Introduction to experiments in ultracold atomic gases

Introduction to BEC & superfluidity

Francesca Maria Marchetti

UAM
UNIVERSIDAD AUTONOMA
DE MADRID

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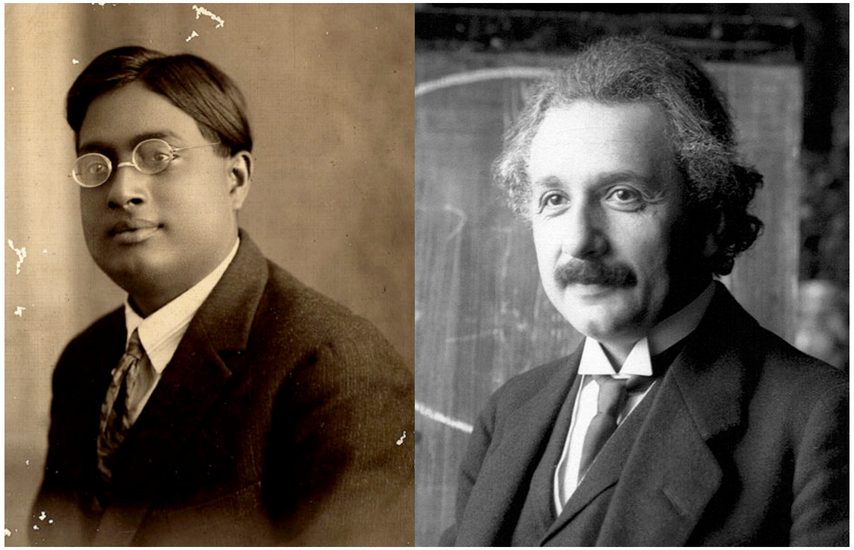
BEC: from 1925 to 1995

- 1924/1925

Following the work of Bose on the statistical description of light quanta, Einstein predicted that a gas of non-interacting massive bosons, below a critical temperature, undergoes a phase transition associated with the condensation of the atoms in the lowest energy state: Bose-Eistein condensation (BEC)



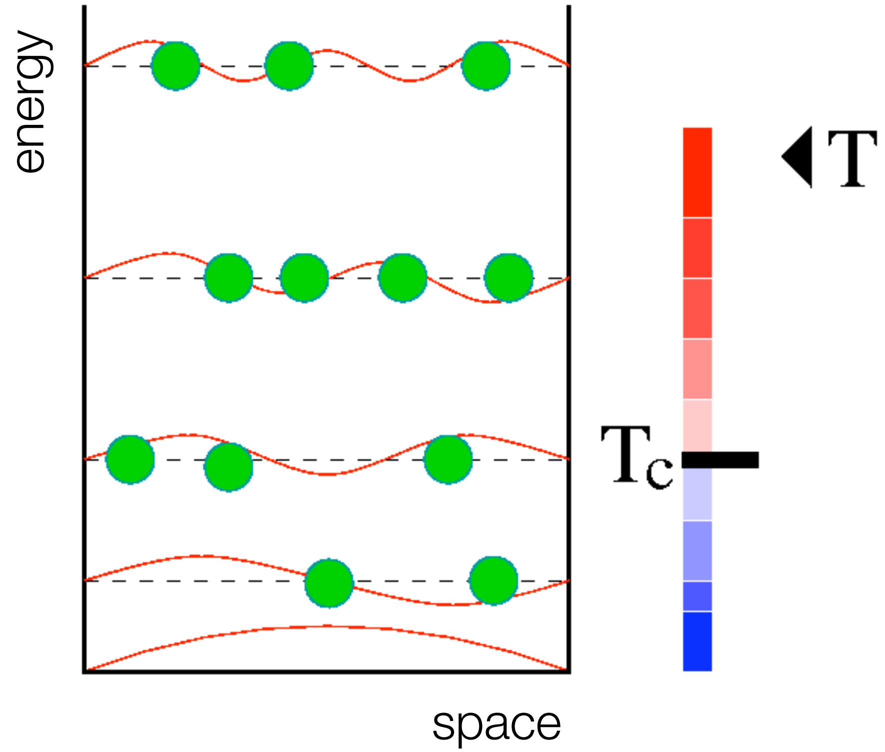
Satyendranath Bose Albert Einstein

"…A separation is affected; some part condenses, the rest remains a 'saturated ideal gas'…"

"…condensation without attractive forces…"

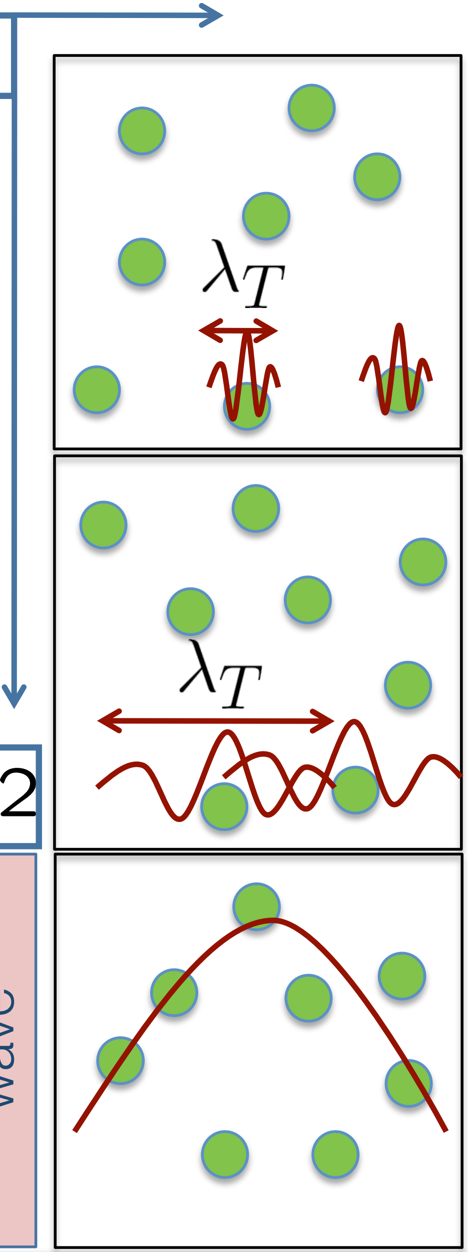
Link to animation

Macroscopic occupation of the ground state



High temperatures: billiard balls

lowering T



$$\lambda_T = \left(\frac{2\pi\hbar^2}{mk_BT}\right)^{1/2}$$

$$n\lambda_T^3 \geq 2.612$$

Giant matter-wave

Quantum-statistical phase transition
(it occurs even in absence of
interactions)

BEC

NON INTERACTING
IDEAL BOSE GAS

⇒ paradigm of quantum statistical mechanics

- indistinguishability
- wave nature of particles
- thermal equilibrium

⇒ macroscopic quantum phenomena

- macroscopic wavefunction (many-body ground state wf is the product of N indentical single-particle ground-state wfs)
- similarly for weak interactions (quantum depletion = 1% for alkali condensates)

BEC vs. Superfluidity

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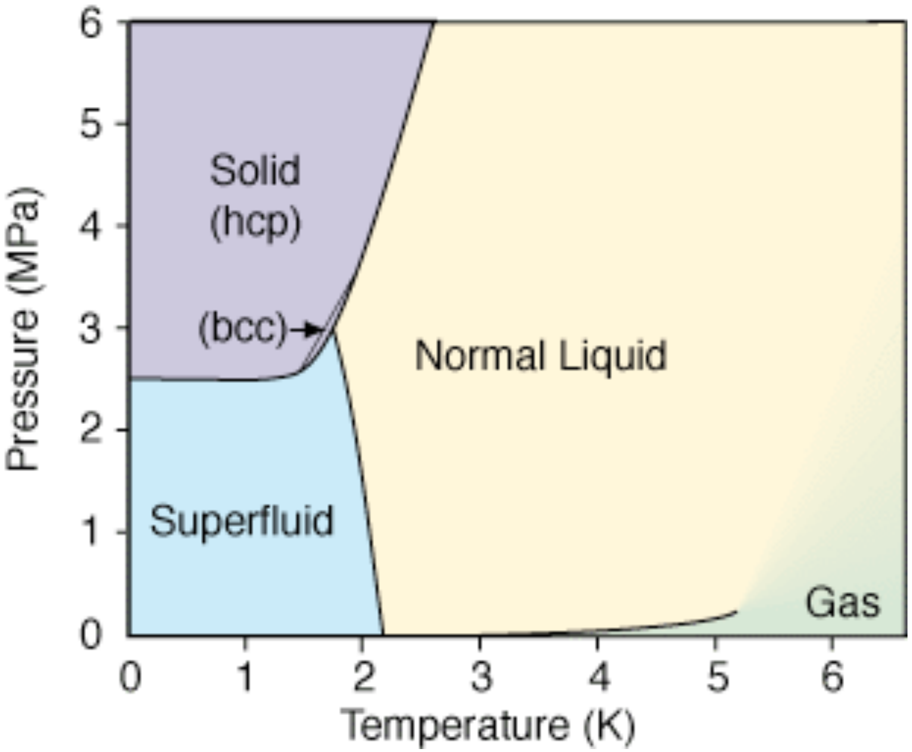
BEC: from 1925 to 1995

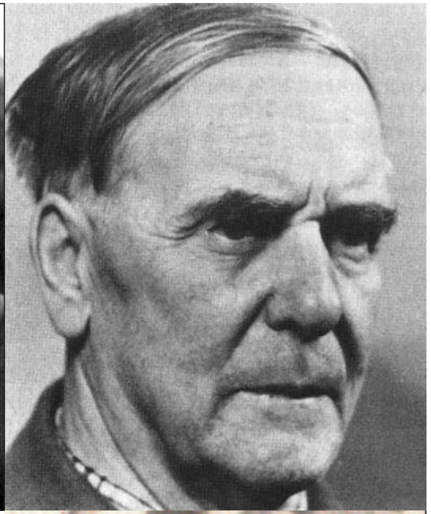
- <u>1938</u> Discovery of superfluidity in liquid helium ^{4}He (Allen & Misener; Kapitza).

What's the relation between BEC & superfluidity?



Peter L. Kapitza

Jack Allen



Don Misener

BEC: from 1925 to 1995

- 1938 Discovery of superfluidity in liquid helium ^{4}He (Allen & Misener; Kapitza).

What's the relation between BEC & superfluidity?

- Immediately after, London suggested the connection between the superfluidity of ^{4}He and BEC

⇒ first to bring out the idea of BEC displaying quantum behaviour on a macroscopic scale

- controversial issue for decades

The theory of superfluidity of Landau does not explicitly mention BEC!

- E.g., Landau's criterion

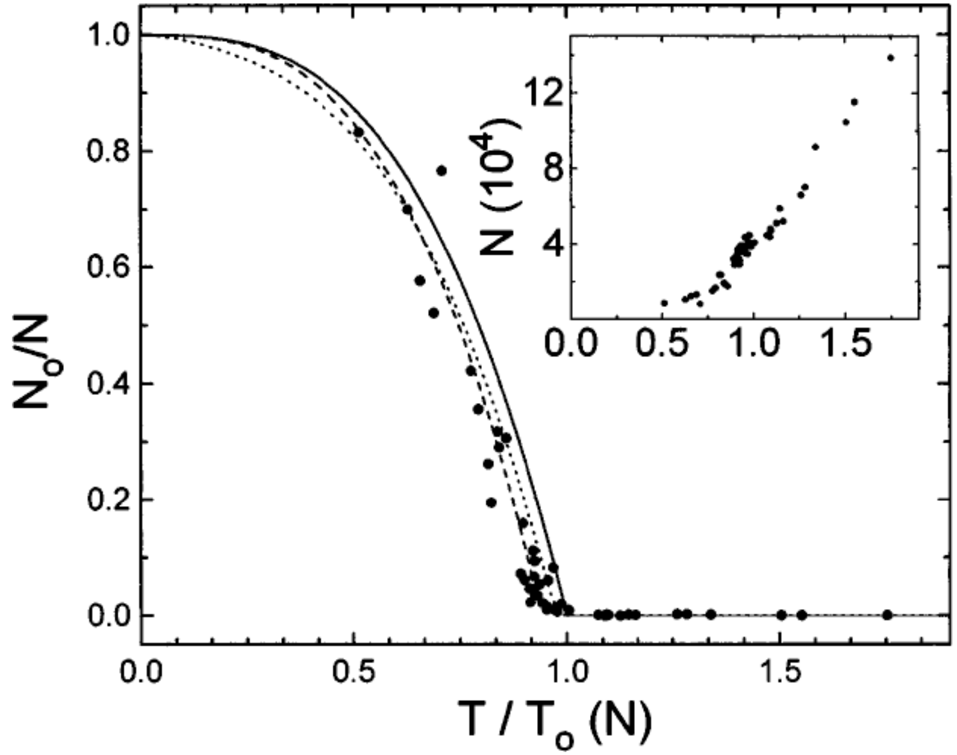
$$v_c = min \frac{E_p}{p}$$

Fritz London

Condesate fraction

Ultracold gases of bosonic atoms

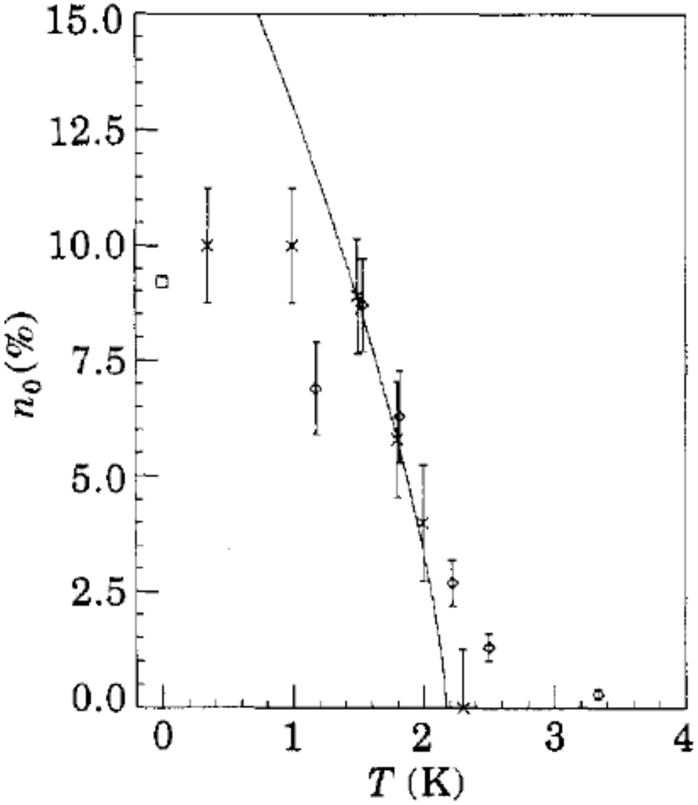
condensate fraction in a BEC of Rubidium ultracold atoms (rather good agreement with predictions for an ideal Bose gas model)



[J. R. Ensher *et al.*, PRL **77**, 4984 (1996)]

Superfluid ^{4}He

condensate fraction in superfluid 4He at constant density



[W.M. Snow *et al.*, Europhys. Lett **19**, 403 (1992)]

BEC: from 1925 to 1995

- 1947 microscopic theory of interacting Bose gases (Bogoliubov)

$$E_p = \sqrt{\epsilon_p(\epsilon_p + 2gn)}$$

…provides the microscopic picture behind Landau's theory

Nikolai N. Bogoliubov

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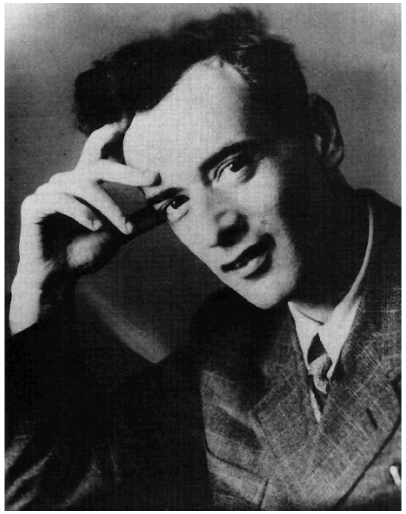
…provides the microscopic picture behind Landau's theory

- 1951 off-diagonal long range order (Landau&Lifshitz; Penrose)

- and much more theoretical work…

QUEST TO REALISE A BEC:
Search of weakly interacting Bose gases

Nikolai N. Bogoliubov



Lev D. Landau

BEC vs. Superfluidity

NON INTERACTING IDEAL BOSE GAS

⇒ paradigm of quantum statistical mechanics

- indistinguishability
- wave nature of particles
- thermal equiibrium

⇒ macroscopic quantum phenomena

- macroscopic wavefunction (many-body ground state wf is the product of N indentical single-particle ground-state wfs)
- similarly for weak interactions (quantum depletion = 1% for alkali condensates)

IDEAL BECs ARE NOT SUPERFLUID

INTERACTING BOSE GAS

⇒ mainly related to transport phenomena (flow without friction)

- is essential the form of the dispersion of the elementary excitations (Landau criterion)

$$\boxed{E_p = \sqrt{\epsilon_p(\epsilon_p + 2gn)}} \qquad \boxed{v_c = min\frac{E_p}{p}}$$

- interactions are essential (change the dispersion to phonon-like)
- superfluidity is possible even with few% of atoms in the ground state (see ^{4}He)

LINK BETWEEN BEC & SUPERFLUIDITY: ORDER PARAMETER and ODLRO

BEC vs. Superfluidity

NON INTERACTING
IDEAL BOSE GAS

INTERACTING
BOSE GAS

Ideal Bose-Einstein condensates are not superfluid, but also there are superfluid systems that do not display Bose-Einstein condensation (e.g., 2D)

IDEAL BECs ARE NOT SUPERFLUID

LINK BETWEEN BEC & SUPERFLUIDITY: ORDER PARAMETER and ODLRO

BEC in other systems

- BEC is involved in several macroscopic quantum phenomena (even if some systems are not ideal Bose gases):

macroscopic occupation of a single quantum state

⇒ ^{4}He (but is a strongly interacting system)

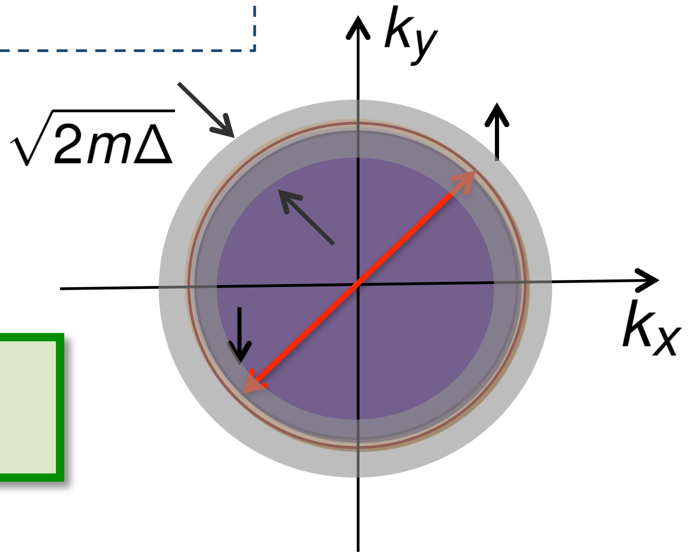
⇒ superconductors (BEC of Cooper pairs)

(the BEC-BCS crossover)

⇒ ^{3}He (also fermions)

⇒ lasers (but out of equilibrium: requires inversion of the population)

⇒ …



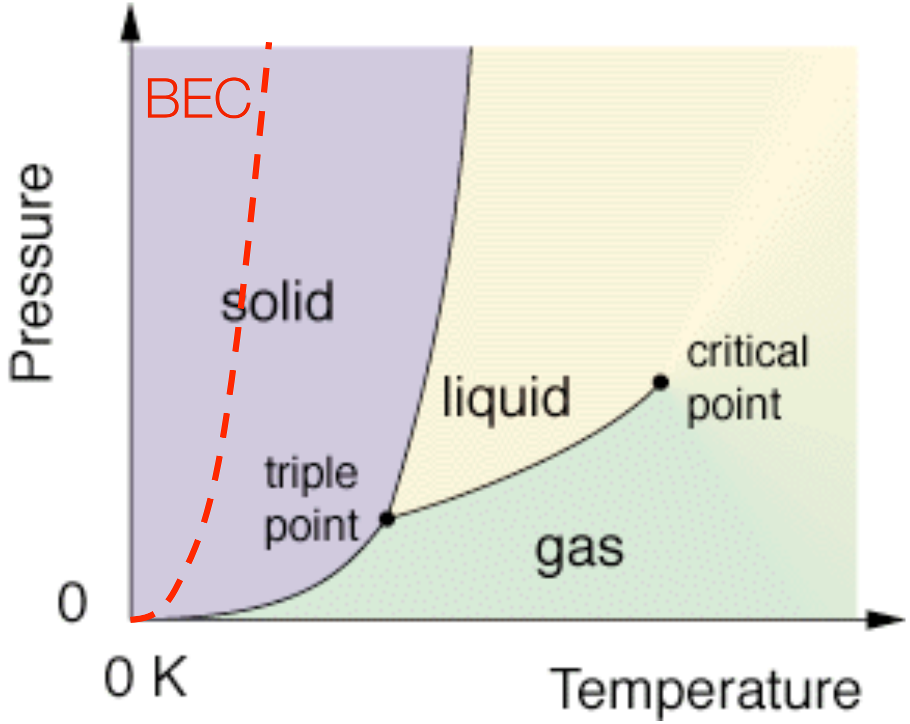
QUEST TO REALISE A BEC:
Search of weakly interacting Bose gases

Searching for weakly interacting Bose gases

Why so hard?

⇒At very low T most substances are solid (or liquid) & interaction becomes large

- The pressure versus temperature phase transition line for BEC falls into the region where the equilibrium phase is a solid



$$P = \frac{2E}{3V} \simeq \left(\frac{m}{2\pi}\right)^{3/2} (k_B T)^{5/2}$$

A BEC (in the true chemical thermal equilibrium) is unstable

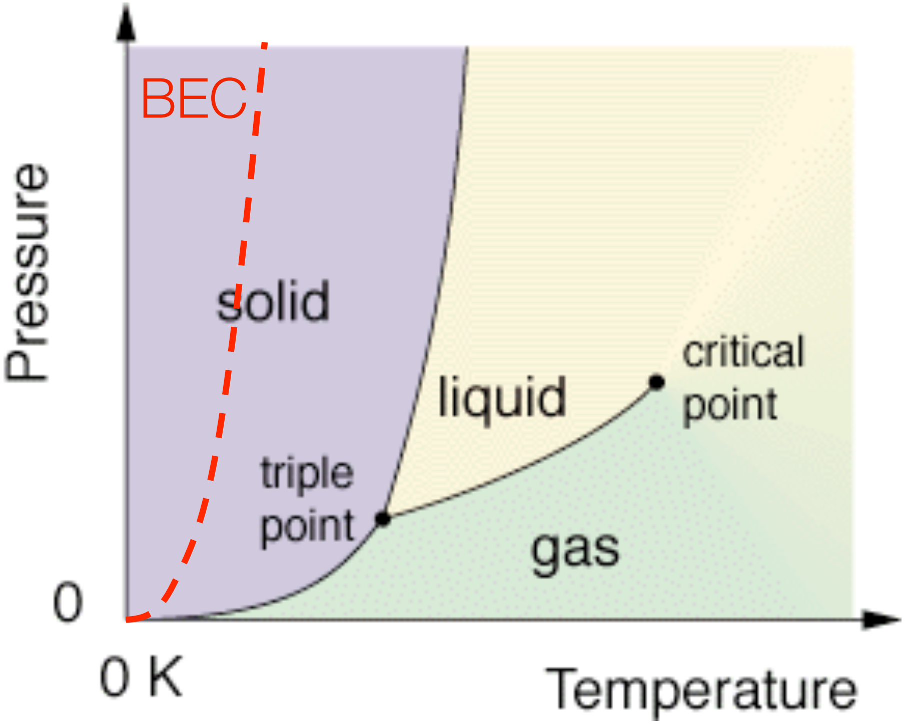
Why dilute and why ultracold

1. metastable equilibrium

$$\tau_3 \ll \tau_2$$

(3-body recombination rate << 2-body scattering rate)

- Towards the formation of a solid: of the three atoms colliding, two form a molecule and the third one can carry away the residual energy



$$\tau_3 \sim n^3 \ll \tau_2 \sim n^2$$

possible at very low densities

- Still 2-body interactions can guarantee kinetic thermal equilibrium

Why dilute and why ultracold

1. metastable equilibrium: requires the gas to be diluted

$$\boxed{n \sim 10^{13} - 10^{15}\mathrm{cm}^{-3}}$$

⇒ the gas has a finite lifetime of the order between seconds and minutes, after which it becomes a solid

2. quantum degeneracy: requires the gas to be ultracold

$$\boxed{T \sim 100\mathrm{nK} - \mu\mathrm{K}}$$

$$n\lambda_T^3 = n\left(\frac{2\pi\hbar^2}{mk_BT}\right)^{3/2} > 2.61$$

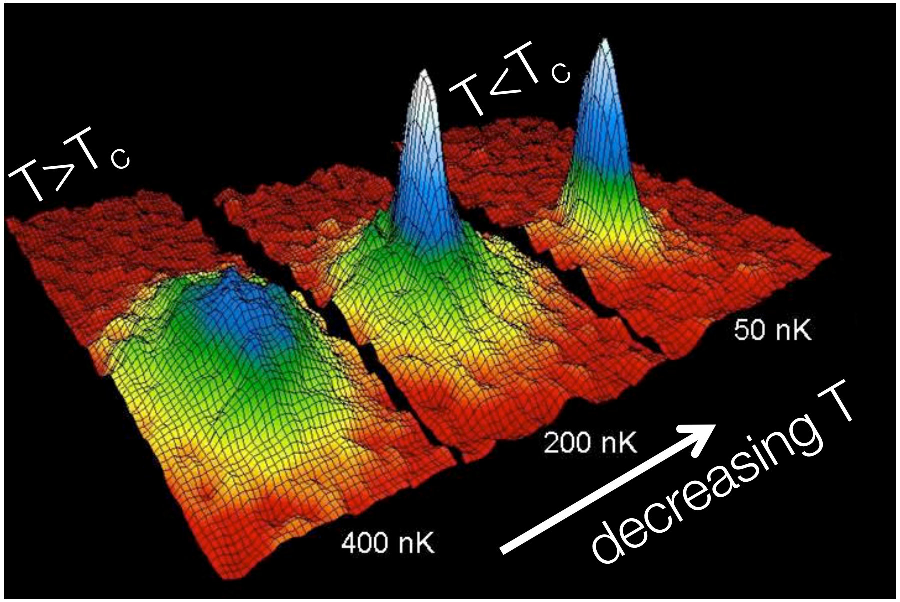
3. Trapping (atoms must be thermally isolated from all material walls)

⇒ Necessity of very sophisticated cooling and trapping techniques

From 1925 to 1995:
it took 70 years to realise a BEC in dilute atomic gases

BEC: from 1925 to 1995

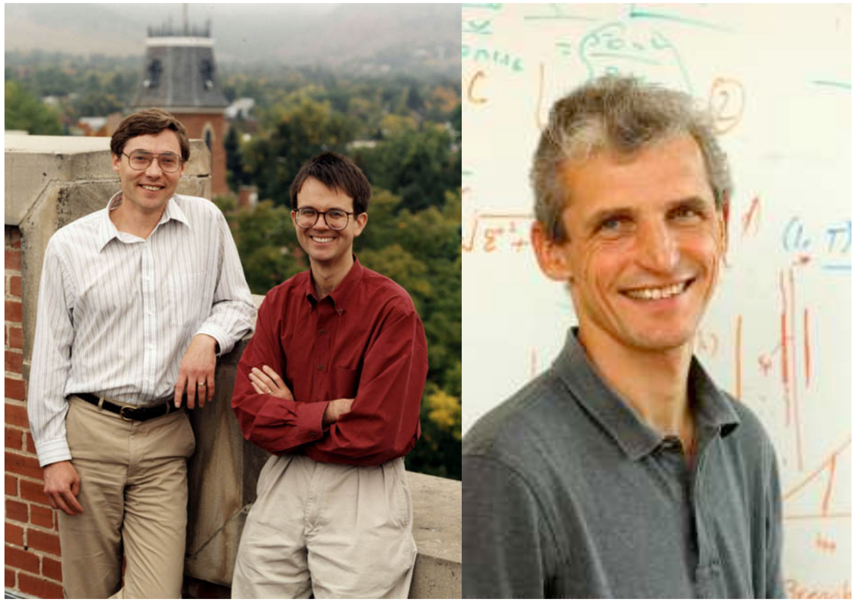
- 1995 BEC in alkali atoms (^{87}Rb, ^{23}Na, ^{7}Li, …)



Coolest system in the universe!

$$T \sim 500\text{nK} - \mu\text{K}$$
$$n \sim 10^{11} - 10^{13}\text{cm}^{-3}$$

Nobel prize (2001)

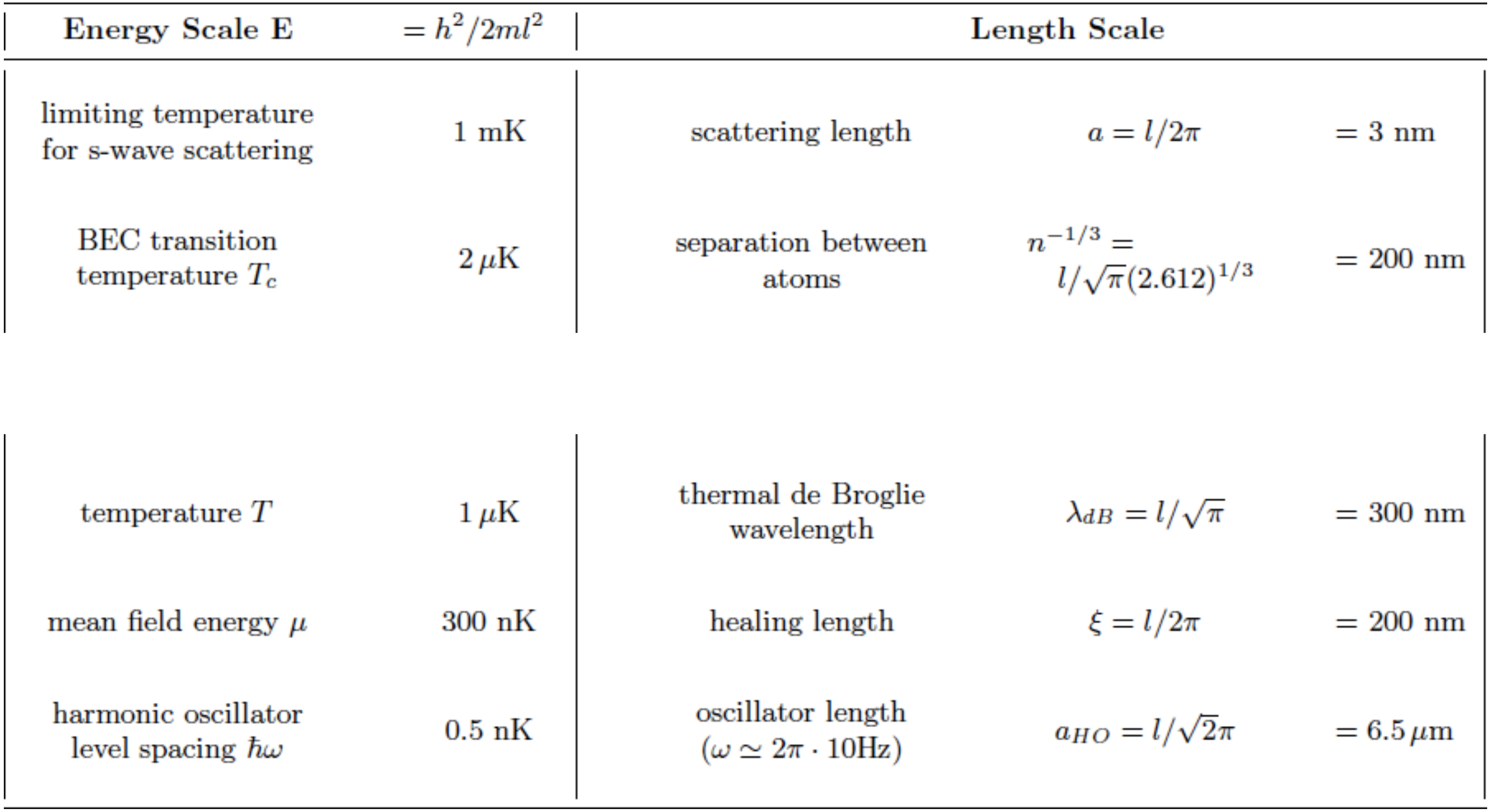


Carl Wieman & Eric Cornell   Wolfgang Ketterle

Hierarchy of energy and length scales

⇒ Simplifies the description of BECs

$n \sim 10^{14}\text{cm}^{-3}$



Energy Scale E	$= h^2/2ml^2$	**Length Scale**		
limiting temperature for s-wave scattering	1 mK	scattering length	$a = l/2\pi$	$= 3$ nm
BEC transition temperature T_c	$2\,\mu$K	separation between atoms	$n^{-1/3} = l/\sqrt{\pi}(2.612)^{1/3}$	$= 200$ nm
temperature T	$1\,\mu$K	thermal de Broglie wavelength	$\lambda_{dB} = l/\sqrt{\pi}$	$= 300$ nm
mean field energy μ	300 nK	healing length	$\xi = l/2\pi$	$= 200$ nm
harmonic oscillator level spacing $\hbar\omega$	0.5 nK	oscillator length ($\omega \simeq 2\pi \cdot 10$Hz)	$a_{HO} = l/\sqrt{2}\pi$	$= 6.5\,\mu$m

New window into the quantum world

⇒ At first, interest was to realise a BEC as close as possible to the ideal case

⇒ rapid development since the achievement of the first BEC (1995) has been breathtaking

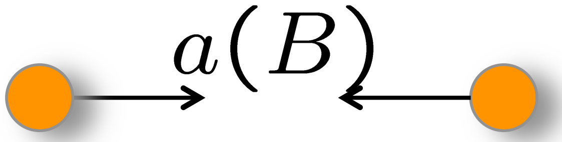
⇒ Ultracold atoms became ideal model systems for a host of phenomena:

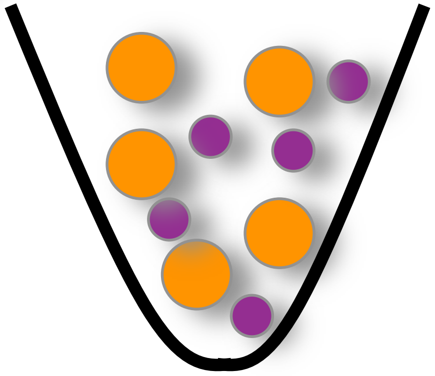
- Diluteness = absence of not well understood interactions
- Control
- Manipulation
- Precise probe
    - ✓ Tune the interaction strength (e.g., Feshbach resonances)
    - ✓ Bosons, fermions, mixtures
    - ✓ Simulate crystals (optical lattices)
    - ✓ Reduced dimensions (2D, 1D, 0D)
    - ✓ Disorder
    - ✓ …

⇒ Special role of cold atom experiments: perform “quantum simulations” of condensed matter systems

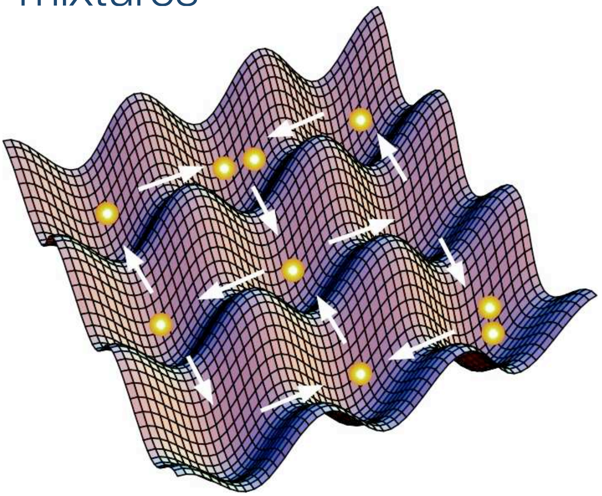
Ultracold atoms today

- Tune the interaction strength (Feshbach resonances)

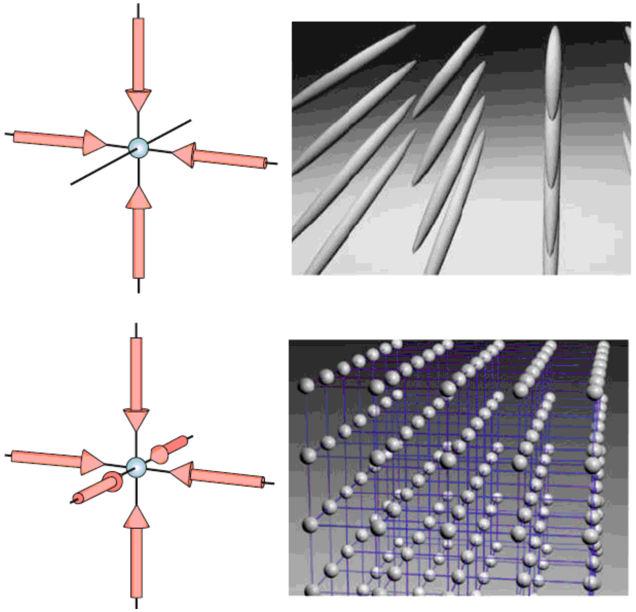




- Bosons, Fermions, mixtures
- Optical lattices



- Reduced dimensions (2D, 1D, 0D)
- Disorder

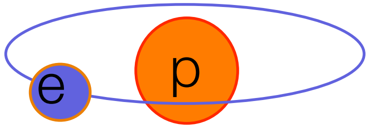


[Bloch *Nature Physics* (2005)]

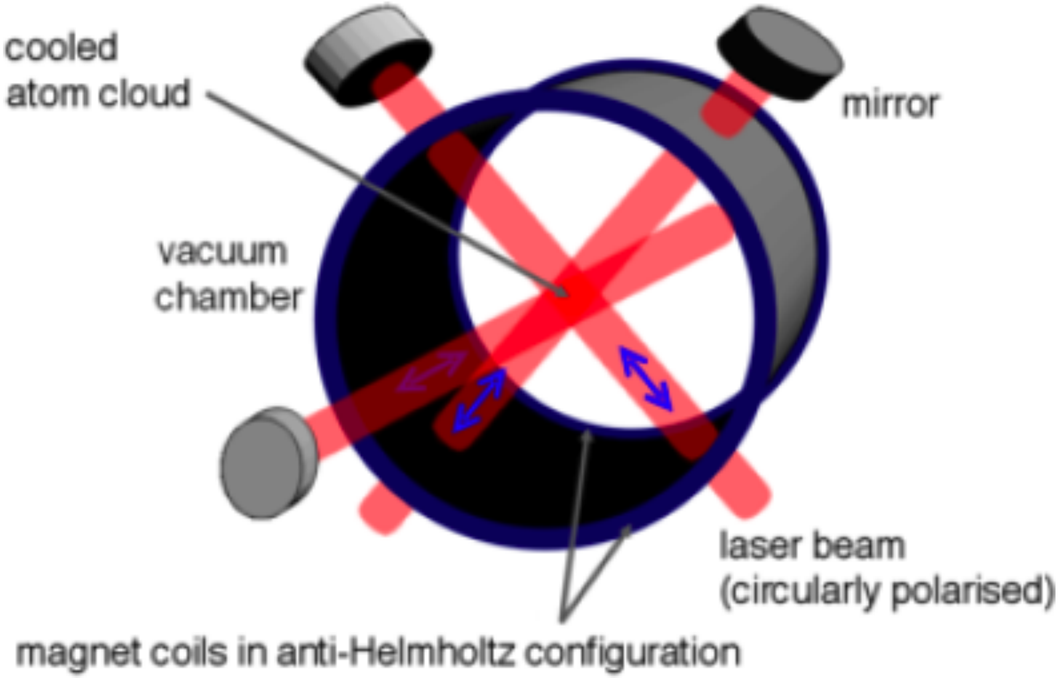
Simulate solid state systems
(with advantage of external control)

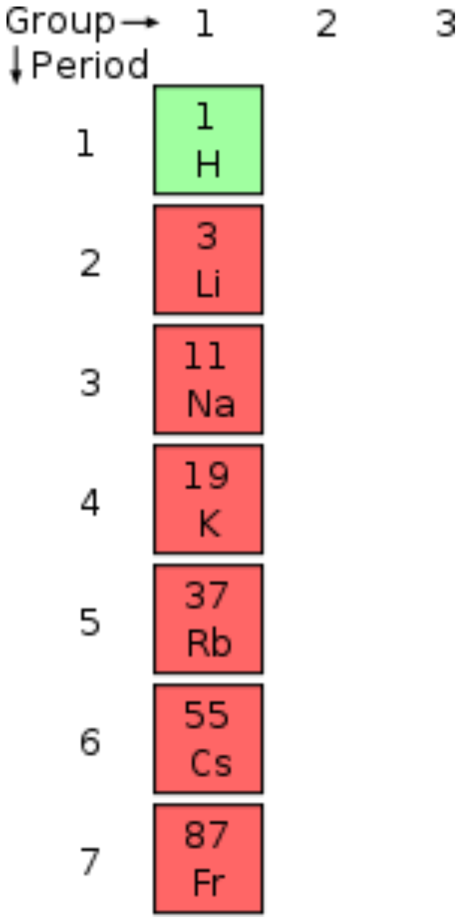
Dilute ultracold atomic gases: Experiments

- 1959 spin-polarized (by a magnetic field) hydrogen proposed as a good candidate for a weakly interacting Bose gas



- ’80 Developments in magnetic trapping, laser and evaporative cooling of alkali atoms

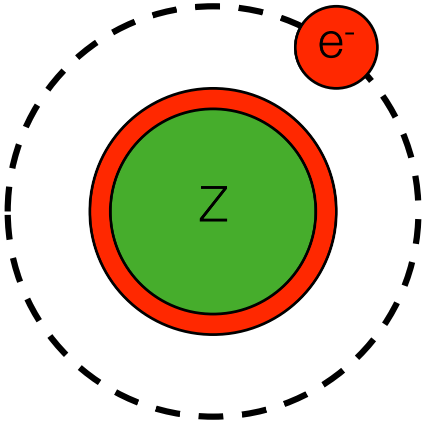




Group→ ↓Period	1	2	3
1	1 H		
2	3 Li		
3	11 Na		
4	19 K		
5	37 Rb		
6	55 Cs		
7	87 Fr		

Alkali atoms

- Electronic spin S=J=1/2, nuclear spin I
- Z odd (neutral atoms = same number of electrons and protons)
- N determines the statistics
  - A=Z+N odd for bosons (N even)
  - A=Z+N even for fermions (N odd)

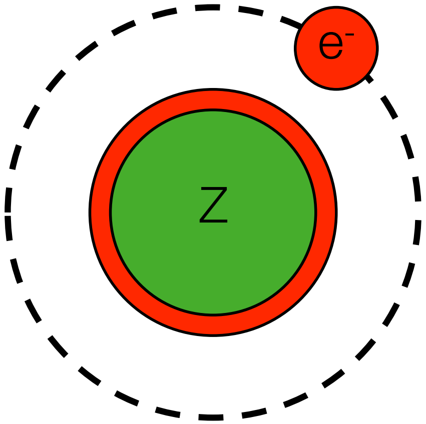


bosons	^{85}Rb	I=5/2
	^{87}Rb	I=3/2
	^{23}Na	I=3/2
	^{7}Li	I=3/2
fermions	^{40}K	I=4
	^{6}Li	I=1

At very low temperatures atoms are in their electronic ground state ($\ell = 0$).

The internal states are the hyperfine states

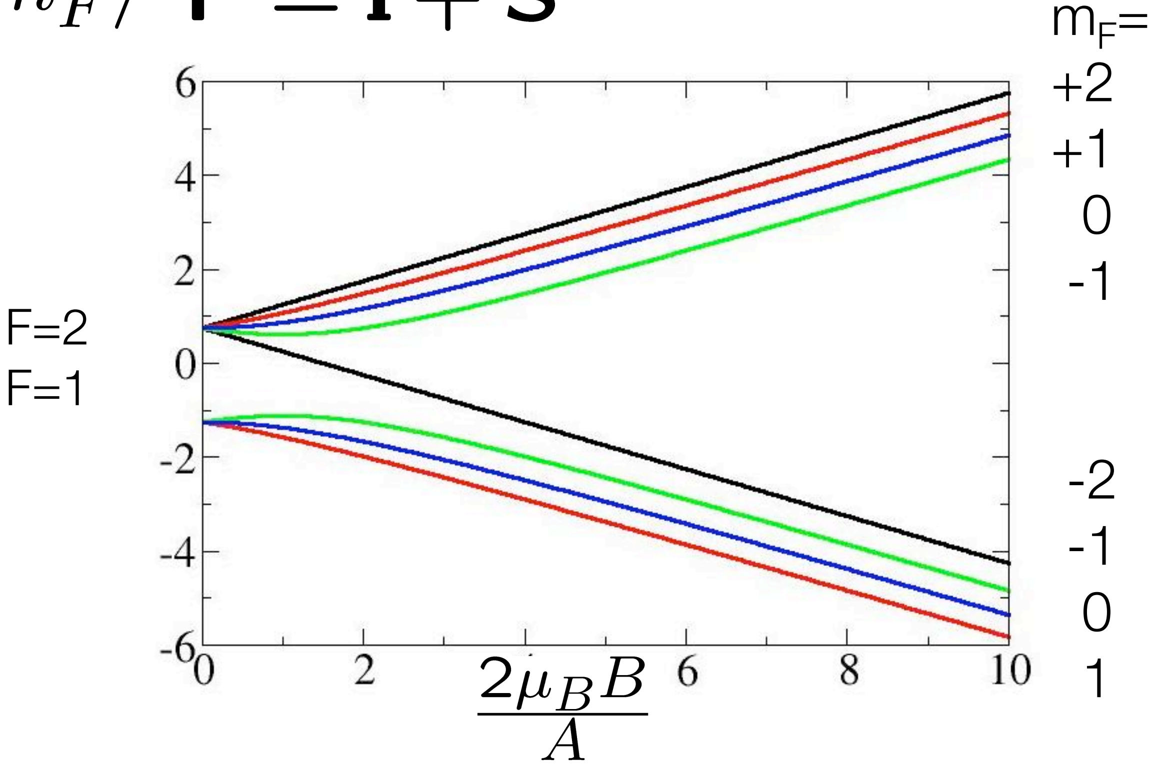
Hyperfine levels and Zeeman splitting



- Electronic spin S=J=1/2, nuclear spin I

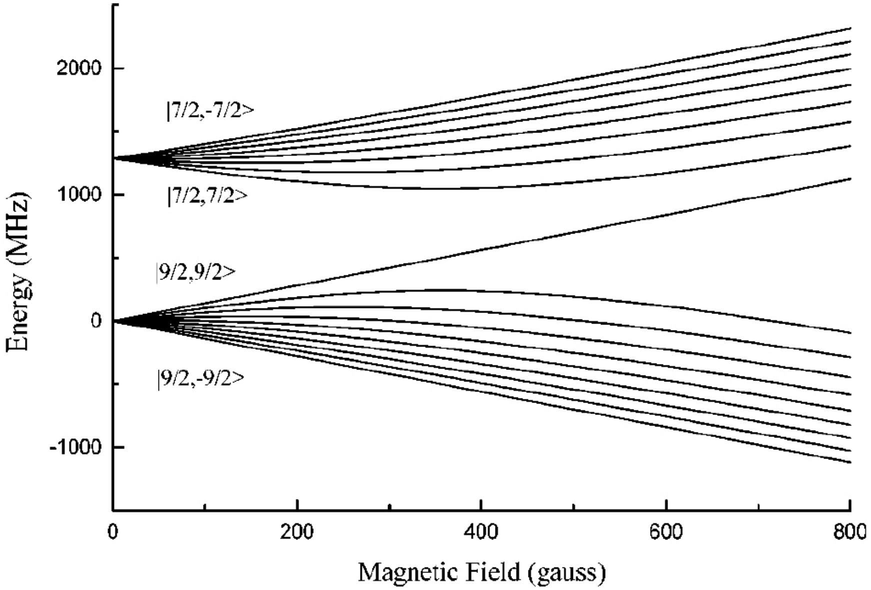
$$\hat{H} = A\hat{\mathbf{I}}\cdot\hat{\mathbf{S}} + 2\mu_B B \hat{S}_z$$

- Hyperfine levels $|F, m_F\rangle$ $\hat{\mathbf{F}} = \hat{\mathbf{I}} + \hat{\mathbf{S}}$
- I=3/2 (^{87}Rb, ^{23}Na, ^{7}Li)

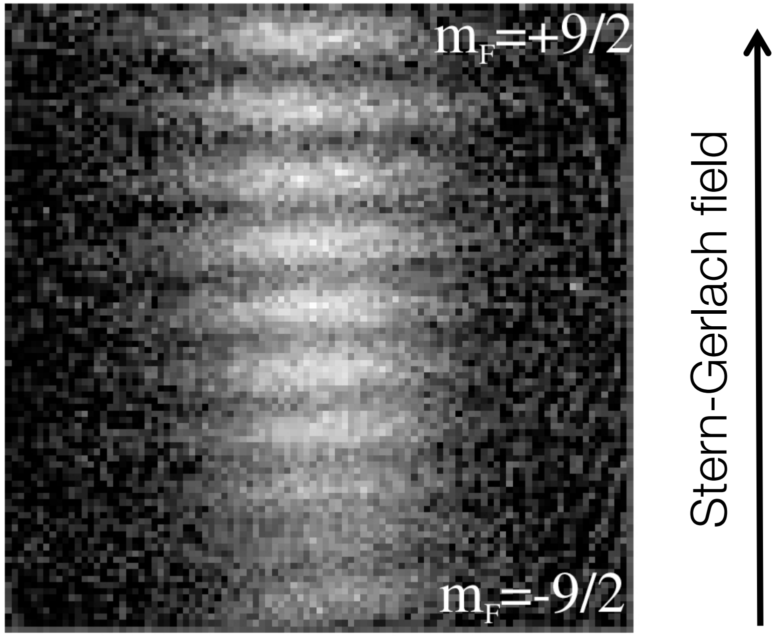


Hyperfine levels and Zeeman splitting

- I=4 (^{40}K)



[J. L. Bohn *et al.* *PRA* **59**, 3660 (1999)]

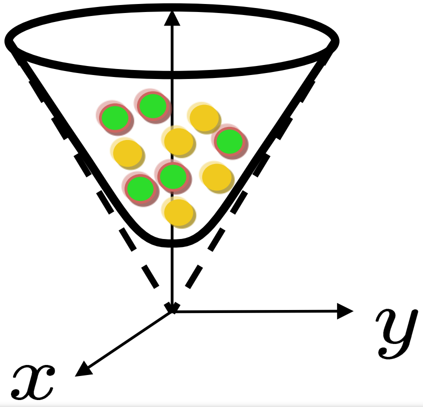


[T. Loftus *et al.* *PRL* **88**, 173201 (2002)]

1. Control the populations of atoms in different hyperfine states

2. Magnetic trapping

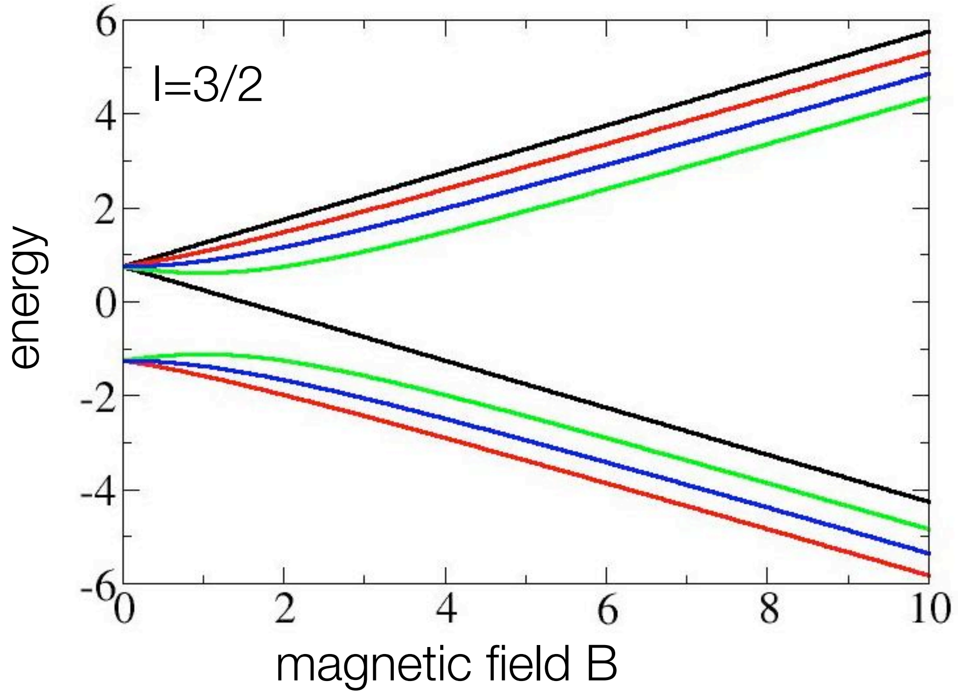
$$\Delta E_{\text{hyp}} \gg k_B T$$



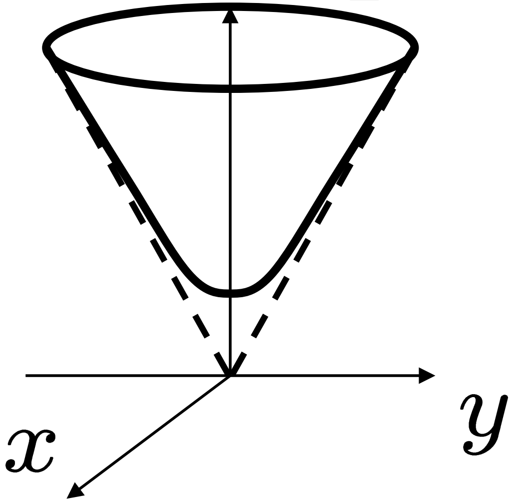
Trapping the atoms magnetically

- $\mu_\alpha > 0$ high-field seeking states
- $\mu_\alpha < 0$ low-field seeking states

$$\boxed{E_\alpha \simeq \text{const} - \mu_\alpha B}$$



$$V(\mathbf{r}) = \frac{1}{2}\bar{\omega}^2 r^2$$



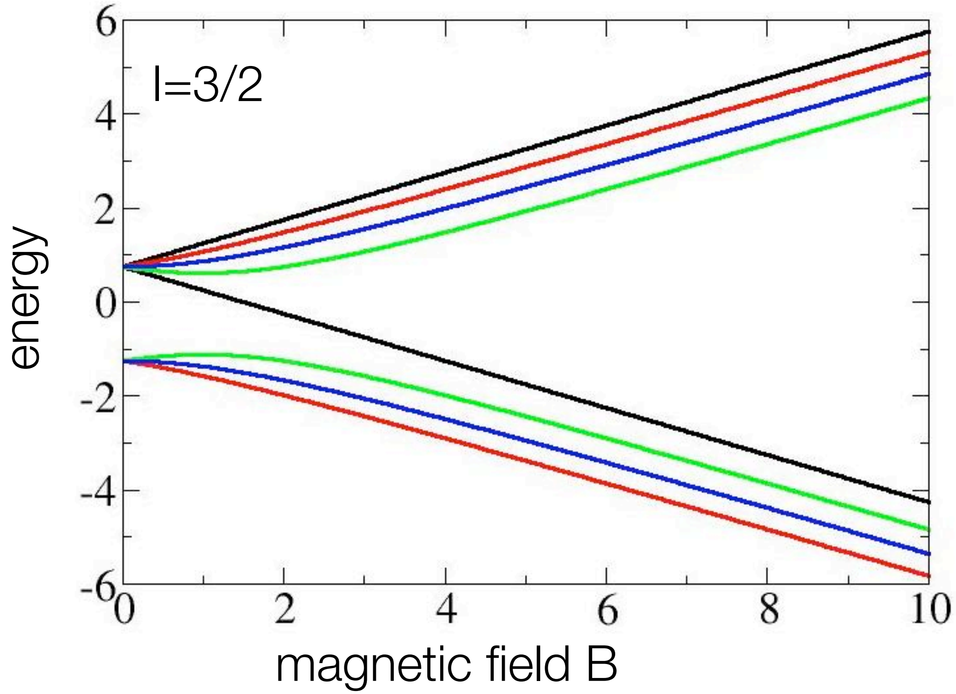
- Atoms moving slowly follow the direction of the local field adiabatically

Atoms in an inhomogeneous field experience a spatially-varying potential

Trapping the atoms magnetically

- $\mu_\alpha > 0$ high-field seeking states
- $\mu_\alpha < 0$ low-field seeking states

$$\boxed{E_\alpha \simeq \text{const} - \mu_\alpha B}$$



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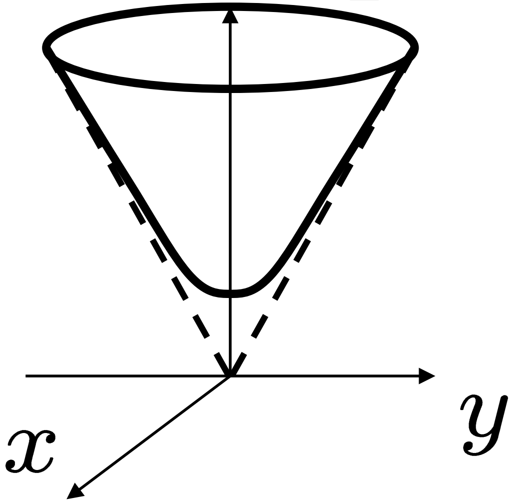
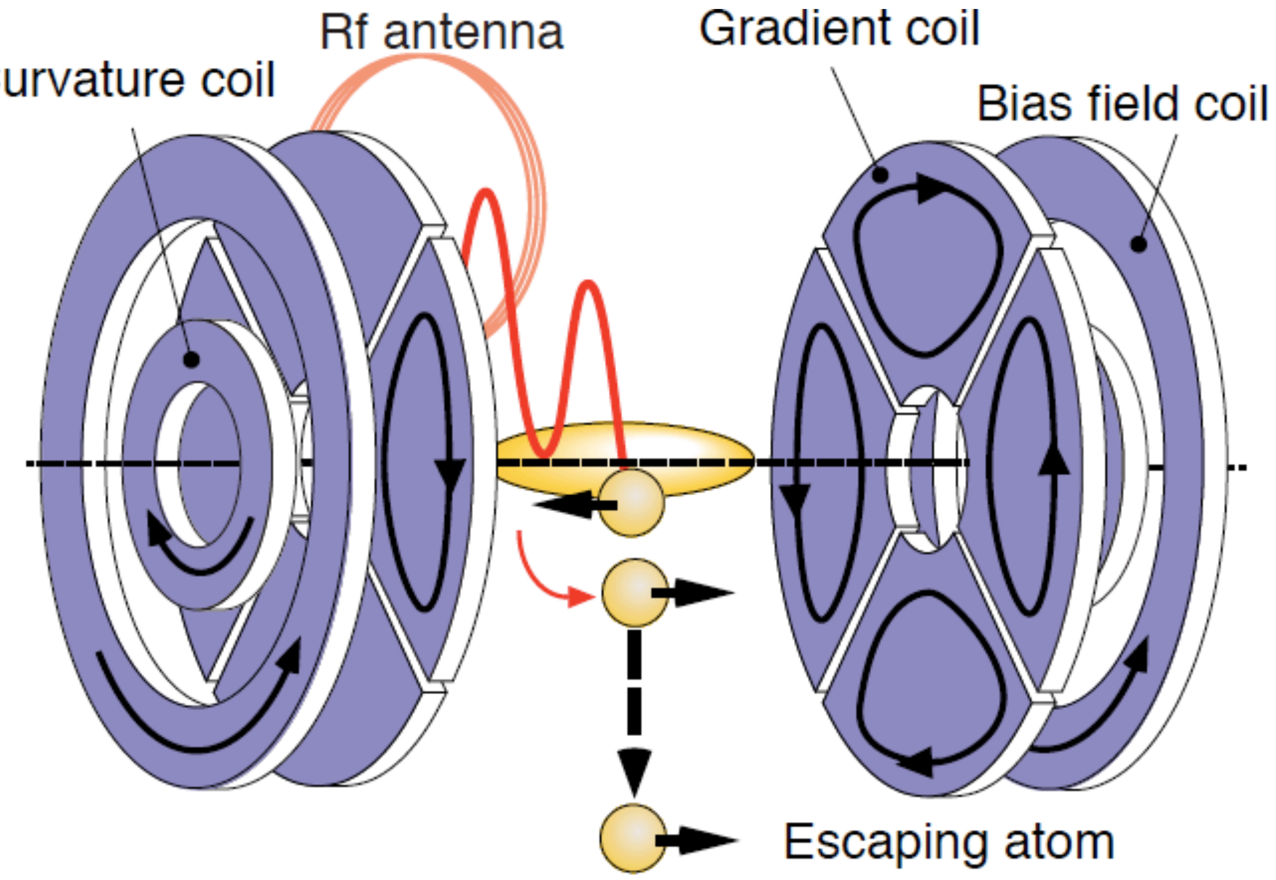


$\Rightarrow$ N.B. if the magnetic field is too small, atoms can flip their spin to a high-filed seeking state and become untrapped (trap loss region)

Trapping the atoms magnetically



[W. Ketterle *et al.*, Varenna (1998)]

⇒ Full optical access
⇒ Coils can be placed outside a vacuum chamber

Optical traps

- The interaction of the atoms with laser fields provides another possibility of confinement (as well as laser cooling).
- Dipolar approximation

$$H = -\underbrace{\mathbf{d}}_{\text{dipole}} \cdot \underbrace{\mathbf{E}(\mathbf{r}, t)}_{\text{electric field}}$$

- Second order (time-dependendent) perturbation theory

$$U(\mathbf{r}) = -\frac{1}{2}\underbrace{\alpha(\omega)}_{\text{dynamic polarisability}}\underbrace{\overline{E^2(\mathbf{r}, t)}}_{\text{time average}}$$

- If the intensity of the electric field varies with the position, the atoms are subjected to a force $-\nabla U(\mathbf{r})$

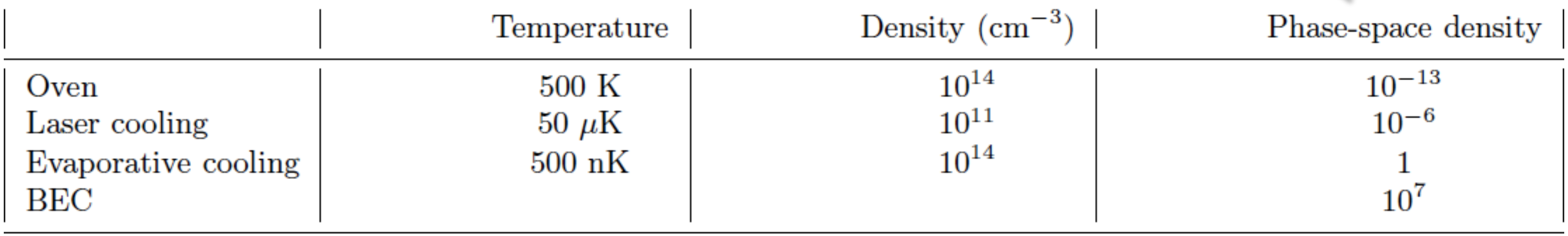
1. Attractive: if the laser is red-detuned (from an atomic resonance frequency)
2. Repulsive: if the laser is blue-detuned

Cooling to BEC

⇒ Typilcal multistage cooling process

- Gas temperature is reduced by a factor 10^9!!!
- in each step the ground state population increases by 10^6!!

$$\rho = n\lambda_T^3 = n\left(\frac{2\pi\hbar^2}{mkT}\right)^{3/2}$$



	Temperature	Density (cm^{-3})	Phase-space density
Oven	500 K	10^{14}	10^{-13}
Laser cooling	50 μK	10^{11}	10^{-6}
Evaporative cooling	500 nK	10^{14}	1
BEC			10^{7}

⇒ Several steps of laser cooling are applied before the cloud is transferred into a magnetic trap

⇒ Last cooling step to reach a BEC is the evaporative cooling technique