

Title: Probing and Controlling Quantum Matter in Artificial Crystals of Light

Date: Jun 23, 2015 09:00 AM

URL: <http://pirsa.org/15060023>

Abstract: More than 30 years ago, Richard Feynman outlined the visionary concept of a quantum simulator for carrying out complex physics calculations. Today, his dream has become a reality in laboratories around the world. All this has become possible using complex experimental setups of thousands of optical elements, allowing atoms to be cooled to Nanokelvin temperatures, where they almost come to rest. The atoms can then be trapped and manipulated in arrays of millions of microscopic light traps. Such 'light crystals' allow an unprecedented view into the microscopic world of quantum materials and have enabled the most precise atomic clocks to date that are fundamental to next generation timing and navigation applications.

In my talk, I will give an introduction how such quantum simulators can be realized at the lowest man-made known temperatures and outline some of their applications ranging from condensed matter physics over statistical physics to high energy physics with table-top experiment.

Introduction

- 1 Optical Lattices/Detection**
- 2 Many-Body Physics with Cold Atoms**

Hubbard Models/Quantum Phase Transition
Quantum Magnetism
Unitary Fermi Gas BEC/BCS
BKT Transition/Low-D Physics
Long Range Interactions
....more exotic systems

- 3 Artificial Gauge Fields/Geometric Band Properties**
- 4 Non-Equilibrium Physics/Statistical Physics**

Outlook

The Challenge of Many-Body Quantum Systems

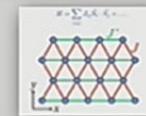
- **Understand and Design Quantum Materials -**

one of the biggest challenge of Quantum Physics in the 21st Century

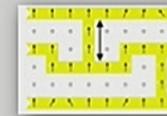


- **Technological Relevance**

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 $T=0$



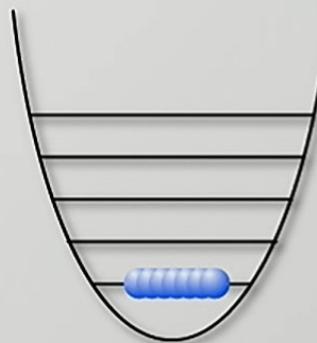
University of Colorado at Boulder



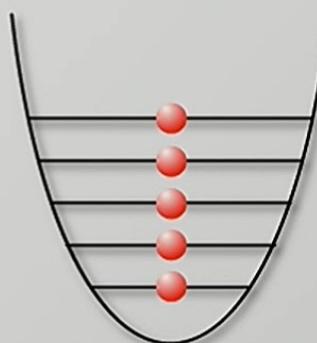
University of Colorado at Boulder



EPA/PRB



**Bose-Einstein
Condensates e.g. ${}^{87}\text{Rb}$**



**Degenerate Fermi Gases
e.g. ${}^{40}\text{K}$**



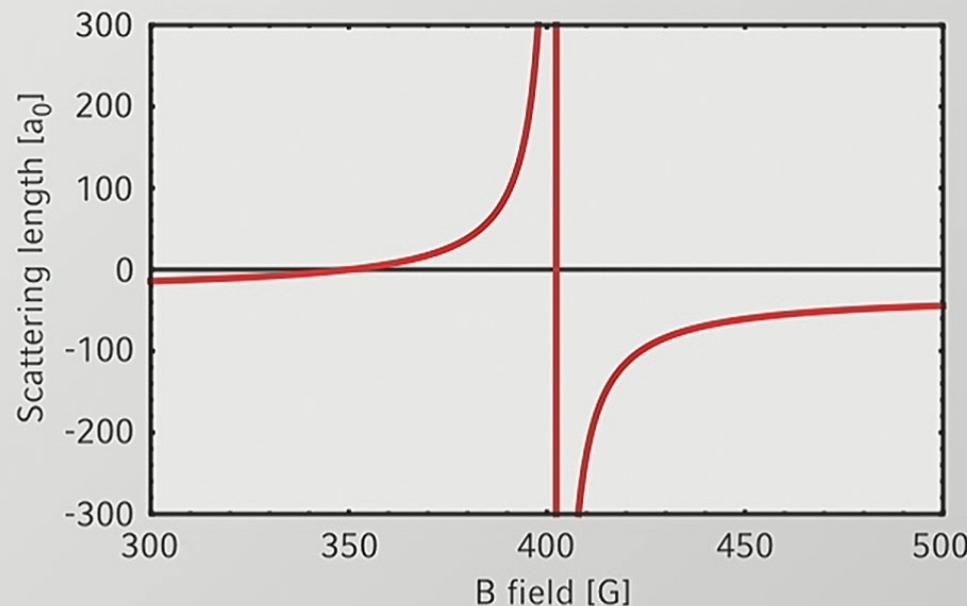


courtesy: T. Hänsch



courtesy: T. Hänsch

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



Short ranged
s-wave
interactions!

Watch out for inelastic
collisions (three body
losses...)!

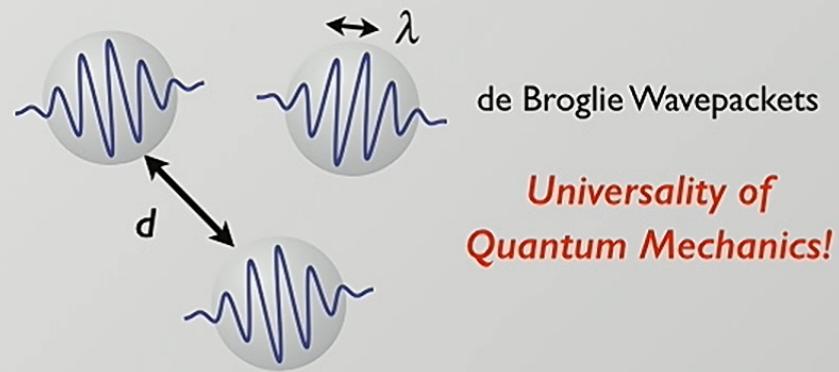
Feshbach resonance allow us to control interactions!

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



Quantum Regime

$$\lambda/d \gtrsim 1$$

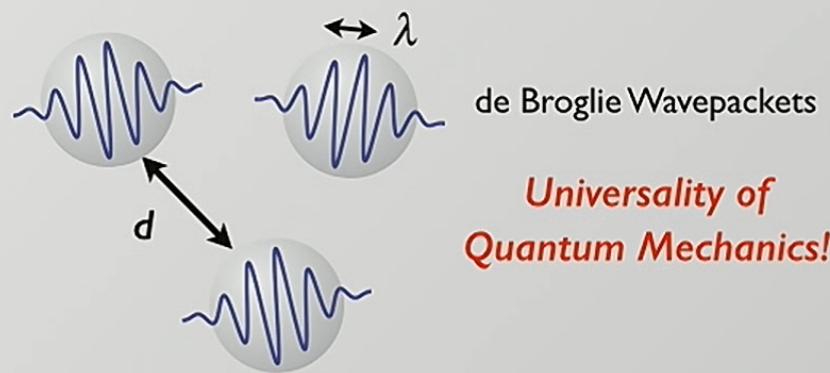


de Broglie Wavepackets

*Universality of
Quantum Mechanics!*

Quantum Regime

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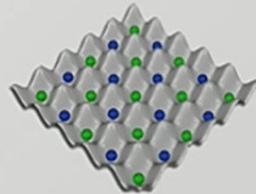


de Broglie Wavepackets

**Universality of
Quantum Mechanics!**

Ultracold Quantum Matter

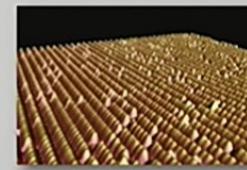
- ▶ **Densities:** $10^{14}/\text{cm}^3$
(100000 times thinner than air)
- ▶ **Temperatures:** few $n\text{K}$
(100 million times lower than outer space)



Same λ/d !

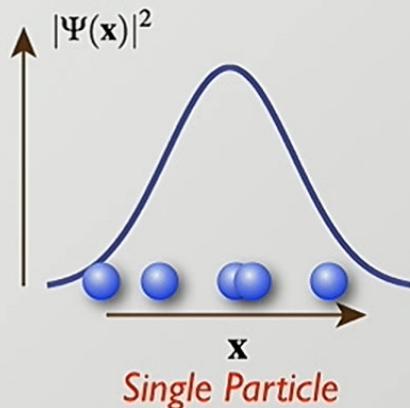
Real Materials

- ▶ **Densities:** $10^{24}-10^{25}/\text{cm}^3$
- ▶ **Temperatures:** $m\text{K} -$
several hundred K



(Neuchatel)

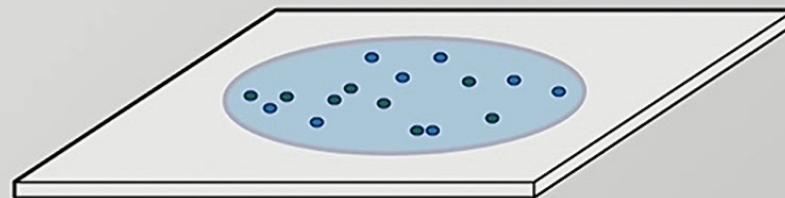
Measuring a Quantum System



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

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

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



Correlated 2D Quantum Liquid

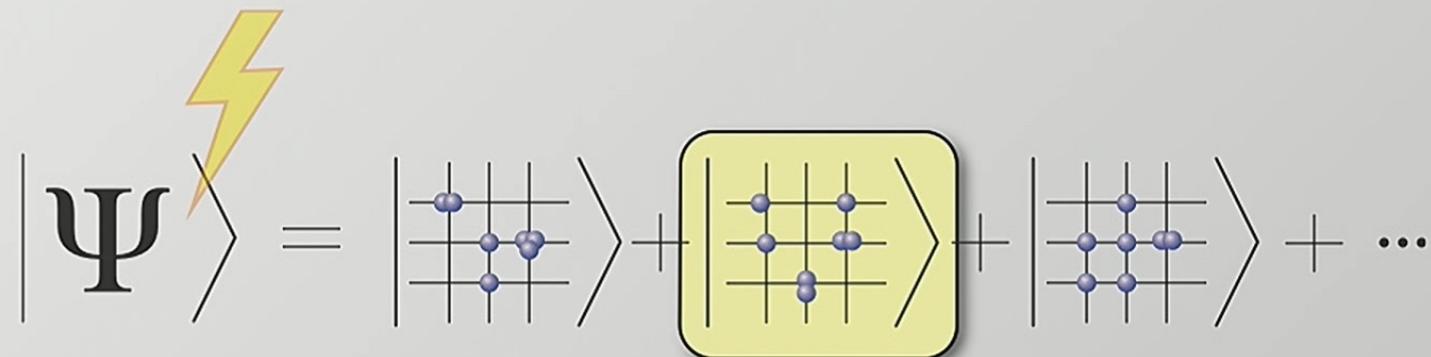
$\Psi(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \dots, \mathbf{x}_N)$

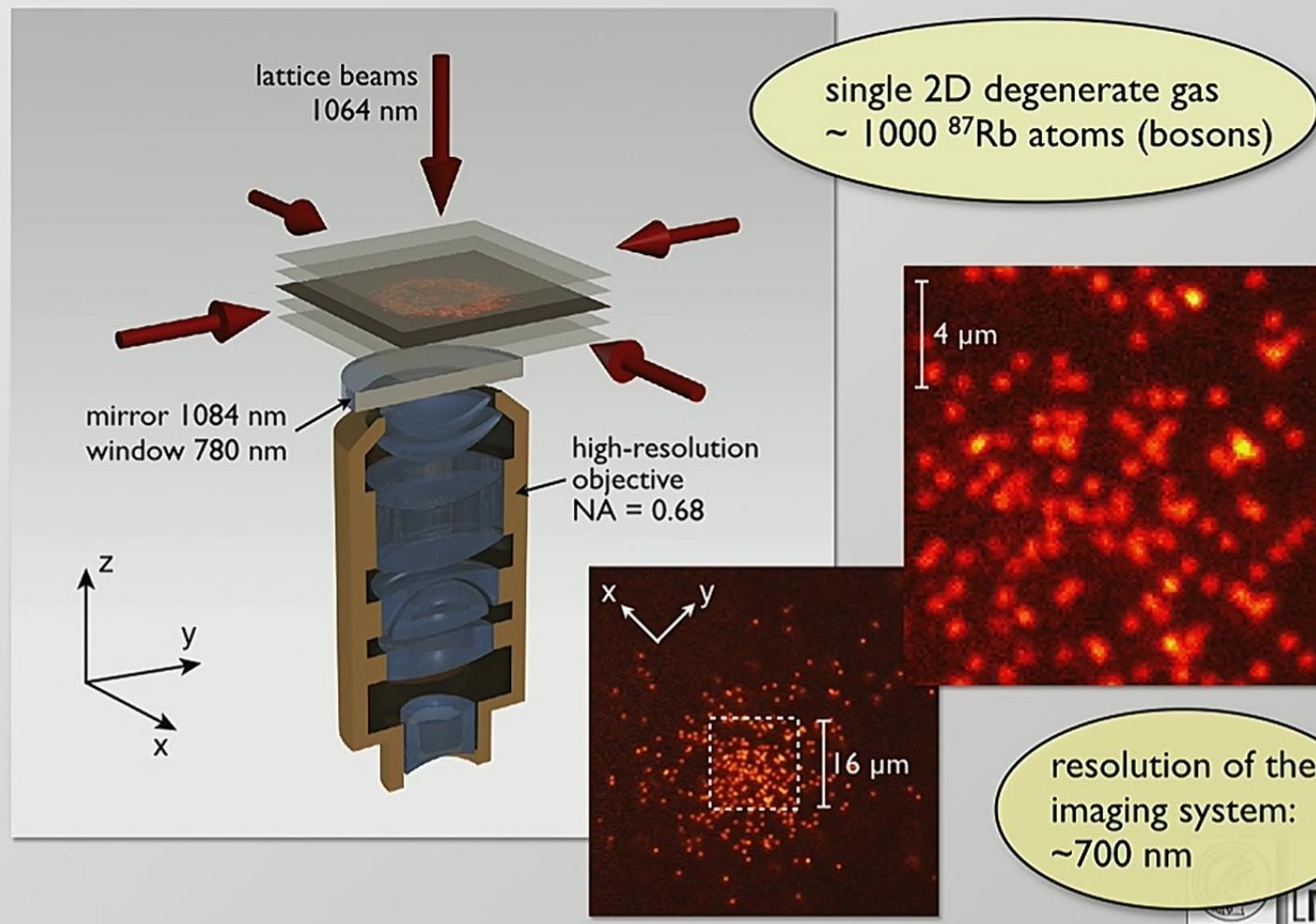
$|\Psi(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \dots, \mathbf{x}_N)|^2$

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

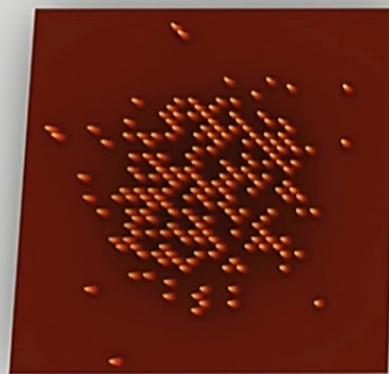
Enables Measurement of Non-local Correlations

Local occupation measurement

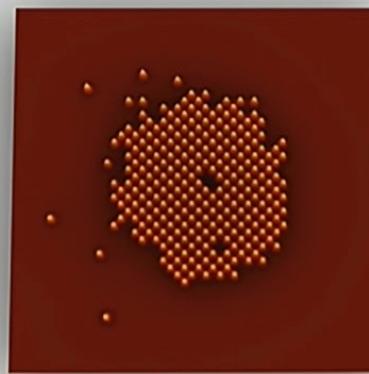
$$|\Psi\rangle = \left| \begin{array}{|c|c|c|} \hline & & \\ \hline & & \\ \hline & & \end{array} \right\rangle + \left| \begin{array}{|c|c|c|} \hline & & \\ \hline & & \\ \hline & & \end{array} \right\rangle + \left| \begin{array}{|c|c|c|} \hline & & \\ \hline & & \\ \hline & & \end{array} \right\rangle + \dots$$




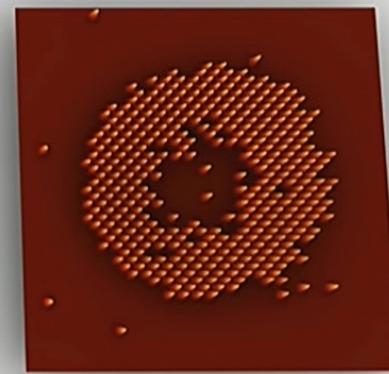
Snapshot of an Atomic Density Distribution



BEC



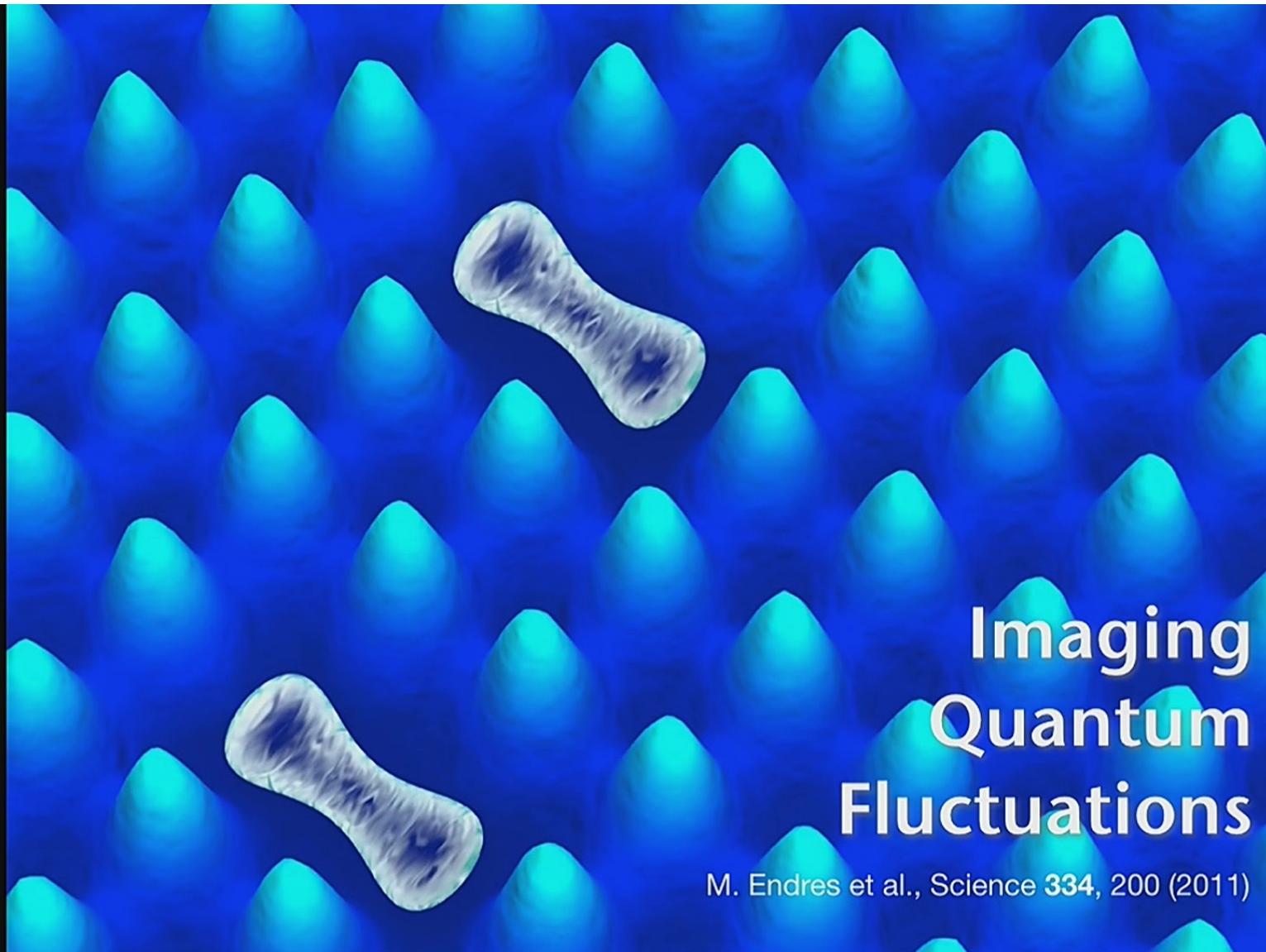
$n=1$
Mott Insulator



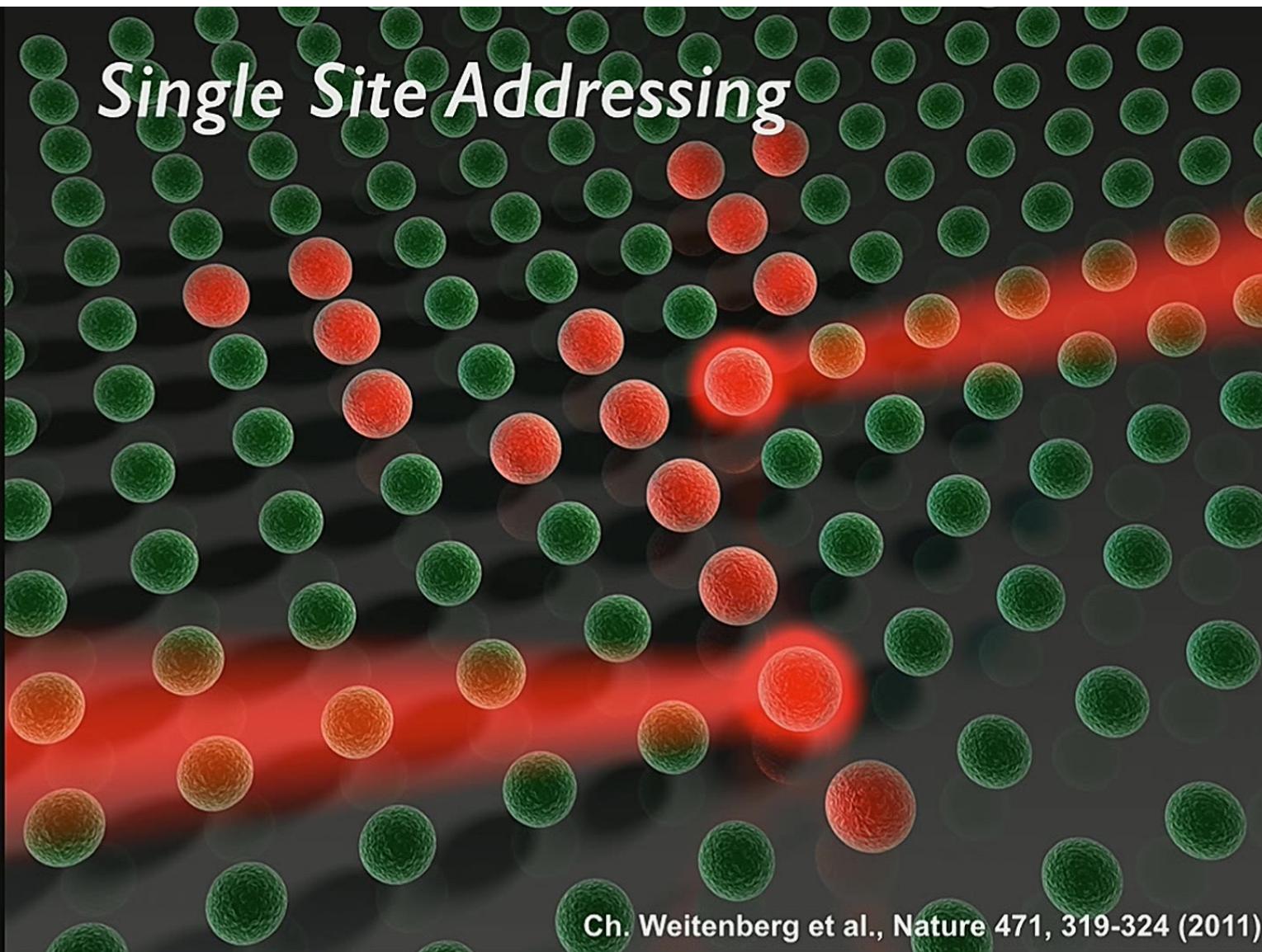
$n=1$ & $n=2$
Mott Insulator

J. Sherson et al. Nature 467, 68 (2010); see also: W. Bakr et al. Science 329, 547 (2010)



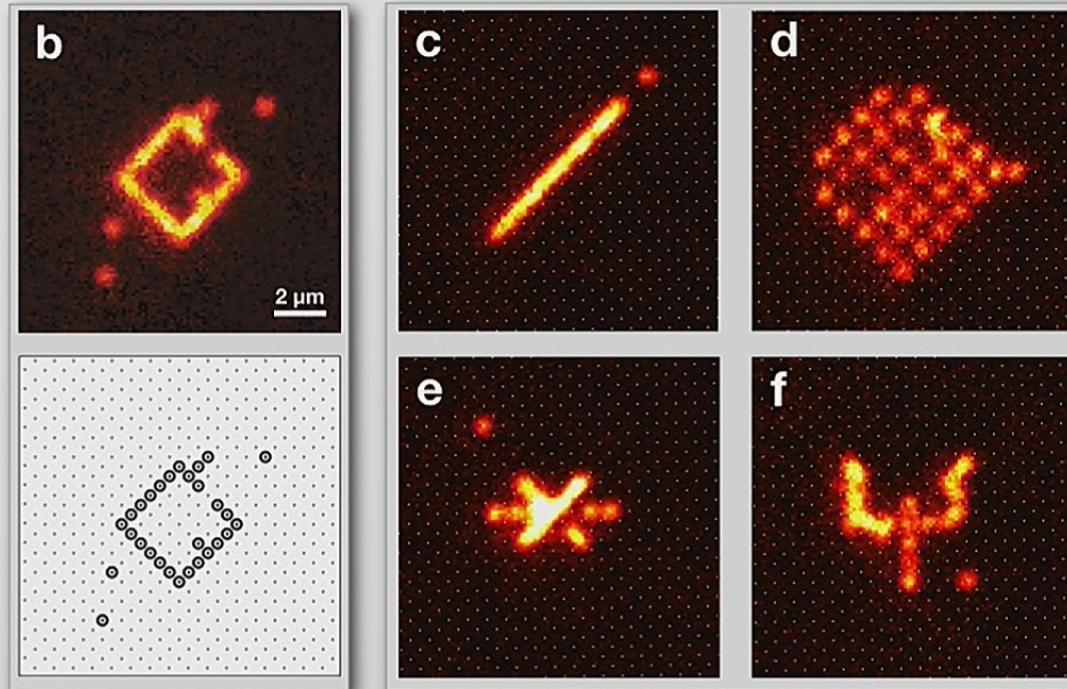


Single Site Addressing



Addressing

Coherent Spin Flips - Positive Imaging



Subwavelength spatial resolution: 50 nm

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

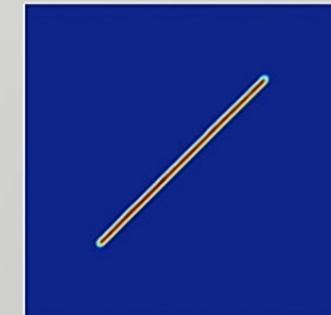
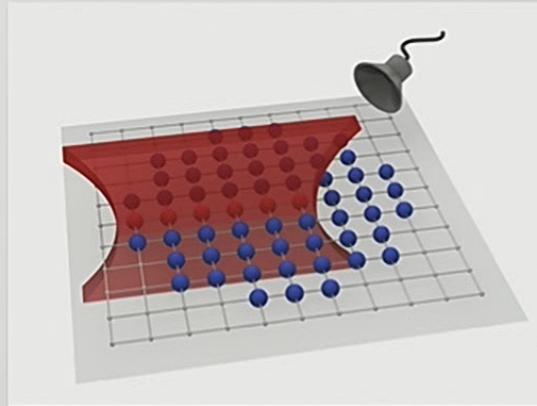


Addressing

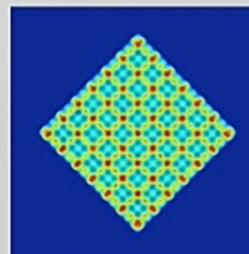
Arbitrary Light Patterns



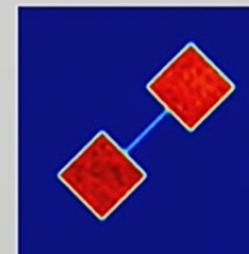
Digital Mirror Device
(DMD)



Measured Light Pattern



Exotic Lattices



Quantum Wires



Box Potentials

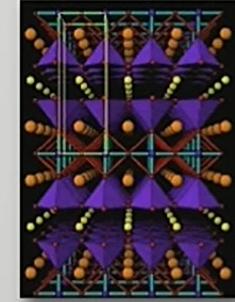
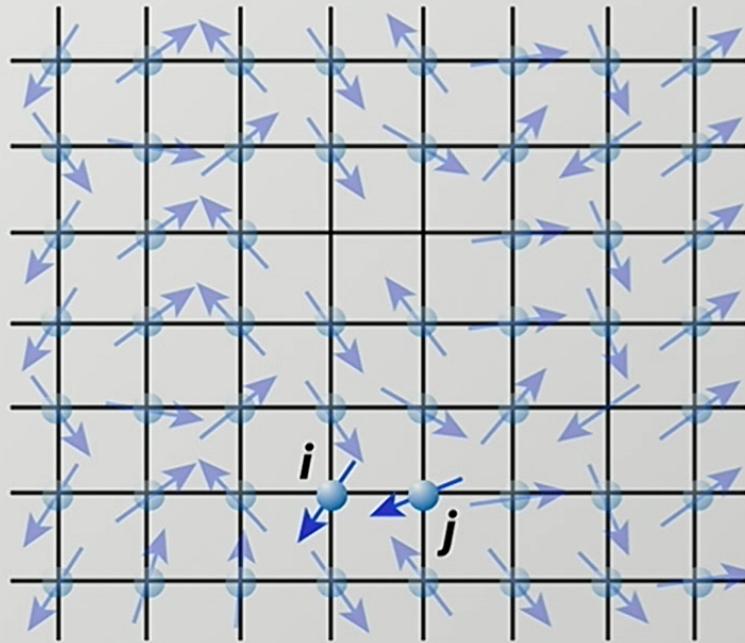
Almost Arbitrary Light Patterns Possible!

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



Strongly Correlated Electronic Systems

$$H = -J \sum_{\langle i,j \rangle, \sigma} \hat{c}_{i,\sigma}^\dagger \hat{c}_{j,\sigma} + U \sum_i \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow} + V_0 \sum_{i,\sigma} R_i^2 \hat{n}_{i,\sigma}$$



In strongly correlated electron system **spin-spin interactions** exist.

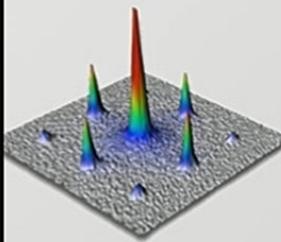
$$-J_{ex} \vec{S}_i \cdot \vec{S}_j$$

Underlying many solid state & material science problems:
Magnets, High-Tc Superconductors, Spintronics

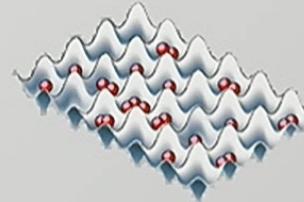


From Weak to Strong Interactions

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



Weak Interactions

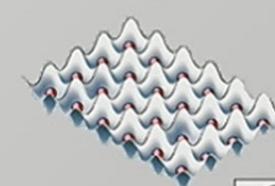


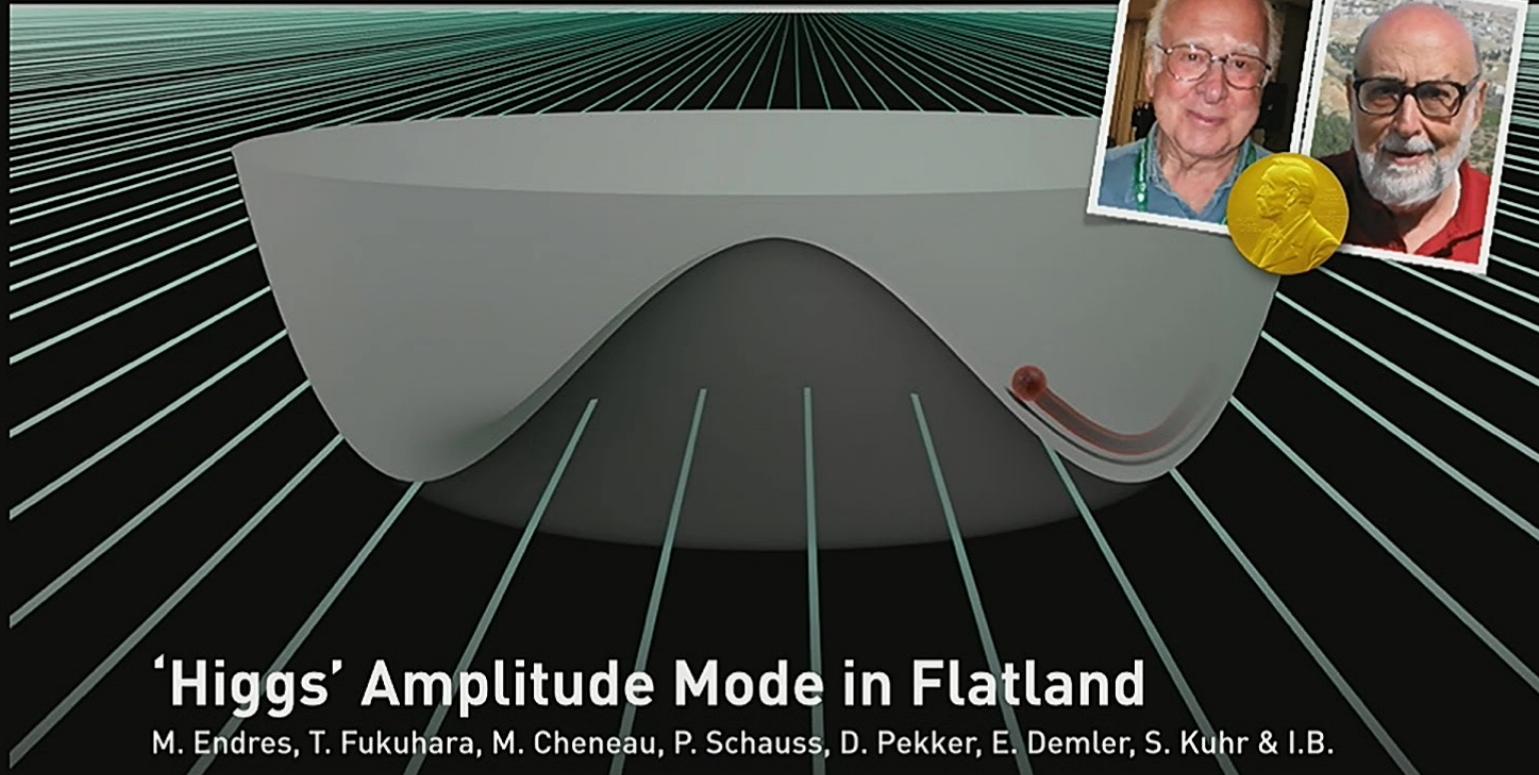
Quantum Phase Transition

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



Strong Interactions





'Higgs' Amplitude Mode in Flatland

M. Endres, T. Fukuhara, M. Cheneau, P. Schauss, D. Pekker, E. Demler, S. Kuhr & I.B.

M. Endres et al. Nature (2012)

Chubukov & Sachdev, PRB 1993; Sachdev, PRB 1999; Zwerger, PRL 2004; Altman, Blatter, Huber, PRB 2007, PRL 2008; U. Bissbort et al. Phys. Rev. Lett. (2011); D. Podolsky, A. Auerbach, D. Arovas, PRB 2011



Hubbard Models - Status and Challenges

Bose Hubbard

- Mott insulators (interference pattern, density, compressibility, doublon fraction,...)
- Quantum fluctuations/Hidden Order
- Mode spectroscopy (Sound wave, 'Higgs' amplitude mode, ...)
- Transport (Quenches)
- Single Site Imaging
- *TODO: quantum critical region - homogeneous systems*

Fermi Hubbard

- Mott insulators (doublon fraction, compressibility)
- Short ranges magnetic correlations
- Transport measurements (role of interactions, integrability, dimension...)
- First single site imaging of fermions in lattices
- *TODO: No AF order yet (but hopefully close, new cooling ideas implemented)*
- *TODO: Can we find d-wave superconducting phase in Hubbard model?*



Superexchange based

- Superexchange, Singlet Triplet (Double Quantum Dot)
- Single spin impurity propagation (from strong to weak coupling)
- Direct detection of bound magnons
- Entanglement spreading in spin chains
- Non-equilibrium dynamics in quantum magnets
- RVB dynamics on plaquettes (building blocks for larger systems? dynamics?)
- TODO: AFM order for fermions (short ranged above T_{Neel} observed)
- TODO: Spin charge separation, triplon excitations in VBS, deconfined criticality?
- TODO: SU(N) extensions, Kondo lattice models...

Other mappings

- density based (with constraints) - quantum Ising
- Long ranged quantum Ising (Rydbergs, dipole-dipole)
- Molecules in lattices (dipole-dipole)

TODO: Exotic Spin Models





Hans Bethe
(1906-2005)

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

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

General
1-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); P. Preiss et al., Science (2015)



Long-Range Interactions

Long Ranged Interactions - Dipole-Dipole

- *Polar molecules*

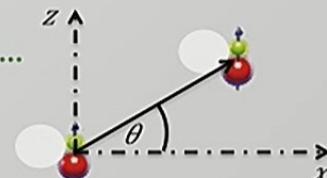
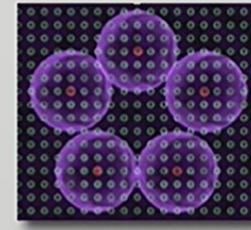
(degenerate yet, but maybe good enough for MBL)

- *Rydberg atoms* (frozen, dressed)

- *TODO: Supersolids for dressed Rydberg atoms*

- *TODO: bi-layer condensates, Haldane insulator (Spin-1) chain, ...*

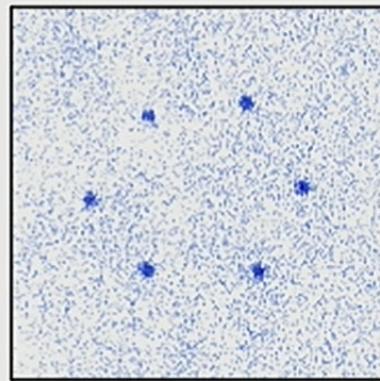
$$H = -t \sum_i (b_i^\dagger b_{i+1} + \text{H.c.}) + \frac{U}{2} \sum_i n_i(n_i - 1) \\ + \sum_{i,r>0} \frac{V}{r^3} n_i n_{i+r}$$



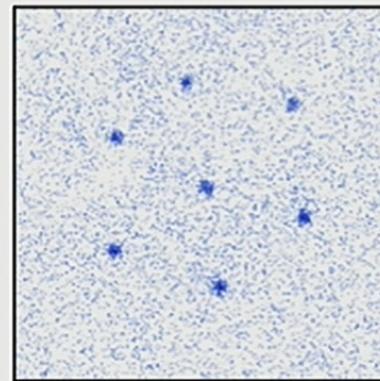
'Infinite Range' - Cavity Systems



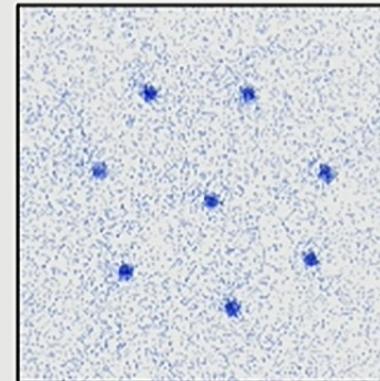
Single-Shot Rydberg Crystal Configurations



6



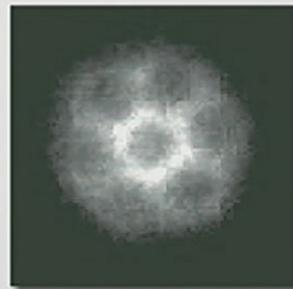
7



8

Rydberg Crystal configurations

I) Rotation

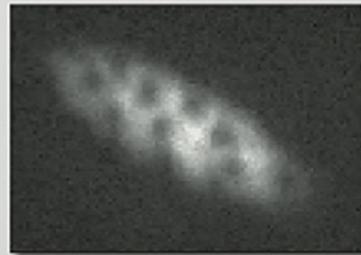


In rapidly rotating gases, **Coriolis force** is equivalent to **Lorentz force**.

$$\mathbf{F}_L = q \mathbf{v} \times \mathbf{B} \iff \mathbf{F}_C = 2m \mathbf{v} \times \boldsymbol{\Omega}_{\text{rot}}$$

K. Madison et al., PRL (2000)
J.R. Abo-Shaeer et al. Science (2001)

2) Raman Induced Gauge Fields



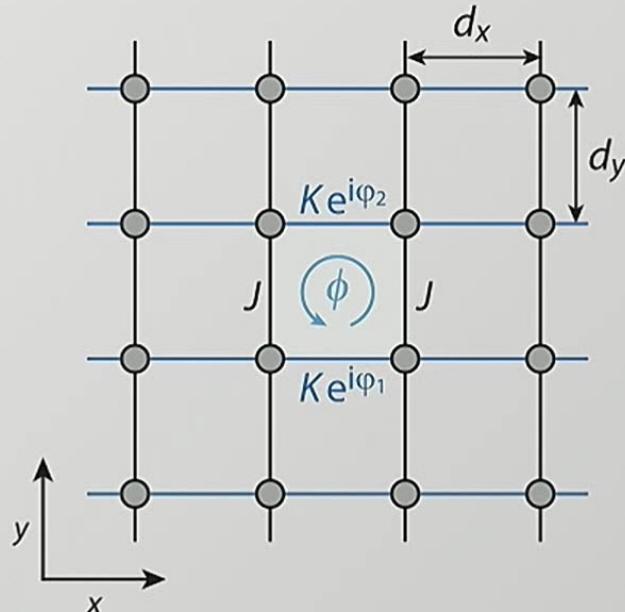
Spatially dependent optical couplings lead to a **Berry phase** analogous to the **Aharonov-Bohm phase**

Y. Lin et al., Nature (2009)



Controlling atom tunneling along x with Raman lasers leads to effective tunnel coupling with spatially-dependent Peierls phase $\varphi(\mathbf{R})$

$$\hat{H} = - \sum_{\mathbf{R}} \left(K e^{i\varphi(\mathbf{R})} \hat{a}_{\mathbf{R}}^\dagger \hat{a}_{\mathbf{R}+\mathbf{d}_x} + J \hat{a}_{\mathbf{R}}^\dagger \hat{a}_{\mathbf{R}+\mathbf{d}_y} \right) + \text{h.c.}$$



Magnetic flux through a plaquette:

$$\phi = \int_{\text{plaquette}} B dS = \varphi_1 - \varphi_2$$

D.Jaksch & P.Zoller, New J. Phys. (2003)

F.Gerbier & J.Dalibard, New J. Phys. (2010)

N.Cooper, PRL (2011)

E.Mueller, Phys. Rev. A (2004)

L.-K.Lim et al., Phys. Rev.A (2010)

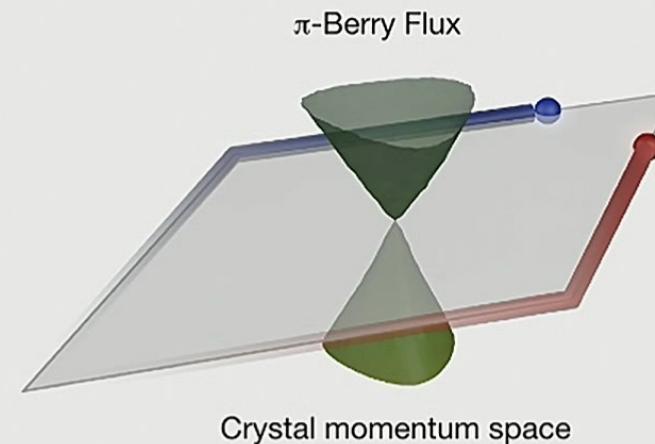
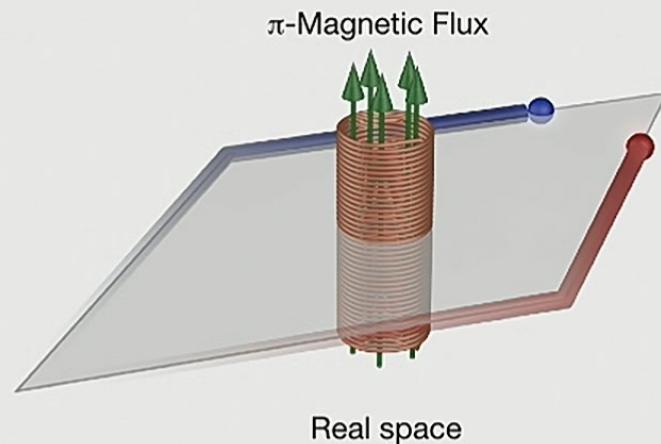
A.Kolovsky, Europhys. Lett. (2011)

see also: lattice shaking

E.Arimondo, PRL(2007), K.Sengstock, Science (2011),
M.Rechtsman & M.Segev, Nature (2013)



An Aharonov Bohm Interferometer for Determining Bloch Band Topology



D. Abanin E. Demler

Theory: D. Abanin et al. PRL 110, 165304 (2013)
Experiment: L. Duca et al. Science (2015)

Non-Equilibrium Dynamics

- Quantum Quenches (global, local)
 - CDW evolution
 - single spin impurity
 - bound magnons
 - RVB plaquette dynamics
 - mass transport
 - Lieb-Robinson bounds
 - Entropy-, mass-, spin-transport...

*Improvement in numerical methods
urgently needed!*

- Thermalization

(ETH, integrability, pre-thermalization, *do things change in artificial gauge fields?*)

- Many-Body Localization

(robust even at higher temperatures - but need isolated quantum system!)

- Universality?

- Cosmology (Black hole physics, Inflation)

- Relativistic Dynamics (Klein tunneling, Veselago lenses,...)



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Many-Body Localisation

Thermalization

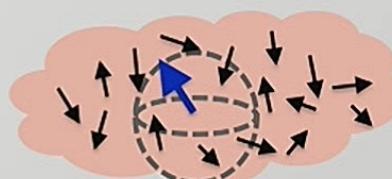


Quantum correlations in local d.o.f are rapidly lost as these get entangled with the rest of the system.



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!



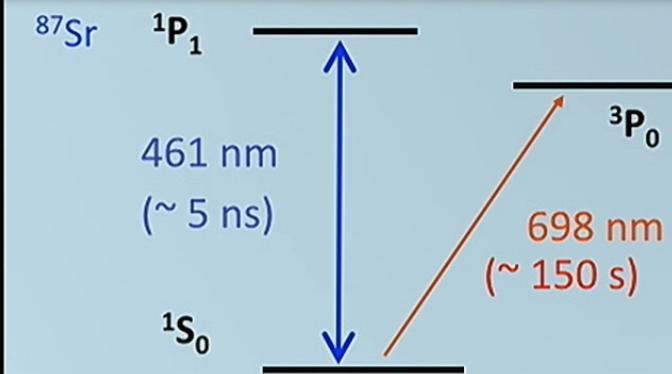
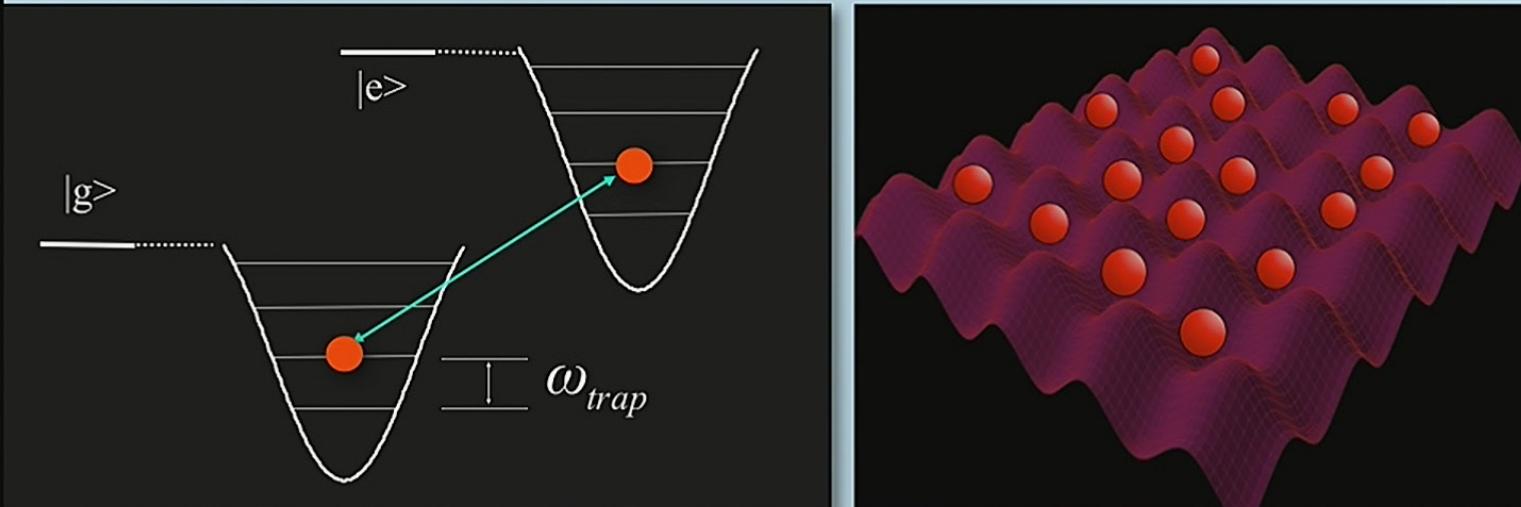
The many-body localization transition

= elusive interface between quantum and classical worlds

D. M. Basko, I. L. Aleiner, B. L. Altshuler, Ann. Phys. (2006).
I.V. Gornyi, A. D. Mirlin, D. G. Polyakov, Phys. Rev. Lett. (2005).
J. Z. Imbrie, arXiv:1403.7837 (2014).
A. Pal & D. Huse, Phys. Rev. B 82, 174411 (2010).....many others.....



The best clock: atoms in optical lattices



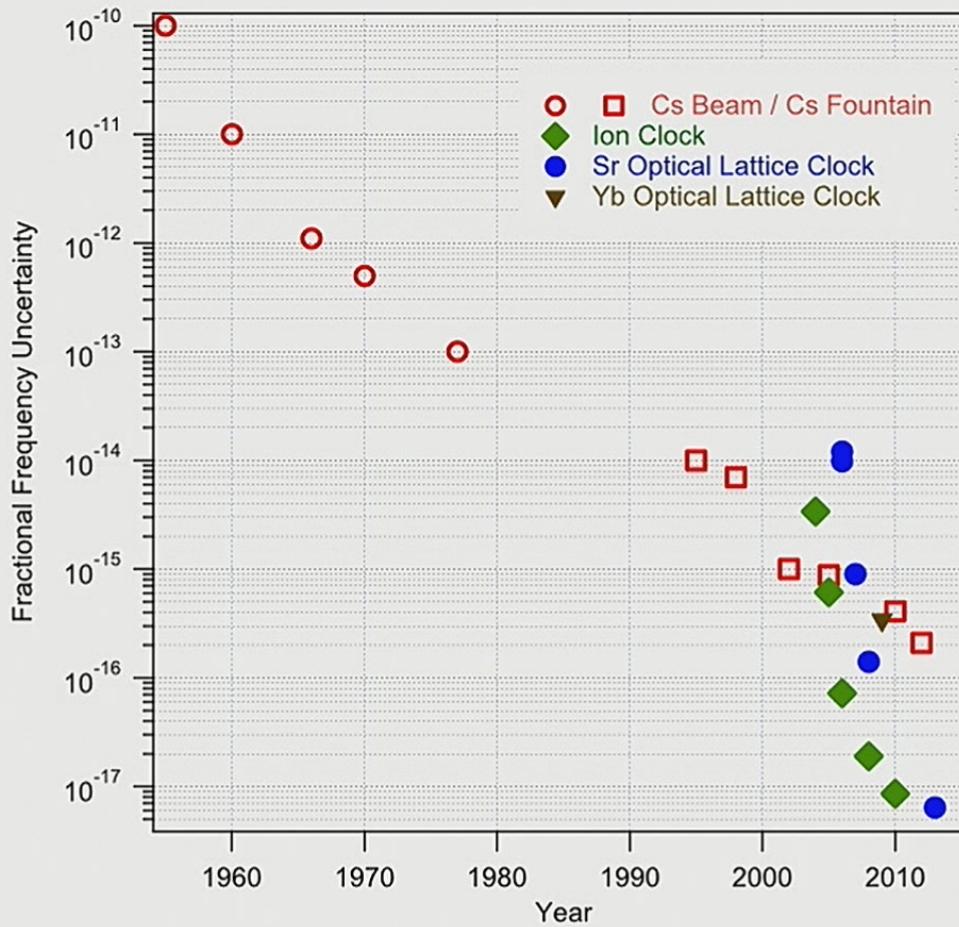
Quality factor $> 10^{17}$

Optical dipole moment
 $\sim 10^{-4} - 10^{-5}$ Debye

Boyd et al., Science 314, 1430 (2006).

from: Jun Ye (JILA, Boulder)

Sr clock – a new frontier for stability & accuracy





The inaccuracy of such a clock corresponds to 1s over
the entire lifetime of the universe!



Outlook

- Hofstadter Butterfly
 - Novel (Topologically) Correlated Phases in Strong Fields, e.g. Fractional Chern Insulators
 - $SU(N)$ Quantum Magnets
 - Controlled Quasiparticle Manipulations
 - Non-Equilibrium Dynamics (Universality?)
 - Thermalization in Isolated Quantum Systems
 - Lieb-Robinson in 2D?
 - Entanglement Measures in Dynamics
 - Rydberg Quantum Crystals
 - Supersolids
 - Cosmology
 - High Energy Physics
 - Quantitative testbeds for theory!
- ⋮

