25. August 2023

양자정보과학 여름학교

Ultracold atomic quantum simulator

Realizing Feynman’s dream

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NRF National Research Foundation of Korea

KAIST

Outline

Short introduction to optical lattice system

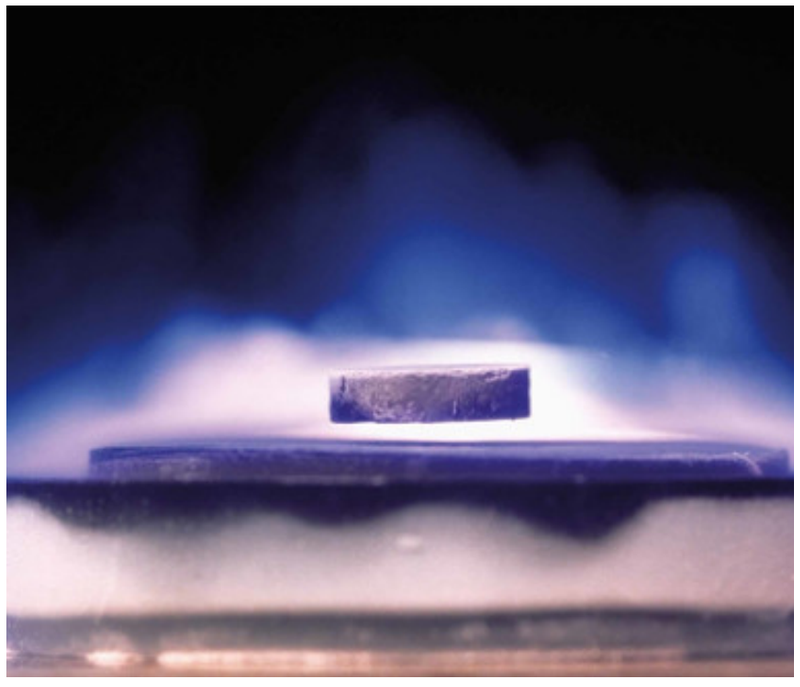
Ultracold atoms in optical lattice

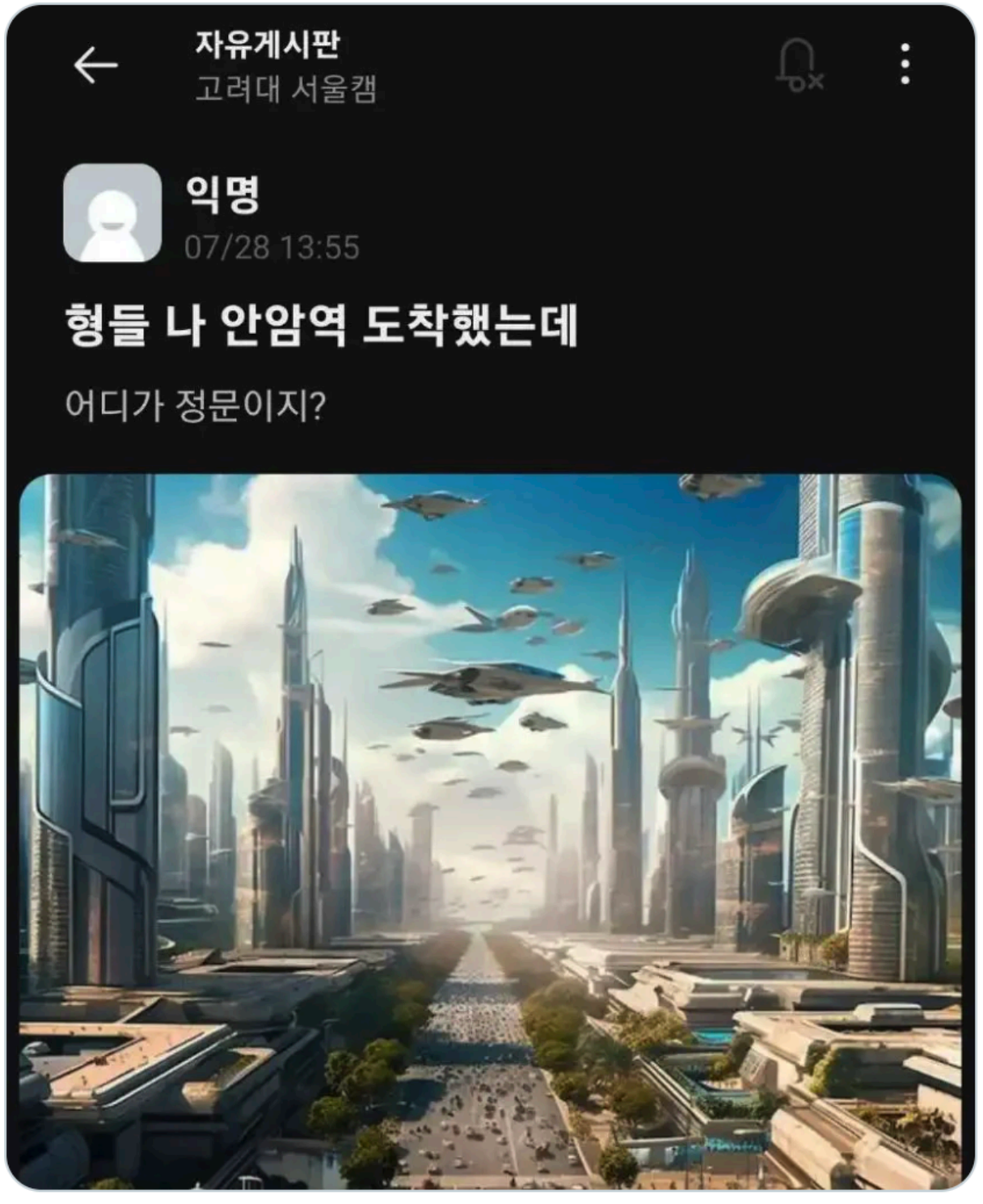
Imaging and addressing of many-body quantum state

Motivations

Understand and Design novel quantum material

One of the biggest challenge of modern



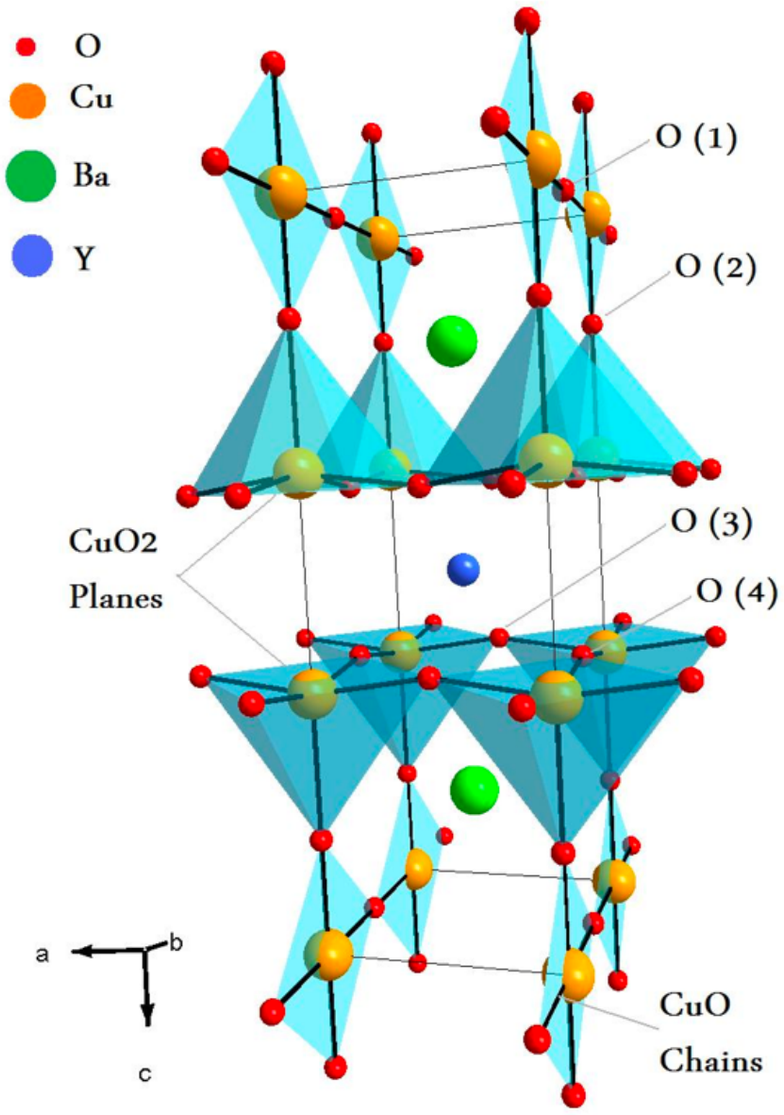


High temperature superconducti

Motivations

Why it is difficult?

Many-body quantum problem is usually intractable with classical computers



a. Complex structures and lacks of experimental controllabilities

b. Strong interactions and limits of perturbative approaches

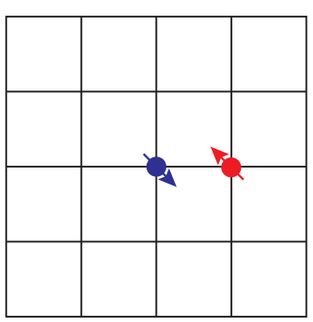
c. Even the simple model has no exact solution

$$H = -t \sum_{(i,j),\sigma} \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + V \sum_{i,\sigma,\sigma'} \hat{c}^{\dagger}_{i\sigma} \hat{c}^{\dagger}_{i\sigma'} \hat{c}_{i\sigma'} \hat{c}_{i\sigma}$$

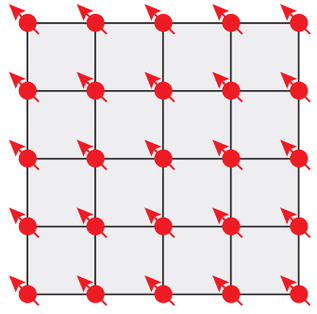
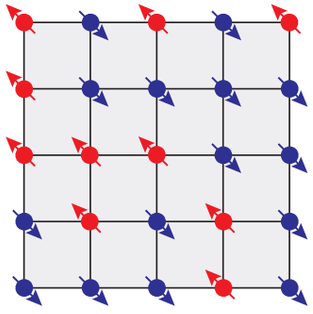
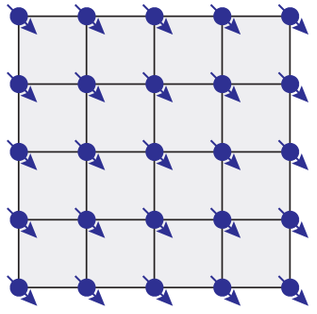
Fermi-Hubbard model

Quantum complexity

Hilbert space scales with exponential with the particle number



e.g. spin-1/2 in a square 2D lattice.

$$|\Psi\rangle = c_1$$  $$+ c_2$$  $$\cdots + c_N$$ 

Number of possible configuration 2^N

Motivations



State of the art ~ 40 spins (2D)

Adding SINGLE spin requires DOUBLING of the system

For N=300, 2^{300} : estimated number of protons in the universe

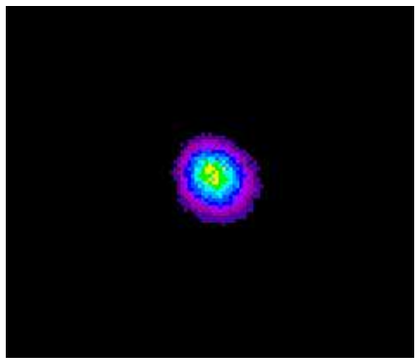
Motivations

Atomic Molecular and Optical (AMO) physics

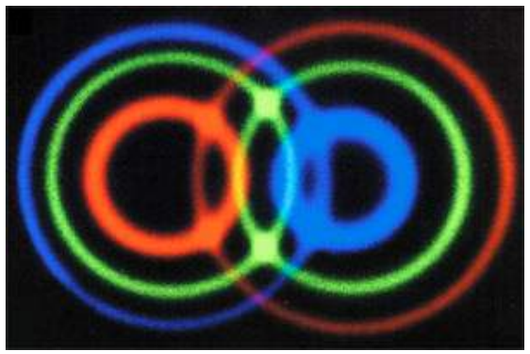
- Control of single and few particles

- Atoms/ions are identical and have long coherence

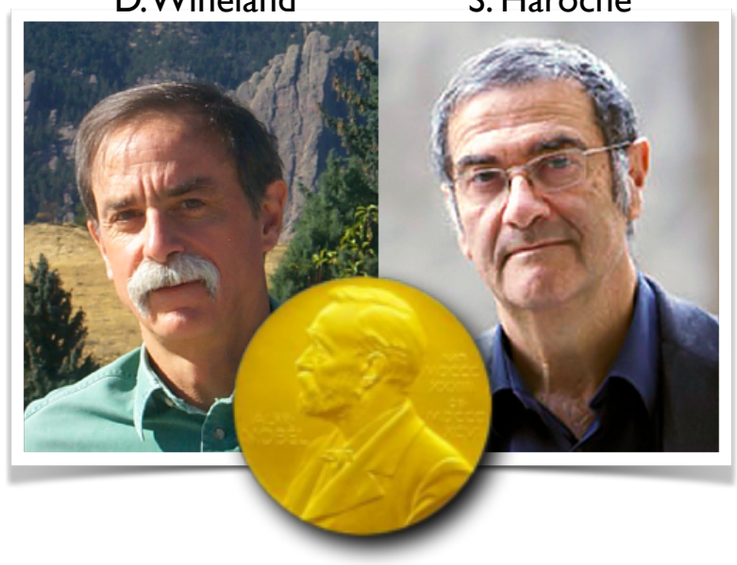
Single atom/ion



Photons



D. Wineland S. Haroche



Towards ultimate control of many-body quantum system

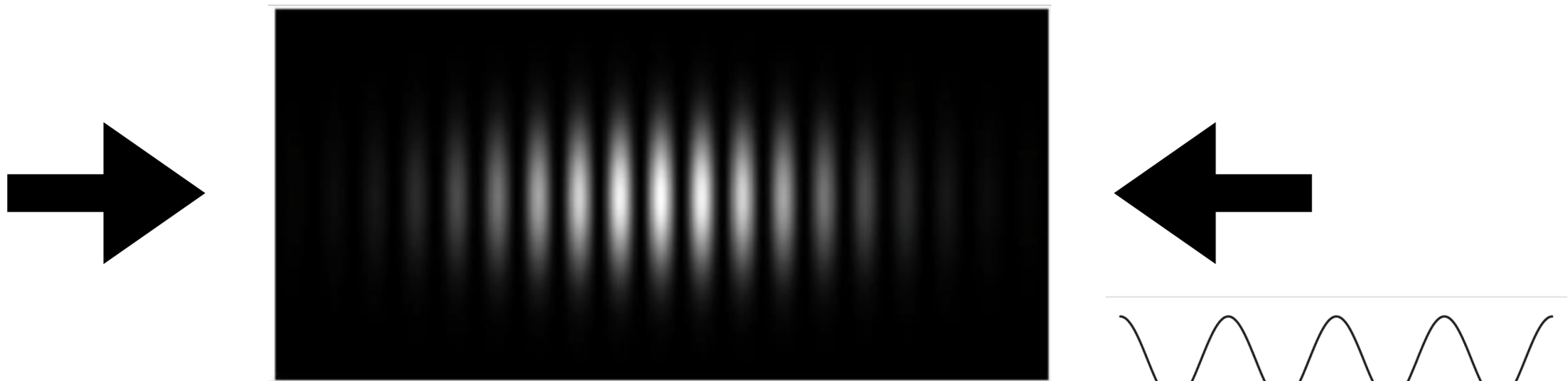


R. Feynman's Vision

Build a quantum simulator that could imitate any quantum system

How do we build a quantum simulator?

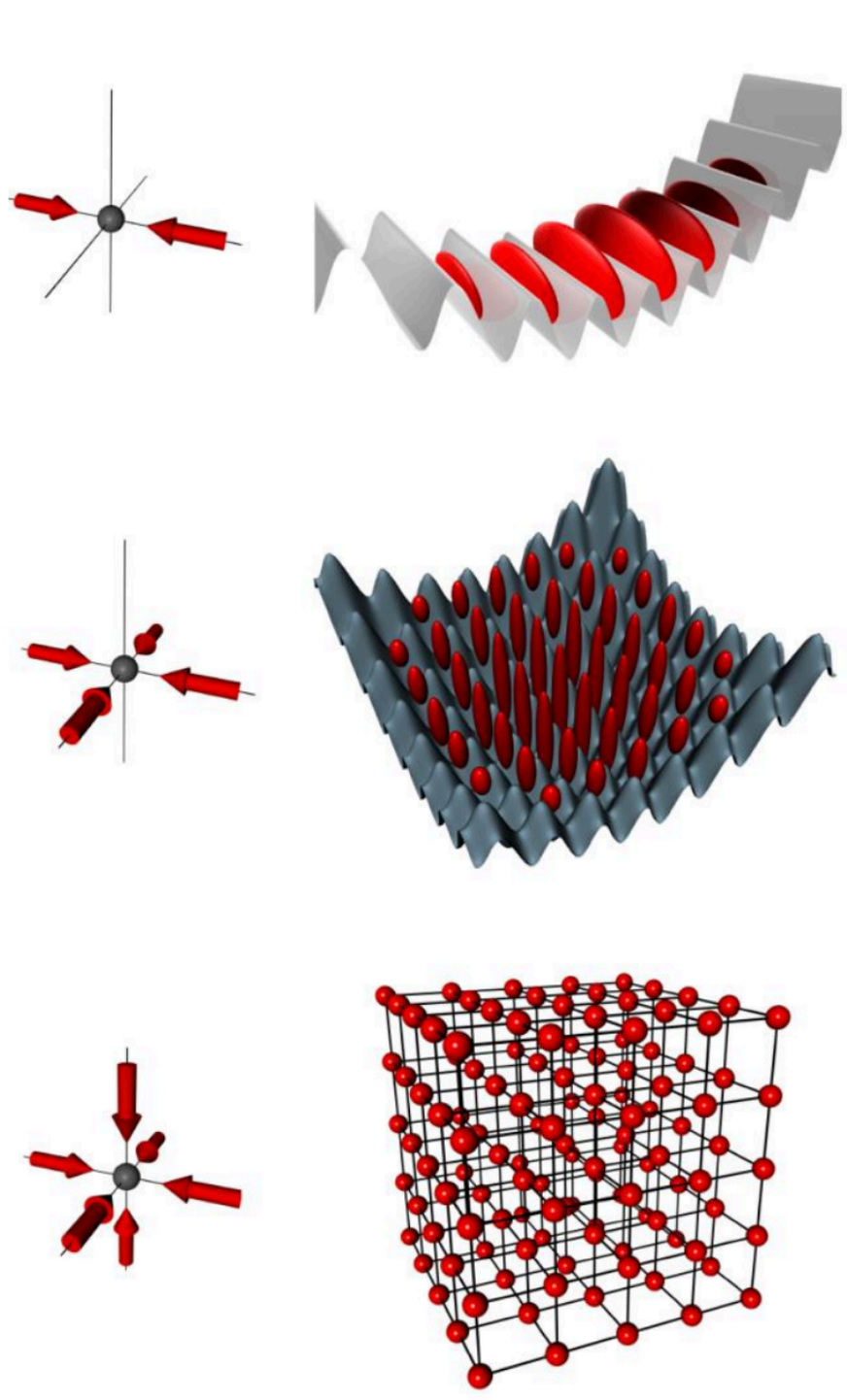
Optical lattice

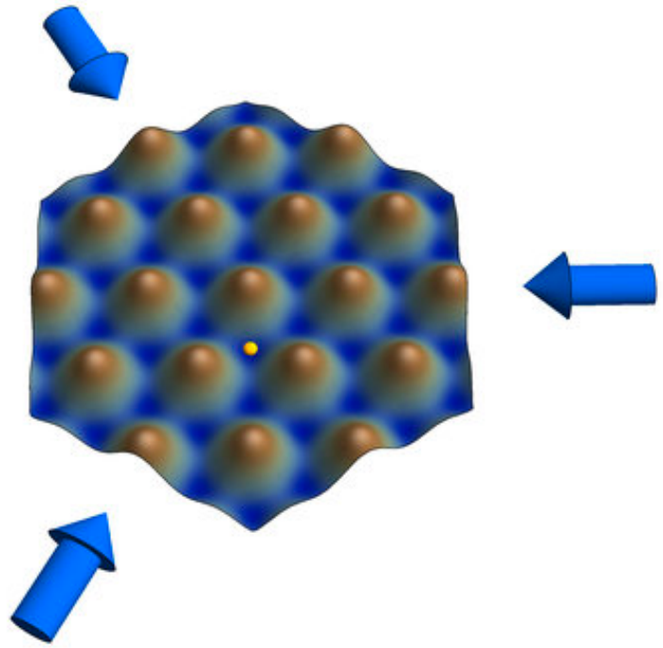


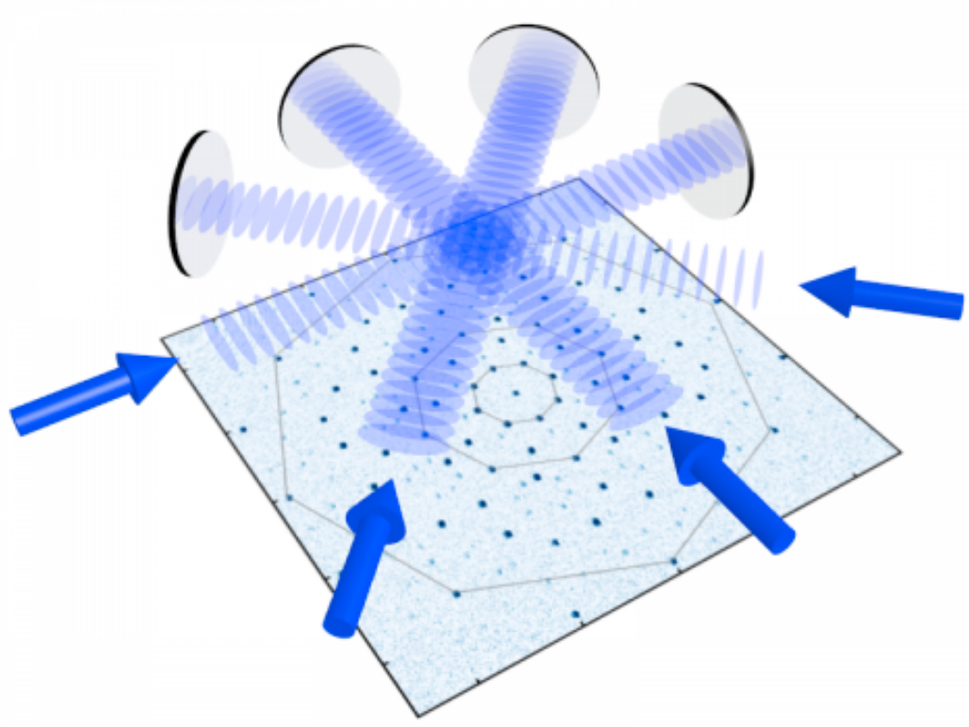
Defect free & perfect artificial crystal !!

Optical lattice

Various lattice geometry from interference patterns







S

SuperLaser123

구독자 731명

T. Hänsch

홈 동영상 재생목록 채널 토론 정보

S

SuperLaser123

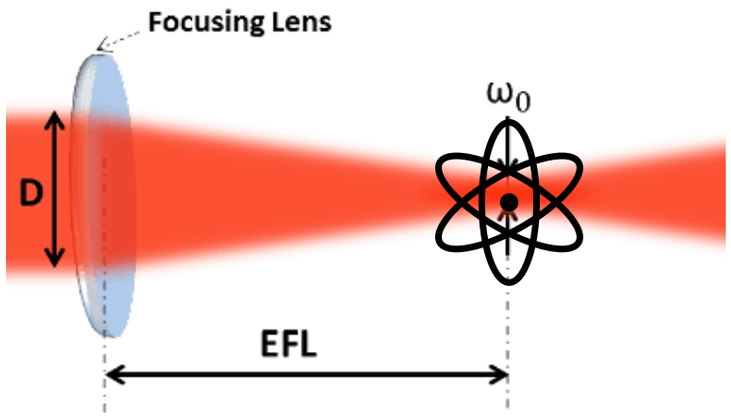
구독자 731명

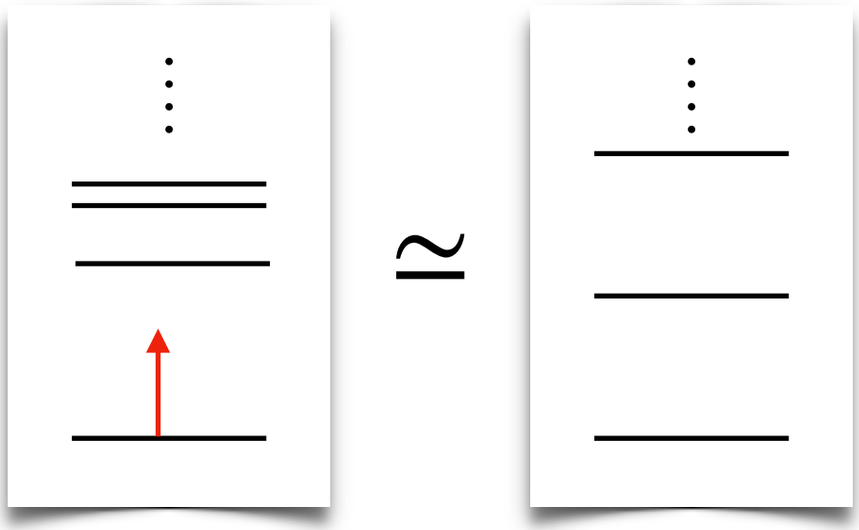
T. Hänsch

홈 동영상 재생목록 채널 토론 정보

Atomic polarizability

Optical dipole potentials





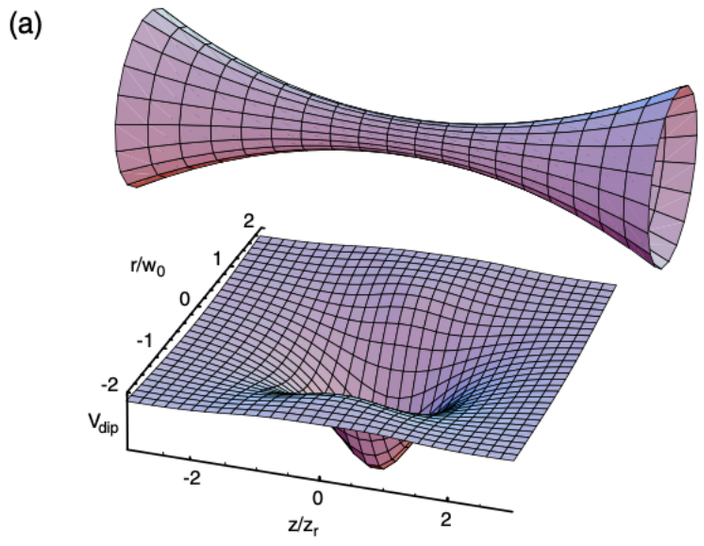
$\simeq$

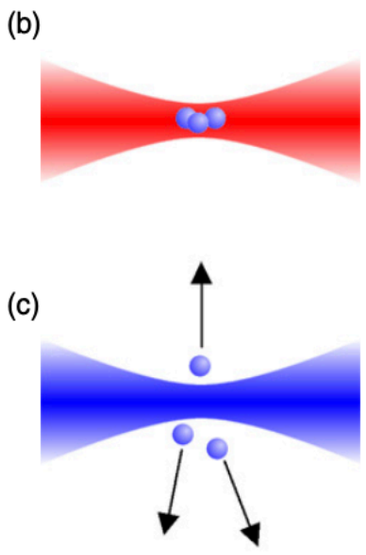
$$U = -\mathbf{P}\cdot\mathbf{E}$$

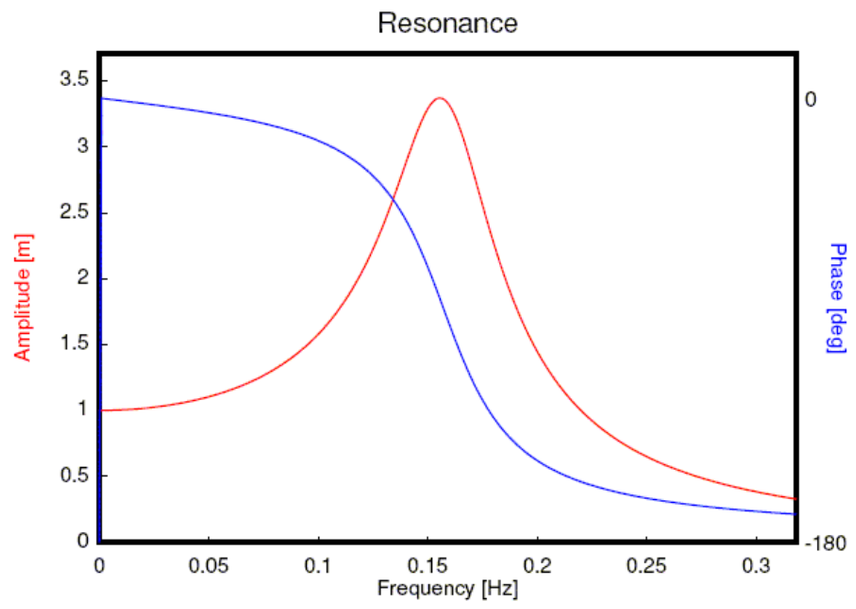
$\mathbf{P} \propto \mathbf{E}$ (Red-detuned)

$\mathbf{P} \propto -\mathbf{E}$ (Blue-detuned)

SHO



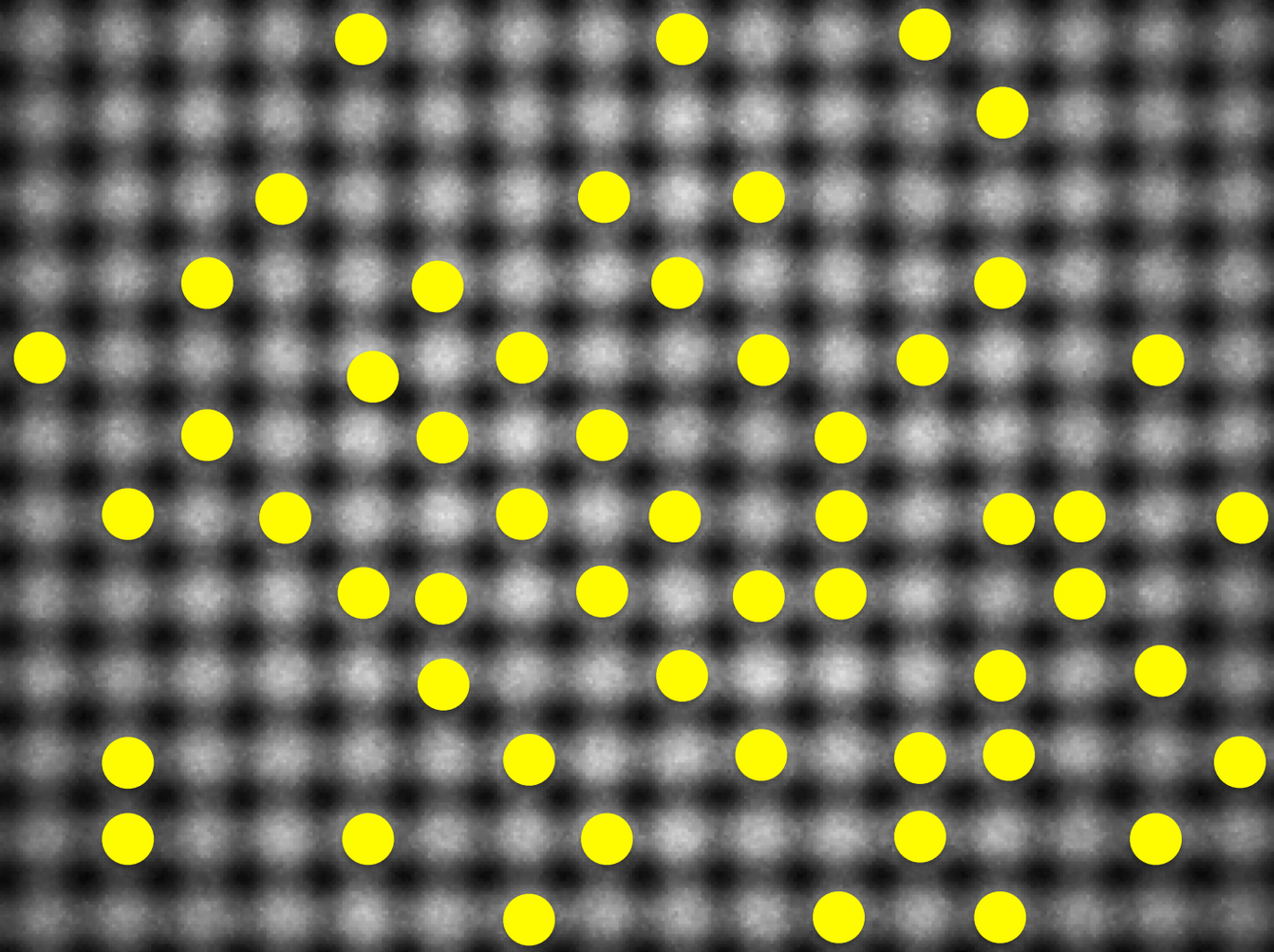




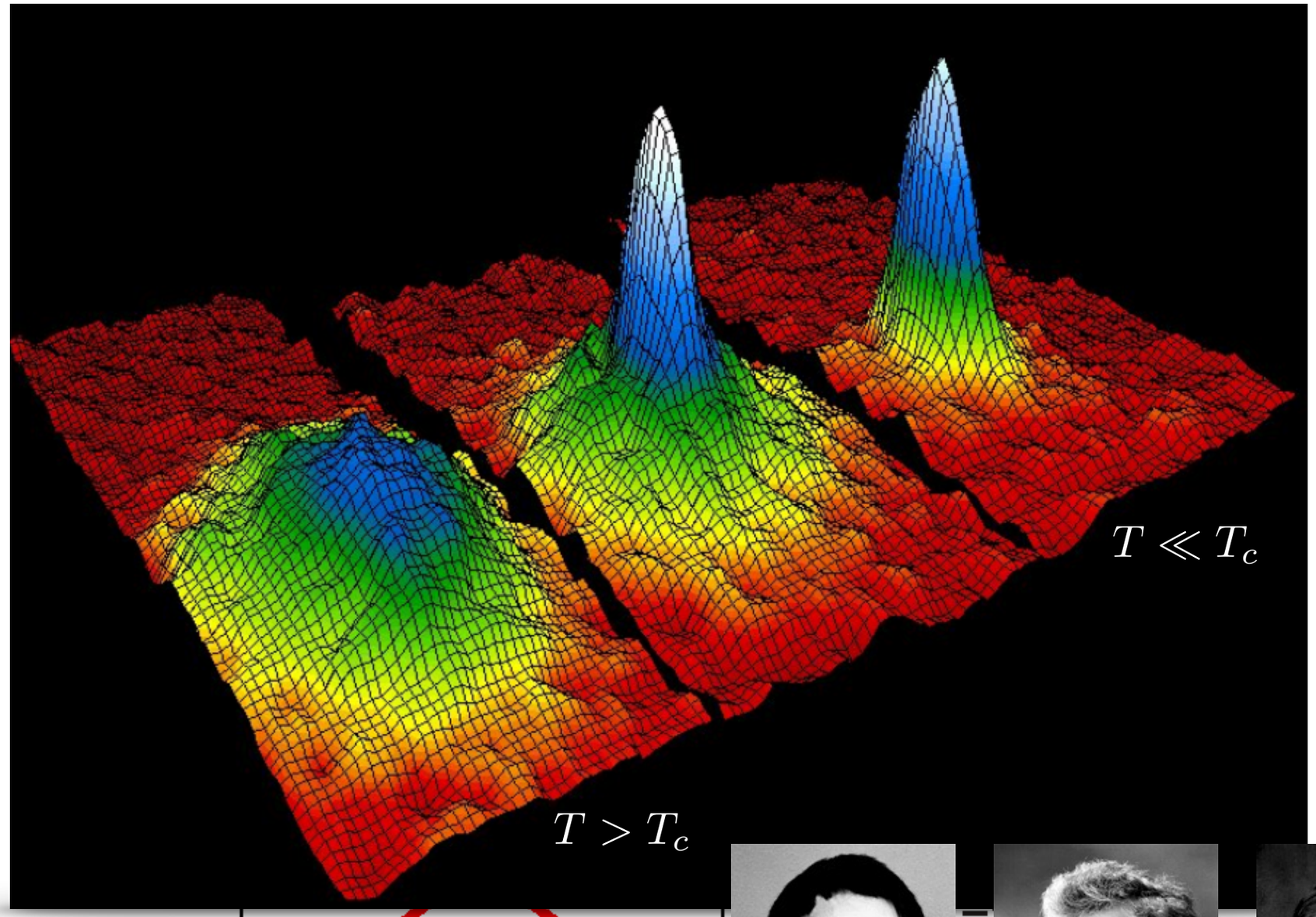
Trapping potential from sound wave

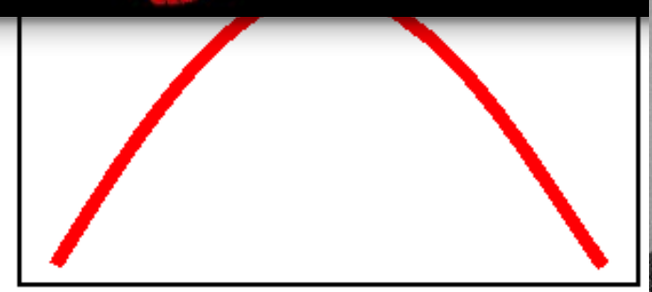


- N ~ 1,000 - 10,000 particles
- Bosons, Fermions, and mixture
- Classically trackable & intractable regime



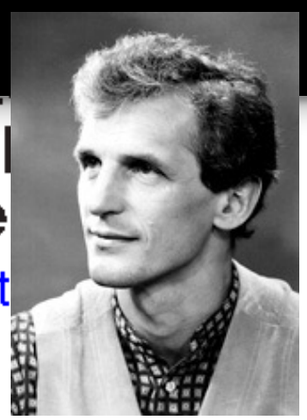
Ultracold atoms



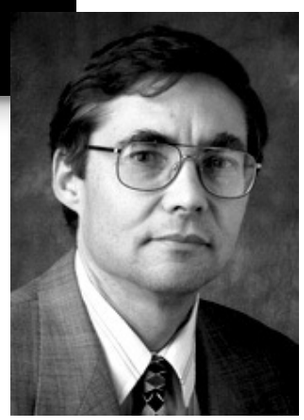




Eric A. Cornell



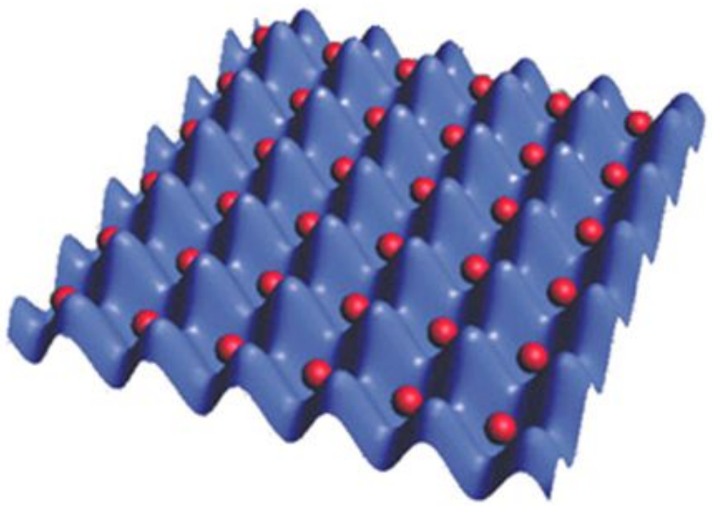
Wolfgang Ketterle



Carl.E.Wieman

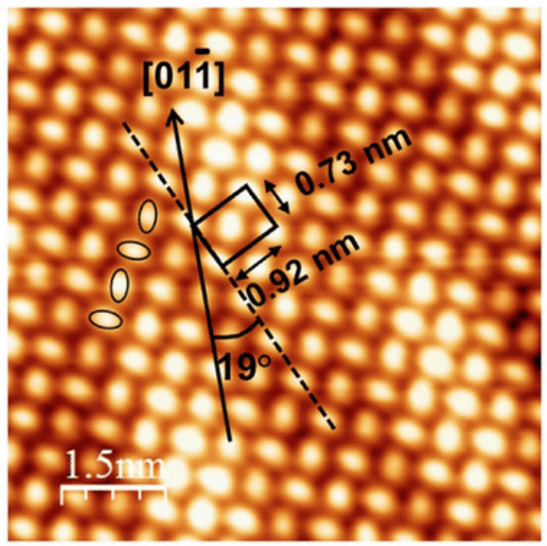
Simulating condensed matter systems

Ultracold atomic matter



- Density: $10^{14}/\text{cm}^3$
  (10,000 times thinner than air)
- Temperature: **few nK**
  (100 million times colder than outer space)

Real material

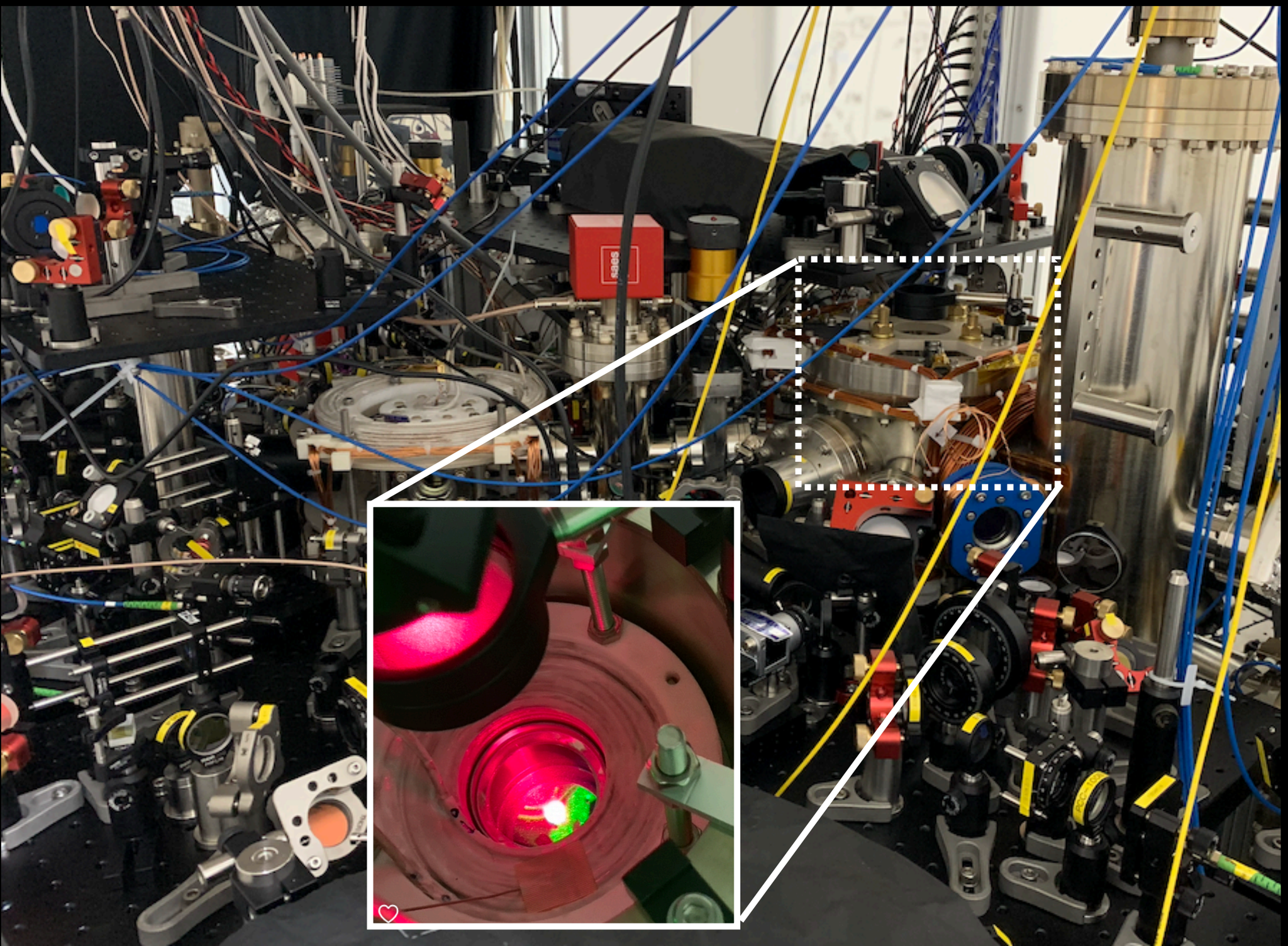


- Density: $10^{23} \sim 10^{24}/\text{cm}^3$
- Temperature: **few mK - 100 K**

Same λ_{dB}/d !

Highly isolated from its environment

Not connected to external reservoir



Ultracold atoms in optical lattices

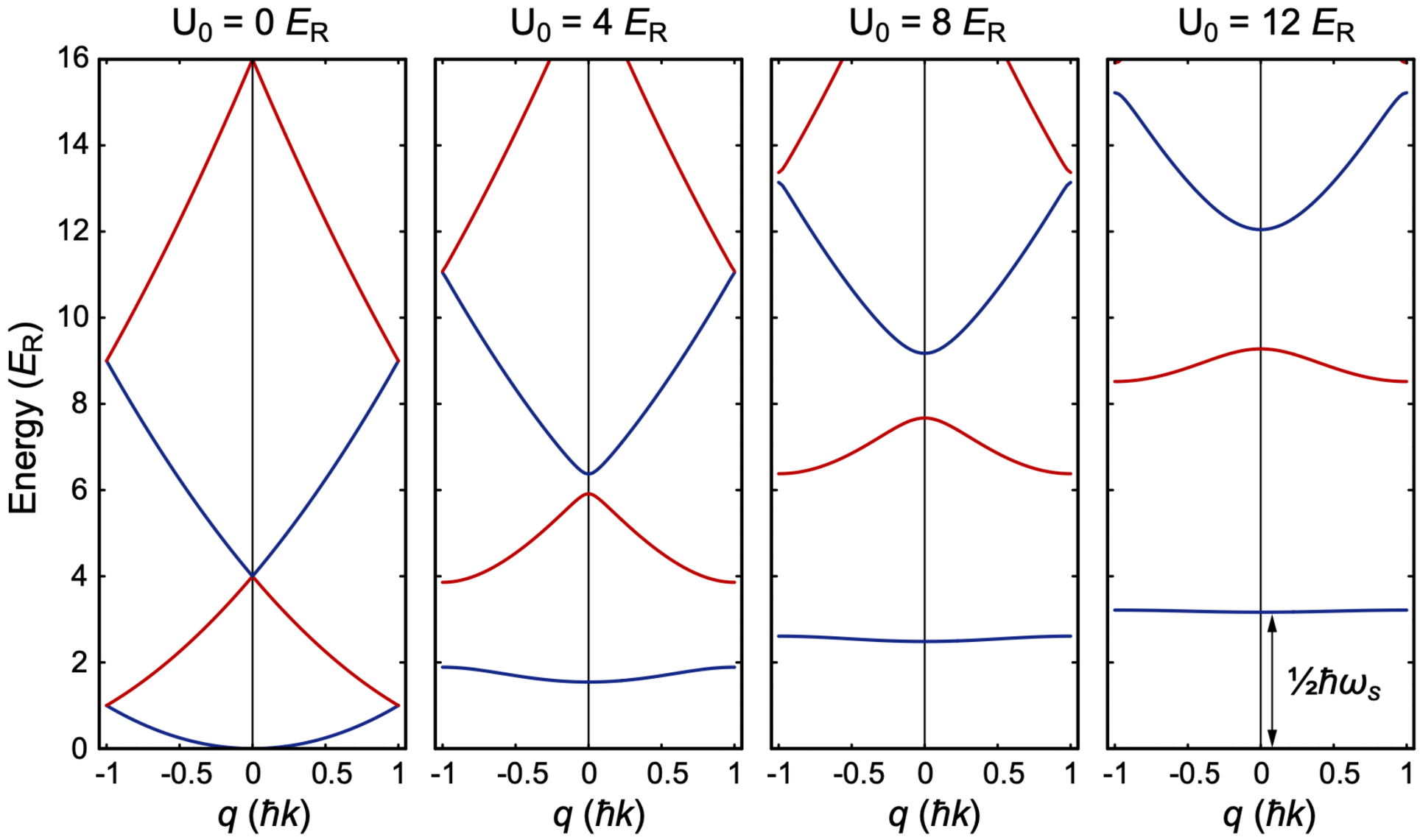
Nature Physics, **1**, 23 (2005)
Review of Modern Physics. **80**, 885 (2008)
Nature Reviews Physics **2**, 411 (2020)

Band structure

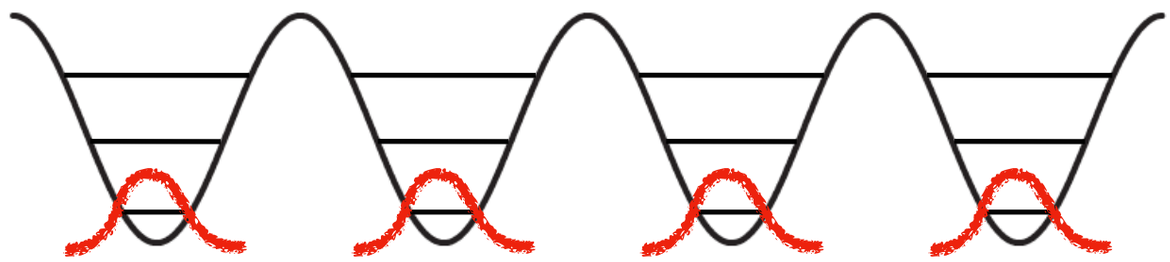
U_0: Depth of the lattice



$$E_R = \frac{\hbar k^2}{2m}$$



Band structure



$w_j(x - x_j)$

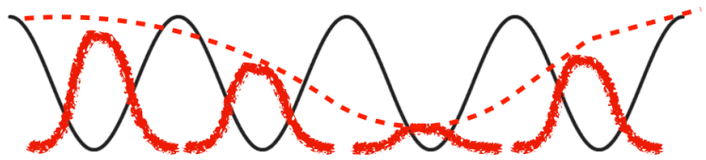
$$\psi_q(x) = \sum_j e^{iqx_j} w_j(x - x_j)$$

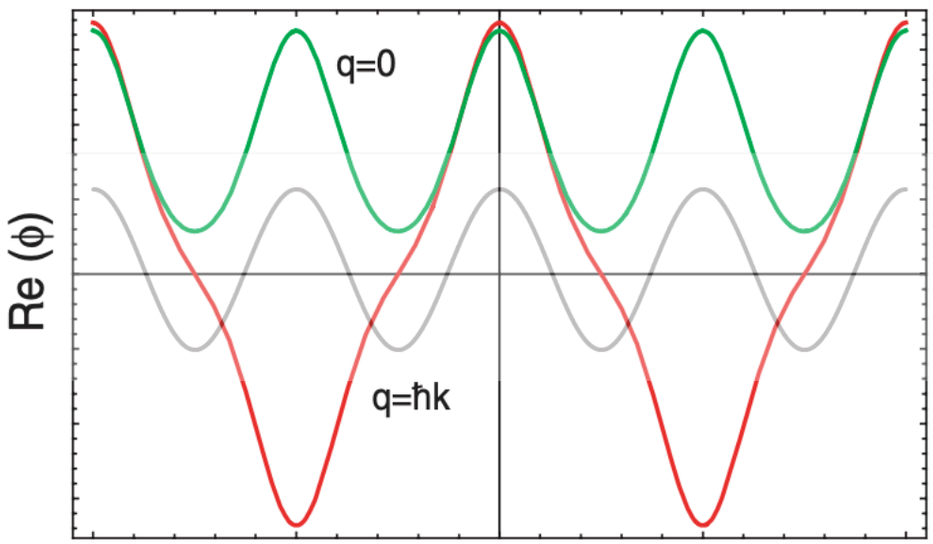
* At higher lattice depth, the eigenstate is less sensitive to the phase between each well

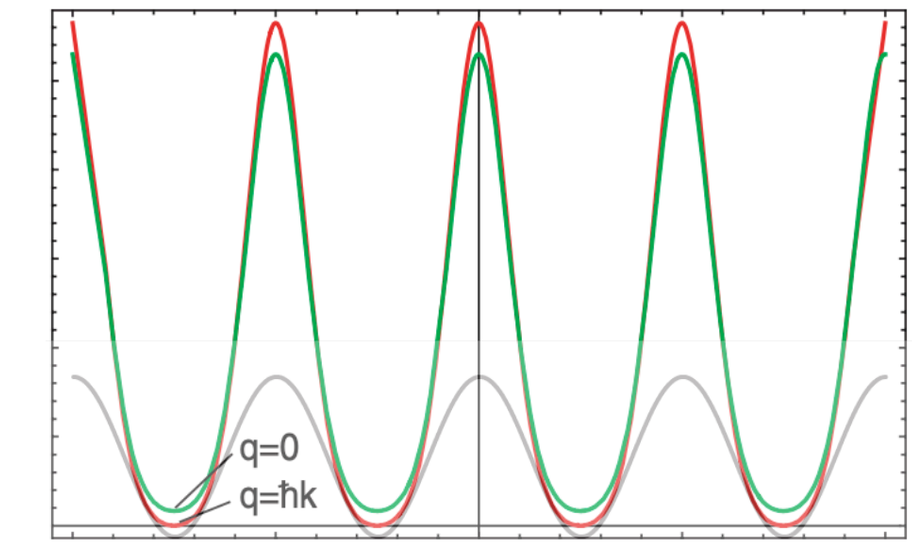
Band structure

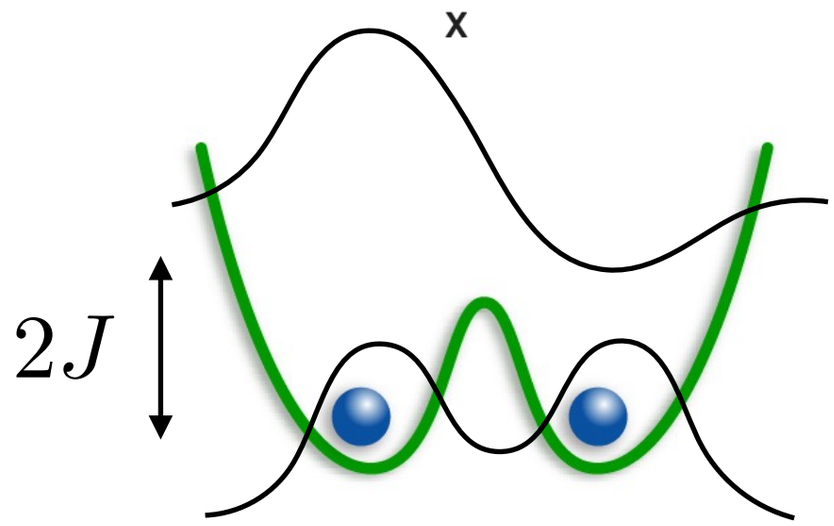
Bloch wavefunction at q=0 and q=$\hbar k$

$$\psi_q(x) = \sum_j e^{iqx_j} w_j(x - x_j)$$







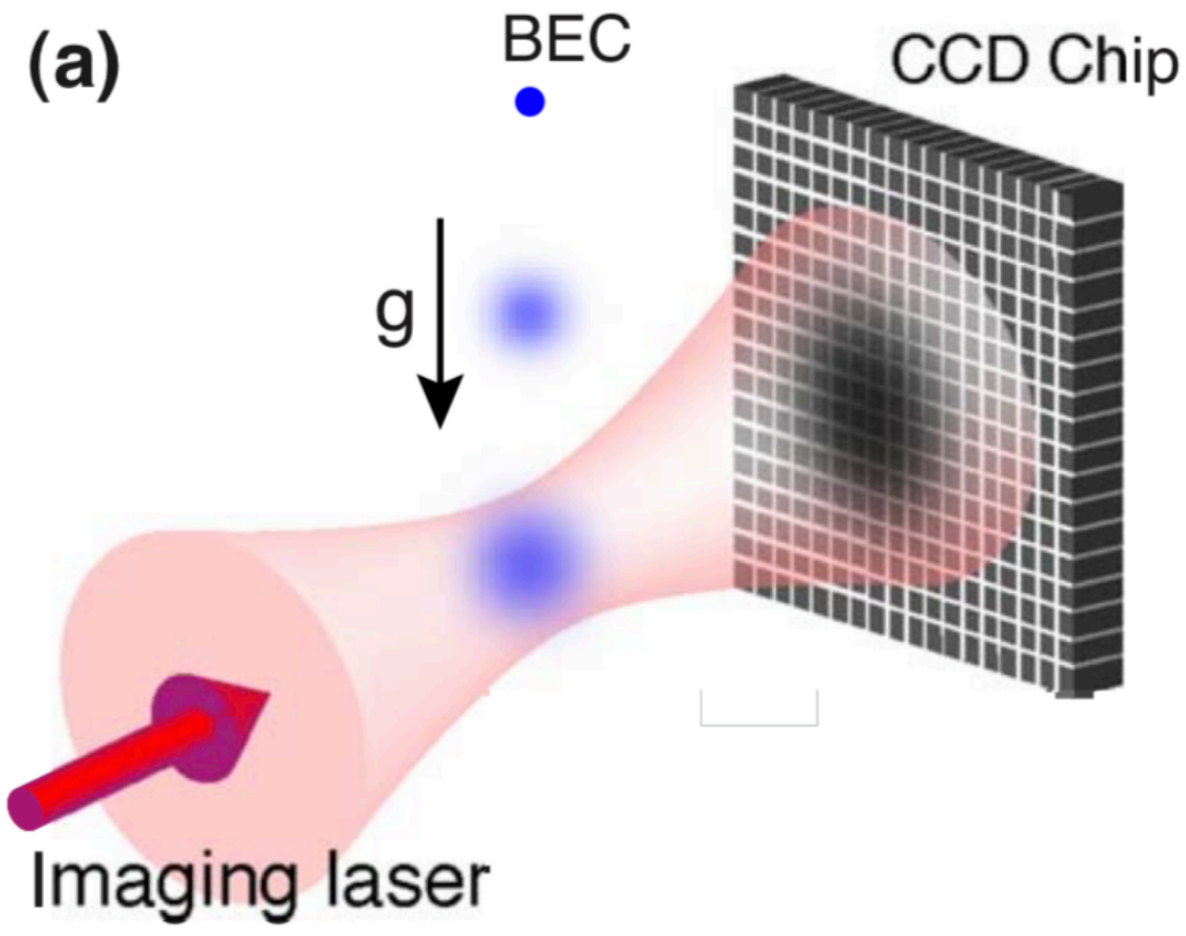


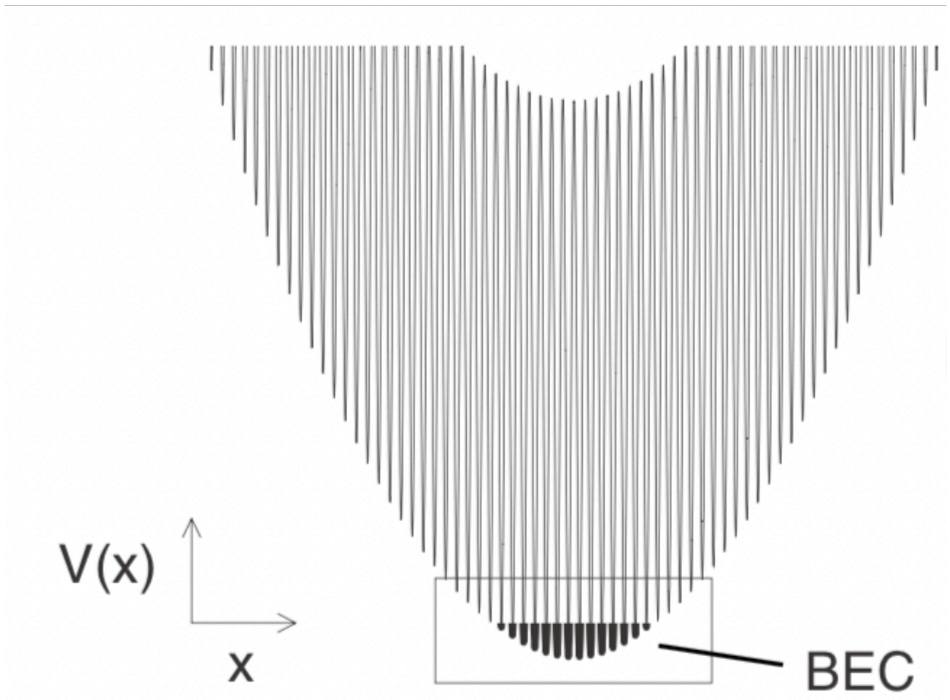
$$\psi_e = \frac{1}{\sqrt{2}}(\psi_l - \psi_r)$$

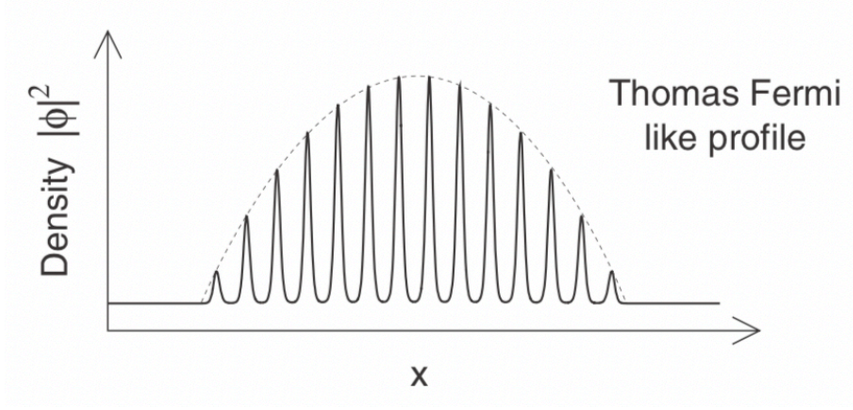
$$\psi_g = \frac{1}{\sqrt{2}}(\psi_l + \psi_r)$$

Time-of-flight of BEC in lattice

Q: What happens when we suddenly turn off the lattice?



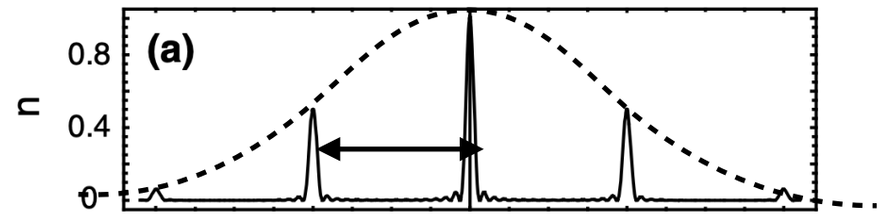




Time-of-flight of BEC in lattice

Q: Three different length scales

1) Peak distance
2) Peak width
3) Overall envelop



$$l = \frac{2\hbar k t}{m}$$

Wannier envelop Grating interference

$$n_{tof}(x,t) = |w(x)|^2 \sum_{j,k} e^{\frac{imx}{\hbar t}(x_j - x_k)} \langle \hat{a}_i^\dagger \hat{a}_k \rangle$$

