Boulder Summer School 2021: Ultracold Matter

Eric Cornell

Q: Why Cold? Why ultra?

A: MAGNIFY the effects of quantum mechanics

Precision measurement and spectroscopy: reduce accessible states: simplify state preparation

Suppress Doppler shifts, other decoherence

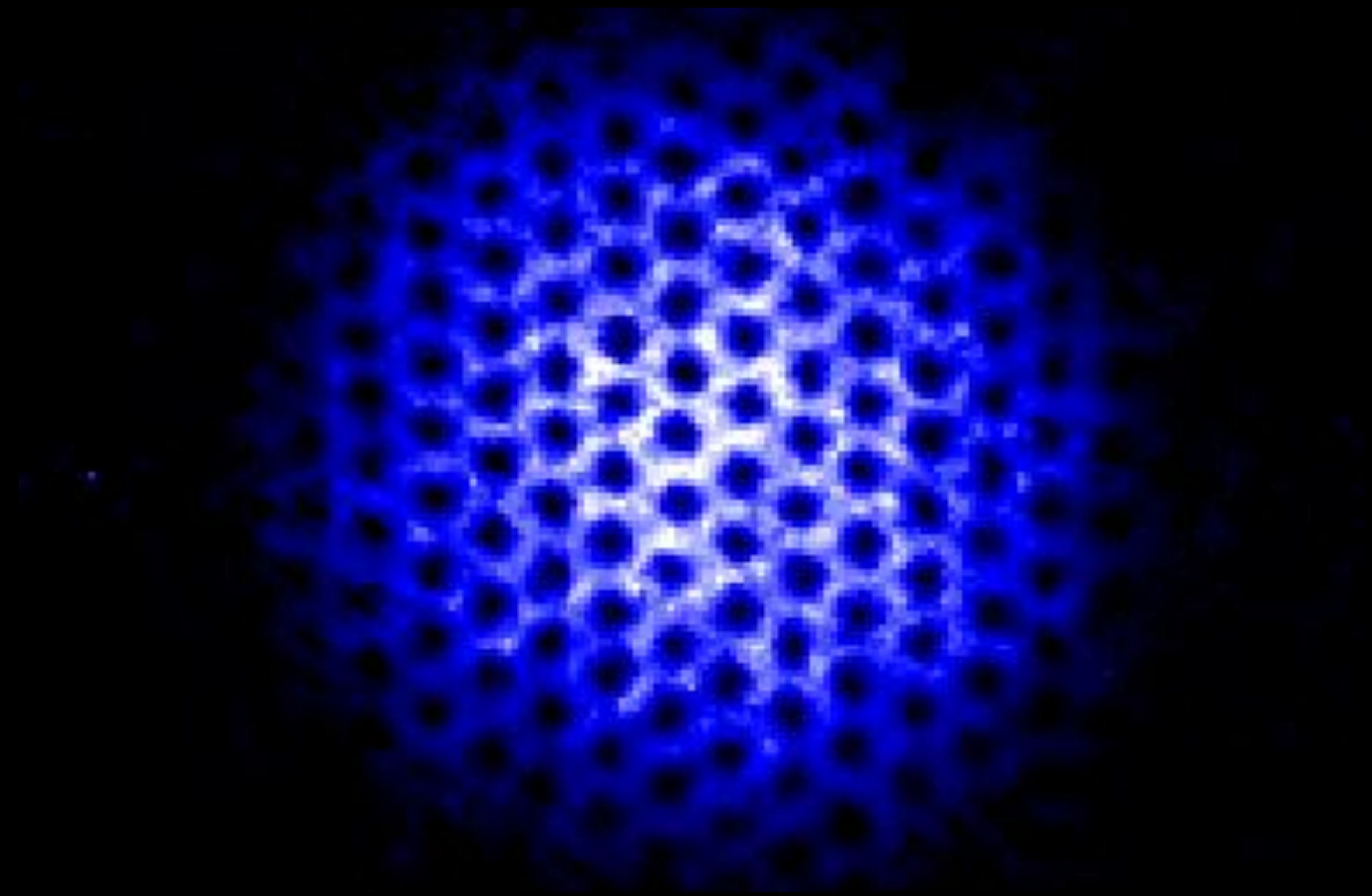
Enhance (or suppress) and simplify interaction effects.

Degenerate gases

Today's talk: a discussion on why ultracold atom experiments look the way they do.

May be worth thinking about, revisiting, as ultracold atoms move from experiment to tool, to technology.

Presentation totally informal. Questions highly welcome.



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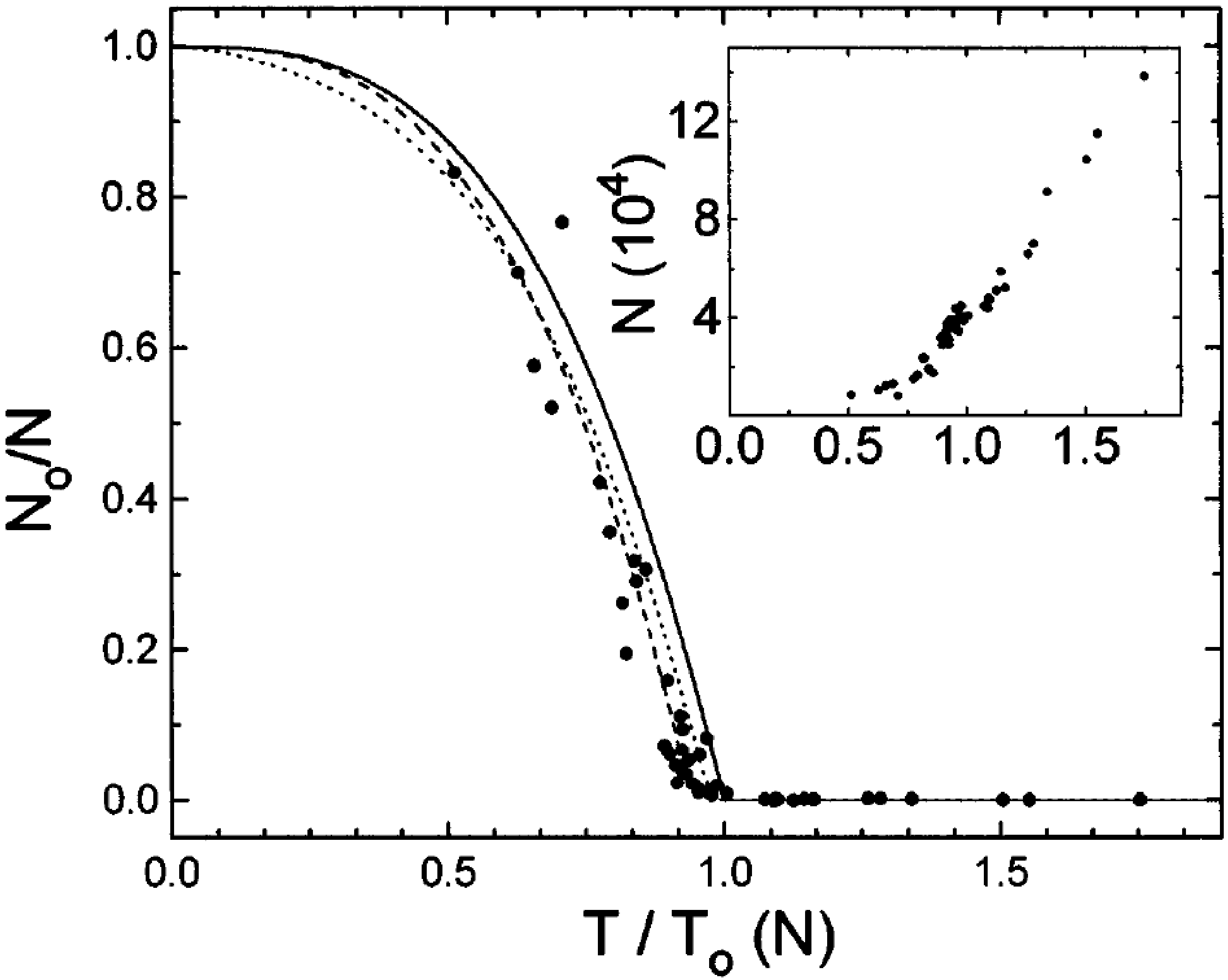
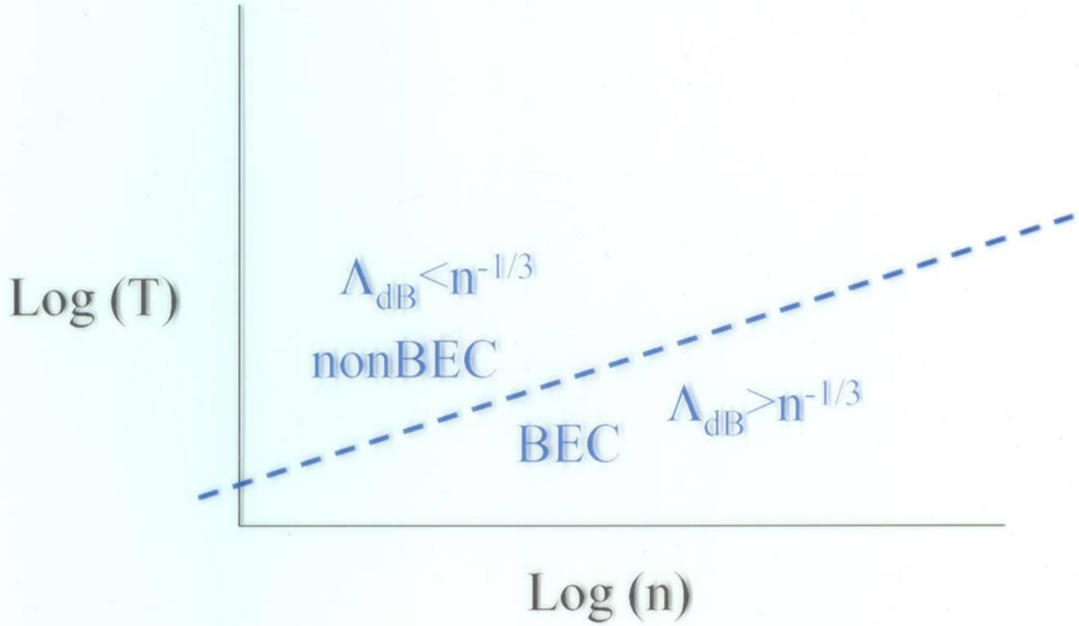
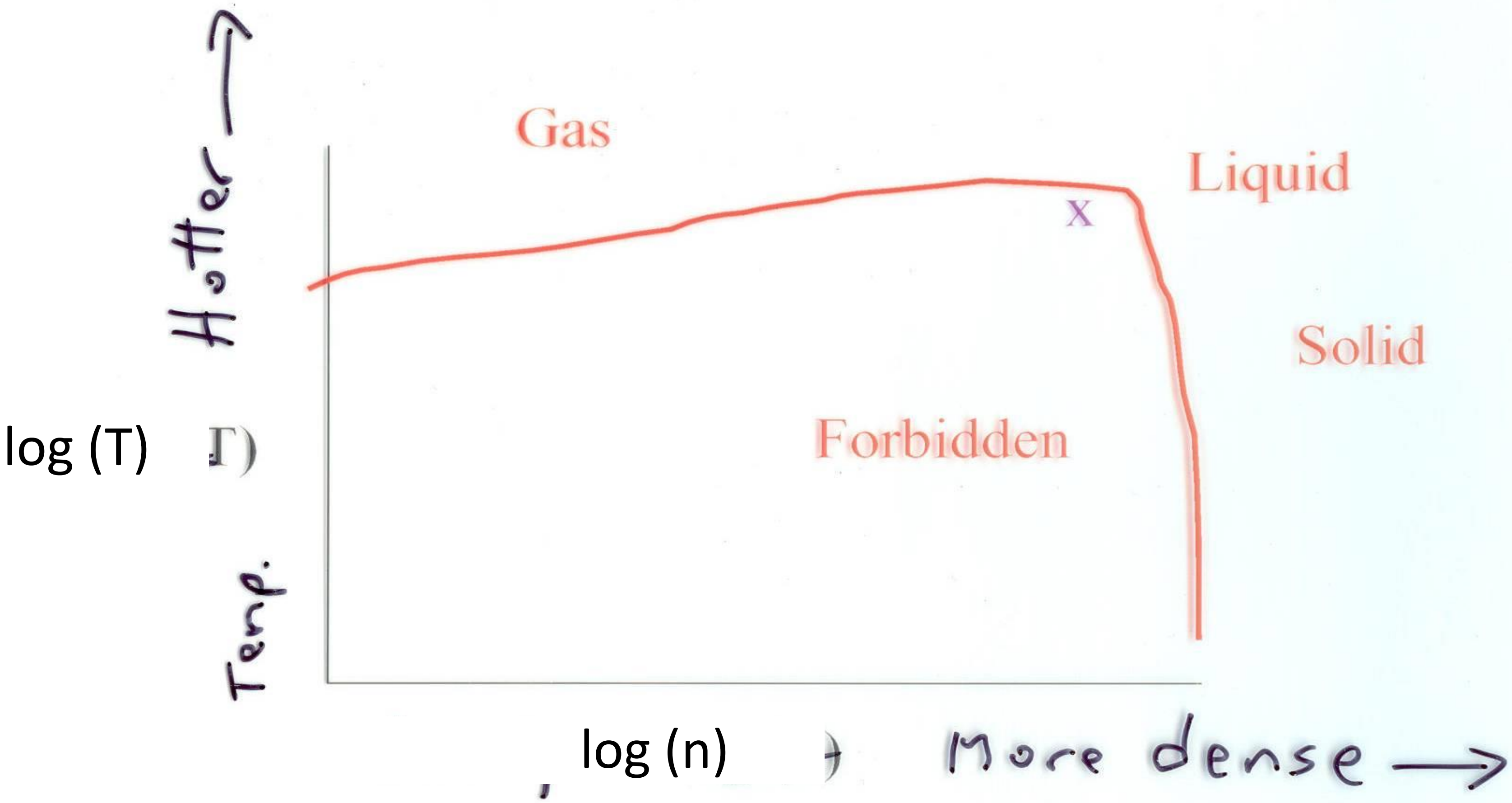


Bose-Einstein Condensation in a Dilute Gas: Measurement of Energy and Ground-State Occupation, J. R. Ensher, D. S. Jin, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Phys. Rev. Lett. 77, 4984 (1996)

Bose-Einstein condensation: not brute-force cooling.
Indistinguishability a force to be reckoned with.
BEC: a “temperature divider”

BEC happens when interatomic spacing is comparable to thermal deBroglie wavelength.

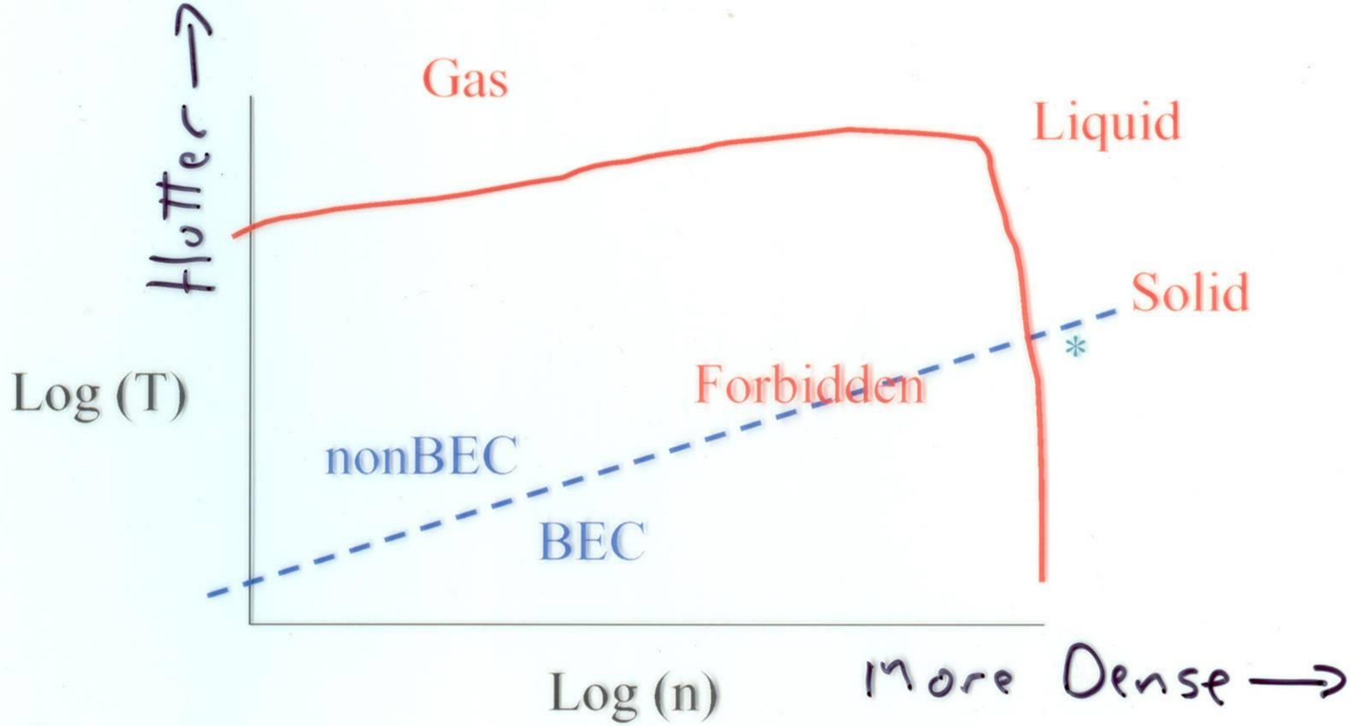




Example: $H_2 0$ at 20 C, 0.1 gm/cc

Forbidden!

Forbidden Science!

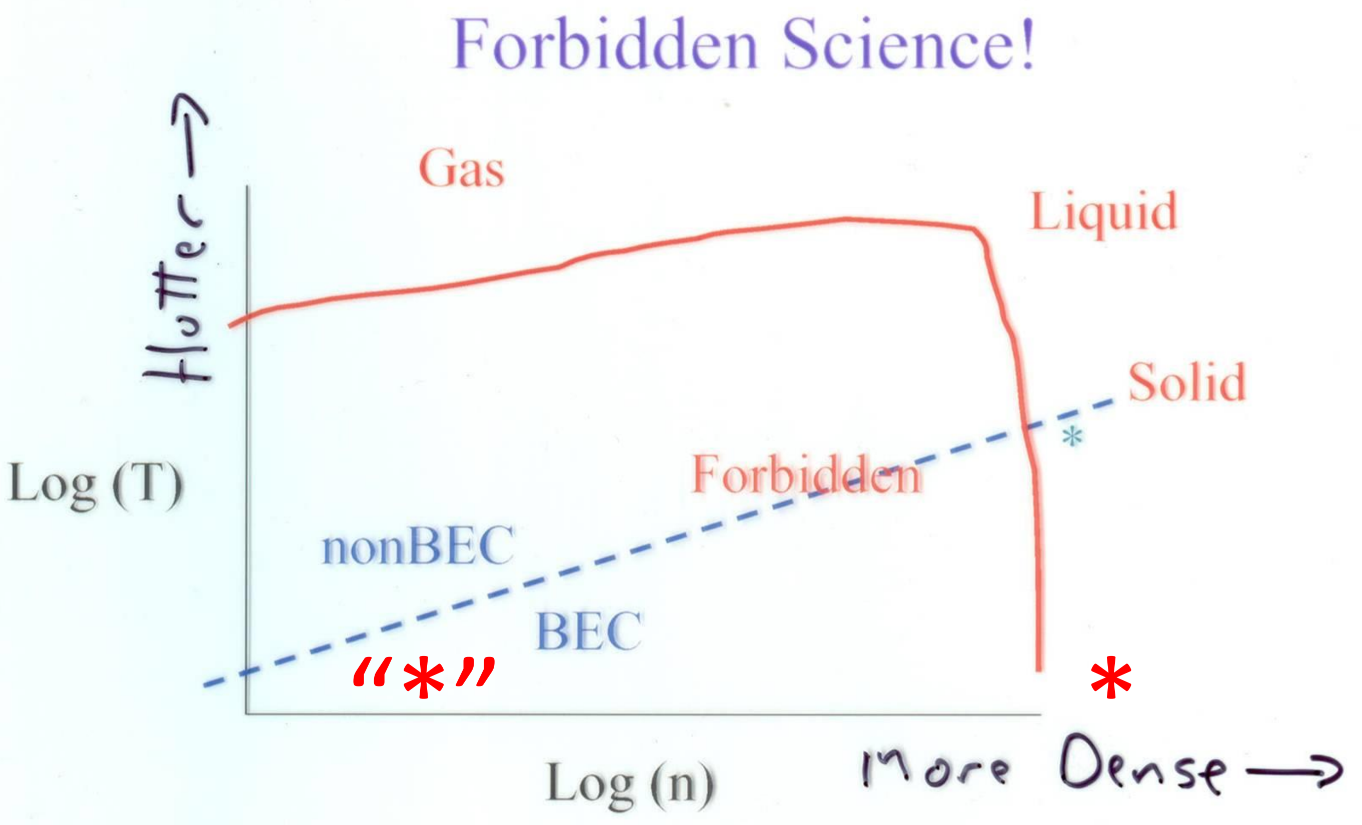


Solids can't Bose condense: BEC is forbidden!

The sole exception: Helium remains a liquid in the BEC zone.

← *

Equilibrium Rb vapor density @ 300 nK, << 1/(Volume of solar system)



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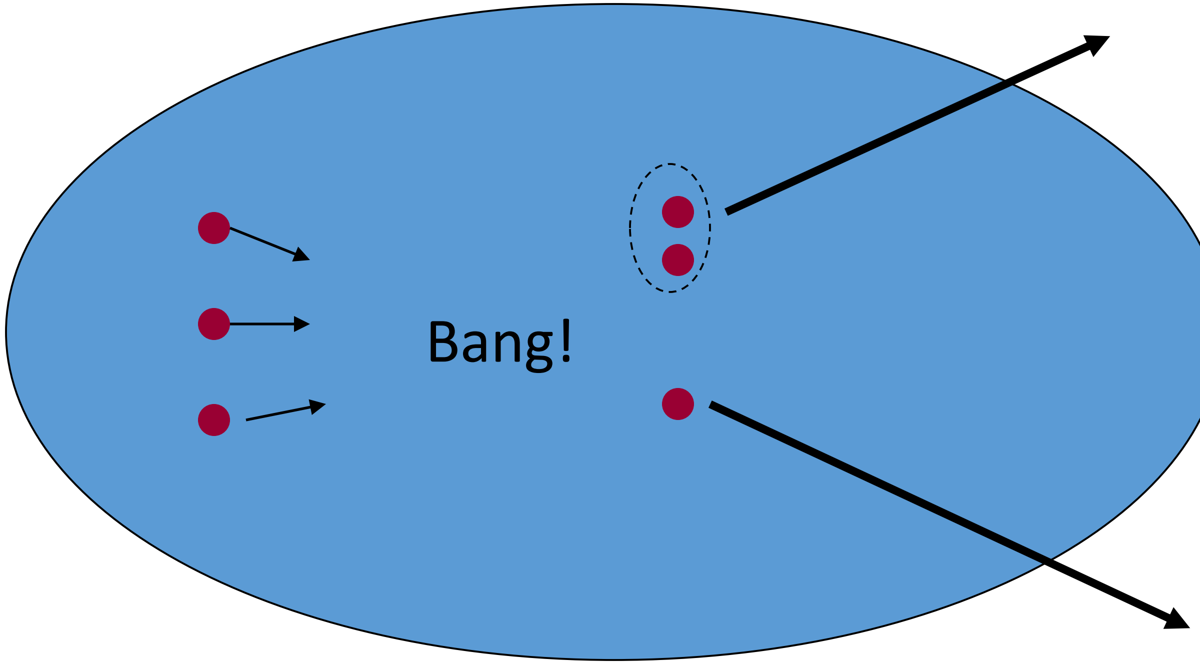
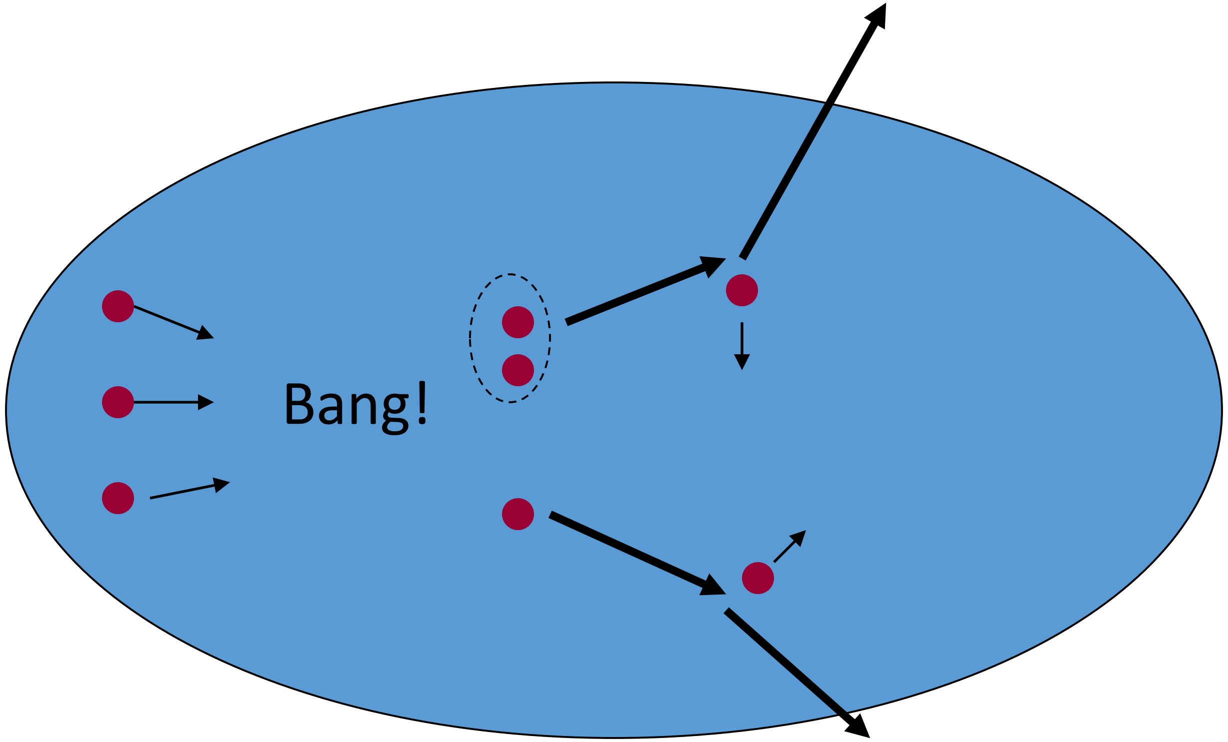
BEC experiments must be completed within limited time.



Three-body molecular-formation process causes condensate to decay, and heat!
Lifetime longer at lower density, but physics goes more slowly at lower density!

Dominant source of heat:



Decay products from three-body recombination can collide "as they depart", leaving behind excess energy in still-trapped atoms.

Three-body collisions lead to loss.
Many sequential two-body collisions lead to thermalization.

The need to have many two-body collisions for every three-body collision
sets a limit on upper limit density.

That limit on density, plus the need to be degenerate, sets a temperature scale for cold-atom BEC
.   Too low for dilution fridge

Bose-Einstein condensation: not brute-force cooling.
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Cooling stuff

Doppler molasses

Sisyphus and related

evaporation

expansion

Sideband cooling

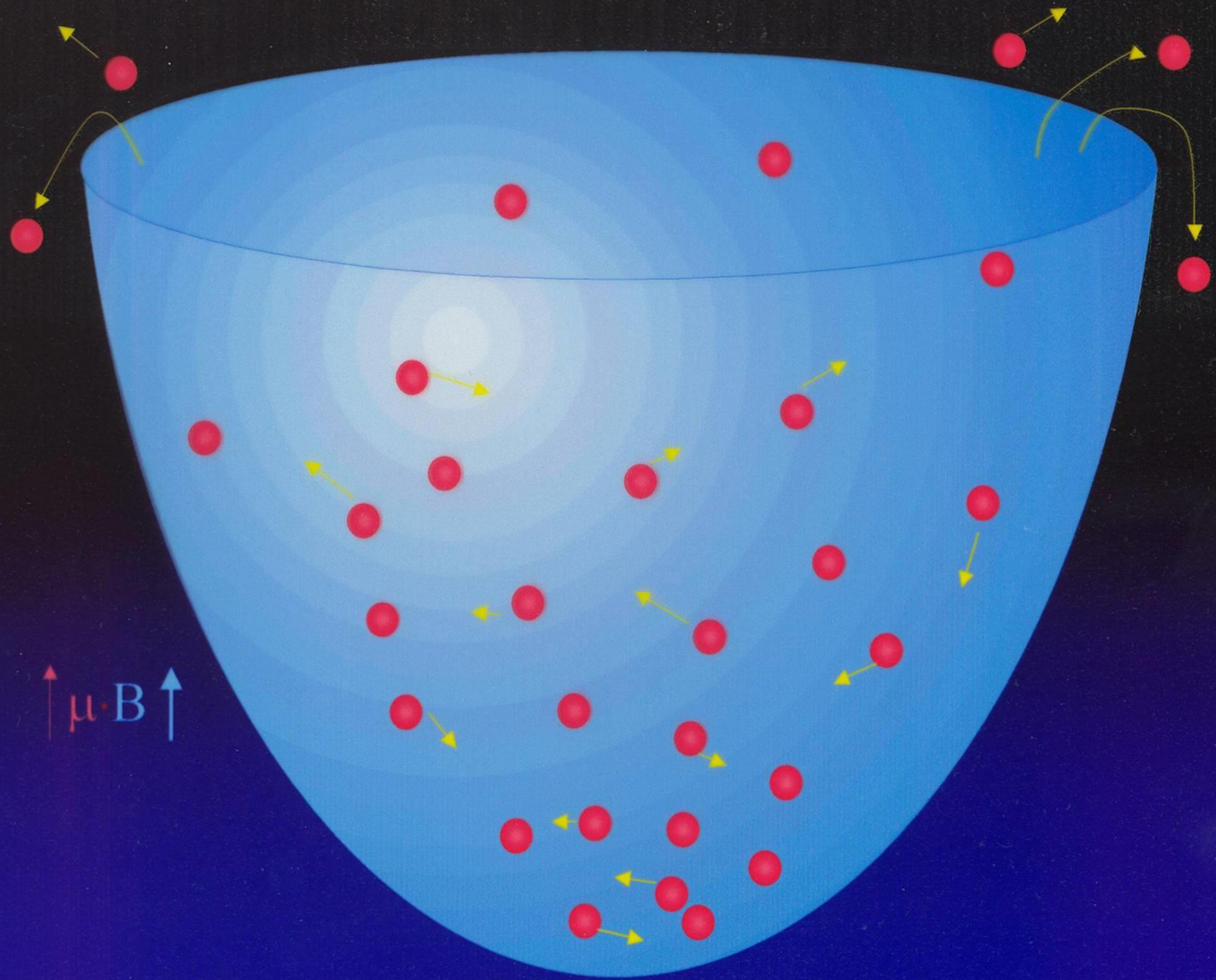

Laser Trap

Carnot cycle

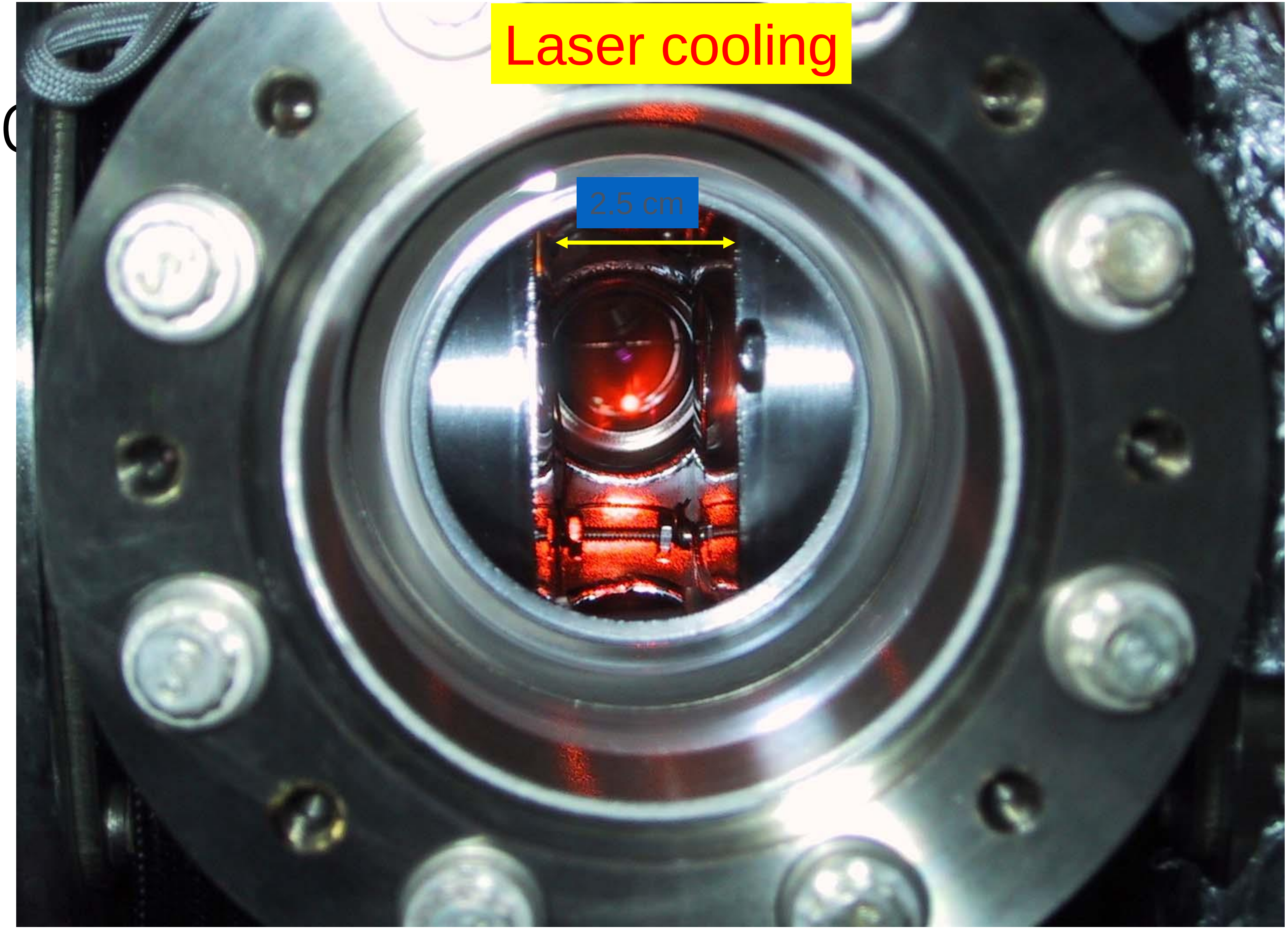
Black-body radiation and molecules

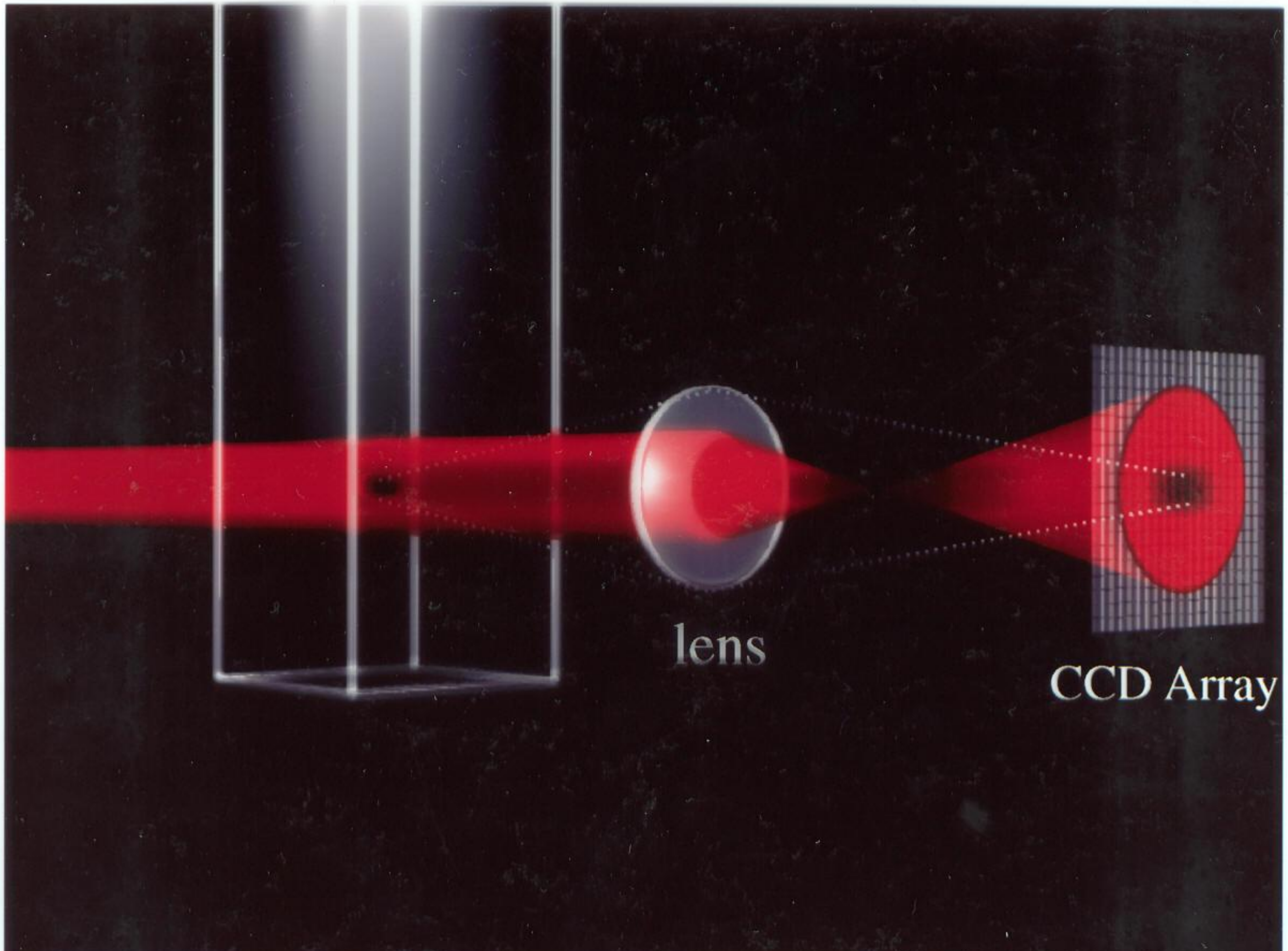
Can we do optical cooling to degeneracy?

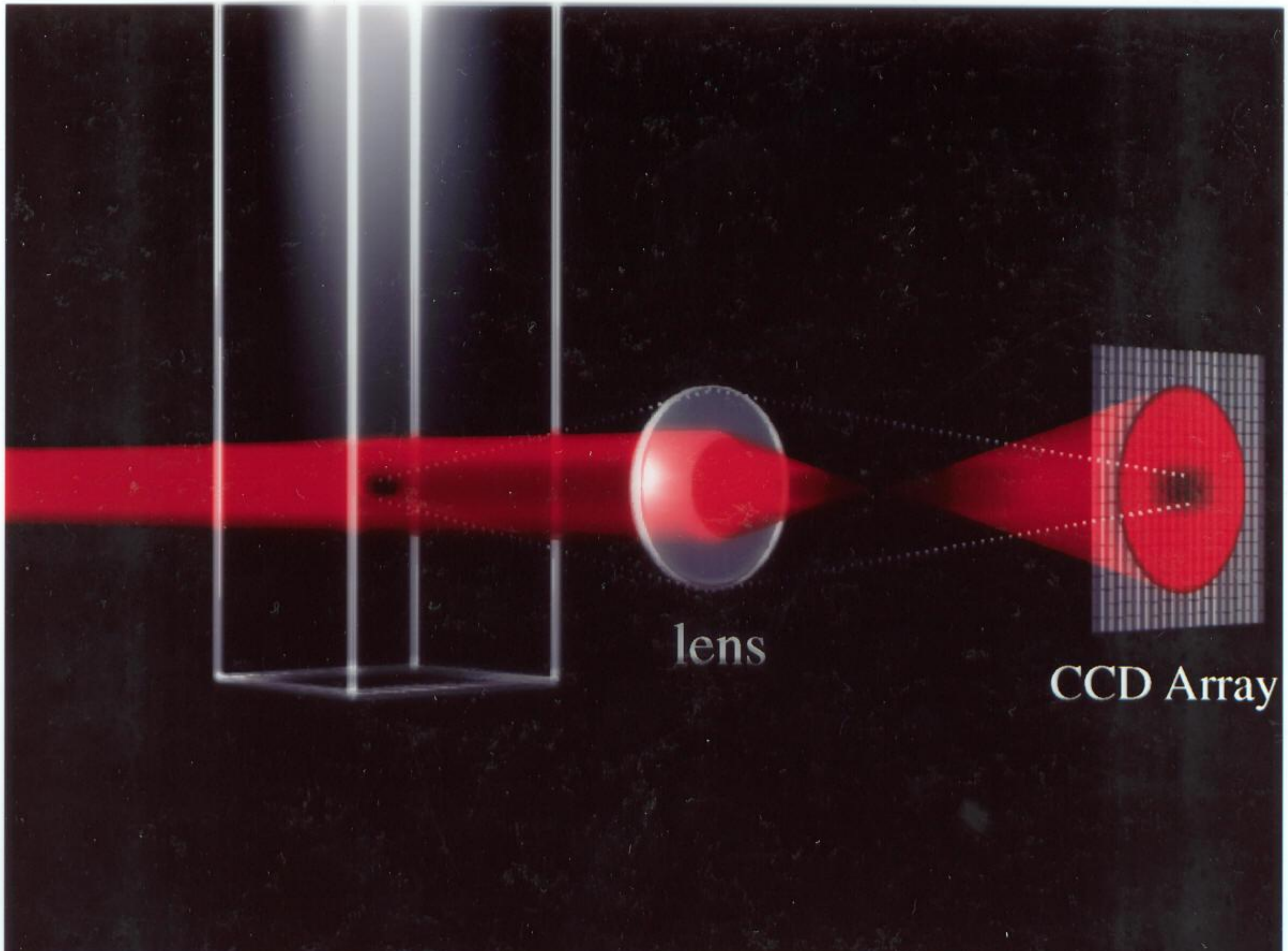
Magnetic trapping and evaporative cooling



Evaporation.
Good, but slow.
Tweezer story. Back to cooling methods
chips.
miniaturization


Laser cooling
2.5 cm


lens
CCD Array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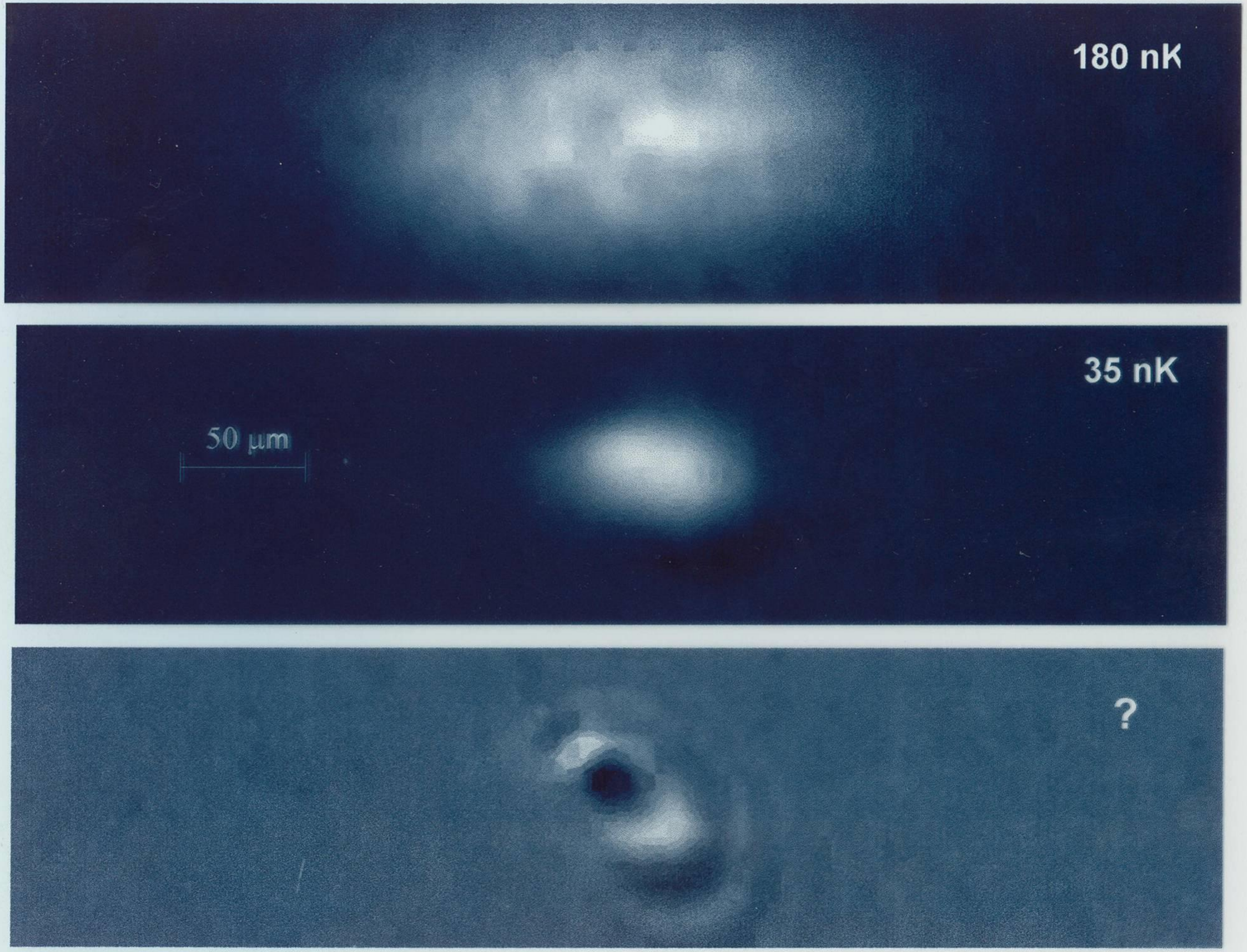
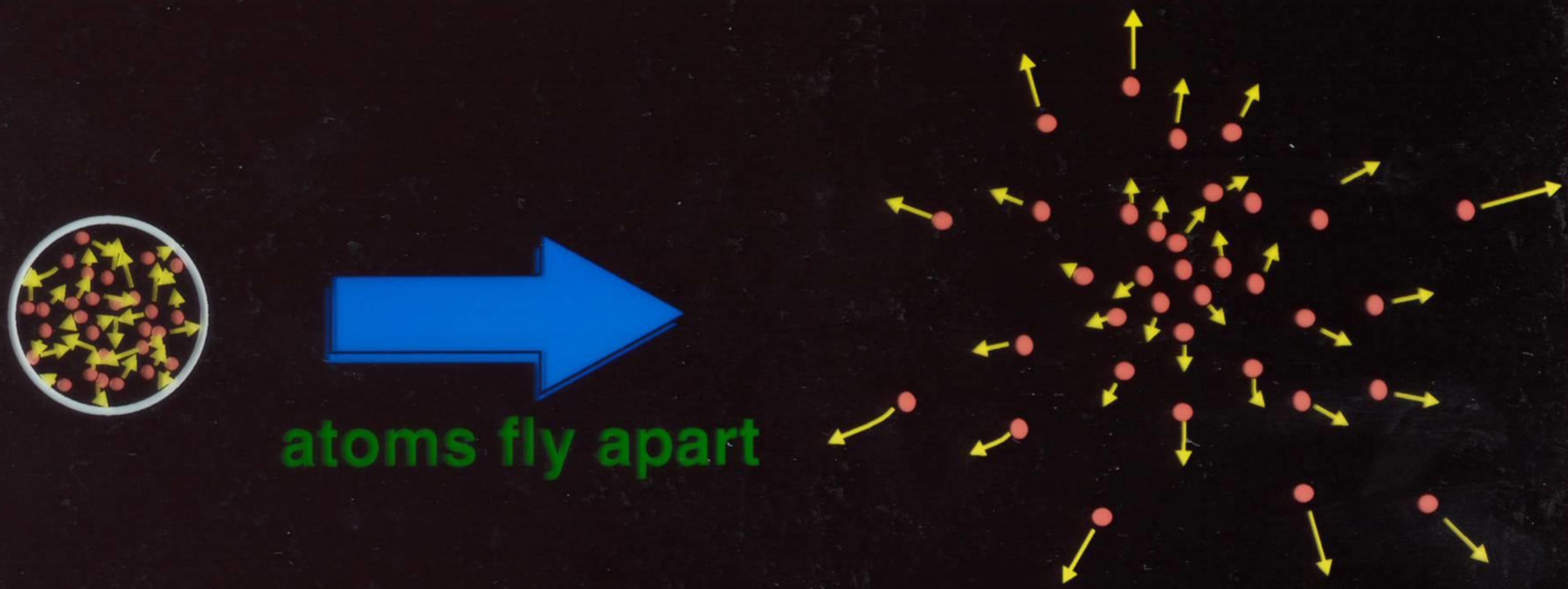
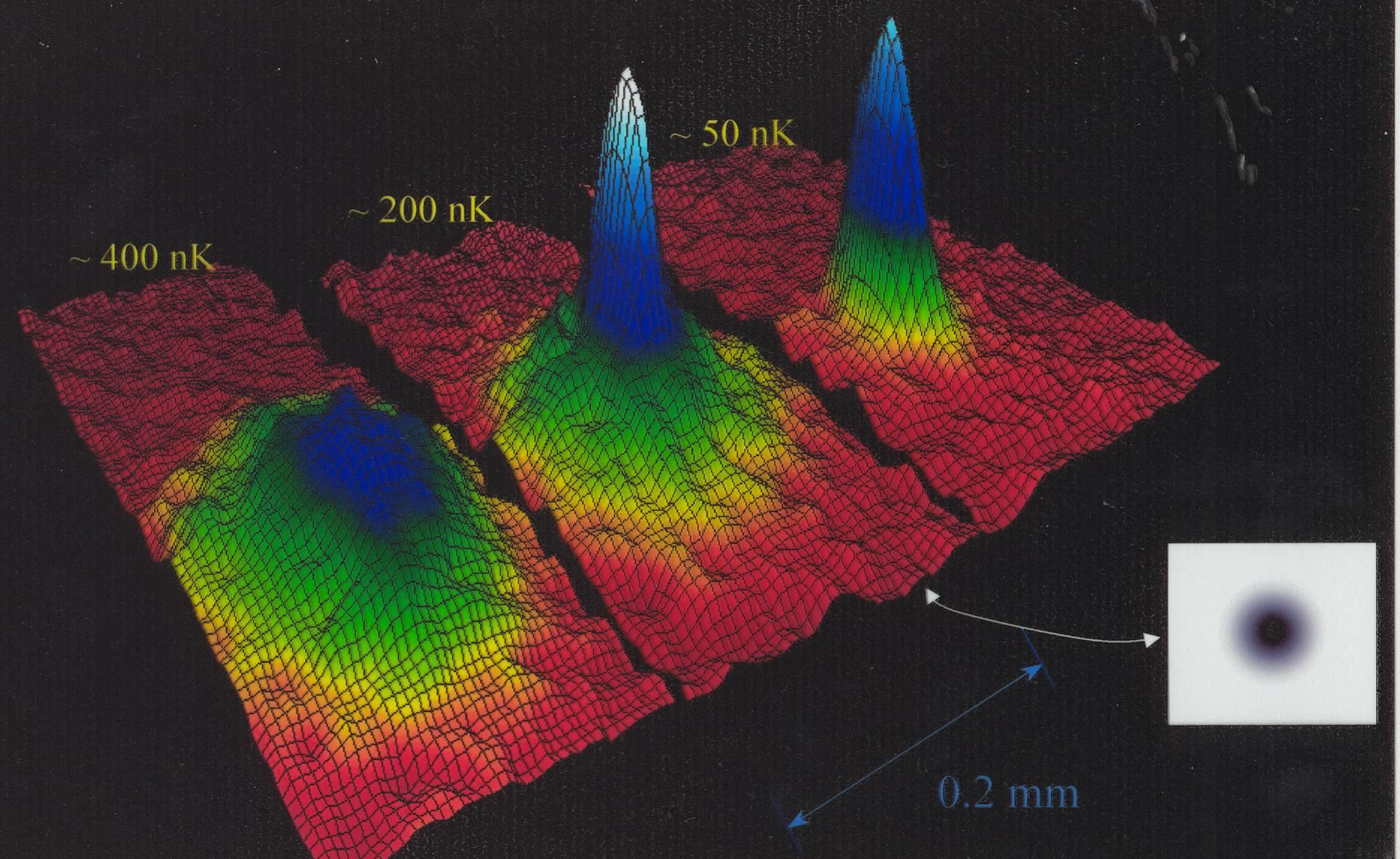
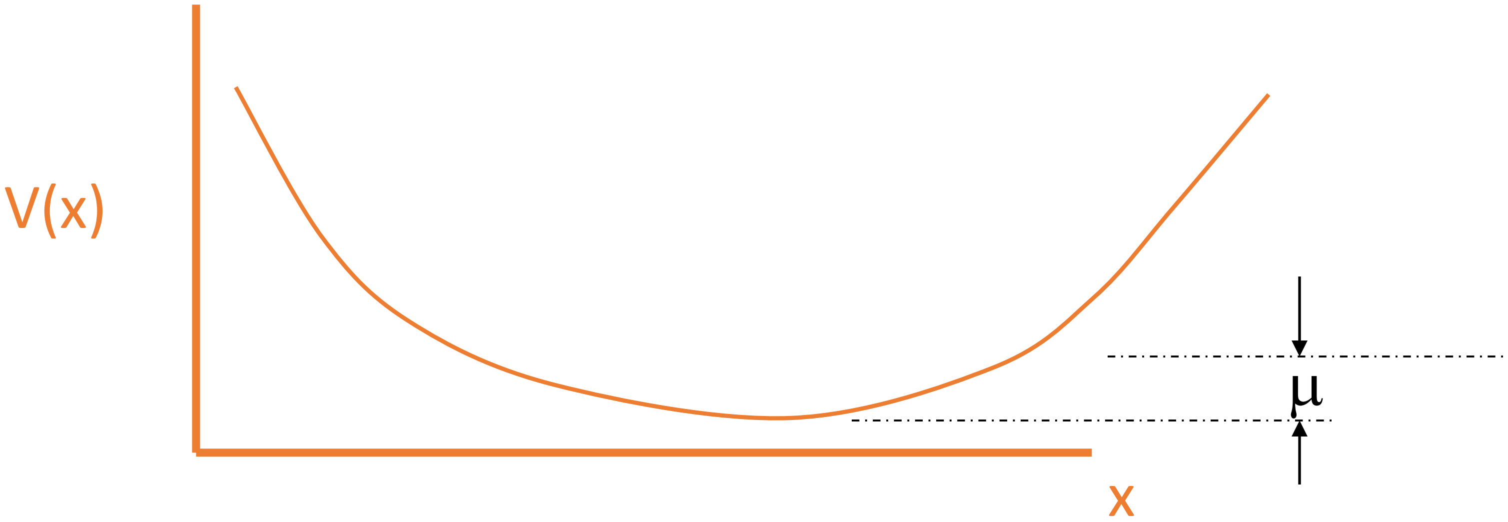

180 nK
35 nK
50 µm
?

Turn magnetic trap off

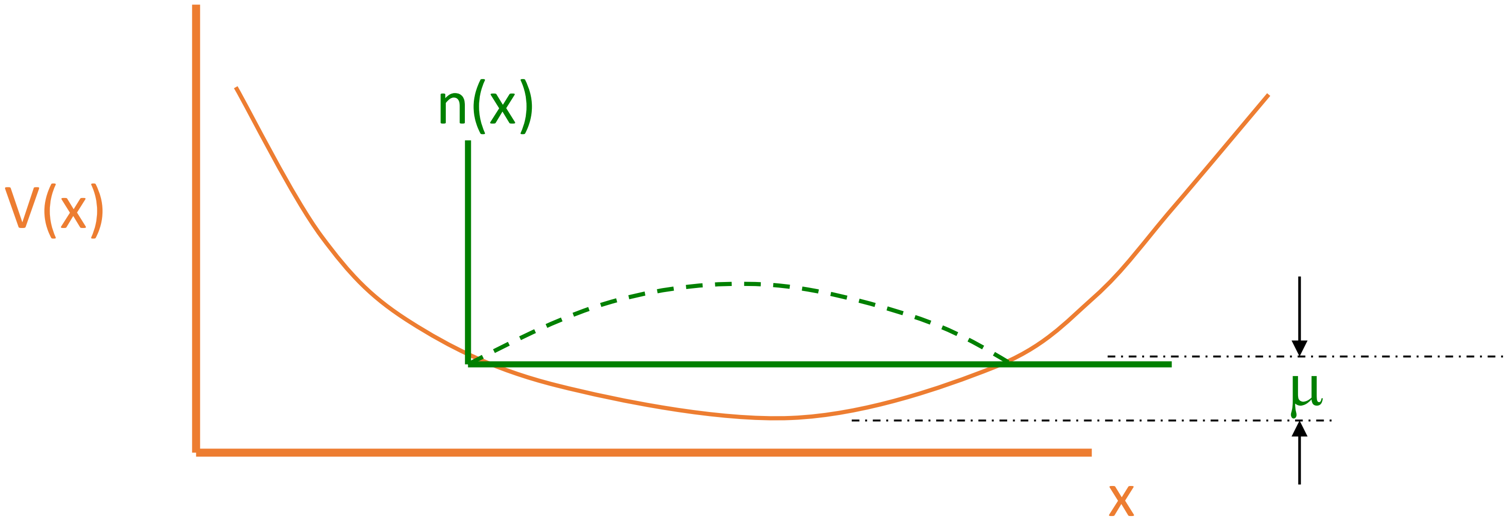


2 D velocity/density distributions





Self-interacting condensate expands to fill confining potential to height μ



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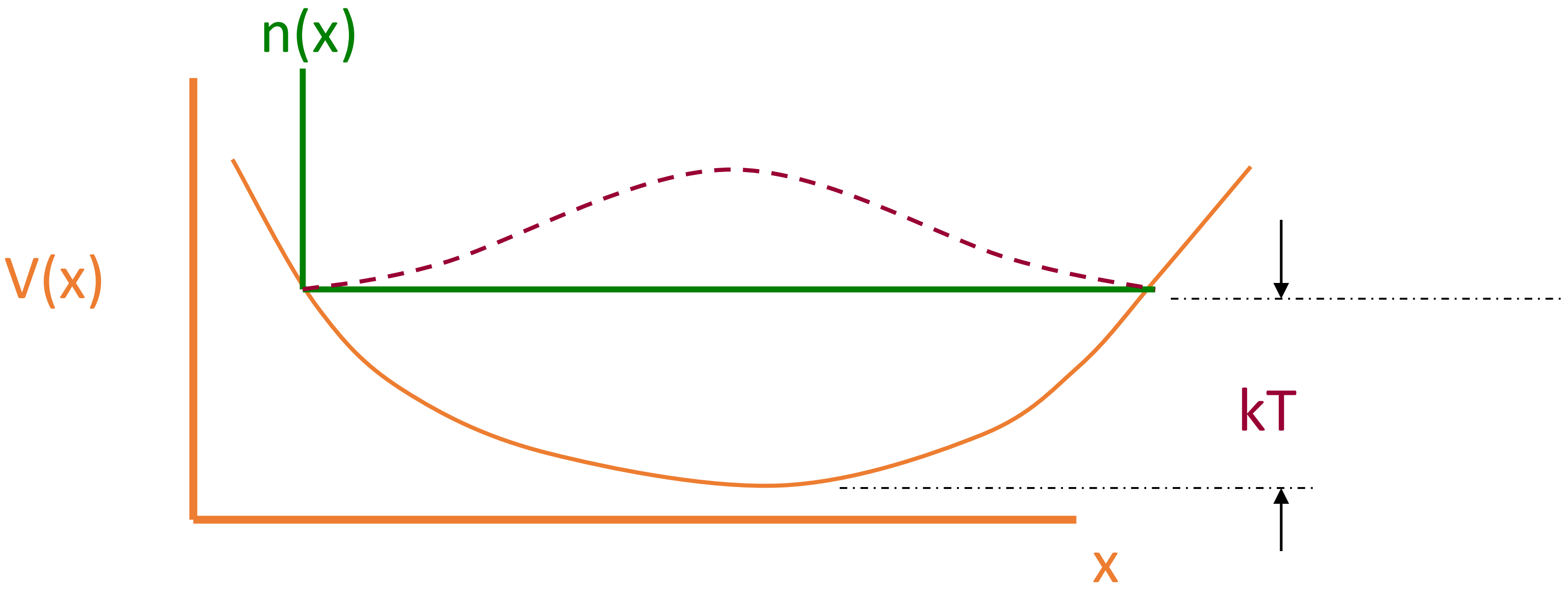
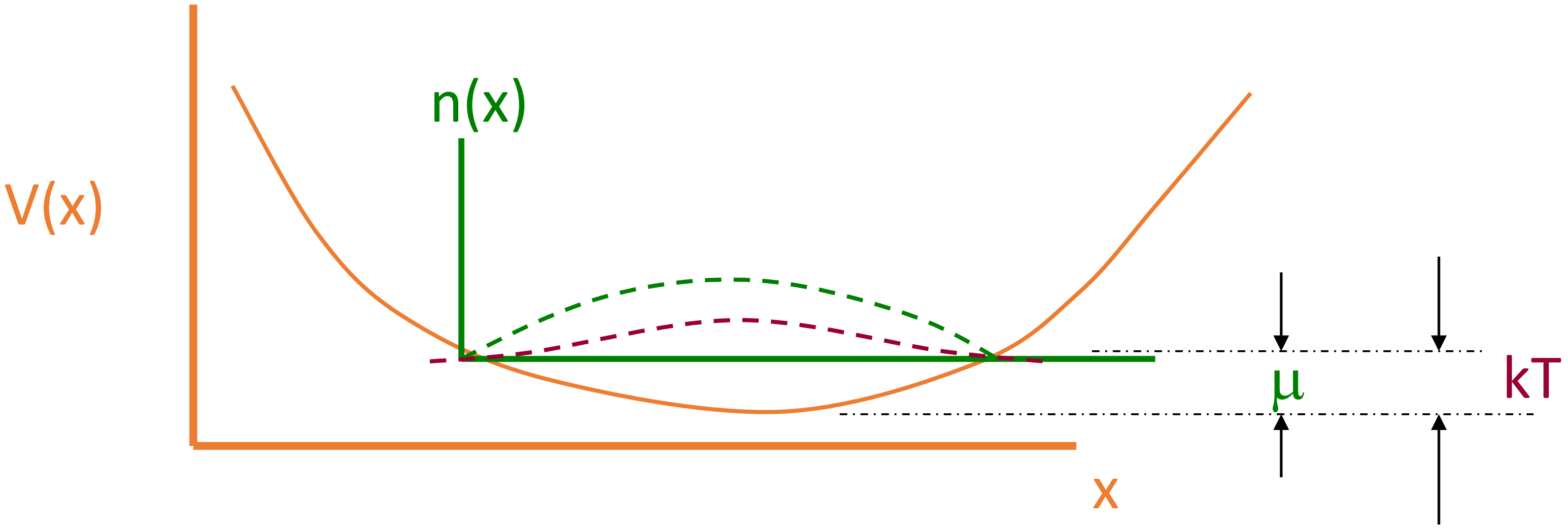


Cloud of thermal excitations made up of atoms on trajectories that go roughly to where the confining potential reaches kT



When kT < μ then there are very few thermal excitations extending outside of condensate. Thus evaporation cooling power is small.

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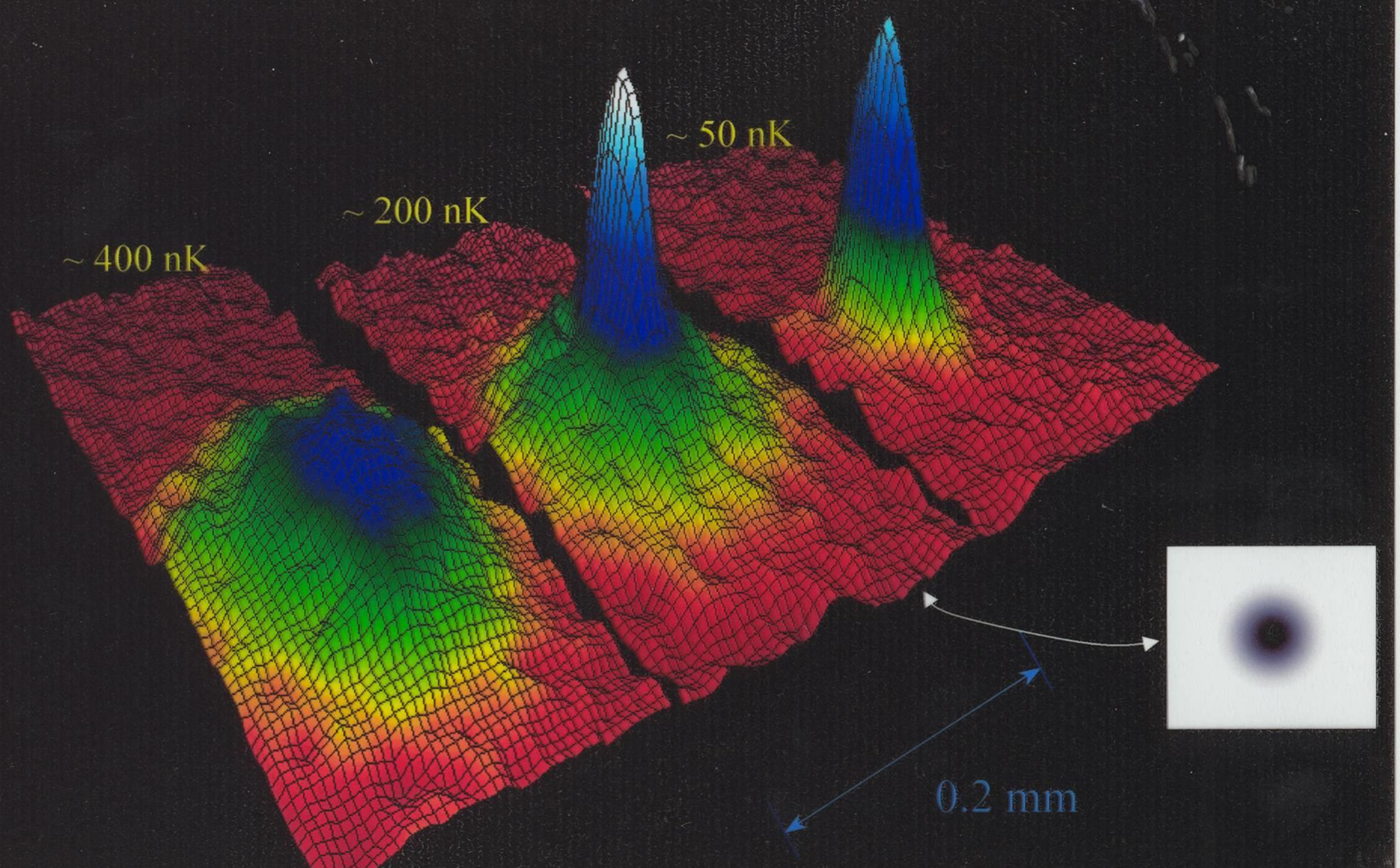
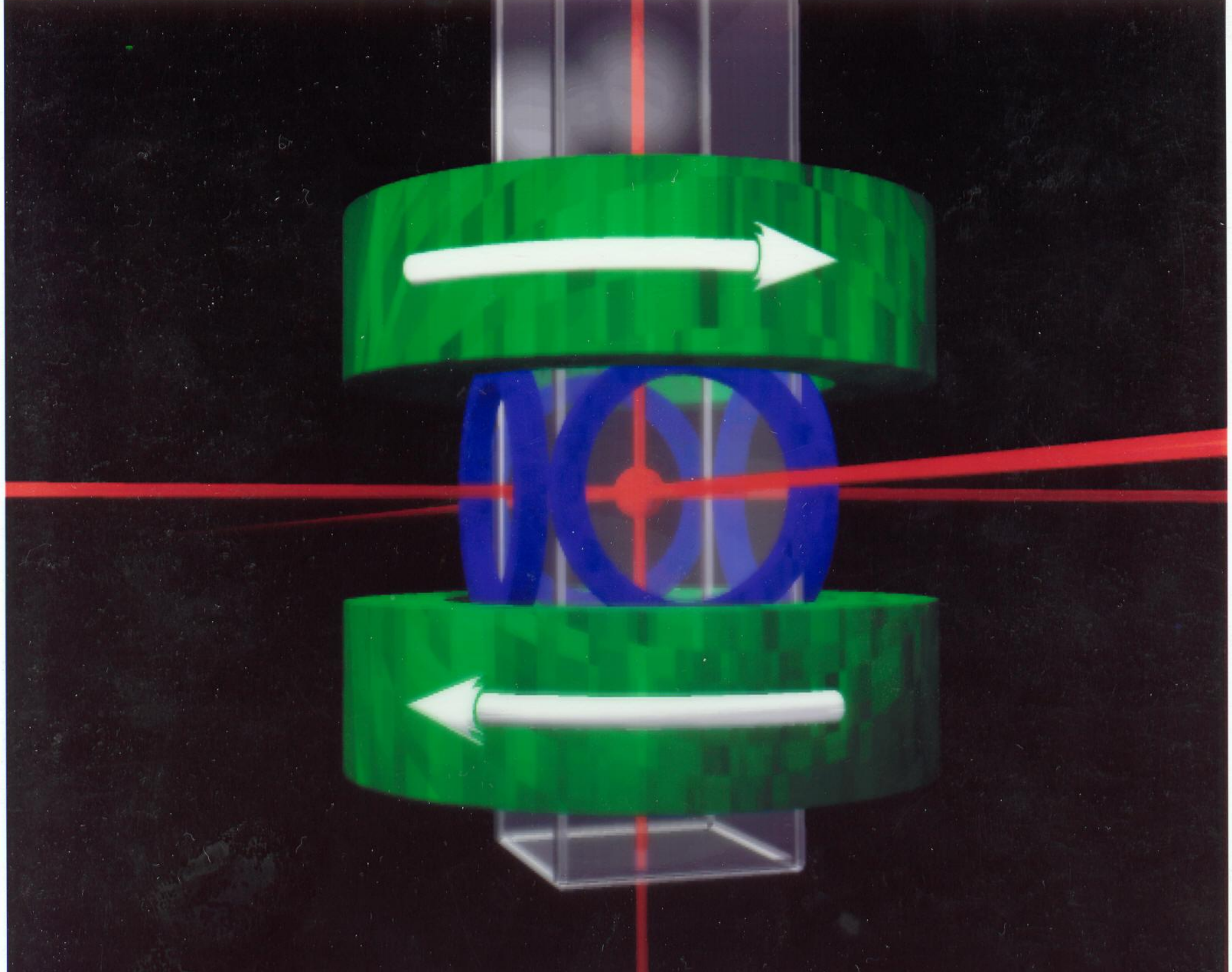
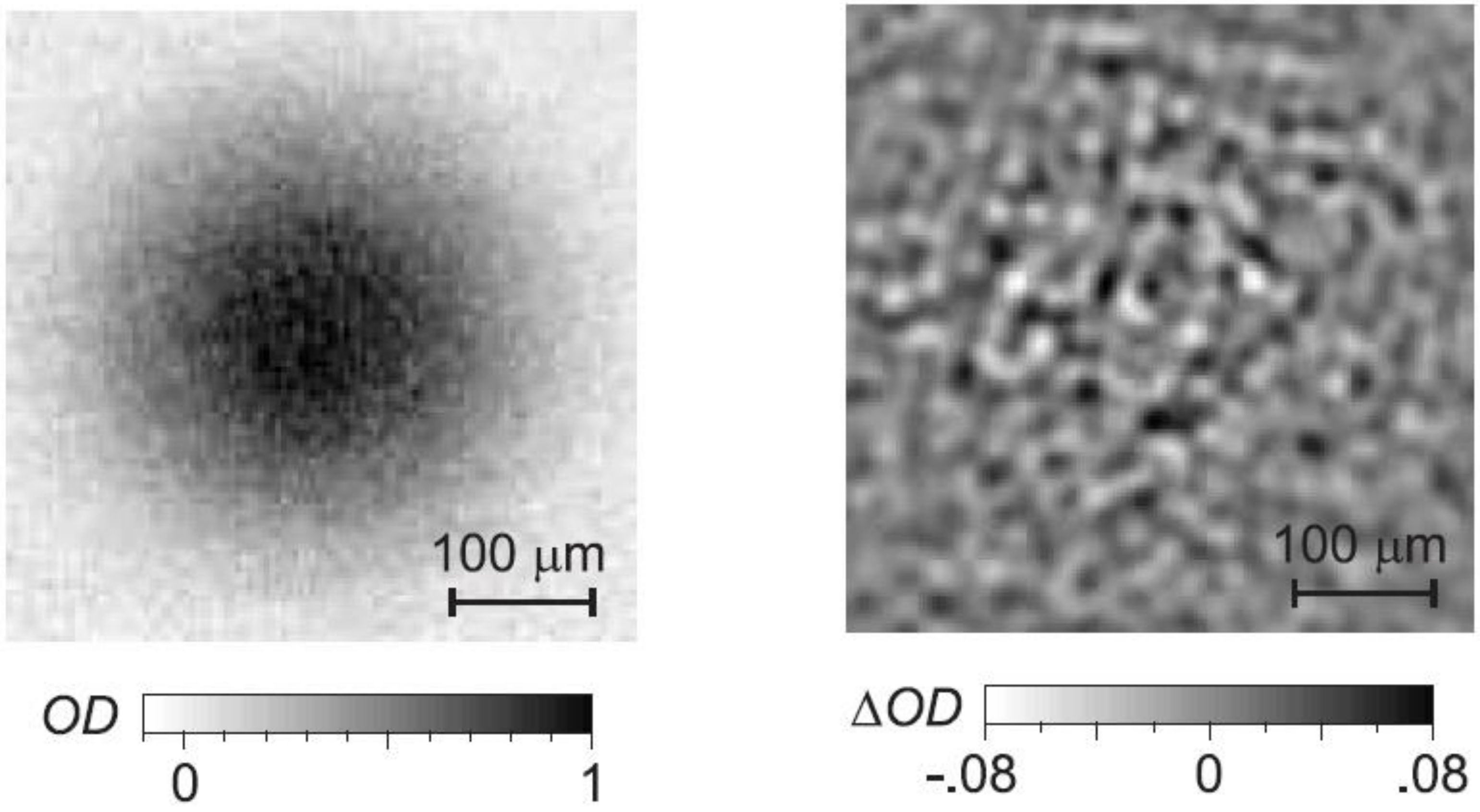
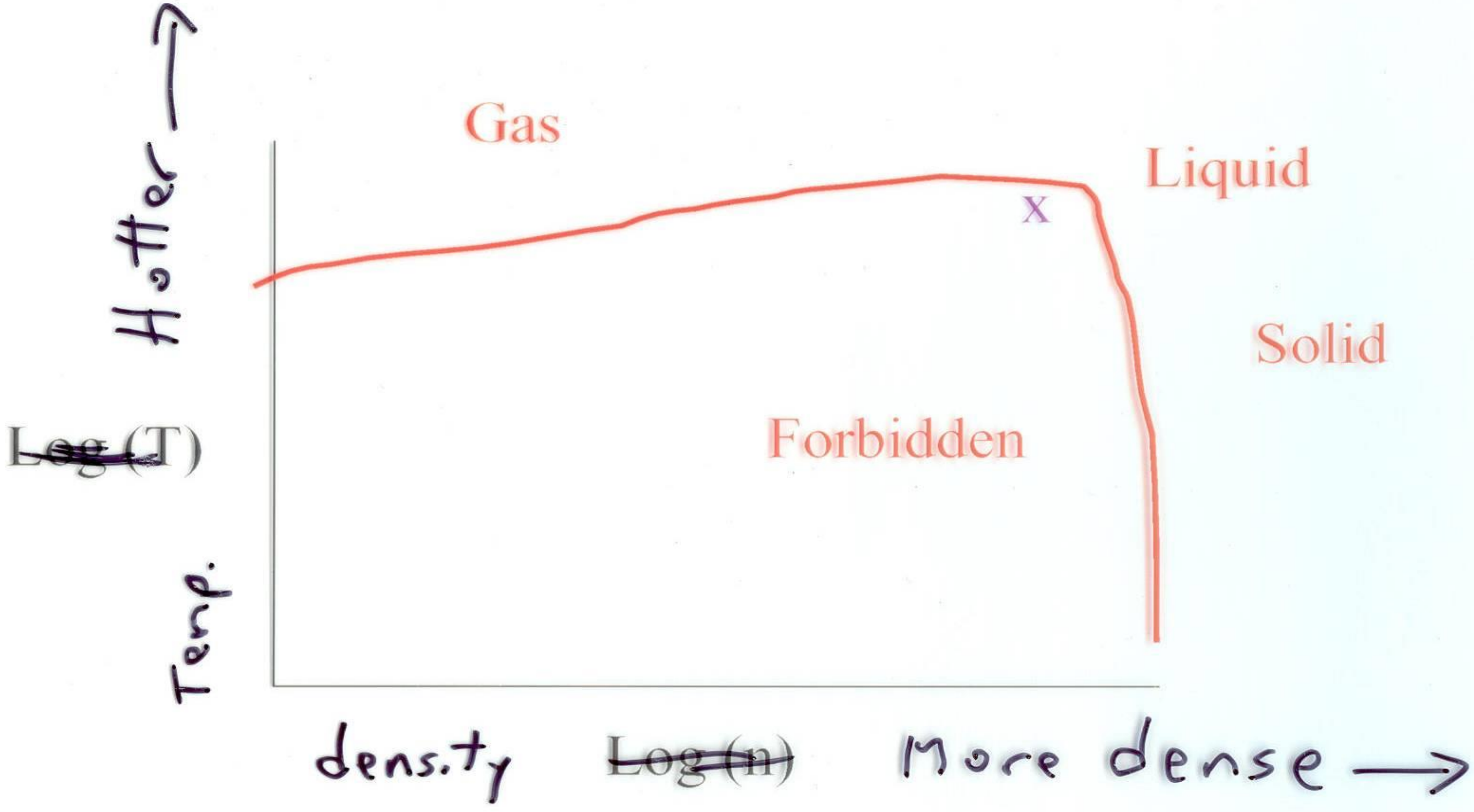




Atom shot noise limited imaging



Data from lab of Debbie Jin.



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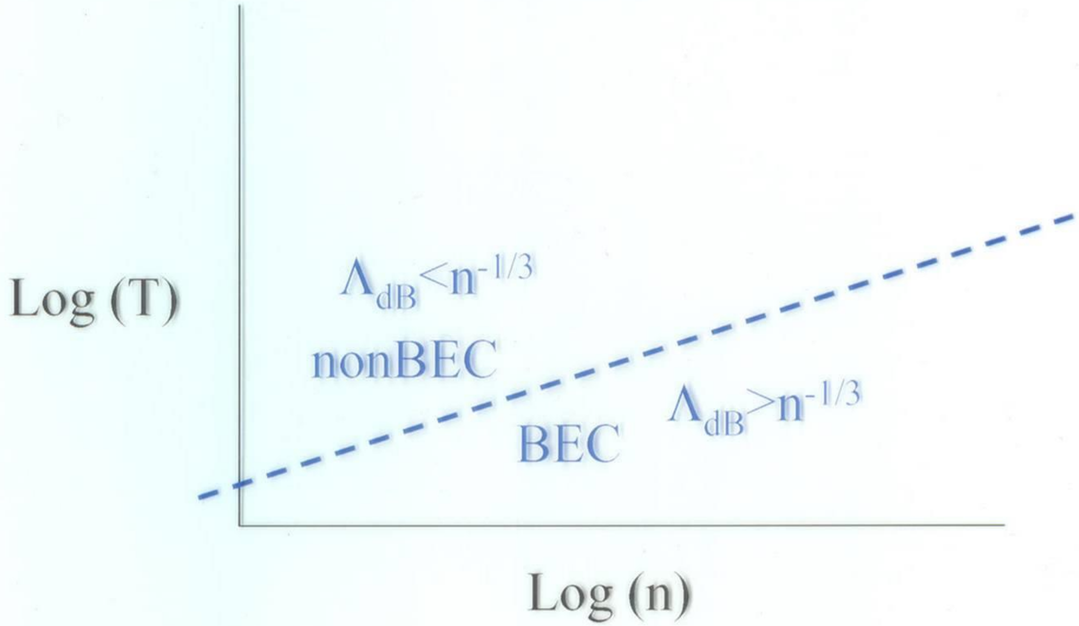

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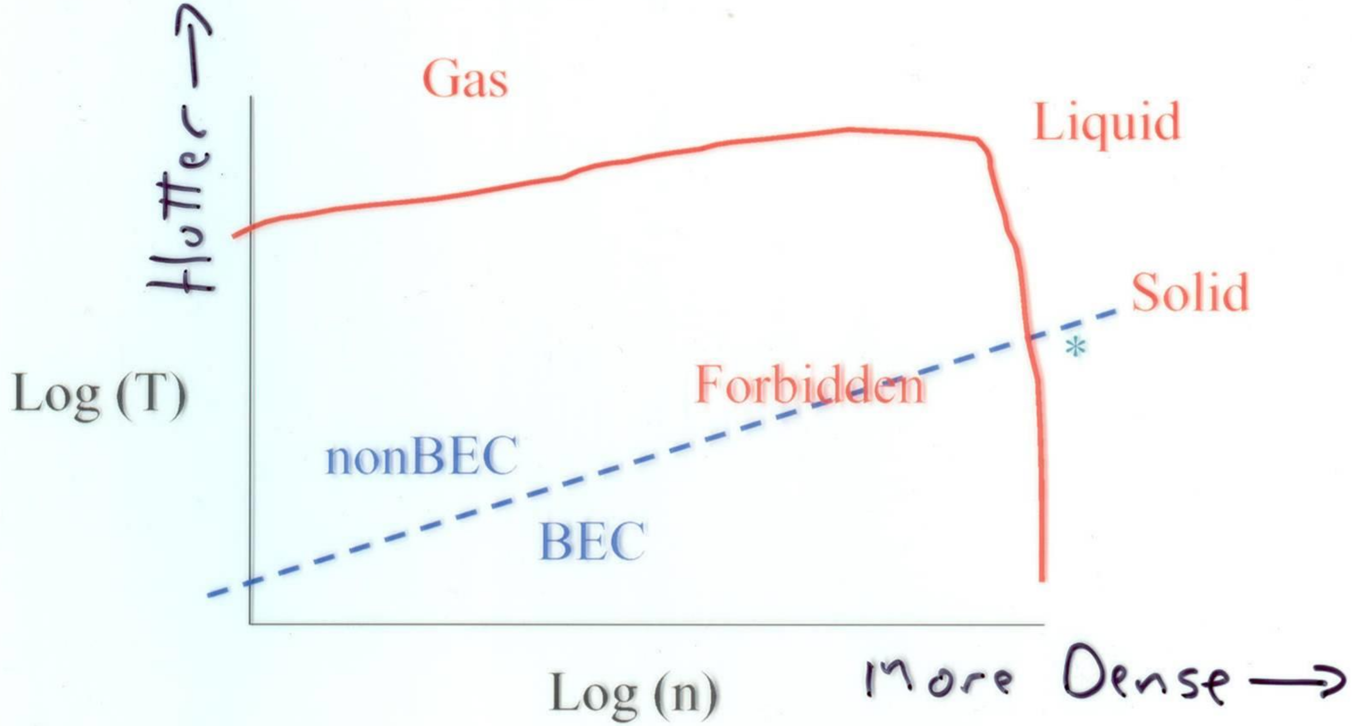

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N.B: imaging atoms with light is not the only way to detect them:

I think we will hear from Chris Westbrook about detecting individual metastable atoms.

The basic loop.

Cooling. Minimum temperature. Stray heating.

Confinement. Magnetic. Optical. Reduced dimensions. Arrays

Observables. Images. Shot noise. Atom counting.

Interactions. The G-P equation. Speed of sound.

Time-varying interactions.
feshbach resonance. Reduced dimensions.

Thermal fluctuations.

A range of numbers.

QM: Particle described by Schrödinger equation

$$\left(-\frac{\hbar^2}{2m}\Delta + V_{extern}\right)\psi(\vec{r}) = E\psi(\vec{r})$$

BEC: many weakly interacting particles
→ Gross-Pitaevskii equation

$$\left(-\frac{\hbar^2}{2m}\Delta + V_{extern} + \underbrace{\frac{4\pi\hbar^2 a}{m}\left|\psi(\vec{r})\right|^2}\right)\psi(\vec{r}) = \mu\psi(\vec{r})$$

The condensate is
self-interacting (usually self-repulsive)

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→ Gross-Pitaevskii equation

$$\left(-\frac{\hbar^2}{2m}\Delta + V_{extern} + \frac{4\pi\hbar^2 a}{m}\left|\psi(\vec{r})\right|^2\right)\psi(\vec{r}) = i\hbar\frac{\partial\psi(\vec{r})}{\partial t}$$

Can be solved in various approximations.

The Thomas-Fermi approximation:
ignore KE term, look for stationary states

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μ

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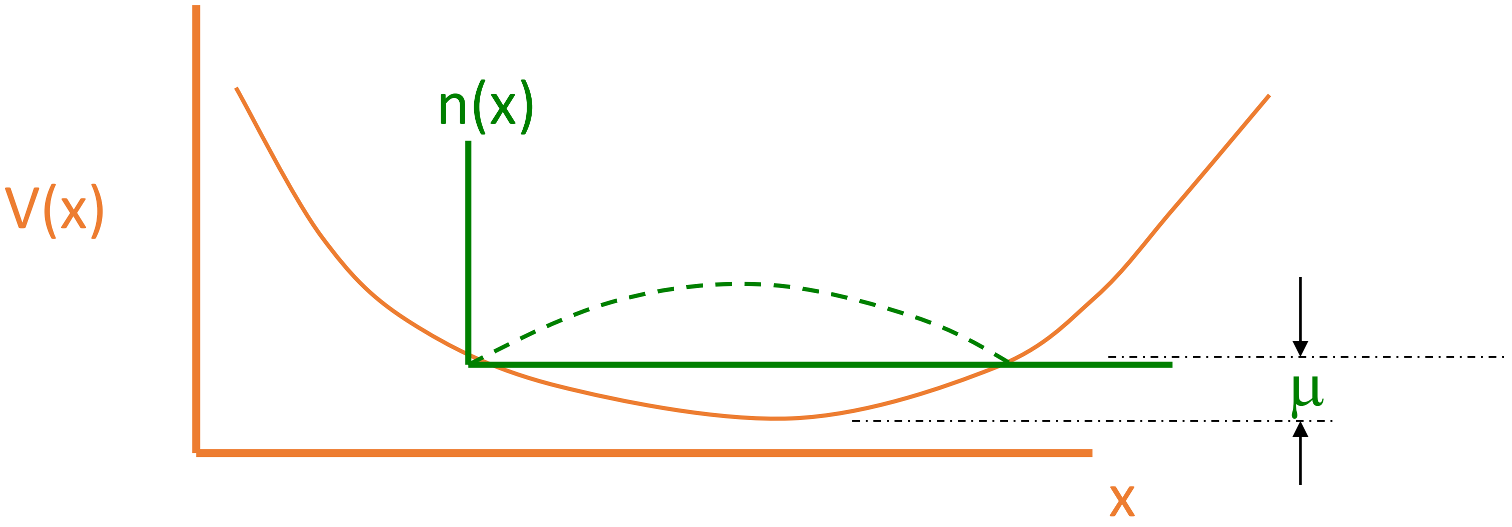

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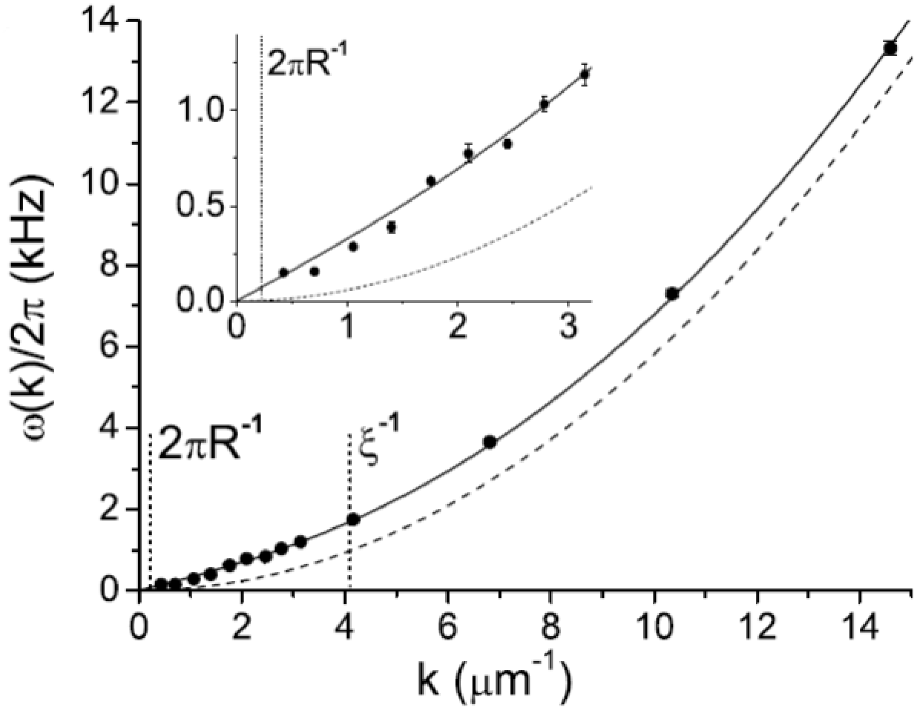


Data from Nir Davidson

speed of sound:

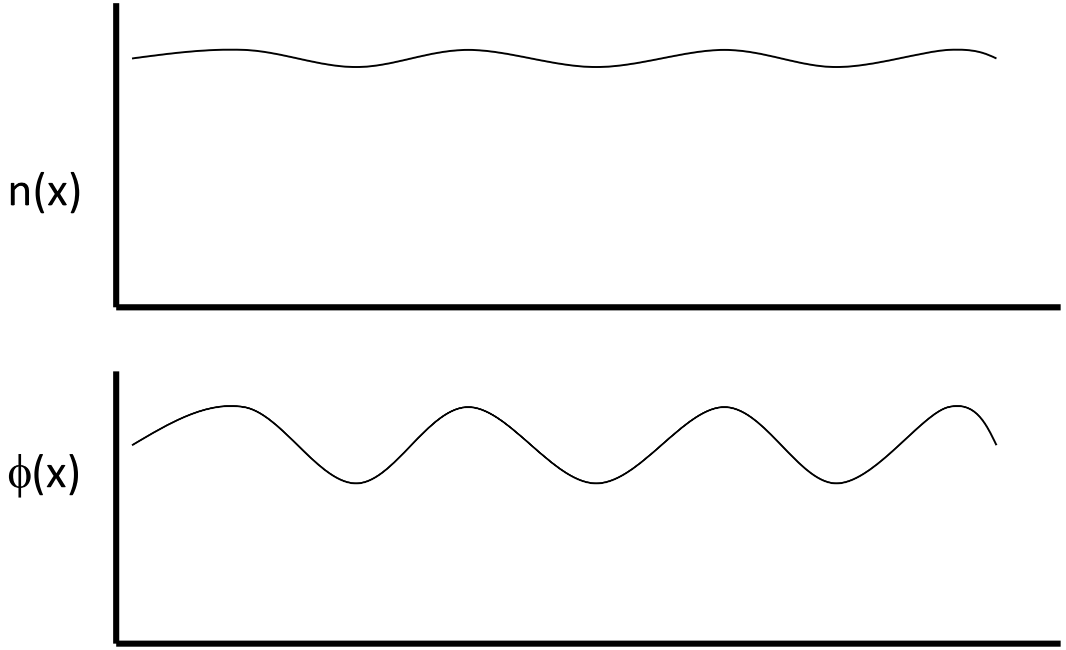
$c = (\mu/m)^{1/2}$

Healing length:

$\xi = (hbar^2/m)^{1/2}$

Chemical potential:

$\mu = 4\ \pi\ hbar^2\ a\ n\ /m$



Long wavelength
excitations
(k << 1/ξ)

relatively little
density fluctuation,
large phase fluctuation
(which we can’t directly
image).