Research Frontiers in Atomic, Molecular & Optical (AMO) Physics

Subhadeep Gupta

Table Top Experimental Physics
all in one room, small groups (2-6)
Typ: vacuum, lasers, electronics

Traditionally – studies of atomic structure using precision (laser) spectroscopy.

Traditional techniques have started to interface with other areas in physics (mainly CM)

Today: A survey of the "frontier". Some highlights.
Focus on ultracold atoms research.
Anything you would like to ask…

UW Physics NSF-REU, 07/18/2008

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Precision Measurements	**Trapped Ions**	**Bose Gases**	**Optical Lattices**	**Mesoscopic Quantum Systems**
Atomic Clocks	**Quantum Optics and Cavity QED**	**Fermi Gases**	**Cold Molecules**	**Ultrafast Phenomena**
Quantum Information	**Hot Topics I**	**Excursions**	**Hot Topics II**	**Lab Tours**

Wikipedia:

Atomic physics (or atom physics) is the field of physics that studies atoms as an isolated system of electrons and an atomic nucleus. It is primarily concerned with the arrangement of electrons around the nucleus and the processes by which these arrangements change.

This includes ions as well as neutral atoms and, unless otherwise stated, for the purposes of this discussion it should be assumed that the term *atom* includes ions. As with many scientific fields, strict delineation can be highly contrived and atomic physics is often considered in the wider context of *atomic, molecular, and optical physics*.
Physics research groups are usually so classified.

Do not believe everything that's in Wikipedia!

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External degrees of freedom:
position, momentum, trapping, many-body

Strong controllable interactions between atoms

Strong controllable interactions between atoms and photons/Quantum Optics

Quantum Information Science

Other New stuff

UW Atomic Physics

Elementary Particle Theory – tested with atoms

Hans Dehmelt (Nobel, '89)
Norval Fortson
Blayne Heckel
Tom Loftus

e-, e+, g-2, QED
At. PNC Tl EW Z0 boson
At. EDM Hg SUSY etc.

Optical Atomic Clocks

Warren Nagourney

Ba+, In+
Variations in α
(fine structure 'constant')

Quantum Information

Boris Blinov

Ba+

Ultracold Atoms/ Quantum Gases

Deep Gupta

Li, Yb (started Sep 2007)

Precision Mass Measurements

Bob Van Dyck

m(^{3}H-^{3}He)

Single Ion Detection

2001 Hg EDM search (new one underway!)

Result:

$[-10.6 \pm 4.9_{stat.} \pm 4.0_{syst.}] \times 10^{-29}$ *e* cm

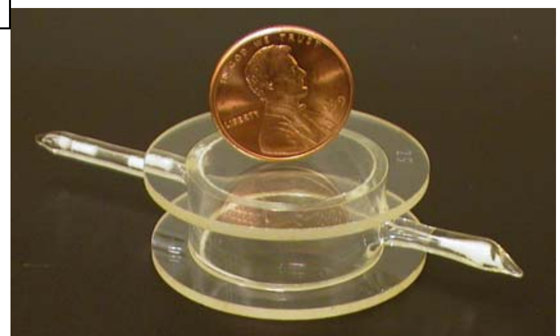
d(^{199}Hg) < 2.1 x 10^{-28} *e* cm

Romalis, Griffith, Jacobs, Fortson

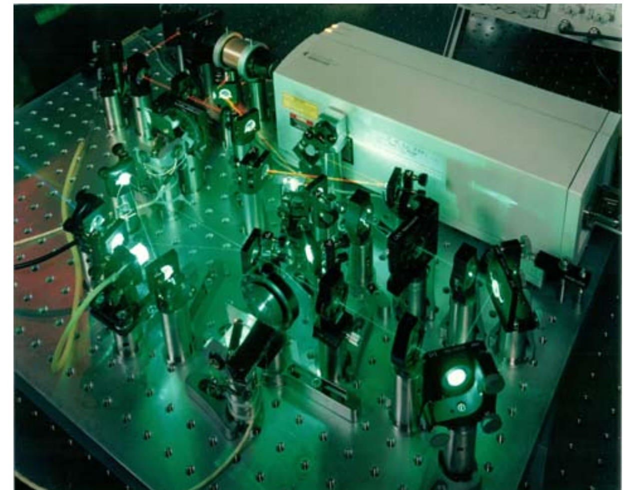
Frequency uncertainty = 1 nHz

~ 80 days data

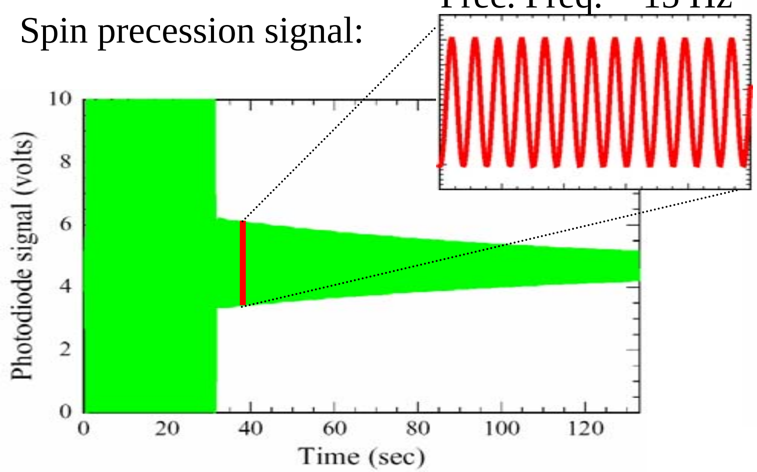
Vapor cells:
10^{14} Hg atoms
Coherence time 200 sec
Wall resistance > 10^{16} Ω

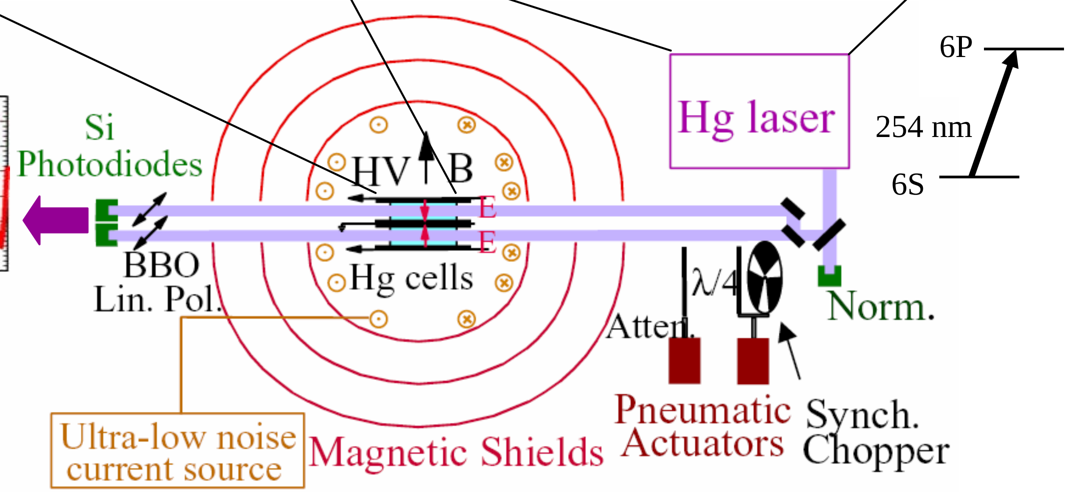


6mW, 254 nm laser from quadrupled 1016 diode:



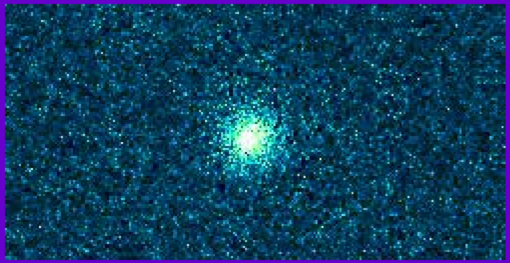
Spin precession signal:



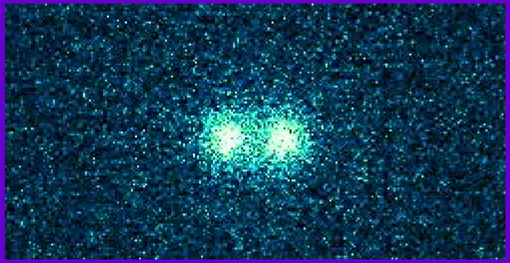


Trapped ions = qubits

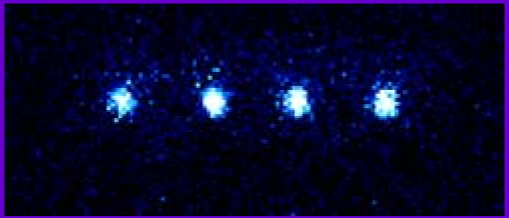
Individual ions suspended in free space



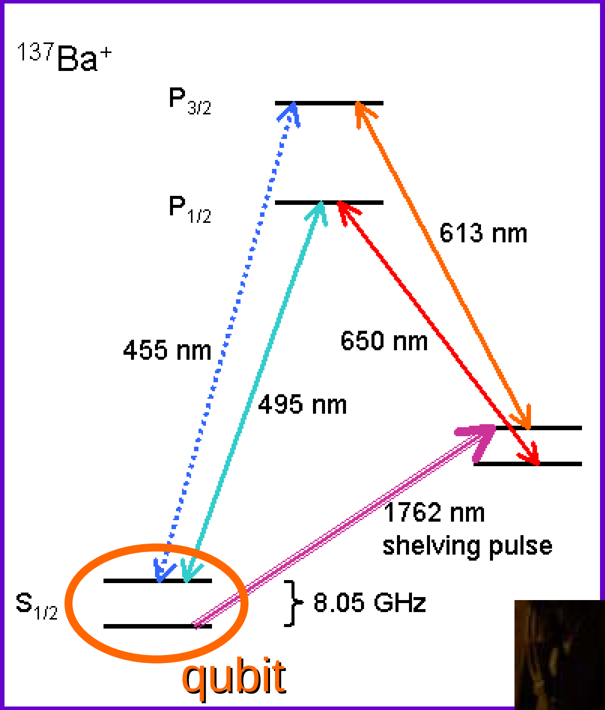
1 qubit

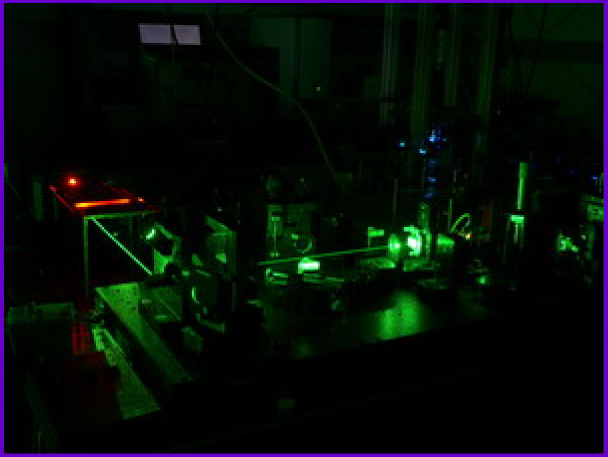


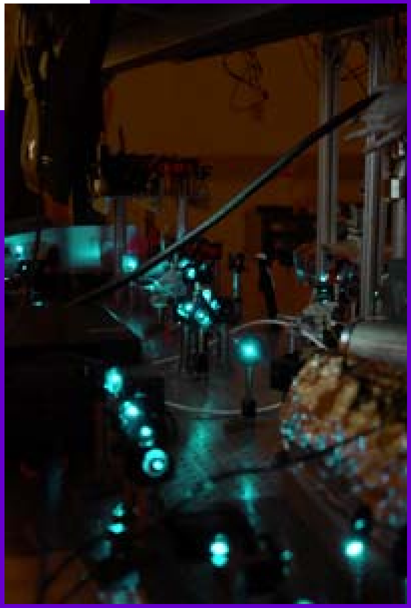
2 qubits

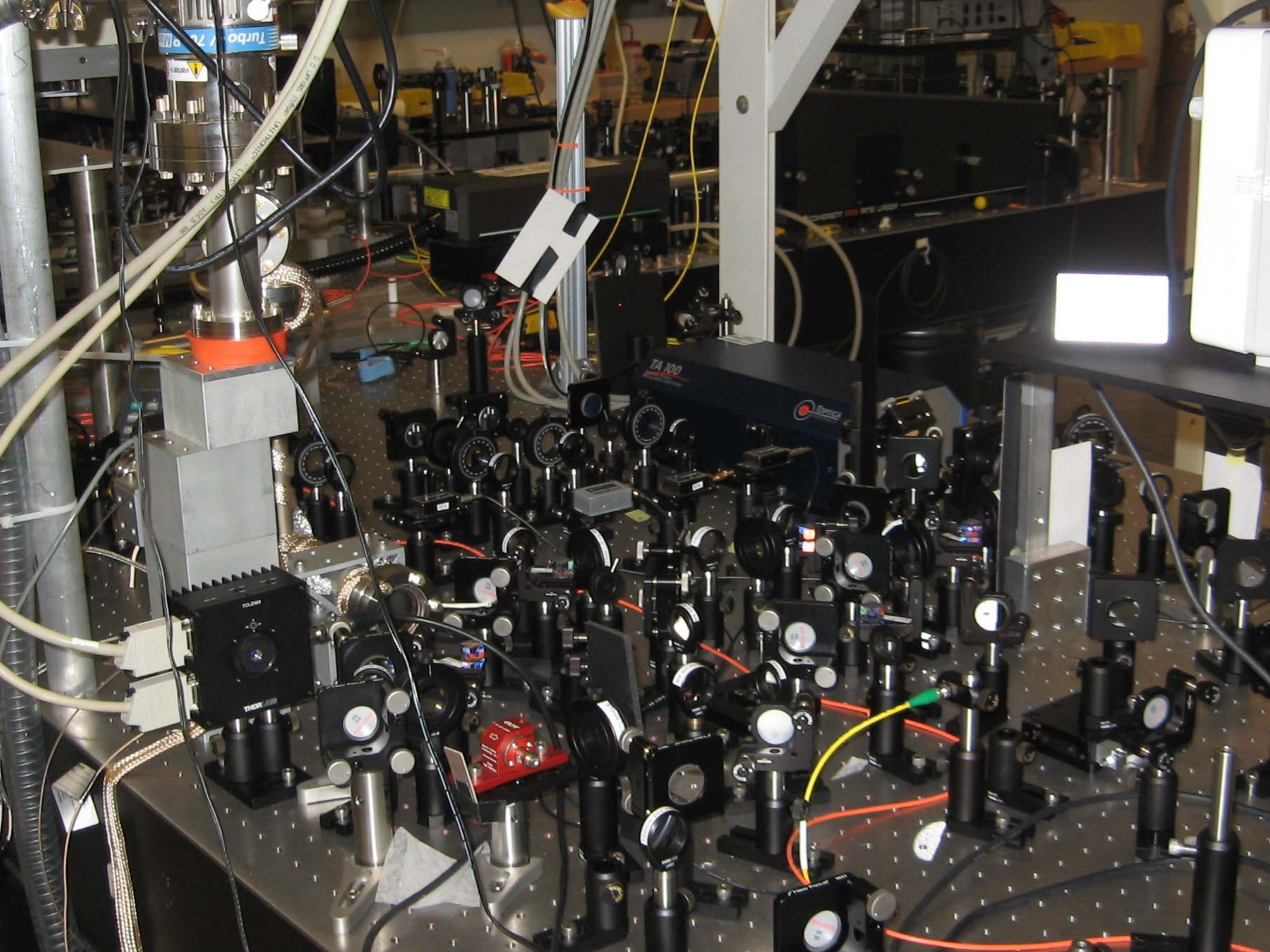


4 qubits

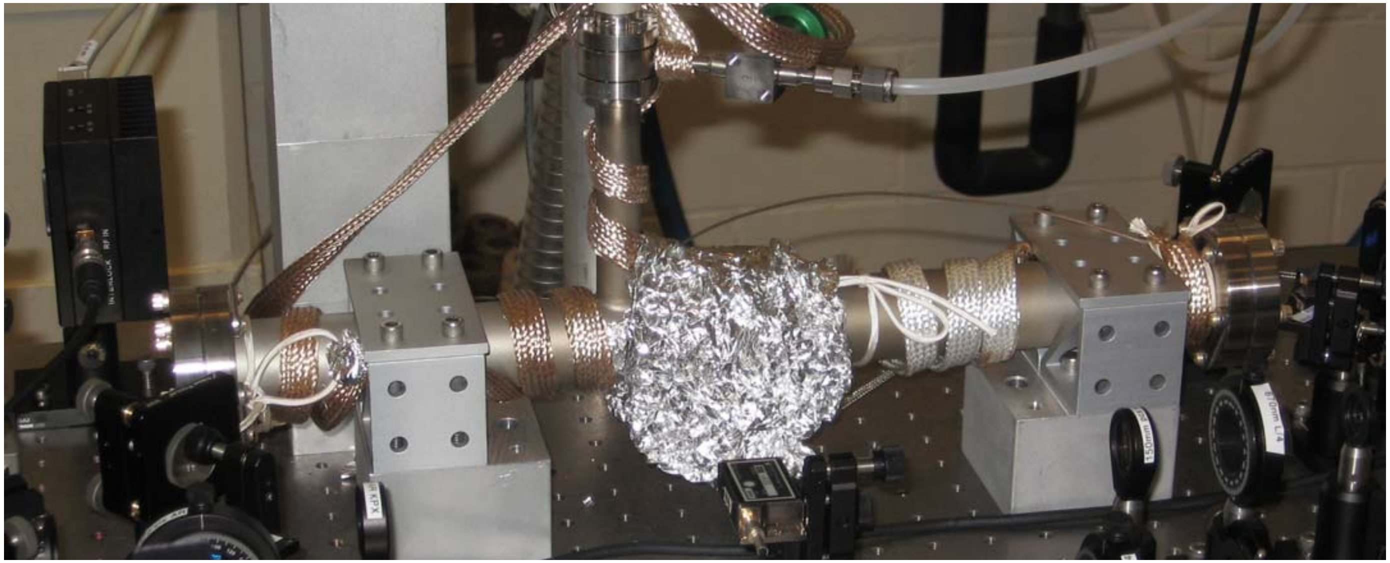


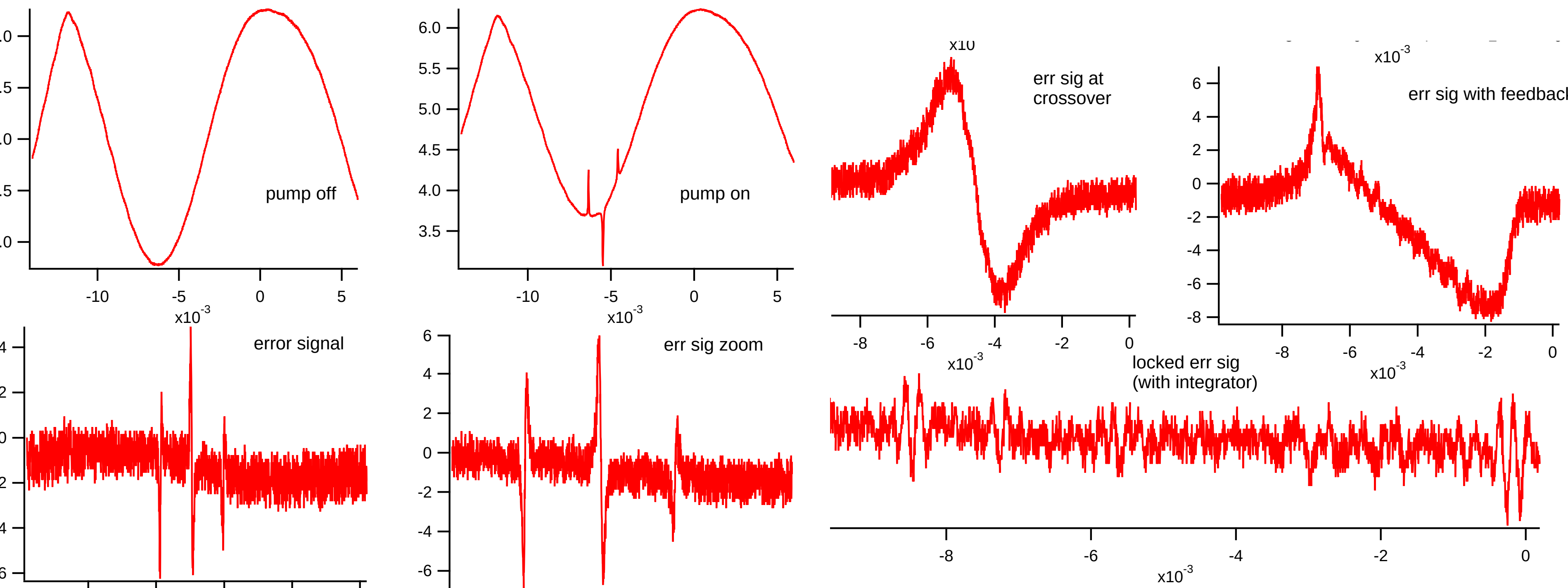





TA 100

Example table-top project: Saturated Absorption Laser Spectrocsopy





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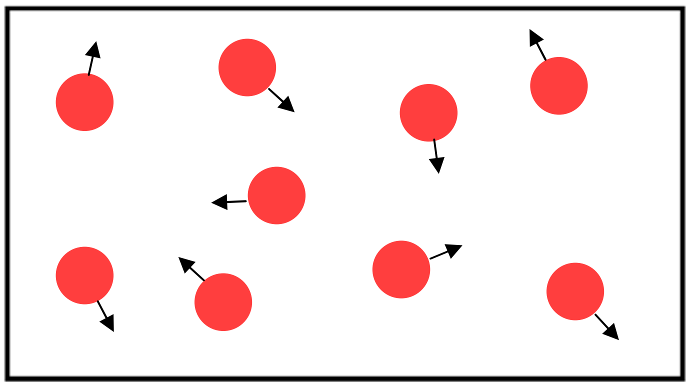
Quantum Degeneracy in a gas of atoms

1 atom per quantum state



N atoms
V volume
T temperature

$(\Delta x)^3 \sim V$ $\qquad$ $(\Delta p)^3 \sim (m\, k_B\, T)^{3/2}$

$$\text{Number of atoms} = \frac{\text{(available position space) (available momentum space)}}{\hbar^3}$$

Quantum Phase Space Density

$$\frac{n\,\hbar^3}{(m\, k_B\, T)^{3/2}} \sim 1 \qquad (n=N/V)$$

Air $n \sim 10^{19}/\text{cm}^3$, $T_c \sim 1\text{mK}$
Stuff $n \sim 10^{22}/\text{cm}^3$, $T_c \sim 0.1\text{K}$
Everything (except He) is solid

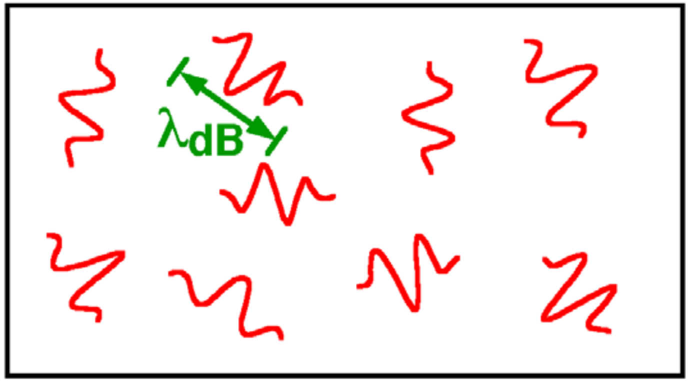
Dilute metastable gases $n \sim 10^{14}/\text{cm}^3$

$T_c \sim 1\mu\text{K}$!! Ultracold !!

and ~ non-interacting

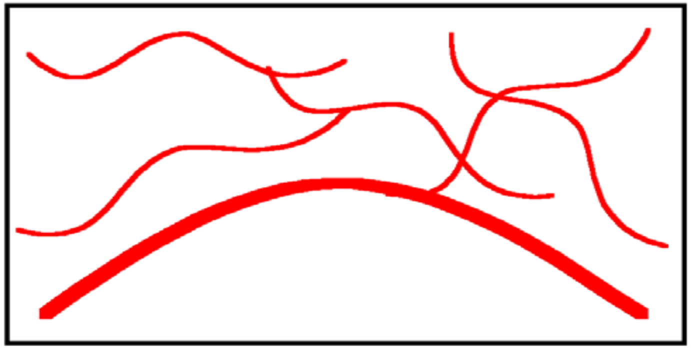
Bose-Einstein Condensation (BEC)

$$\lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}} \quad n = \frac{N}{V}$$

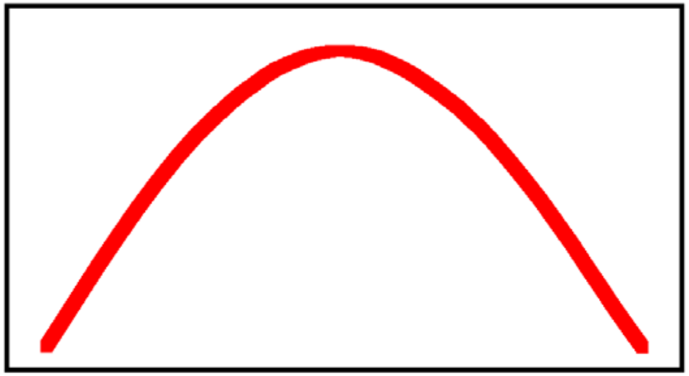


$$n\lambda_{dB}^3 << 1$$

Quantum Phase Space Density

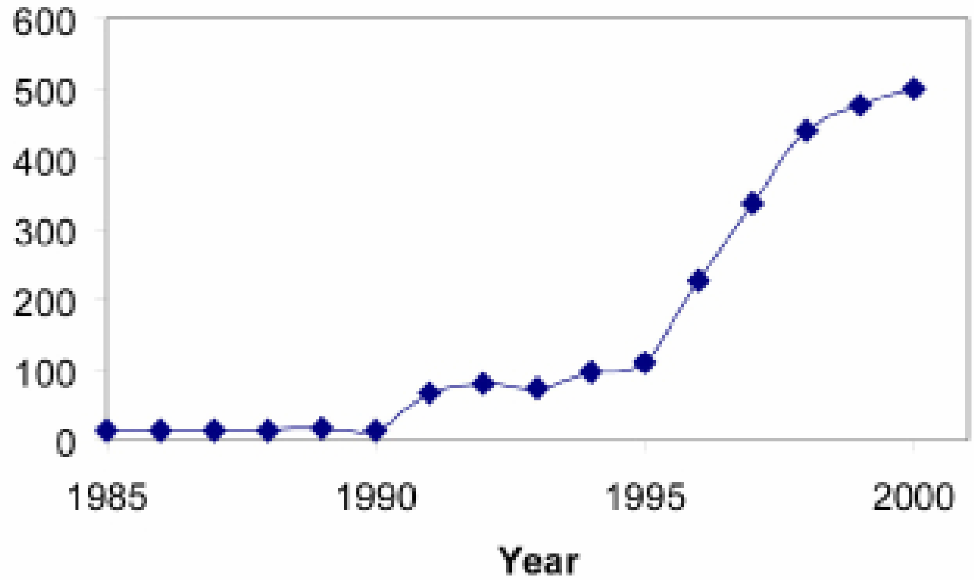


$$n\lambda_{dB}^3 \sim 1$$



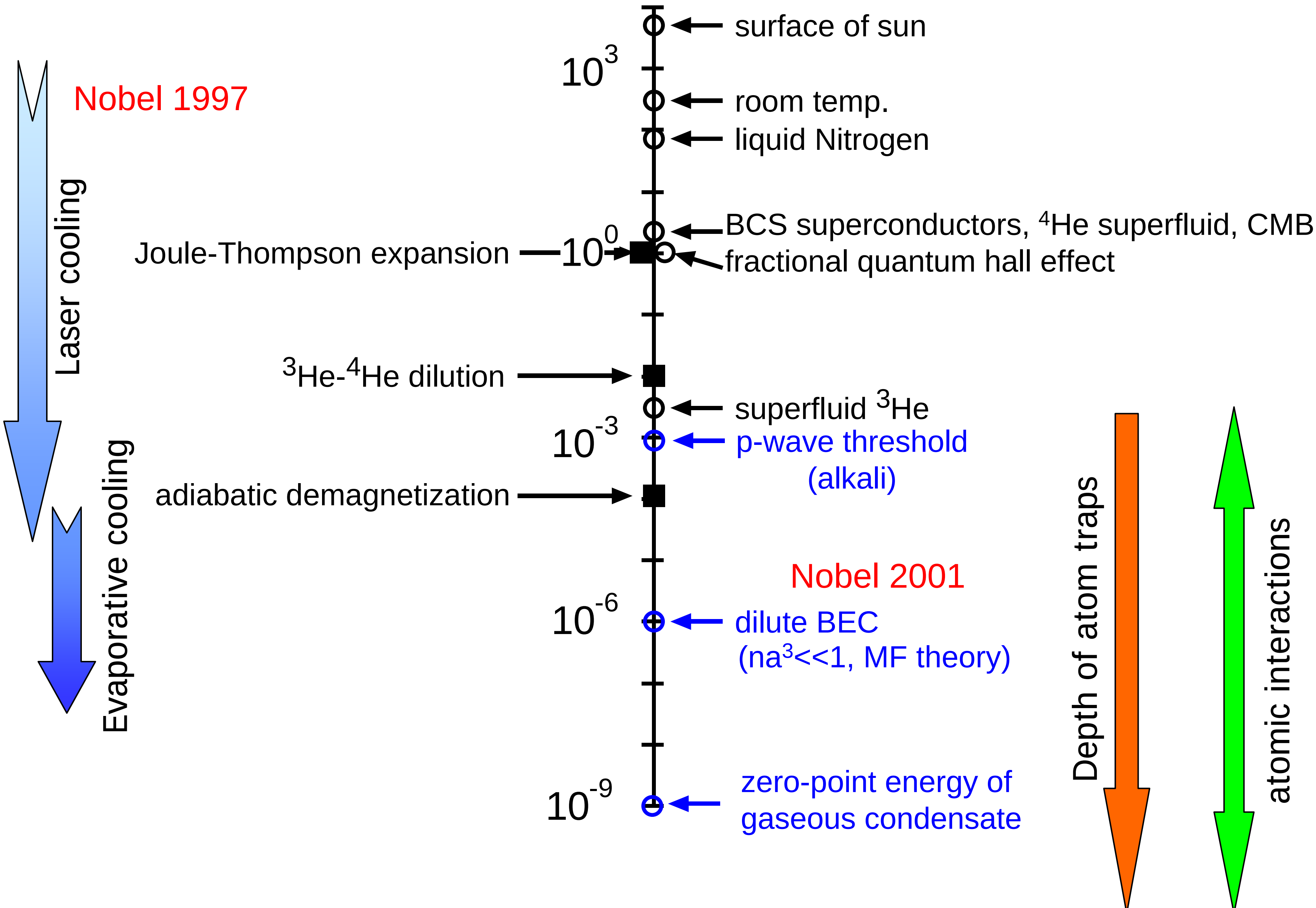
$$n\lambda_{dB}^3 >> 1$$


American Association for the Advancement of Science
Science
22 December 1995
$7.00
Vol. 270 • Pages 1893–2064
Molecule of the Year
the Bose-Einstein Condensate



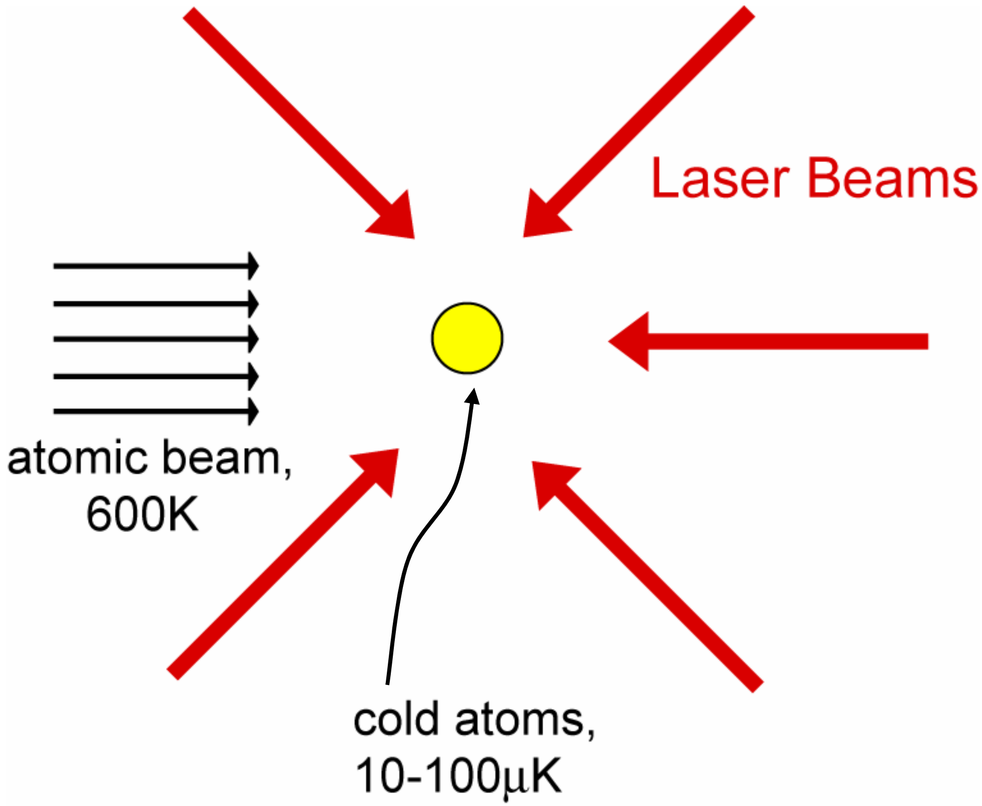
Annual number of published papers, which have the words "Bose" and "Einstein" in their title, abstracts or keywords (ISI database). Reported at APS meeting of the Division of Atomic, Molecular, and Optical Physics.

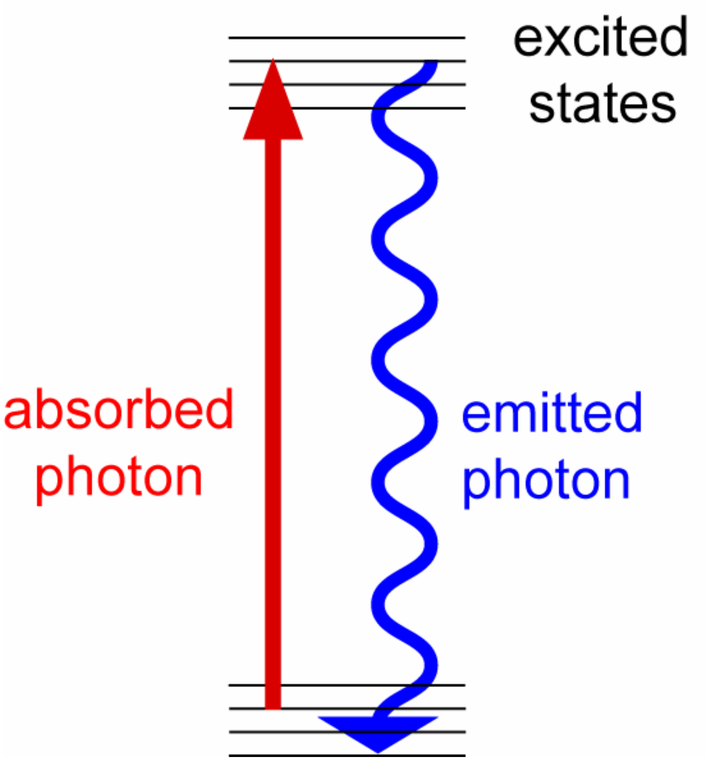
ABSOLUTE TEMPERATURE (log Kelvin scale)



Laser Cooling ???

Laser Cooling ???



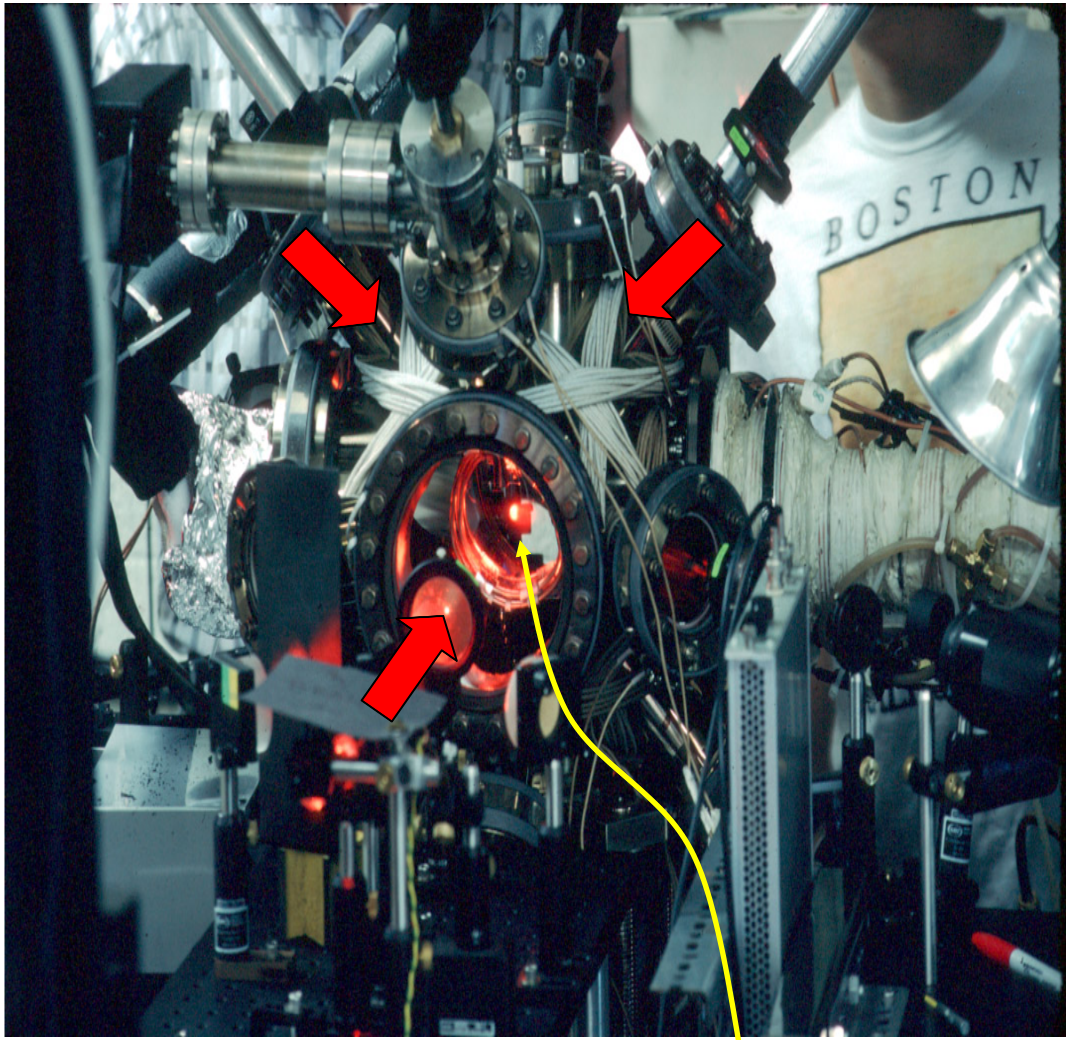


Energy gained < energy lost

=> COOLING !

Utilizing atomic internal degrees of freedom → Alkalis are really nice

Laser Cooling !!!

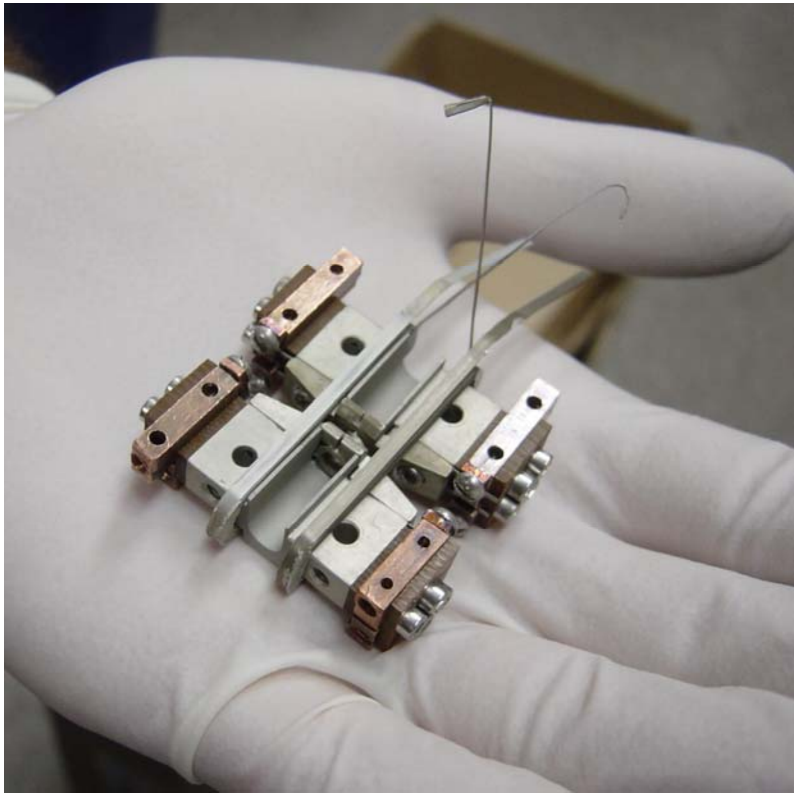


100μK

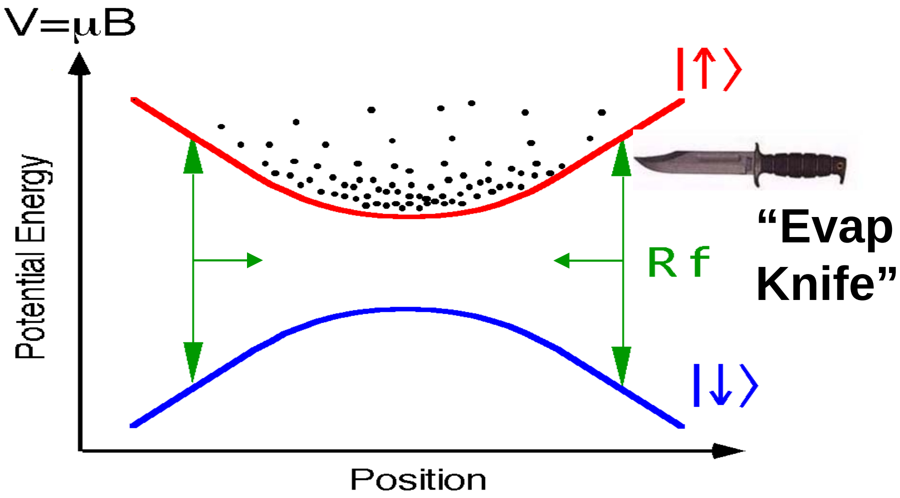
Magneto-Optic Trap (MOT)

But the room is at 300K (!)

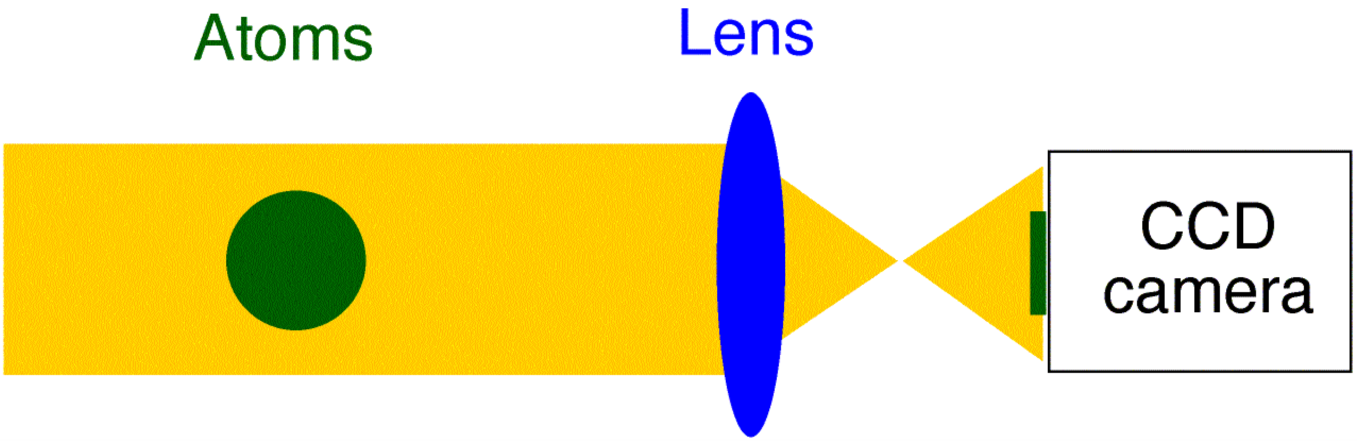
Evaporative Cooling



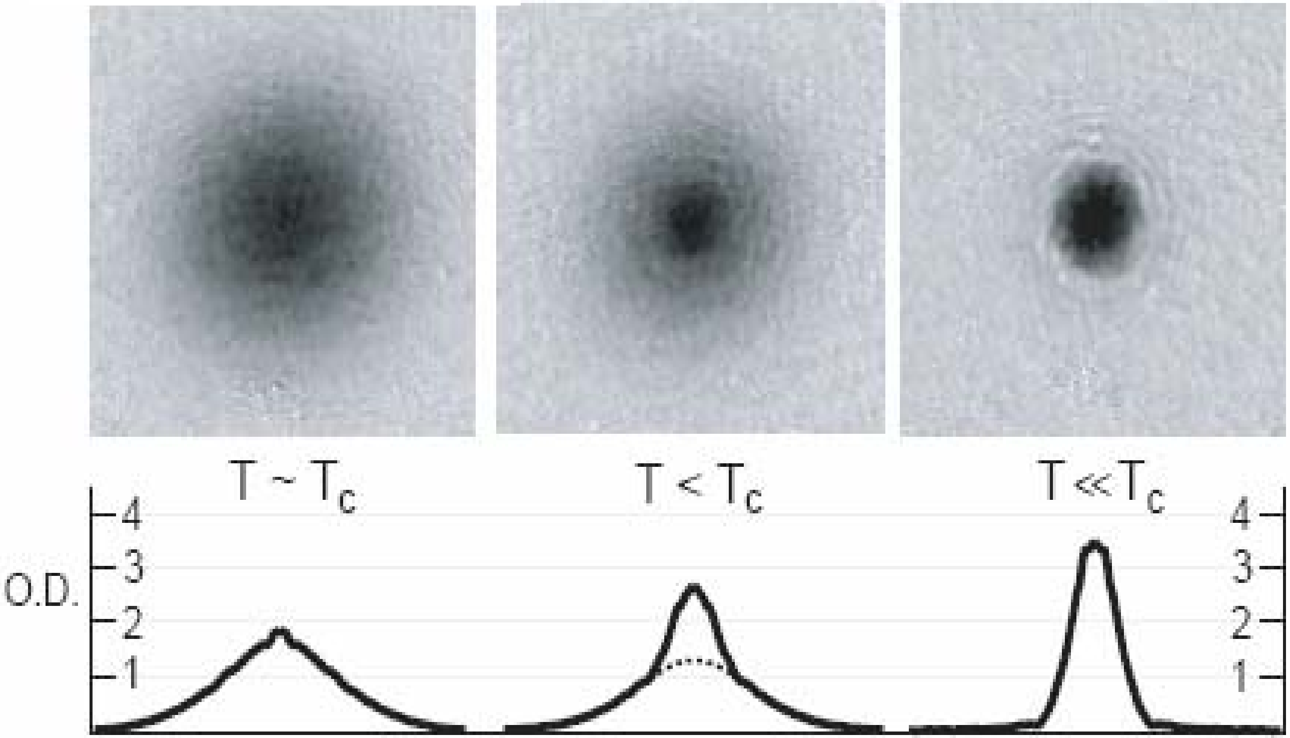
Magnetic field from current
carrying wires produce
harmonic confinement
for "weak-field seekers"

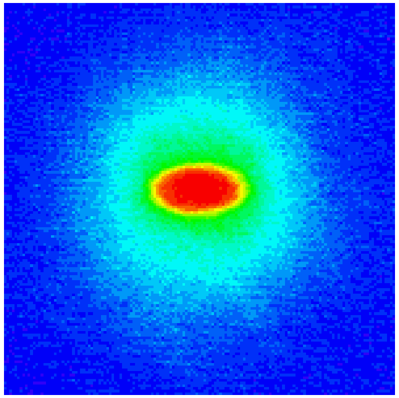


Imaging the Atoms

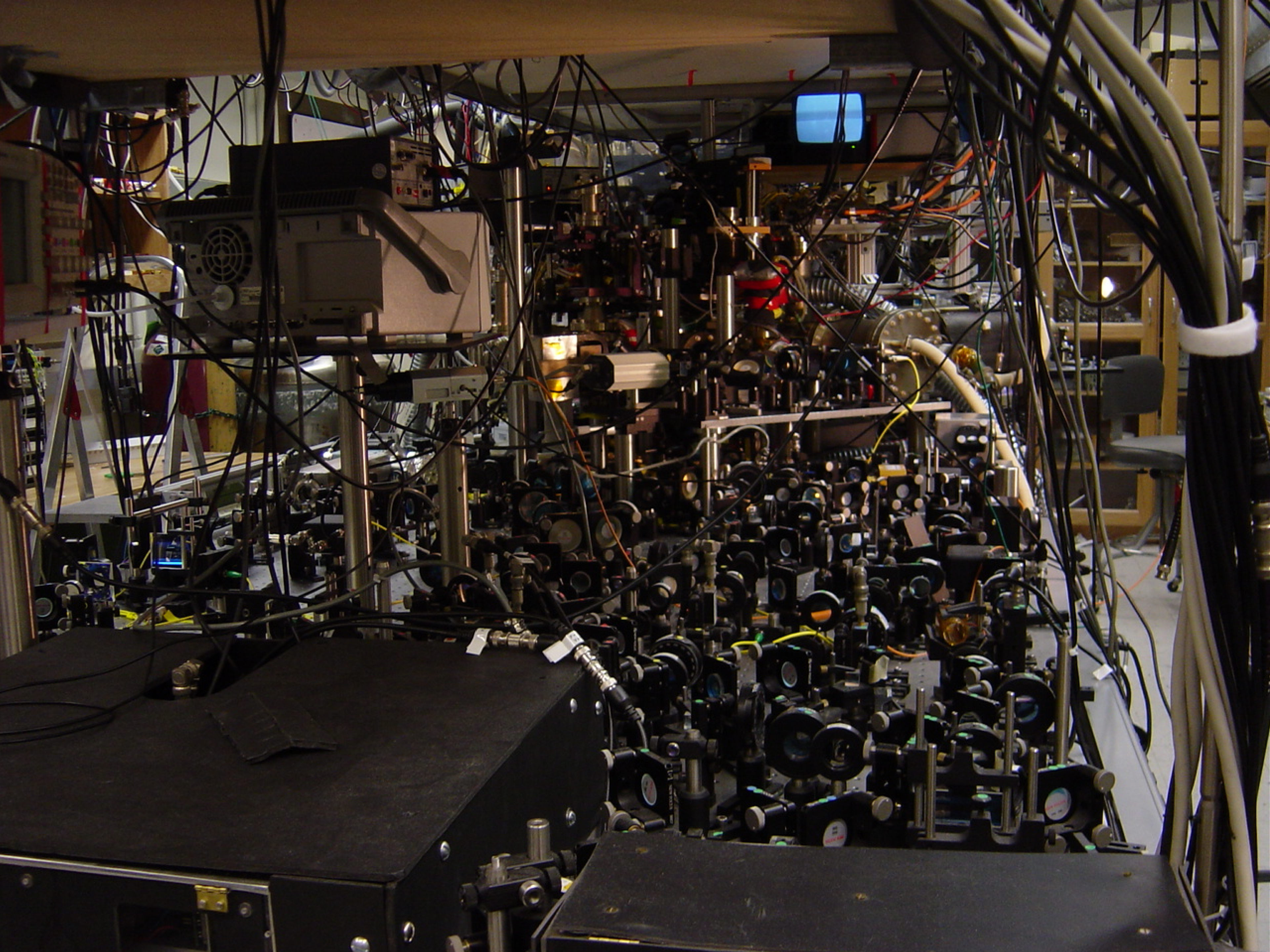


Pulsed atom laser
10^6 atoms/minute





“false color”



Quantum Engineering of Model Systems

Quantum gases as a system to test "old" and realize "new" condensed matter physics

• Density, temperature 100 millions times lower than regular

$\Rightarrow$ Accurate calculations possible

$\Rightarrow$ Can complicate the system in a controllable manner

Using e-m fields, can control (relatively) easily

Temperature & density

Dimensionality

Crystal structure – lattices

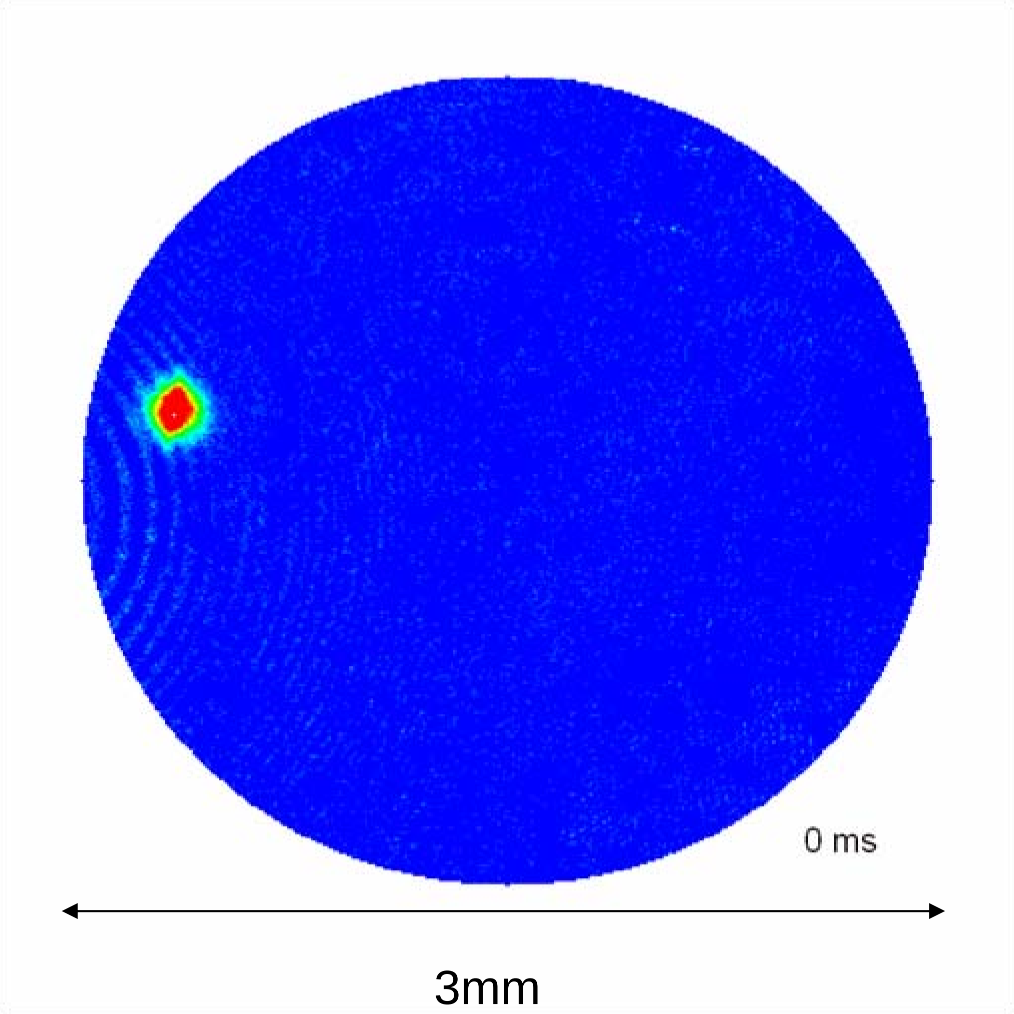
Magnetization

Magnitude & sign of the "charge"

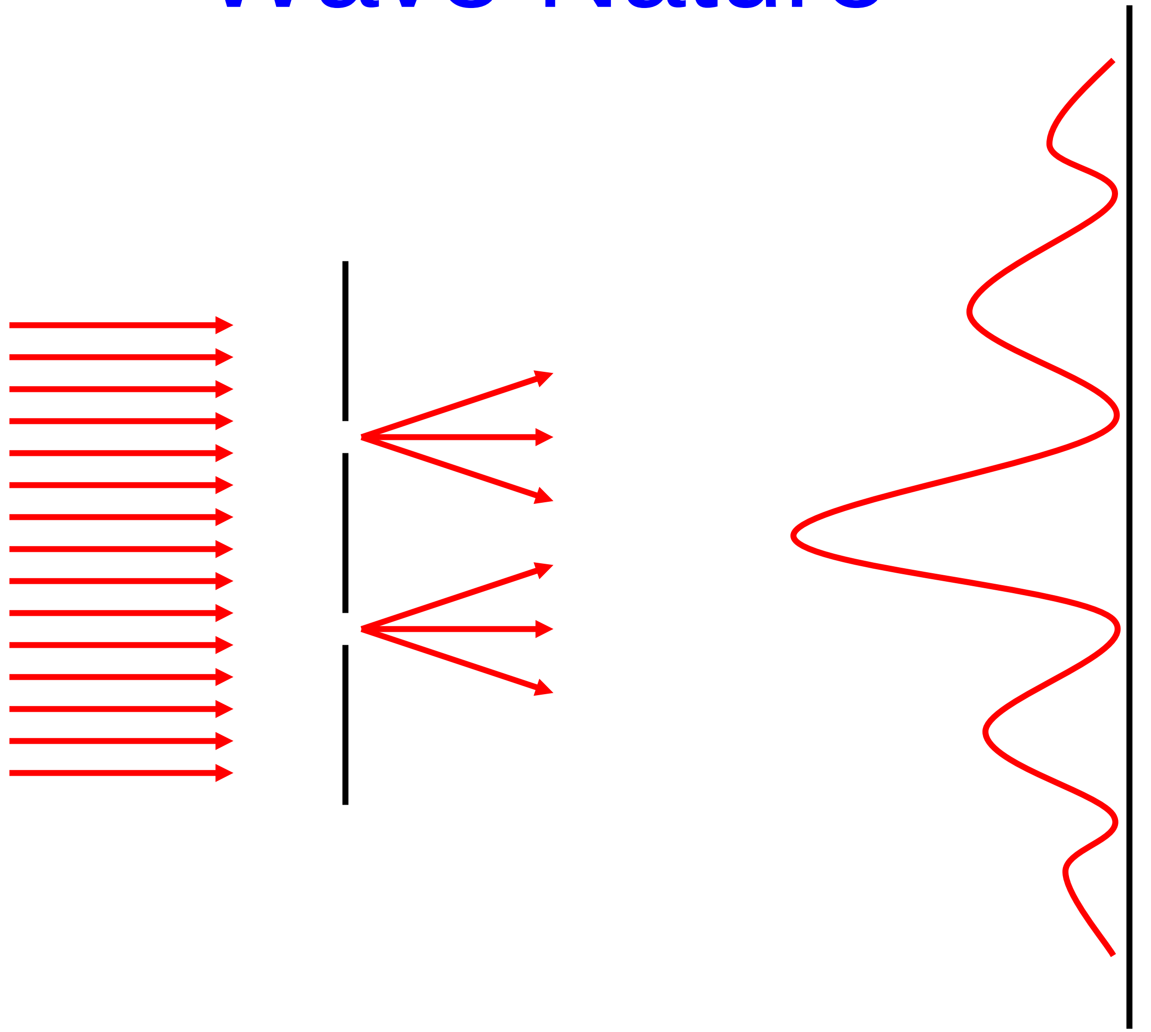
Chemical structure – form molecules

Can completely isolate single particles in "optical lattice" sites for interaction free studies

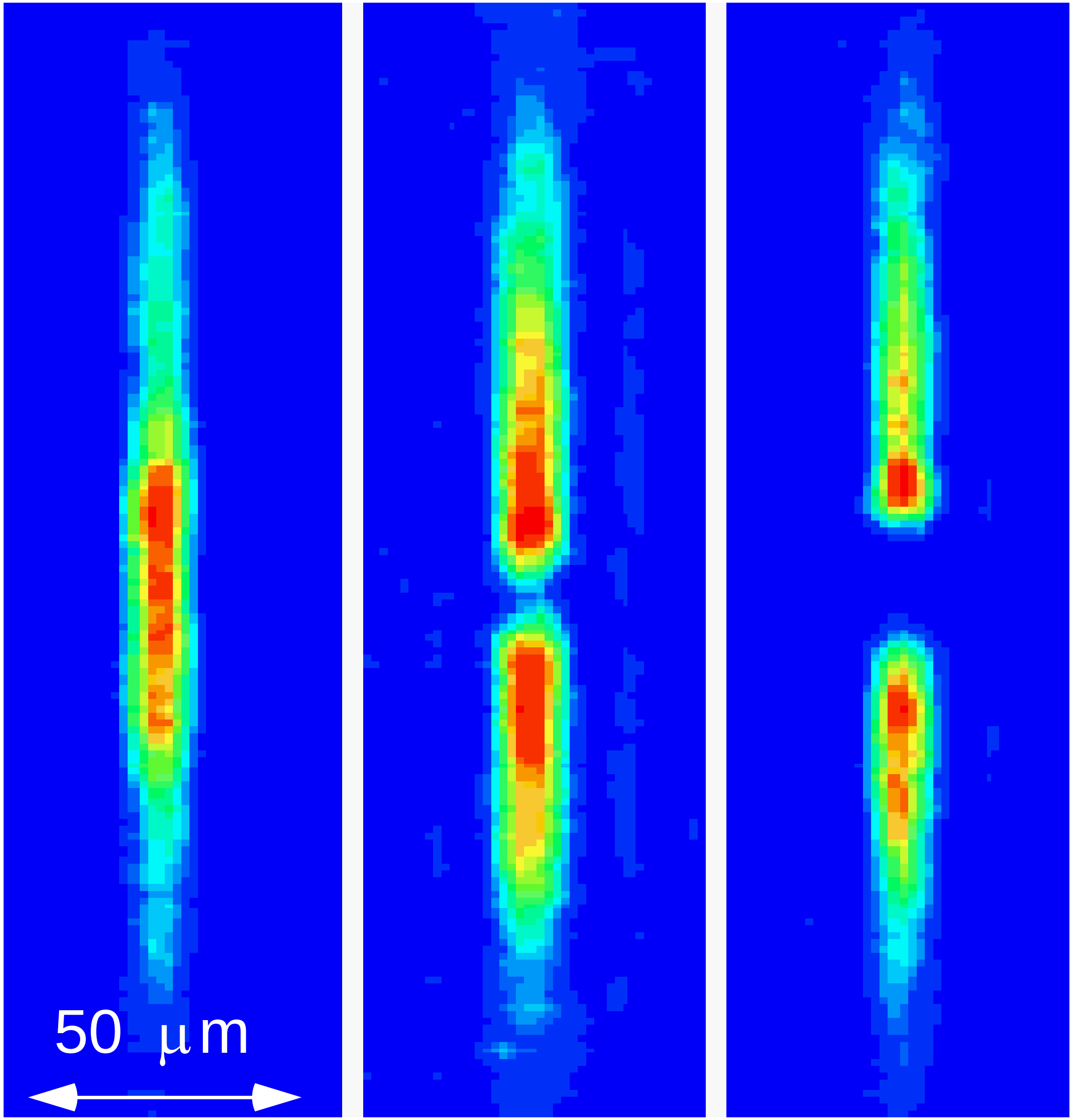
Example: Circular Waveguide for a BEC



Wave Nature



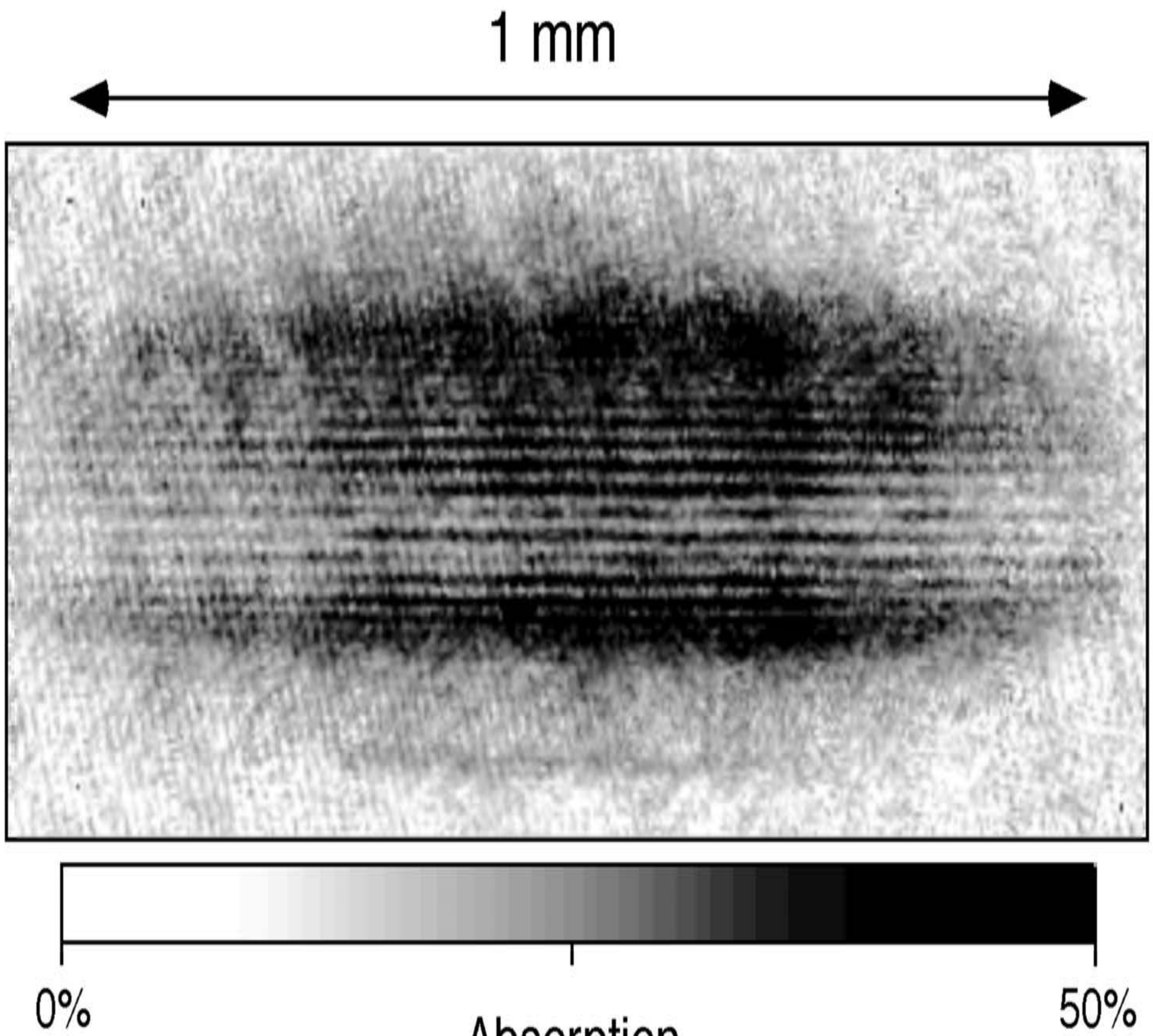
Young's double slit experiment



Cut one BEC, get 2 !

Then let them expand and overlap

Macroscopic matter wave interference

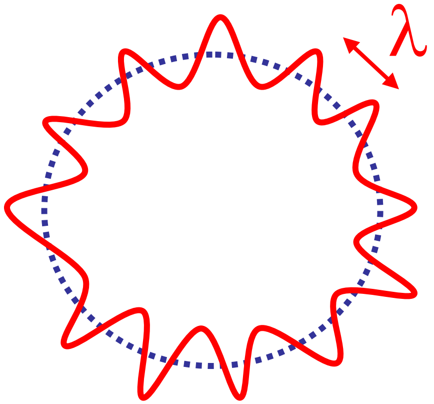


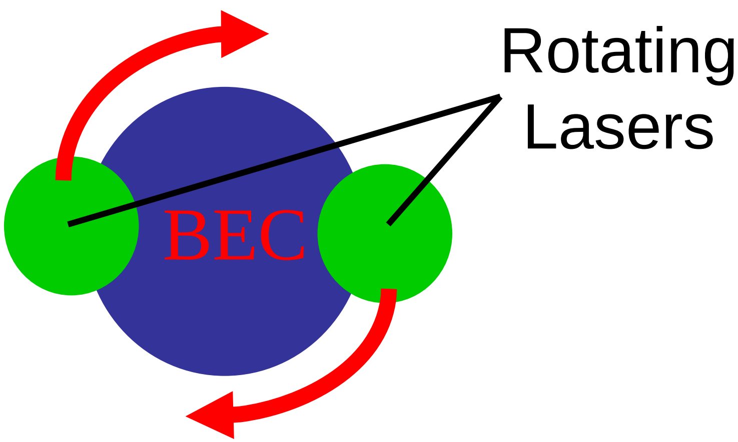
Rotating a SUPERfluid

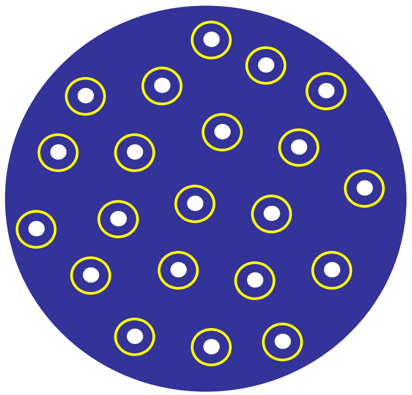
$$\lambda = h/mv \text{ (de Broglie)}$$

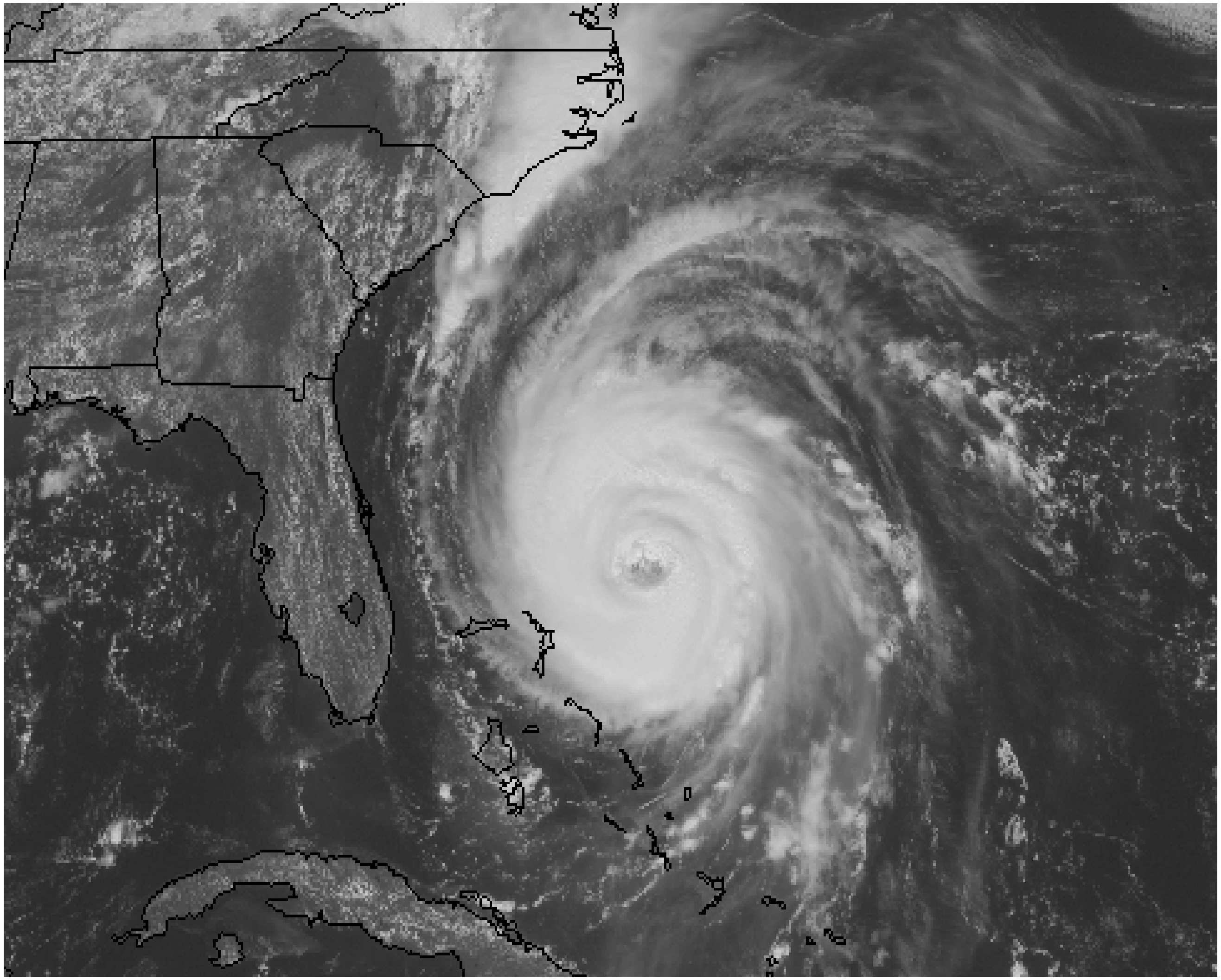
$$2\pi r = n*\lambda$$

$$v*2\pi r = n*h/m$$

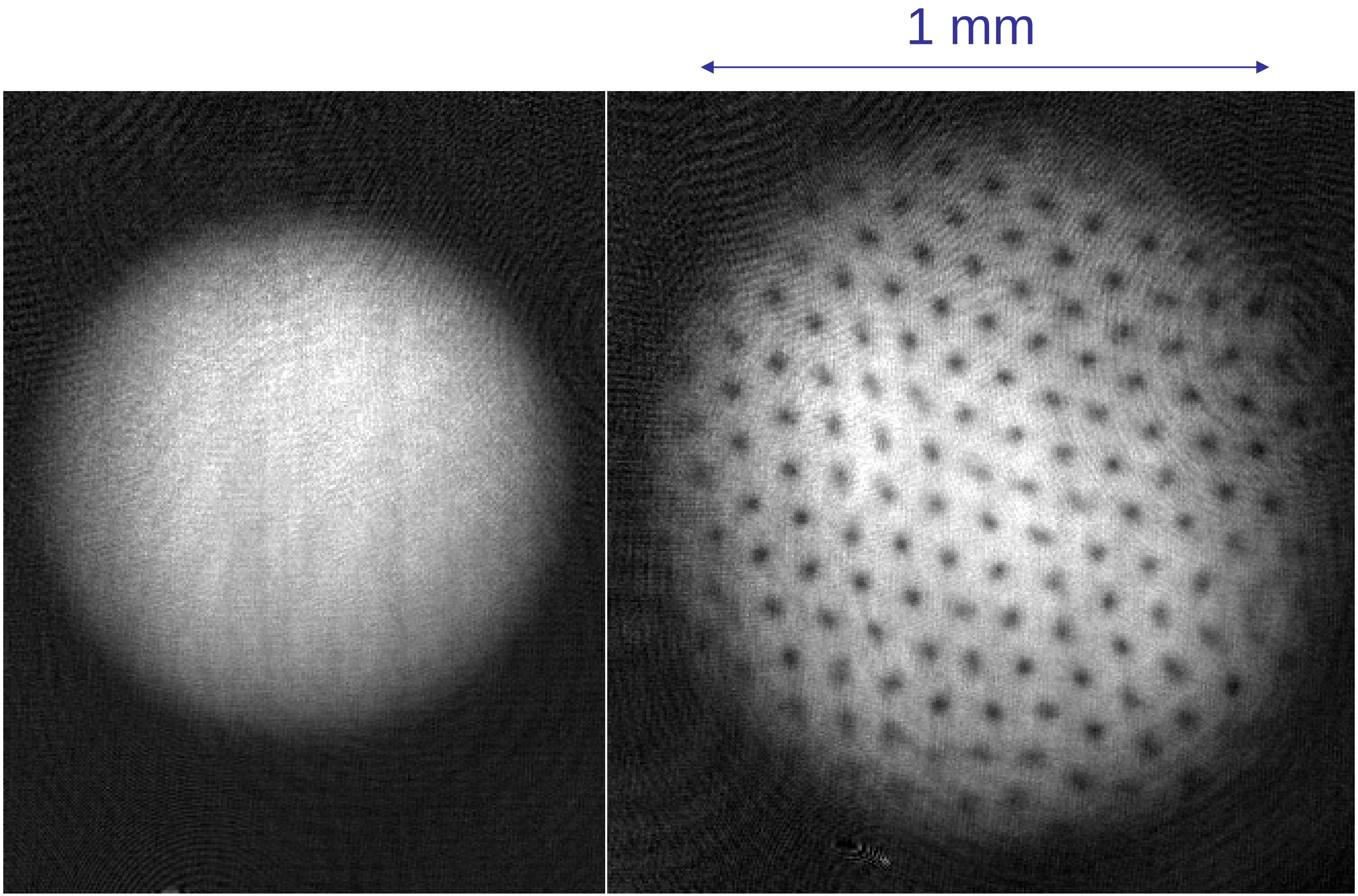








Rotation of a BEC

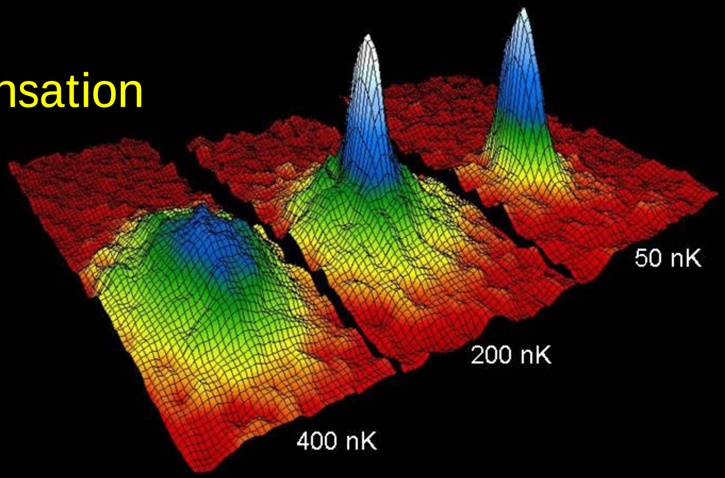


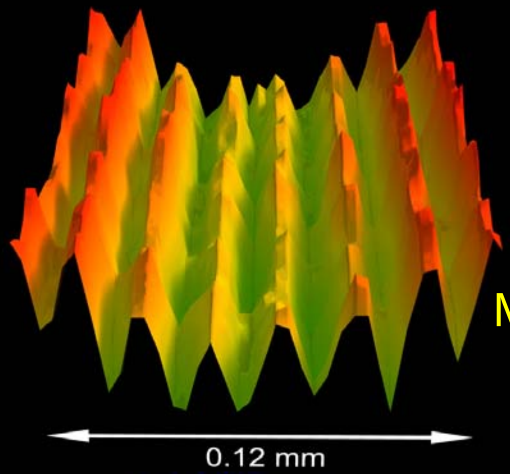
No Rotation

Rotation applied (~160 vortices)

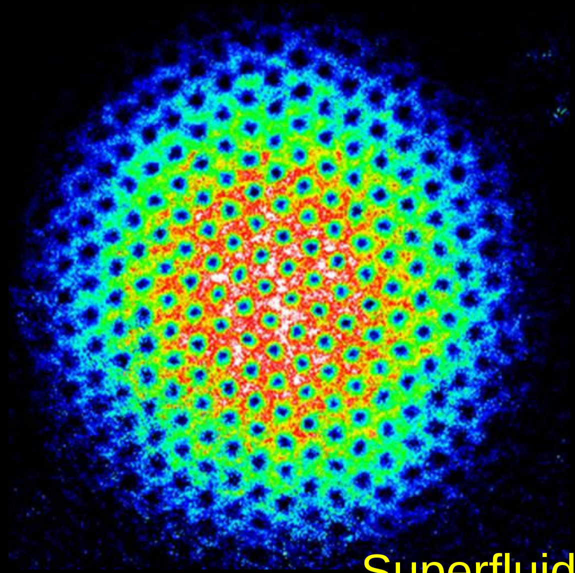
Landmark achievements in ultracold atomic physics

Bose-Einstein condensation
(JILA, MIT, Rice....)



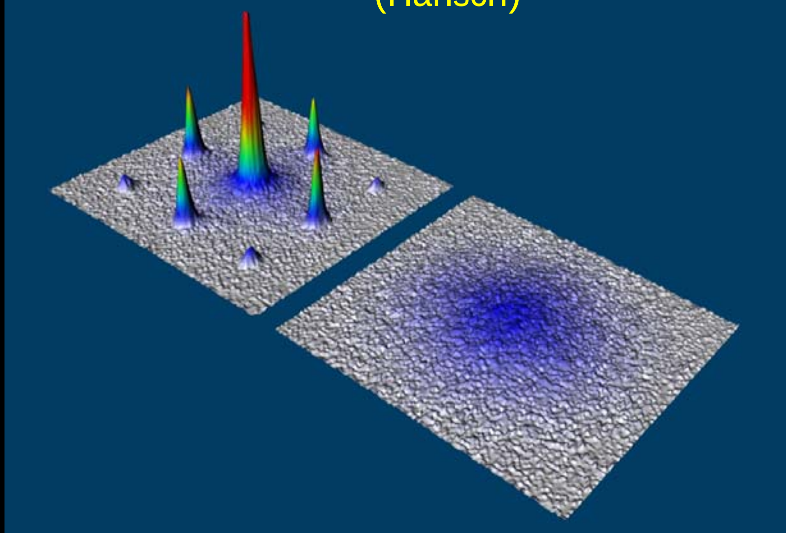


Macroscopic coherence
(Ketterle)

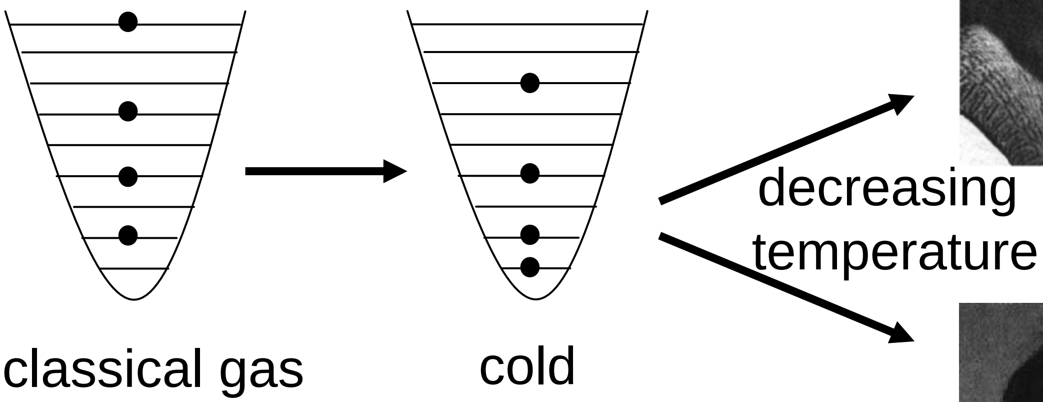


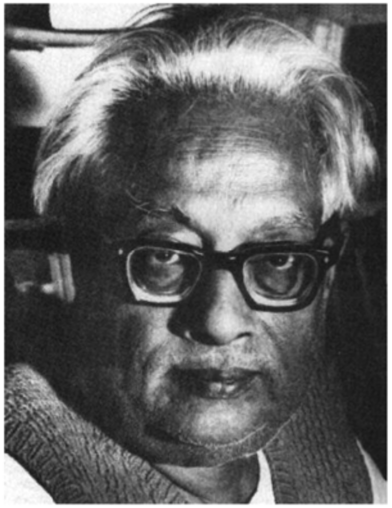
Superfluidity / observation
and study of a vortex lattice
(Dalibard, Ketterle, Cornell)

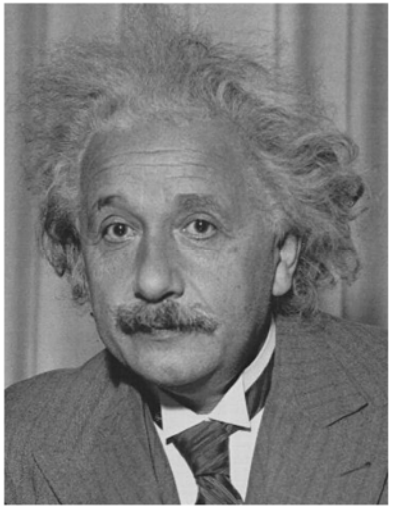
Superfluid to Mott-insulator
quantum phase transition
(Hansch)

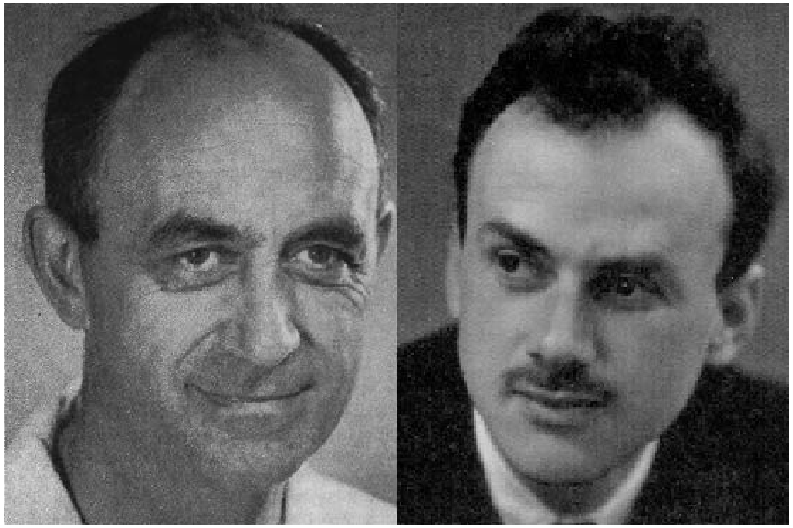


Different Quantum Matters

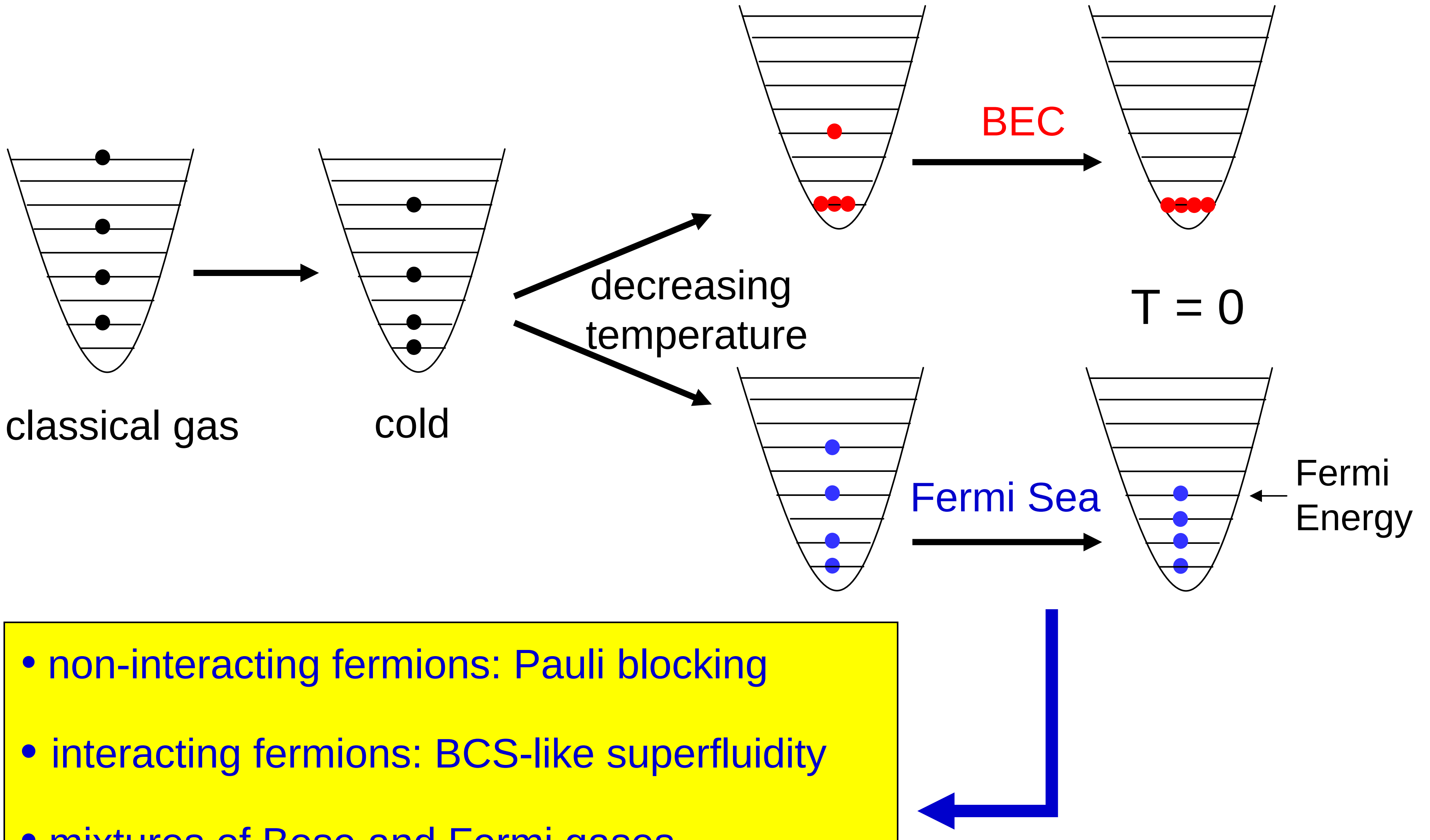




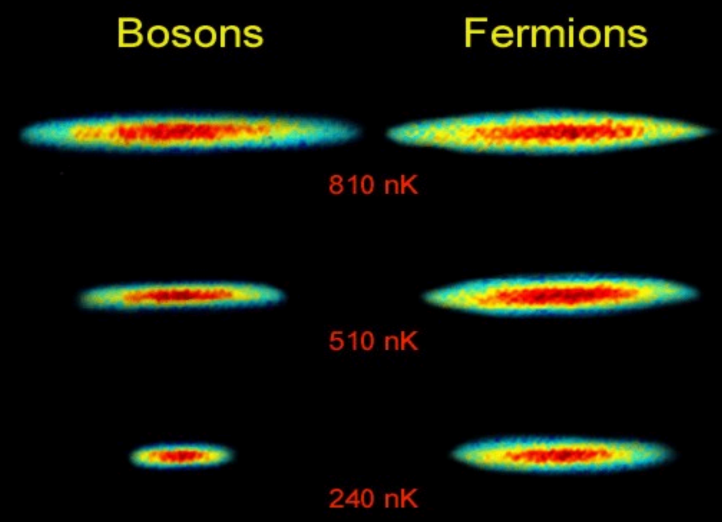




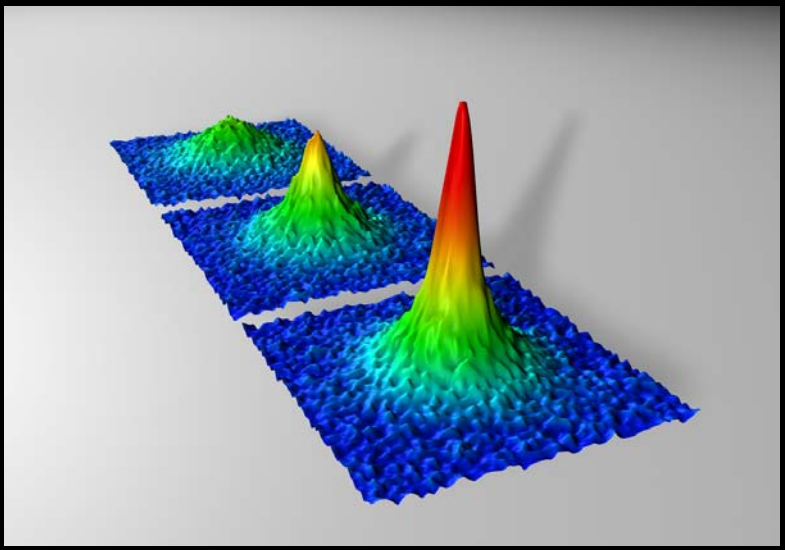
Different Quantum Matters



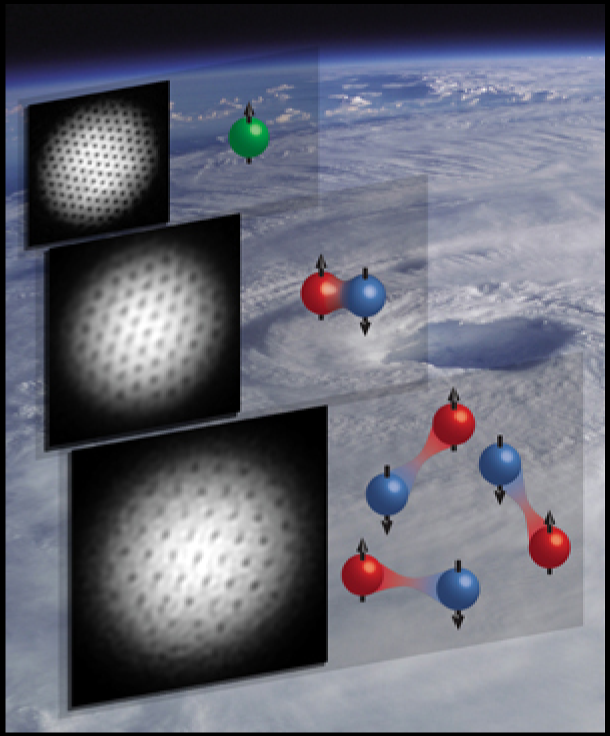
- non-interacting fermions: Pauli blocking
- interacting fermions: BCS-like superfluidity
- mixtures of Bose and Fermi gases



Degenerate Fermi gas



Molecular Bose-Einstein condensate



Superfluidity of Fermi pairs

(Jin, Hulet, Ketterle, Grimm)

Choice of Atoms

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

* Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* * Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Choice of Ultracold Atoms

hydrogen 1 H 1.0079																		**helium 2 He 4.0026**
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	**neon 10 Ne 20.180**
sodium 11 Na 22.990	**magnesium 12 Mg 24.305**												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	**argon 18 Ar 39.948**
potassium 19 K 39.098	**calcium 20 Ca 40.078**		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	**chromium 24 Cr 51.996**	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	**krypton 36 Kr 83.80**
rubidium 37 Rb 85.468	**strontium 38 Sr 87.62**		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	**xenon 54 Xe 131.29**
caesium 55 Cs 132.91	**barium 56 Ba 137.33**	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	**radium 88 Ra [226]**	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

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Nobel Prizes in AMO Physics

2005 – Glauber, Hall, Hansch

2001 – Cornell, Ketterle, Wieman

1997 – Chu, Phillips, Cohen-Tannoudji

1989 – Dehmelt, Paul, Ramsey

1981 – Schawlow, Bloembergen

1966 – Kastler

1964 – Townes, Basov, Prokhorov

1955 – Lamb, Kusch

1944 – Rabi

Improved spectroscopy
- Frequency combs

Study and control
of external degrees

Improved spectroscopy
- Lasers

Study and control of
internal degrees