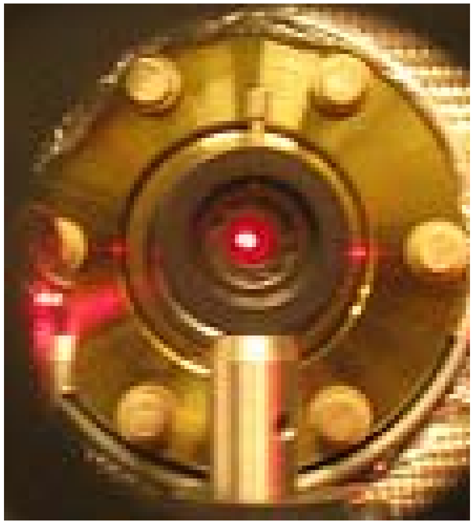
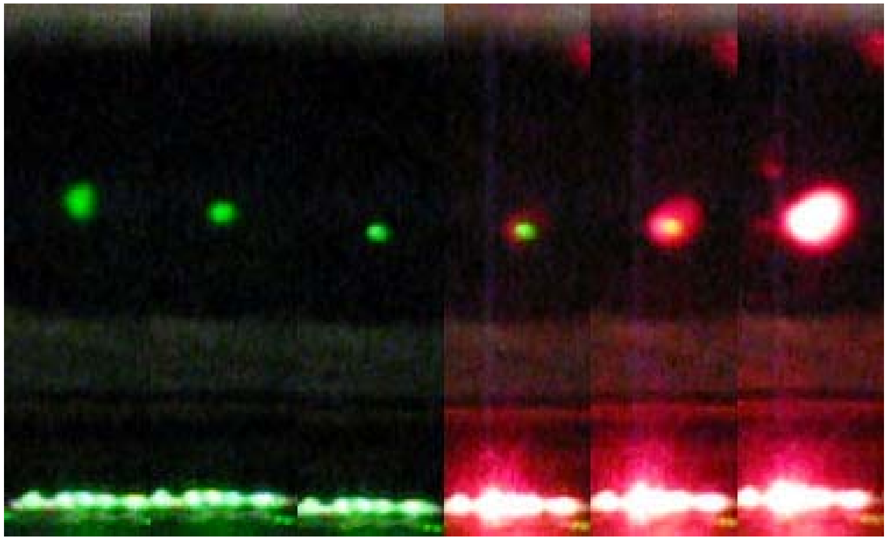
Quantum Gases

Subhadeep Gupta

UW REU Seminar, 11 July 2011

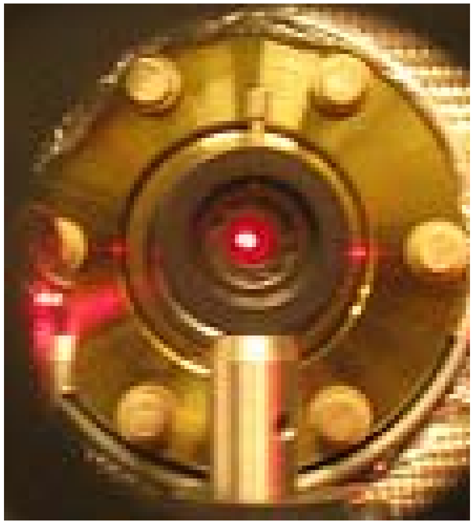


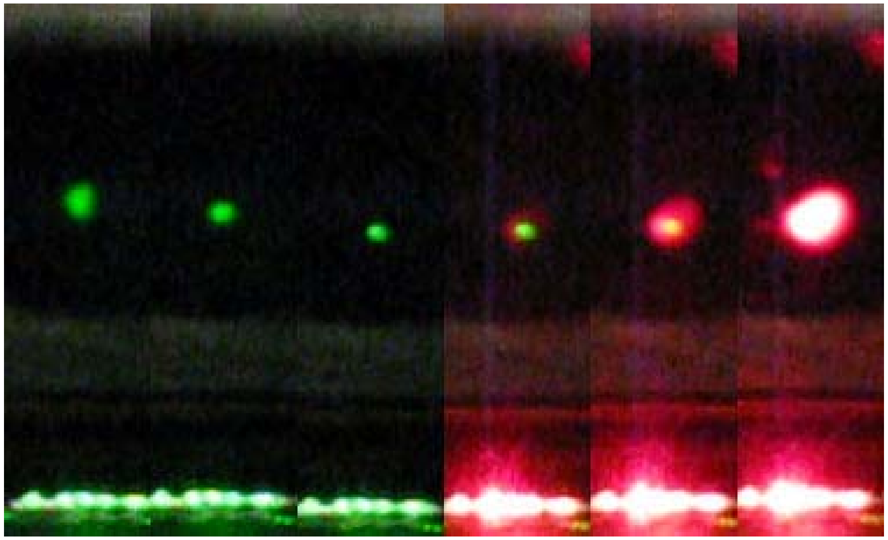


Ultracold Atoms, Mixtures, and Molecules

Subhadeep Gupta

UW REU Seminar, 11 July 2011

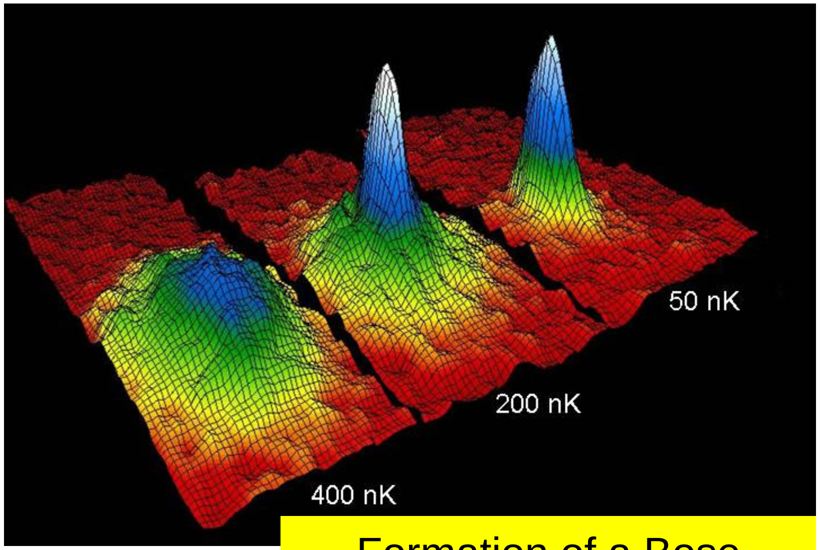




Ultracold Atoms

High sensitivity (large signal to noise, long interrogation times in a well known atomic system)

- Precision measurements (fund const, fund sym, clocks)
- Sensing (accelerations, gravity gradients)



Formation of a Bose-Einstein condensate (BEC) (1995)

Many-body aspects

- Quantum Fluids
- Condensed Matter Physics
- Nuclear Physics

Quantum Engineering (Potentials and Interactions)

- Quantum Information Science
- Quantum Simulation
- Ultracold Molecules (through mixtures)

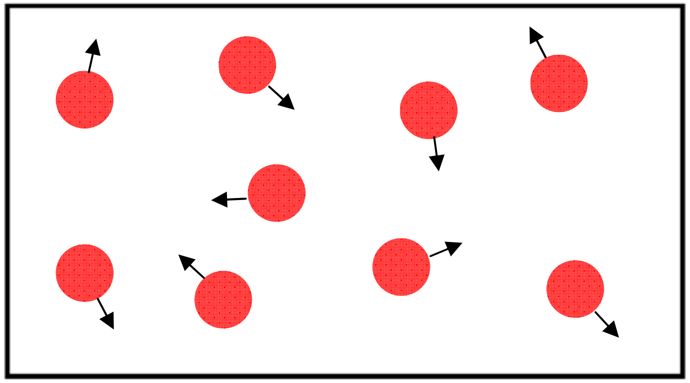
Ultracold Atoms and Molecules at UW

A dual-species experiment (Li-Yb) for
making and studying ultracold polar molecules
and for probing quantum mixtures

Development of precision BEC interferometry (Yb)
for fine structure constant α and test of QED

Quantum Degeneracy in a gas of atoms

1 atom per quantum state



N atoms
V volume
T temperature

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

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

Quantum Phase
Space Density

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

(n=N/V)

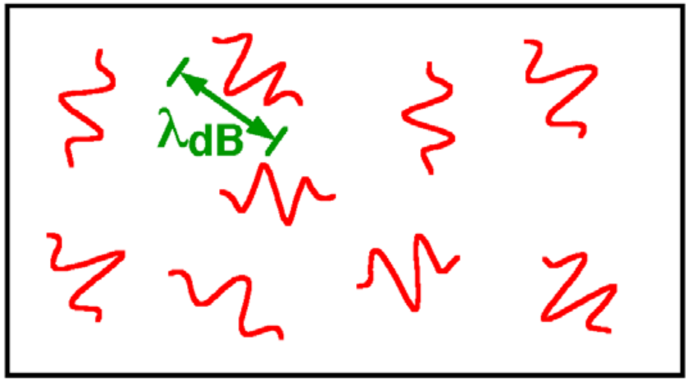
Air n ~ $10^{19}/\text{cm}^3$, $T_c \sim$ 1mK
Stuff n ~ $10^{22}/\text{cm}^3$, $T_c \sim$ 0.1K
Everything (except He) is solid

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

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

and ~ non-interacting

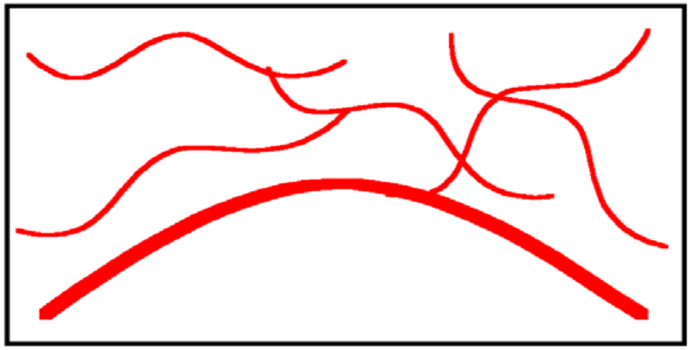
Bose-Einstein Condensation (BEC)



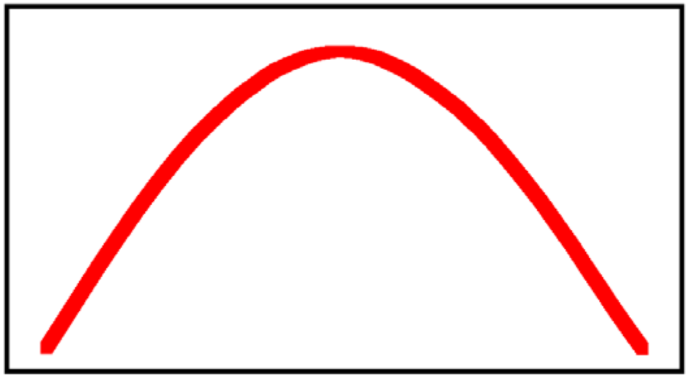
$$\lambda_{\mathrm{dB}} = \frac{h}{\sqrt{2\pi m k_{\mathrm{B}} T}} \quad n = \frac{\mathrm{N}}{\mathrm{V}}$$

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

Quantum Phase
Space Density



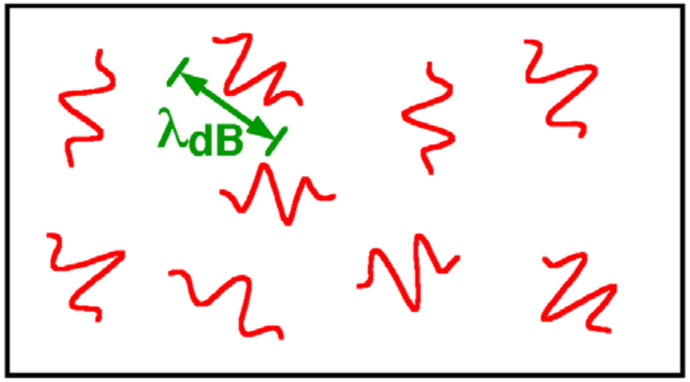
$$n\lambda_{\mathrm{dB}}^{3} \sim 1$$

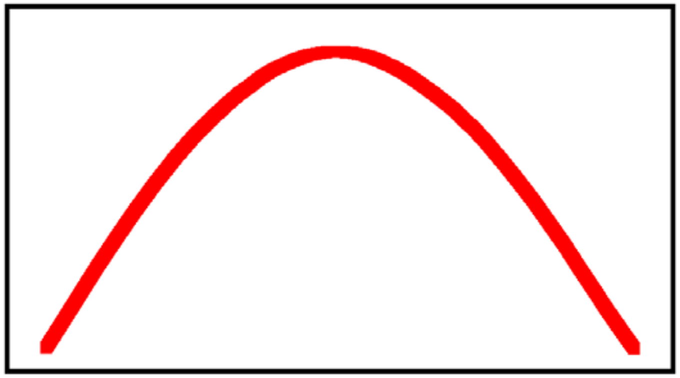


$$n\lambda_{\mathrm{dB}}^{3} >> 1$$

Ordinary gas

Bose-Einstein condensate





atoms flit around randomly

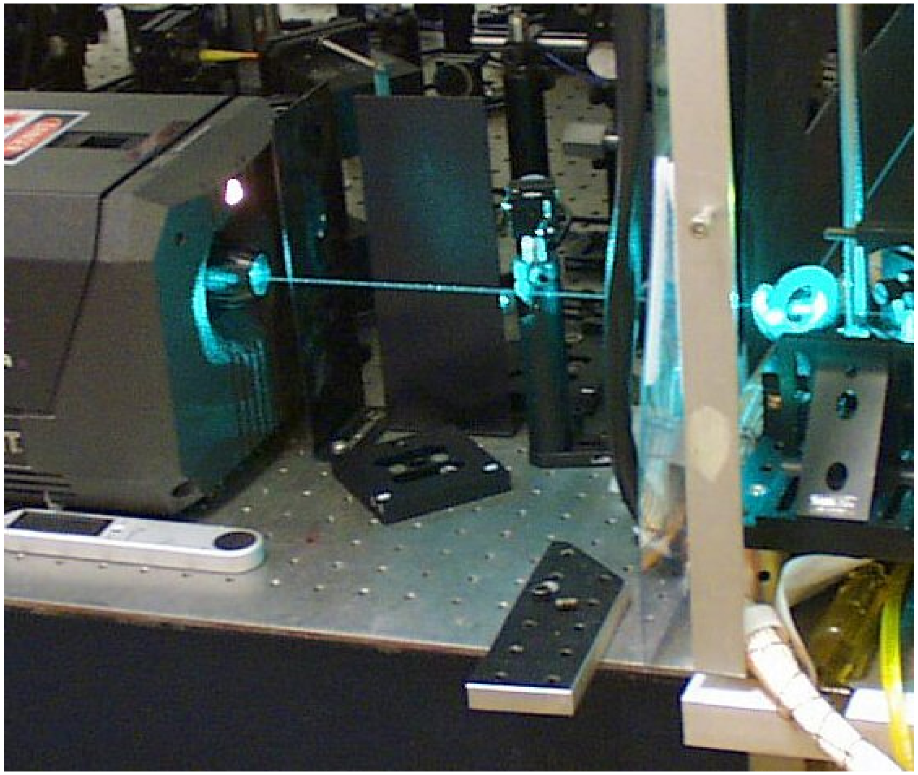
atoms march in lockstep

divergent
incoherent
many small waves
many modes

diffraction limited (directional)
coherent
one big wave
single mode (monochromatic)

Ordinary light

Laser light



divergent	diffraction limited (directional)
incoherent	coherent
many small waves	one big wave
many modes	single mode (monochromatic)

AMERICAN
ASSOCIATION FOR THE
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SCIENCE

SCIENCE

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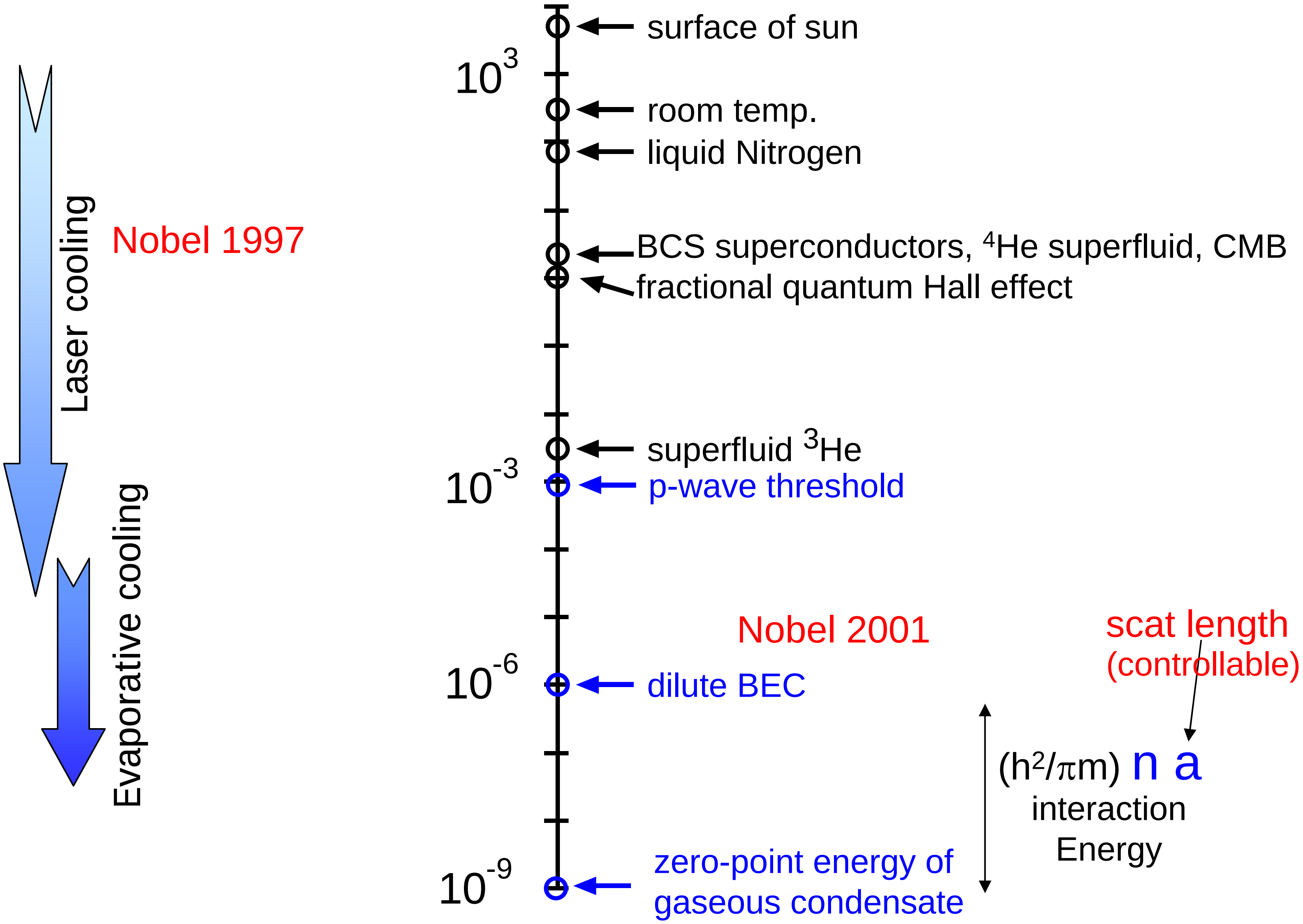
Molecule
of the
Year

the
Bose-Einstein
Condensate

ABSOLUTE TEMPERATURE (log Kelvin scale)



Laser cooling

Nobel 1997

Evaporative cooling

10^3

10^{-3}

10^{-6}

10^{-9}

surface of sun

room temp.

liquid Nitrogen

BCS superconductors, ^{4}He superfluid, CMB

fractional quantum Hall effect

superfluid ^{3}He

p-wave threshold

Nobel 2001

dilute BEC

zero-point energy of gaseous condensate

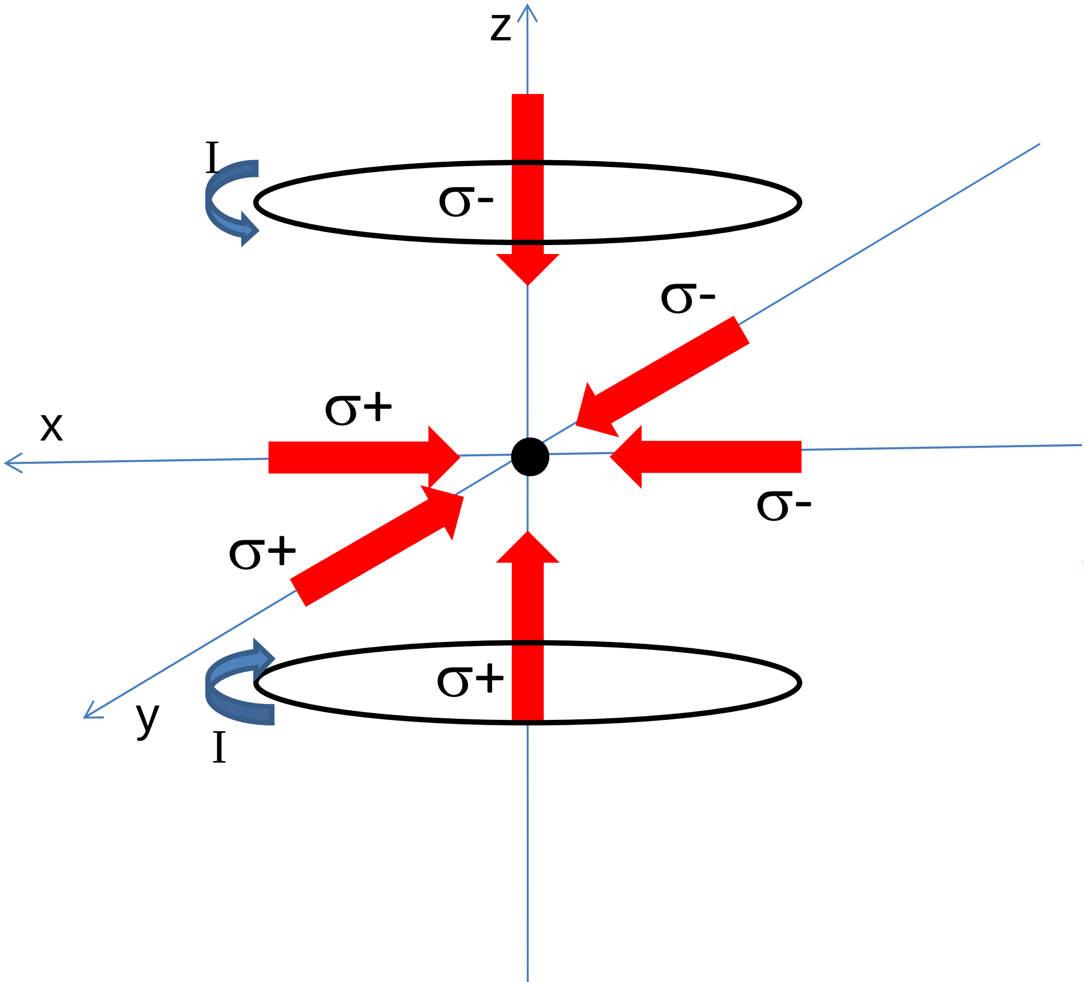
scat length (controllable)

$(h^2/\pi m)\ n\ a$

interaction Energy

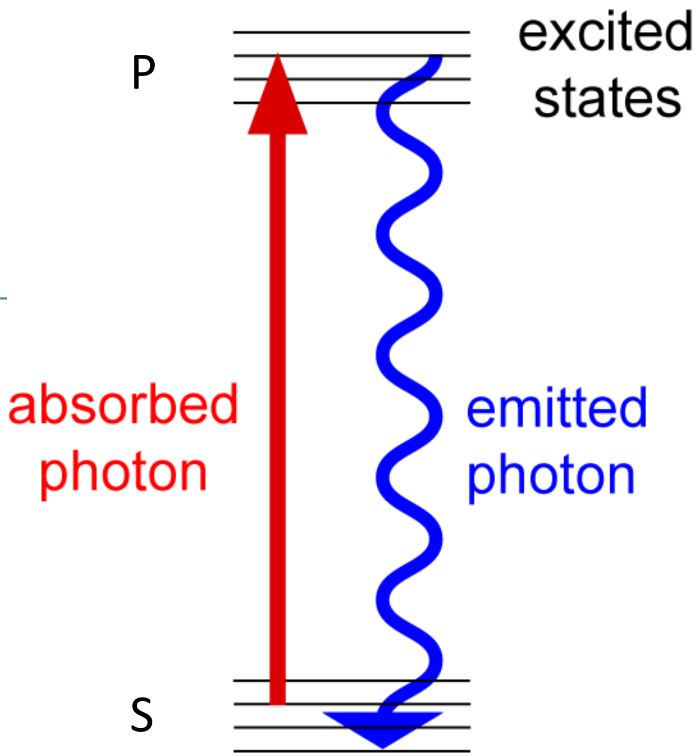
Laser Cooling ???

Laser Cooling



Magneto-Optical Trap (MOT)
“Workhorse” of laser cooling

Atom Source ~ 600 K; UHV environment

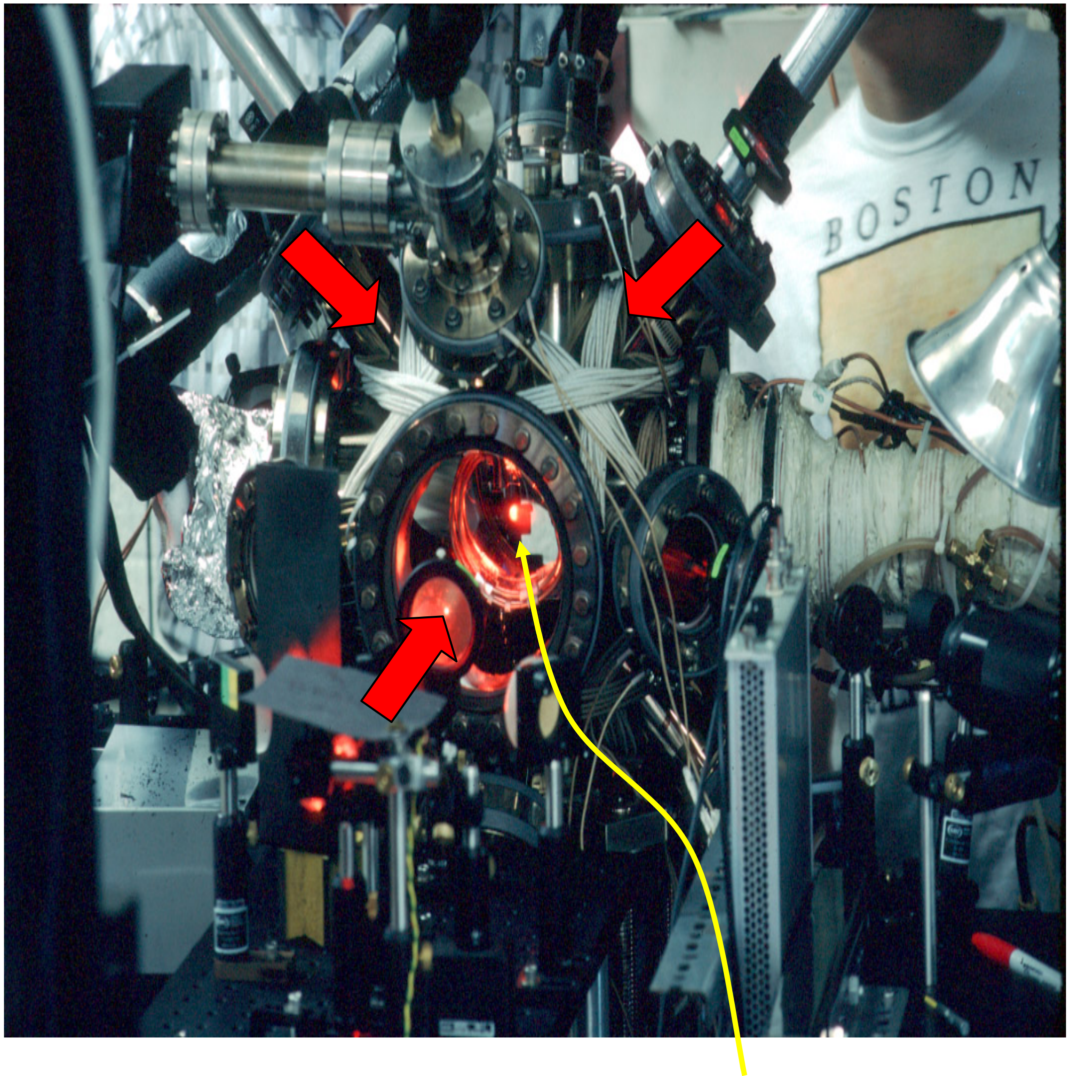


$$\hbar\omega_{\mathrm{abs}} < \hbar\omega_{\mathrm{em}}$$

=> COOLING !

(Need a 2 level system)

Laser Cooling !!!

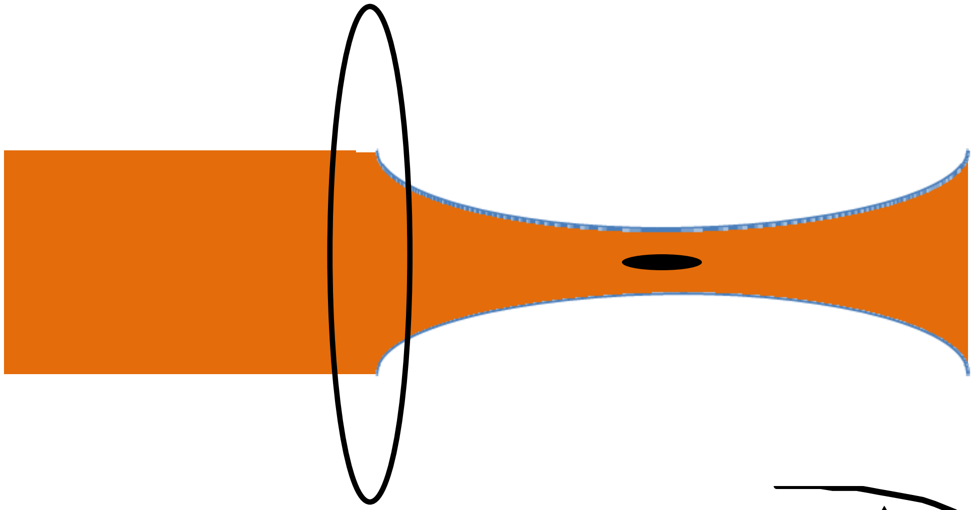


100μK

Magneto-Optic Trap (MOT)

But the room is at 300K (!)

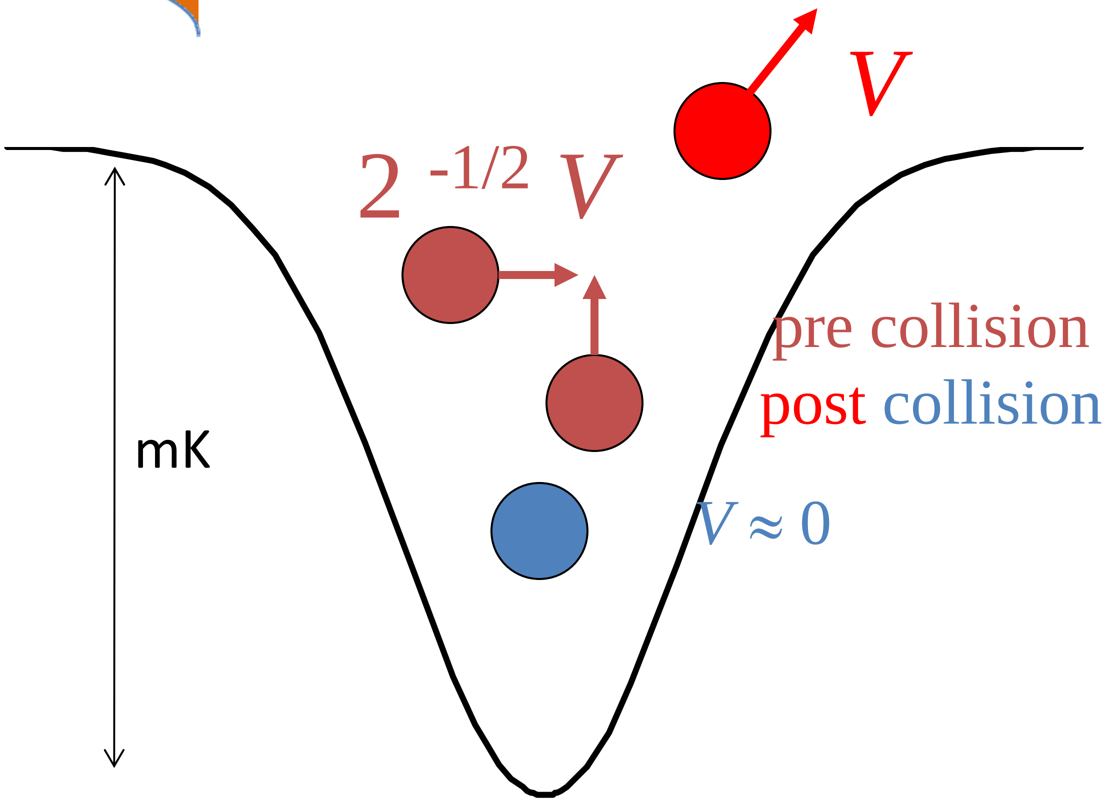
Evaporative Cooling in a Conservative Trap



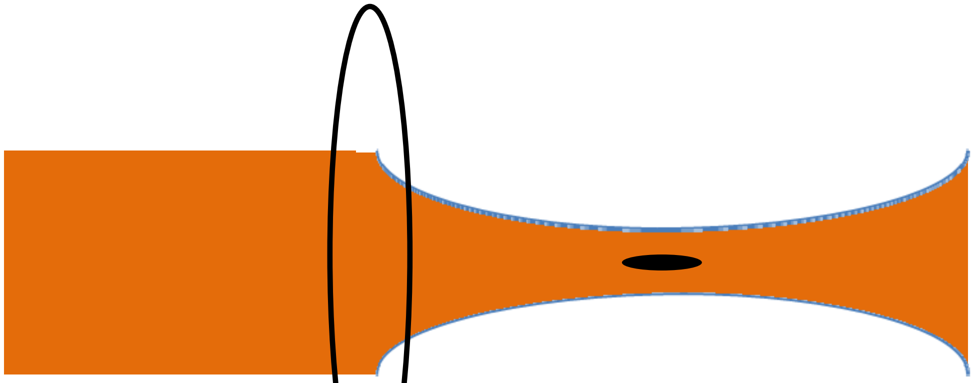
Optical Dipole Trap

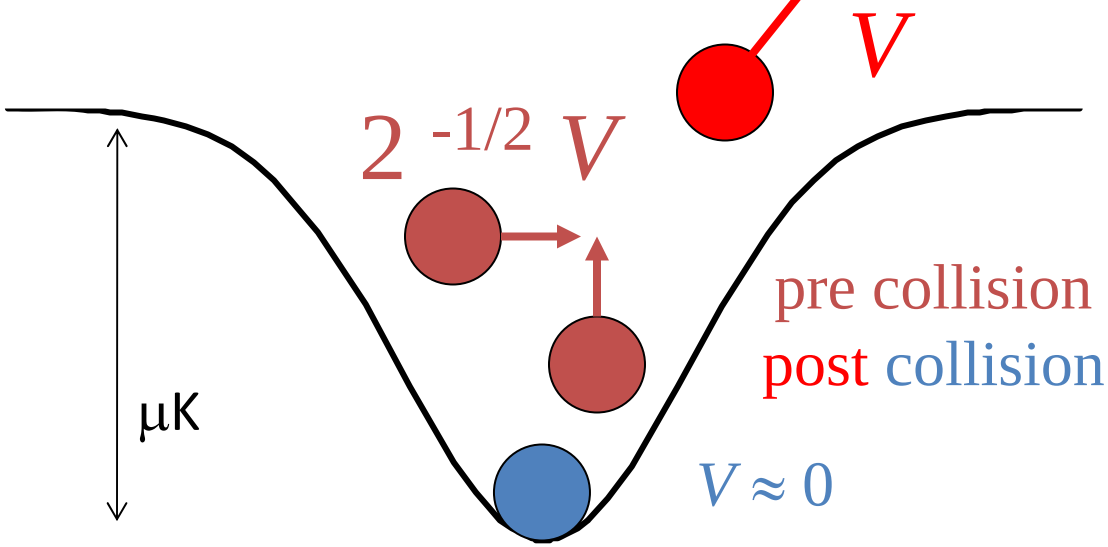
$\omega_L << \omega_{res}$

Depth ~ I/Δ; Heating Rate ~ I/Δ^2



Evaporative Cooling in a Conservative Trap



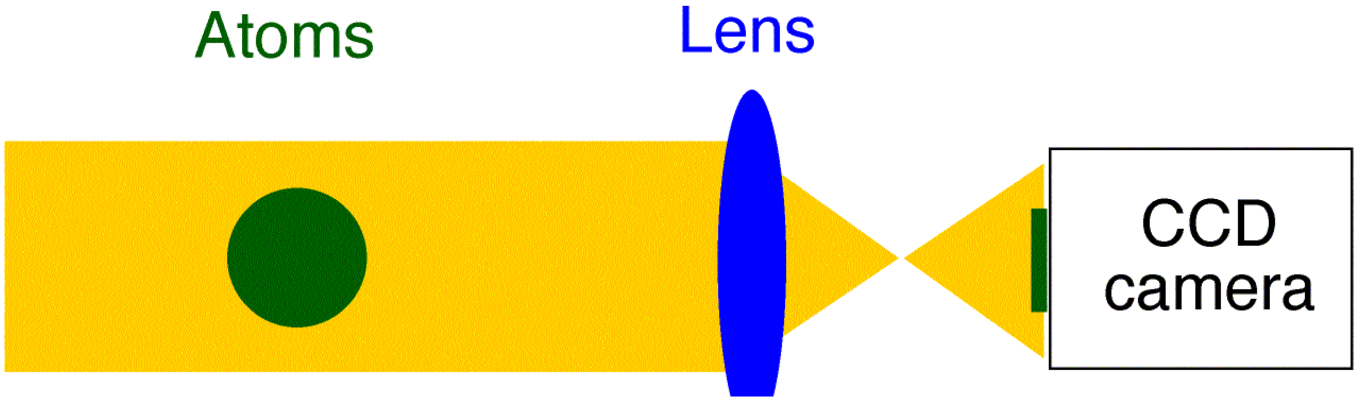


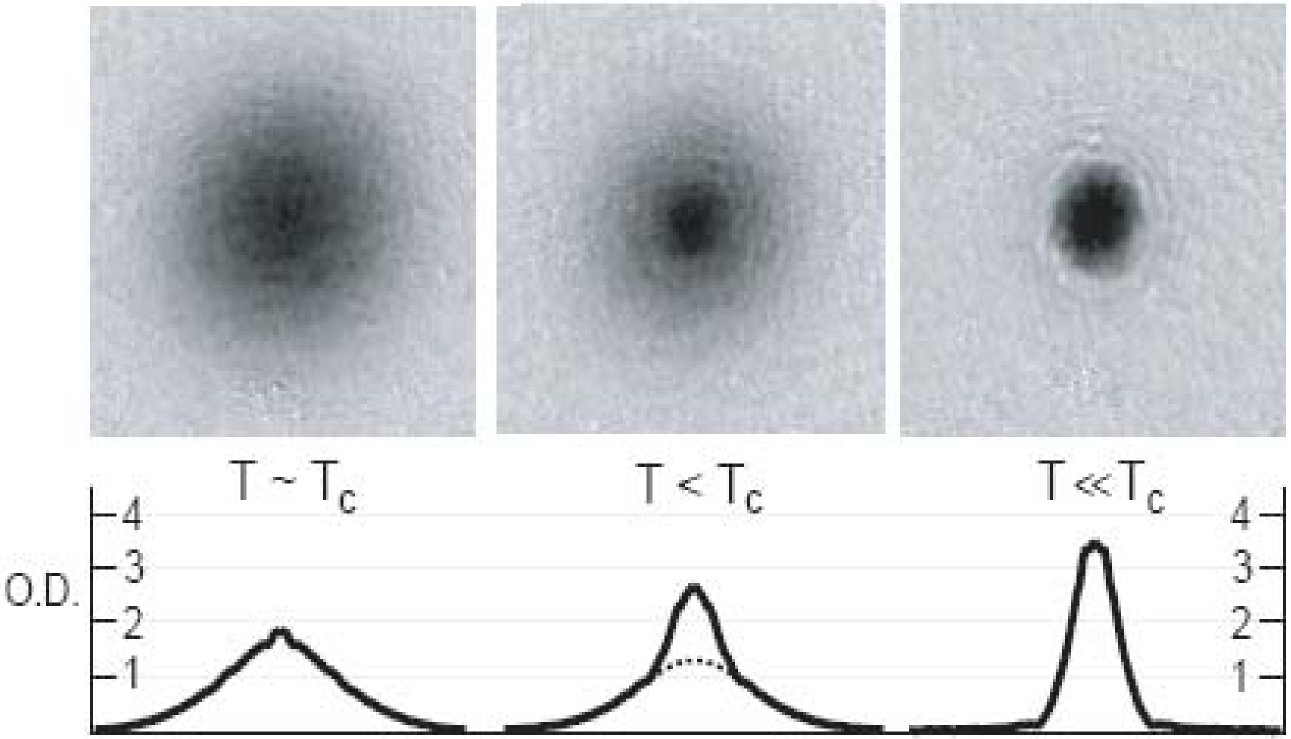
Optical Dipole Trap

$\omega_L << \omega_{res}$

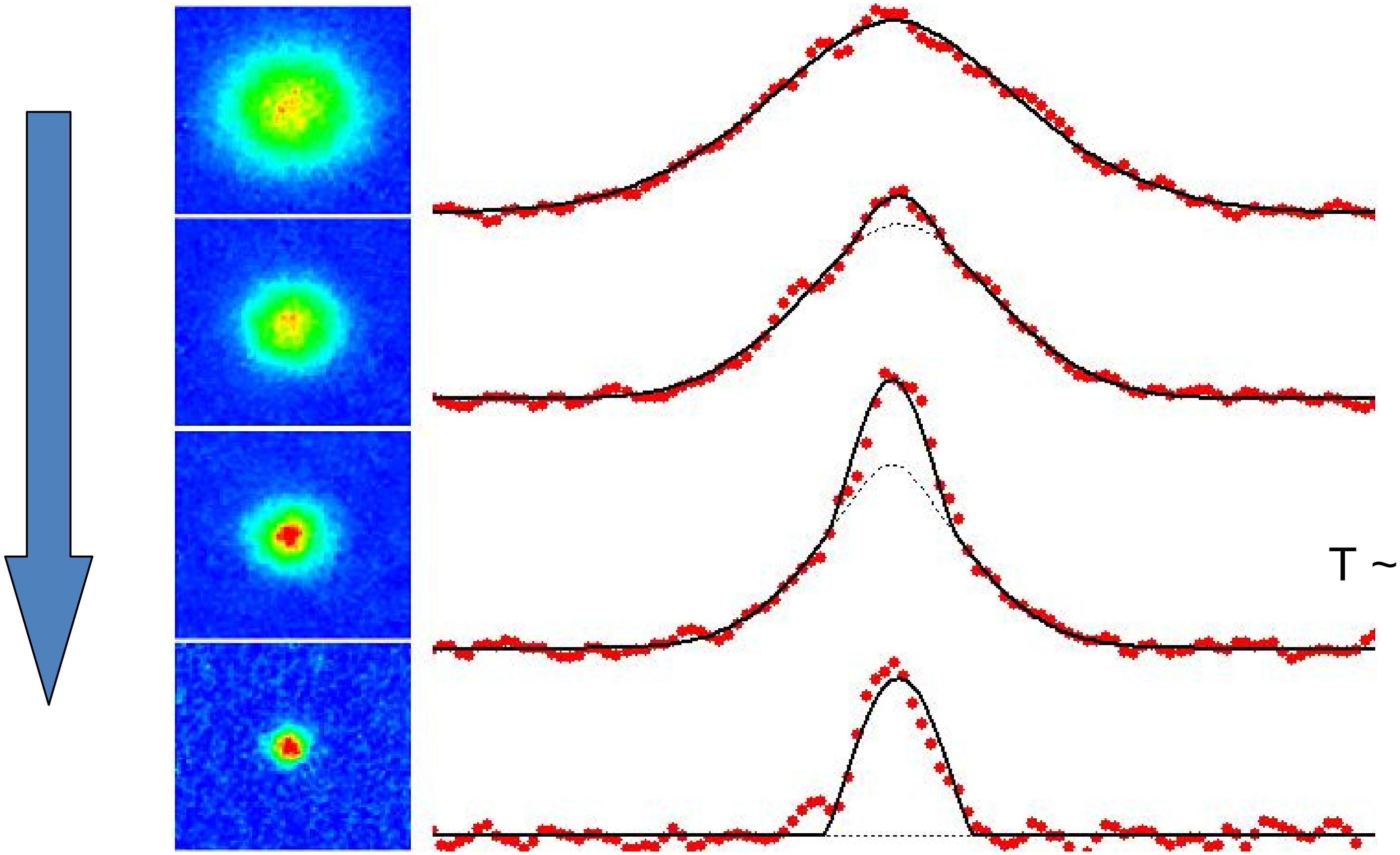
Depth ~ I/Δ; Heating Rate ~ I/Δ^2

Imaging the Atoms





(Formation of a Rb BEC in a magnetic trap, UC Berkeley 2005)

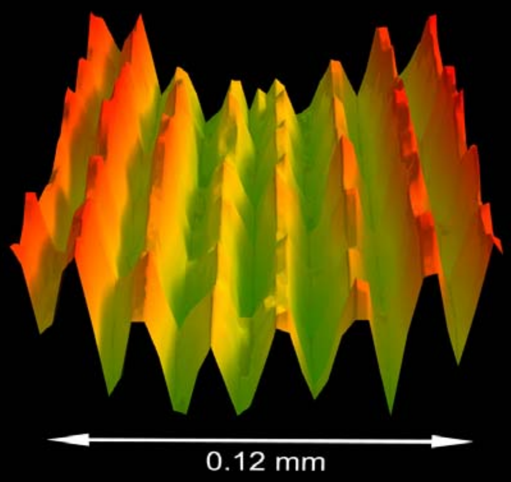


Lower
Temp

T ~ 150nK

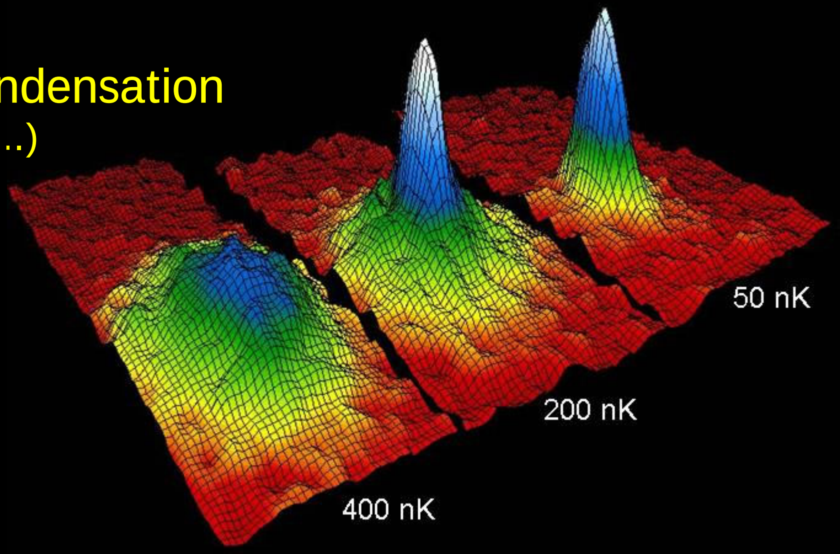
(Formation of a Yb BEC in an optical trap, UW Seattle 2011)

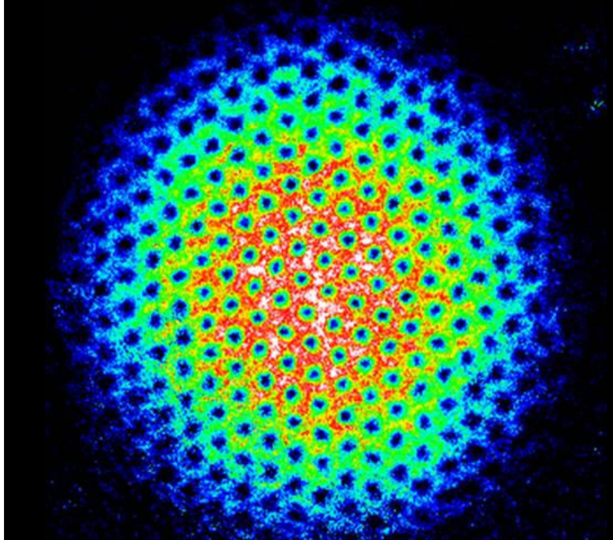
Landmark achievements in ultracold atomic physics



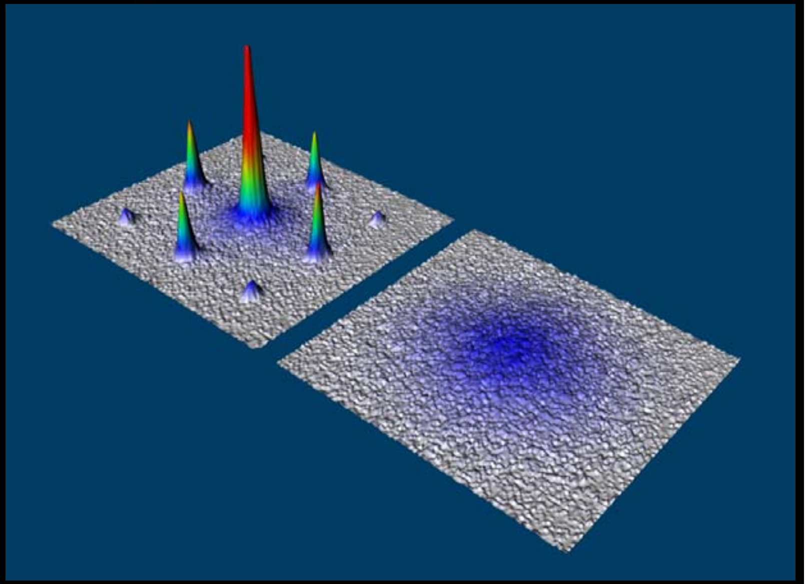
Macroscopic coherence
(Ketterle)

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



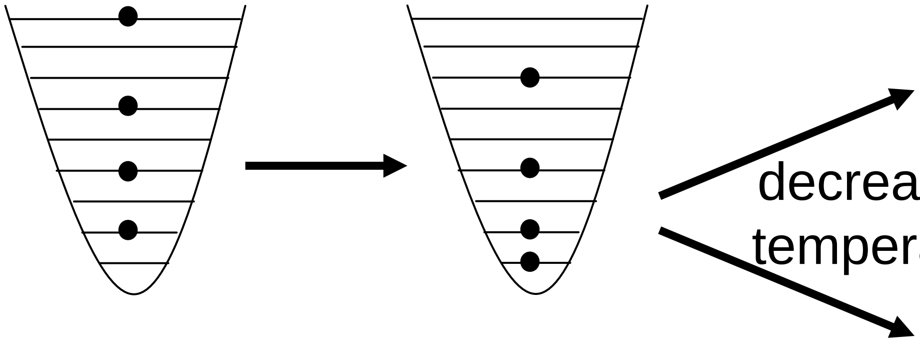


Superfluidity / observation
and study of a vortex lattice
(Dalibard, Ketterle, Cornell)



Superfluid to Mott-insulator
quantum phase transition
(Hansch)

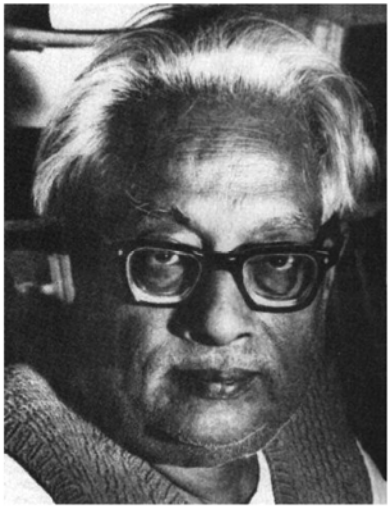
Different Quantum Matters

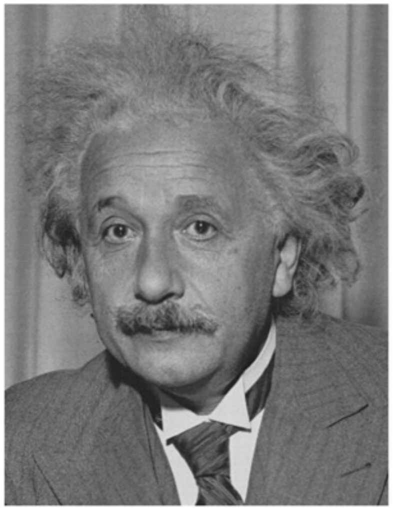


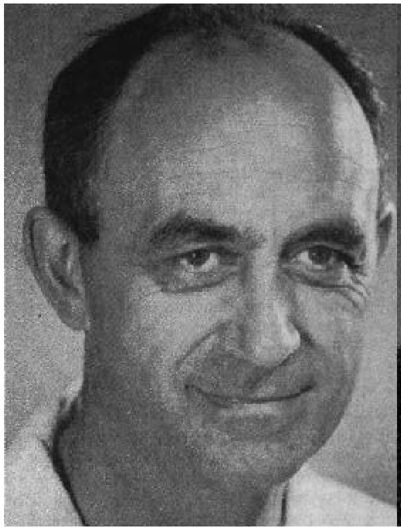
decreasing temperature

classical gas

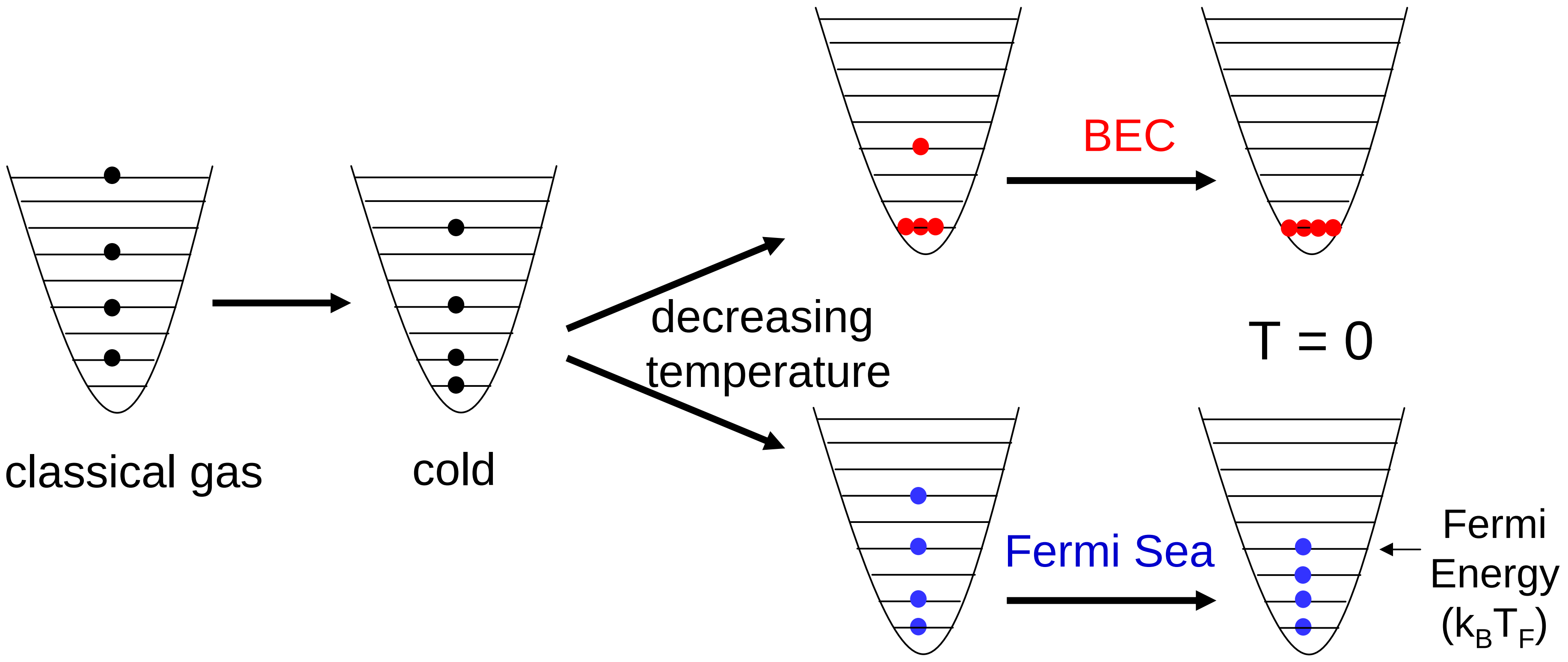
cold







Different Quantum Matters



classical gas

cold

decreasing temperature

BEC

T = 0

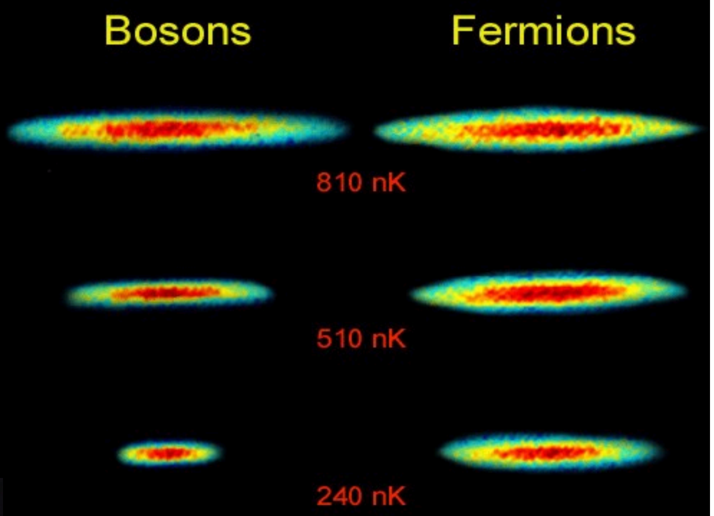
Fermi Sea

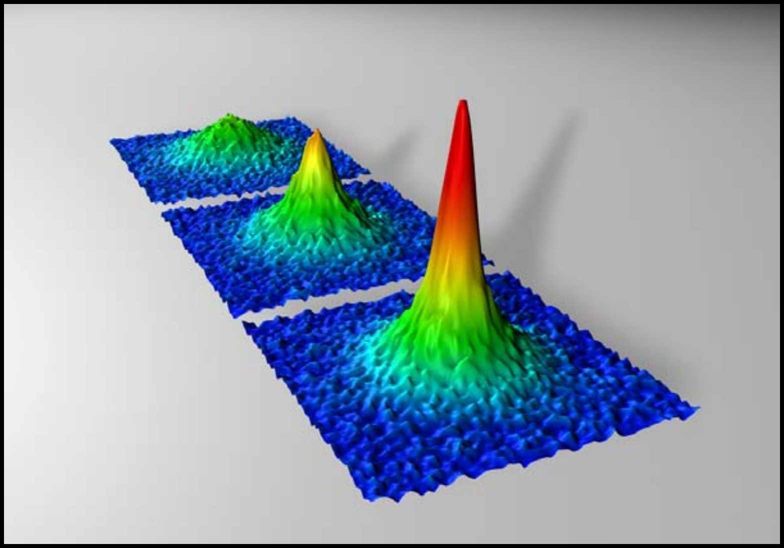
Fermi Energy ($k_B T_F$)

Fermions are much harder to cool because identical (in all respects) fermions will not interact s-wave (a=0). Need another spin state or another species of atom.

Landmark achievements in ultracold atomic physics

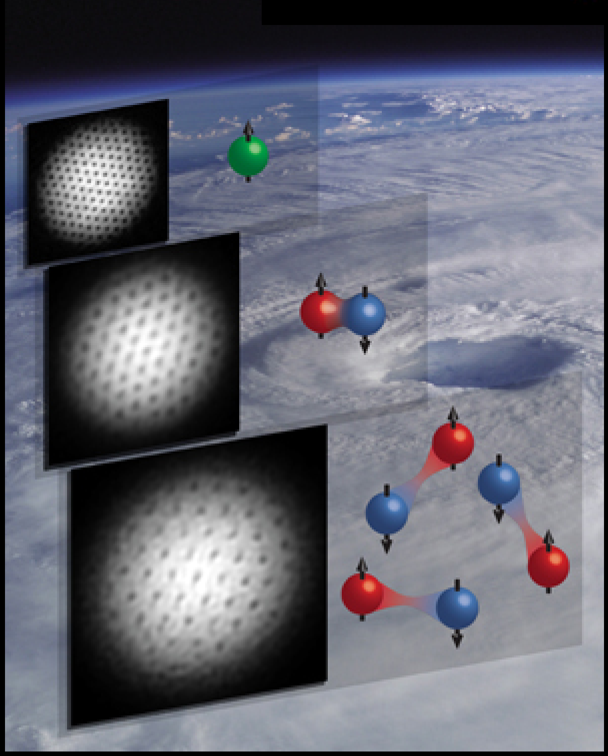
Degenerate Fermi gas





Molecular Bose-Einstein condensate

(Jin, Hulet, Thomas, Ketterle, Grimm)

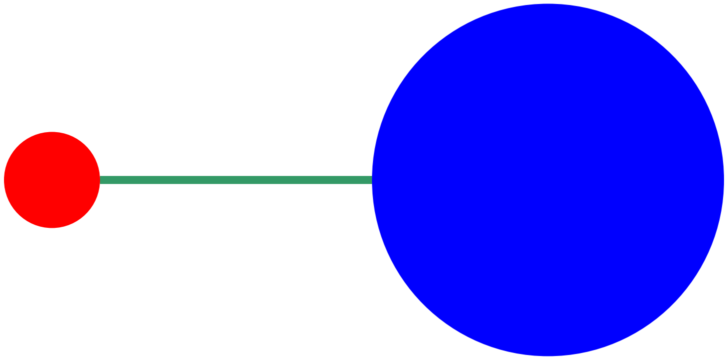


Superfluidity of Fermi pairs

Ultracold Polar Molecules

Realization of new quantum gases based on dipole-dipole interactions (1/r^3 vs 1/r^6 “contact” potential)

Quantum Computing and Simulation

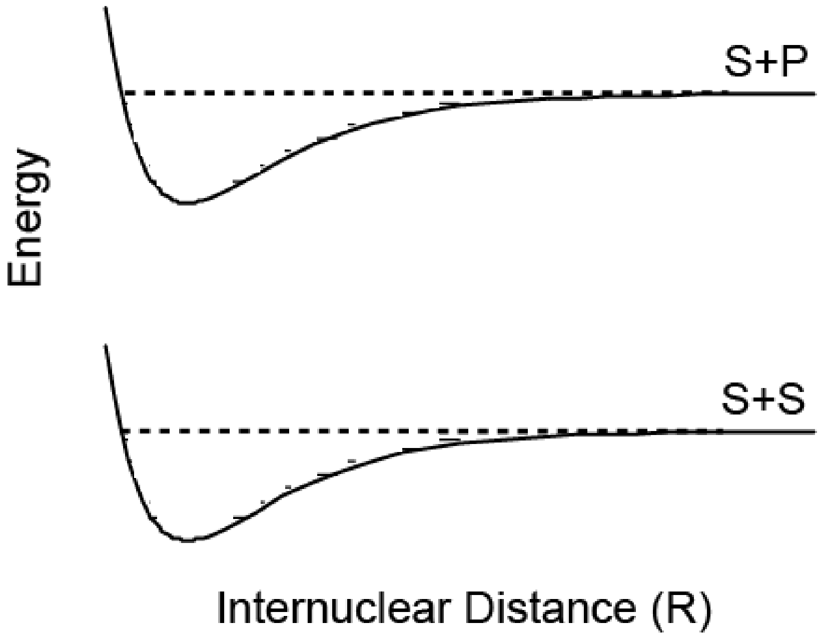


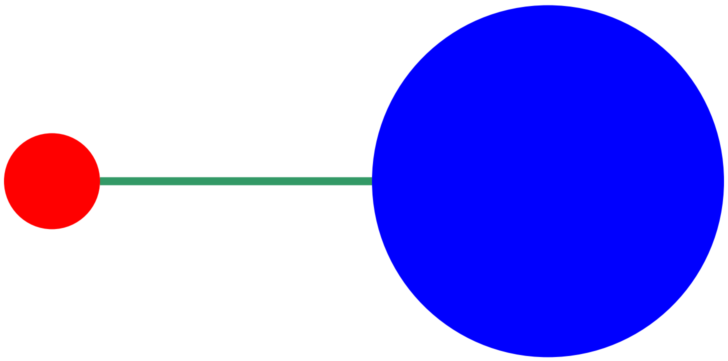
Tests of fundamental symmetries

Spectroscopies for clocks, time variations of fundamental constants

Cold and ultracold controlled Chemistry

Polar (diatomic) Molecules from Ultracold Atoms



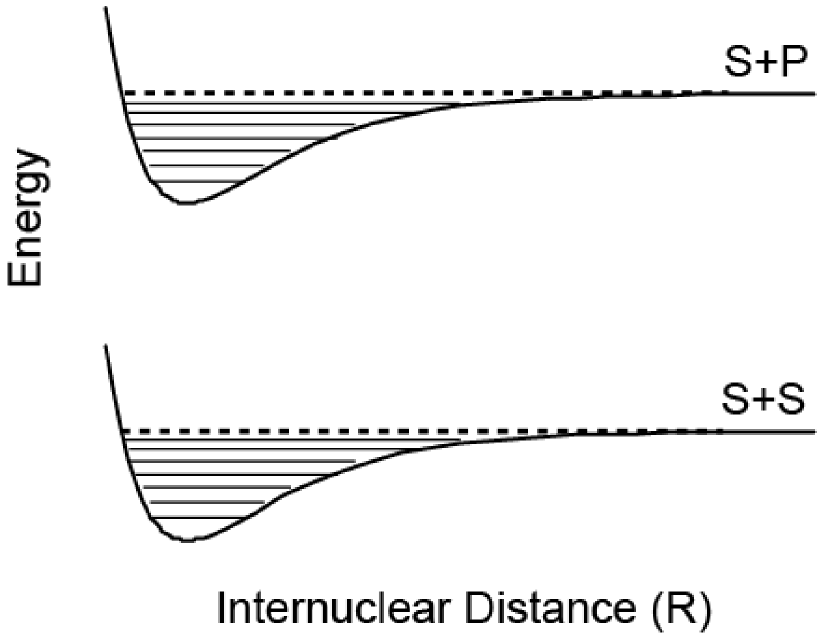


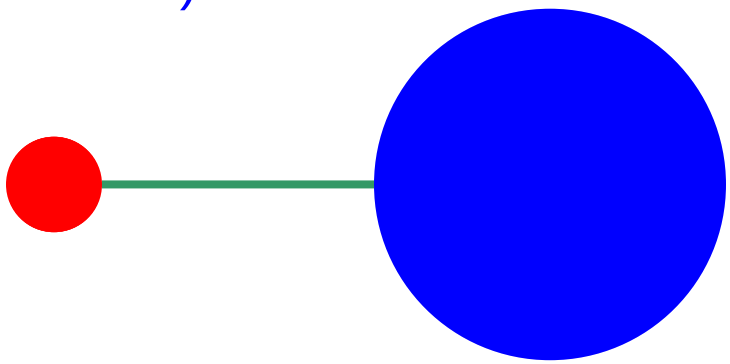
Polar (diatomic) Molecules from Ultracold Atoms

New degrees of freedom bring with them scientific advantages

New degrees of freedom bring with them technical issues

(Hard to cool!)

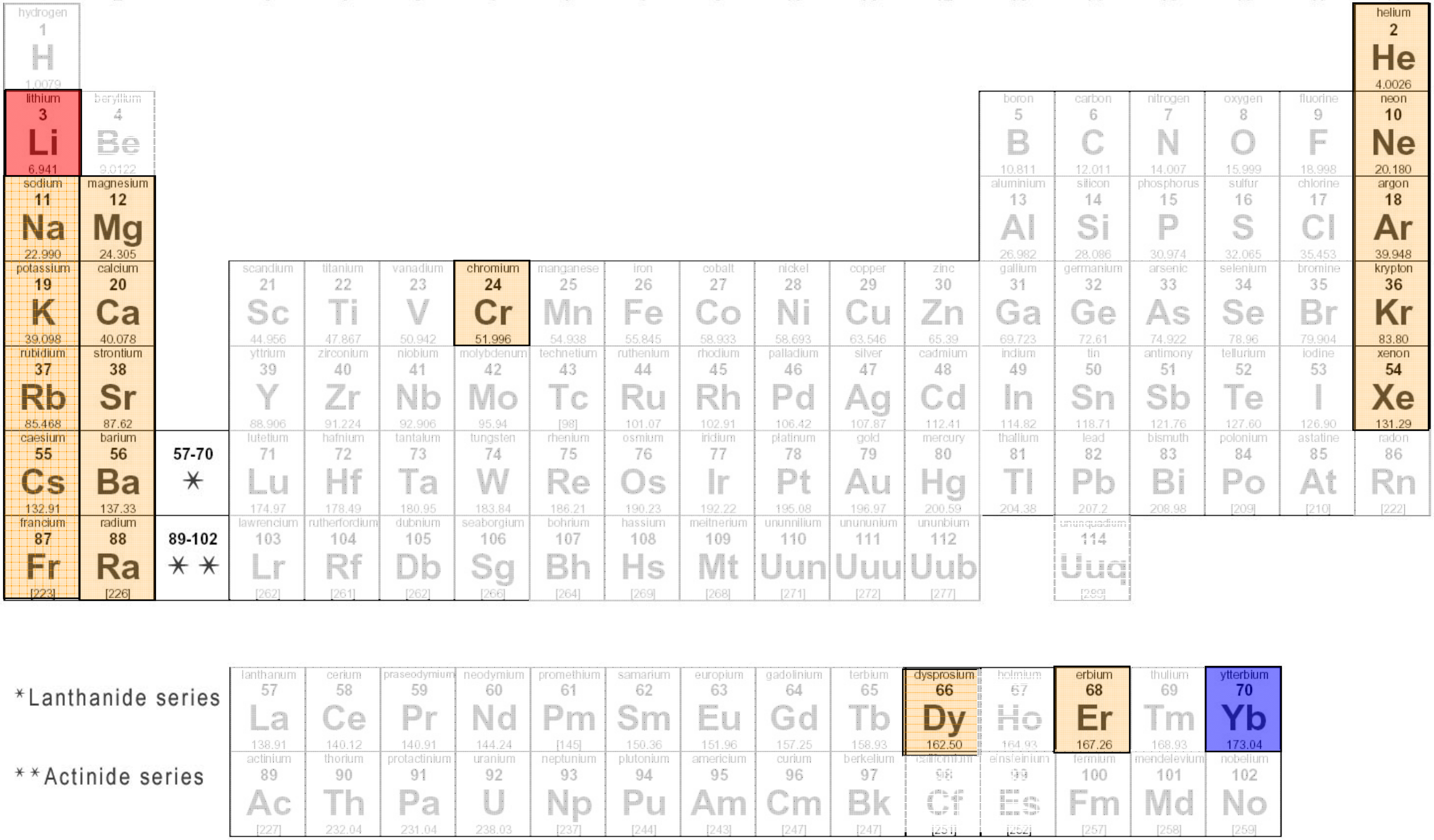




Unequal sharing of electrons

Polarizable at relatively low field

Ultracold Atom Menu

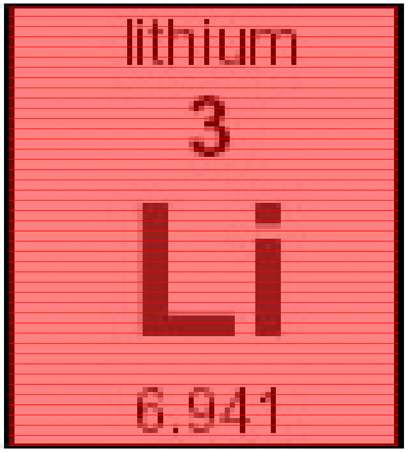


hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 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]

Very different mass, very different electronic structure → strong dipole moment

Selected Molecular Constituents



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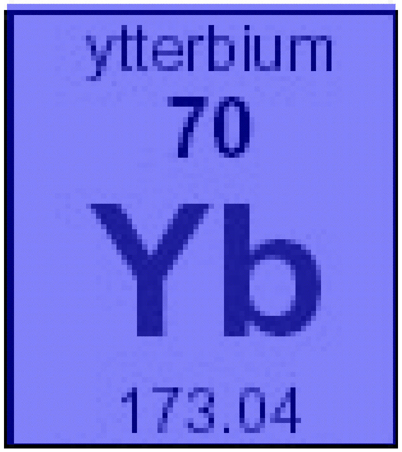
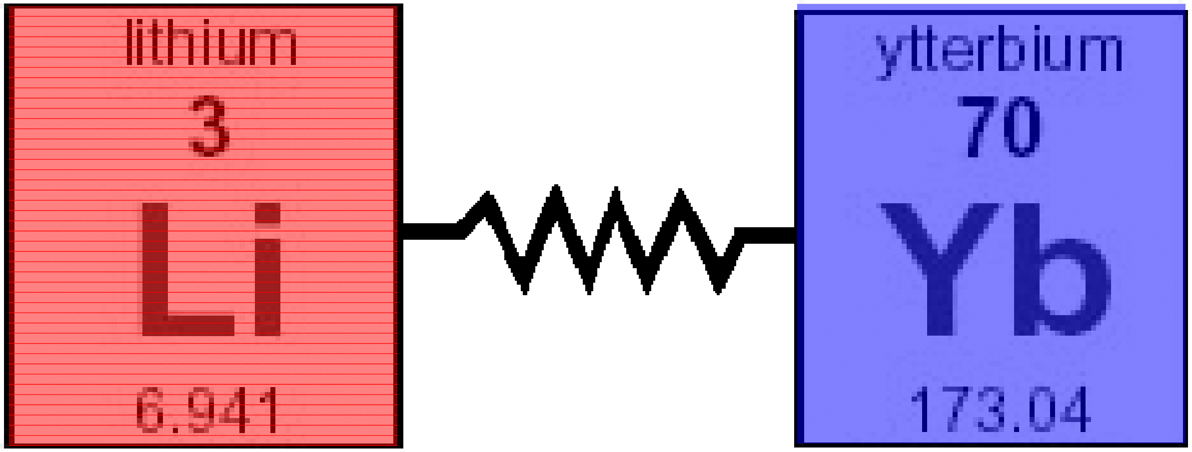


Studies of interacting quantum mixtures
(different statistics, masses)

Microscopic probes of superfluids

Selected Molecular Constituents

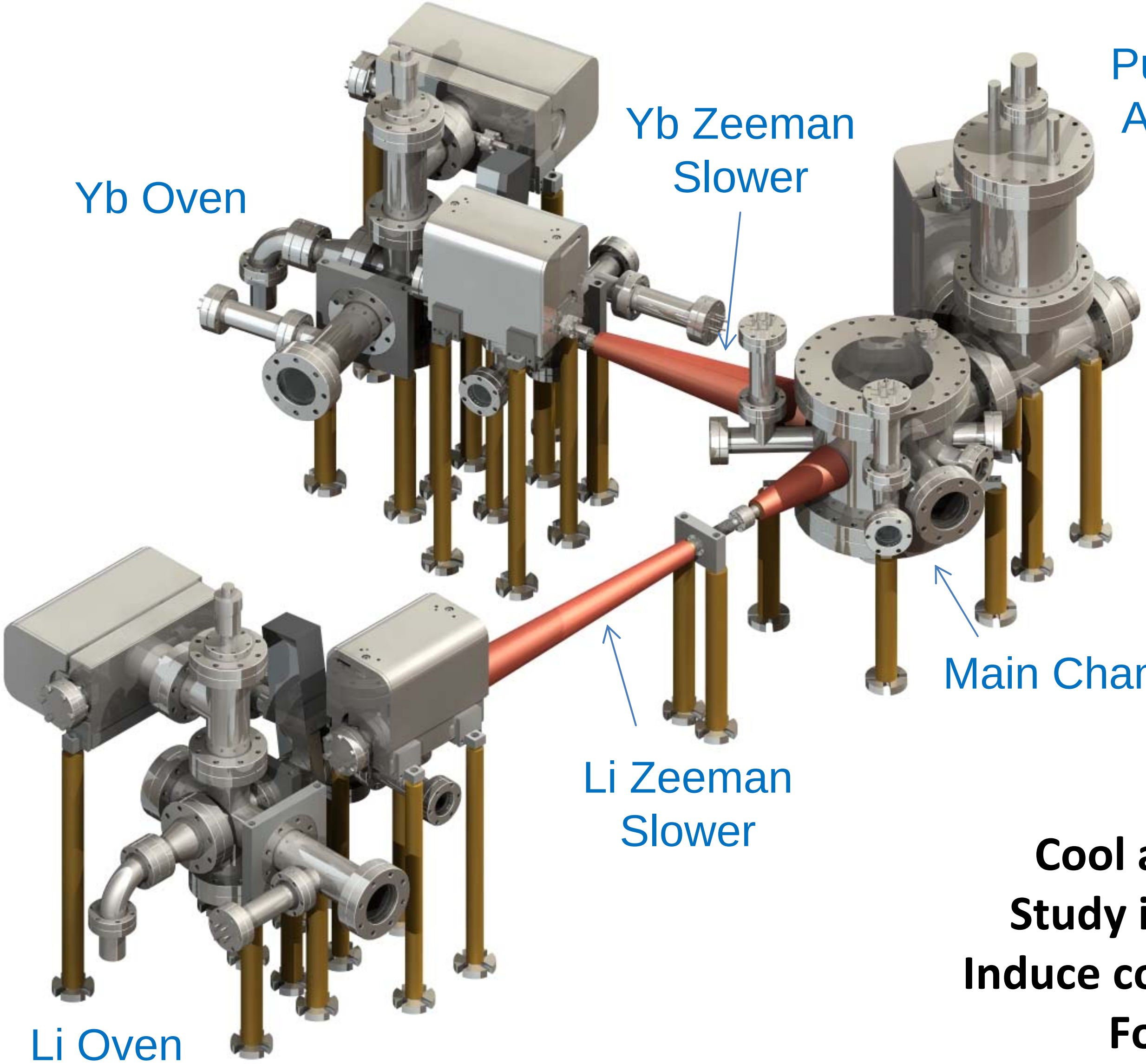


New Quantum Fluid – Dipolar and paramagnetic

Paramagnetic ground state, heavy component
→ candidate for electron EDM search

Quantum computing candidate

Dual Species Apparatus



Yb Oven

Yb Zeeman Slower

Pump Area

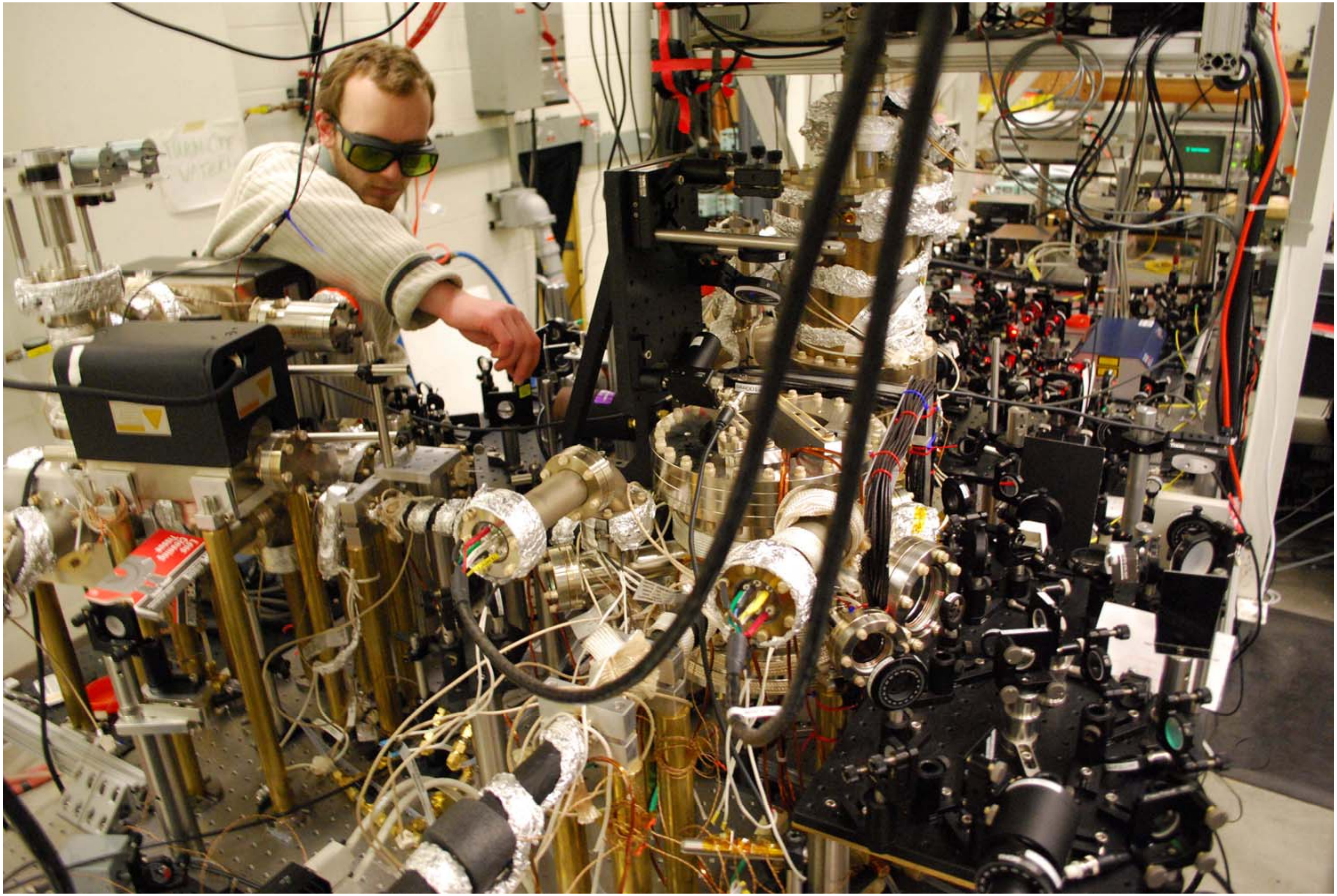
Main Chamber

Li Zeeman Slower

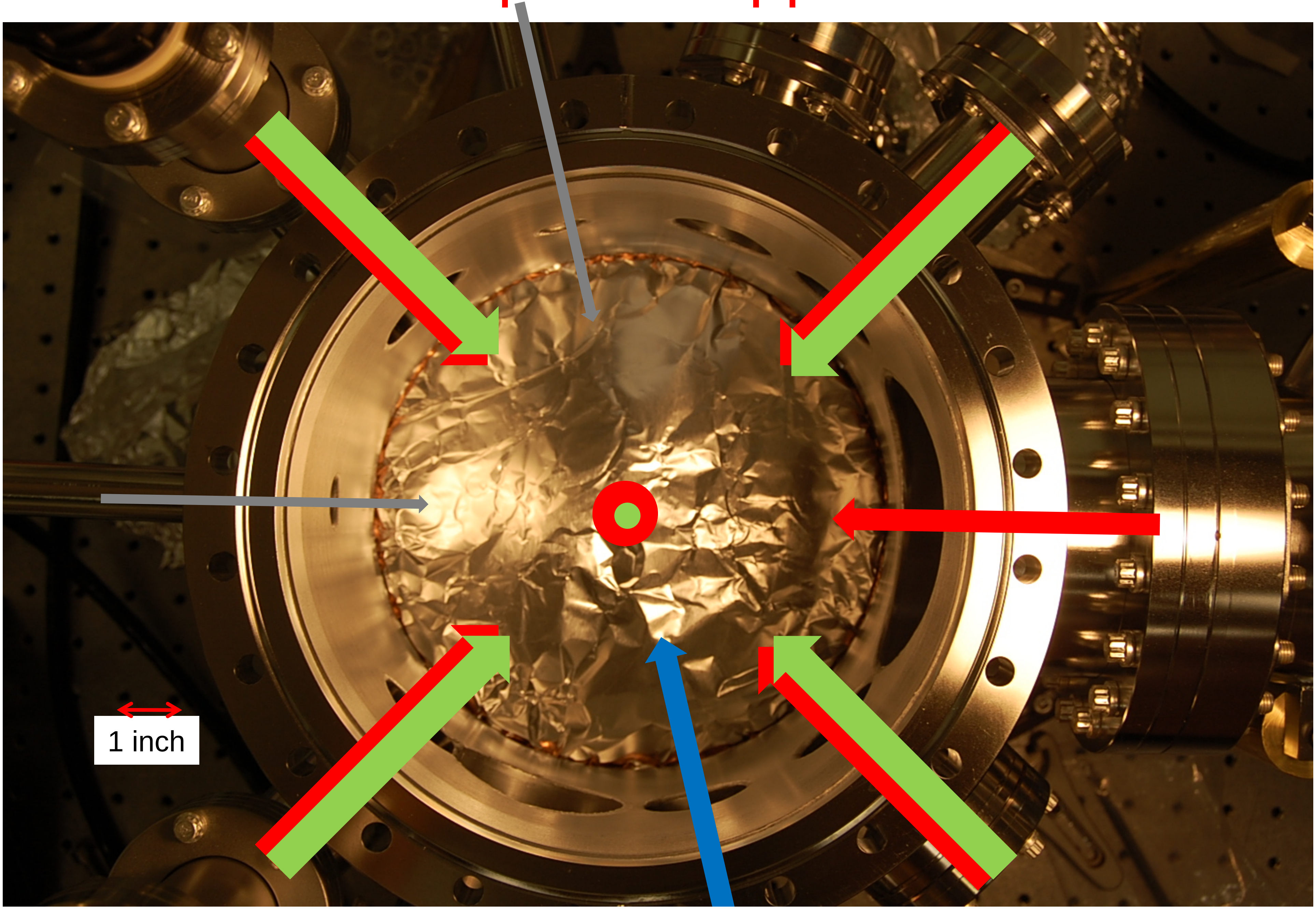
Li Oven

Ultrahigh Vacuum
(UHV < 10^{-10} Torr)

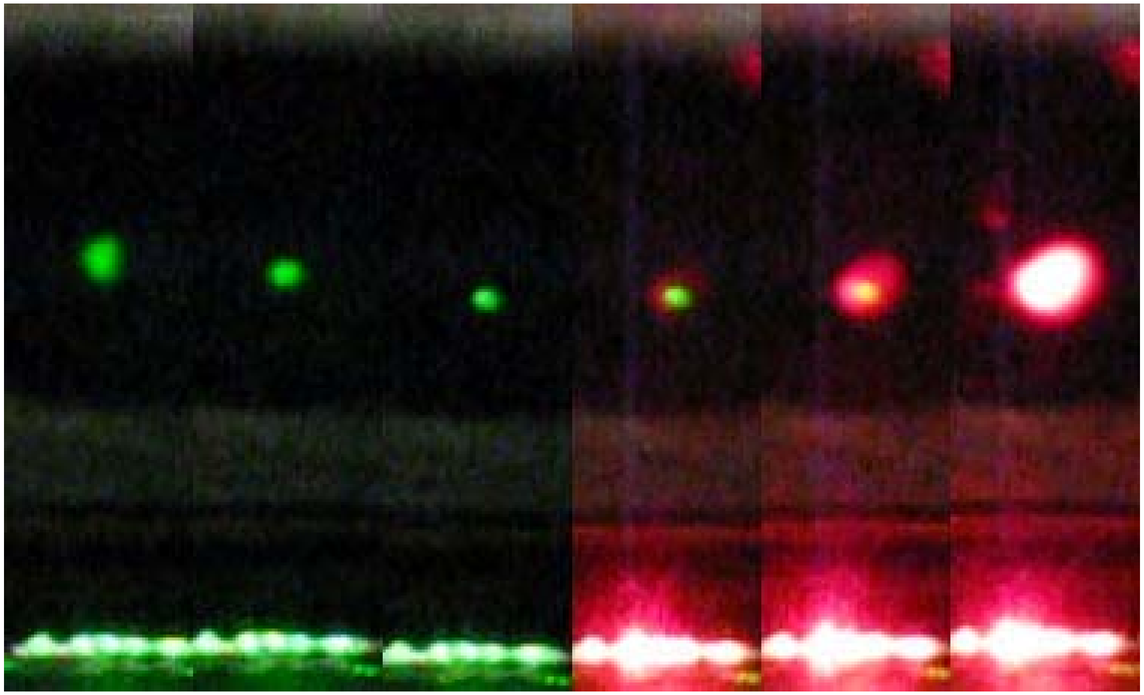
AGENDA
Cool and trap Li and Yb
Study interacting mixture
Induce controlled interactions
Form molecules



Dual Species Apparatus



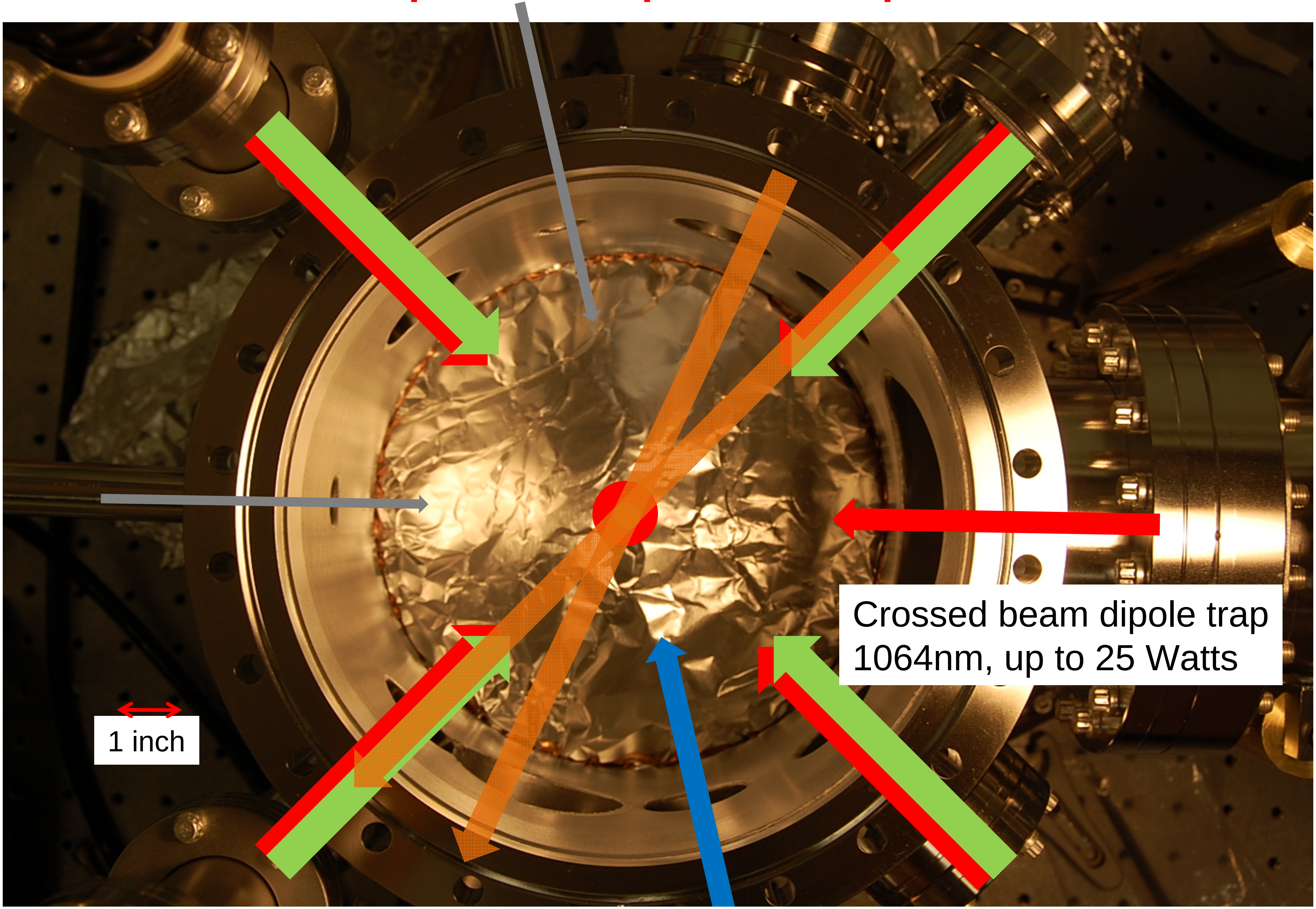
Two-Species MOT



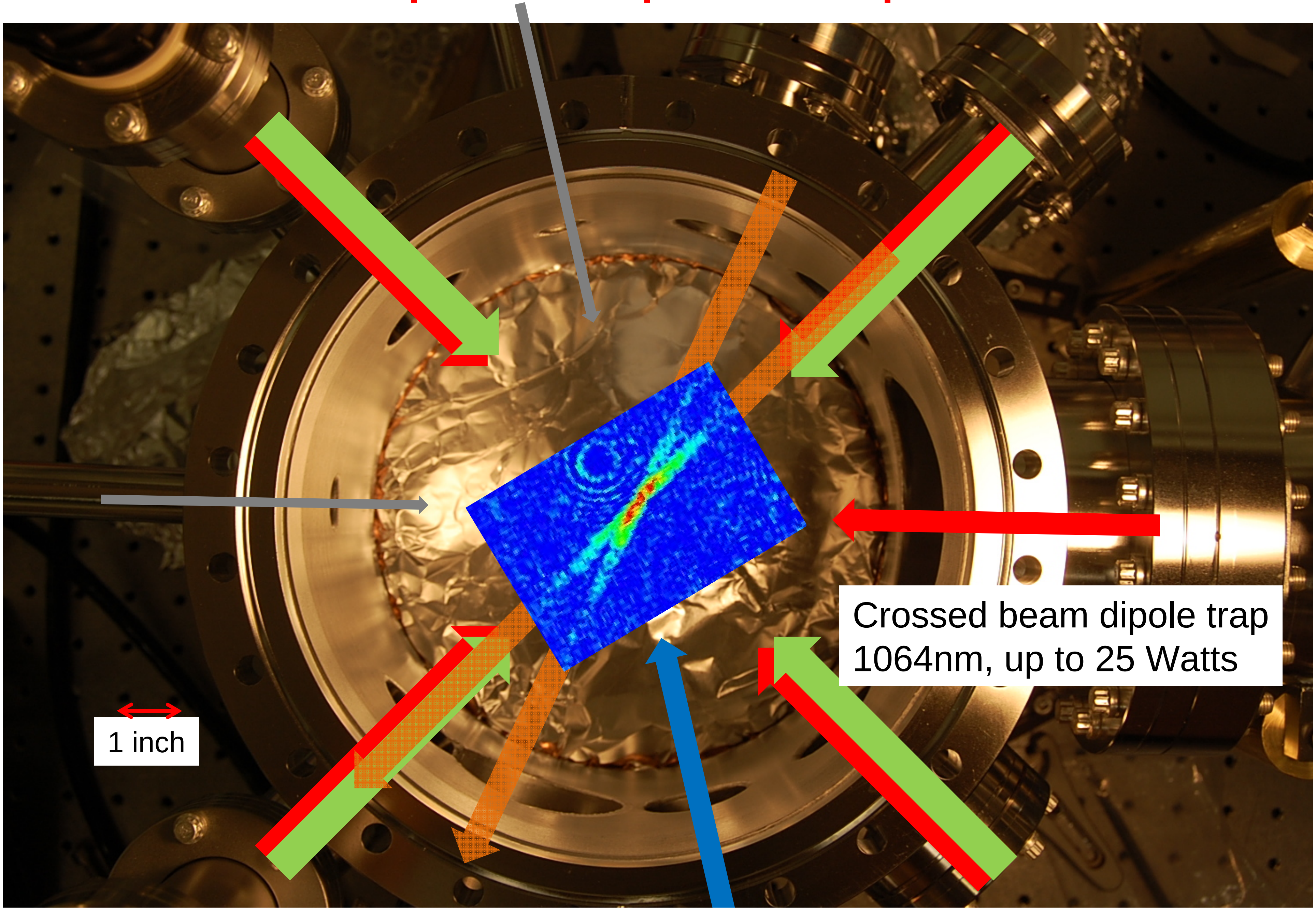
Sequential Loading

The 2 MOTs are optimized at different parameters of magnetic field gradient and also exhibit inelastic interactions

Optical Dipole Trap

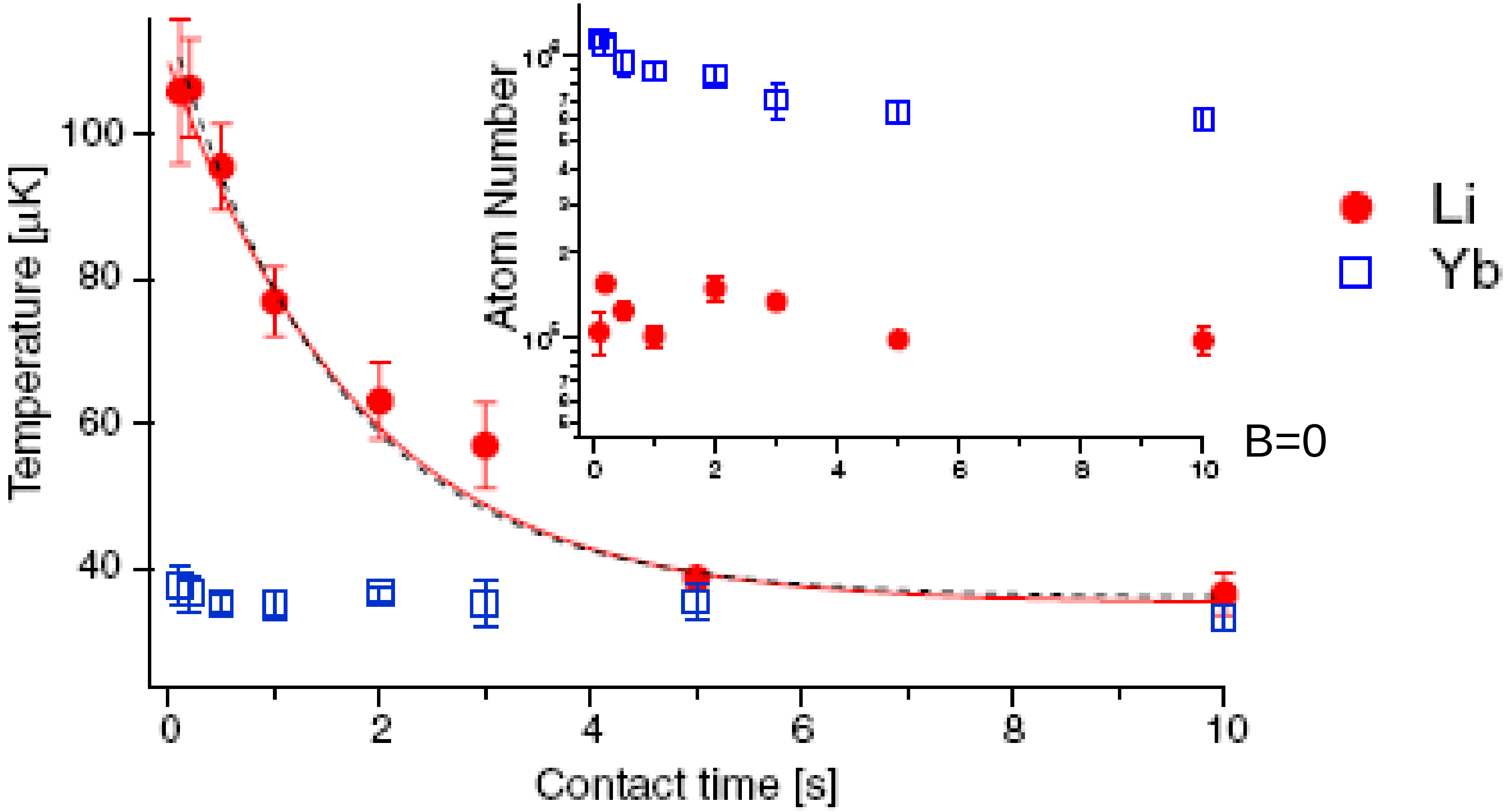


Optical Dipole Trap



Crossed beam dipole trap
1064nm, up to 25 Watts

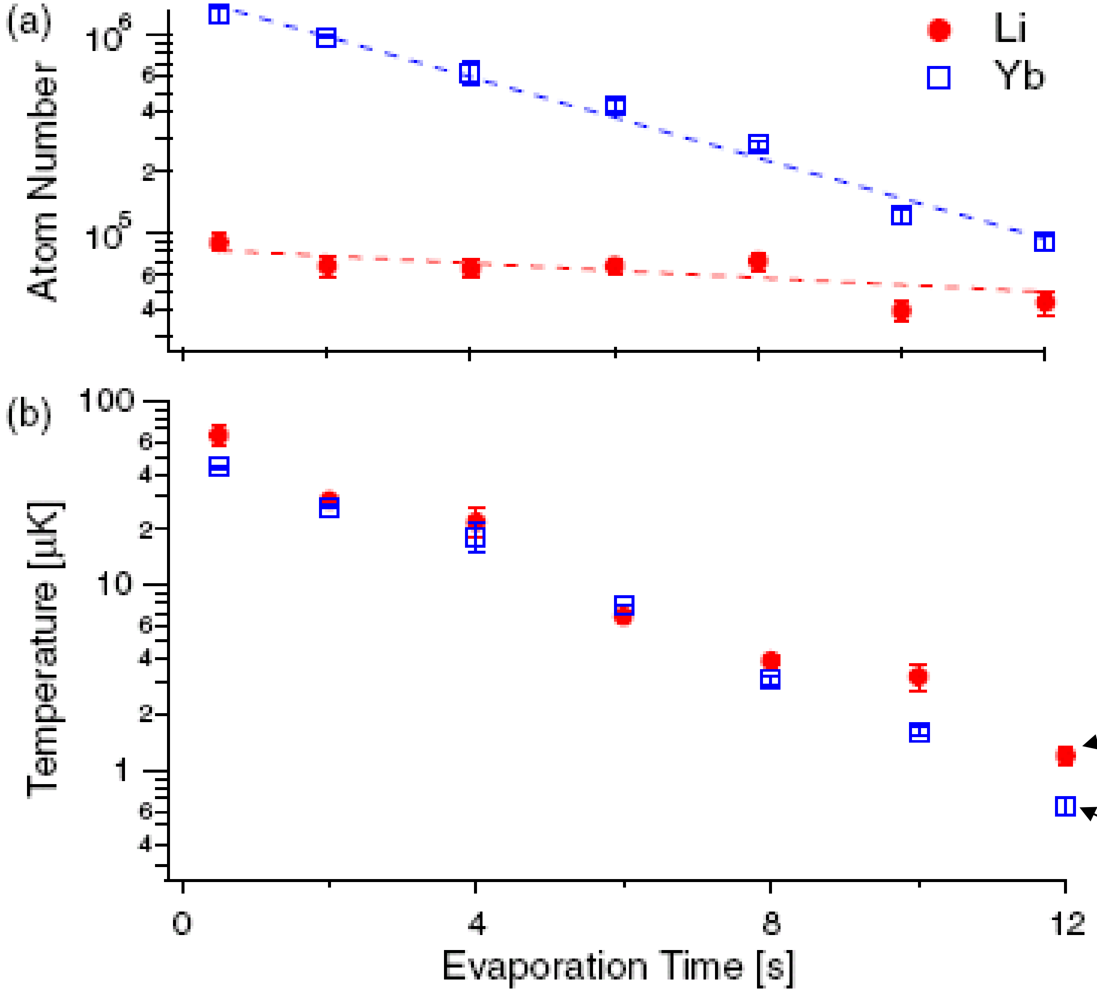
Ground State behavior of Li-Yb mixture



It’s stable!

Extract $|a| = (13 \pm 3)\, a_0$ (~ 0.7nm)

Sympathetic Cooling to below T_F



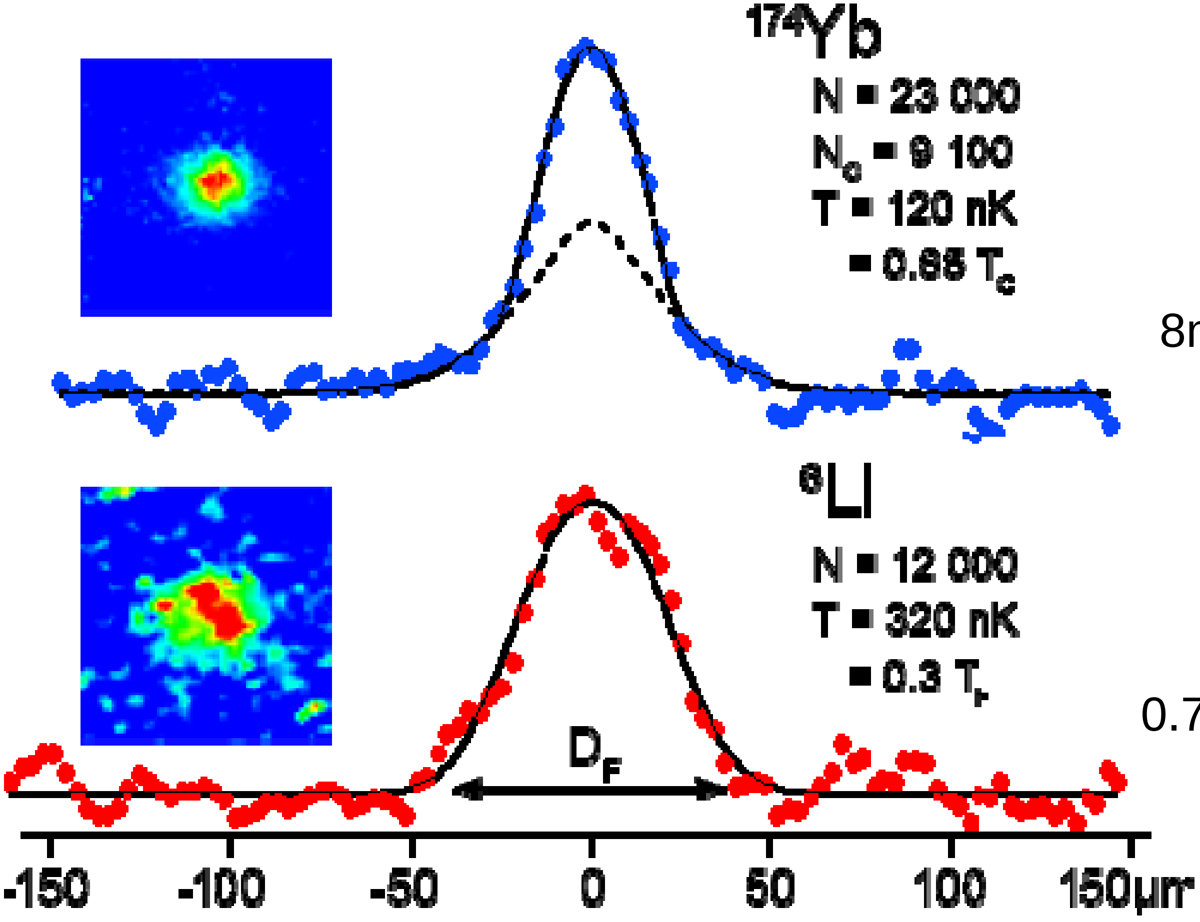
$T/T_F \sim 0.7$

$T/T_{BEC} \sim 4$

Small interspecies scattering length, but light Li provides high relative speed.

Ivanov et al, PRL **106**, 153201 (2011)

Simultaneous Quantum Degeneracy
in alkali + spin-zero system



8ms TOF

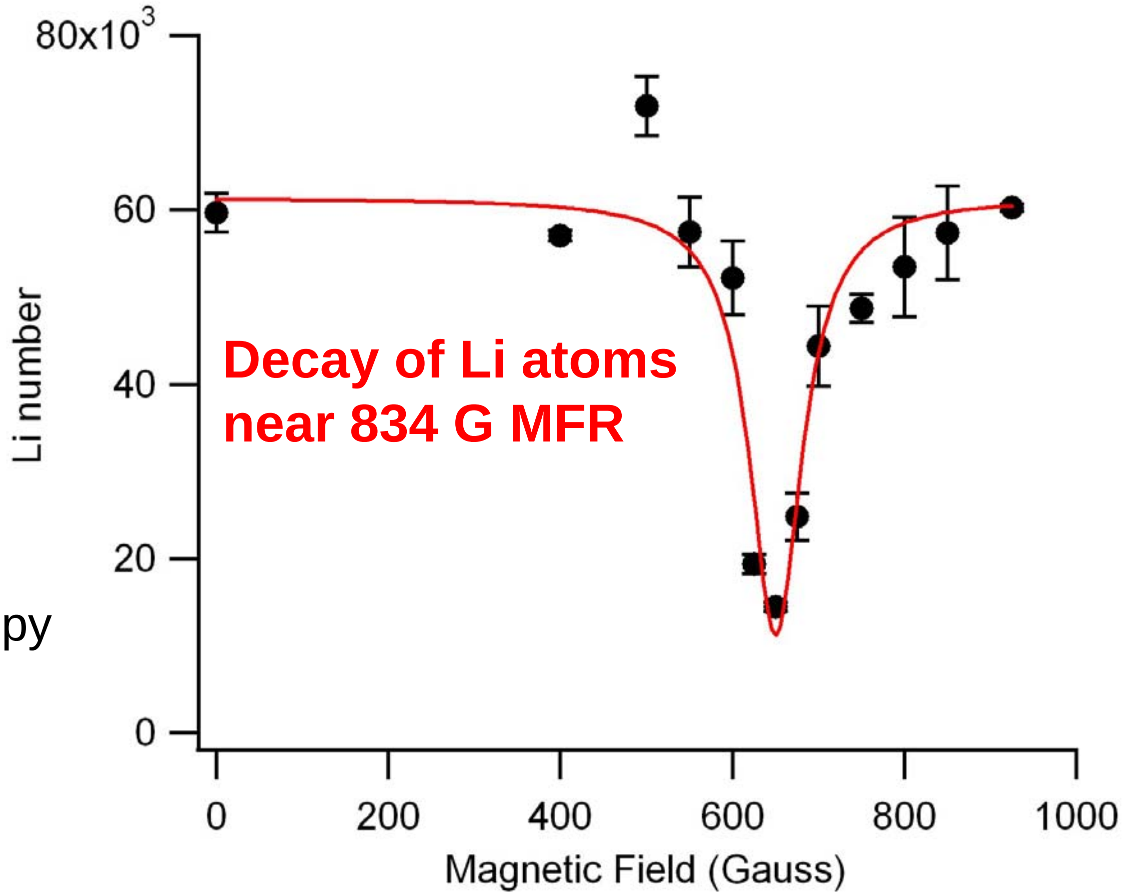
0.7ms TOF

Hansen et al, PRA (Rapid Comm), in press

Towards Interacting Mixtures and Molecules

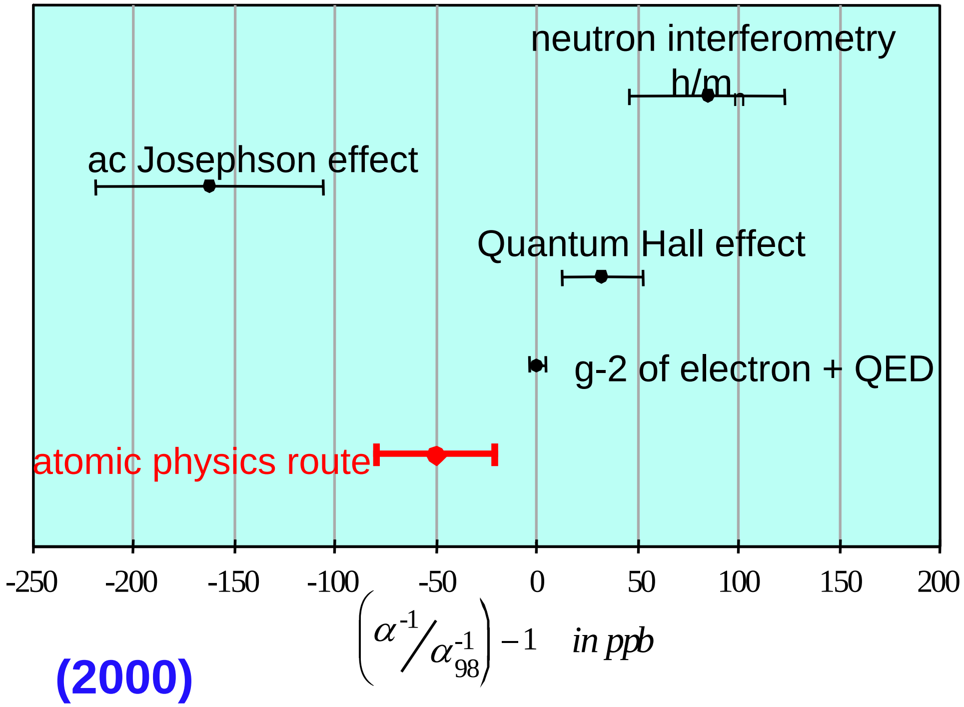
Search for Magnetic
Feshbach Resonances

Atom loss
spectroscopy



**Decay of Li atoms
near 834 G MFR**

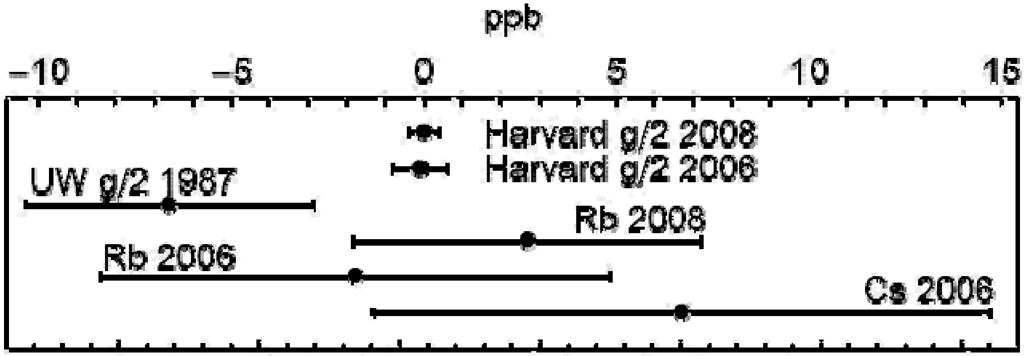
Precision Measurement of Fine Structure Constant α



(2000)

$$\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

Cross-field comparisons
Precision test of QED



(2008)

QED-free Atomic Physics Route to α

0.008 ppb: hydrogen spectroscopy, (Udem et al.,1997; Schwob et al.,1999)

Penning trap mass spectroscopy

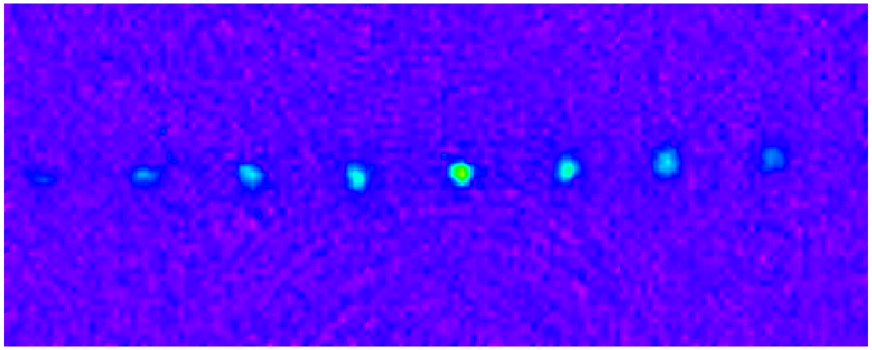
Frequency comb

$$\alpha^2 = \left(\frac{e^2}{\hbar c}\right)^2 = \frac{2R_\infty}{c}\frac{h}{m_e} = \frac{2R_\infty}{c}\frac{M}{M_e}\frac{h}{m}$$

$$\omega_{\text{rec}} = \frac{1}{2}\frac{\hbar}{m}k^2$$

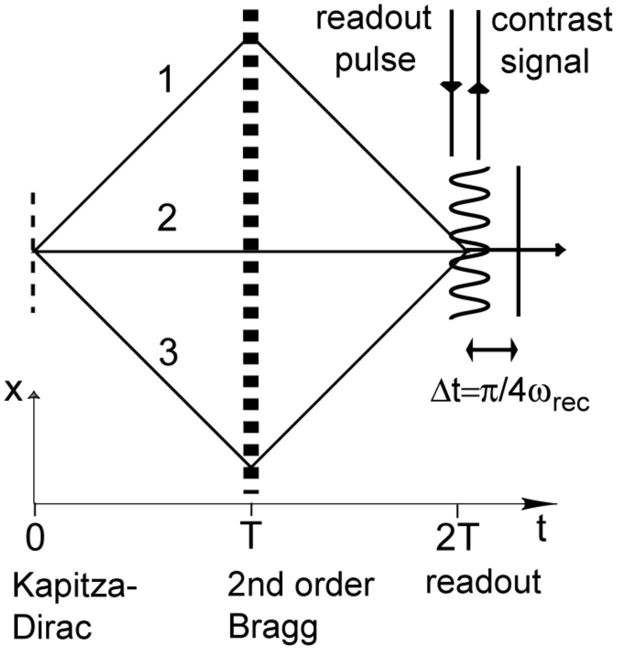
Cs (Berkeley)
Rb (Paris)

0.7 ppb: penning trap mass spectr.
(Beier et al., 2002)



BEC is a bright coherent source for atom interferometry

Contrast Interferometry with a BEC



no sensitivity to mirror vibrations, ac stark shift,
rotation, magnetic field gradients
quadratic enhancement with additional momenta

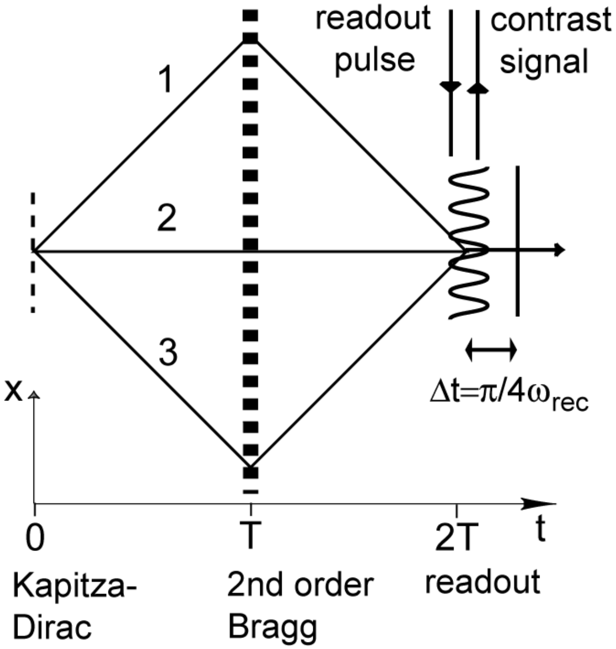
With Na BEC experiment
7ppm precision achieved,
but inaccuracy at 200ppm,
attributed to atomic interactions.

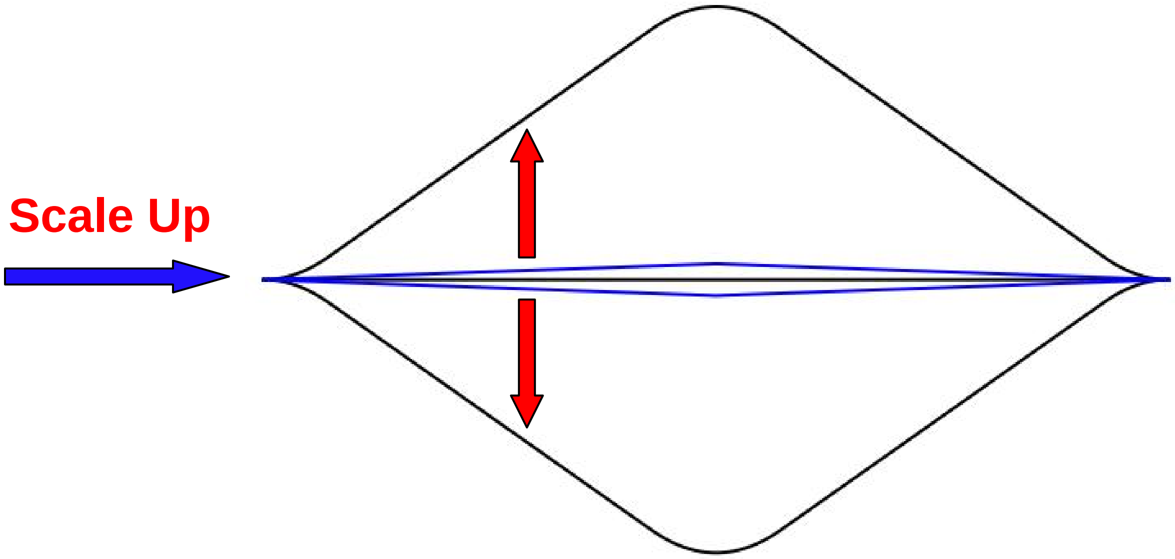
The phase of the matter wave grating is encoded in oscillating contrast.

$$S(T,t) = C(T,t)\sin^2\left(\frac{\Phi_1(t)+\Phi_3(t)}{2} - \Phi_2(t)\right) = C(T,t)\sin^2\left(8\omega_{\text{rec}}T + 4\omega_{\text{rec}}\Delta t\right)$$

The phase of the contrast signal for various T gives ω_{rec}.

Contrast Interferometry with a BEC

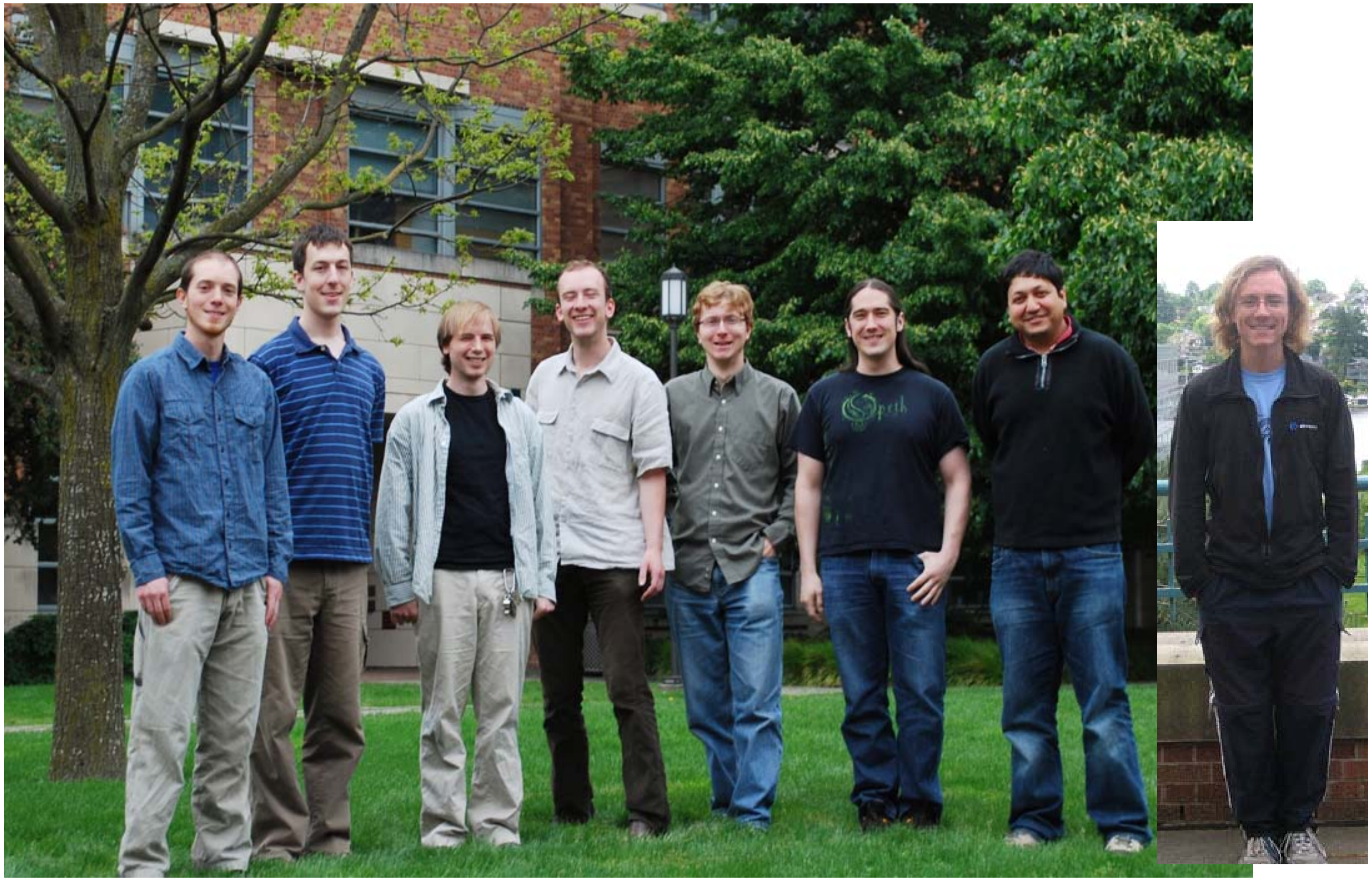




Increase sensitivity by increasing momenta of 1 and 3 by 20-fold and increasing T

Sub-ppb precision in few hours of data
Use of a Yb BEC – no B field sensitivity and multiple isotopes for systematic checks
Atom laser has interactions – careful study of this systematic effect

UW Ultracold Atoms Team



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Grad Students: Anders Hansen, Alex Khramov, Will Dowd, Alan Jamison,
Ben Plotkin-Swing

$$$ - NSF, Sloan Foundation, UW RRF, NIST