Bose-Einstein condensates in optical lattices

Creating number squeezed states of atoms

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Overview

- What is a BEC?
- What is an optical lattice?
- What happens to a BEC in an optical lattice?
- Experiments
  - Mott insulator
  - Collapse and revival of matter waves
- Other interesting bits
- Summary

Bose-Einstein condensation

- Definition: Macroscopic occupation of a single quantum level (usually ground state).
- Due to *saturation* of excited states of system

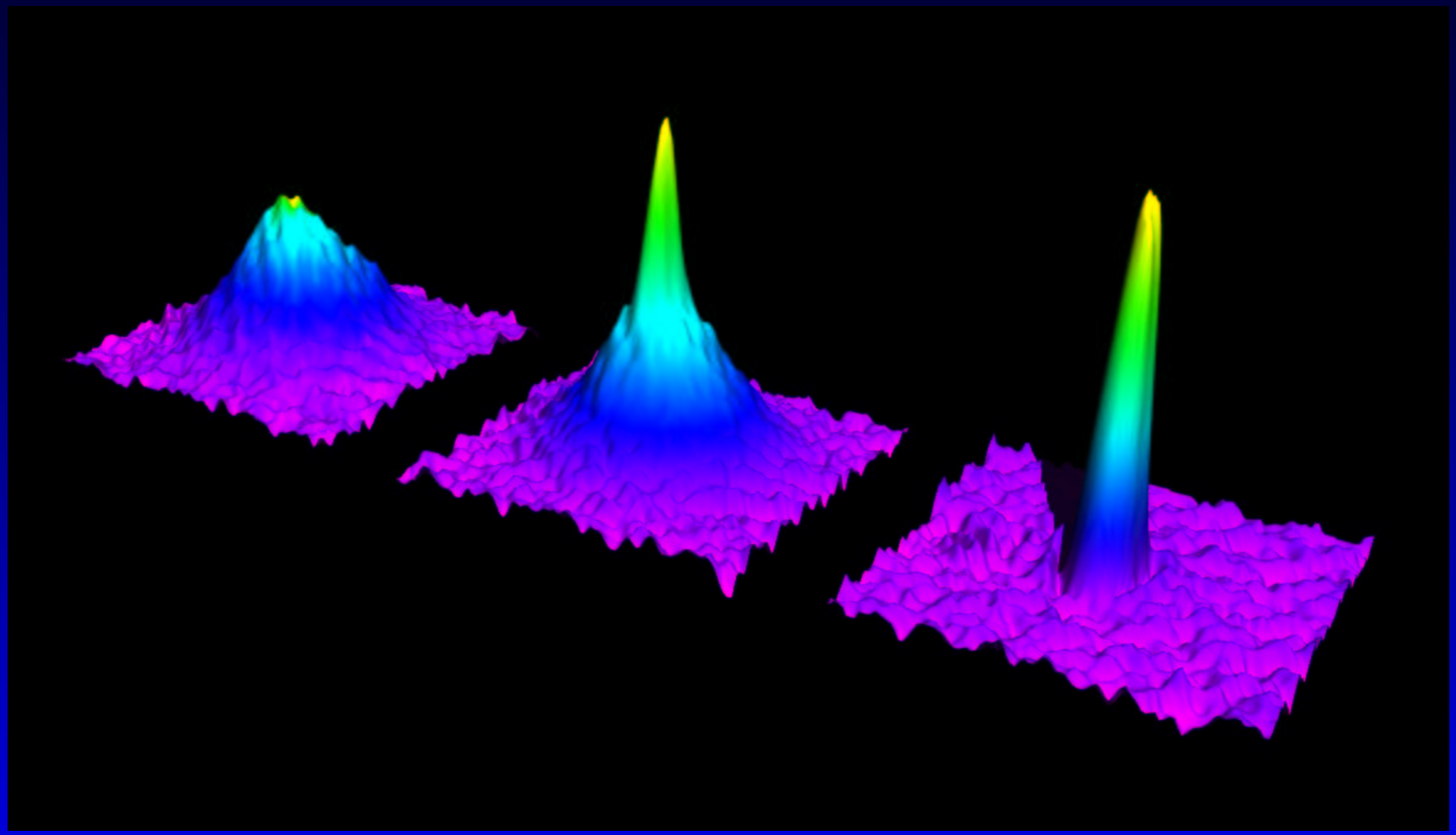
$$\text{Condition}: \quad n\Lambda_{dB}^3 \geq 2.612$$

- Created for the first time in 1995 in atomic Rb
- More than 30 groups have now observed BEC
- Nobel prize for Cornell, Ketterle and Wieman in 2001.

BEC features

- Made by first laser cooling, then evaporative cooling a sample of trapped atoms.
- Occurs at ultracold temperatures $\sim$ 100 nK.
- Typically consist of 10^4–10^7 atoms of eg Rb, Na.
- Best thought of as a *matter wave*, analogous to laser light.
- All atoms are phase coherent i.e. widely spaced atoms can form an interference pattern.
- *Quantum mechanics on a macroscopic scale*

Phase transition



Optical dipole force

- Stark effect: Shift of atomic energy levels in static electric field.
- AC Stark effect: Shift of atomic energy levels due to time-varying electric field of laser.
- In the limit of large deturning from resonance (avoid spontaneous decay)

$$\Delta E(x) \propto \frac{I(x)}{(\omega - \omega_0)^2}$$

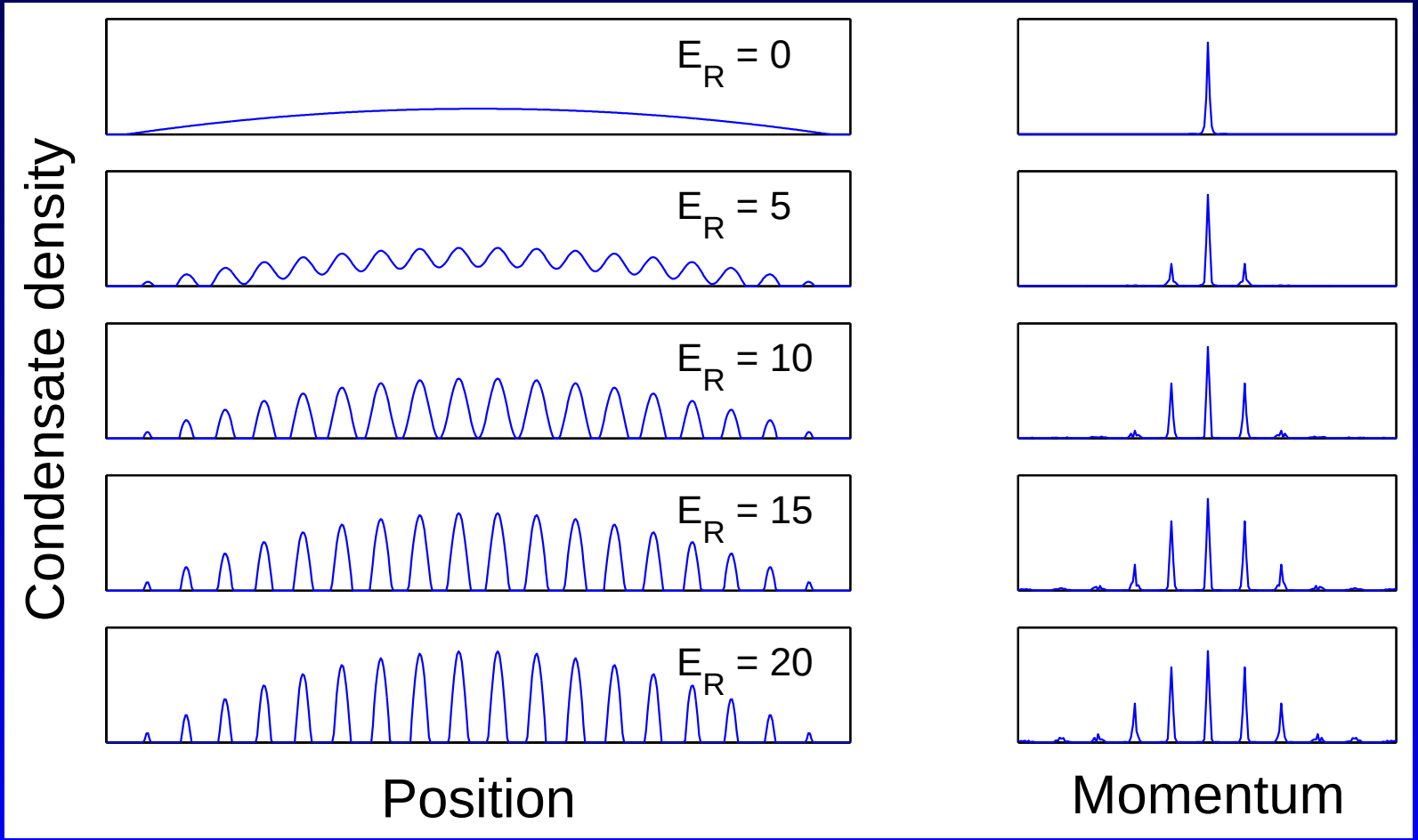
- Remember $F(x) = -dE(x)/dx$, so atoms in a laser beam experience force proportional to gradient of intensity of laser beam

Optical lattices

- Definition : Standing waves of light
- Atoms see series of potential wells (hills).
- If cold enough, atoms can be trapped in single well.
- Blue-detuned : atoms trapped at nodes
- Red-detuned : atoms trapped at anti-nodes
- *Depth of potential easily controlled via laser intensity*

Loading BEC into lattice

- Increase intensity adiabatically
- $V(x) = E_R(t)\cos^2(kx/2), \quad k = 2\pi/\lambda$



The physics

Initially . . .

- Atoms can tunnel between wells
- Each well is approximately a coherent state.
- Variance in atom number is equal to mean.
- System is superfluid.

As laser intensity increases . . .

- Wells become isolated (longer tunnelling time).
- Number fluctuations supressed.
- Heisenberg says — *phase fluctuations increase.*

Quantum phase transitions

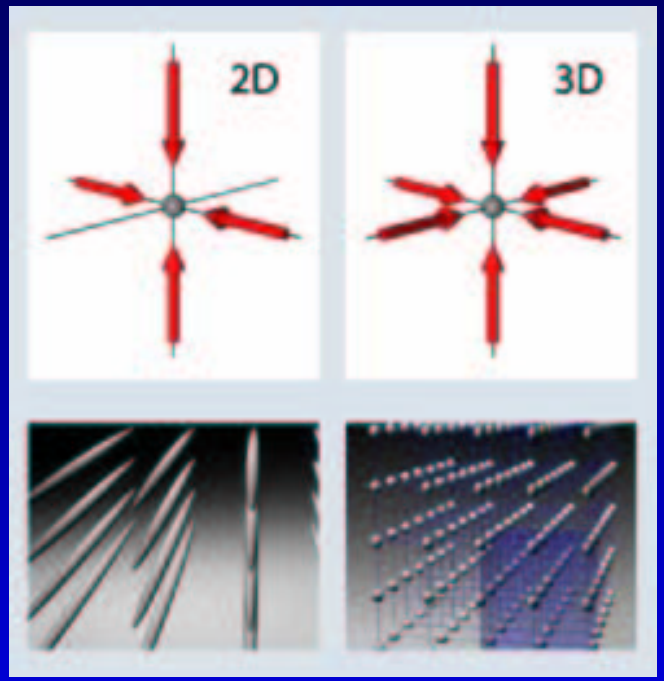
- Classical phase transitions driven by thermal fluctuations.
- Quantum phase transitions driven by quantum fluctuations.
- Occur at T=0 by changing parameters of Hamiltonian.
- Mott insulator : Energy minimised by number states in each well.
- How? — reduce tunnelling rate by increasing lattice depth.

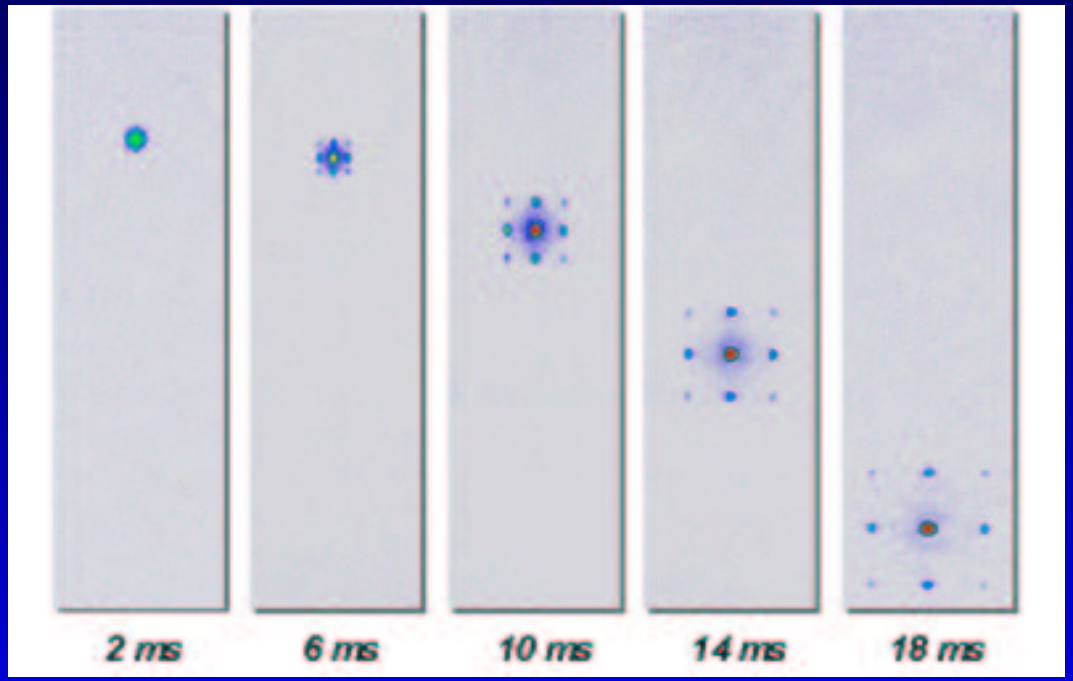
Experiments

1D lattice expt by Orzel et al, Science **291**, 2386 (2001).

3D lattice ext by Greiner et al, Nature **415**, 39 (2002).

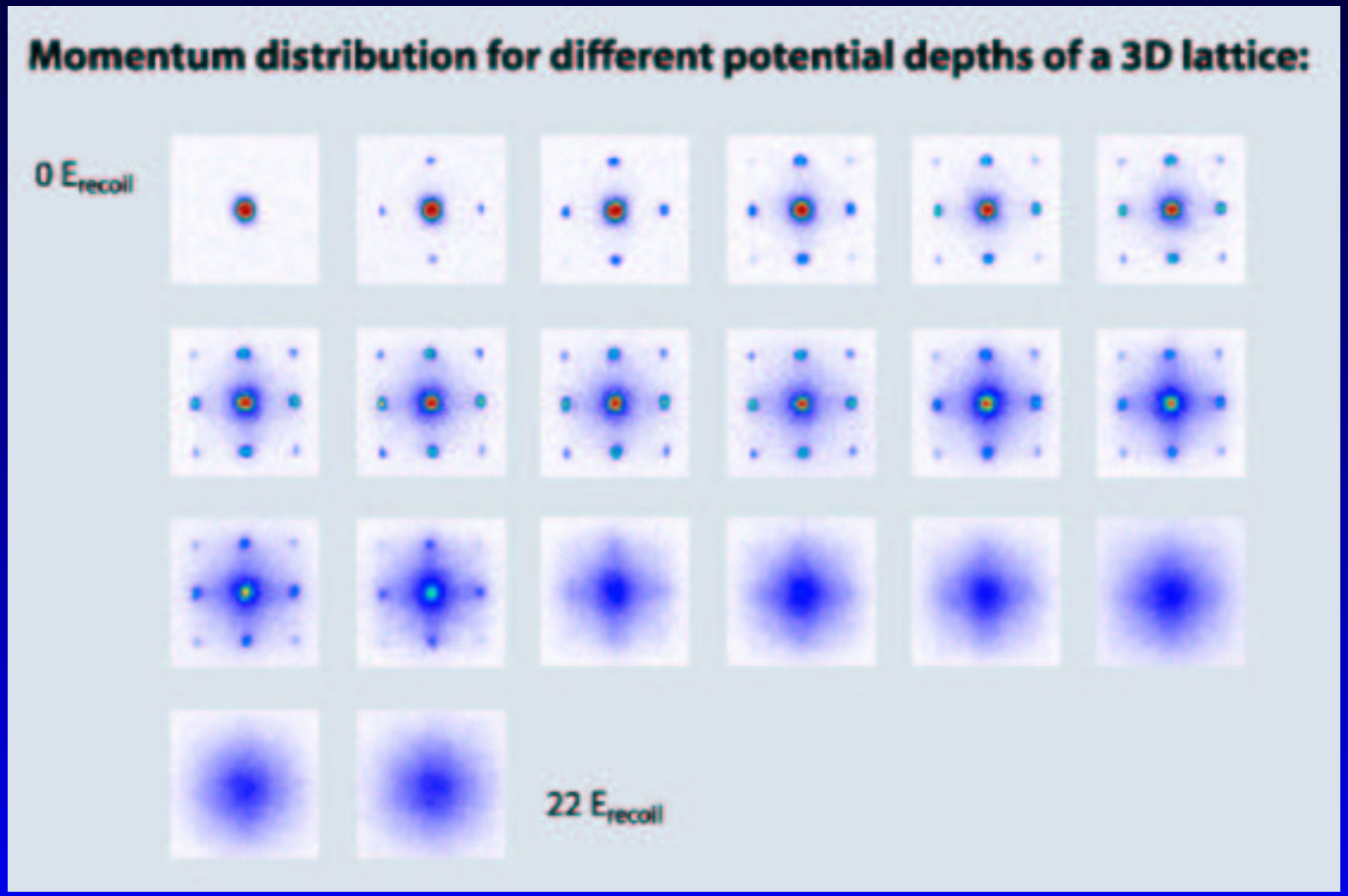
Turn on lattice adiabatically, then switch off suddenly



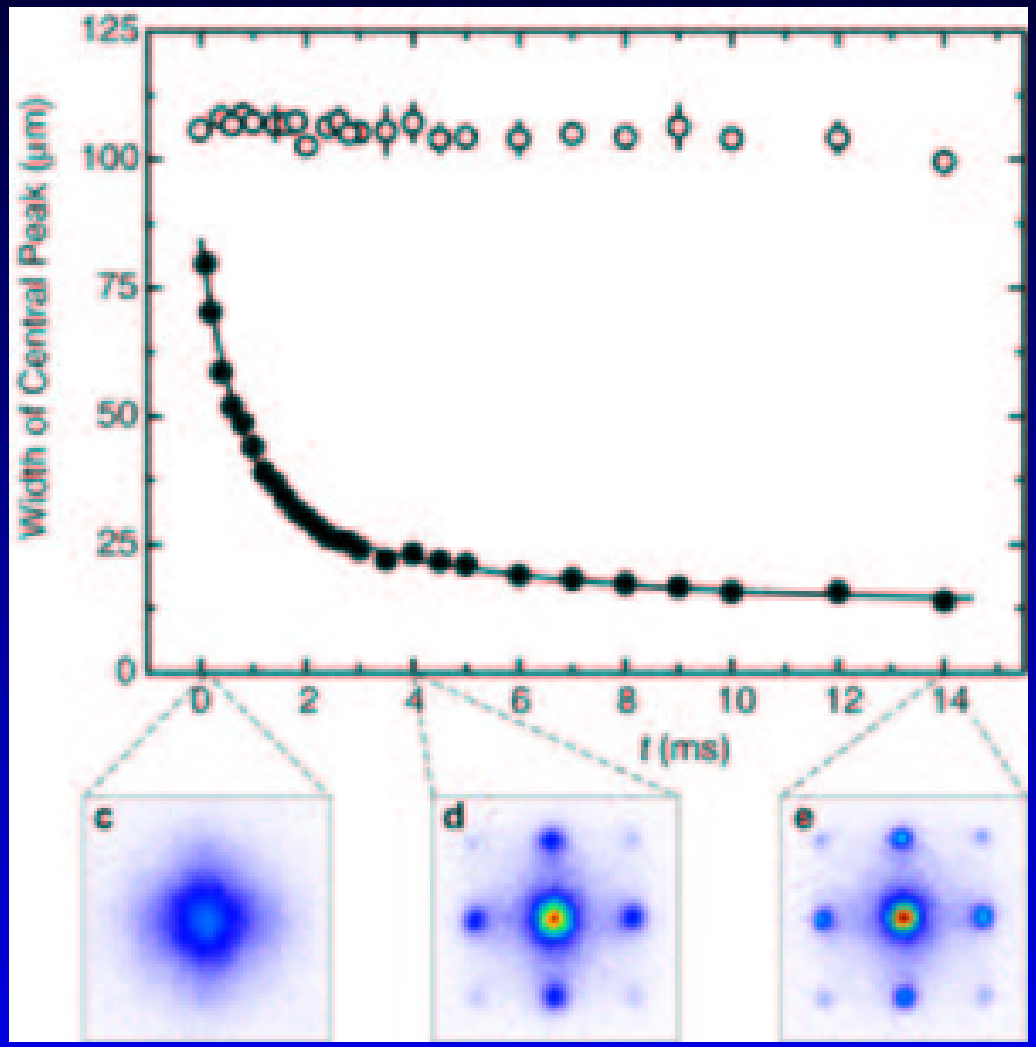


Superfluid to Mott insulator . . .

Images after 18 ms of expansion



. . . and back to superfluid

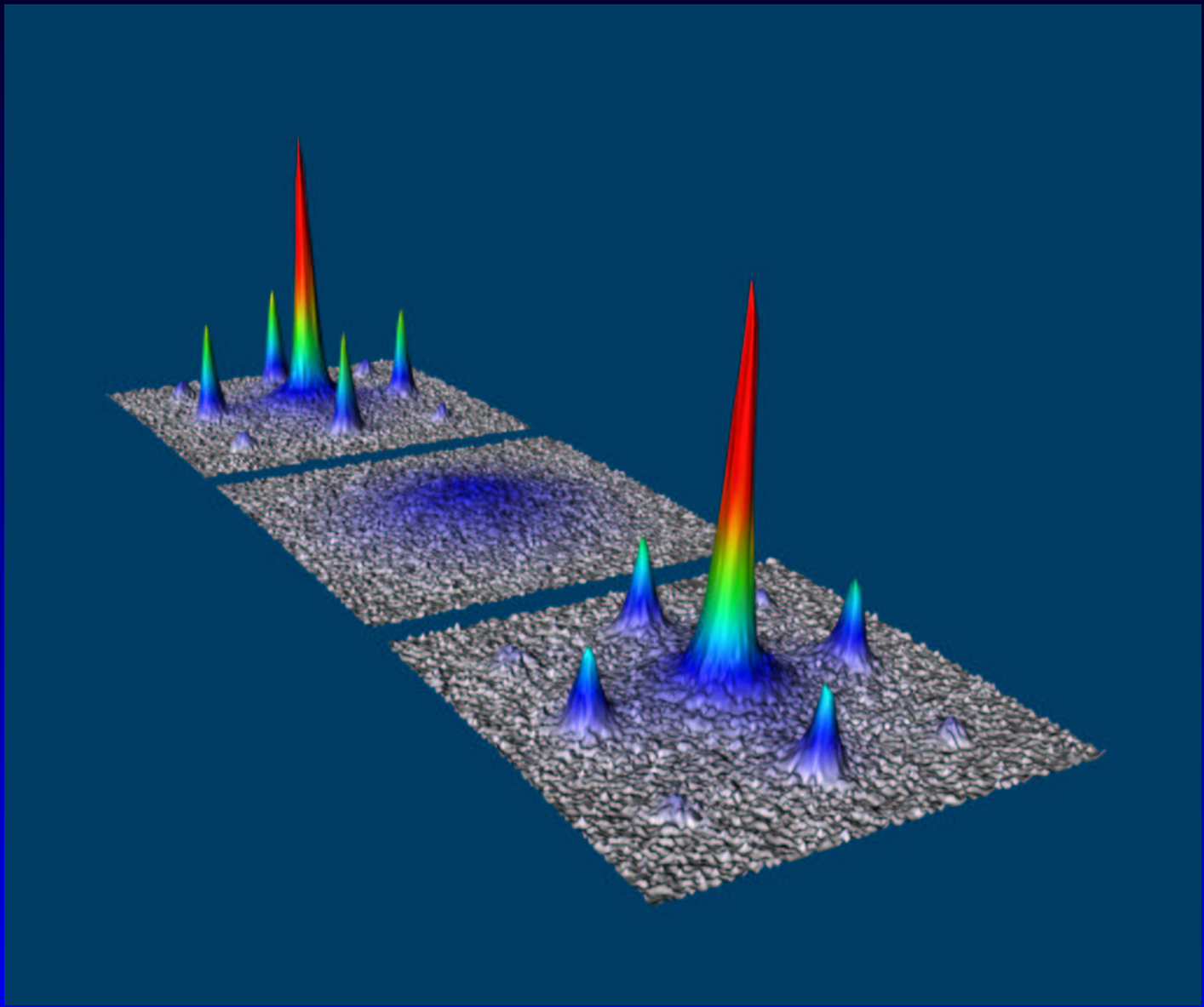


Adiabatic ramp to 22 E_R (80 ms)

Hold (20 ms)

Release to 9 E_R (t ms)

. . . and back to superfluid II



Theory: Bose-Hubbard model

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

J : tunneling matrix element. Decreases with E_R.
U : interaction matrix element. Increases with E_R.

Mott insulator transition: $\frac{U}{nJ} > 5.8 \times z$

n : number of atoms per site
z : number of nearest neighbours

More theory

- Recent results show that disappearance of interference is not a signature of MI phase (Roth and Burnett, condmat/0209066).
- However excitation spectrum was also studied.
- Energy gap appears above lattice depth of 13 E_{recoil}.
- Thus an insulating state was acheived.

Collapse and revival

Coherent state: superposition of number states

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

Ground state Hamiltonian of single well

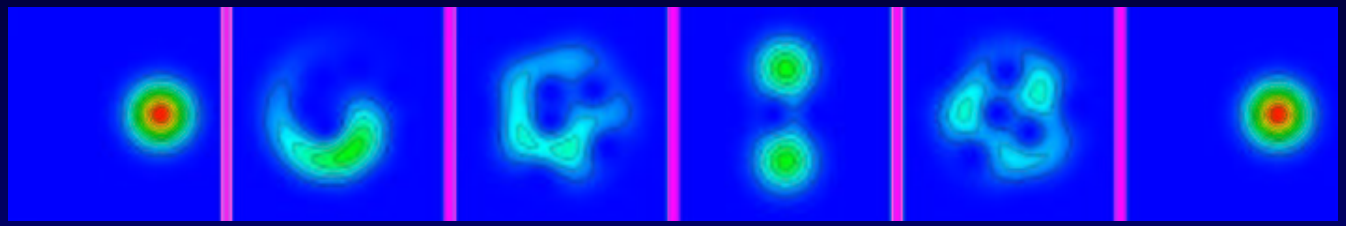
$$\hat{H} = \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Evolution:

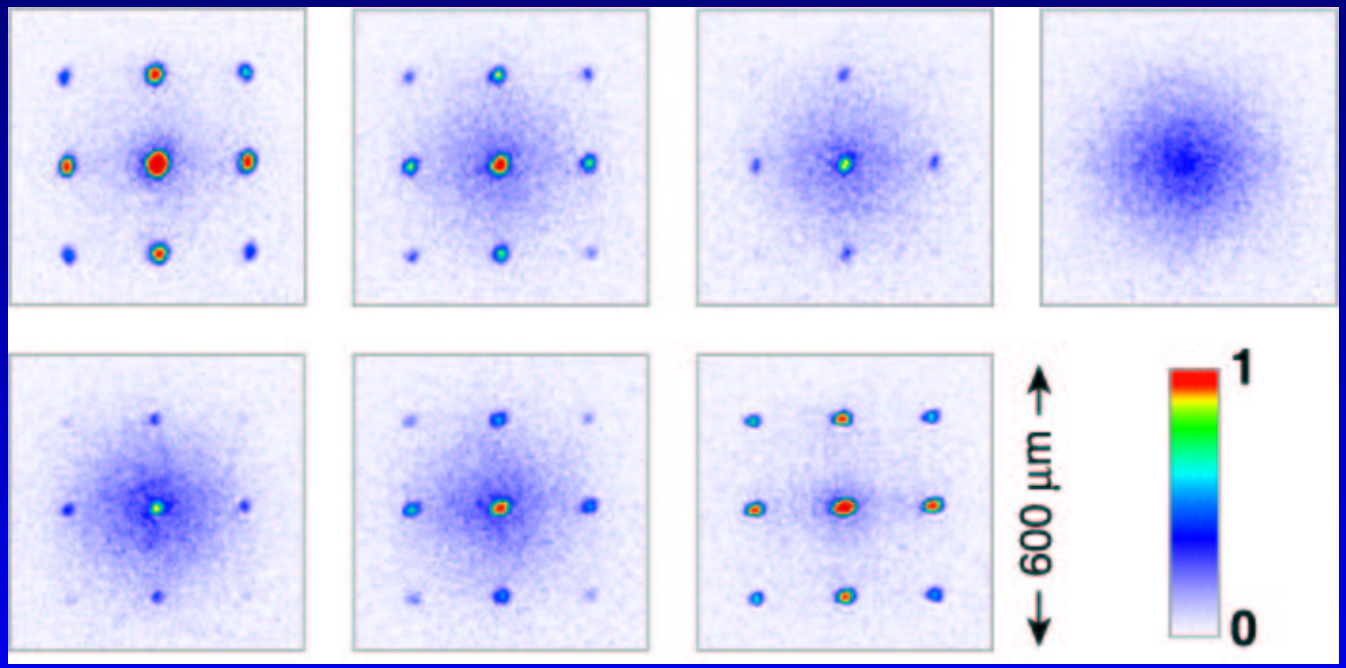
$$|\alpha\rangle(t) = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} e^{-i\frac{1}{2}Un(n-1)t/\hbar} |n\rangle$$

Revival

- All phases match up at times $t_c = U/h$



- Can be realised by sudden switch to Mott insulator state!

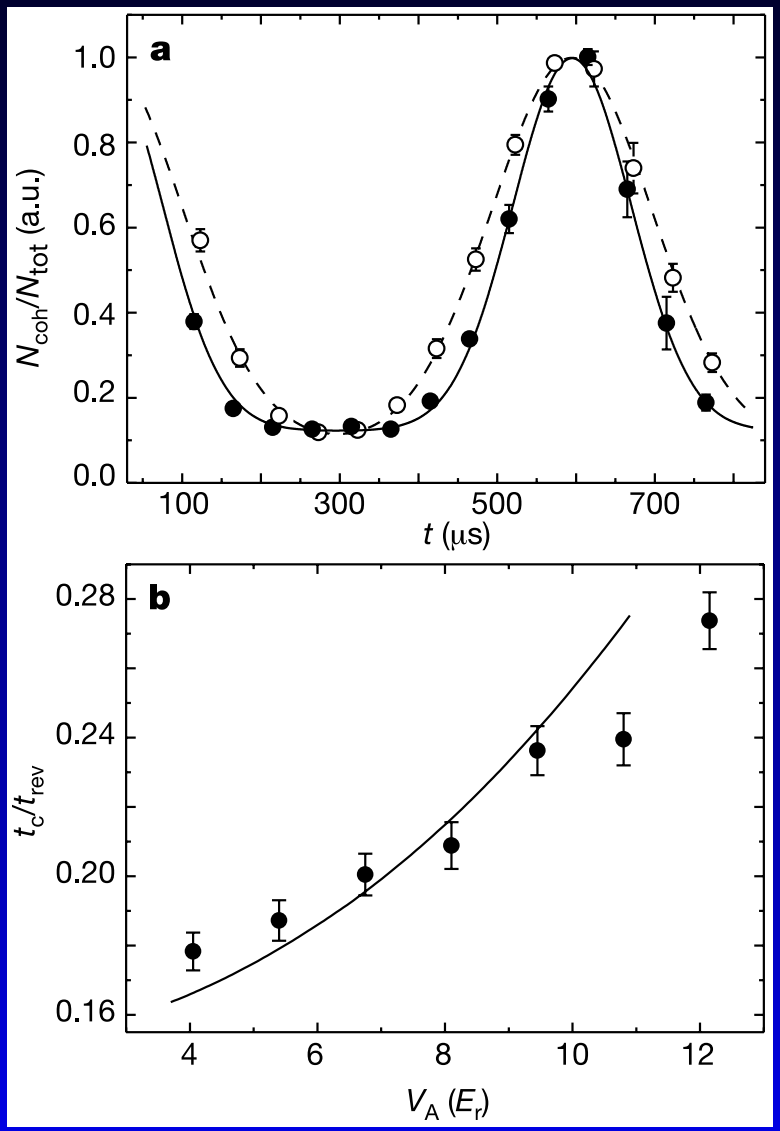


Increasing times in the MI state

Time scales

Revivial time is *independent* of atom number variance.

Collapse time is *dependent* on initial variance of atom number



Other interesting bits

- Proposal (and experiments) on controlled cold collisions
  Two different internal states, each see different lattice.
  Move lattices together — interactions dependent on state.
  Quantum computing???
- Proposal to form Mott insulator with $n = 2$
  Then photoassociate and melt $\Rightarrow$ molecular BEC.
- Why is this interesting?
  Wednesday physics seminar tommorow, 1pm Conference room 2.32D, Physics Annexe (Building 6).
  PAIR CORRELATED ATOM LASER BEAMS
  Dr Karen Kheruntsyan.

Summary

- Introduction to BEC
- Introduction to optical lattices
- Quantum phase transitions
- Superfluid to Mott insulator
- Bose-Hubbard model.
- Collapse and revival of matter waves
- Other proposals for BECs in lattices.

No Microsoft products were used in the making of these slides

Thanks to linux, latex, prosper, and ps2pdf.