DQMP Department of Quantum Matter Physics

Hall effect in interacting systems

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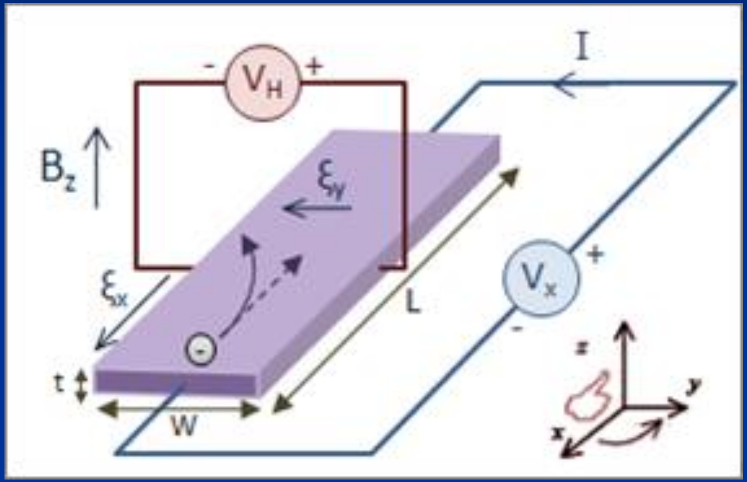
Hall effect



Non interacting ``simple”

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

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

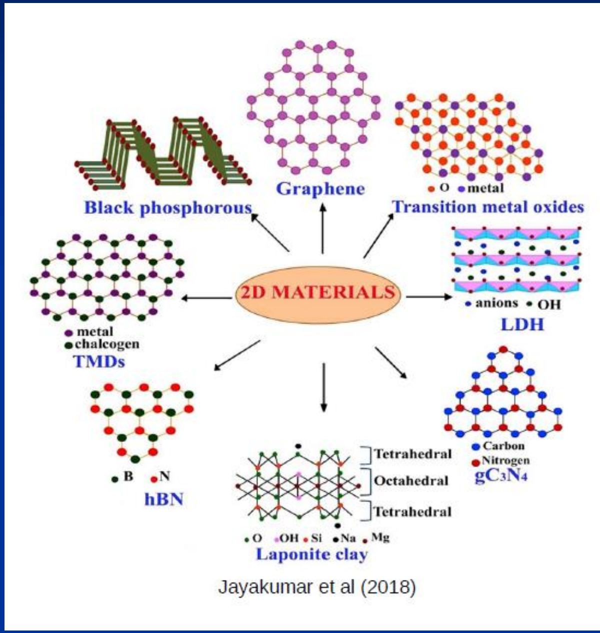
With **interactions**: open question

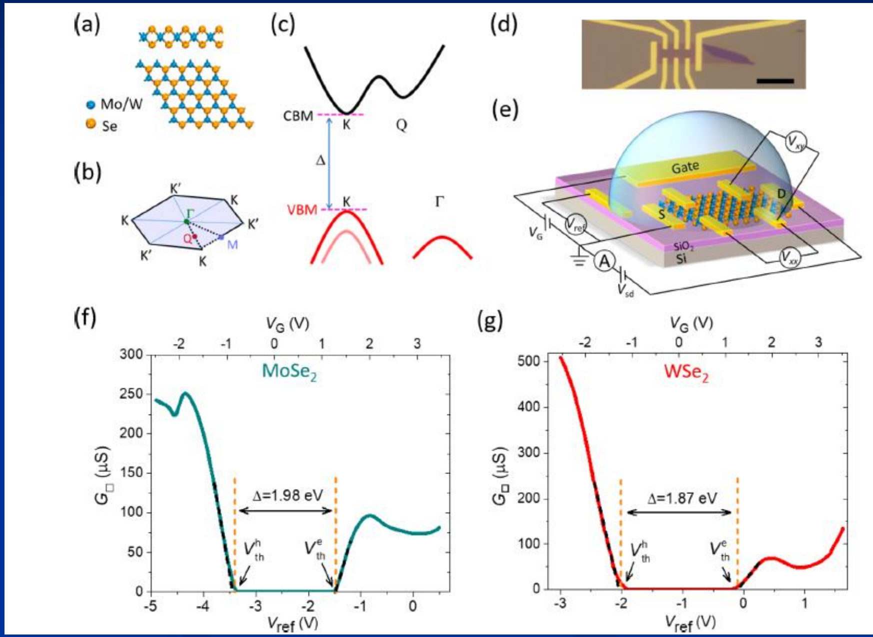
Two interesting situations

- Low density systems (electrostatic doping near an empty band)

- Dimensional effects: quasi-1D coupled systems, moiré (??)

Low density systems





- Novel effect:
  cross quantum capacitance

$$\frac{1}{C} = \frac{1}{C_G} + \frac{1}{C_Q} + \frac{1}{C_s}$$

H. Zhang, C. Berthod, H. Berger, TG, A. Morpurgo, Nano Letters, 19, 8836 (2019)

C. Berthod, H. Zhang, A. Morpurgo, TG, PRR 3, 043036 (2021)

Hall effect

G. Morpurgo, L. Rademaker, C. Berthod, TG, PRR 6 013112 (2024)

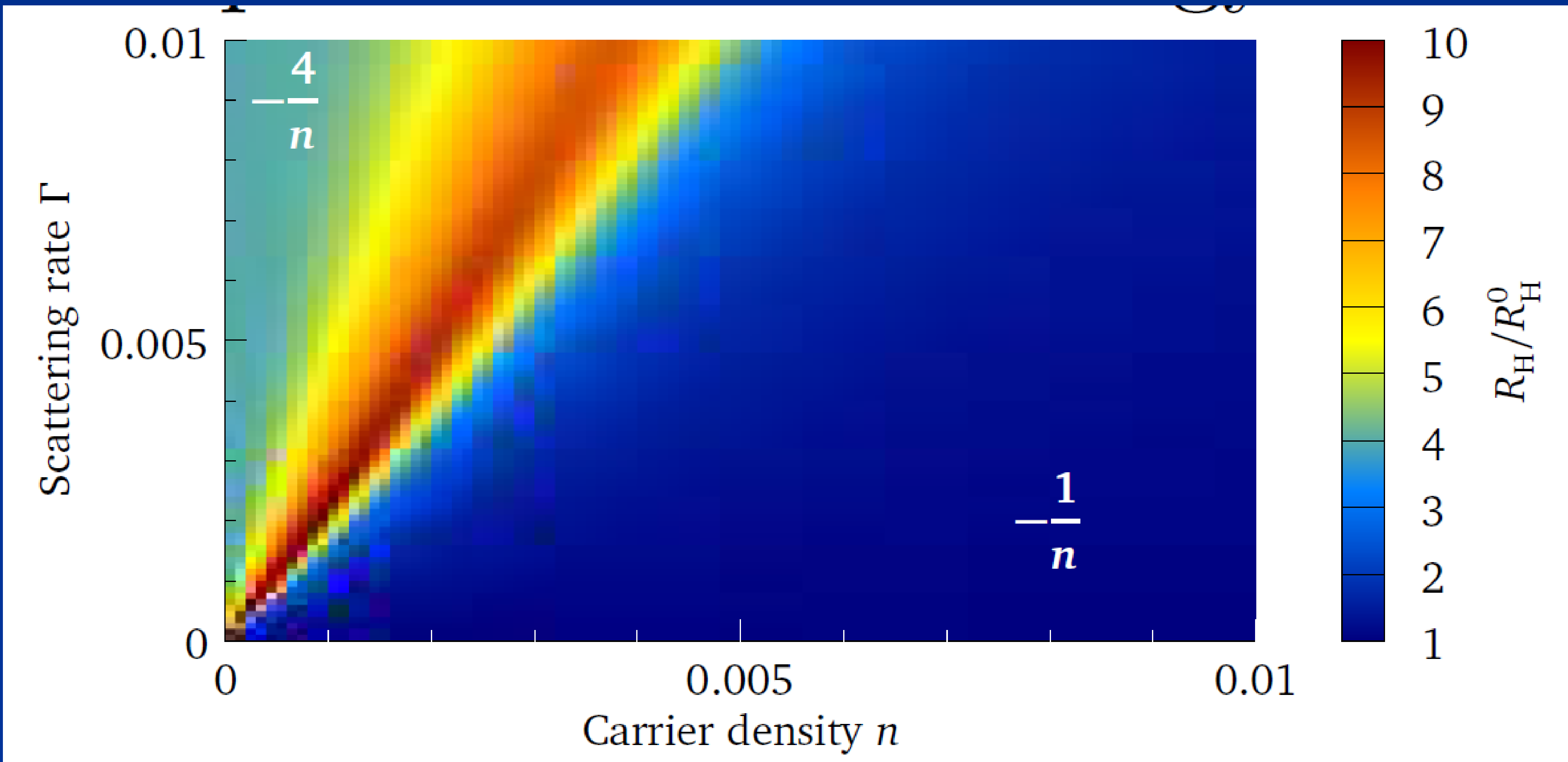
$$\sigma_{xx}^{(0)} \propto \int_{-\infty}^{\infty} d\varepsilon \, [-f'(\varepsilon-\mu)] \int d^2k \, v_{xx}^2 A^2(E_k, \varepsilon)$$

$$\sigma_{xy}^{(1)} \propto \int_{-\infty}^{\infty} d\varepsilon \, [-f'(\varepsilon-\mu)] \int d^2k \left(\frac{v_x v_y}{m_{xy}} - \frac{v_x^2}{m_{yy}} \right) A^3(E_k, \varepsilon)$$

- We consider a local (k-independent) self energy

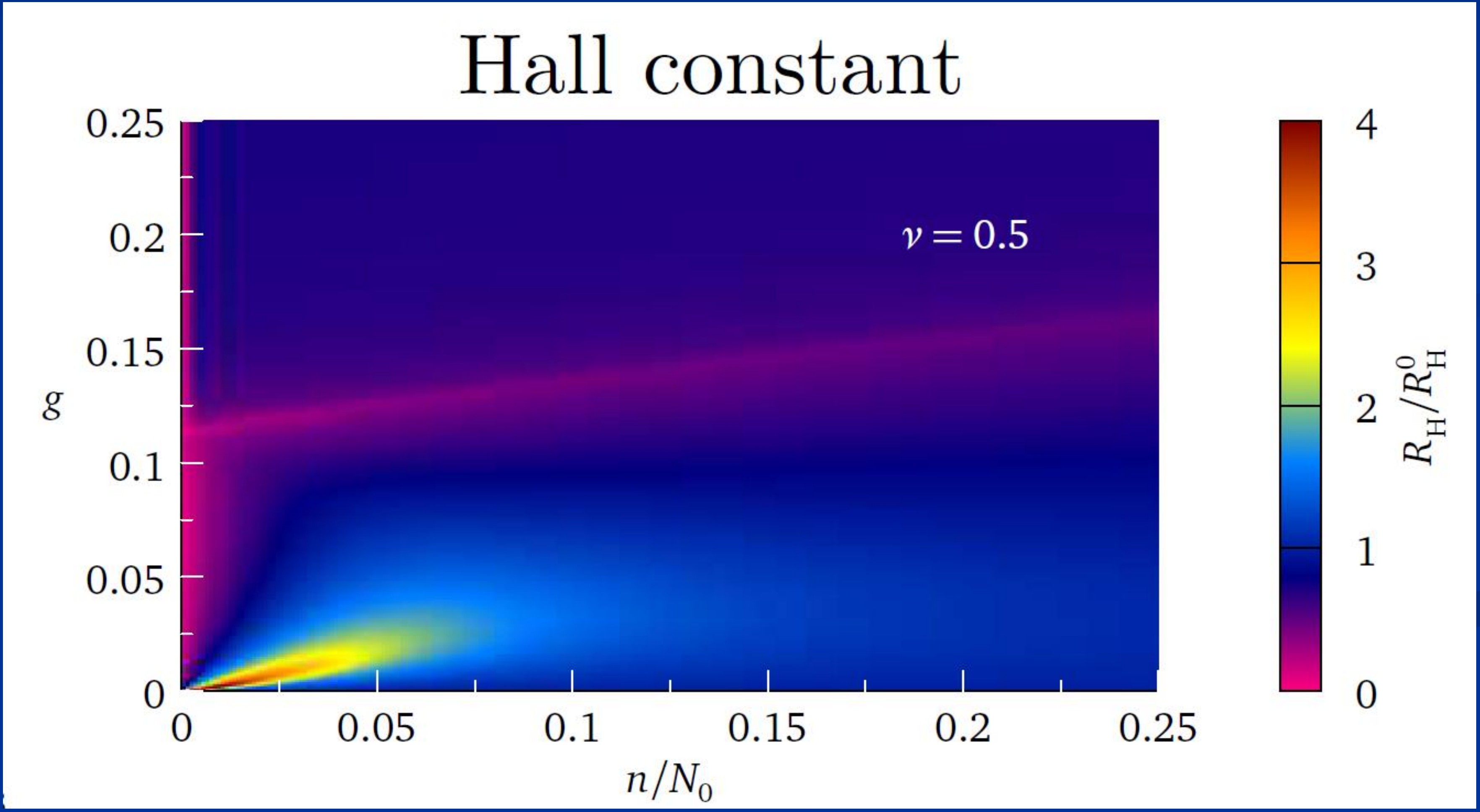
Constant self energy Σ = -iΓ

G. Morpurgo, L. Rademaker, C. Berthod, TG, PRR 6 013112 (2024)



Power-law self energy

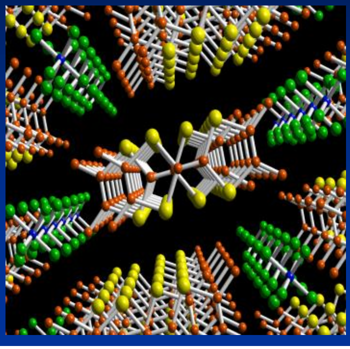
$$\mathrm{Im}\Sigma(\varepsilon) = -g(\varepsilon - \varepsilon_0)^{\nu}$$

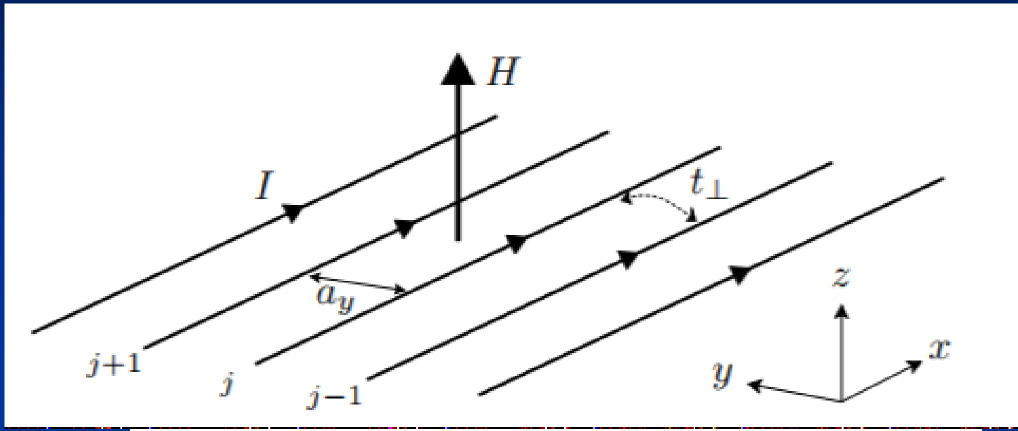


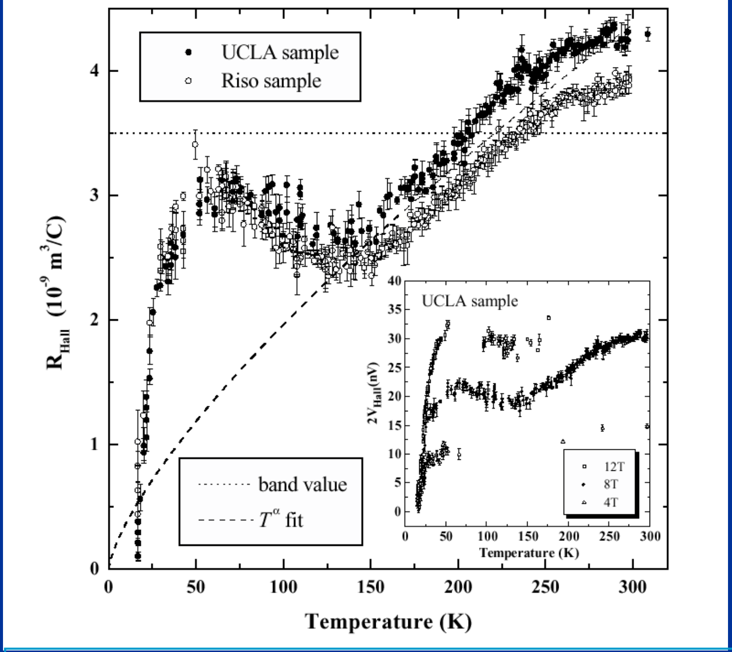
Coupled 1D structures

- Organic conductors/superconductots (Bechgaard salts)
- Cold atomic systems
- Moiré systems ??

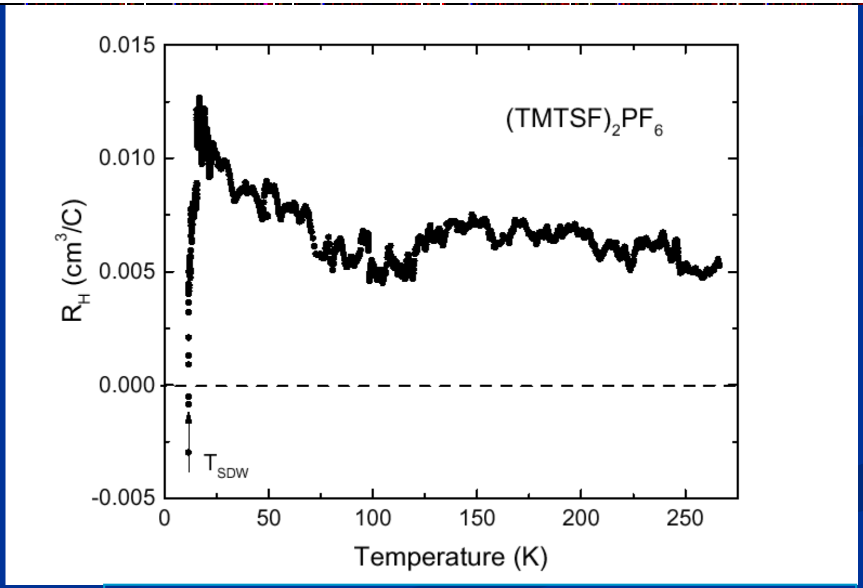
Experiments ?







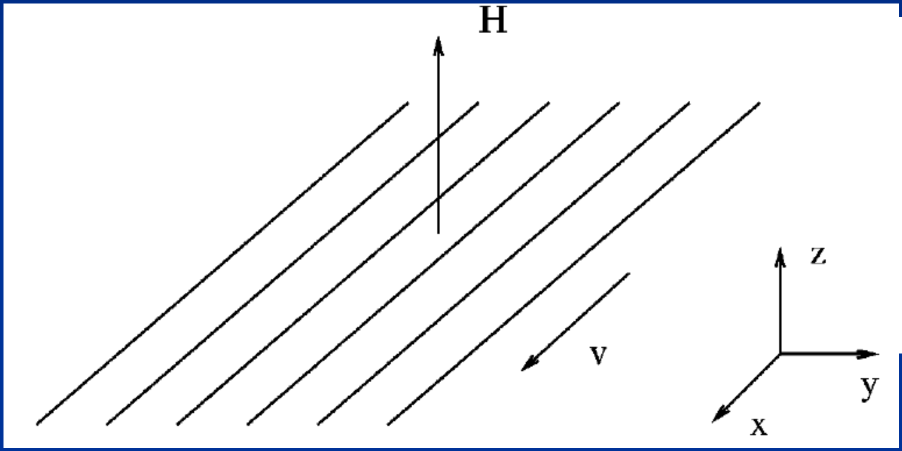
J. Moser et al., PRL 84 2674 (00)



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

Quasi-1D geometry

A. Lopatin, A. Georges, TG PRB 62 (00)



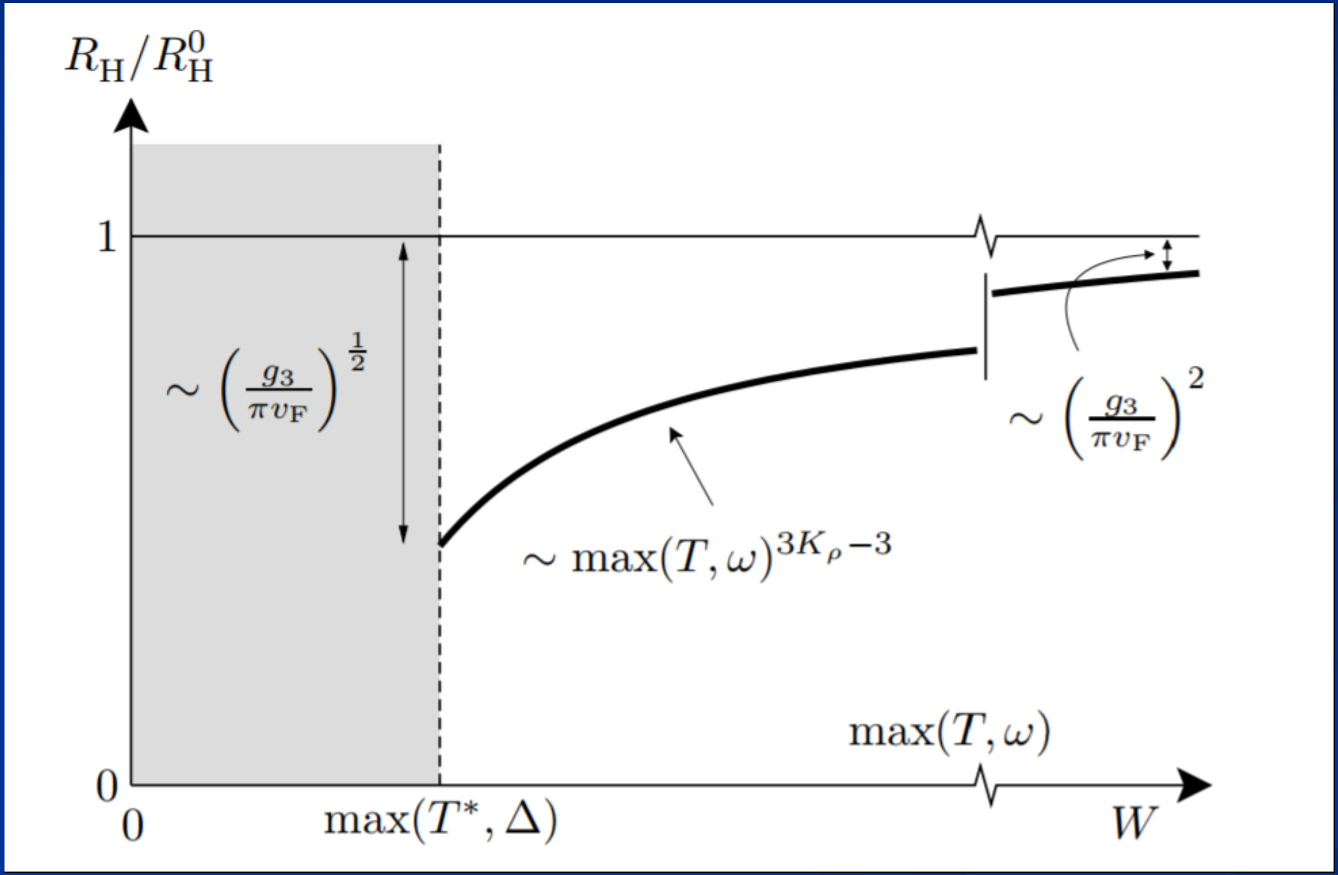
$$H = \int dx \Big[\sum_i v_F \hat{\psi}_i^\dagger \tau_3 (-i\partial_x) \hat{\psi}_i - \alpha \sum_i \hat{\psi}_i^\dagger \partial_x^2 \hat{\psi}_i + g \sum_i \hat{\psi}_{i+}^\dagger \hat{\psi}_{i+} \hat{\psi}_{i-}^\dagger \hat{\psi}_{i-} - t_\perp \sum_{\langle i,j \rangle} \hat{\psi}_i^\dagger \hat{\psi}_j e^{-i\frac{e}{c}A_{i,j}} \Big]$$

$$\epsilon_\pm = \pm v_F (p \mp p_F) + \alpha (p \mp p_F)^2 .$$

α = 0 : usual TLL description of 1D systems

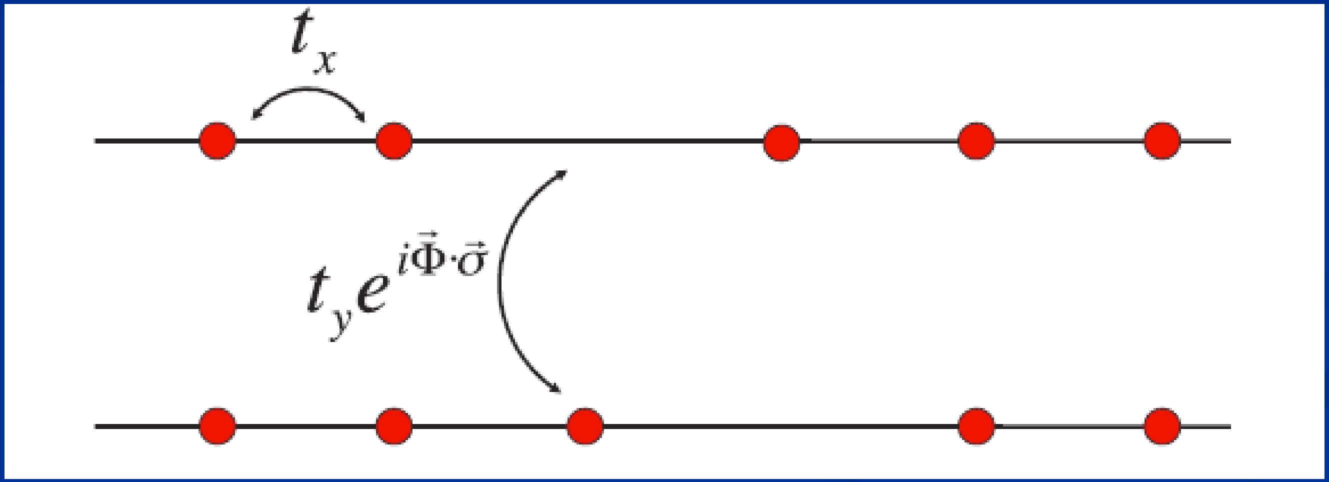
But: α = 0 : Particle hole symmetry; Hall = 0

High temperature regime

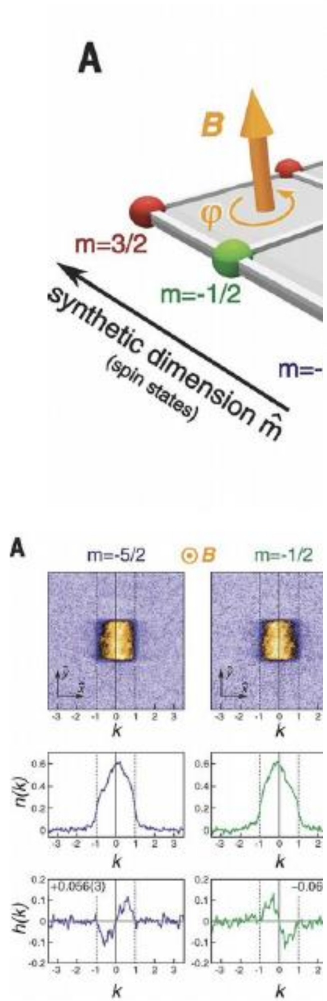


G. Leon, C. Berthod, TG PRB 75, 195123 (2007)

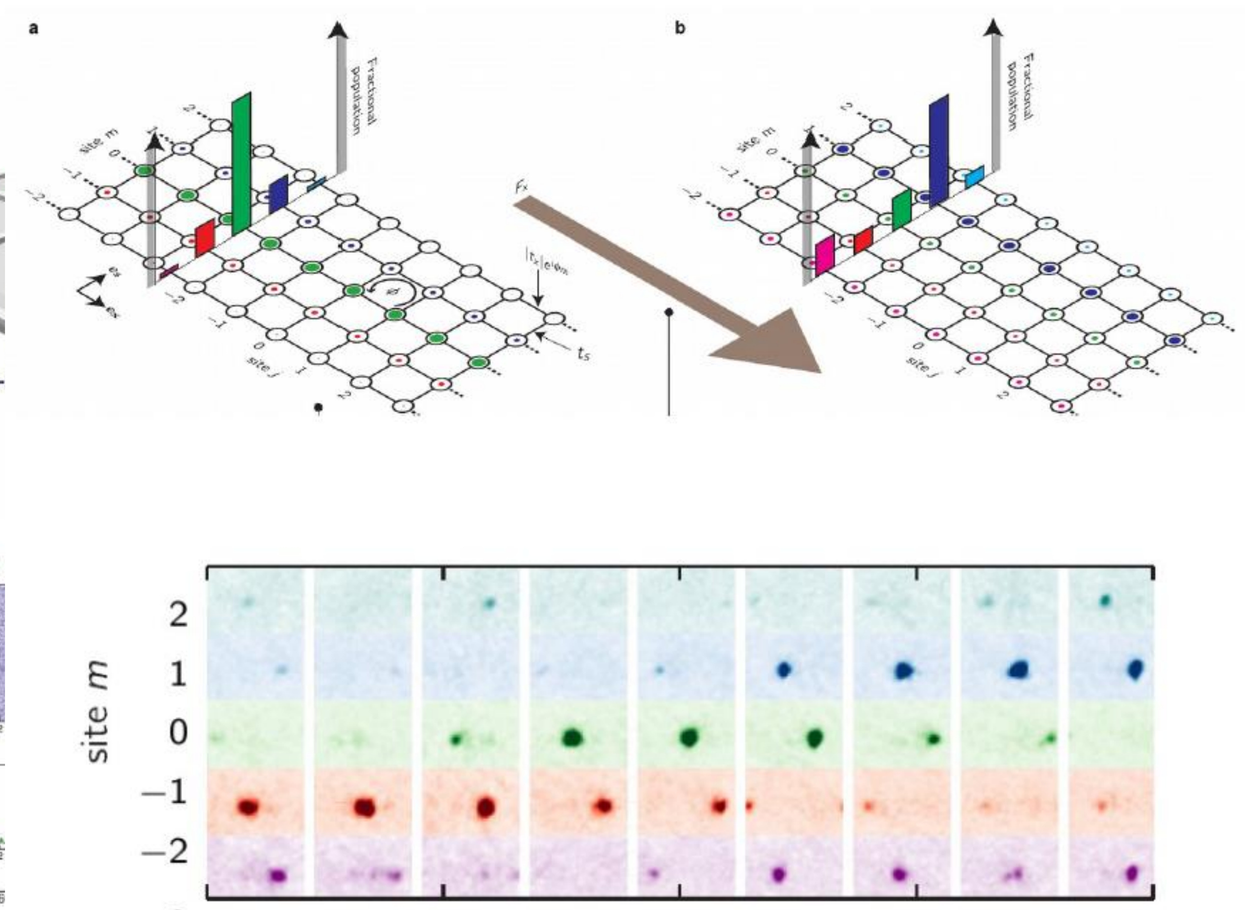
Other geometries: ladders



Synthetic GF / dimensions



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

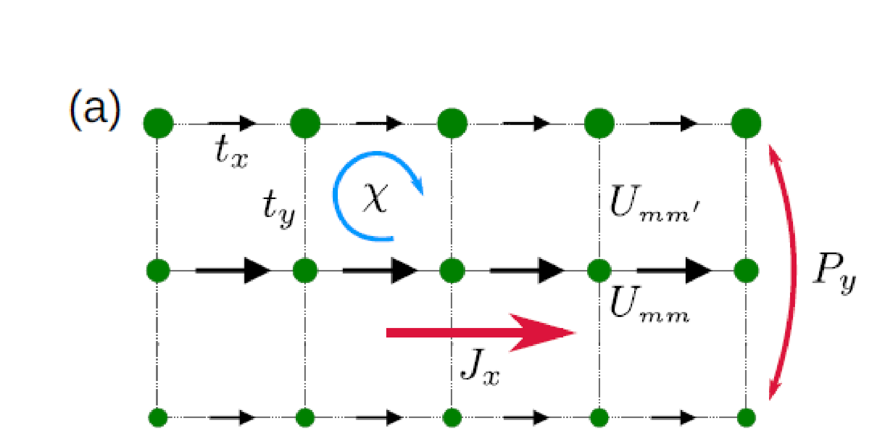


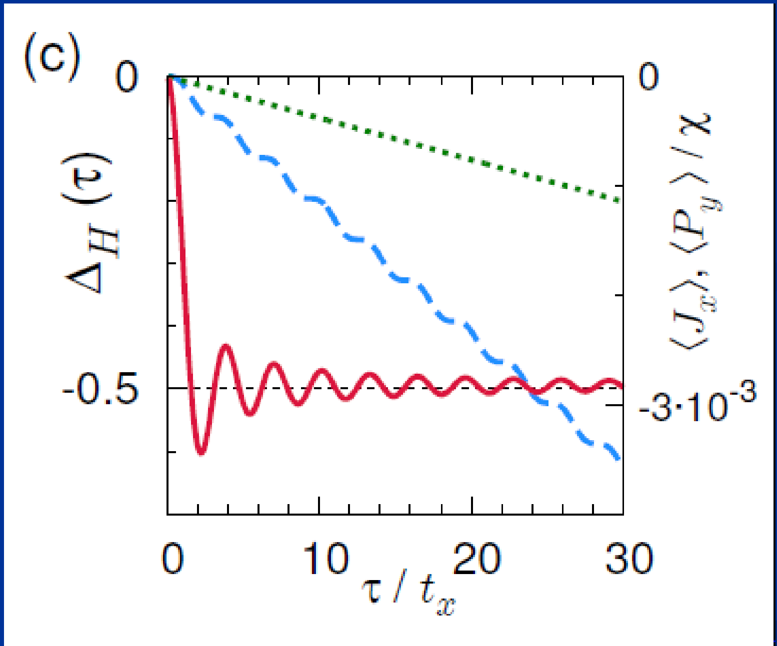
Dina Genkina et al 2019 New J. Phys. 21 053021

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

Hall effect on ladders

S. Greshner, M. Filippone, TG, PRL 122, 083402 (2019)



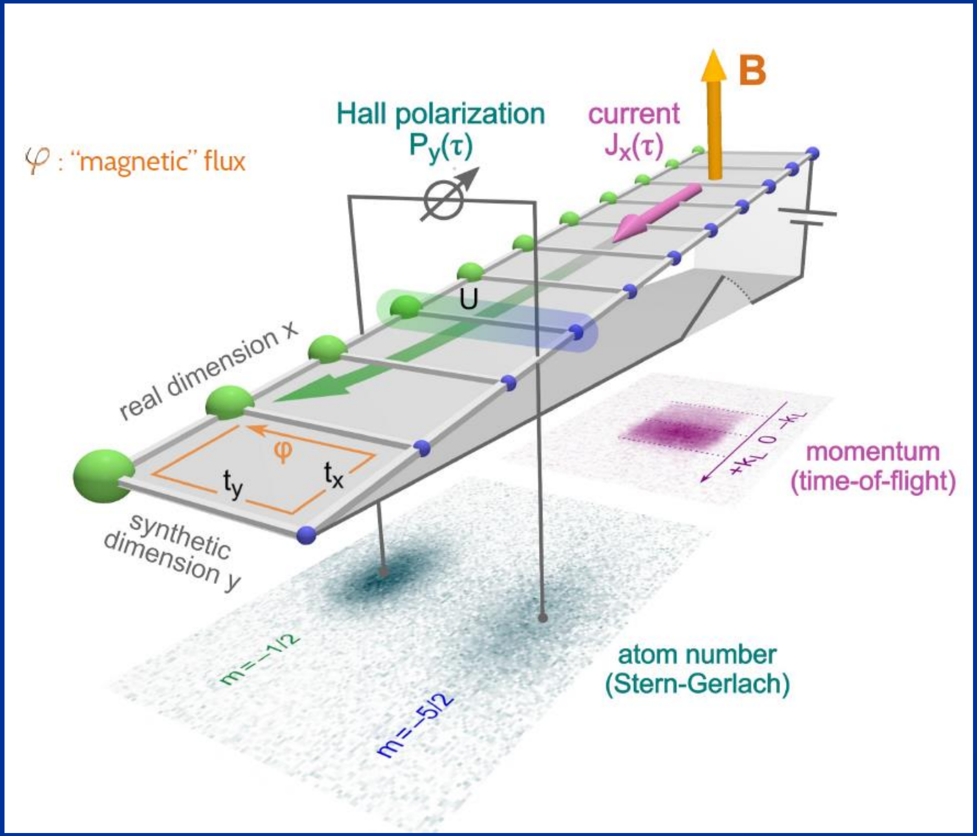


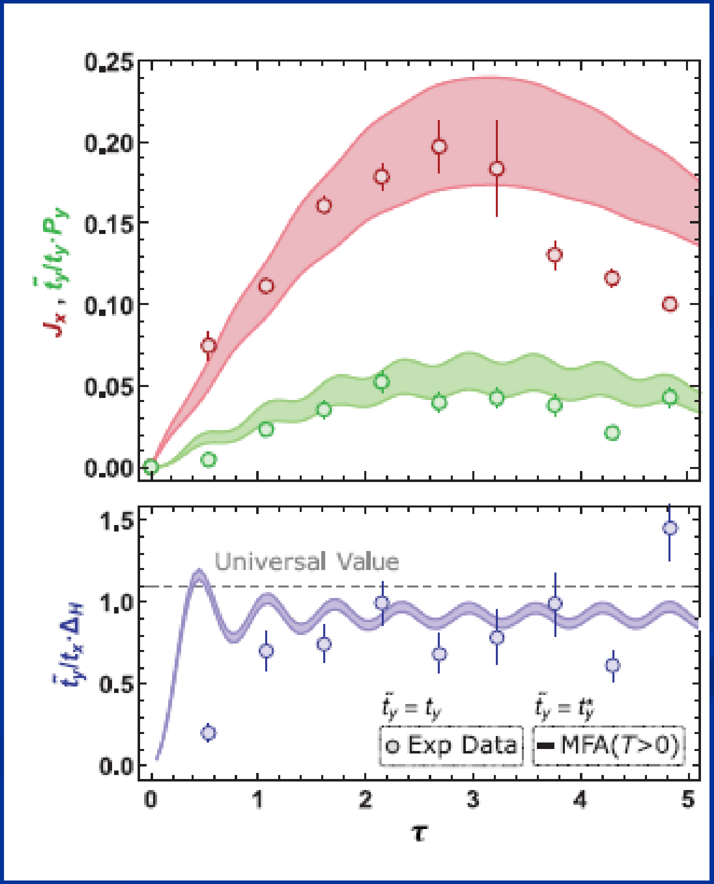
$$\Delta_H = q\mathcal{I}_0(M, t_\perp) \quad \text{and} \quad R_H = -1/n.$$

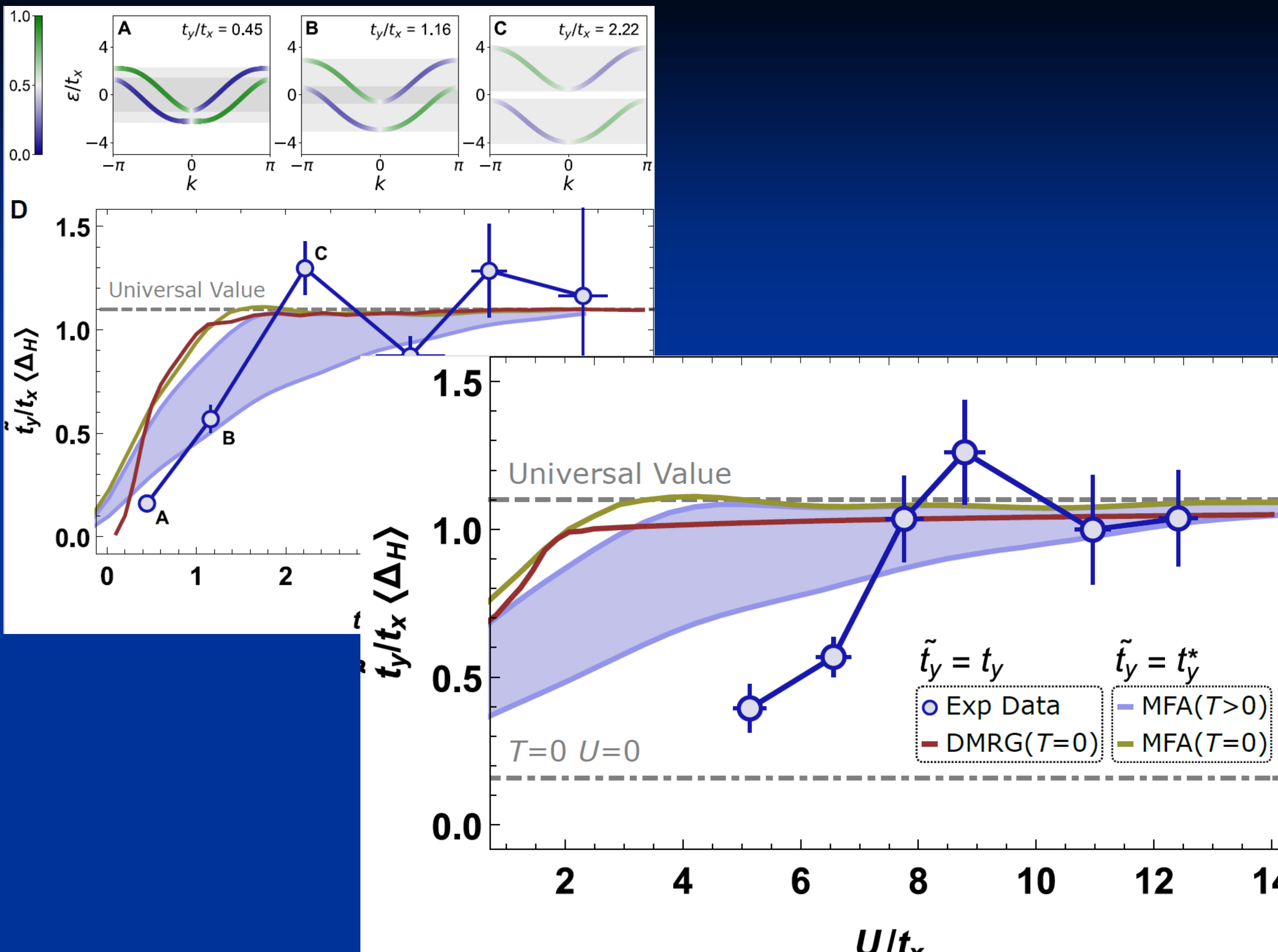
Universal value of Hall resistance

Quantum simulation

T.-W. Zhou, G. Cappellini, D. Tusi, L. Franchi, J. Parravicini, C. Repellin, S. Greschner, M. Inguscio, TG, M. Filippone, J. Catani, L. Fallani, Science (2023).



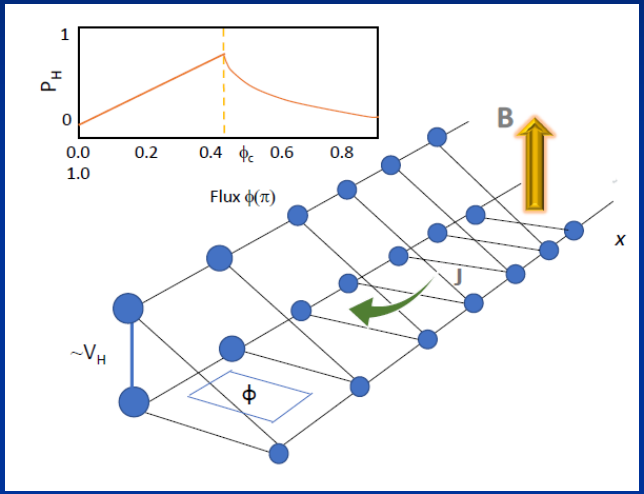




A
t_y/t_x = 0.45
B
t_y/t_x = 1.16
C
t_y/t_x = 2.22
ε/t_x
k
D
Universal Value
$\tilde{t}_y/t_x\,\langle\Delta_H\rangle$
Universal Value
T=0 U=0
$\tilde{t}_y = t_y$
$\tilde{t}_y = t_y^*$
Exp Data
DMRG(T=0)
MFA(T>0)
MFA(T=0)
U/t_x

Analytical derivation

Bosonization: small ty



$$\psi(x)=\sqrt{\rho(x)}e^{i\theta(x)}$$

$$\pi\Pi(x)=\nabla\theta(x)$$

$$\rho(x)=-\frac{1}{\pi}\nabla\phi(x)$$

$$\alpha=-\frac{\partial}{\partial\rho_0}\left(\frac{u}{6\pi^2K}\right),$$

$$\gamma=-\frac{\partial}{\partial\rho_0}\left(\frac{uK}{2\pi^2}\right).$$

$$H = \sum_{p=1,2} H_p + H_{tunn.}$$

$$H_p = \int\frac{dx}{2\pi}\left[uK(\pi\Pi_p)^2+\frac{u}{K}(\partial_x\phi_p)^2\right]+\int dx\left[\alpha(\partial_x\phi_p)^3+\gamma(\pi\Pi_p)^2\partial_x\phi_p\right],$$

$$H_{tunn.} = -\frac{t_\perp}{\pi\alpha}\int dx\cos(\theta_1-\theta_2),$$

Hall voltage

$$V_H = -\frac{\pi^2\gamma\langle j_\rho\rangle}{eu_\rho K_\rho}Ba = -\langle j_\rho\rangle\frac{Ba}{2e}\frac{1}{u_\rho K_\rho}\frac{\partial}{\partial\rho_0}(u_\rho K_\rho),$$

- Hall resistance

$$R_H = \frac{a}{eu_s K_s}\frac{\partial}{\partial\rho_0}(u_s K_s).$$

Charge stiffness !

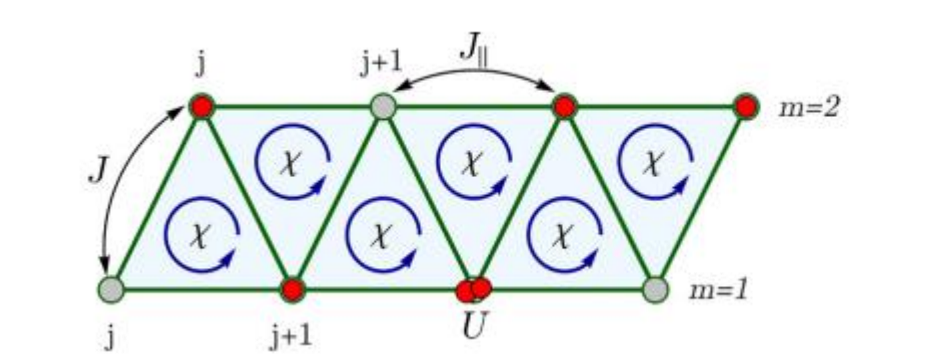
- Galilean system

$$R_H = \frac{aB}{e\rho_0},$$

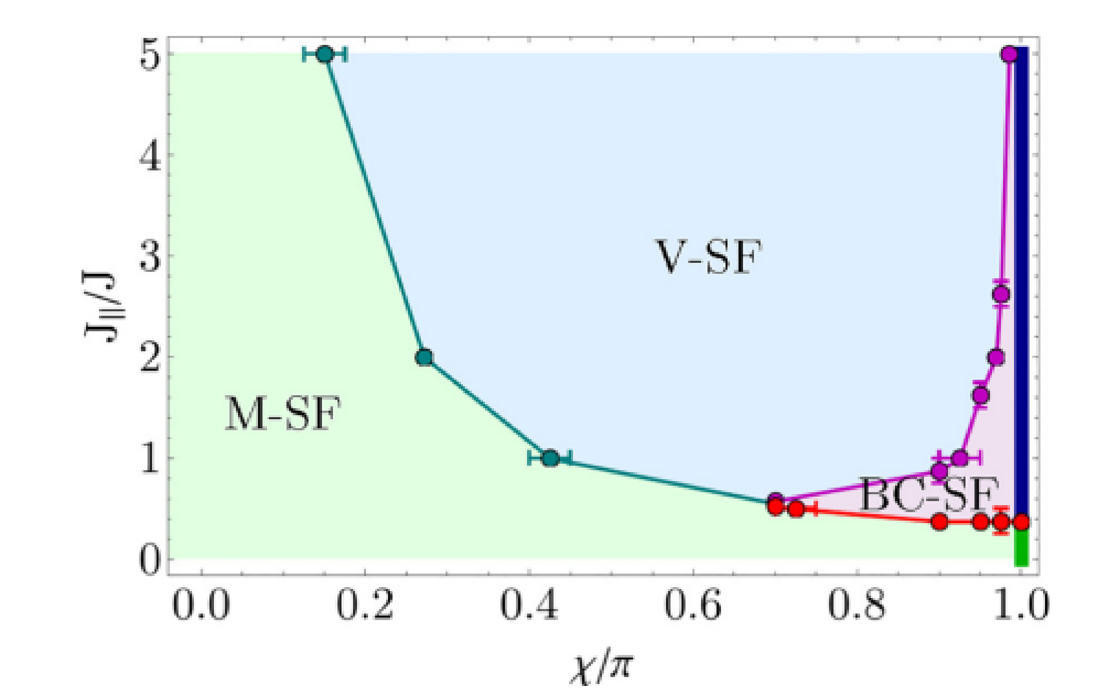
- Near Mott

$$R_H \sim \frac{a}{e}\frac{\mathrm{sign}(\rho_0 - \rho_{0,c})}{|\rho_0 - \rho_{0,c}|},$$

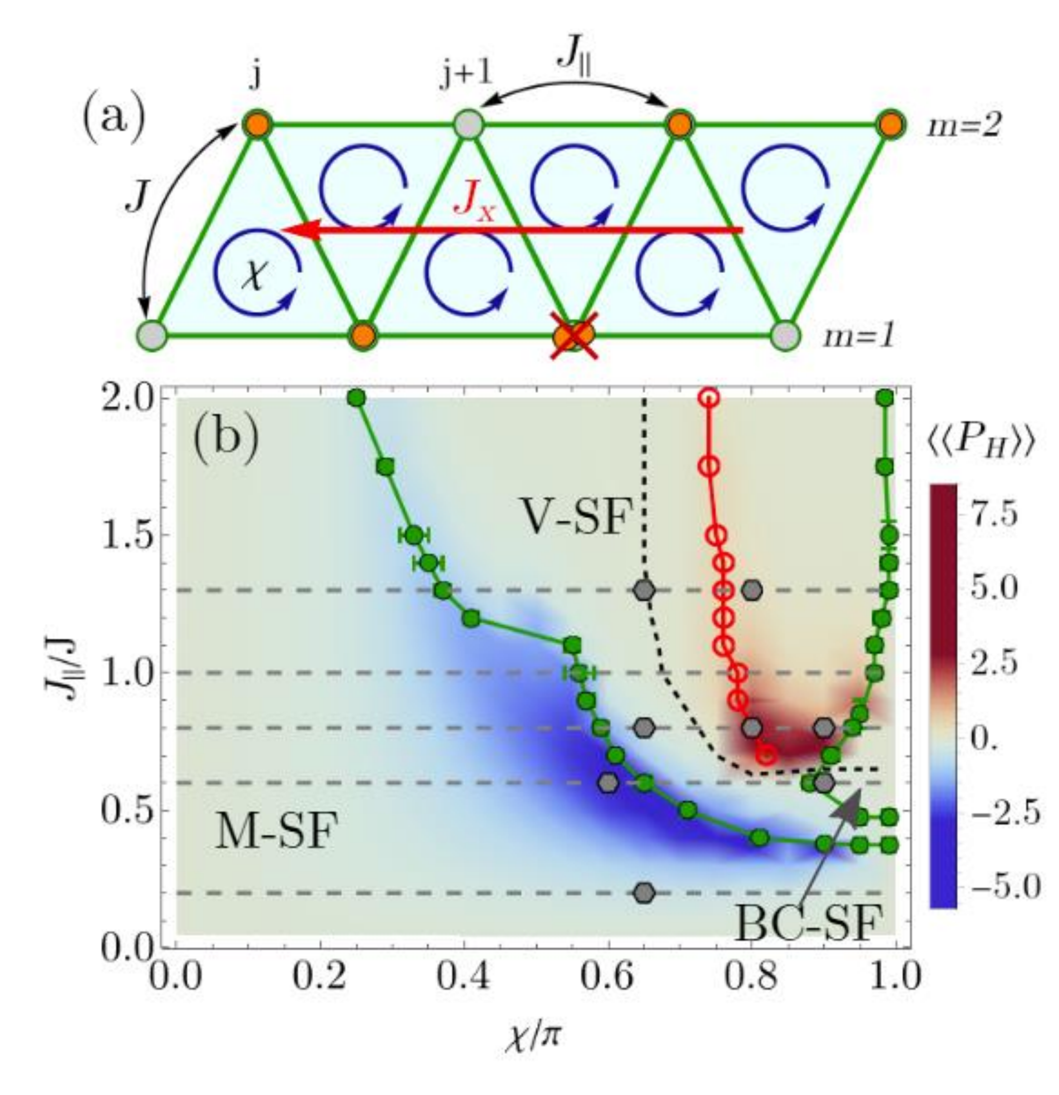
Triangular ladders



C. Halati and TG
PRR 5, 013126 (2023)



Hall effect



C. Halati, TG, arxiv.org/abs/2405.19030

Harcore bosons

Conclusions

- Remarkable properties of Hall effects for interacting quantum systems
- Low density: anomalous behavior of the Hall effect even for parabolic bands
- Ladders: Universal regime: 1/n for large tunnelling or large interactions.
- Confirmed in experiments in cold atomic gases
- Analytic expression for the Hall effect in a TLL
- Experiments in CM !!!!