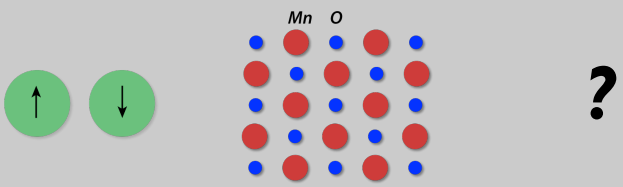
LECTURE 2 - Quantum Magnetism with UCQG

- Superexchange Interactions
- Single Spin Impurity
- Bound Magnons
- AFM Order in the Fermi Hubbard Model
- Probing Hidden AFM in 1D Hubbard Chains
- Direct Imaging of Spin-Charge Separation
- Imaging Polarons - Charge Impurities in an AFM
- Incommensurate AFM in 1D

Superexchange Interactions

Origin of Spin-Spin Interactions – Exchange Interactions



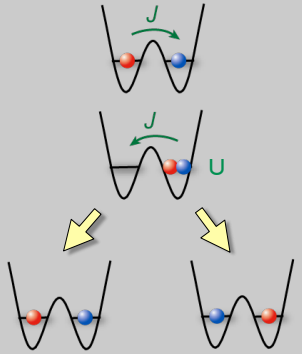
Important ionic solids with no direct exchange between magnetic ions show magnetic ordering (MnO, CuO)!

„Super"-exchange interactions must be at work!

P.W. Anderson, Phys. Rev. **79**, 350 (1950)

Deriving the Effective Spin Hamiltonian (1)

How do we get from $-J\sum_{\langle i,j\rangle}\hat{a}_i^\dagger\hat{a}_j+\frac{1}{2}U\sum_i\hat{n}_i(\hat{n}_i-1)$ to $H=-J_{ex}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$?



$\hat{1}$ + $\hat{X}_{LR}$

Deriving the Effective Spin Hamiltonian (2)

Second order hopping can be written as $H = -2\frac{J^2}{U}\left(1+\hat{X}_{LR}\right)$

$$\hat{X}_{LR}\left[\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}\right] = -\left[\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}\right]$$

$$\hat{X}_{LR}\left[\frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}\right] = +\left[\frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}\right]$$

0 Singlet

-J Triplet

$H = -J_{ex}\hat{P}_{\text{triplet}}$

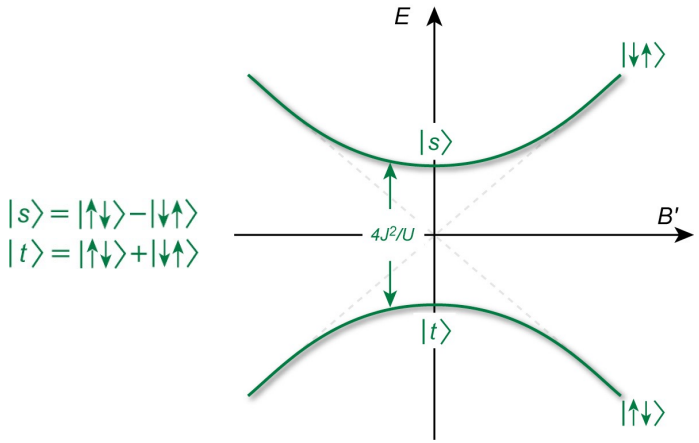
Deriving the Effective Spin Hamiltonian (3)

$\hat{P}_{\text{triplet}} = \hat{P}_{S=1}$

$$\begin{aligned}\mathbf{S}_L\cdot\mathbf{S}_R &= \frac{(\mathbf{S}_L+\mathbf{S}_R)^2}{2} - \frac{3}{4} \\ &= \frac{S(S+1)}{2} - \frac{3}{4} \\ &= \hat{P}_{S=1} - \frac{3}{4}\end{aligned}$$

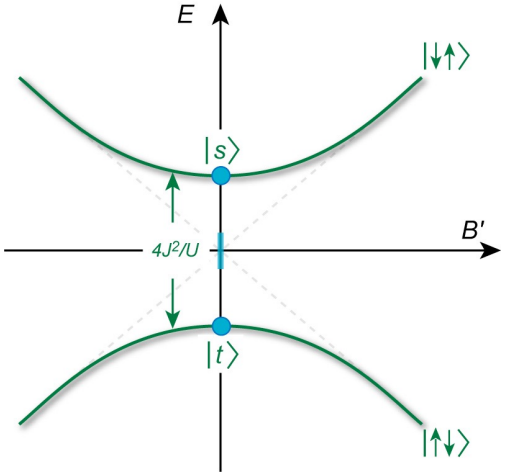
$H = -J_{ex}\left(\mathbf{S}_L\cdot\mathbf{S}_R + \frac{3}{4}\right)$

Direct Detection of Superexchange Interactions

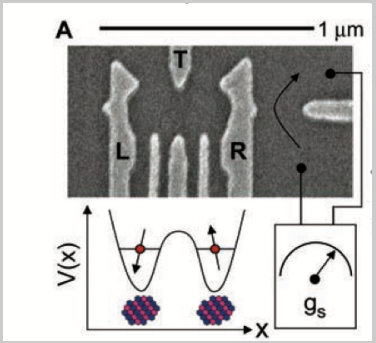


$H_{eff} = -J_{ex}\,\vec{S}_L\cdot\vec{S}_R - \mu_B B'\left(S_{z,L} - S_{z,R}\right)$

Direct Detection of Superexchange Interactions (2)



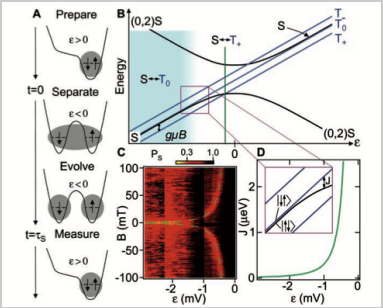
Superexchange Coupling in Quantum Dots



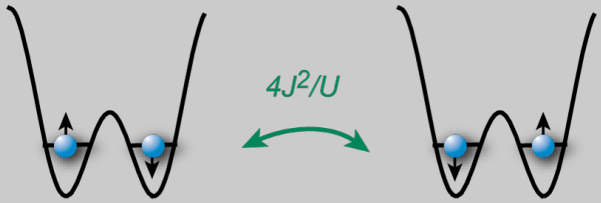
Local control of spin states & interactions between spin states.

J.R. Petta et al., Science **309**, 2180 (2005)

Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots

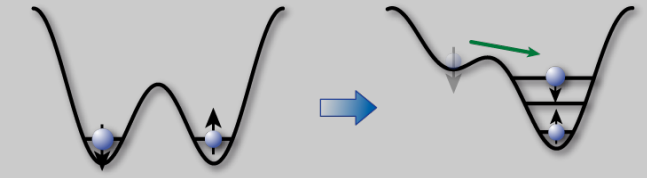


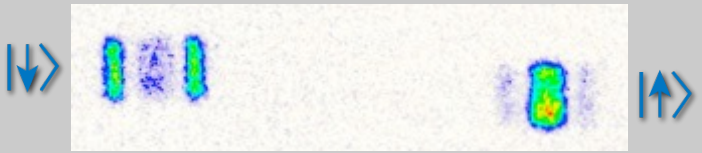
Superexchange induced flopping



$$H_{eff} = -J_{ex}\vec{S}_i \cdot \vec{S}_j$$
$$= -\frac{J_{ex}}{2}\left(\hat{S}_i^+\hat{S}_j^- + \hat{S}_i^-\hat{S}_j^+\right) - J_{ex}\hat{S}_i^z\hat{S}_j^z$$

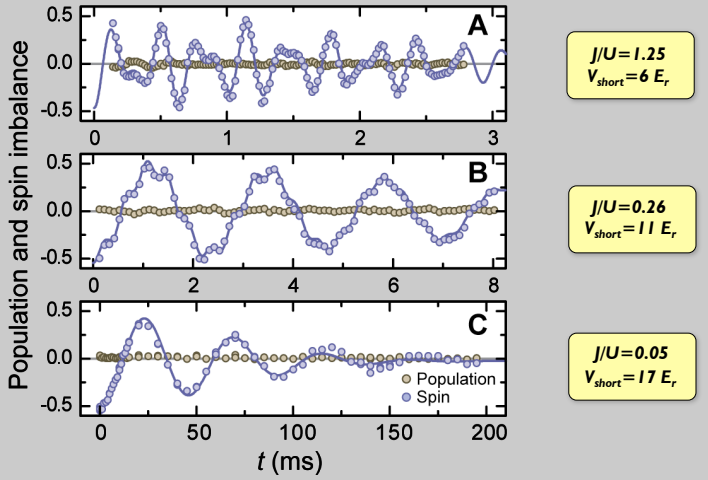
Mapping the Spins





Initial AF order verified in the experiment!

Superexchange induced flopping



J/U=1.25
V_{short}=6 E_r

J/U=0.26
V_{short}=11 E_r

J/U=0.05
V_{short}=17 E_r

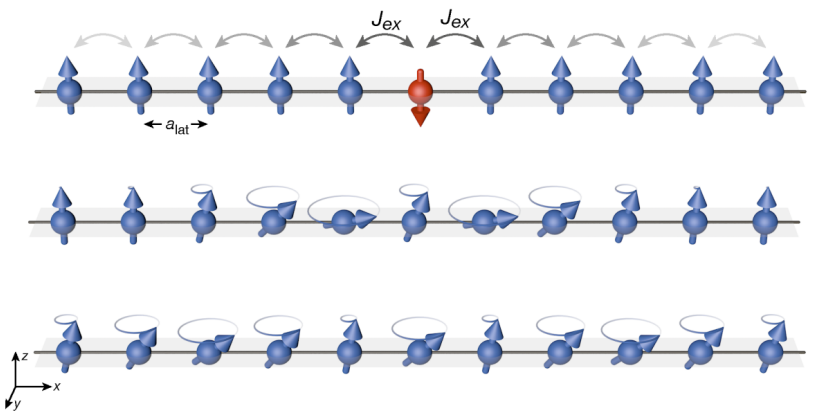
Quantum Dynamic of Mobile Single Spin Impurity

T. Fukuhara, M. Endres, M. Cheneau P. Schauss, Ch. Gross, I. Bloch, S. Kuhr,
U. Schollwöck, A. Kantian, Th. Giamarchi

Sherson et al. Nature 467, 68 (2010),
see also Bakr et al. Nature (2009) & Bakr et al. Science (2010)

www.quantum-munich.de

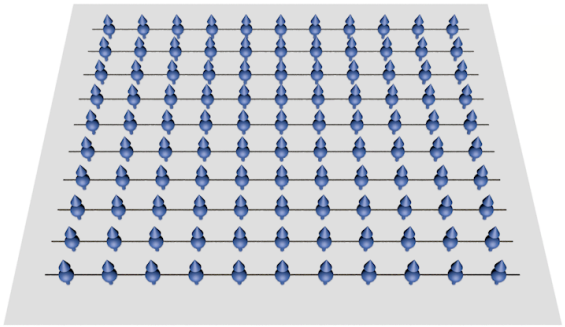
Spin impurity dynamics

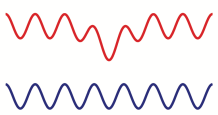


$$-J_{ex}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$$

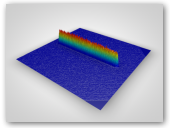
Ferromagnetic Heisenberg Interaction

Spin impurity dynamics



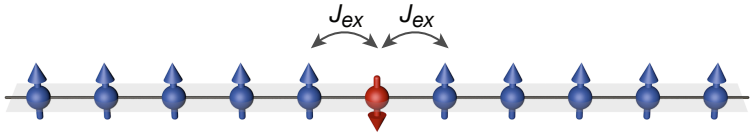


$|2\rangle = |F=2, m_F=-2\rangle$
$|1\rangle = |F=1, m_F=-1\rangle$



Line-shaped light field created with DMD SLM

Spin impurity dynamics



Heisenberg Hamiltonian

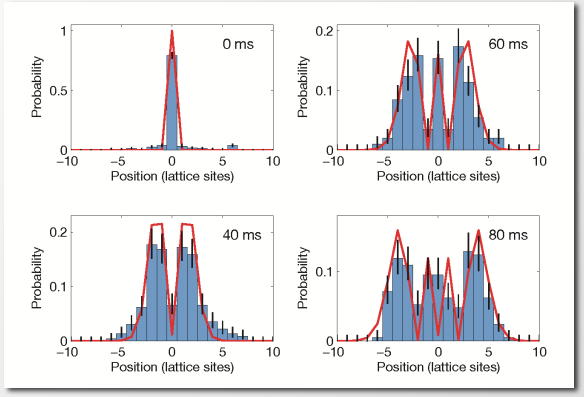
$$H = -J_{ex}\sum\mathbf{S}_i\cdot\mathbf{S}_j = -J_{ex}\sum\left(S_i^xS_j^x + S_i^yS_j^y + S_i^zS_j^z\right)$$

$$= -\frac{J_{ex}}{2}\sum\left(S_i^+S_j^- + S_i^-S_j^+\right) - J_{ex}\sum S_i^zS_j^z$$

$$J_{ex} = 4\frac{J^2}{U}$$

$$H = -J\sum\left(\hat{a}_i^\dagger\hat{a}_j + \hat{a}_i\hat{a}_j^\dagger\right)$$ single particle tunneling

Coherent quantum dynamics of single spin at zero temperature



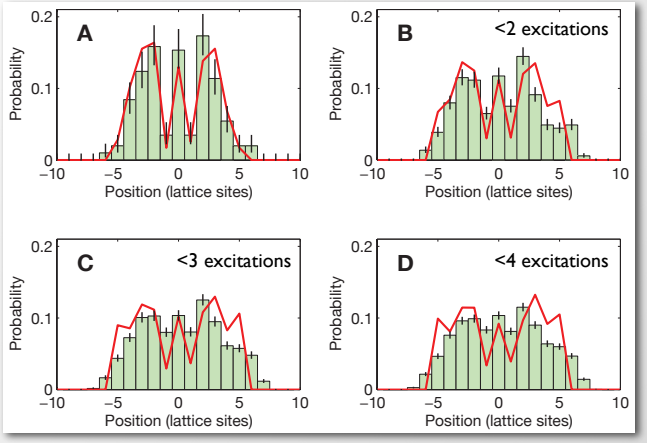
V = 10 *Er*
U/J = 19

$$H = -\frac{J_{ex}}{2}\sum_{\langle i,j\rangle}\left(S_i^+ S_j^- + S_i^- S_j^+\right)$$

$$P_j(t) = \left[\mathcal{J}_j\left(\frac{J_{ex}t}{\hbar}\right)\right]^2$$

Bessel function of the first kind

Effect from hole excitations



V = 10 *Er*
U/J = 19

- Only visibility goes down
- Spreading speed almost independent of holes

Outlook

Quantum Dynamics of Interacting Atoms/Spins

- Effect of Temperature/Holes on Dynamics
- Dynamics of Magnon bound states
- Domain Walls
- Higher Dimensions (1D, 2D, 3D)
- Entropy Transport
- Probe for Quantum Critical Transport
- Direct measurement of Green's function

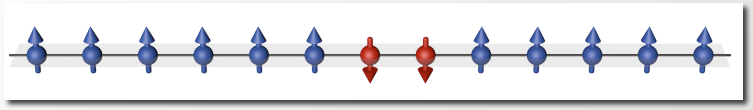
$$G(x_i,x_j,t) \propto \langle \Uparrow | \hat{S}^+(x_j,t)\hat{S}^-(x_i,0) | \Uparrow \rangle$$

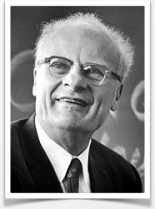
Direct Observation of Magnon Bound States

T. Fukuhara, P. Schauss, S. Hild, J.Zeiher, M. Cheneau, M. Endres, I. Bloch, Ch. Gross

T. Fukuhara et al., Nature **502**, 76 (2013)
for photons: O. Firstenberg et al., Nature **502**, 71 (2013)

Magnon Bound States



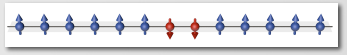


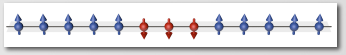
Hans Bethe
(1906-2005)

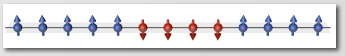
There can be bound states in a Heisenberg spin chain!
Development of Bethe Ansatz.

$$H = -J_{ex}\sum_i \left(\hat{S}_i^x\hat{S}_{i+1}^x + \hat{S}_i^y\hat{S}_{i+1}^y\right) - \Delta\sum_i \hat{S}_i^z\hat{S}_{i+1}^z$$

General
l-string bound states



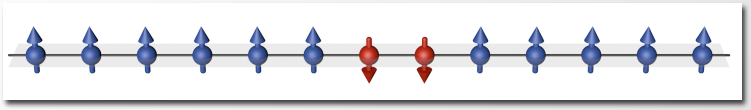


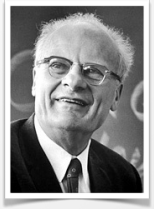


H. Bethe, Z. Phys. (1931)
M. Wortis, Phys Rev. (1963)
M. Takahashi & M. Suzuki Prog. Th. Phys. (1972)
M. Karbach, G. Müller (1997)
see also: **repulsively bound pairs & interacting atoms**
K. Winkler et al. Nature (2006); S. Fölling et al. Nature (2007); Y Lahini et al. PRA (2012)

Quantum Magnetism

Magnon Bound States





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$$H = -J_{ex}\sum_i \left(\hat{S}_i^x\hat{S}_{i+1}^x + \hat{S}_i^y\hat{S}_{i+1}^y\right) - \Delta\sum_i \hat{S}_i^z\hat{S}_{i+1}^z$$

$$H = -\frac{J_{ex}}{2}\sum_i \left(\hat{S}_i^+\hat{S}_{i+1}^- + \hat{S}_i^-\hat{S}_{i+1}^+\right) - \Delta\sum_i \hat{S}_i^z\hat{S}_{i+1}^z$$

H. Bethe, Z. Phys. (1931)
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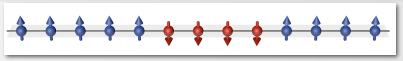
Bound l-string

Eigenenergies:

$$E(k) = -J_{ex}\frac{sin(\nu)}{sin(l\nu)}\left\{\cos(l\nu) - (-1)^l\cos k\right\}$$

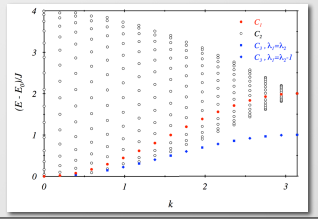


$$\Delta = \cos(\nu)$$

l-string

Maximum propagation velocity: $v_{max,l} = \dfrac{\sin(\nu)}{\sin(l\nu)}$ $v_{max,2} = \dfrac{J}{2\Delta}$

Excitation spectrum:



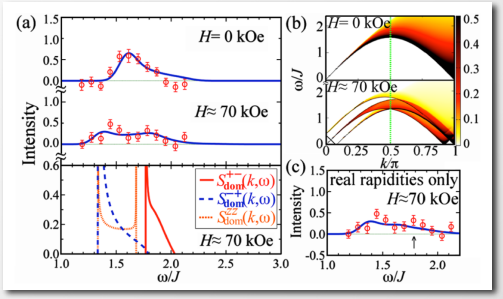
M. Karbach & G. Müller (1997)

Bound magnon

A Challenge for CM Physics

Very difficult to observe in spectroscopic data in real materials!

theory **with** bound states

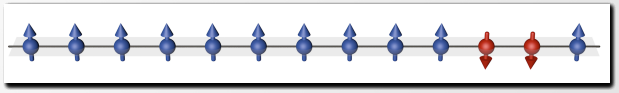


theory **without** bound states

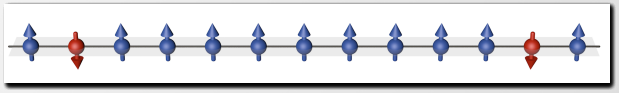
M. Kohno, Phys. Rev. Lett. **102**, 037203 (2009)

Dynamical Evolution

Bound Magnon Motion



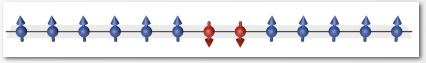
Breakup and Single Spin Motion



M. Ganahl et al., Phys. Rev. Lett. (2012)

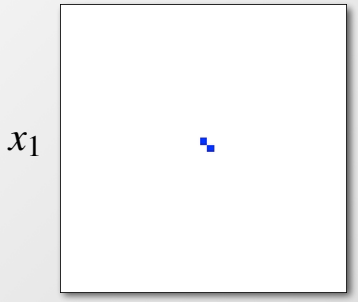
Dynamical Evolution

Initial State:



Pair distribution evolution

$P(x_1, x_2)$

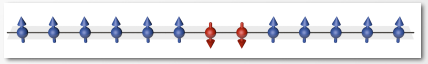


$\Delta = 0$
Non-Interacting

see also: two interacting atoms
Y. Lahini et al., PRA 86, 011603 (2012)

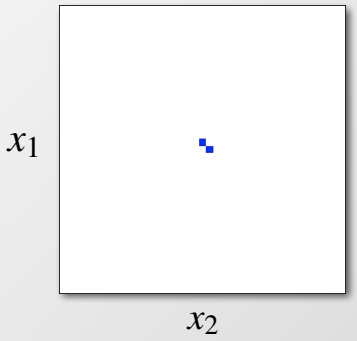
Dynamical Evolution

Initial State:



Pair distribution evolution

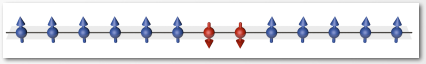
$P(x_1, x_2)$



$\Delta = 1$
Interacting
Isotropic Heisenberg

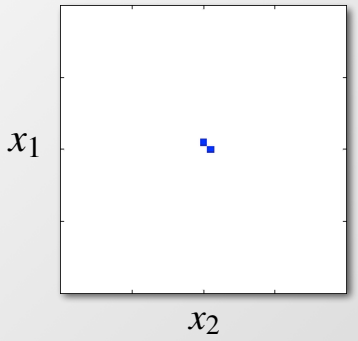
Dynamical Evolution

Initial State:



Pair distribution evolution

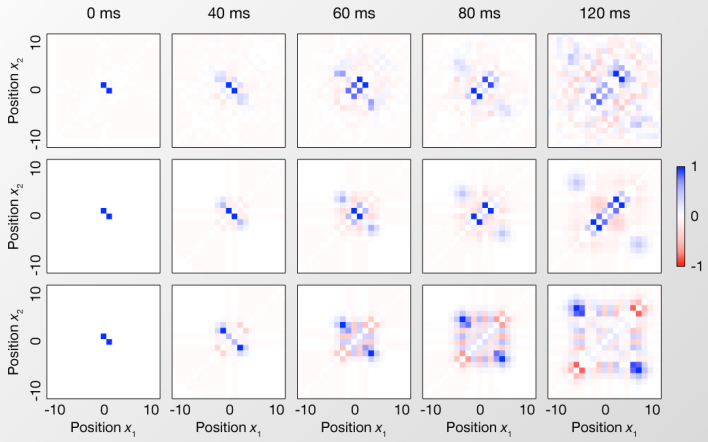
$P(x_1, x_2)$



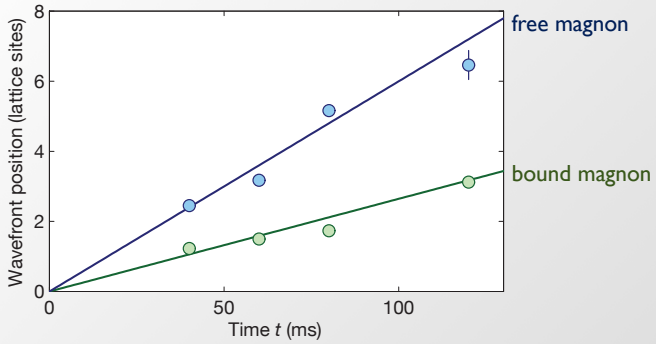
$\Delta = 1.6$
Interacting
Heisenberg

Experimental Results

$$C(x_1,x_2) = P(x_1,x_2) - P(x_1)P(x_2)$$



Propagation Velocity



$$v_f = \frac{J_{ex}a}{\hbar}$$
$$v_b = \frac{J_{ex}a}{2\hbar\Delta}$$

$$\frac{v_f}{v_b} = 2\Delta$$

We find: $\frac{v_f}{v_b} = 2.3(3)$

Outlook

Quantum Dynamics of Interacting Atoms/Spins

- Effect of Temperature/Holes on Dynamics
- Dynamics of l-string bound states
- Domain Walls
- Higher Dimensions (1D, 2D, 3D)
- Entropy Transport
- Probe for Quantum Critical Transport
- Direct measurement of Green's function

$$G(x_i,x_j,t) \propto \langle \Uparrow | \hat{S}^{+}(x_j,t)\hat{S}^{-}(x_i,0) | \Uparrow \rangle$$

M. Knap et al. PRL **111**, 147205 (2013)

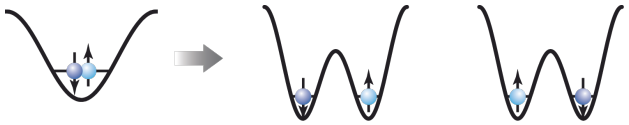
Controlling and Detecting Spin Correlations

S. Trotzky et al., Phys. Rev. Lett 105, 265303 (2010)

Splitting a spin pair

- **Spin pairs** in $|F=1, m_F=\pm1\rangle \equiv |\uparrow\rangle, |\downarrow\rangle$ (repulsive)
- Barrier raised *slowly* to split
  → Crossing a miniature Mott-transition: $n_{\text{Left}} = n_{\text{Right}} = 1$

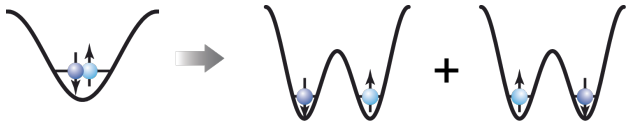
*J. Sebby-Strabley et al., PRL **98** (2007)*



Details on the loading of the Spin-pairs:
*S.T., P. Cheinet et al., Science **319** (2008)*

Splitting a spin pair

- **Spin pairs** in $|F=1, m_F=\pm1\rangle \equiv |\uparrow\rangle, |\downarrow\rangle$
- Barrier raised *slowly* to split *J. Sebby-Strabley et al., PRL **98** (2007)*
  → Crossing a miniature Mott-transition: $n_{\text{Left}} = n_{\text{Right}} = 1$



- **Bosons**: Symmetric wavefunction → Triplet $|t_0\rangle$

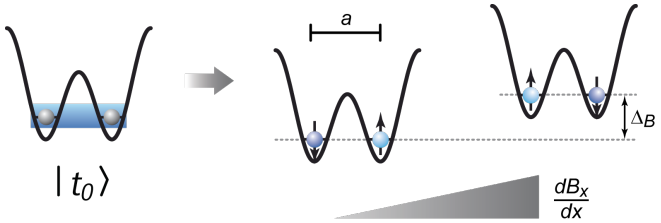
  (Fermions: Antisymmetric wavefunction → Singlet $|s\rangle$)

Details on the loading of the Spin-pairs:
*S.T., P. Cheinet et al., Science **319** (2008)*

Driving Triplet-Singlet oscillations

- **Magnetic field gradient** lifts degeneracy:

$$\Delta_B \propto a \cdot \partial_x B_x$$



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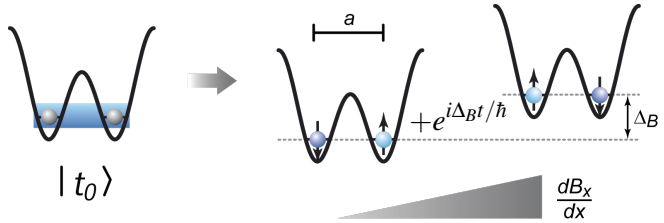
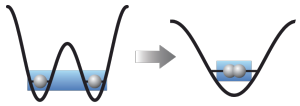


- **Triplet-Singlet oscillations** with frequency $\Delta_B/\hbar$

$|t_0\rangle \leftrightarrow |s\rangle$

How to detect triplets and singlets

- Barrier lowered slowly to **merge** double-wells
  → **Triplet**: both atoms reach the **ground state**



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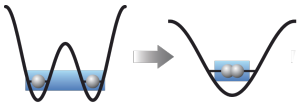
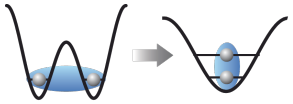


→ **Singlet**: needs anti-symm. spatial wavefunction (Bosons)
One atom transferred to **higher vibrational band**



How to detect triplets and singlets

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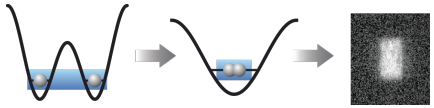

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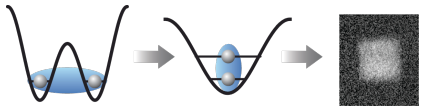


Band-mapping reveals **singlet-contribution in higher Brillouin-Zone**

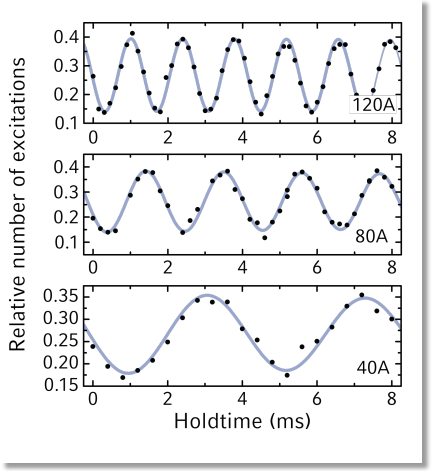
A sensitive probe of next-neighbor spin-correlations in Mott-insulator type many-body systems

	band excitations		STO amplitude	
	bosons	fermions	bosons	fermions
$\|t\rangle$	0%	50%	50%	50%
$\|s\rangle$	50%	0%	50%	50%
$\|\downarrow,\uparrow\rangle$	25%	25%	0%	0%
$\|\uparrow,\downarrow\rangle$	25%	25%	0%	0%
$\|\uparrow,\uparrow\rangle$	0%	50%	0%	0%
$\|\downarrow,\downarrow\rangle$	0%	50%	0%	0%

→ Capable of probing spin-order in strongly correlated phases at low temperatures

Band-mapping reveals **singlet-contribution in higher Brillouin-Zone**

Singlet-Triplet oscillations



- **Load** system and create **spin pairs**
- Split pairs into **triplets**
- Induce **STO** via gradient
- **Merging** and **band-mapping** for detection

→ **Traces of STO** versus holdtime with gradient

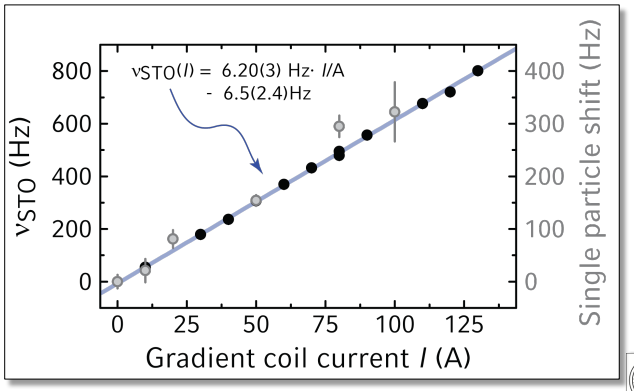
- Vary gradient coil current

S. Trotzky et al., Phys. Rev. Lett. **105**, 265303 (2010) & D. Greif et al., Science 340, 1307–1310 (2013)

Singlet-Triplet oscillations

- **Linear increase** in Frequency with gradient strength
- Frequency = **2x single particle shift** (independently meas.)

→ confirms **2-particle nature** of oscillations

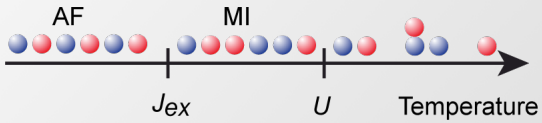


AFM

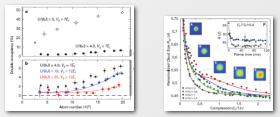
The Quest for AFM Spin Order

Predicted phases at half filling for strong interactions $U/12J > 1$

$$\hat{H} = \sum_{\langle i,j\rangle,\sigma} \left(\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + \text{h.c.}\right) + U\sum_{i} \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

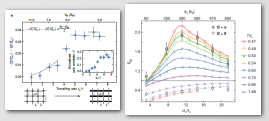


Fermonic Mott Insulator

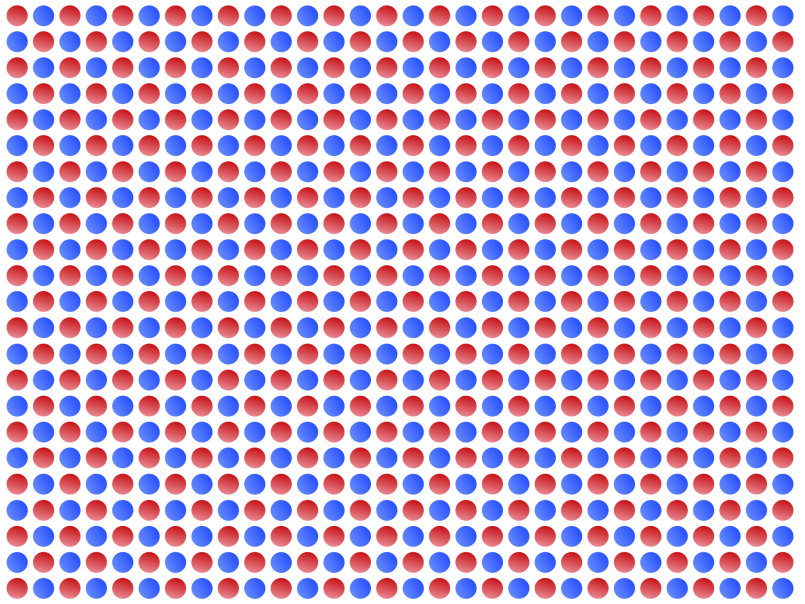


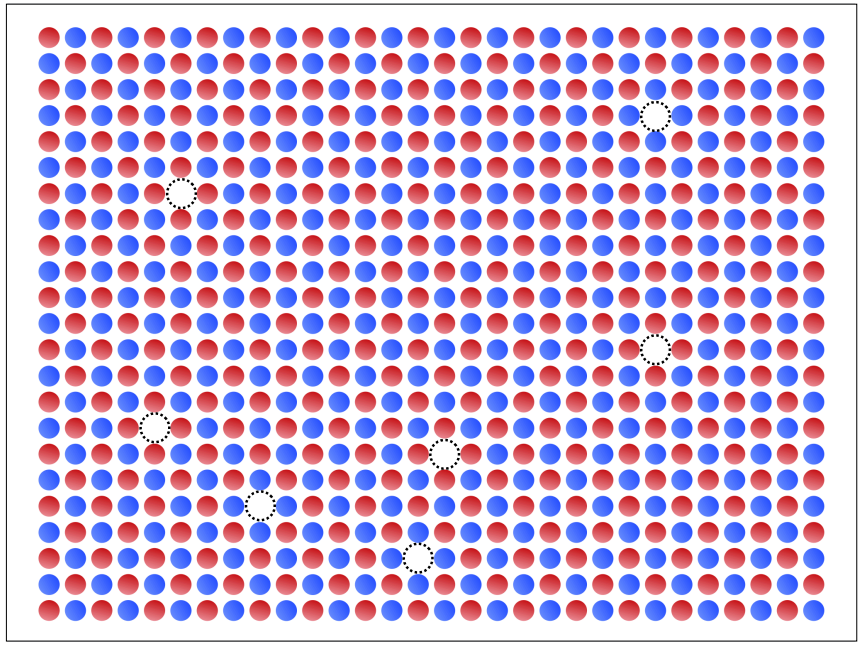
R. Jördens et al., Nature **455**, 204 (2008),
U. Schneider et al., Science **322,** 1520 (2008)

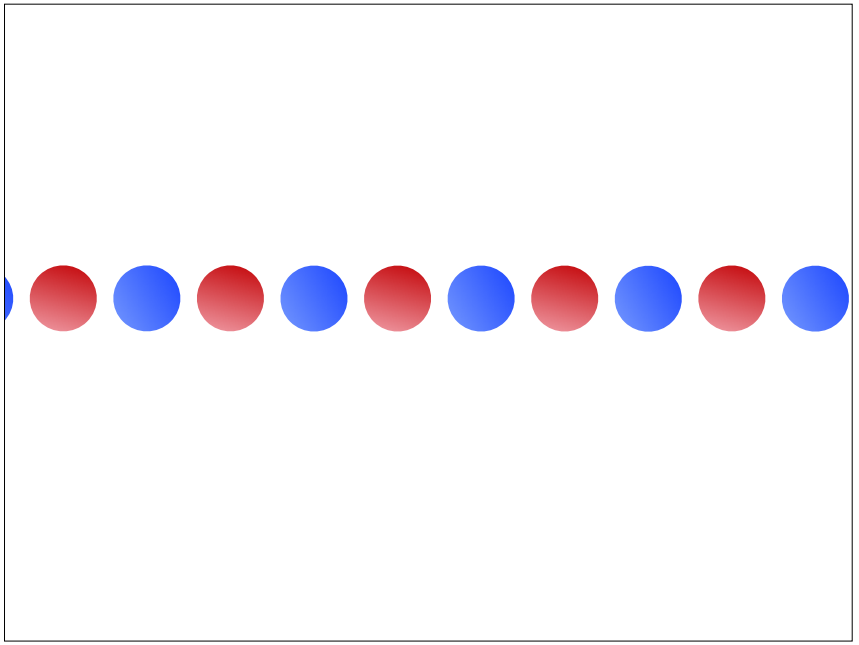
Nearest Neighbour Spin Correlations

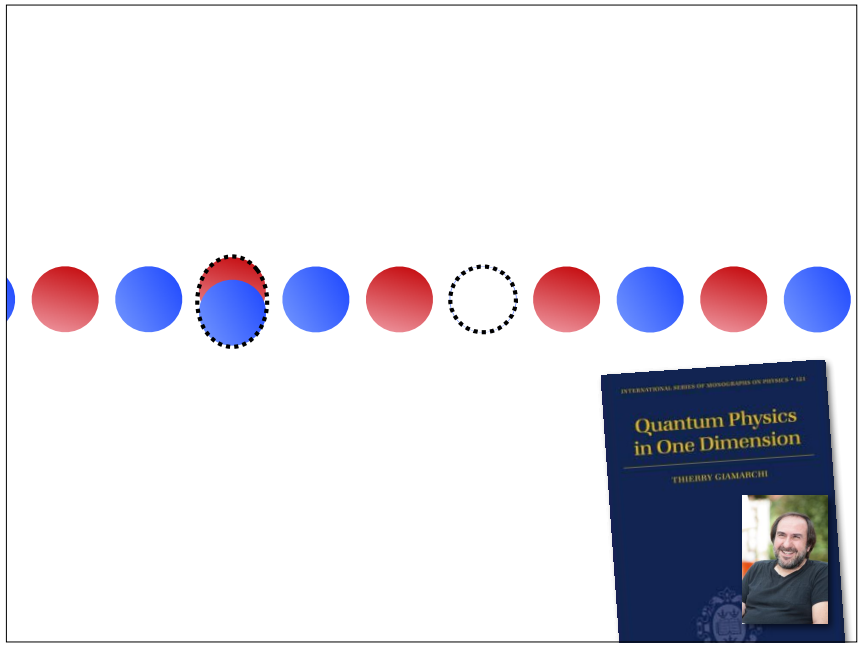


D. Greif et al., Science **340**, 1307 (2013)
R. A. Hart et al., Nature **519**, 211 (2015)



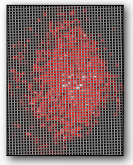




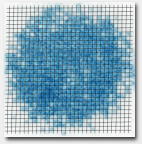


Li-Microscope

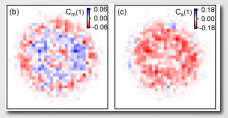
Fermi-Hubbard - 2016-2017



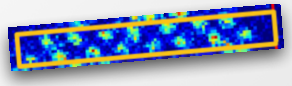
A. Omran *et al.* PRL (2015)



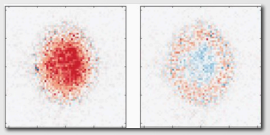
D. Greif *et al.* Science (2016)



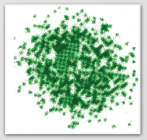
L. Cheuk *et al.* Science (2016)



M. Boll *et al.* Science (2016)



M. Parsons *et al.* Science (2016)

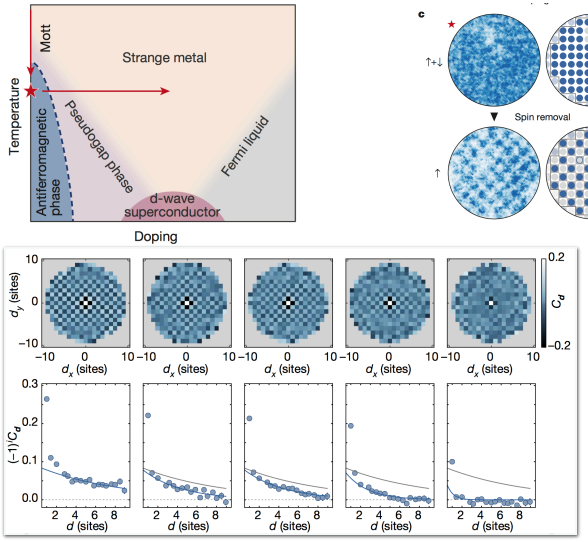


P. Brown *et al.* Science (2017)

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

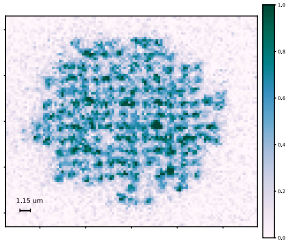
A. Maruzenko et al. Nature (2017), M. Boll et al. Science (2016), T. Hilker et al. Science (2017),
L. Cheuk et al. Science (2016), P. Brown et al. Science (2017)

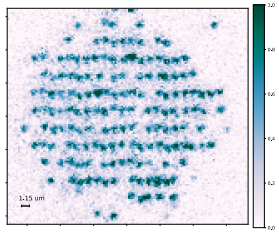
AFM Order in the Fermi Hubbard Model



A. Mazurenko et al., Nature **545**, 462

Mott Insulators





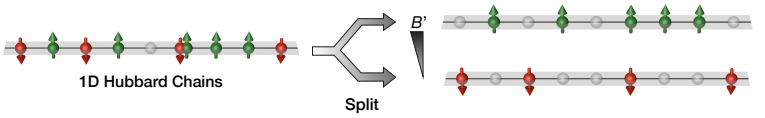
Mott Insulator
(Short-Short Lattice)

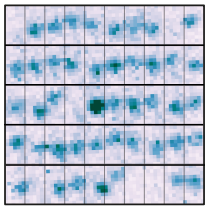
Mott Insulator
(Short-Long Lattice)

No Parity Projection!

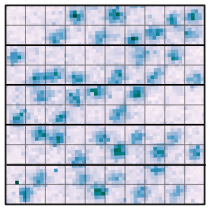
Holes-Doublons Distinguishable

Spin & Charge Resolved Imaging

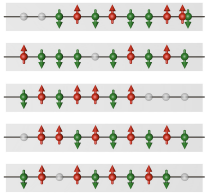




1D Chains (spin unresolved)



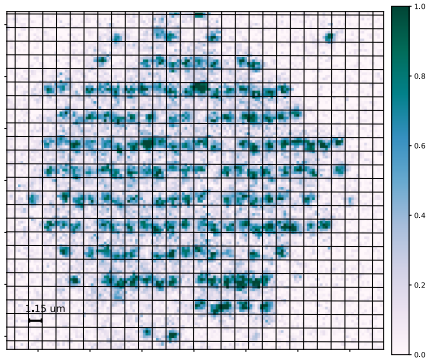
Split 1D Chains (spin resolved)



Reconstruction

M. Boll et al.; Science **353**, pp. 1257 (2016)

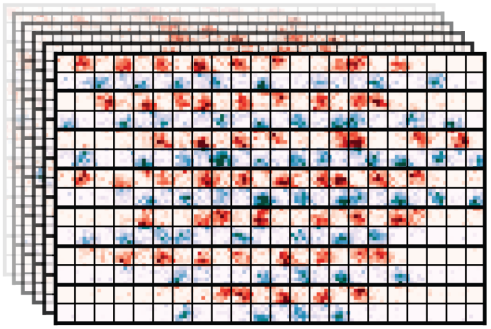
Spin-Charge Resolved Detection



Charge Resolved **Spin Un-Resolved**

Spin-Charge Resolved Detection

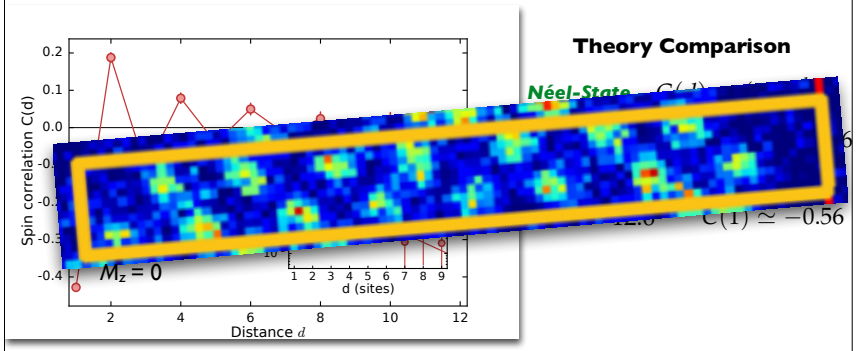
Spin Resolved



Charge Resolved

Spin Correlations

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



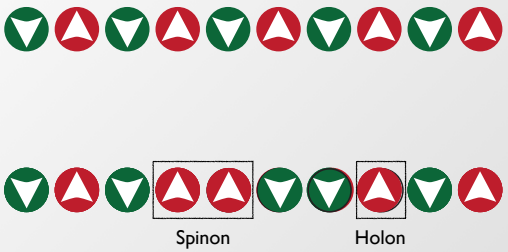
Theory Comparison

Néel-State

$C(1) \simeq -0.56$

M. Boll et al.; Science **353**, pp. 1257 (2016)
see also 2d work Harvard & MIT

Dynamical Spin-Charge Separation



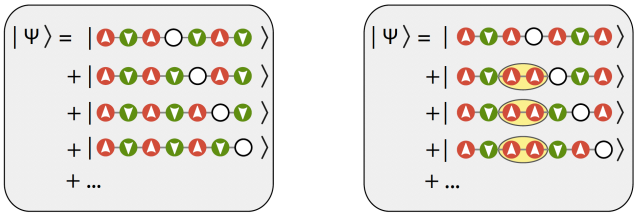
Hole can move freely in AFM environment!

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

Charge & Spin Order around Hole

Minimize Energy ⇨ **Two Conditions**

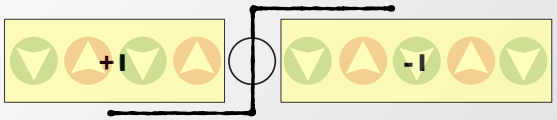
- Holes want to delocalise
- Spins want to align antiferromagnetically



Ground State

Excited State

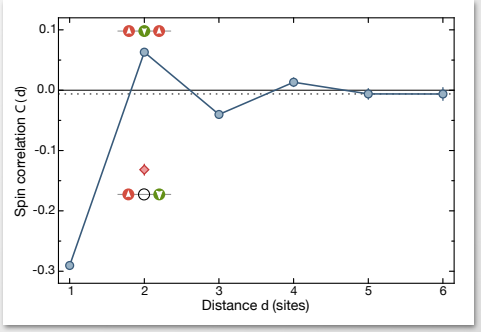
Microscopic Origin of SC —Separation



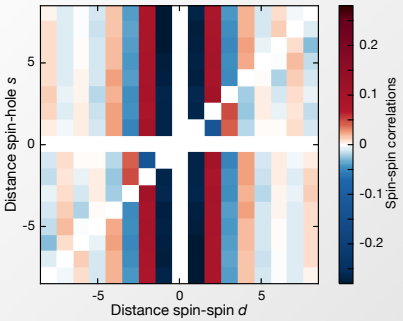
Hole introduce domain wall
"parity" kinks in AFM background!

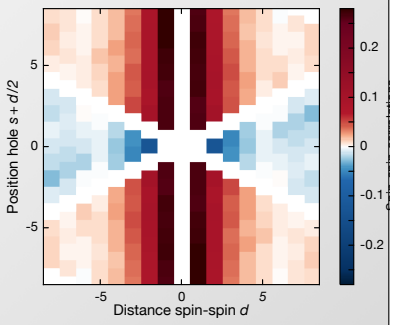
AFM order around hole

$$C_{s,h}(d=2)\langle \hat{S}_z(i)\hat{S}_z(i+2)|\hat{h}_{i+1}\rangle$$



AFM around Holes

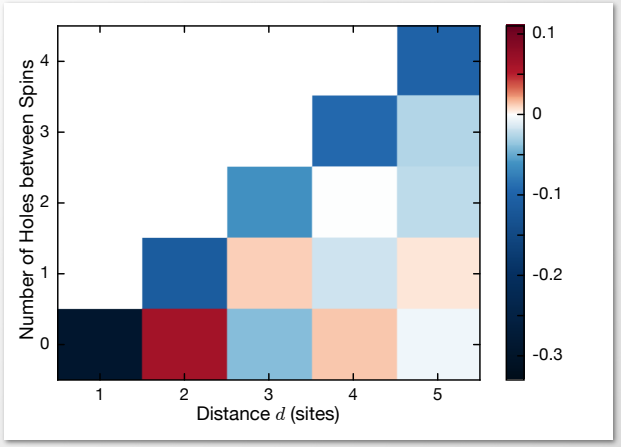




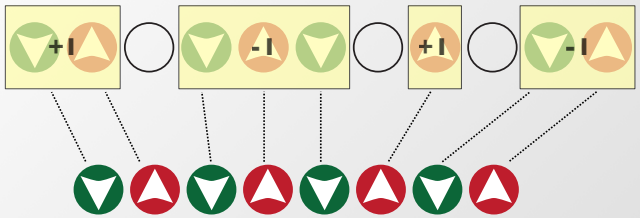
$$C_{s,h}(s,d)=\langle \hat{S}_z(i)\hat{h}_{i+s}\hat{S}_z(i+d)\rangle \qquad C_{s,h}(s,d)=(-1)^d\langle \hat{S}_z(i)\hat{h}_{i+s}\hat{S}_z(i+d)\rangle$$

T. Hilker, *Science* (in press)

AFM with holes in between..



Hidden (Topological?) Order in the 1D Hubbard



Heisenberg AFM in "Squeezed Space"

$$\Psi(x_1,\ldots,x_N) = \Psi_{SF}(x_1,\ldots,x_N)\Psi_{\text{Heis}}(y_1,\ldots,y_M)$$

F.Woynarovich J. Phys. C (1982)
M. Ogata & H. Shiba Phys. Rev. B (1990)

String Correlator

$$O_{top} = \langle \hat{S}^z(0)(-1)^{\sum_{j=1}^{d-1} 1-\hat{n}_j}\hat{S}_z(d)\rangle$$

H.V. Kruis, I.P. McCulloch, Z. Nussinov & J. Zaanen EPL (2004)
H.V. Kruis, I.P. McCulloch, Z. Nussinov & J. Zaanen Phys. Rev. B (1990)

Order Parameters

Typical Order Parameter in Landau Paradigm of Phase Transition

$$\lim_{|\mathbf{x}-\mathbf{y}|\to\infty}\langle\hat{A}(\mathbf{x})\hat{A}(\mathbf{y})\rangle = c$$

Order Parameter:

Examples: gnetism, AFM,...)

Function)

General classification scheme for all phases of matter ???

Order Parameter Charact… …ound State Correlations
Local ordering!

String Order in 1D Systems

E.g. in 1D gapped systems where $\langle\hat{A}(\mathbf{x})\hat{A}(\mathbf{y})\rangle$ decays exponentially with distance

However, they can show hidden non-local order:

$$\lim_{|\mathbf{x}-\mathbf{y}|\to\infty}\langle\hat{A}(\mathbf{x})\left(\prod_{\mathbf{z}\in S(\mathbf{x},\mathbf{y})}\hat{B}(\mathbf{z})\right)\hat{A}(\mathbf{y})\rangle = c$$

We say the order is hidden, because a "global view" of the underlying state is required. (**Topological Order:** X.-G. Wen)

Allows us to characterize state only via its ground state correlations!

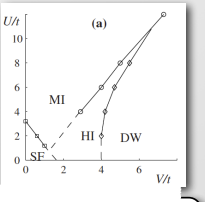
M. den Nijs, K. Rommelse, Phys. Rev. B 40, 4709 (1989).
E. Kim, G. Fa´th, J. So´lyom, D. Scalapino, Phys. Rev. B 62, 14965 (2000)
E. G. Dalla Torre, E. Berg, E. Altman, Phys. Rev. Lett. 97, 260401 (2006)
F. Anfuso, A. Rosch, Phys. Rev. B 75, 144420 (2007)
E. Berg, I E. Dalla Torre, T. Giamarchi, E. Altman, Phys. Rev. B 77, 245119 (2008)

An Example: Haldane Insulator in 1D

E. G. Dalla Torre, E. Berg, E. Altman, Phys. Rev. Lett. 97, 260401 (2006)
E. Berg, I E. Dalla Torre, T. Giamarchi, E. Altman, Phys. Rev. B 77, 245119 (2008)

$$H = -J\sum_i(\hat{a}_i^\dagger\hat{a}_{i+1} + \text{h.c.}) + \frac{1}{2}U\sum_i\hat{n}_i(\hat{n}_i-1) + V\sum\hat{n}_i\hat{n}_{i+1}$$

Bose-Hubbard with next-neighour interaction



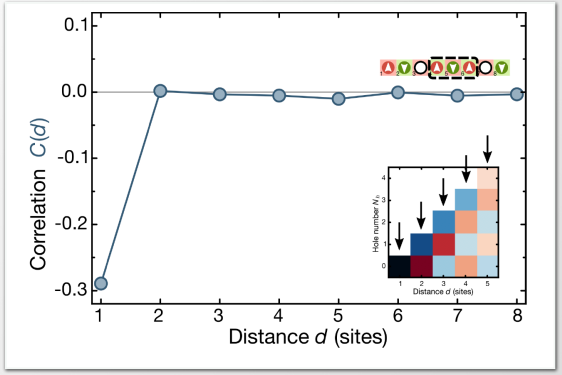
0 -1 0 0 +1 0 0 -1 0 +1 0 0 0 -1

A Hidden Antiferromagnet!

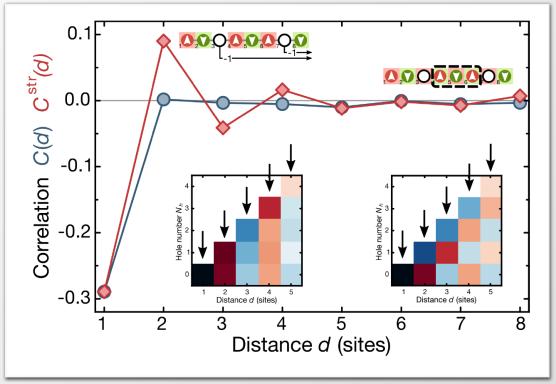
Hidden Non-local Order Captured by String Correlator

$$\mathcal{O}_S^2 = -\lim_{|i-j|\to\infty}\left\langle\delta\hat{n}_i\left(\prod_{i<k<j}e^{i\pi\delta\hat{n}_k}\right)\delta\hat{n}_j\right\rangle$$

Two Point Correlator - Doped Chains



Two Point Correlator - Doped Chains



Incommensurate AFM in 1D

G. Salomon *et al.* arXiv:1803.08892

Incommensurate Magnetism

Density Doping

$\langle S^z_0 S^z_d \rangle \simeq A_n e^{-d/\xi_n} \cos(\pi n d)$

Finite Magnetization

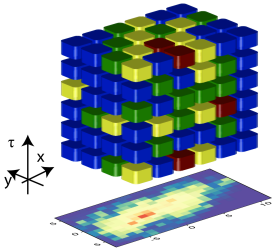
$\langle S^z_0 S^z_d \rangle \simeq A_m e^{-d/\xi_m} \cos(\pi(1-2m)d)$

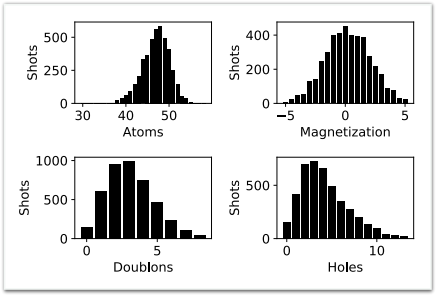
Very challenging test for experiment!

Luttinger Liquid Theory

F.D.M. Haldane J. Phys. C: Solid State Phys. **14** 2585, 1981

Incommensurate Magnetism - Data Analysis

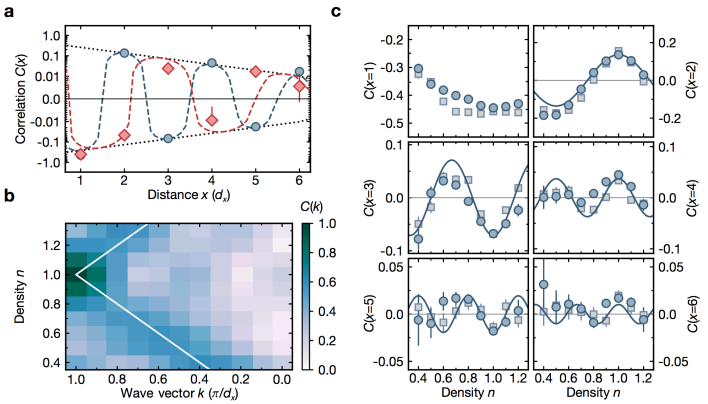




Single Spin and
Single Atom Sensitivity !

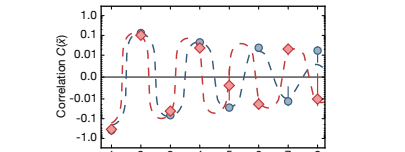
Select shots with defined magnetisation and/or density !

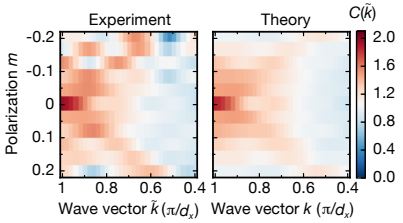
Incommensurate Magnetism - Density Doping

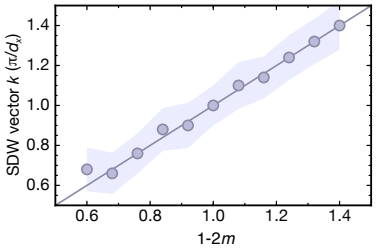


$$\langle S_0^z S_d^z \rangle \simeq A_n e^{-d/\xi_n} \cos(\pi n d)$$

Incommensurate Magnetism - Finite Magnetisation

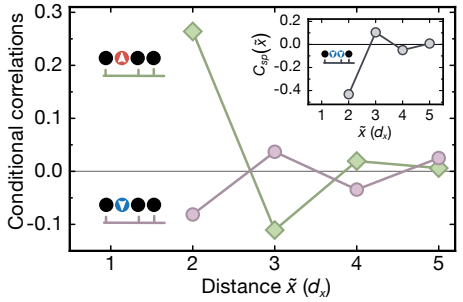






$$\langle S_0^z S_d^z \rangle \simeq A_m e^{-d/\xi_m} \cos(\pi(1-2m)d)$$

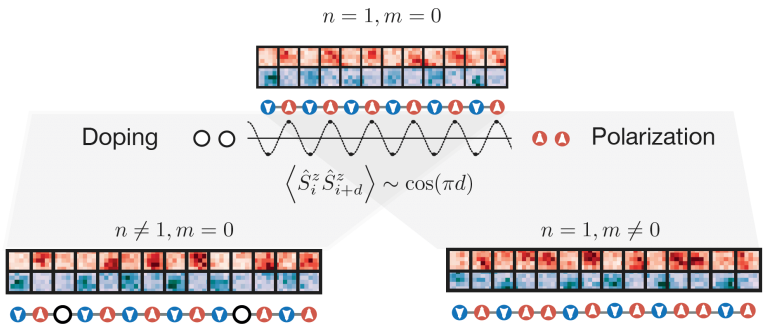
Incommensurate Magnetism - Finite Magnetisation



#2: Spinon = Quantum Domain Walls in Squeezed Space

AFM

Quantum Domain Walls: Microscopic Picture



Holon **Spinon**

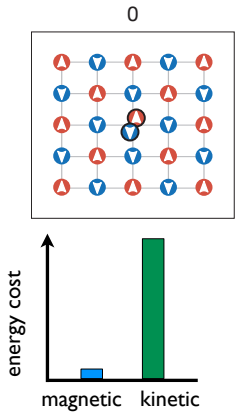
Quantum Domain Walls

LMU

Charge Impurities in 2D

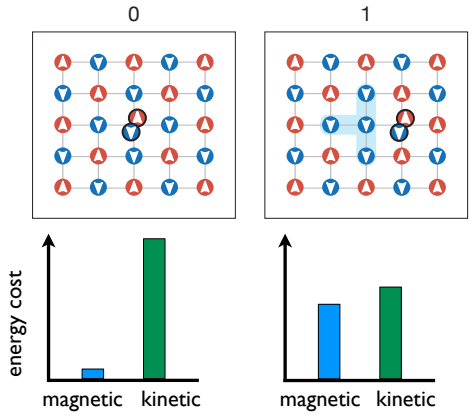
Competing Energy Costs: Kinetic vs Magnetic

$t \gg J$



Competing Energy Costs: Kinetic vs Magnetic

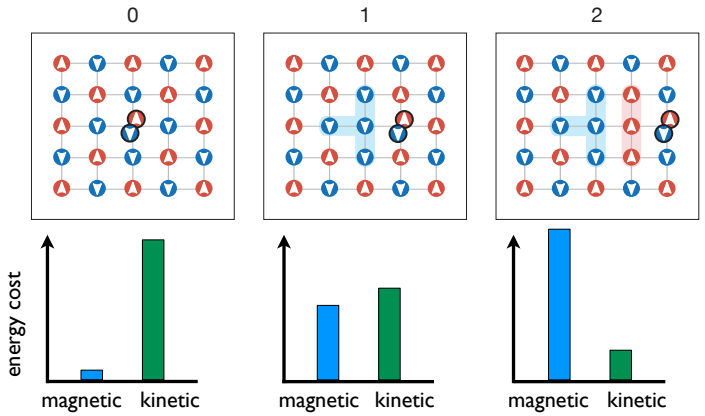
$t \gg J$ Hopping events



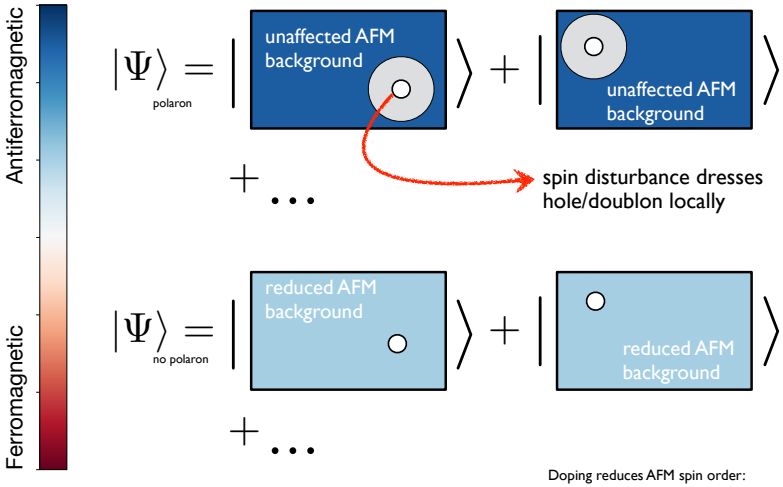
Competing Energy Costs: Kinetic vs Magnetic

$t \gg J$

Hopping events

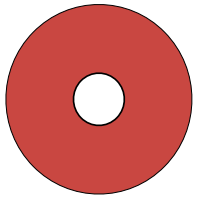


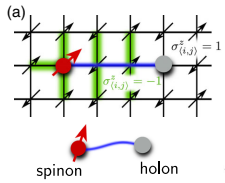
Ground State?



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

Polarons in the FHM



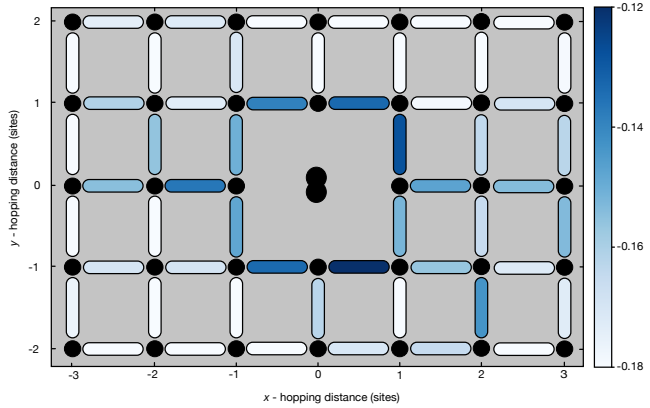


Grusdt *et al.*, PRX 8 2018

- **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

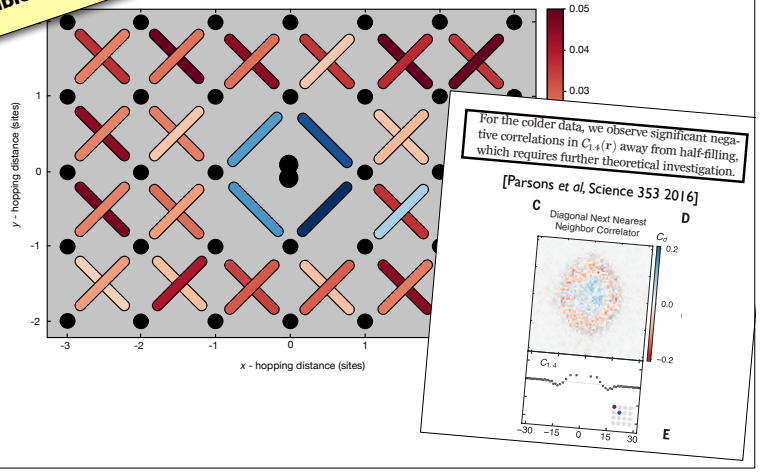
C(1) Local Spin Correlations Around Doublon



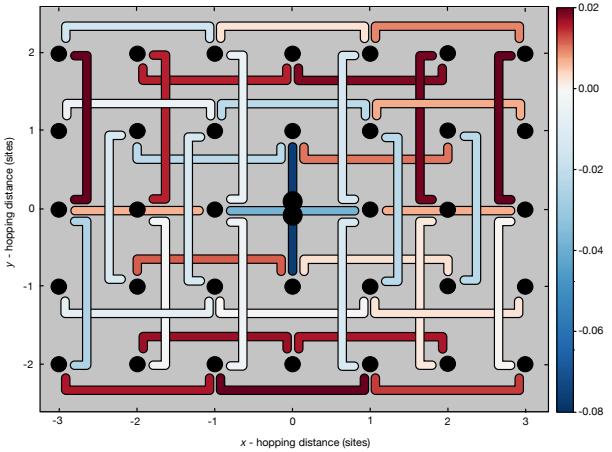
Conditioned C(1) Correlator

C(1,1) Local Spin Correlations around Doublon

Doublons induce sign flip !

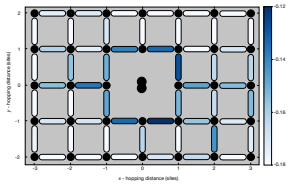


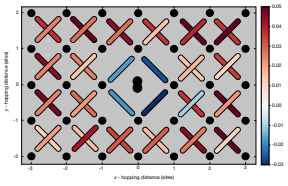
C(2) Local Spin Correlations around Doublon

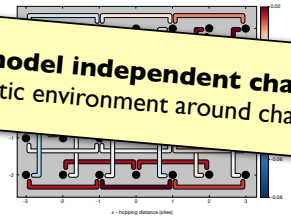


FHM Spin-Charge Interaction

Magnetic Polaron Size



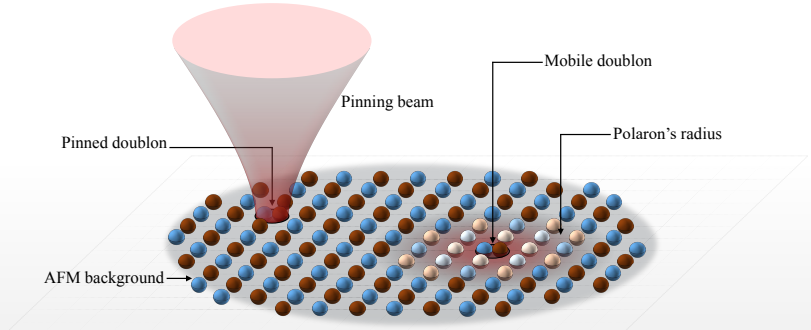




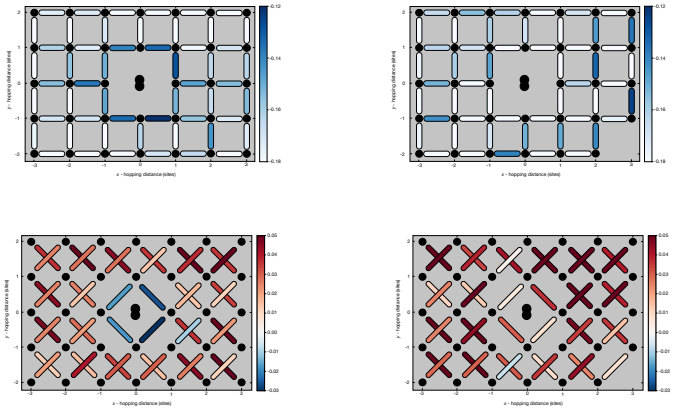
Complete **model independent characterisation** of magnetic environment around charge impurity

FHM Spin-Charge Interaction

Changing Charge Mobility



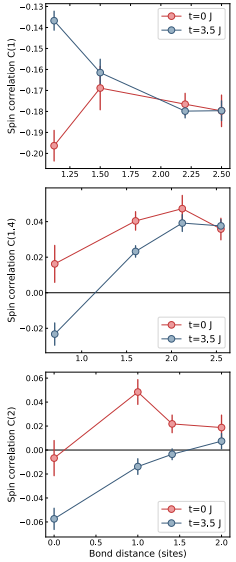
Spin Correlations Around Doublon



Mobile **Pinned**

FHM Spin-Charge Interaction

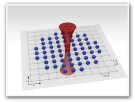
Magnetic Polaron Size

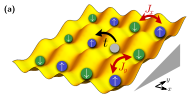


FHM Spin-Charge Interaction

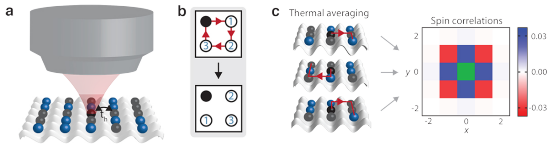
Outlook

- **Polaron-Polaron** correlations
- **Timescale** of polaron formation
- **Mixed dimensions**
- **Dynamical spin-charge separation 1D**
- **Dynamical Nagaoka effect**



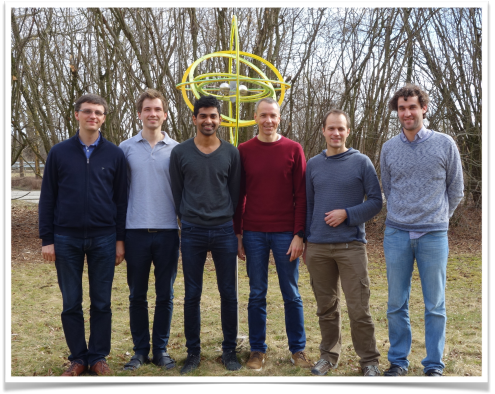


Grusdt *et al*, arXiv:1806.04426 2018



Kanász-Nagy *et al*, PRB 96 2017

Thank you!



Timon Joannis Jayadev I.B. Christian Guillaume

Pimonpan

Dominik

Theory:

Eugene

Fabian

Rydberg atoms

- hydrogen-like wave function
  - quantum defect

$$E_{nlj} = -\frac{\mathrm{Ry}}{[n-\delta_{lj}(n)]^2}$$

- Strong switchable interactions

^{87}Rb 43S$_{1/2}$

^{87}Rb 5S$_{1/2}$

Ø 0.5nm

Ø 250 nm

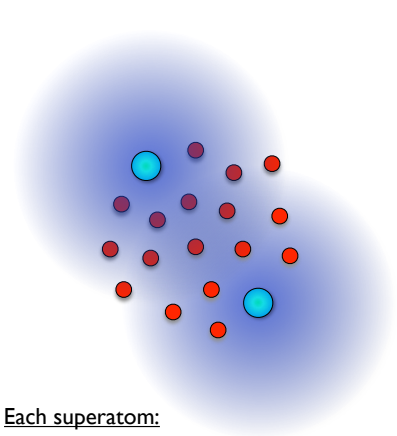
Property	Scaling	^{87}Rb 43S
Radius	$(n^*)^2$	2400 a_0 = 127nm
Lifetime (dominated by black body radiation for large n)	$(n^*)^2$	45 μs @ 20°C
van der Waals coefficient	$(n^*)^{11}$	$C_6 = -1.7 \times 10^{19}$ a.u.
Blockade radius (Ω=2π 200 kHz)	$(n^*)^2$	~ 5 μm

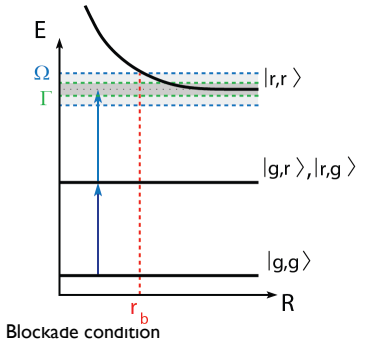
Saffman, Walker, & Mølmer Rev. Mod. Phys. (2010)

see work in: Paris, Madison, Palaiseau, Stuttgart, Heidelberg, Durham, Michigan....

Rydberg Crystals

Rydberg blockade





Blockade condition

$$\mathcal{V}_{\mathrm{vdW}} = \frac{C_6}{r^6} > \hbar \max(\Gamma, \Omega)$$

Each superatom:

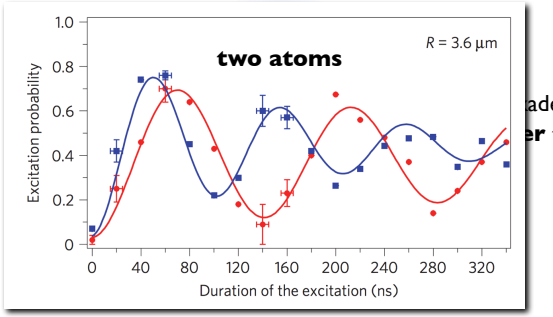
$$\frac{1}{\sqrt{N}}(|r,0,0,0,\ldots\rangle + |0,r,0,0,\ldots\rangle + |0,0,0,\ldots,r\rangle)$$

$$r_{\mathrm{b}} \equiv \sqrt[6]{\frac{C_6}{\hbar\Omega}}$$

M. Lukin et al. PRL **87**, 037901 (2001)

Rydberg Crystals

Rydberg blockade



ade radius
r than cloud size!

$\sqrt{N}\Omega_1$ Rabi Oscillations speed up!

Each superatom:

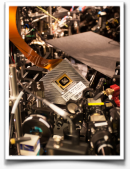
$$\frac{1}{\sqrt{N}}(|r,0,0,0,\ldots\rangle + |0,r,0,0,\ldots\rangle + |0,0,0,\ldots,r\rangle)$$

M. Lukin et al. PRL **87**, 037901 (2001)

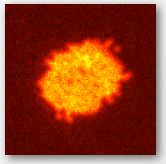
see work by A. Browaeys & Ph. Grangier, M. Saffman, A. Kuzmich, T. Pfau...

DMD Adressing

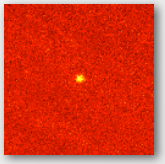
Ultimate Size Control in 2D



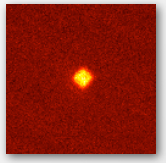
Digital Mirror Device (Size Control)



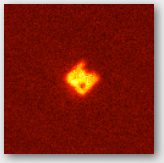
Initial MI



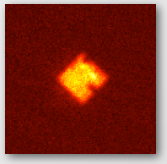
Single Atom



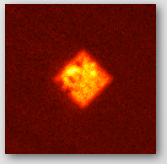
3x3



5x5



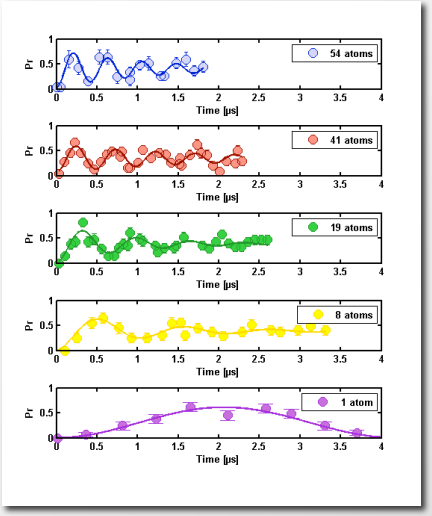
7x7

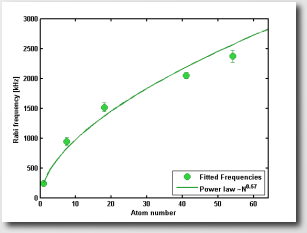


8x8

atoms

Collective Many-Body Rabi Oscillations

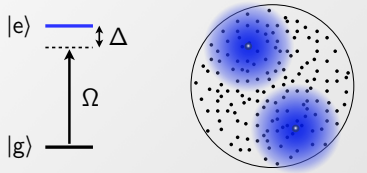




Single atom non-linearity controls dynamics of >50 atoms!

J. Zeiher et al., Phys. Rev. X **5**, 031015 (2015)

The frozen Rydberg gas - long range QM



no mechanical motion on the timescale of the internal dynamics

$$H = \frac{\hbar\Omega}{2}\sum_i\left(\sigma_{eg}^{(i)} + \sigma_{ge}^{(i)}\right) + \sum_{i\neq j}\frac{V_{ij}}{2}\sigma_{ee}^{(i)}\sigma_{ee}^{(j)} - \Delta\sum_i\sigma_{ee}^{(i)}$$

coherent coupling

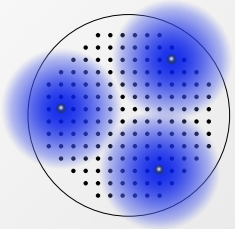
interaction between Rydberg atoms

"chemical potential"

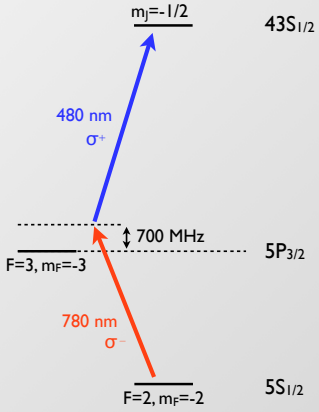
$$V_{ij} = C_\alpha|r_i - r_j|^{-\alpha}$$

This work: α=6, repulsive

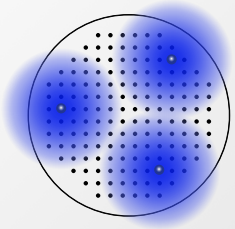
Excitation and detection of the Rydberg atoms



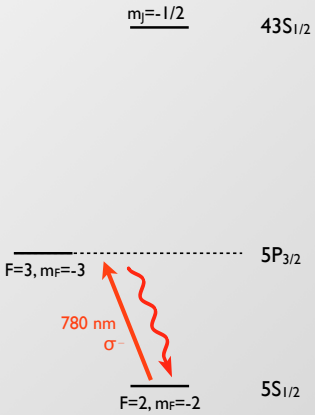
- two-photon Rabi frequency: $\Omega/2\pi$ = 170(20) kHz
- resonant excitation: $\Delta = 0$
- blockade radius: R_b = 4.9(1) μm



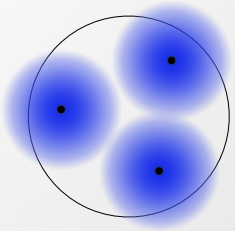
Excitation and detection of the Rydberg atoms

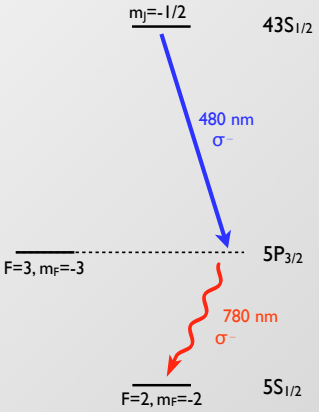


- removal pulse duration: 10 μs
- survival probability: 0.1 %



Excitation and detection of the Rydberg atoms

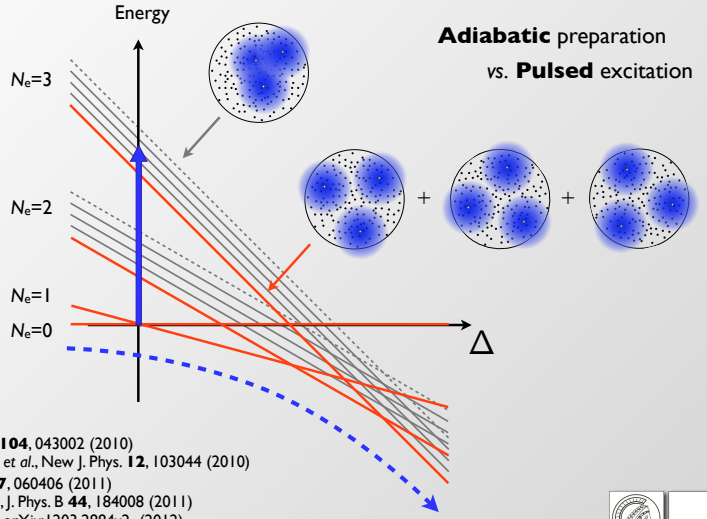




- deexcitation pulse duration: 2 μs
- detection efficiency: 75(10) %
- overall resolution: ~ 500 nm

Rydberg Crystal

Energy spectrum of the Rydberg gas



Pohl *et al.*, PRL **104**, 043002 (2010)
Schachenmayer *et al.*, New J. Phys. **12**, 103044 (2010)
Ji *et al.*, PRL **107**, 060406 (2011)
van Bijnen *et al.*, J. Phys. B **44**, 184008 (2011)
Gärttner et al., arXiv:1203.2884v2 (2012)

PRL **104,** 043002 (2010) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2010

Dynamical Crystallization in the Dipole Blockade of Ultracold Atoms

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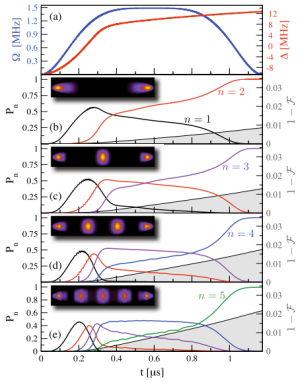
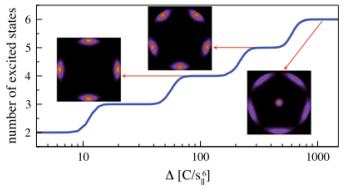
[3]*Physics Department, Harvard University, Cambridge Massachusetts 02138, USA*
(Received 26 July 2009; revised manuscript received 23 October 2009; published 27 January 2010)



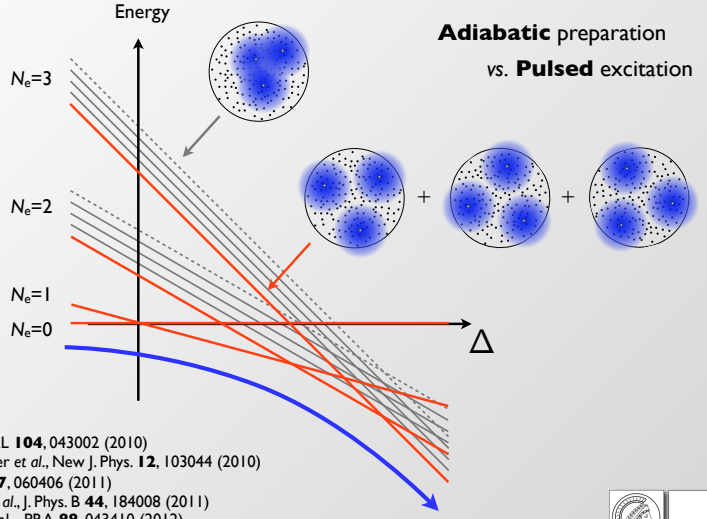


Coherent Control of Many-Body System through Adiabatic Sweeps

Theory see:
T. Pohl et al. PRL 2010; G. Pupillo et al. PRL 2010,
R.M.W van Bijnen et al. J. Phys. B: At. Mol. Opt. Phys. (2011)
see also: H. Weimer et al., PRL 2008

Rydberg Crystal

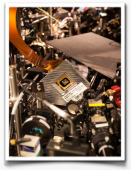
Energy spectrum of the Rydberg gas



T. Pohl *et al.*, PRL **104**, 043002 (2010)
J. Schachenmayer *et al.*, New J. Phys. **12**, 103044 (2010)
Ji *et al.*, PRL **107**, 060406 (2011)
R. van Bijnen *et al.*, J. Phys. B **44**, 184008 (2011)
M. Gärttner et al., PRA **88**, 043410 (2012)
D. Petrosyan J. Phys. B **46**, 141001 (2013)

Rydberg Crystal

Ultimate Size Control in 2D



Digital Mirror Device (Size Control)

Fluctuating Size and

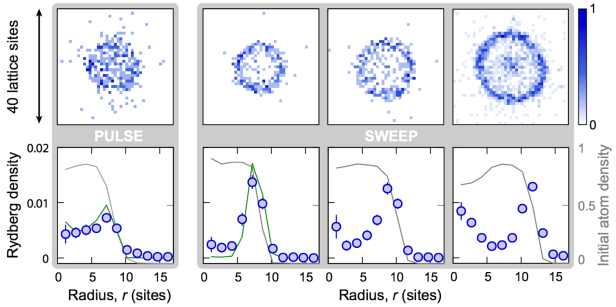
- **Sub Shot Noise Atom Number Preparation**
- **Geometric & atom number control** (crucial e.g. for quantum criticality)
- **Hard wall potentials realized** (crucial for edge states)

Size & atom number perfectly controlled

Rydberg

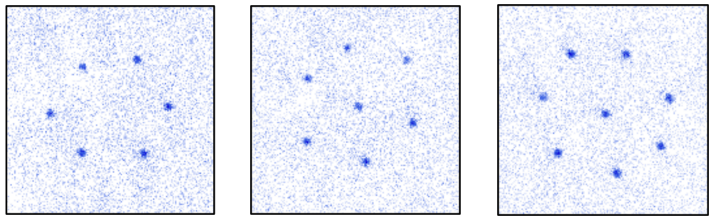
Adiabatic Sweeps in 2D

Pulsed vs sweeped excitation - localization of excitations to border of system!



Rydberg

Single-Shot Rydberg Crystal Configurations

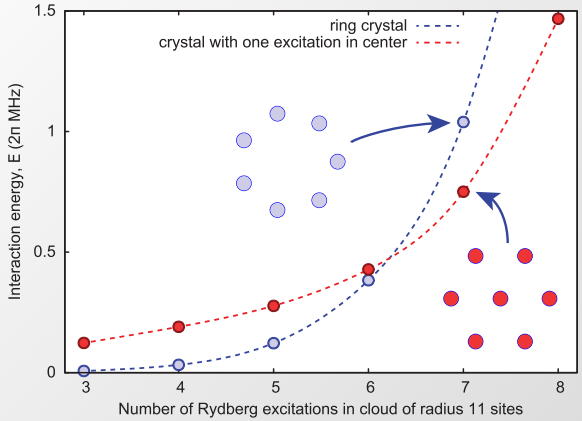


6 7 8

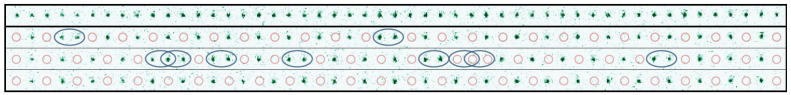
Rydberg Crystal configurations

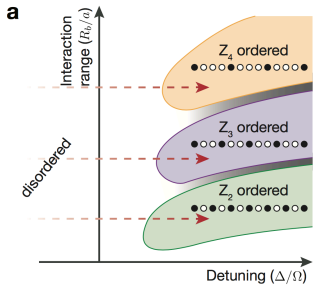
Rydberg Crystals

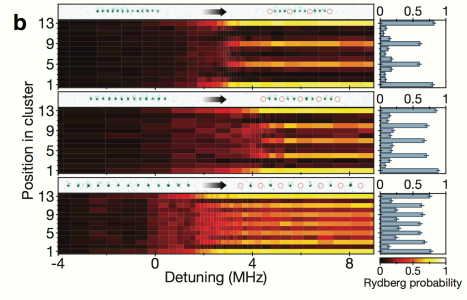
Configurational Change



Alternative Systems







H. Bernien *et al.* arXiv:1707.04344

Outlook

Smaller Blockade/Larger Cloud

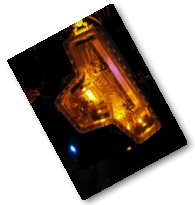
- ✓ Larger Rydberg Crystals
- ✓ Larger Rydberg Atoms cp. to Lattice Spacing
- ✓ Adiabatic Sweeps to Deterministically Prepare Crystal Structures
- ✓ Show Coherence of Crystalline Superpositions! a Quantum Crystal?

T. Pohl et al, (2010), van Bijnen et al. (2011), Gärtner et al. (2012),...

Larger Blockade/Smaller Cloud

- ✓ Collectively enhanced Rabi oscillations
- ✓ Large Entangled states (e.g. EIT schemes)

M. Lukin et al. (2001), D. Moller et al. (2008), M. Müller et al. (2009), H. Weimer et al. (2009)...



Dressed Rydberg Atom Regime

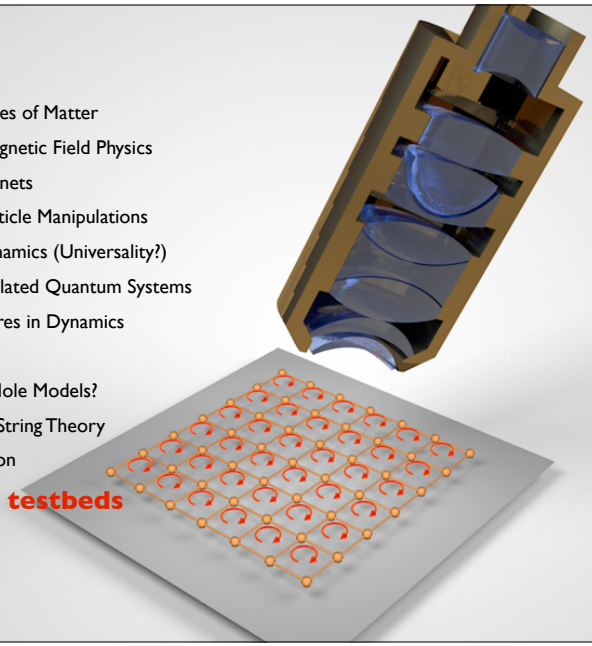
- ✓ Admix controlled long range interactions

G. Pupillo et al, (2010), Henkel et al. (2010), Schachenmeyer et al. (2010), Honer et al. (2010), Cinti et al. (2010), Johnson & Rolston (2010)...

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!



UQUAM ultracold quantum matter

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