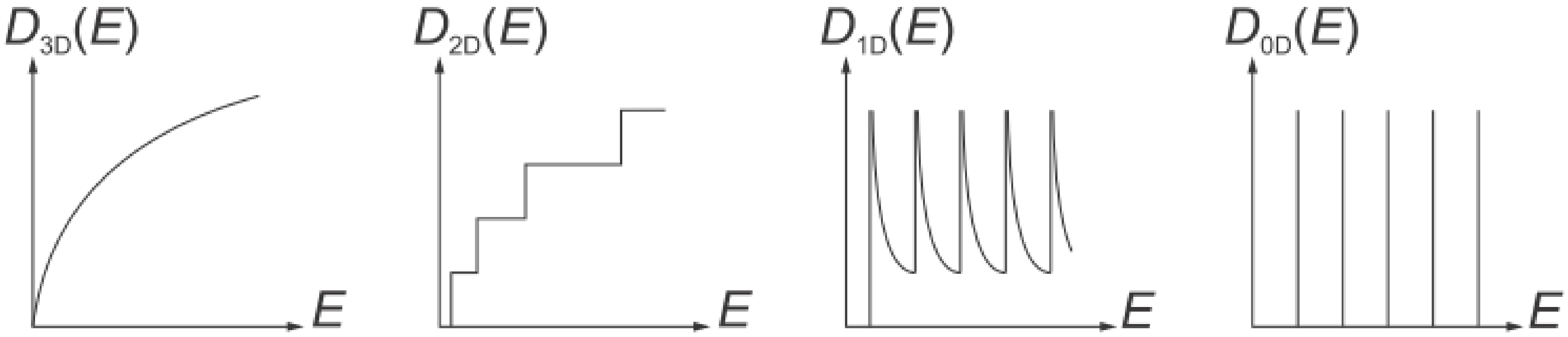


Quantenmaterials

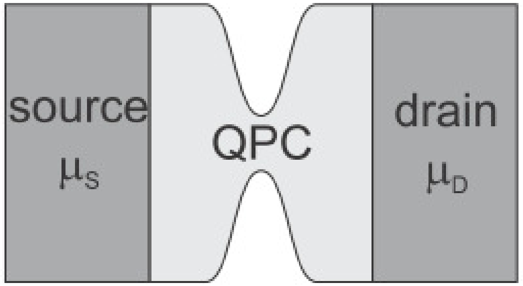
Low-dimensional charge-carrier systems



Density of states



Quantized conductance



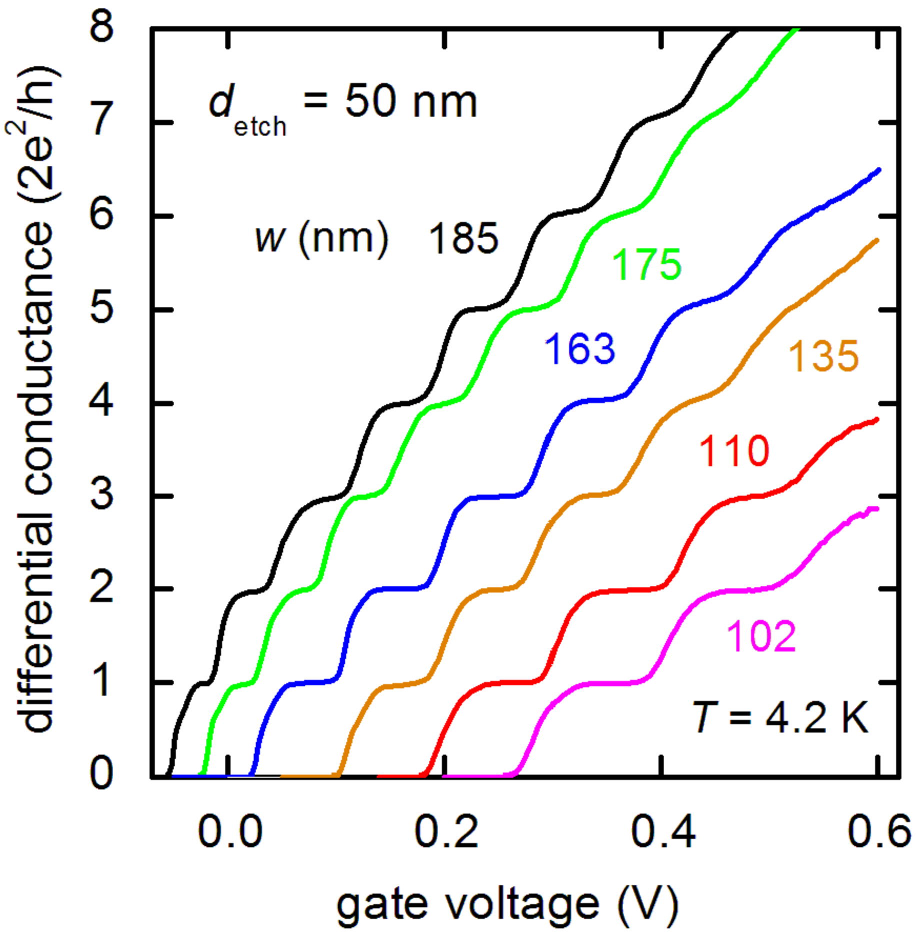
$$dI = -e \cdot dn \cdot v$$

$$= -2e \frac{dk}{2\pi} \frac{1}{\hbar} \frac{dE}{dk} = -\frac{2e}{h} dE$$

$$g = \frac{dI}{dV}$$

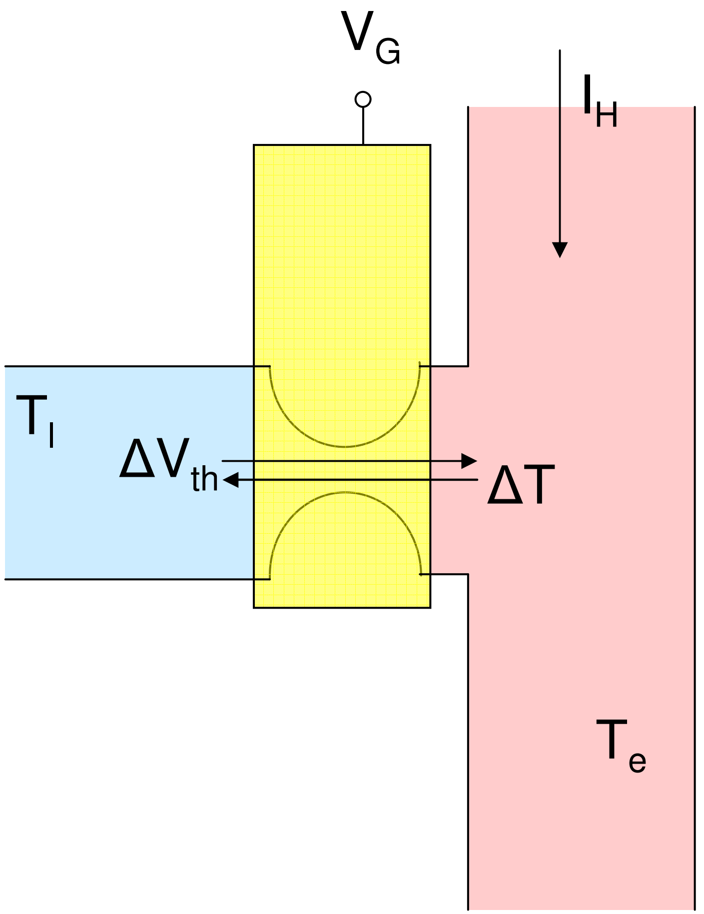
$$\boxed{g_i = \frac{2e^2}{h}}$$

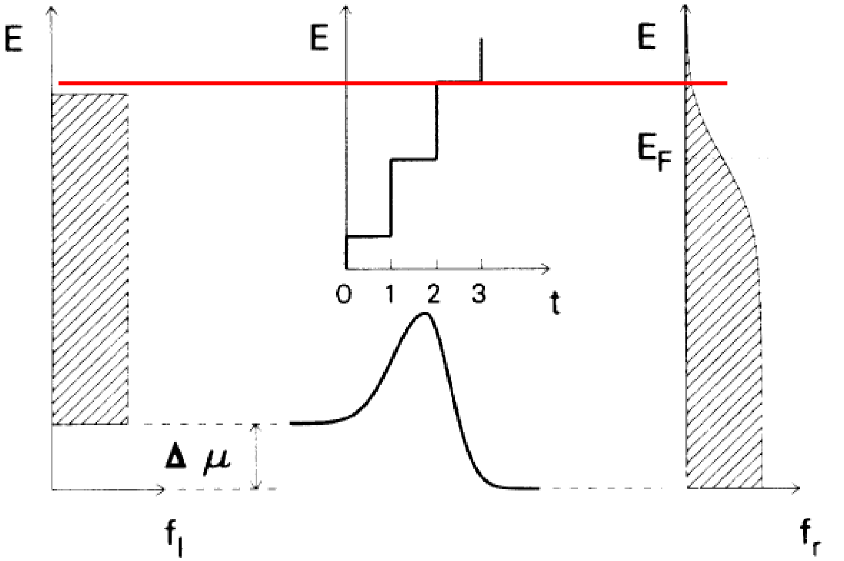
B.J. van Wees, *et al.*,
PRL **60**, 848 (1988).
D.A. Wharam, *et al.*,
J. Phys. C: **21**, L209 (1988).



G. Apetrii *et al.*,
Sem. Sci. Technol. **17**, 735 (2002).

Thermopower in Quantum Point Contacts



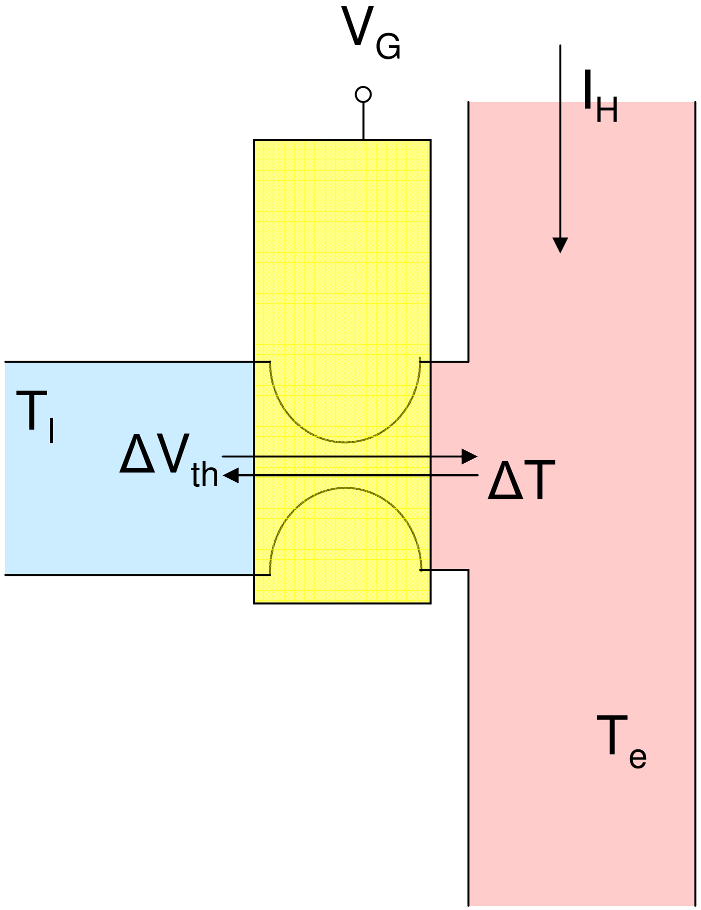


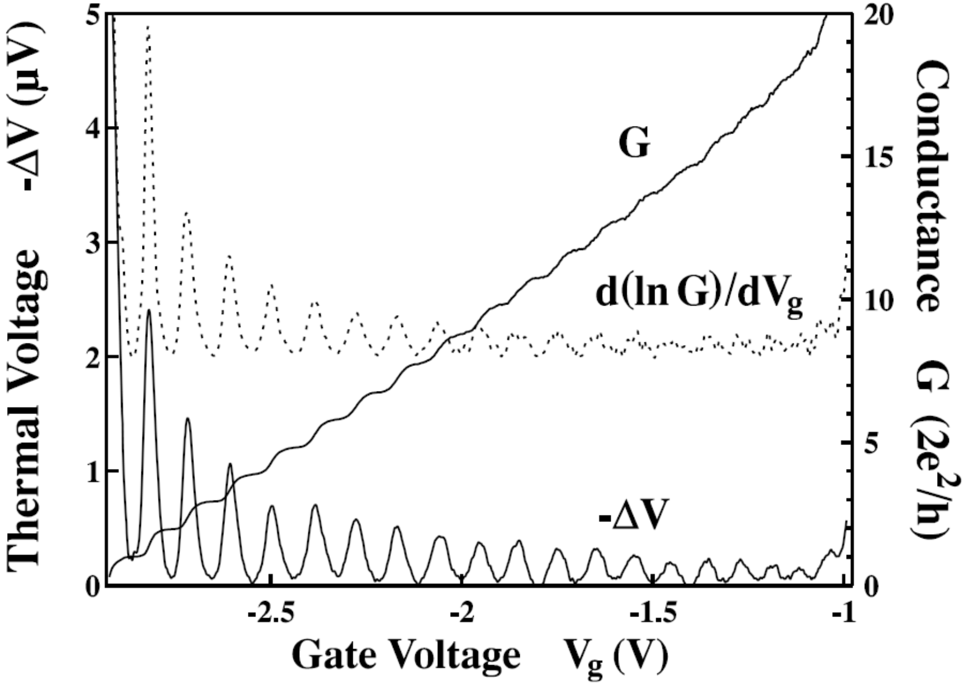
$$S = \lim_{\Delta T \to 0} \left. \frac{V}{\Delta T} \right|_{I=0}$$

$$S^{Mott} = -\frac{\pi^2 k_B^2}{3e} \left(T_e + T_l\right) \frac{\partial (\ln G)}{\partial \mu}$$

L.W. Molenkamp *et al.*, Phys. Rev. Lett. **65** 1052 (1990)

Thermopower in Quantum Point Contacts





$$S^{Mott} = -\frac{\pi^2 k_B^2}{3e}(T_e + T_l)\frac{\partial(\ln G)}{\partial\mu}$$

N.J. Appleyard *et al.*, Phys. Rev. Lett. **81** 3491 (1998)

Quasi-1-dim. charge carrier transport:

Single particle transmission properties

Landauer approach and wave packet modelling

apply well: e.g.

+ quantized conductance

B.J. van Wees, *et al*., PRL **60**, 848 (1988)
D.A. Wharam, *et al*., J. Phys. C: **21**, L209 (1988).

+ wavefunction hybridization in coupled QWRs

S.F.Fischer, *et al.*, Nature Physics **2,** 91 (2006); Phys. Rev. B **74**, 115324 (2006).
SFF, Int. J. Mod. Phys. B 21, 1326 (2007) ; Adv. in Solid State Physics, 47, 55 (2008).

SFF,*et al.,* J. Physics, Conf. **193,** 012043 (2009)

+ thermopower in QPCs – Mott relation holds

L.W. Molenkamp *et al*., Phys. Rev. Lett. **65** 1052 (1990)
N.J. Appleyard *et al.*, Phys. Rev. Lett. **81** 3491 (1998)

+ quäntized thermal conductance

O. Chiatti, *et al*. Phys. Rev. Lett. 97, 056601 (2006).
J. Nicholls, *et al.* J. Phys.: Condens. Matter 20 (2008) 164210

Quantum transport & spin phenomena

Open issues

Non-equilibrium phenomena

o reservoirs at non-thermal equilibrium: effect on de/-coherence

o non-linear-response regime

Many-body effects

o electron-electron interactions (low-density Fermi-liquid)

o correlation of spin fluctuations

o e-e and charge-spin interactions (Luttinger-liquid)

Dynamics

o dynamical spin polarization

o correlation of spin fluctuations

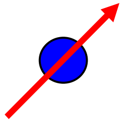
QPC in low-density regime

Need of many-body physics:

„0.7-conductance anomaly“

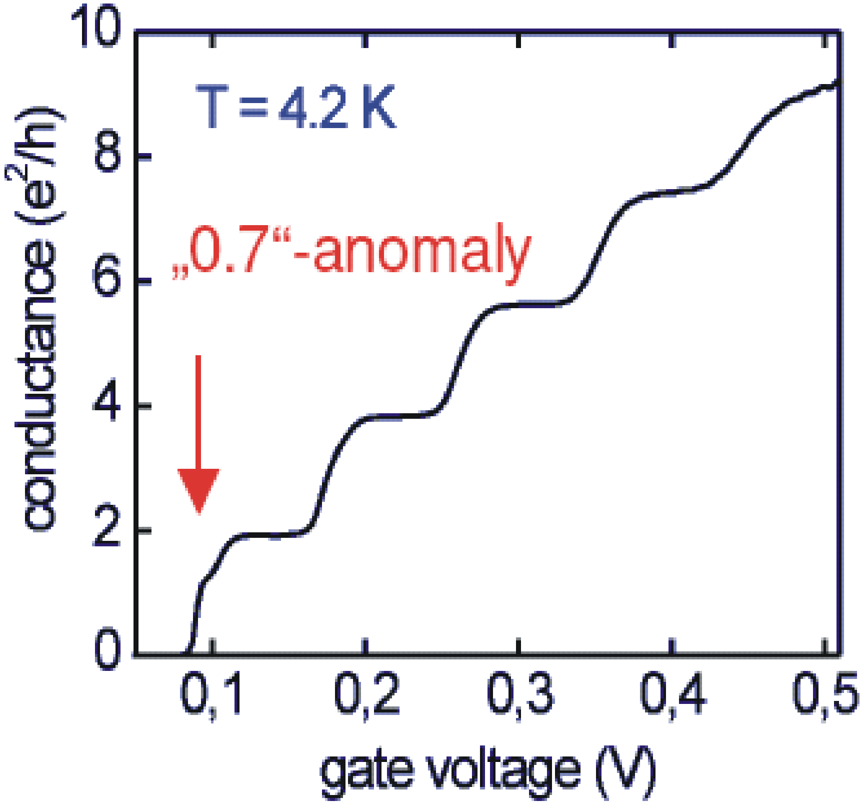
Spin-related phenomenon:

Spin polarization,



dynamical spin scattering,

Kondo-like processes



(numerous experimental and theoretical Investigations...)

QPC in low-density regime

Thermopower $S(V_g)$

→deviations fromsingle-particle behaviour at the 0.7 structure

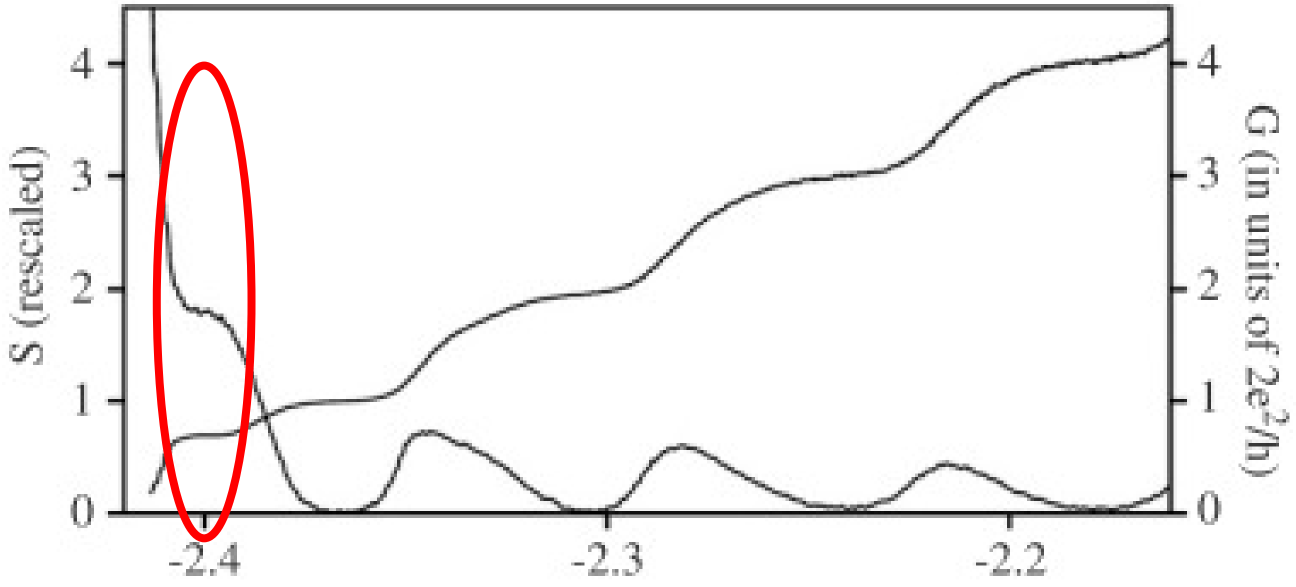


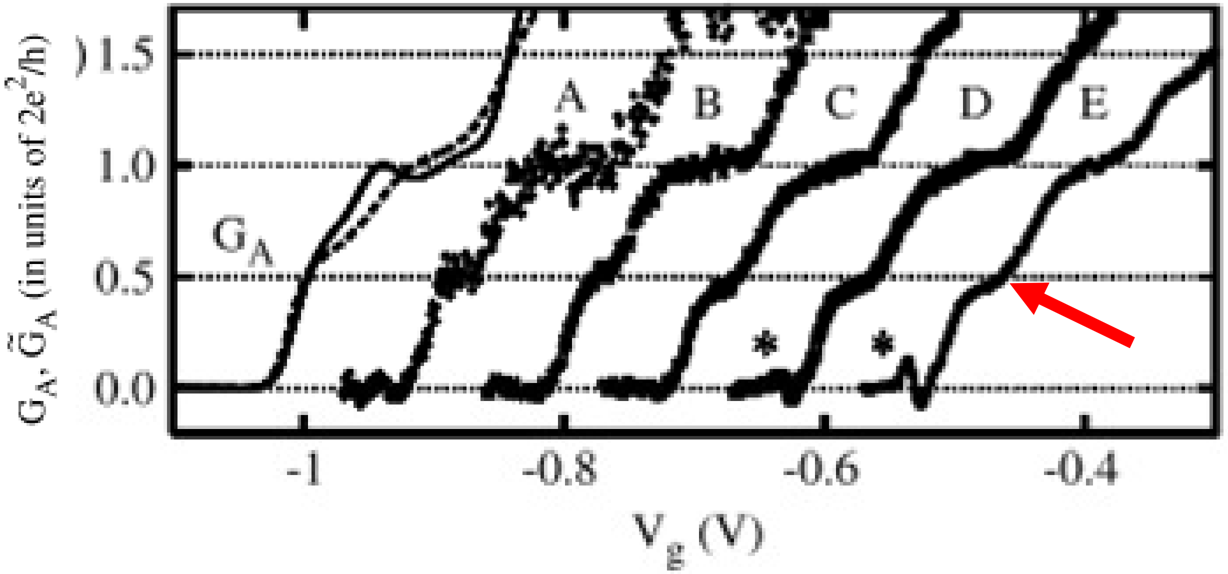
Figure 3. Simultaneous thermopower S and conductance G measurements at $T = 0.3$ K of a 1D constriction close to pinch-off [14]. According to the Cutler–Mott relation (equation (1)) a plateau in G should be accompanied by a zero in S—this prediction holds for the plateaus at $N \times 2e^2/h$ for $N = 1, 2, 3$, and 4, but breaks down on the 0.7 structure at $V_g = -2.4$ V.

O. Chiatti, *et al*. Phys. Rev. Lett. 97, 056601 (2006).
J. Nicholls, *et al.* J. Phys.: Condens. Matter 20 (2008) 164210

QPC in low-density regime

Thermal conductance characteristics κ(V g)

→deviations from single-particle behaviour at the 0.7 structure



→ quantum dots?
→ long wires?
→ magnetic fields?

near 0.7 structure: breakdown of the Wiedemann–Franz relation, giving an unexpected plateau in thermal conductance at $L_0\,T \times (G_0/2)$.

O. Chiatti, *et al*. Phys. Rev. Lett. 97, 056601 (2006).
J. Nicholls, *et al.* J. Phys.: Condens. Matter 20 (2008) 164210

Pre-Summary

Low-dimensional charge carrier and spin transport: Model systems

- o Independent lattice and charge carrier temperature possible
- o energy scales can be designed experimentally (subbands)
- o Selection of energy, momentum and spin of charge carriers
- o integrated “lab on the chip”

Open issues

some of which …

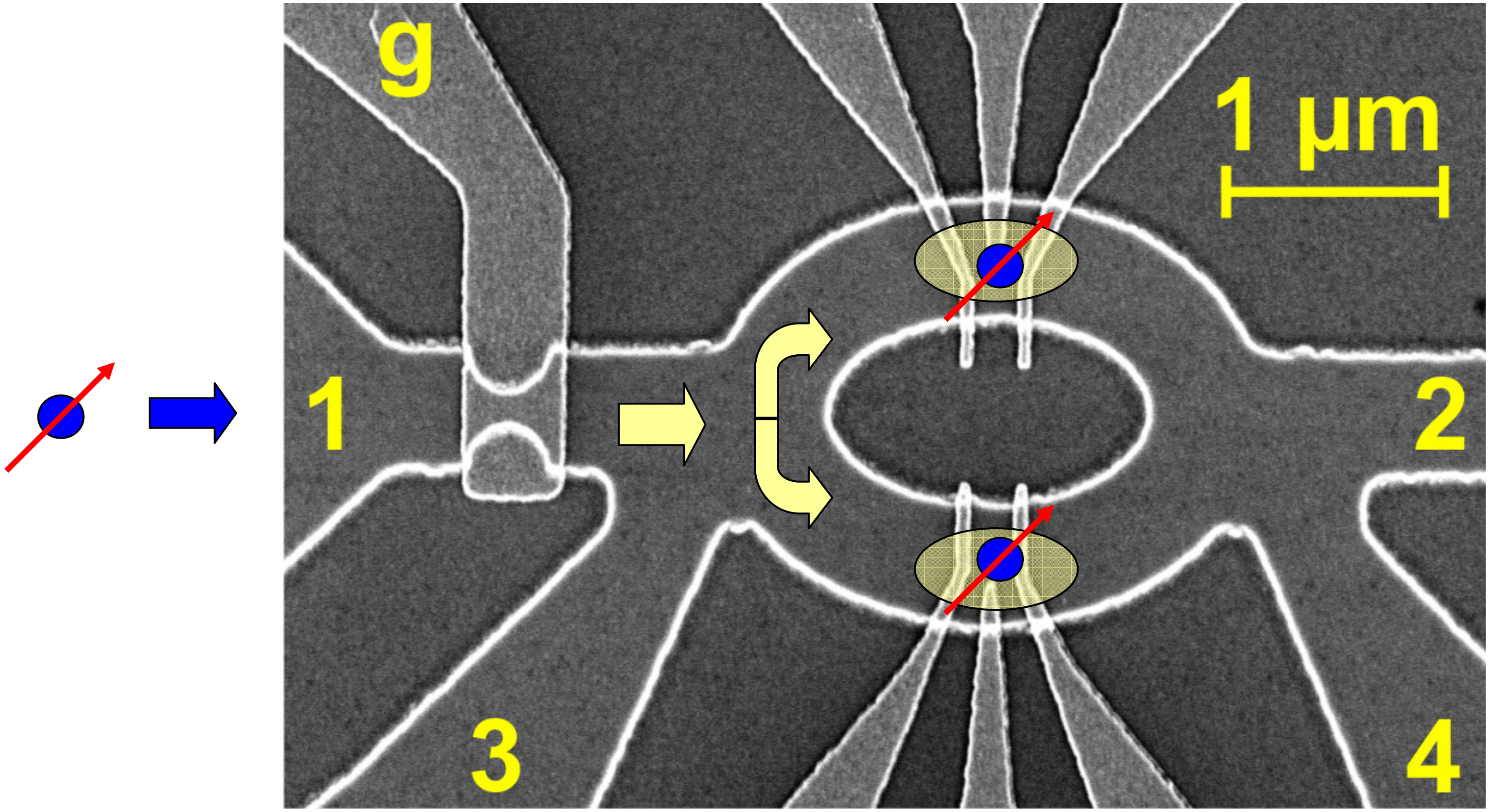
are possibly interesting for spin caloritronic

- o 2D: spin-dependent phonon-drag
- o ballistic transport – Spin-Seebeck (?)
- o many body effects , spin effects on coherence
- o spin fluctuations and correlations

Towards spin-dep. coherence meas.

→ Our approach: Quantum-wire interferometer

Quantum point contacts: Electron-mode filter
Quantum-wire ring : phase-senitive interferometer
Quantum dots : tunable spin traps



Getting there…

Spin-dependent coherence properties

Aharonov-Bohm interferometer + single-level quantum dot:

If no spin flip occurs → interference of both paths, which gives rise to a flux-dependent current.
Visibility : contains information about the degree of coherence.

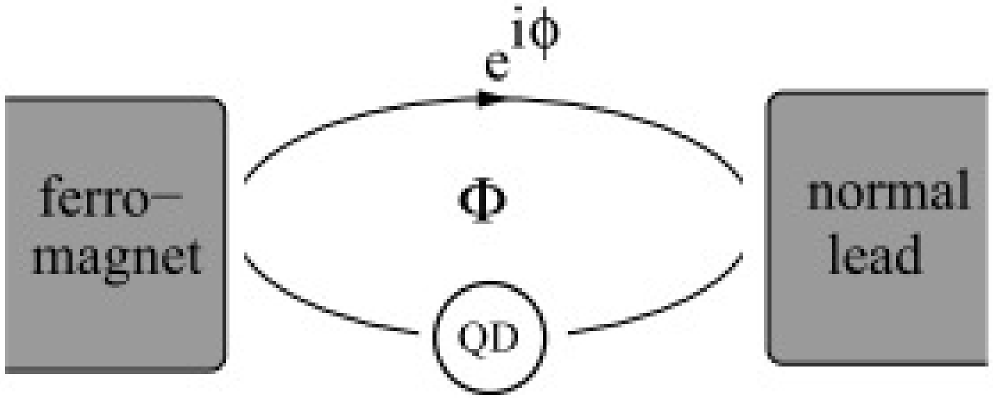


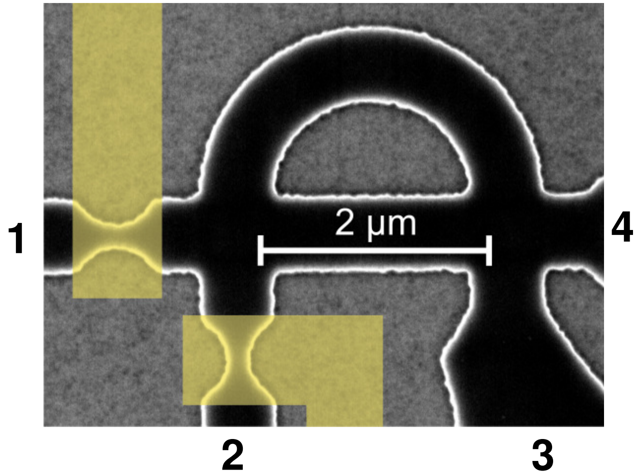
FIG. 1: Setup of single-dot Aharonov-Bohm interferometer with one spin-polarized lead.

In the case of an infinite intra-dot Coulomb repulsion the coherence as well as the visibility of the current are strongly influenced by the spin polarization and the transport direction (FM → NM vs.NM → FM).

B. Hiltscher, M. Governale, J. König, PRB (2010).

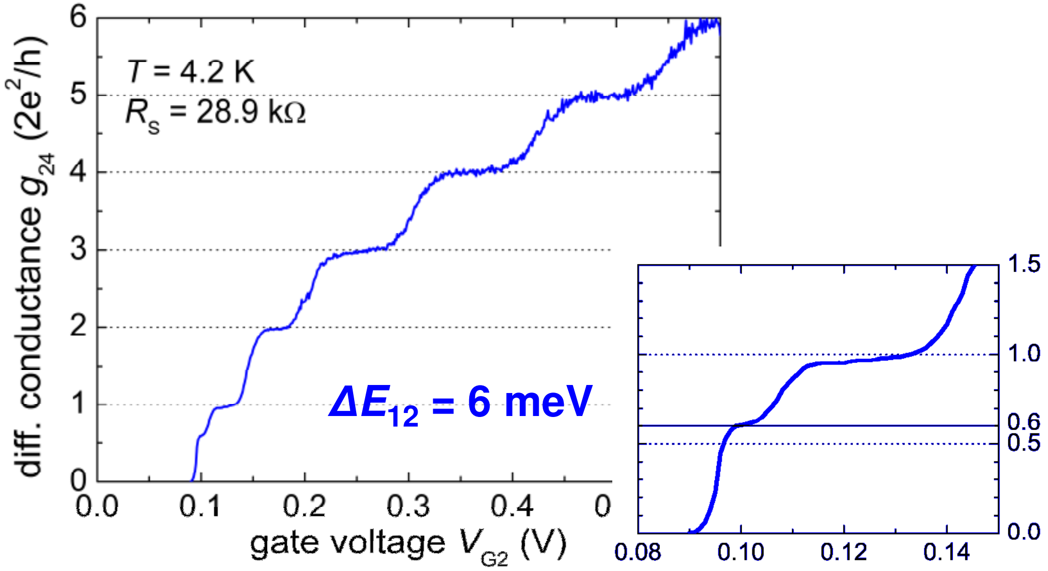
Quantum-wire interferometer with mode filter

Quantum point contact

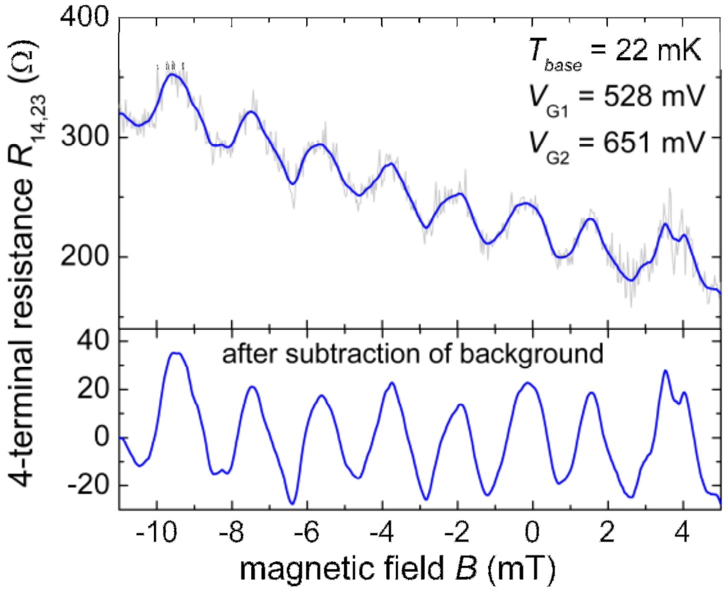


Quantum ring

Quantized conductance



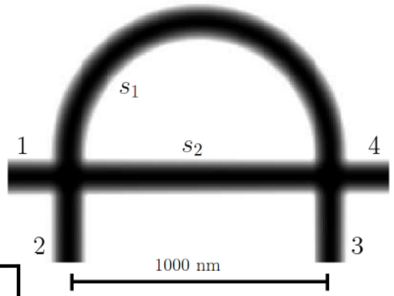
Quantum interference



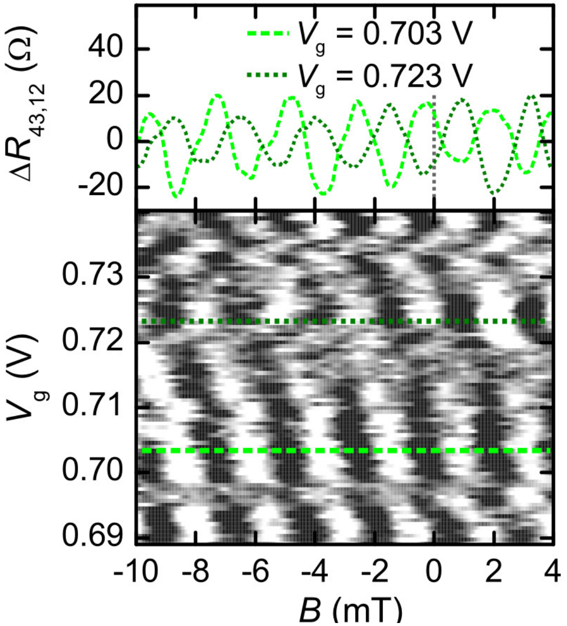
Phase evolution

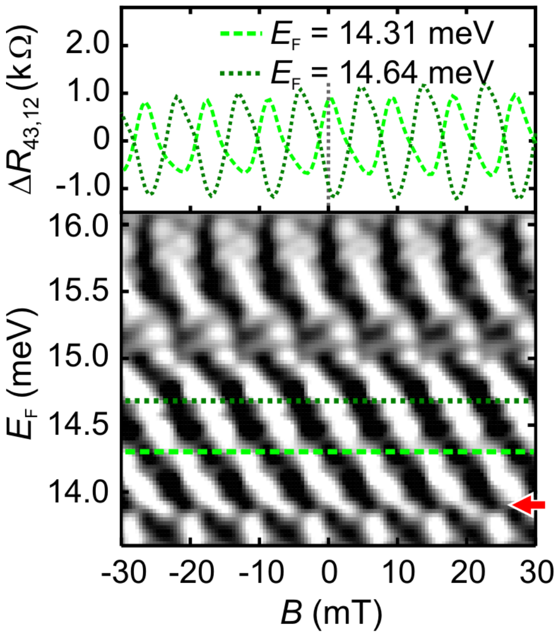
Experiment:

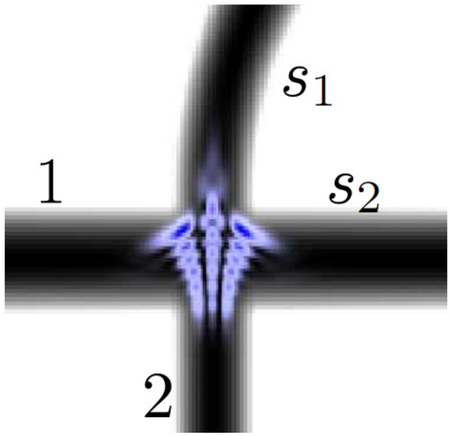
Simulation:



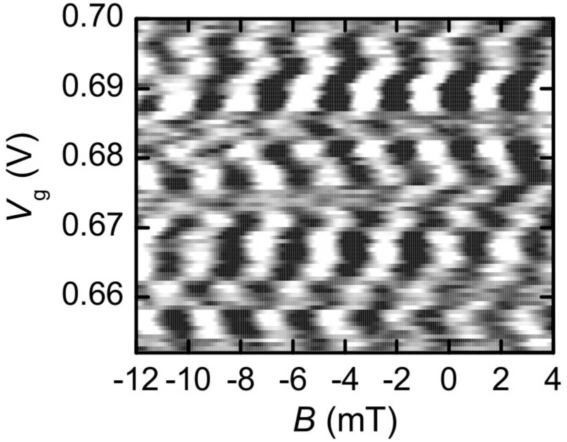
Non-local

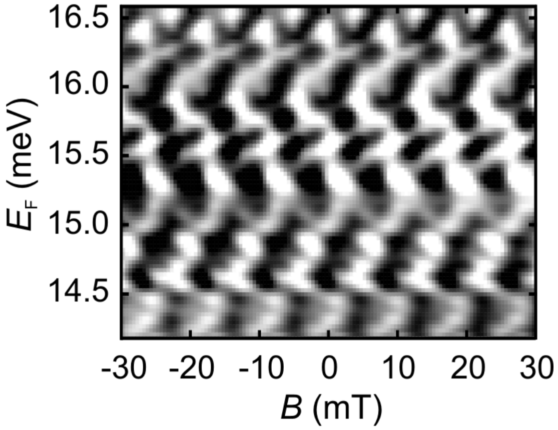






Local





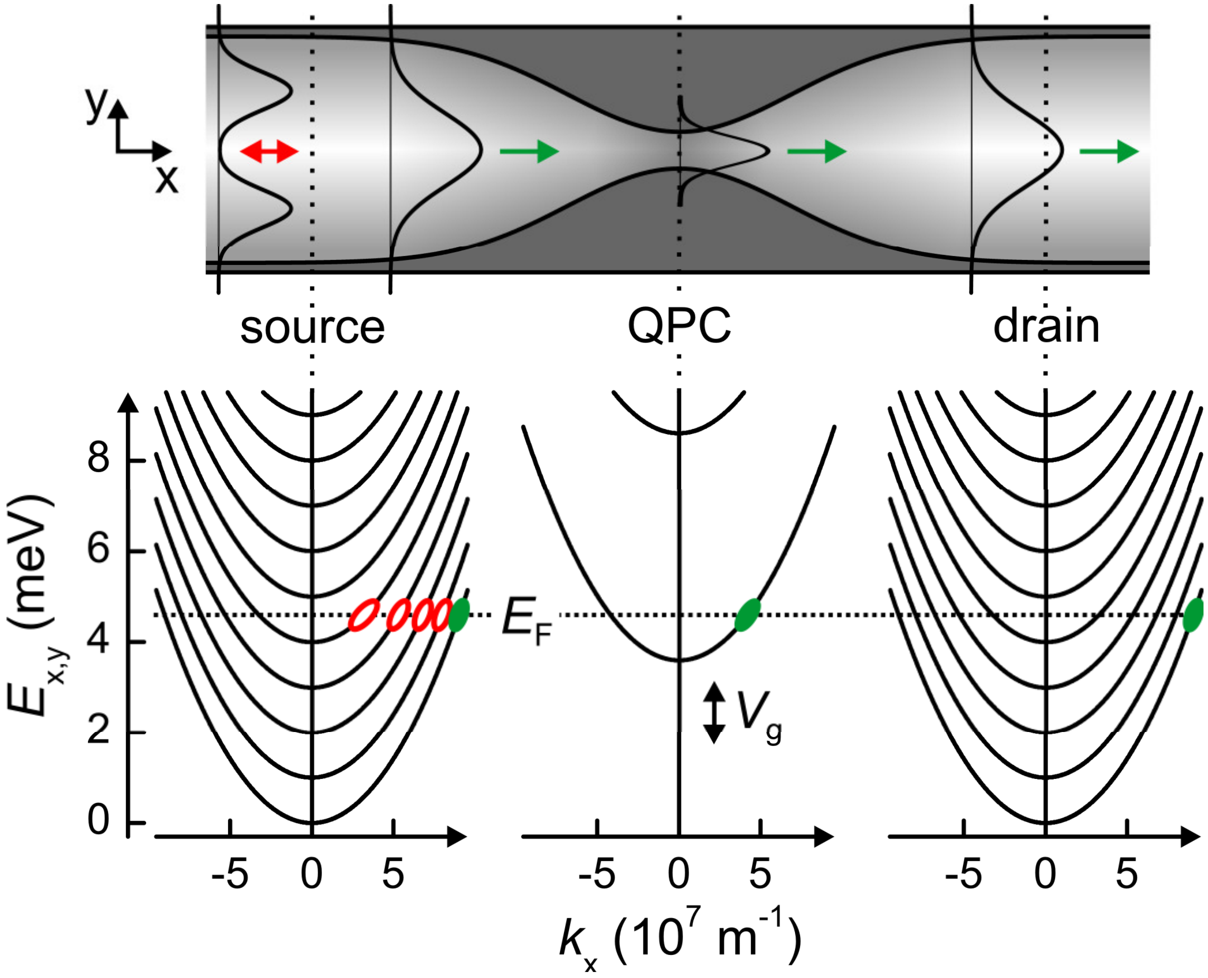
Tobias Kramer,
Uni Regensburg

S.S. Buchholz *et al.*,
PRB **82**, 045432 (2010)

C. Kreisbeck, *et al.*,
PRB **82**, 165329 (2010)

Injection of mode-filtered electrons

QPC: Energy and momentum selection



Adiabatic constriction

Dispersion relation

→ **Selective**

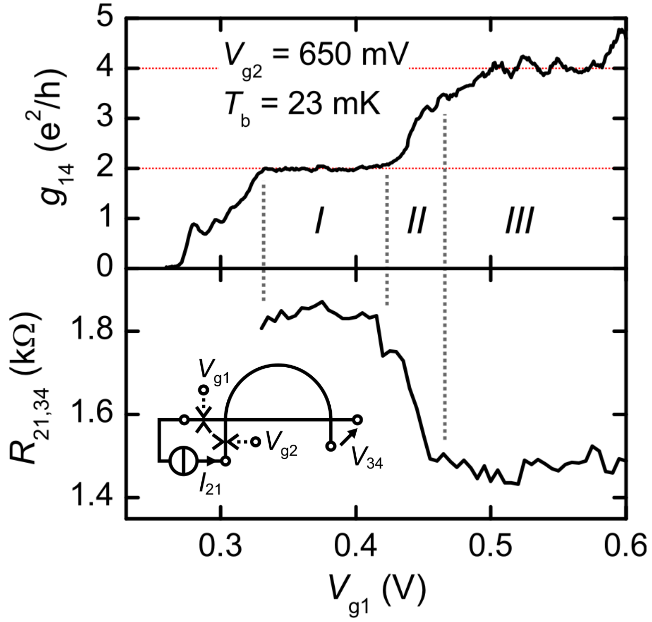
Mode coupling

S.S. Buchholz *et al.*,
APL **98**, 102111 (2011)

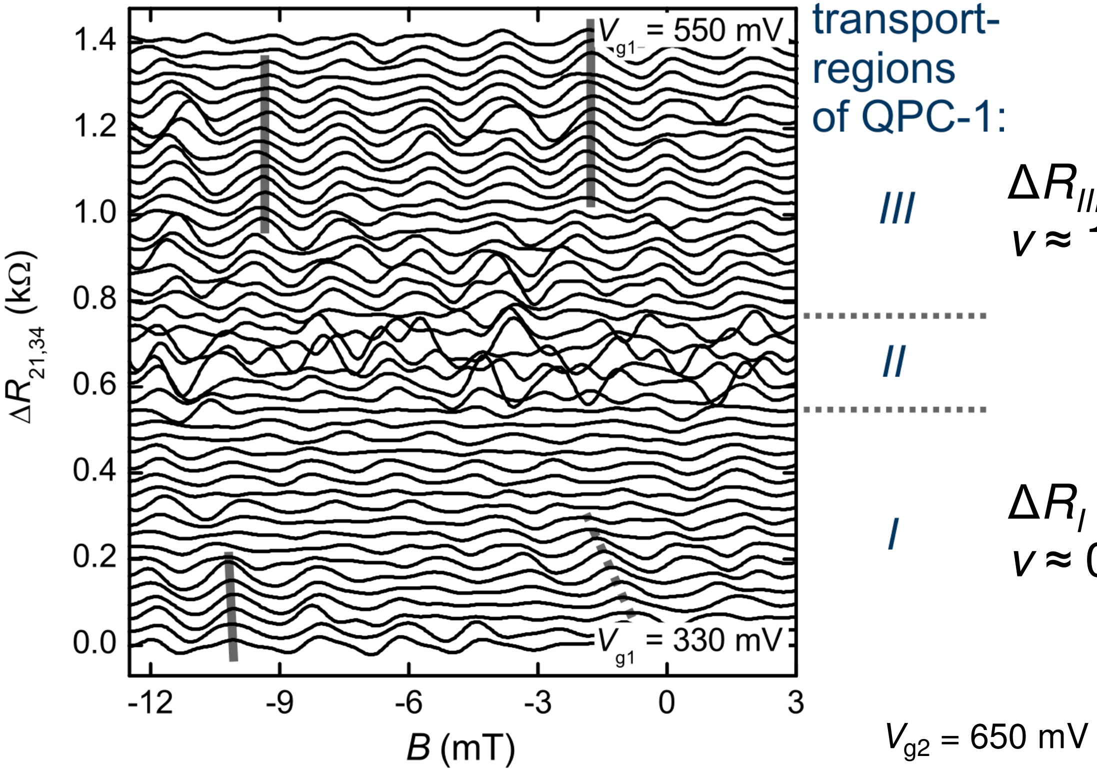
$$(n-\frac{1}{2})\hbar\omega_{t,\mathrm{EWG}}+\frac{\hbar^2k^2_{\ell,\mathrm{EWG}}}{2m^*}=E_0+(n-\frac{1}{2})\hbar\omega_{t,\mathrm{QPC}}+\frac{\hbar^2k^2_{\ell,\mathrm{QPC}}}{2m^*}$$

Single-mode quantum interference

Quantized conductance



Aharonov-Bohm resistance oscillations



transport-regions of QPC-1:

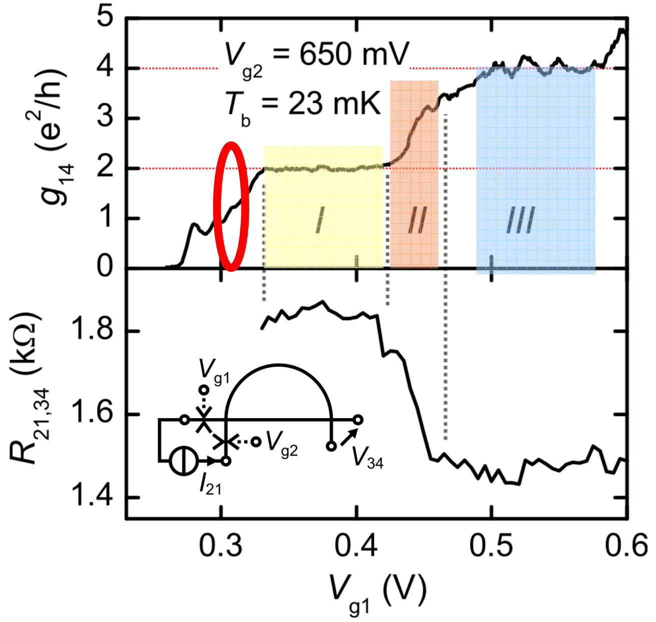
$\Delta R_{III} \approx 48\ \Omega$
$v \approx 1.6\ \%$

$\Delta R_{I} \approx 30\ \Omega$
$v \approx 0.8\ \%$

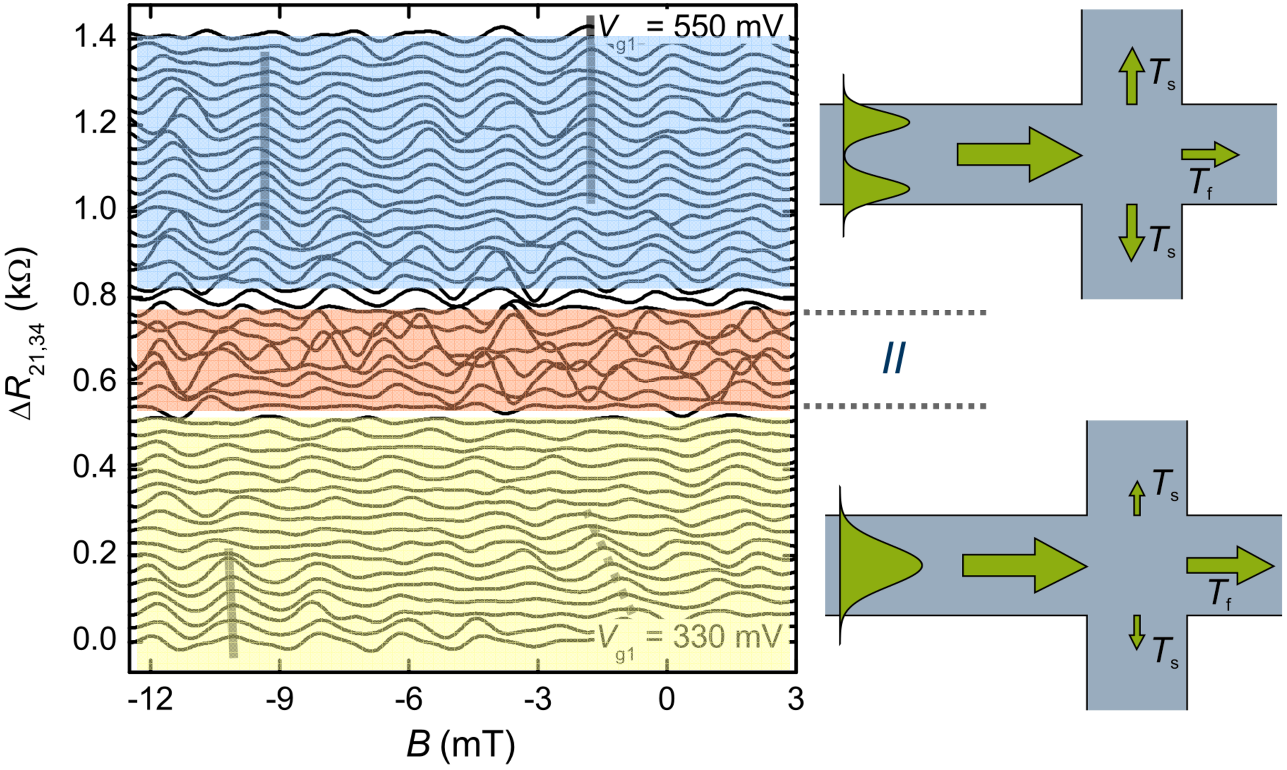
S.S. Buchholz *et al.*,
APL **98**, 102111 (2011)

Single-mode quantum interference

Quantized Conductance



Aharonov-Bohm resistance oscillations



S.S. Buchholz *et al.*,
APL **98**, 102111 (2011)

Our recent experiments…

+ noise measurements: determination of electron temperature (thermal noise)

+ establish temperature gradient across interferometer (current induced heating, non-local setup)

+ decoherence due to non-local heating (determination of AB-amplitude, visibility)

Details in the discussion…