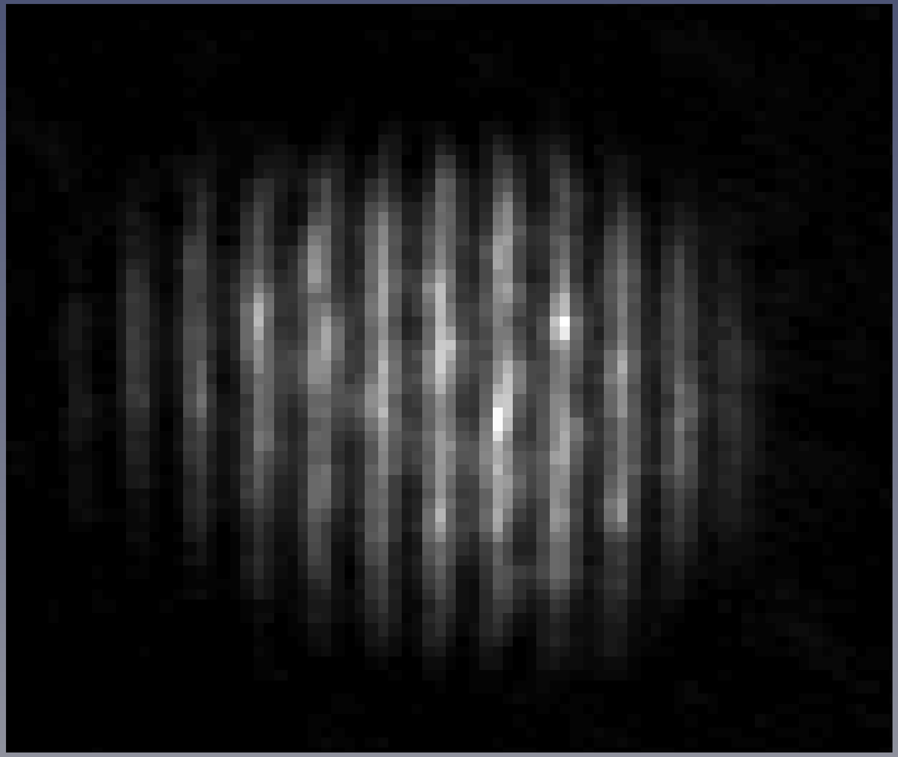
Atom Optics & Bose-Einstein Condensation



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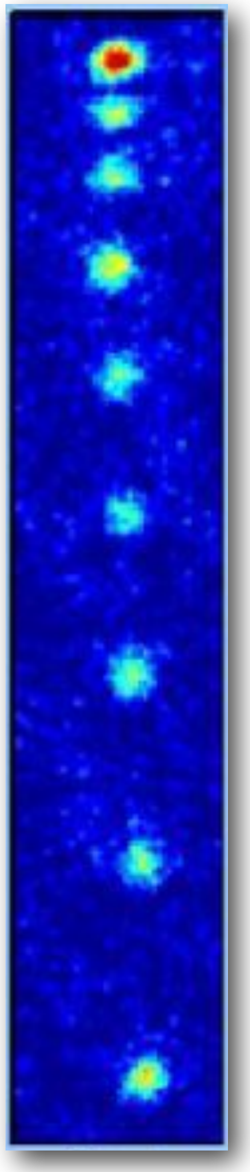
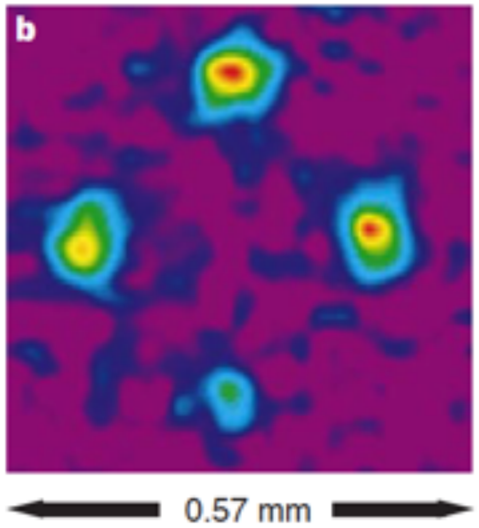
Atom Optics

Reversal of the usual roles of light and matter: EM fields are used to manipulate matter in order to **study, utilize, or manipulate the wave nature of matter**.

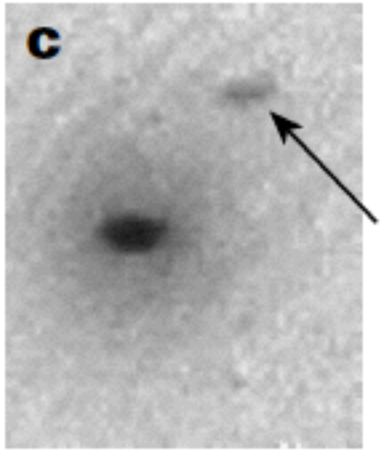
Laser light (and magnetic fields) are typically used to create atomic beamsplitters, mirrors, waveguides, interferometers, etc.



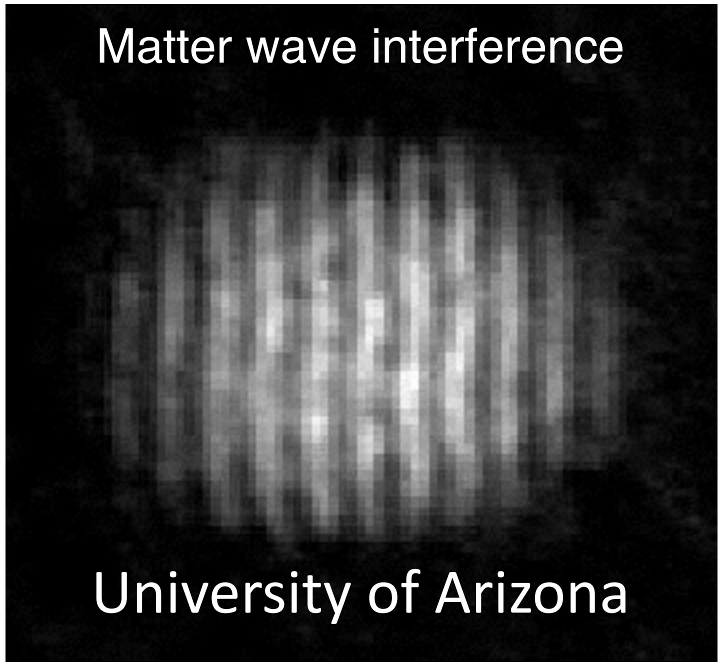
Mode-locked atom laser (Yale)



Atomic 4-wave mixing (NIST)

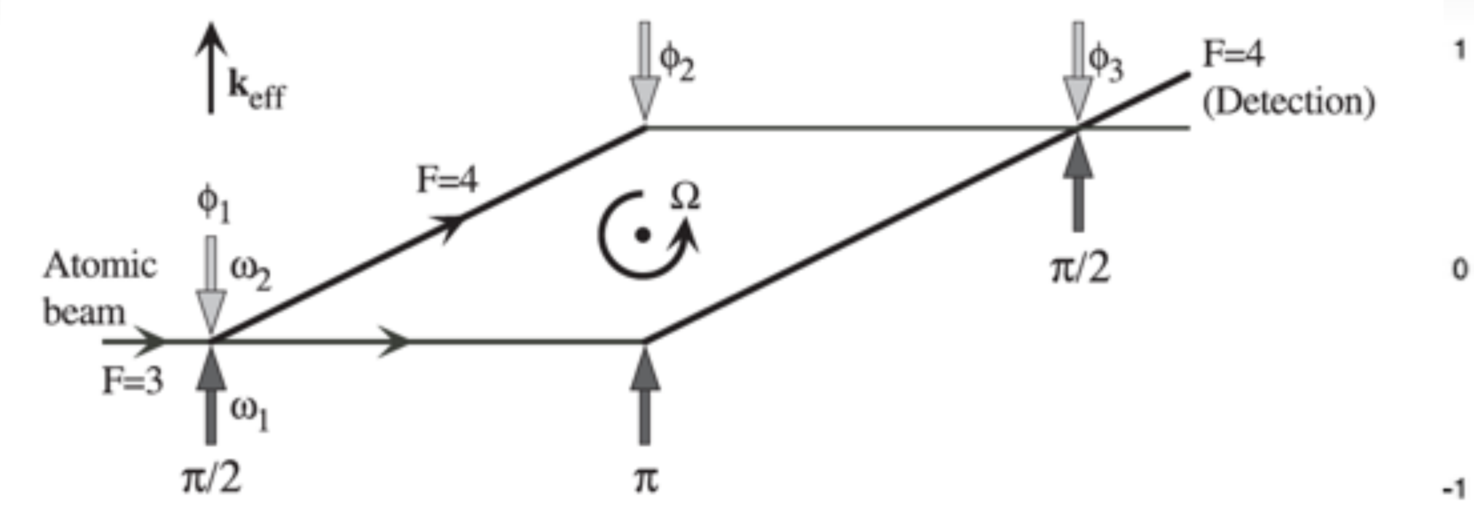


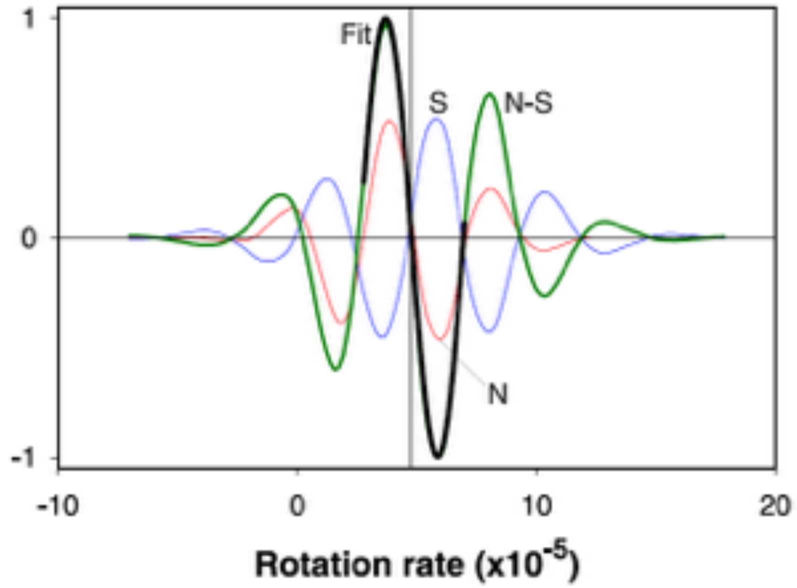
Matter-wave amplification (MIT)



Example: atom interferometry

Atom interferometers, Accelerometers, Gravimeters (Yale/Stanford/AOSense)





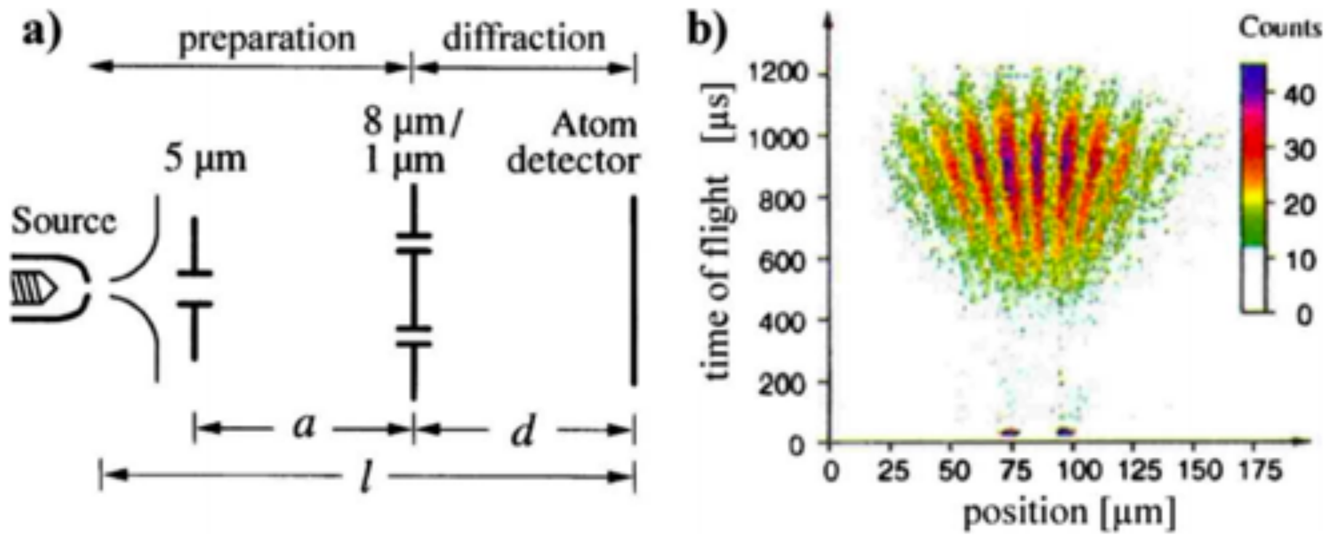
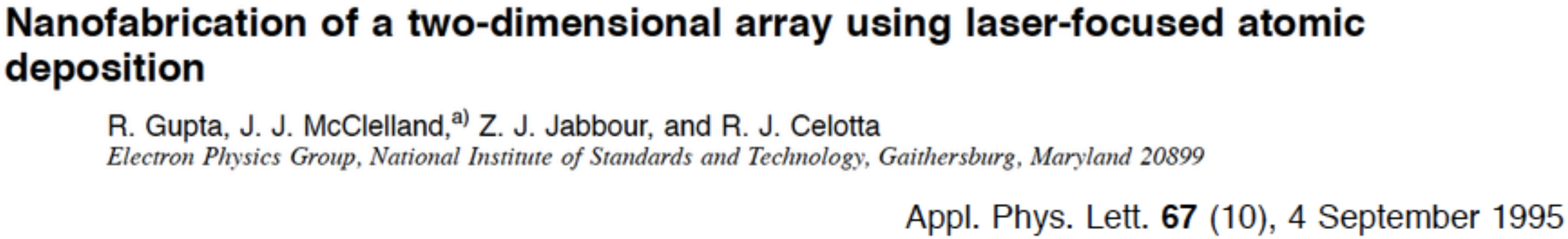


FIG. 4. (Color online) Double-slit experiment with He*. (a) Schematic. (b) Atom interference pattern with $a=1.05$ m and $d=1.95$ m recorded with a pulsed source. Adapted from Kurtsiefer *et al.*, 1997.

Nature **386**, 150 (1997)

Example: Atom manipulation with lasers

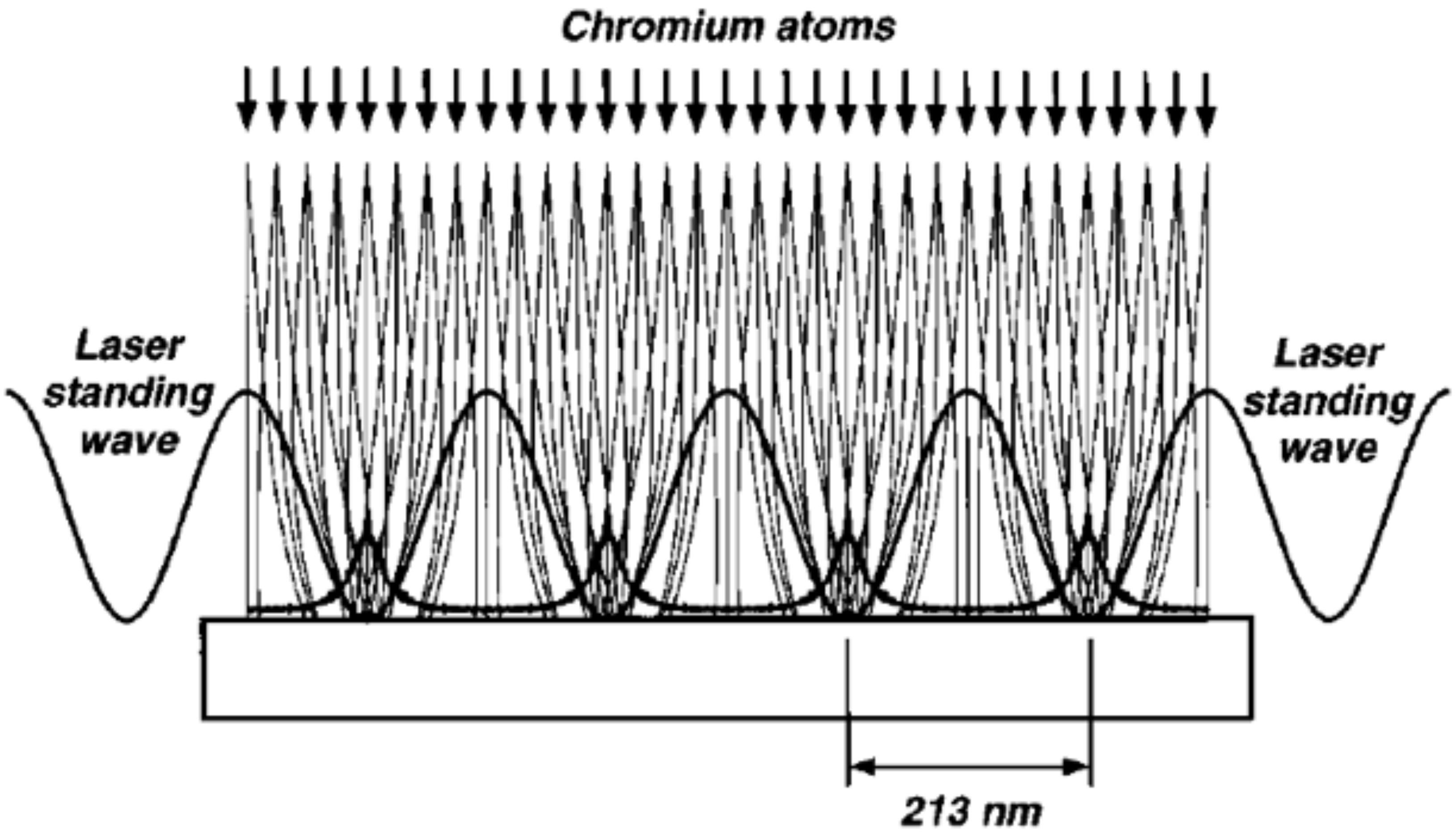
Atoms can be attracted to high intensity regions of a laser field. Use lasers to redirect atomic motion: mirrors, lenses, etc.

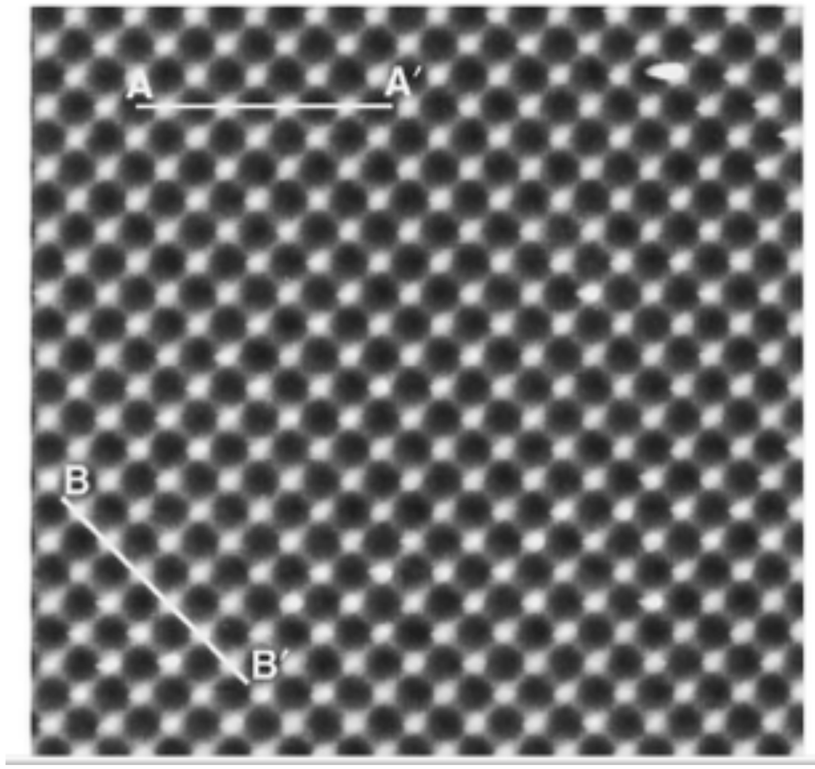


Nanofabrication of a two-dimensional array using laser-focused atomic deposition

R. Gupta, J. J. McClelland,[a] Z. J. Jabbour, and R. J. Celotta
Electron Physics Group, National Institute of Standards and Technology, Gaithersburg, Maryland 20899

Appl. Phys. Lett. **67** (10), 4 September 1995





Atom Optics Toolkit

Optics

Mirrors
Lenses
Beamsplitters
Waveguides
Polarizers
Waveplates

Atom Optics

Lasers
Magnetic fields
Material slits and gratings

Atomic Source

Momentum selection

- Filter out all but a small portion of the momentum distribution of a thermal source

Laser cooling

- Increase the number of slow atoms by **cooling** an atomic vapor with laser light

Bose-Einstein Condensation

- An intense, coherent group of atoms all in the same state: the matter equivalent of laser light

Why?

Precision measurement techniques

- Ex: atom interferometers for sensitive detection of rotations, accelerations (such as gravity), magnetic fields [Cronin]

Atomic properties

- Ex: Cold atoms for precision spectroscopy (negligible Doppler shifts), atomic structure [Jones]

Quantum Information and Control

- Ex: manipulating the internal states of atoms for information storage and processing (like polarization control of light, but with more than just 2 orthogonal states) [Jessen]

Studies of Basic Physics

- Ex: new approaches to tackling long-standing problems in physics: fluid dynamics, turbulence, phase-transition dynamics [Anderson]

Atom Optics: Many Ingredients!

Optics

Electronics

Laser construction

Atom trapping

Vacuum chamber

Laser Cooling

Bose-Einstein condensation

Atom Optics

Statistical Mechanics

Quantum Mechanics

E & M

Wave physics

Fluid Dynamics

Condensed Matter Physics

Context

What is the nature of light and matter?

How do we mathematically describe light and matter?
How do light and matter interact?
How can we manipulate light?
How can we manipulate matter?
How can we manipulate and use light and matter to our advantage?

How to count?
How do we keep track of how much light, how much matter?

Physics: *our guide to the study of light and matter*

Fundamental postulate of physics: a mathematical system can be constructed that directly corresponds to the states and dynamics of physical systems.

The Scientific Discipline of Physics: A chronology of continuous development of mathematical systems and experimental methods that describe aspects of the natural world with increasing mathematical accuracy, precision, and utility.

optics
classical mechanics
electrodynamics
fluid mechanics
statistical physics and thermodynamics
quantum physics
...

There are things we might not intuitively understand, but that's of a secondary concern. Let's first do the experiments and work on getting the theory right (ie, the mathematical system).

Physics as of 1900

Light is made of waves

1801	Young (double slit)
1818	Fraunhofer (diffraction grating)
1818	Arago, Fresnel (diffraction)
1850	Fizeau, Foucoult (speed of light in medium)

Electricity and Magnetism

1830	Faraday (postulated existence of E&M fields)
1860	Maxwell (assembled equations for E&M)

Matter

Reality and nature of atoms and molecules not yet known or fully accepted!

1897	JJ Thomson (discovers electron - "plum pudding" model of atom)
	Not yet discovered: nucleus (1909 - Rutherford, Geiger, Marsden), neutron (1932 - Chadwick)

Absorption and emission of light (Interaction of Light and Matter)

1814	Fraunhofer (absorption lines)	
1823	Hershel (identifying elements through spectra)	
1859	Krichoff (chemical composition of stars through spectra)	
1885	Balmer (equation for H visible spectrum)	Why?
1887	H. Hertz (discovers photoelectric effect)	Why?
1888	Rydberg (full equation for spectrum of H)	Why?
1893	Wien (displacement law: peak wavelength of blackbody ~ T^{-1})	
1896	Wien (distribution law: spectral intensity of thermal emission, OK for short wavelengths)	
1900	Rayleigh (spectral intensity of thermal emission, approximate for long wavelengths)	
1900	Lummer, Prigsheim, Rubens, Kurlbaum (radiation measurements in disagreement with Wien law)	Why?

Do atoms exist? *Is matter fundamentally quantized?*

Democritus (4th century BCE)

Everything is composed of indivisible components called atoms, and in between atoms there is empty space.

Philosophical discussion by Lucretius (1st century BCE), *The Nature of the Universe.*

John Dalton, 1808: *A New System of Chemical Philosophy*

Dalton's atomic theory

1. Different elements made of small material particles called atoms.
2. Different atoms of a given element are completely identical.
3. Atoms cannot be subdivided, created, or destroyed.
4. Atoms of different elements combine in whole-number ratios to form compounds.
5. Atoms are combined, separated, and rearranged in chemical reactions.

Johann Loschmidt, 1865

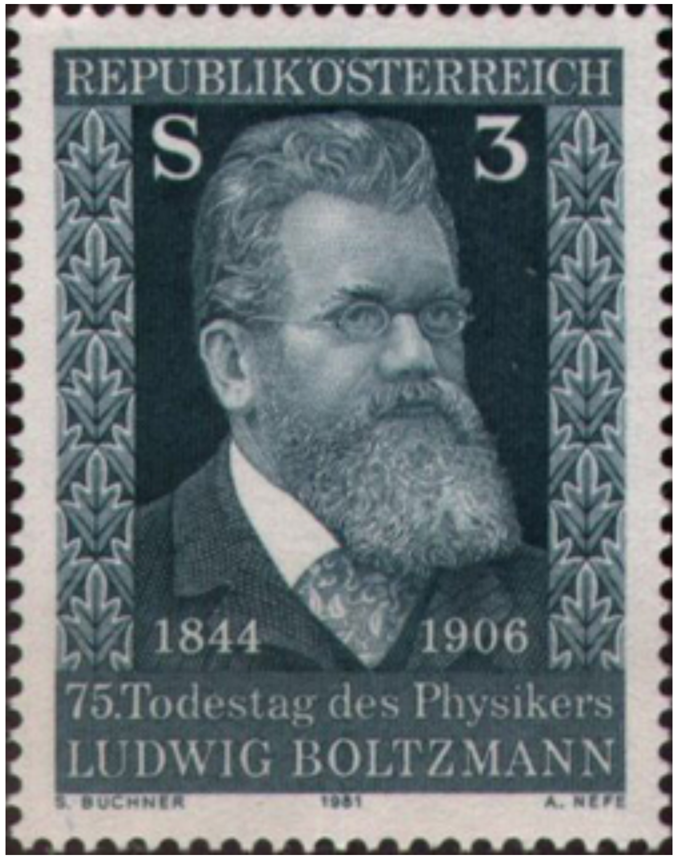
Calculated the size of molecules in air

[Proc. Acad. Sci. Vienna ***52****, 395 (1865)]*

Ludwig Boltzmann and Entropy

Entropy: the thermodynamic quantity that accounts for the observation that natural phenomena tend to occur in a preferred direction.

2nd law of thermodynamics: entropy of an isolated system never decreases, but increases until the system reaches a state of maximum entropy - thermal equilibrium (Carnot 1824, Claussius 1865).



$S = k.\log W$

Boltzmann: entropy is a measure of the number of ways that a macroscopic state can be realized. Need to be able to count the number of possible configurations (microstates) that lead to a macroscopic state (distribution).

How to count the number of configurations???

Boltzmann **assumed discretization** of phase space for atoms in a gas as a calculation tool (not physical reality).

The equilibrium distribution/macrostate is the one with the highest degree of disorder or unpredictability of configuration. Entropy: measure of the disorder.

Statistical Mechanics

Fundamental postulate of Statistical Mechanics:

An isolated system in equilibrium is found with equal probabilities in each of the accessible microstates (the configurations that are consistent with the macroscopic parameters of the system, such as total energy, particle number, pressure,...)

Heads or tails?

1 flip: H (P = 0.5), T (P = 0.5)

4 flips: 16 ways to arrange
P = 1/16 = 0.0625 each

	If order doesn't matter	
HHHH	HHHH	4 heads: P = 0.0625
HHHT	HHHT	3 heads: P = 0.25
HHTH	HHTH	
HTHH	HTHH	
THHH	THHH	
HHTT	**HHTT**	**2 heads: P = 0.375**
HTHT	**HTHT**	
HTTH	**HTTH**	
THHT	**THHT**	
THTH	**THTH**	
TTHH	**TTHH**	
TTTH	TTTH	1 head: P = 0.25
TTHT	TTHT	
THTT	THTT	
HTTT	HTTT	
TTTT	TTTT	0 heads: P = 0.0625

Many flips, order doesn't matter

g flips, *n* heads

Total number of "states" (sequences)

$$\Omega = 2^g$$

Probability for each

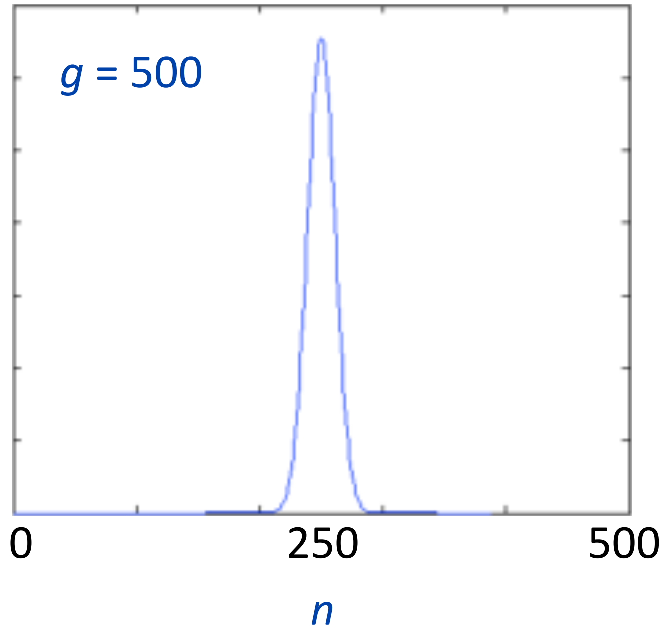
$$P_1 = 1/\Omega$$

Probability for *n* heads in *g* flips

$$P(g,n) = w(g,n) * P_1$$

number of states with *n* heads

$$w(g,n) = \left(\begin{array}{c} g \\ n \end{array} \right) = \frac{g!}{n!(g-n)!}$$



$$\Omega \sim 10^{150}$$

comparison: Universe is about 10^{27} ns old.

Atomic theory of matter

Atomist’s position: Gases, liquids, solids - everything is made of atoms, as according to Dalton’s theory.

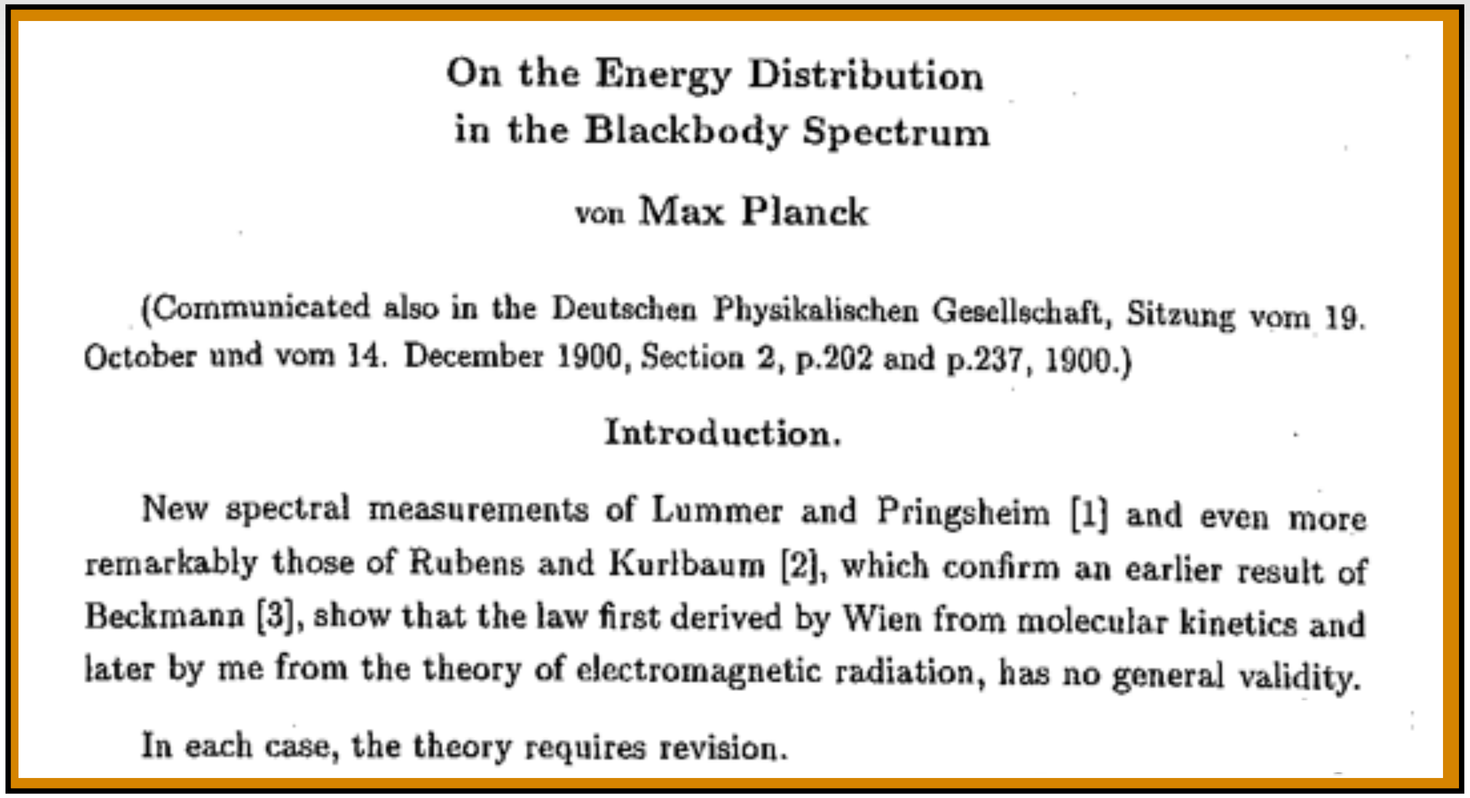
Accepted by chemists, but not widely believed by physicists in the 1800s, even by the early 1900s. **Atoms were at most a ‘convenient fiction’.**

Jean Babtiste Perrin: confirmed and solidified the existence of atoms and molecules ~1908

Wave theory of atoms (matter) was developed **less than 20 years** after the conclusive acceptance of the atomistic nature of matter!

Max Planck: need to understand matter to understand light

Central question: How to calculate the distribution of energy in the blackbody spectrum?



On the Energy Distribution
in the Blackbody Spectrum

von Max Planck

(Communicated also in the Deutschen Physikalischen Gesellschaft, Sitzung vom 19. October und vom 14. December 1900, Section 2, p.202 and p.237, 1900.)

Introduction.

New spectral measurements of Lummer and Pringsheim [1] and even more remarkably those of Rubens and Kurlbaum [2], which confirm an earlier result of Beckmann [3], show that the law first derived by Wien from molecular kinetics and later by me from the theory of electromagnetic radiation, has no general validity.

In each case, the theory requires revision.

Assumption 1: Thermal cavity, oscillators in the walls radiate energy.

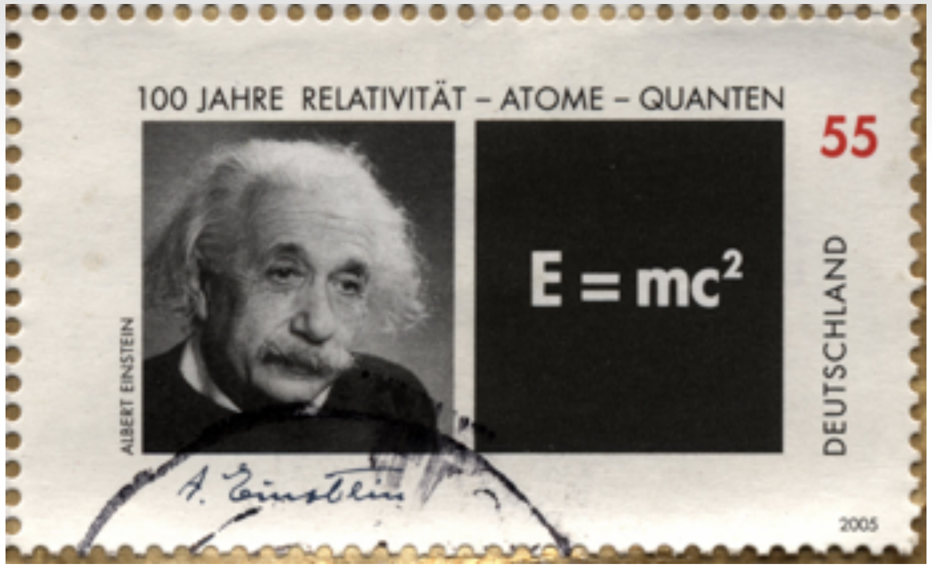
What is an oscillator? Tiny radiating antenna, not an atom.

How much energy is radiated per oscillator?

Assumption 2: Energy ***of the oscillators*** is countable in discrete units. A mathematical tool. (Planck quantized the oscillators, not the field!) Assumed equilibrium with classical EM field.

Finally, maximize entropy by finding the energy distribution with the largest number of microstates.

Albert Einstein



1905: postulated that **EM field** energy is quantized in units of $h\nu$.

Planck's constant.
$\hbar = h/(2\pi)$

1908: postulated that EM field momentum is quantized in units of h/λ.

1917: postulated the existence of spontaneous and stimulated emission. Re-derives Planck radiation law using steady-state hypothesis involving absorption and emission of radiation by matter.

Satyendra Nath Bose: *how to 'count light'*

S. N. Bose, "Planck's Law and Light Quantum Hypothesis", *Z. Phys.* **26** (1924).

"logical flaw" in deriving Planck law

"**All derivations up to now use** ... the relation between the radiation density and the mean energy of an oscillator, and they make assumptions about the number of degrees of freedom of the ether ... derived ... from **classical theory**. **This is the unsatisfactory feature in all derivations.**"

Use light quantum hypothesis instead

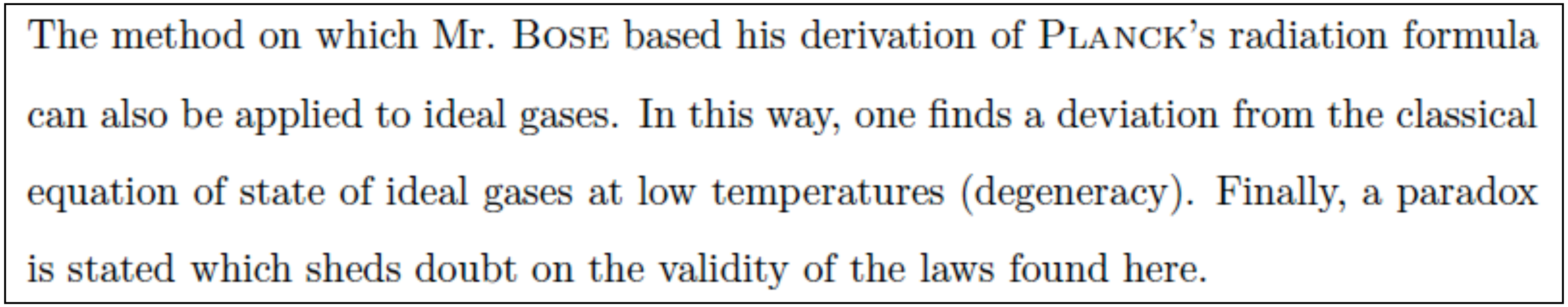
"[Einstein's] light quantum hypothesis combined with statistical mechanics (as it was formulated to meet the needs of the quantum theory) appears sufficient for the derivation of the law independent of classical theory. In the following I shall sketch the method briefly."

- Assumes energy quantization of light (Einstein)
- Reduces problem to one of counting states, probabilities (Boltzmann, Planck).
- **Divides phase space into cells of size h^3.**
- Specifically allows cells to have more than 1 quantum **(--> Bose statistics).** (Different from Boltzmann, where each particle has its own set of cells, statistical independence.)
- Maximizes entropy for a distribution of cell occupation probabilities (Boltzmann, Planck)
- Derives Planck law without assumptions of classical electrodynamics.

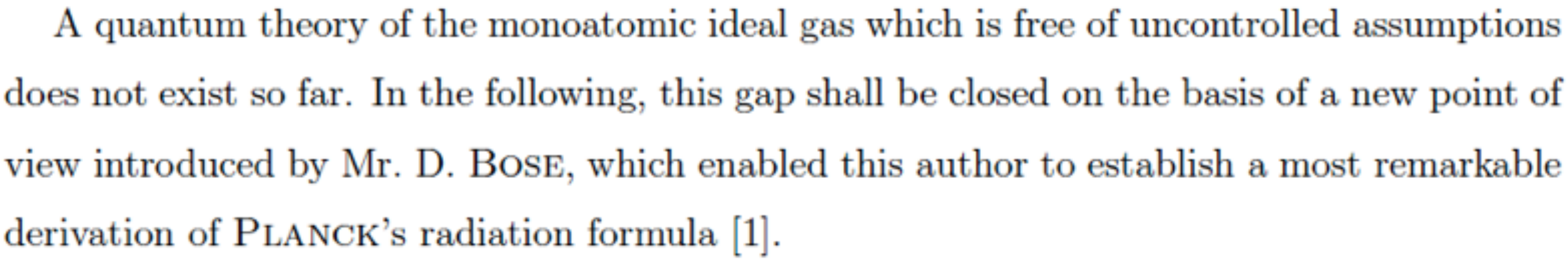
Albert Einstein: *how to ‘count atoms’*

A. Einstein, “Quantum theory of the monoatomic ideal gas”, *Sitzungsber. Preuss. Akad. Wiss.* **Proc. XXII**, 261 (1924).

A. Einstein, “Quantum theory of the monoatomic ideal gas, Second treatise”, *Sitzungsber. Preuss. Akad. Wiss.* **Proc. I**, 3 (1925).



The method on which Mr. Bose based his derivation of Planck’s radiation formula can also be applied to ideal gases. In this way, one finds a deviation from the classical equation of state of ideal gases at low temperatures (degeneracy). Finally, a paradox is stated which sheds doubt on the validity of the laws found here.



A quantum theory of the monoatomic ideal gas which is free of uncontrolled assumptions does not exist so far. In the following, this gap shall be closed on the basis of a new point of view introduced by Mr. D. Bose, which enabled this author to establish a most remarkable derivation of Planck’s radiation formula [1].

Applying the new idea to atoms

- Divide phase space into cells of volume h^3.
    - **An early version of the uncertainty principle**
- Specify a distribution of particle numbers or probabilities among cells
- Allow cells to have 0, 1, 2, ... particles (Bose statistics)
- Boltzmann's theorem provides entropy
- For *S*-->0 as *T*-->0, only 1 way to place atoms among cells: all in lowest energy state
- Establish *phase space density* (not Einstein's wording) as a measure of "degeneracy"
- For small enough *T*:

A separation occurs; a part "condenses", the rest remains a "saturated ideal gas"

- The two parts are in thermal equilibrium with each other

...the [entropy] formula indirectly expresses a certain hypothesis concerning a mutual influence of the molecules of a, at present, totally mysterious kind...
[ie, they are not statistically independent, as in Boltzmann statistics]

Phase Space

Phase Space = Coordinate Space $\otimes$ Momentum space

A point in 6D phase space: labeled by **r**, **p**.

Volume of a cell in phase space: $\Delta x \Delta y \Delta z \Delta p_x \Delta p_y \Delta p_z$.

Classical: arbitrary, no lower limit to the cell volume.

Quantum: $\boldsymbol{h^3}$ (**Bose**)

If phase space volume is finite, finite number of cells of volume h^3:

$$N_{cells} \sim V \cdot p_{max}^3 \cdot \frac{1}{h^3} \sim V/\lambda_{dB}^3$$

$$\lambda_{dB} = \sqrt{\frac{2\pi\hbar^2}{mk_B T}}$$

Phase space density for *N* identical particles:

$$\rho \sim N/N_{cells} \sim (N/V)\lambda_{dB}^3 \sim n\lambda_{dB}^3$$

Einstein: degeneracy for $\rho > 1$ (approximately)

Bose-Einstein Distribution

B.E.D. is the highest entropy way to distribute a given number of particles in a certain potential, with: (1)Fixed total energy *E,* (2) Fixed atom number *N*

(Modern notation)

B.E.D.: particle number in state *i* (set of quantum numbers)

$$N_i = \frac{1}{\exp[(\epsilon_i - \mu)/k_B T)] - 1}$$

μ = chemical potential

$$N = \sum_i N_i$$

For light: $\mu = 0$, no *N* constraint. One constraint (*E*) needs one parameter (*T*) to regulate distribution.

$$E = \sum_i \epsilon_i N_i$$

For matter: atom number constraint (*N*): needs a new parameter (μ) to regulate distribution.

phase space density

$$\rho = n\lambda_{dB}$$

number density

$$n \sim N/V$$

thermal deBroglie wavelength

$$\lambda_{dB} = \sqrt{\frac{2\pi\hbar^2}{mk_BT}}$$

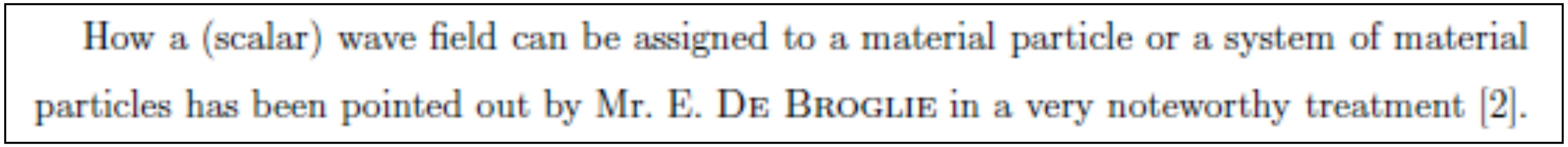
BEC: $\rho > 1$ (approximately)

Einstein, Louis deBroglie, and Atom Optics

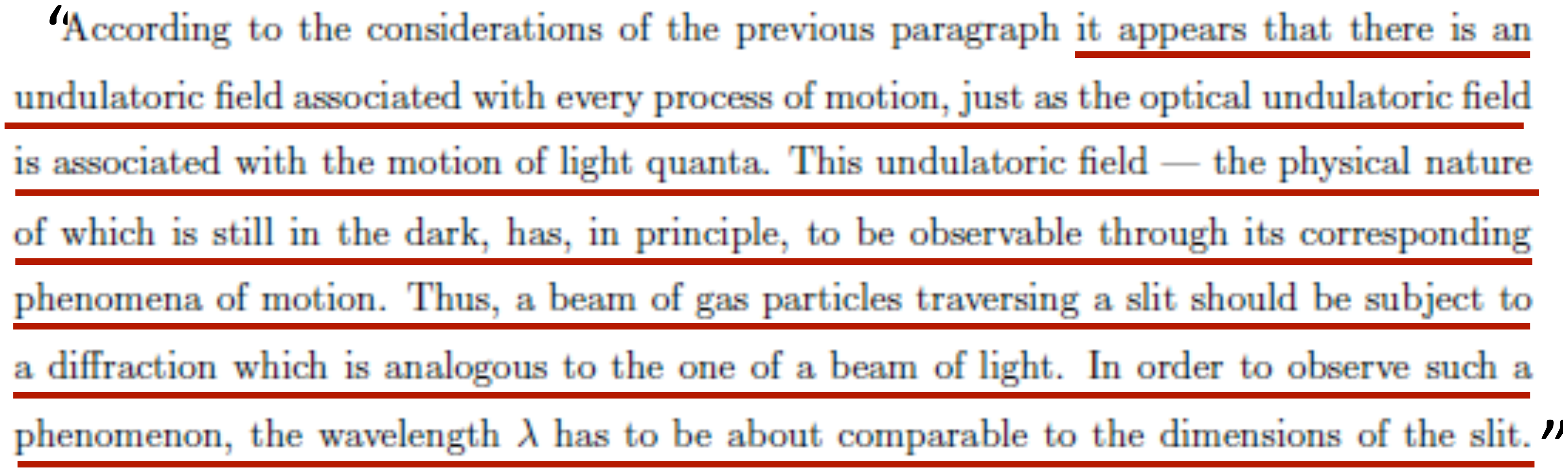
Louis deBroglie

Schrodinger, QM

from Einstein, 1925



How a (scalar) wave field can be assigned to a material particle or a system of material particles has been pointed out by Mr. E. De Broglie in a very noteworthy treatment [2].



"According to the considerations of the previous paragraph it appears that there is an undulatoric field associated with every process of motion, just as the optical undulatoric field is associated with the motion of light quanta. This undulatoric field — the physical nature of which is still in the dark, has, in principle, to be observable through its corresponding phenomena of motion. Thus, a beam of gas particles traversing a slit should be subject to a diffraction which is analogous to the one of a beam of light. In order to observe such a phenomenon, the wavelength λ has to be about comparable to the dimensions of the slit."

Experimental atom optics and the pursuit of Bose-Einstein condensation have developed together since Einstein's paper.

Matter wave diffraction

C. Davisson and L. Germer, “The Scattering of Electrons by a Single Crystal of Nickel”, *Nature* **119**, 558 (1927)

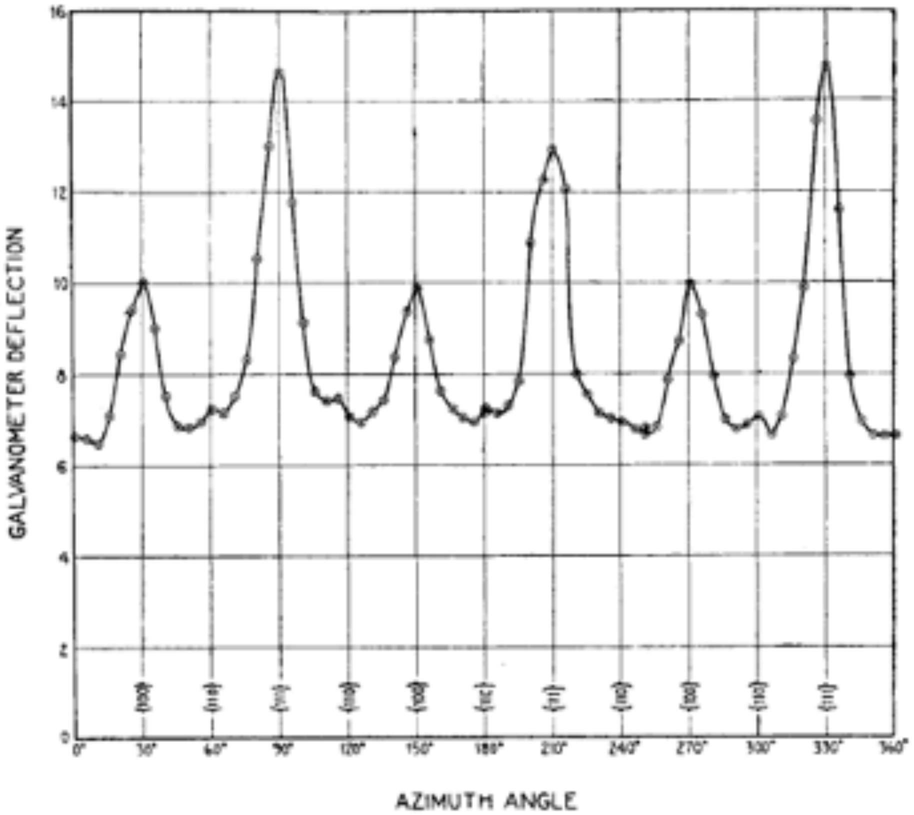
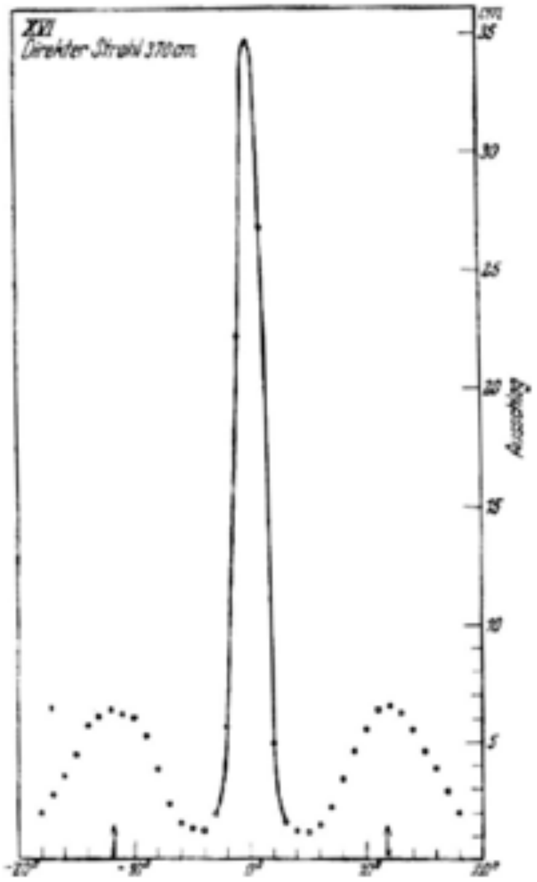


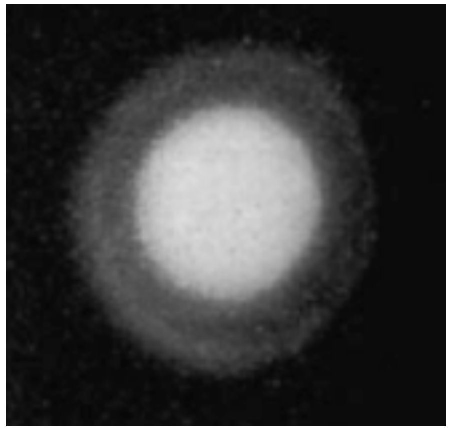
FIG. 2.—Intensity of electron scattering vs. azimuth angle—54 volts, co-latitude 50°.

Estermann, I., and A. Stern, 1930, “Beugung von molekularstrahlen (bending of molecular rays),” Z. Phys. **61**, 95.



diffraction of He atoms from LiF crystal surface

G.P. Thomson, “The Diffraction of Cathode Rays by Thin Films of Platinum”, *Nature* **120**, 802 (1927)



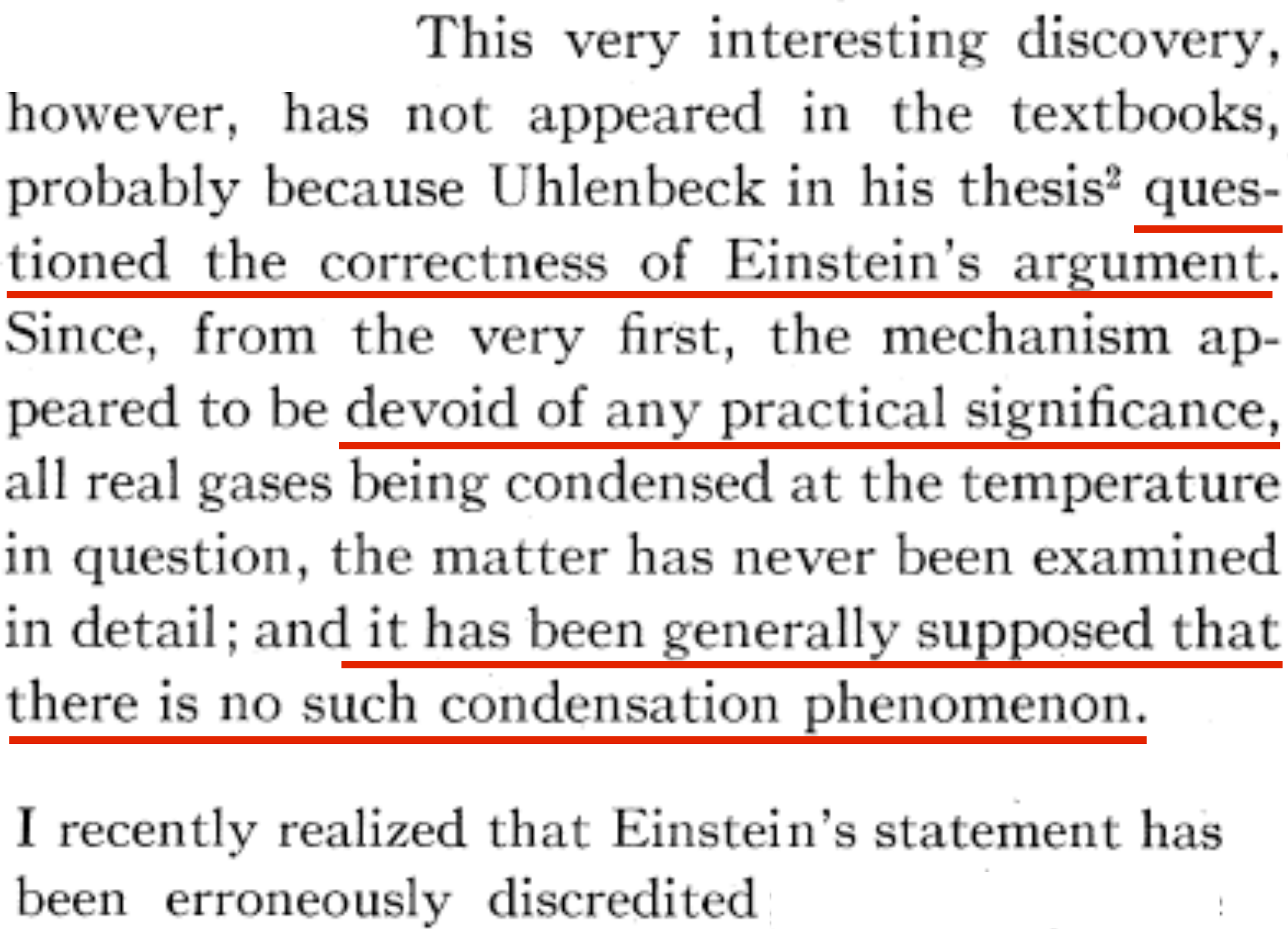
Bose-Einstein Condensation

Fritz London

Nature 141, 643 (1938), *The λ-Phenomenon of Liquid Helium and the Bose-Einstein Degeneracy*

... in the course of time the degeneracy of the Bose-Einstein gas has rather got the reputation of having only a purely imaginary existence.

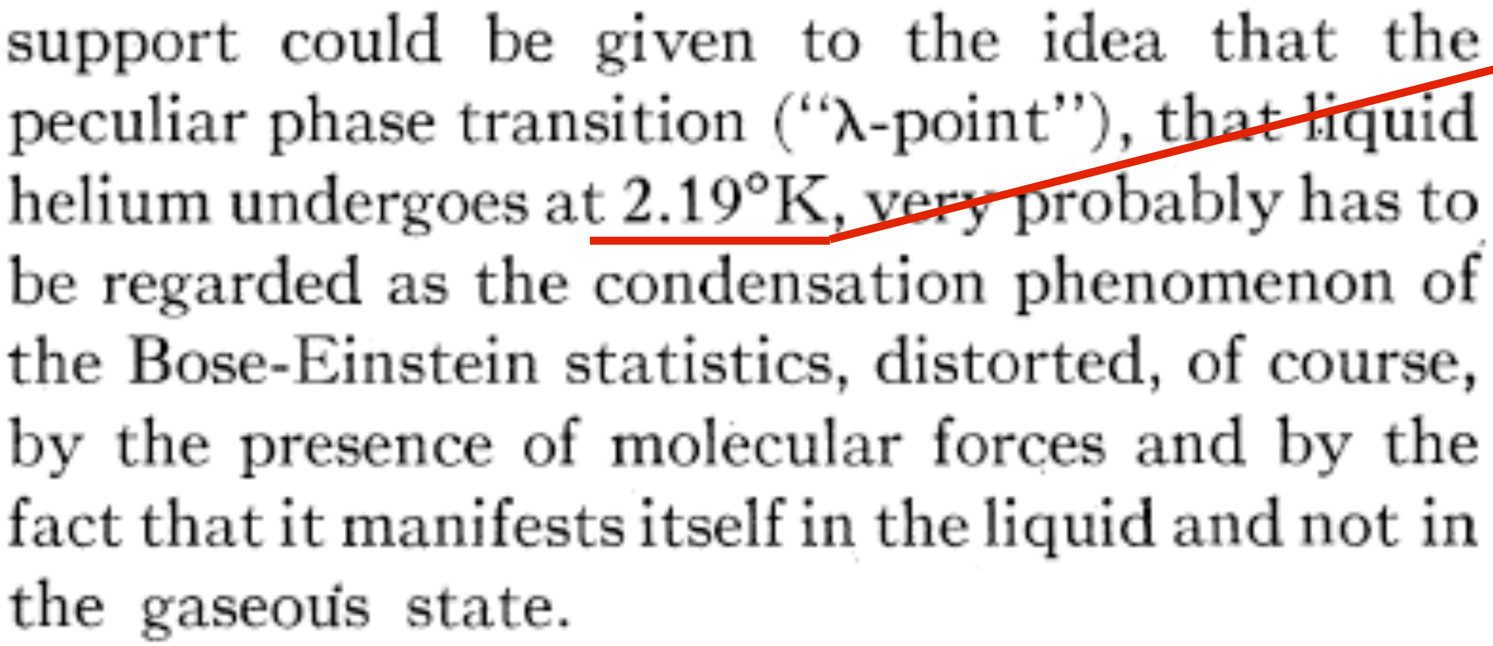
Phys. Rev. 54, 947 (1938), *On the Bose-Einstein Condensation*



This very interesting discovery, however, has not appeared in the textbooks, probably because Uhlenbeck in his thesis[2] questioned the correctness of Einstein's argument. Since, from the very first, the mechanism appeared to be devoid of any practical significance, all real gases being condensed at the temperature in question, the matter has never been examined in detail; and it has been generally supposed that there is no such condensation phenomenon.

I recently realized that Einstein's statement has been erroneously discredited

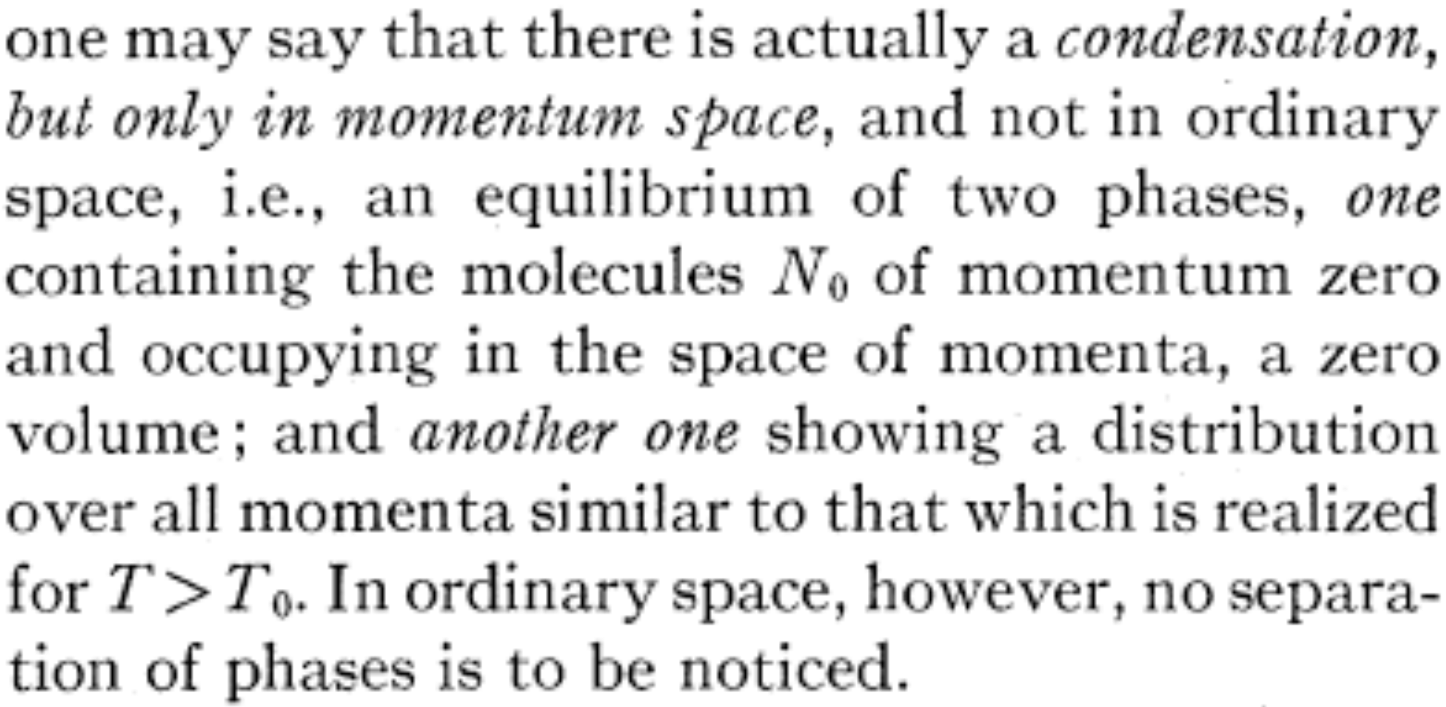
London: BEC and SF Helium



support could be given to the idea that the peculiar phase transition ("λ-point"), that liquid helium undergoes at 2.19°K, very probably has to be regarded as the condensation phenomenon of the Bose-Einstein statistics, distorted, of course, by the presence of molecular forces and by the fact that it manifests itself in the liquid and not in the gaseous state.

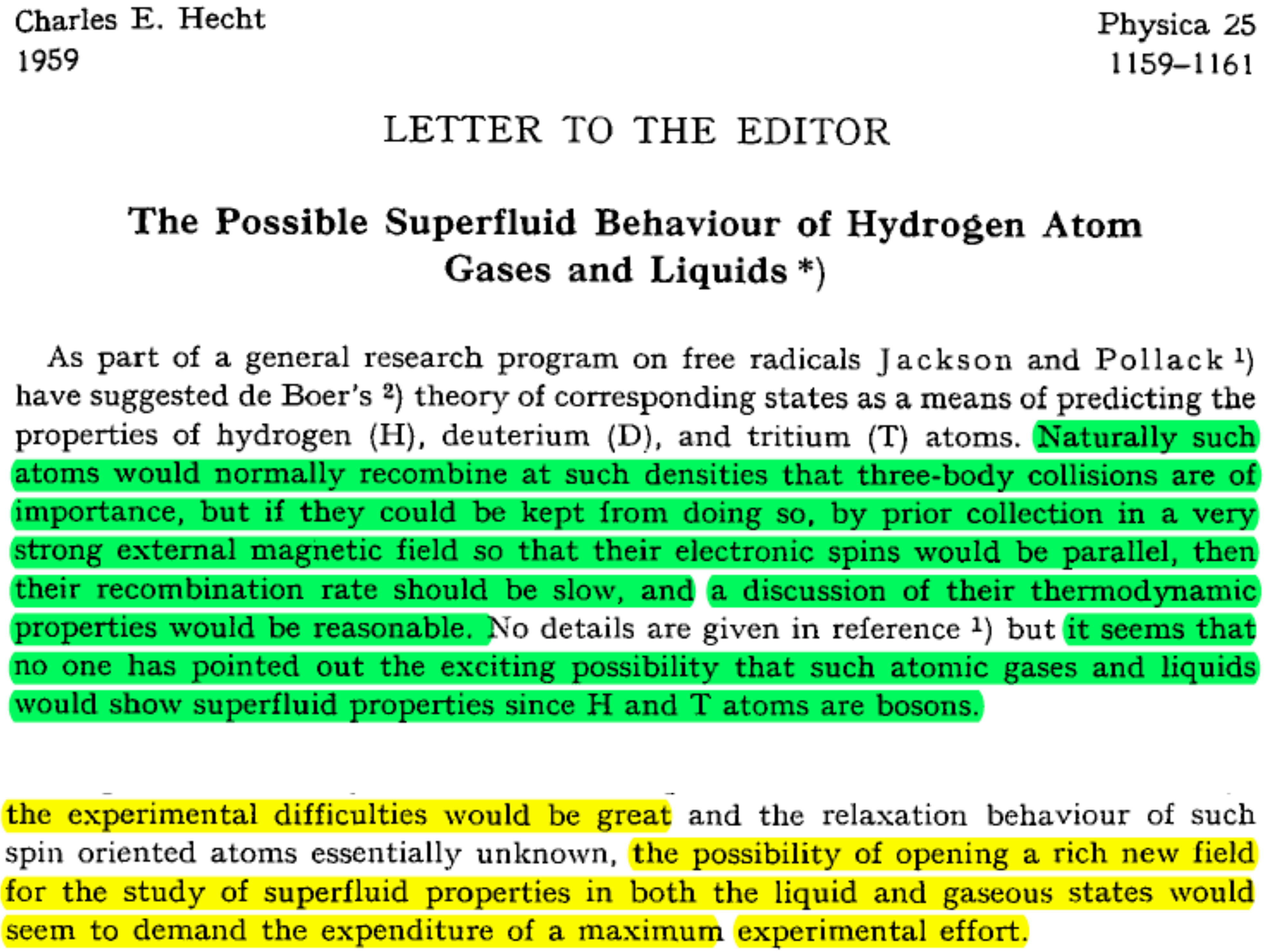
London: 3.09 K

Einstein seems to have noticed this too, but didn't say much about it.



one may say that there is actually a *condensation*, *but only in momentum space*, and not in ordinary space, i.e., an equilibrium of two phases, *one* containing the molecules N_0 of momentum zero and occupying in the space of momenta, a zero volume; and *another one* showing a distribution over all momenta similar to that which is realized for $T > T_0$. In ordinary space, however, no separation of phases is to be noticed.

Charles Hecht: superfluidity of atomic gases



Charles E. Hecht
1959

Physica 25
1159–1161

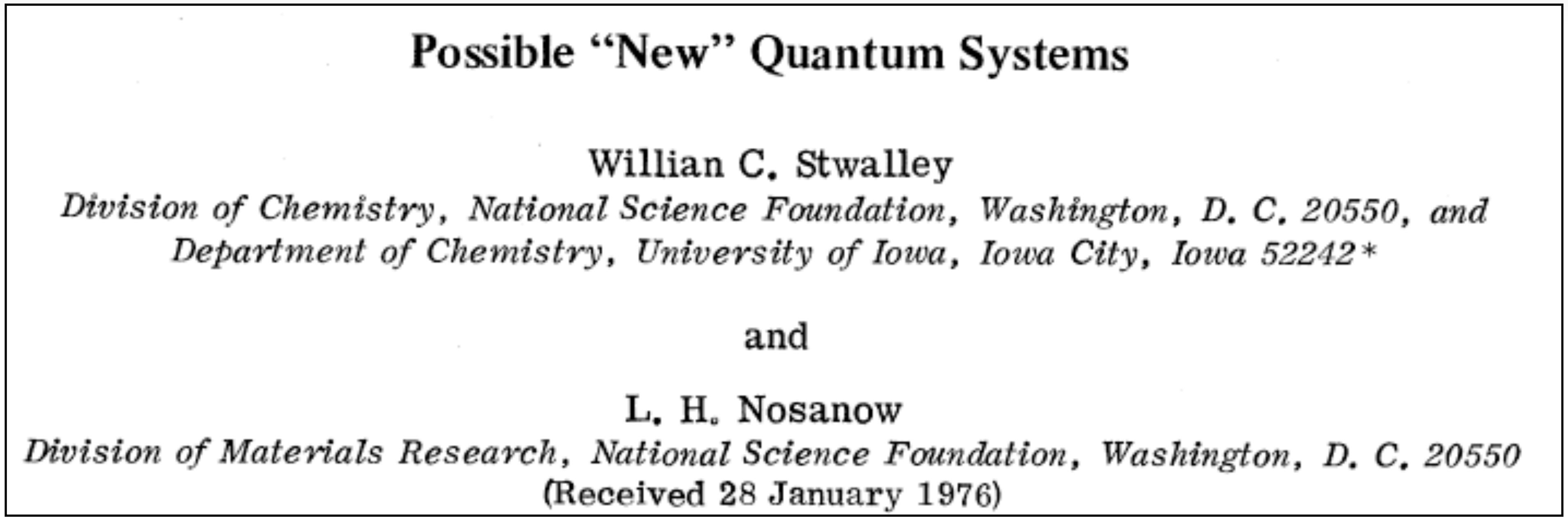
LETTER TO THE EDITOR

The Possible Superfluid Behaviour of Hydrogen Atom Gases and Liquids *)

As part of a general research program on free radicals Jackson and Pollack 1) have suggested de Boer's 2) theory of corresponding states as a means of predicting the properties of hydrogen (H), deuterium (D), and tritium (T) atoms. Naturally such atoms would normally recombine at such densities that three-body collisions are of importance, but if they could be kept from doing so, by prior collection in a very strong external magnetic field so that their electronic spins would be parallel, then their recombination rate should be slow, and a discussion of their thermodynamic properties would be reasonable. No details are given in reference 1) but it seems that no one has pointed out the exciting possibility that such atomic gases and liquids would show superfluid properties since H and T atoms are bosons.

the experimental difficulties would be great and the relaxation behaviour of such spin oriented atoms essentially unknown, the possibility of opening a rich new field for the study of superfluid properties in both the liquid and gaseous states would seem to demand the expenditure of a maximum experimental effort.

W. Stwalley and L. Nosanov



Possible "New" Quantum Systems

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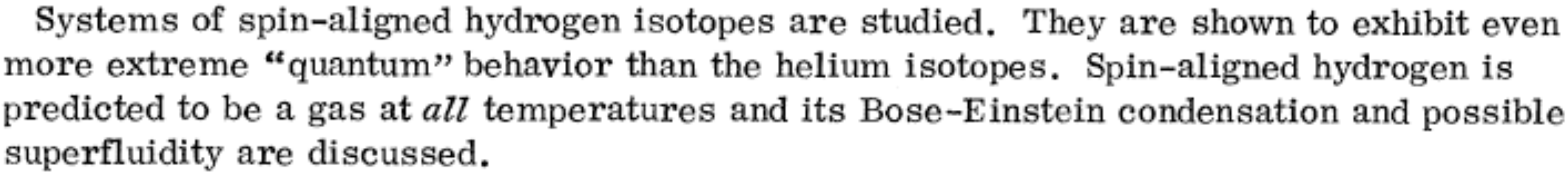
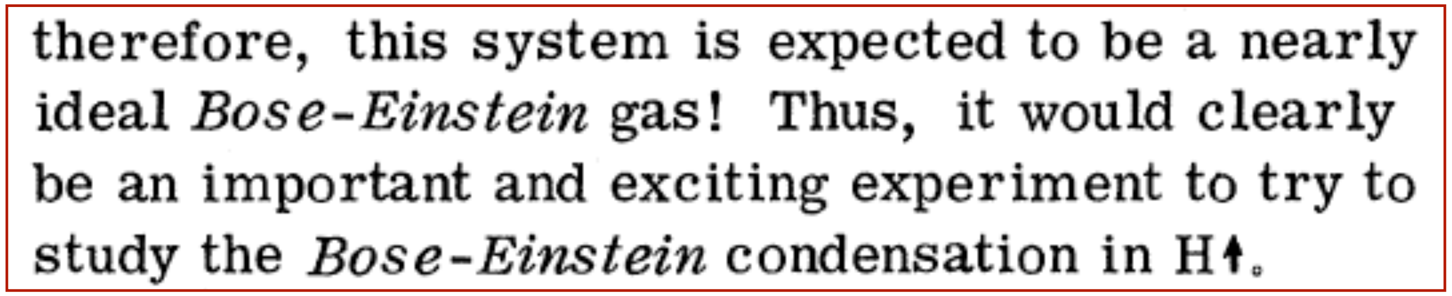
(Received 28 January 1976)

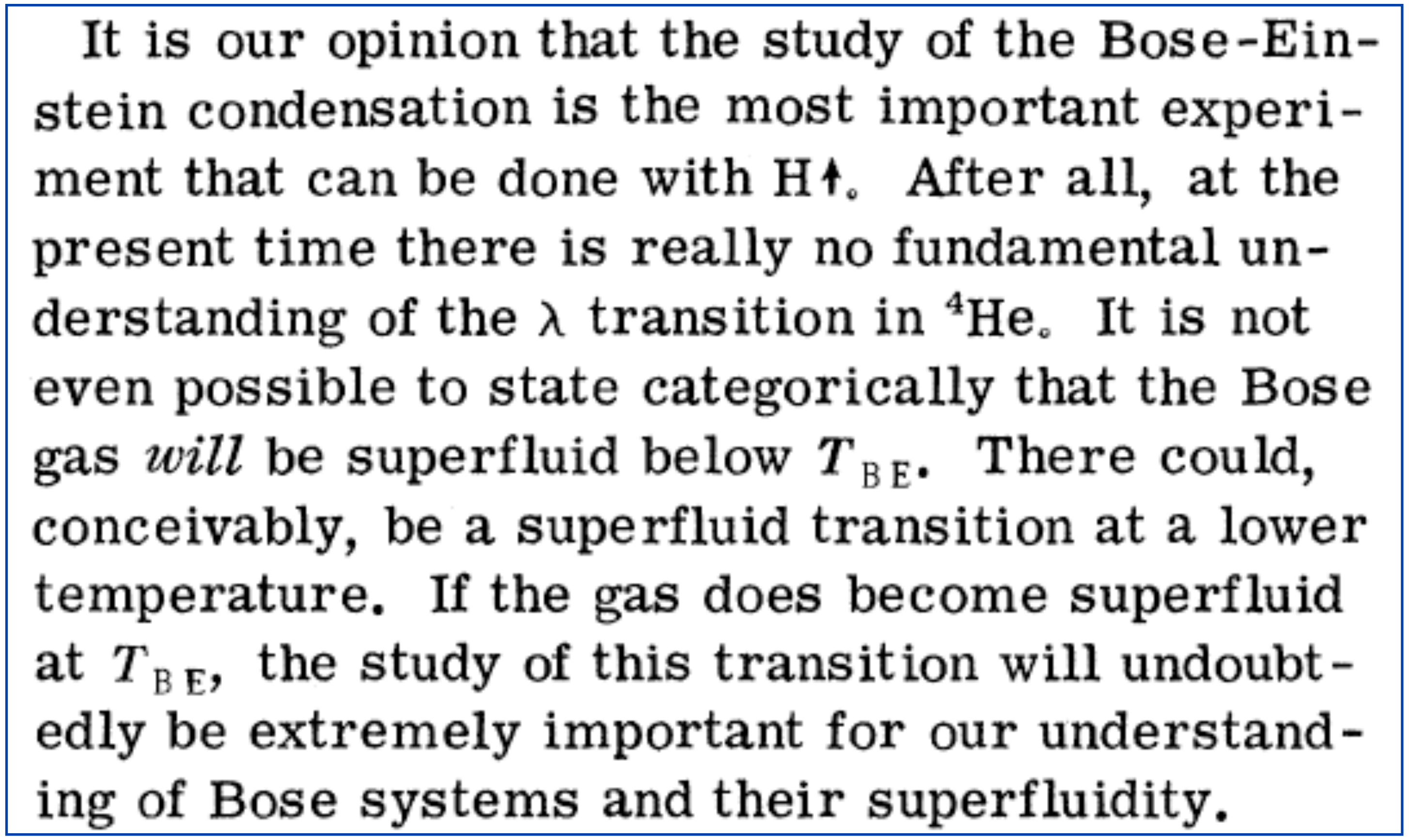
PRL 36, 910 (1976)



Systems of spin-aligned hydrogen isotopes are studied. They are shown to exhibit even more extreme "quantum" behavior than the helium isotopes. Spin-aligned hydrogen is predicted to be a gas at *all* temperatures and its Bose-Einstein condensation and possible superfluidity are discussed.



therefore, this system is expected to be a nearly ideal *Bose-Einstein* gas! Thus, it would clearly be an important and exciting experiment to try to study the *Bose-Einstein* condensation in H$\uparrow$.



It is our opinion that the study of the Bose-Einstein condensation is the most important experiment that can be done with H$\uparrow$. After all, at the present time there is really no fundamental understanding of the λ transition in ^{4}He. It is not even possible to state categorically that the Bose gas *will* be superfluid below T_{BE}. There could, conceivably, be a superfluid transition at a lower temperature. If the gas does become superfluid at T_{BE}, the study of this transition will undoubtedly be extremely important for our understanding of Bose systems and their superfluidity.

What’s all the fuss about? What makes a BEC special?

1. **Coherence**: well-defined quantum phase relationship between points in space-time.

2. **Macroscopically occupied state**: QM works well for many particles in a single state, not just the state of one particle. Not obvious *a priori* in QM. Extension of QM to large systems, condensed matter, connections to classical physics? (Can determine microscopic configuration by measuring macroscopic properties, such as system size: unusual.)

3. **Macroscopically observable**: see the relevance of quantum mechanics in a single measurement, as opposed to the sum of many measurements on identically prepared single particles.

The matter equivalent of a large-amplitude coherent electric field, such as laser light.

Atom Optics, Atom Cooling, Atom Manipulation

BEC is probably in the minds of increasing numbers of people after Stwalley and Nosanov, but is not often mentioned in the literature.

1970	**Ashkin (Bell labs) – 1970** First observation of optical trapping. Proposes atom trapping with light.	**Ashkin (Bell labs) – 1970** Proposes radiation pressure force for atom manipulation.		
1975	**Hansch, Schawlow (Stanford)– 1975** Propose laser cooling of a gas.	**Wineland (NIST), Dehmelt (UWash)– 1975** Propose laser cooling of ions.		
1978	**Wineland, Drullinger, Walls (NIST Boulder)– 1978** Observation of laser cooling of **ions**.	**Cook (UCalif) – 1979, 1980** Th. analysis of atomic motion in resonant radiation fields.	**Ashkin grp (Bell labs) – 1979, 1980** Expt observations of resonant radiation pressure on atom motion	**Letokhov group (USSR) – 1979, 1981** Demonstrations of deceleration of atoms with laser light
1980	**Gordon, Ashkin (Bell labs) –1980** Detailed analysis of motion of atoms in a radiation trap	**Wing (OSC) –1980** Proposes magnetostatic trapping of atoms.		
1982	**Phillips, Metcalf (NIST)– 1982** Deceleration of Na atoms with laser light			
1983	**Pritchard (MIT) –1983** Proposal for cooling atoms in magnetic trap for spectroscopy. **Notes BEC motivation.**	**Dalibard, Reynaud, Cohen-Tannoudji (ENS) –1983** Proposal for 3D optical traps for atoms	**Pritchard grp (MIT)– 1983** First of experiments showing diffraction of atom waves with laser light, gratings.	

"collective behavior" of neutral atoms

Approaching BEC

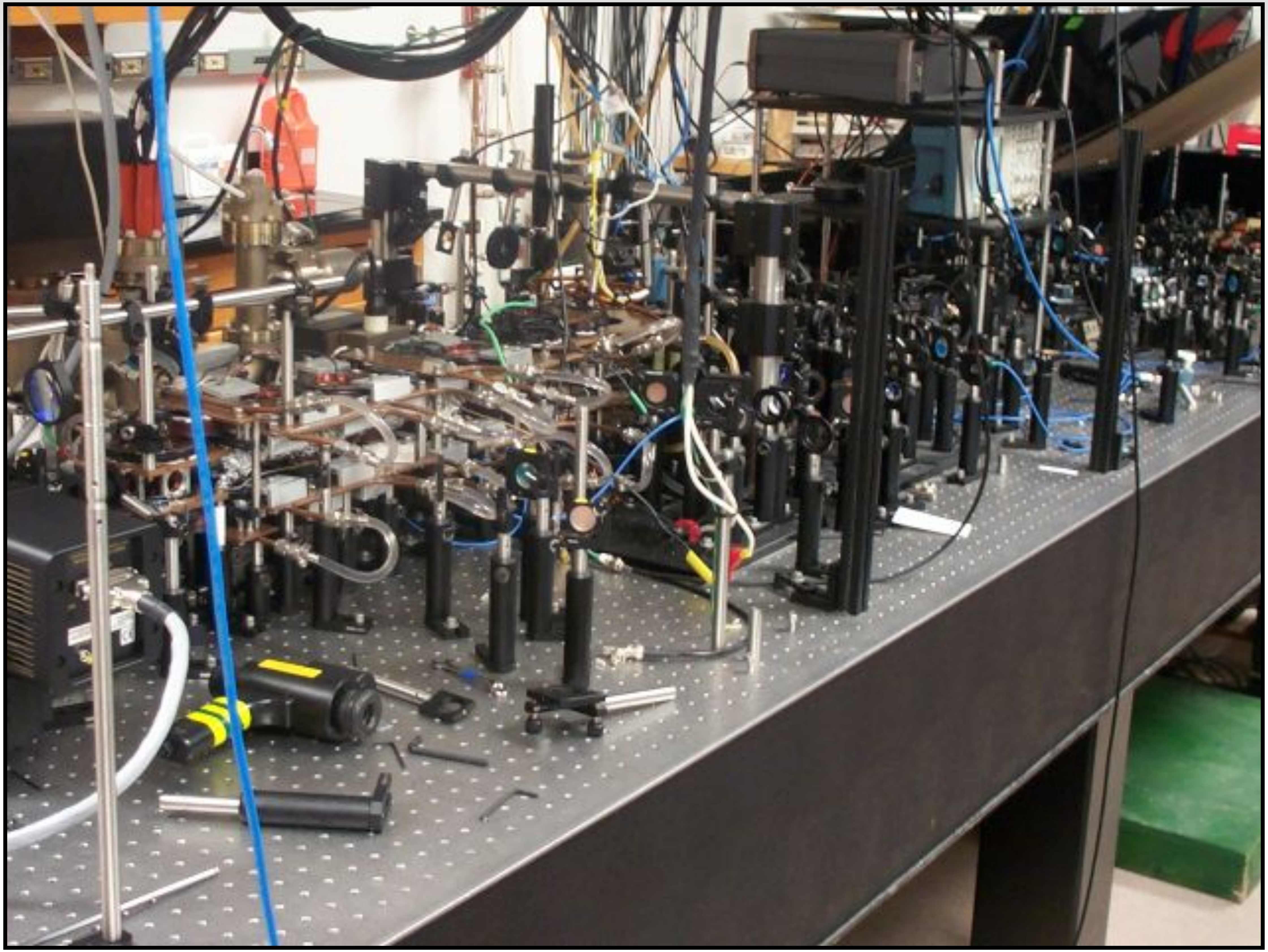
1985	**Phillips grp (NIST), Metcalf grp (SUNY), Dalibard – 1985** Stopping Na atoms with laser light (Zeeman slower)	**Ertmer, Blatt, Hall, Zhu (JILA) – 1985** Stopping of Na atoms with laser light (Zeeman slower)	**Phillips grp (NIST), Metcalf grp (SUNY) – 1985** Observation of magnetically trapped atoms	**Chu, Hollberg, Bjorkholm, Cable, Ashkin (Belllabs) – 1985** Optical molasses observations
1986	**Watts, Wieman (JILA) – 1986** Stopping of Cs atoms with diode laser light	**Aspect, Dalibard, Heidmann, Salomon, Cohen-Tannoudji (ENS) – 1986** Cooling with simulated emission	**Pritchard, Raab, Bagnato (MIT), Wieman, Watts (JILA) – 1986** Spontaneous force light trap proposal	**Vigue (ENS) – 1986** BEC is **unlikely to be observed** in alkali atomic gases
1987	**Pritchard grp (MIT) – 1987** Continuous stopping Na atoms with laser light, loading into magnetic trap.	**Bagnato, Pritchard, Kleppner (MIT) – 1987** Analysis of BEC of atoms in potential well.	**Hess (Bell labs), Kleppner grp (MIT) – 1987** Hydrogen atoms confined in a magnetic trap. BEC is motivation.	**Chu grp (Bell labs) – 1987** Trapping Na atoms with radiation pressure and magnetic fields (first MOT)
		Cohen-Tannoudji grp (ENS) – 1987 Channeling of atoms in a laser standing wave		
1988	**Wieman grp (JILA) – 1988** Vapor cell optical molasses of Cs using diode lasers.	**Phillips grp (NIST) – 1988** Observation of laser cooling below Doppler limit.	**Kleppner grp (MIT) – 1988** Evaporative cooling of magnetically trapped hydrogen	**Dalibard, Cohen-Tannoudji (ENS) – 1989** Analysis of polarization gradient cooling, beating the Doppler limit.
1990	**Wieman grp (JILA) – 1990** Vapor cell trap (MOT) with Cs atoms.	**Kasevich, Riis, Chu, DeVoe (Stanford) – 1990** Atomic fountain, RF spectroscopy of laser cooled Na atoms.	**Kasevich, Wiess, Chu (Stanford) – 1990** Evanescent wave normal-incidence mirror for laser cooled atoms.	**Phillips grp (NIST) – 1990** Atom trapping in 3D optical standing wave (optical lattice)

Main ideas are now in place, now need to make it all work.

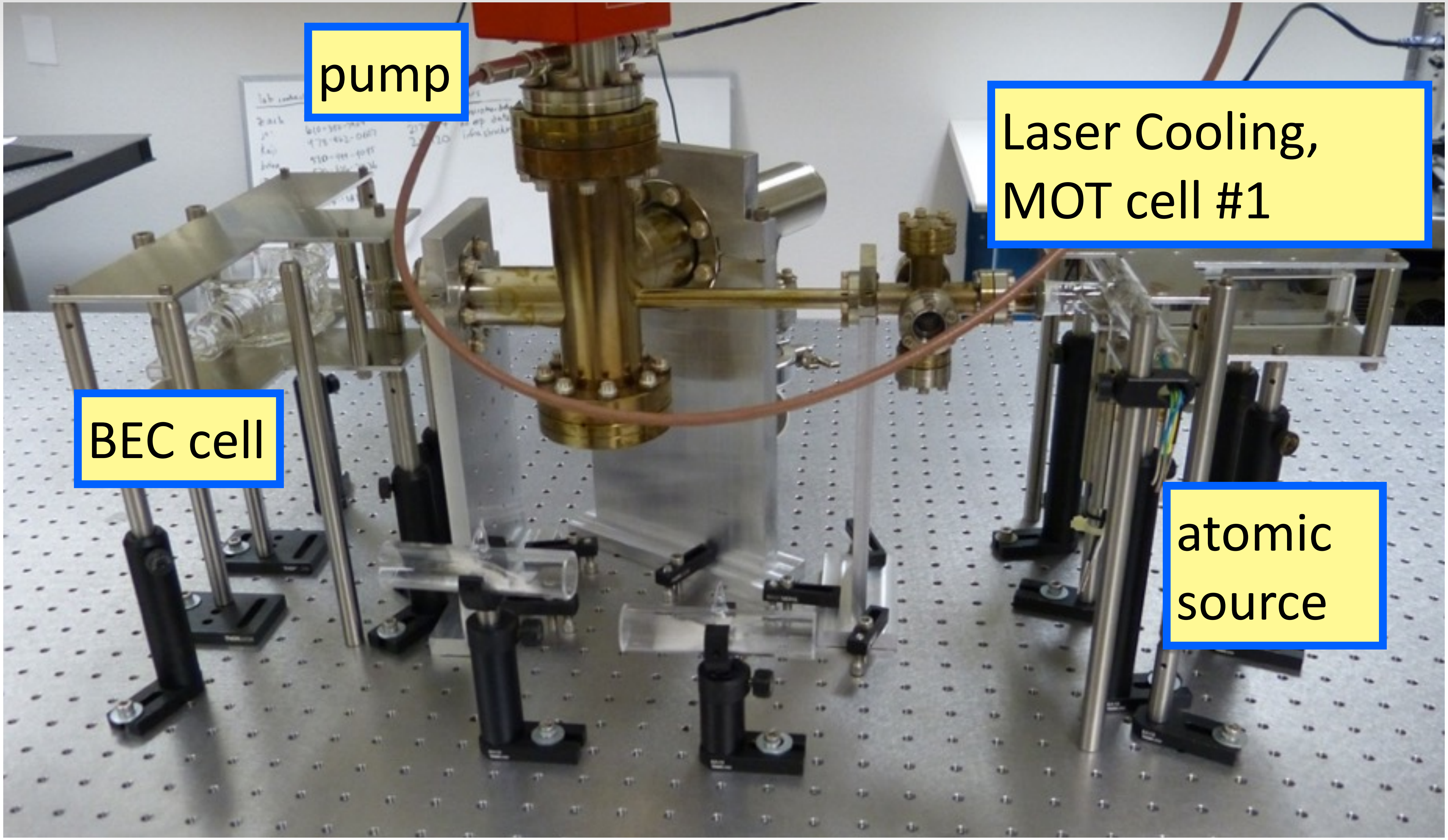
First BECs achieved in 1995

Cornell & Wieman (JILA), Ketterle (MIT), Hulet (Rice)

BEC apparatus, University of Arizona



System overview: vacuum chamber



BEC Step 1: *pick a substance*

Use a Solid? Liquid? Gas?

Gas: weakly interacting. Can make a vapor out of many different elements.

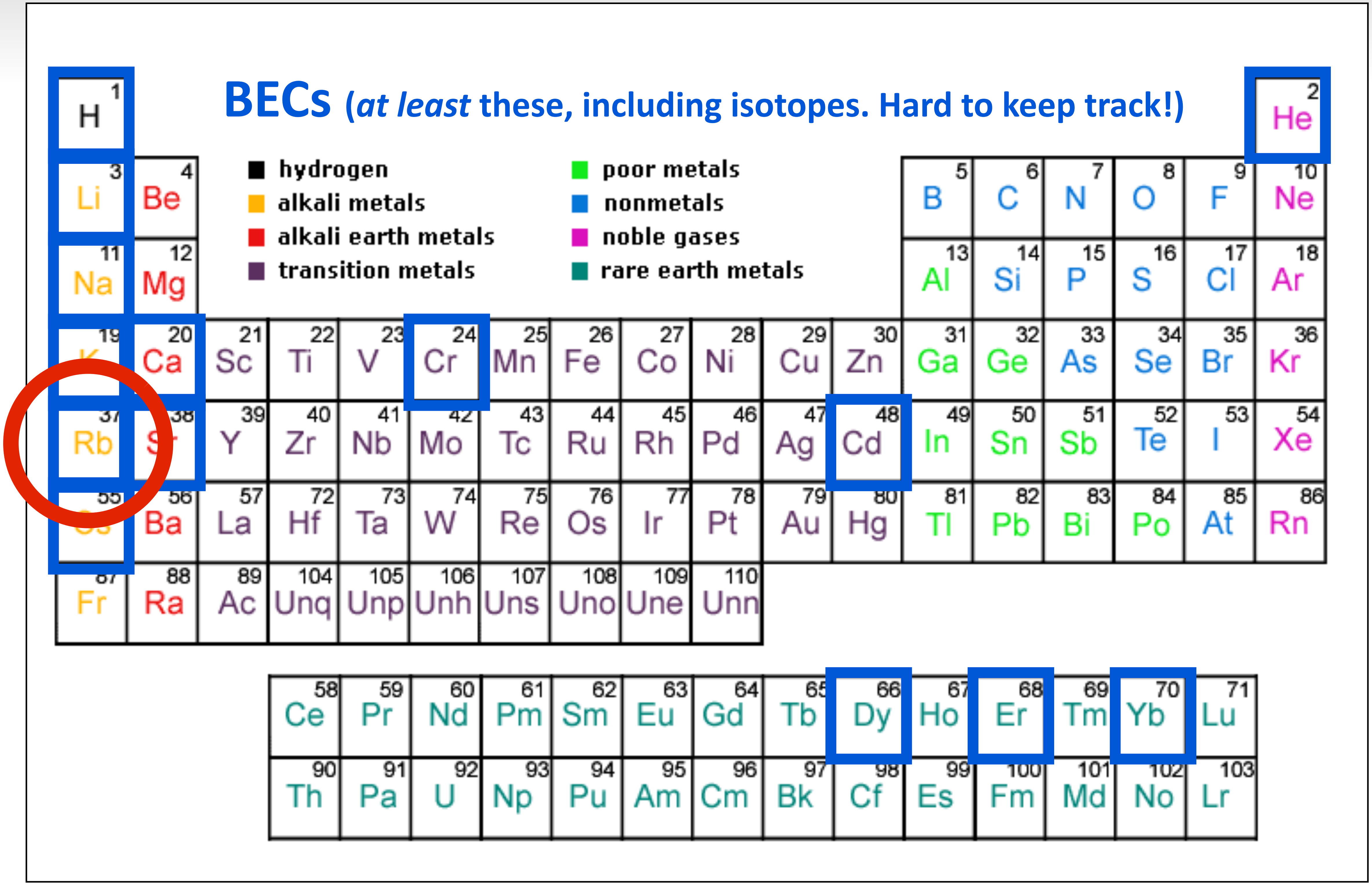
What element? Won't atoms solidify as T --> 0?

Generally, Yes (except Helium, stays liquid as T --> 0)

BUT: if density stays very low, time scales for molecular recombination are very long.

Atomic BEC will not be in true thermodynamic equilibrium, but in a long-lived metastable state.

Choices



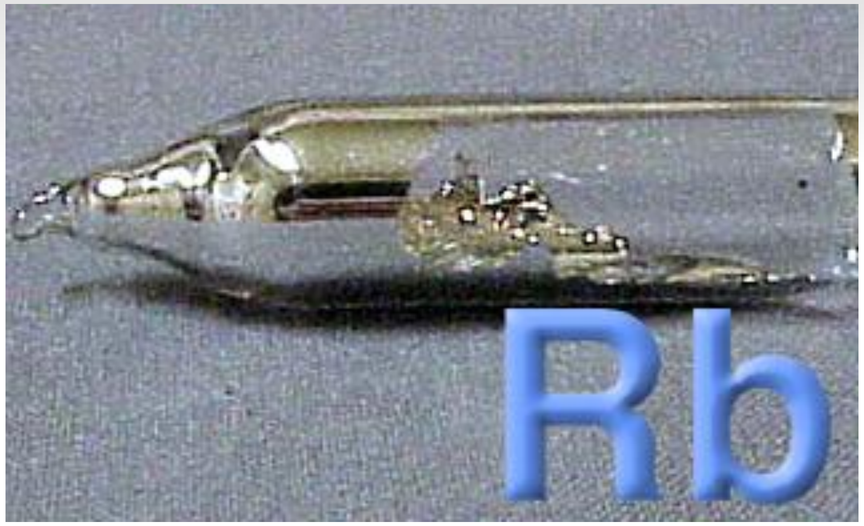
BECs (*at least* these, including isotopes. Hard to keep track!)

■ hydrogen
■ alkali metals
■ alkali earth metals
■ transition metals
■ poor metals
■ nonmetals
■ noble gases
■ rare earth metals

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 S	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

^{87}Rb



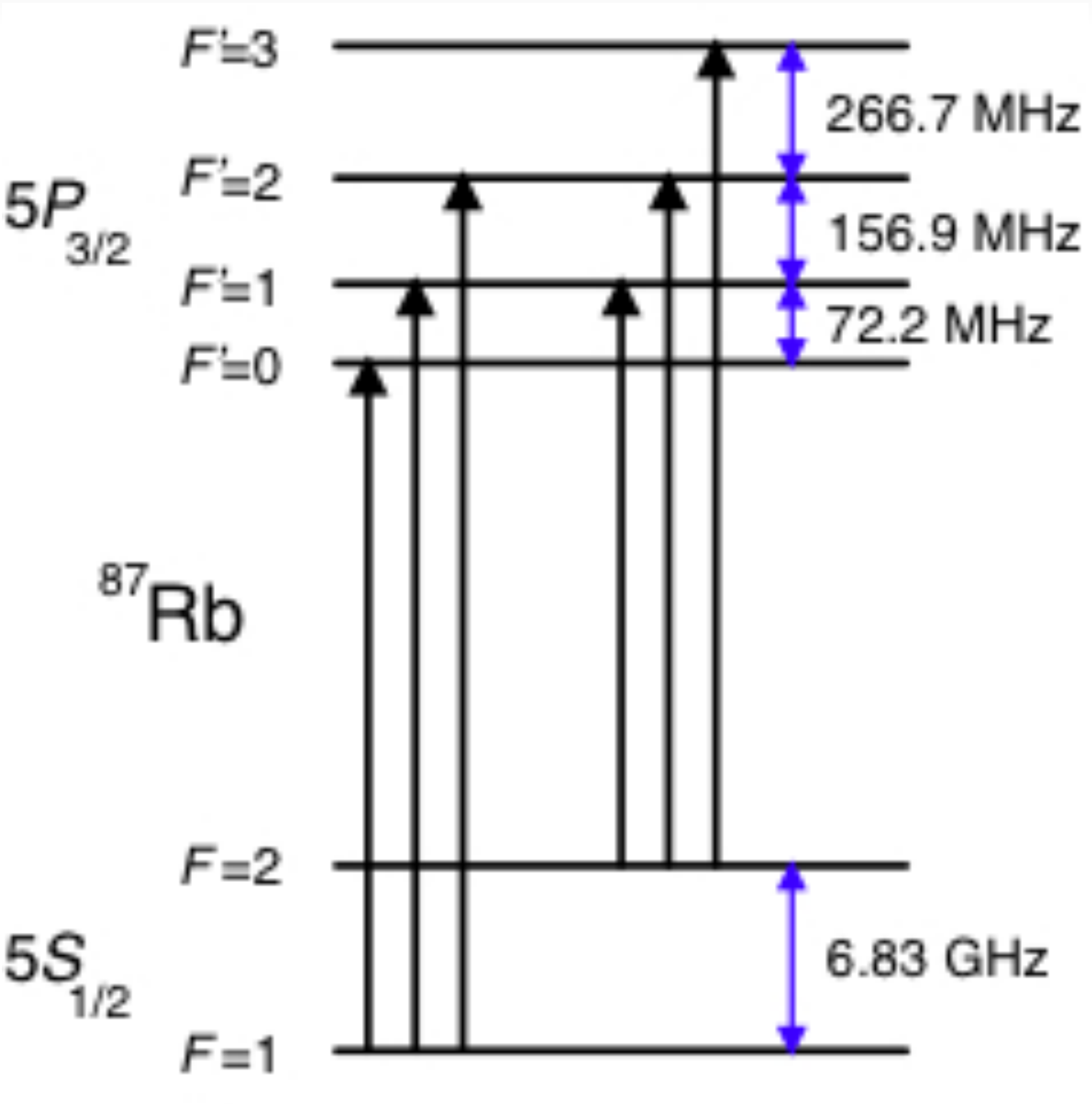
^{85}Rb: 37 protons, 48 neutrons, 37 electrons

^{87}Rb: 37 protons, 50 neutrons, 37 electrons

Why BEC with ^{87}Rb?

- Easy to obtain, easy to make a vapor.
- Neutral (weak interactions).
- Bosonic.
- Hydrogenic: one unpaired electron ($5s^1$) in ground state (simple atomic structure for laser interactions...)
- nice interaction parameters

^{87}Rb Level structure



Primary transition: 780 nm

Easily accessible with cheap diode lasers: atom-light interactions are important!

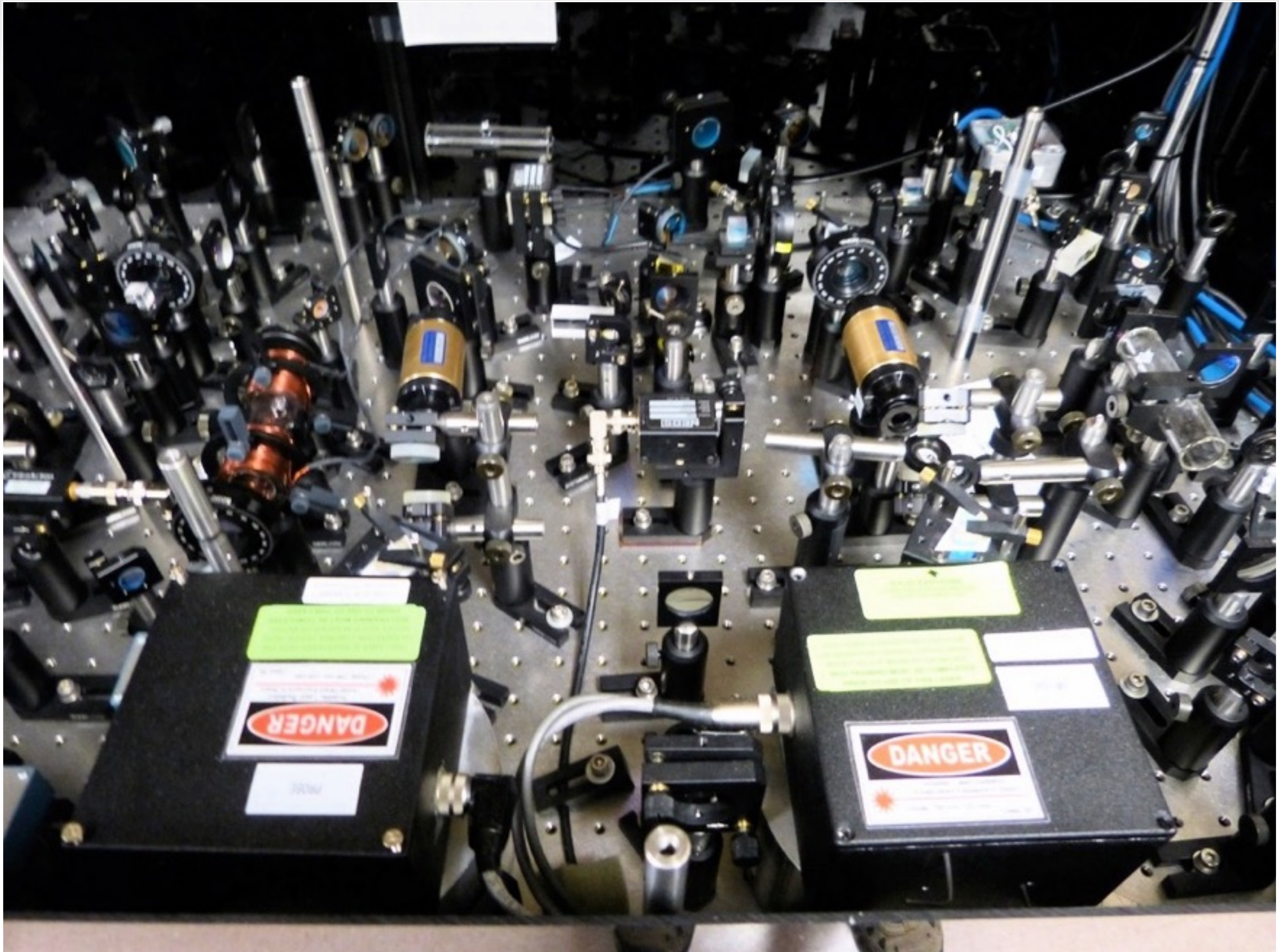
$$\boldsymbol{F} = \boldsymbol{S} + \boldsymbol{L} + \boldsymbol{I}$$

$|F, m_F\rangle$ atomic state notation.

F: total angular momentum quantum number

m_F: magnetic quantum number

Diode Lasers



Atom-light interaction: far from resonance

AC Stark shift: laser's oscillating electric field induces an oscillating atomic electric dipole moment.

Field and atom interact: atomic levels shift in energy (-**d**.***E***), depends on oscillation frequency.

--> Atom experiences a potential well or hill induced by laser:

$$U = \frac{\hbar\Gamma}{8}\frac{I/I_{\rm sat}}{\Delta/\Gamma}$$

Blue detuning: $\Delta>0$, $\omega>\omega_0$
Atoms repelled by laser

Red detuning: $\Delta<0$, $\omega<\omega_0$
Atoms **attracted** to laser

(error in handout slides)

Atom-light interaction: near resonance light scattering

Atom absorbs photon from a laser (frequency ω) tuned near atomic resonance (frequency ω_0). Followed by spontaneous emission.

Scattering rate

$$\gamma = \frac{\Gamma}{2} \frac{I/I_{\mathrm{sat}}}{1 + I/I_{\mathrm{sat}} + 4(\Delta/\Gamma)^2}$$

Faster scattering for larger I/I_{sat}, smaller Δ

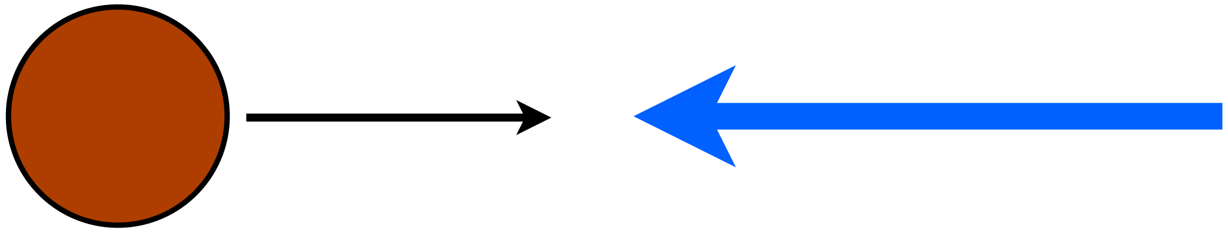
Scattering force due to absorption from a single beam:

$$F = dp/dt \sim \hbar k \gamma$$

What about scattering force due to spontaneous emission?

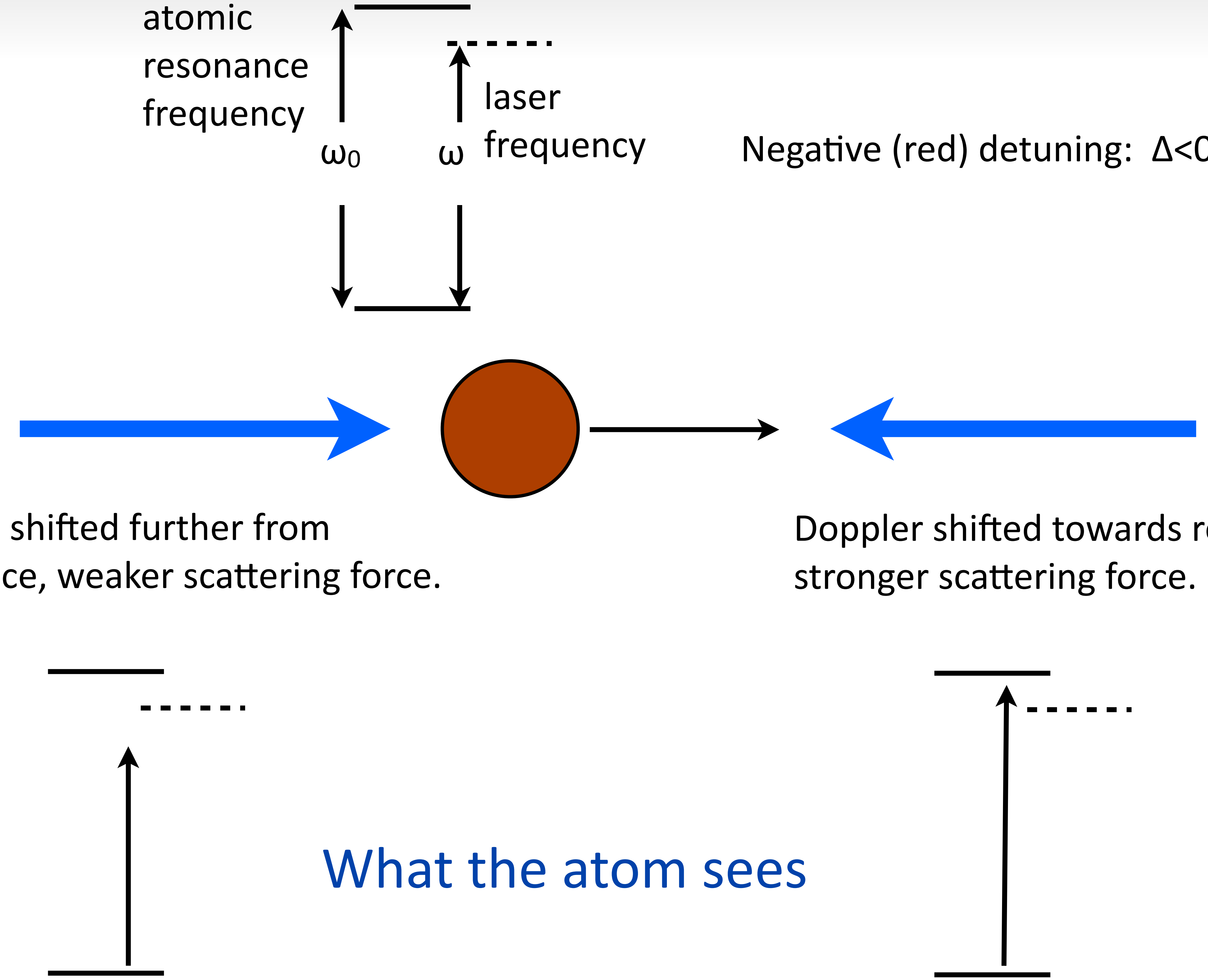
Laser cooling

Idea: slow atoms down (= cooling)
by scattering light from lasers



Every photon absorbed: atom momentum drops by $\hbar k$ along laser direction, atom slows down in this particular direction

Doppler cooling



Negative (red) detuning: $\Delta<0$, $\omega<\omega_0$

Doppler shifted further from resonance, weaker scattering force.

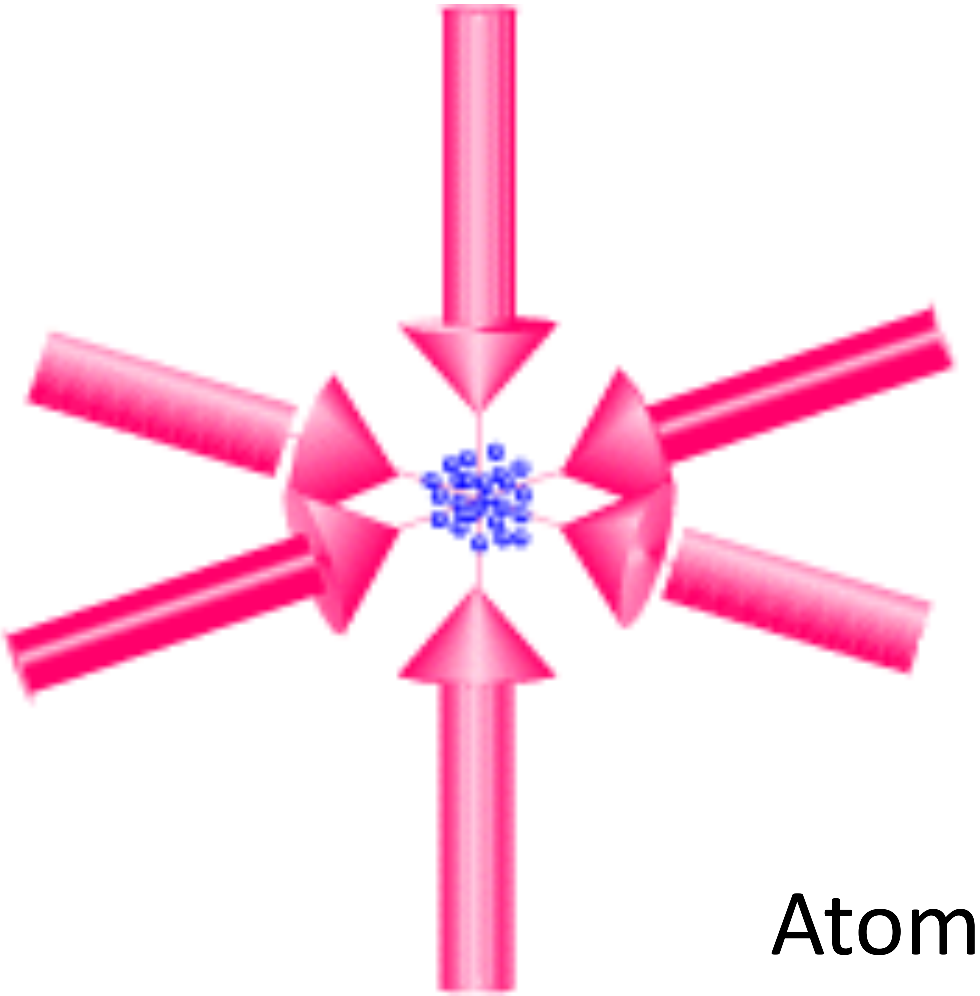
Doppler shifted towards resonance, stronger scattering force.

What the atom sees

3D Doppler cooling

Lasers from all directions, tuned below resonance.

3D cooling, but no spatial dependence of force: no trapping



Atoms cooled in x, y, z

$$T \sim 10\mu\mathrm{K} \rightarrow \bar{v} \sim 50\mathrm{mm/s} \sim 0.2\mathrm{km/hr}$$

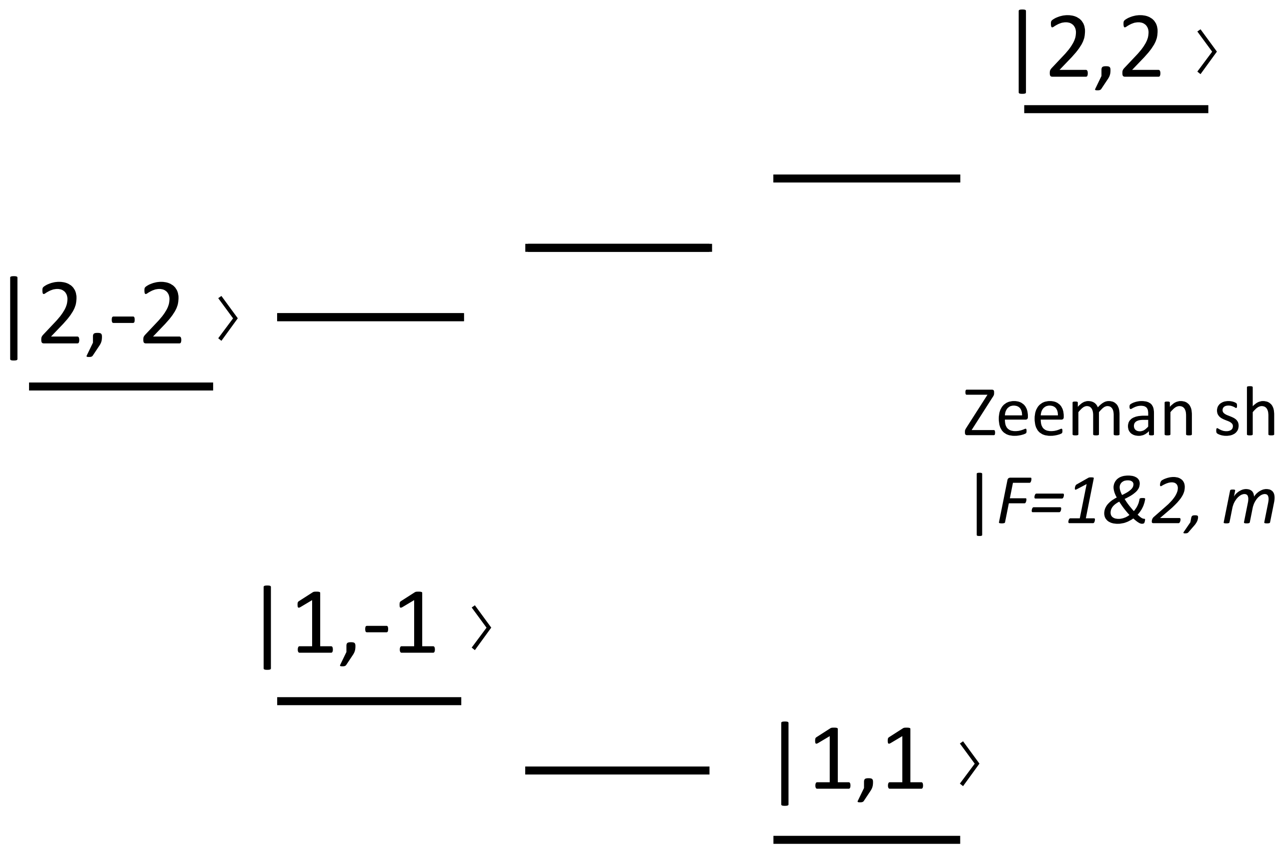
(typical)

Magneto-Optic Trap (MOT)

Add magnetic field gradient: Zeeman shifts

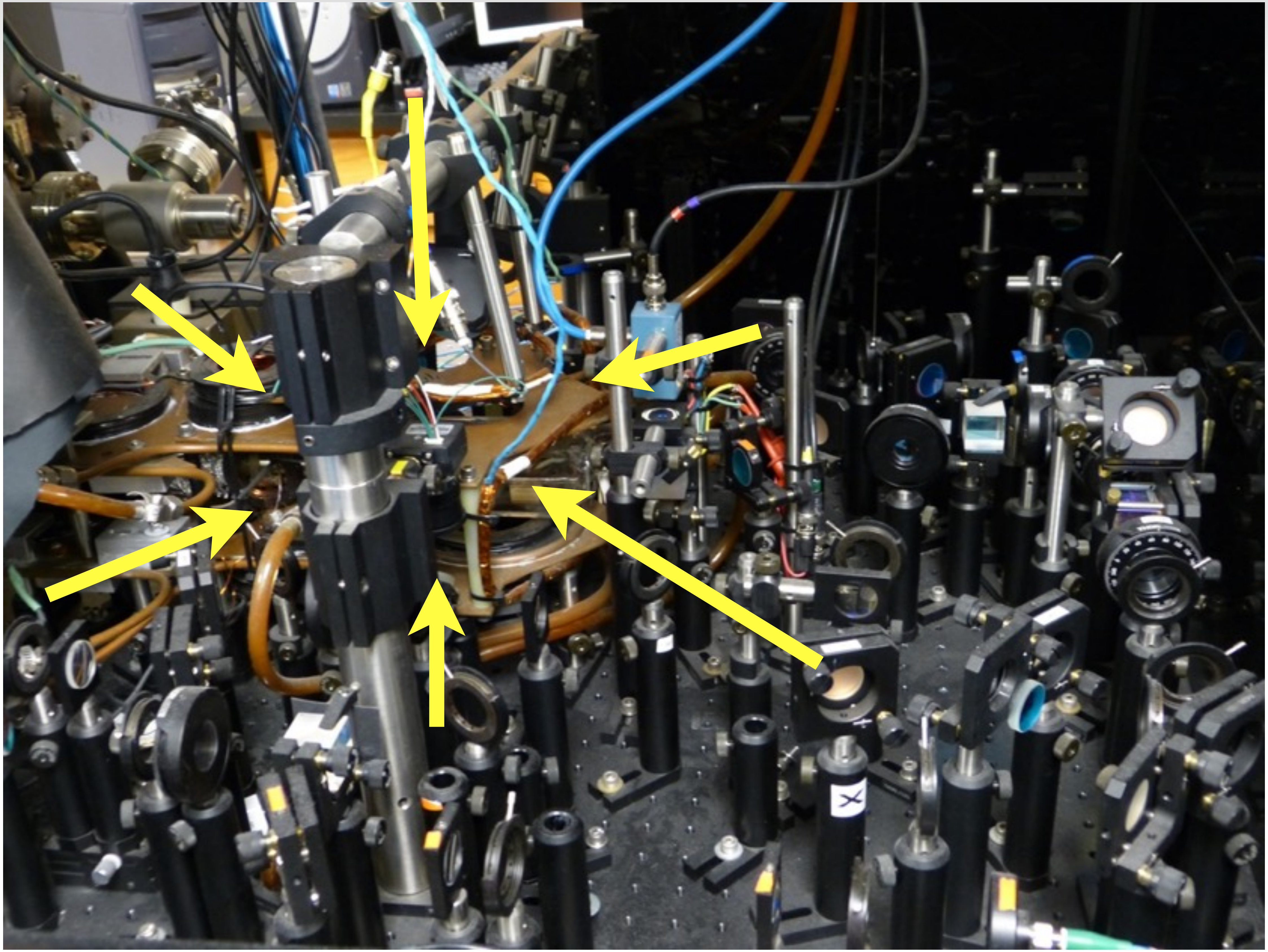
Now: spatial dependence on atomic resonance frequency.

--> Spatial dependence to scattering force:
atoms cooled *and* trapped

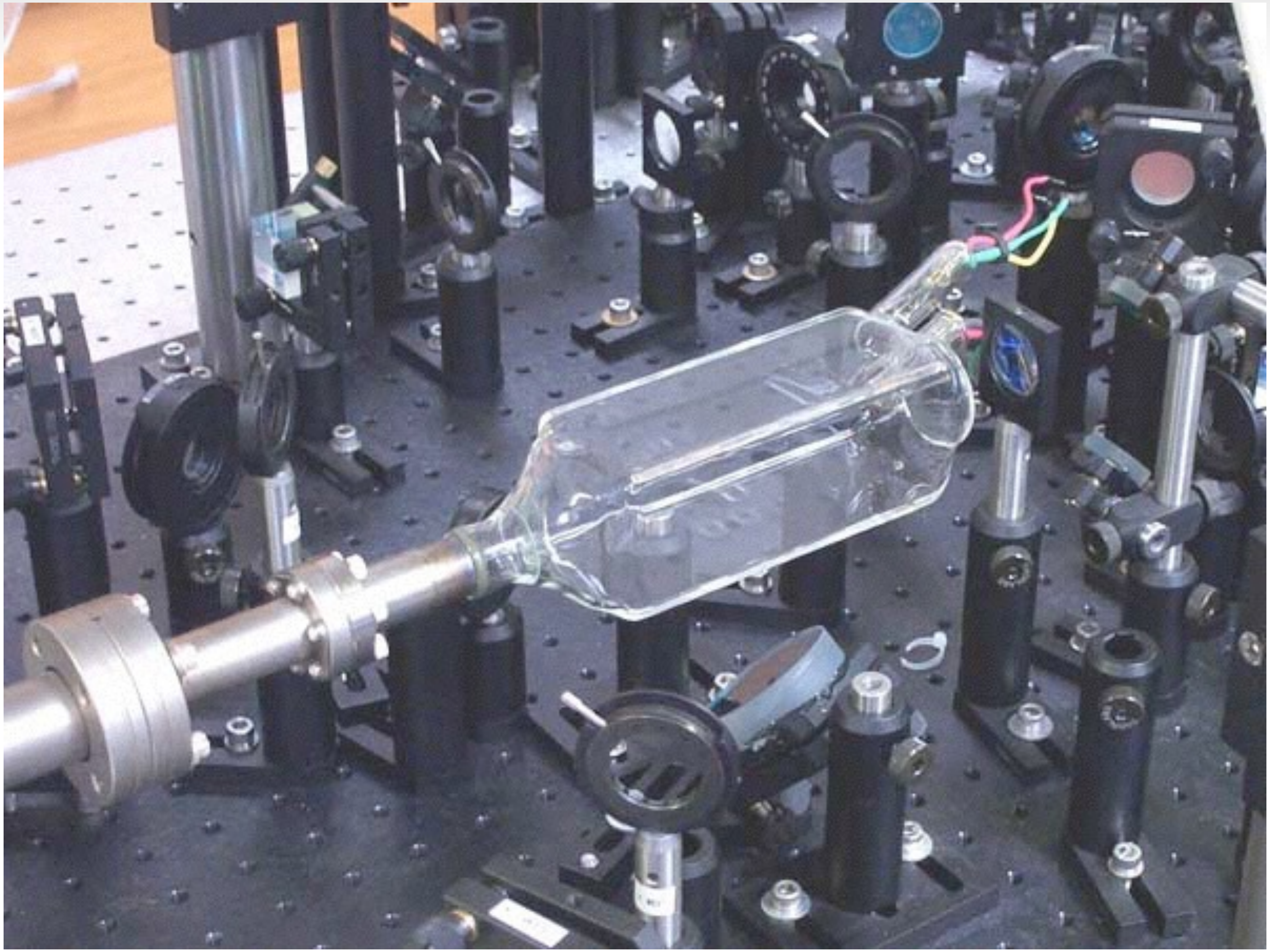


Zeeman shifts of the magnetic
$|F=1\&2, m_F\rangle$ sublevels of ^{87}Rb (general idea)

Magneto-Optic Trap (MOT) optics



MOT optics, without magnetic field coils



MOT

MOT parameters

T: about 10 μK
n: about 10^{10} cm^{-3}
(dry air: about 10^{19} cm^{-3})
m_{Rb}: 1.5 x 10^{-25} kg
λ_{dB}: 0.06 μm

$$\lambda_{dB} = \sqrt{\frac{2\pi\hbar^2}{mk_BT}}$$

$\rho = n\,\lambda_{\text{dB}}^3$: 2 x 10^{-6}

Laser cooling is very effective!
(increase of about x10^{13} in PSD from room temp vapor)

But still another x10^6 to go for BEC.

Magnetic trapping

Remove lasers, confine atoms in magnetic fields.

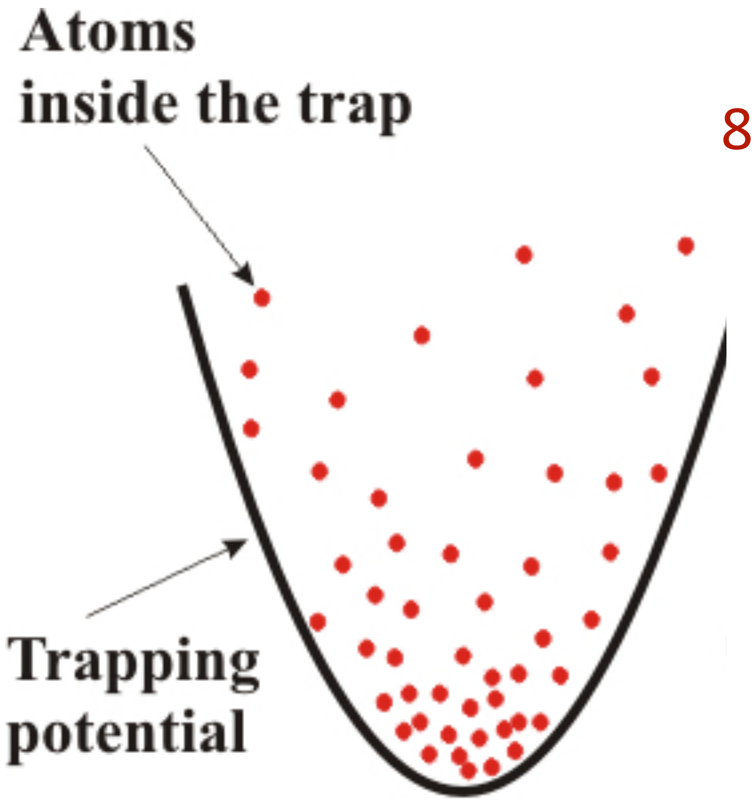
1. Apply a magnetic field ***B***.

2. Zeeman shift U_Z of state $|F, m_F\rangle$ is proportional to $m_F|B|$.

3. For ^{87}Rb $|1,-1\rangle$ state, U_Z increases with increasing $|B|$: energy is smaller for smaller $|B|$ --> there is a trapping force that will push these atoms towards smaller $|B|$.

Magnetic trapping

Magnetic trap: engineer a magnetic field that has a local minimum of |B|, spin polarize the atoms so that all atoms are pushed towards this minimum.



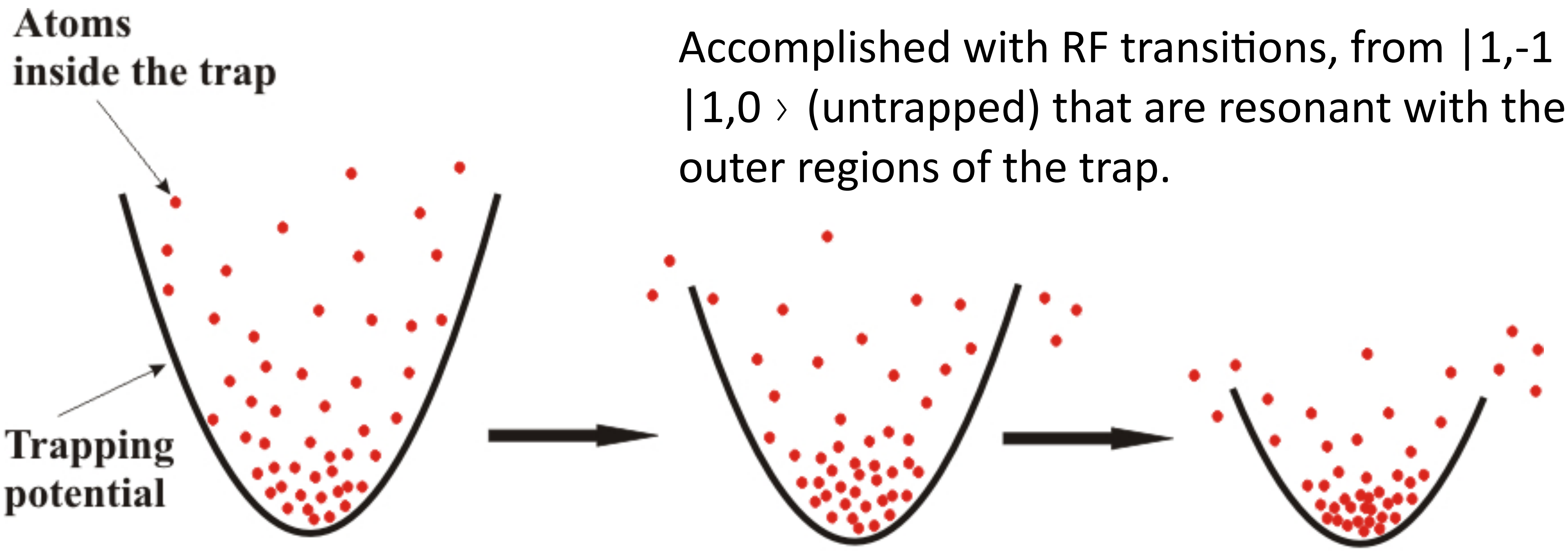
$^{87}\mathrm{Rb}\ |1,-1\rangle$ atoms

To trap, turn off lasers, turn on magnetic trapping field.

Evaporative Cooling

The basic idea:

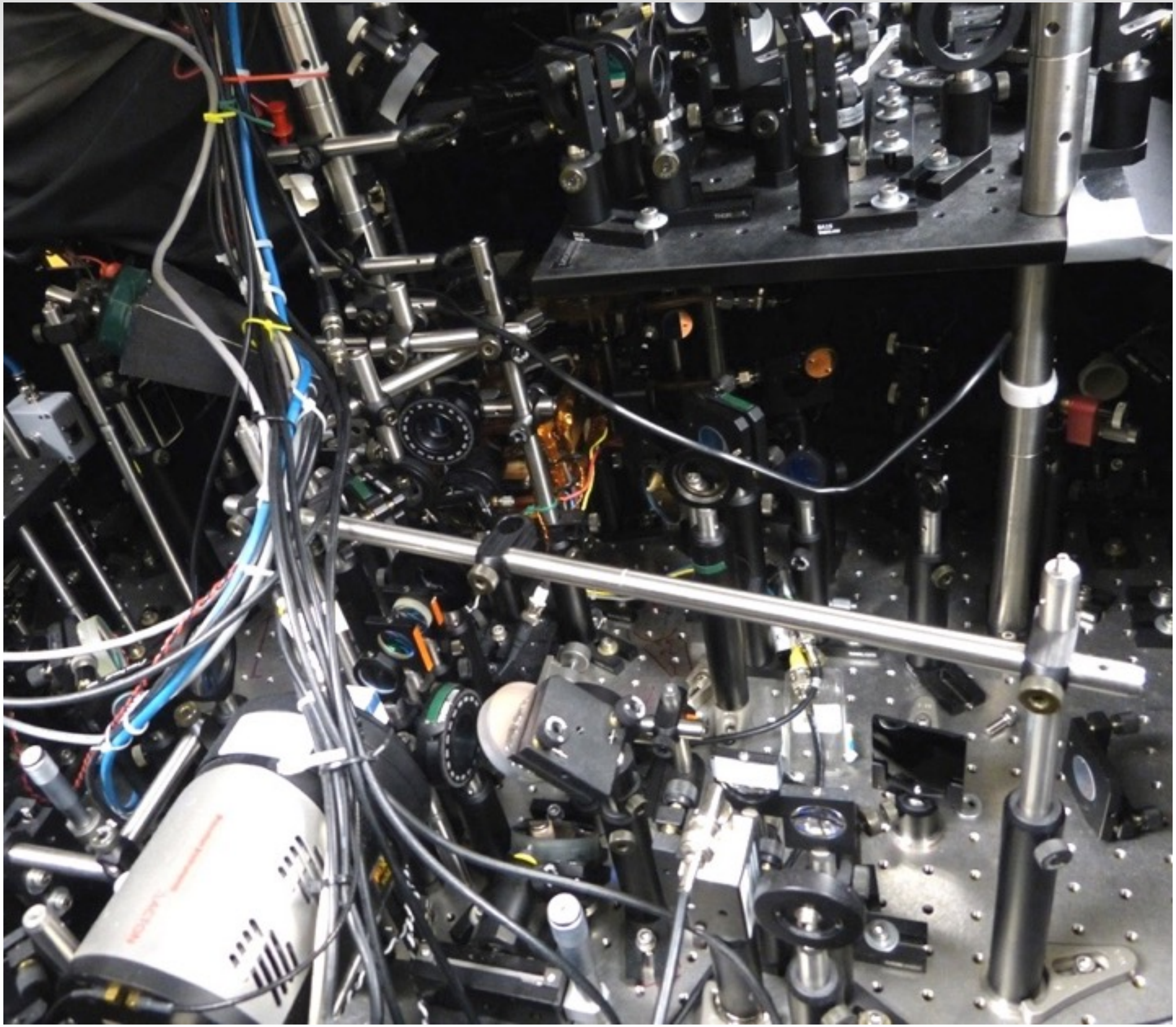
1. Eject the most energetic atoms from the trap. The remainder will re-thermalize to a lower temperature.
2. Repeat until BEC is reached.
3. In practice, lose about 99% of atoms in the process.



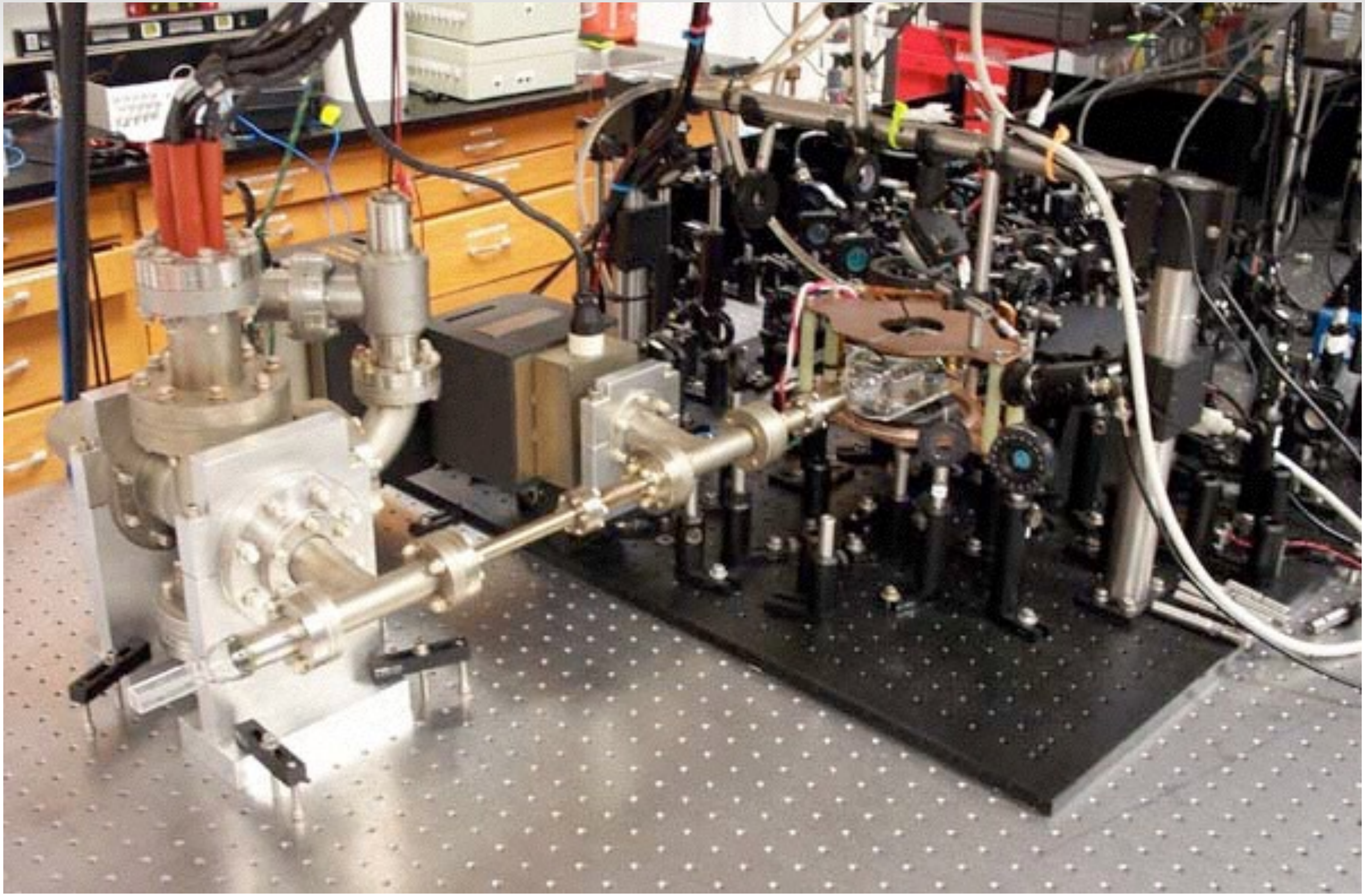
Accomplished with RF transitions, from $|1,-1\rangle$ to $|1,0\rangle$ (untrapped) that are resonant with the outer regions of the trap.

Illustration from Raithel group web page, U. Michigan

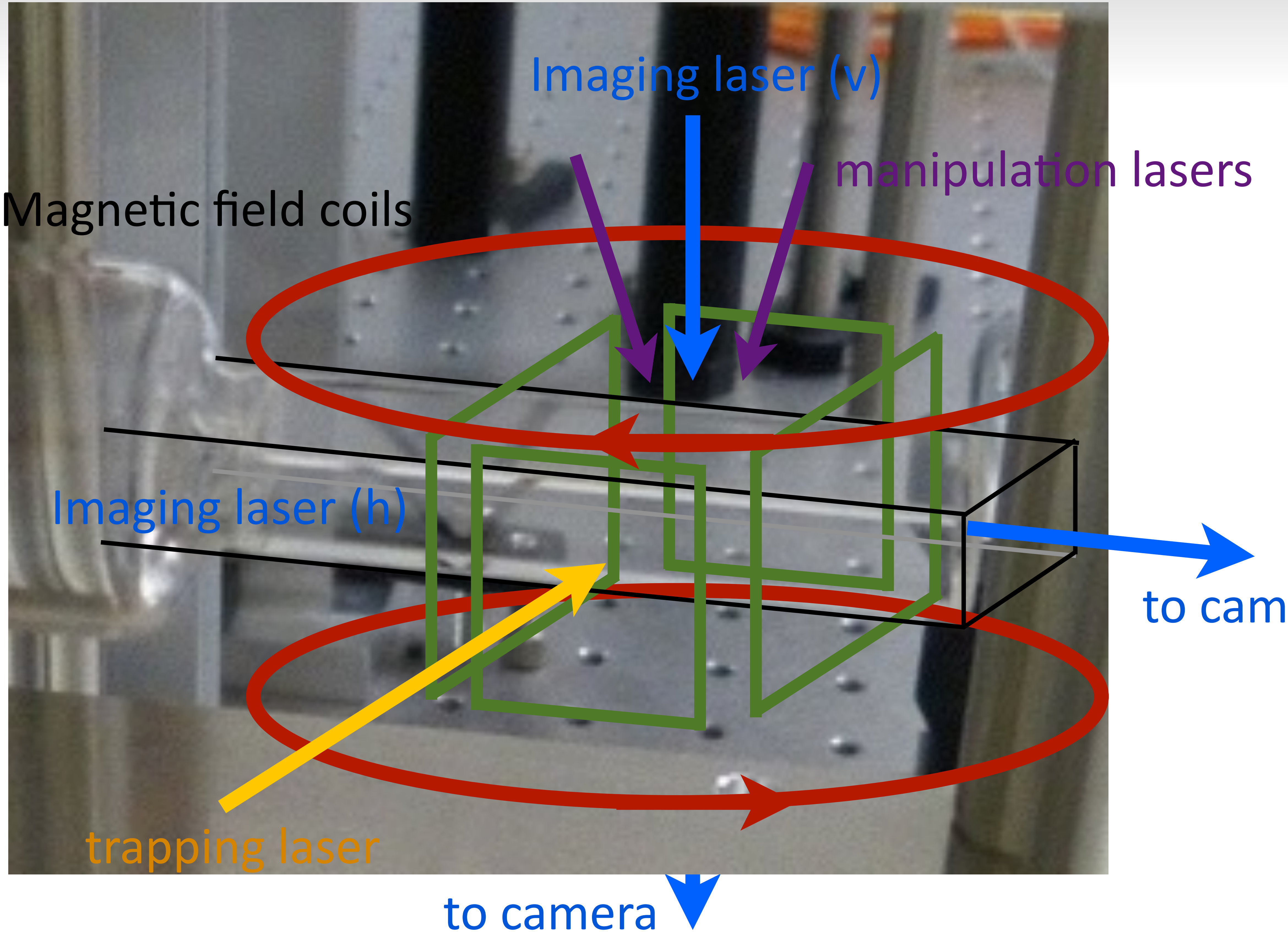
Magnetic trapping and BEC region



BEC cell, no optics



BEC chamber, diagram



Imaging laser (v)

manipulation lasers

Magnetic field coils

Imaging laser (h)

to camera

trapping laser

to camera

Seeing the atoms

Absorptive probe beam,
tuned near resonance

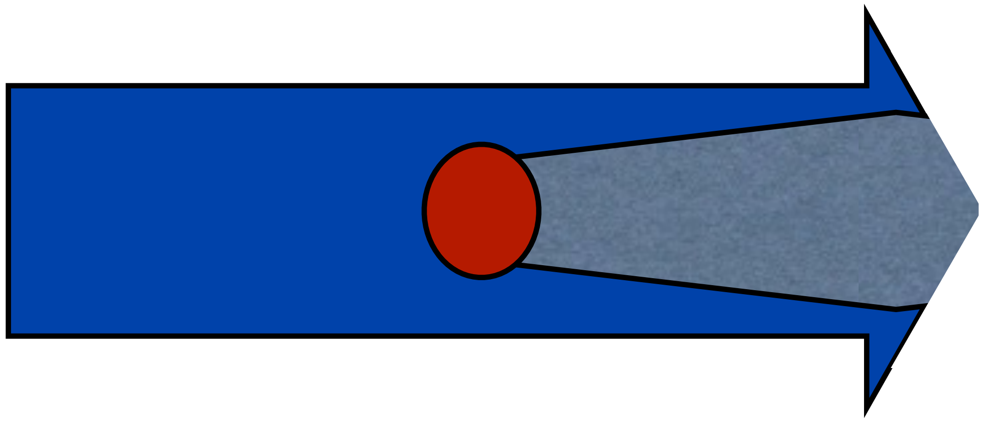
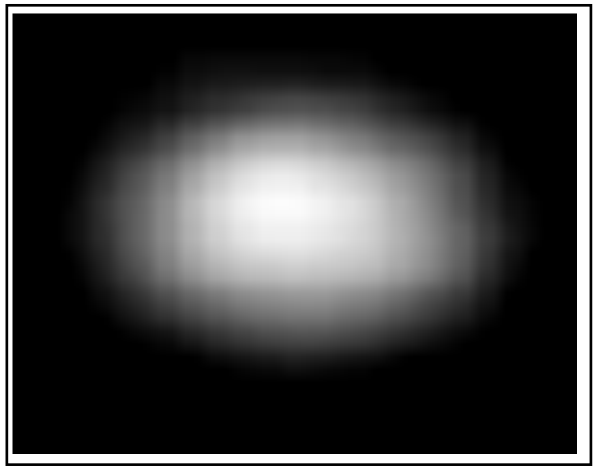


Image the “shadow” onto
CCD camera

BEC

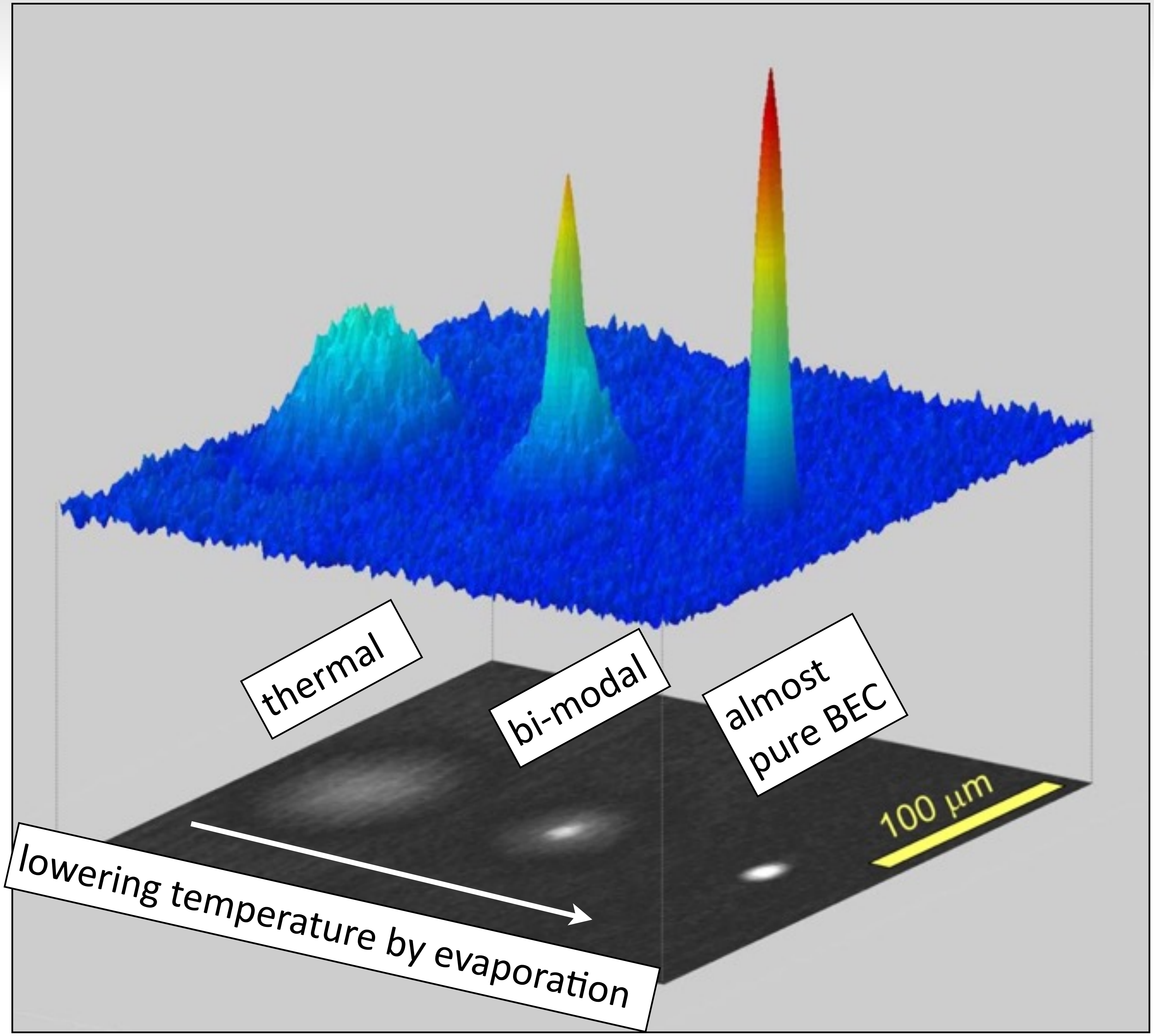


Inverted
grayscale

~ 50 µm
across

Or release BEC from the trap and image after a time of flight: larger object to study.

One sign of a BEC: bi-modal density distribution



Extracting atom cloud parameters

Very general ideas!

- Fit measured bi-modal distribution.

$$n(\vec{r}) = n_0(1 - (x/R_x)^2 - (y/R_y)^2 - (z/R_z)^2), \; n(\vec{r}) \geq 0$$

for the BEC. Shape is ~ Gaussian for thermal portion (harmonic trap)

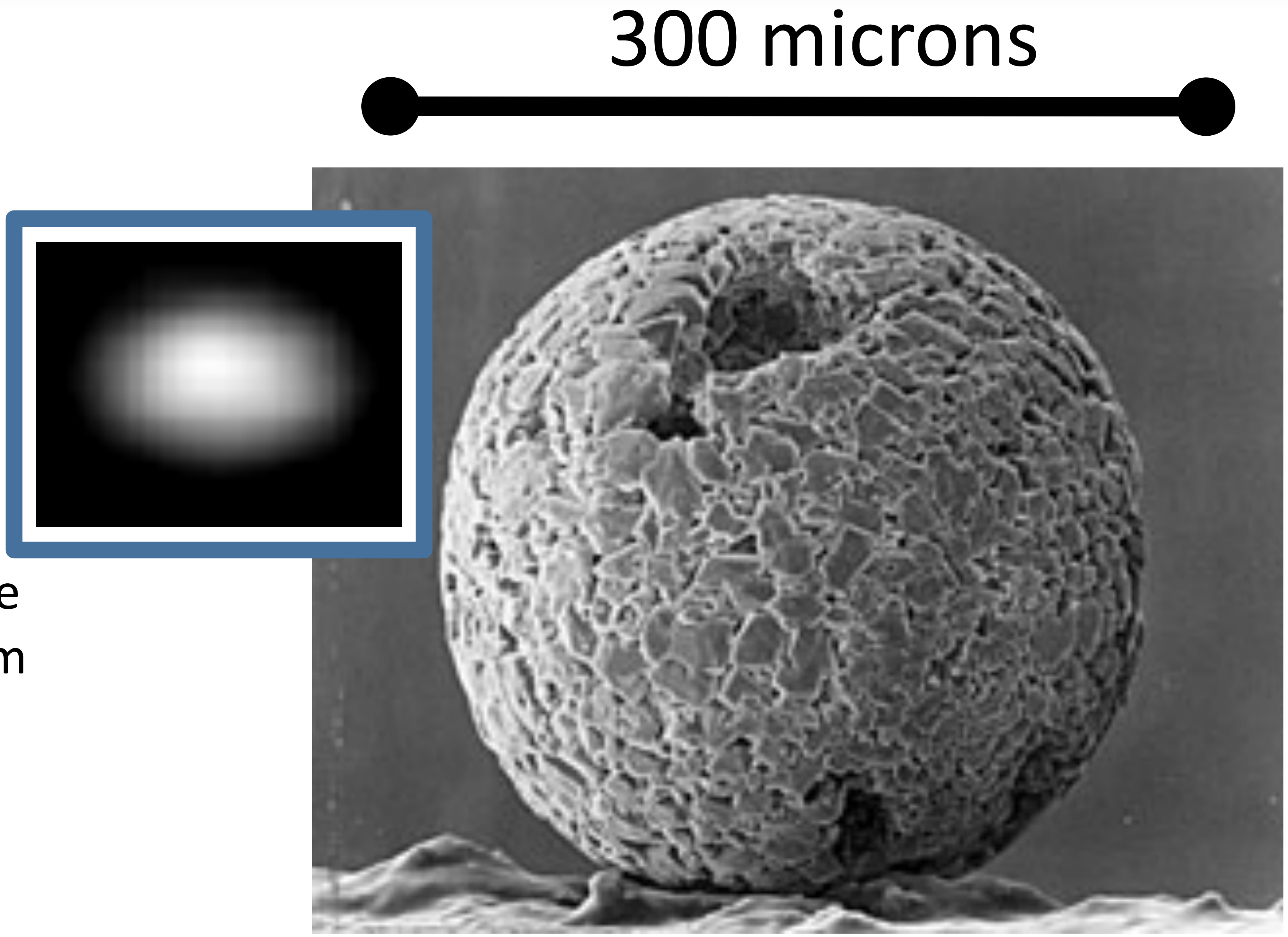
- Max. absorption --> peak density of atoms
- Density, radii --> number of atoms
- Width of **thermal** distribution --> temperature

BEC

Tiny droplet of quantum fluid

Two million ^{87}Rb atoms,
T=50 nK,
confined magnetically,
~100 microns in diameter
(thickness of hair, paper, dust).
speed: about 4 mm/s
lifetime: about 1 minute

Densities 1 million times more dilute than air: weakly interacting quantum fluid.



Interplanetary dust particle.
Don Brownlee (University of Washington)

BEC wavefunction

For our purposes, the state of the condensed portion is well-described by the many-body wavefunction Ψ(**r**,t).

$$\Psi(\vec{r},t) = \sqrt{n(\vec{r},t)}\,\exp[i\varphi(\vec{r},t)]$$

BEC particle density

BEC phase

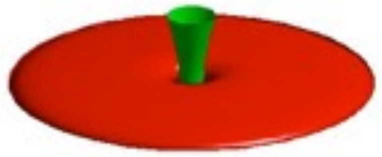
$$|\Psi(\mathbf{r},t)|^2 = n(\mathbf{r},t)$$

With a wave function for the BEC, we can use a modified Schrodinger Equation to determine fluid dynamics

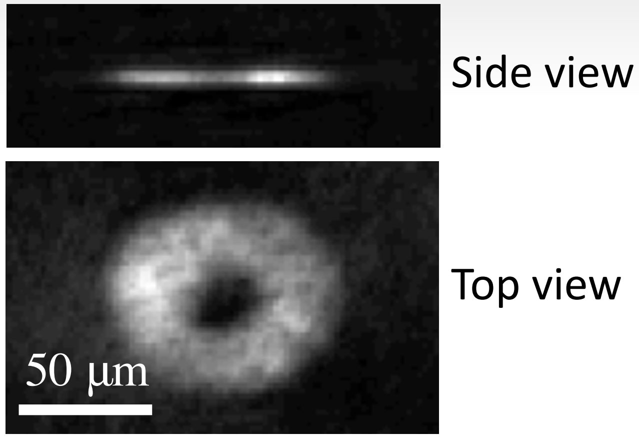
Fluid dynamics

Water + cinnamon + spoon

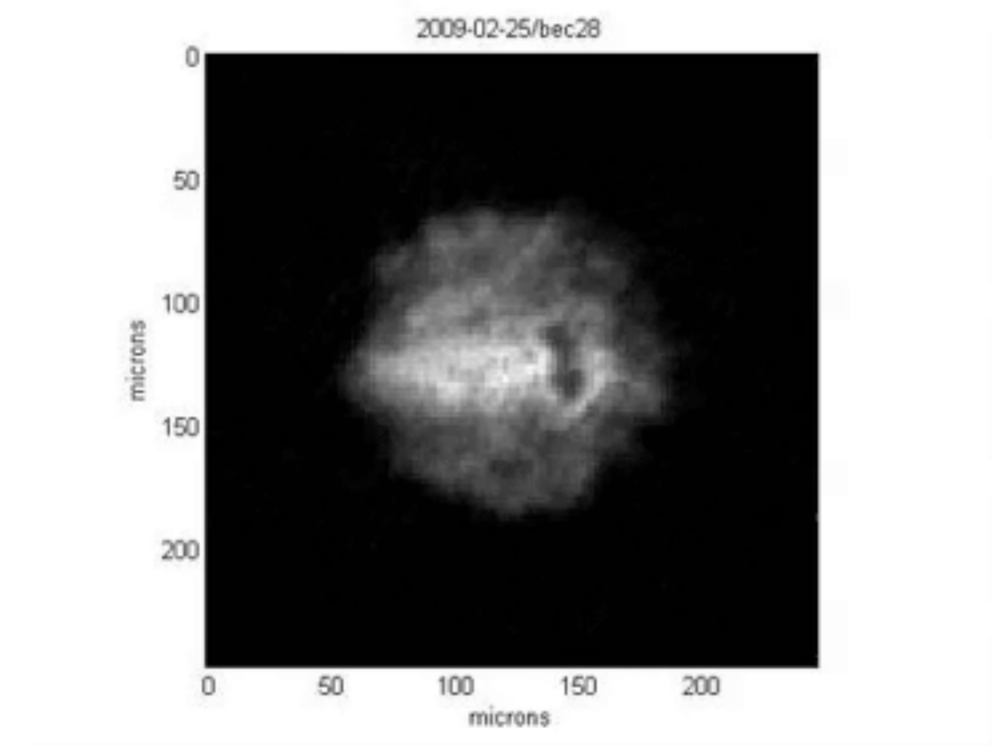
Stirring a BEC with a laser: vortices



BEC in trap (not expansion)



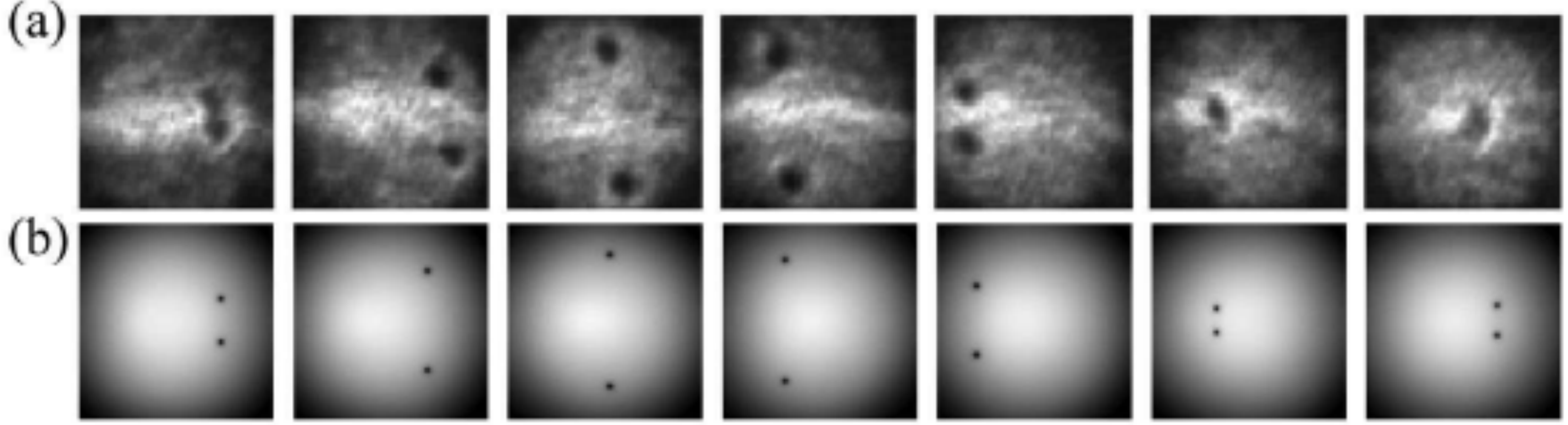
Beam swipes through BEC (left to right) forming a vortex dipole.



200 ms between images, ~1.25 sec orbital period

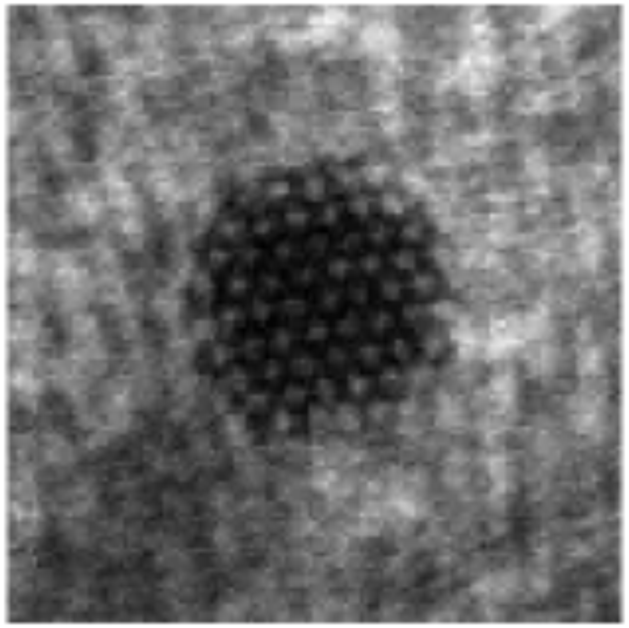
(1 orbit shown, continuous loop)

Images taken after release from trap, expansion

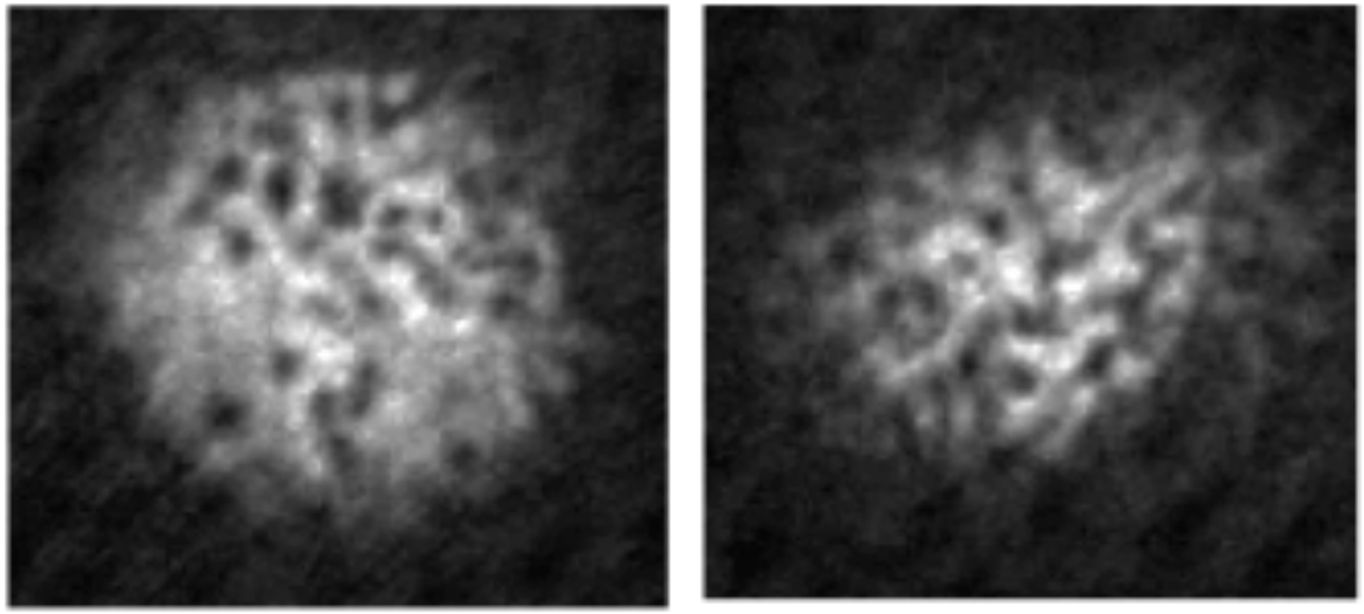


Phys. Rev. Lett. 104, 160401 (2010)
Observation of vortex dipoles in an oblate Bose-Einstein condensate
T.W. Neely, E.C. Samson, A.S. Bradley, M.J. Davis, BPA

Vortices: indicators of fluid dynamics



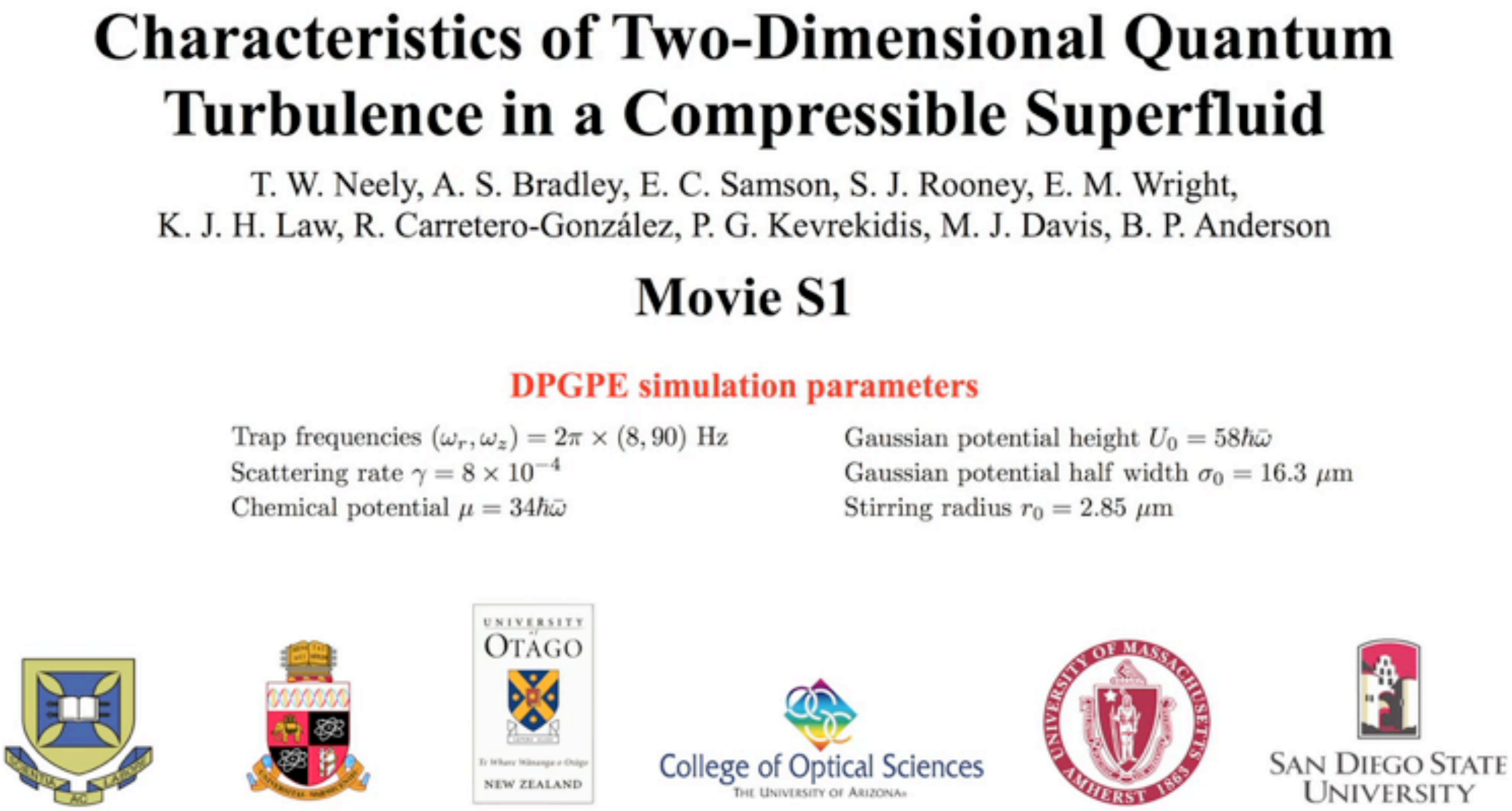
Uniformly rotating BEC



Turbulence in a BEC

> "The role of vortex structures is seen as of central importance, while a statistical approach is needed to cope with the irregularity of turbulent flow at all scales.
> **No fully satisfactory treatment combining these aspects has yet been found."**
>
> - A Voyage Through Turbulence,
> Davidson, Kaneda, Moffatt, Sreenivasan, eds.

Stirring a BEC: simulation



Characteristics of Two-Dimensional Quantum Turbulence in a Compressible Superfluid

T. W. Neely, A. S. Bradley, E. C. Samson, S. J. Rooney, E. M. Wright,
K. J. H. Law, R. Carretero-González, P. G. Kevrekidis, M. J. Davis, B. P. Anderson

Movie S1

DPGPE simulation parameters

Trap frequencies $(\omega_r, \omega_z) = 2\pi \times (8, 90)$ Hz
Scattering rate $\gamma = 8 \times 10^{-4}$
Chemical potential $\mu = 34\hbar\bar{\omega}$

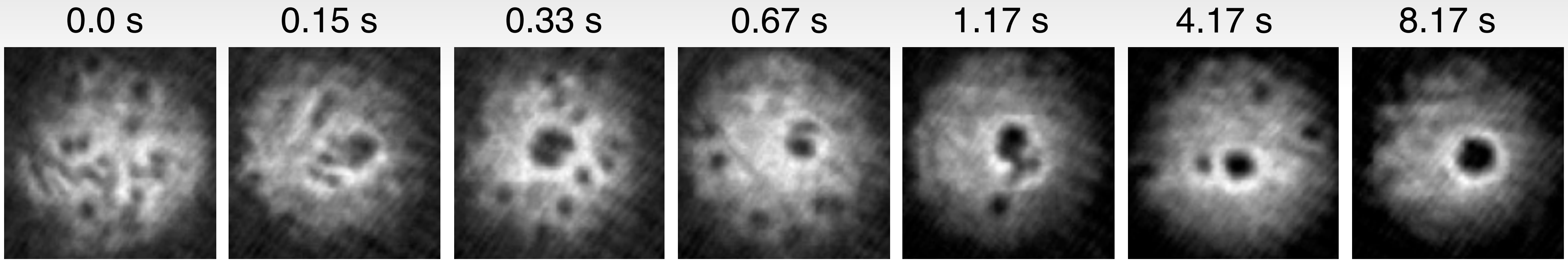
Gaussian potential height $U_0 = 58\hbar\bar{\omega}$
Gaussian potential half width $\sigma_0 = 16.3\ \mu$m
Stirring radius $r_0 = 2.85\ \mu$m

UNIVERSITY of OTAGO
NEW ZEALAND

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

SAN DIEGO STATE UNIVERSITY

Experimental results



- **Generation of 2DQT from small-scale forcing** is possible, with minimal acoustic excitation.

- **Vortices rapidly distributed** throughout system, much faster than annihilation rates.

- Vortex **decay rates are slow**, perhaps surprisingly. Might have occurred immediately.

- **Vortices remain visible**: aligned with tight axis. **2D superfluid dynamics (in a 3D system)**

- Vortices are not immediately pinned to central barrier, **large scale flow (PC) develops *after* the small-scale forcing.**

- **Temperature sensitivity**: hard to predict the outcome, only observed within a narrow range of temperatures. **Roles of dissipation, trap geometry, and stirring are all important.**

Turbulence in BECs

- **How universal is Turbulence? -** vortex turbulence in superfluids **(quantum turbulence)** shares characteristics with classical fluid turbulence, but the manifestations of vortices and fluid dynamics are substantially different. How far do the connections between classical and quantum turbulence extend?

- Why? **Wavefunction**, quantum fluid dynamics follows (nonlinear) **Schrodinger equation** (vs Navier-Stokes), **Vortices. Link turbulence to the principles of QM.**

- **BECs** enable **study and control vortices**, quantitatively accurate **numerical simulations** built from first principles of quantum mechanics. Makes BECs excellent platform for quantum turbulence studies and linking experimental, theoretical, and numerical approaches.

Come visit our BEC labs!

Rooms 566 and 572

Recent papers

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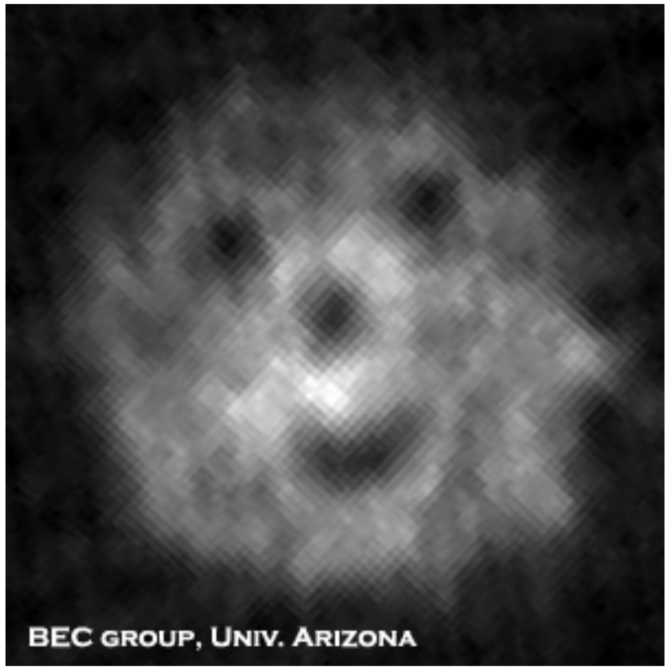

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