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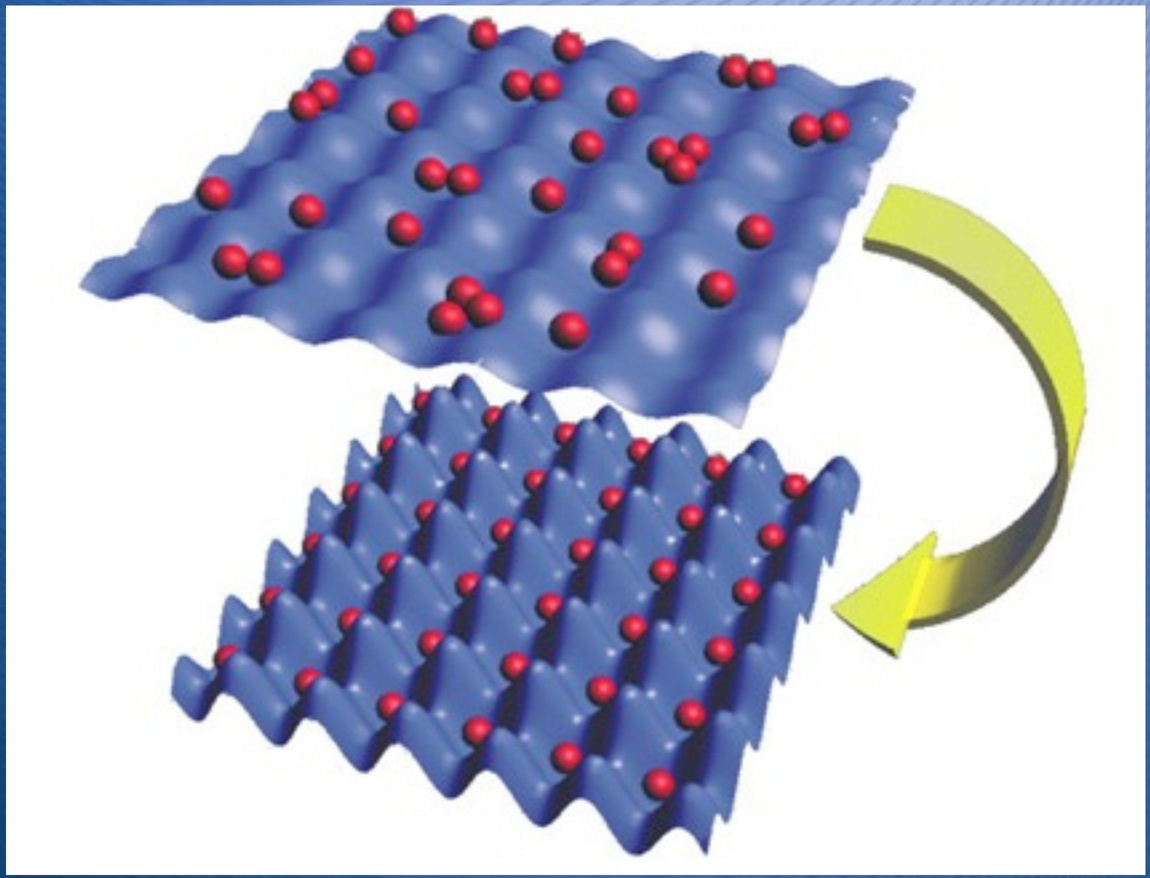
Swiss Federal Institute of Technology Zurich

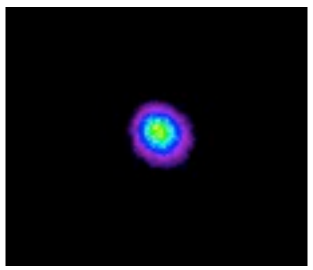
DPHYS
Department of Physics
Institute for Theoretical Physics

Ultracold atomic gases as quantum simulators



Feynman's quantum simulator

- We are able to control single quantum systems

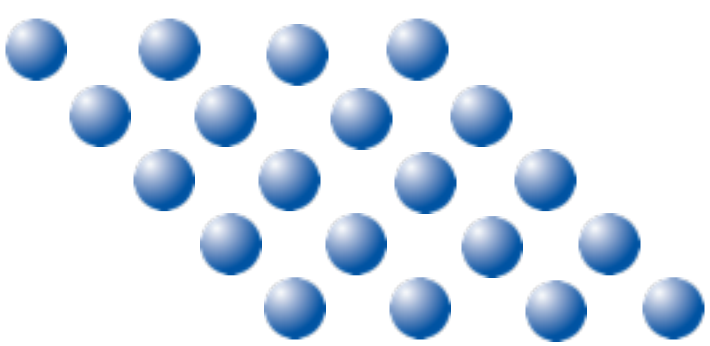


Single Atoms and Ions

Photons

Quantum Dots

- New challenges:
  control, engineer and understand complex quantum system



R. P. Feynman's Vision

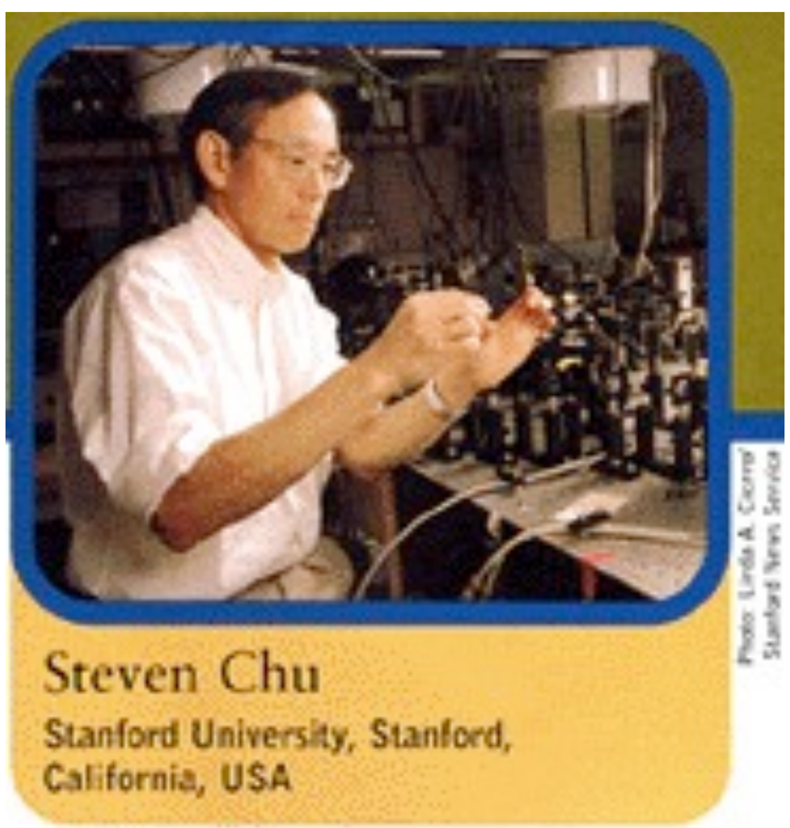
A Quantum Simulator to study the quantum dynamics of another system.

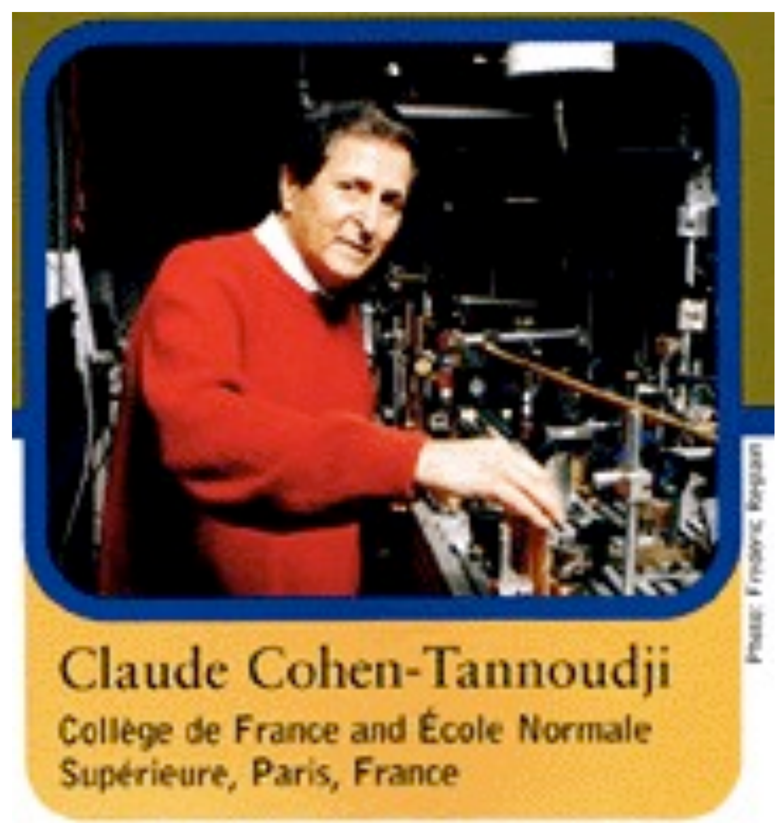
R.P. Feyman, Int. J. Theo. Phys. (1982)
R.P. Feynman, Found. Phys (1986)

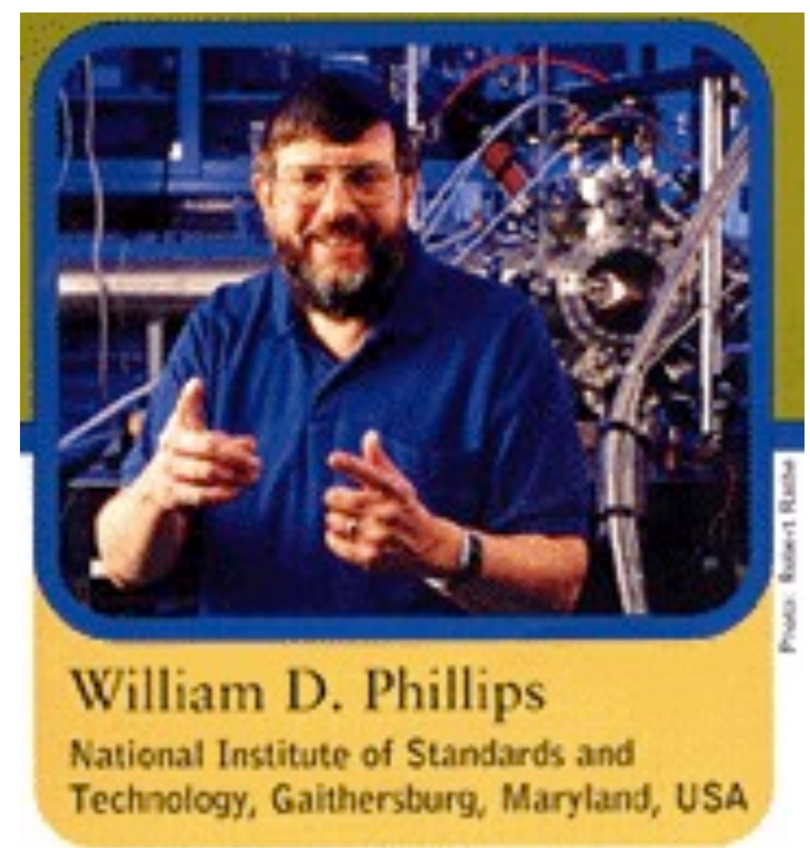
1997 Nobel Prize in Physics

Steven Chu,Claude Cohen-Tannoudji and William D.Phillips

share 1997 Nobel Prize for the development of methods to cool and trap atoms with laser right.







2001 Nobel Prize in Physics

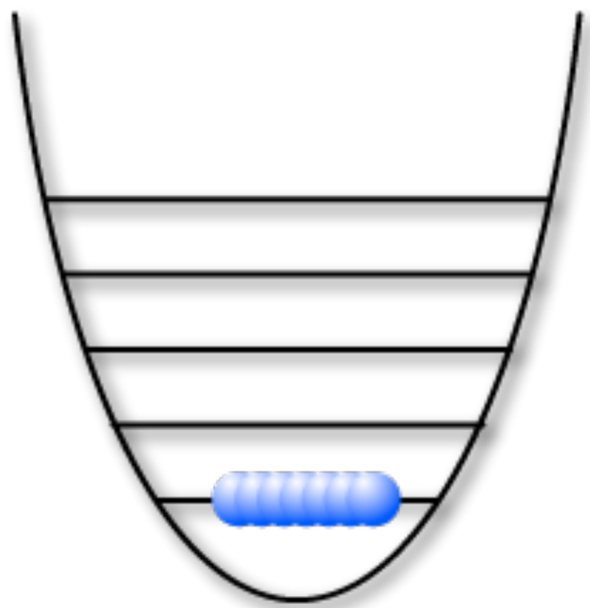
Carl Wieman , Eric Cornell and Wolfgang Ketterle

share 2001 Nobel Prize for the achievement of BEC in dilute gases of alkali atoms and for the early fundamental studies of the properties of the condensates .

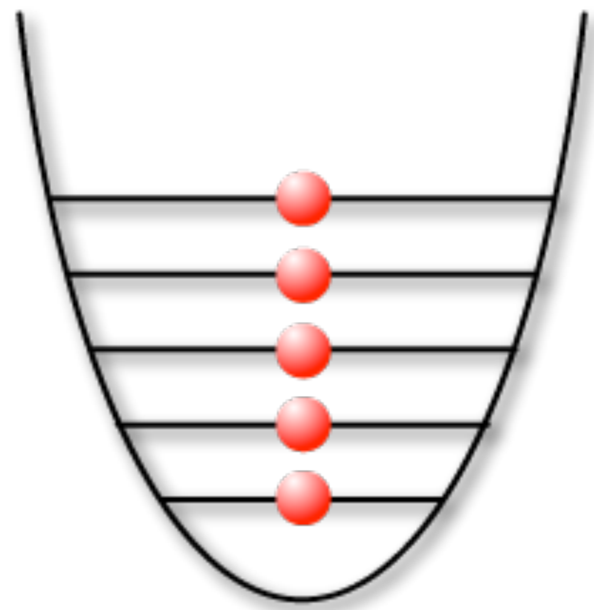
Our Starting Point – Ultracold Quantum Gases

Parameters:
Densities: 10^{15} cm^{-3}
Temperatures: Nano Kelvin
Atom Numbers 10^6

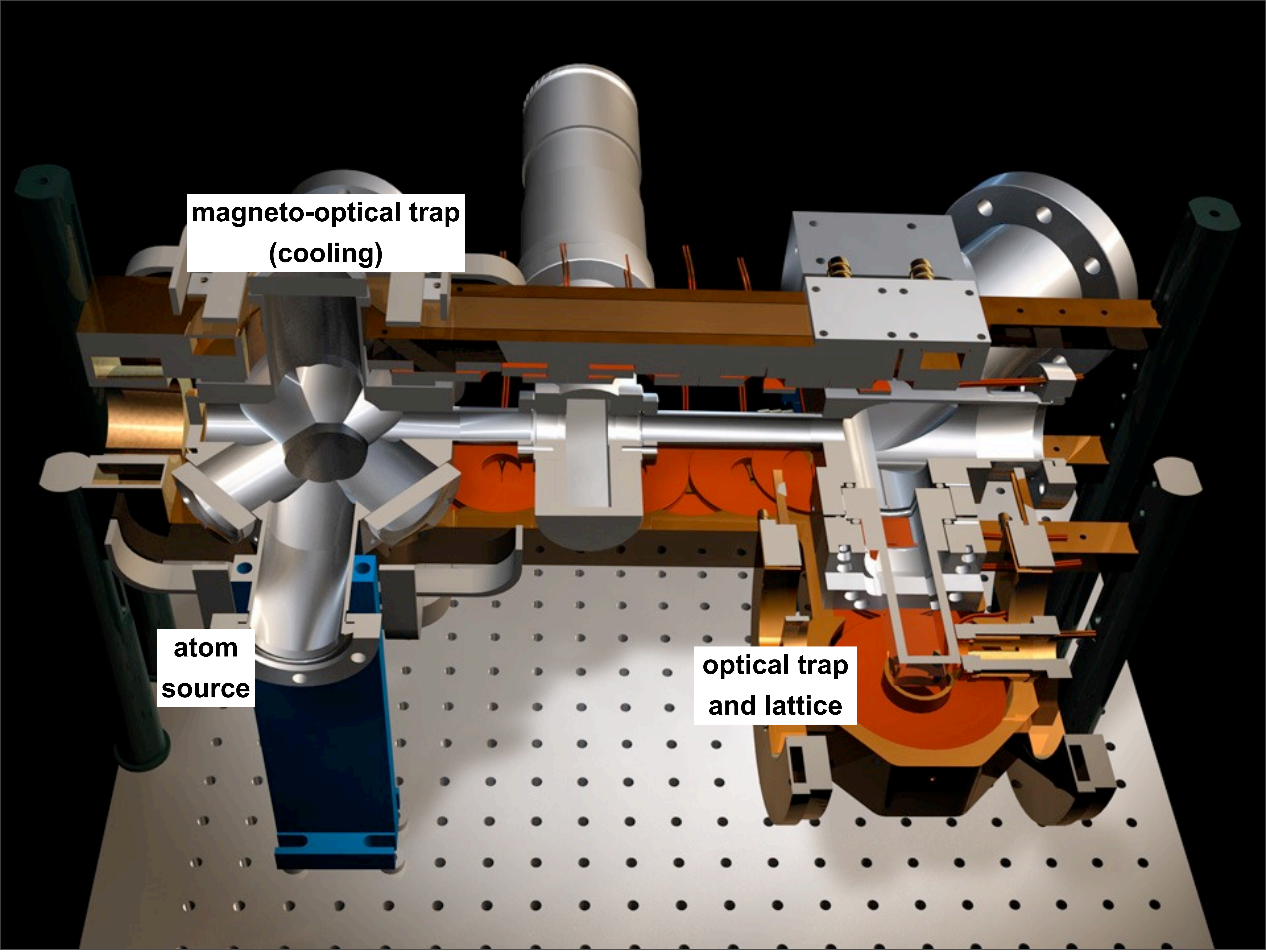
Ground States at T=0



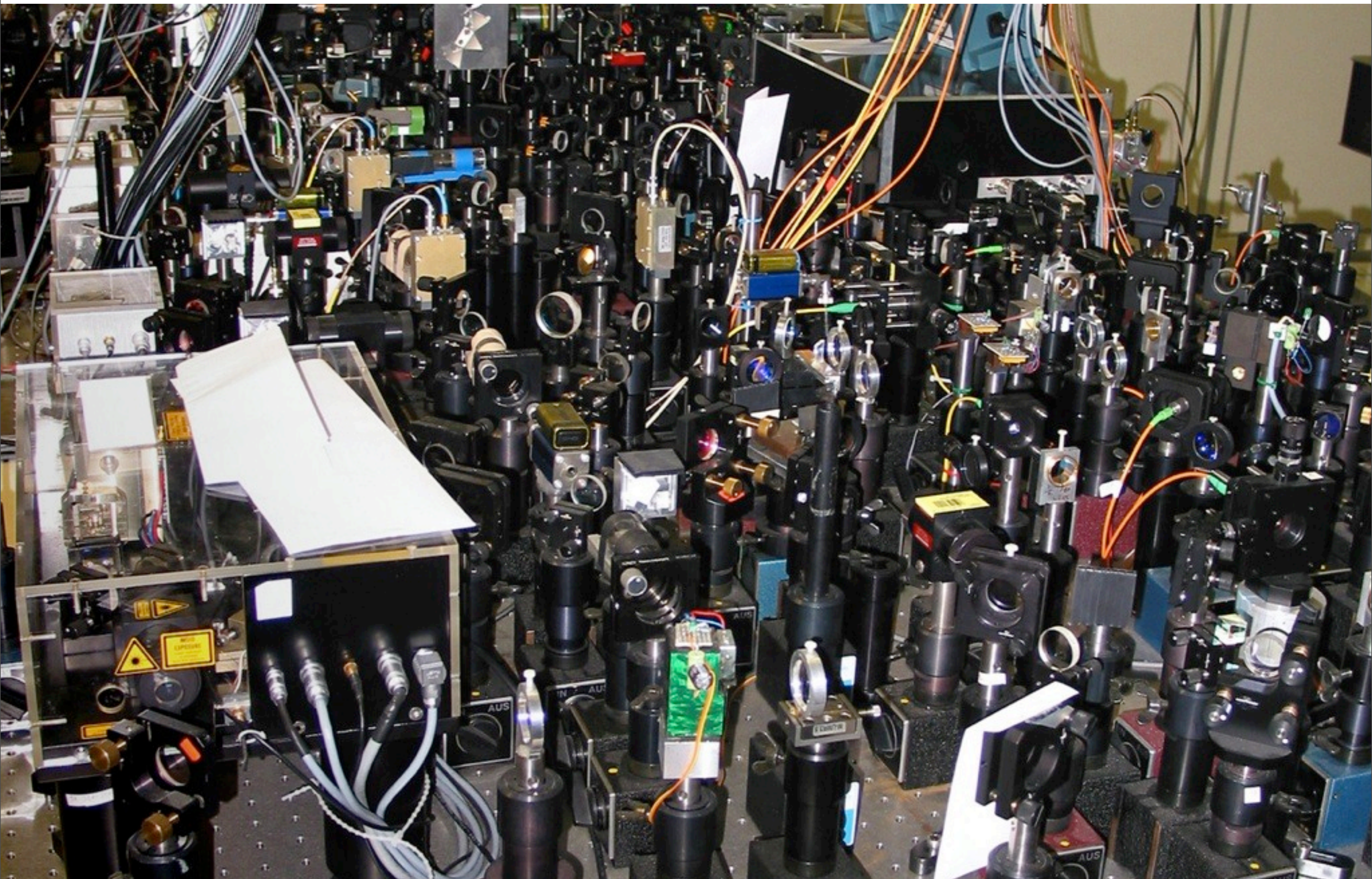
Bose-Einstein Condensates e.g. ^{87}Rb

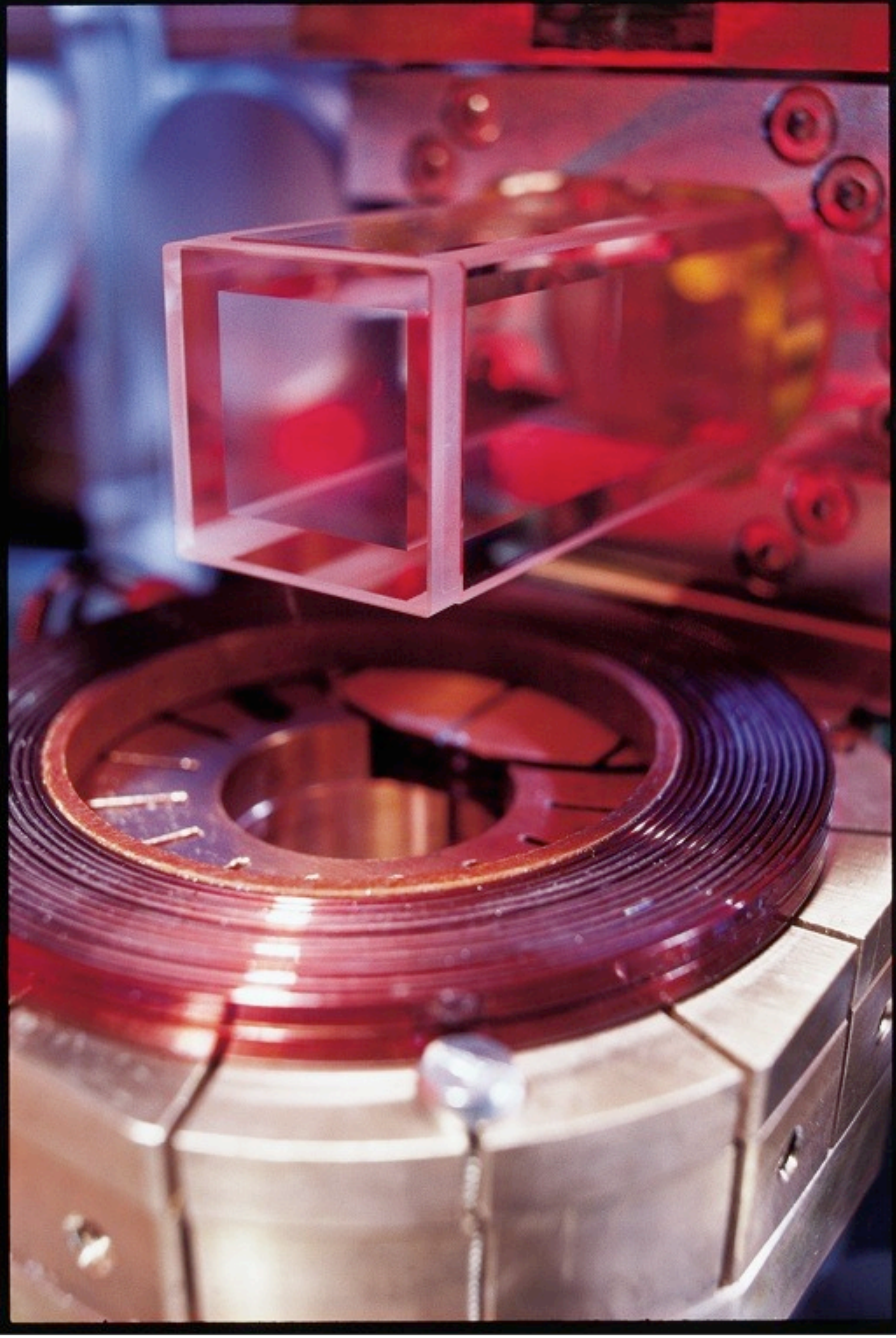


Degenerate Fermi Gases e.g. ^{40}K


magneto-optical trap
(cooling)
atom
source
optical trap
and lattice

And a lot of optics and electronics !



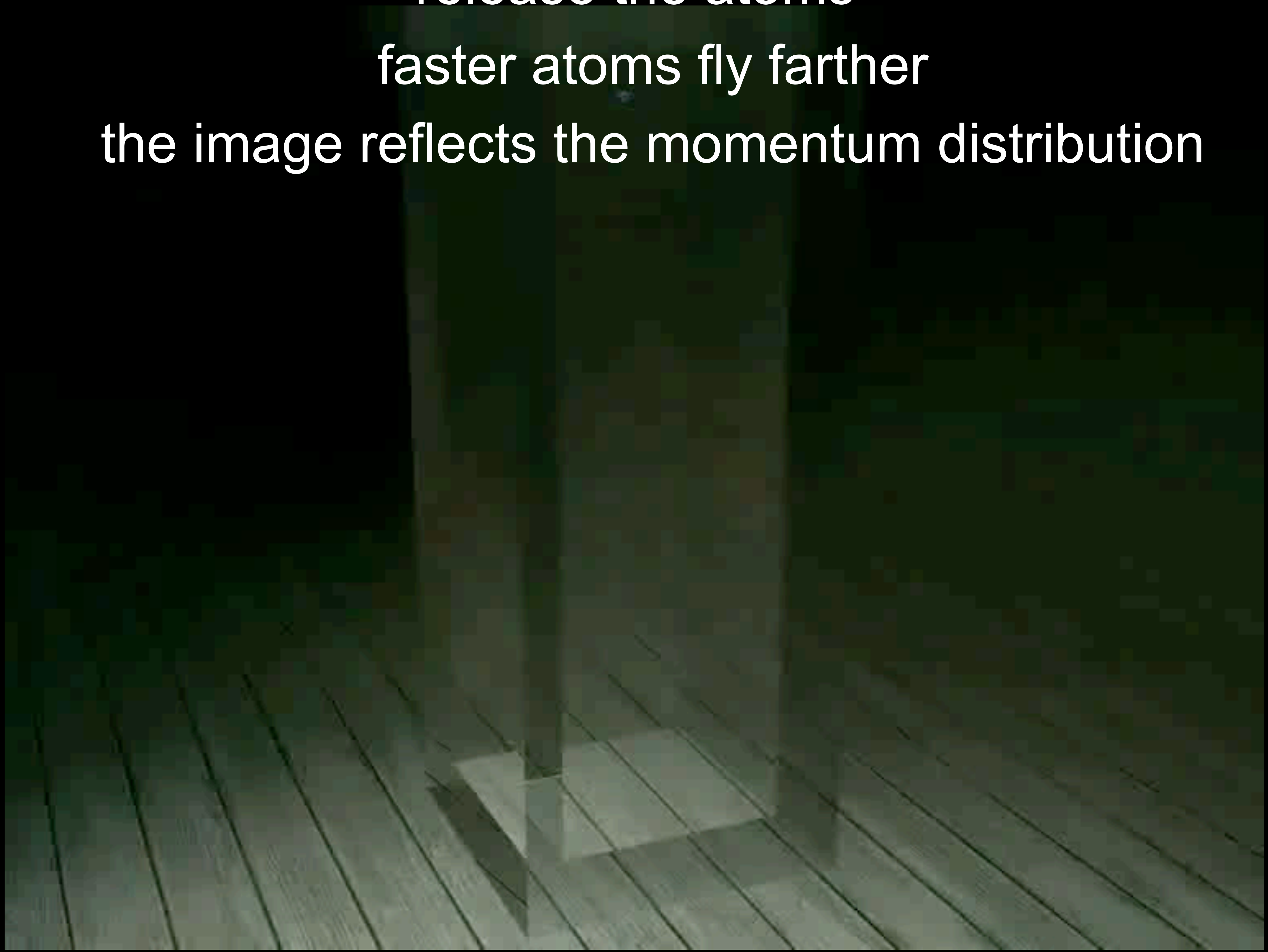


How do we detect these quantum gases ?

release the atoms

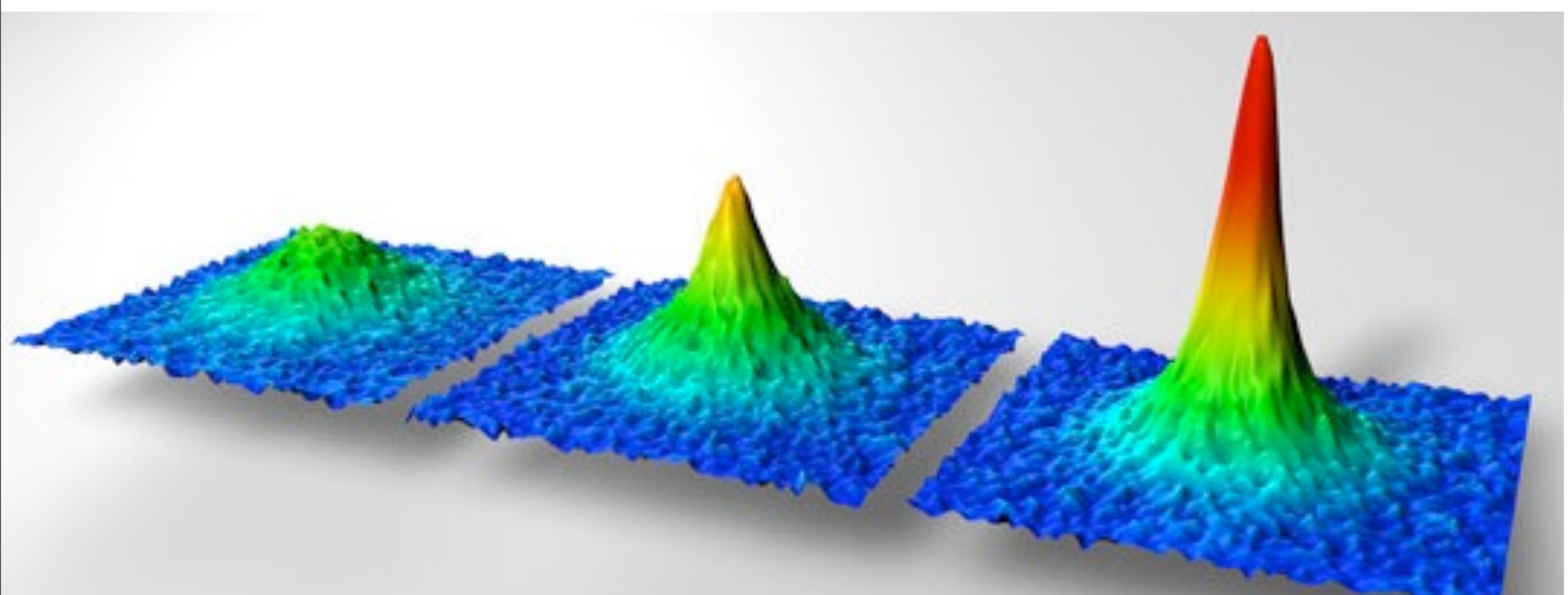
faster atoms fly farther

the image reflects the momentum distribution

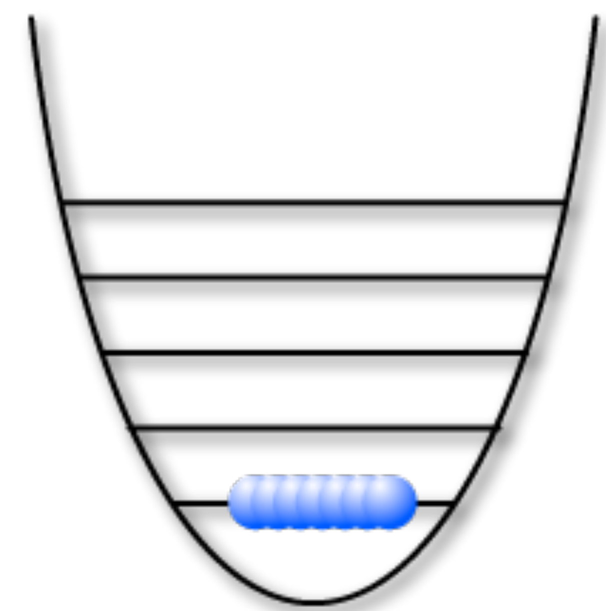


Bose-Einstein condensation in cold atomic gases

- At close to zero temperatures, a macroscopic fraction of all atoms in a Bose gas occupy the same quantum state
- A diverging occupation of the zero momentum state

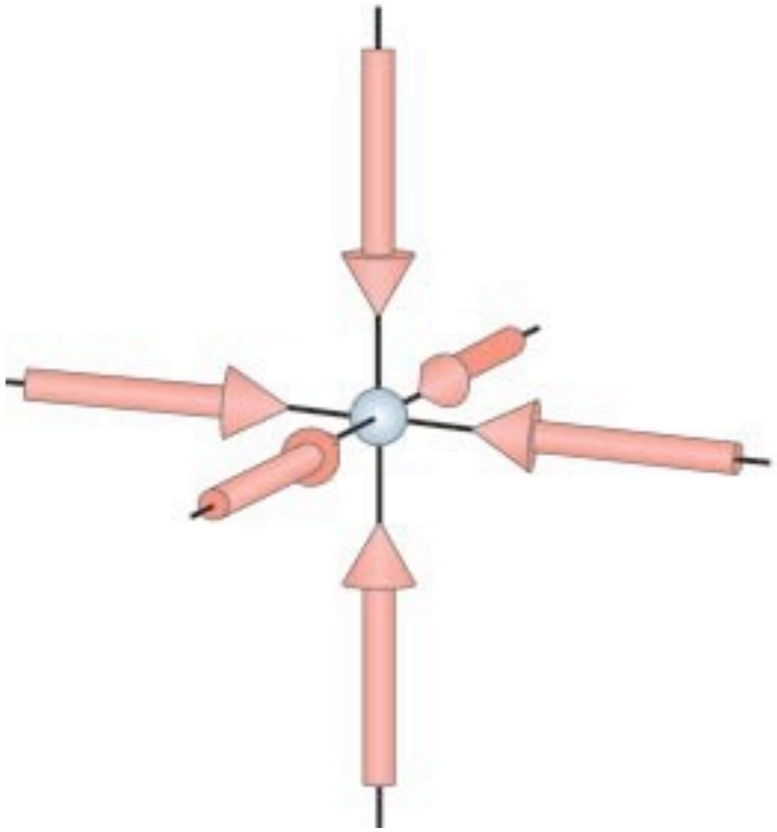


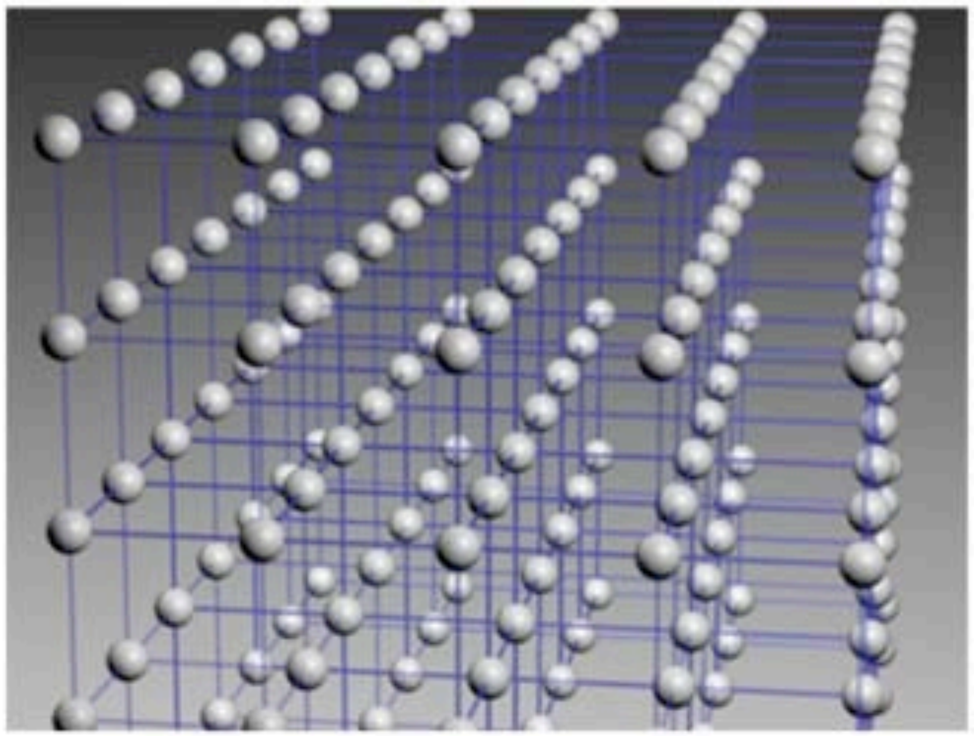
Momentum distribution function



Optical lattices

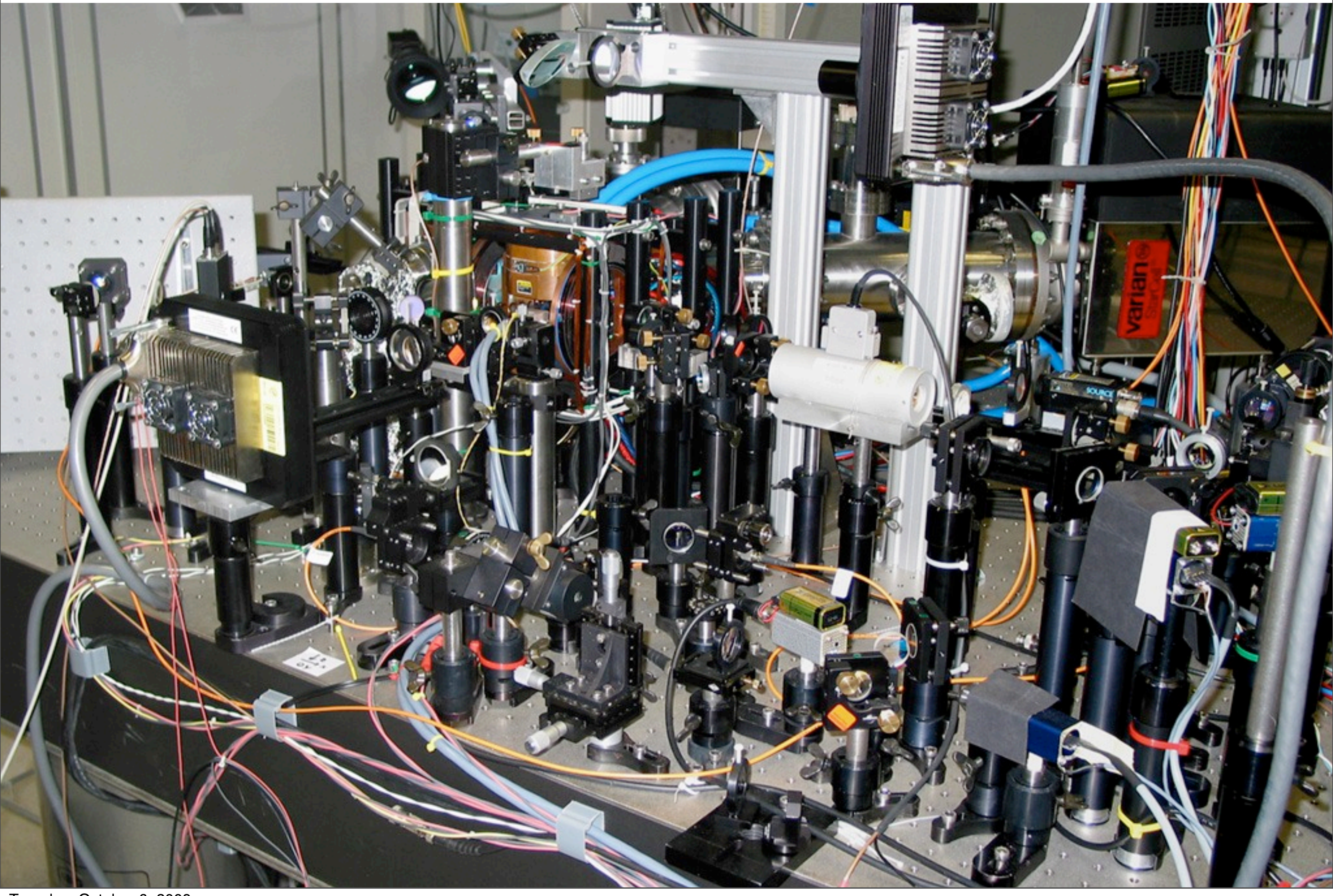
- formed by standing waves from three pairs of laser beams





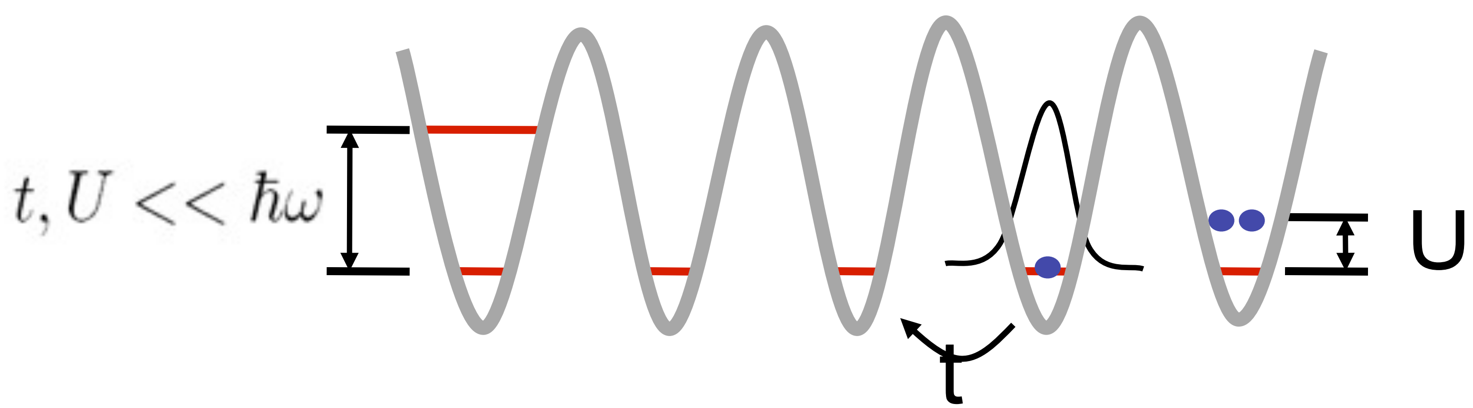
- realize quantum **lattice** models of fermions or bosons

Table 2



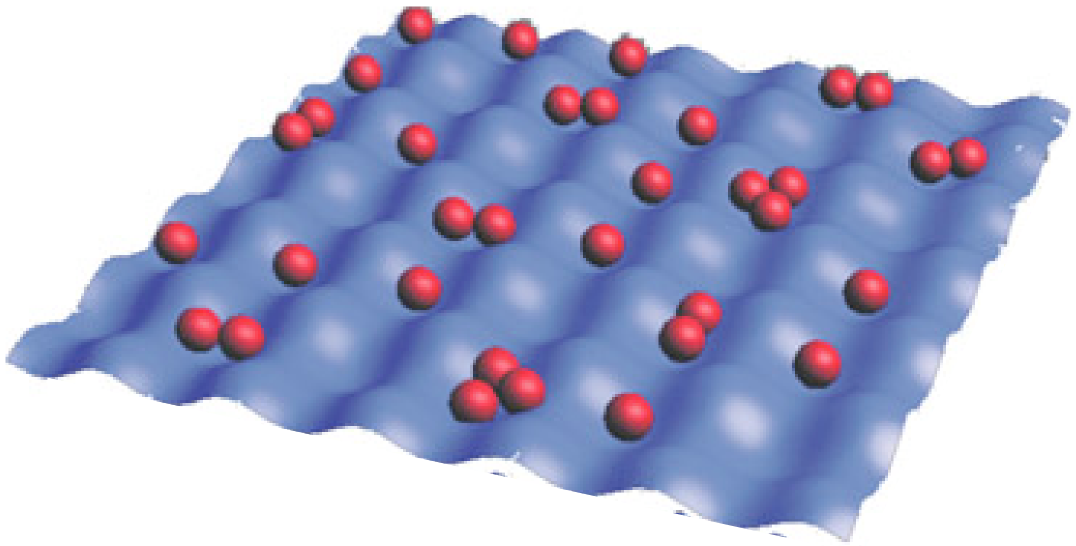
Optical lattices and the Hubbard model

- Lasers couple to the dipole moment of the atoms
  - atoms prefer to sit at the amplitude maxima (AC Stark effect)
  - a periodic potential with periodicity half of the wave length
  - obtain a Hubbard model for the lowest band



- Tunable and controlled
  - Laser amplitude determines *U* and *t*
  - Spatially varying couplings using optical superlattices
- Flexible
  - fermionic or bosonic atoms or mixtures are possible

Condensed matter phenomena in cold atoms



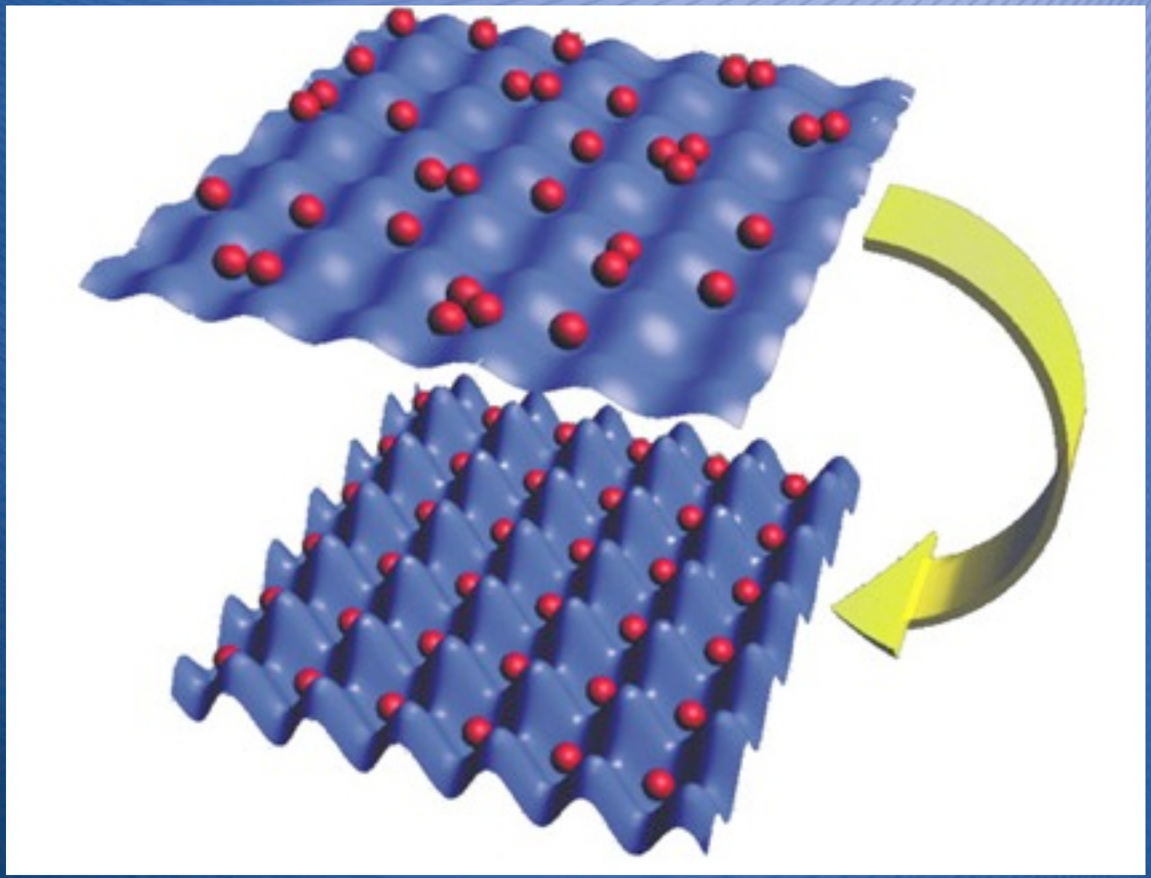
Condensed Matter

- Disordered
- Unknown interactions
- Little control

Cold Atoms

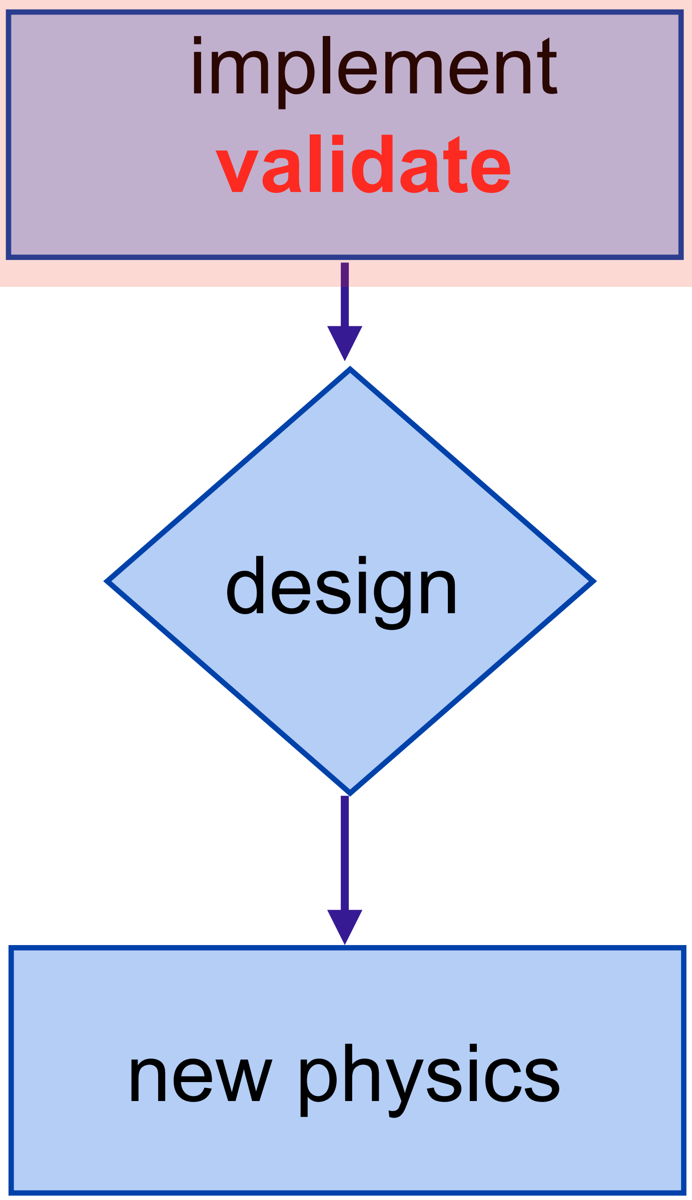
- Tunable dispersion
- Tunable interactions
- Perfect control
- Clean or controlled disorder
- Engineered Hamiltonians

Validating a quantum simulator: does it really work?



DARPA Optical Lattice Emulator program

- Goal : build an optical lattice emulator to solve the prototypical models of condensed matter physics



1. Validate / calibrate against known models (bosons)

2. Design a model with unknown physics (fermions)

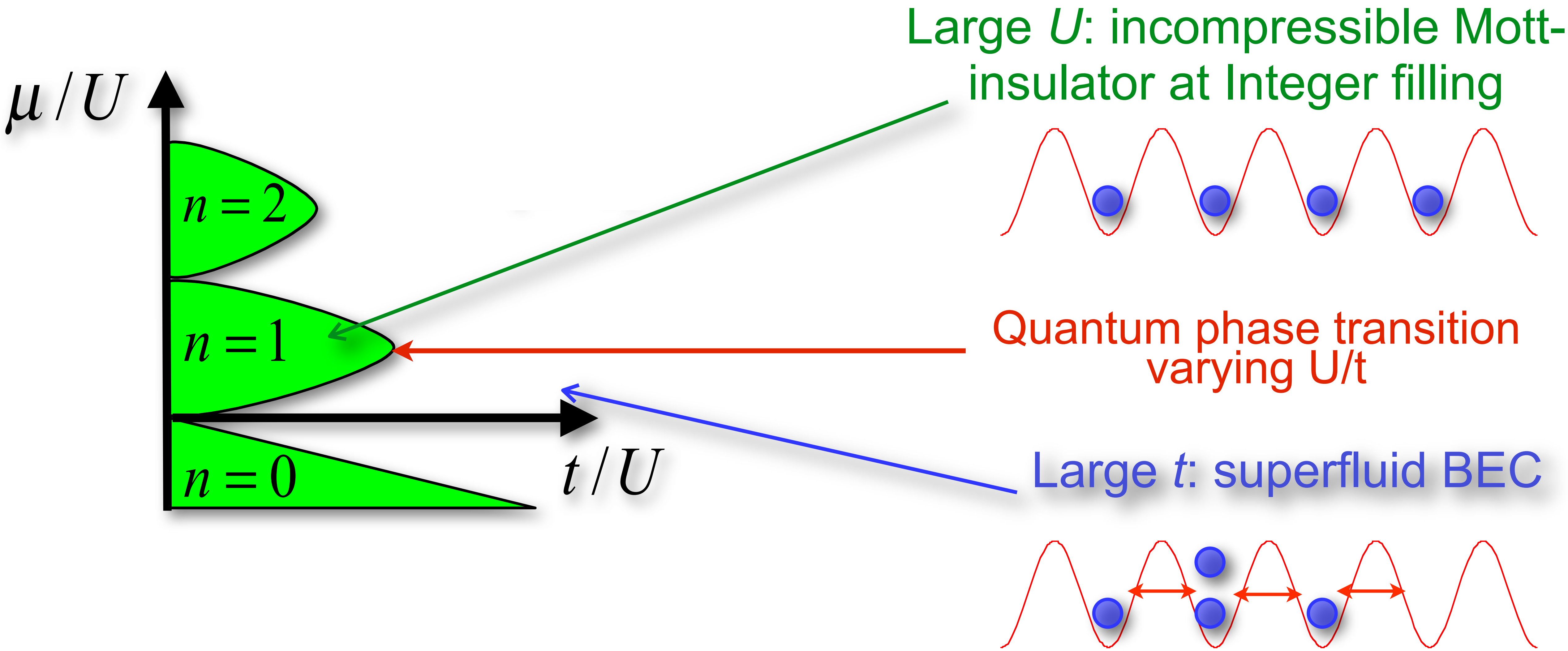
3. Learn new physics assuming all parameters of the device are still under control

Bose-Hubbard model

Fisher *et al*, PRB 1989

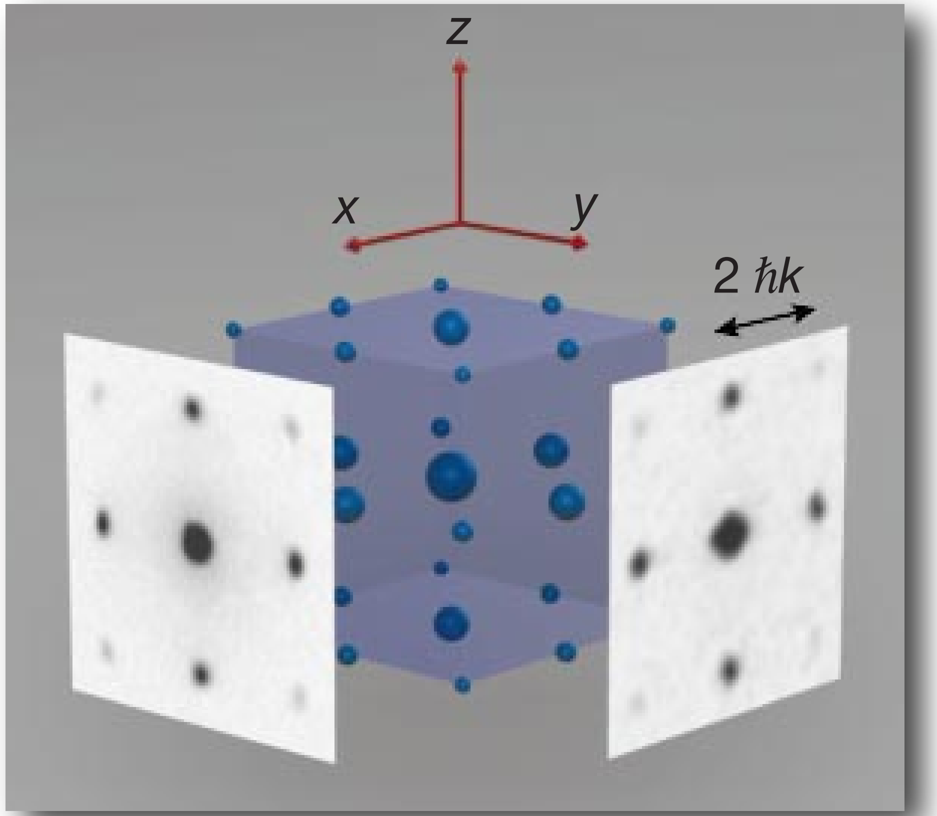
- Use bosonic atoms for validation

$$H = -t \sum_{\langle i,j \rangle} \left(b_i^\dagger b_j + b_j^\dagger b_i \right) + U \sum_i n_i (n_i - 1)/2 - \mu \sum_i n_i$$

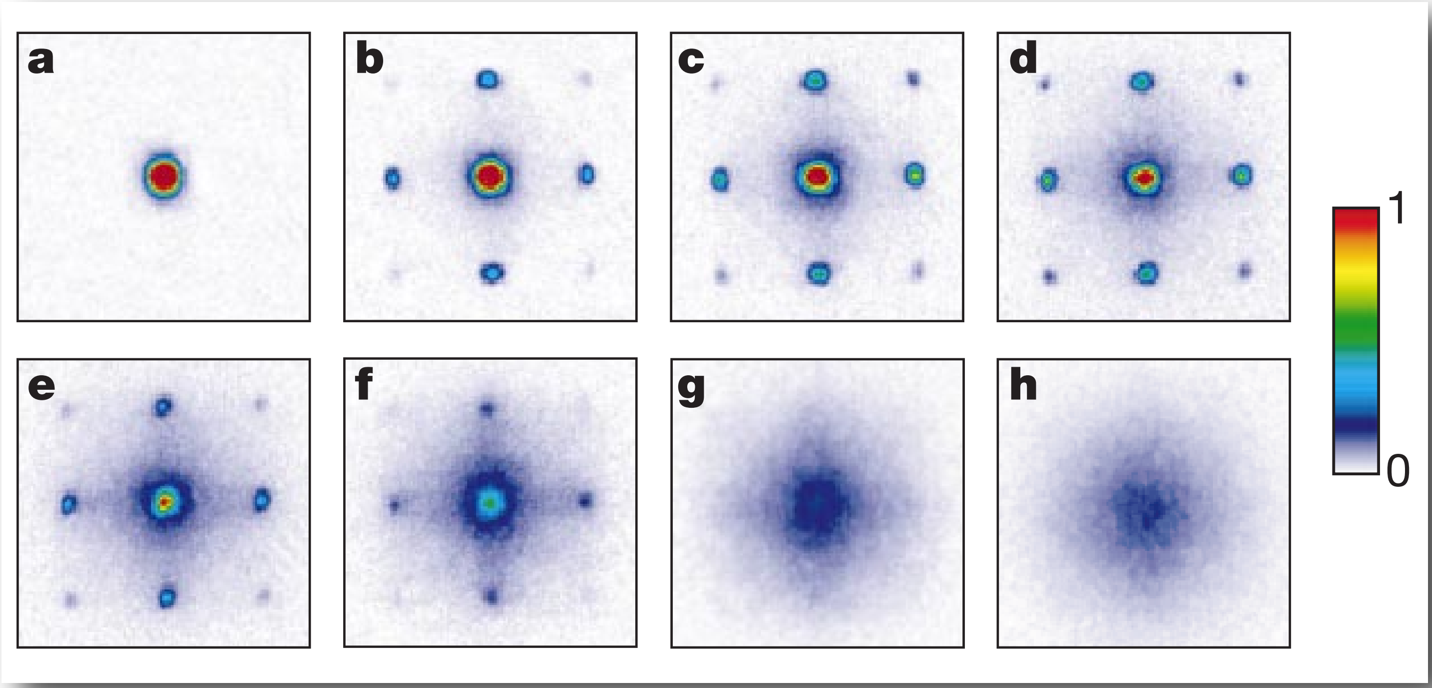


The first optical lattice experiments

- Quantum phase transition as lattice depth is increased
  - Greiner et al, Nature (2002)
  - measuring the momentum distribution function in time-of-flight images



small *U*/*t*: condensate

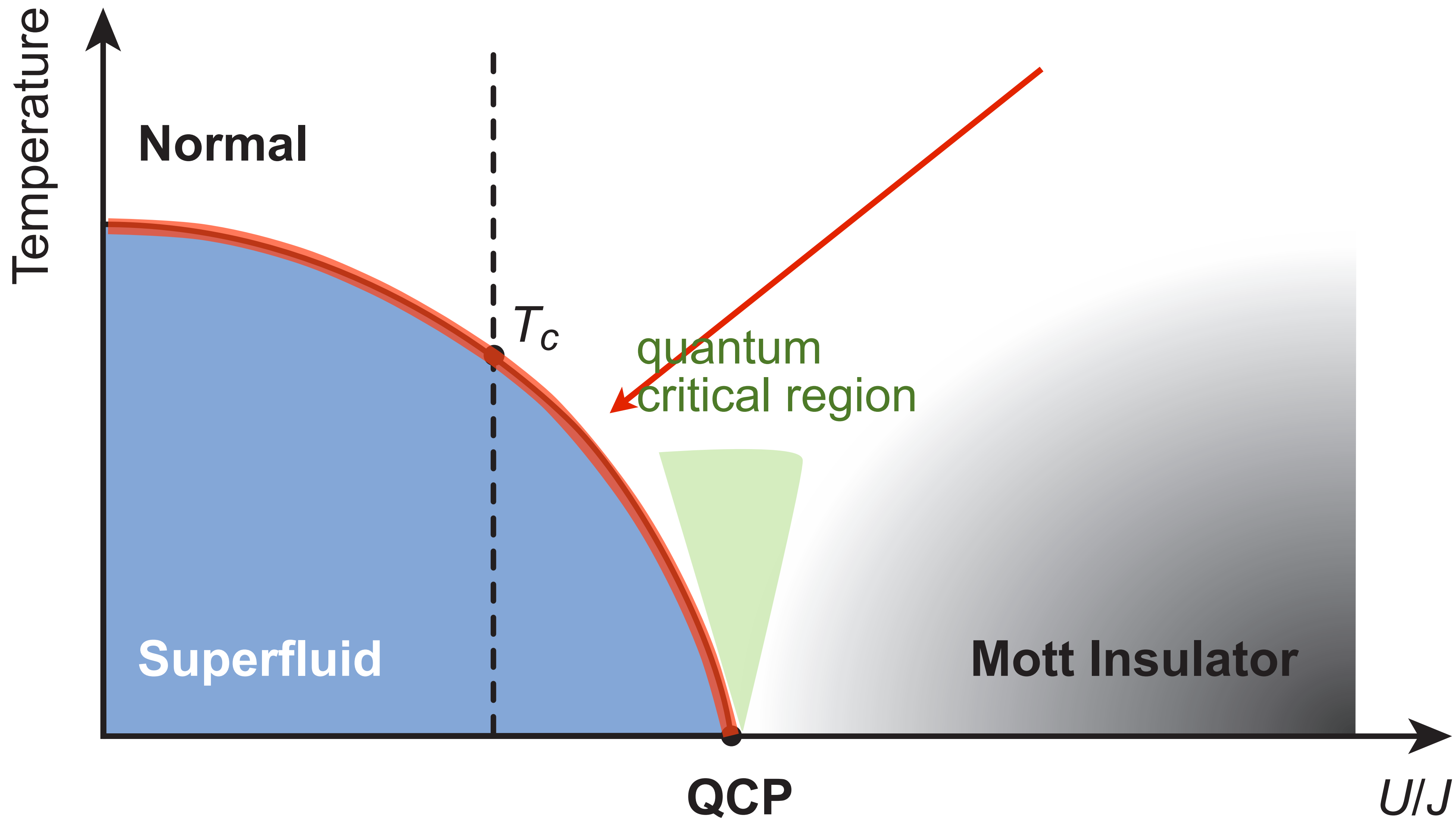


large *U*/*t*: Mott insulator

Can this be made more quantitative?

Quantitative validation: the phase diagram

- Bosons in a 3D optical lattice at filling $n = 1$
- Measure suppression of T_c close to the Mott insulator



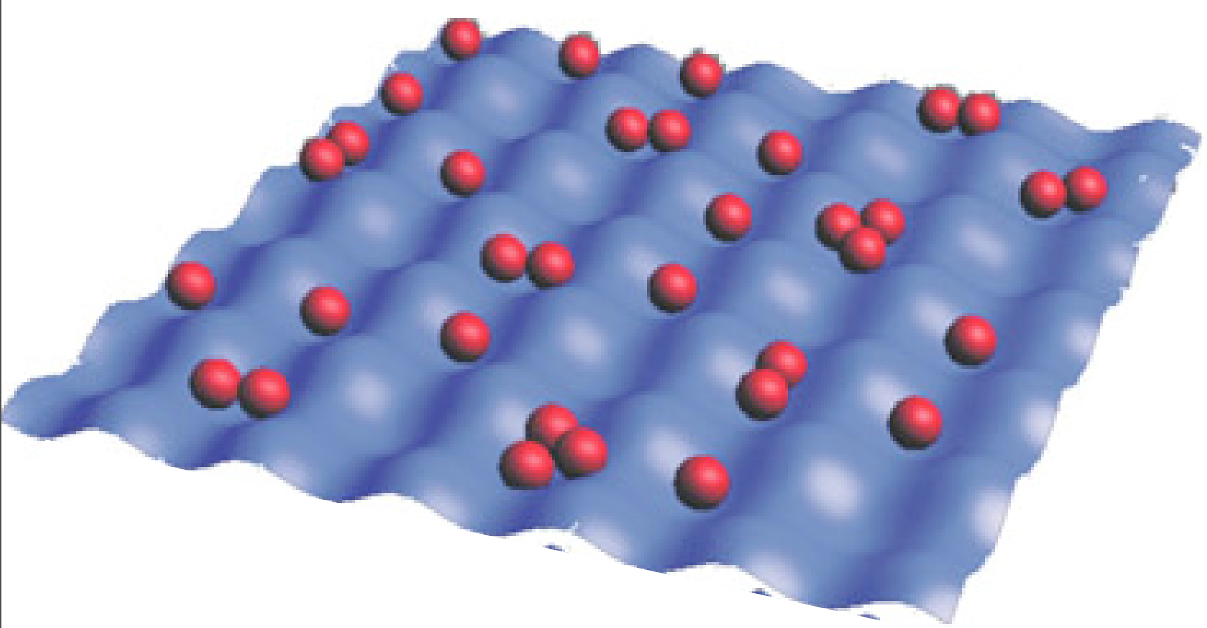
Validation by Quantum Monte Carlo simulations

- Approximation-free QMC simulations
  - worm algorithm
  - Prokof'ev, Svistunov and Tupitsyn, Sov. Phys. - JETP (1998)
  - up to 500,000 atoms
  - 220 x 220 x 200 ≈ 10 million sites
- We can model all details of the experiment
  - accurate microscopic model
  - same system size, particle numbers
  - temperature and entropy matched to experiment
  - measure quantities as observed in experiment
- Does the experiment agree with the QMC simulations?

Ab-initio mapping to the Hubbard model

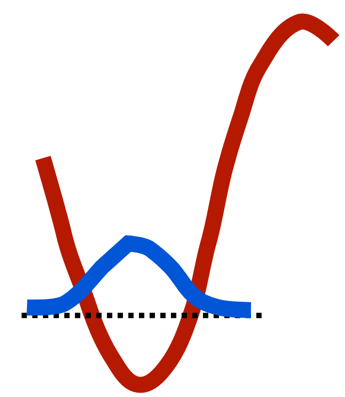
$$H = \int d^3r \psi^\dagger(\vec{r}) \left(-\frac{\hbar^2}{2\boxed{m}}\Delta + V_{\rm opt}(\vec{r}) \right) \psi(\vec{r}) + \frac{\boxed{g}}{2} \int d^3r \psi^\dagger(\vec{r})\psi^\dagger(\vec{r})\psi(\vec{r})\psi(\vec{r})$$

$$V_{\rm opt}(r,z) = -\boxed{V_0} e^{-2r^2/\boxed{w^2}(z)} \sin^2(\boxed{k}z) \qquad g = \frac{4\pi\hbar^2 a_s}{m}$$



$$\psi(\vec{r}) = \sum_i w(\vec{r} - \vec{r}_i) b_i$$

express the bosonic field operator in terms of Wannier functions



$$H = -\boxed{t} \sum_{\langle ij \rangle} \left(b_i^\dagger b_j + \text{h.c.} \right) + \boxed{U} \sum_i n_i(n_i - 1)/2 - \mu \sum_i n_i + \boxed{V} \sum_i r_i^2 n_i$$

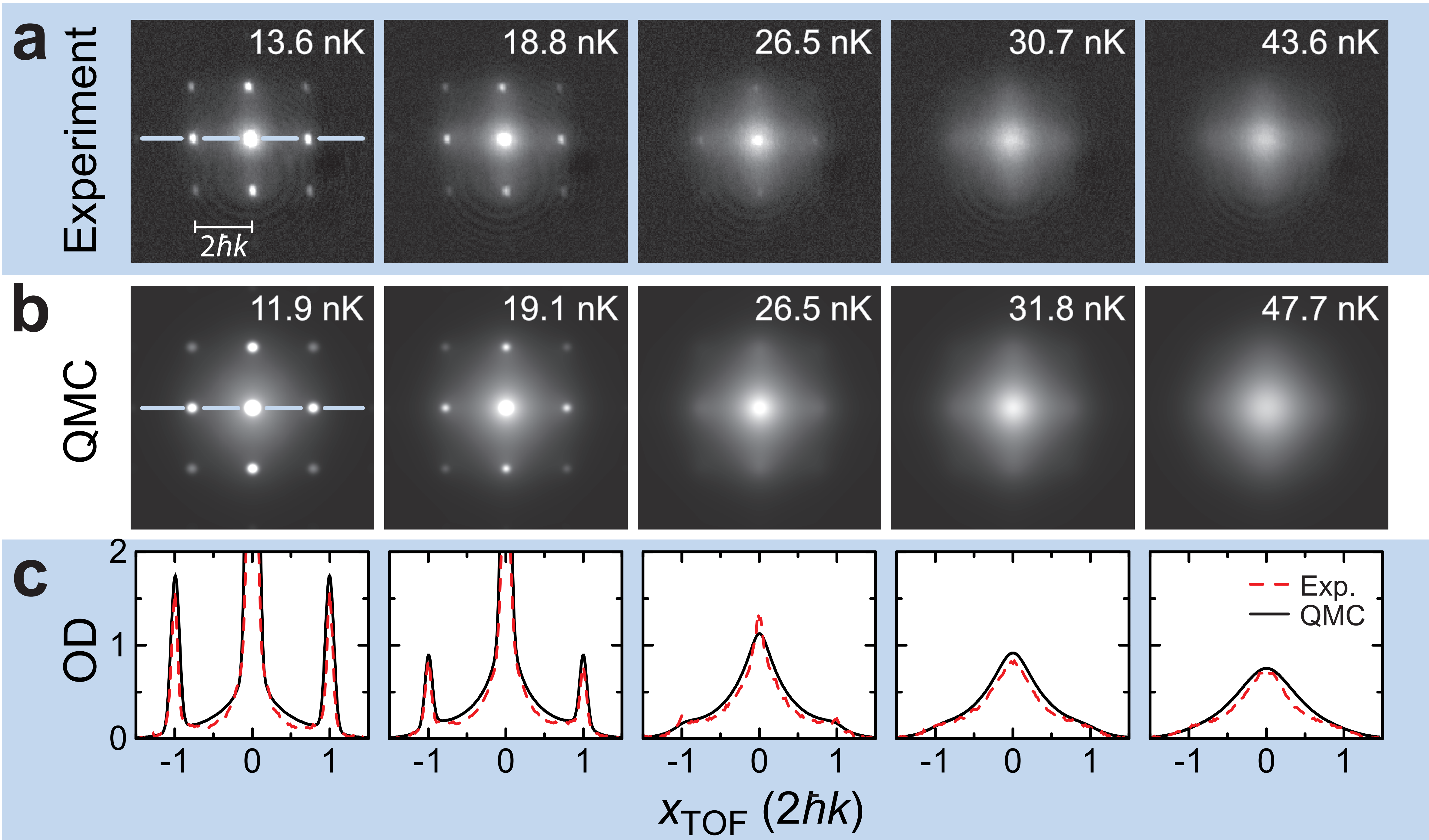
Validation by Quantum Monte Carlo simulations

- Model all details of the experiment
  - accurate microscopic model
  - keeping the density at $n = 1$
  - determining the temperature
  - calculate what the experiment should see

- Does the experiment agree with the QMC simulations?

Comparison QMC-experiment: small *U/t*

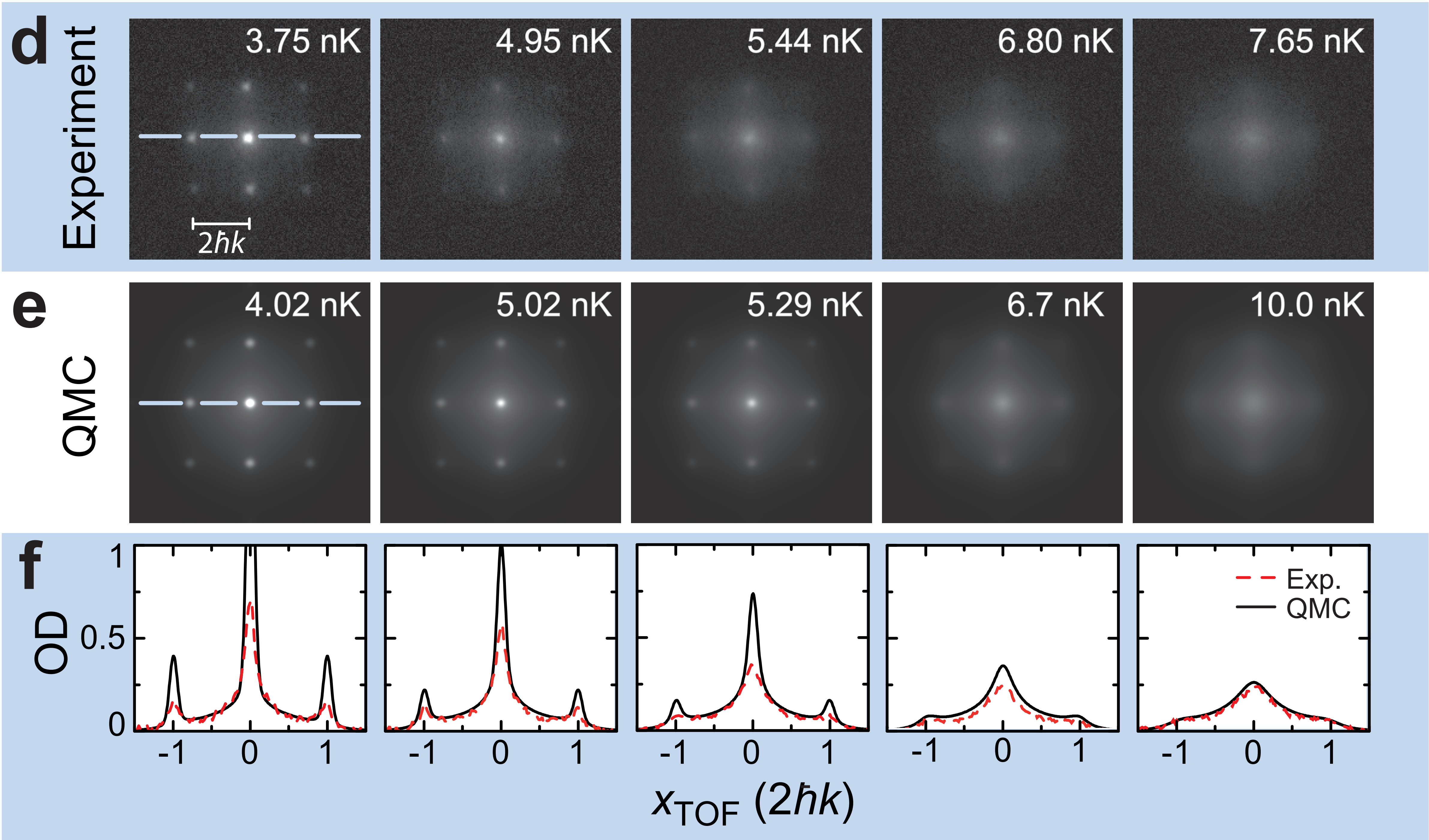
$$V_0 = 8E_r\,,\quad U/J = 8.11\,,\quad T_c = 26.5\text{nK}$$



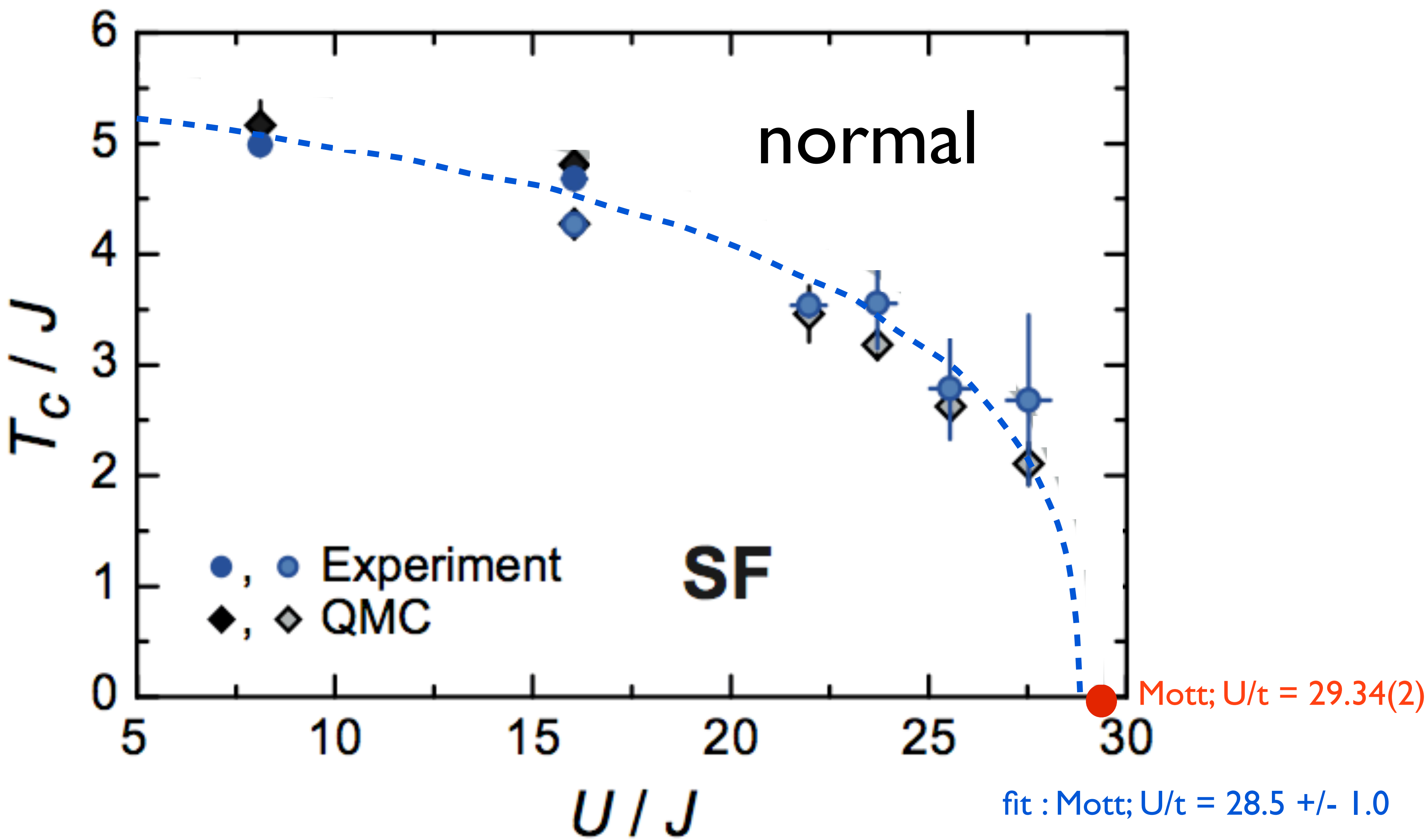
Tuesday, October 6, 2009

Comparison QMC-experiment: large *U/t*

$$V_0 = 11.75E_r\,,\quad U/J = 27.5\,,\quad T_c = 5.31\text{nK}$$



Phase diagram obtained by the quantum simulation



Collaborators

FNSNF
Swiss National Science Foundation

MaNEP
SWITZERLAND

DARPA

- Simulations
  - Lode Pollet (ETH → UMass → Harvard)
  - Nikolay Prokof’ev (UMass)
  - Vito Scarola (ETH & UC Berkeley → VATech)
  - Boris Svistunov (UMass)
  - Ping Nang Ma (Hong Kong →ETH)

- Experiments
  - Stefan Trotzky (Mainz → Munich)
  - Immanuel Bloch (Mainz → Munich)
  - Ute Schnorrberger (Mainz → Munich)
  - Fabrice Gerbier (Paris)