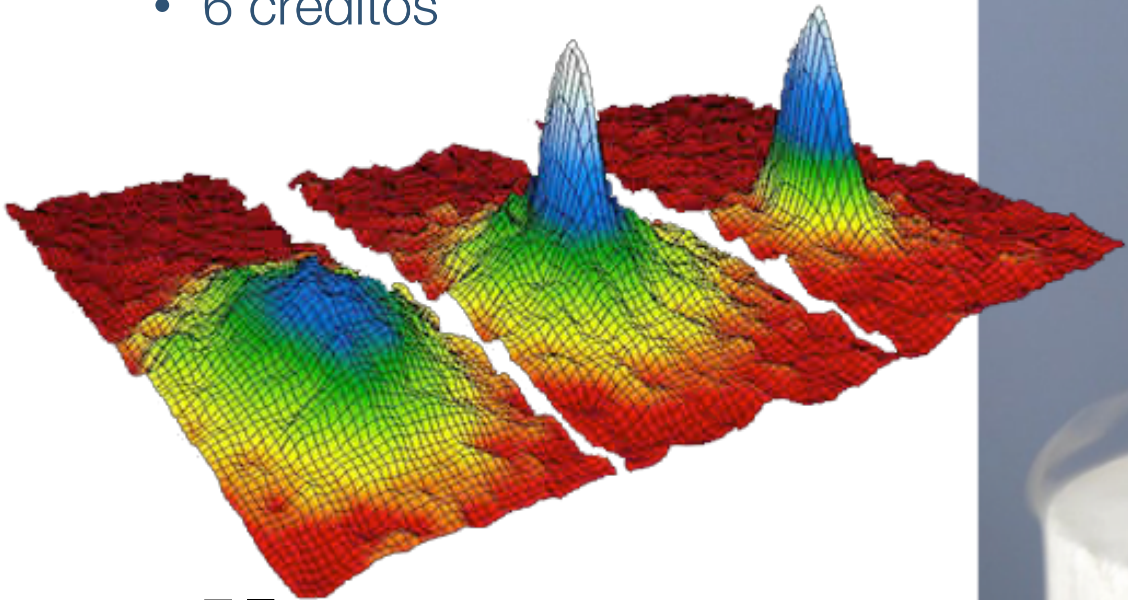
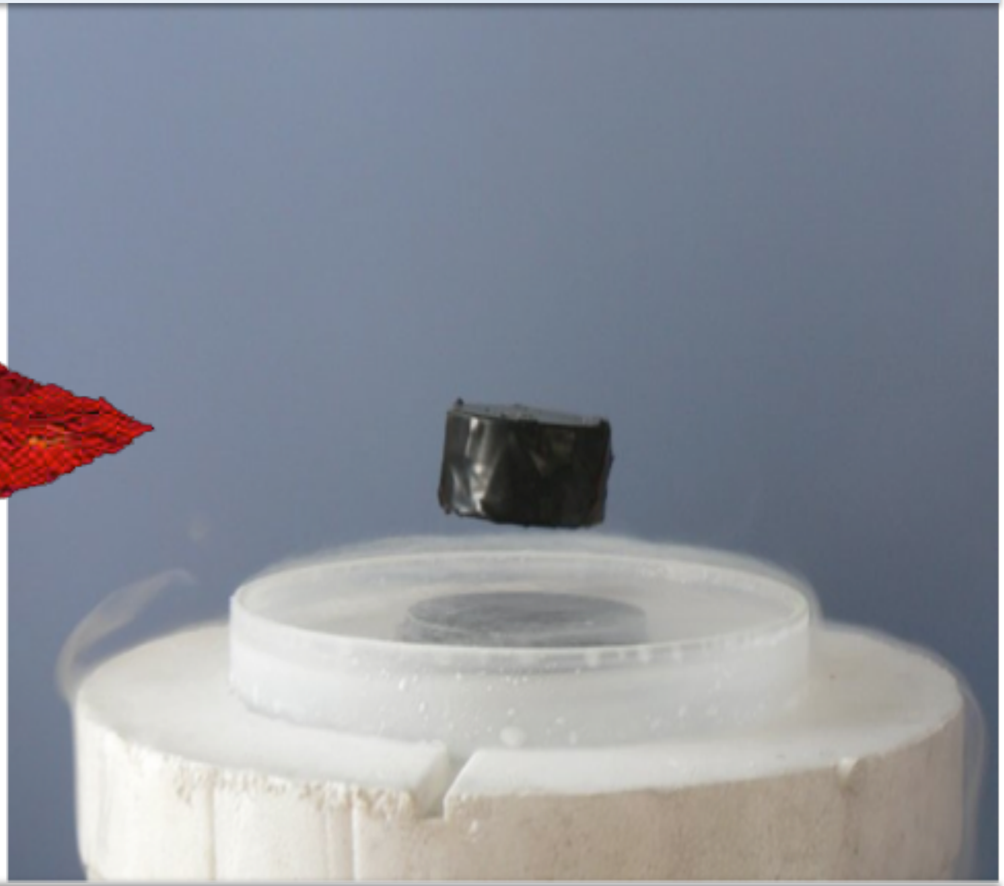
Introducción a la Superconductividad y Supefluidez

Curso de Mecánica Estadística Avanzada

- asignatura optativa (secundo semestre)
- 6 créditos





UNIVERSIDAD AUTONOMA DE MADRID

UAM, January—May 2013

Introduction to BEC & superfluidity

Macroscopic occupation of the ground state

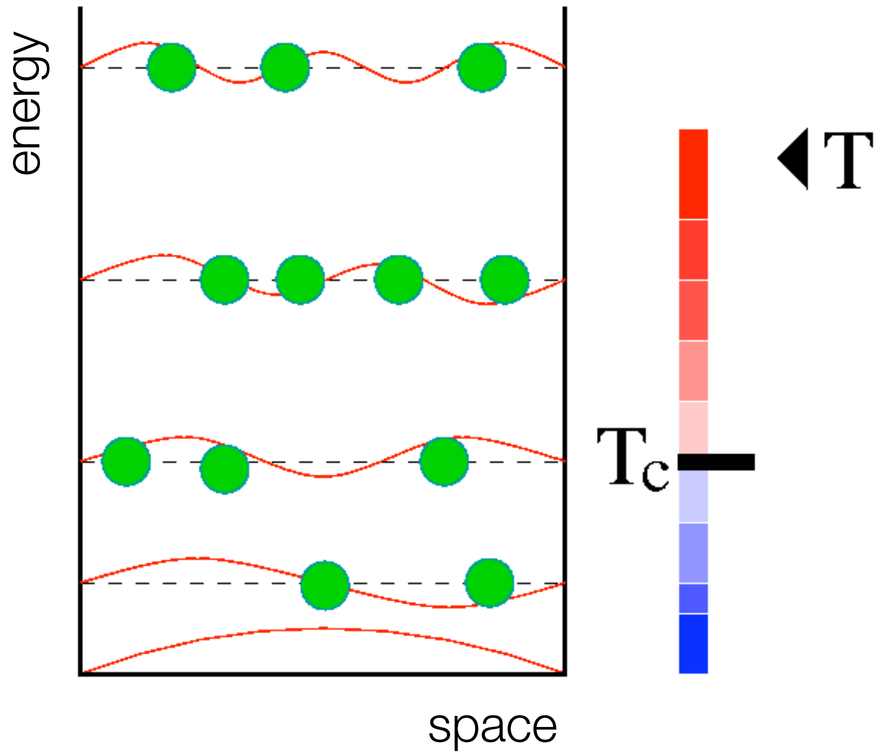
High temperatures: billiard balls

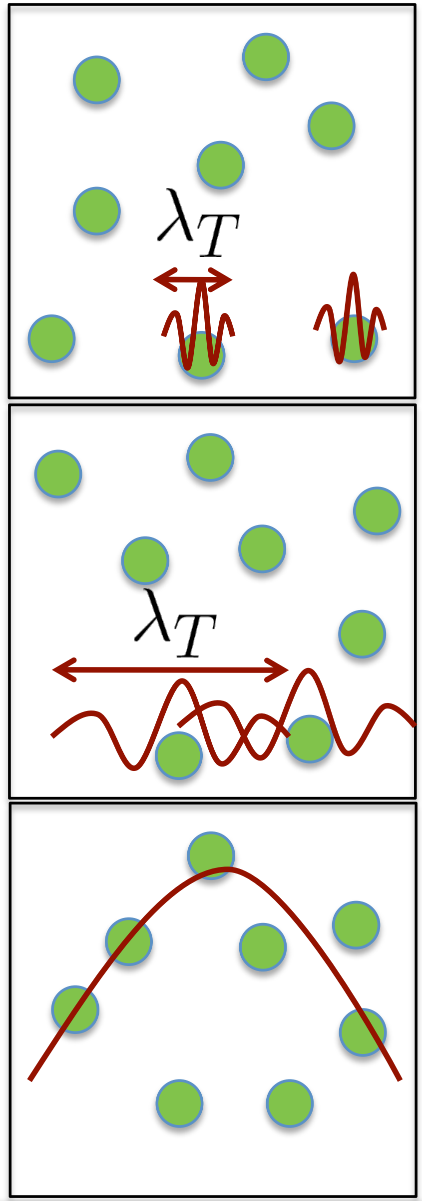
lowering T

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

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

Giant matter-wave



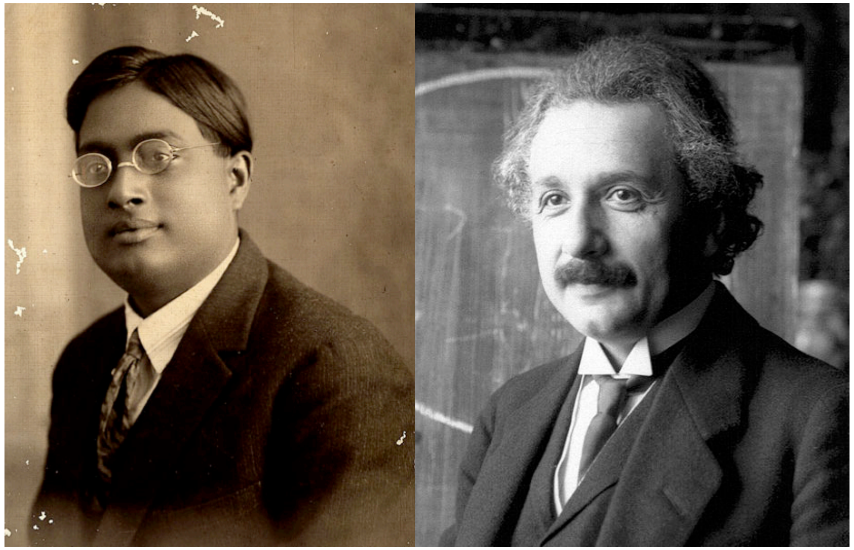


Quantum-statistical phase transition (it occurs even in absence of interactions)

BEC: 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-Einstein condensation (BEC)



Satyendranath Bose   Albert Einstein

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

"...condensation without attractive forces..."

BEC

NON INTERACTING
IDEAL BOSE GAS

⇒ paradigm of quantum statistical mechanics

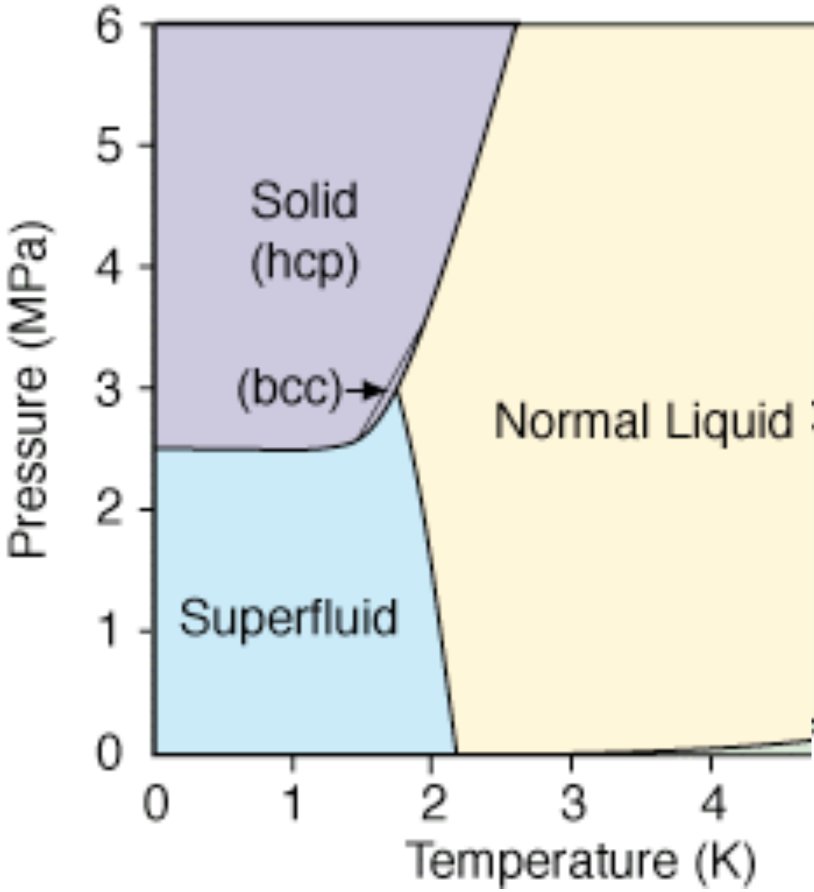
- indistinguishable particles
- wave nature of particles
- thermal equilibrium

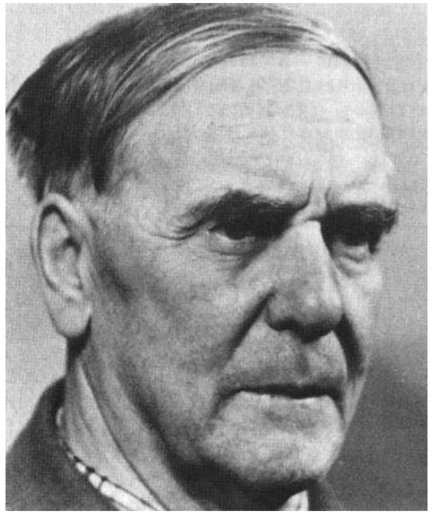
⇒ macroscopic quantum phenomena

- macroscopic wavefunction (many-body ground state wavefunction is the product of N identical single-particle ground-state wavefunctions)

BEC: from 1925 to 1995

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





Peter L. Kapitza

Don Misener

John F. Allen

BEC: from 1925 to 1995

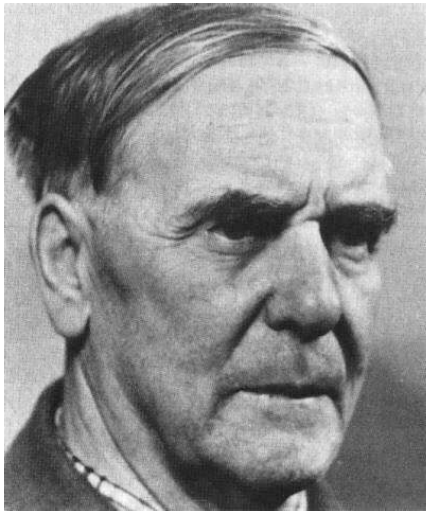
- 1938 Discovery of superfluidity in liquid helium ^4He (Allen & Misener; Kapitza).

What's the relation between BEC & superfluidity?

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

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

- It was a source of debate for decades
- e.g., the Landau's criterion for superfluidity does not explicitly mention the notion of BEC
- it is now recognised that superfluidity in ^4He is related to BEC (though, because of strong interactions in ^4He, there is a strong reduction of the lowest energy state occupancy)



Peter L. Kapitza

Fritz London

BEC: from 1925 to 1995

- 1947 microscopic theory of interacting Bose gases (Bogoliubov)

> …provides the microscopic picture behind Landau's theory

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

- and much more theoretical work…
  (which we are going to see in class)

Nikolai N. Bogoliubov

Lev D. Landau

BEC vs. Superfluidity

NON INTERACTING IDEAL BOSE GAS	INTERACTING BOSE GAS

⇒ paradigm of quantum statistical mechanics

- indistinguishable particles
- wave nature of particles
- thermal equilibrium

⇒ macroscopic quantum phenomena

- macroscopic wavefunction (many-body ground state wavefunction is the product of N identical single-particle ground-state wavefunctions)

IDEAL BECs ARE NOT SUPERFLUID

⇒ mainly related to transport phenomena (flow without friction)

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

- interactions are essential (change the dispersion from quadratic to phonon-like)

- superfluidity is possible even with few% of atoms in the ground state (see ^4He)

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)

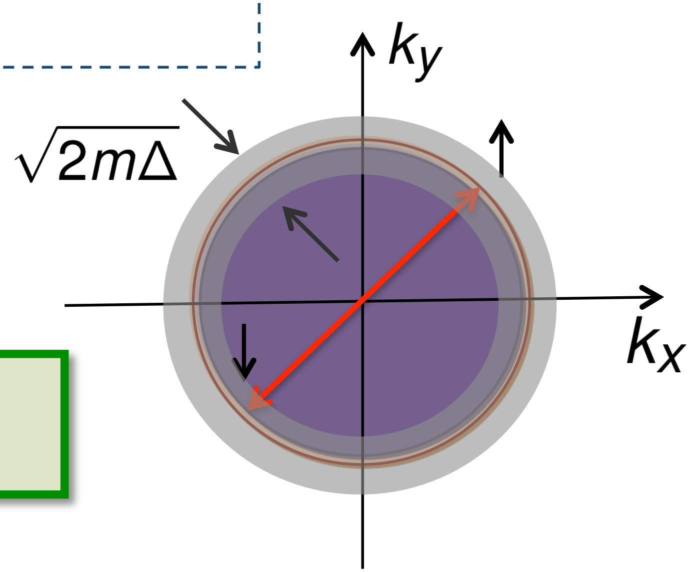
⇒ superconductors (BEC of Cooper pairs)

(we will see 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

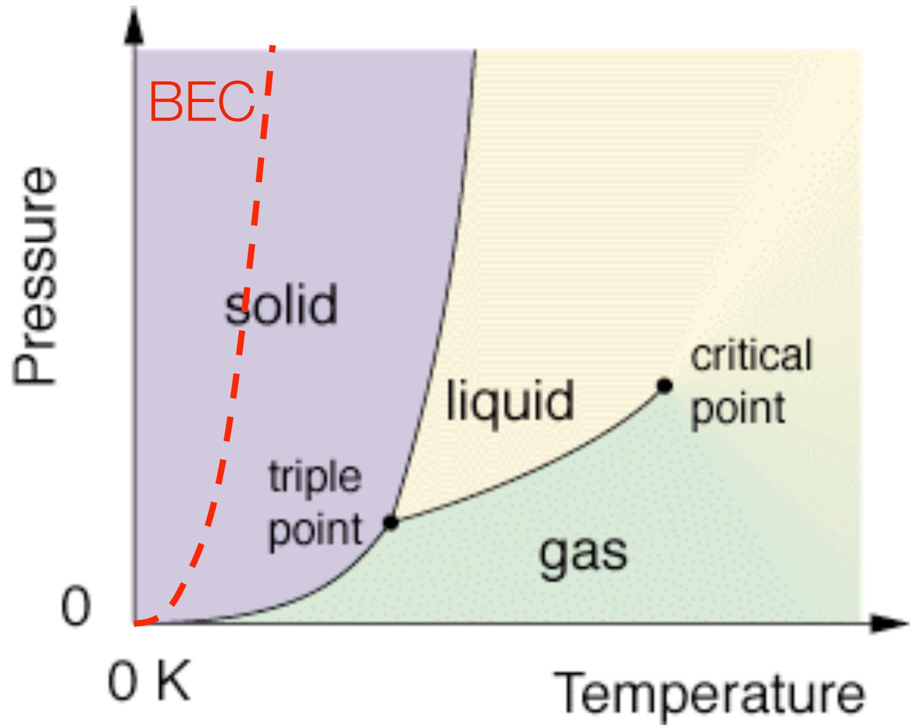
Searching for weakly interacting Bose gases

Why so hard?

⇒At very low T most substances are in the solid (or liquid) phase & interaction becomes strong

- BEC in its ideal form can be realised only in conditions of metastability

- Thermal equilibrium but the gas has a finite lifetime

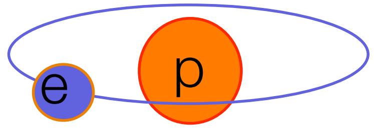


70 years to realise a BEC in dilute atomic gases

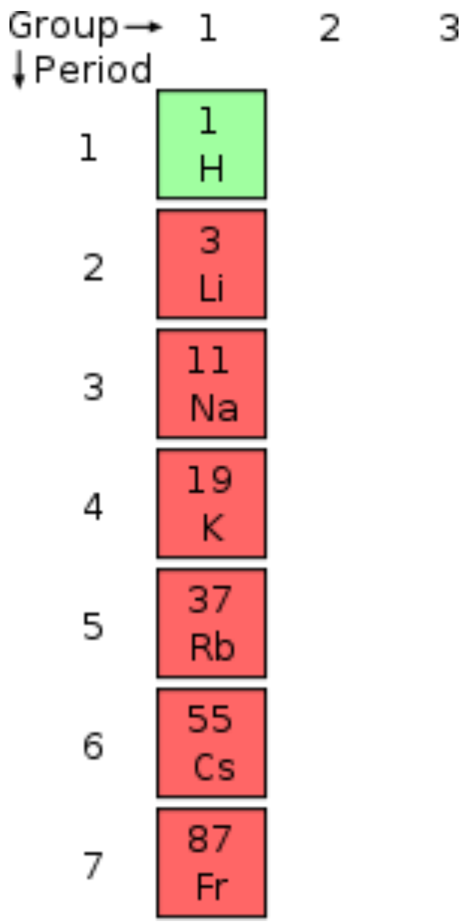
very sophisticated cooling and trapping techniques

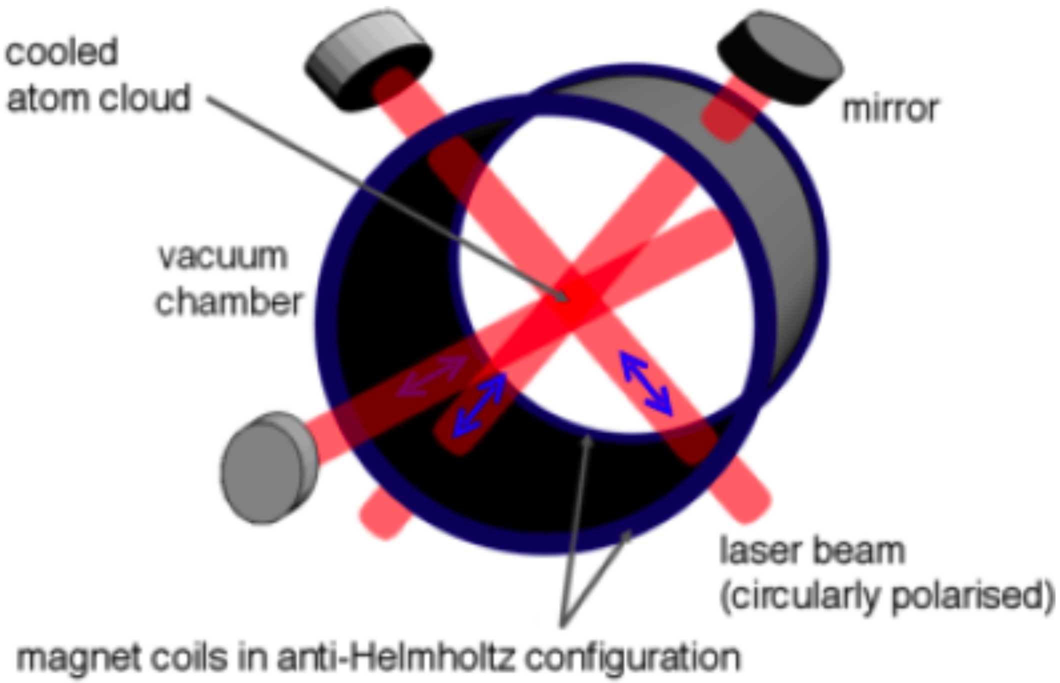
Dilute ultracold atomic gases: Experiments

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



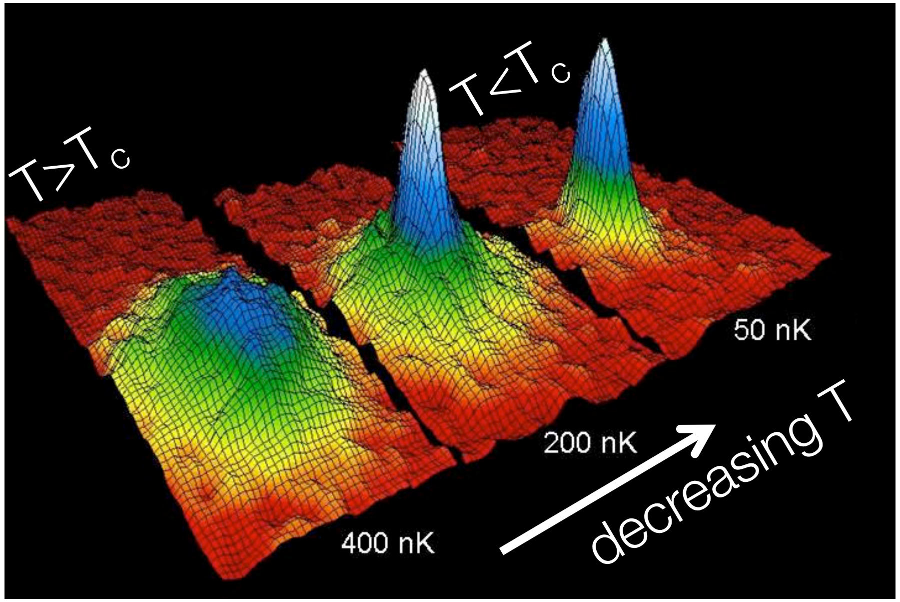
- '80 Developments in magnetic trapping, laser and evaporative cooling of alkali atoms





First realisation of a BEC in ultracold gases

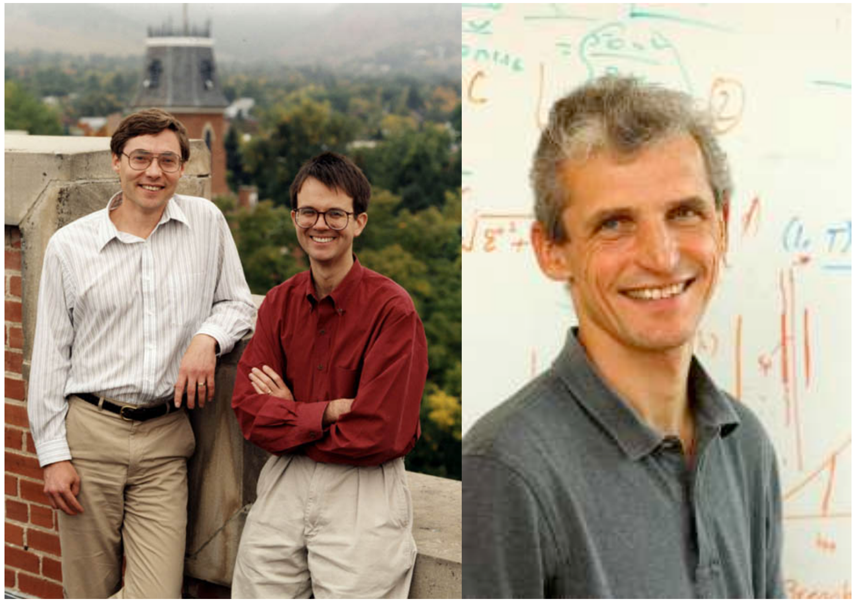
- 1995 BEC in alkali atoms (^{87}Rb, ^{23}Na, ^{7}Li, …)



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)

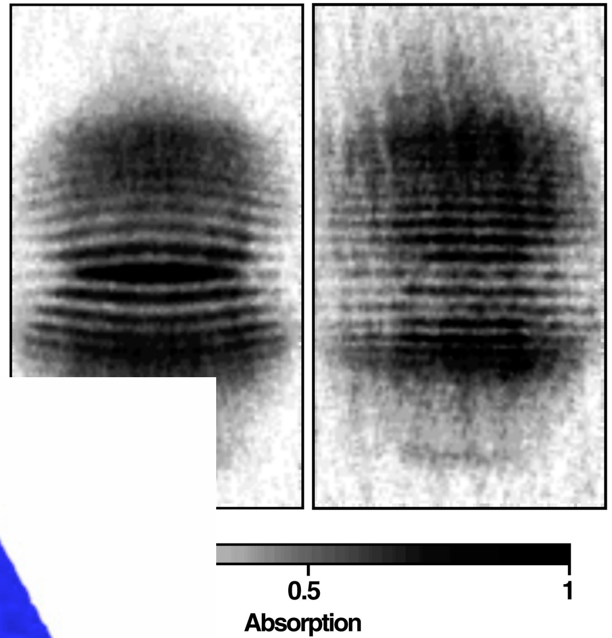


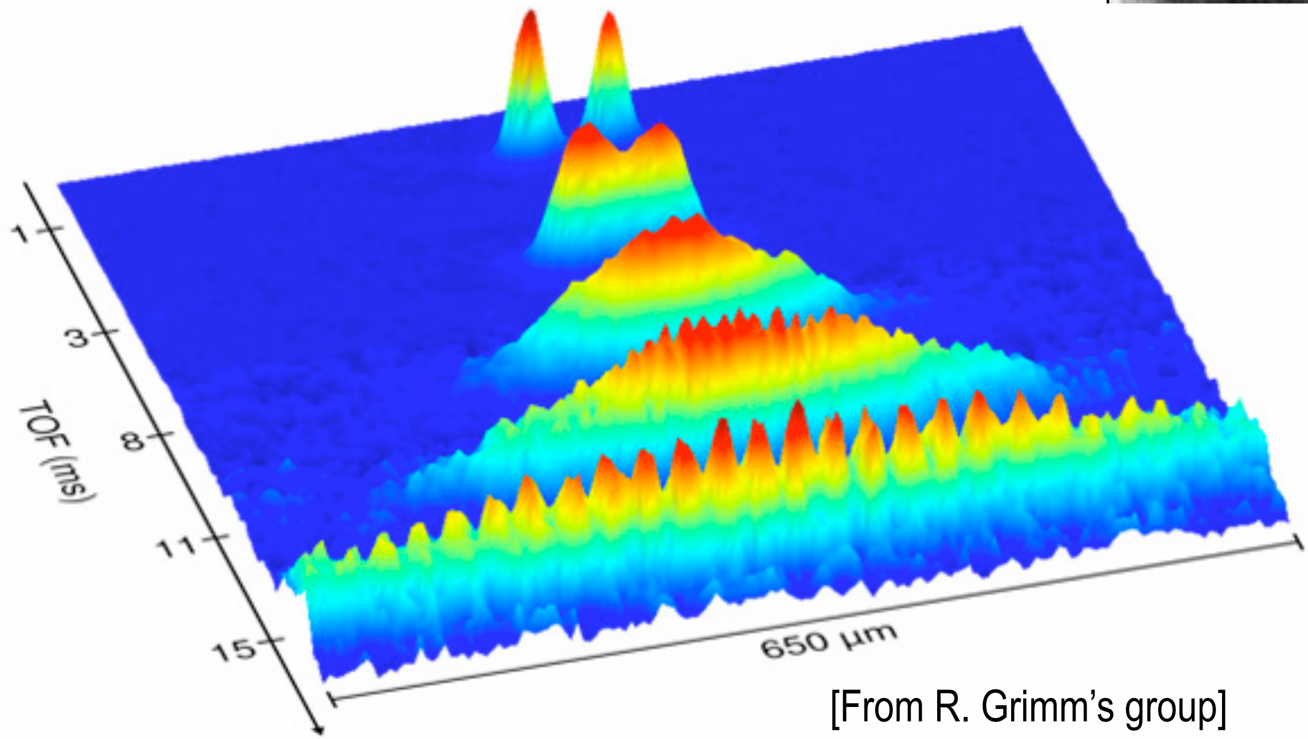
Carl Wieman & Eric Cornell   Wolfgang Ketterle

BEC & superfluidity

- Landau criterion
- Macroscopic phase coherence

[Andrews *et al*. Science (1997)]



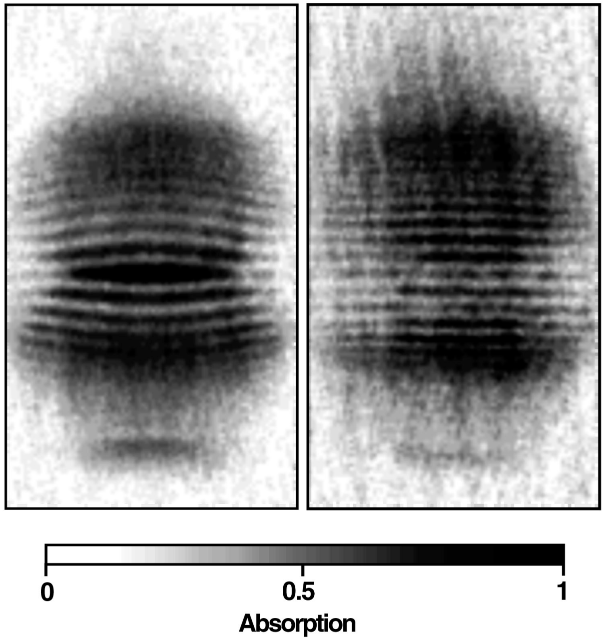


[From R. Grimm's group]

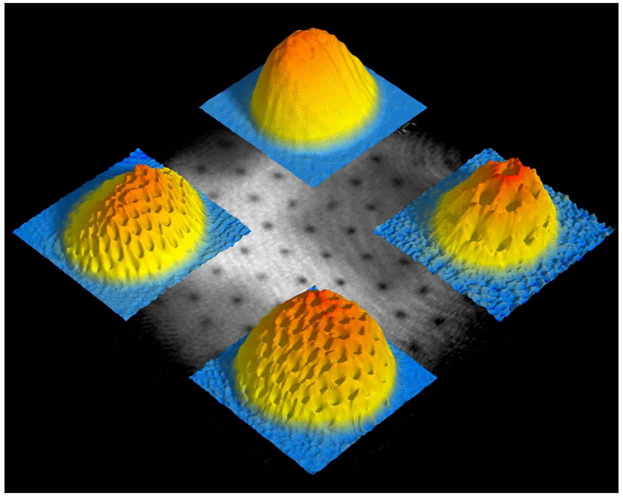
BEC & superfluidity

- Landau criterion
- Macroscopic phase coherence
- Quantised vortices
  (rotating condensates)

[Andrews *et al*. Science (1997)]



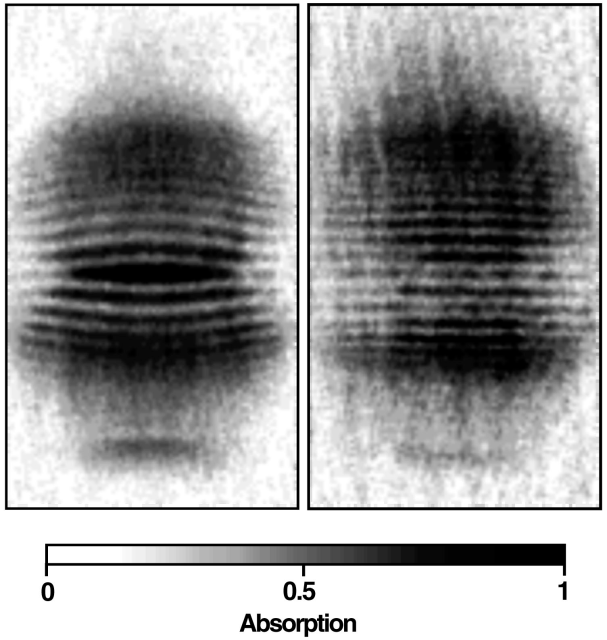
[Abo-Shaeer *et al. Science* (2001)]



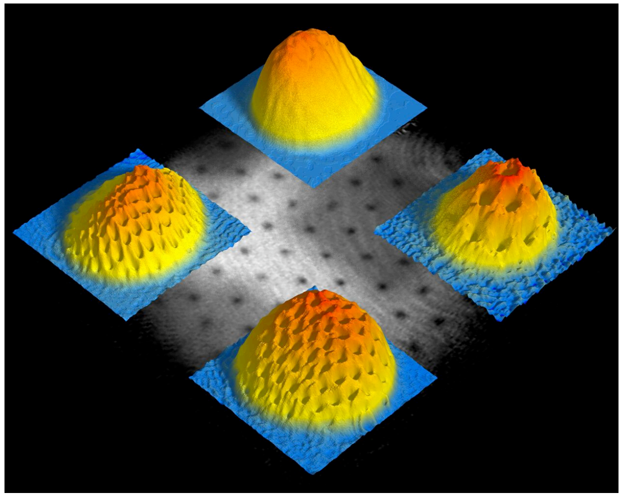
BEC & superfluidity

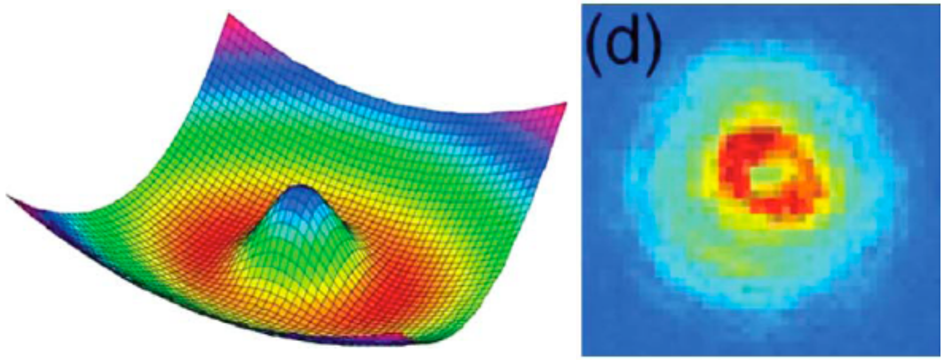
- Landau criterion
- Macroscopic phase coherence
- Quantised vortices
- Metastable persistent flow

[Andrews *et al*. Science (1997)]



[Abo-Shaeer *et al. Science* (2001)]

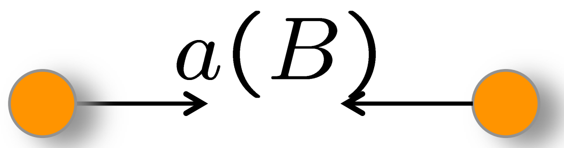


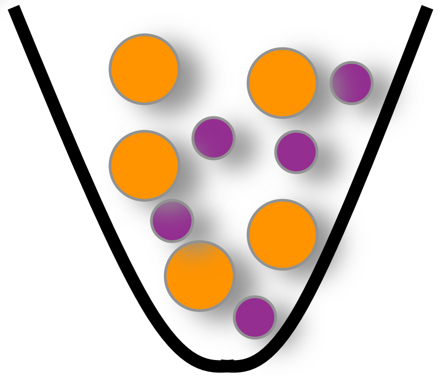


[Ryu *et al. PRL* (2007)]

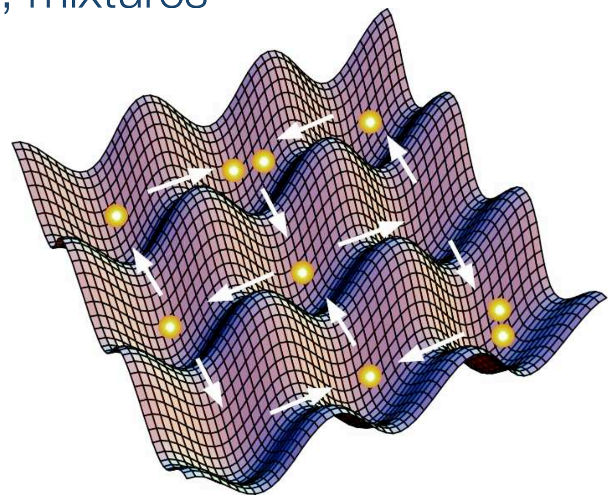
Ultracold atoms today

- Tune the interaction strength (Feshbach resonances)

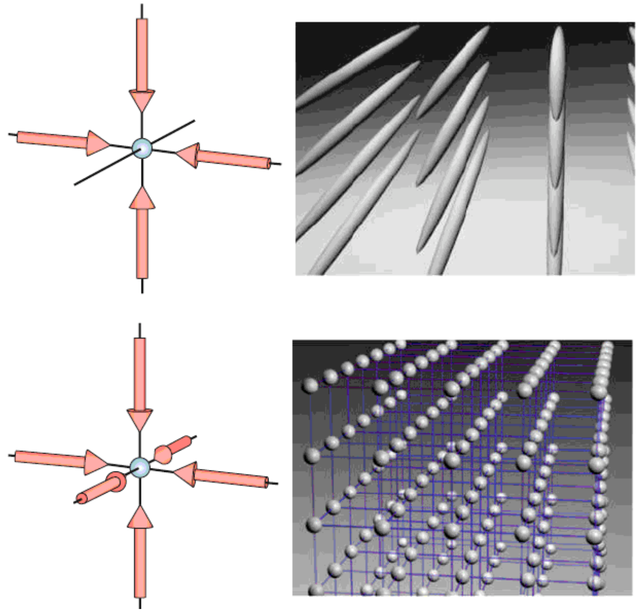




- Bosons, Fermions, mixtures
- Optical lattices



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



[Bloch *Nature Physics* (2005)]

Simulate solid state systems
(with advantage of external control)

Synopsis for the first half of the course

1. BEC: ideal Bose gas & weak interactions
2. BEC & superfluidity (Landau criterion and response to a moving defect)
3. Gross-Pitaevskii equation (non uniform condensates)
4. experiments in ultracold atoms (elements)
5. Applications: interference between two BECs
   ⇒ Josephson coupling & oscillations: analogy with superconductors
6. Applications: rotating BEC & vortices
   ⇒ vortex lattices
7. ...

List of possible topics for the presentation

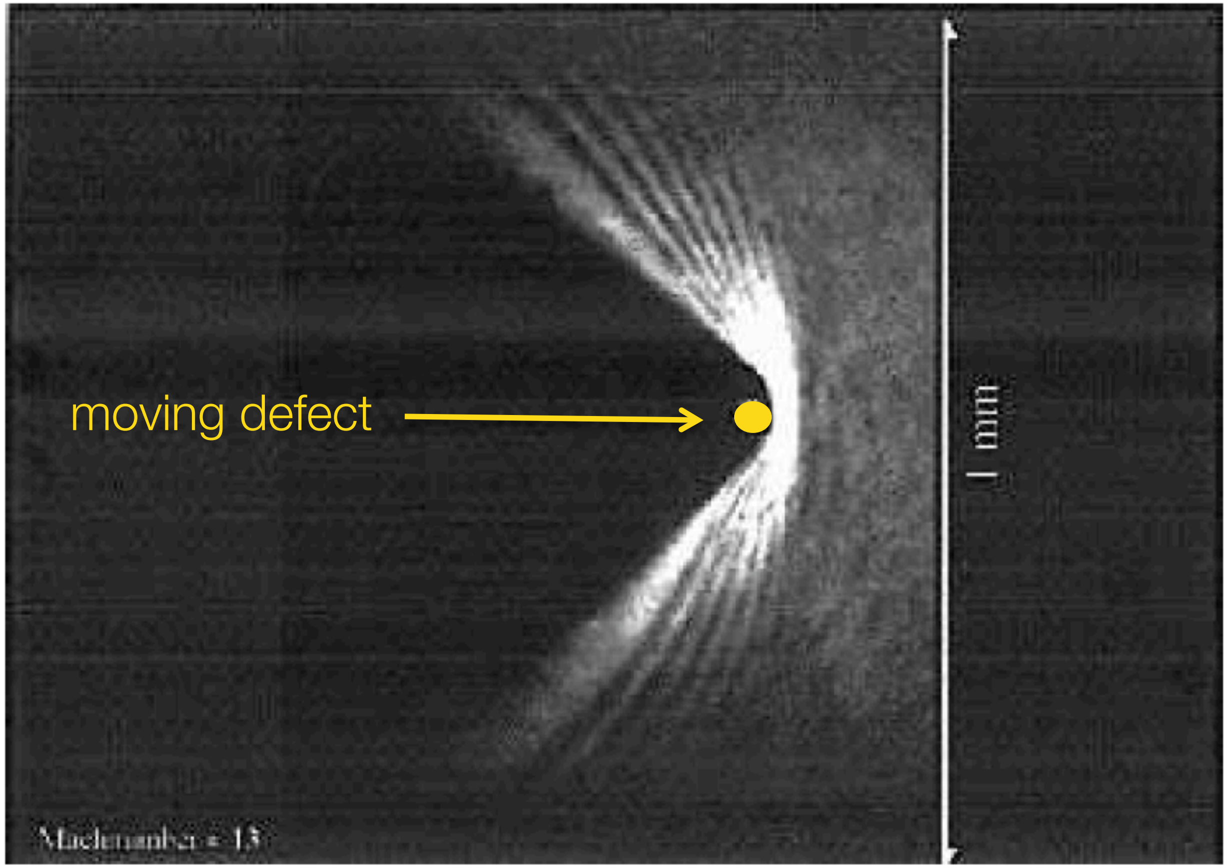
1. How to measure the speed of sound in a superfluid (ultracold atomic BEC)
2. Defect moving through a superfluid and Cherenkov radiation
3. Interference between two expanding condensates and the Josephson effect
4. Rotating superfluids and vortices
5. …
6. BEC-BCS crossover
7. Imbalanced Fermi mixtures and analogy with a BCS superconductor in a Zeeman magnetic field
8. Your proposals!

Moving defect in a BEC & Cherenkov radiation

$$v < v_c$$

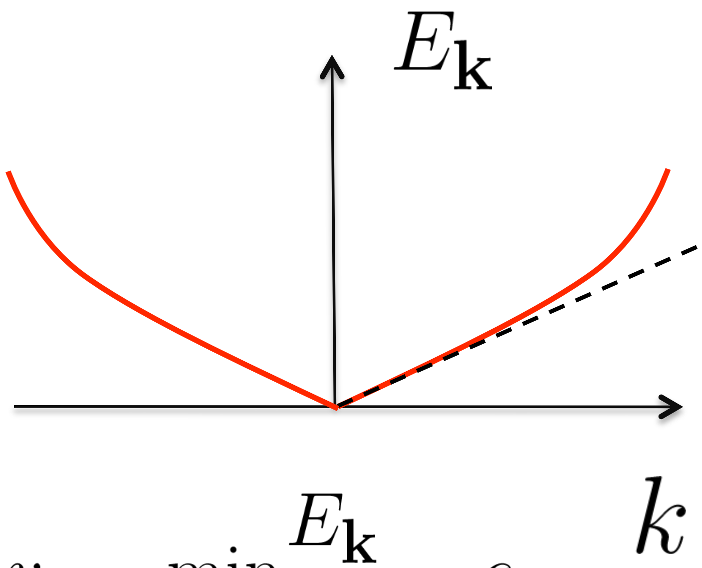
Moving defect in a BEC & Cherenkov radiation

$$v > v_C$$



[from E. Cornell's group]

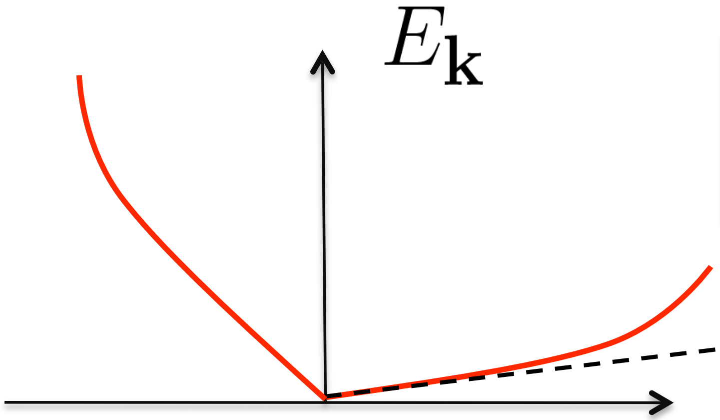
Moving defect in a BEC & Cherenkov radiation



sound velocity $c_s = \sqrt{\dfrac{gn}{m}}$

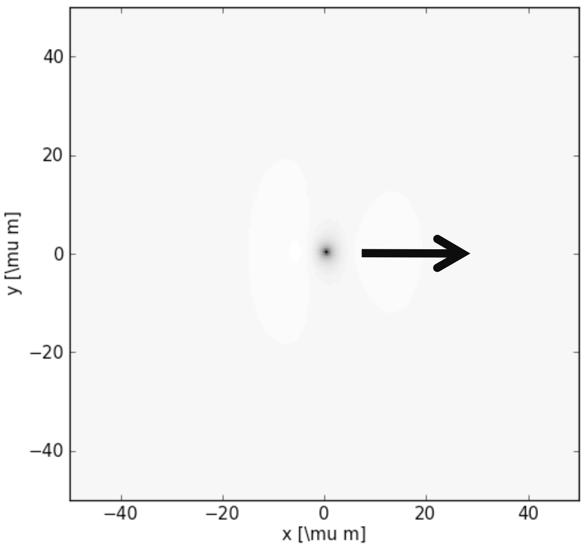
$$v_c = \min \frac{E_{\mathbf{k}}}{k} = c_s$$

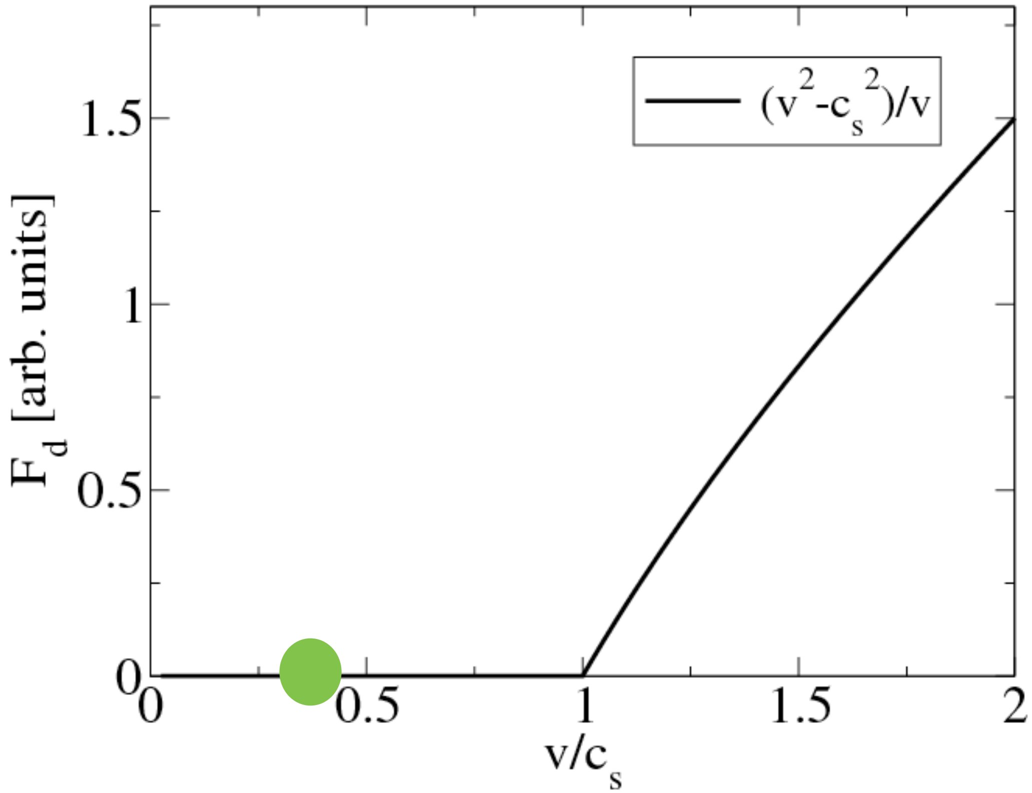
Moving defect in a BEC & Cherenkov radiation



$$c_s - v > 0$$

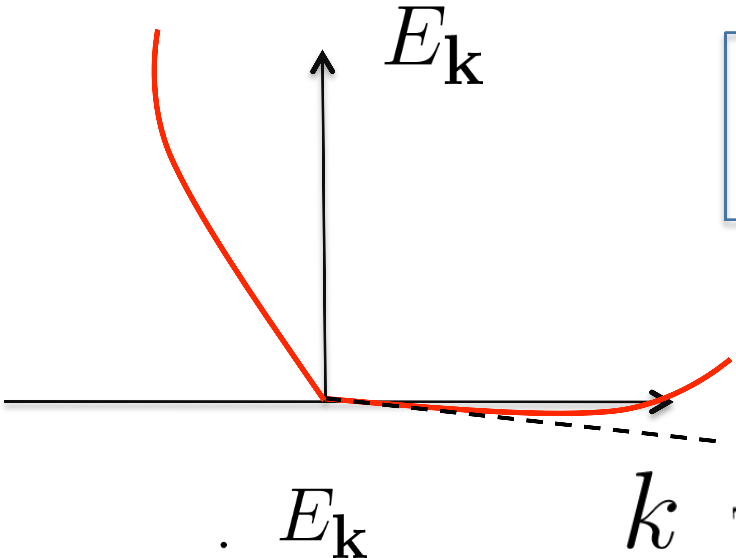
$$v_c = \min \frac{E_{\mathbf{k}}}{k} = c_s$$





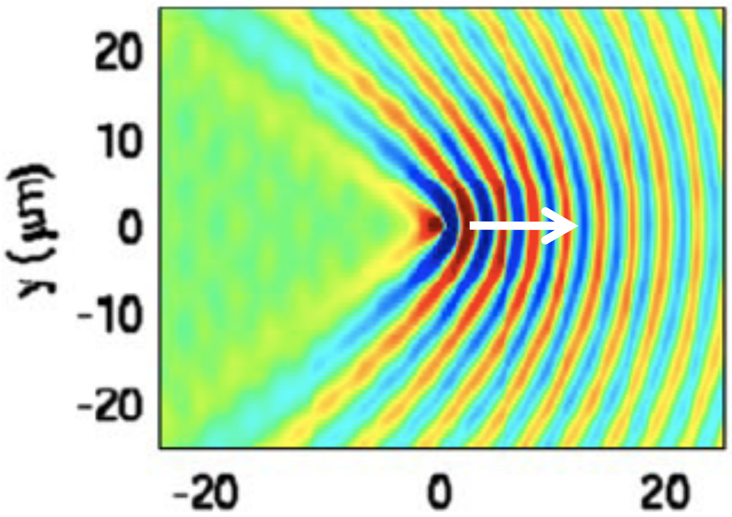
[G. E. Astrakharchik and L. P. Pitaevskii, PRA (2004)]
[I. Carusotto et al., PRL (2006)]

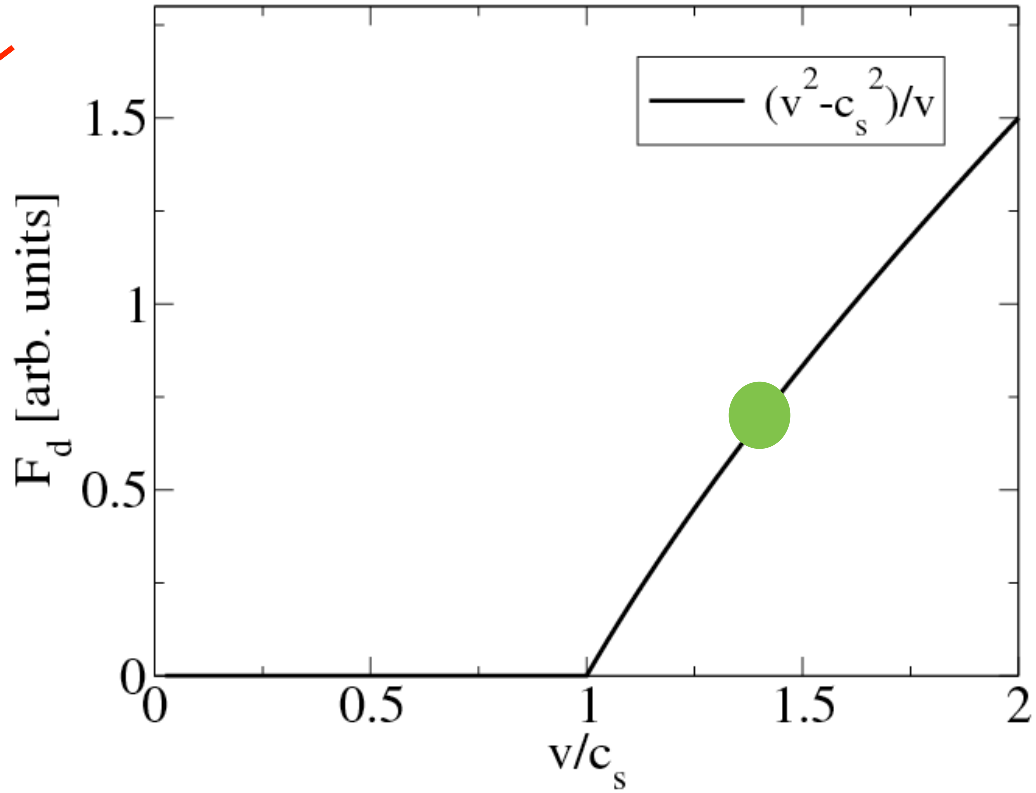
Moving defect in a BEC & Cherenkov radiation



$$c_s - v < 0$$

$$v_c = \min \frac{E_{\mathbf{k}}}{k} = c_s$$

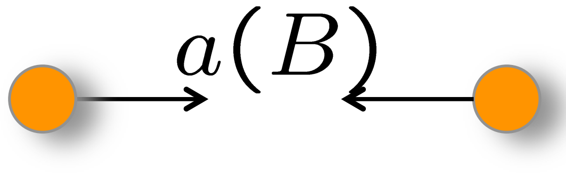




[G. E. Astrakharchik and L. P. Pitaevskii, PRA (2004)]
[I. Carusotto et al., PRL (2006)]

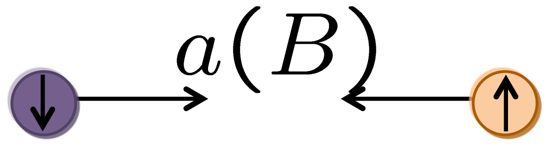
BEC-BCS crossover

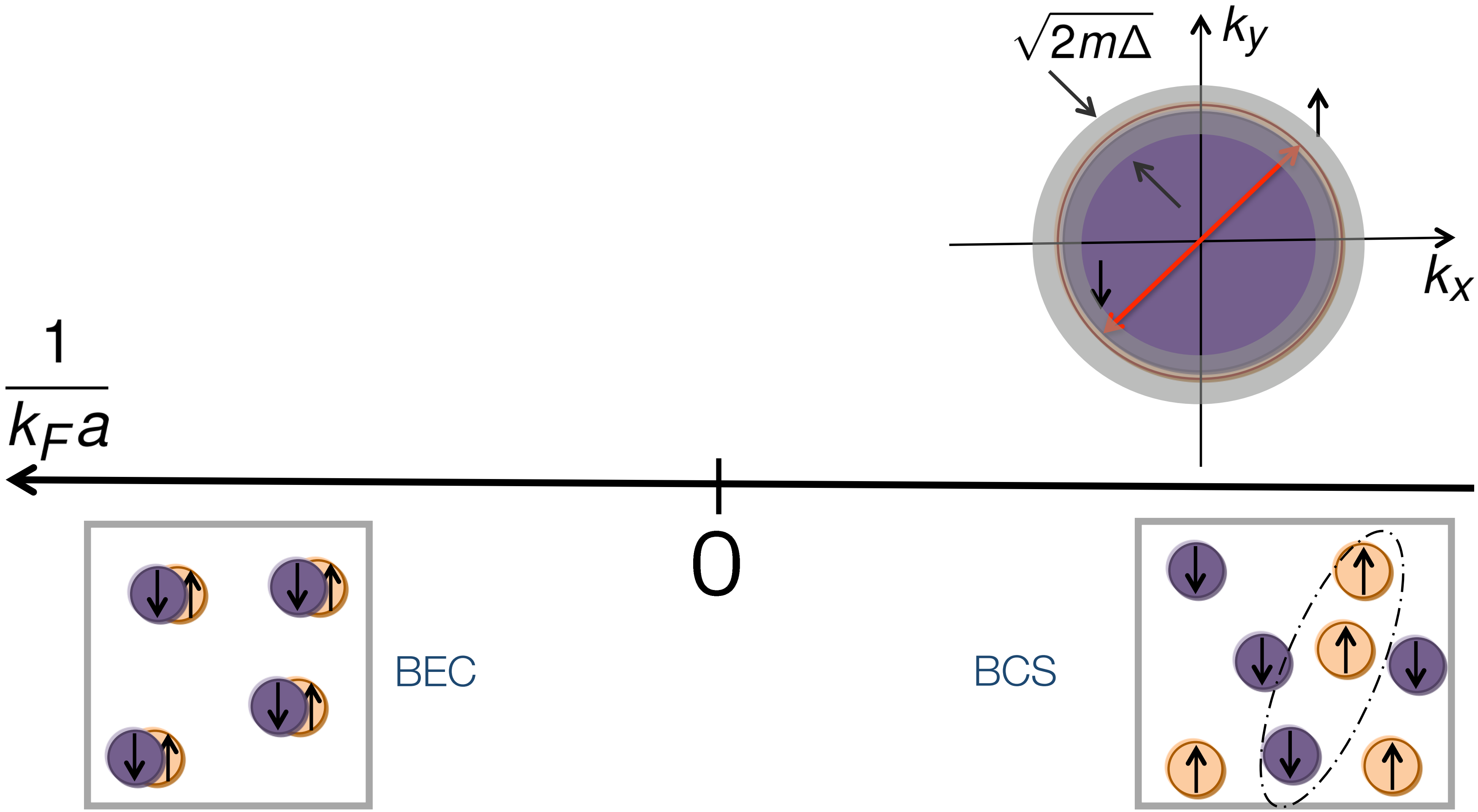
- Tune the interaction strength (Feshbach resonances)



BEC-BCS crossover

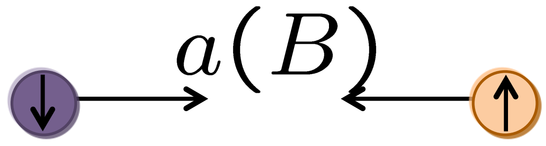
- Tune the interaction strength (Feshbach resonances)





Imbalanced Fermi mixtures

- Tune the interaction strength (Feshbach resonances)



Can superfluidity persist in presence of a population imbalance?

Analogy with a superconductor in a magnetic Zeeman field