Probing and Controlling Quantum Matter at the Single Atom Level

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€ MPG, European Union, DFG
$ DARPA (OLE)

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Outline

Introduction

1. **Single Atom Imaging**

2. **Three Applications**

   SF-Mott Insulator Transition/Thermometry/
   Quantum Fluctuations

   Fermionic Quantum Gas Microscope

   Controlling Single Spins

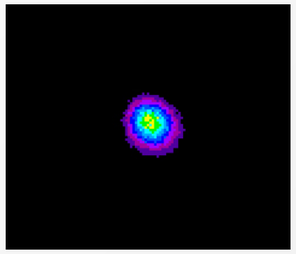
   'Higgs'-Amplitude Mode in 2D

3. **Observation of Many-Body Localisation**

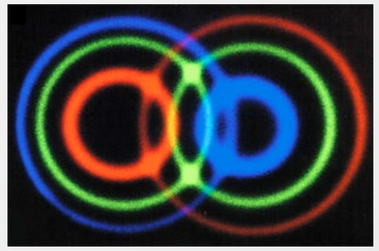
Outlook

The Challenge of Many-Body Quantum Systems

Control of single and few particles

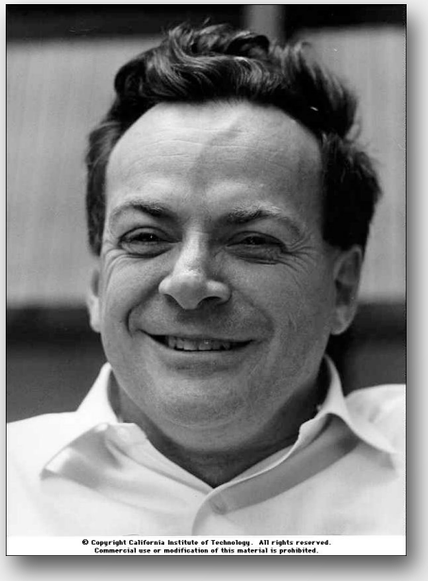


Single Atoms and Ions



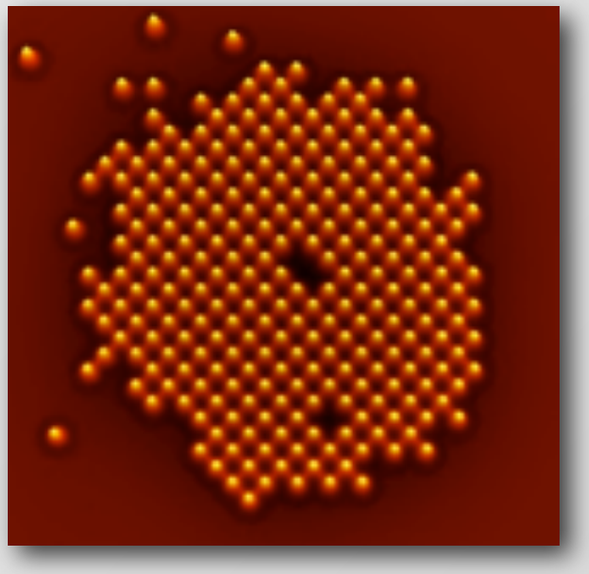
Photons

Challenge: ... towards ultimate control of many-body quantum systems



R. P. Feynman's Vision

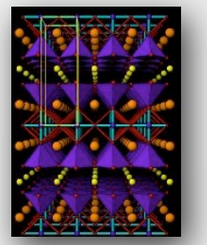
A Quantum Simulator to study the dynamics of another quantum system.

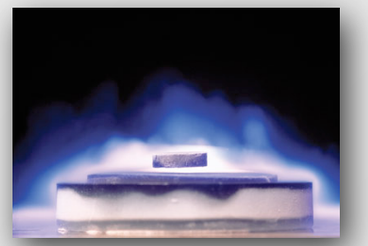


Crystal of Atoms Bound by Light

The Challenge of Many-Body Quantum Systems

- **Understand and Design Quantum Materials** -
  one of the biggest challenge of Quantum Physics in the 21st Century

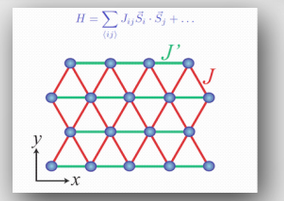




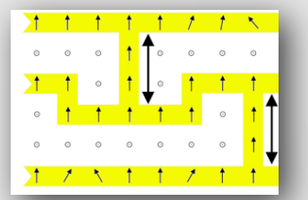
- **Technological Relevance**

  High-Tc Superconductivity (Power Delivery)

  Magnetism (Storage, Spintronics...)



  Novel Quantum Sensors (Precision Detectors)



  Quantum Technologies
  (Quantum Computing, Metrology, Quantum Sensors,...)

Many cases: lack of basic understanding of underlying processes

Difficulty to separate effects: probe impurities, complex interplay, masking of effects...

Many cases: even simple models "not solvable"

Need to synthesize new material **to analyze effect of parameter change**

Starting Point – Ultracold Quantum Gases

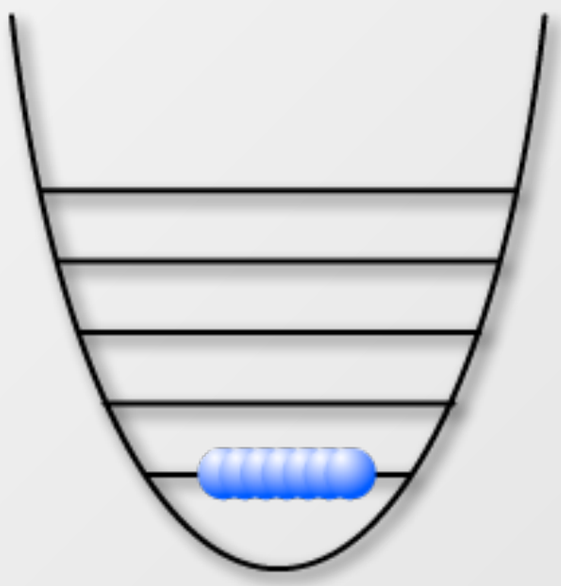
Parameters:

Densities: 10^{15} cm^{-3}

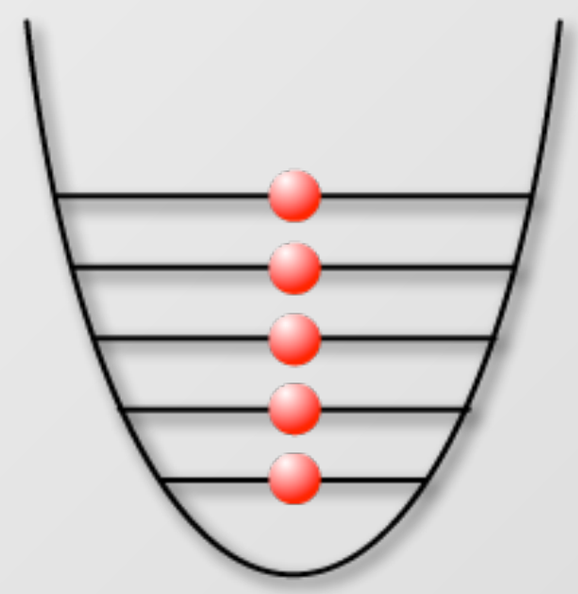
Temperatures: Nano Kelvin

Atom Numbers 10^{6}

Ground States at T=0

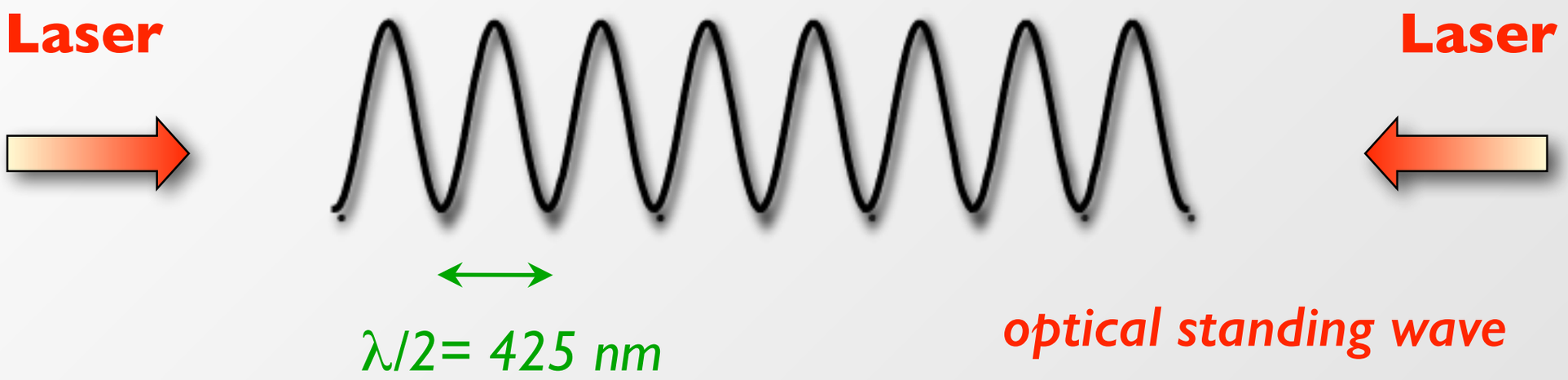


Bose-Einstein Condensates e.g. ^{87}Rb



Degenerate Fermi Gases e.g. ^{40}K

Optical Lattice Potential – Perfect Artificial Crystals

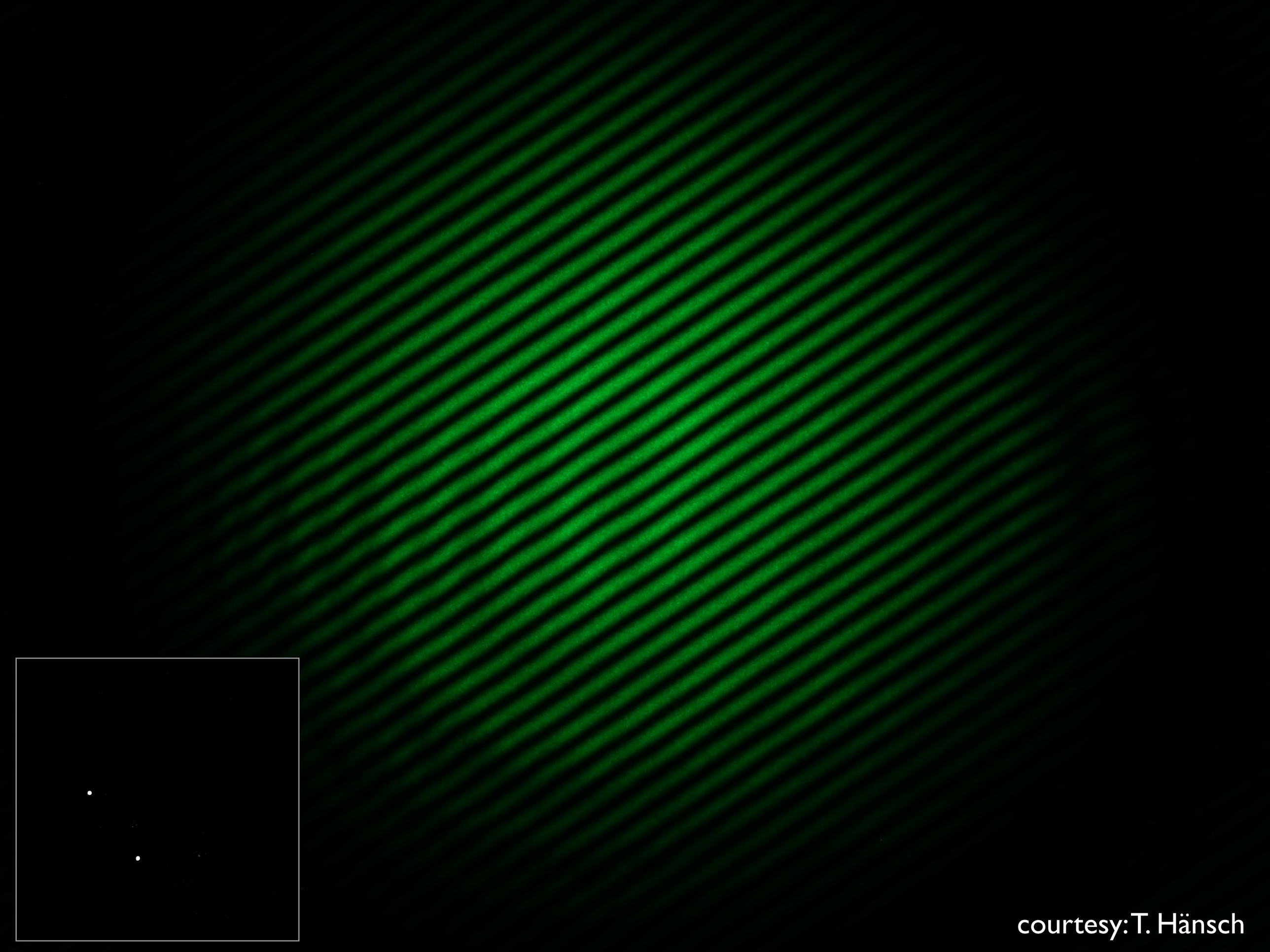


Fourier synthesize aribtrary lattices:

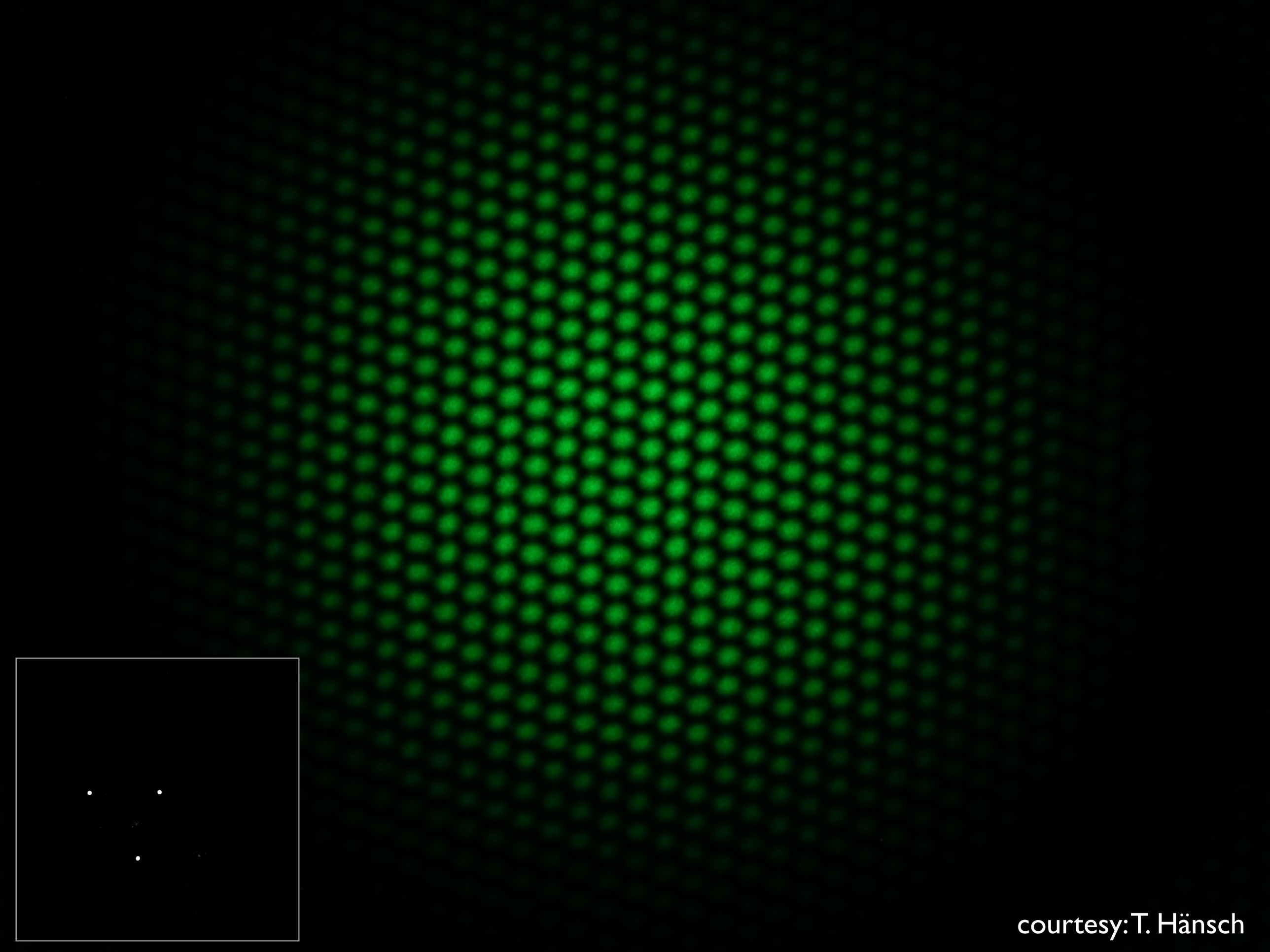
- Square
- Hexagonal/Triangular/Brick Wall
- Kagomé
- Superlattices
- *Spin dependent lattices*
- *Gauge fields, Spin Orbit,…*

Special case: flux lattices...

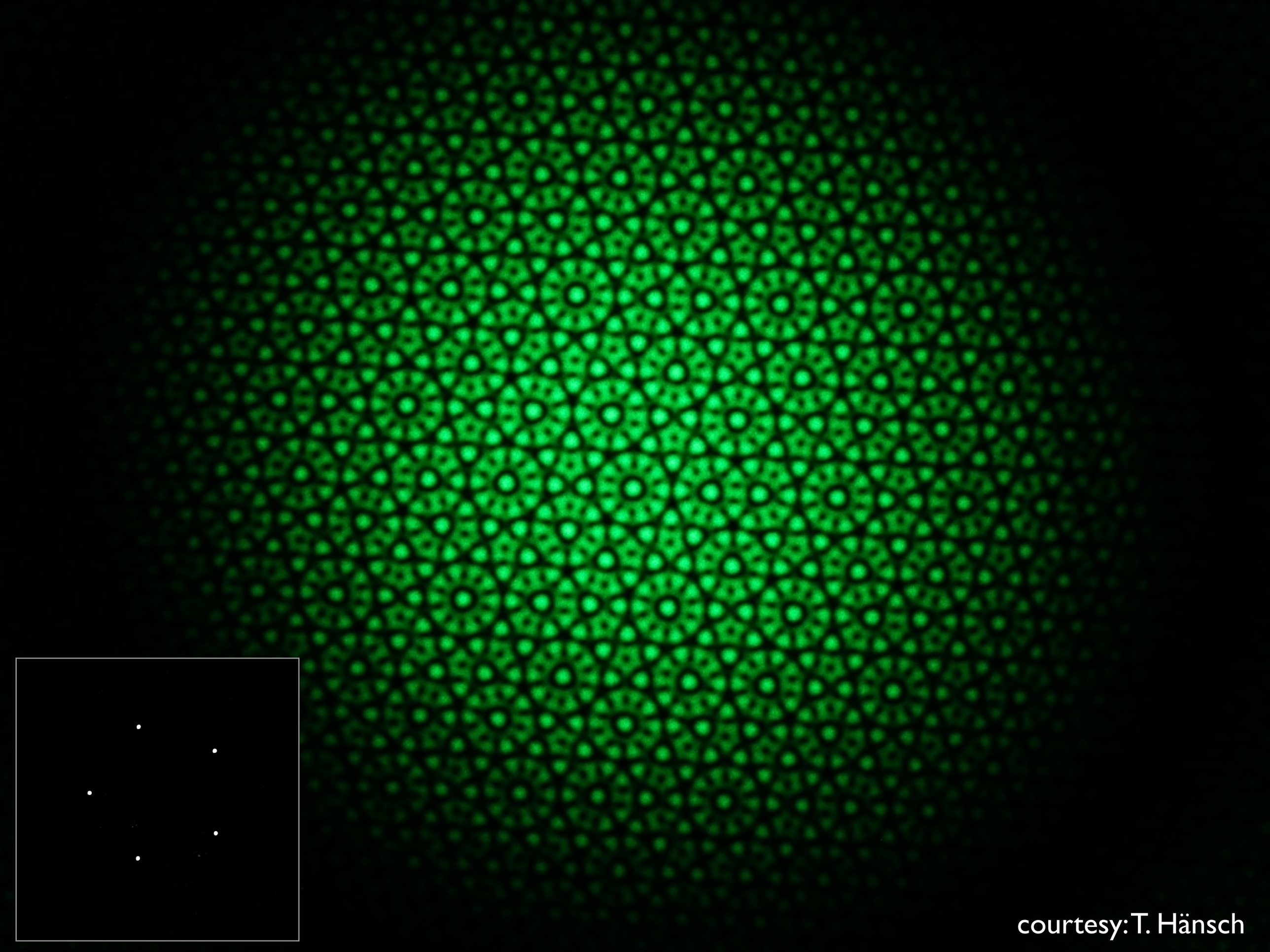
Full **dynamical** control over **lattice depth, geometry, dimensionality!**



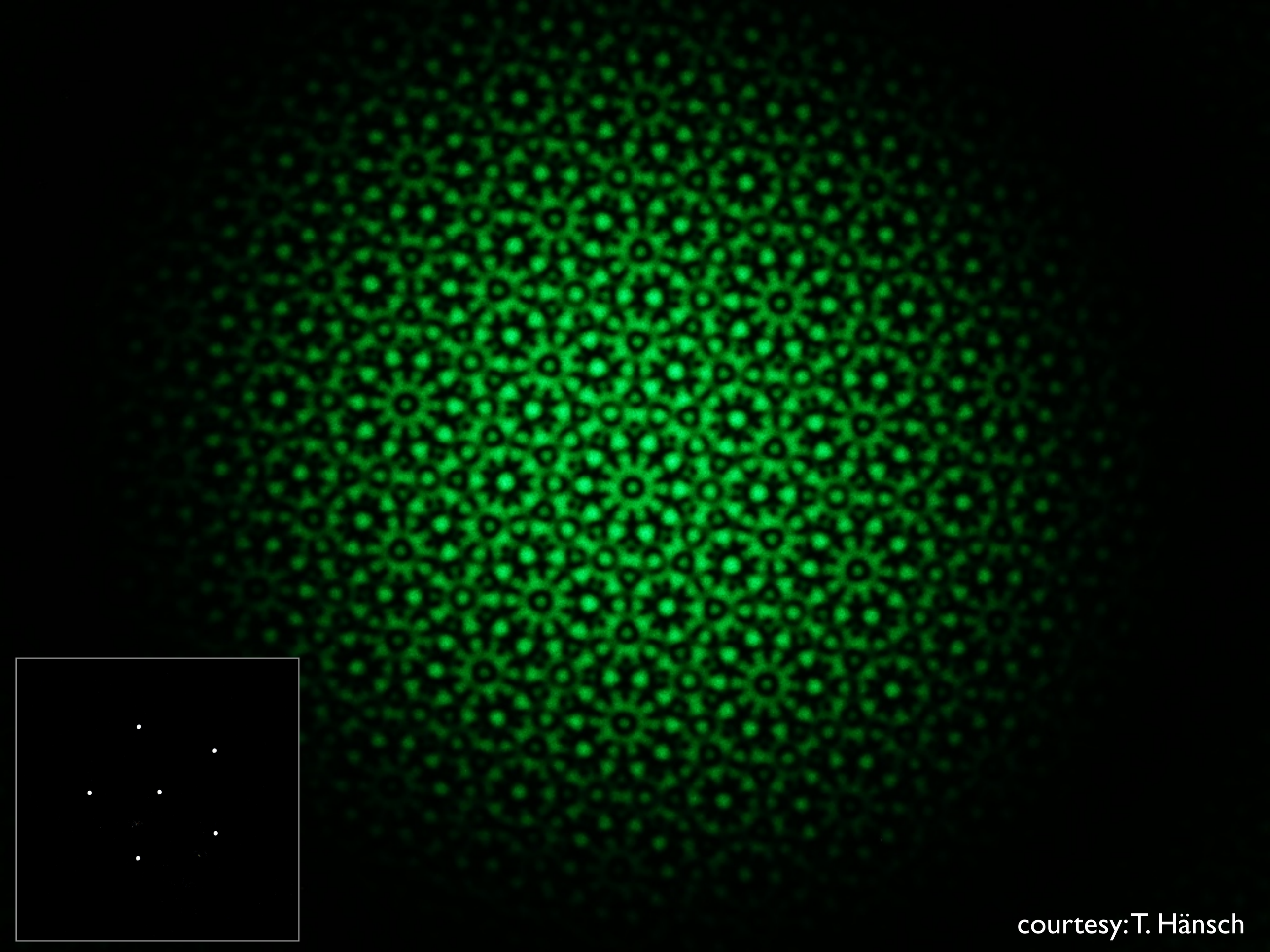
courtesy: T. Hänsch



courtesy: T. Hänsch



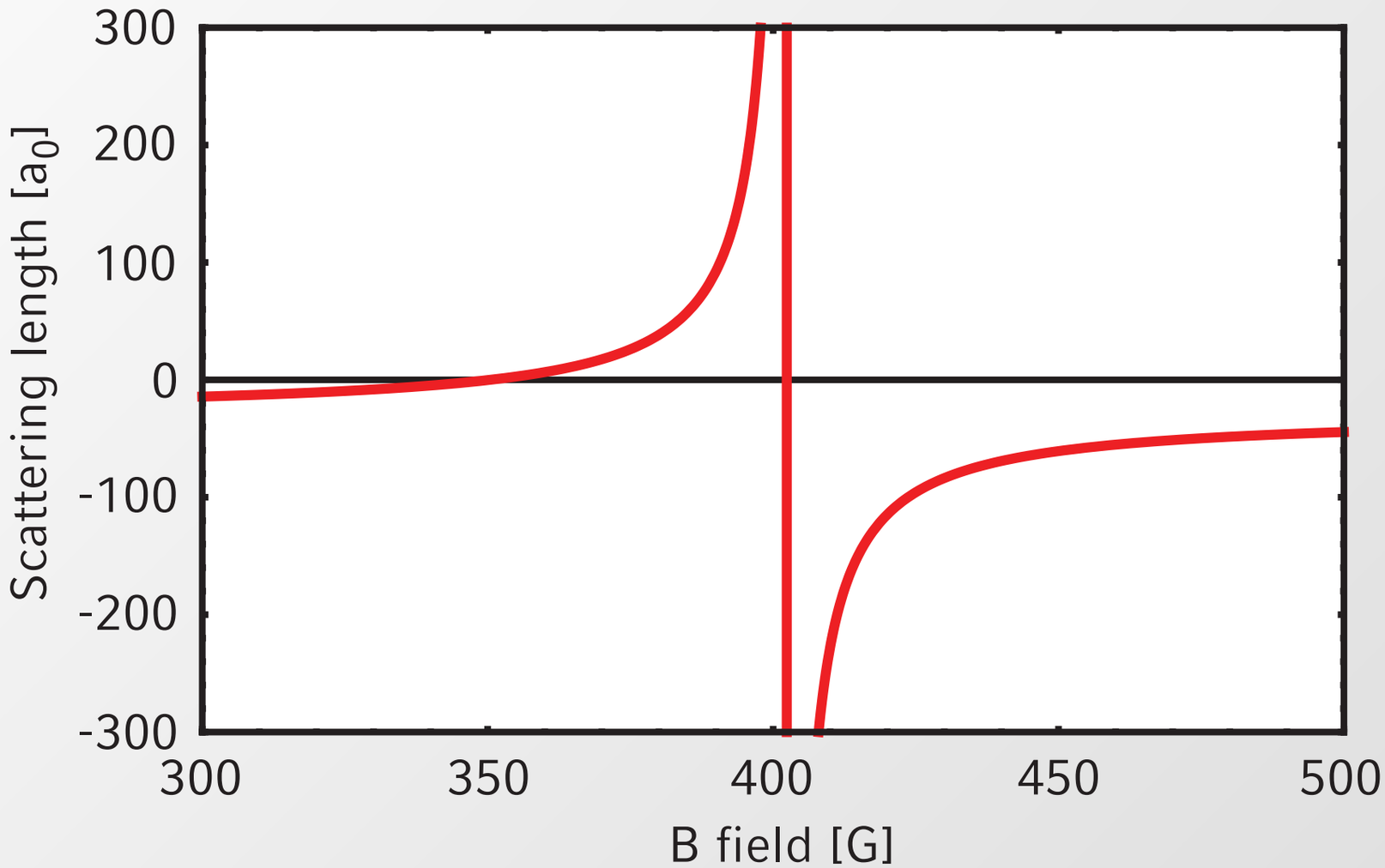
courtesy: T. Hänsch



courtesy: T. Hänsch

Tuning Interactions

^{39}K-^{39}K Feshbach resonance



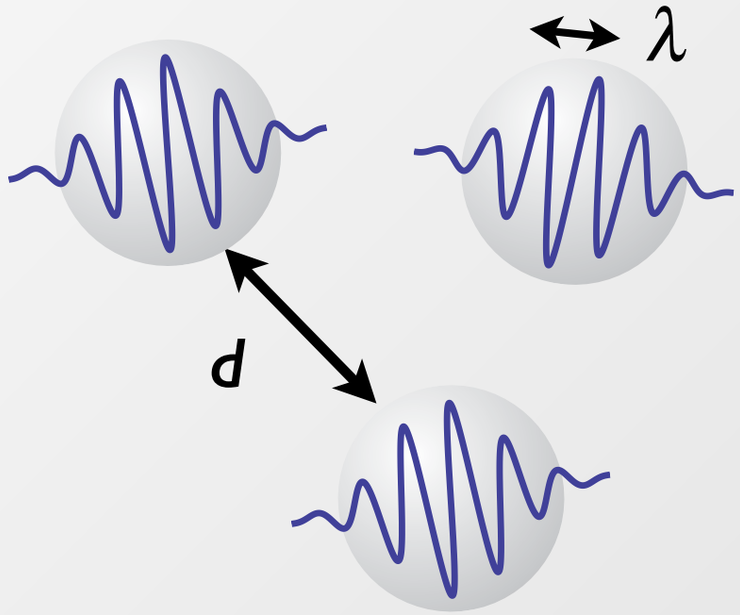
Feshbach resonance allow us to control interactions!

Chin, C., Grimm, R., Julienne, P. & Tiesinga, E. *Rev. Mod. Phys.* **82,** 1225–1286 (2010).

From Artificial Quantum Matter to Real Materials

Quantum Regime

$$\lambda / d \gtrsim 1$$

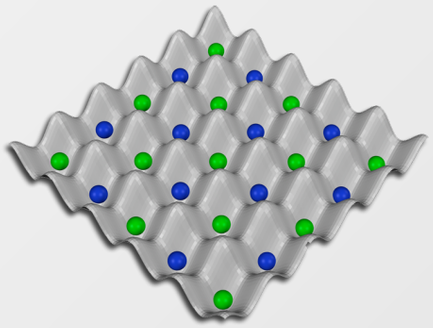


de Broglie Wavepackets

Universality of Quantum Mechanics!

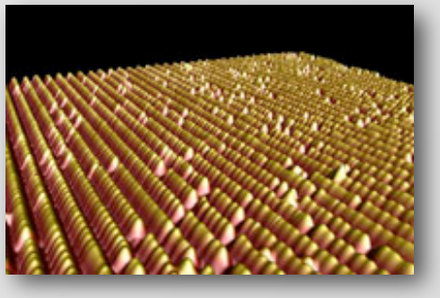
Ultracold Quantum Matter

- **Densities:** $10^{14}/cm^3$
  (100000 times thinner than air)
- **Temperatures:** *few nK*
  (100 million times lower than outer space)



Real Materials

- **Densities:** 10^{24}-$10^{25}/cm^3$
- **Temperatures:** *mK – several hundred K*



(Neuchatel)

Same λ / d !

Bose-Hubbard Hamiltonian

Expanding the field operator in the Wannier basis of localized wave functions on each lattice site, yields :

$$\hat{\psi}(\boldsymbol{x}) = \sum_i \hat{a}_i w(\boldsymbol{x} - \boldsymbol{x}_i)$$

Bose-Hubbard Hamiltonian

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Tunnelmatrix element/Hopping element

$$J = -\int d^3x \, w(\boldsymbol{x} - \boldsymbol{x}_i) \left(-\frac{\hbar^2}{2m} \nabla^2 + V_{lat}(\boldsymbol{x}) \right) w(\boldsymbol{x} - \boldsymbol{x}_j)$$

Onsite interaction matrix element

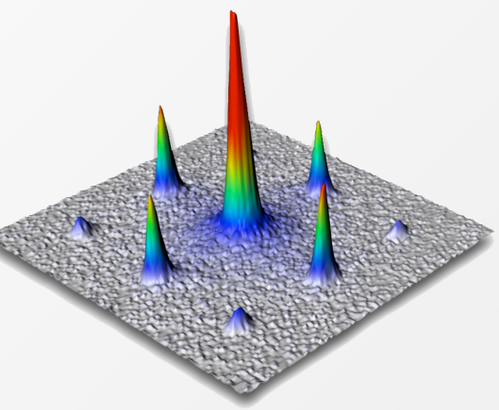
$$U = \frac{4\pi \hbar^2 a}{m} \int d^3x \left| w(\boldsymbol{x}) \right|^4$$

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

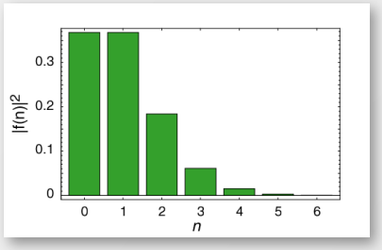
Mott Insulators now at: Munich, Mainz, NIST, ETHZ, Texas, Innsbruck, MIT, Chicago, Florence,...
see also work on JJ arrays H. Mooij et al., E. Cornell,...

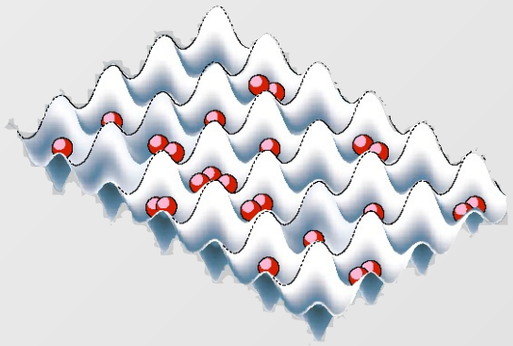
From Weak to Strong Interactions

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



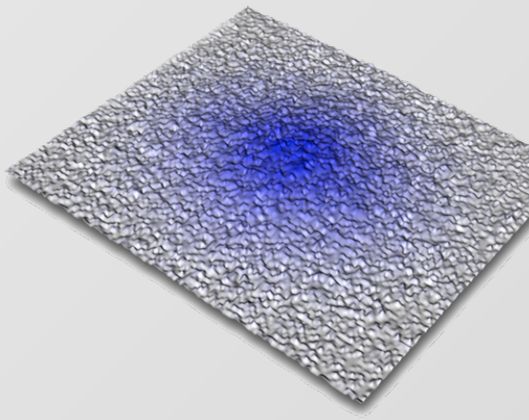
Weak Interactions



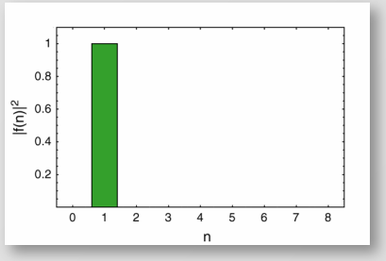


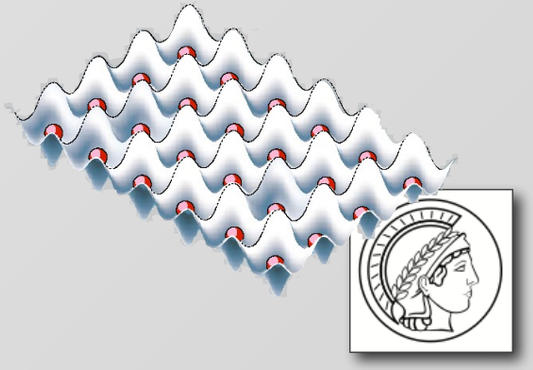
Quantum Phase Transition

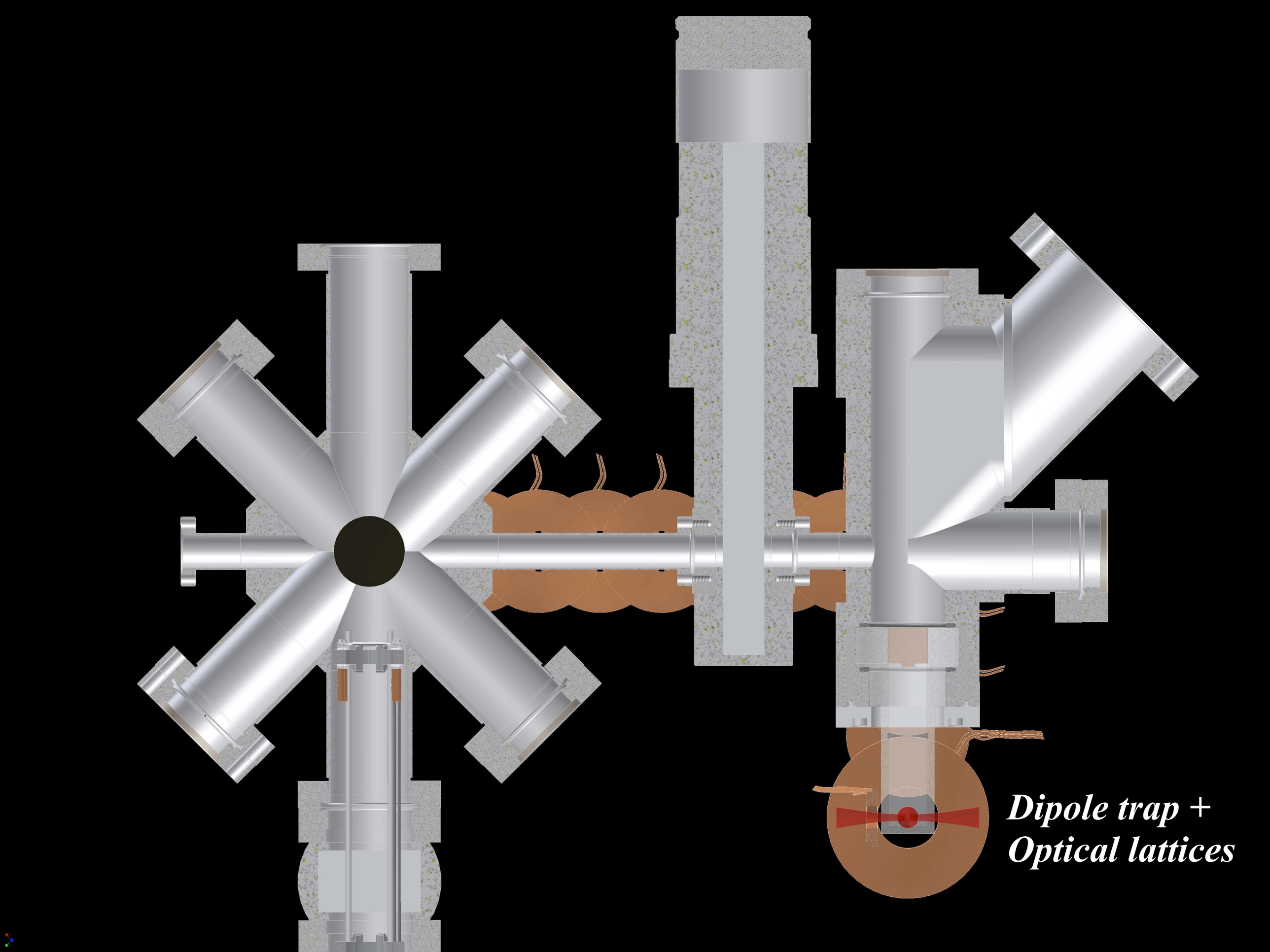
see S. Sachdev & B. Keimer Phys. Today 2011



Strong Interactions





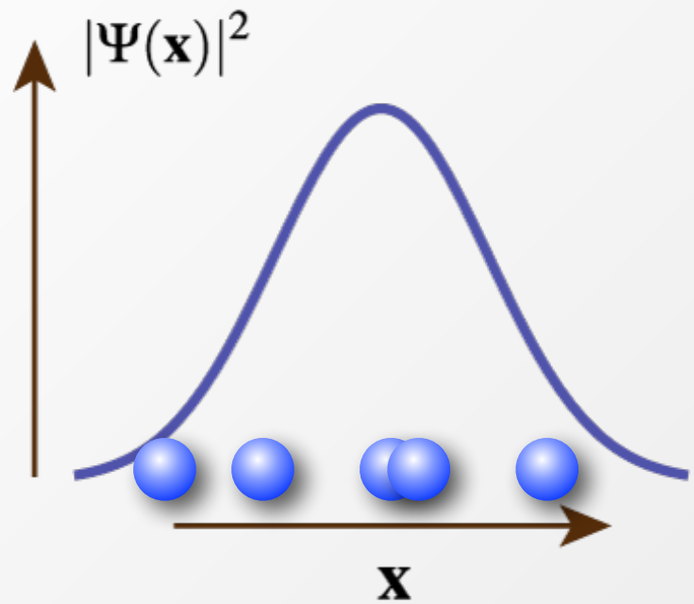

Dipole trap +
Optical lattices


And a Lot of
Lasers & Optics...

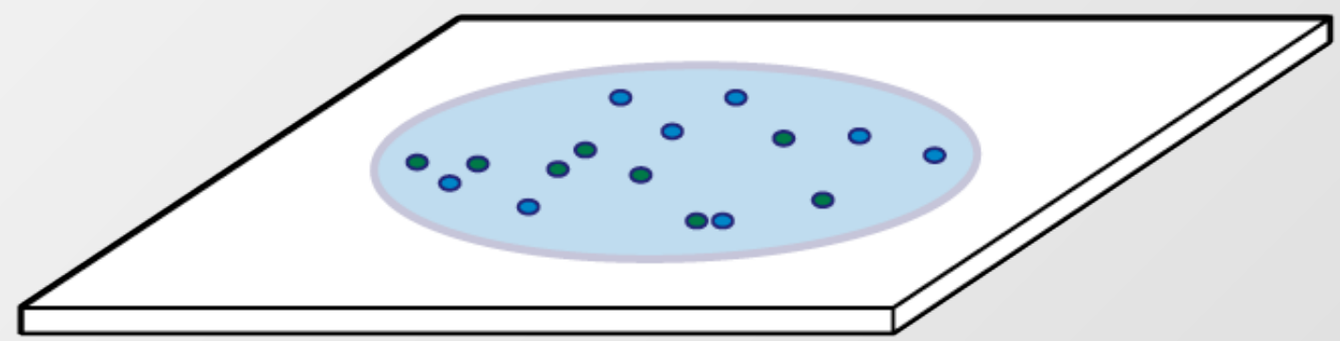
Single Atom Detection in a Lattice

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

Measuring a Quantum System



Single Particle



Correlated 2D Quantum Liquid

$\Psi(\mathbf{x})$ wave function

$|\Psi(\mathbf{x})|^2$ probability distribution

$\Psi(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \ldots, \mathbf{x}_N)$

$|\Psi(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \ldots, \mathbf{x}_N)|^2$

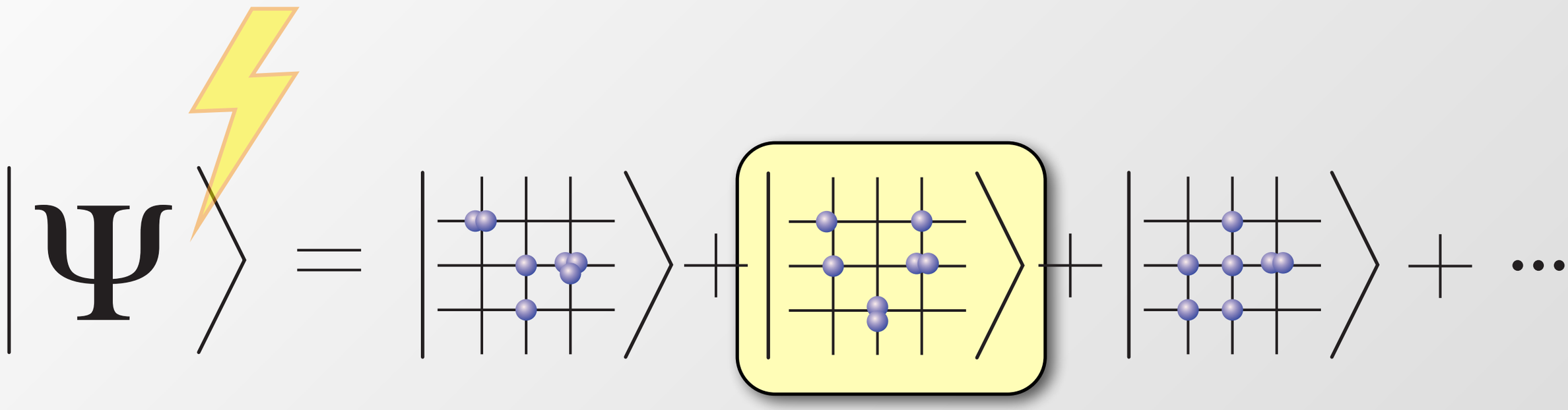
averaging over single-particle measurements, we obtain $|\Psi(\mathbf{x})|^2$

For many-body system: need access to single snapshots of the many-particle system!

Enables Measurement of Non-local Correlations

Measuring a Many-Body Quantum System

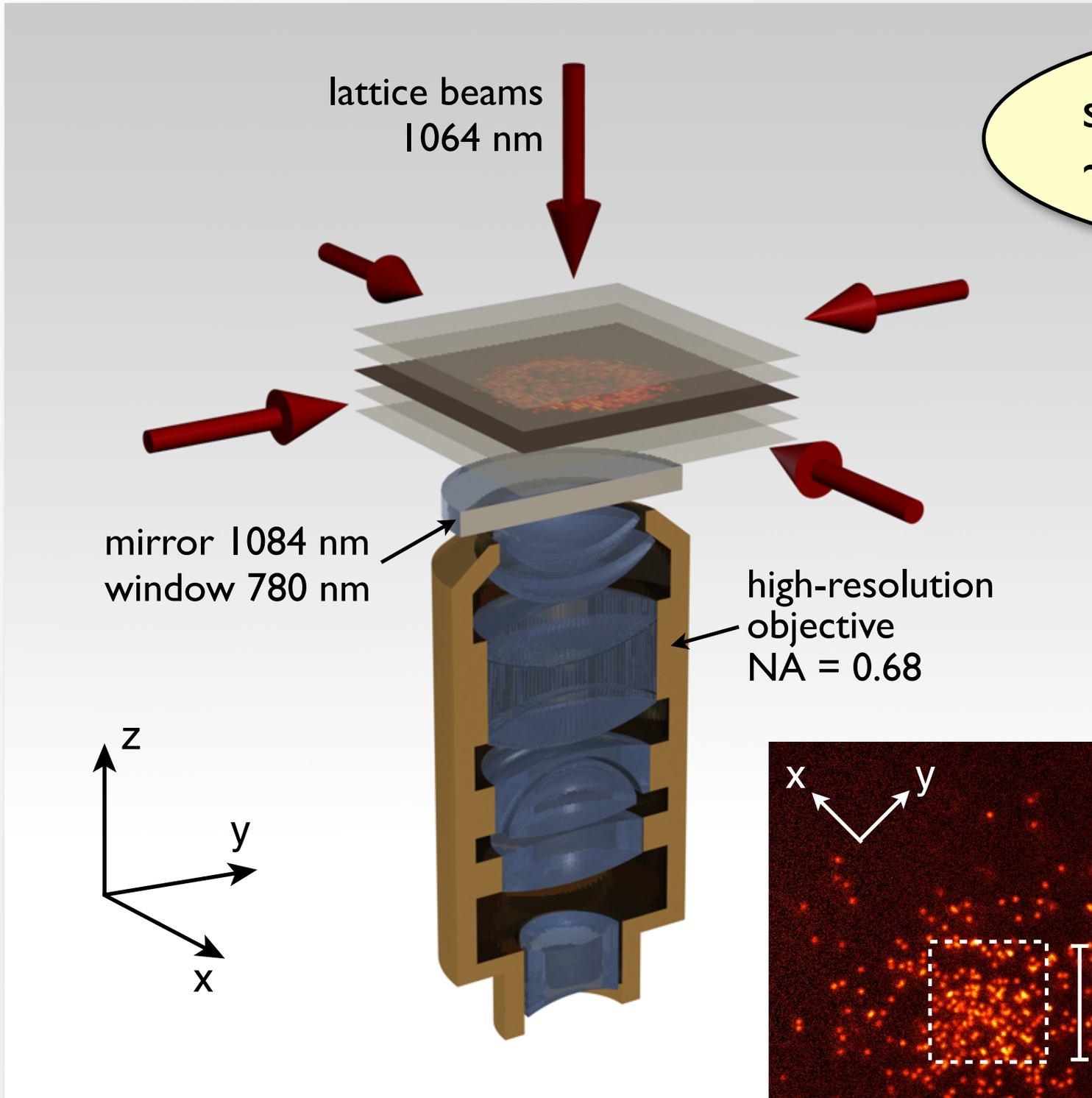
Local occupation measurement



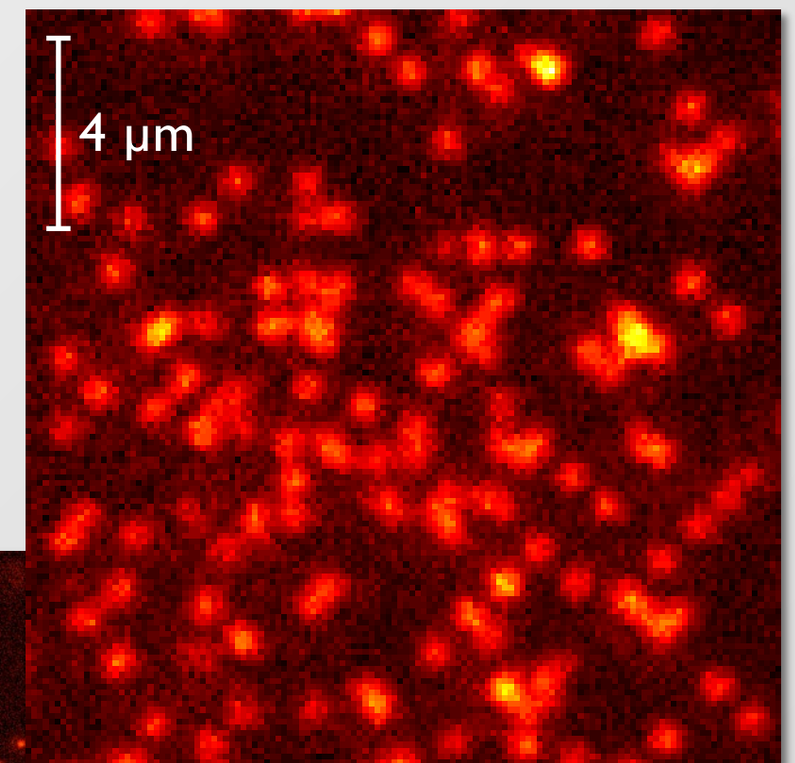
Enables access to all position correlation between particles!

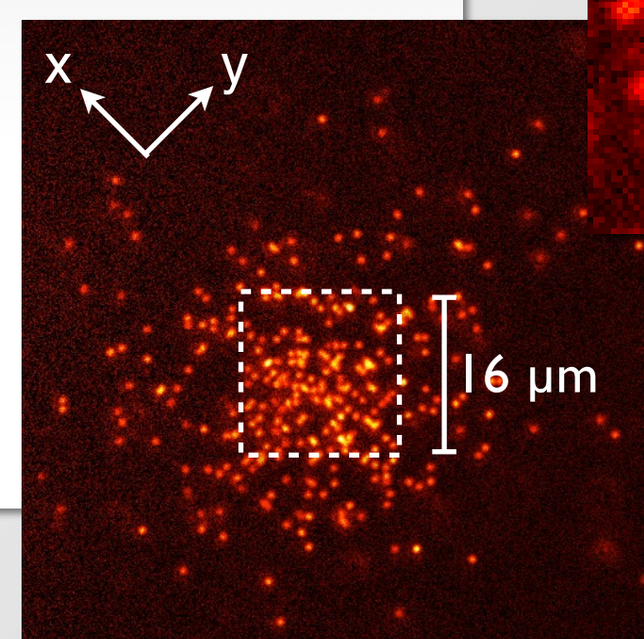
Extendable to other observables (e.g. local currents etc…)

Experimental Setup



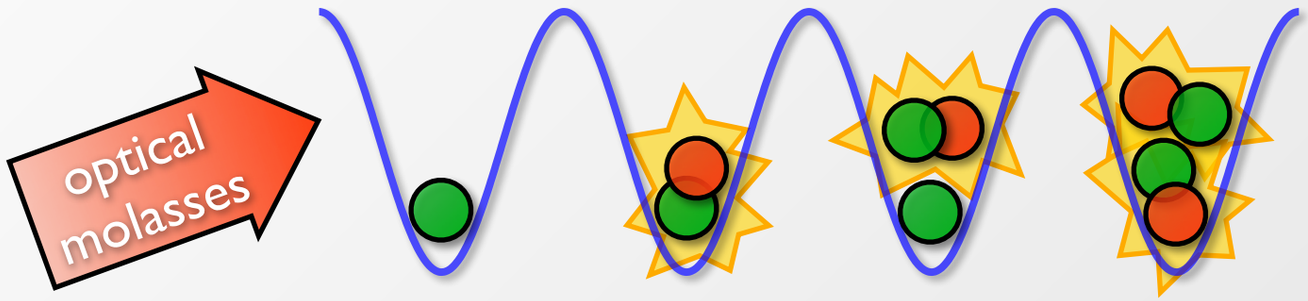
single 2D degenerate gas
~ 1000 ^{87}Rb atoms (bosons)





resolution of the imaging system: ~700 nm

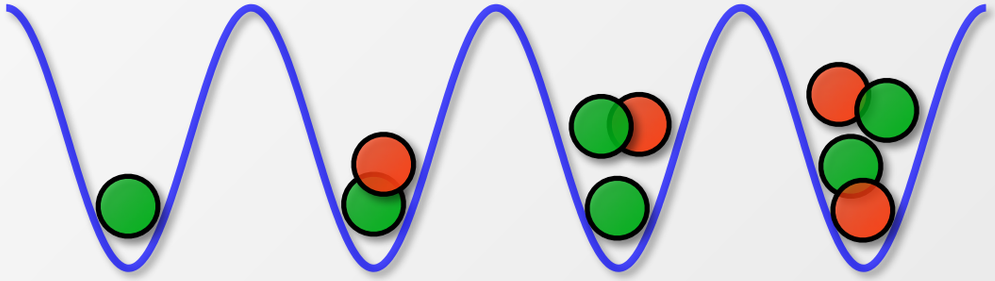
Parity projection



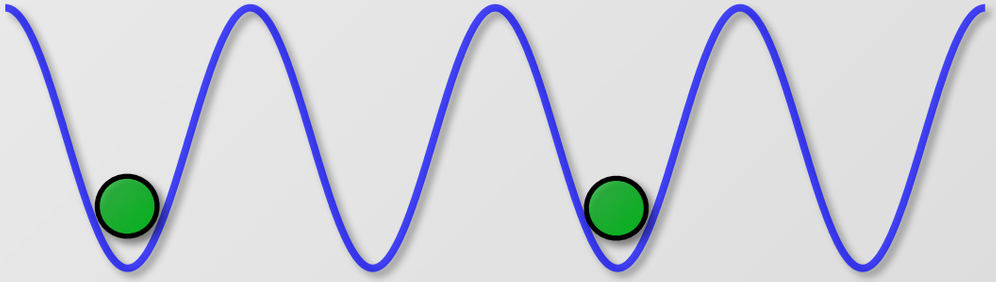
dePue *et al.*, PRL **82**, 2262 (1999)

Light-induced
collisions

initial density distribution



measured density distribution



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

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

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

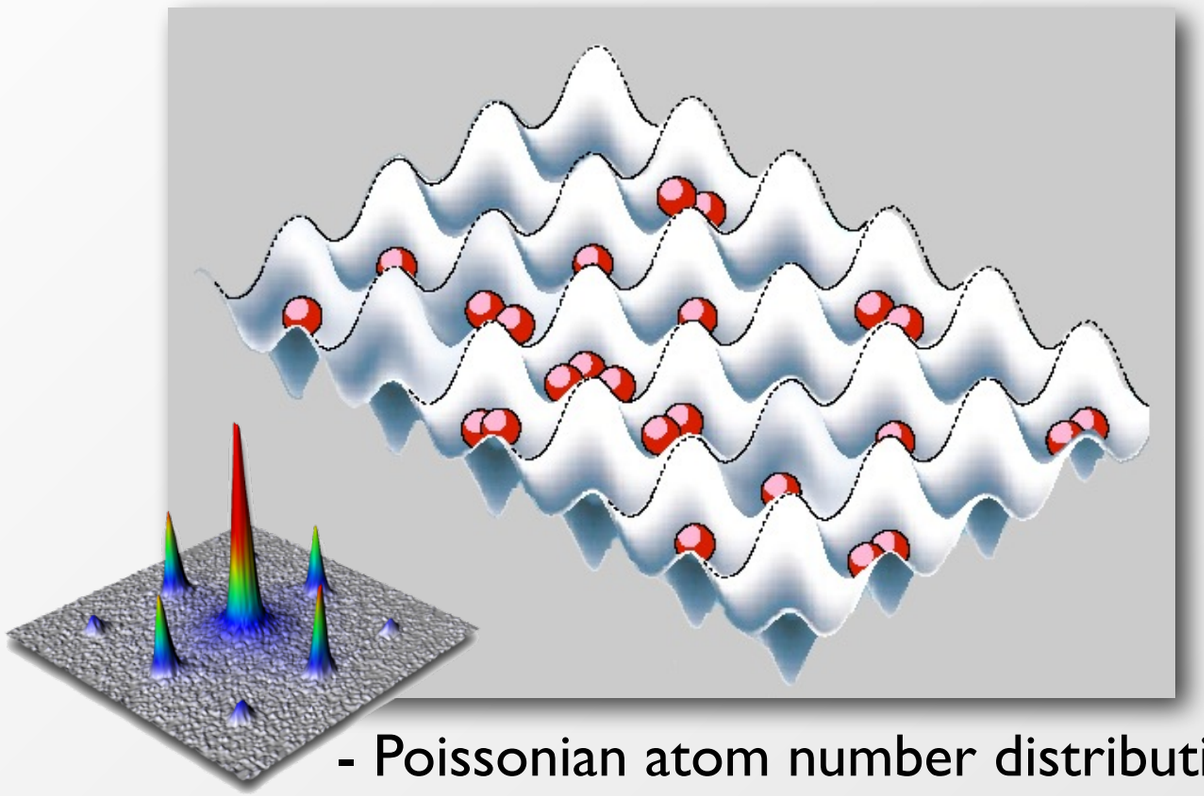
see also E. Kapit & E. Mueller, Phys. Rev. A **82**, 013644 (2010)

In-Situ Imaging of a Mott Insulator

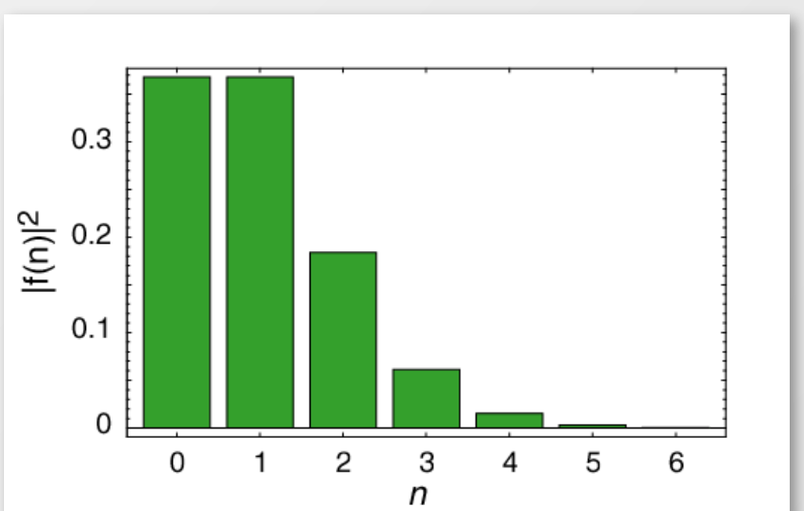
J. Sherson et al. Nature **467**, 68 (2010),
see also S. Fölling et al. Phys. Rev. Lett (2006), G.K. Campbell et al. Science (2006)
N. Gemelke et al. Nature (2009), W. Bakr et al. Science (2010)

Mott Insulators

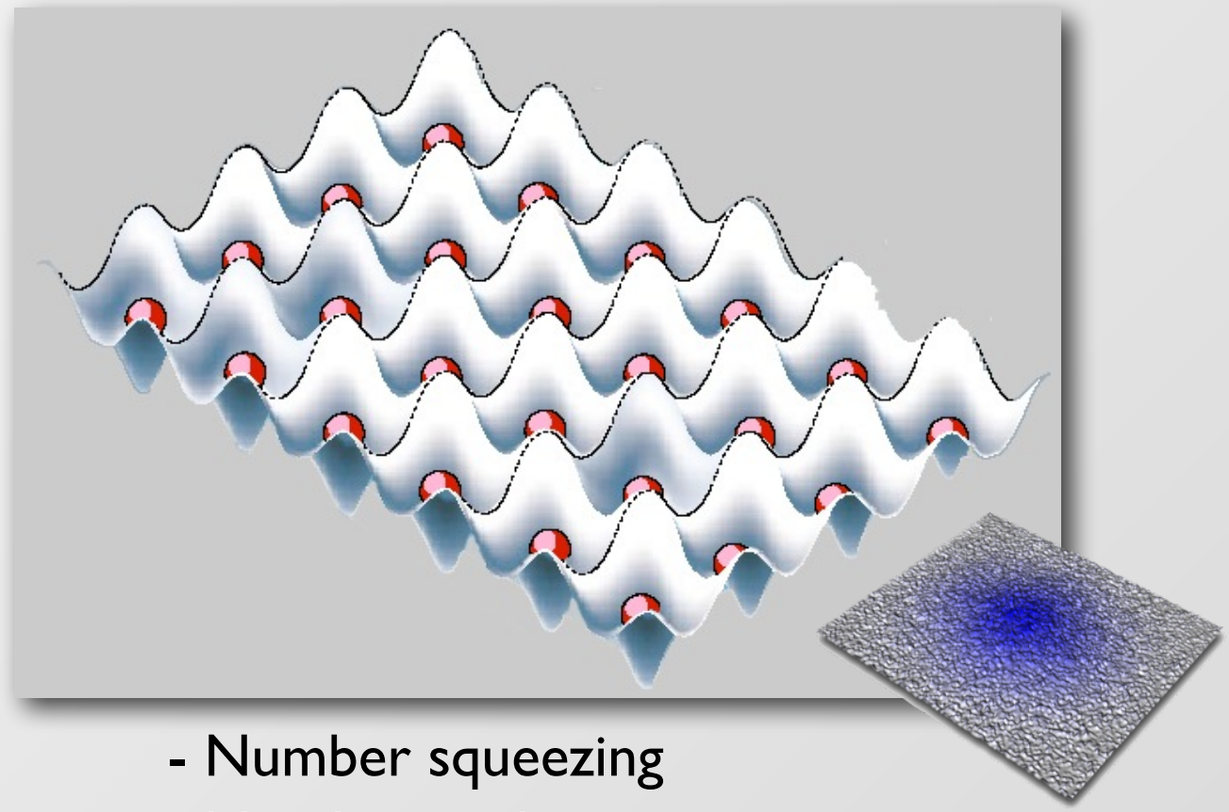
Superfluid



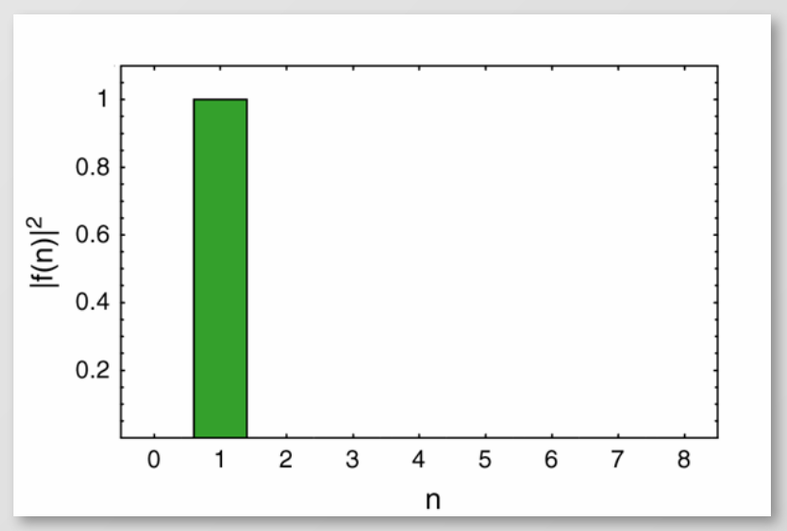
- Poissonian atom number distribution
- Long range phase coherence



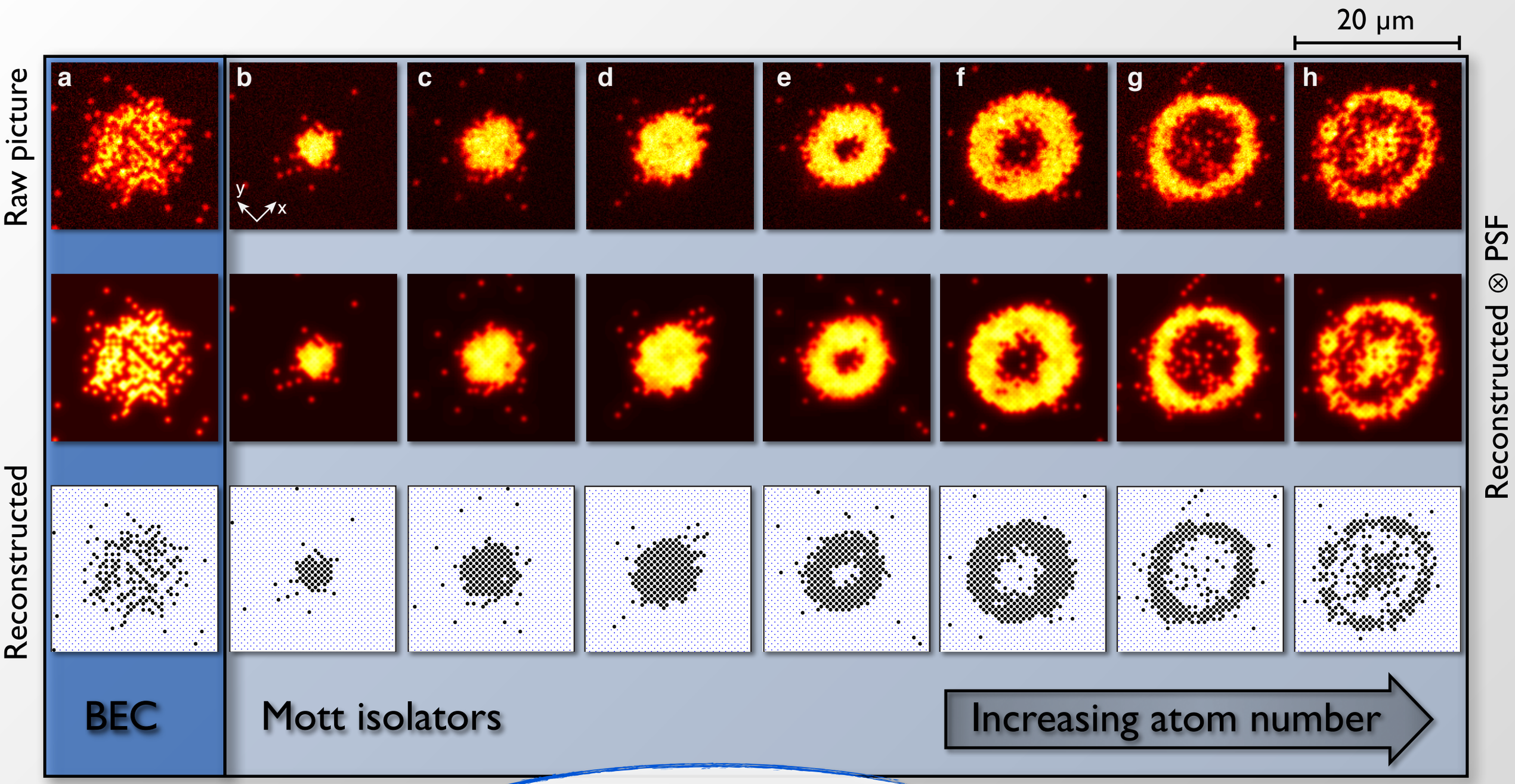
Mott-Insulator



- Number squeezing
- No phase coherence



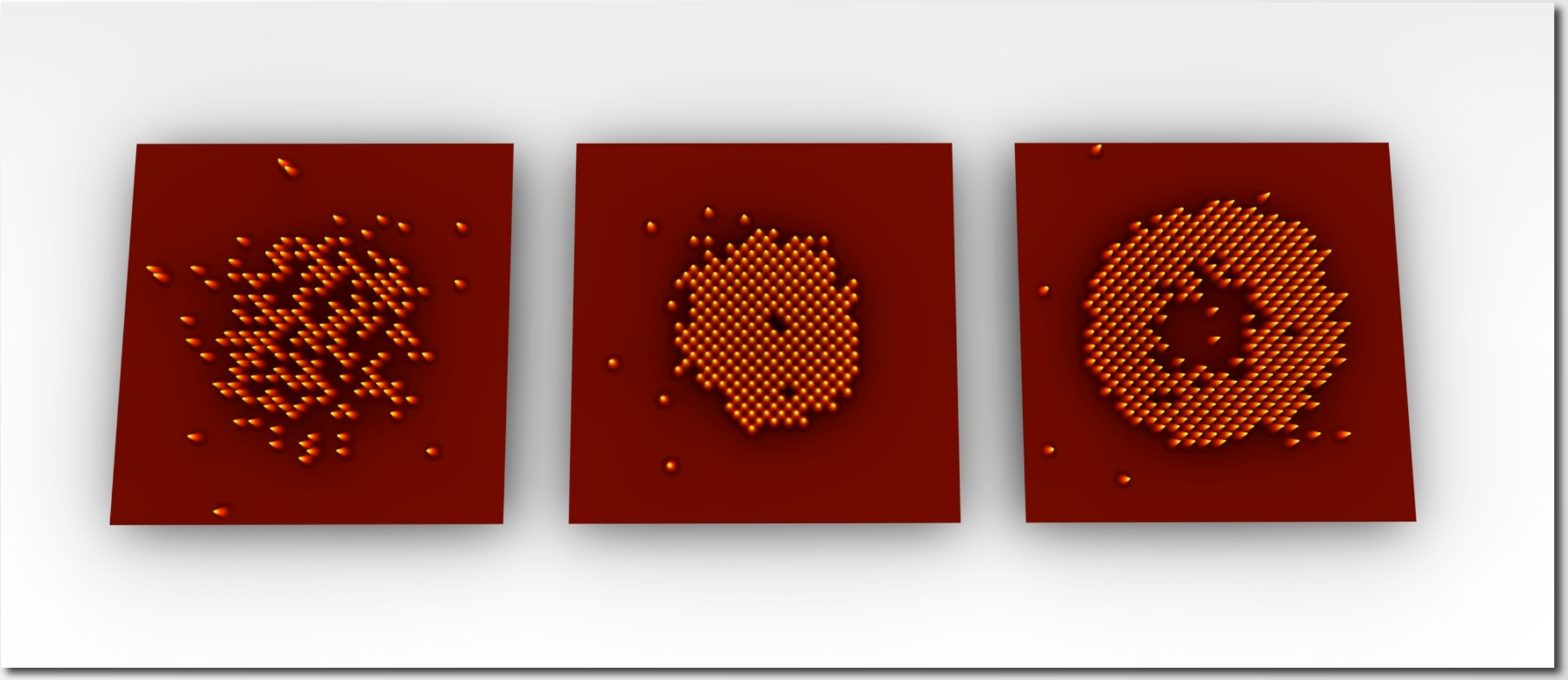
In-situ observation of a Mott insulator



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

⇒ only thermal fluctuations

Snapshot of an Atomic Density Distribution

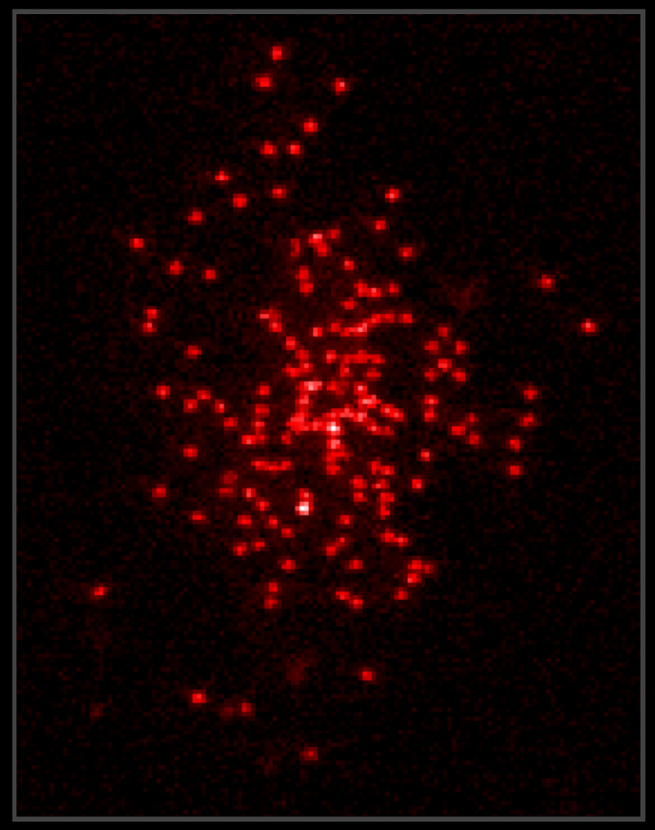


BEC

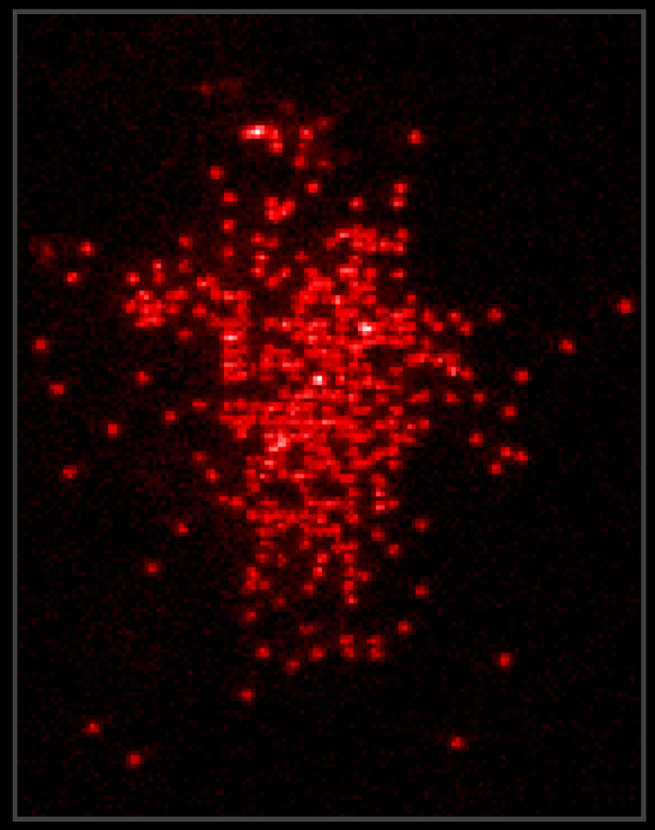
n=1
Mott Insulator

n=1 & n=2
Mott Insulator

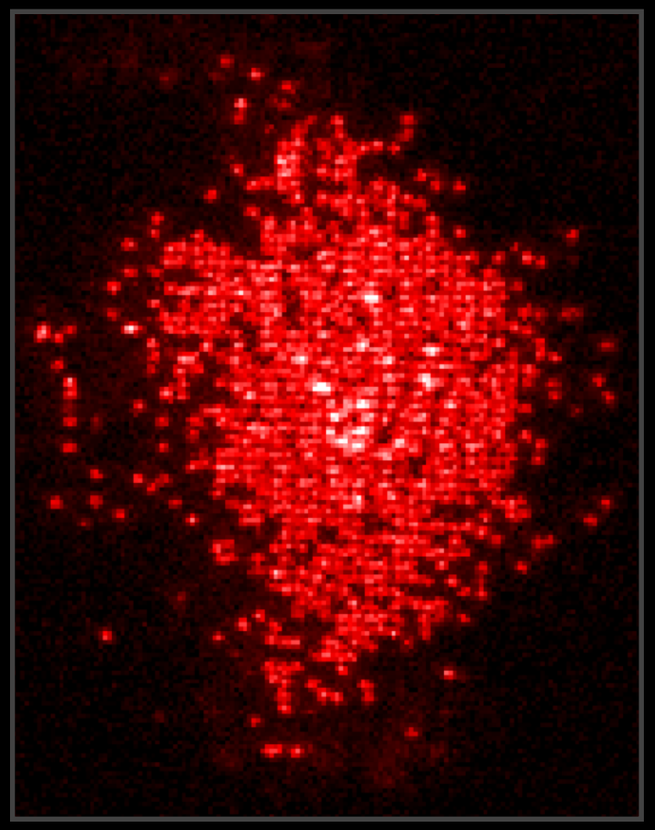
J. Sherson *et al.* Nature **467**, 68 (2010)



dilute



medium



dense - Band Insulator

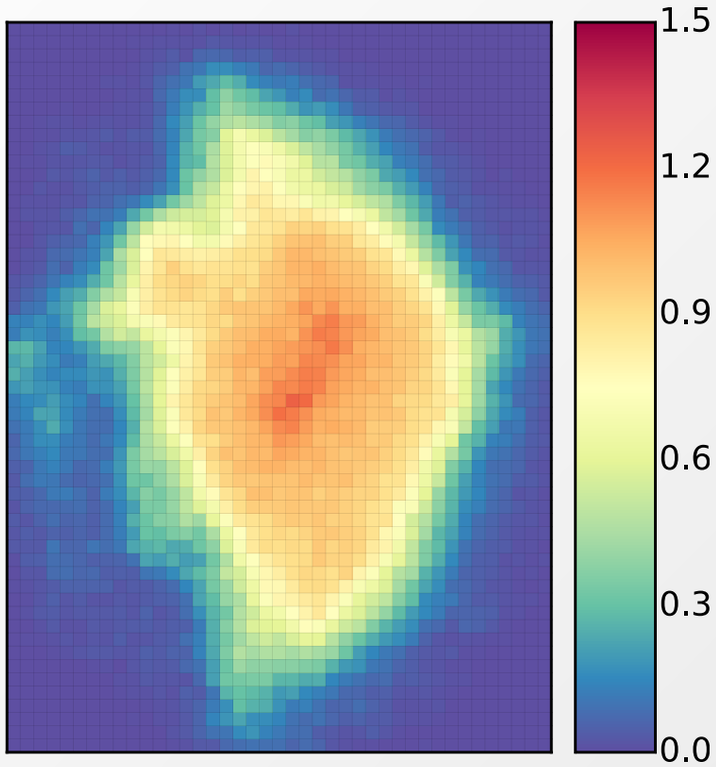
Single Atom Fluorescence Imaging 6-Li

A. Omran et al. arXiv:1510.04599 (2015) (PRL in print)

see also work at Strathclyde, Harvard, MIT, Toronto….

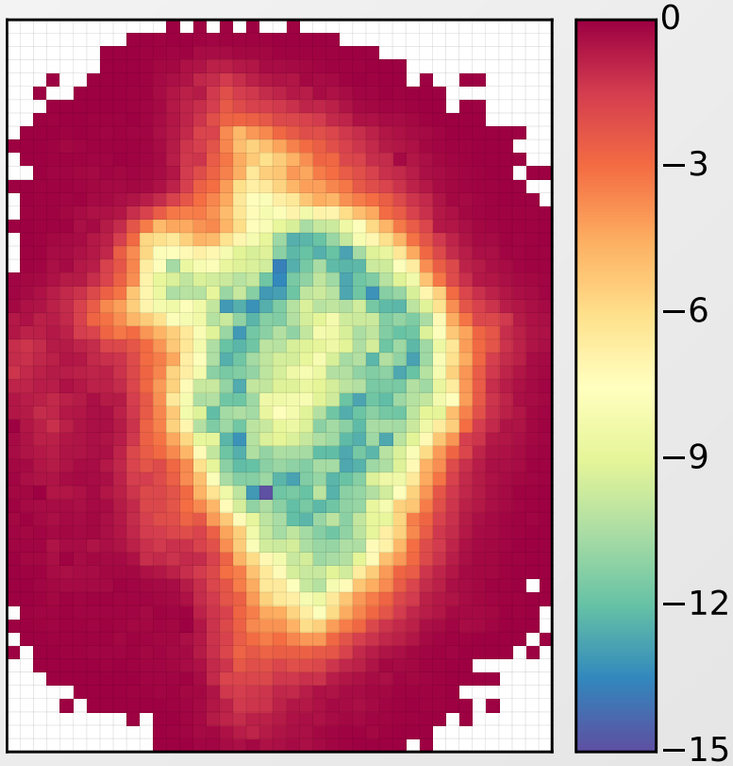
Site Resolved Many-Body State Analysis

Average density



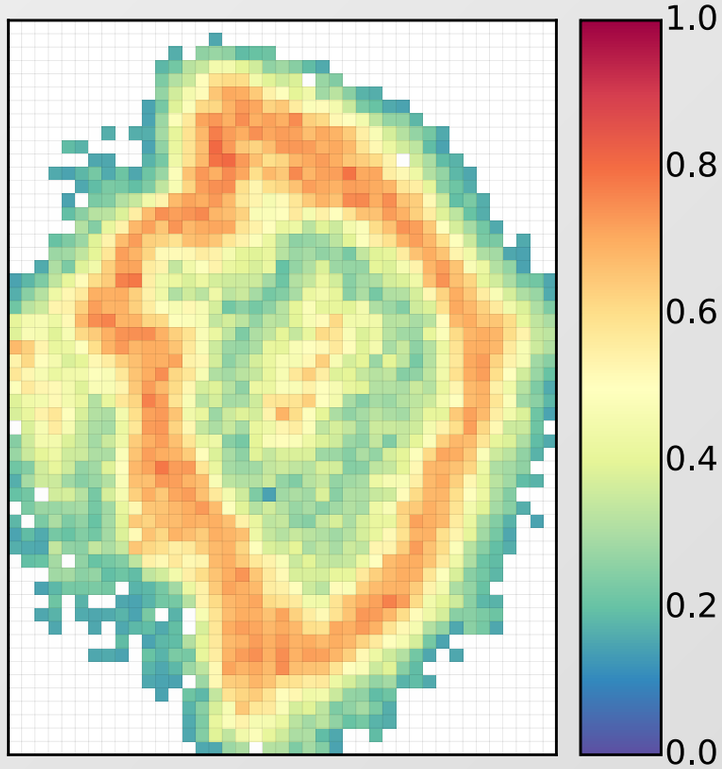
$\bar{n}_i$

Number squeezing (*dB*)



$\frac{\sigma^2_{n,i}}{\bar{n}_i}$

Entropy (k_B)

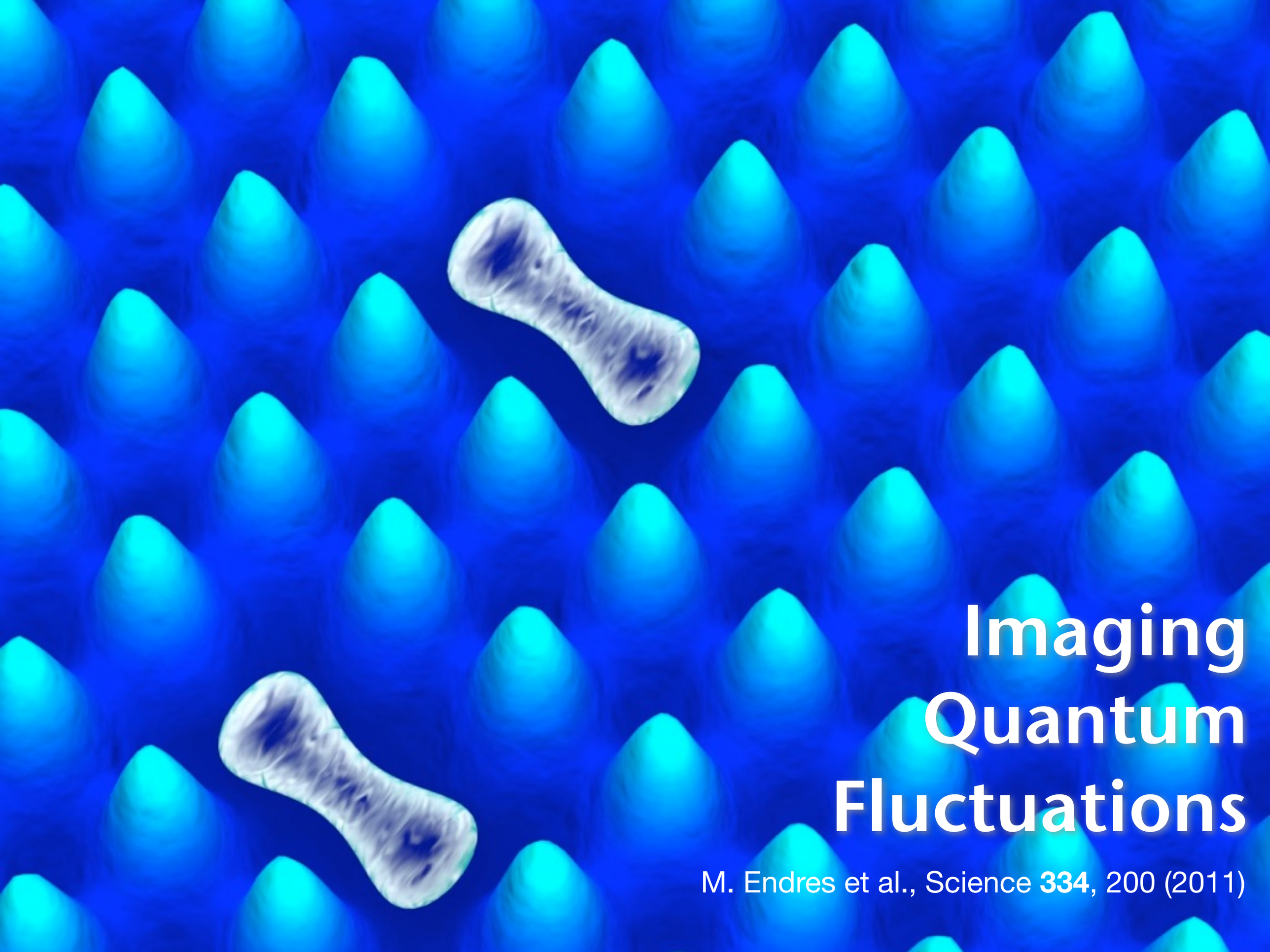


$$S_i = -k_B \sum_{j \in 0,1,2} p_{i,j} \log p_{i,j}$$

Analysis from ~500 single shot images!

Assume Grand Canonical also allows to obtain μ,T,k…

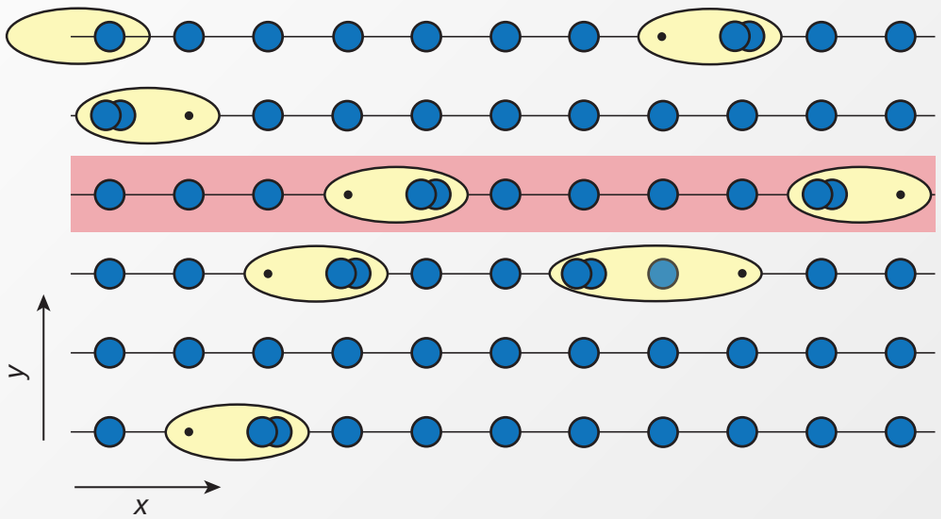
A. Omran et al. arXiv:1510.04599 (2015)

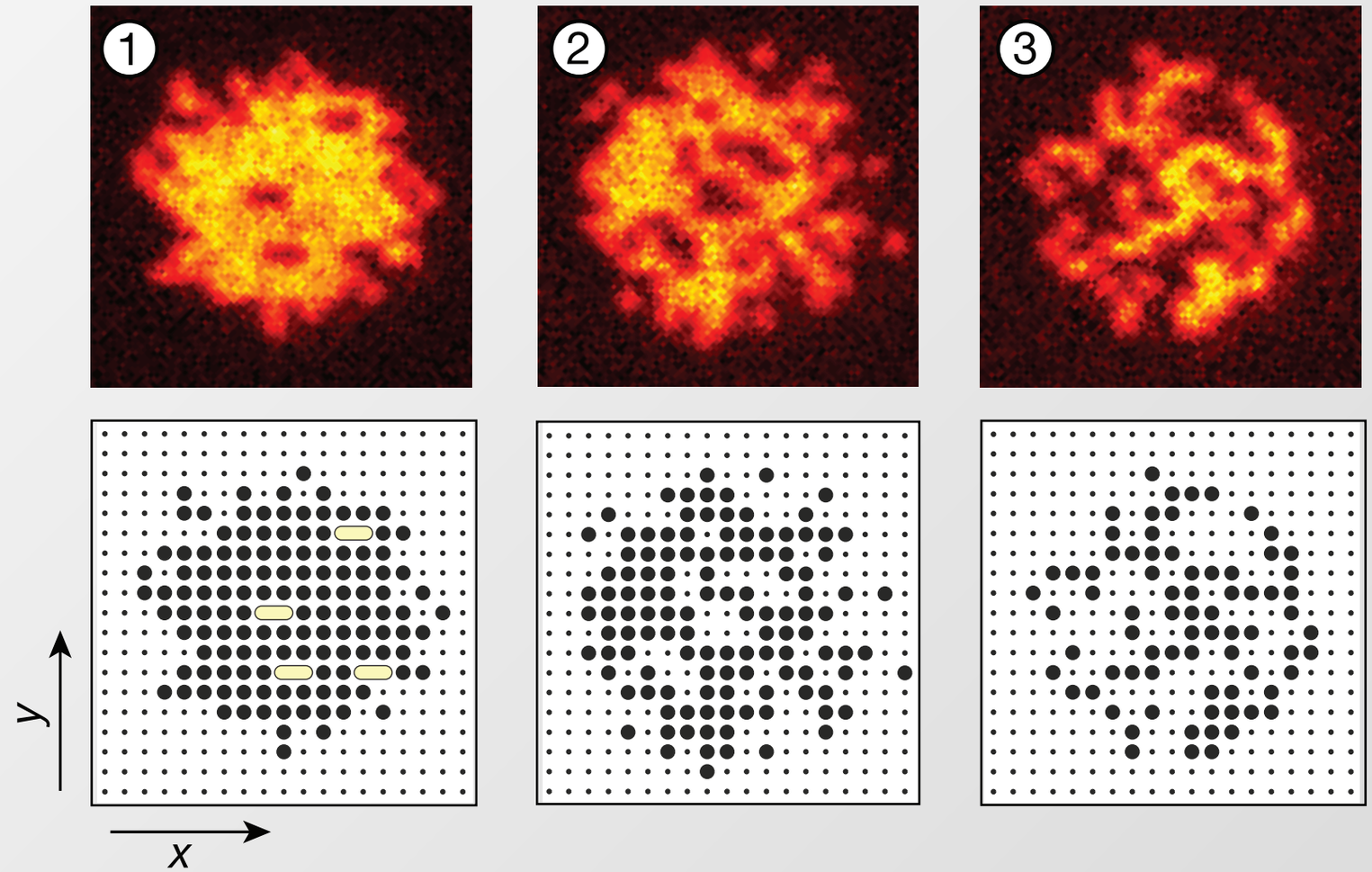


Imaging Quantum Fluctuations

M. Endres et al., Science **334**, 200 (2011)

Quantum Correlated Particle Hole Correlations





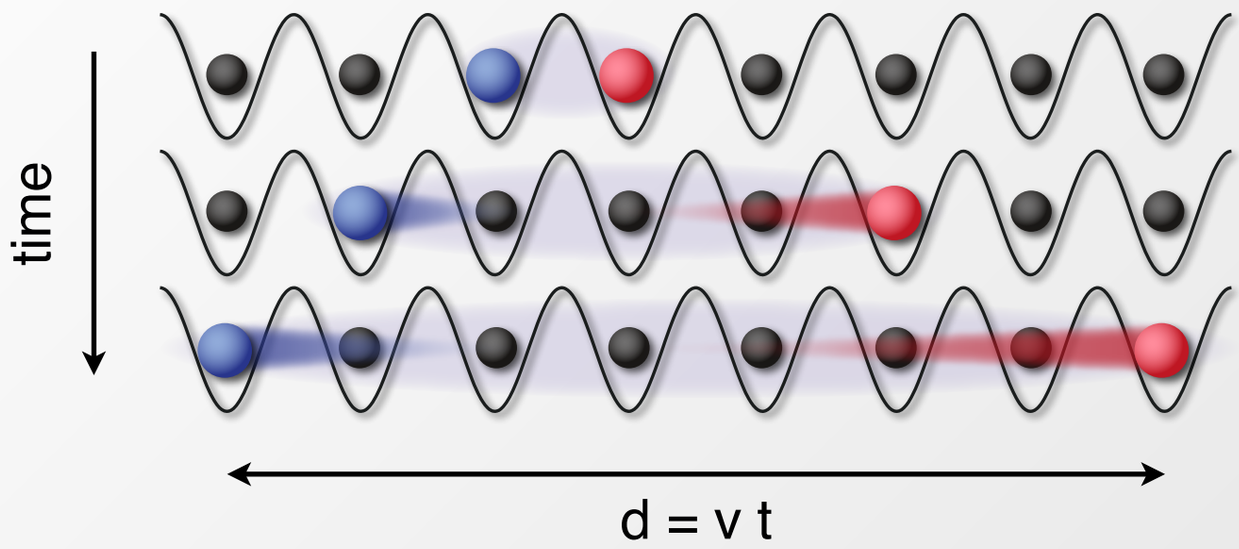
J/*U*=0.06 *J*/*U*=0.11 *J*/*U*=0.3

$$C(d) = \langle \hat{s}_k \hat{s}_{k+d} \rangle - \langle \hat{s}_k \rangle \langle \hat{s}_{k+d} \rangle$$

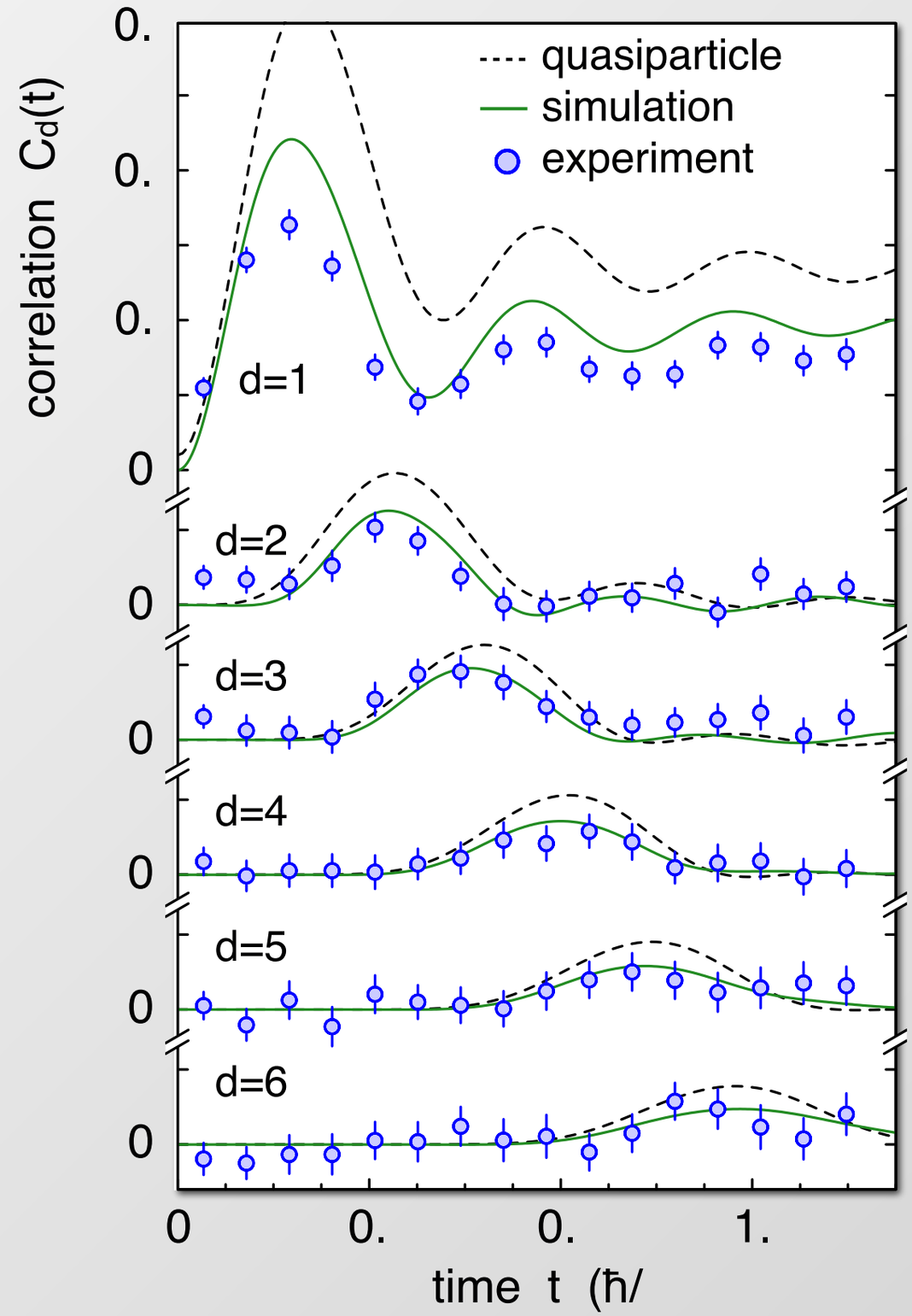
Two point correlator

Light-cone spreading of correlations

- Quasiparticle dynamics



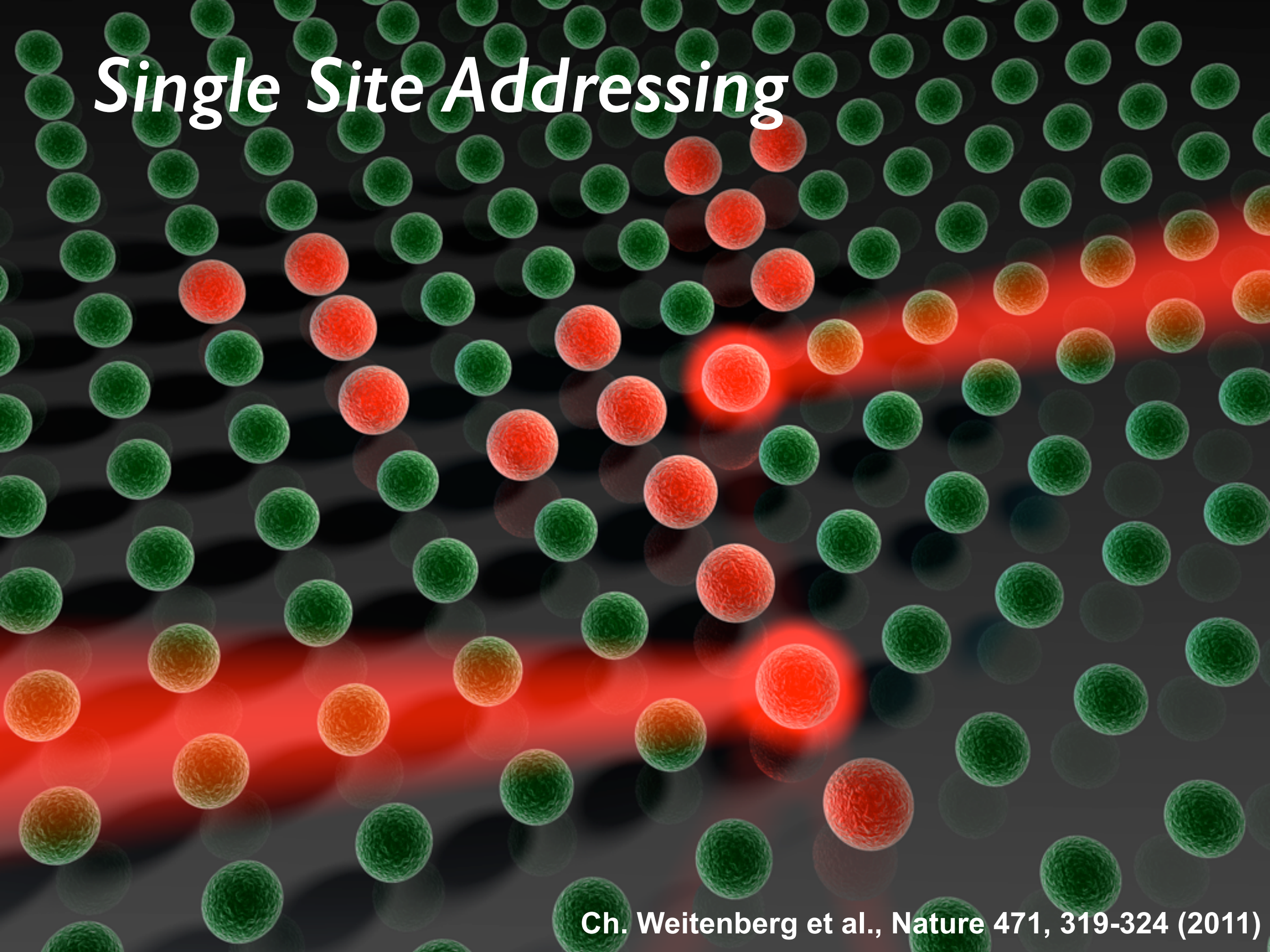
E. Lieb & D.W. Robinson (1972)
Bravyi, Hastings and Verstraete (2006)
Calabrese and Cardy (2006)
Eisert and Osborne (2006)
Nachtergaele, Ogata and Sims (2006)
... and many others since then



Long range interactions:
P. Richerme et al. Nature (2015) & P. Jurcevic et al. Nature (2015)

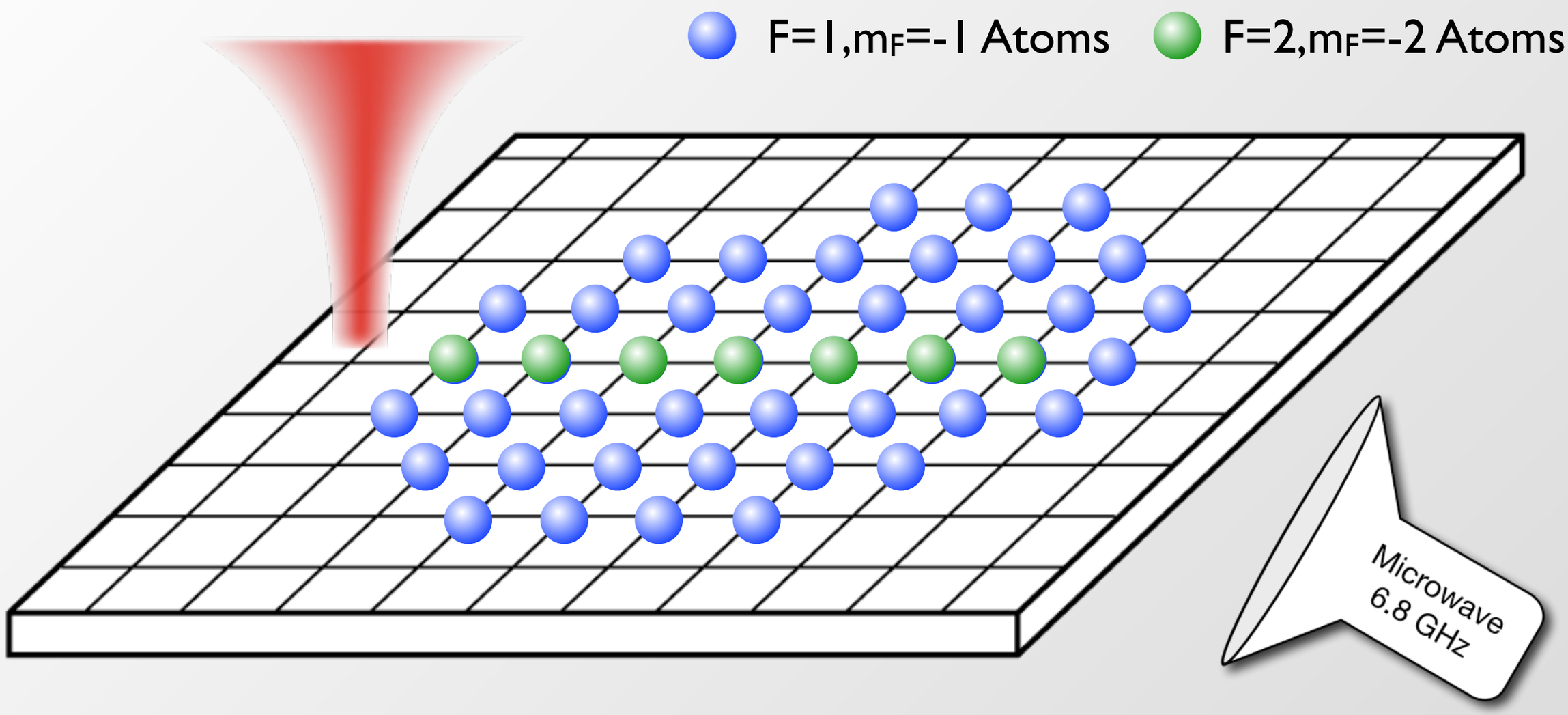
M. Cheneau et al. Nature (2012)

Single Site Addressing



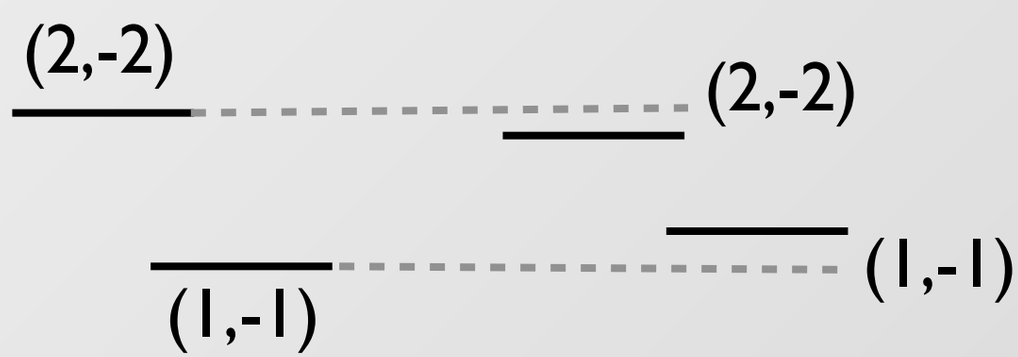
Ch. Weitenberg et al., Nature 471, 319-324 (2011)

Coherent Addressing of Atoms



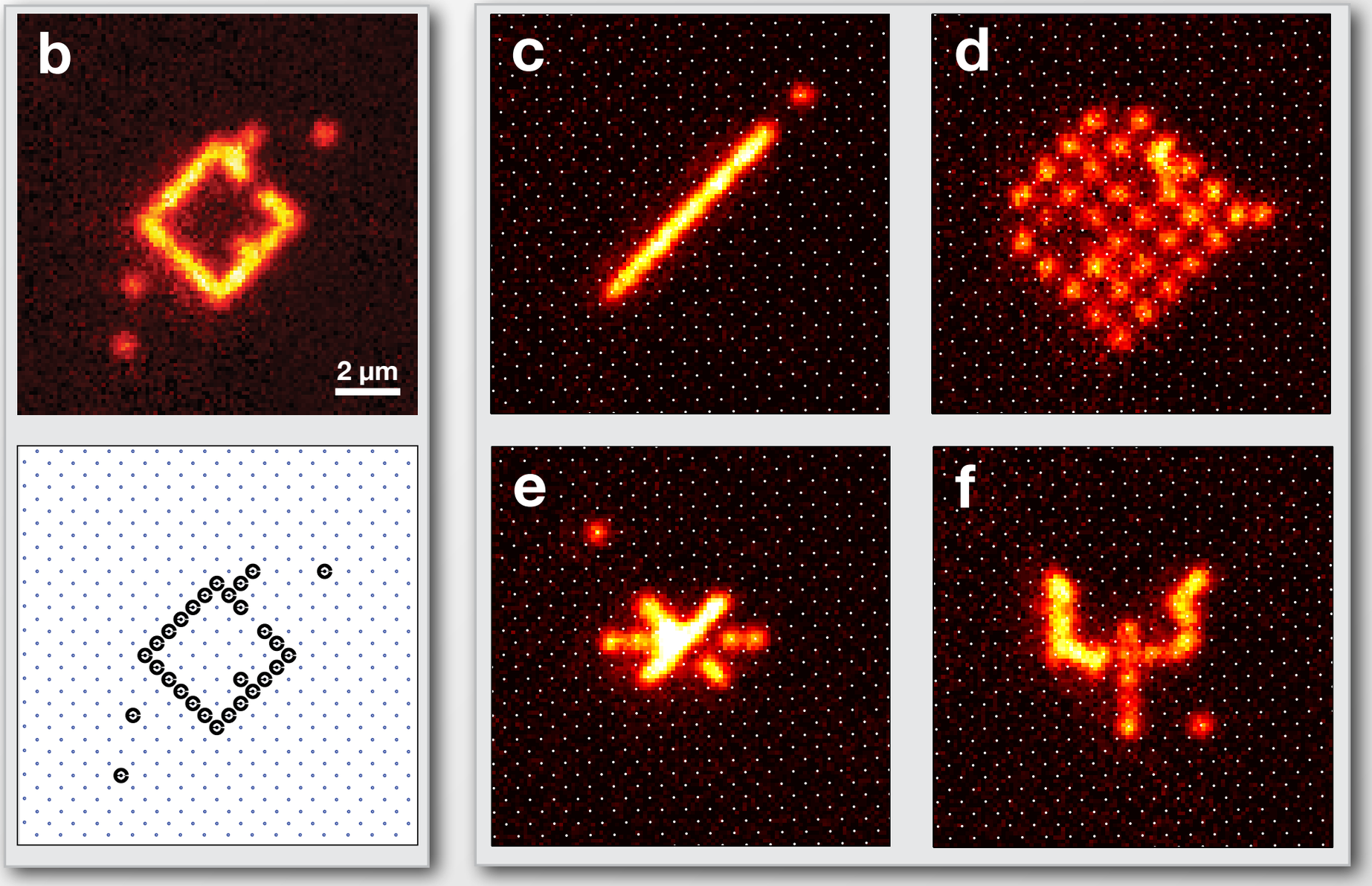
Differential light shift allows to coherently address single atoms!

Landau-Zener Microwave sweep to coherently convert atoms between spin-states.



D.S. Weiss et al., PRA (2004),
Zhang *et al.*, PRA (2006)

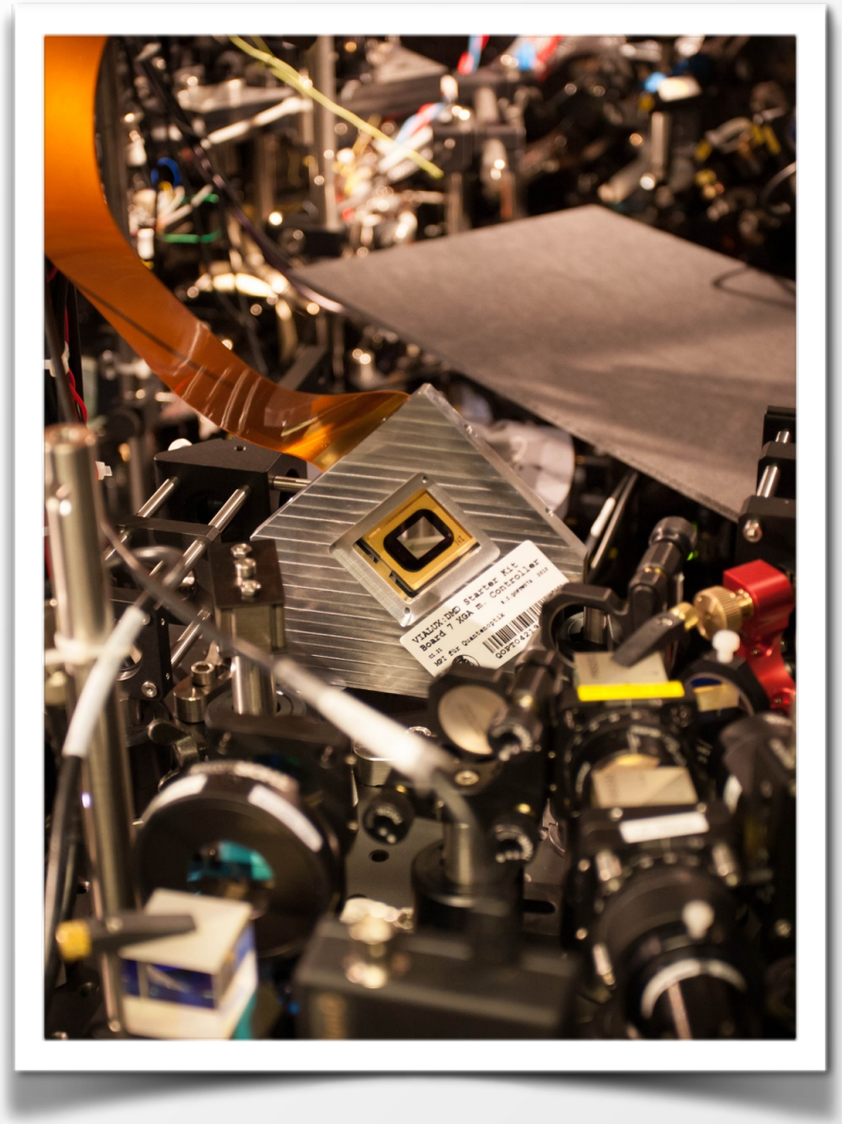
Coherent Spin Flips - Positive Imaging



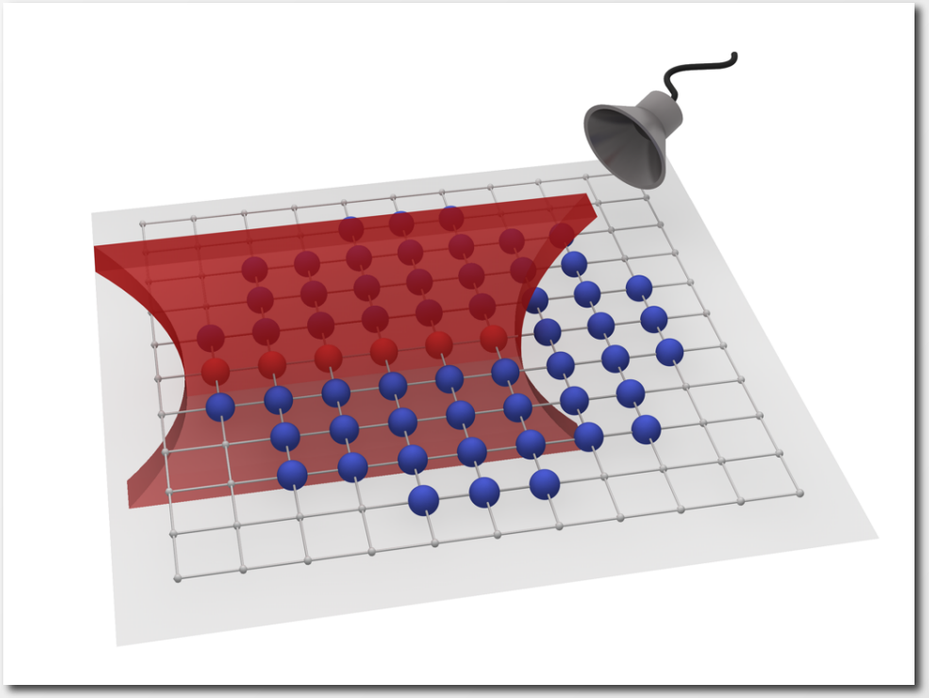
Subwavelength spatial resolution: 50 nm

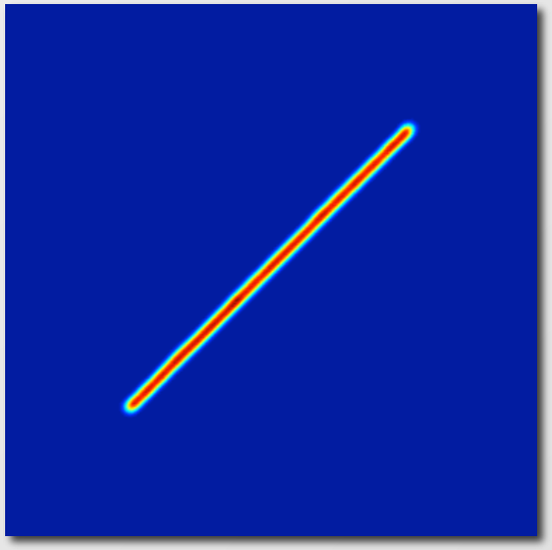
Ch. Weitenberg et al., Nature **471**, 319-324 (2011)

Arbitrary Light Patterns

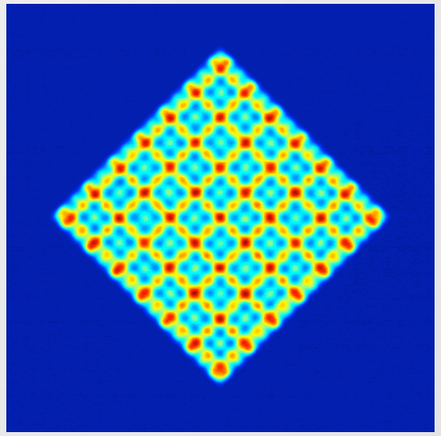


Digital Mirror Device (DMD)

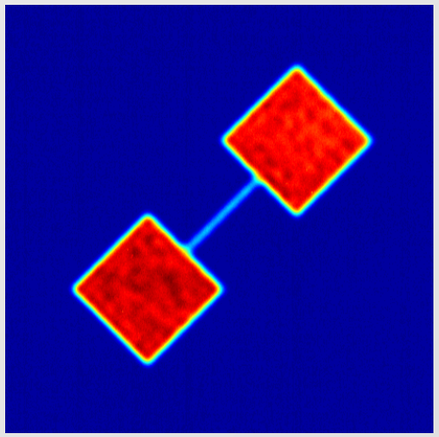




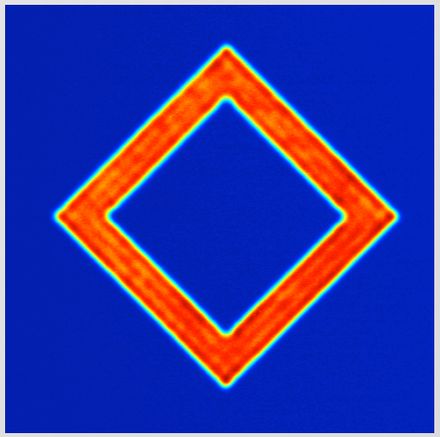
Measured Light Pattern



Exotic Lattices



Quantum Wires

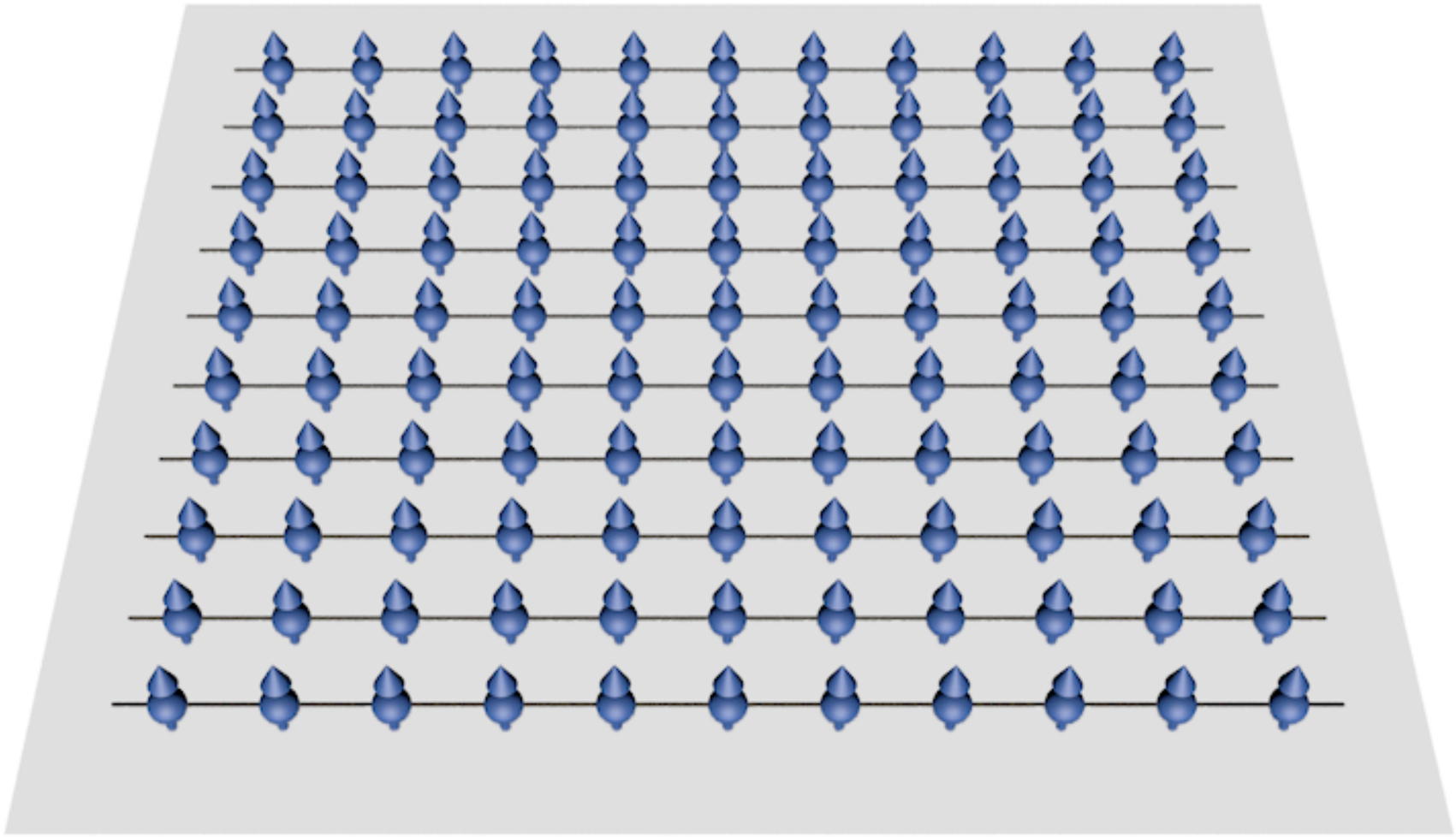


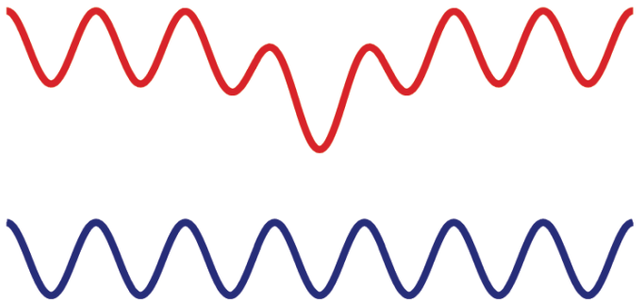
Box Potentials

Almost Arbitrary Light Patterns Possible!

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

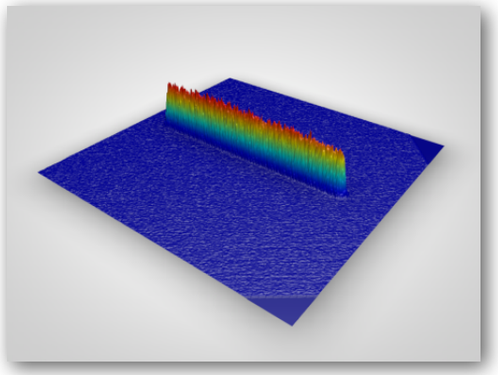
Spin impurity dynamics





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

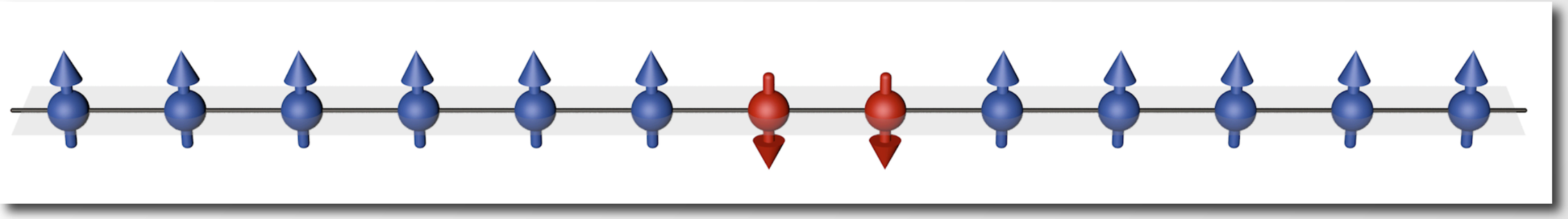
$|1\rangle = |F=1, m_F=-1\rangle$



Line-shaped light field created with DMD SLM

T. Fukuhara et al., Nature Physics **9**, 235 (2013)

Magnon Bound States

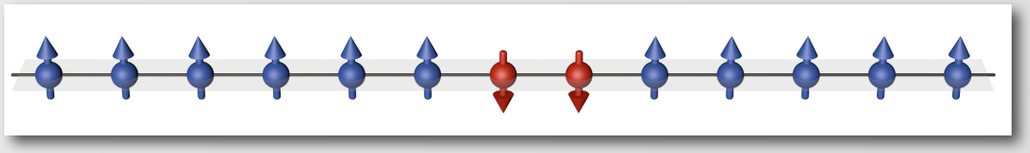


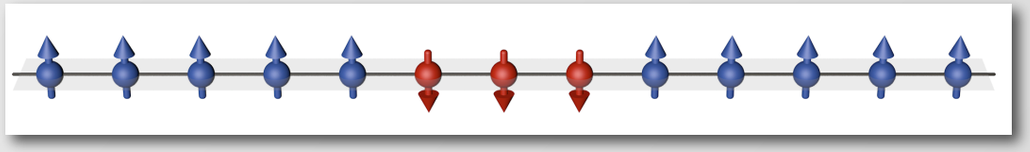
Hans Bethe
(1906-2005)

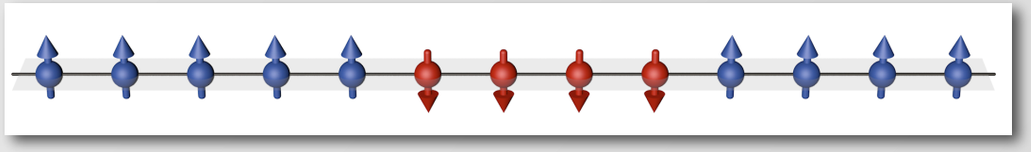
There can be bound states in a Heisenberg spin chain!
Development of Bethe Ansatz.

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

General
l-string bound states



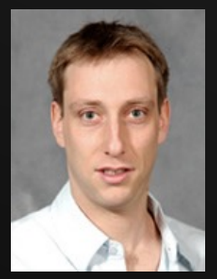




H. Bethe, Z. Phys. (1931)
M. Wortis, Phys Rev. (1963)
M. Takahashi & M. Suzuki Prog. Th. Phys. (1972)
M. Karbach, G. Müller (1997)
see also: **repulsively bound pairs & interacting atoms**
K. Winkler et al. Nature (2006); S. Fölling et al. Nature (2007); Y Lahini et al. PRA (2012)

Many-Body Localisation using Ultracold Atoms

M. Schreiber et al. Science **349**, 842 (2015)
P. Bordia et al. arXiv 1509.00478


E. Altman


R. Vosk


M. Fischer

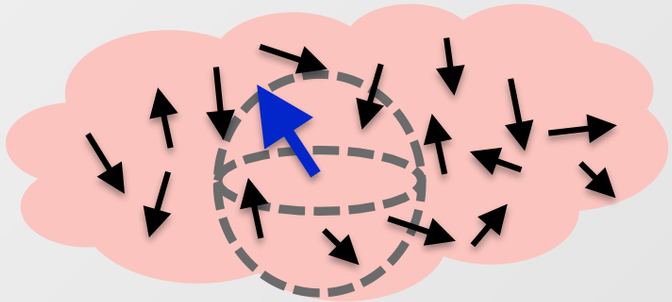
Motivation

Thermalization

Quantum correlations in local d.o.f are rapidly lost as these get entangled with the rest of the system.

Classical hydro description of remaining slow modes (conserved quantities, and order parameters).

Many-body localization



Local quantum information persists indefinitely.

Need a fully **quantum** description of the long time dynamics!

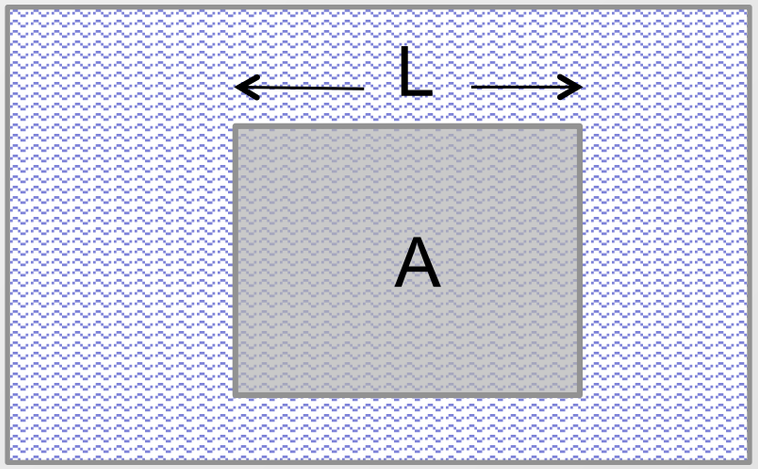
?

The many-body localization transition = elusive interface between quantum and classical worlds

Eigenstate Thermalisation Hypothesis

Deutsch (91), Srednicki (94,98), Rigol, Dunjko & Olshanii (2009)

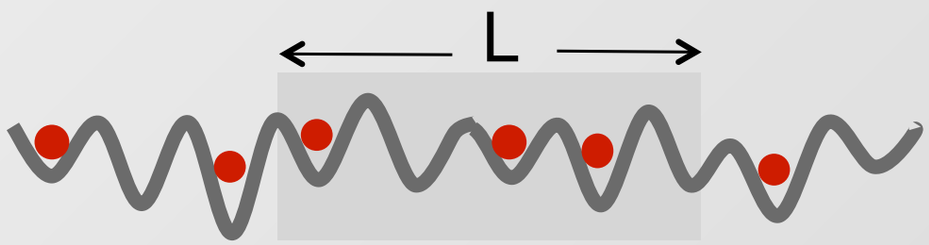
$$\rho_A = \frac{1}{Z_A} e^{-\beta H_A}$$



$$S_A \equiv \mathrm{tr}\left[\rho_A \ln \rho_A\right] \propto L^d$$

Anderson localization is
an example where ETH fails:

"Area law" entropy even in
high energy eigenstates



$$S_A \propto L^{d-1}$$

Many body localization = stability of such localized states to interactions

System fails to act as its own heat bath!

Approaching Many-Body Localization from Disordered Luttinger Liquids
C. Karrasch, J. E. Moore
Subjects: Strongly Correlated Electrons (cond-mat.str-el)
28. arXiv:1506.00592 [pdf, other]
Protection of topological order by symmetry and many-body loc
Andrew C. Potter, Ashvin Vishwanath
Comments: 17 pages, 4 figures
Subjects: Disordered Systems and Neural Networks (cond-mat.
29. arXiv:1505.07089 [pdf, other]
Dynamics of many-body localisation in a translation invariant qu
Merlijn van Horssen, Emanuele Levi, Juan P. Garrahan
Comments: 5 pages, 4 figures
Subjects: Statistical Mechanics (cond-mat.stat-mech); Quantum
30. arXiv:1505.06343 [pdf, ps, other]
Many-body ground state localization and coexistence of localize
Yucheng Wang, Haiping Hu, Shu Chen
Comments: 5 pages, 6 figures
Subjects: Disordered Systems and Neural Networks (cond-mat.
31. arXiv:1505.05386 [pdf, other]
Revisiting Many-body Localization with Random Networks of Te
Benoît Descamps, Frank Verstraete
Comments: 3 figures
Subjects: Quantum Physics (quant-ph)
32. arXiv:1505.05147 [pdf, other]
Many-Body Localization of Symmetry Protected Topological States
Kevin Slagle, Zhen Bi, Yi-Zhuang You, Cenke Xu
Comments: 5 pages 2 figures
Su
33.
Ou
L. I
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Su
34.
Tota
J. Goold, C. Gogolin, S. R. Clark, J. Eisert, A. Scardicchio, A. Silva
Comments: Slight Restructuring of the manuscript and additional analysis performed
Subi
35.
Mar
Xiao
Com
Sub
36.
Mar
Ran
Com
Sub
37.
Loca
Alexander L. Burin
Comments: Modified version after review
Subjects: Disordered Systems and Neural Networks (cond-mat.dis-nn)
38. arXiv:1503.06147 [pdf, other]
Many-body localization characterized from a one-particle perspective

ntum Physics (quant-ph)

at.stat-mech); Strongly Correlated Electrons (cond-mat.str-el)

le particle and many-body problems

Pioneering work:
D. M. Basko, I. L. Aleiner, B. L. Altschuler, Ann. Phys. (2006).

Good review/intro:
D. A. Huse, R. Nandkishore, V. Oganesyan,
Annu. Rev. Cond. Mat. 6, 15 (2015)

R. Vosk & E. Altman,
Annu. Rev. Cond. Mat. 6, 383 (2015)

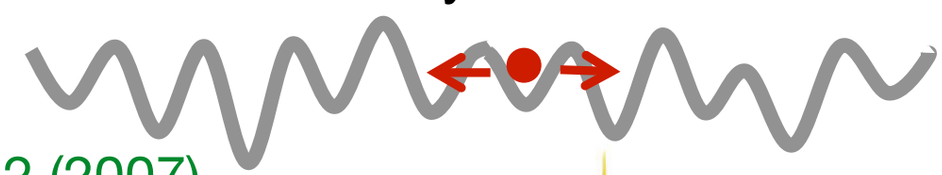
No Experiments!

Two Experiments!
ultracold atoms &
ions (see C. Monroe group)

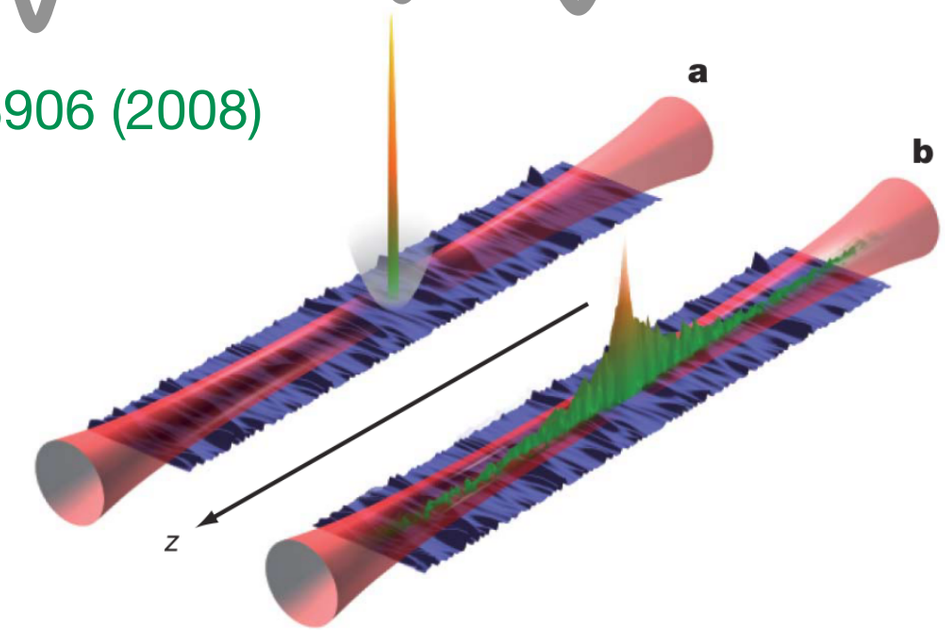
Measuring Localisation

Anderson localization:

Ready…Set…Go!



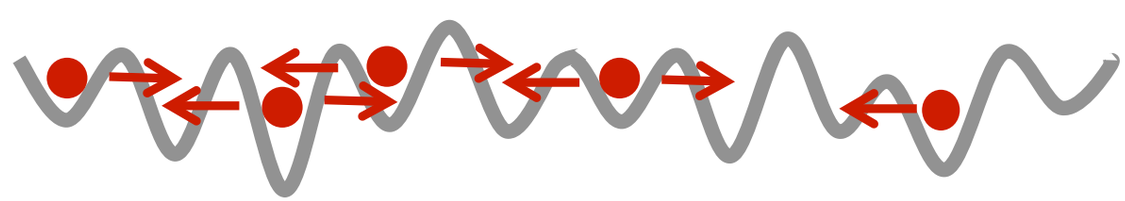
T. Schwartz et al. Nature **446**, 52 (2007)
Y. Lahini, et al. Phys. Rev. Lett. **100**, 013906 (2008)
J. Billy et. al. Nature 2008 (Inst. Opt.)
G. Roati et. al. Nature 2008 (LENS)

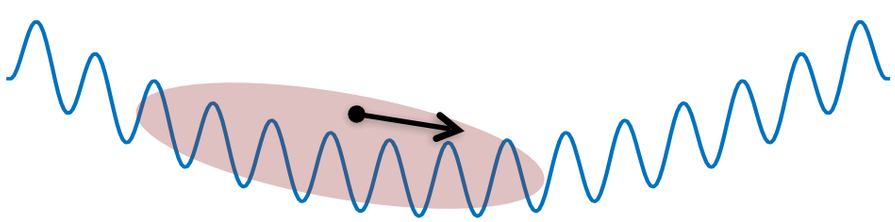


Many-body localization:

Ready…Set…Go!

Fastest timescale: local probe!



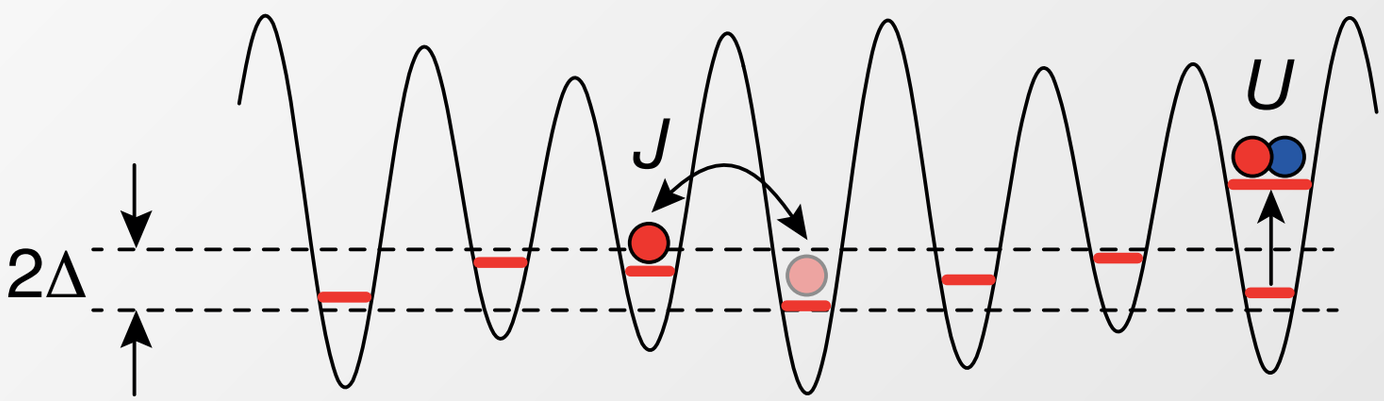


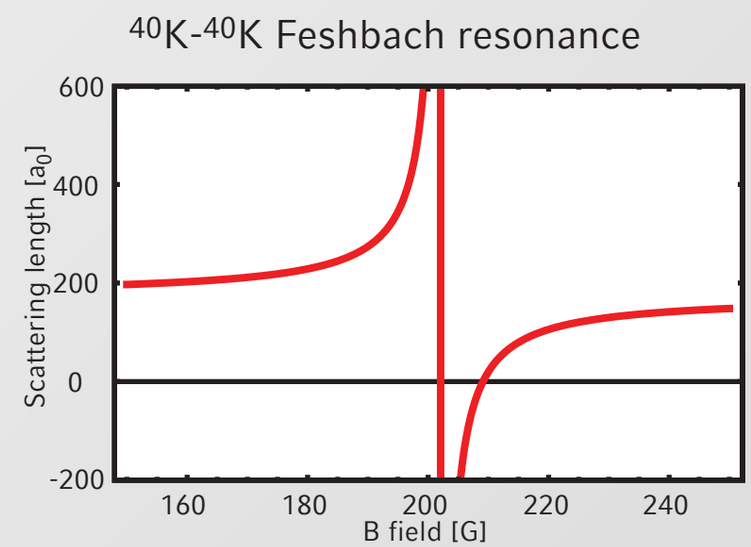
Slowest timescale: global probe

Kondov et al. (DeMarco) Phys. Rev. Lett. 114, 083002 (2015)

Our System - 1D Quasi-Disordered Fermi-Hubbard

$$H = -J\sum_{i,\sigma}\left(\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i+1,\sigma} + H.c.\right) + \Delta\sum_{i,\sigma} sin\left(2\pi\alpha i + \phi\right)\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i,\sigma} + U\sum_{i}\hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$





Without interactions U=0 : Aubry-André model

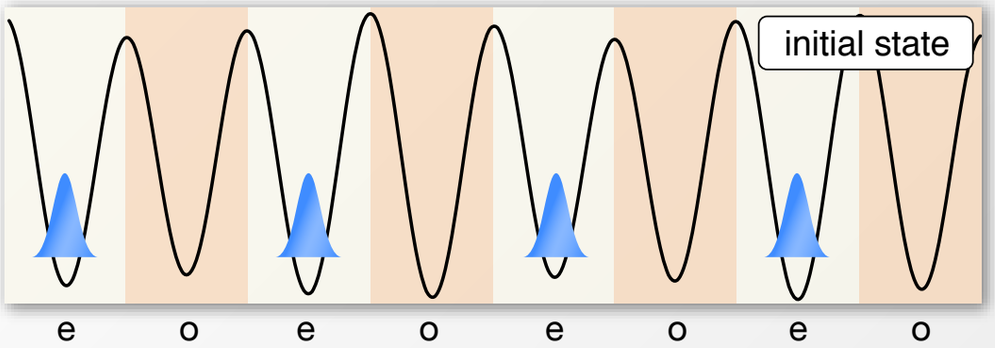
- Homogenous tunneling but quasi-random onsite energies
- α is the incommensurability ratio, irrational, in the experiment ≈ 0.721

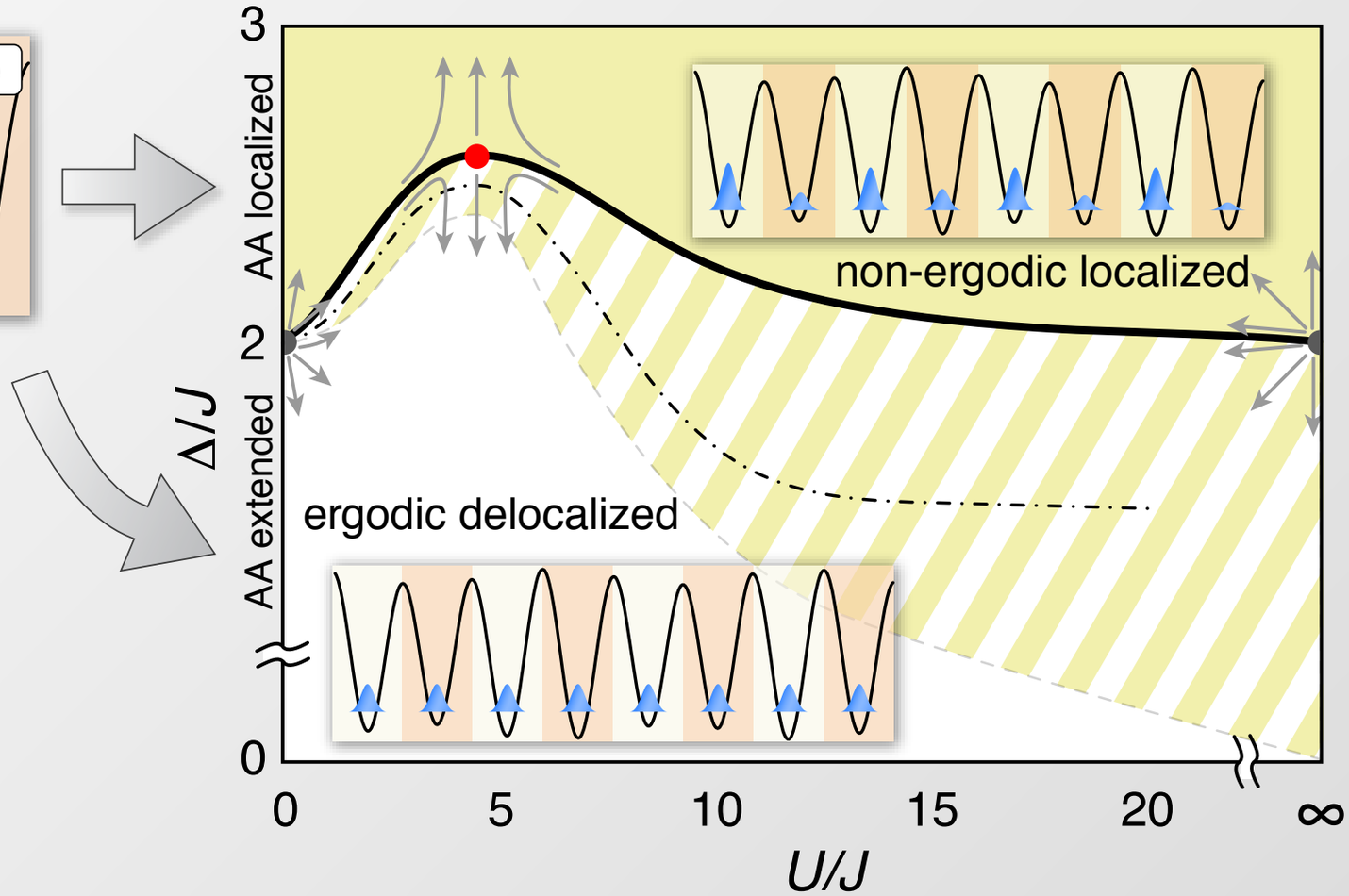
All eigenstates extended for Δ/J < 2

<u>All eigenstates exponentially localised for Δ/J > 2</u>

G. Roati et al. Nature (2008)

Probing the Interacting Aubry-André Model





Three Step Procedure

1) Prepare CDW (with different doublon densities)
2) Evolve in disorder
3) Readout CDW (disorder averaged)

Main Observable: **Imbalance** $I = \frac{N_e - N_o}{N_e + N_o}$

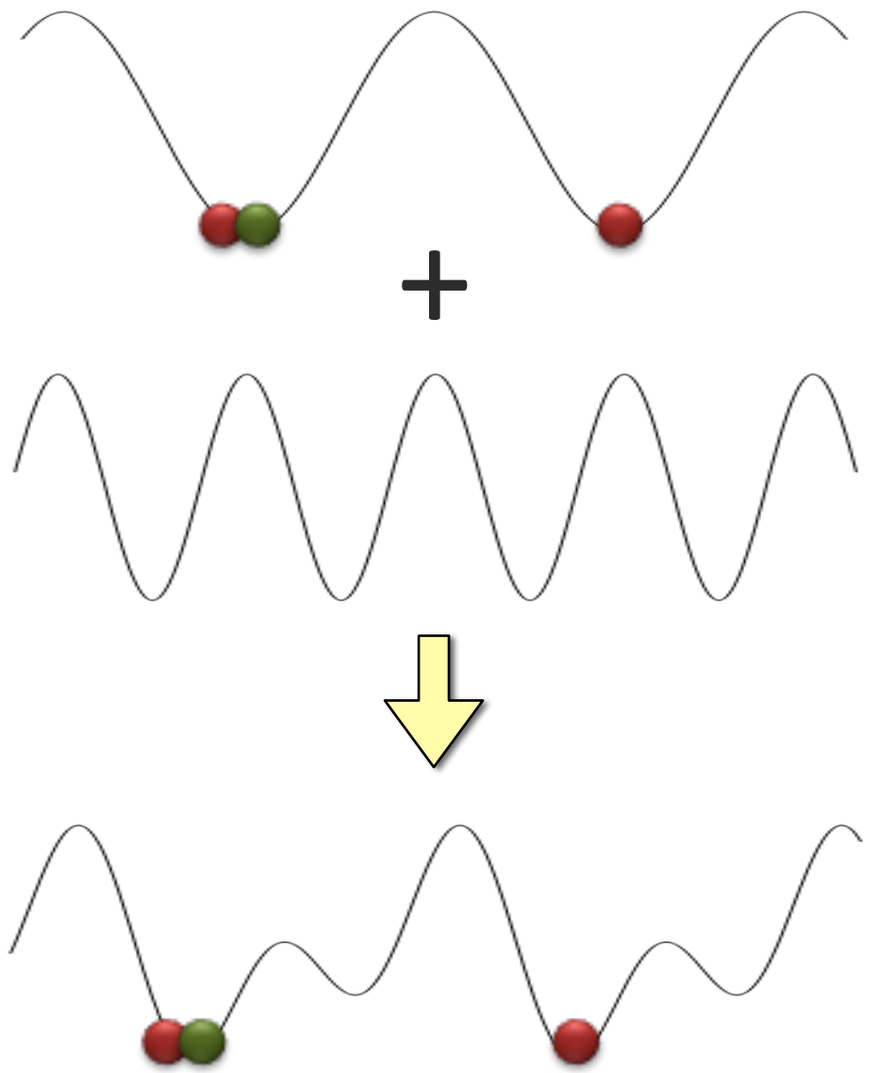
Hamming Distance

$$D(t) = \frac{N}{2}\left[1 - I(t)\right]$$

(see P. Hauke & M. Heyl, PRB 2015)

Preparing the CDW Wave

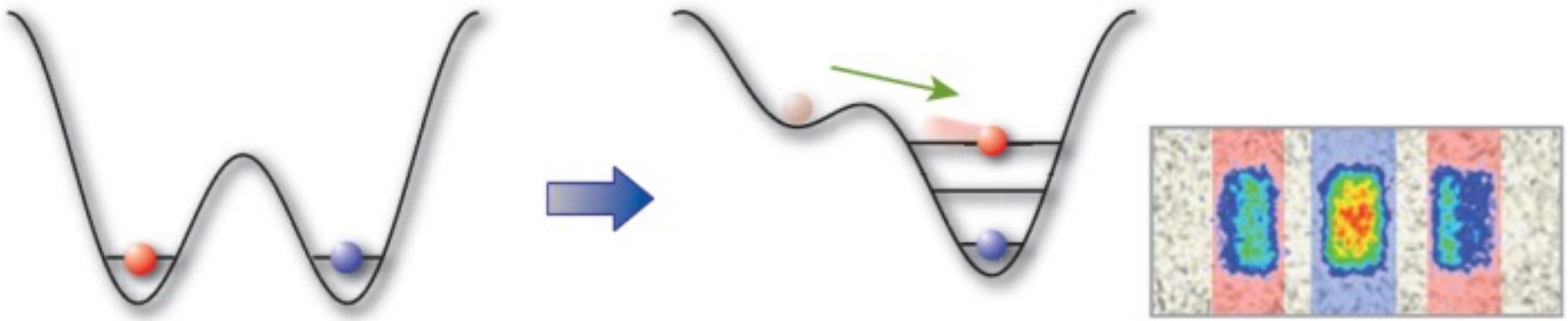
Superimpose **two lattices**, with: $\lambda_l = 2\lambda_s$ (here 532 nm & 1064 nm)



Adiabatic ramp-up with correct relative phase

All particles localised on even sites I>95%

Site resolved even-odd detection



Merge wells in presence of tilt

↓

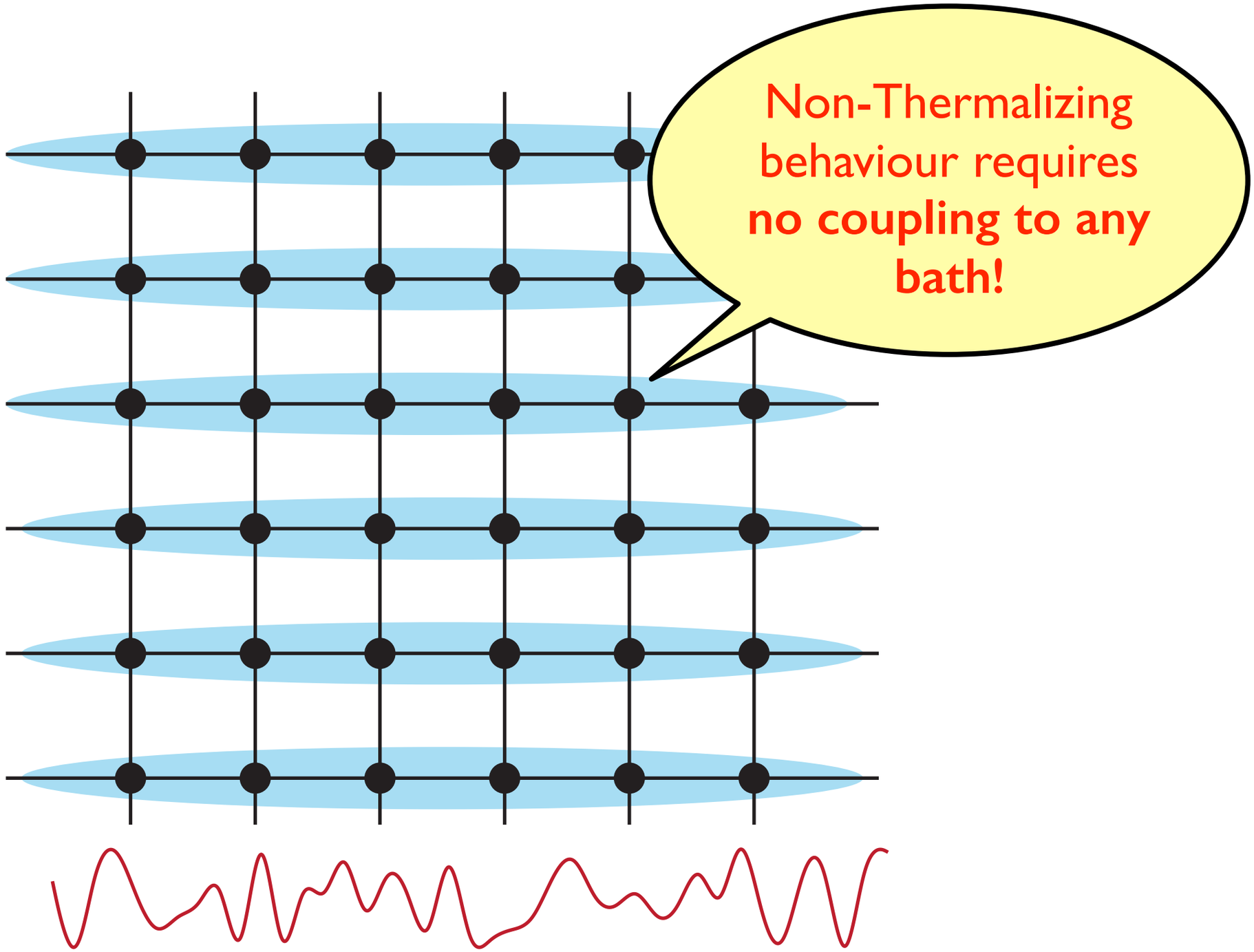
Band mapping

↓

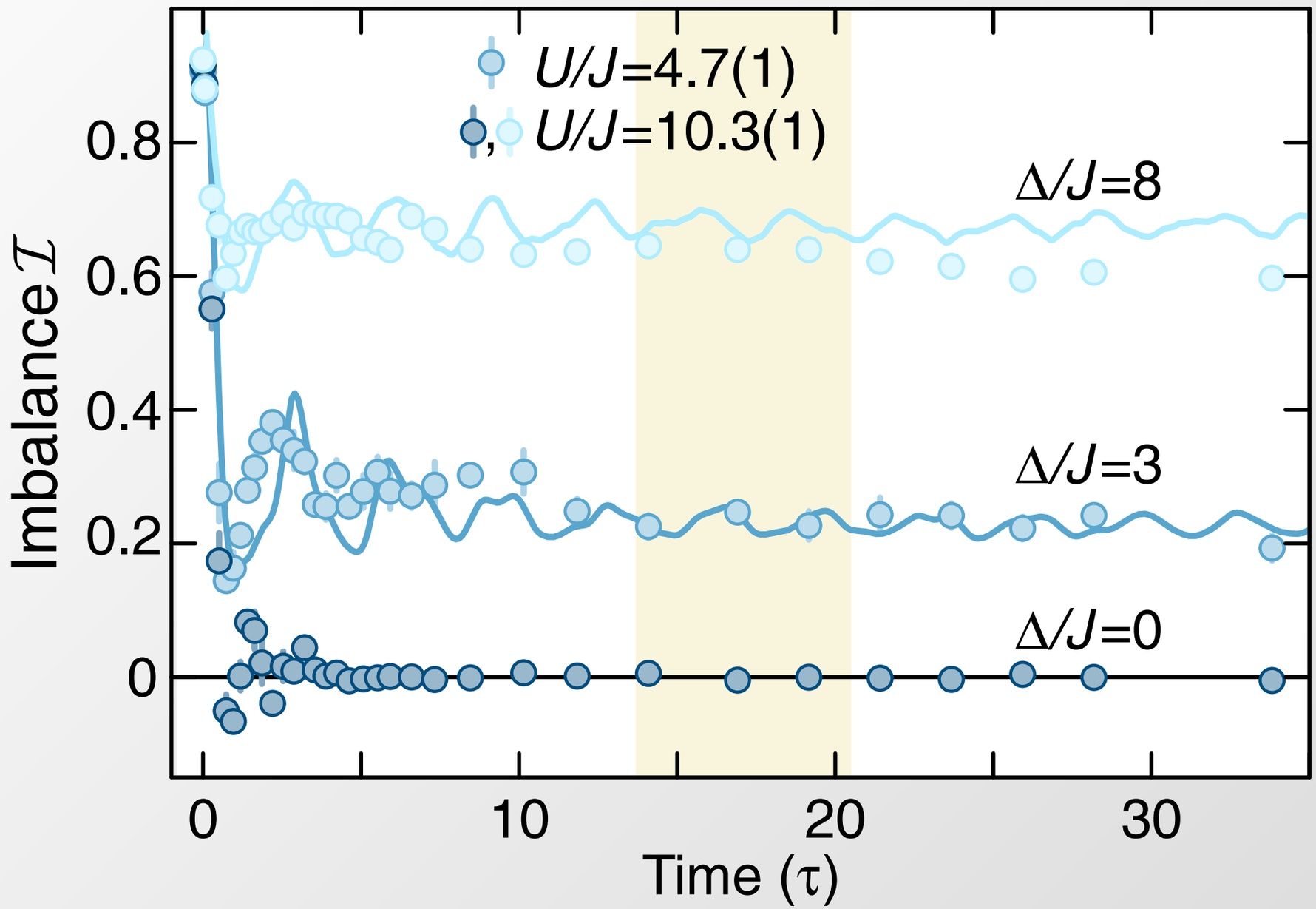
Absorption imaging after TOF

$$I = \frac{N_e - N_o}{N_e + N_o}$$

Experimental Setup 1D

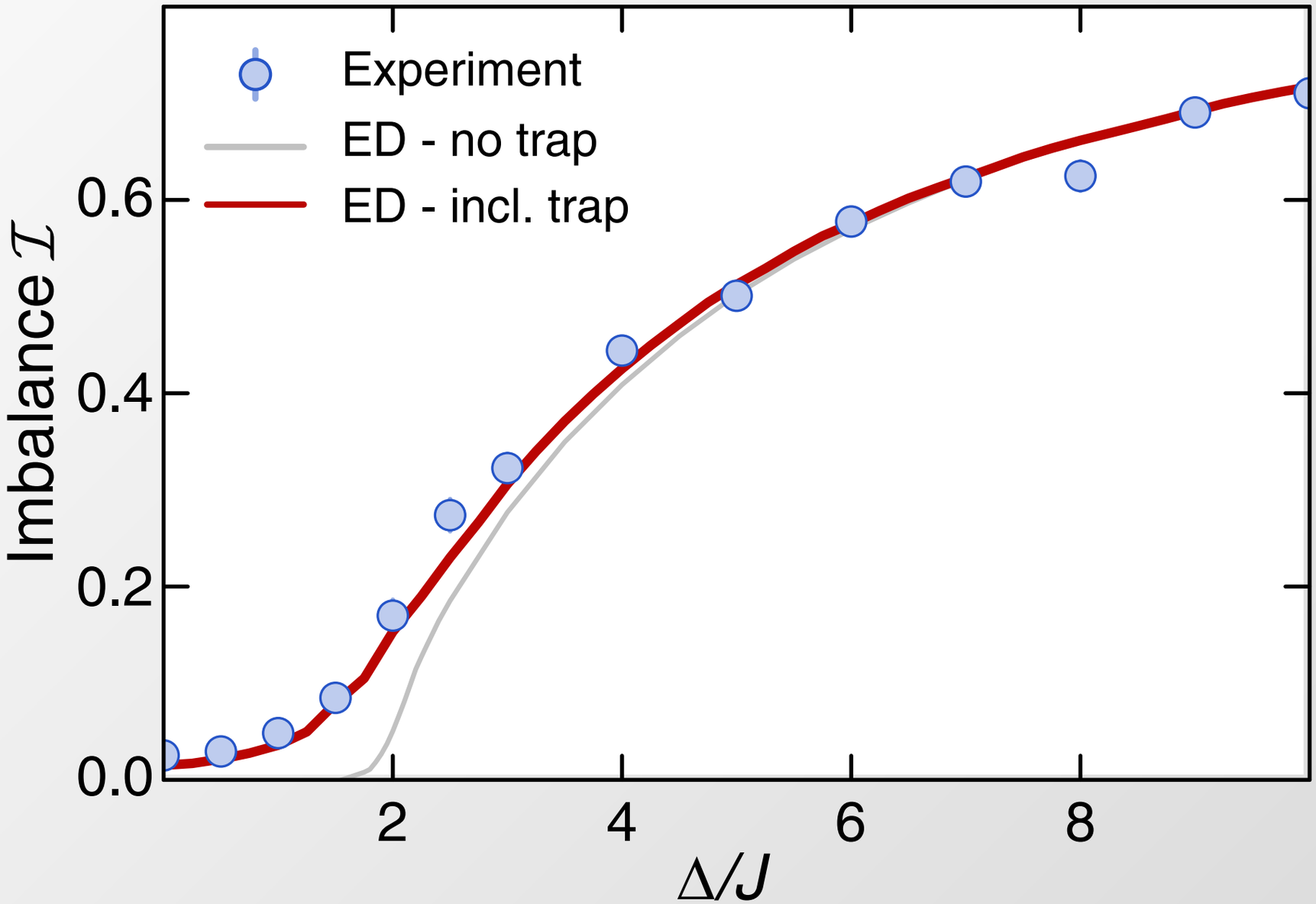


Time Evolution

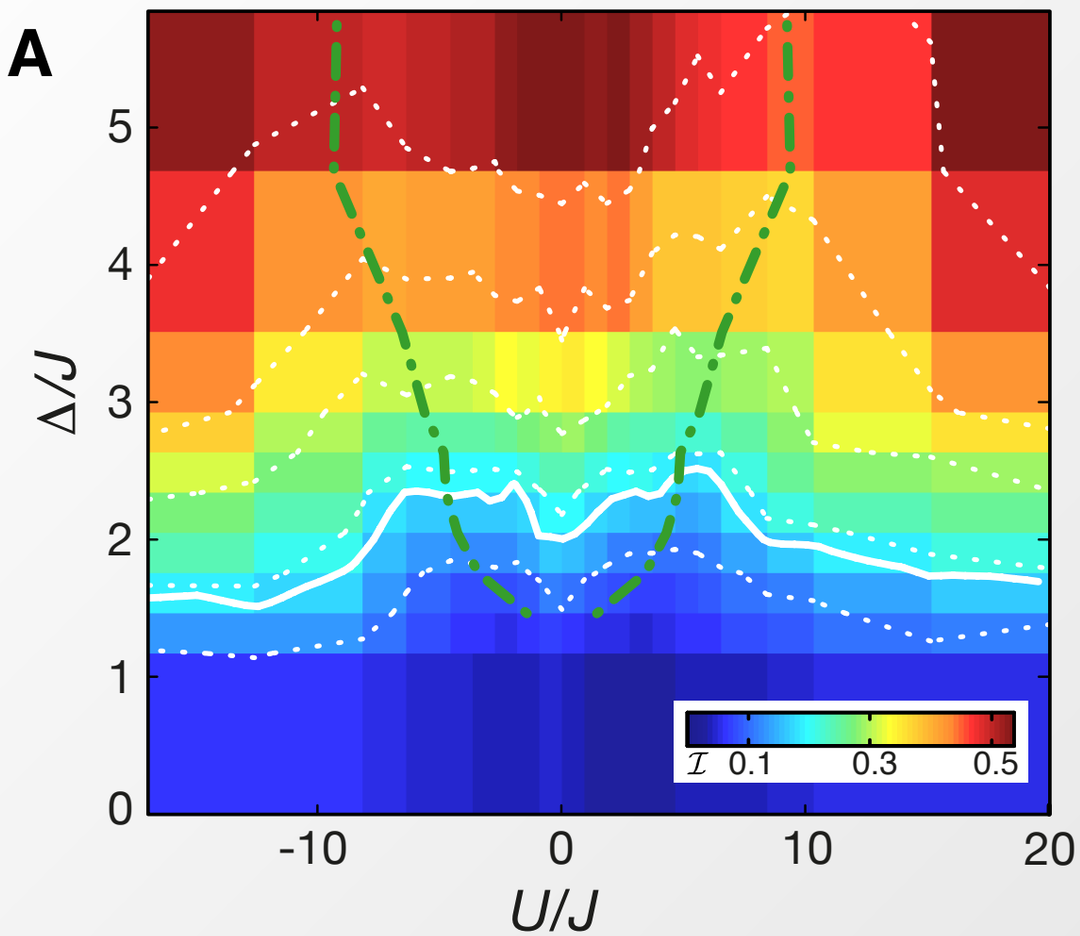


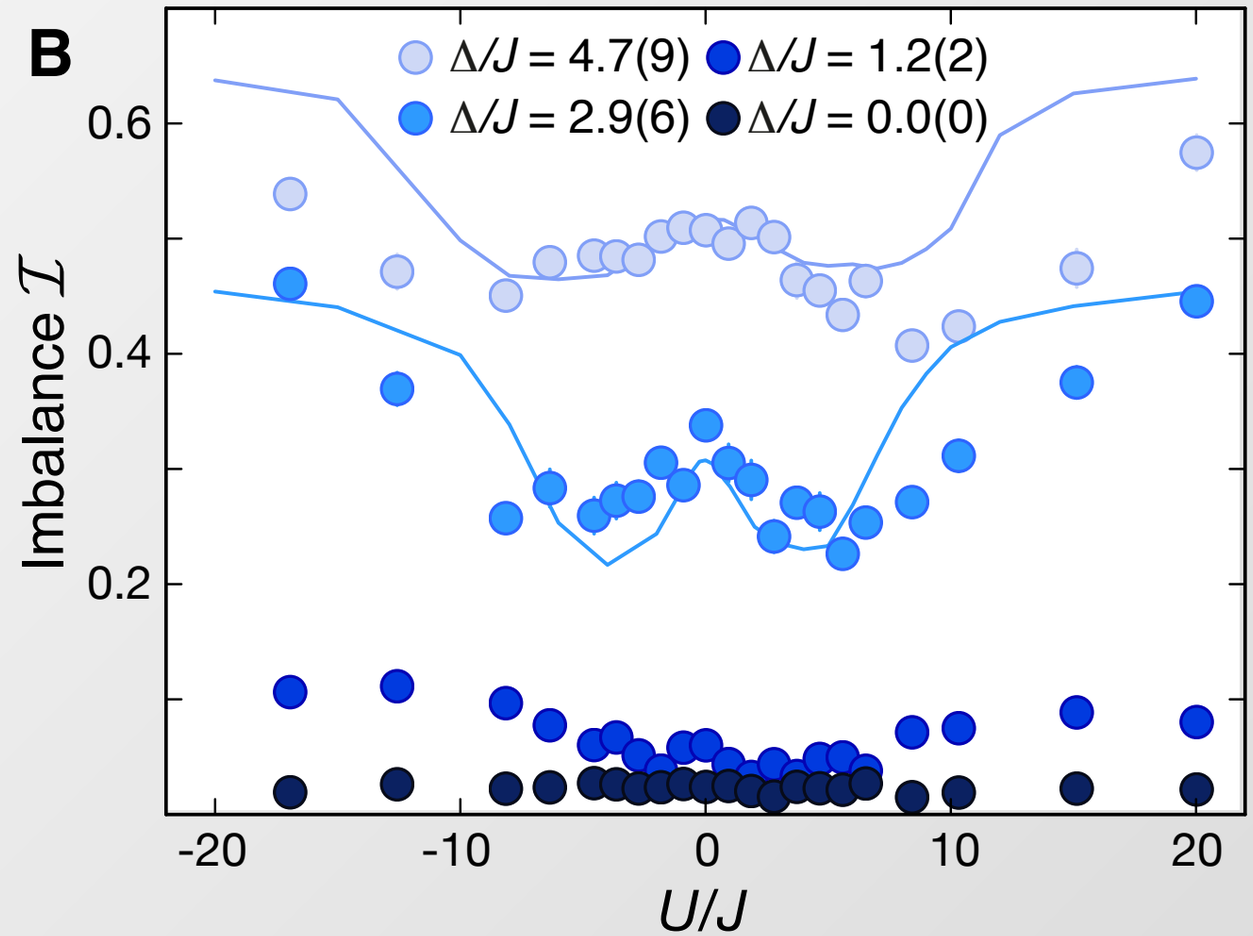
Non-ergodic, non-thermalizing quantum evolution !

U=0 - Anderson Localization



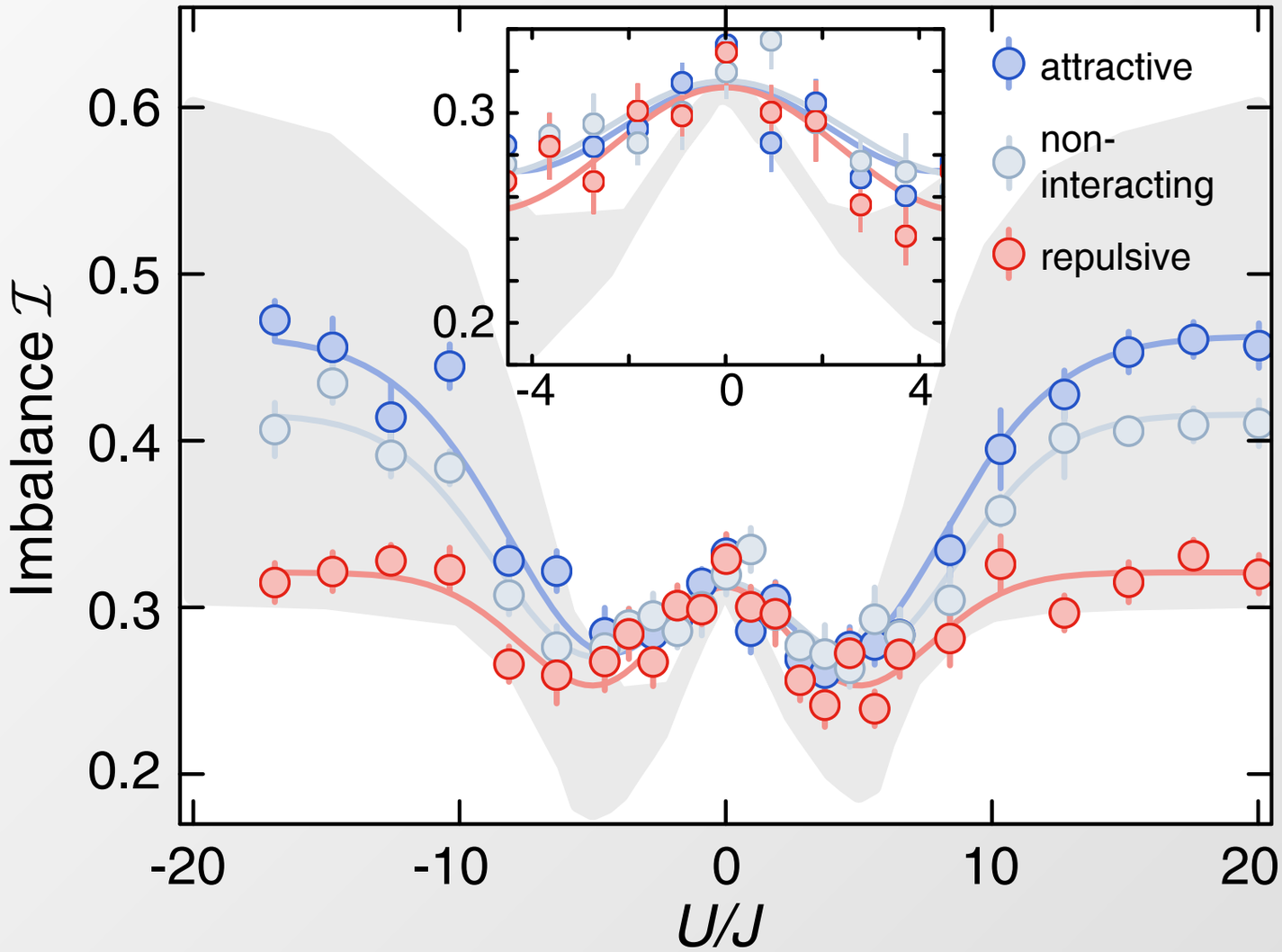
Imbalance vs U/J





1) **Localisation for all Interactions**
2) Characteristic W-shape
3) Dynamical U vs -U symmetry

Influence of Initial Doublon Fraction



>50% doubloons

40% doublons

no doublons

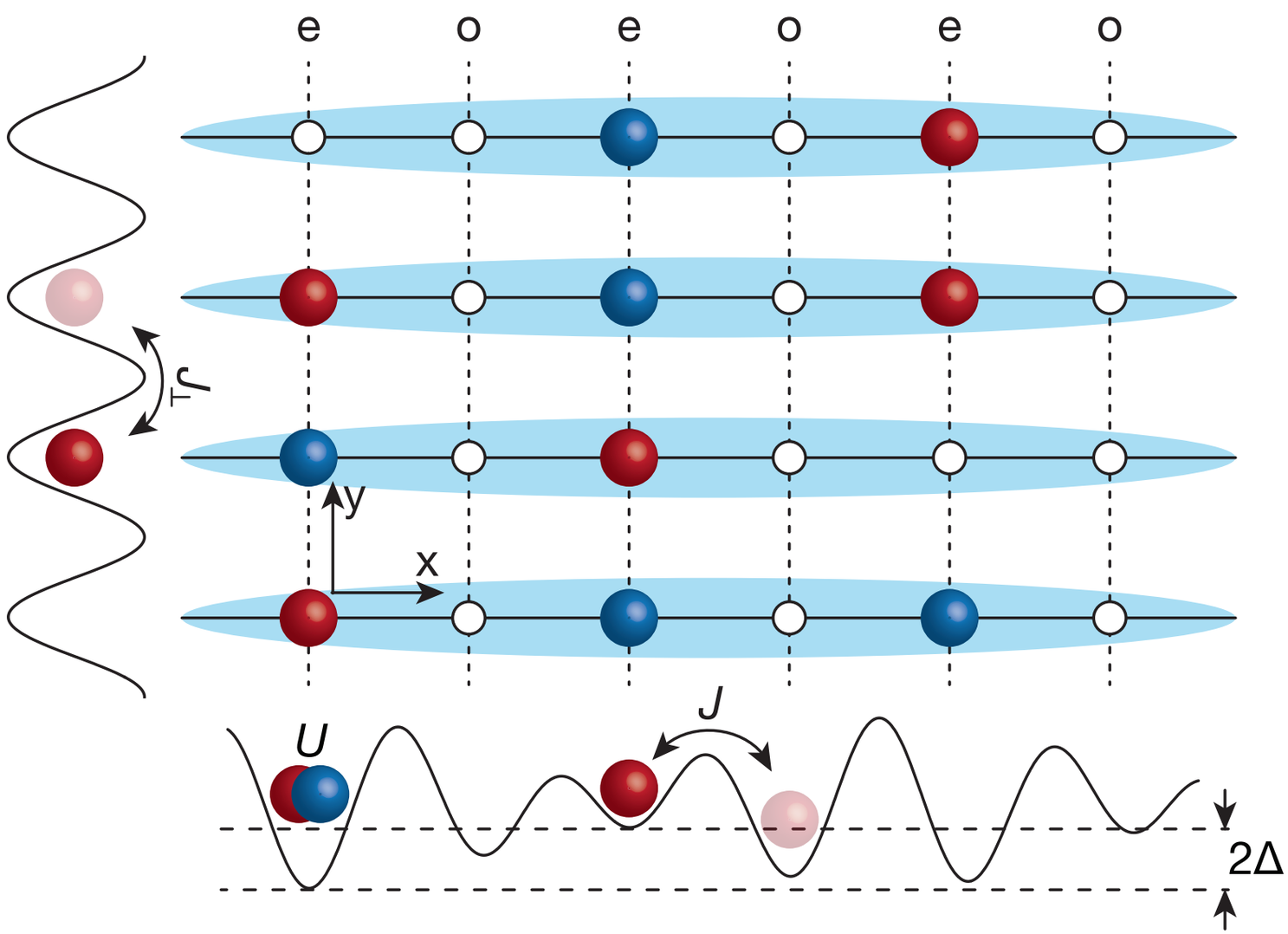
Kinetic energy of doublons for large U $J_{\mathrm{dbl}} = J^2/U$

Doublons see effectively larger disorder $\frac{J_{\mathrm{dbl}}}{\Delta} \ll \frac{J}{\Delta}$

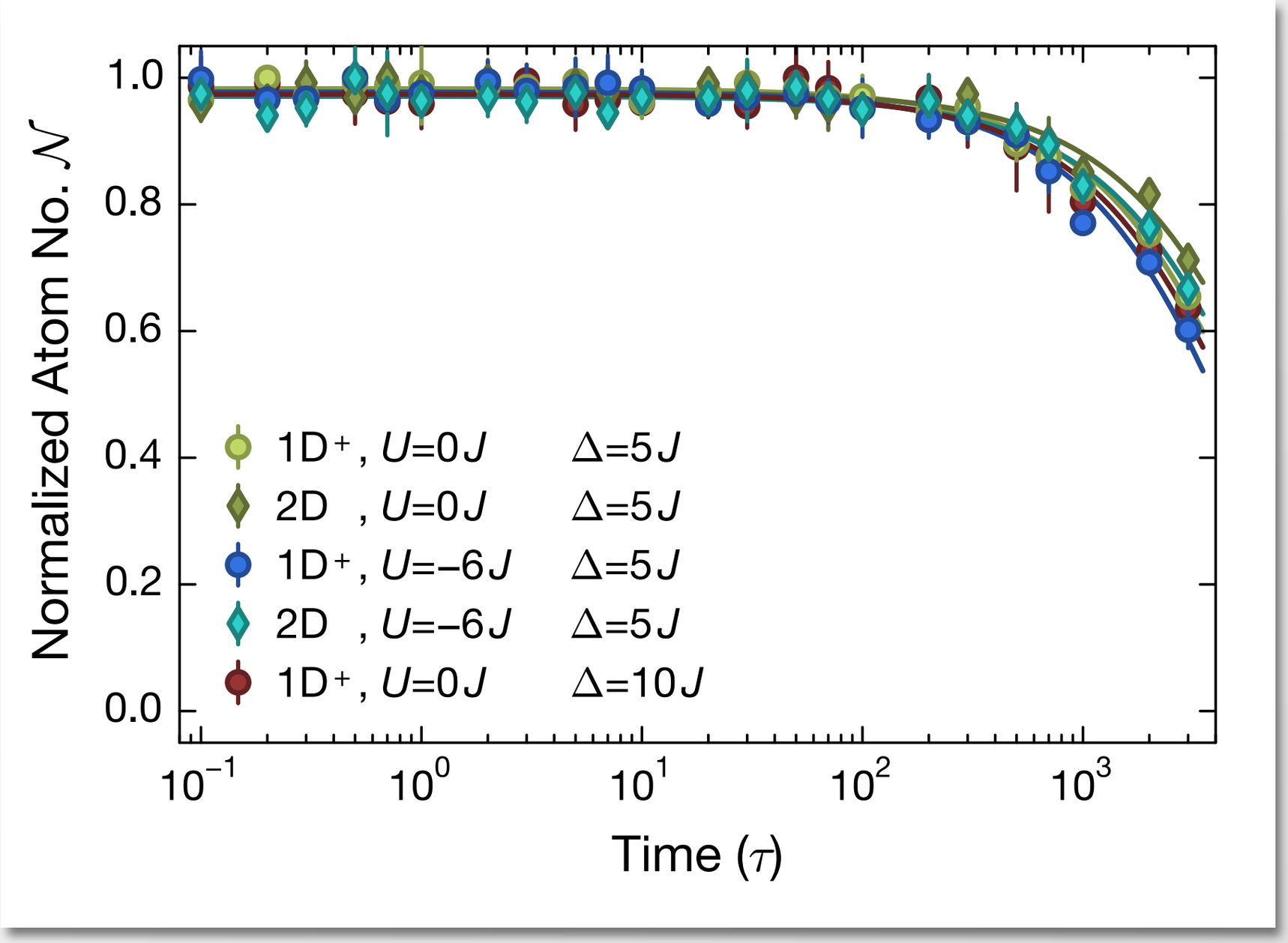
Changing Dimensionality & Very Long Time Behaviour

P. Bordia et al. arXiv 1509.00478

Experimental Setup 2D

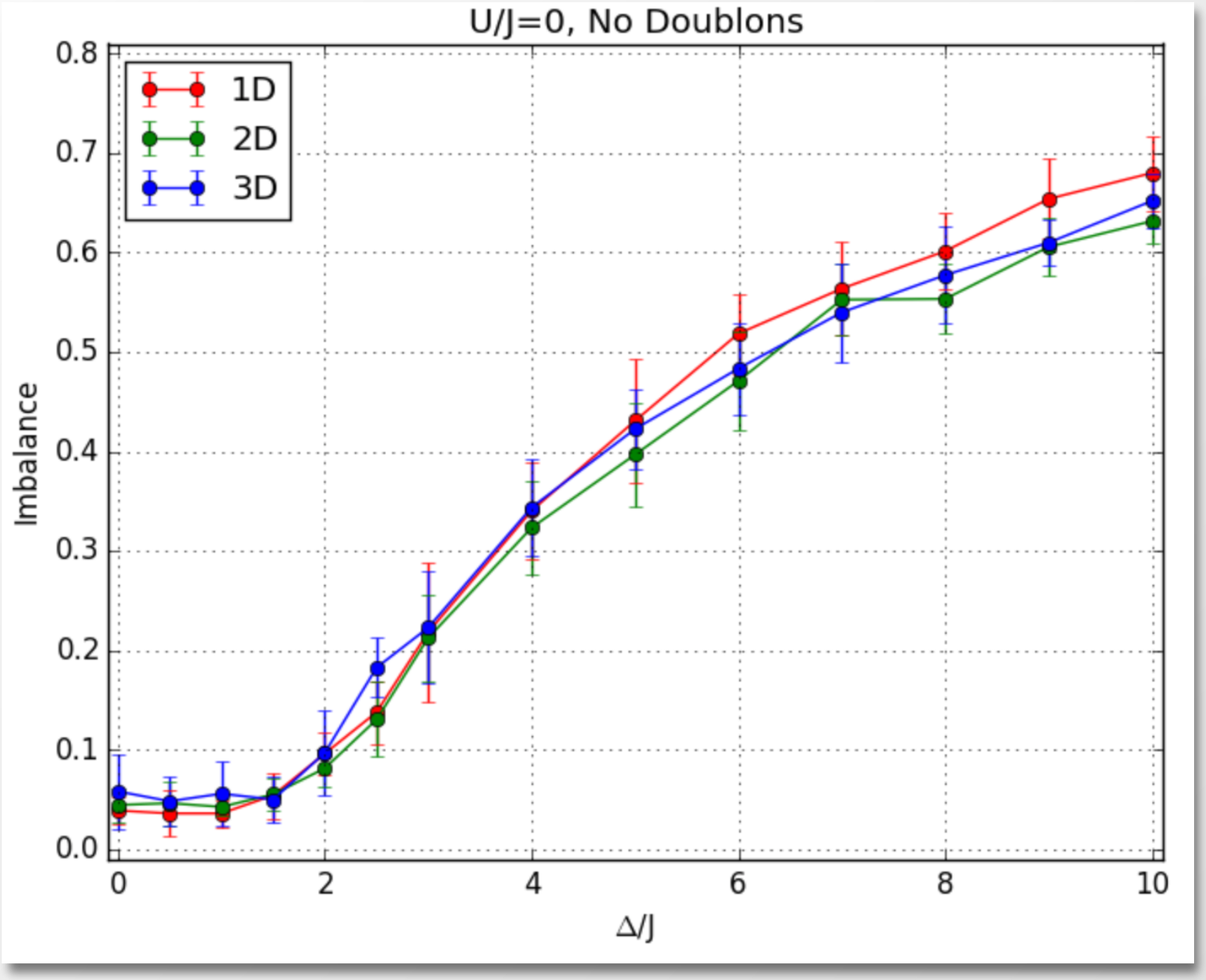


Particle Number Lifetime



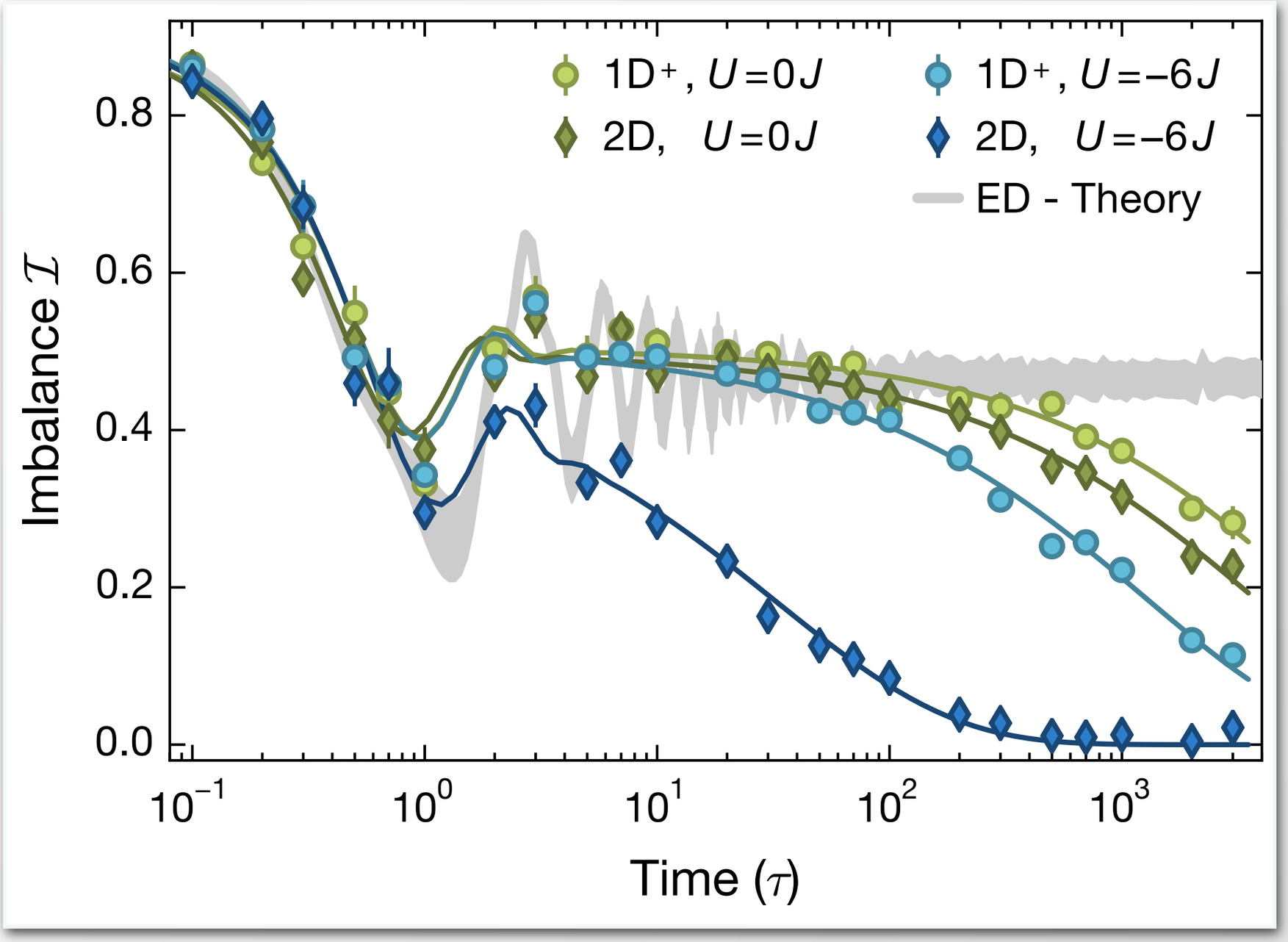
Atom lifetime enables us to **observe dynamics** up to **2000-4000 τ** !

U=0 - Dimensionality



1d Quasiperiodic Disorder - different couplings along y & z

Destruction of MBL



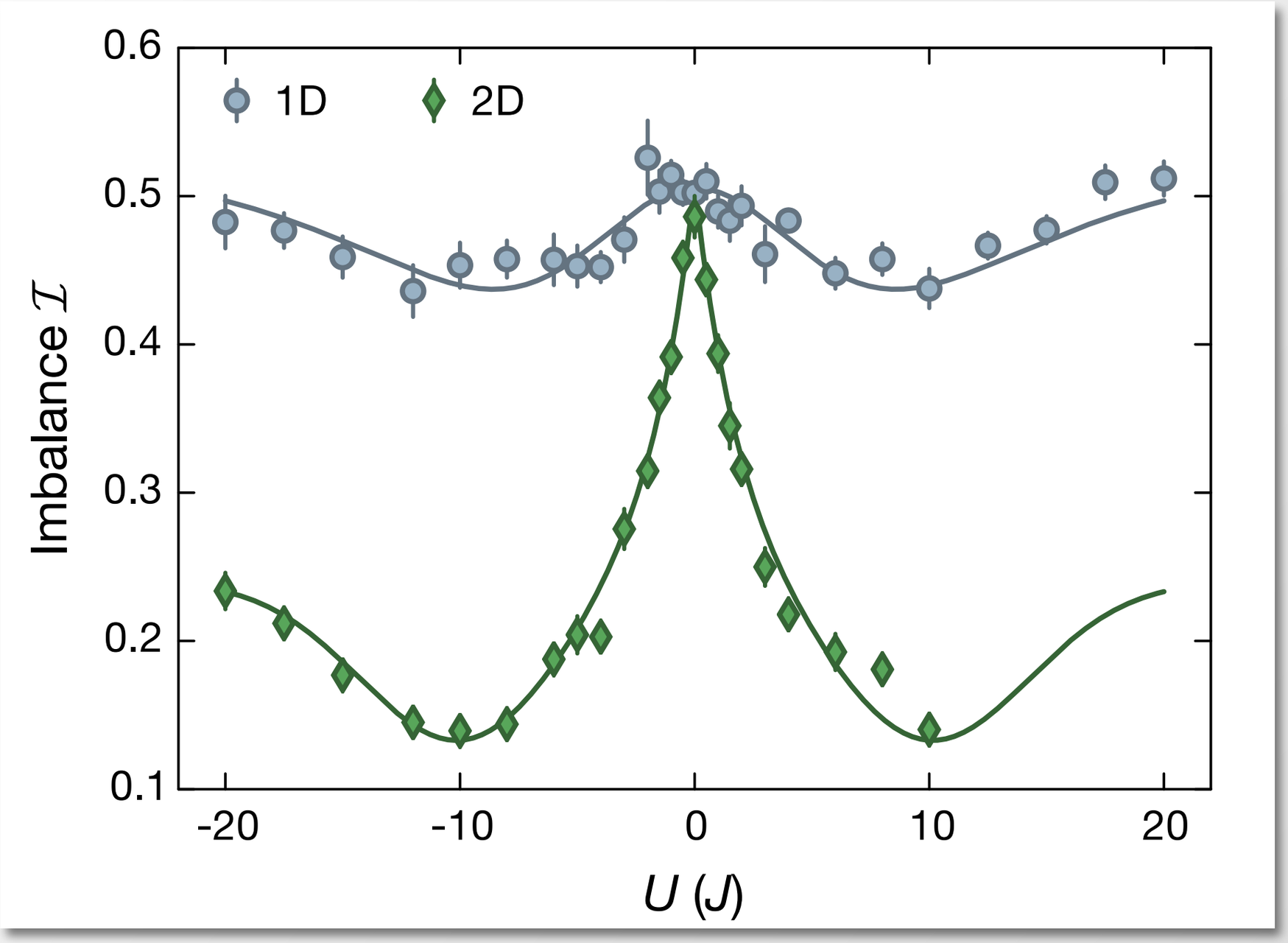
Long time decay fit

$$o \cdot e^{(-t/\tau)^{\alpha}}$$

- MBL unstable for coupling between tubes
- Fundamental difference between Anderson and MBL!

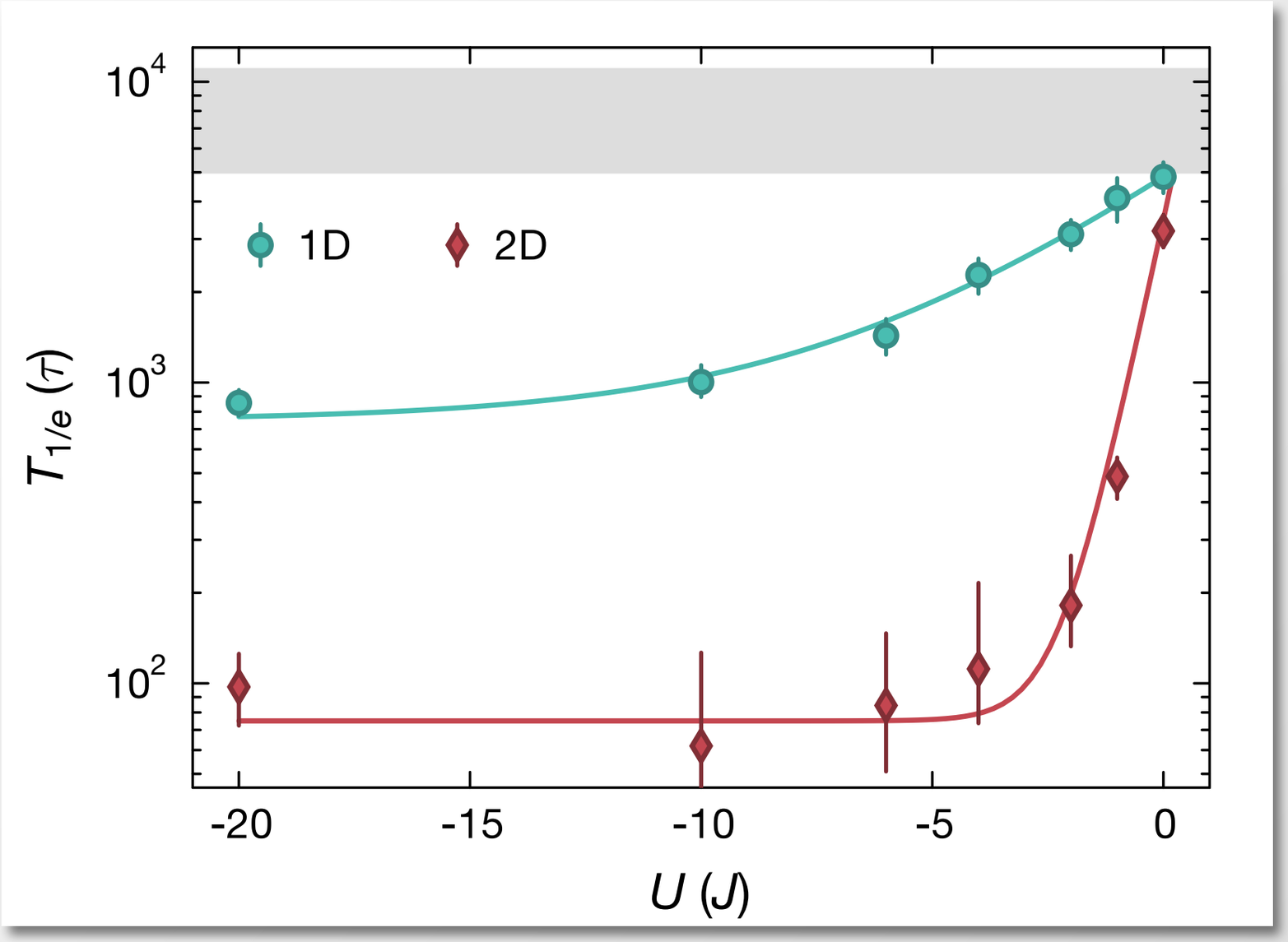
cf. Reichl, Mueller 1508.00472v2 & Bar Lev, Reichman: 1508.05391

Destruction of MBL in Higher Dimensions

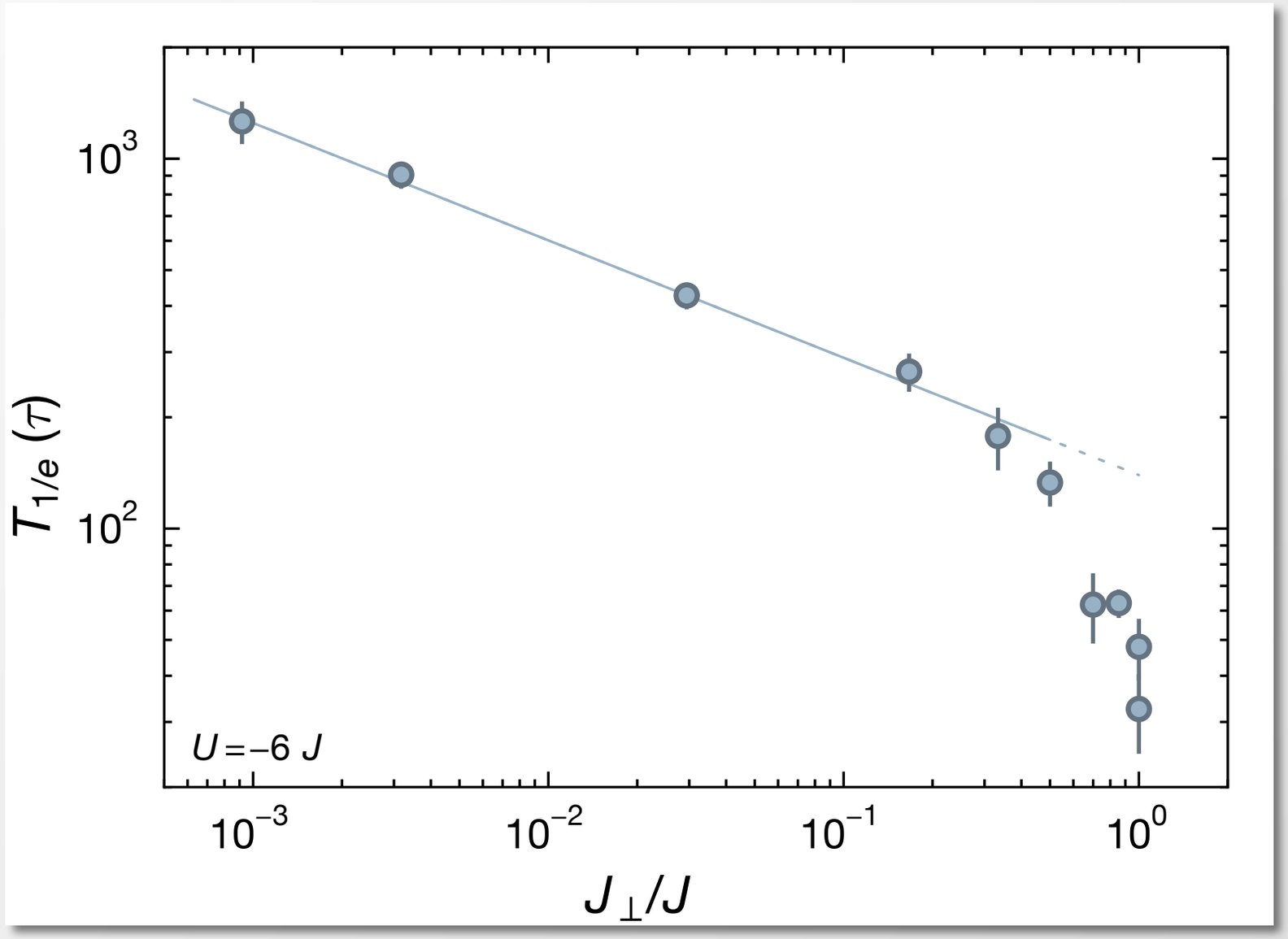


1d Quasiperiodic Disorder - different couplings along y & z

Lifetime 1D vs 2D



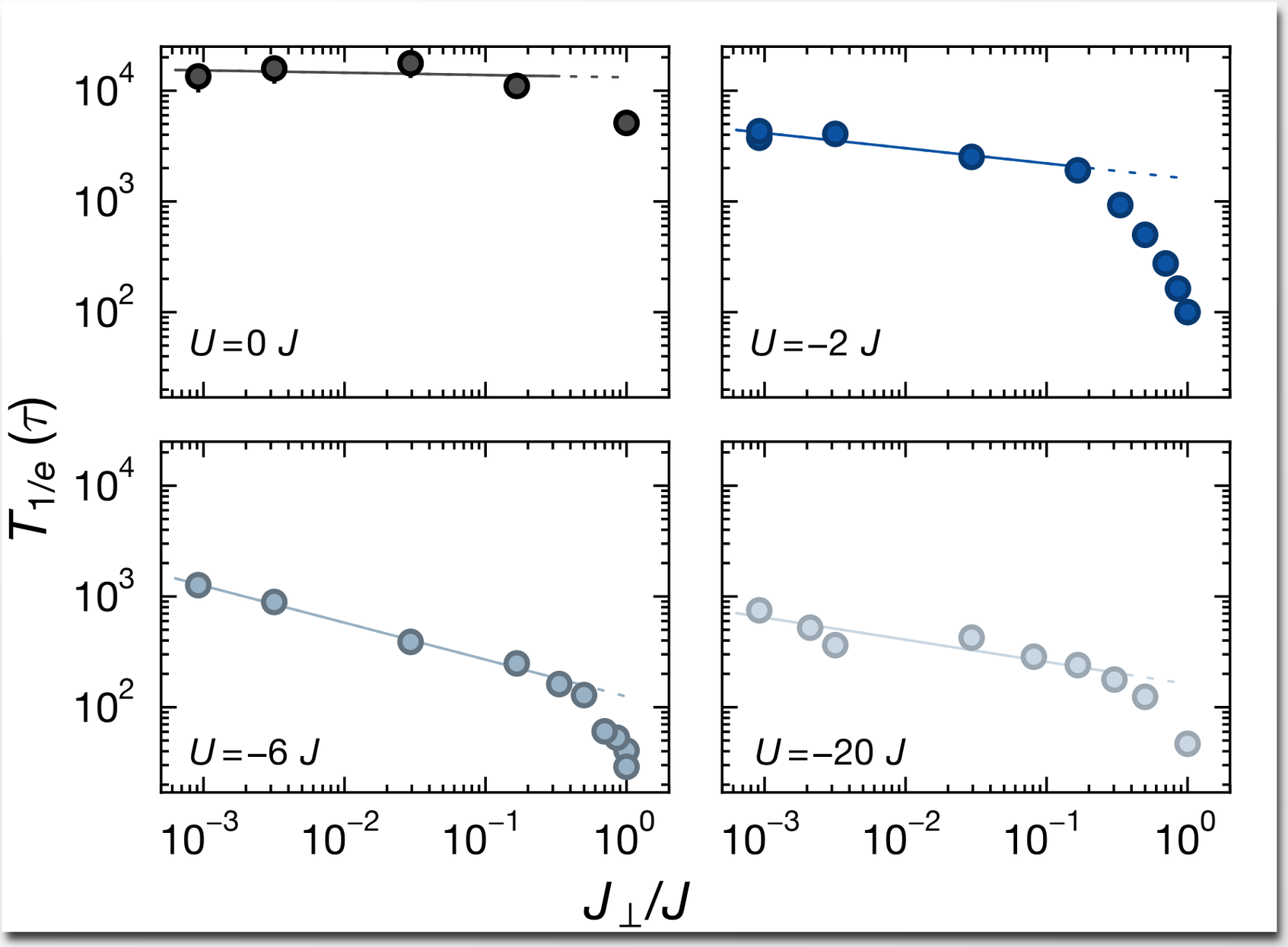
MBL Lifetime Limit



$\Delta = 5J$

MBL lifetime limited only by **residual transverse coupling**.

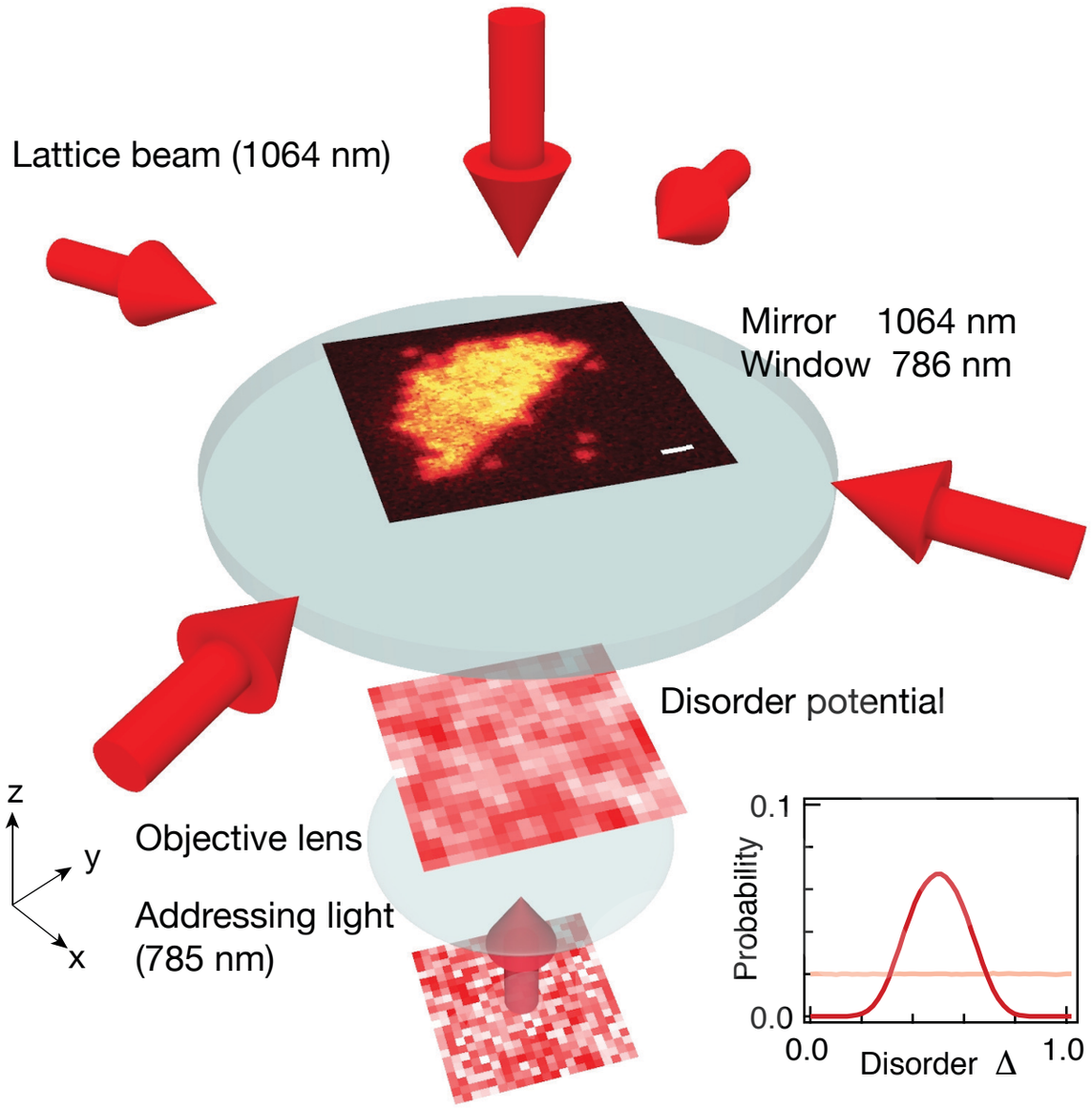
Systematic Analysis



Disorder strength $\Delta = 5J$

Probing the MBL Transition via Domain Wall Dynamics

Domain Wall Dynamics in Disorder

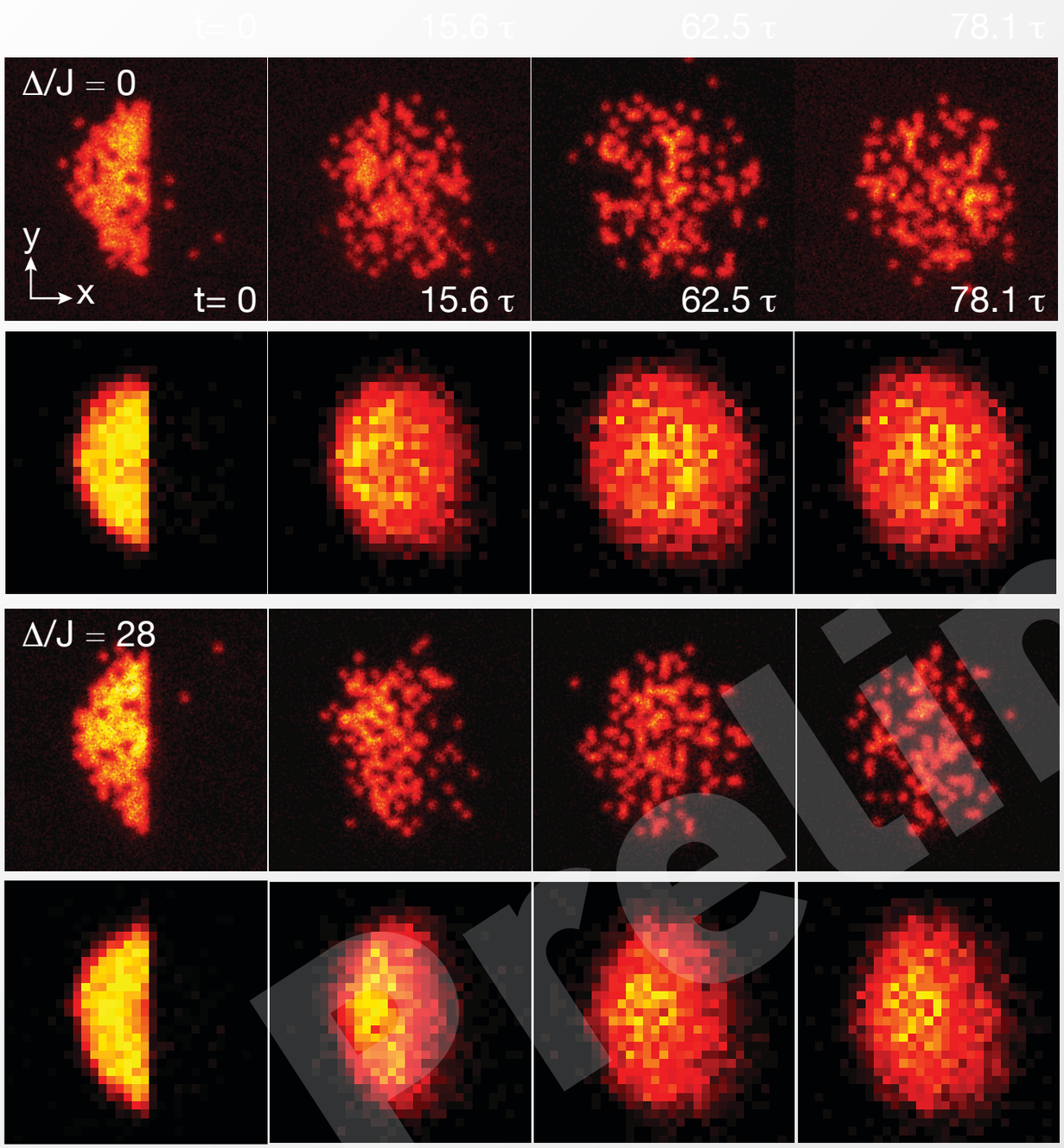


2D interacting bosons in disorder

Parameters: U/J ~ 20

true 2D (correlated) disorder

Time Evolution of Domain Wall in Disorder



$$\Delta/J = 0$$

System spreads over entire system size (thermalizing)

$$\Delta/J = 28$$

Domain wall gets stuck! (non-thermalizing)

Outlook

So far: good qualitative and in parts quantitative understanding!

- MBL for different dimensionalities? 1D/2D/3D - Disorder Dimension
- **Coupling to outside world** - Photon Scattering destruction of MBL?
- Optical Conductivity - Ergodic vs MBL phase
- Local fluctuation measurements with Quantum Gas Microscopes
- Measuring **localization length**? dynamical (domain walls)? impurities?
- Critical slowing down?
- Entanglement Entropy growth?
- MBL in driven systems

Outlook

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- Novel Correlated Phases in Strong Fields, Transport Measurements
- Fractional Chern Insulators
- Novel Topological Insulators
- Image Edge States - directly/spectroscopically
- Measure spatially resolved full current distribution
- Non-equilibrium dynamics in gauge fields
- Thermalization? Many-Body Localization
- SU(N) Fermi Hubbard Models
- Rydberg Gases

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