Evidence for Helical Nuclear Spin Order in GaAs Quantum Wires

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Concepts in Spintronics, KITP UC Santa Barbara, 3.10.2013

Fully tunable Spin-Orbit Hamiltonian governing coherent corrections to conductivity

Acknowledgements

quantum wires

experiments
C. Scheller, T.-M. Liu,
Basel

CEO wires growth
L. Pfeiffer, K. West
Bell Labs & Princeton

samples, discussions
G. Barak, A. Yacoby
Harvard University

CBT thermometers
M. Meschke, J. Pekola
Aalto University, Helsinki

theory
B. Braunecker, UA Madrid/St. Andrews
D. Loss, Basel
P. Simon, U Paris Sud

Scheller, Liu, Barak, Yacoby, Pfeiffer, West, and Zumbühl, arXiv1306:1940

Conductance quantization in 1D

GaAs Quantum point contacts (Quantum Hall effect)

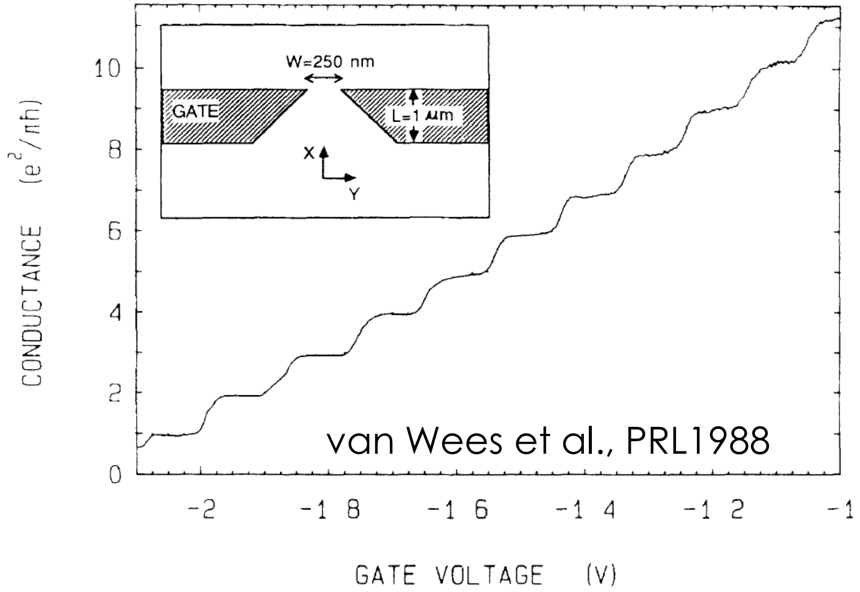
exact cancellation
1D density of states
electron velocity
vs. electron number

ballistic (no disorder)
non-interacting

2-terminal
conductance

$$g = \underbrace{N}_{\text{number of modes}} \cdot \underbrace{2}_{\text{spin degeneracy}} \cdot \frac{e^2}{h}$$

Landauer quantization



van Wees et al., PRL1988

Wharam et al., JPC1988

Interacting 1D electrons, Luttinger liquids

infinite Luttinger liquid: $g = N K 2e^2/h$
(Luttinger interaction parameter $K \leq 1$)

Apel & Rice, PRB 1982
Kane & Fisher, PRL, PRB 1992

clean, finite wire
Fermi liquid (non-interacting) leads
unaffected by interactions
$g = N 2e^2/h$

Maslov & Stone, PRB 1995
Safi & Schulz, PRB 1995
Ponomarenko, PRB 1995
Oreg & Finkel'stein, PRB 1996

2 terminal g: contact resistance, outside wire

Picciotto et al., Nature 2001

disorder: reduced g
power-law due to wire e-e only
(weak scattering inside wire with LL features)

Ogata & Fukuyama PRL 1994
Tarucha et al., SSC 1994
Maslov, PRB 1995

finite conductance ~ 1/L at T = 0

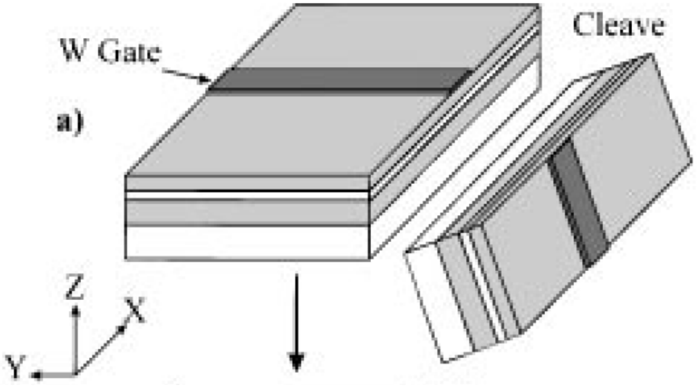
Luttinger liquid?

GaAs Cleaved Edge Overgrowth Quantum Wires

ultraclean, ballistic, micron long wires
density-tunable with gate
among the best realizations of a Luttinger liquid in nature

Auslaender et al., PRL2000	LL resonant tunneling
Auslaender et al., Science 2002	**charge mode velocity (faster)**
Tserkovnyak et al., PRL 2002	finite size effects
Tserkovnyak et al., PRB 2003	interference, zero bias anomaly
Auslaender et al., Science 2005	**spin-charge separation**, localization
Steinberg et al., PRB 2006	localization
Steinberg et al., NP 2008	**charge fractionalization**
Barak et al., NP 2010	beyond LL

GaAs Cleaved Edge Overgrowth (CEO) Quantum Wires



a) AlGaAs/GaAs quantum well
Si doping above well
2D electron gas (2DEG)
500 nm deep
n ~ 2 10^{11} cm^{-2}, $\mu > 10^6$ $cm^2/(Vs)$
tungsten surface gate
cleave in UHV

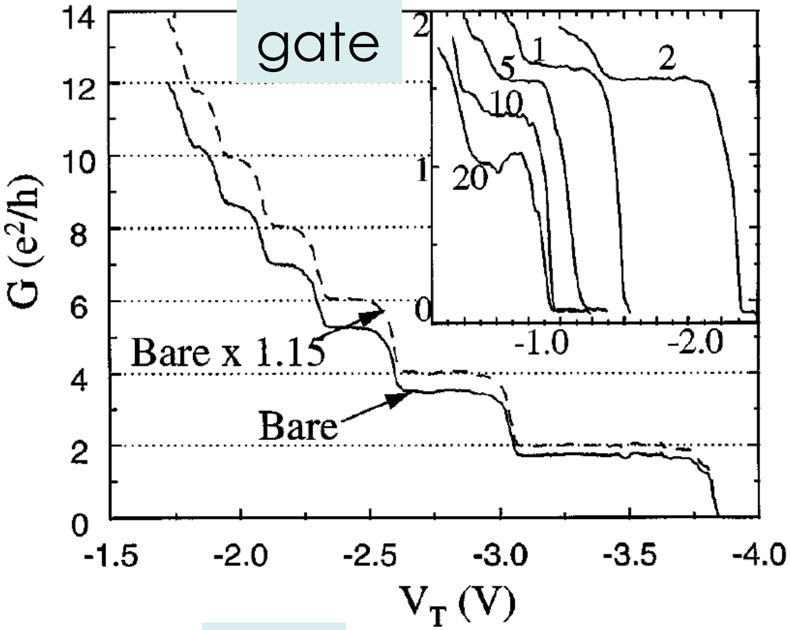
b) overgrow cleavage plane with
modulation doping sequence
gives charges at edge
few modes
strong overlap 2DEG to edge
intimate 2D-1D coupling

c) use gate to deplete 2DEG below
control edge density & # modes

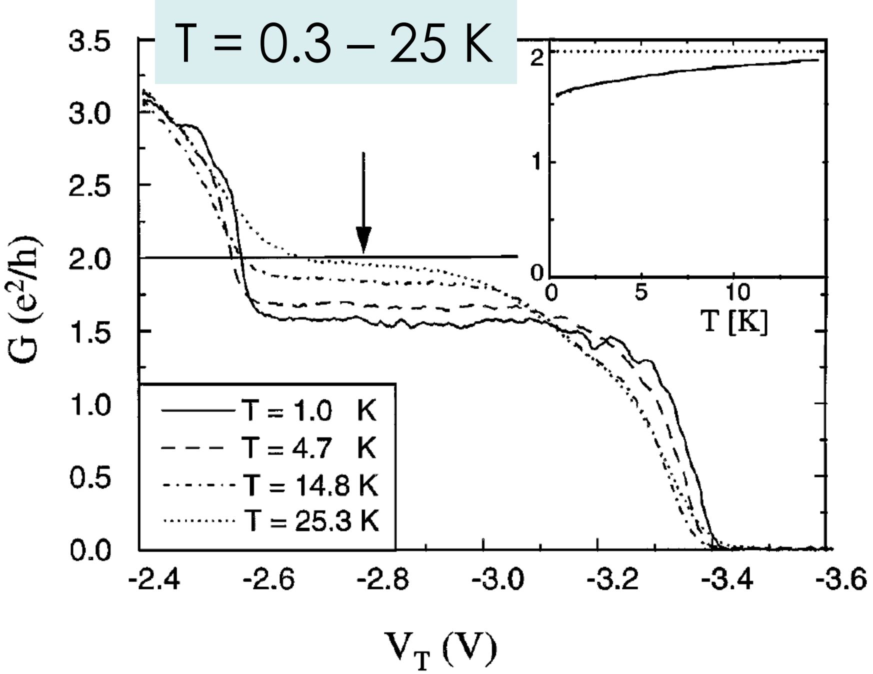
Pfeiffer et al., JCG 1993
Yacoby et al., SSC 1996
Yacoby et al., PRL 1996

Non-Universal Conductance Quantization

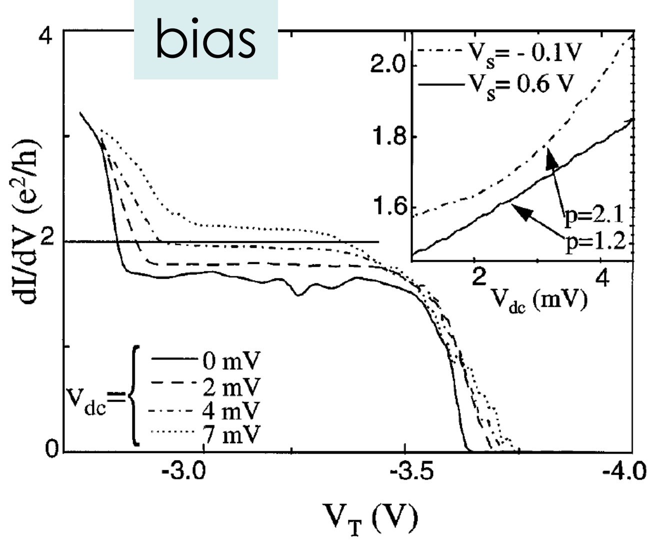
A. Yacoby, L. Pfeiffer et al., PRL 1996



gate



T = 0.3 – 25 K



bias

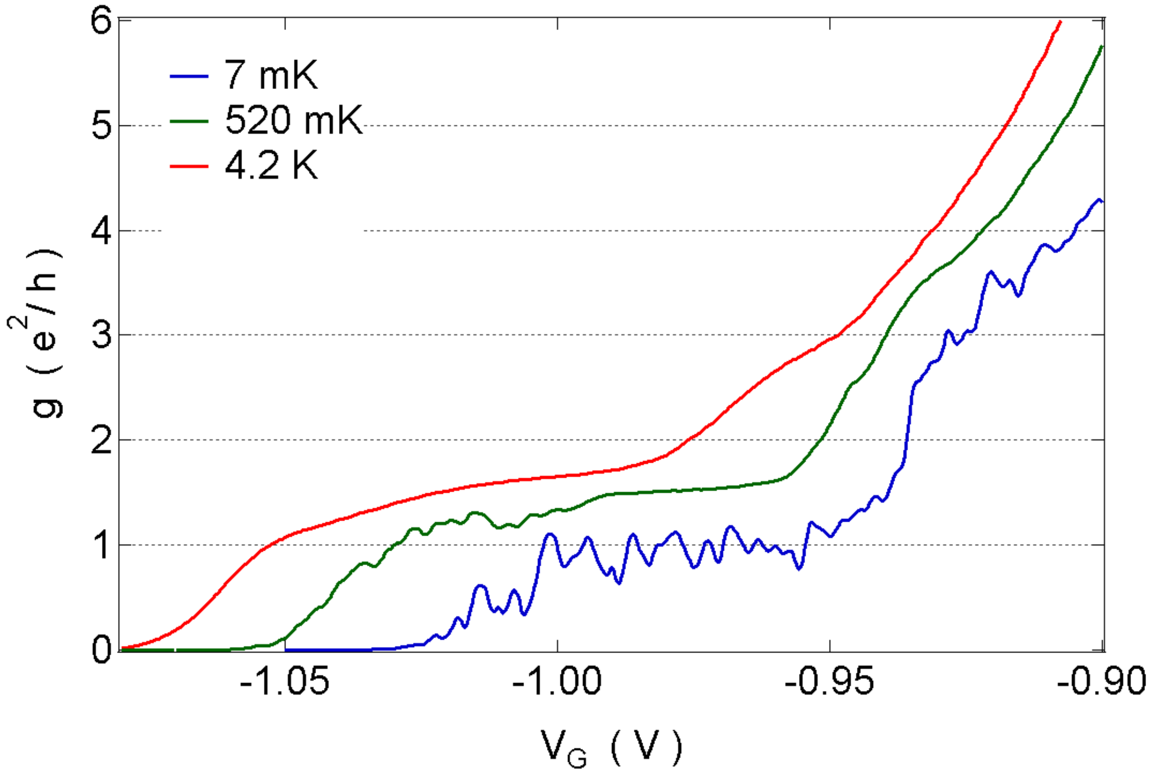
cleaved edge overgrowth GaAs wires
ballistic wires
$g<2\ e^2/h$ per mode, flat plateaus
$g=2$ at high T and high bias

Picciotto, Yacoby et al., PRL2000

unresolved mystery

T > 0.3 K

Single wire



Same qualitative behavior (reduced quantization)
NEW: $\delta g \sim 1\ e^2/h$ at low T, towads 2 e^2/h at high T

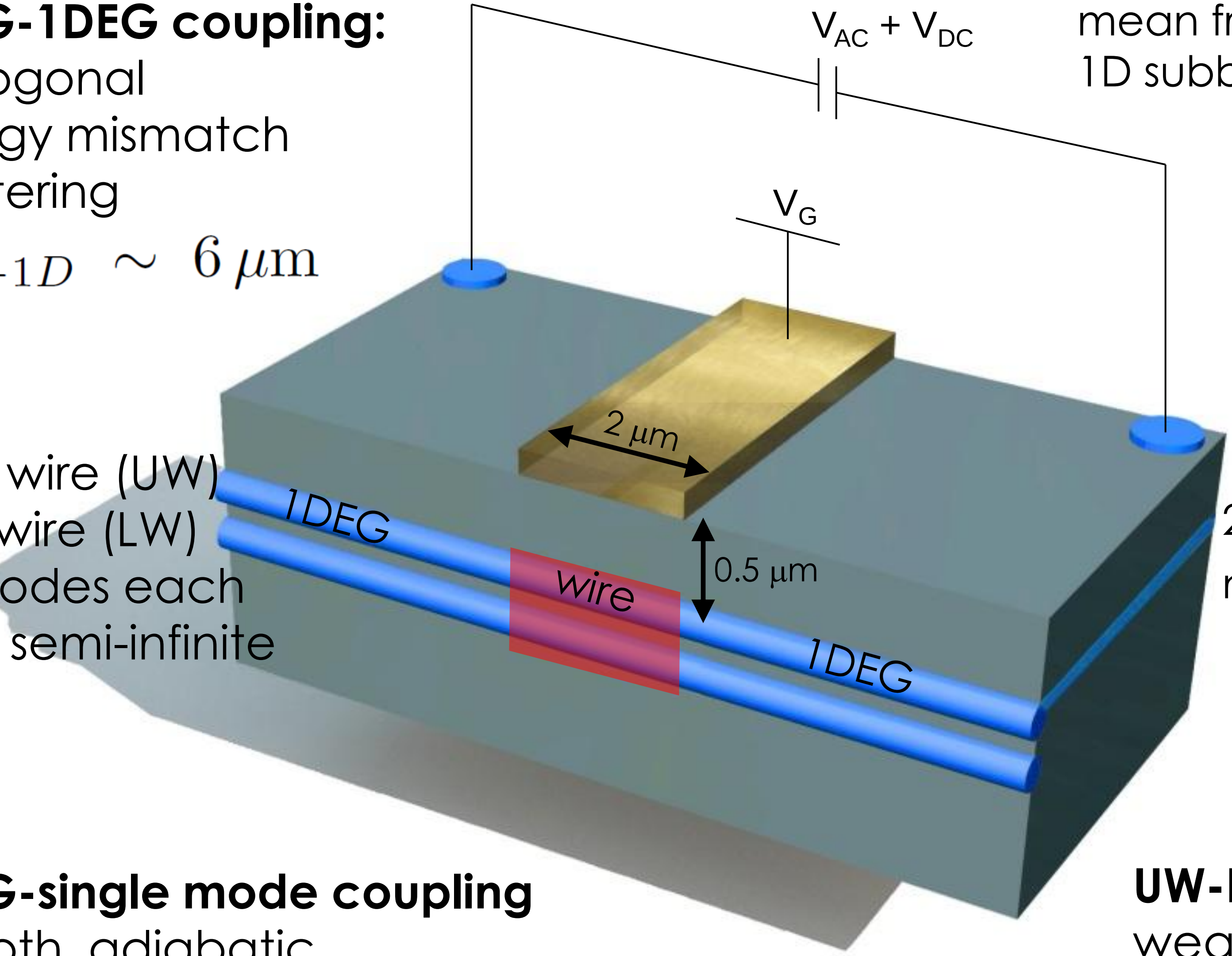
weak, short conductance plateaus, hard to work with

other samples are not available, new samples very difficult to make

Double wire samples

2DEG-1DEG coupling:
orthogonal
energy mismatch
scattering
$\ell_{2D-1D} \sim 6\,\mu\text{m}$

mean free path 20 µm
1D subbands 15 meV



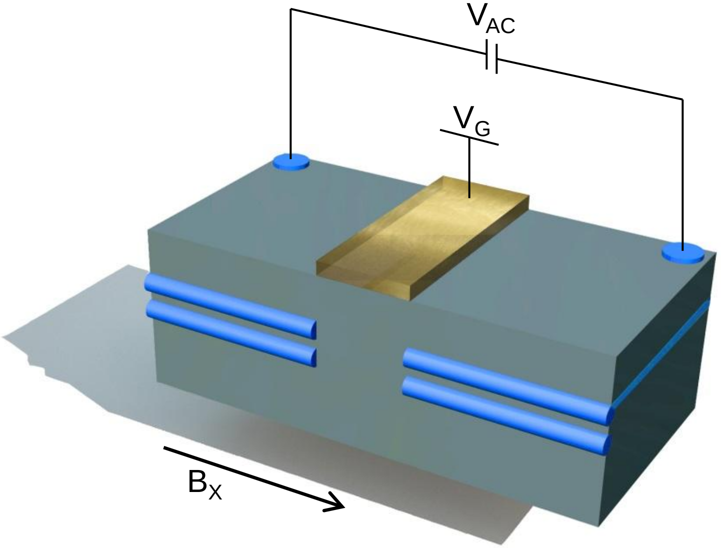
upper wire (UW)
lower wire (LW)
few modes each
1DEG, semi-infinite

2DEG
no lower 2DEG

1DEG-single mode coupling
smooth, adiabatic
$\lambda_F < 200$ nm

UW-LW coupling
weak tunneling
$g \sim 0.03\ e^2/h$
(2 µm segment)

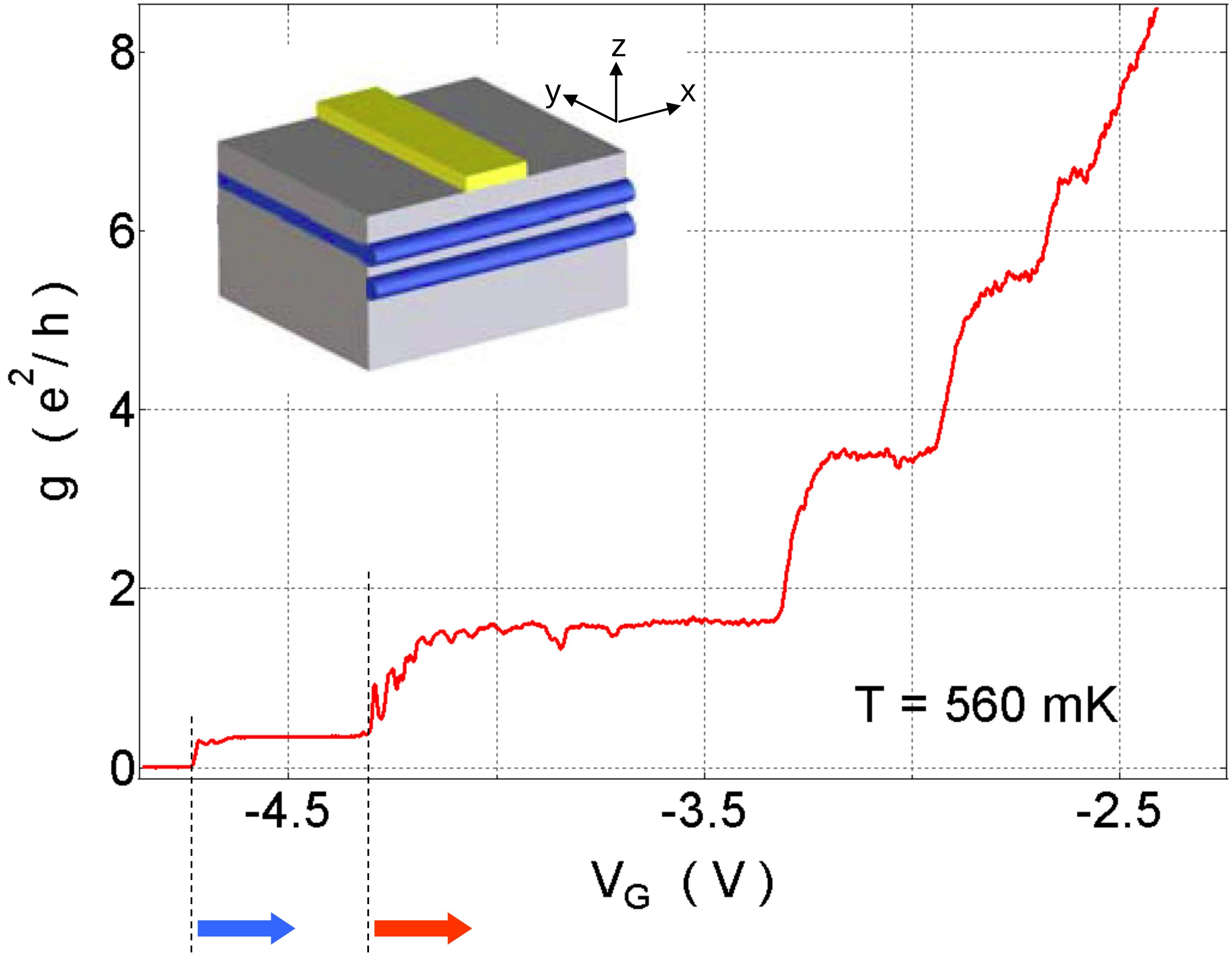
Surface gate: deplete UW, then LW



L. Pfeiffer, K. West (Bell labs / Princeton)
G. Barak, A. Yacoby (Weizmann / Harvard)

- V_G tunes simultaneously UW and LW density
- screening important
- single mode in both UW and LW
  both wires conduct in parallel
  most simple model: $g = g_{UW} + g_{LW}$
  (weak tunneling)

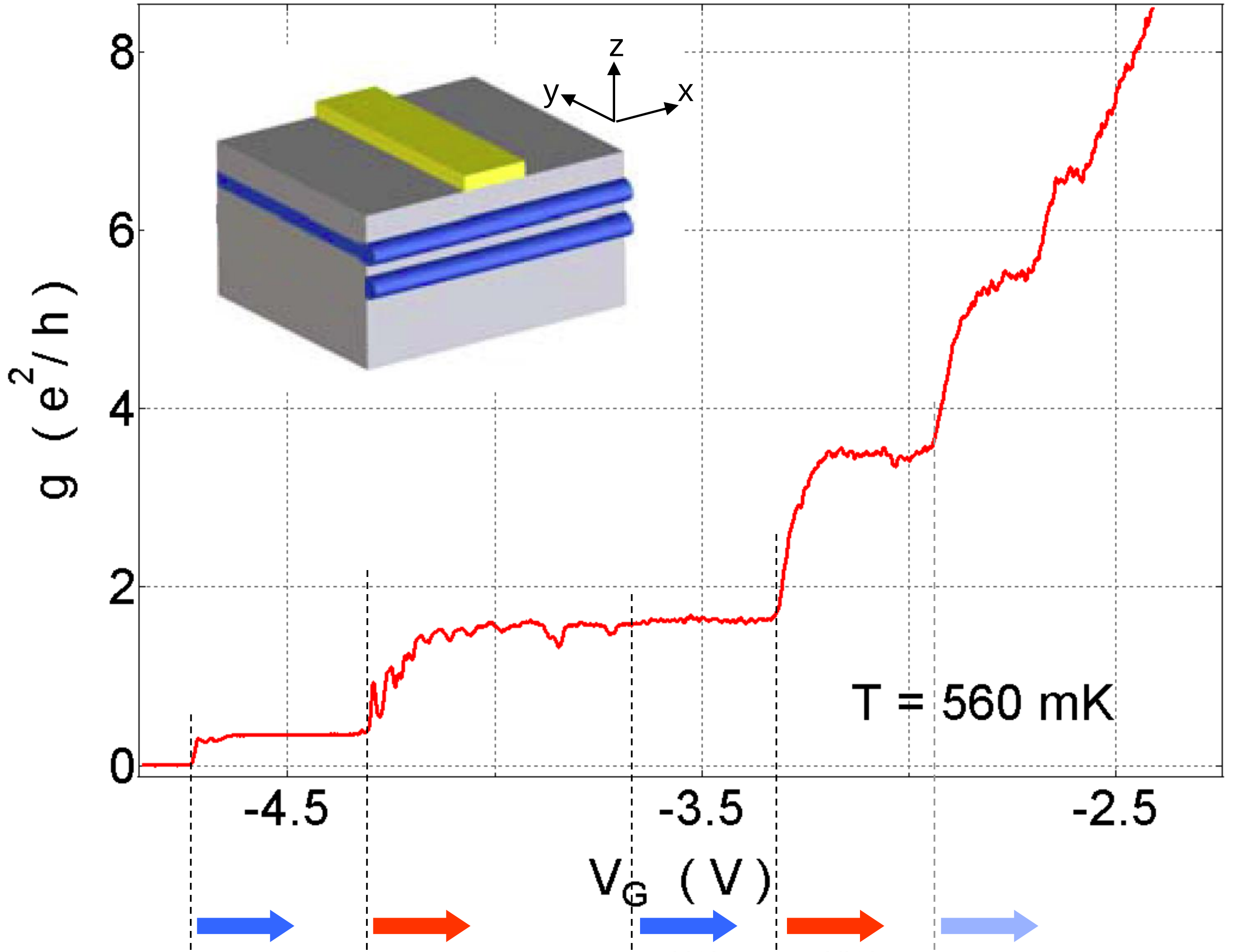
Identify Modes / Wires



LW
mode 1

+ UW
mode 1

Identify Modes / Wires



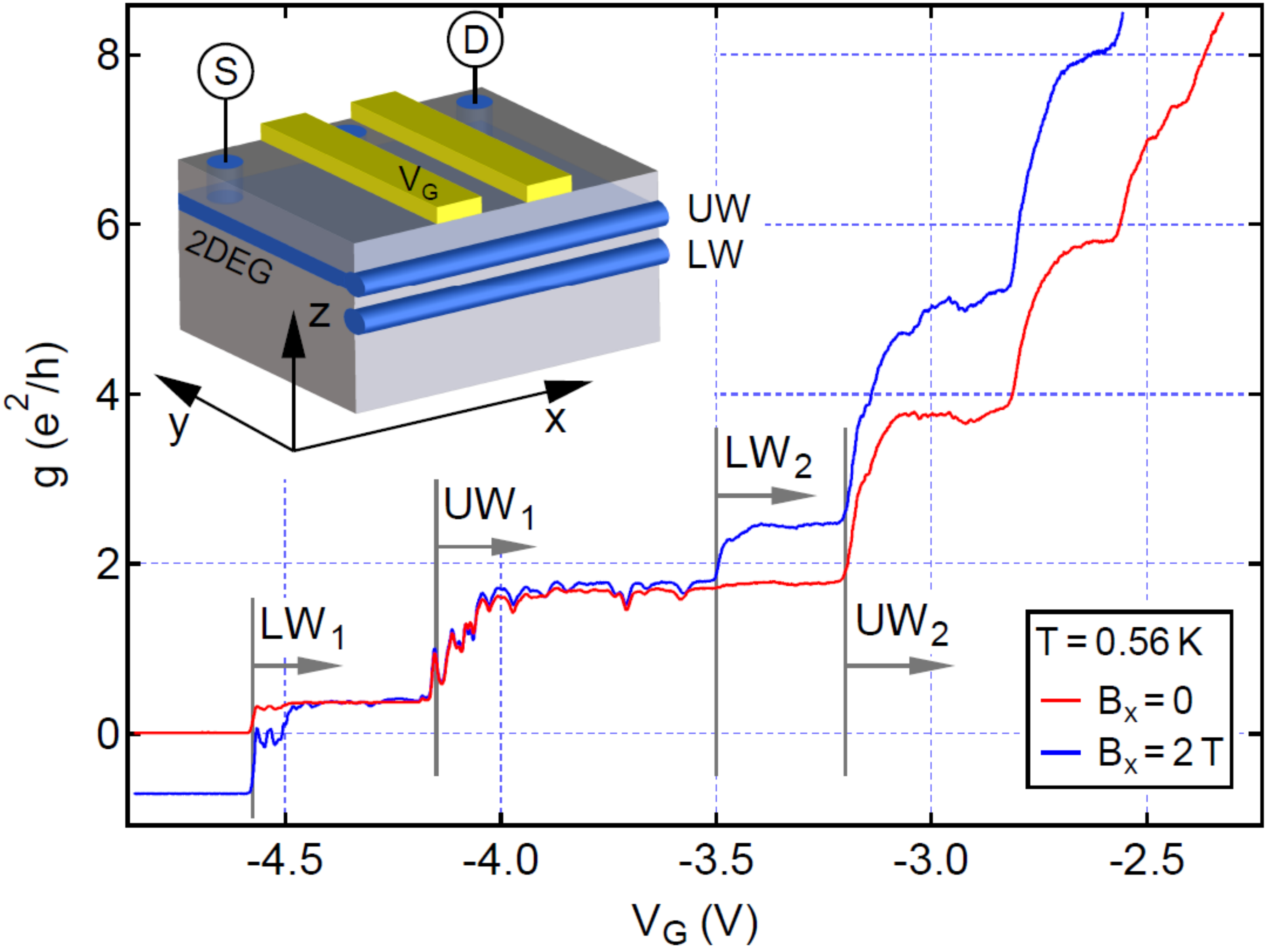
LW
mode 1

+ UW
mode 1

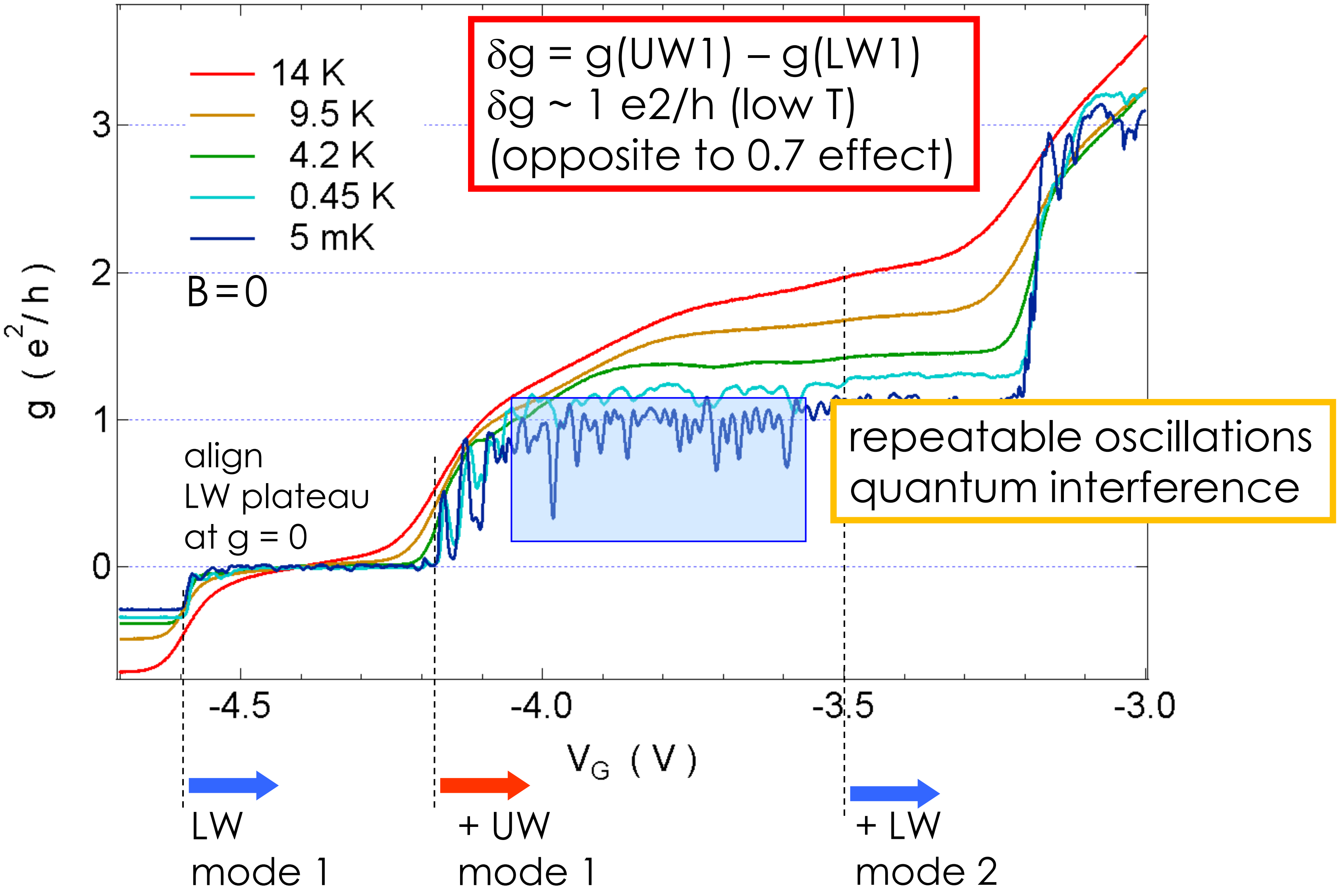
+ LW
mode 2
(weak coupling)

+ UW
mode 2

Identify Modes: B-dependence



Temperature Dependence



δg = g(UW1) – g(LW1)
δg ~ 1 e2/h (low T)
(opposite to 0.7 effect)

repeatable oscillations
quantum interference

align
LW plateau
at g = 0

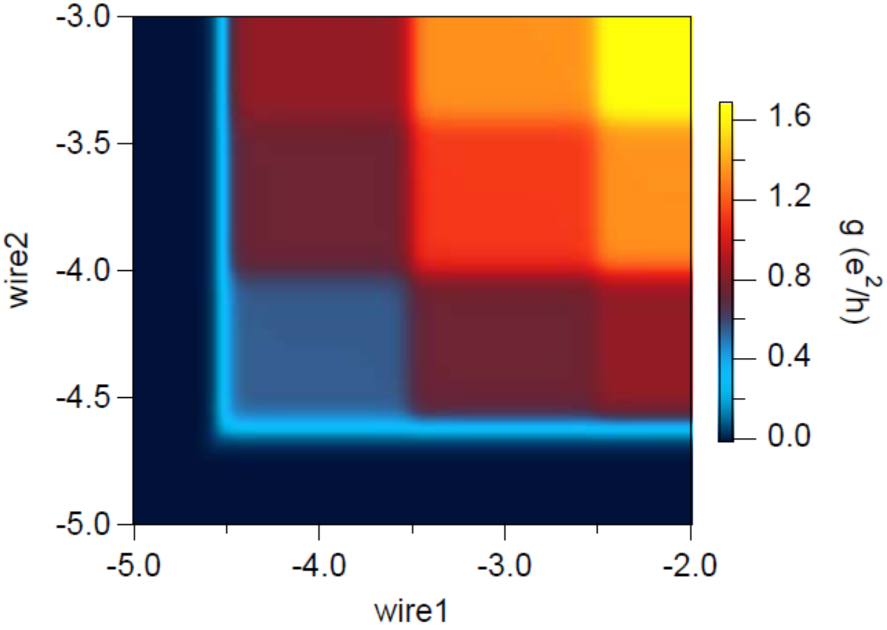
LW
mode 1

+ UW
mode 1

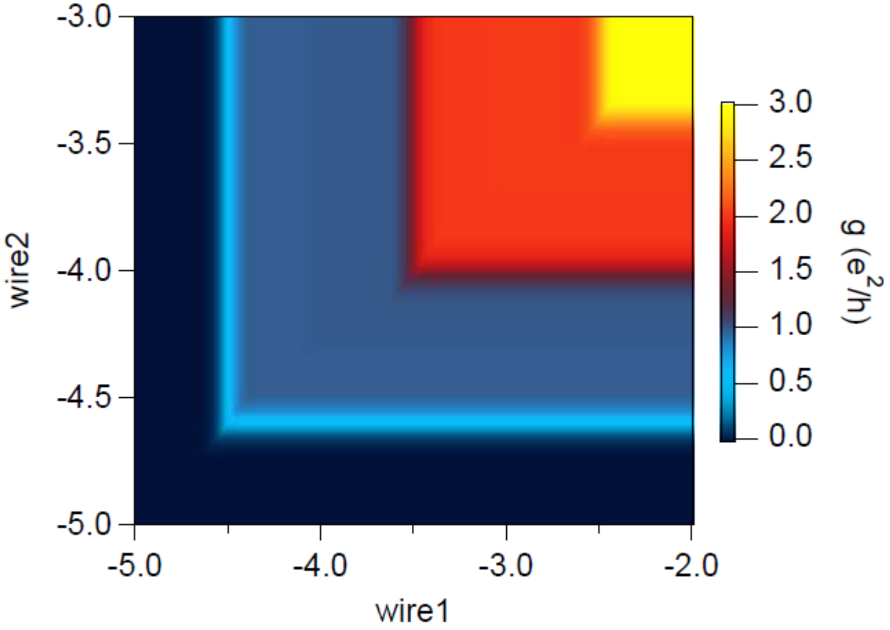
+ LW
mode 2

Adiabatic vs classical resistance addition

- Classical addition of resistances: $R_{tot} = R_1+R_2$ (Ohm’s law)
- Addition of resistances in the ballistic regime: $R_{tot} = \max\{R_1,R_2\}$

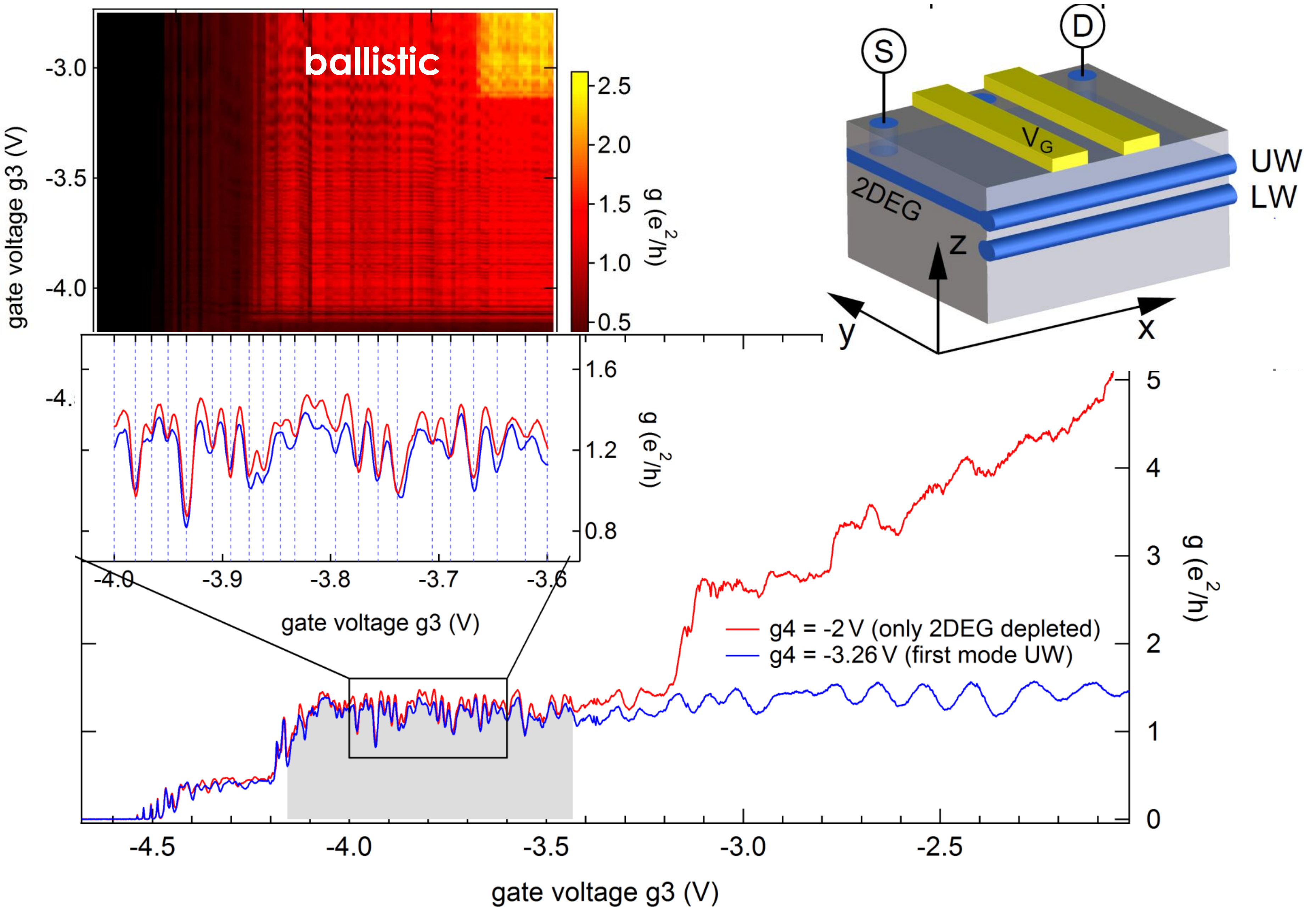


classical addition

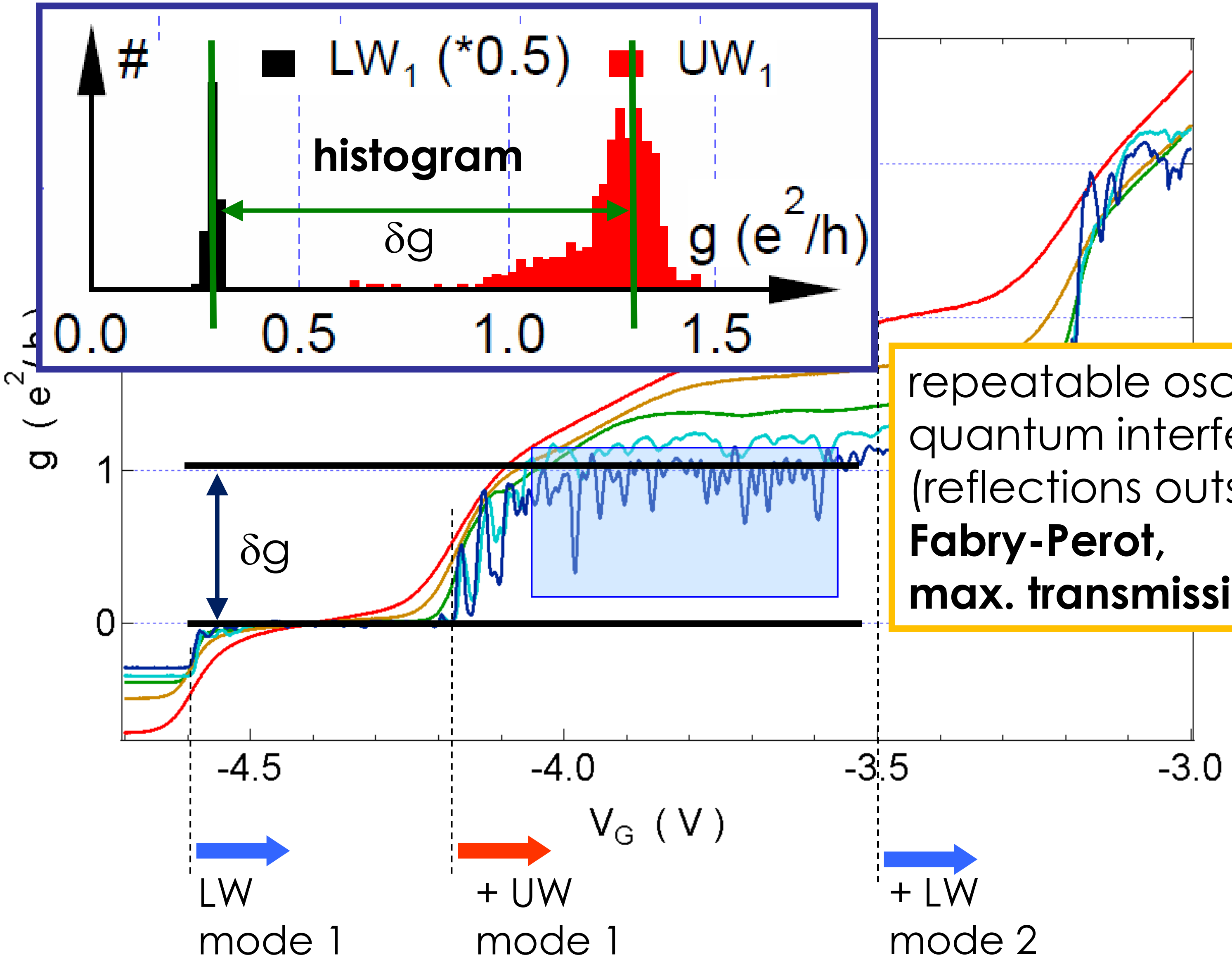


ballistic regime

Use adjacent gates (2 μm gap between)

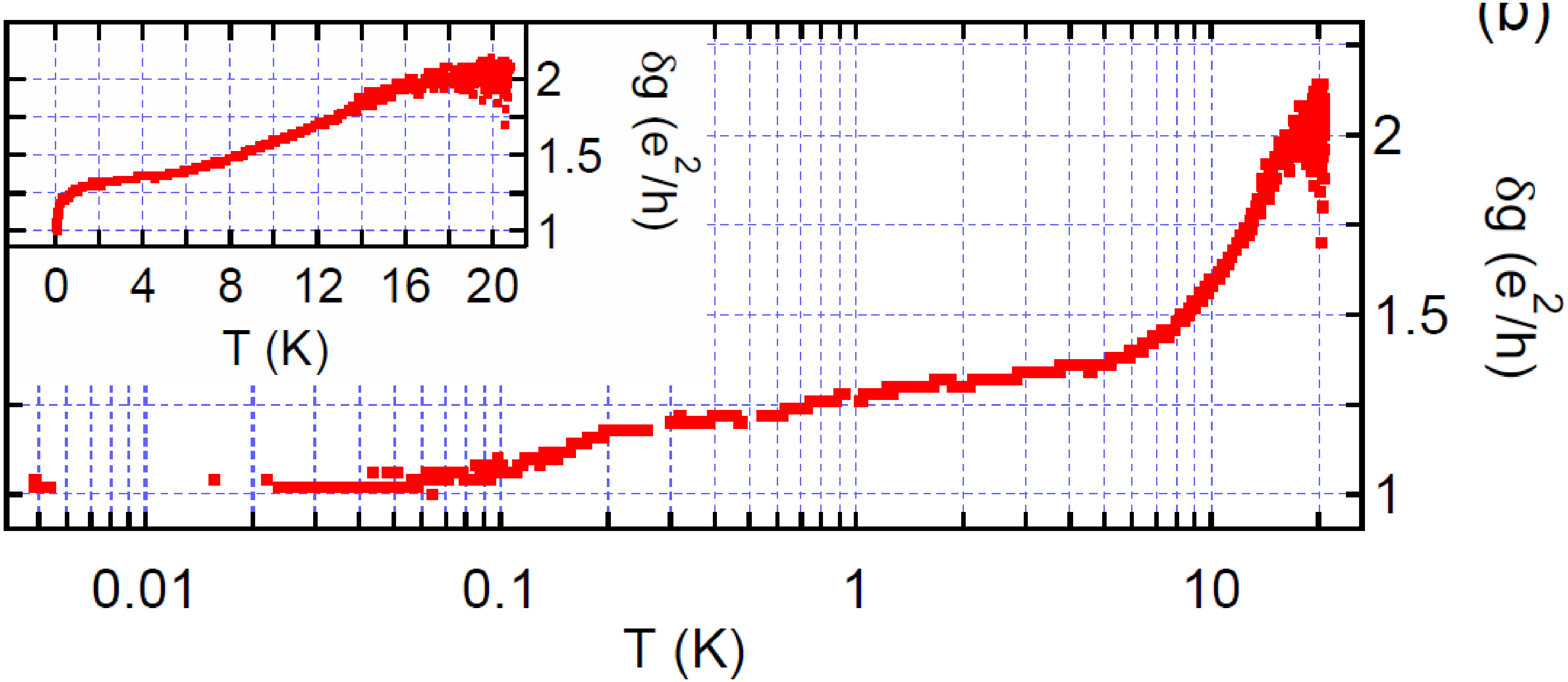


Temperature Dependence



repeatable oscillations
quantum interference
(reflections outside wire)
Fabry-Perot,
max. transmission ~ 1

from 2 to 1 e^2/h



- transition from 2 to 1 e^2/h
  over a very broad range of temperatures
- breaking of electron spin degeneracy:
  reduction of g by factor of 2
- g independent of T below 100 mK

Electron Temperature Measurements

use two independent methods

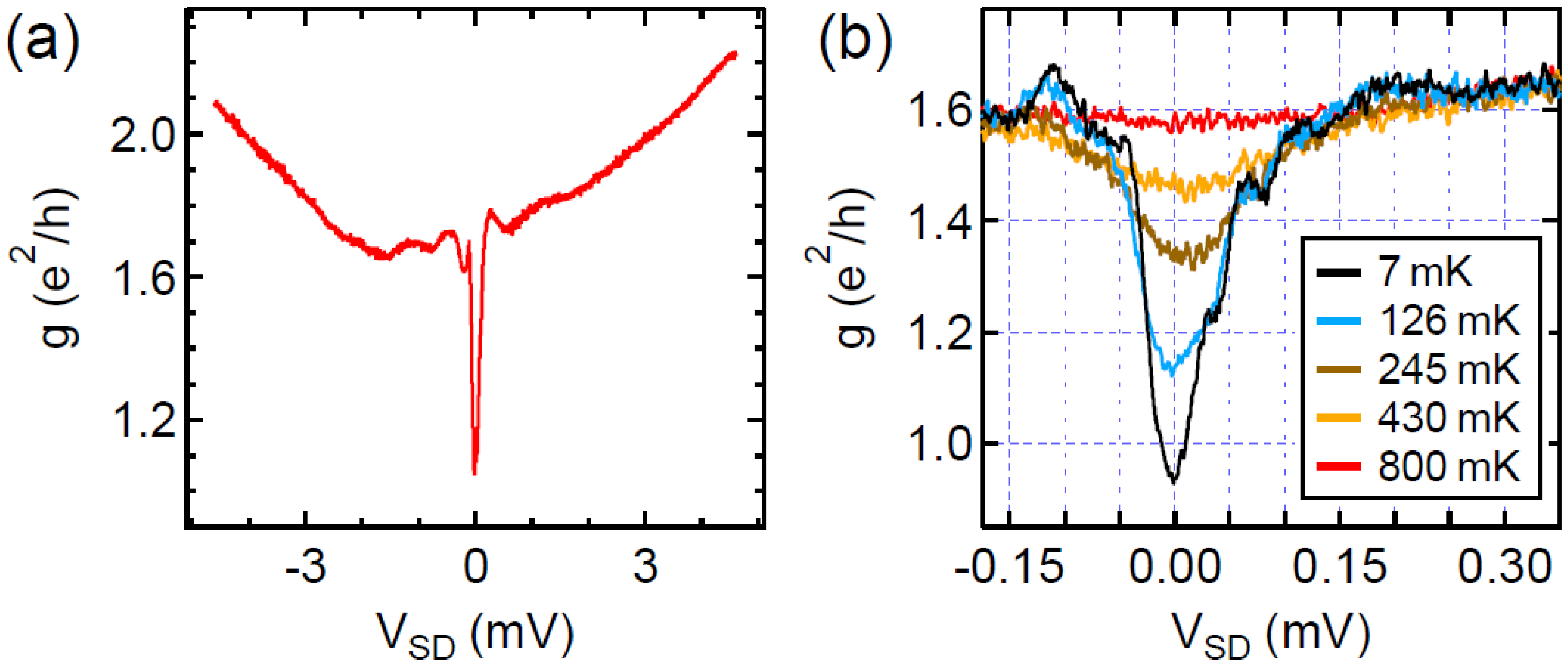
1. on-chip FQHE thermometer: upper bound on T:
   T < 30 mK

2. independent cool down with
   Coulomb blockade thermometers
   (Meschke & Pekola, Aalto Univ., Finland)

   T ~ 10 mK for identical setup, cold finger, chip carrier etc.

both of these independent measurements give temperatures much smaller than 100 mK

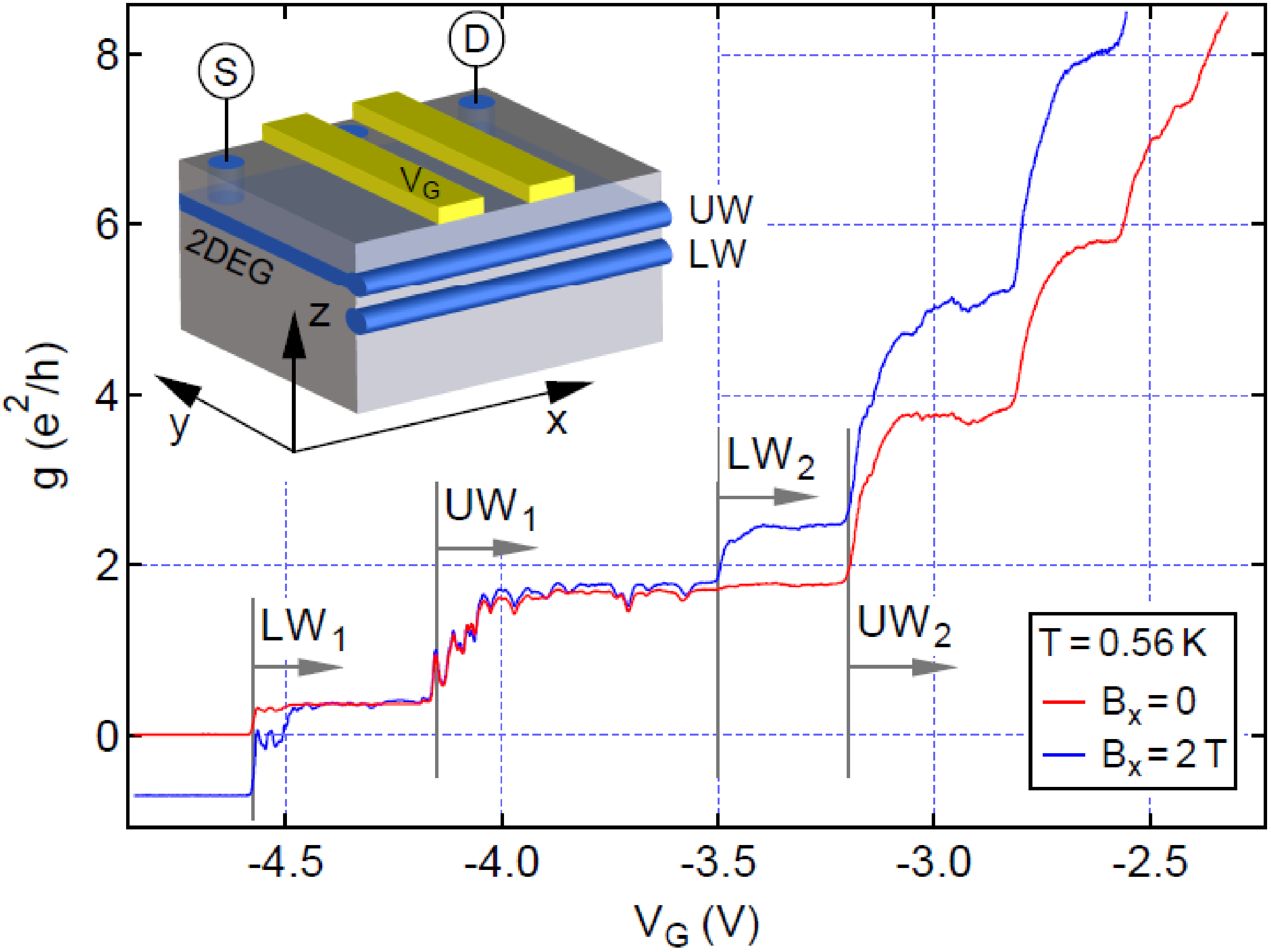
Source-drain bias: zero bias dip



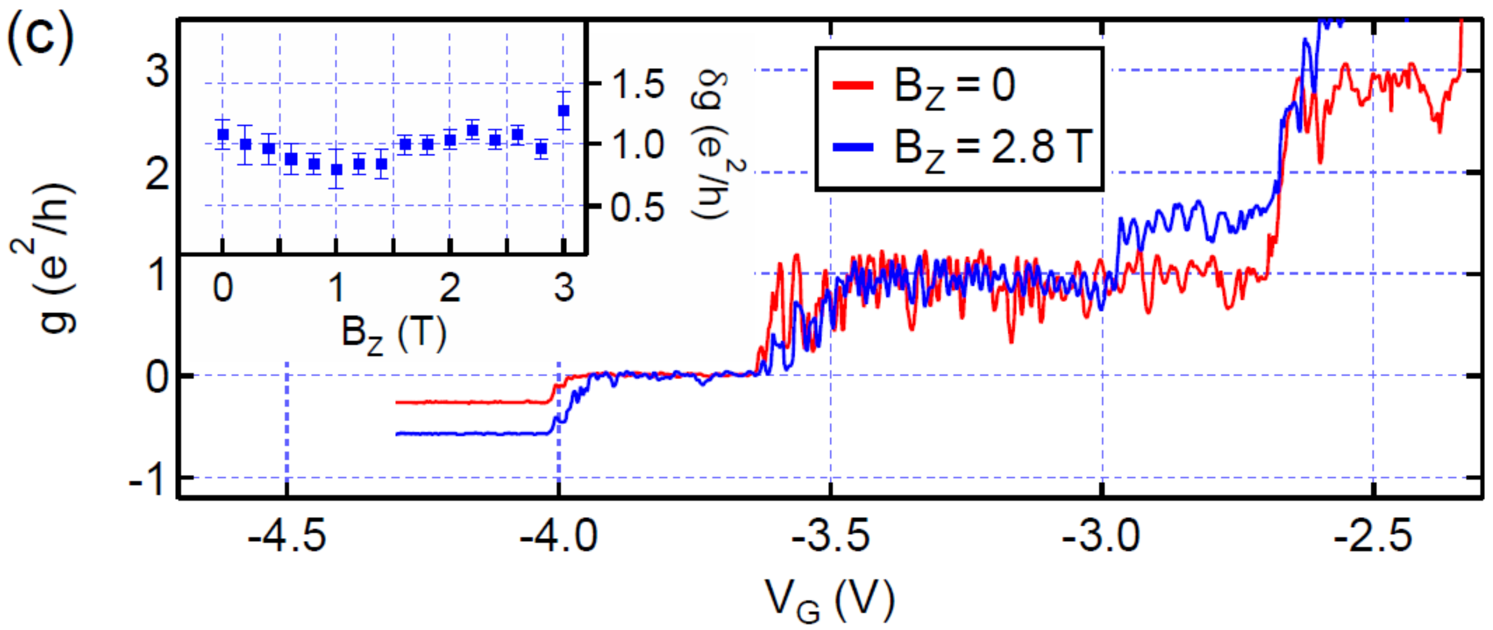
- bias and temperature data: very similar
- bias drops across contacts, causing heating (not across ballistic wire)

Scheller et al., arXiv:1306.1940

B-field independence



B-field independence



- at B_Z=3 T: ν=3 and Zeeman splitting E_Z >> kT
- Landau level spin splitting resolved for B_Z > 0.3 T

Summary

- δg: from 2 to 1 e2/h
  (T from 20 K to 0.1 K) at B = 0
- δg T independent below 0.1 K
  (device cools to much lower T)
- zero bias dip (similar to T)
- B field independence, several wires (double and single)
  (no Zeeman splitting apparent)
- δg reduction by factor of 2 suggests lifting of spin degeneracy

Possible Explanations?

- **Noninteracting electrons** (wire + leads) => $g = NT{*}2e^2/h$

  Transmission $T < 1$, in contradiction to ballistic wires ↯

  (energy and T dependence)

- **Infinite Luttinger Liquid:** $g = NK{*}2e^2/h$ ↯
- **Clean LL with Fermi leads:** $g = N{*}2e^2/h$ ↯
- **Spin-orbit coupling** ↯
- **Disordered LL with Fermi leads:**

  $g(K_c) < N{*}2e^2/h$

  $g \sim 1/L$ constant for $L_T > L$ (thermal freeze-out)

  BUT

  $L_T > L$ for $T < 0.6$ K, δg not constant for $T < 0.6$ K ↯

  δg not power law

Possible Explanations? (2)

- **LL correlations also outside 2 μm wire**

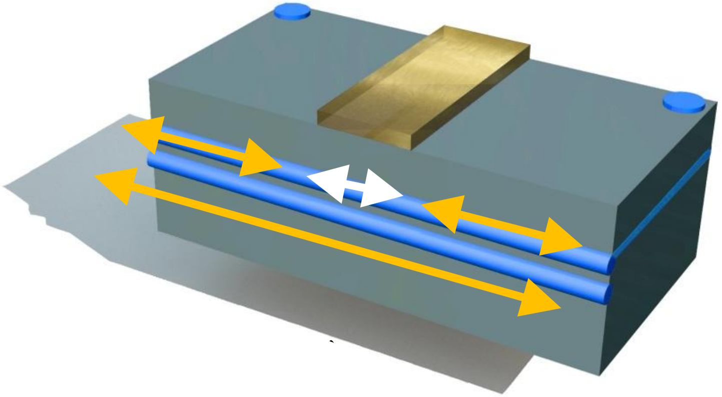
2D-1D coupling scale sets system size ~ 14 μm

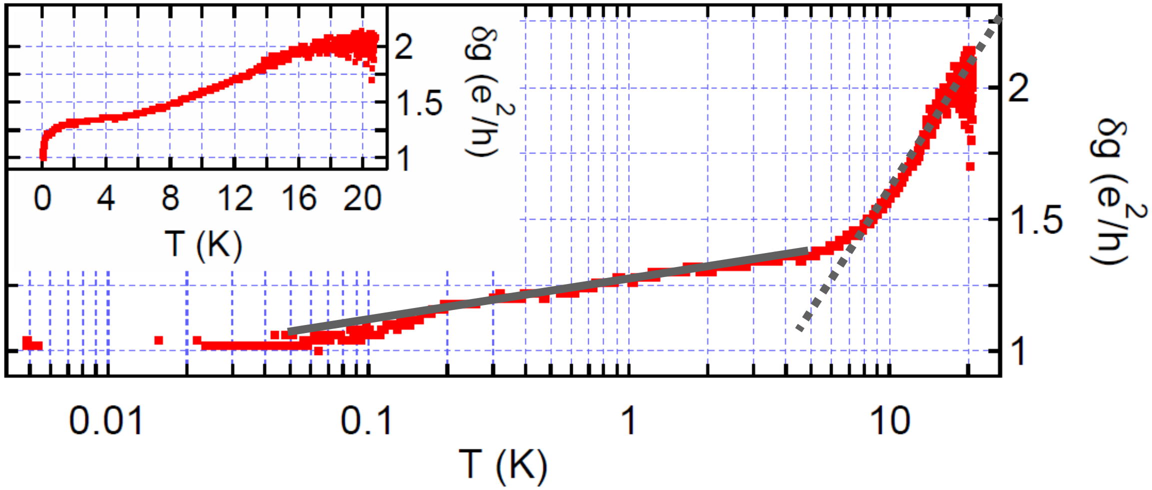
consistent with data

(two power laws, two saturation temperatures)

g-saturation value: coincidence

depends on density, disorder, B, etc.



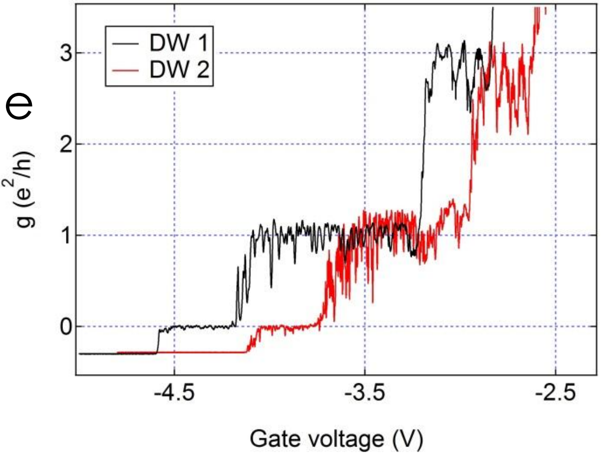


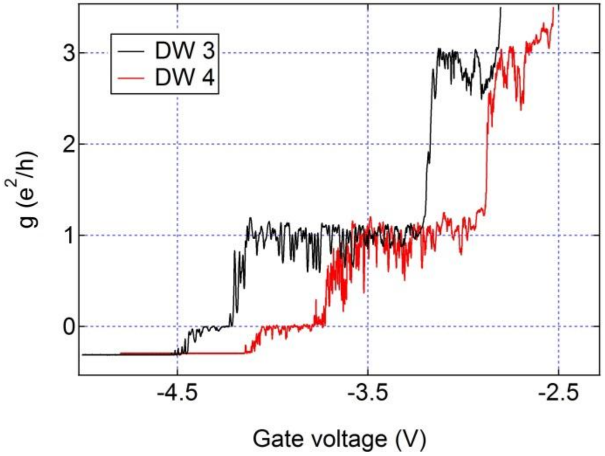
Robust feature: 1 e^2/h step height

- **Quantitative agreement:**

  4DWs on the same sample

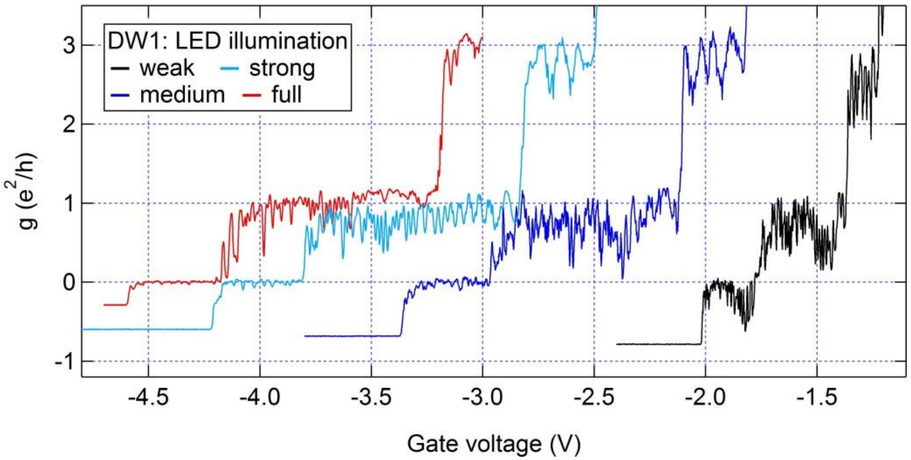
  SW samples





- **Robust against variation of 2D-1D coupl.**

  (variation of 2DEG density and overall density in wires with LED)

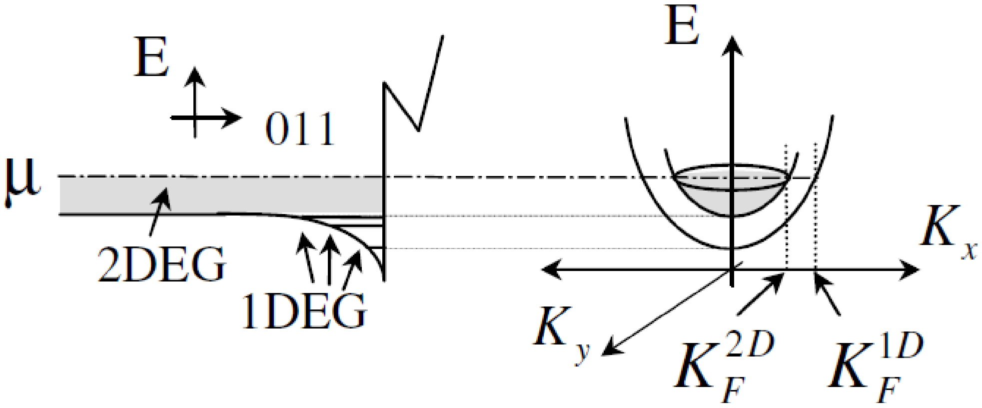


Scheller et al., arXiv:1306.1940

Reduced Conductance Quantization
Boltzmann 2D-1D contact scattering model

coupling
a) from 2D to few modes, semi-infinite wire, with weak LL correl.
b) from semi-infinite wire to single mode wire

$$G = G_Q/\sqrt{1 + 2\Gamma_{\mathrm{BS}}/\Gamma_{\mathrm{2D}}}$$



2D-1D coupling requires momentum scattering

Yacoby et al., PRL 1996
Picciotto et al., PRL 2000

Γ_{BS} : wire back scattering
LL enhanced at low-T
Γ_{2D}: 2D-1D scattering
LL suppressed at low-T
(vanishing LL DOS)

G arising from contacts, not single mode wire

rule out, since
- this predicts g -> 0 at T -> 0 (not seen)
- 2D-1D coupling sensitivity (not seen), energy dependence (not seen)

Reduced Conductance Quantization
Model 4: Wigner Crystal, Heisenberg Chain

Matveev PRL, PRB 2004

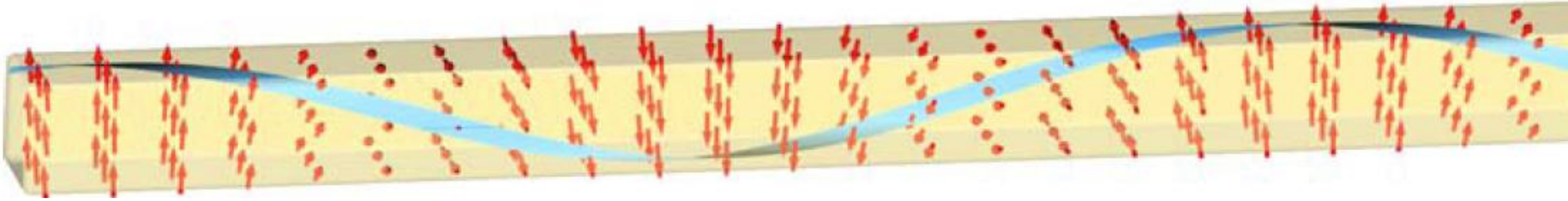
at very low densities, large r_S
finite length Wigner Crystal
antiferromagnetic Heisenberg chain,
exponentially small exchange coupling J

present wires not in this very low density regime

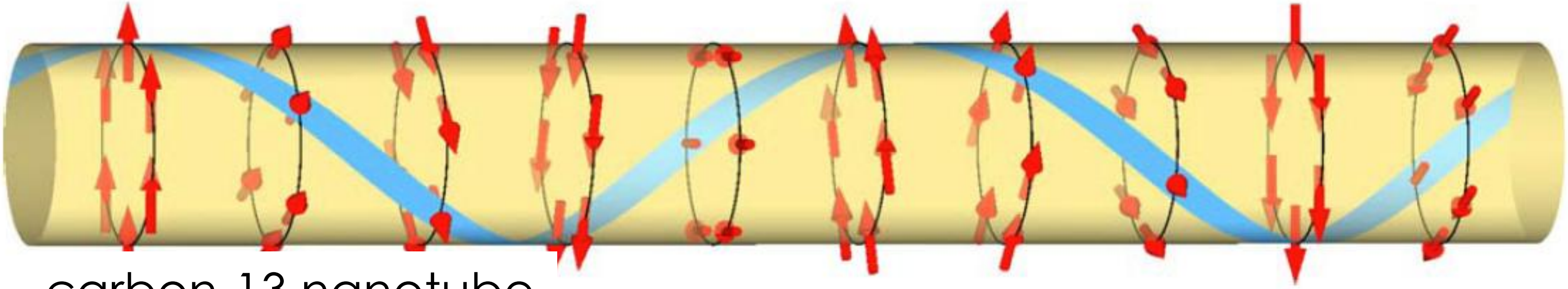
also, this model predicts qualitatively opposite T-dependence:
low $T \ll J$: $2e^2/h$
high $T \gg J$: $1e^2/h$

Nuclear Helimagnet

Luttinger liquid (1D)
RKKY interaction via hyperfine coupling
$T^* = T^*(K_C)$ here $K_C \sim 0.3$ to 0.4, $T^* \sim 0.2$ K to 0.6 K



GaAs wire

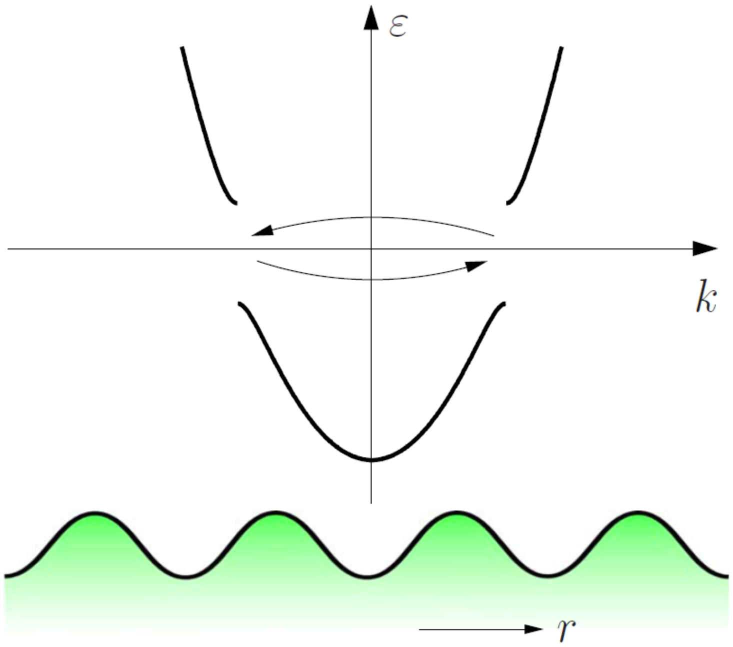


carbon-13 nanotube

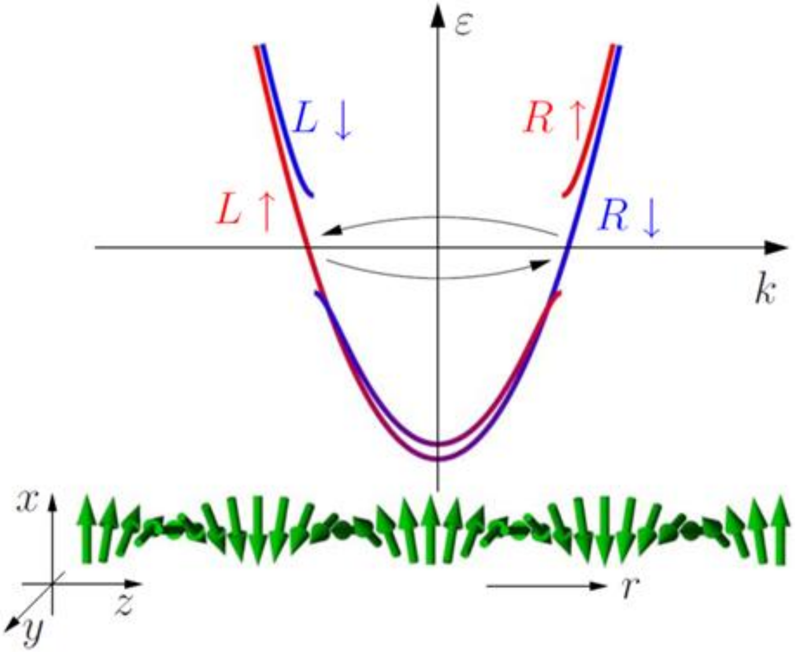
Braunecker, Simon & Loss, PRL, PRB2009

Spin-Selective Peierls Transition in a Luttinger Liquid

Peierls: metal – insulator transition
induced by $\lambda_F/2$ periodic potential



spin selective Peierls transition

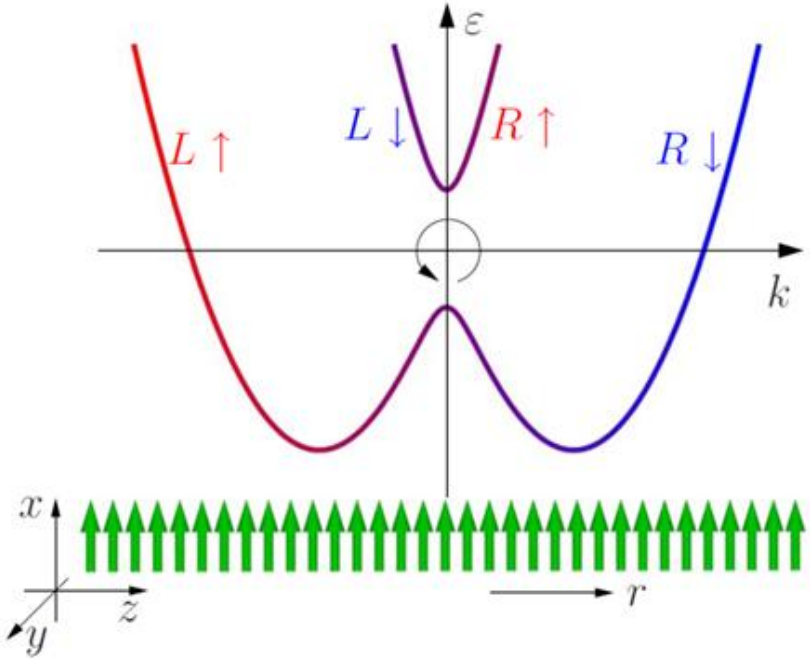


induced by nuclear Helimagnet
gap pinned at Fermi energy
freeze ½ of modes
spin selective, g = 1 e^2/h

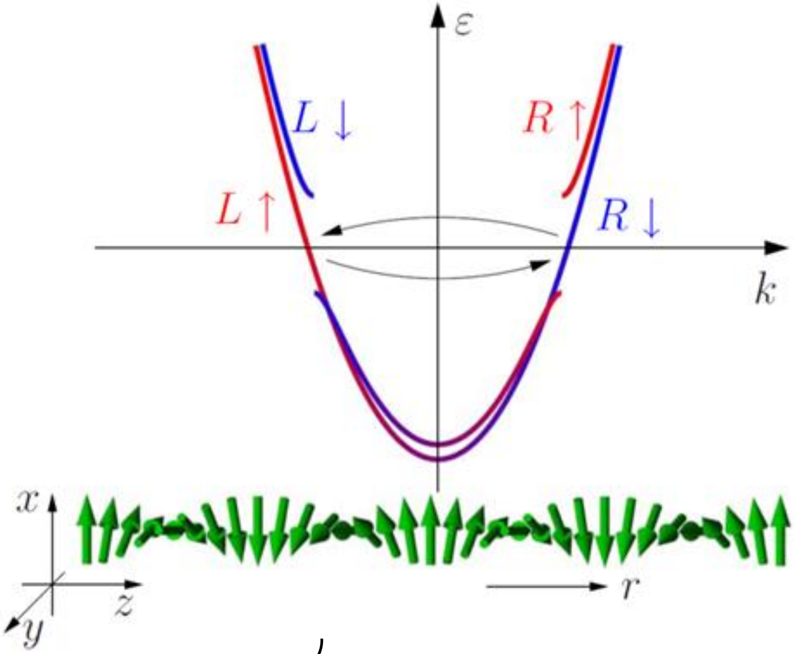
Braunecker, Japardize,
Klinovaja & Loss, PRB 2010

Spin-Selective Peierls Transition in a Luttinger Liquid

1D + SOI + B_{ext} (SO-gap)



spin selective Peierls transition



$$\psi_\sigma \to e^{\mathrm{i}k_{\mathrm{so}} r}\psi_\sigma$$

induced by
- spin-orbit coupling
- nuclear Helimagnet (equivalent)

freeze ½ of modes

spin selective, g = 1 e^2/h

Braunecker, Japardize, Klinovaja & Loss, PRB 2010

Nuclear order in bulk

- seen in some metals (ferro / antiferromagnetic)
  RKKY mediated by conduction electrons
- typical ordering temperatures nK, μK
  e.g. Oja and Lounasmaa, RMP1997
  (sometimes ferro at pos. T, and antiferro at neg. T)
- ~mK ordering in special materials
  (van-Vleck paramagnets $PrNi_5$, $PrCu_6$)

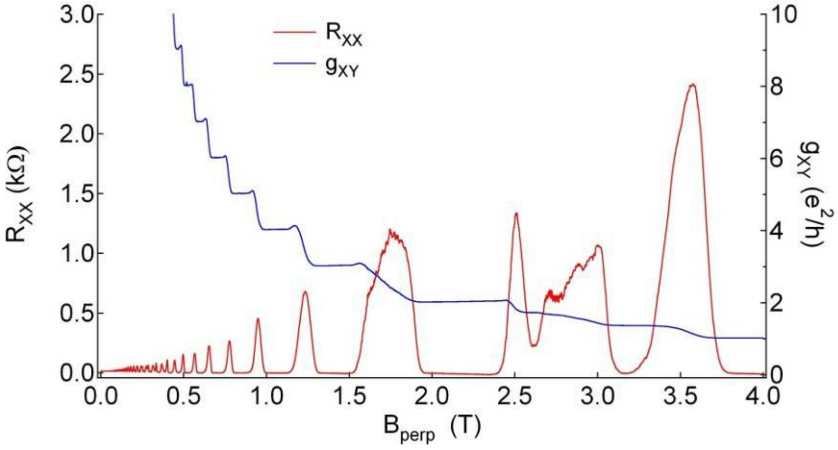
Luttinger liquid (1D)
cross-over temperature $T^* = T^*(K_C)$ as large as 1K for small K_C

full nuclear polarization $T \ll T^*$
zero polarization $T \gg T^*$: wide transition

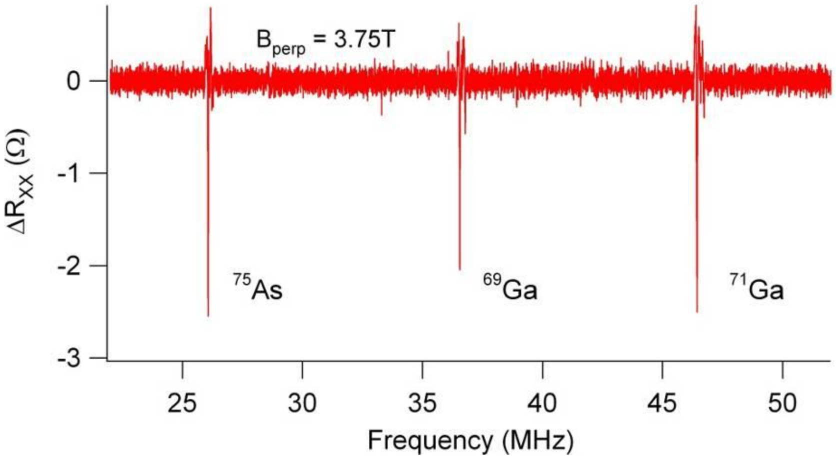
K_C here not trivial, between 0.4 and 0.3
corresponding to $T^* \sim 0.2$ and 0.6 K

Resistively detected NMR

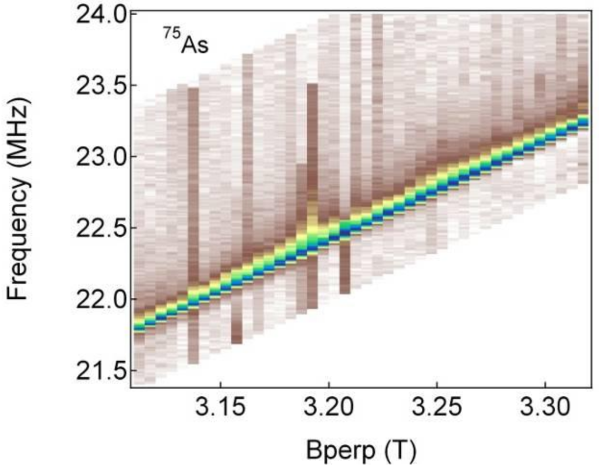
Quantum Hall regime



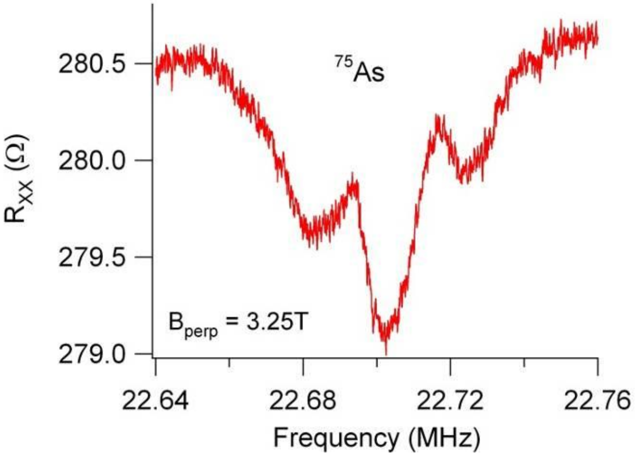
3 isotopes



NMR resonance condition



^{75}As quadrupolar splitting



[] Desrat, Maude, Potemski, Portal, PRL **88**, 25 (2002)

Summary & Outlook

evidence for helical nuclear-spin order in GaAs quantum wires

- wire g ~ 1 e^2/h for T < 100 mK (g ~ 2 e^2/h at T > 15 K)
  zero bias dip, similar to T-dependence
- robust: several wires, single/double wires
  insensitive to B and density/disorder
- lifting of electron spin degeneracy at B=0
- helical nuclear magnetism in the Luttinger liquid regime
  consistent is: factor of 2, ordering temperature, broad, insensitivity to B, n
- no direct evidence for nuclear spins
- possibly the resolution of "non-universal conductance quantization"

future: nuclear spins?

- magnon / tunneling spectroscopy
- thermo power
- magnetic sensing
- double wire B-field equivalent to spin-orbit coupling
  + tunneling (new devices)

(Scheller et al., arXiv:1306.1940)

Acknowledgements

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theory
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D. Loss, Basel
P. Simon, U Paris Sud

SOLID

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European Microkelvin Collaboration

QSIT Quantum Science and Technology
National Centre of Competence in Research