Spin-charge separation and hidden correlations

in Fermi-Hubbard chains

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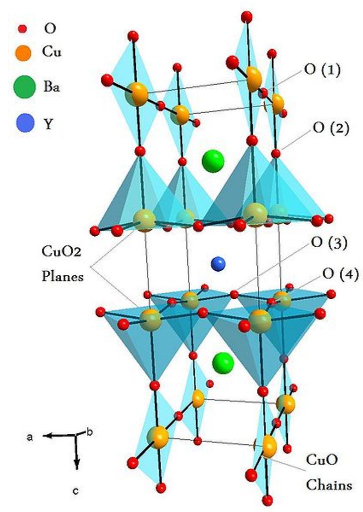
Max-Planck-Institut für Quantenoptik, Garching

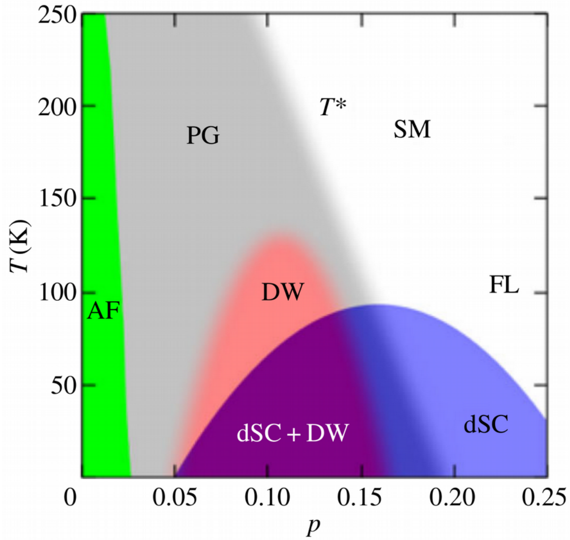
Quantum Science and Quantum Technologies, Trieste, 11.09.17

Why studying the Hubbard model?

Most prominent toy model for high temperature superconductivity



Cuprate ($YBa_2Cu_3O_7$) unit cell
(Wikipedia)



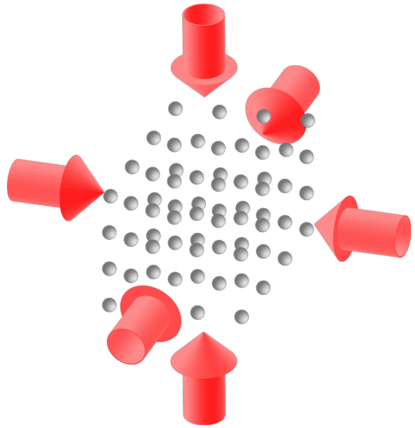
Phase diagram
(Sachdev 2016)

The Hubbard model

$$\hat{H} = -t \sum_{<i,j>,\sigma} (\hat{c}^\dagger_{i,\sigma}\hat{c}_{j,\sigma} + h.c.) + U \sum_i \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

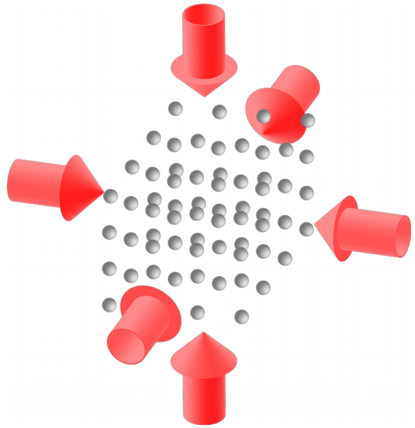
Review: Lee, RMP 2006

Implementing the Hubbard model with AMO systems



Optical lattice by
interfering
laser beams

Implementing the Hubbard model with AMO systems

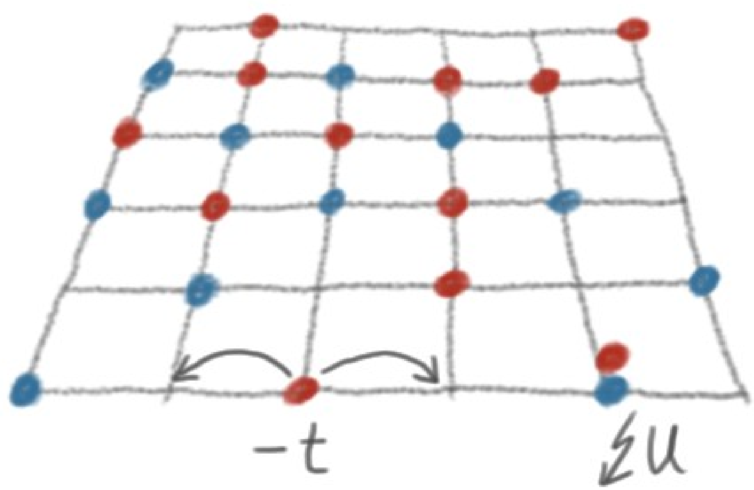


Optical lattice by interfering laser beams

Fermions:

Spin independent hopping, Pauli blocking and onsite interactions

$$\hat{H} = -t \sum_{<i,j>,\sigma} (\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + h.c.) + U \sum_{i} \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$



Reviews:
Bloch, RMP 2008
Nascimbene, Nat. Phys. 2012
Gross, Science 2017

This talk: One dimension!

Why?

Universal Physics (Luttinger liquids)

Demonstration / a fresh view on fundamental effects

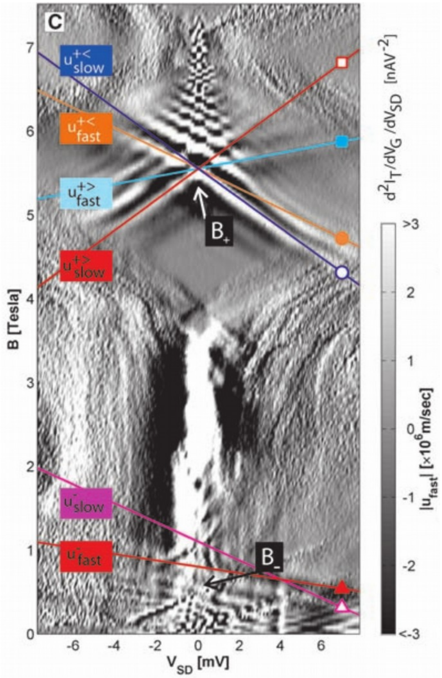
Spin-charge separation: $\hat{H} = \hat{H}_C + \hat{H}_S$

Stepping stone to explore uncharted territory

Development of novel techniques

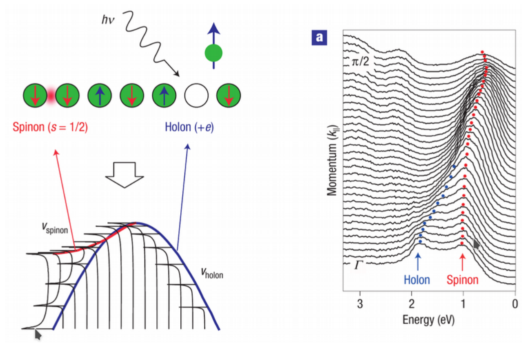
Measurement of novel techniques → topological order

Spin-charge separation experiments in solid-state



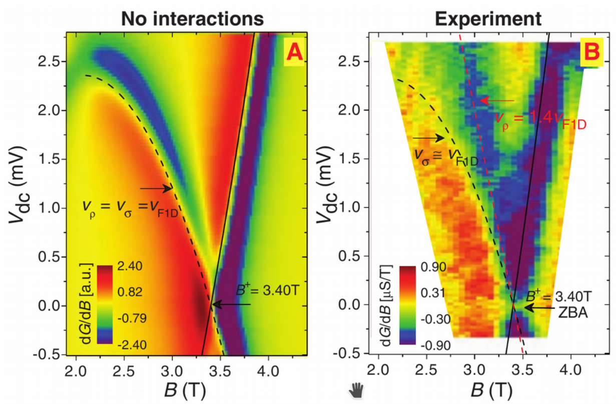
Tunnel current

Auslaender, Science 2015



ARPES

Kim, Nat. Phys. 2006



Tunnel current

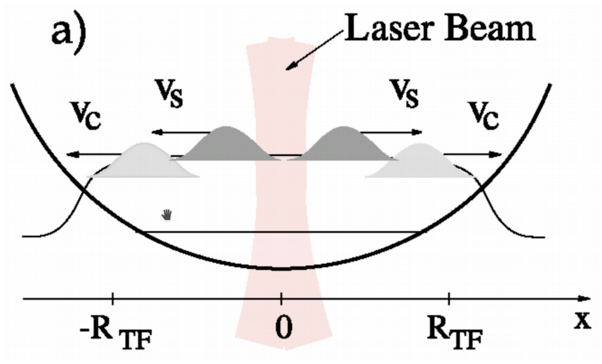
Jompol, Science 2009

Earlier exp.: Kim, PRL 1996 | Segovia, Nature 1999

Reviews: Voit, Rep. Prog. Phys. 1995 | Deshpande, Nature 2010 | T. Giarmarchi's book

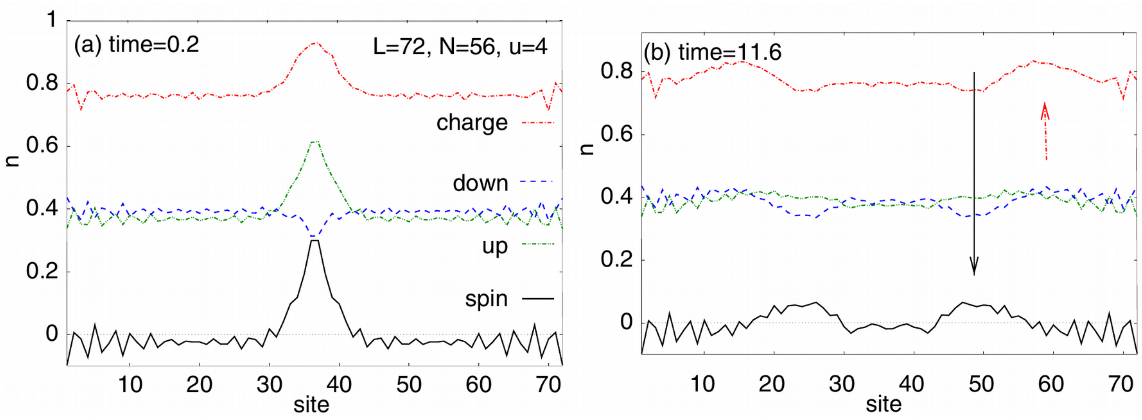
Spin-charge separation in ultracold atoms

Observe the dynamics directly!



1d continuum

Recati, PRL 2003



1d Fermi-Hubbard

Kollath, PRL 2005

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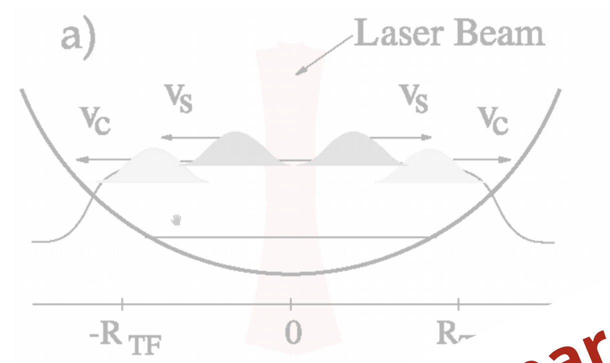
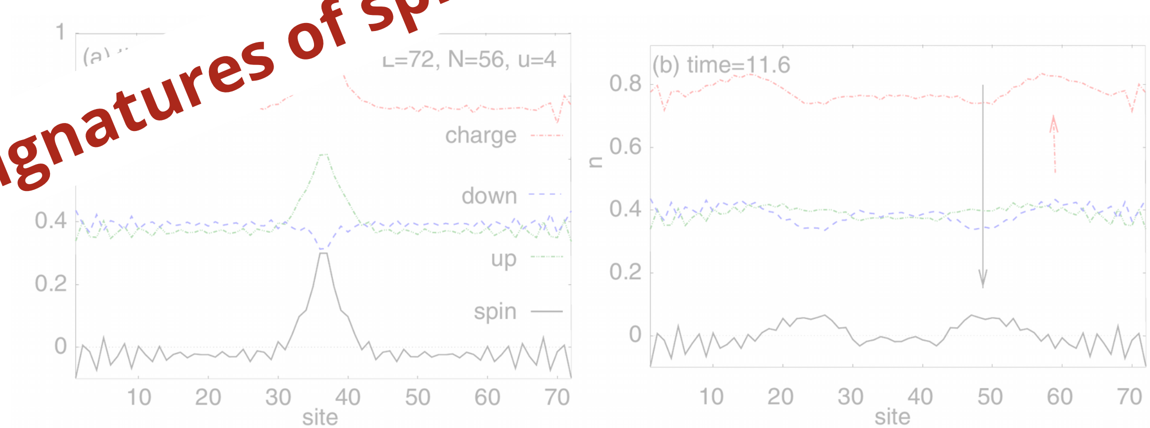


1d con…

… 2003

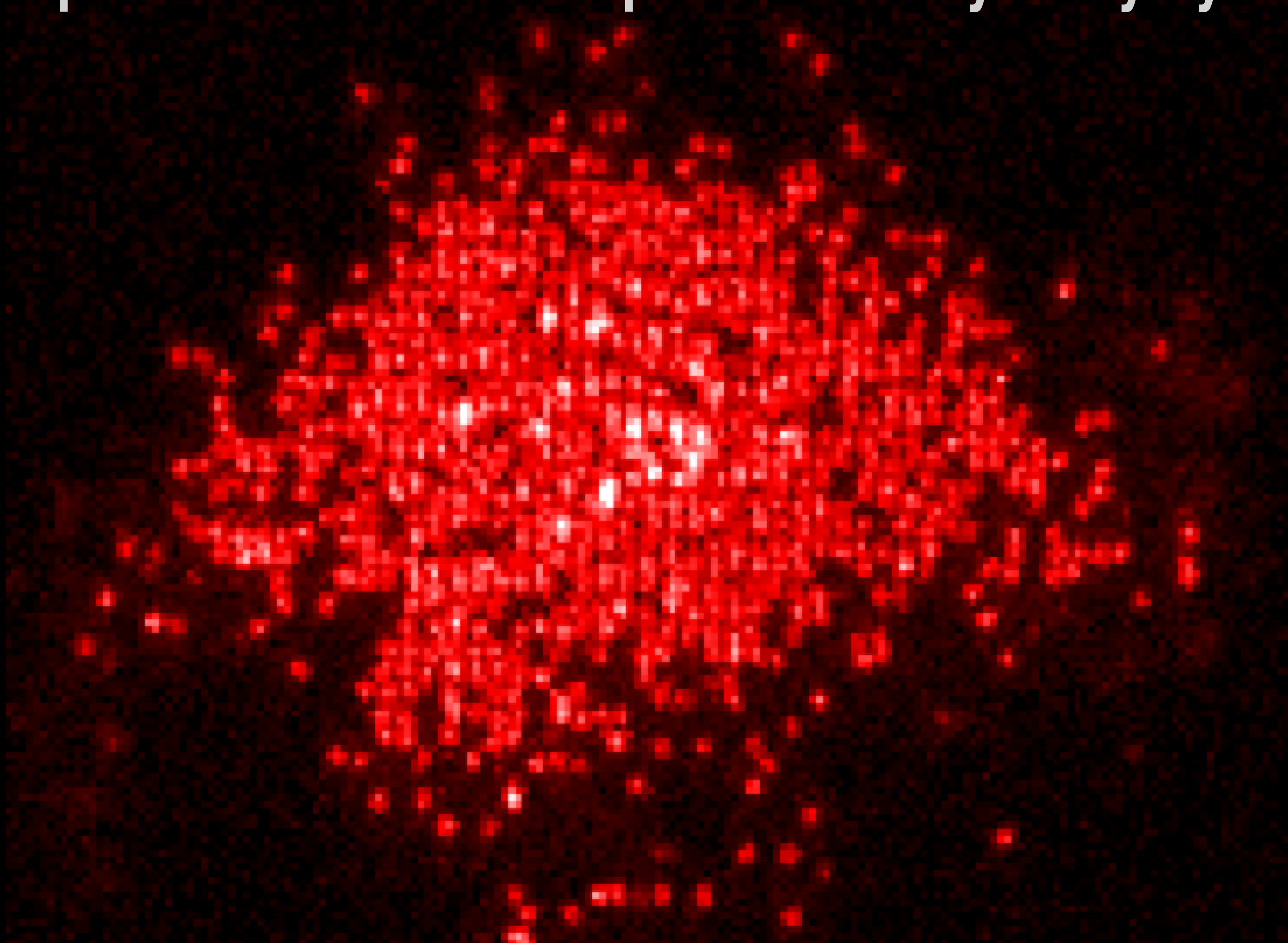


1d Fermi-Hubbard

Kollath, PRL 2005

This talk: Signatures of spin-charge separation in equilibrium!

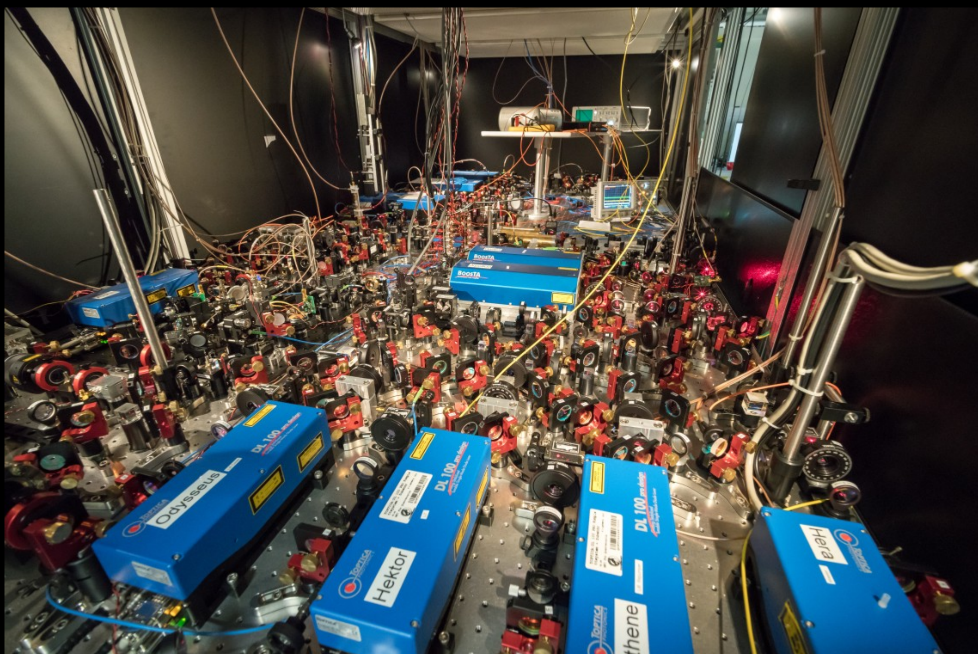
Snapshot of a fermionic quantum many-body system

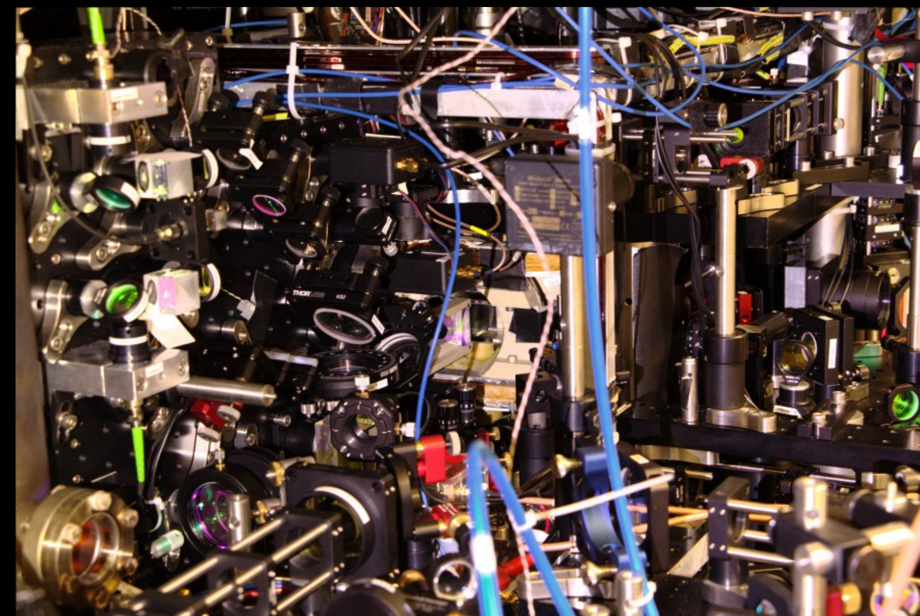


Also at: MIT, Harvard, Toronto, Glasgow

THE MACHINE

The fermi gas microscope @ MPQ





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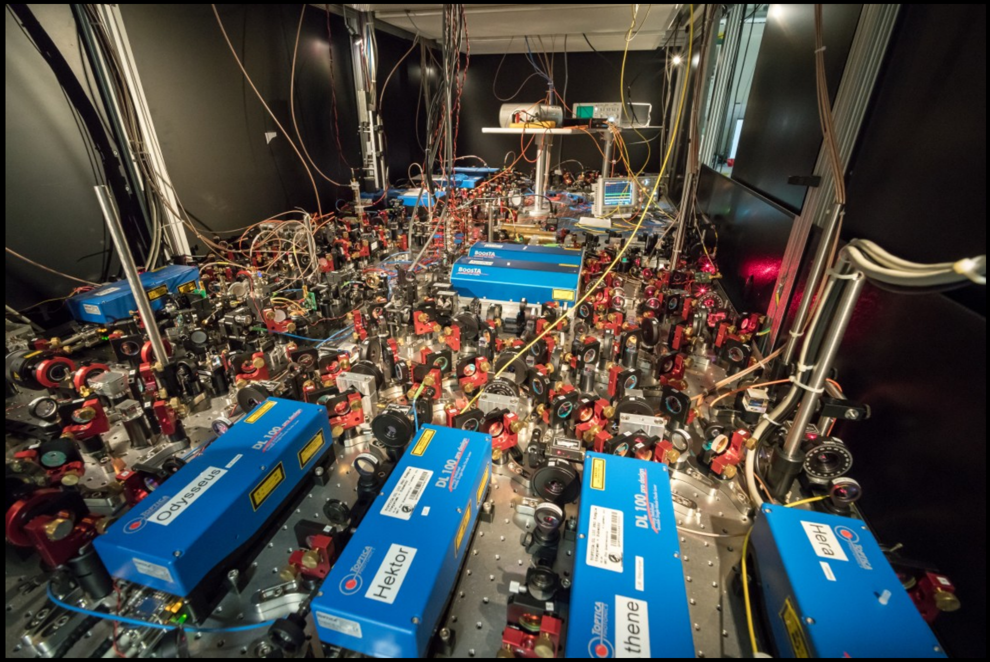

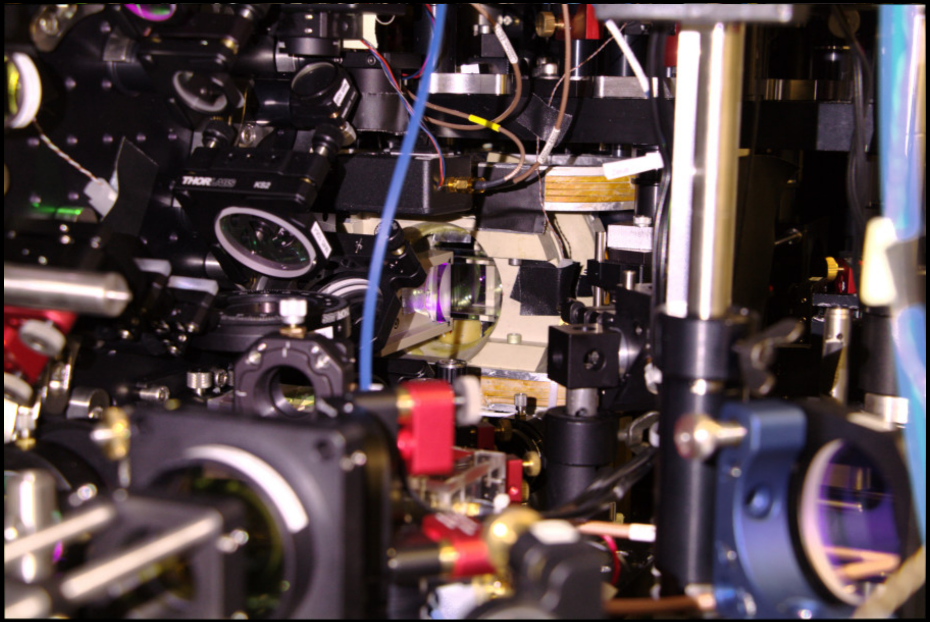

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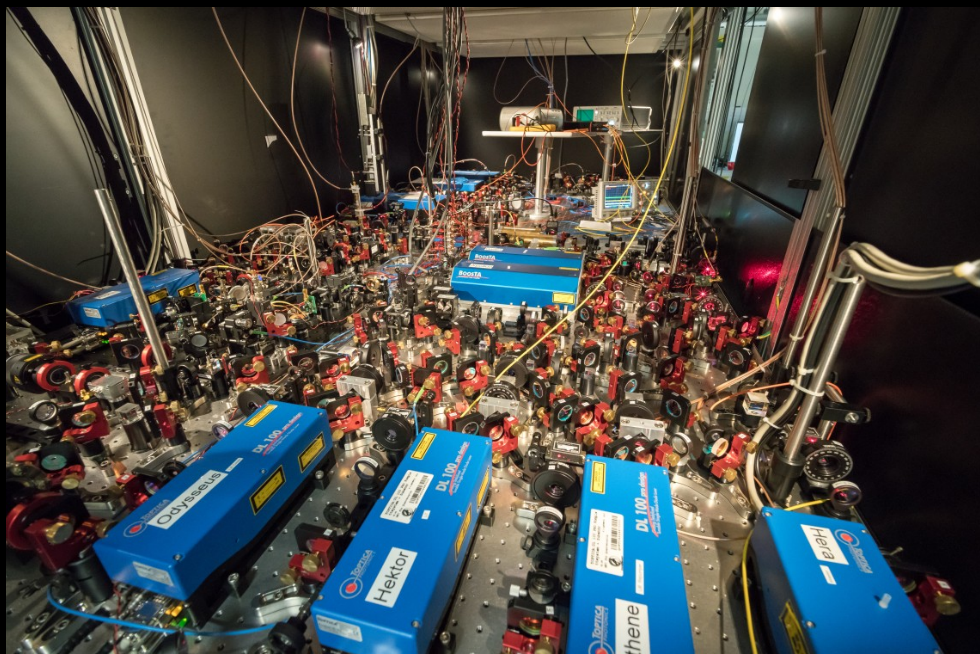
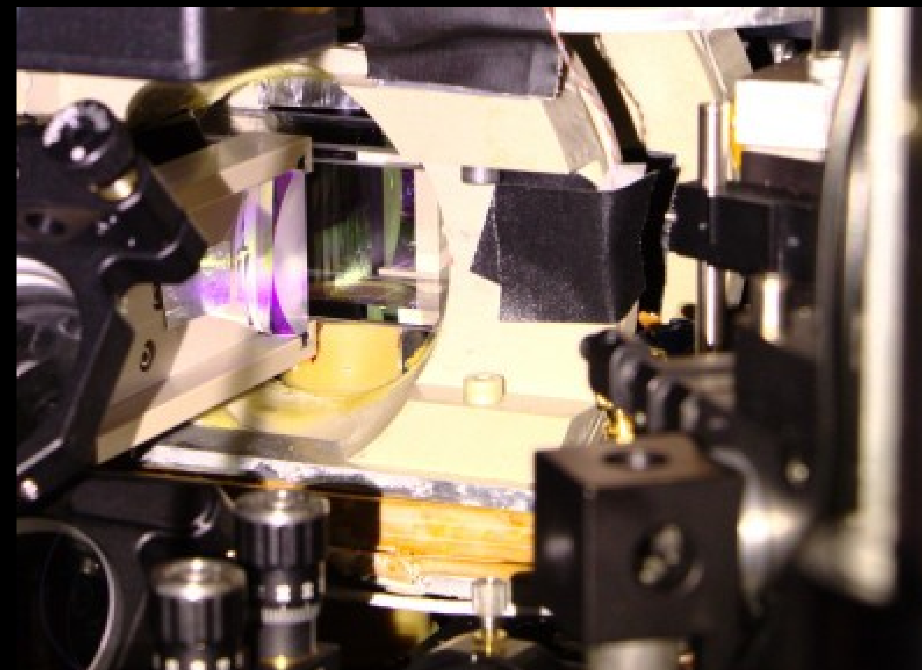
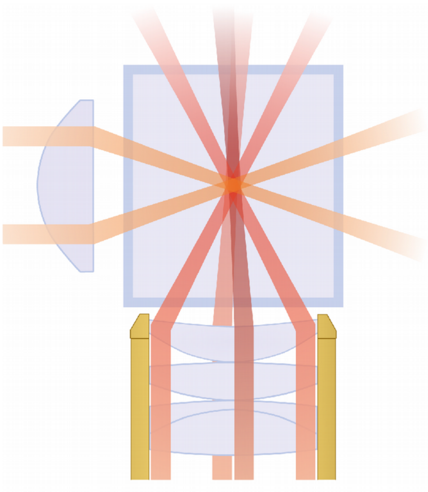
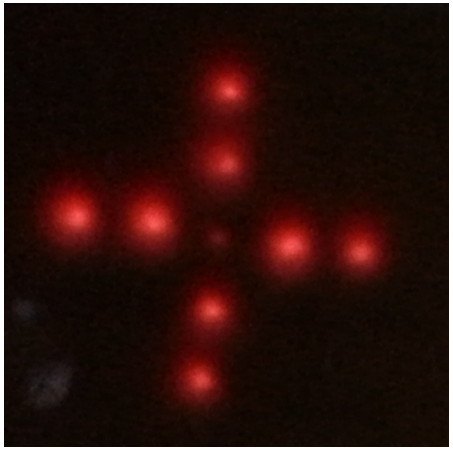




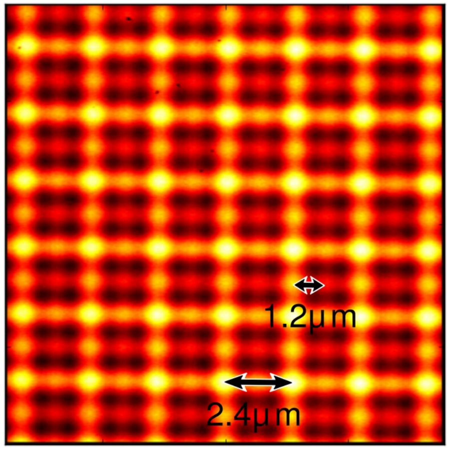
Versatile lattice geometries with large spacing



Schematic



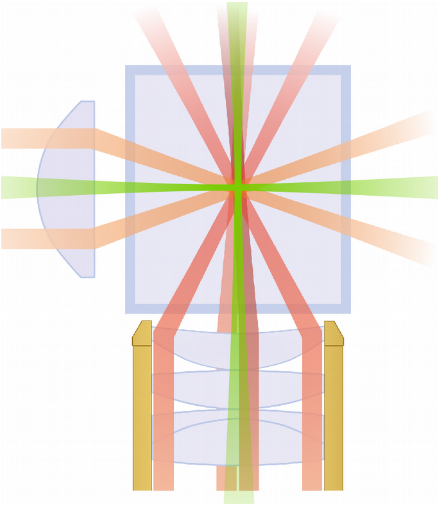
Superlattice input pattern

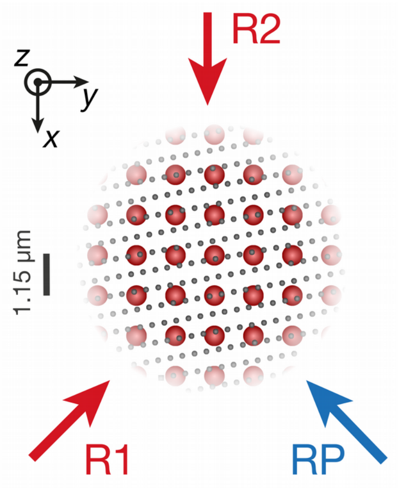


Superlattice potential

Dedicated imaging system

Separation of the “physics” from the imaging



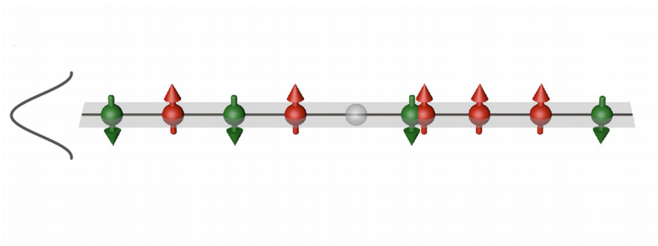


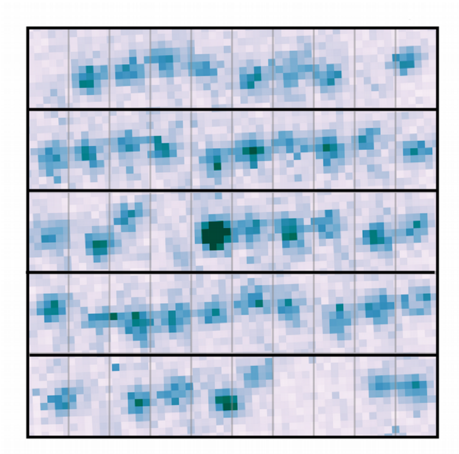
Pinning lattice oversamples
physics lattice more than twice

Imaging by **Raman sideband cooling** in the pinning lattice

Omran, PRL 2015

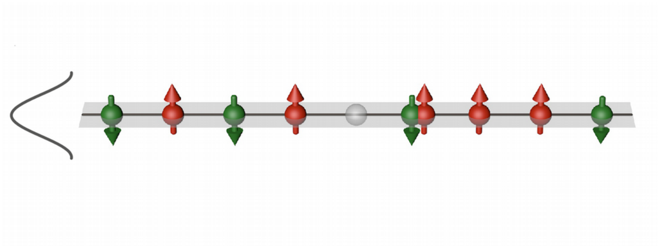
Local spin and charge detection in Hubbard chains

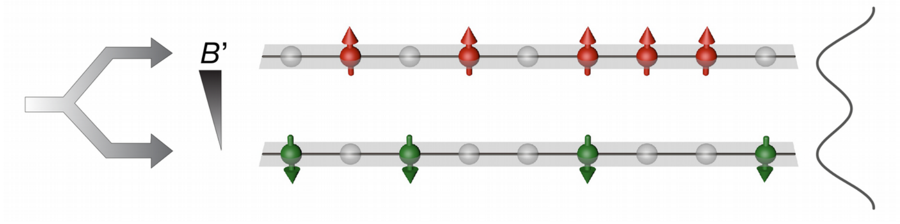


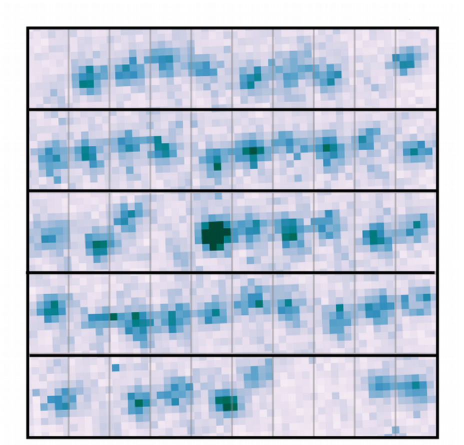


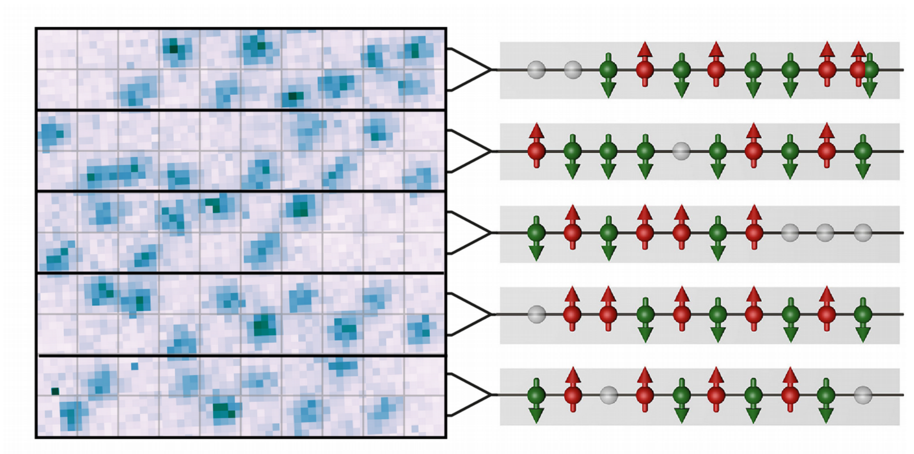
Boll, Science 2016

Local spin and charge detection in Hubbard chains







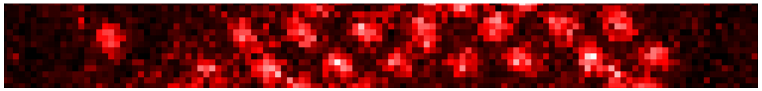


Full local information: Density and spin state

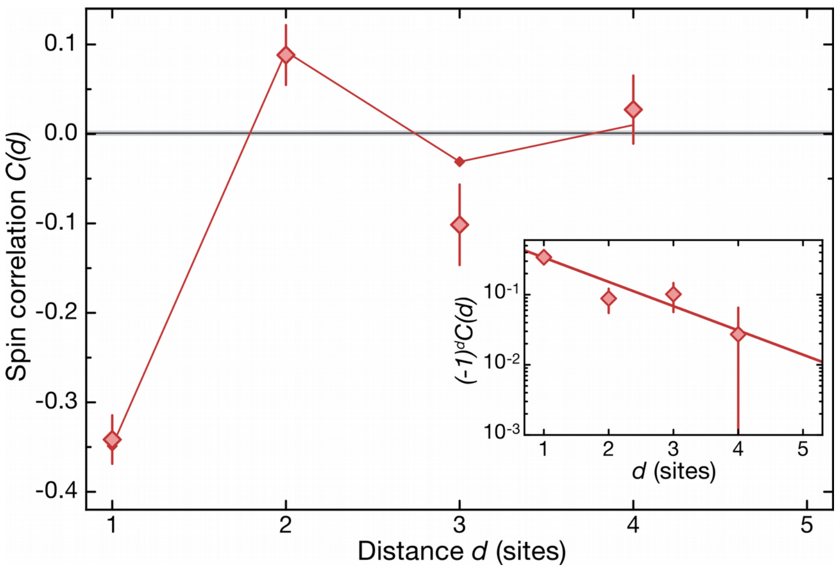
Boll, Science 2016

MAGNETIC CORRELATIONS IN 1D

Two components @ half filling



$$C(d) = 4\langle \hat{S}^z_i \hat{S}^z_{i+d} \rangle$$



Spin correlation range: $\xi = 1.3\,\text{sites}$

Entropy: $S = 0.5 k_B$

Boll, Science 2016

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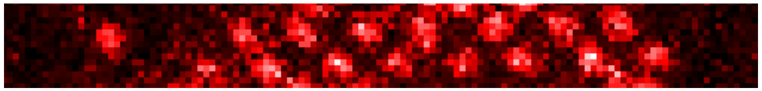

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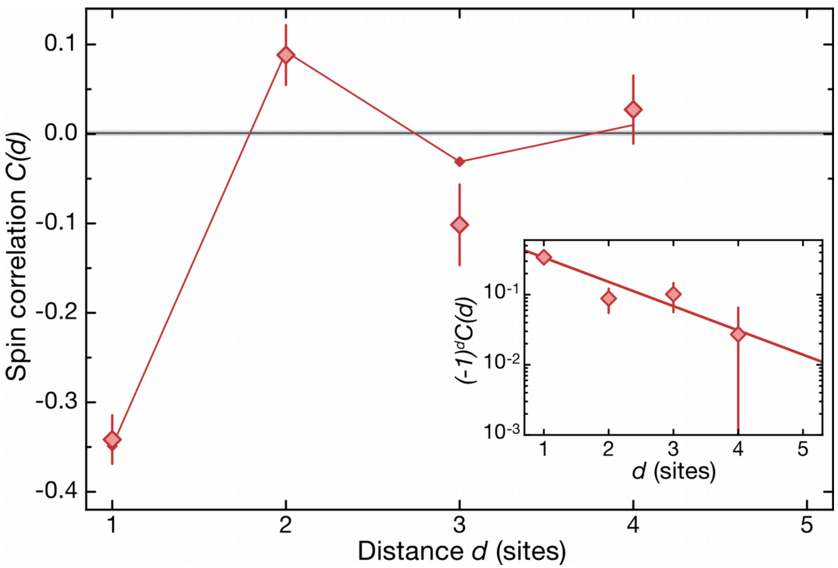

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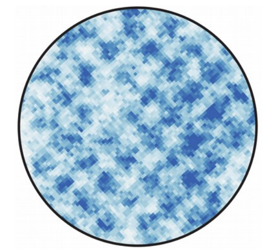
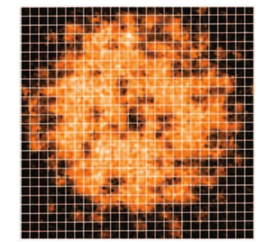
Boll, Science 2016

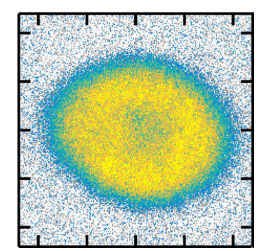
Experiments in 2D



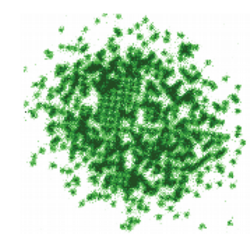
Mazurenko, Nature 2017



Cheuck, Science 2016



Drewes, PRL 2017

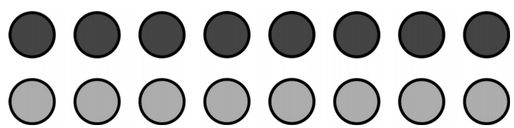


Brown, arXiv: 1612.07746

Interplay of spin and charge @ lower filling

Charge sector: Delocalization

$$\hat{H} = -t \sum_{i,\sigma} (\hat{c}^{\dagger}_{i,\sigma} \hat{c}_{i+1,\sigma} + \mathrm{hc}) + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$



Ogata, Shiba PRB 1990

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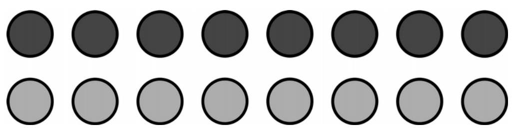

Spin sector: AFM "order"

$$\hat{H}_{\mathrm{Heis}} = J \sum_{i} \hat{S}_i \cdot \hat{S}_{i+1}$$

Ogata, Shiba PRB 1990

Interplay of spin and charge @ lower filling

Charge sector: Delocalization

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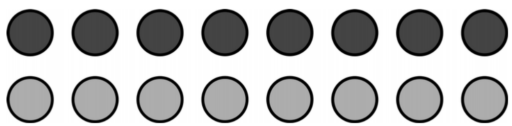

Spin sector: AFM “order”

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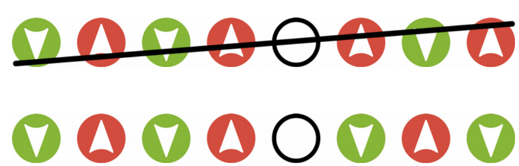
Solution: Anti-aligned spins around holes

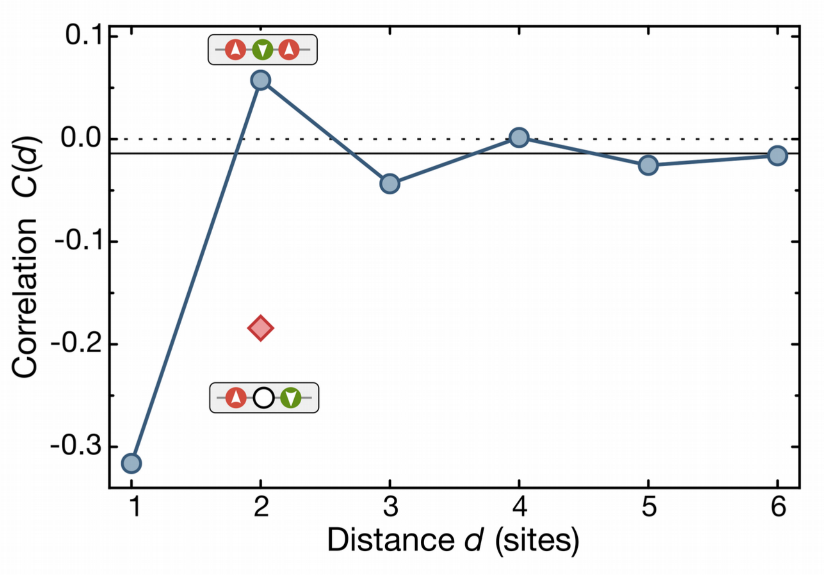


Ogata, Shiba PRB 1990

Spin-hole-spin correlations

$$C_{SH,N_h}(d) = 4 \langle \hat{S}^z_i \hat{S}^z_{i+d} \rangle_{\circ_i \{\bullet\}_{N_h} \circ_{i+d}}$$

Magnetism around a single hole



Spins around the hole behave much as if they were direct neighbors

Hilker, Science 2017

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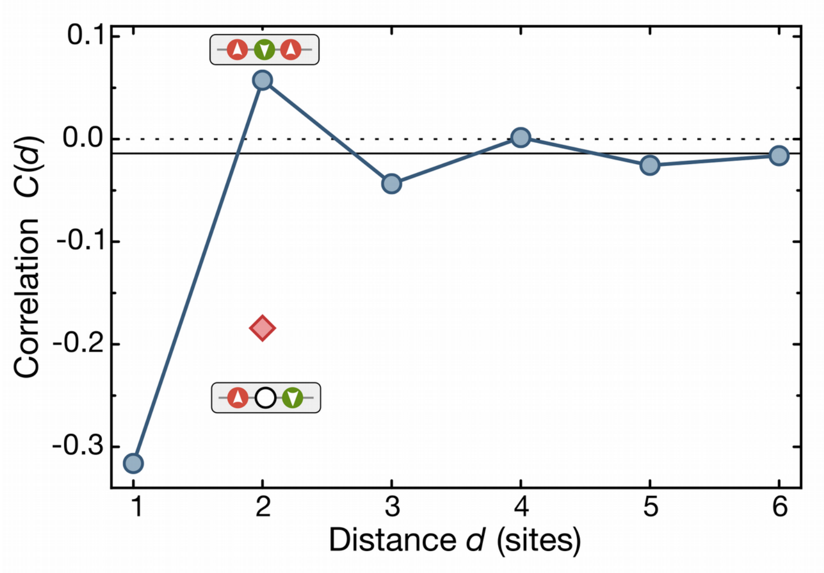
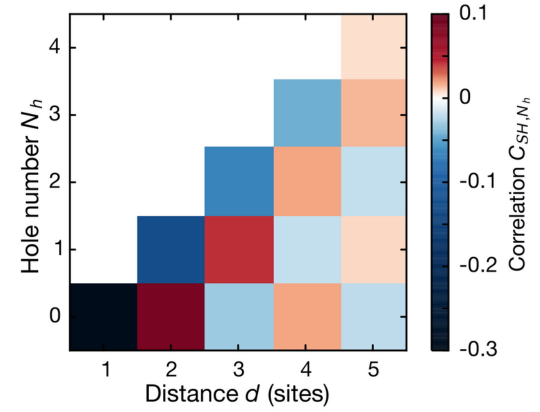


More holes



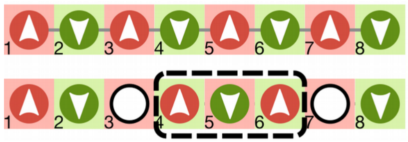
Spins around the hole behave much as if they were direct neighbors

Hilker, Science 2017

Hidden correlations in 1d Hubbard chains

Dominant effect of holes:
AFM parity flips suppresses the standard 2-point correlator

$$C(d) = 4\left(\langle \hat{S}_i^z \hat{S}_{i+d}^z \rangle - \langle \hat{S}_i^z \rangle \langle \hat{S}_{i+d}^z \rangle\right)$$



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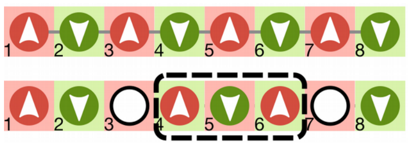
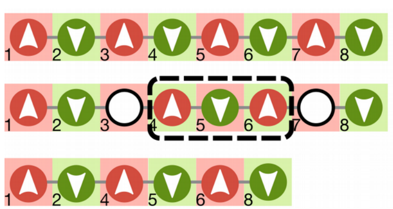


Correlations only "hidden"

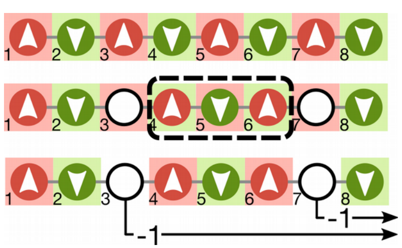
Squeezed space



Discard sites with holes

Zaanen group: Kruis, PRB 2004, EPL 2004

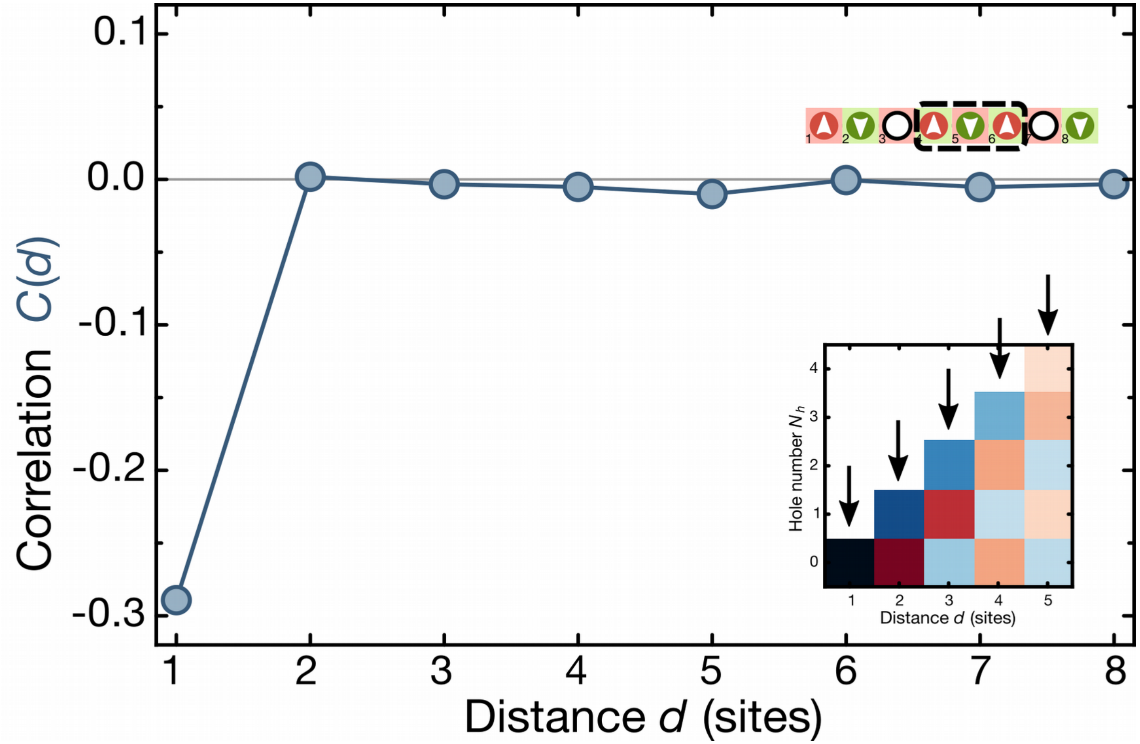
String correlator



$$C^{\mathrm{str}}(d) = 4\left\langle \hat{S}^z_i \left(\prod_{j=1}^{d-1}(-1)^{(1-\hat{n}_{i+j})}\right)\hat{S}^z_{i+d}\right\rangle_{\bullet_i \bullet_{i+d}}$$

cf. hidden order in Haldane phase

Detecting hidden correlations via string correlators



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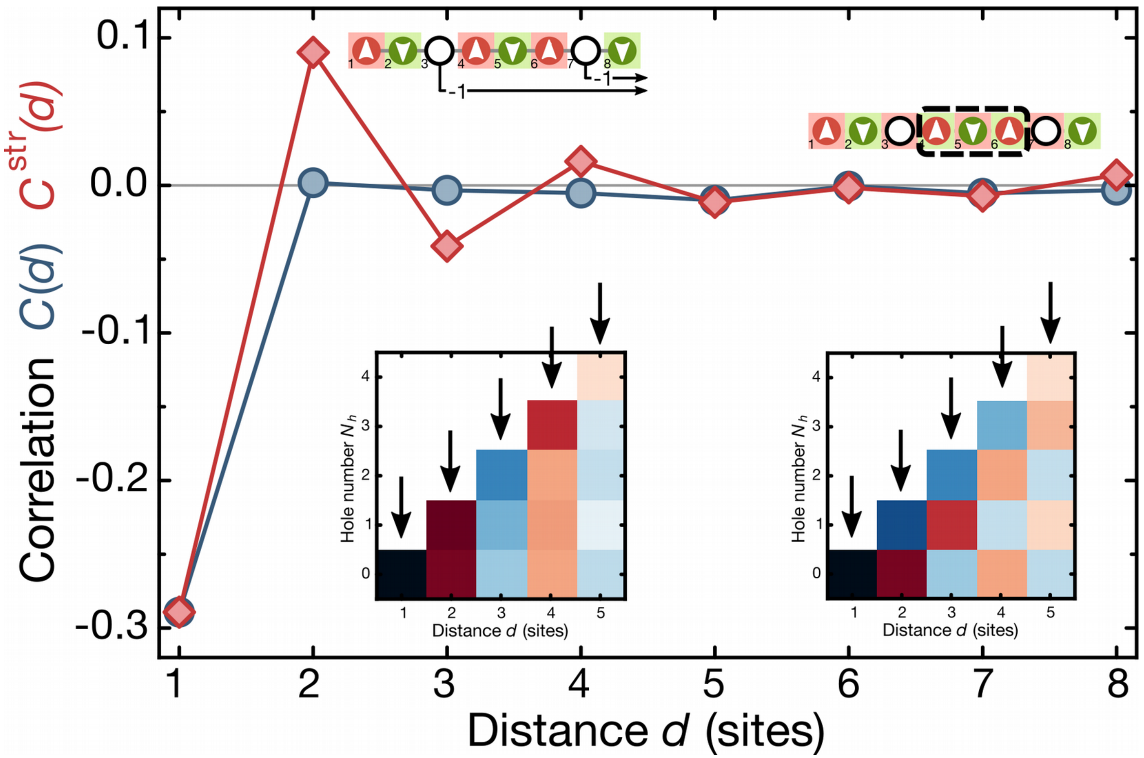
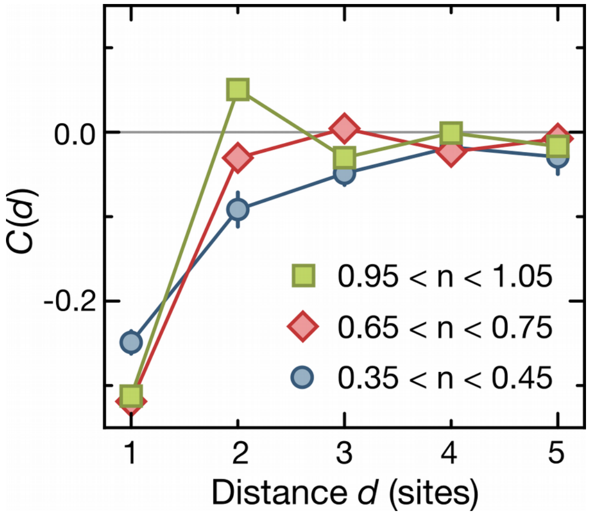
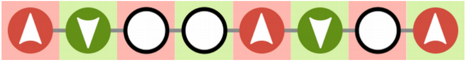


Correlations @ “fixed” doping

Standard 2-point correlator





Hilker, Science 2017

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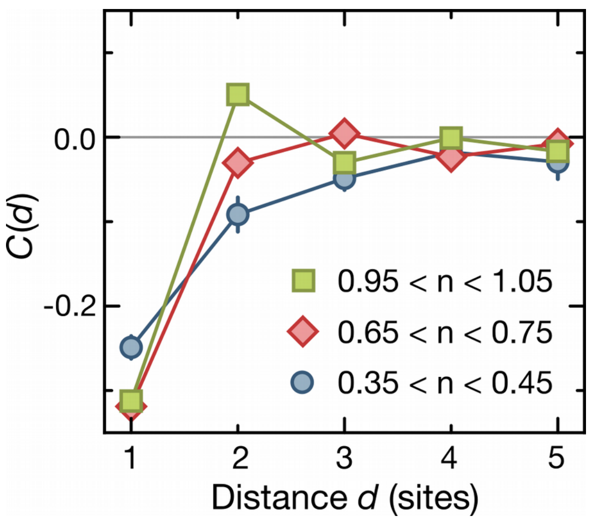
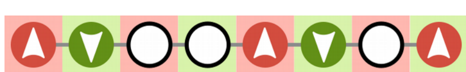
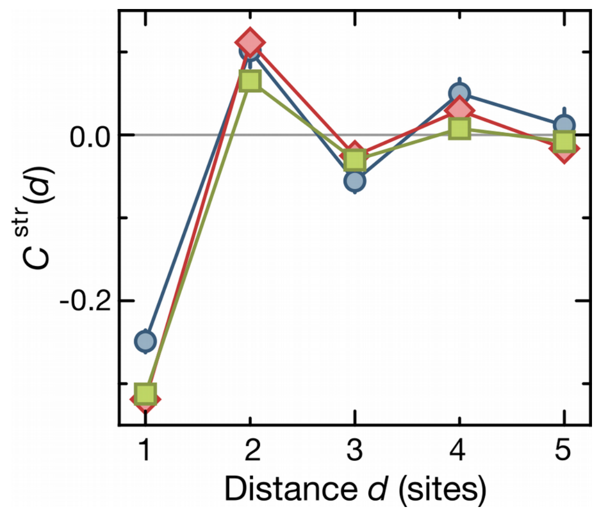
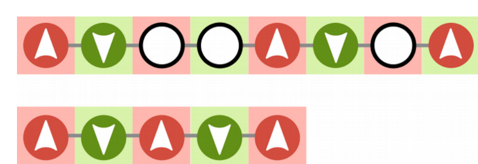




Squeezed space 2-point

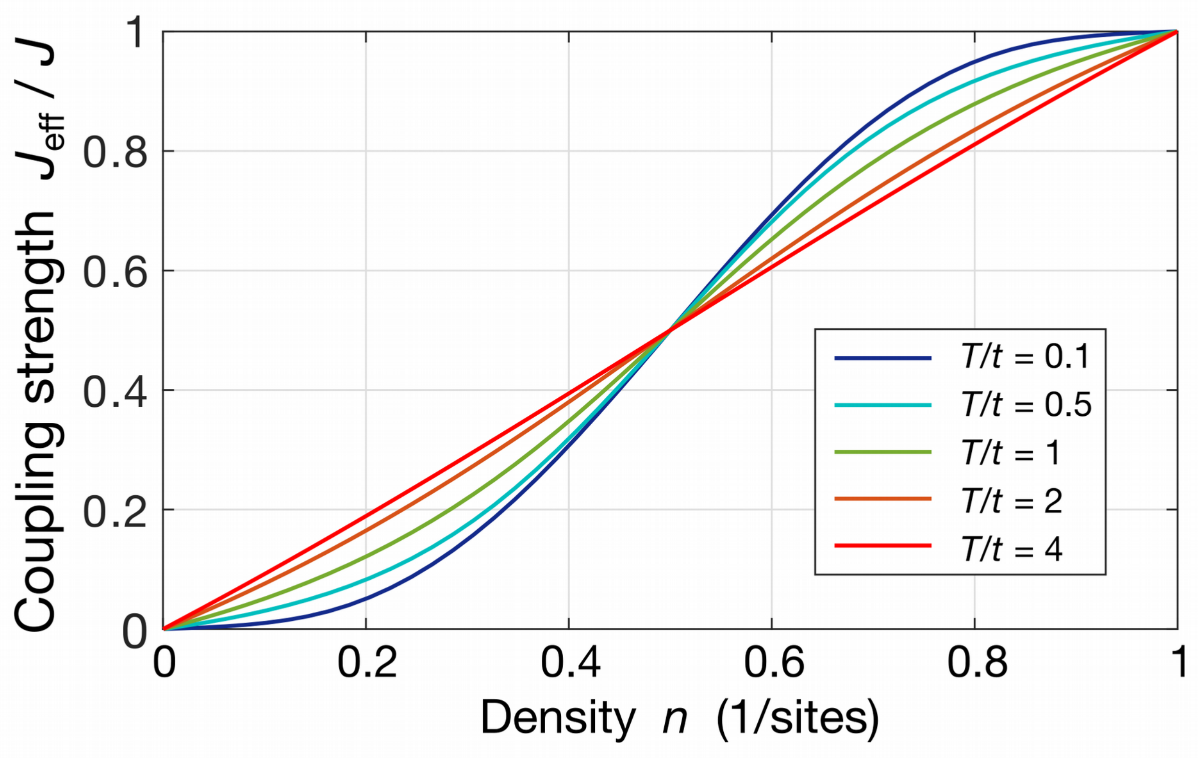




Hilker, Science 2017

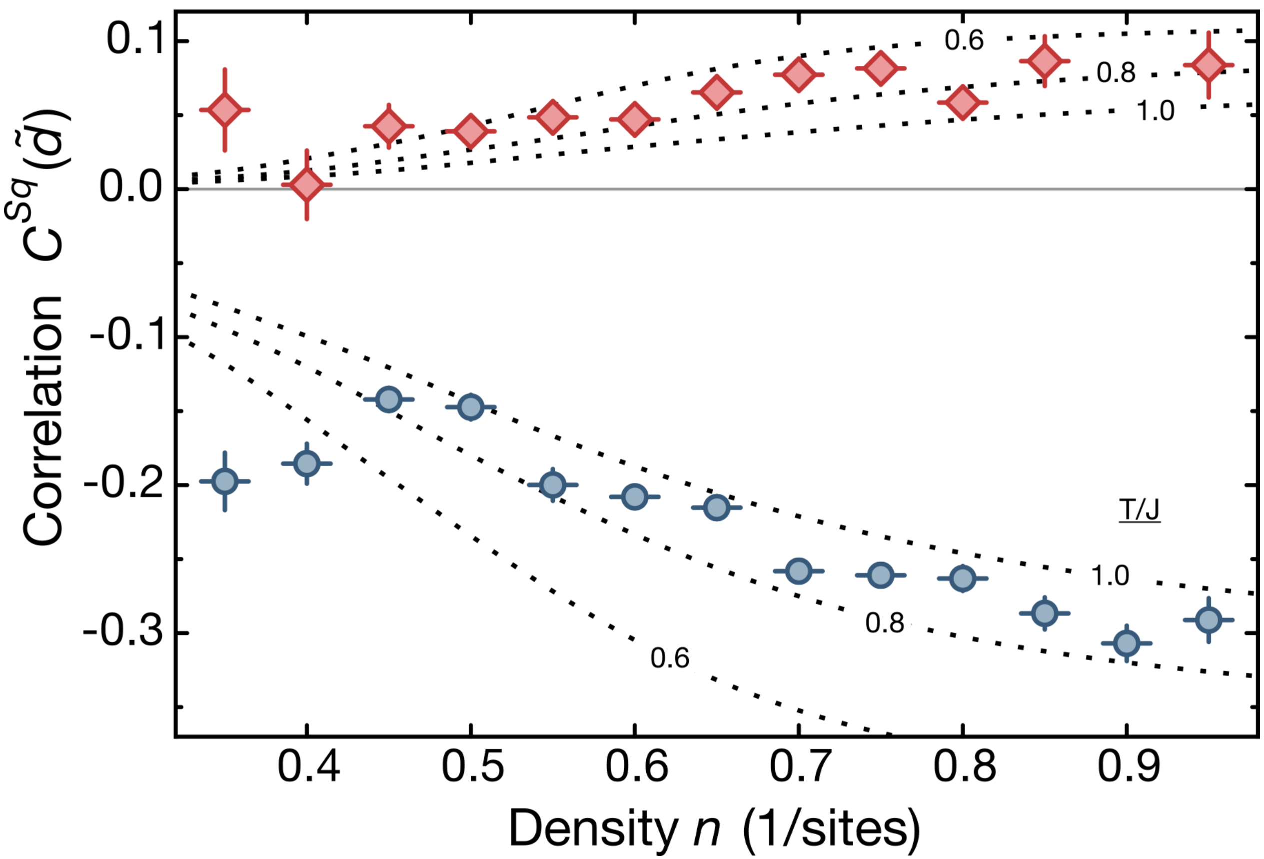
Squeezed space correlations at finite temperature

Spin in squeezed space: $\hat{H}_{sq} = J_{eff}(n, T) \sum_i \hat{S}_i \cdot \hat{S}_{i+1}$



Theory: F. Grusdt, E. Demler

Does this work in the experiment?



Effective Heisenberg model: $\hat{H}_{sq} = J_{eff}(n, T) \sum_i \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_{i+1}$

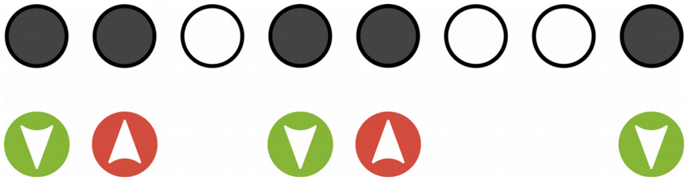
Hilker, Science 2017

Spin-charge separation at short distance

Luttinger liquid: Only valid at low energy / long wavelength

Here: Mostly short distance physics!

Large U limit:
Full separation at all length scales in the Hubbard model

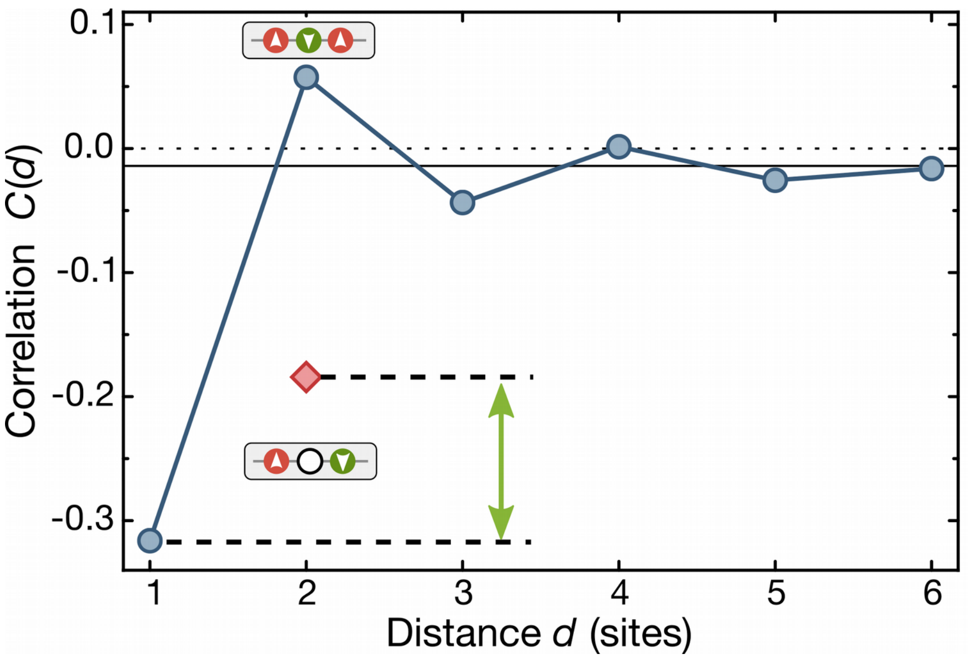


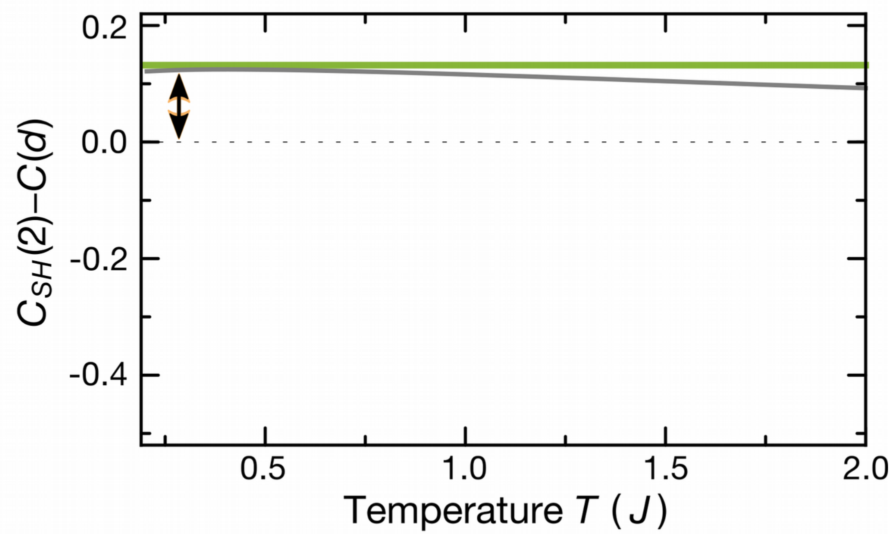
$$\Psi(x, \sigma) = \Psi_{\mathrm{ff}}(x_i)\Psi_{\mathrm{Heis}}(\tilde{x}_i, \sigma)$$

Ogata, Shiba, PRB 1990

Are spins and holes really independent

Experiment: finite $\frac{U}{t} = 8$





Even at T=0: **Hole between spins modifies the correlator!**

→ No perfect spin-charge separation at short range.

People

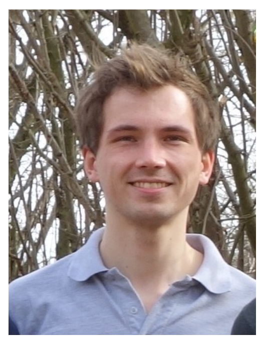
I. Bloch

G. Salomon

T. Hilker

A. Omran

M. Boll



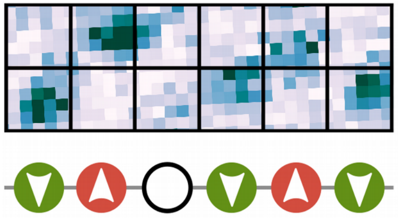
J. Koepsell

J. Vijayan

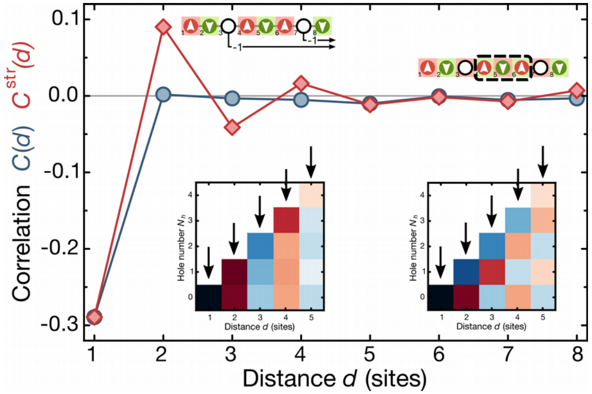
Theory support: *AFM:* J. Nespolo, L. Pollet | *Spin-charge:* F. Grusdt, E. Demler

Summary

Detecting all local
degrees of freedom
of the Hubbard model

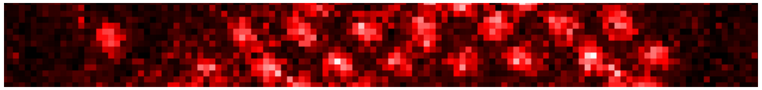


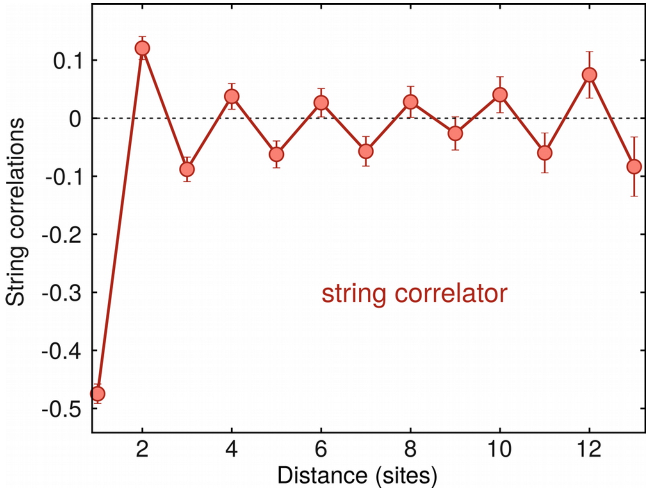
Spin-charge separation
via “hidden” correlations
in equilibrium



What's next?

What can we learn from post-selection?





- Spin-charge separation dynamically
- Valence bond solid to AFM crossover
- Extension to 2d