Atomare kvantegasser
Når ultrakoldt bliver 'hot'

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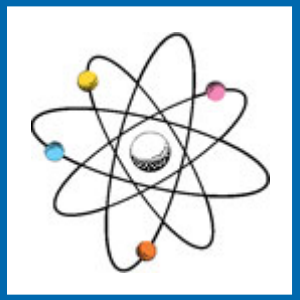
Aarhus Universitet

Plan for foredraget

- Hvad er en atomar kvantegas?
- Hvordan laver man/vi en kvantegas?
- Eksempler på hvorfor kvantegasser er spændende og relevante
  - også i gymnasiet
- Kvantegasser i gymnasiets fysik-undervisning

Hvad er en atomar kvantegas ?

Klassisk atomar gas



Bohr's atommodel 1913:
Elektronernes bevægelse i atomer skal beskrives kvantemekanisk

Bevægelse af atomet som helhed:

$$E = \frac{p^2}{2m} + V(\mathbf{r})$$

Klassisk beskrivelse

Antal atomer med bevægelses-energi E **:**

$$f(E) = \exp\left[-\frac{E-\mu}{k_B T}\right]$$

Maxwell-Boltzmann statistik

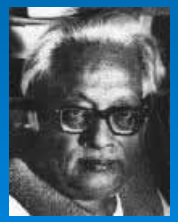
Atomar Kvantegas

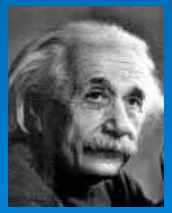
- Atomer der er så kolde at antallet af atomer i en given energitilstand ikke længere er givet ved Maxwell-Boltzmann statistik:

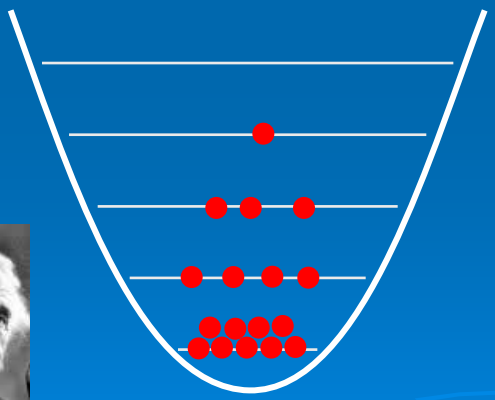
$$N(E) = \exp\left[-\frac{E-\mu}{k_B T}\right] \xrightarrow{T \to 0} N(E_\nu) = \frac{1}{\exp\left[(E_\nu - \mu)/k_B T\right] \pm 1}$$

Bosoner

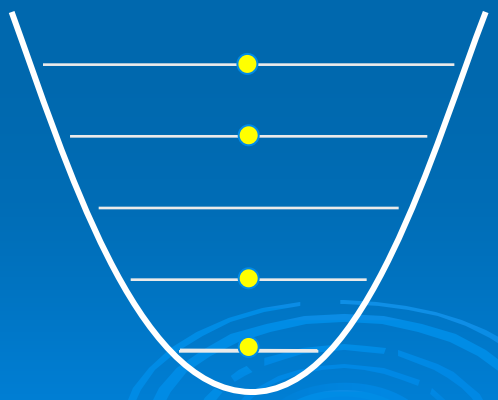
Fermioner







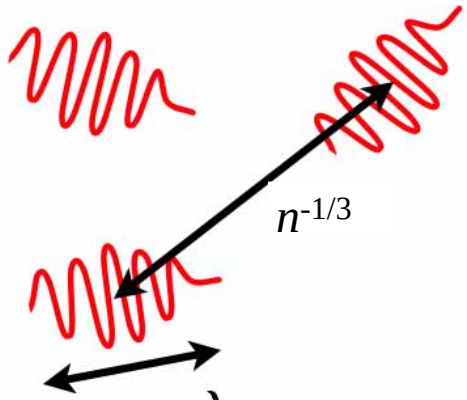
Bose-Einstein kondensat (BEC)



Højst 1 atom pr tilstand

Degenereret Fermi gas

Alternativt billede af Bose-Einstein kondensation



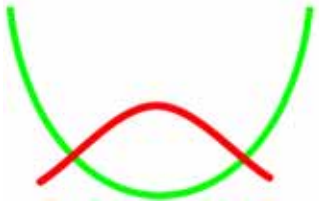
$$\sim \lambda_{\text{De Broglie}}$$

$$\lambda_{\text{De Broglie}} = \frac{h}{m v} \sim \frac{h}{\sqrt{m k_B T}}$$

$$T_c = 0.94 \frac{\hbar \omega}{k_B} \times N^{\frac{1}{3}} \approx 5\,\text{nK} \times N^{\frac{1}{3}}$$

$$T \gg T_c$$

$$T \sim T_c$$



$$T \ll T_c$$

Atom-laser

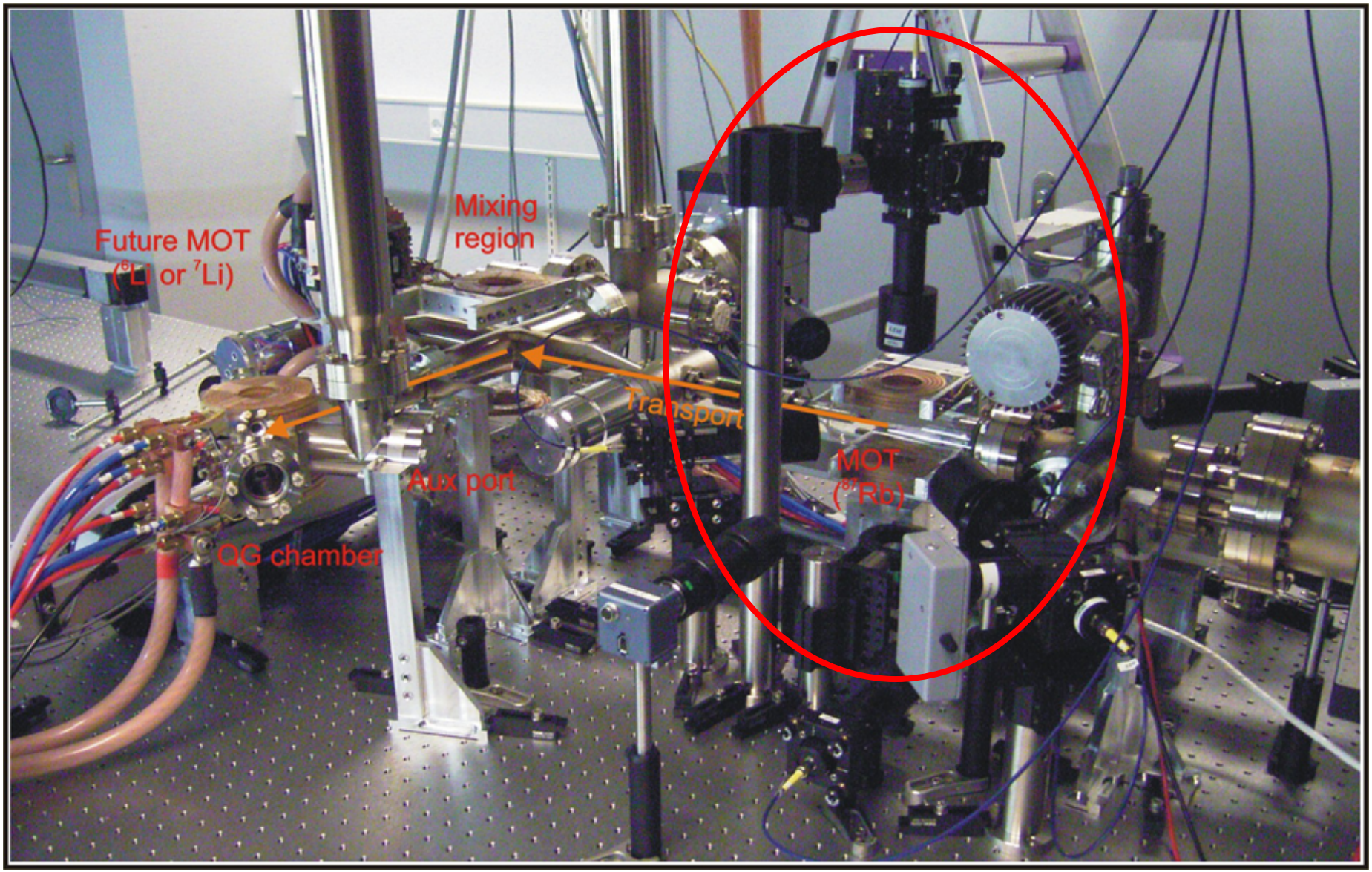
Hvorfor er kvantegasser interessante?

- Bose-Einstein kondensater:
  - Ideelle kvantesystemer: Alle atomer er i samme tilstand
  - Makroskopisk kvantemekanik
  - Væld af kvante-manipulations værktøjer

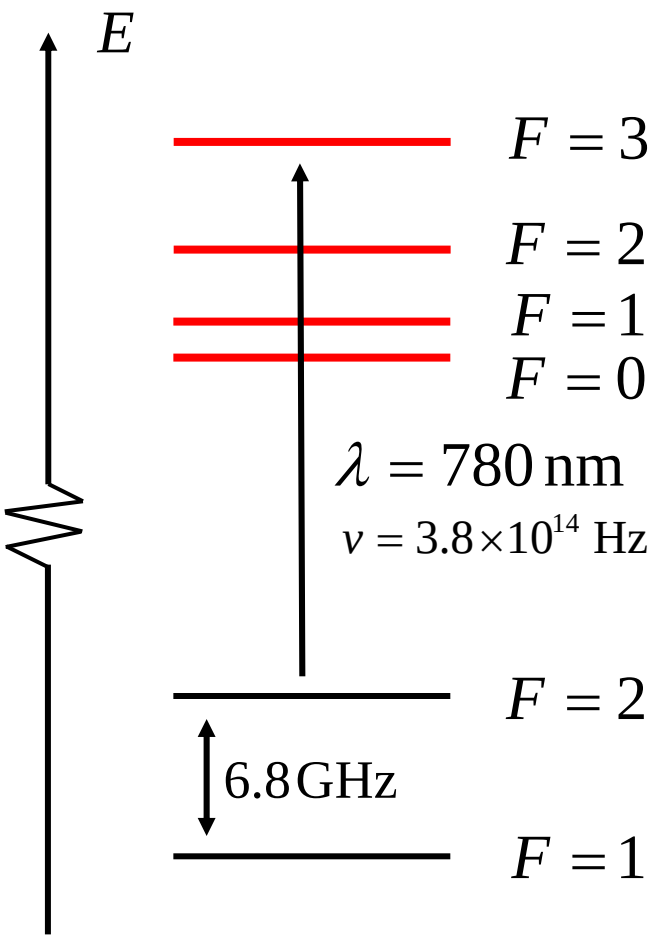
- Fermi-gasser
  - Pauli-princippet: komplementært til BEC
  - Tættere på dagligdags kvantegasser
  - Cooper par / Superledning

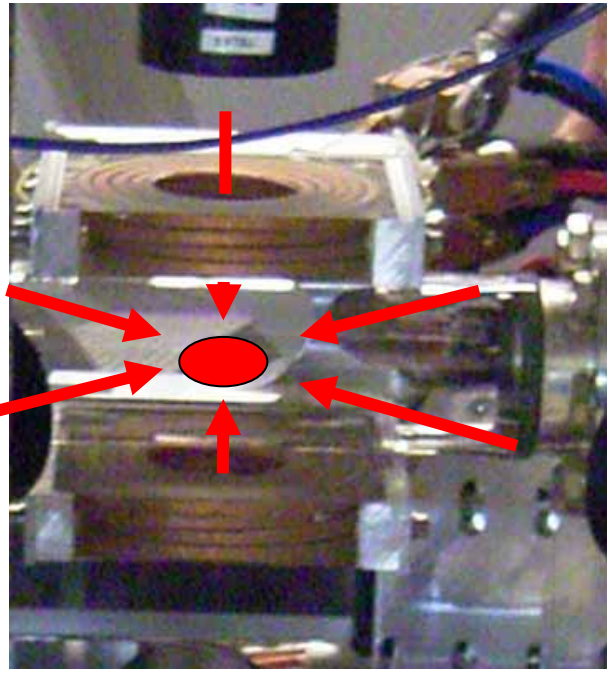
Hvordan laver man/vi et Bose-Einstein kondensat?

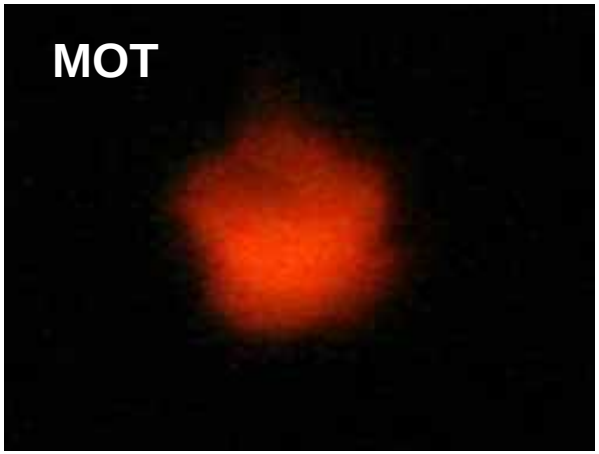
Vort BEC eksperiment



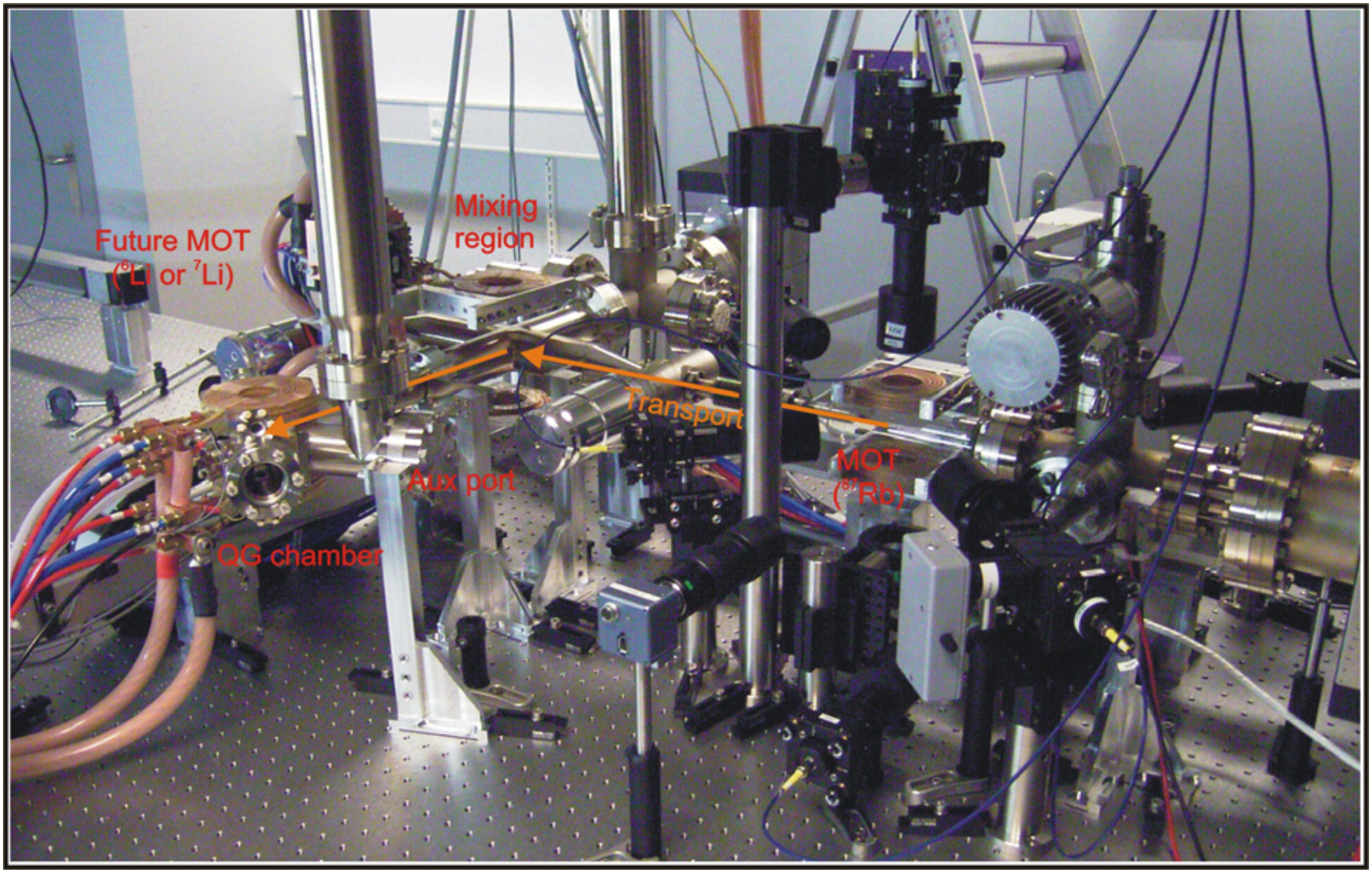
^{87}Rb Magneto-Optisk Fælde







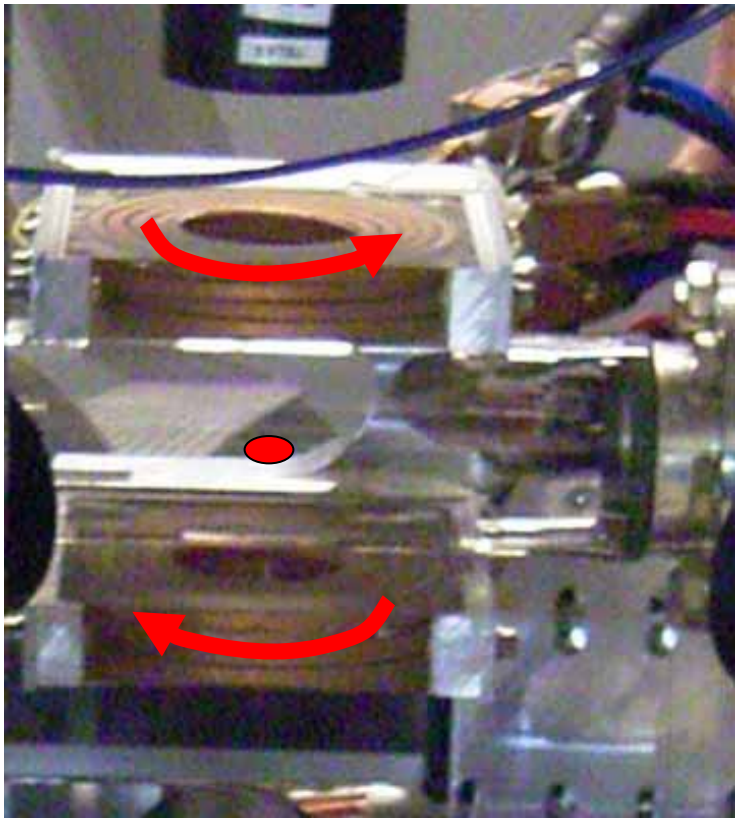
N ~ 1 milliard ^{87}Rb atomer
opsamles på 2-10 sekunder

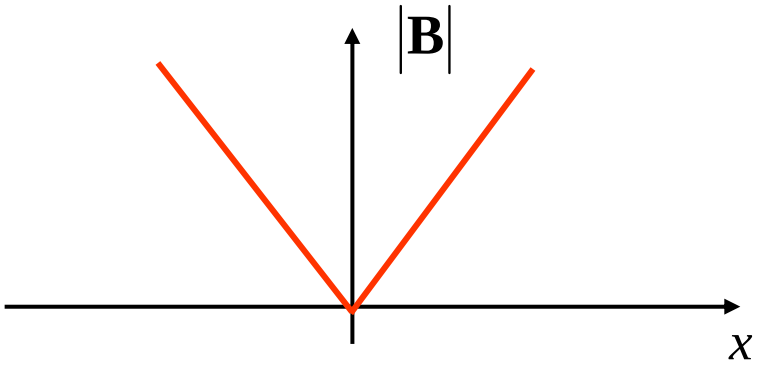

Future MOT
(^{6}Li or ^{7}Li)
Mixing
region
Transport
MOT
(^{87}Rb)
Aux port
QG chamber

Magnetisk fangning

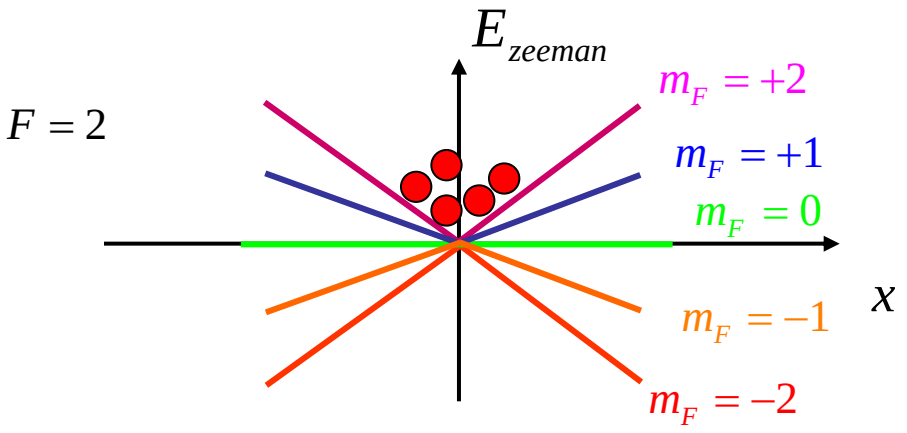
Efter MOT-fasen:

- Køle-laserstråler slukkes
- Optisk pumpning til $|F = 2; M_F = 2\rangle$
- Strøm: 17 A → 300 A





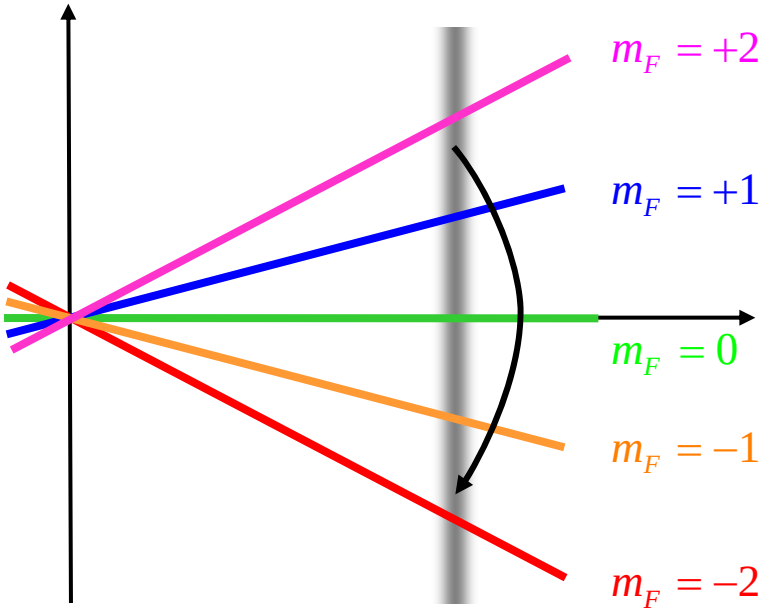
$$E_{zeeman} = \tfrac{1}{2}\,\mu_B\,|\mathbf{B}|\,m_F$$



Fældedybde = 3 mK = 0.25 μeV

Film

Fordampningskøling



Resonansbetingelse:

$$\hbar\omega_{RF} = \tfrac{1}{2}\mu_B \left|\mathbf{B}(\mathbf{r})\right| \Delta m_F = \tfrac{1}{2}\mu_B \left|\mathbf{B}(\mathbf{r})\right|$$

Radiobølger fjerner selektivt de mest energirige atomer

Tal:

- RF-sweep: 55 MHz → 930 kHz
- Atom-tal: $10^9 \rightarrow 2 \times 10^5$
- Temperatur: 350 μK → 200 nK

Absorptions afbildning

$$T[x,y] = \frac{I[x,y]}{I_0[x,y]} = \exp\left[-\sigma \int_{-\infty}^{\infty} n[x,y,z]\,dz\right]$$

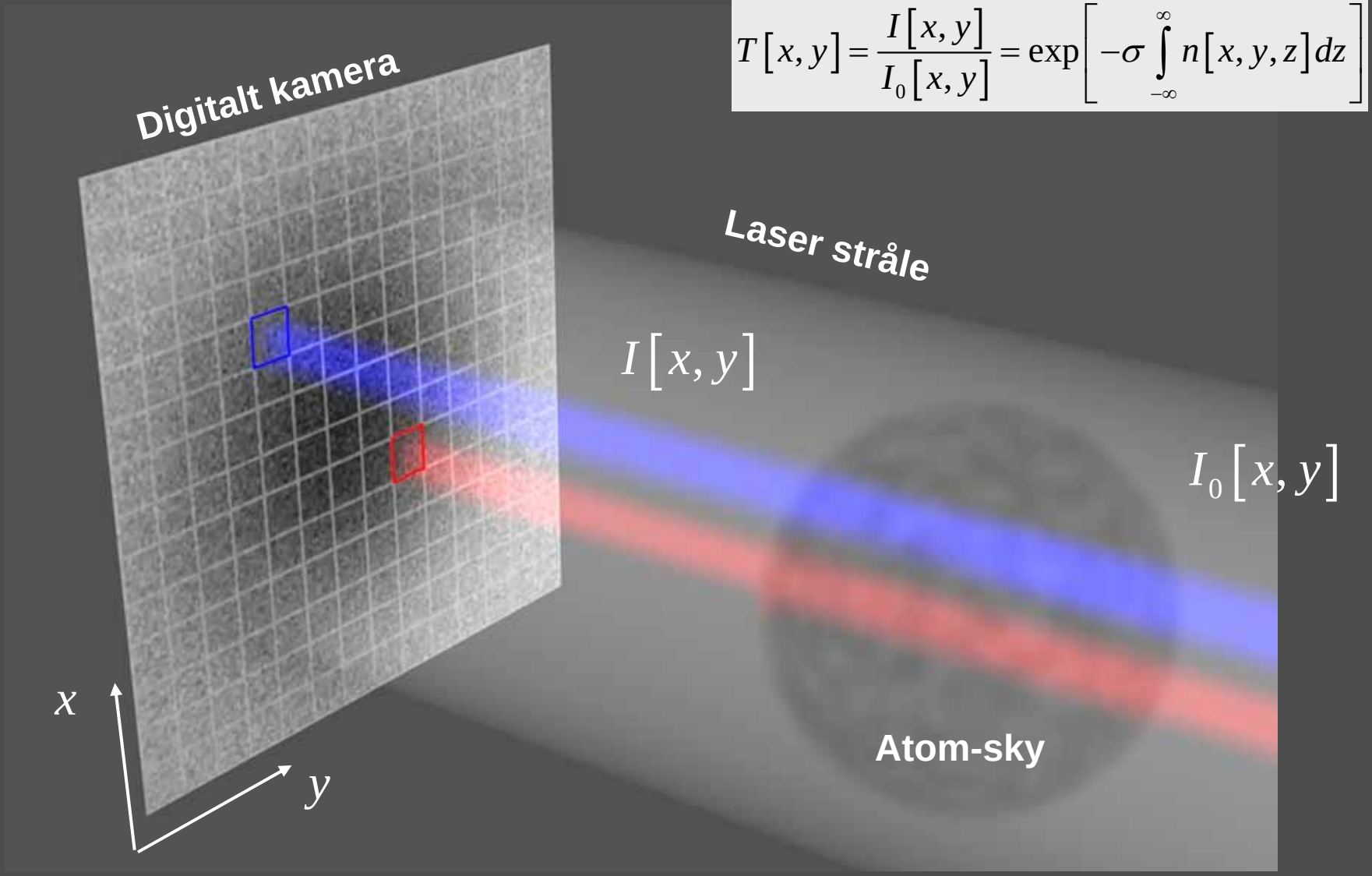
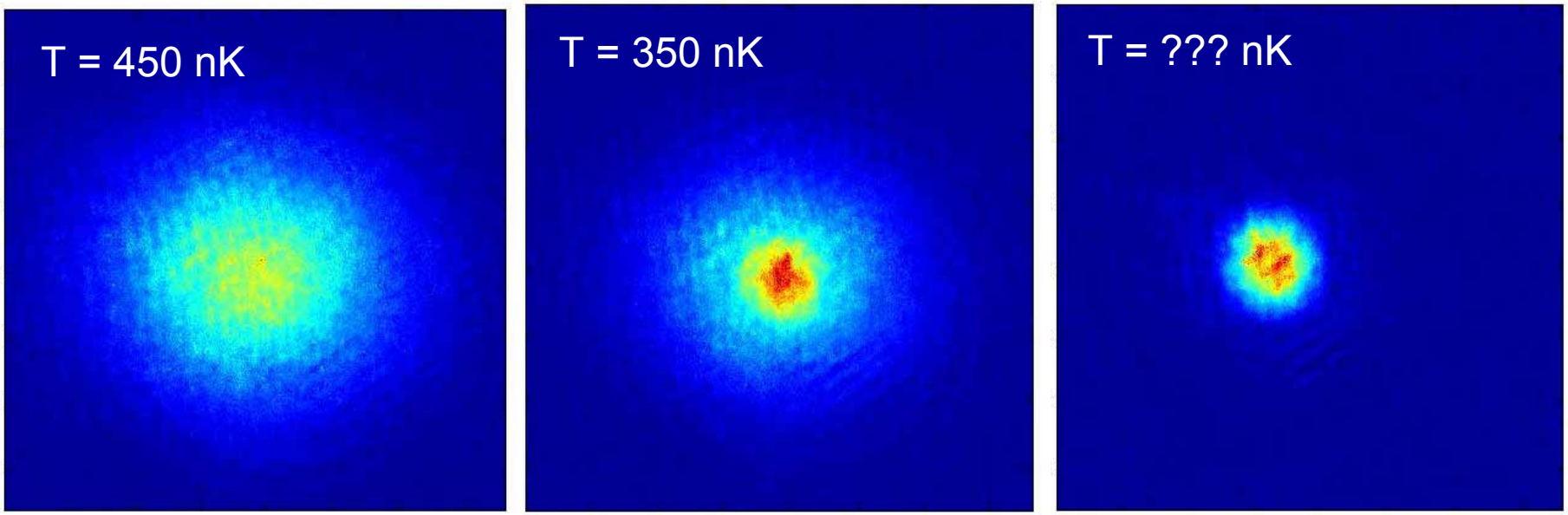


Illustration af I. Bloch, Uni Mainz

Slutning af fordampningskøling

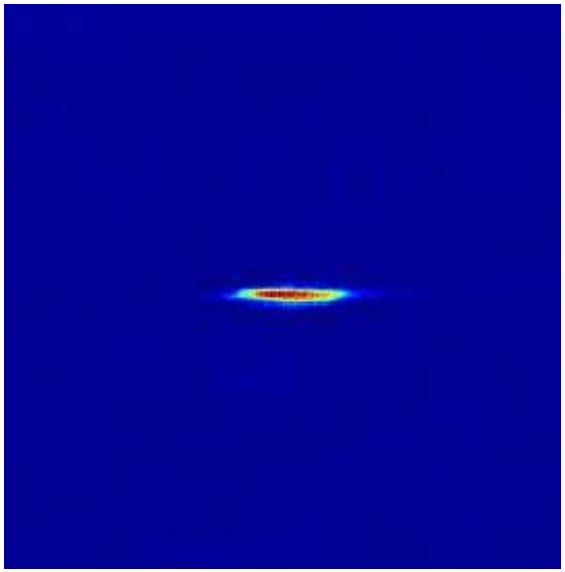


Termisk sky

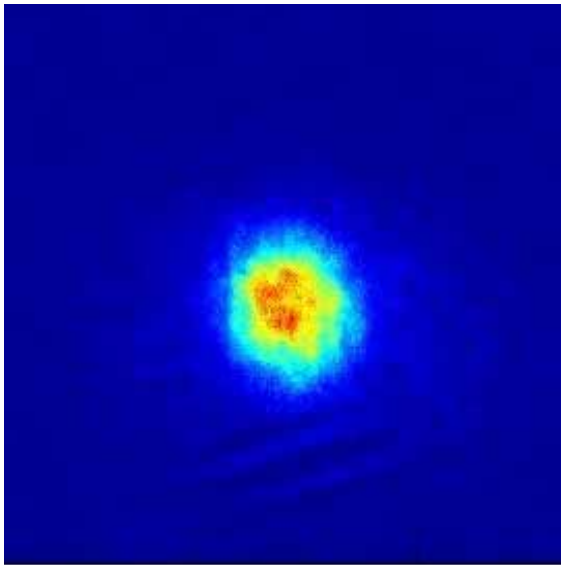
Bose-Einstein kondensat

Ekspansion af BEC

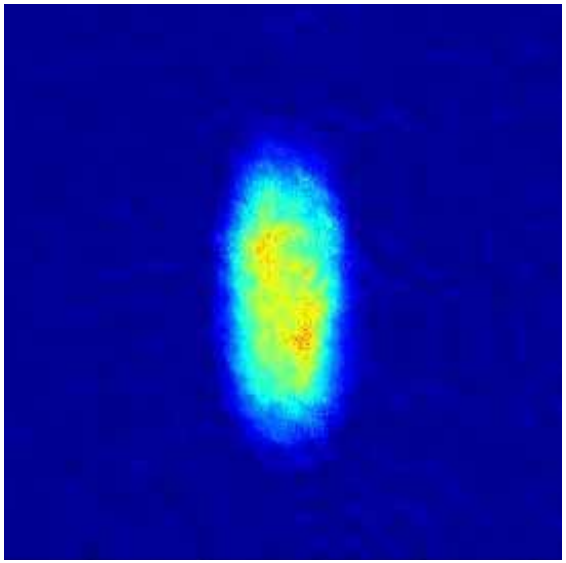
I fælden



Ekspansionstid = 15 ms



Ekspansionstid = 30 ms



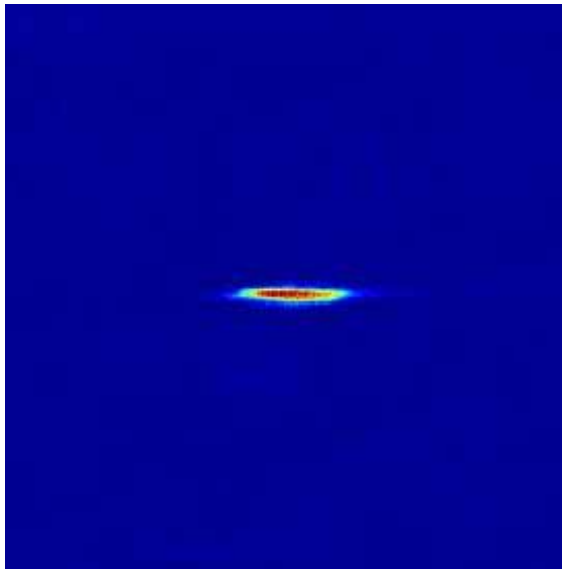
Termisk sky: Bliver rund under ekspansion

BEC: Inverterer under ekspansion

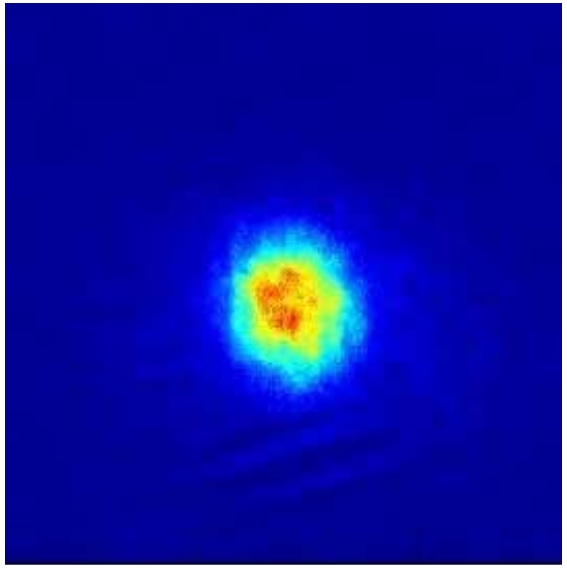
Visuel evidens for Heissenbergs ubestemthedsrelation !!!

Billeder af BEC ~ billeder af bølgefunktion

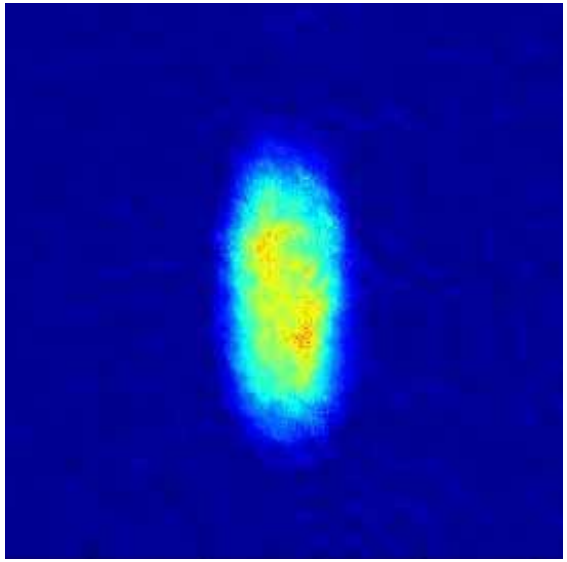
I fælden



Ekspansionstid = 15 ms



Ekspansionstid = 30 ms



$$OD[x,y] = \sigma \int_{-\infty}^{\infty} n(x,y,z)\,dz = \sigma N_0 \int_{-\infty}^{\infty} \left|\psi(x,y,z)\right|^2 dz$$

hvor:

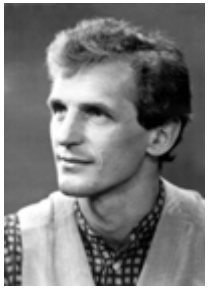
$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(x,y,z)\right]\psi(x,y,z) = \mu\,\psi(x,y,z)$$

Man kan fotografere 2D snit af bølgefunktionen!

The Nobel Prize in Physics 2001

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

Eric A. Cornell
University of Colorado



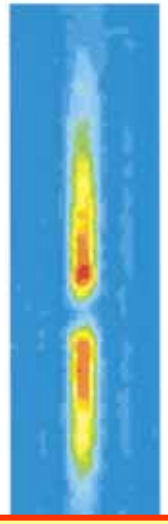
Wolfgang Ketterle
MIT

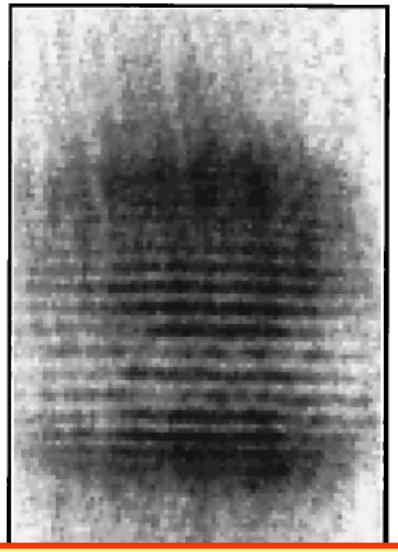
Carl Wieman
University of Colorado

E. A. Cornell and C. E. Wieman, Rev. Mod. Phys. **74**, 875 (2002)
W. Ketterle, Rev. Mod. Phys. **74**, 1131 (2002)

Eksempler

Eksempel 1: Interferens





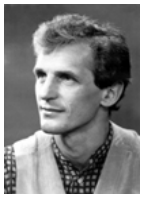
Så, atom + atom = vacuum !!!

RESEARCH ARTICLE

Observation of Interference Between Two Bose Condensates

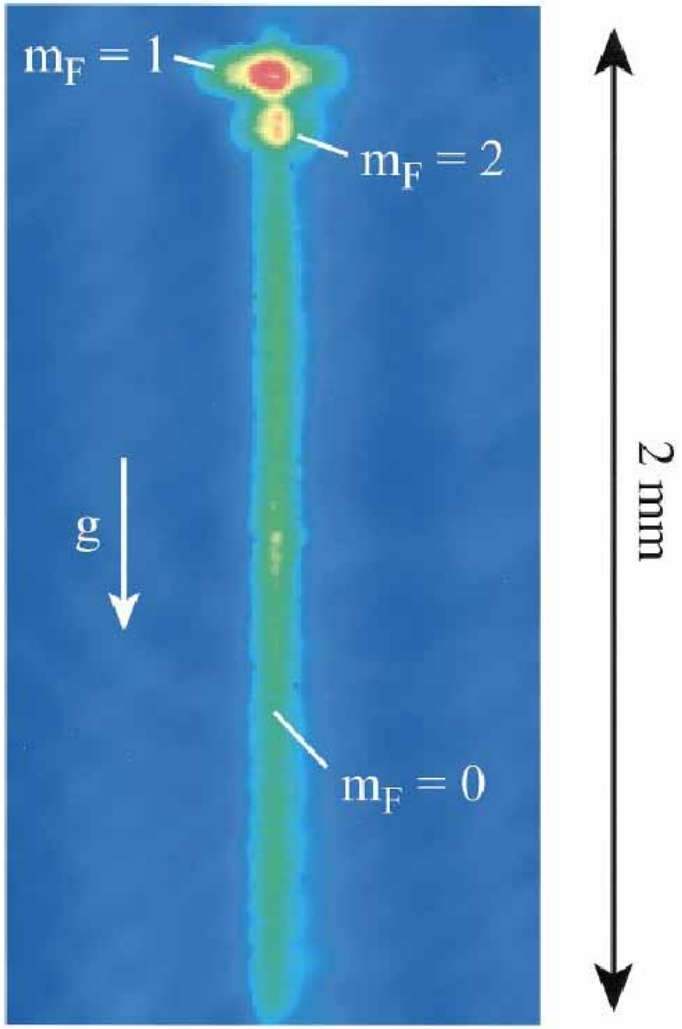
M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, W. Ketterle

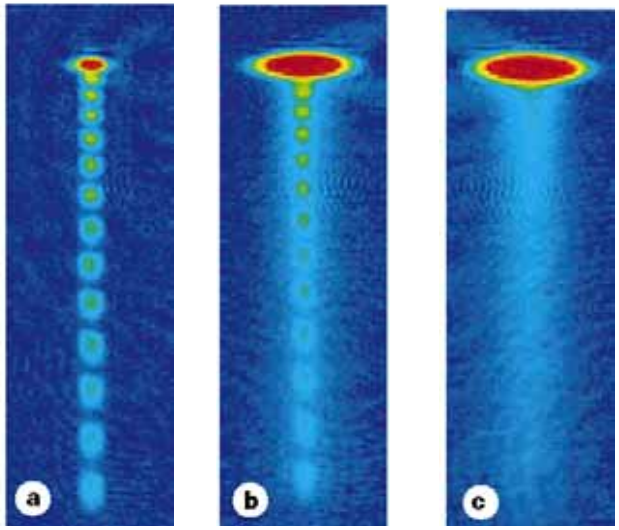
SCIENCE • VOL. 275 • 31 JANUARY 1997



Wolfgang Ketterle
MIT

Eksempel 2: Atomlaseren





Measurement of the spatial coherence of a trapped Bose gas at the phase transition

I. Bloch, T. W. Hänsch & T. Esslinger

Sektion Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, D-80799 Munich, Germany, & The Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany

NATURE | VOL 403 | 13 JANUARY 2000 | www.nature.com

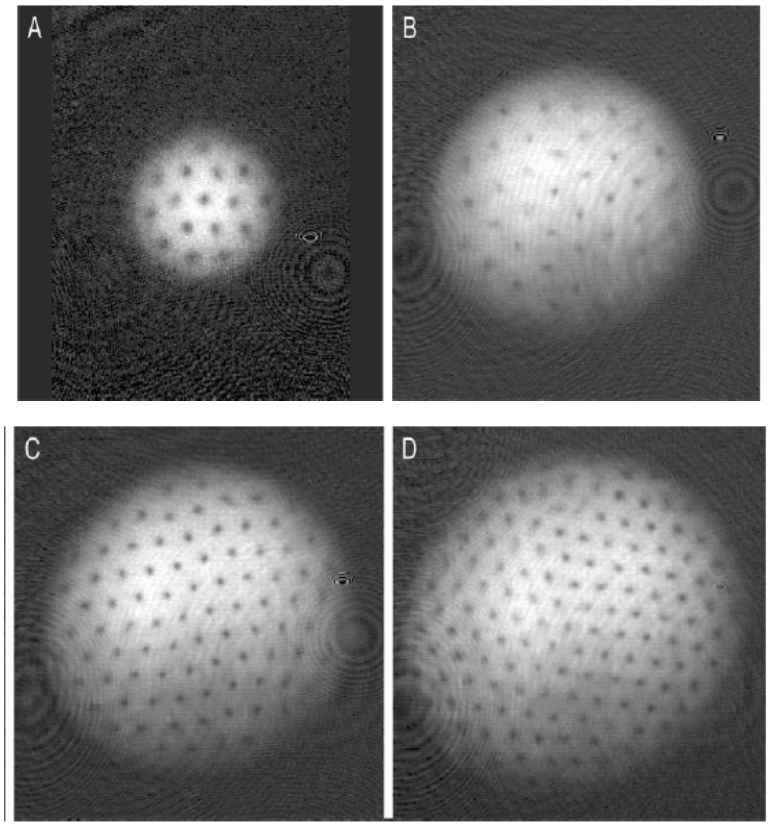
Nobel 2005

Eksempel 3: Hvirvelstrømme

Observation of Vortex Lattices in Bose-Einstein Condensates

J. R. Abo-Shaeer, C. Raman, J. M. Vogels, W. Ketterle

20 APRIL 2001 VOL 292 SCIENCE www.sciencemag.org



Bose-Einstein kondensater
i
gymnasie-undervisningen

Hvorfor BEC i gymnasiet?

Kvantemekanik er kommet for at blive

BEC er et glimrende udgangspunkt for diskussion af:

- Partikel-bølge dualitet
- Schrödingerligningen
- Bølgefunktionen og dens fortolkning
- Heissenbergs ubestemthedsrelation
- Bosoner vs fermioner
- Temperatur

Problem: Mangel på undervisningsmateriale

Vi kan (snart) tilbyde...

Gymnasie BEC-pakke bestående af:

Noter som beskriver:

1. Hvad et BEC er og hvorfor BEC'ere er interessante
2. Kvantemekanik for partikel i harmonisk fælde
3. Hvordan man laver og studerer et BEC

Eksperimentelle billeder:

1. til måling af den kritiske temperatur
2. som viser BEC'et blive dannet
3. som viser ekspansionen for termisk sky og BEC

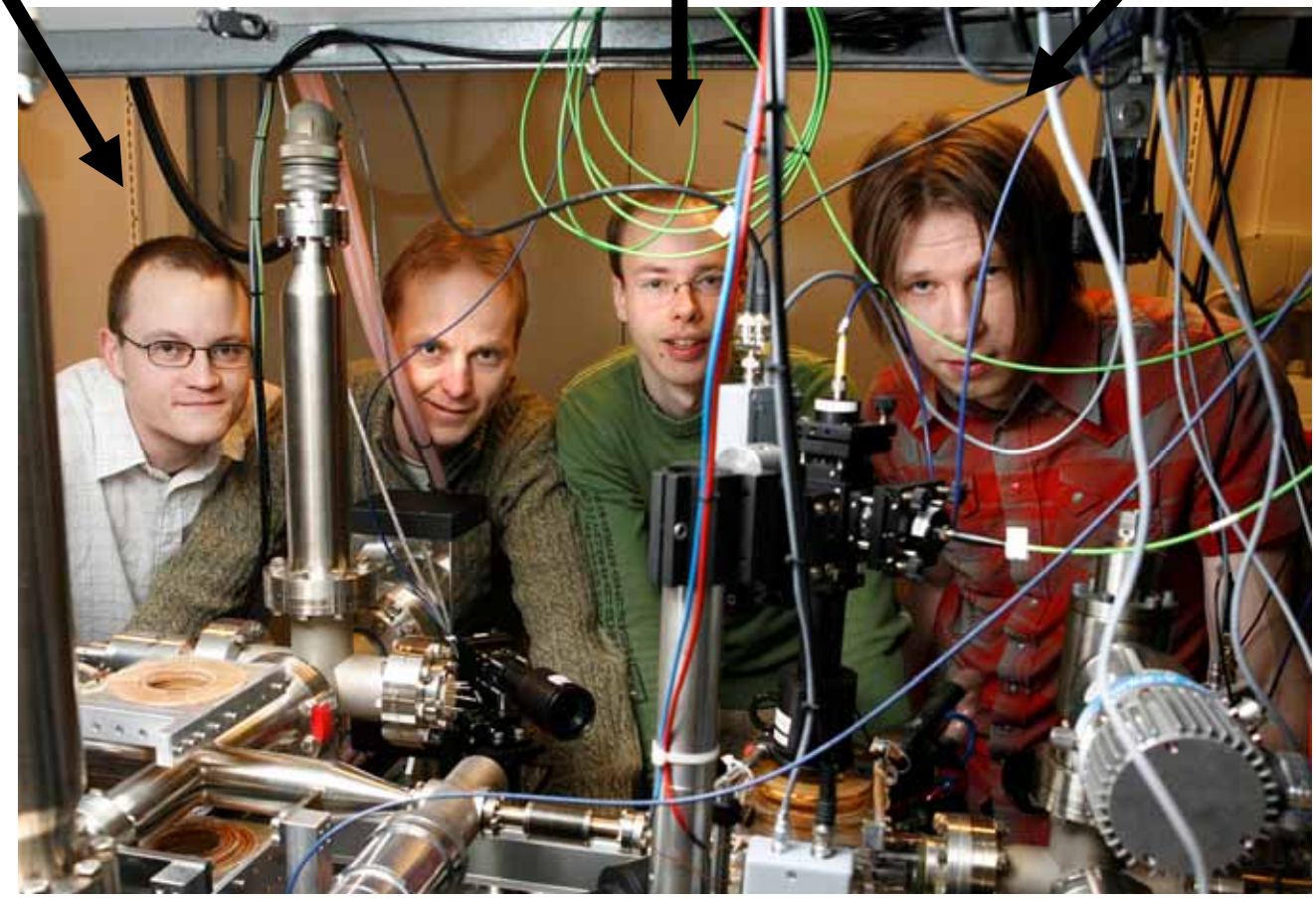
samt software til analyse af billeder på PC

Igangværende forskningsprojekter

- BEC i periodiske potentialer
- Magnetisk Sisyphus køling
- Kvantegas af:
  - ^{6}Li (fermioner)
  - ^{7}Li (bosoner)

Kvantegasgruppen

Sune Mai

Jesper Fevre Bertelsen

Henrik Kjær Andersen