DQMP Department of Quantum Matter Physics

From fermions to spinons and holons, a tale of dimensionality

http://giamarchi.dqmp.ch

UNIVERSITÉ DE GENÈVE

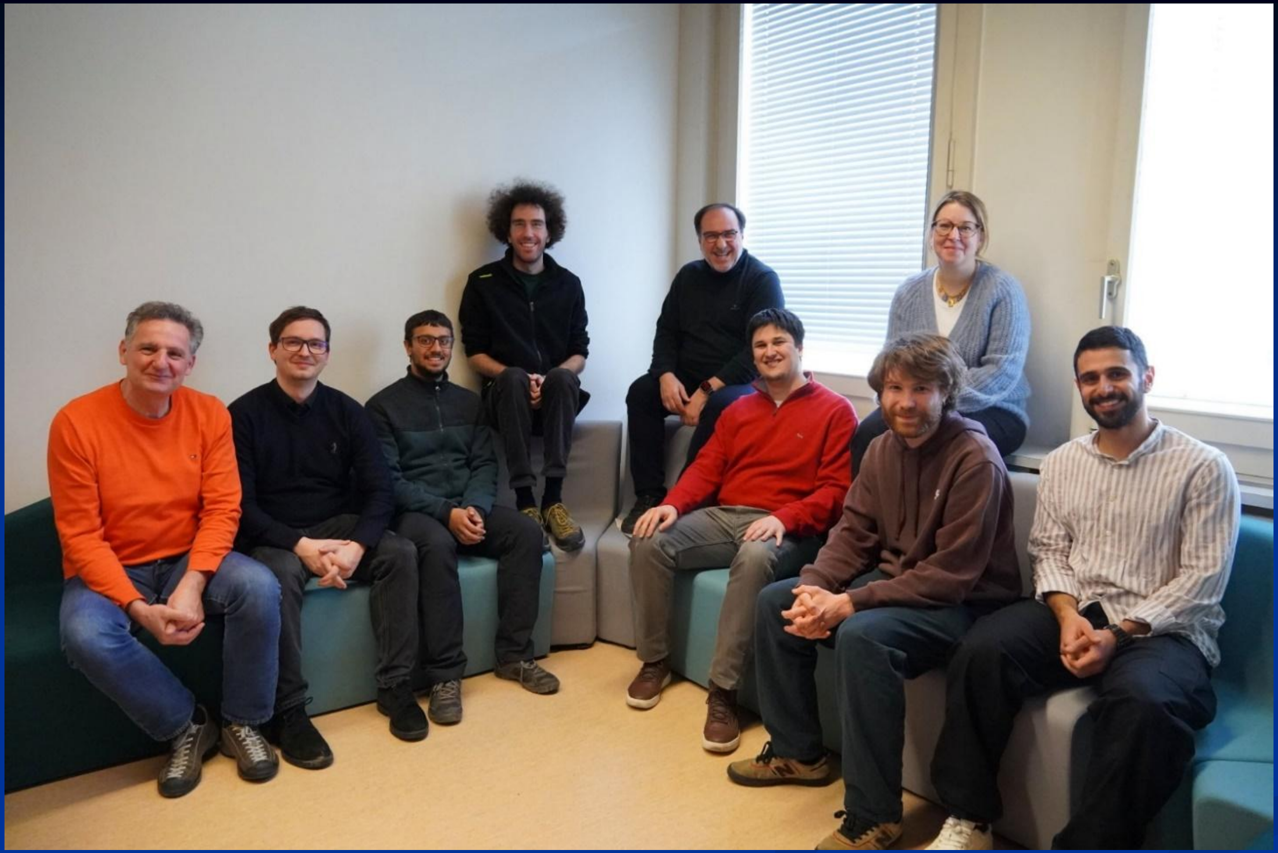
FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

MaNEP SWITZERLAND



R. Citro

E. Orignac



C. Kollath

M. Cazalilla

C. Berthod, C. Halati, S. Sur, G. Morpurgo, TG, L. Gotta, F. Hartmeier, D. Bertolusso, L. Pizzino

H.J. Schulz, M. Cazalilla, R. Citro, C. Kollath, E. Orignac,

Condensed matter: P. Bouillot, R. Chitra, A. Tsvelik, C. Varma, ….
Exp Groups: C. Berthier, L. Degiorgi, M. Dressel, B. Grenier, D. Jerome, S. Petit, C. Ruegg, V. Simonet, A. Zheludev,…

Cold atoms: V. Cheianov, E. Demler, A. Ho, L. Sanchez-Palencia, U. Schollwoeck, P. Torma, M. Zvonarev,…
Exp Groups: I. Bloch, J.P. Brantut, T. Esslinger, L. Fallani, R. Hulet, M. Inguscio, F. Minardi, G. Modugno, H.C. Nagerl, G. Roati, ….

How to master materials ?

- Understood: free electrons
- Real systems : Coulomb interaction

E ~ 10 000 K !

- Properties of realistic systems ?

- Free electron theory works quite well : Landau Fermi liquid

$$m \rightarrow m^*$$

One dimensional quantum systems

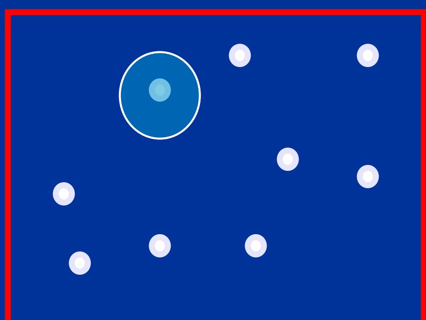
A good reason to work on 1D

However, my personal reason for working on one-dimensional problems is merely that they are fun. A man grows stale if he works all the time on the insoluble and a trip to the beautiful work of one dimension will refresh his imagination better than a dose of LSD.

Freeman Dyson (1967); review in Physics today of the book by E.H. Lieb and D.C. Mattis

Why is 1D special (and interesting) ?

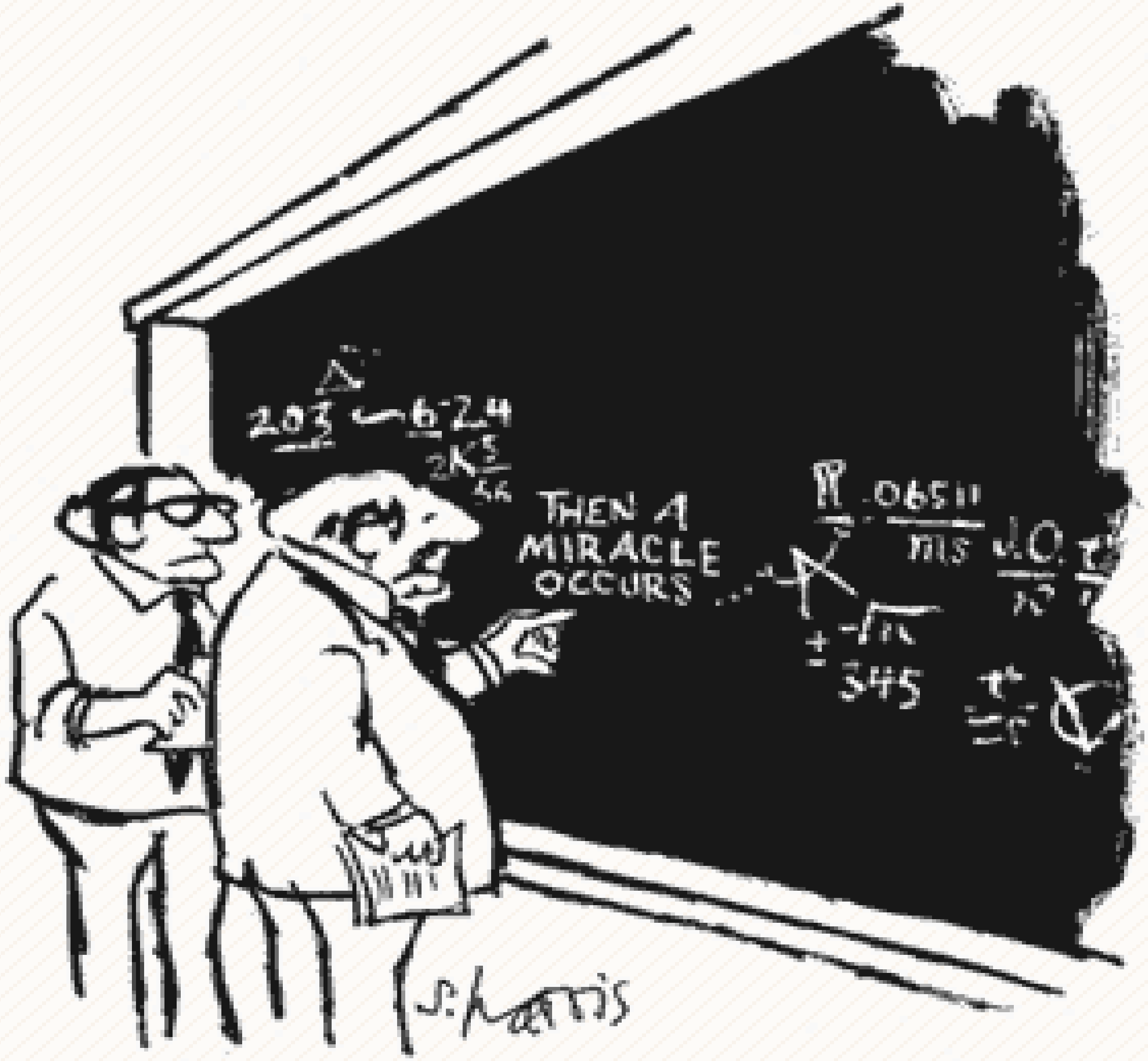
- No individual excitation can exist (only collective ones)



- Strong quantum fluctuations

$$\psi = |\psi| e^{i\theta}$$

Difficult to order

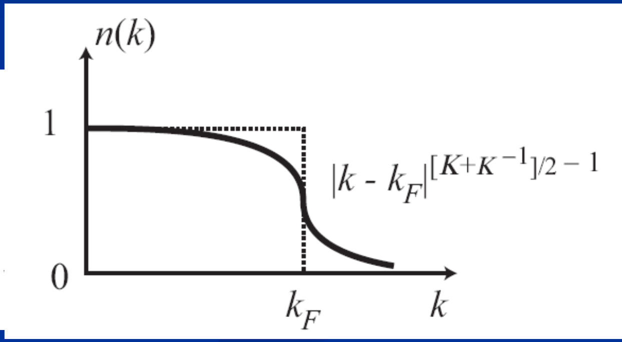


"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Tomonaga-Luttinger liquids

- No separation of statistics and interactions
- Criticality:

$$\langle\rho(x,\tau)\rho(0)\rangle = \rho_0^2 + \frac{K}{2\pi^2}\frac{y_\alpha^2 - x^2}{(x^2+y_\alpha^2)^2} + \rho_0^2 A_2 \cos(2\pi\rho_0 x)\left(\frac{\alpha}{r}\right)^{2K}$$
$$+ \rho_0^2 A_4 \cos(4\pi\rho_0 x)\left(\frac{\alpha}{r}\right)^{8K}$$



- Few parameters control all physical properties:

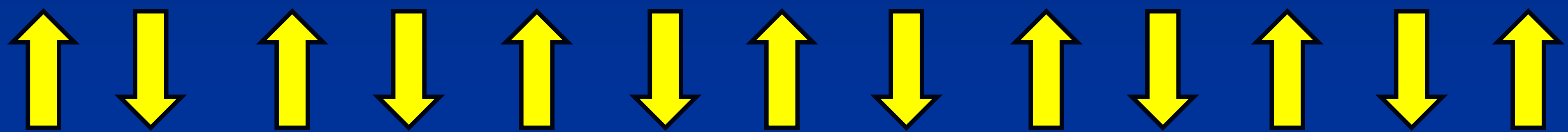
u: velocity of excitations (sound velocity)

K: controls all exponents

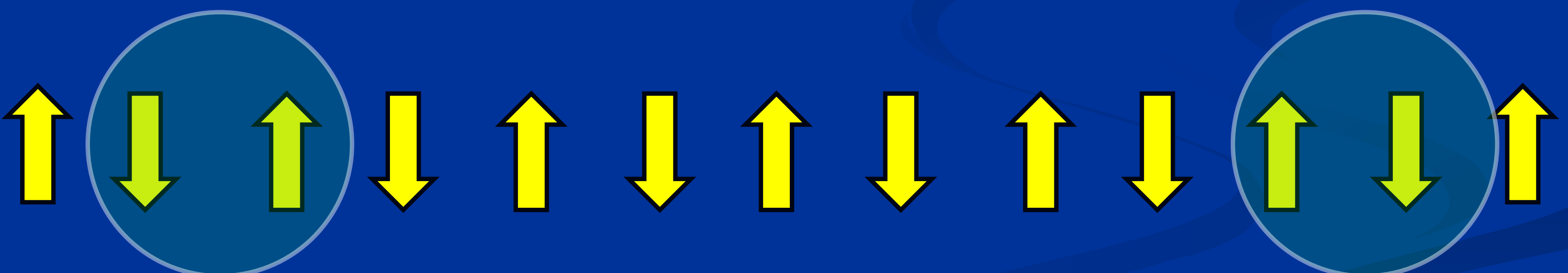
A: non-universal amplitudes

Fractionalization of excitations

$$H = J\sum_i \vec{S}_i \cdot \vec{S}_{i+1}$$

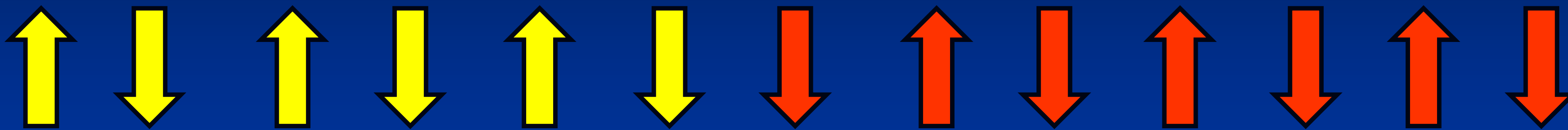


$\Delta S = -1$ $E =$ ò(q) Magnon



$\Delta S = -1/2$ Spinons $\Delta S = -1/2$

Magnons and spinons: 1 = ½ + ½

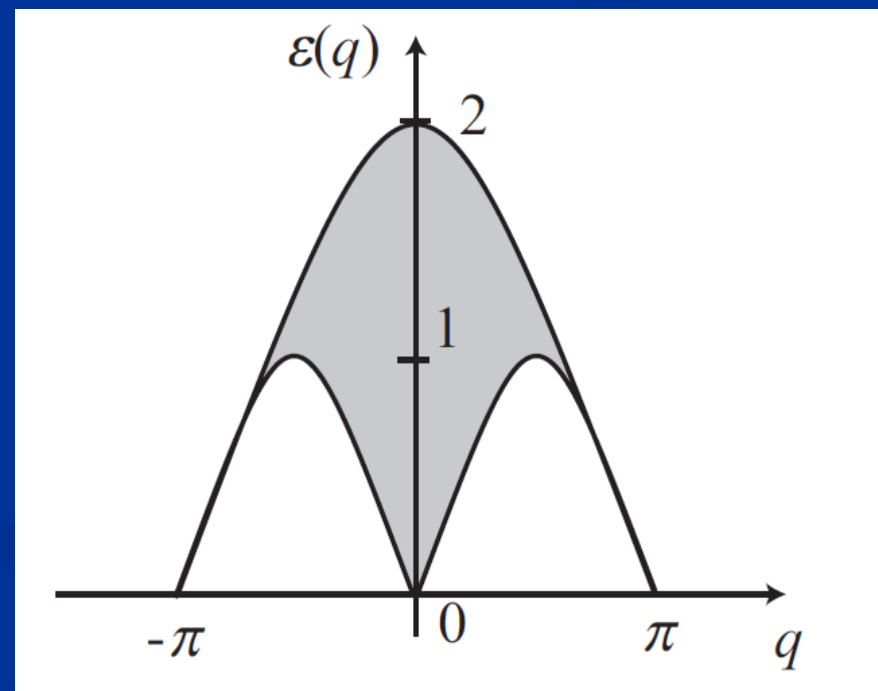


- Hidden (topological) order parameters

- Continuum of excitations

$$E(k) = \cos(k_1) + \cos(k_2)$$

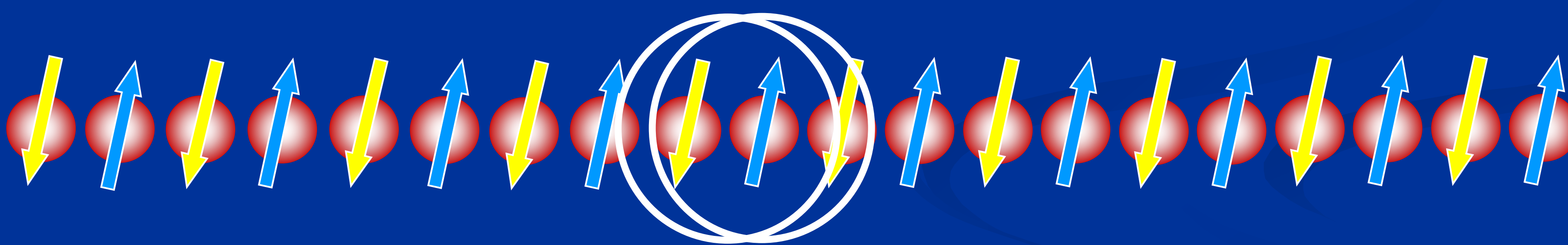
$$k = k_1 + k_2$$



Deconstruction of the electron: spin-charge separation

Spin

Charge



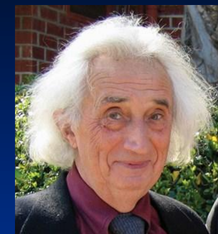
Spinon

Holon

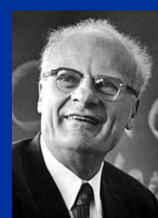
How to treat
(20th century)

- ``Standard” many body theory



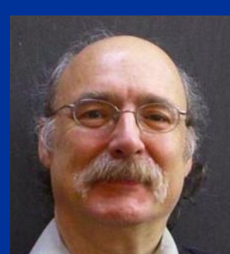




- Exact Solutions (Bethe ansatz)



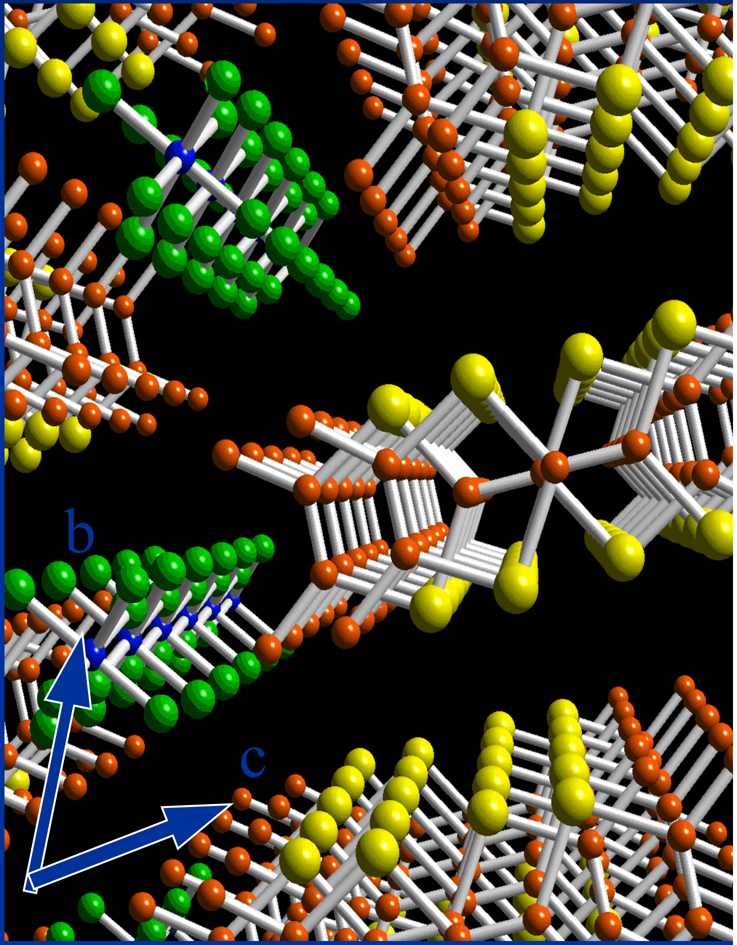

- Field theories (bosonization, CFT)

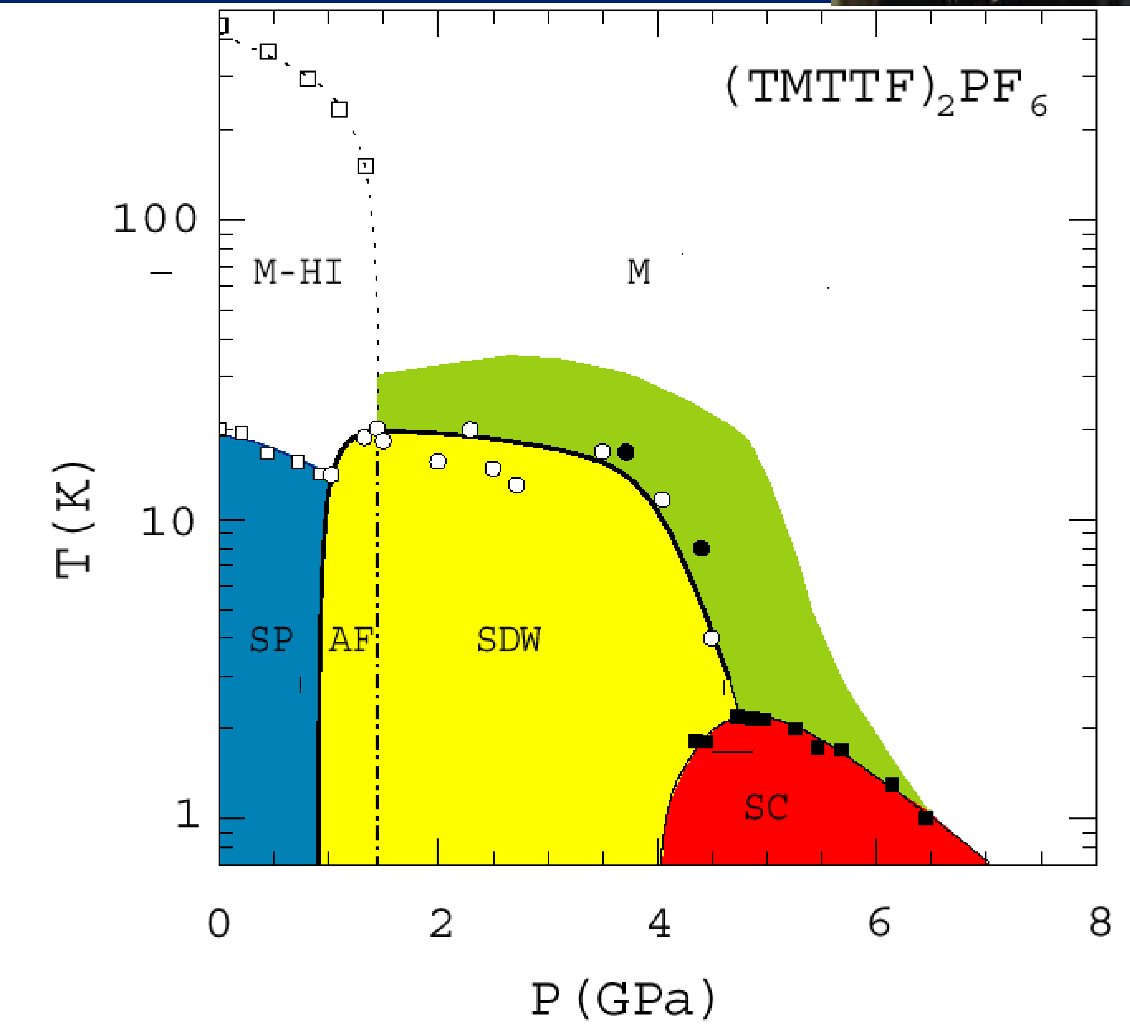




- Numerics (DMRG, MC, etc.)

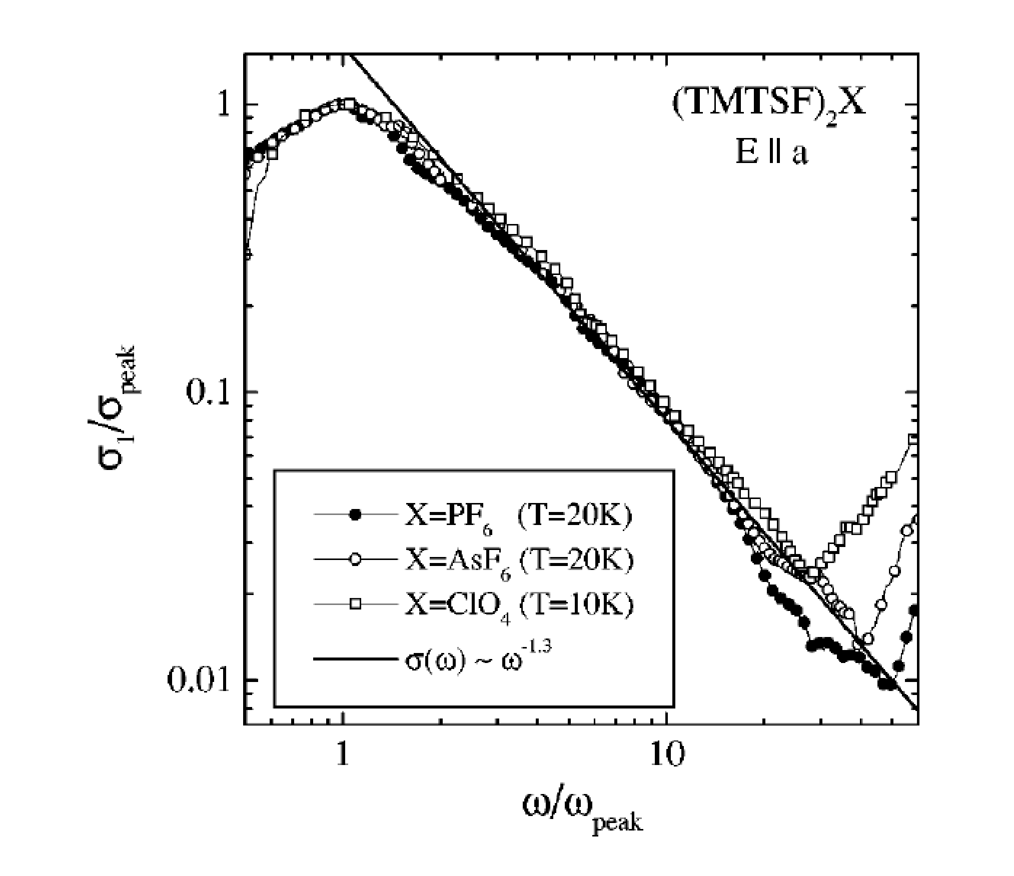

Organic conductors





D. Jaccard et al., J. Phys. C, 13 L89 (2001)

Optical conductivity



$$\sigma(\omega) \propto \omega^{\nu}$$

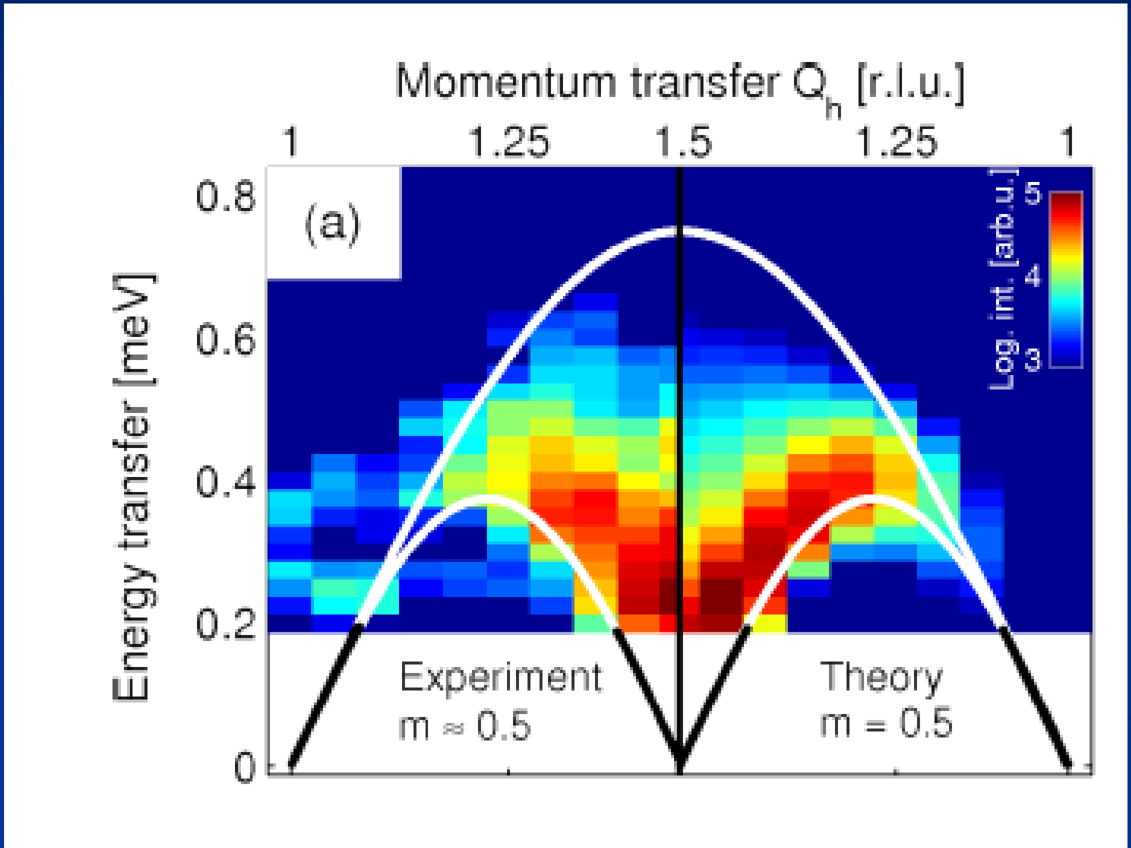
TG PRB (91) :
Physica B 230 (1996)

A. Schwartz et al. PRB 58 1261 (1998)

First observation of LL !!

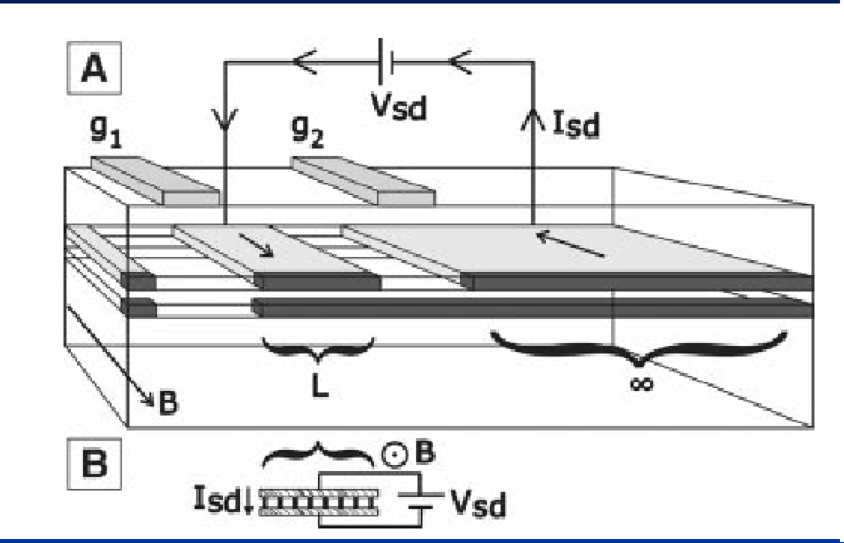
Fractionalization

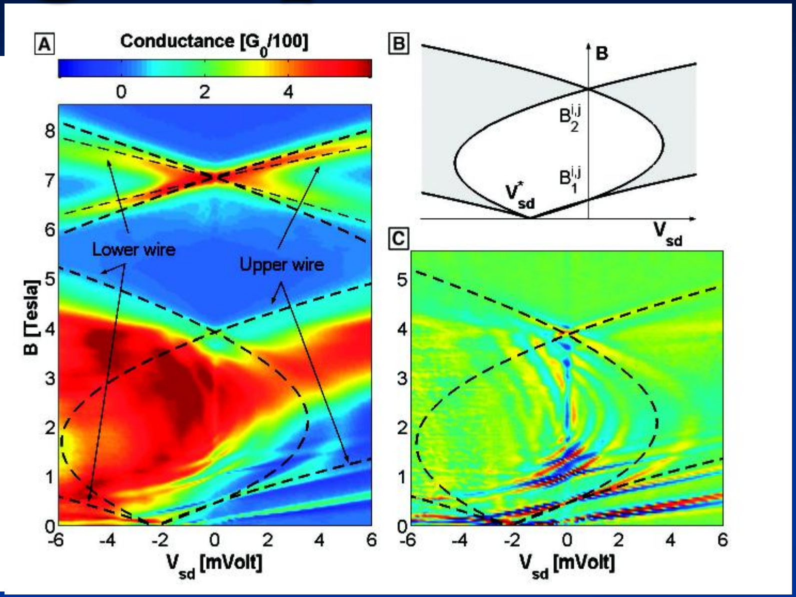
Quantum spin systems



B. Thieleman et al. PRL 102, 107204 (2009)

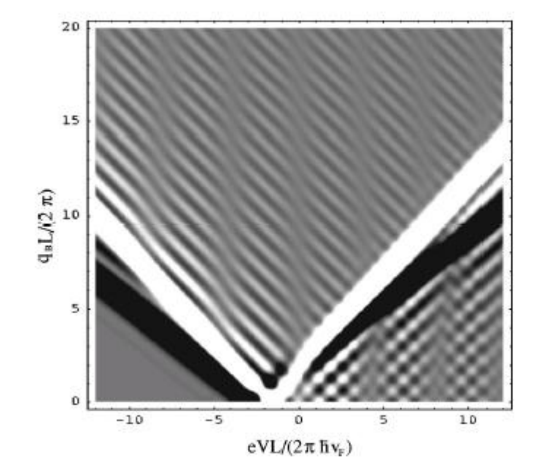
Spin charge separation





O.M Ausslander et al., Science **298** 1354 (2001)

Y. Tserkovnyak et al., PRL **89** 136805 (2002) ; PRB **68** 125312 (2003)



1D in the 21st century

Drastic evolution of the 1d world

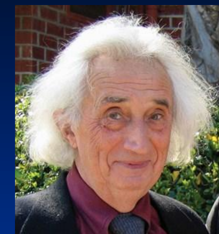
- New methods (DMRG, correlations from BA, etc.)
- New systems (cold atoms, magnetic insulators, etc.)
- New questions (strong SOC, out of equilibrium, etc)

Novel theoretical description

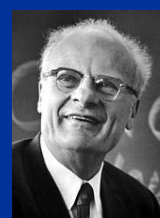
- Field theory:
  - Asymptotically true: ($r >> a$; $t >> t0$; $T << J$)
  - Amplitudes and TLL parameters unknown
- Numerics:
  - Efficient at short time, short distance
  - Takes into account the full microscopic model
- Best of both worlds: combine numerics (DMRG) or BA and field theory : essentially exact !

- \`\`Standard” many body theory



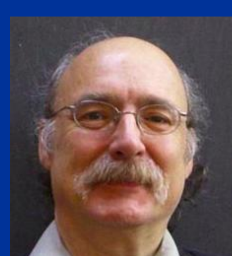




- Exact Solutions (Bethe ansatz)




- Field theories (bosonization, CFT)





- Numerics (DMRG, MC, etc.)

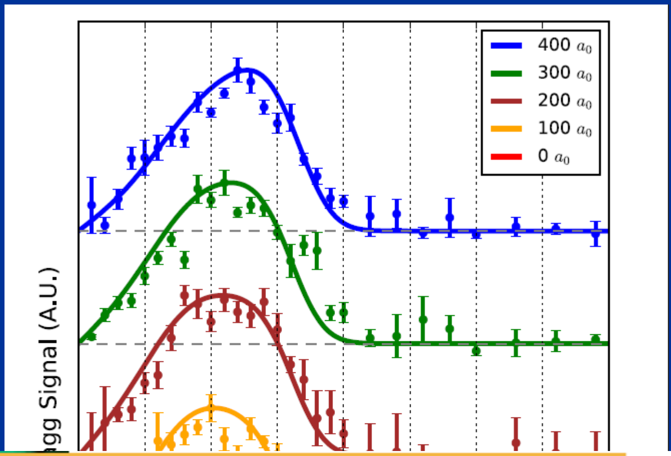

Charge velocity

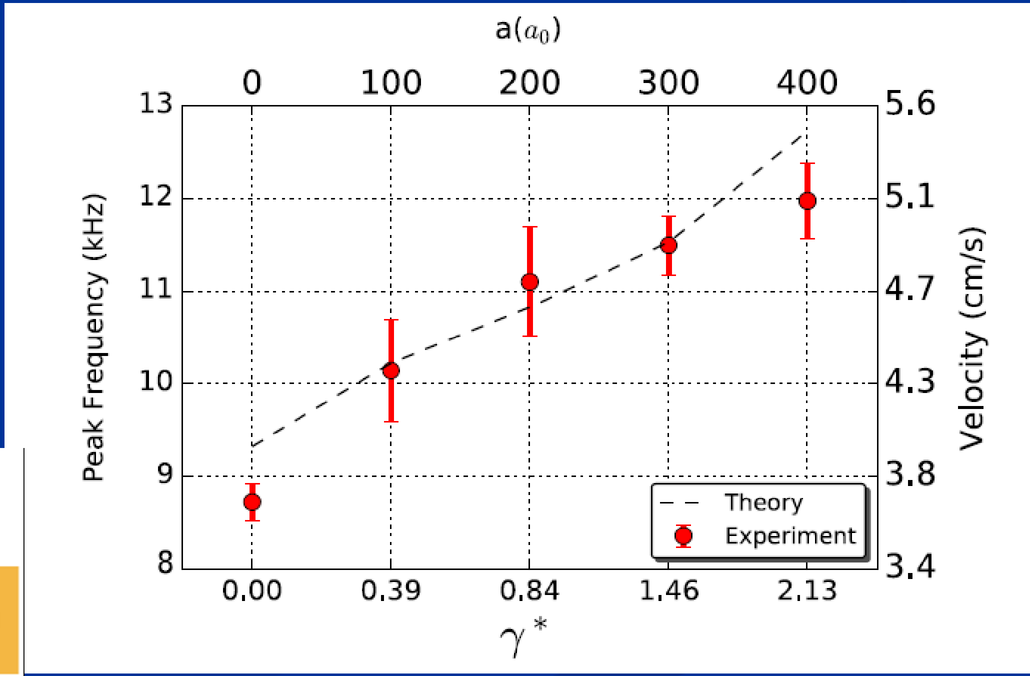
PHYSICAL REVIEW LETTERS **121,** 103001 (2018)

Editors' Suggestion

Measurement of the Dynamical Structure Factor of a 1D Interacting Fermi Gas

T. L. Yang,[1] P. Grišins,[2] Y. T. Chang,[1] Z. H. Zhao,[1] C. Y. Shih,[1] T. Giamarchi,[2] and R. G. Hulet[1]



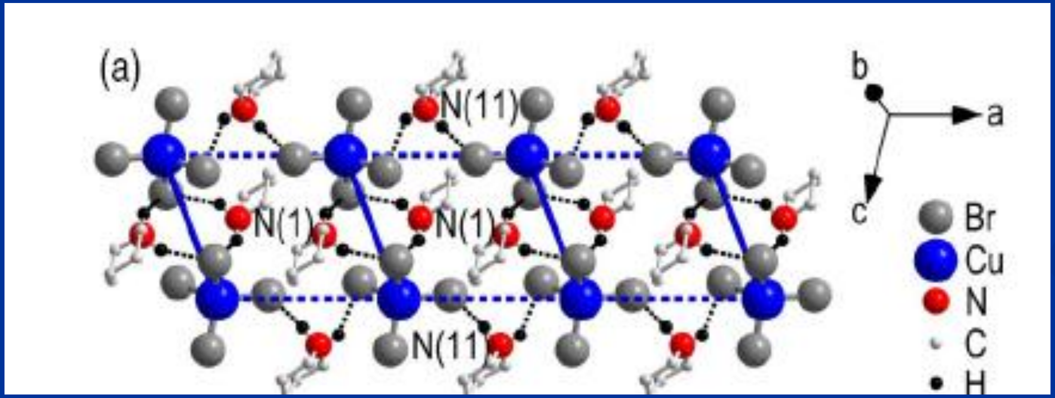


ULTRACOLD ATOMS CONFIRM 55-YEAR-OLD PHYSICS THEORY

https://www.futurity.org/one-dimensional-electrons-physics-1858622/

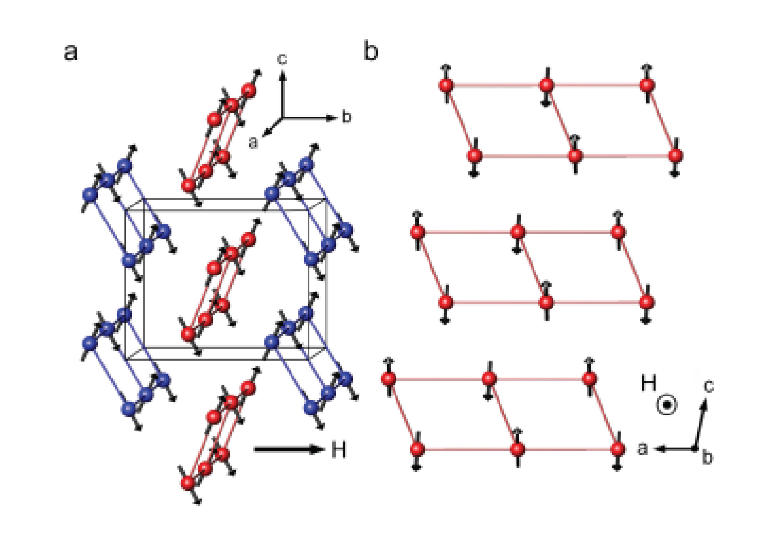
Quantum spin systems

TG, Ch. Rüegg, O. Tchernyshyov, Nat. Phys. 4 198 (08)



M. Klanjsek et al.,

PRL 101 137207 (2008)



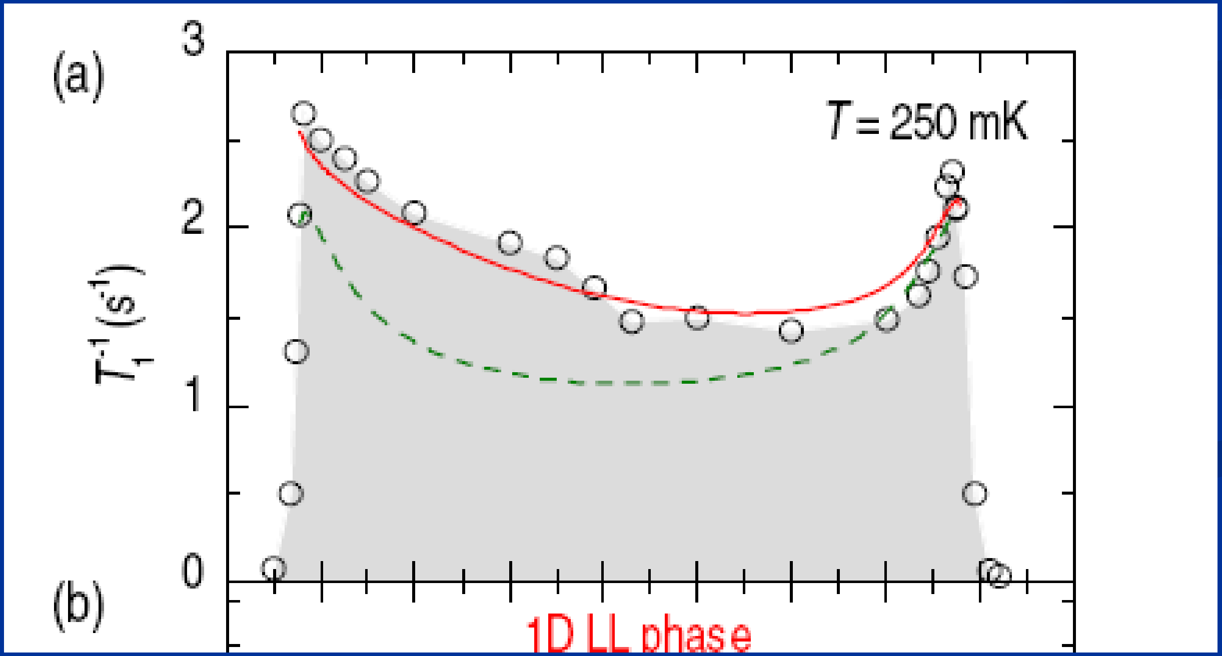
B. Thielemann et al.,

PRB **79**, 020408® 2009


NMR relaxation time

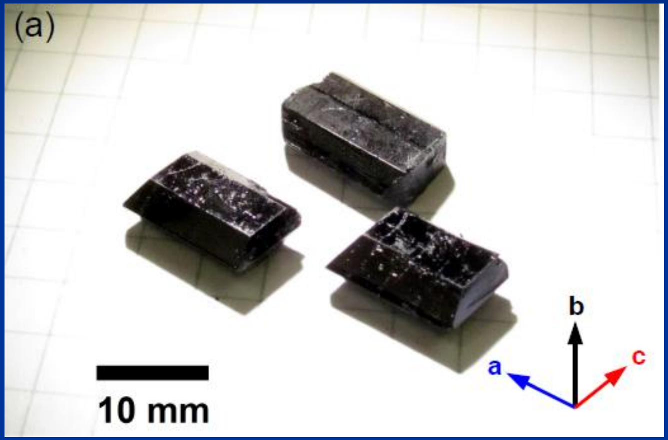
M. Klanjsek et al., PRL 101 137207 (2008)

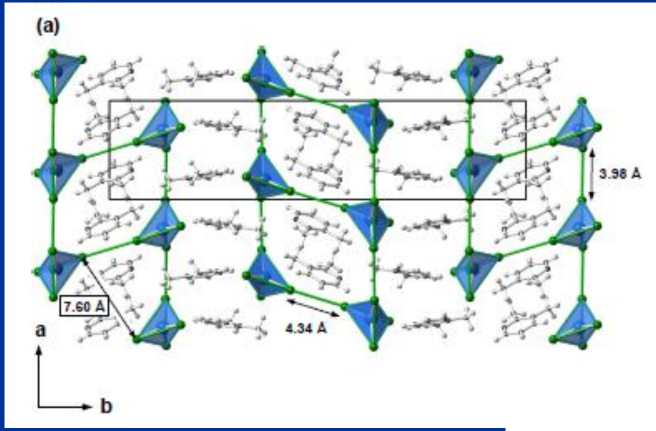

$$T_1^{-1} = \frac{\hbar\gamma^2 A_\perp^2 A_0^x}{k_B u}\cos\left(\frac{\pi}{4K}\right)B\left(\frac{1}{4K}, 1 - \frac{1}{2K}\right)\left(\frac{2\pi T}{u}\right)^{(1/2K)-1},$$

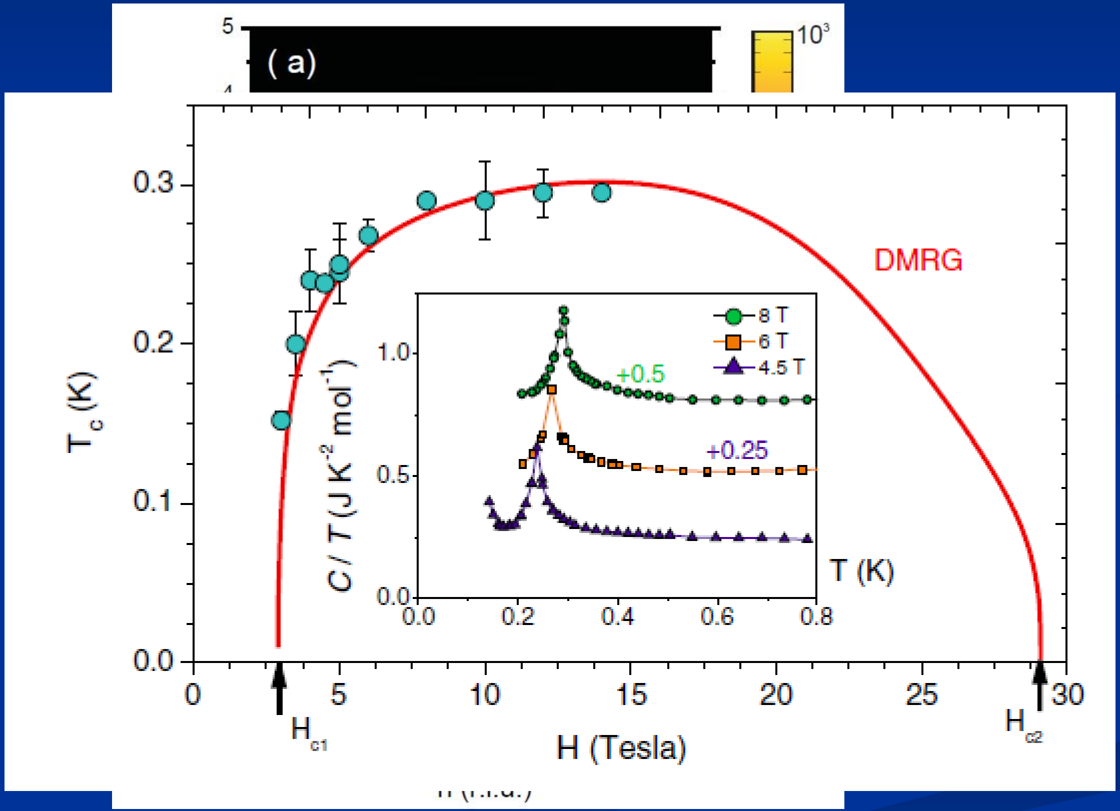


Hamiltonian reconstruction

D. Schmidiger et al. PRL 108 167201 (2012)

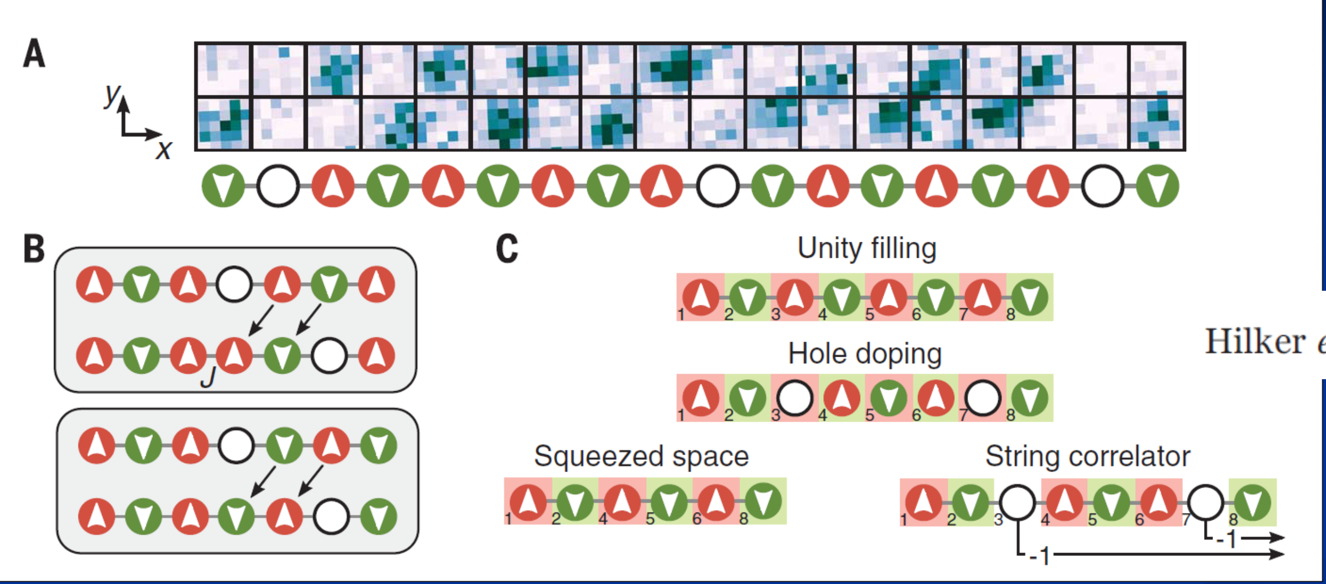






$$\mathcal{H} = J_{\text{leg}} \sum_{l,j} S_{l,j} \cdot S_{l+1,j} + J_{\text{rung}} \sum_{l} S_{l,1} \cdot S_{l,2} - g\mu_B H \sum_{l,j} S_{l,j}^{z}.$$

Spin-charge separation



Hilker *et al.*, *Science* **357**, 484–487 (2017)

QUANTUM GASES

Spin-charge separation in a one-dimensional Fermi gas with tunable interactions

Ruwan Senaratne[1]†, Danyel Cavazos-Cavazos[1]†, Sheng Wang[2,3], Feng He[3,4], Ya-Ting Chang[1], Aashish Kafle[1], Han Pu[1], Xi-Wen Guan[2,5]*, Randall G. Hulet[1]*

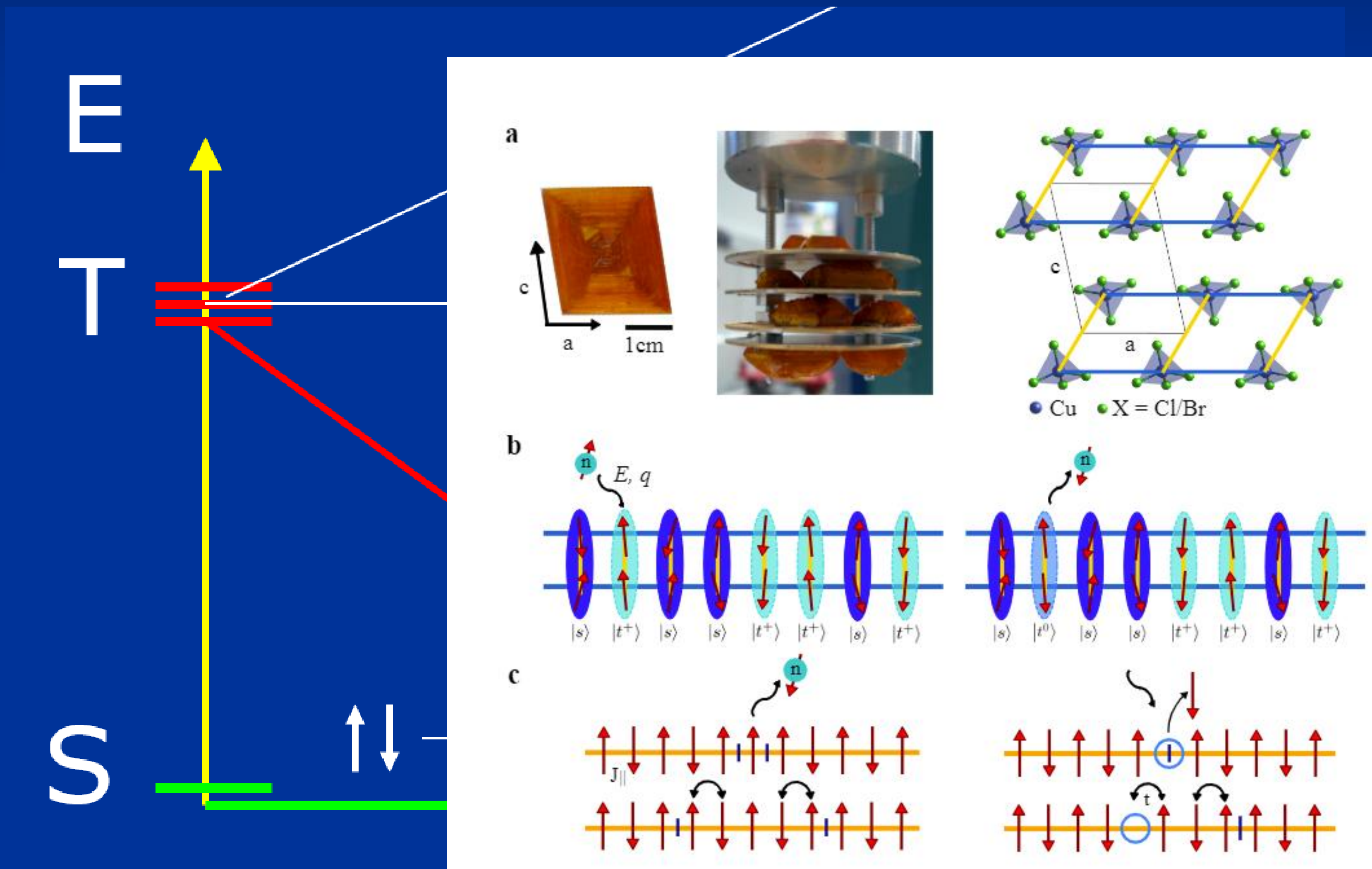
SCIENCE · 16 Jun 2022 · Vol 376, Issue 6599 · pp. 1305-1308

A. Kafle, R. Senaratne, D. Cavazos-Cavazos, H.-Y. Cui, TG, H. Pu, X.-W. Guan, R. G. Hulet, arxiv/arXiv:2512.08866

Quantum simulations from CM

Supersymmetric spin/charge dyn.

P. Bouillot et al. PRB 83, 054407 (2011)
B. Wehinger, F. Lisandrini et al Nat Comm 16 3228 (2025)



Quantitative agreement with the predictions of the Tomonaga-Luttinger liquid

End of the story ...... ??????

NO! TLL plays the same role than Fermi liquid did

Beyond Tomonaga-Luttinger liquids

- 1D additional perturbation:

Lattice (Mott transition), disorder (Bose glass) etc.
Multicomponents, mixtures, ….

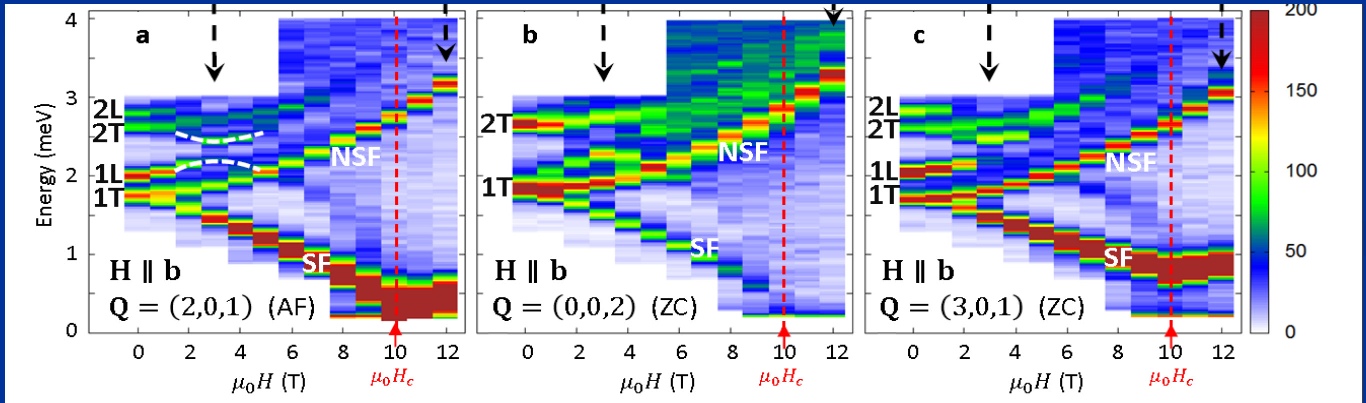
- New type of quantum critical points (e.g. topological)…

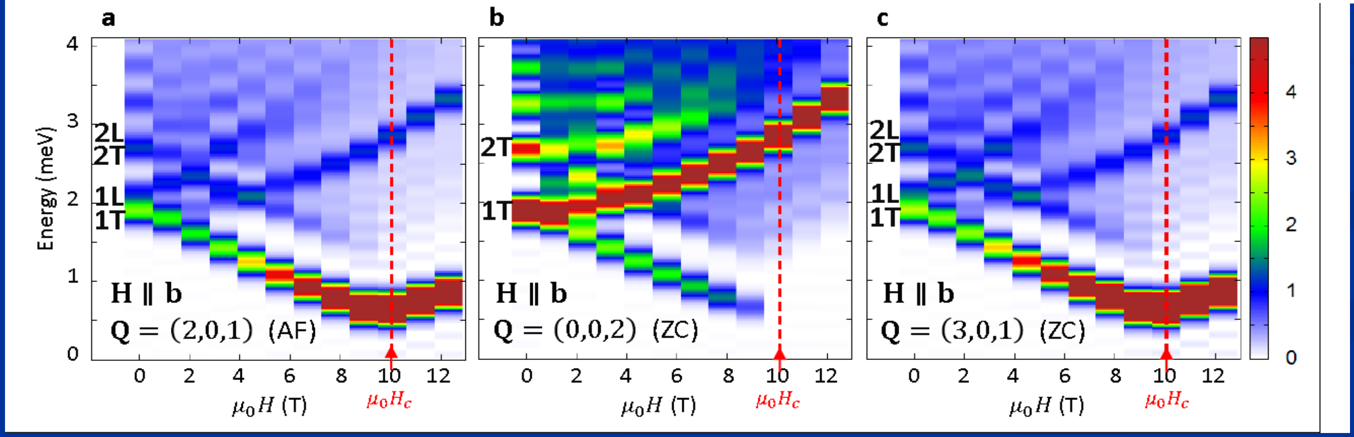
Double topological transition

Topological quantum phase transition in the Ising-like antiferromagnetic spin chain BaCo2V2O8

Q. Faure, S. Takayoshi, et al. Nat. Phys 14, 716 (2018)



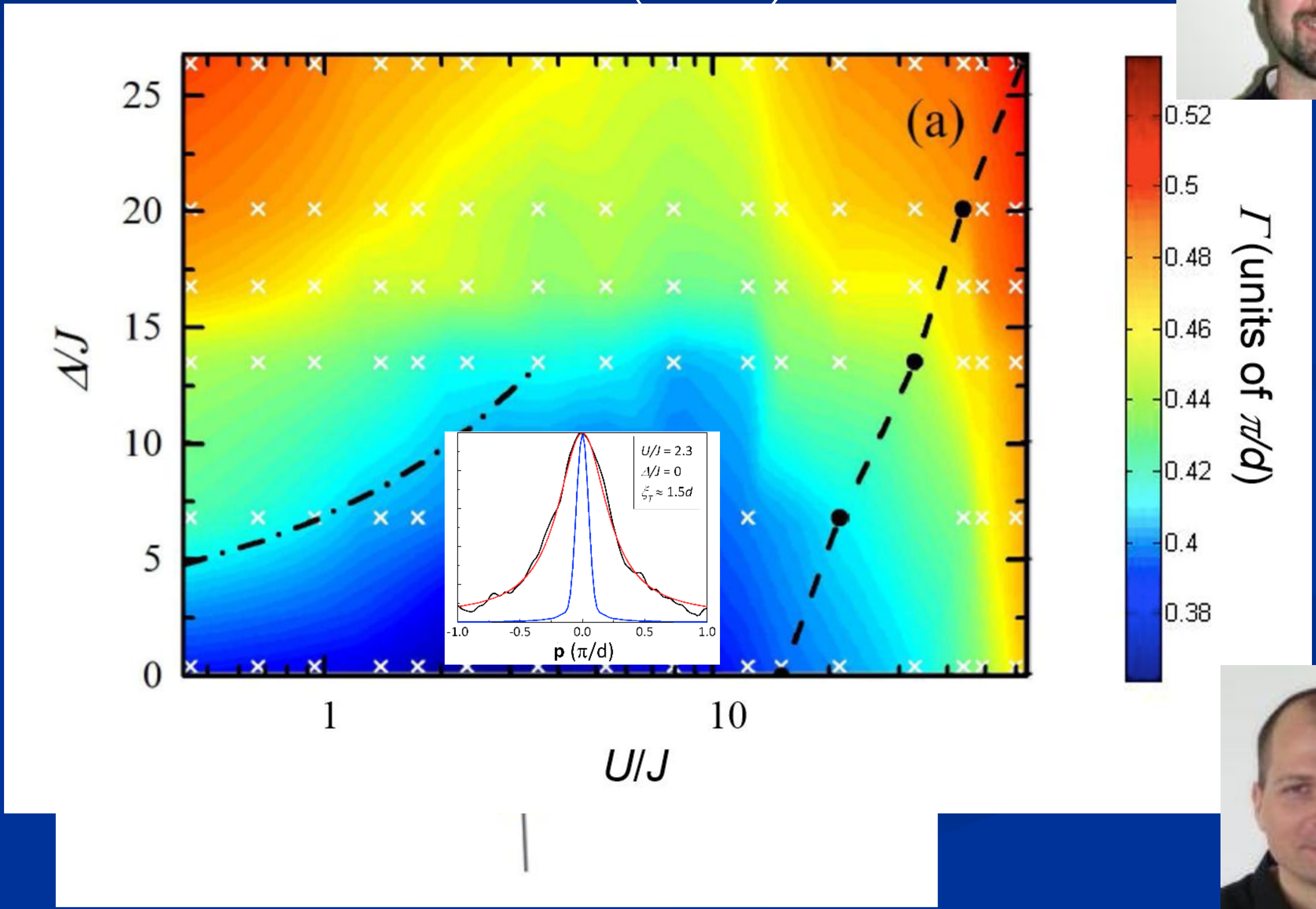





Quasi-periodics and interactions

C. D'Errico, E. Lucioni et al. PRL (2014);

L. Gori et al PRA 93 033650 (2016)



Beyond Tomonaga-Luttinger liquids

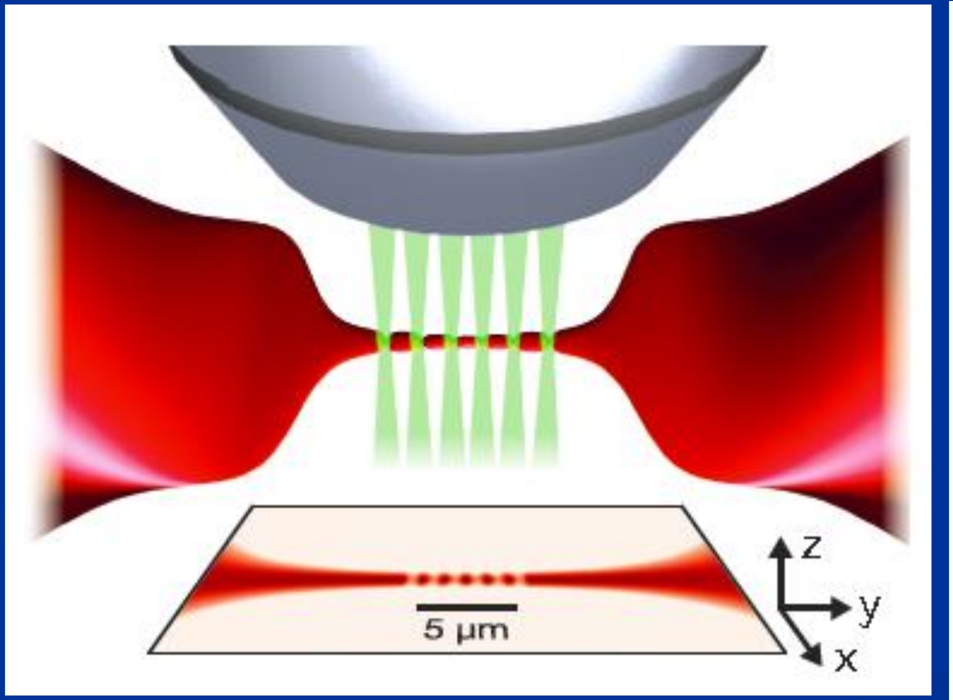
- 1D additional perturbation:
Lattice (Mott transition), disorder (Bose glass) etc.
Multicomponents, mixtures, ….

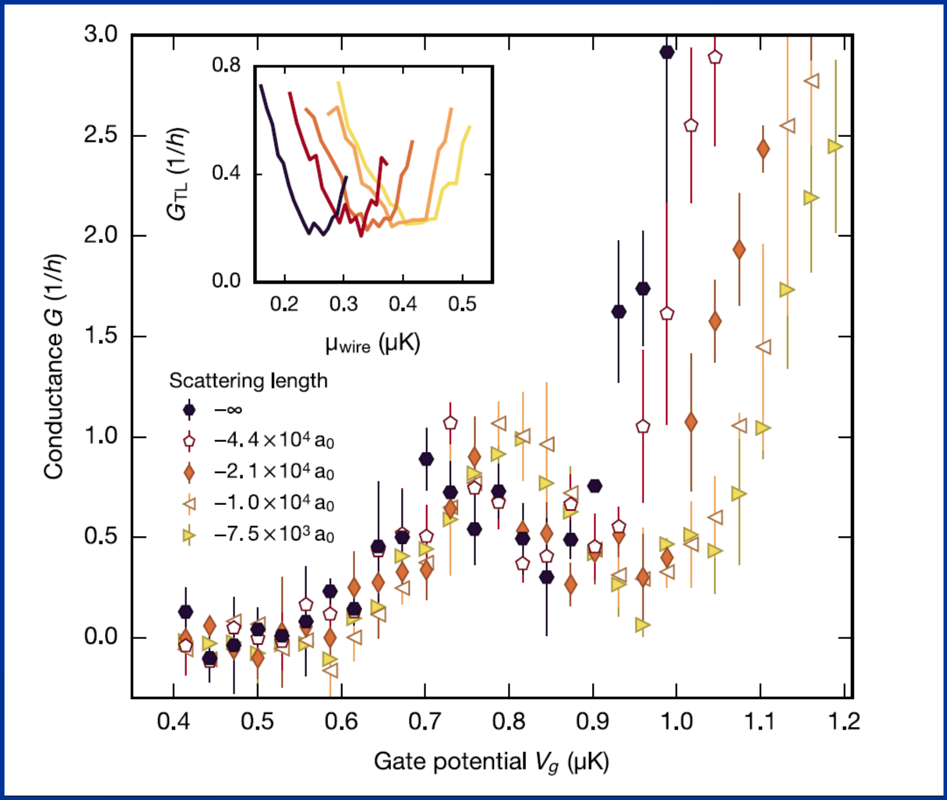
- New type of quantum critical points (e.g. topological)…

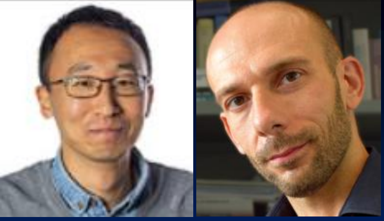
- Transport; Out of equilibrium situations.

Quantum transport in 1D

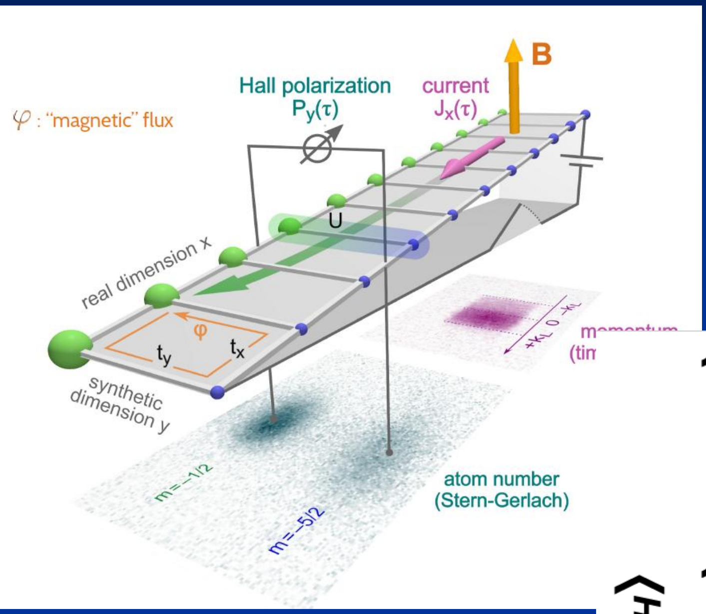
M. Lebrat, P. Grisins et al., PRX 8 011053 (2018)



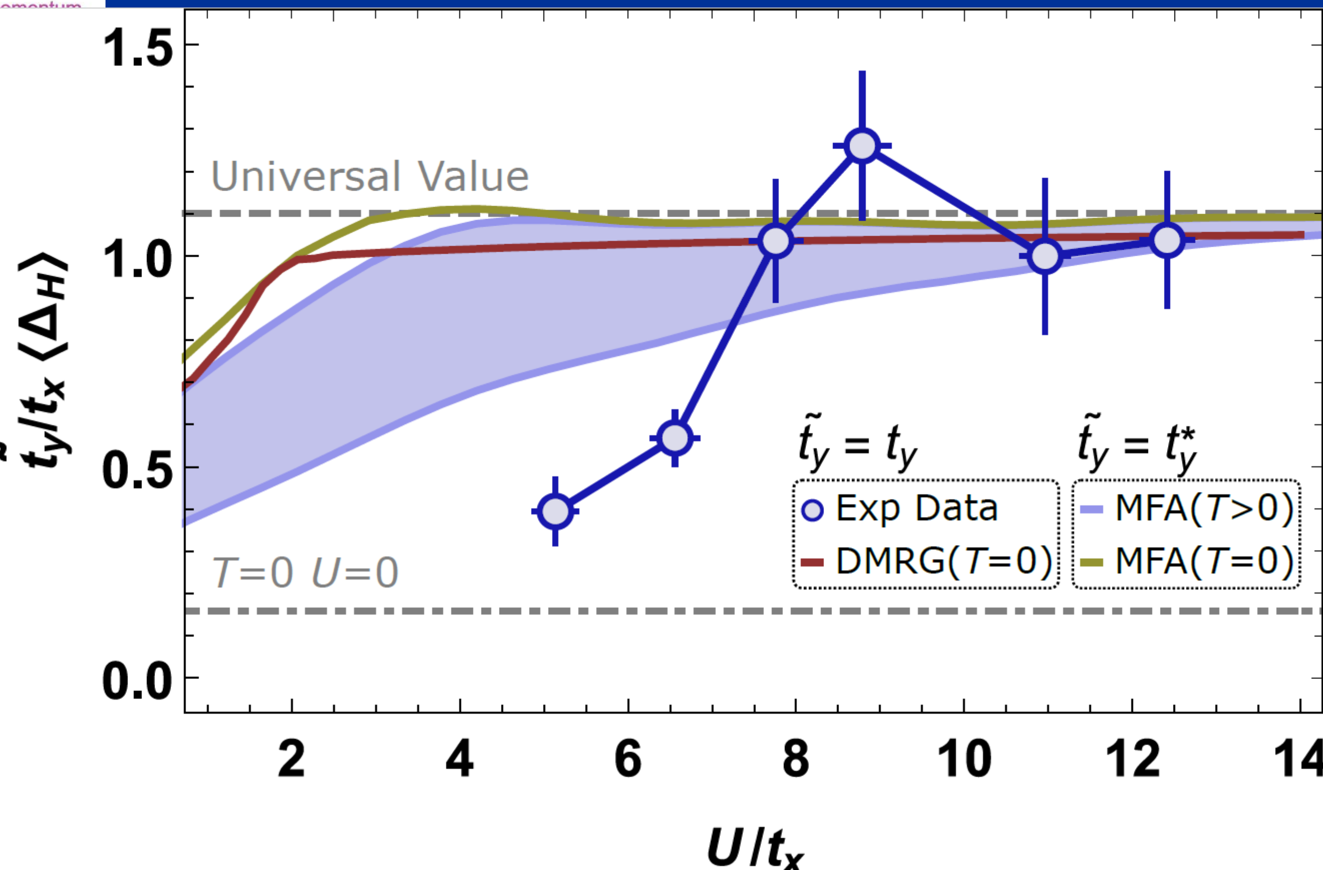




Hall effect in ladders



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).



Beyond Tomonaga-Luttinger liquids

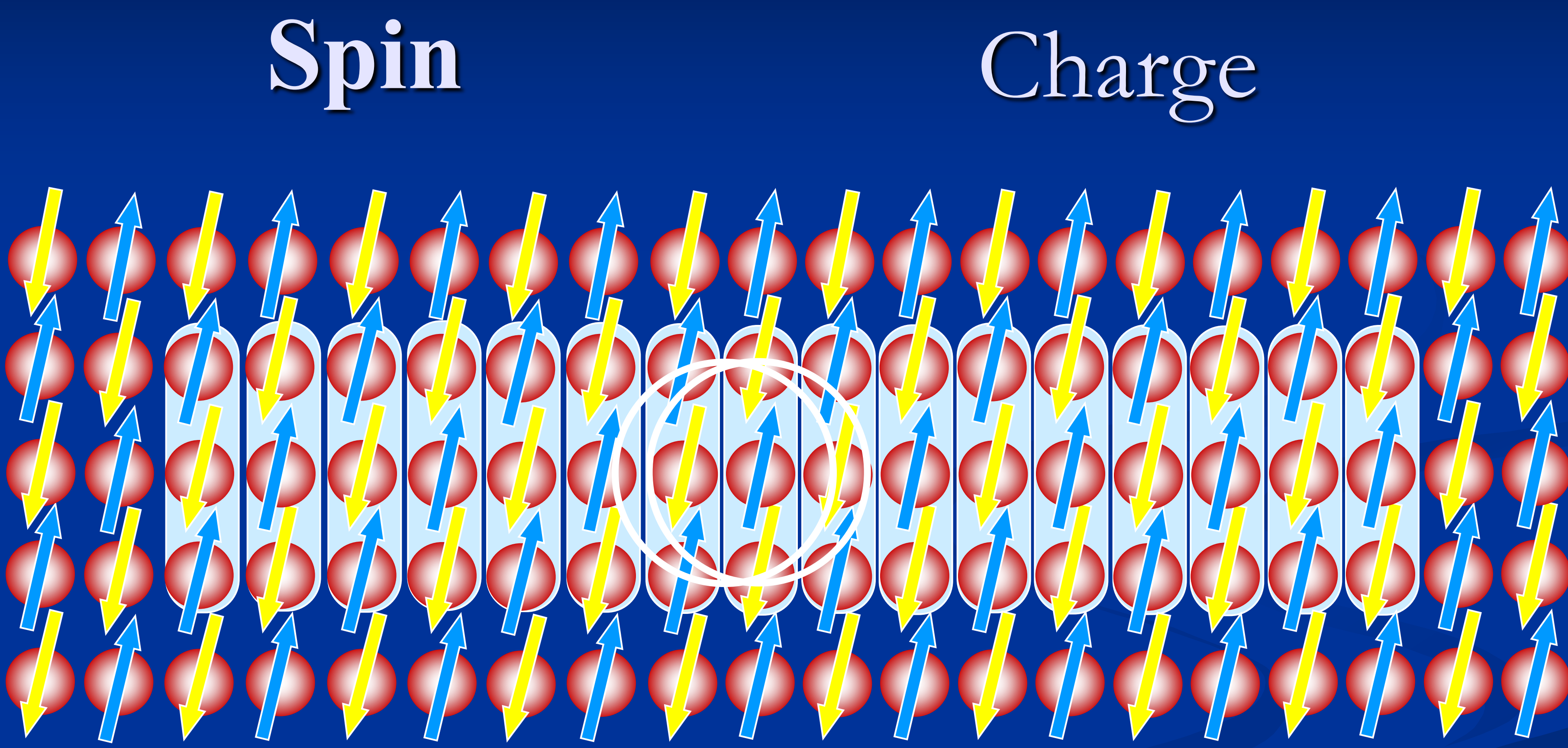
- 1D additional perturbation:
Lattice (Mott transition), disorder (Bose glass) etc.
Multicomponents, mixtures, ….

- New type of quantum critical points (e.g. topological)…

- Transport; Out of equilibrium situations.

- Dimensional crossover 1d – 2d/3d

Spin-Charge Separation higher D ?



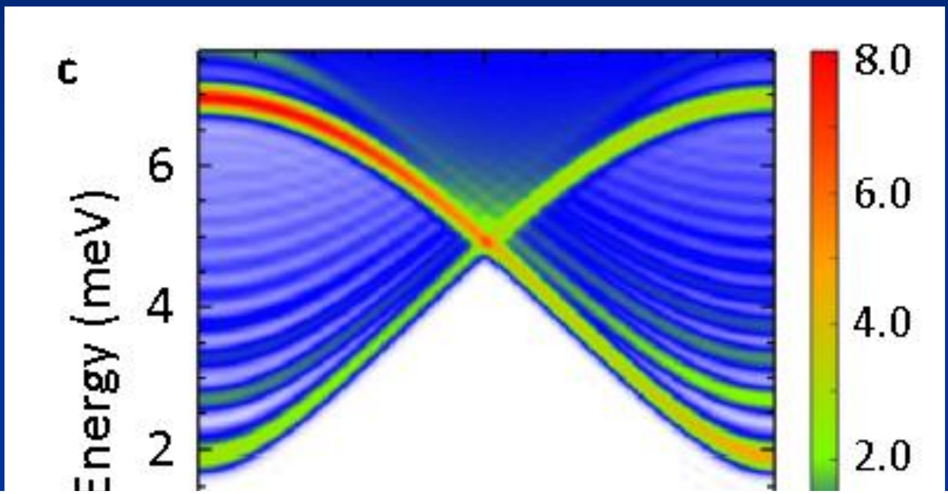
Energy increases with spin-charge separation

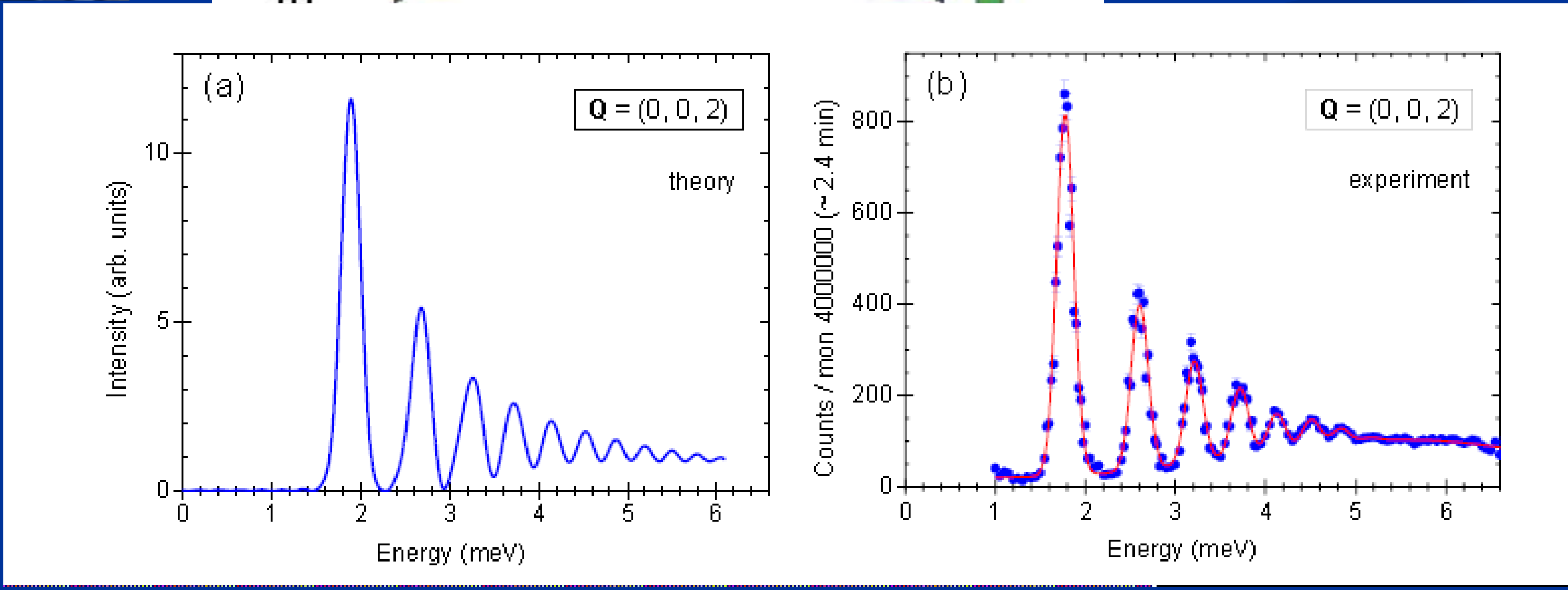
Confinement of spin-charge: « quasiparticle »

Confinement of spinons BaCoVO

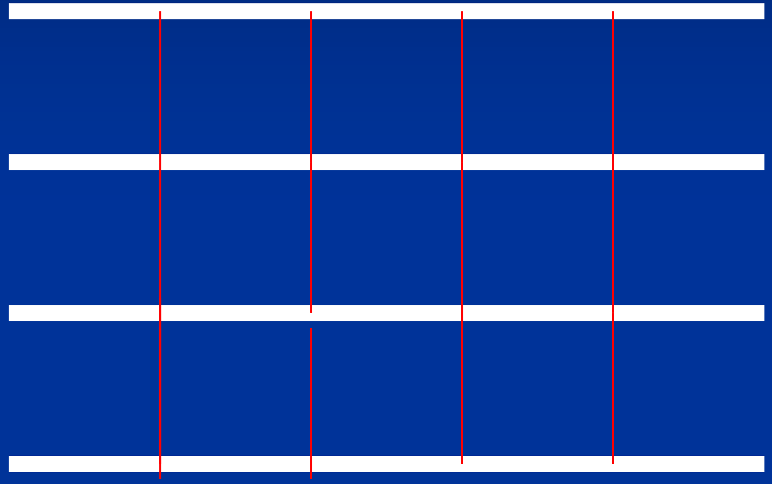
Q. Faure, S. Takayoshi, et al. Nat. Phys 14, 716 (2018)

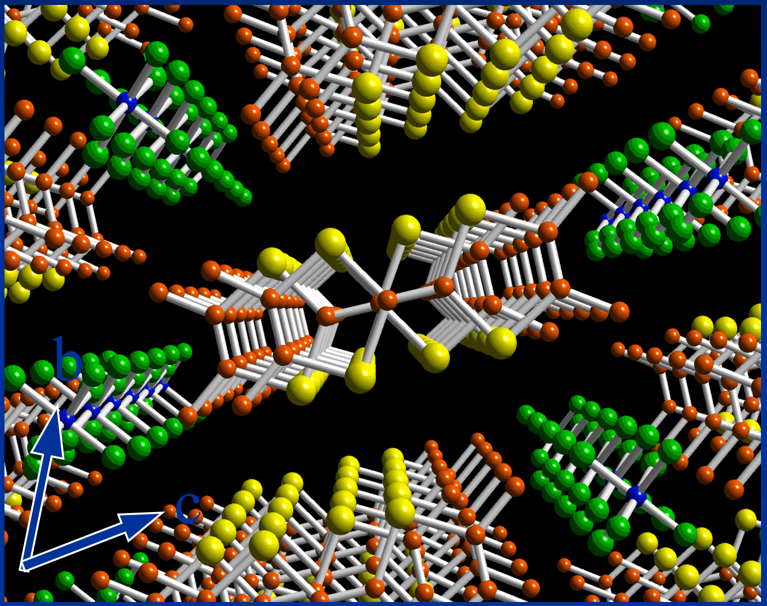


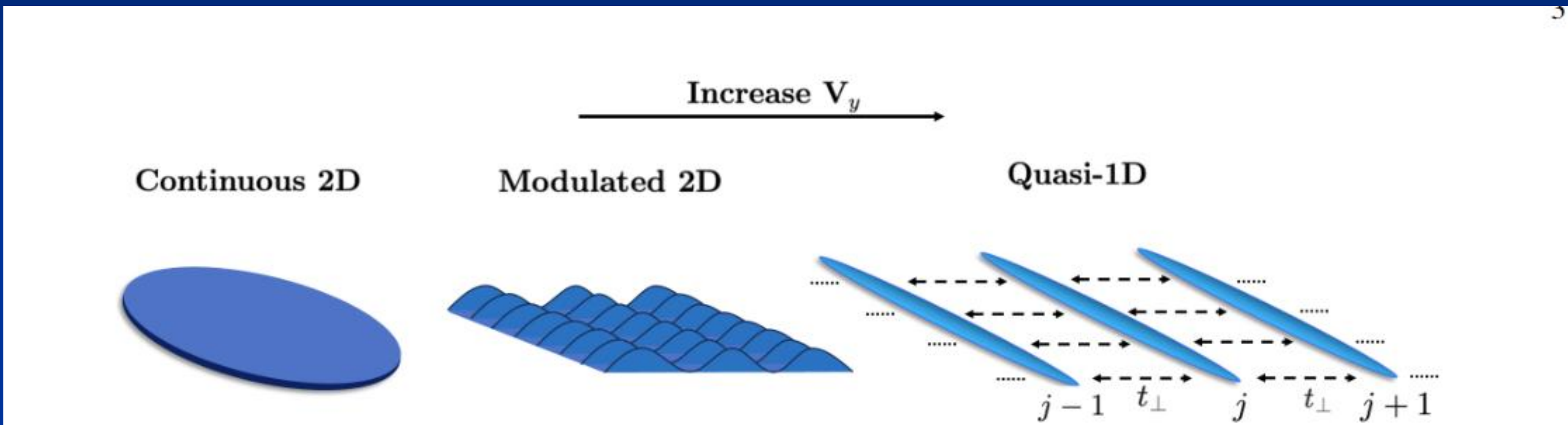


Intermediate dimensionality





- Bosons:



Strongly-interacting bosons at 2D-1D dimensional crossover

Hepeng Yao, Lorenzo Pizzino, Thierry Giamarchi

SciPost Phys. 15, 050 (2023) · published 7 August 2023

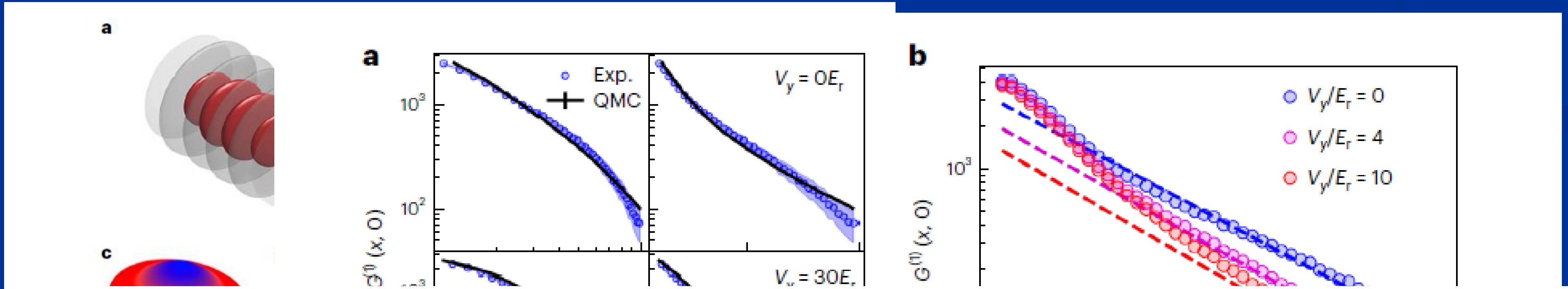
nature physics

Article

https://doi.org/10.1038/s41567-024-02459-3

Observation of the 2D–1D crossover in strongly interacting ultracold bosons

Yanliang Guo[1,3], Hepeng Yao[2,3], Satwik Ramanjanappa[1], Sudipta Dhar[1], Milena Horvath[1], Lorenzo Pizzino[2], Thierry Giamarchi[2], Manuele Landini[1] & Hanns-Christoph Nägerl[1]



SCIENCE ADVANCES | RESEARCH ARTICLE

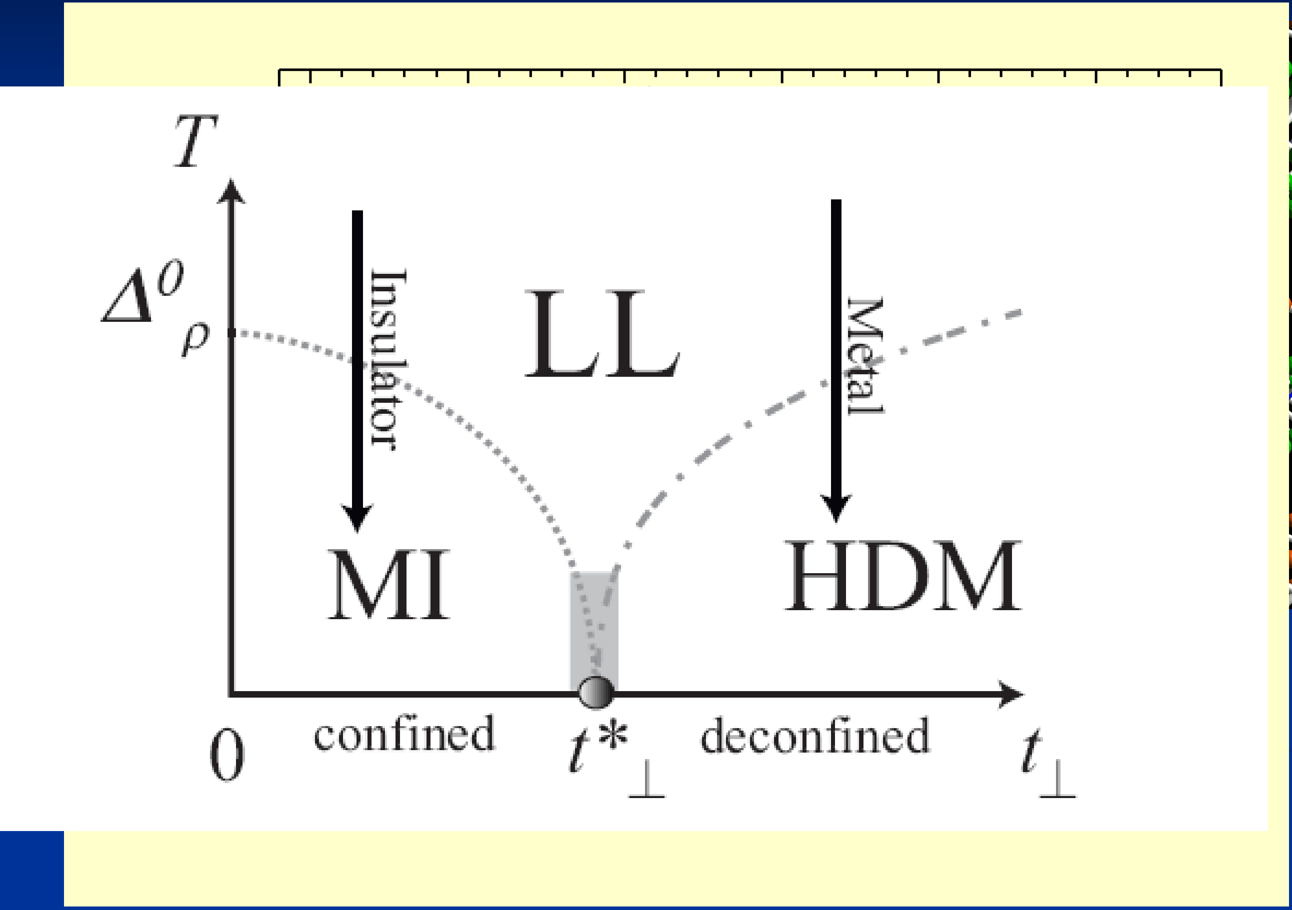
PHYSICS

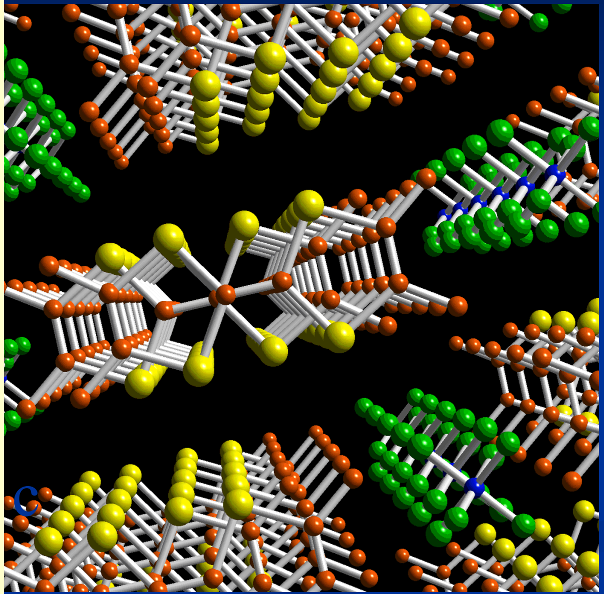
Anomalous cooling of bosons by dimensional reduction

Yanliang Guo[1]†, Hepeng Yao[2]†, Sudipta Dhar[1], Lorenzo Pizzino[2], Milena Horvath[1], Thierry Giamarchi[2], Manuele Landini[1], Hanns-Christoph Nägerl[1]*

Fermions

Deconfinement





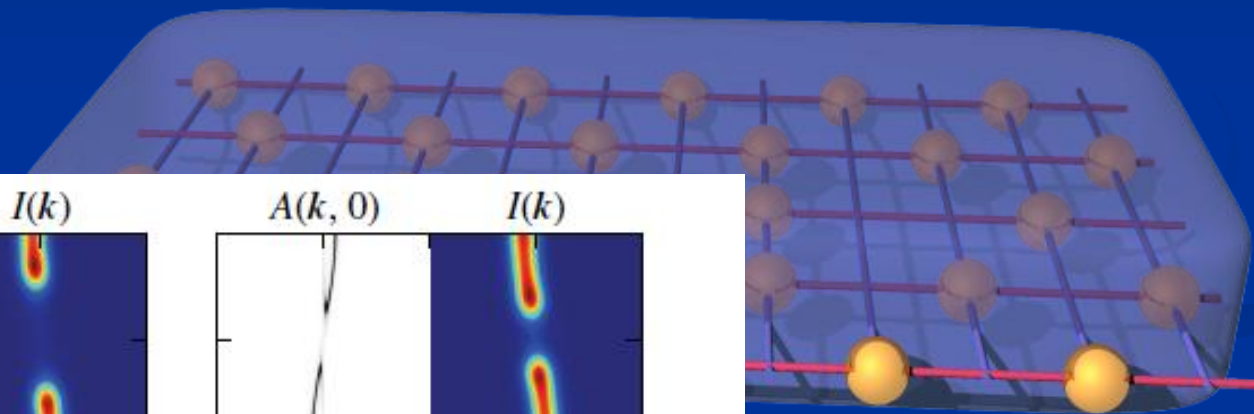
TG Chemical Review 104 5037 (2004)

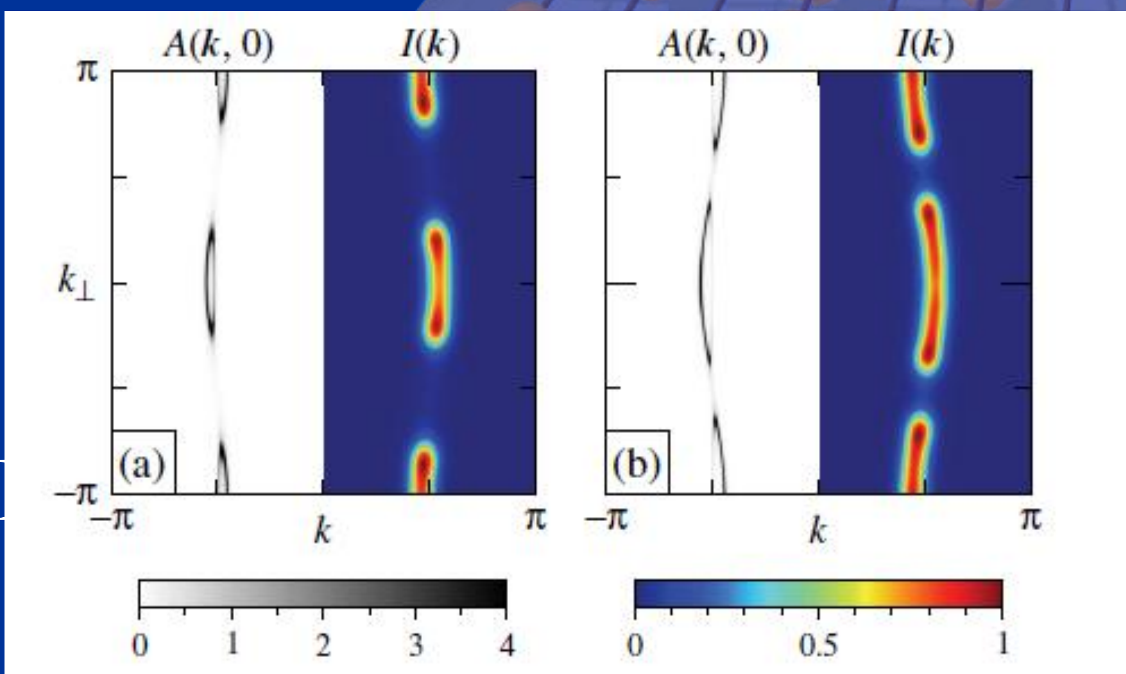
P. Auban-Senzier, D. Jérome, C. Carcel and J.M. Fabre J de Physique IV, (2004)
A. Pashkin, M. Dressel, M. Hanfland, C. A. Kuntscher, PRB 81 125109 (2010)

D. Jaccard et al., J. Phys. C, 13 L89 (2001)

Self-consistent bath (DMFT)

S. Biermann, A. Georges, A. Lichtenstein, TG, PRL 87 276405 (2001)
C. Berthod et al. PRL 97, 136401 (2006)





determined

DMRG + Mean Field

Solving 2D and 3D lattice models of correlated fermions - combining matrix product states with mean field theory

Gunnar Bollmark,[1] Thomas Köhler,[1] Lorenzo Pizzino,[2] Yiqi Yang,[3] Johannes S. Hofmann,[4] Hao Shi,[5] Shiwei Zhang,[6] Thierry Giamarchi,[2] and Adrian Kantian[1,7]

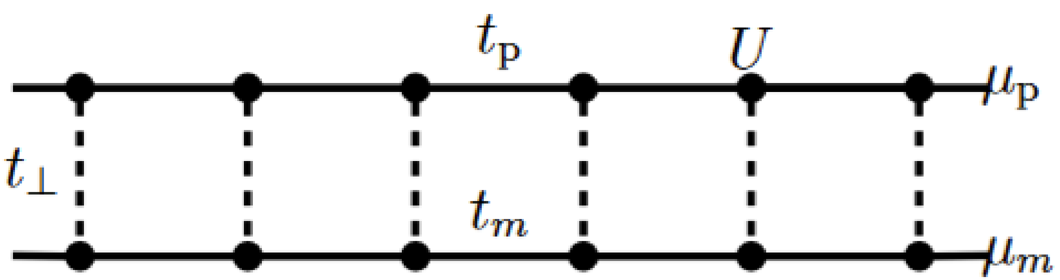
Phys. Rev. X **13**, 011039 – Published 15 March 2023

1. arXiv:2507.18707 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el

Strong enhancements to superconducting properties of 1D systems from metallic reservoirs

Authors: J. E. Ebot, Sam Mardazad, Lorenzo Pizzino, Johannes S. Hofmann, Thierry Giamarchi, Adrian Kantian

(a)



Related directions

- Compare superfluidity with Leggett's inequalities [H. Yao, L. Pizzino]
- Other coupling of the 1D structures (e.g. triangular lattice) [X. Zhou]
- Disorder in such Q-1D geometries [G. Morpurgo, TG, PRR (2024)]

Conclusions

- 1D physics has remarkable features
- Luttinger liquid theory provides a framework to study this physics, and to go beyond
- Beautiful and challenging questions going beyond the Tomonaga-Luttinger liquids
- Requires interplay of analytical and numerical techniques (and new ideas!) to make progress
- Many experimental realizations both in condensed matter and in cold atoms