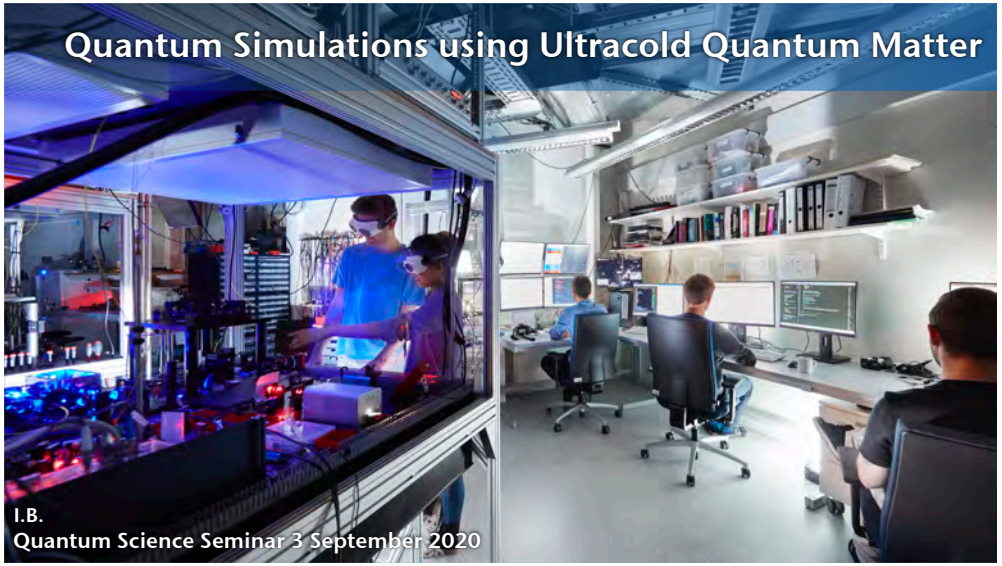
Quantum Simulations using Ultracold Quantum Matter



I.B.
Quantum Science Seminar 3 September 2020

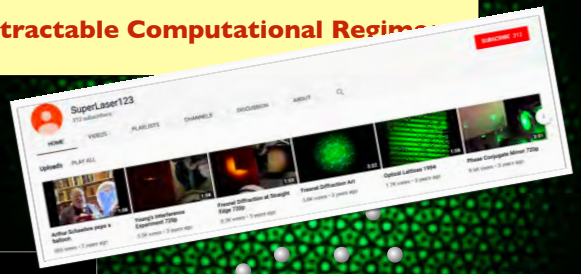
Outline

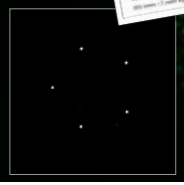
- Introduction
- Quantum Gas Microscopy of Fermi Hubbard Model
  - Fundamentals
  - Bilayer Readout
  - Fractionalization and Dynamical Spin-Charge Separation
  - Imaging Magnetic Polarons in 2d
  - From Polaron to Fermi-Liquid
- Outlook

Quantum Spin Systems

Particle Systems: Bosons, Fermions, Mixtures

Classically Intractable Computational Regime





Few particles up to 1000s of particles !

courtesey: T. Hänsch

Quantum Gas Microscopy

Measuring a Many-Body Quantum System

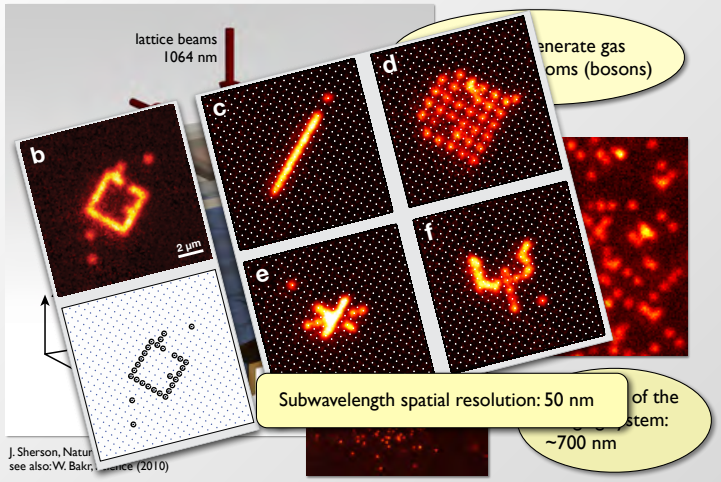
Local occupation measurement

$$|\Psi\rangle = |\,\cdot\,\rangle + |\,\cdot\,\rangle + |\,\cdot\,\rangle + \dots$$

Enables access to all position correlation between particles!

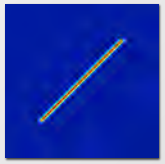
Extendable to other observables (e.g. local currents etc…)

Experimental Setup

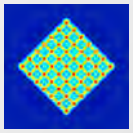


Arbitrary Light Patterns

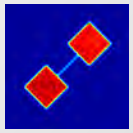
Digital Mirror Device
(DMD)



Measured Light Pattern



Exotic Lattices



Quantum Wires

Box Potentials

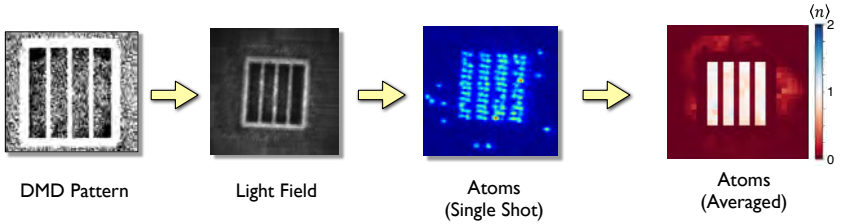
(but: fight Laser Speckle)

Almost Arbitrary Light Patterns Possible!

Single Spin Impurity Dynamics, Domain Walls, Quantum Wires, Novel Exotic Lattice Geometries, ...

Potential Shaping

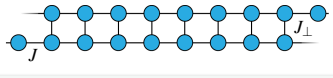
Example: Hubbard ladders in homogeneous potential

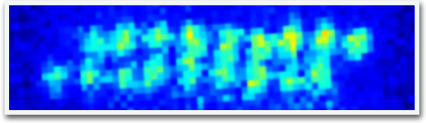


DMD Pattern | Light Field | Atoms (Single Shot) | Atoms (Averaged)

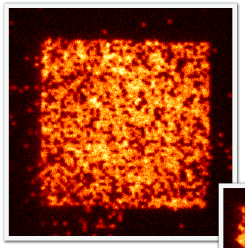
Flexible Geomtries and Larges Sizes

Quantum Ladders with flexible edge geometries (SPT Phases)

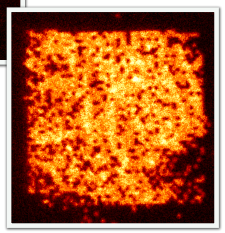




Fully tuneable coupling strengths



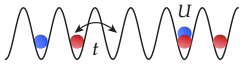
Large Scale MI in Box Potentials



50x50 atoms

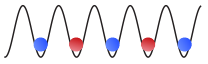
Fermi Hubbard Model (FHM)

Fermi-Hubbard Model



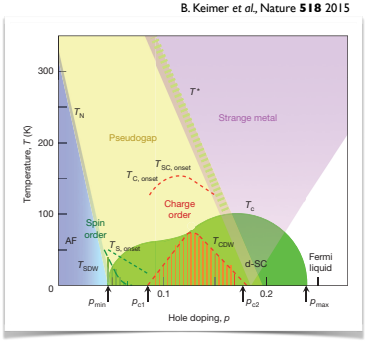
AFM Heisenberg Model

Half filling & strong interaction



$$H = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j \qquad J = \frac{4t^2}{U}$$

B. Keimer *et al.*, Nature **518** 2015

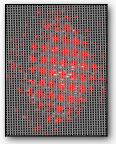


Away from half filling: ***t-J* model**
competition between

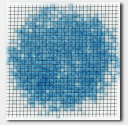
hole delocalization ↔ ***magnetic order***

A. Maruzenko et al. Nature (2017), M. Boll et al. Science (2016), T. Hilker et al. Science (2017),
L. Cheuk et al. Science (2016), P. Brown et al. Science (2017)

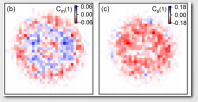
Fermi-Hubbard - 2016-2017



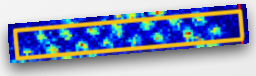
A. Omran et al. PRL (2015)



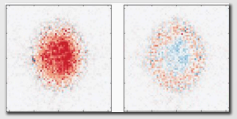
D. Greif et al. Science (2016)



L. Cheuk et al. Science (2016)



M. Boll et al. Science (2016)

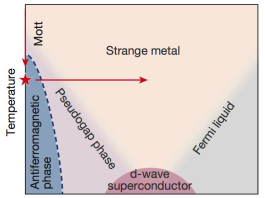


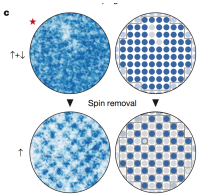
M. Parsons et al. Science (2016)

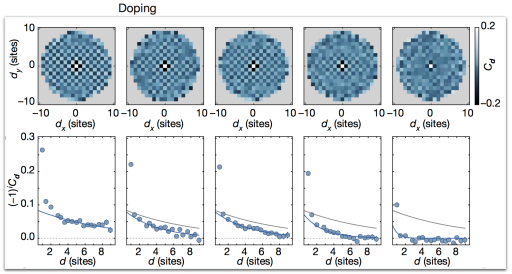
AFM Correlations (Short, Medium & Long Ranged) now visible!

A. Maruzenko et al. Nature (2017), M. Boll et al. Science (2016), T. Hilker et al. Science (2017),
L. Cheuk et al. Science (2016), P. Brown et al. Science (2017)

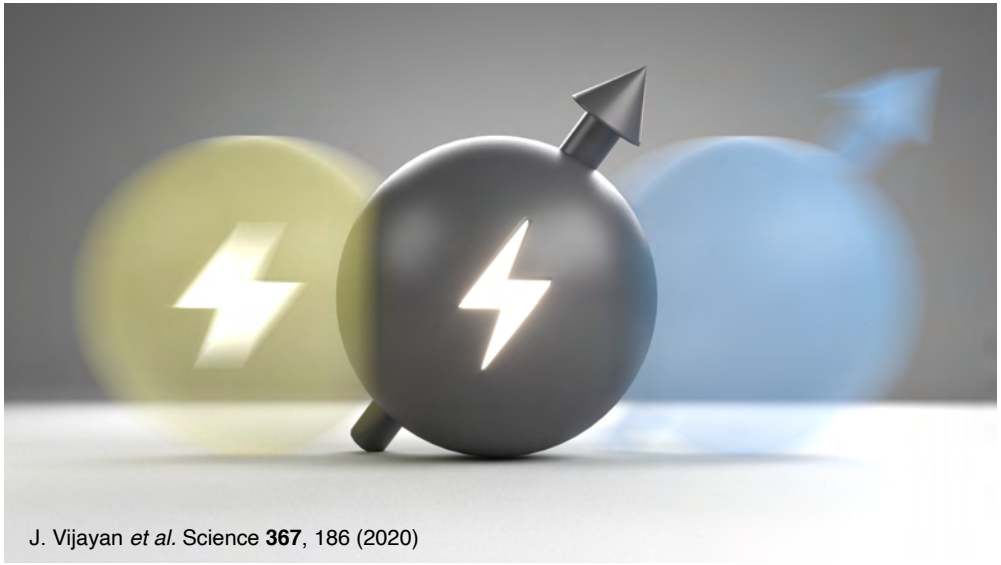
AFM Order in the Fermi Hubbard Model







A. Mazurenko et al.,
Nature **545**, 462 (2017)



J. Vijayan *et al.* Science **367**, 186 (2020)

The Electron

Charge -e

Spin 1/2

Fractionalization

Deconfinement of Quasi-particles that make up the elementary particle

Charge -e

Spin 1/2

Quasi-Particle

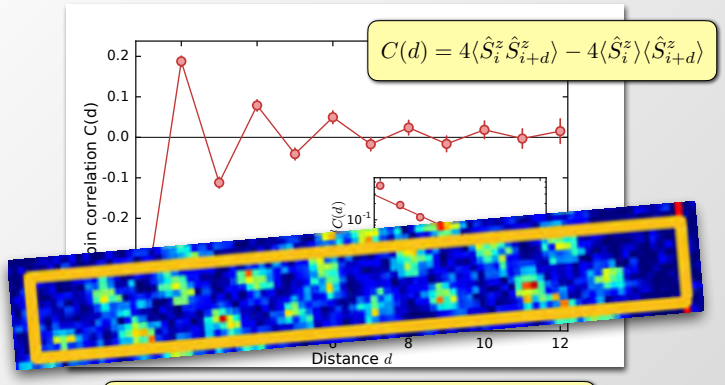
Quasi-Particle

AFM

Incommensurate Magnetism

Postselection to $M_z = 0$!

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



$\xi(0,T)$ **Largest possible decays length !**

LMU

The Electron

Charge -e

Spin 1/2

Fractionalization

Deconfinement of Quasi-particles that make up the elementary particle

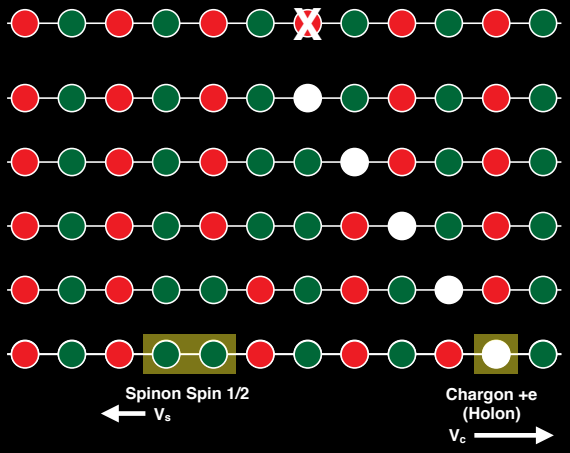
Charge -e

Spin 1/2

Quasi-Particle

Quasi-Particle

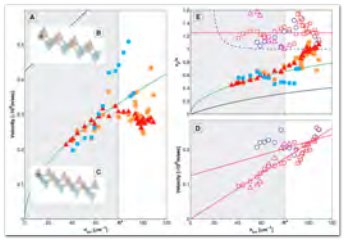
Fractionalization



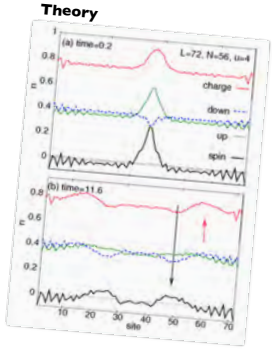
Previous Work

Spin-Charge Separation

Experiment



Theory

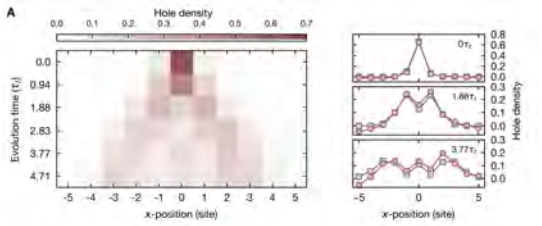


Spectroscopic determination:
C. Kim, et al. Phys. Rev. Lett. **77**, 4054 (1996)
O.M. Auslaender et al. Science **308**, 88 (2005)

DMRG Simulation:
C. Kollath, U. Schollwöck, W. Zwerger
Phys. Rev. Lett. **95**, 176401 (2005)

FHM Dynamics

Dynamical Spin Charge Separation



Hole Dynamics

$$\langle \hat{h}_i \rangle$$

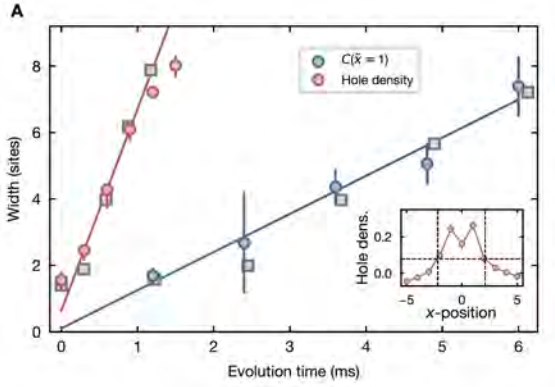
Spin Dynamics

$$C(1) = \langle \hat{S}_i^z \hat{S}_{i+1}^z \rangle$$

(squeezed space)

FHM Dynamics

Spin & Charge Velocities



Fractionalization - Hole Shedding Spinon

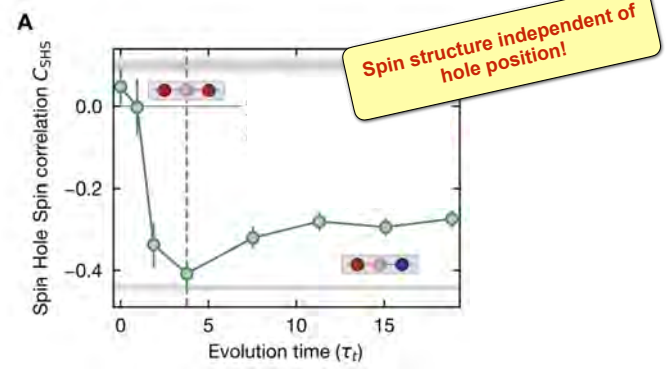
Spin attached to hole

$$\langle \hat{S}^z_{i-1}\, \hat{h}_i\, \hat{S}^z_{i+1} \rangle > 0$$

$$\langle \hat{S}^z_{i-1}\, \hat{h}_i\, \hat{S}^z_{i+1} \rangle < 0$$

Hole got rid of spin

Spin-Hole-Spin Correlations



$$\langle \hat{S}^z_{i-1}\, \hat{h}_i\, \hat{S}^z_{i+1} \rangle$$

Seeing the Spinon

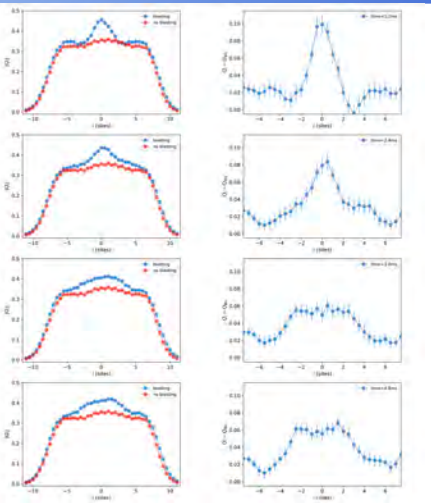
$$\hat{Q}_i = \sum_j \hat{S}^z_j f_L(|x_i - x_j|)$$

$\langle |\hat{Q}_i| \rangle$

Magnitude of Magnetization in length *L*

related $\langle \hat{Q}^2_i \rangle$

Magnetization Fluctuations in Region L

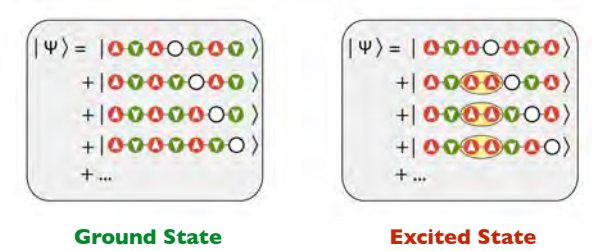


Hidden Order in the Ground State

Charge & Spin Order around Hole

Minimize Energy ⇨ **Two Conditions**

- Holes want to delocalise
- Spins want to align antiferromagnetically



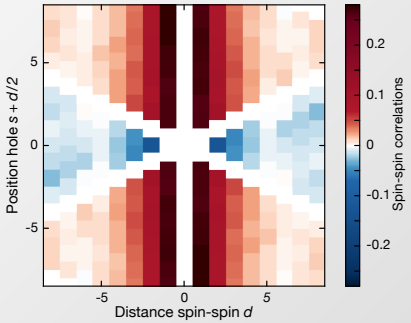
Ground State **Excited State**

Microscopic Origin of SC —Separation

Hole introduce domain wall
"parity" kinks in AFM background!

Hole = Non local topological excitations!

AFM around Holes



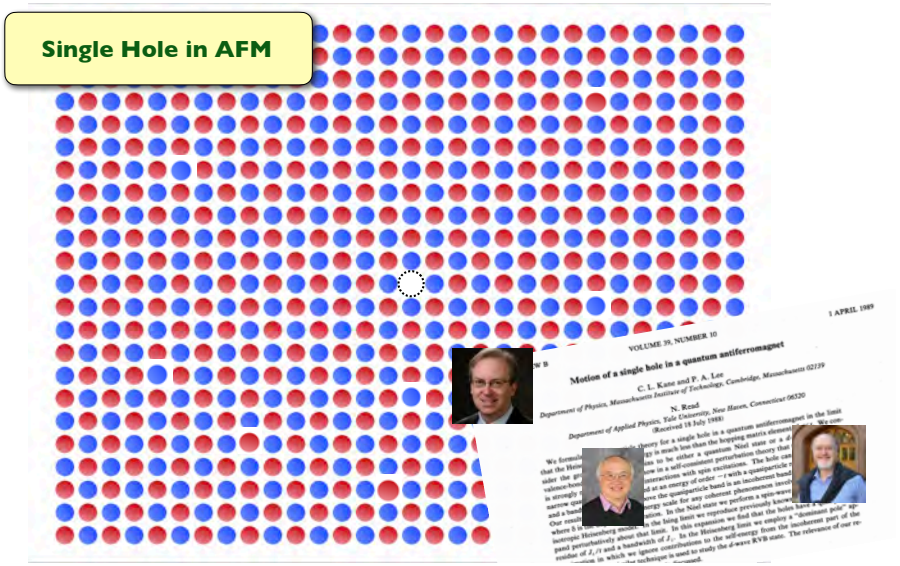
$$C_{s,h}(s,d) = (-1)^d \langle \hat{S}_z(i) \hat{h}_{i+s} \hat{S}_z(i+d) \rangle$$

Hidden (Topological) Order in the 1D Hubbard

Charge Impurities in 2D

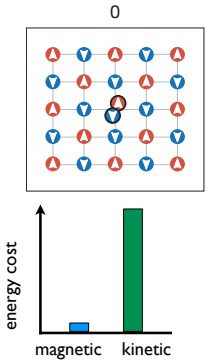
J. Koepsell *et al.* Nature **572**, 358 (2019)

Single Hole in AFM



Competing Energy Costs: Kinetic vs Magnetic

$t \gg J$

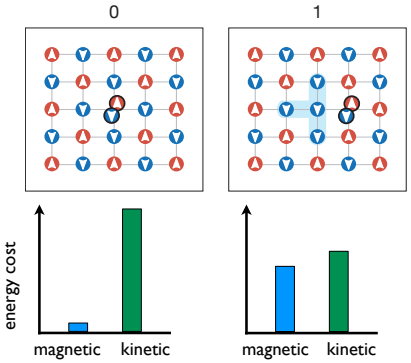


Polaron

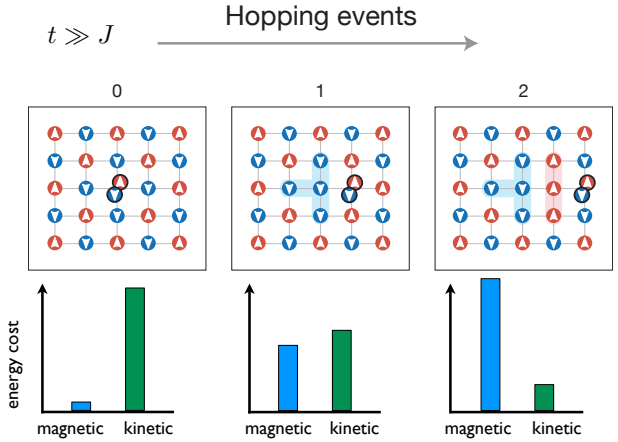
Competing Energy Costs: Kinetic vs Magnetic

$t \gg J$

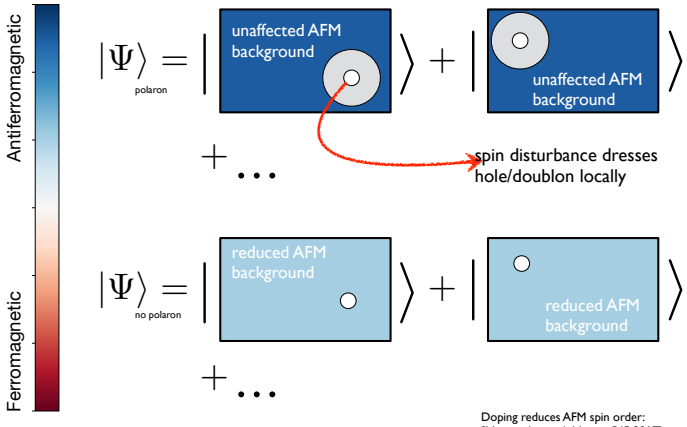
Hopping events



Competing Energy Costs: Kinetic vs

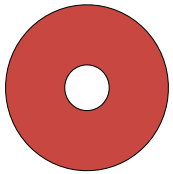


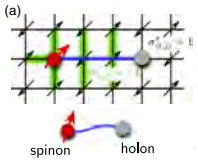
Ground State?



Doping reduces AFM spin order:
[Mazurenko *et al.*, Nature 545 2017]

Polarons in the FHM





Grusdt *et al.*, PRX 8 2018

- **Semiclassical considerations**

$$R \simeq \left(\frac{t}{J}\right)^{\frac{1}{4}}$$ Auerbach, Springer 1994

- **Nagaoka ferromagnetism**
  Large *t/J* (large *U*): dressing becomes ferromagnetic

  Nagaoka, Phys. Rev. 147 1966

- **Quasiparticle** with bandwidth W=2J :
  Chernyshev and Wood, arXiv:cond-mat/0208541, 2002

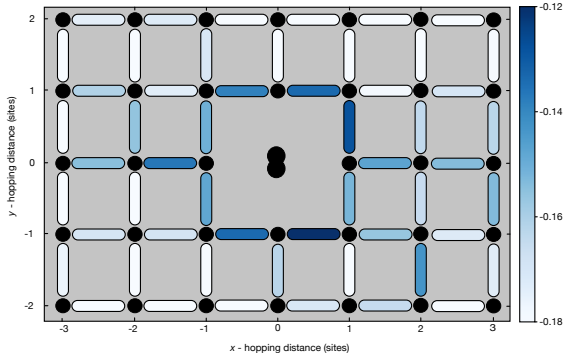
- **Attraction between polarons**
  ⟶ superconductivity, stripes?

- **String picture**: spinon-holon binding string length

$$L \simeq \left(\frac{t}{J}\right)^{\frac{1}{3}}$$

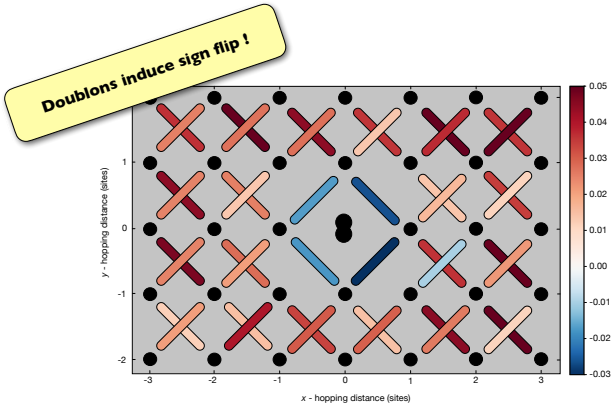
Lee *et al.*, Rev. Mod. Phys. **78** 2006
Schrieffer *et al.*, PRB **39** 1988

C(1) Local Spin Correlations Around

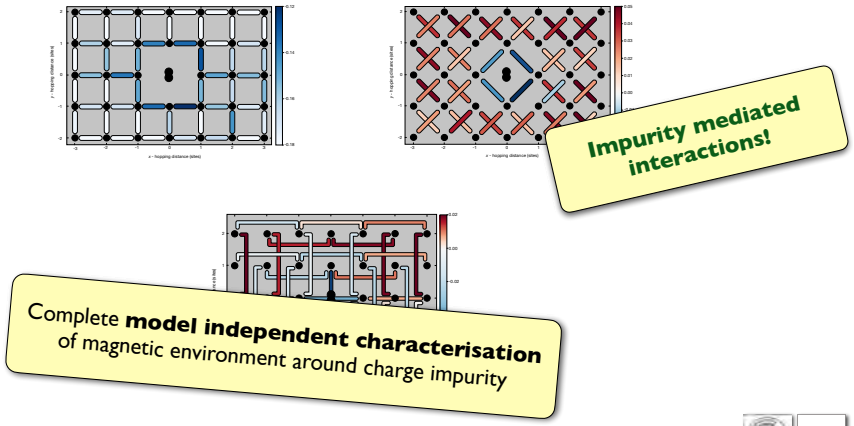


Conditioned C(1) Correlator

C(1,1) Local Spin Correlations around



Magnetic Polaron Size

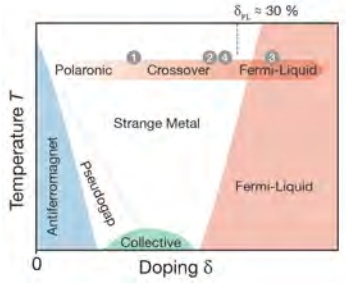


related: detection of string patterns Ch. S. Chiu *et al.* Nature (2019)

Polaron Breakdown into Fermi-Liquid

check arXiv soon…..

Doping 2d Antiferromagnets



New observables from QGM's (with full resolution)

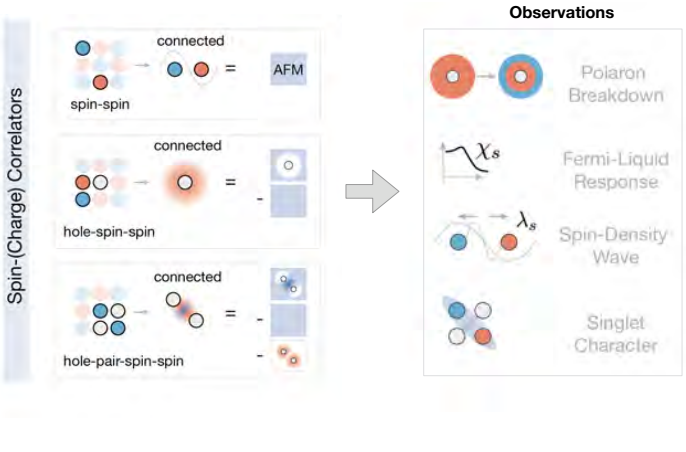
2-point **3-point** **4-point**

Correlations

- Cuprates: nature of charge carriers changes from (polaron) hole-like to electron-like at around 19% doping
  [Badoux et al. Nature 531, 2016]
- Pseudogap + Strange Metal behaviour in the < 19% doping regime. What is the link to polarons and antiferromagnetic correlations?
- QMC of Fermi-Hubbard model: single-particle bandwidth is polaronic (order J) up to around 30% doping, then free-particle like (8t)
  [Preuss et al. PRL 79, 1997]
- Numerical Simulations suggest a Spin-Density-Wave in Fermi-Liquid regime, with spin-structure peak moving (pi,pi) over (0,pi) to (0,0) (expected from random-phase approximation and noninteracting Fermions)
  [Moreo et al. PRB 41, 1990]
  [Furukawa&Imada, Jour. Phy. Soc. J. 61, 1992]
- Magnetic Susceptibility (q=0,w=0) predicted to rise for PG+SM phase dopings, then drop like weakly interacting Fermi-Liquid
  [Moreo, PRB 48, 1993]

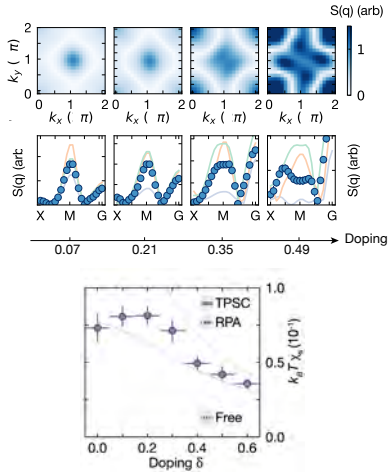
check arXiv soon…..

Connected vs. Disconnected Correlations



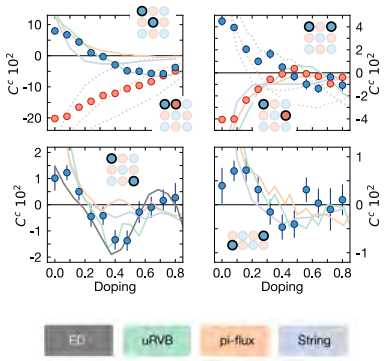
Spin-Spin Correlations (2-point)

Spin Structure Factor + Susceptibility



- Spin-Density Wave behaviour for extreme dopings
- Incommensurate peak moving from (pi,pi) to (pi,0)
- Magnetic Susceptibility expected from weakly interacting Fermi-Liquid: monotonic decrease with doping
- Pink curve: Noninteracting Fermions
- Two regimes in experiment:
  0-30% doping: constant/increase
  >30% doping: monotonic decrease
  (susc. can be computed via fluctuation dissipation for q=0)

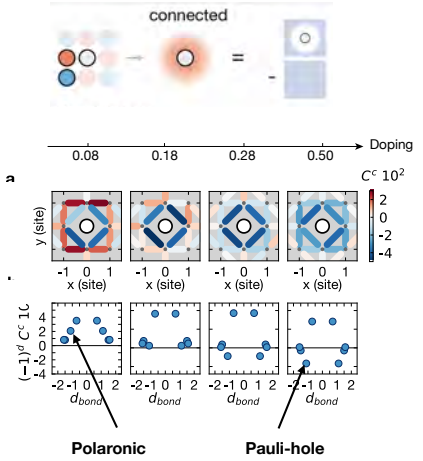
Spin-Spin Correlator



- Most correlations change sign around 20-30% doping
- Weakly oscillating magnetism with doping
- Extreme dopings: Spin-Density Wave expected from Fermi-Liquid/ Noninteracting Fermions
- Comparison to 4 numerical simulations
  (ED: has large finite size offsets
  RVB states:
  - ED: large finite size (only C(2,2) shown with scaling factor)
  - pi-flux good for low doping
  - uniform: very good agreement all dopings
  - string: ok for low dopings

Hole-Spin-Spin Correlations (3-point)

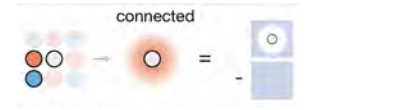
Hole-Spin-Spin Correlator

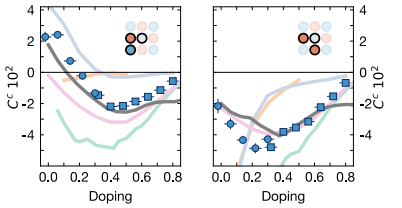


- polaronic correlations <20% doping
- polaron breakdown 20-40% doping
- transformation into Pauli-hole driven correlations for dopings >40%
- very good agreement with ED (T=0.4t)

Polaron to Fermi Liquid

Hole-Spin-Spin Correlator





ED | uRVB | pi-flux | String | Nonint

- polaronic correlations <20% doping
- polaron breakdown 20-40% doping
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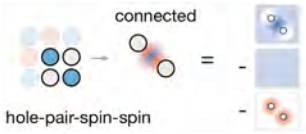
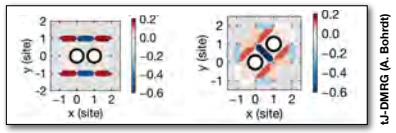
- very good agreement with ED (T=0.4t)

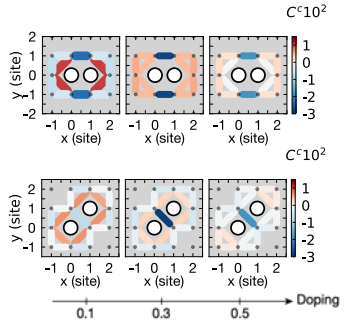
Hole-Hole-Spin-Spin Correlations (4-point)

Probing Interactions



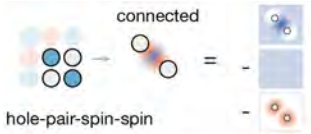


- Singlet-character of spins around hole-pairs seen with DMRG
- Experiment sees antiferromagnetic features
- Explanation: Pauli-hole driven + dh fluctuations
- Key observation: Qualitative features of paired holes already built in
- Pairing affects correlations (mostly) **quantitatively**, *not* qualitatively



Polaron to Fermi Liquid

Probing Interactions



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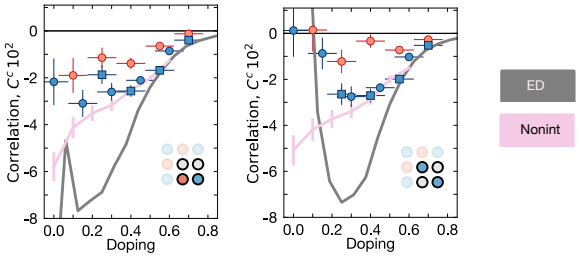
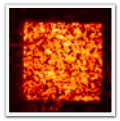


Scaling Up

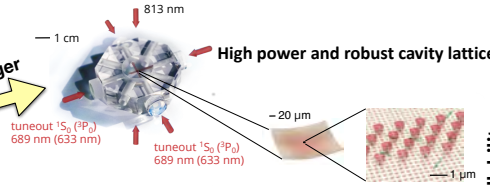
Next 1-2 years

Ultracold Atoms

~1000 atoms

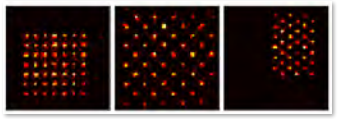


larger



Tweezer Arrays

~100 atoms



Ion Traps

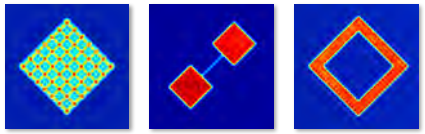
~50 atoms

Big advantage: all atoms (molecules) are the same! (built by nature)

Controllability

Challenges

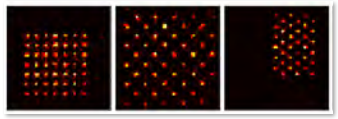
Programmability



Programmable Lattices | Quantum Wires | Box Potentials

Almost Arbitrary Light Patterns Possible!

(but: fight Laser Speckle)



Unique Geometries (reconfigurable on the fly)

LMU

Outlook

- Search for New Phases of Matter
- Extremely Strong Magnetic Field Physics
- Novel Quantum Magnets
- Controlled Quasiparticle Manipulations
- Non-Equilibrium Dynamics (Universality?)
- Thermalization in Isolated Quantum Systems
- Entanglement Measures in Dynamics
- Supersolids
- Cosmology - Black Hole Models?
- High Energy Physics/String Theory
- New clocks/Navigation

Quantitative testbeds for theory!