Introduction to experiments in ultracold atomic gases – part 2

Introduction to BEC & superfluidity

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UAM, May 2012

Memo: Dilute & ultracold

1. metastable equilibrium: dilute gas

$$\tau_3 \ll \tau_2$$

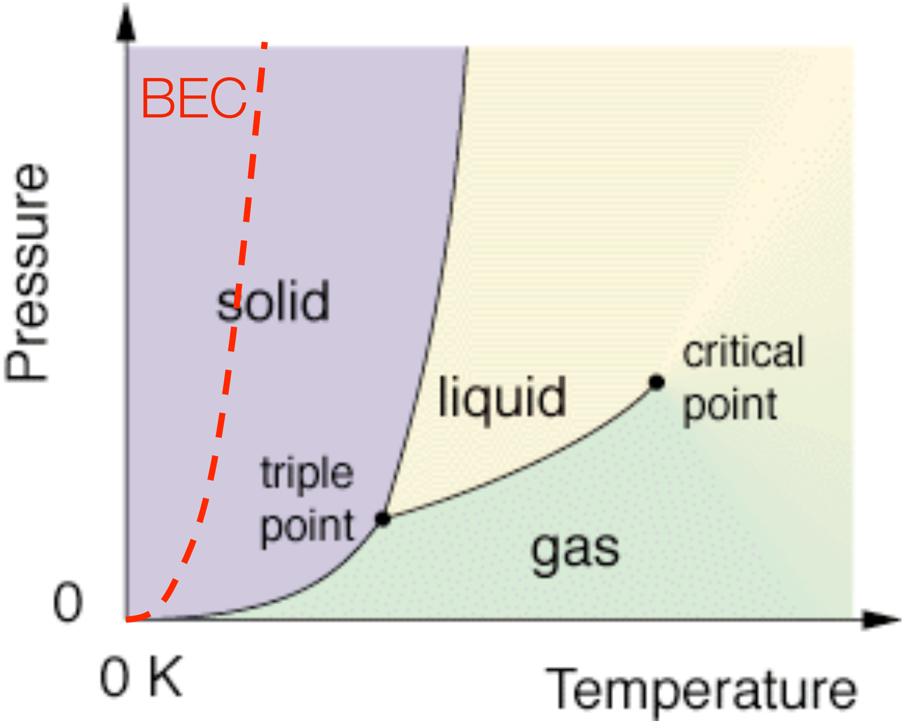
$$n \sim 10^{13} - 10^{15}\mathrm{cm}^{-3}$$

2. quantum degeneracy: cold gas

$$\rho = n\lambda_T^3 = n\left(\frac{2\pi\hbar^2}{mk_BT}\right)^{3/2} > 1$$

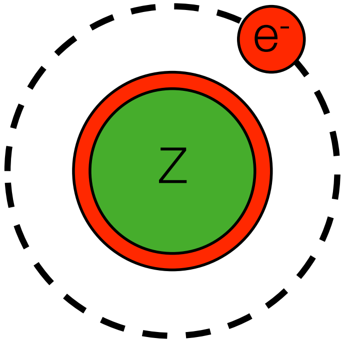
$$T \sim 100\mathrm{nK} - \mu\mathrm{K}$$

3. Trapped gas

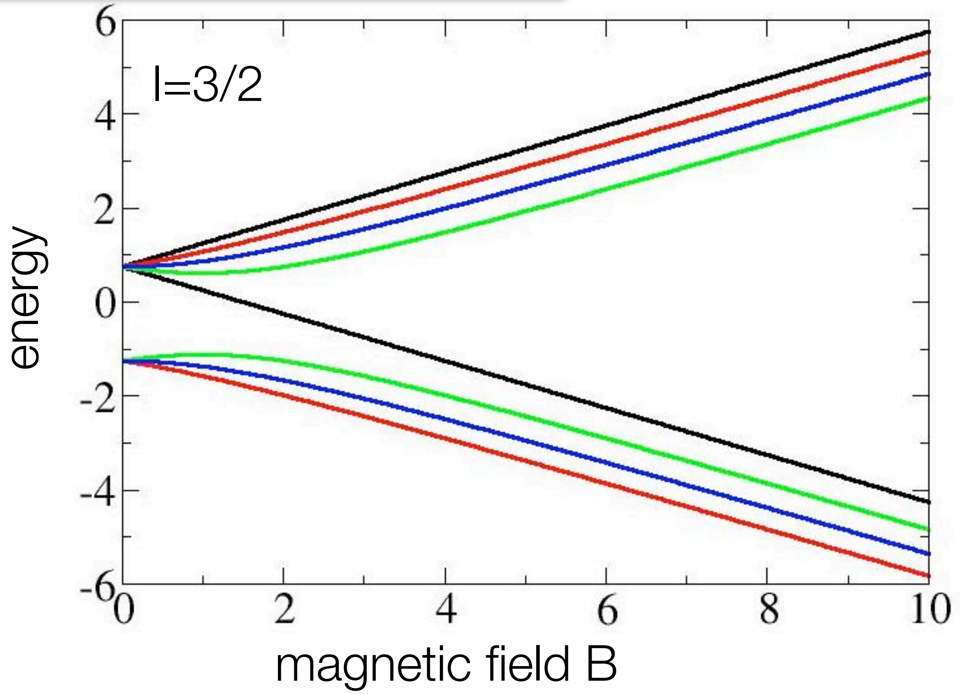


Memo: Alkali atoms & magnetic trapping

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

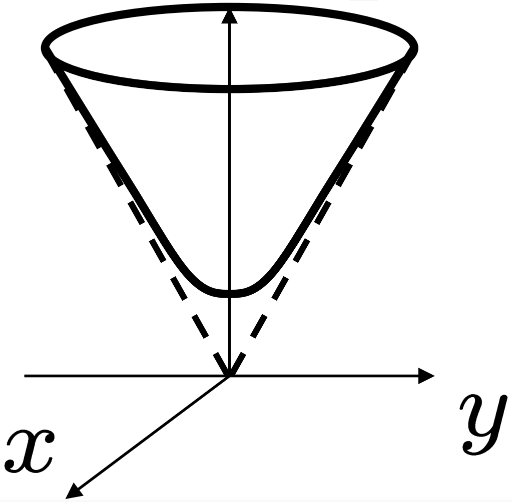


$$\boxed{E_\alpha \simeq \text{const} - \mu_\alpha B}$$



Atoms in an inhomogeneous field experience a spatially-varying potential

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

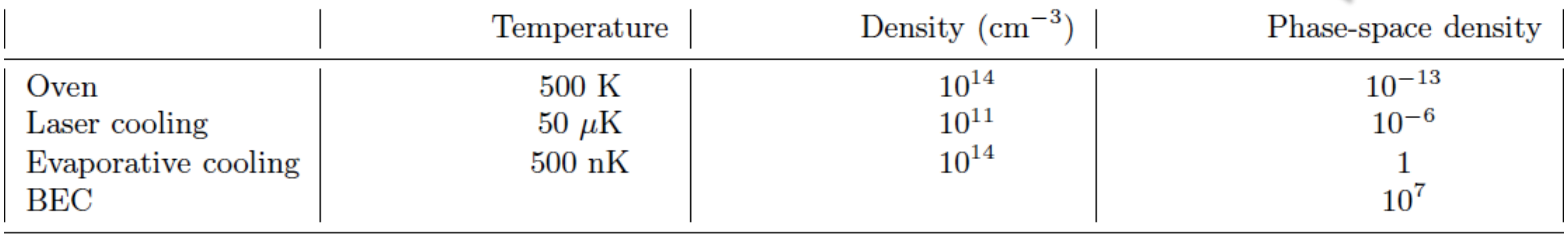


Cooling to BEC

⇒ 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

Laser cooling & Optical traps

- The interaction of the atoms with laser fields provides another possibility of confinement, as well as laser cooling

$$U(\mathbf{r}) = -\frac{1}{2}\alpha(\omega)\overline{E^2(\mathbf{r},t)}$$

dynamic polarisability

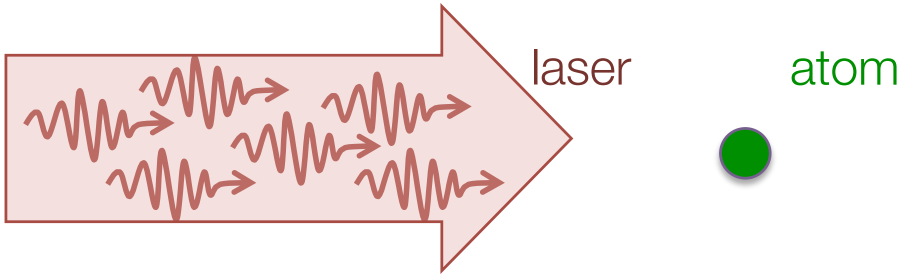
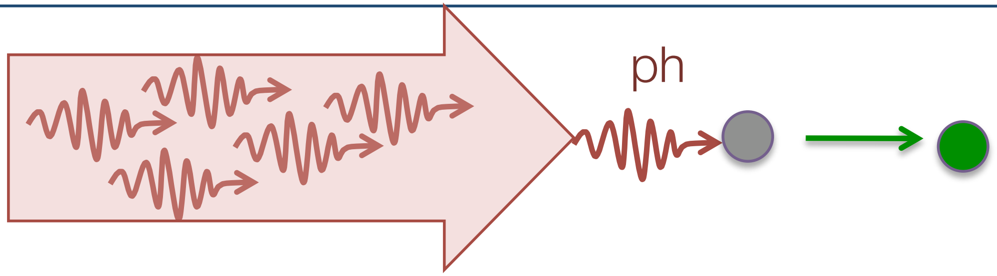
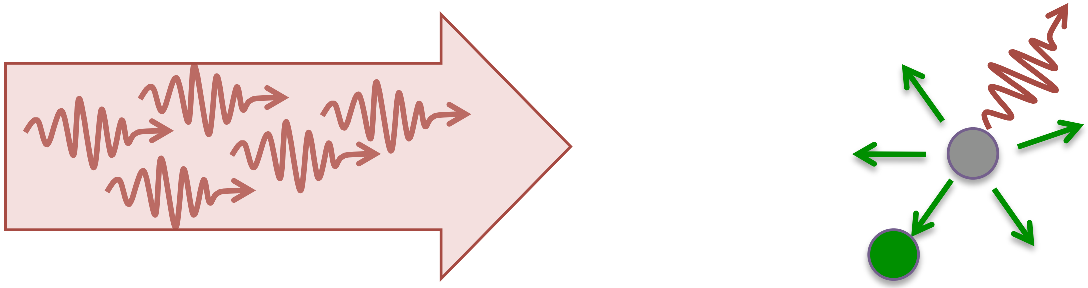
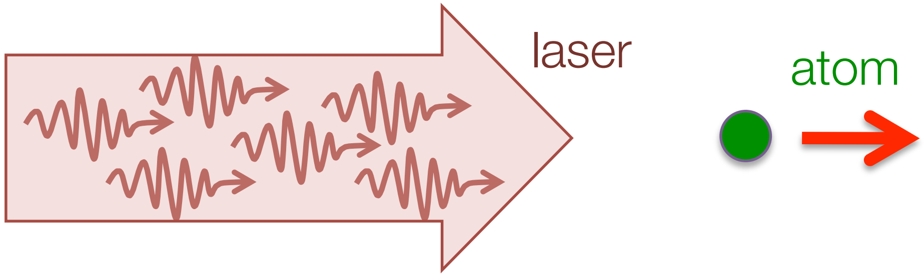
time average

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

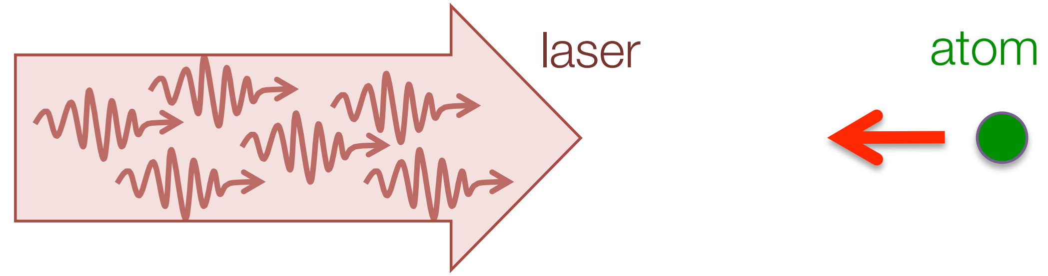
1. Attractive: if the laser is red-detuned (an electronic transition in the atom)
2. Repulsive: if the laser is blue-detuned

Nobel prize 1997 (Chu, Cohen-Tannoudji, Phillips): “for development of methods to cool and trap atoms with laser light”

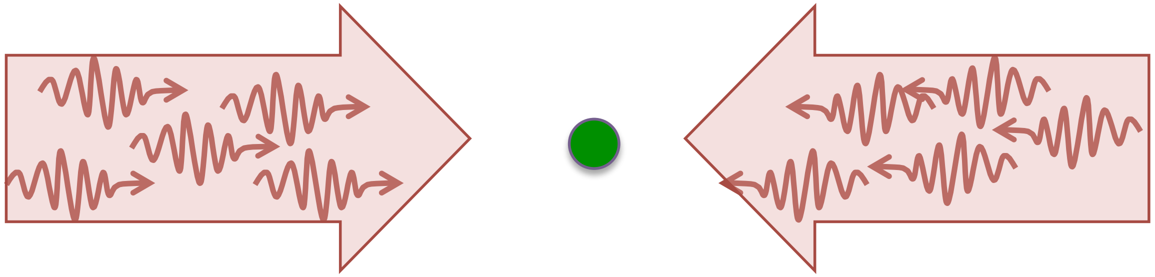
Laser cooling

	Laser tuned close to an atomic resonance, otherwise the atom don't "see" it
	atom absorbs one photon & moves in the laser direction
	it then emits a photon in a random direction and gets a recoil in the opposite direction
	on average, the atom accelerate in the laser direction

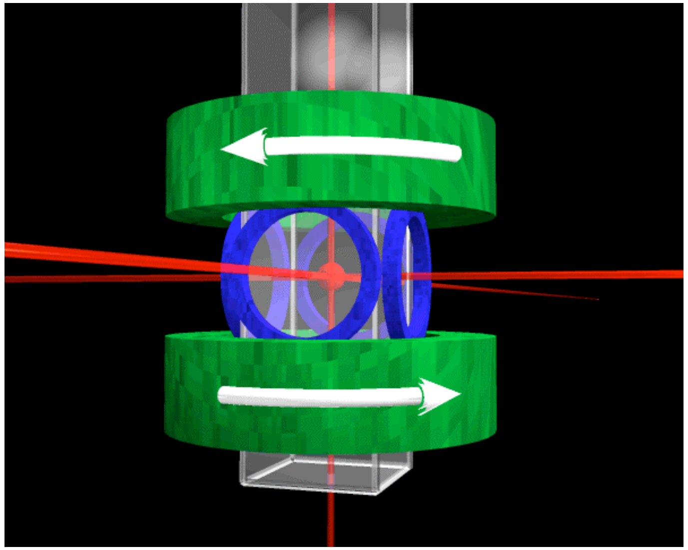
Laser cooling



if the atom initially moves against the laser (with a frequency just below the resonance), the atom slows down



adding a second laser, the atom has no escape (in 3D 6 lasers are needed to slow atoms down in all directions



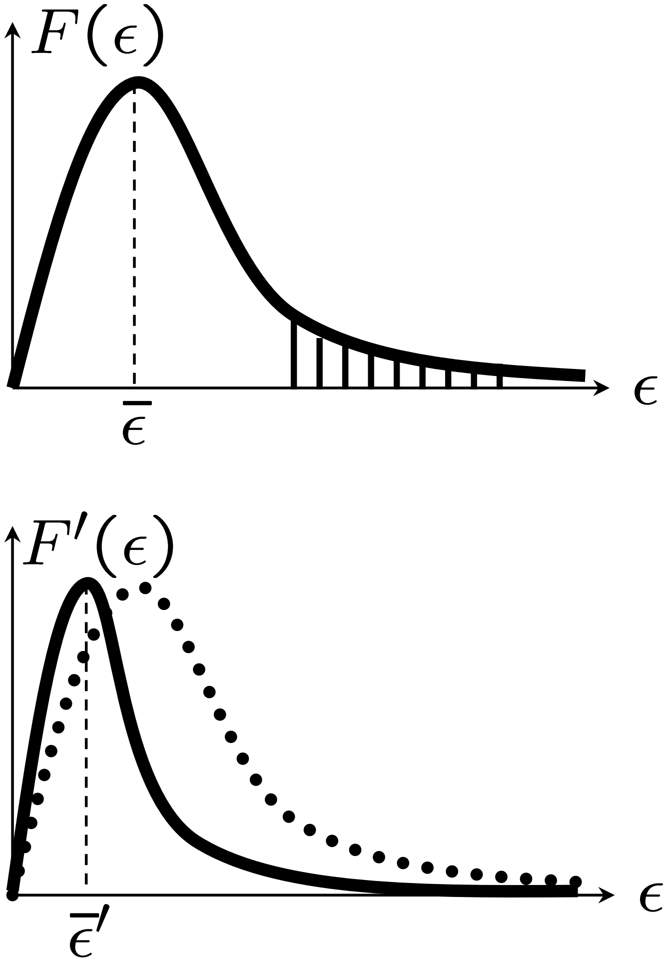
Link to animation 1

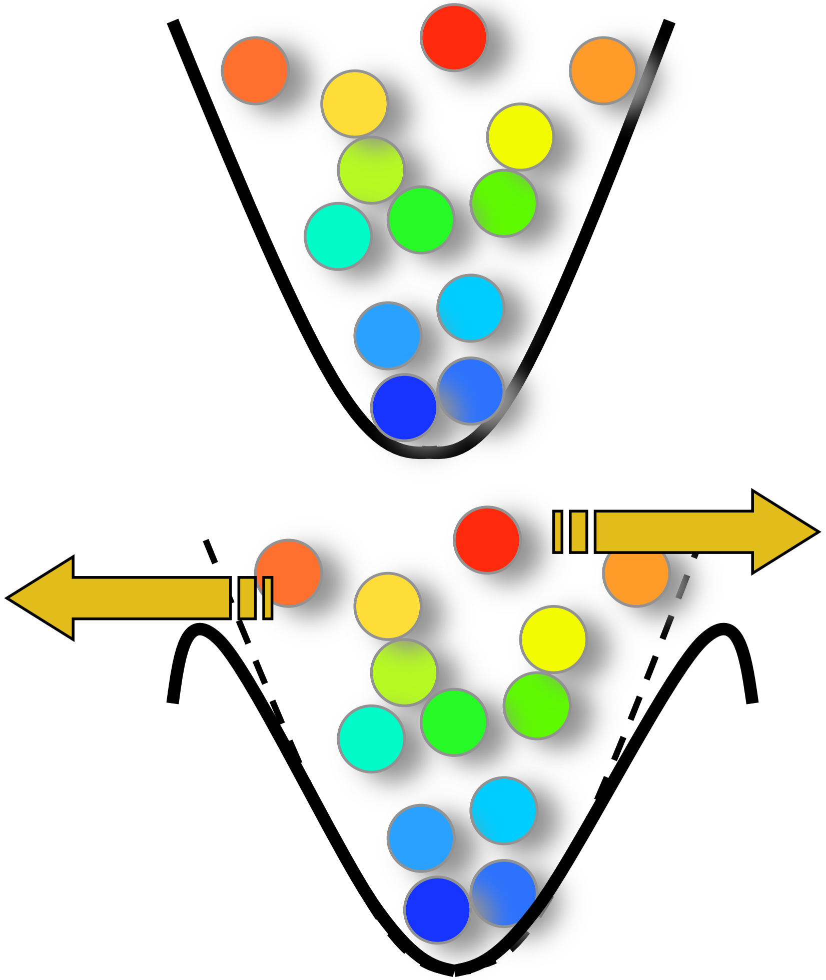
Link to animation 2

Link to animation 3

Evaporative cooling

1. Remove from the trap the high-energy tail of the thermal distribution
2. Remaining atoms rethermalise to a lower temperature (i.e., high energy tail is repopulated by collisions)





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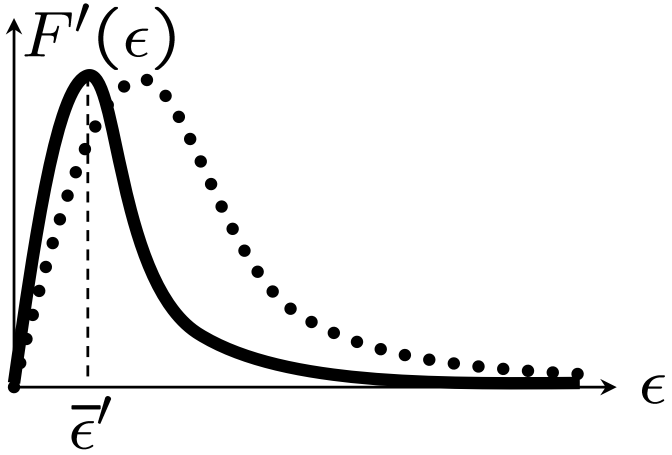

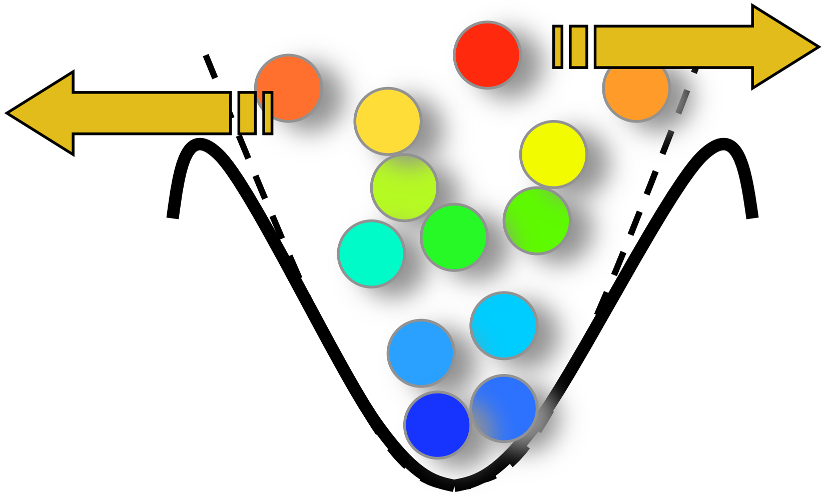

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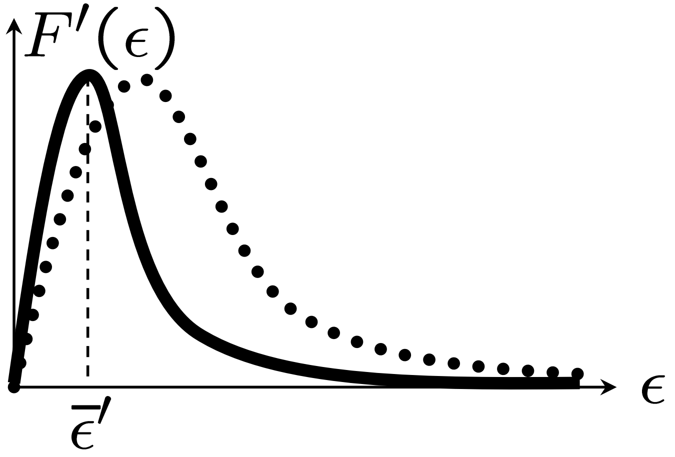
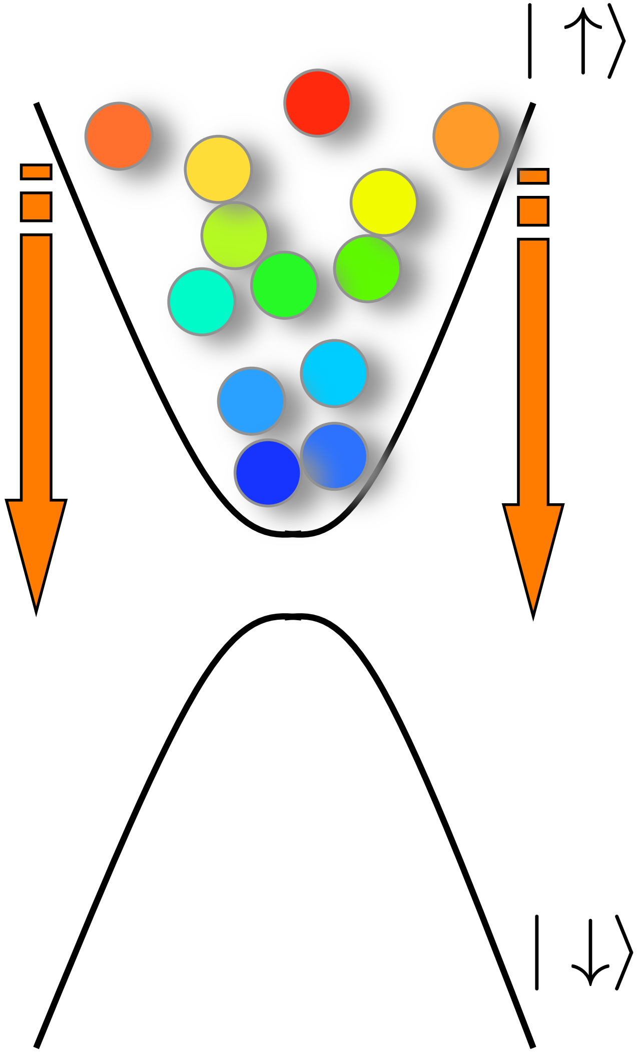
[Link to animation]



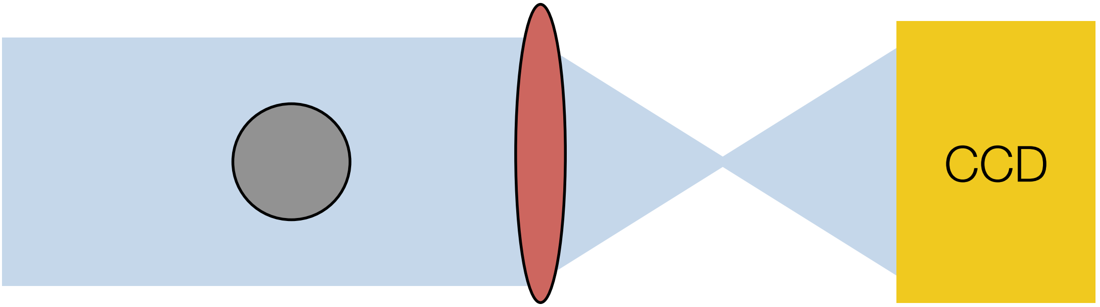


Probe the atomic cloud

⇒ Optical diagnostics: atoms are illuminated with a laser beam and images of the shadow cast by the atoms are recorded on a CCD

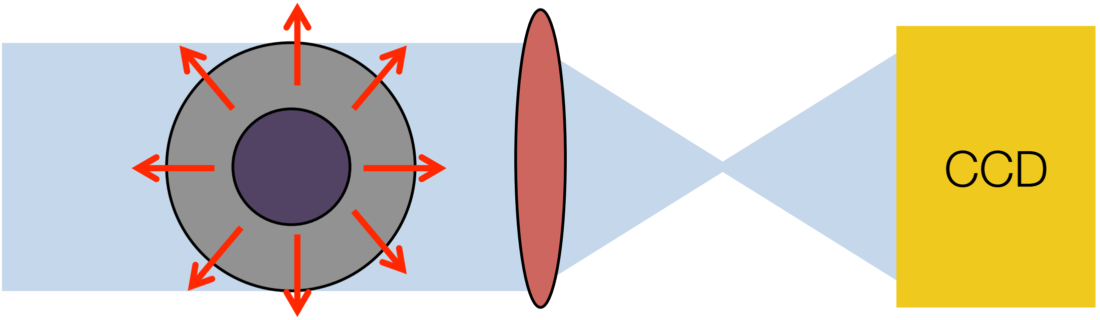
⇒ Absorptive or dispersive imaging

1. In-situ imaging: space distribution $n(\mathbf{r})$



2. Time of flight: momentum distribution

$$\lim_{t\bar{\omega}\gg 1} n(\mathbf{r},t) \propto n(\mathbf{p}=\frac{m\mathbf{r}}{t})$$



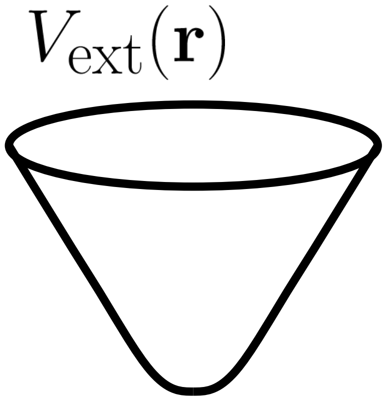
Quantitative analysis of images

Following lectures

⇒ Probing consists in providing density distributions of the atomic cloud, either trapped or in ballistic expansion

⇒ All properties of the condensate and thermal cloud are inferred from these density distributions and the comparison with theoretical modeling

⇒ Distribution in space determined by the trap potential



1. High temperatures $T \geq T_c$: the distribution can be evaluated in the semi-classical approximation

$$n(\mathbf{r}) = n_T(\mathbf{r}) \simeq \lambda_T^{-3} g_{3/2}(e^{\beta[\mu - V_{\text{ext}}(\mathbf{r})]})$$

1. Low temperatures (pure condensates) $T \ll T_c$

$$n(r) = n_0(\mathbf{r}) \begin{cases} \text{Ideal gas} \\ \text{Tomas-Fermi limit} \end{cases}$$

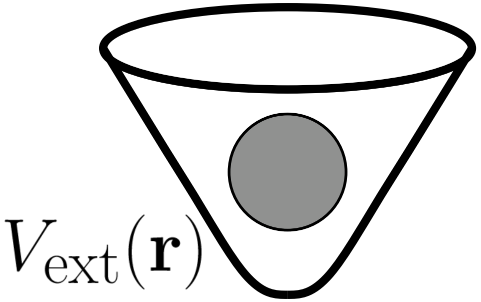
2. Intermediate regime: bimodal distribution $T \lesssim T_c$

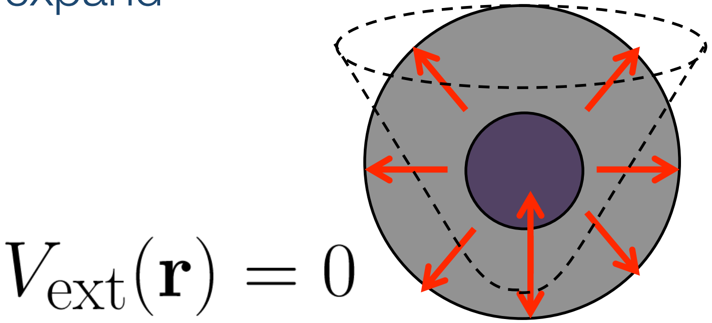
$$n(r) = n_0(\mathbf{r}) + n_T(\mathbf{r})$$

Time of flight measurements

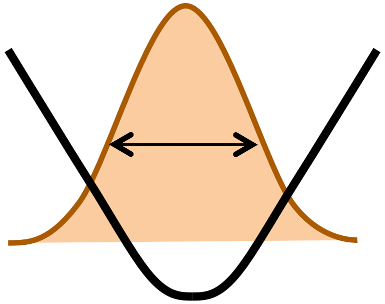
Following lectures

⇒ Much experimental information is obtained by switching off the confining trap and letting the gas free to expand

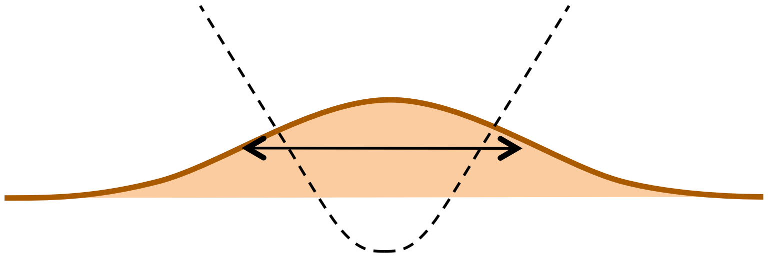




1. Let's consider the simple case of an ideal gas (Schrödinger equation)



$$\boxed{p \sim \frac{mr}{t}}$$



$$e^{-\frac{1}{2}\left(\frac{r}{a_\omega}\right)^2}$$

$$e^{-\frac{1}{2}\left(\frac{pa_\omega}{\hbar}\right)^2}$$

N.B. the phase evolves classically

$$\phi \sim \frac{mr^2}{2\hbar t}$$

2. For the thermal component, we will explicitly show that

$$\lim_{t\bar{\omega}\gg 1} n(\mathbf{r},t) \propto n(\mathbf{p} = \frac{m\mathbf{r}}{t})$$

Time of flight measurements

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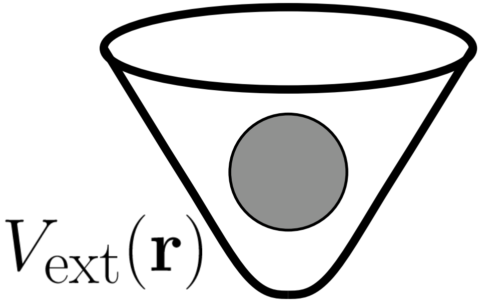
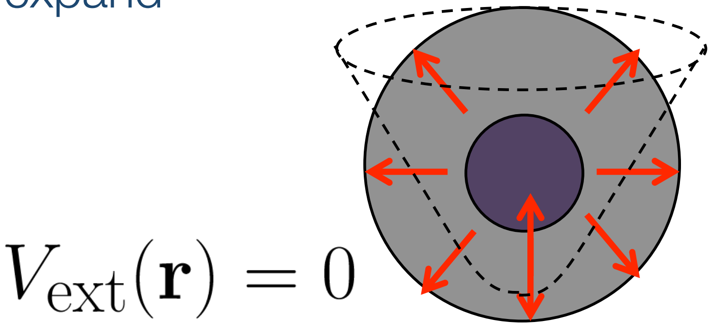
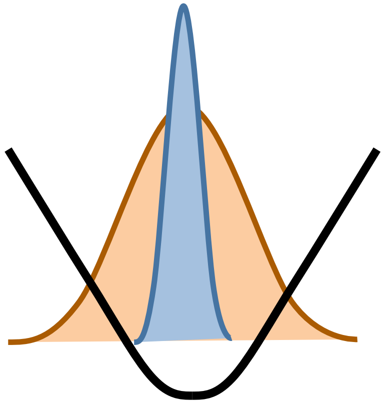
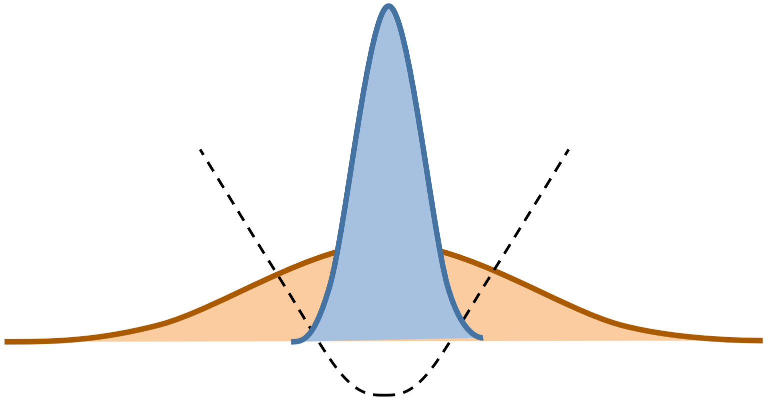




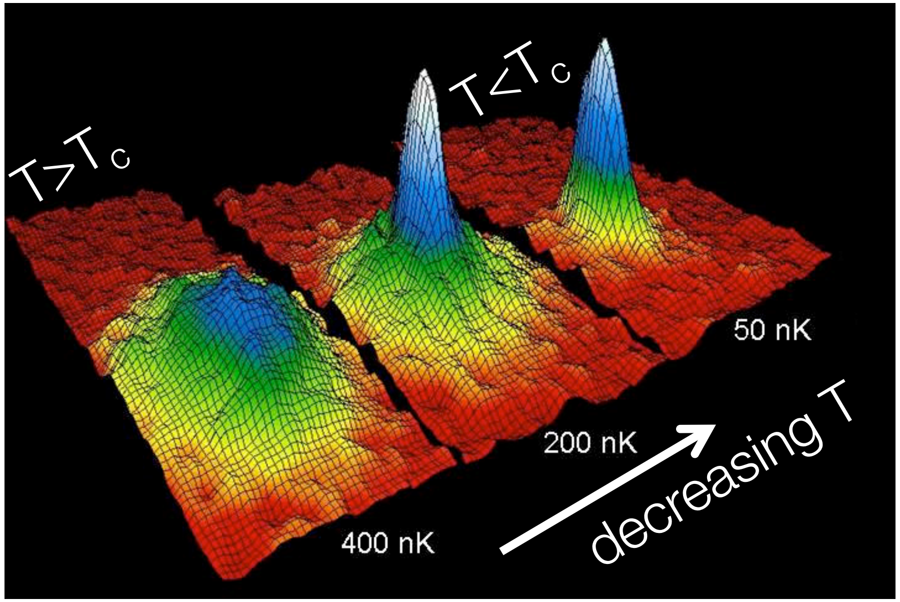
3. Bimodal distribution $n(r) = n_0(\mathbf{r}) + n_T(\mathbf{r})$





First realisation of a BEC in ultracold atoms

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



Coolest system in the universe!

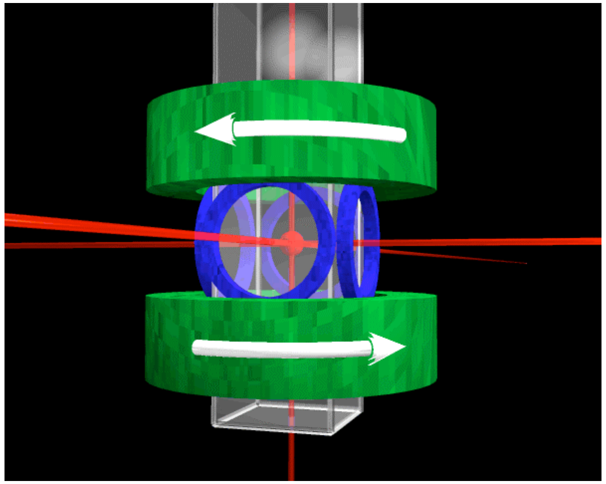
$$T \sim 500\text{nK} - \mu\text{K}$$
$$n \sim 10^{11} - 10^{13}\text{cm}^{-3}$$

Nobel prize (2001)

Carl Wieman & Eric Cornell

Wolfgang Ketterle

First BEC in ^{87}Rb (Boulder, June 1995)



$|F = 2, m_F = 2\rangle$

[M. H. Anderson *et al*. Science **269**, 198 (1995)]

oven $T \simeq 300\text{K}$

laser cooling $T \simeq 90\mu\text{K}$

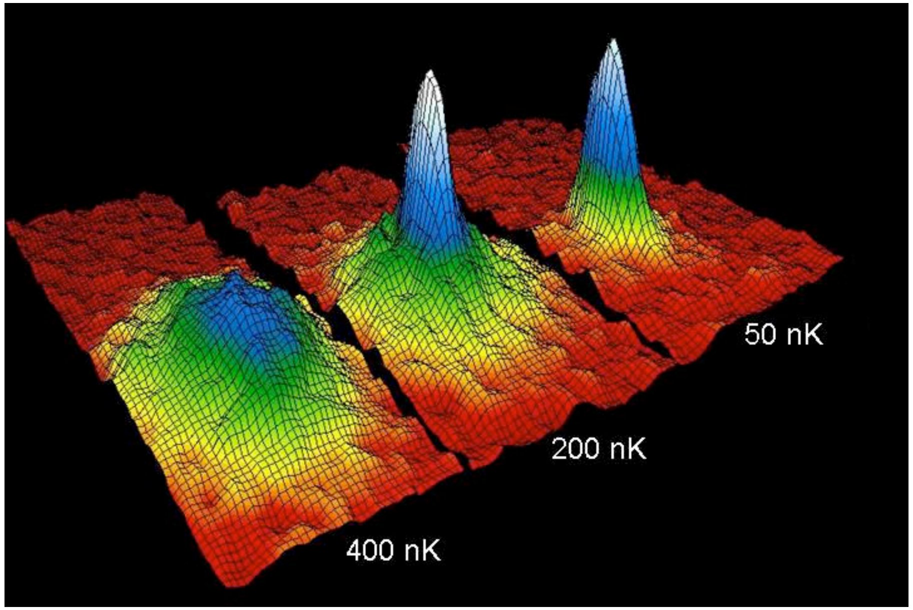
$n \simeq 2\ 10^{10}\ \text{cm}^{-3}$

⇒ evaporative cooling in TOP trap

$T_c \simeq 170\text{nK}$

$n \simeq 2.6\ 10^{12}\ \text{cm}^{-3}$

momentum distribution bimodality



expansion & probe

BEC in ^{23}Na (MIT, September 1995)

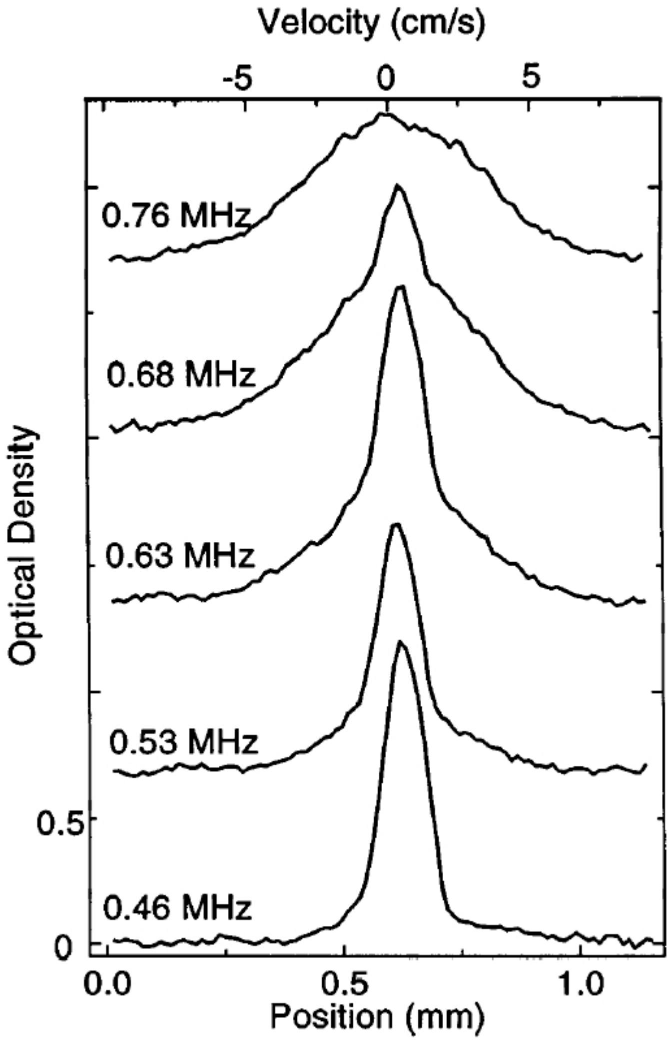
$$|F=1, m_F=-1\rangle$$

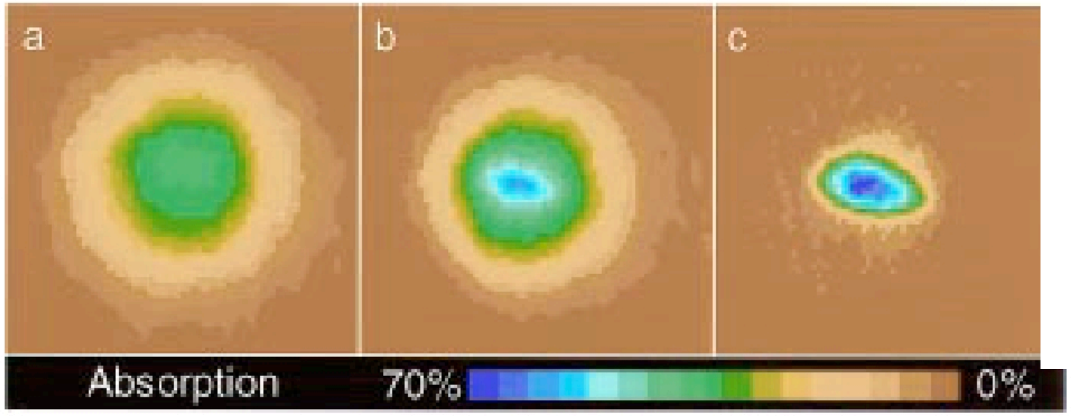
⇒ evaporative cooling in optical plug trap

$$T_c \simeq 2.0\mu\text{K}$$
$$n \simeq 1.5\ 10^{14}\ \text{cm}^{-3}$$

- Bimodal distribution
- Non-isotropic velocity distribution

[K. B. Davis *et al*. PRL **75**, 3969 (1995)]





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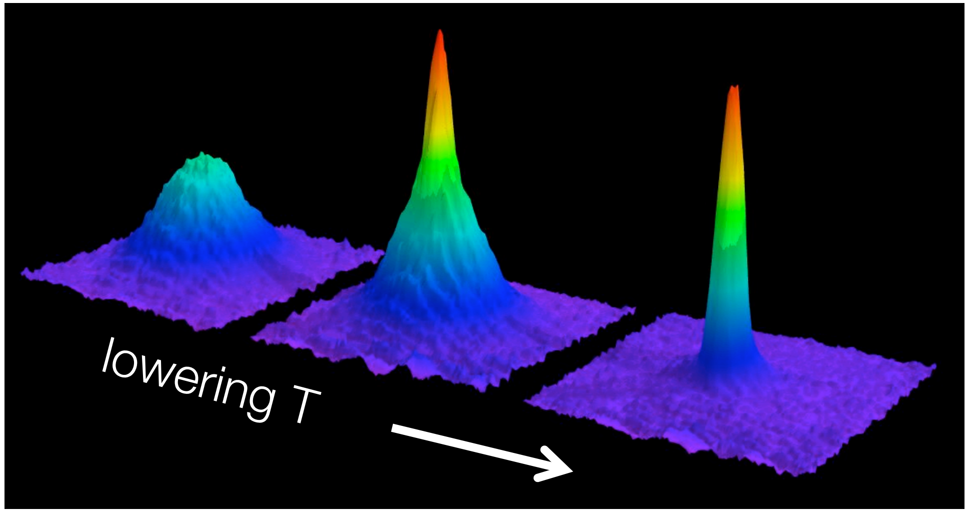
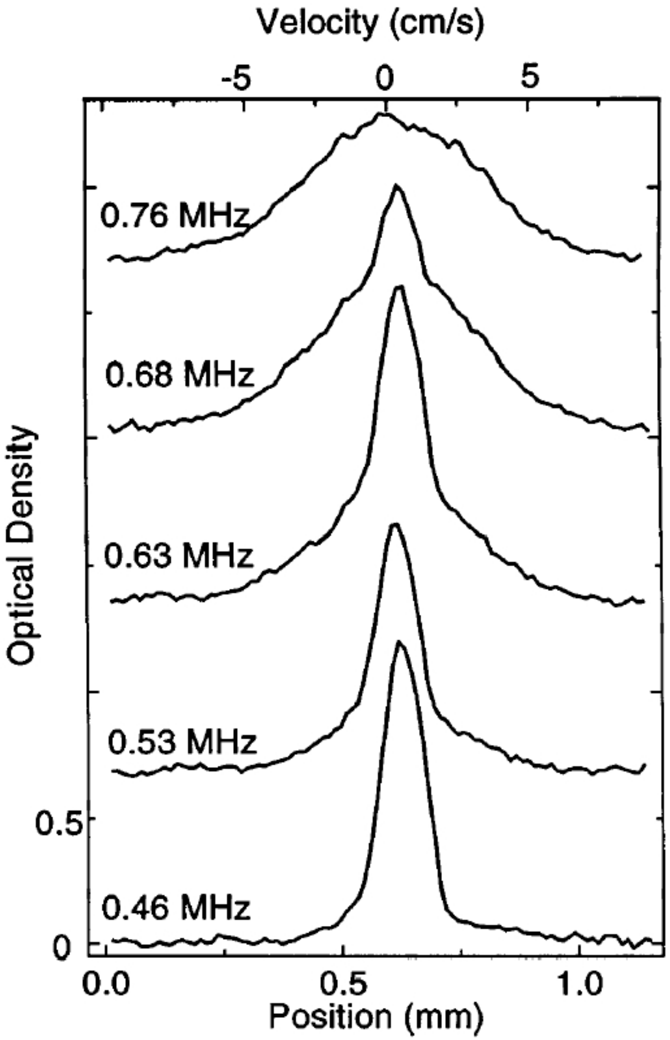


[K. B. Davis *et al*. PRL **75**, 3969 (1995)]



Extracting static quantities

Following lectures

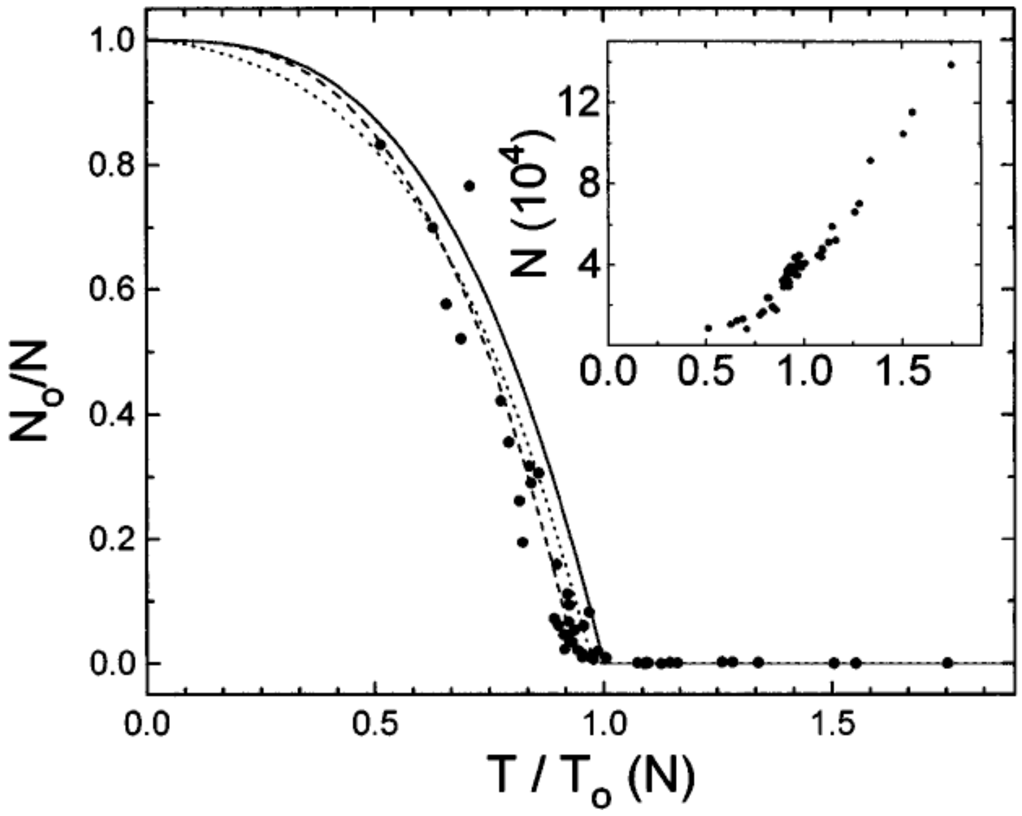
1. Temperature: determined by the shape of the spatial wings of the distribution (thermal cloud)
2. Chemical potential: given by the size of the condensate (Thomas-Fermi approximation)
3. Total number of atoms: integral of either the space or momentum distribution
4. Condensate fraction: bimodal distribution

Condensate fraction

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

$$k_B T_c = \frac{\hbar \omega \bar{N}^{1/3}}{[\zeta(3)]^{1/3}}$$

$$n_0 = 1 - \left(\frac{T}{T_c}\right)^3$$

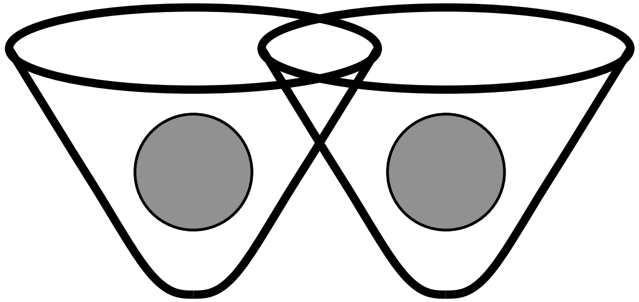


[J. R. Ensher *et al.*, PRL **77**, 4984 (1996)]

Macroscopic phase coherence

Following lectures

Interference between two condensates

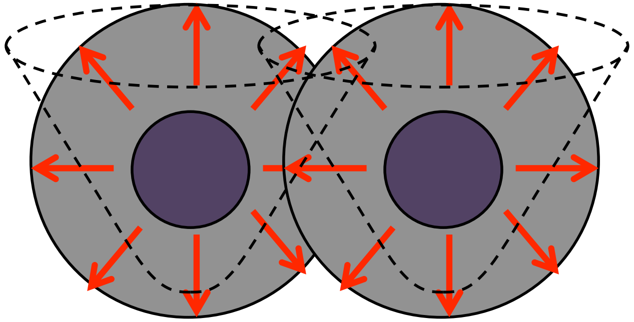


Macroscopic phase coherence

Following lectures

Interference between two condensates

(time of flight evolution)



Macroscopic phase coherence

Following lectures

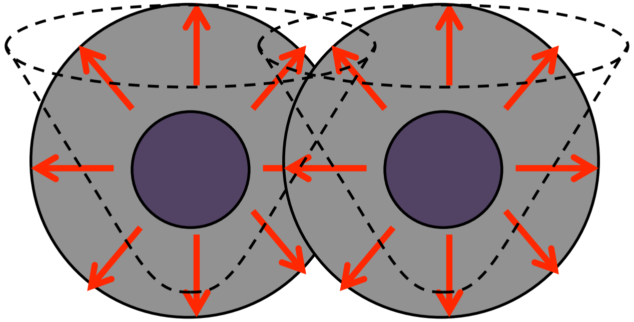
Interference between two condensates

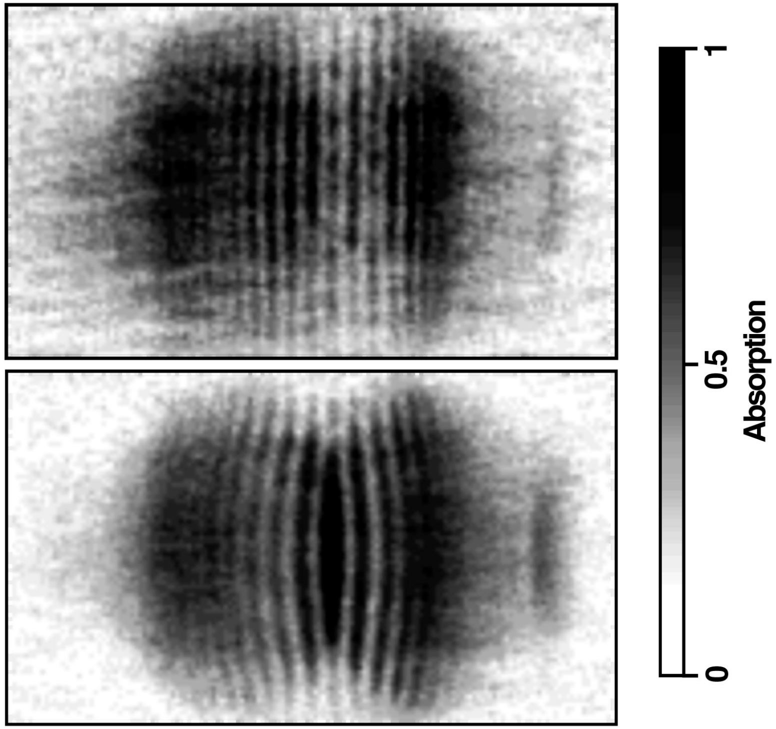
(time of flight evolution)

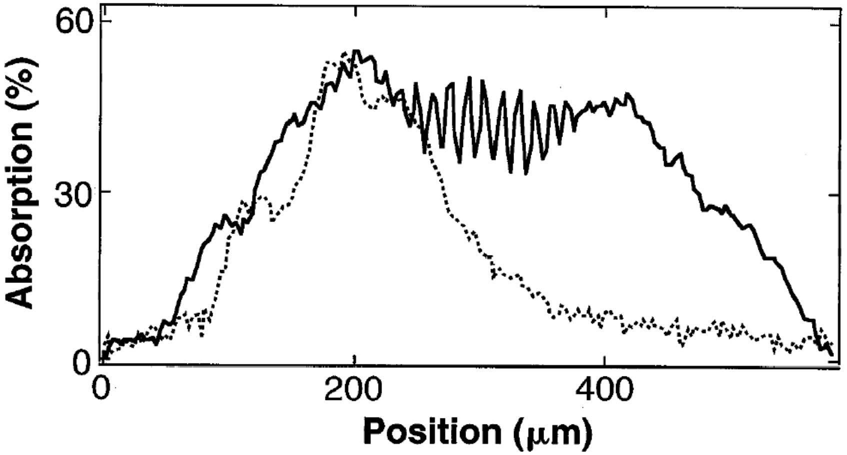
$$t = 40\text{ms}$$
$$d \simeq 40\mu\text{m}$$
$$\lambda \simeq 20\mu\text{m}$$

$$\boxed{\lambda = \frac{ht}{md}}$$

[M. R. Andrews *et al*. Science **275**, 637 (1997)]







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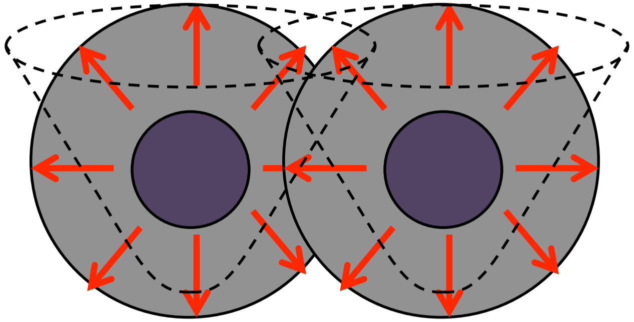
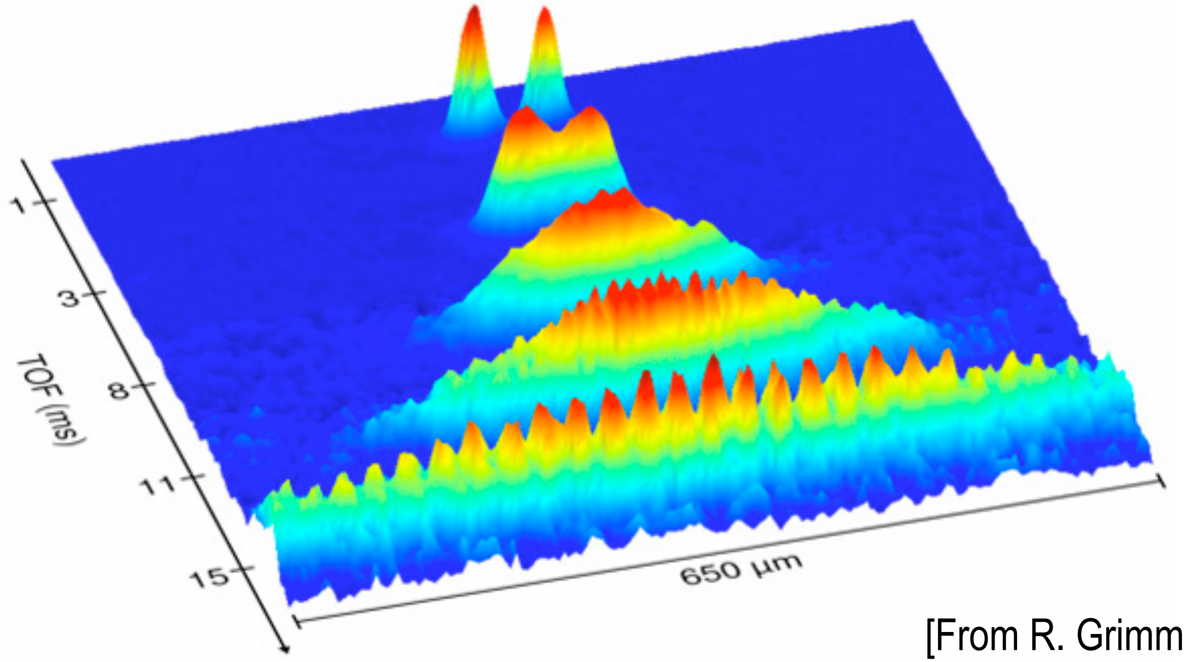


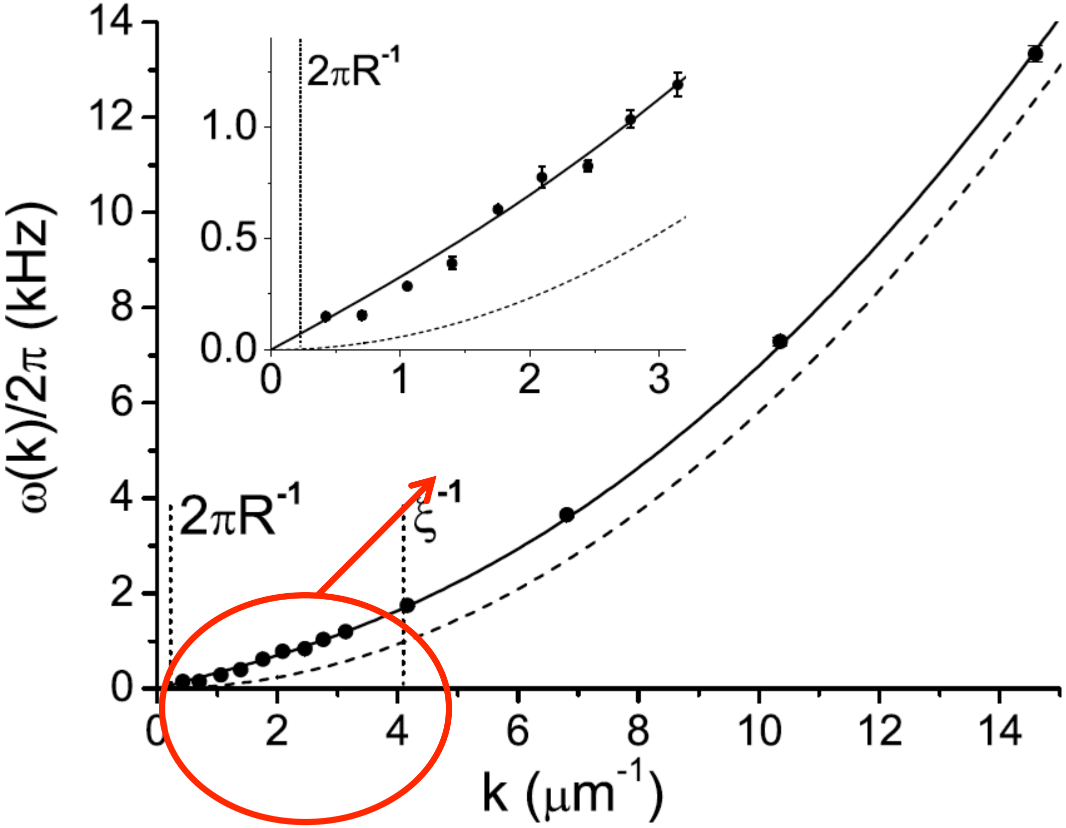


[From R. Grimm's group]

BEC & superfluidity

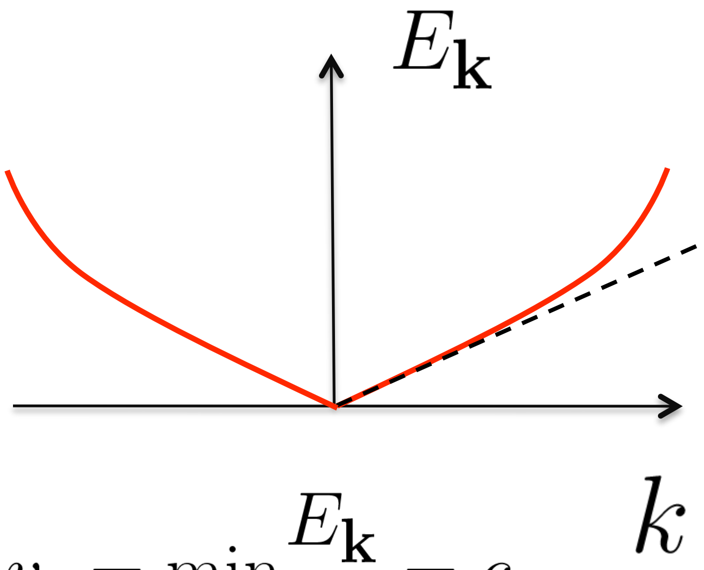
Spectrum of excitations

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



[Steinhauer *et al.* PRL (2002)]

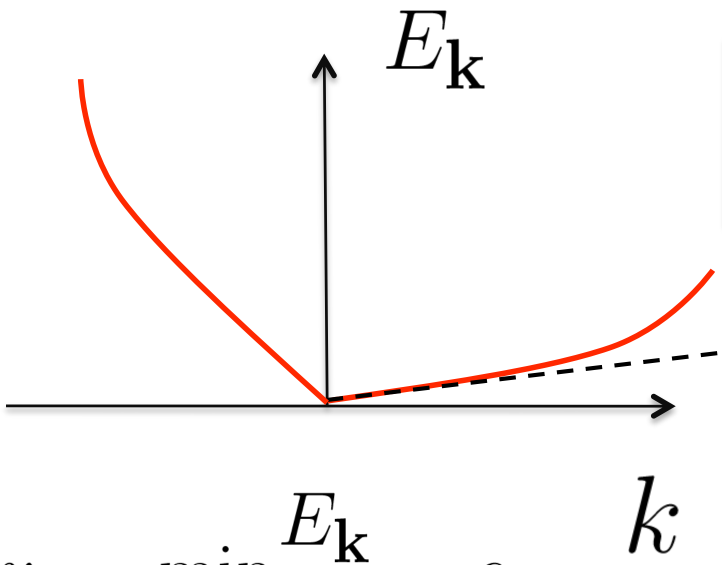
BEC & superfluidity



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

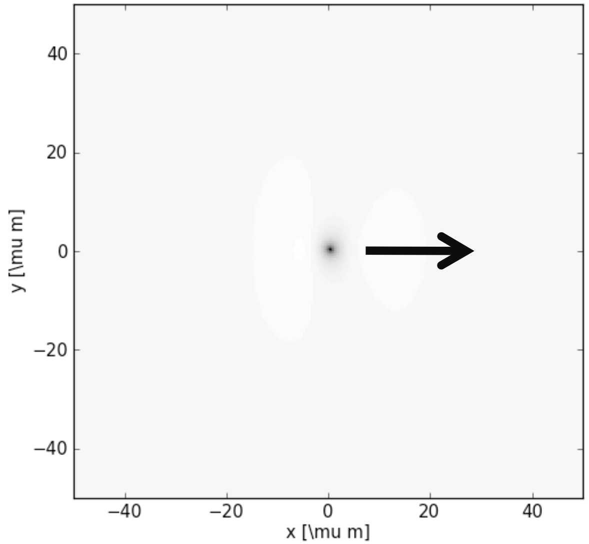
$$v_c = \min \frac{E_{\mathbf{k}}}{k} = c_s$$

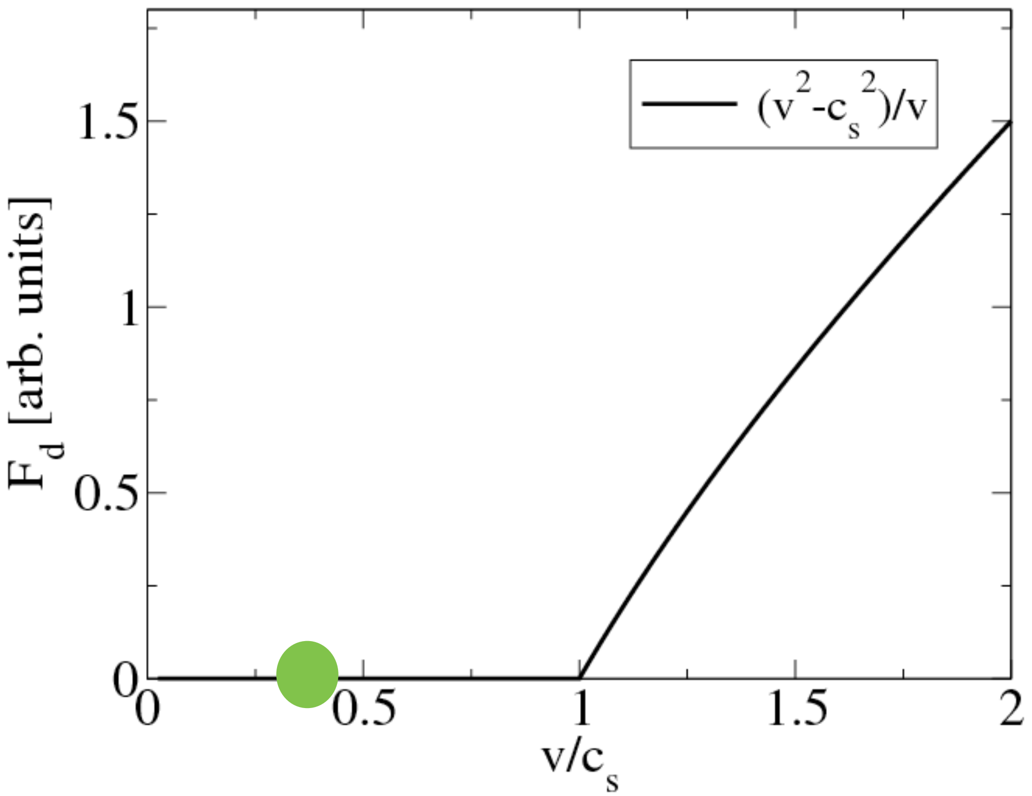
BEC & superfluidity



$$\boxed{c_s - v > 0}$$

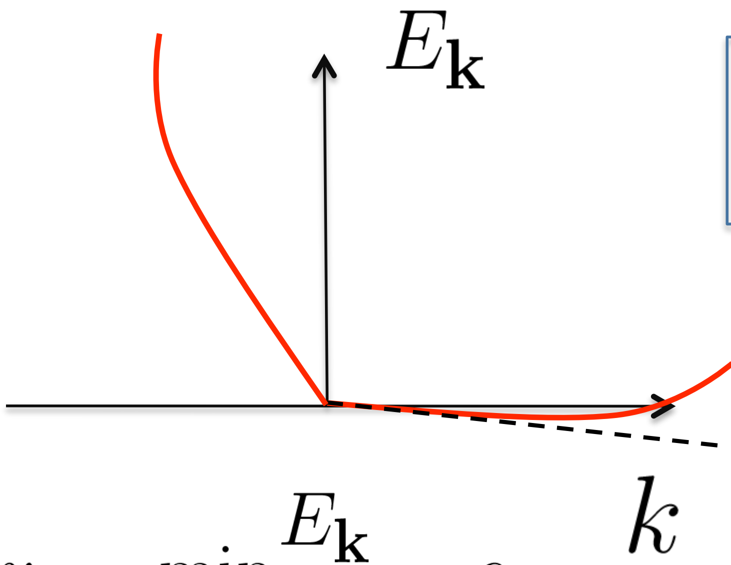
$$v_c = \min \frac{E_{\mathbf{k}}}{k} = c_s$$





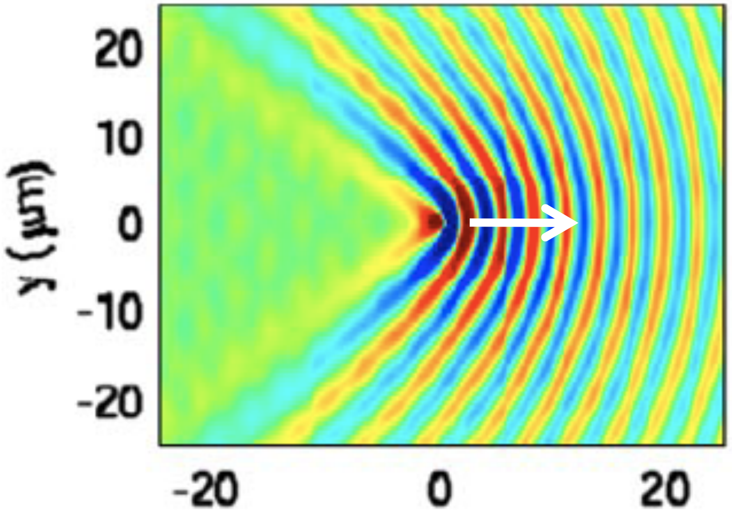
[G. E. Astrakharchik and L. P. Pitaevskii, PRA (2004)]
[I. Carusotto et al., PRL (2006)]

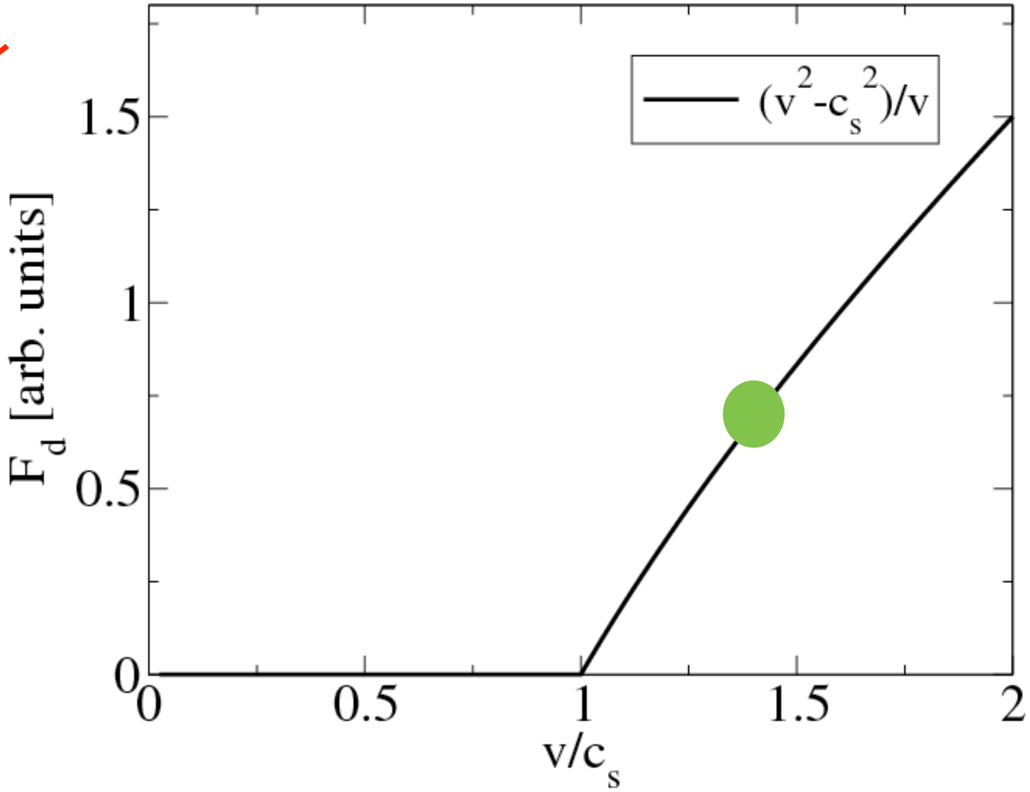
BEC & superfluidity



$$\boxed{c_s - v < 0}$$

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





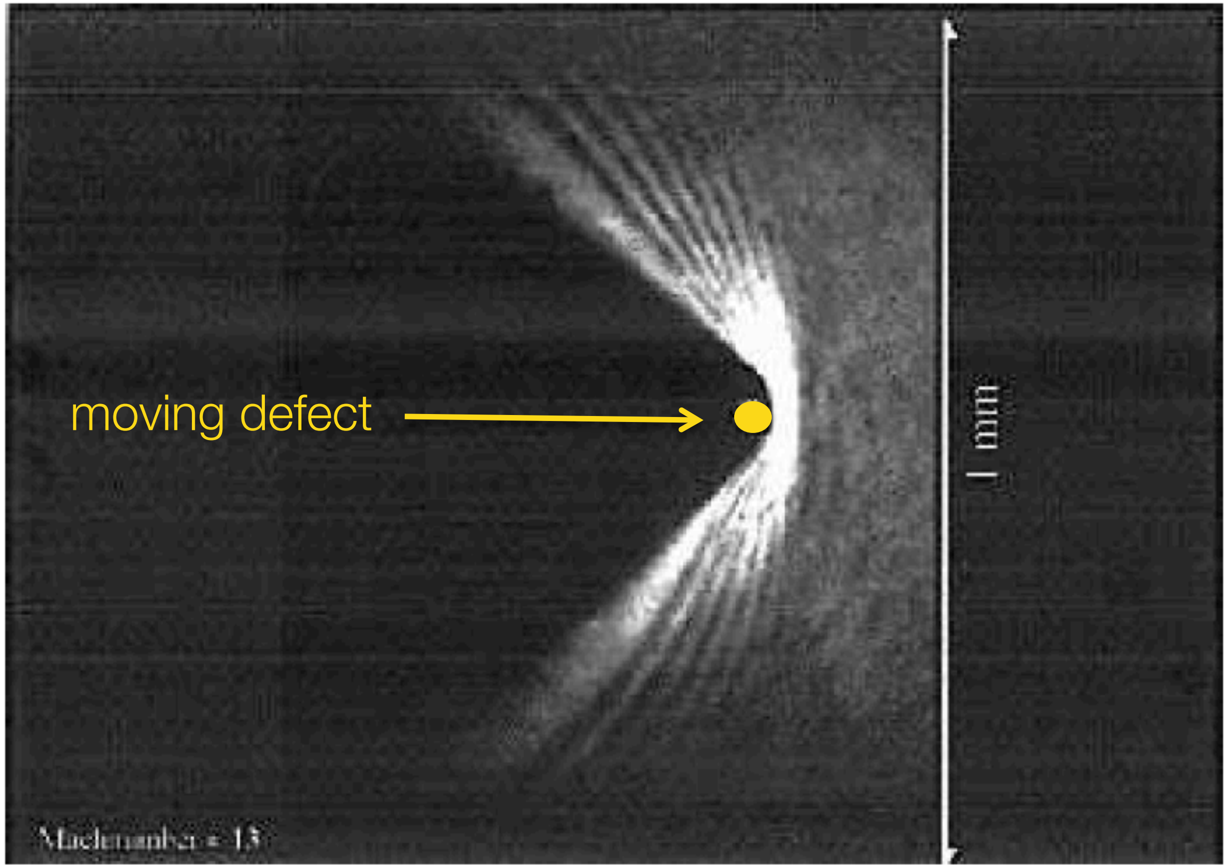
[G. E. Astrakharchik and L. P. Pitaevskii, PRA (2004)]
[I. Carusotto et al., PRL (2006)]

BEC & superfluidity

$$v < v_c$$

BEC & superfluidity

$$v > v_c$$



[from E. Cornell's group]

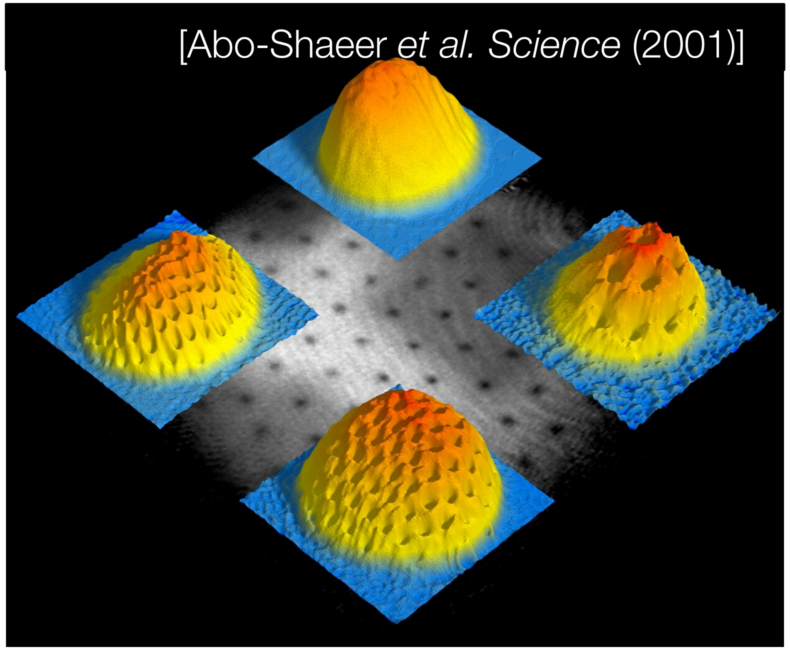
BEC & superfluidity

Quantised vortices in rotating condensates

$$\oint \mathbf{v}_s \cdot d\mathbf{l} = 2\pi\frac{\hbar}{m}(0, \pm 1, \ldots)$$

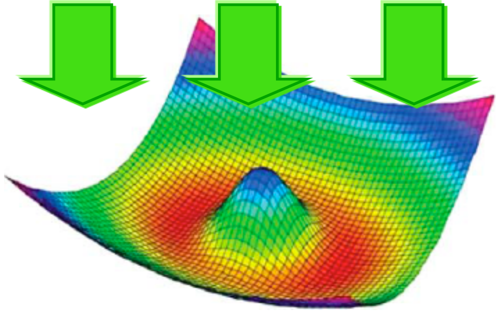
ground state is flowless & vortices need external driving

vortices are unstable solutions if rotation is halted

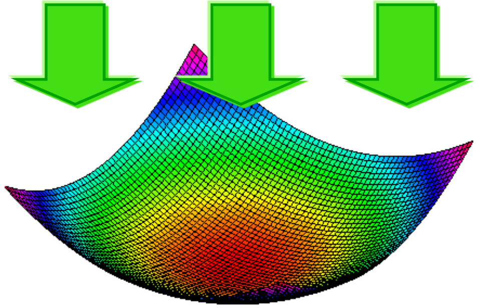

[Abo-Shaeer *et al. Science* (2001)]

BEC & superfluidity

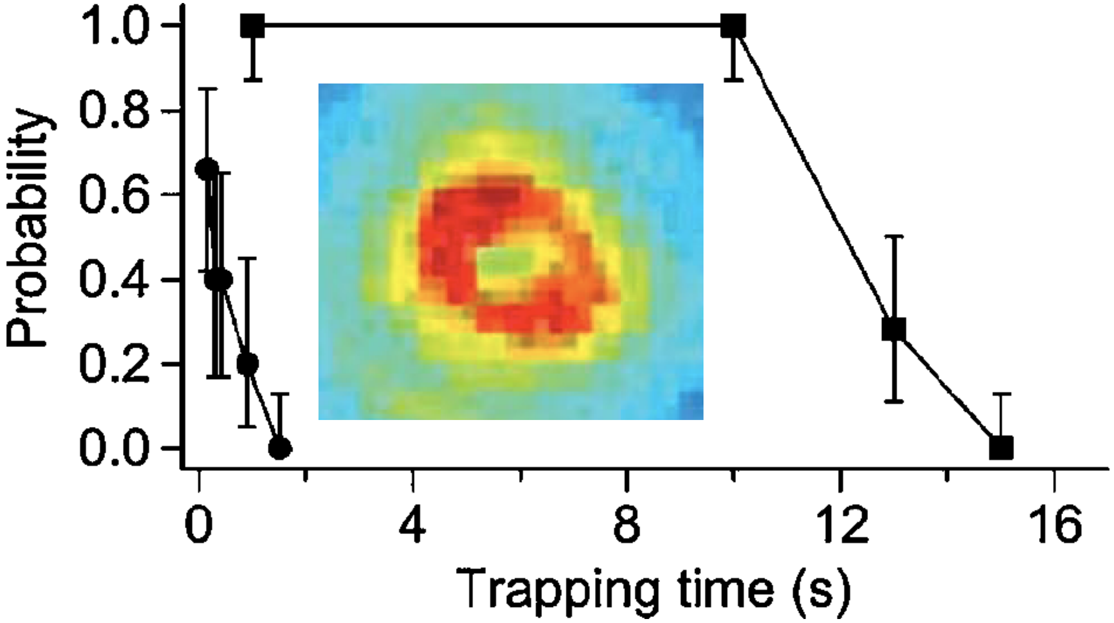
Metastable persistent flow



Gauss-Laguerre beam
('rotating drive')

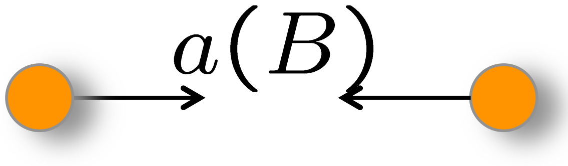


[Ryu *et al. PRL* (2007)]



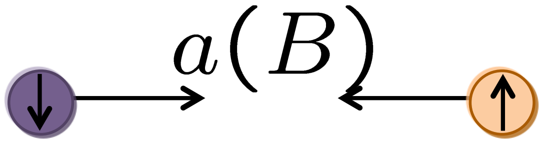
BEC-BCS crossover

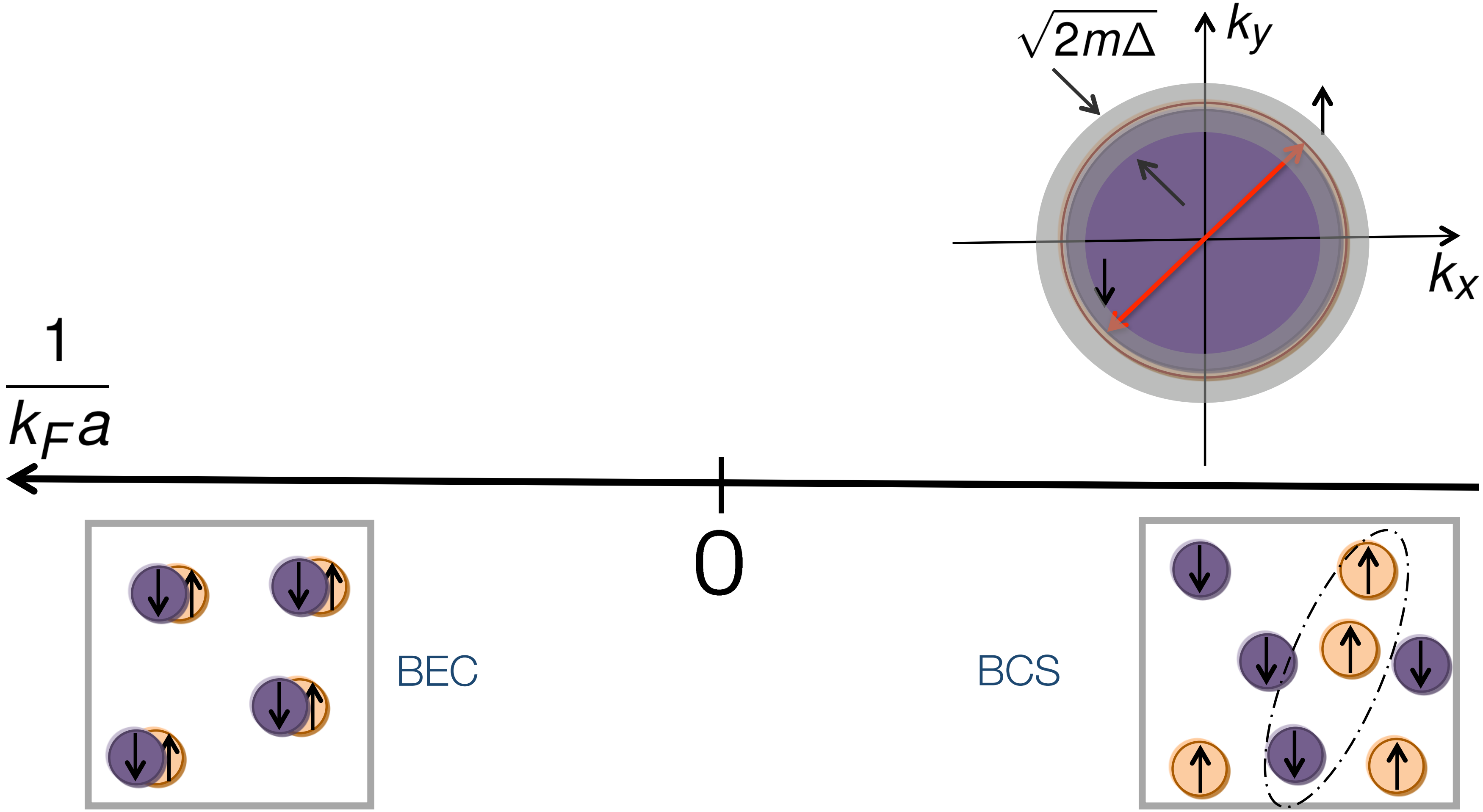
- Tune the interaction strength (Feshbach resonances)



BEC-BCS crossover

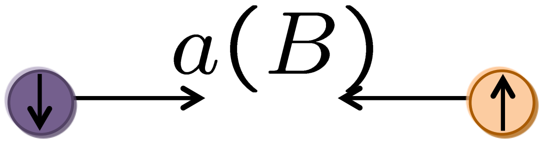
- Tune the interaction strength (Feshbach resonances)





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