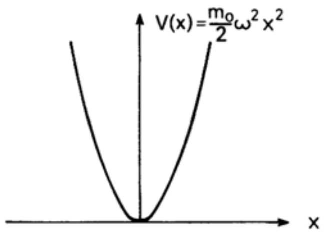
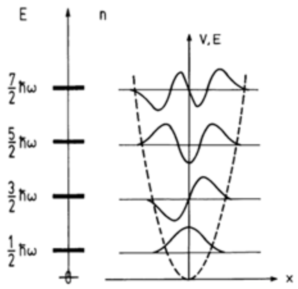
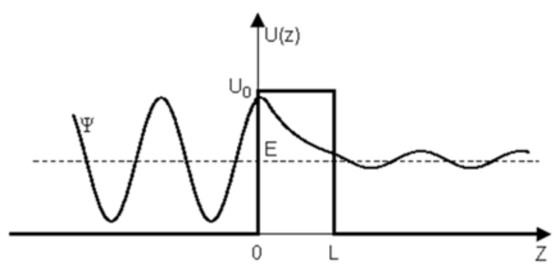
Experimental Quantum Physics

The starting point

Level 0.1: We want to have fun with experimental quantum mechanics…







… and gain as much control as possible over the processes

Level 1.0: Do something "useful" with the systems: e.g Quantumsimulation

"complex" q.m. system

$$\Psi(t=0)$$

time evolution with H

$$\Psi(t) = \exp(-iHt/\hbar)\Psi(0)$$

mapping →

"simple" model system

$$\Psi'(t=0)$$

time evolution with H'

$$\Psi'(t) = \exp(-iH't/\hbar)\Psi\prime(0)$$

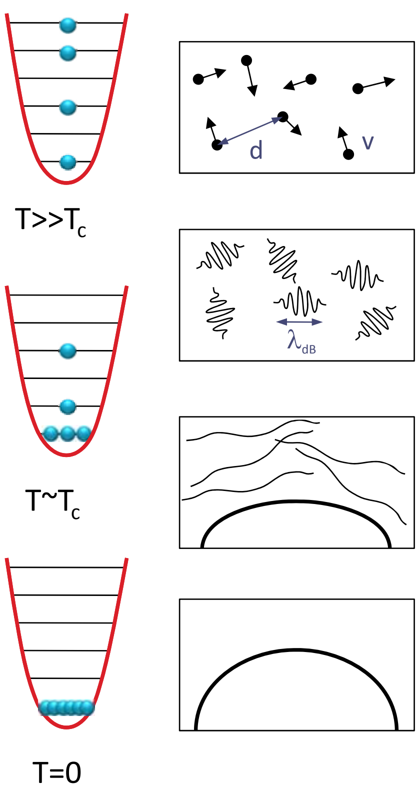
← mapping

We need a quantum lab!

There are various ways to generate that,
we will only consider neutral atoms

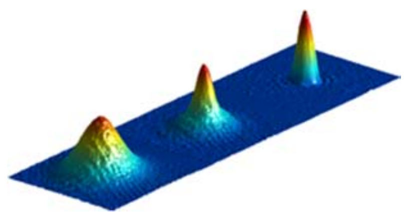
One of the main ingredients of the quantum laboratory

Bose Einstein Condensate



Some properties of BEC

- Macroscopic occupation of **one** quantum mechanical level
- Coherent matter wave :
  ➡ **matter wave interference**
- **Interaction** between atoms dominates ground state as well as dynamical behavior

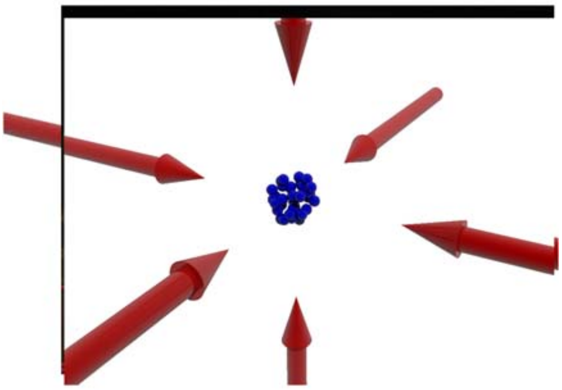


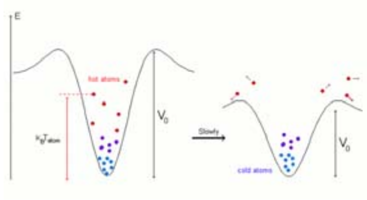
- **Excellent control** over all (most,…) experimental parameters

Theoretical prediction 1924/5: A. Einstein and S. N. Bose
First experimental realization 1995
BEC in dilute alkali gases: E. A. Cornell, W. Ketterle and C. E. Wieman

Experimental realization of BEC

2D-MOT → 3D-MOT → Molasses → Magnetic trap → Evaporation



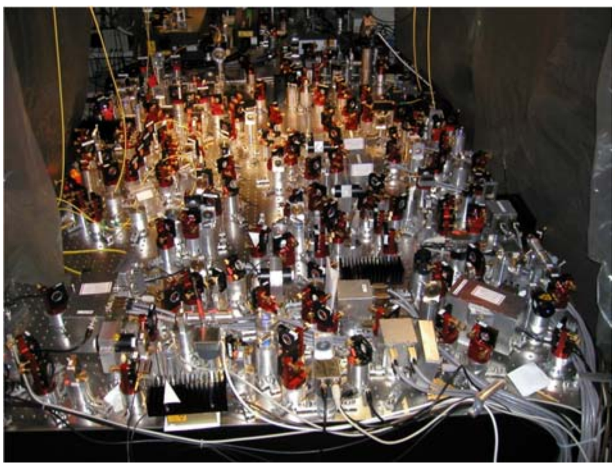


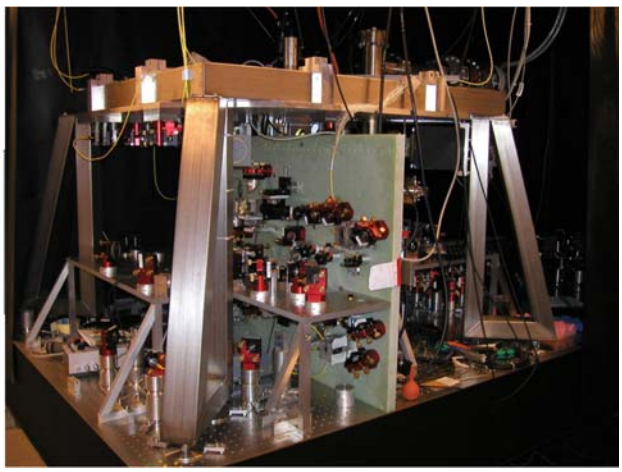
Laser cooling

$n=10^4 cm^{-3}$ T=300K	$n=10^{10} cm^{-3}$ T=10-100µK	$n=10^{14} cm^{-3}$ T=100nK

Experimental realization of BEC

2D-MOT → 3D-MOT → Molasses → Magnetic trap → Evaporation

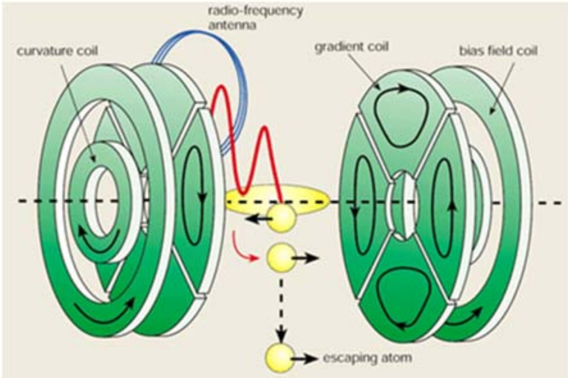




Laser cooling

$n=10^4 cm^{-3}$ T=300K	$n=10^{10} cm^{-3}$ T=10-100µK	$n=10^{14} cm^{-3}$ T=100nK

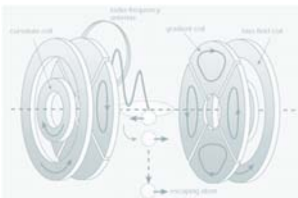
2D-MOT → 3D-MOT → Molasses → **Magnetic trap** → **Evaporation** → Dipol trap

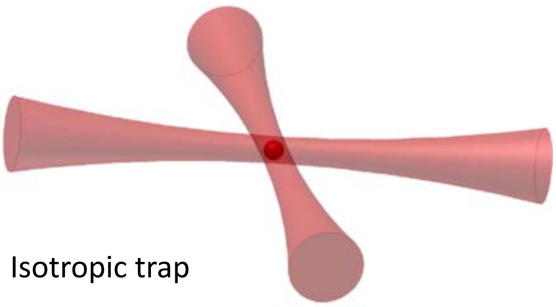


Particle number from 10^{10} down to 10^{6}

$n=10^4 cm^{-3}$ T=300K	$n=10^{10} cm^{-3}$ T=10-100µK	$n=10^{14} cm^{-3}$ T=100nK

2D-MOT → 3D-MOT → Molasses → Magnetic trap → Evaporation → **Dipole trap**





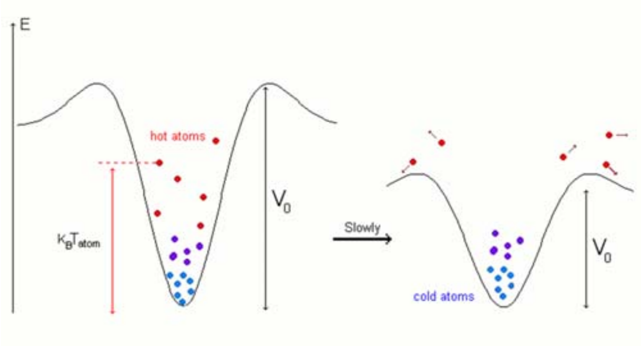
Isotropic trap

Elongated trap

$n=10^4 cm^{-3}$ T=300K	$n=10^{10} cm^{-3}$ T=10-100µK	$n=10^{14} cm^{-3}$ T=100nK

Experimental realization of BEC

2D-MOT → 3D-MOT → Molasses → Magnetic trap → Evaporation



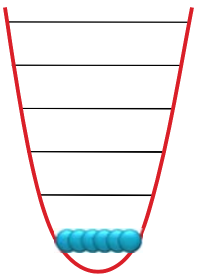
Particle number from 10^{10} down to 10^6

$n=10^4 cm^{-3}$ T=300K → $n=10^{10} cm^{-3}$ T=10-100μK → $n=10^{14} cm^{-3}$ T=100nK

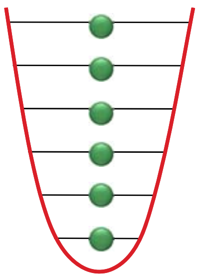
One, two,…more…

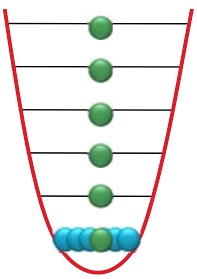
Exploiting the different quantum statistics

Degenerate Bose gas



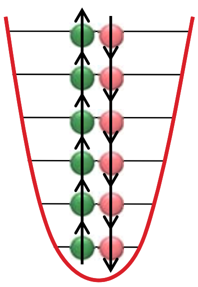
Degenerate Fermi gas





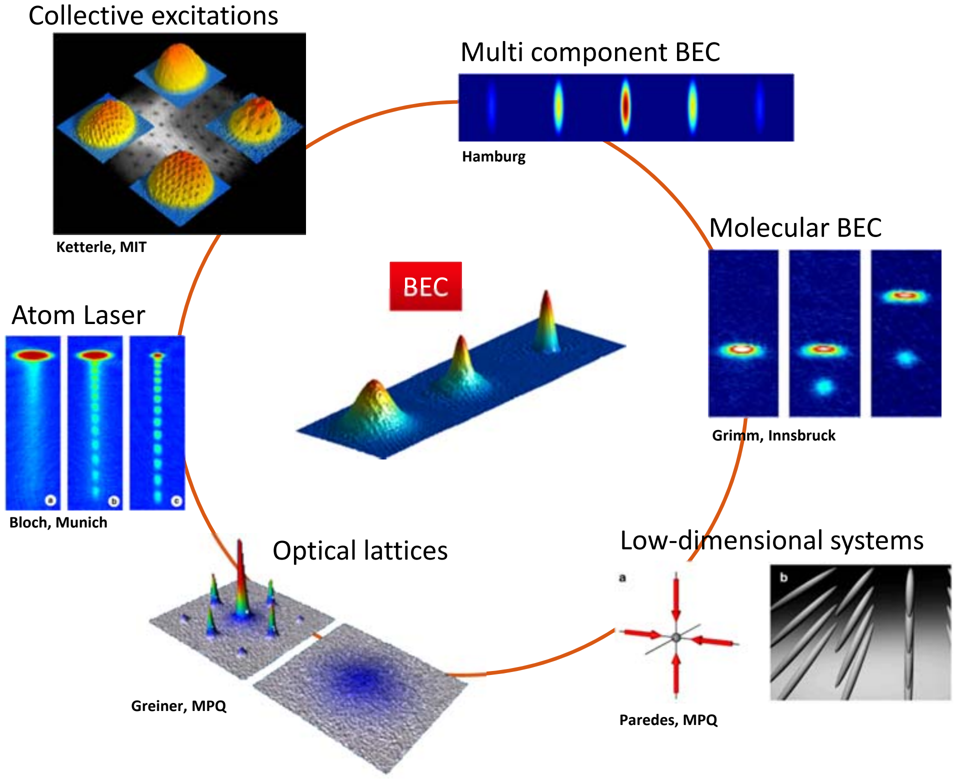
Various combinations:

- Bose – Fermi mixtures
- ➢ Fermionic Molecules
- Mixtures of spin components
- ➢ Bosonic molecules



Physics with Bose-Einstein condensates

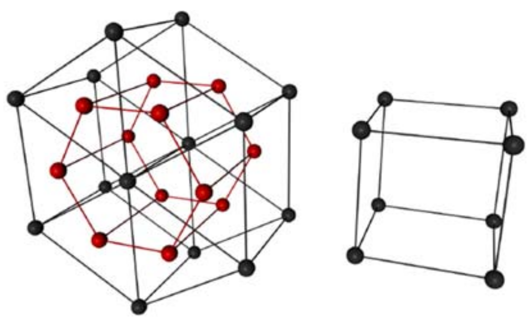
Ok, so we have a fancy quantum mechanical system with quite some control, but what to simulate with it?



Non-exclusive choice of applications

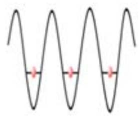
Benefits of OL

- **Almost arbitrary lattice geometries** can be realized using interfering laser beams
- **No** lattice imperfections
- **No** impurity atoms (only if desired)
- **Continuous tuning** of lattice parameters
- **Almost perfect model system**

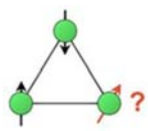


Motivation and Applications

- **Solid state models**



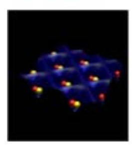
- **Quantum magnetism**



- **Cold chemistry**

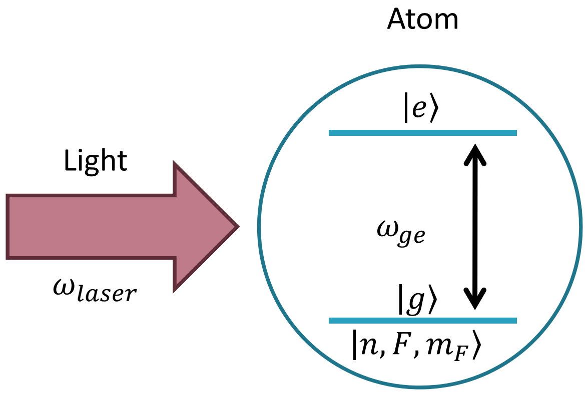
- **Atomic clocks**

- **Quantum information**



- **Exotic super conductors**

Back to some basic atomic physics

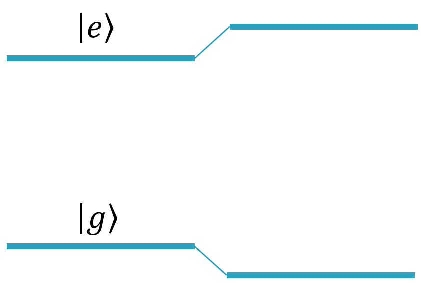


The two systems couple together via electric dipole transitions

Transition matrix element

$$\langle e|e\vec{r}|g\rangle$$

Coupling of the two systems leads to a shift of the energy levels

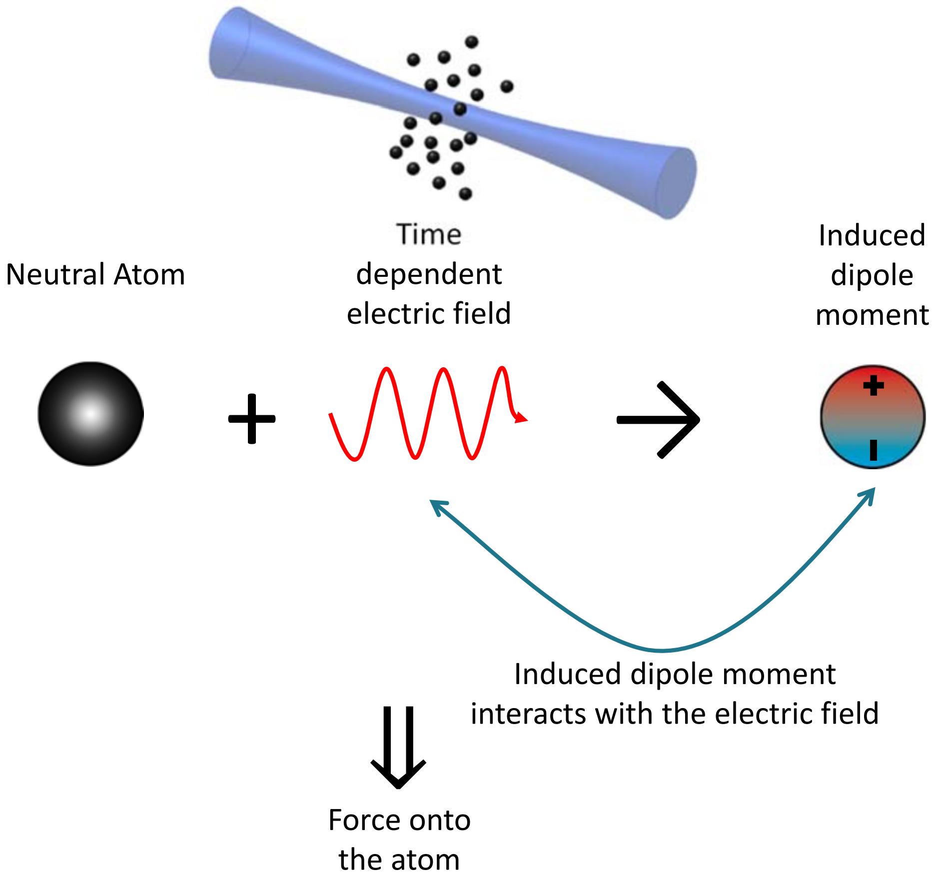


The shift is proportional to

$$\Delta E \sim \left|\vec{E}\cdot\langle e|e\vec{r}|g\rangle\right|^2 \sim I(r)$$

In words: The (potential) energy of the respective atomic level depends on the **intensity distribution** of the light field

Atoms in an off-resonant laser beam



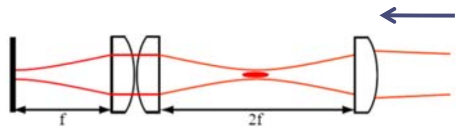
Periodic potentials

Optical dipole potential:

$$U(r) \sim \pm I(r)$$

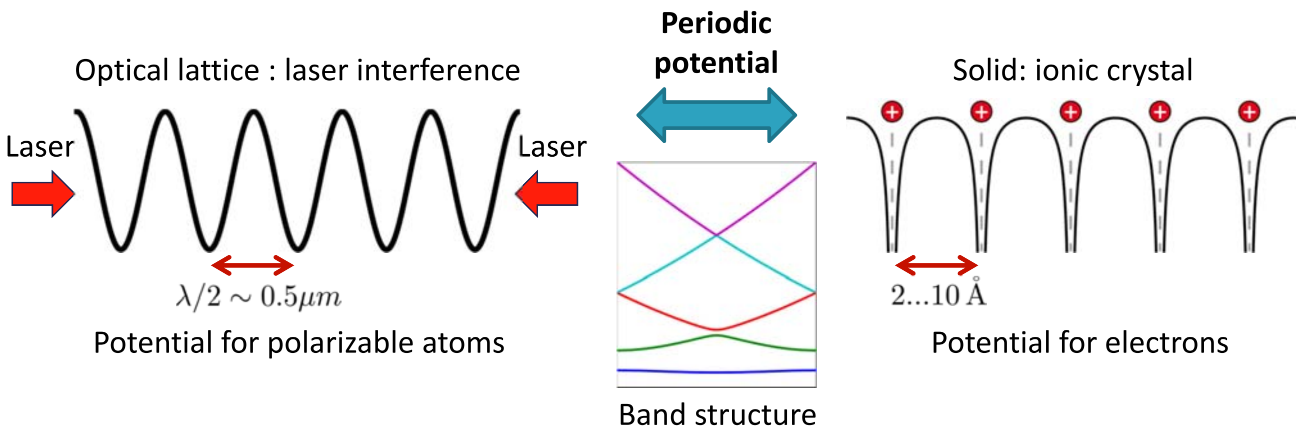
- Potential is proportional to the intensity distribution of the light field
- Sign depends on wavelength of the laser (usually "-")

Simplest case: 1D lattice by retro reflecting a laser beam

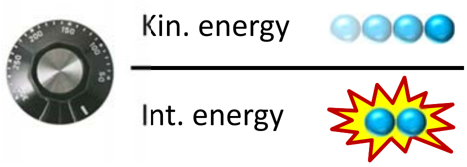


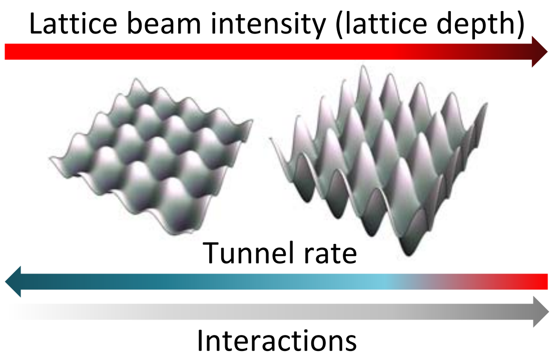
$$I_{1D} \sim I(r) \cdot \cos^2(kz)$$

Optical lattices: Light crystals



Optical lattices:
- No phonons (Lattice structure is rigid)
- No localized impurities or defects
- Highly **controllable !**



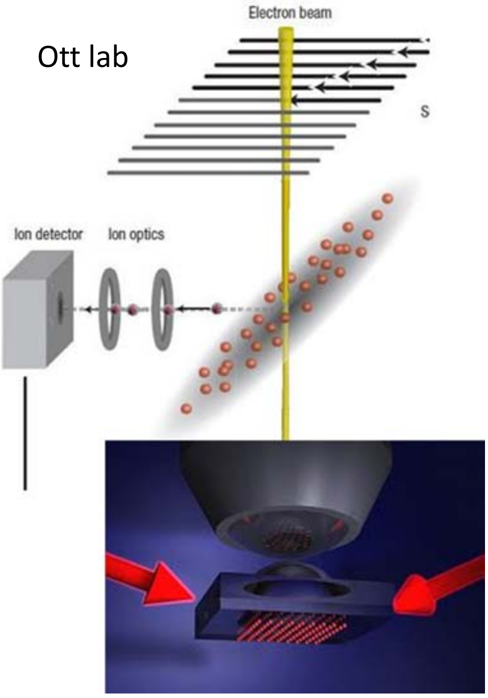


Ways to measure what's going on

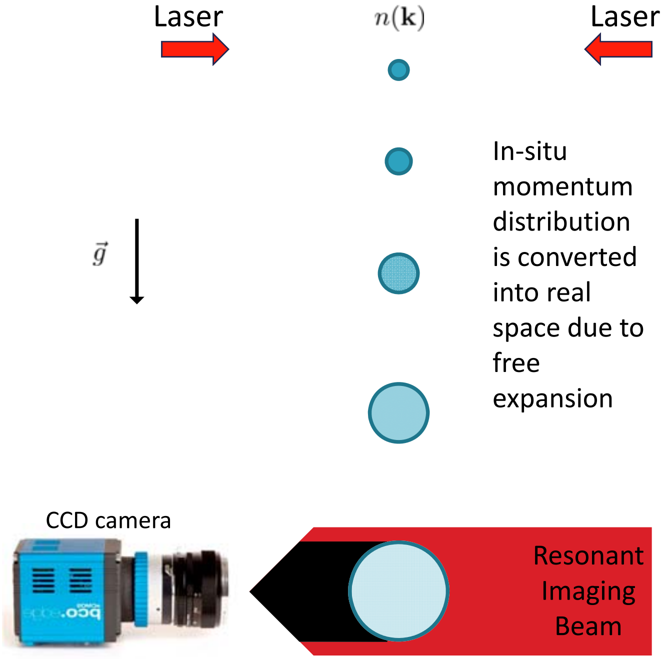
Direct site resolved imaging

Imaging after release from lattice

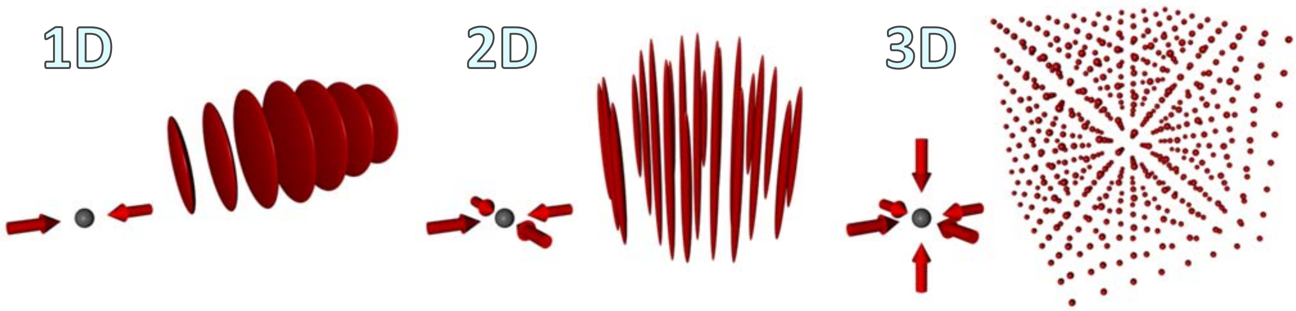
Ott lab



Weiss, Greiner, Bloch and other labs

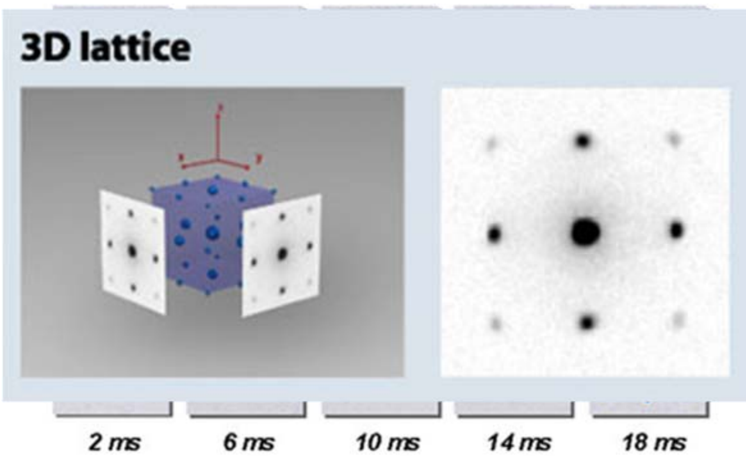


Tuneable lattice geometries



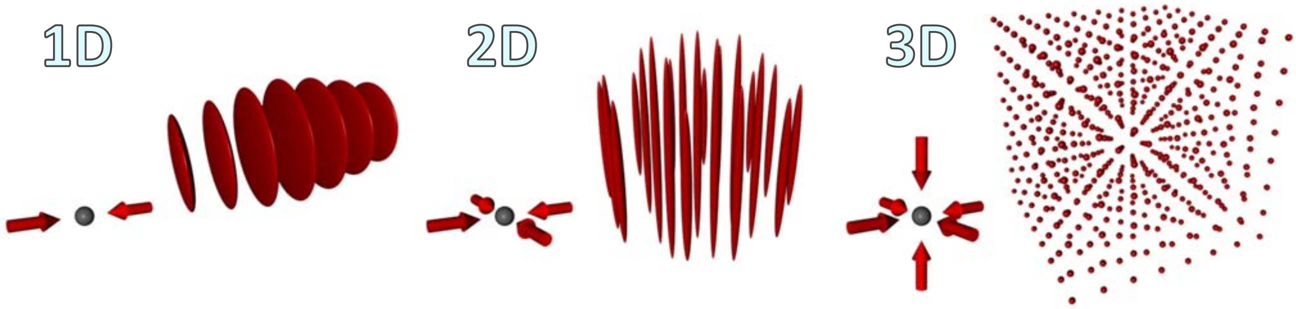
Most simple case: make the mutually orthogonal sets of beams independent

$$V(x, y, z) \sim -V_{x,0} \cos^2 k_x x - V_{y,0} \cos^2 k_y y - V_{z,0} \cos^2 k_z z$$

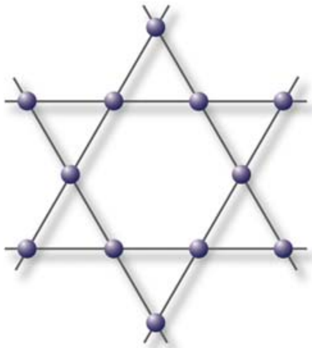


Greiner et al.

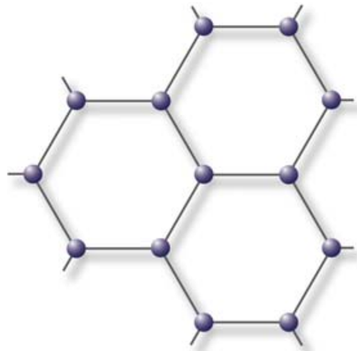
Dimensionality and Geometry



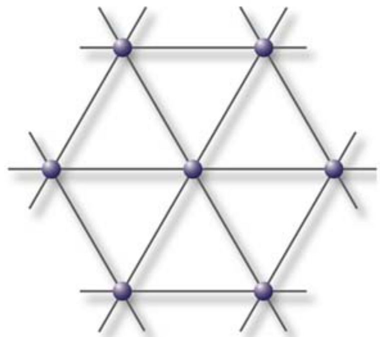
Kagomé



Honeycomb



Triangular



Jo et al.,Phys. Rev. Lett. 108, 045305 (2012)

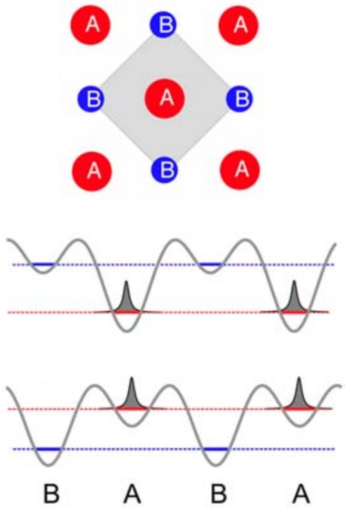
Soltan-Panahi et al., Nature Physics 7, 434 (2011)
Tarruell et al., Nature 483, 302 (2012)

Becker et al., New J. Phys. 12, 065025 (2010)

Overview on novel geometries:
Windpassinger & Sengstock
Rep. Prog. Phys. 76, 086401 (2013)

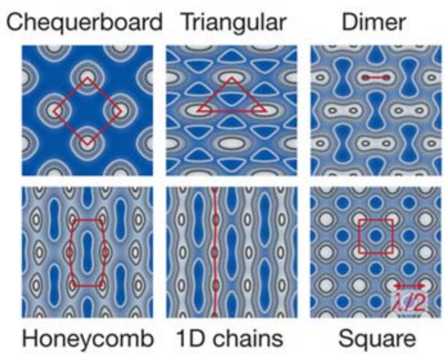
Toolbox of tunable lattice geometries

Double well lattices

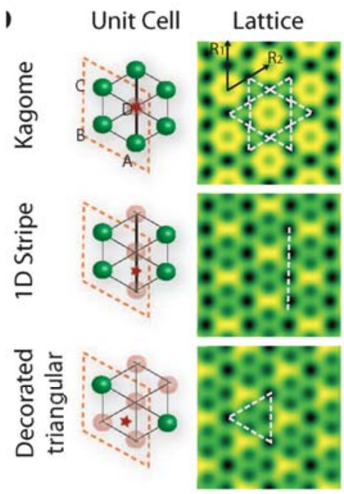


e.g. J. Porto (NIST),
A. Hemmerich (Hamburg),
I. Bloch (MUC),
M. Weitz (Bonn)

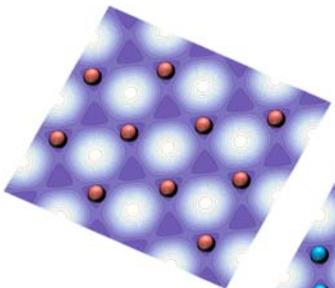
Variable geometries

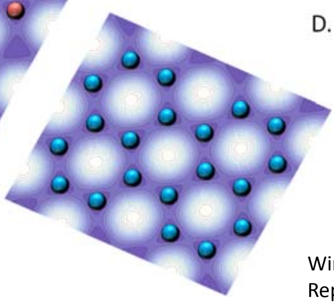


T. Esslinger (ETH)



D. Stamper-Kurn (Berkeley)





K. Sengstock (Hamburg)

Windpassinger & Sengstock
Rep. Prog. Phys. 76, 086401 (2013)