Non-Equilibrium Dynamics and Single-Site Imaging of Ultracold Atoms in Optical Lattices

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Ulrich Schneider, Sebastian Will,
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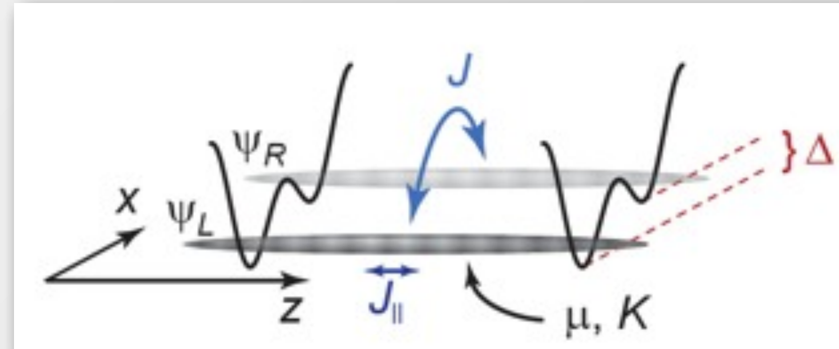
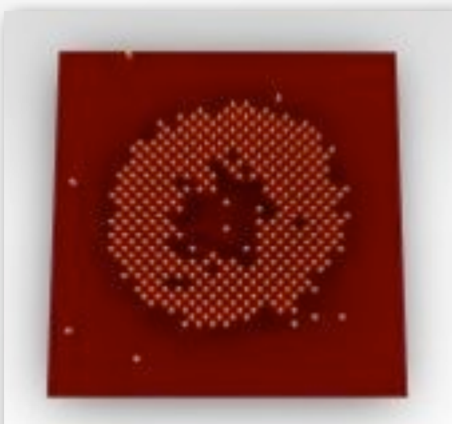
Theory collaboration:
Ehud Altman, Sebastian Huber

www.quantum-munich.de

Outline

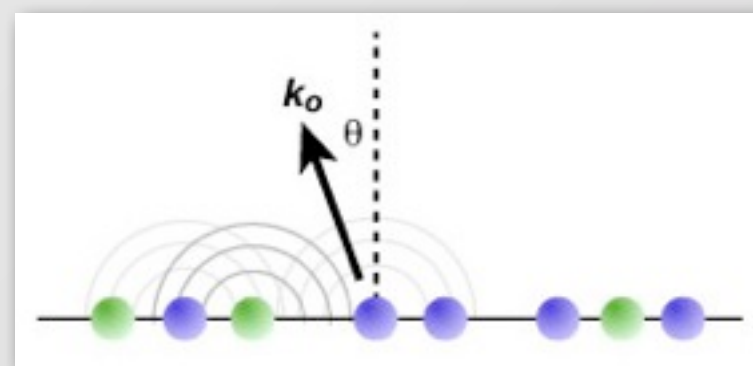
- Landau Zener Dynamics in Coupled 1D Bose Liquids





- Imaging Atoms with Single-Site and Single-Atom Resolution in Optical Lattices

- Coherent Light Scattering from Correlated Quantum Gases



Generalized Landau Zener Sweeps for 1D Many Body Systems

Yuao Chen, Sebastian Huber, Stefan Trotzky
I.B. , Ehud Altman

Y.-A. Chen & S. Huber et al., Nature Physics (in print)

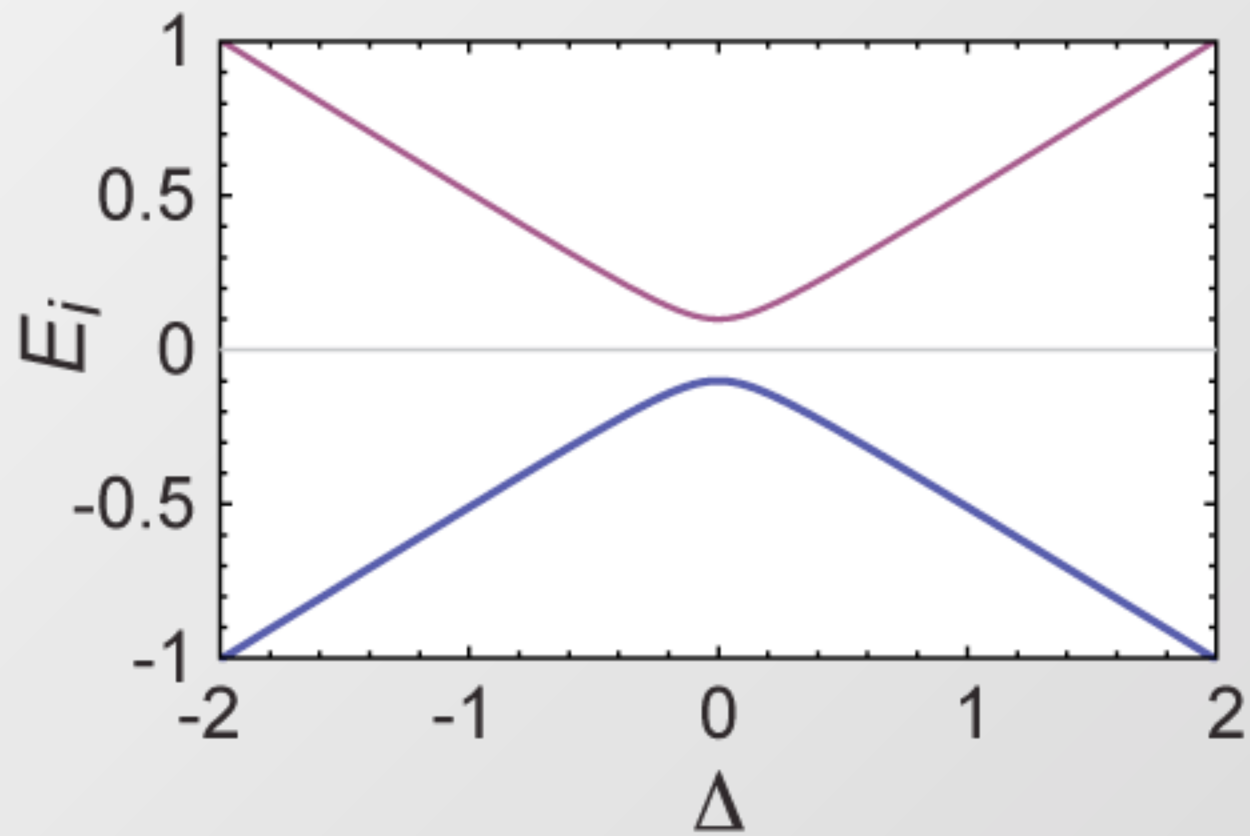
Landau Zener Transitions

Two level system

$$P_{adiab} = 1 - e^{-2\pi \frac{J^2}{\alpha}}$$

$$\Delta(t) = \alpha \cdot t$$

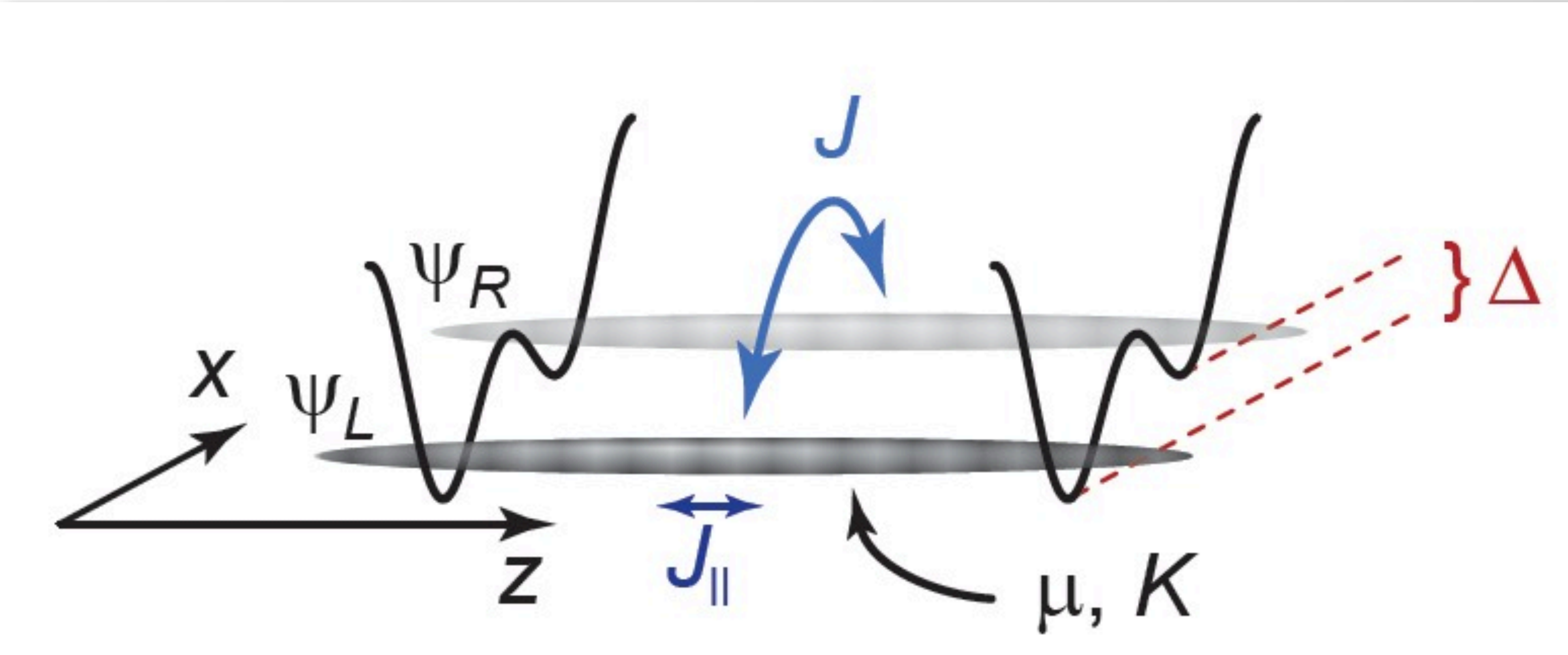
Time dependent energy change of single particle levels.



L. Landau, Phys. Z. Sow. 1932, C. Zener, Proc. R. Soc. A 1932

Generalizations to Many-Body Systems (examples):
A. Altland & V. Gurarie, PRL 2008, J. Liu, B. Wu, and Q. Niu, PRL 2003 and D. Withaut, E. Graefe & H.J. Korsch, PRA 2008

The System - Pairwise Coupled 1D Bose Liquids



Optical Superlattices

Superimpose two standing waves **with controllable phase & amplitude.**

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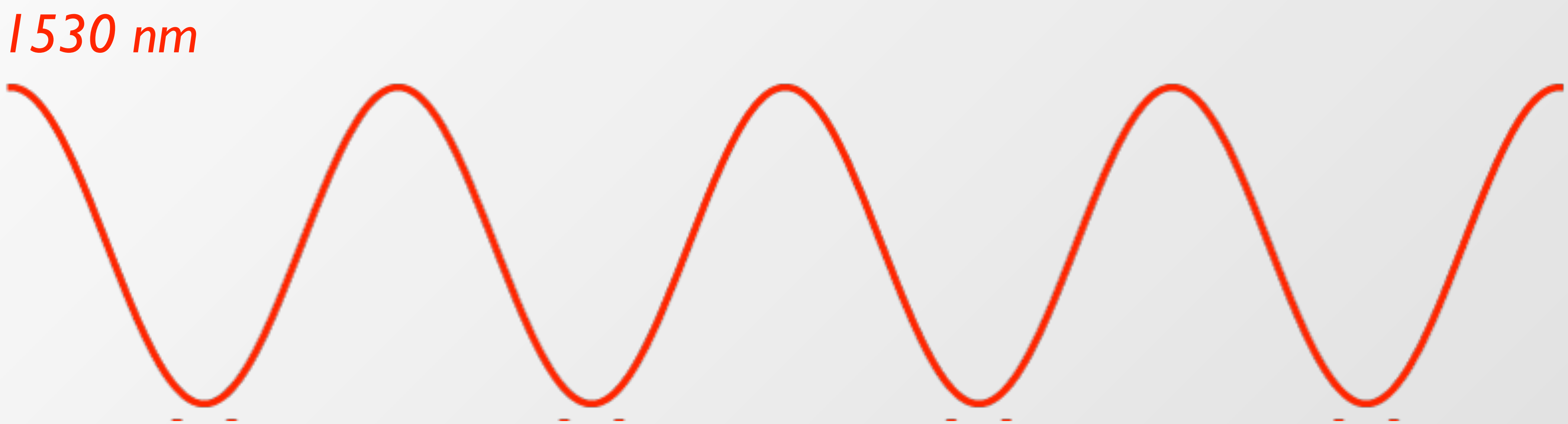
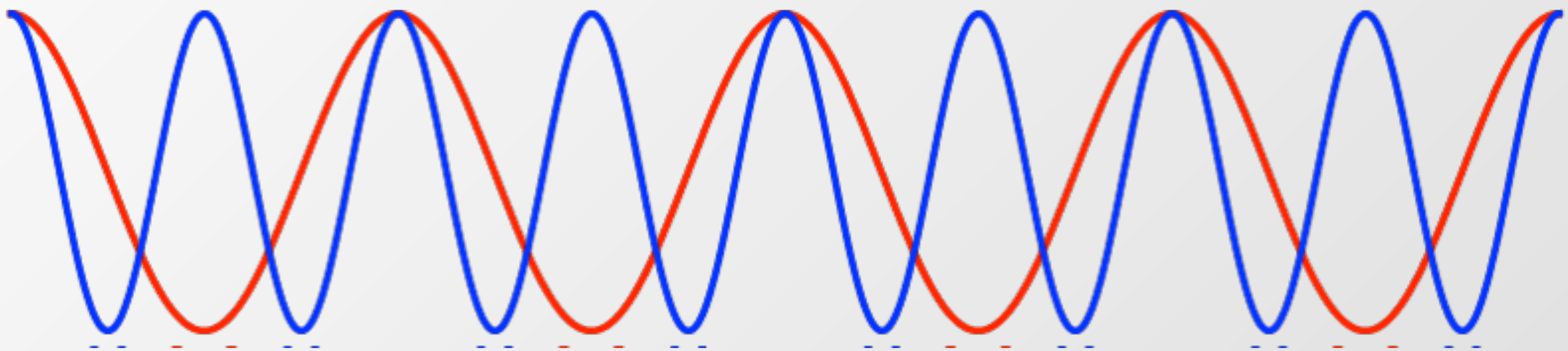


Optical Superlattices

Superimpose two standing waves **with controllable phase & amplitude.**

1530 nm + *765 nm*



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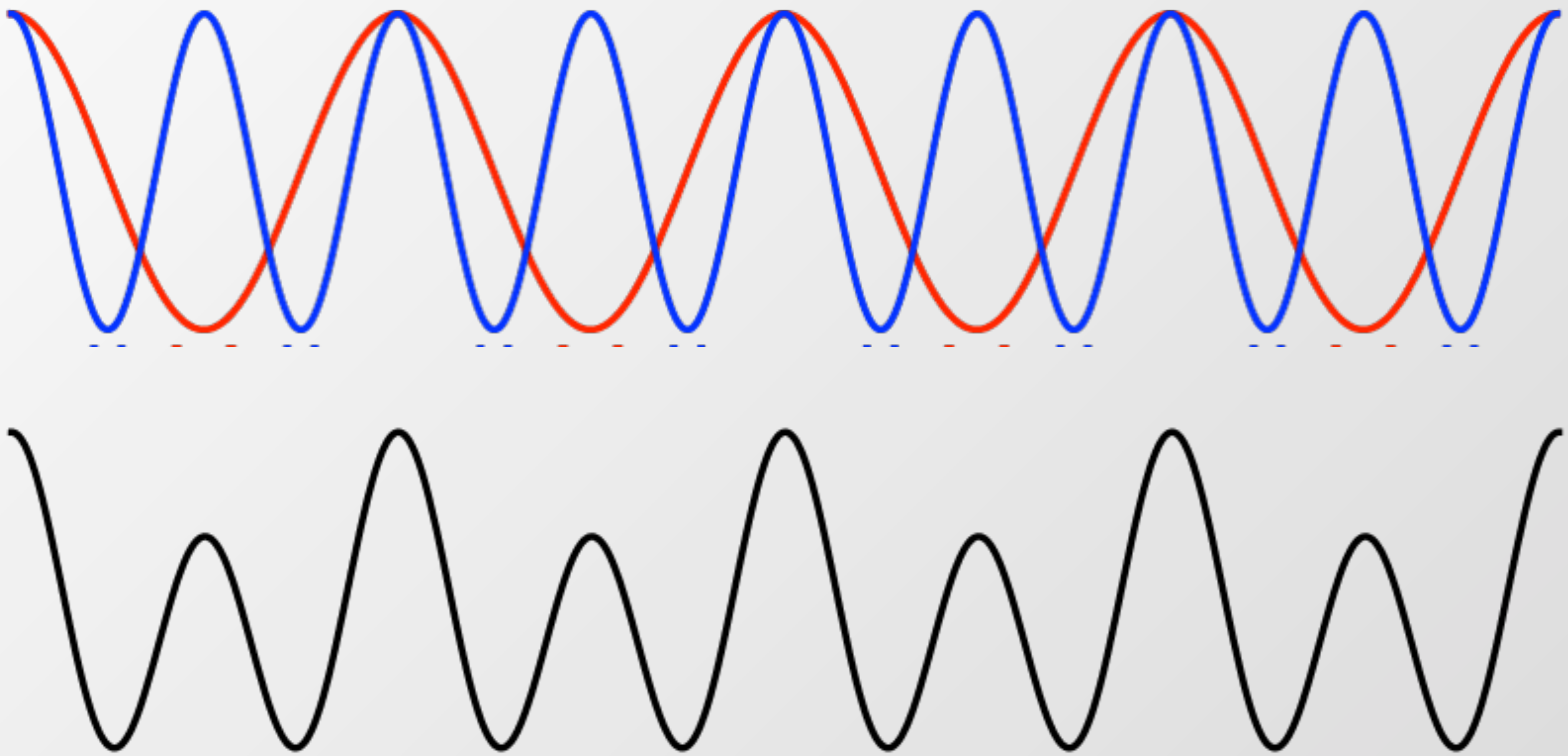


Array of double wells

Controllable Parameters

- **Original**

All parameters can be changed dynamically & in-situ!

Controllable Parameters

- **Original**

- **Intra & Interwell Barrier Depth**

All parameters can be changed dynamically & in-situ!

Controllable Parameters

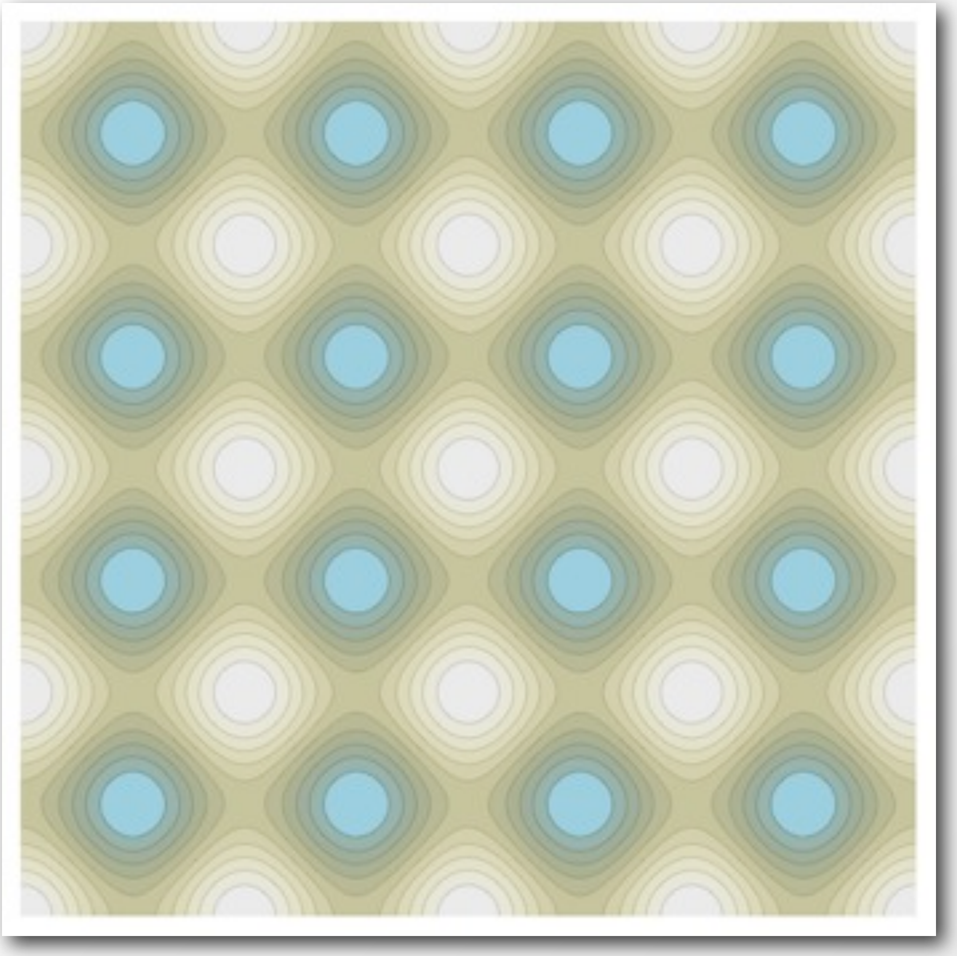
- **Original**

- **Intra & Interwell Barrier Depth**

- **Potential Bias**

All parameters can be changed dynamically & in-situ!

2D Superlattice Geometries (1 SL)



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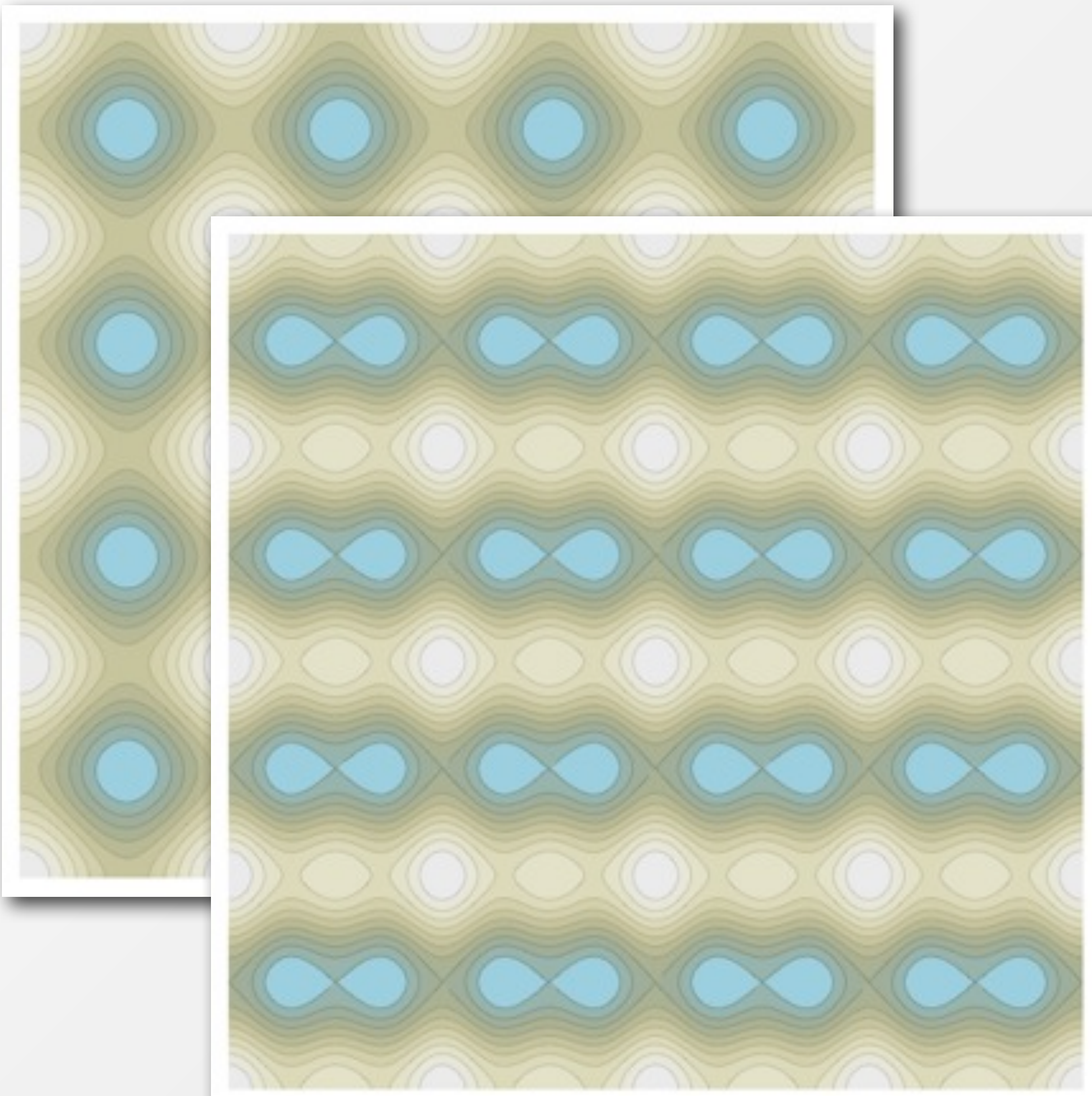

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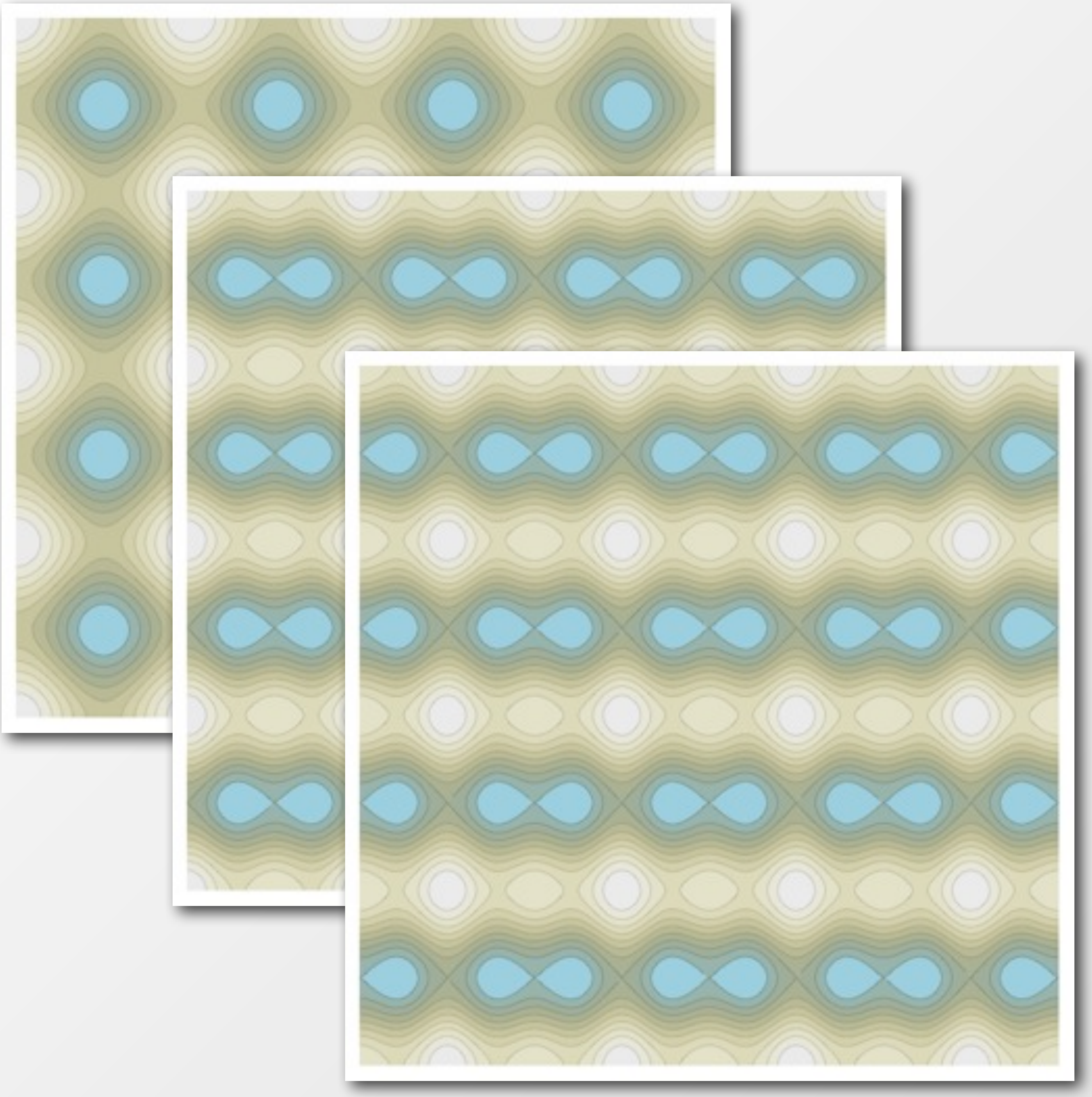

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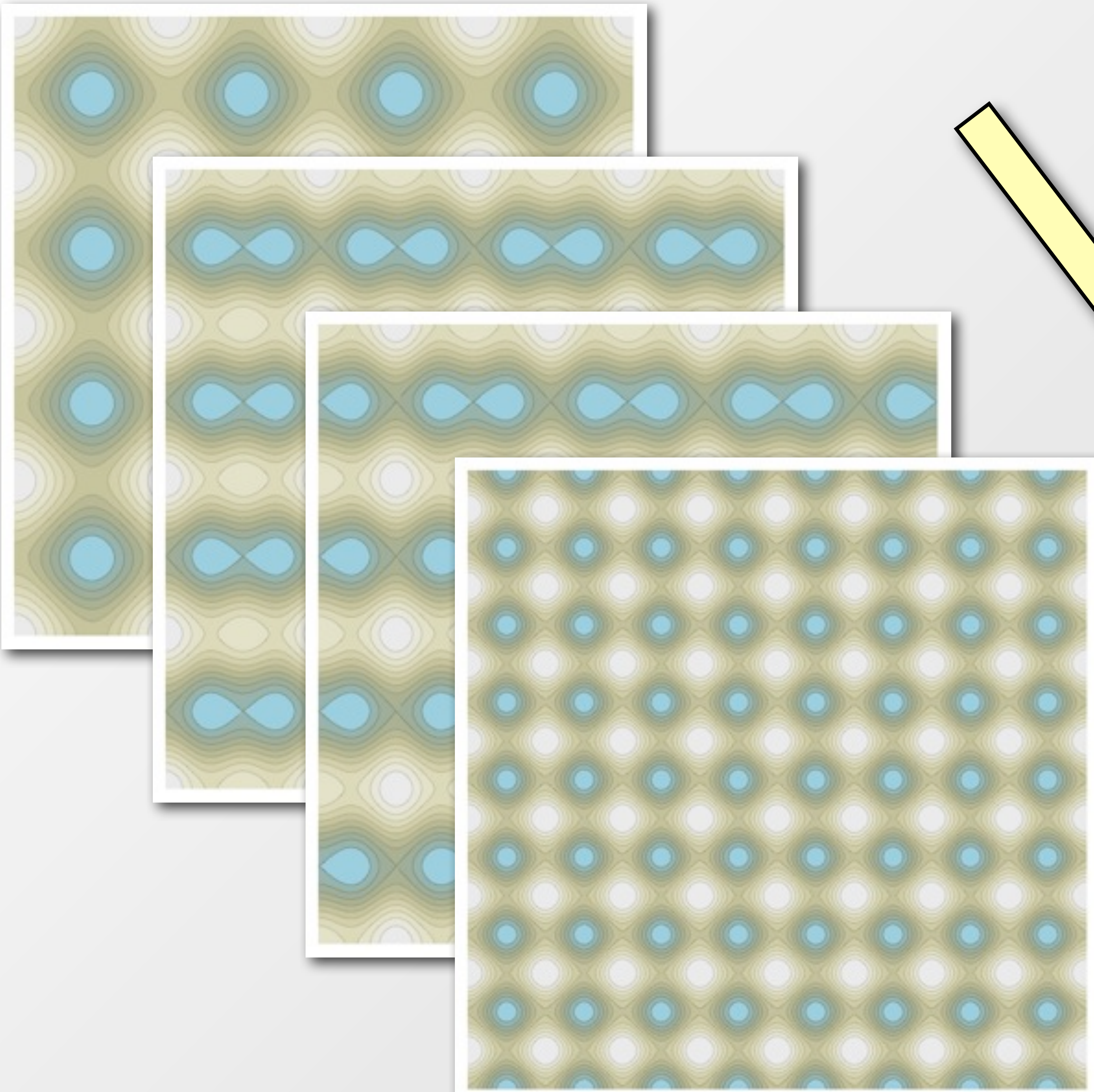
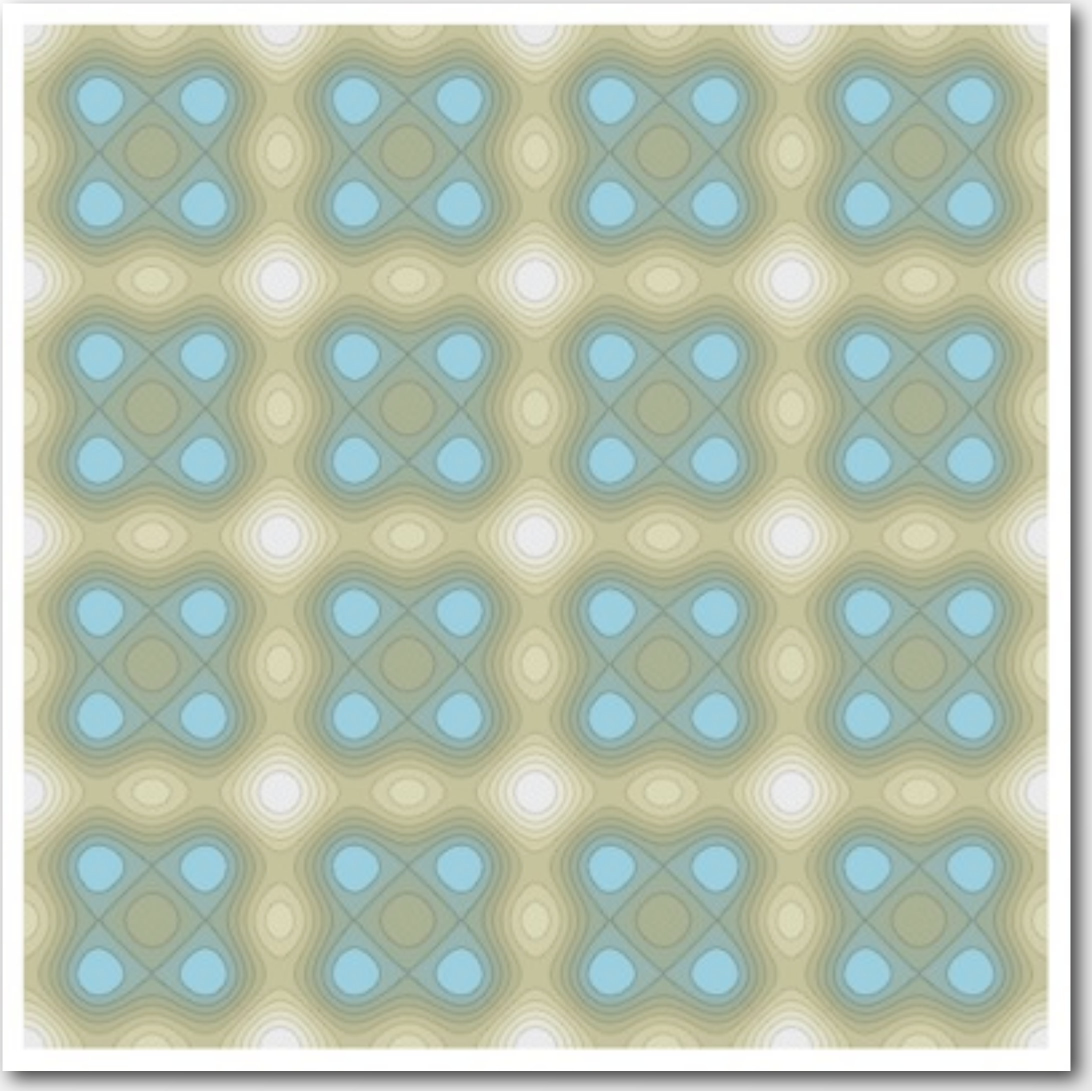


Controllable couplings and dynamics

Superlattice useful for controlling and detecting spin correlations

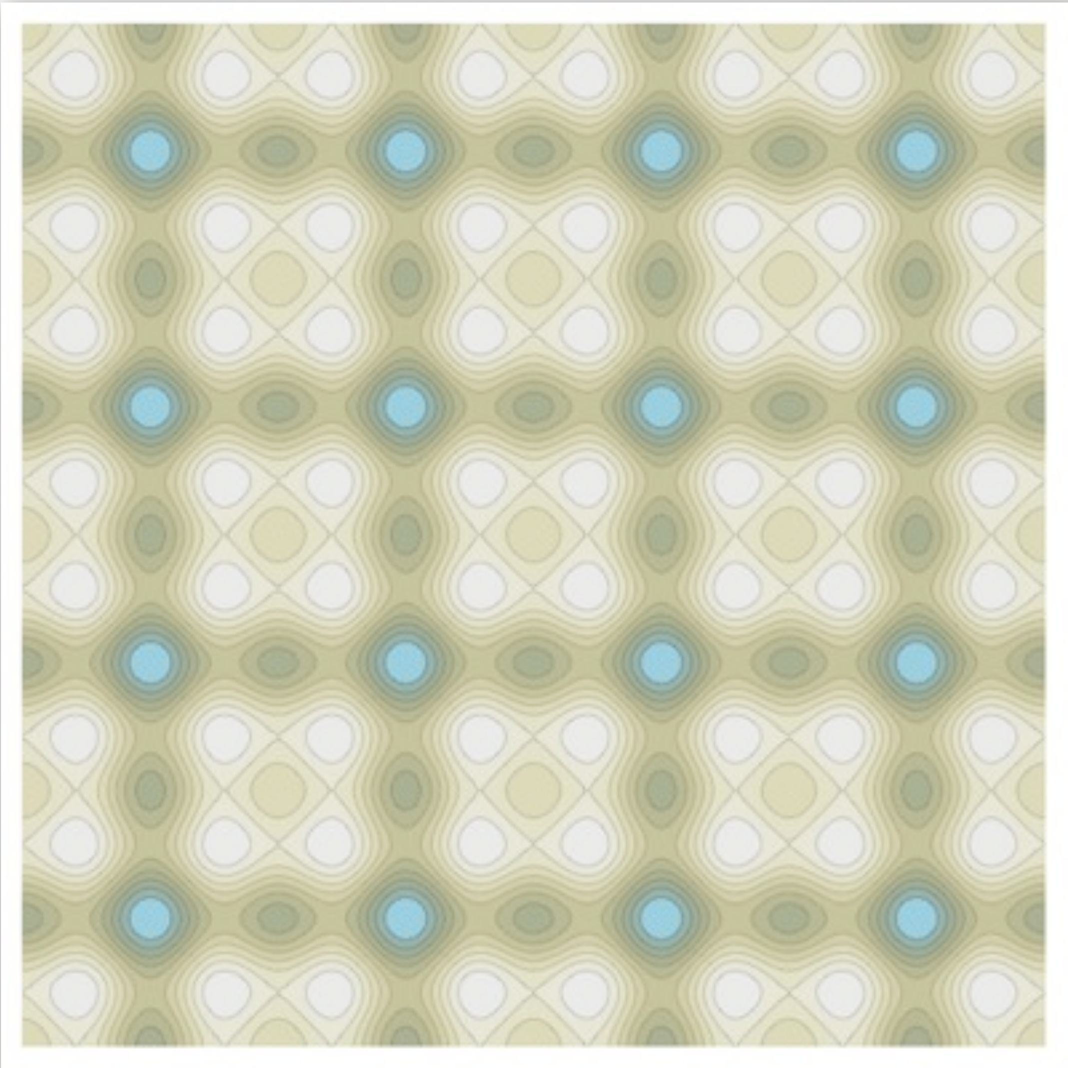
see S. Trotzky *et al.*, arXiv:1009.2415

2D Superlattice Geometries (2 SL)



Coupled Plaquette Systems

see B. Paredes & I. Bloch, PRA **77**, 23603 (2008)
S. Trebst et al., PRL **96**, 250402 (2006)



Higher Lattice Orbital Physics

see V. Liu, A. Ho, C. Wu work
exp: related to A. Hemmerich's talk

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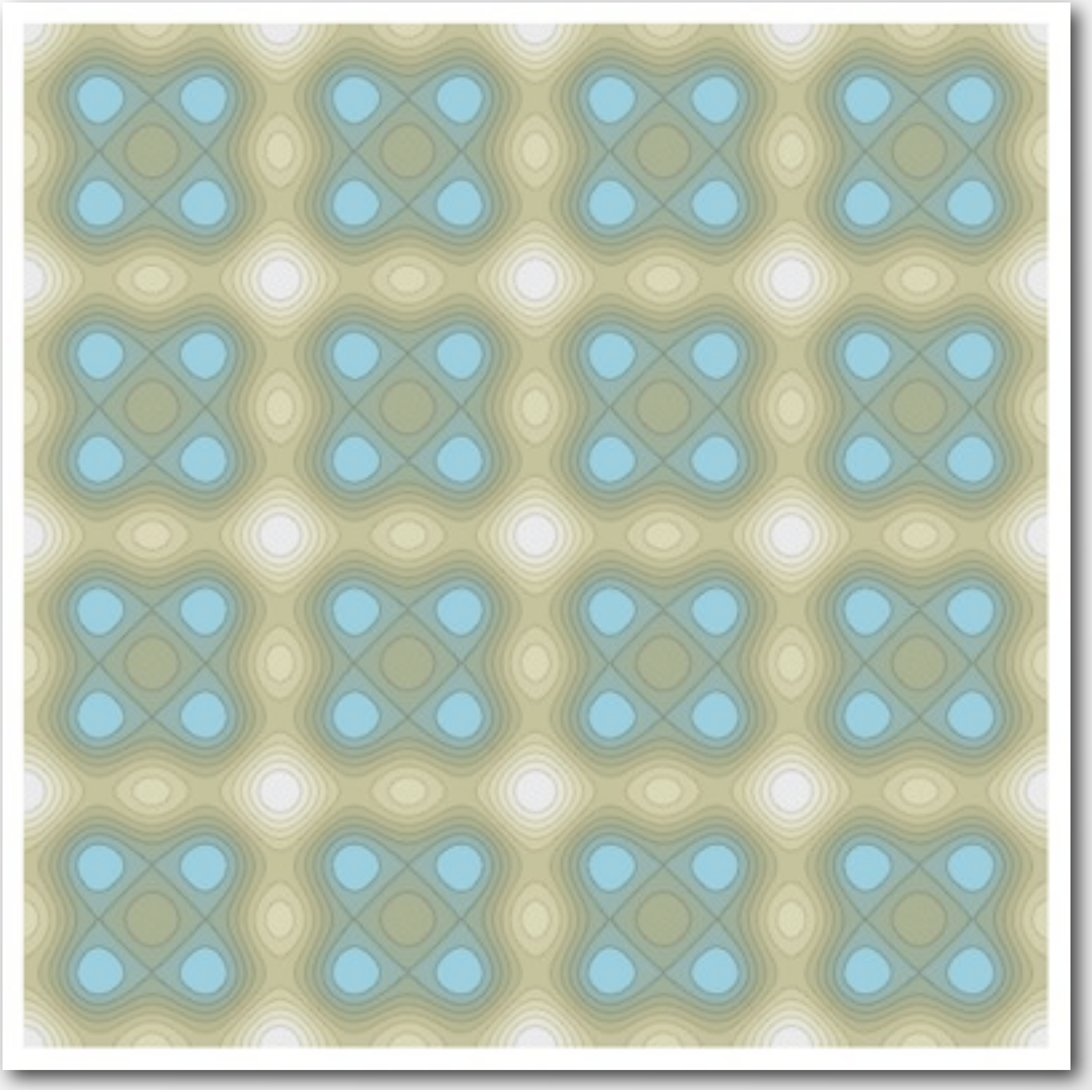

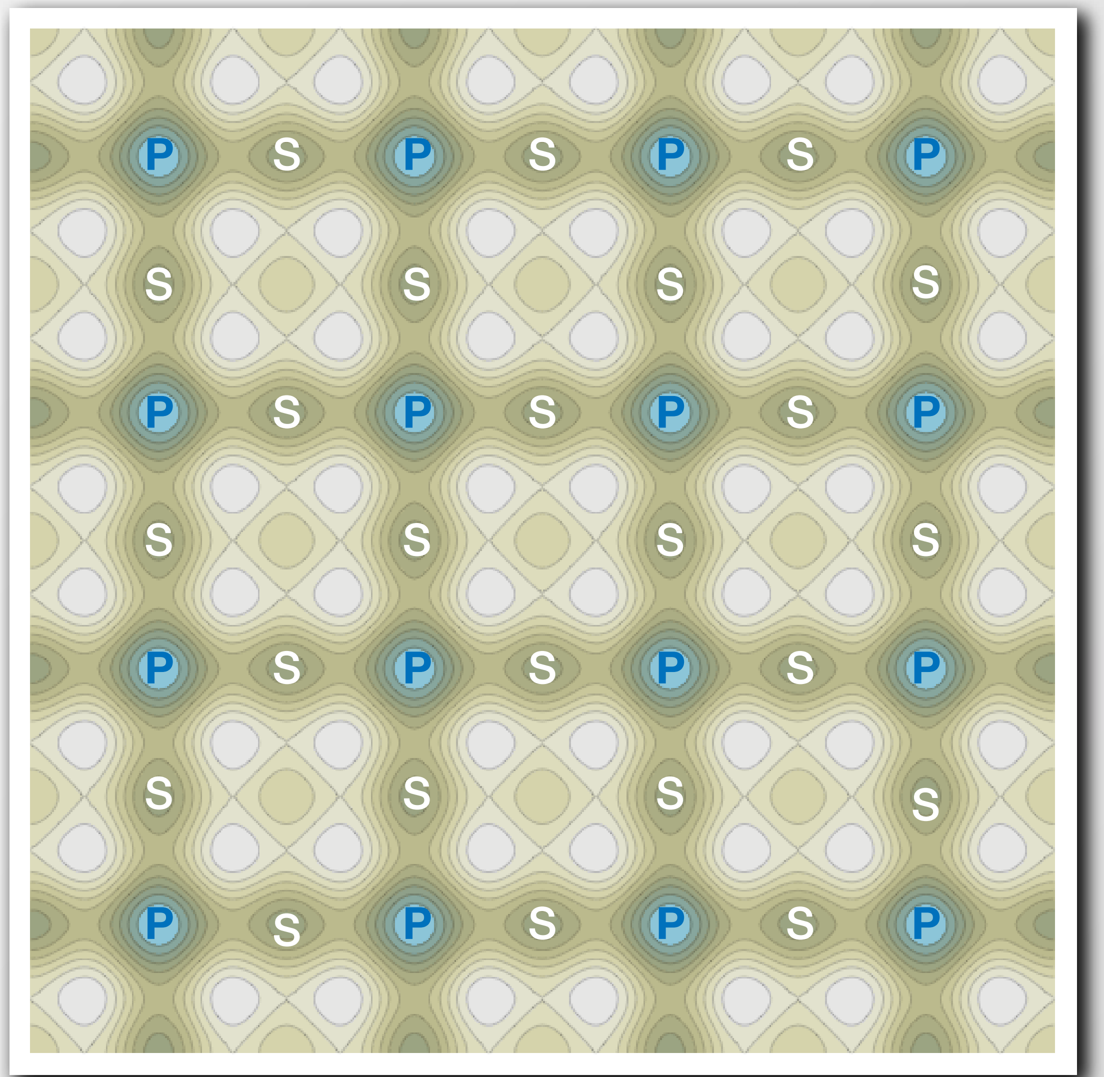

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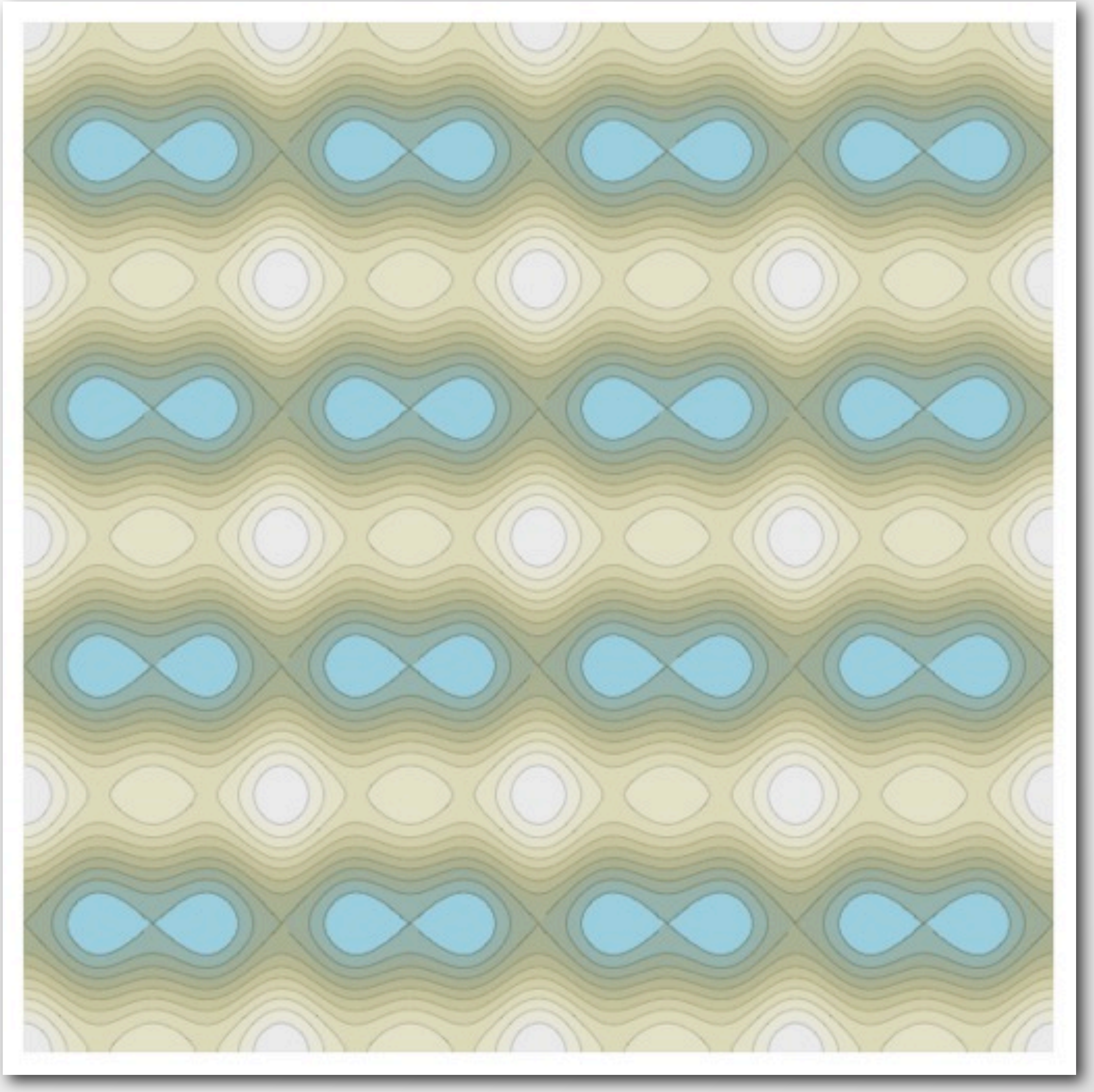
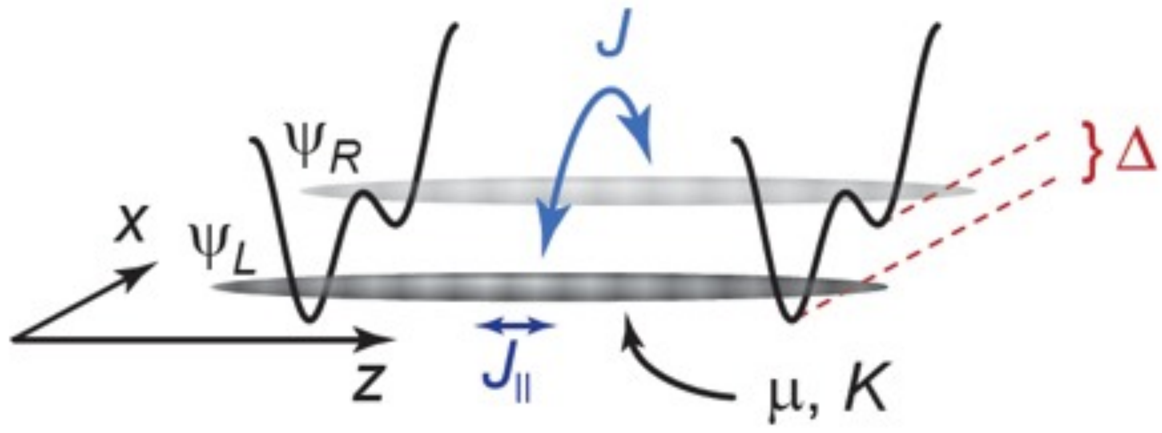
Pairwise Coupled 1D Tubes



Coupled 1D Luttinger Liquids - several hundred in parallel

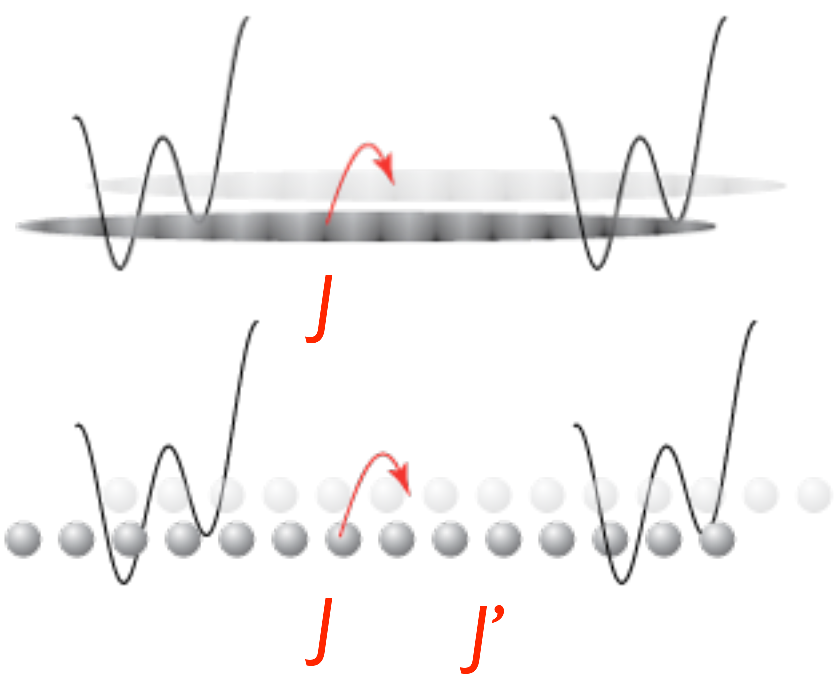
K controlled via additional lattice in z-direction

The System



Coupled 1D bosonic quantum gases

Rabi & JJ Regime: see also Th. Giamarchi, *Quantum Physics in One Dimension*

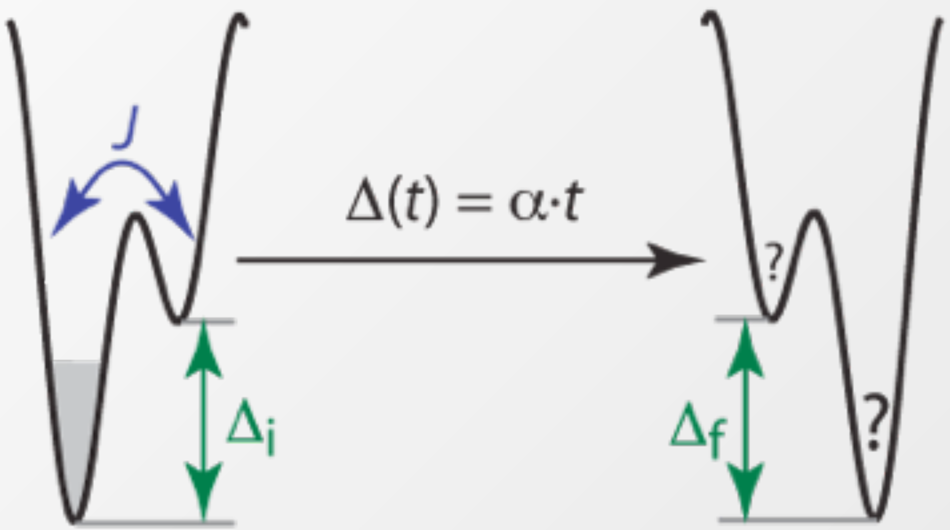


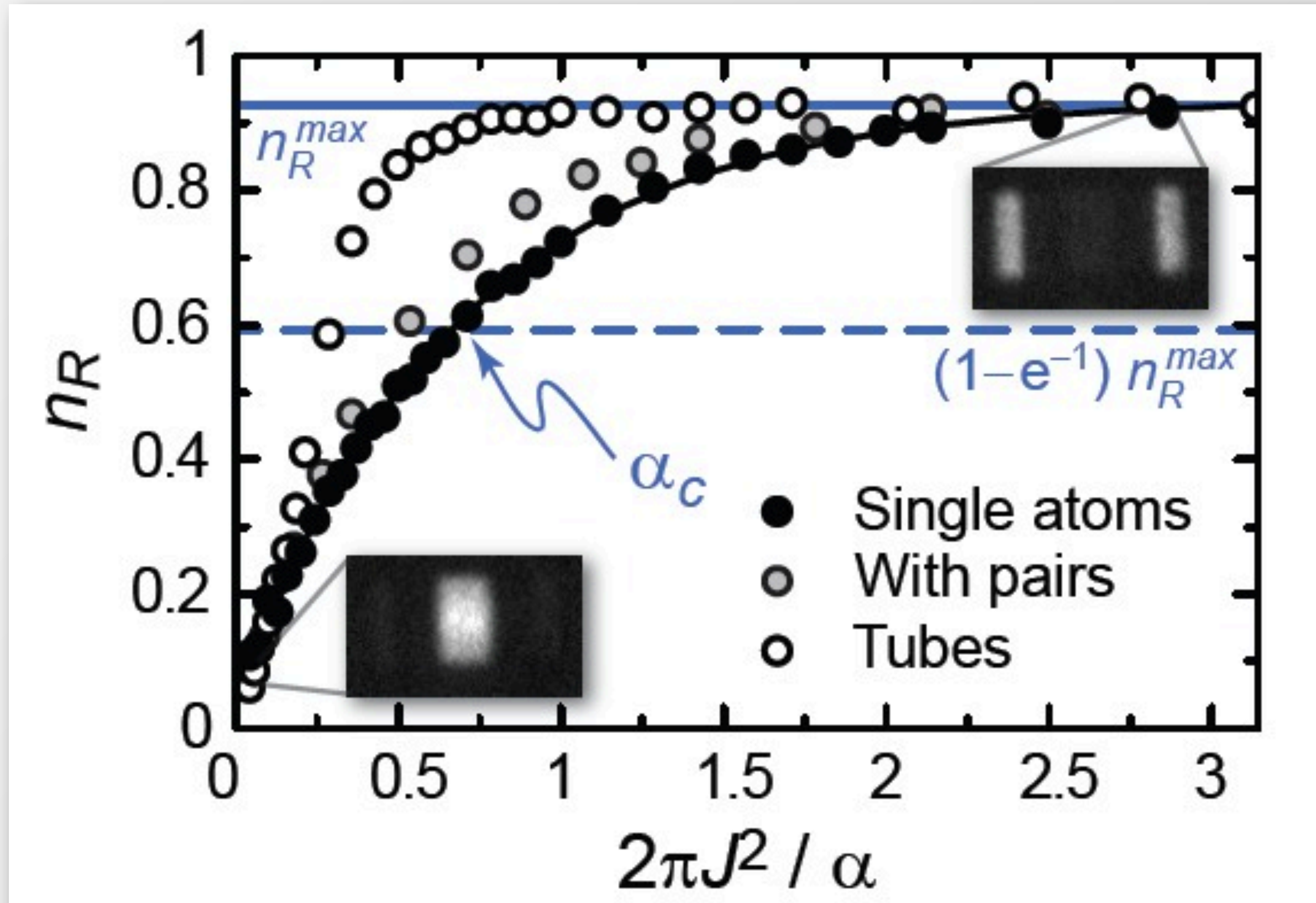
Change interactions (correlations) *K* and condensate fraction along tube via lattice along the z-direction.

refs.: 1D lattice: B. Paredes et al., Nature 2004 & Stöferle et al. PRL 2004, Fertig PRL 2005
JJ 3d BEC: M. Oberthaler, PRL 2003, see also: AtomChips J. Schmiedmayer, J. Reichel, Ph. Treutlein

Forward Sweep

Evaluate population in right tube n_R after sweep.





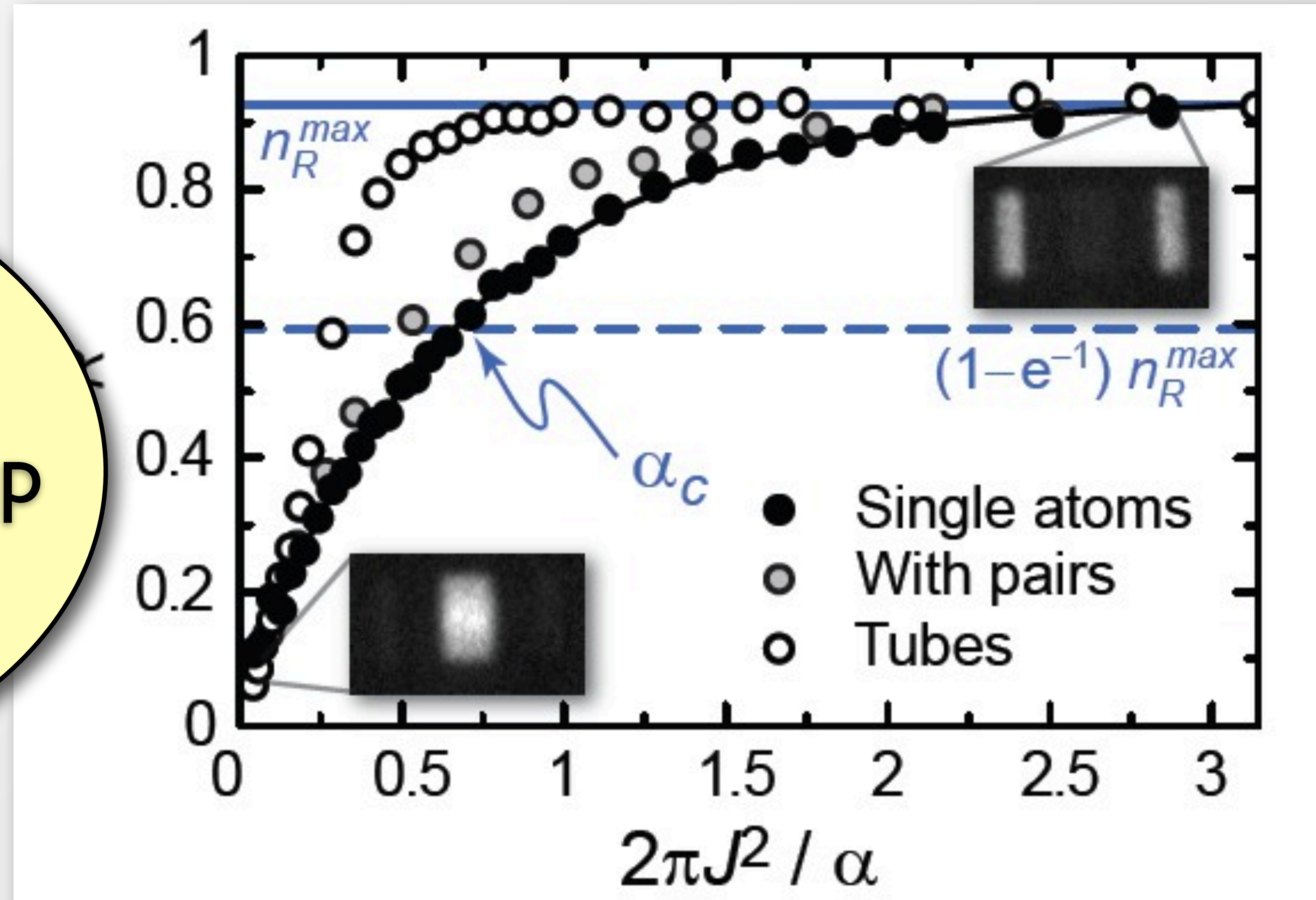
Characteristic sweep rate: α_c

Forward Sweep

Evaluate population in right tube

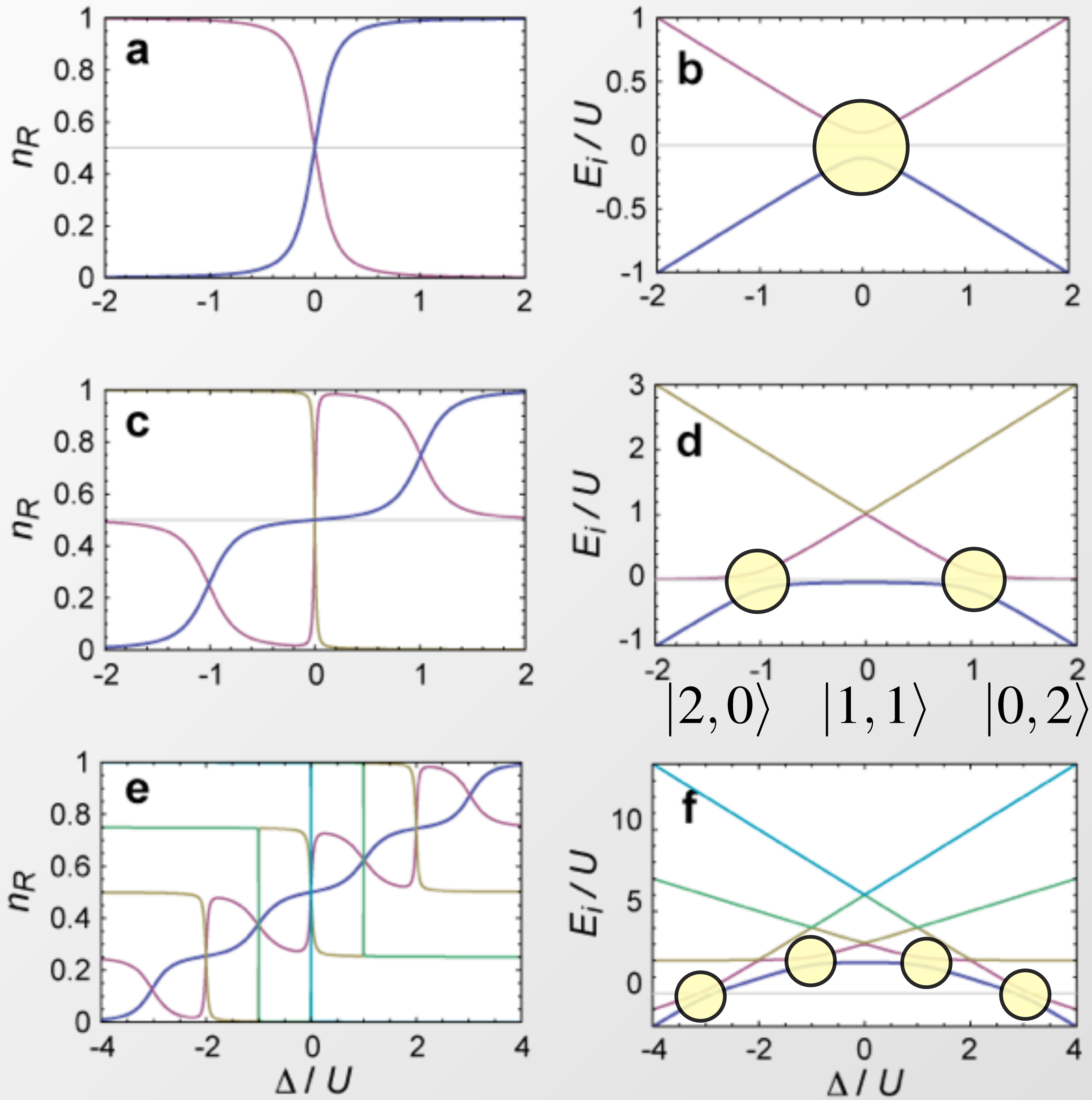
n_R af

Interactions seem to allow faster ramp rates!



Characteristic sweep rate: α_c

Understanding Interaction Effects (U/J=10)



1 atom

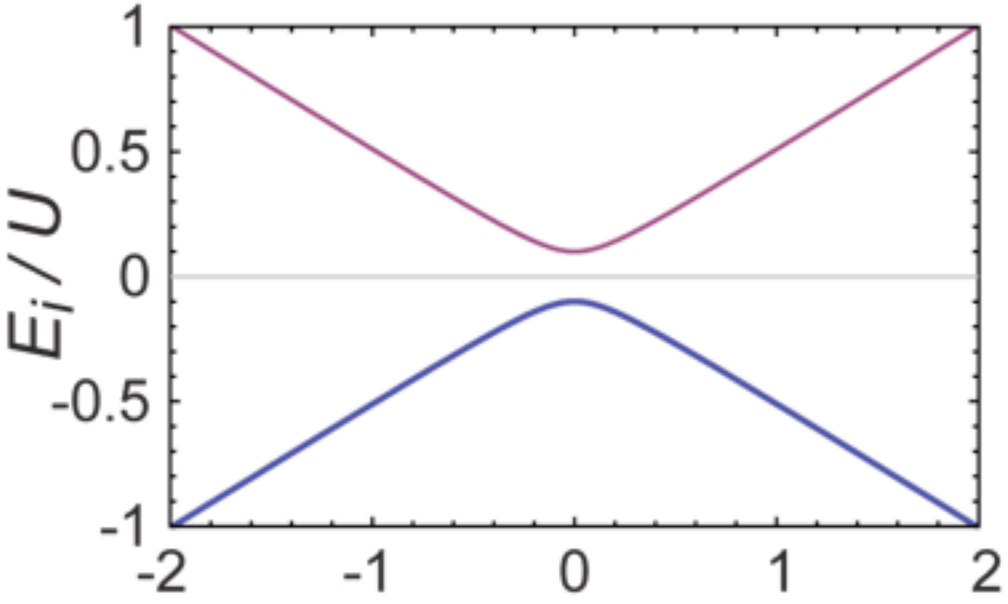
2 atoms

4 atoms

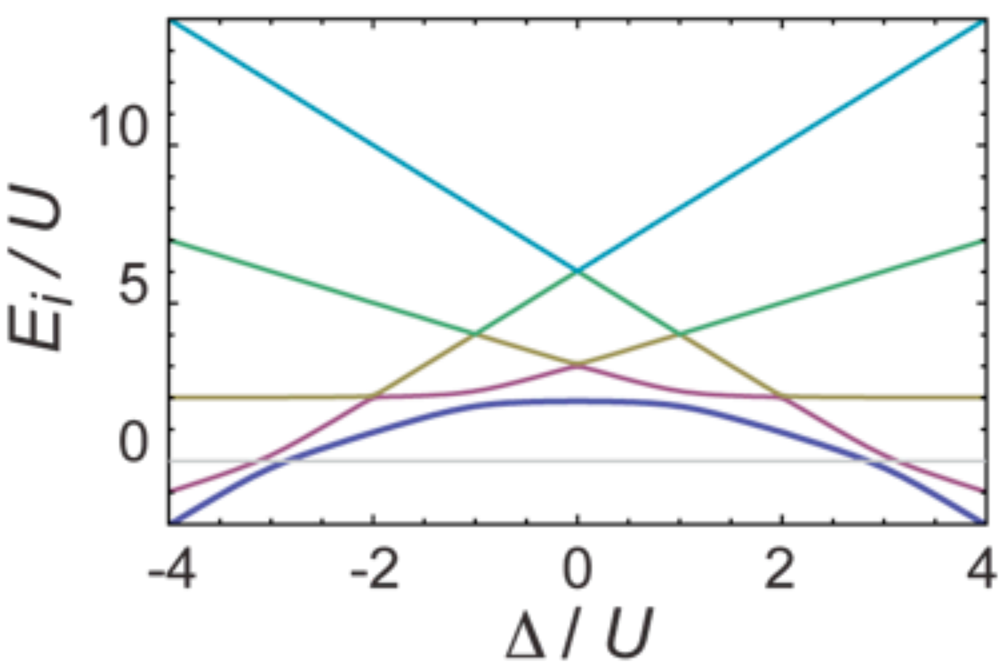
Interactions spread out single particle tunneling resonances over $E \approx \mu$

- Tunneling - Non-Interacting vs Strongly Interacting

Non-Interacting LZ Sweep



Strong Interaction - Blockade Regime



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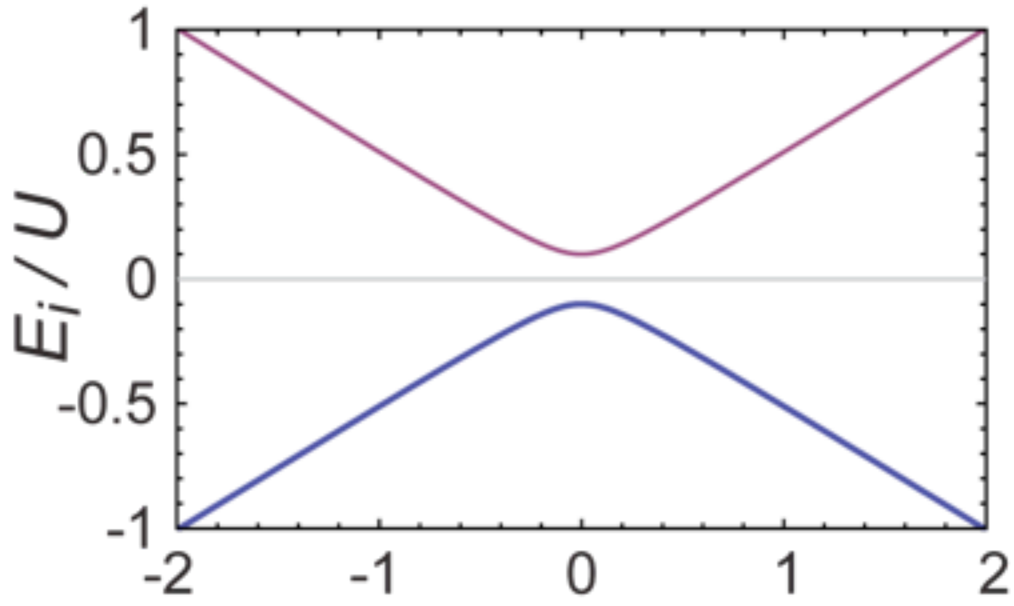

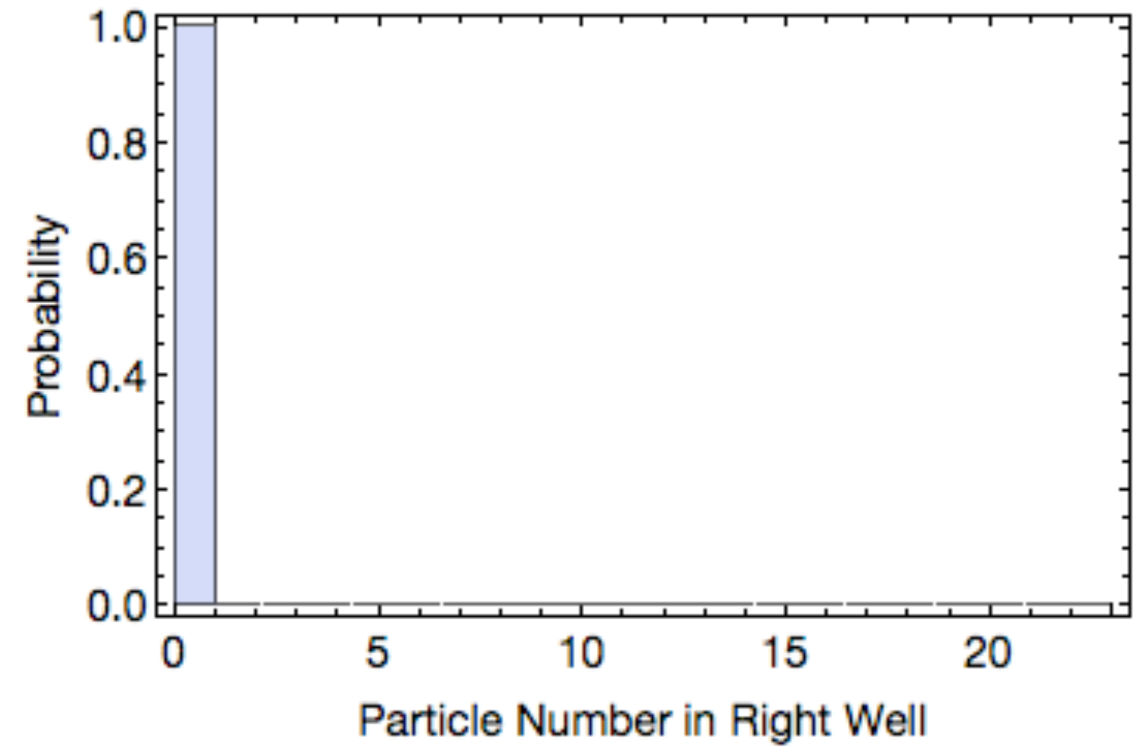

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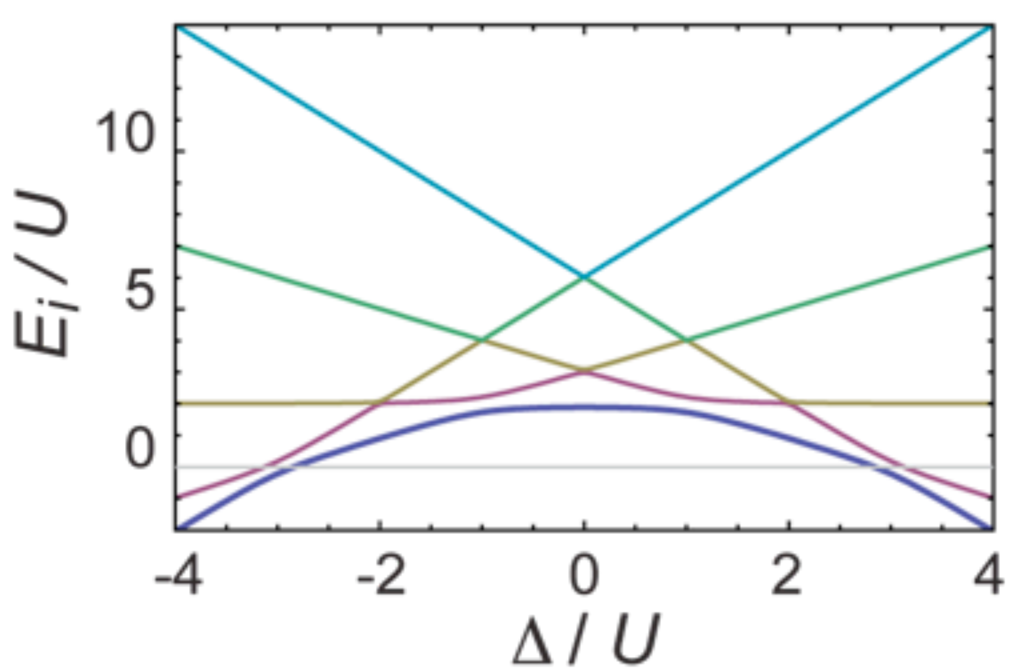

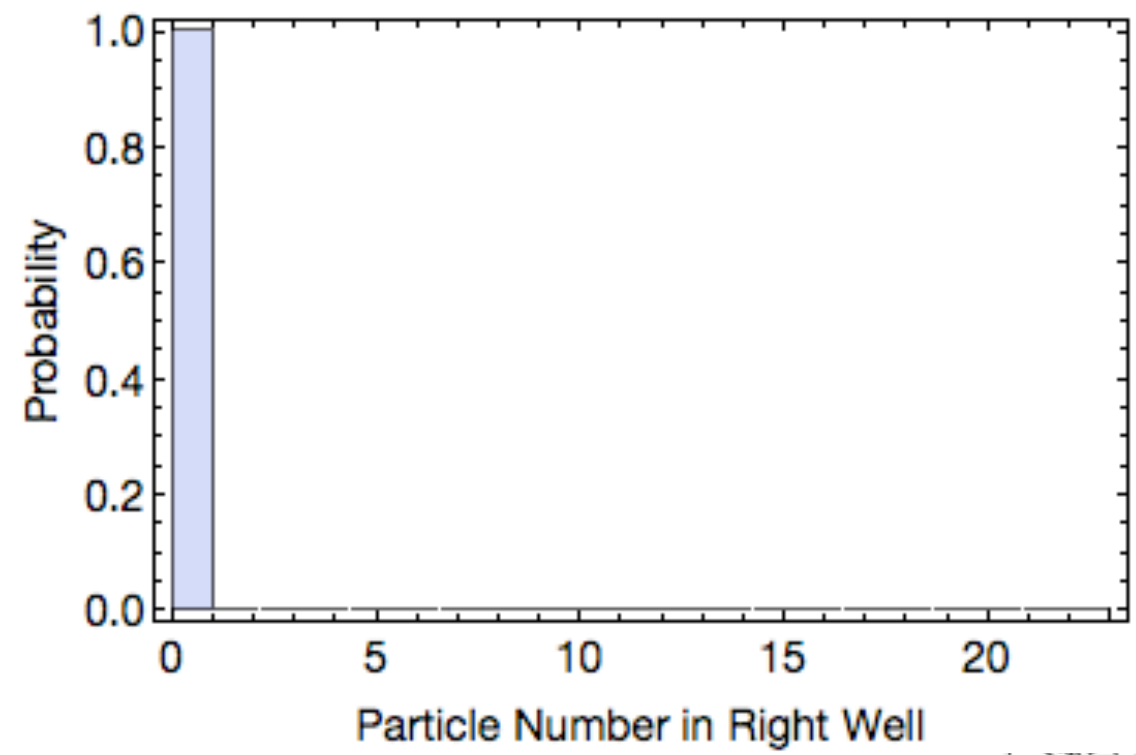

- Tunneling - Non-Interacting vs Strongly Interacting

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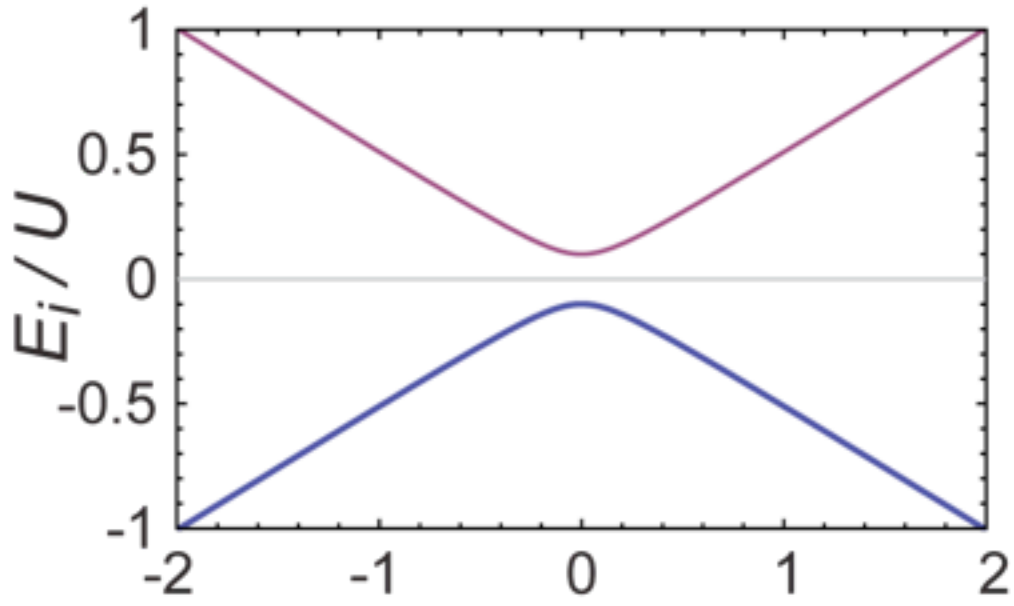

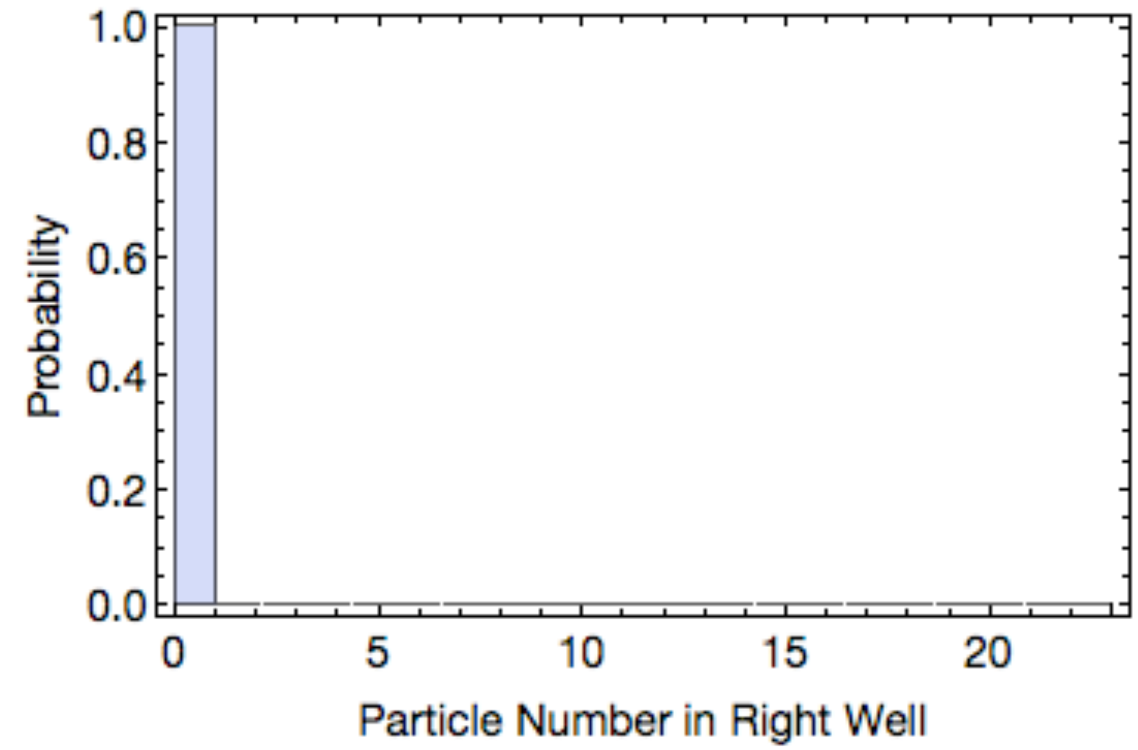

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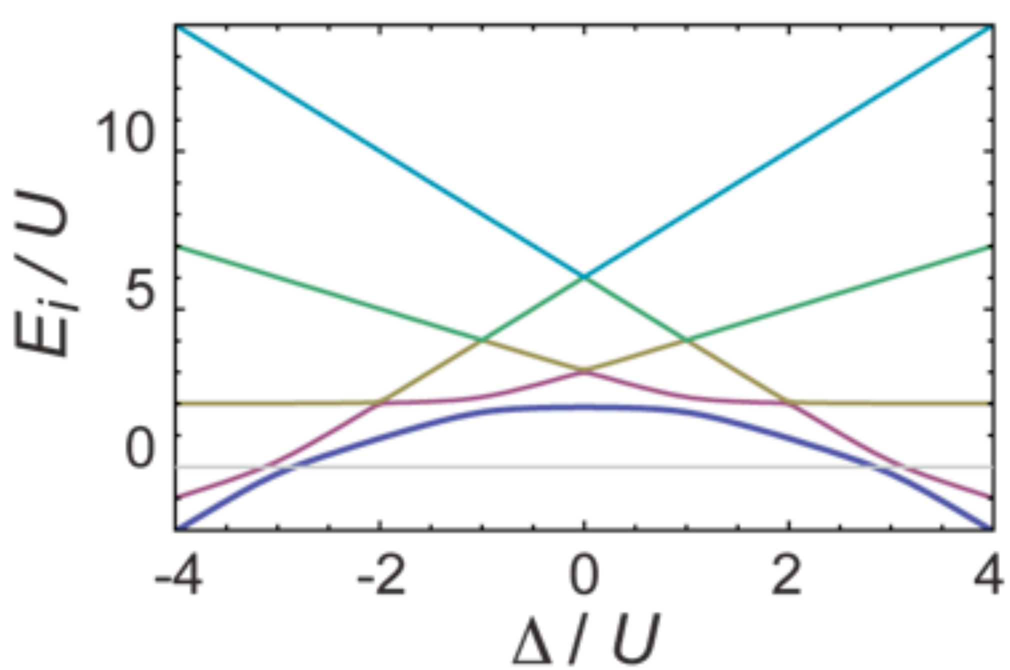
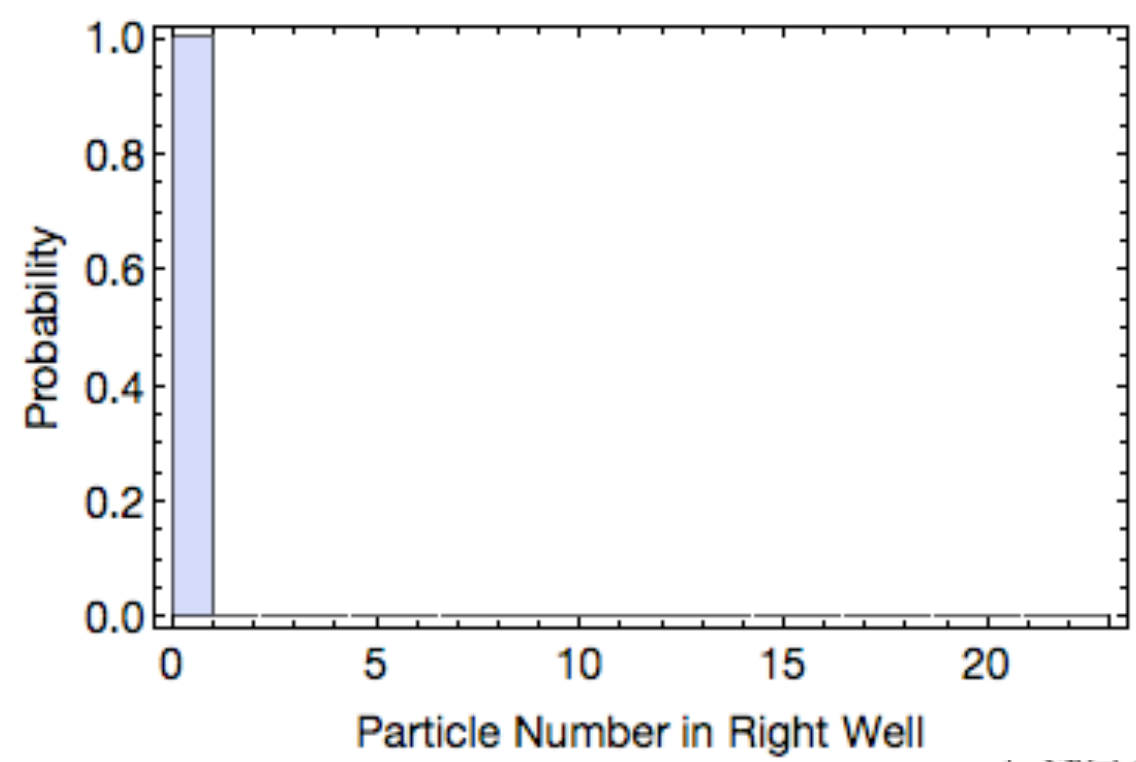




Understanding Interaction Effects

Interacting two mode model:

$$\hat{H} = -J\left(\hat{a}_L^{+}\hat{a}_R + h.c.\right) + \frac{U}{2}\left(\hat{n}_L\left(\hat{n}_L - 1\right) + \hat{n}_R\left(\hat{n}_R - 1\right)\right) + \frac{\Delta}{2}\left(\hat{n}_L - \hat{n}_R\right)$$

Matrix elements in $|n_L, n_R\rangle$ basis.

$$\begin{aligned} H_{i+1,i} &= \langle n-i+1, i-1|\hat{H}|n-i, i\rangle \\ &= -\sqrt{i}\sqrt{n-i+1}J \end{aligned}$$

Probability to stay in ground state: $P_{ad} = |\langle 0,n|\psi(T)\rangle|^2$

Non-interacting

$$P_{ad} = P_{lz}(\alpha)^n$$

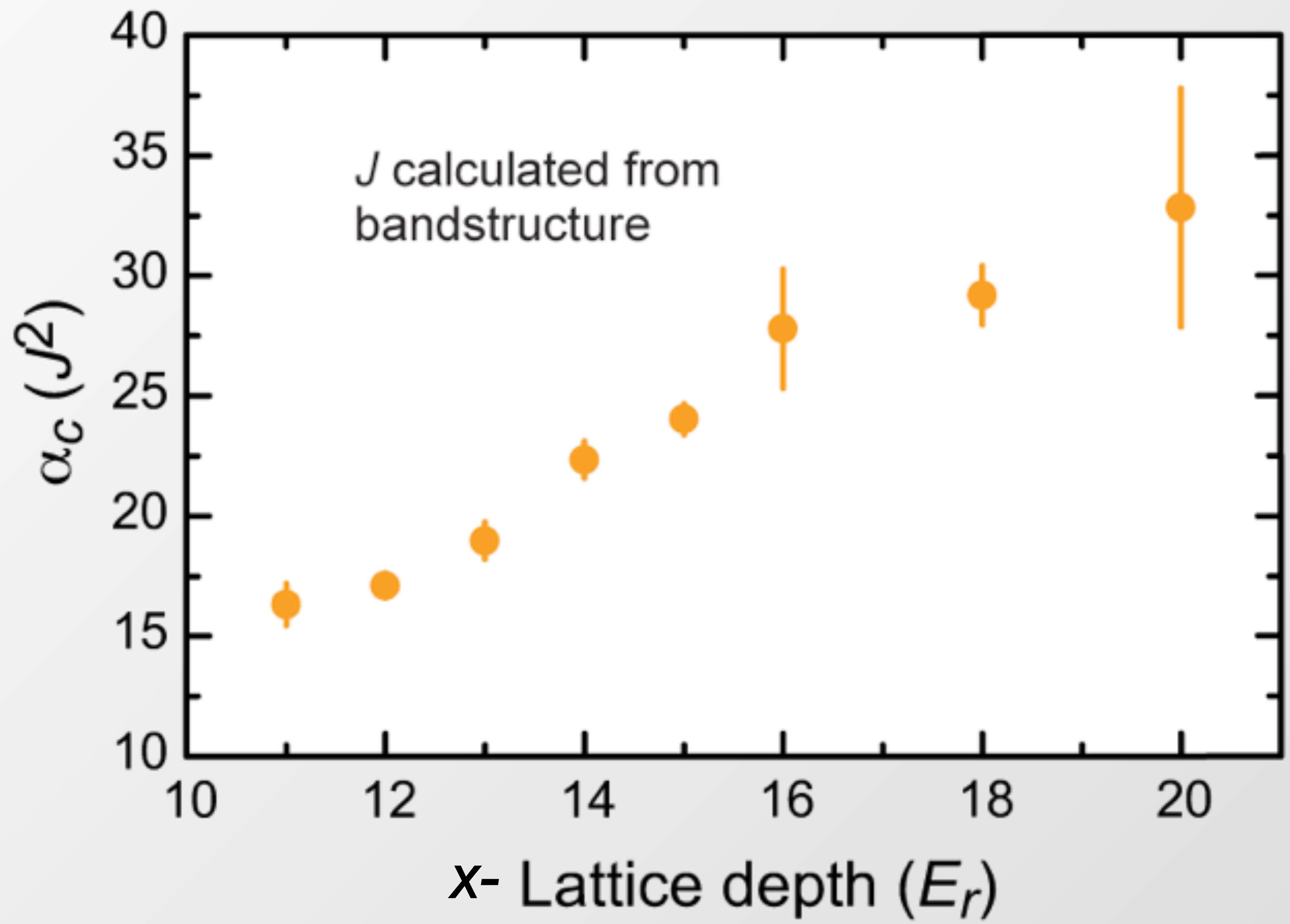
Strongly interacting (split resonances)

$$P_{ad} = \prod_{i=1}^{n} P_{lz}(\alpha/\beta_i^2)$$

make use of bosonic enhancement!

Forward Sweep - Interaction Effects

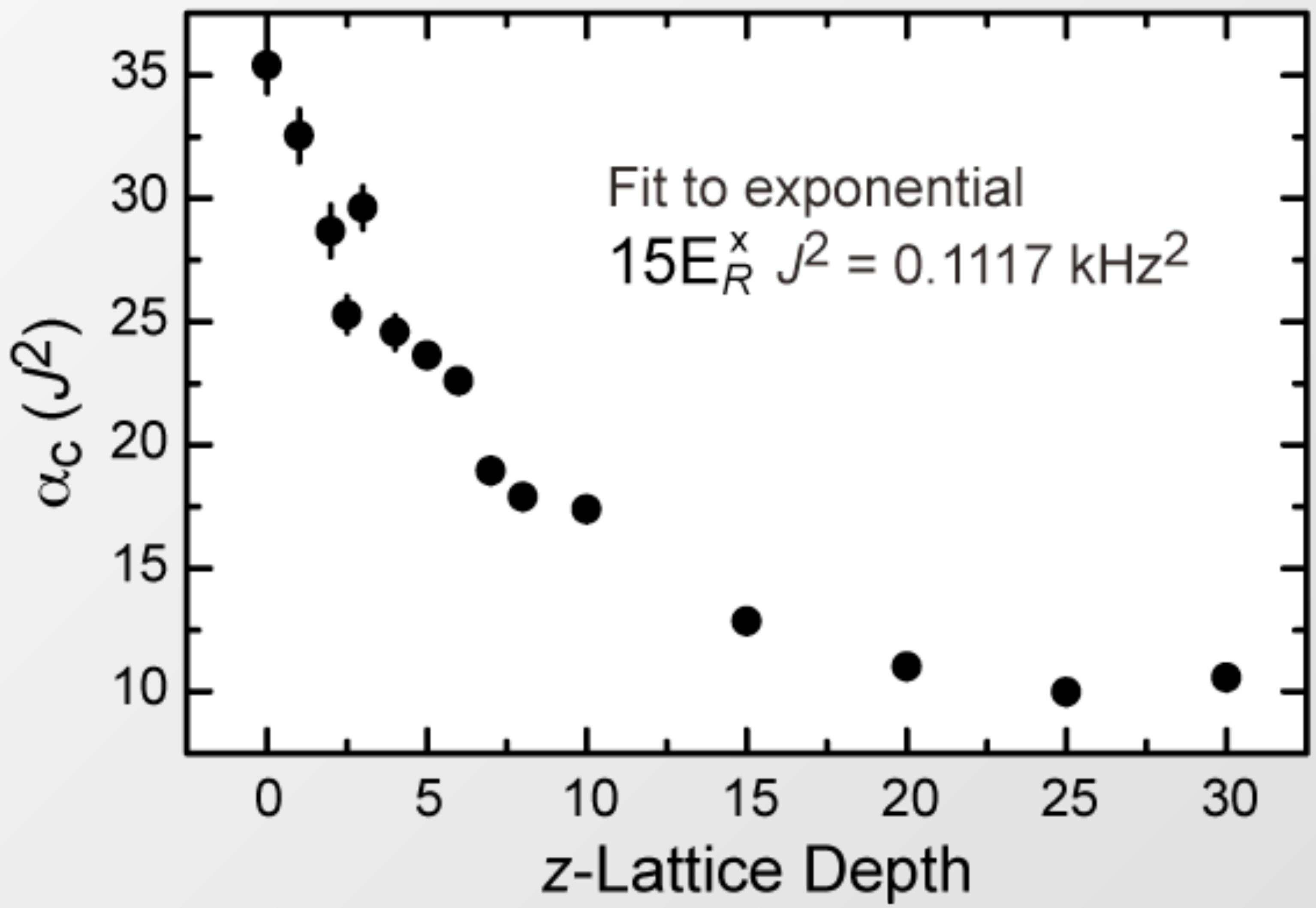
Increase intertube U/J ratio allows faster sweeps!

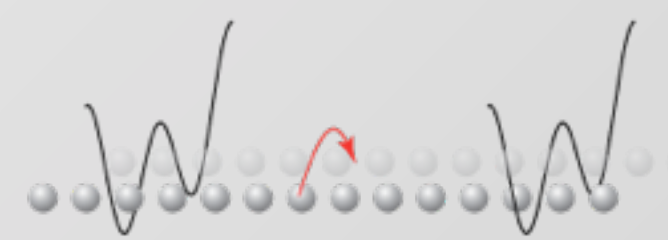


Blockade regime

Effect of Correlations - Changing K

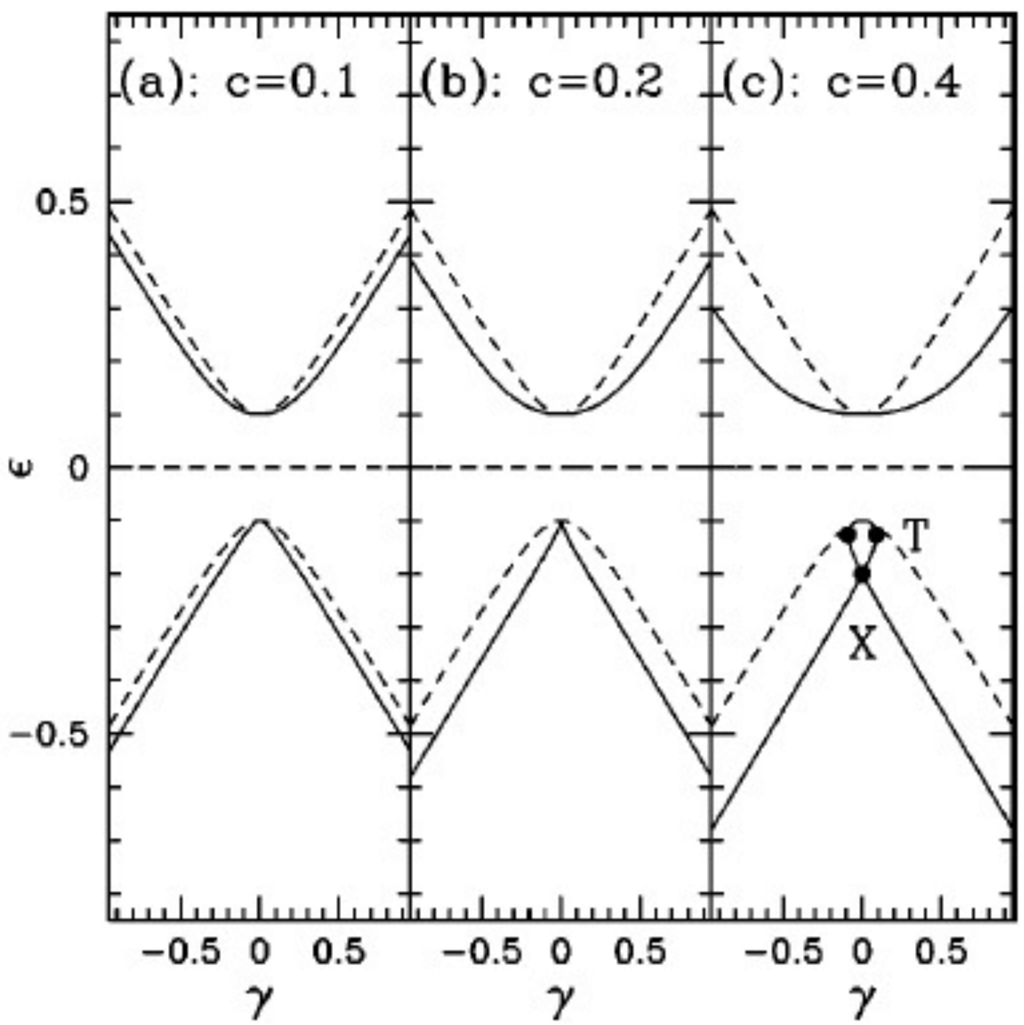
Increase in z-Lattice shortens correlation length (MI transition)

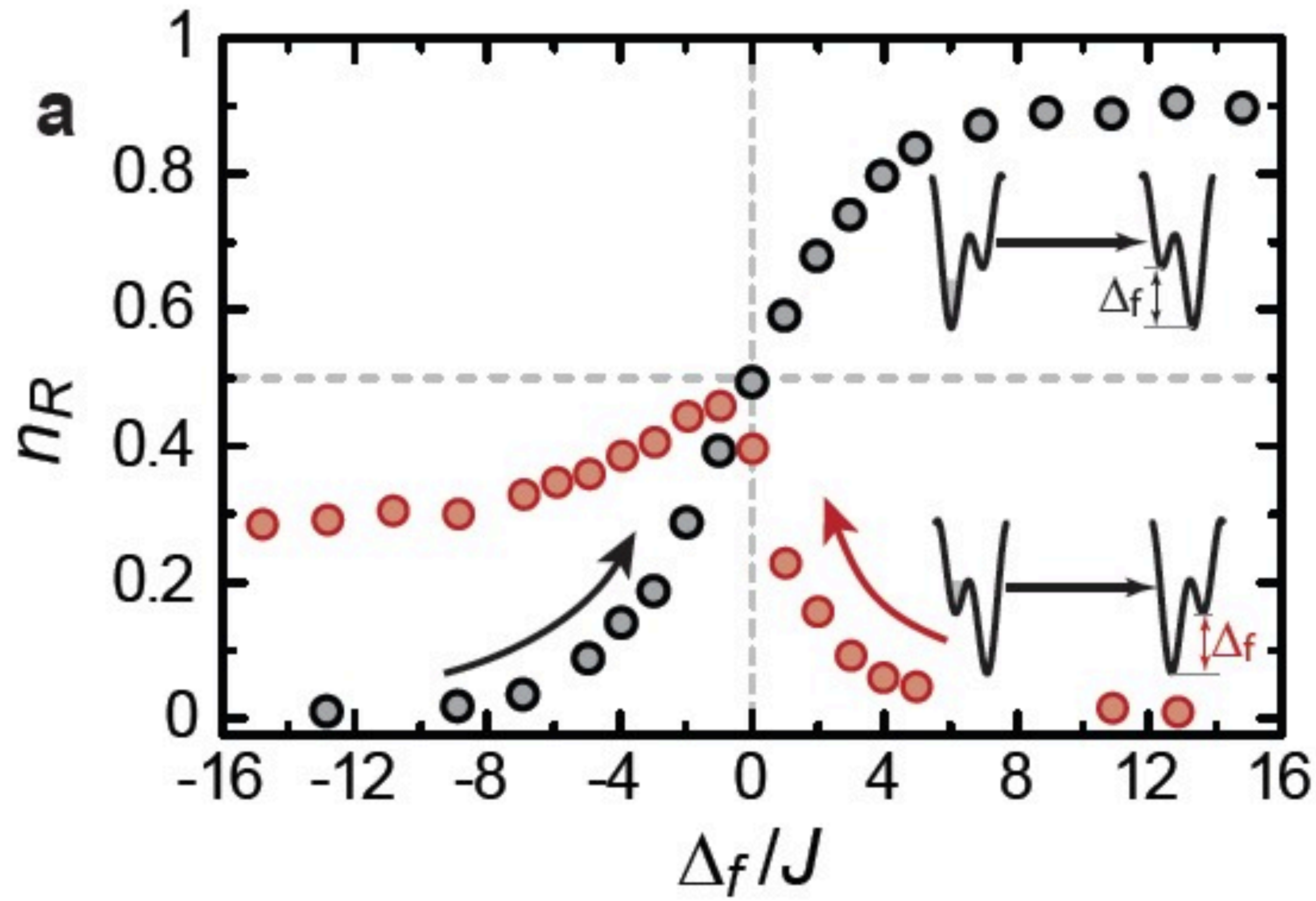




back to single particles for short correlations → slower critical ramp speed needed

Reverse Sweep





Loop solutions in GPE equation...

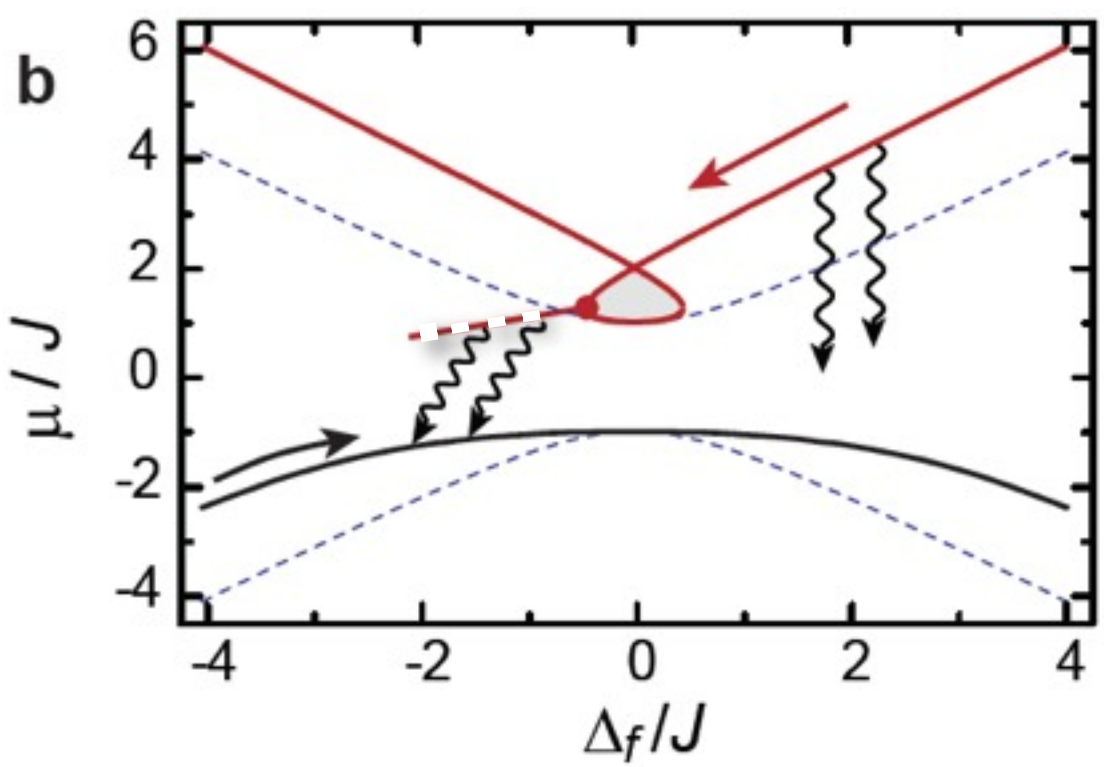
e.g. Biao Wu & Qian Niu PRA **61**, 023402 (2000)

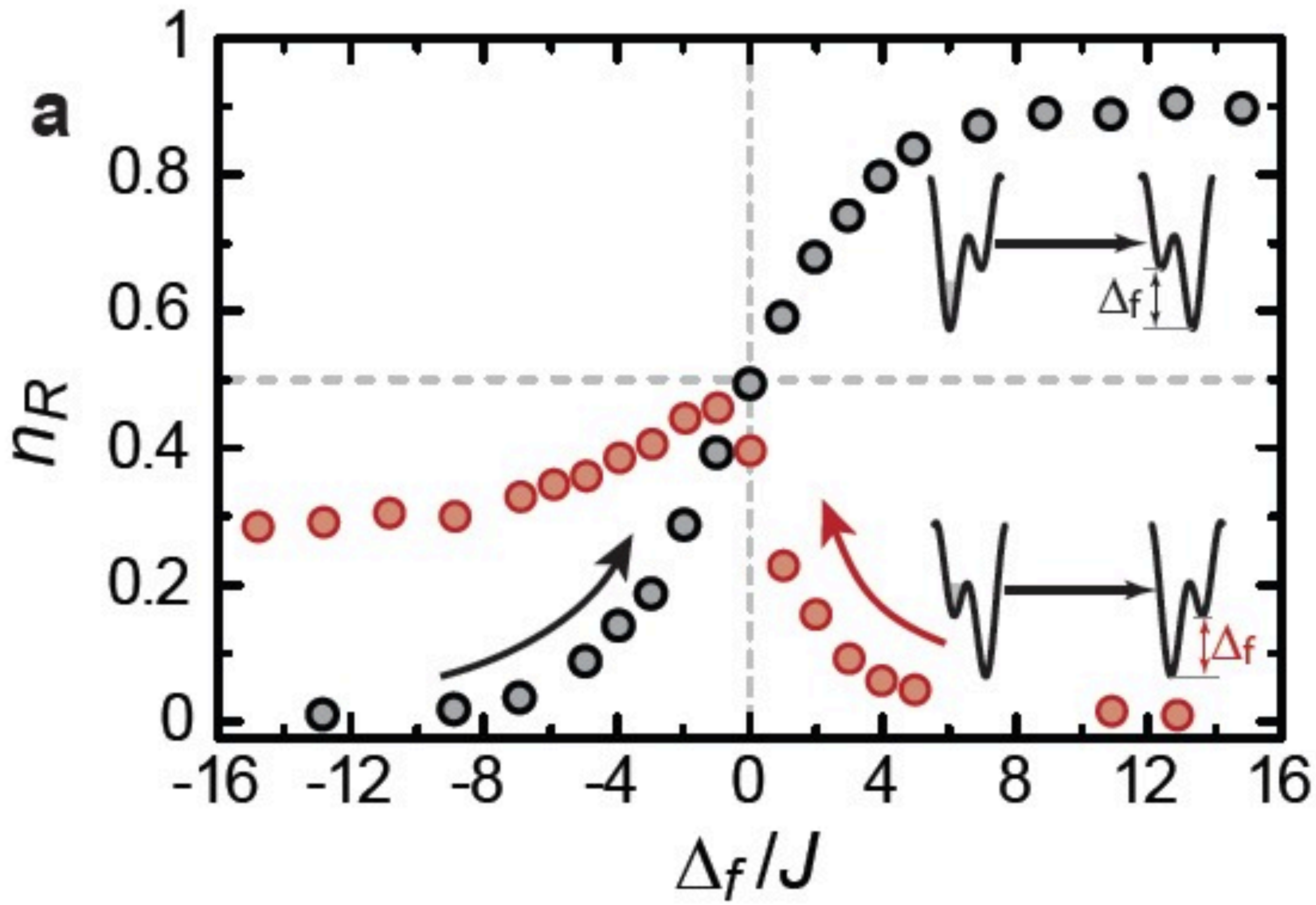
Effective non-linearity in mean field

$$\eta = \frac{U\Phi^2}{J}$$

Reverse sweep with decreased fidelity!

Reverse Sweep





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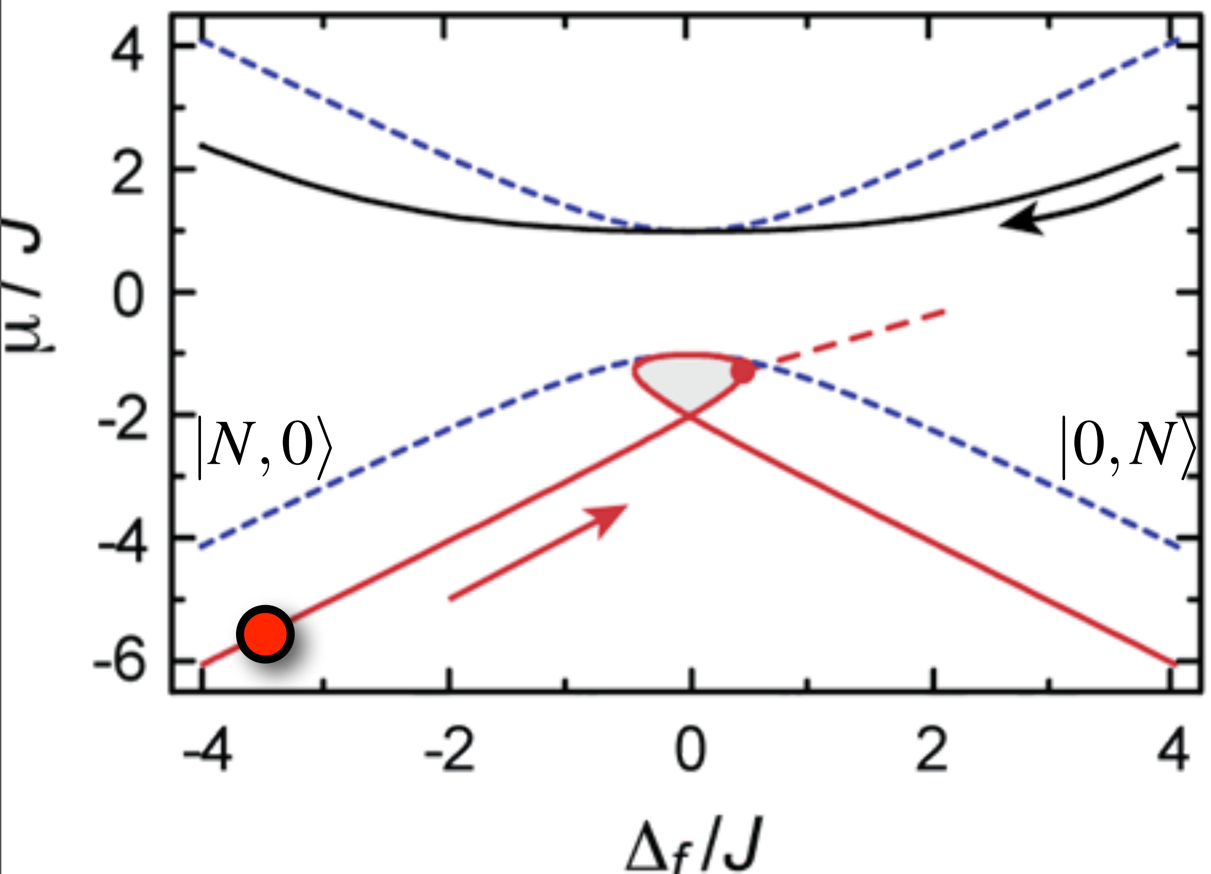
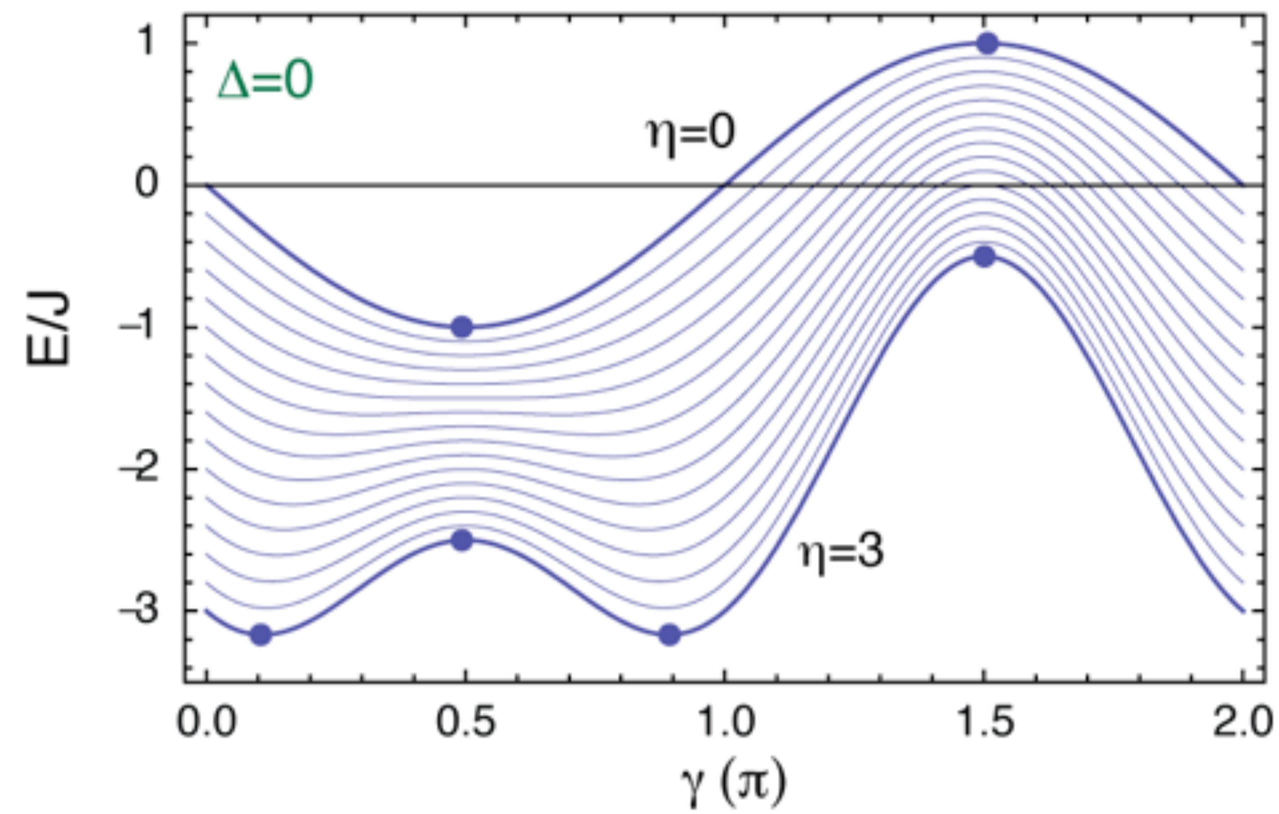
Attractive Interactions - Loop Structure

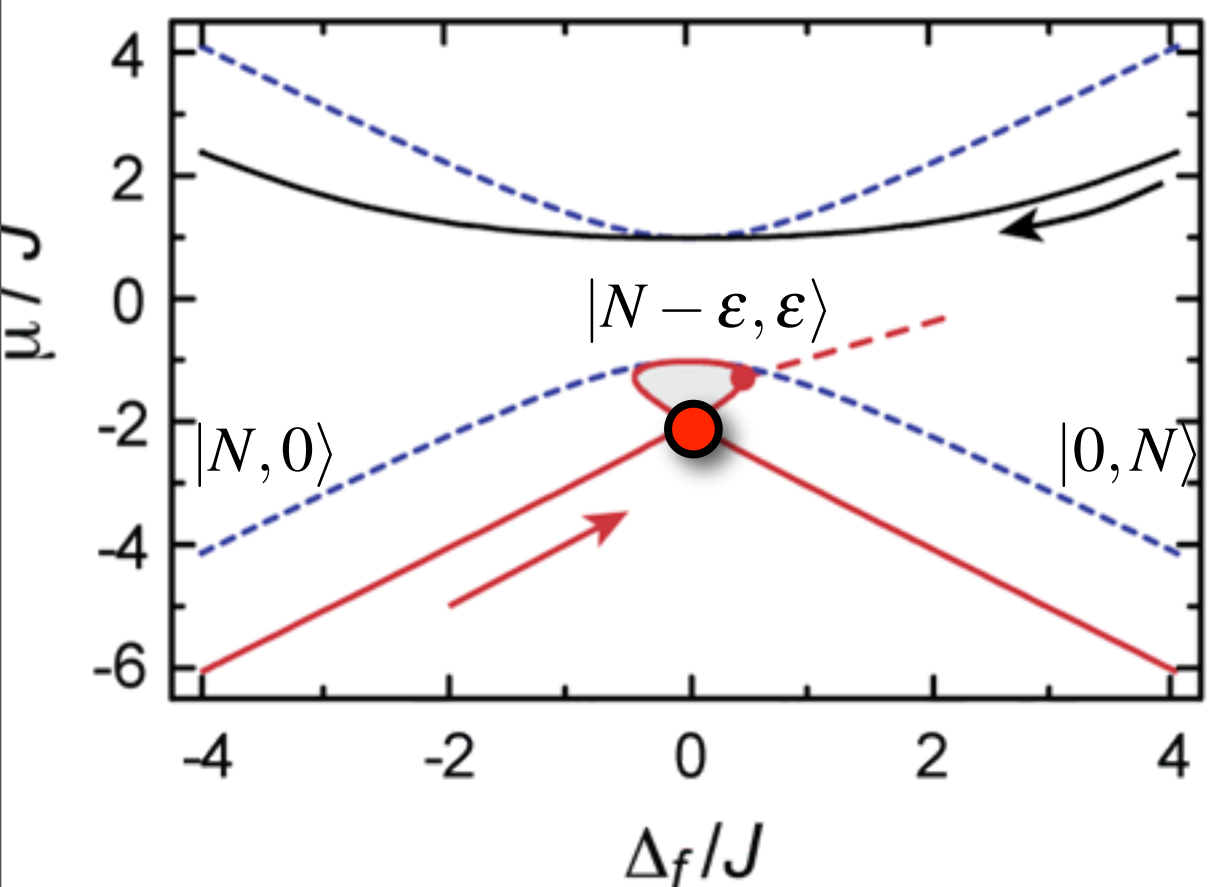


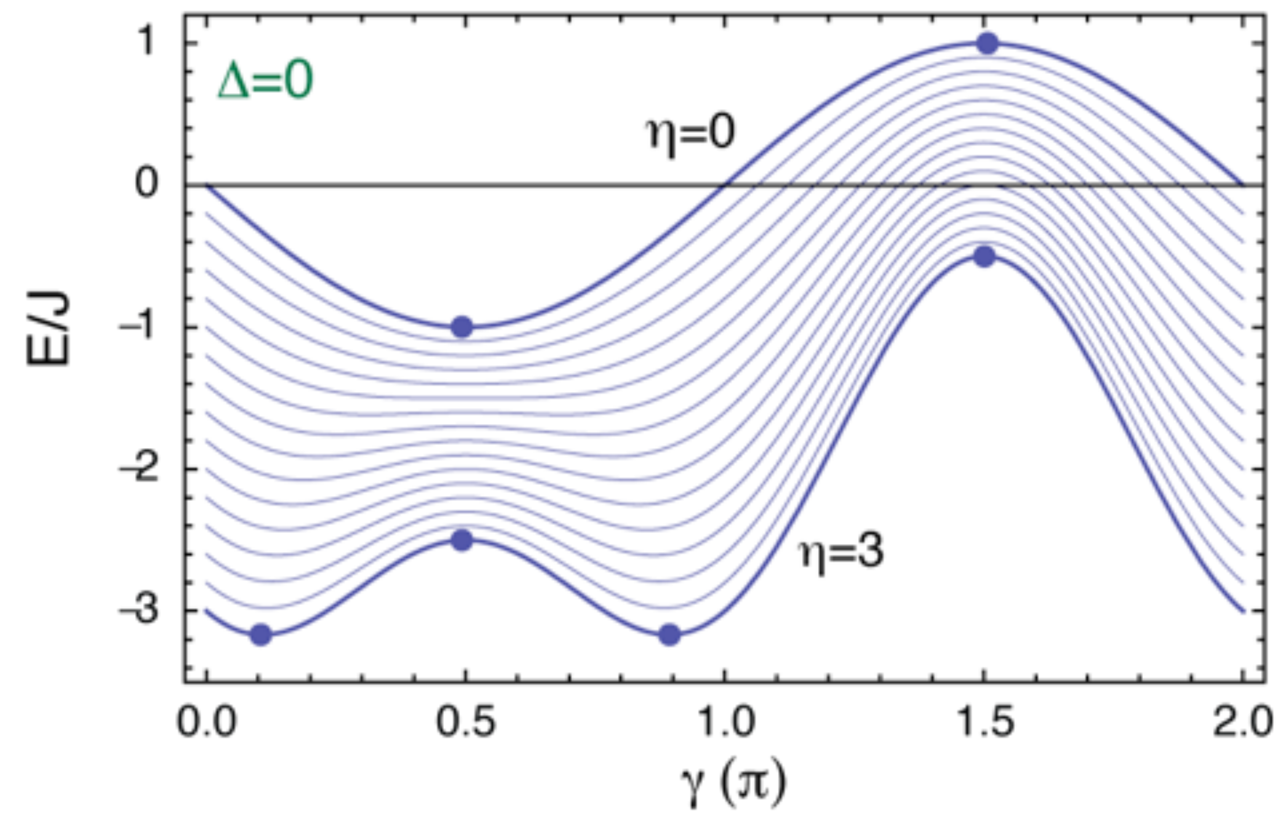


$$\psi_1 = \cos(\gamma/2) \quad \psi_2 = \sin(\gamma/2)$$

$$\mathscr{H}[\psi_1, \psi_2] \quad = -2J\psi_1\psi_2 + \Delta\left(|\psi_1|^2 - |\psi_2|^2\right) + U\left(|\psi_1|^4 + |\psi_2|^4\right).$$

Attractive Interactions - Loop Structure





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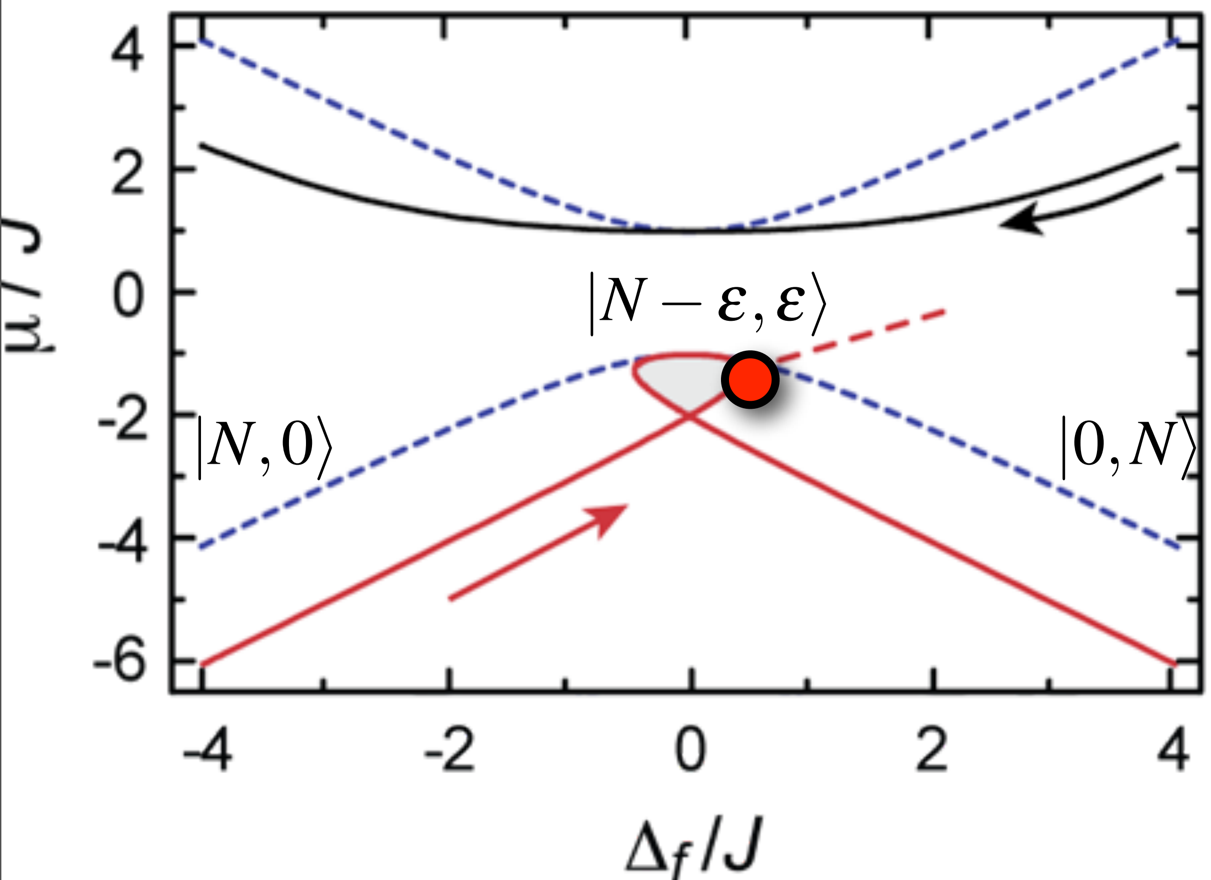

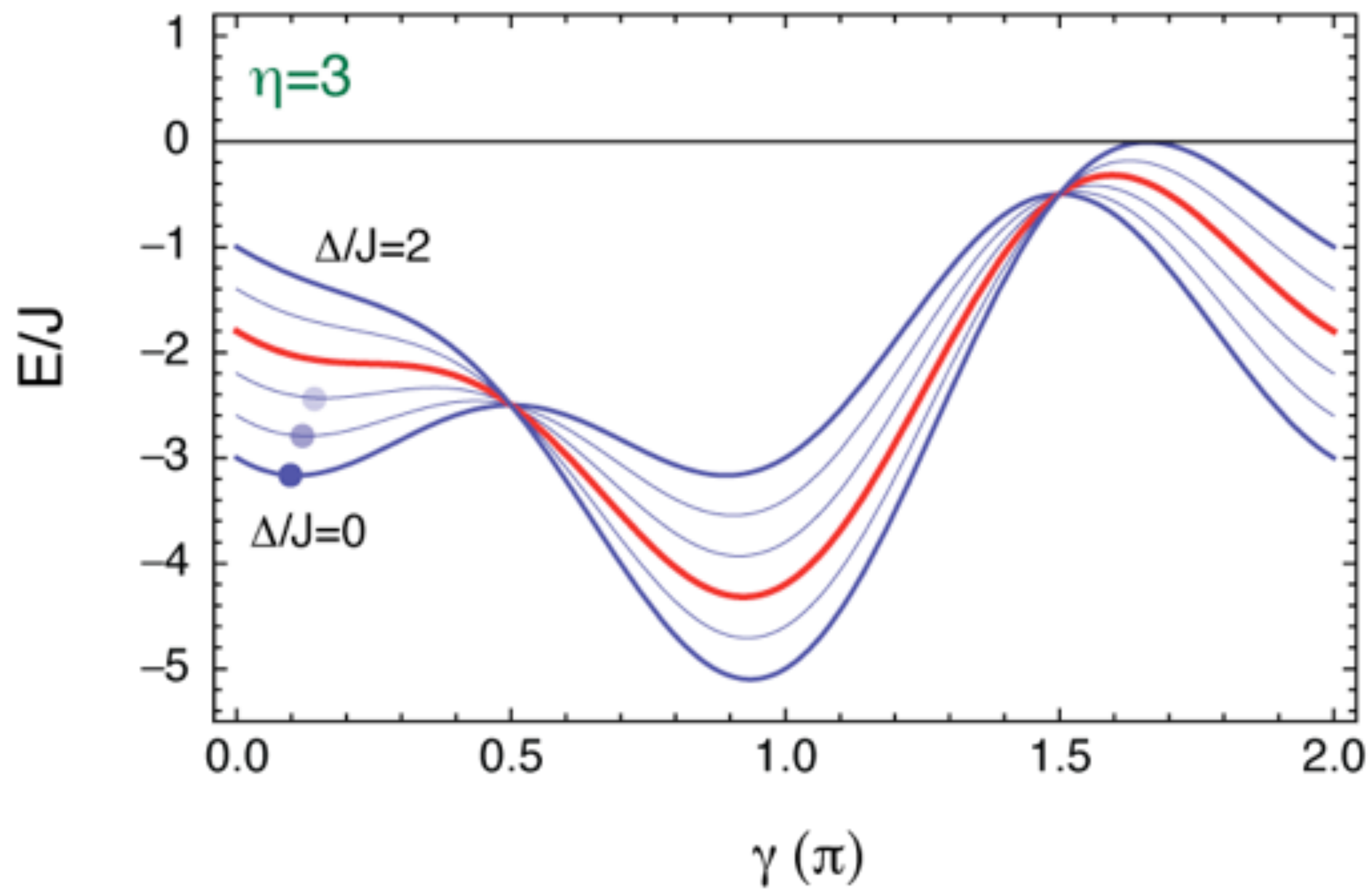

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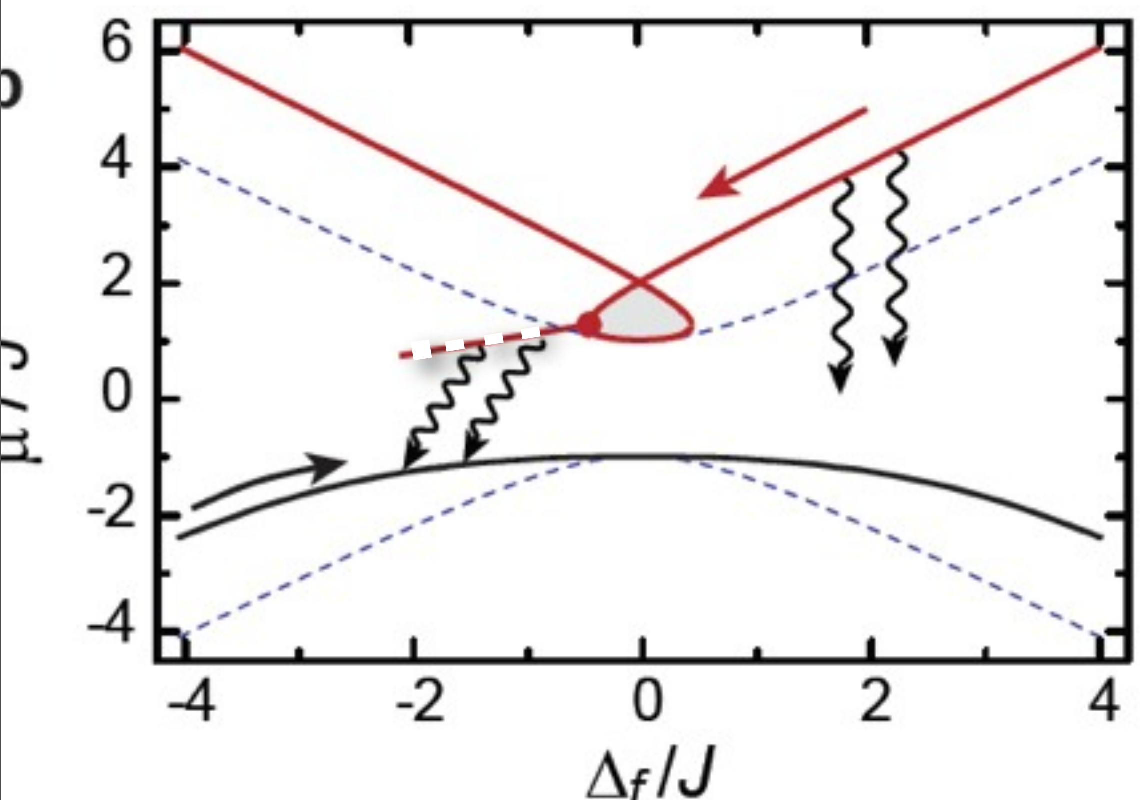
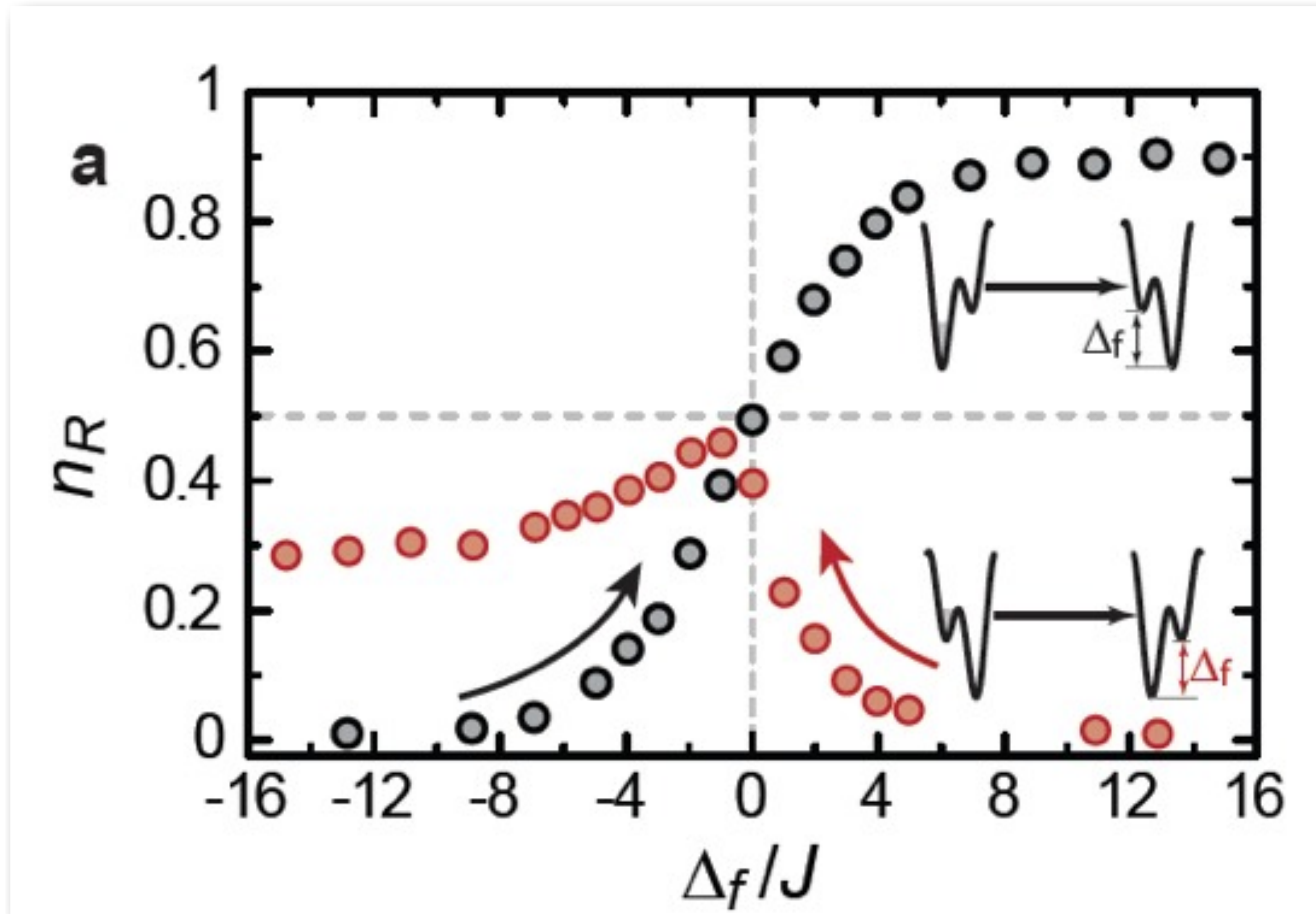
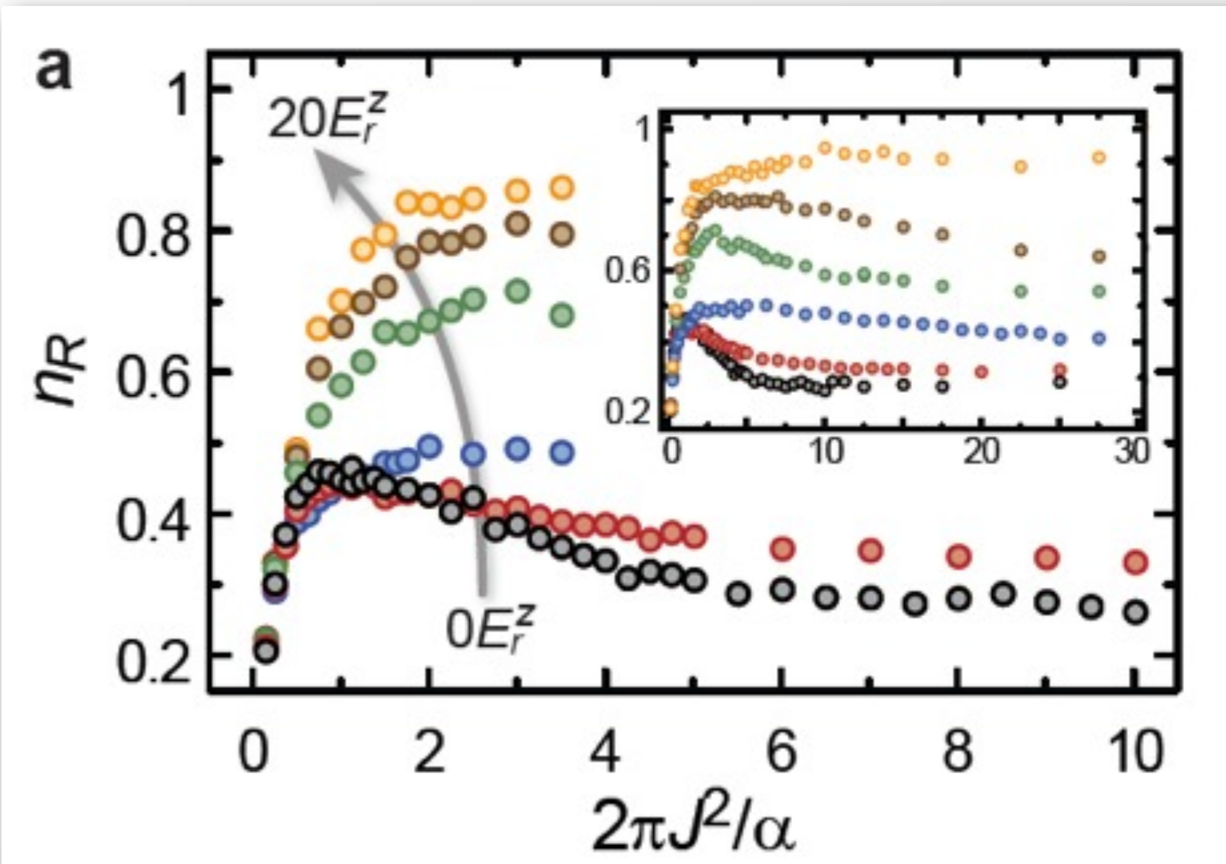


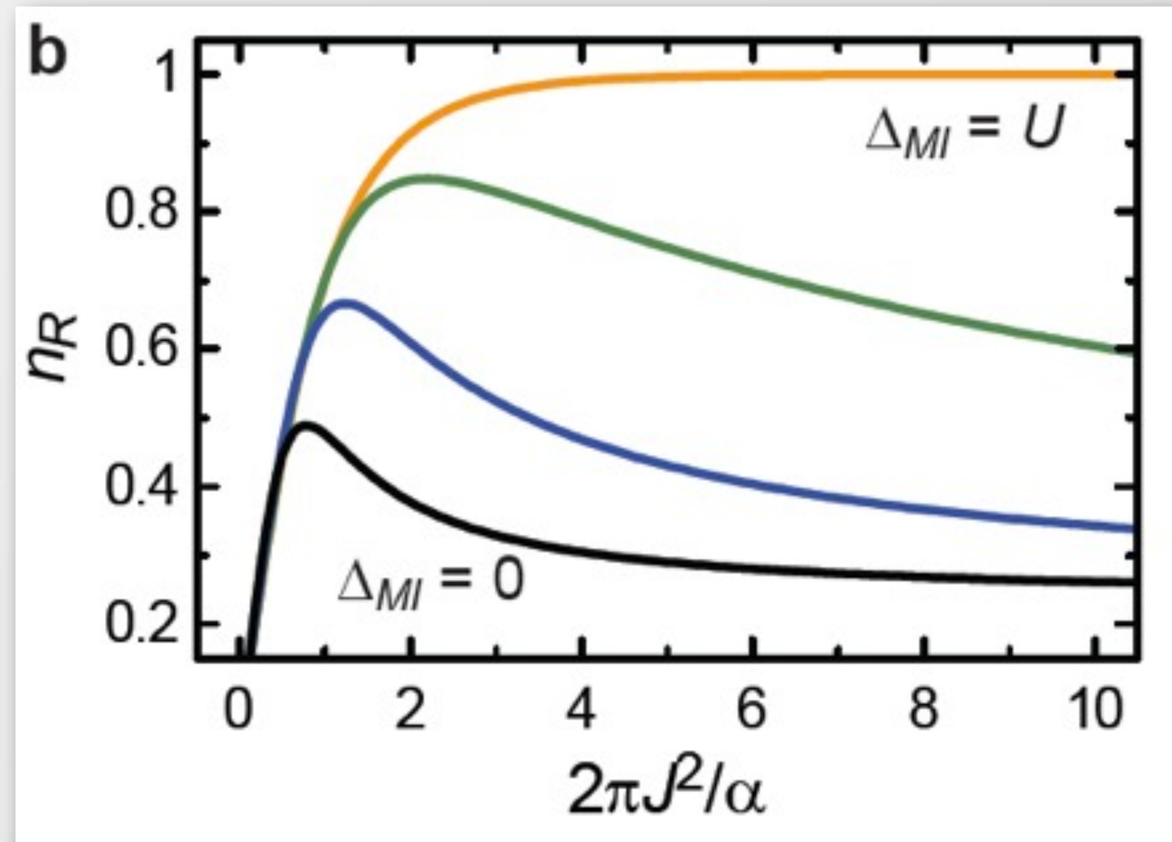


Inverse Sweep for 1D Bose Liquids

Breakdown of adiabaticity *for slower sweep rates!*



Experiment

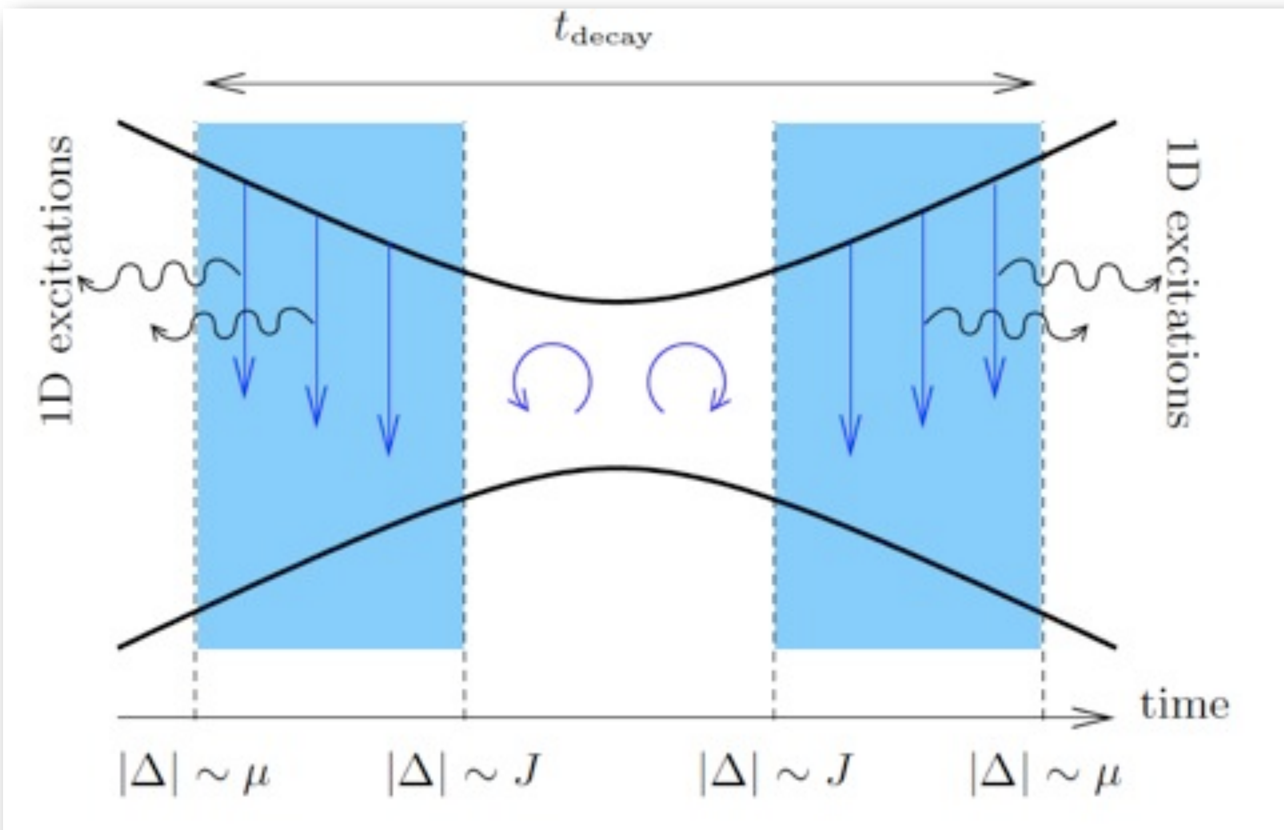


Theory model based on
Luttinger Liquid description
of 1D Bose liquid

An Intrinsic Bath: Coupling to Phonons

- 1D Bose gas: low-energy excitations (phonons)

  → "Intrinsic bath" enables decay for $J < |\Delta| < \mu$



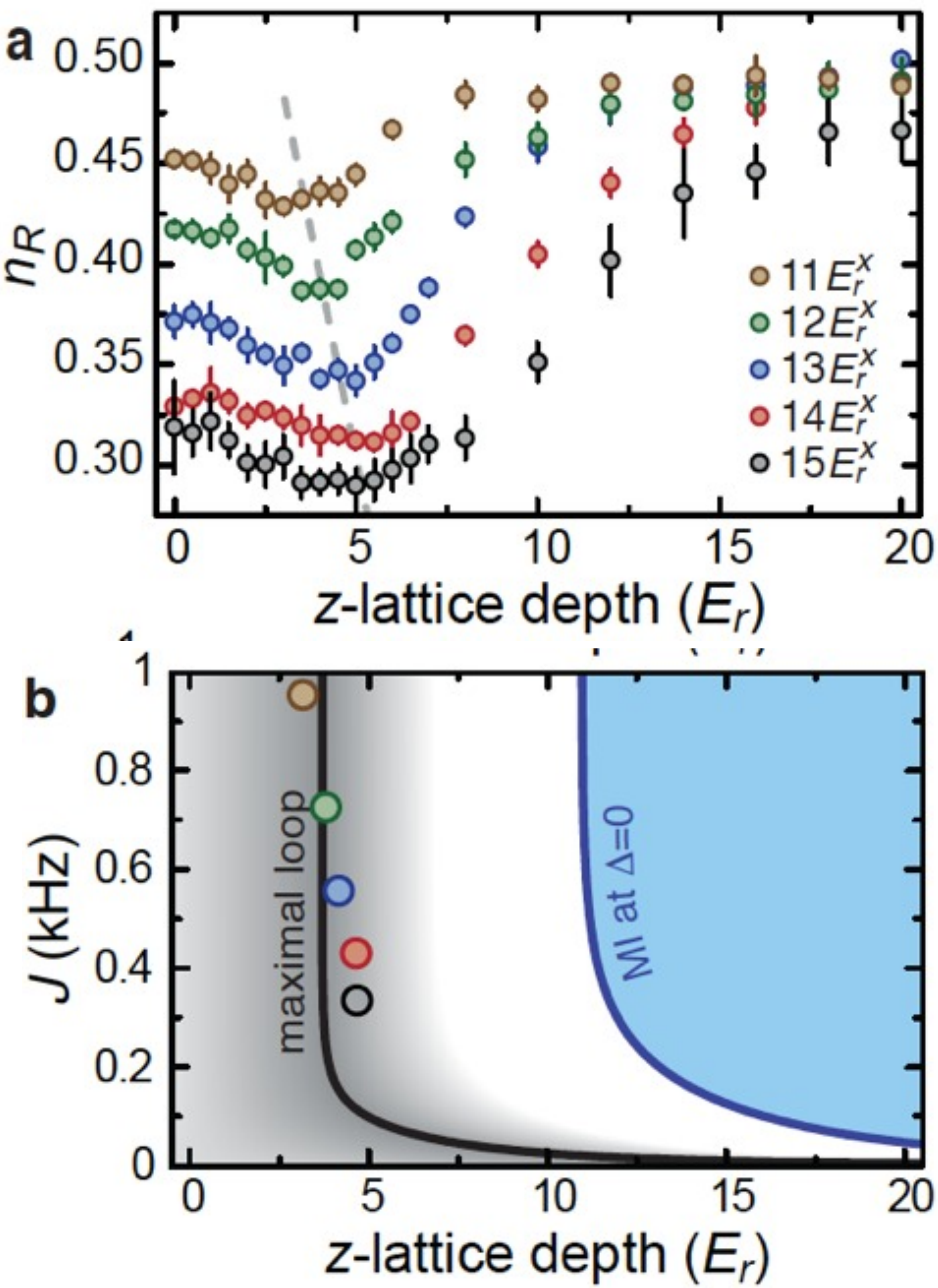
Decay of atoms and pairs into lower mode:

$$\dot{\rho} = -(\Gamma_1 + 2\Gamma_2)\rho^2 \equiv -\Gamma\rho^2$$

$$P_R = \rho_0/[1 + (2\rho_0/\alpha)\int_{\Delta_{lo}}^{\Delta_{hi}} d\Delta\Gamma(\Delta)]$$

- Slower sweep = more efficient decay.

Transfer Efficiency vs Interactions



Minimum in transfer efficiency

Maximum loop structure in energy spectrum

Further increase in z-lattice depth depletes condensate fraction **and** phonon decay modes are shut off at Mott transition !

Conclusion

Ground State Sweep

- Enhanced sweep rate by splitting single resonance to multiple resonances. Atoms ***tunnel one-by-one***, ⇨ each transition Bose-enhanced
- Depleting condensate by driving system intro correlated regime
  ⇨ Single particle LZ restored

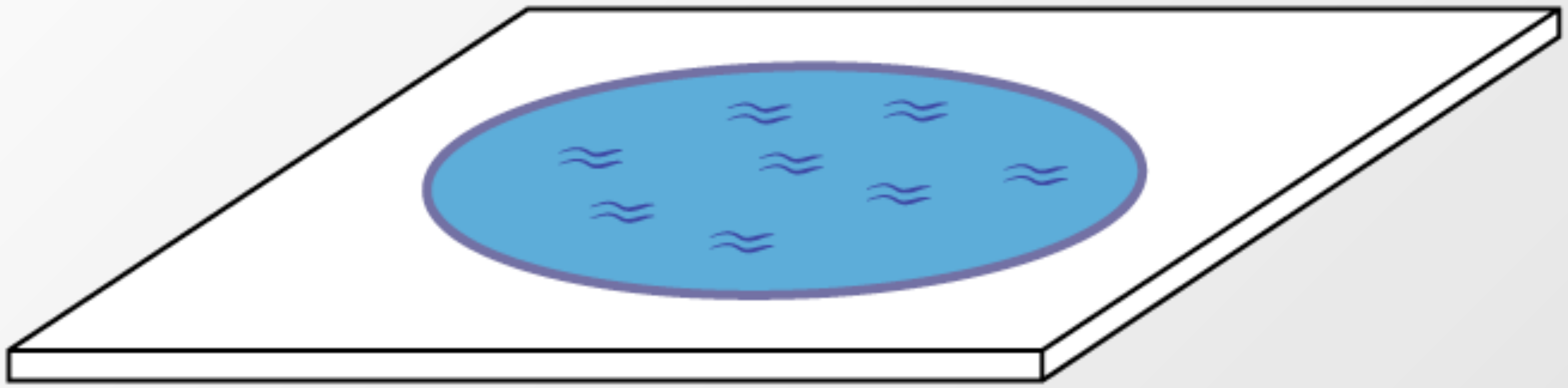
Inverse Sweep

- Loop structure develops for large non-linearities $U\Phi^2/J$
- **Catastrophic fate** for condensate entering loop during LZ sweep
- Breakdown of adiabaticity ⇨ slower sweep rates less transfer
- Fidelity in LZ sweep restored for vanishing loop and when phonon decay modes are shut off (MI transition in quantum ladder)

Single Atom Detection in a Lattice

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

Particle-by-Particle Imaging of a Quantum Liquid

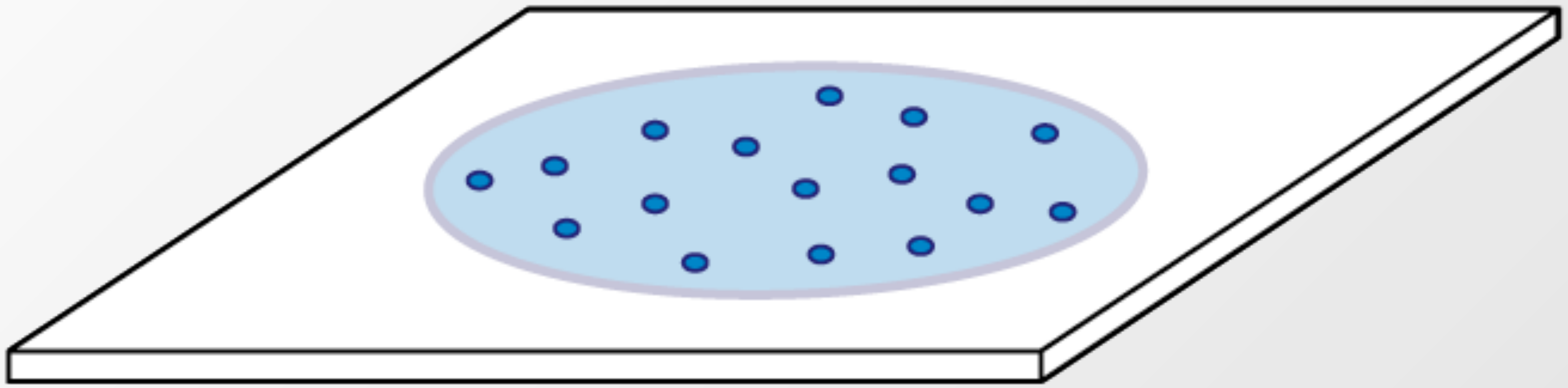


Correlated 2D Quantum Liquid

Goal: Detect Particle Positions in Single Snapshots!

In Lattice with Single Site Resolution and Spin Resolved

Particle-by-Particle Imaging of a Quantum Liquid



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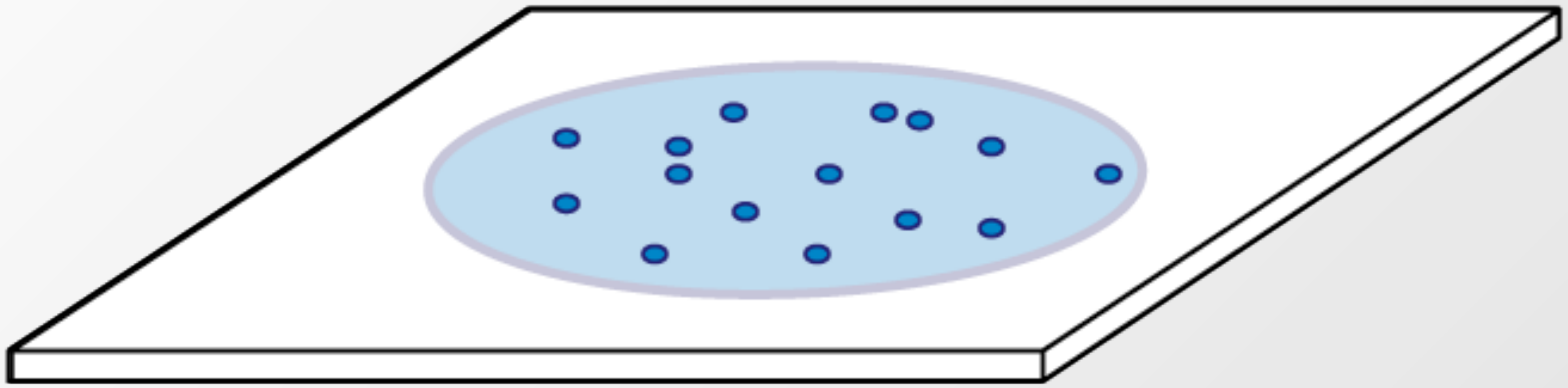
Particle-by-Particle Imaging of a Quantum Liquid



Correlated 2D Quantum Liquid

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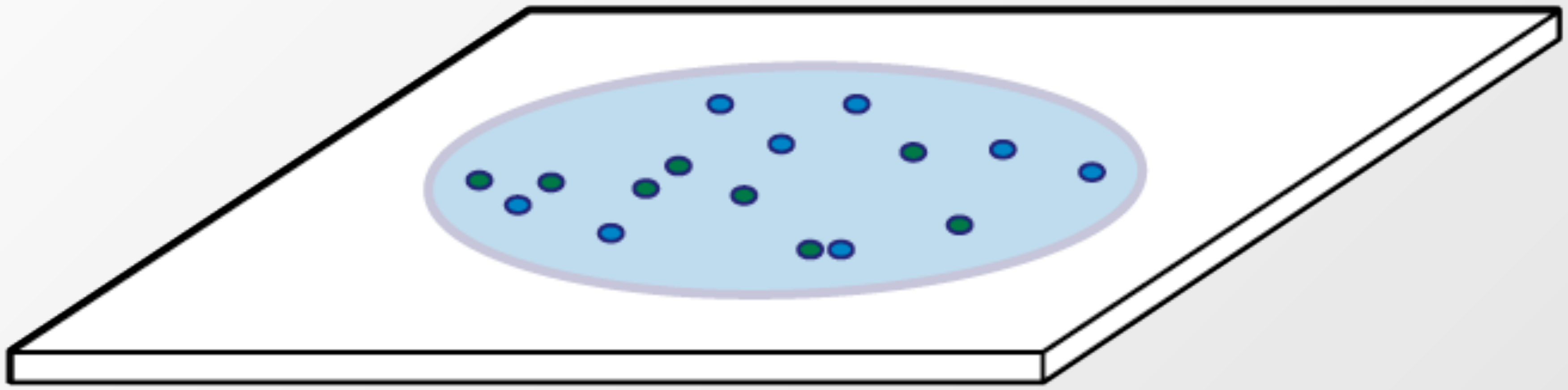
In Lattice with Single Site Resolution and Spin Resolved

Particle-by-Particle Imaging of a Quantum Liquid

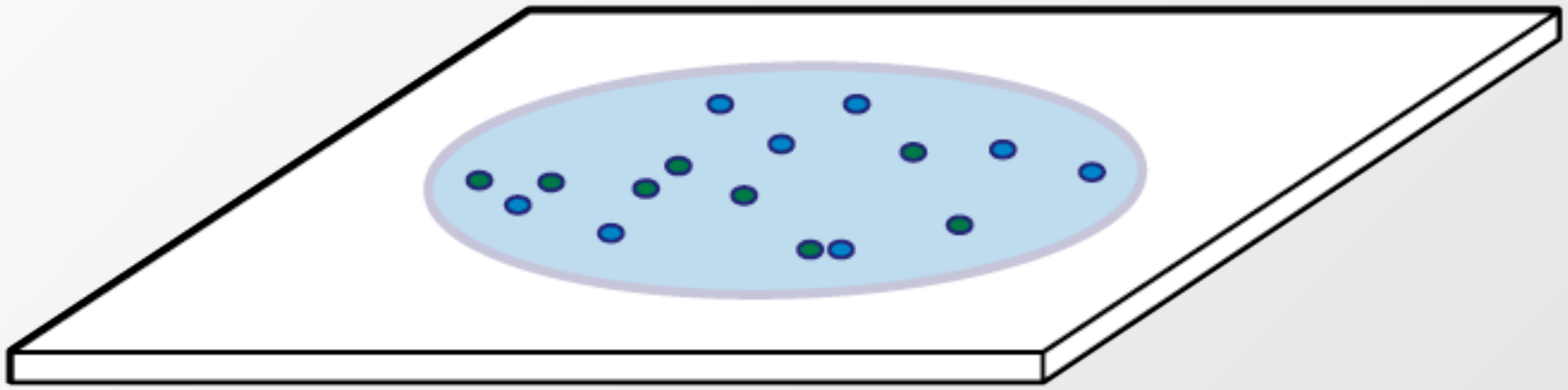


Correlated 2D Quantum Liquid

Goal: Detect Particle Positions in Single Snapshots!

In Lattice with Single Site Resolution and Spin Resolved

Particle-by-Particle Imaging of a Quantum Liquid



Correlated 2D Quantum Liquid

Goal: Detect Particle Positions in Single Snapshots!

In Lattice with Single Site Resolution and Spin Resolved

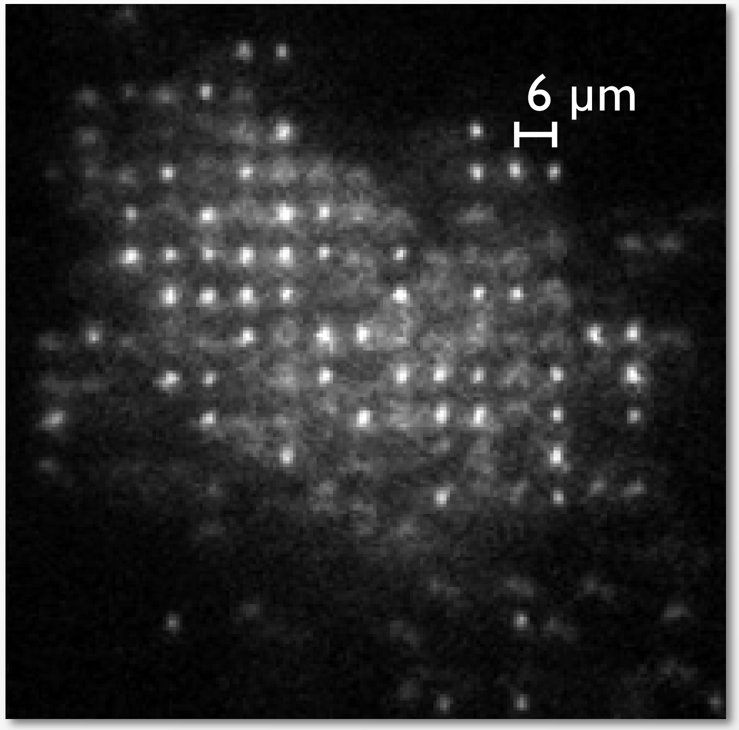
Measureable Quantities: Particle number fluctuations, compressibilities, density-density correlations, string order.....

$$n_\sigma(\mathbf{R}) \qquad \langle n_\sigma(\mathbf{R}) n_{\sigma'}(\mathbf{R}')\rangle \qquad \langle \mathbf{S}_i \mathbf{S}_j \mathbf{S}_k \ldots \rangle$$

singe site resolved!

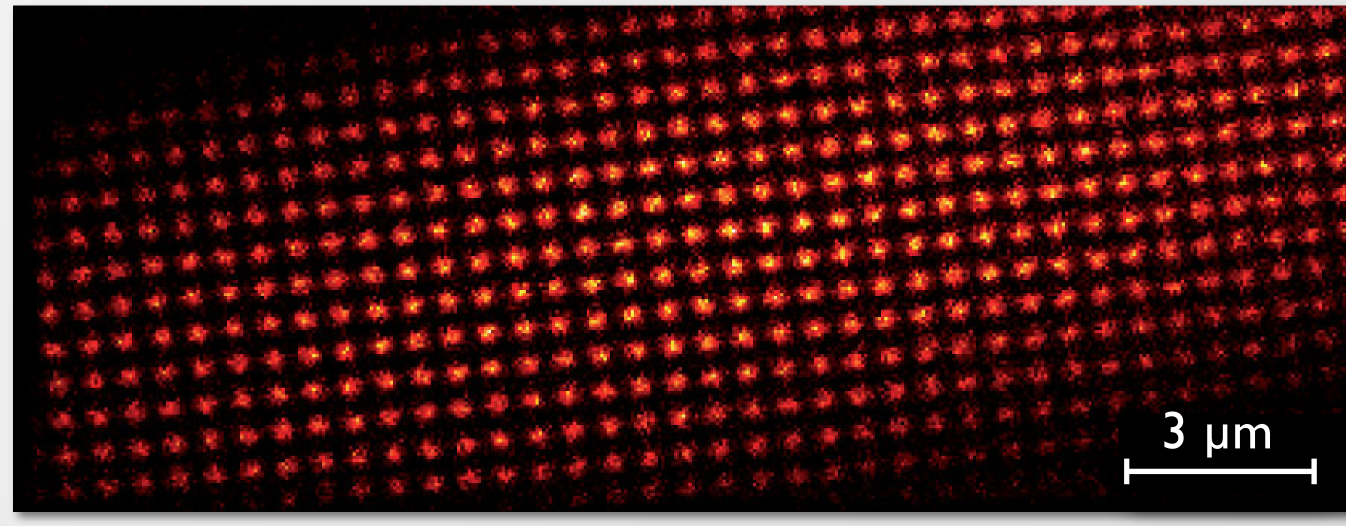
State of the Art

David Weiss, Pennsylvania State University
Nature Physics 3, 556 (2007)



fluorescence imaging

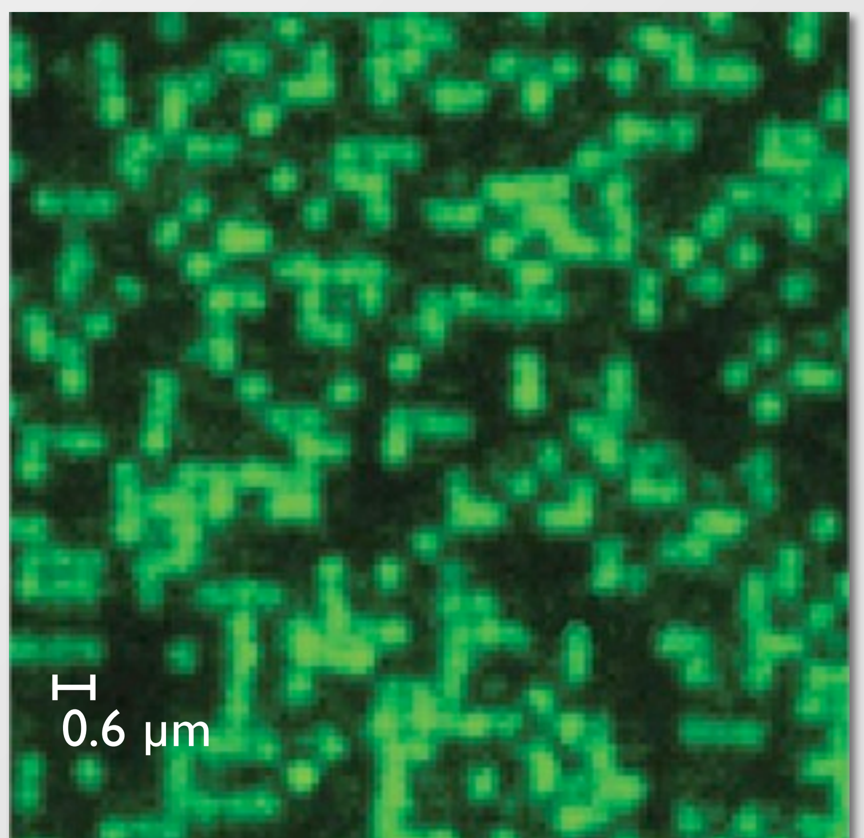
Herwig Ott, Mainz University
Phys. Rev. Lett. 103, 080404 (2009)



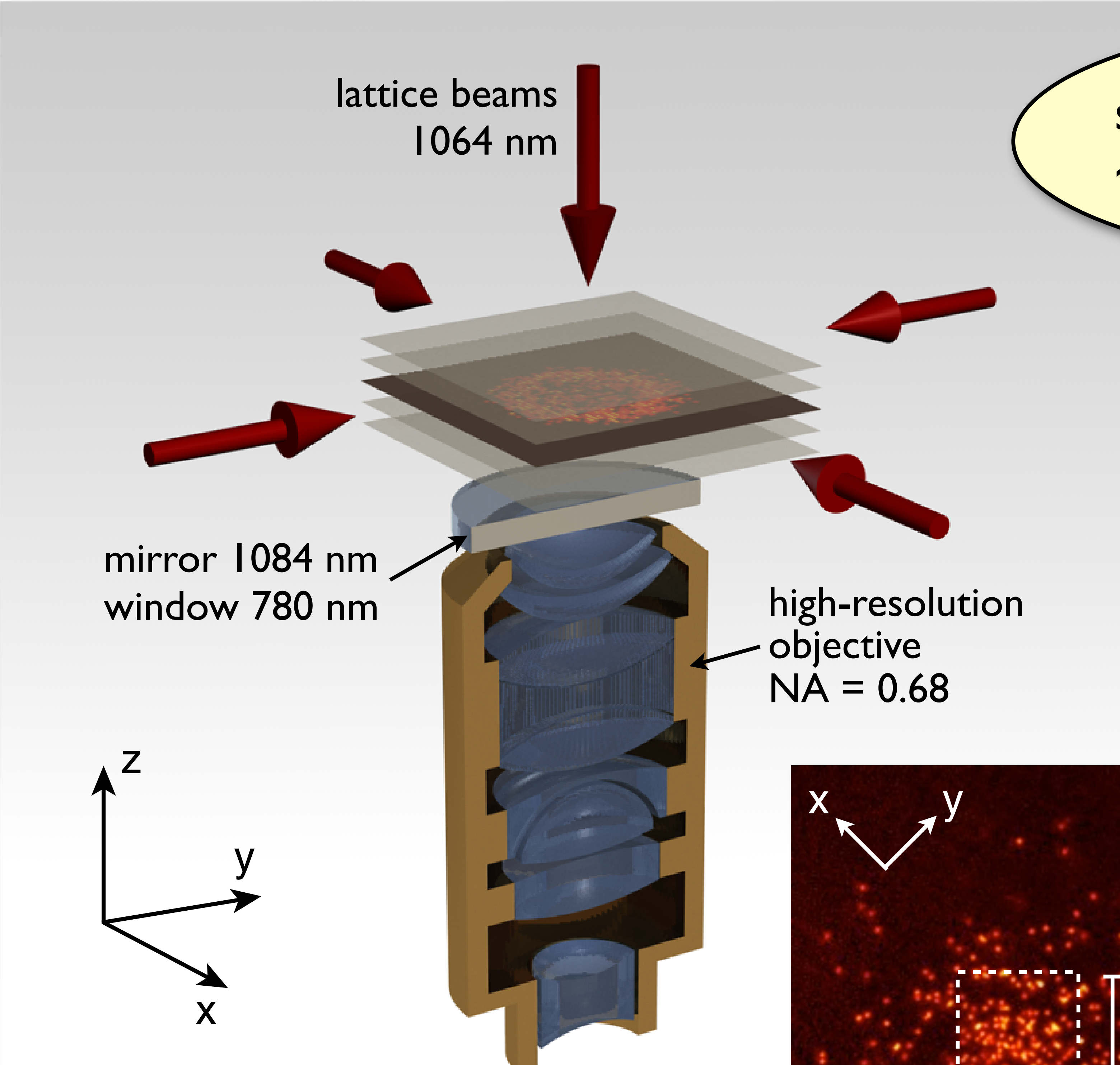
electron microscopy

Markus Greiner, Harvard
Nature 462, 74 (2009)

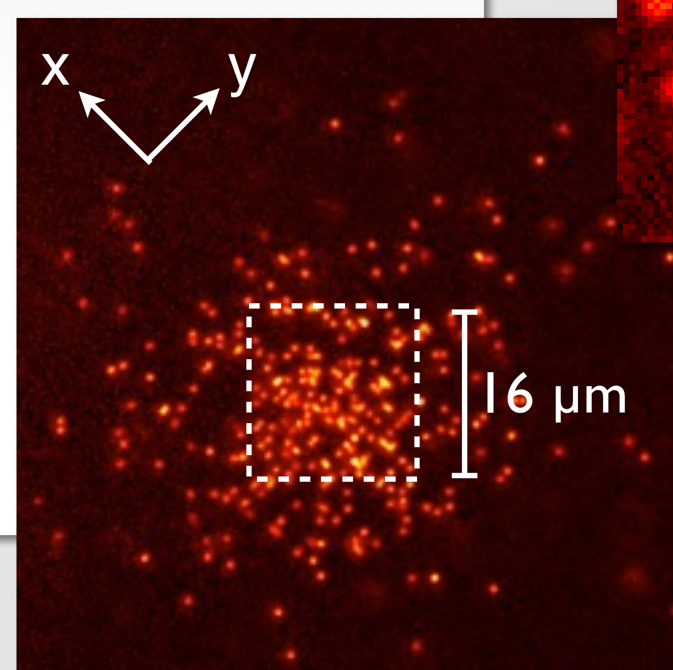
fluorescence imaging

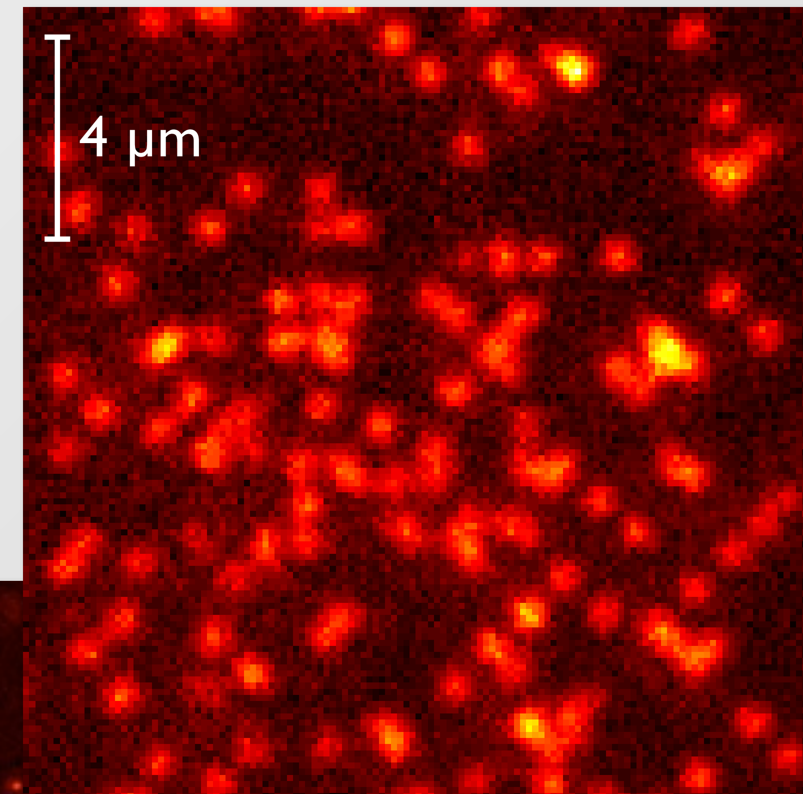


Experimental Setup



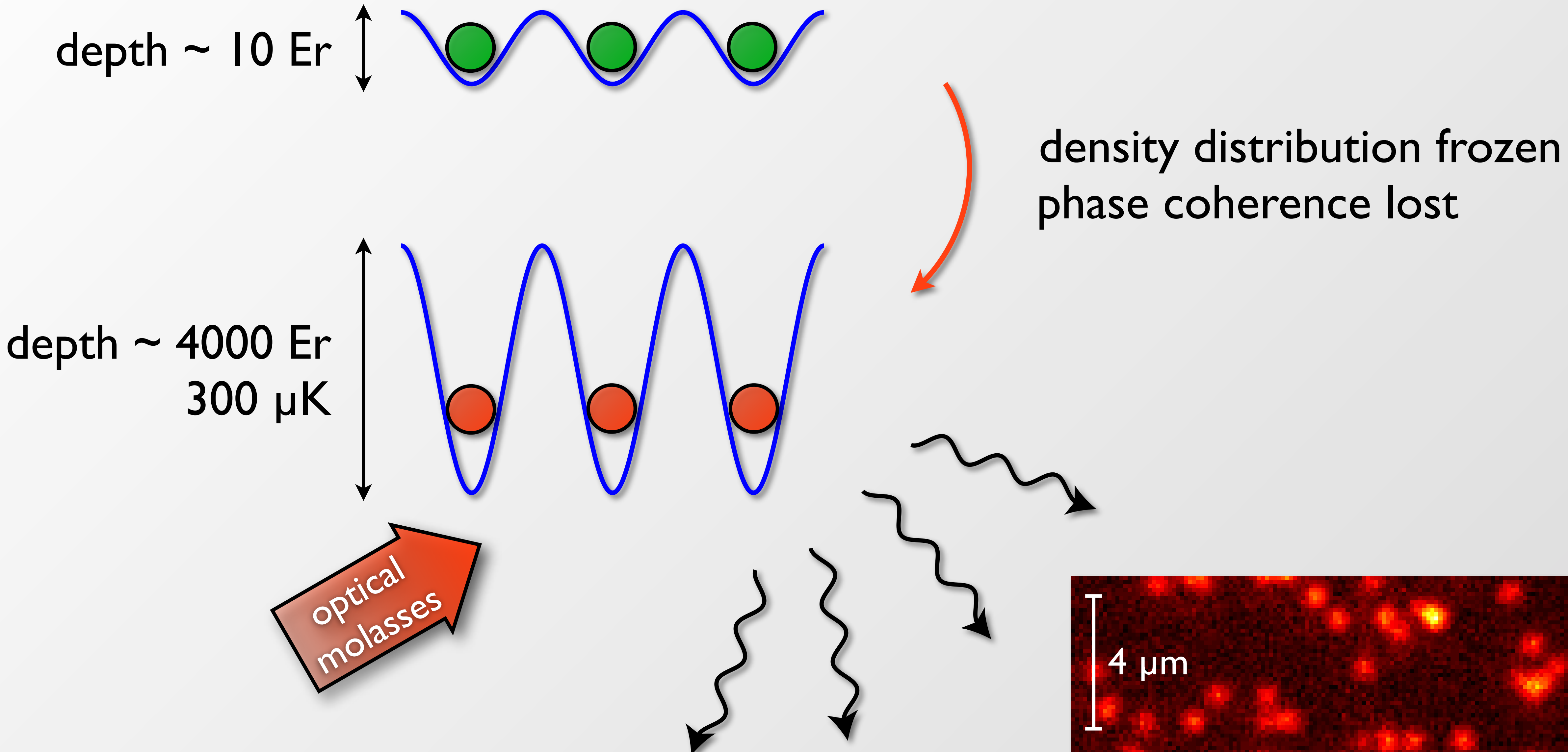
single 2D degenerate gas
~ 1000 ^{87}Rb atoms (bosons)



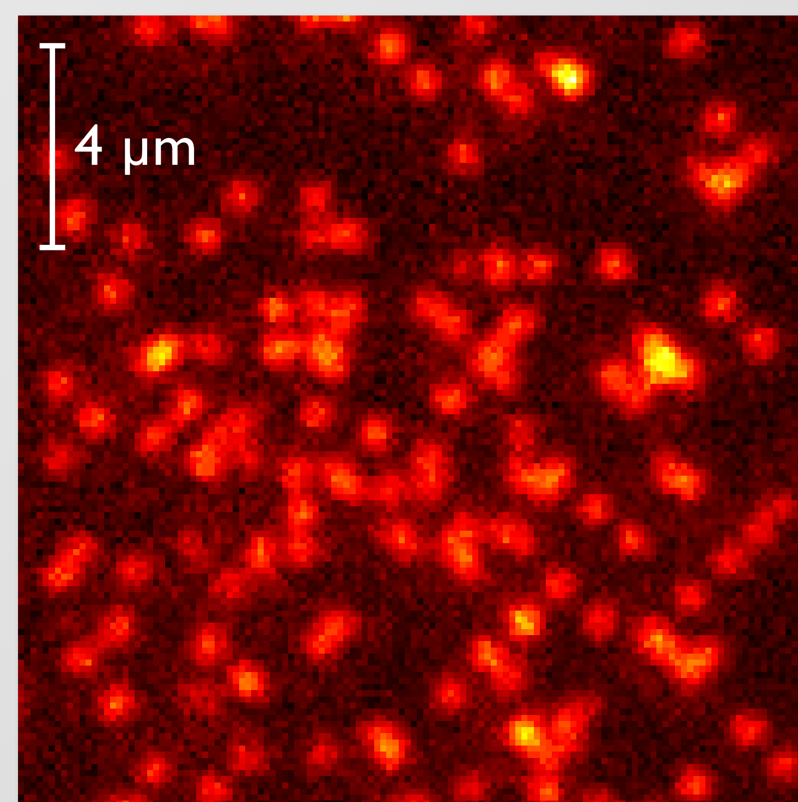


resolution of the imaging system: ~700 nm

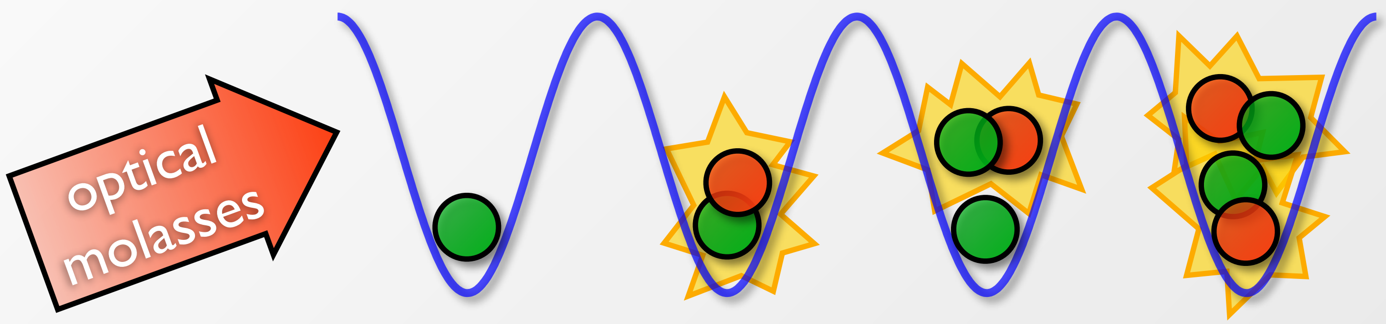
Fluorescence imaging



fluorescence rate / atom: 60 kHz
~ 5000 photons / atom collected in 900ms



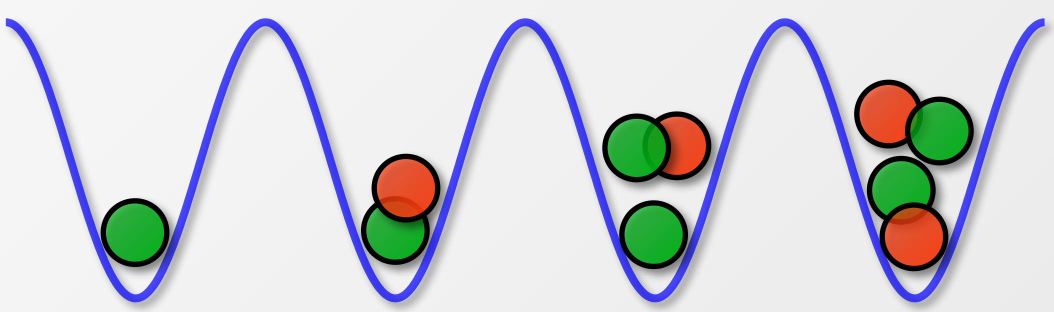
Parity projection



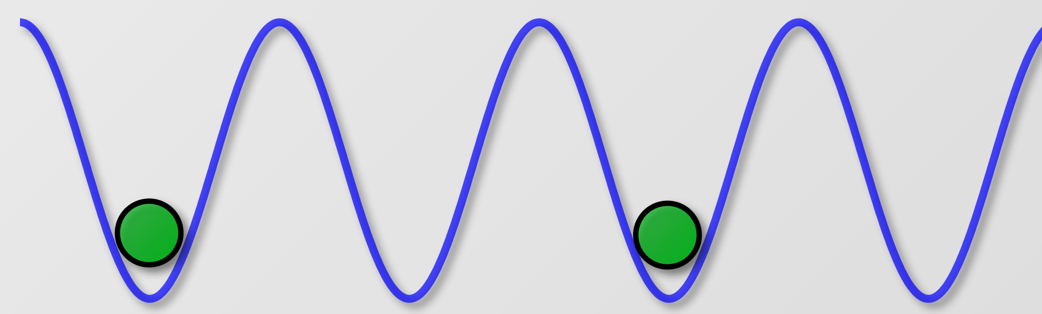
dePue *et al.*, PRL **82**, 2262 (1999)

Light-induced collisions

initial density distribution



measured density distribution



measured occupation: $n_{\text{det}} = \text{mod}_2 n$

measured variance: $\sigma^2_{\text{det}} = \langle n^2_{\text{det}} \rangle - \langle n_{\text{det}} \rangle^2$

parity projection $\Rightarrow$ $\langle n^2_{\text{det}} \rangle = \langle n_{\text{det}} \rangle$

see also E. Kapit & E. Mueller, arXiv:1004.4903

Parity projection

Weakly interacting BEC

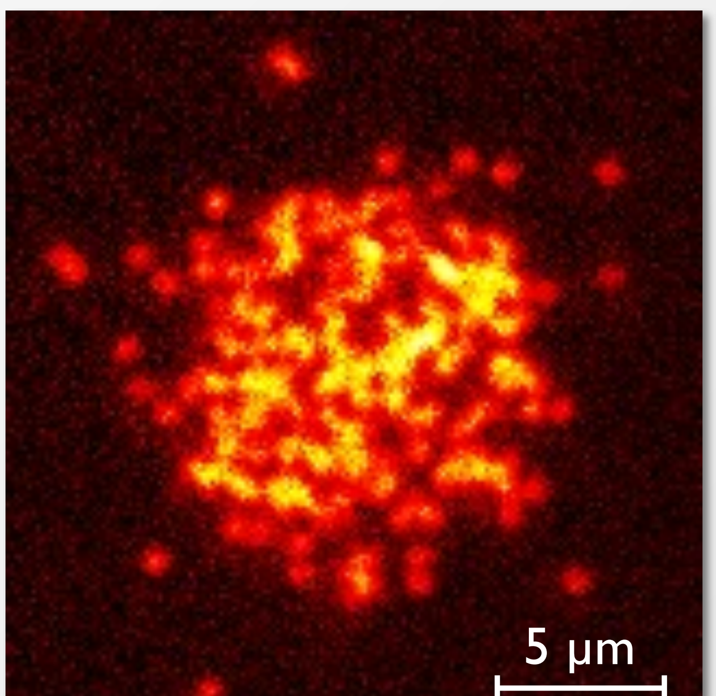
$$|\alpha\rangle = e^{-|\alpha^2|/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

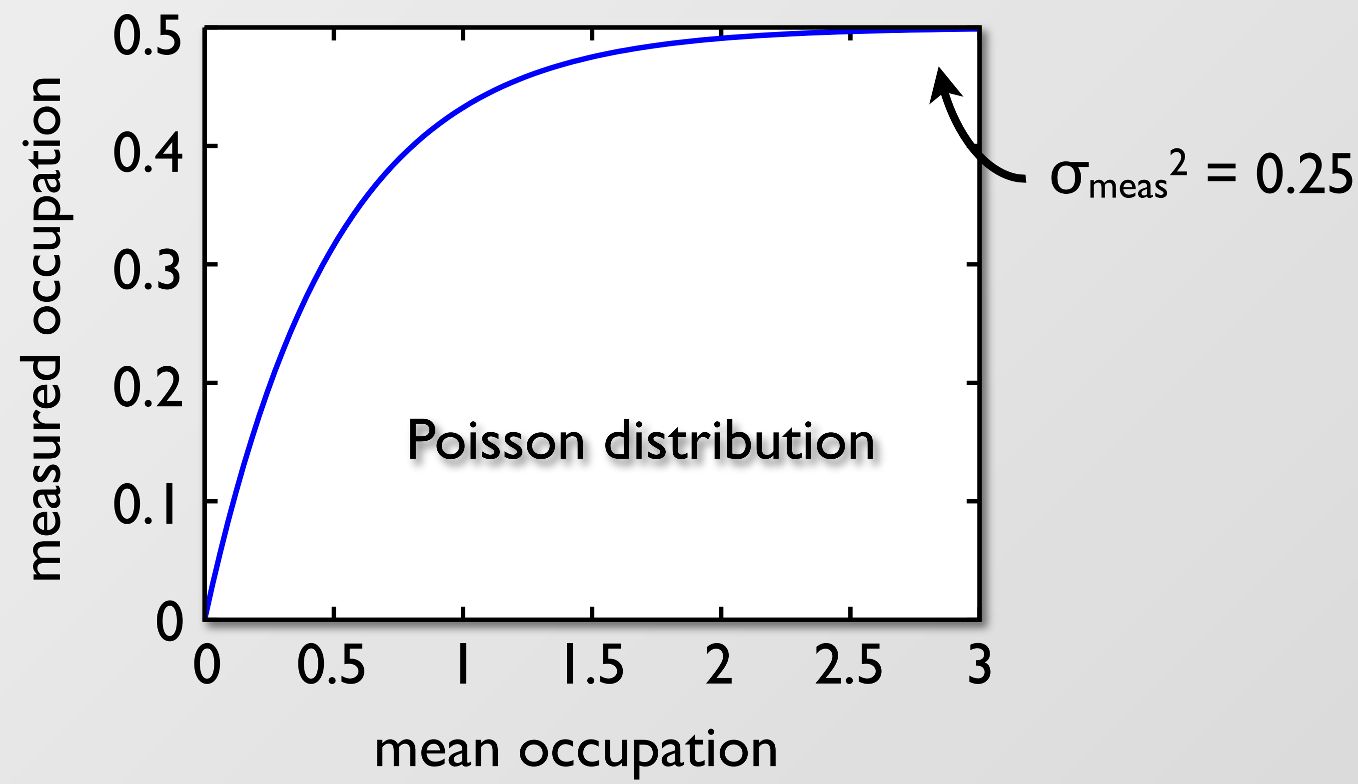
Coherent State

$$p_n = \frac{e^{-\bar{n}} \bar{n}^n}{n!}$$

On-Site Poissonian
atom number distribution

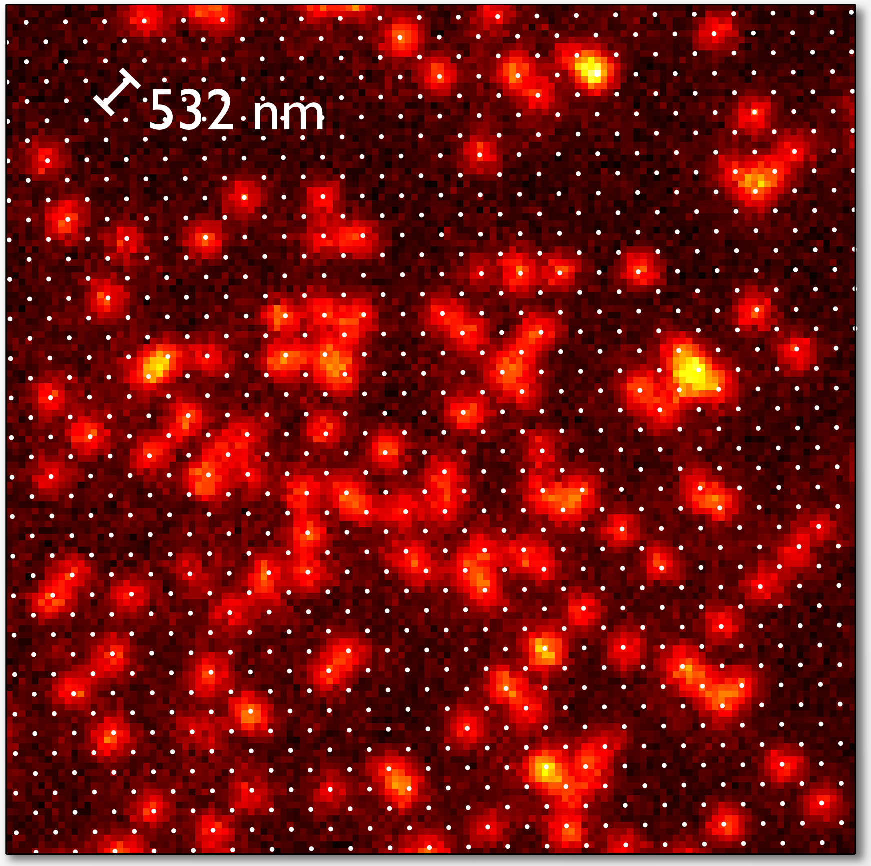
Measured density of a quasi-BEC

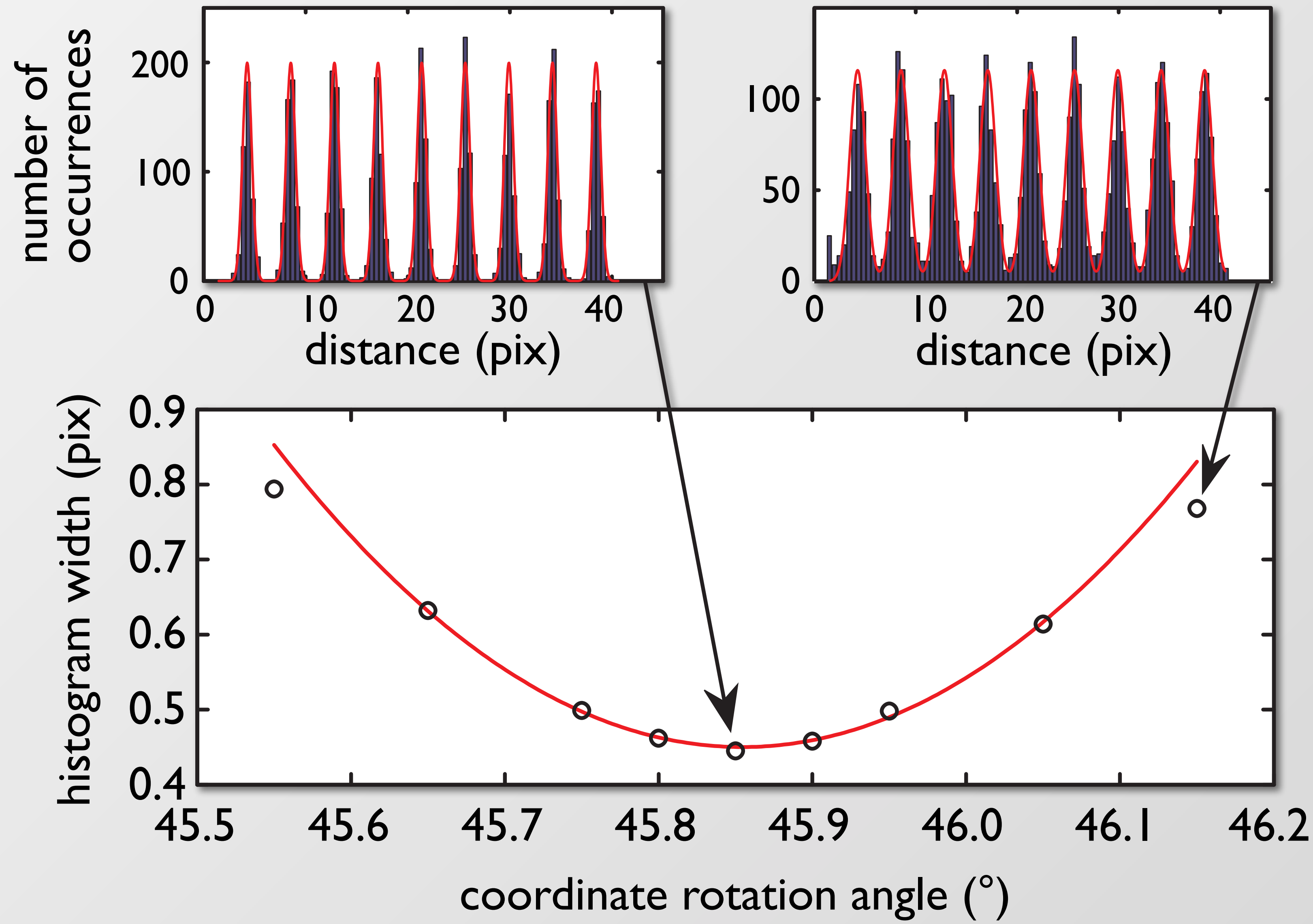




$$\bar{n}_{\mathrm{det}} = \sum_n p_n \,\mathrm{mod}_2 n = \sum_{n\,\mathrm{odd}} p_n = \frac{1}{2}\left(1 - e^{-2\bar{n}}\right)$$

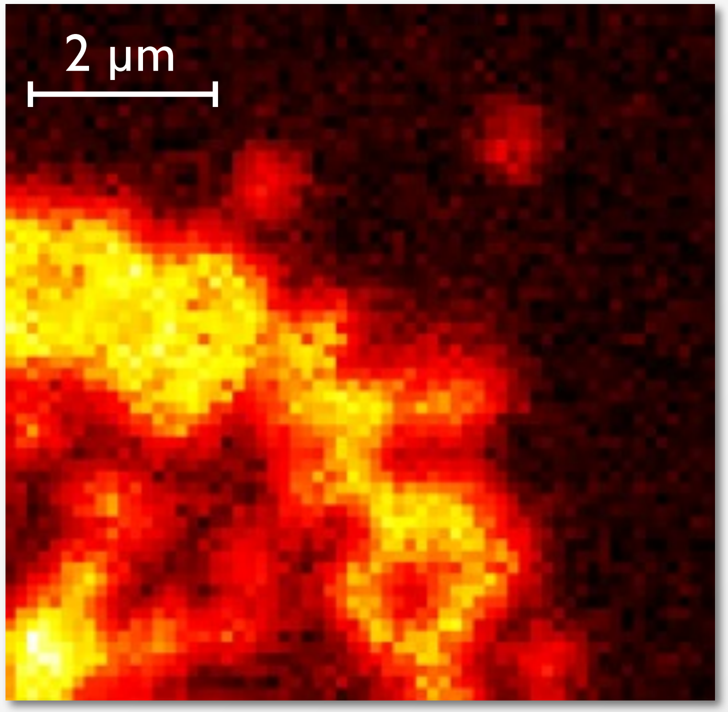
Revealing the lattice structure



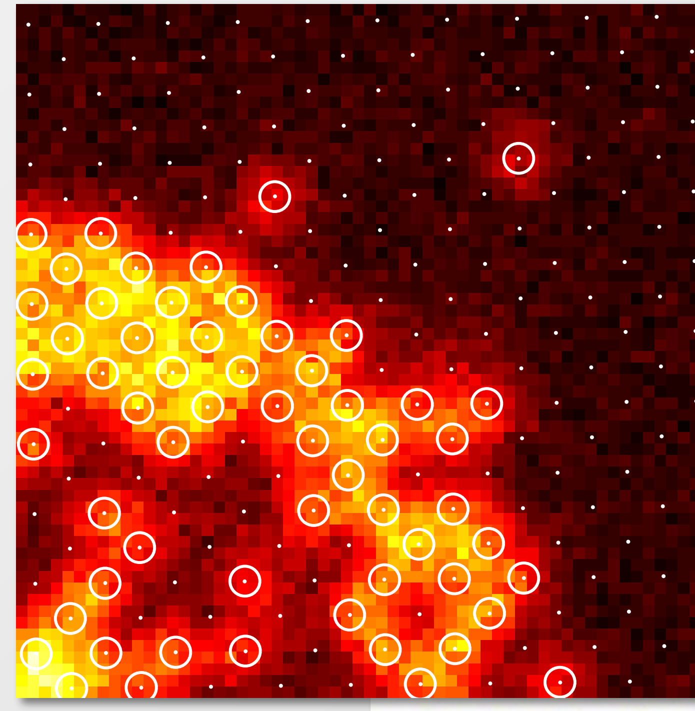


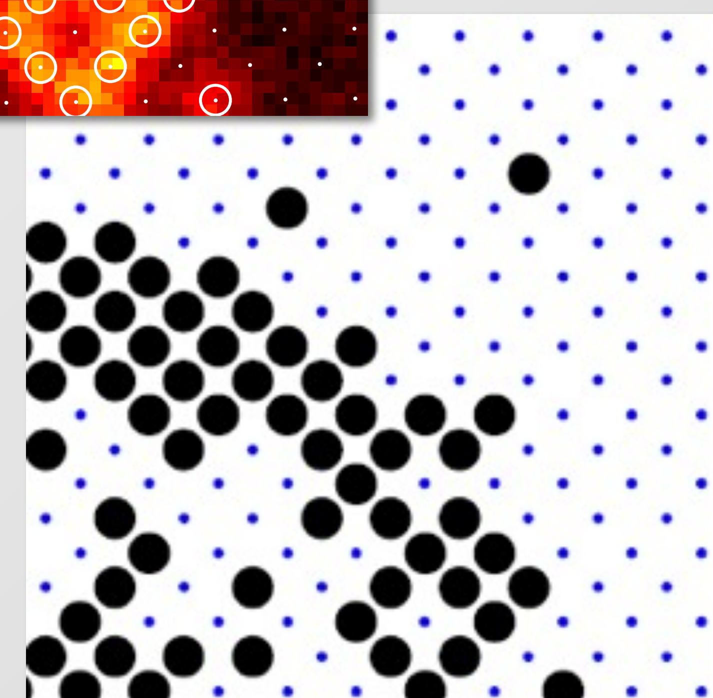
Averaging over several shots allows to determine lattice angles with < 10^{-3} precision

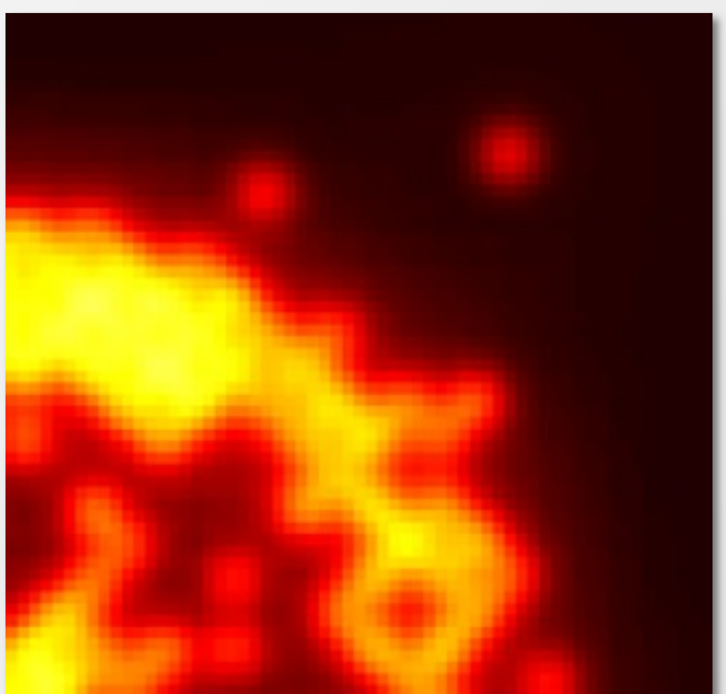
Reconstruction of site occupation



Reconstruction algorithm







Digitized image convoluted with point-spread function

digitized image
no experimental noise

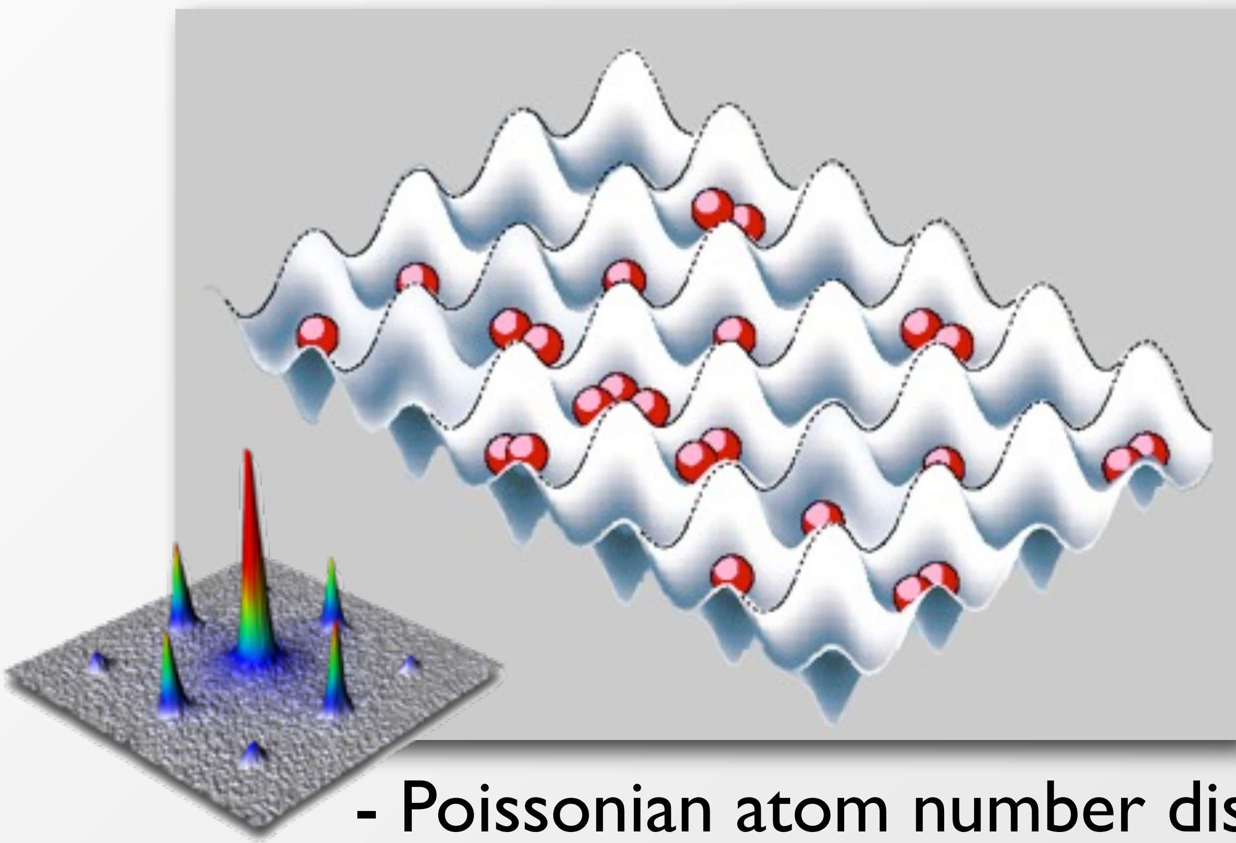
In-Situ Imaging of a Mott Insulator

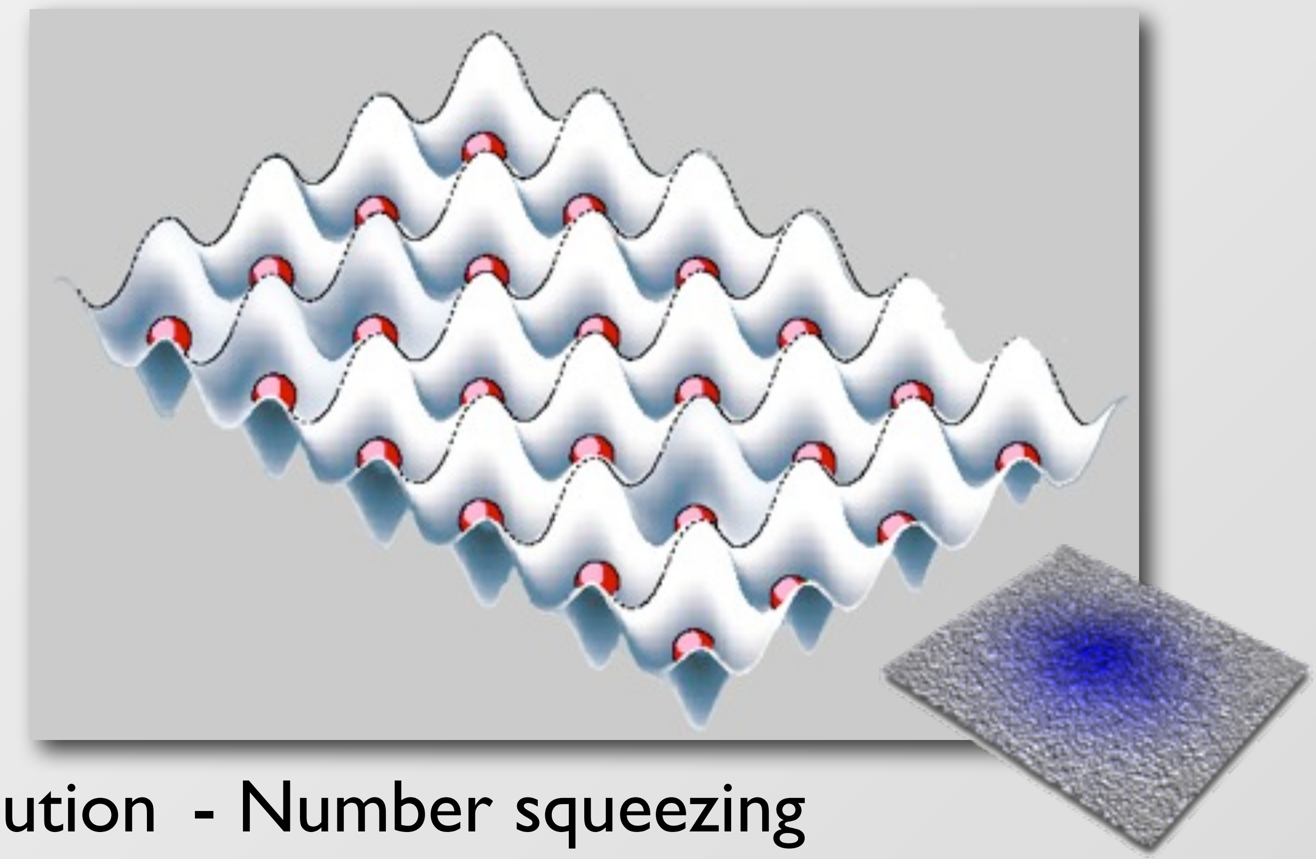
Sherson et al. Nature **467**, 68 (2010),
see also Bakr et al. Nature (2009) & Bakr et al. Science (2010)

Mott Insulators

Superfluid

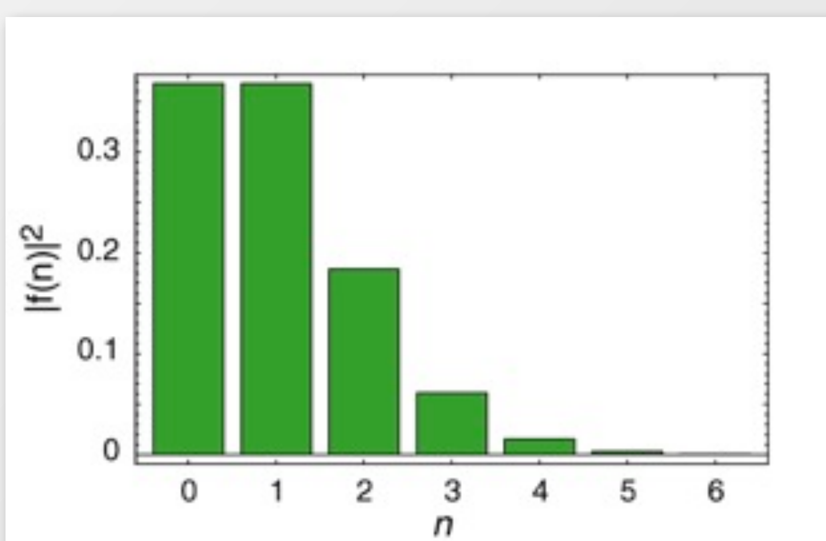
Mott-Insulator

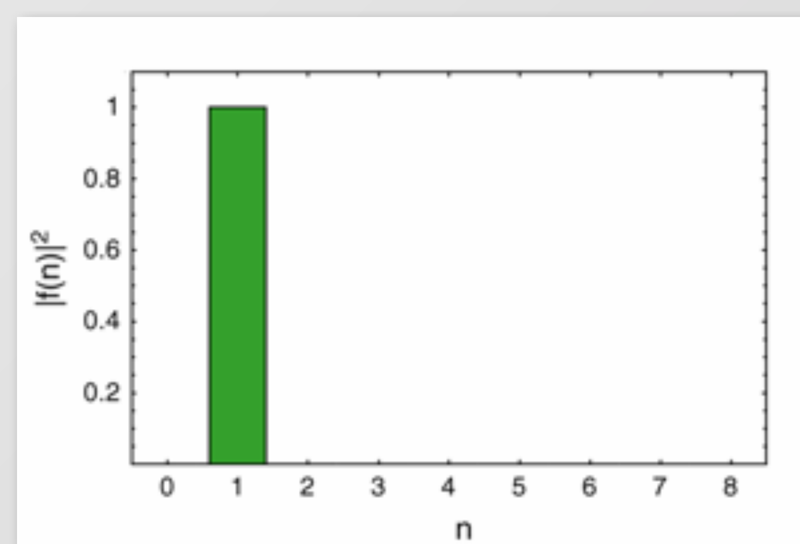




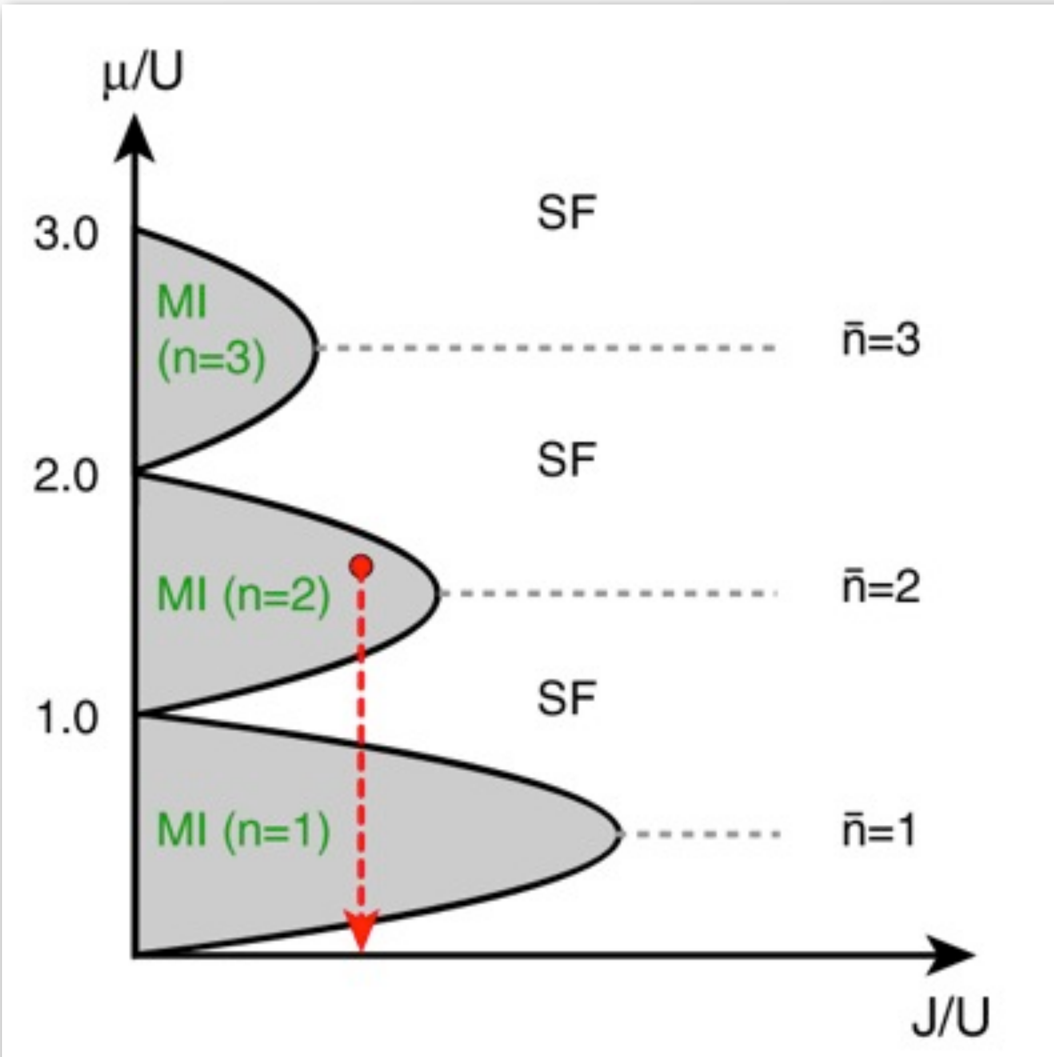
- Poissonian atom number distribution
- Long range phase coherence

- Number squeezing
- No phase coherence

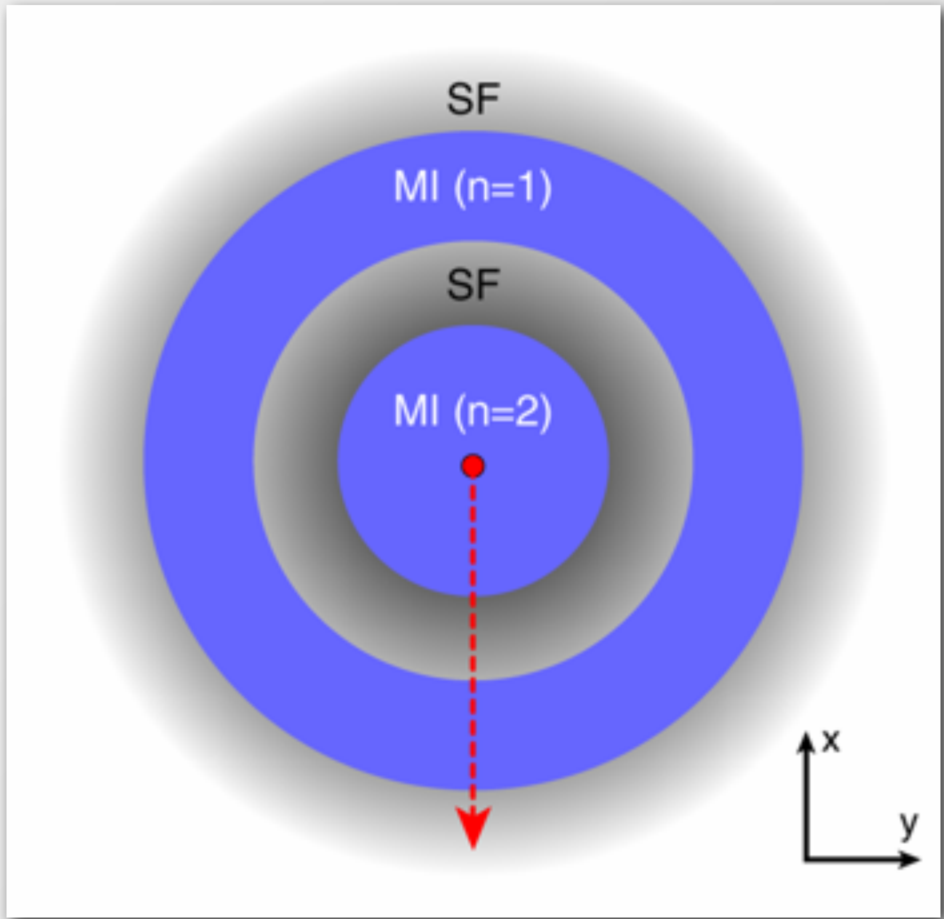




Bose-Hubbard Phase Diagram



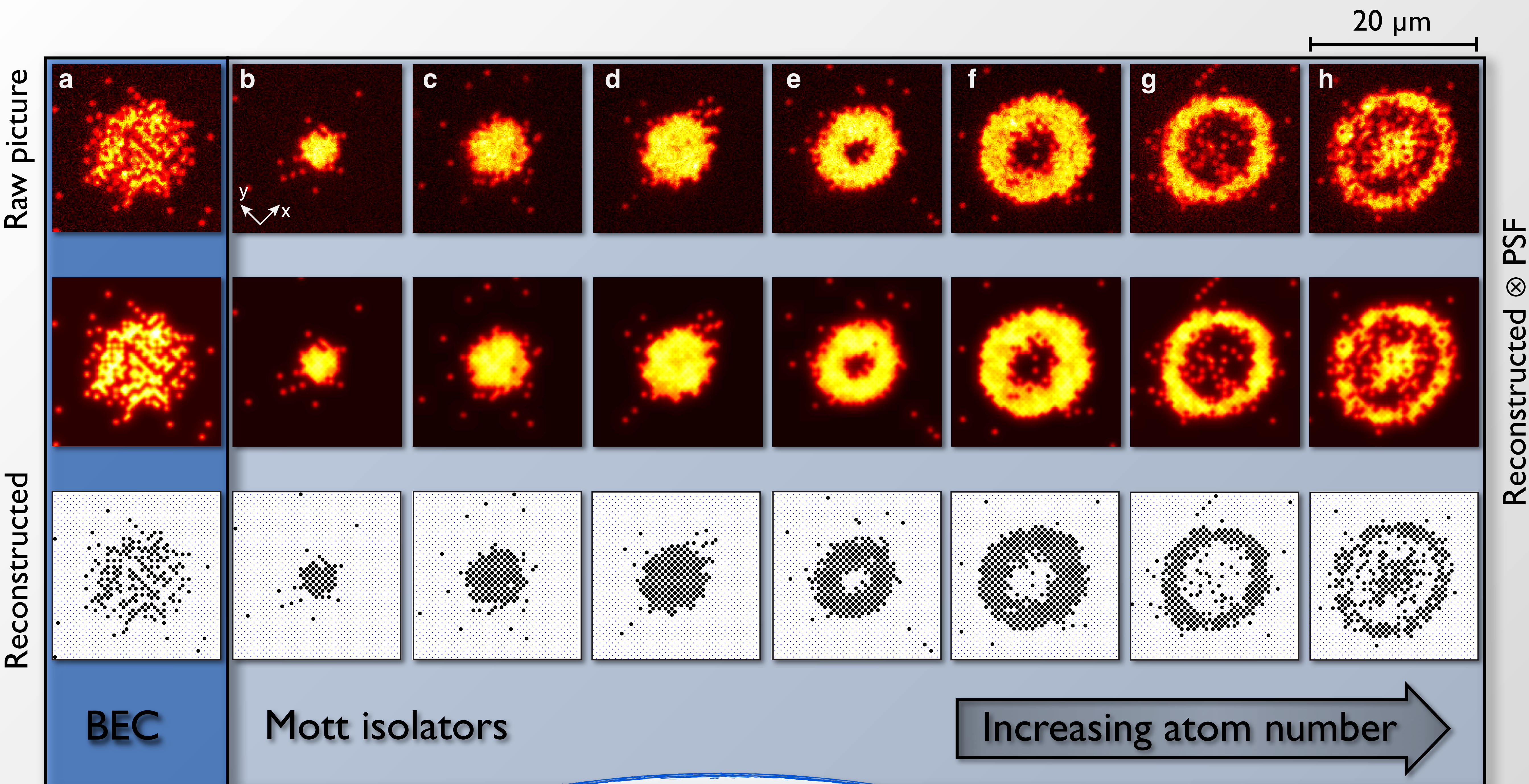
M.P.A. Fisher *et al.* PRB **40**, 546 (1989)
D. Jaksch *et al.* PRL **81**, 3108 (1998)



Inhomogeneous system:
effective local chemical potential

$$\mu_{loc} = \mu - \varepsilon_i$$

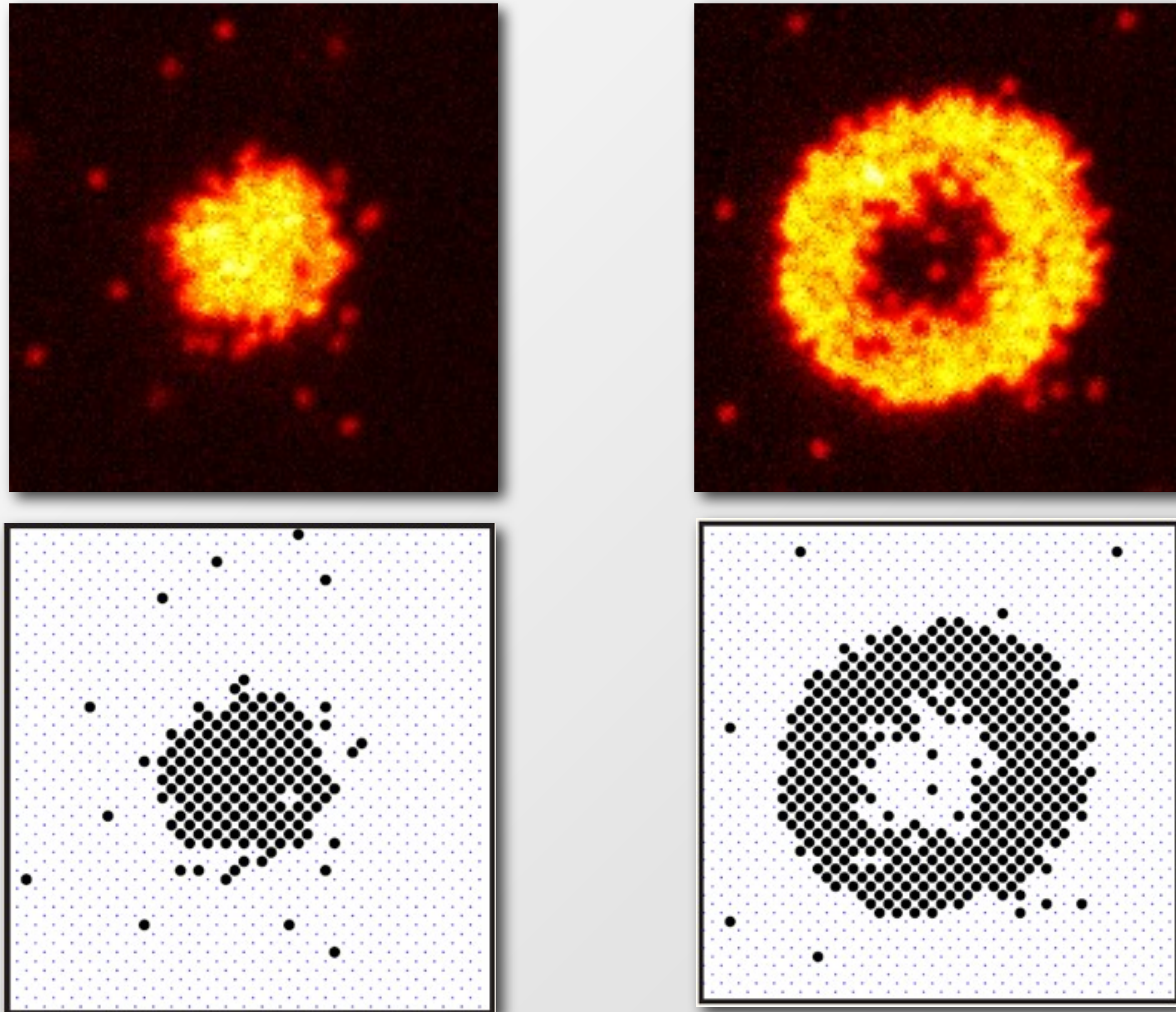
In-situ observation of a Mott insulator



for the Mott insulators: U/J ~ 300 (critical U/J ~ 16)

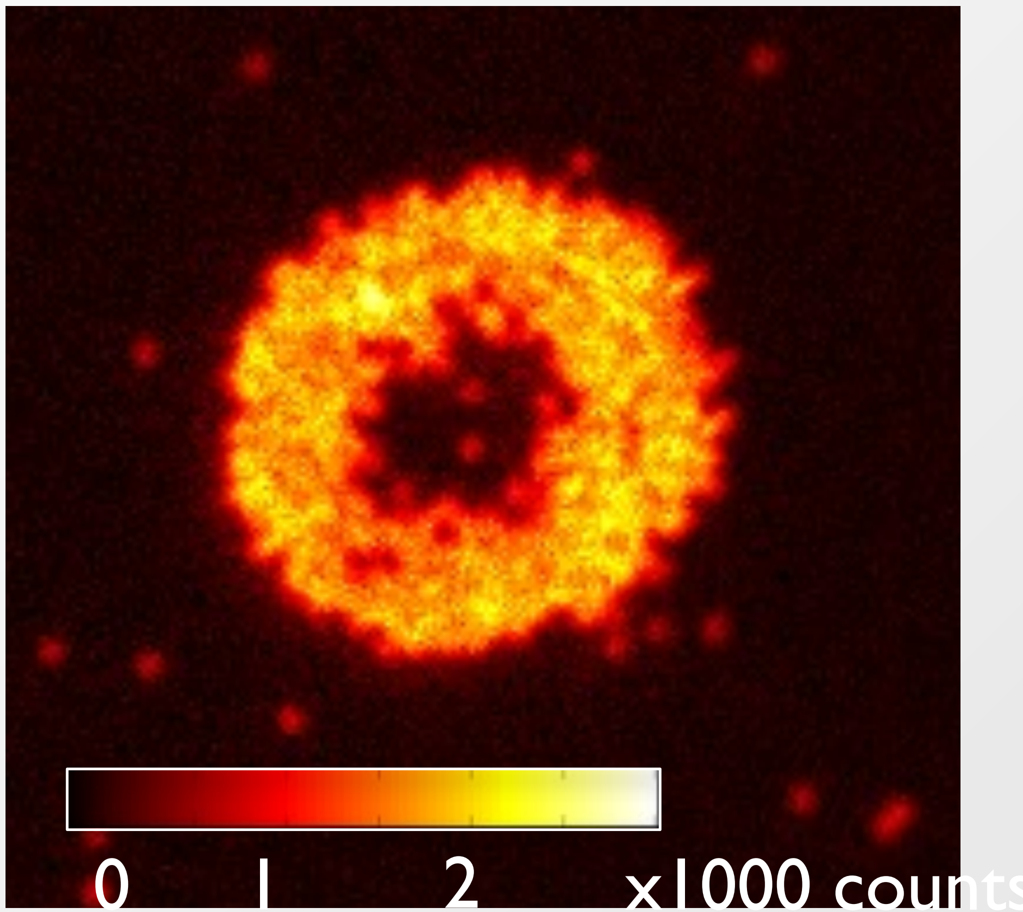
⇒ only thermal fluctuations

Images of Mott Insulators



Mott Insulators

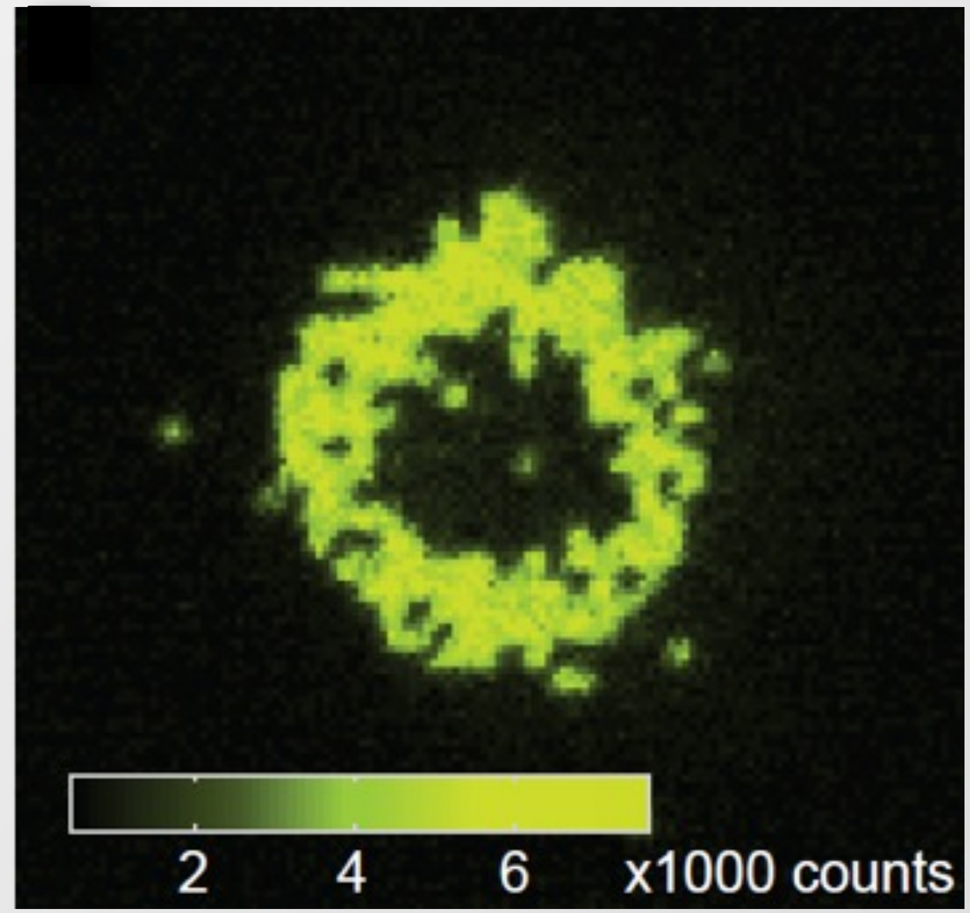
Garching



Sherson et al., Nature (2010)

$T = 0.071(5)\ U/k_B$

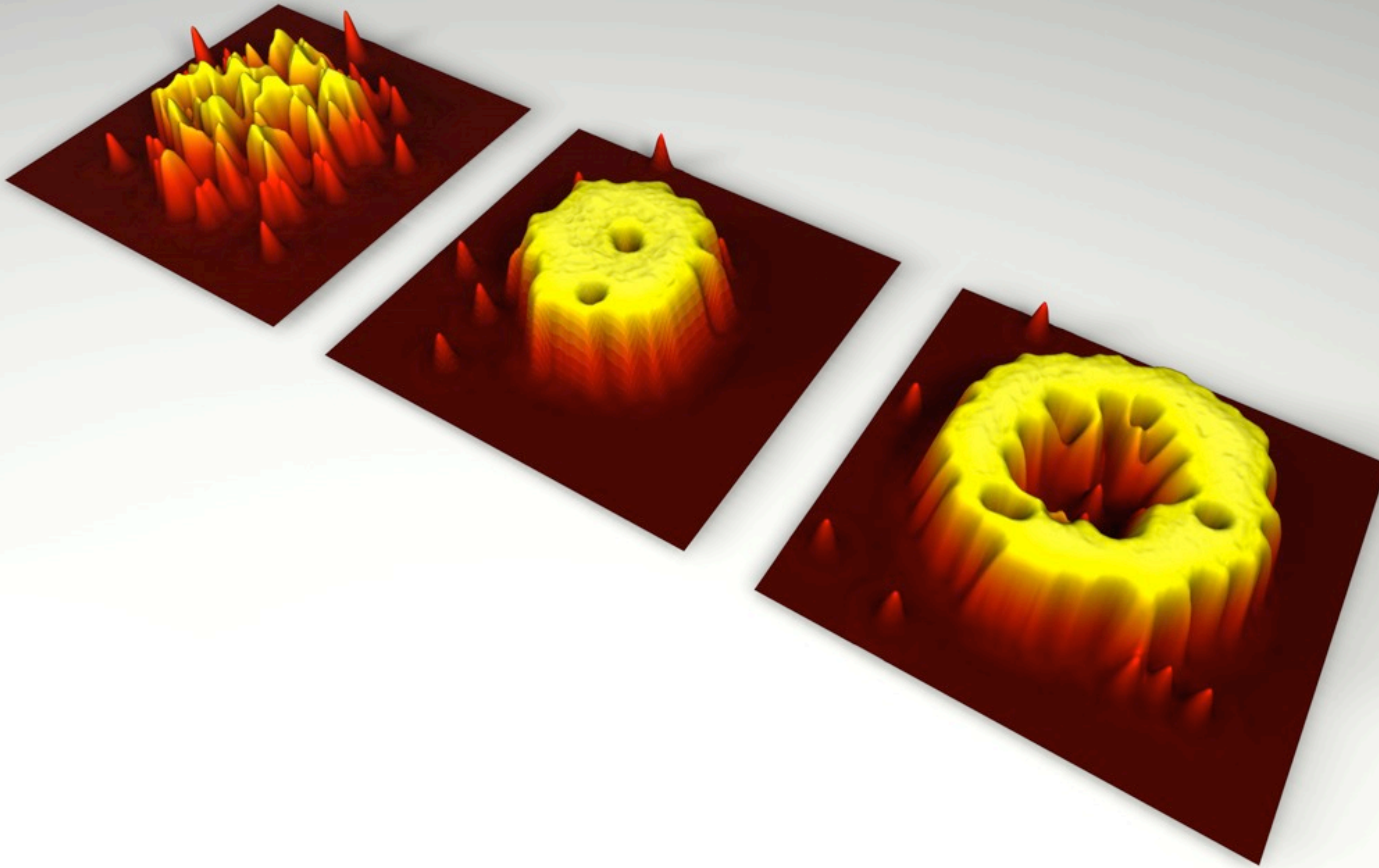
Harvard



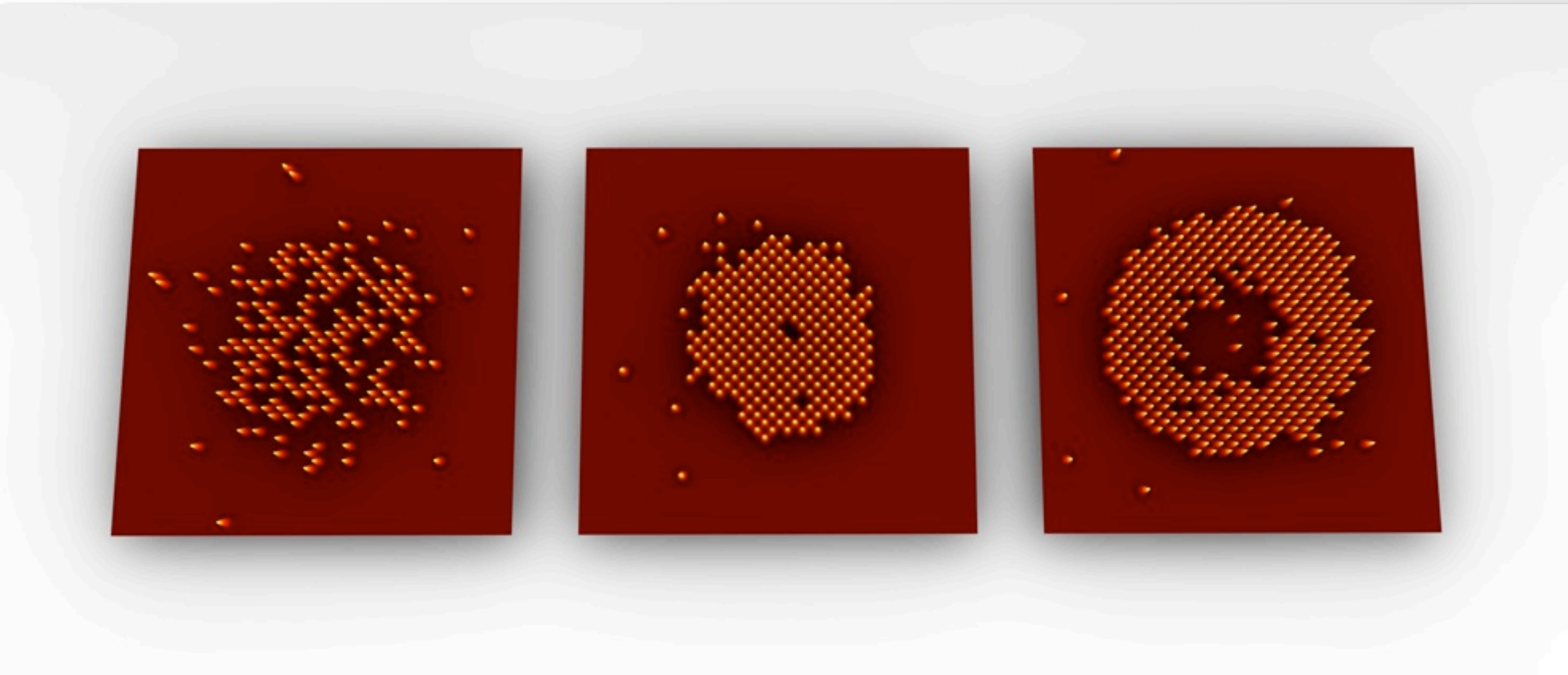
Bakr et al., Science (2010)

$T \sim 0.15\ U/k_B$

Both MIs are well below the melting temperature of $T = 0.2\ U/k_B$



Reconstructed Atom Distribution



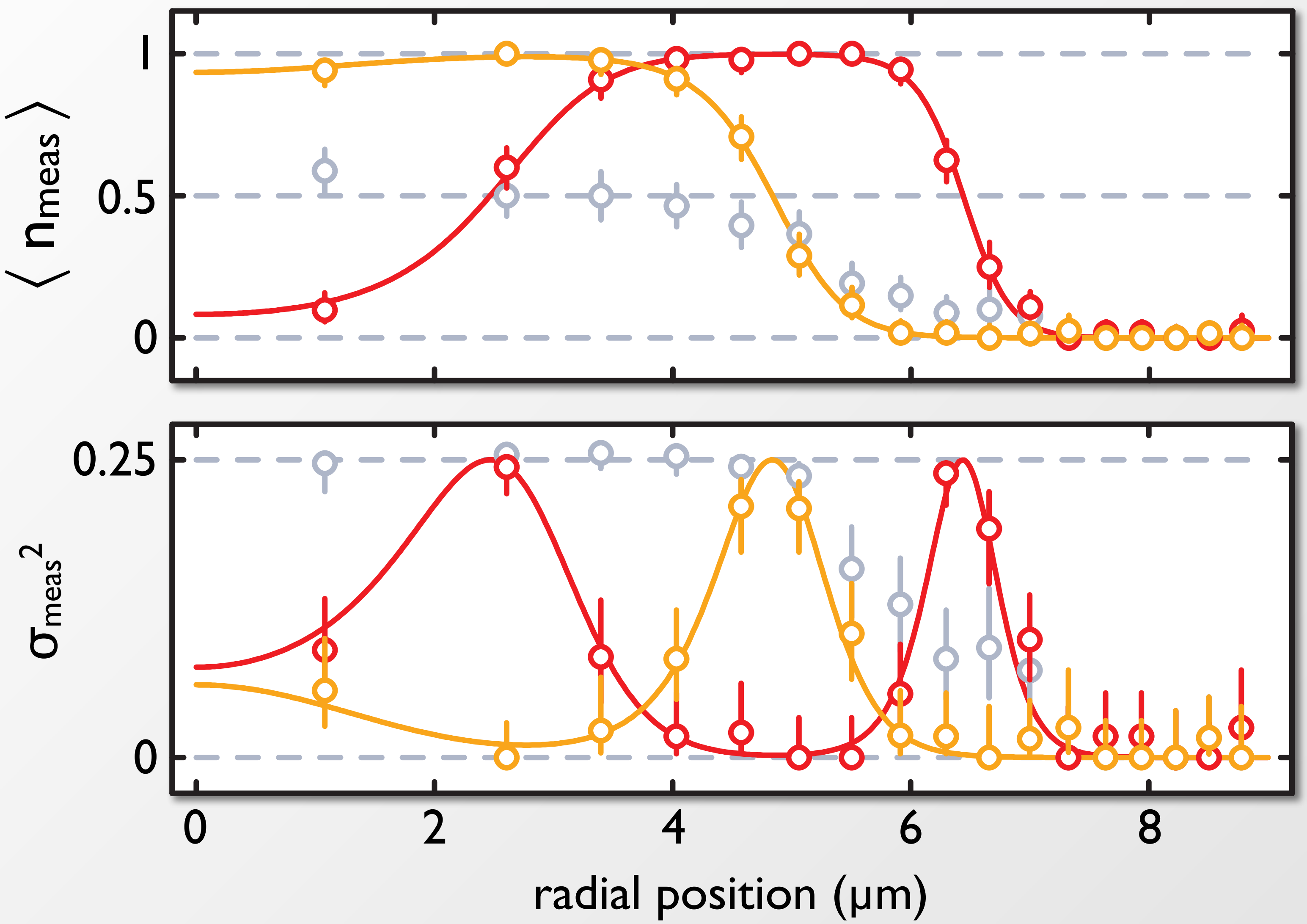
BEC

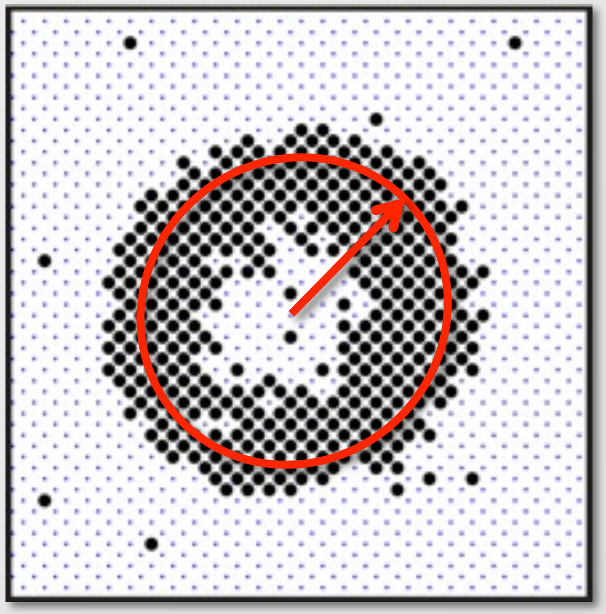
n=1
Mott Insulator

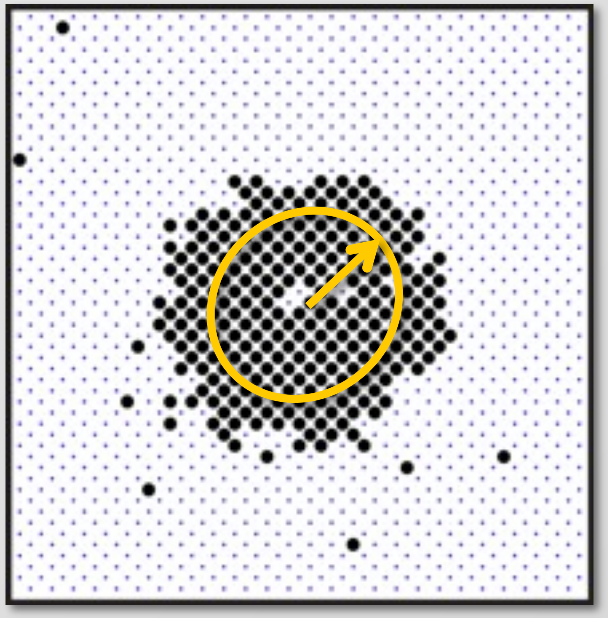
n=1 & n=2
Mott Insulator

J. Sherson *et al.* Nature **467**, 68 (2010)

Analysis of the site occupancy

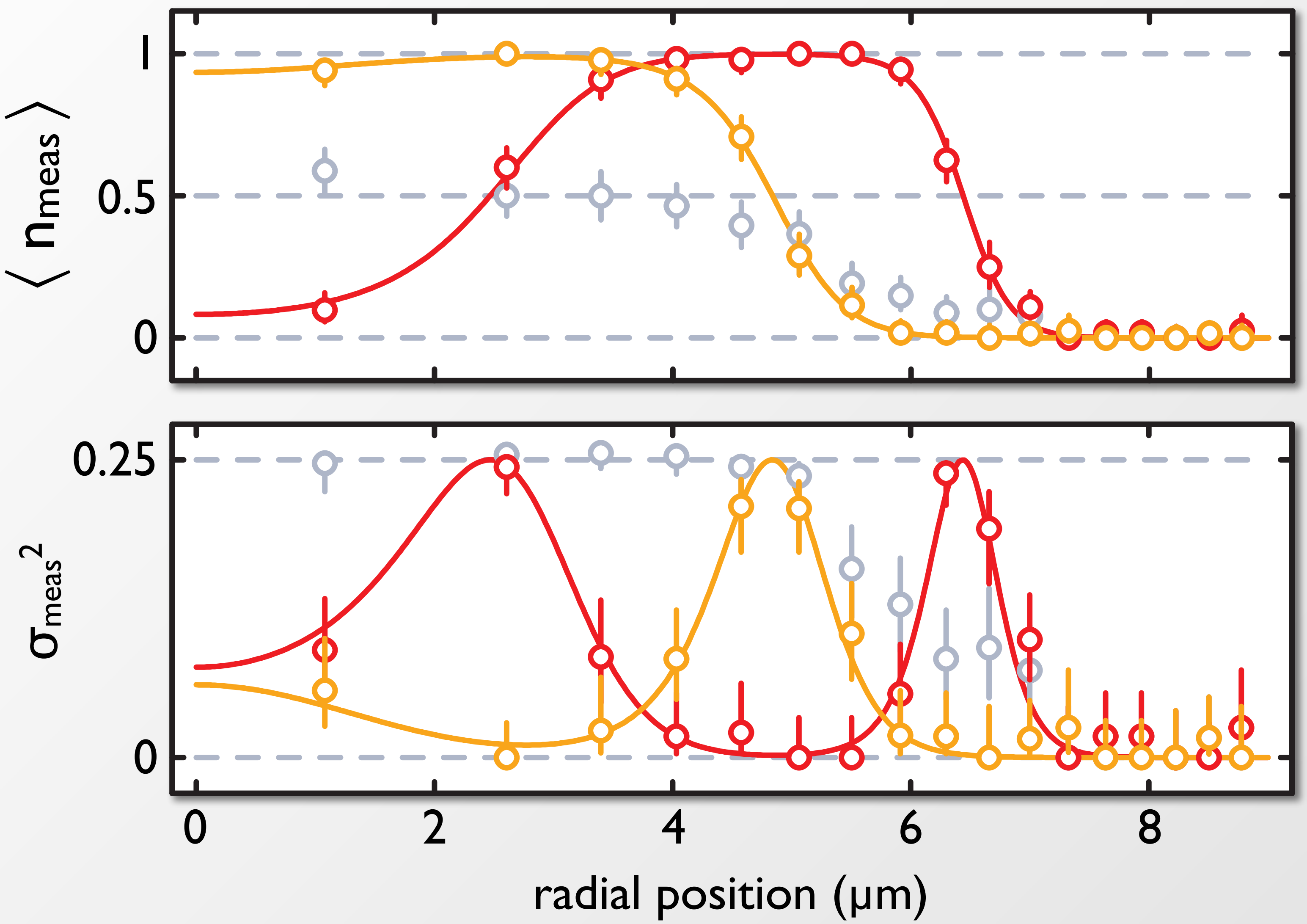


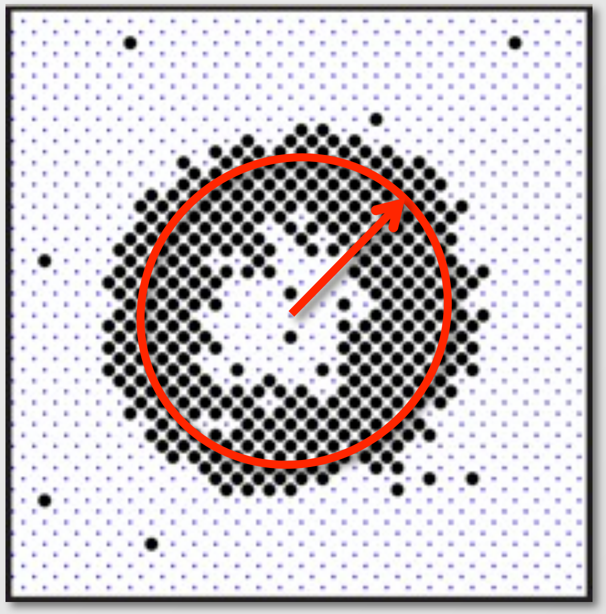




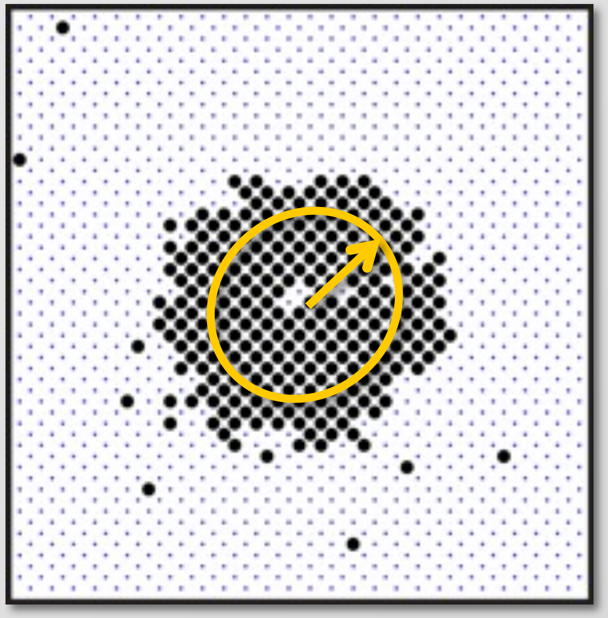
Each data set corresponds to a *single* picture

Analysis of the site occupancy





T = 0.074(5) U/k_B, μ = 1.17(1) U
N = 610(20)



T = 0.090(5) U/k_B, μ = 0.73(3) U
N = 300(20)

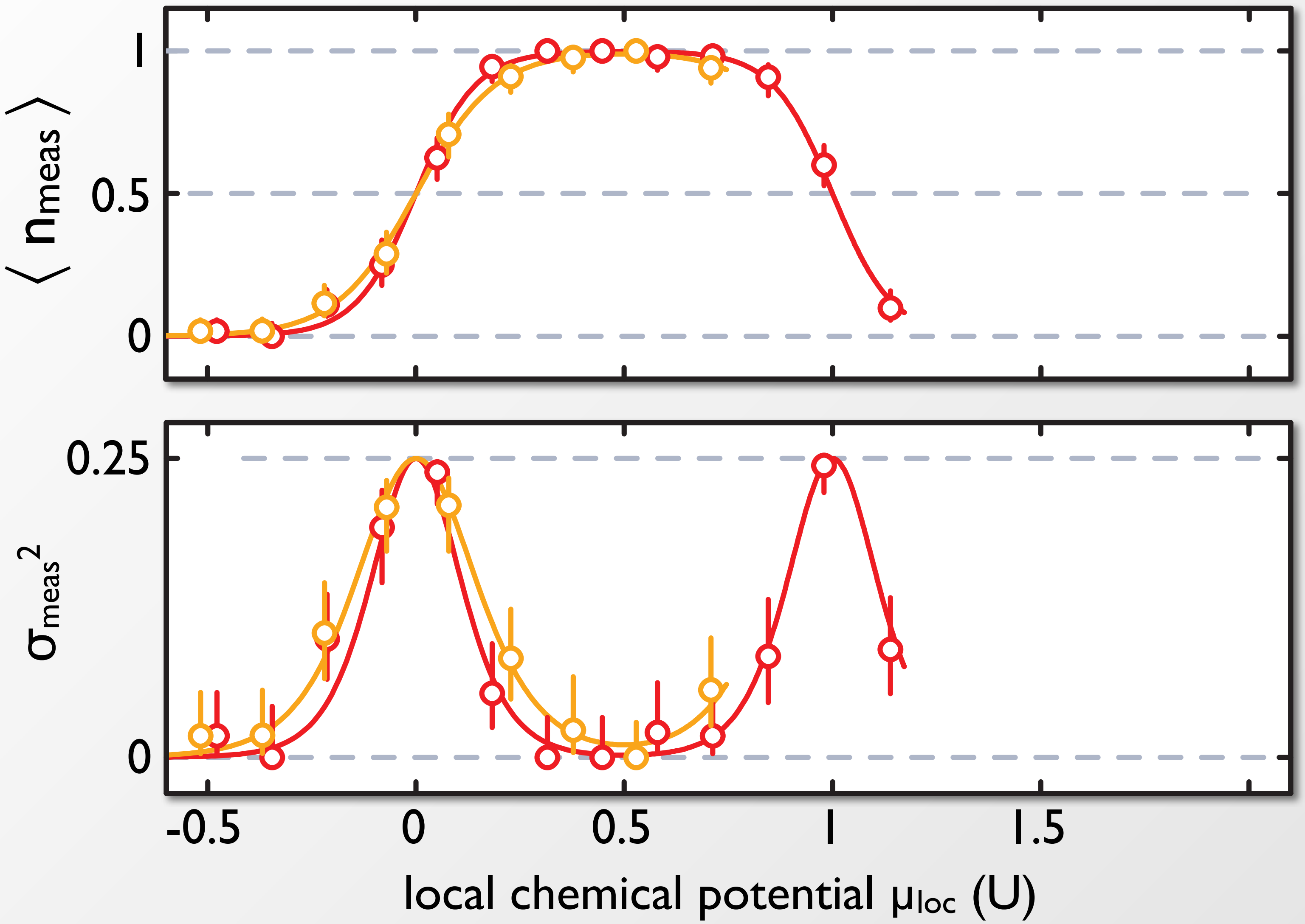
Simple Theory - Atomic Limit Mott Insulator

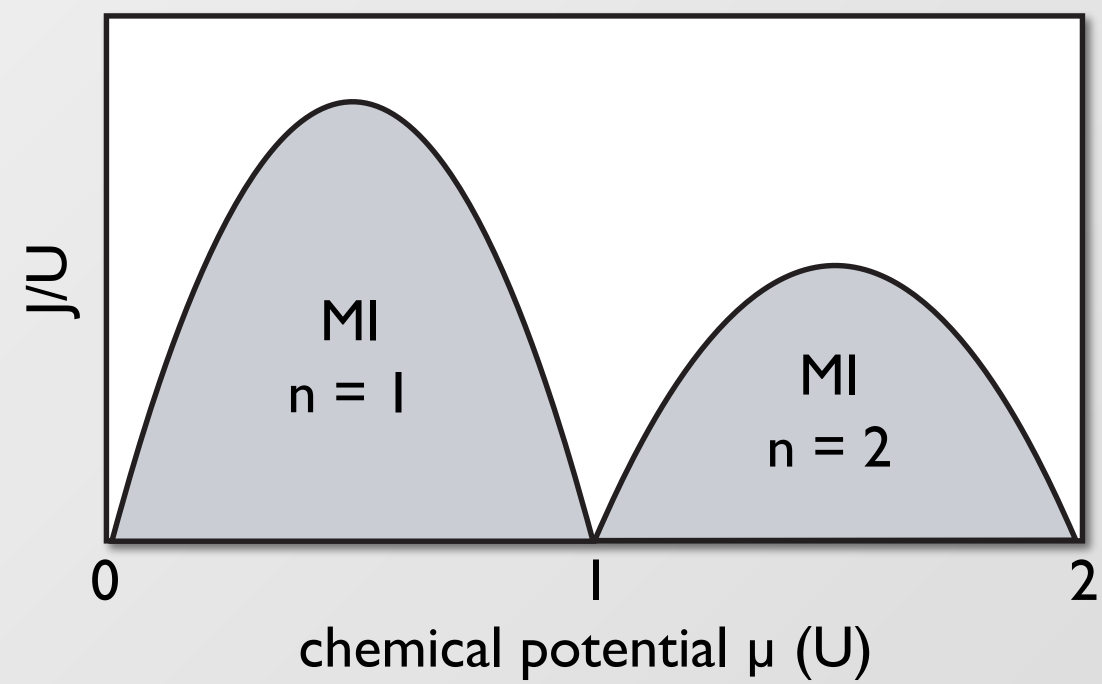
occupation probability: $p_n(r) = \frac{e^{-\beta(E_n - \mu(r)n)}}{Z(r)}$

interaction energy: $E_n = \frac{1}{2}Un(n-1)$

fit parameters: $T/U, \mu/U, U/\omega^2$

Analysis of the site occupancy

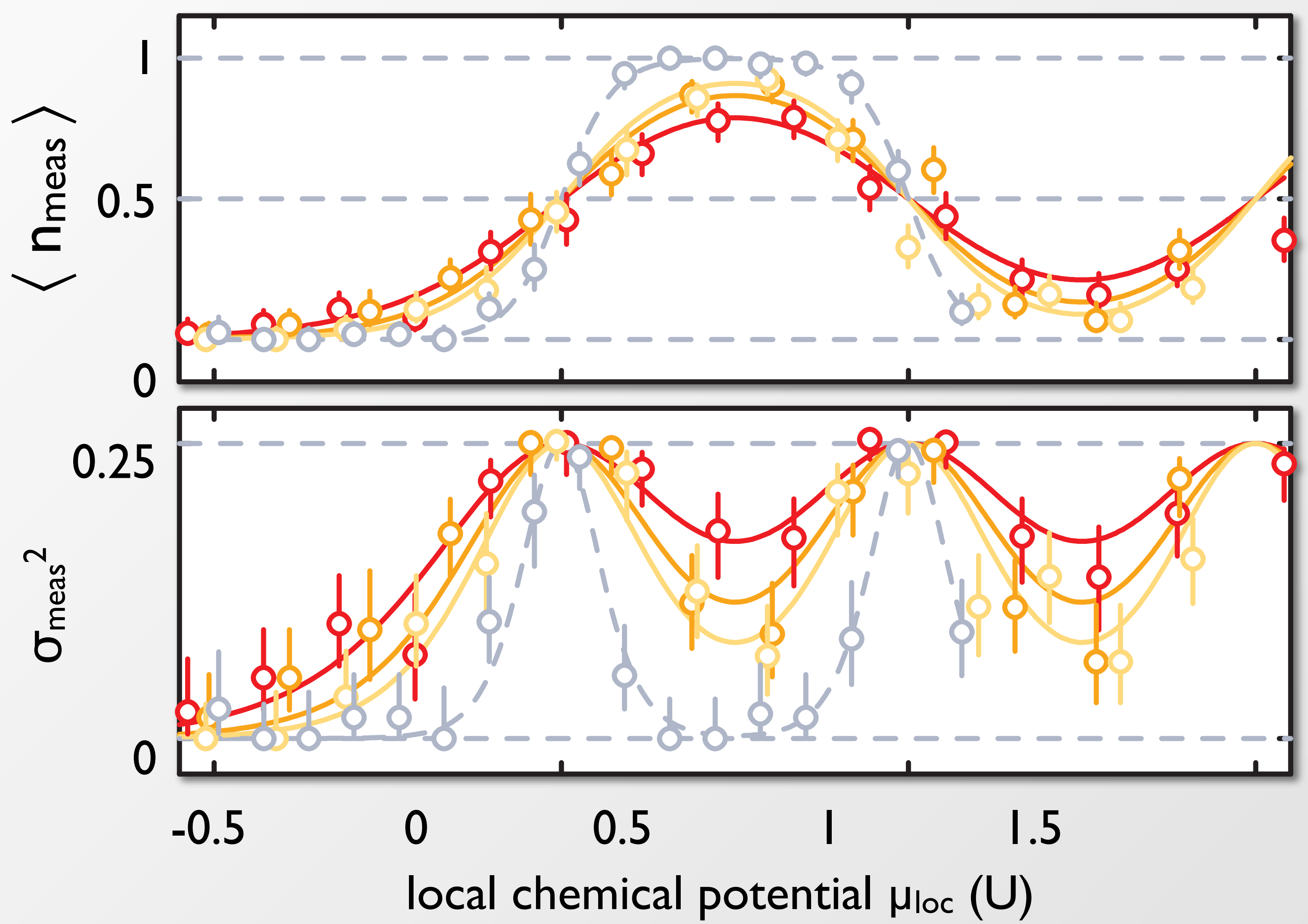


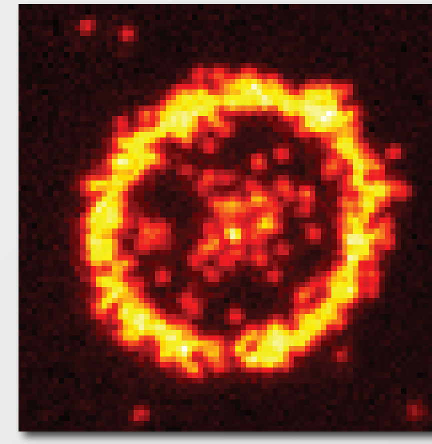


local entropy: $S(r) = -k_B \sum_n p_n(r) \log p_n(r)$

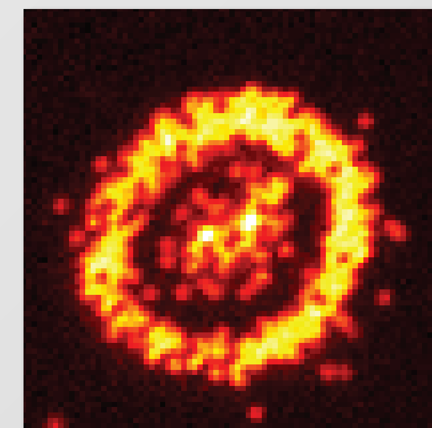
Total entropy/particle
$S/N = 0.34(2)\ k_B$

"Melting" of a Mott insulator

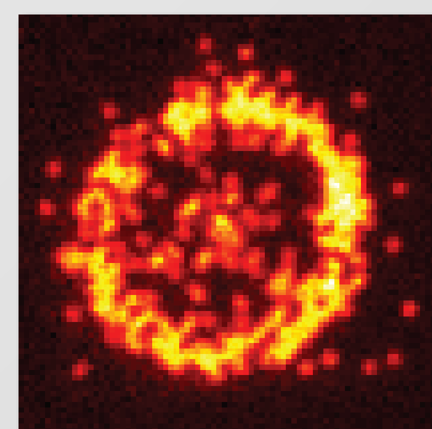




T = 0.17(1) U/kB
μ = 2.08(4) U



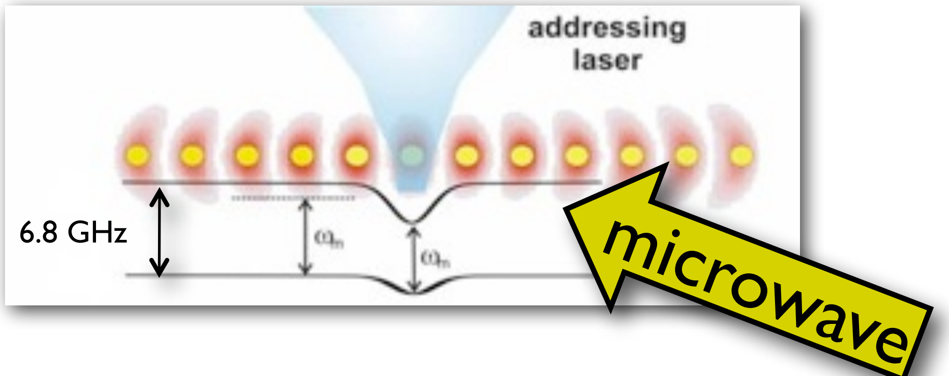
T = 0.20(2) U/kB
μ = 2.10(5) U



T = 0.25(2) U/kB
μ = 2.06(7) U

F. Gerbier, *PRL* **99**, 120405 (2007)

Single Site Addressing



single site relative light shift ~ 100 kHz

spin flips of individual atoms in the lattice

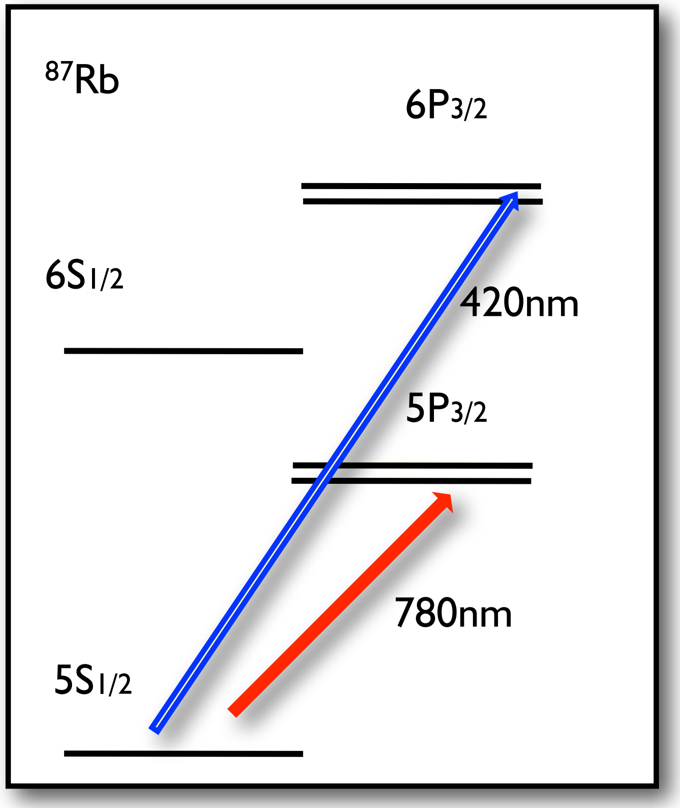
|1>=|F=2,m_F=-2>

|0>=|F=1,m_F=-1>

Single site adressing possible without single image resolution! Only relative lightshift counts.

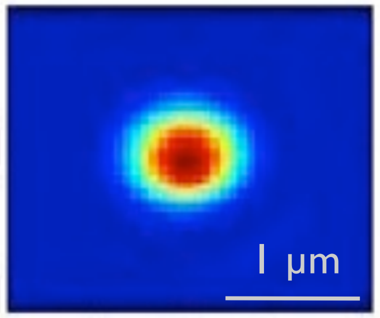
See also: Zhang *et al.*, PRA **74**, 042316 (2006)

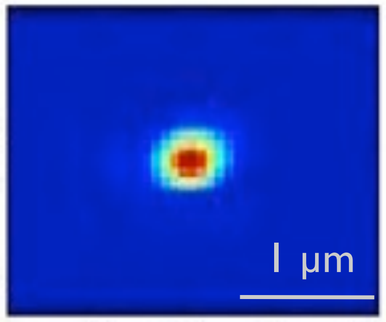
Addressing



red transition 724(4) nm

blue transition 385(6) nm





measured resolutions