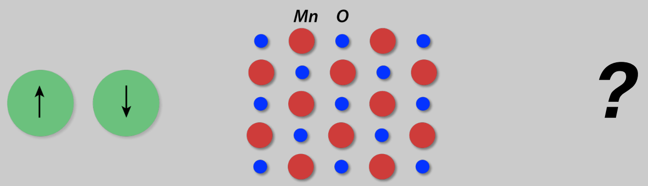
Superexchange Interactions

Origin of Spin-Spin Interactions – Exchange Interactions



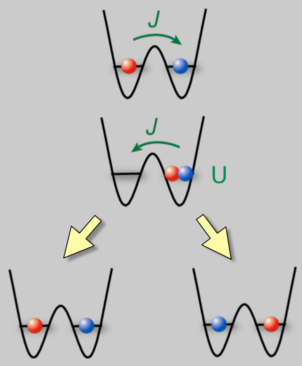
Important ionic solids with no direct exchange between magnetic ions show magnetic ordering (MnO, CuO)!

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



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

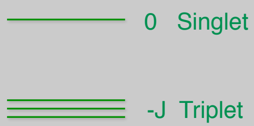
Deriving the Effective Spin Hamiltonian (2)

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

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

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

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



Deriving the Effective Spin Hamiltonian (3)

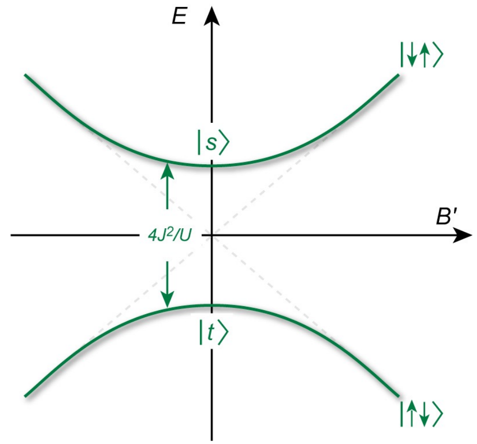
$$\hat{P}_{\text{triplet}} = \hat{P}_{S=1}$$

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

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

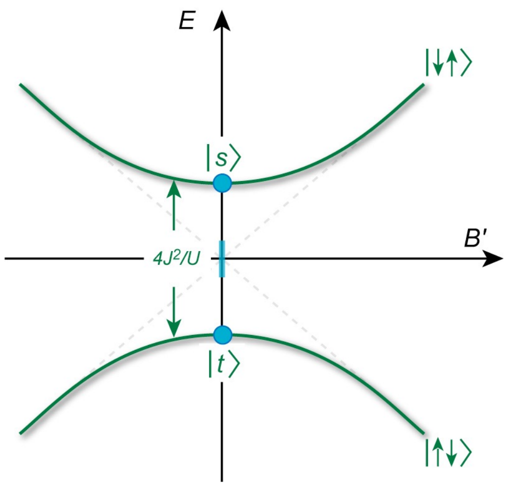
Direct Detection of Superexchange Interactions

$|s\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$
$|t\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

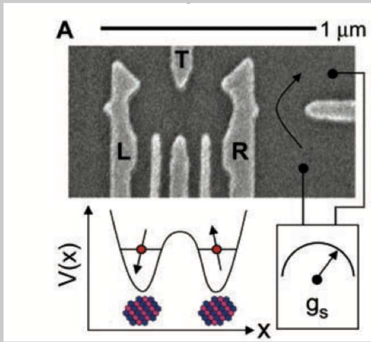


$$\boxed{H_{eff} = -J_{ex}\, \vec{S}_L \cdot \vec{S}_R - \mu_B B'\left(S_{z,L} - S_{z,R}\right)}$$

Direct Detection of Superexchange Interactions (2)



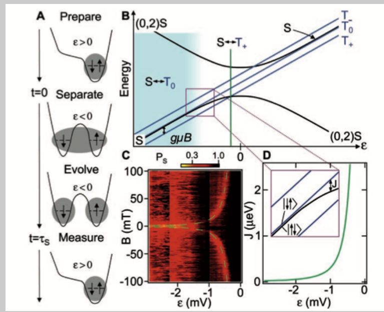
Superexchange Coupling in Quantum Dots



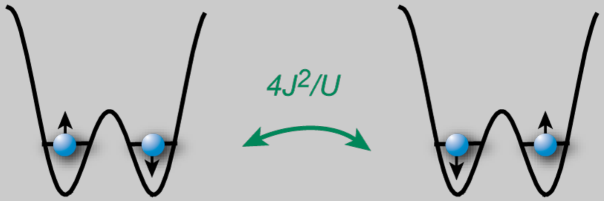
Local control of spin states & interactions between spin states.

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

Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots

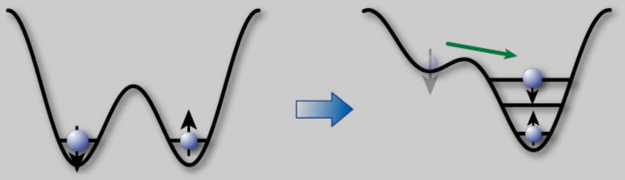


Superexchange induced flopping



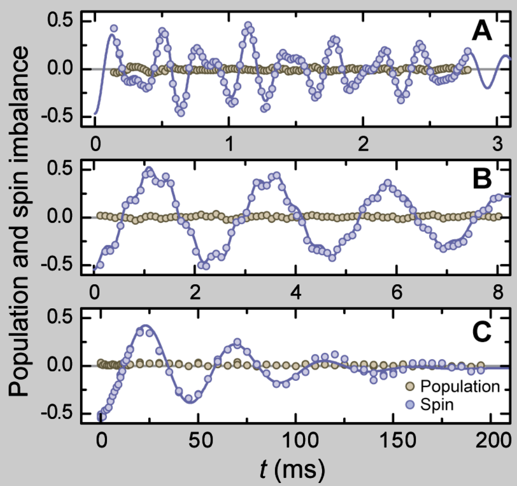
$$H_{eff} = -J_{ex}\vec{S}_i \cdot \vec{S}_j$$
$$= -\frac{J_{ex}}{2}\left(\hat{S}_i^+\hat{S}_j^- + \hat{S}_i^-\hat{S}_j^+\right) - J_{ex}\hat{S}_i^z\hat{S}_j^z$$

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

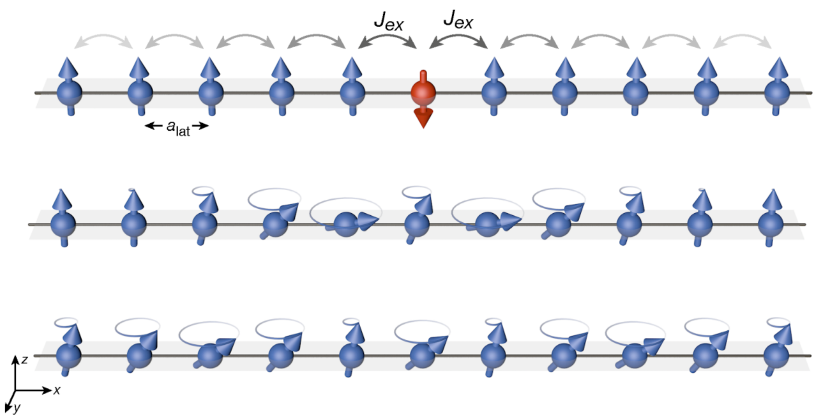
J/U=0.05
V_{short}=17 E_r

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

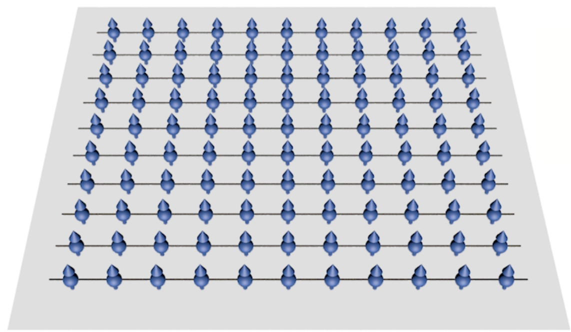
Sherson et al. Nature 467, 68 (2010),
see also Bakr et al. Nature (2009) & Bakr et al. Science (2010)

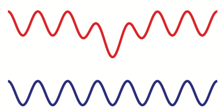
Spin impurity dynamics



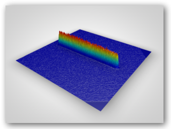
$-J_{ex}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$ *Ferromagnetic Heisenberg Interaction*

Spin impurity dynamics



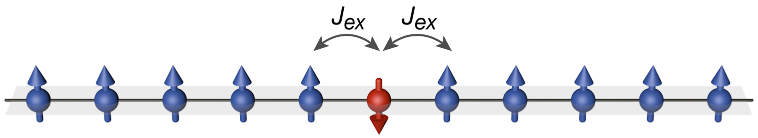


|2> = |F=2, m_F=-2>
|1> = |F=1, m_F=-1>



Line-shaped light field created with DMD SLM

Spin impurity dynamics



Heisenberg Hamiltonian

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

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

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

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

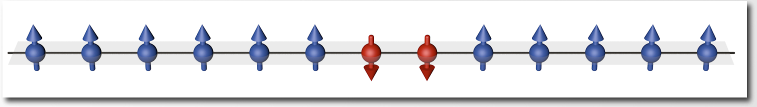
Direct Observation of Magnon Bound States

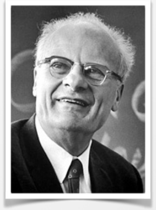
T. Fukuhara, P. Schauss, S. Hild, J.Zeiher, M. Cheneau, M. Endres, I. Bloch, Ch. Gross

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

www.quantum-munich.de

Magnon Bound States



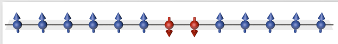


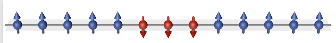
Hans Bethe
(1906-2005)

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

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

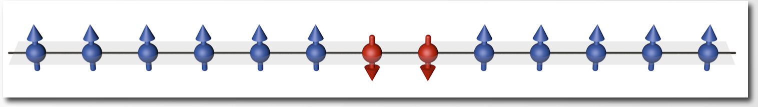
General
l-string bound states

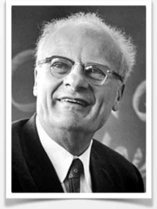




H. Bethe, Z. Phys. (1931)
M. Wortis, Phys Rev. (1963)
M. Takahashi & M. Suzuki Prog. Th. Phys. (1972)
M. Karbach, G. Müller (1997)
see also: **repulsively bound pairs & interacting atoms**
K. Winkler et al. Nature (2006); S. Fölling et al. Nature (2007); Y Lahini et al. PRA (2012)

Magnon Bound States





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

H. Bethe, Z. Phys. (1931)
M. Wortis, Phys Rev. (1963)
M. Takahashi & M. Suzuki Prog. Th. Phys. (1972)
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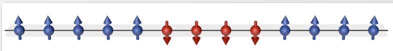
Bound l-string

Eigenenergies:

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

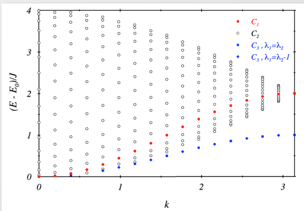


$$\Delta = \cos(\nu)$$

l-string

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

Excitation spectrum:



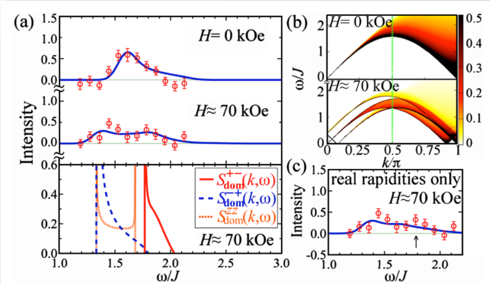
M. Karbach & G. Müller (1997)

Bound magnon

A Challenge for CM Physics

Very difficult to observe in spectroscopic data in real materials!

theory with bound states

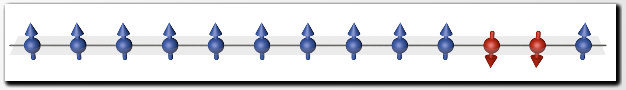


theory without bound states

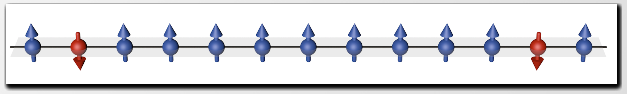
M. Kohno, Phys. Rev. Lett. **102**, 037203 (2009)

Dynamical Evolution

Bound Magnon Motion

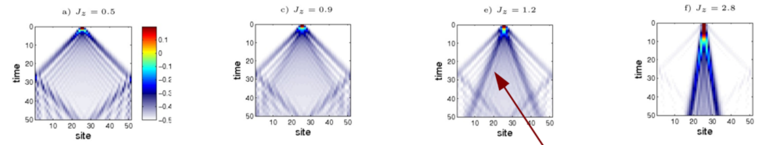


Breakup and Single Spin Motion



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

Two-spin excitation in FM

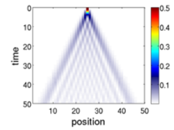


Sz

Jz =0.5 Jz =0.9 Jz =1.2 Jz =2.8

- Two distinct propagation branches beyond Jz =0.7
- New lower branch is *bound state*
- It dominates at large Jz, with decreasing velocity
- Low entanglement entropy (see below)

P(↑↑)

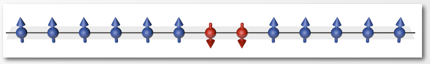


From: H.G. Evertz

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

Dynamical Evolution

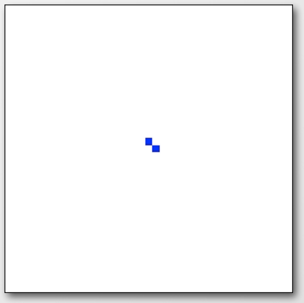
Initial State:



Pair distribution evolution

$P(x_1, x_2)$

x_1



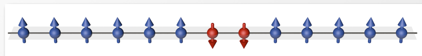
x_2

$\Delta = 0$
Non-Interacting

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

Dynamical Evolution

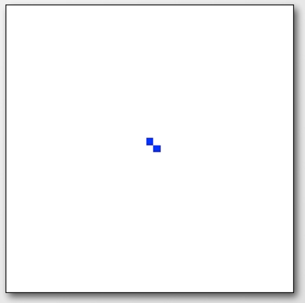
Initial State:



Pair distribution evolution

$P(x_1, x_2)$

x_1



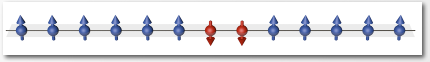
x_2

$\Delta = 1$
Interacting
Isotropic Heisenberg

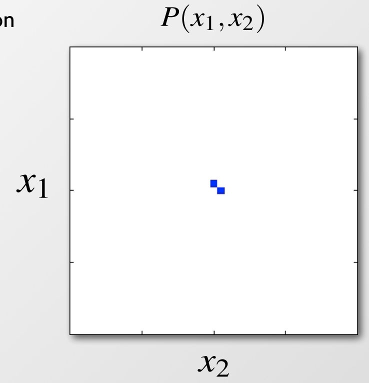
Magnon Bound State

Dynamical Evolution

Initial State:



Pair distribution evolution

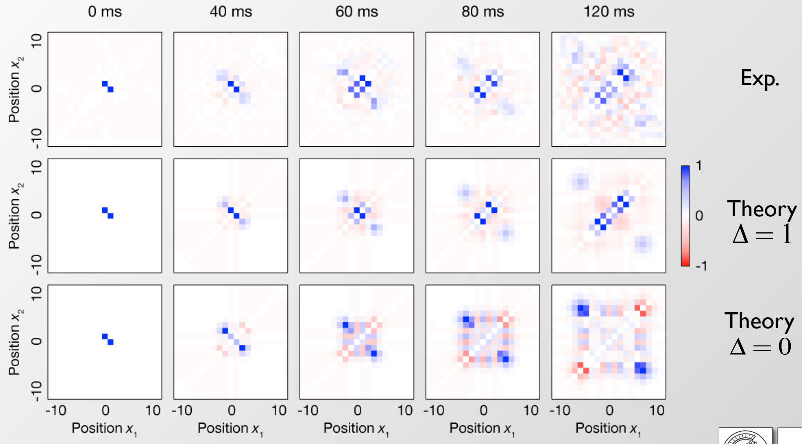


$\Delta = 1.6$
Interacting Heisenberg

Magnon Bound State

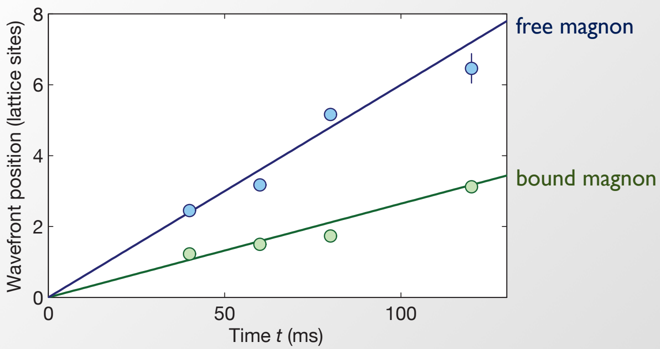
Experimental Results

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



Magnon Bound State

Propagation Velocity



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

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

Quantum Magnetism

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

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

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

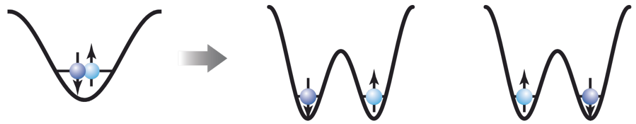
Controlling and Detecting Spin Correlations

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

Splitting a spin pair

- **Spin pairs** in $|F=1, m_F=\pm 1\rangle = |\uparrow\rangle, |\downarrow\rangle$ (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 $|F=1, m_F=\pm 1\rangle \equiv |\uparrow\rangle, |\downarrow\rangle$
- Barrier raised *slowly* to split
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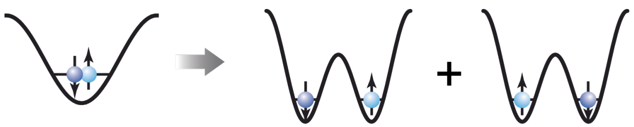
J. Sebby-Strabley et al., PRL ***98*** *(2007)*



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

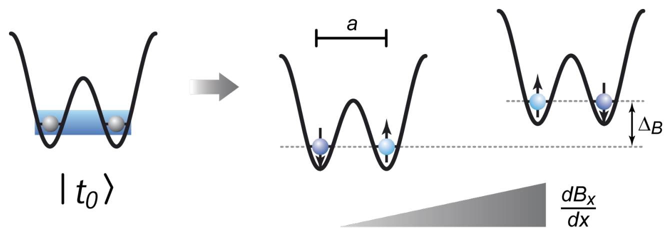
(Fermions: Antisymmetric wavefunction → Singlet $|s\rangle$)

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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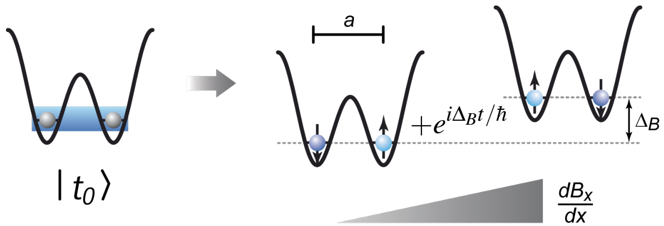


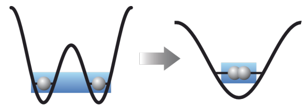
- **Triplet-Singlet oscillations** with frequency $\Delta_B/\hbar$

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

LMU

How to detect triplets and singlets

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



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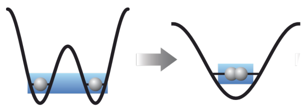
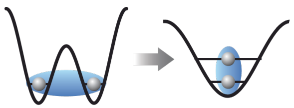


→ **Singlet**: needs anti-symm. spatial wavefunction (Bosons)
One atom transferred to **higher vibrational band**



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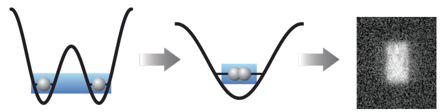

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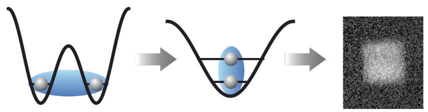
One atom transferred to **higher vibrational band**



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

LMU

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

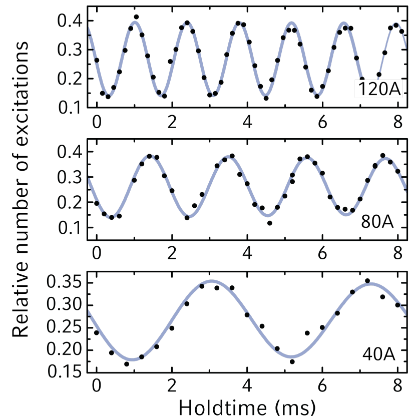
	band excitations		STO amplitude	
	bosons	fermions	bosons	fermions
$\|t\rangle$	0%	50%	50%	50%
$\|s\rangle$	50%	0%	50%	50%
$\|\downarrow,\uparrow\rangle$	25%	25%	0%	0%
$\|\uparrow,\downarrow\rangle$	25%	25%	0%	0%
$\|\uparrow,\uparrow\rangle$	0%	50%	0%	0%
$\|\downarrow,\downarrow\rangle$	0%	50%	0%	0%

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

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

LMU

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

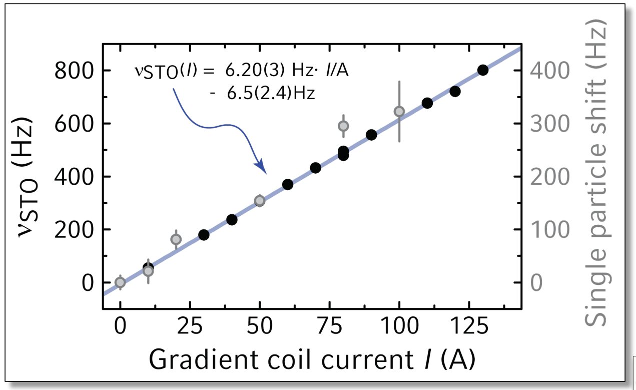
- Vary gradient coil current

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

LMU

Singlet-Triplet oscillations

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



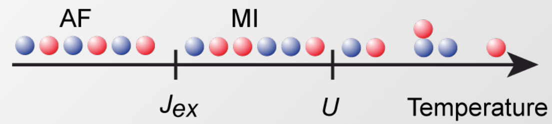
LMU

AFM

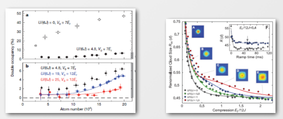
The Quest for AFM Spin Order

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

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

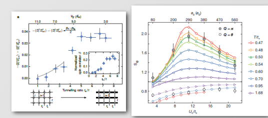


Fermionic Mott Insulator



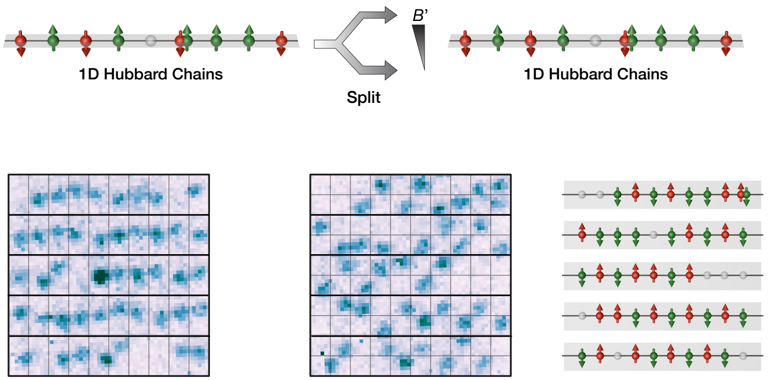
R. Jördens et al., Nature **455**, 204 (2008),
U. Schneider et al., Science **322**, 1520 (2008)

Nearest Neighbour Spin Correlations



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

AFM — Spin & Charge Resolved Imaging



1D Chains (spin unresolved)

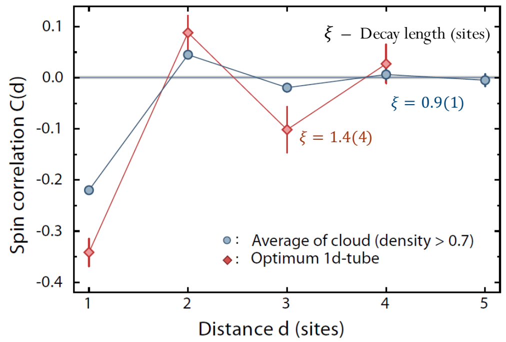
Split 1D Chains (spin resolved)

Reconstruction

T. Hilker et al.; arXiv:1605.05672

AFM — Spin Correlations

$$C(d) = 4\langle \hat{S}_i^z \hat{S}_{i+1}^z \rangle - 4\langle \hat{S}_i^z \rangle \langle \hat{S}_{i+1}^z \rangle$$



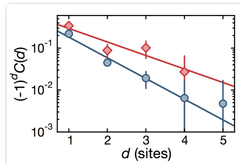
Theory Comparison

Néel-State $C(d) = (-1)^d$

1d Heisenberg (GS) $C(1) \simeq -0.6$

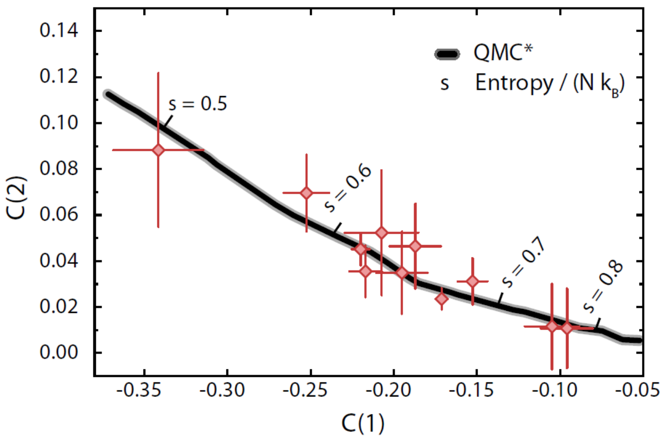
1d Fermi Hubbard

$U/t = 12.6 \quad C(1) \simeq -0.56$



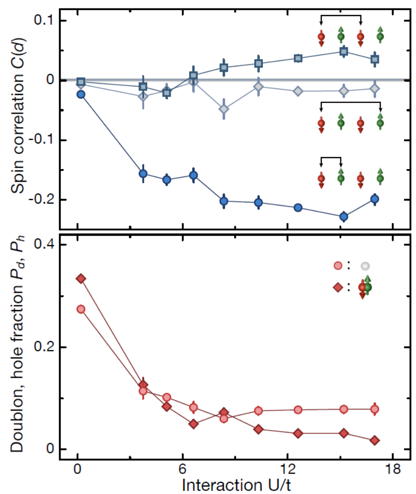
T. Hilker et al.; arXiv:1605.05672
see also work in Harvard (M. Greiner)

AFM — Spin Correlation vs Entropy



*Theory: Gorelik et al. PRA **85** 061602 (2012)

AFM — Spin Correlation & Density Fluctuations



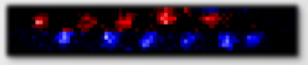
Adiabatic State Preparation

- **Constant entropy (not temperature)**
- **Saturation for *U/t* >8 (strong coupling limit)**

Summary & Outlook

Summary

- Demonstrated spin & charge resolved imaging of 1d Hubbard chains
- Measure AFM spin correlations up to d=3-4
- Minimum Entropy per particle reached S/N = 0.5 k_B

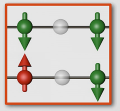


Outlook

- Imaging directly extendable to 2d !
- Doped Mott insulators (away from half filling)
- Evaluation of almost arbitrary correlations
- **Example:** Spin correlations around holes

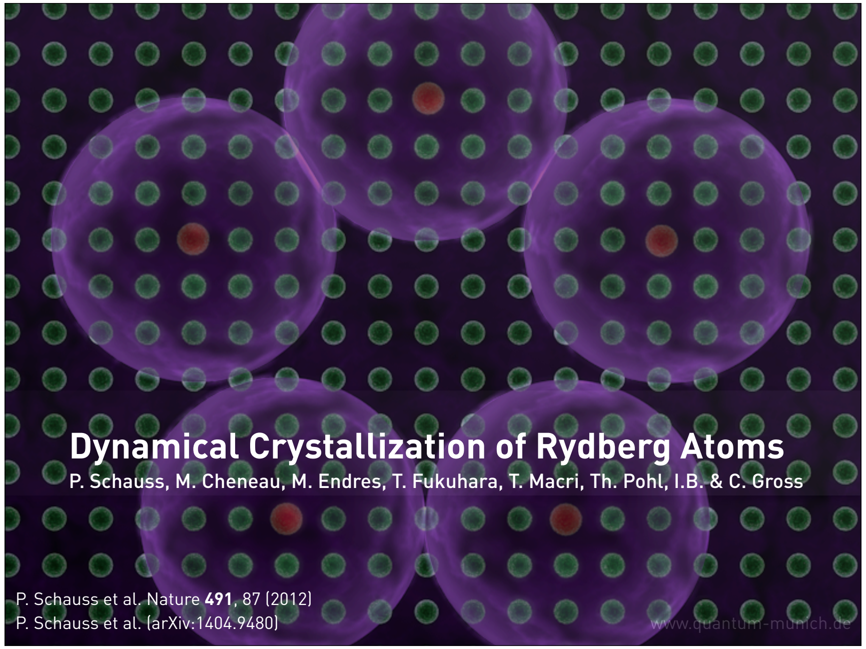
  1d: domain walls, 2d: local ferromagnetism (?)

  Hole attraction ?
- Get colder



Spin correlations around holes (doped MI)

$\langle \hat{S}^z_i \, \hat{n}^h_{i+1} \, \hat{S}^z_{i+2} \rangle$

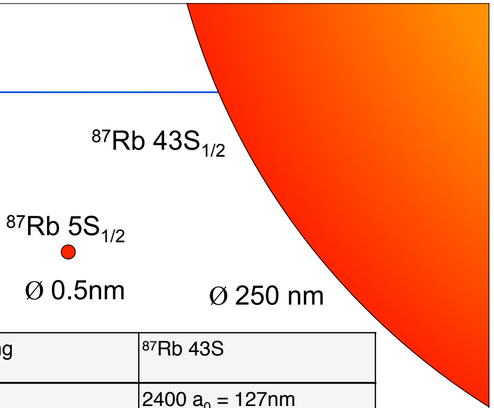


Rydberg atoms

- hydrogen-like wave function
  - quantum defect

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

- Strong switchable interactions

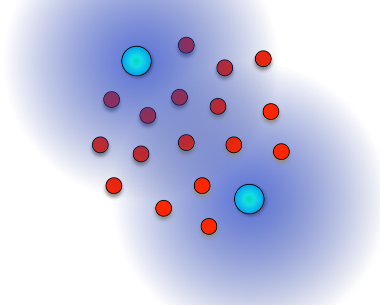


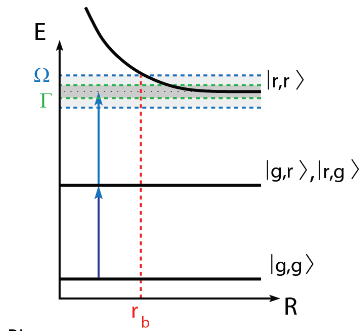
Property	Scaling	^{87}Rb 43S
Radius	$(n^*)^2$	2400 a_0 = 127nm
Lifetime (dominated by black body radiation for large n)	$(n^*)^2$	45 μs @ 20°C
van der Waals coefficient	$(n^*)^{11}$	$C_6 = -1.7 \times 10^{19}$ a.u.
Blockade radius ($\Omega = 2\pi$ 200 kHz)	$(n^*)^2$	~ 5 μm

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

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

Rydberg blockade





Blockade condition

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

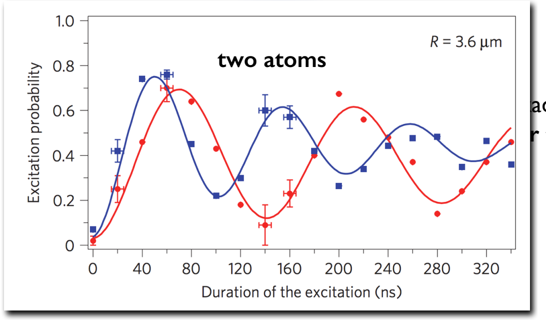
Each superatom:

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

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

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!

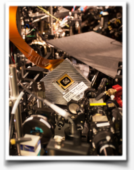
Each superatom:

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

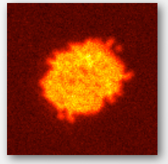
M. Lukin et al. PRL **87**, 037901 (2001)

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

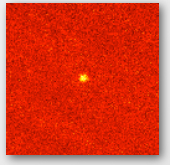
DMD Adressing — Ultimate Size Control in 2D



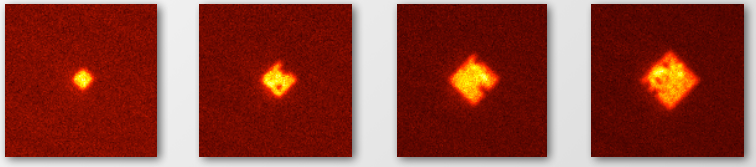
Digital Mirror Device (Size Control)



Initial MI



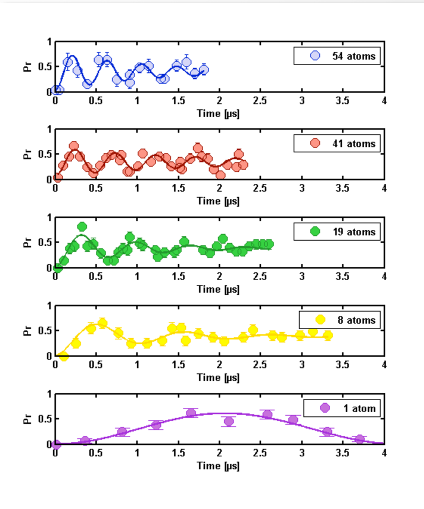
Single Atom



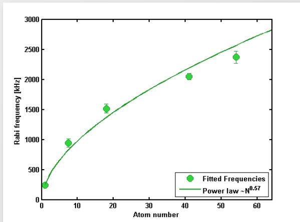
3x3 5x5 7x7 8x8

atoms

Rydberg — Collective Many-Body Rabi Oscillations

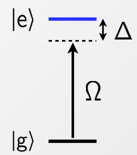


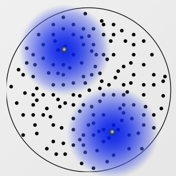
Preliminary Raw Data



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

Rydberg Crystal — 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

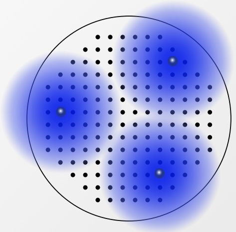
interaction between Rydberg atoms

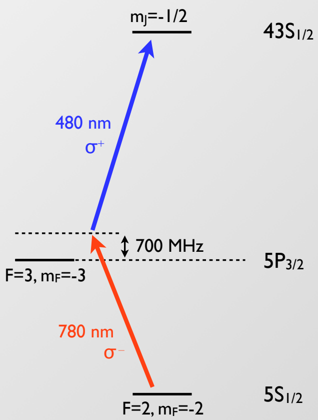
$V_{ij} = C_\alpha |r_i - r_j|^{-\alpha}$

"chemical potential"

This work: α=6, repulsive

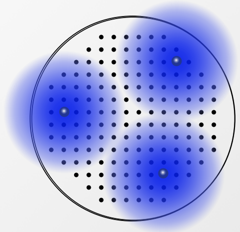
Excitation and detection of the Rydberg atoms

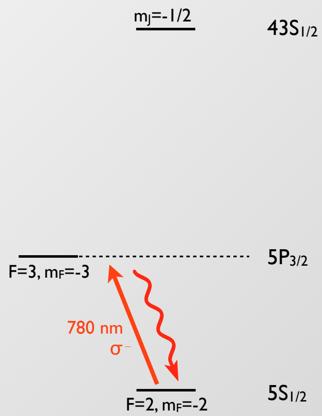




- two-photon Rabi frequency: $\Omega/2\pi$ = 170(20) kHz
- resonant excitation: Δ = 0
- blockade radius: R_b = 4.9(1) µm

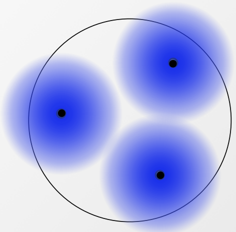
Excitation and detection of the Rydberg atoms

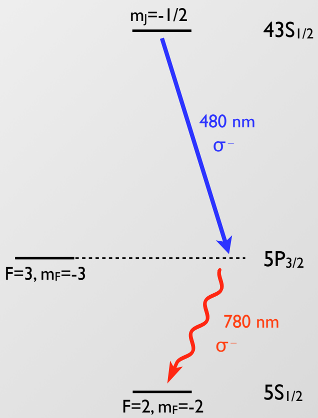




- removal pulse duration: 10 µs
- survival probability: 0.1 %

Excitation and detection of the Rydberg atoms





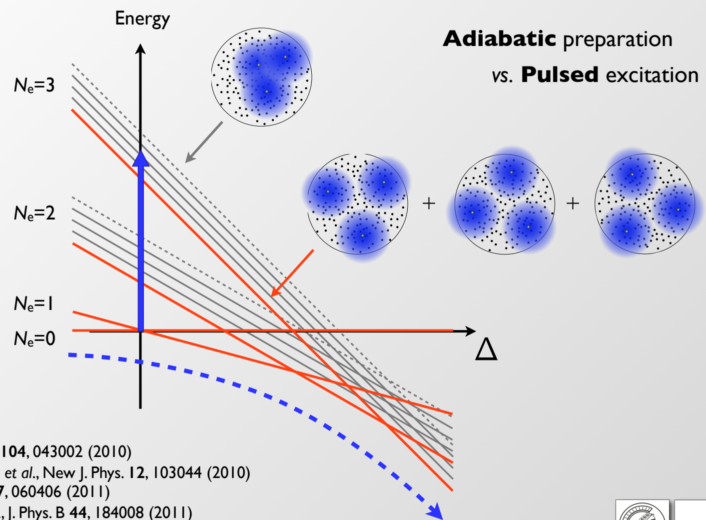
- deexcitation pulse duration: 2 µs
- detection efficiency: 75(10) %
- overall resolution: ~ 500 nm

Rydberg Crystal

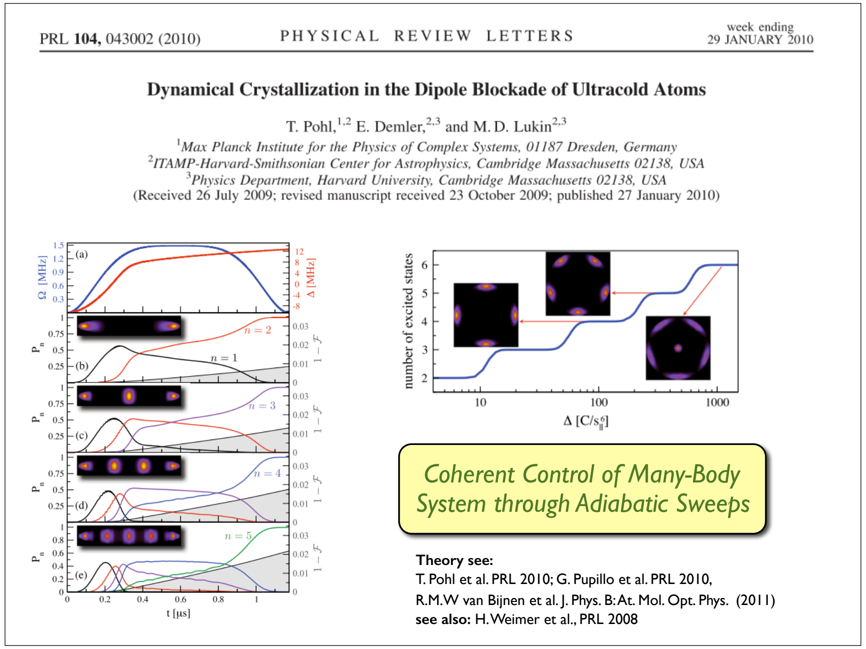
Energy spectrum of the Rydberg gas

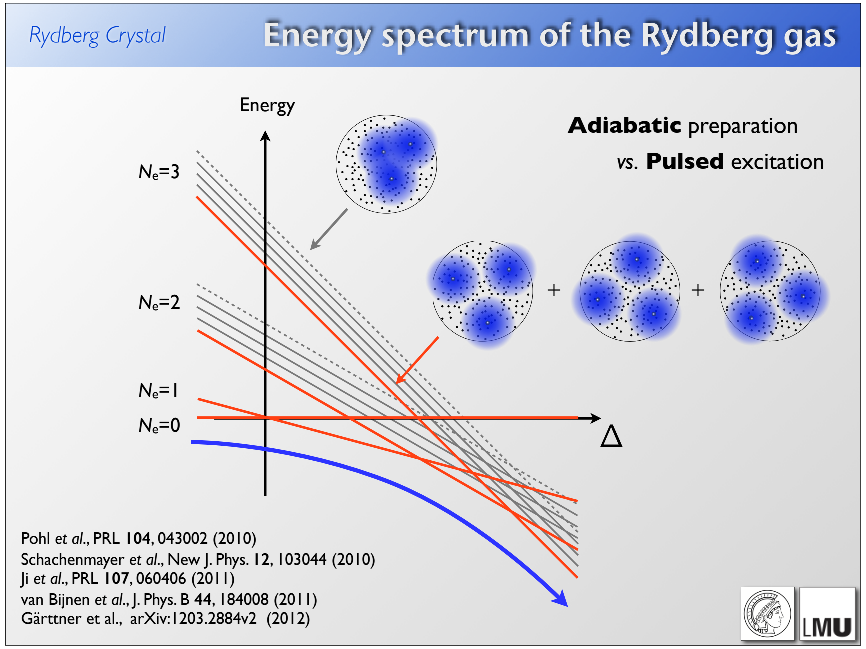
Adiabatic preparation

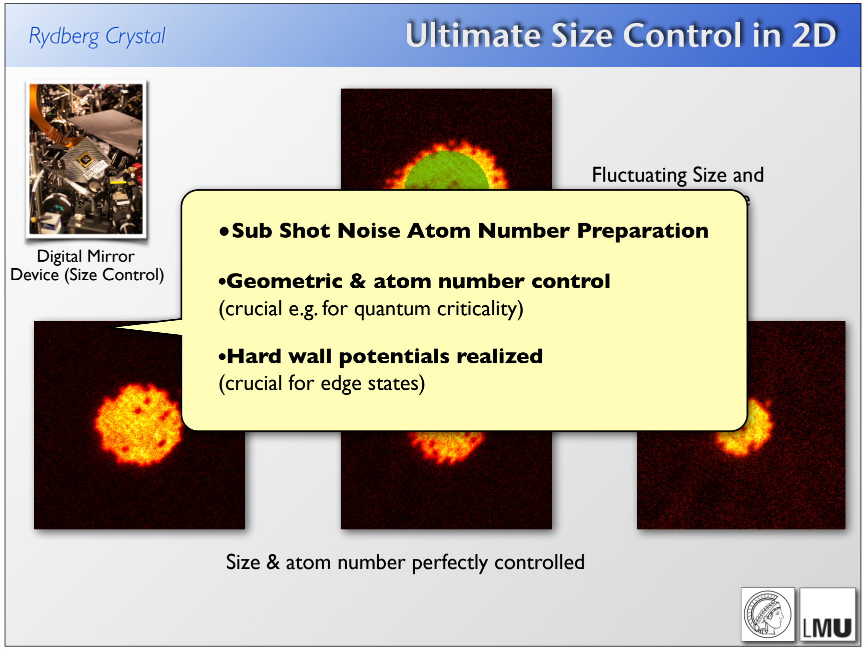
vs. **Pulsed** excitation

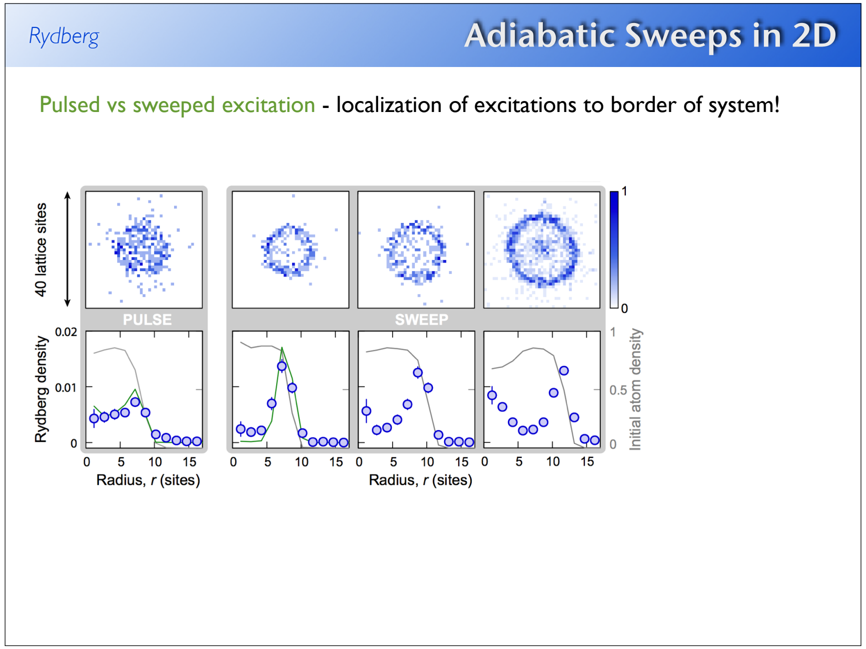


Pohl *et al.*, PRL **104**, 043002 (2010)
Schachenmayer *et al.*, New J. Phys. **12**, 103044 (2010)
Ji *et al.*, PRL **107**, 060406 (2011)
van Bijnen *et al.*, J. Phys. B **44**, 184008 (2011)
Gärttner et al., arXiv:1203.2884v2 (2012)

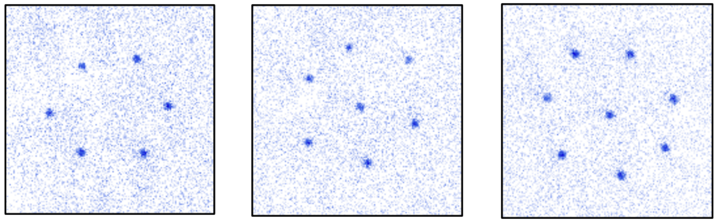

PRL 104, 043002 (2010)
PHYSICAL REVIEW LETTERS
week ending 29 JANUARY 2010
Dynamical Crystallization in the Dipole Blockade of Ultracold Atoms
T. Pohl,[1,2] E. Demler,[2,3] and M. D. Lukin[2,3]
[1]Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany
[2]ITAMP-Harvard-Smithsonian Center for Astrophysics, Cambridge Massachusetts 02138, USA
[3]Physics Department, Harvard University, Cambridge Massachusetts 02138, USA
(Received 26 July 2009; revised manuscript received 23 October 2009; published 27 January 2010)
number of excited states
Δ [C/s]
t [μs]
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
Energy
Adiabatic preparation
vs. Pulsed excitation
Ne=3
Ne=2
Ne=1
Ne=0
Δ
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)
LMU


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
LMU


Rydberg
Adiabatic Sweeps in 2D
Pulsed vs sweeped excitation - localization of excitations to border of system!
40 lattice sites
PULSE
SWEEP
Rydberg density
Initial atom density
Radius, r (sites)
Radius, r (sites)

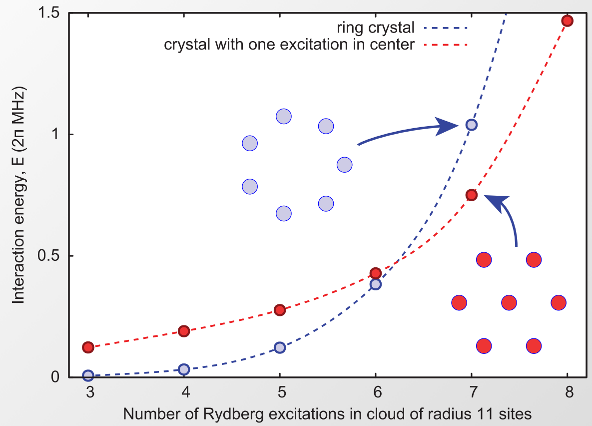
Single-Shot Rydberg Crystal Configurations



6 7 8

Rydberg Crystal configurations

Configurational Change

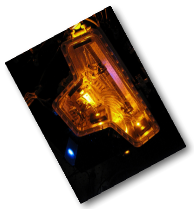


Outlook

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)...