Physics of New Quantum Phases in Superclean Materials
Tokyo, Dec. 15, 2005

学習院

Experimental study of atomic Bose-Einstein condensates with internal degrees of freedom

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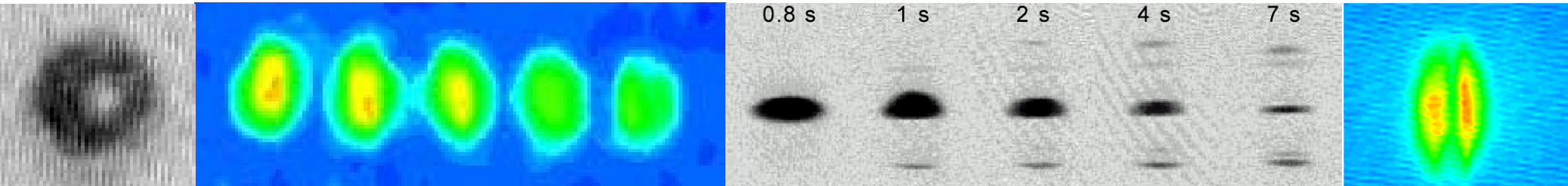
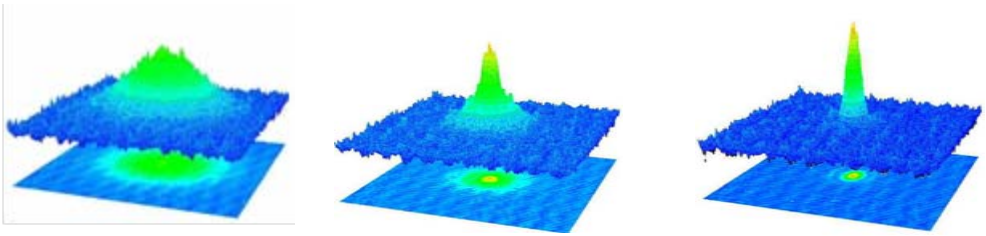


Outline

1. Motivation
2. Experimental apparatus
3. Atomic BEC with internal degrees of freedom
   - Dynamical Properties of ^{87}Rb Spin-2 BEC
   - Optical Confinement of Binary BEC
   - Vortex Formation via magnetic field reversal
4. Summary

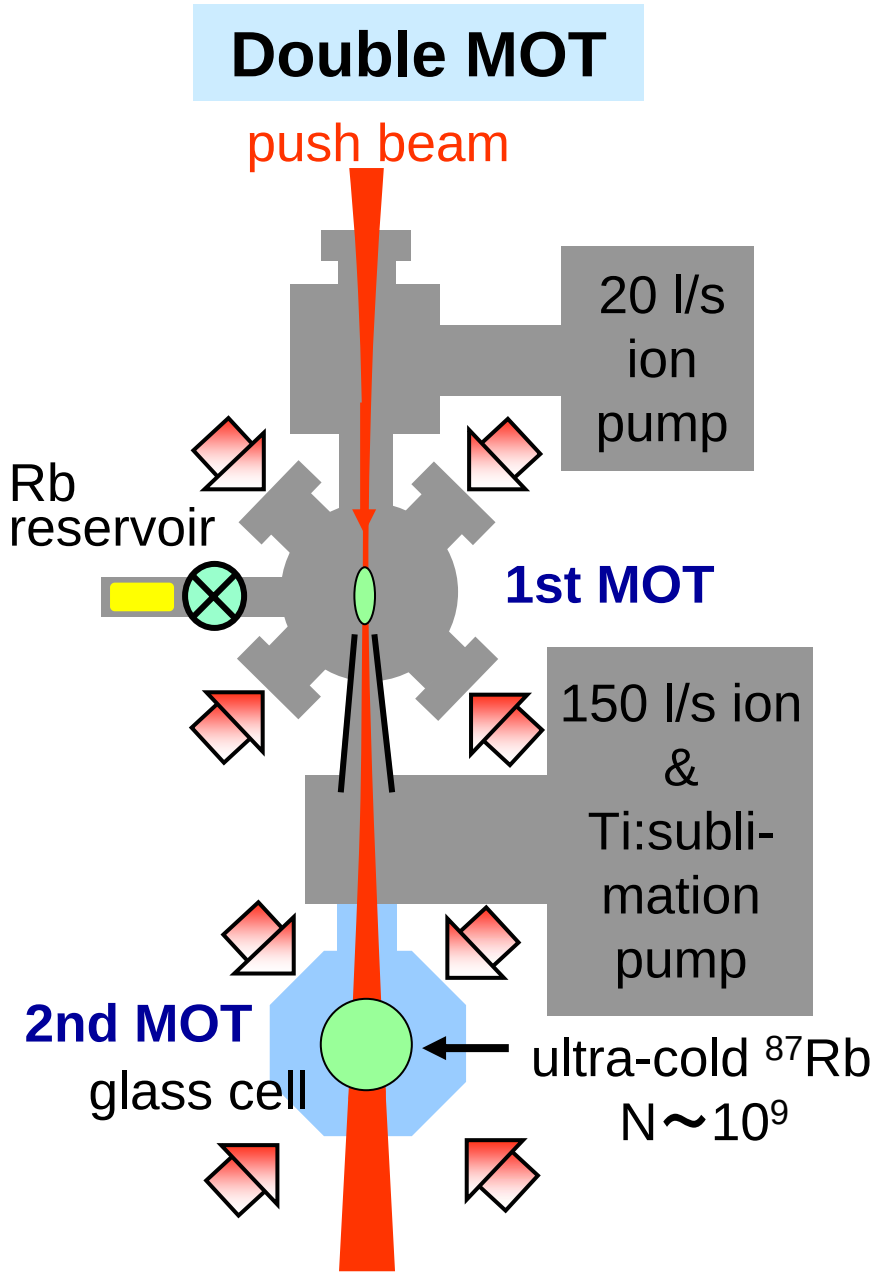


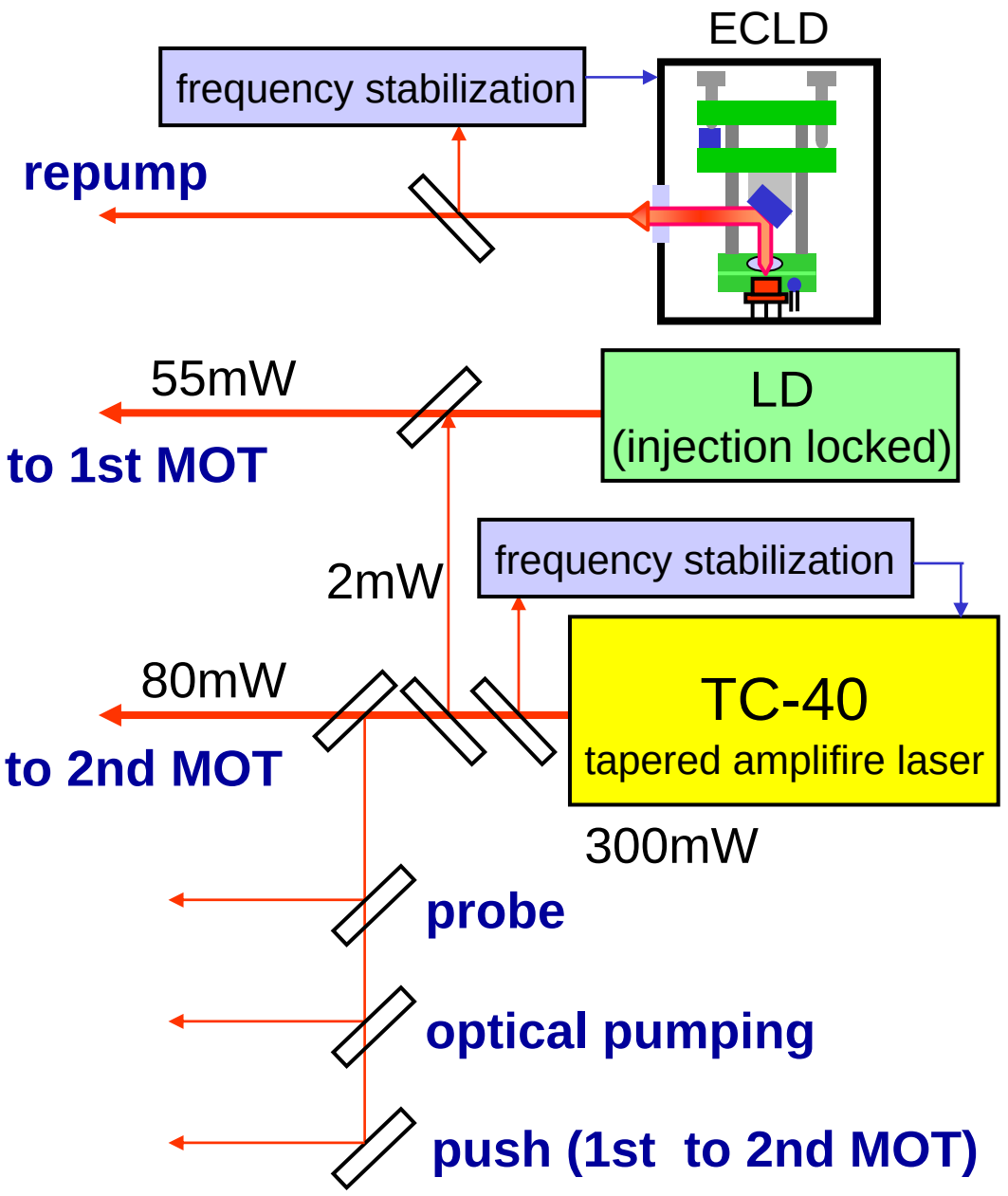
Our point of view

Research on atomic BEC

Quantum optics atom laser, atom chip..	VS	Condensed matter physics new quantum fluid.
Also in atoms vortex, spinor…	VS	Distinctive or unique dynamics, ?
Qualitative phenomena	VS	Quantitative theory

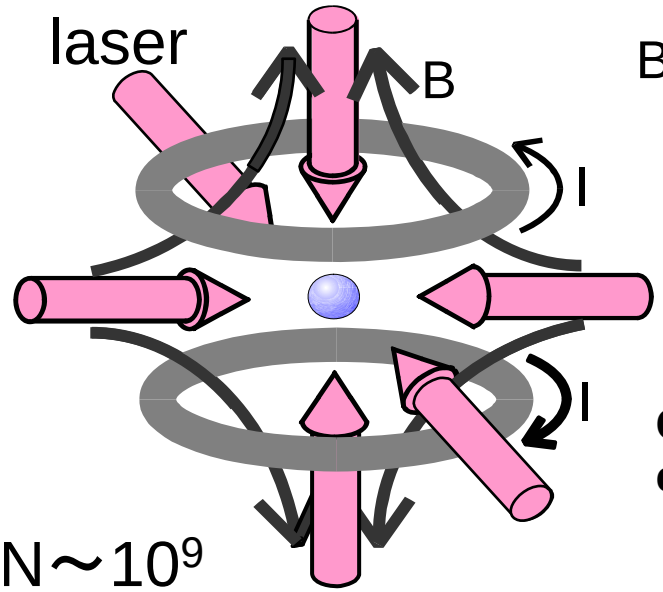
Experimental Setup



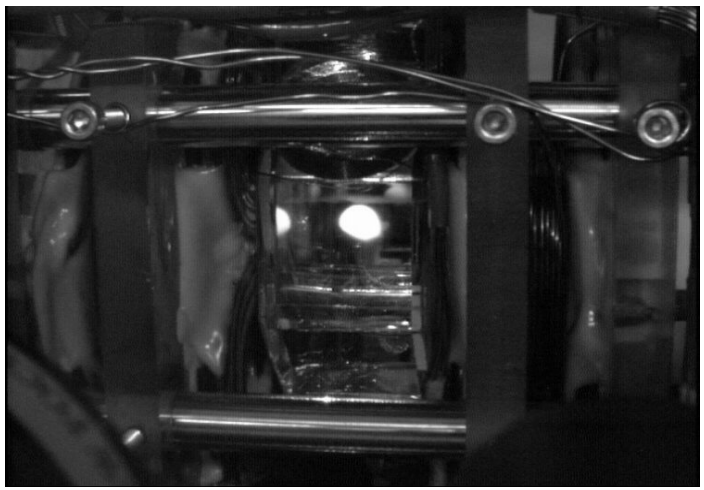


Making of atomic BEC

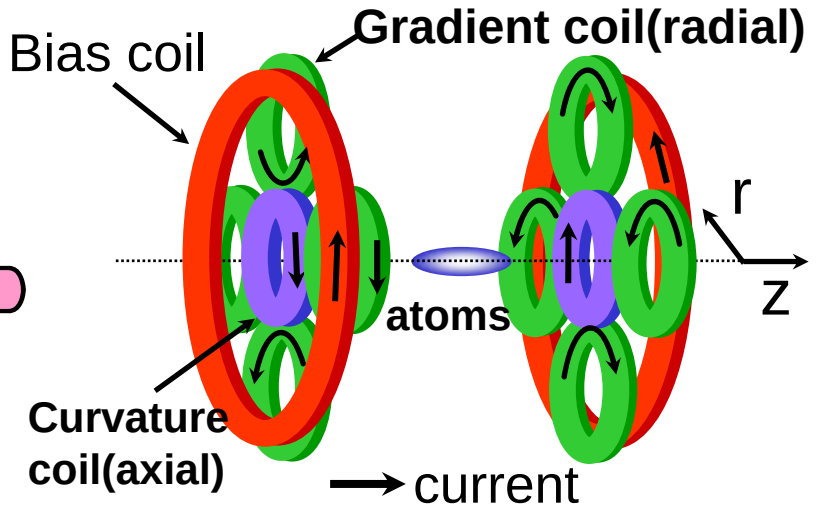
Magneto-Optical Trap(MOT)



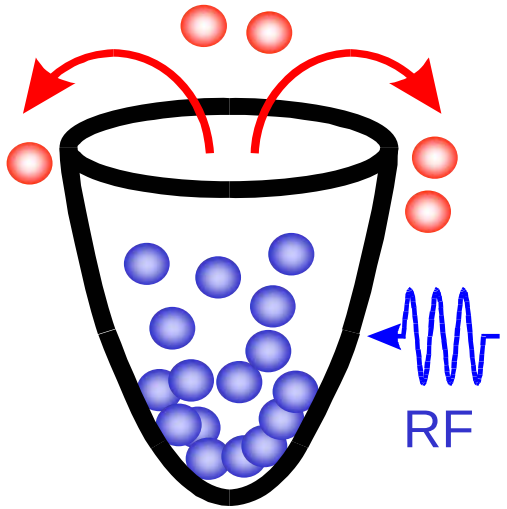
N～10^9

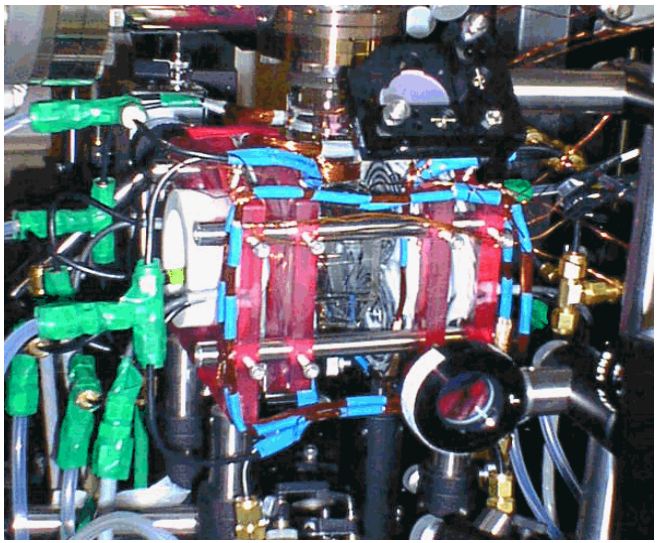


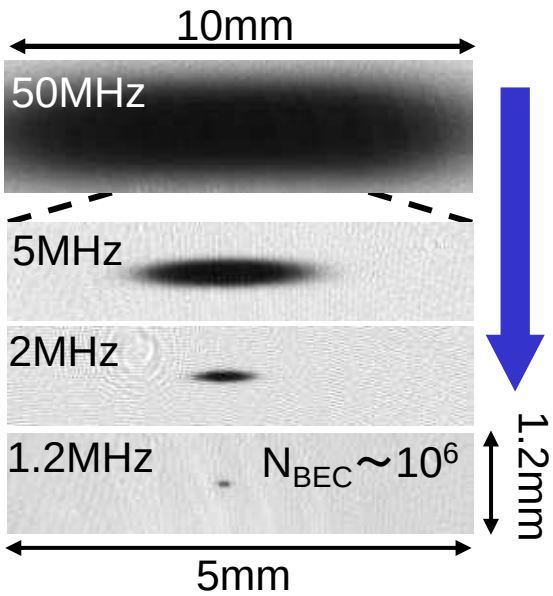
Magnetic trap



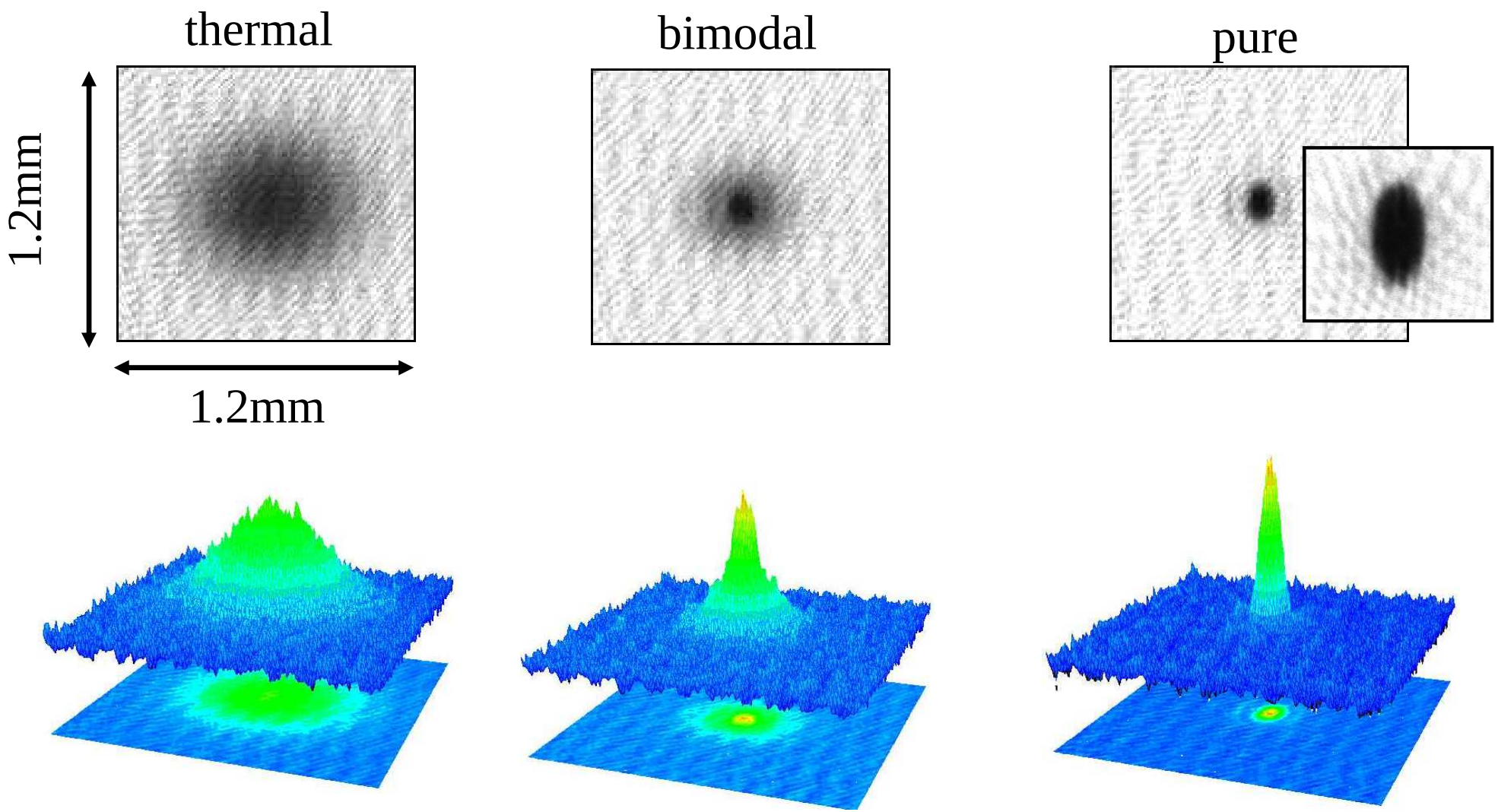
Evaporative cooling







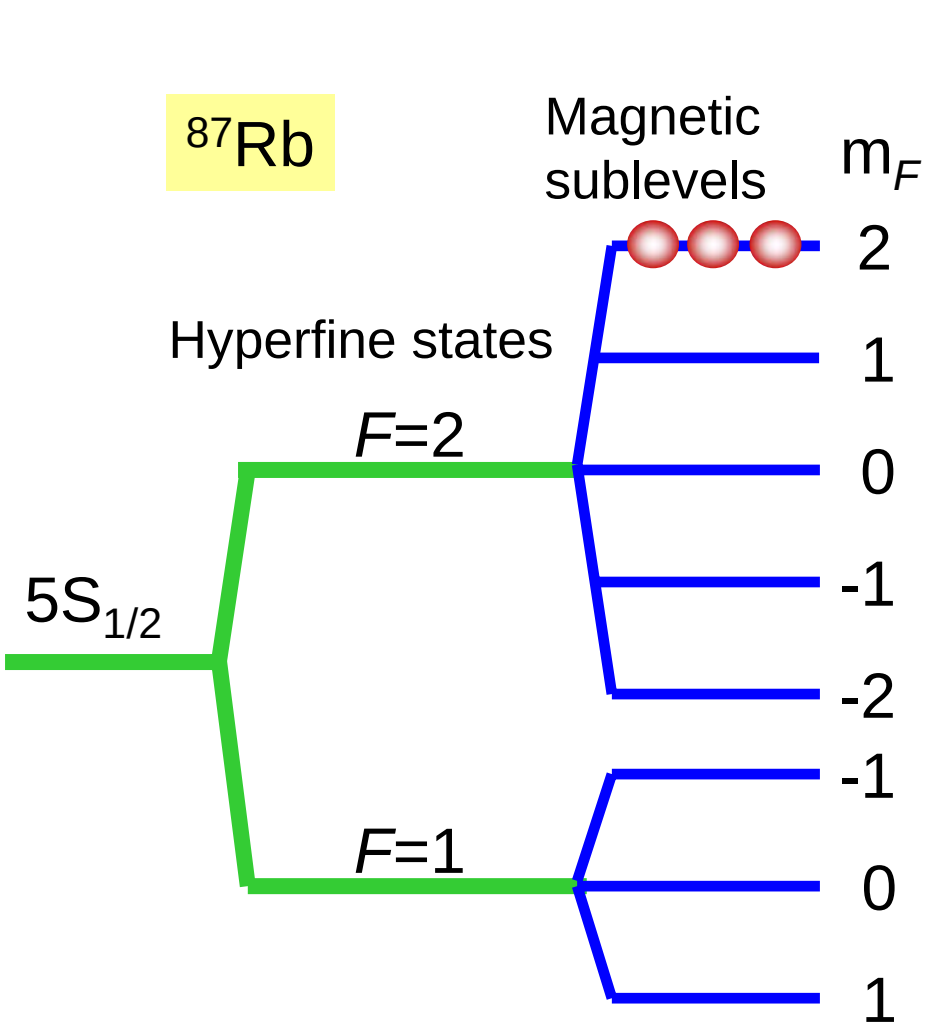
Time Of Flight measurement of atomic BEC



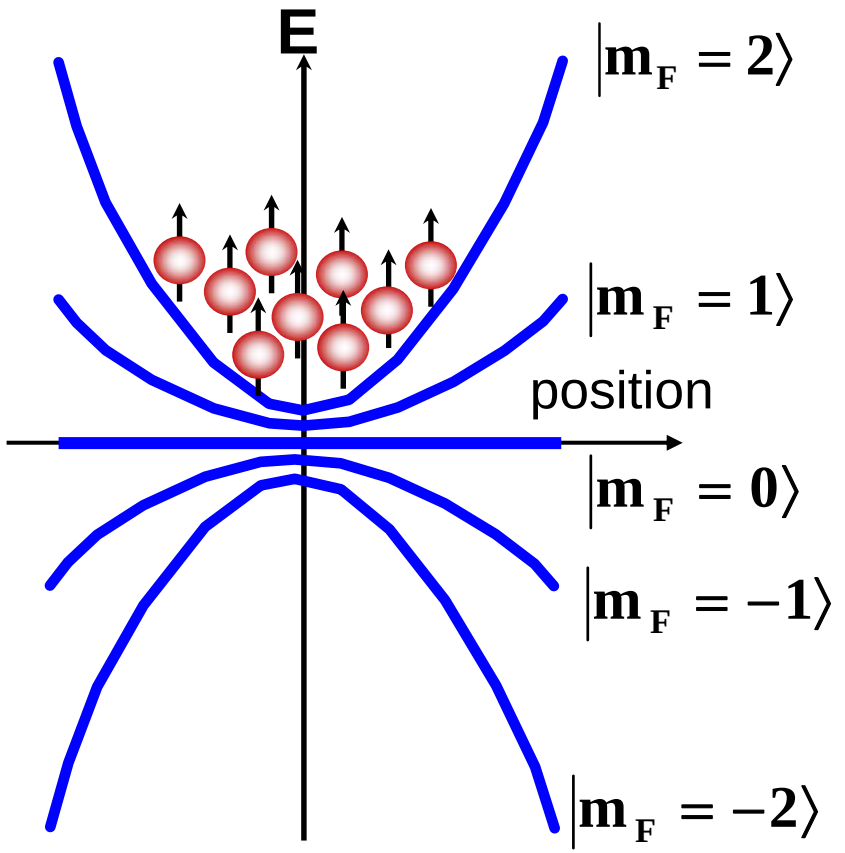
Critical temperature : ~500nK

Atoms in a magnetic trap

No spin degrees of freedom in a Magnetic trap

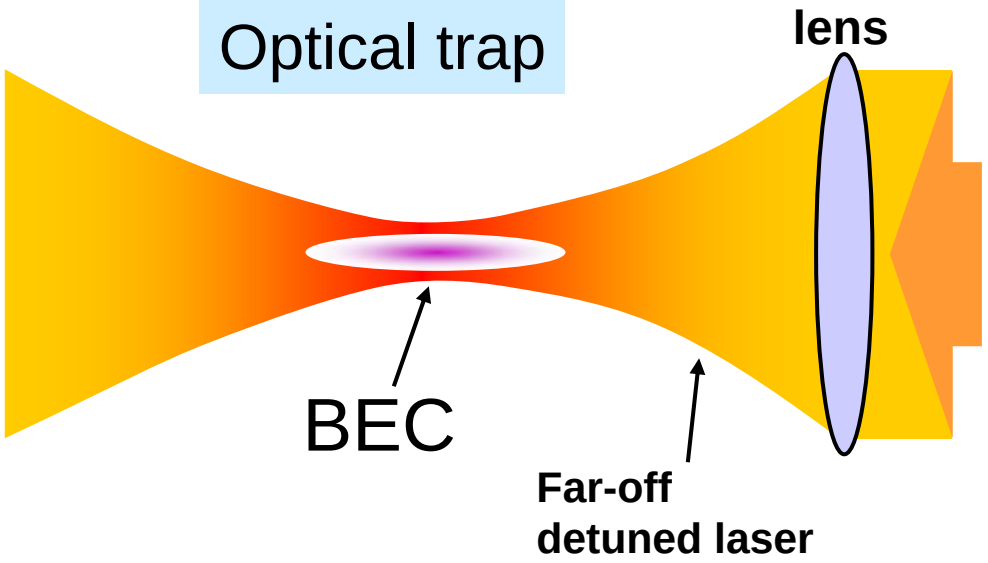


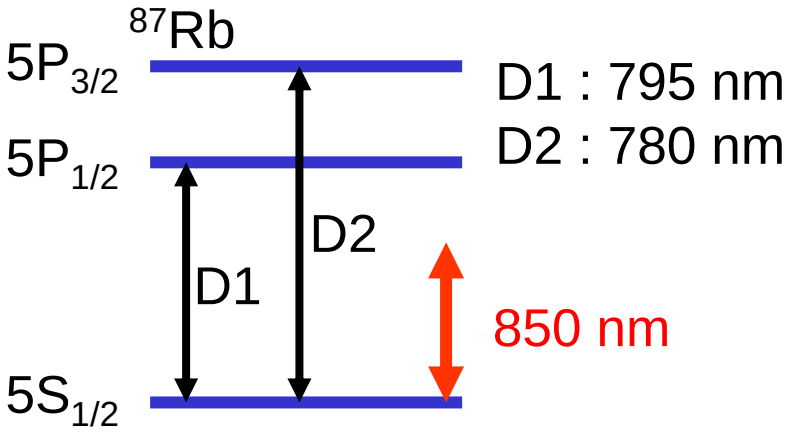
Magnetic potential for $F = 2$



Atoms in an optical trap

Optical trap





Optical trap potential

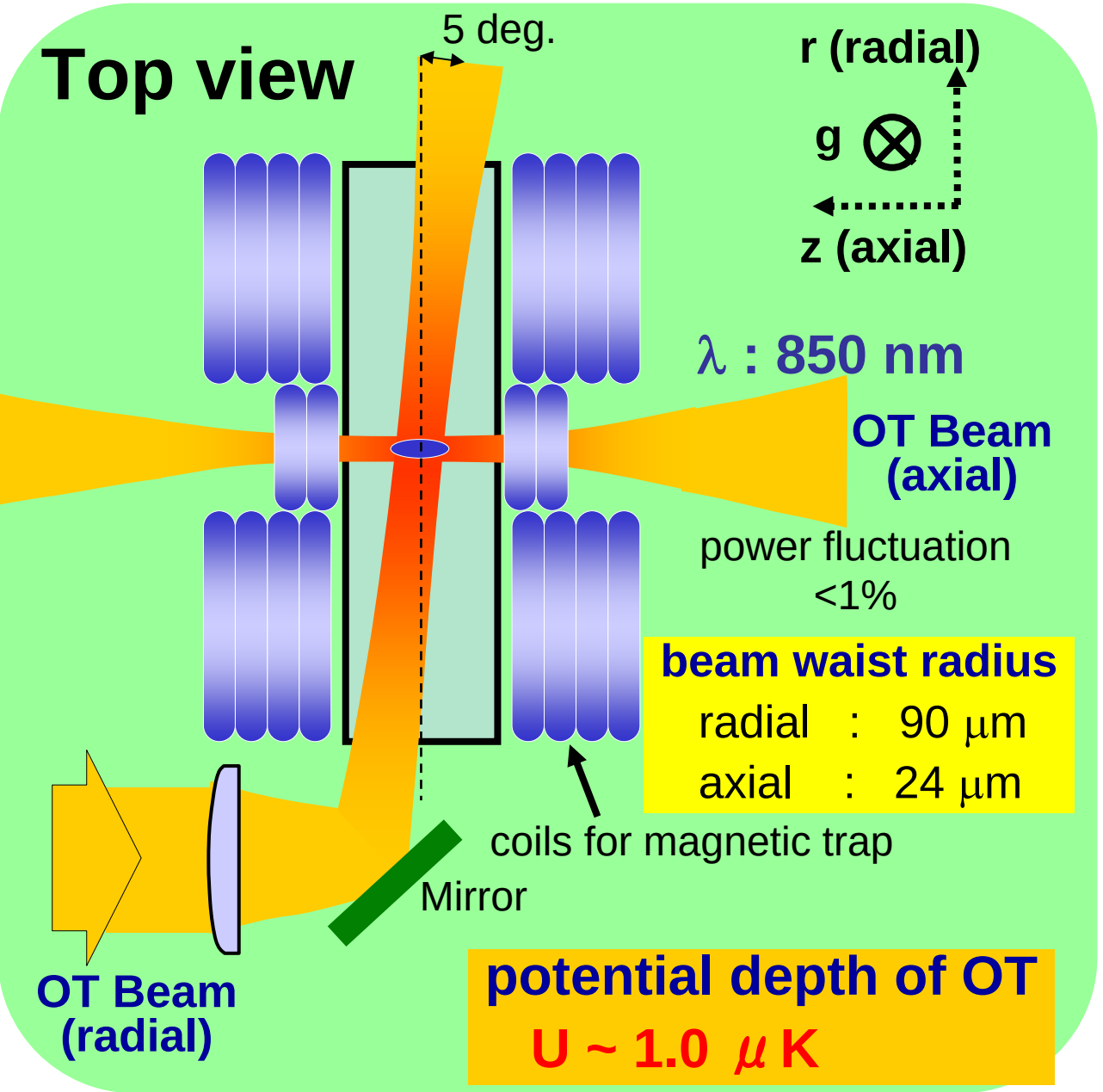
$$U = -\frac{1}{2}\alpha \cdot |E|^2$$

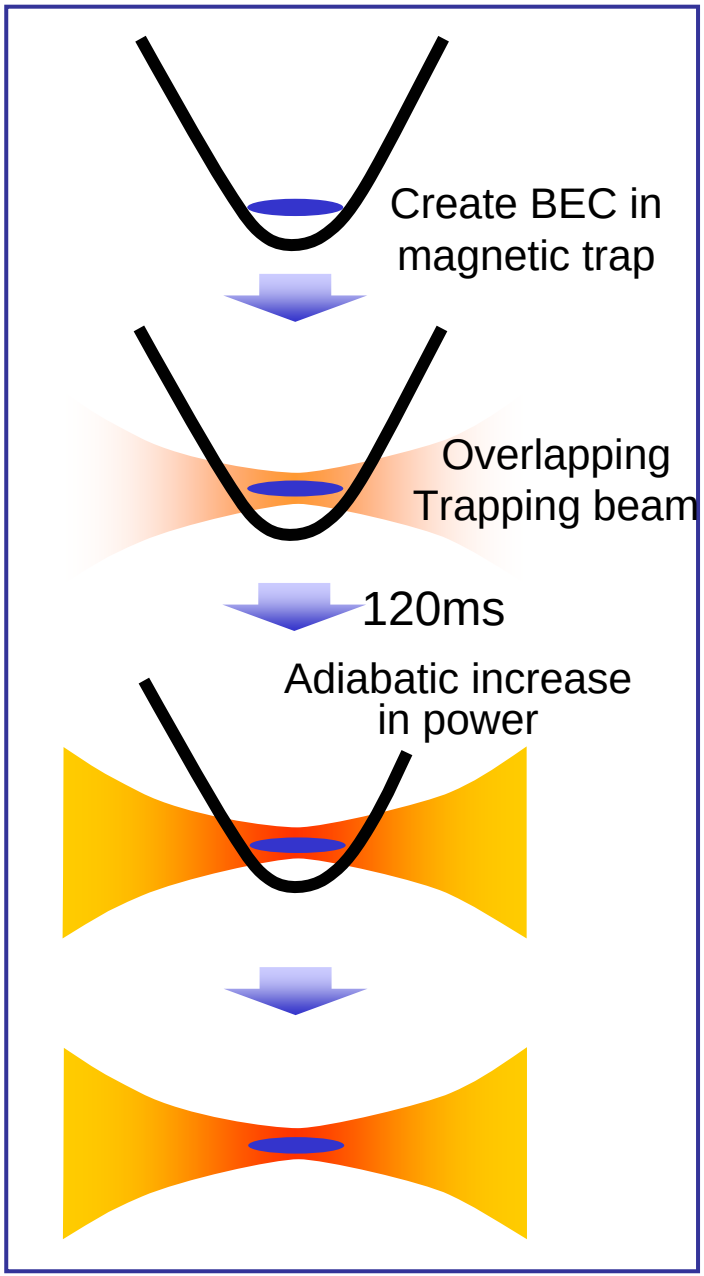
$$\propto -\frac{P}{\Delta}$$

α : polarizability, E :electric field
P : laser power
Δ : detuning (f_{laser}-$f_{resonace}$)

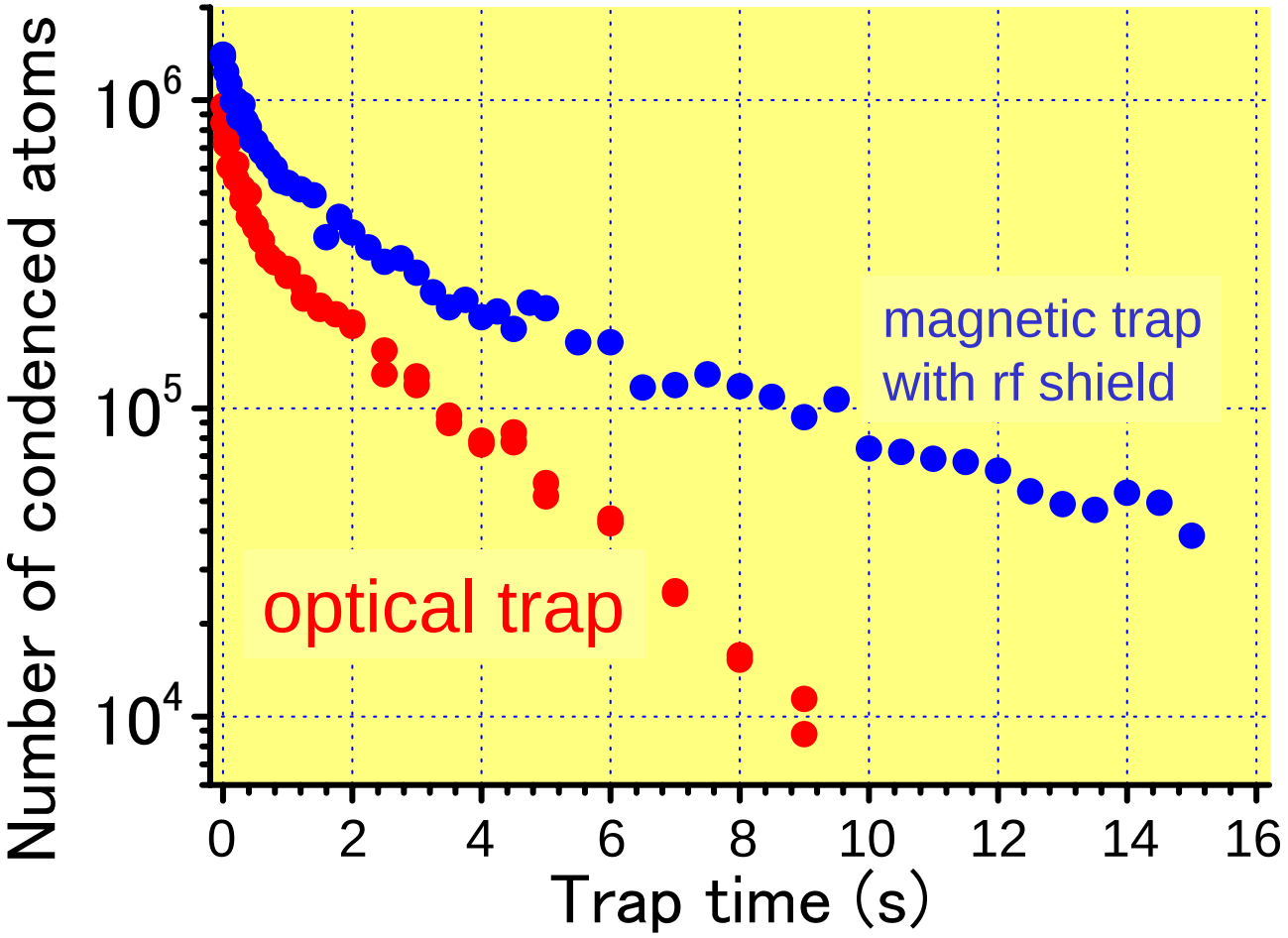
spin degrees of freedom are liberated in an optical trap

Setup of Optical Trap





Lifetime of BEC in Optical Trap - Stretched State ($F=2, m_F=-2$) -



loss rate

(in the region of $N < 1 \times 10^5$)

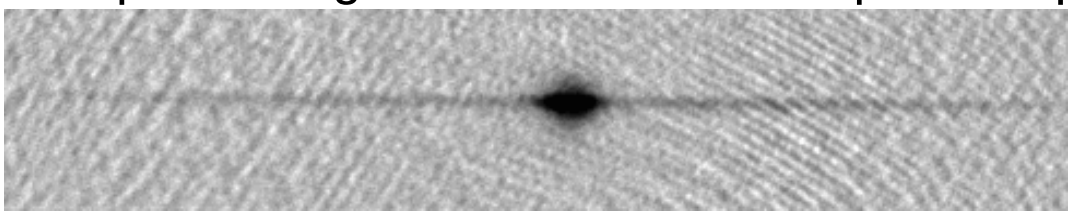
$\tau_{\text{magnetic trap}} \sim 7$ s

$\tau_{\text{optical trap}} \sim 4$ s

photon scattering rate

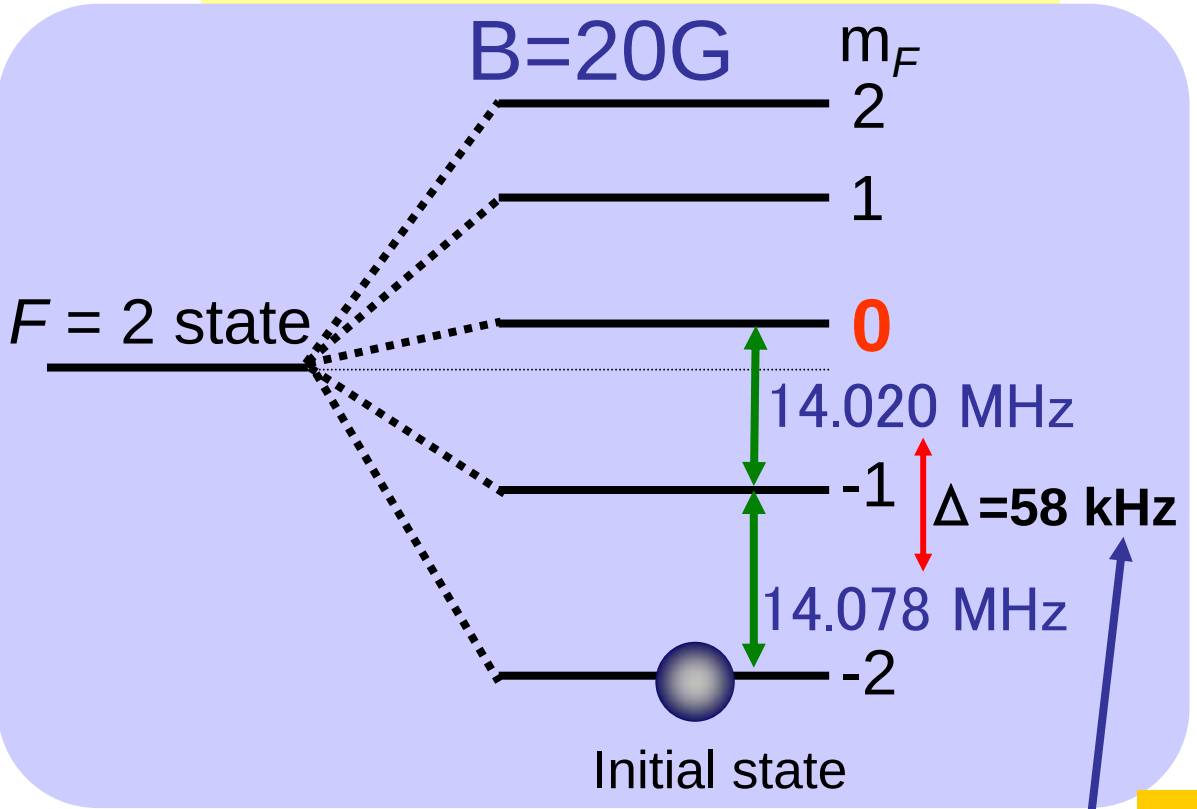
2×10^{-3} /s

absorption image of the BEC in the optical trap



Manipulation of Spin States

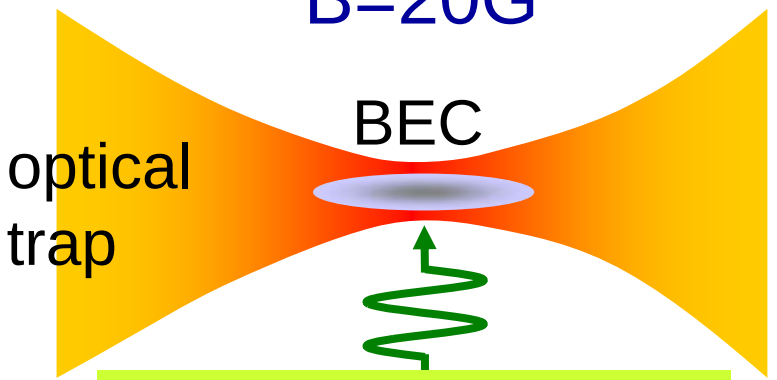
energy level diagram of ^{87}Rb ground hyperfine states



It is possible to selectively prepare any states.

homogeneous magnetic field

B=20G



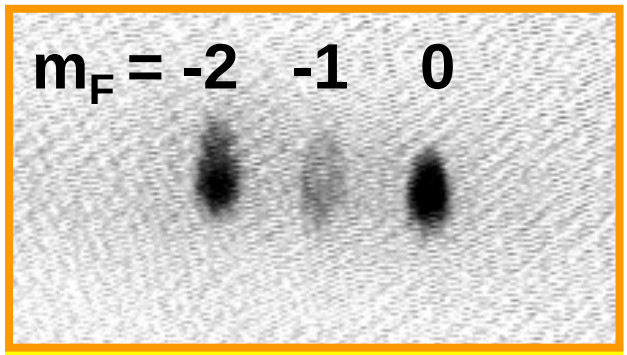
rf field
(Frequency is swept)

Parameter of rf field

center frequency : 14.078 MHz
sweep range : 80 kHz
sweep time : 1～3 ms

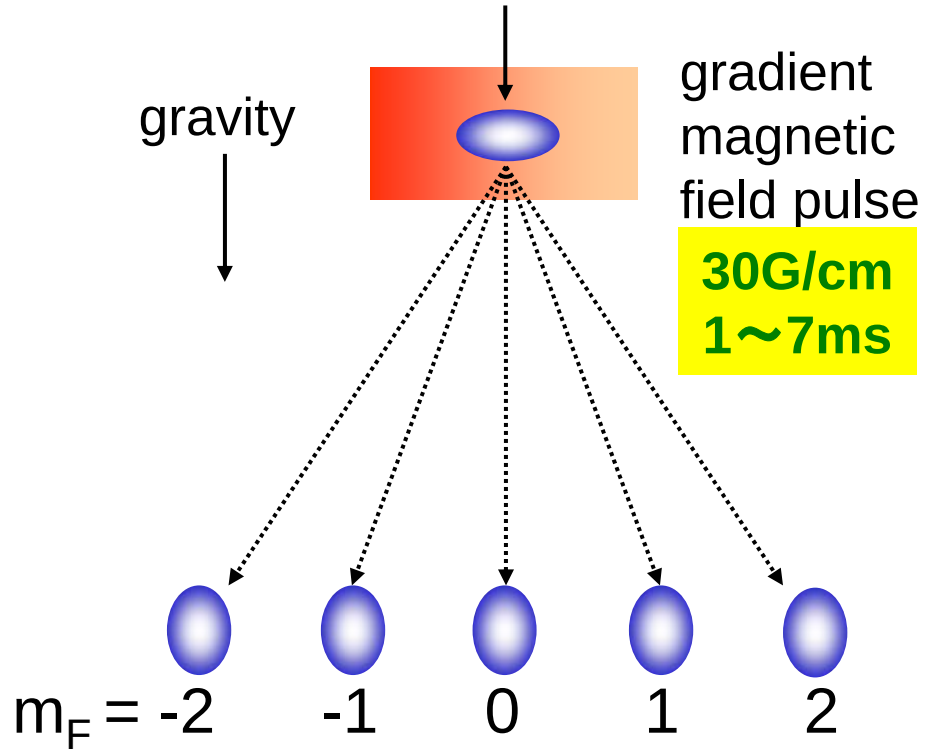
Creation of BEC in $m_F = 0$ state

$m_F = -2$ & 0 mixed BEC



$|-2\rangle : |0\rangle = 1:1$

Spatial separation by Stern-Gerlach method



We could prepare highly polarized (almost pure) m_F=0 BEC. Transfer rate＞ 90%

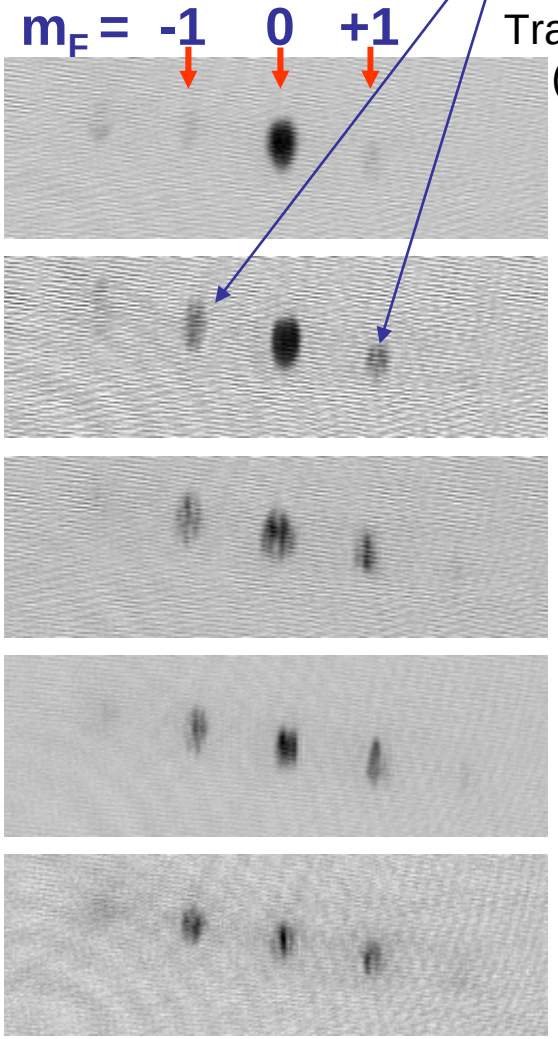
Decay of F=2, m_F=0 BEC in OT at B = 1.5G

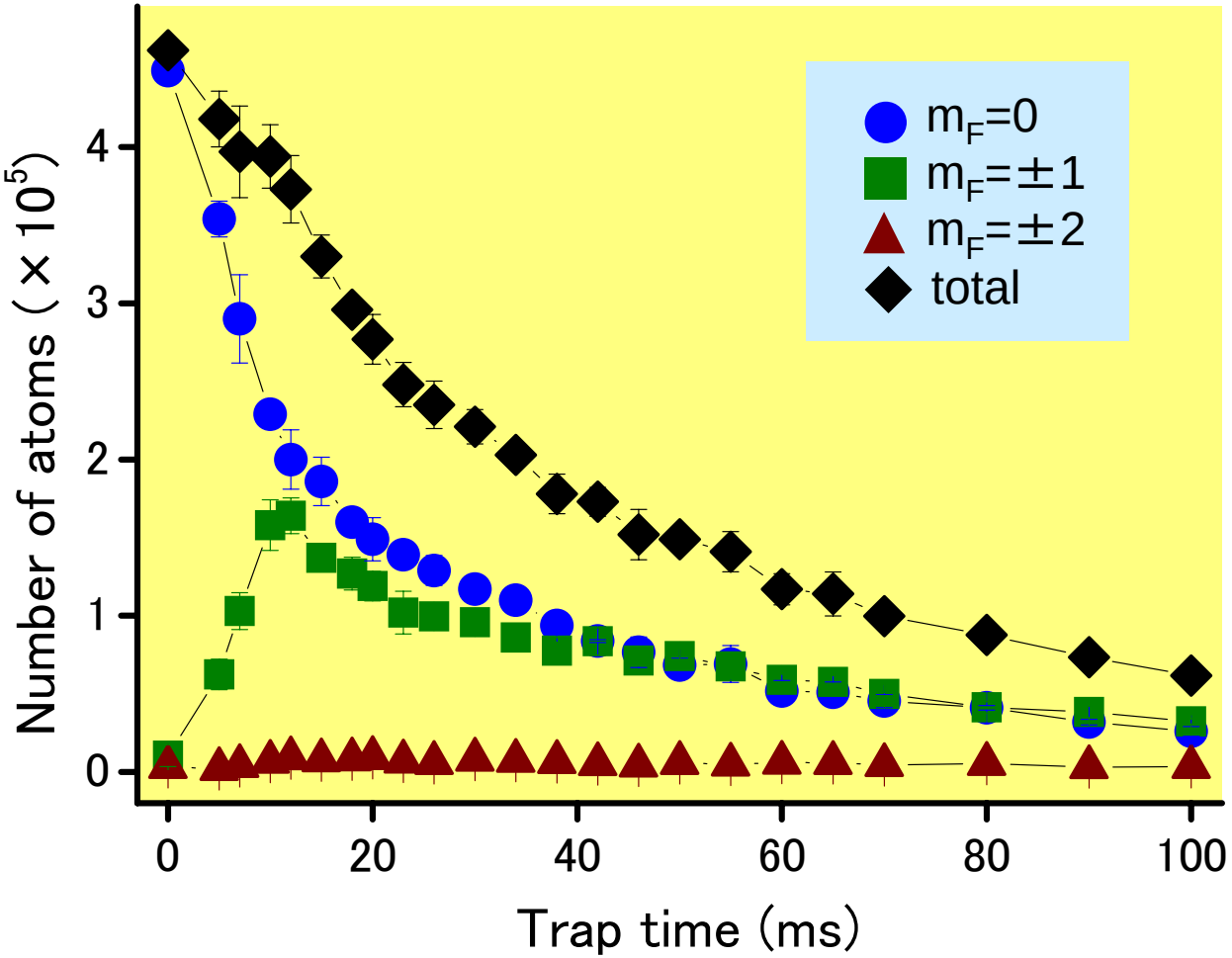
Atoms in BEC initially polarized in F=2, m_F=0 state.

m_F=±1 components appeared during decay process.

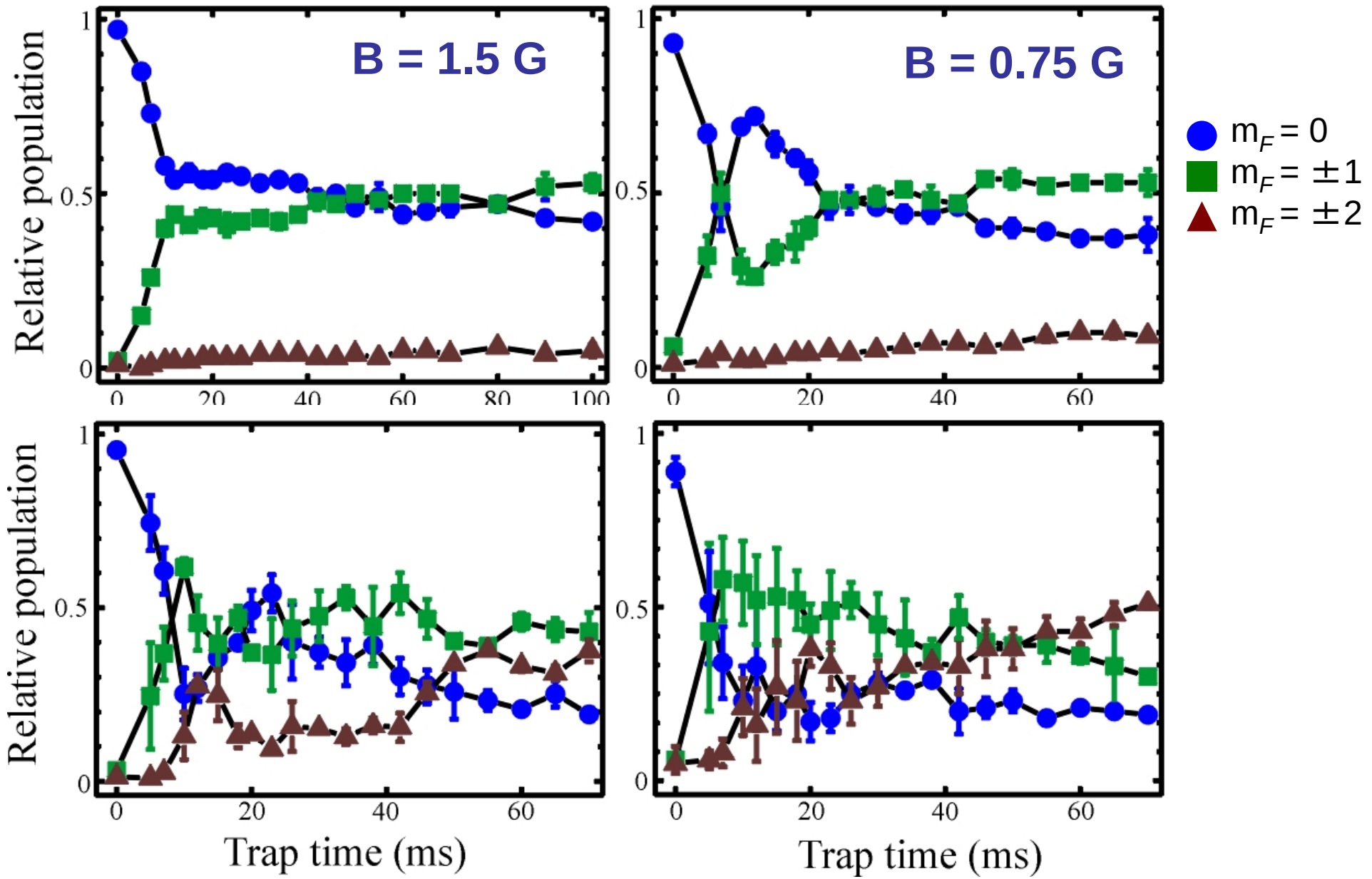
Time evolution

Total-spin-conserved spin-relaxation process





Magnetic field dependence of spin-mixing dynamics



Oscillation in spin populations@ B = **0.75G**, **0.3G**

cf. F=1 Josephson Oscillation:
Nature Physics 1, 111 (2005)

Evolution of Condensates in Optical Trap

Spin-dependent free energy

$$E_{spin} = c_1 \langle \vec{F} \rangle^2 n + c_2 |\langle S \rangle|^2 n - q\langle F_z^2 \rangle - p\langle F_z \rangle$$

Spin-dependent mean field energy

$\Delta m_F = \pm 1$

Spin-dependent mean field energy

$\Delta m_F = \pm 2$

Quadratic Zeeman

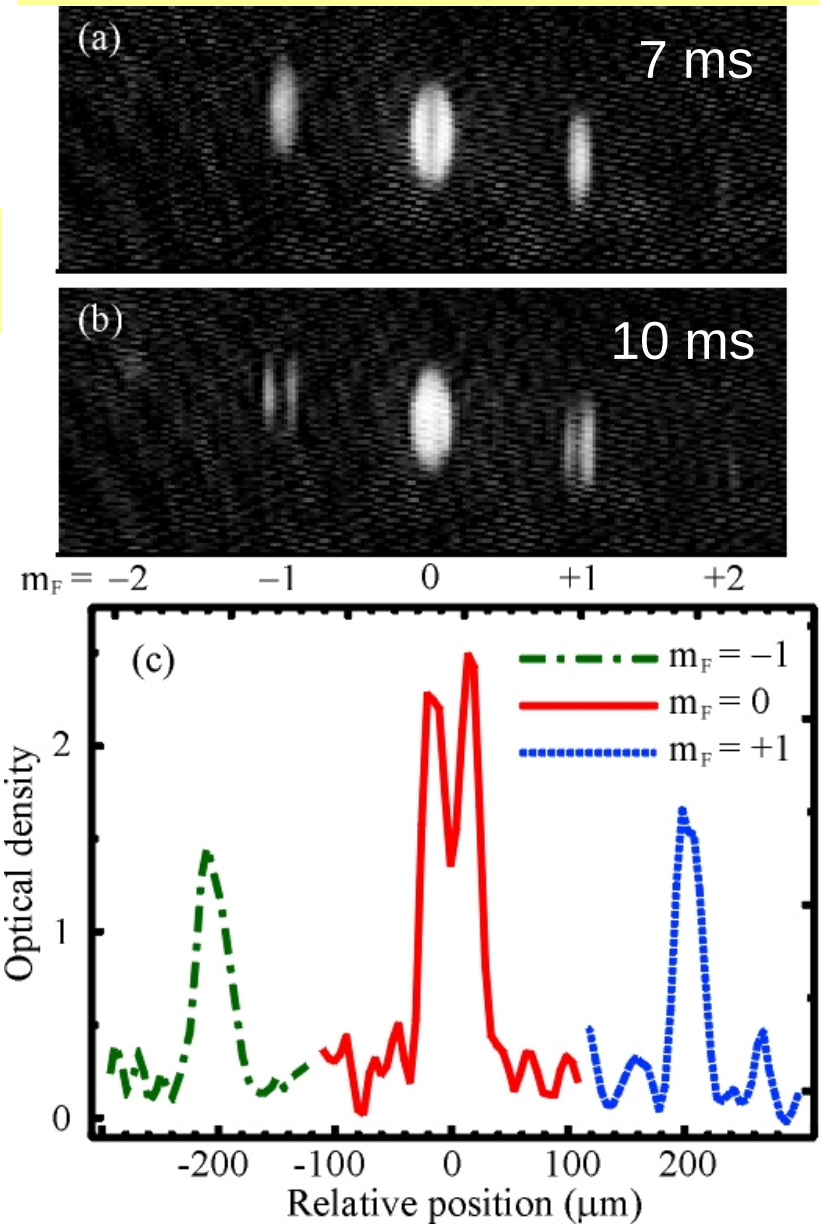
Linear Zeeman

n : density of condensates

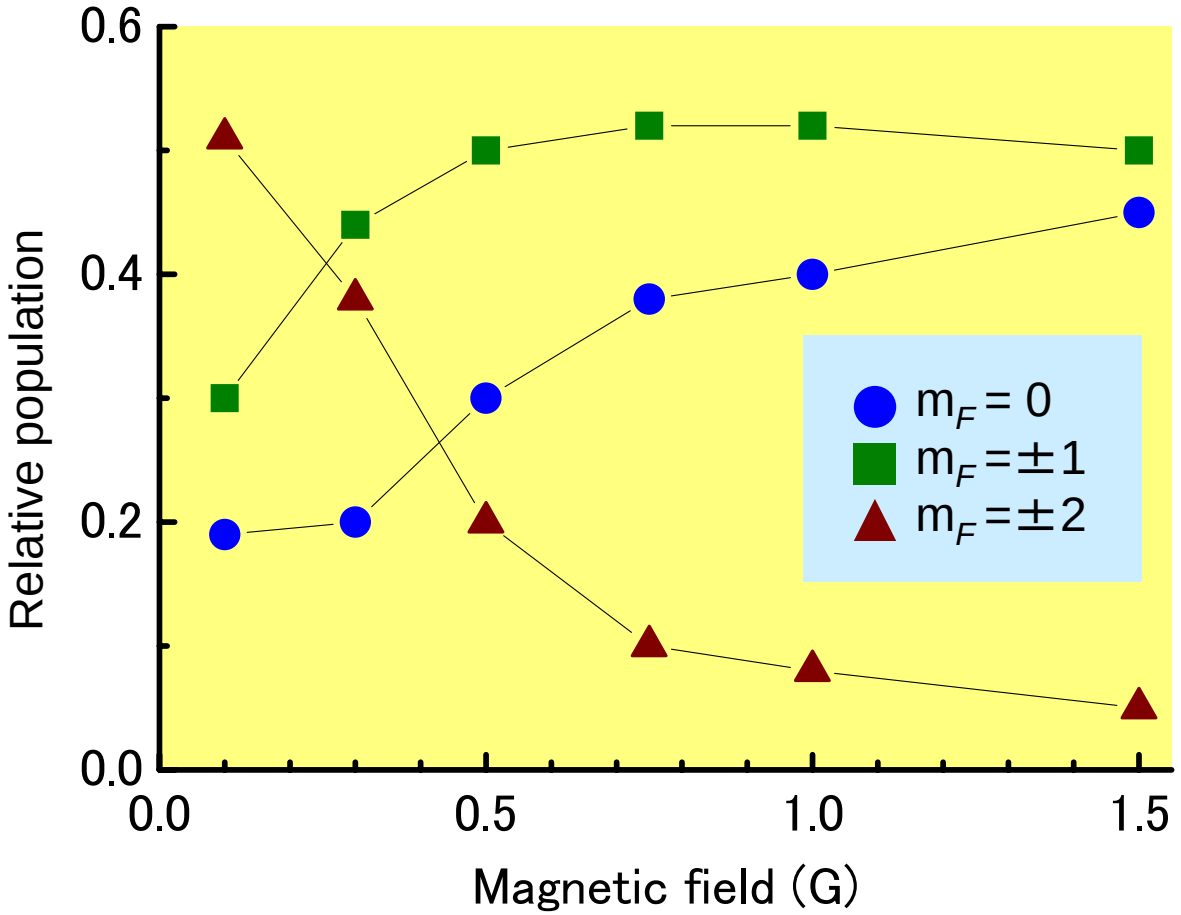
$|\langle S \rangle|^2$: spin-singlet amplitude

Spin exchanges occur more frequently at the high density region.

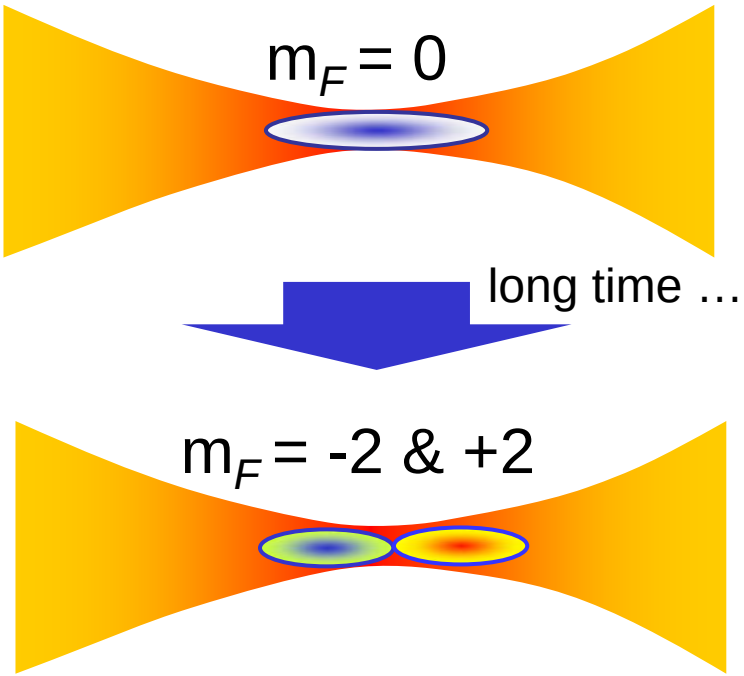
External magnetic field : B = 0.75 G



Relative Populations of Each Component after 70-ms Evolution - Magnetic Field Dependence -



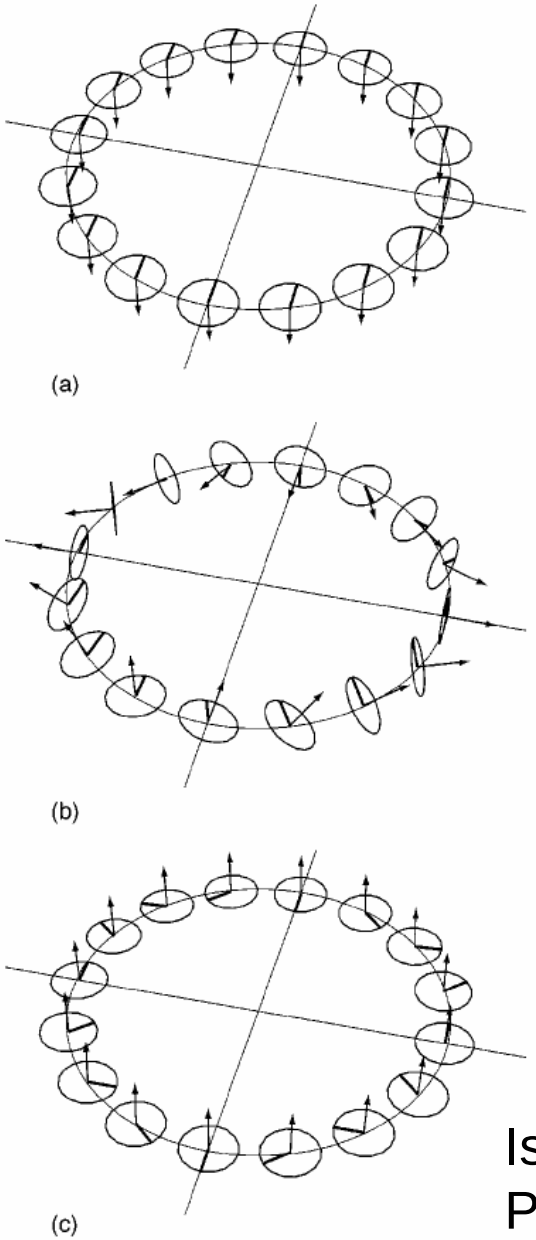
Kuwamoto et al.
Phys. Rev. A 69, 063604 (2004).



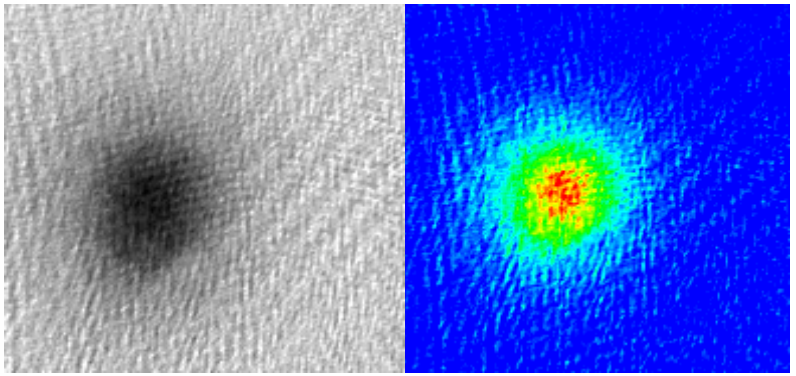
If the $F = 2$ ^{87}Rb BEC has anti-ferromagnetic properties, the mixture of $m_F = -2$ and $m_F = +2$ is one of the ground states at a zero magnetic field. **[M.Ueda & M.Koashi, PRA, 65, 063602 (2002)]**

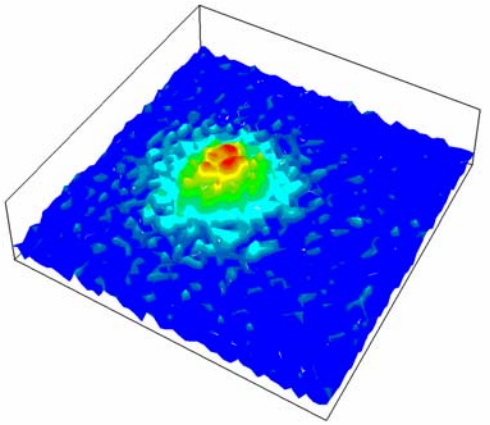
Vortex Formation via magnetic field reversal

PHYSICAL REVIEW A **61** 063610

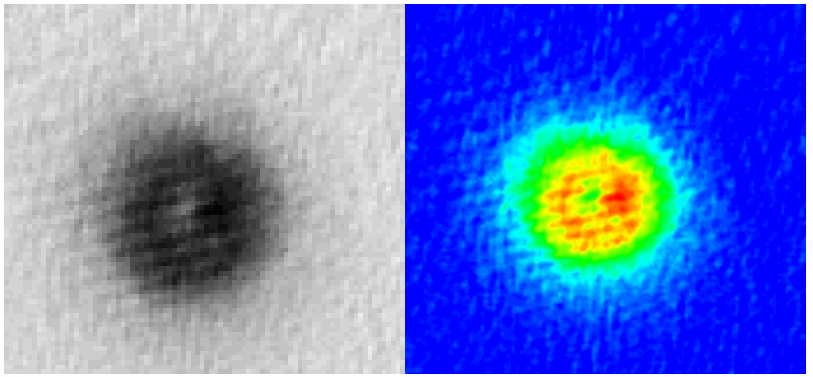


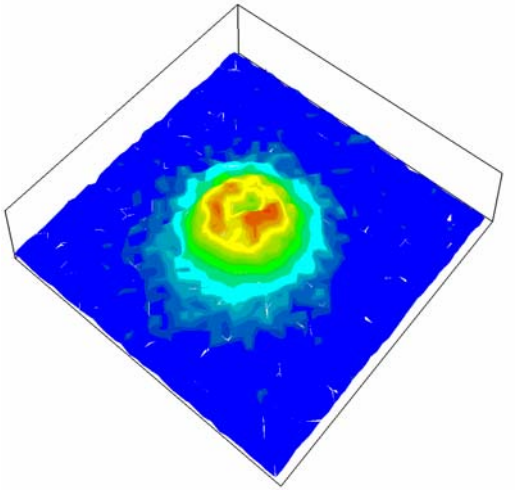
Normal BEC





Charge-4 Vortex





Isoshima et al.
Phys. Rev. A 61, 063610 (2000)

Summary

- Dynamical Properties of ^{87}Rb Spin-2 BEC

  Decay at various magnetic field strengths

  → Spin relaxation, population oscillation

  → Antiferromagnetic

- Optical Confinement of Binary BEC
- Vortex Formation via magnetic field reversal

  Charge 4 vortex, up to 10 msec

Future prospect

Coherent collision in F=2 BEC

Dymanics in binary BEC: spin and external degrees of freedom

Coreless vortex, spin texture