DQMP Department of Quantum Matter Physics

Quantum transport in (1D) cold atomic systems

T. Giamarchi

http://dqmp.unige.ch/giamarchi/

UNIVERSITÉ DE GENÈVE

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SWISS NATIONAL SCIENCE FOUNDATION

SCIENCE TO SHAPE THE FUTURE OF THE ARMY
ARMY RESEARCH OFFICE
1951

MaNEP SWITZERLAND

Theory:

A.-M. Visuri M. Filippone





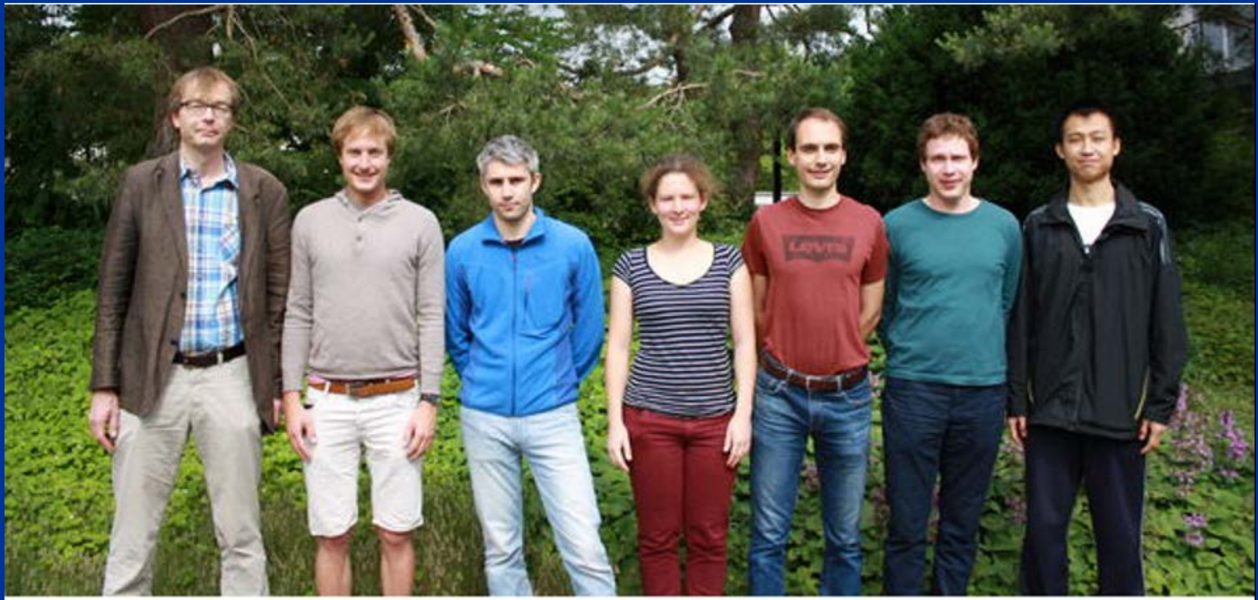

S. Uchino
Waseda U.

P. Grisins
X-rite

S. Greschner

C. Bardyn

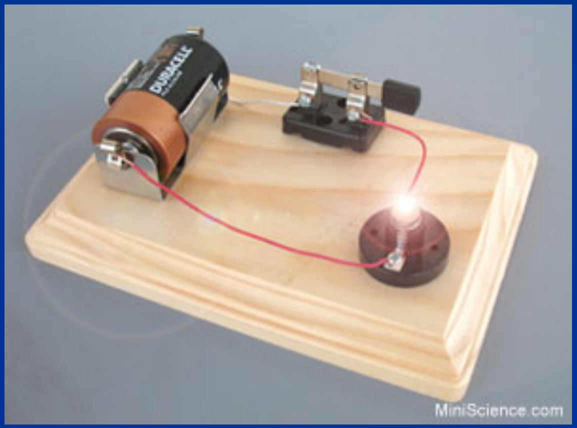
Experiments:
Esslinger's
Brantut's
Groups
(ETHZ/EPFL)



From left to right: Tilman Esslinger, Dominik Husmann, Jean-Philippe Brantut, Laura Corman, Martin Lebrat, Samuel Häusler, Muqing Xu

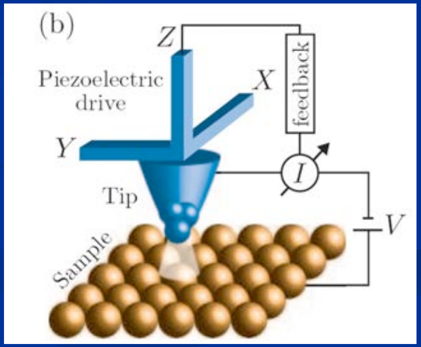
Transport

- Condensed matter: a «routine» probe for materials



- Theoretically:
  complicated !
  Out of equilibrium

- Typical situation



- Often (but not always !) : linear response I=G V

Questions

- I=f(V) Reflects the properties of the system (interferences – metal, insulator, etc.)
- Methods ?

  Kubo; Memory function; Landauer; Keldysh;

  …..

- Expectations for small V: $V = RI$

  $$R = R_{contact} + R_{system}$$

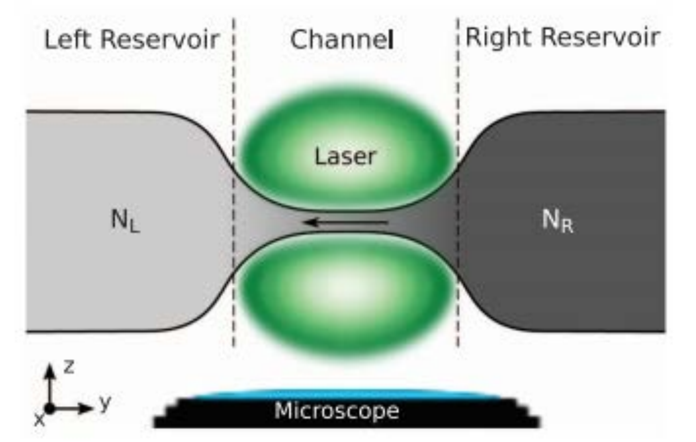
- Other transport(s): spin, temperature, etc.

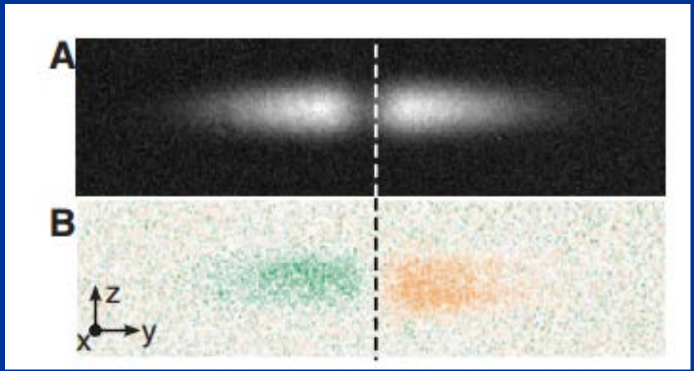
Cold atoms

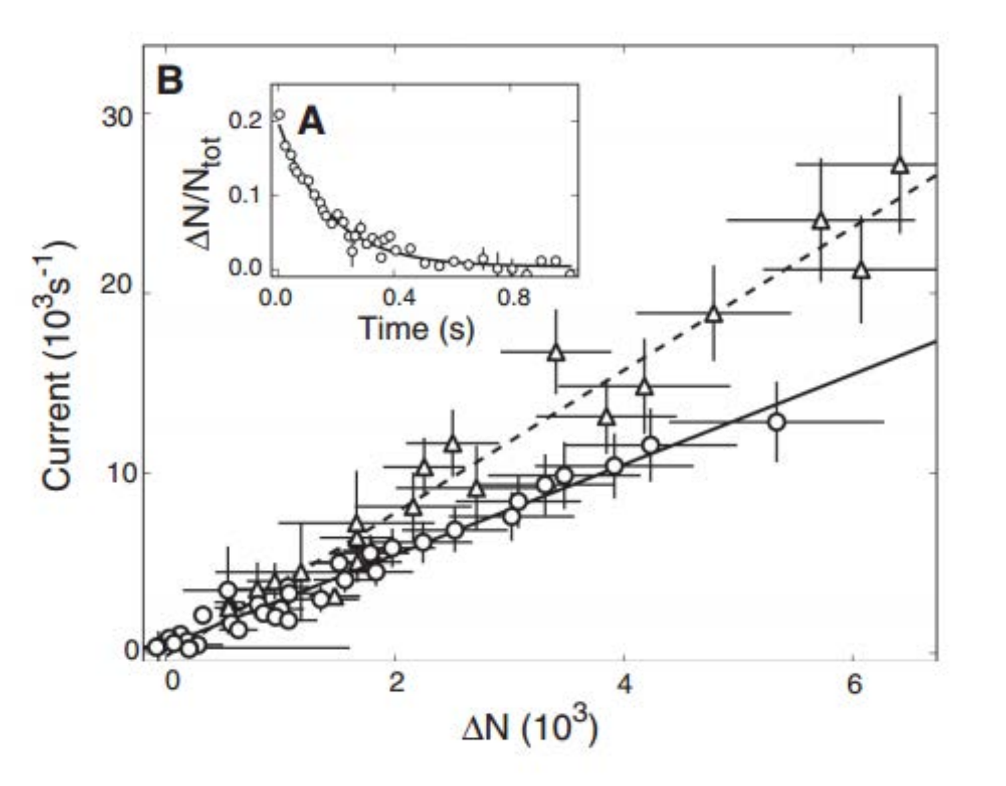
Conduction of Ultracold Fermions Through a Mesoscopic Channel

Jean-Philippe Brantut, Jakob Meineke, David Stadler, Sebastian Krinner, Tilman Esslinger*

SCIENCE VOL 337 31 AUGUST 2012



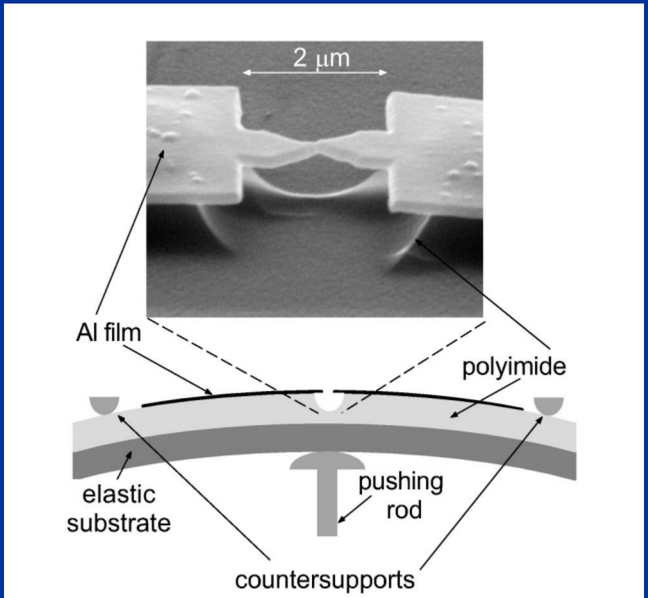


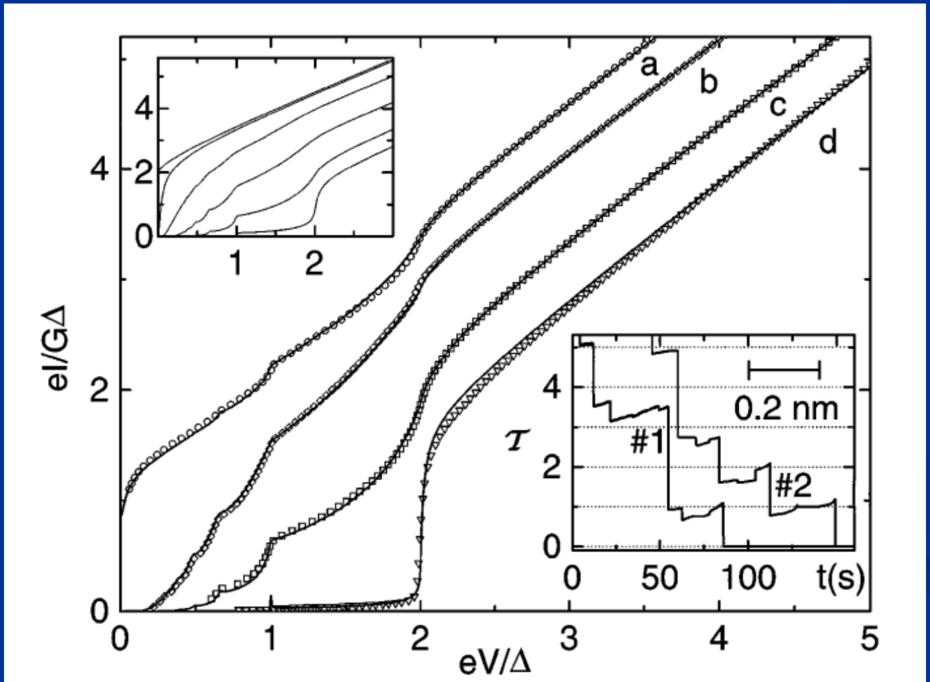


Zero dimensional structure: Quantum Point Contact

S-S Quantum point contact

- Theory: Blonder, Tinkham, Klapwijk (1982); Averin, Bardas (1995); Cueva, Martin-Rodero, Yetati (1996)

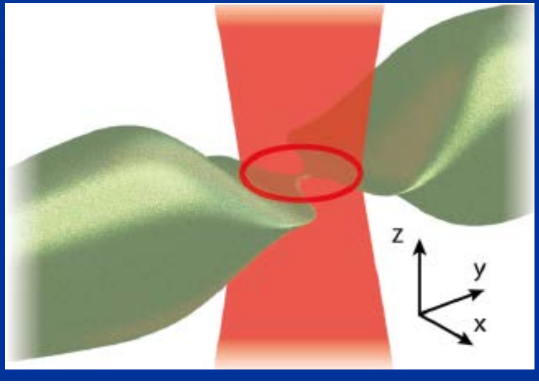


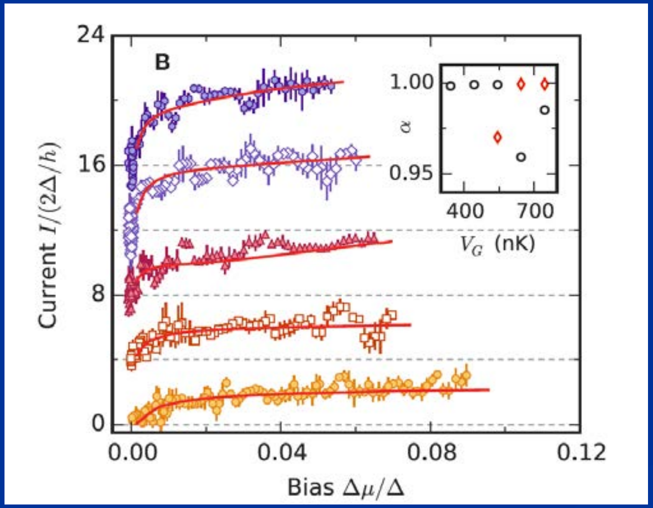


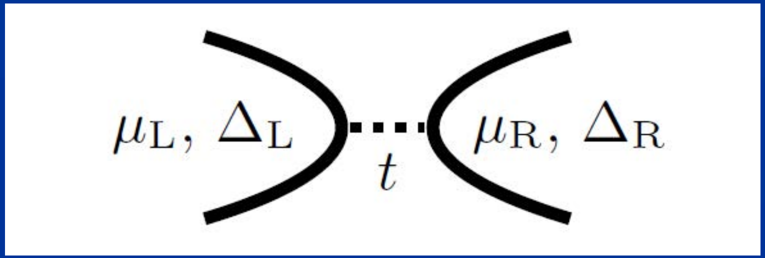
E. Scheer et al. PRL 78 3535 (1997)

Quantum point contact

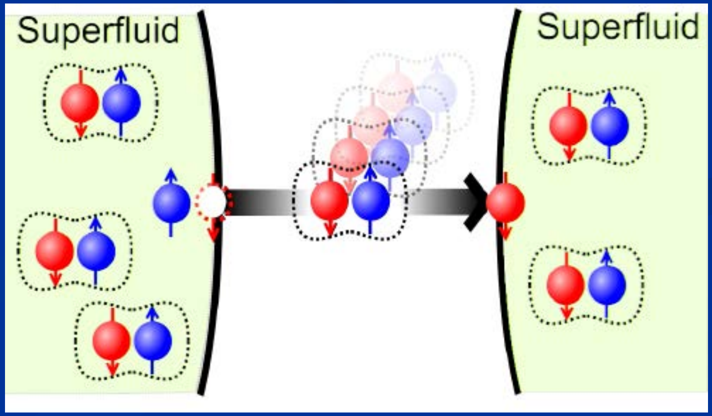
D. Husmann, S. Uchino, et al. Science 350 62667 (2015).







- Quantum point contact: multiple Andreev reflexions



One dimensional structure

Observation of quantized conductance in neutral matter

Sebastian Krinner[1], David Stadler[1], Dominik Husmann[1], Jean-Philippe Brantut[1] & Tilman Esslinger[1]

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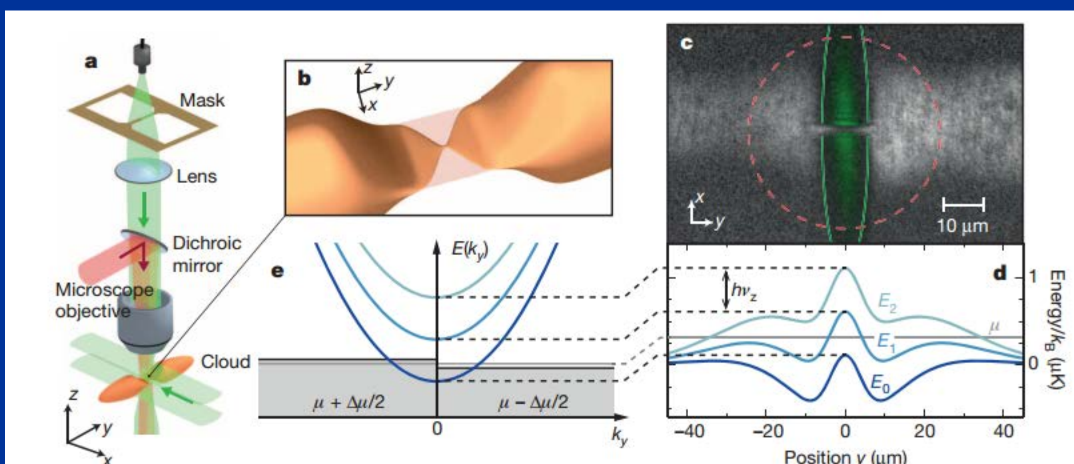
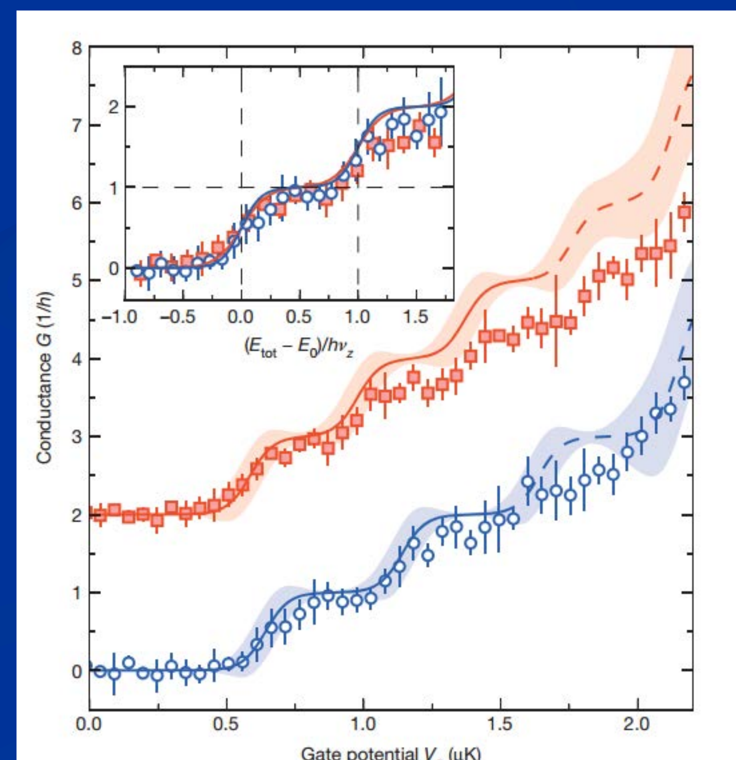
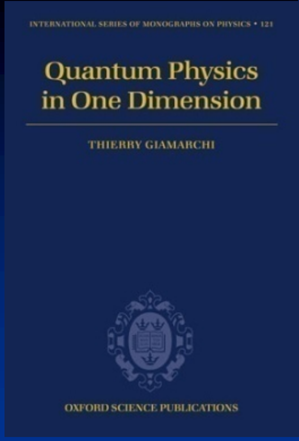


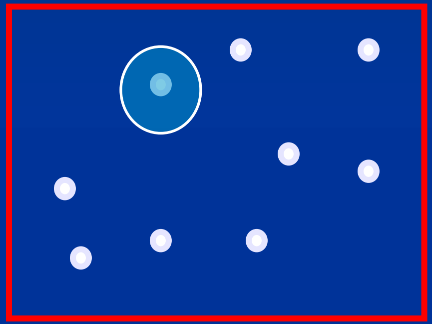


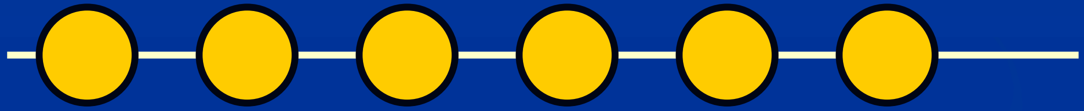
With interactions ?

One dimension is special !

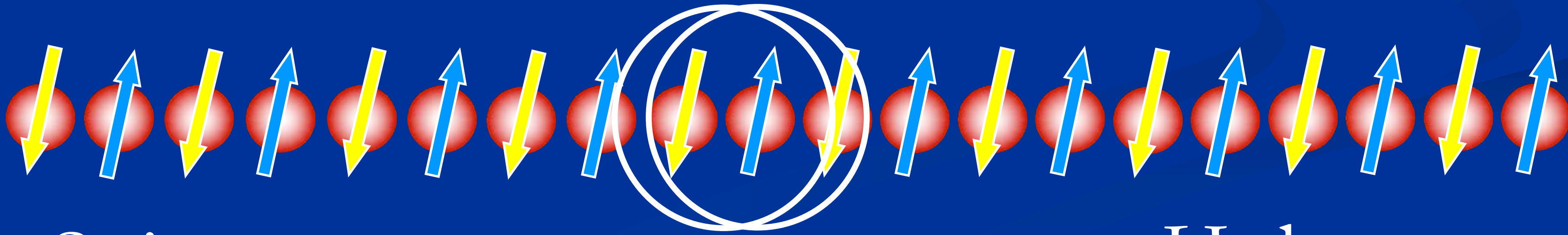


- Only collective excitations





- Spin charge separation !



Spinon

Holon

Weak periodic lattice in 1D

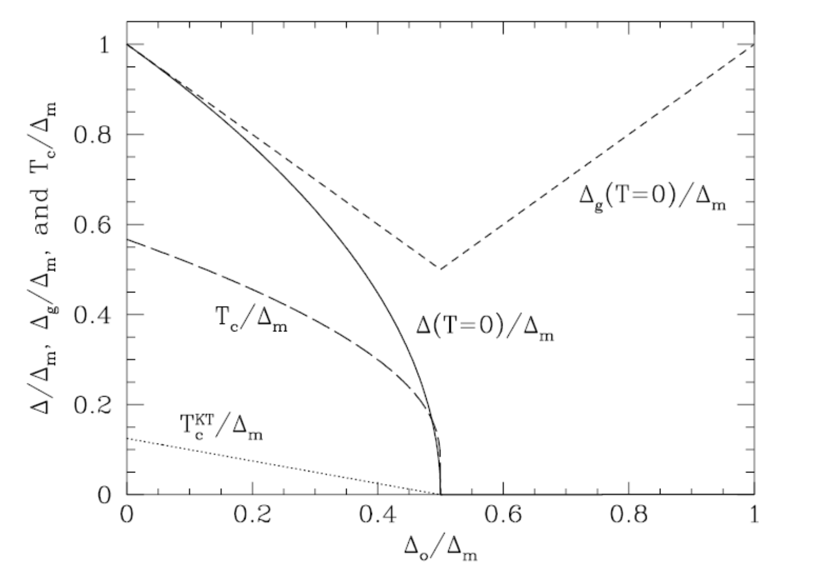
- No interactions: band insulator
- Attraction: singlet superconductor
- Superconductor resists "scattering" (disorder, potentials, etc.)
- Expect a competition band insulator-superconductivity

Eur. Phys. J. B **10**, 649–662 (1999)

THE EUROPEAN PHYSICAL JOURNAL B
EDP Sciences

From semiconductors to superconductors: a simple model for pseudogaps

P. Nozières and F. Pistolesi[a]

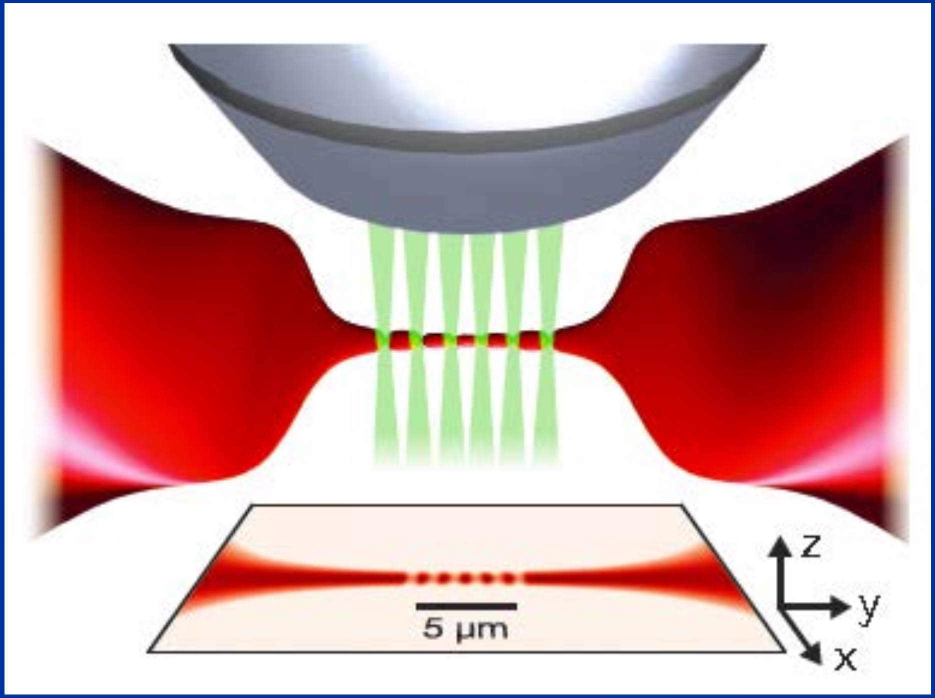


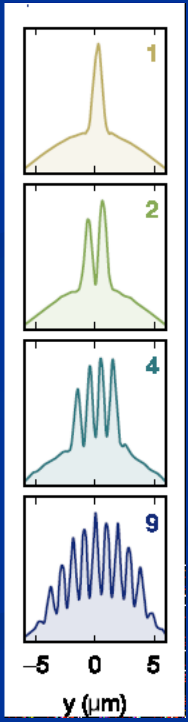
- Mean-Field
- Superconductor-Band insulator transition

- Always true ?
- How to test experimentally ?

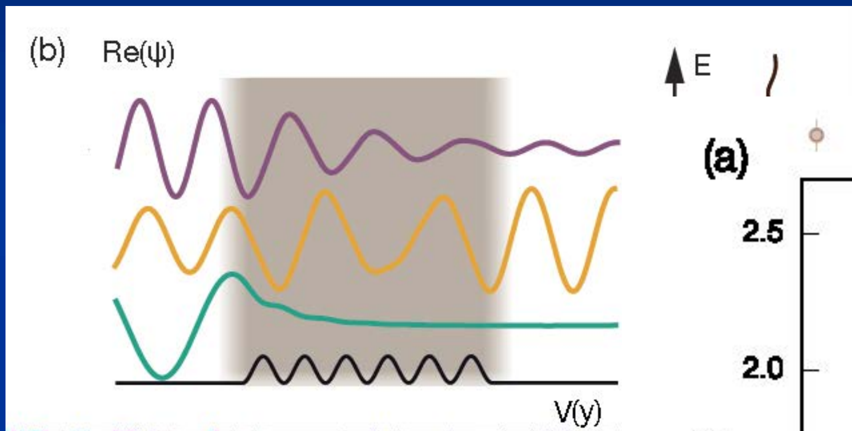
Atomtronic

M. Lebrat, P. Grisins et al., PRX 8 011053 (18)

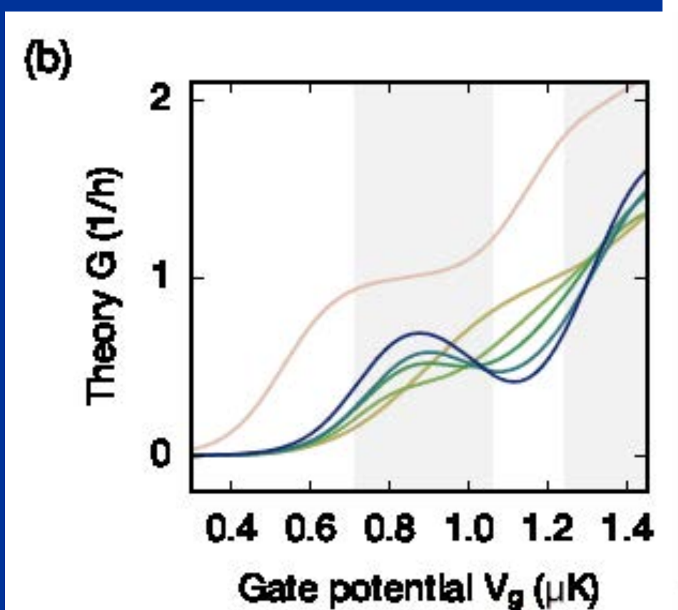


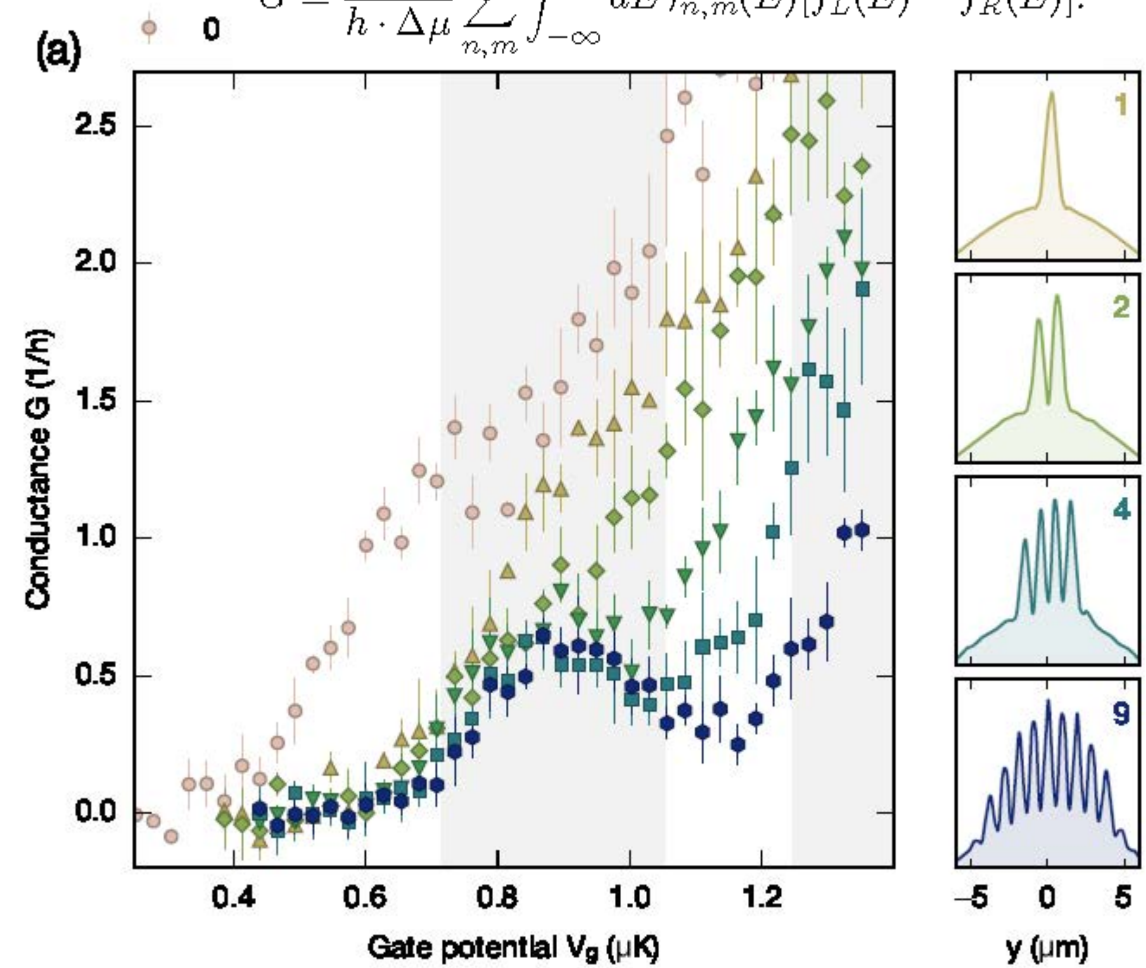


No interactions: band insulator



$$G = \frac{1}{h \cdot \Delta\mu} \sum_{n,m} \int_{-\infty}^{\infty} dE\, \mathcal{T}_{n,m}(E)\,[f_L(E) - f_R(E)].$$





What happens with interactions?

$$H = H_{\mathrm{GY}} + H_{\mathrm{lattice}},$$

$$H_{\mathrm{GY}} = -\frac{\hbar^2}{2m}\sum_i \frac{\partial^2}{\partial y_i^2} + g_1 \sum_{i<j} \delta(y_i - y_j),$$

$$H_{\mathrm{lattice}} = \int dy\, V(y)\rho(y),$$

Luther-Emery liquid

- Gap in the spin sector (singlet pairing)

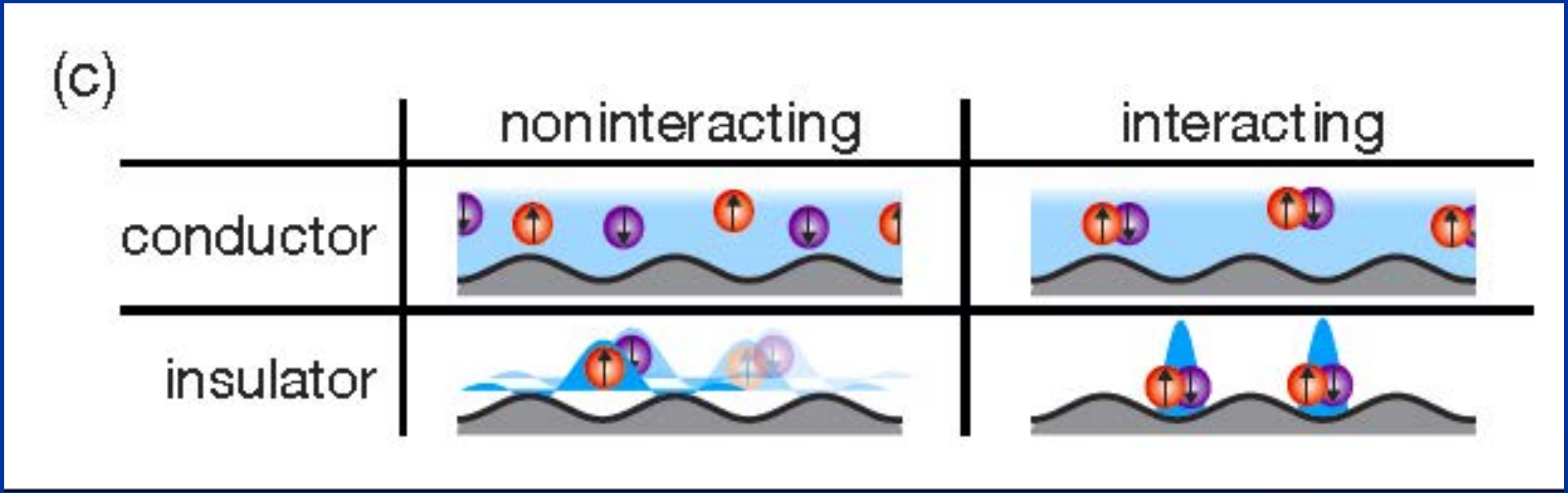
$$\rho(y) = \rho_0 - \frac{\sqrt{2}}{\pi}\nabla\phi_c(y) + 2\rho_0 f_s \cos\left(2k_F y - \sqrt{2}\phi_c(y)\right) + 2C\rho_0 \cos\left(4k_F y - 2\sqrt{2}\phi_c(y)\right),$$

- Conductance determined by the charge sector

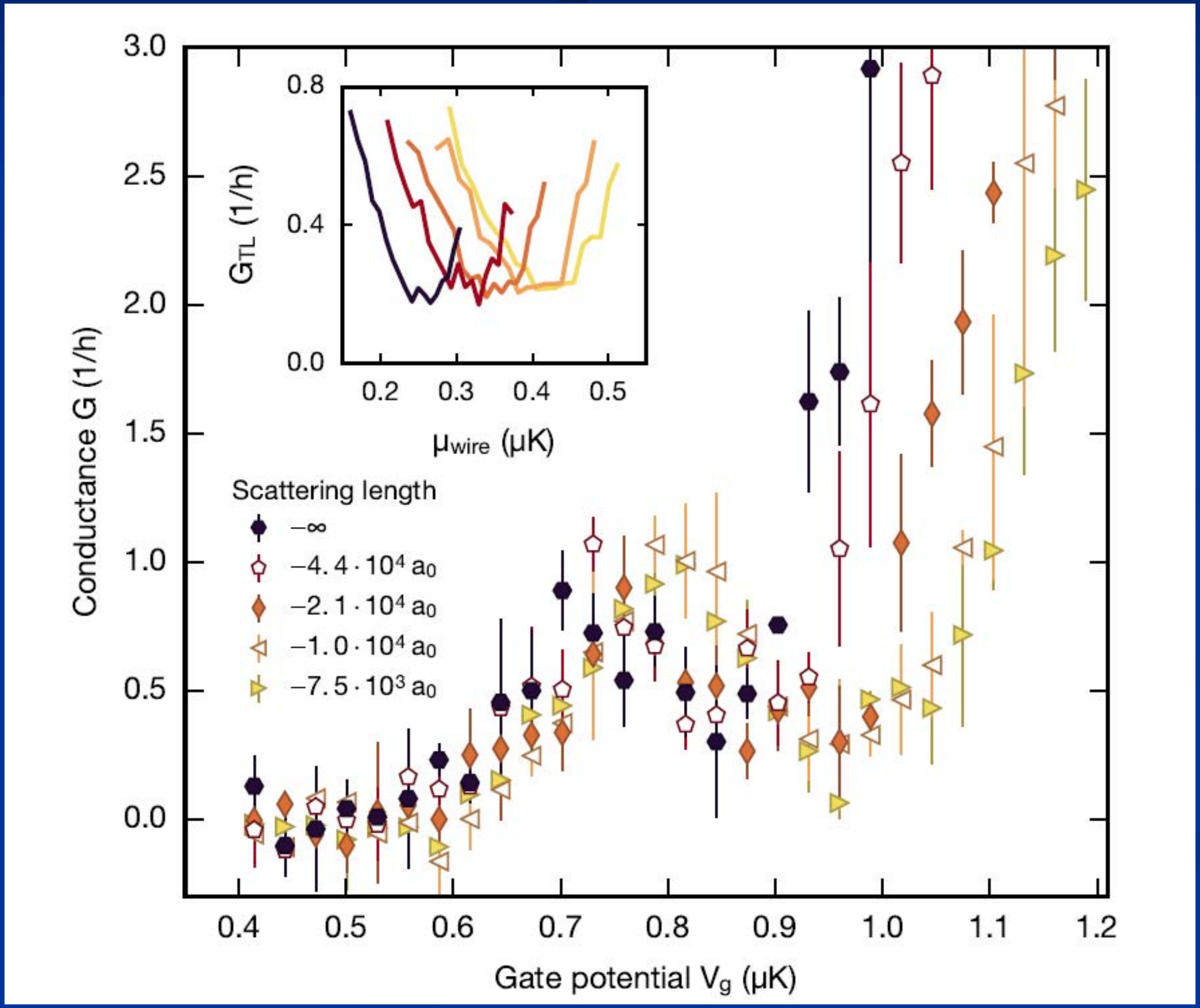
$$\mathcal{H}_\mu(y) = -\mu(y)\rho(y) = \mu(y)\frac{\sqrt{2}}{\pi}\nabla\phi_c,$$

$$I_{\uparrow\downarrow}(y) = \frac{\sqrt{2}}{\pi}\partial_t\phi_c(y,t)$$

Many-body insulator ``pinned" L.E. liquid



Experimental evidence for L.E. liquid

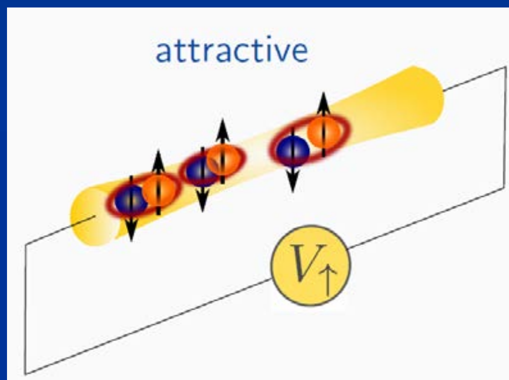


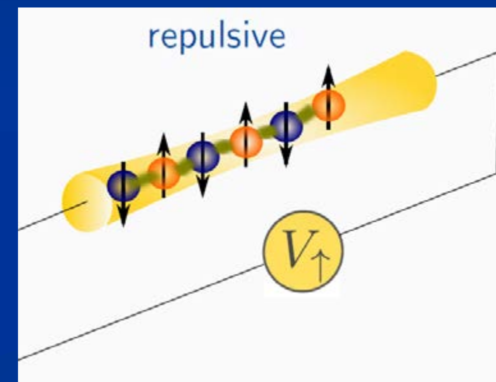
Spin transport

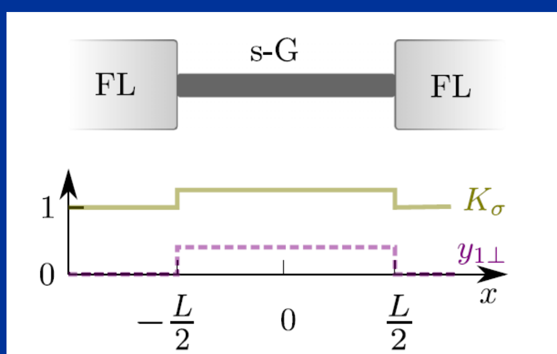
A.-M. Visuri, M. Lebrat, S. Häusler, L. Corman and TG, PRR **2**, 023062 (2020)

Spin transport and spin drag

$$J_\sigma = \langle j_\uparrow - j_\downarrow \rangle = G_\sigma (\mu_\uparrow - \mu_\downarrow)$$







$$\begin{pmatrix} I_\uparrow \\ I_\downarrow \end{pmatrix} = \begin{pmatrix} G_{\uparrow\uparrow} & \Gamma \\ \Gamma & G_{\downarrow\downarrow} \end{pmatrix} \begin{pmatrix} \Delta\mu_\uparrow \\ \Delta\mu_\downarrow \end{pmatrix}$$

Spin Drag: $\Delta\mu_\uparrow$ $I_\downarrow$ $I_\downarrow = \Gamma \Delta\mu_\uparrow$

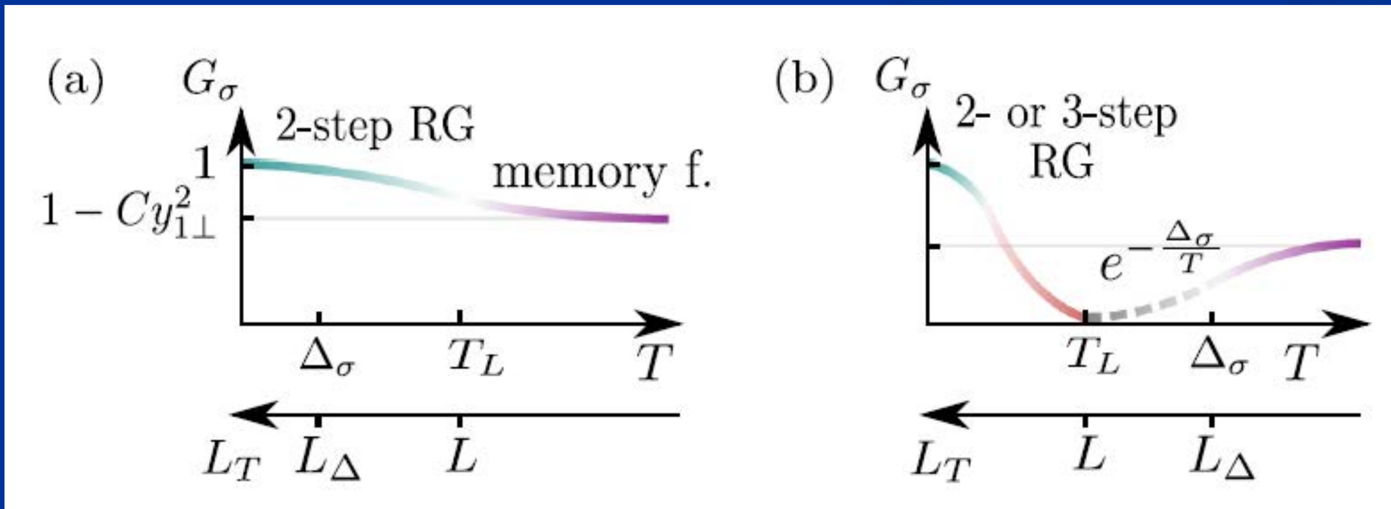
Solution (using Sine-Gordon)

$$H_\nu^0 = \frac{1}{2\pi}\int dx \left\{ v_\nu K_\nu [\partial_x \theta_\nu(x,t)]^2 + \frac{v_\nu}{K_\nu}[\partial_x \phi_\nu(x,t)]^2 \right\}.$$

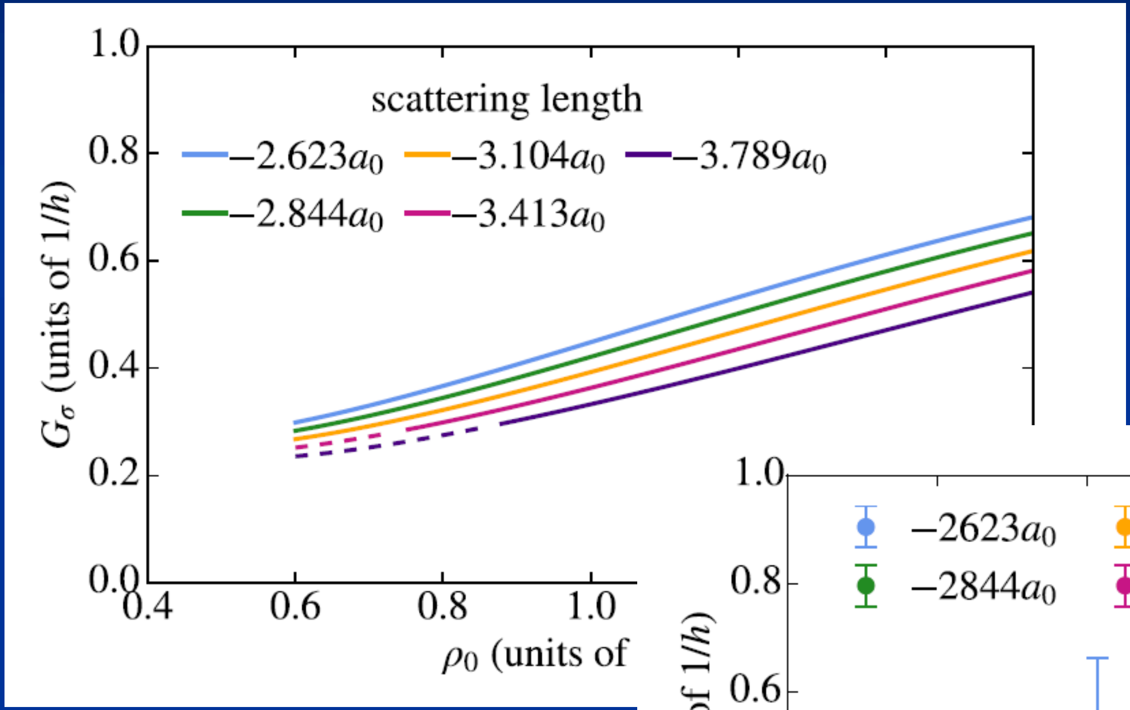
$$\frac{2g_{1\perp}}{(2\pi\alpha)^2}\int_{-\frac{L}{2}}^{\frac{L}{2}} dx \cos[2\sqrt{2}\phi_\sigma(x,t)],$$

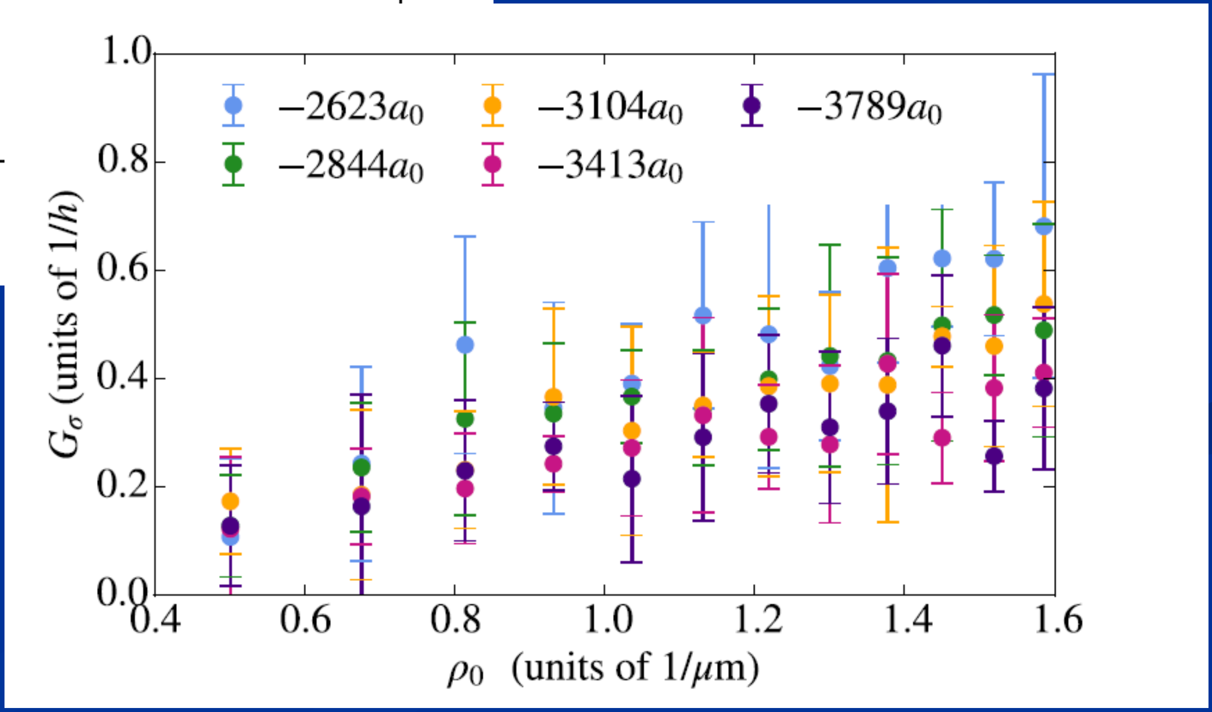
$$J \propto \partial_t \phi_\sigma$$

	weak coupling $L \ll L_\Delta$ $\Delta_\sigma \ll T_L$	strong coupling $L_\Delta \ll L$ $T_L \ll \Delta_\sigma$
high temperature $\Delta_\sigma, T_L \ll T$	memory function $G_\sigma - 1 \propto -y_{1\perp}^2 L(T/\Lambda)^{4K_\sigma - 3}$	
intermediate temperature $T_L \ll T \ll \Delta_\sigma$ $\Delta_\sigma \ll T \ll T_L$	2-step RG $G_\sigma - 1 \propto$ $-y_{1\perp}^2(T/\Lambda)^2$	$e^{-\frac{\Delta_\sigma}{T}}$
low temperature $T_f \ll T \ll T_L, \Delta_\sigma$		2-step RG $G_\sigma \propto f^2(T/\Lambda)^2$
low temperature $T \ll T_f$		3-step RG $G_\sigma - 1 \propto$ $-y_{1\perp}^2(T/\Lambda)^2$

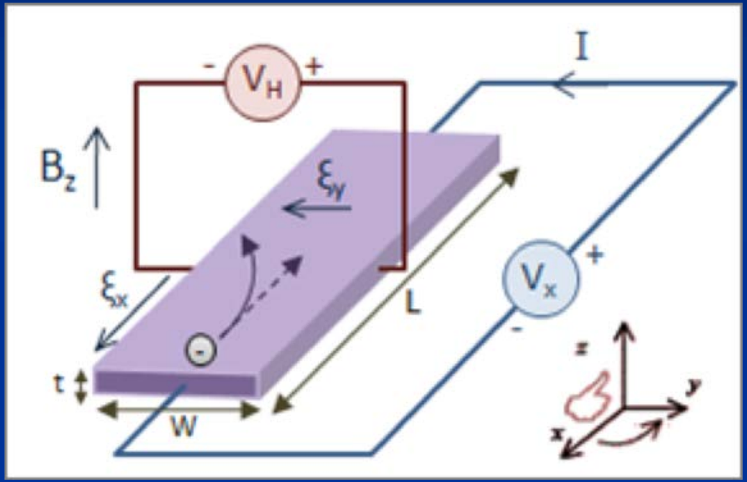


Comparison with experiments





Hall effect



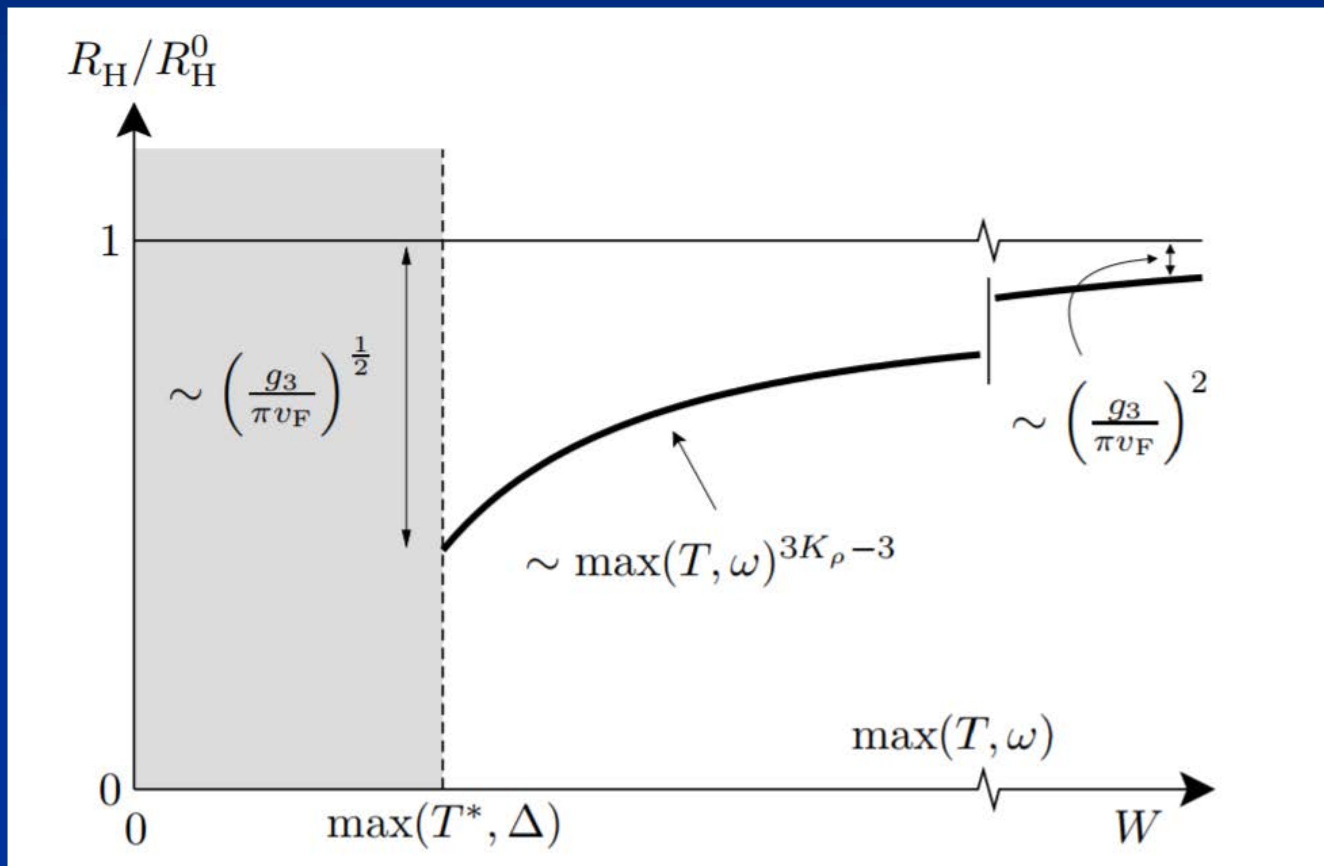
Non interacting ``simple”

$$R_h = \frac{V_\perp}{I_\| B} \propto \frac{1}{n}$$

No interactions: curvature of fermi surface
- topological formula (Thouless-Kohmoto)

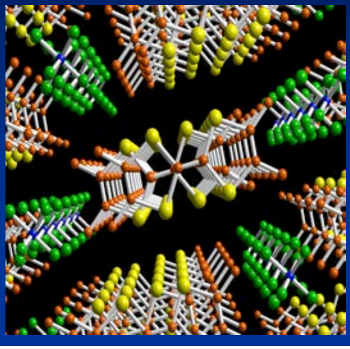
With interactions: open question

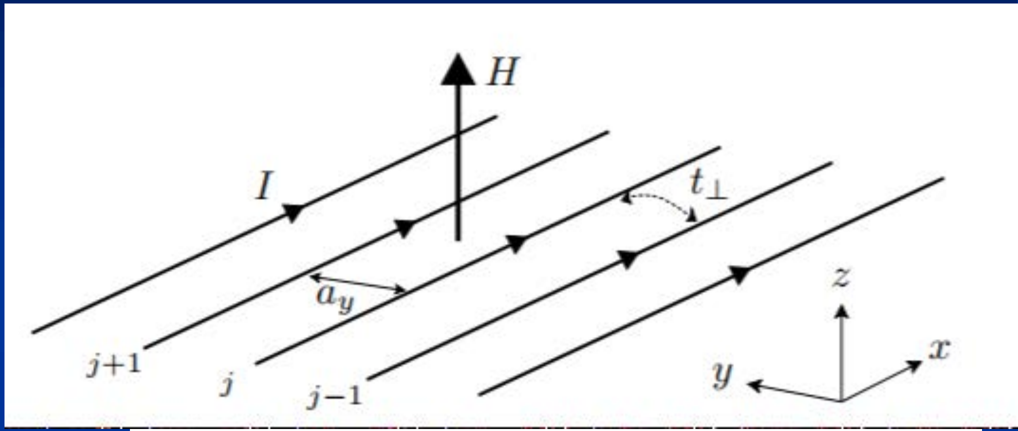
High temperature regime

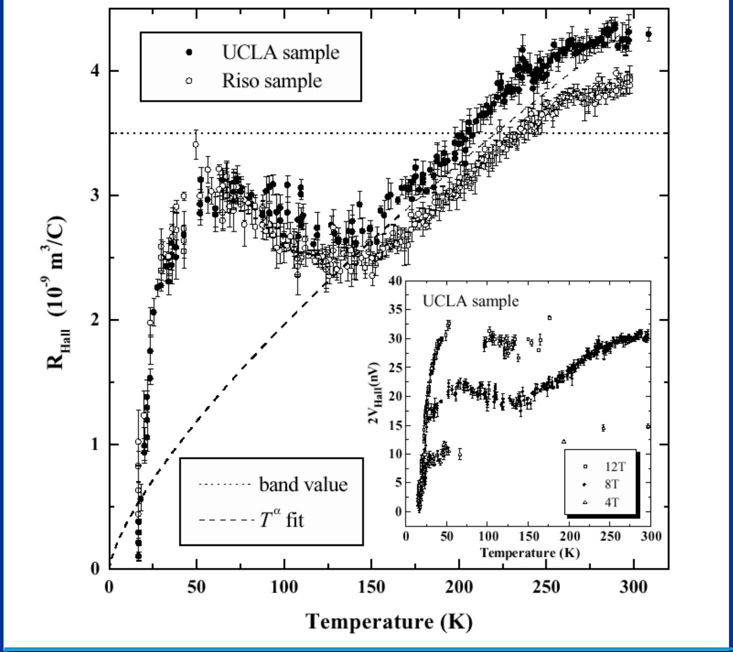


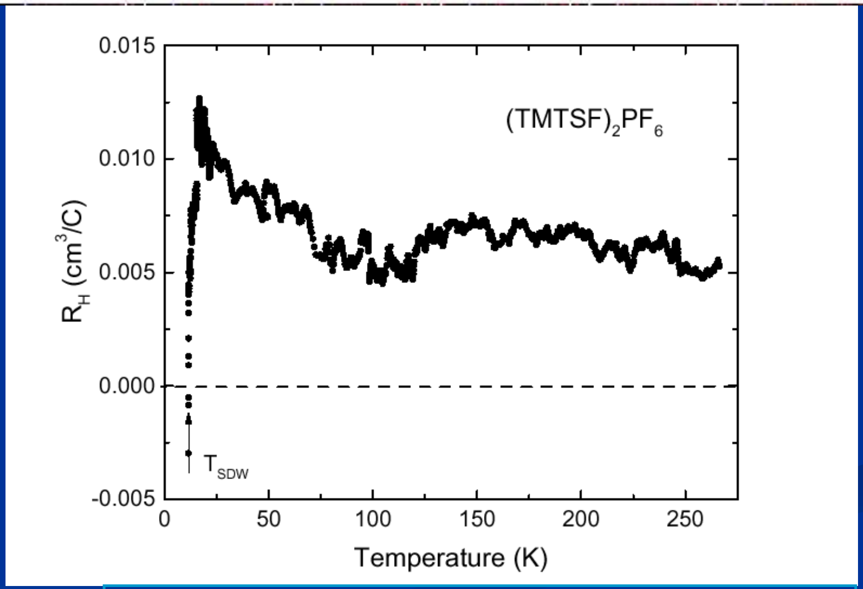
G. Leon, C. Berthod, TG PRB 75, 195123 (2007)

Condensed matter





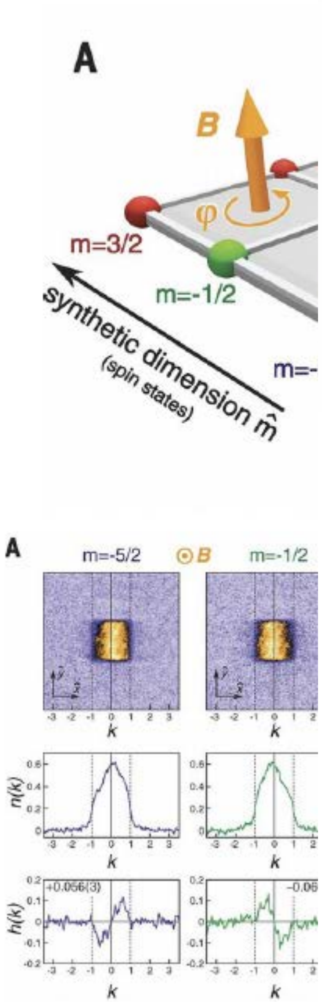




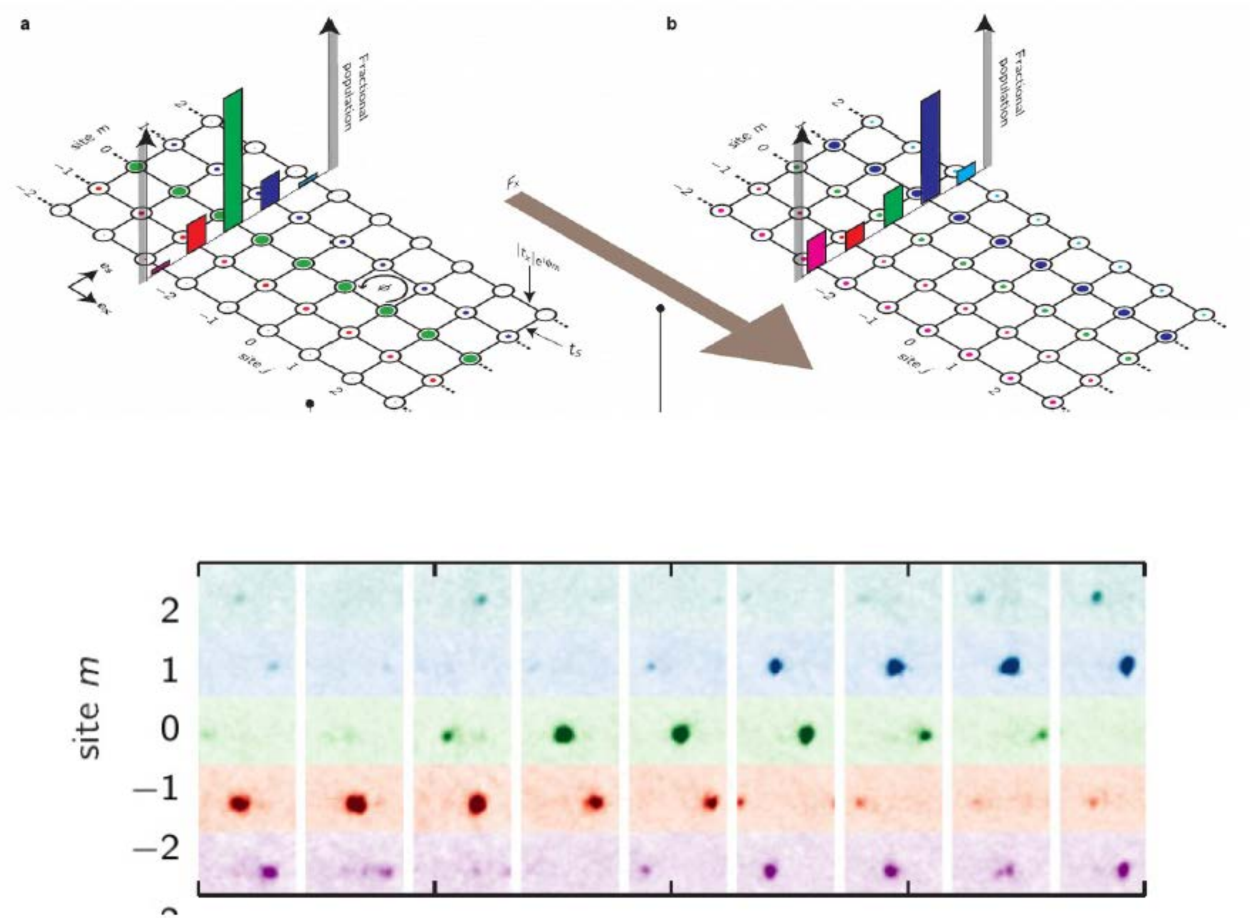
J. Moser et al., PRL 84 2674 (00)

G. Mihaly et al., PRL 84 2670 (00)

Cold atoms (balistic !)



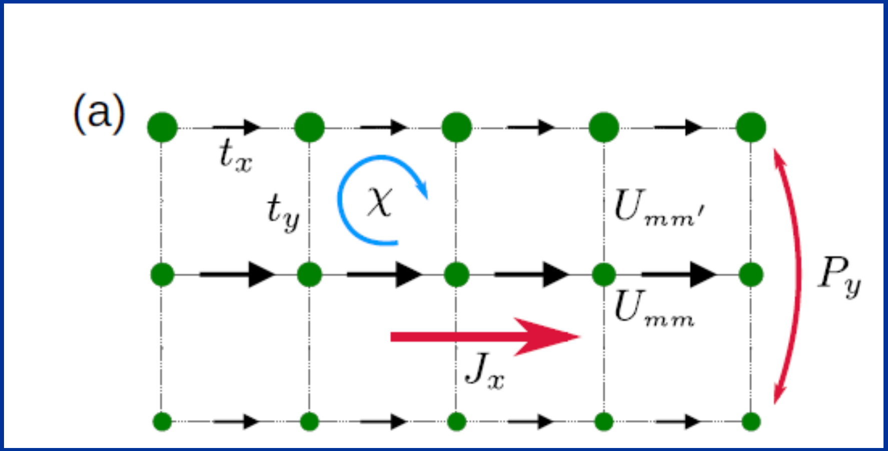
Fallani's group (Florence) **Scien**



Spielman's group (Maryland) **arXiv:1804.06345**

Hall effect on ladders

S. Greshner, M. Filippone,
TG, PRL 122, 083402 (19)

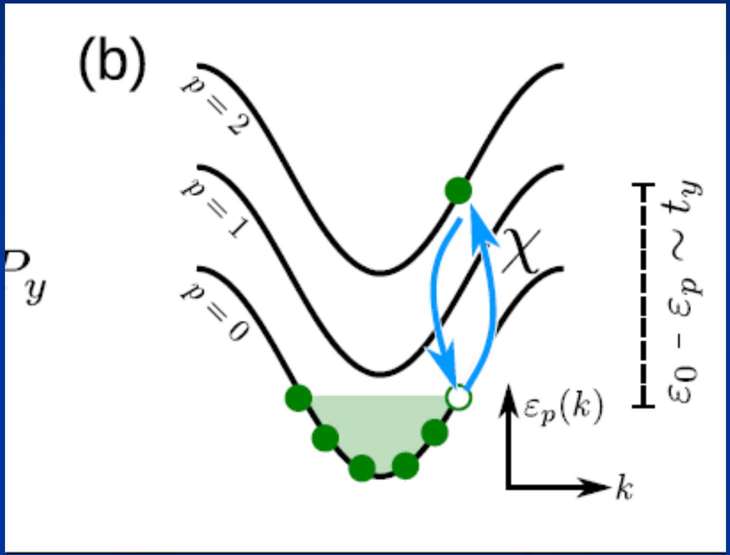


Analytic: calculation on a ring

Experiments: out of equilibrium

Analytic calculations

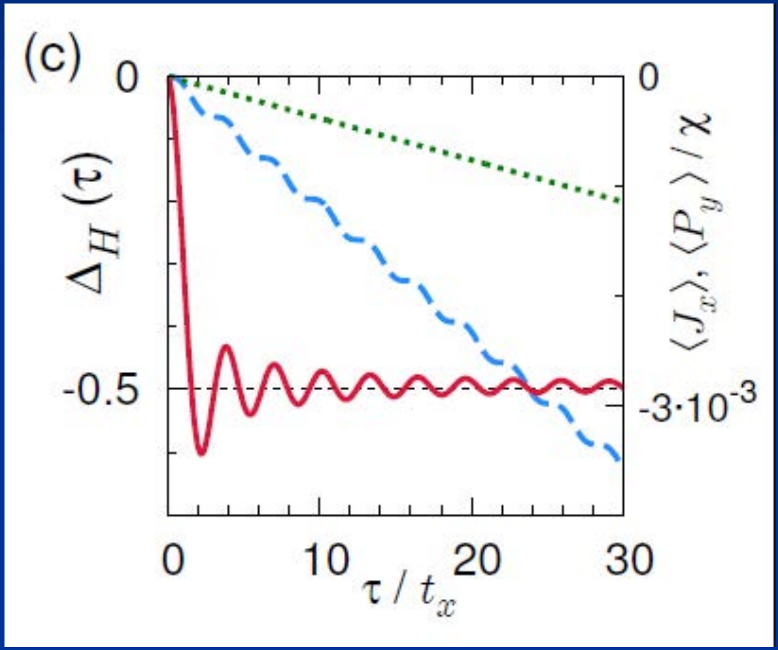
$$\Delta_{\mathrm{H}} = \left. \frac{\langle P_y \rangle}{\chi \cdot \langle J_x \rangle} \right|_{\chi \to 0}$$

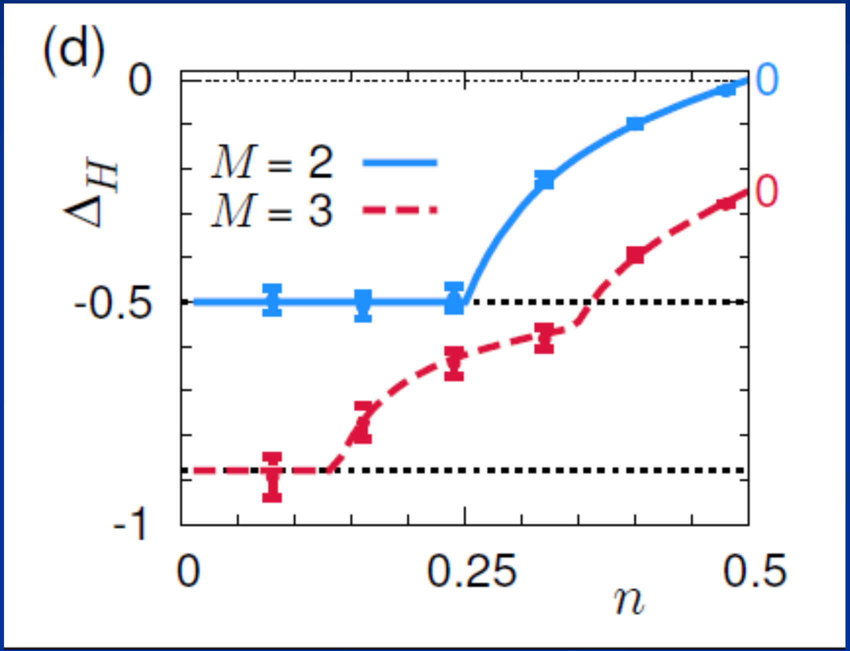


$$\Delta_H = \frac{\sum_{p<P} v_{F,p} \mathcal{I}_p}{\sum_{p<P} v_{F,p}}, \qquad R_H = \frac{-\Delta_H}{\sum_{p<P} n_p \mathcal{I}_p}.$$

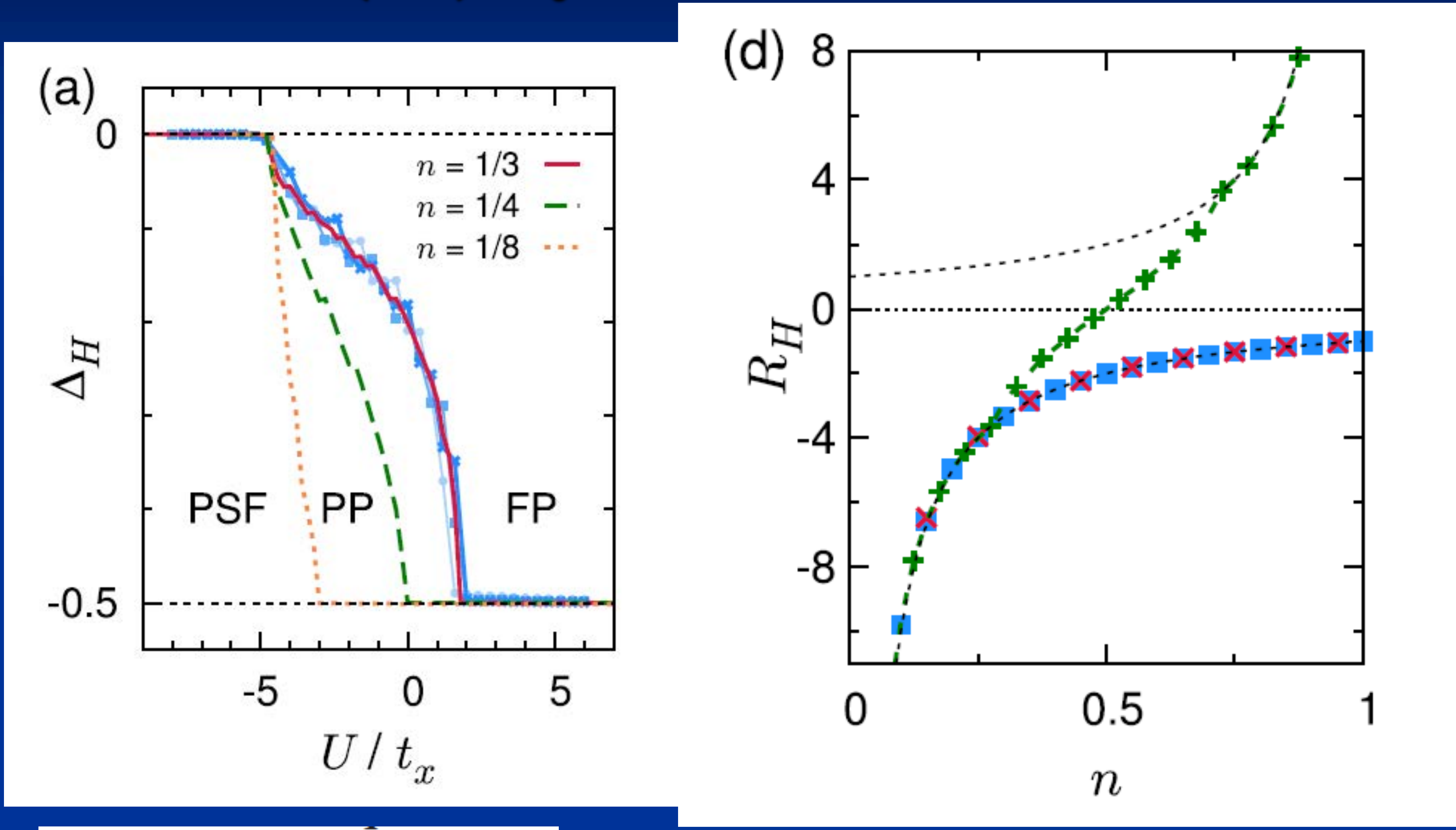
$$\Delta_H = q\mathcal{I}_0(M, t_\perp) \quad \text{and} \quad R_H = -1/n.$$

Numerics





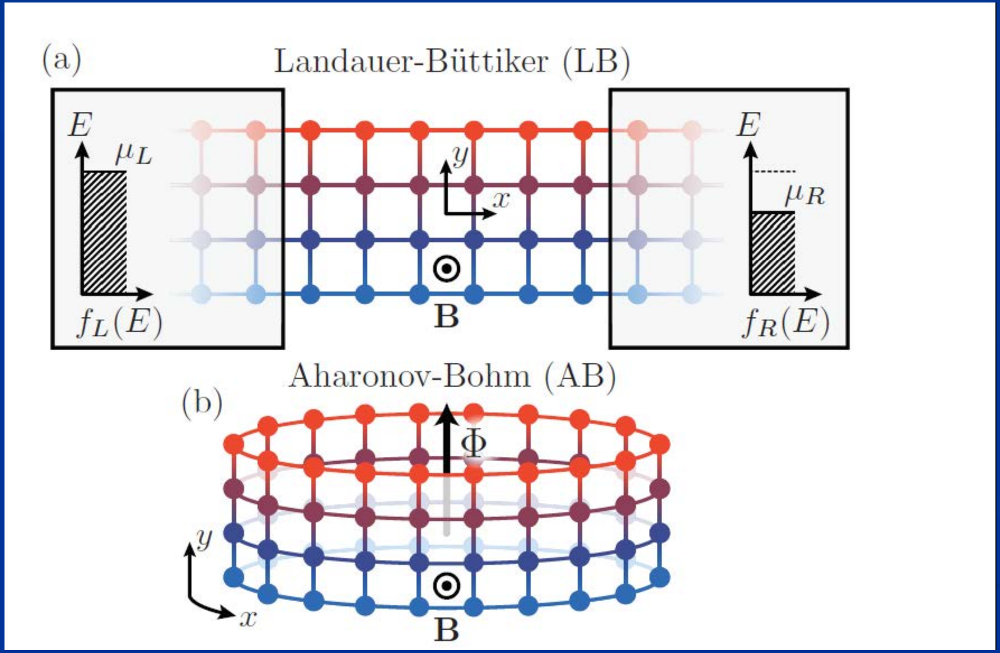
SU(M) symmetric ladders



$$\langle P_y \rangle = \chi \mathcal{I}_0 \langle 0 | J_x | 0 \rangle$$

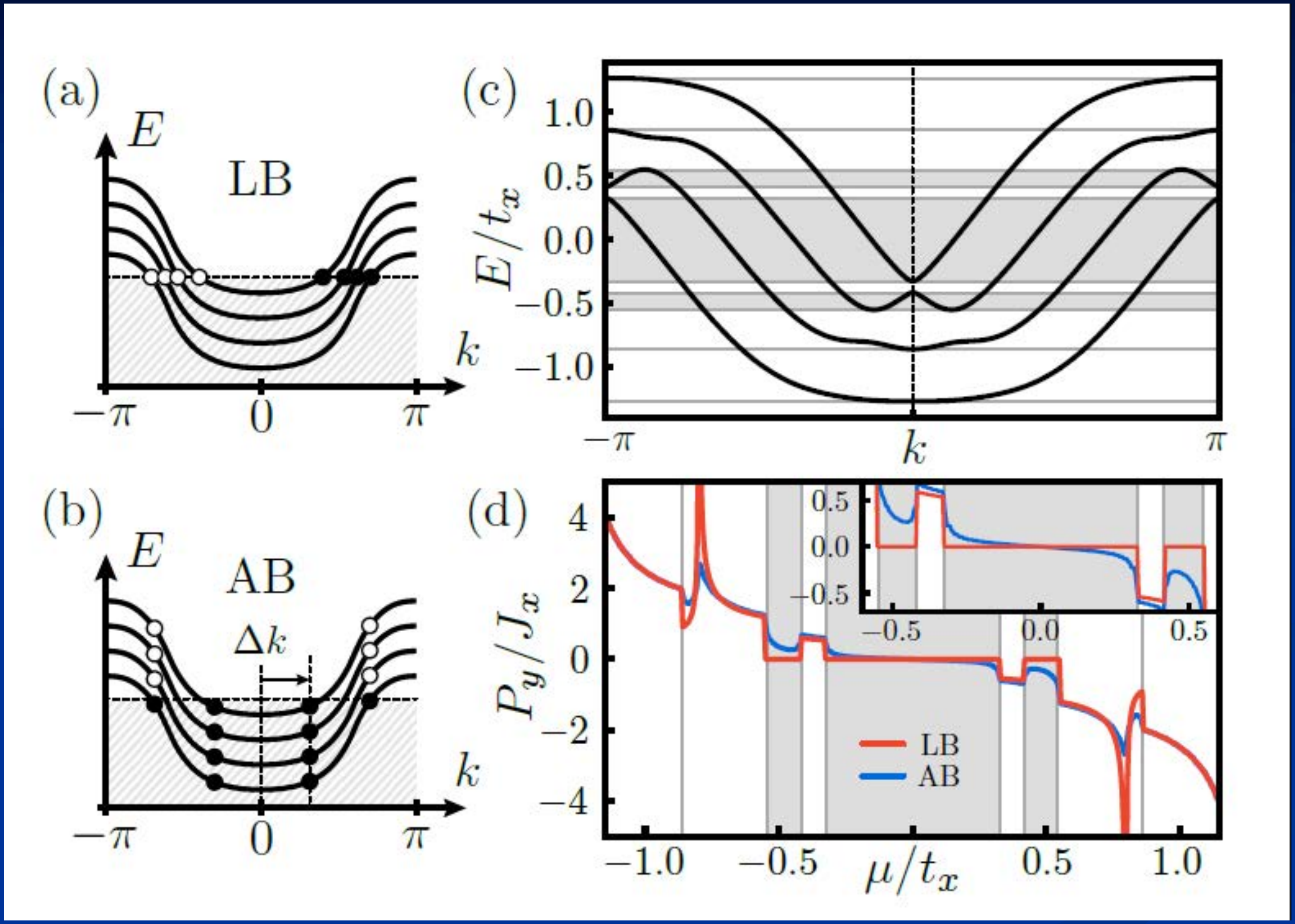
Vanishing Hall response

M. Filippone, C.E. Bardyn, S. Greshner, TG, PRL 123, 086803 (19)



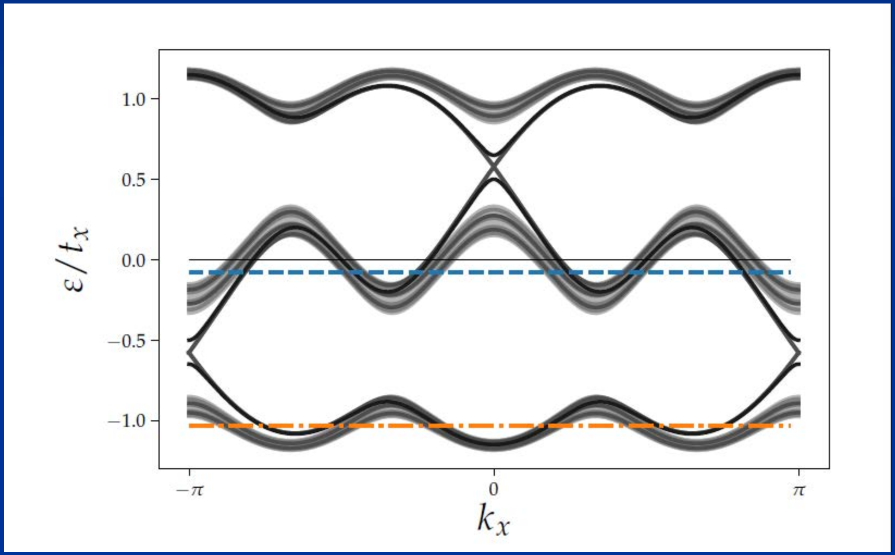
$$\frac{P_y^{\mathrm{AB}}}{J_x} = -D^{-1} \lim_{\omega \to 0} \sigma_{\mathrm{H}}(0,\omega) \,.$$

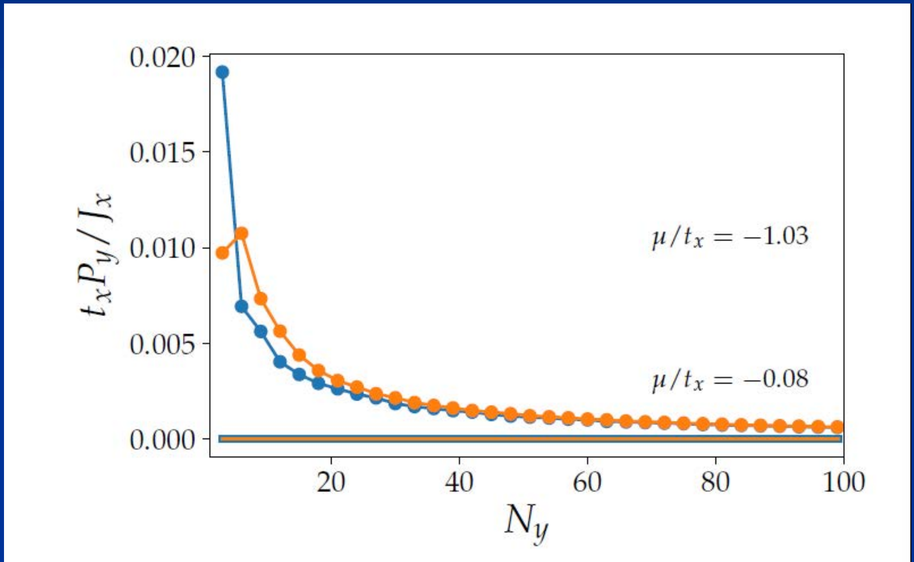
$$\frac{P_y^{\mathrm{LB}}}{J_x} = -G^{-1} \lim_{\omega \to 0} \frac{1}{2\pi} \int dk \, e^{ikx} \frac{\sigma_{\mathrm{H}}(k,\omega)}{\omega + i0^+} \,,$$



Exact zero of the Hall effect for LB geometry

Topological origin





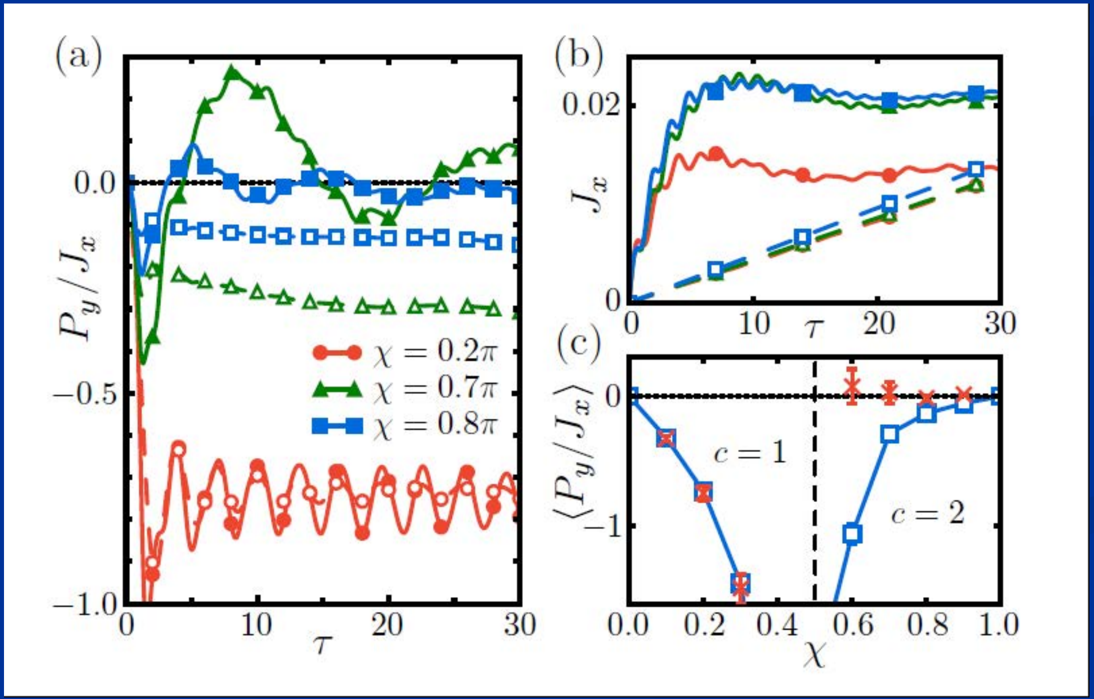
$$c(\mu) = N_y$$

Central charge

Robustness to perturbations

Temperature: energy gap

Interacting systems:



Conclusions/Perspectives

- Calculations and measurements of quantum transport with cold atomic systems
- Novel situations and effects (Luther-Emery liquid, spin transport, etc.)
- Many exciting possibilities (hall, etc.) and challenging theory questions