Probing Non-Equilibrium Dynamics Using Ultracold Quantum Gases in Optical Lattices

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Outline

Introduction

Single Atom Imaging

Applications

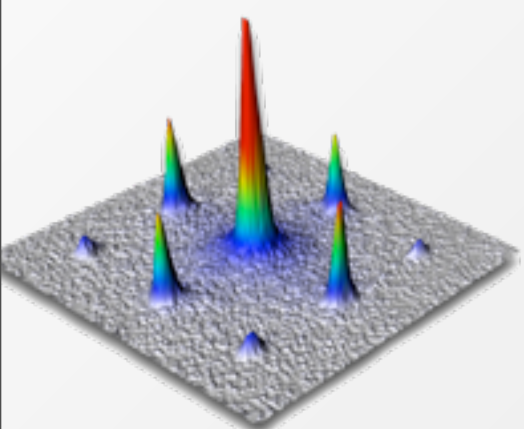
Tracking the Motion of a Single Spin Impurity

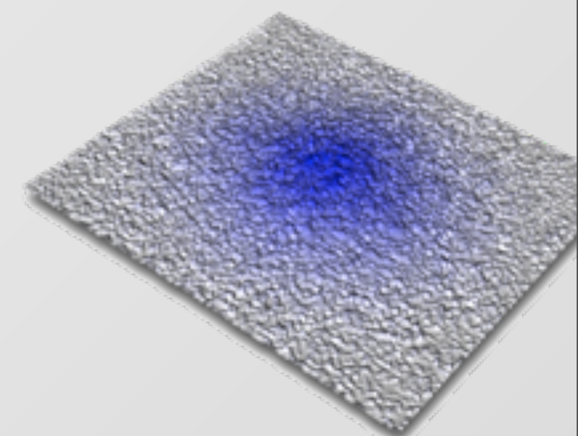
Observation of Crystalline States of Rydberg Atoms

Measuring Zak-Berry Phase of Topological Bloch Bands

From Weak to Strong Interactions

$$\gamma = \frac{\text{Interaction Energy}}{\text{Kinetic Energy}} >> 1$$



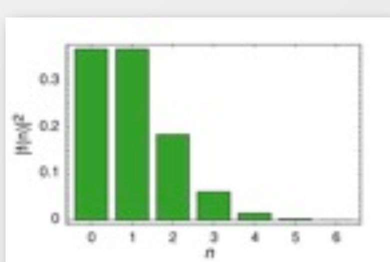


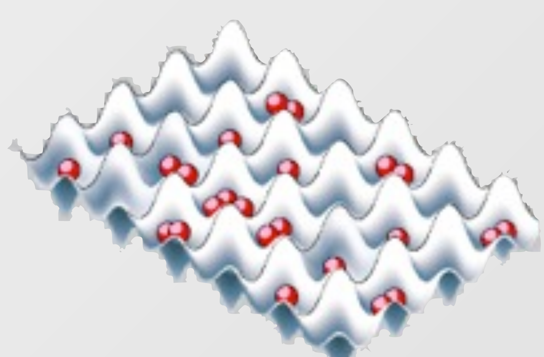
Quantum Phase Transition

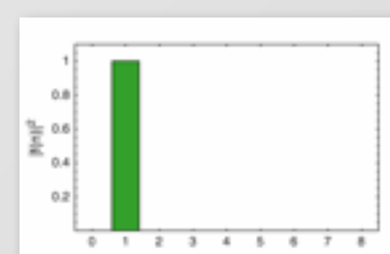
See S. Sachdev & B. Keimer Phys. Today 2011

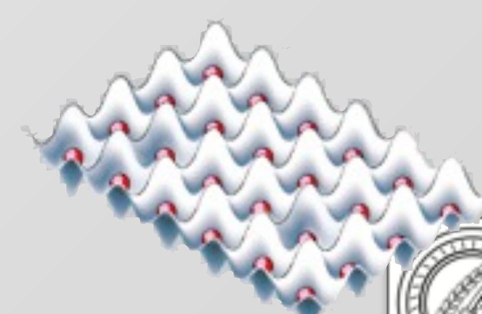
Weak Interactions

Strong Interactions







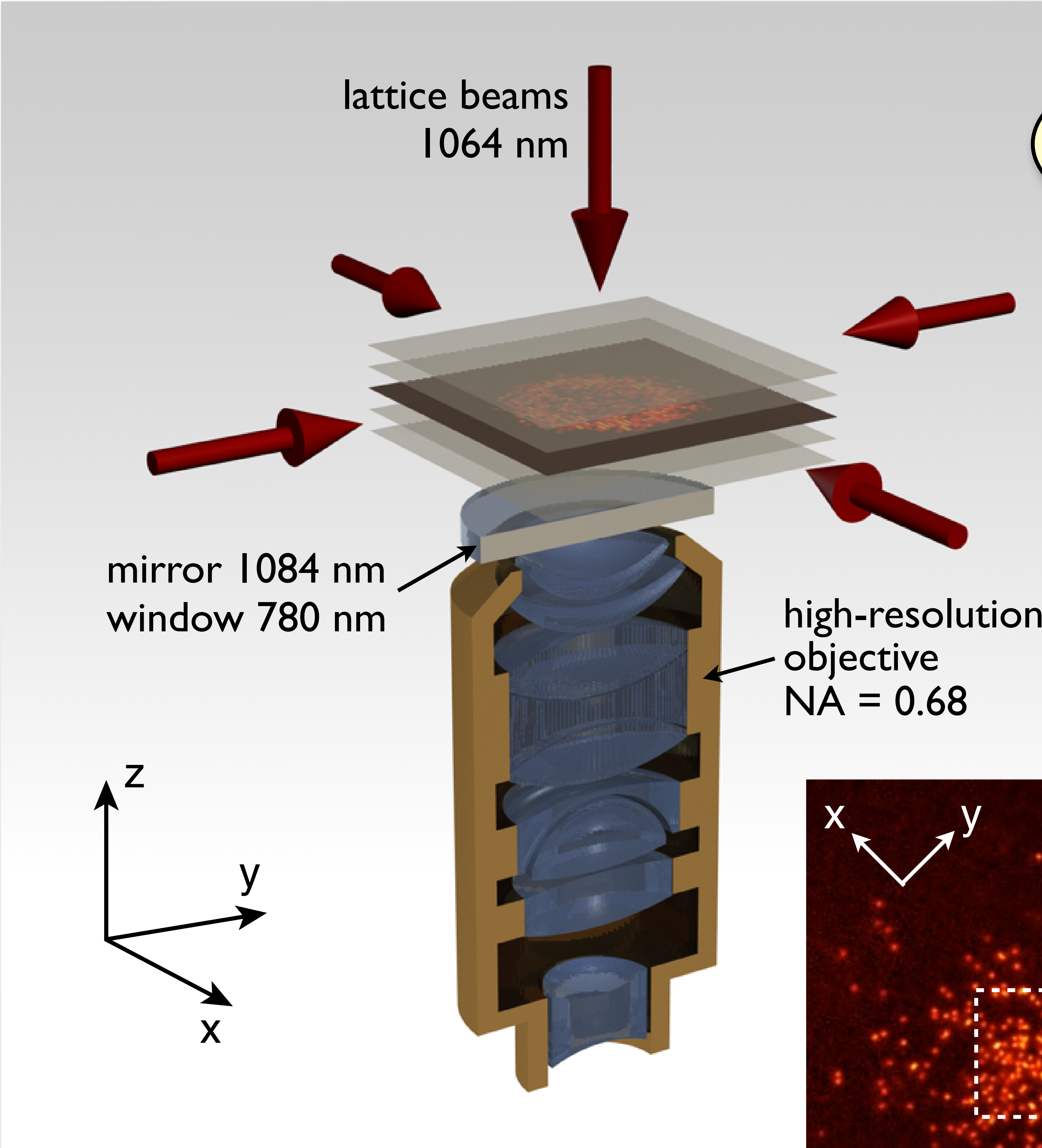


Single Atom Detection in a Lattice

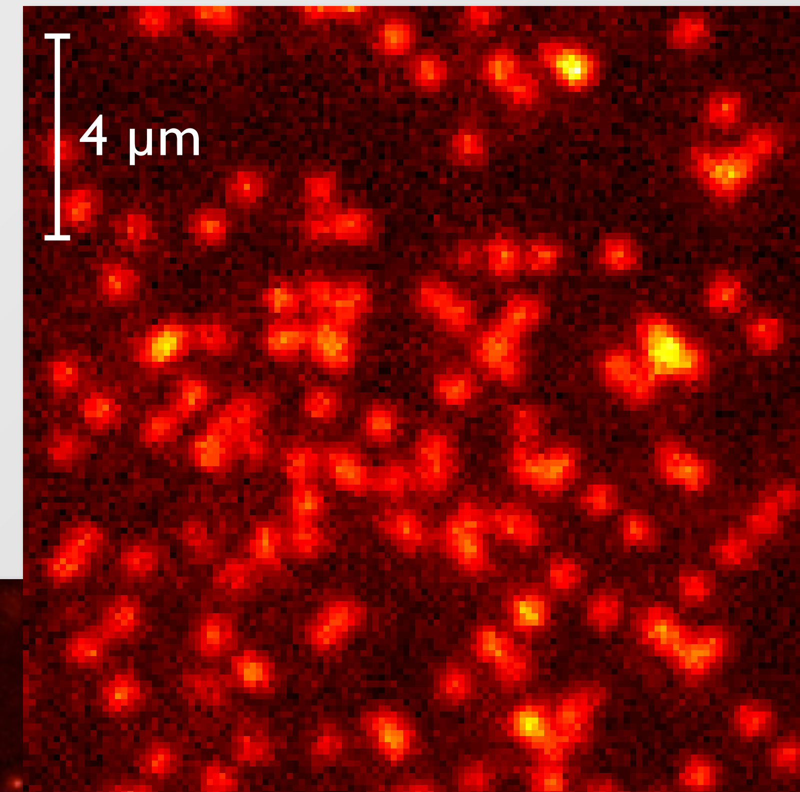
J. Sherson, Ch. Weitenberg, M. Endres, M. Cheneau, T. Fukuhara, P. Schauss, J. Sherson, I.B., S. Kuhr

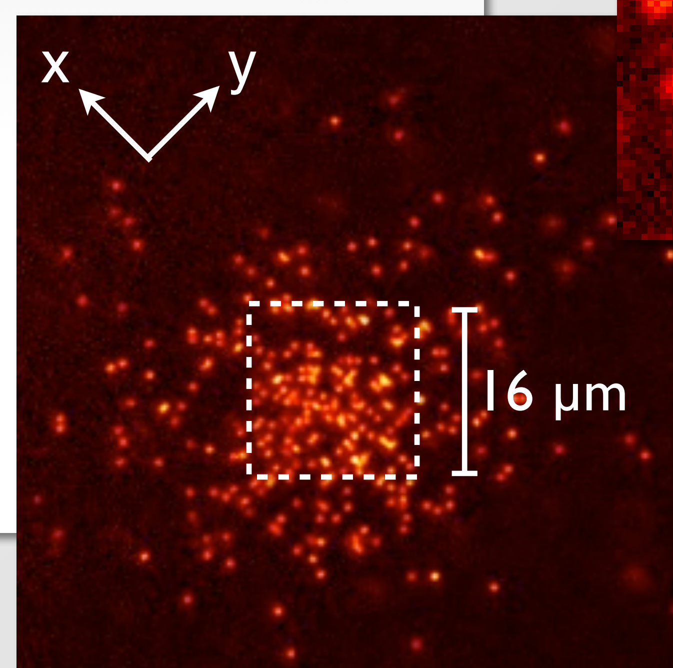
Sherson et al. Nature 467, 68 (2010),
see also Bakr et al. Nature (2009) & Bakr et al. Science (2010)

Experimental Setup



single 2D degenerate gas
~ 1000 ^{87}Rb atoms (bosons)

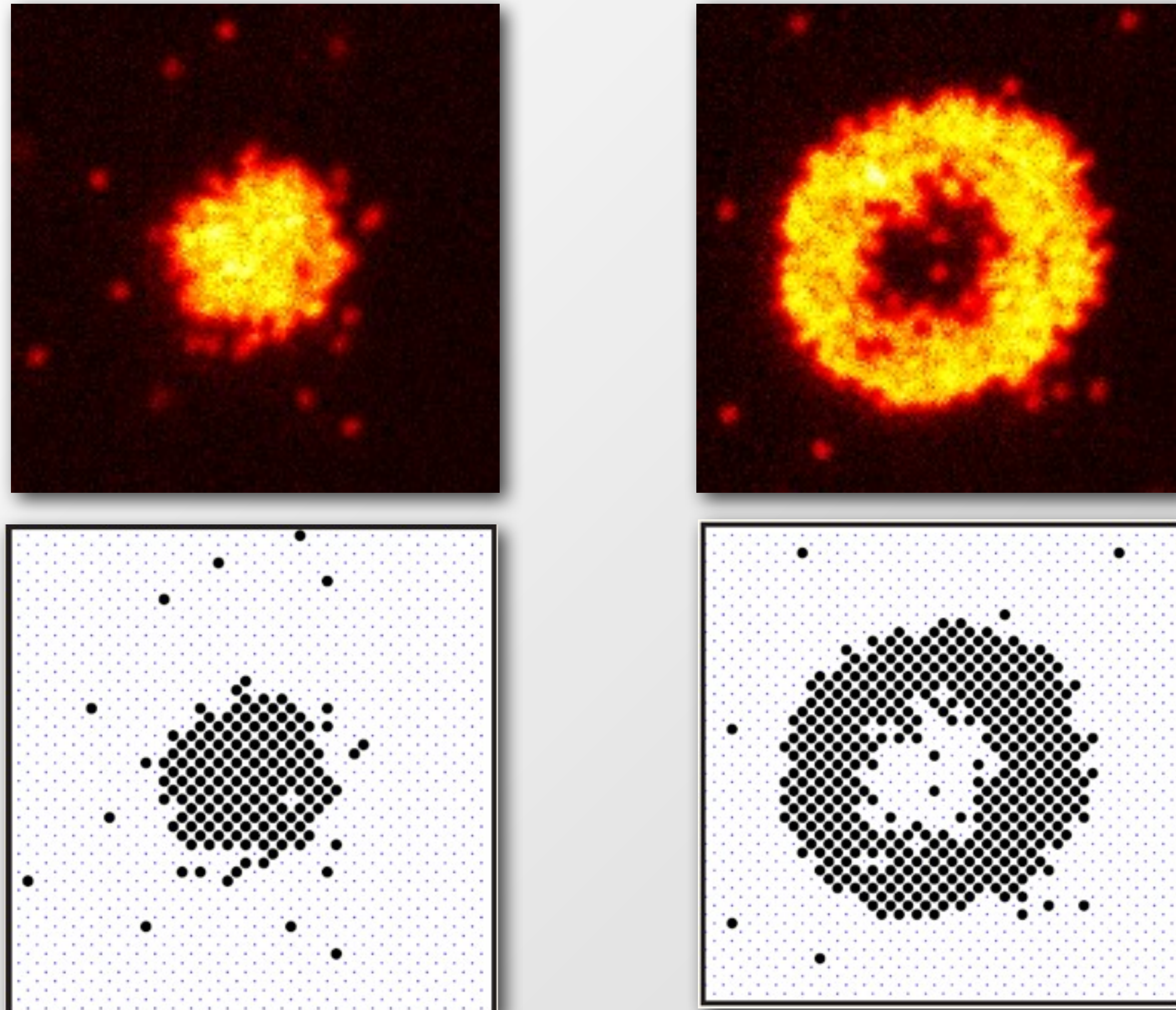




resolution of the imaging system: ~700 nm

see also: Harvard (M. Greiner group)

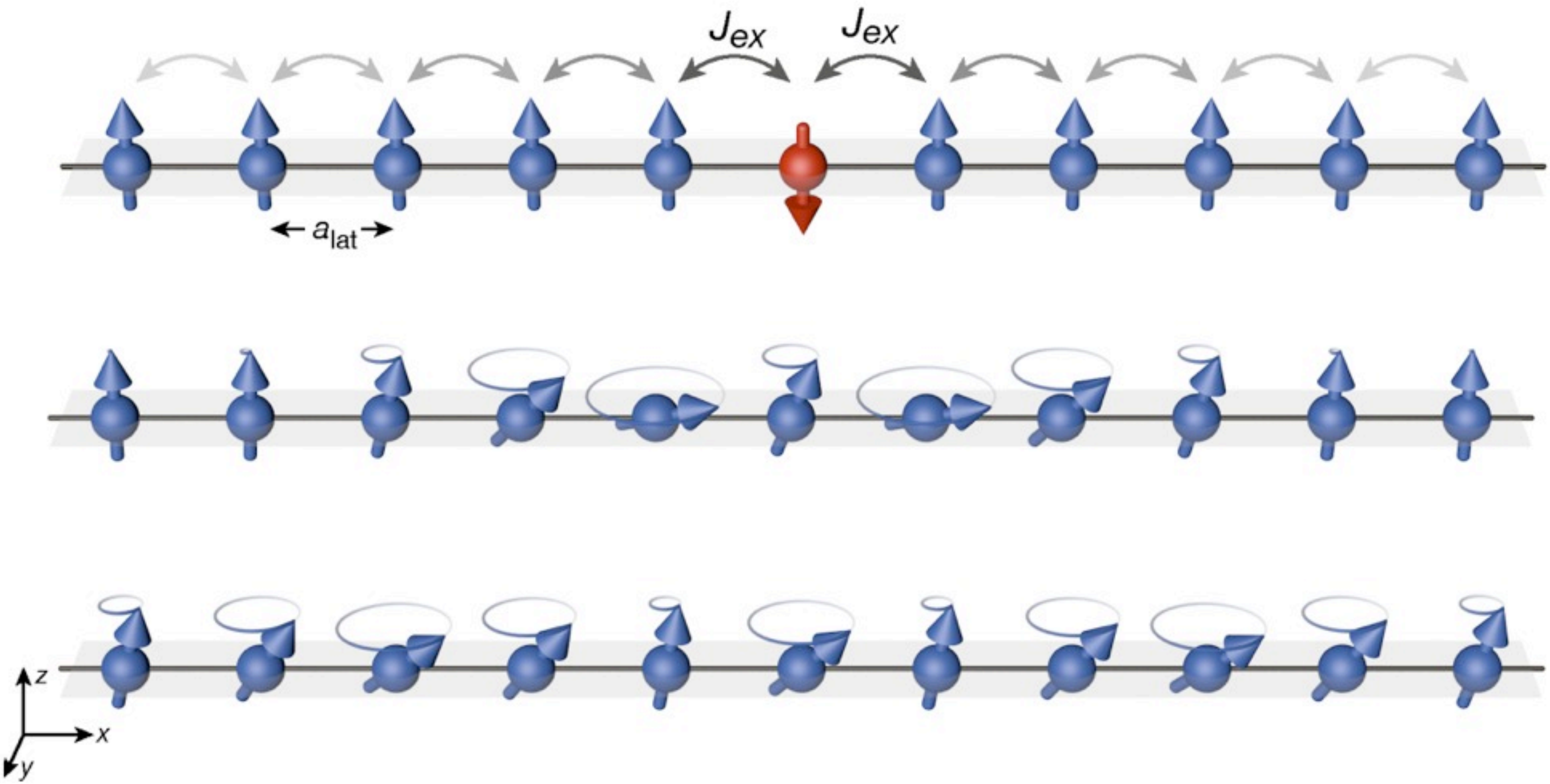
Images of Mott Insulators



Quantum Dynamics 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

Spin impurity dynamics

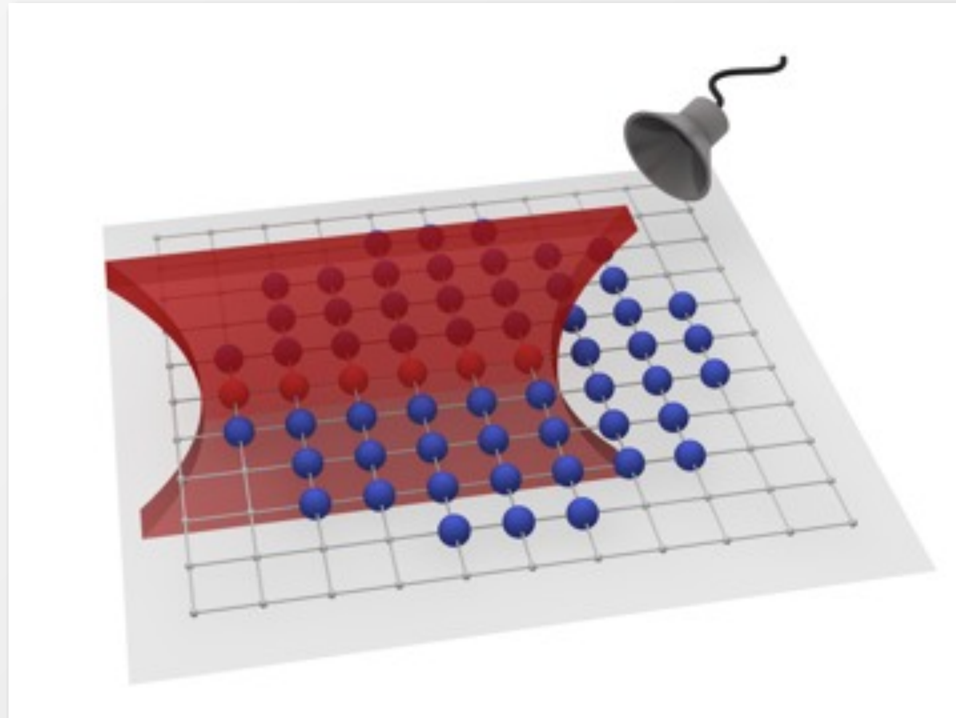


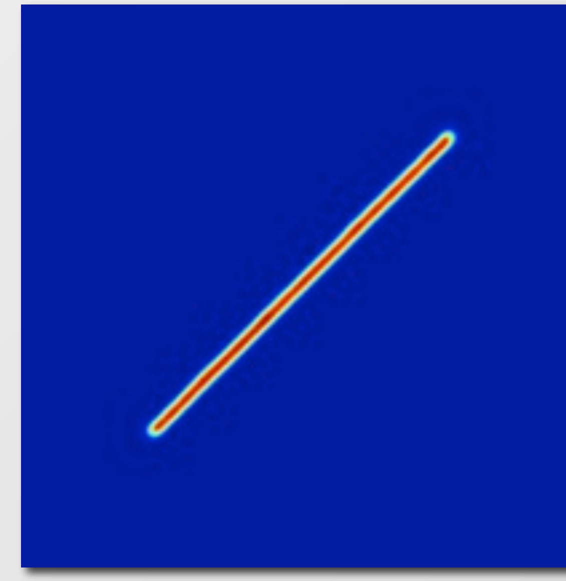
$$-J_{ex}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$$

Ferromagnetic Heisenberg Interaction

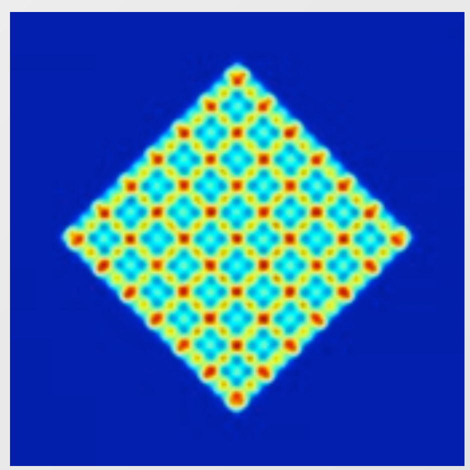
Arbitrary Light Patterns

Digital Mirror Device (DMD)

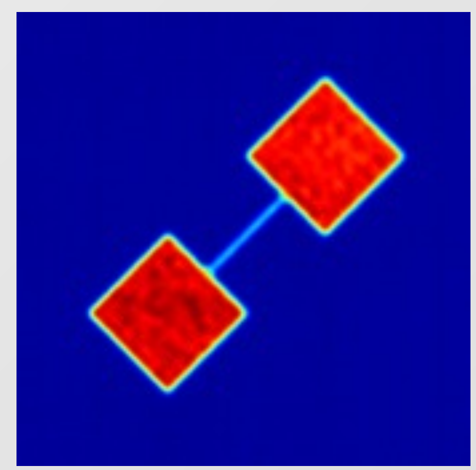




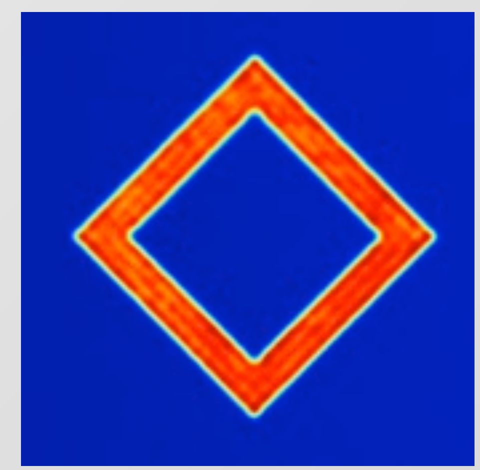
Measured Light Pattern



Exotic Lattices



Quantum Wires

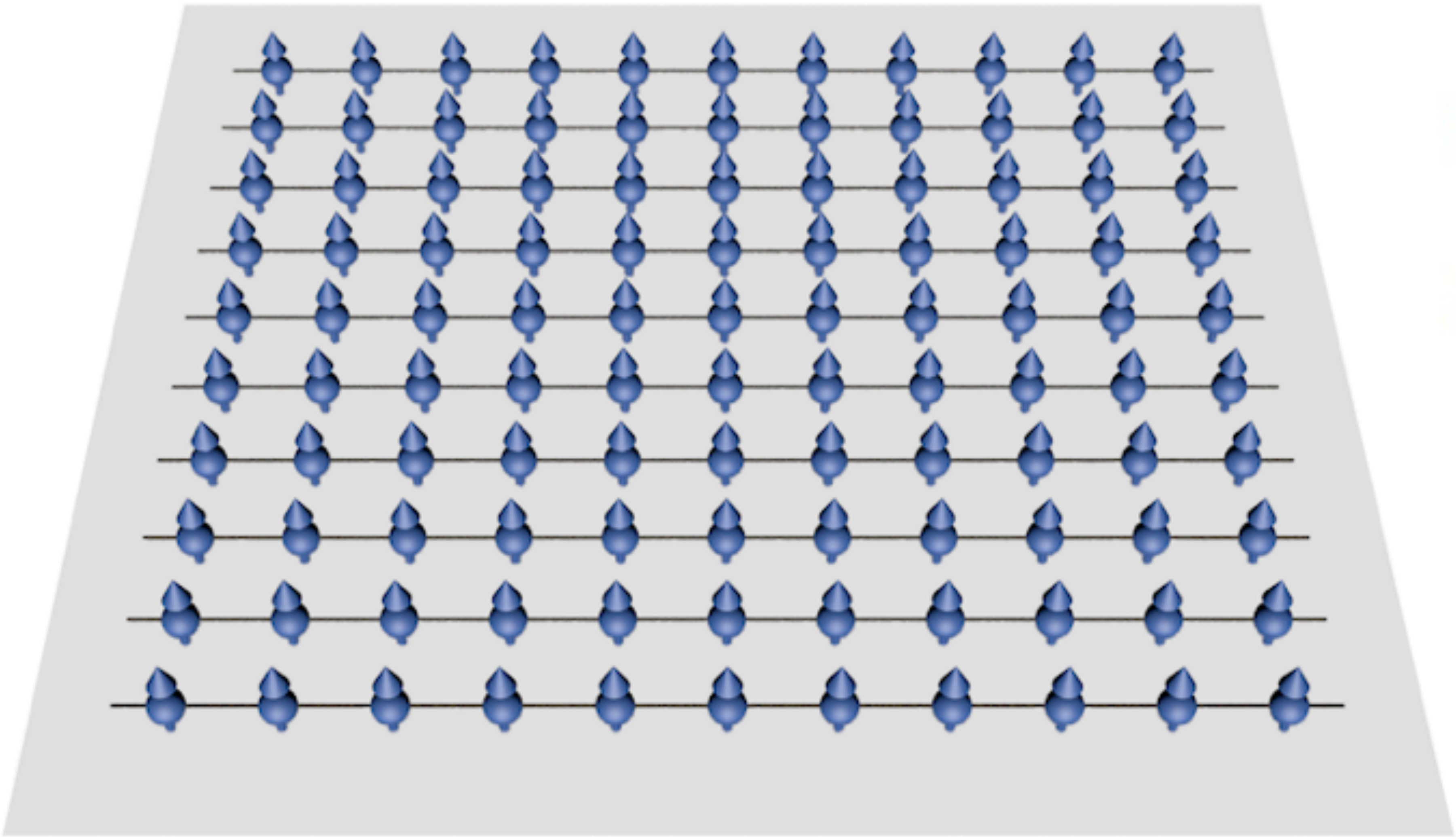


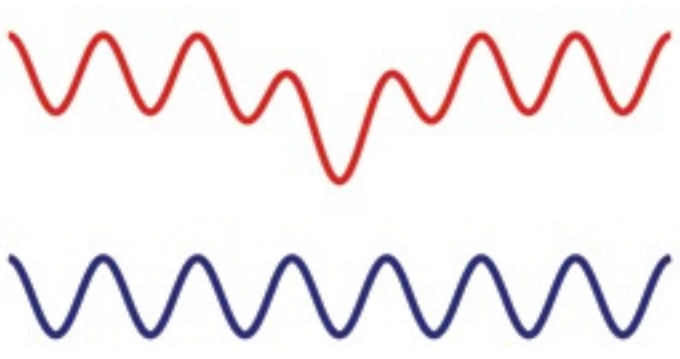
Box Potentials

Almost Arbitrary Light Patterns Possible!

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

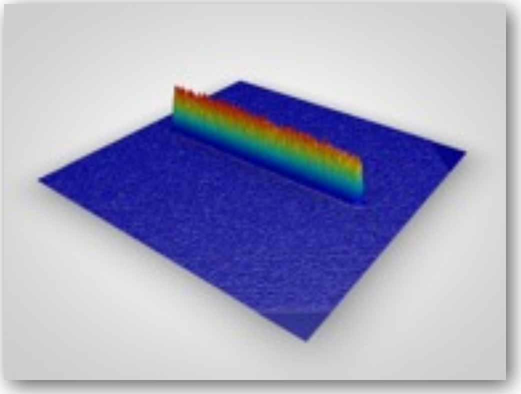
Spin impurity dynamics





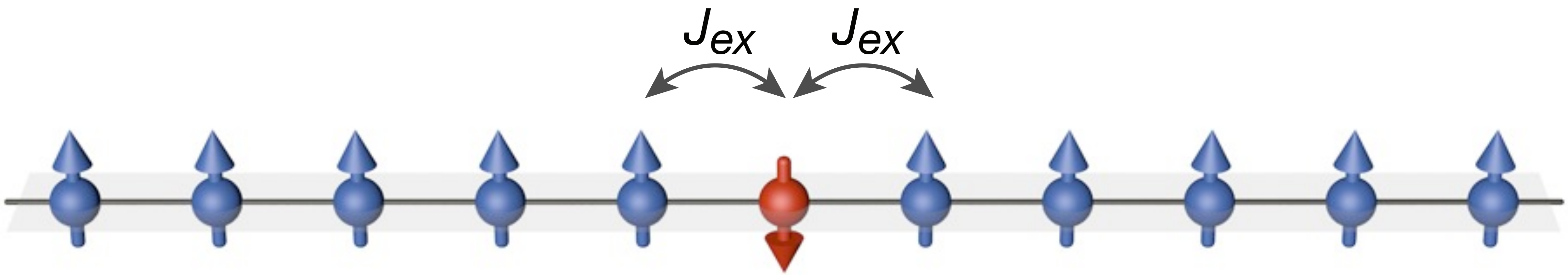
$|2\rangle$ = $|F=2, m_F=-2\rangle$

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



Line-shaped light field created with DMD SLM

Spin impurity dynamics



Heisenberg Hamiltonian

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

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

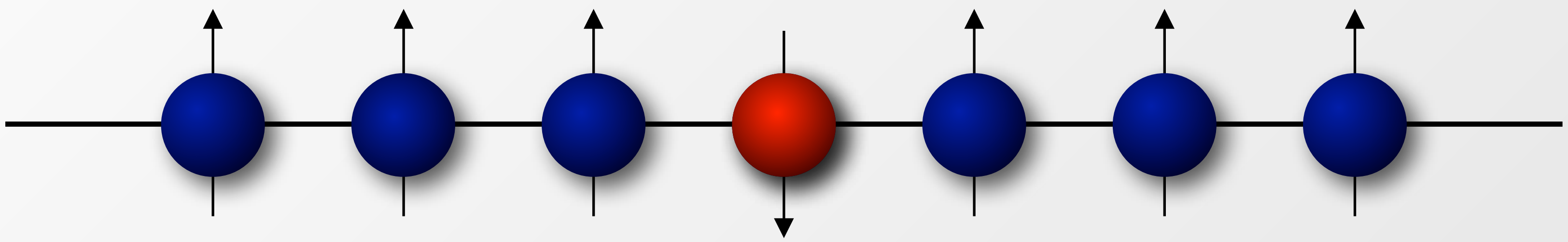
$$J_{ex} = 4\frac{J^2}{U}$$

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

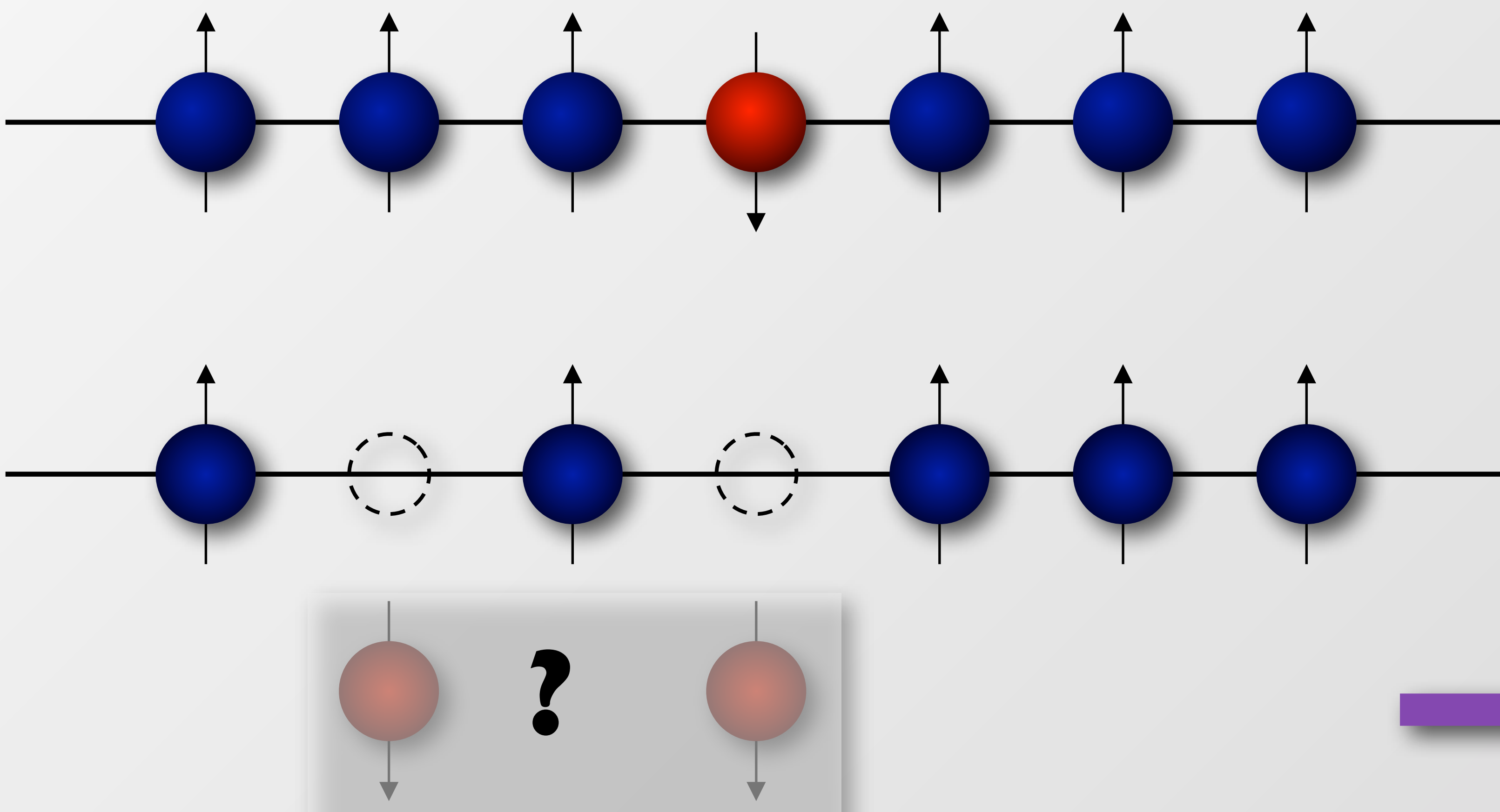
Detection and "Post-selection"

Our detection is not spin-resolved.

Positive image Remove the other spin component (bath spin) before detection



Negative image Measure spin impurities as empty sites by pushing out the impurities

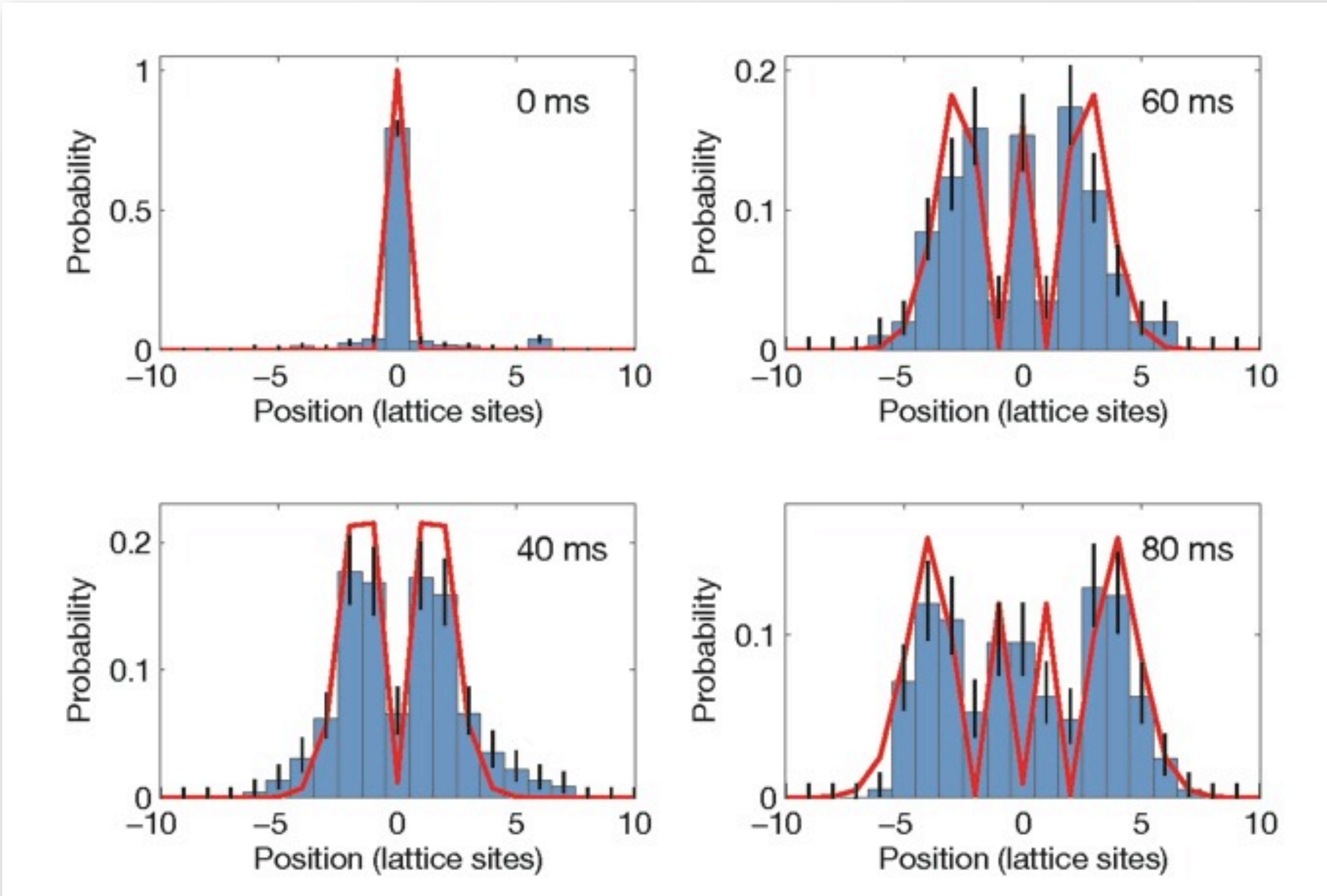


If we only use samples with one empty site …

- the position of the impurity can be determined
- system has no extra excitation

→ **" zero temperature"**

Coherent quantum dynamics of single spin at zero temperature



$V = 10\ Er$

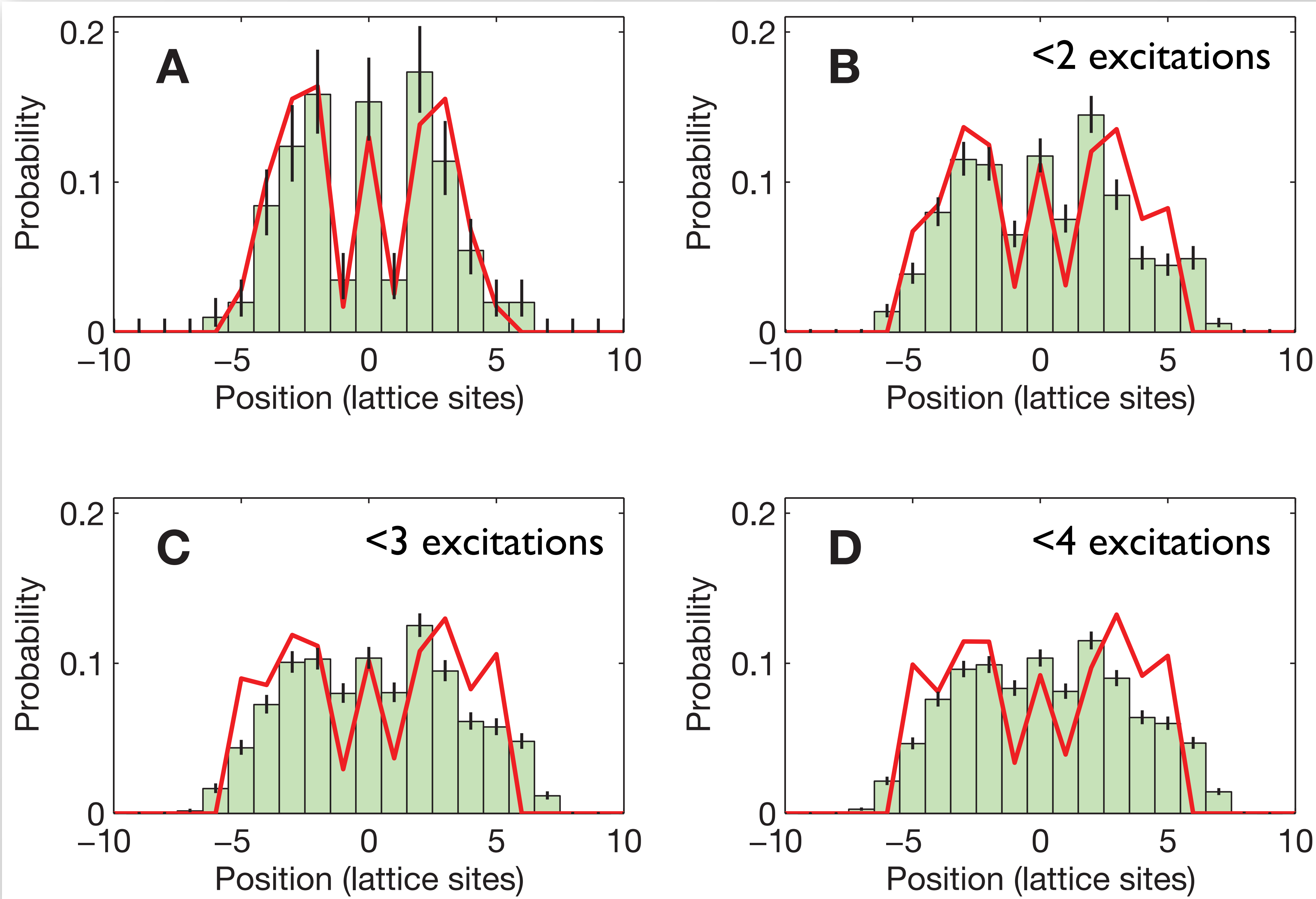
$U/J = 19$

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

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

Bessel function of the first kind

Effect from hole excitations

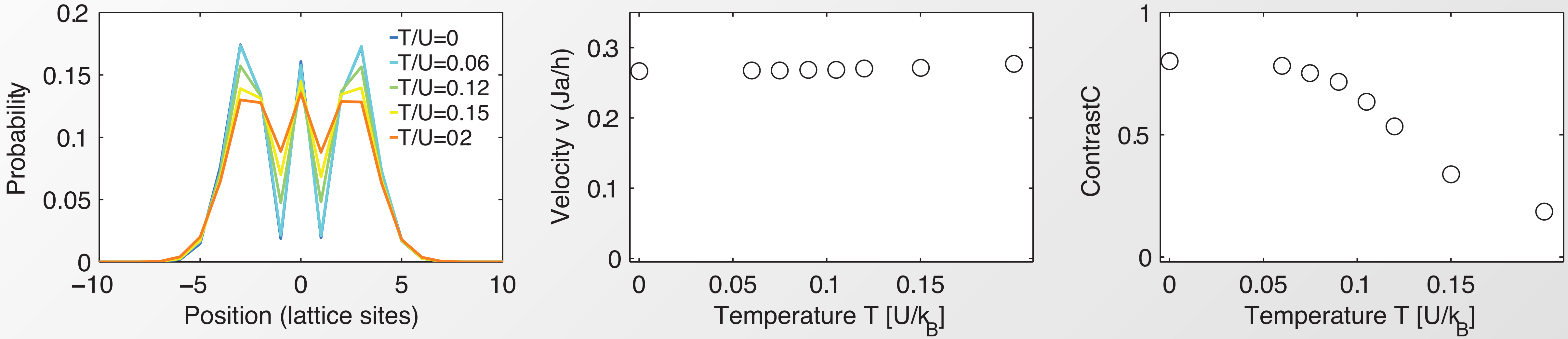


V = 10 *Er*
U/J = 19

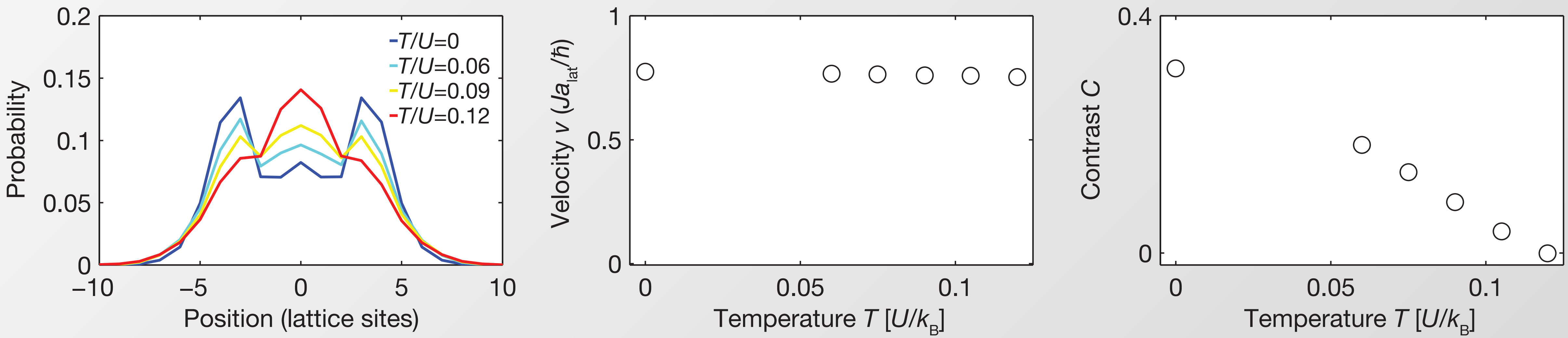
- Only visibility goes down
- Spreading speed almost independent of holes

Temperature Effects

V_{lat}=10 E_r

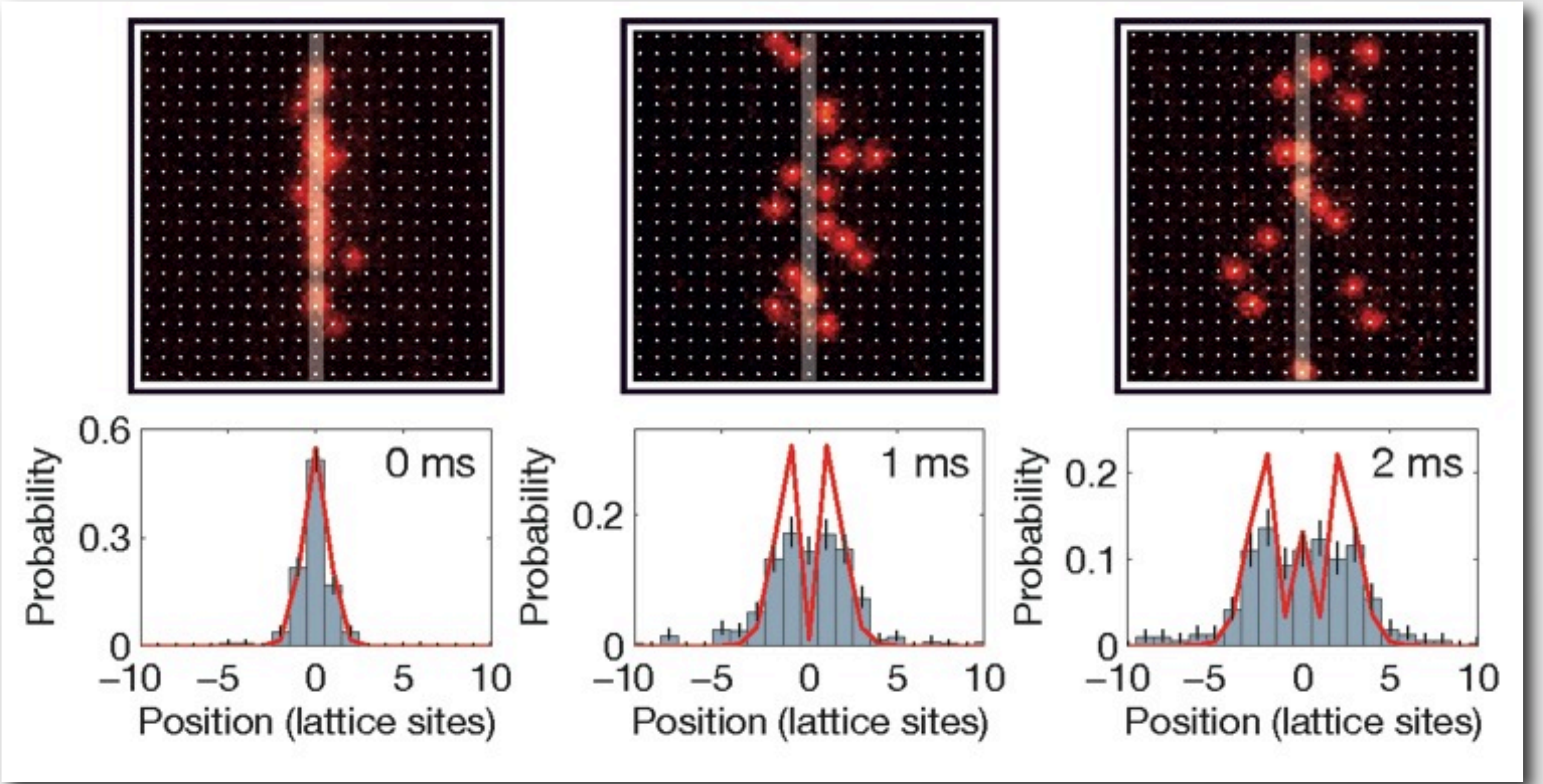


V_{lat}=5 E_r



Propagation speed almost constant, Coherence affected!

Positive Imaging

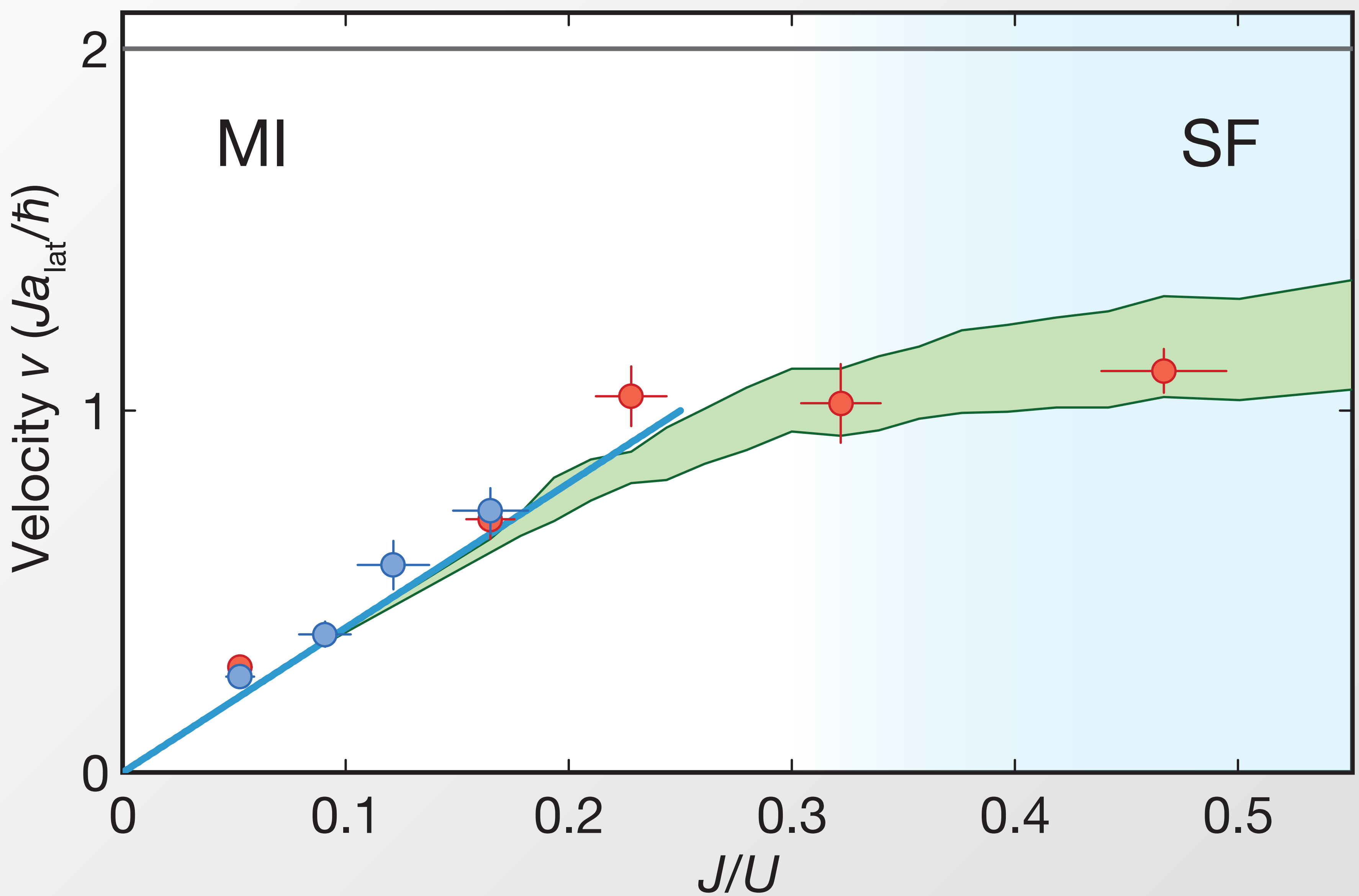


$V = 4\ Er, J/U = 0.32$

$(J/U)_c \approx 0.3$ for 1D

Ramp-down time for pinning beam is 1 ms

Propagation velocty



Reference value:

$$v = \frac{2Ja_{lat}}{\hbar}$$ Free particle tunneling

Outlook

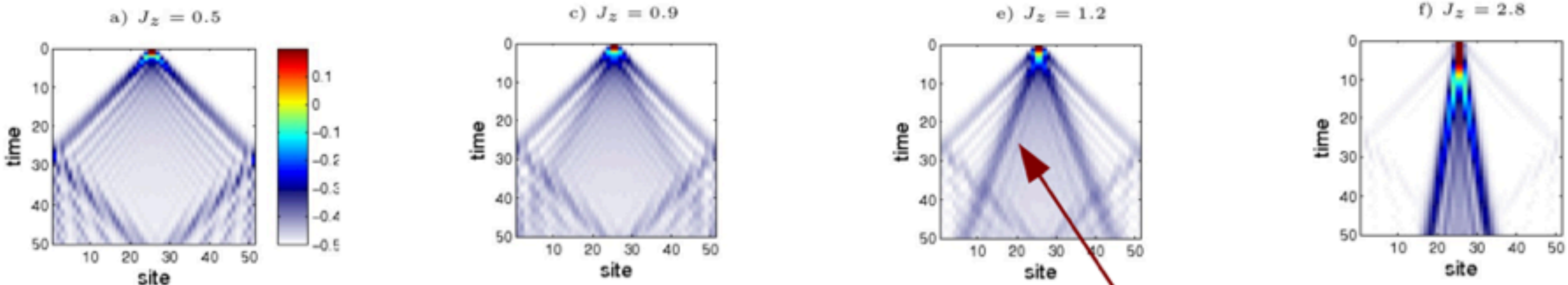
Quantum Dynamics of Interacting Atoms/Spins

- 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

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

Two-spin excitation in FM

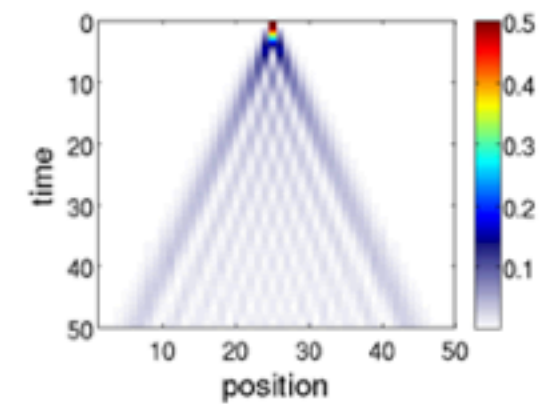
S_z



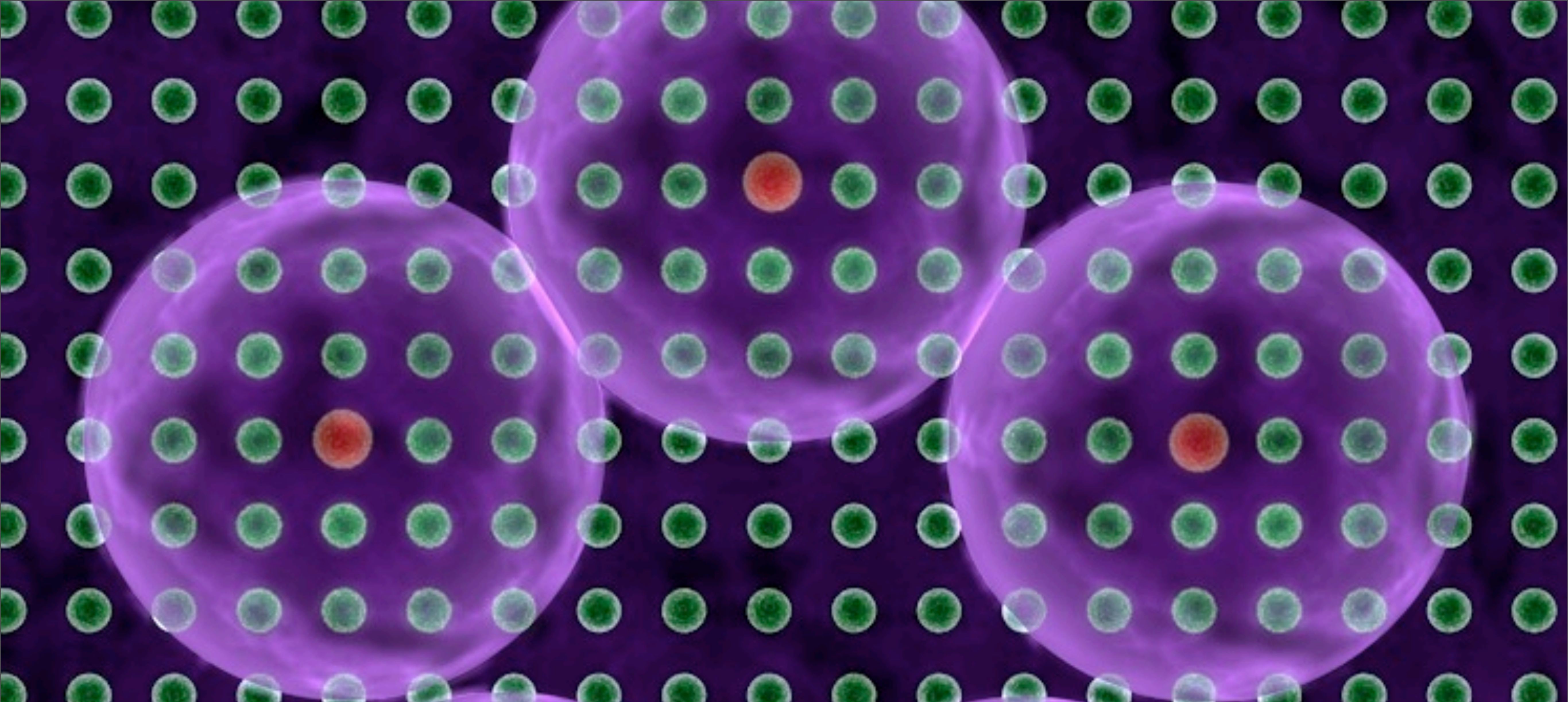
$J_z = 0.5$ $J_z = 0.9$ $J_z = 1.2$ $J_z = 2.8$

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

P(↑↑)



From: H.G. Evertz



Dynamical Formation of Rydberg Crystals

P. Schauss , M. Cheneau, M. Endres, T. Fukuhara, Th. Pohl, S. Kuhr & I.B.

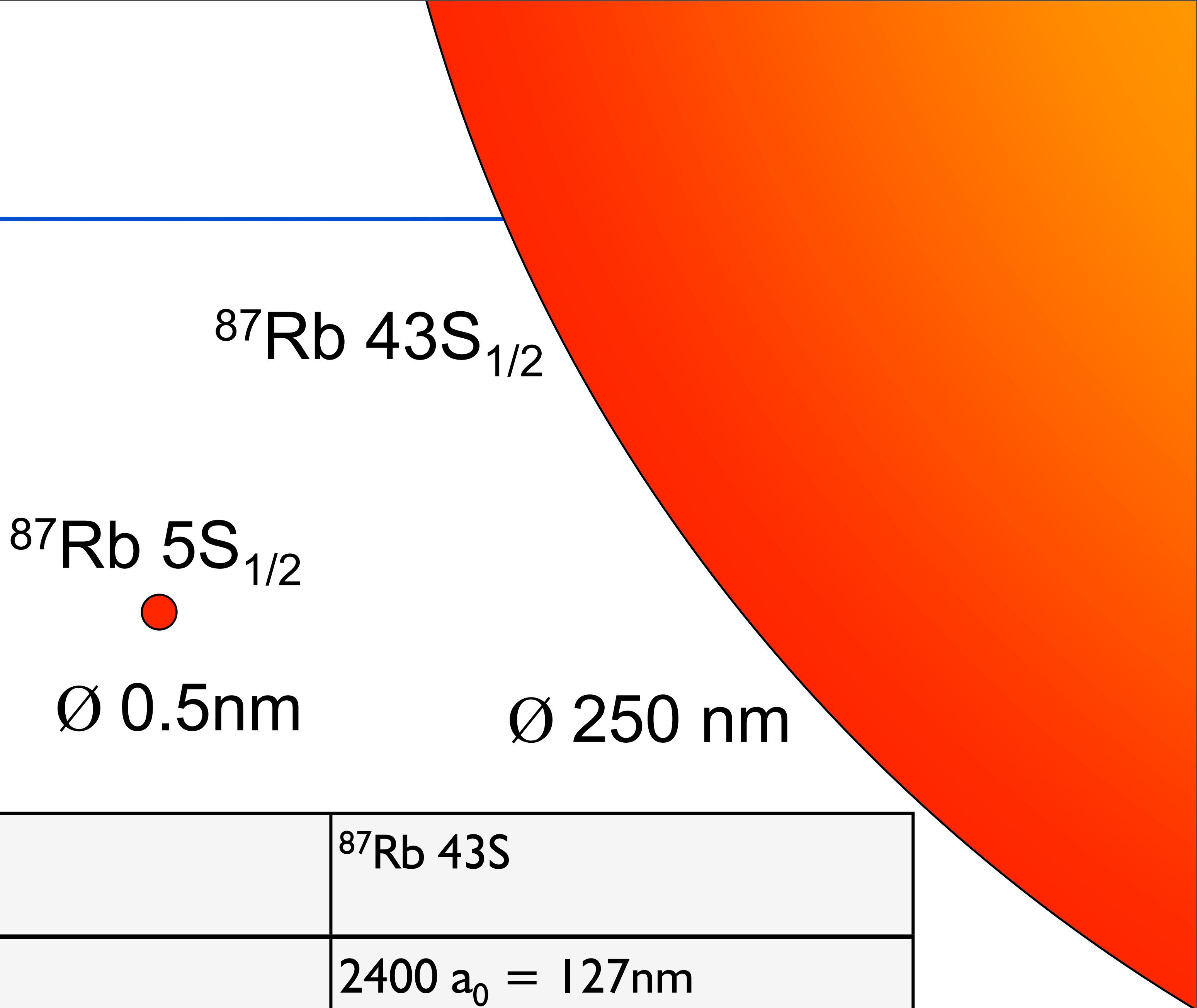
(submitted)

Rydberg atoms

- hydrogen-like wave function
    - quantum defect

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

- Strong switchable interactions

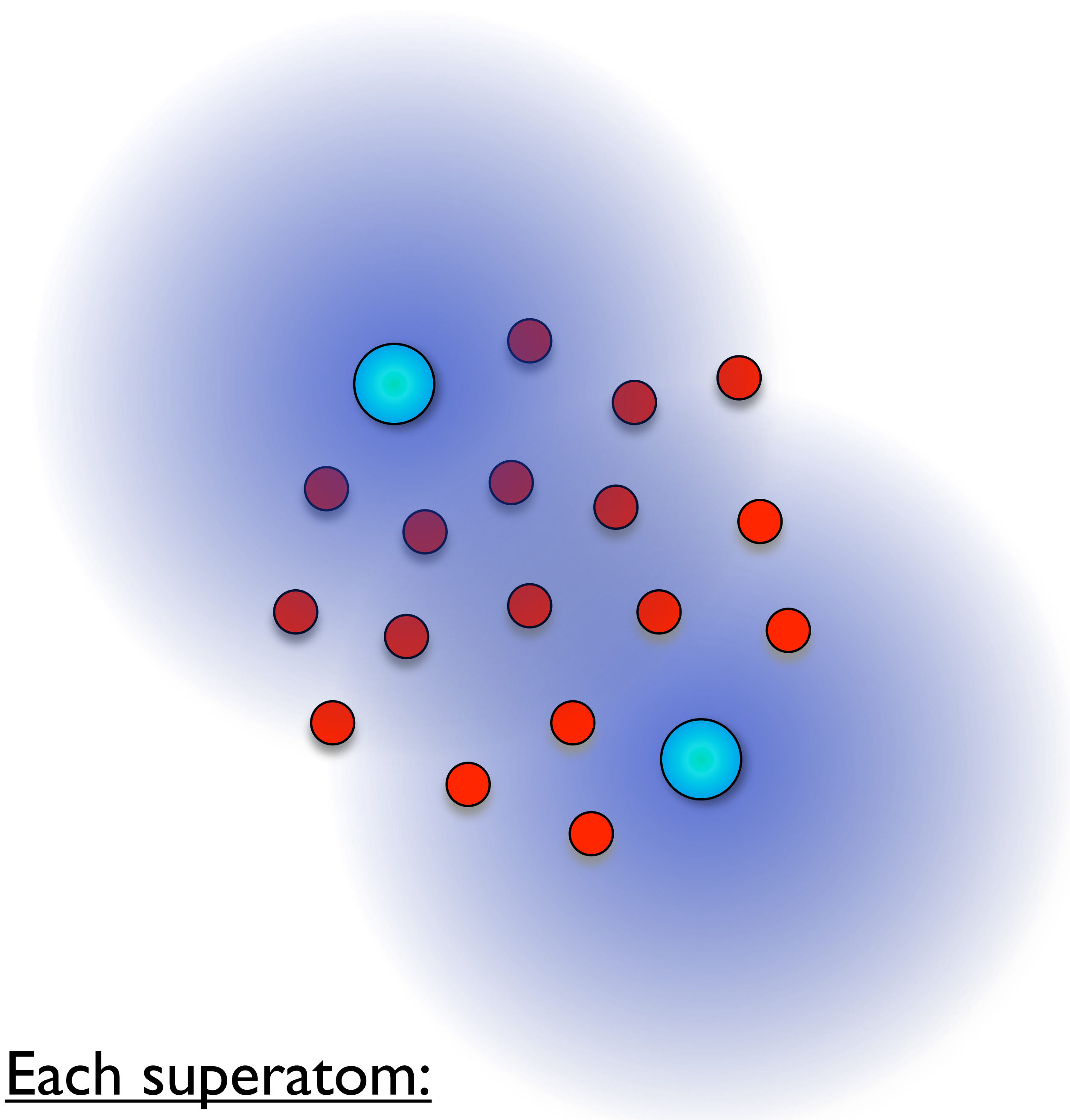


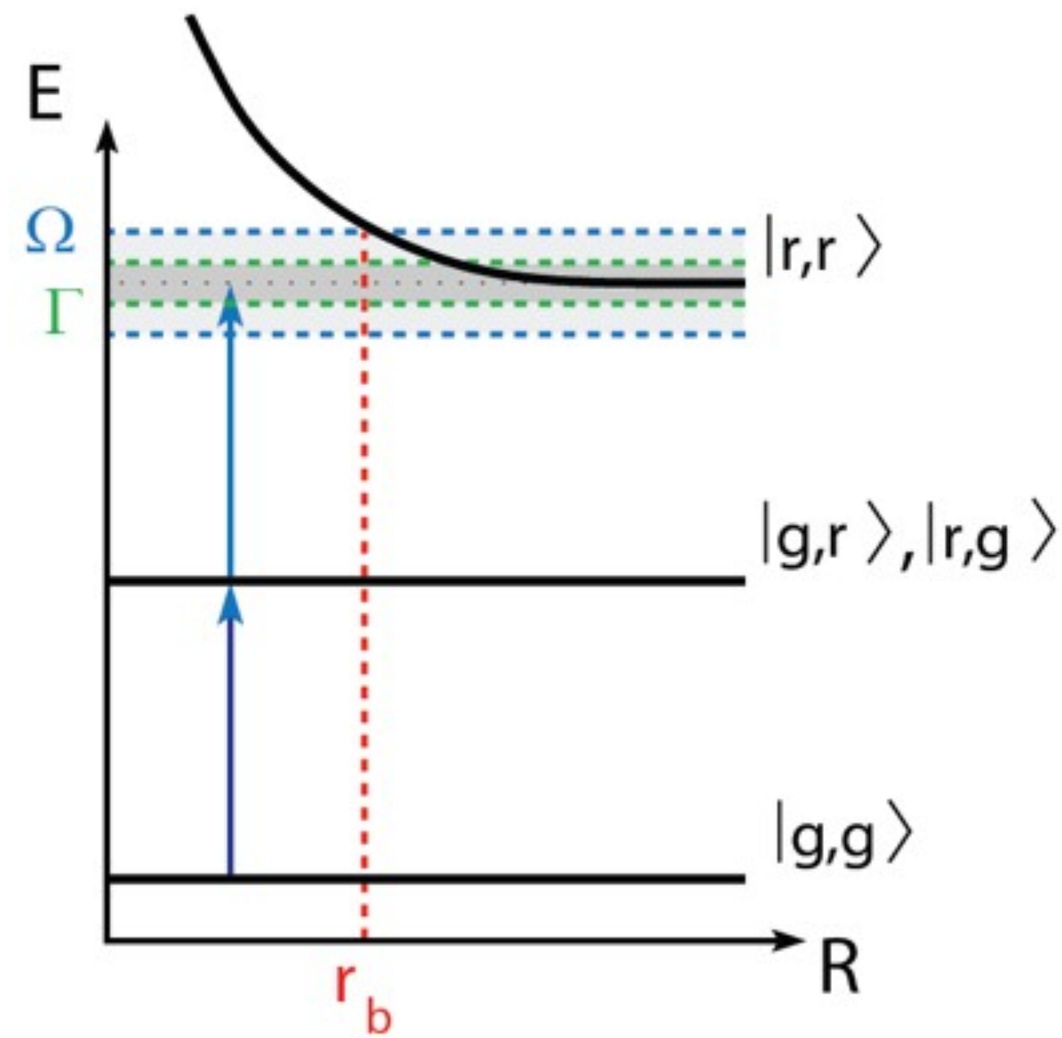
Property	Scaling	^{87}Rb 43S
Radius	$(n^*)^2$	$2400\ a_0 = 127$nm
Lifetime (dominated by black body radiation for large n)	$(n^*)^2$	45 μs @ 20°C
van der Waals coefficient	$(n^*)^{11}$	$C_6 = -1.7 \times 10^{19}$ a.u.
Blockade radius (Ω=2π 200 kHz)	$(n^*)^2$	$\sim 5\ \mu$m

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

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

Rydberg blockade





Blockade condition

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

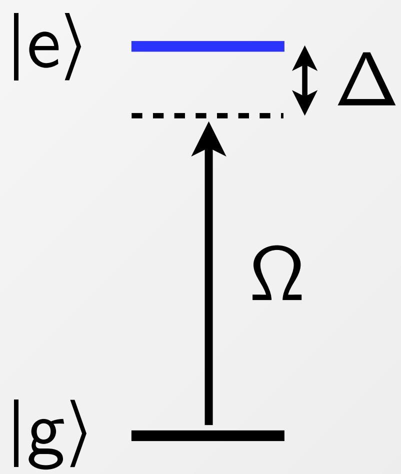
$$r_{\mathrm{b}} \equiv \sqrt[6]{\frac{C_6}{\hbar\Omega}}$$

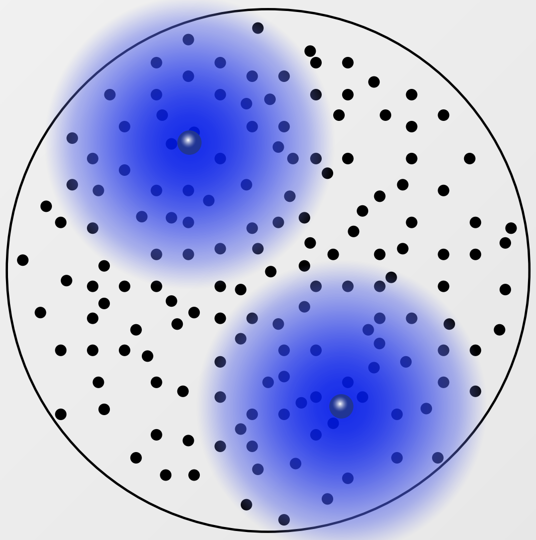
Each superatom:

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

M. Lukin et al. PRL (2001)

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

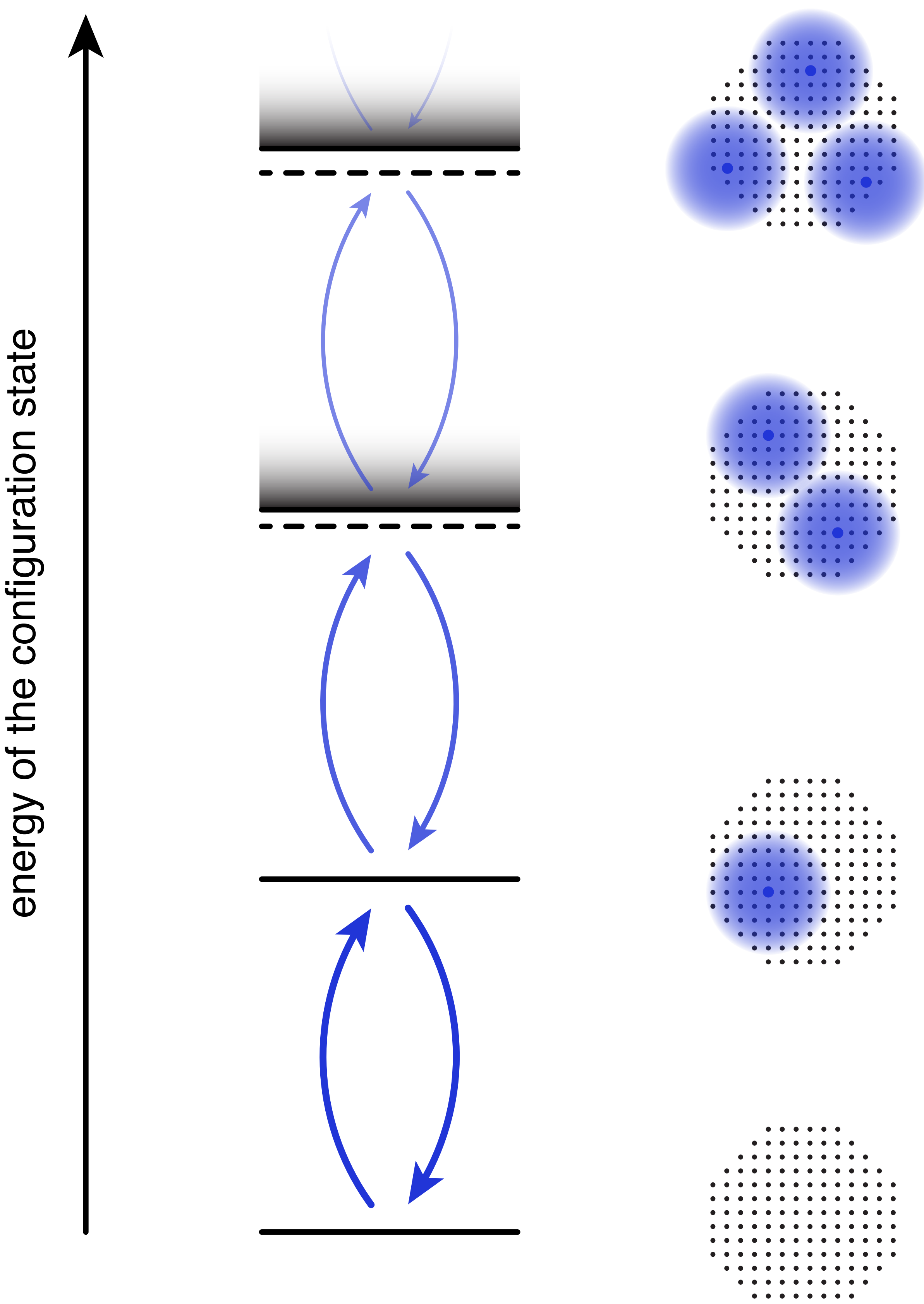
interaction between Rydberg atoms

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

This work: α*=6, repulsive*

"chemical potential"

Excitation Path



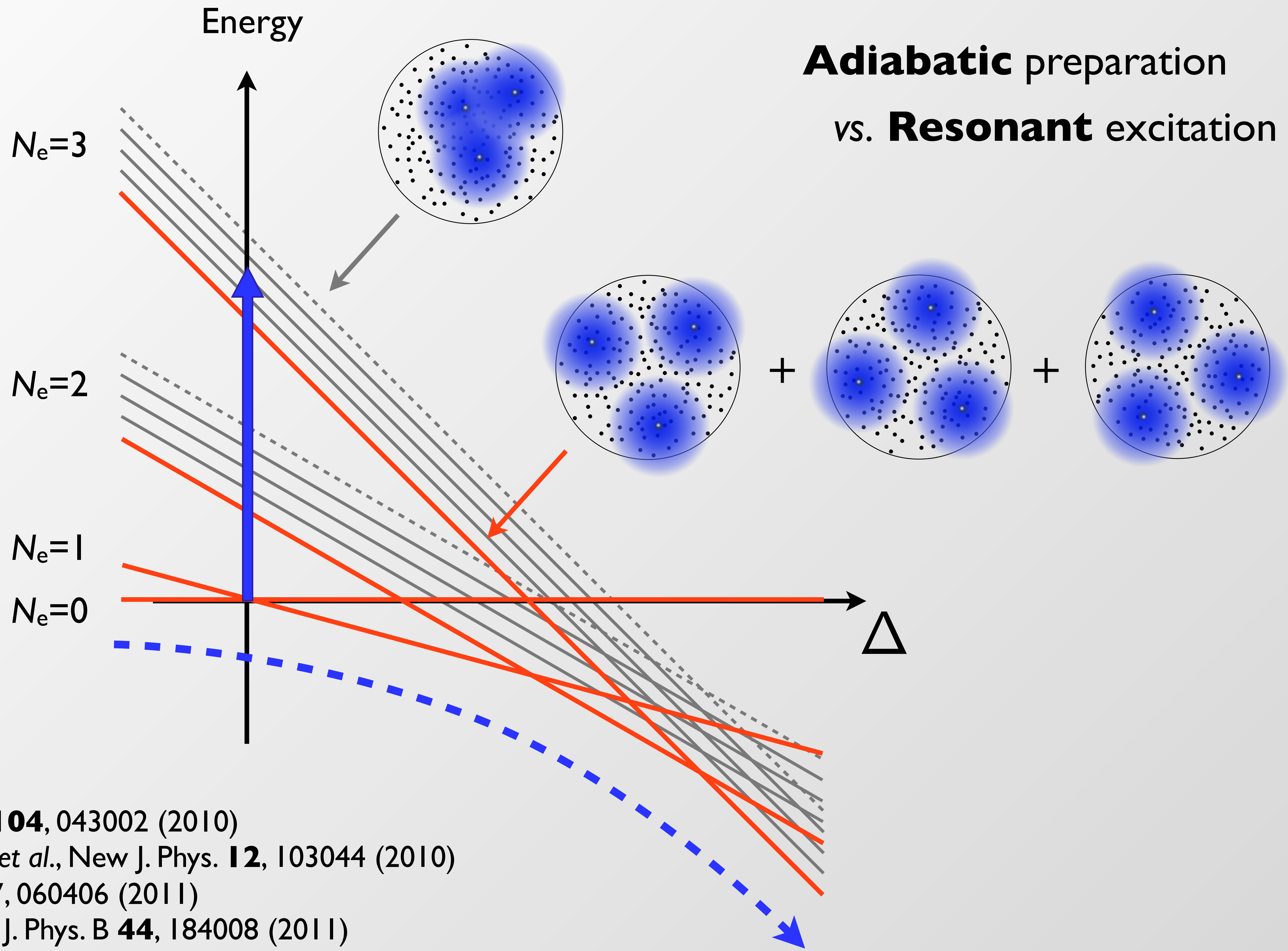
Theory see:

H. Weimer et al., PRL 2008

T. Pohl et al. PRL 2010

G. Pupillo et al. PRL 2010

Dynamical crystallization of the Rydberg gas



Adiabatic preparation

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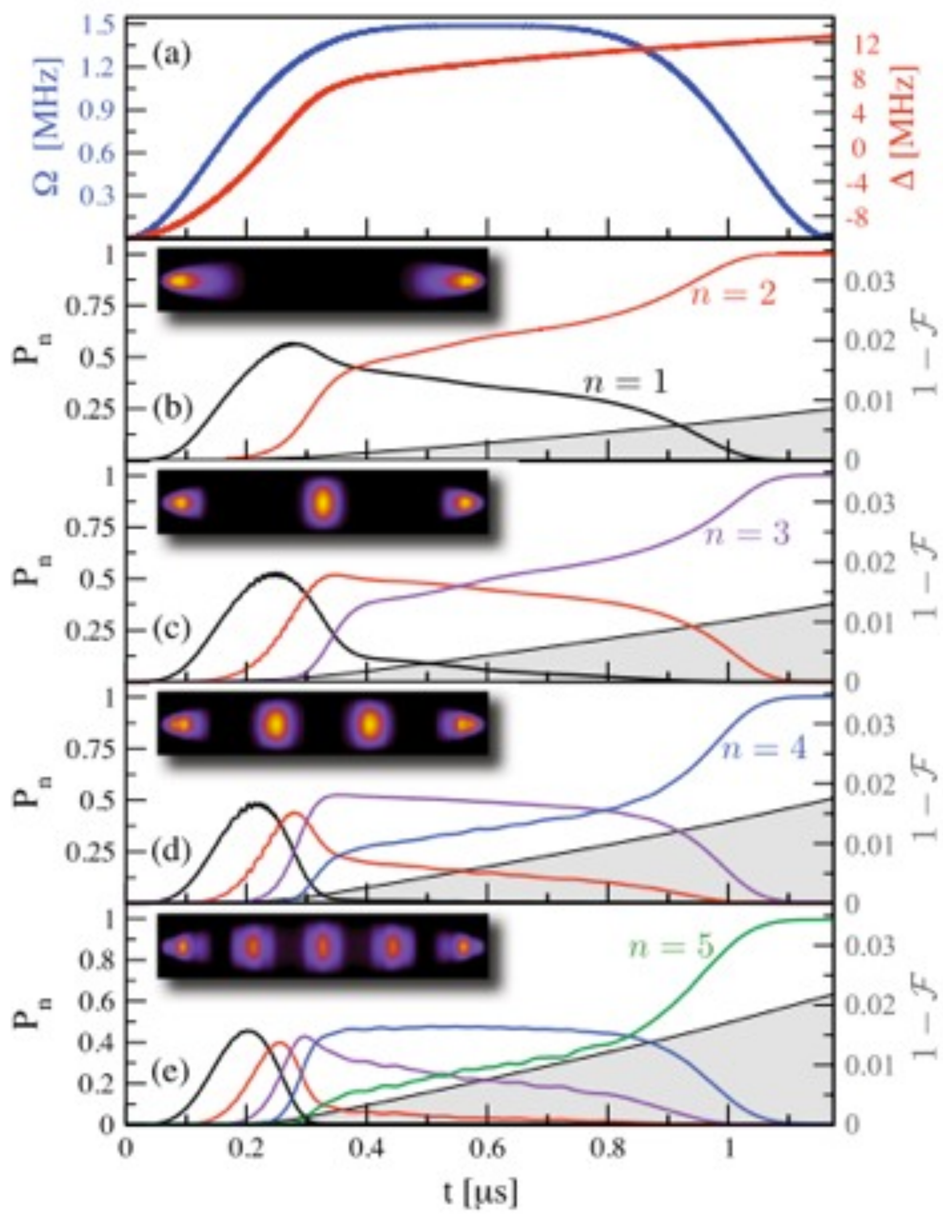
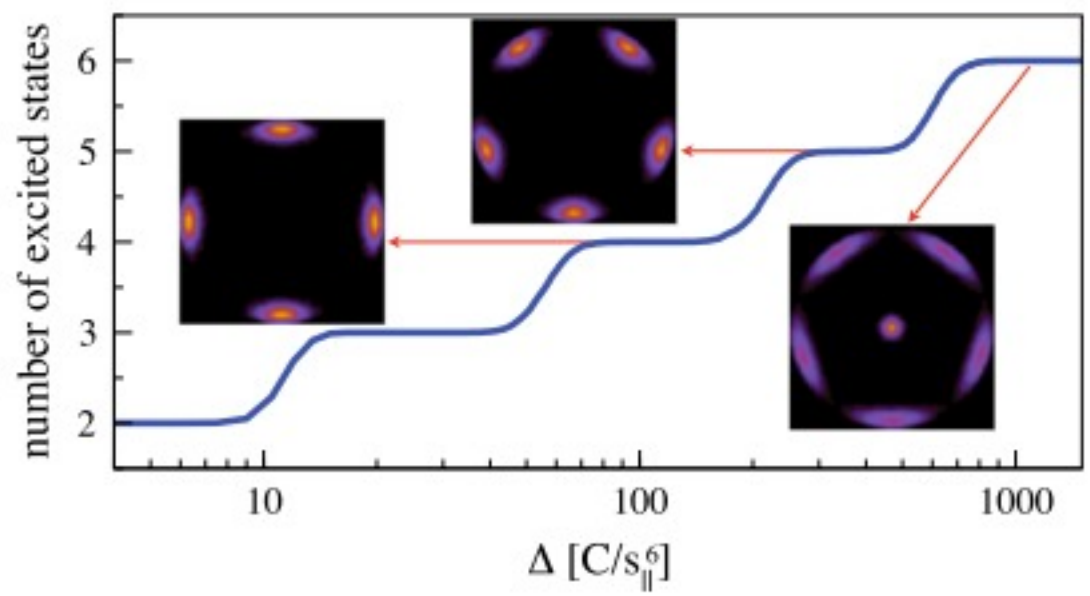
[3]*Physics Department, Harvard University, Cambridge Massachusetts 02138, USA*
(Received 26 July 2009; revised manuscript received 23 October 2009; published 27 January 2010)

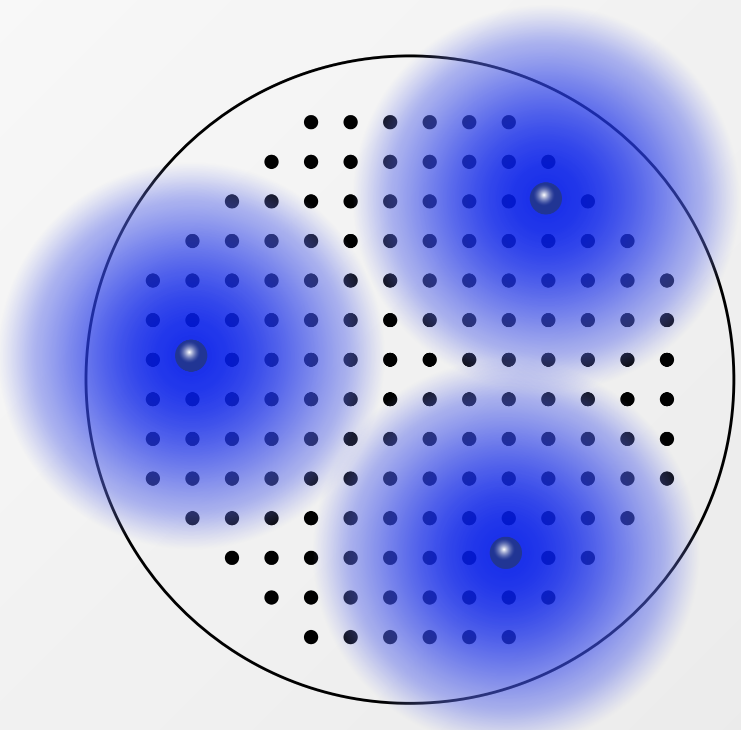


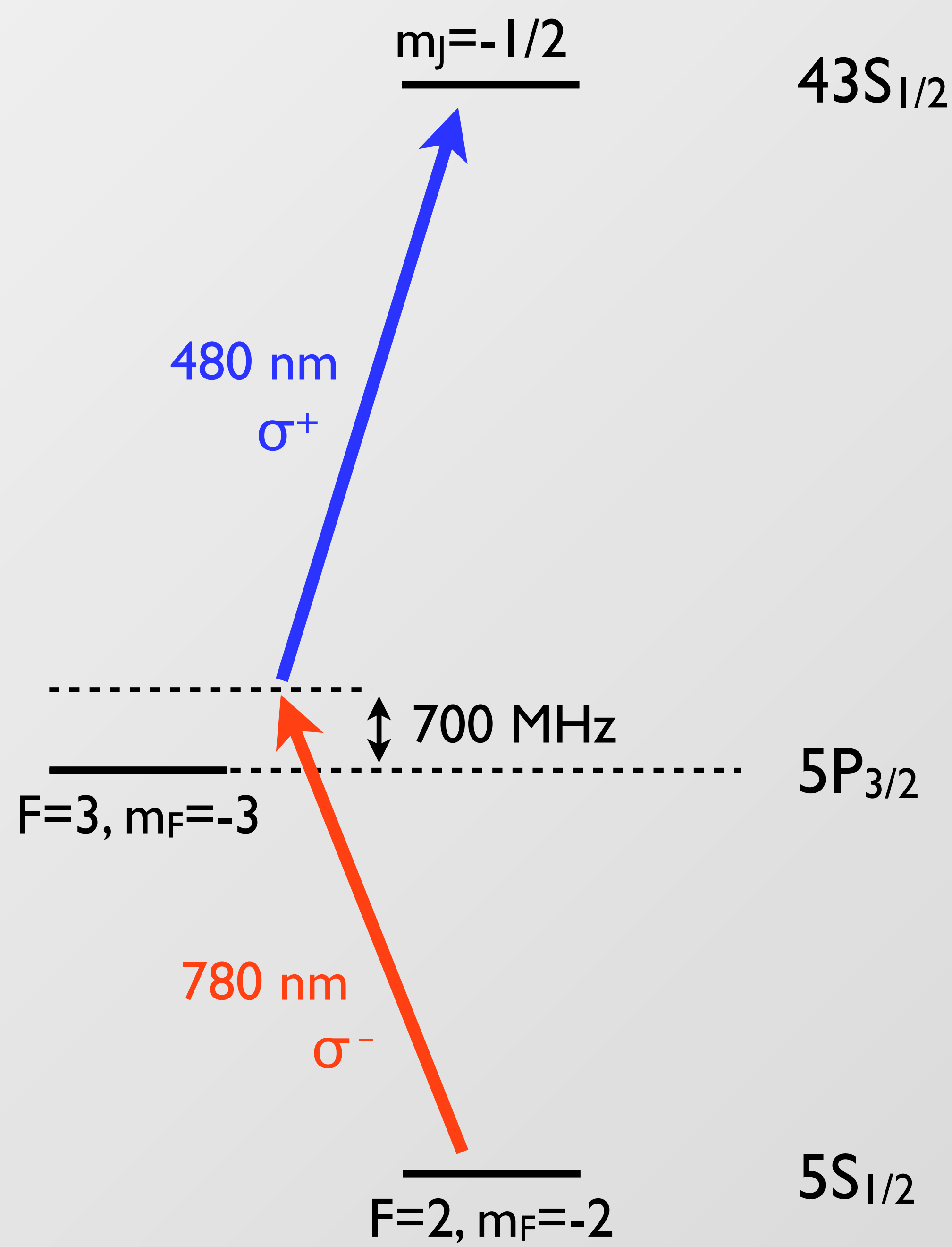


Rydberg atoms organize in crystalline excitations patterns!

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

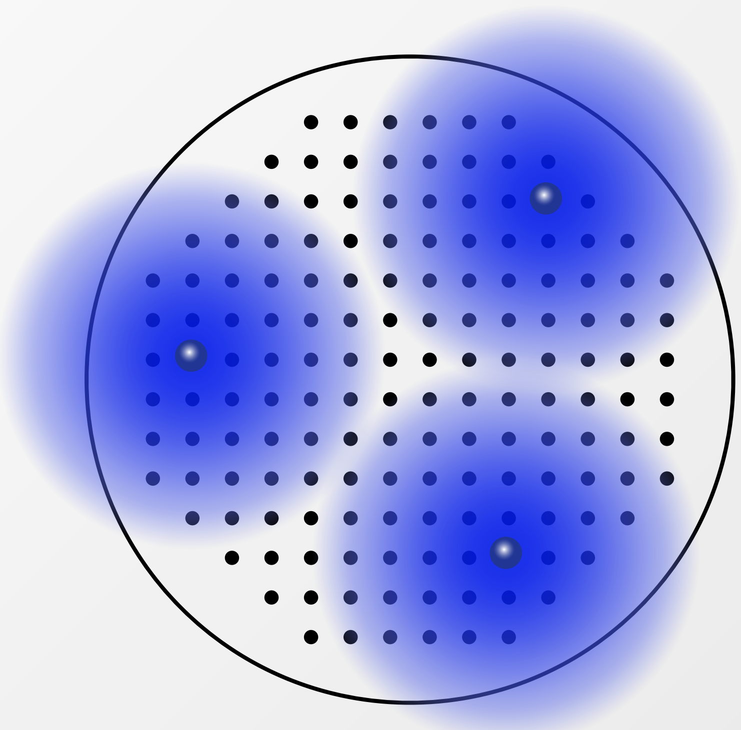
Excitation and detection of the Rydberg atoms

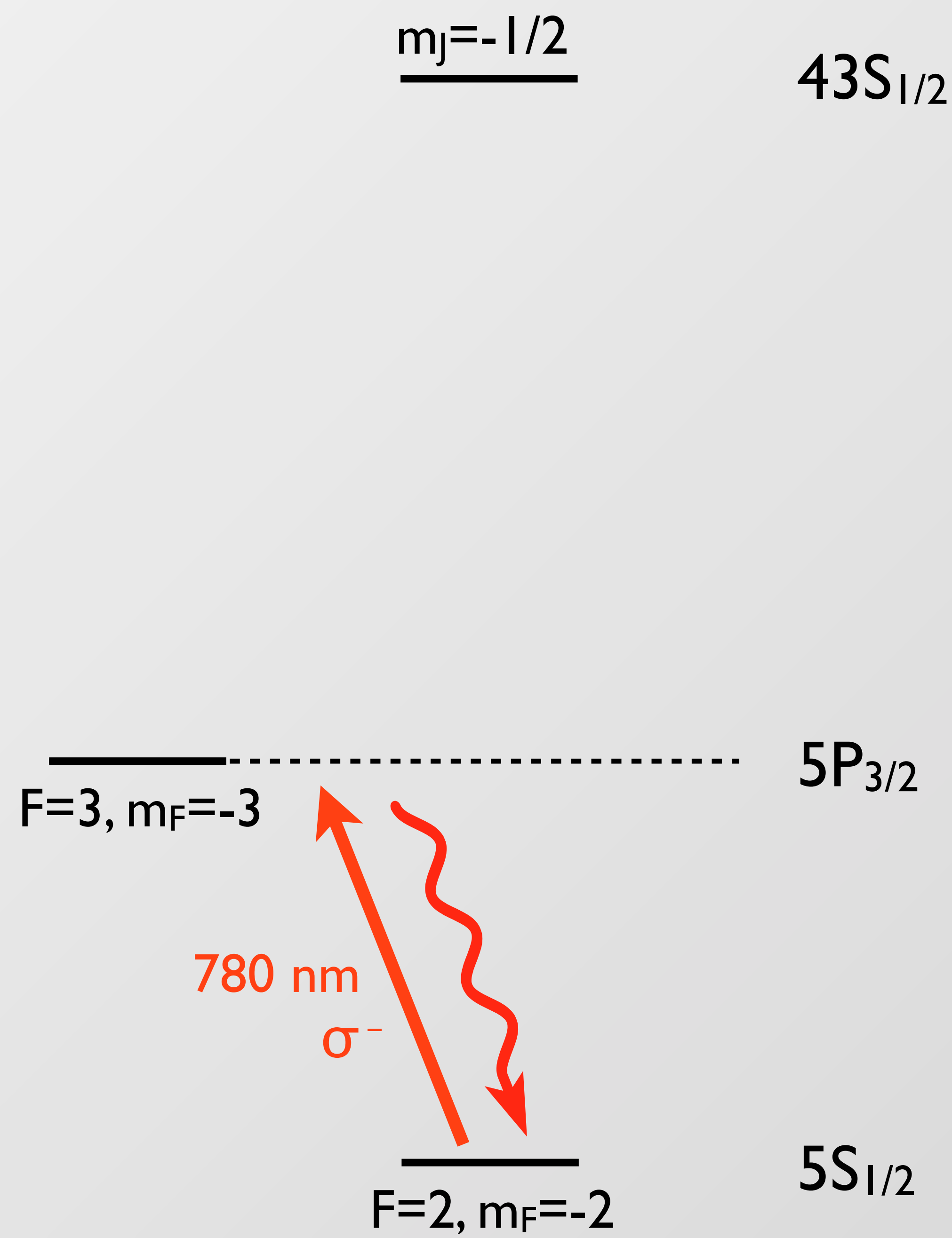




- two-photon Rabi frequency: $\Omega/2\pi$ = 170(20) kHz
- resonant excitation: $\Delta = 0$
- blockade radius: R_b = 4.9(1) μm

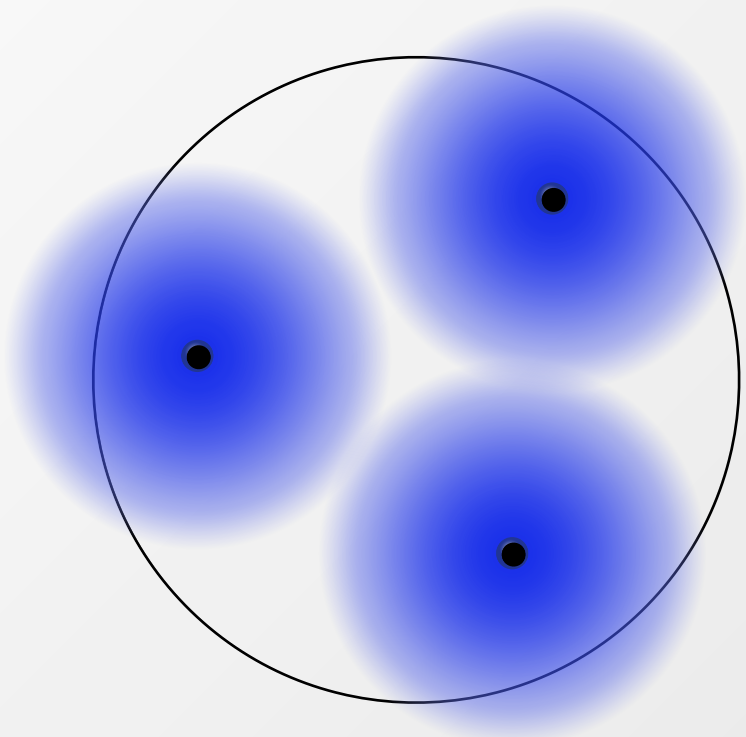
Excitation and detection of the Rydberg atoms

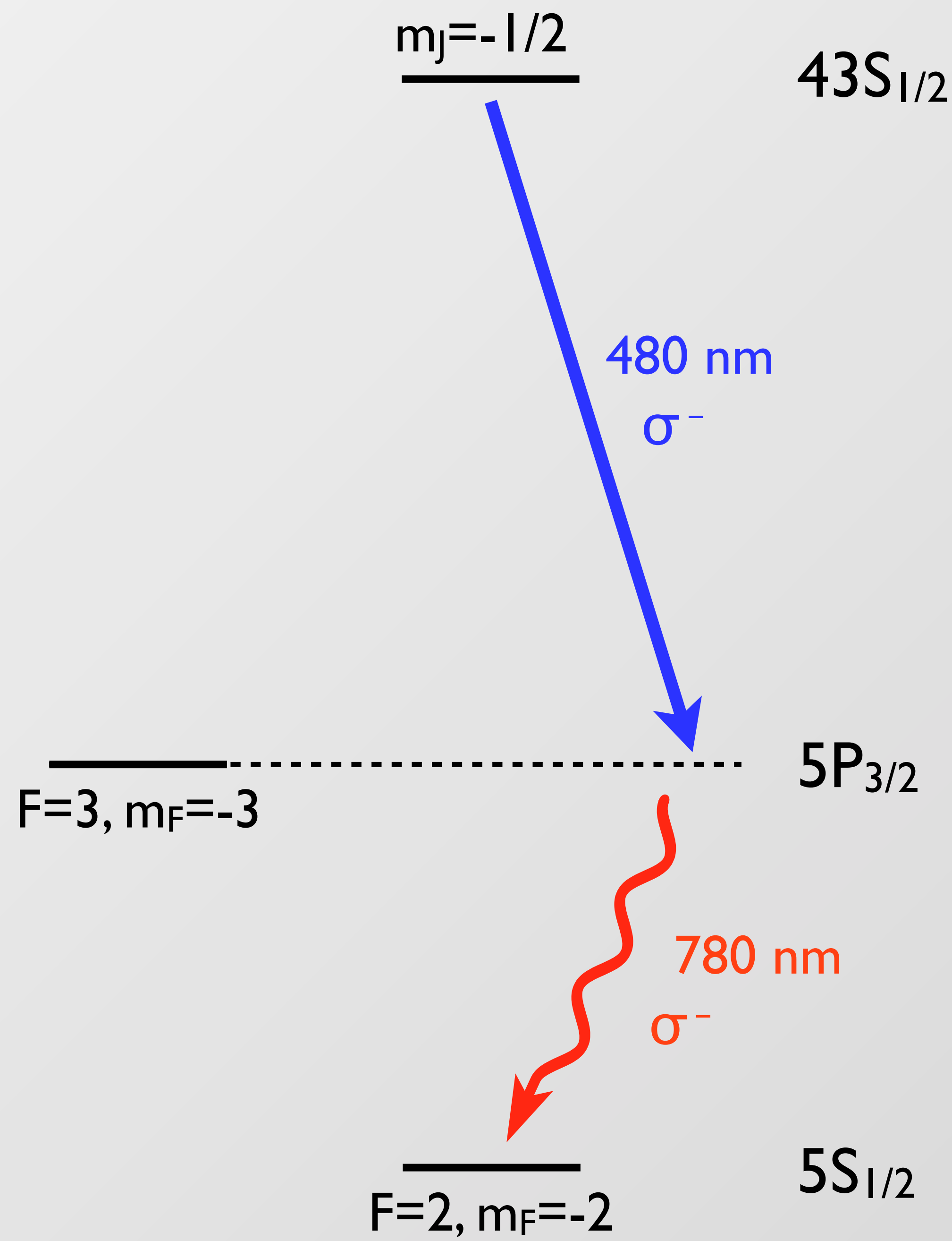




- removal pulse duration: 10 µs
- survival probability: 0.1 %

Excitation and detection of the Rydberg atoms





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

Snapshots of the excitation pattern

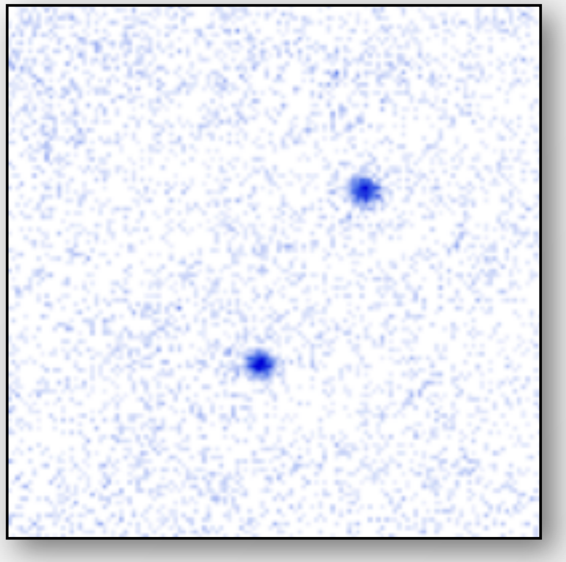
"Small" clouds:

150(30) atoms
diameter 7.2(8) μm
676 pictures

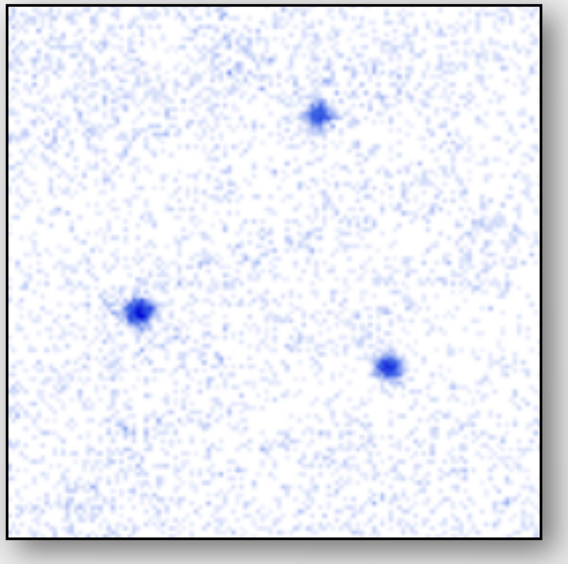
"Large" clouds:

390(30) atoms
diameter 10.8(8) μm
1654 pictures

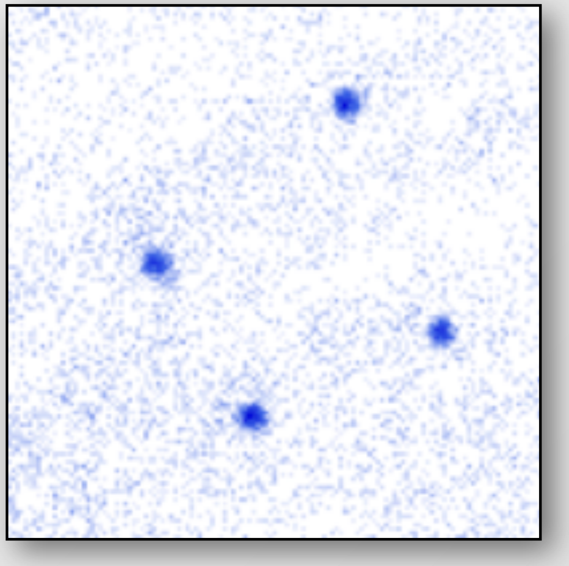
18 μm



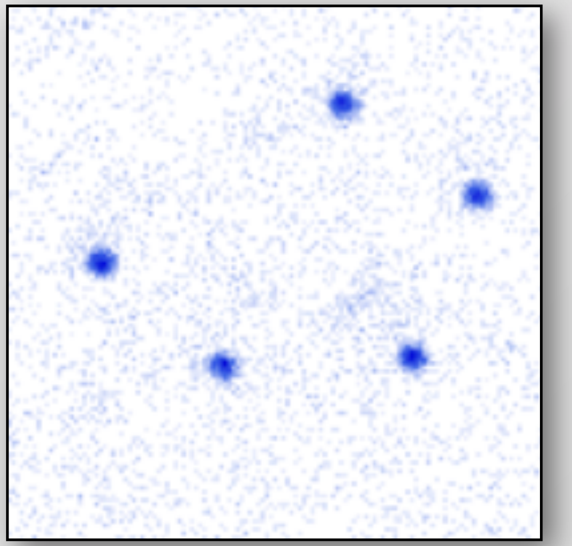
191 pictures



65 pictures

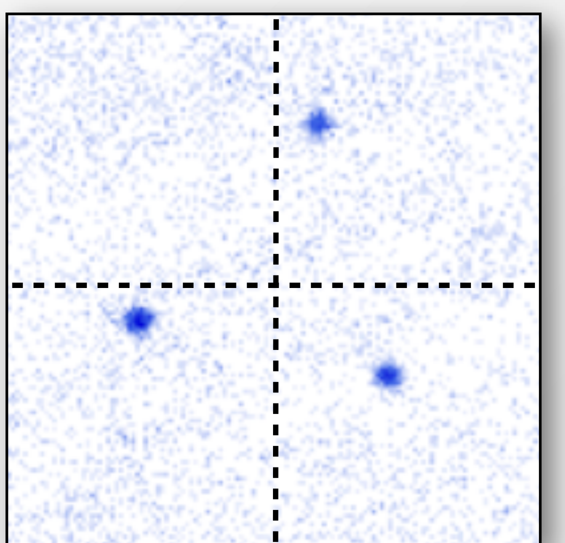


177 pictures

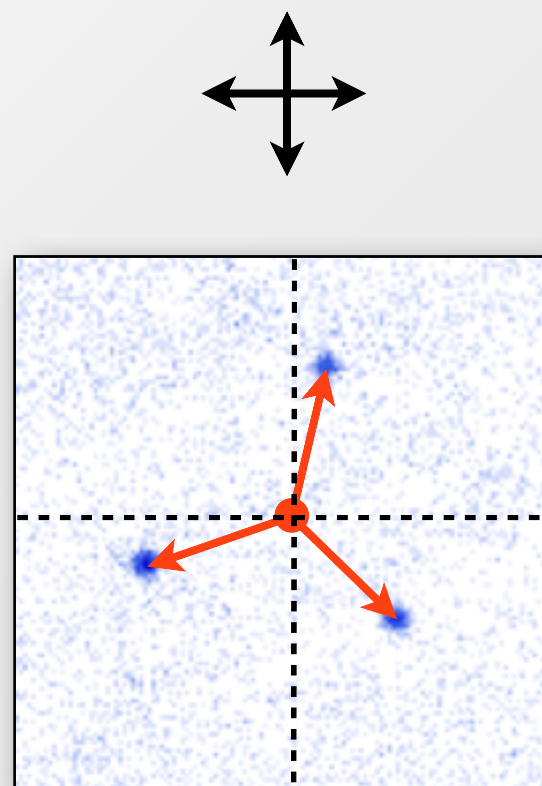


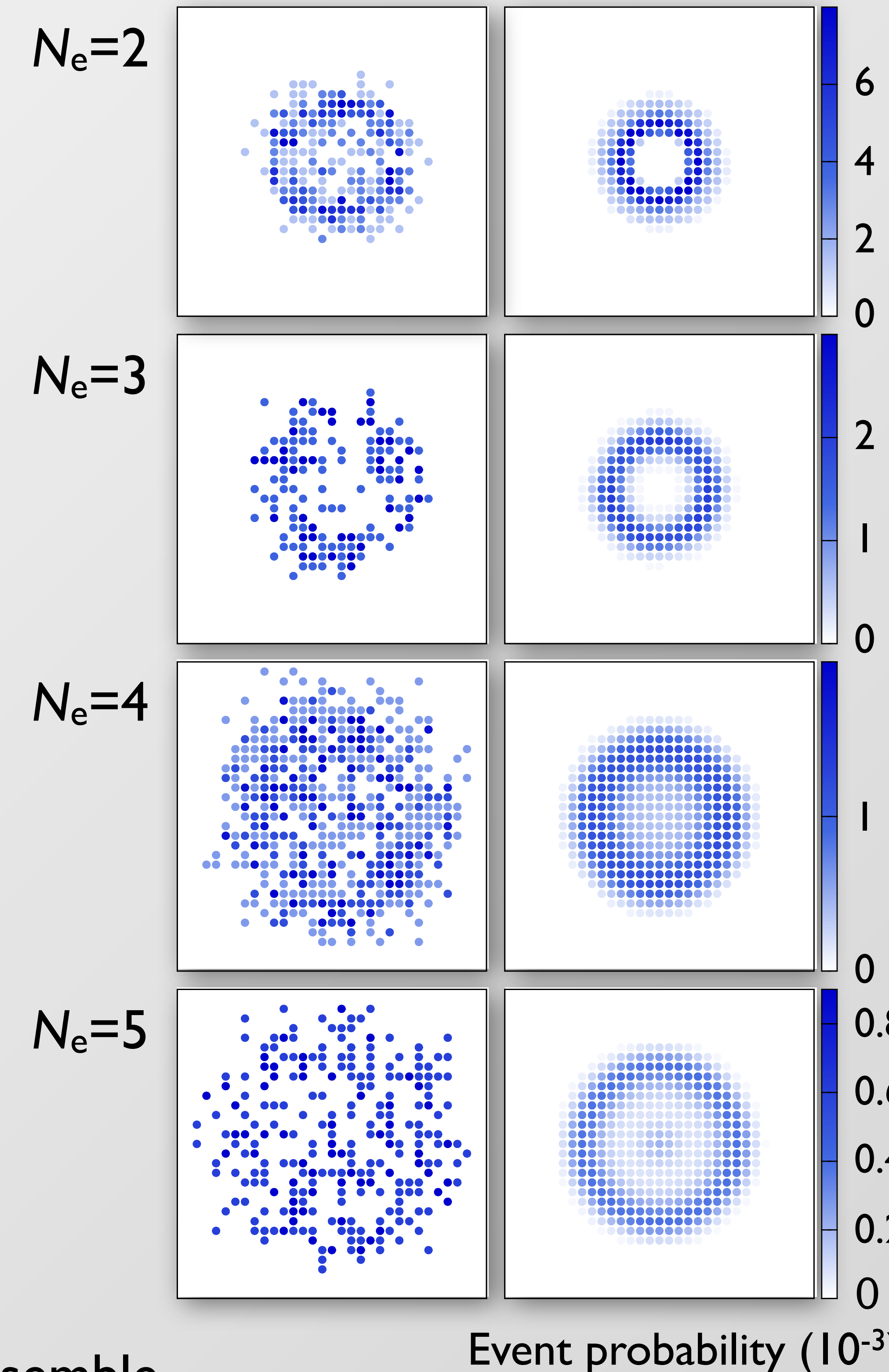
64 pictures

Revealing mesoscopic structures



centre onto
the barycenter





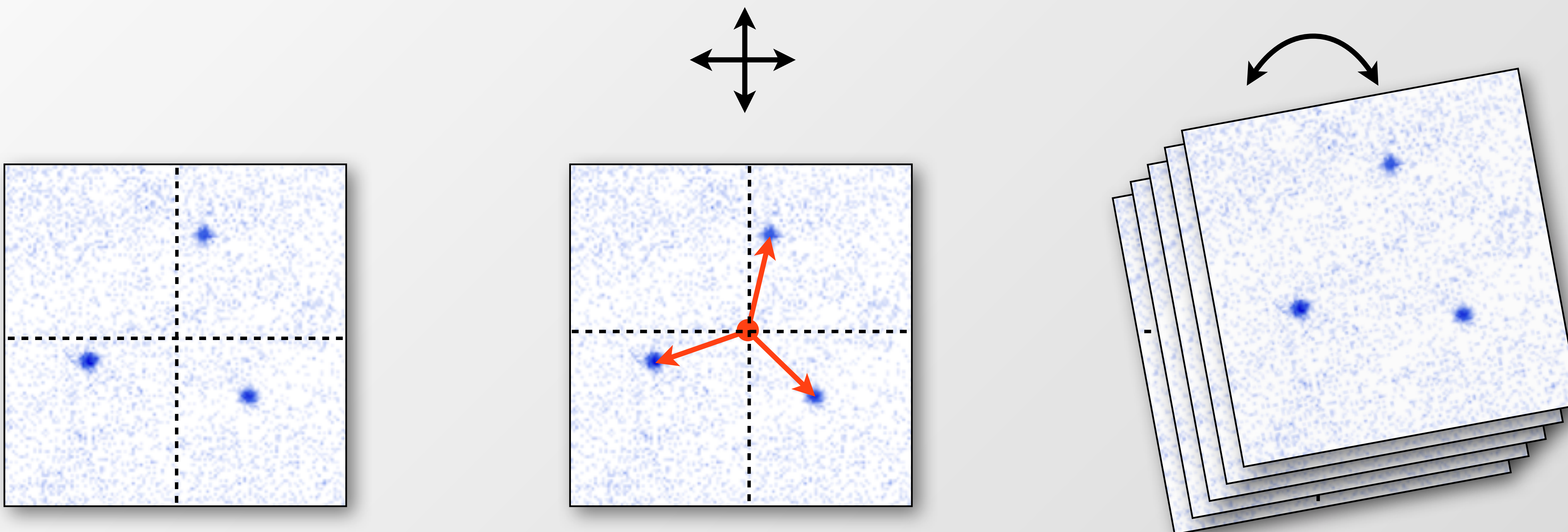
Numerical simulations:

- exact dynamics (truncated Hilbert space)
- average over initial states from the grand canonical ensemble

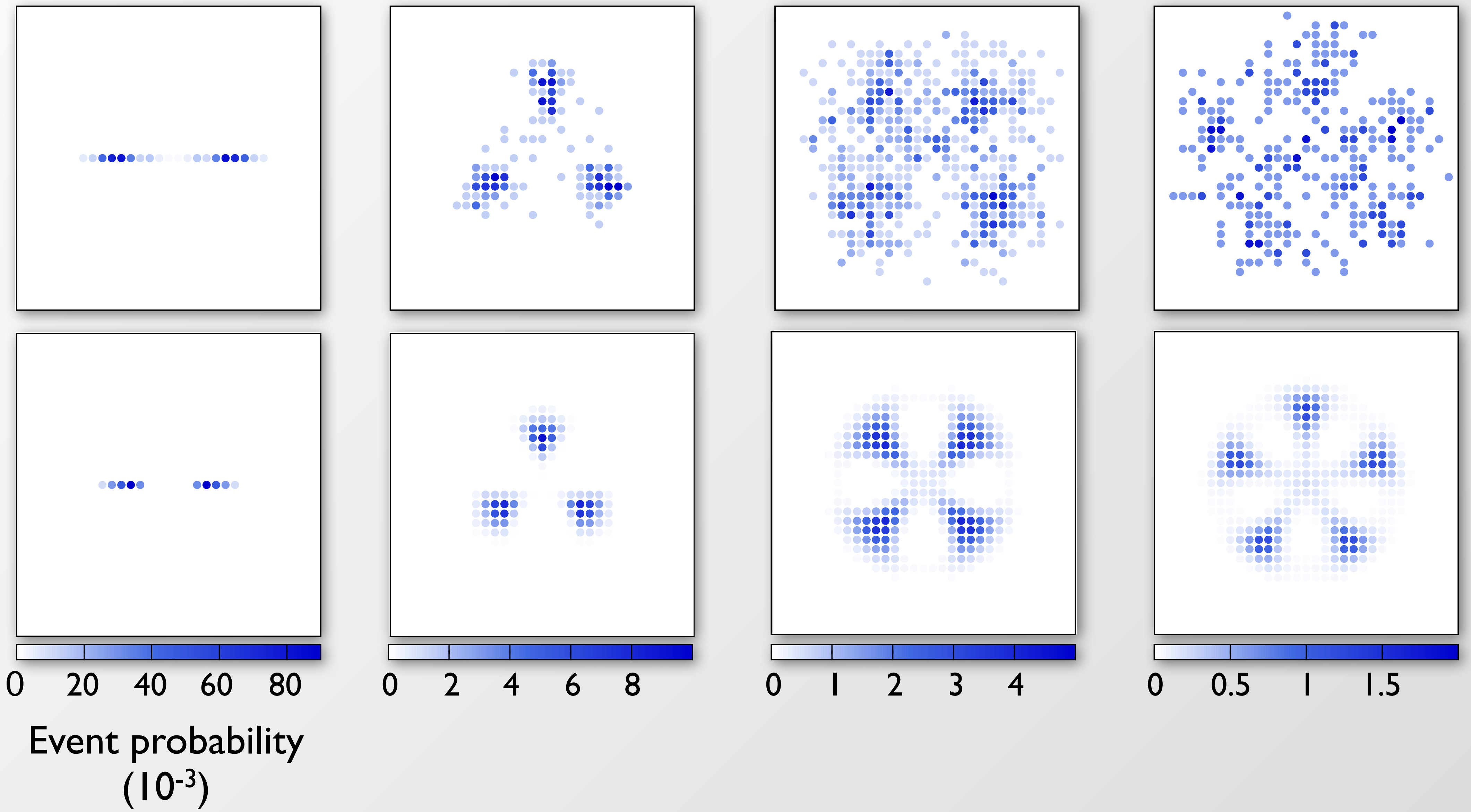
Revealing mesoscopic structures

centre onto
the barycenter

align with a
reference axis



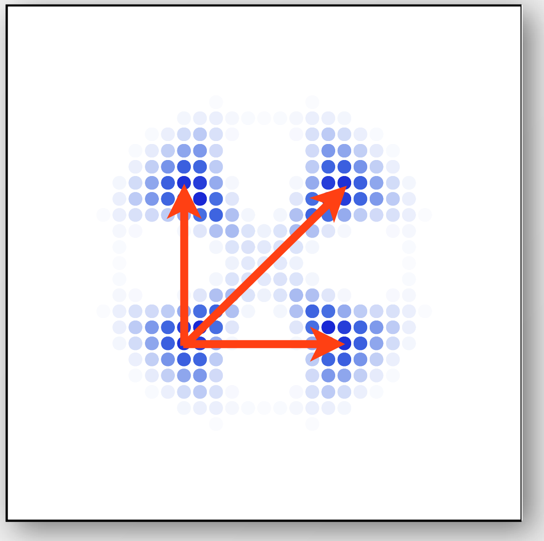
Revealing mesoscopic structures

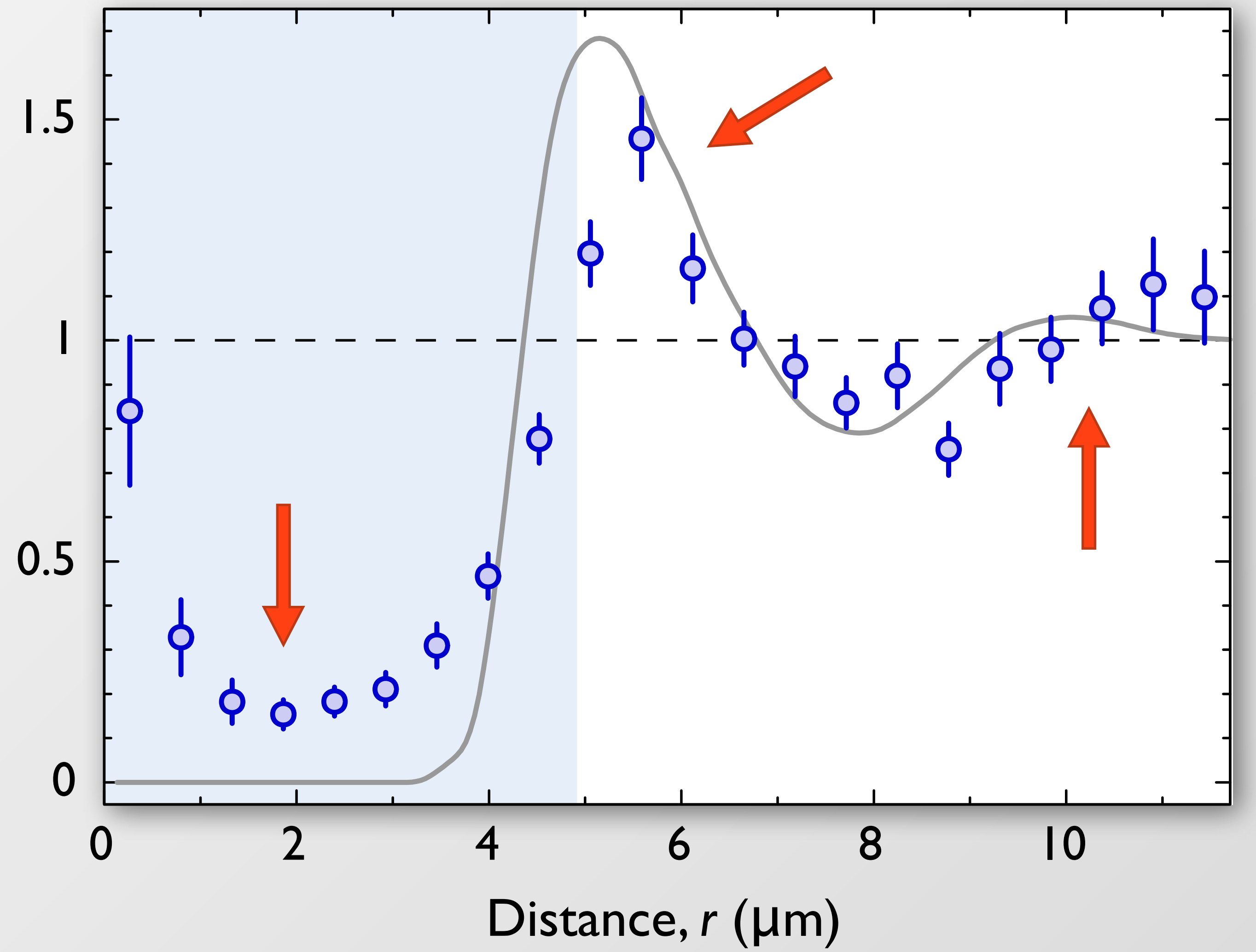


Correlation functions

Pair correlation function:

$$g^{(2)}(r) = \frac{\sum_{i \neq j} \delta_{r,r_{ij}} \langle \sigma_{ee}^{(i)} \sigma_{ee}^{(j)} \rangle}{\sum_{i \neq j} \delta_{r,r_{ij}} \langle \sigma_{ee}^{(i)} \rangle \langle \sigma_{ee}^{(j)} \rangle}$$





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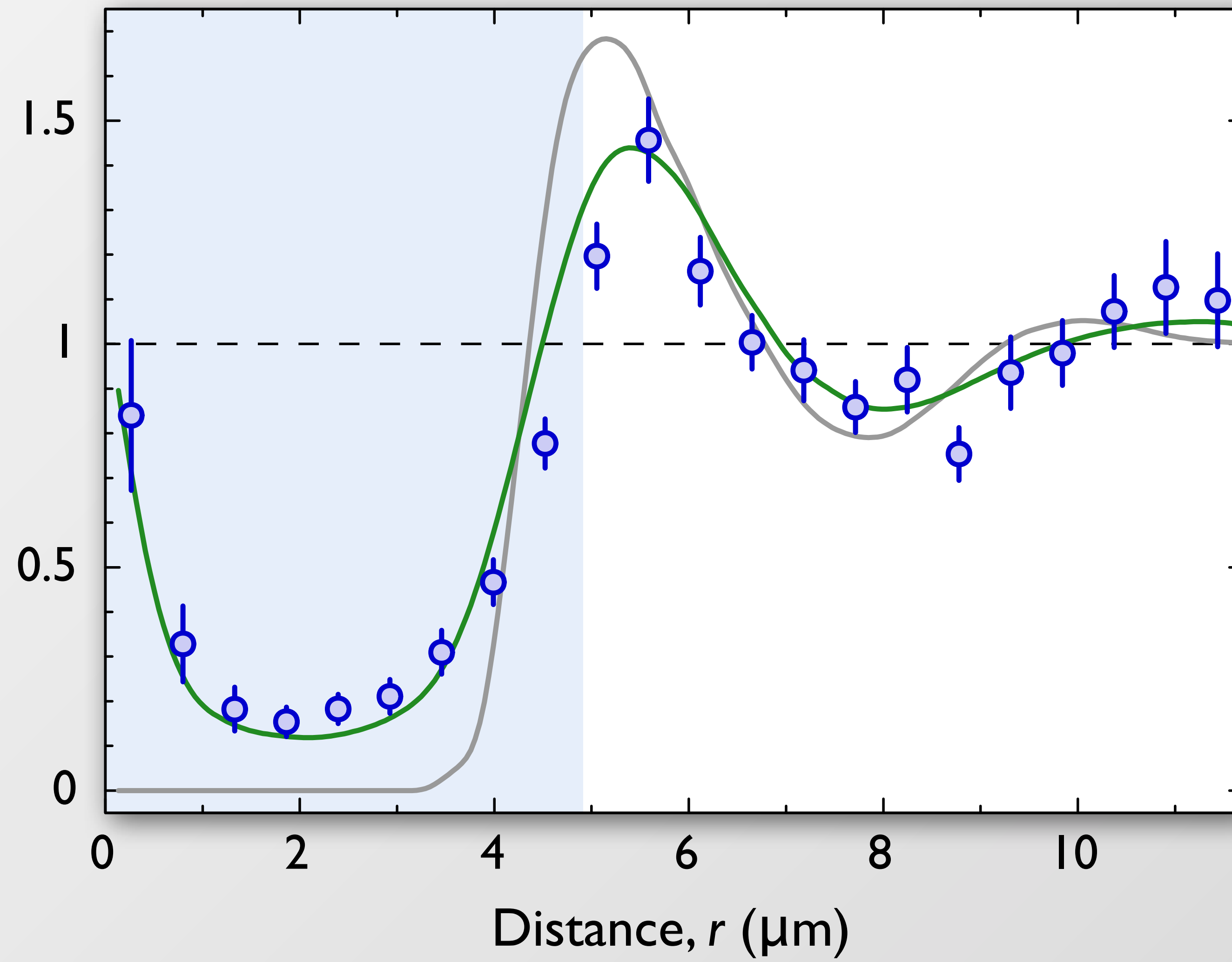


Deviations due to:

- hopping during the fluorescence imaging – *probability ~ 1 %*
- imperfect removal of the ground state atoms – *0.2 atoms per image*
- residual motion of the Rydberg atoms before imaging – *± 0.5 μm*

Blockade radius measurement, see also: Schwarzkopf et al. PRL (2011)

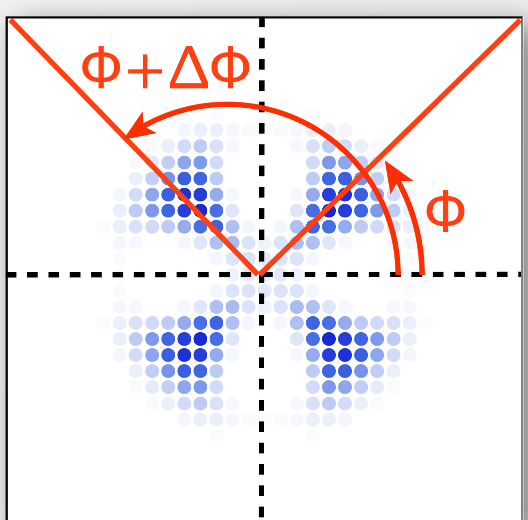
Correlation functions

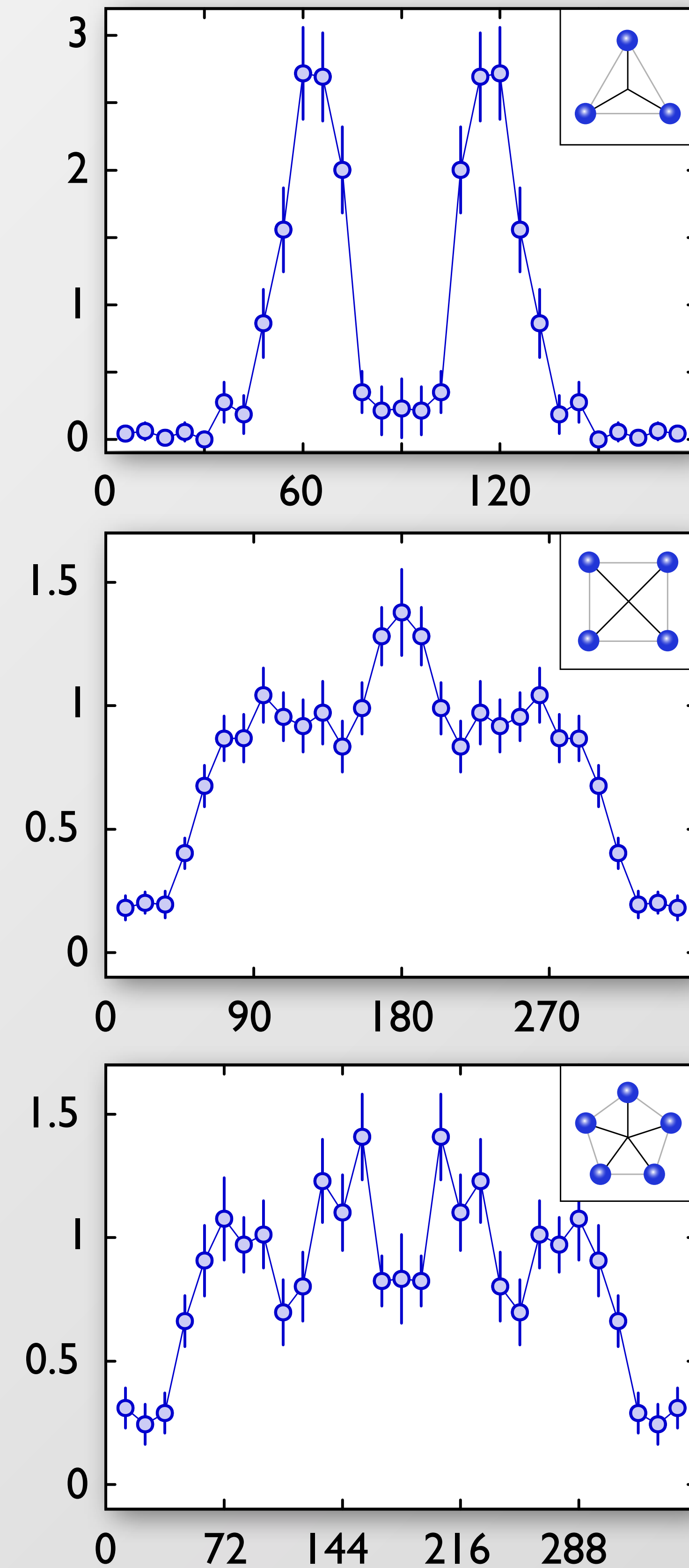
effective 1D crystals along the circumference of the system

Azimuthal correlation function:

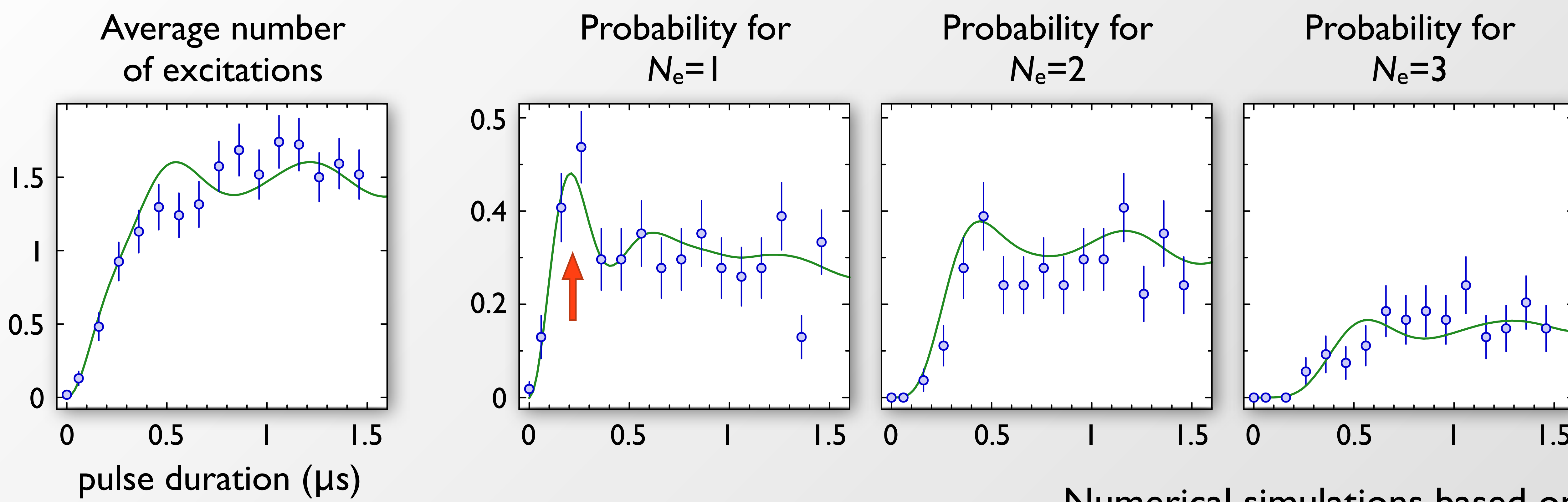
$$\tilde{g}^{(2)}(\Delta\phi) = \int \frac{d\phi}{2\pi} \frac{\langle n(\phi) n(\phi+\Delta\phi)\rangle}{\langle n(\phi)\rangle\langle n(\phi+\Delta\phi)\rangle}$$

with $n(\phi) = \sum_i \delta_{\phi,\phi_i}\, \sigma_{ee}^{(i)}$





Time evolution



Numerical simulations based on typical initial states observed in the experiment

- fast dynamics compared to $\pi/\Omega \simeq 3$ μs

  ⇒ *collective enhancement of the coupling strength*

⇨ for N_e = 1:

$\pi/(\sqrt{N_{at}}\,\Omega)$ = 220(40) ns

- different timescales for the different number of excitations

  ⇒ *reduced overlap between the states coupled by the optical radiation*

(some) evidence for the coherence of the many-body state

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 Rybderg 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)...

Measuring Zak-Berry Phase of Topological Bands

M. Aidelsburger, M. Atala, J. Barreiro & I.B.
D. Abanin, T. Kitagawa, E. Demler

www.quantum-munich.de

Berry Phase in Quantum Mechanics

$$\Psi(R) \rightarrow e^{i(\varphi_{\rm Berry}+\varphi_{\rm dyn})}\ \Psi(R)$$

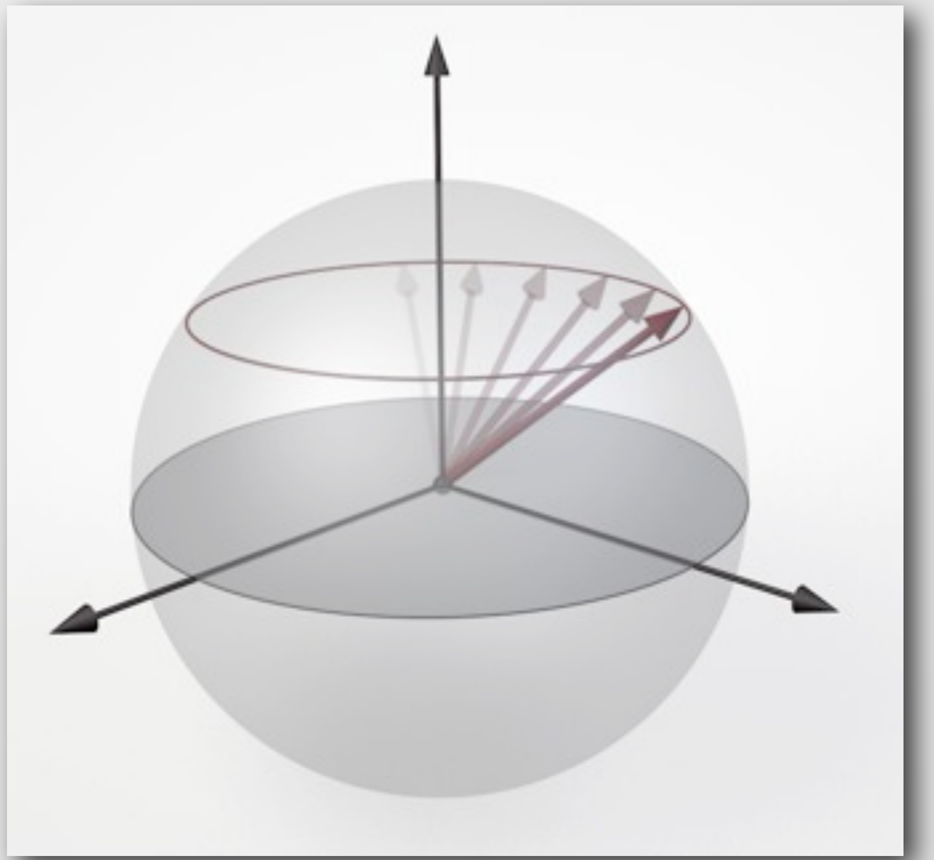
Adiabatic evolution through closed loop

$$\varphi_{\rm Berry} = -\oint_{\mathcal{C}} A_n(R)dR = -i\oint_{\mathcal{C}} \langle n(R)|\nabla_R|n(R)\rangle\, dR$$

$$\varphi_{\rm Berry} = \oint_{\mathcal{A}} \Omega_n(R)\, dA$$

Berry Phase

M.V. Berry, Proc. R. Soc. A (1984)



Example: Spin-1/2 particle in magnetic field

Berry connection

$$A_n(R) = i\langle n(R)|\nabla_R|n(R)\rangle$$

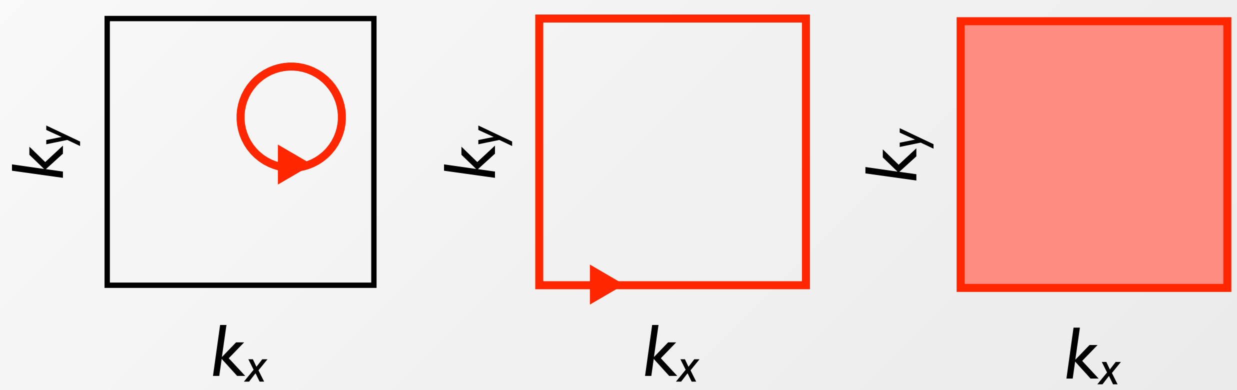
Berry curvature

$$\Omega_{n,\mu\nu}(R) = \frac{\partial}{\partial R^\mu}A_{n,\nu} - \frac{\partial}{\partial R^\nu}A_{n,\mu}$$

Berry Phase for Periodic Potentials

$$\Psi_k(\mathbf{r}) = e^{i\mathbf{kr}} u_k(\mathbf{r})$$ Bloch wave in periodic potential

Adiabatic motion in momentum space generates Berry phase!



Berry phase is fundamental to characterize topology of energy bands

$$n_{\text{Chern}} = \frac{1}{2\pi}\oint_{BZ} A_k dk = \frac{1}{2\pi}\int_{BZ} \Omega_k \, d^2k \quad \Longleftrightarrow \quad \sigma_{xy} = n_{\text{Chern}}\, e^2/h$$

Chern Number (Topological Invariant)

Quantized Hall Conductance

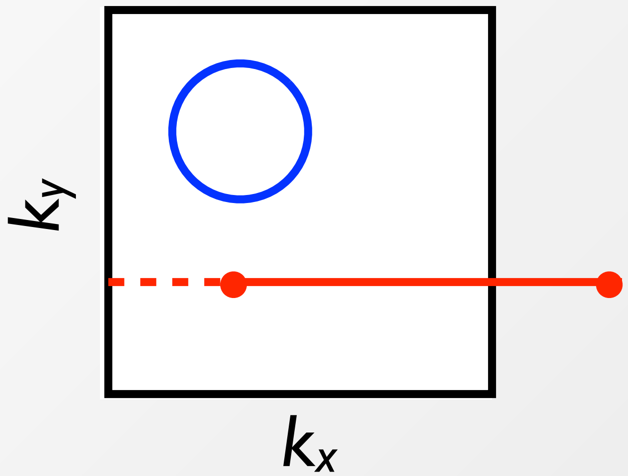
Thouless, Kohmoto, den Nijs, and Nightingale (TKNN), PRL
Kohmoto Ann. of Phys. 1985

What is the extension to 1D

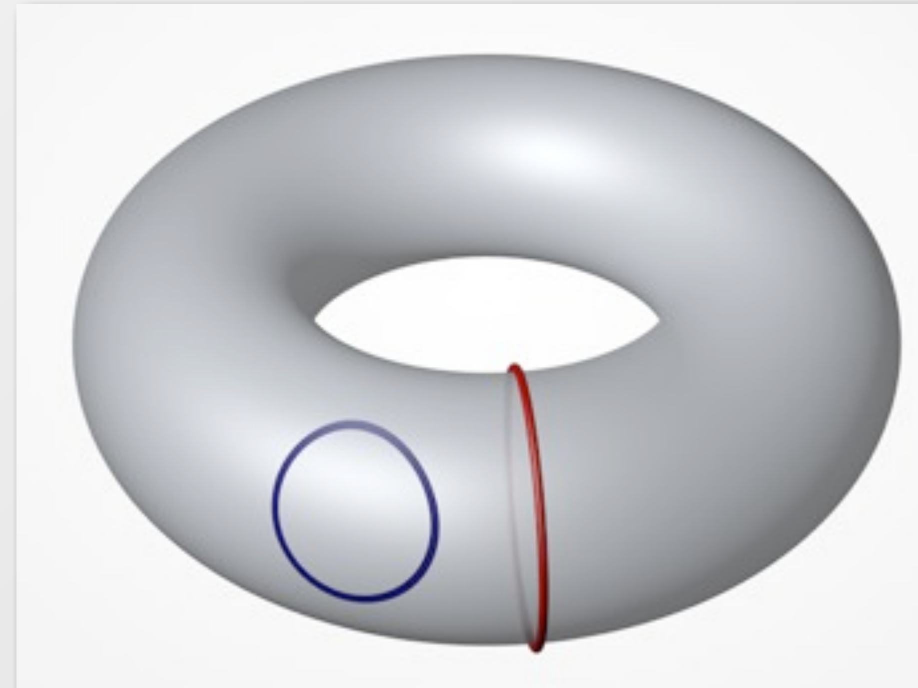
Mention Problem with going on a line is generally **NOT A LOOP IN PARAMETER SPACE!**

Zak Phase

2D Brillouin Zone



going straight means going around!



Band structure has topology of a torus!

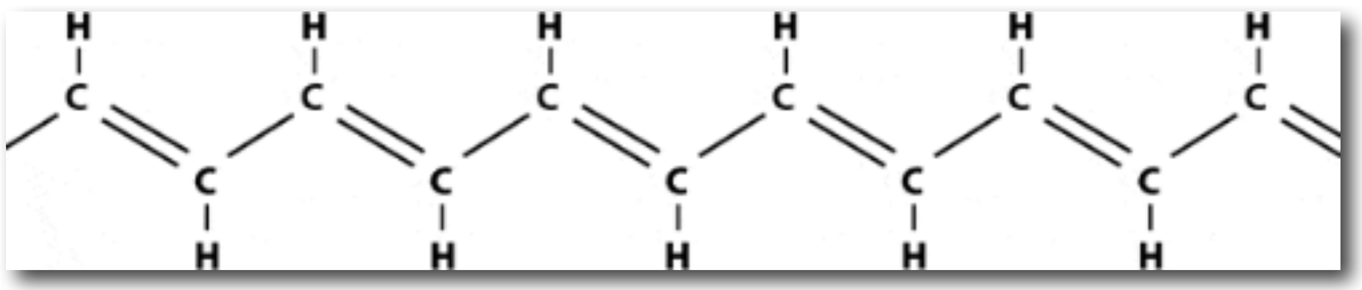
$$\varphi_{\mathrm{Zak}} = \int_{k_0}^{k_0+G} A(k)\,dk = i\int_{k_0}^{k_0+G} \langle u_k|\partial_k|u_k\rangle\,dk$$

Zak Phase - the 1D Berry Phase

J. Zak, Phys. Rev. Lett. 62, 2747 (1989)

Non-trivial Zak phase indicates topological band.

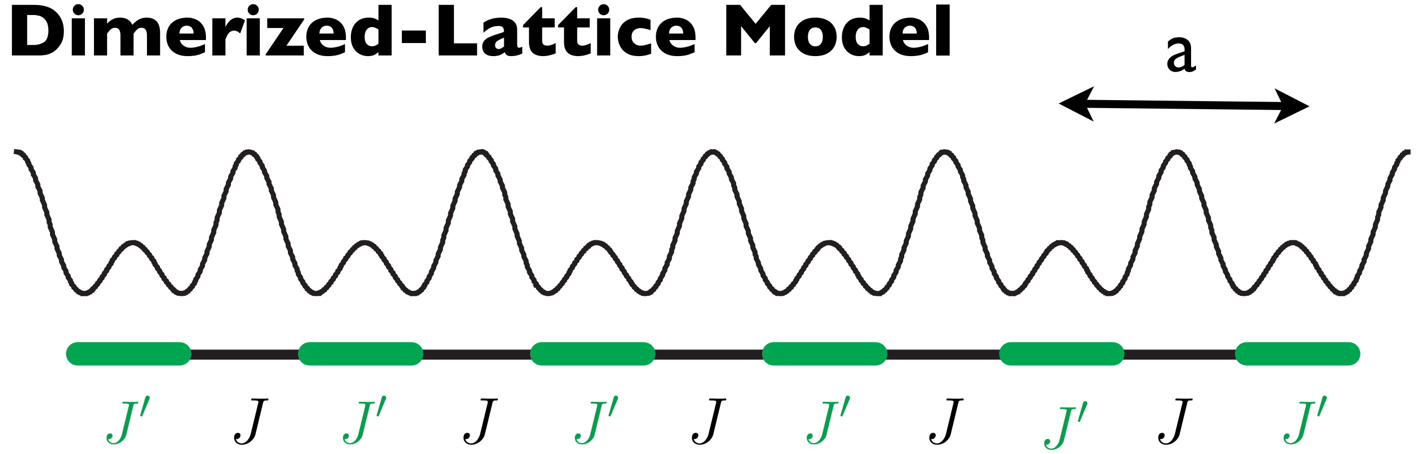
Su-Shrieffer-Heeger Model (SSH)



Polyacetylene

W. P. Su, J. R. Schrieffer & A. J. Heeger
Phys. Rev. Lett. 42, 1698 (1979).

Dimerized-Lattice Model

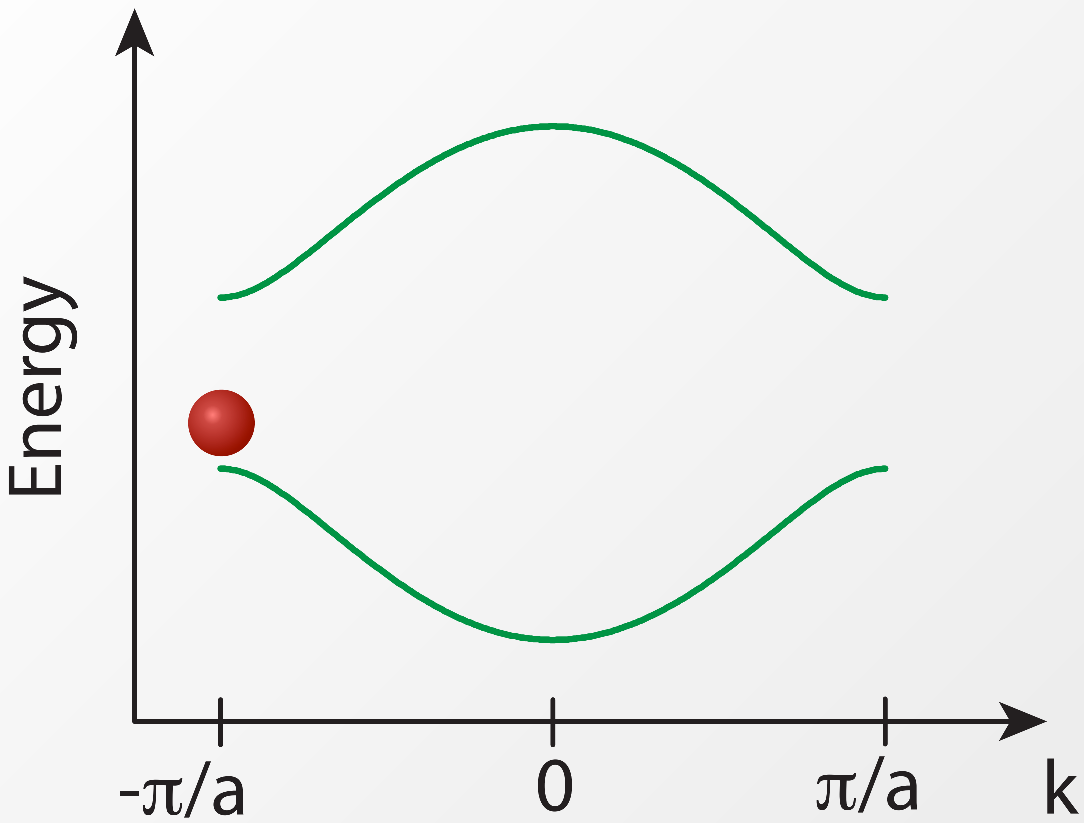


$$H_{\mathrm{SSH}} = -\sum_n \left\{ J a_n^\dagger b_n + J' a_n^\dagger b_{n-1} + \mathrm{h.c.} \right\}$$

- Topological Band
- Edge States (for finite system)
- Fractional Charge

R. Jackiw and C. Rebbi, Phys. Rev. D 13, 3398 (1976)
J. Goldstone and F. Wilczek, Phys. Rev. Lett. 47, 986 (1981)

SSH Energy Bands - Eigenstates



...ABABABAB... Lattice Structure....

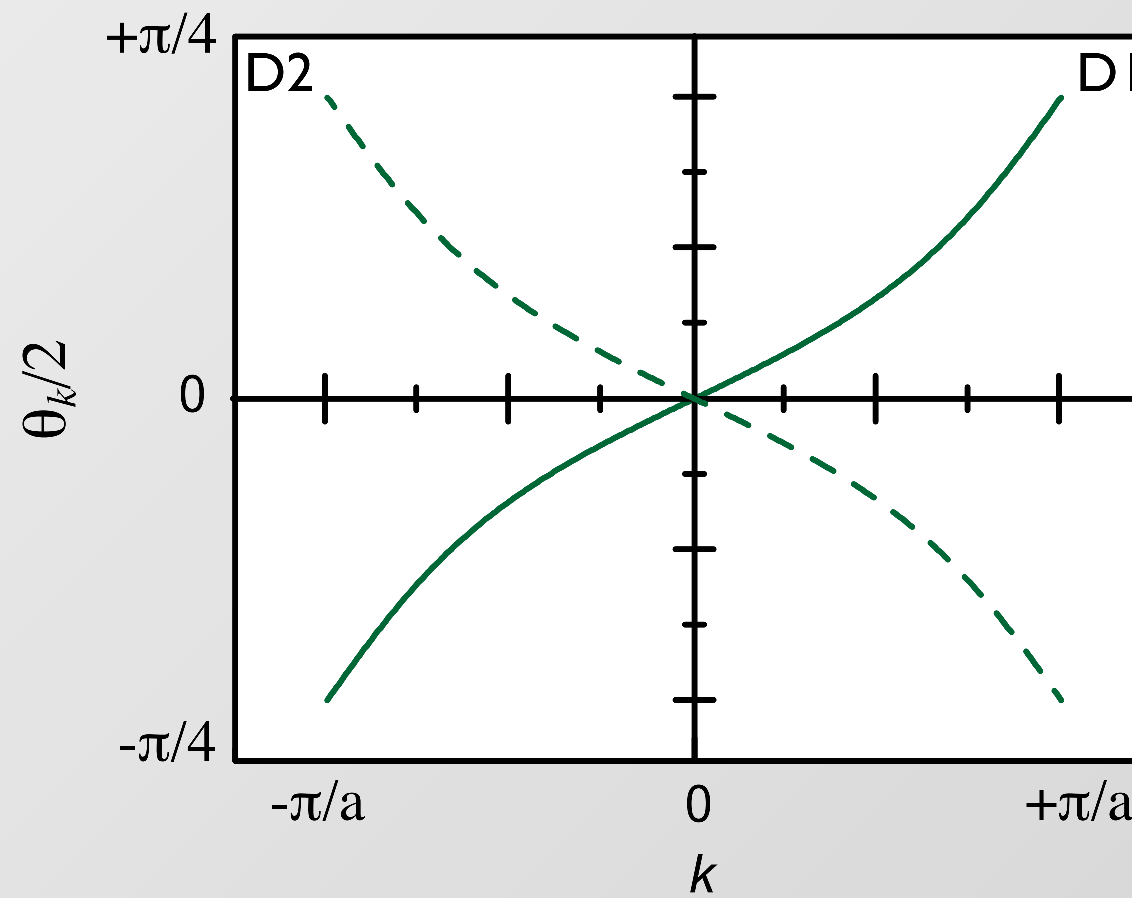
$$\psi_k(x) = \sum_n \begin{cases} \alpha_k \, e^{ikx_n} \\ \beta_k \, e^{ik(x_n+a/2)} \end{cases}$$

Eigenstates

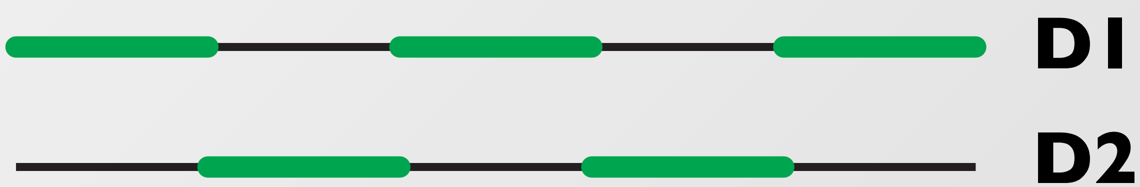
$$\begin{pmatrix} \alpha_k \\ \beta_k \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \pm 1 \\ e^{i\theta_k} \end{pmatrix}$$

$$\varphi_{\mathrm{Zak}} = \frac{i}{2} \int_0^G \partial_k \theta_k \, dk = \pm \frac{\pi}{2}$$

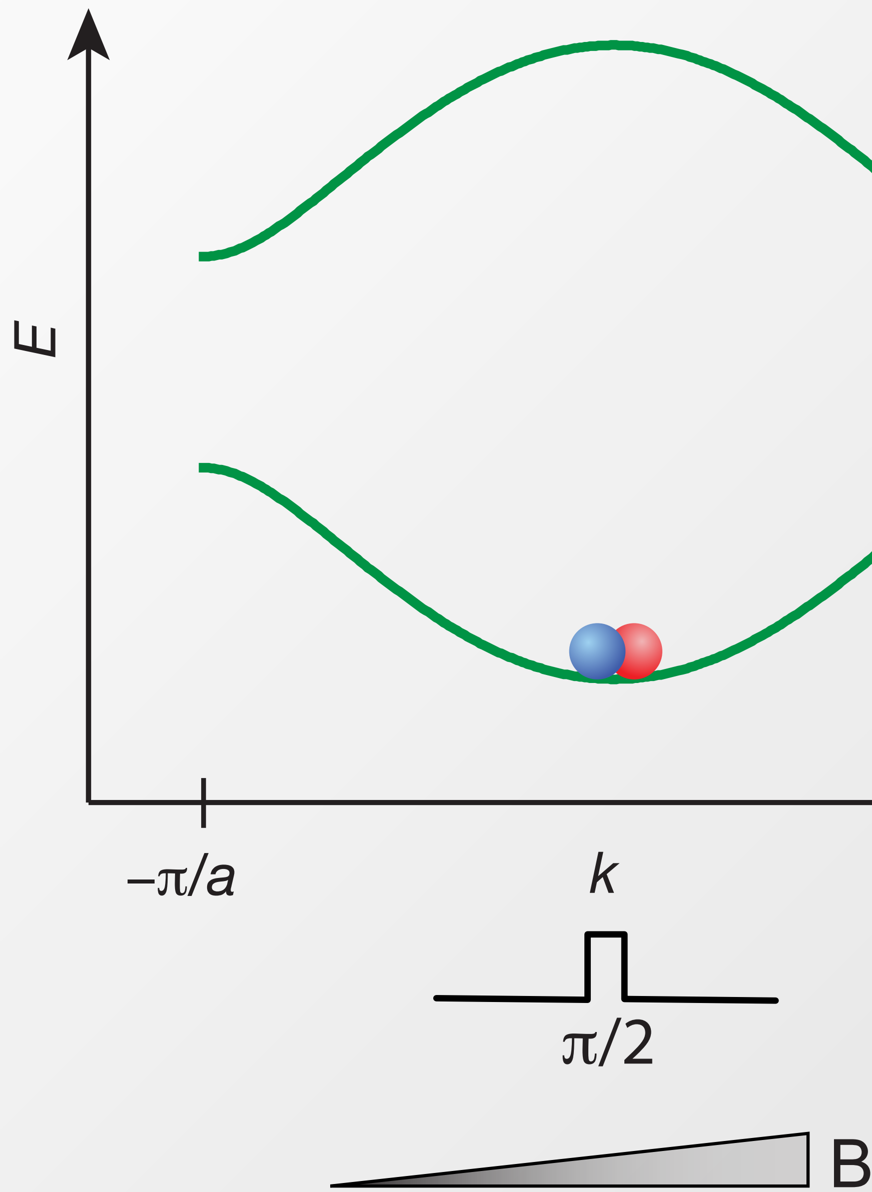
Zak-Berry Phase SSH Model

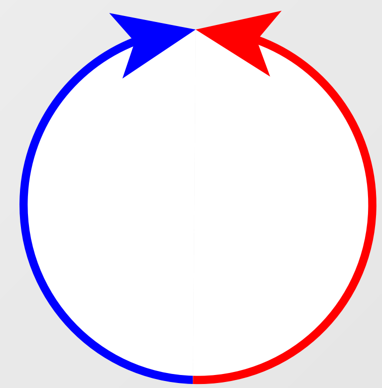


For the two dimerized configurations!



Measuring the Berry-Zak Phase (SSH Model)



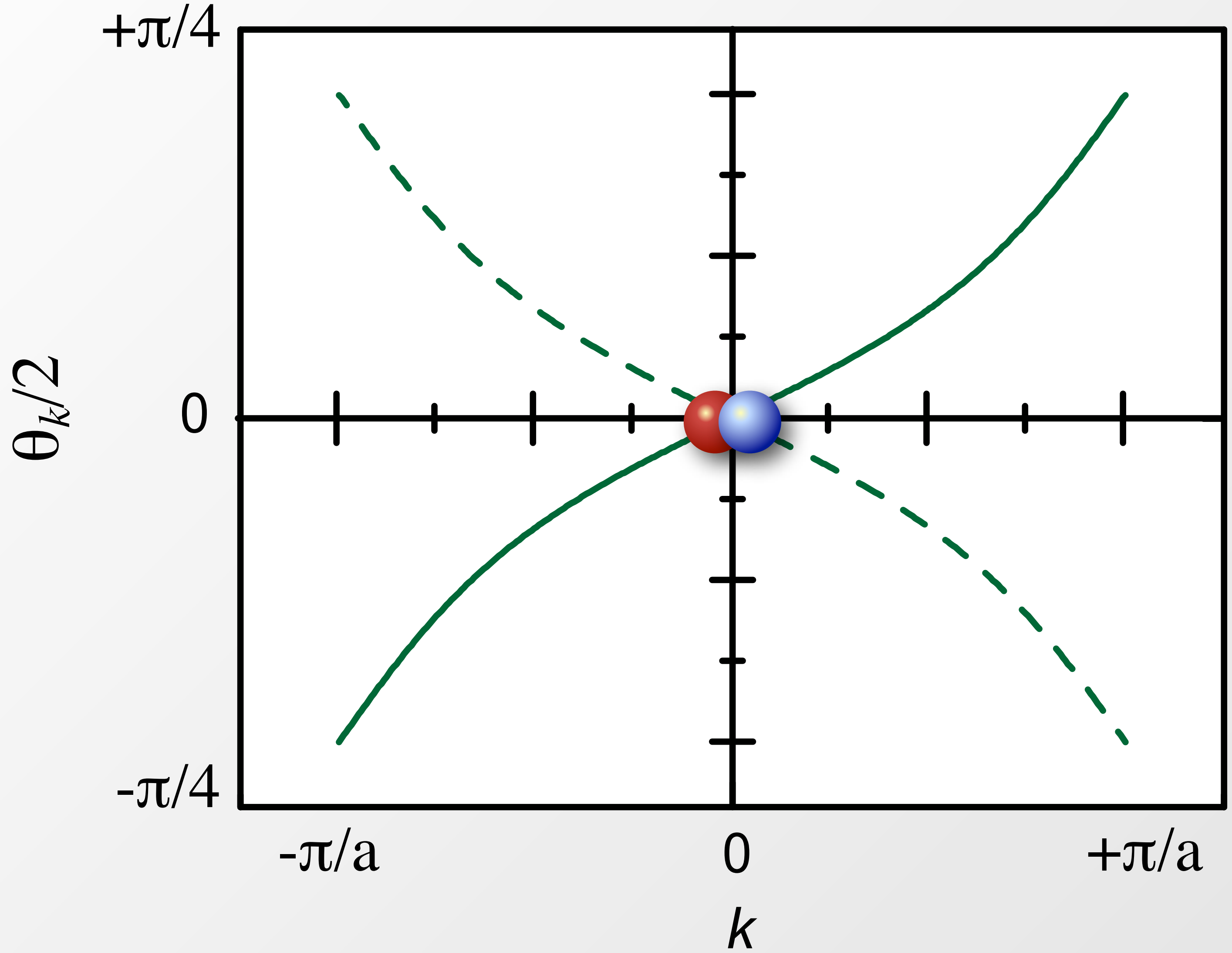


Closed Loop in *k*-Space

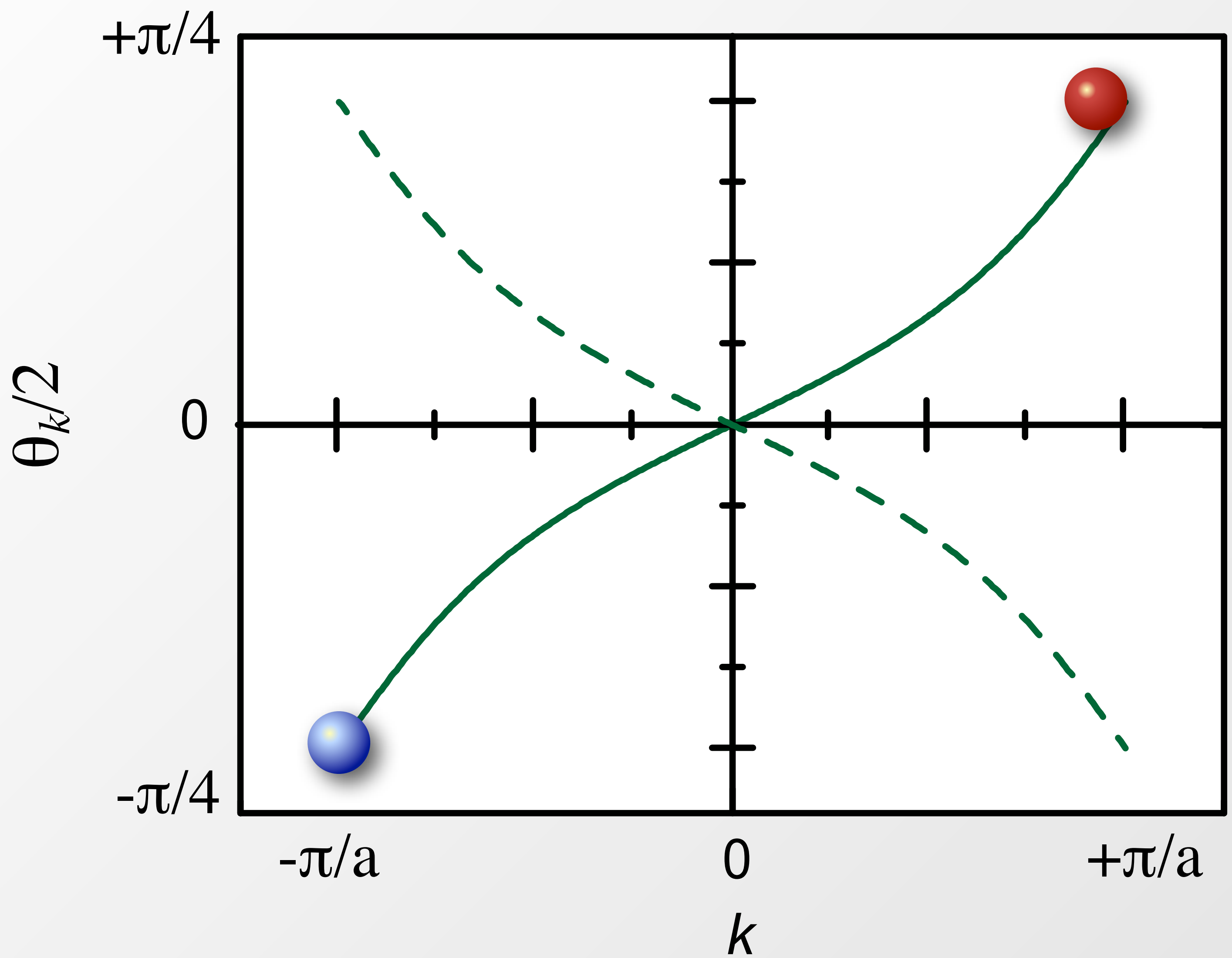
What have we measured:

$$\varphi_{\text{tot}} = \varphi_{\text{Zak}} + \cancel{\varphi_{\text{dyn}}} + \varphi_{\text{Zeeman}}$$

Photon Echo Sequence

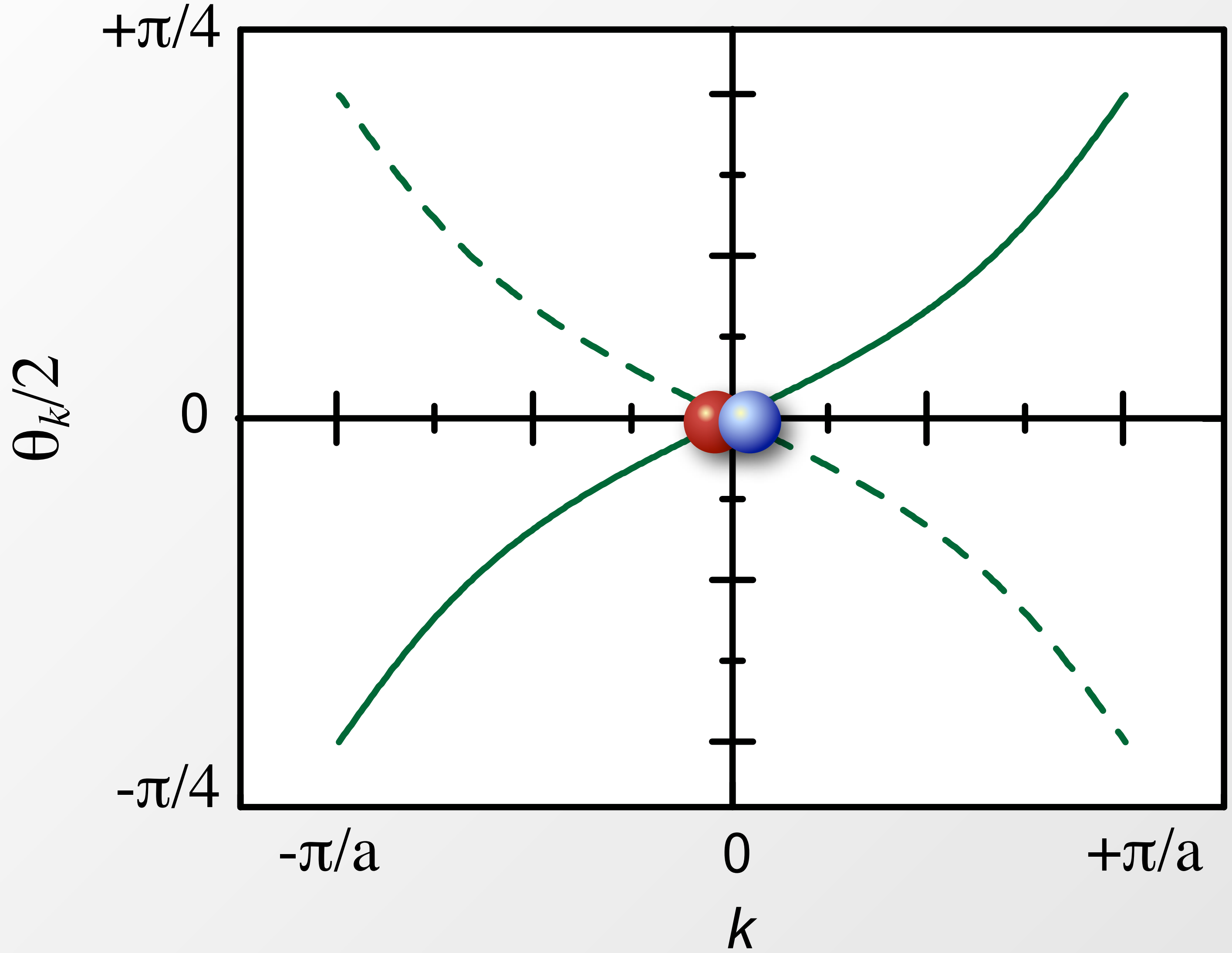


Photon Echo Sequence

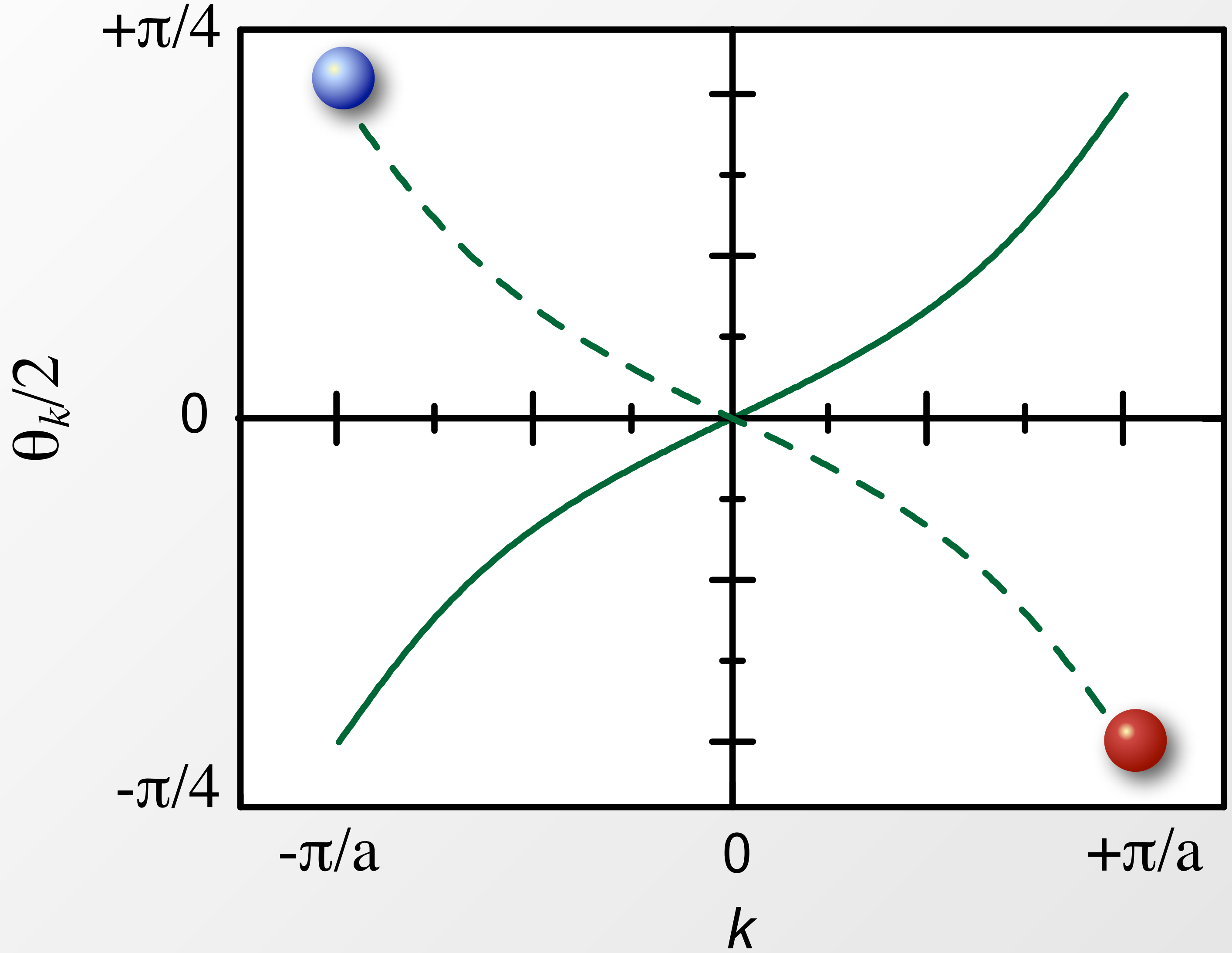


$$\varphi_{\text{tot}} = \varphi_{\text{Zak}} + \varphi_{\text{dyn}} + \varphi_{\text{Zeeman}}$$

Photon Echo Sequence



Photon Echo Sequence



Photon Echo pi-Puls

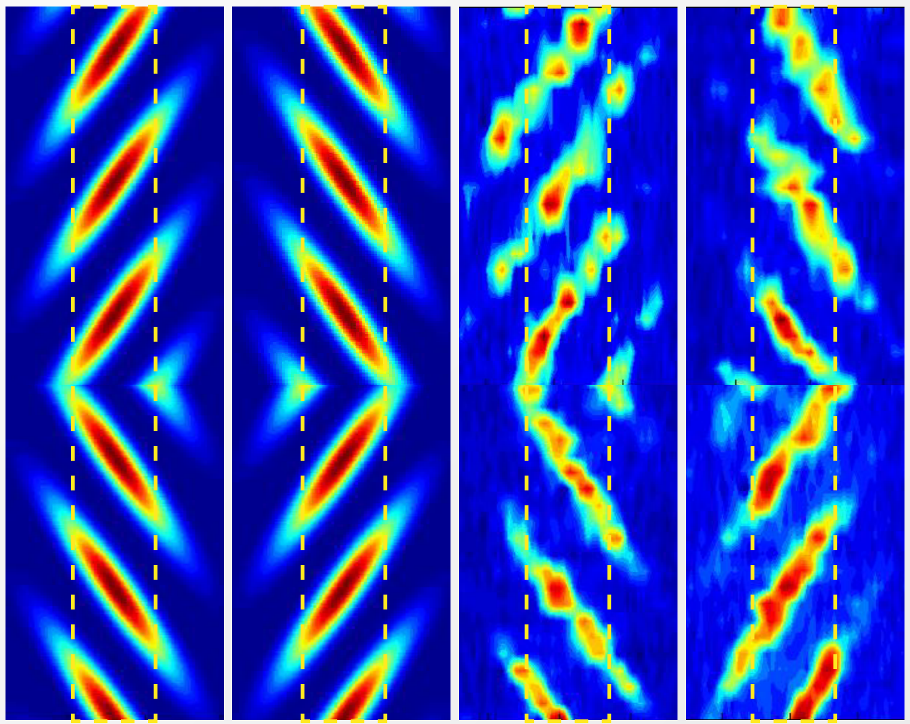
+Change of Dimerization

$$\varphi_{\text{tot}} = \left(\varphi_{\text{Zak}}^{\text{D1}} - \varphi_{\text{Zak}}^{\text{D2}}\right) + \varphi_{\text{dyn}} + \varphi_{\text{Zeeman}}$$

Bloch Oscillations - Experiment

Theory Experiment

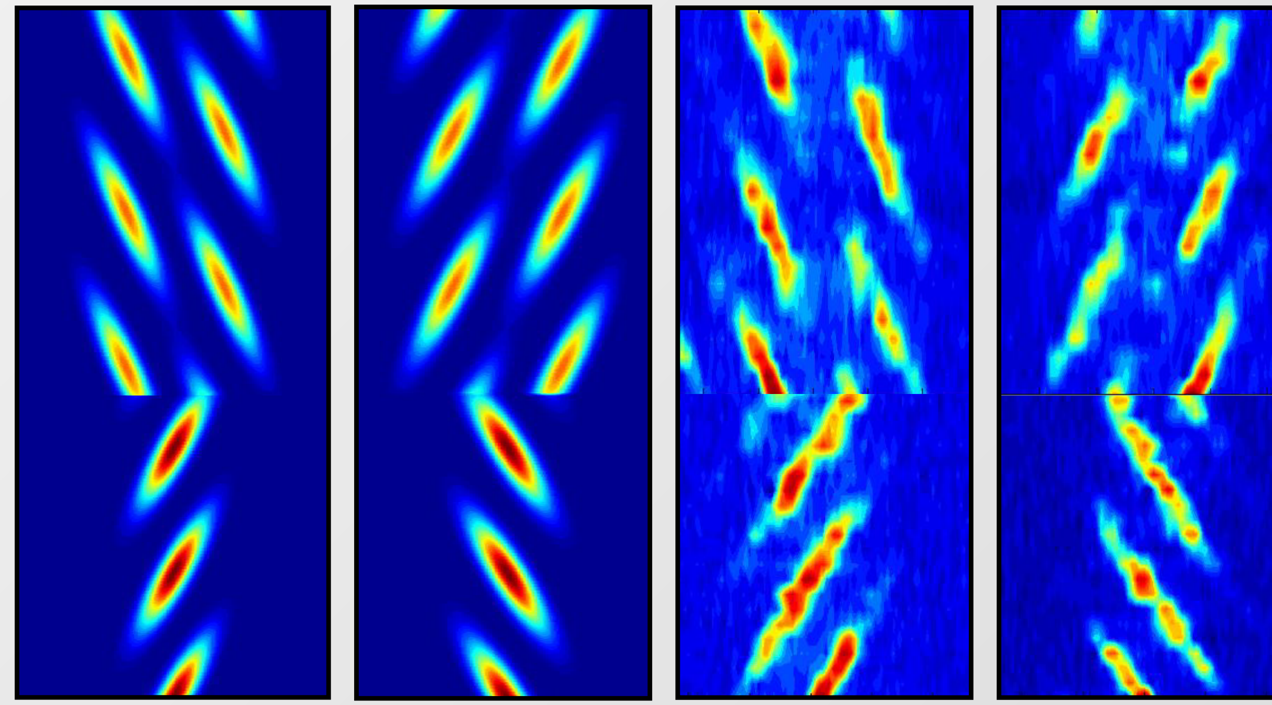
Time



Momentum *k*

without dimerization swapping

Theory Experiment

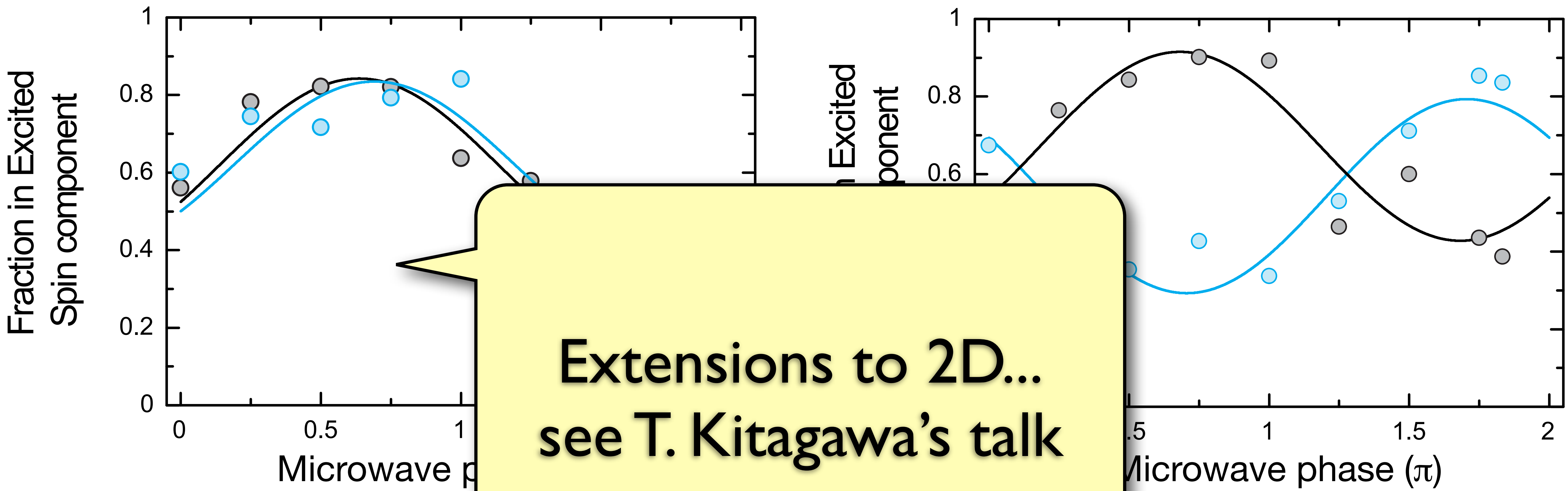


Momentum *k*

without dimerization swapping

Bloch oscillations in gradient field!

Ramsey Fringes



Extensions to 2D... see T. Kitagawa's talk

without dimeriz... | ...merization swapping

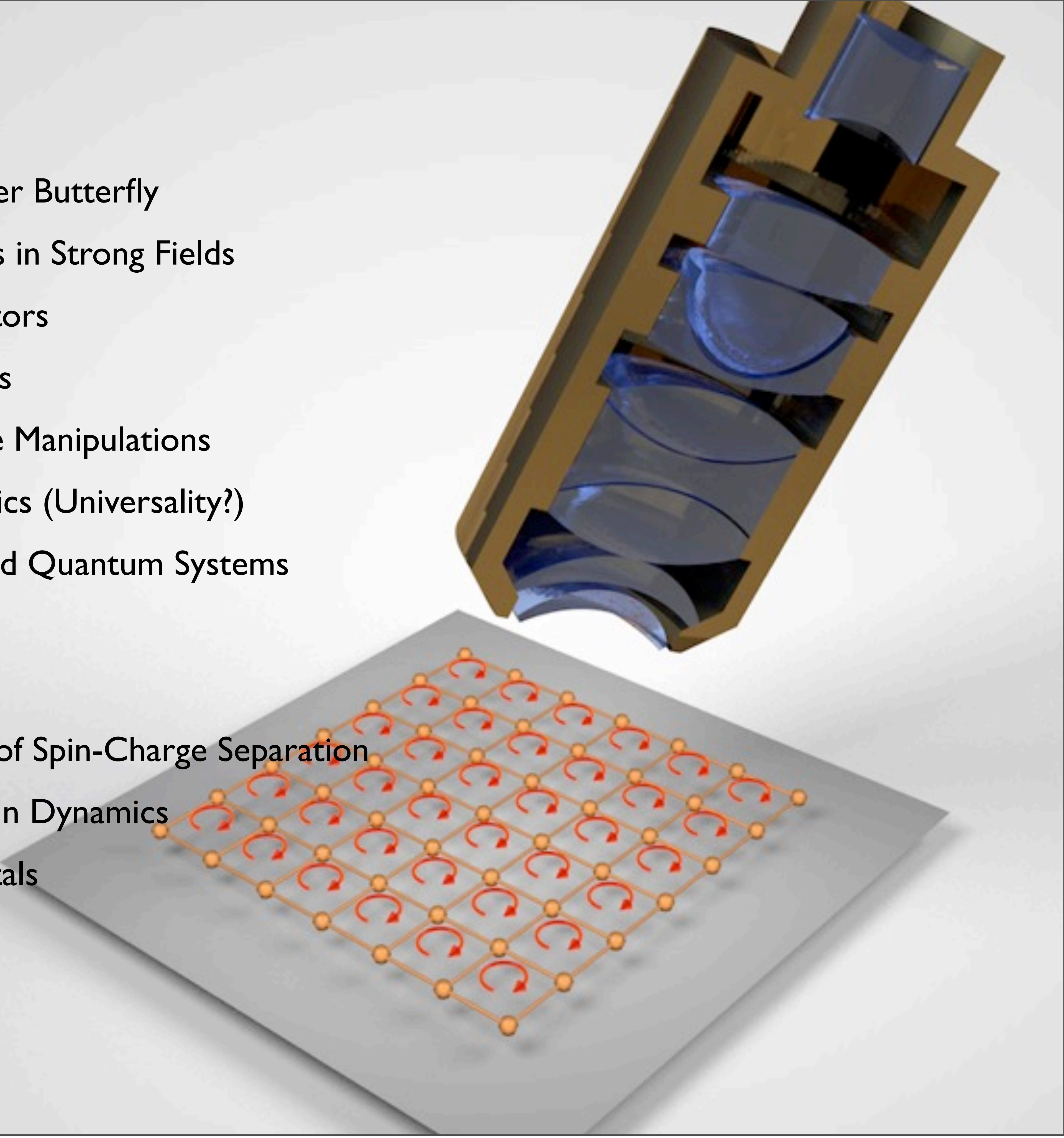
Measured Topological Berry-Zak Phase:

$$\Delta\varphi_{Zak} = 1.02(4)\pi$$

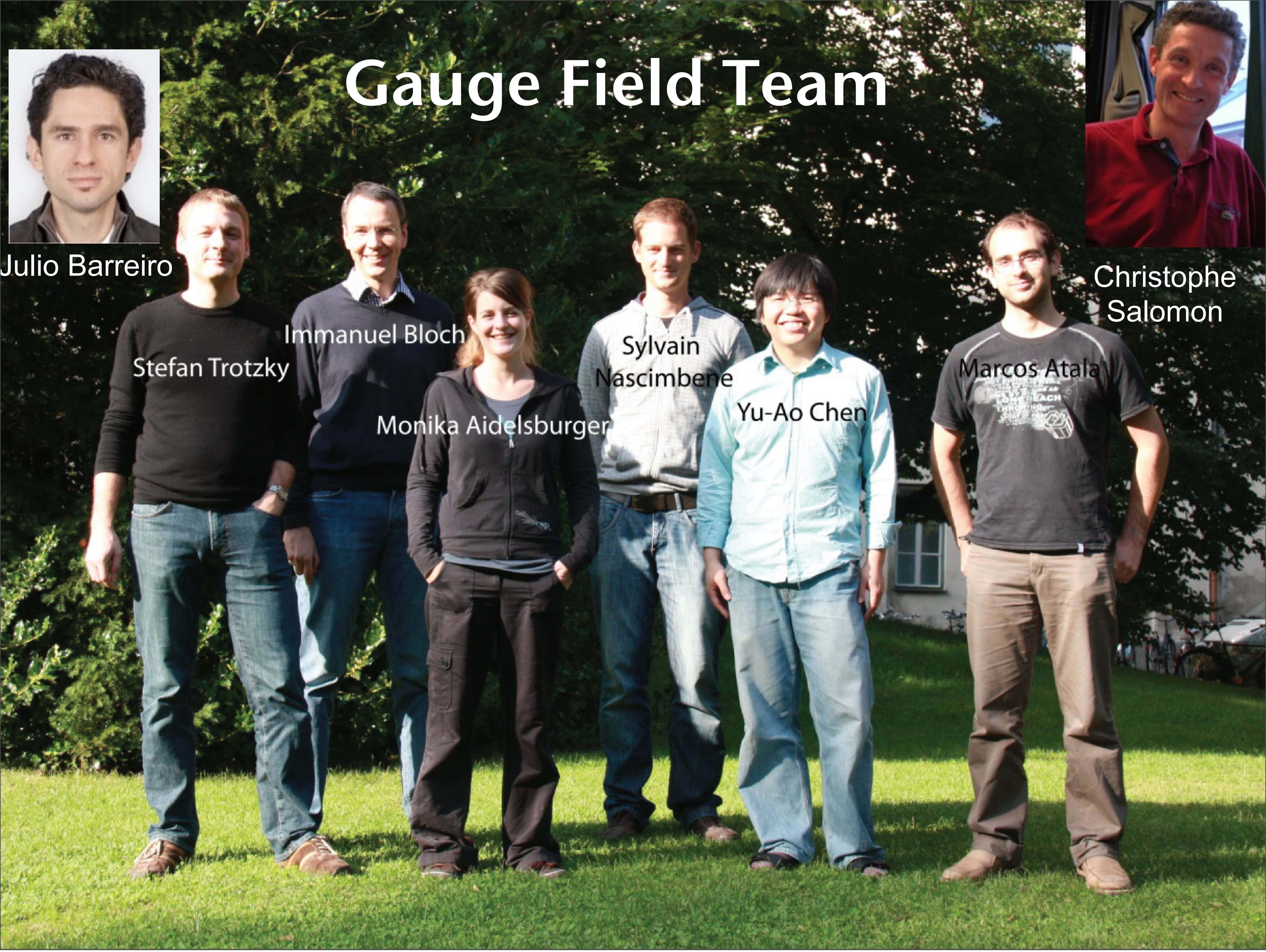
Outlook

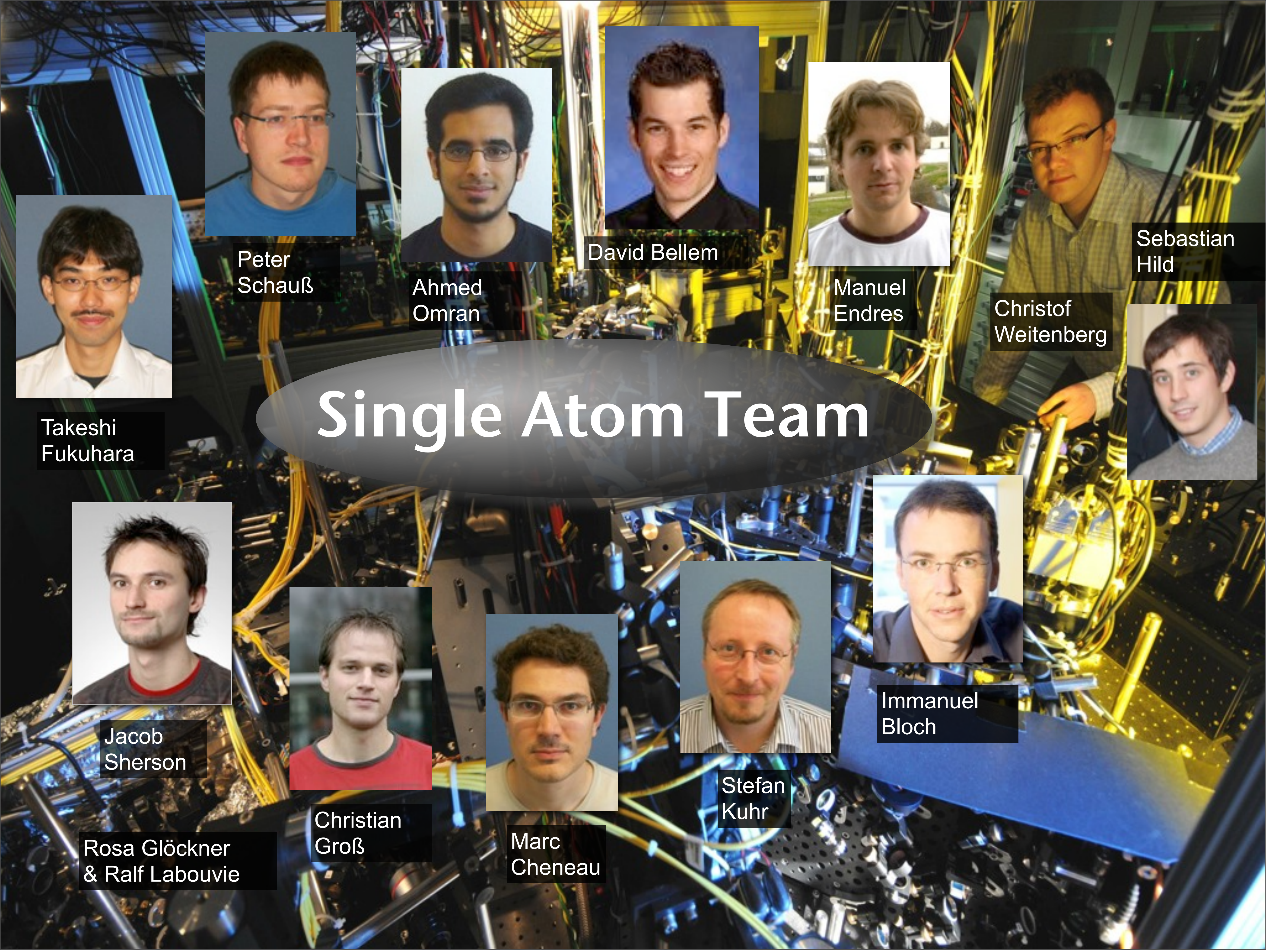
- Rectified Flux, Hofstatdter Butterfly
- Novel Correlated Phases in Strong Fields
- Novel Topological Insulators
- SU(N) Quantum Magnets
- Controlled Quasiparticle Manipulations
- Non-Equilibrium Dynamics (Universality?)
- Thermalization in Isolated Quantum Systems
- Lieb-Robinson in 2D?
- String Order in 2D?
- Dynamical Observation of Spin-Charge Separation
- Entanglement Measures in Dynamics
- Rydberg Quantum Crystals

⋮



Gauge Field Team




Single Atom Team
Peter Schauß
Ahmed Omran
David Bellem
Manuel Endres
Sebastian Hild
Christof Weitenberg
Takeshi Fukuhara
Jacob Sherson
Christian Groß
Marc Cheneau
Stefan Kuhr
Immanuel Bloch
Rosa Glöckner & Ralf Labouvie


Thank you!
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