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

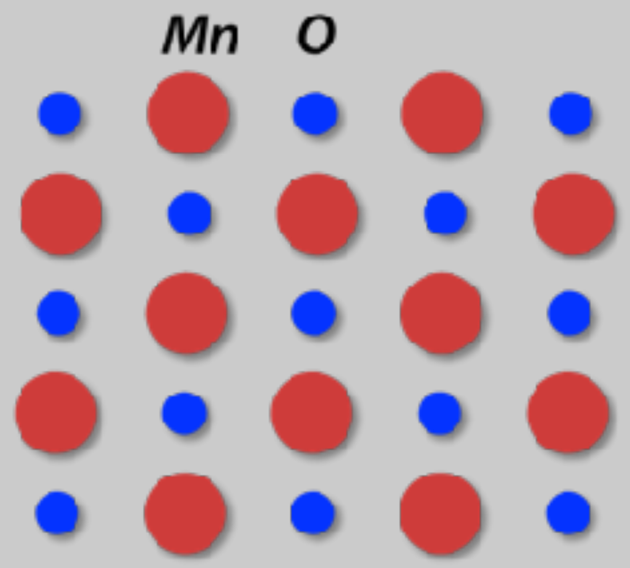
Direct Imaging of Spin-Charge Separation

Incommensurate AFM in 1D

Imaging Polarons - Charge Impurities in an AFM

Superexchange Interactions

Origin of Spin-Spin Interactions
– Exchange Interactions -



?

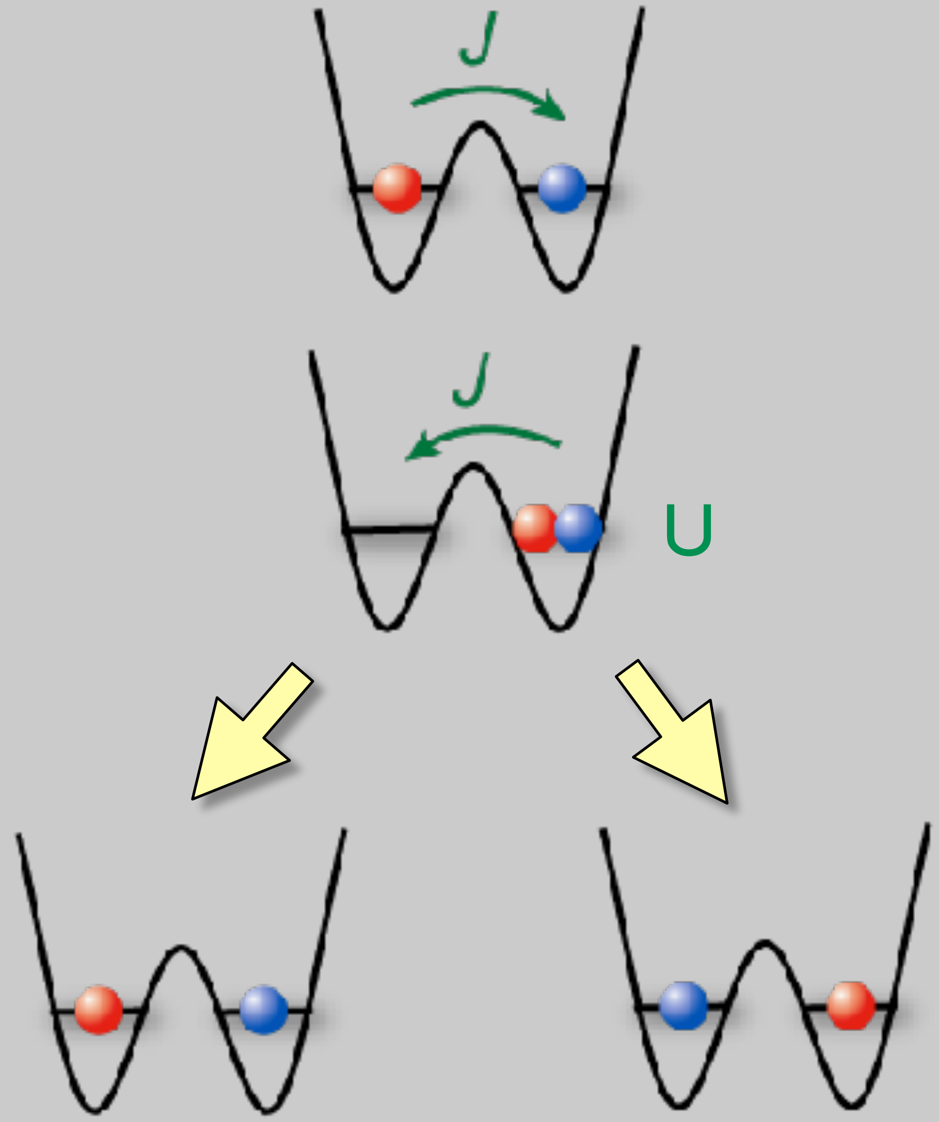
Important ionic solids with no direct exchange between magnetic ions show magnetic ordering (MnO, CuO)!

„Super"-exchange interactions must be at work!

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

Deriving the Effective Spin Hamiltonian (I)

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)

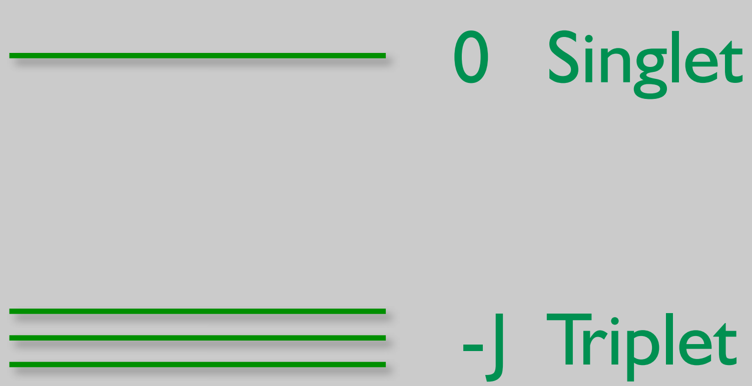
Second order hopping can be written as

$$H = -2\frac{J^2}{U}\left(1 + \hat{X}_{LR}\right)$$

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

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

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



Deriving the Effective Spin Hamiltonian (3)

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

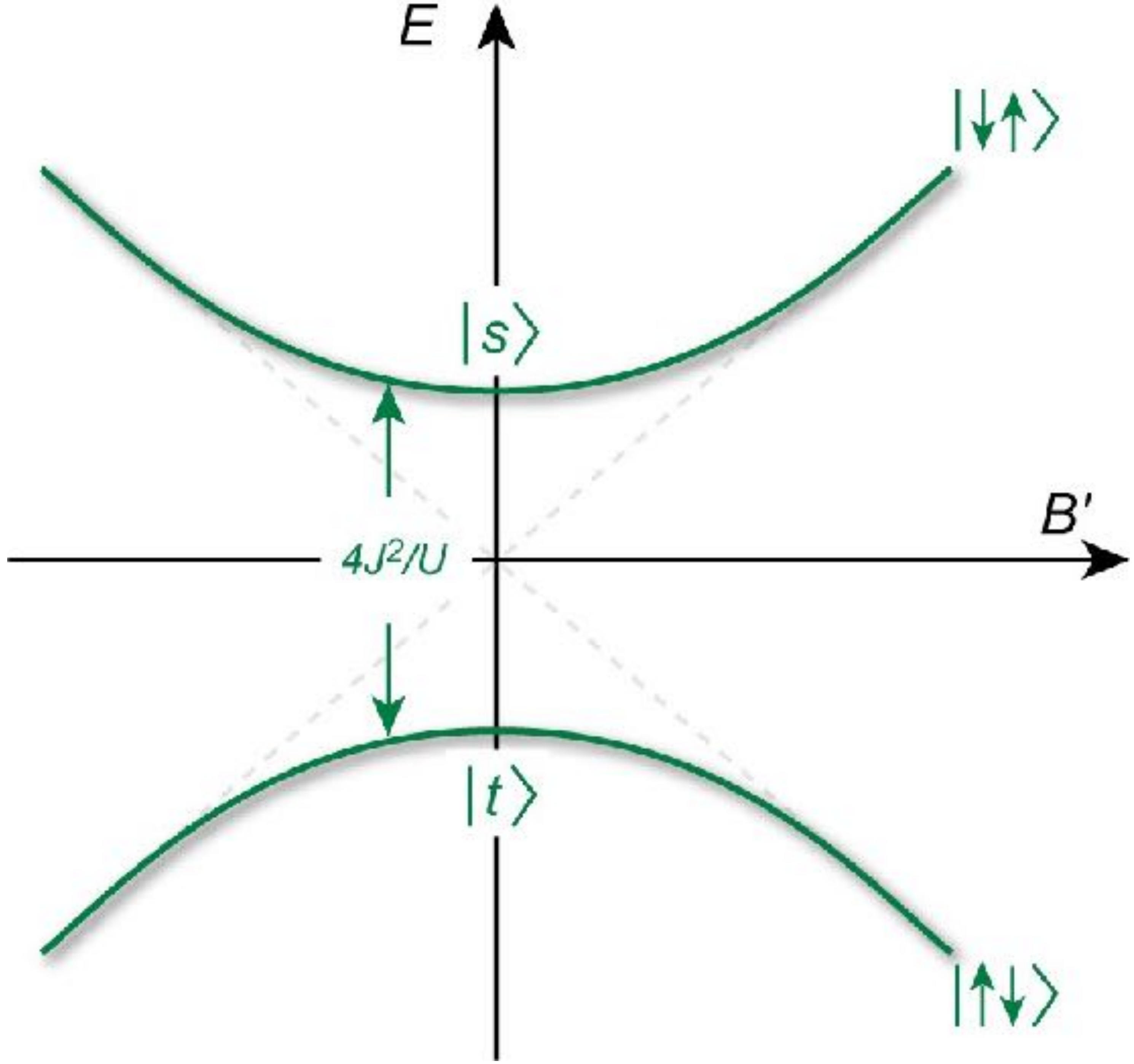
$$\begin{aligned} \mathbf{S}_L \cdot \mathbf{S}_R &= \frac{(\mathbf{S}_L + \mathbf{S}_R)^2}{2} - \frac{3}{4} \\ &= \frac{S(S+1)}{2} - \frac{3}{4} \\ &= \hat{P}_{S=1} - \frac{3}{4} \end{aligned}$$

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

Direct Detection of Superexchange Interactions

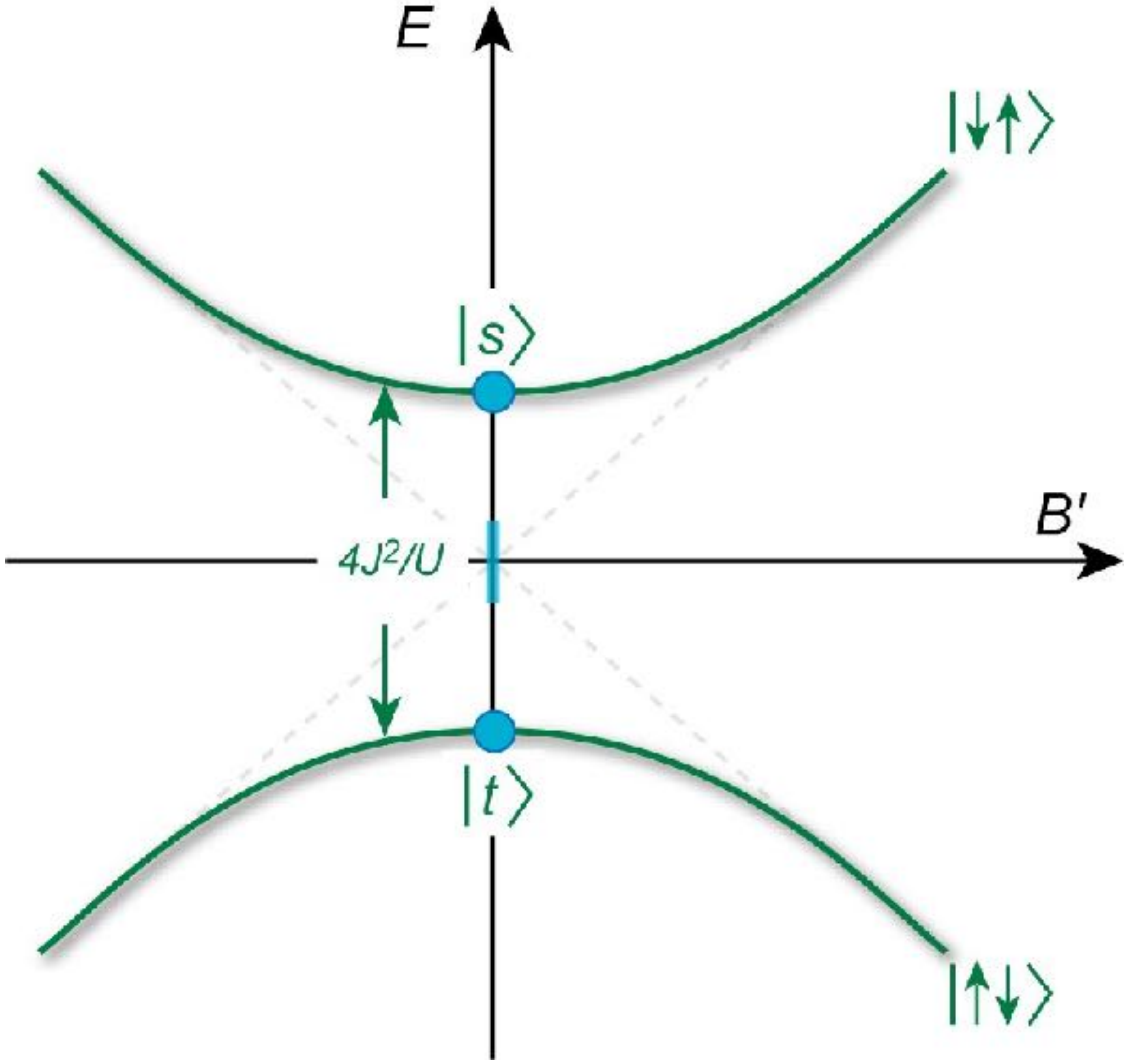
$|s\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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

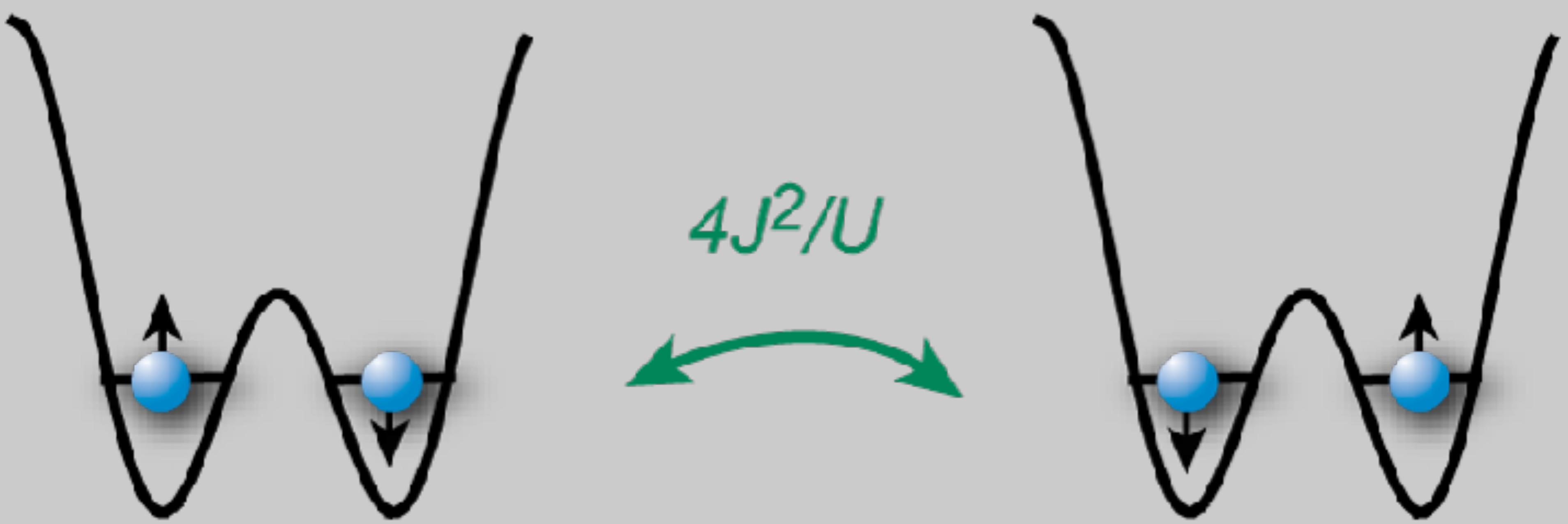


$$H_{eff} = -J_{ex}\,\vec{S}_L \cdot \vec{S}_R - \mu_B B'\left(S_{z,L} - S_{z,R}\right)$$

Direct Detection of Superexchange Interactions (2)

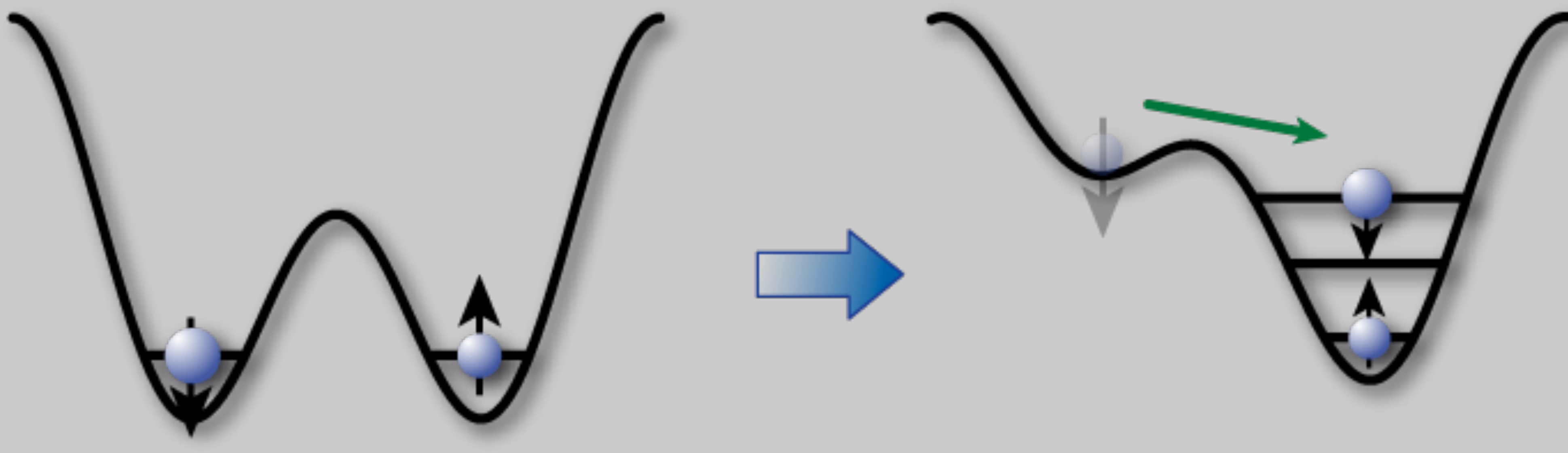


Superexchange induced flopping



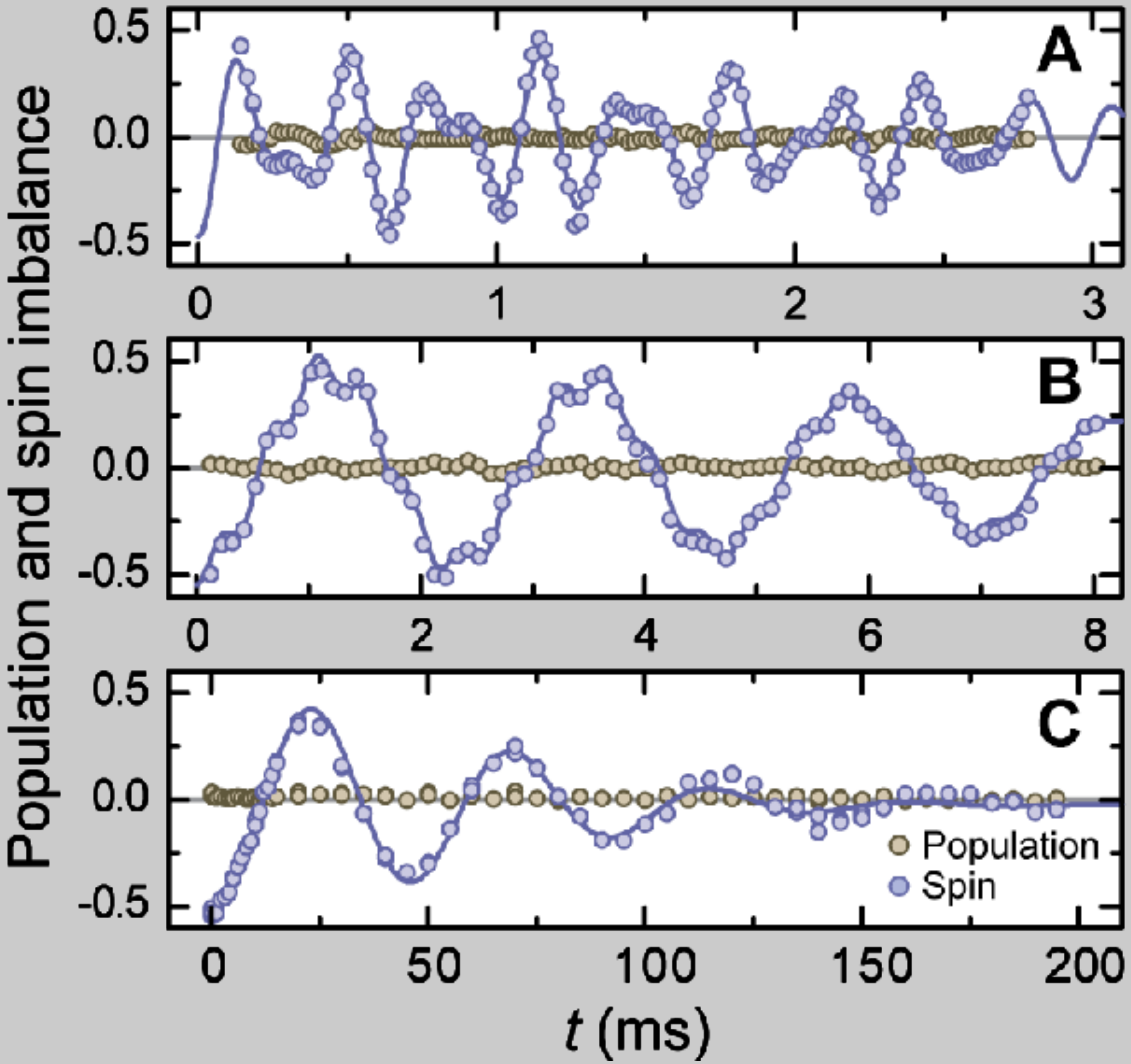
$$H_{eff} = -J_{ex}\vec{S}_i \cdot \vec{S}_j$$
$$= -\frac{J_{ex}}{2}\left(\hat{S}_i^+\hat{S}_j^- + \hat{S}_i^-\hat{S}_j^+\right) - J_{ex}\hat{S}_i^z\hat{S}_j^z$$

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

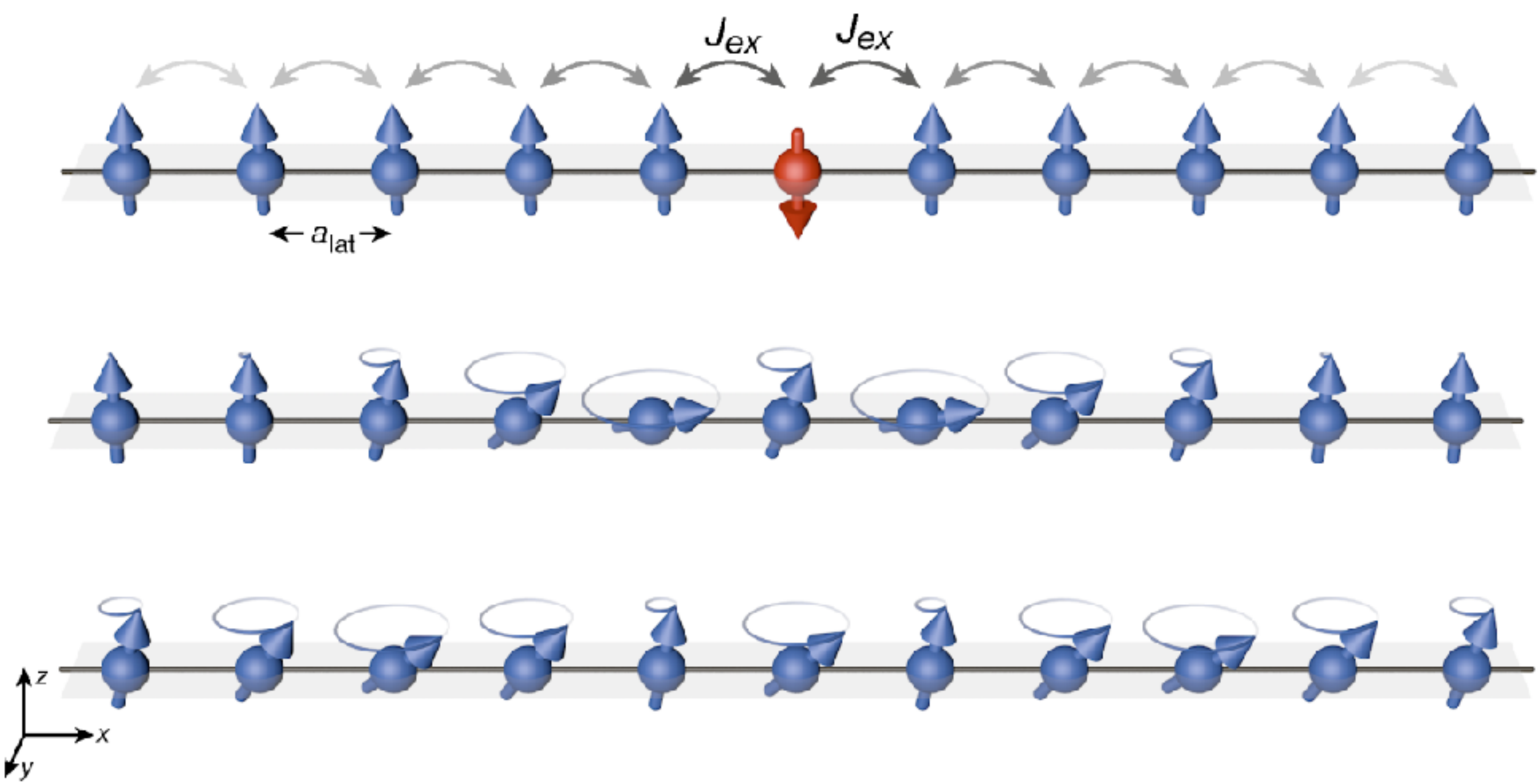
***J/U* = 0.05**
V_{short}* = 17 *E_r

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)

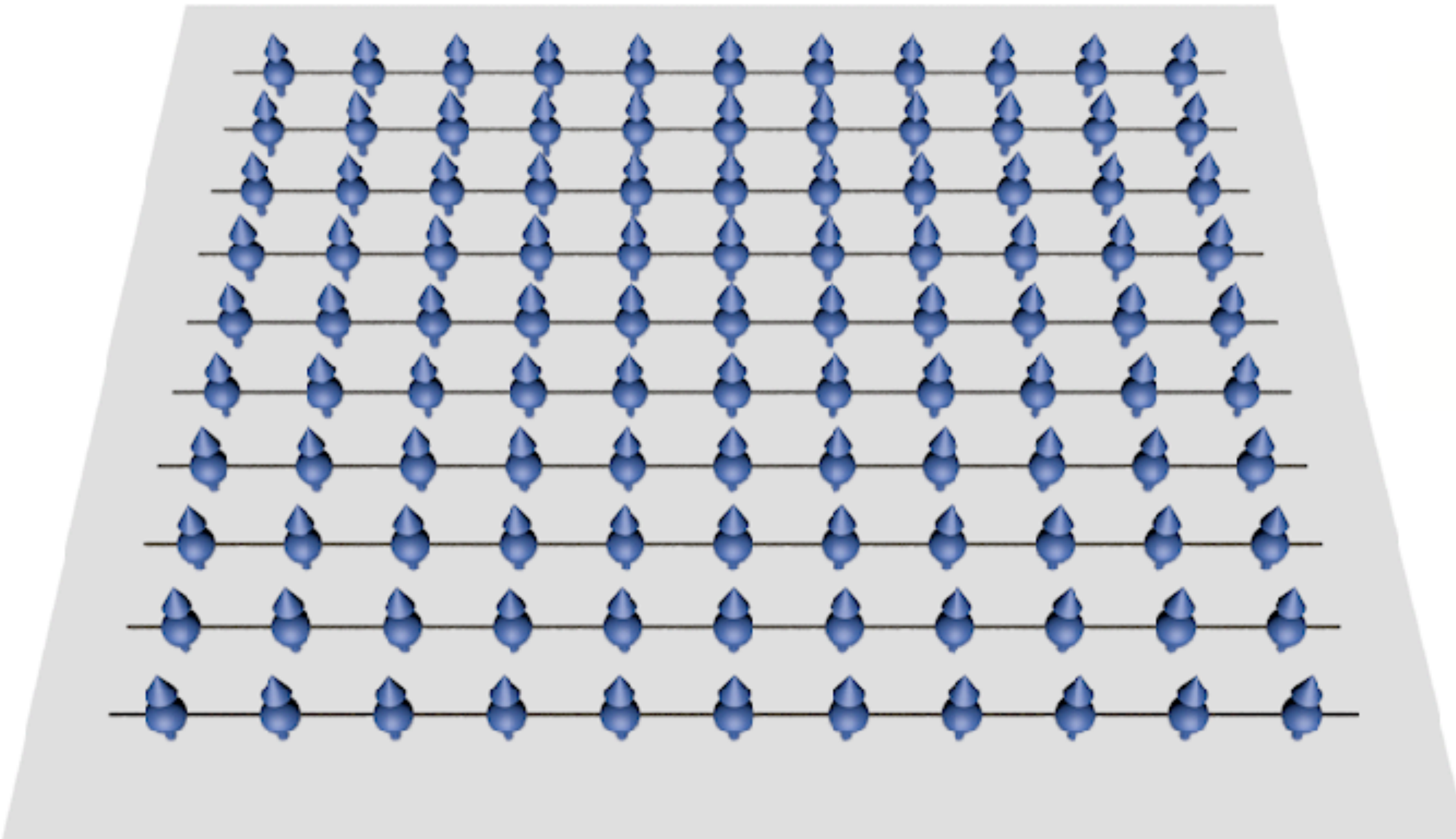
Spin impurity dynamics

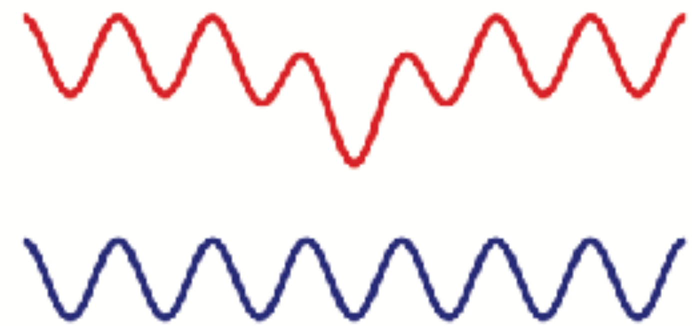


$$-J_{ex}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$$

Ferromagnetic Heisenberg Interaction

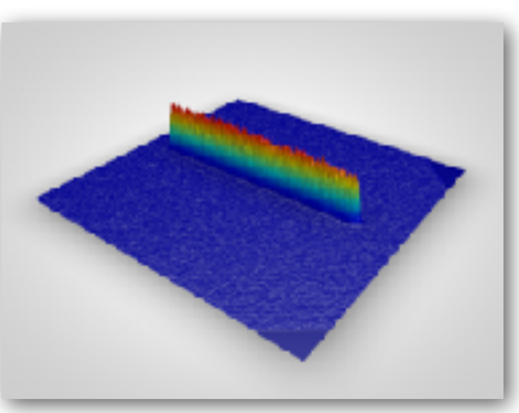
Spin impurity dynamics





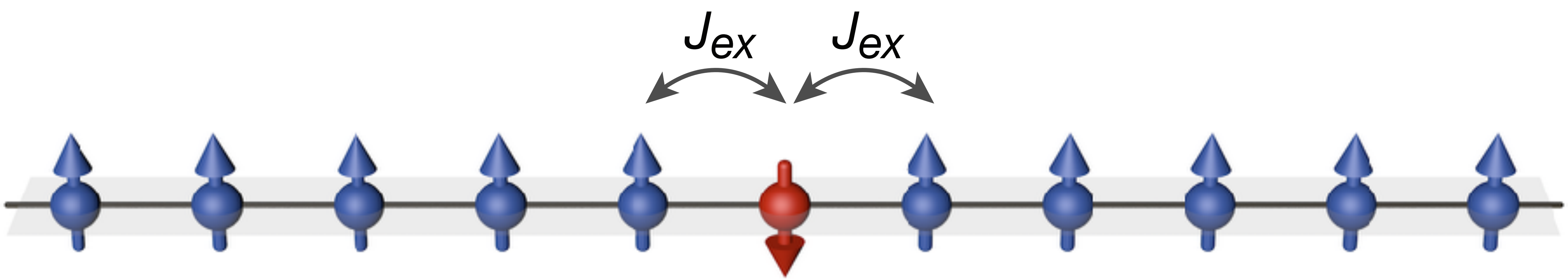
$|2\rangle = |F=2, m_F=-2\rangle$

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



Line-shaped light field created with DMD SLM

Spin impurity dynamics



Heisenberg Hamiltonian

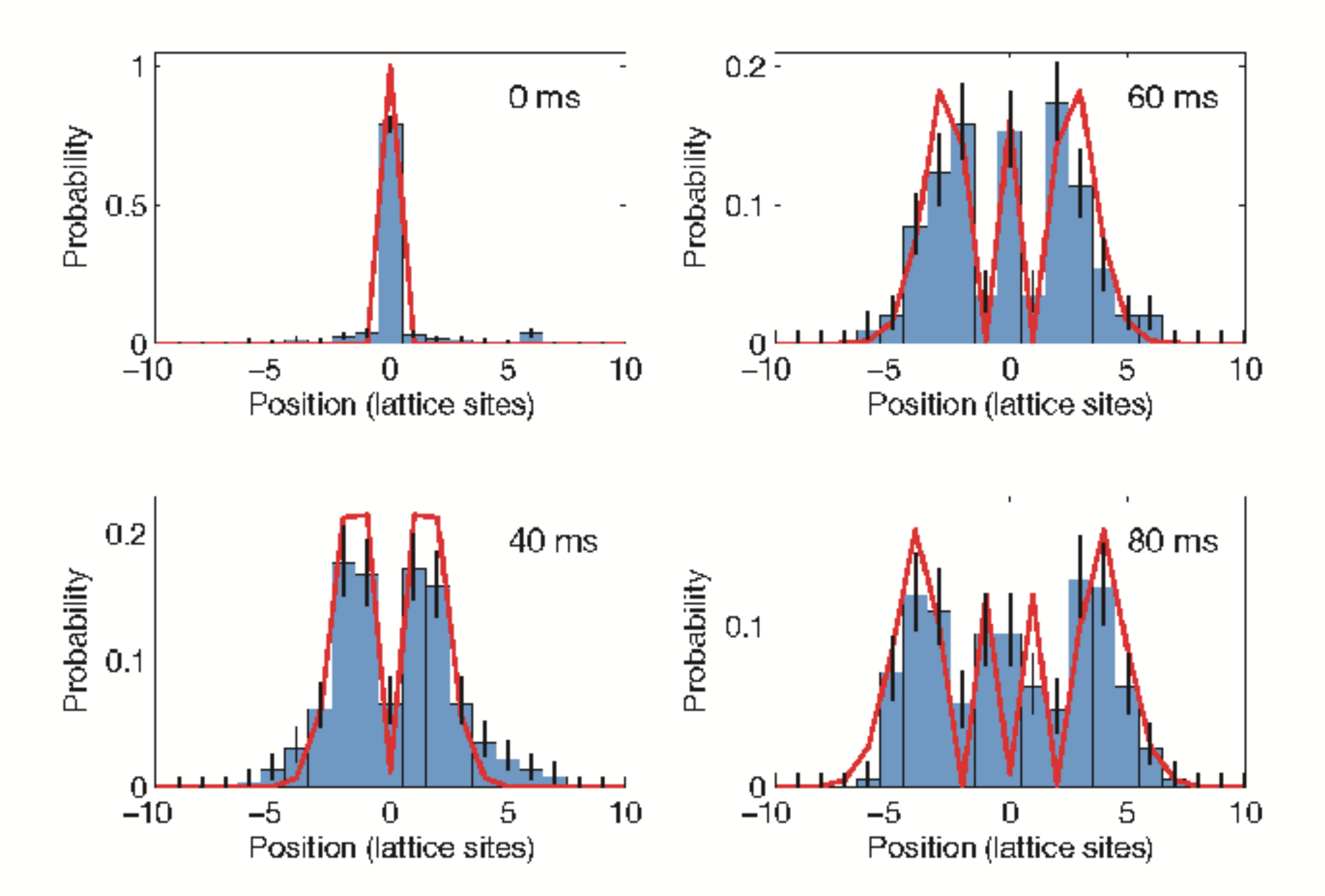
$$H = -J_{ex} \sum \mathbf{S}_i \cdot \mathbf{S}_j = -J_{ex} \sum \left(S_i^x S_j^x + S_i^y S_j^y + S_i^z S_j^z \right)$$

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

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

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

Coherent quantum dynamics of single spin at zero temperature



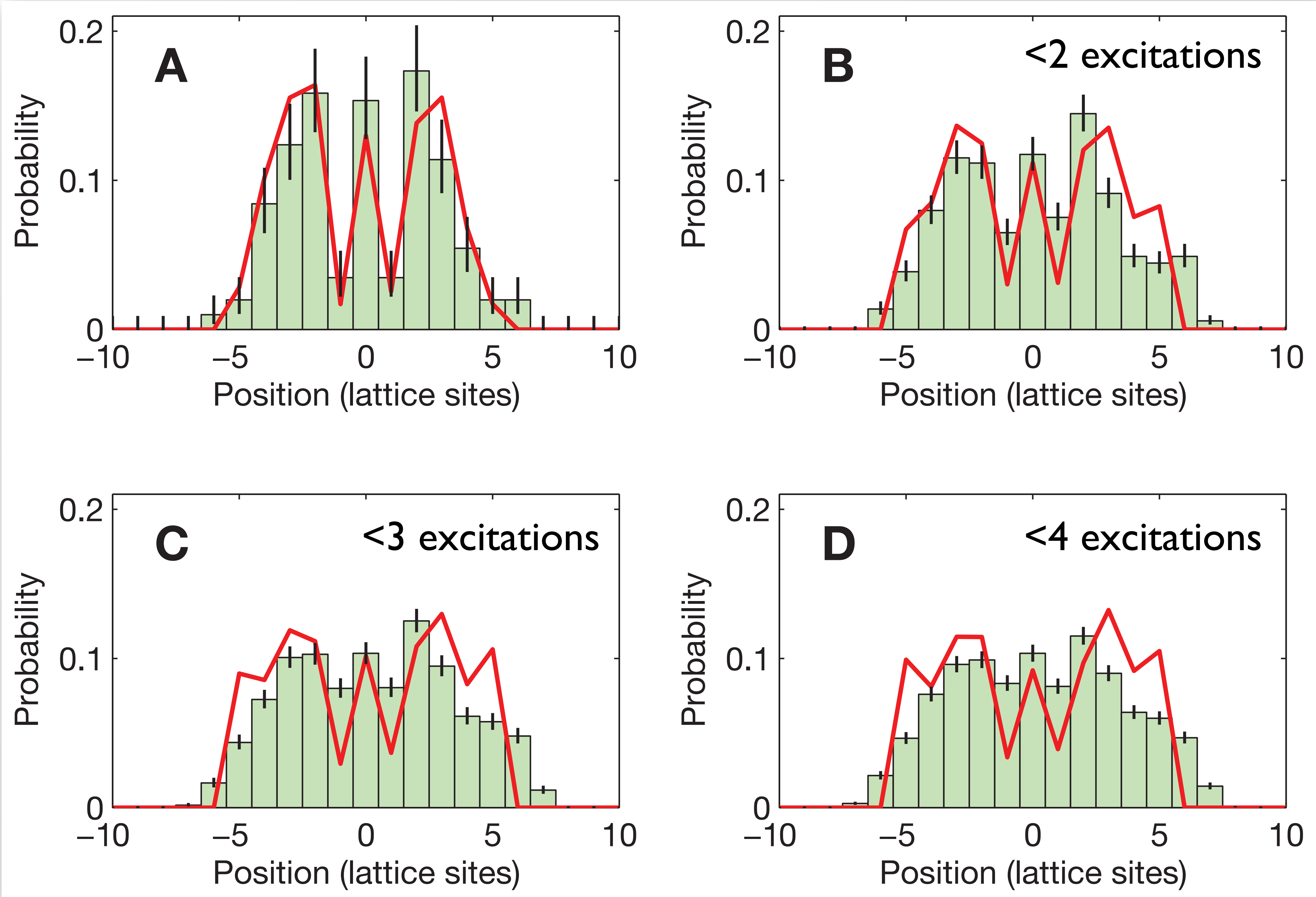
V = 10 Er
U/J = 19

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

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

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

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

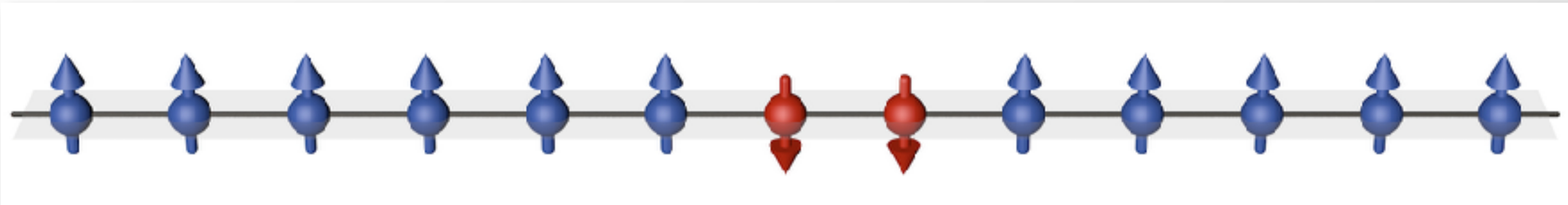
$$G(x_i, x_j, t) \propto \langle \Uparrow | \hat{S}^{\dagger}(x_j, t) \hat{S}^{-}(x_i, 0) | \Uparrow \rangle$$

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

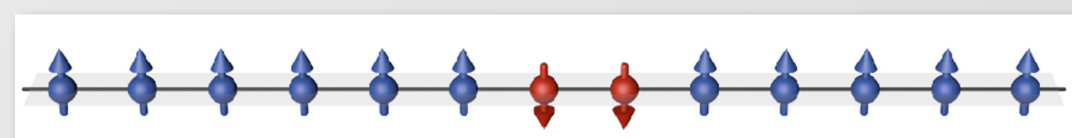


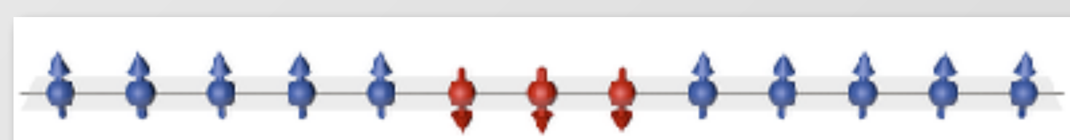
Hans Bethe
(1906-2005)

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

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

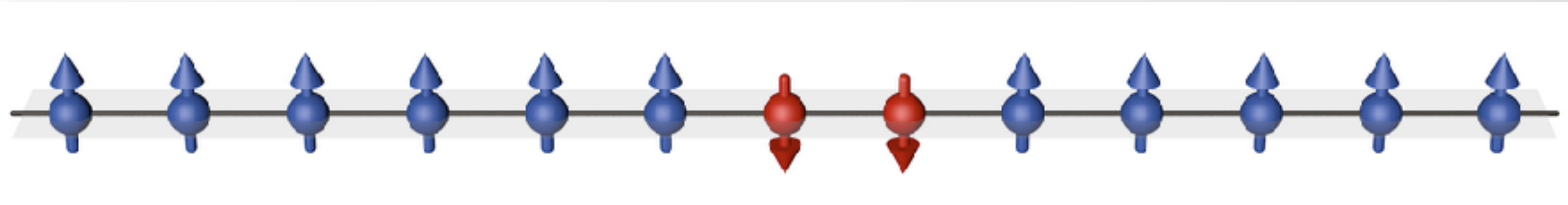
General
l-string bound states





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)

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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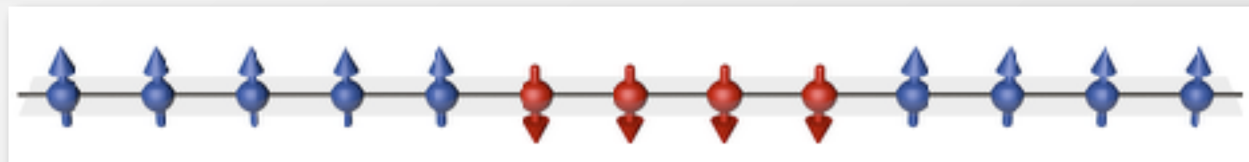
Bound l-string

Eigenenergies:

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

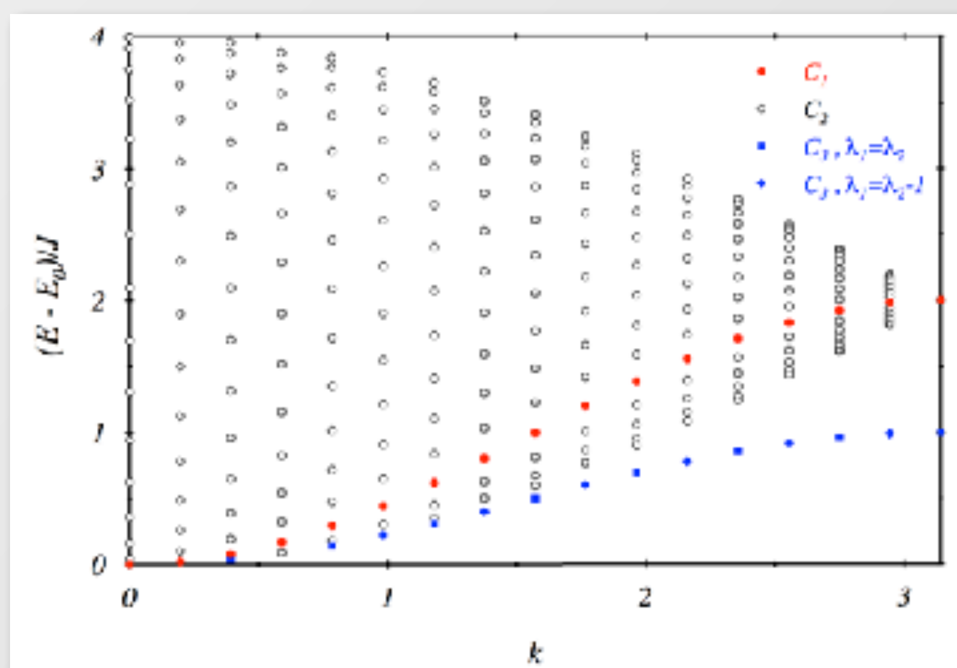


$$\Delta = \cos(\nu)$$

l-string

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

Excitation spectrum:



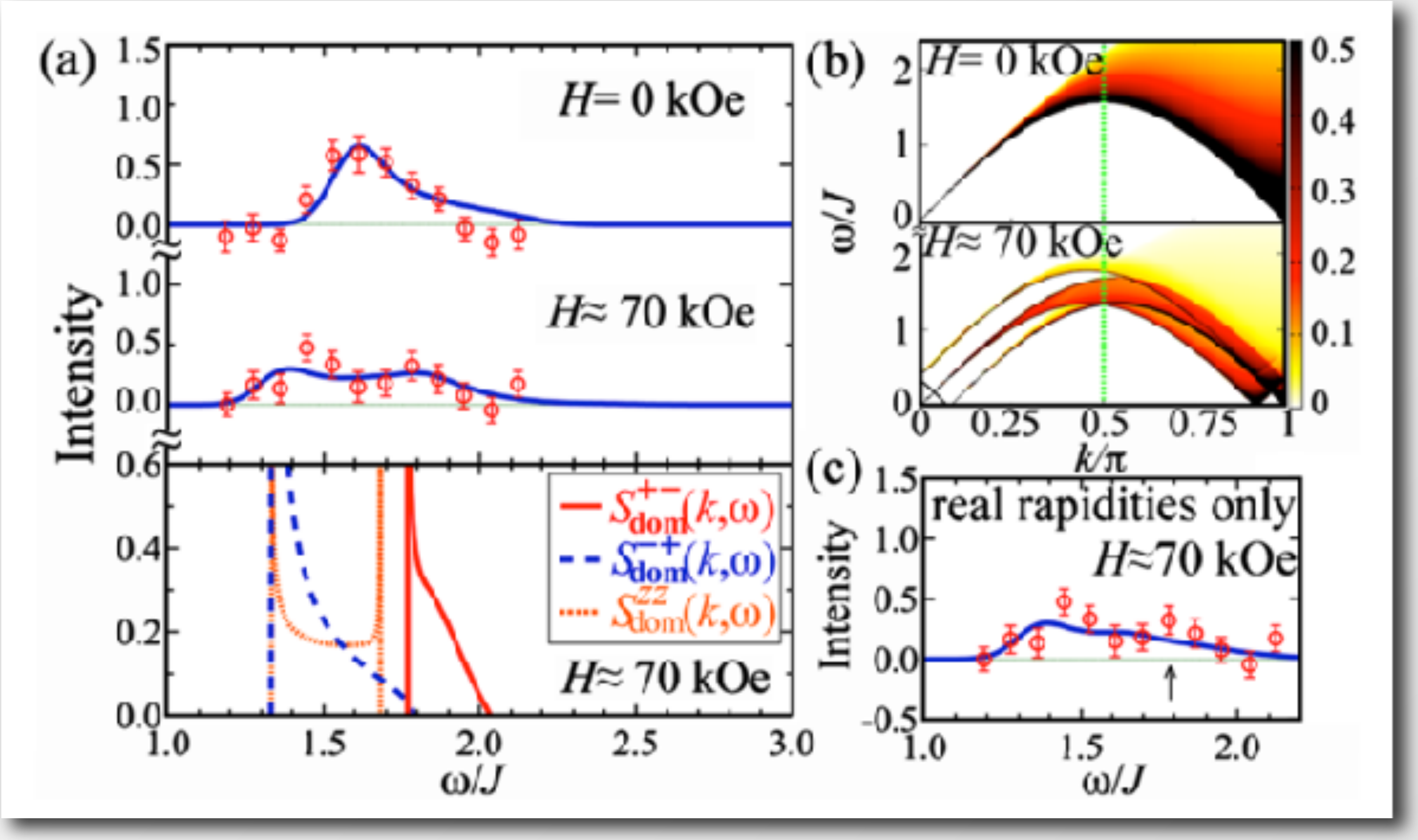
M. Karbach & G. Müller (1997)

Bound magnon

A Challenge for CM Physics

Very difficult to observe in spectroscopic data in real materials!

theory **with** bound states

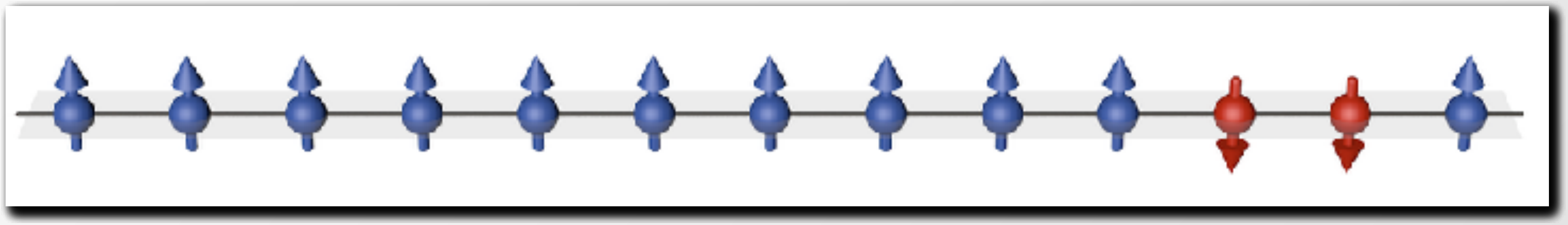


theory **without** bound states

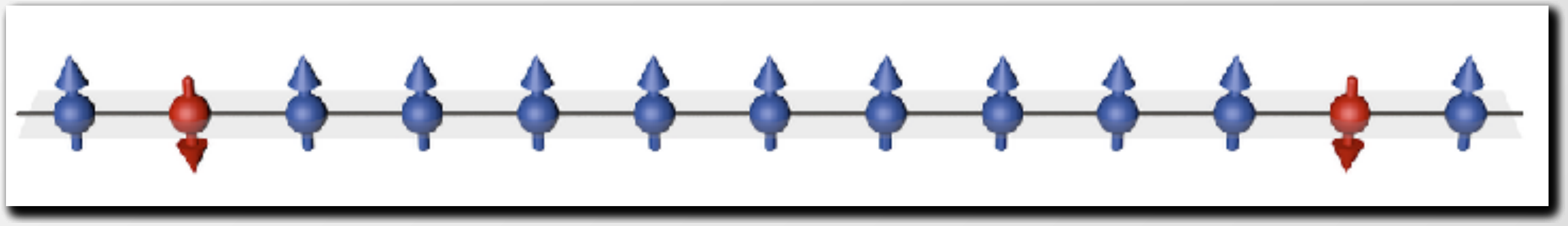
M. Kohno, Phys. Rev. Lett. **102**, 037203 (2009)

Dynamical Evolution

Bound Magnon Motion



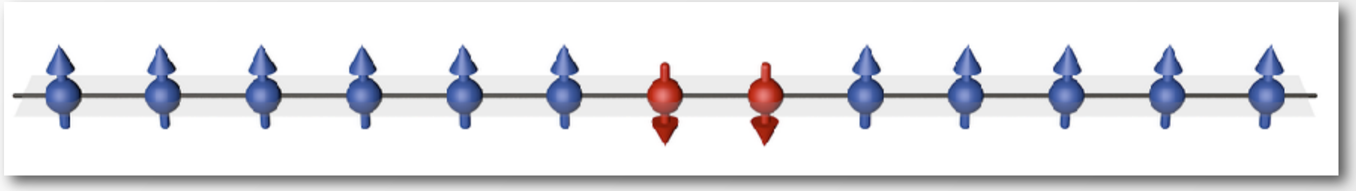
Breakup and Single Spin Motion



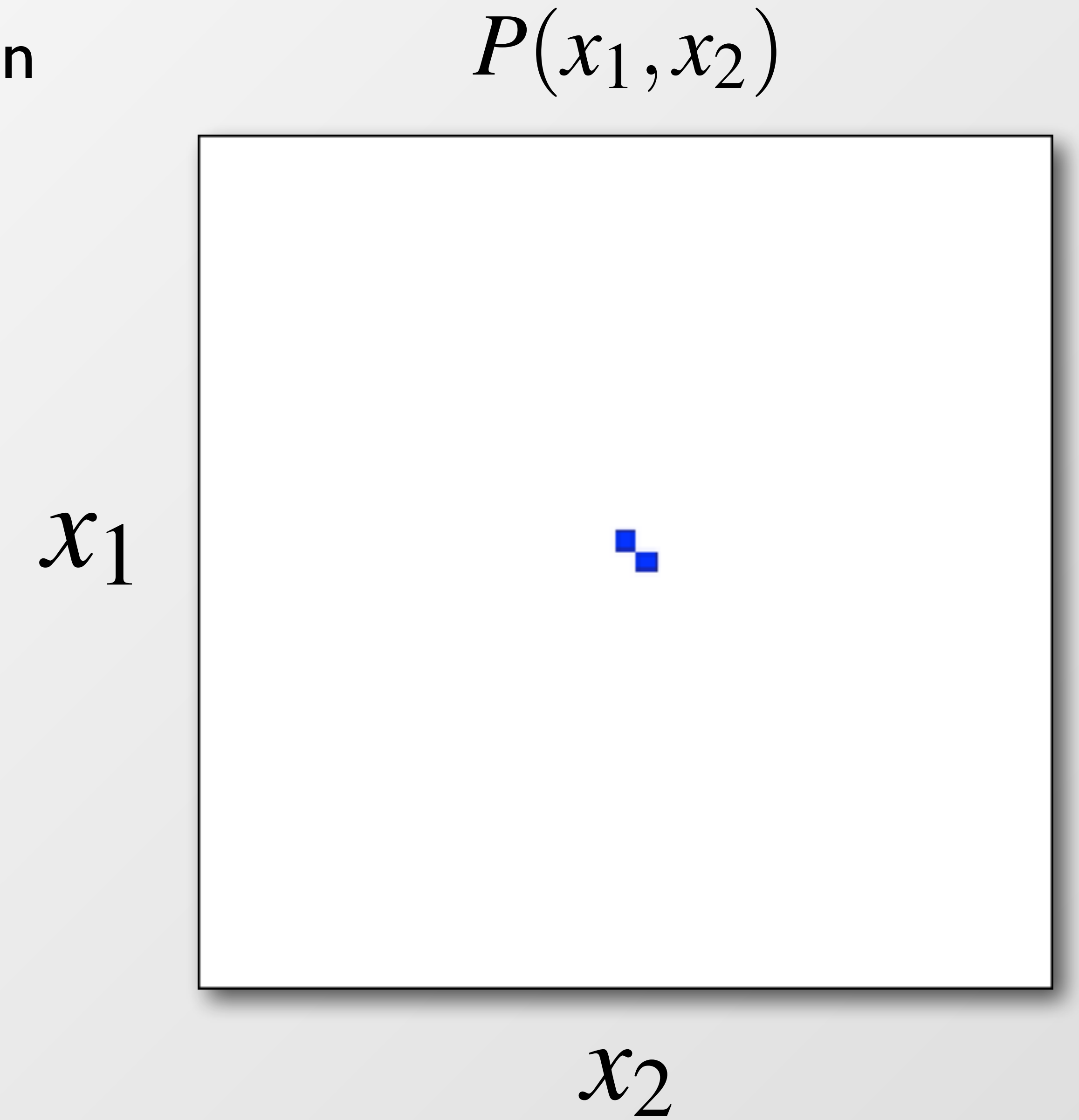
M. Ganahl et al., Phys. Rev. Lett. (2012)

Dynamical Evolution

Initial State:



Pair distribution evolution



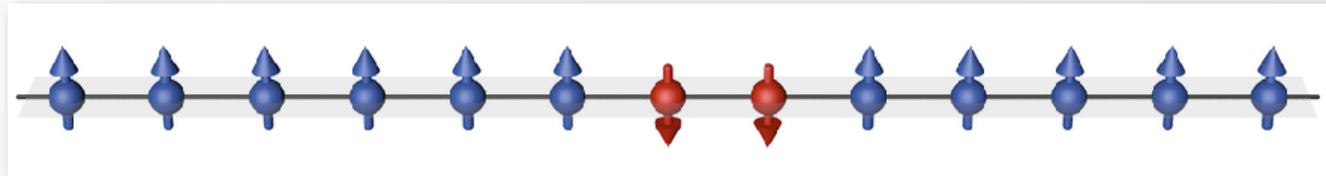
$\Delta = 0$

Non-Interacting

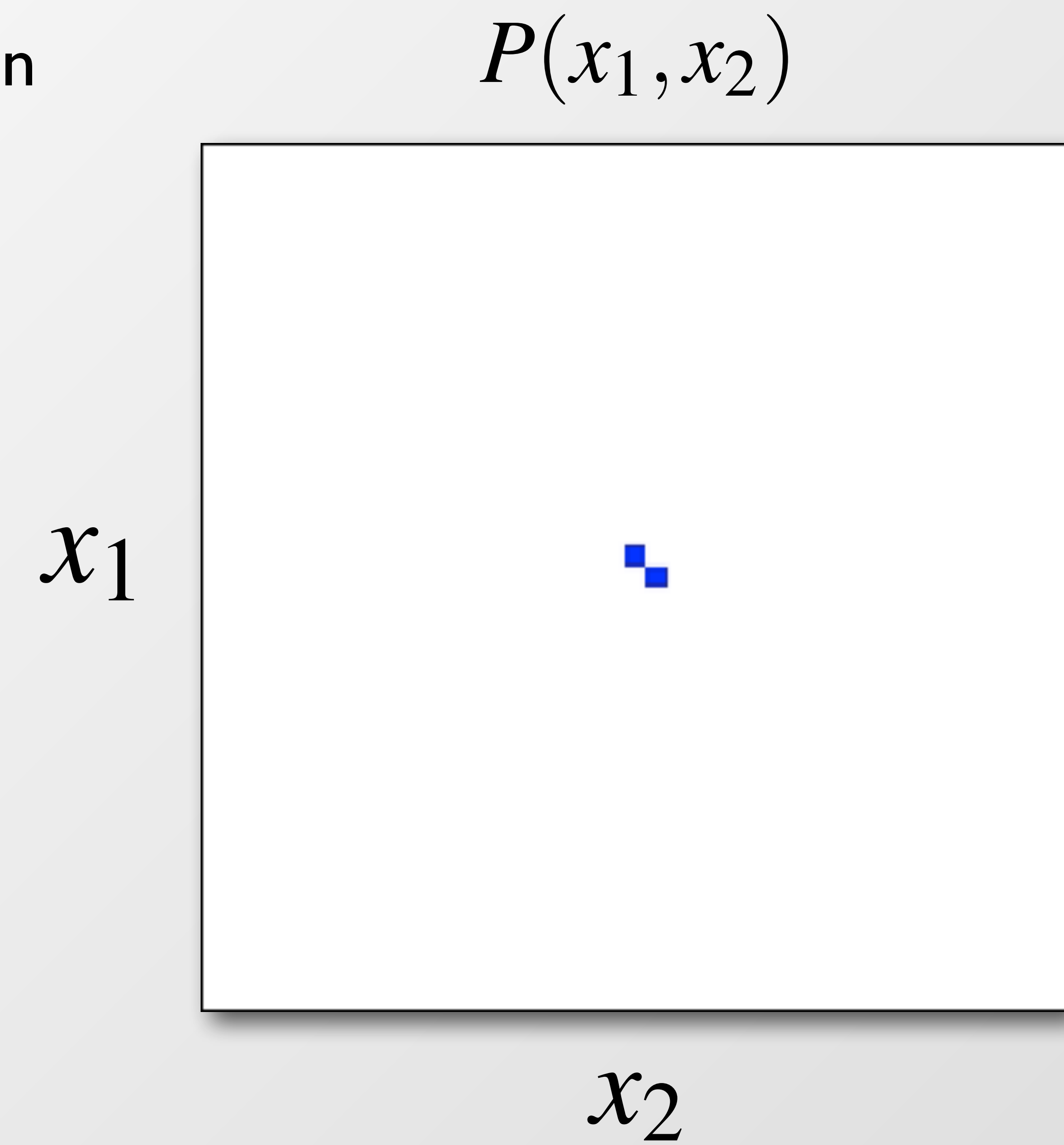
see also: two interacting atoms
Y. Lahini et al., PRA 86, 011603 (2012)

Dynamical Evolution

Initial State:



Pair distribution evolution

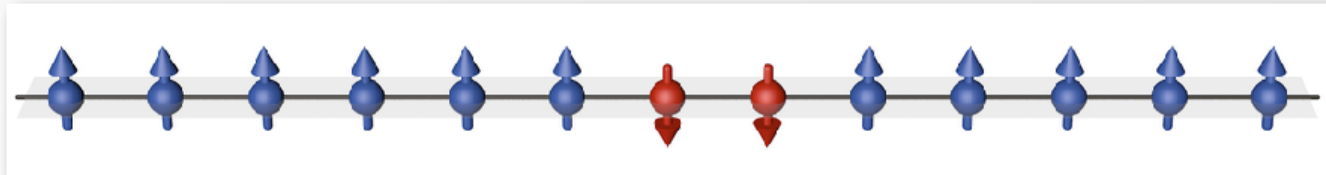


$\Delta = 1$

Interacting
Isotropic Heisenberg

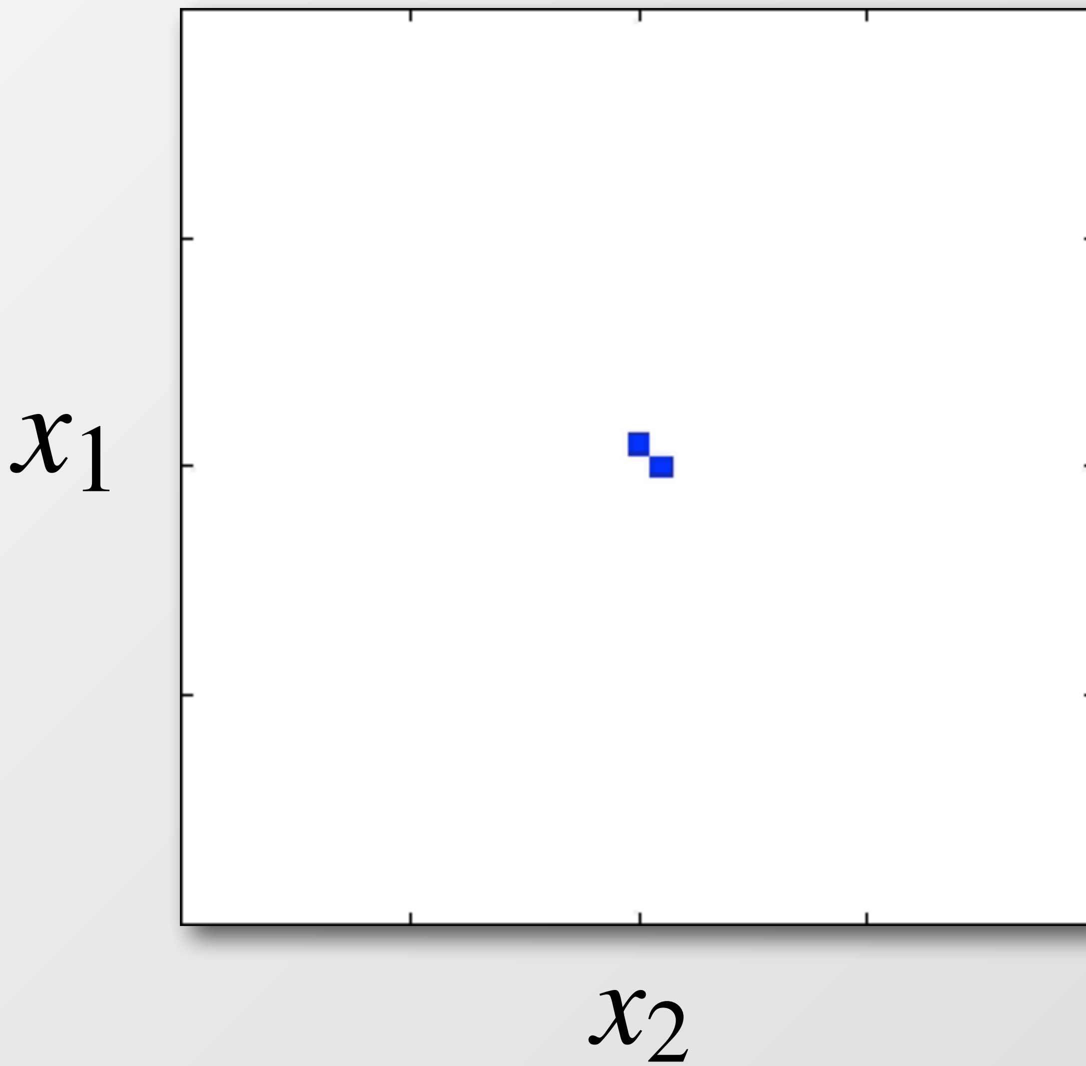
Dynamical Evolution

Initial State:



Pair distribution evolution

$P(x_1, x_2)$

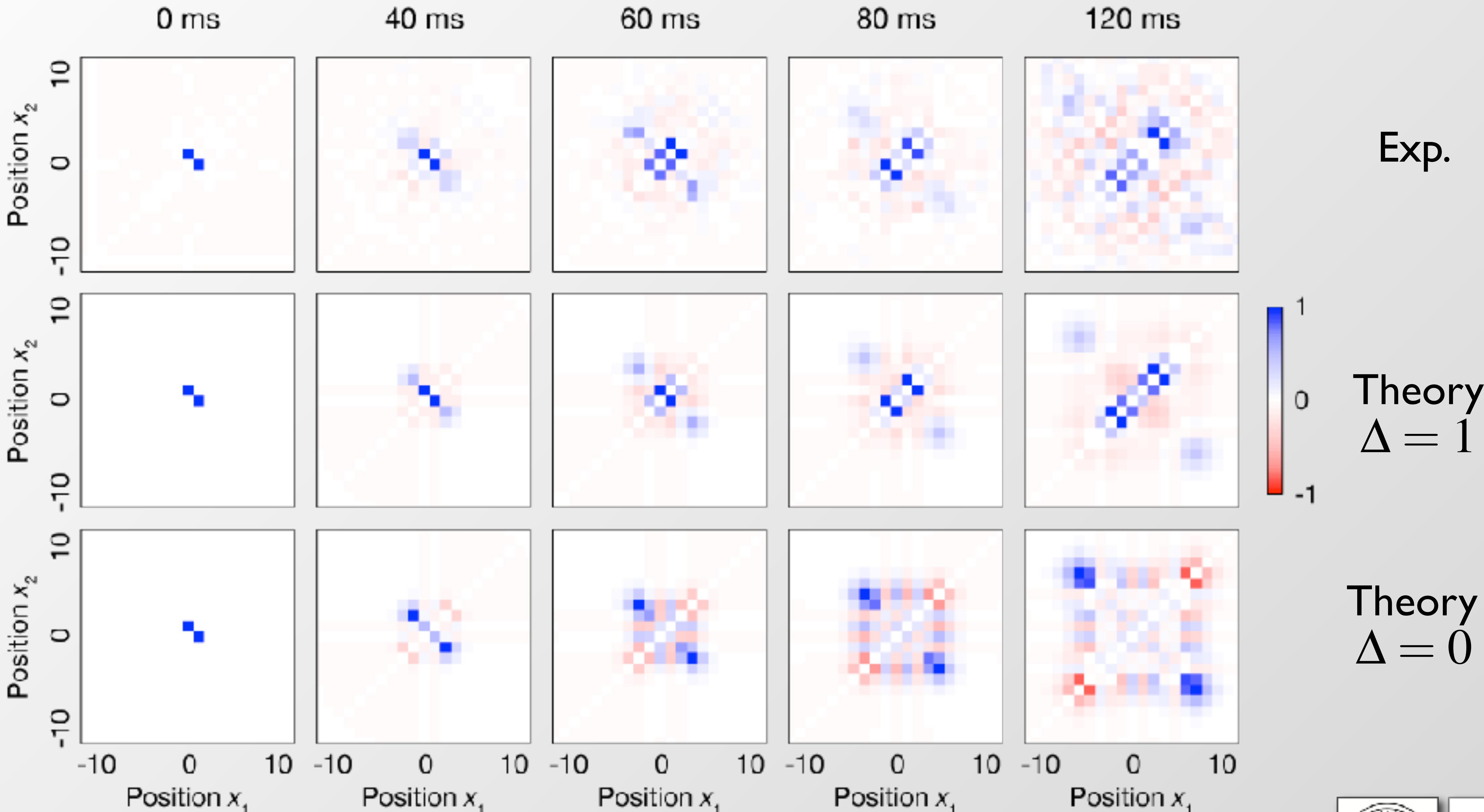


$\Delta = 1.6$

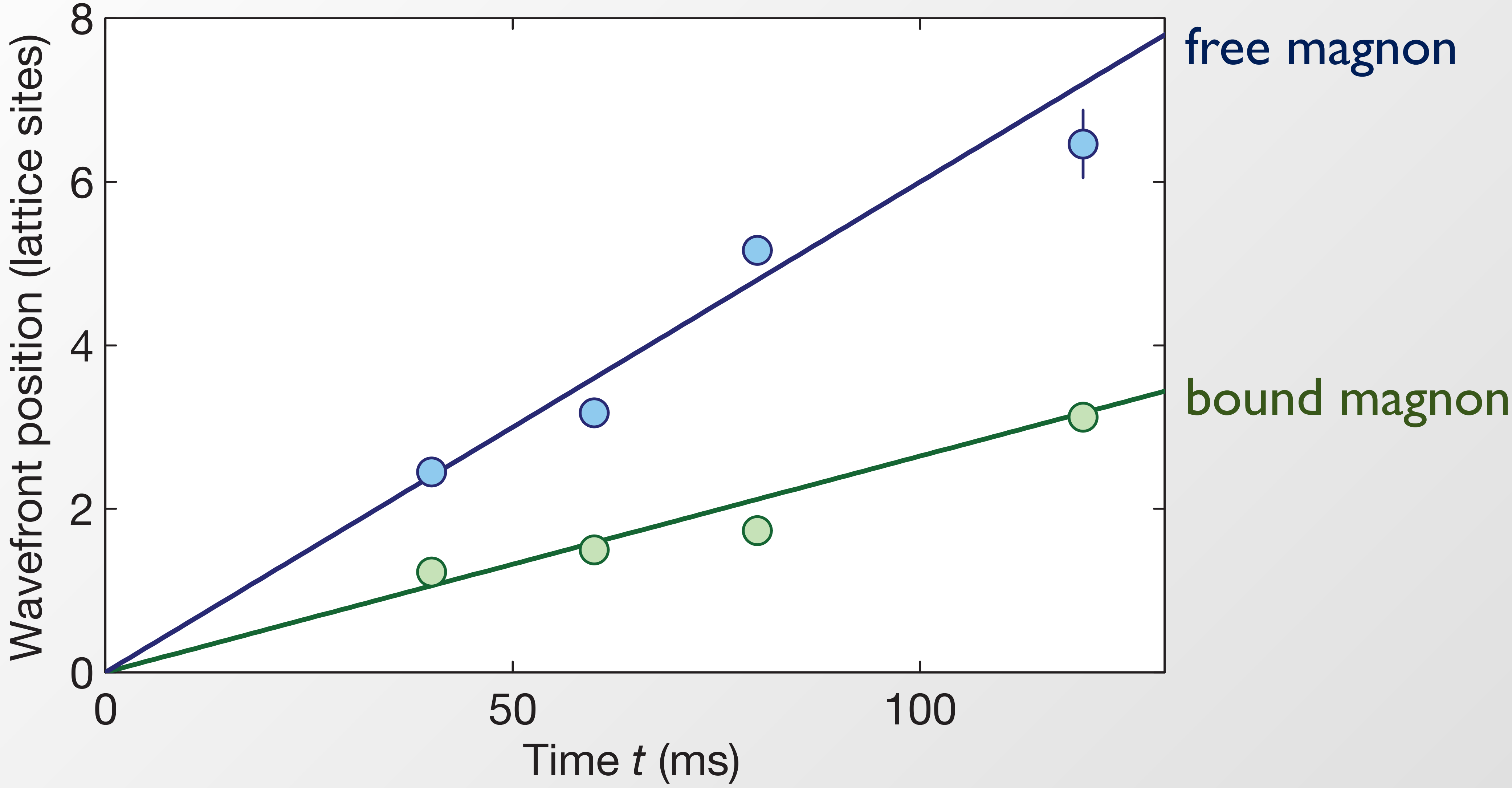
Interacting Heisenberg

Experimental Results

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



Propagation Velocity



$$v_f = \frac{J_{ex} a}{\hbar}$$

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

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

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

Outlook

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

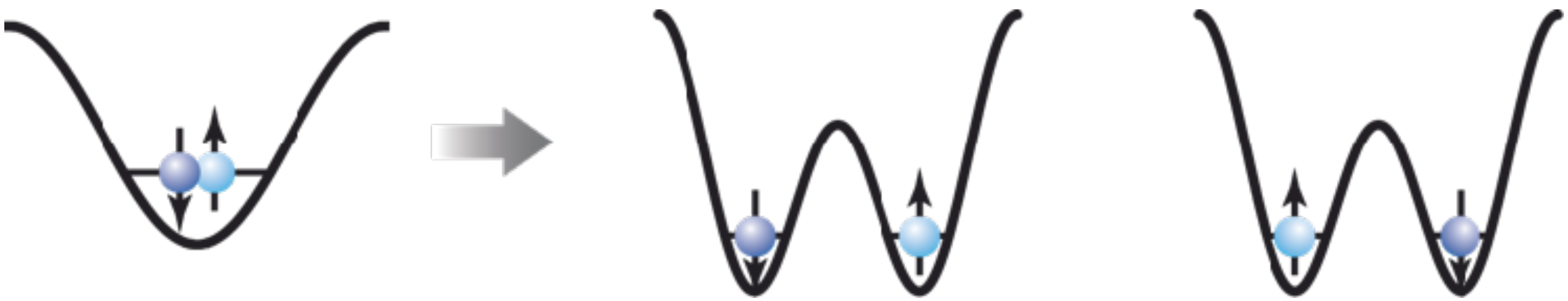
M. Knap et al. PRL **111**, 147205 (2013)

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

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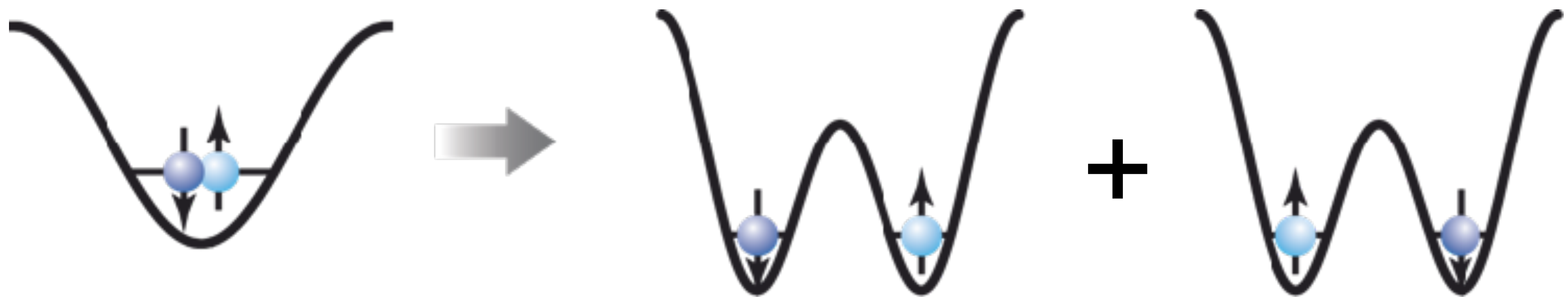


- **Bosons**: Symmetric wavefunction → Triplet $|t_0\rangle$

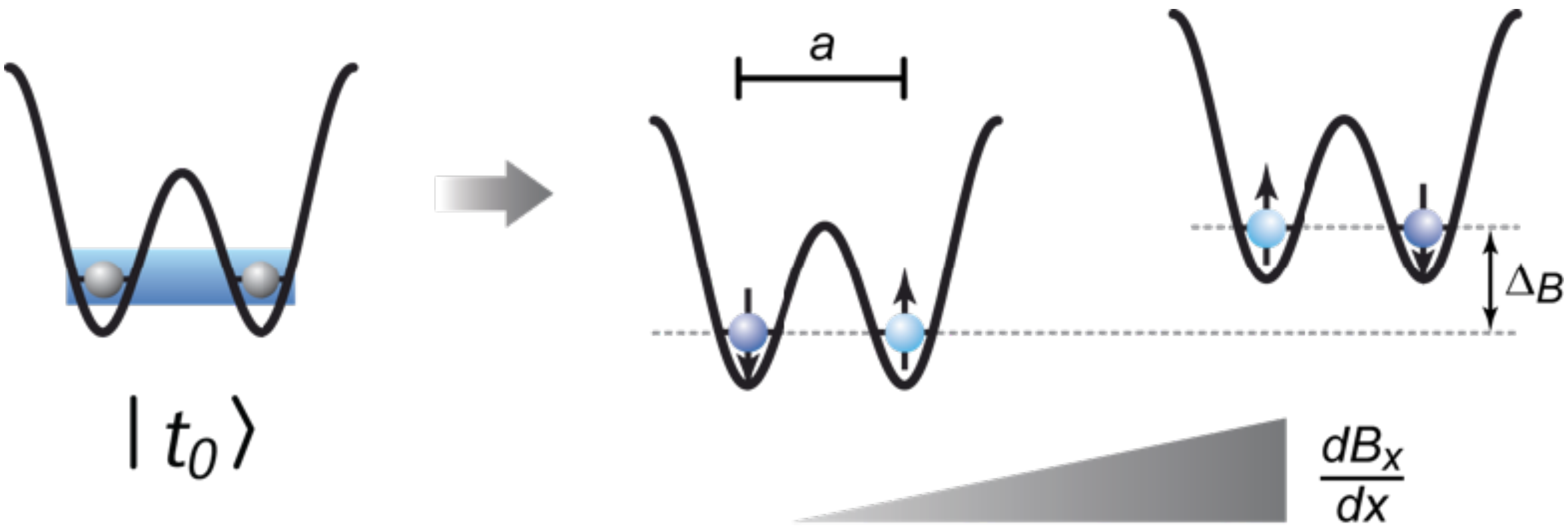
  (Fermions: Antisymmetric wavefunction → Singlet $|s\rangle$)

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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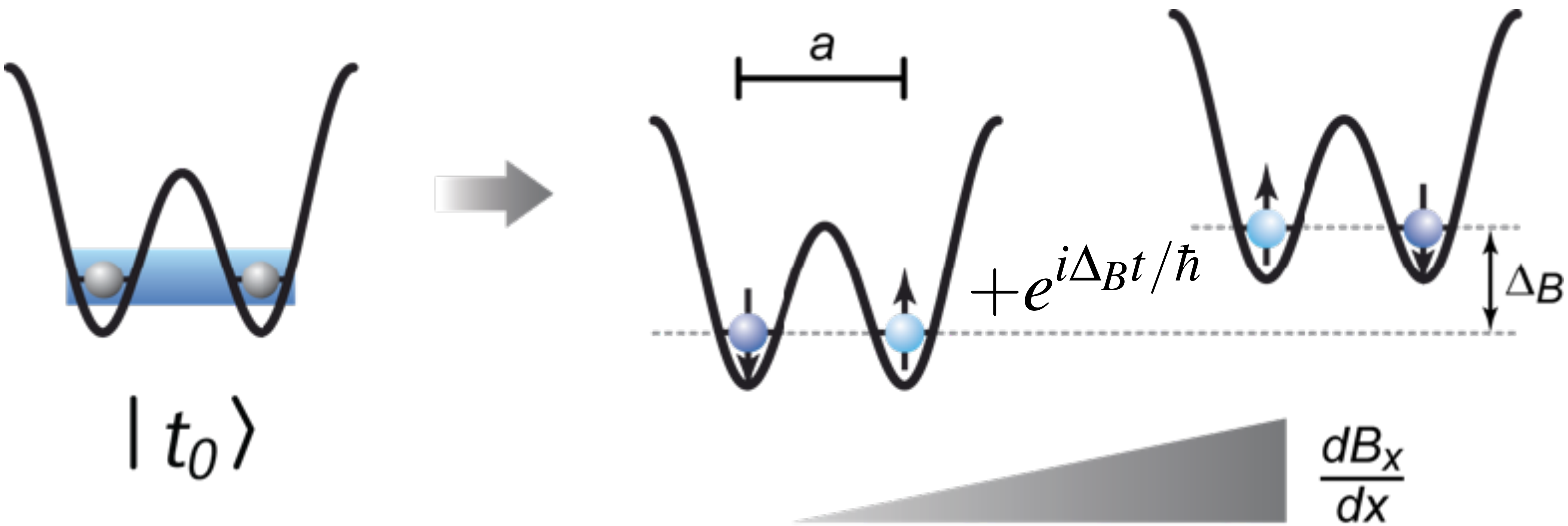


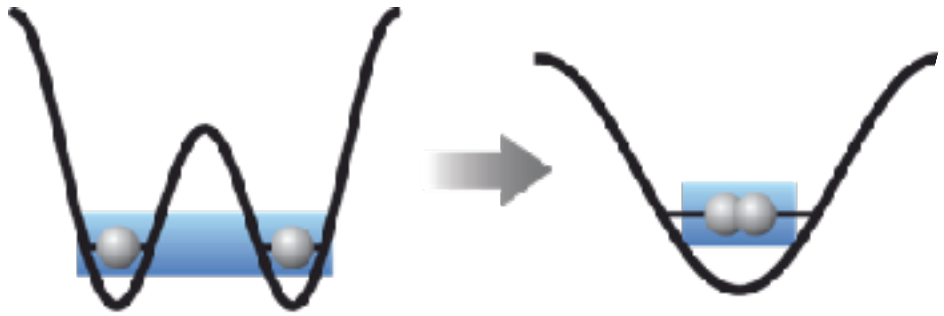
- **Triplet-Singlet oscillations** with frequency $\Delta_B / \hbar$

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

How to detect triplets and singlets

- Barrier lowered slowly to **merge** double-wells

  → **Triplet**: both atoms reach the **ground state**



How to detect triplets and singlets

- Barrier lowered slowly to **merge** double-wells

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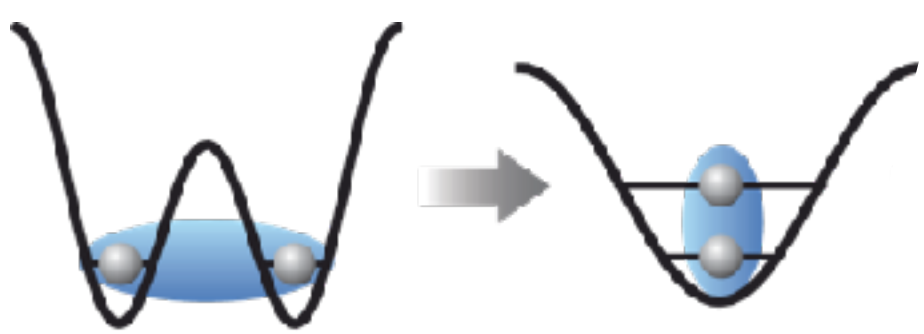
  → **Singlet**: needs anti-symm. spatial wavefunction (Bosons)

  One atom transferred to **higher vibrational band**



How to detect triplets and singlets

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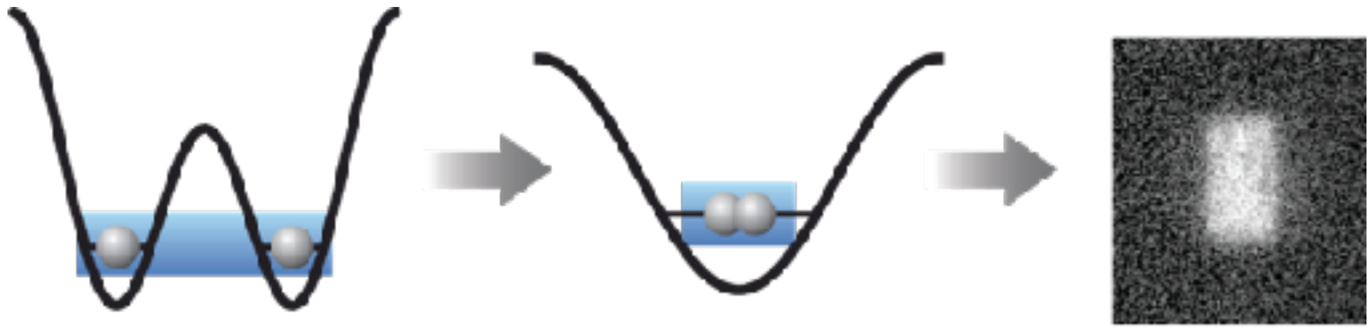

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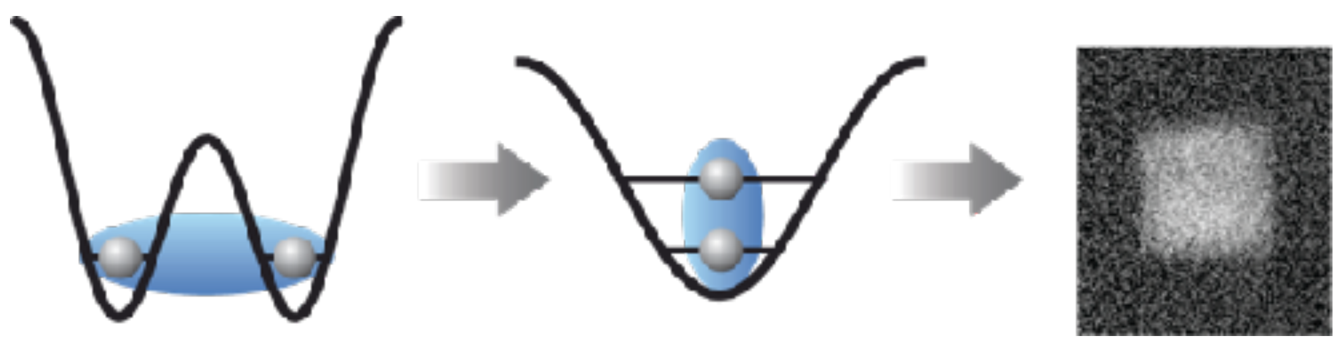


Band-mapping reveals **singlet-contribution in higher Brillouin-Zone**

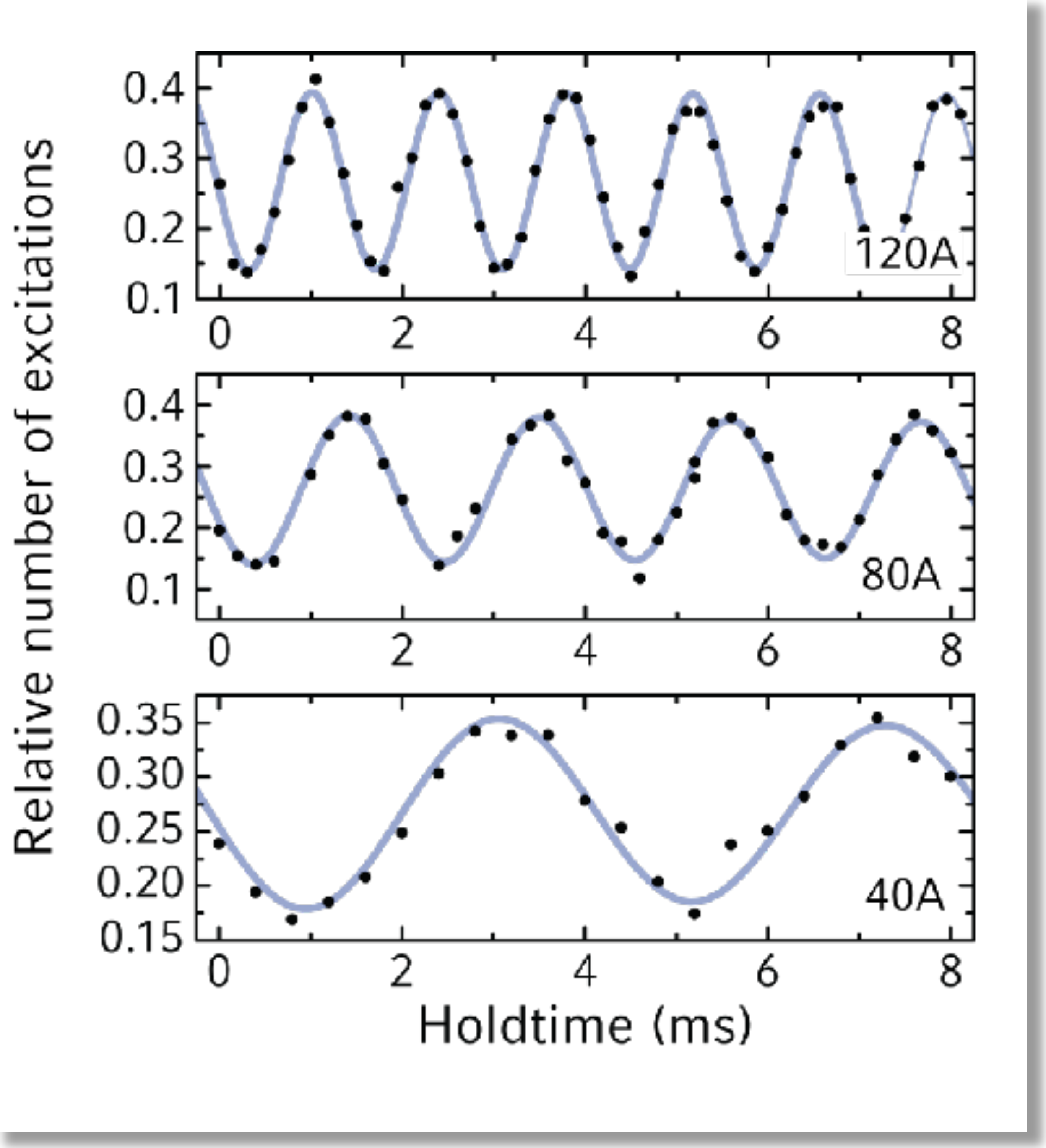
A sensitive probe of next-neighbor spin-correlations in Mott-insulator type many-body systems

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

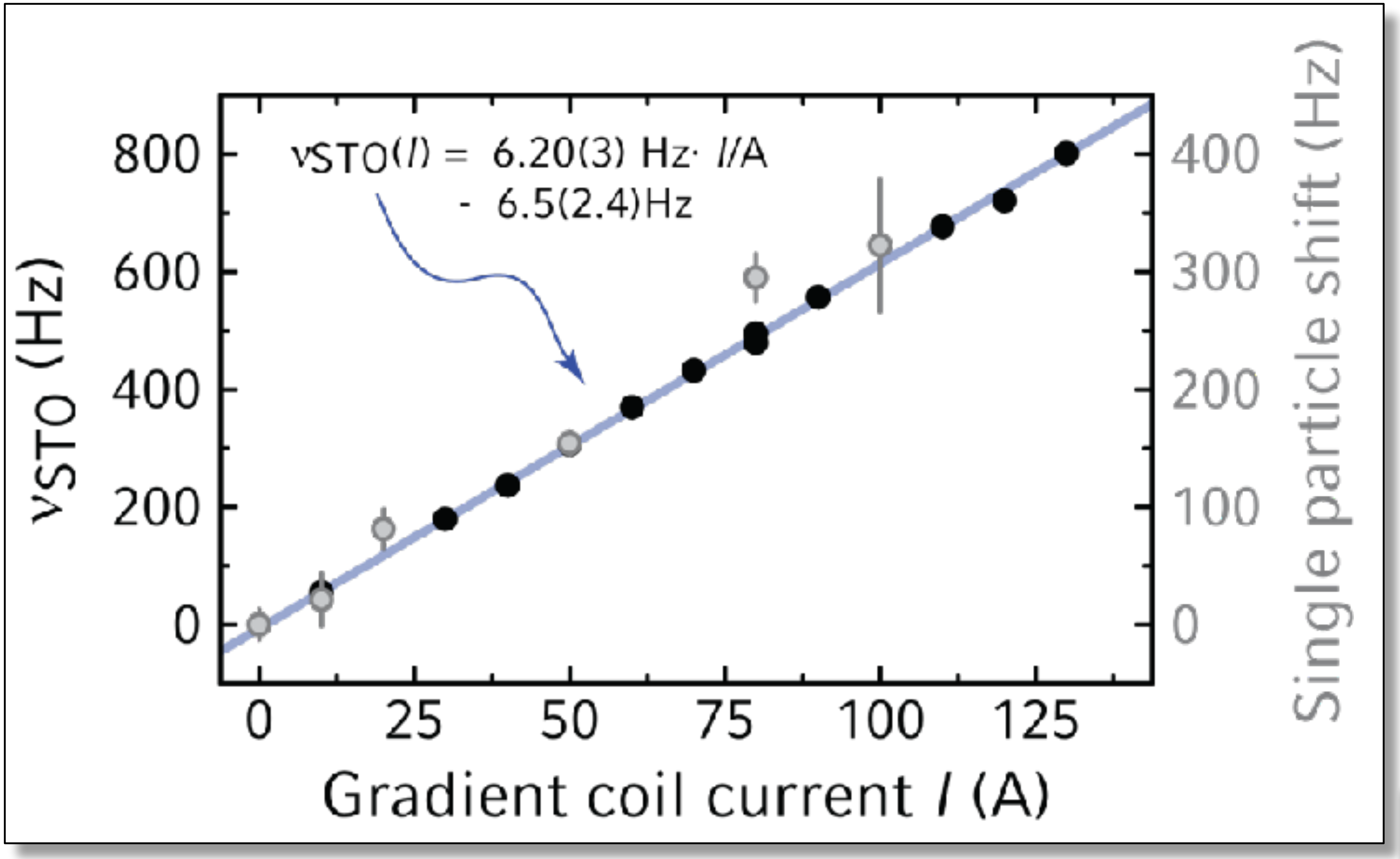
→ **Traces of STO** versus holdtime with gradient

- 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

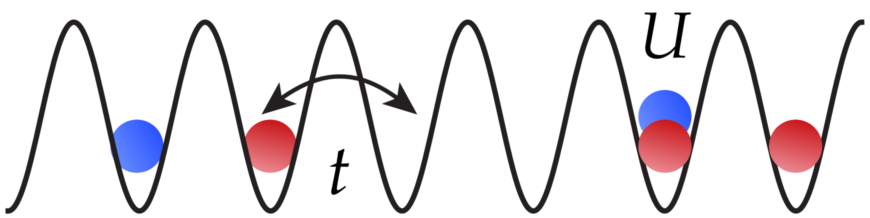
- **Linear increase** in Frequency with gradient strength
- Frequency = **2x single particle shift** (independently meas.)
  → confirms **2-particle nature** of oscillations



Controlling and Detecting Spin Correlation in Doped FHM

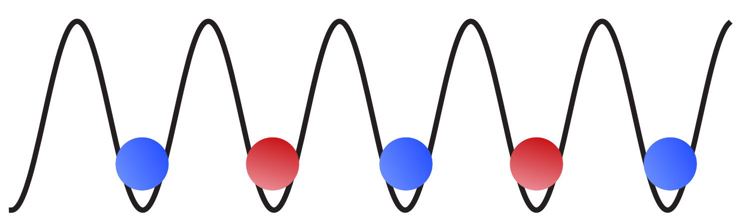
Fermi Hubbard Model (FHM)

Fermi-Hubbard Model



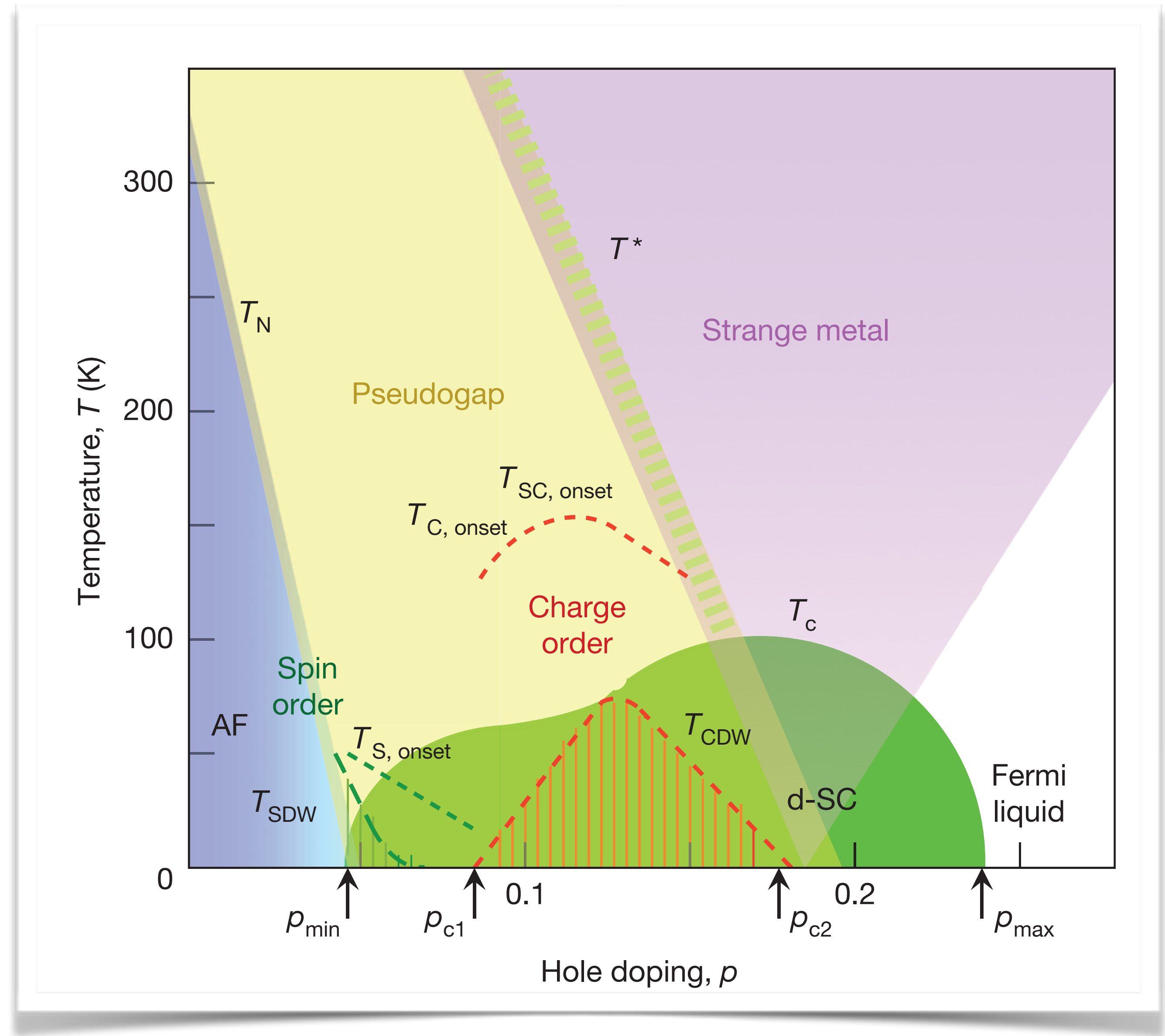
AFM Heisenberg Model

Half filling & strong interaction



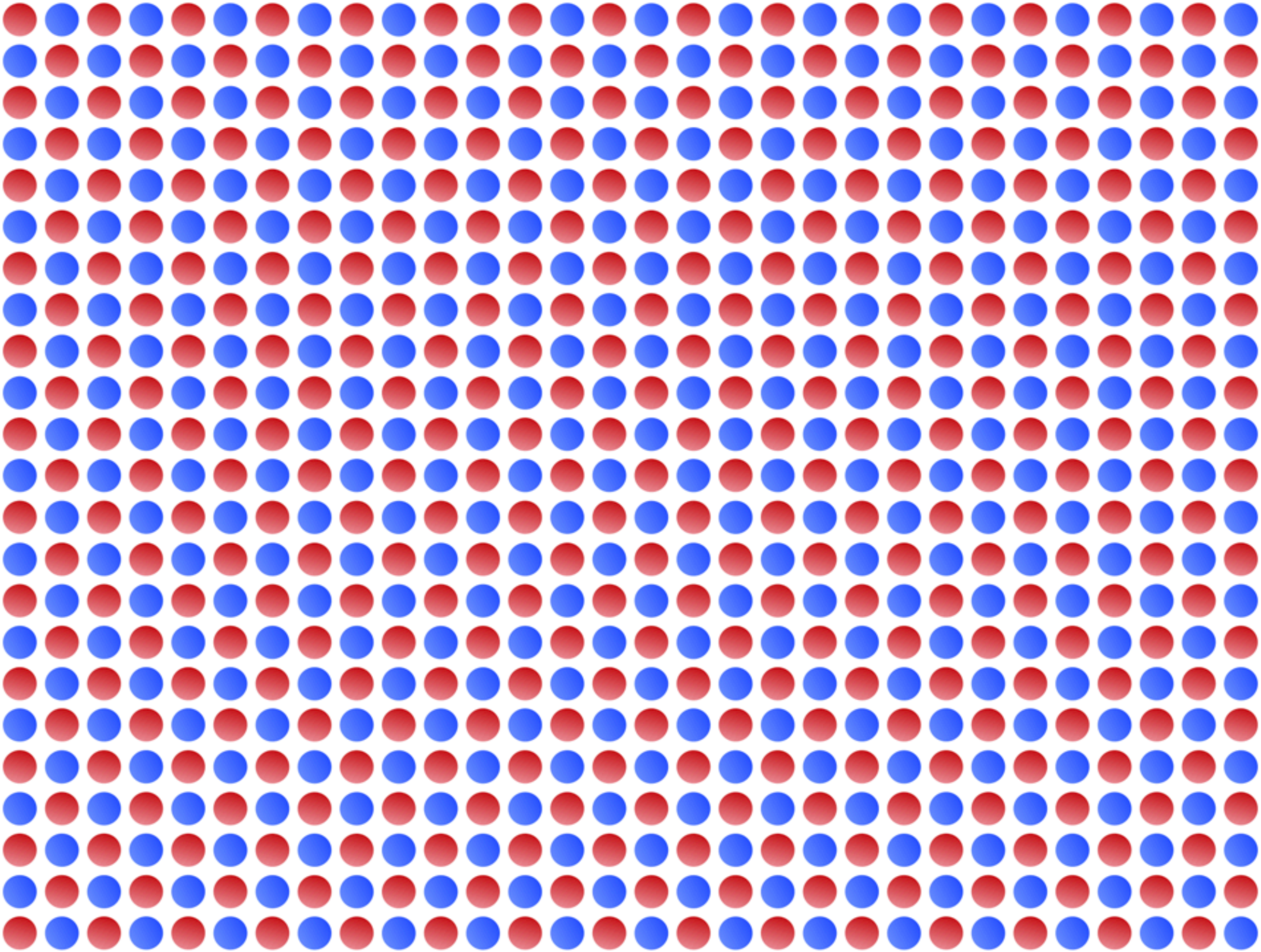
$$H = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j \qquad J = \frac{4t^2}{U}$$

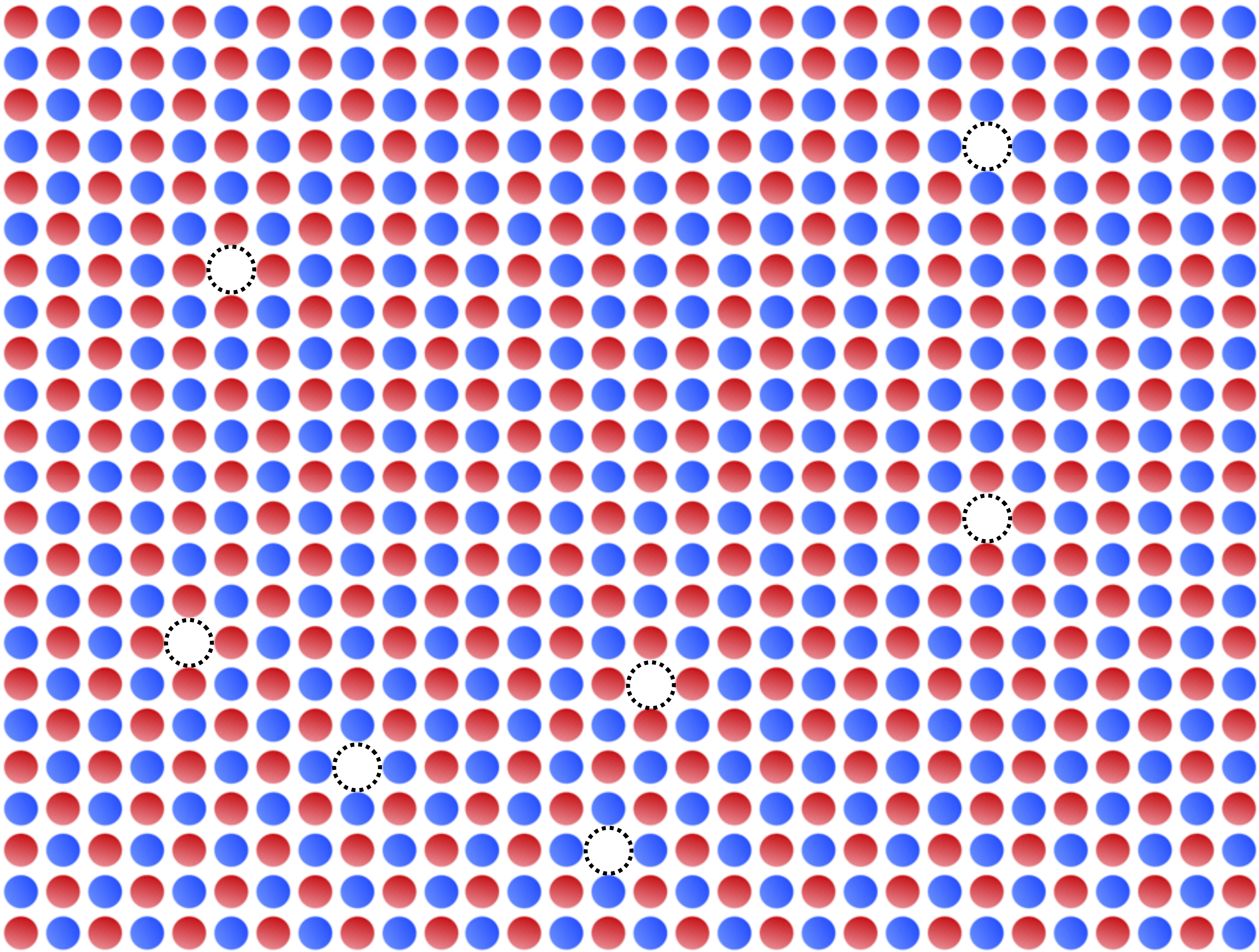
B. Keimer *et al.*, Nature **518** 2015

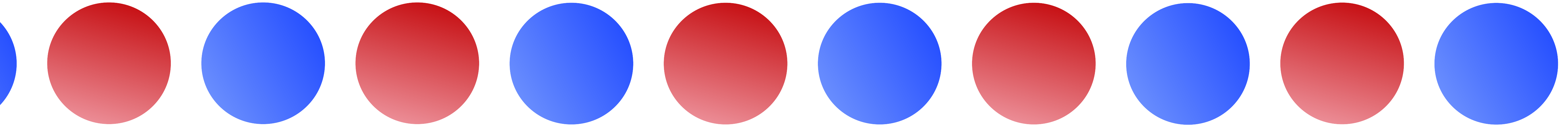


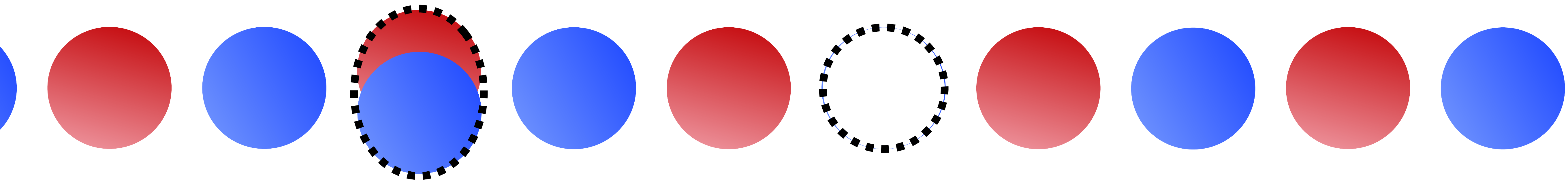
Away from half filling: ***t*-*J* model**
competition between

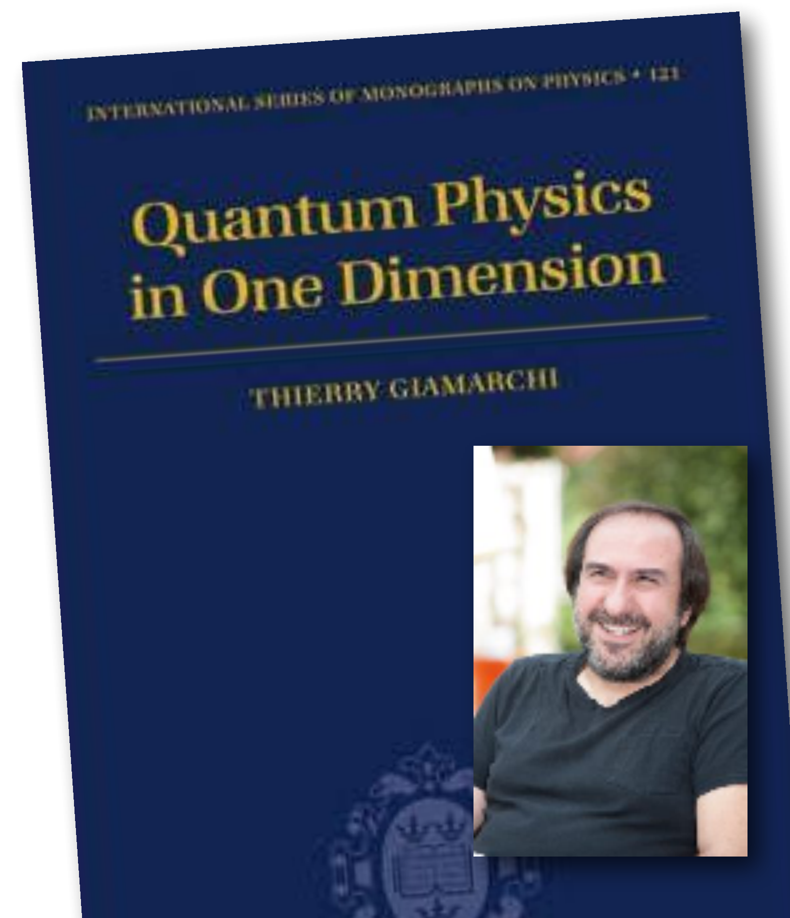
hole delocalization ↔ ***magnetic order***



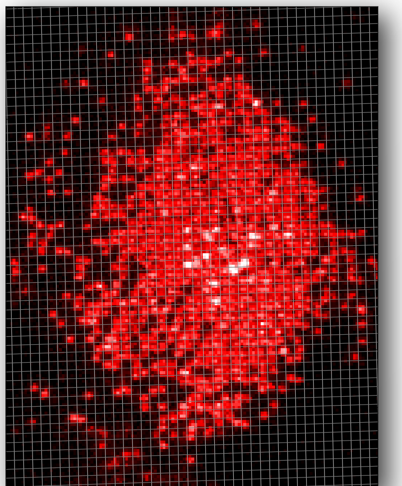




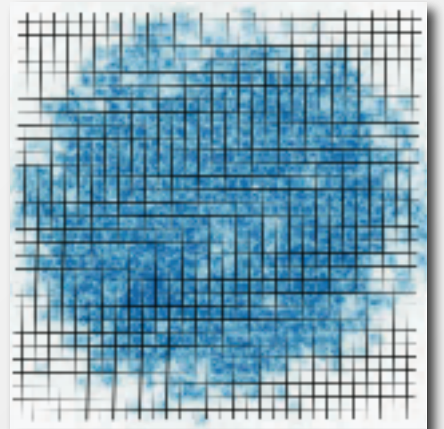



INTERNATIONAL SERIES OF MONOGRAPHS ON PHYSICS • 121
Quantum Physics
in One Dimension
THIERRY GIAMARCHI

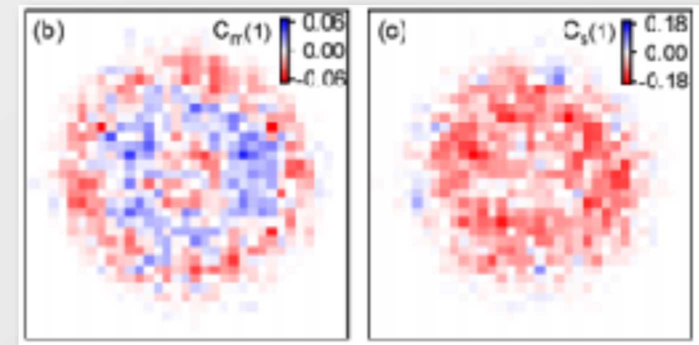
Fermi-Hubbard - 2016-2017



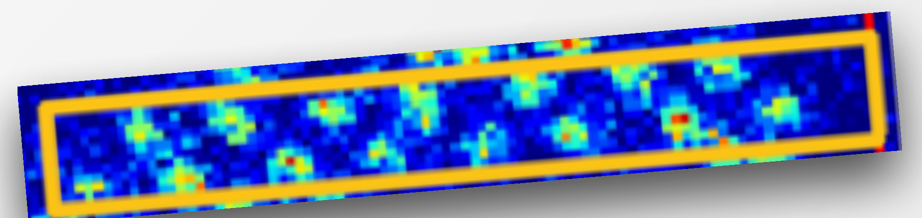
A. Omran *et al.* PRL (2015)



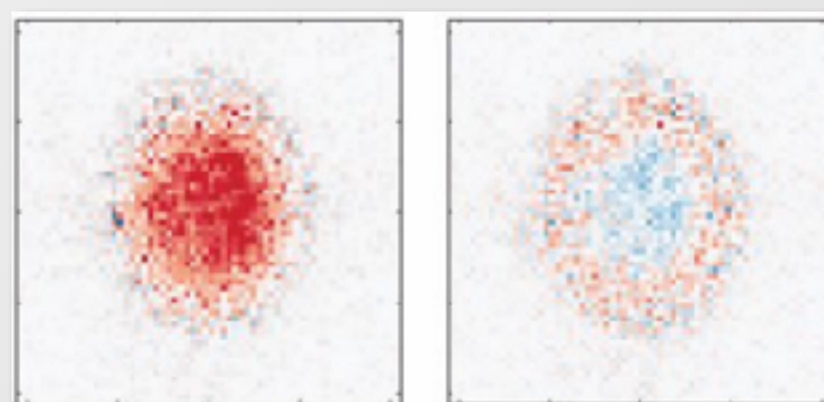
D. Greif *et al.* Science (2016)



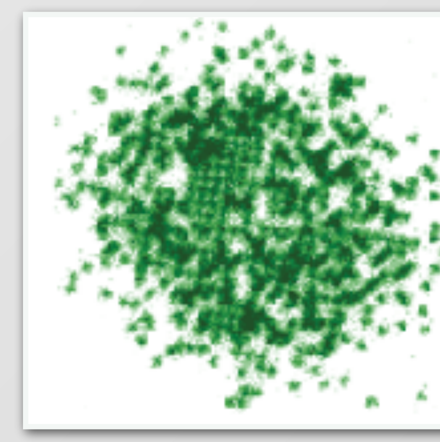
L. Cheuk *et al.* Science (2016)



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



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

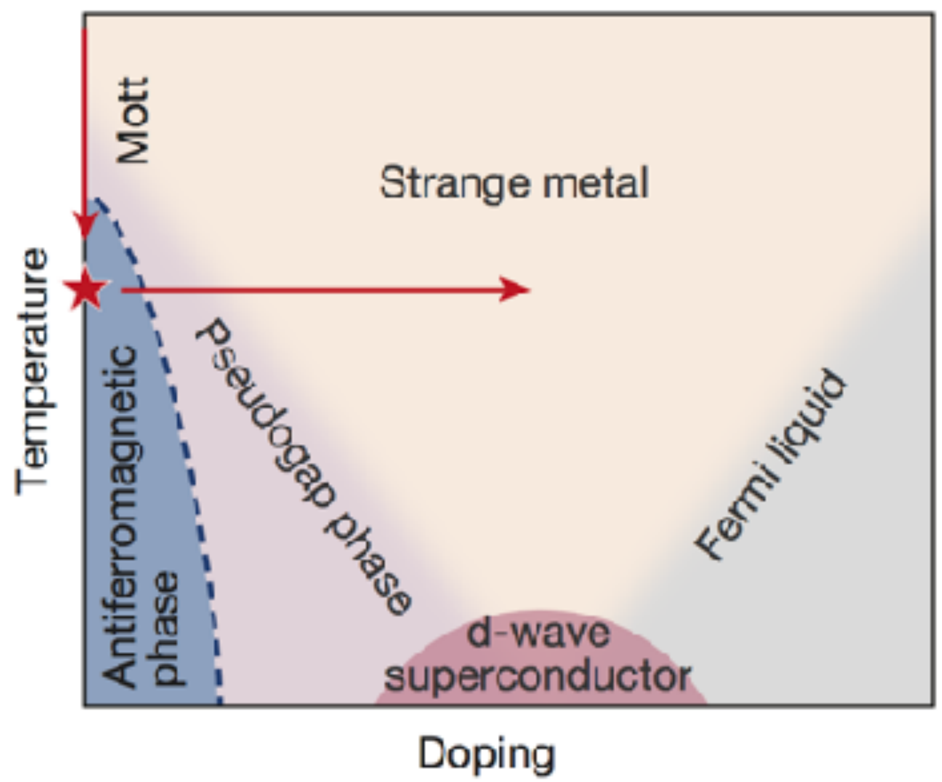


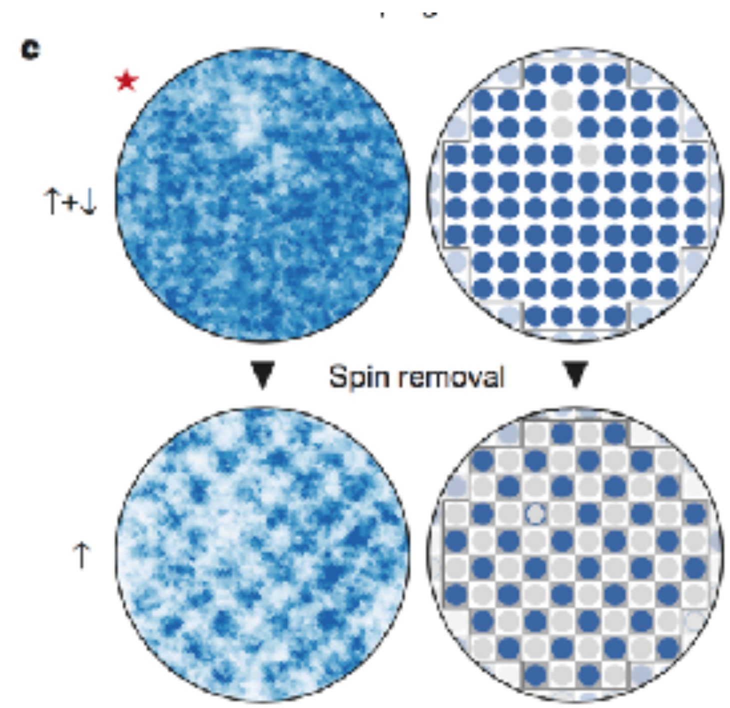
P. Brown *et al.* Science (2017)

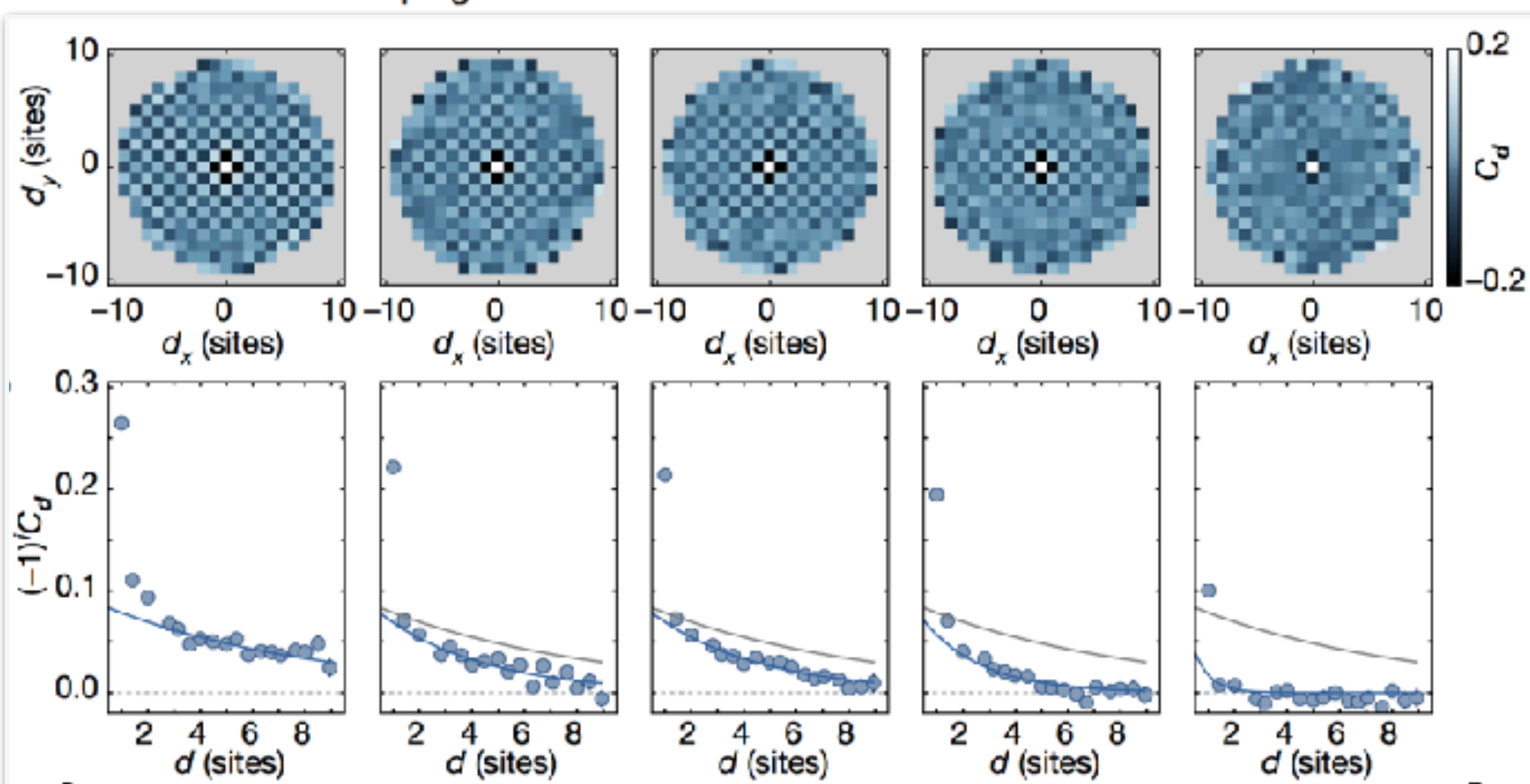
AFM Correlations (Short, Medium & Long Ranged) now visible!

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

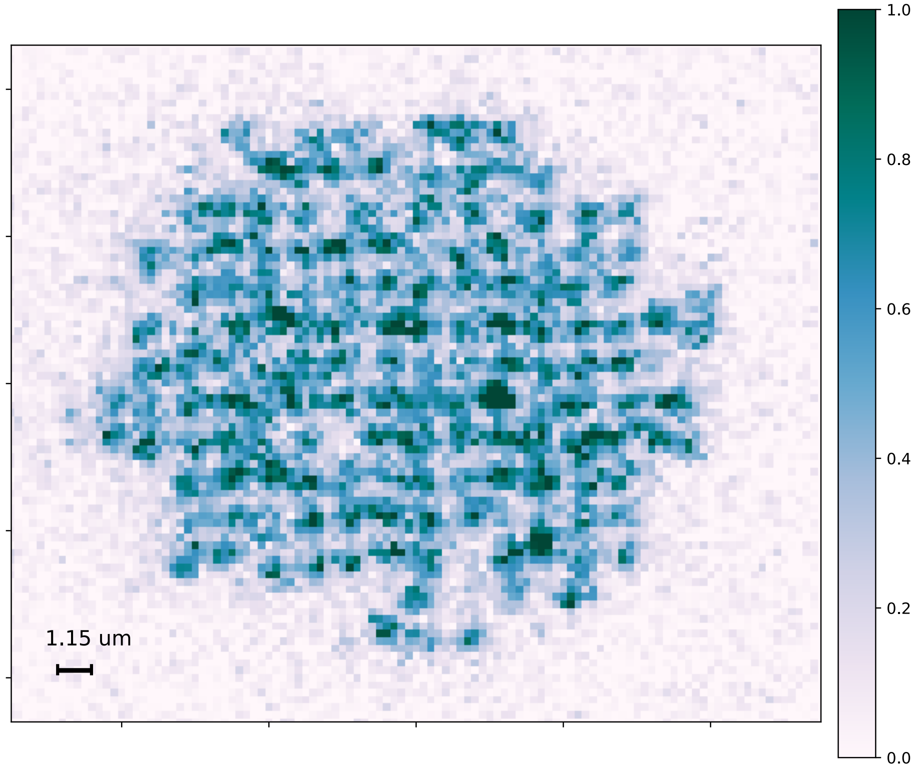




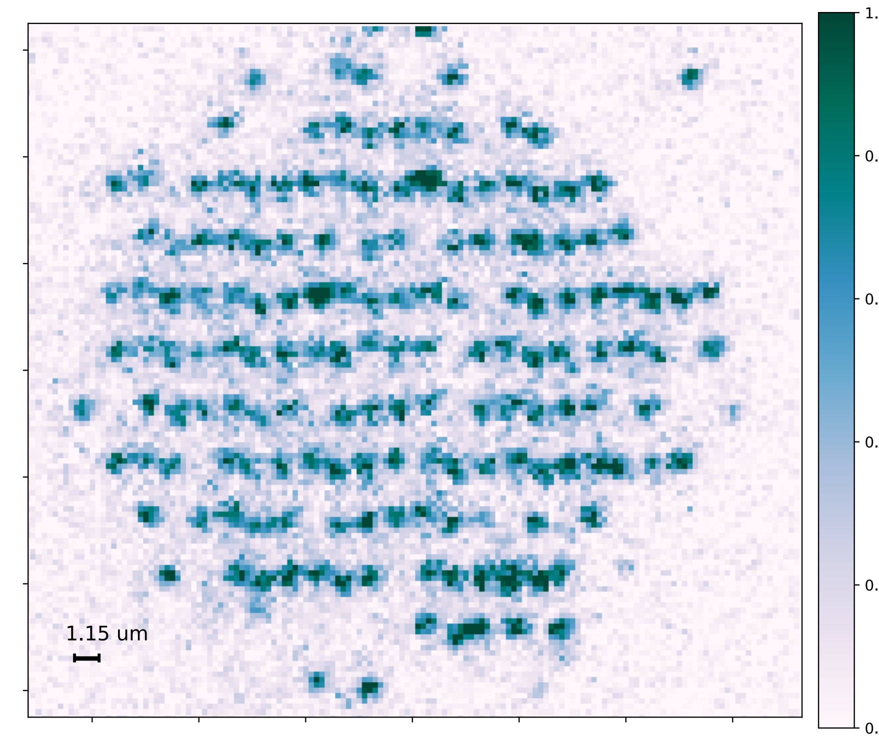


A. Mazurenko et al.,
Nature **545**, 462

Mott Insulators



Mott Insulator
(Short-Short Lattice)

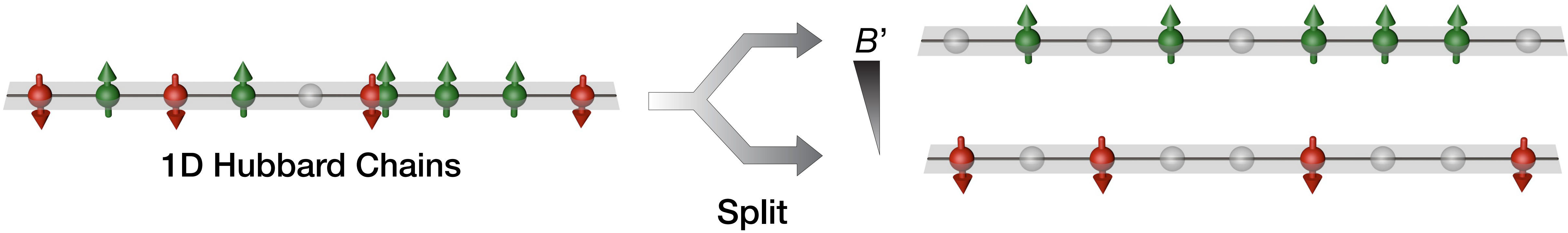


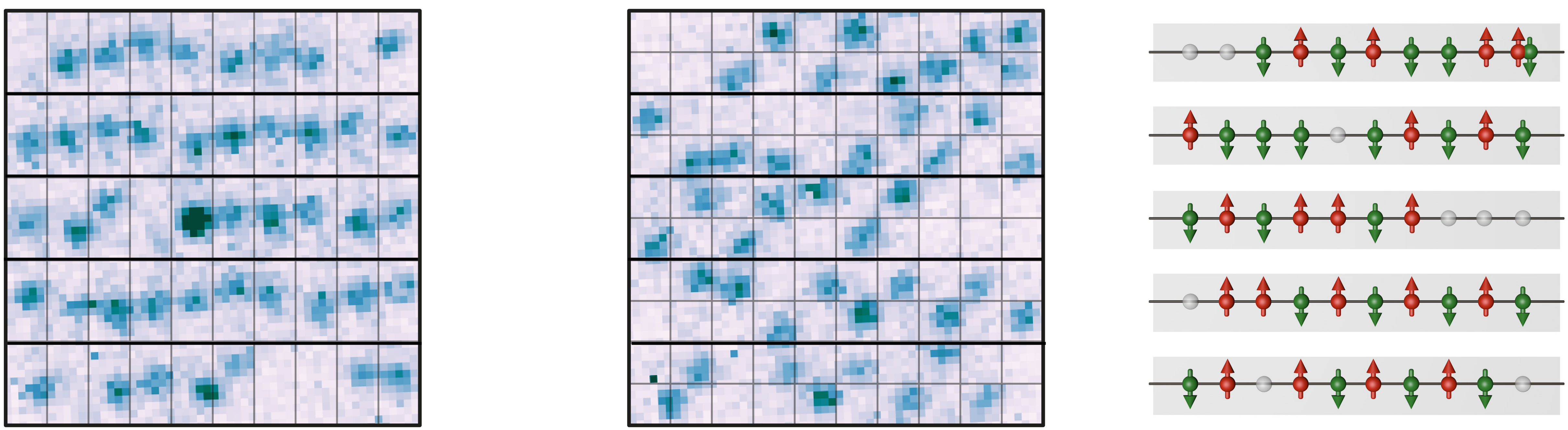
Mott Insulator
(Short-Long Lattice)

No Parity Projection!

Holes-Doublons Distinguishable

Spin & Charge Resolved Imaging

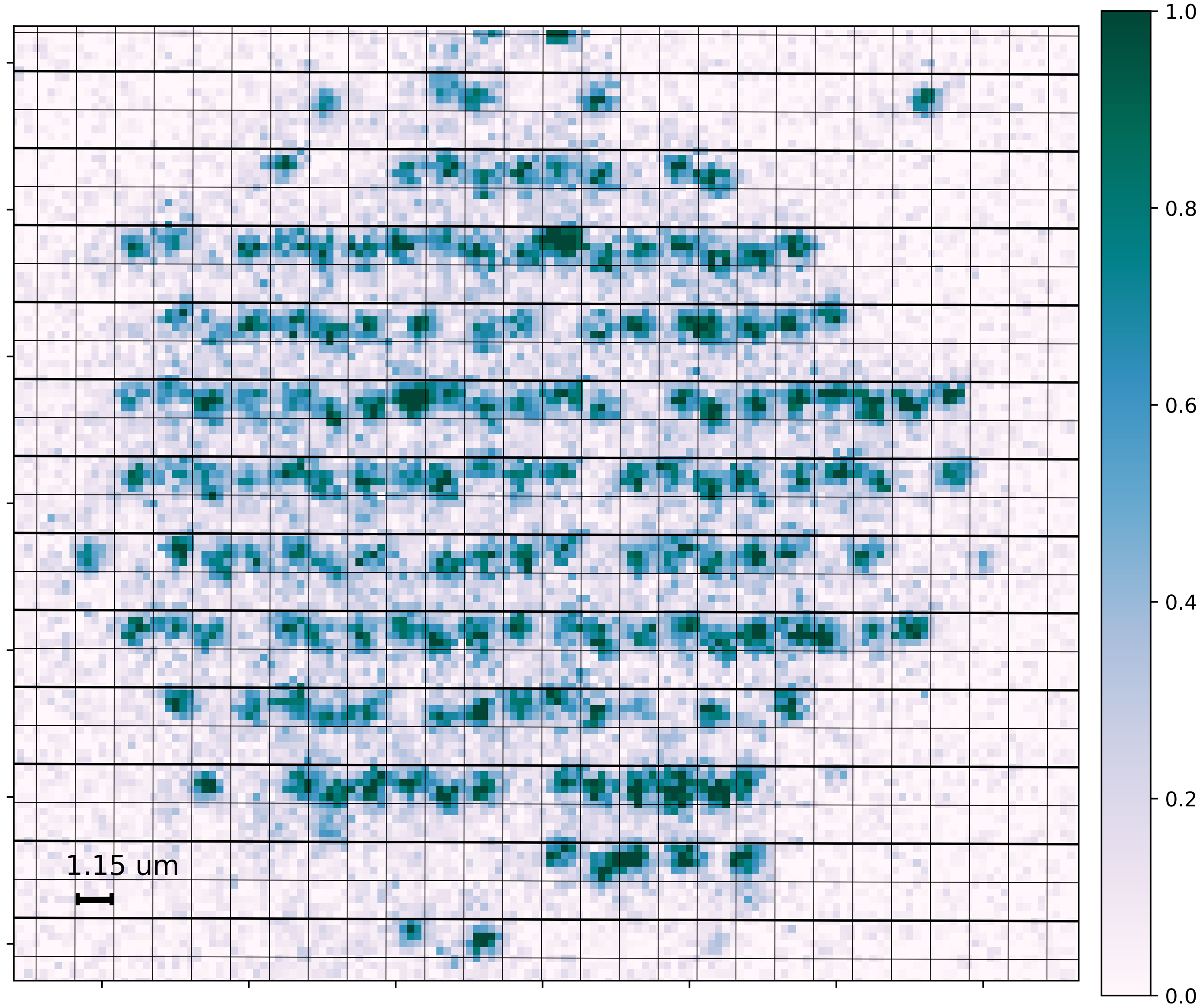




1D Chains (spin unresolved) Split 1D Chains (spin resolved) Reconstruction

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

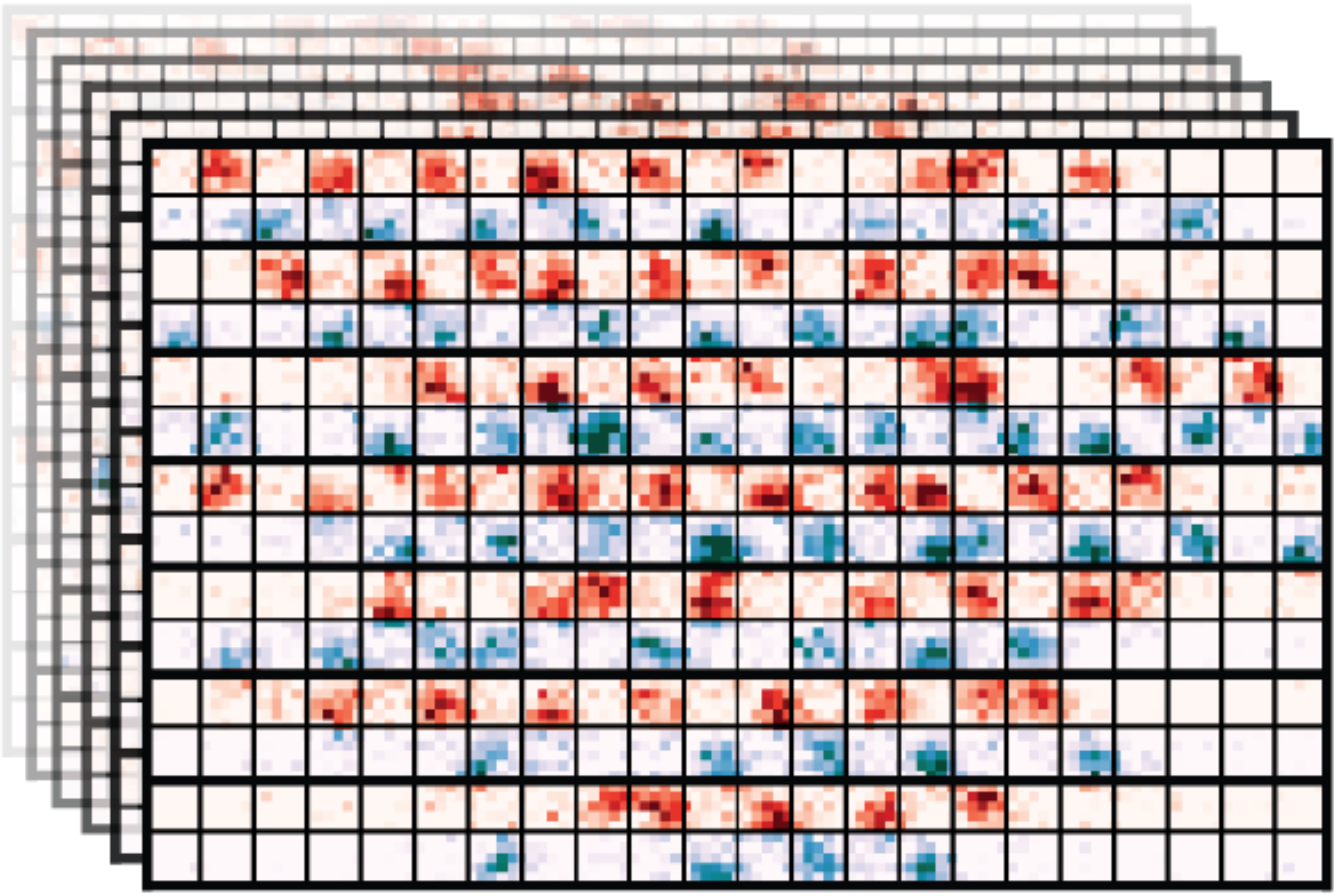
Spin-Charge Resolved Detection



Charge Resolved **Spin Un-Resolved**

Spin-Charge Resolved Detection

Spin Resolved

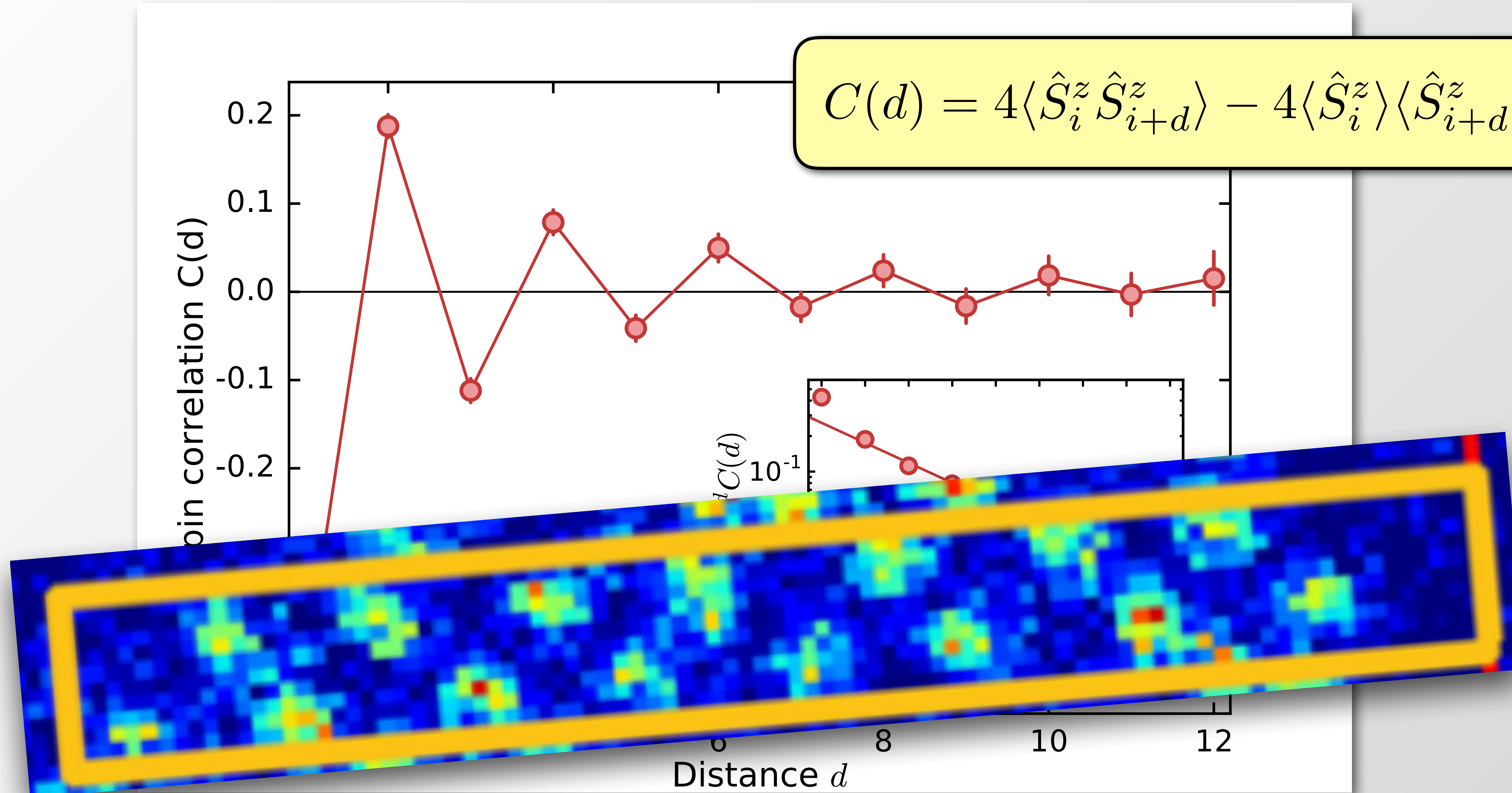


Charge Resolved

Incommensurate Magnetism

Postselection to $M_z = 0$!

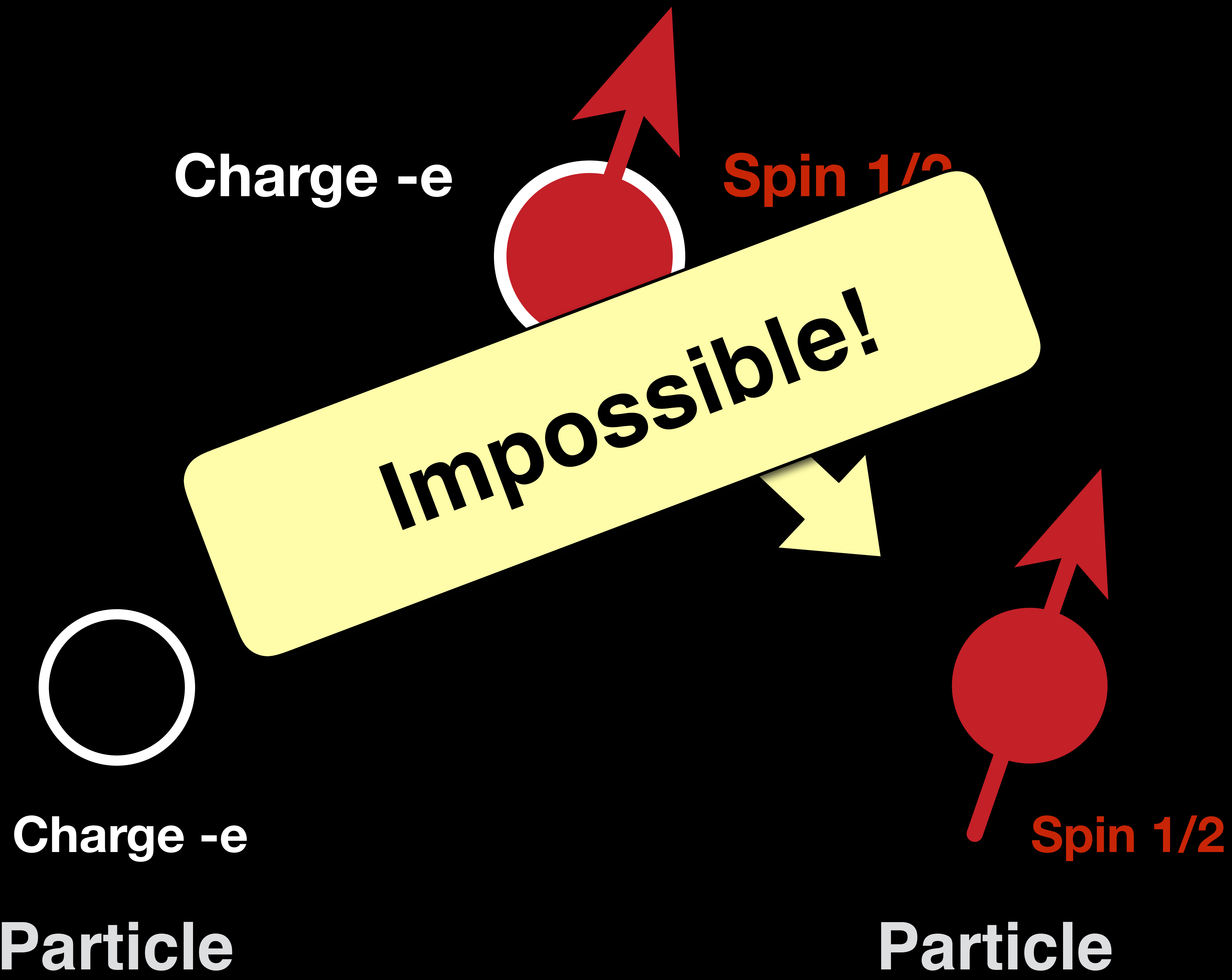
$$C(d) = 4\langle \hat{S}^z_i \hat{S}^z_{i+d}\rangle - 4\langle \hat{S}^z_i\rangle\langle \hat{S}^z_{i+d}\rangle$$



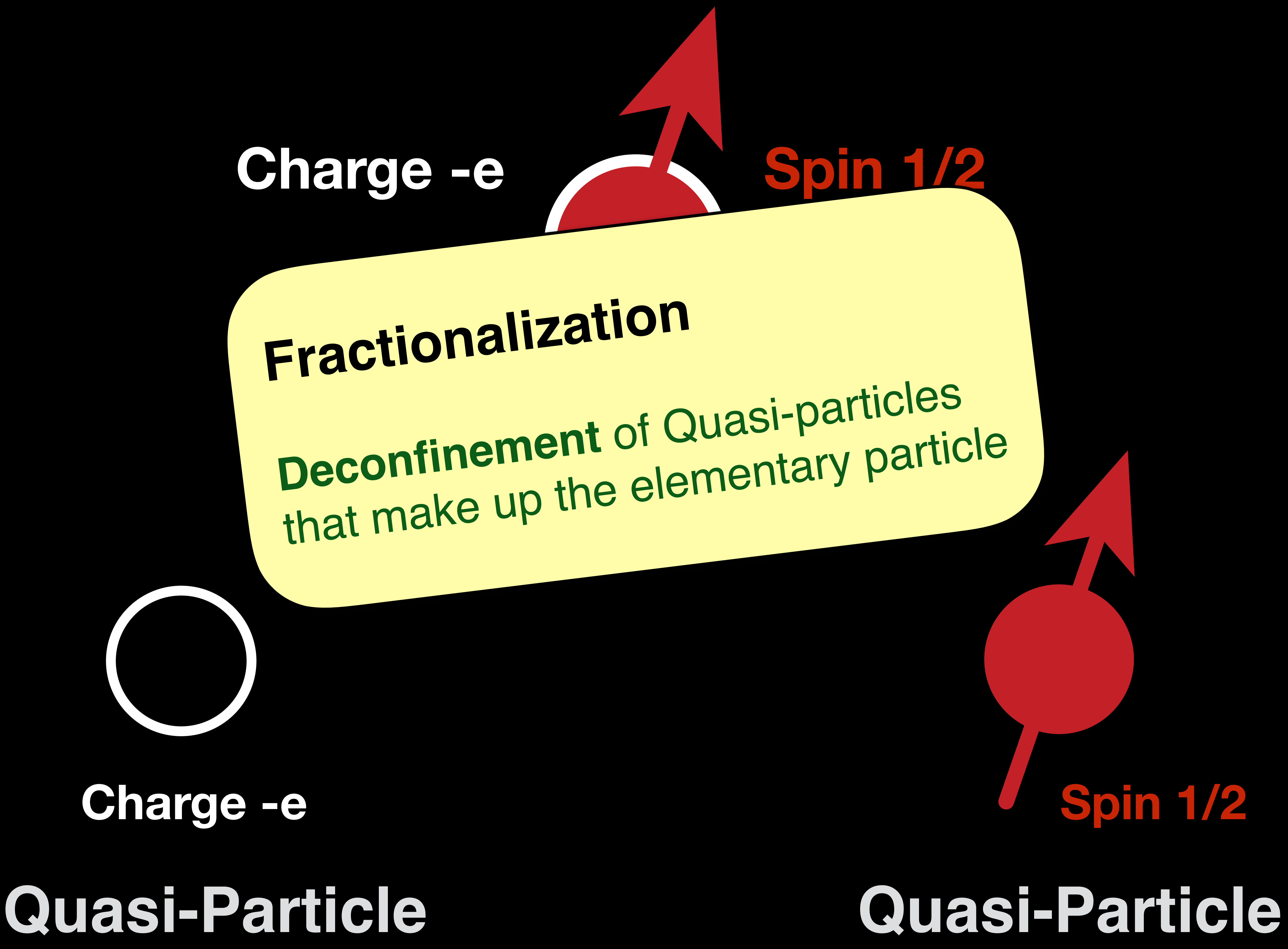
$\xi(0,T)$ **Largest possible decays length !**

Fractionalization &
Dynamical Spin-Charge Separation

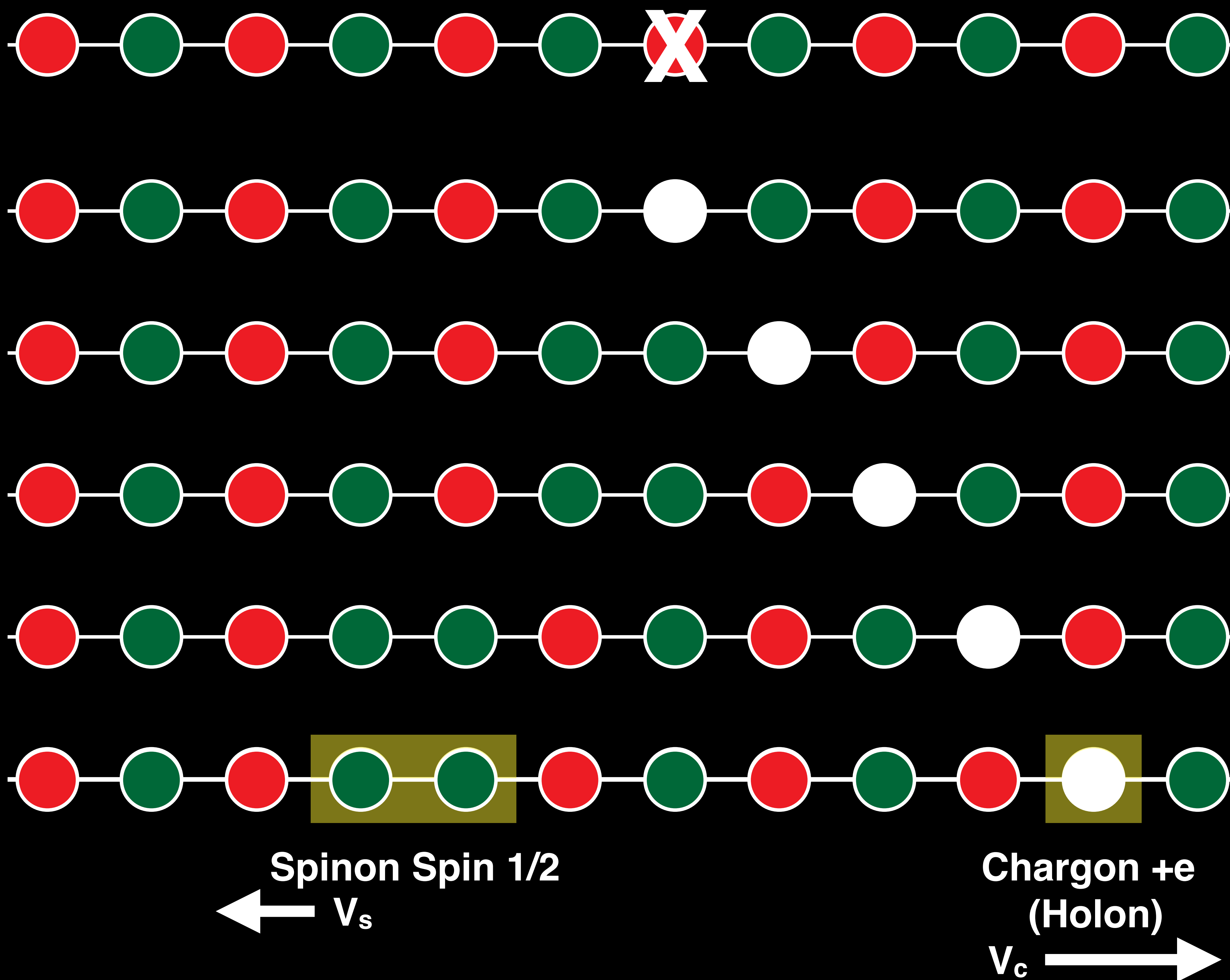
The Electron



The Electron

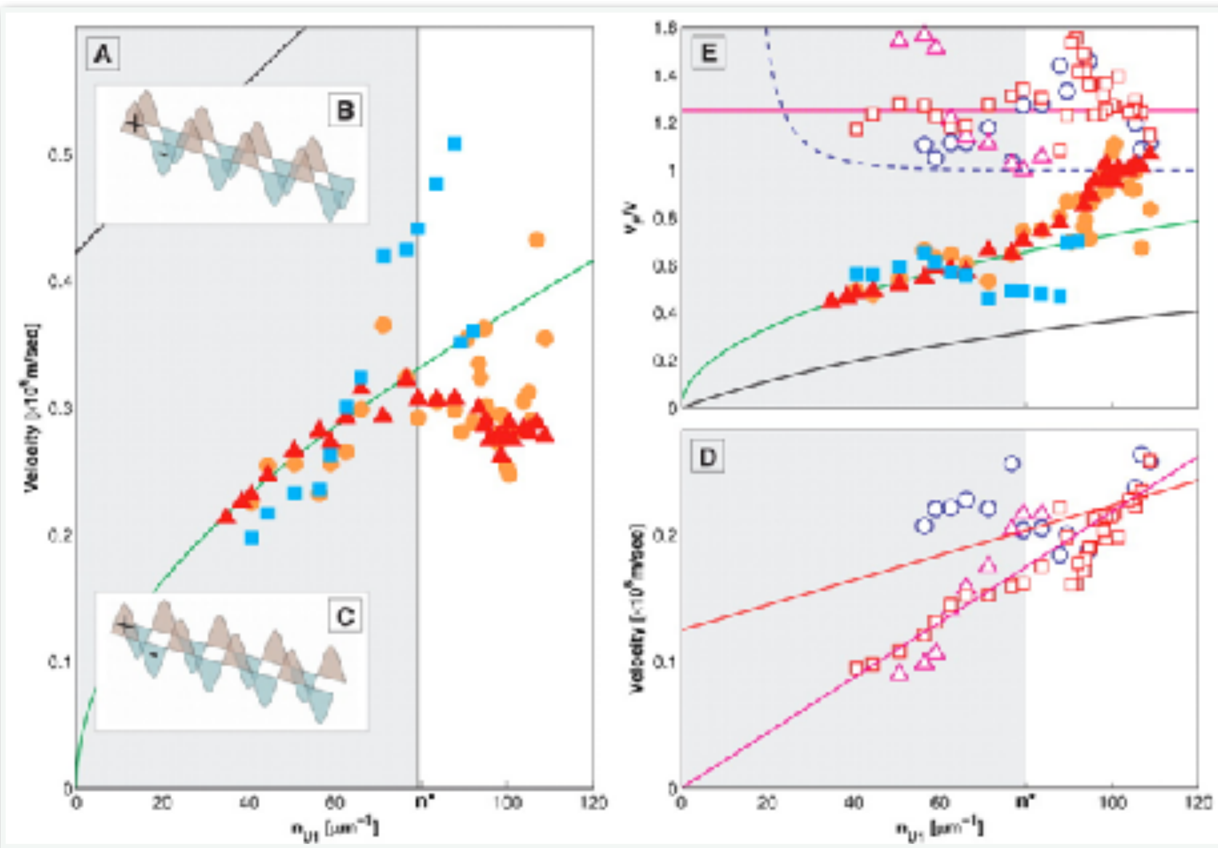


Fractionalization

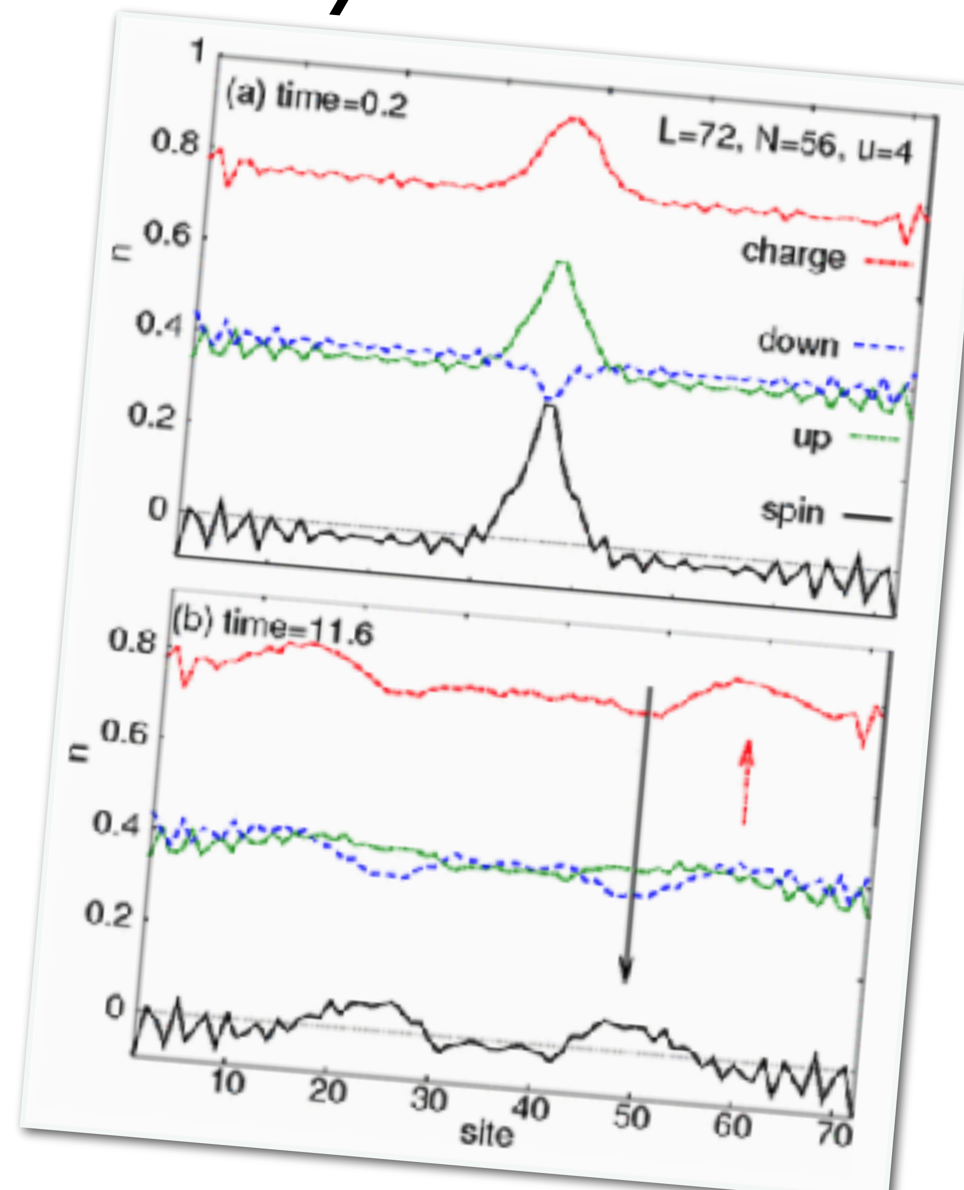


Spin-Charge Separation

Experiment



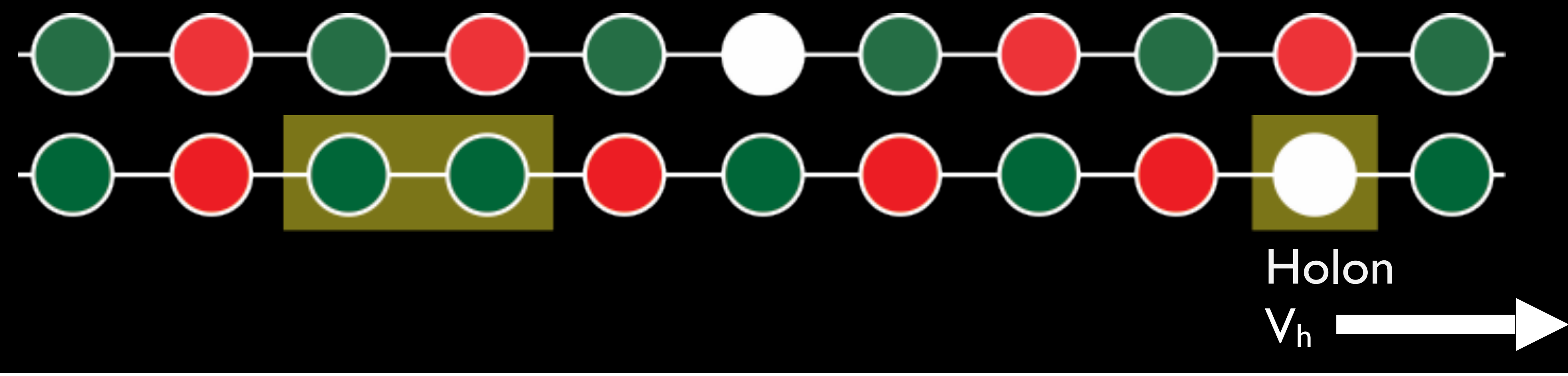
Theory

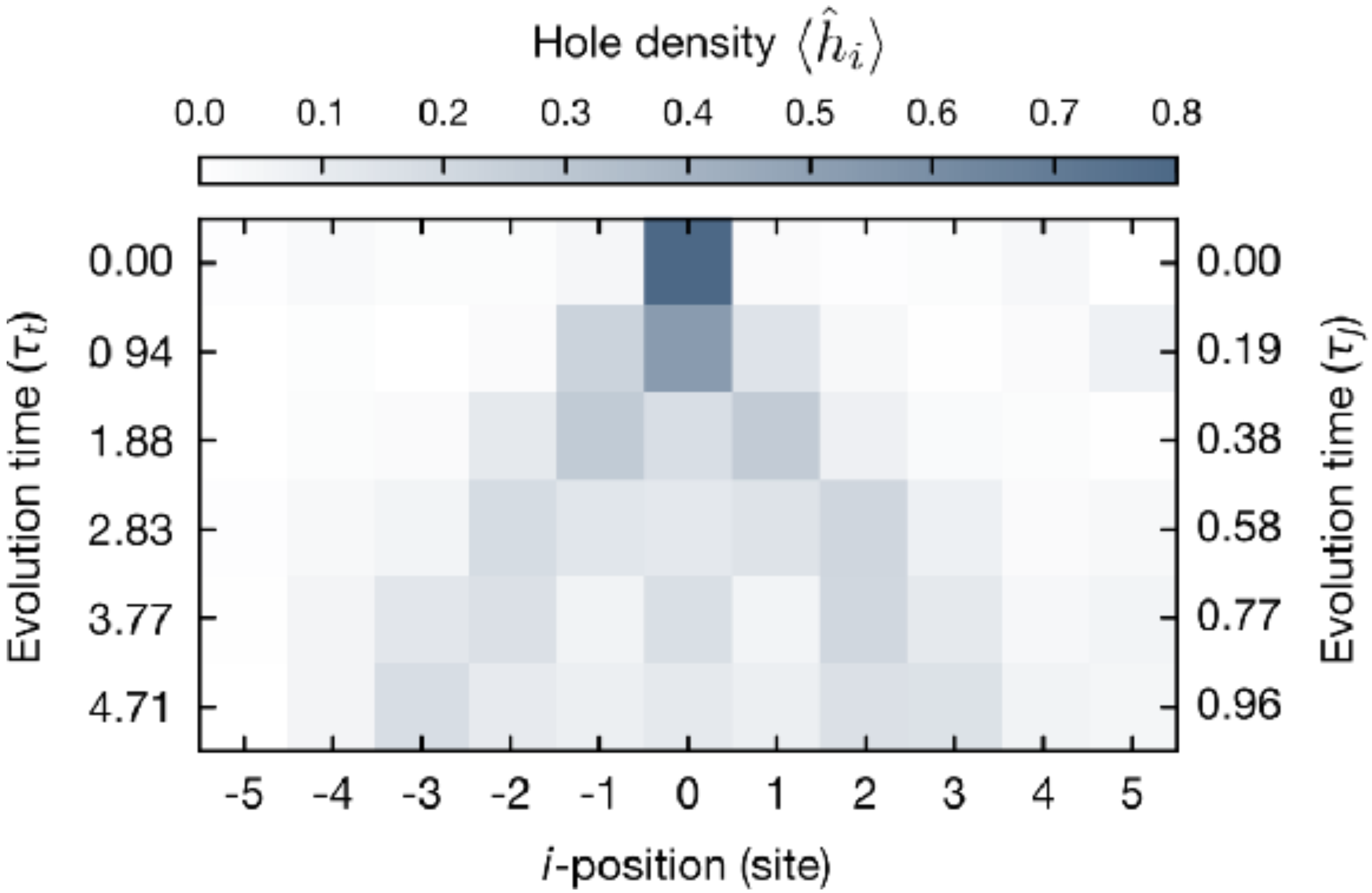


Spectroscopic determination:
C. Kim, et al. Phys. Rev. Lett. **77**, 4054 (1996)
O.M. Auslaender et al. Science **308**, 88 (2005)

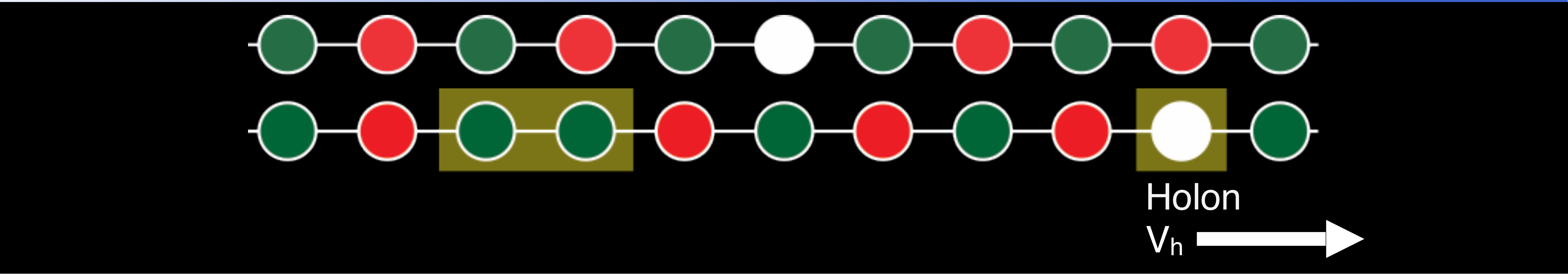
DMRG Simulation:
C. Kollath, U. Schollwöck, W. Zwerger
Phys. Rev. Lett. **95**, 176401 (2005)

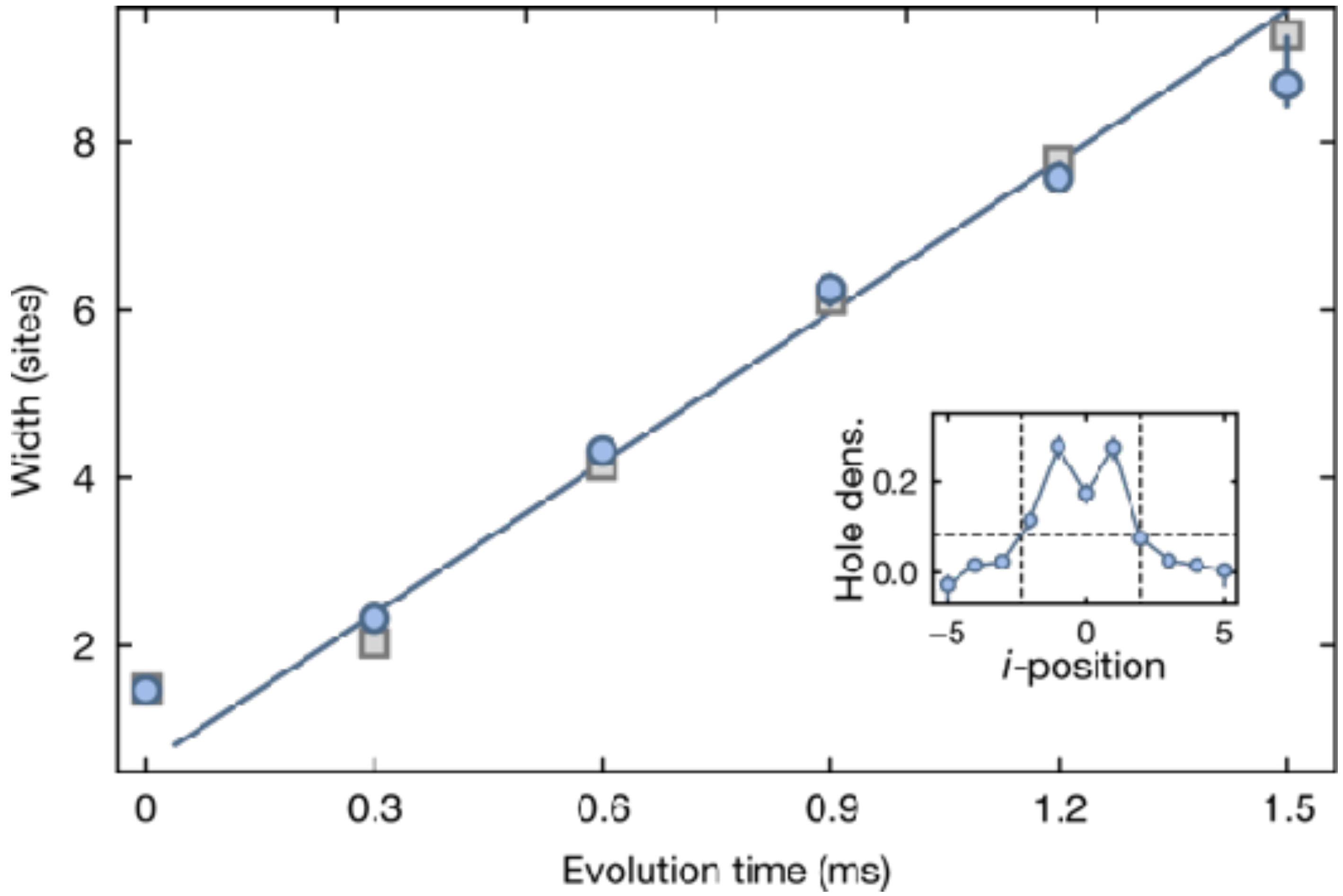
Holon dynamics



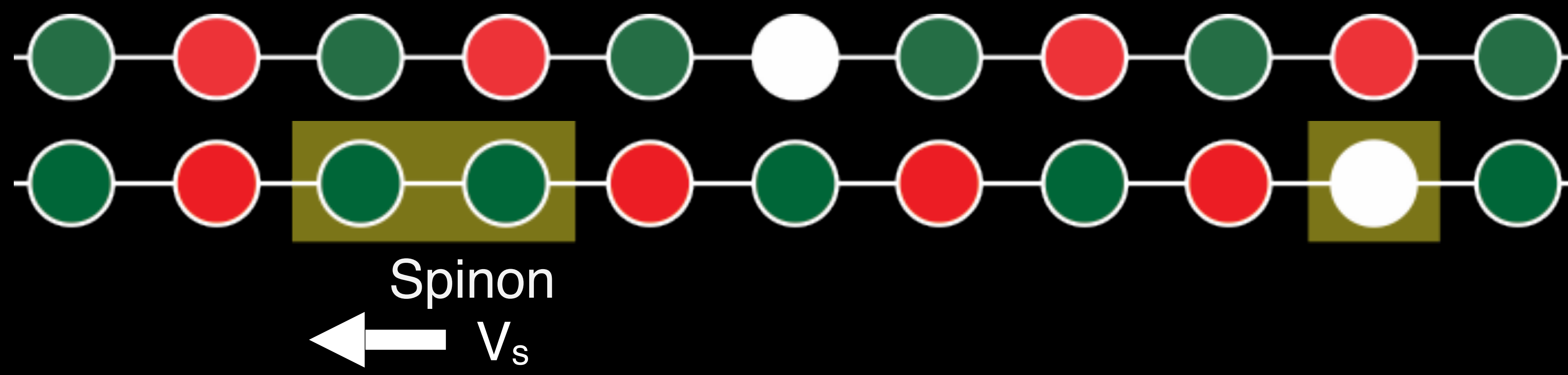


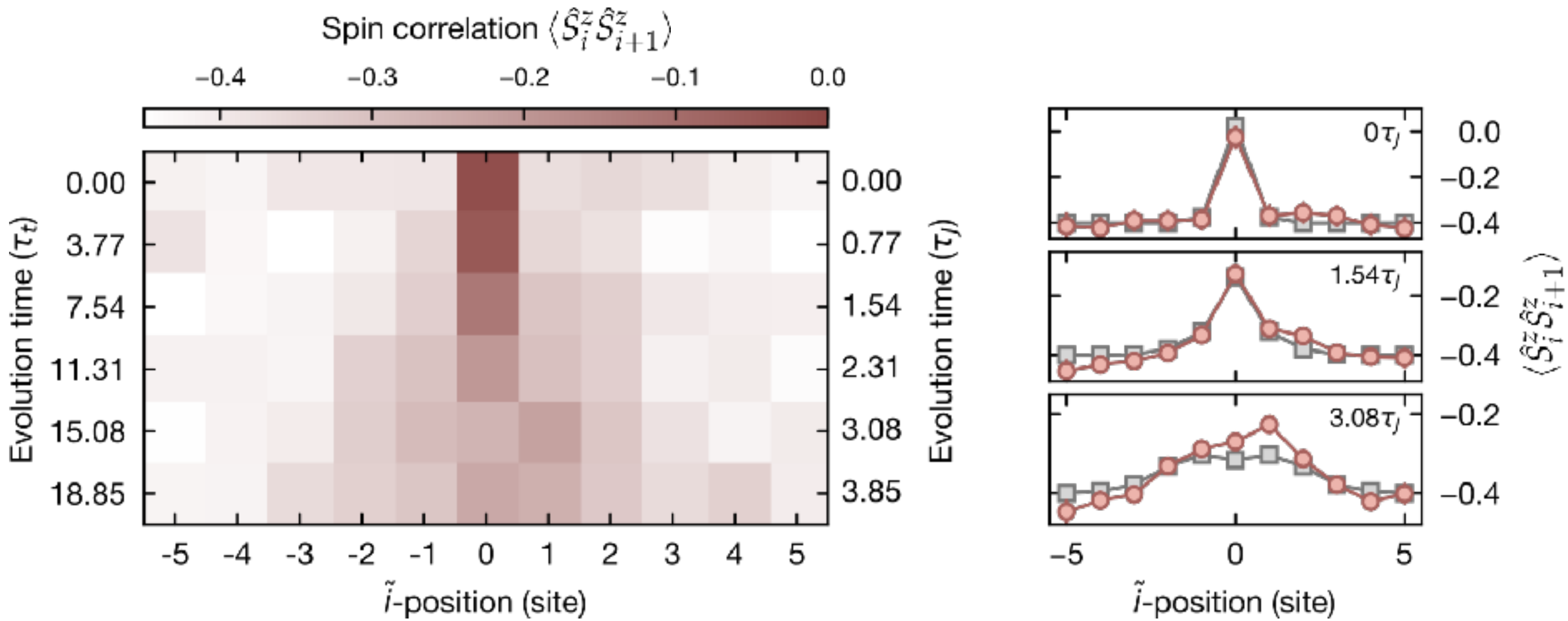
Holon dynamics



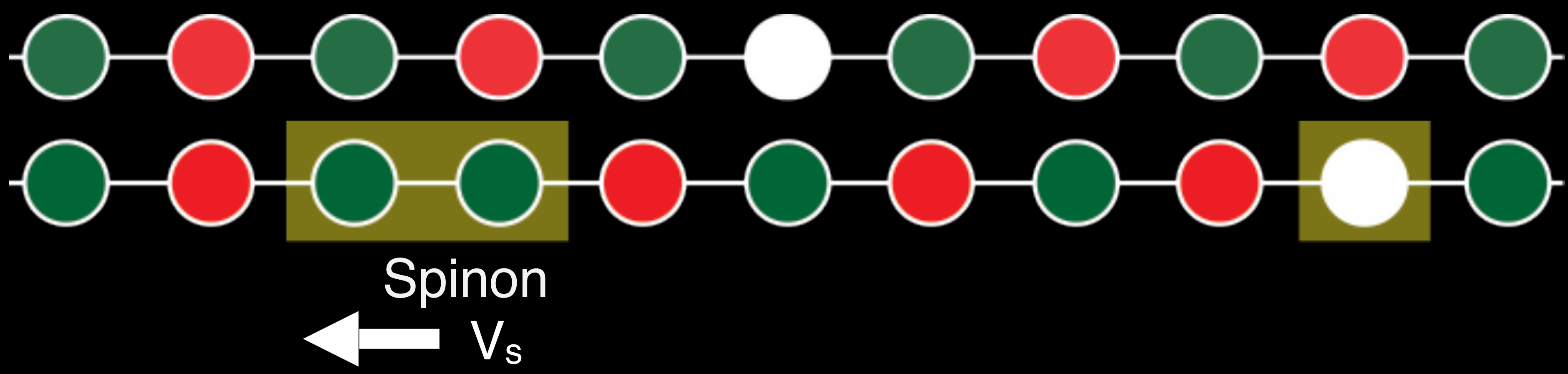


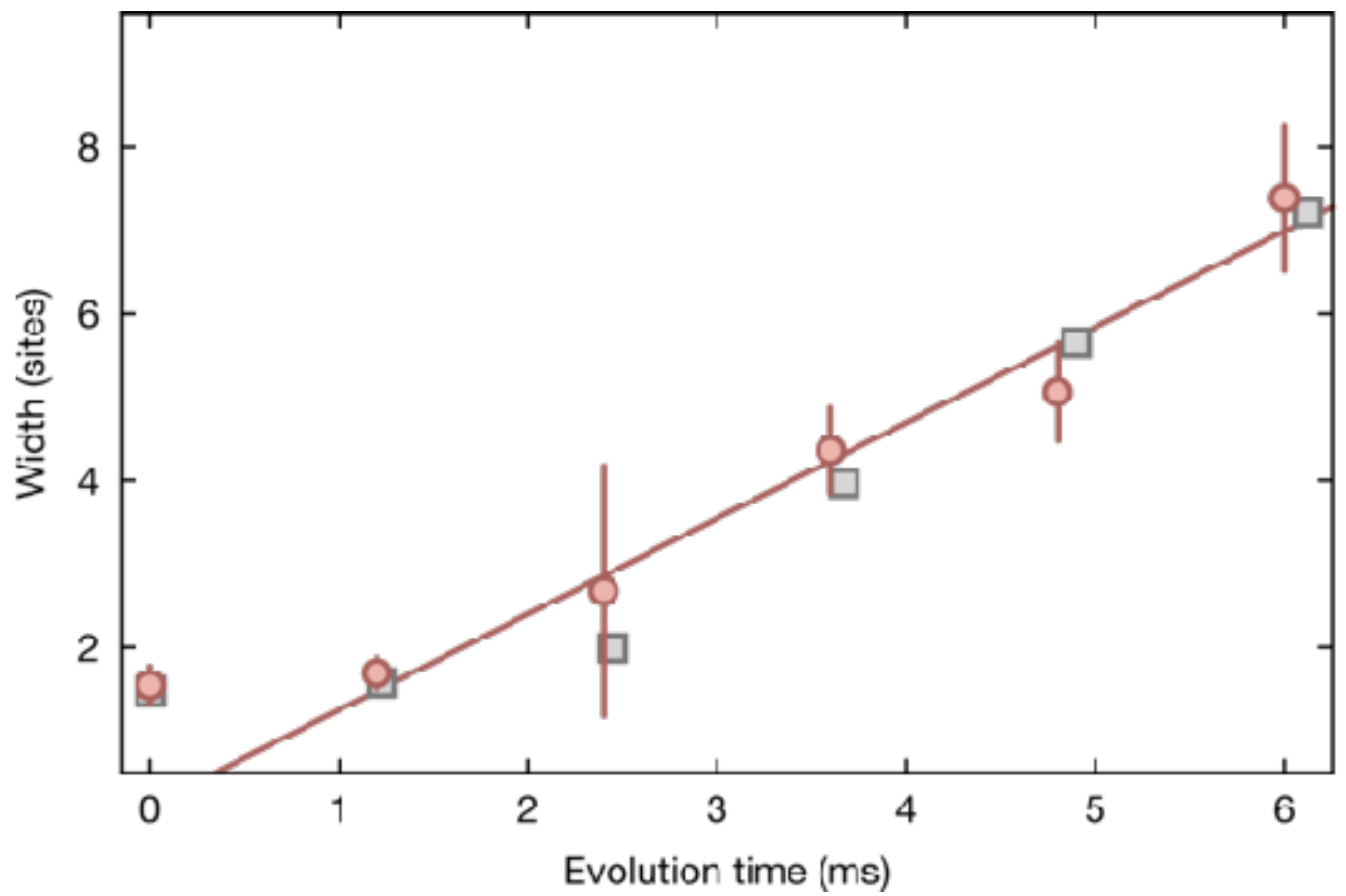
Spinon dynamics



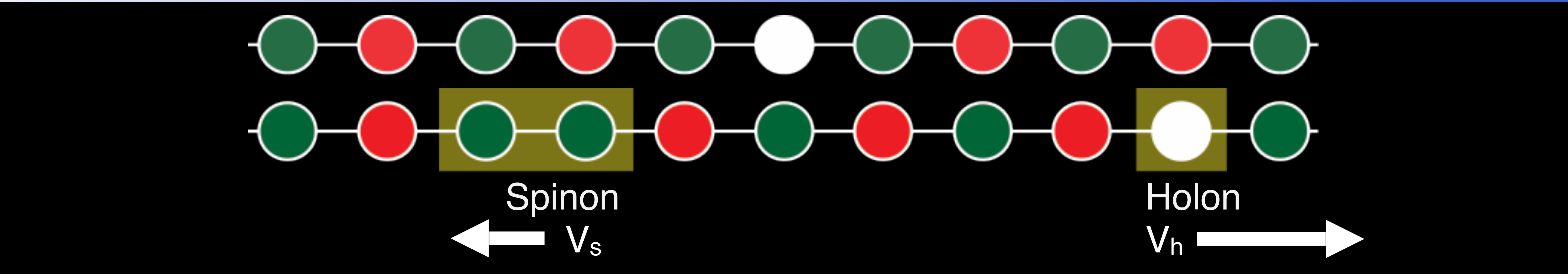


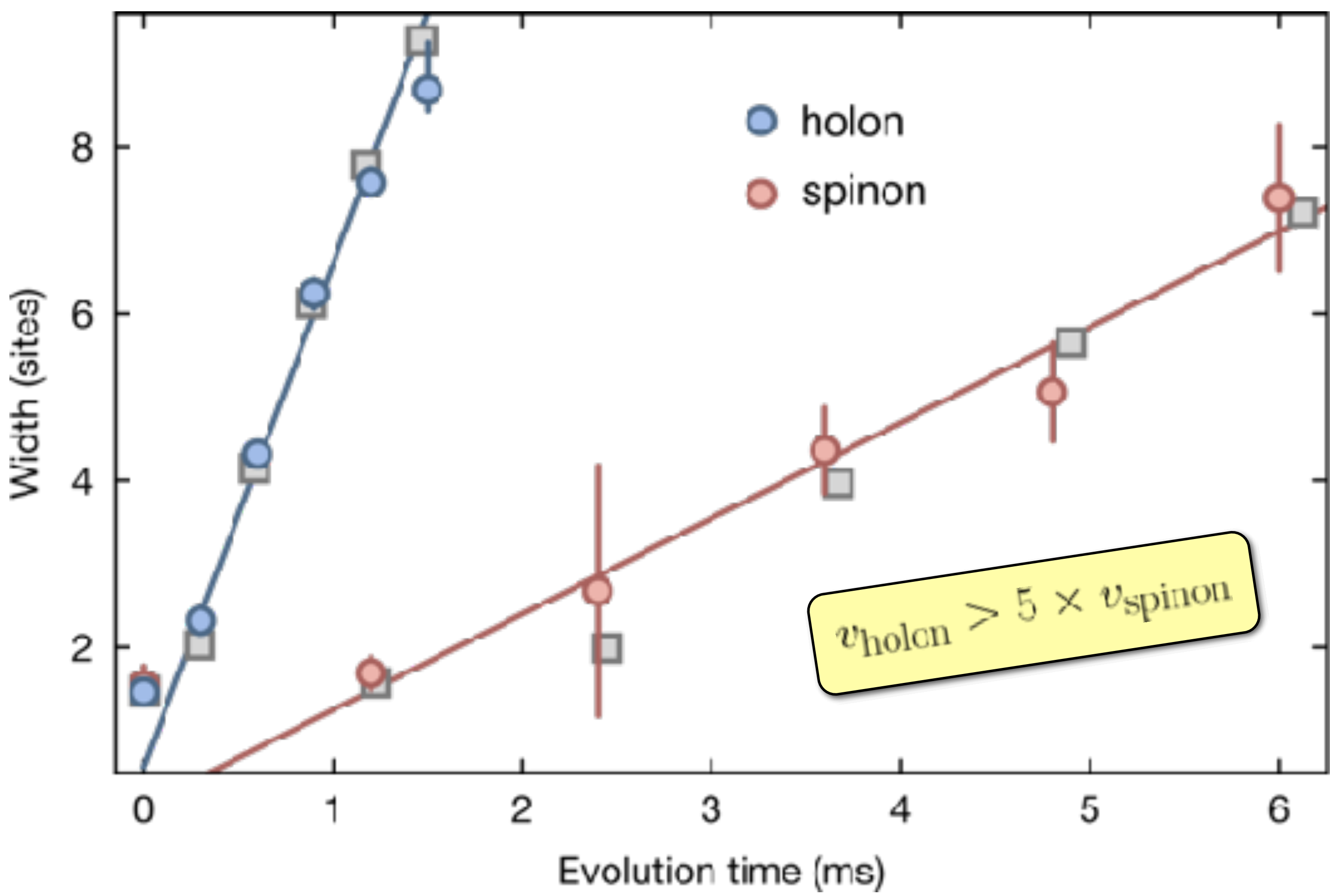
Spinon dynamics



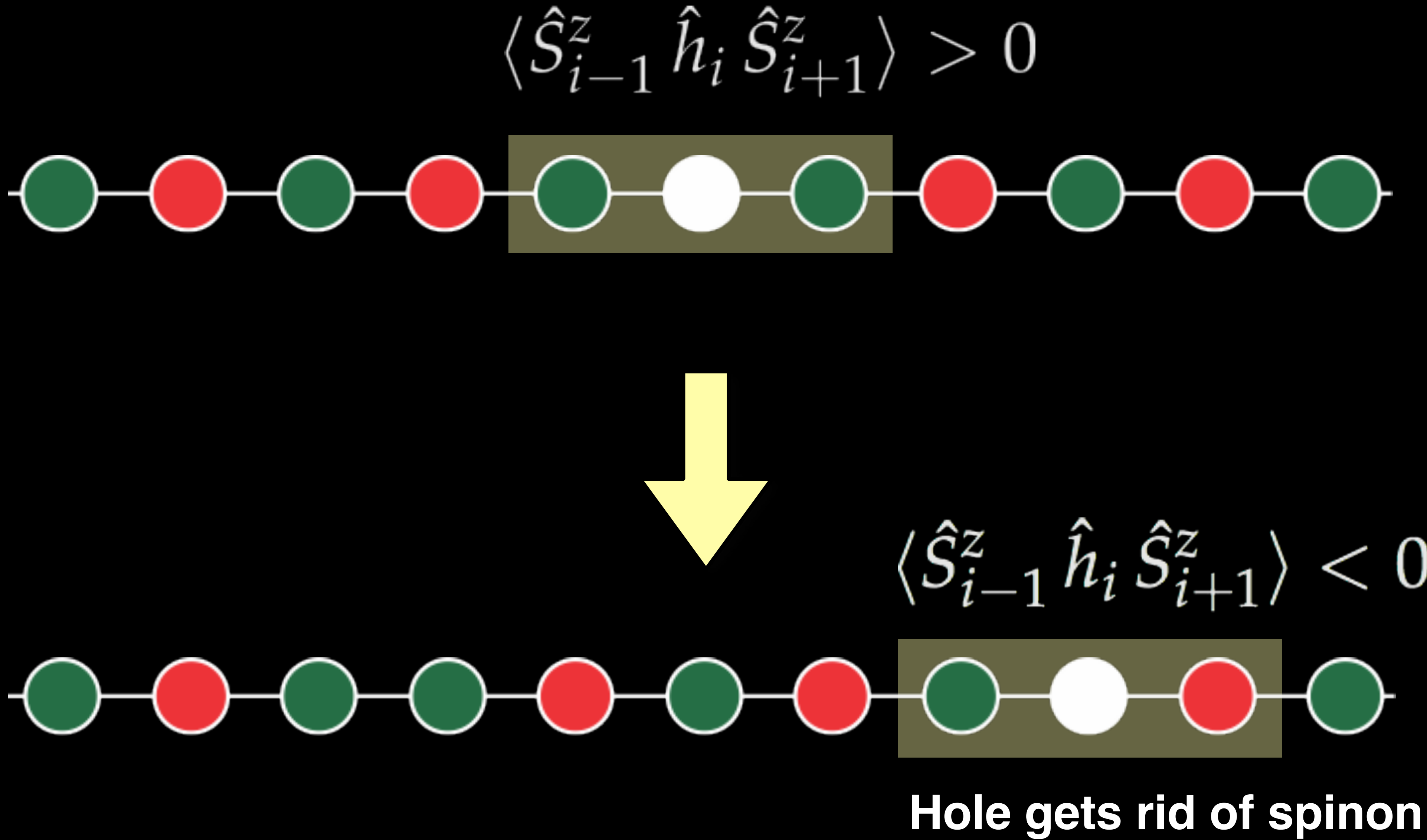


Comparison of velocities

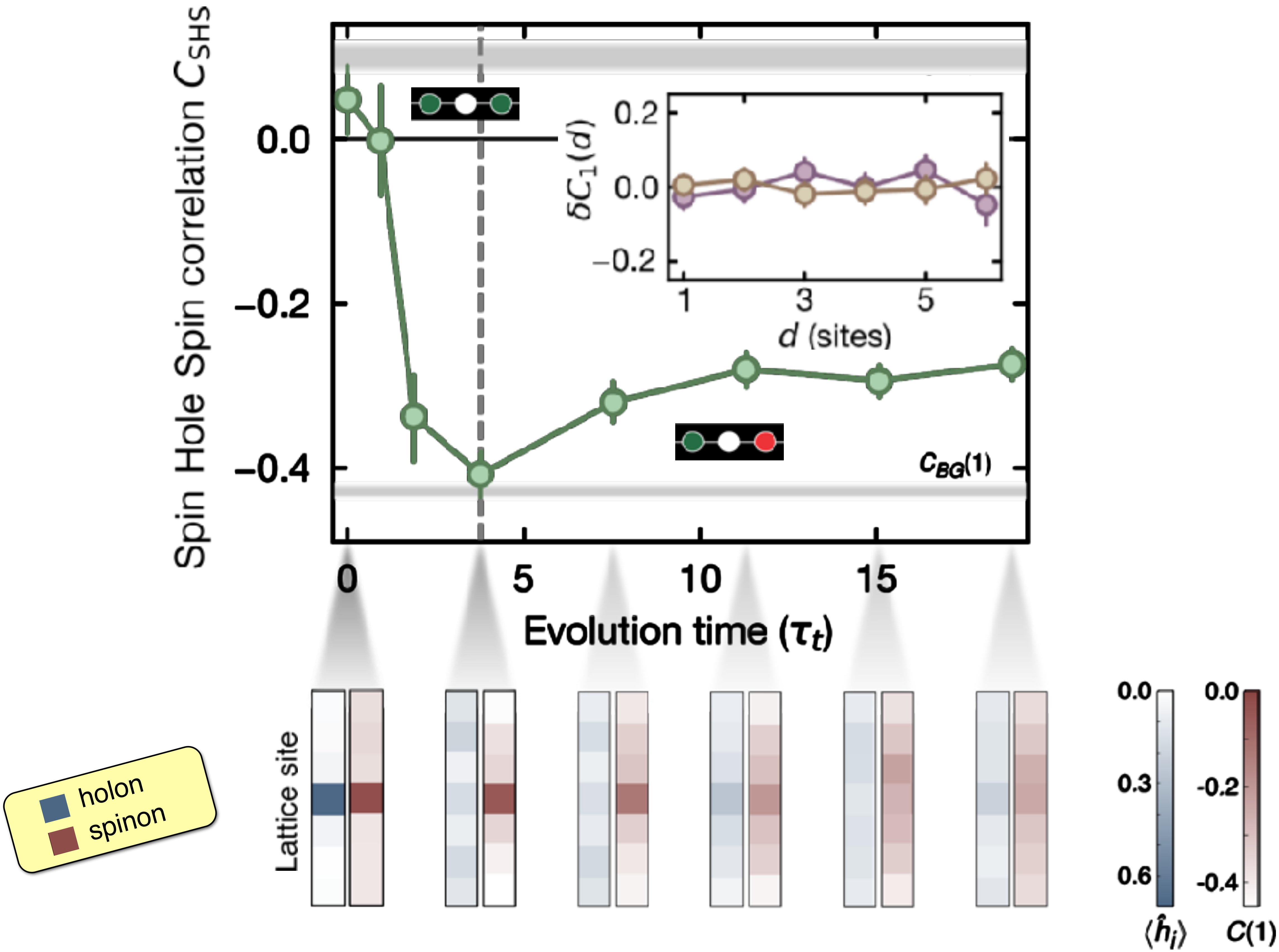




Absence of binding between quasiparticles

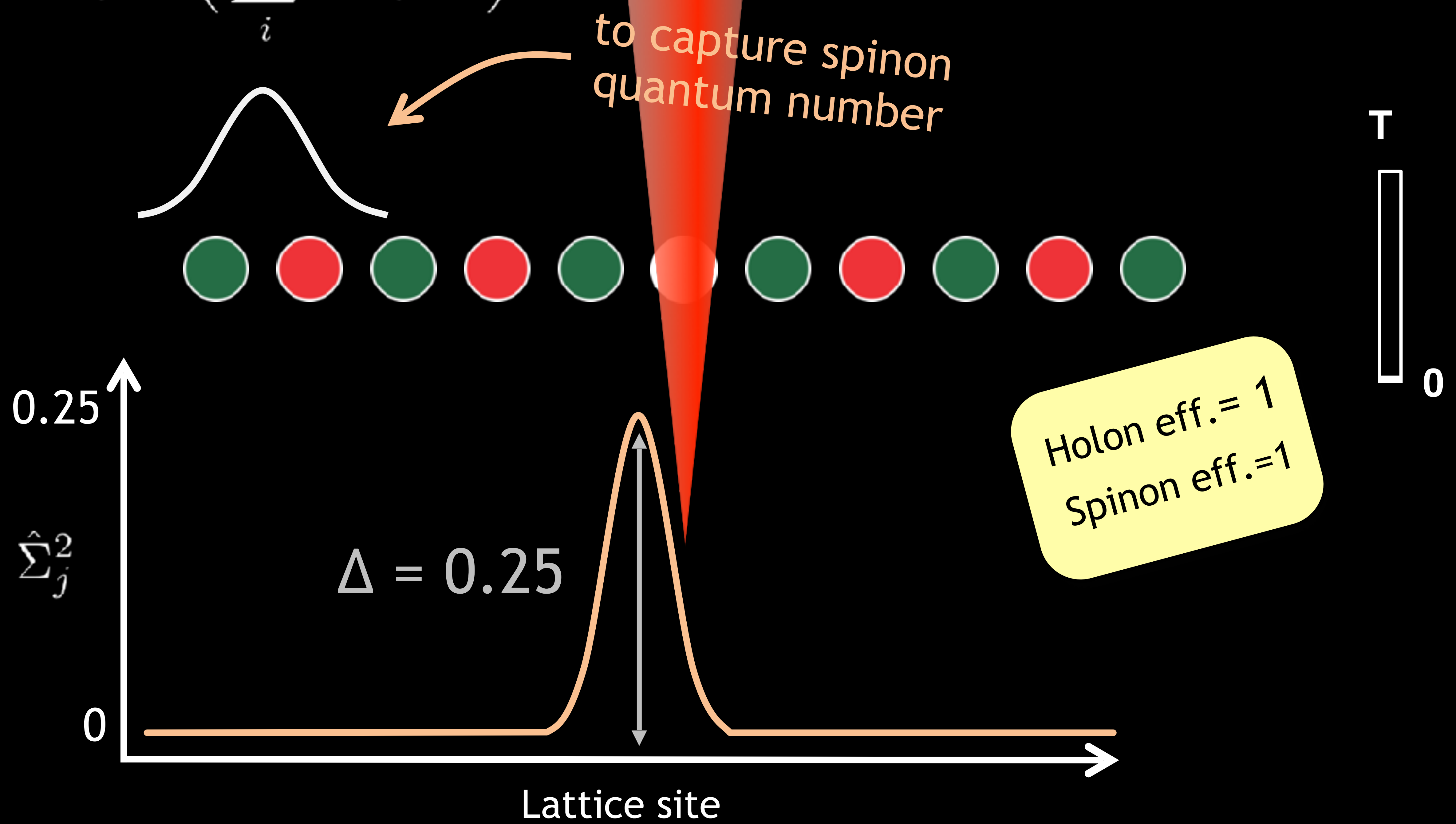


Spin-hole-spin correlator

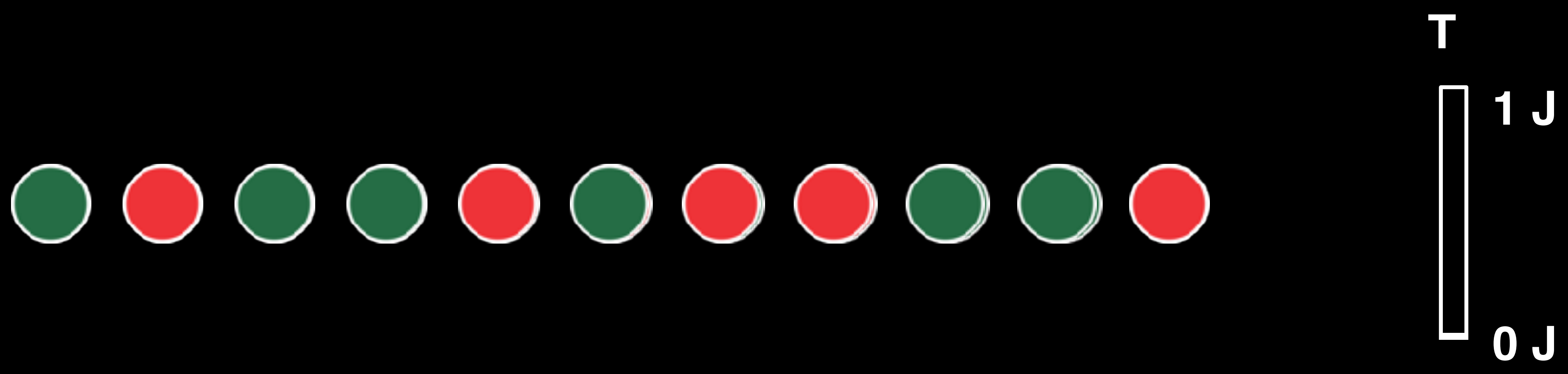


Fractionalization at zero temperature

$$\hat{\Sigma}_j^2 = \Big(\sum_i \hat{S}_i^z f_j^\sigma(i) \Big)^2$$

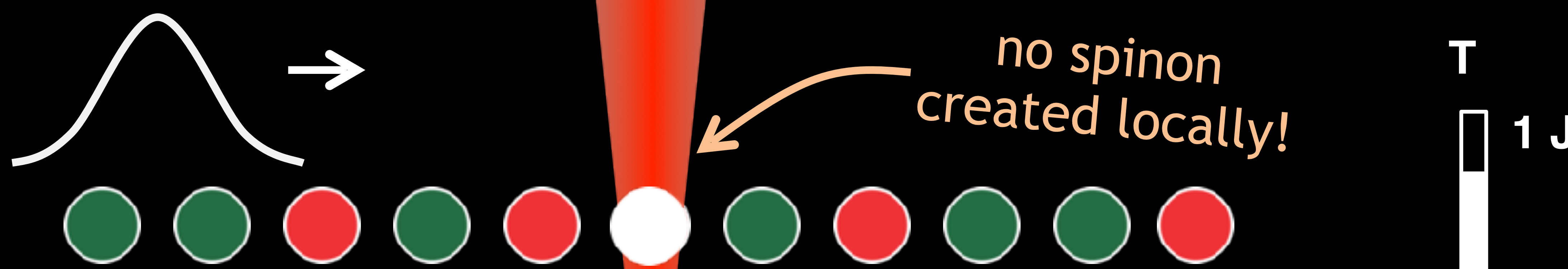


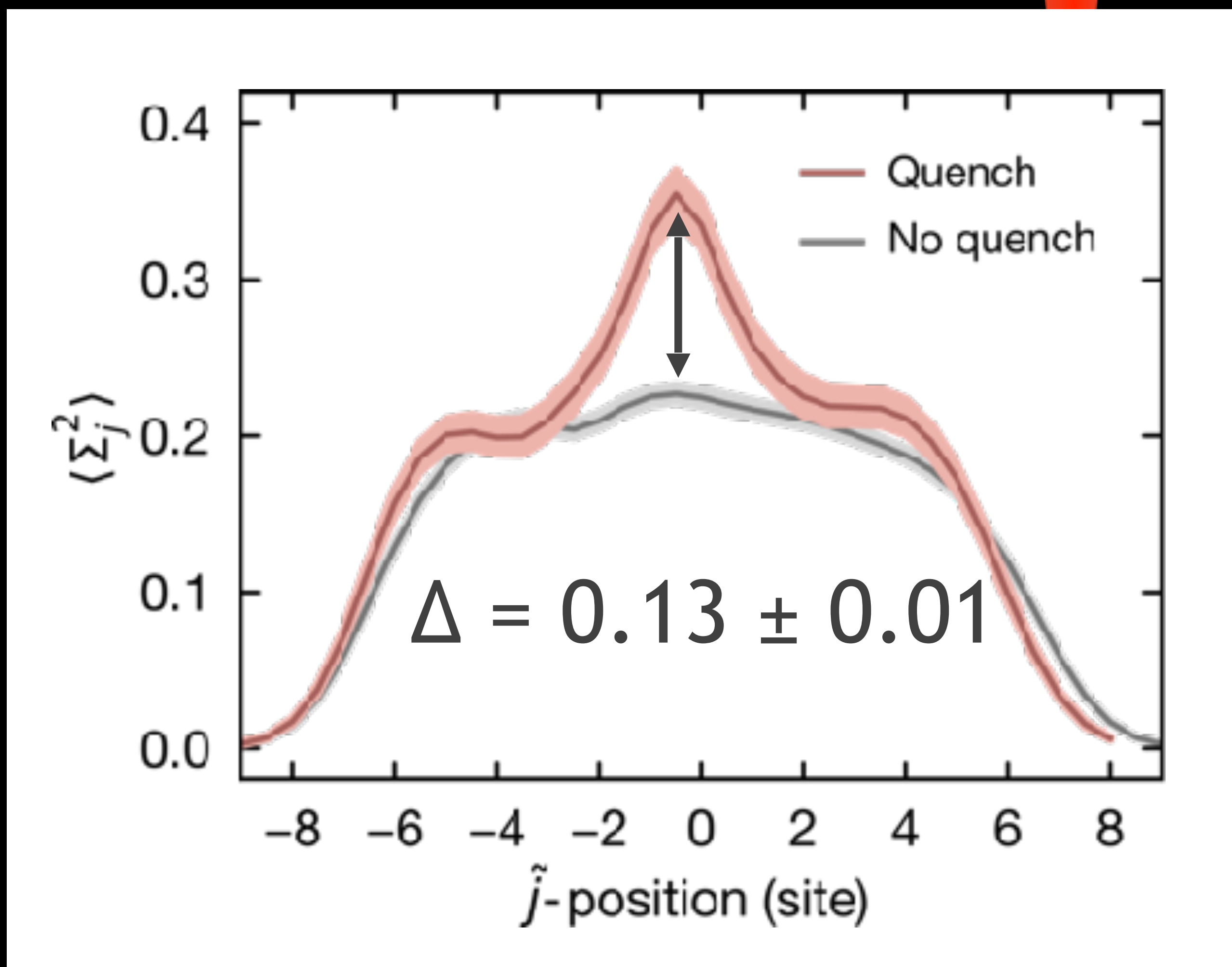
Fractionalization at <u>non-zero</u> temperature

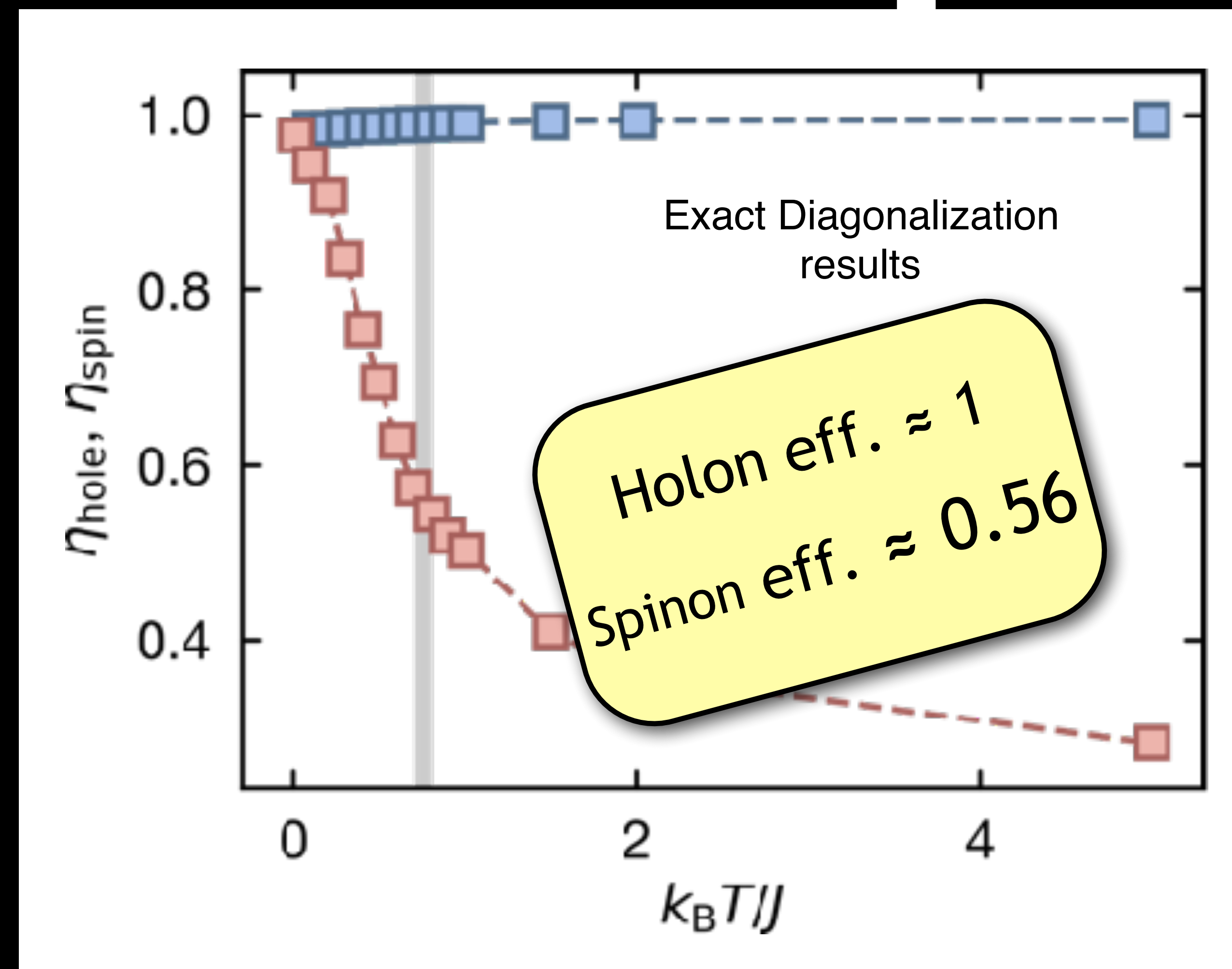


Fractionalization at non-zero temperature

$$\hat{\Sigma}_j^2 = \left(\sum_i \hat{S}_i^z f_j^\sigma(i)\right)^2$$





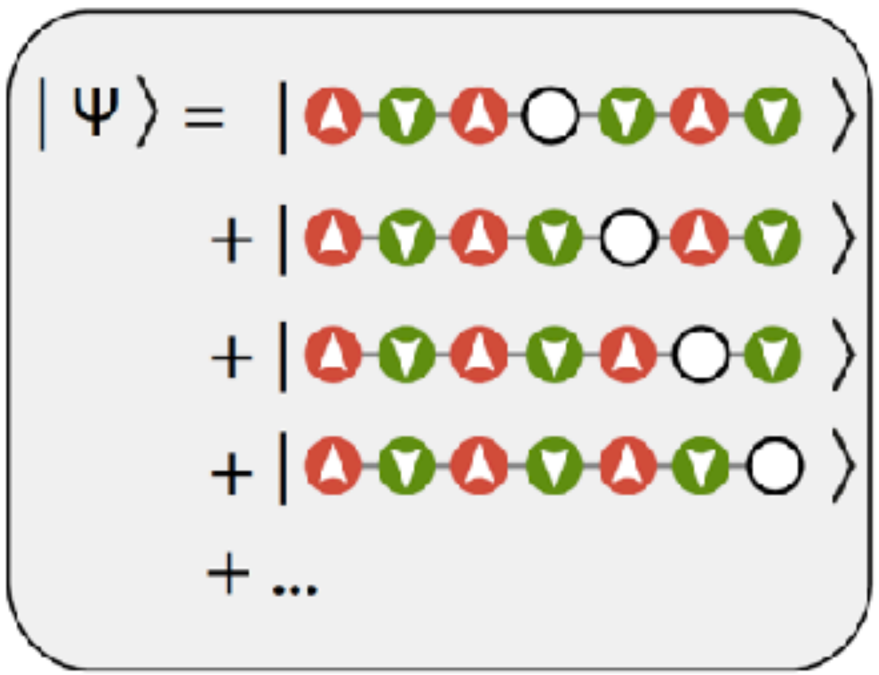


How is fractionalisation connected to hidden order in the ground state?

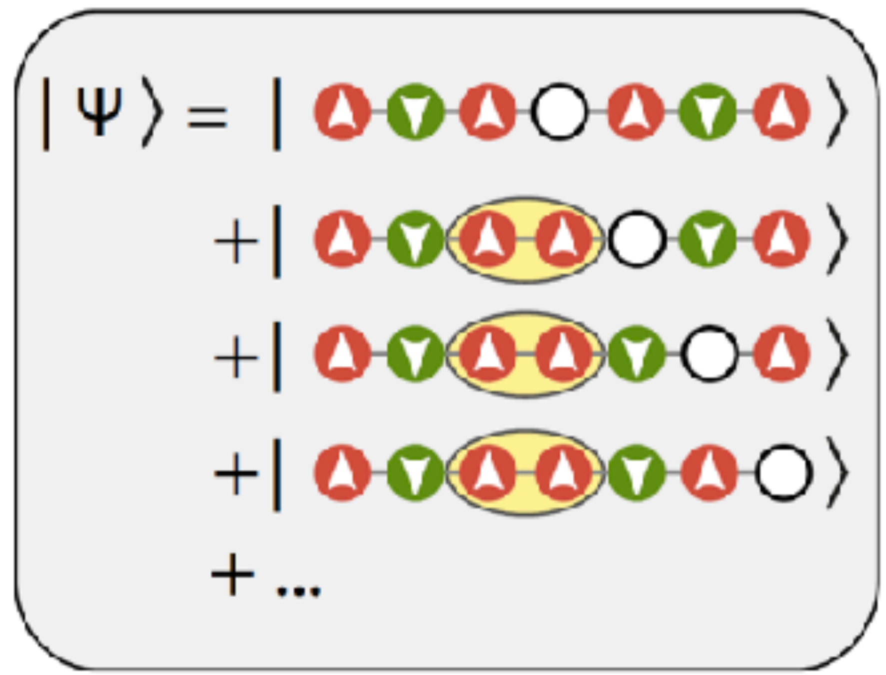
Charge & Spin Order around Hole

Minimize Energy ⇨ **Two Conditions**

- Holes want to delocalise
- Spins want to align antiferromagnetically

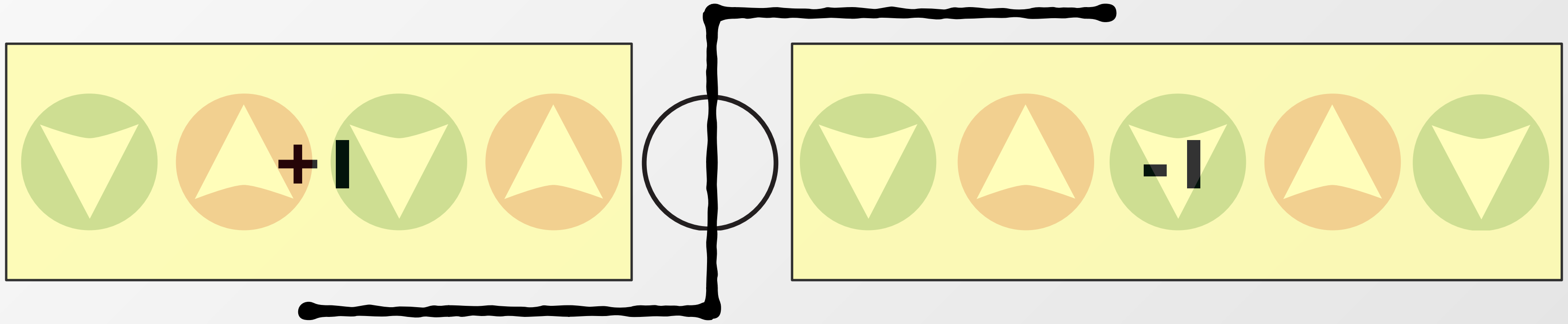


Ground State



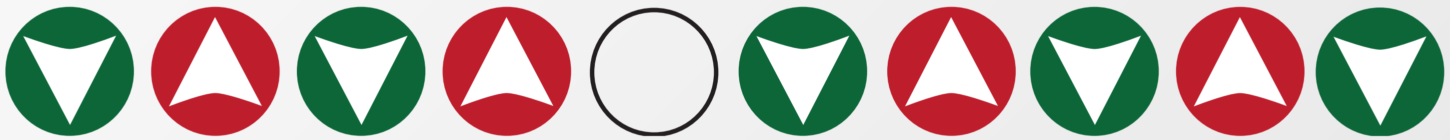
Excited State

Microscopic Origin of SC —Separation

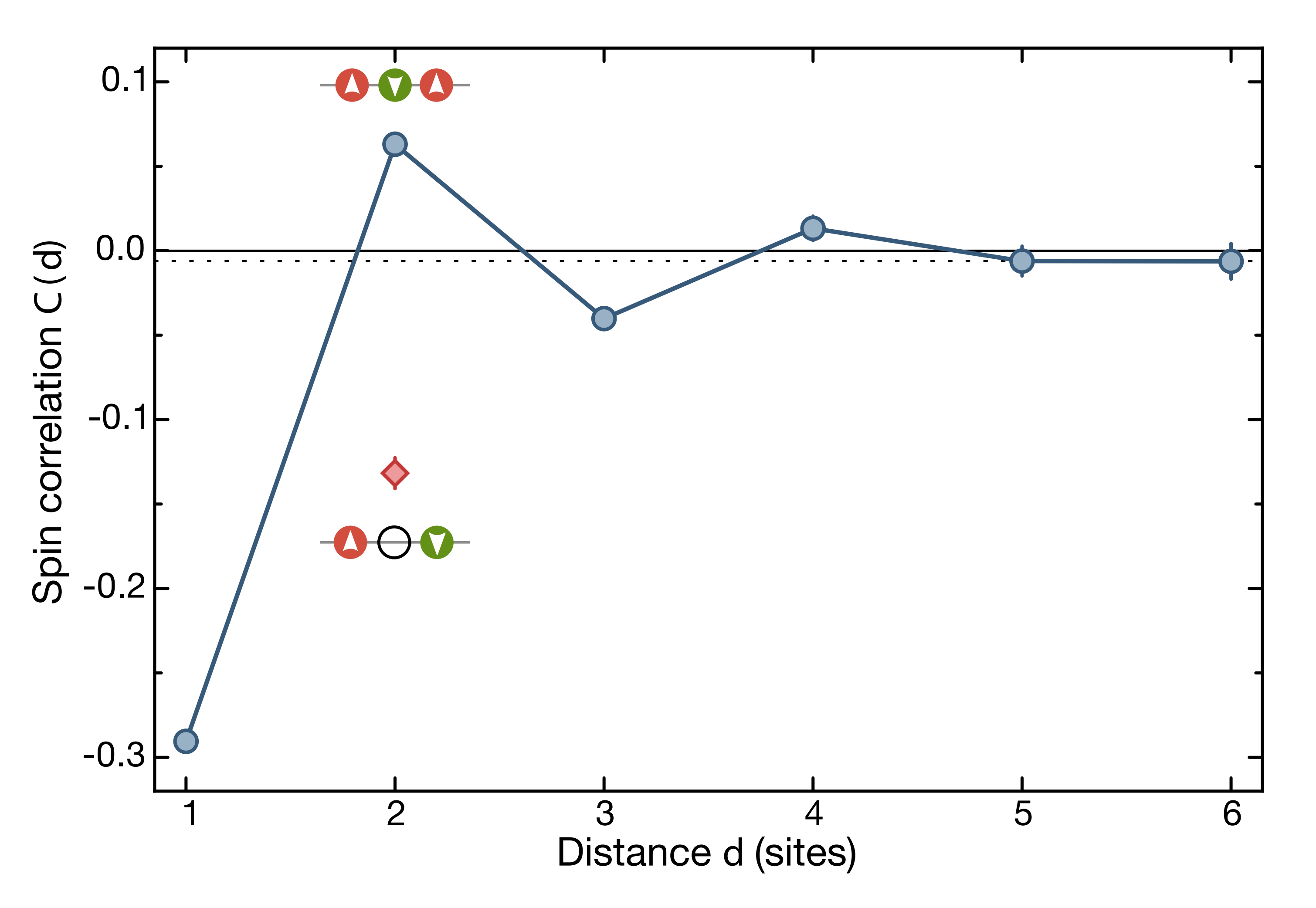


Hole introduce domain wall
"parity" kinks in AFM background!

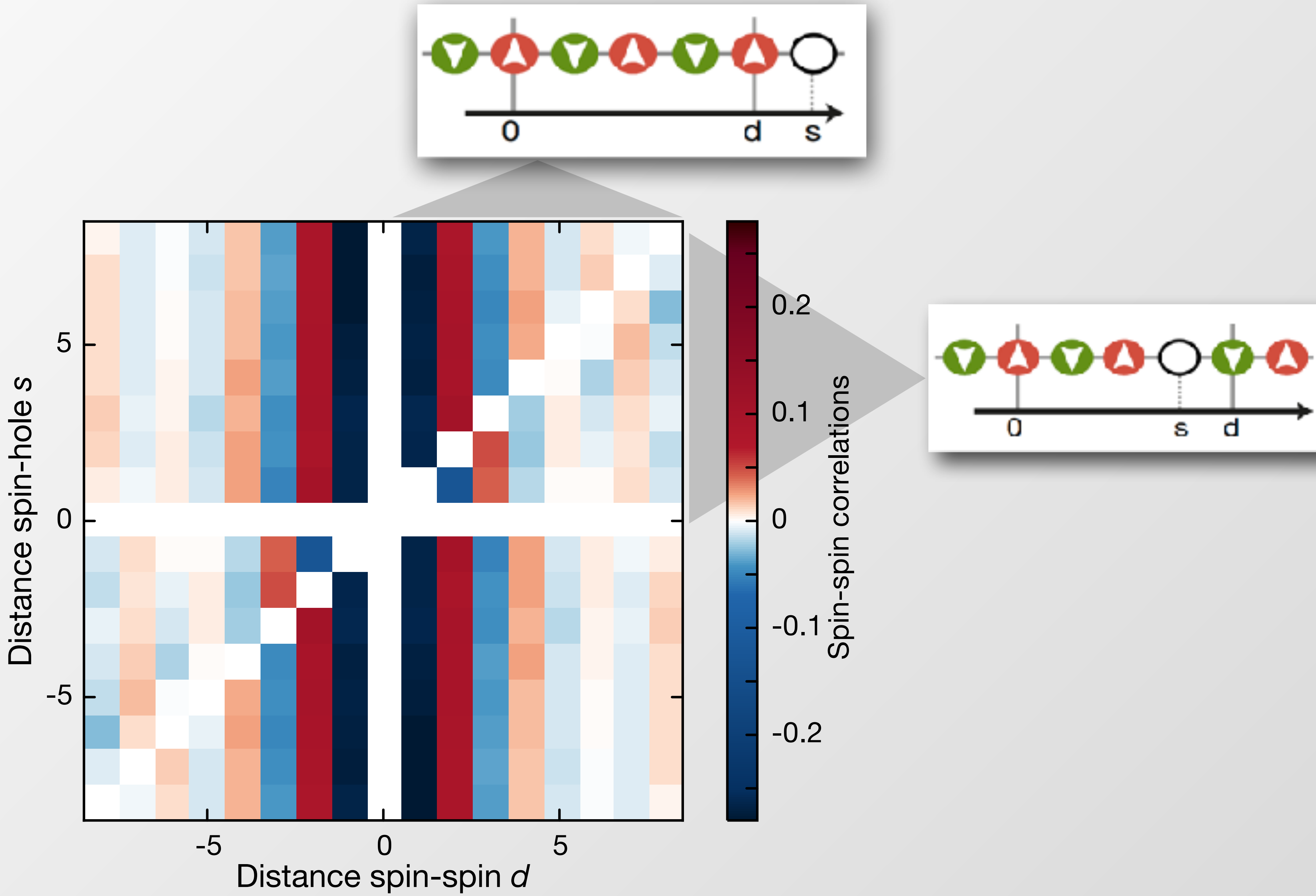
AFM order around hole



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

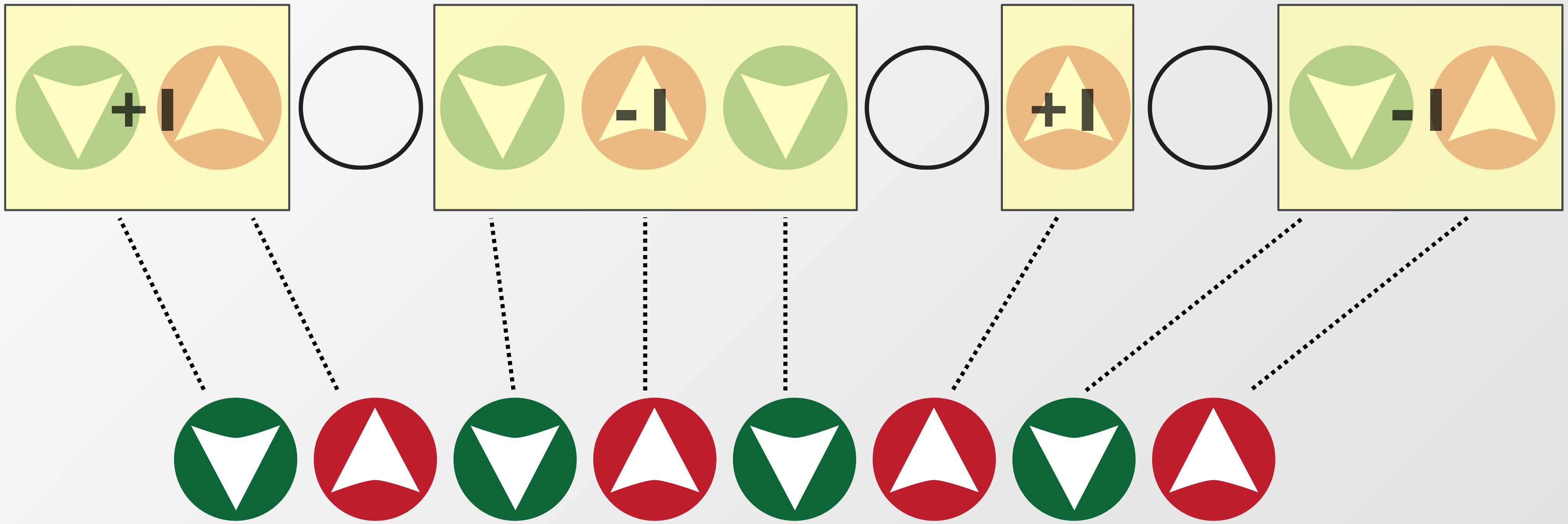


AFM around Holes



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

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)

or

General classification scheme for all phases of matter ???

Order Parameter Chara

und 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:

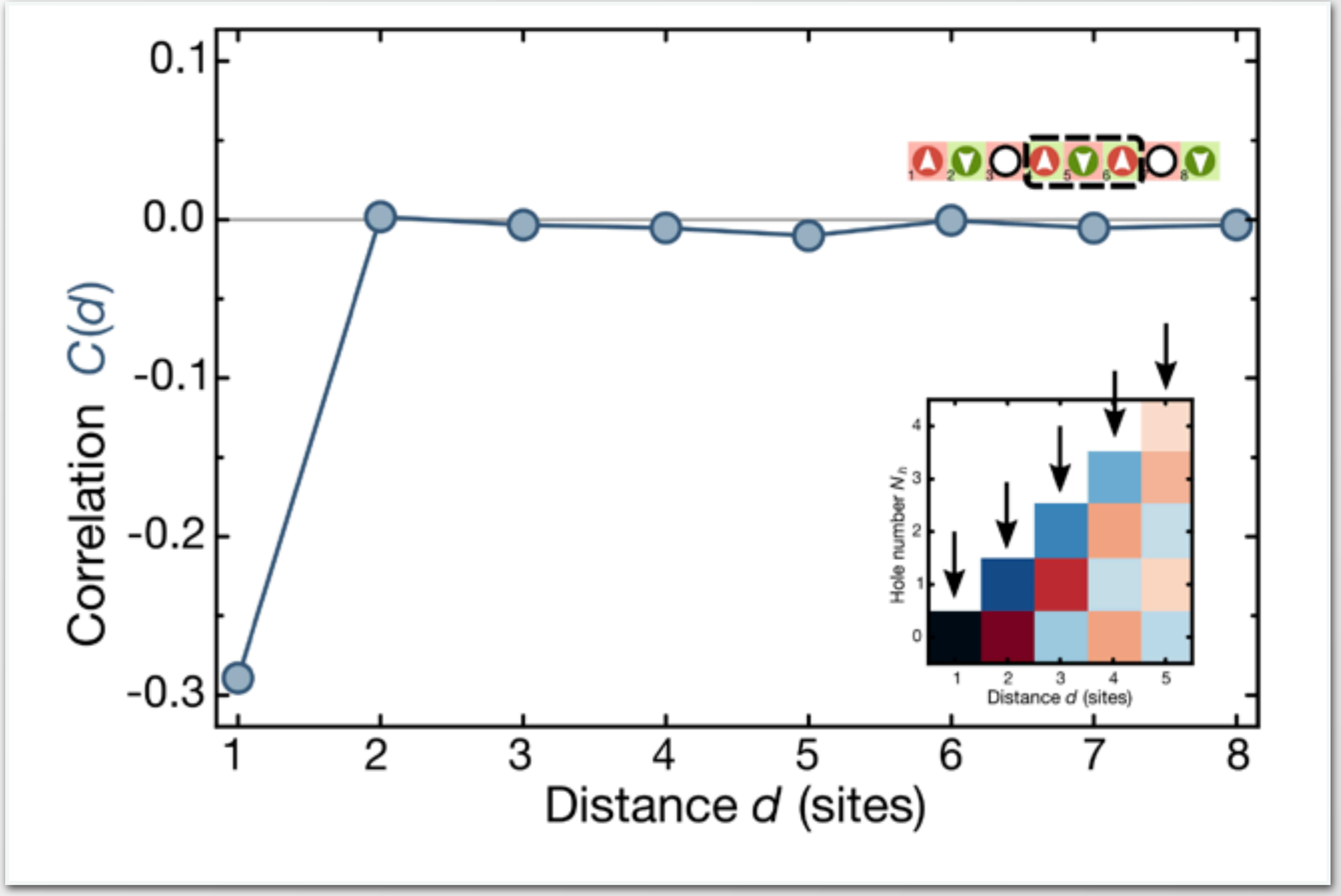
$$\lim_{|\mathbf{x}-\mathbf{y}|\to\infty} \langle \hat{A}(\mathbf{x}) \left(\prod_{\mathbf{z}\in S(\mathbf{x},\mathbf{y})} \hat{B}(\mathbf{z}) \right) \hat{A}(\mathbf{y}) \rangle = c$$

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

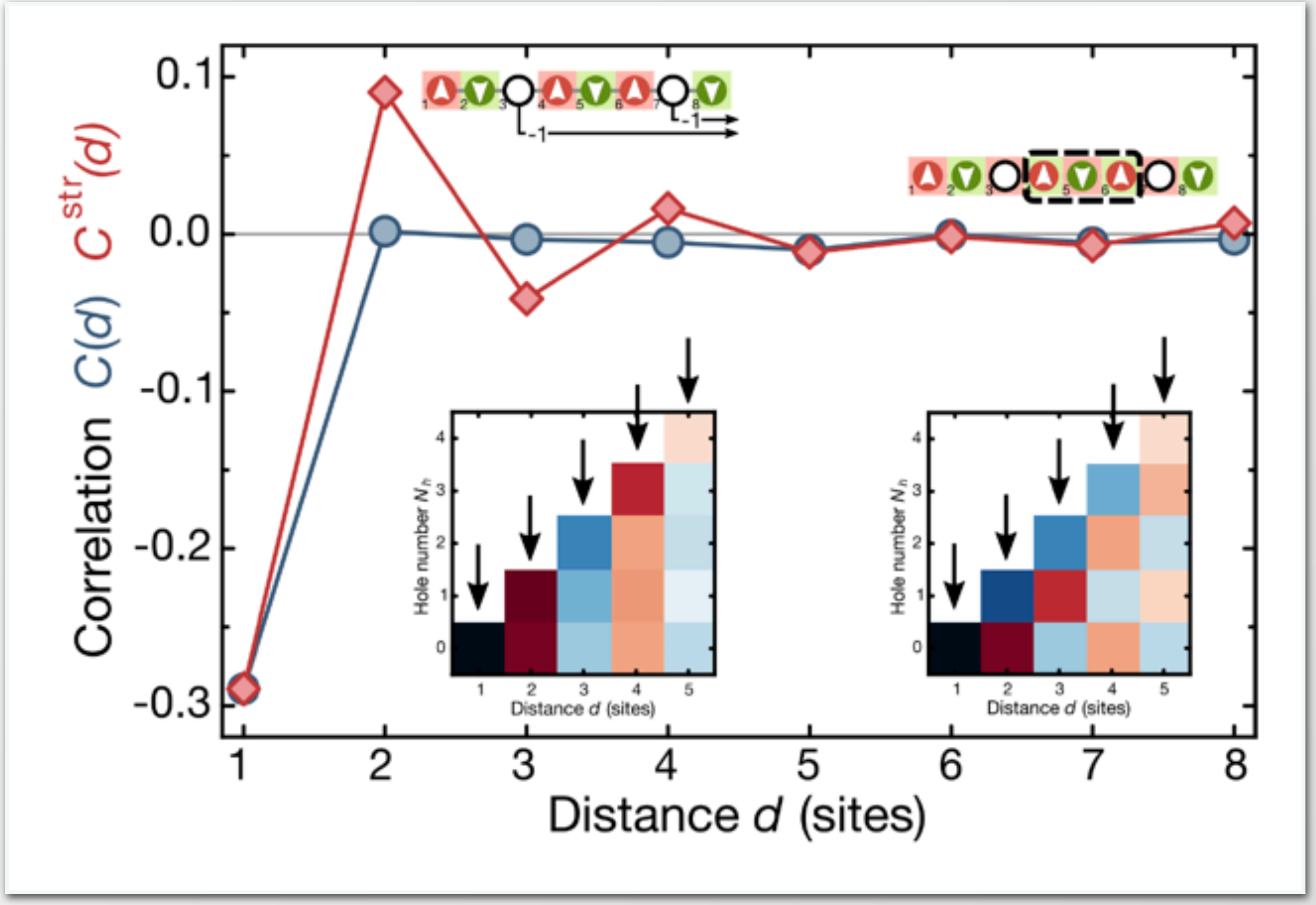
Allows us to characterize state only via its ground state correlations!

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, 1 E. Dalla Torre, T. Giamarchi, E. Altman, Phys. Rev. B 77, 245119 (2008)

Two Point Correlator - Doped Chains



Two Point Correlator - Doped Chains



Incommensurate AFM in 1D

G. Salomon *et al.* Nature **565**, 56–60 (2019)

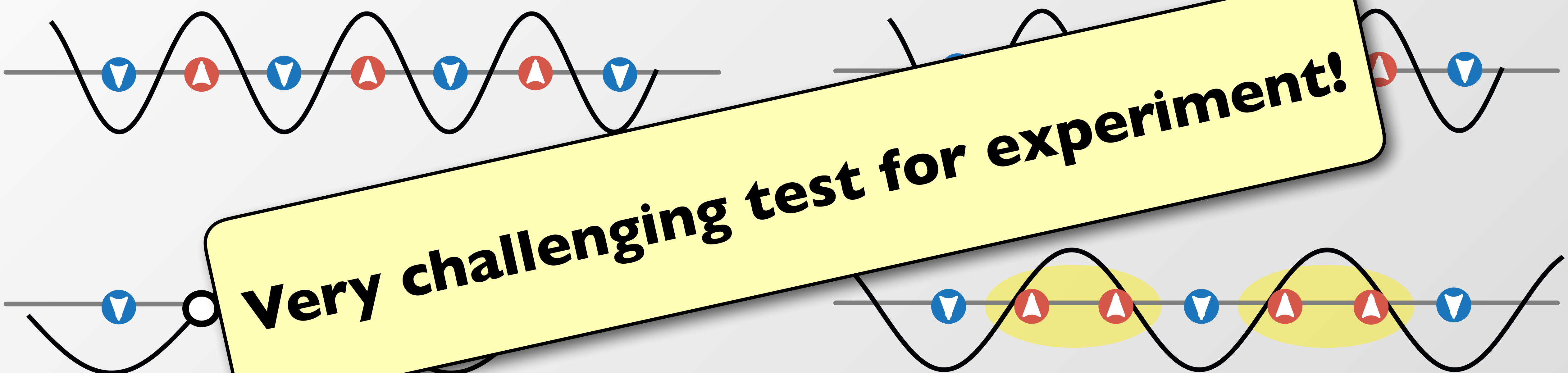
Incommensurate Magnetism

Density Doping

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

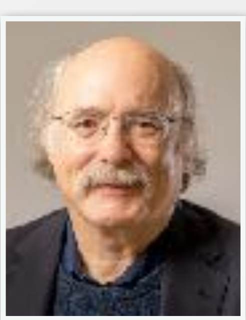
Finite Magnetization

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



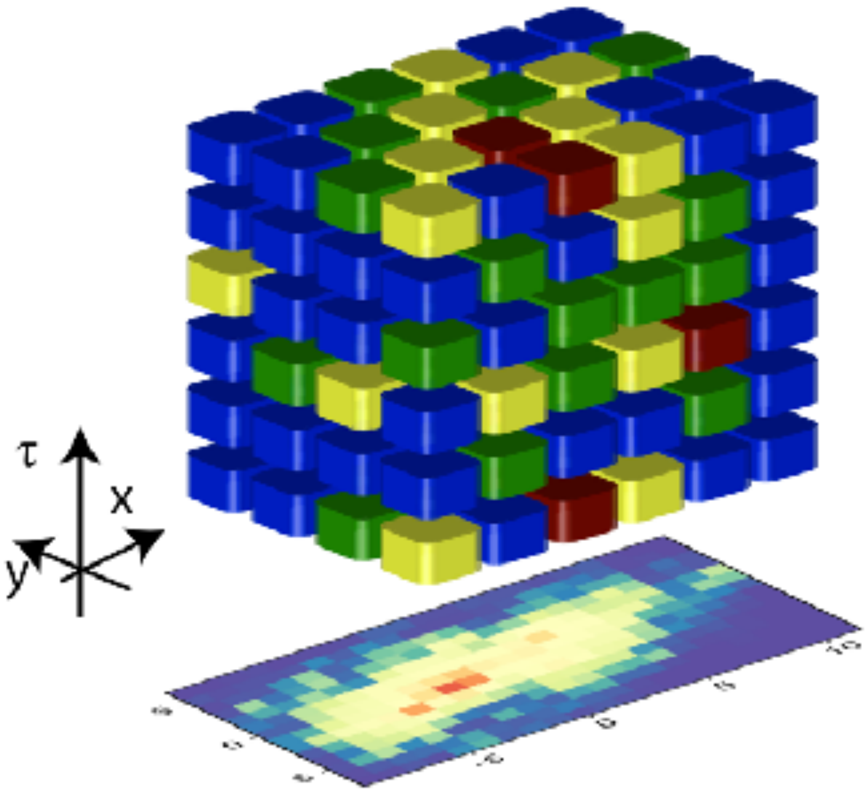
Very challenging test for experiment!

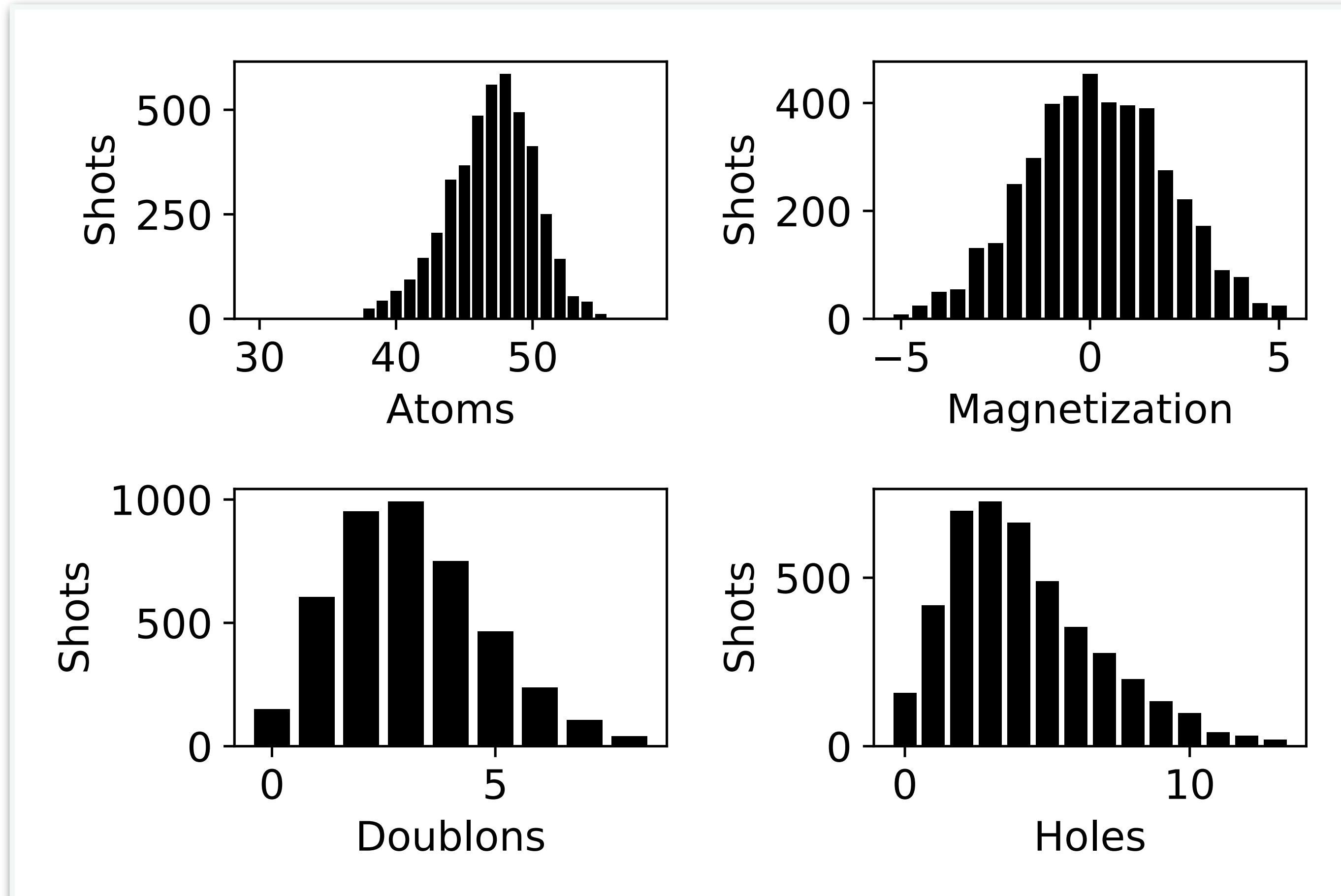
Luttinger Liquid Theory



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

Incommensurate Magnetism - Data Analysis

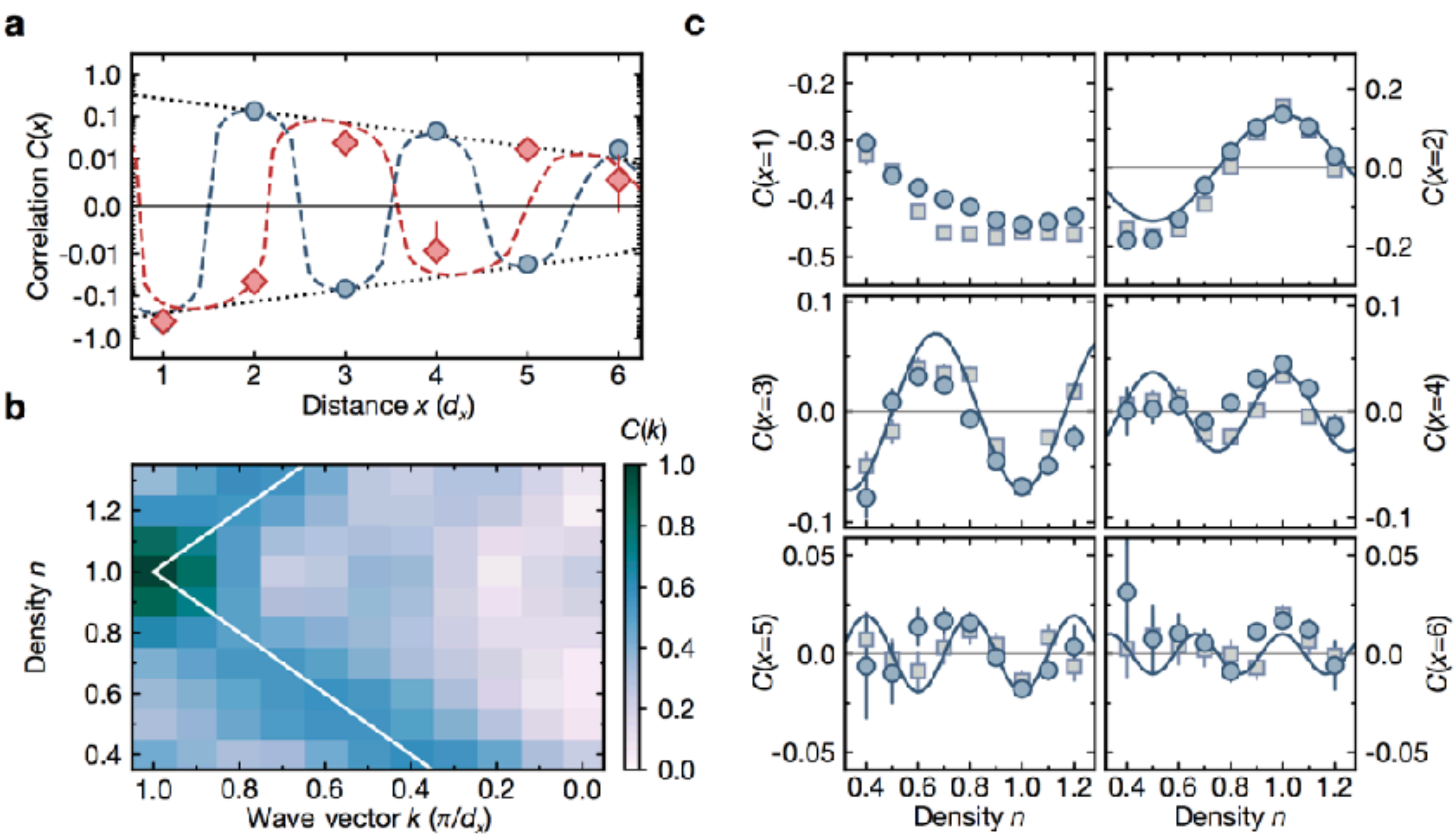




Single Spin and Single Atom Sensitivity !

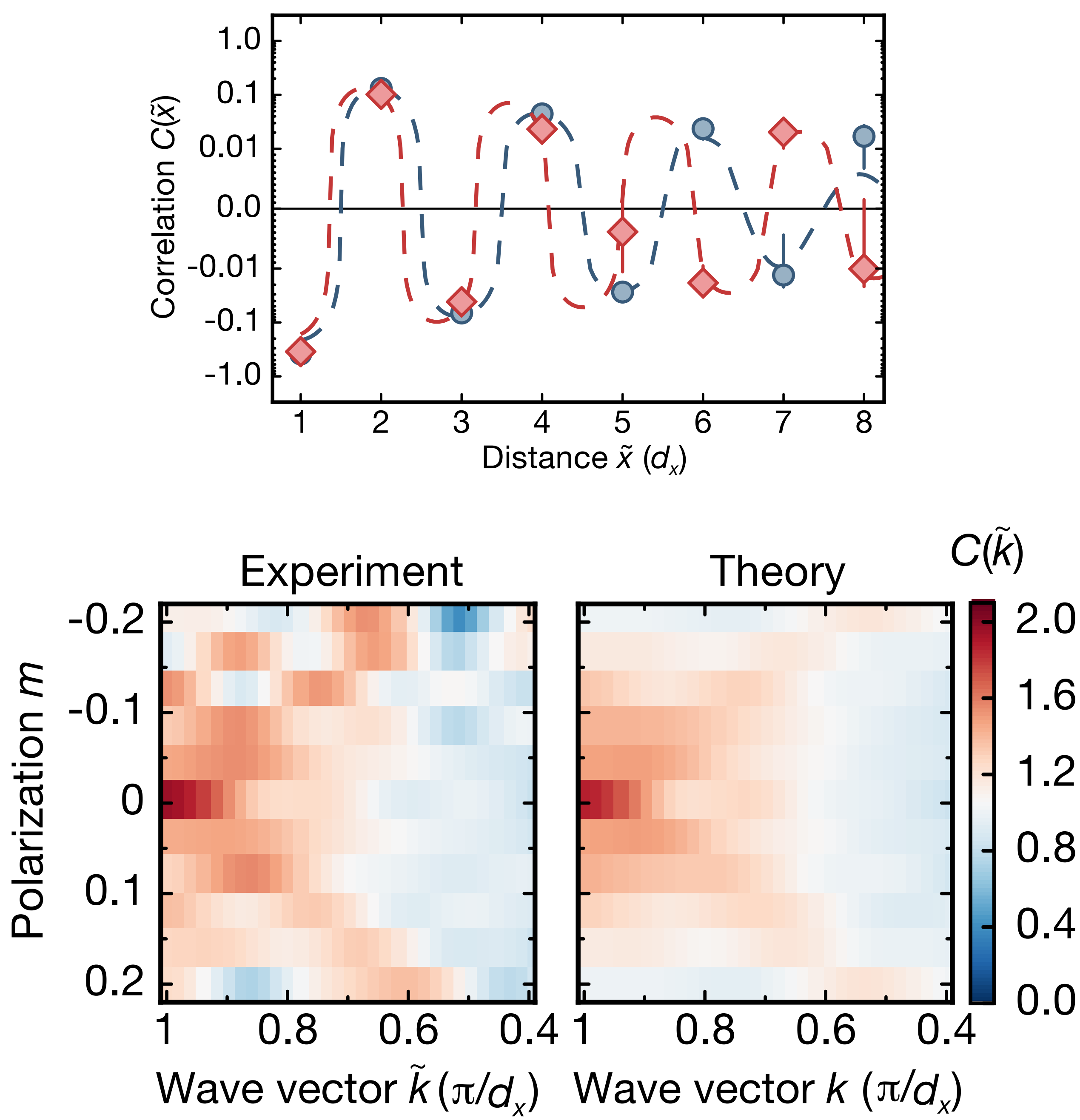
Select shots with defined magnetisation and/or density !

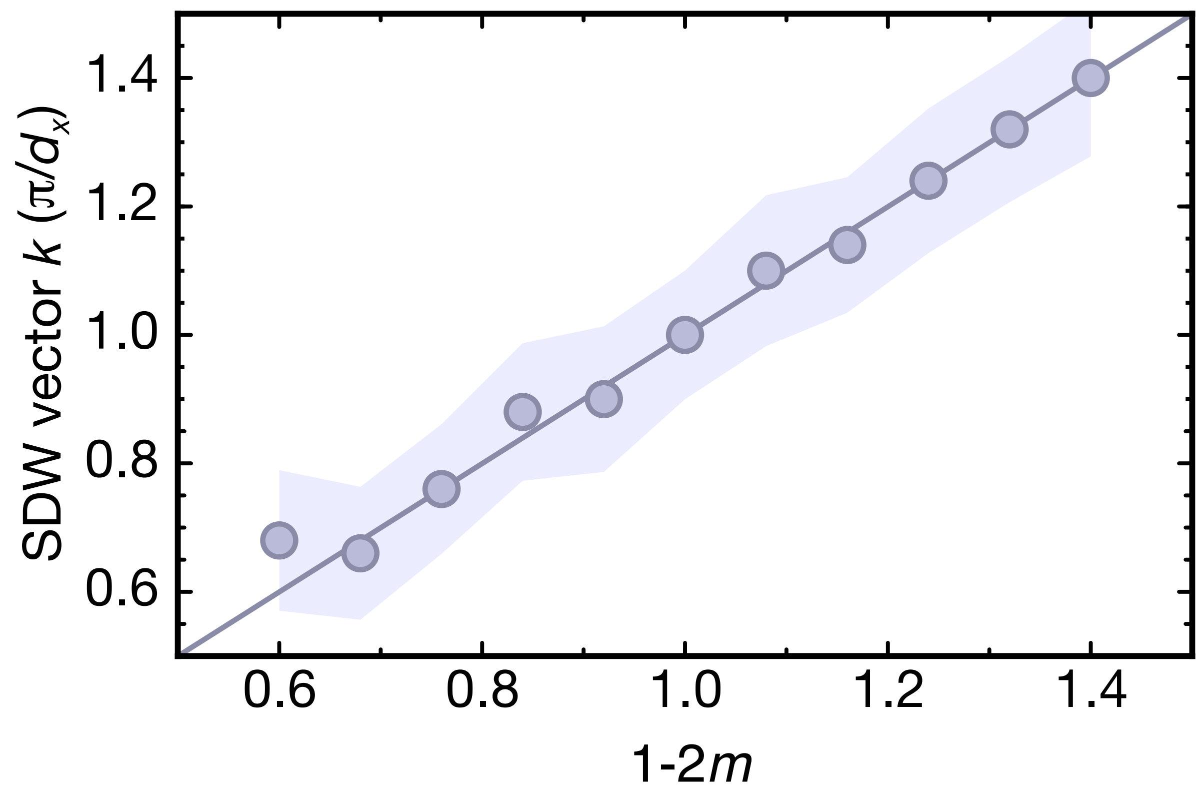
Incommensurate Magnetism - Density



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

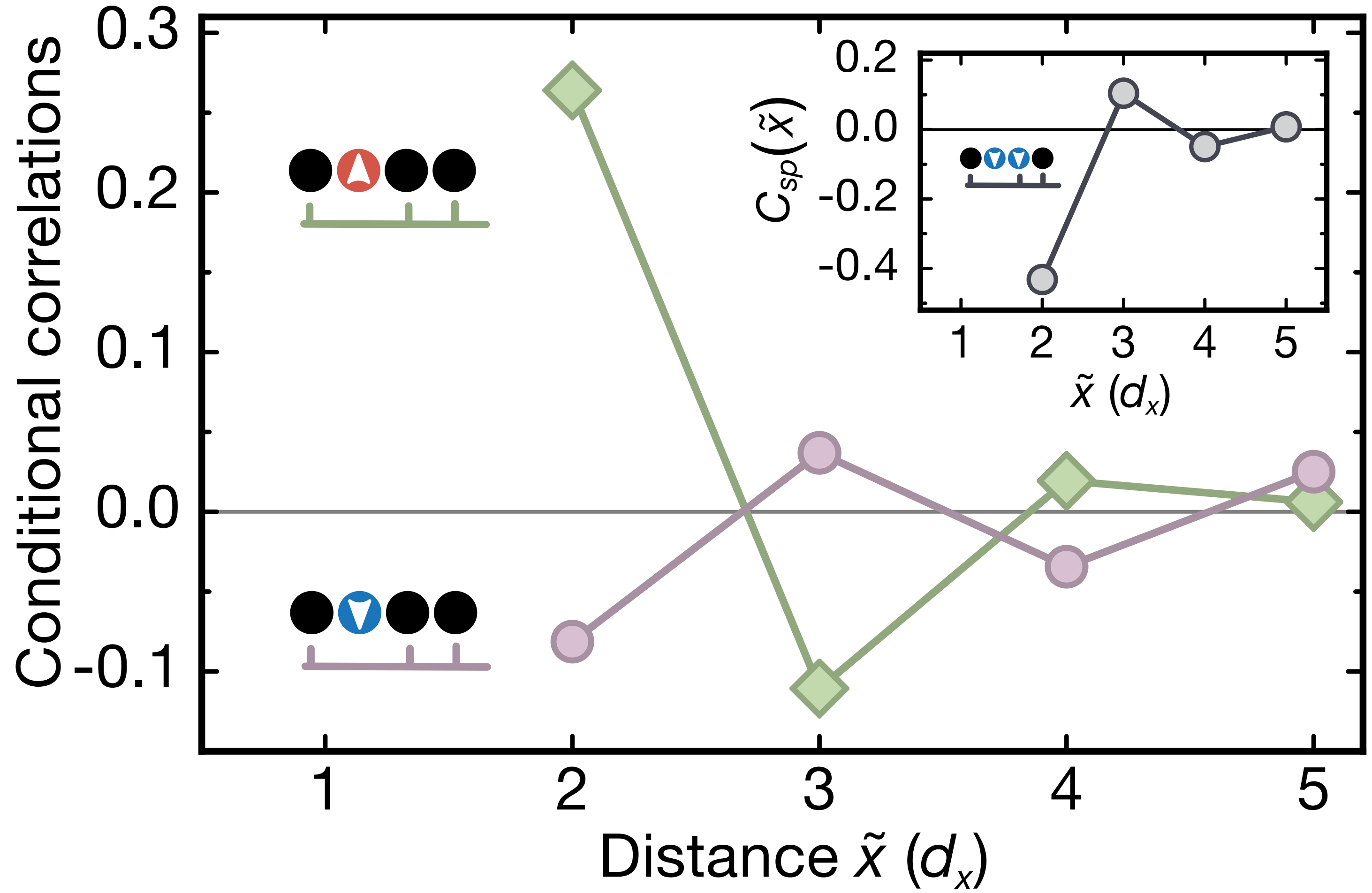
Incommensurate Magnetism - Finite





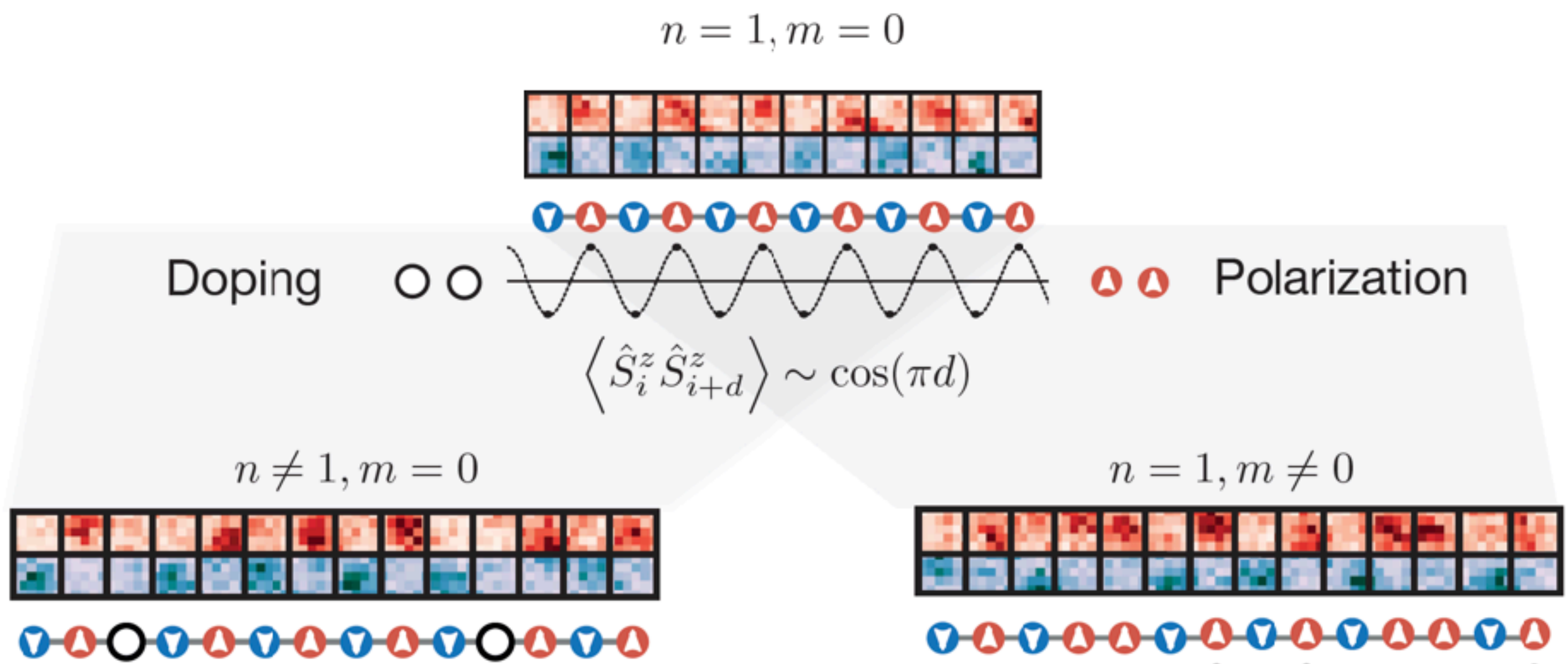
$$\langle S_0^z S_d^z \rangle \simeq A_m e^{-d/\xi_m} \cos(\pi(1-2m)d)$$

Incommensurate Magnetism - Finite



#2: Spinon = Quantum Domain Walls in Squeezed Space

Quantum Domain Walls: Microscopic Picture

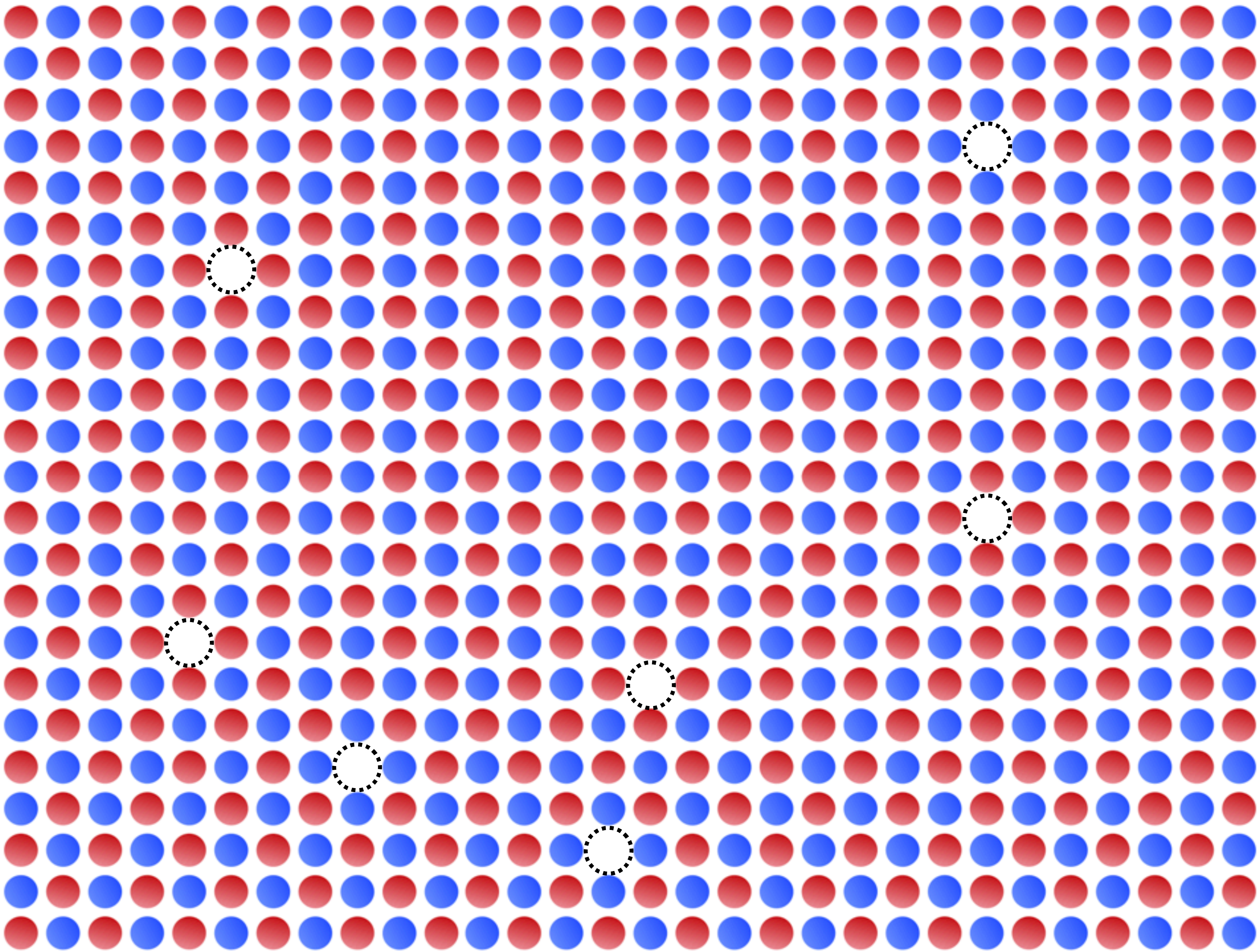


Holon **Spinon**

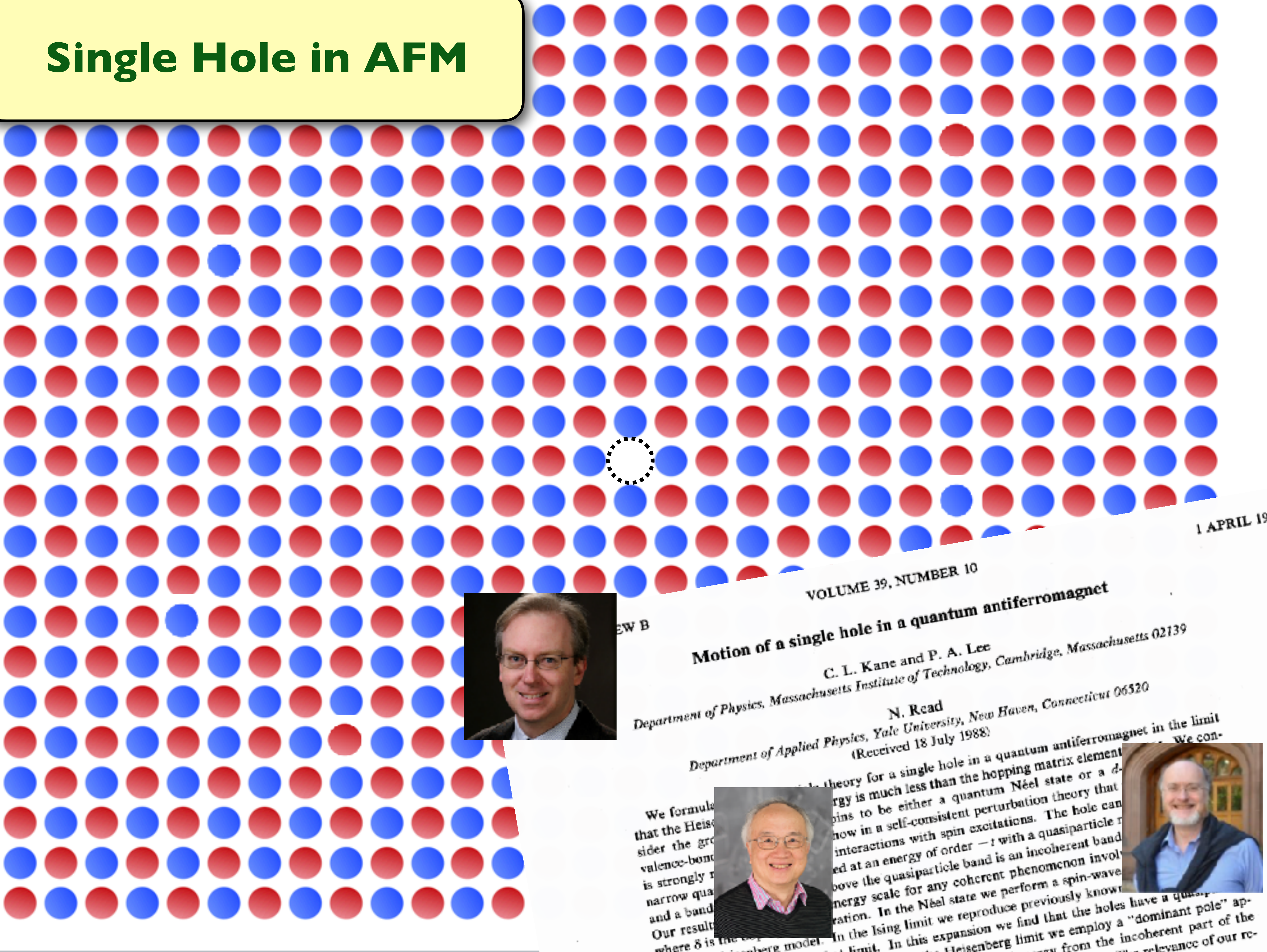
Quantum Domain Walls

Charge Impurities in 2D

J. Koepsell et al. arXiv:1811.06907 (Nature *in print*)



Single Hole in AFM



1 APRIL 19

VOLUME 39, NUMBER 10

EW B

Motion of a single hole in a quantum antiferromagnet

C. L. Kane and P. A. Lee

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

N. Read

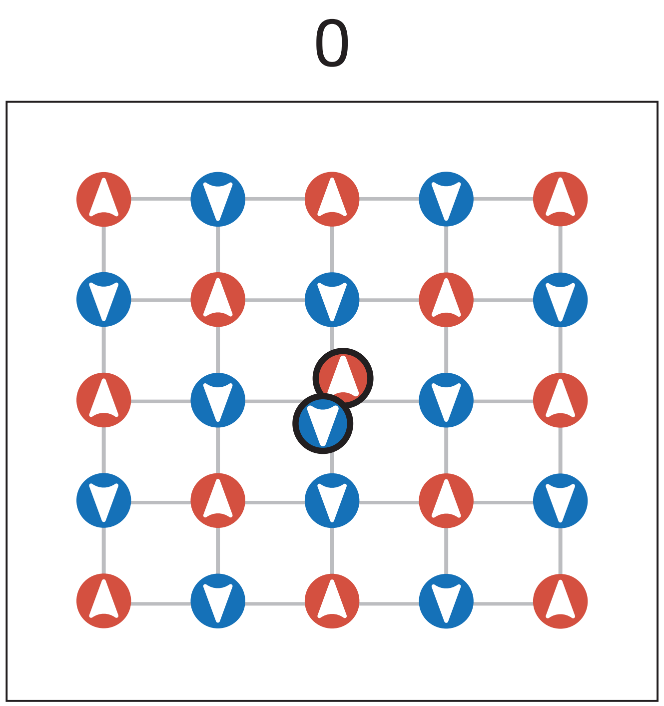
Department of Applied Physics, Yale University, New Haven, Connecticut 06520

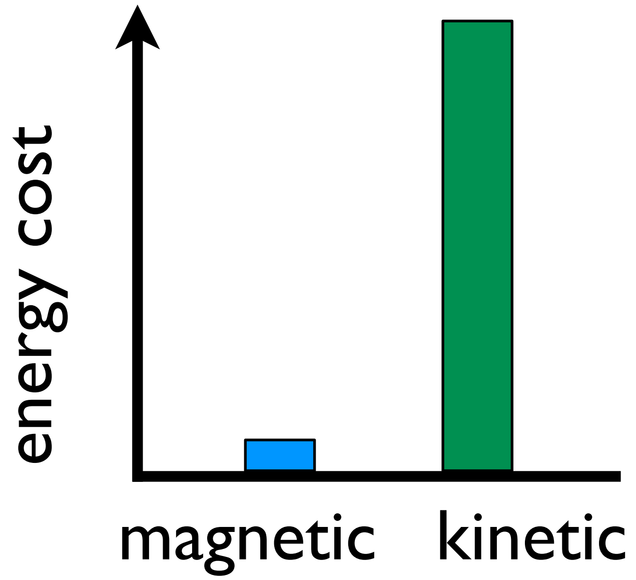
(Received 18 July 1988)

We formula ... theory for a single hole in a quantum antiferromagnet in the limit that the Heise ... rgy is much less than the hopping matrix element ... We consider the gr ... pins to be either a quantum Néel state or a d- valence-bon ... how in a self-consistent perturbation theory that is strongly r ... interactions with spin excitations. The hole can narrow qua ... ed at an energy of order $-t$ with a quasiparticle and a band ... bove the quasiparticle band is an incoherent band Our result ... nergy scale for any coherent phenomenon invol where δ is the ... ration. In the Néel state we perform a spin-wave ... isenberg model. ... In the Ising limit we reproduce previously know ... the holes have a quasi- ... limit. In this expansion we find that the holes have a "dominant pole" ap- ... Heisenberg limit we employ a "dominant pole" ap- ... from the incoherent part of the ... relevance of our re-

Competing Energy Costs: Kinetic vs Magnetic

$$t \gg J$$

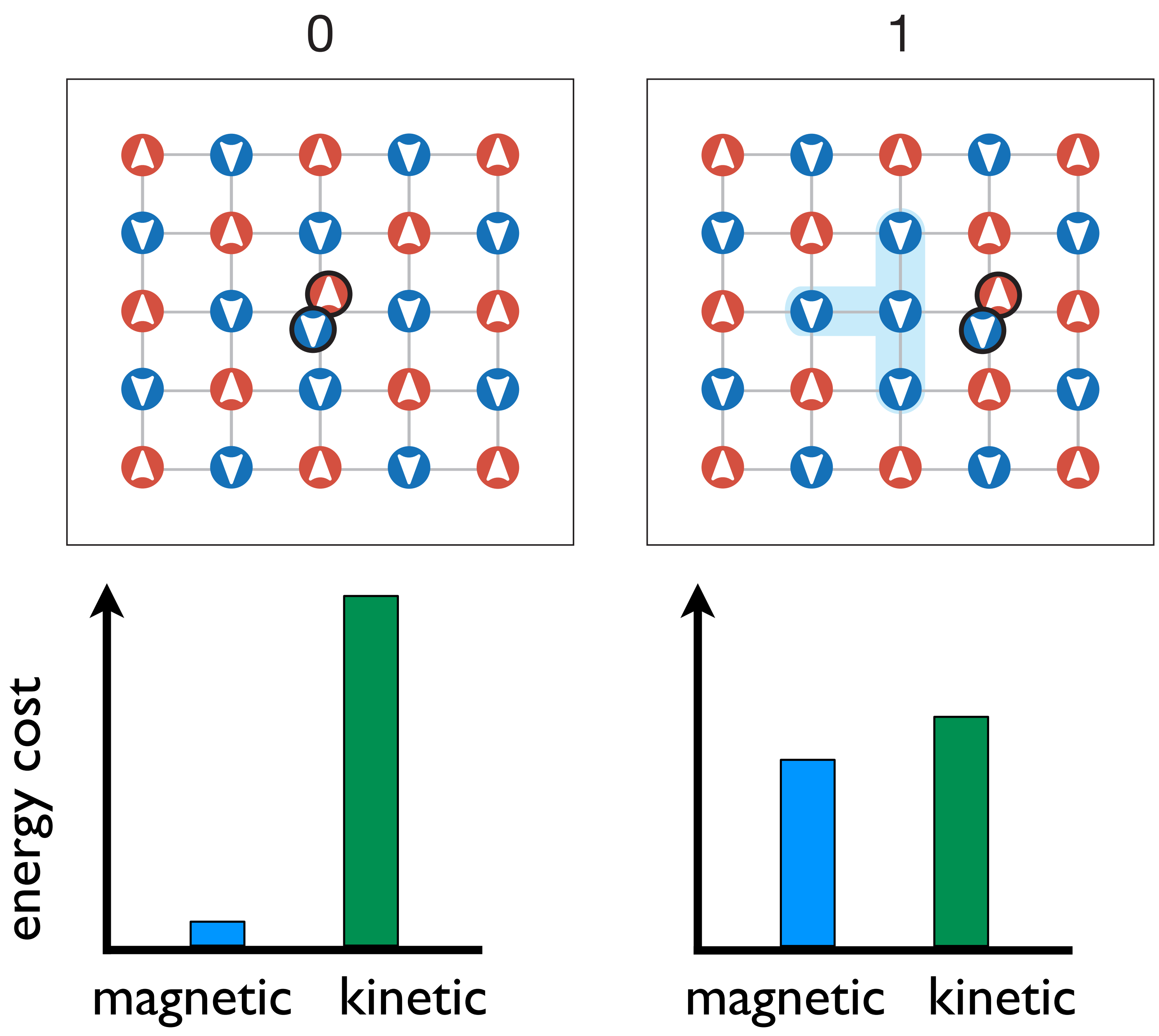




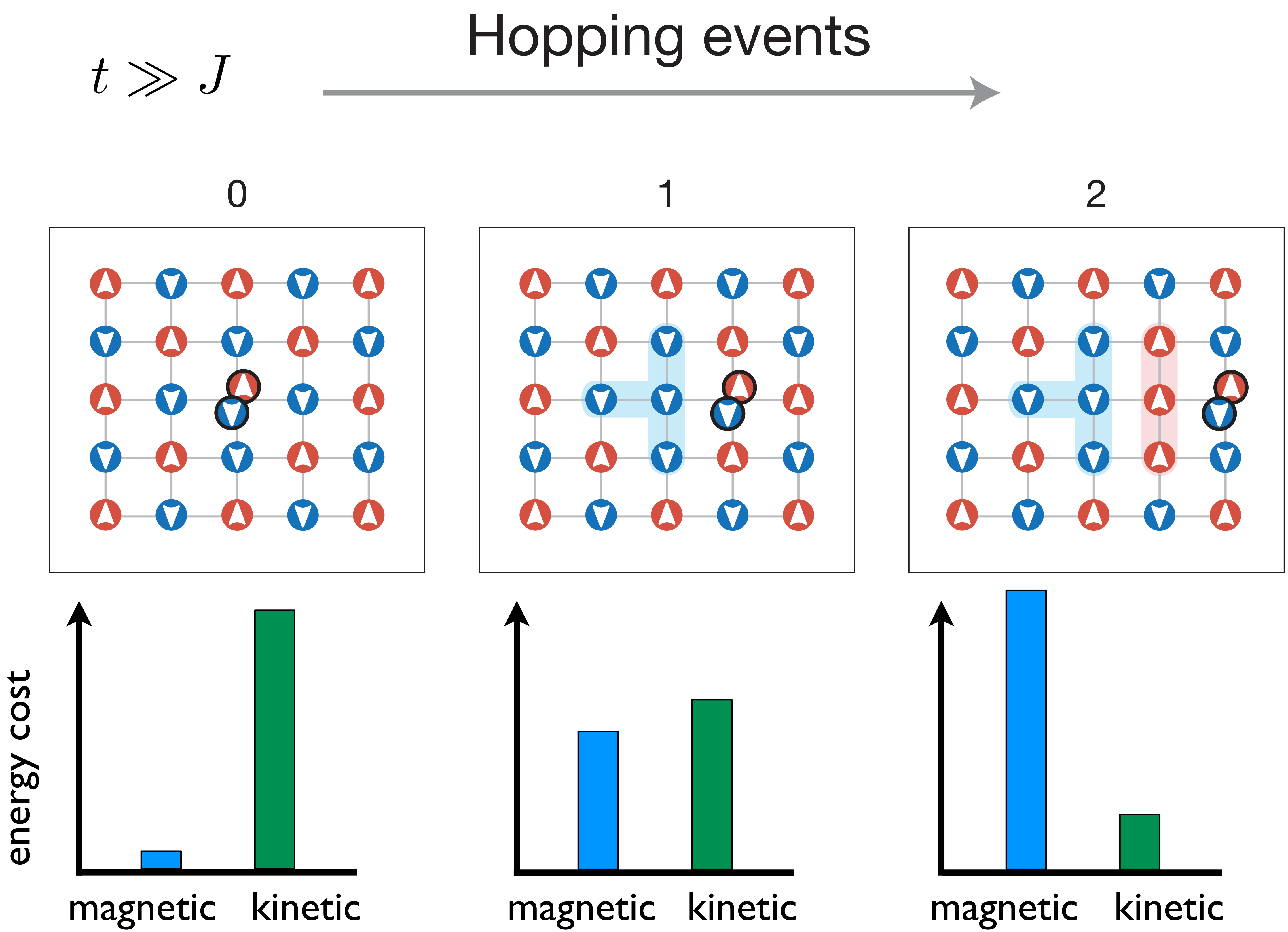
Competing Energy Costs: Kinetic vs Magnetic

$t \gg J$

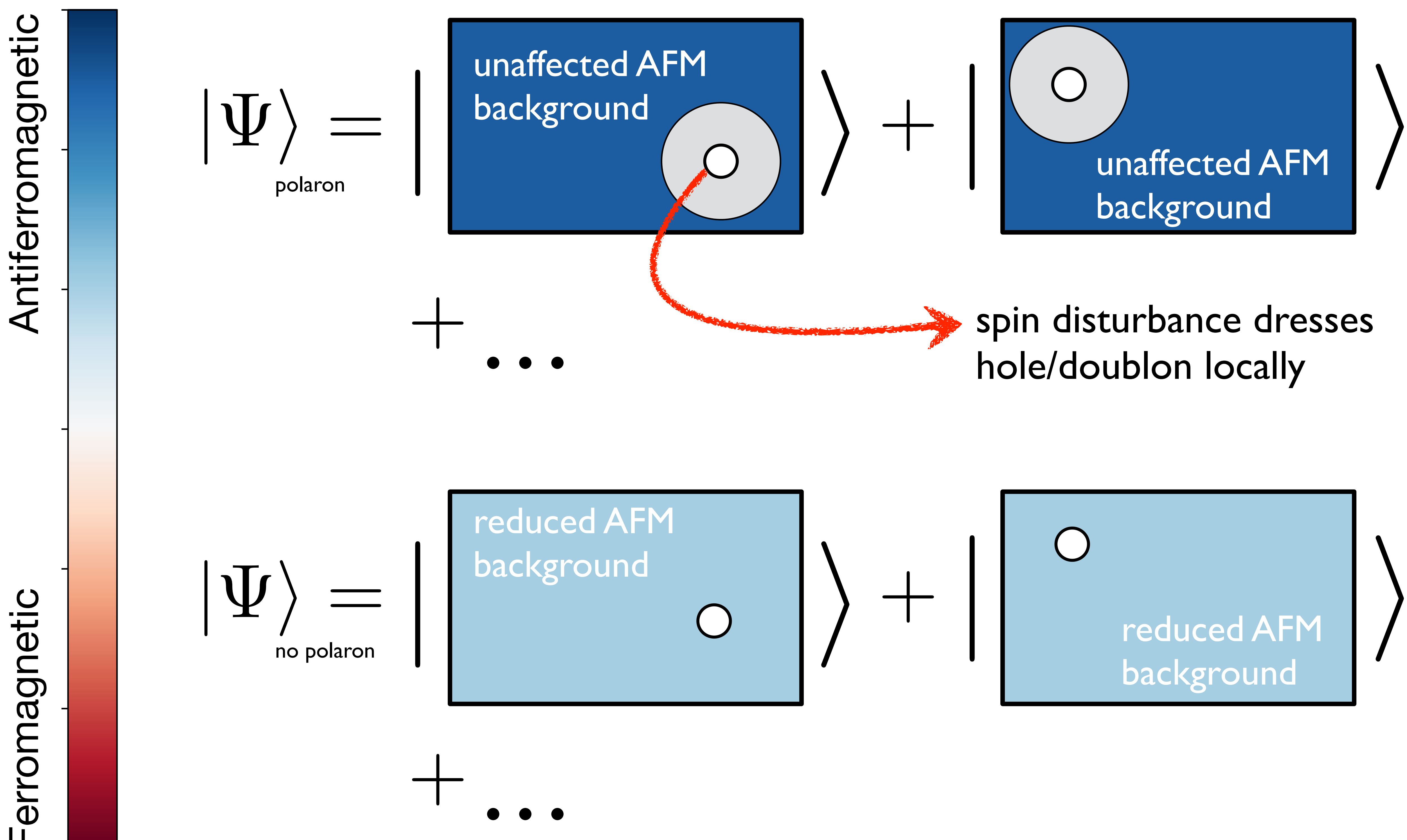
Hopping events



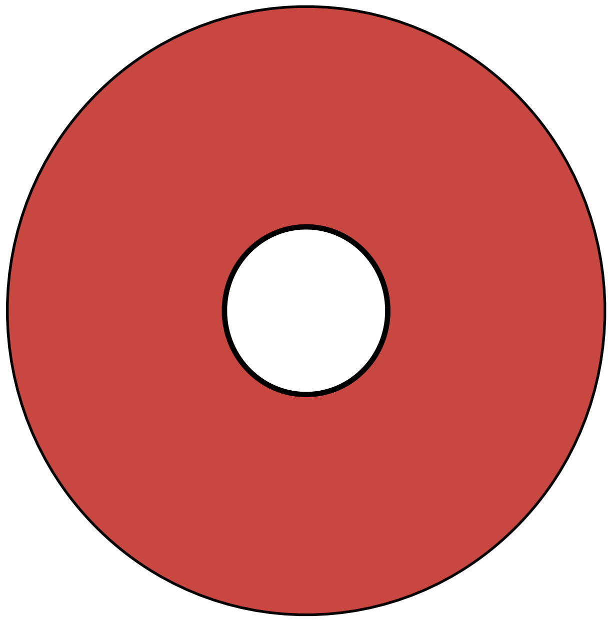
Competing Energy Costs: Kinetic vs Magnetic

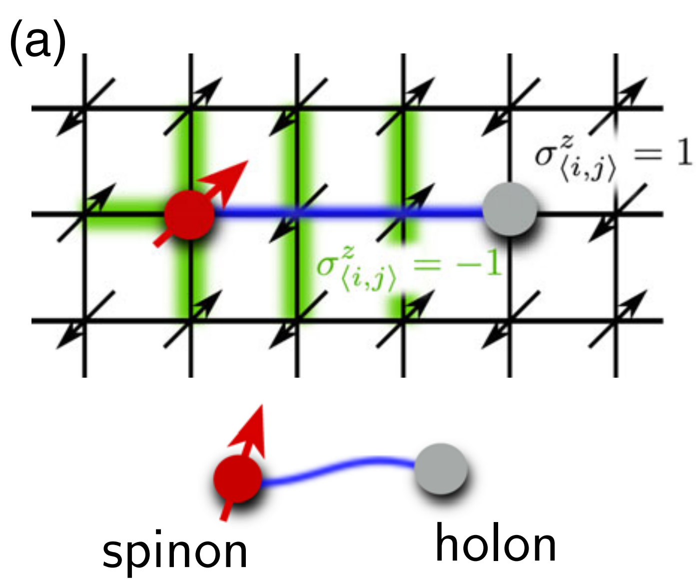


Ground State?



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





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

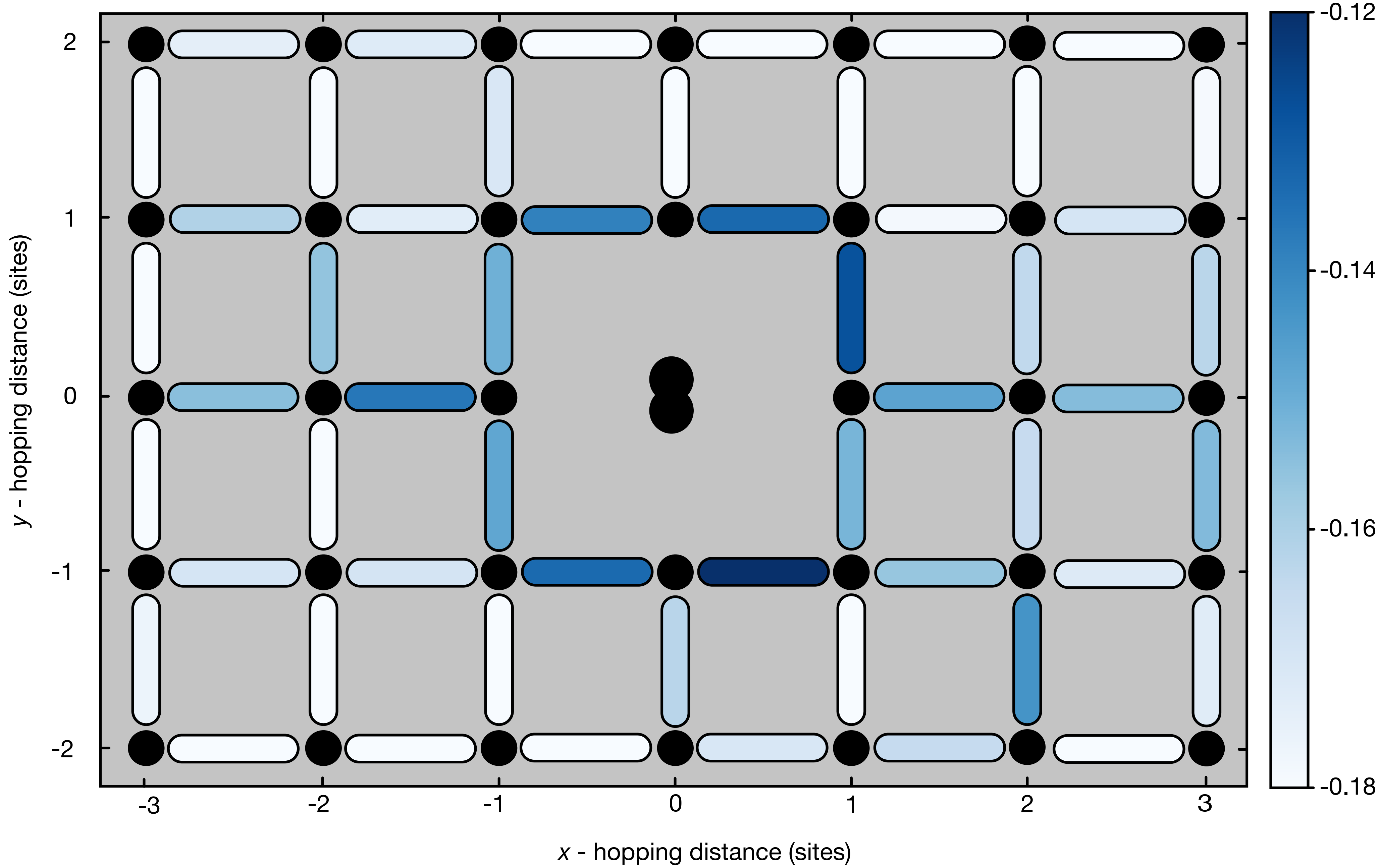
- **Attraction between polarons**
  ⟶ superconductivity, stripes?

- **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

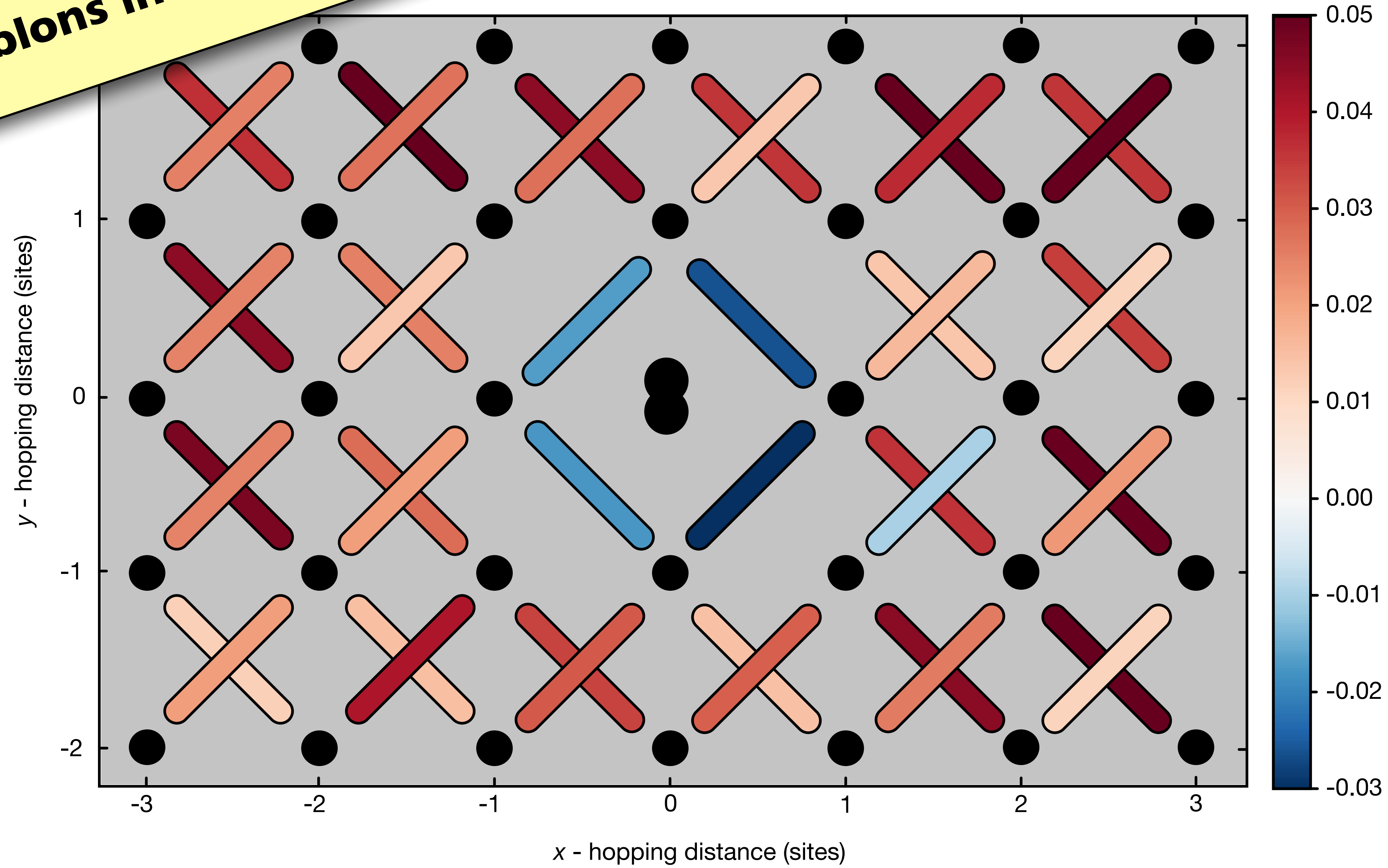
C(1) Local Spin Correlations Around Doublon



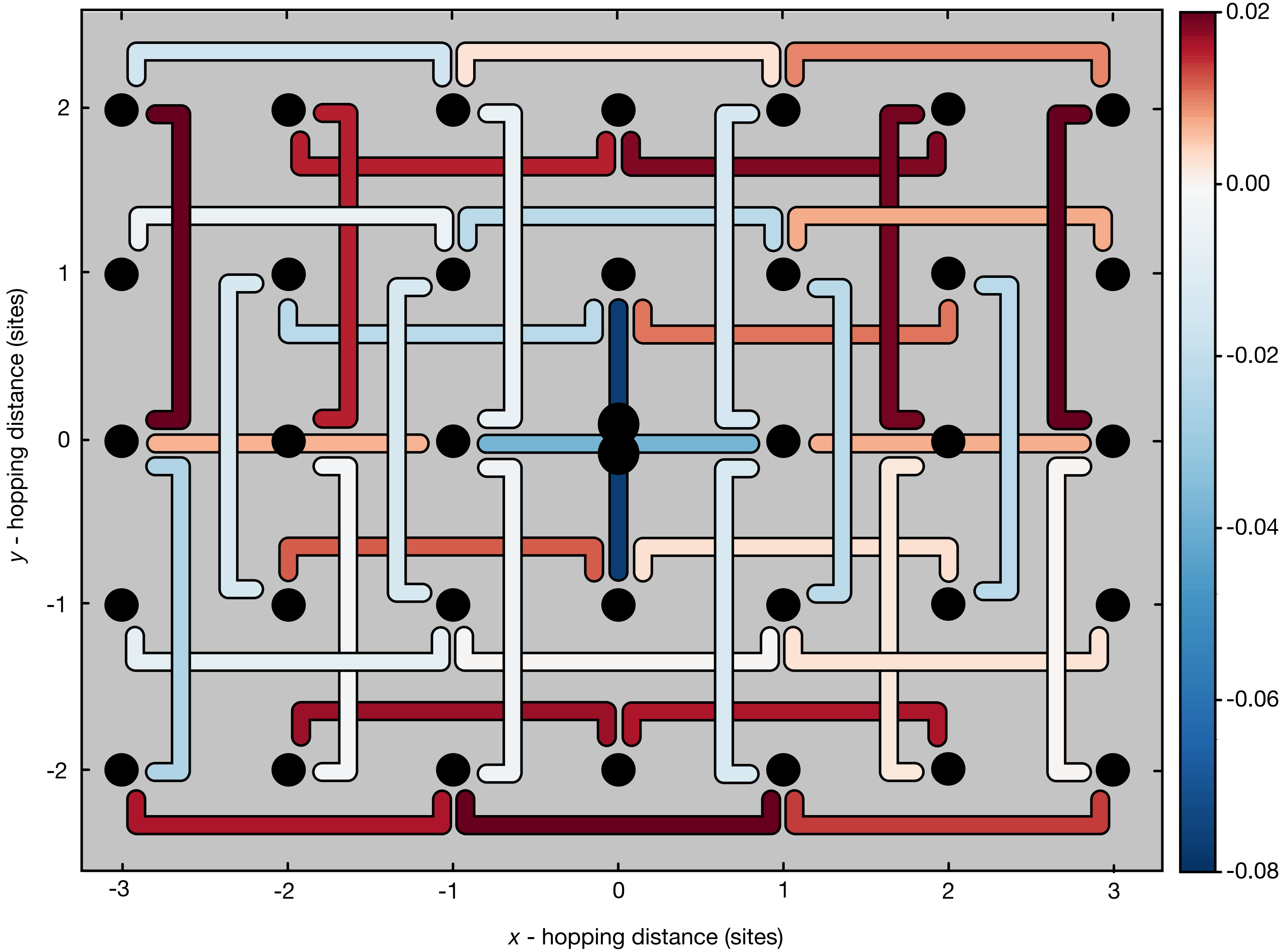
Conditioned C(1) Correlator

C(1,1) Local Spin Correlations around Doublon

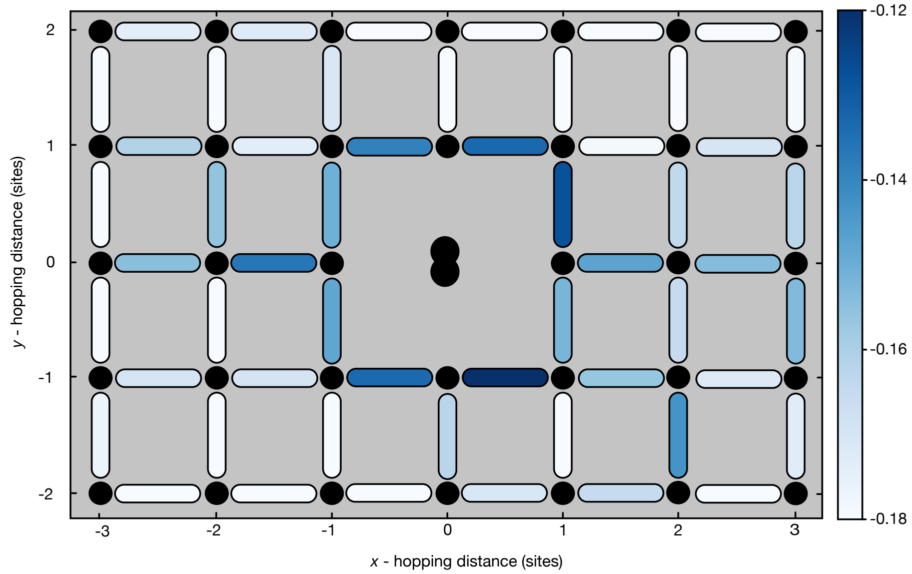
Doublons induce sign flip !

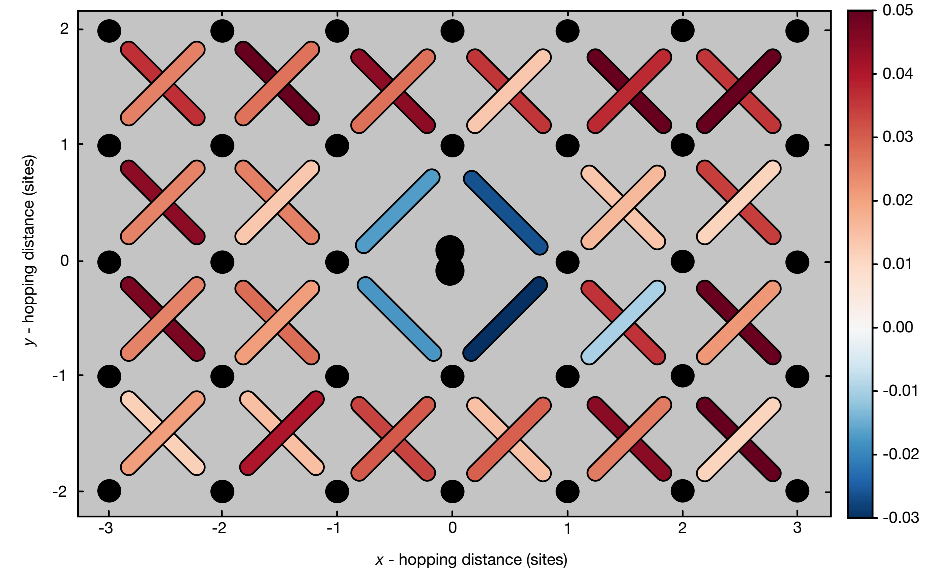


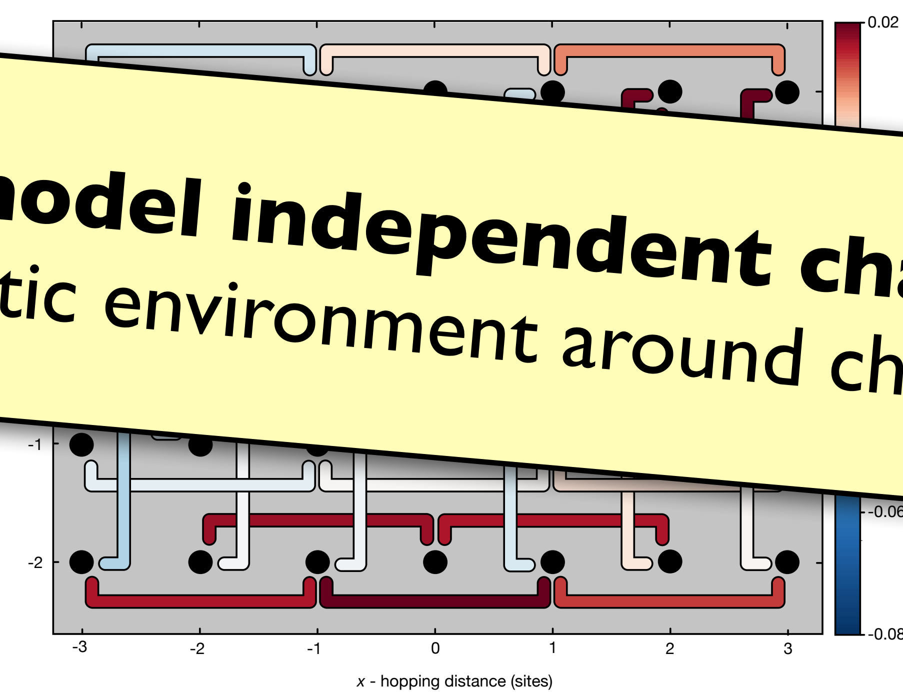
C(2) Local Spin Correlations around Doublon



Magnetic Polaron Size

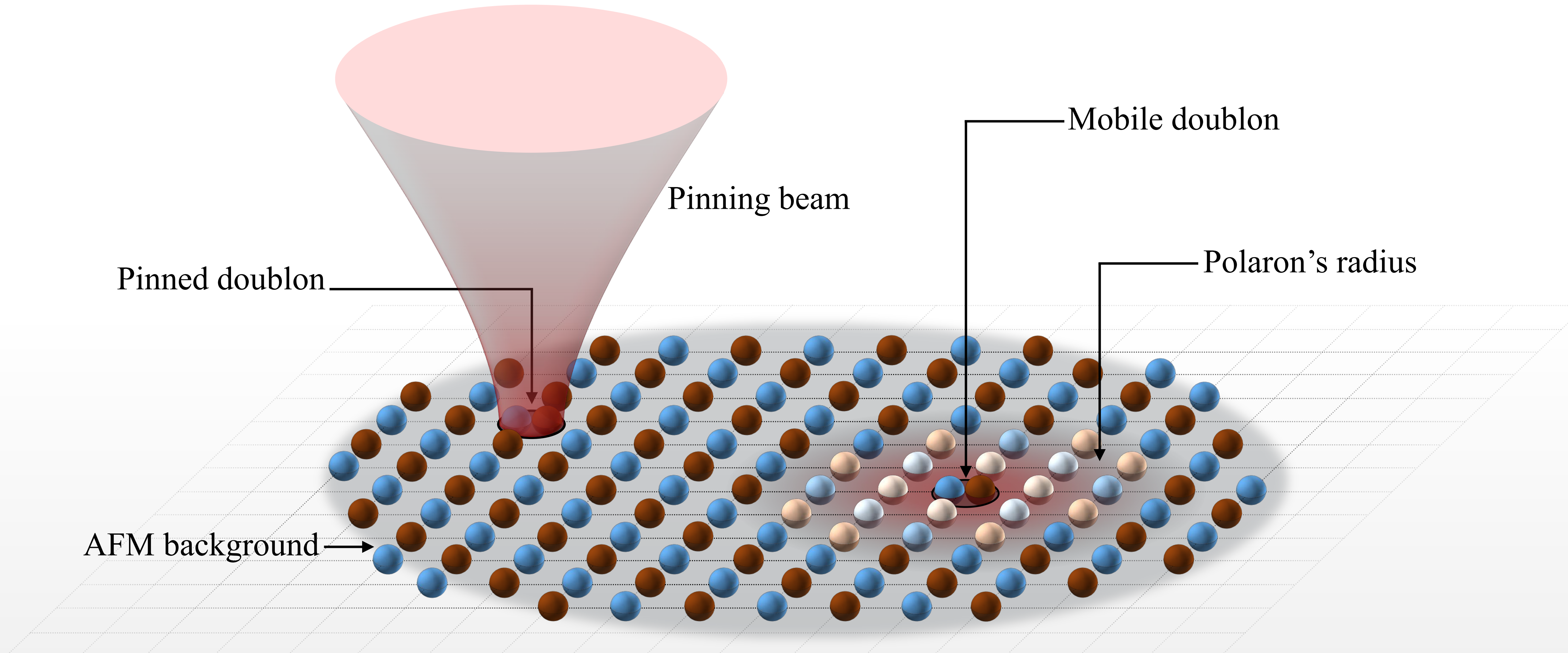




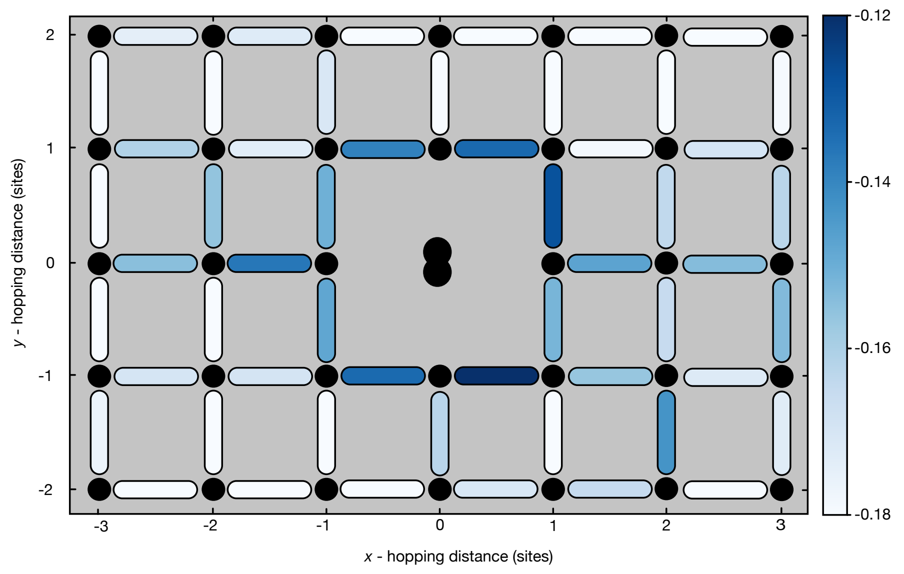


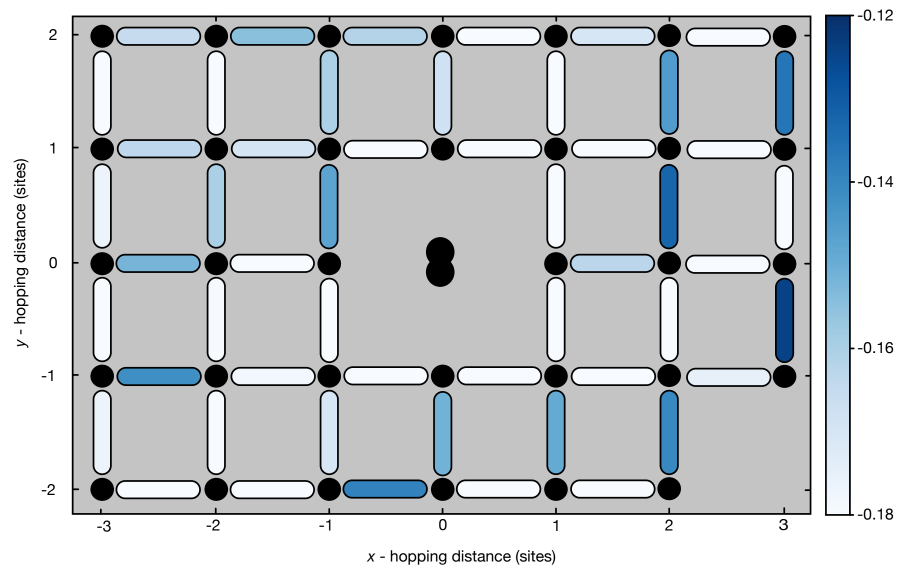
Complete **model independent characterisation** of magnetic environment around charge impurity

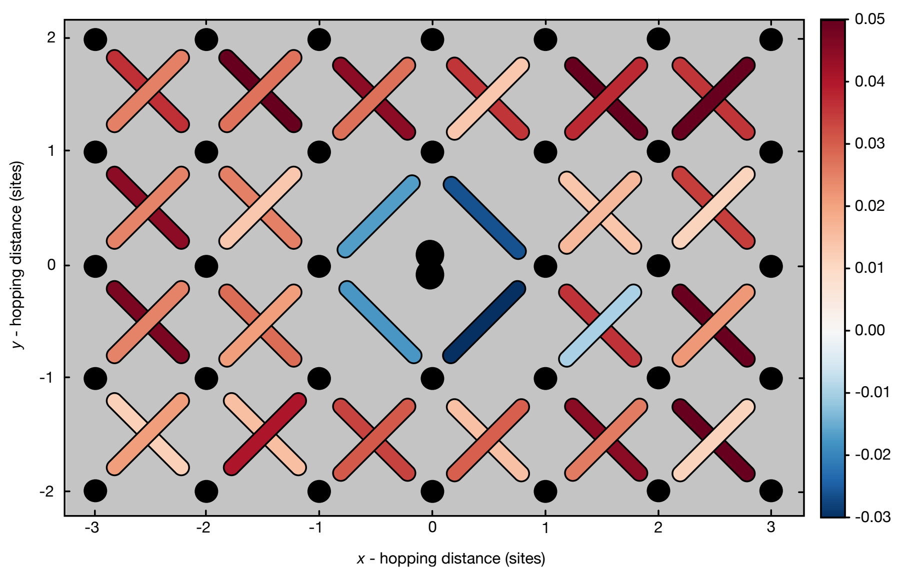
Changing Charge Mobility

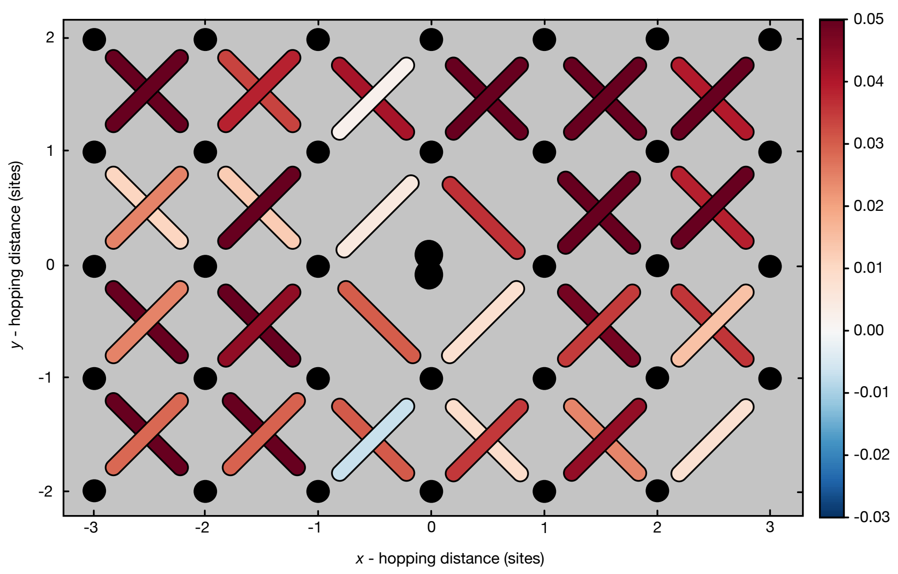


Spin Correlations Around Doublon







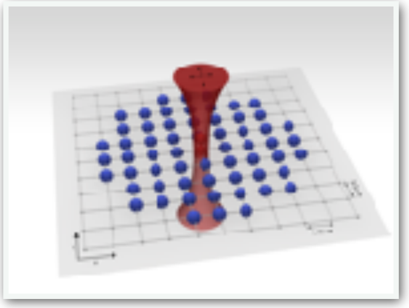


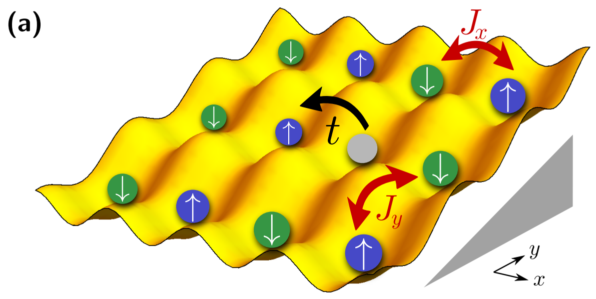
Mobile

Pinned

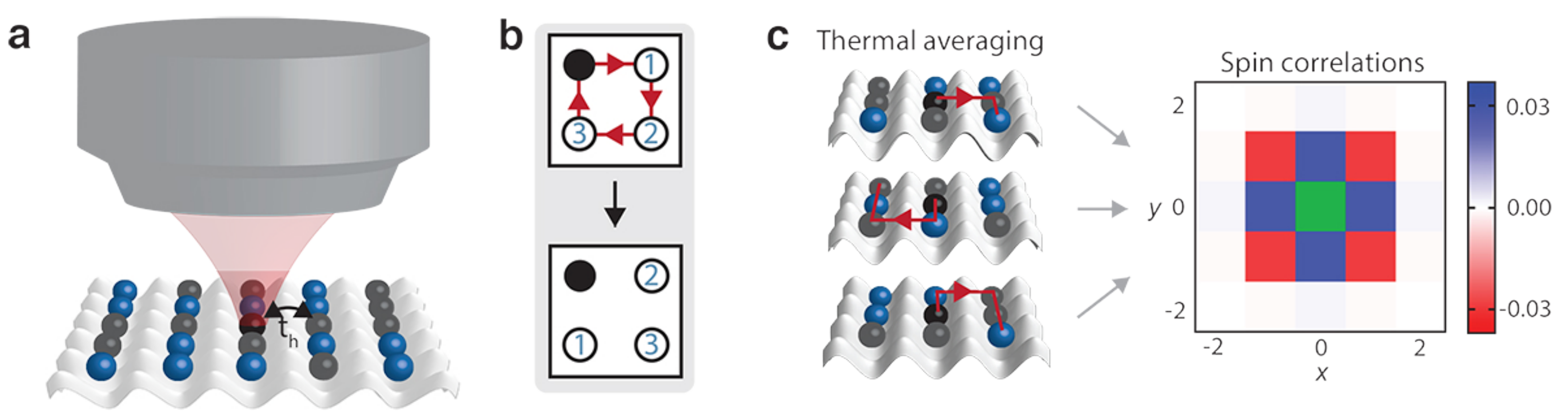
Outlook

- **Polaron-Polaron** correlations
- **Timescale** of polaron formation
- **Mixed dimensions**
- **Dynamical Nagaoka effect**





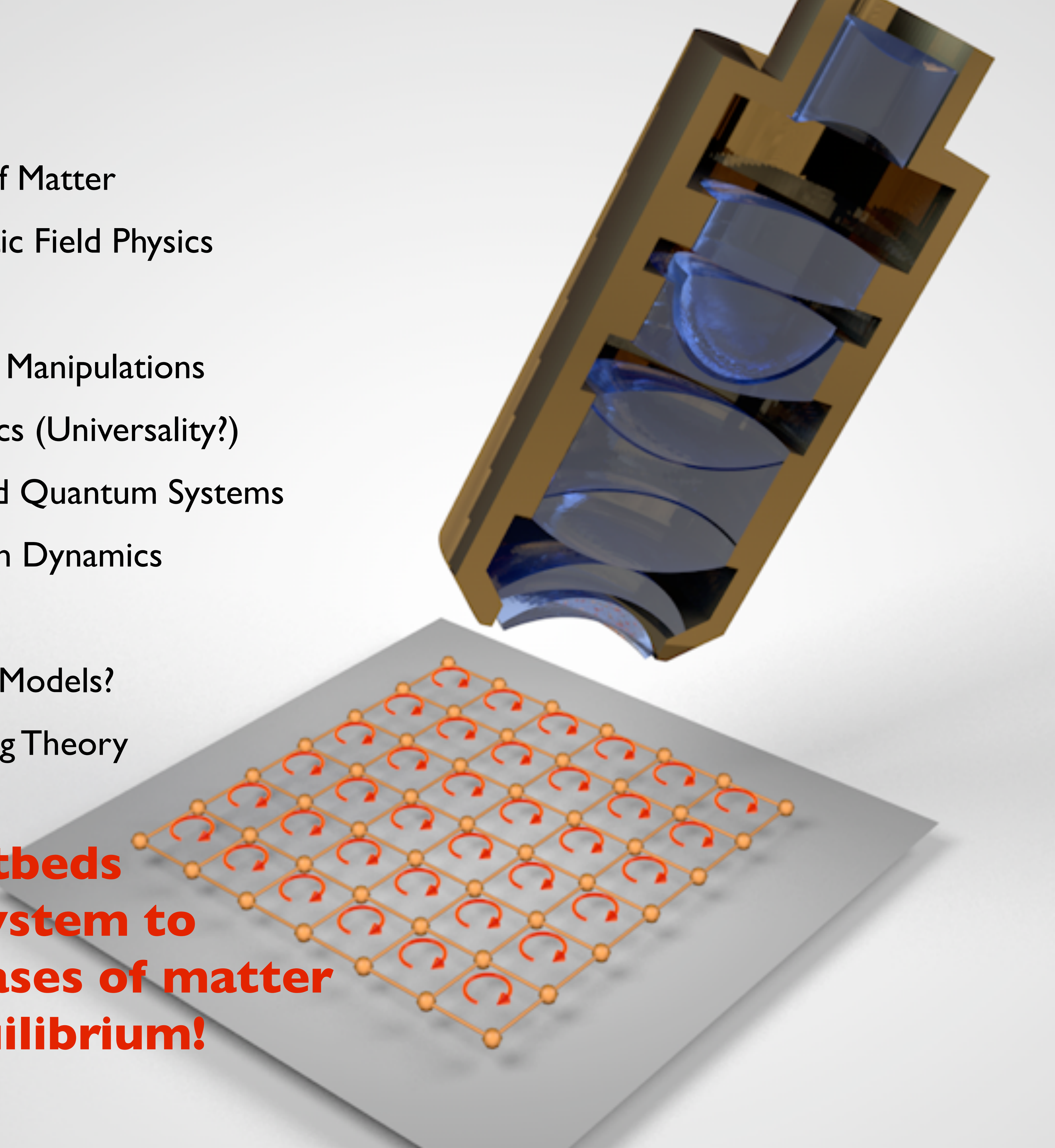
Grusdt *et al*, arXiv:1806.04426 2018



Kanász-Nagy *et al*, PRB 96 2017

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



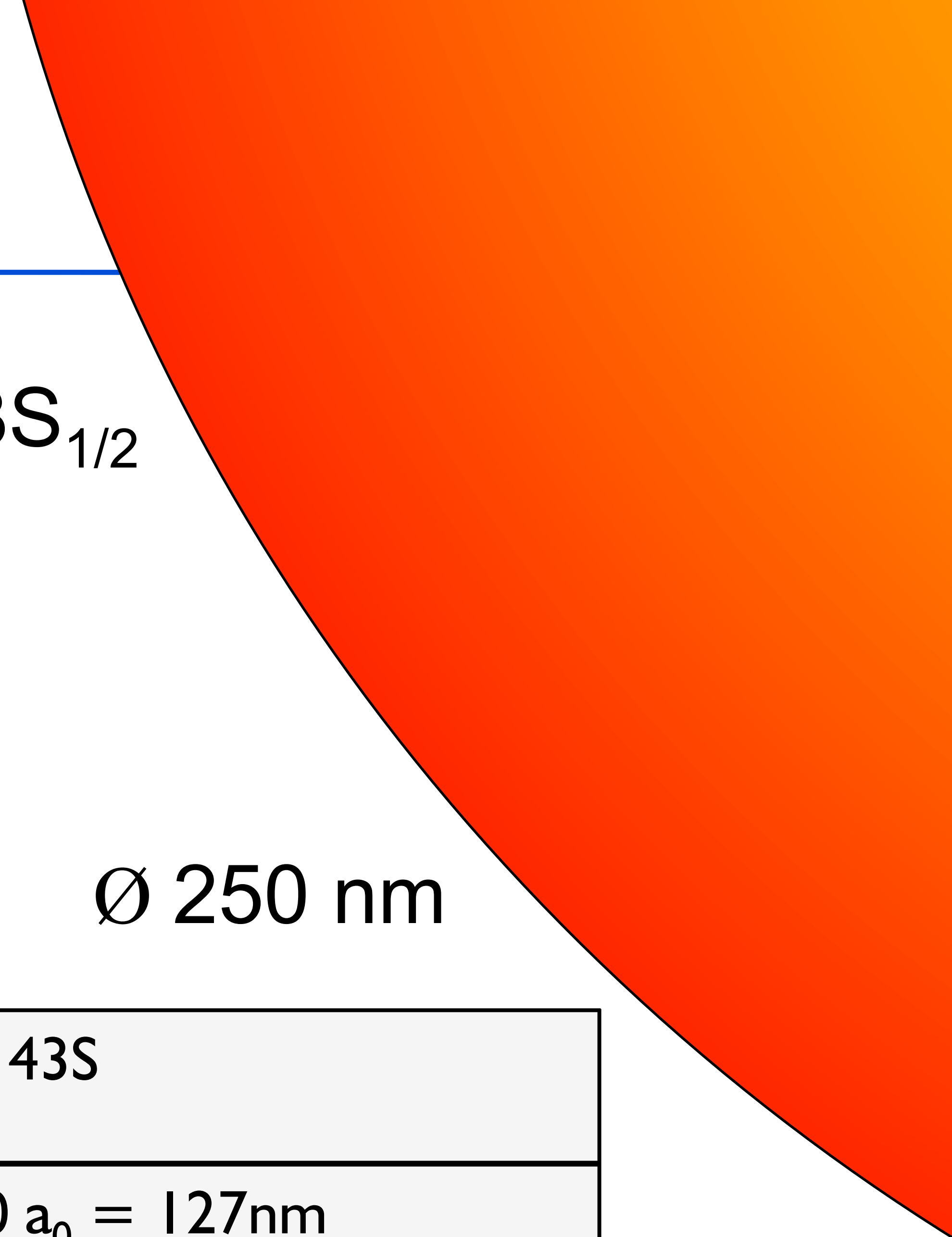
Quantitative testbeds for theory and system to discover new phases of matter in and out of equilibrium!

⋮

Rydberg atoms

- hydrogen-like wave function
  - quantum defect

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



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

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

Ø 0.5nm

Ø 250 nm

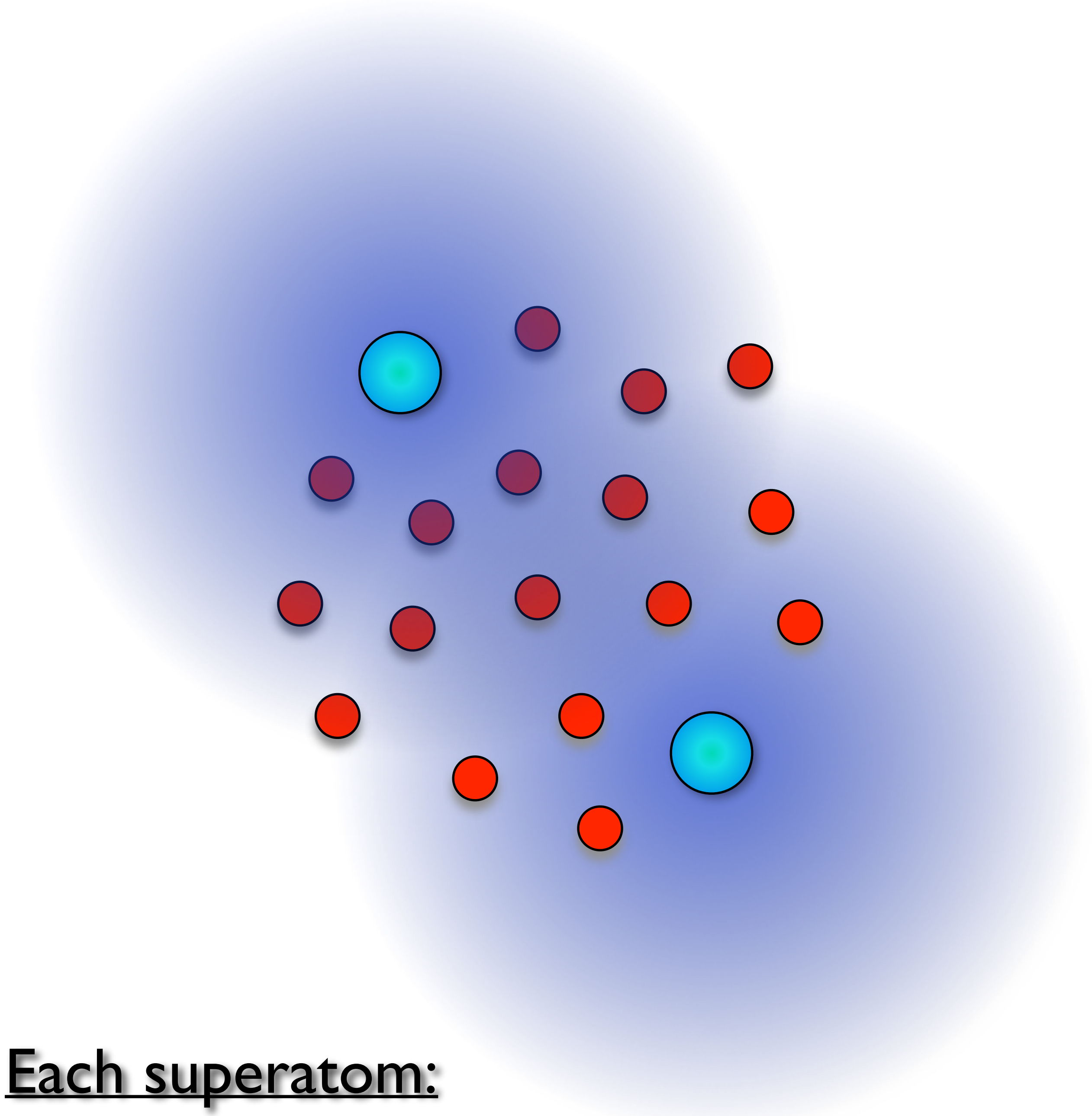
- Strong switchable interactions

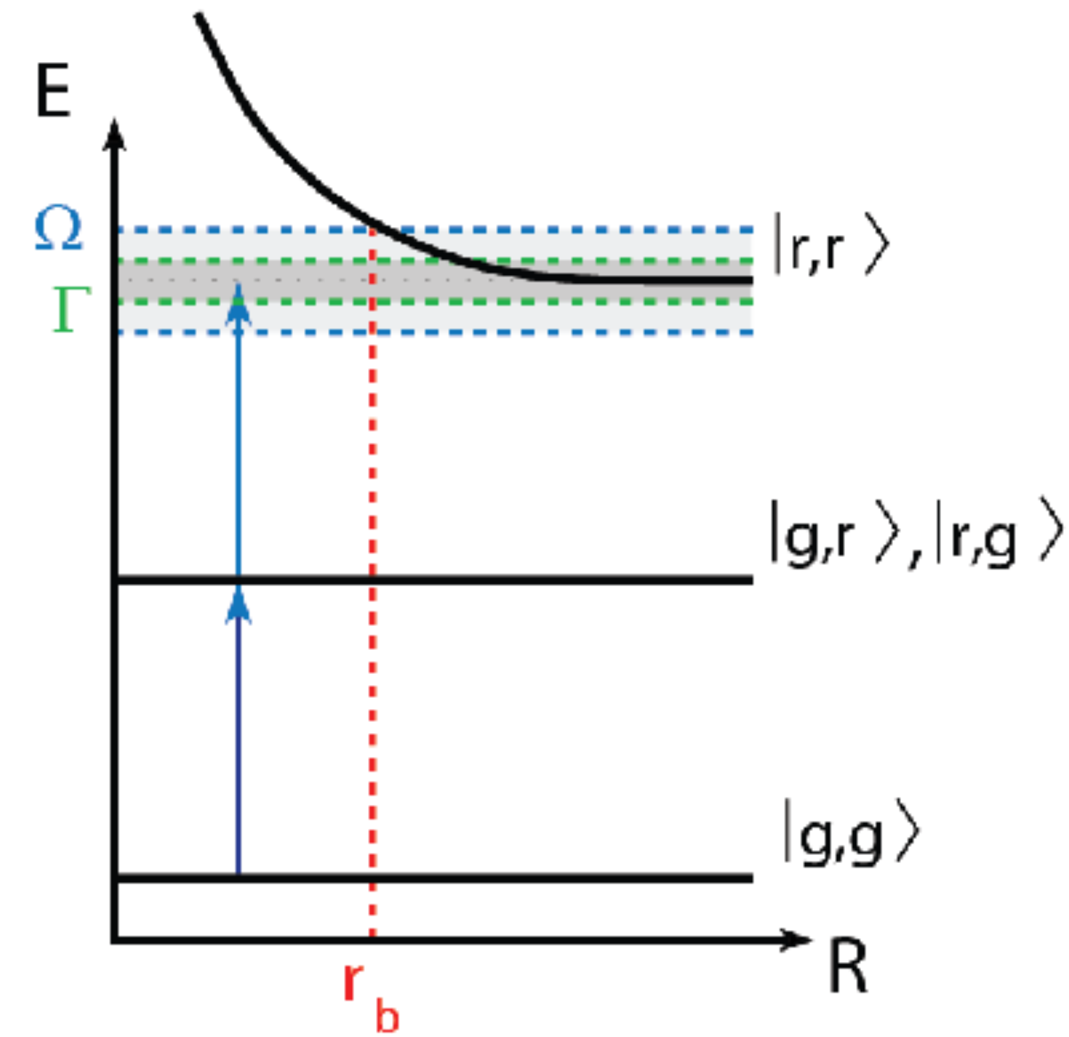
Property	Scaling	^{87}Rb 43S
Radius	$(n^*)^2$	$2400\ a_0 = 127$nm
Lifetime (dominated by black body radiation for large n)	$(n^*)^2$	45 μs @ 20°C
van der Waals coefficient	$(n^*)^{11}$	$C_6 = -1.7 \times 10^{19}$ a.u.
Blockade radius ($\Omega = 2\pi$ 200 kHz)	$(n^*)^2$	$\sim 5\ \mu$m

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

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

Rydberg blockade





Blockade condition

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

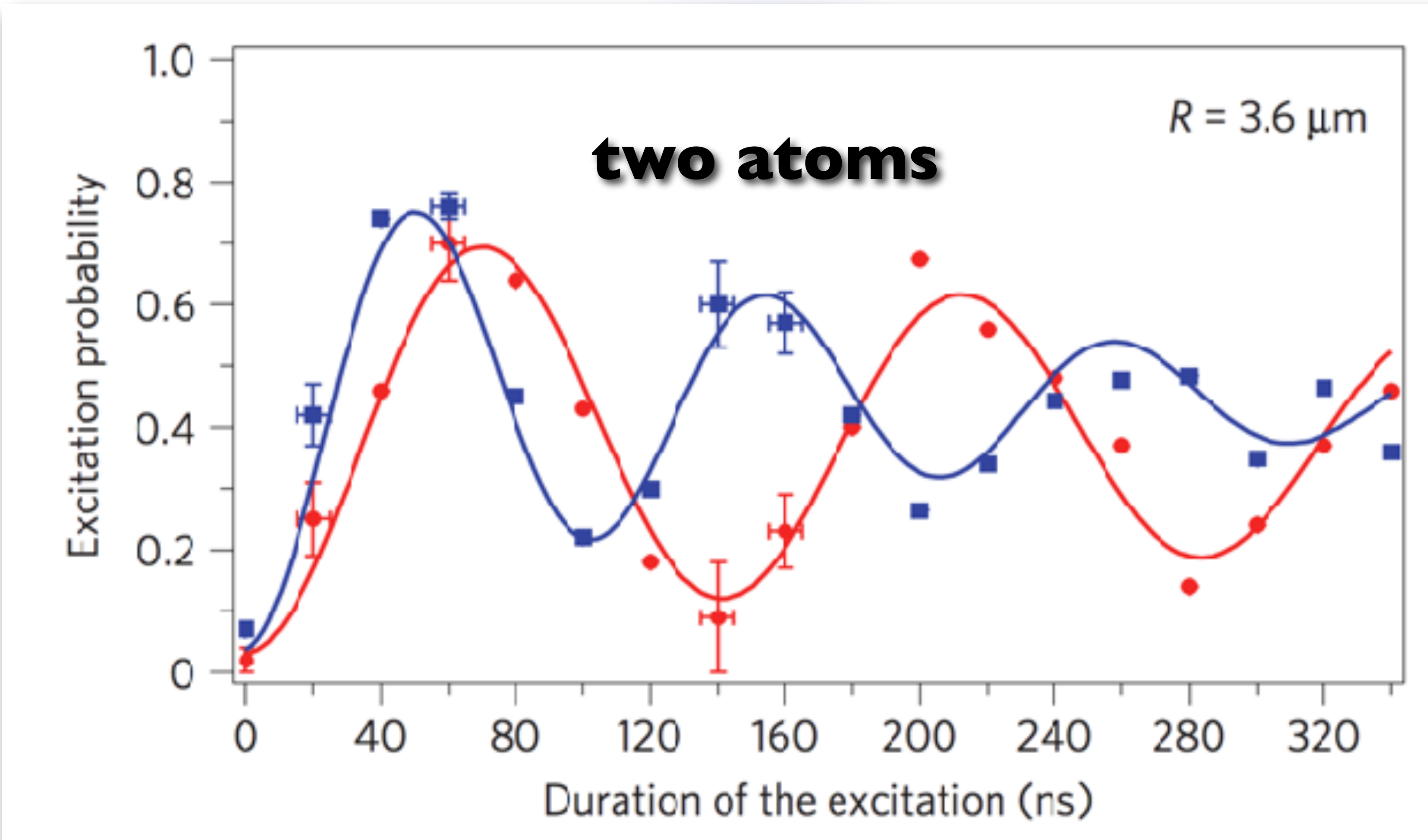
$$r_{\rm b} \equiv \sqrt[6]{\frac{C_6}{\hbar\Omega}}$$

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 **87**, 037901 (2001)

Rydberg blockade



ade radius

er than cloud size!

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

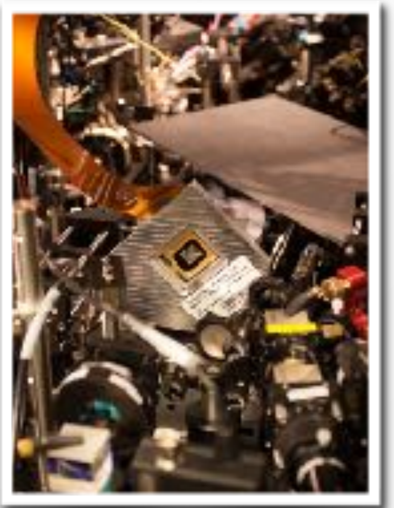
<u>Each superatom:</u>

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

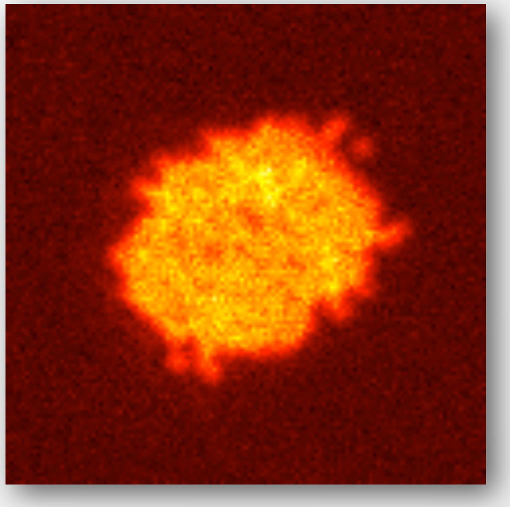
M. Lukin et al. PRL **87**, 037901 (2001)

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

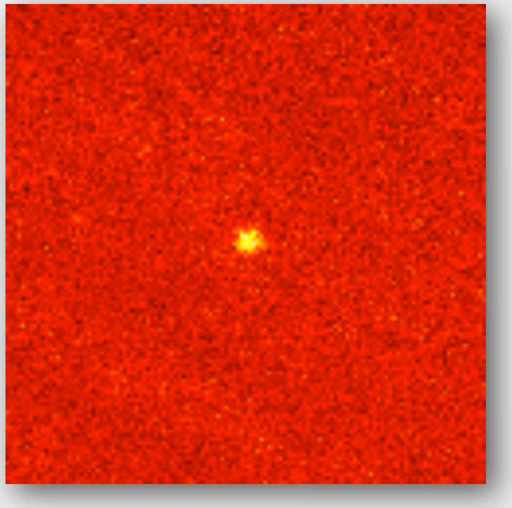
Ultimate Size Control in 2D



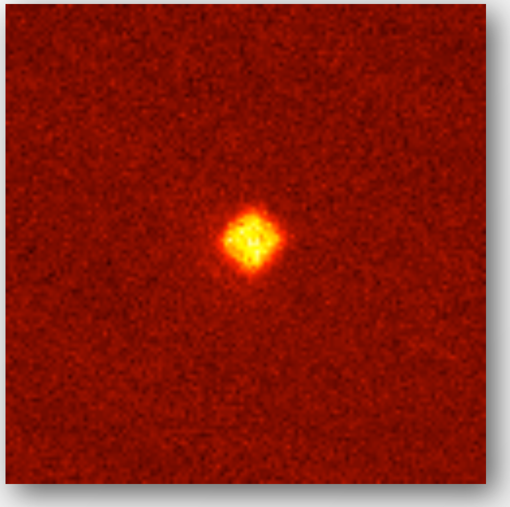
gital Mirror
ze Control)



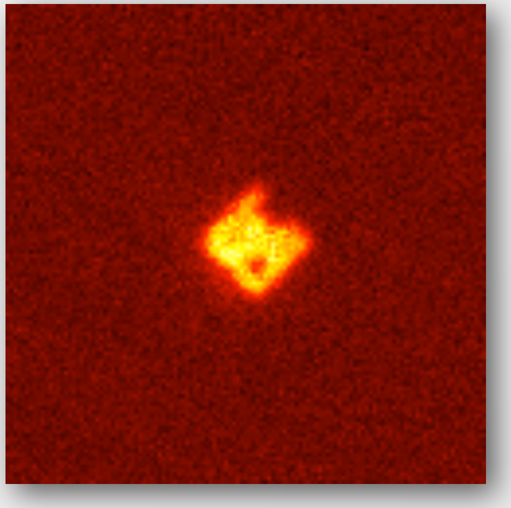
Initial MI



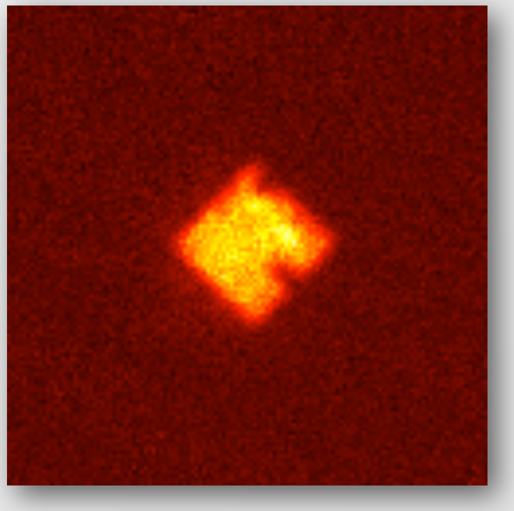
Single Atom



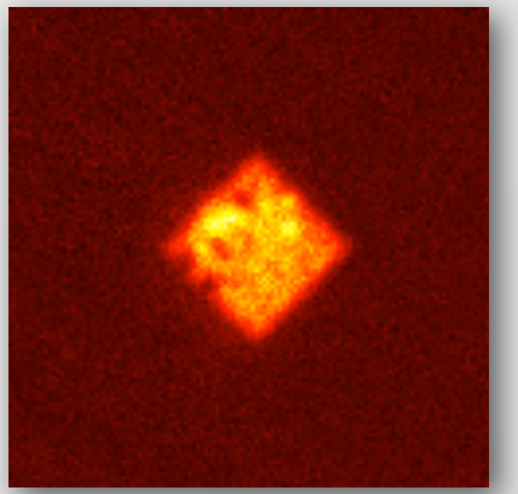
3x3



5x5



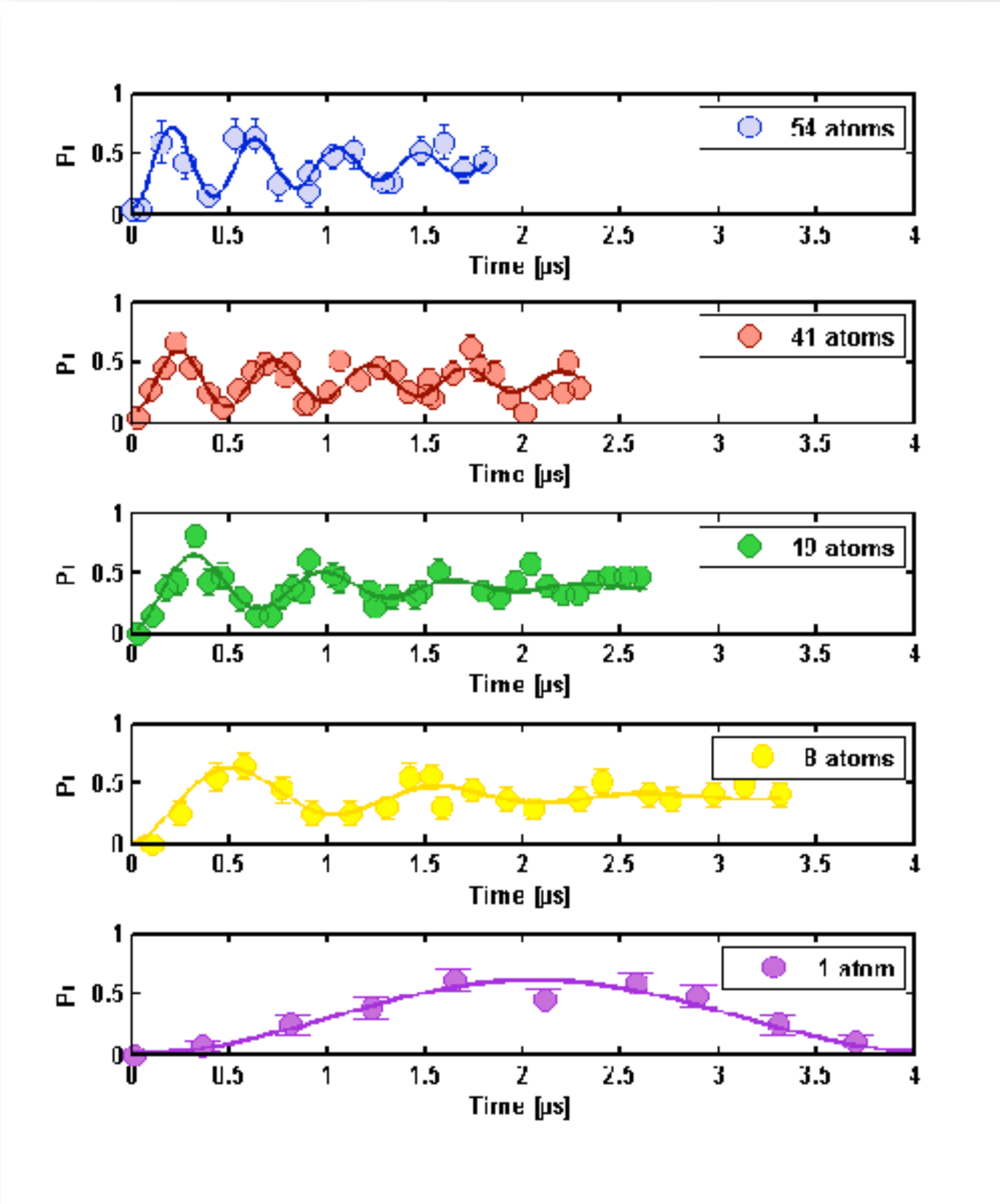
7x7

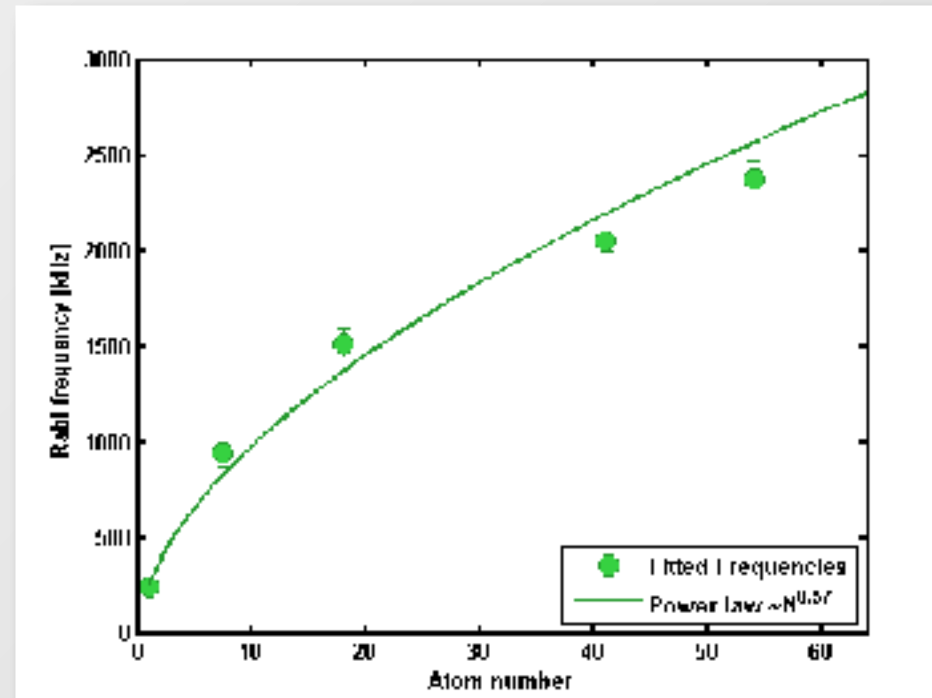


8x8

atoms

Collective Many-Body Rabi Oscillations

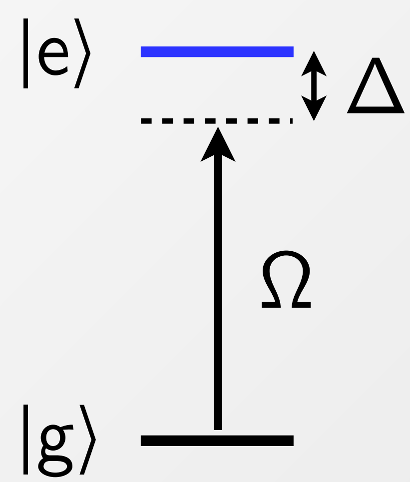


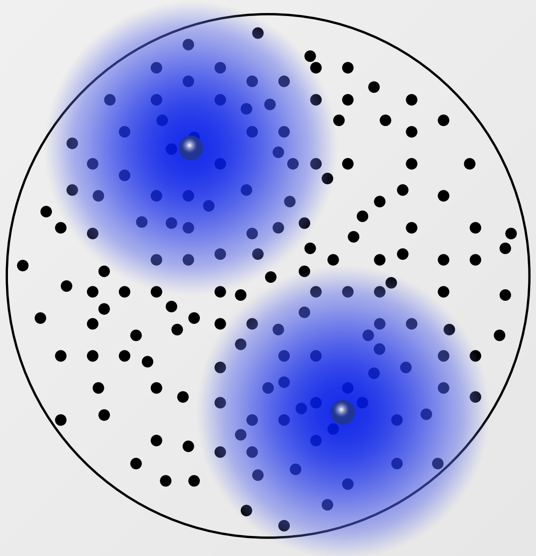


Single atom non-linearity controls dynamics of >50 atoms!

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

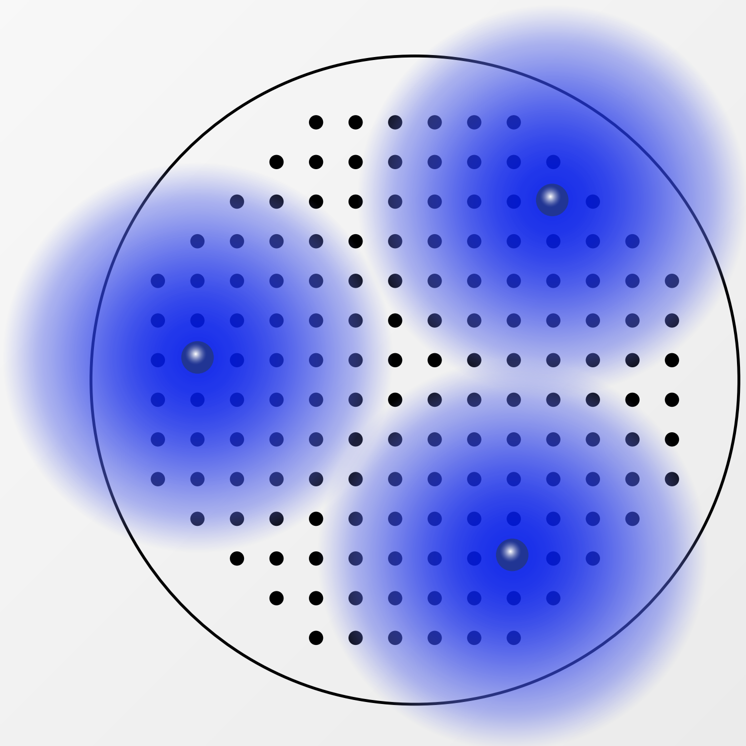
interaction between Rydberg atoms

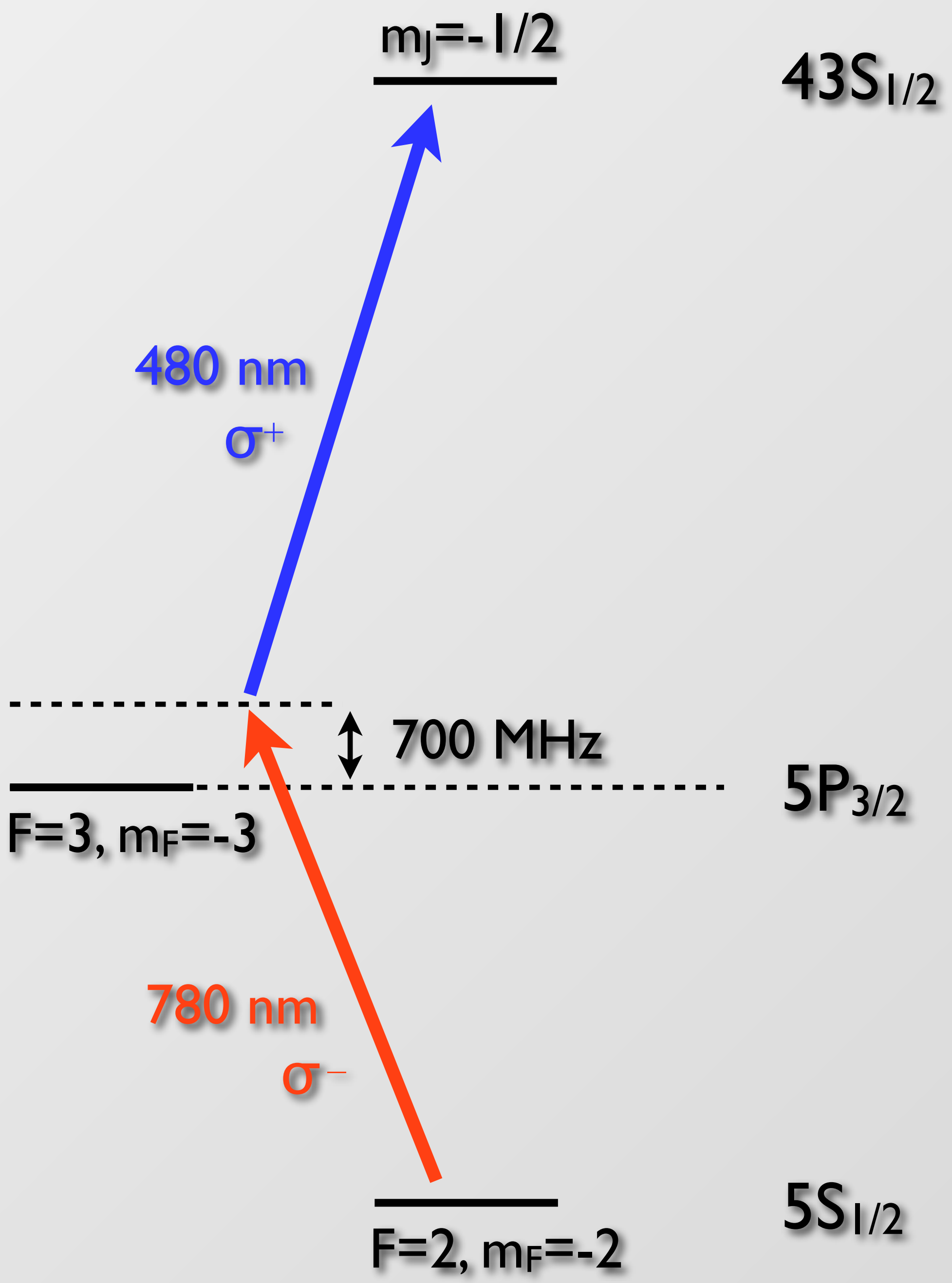
$$V_{ij} = C_\alpha |r_i - r_j|^{-\alpha}$$

This work: α=6, repulsive

"chemical potential"

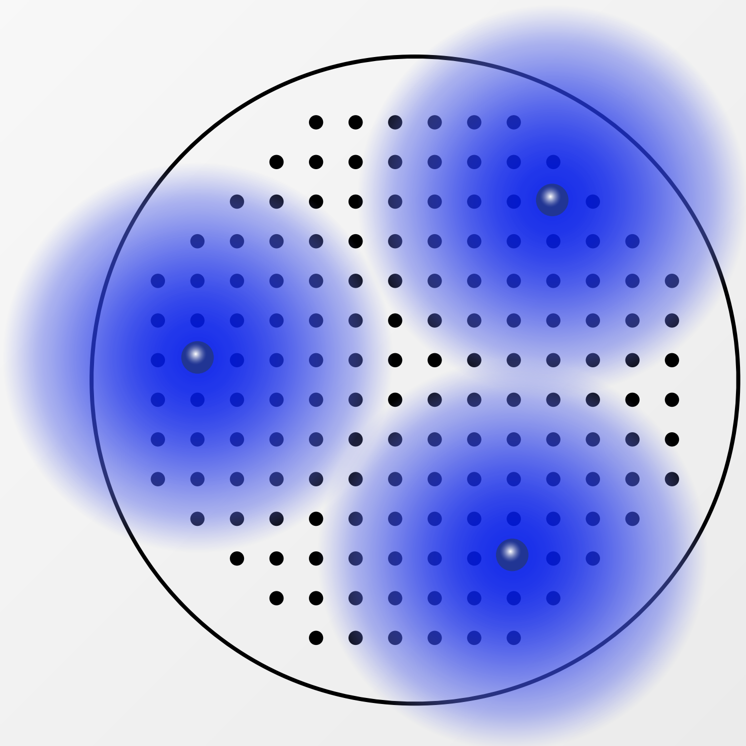
Excitation and detection of the Rydberg atoms

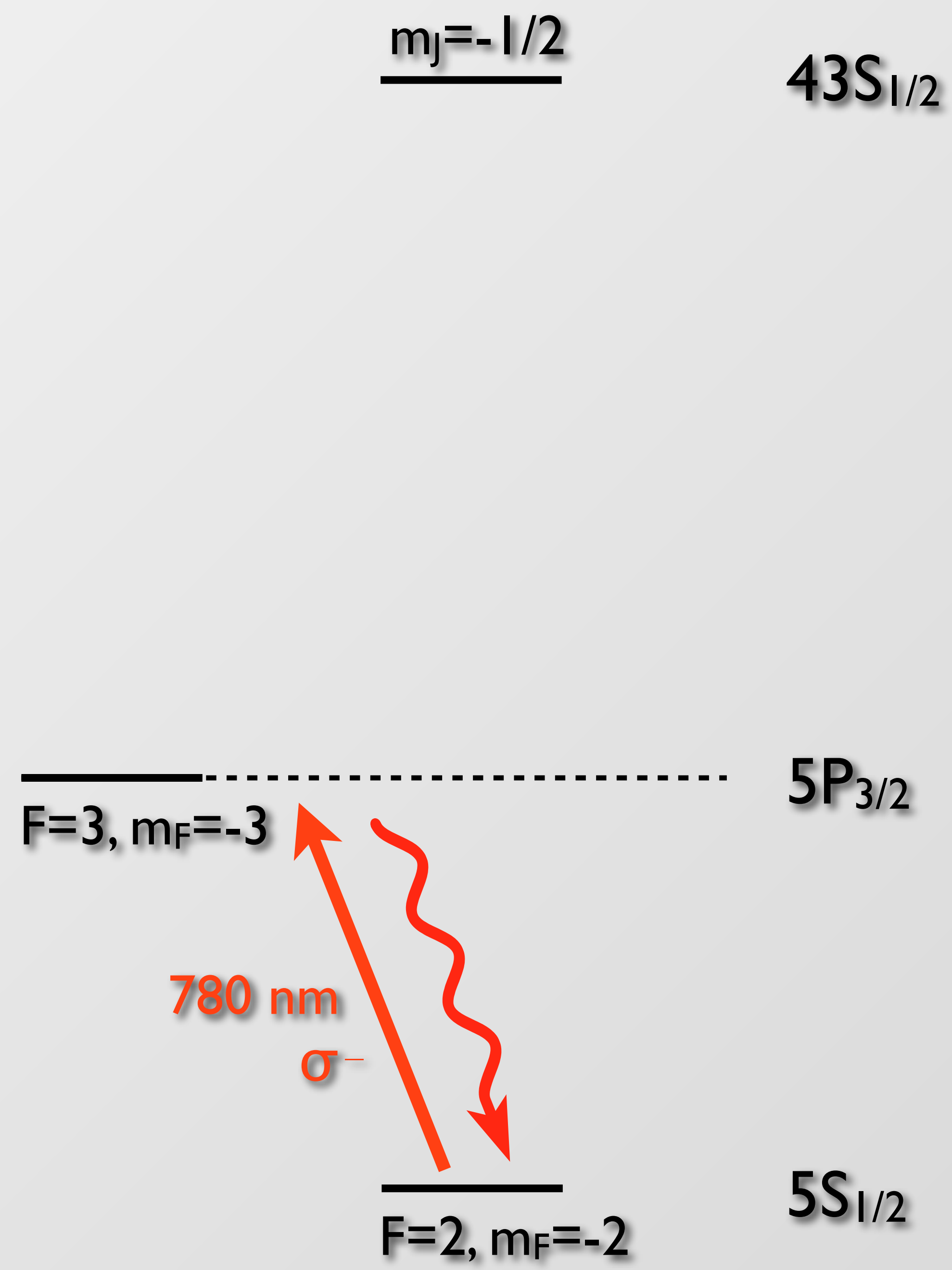




- two-photon Rabi frequency: $\Omega/2\pi$ = 170(20) kHz
- resonant excitation: $\Delta = 0$
- blockade radius: R_b = 4.9(1) µm

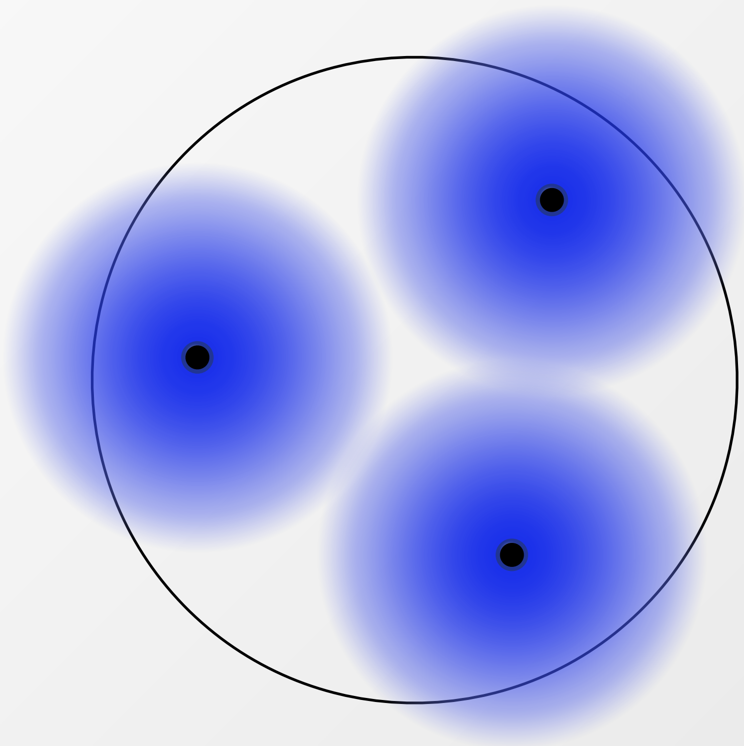
Excitation and detection of the Rydberg atoms



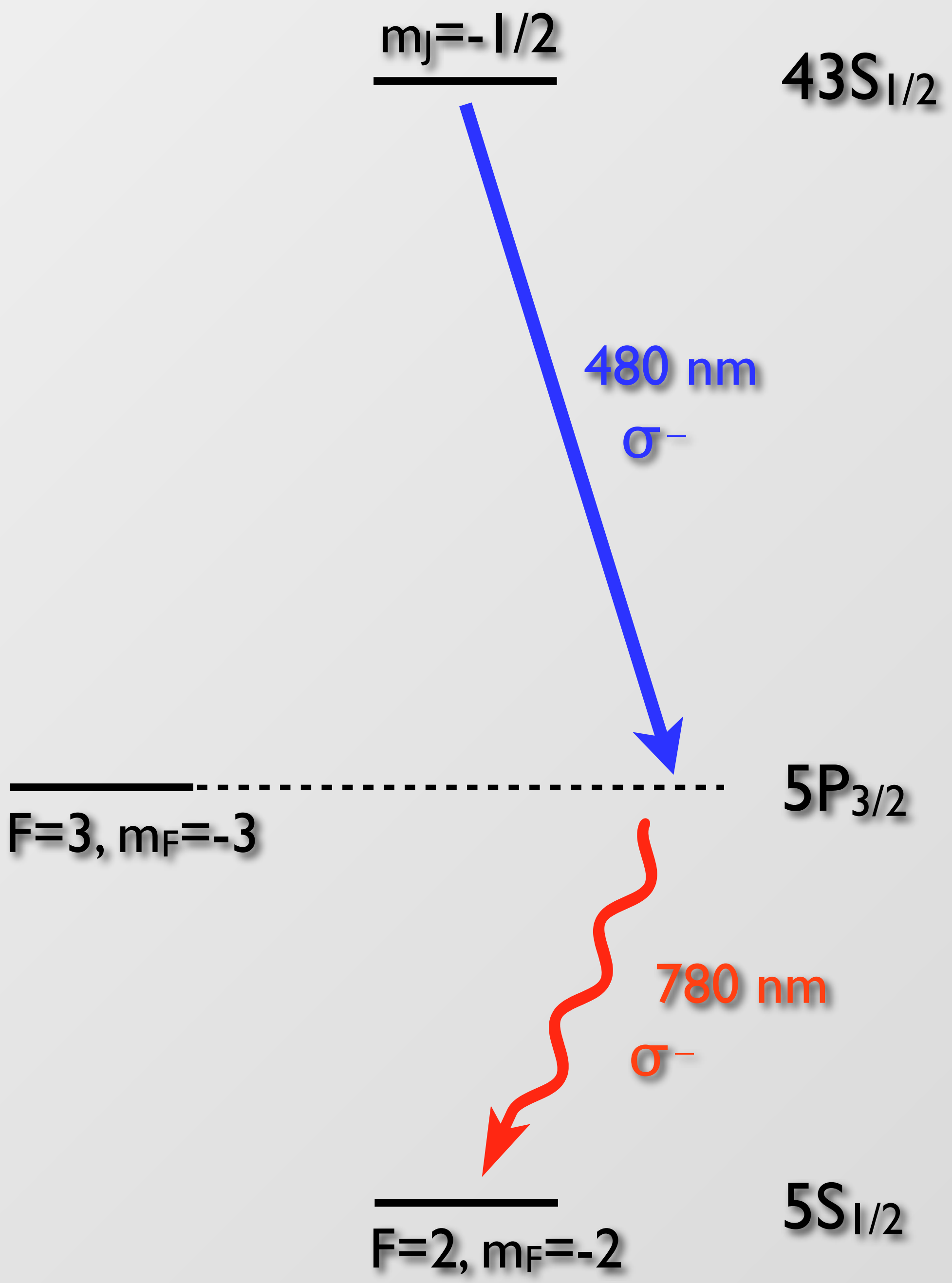


- removal pulse duration: 10 µs
- survival probability: 0.1 %

Excitation and detection of the Rydberg atoms



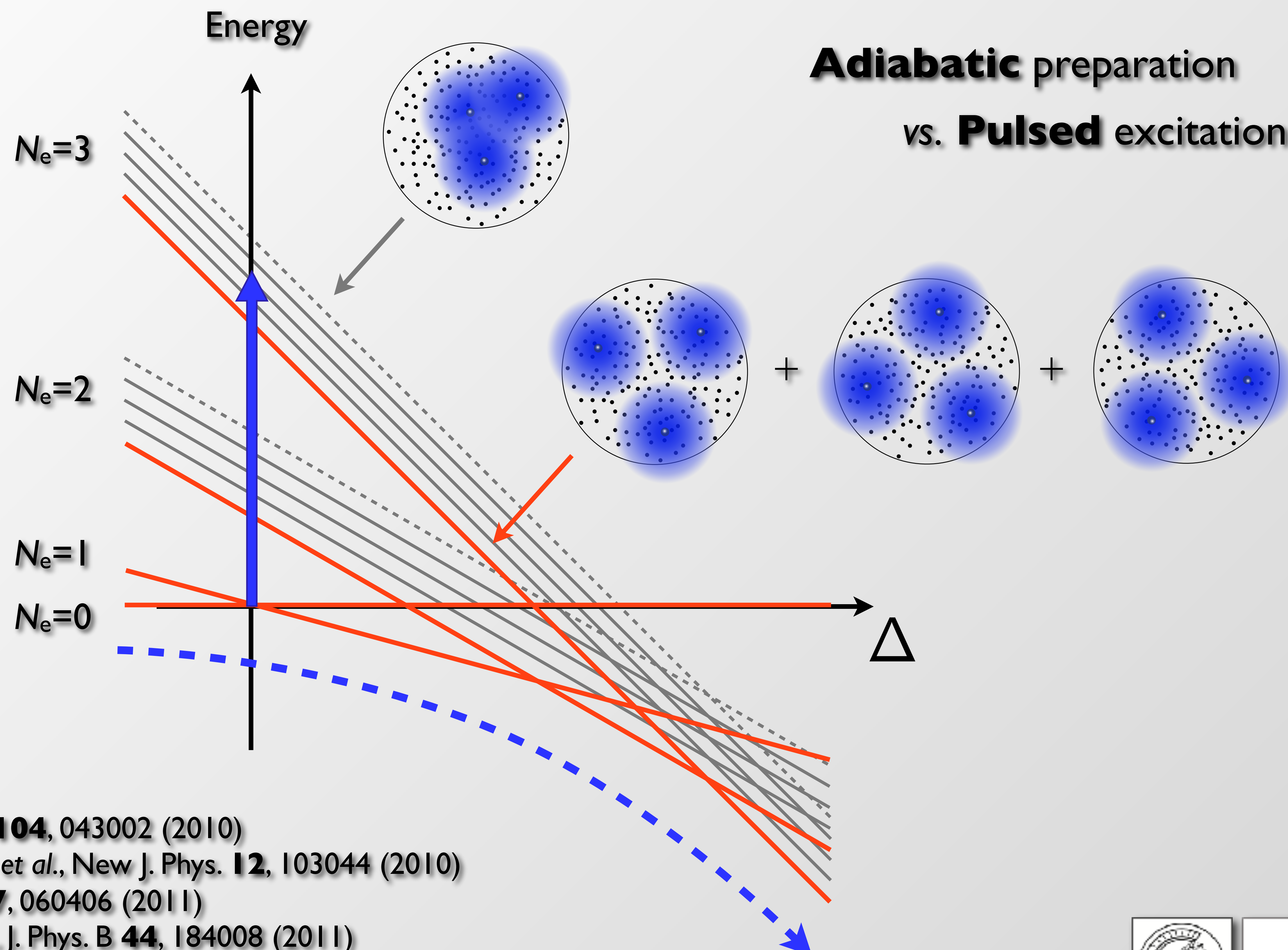
- deexcitation pulse duration: 2 μs
- detection efficiency: 75(10) %
- overall resolution: ~ 500 nm



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

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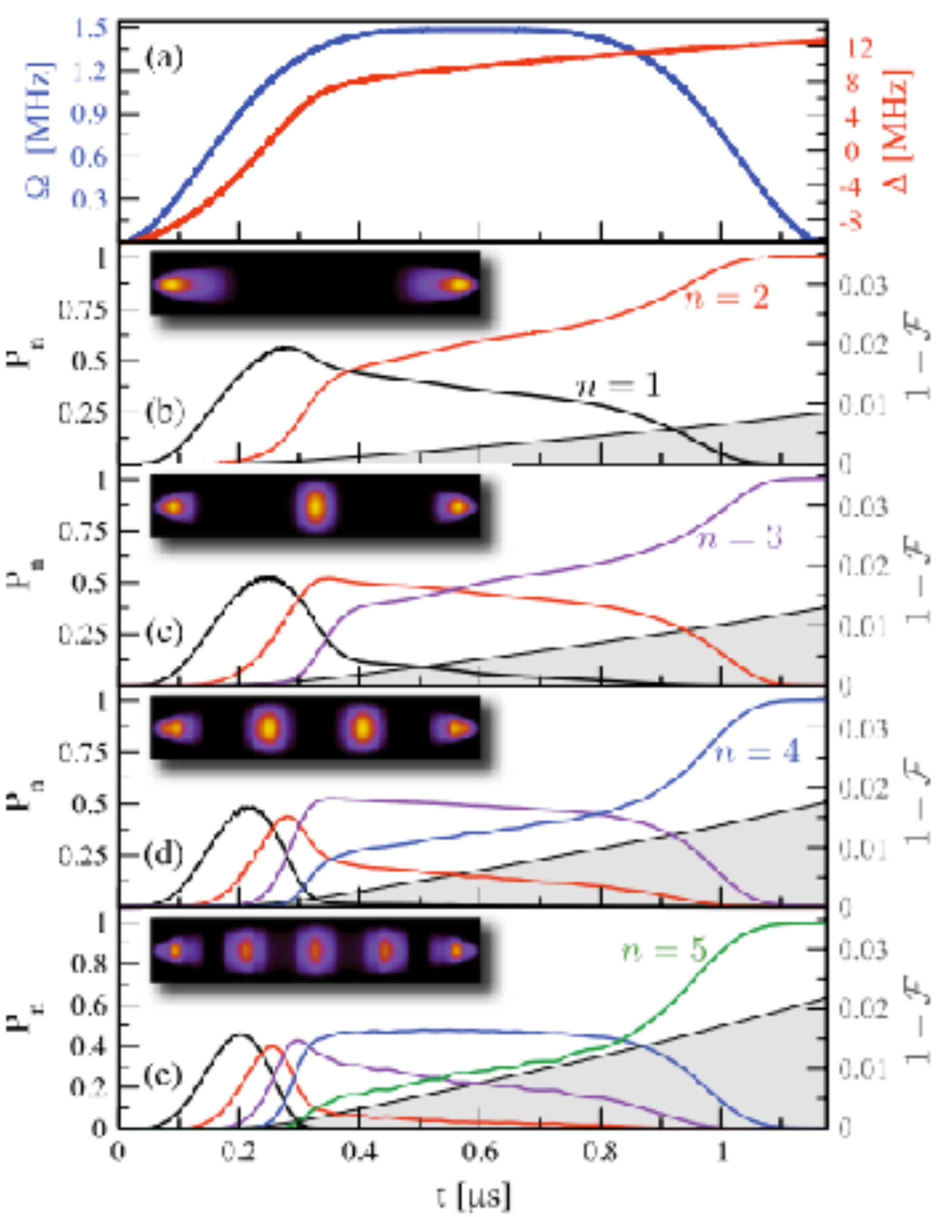
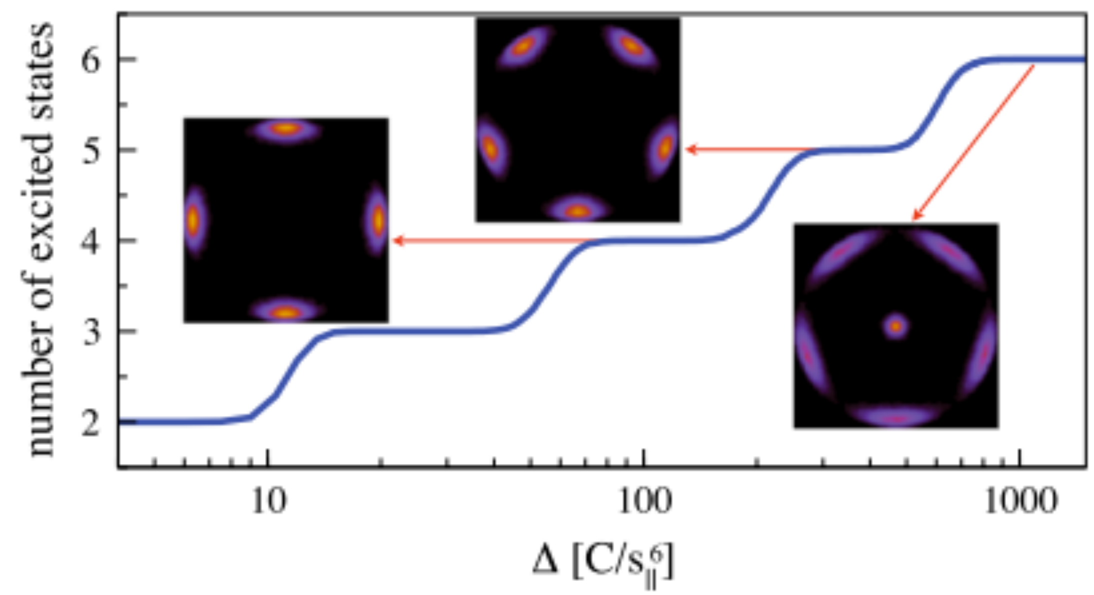
[2]*ITAMP-Harvard-Smithsonian Center for Astrophysics, Cambridge Massachusetts 02138, USA*
[3]*Physics Department, Harvard University, Cambridge Massachusetts 02138, USA*
(Received 26 July 2009; revised manuscript received 23 October 2009; published 27 January 2010)





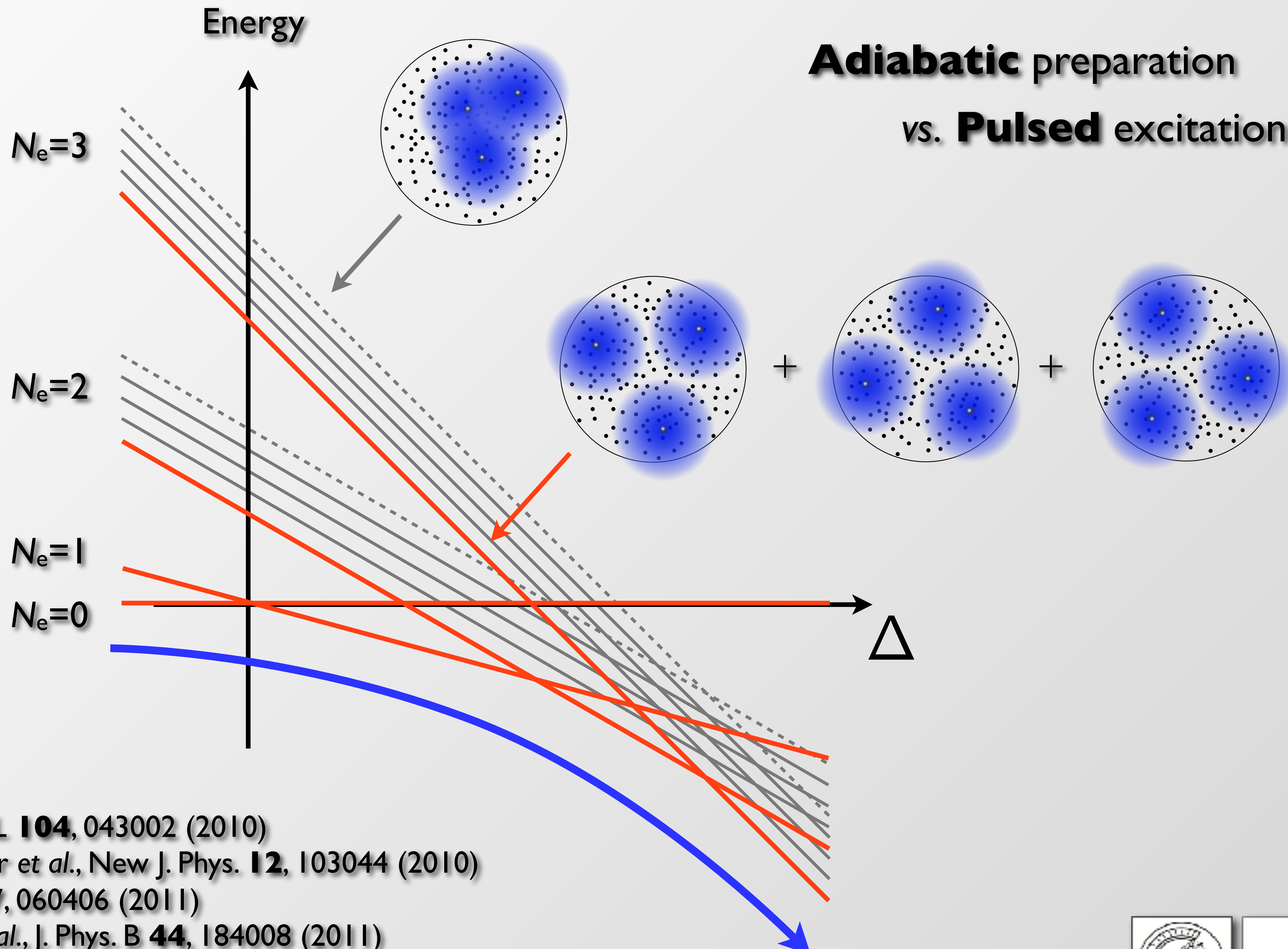
Coherent Control of Many-Body System through Adiabatic Sweeps

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

Energy spectrum of the Rydberg gas

Adiabatic preparation

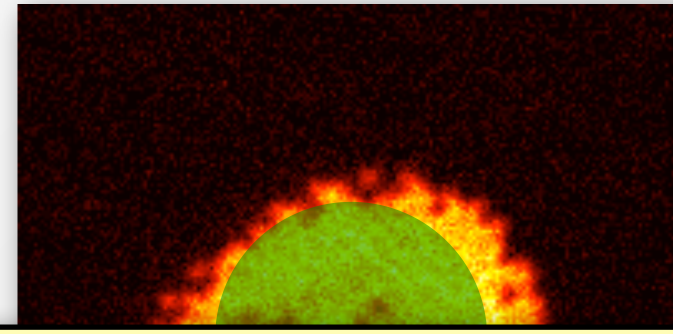
vs. **Pulsed** excitation



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)

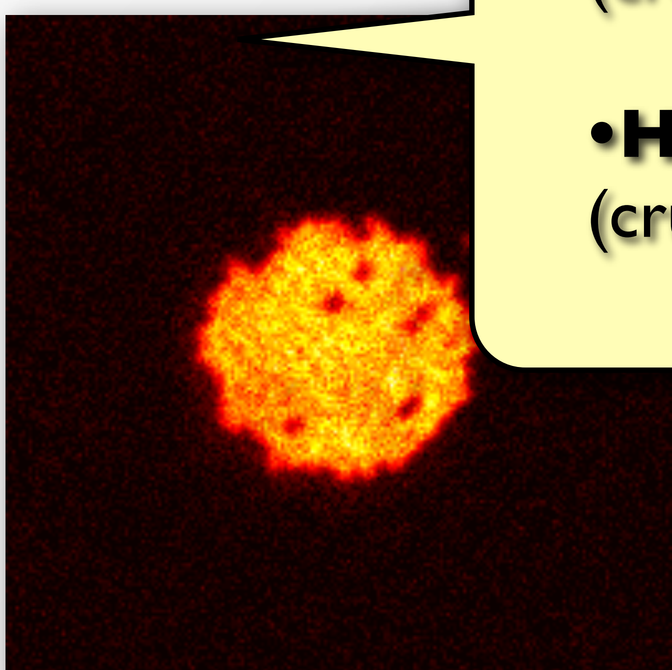
Ultimate Size Control in 2D

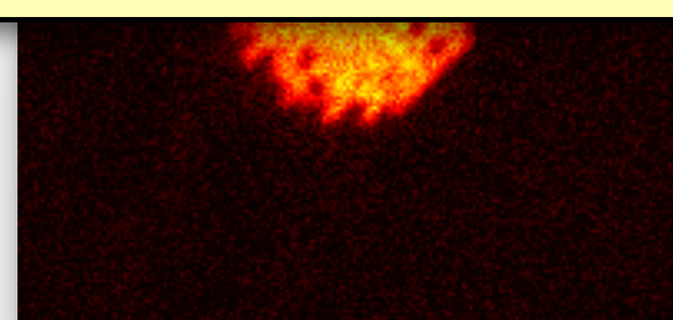
gital Mirror
ze Control)

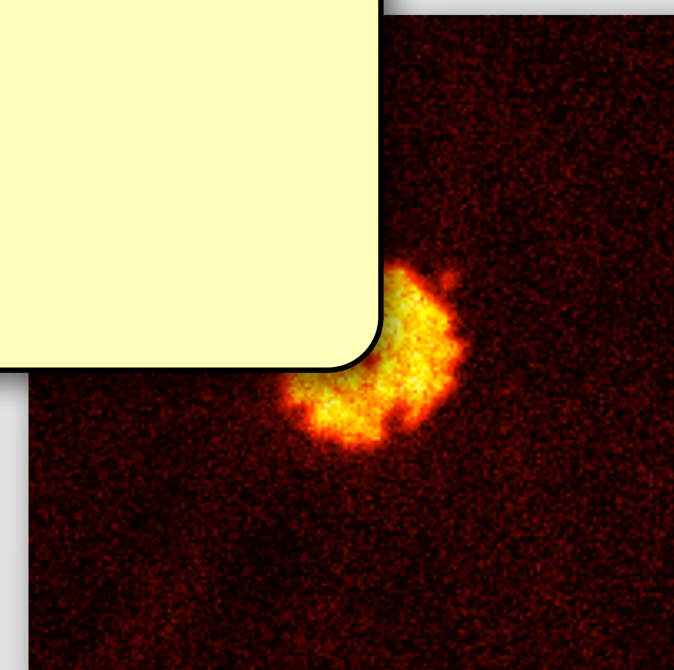


Fluctuating Size and

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





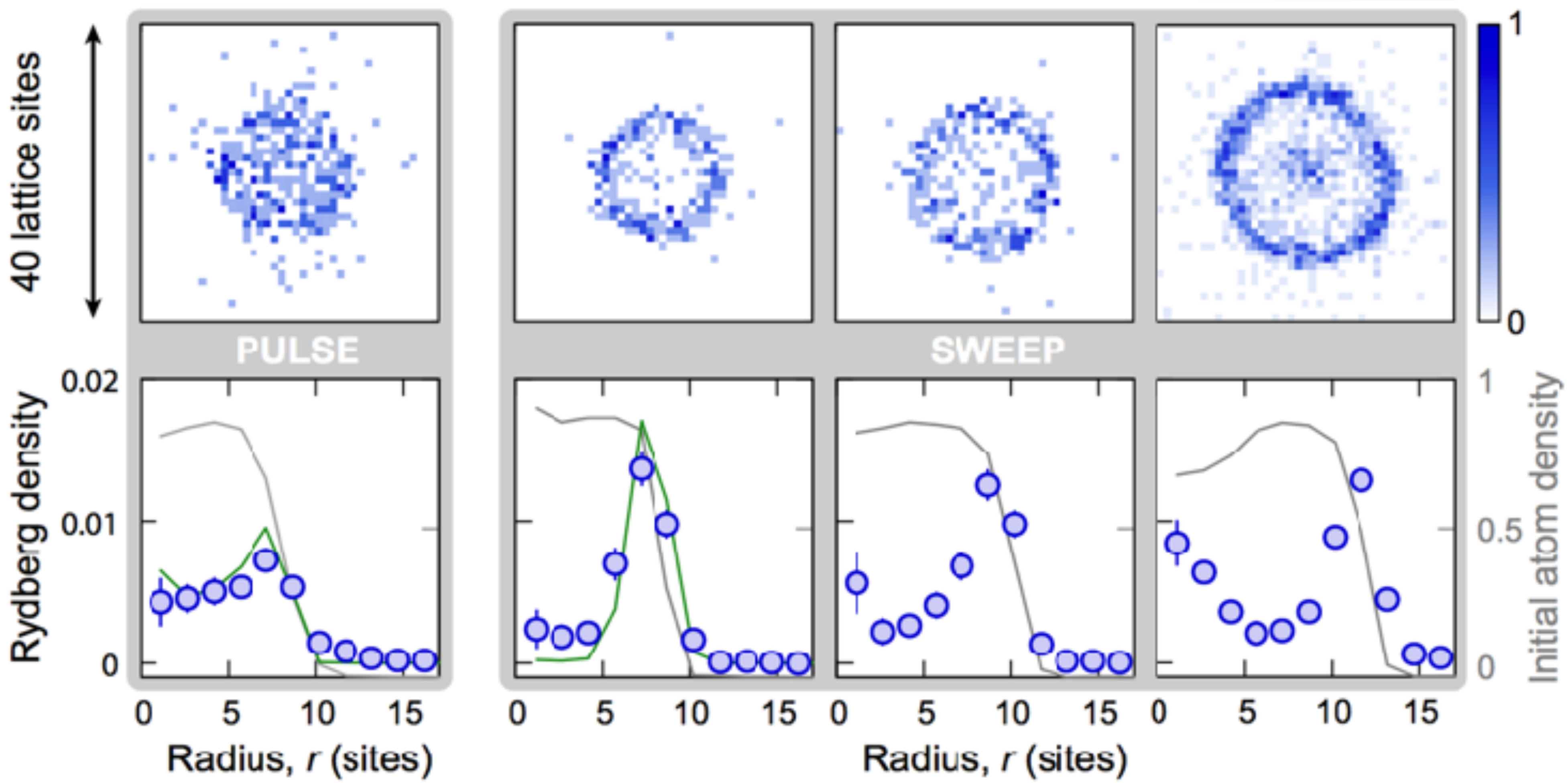


Size & atom number perfectly controlled

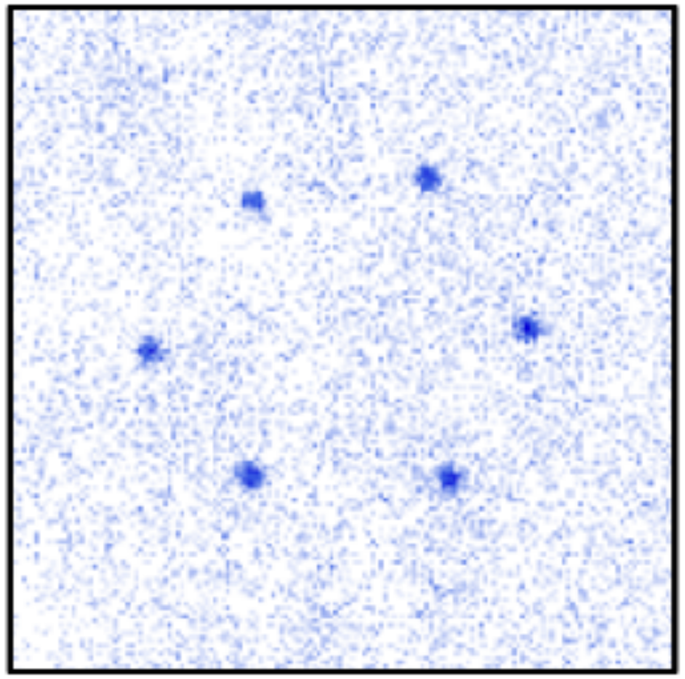
LMU

Adiabatic Sweeps in 2D

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



Single-Shot Rydberg Crystal Configurations



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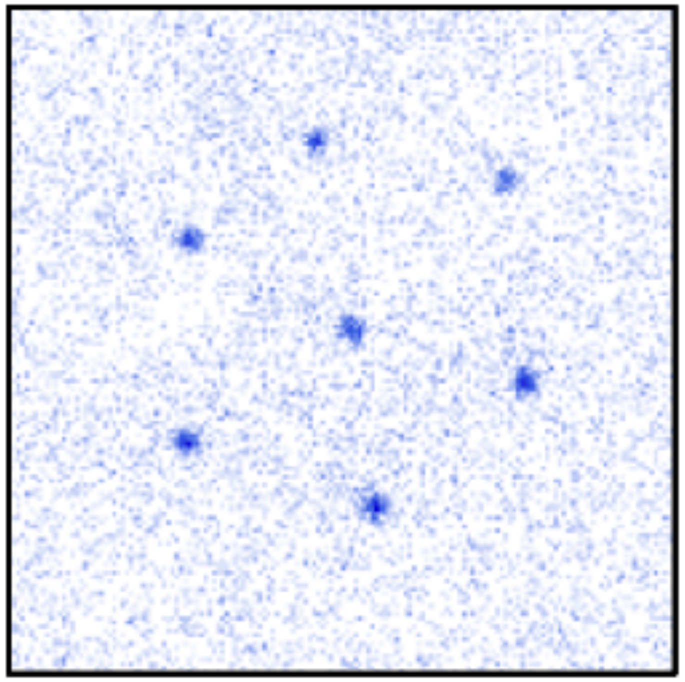

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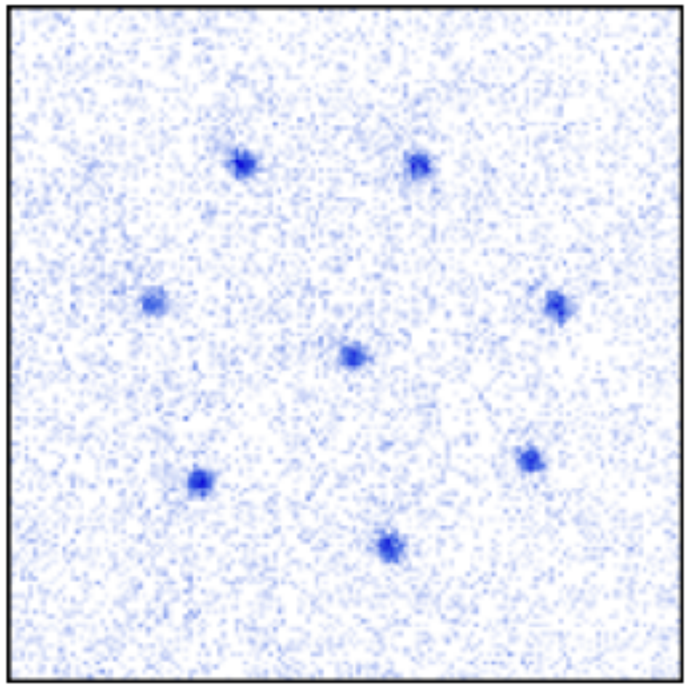

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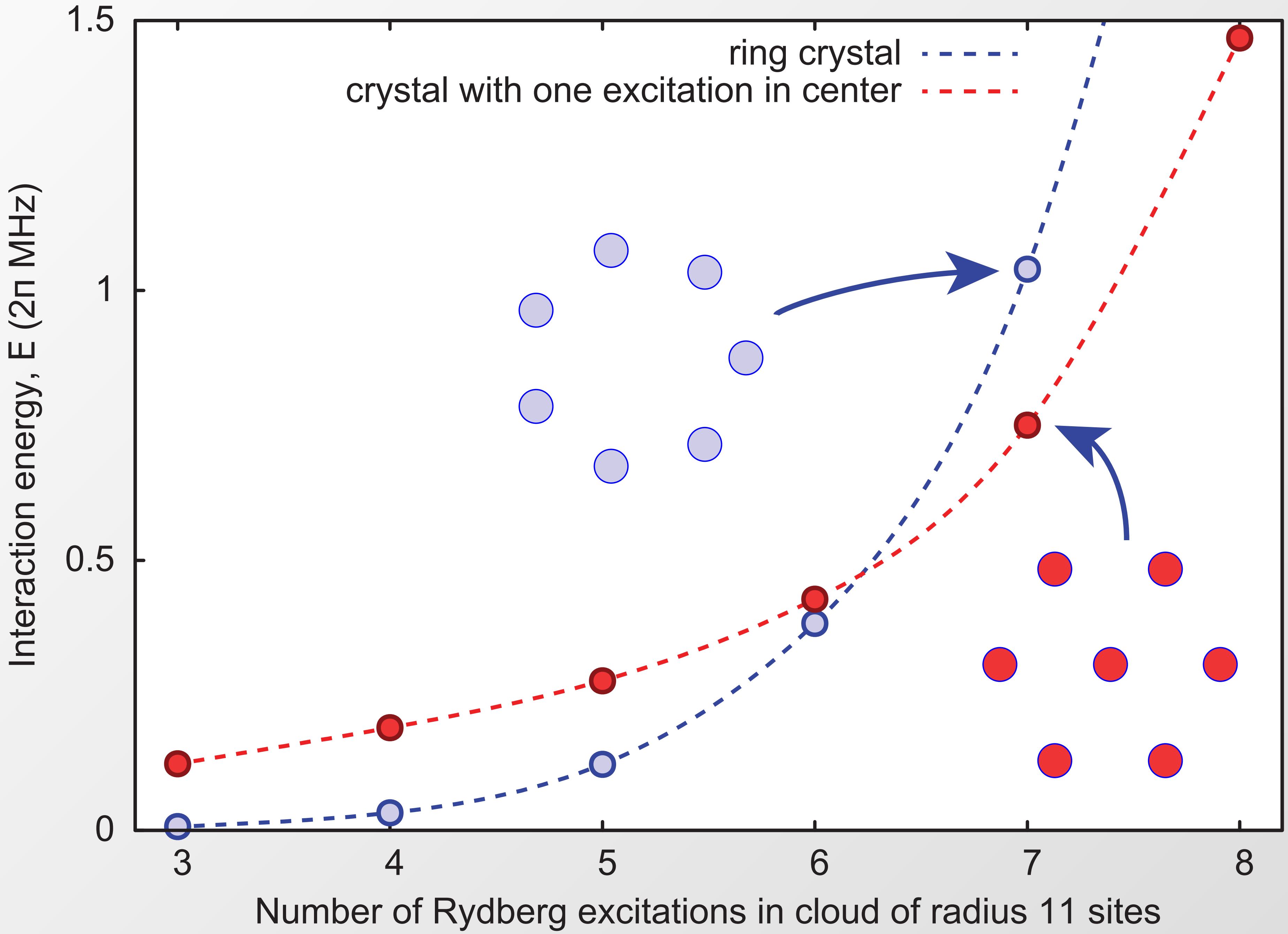
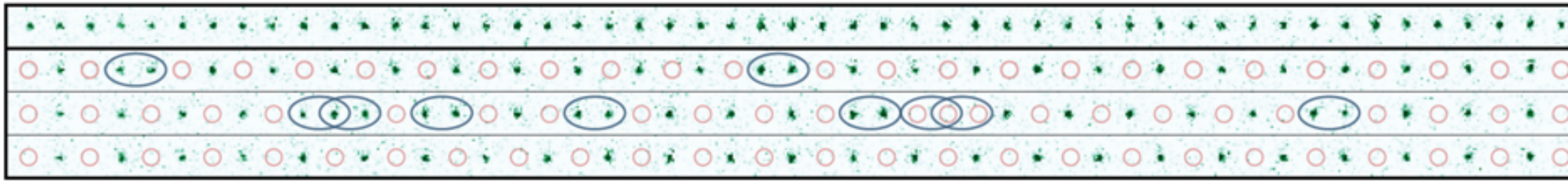
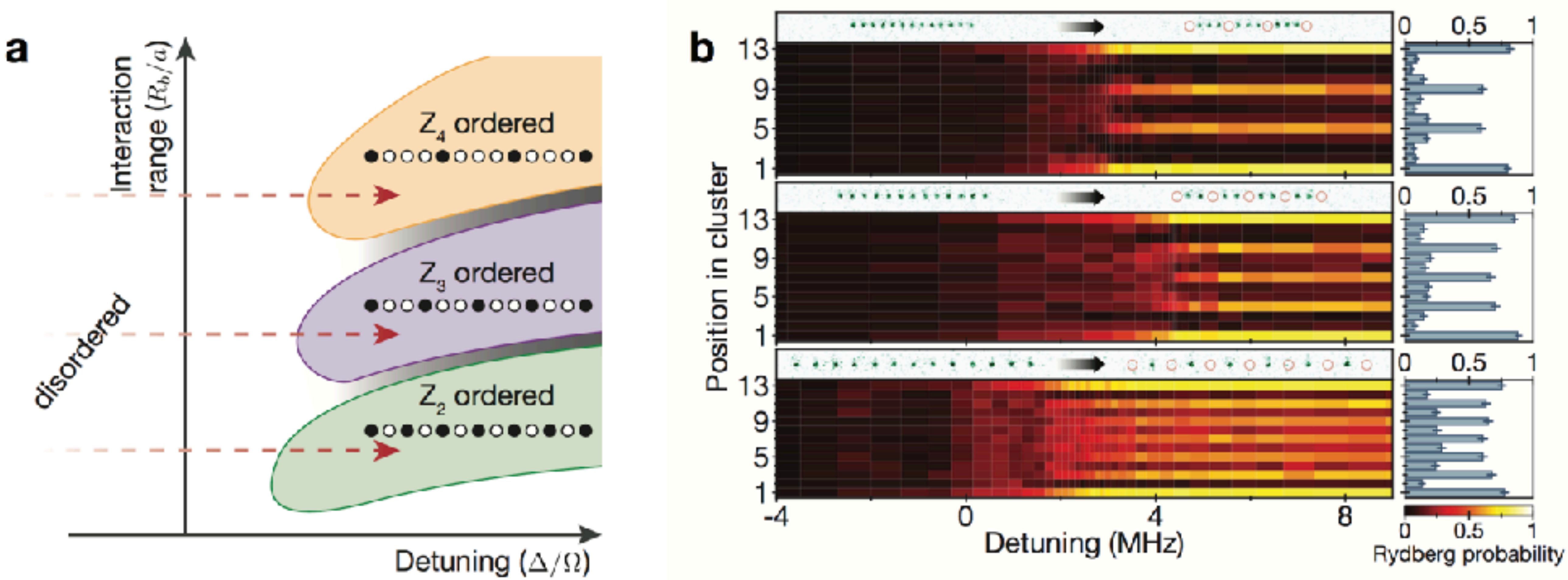
Rydberg Crystal configurations

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

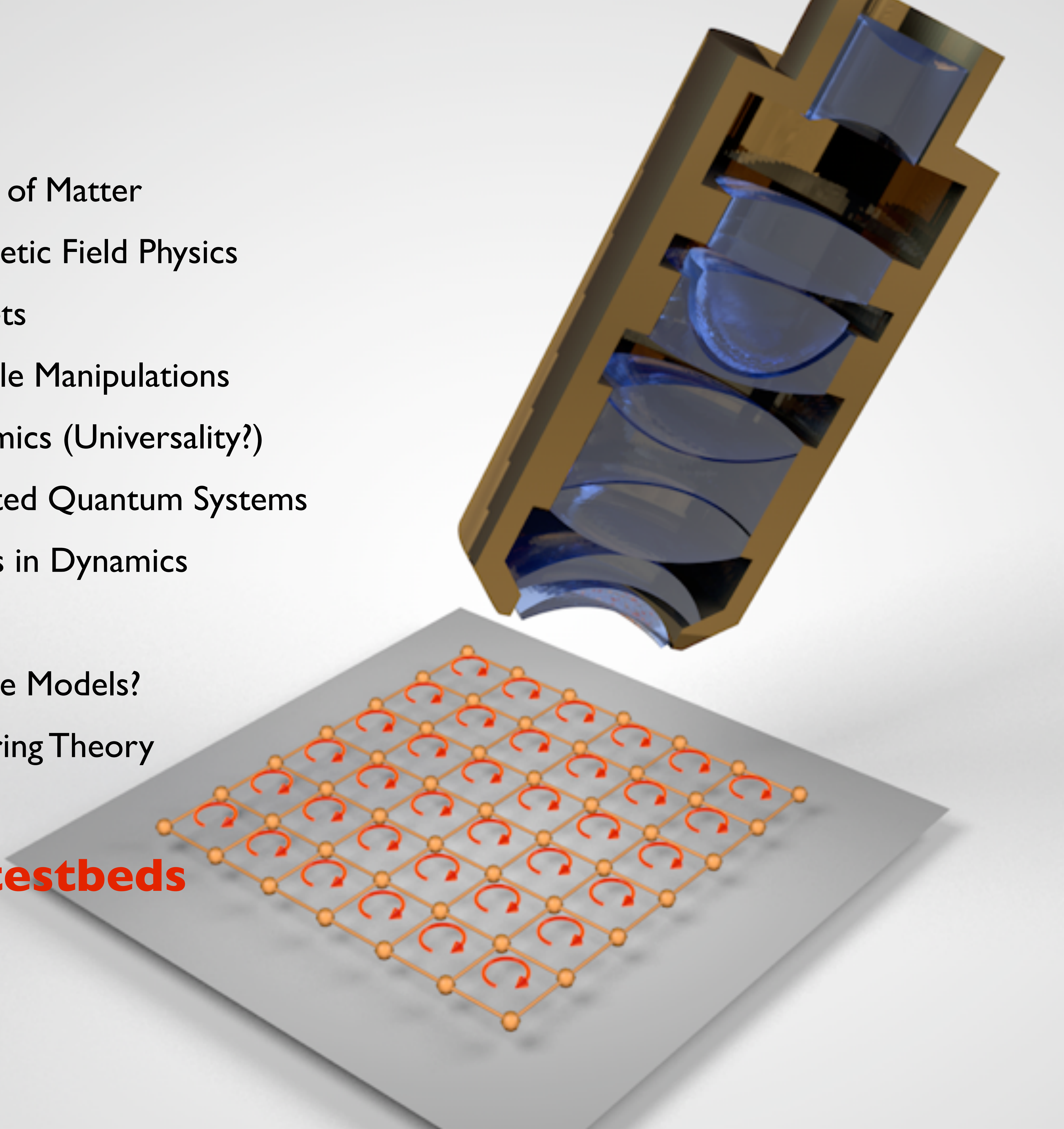
G. Pupillo et al, (2010), Henkel et al. (2010), Schachenmeyer et al. (2010), Honer et al. (2010), Cinti et al. (2010), Johnson & Rolston (2010)...

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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