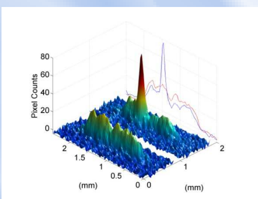
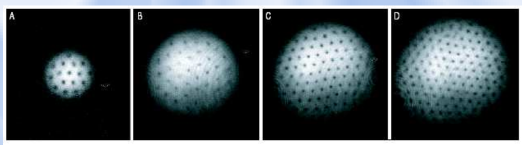
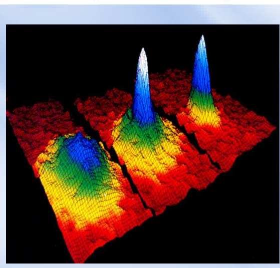
What are we going to talk about:
BEC and Nonlinear Atom Optics

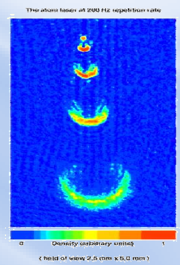




Nobel Prize Winners

E. A. Cornell	W. Ketterle	C. E. Wieman
1961-	1957-	1951-
JILA and NIST Boulder, Co, USA	MIT, Cambridge.Ma USA	JILA and UC, Boulder, Co, USA





Plan

1. Facts about BEC
2. Atom cooling
3. Atom trapping
4. Condensates and diagnostics
5. Coherence and excitations
6. Nonlinear Atom Optics
7. Lattices
8. Feshbach Resonance
9. Solitons and Vorteces
10. Spinor condensates
11. Tons more …

Uniwersytet Warszawski — Wydział Fizyki

Some history

- 1925 Theory of condensation
- 1938 Superfluid helium discovery
- 1941 Landau theory
- 1980 Cooling – breaking mK limit
- 1995 BEC in neutral gas observed

Uniwersytet Warszawski Wydział Fizyki

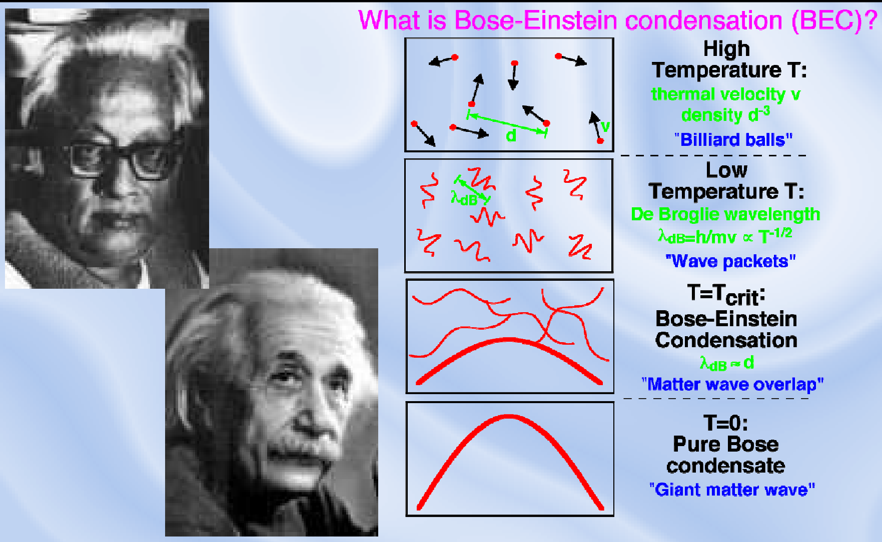
Some characteristics

Statistics → $$N_i = \frac{1}{\exp[(\varepsilon_i - \mu)/kT] - 1}$$

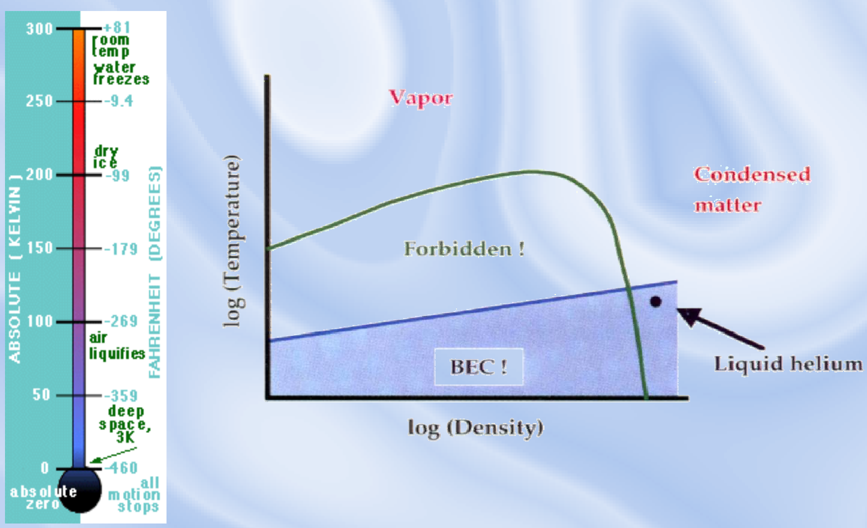
Critical temperature → $$kT_c = \frac{2\pi\hbar^2}{m}\left(\frac{\rho}{2.612}\right)^{2/3}$$

de Broglie'a wavelength → $$\lambda(T) = \frac{h}{p} = \sqrt{(h^2/3mkT)}$$

Lost identity



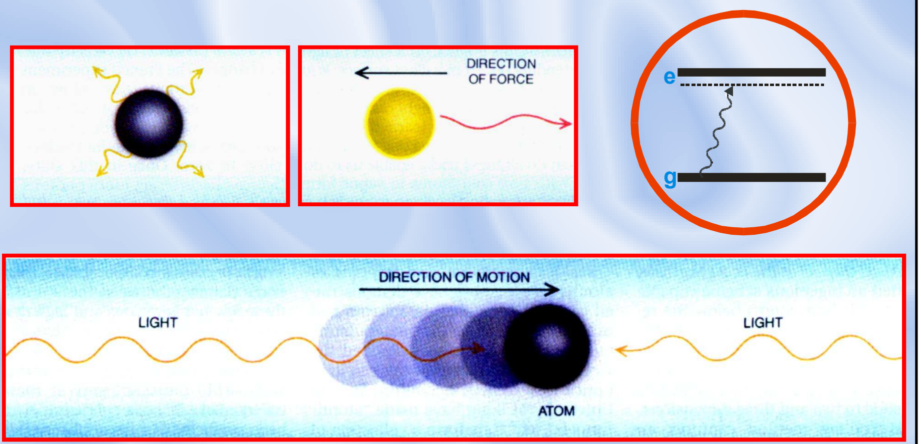
BEC – methastable state



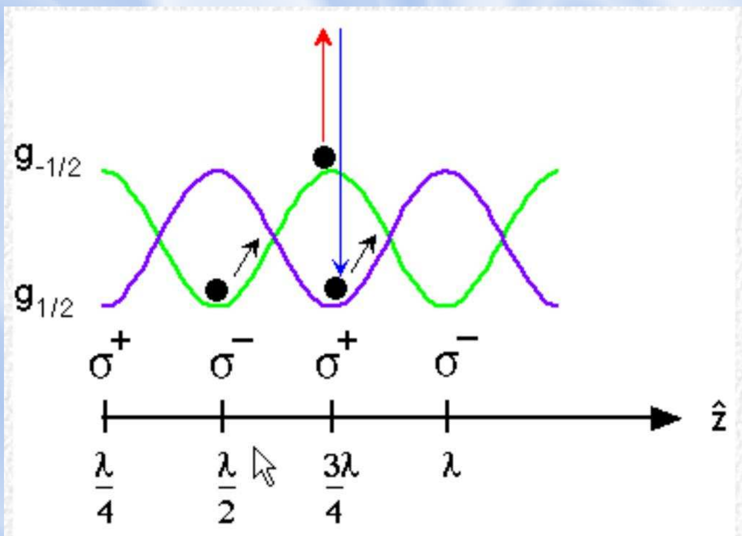
Cooling of Neutral Atoms

1. Doppler cooling
2. Sisyphus cooling
3. Whatever else cooling
3. Evaporative cooling !!!!

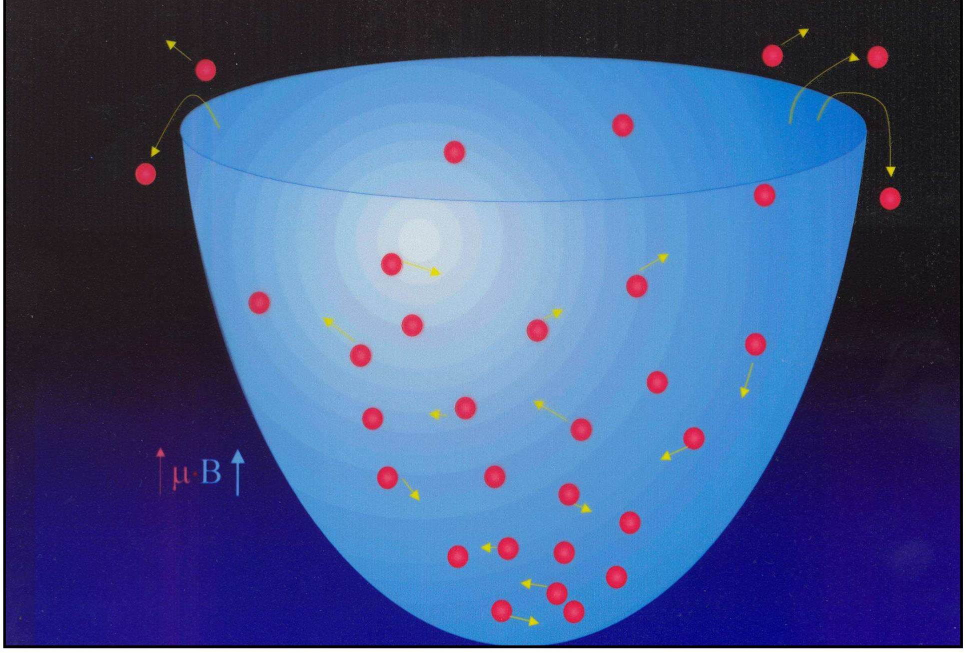
Doppler cooling



Sisyphus cooling

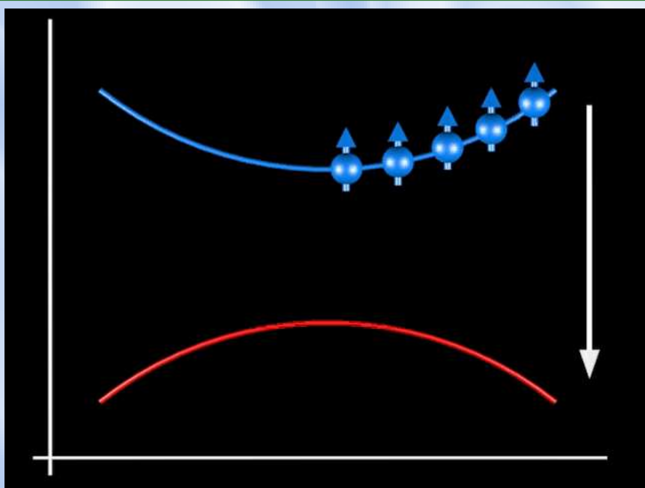


Magnetic trapping and evaporative cooling



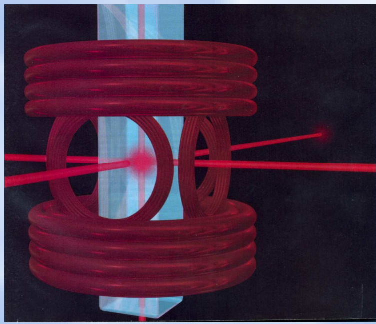
Evaporative cooling

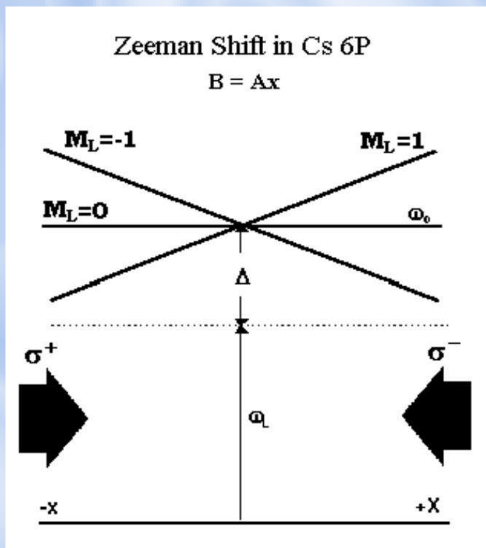
Evaporative colling



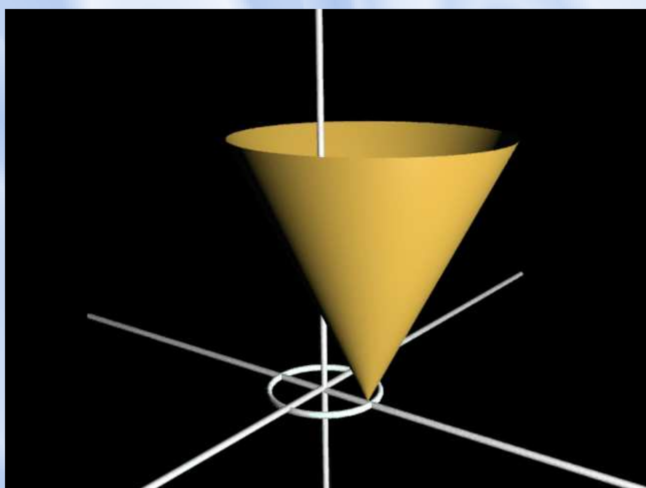
Optical Scalpel

Magneto-optical trap

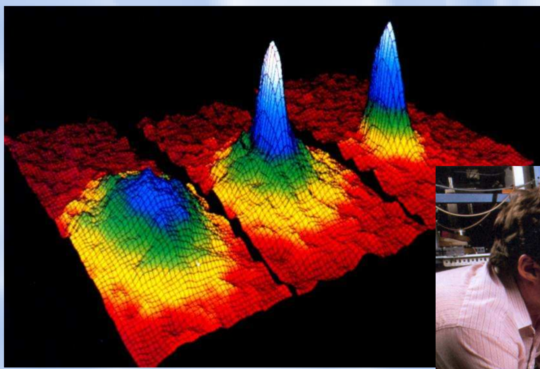




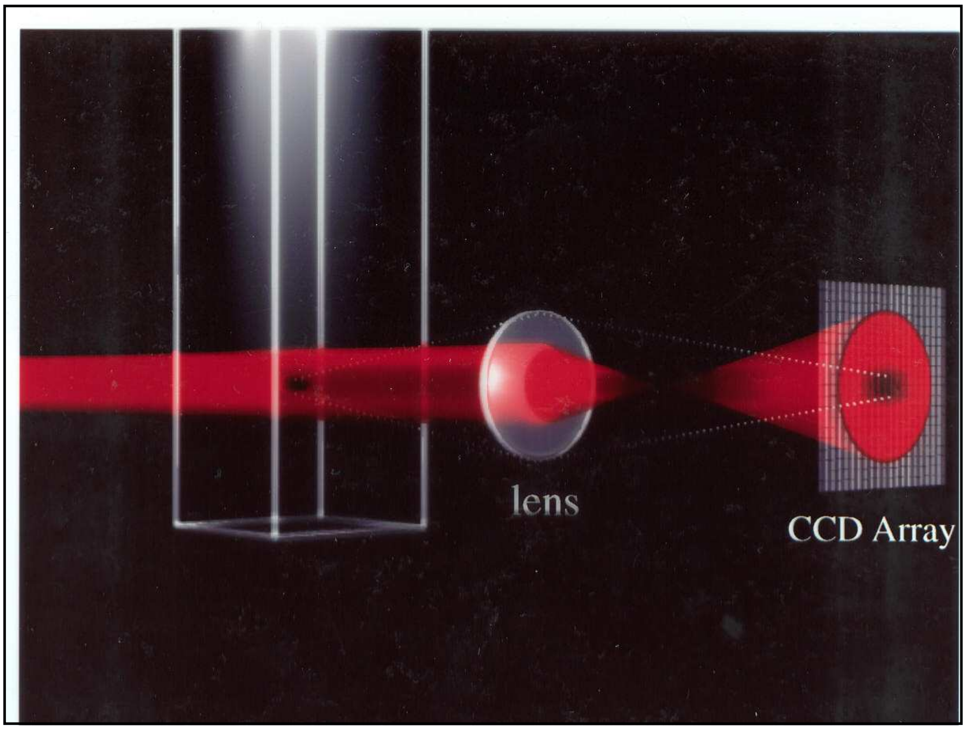
T.O.P



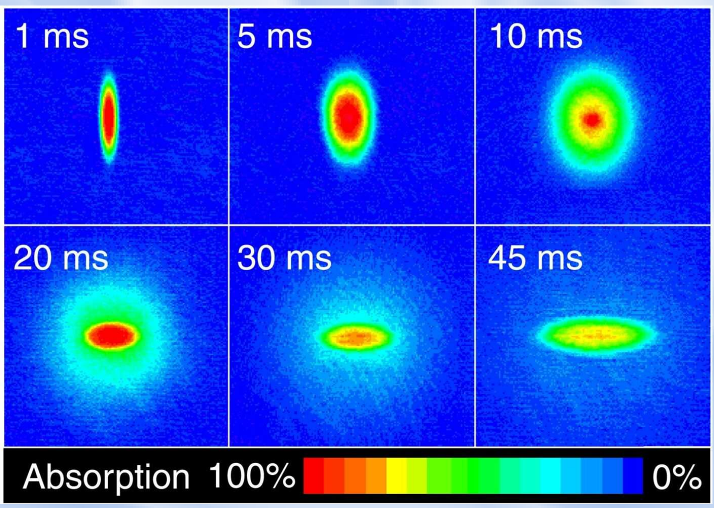
Condenssate at last



JILA,COLORADO‘95

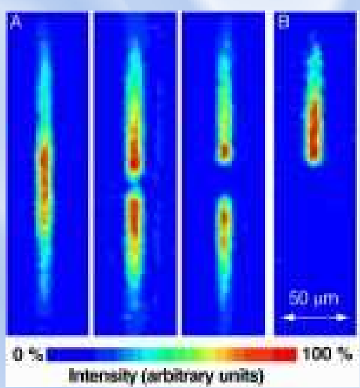


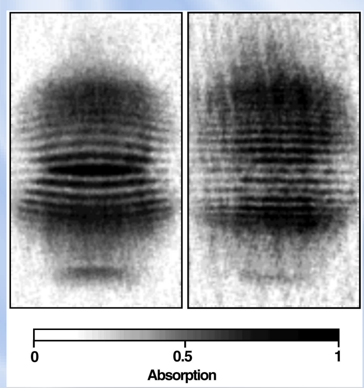
Free expansion



(W.Ketterle)

Interference





(W.Keterle, Science 1997)

Excitations

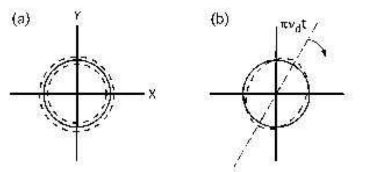


FIG. 1. In the unperturbed trap, contours of equipotential in the transverse plane are symmetric (solid line). To drive the $m = 0$ excitation (a) we apply a weak harmonic modulation with frequency ν_d to the trap radial spring constant. The $m = 2$ drive (b) breaks axial symmetry with elliptical contours which rotate at $\nu_d/2$. The amplitude of perturbation is shown exaggerated for clarity.

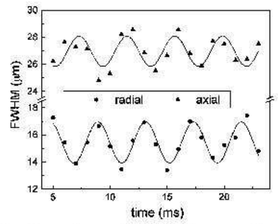
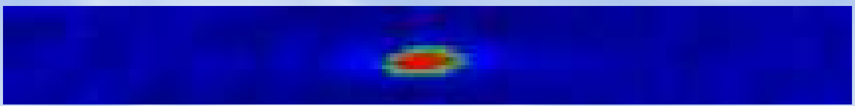


FIG. 2. We apply a weak $m = 0$ drive to an $N \approx 4500$ condensate in a 132 Hz (radial) trap. Afterward, the freely evolving response of the condensate shows radial oscillations. Also observed is a sympathetic response of the axial width, approximately 180° out of phase. The frequency of the excitation is determined from a sine wave fit to the freely oscillating cloud widths. Each data point represents a single destructive condensate measurement.

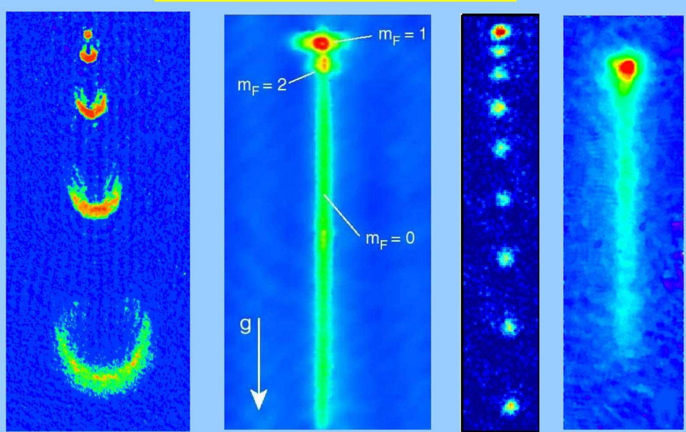


(C.E. Wieman, E.A. Cornell '96)

Galery

Atom laser gallery

Height:
5, 2, 0.5, 1 mm



MIT '97 Munich '99 Yale '98 NIST '99

Condensate Splitting

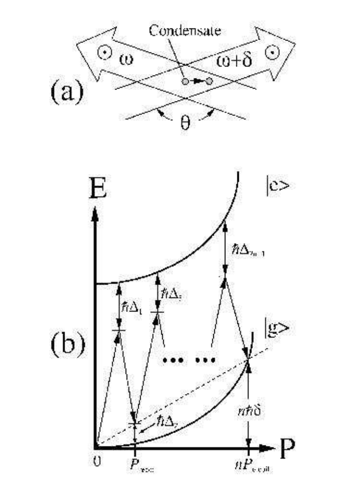


FIG. 1. Experimental arrangement of the laser beams (a) and partial transition diagram (b) for nth order Bragg diffraction. The parabolas correspond to the $P^2/2M$ kinetic energy.

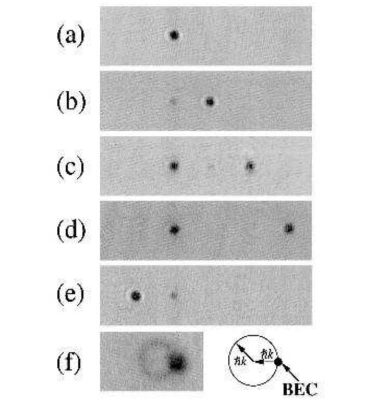


FIG. 3. Optical depth images of condensates which were first adiabatically expanded and then Bragg diffracted. (a), (b), (c), (d), and (e) are images taken 5.6 ms after Bragg pulses with frequency differences of $\delta/2\pi = 0, 98, 200, 300$, and -98 kHz, respectively. (f) is an image where spontaneous emission occurred using a single laser beam. The width of the field of view is 2.3 mm × 0.5 mm.

(W.D. Philips, 1999)

Nonlinear Optics versus BEC

Puls propagation

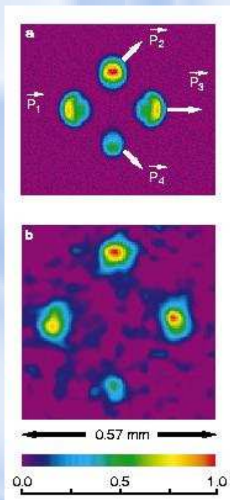
$$\frac{\partial A}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + i\frac{\gamma_{xx}}{2}\frac{\partial^2 A}{\partial x^2} + i\frac{\gamma_{yy}}{2}\frac{\partial^2 A}{\partial y^2} + i\gamma_{NL}|A|^2 A$$

BEC evolution

$$\frac{\partial \psi}{\partial t} = \frac{i\hbar}{2m}\left(\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2}\right) + V(x,y,z)\psi + i\frac{U_0}{\hbar}|\psi|^2\psi$$

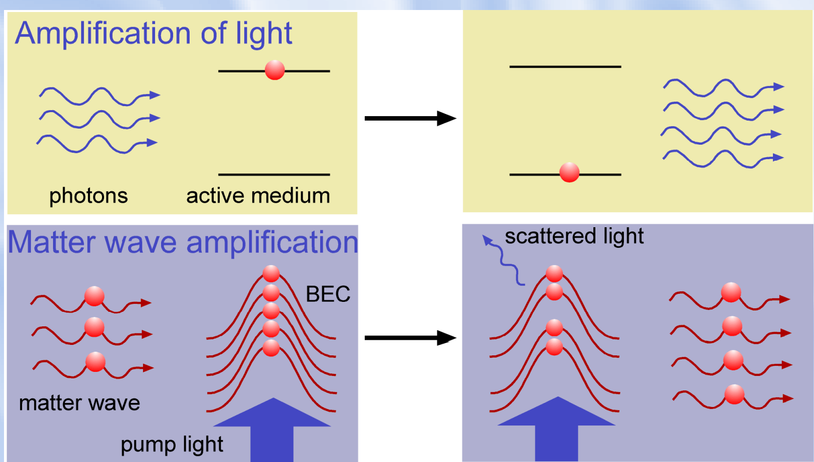
Uniwersytet Warszawski Wydział Fizyki

Four Wave Mixing

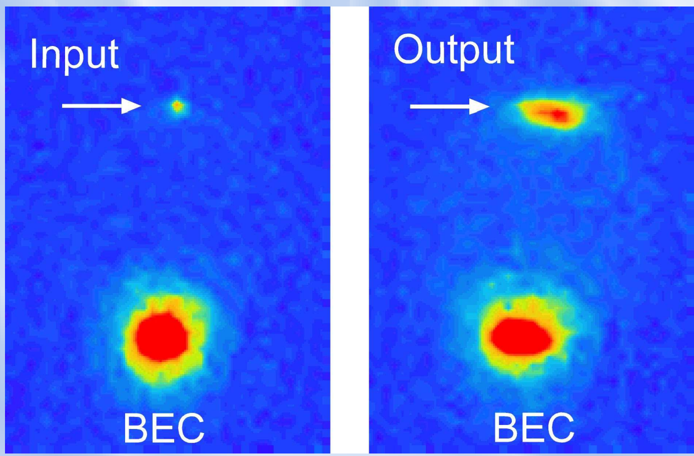


(W.D. Phillips, Nature, 1999)

Atomic Amplifier

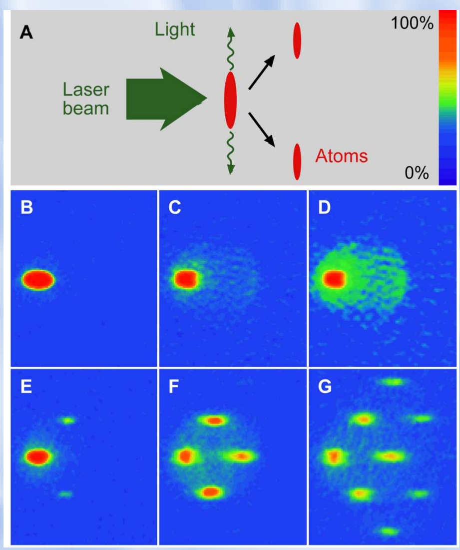


Amplifier

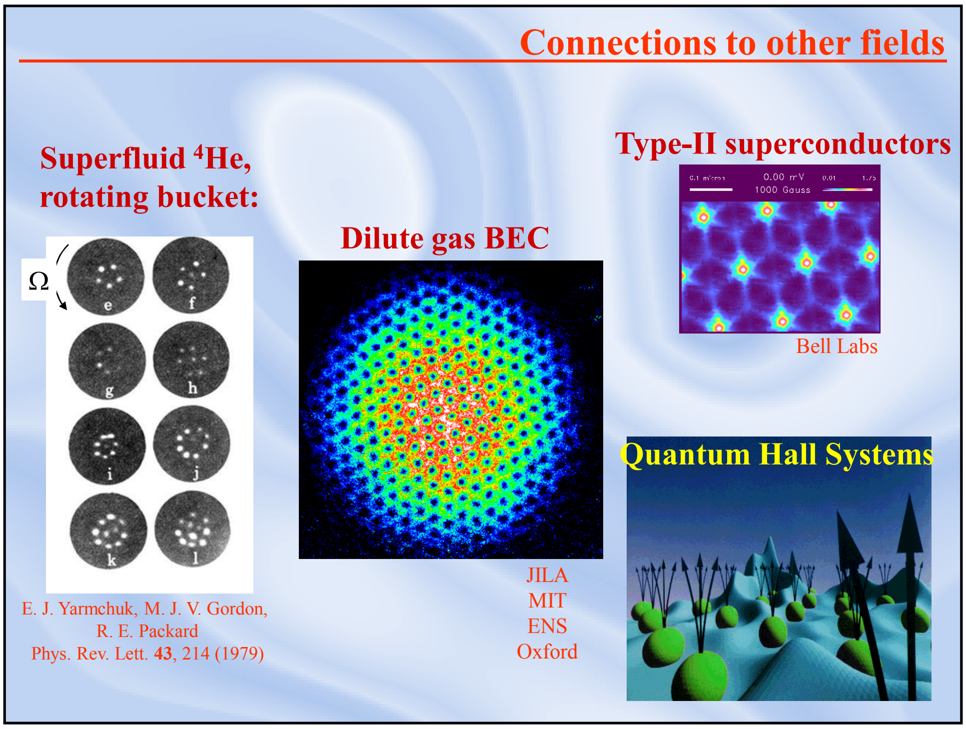


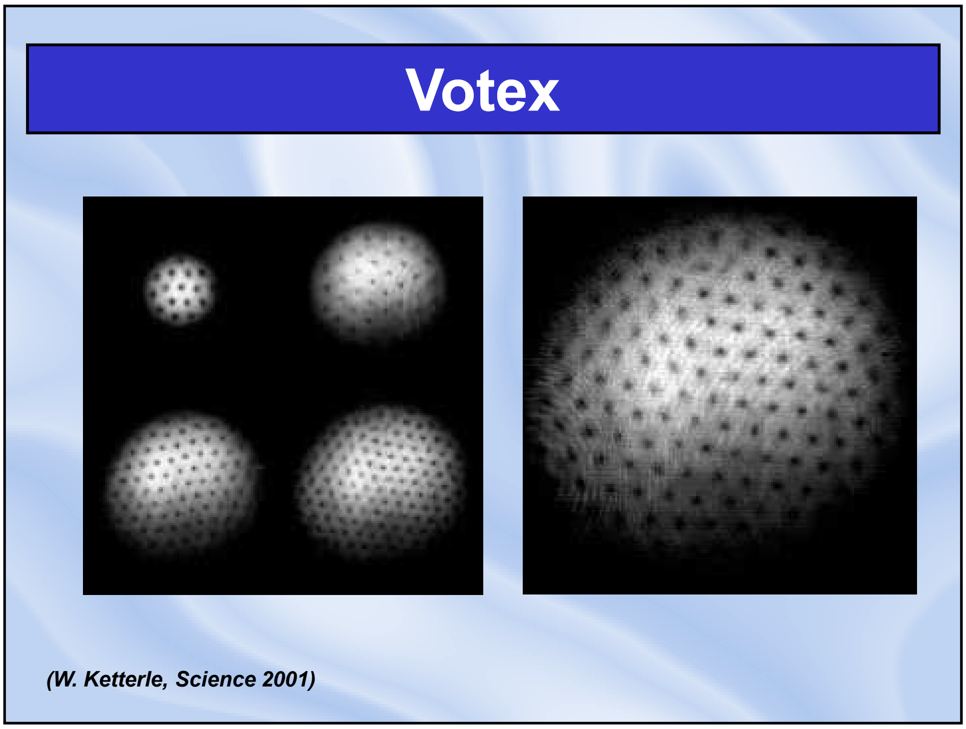
Ketterle (Nature, 1999)

Supperradiant Rayleigh scattering



(W. Ketterle, Science 1999)


Connections to other fields
Superfluid ^{4}He,
rotating bucket:
Ω
E. J. Yarmchuk, M. J. V. Gordon,
R. E. Packard
Phys. Rev. Lett. **43**, 214 (1979)
Dilute gas BEC
JILA
MIT
ENS
Oxford
Type-II superconductors
Bell Labs
Quantum Hall Systems


Votex
(W. Ketterle, Science 2001)

How to observe vortex

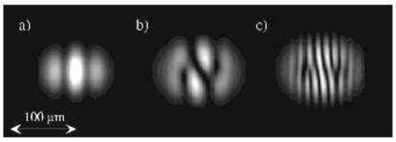


FIG. 2. Expected fringe pattern of a Bose-Einstein condensate initially splitted into two parts and undergoing a free expansion phase. Figure (a) is without a vortex and (b,c) are with a vortex. For (b), close to our experimental conditions, the fringe spacing x_s is equal to 39 μm, and it is equal to the separation of the vortex cores after expansion $|\mathbf{r}_1 - \mathbf{r}_1'|$. (c) same as (b), with a fringe spacing $x_s = 13\ \mu\text{m} = |\mathbf{r}_1 - \mathbf{r}_1'|/3$ (this fringe spacing is too small to be detected in our experimental setup). For (b) and (c), the relative phase of the two condensates is π.

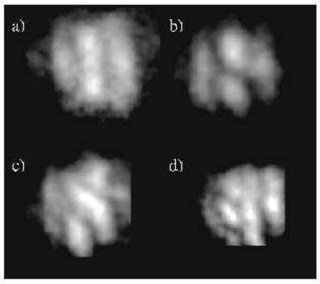


FIG. 4. Interference pattern measured in the $m = +2$ channel with no (a), one (b) and (c), and several (d) vortices. For these pictures, $\tau_1 = 0.688$ ms and $\tau_2 = 1.320$ ms. The stirring frequency was set to $\Omega = 2\pi \times 125$ Hz (a), $\Omega = 2\pi \times 130$ Hz (b-c), and $\Omega = 2\pi \times 154$ Hz (d). The patterns (b) and (c) were recorded with the same initial conditions, and the change in the interference pattern results from a change in the relative phase of the two parts of the condensate.

J. Dalibard, 2001

Solitons

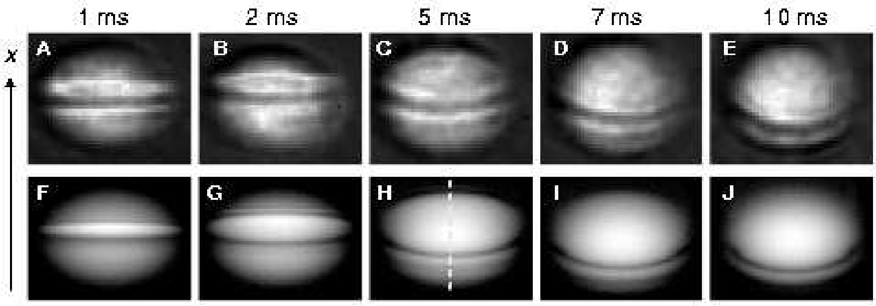
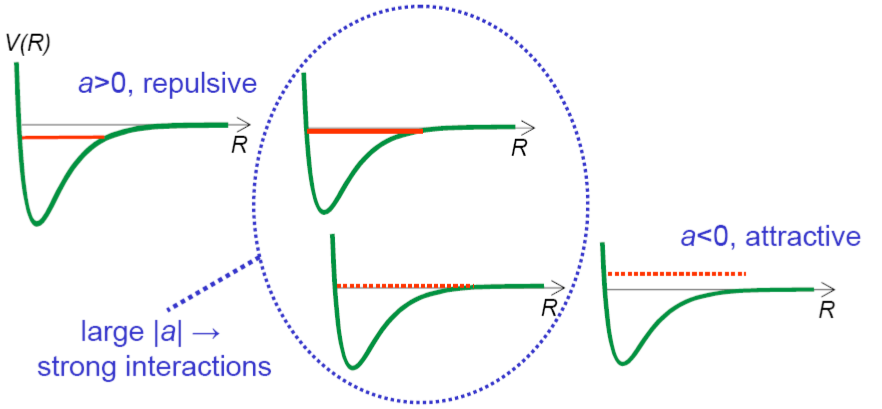


Fig. 3. Experimental (A to E) and theoretical (F to J) images of the integrated BEC density for various times after we imprinted a phase step of $\sim 1.5\pi$ on the top half of the condensate with a 1-μs pulse. The measured number of atoms in the condensate was 1.7 (± 0.3) $\times 10^6$, and this value was used in the calculations. A positive density disturbance moved rapidly in the $+x$ direction, and a dark soliton moved oppositely at significantly less than the speed of sound. Because the imaging pulse (27) is destructive, each image shows a different BEC. The width of each frame is 70 μm.

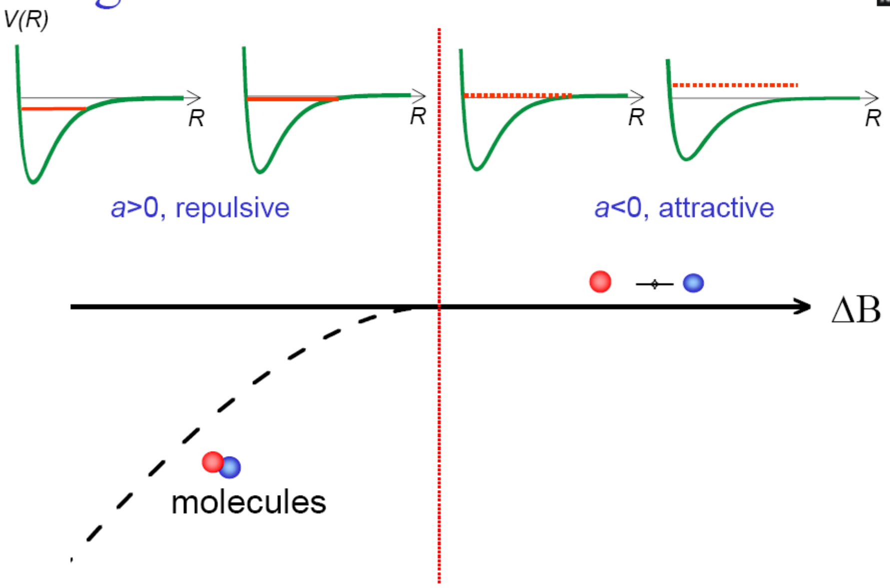
(Phillips, Science 1999)

Controlling interactions

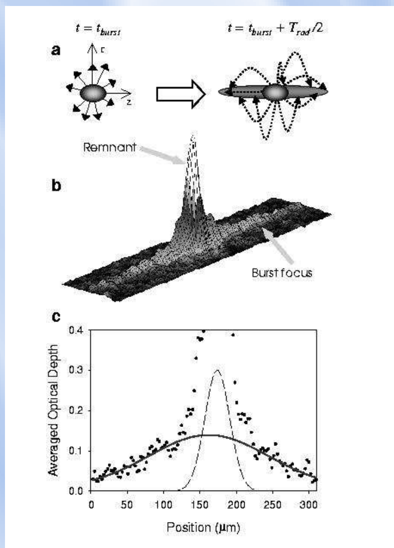
- Interactions are characterized by the s-wave scattering length, *a*
- *a* depends sensitively on the depth of the potential

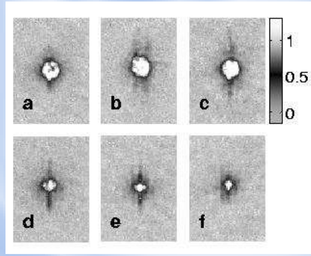


Magnetic-field Feshbach resonance



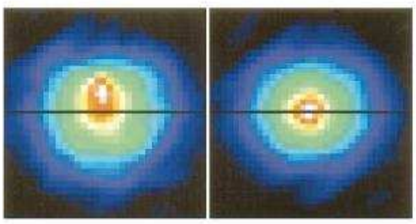
Bose Nova





(E.A. Cornell, C.E. Wieman, Nature 2001)

Sympathetic cooling



(a) (b)

FIG. 3(color). Two 475 μm by 475 μm false-color absorption images of $|2,2\rangle$ atoms. (a) A cloud of two overlapping condensates illuminated so that only the $|2,2\rangle$ state atoms are visible. The condensate (white, red, and yellow) is shifted upwards relative to the center of the thermal uncondensed cloud (green, blue, and purple) due to interactions with the $|1,-1\rangle$ condensate ($|1,-1\rangle$ atoms not visible). (b) A cloud of pure $|2,2\rangle$ atoms cooled to a comparable temperature as in (a). The black line is a guide to the eye going through the center of both thermal clouds.

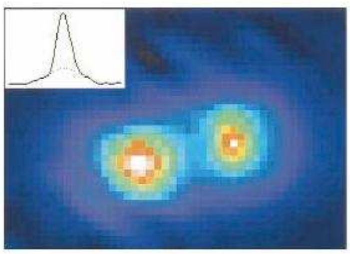
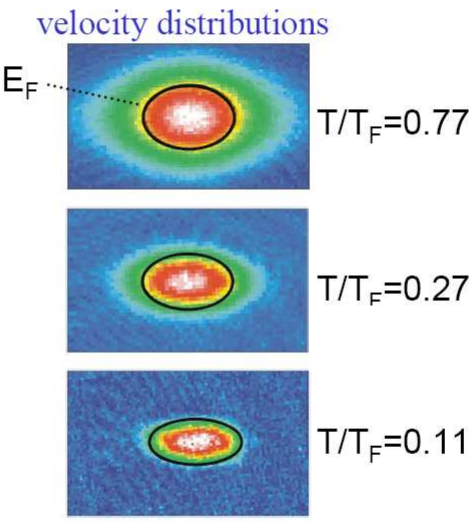
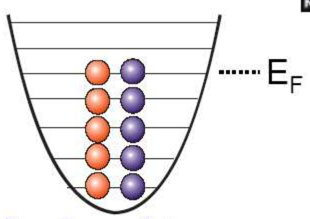


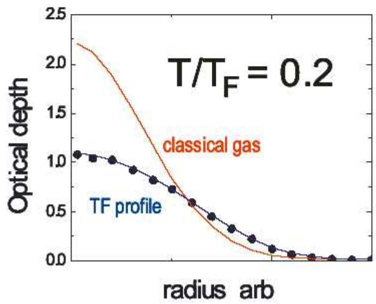
FIG. 2(color). A false-color absorption image (475 μm by 675 μm) showing condensates of both $|2,2\rangle$ (left) and $|1,-1\rangle$ (right) states that were created simultaneously by sympathetic cooling. The condensates are separated because the trap axis was tilted 40 mrad to produce a component of the gravitational force along the weak spring constant direction. The noncondensed parts of the clouds (purple and dark blue) still overlap. The shape of both of the condensates is a function of expansion time, but the difference in their ellipticities reflects the fact that they have different initial confinements and therefore expand at different rates. The inset shows a vertical trace through the cloud on the left. The dotted line is to guide the eye in distinguishing the broad thermal background from the narrow condensate peak.

(E.A. Cornell, C.E. Wieman 1997)

Quantum degeneracy







Eric Cornell

Eric Cornell received the 2001 Nobel Prize in Physics for his currently a JILA Fellow, a staff member at NIST (Boulder), and Adjoint Professor in the Physics Department at the University of Colorado at Boulder

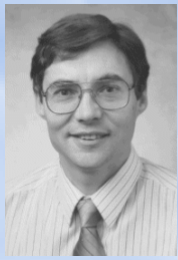
Cornell was co-leader of the research team that was the first to observe a Bosse-Einstein condensate of magnetically trapped atoms in June, 1995. This team has, since then, significantly contributed to the understanding of the geometric, thermodynamic, and mechanical properties of cold-atom Bose-Einstein condensates. Cornell recived his BS degree from Stanford University and, in 1990, his Ph.D from MIT Past awards include the Stratton Award (1995), the Carl Zeiss Award (1996), the Fritz London Prize(1996), the LI Rabi Prize (1997), and the King Faisal International Prize (1997)

Wolfgang Ketterle

Wolfgang Ketterle received the 2001 Nobel Prize for Physics for his contributions to the understanding of Bose-Einstein condensates. Since 1995, Ketterle and his group have developed novel techniques for probing condensates such as non-destructive imaging and optical trapping; have pioneered methods for better condensate confinement; and have studied important BEC topics such as condensate formation and manipulation.

Ketterle received his diploma thesis from the Technical Univ. of Munich in 1982, working on theoretical solid-state physics. Under the direction of Professor Herbert Walther at the University of Munich, he received his PhD in 1986, studying experimental molecular spectroscopy. His postdoctoral work included laser spectroscopy of molecules at the Max-Planck Institute for Quantum Optics in and Combustion diagnostics in Geidelberg. In 1990, he joined Professor David Pritchard's group in RLE as a postdoctoral associate. Ketterle was appointed to the MIT faculty in the Department of Physics as an assistant professor in 1993, and his promotion to full professor was recently announced.

Carl Wieman



Carl Wieman received the 2001 Nobel Prize in Physics for his work on cold-atom Bose-Einstein condensation. Wieman is currently Professor of Physics at the University of Colorado aswell as a JILA Fellow.

Wieman's research has involved the use of lasers and atoms to explore fundamental problems in physics. His group has carried out a variety of precise laser-spectroscopy measurements including the most accurate measurements of parity nonconservation in atoms. He also has investigate the physics of ultracold atoms. In collaboration with Eric Cornell, Wieman developed the cooling techniques that allowed them to create the first Bose-Einstein condensate in an atomic vapor. Much of Wieman's recent research has involved the study of condensate properties and improved ways to create and study condensates. He also continues to investigate novel techniques for improved optical trapping and cooling of atoms.