World of ultracold atoms

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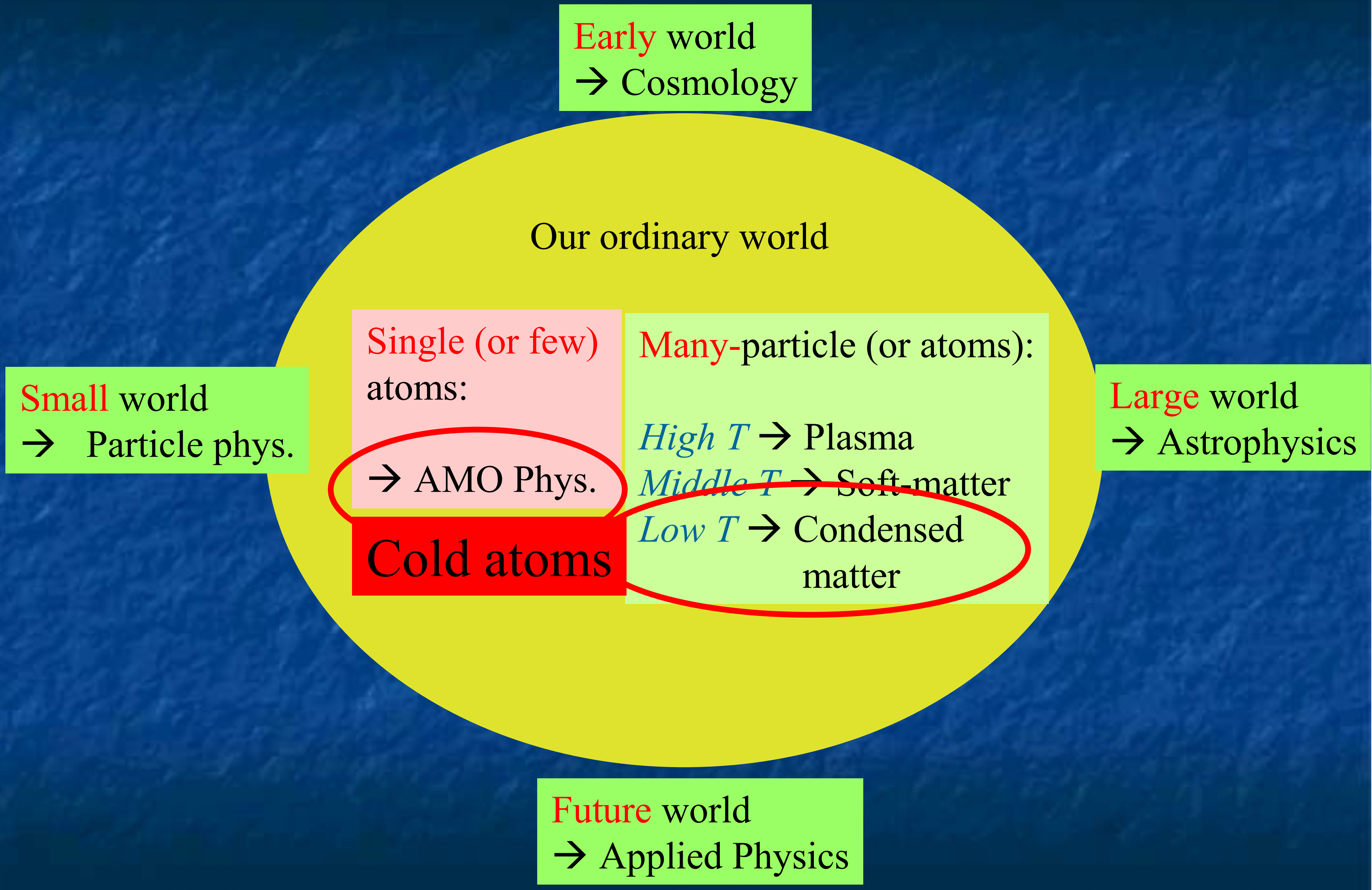


Early world
→ Cosmology

Our ordinary world

Small world
→ Particle phys.

Single (or few) atoms:
→ AMO Phys.

Cold atoms

Many-particle (or atoms):
High T → Plasma
Middle T → Soft-matter
Low T → Condensed matter

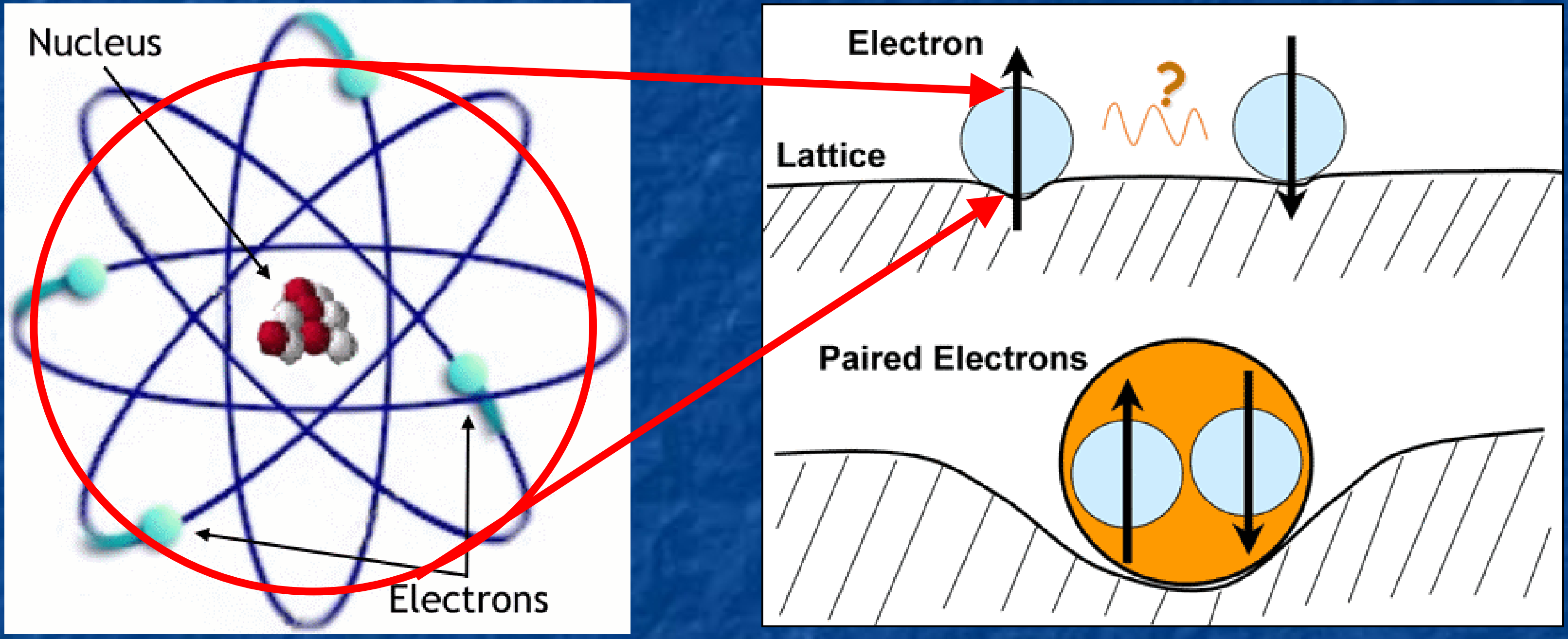
Large world
→ Astrophysics

Future world
→ Applied Physics

Ultracold atoms as an emergent field….

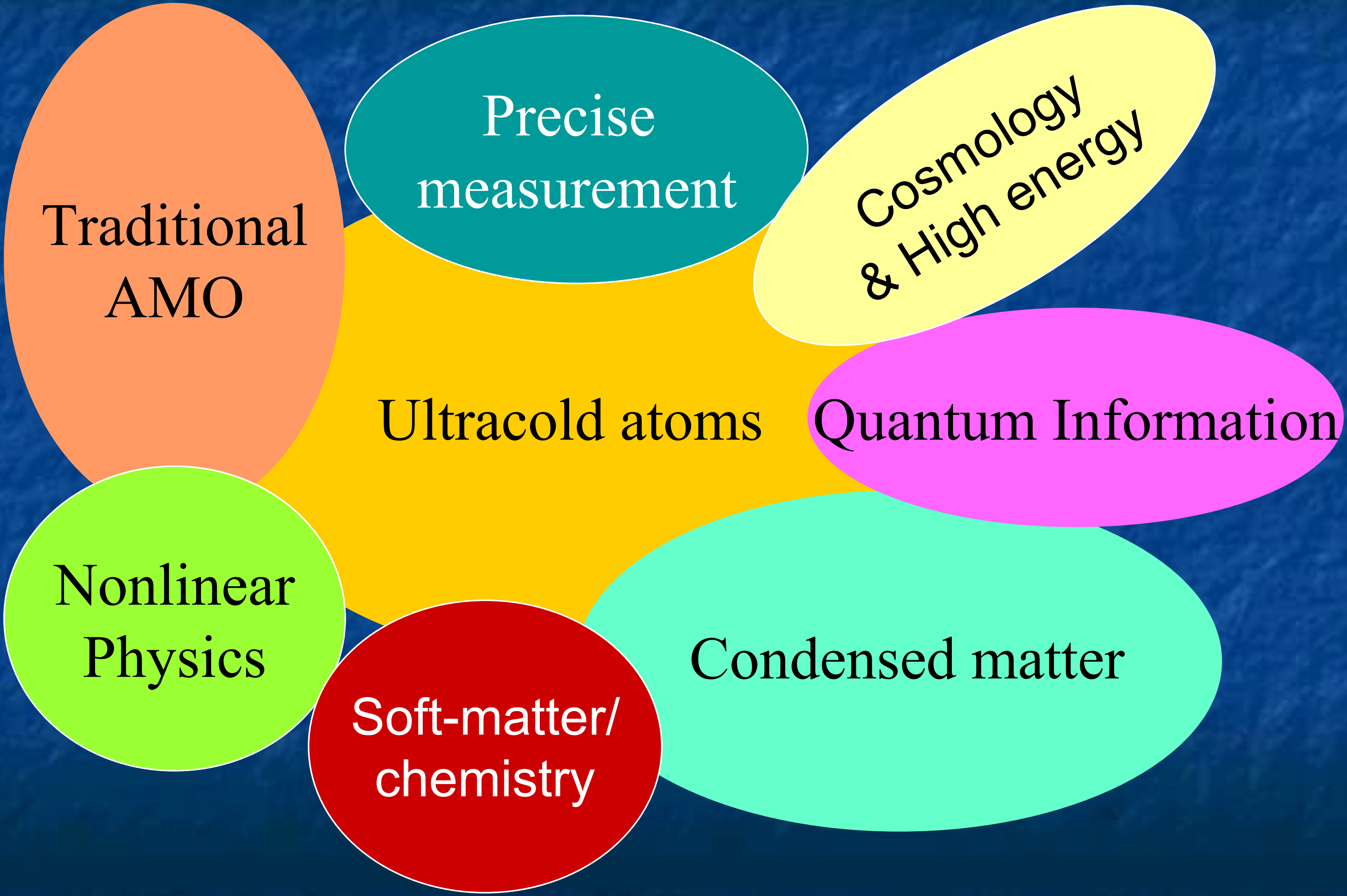
Atomic, Molecular, and Optical Physics

Condensed matter Physics



Systems of ultracold atoms can be understood as a many-body system of atoms, which are strongly affected by the fruitful internal degrees of freedom of each single atom.

An Interdisciplinary field



Traditional AMO

Precise measurement

Cosmology & High energy

Ultracold atoms

Quantum Information

Nonlinear Physics

Soft-matter/ chemistry

Condensed matter

How cold is an "ultracold system" ?

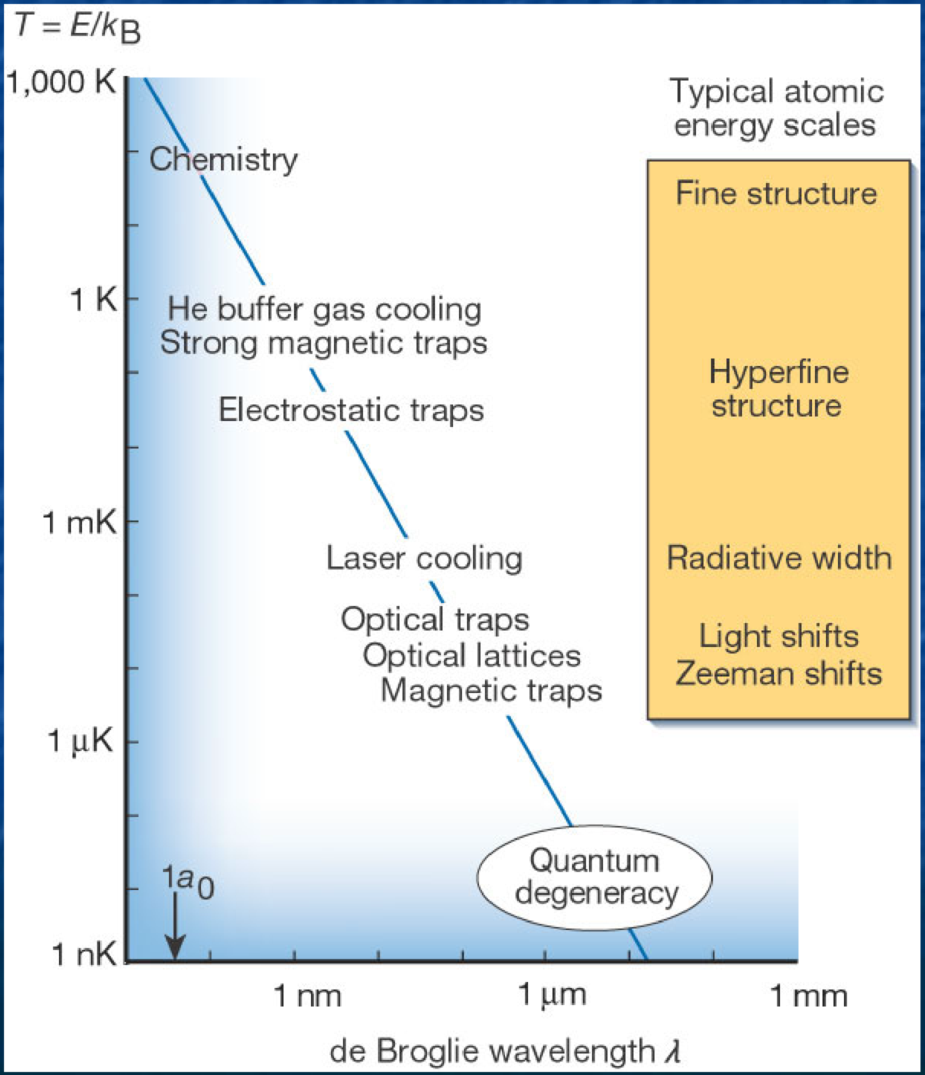
Thermal wavelength

$$k_B T \sim \frac{\hbar^2}{2m}\left(\frac{2\pi}{\lambda}\right)^2$$

Quantum degeneracy:

$\lambda \sim L \sim 1-100\mu\text{m}$

$T < 1\mu\text{K}$



Why low temperature ?

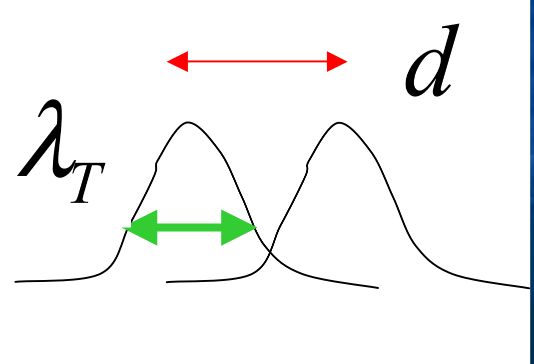
Ans: To see the quantum effects !

Uncertainty principle: $\Delta x \Delta p \geq \hbar$

$$\frac{\Delta p^2}{2m} \sim k_B T \rightarrow \Delta x \sim \frac{\hbar}{\Delta p} \sim \frac{\hbar}{\sqrt{2mk_B T}} \equiv \lambda_T, \text{ Thermal wavelength}$$

Therefore, if $T \downarrow \ \Rightarrow \lambda_T \uparrow$

Quantum regime when $\lambda_T \geq d \sim n^{-1/3}$



Why strong interaction ?

P. Anderson: “Many is not more”

Because interaction can make
“many” to be “different” !

Example: 1D interacting electrons
→ crystalization and no fermionic excitation

How to make interaction stronger ?

$$H = \sum_{j=1}^{N} \left(\frac{\mathbf{p}_j^2}{2m} + V(x_j) \right) + \frac{1}{2} \sum_{i \neq j}^{N} U(x_i - x_j)$$

1. $U(x)$ becomes stronger

2. $E_k \sim k_B T$ becomes smaller or m becomes smaller

3. $V(x)$ changes to make lower dimension

4. N becomes larger (for short interaction);
   smaller for long range interaction

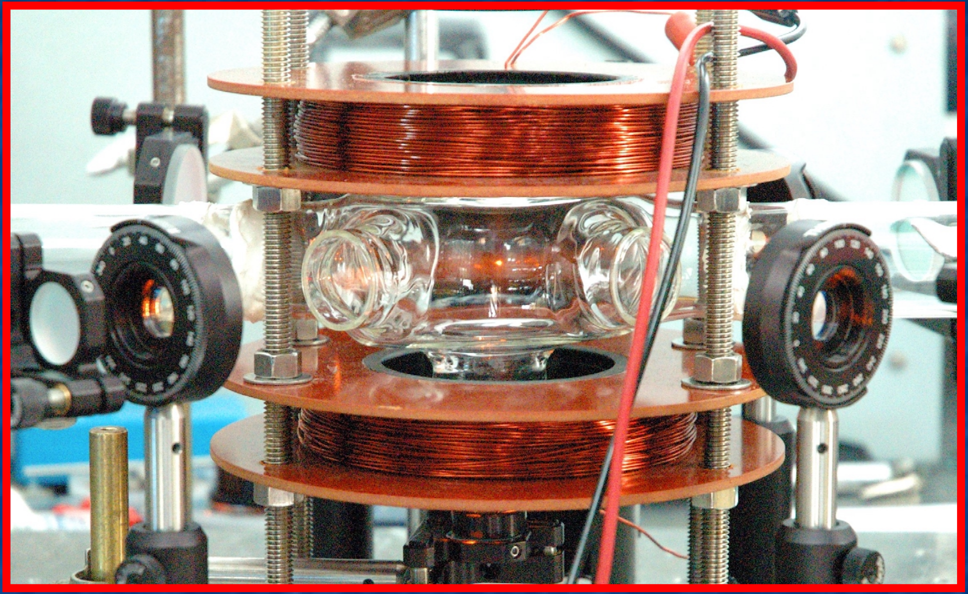
How to reach ultracold temperature ?

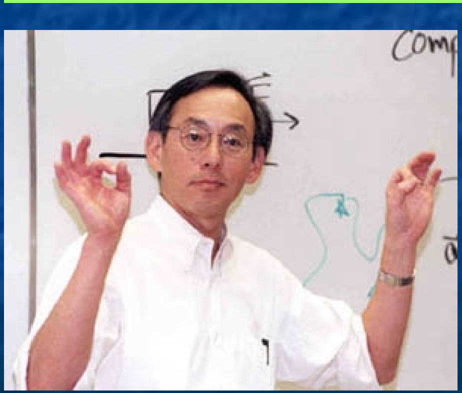
See also: Prof. Yu’s talk

1. Laser cooling !
(few K→ mK)

Use red detune laser
+ Doppler effect

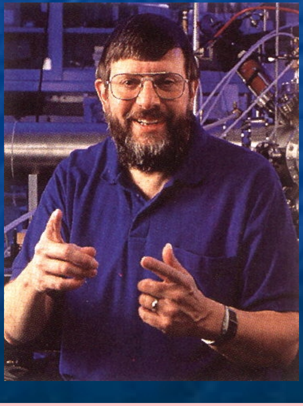
1997 Nobel Price





Steven Chu

Claude Cohen-Tannoudji

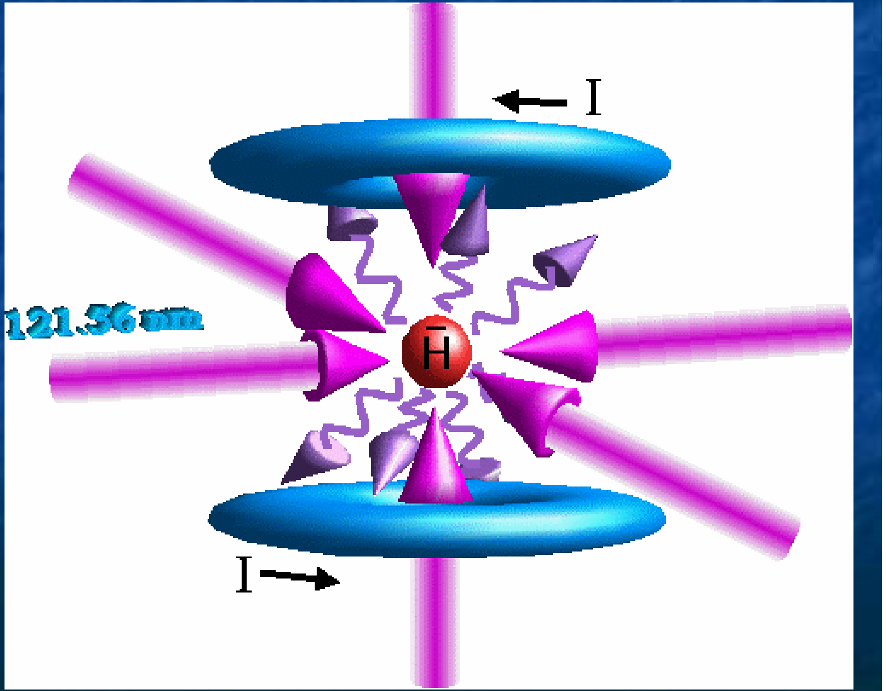


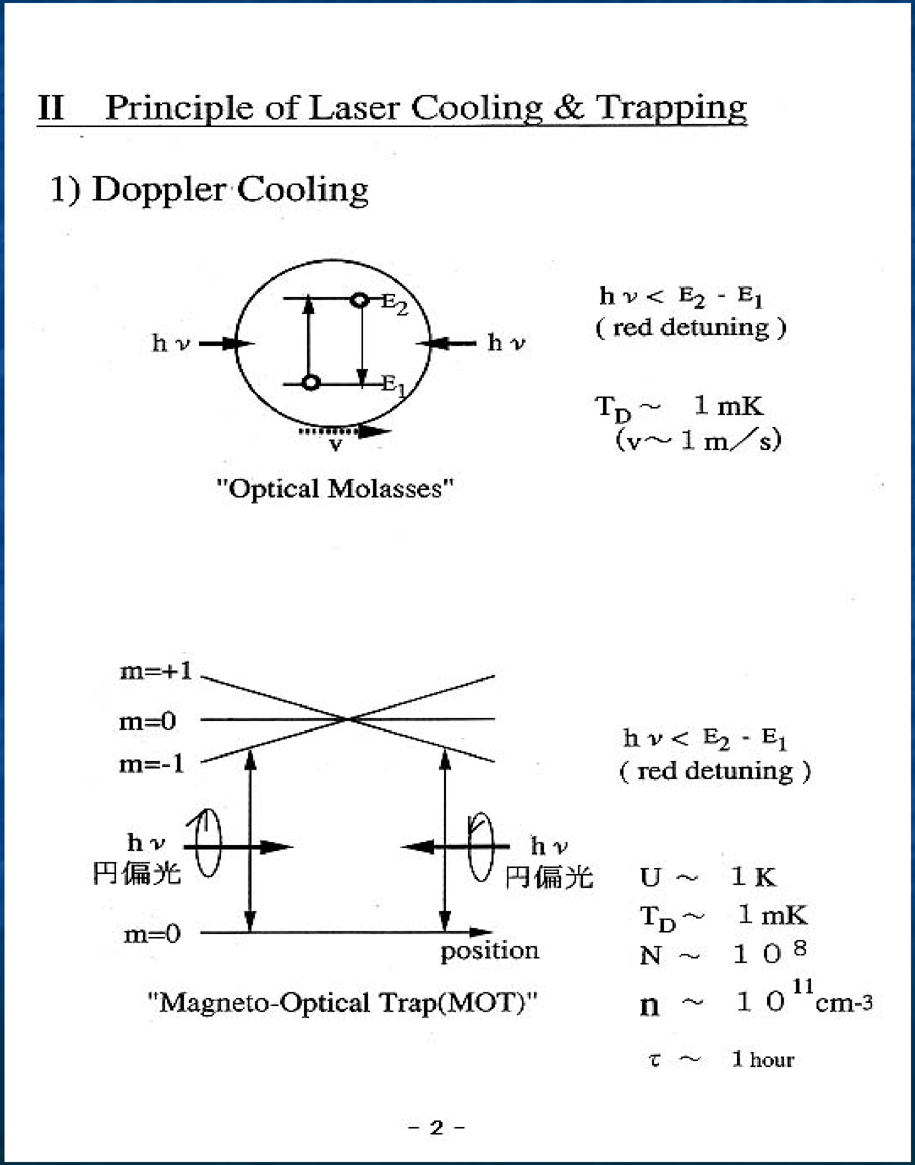
Williams D. Phillips

How to reach ultracold temperature ?

1. Laser cooling !
(1997 Nobel Price)

Use red detune laser
+ Doppler effect





II Principle of Laser Cooling & Trapping

1) Doppler Cooling

$h\nu < E_2 - E_1$
(red detuning)

$T_D \sim$ 1 mK
($v \sim$ 1 m/s)

"Optical Molasses"

$h\nu < E_2 - E_1$
(red detuning)

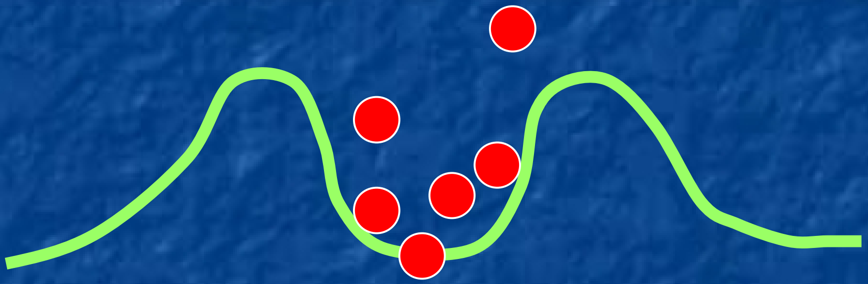
"Magneto-Optical Trap(MOT)"

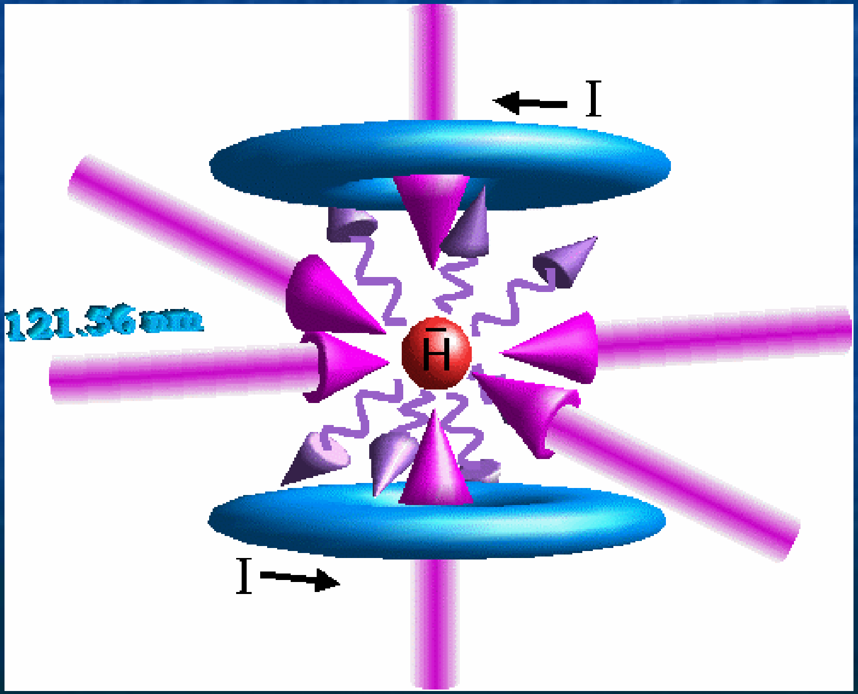
$U \sim$ 1 K
$T_D \sim$ 1 mK
$N \sim 10^8$
$n \sim 10^{11}$ cm-3
$\tau \sim$ 1 hour

How to reach ultracold temperature ?

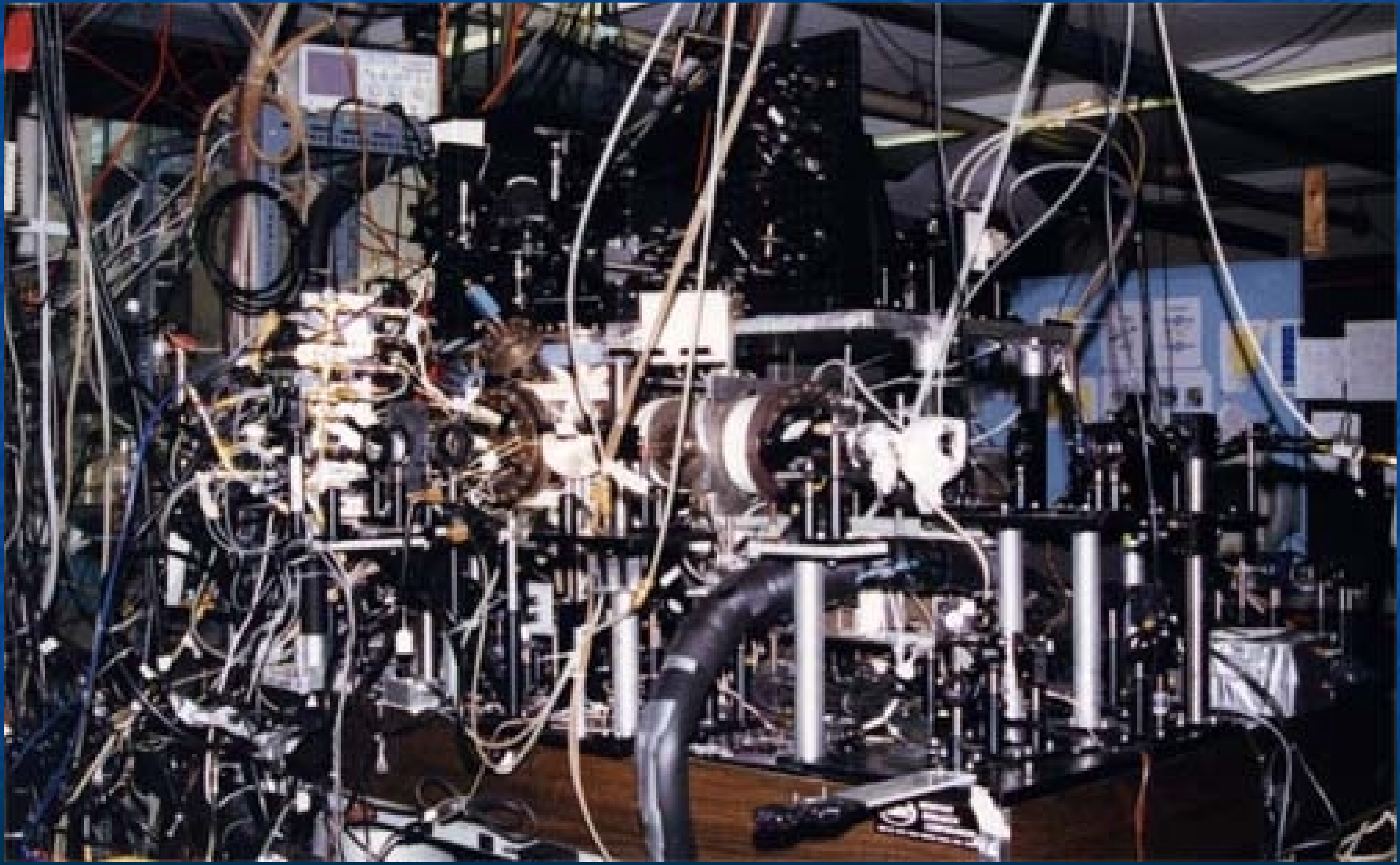
2. Evaporative cooling !

Reduce potential barrial
+thermal equilibrium



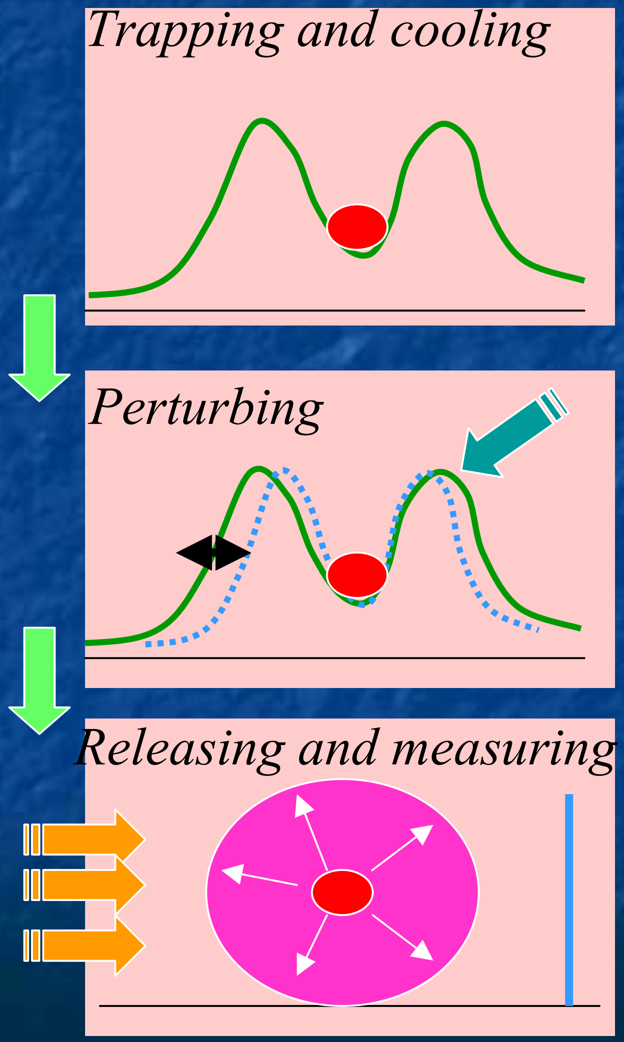


Typical experimental environment



MIT

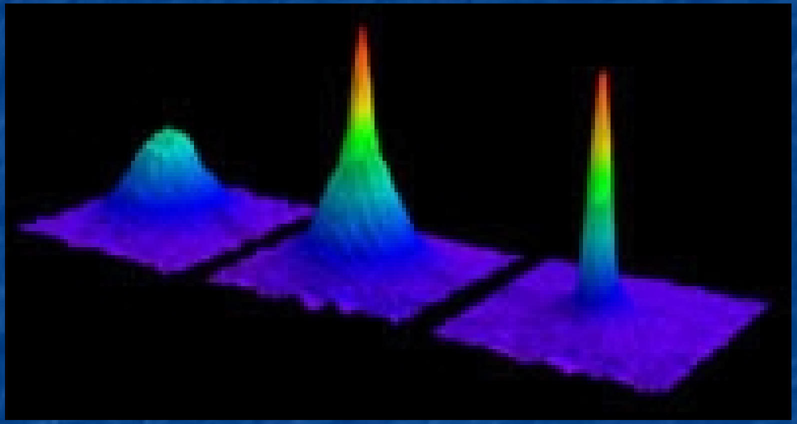
How to do measurement ?



Trapping and cooling

Perturbing

Releasing and measuring



BEC

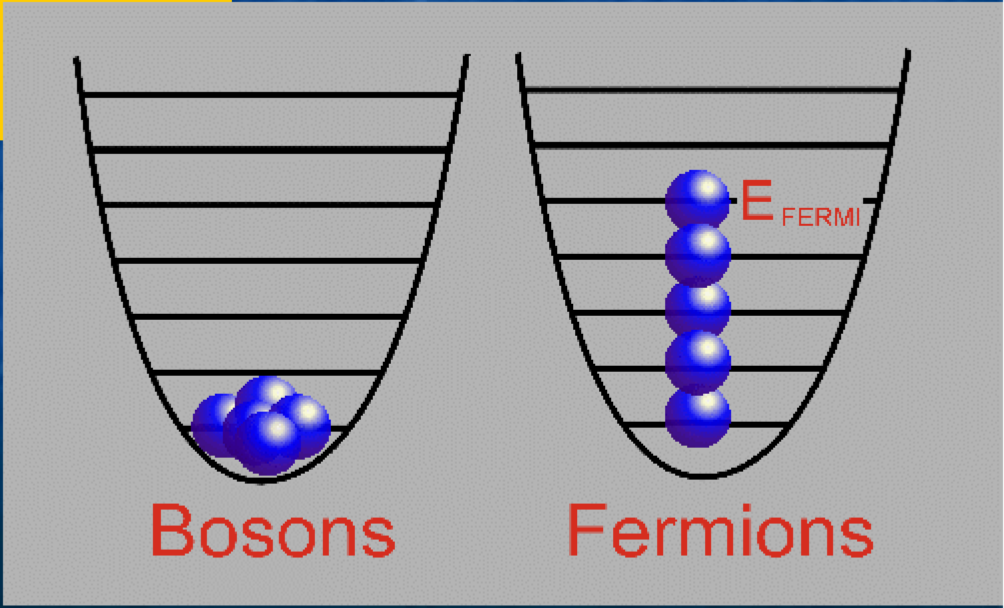
(2001 Nobel Price)

What is Bose-Einstein condensation ?

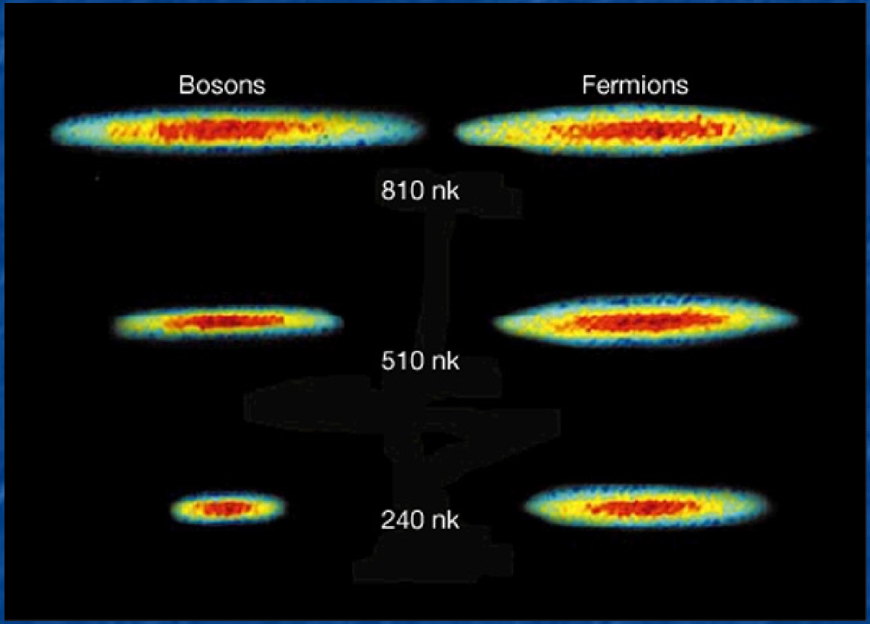
$\Psi(x_1, x_2) = \pm\Psi(x_2, x_1)$, + for boson and - for fermion

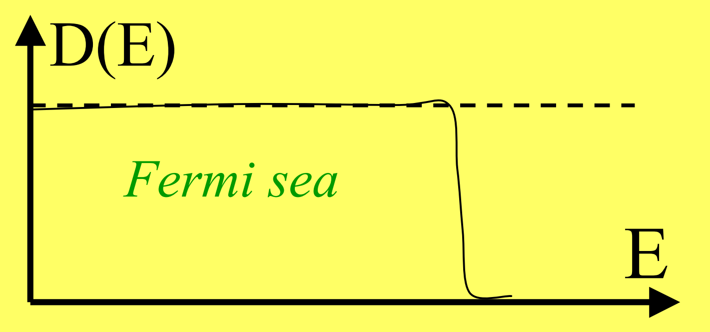
Therefore, for fermion we have $\Psi(x, x) = 0$,
i.e. fermions like to be far away,
but bosons do like to be close !

When T is small enough, noninteracting bosons like to stay in the lowest energy state, i.e. BEC

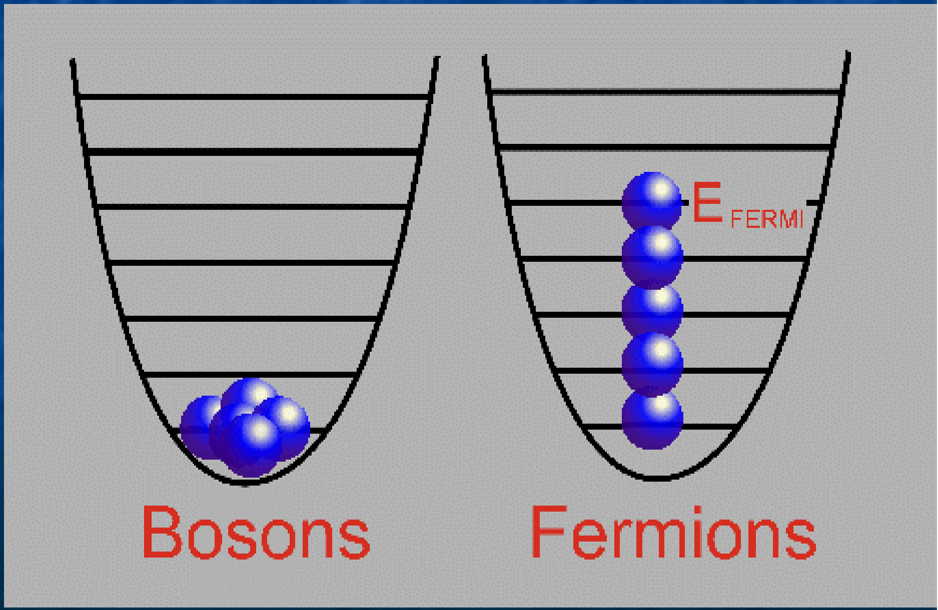


How about fermions in T=0 ?

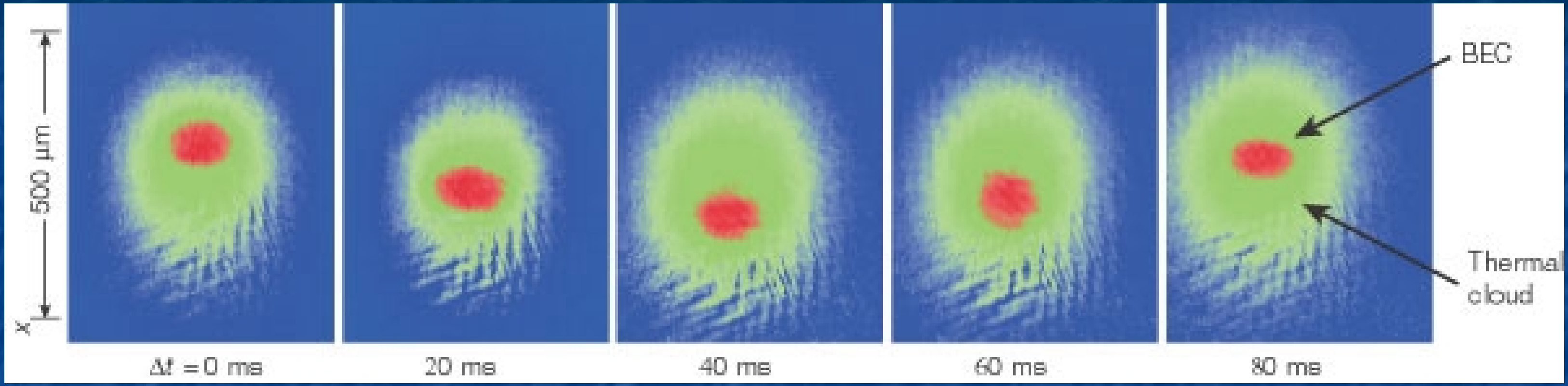




When T-> 0, noninteracting fermions form a compact distribution in energy level.

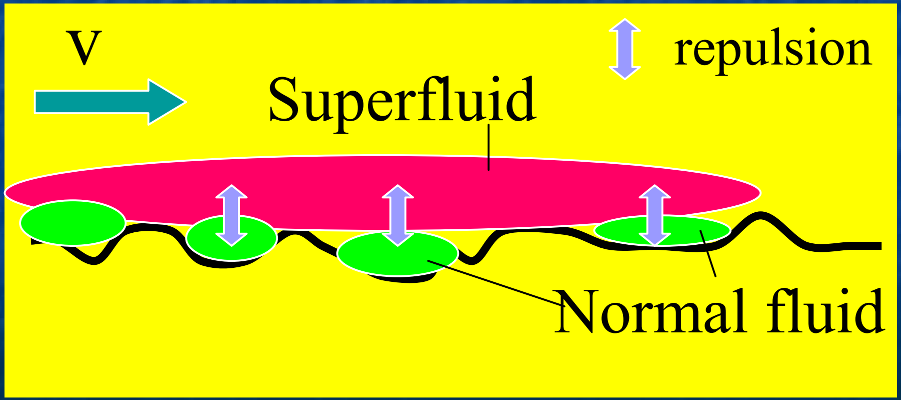


BEC and Superfluidity of bosons



(after Science, **293**, 843 ('01))

BEC ≠ superfluidity



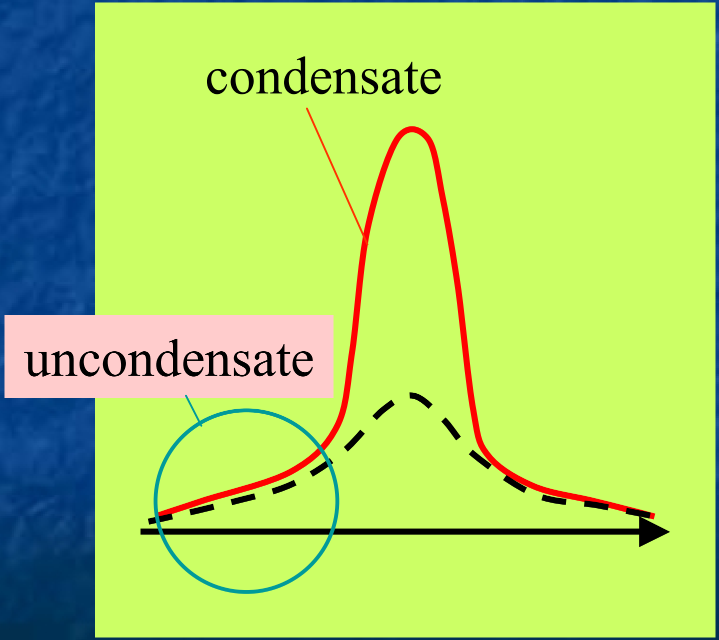
V

repulsion

Superfluid

Normal fluid

Landau's two-fluid model

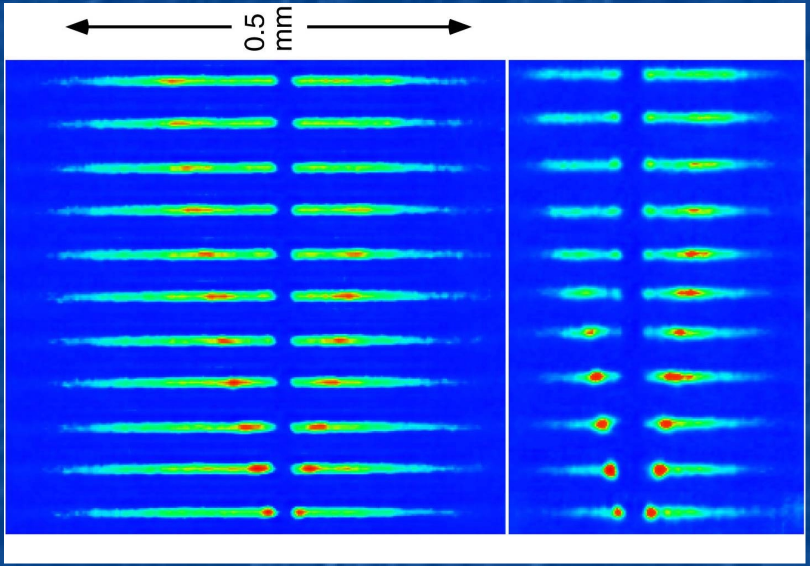


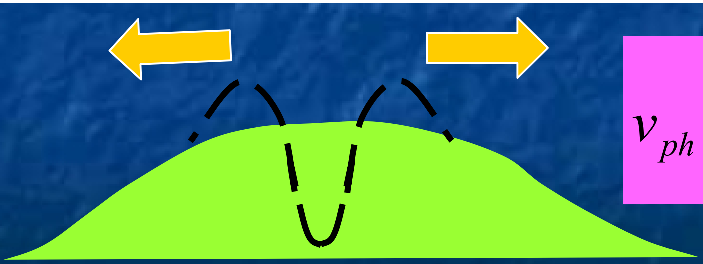
condensate

uncondensate

Phonons and interference in BEC

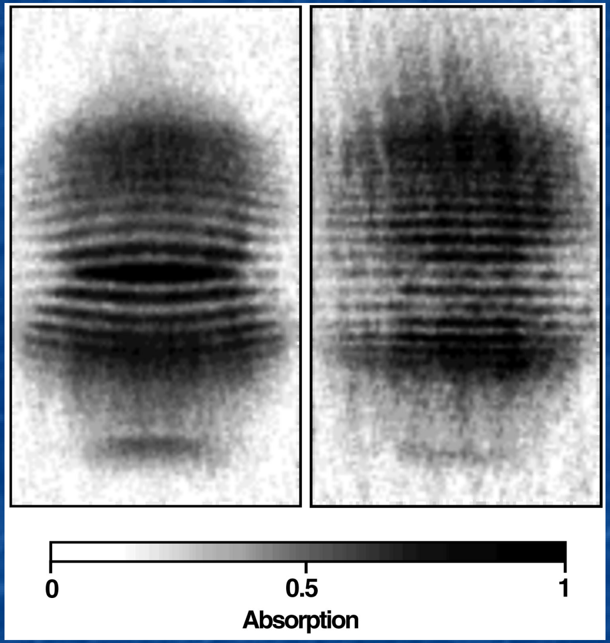
Phonon=density fluctuation





$$v_{ph} = \sqrt{\frac{n_0 U}{m}}$$

Interference

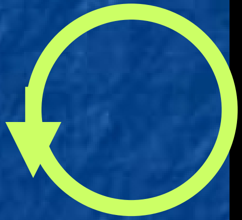


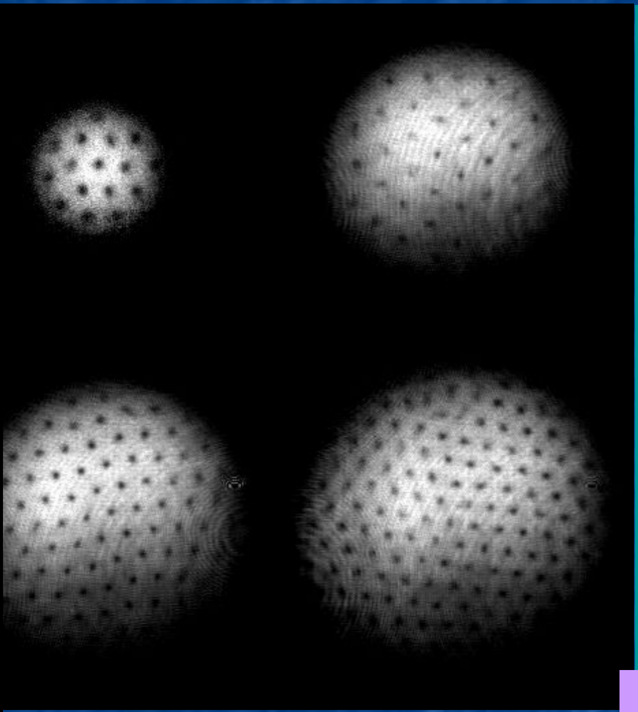
(after Science **275**, 637 ('97))

Matter waves ?

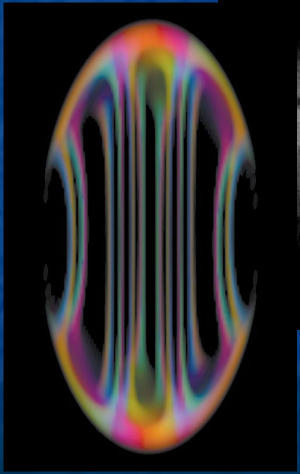
Vortices in condensate

Vortex = topological disorder

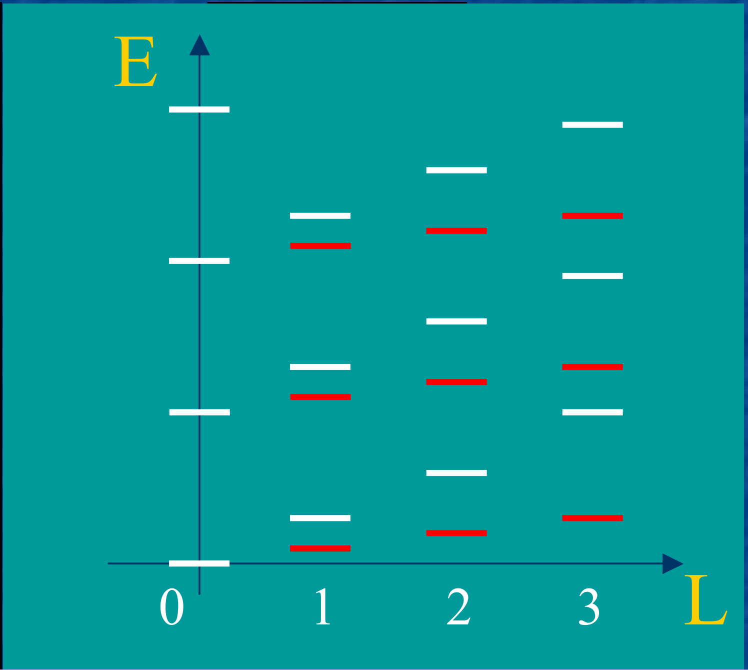




(after Science **292**, 476 ('01))



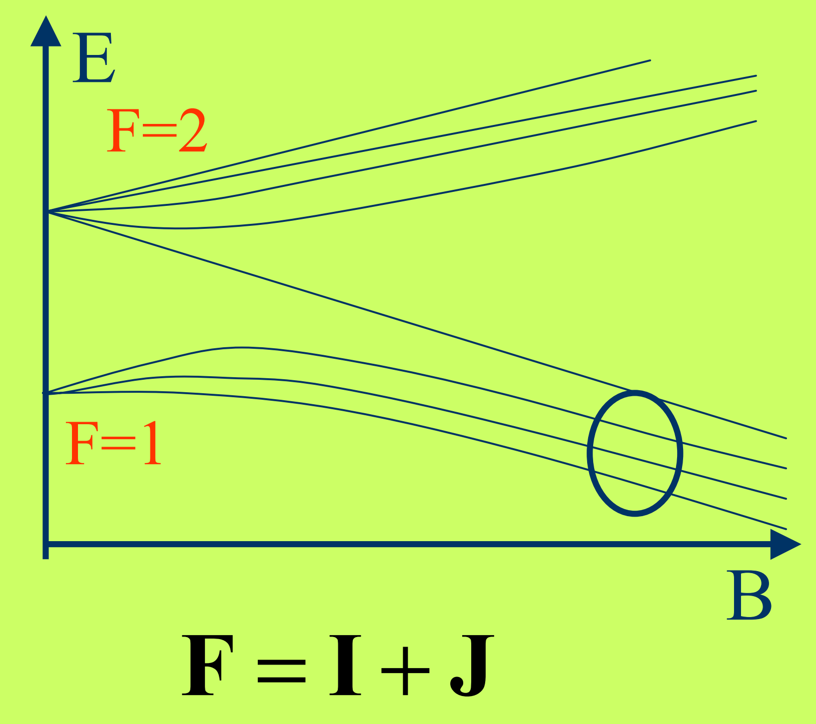
(after PRL **87**, 190401 ('01))



$$E_{n,l} = \omega_0 \sqrt{l + 3n + 2nl + 2n^2} - l\omega_{ext}$$

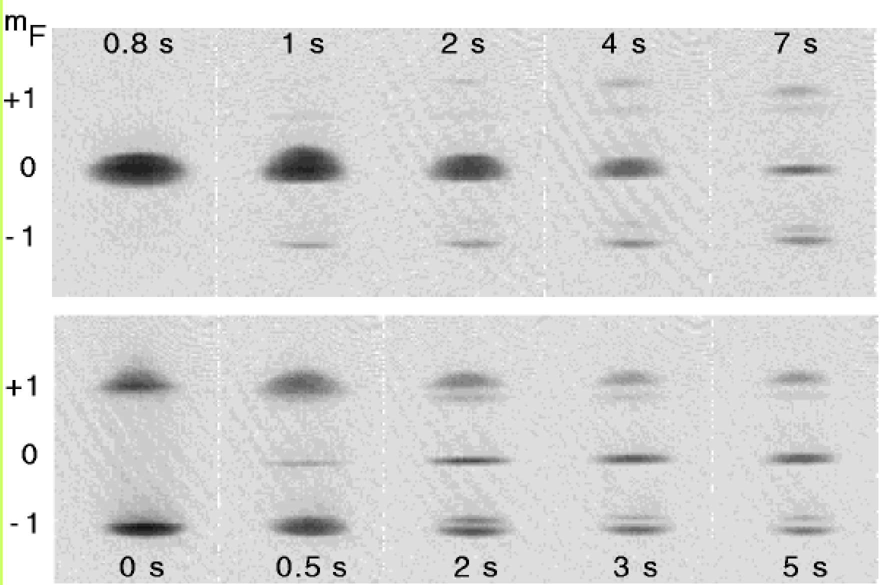
Vortices melting, quantum Hall regime ?

Spinor condensation in optical trap



$$\mathbf{F} = \mathbf{I} + \mathbf{J}$$

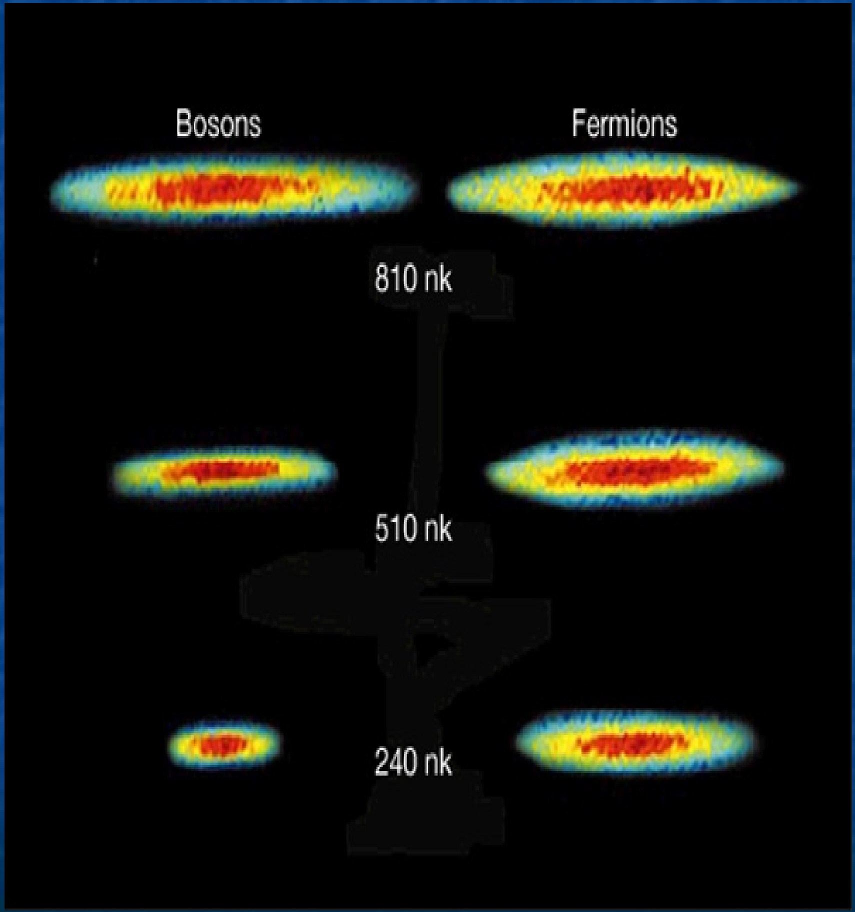
Na $\left|F = 1, m_F = \pm 1, 0\right\rangle$



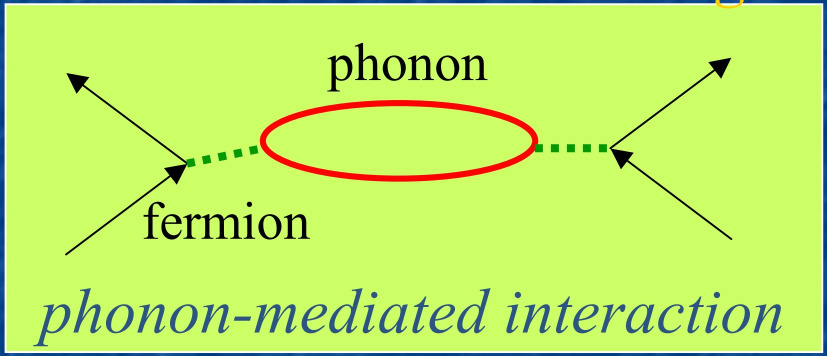
(see for example, cond-mat/0005001)

$$H = \int d\mathbf{r} \left[-\hat{\psi}_i^+ \frac{\nabla^2}{2m} \hat{\psi}_i + \frac{g_0}{2} \hat{\psi}_i^+ \hat{\psi}_j^+ \hat{\psi}_j \hat{\psi}_i + \frac{g_2}{2} \left(\hat{\psi}_i^+ \mathbf{F}_{ij} \hat{\psi}_j \right) \cdot \left(\hat{\psi}_k^+ \mathbf{F}_{kl} \hat{\psi}_l \right) \right]$$

Boson-fermion mixtures

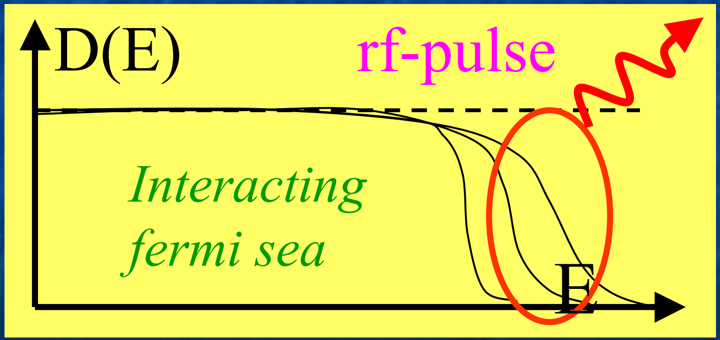


Fermions are noninteracting !



phonon-mediated interaction

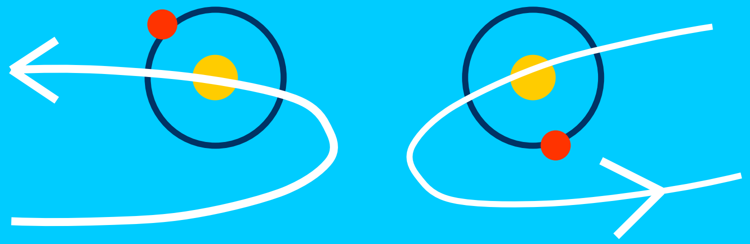
$^{40}K - ^{87}Rb,\ ^{6}Li - ^{7}Li,$ or $^{6}Li - ^{23}Na$



Sympathetic cooling

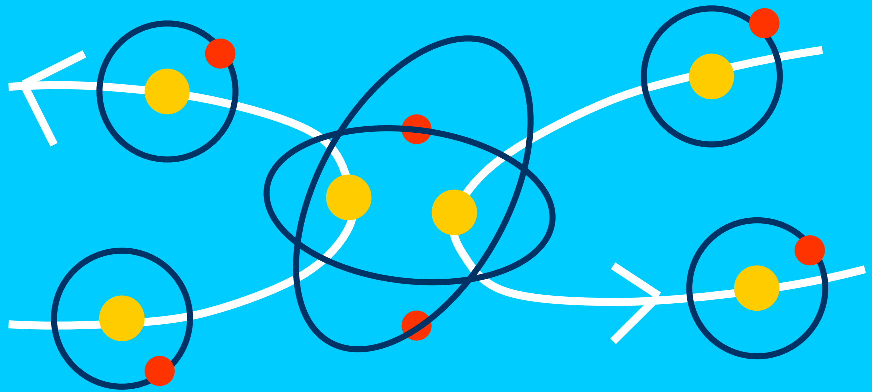
Feshbach Resonance

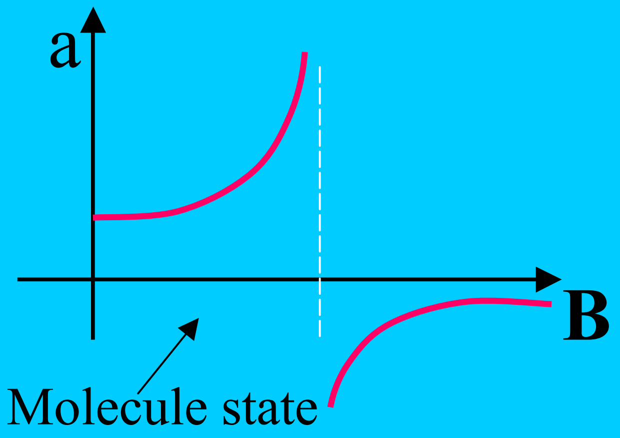
(i) Typical scattering:



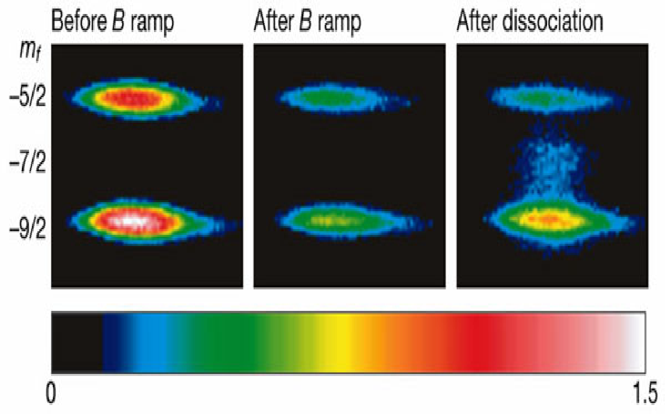
$$a = a_0\left(1 + \frac{\Delta B}{B - B_0}\right)$$

(ii) Resonant scattering:



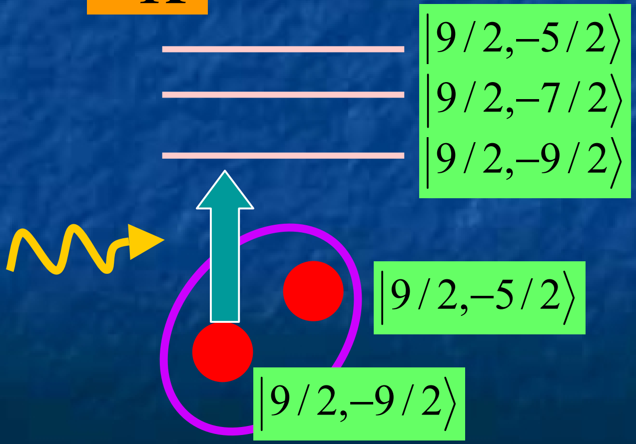


Molecule and pair condensate



(JILA, after Nature **424**, 47 ('03))

^{40}K



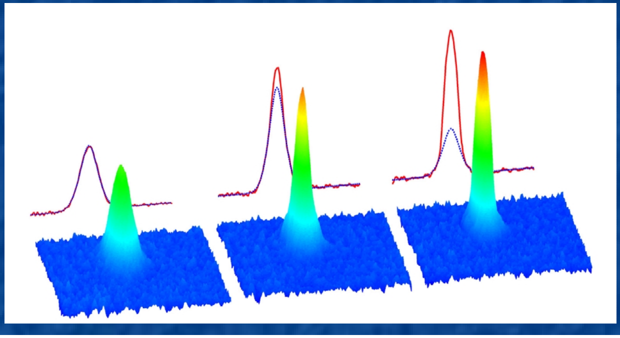
$|9/2,-5/2\rangle$

$|9/2,-7/2\rangle$

$|9/2,-9/2\rangle$

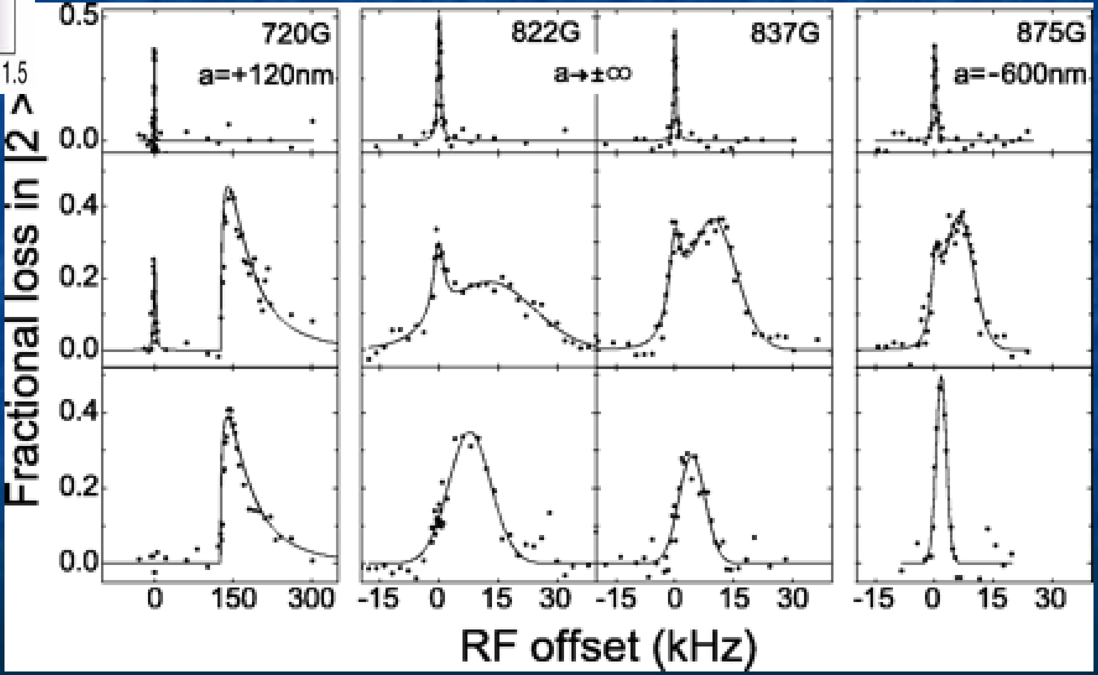
$|9/2,-5/2\rangle$

$|9/2,-9/2\rangle$



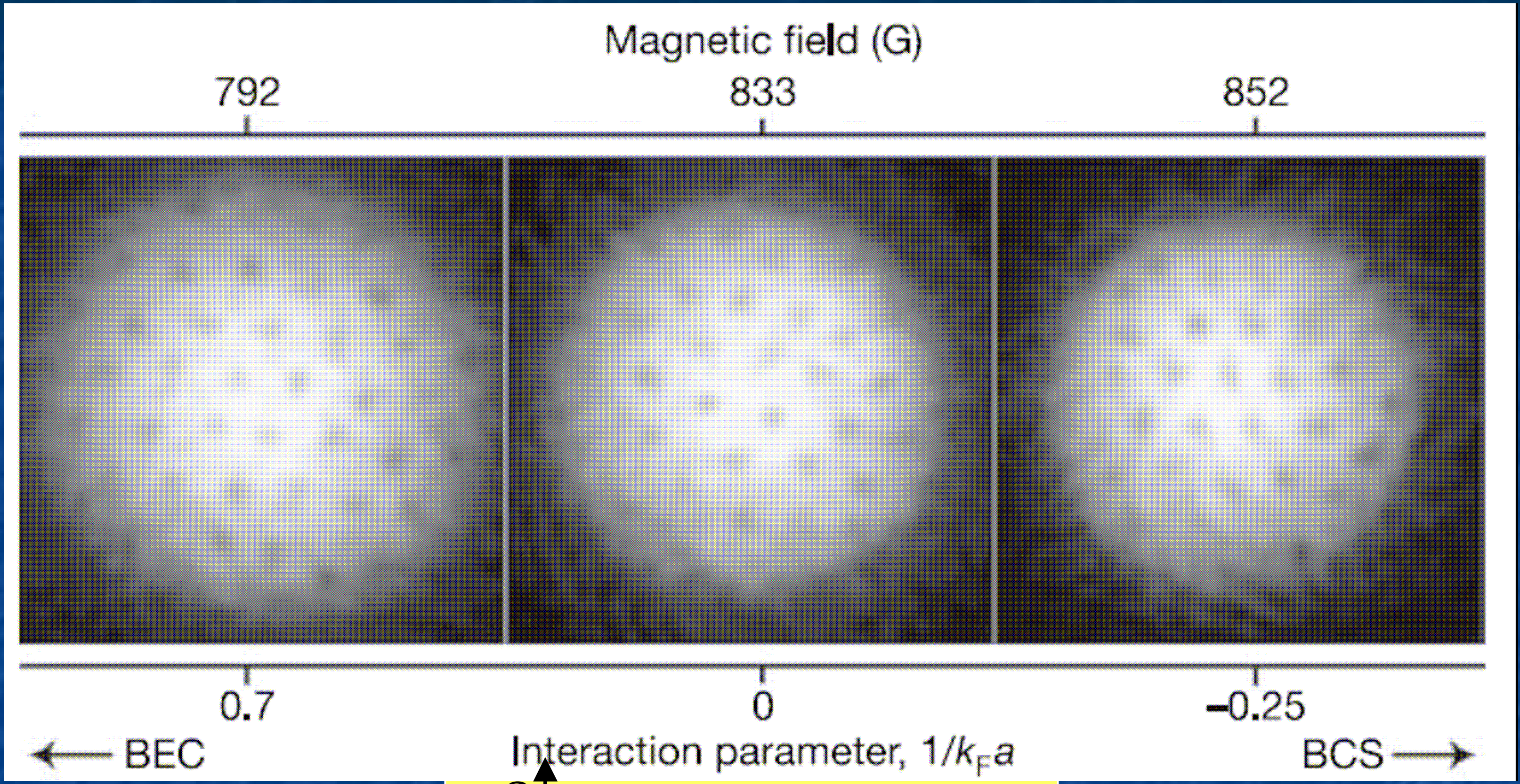
(MIT group, PRL **92**, 120403 ('04))

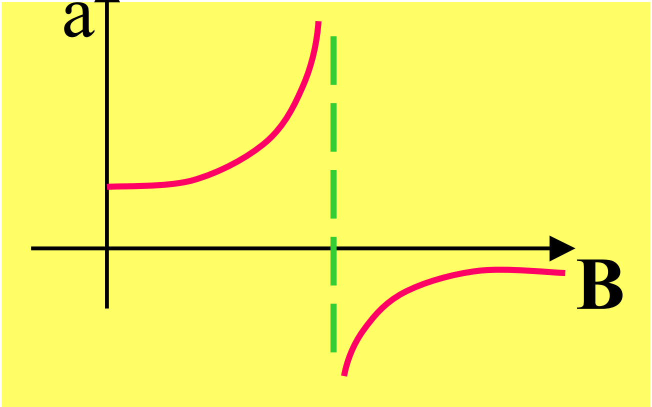
^6Li



(Innsbruck, after Science **305**, 1128 ('04))

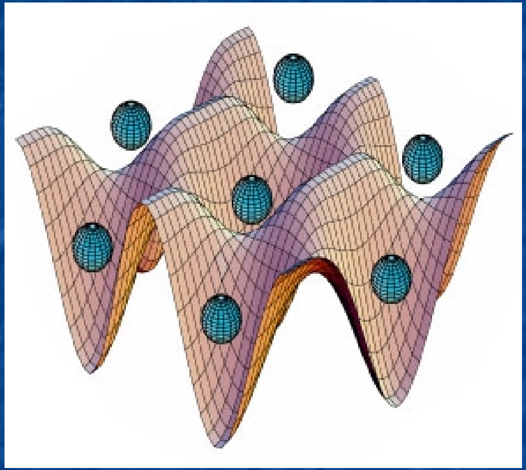
First evidence of superfluidity of fermion pairing



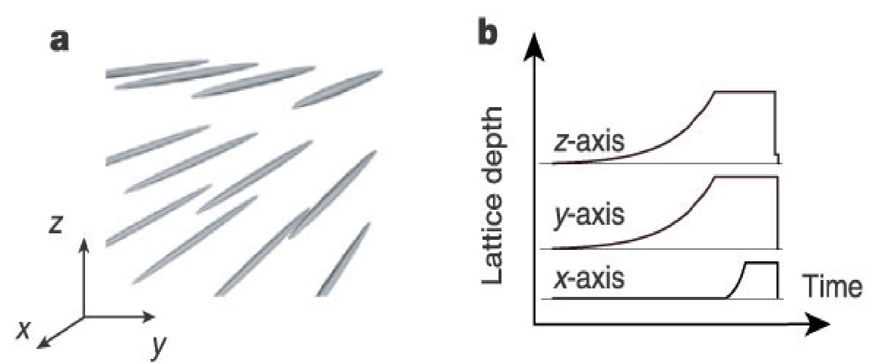


Optical lattice

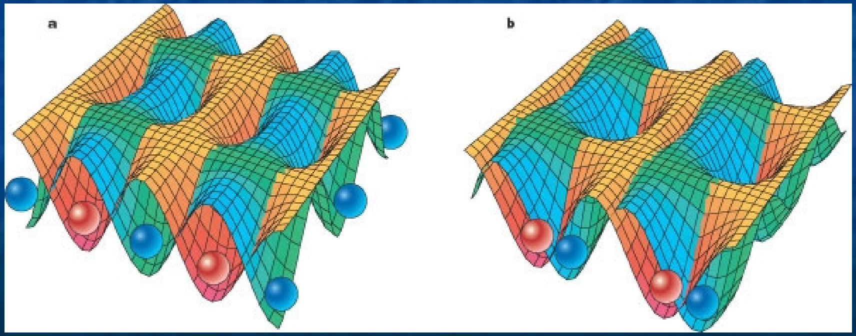
3D lattice

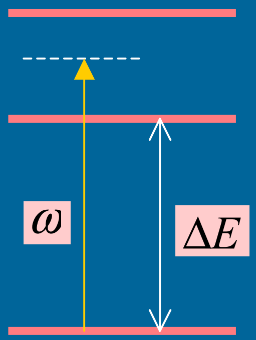


1D lattice

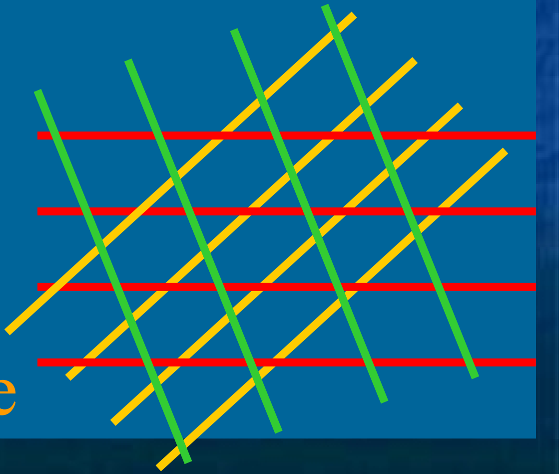


Entanglement control





$$V_0 \propto -\frac{|\Omega_R|^2(\omega-\Delta E)}{(\omega-\Delta E)^2+\Gamma^2}$$

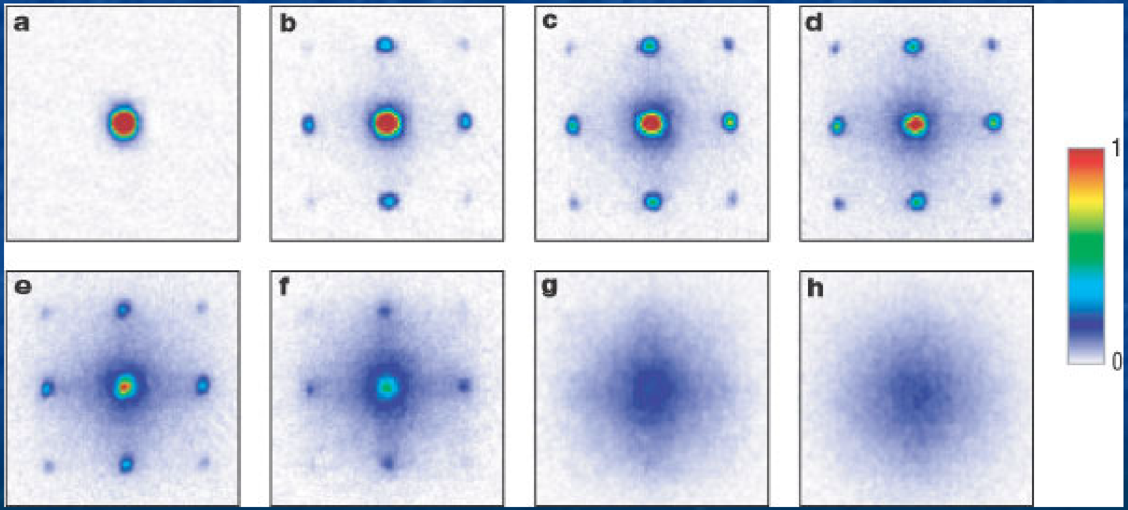


other lattice

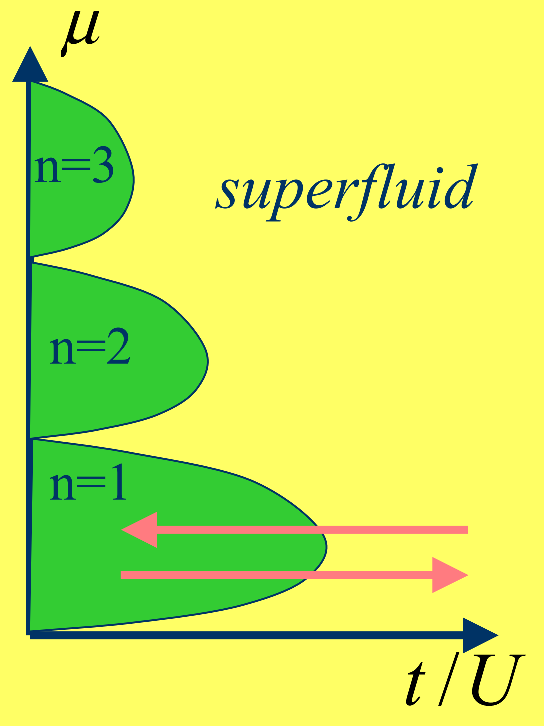
Mott-Insulator transition

Bose-Hubbard model

$$H = -t \sum_{<i,j>} a_i^+ a_j + U \sum_i a_i^+ a_i (a_i^+ a_i - 1) - \mu \sum_i a_i^+ a_i$$



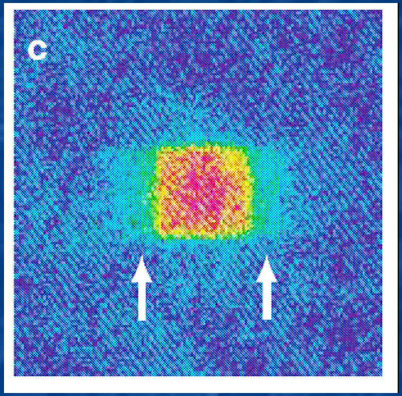
(after Nature **415**, 39 ('02))

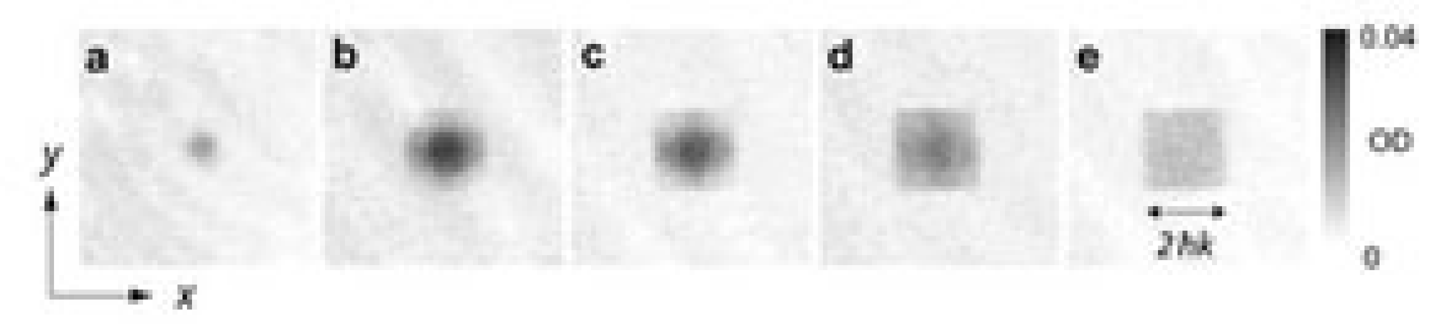


Fermions in optical lattice

Fermi Hubbard model

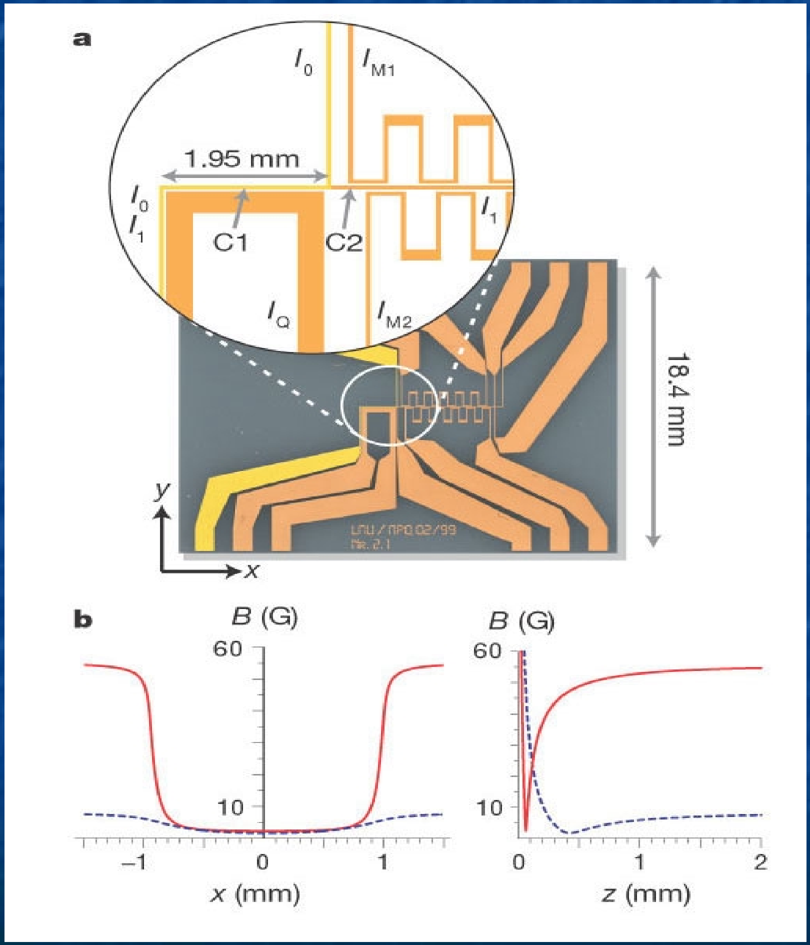
$$H = -t \sum_{<i,j>} a_{i,s}^{+} a_{j,s} + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

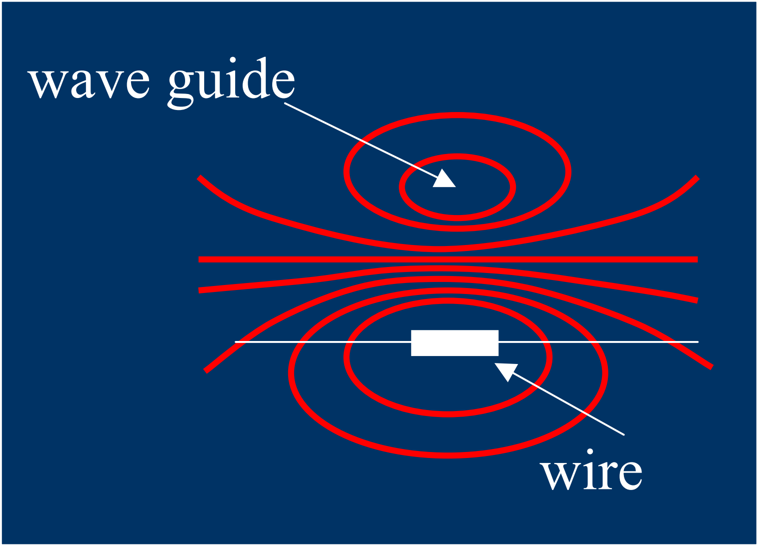




Superfluidity of fermion pairing in lattice is also realized.

Transport in 1D waveguide





wave guide

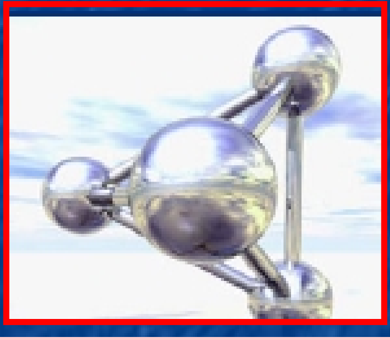
wire

Interference ?

Finite temperature
+ semiconductor technique

Cold dipolar atoms/molecules

(1) Heteronuclear molecules



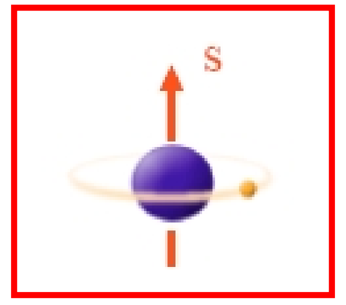
(a) Direct molecules

p~ 1-5 D

(b) But difficult to be cooled

(Doyle, Meijer, DeMille etc.)

(2) Atoms with large magnetic moment



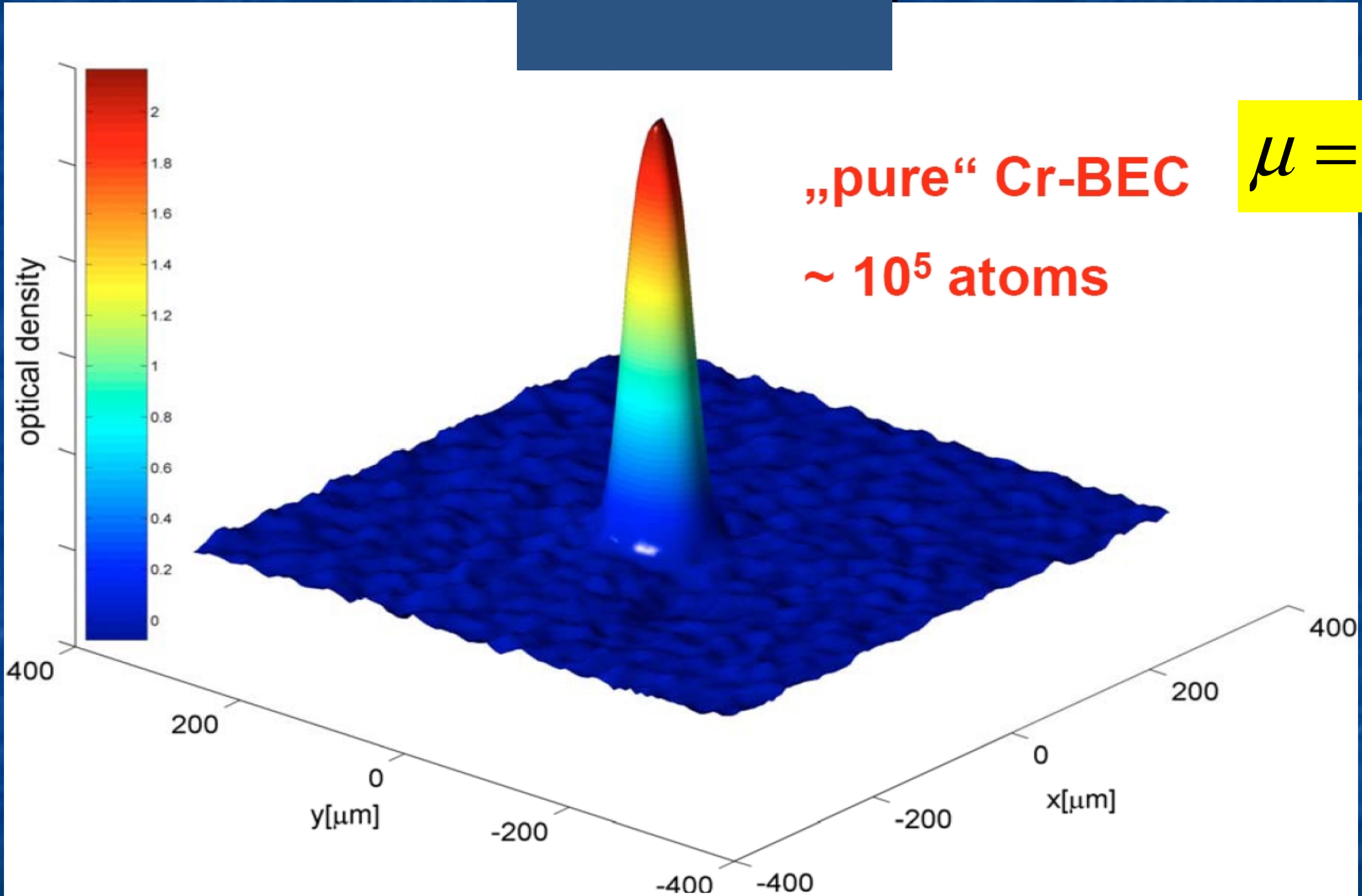
Small moment $\mu \sim 6\mu_B$ (for Cr)

But it is now ready to go !

(Stuhler etc.)

$$\mathrm{p} \sim 1\mathrm{D}, \mathrm{U}_{\mathrm{dd}} \sim 10\mu\mathrm{K}, \quad \mu = 1\mu_{\mathrm{B}}, \mathrm{U}_{\mathrm{dd}} \sim 1\mathrm{nK}$$

Condensate (superfluid)



„pure“ Cr-BEC

~ 10^5 atoms

$\mu = 6\mu_B$

A. Griesmaier et al., PRL 94, 160401 (2005)

T_c~700 nK

Artificial dipoles:

(1)Feshbach resonance

(KRb, JILA, ETH, etc.)

But not in ground state

weak dipole moment

short life time

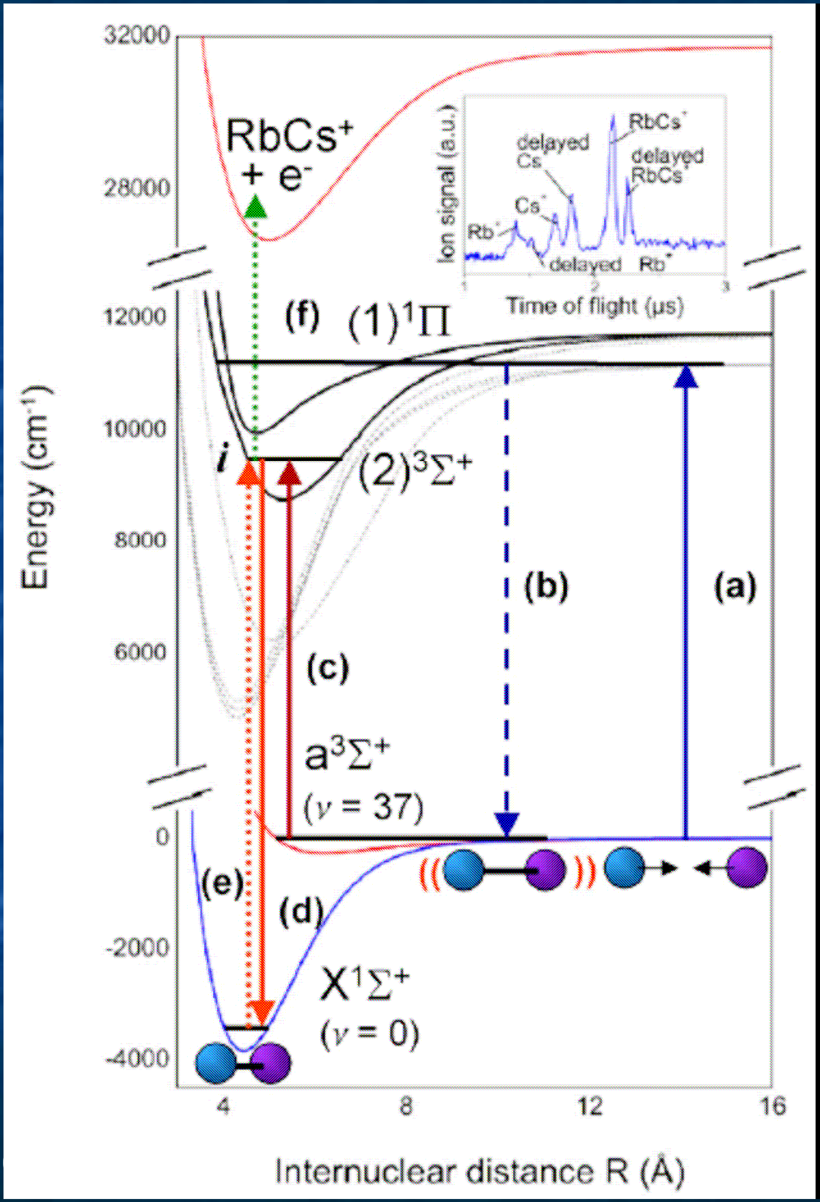
(2) photo-association

(RbCs, Yale, etc.)

Now in ground state

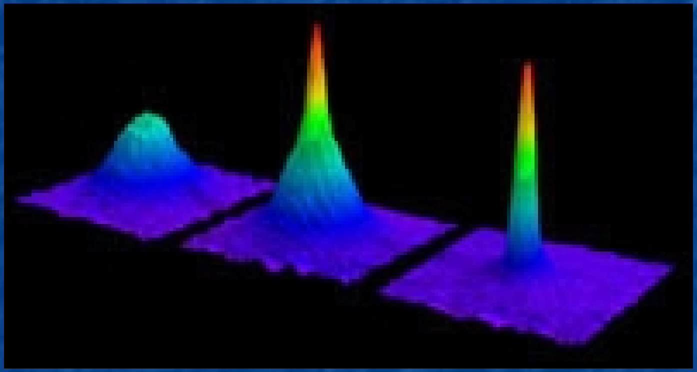
But number of atoms

are still small

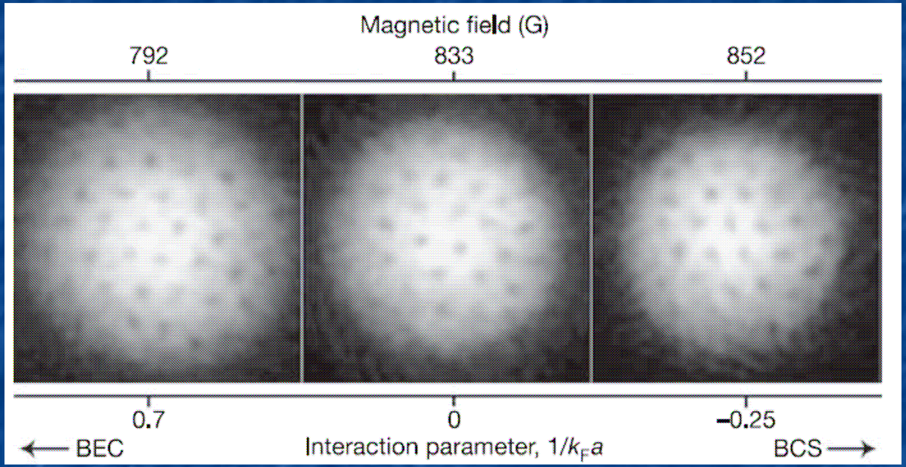


(J. Sage, et. al., PRL, **94**, 2030

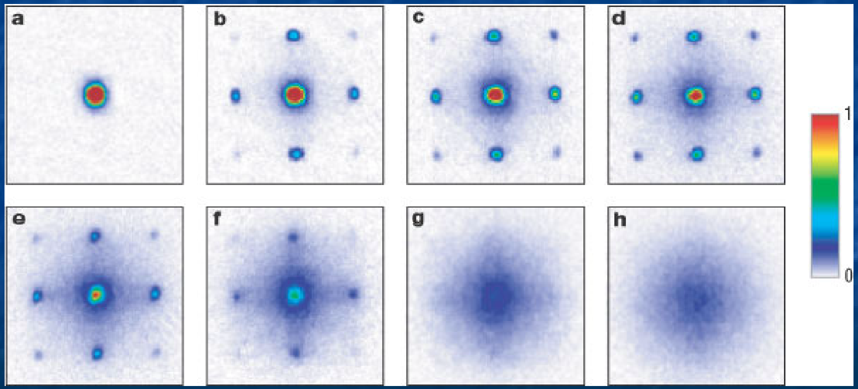
Gallery of pictures



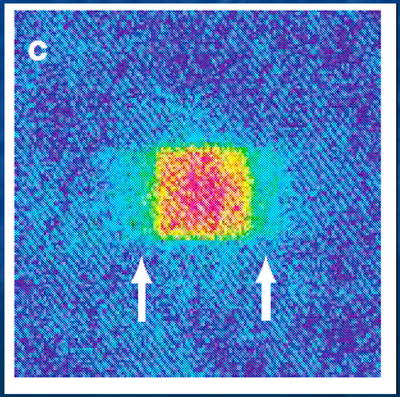
Bose-Einstein Condensation



BEC-BCS crossover



Superfluid-Mott insulator transition



Fermi surface in optical lattice