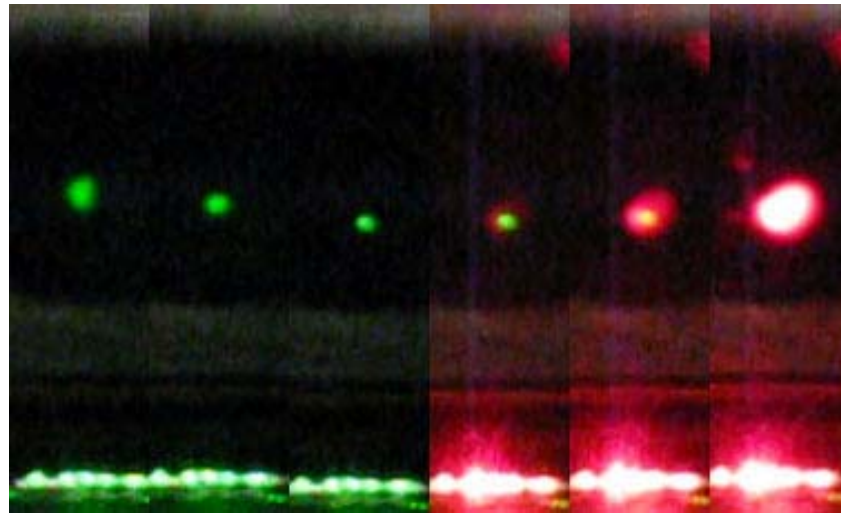


# Quantum Degenerate Mixtures of Lithium and Ytterbium

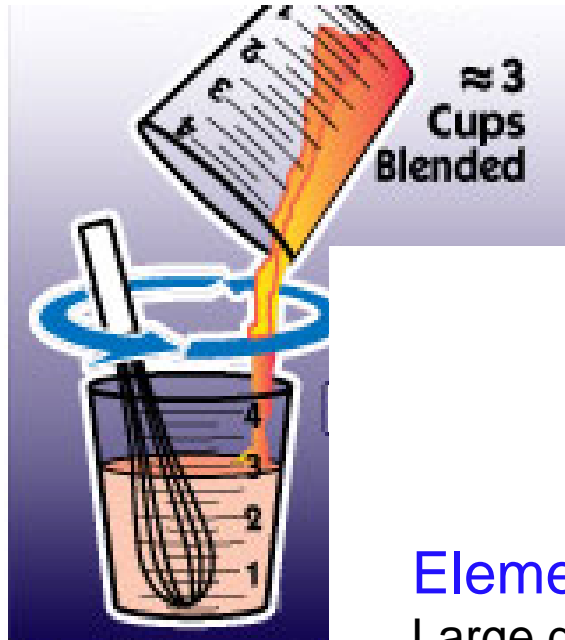
Subhadeep Gupta  
University of Washington, Seattle  
UW INT Workshop, 16th May 2011



# Mixtures

## Spin Mixtures

Distinguishability for technical (cooling) and scientific (strong interactions & polarized gases)



## Isotopic mixtures

Further ease of cooling  
Different statistics  
(slightly) heteronuclear

## Elemental Mixtures

Large differences in mass, electronic structure.

Heteronuclear – dipolar molecules  
Species selective techniques

# Colds Atoms Menu

hydrogen 1 H 1.0079																			helium 2 He 4.0026
<b>lithium</b> 3 <b>Li</b> 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	<b>chromium</b> 24 <b>Cr</b> 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	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	lutetium 71 Lu 174.97	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]	57-70 *	lanthanum 57 La [227]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [269]	unnilium 110 Uun [271]	ununium 111 Uuu [272]	unbibium 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	<b>dysprosium</b> 66 <b>Dy</b> 162.50	holmium 67 Ho 164.93	<b>erbium</b> 68 <b>Er</b> 167.26	thulium 69 Tm 168.93	<b>ytterbium</b> 70 <b>Yb</b> 173.04
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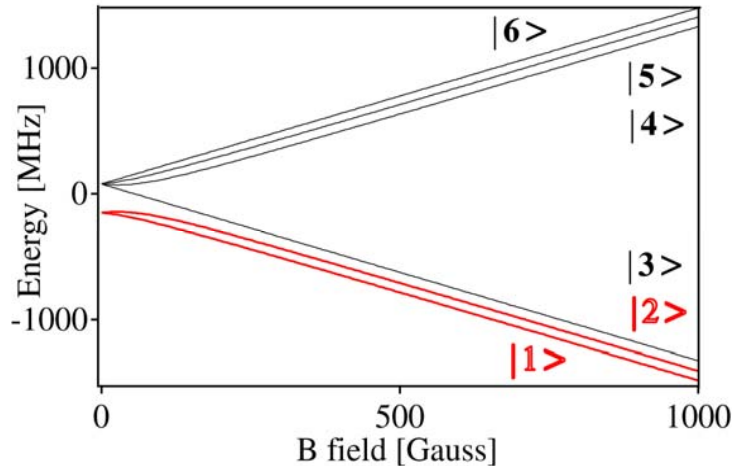
\*\* Actinide series

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]
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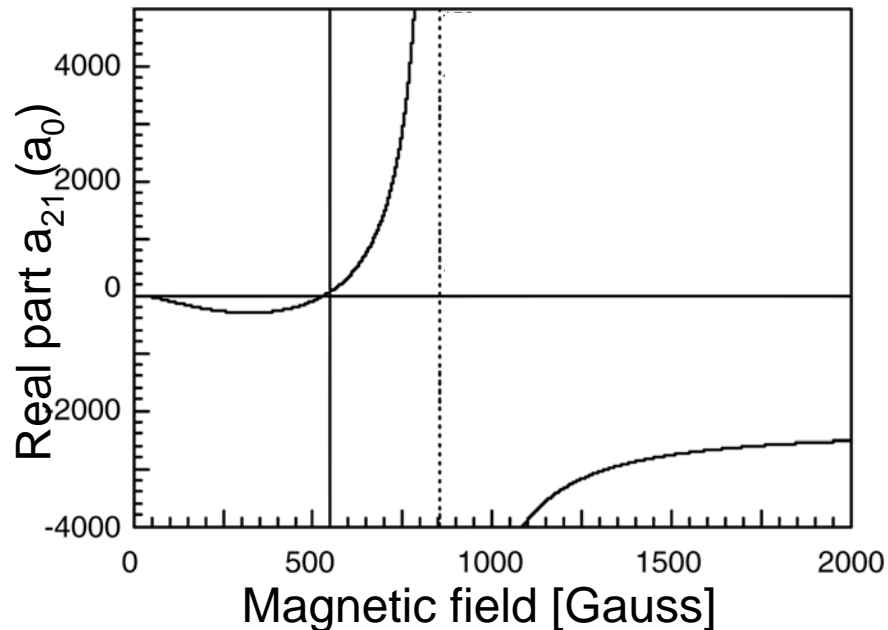
Li and Yb have different electronic structure and very different mass

# A little about ${}^6\text{Li}$

## Ground State of ${}^6\text{Li}$



## Magnetic Feshbach Resonance (MFR)



## Established cooling methods:

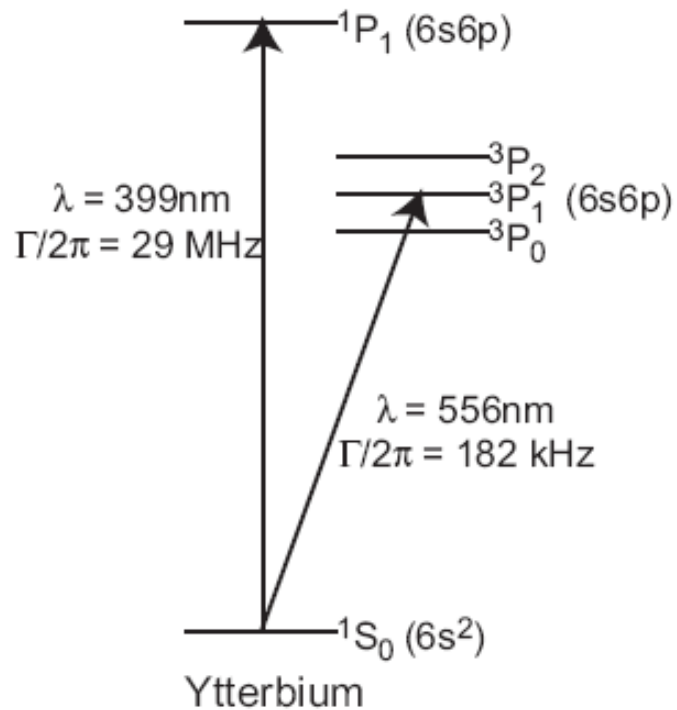
Red laser cooling line at 671nm

Evaporative cooling to degeneracy  
2-spin states at a convenient B  
in an optical trap

Sympathetic cooling by a boson  
( ${}^7\text{Li}$ ,  ${}^{23}\text{Na}$ ,  ${}^{87}\text{Rb}$ ) in a magnetic trap

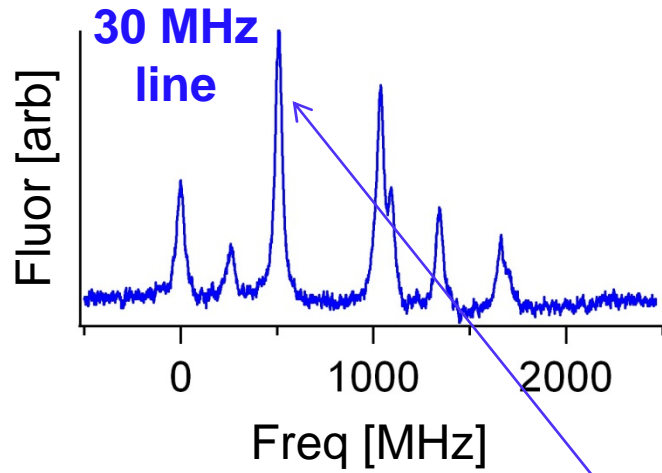
Molecular BEC/Fermi Superfluid/  
Universal Physics/ BEC-BCS crossover  
near Feshbach Resonance at 834G.

# A little about Yb

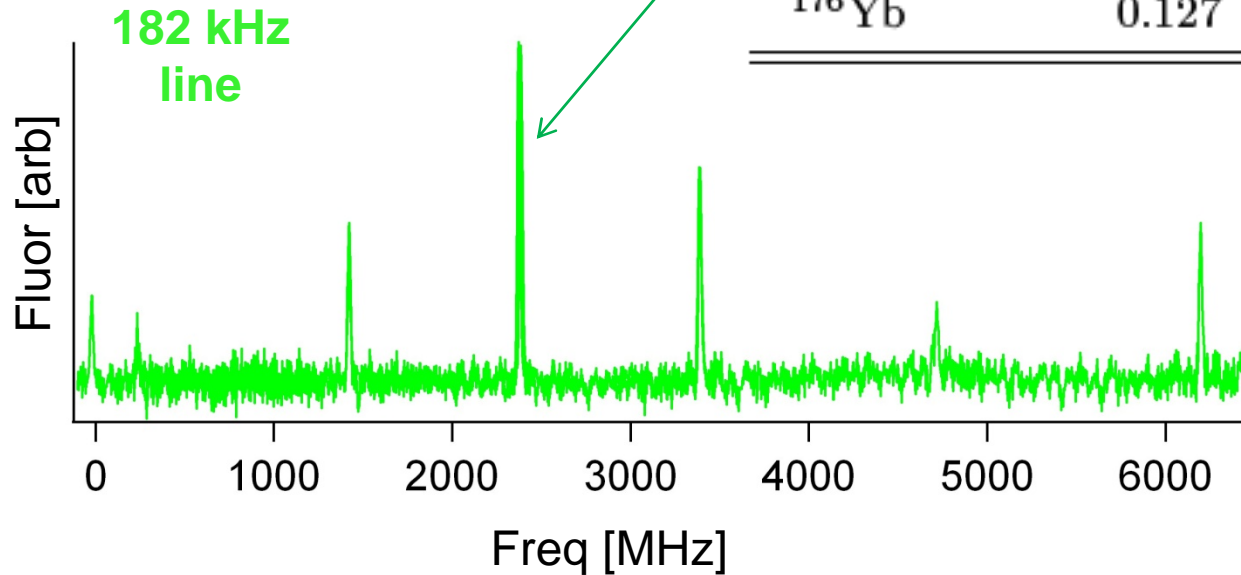


Isotope	Natural Abundance	Nuclear spin
$^{168}\text{Yb}$	0.0013	0
$^{170}\text{Yb}$	0.0305	0
$^{171}\text{Yb}$	0.143	1/2
$^{172}\text{Yb}$	0.219	0
$^{173}\text{Yb}$	0.161	5/2
$^{174}\text{Yb}$	0.318	0
$^{176}\text{Yb}$	0.127	0

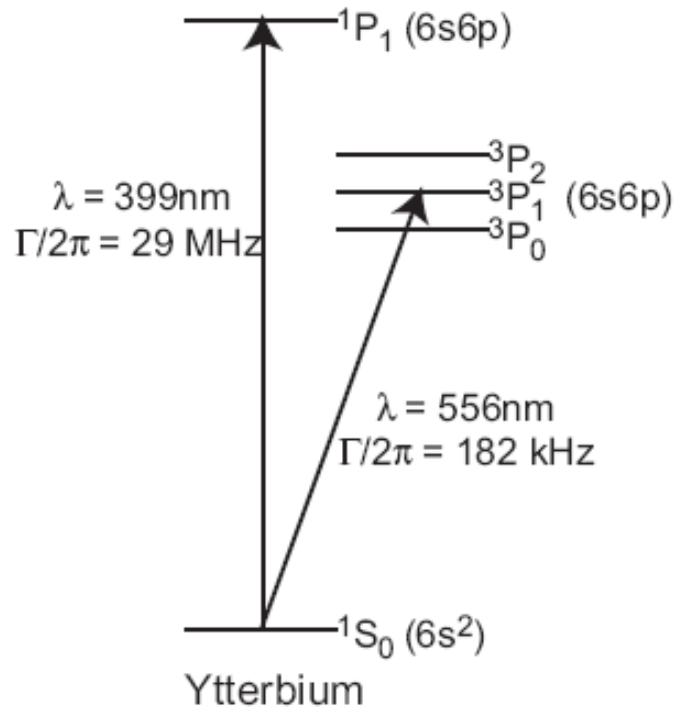
# A little more about Yb



Isotope	Natural Abundance		Nuclear spin
$^{168}\text{Yb}$	0.0013		0
$^{170}\text{Yb}$	0.0305		0
$^{171}\text{Yb}$	0.143		1/2 <b>F</b>
$^{172}\text{Yb}$	0.219		0
$^{173}\text{Yb}$	0.161	10.55nm	5/2 <b>F</b>
$^{174}\text{Yb}$	0.318	5.55nm	0
$^{176}\text{Yb}$	0.127		0



# A little more about Yb



Many isotopes cooled to degeneracy (Kyoto)

Atomic clock on  $1S_0 \rightarrow 3P_0$  (NIST, others)

Heavy – useful for precision measurements  
eg. e-EDM search in  $3P_2$

Yb fermions in optical lattice

Quantum simulation, quantum computation

When mixed with alkali:

Good collisions only - spin-zero ground state

Additional species selectivity with B field gradient

Possibility of paramagnetic polar molecules

# The Li-Yb combination

Ground States: Collisionally stable mixture expected. However very small thermalization factor ( $\sim 21$  collisions per particle for thermalization).

Mass Ratio = 29, B-F and F-F combos available

new collisional regime ( $> 13.6$ )

new many-body regime (highly mismatched Cooper pairs?)

Tunable interactions

Magnetic Feshbach resonances – available?

Optical Feshbach resonances – usable?

Microscopic/Impurity probe of the  ${}^6\text{Li}$  superfluid

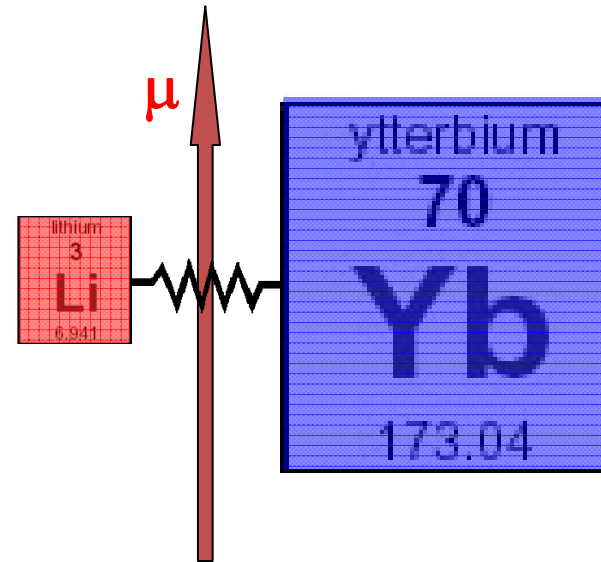
**Other similar mixtures:**

**Rb+Yb (Dusseldorf, NIST), Li+Yb (Kyoto), Rb+Sr (Innsbruck)**



# The Li-Yb combination

A paramagnetic polar molecule  
with electronic degree of freedom



**Dipolar physics**

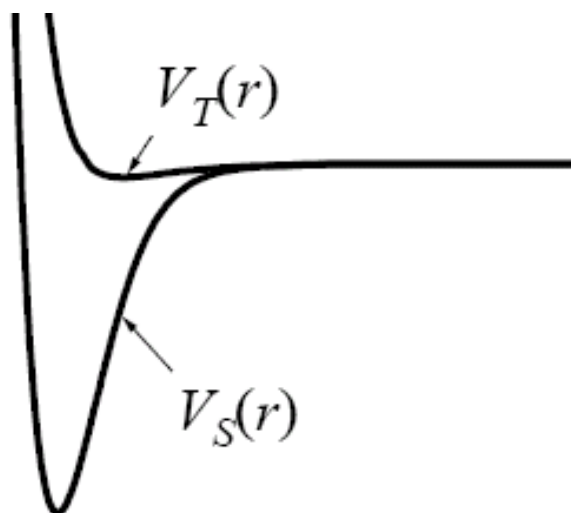
**Quantum simulation of lattice spin models**

**Quantum computing**

**Sensitive test of fundamental symmetries (e-EDM)**

Ground state molecule production by ultracold atom association in Jin/Ye group (KRb), Weidemuller (LiCs), DeMille (RbCs), Nagerl (Cs<sub>2</sub>),...

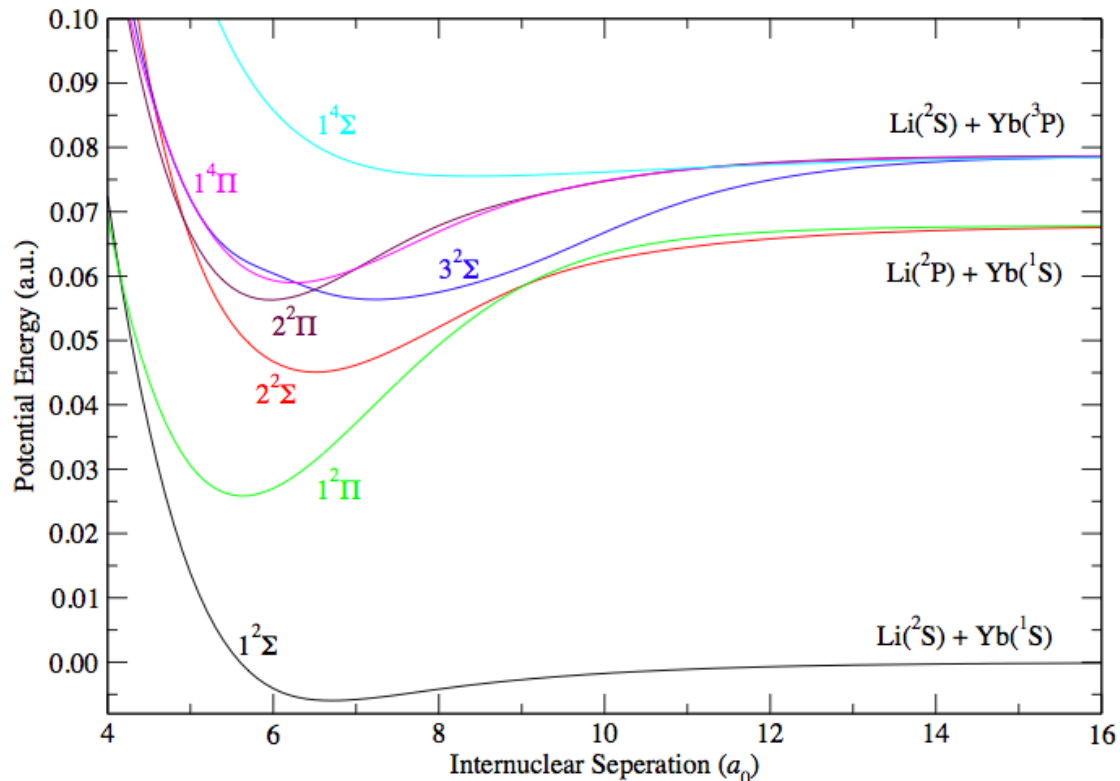
# Feshbach resonance in LiYb?



Only doublet-sigma ground state potential for alkali+spin-singlet collisions. No “usual” MFR.

Weak MFRs may exist  
[Hutson and co-workers,  
PRL 105, 153201 (2010)]

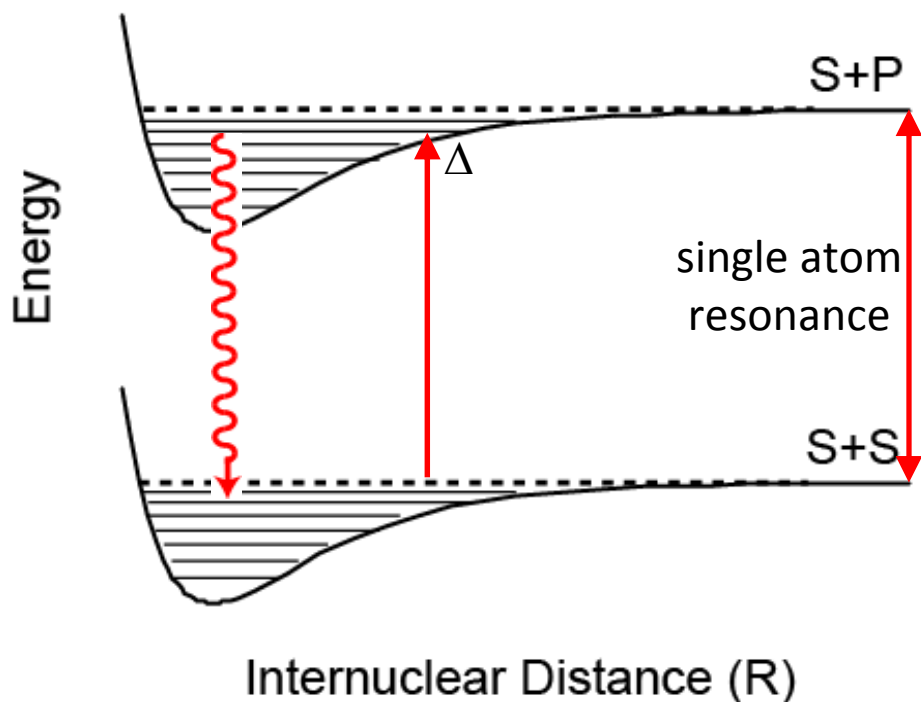
MFR through coupling between singlet and triplet ground state potentials in alkali+alkali collisions



Ab-initio Li-Yb potentials from Zhang et al.  
JCP 133, 044306 (2010).

# Optical Feshbach Resonance

Optically connect free particles with an excited molecular state.  
Initial proposal by Shlyapnikov and others [PRL 77, 2913 (1996)].



[First observation in Grimm group  
Theis et al, PRL **93**, 123001 (2004)]

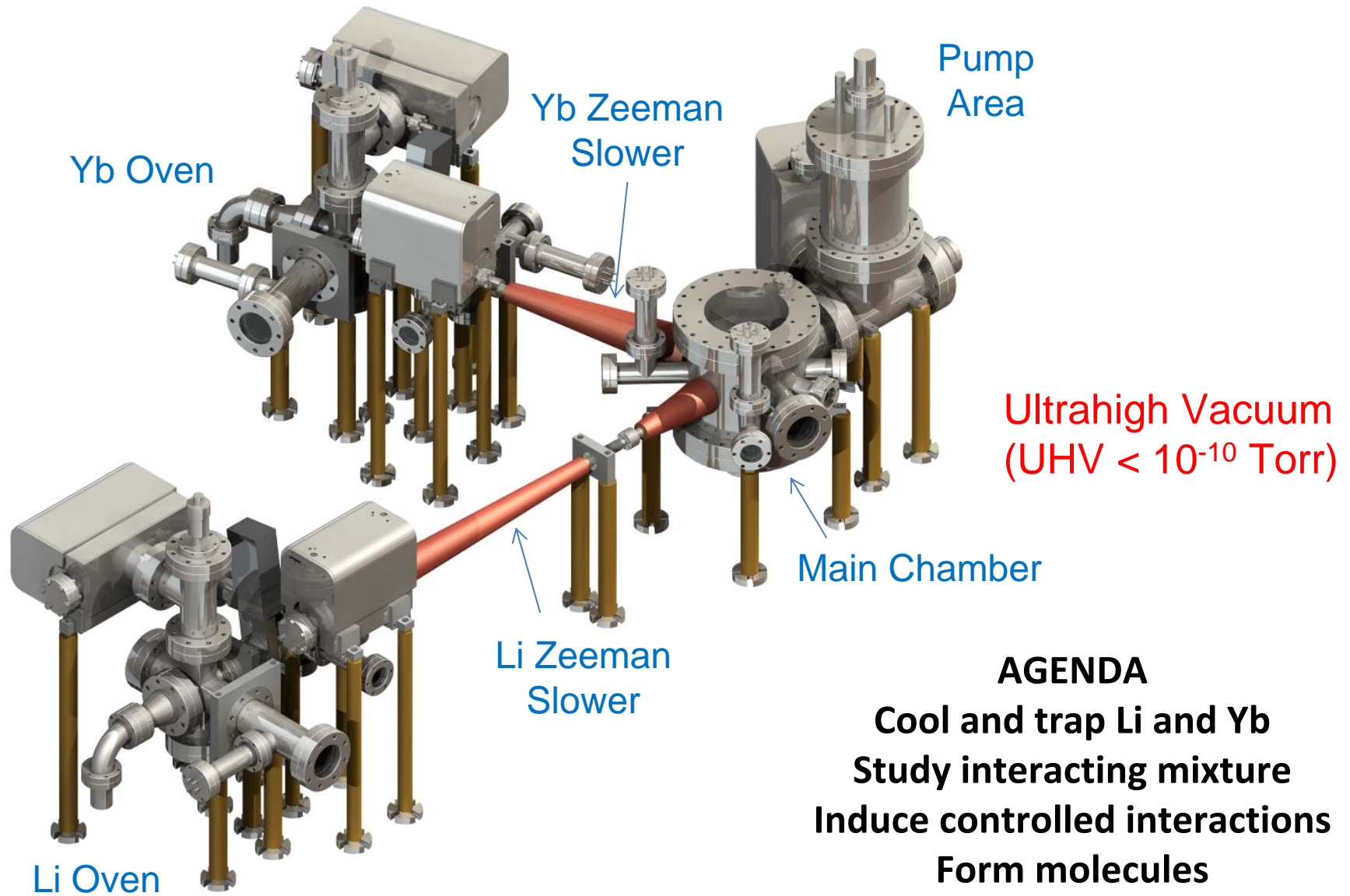
Optical Feshbach  
Resonance

[Grimm, Takahashi, Killian, Jun Ye]

Photoassociation  
Resonance

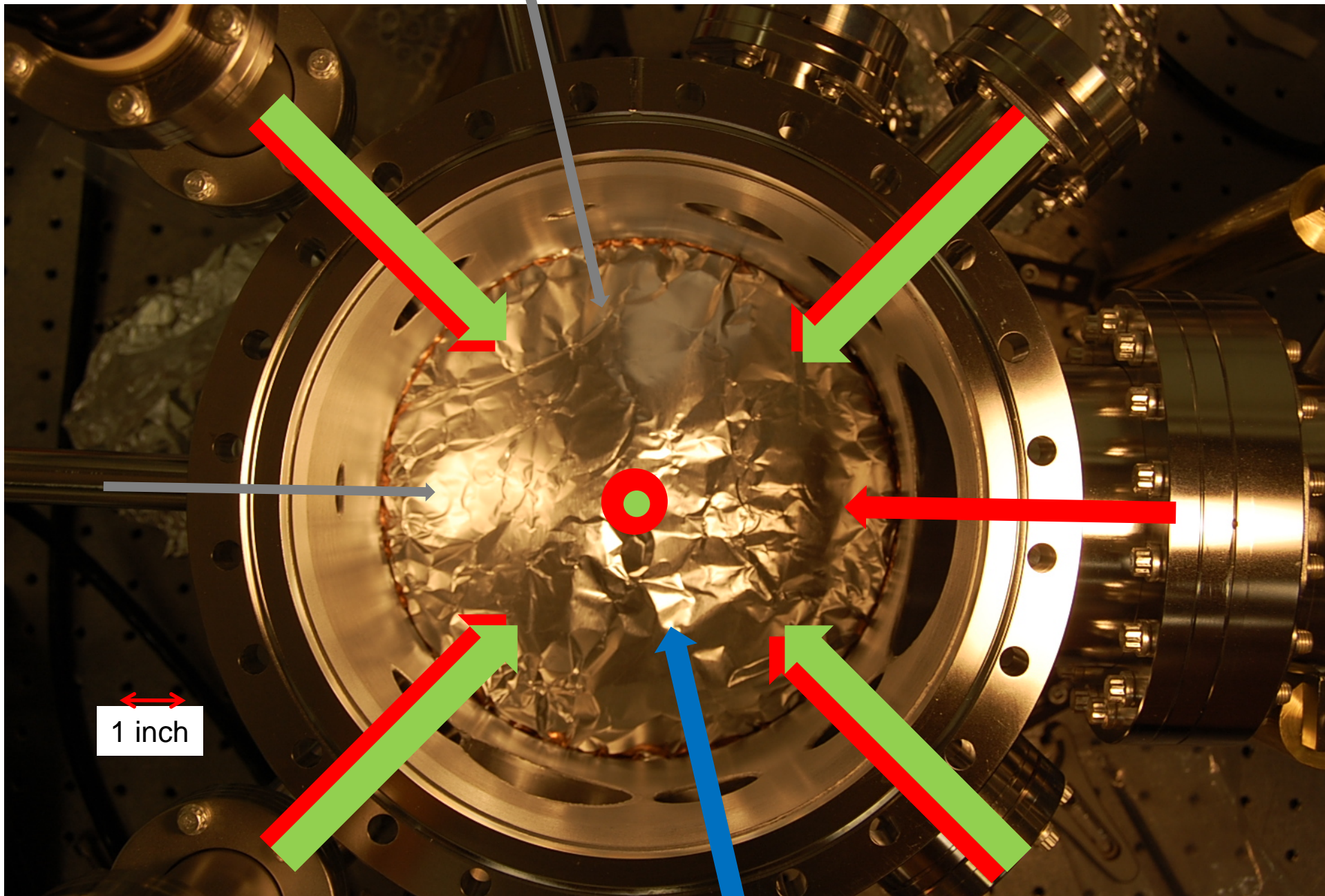
Further theory work by Bohn, Julienne, co-workers  
More applicable with narrow optical transitions

# Co-trapping of Li and Yb

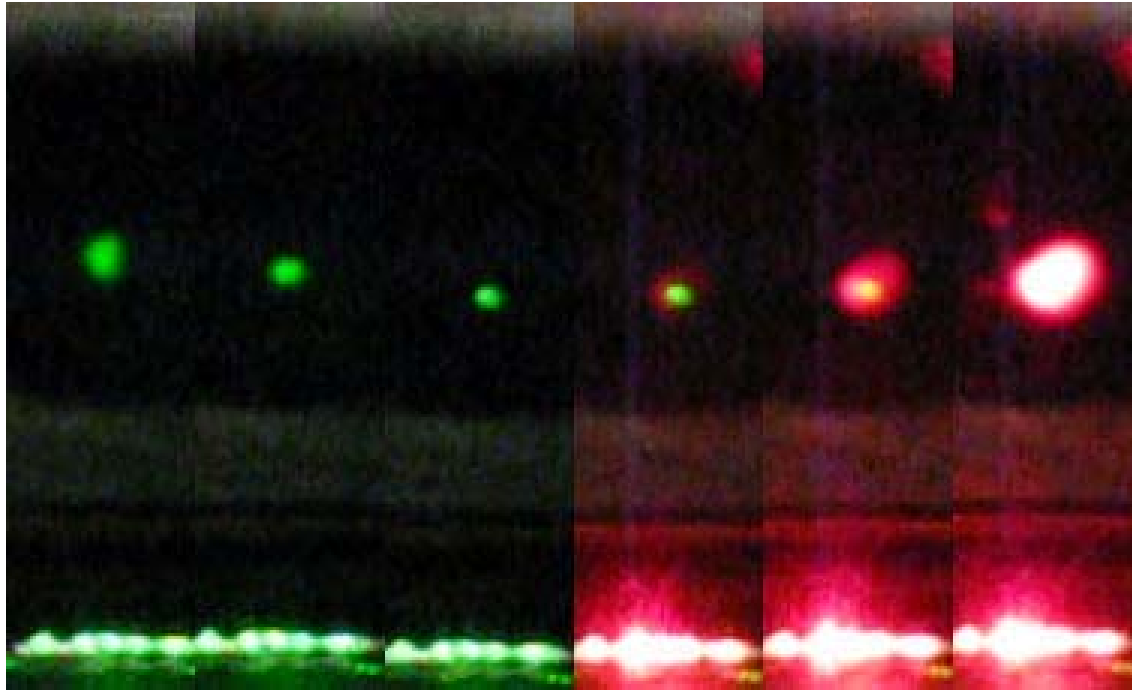




# Dual Species Apparatus



# Yb MOT and double MOT

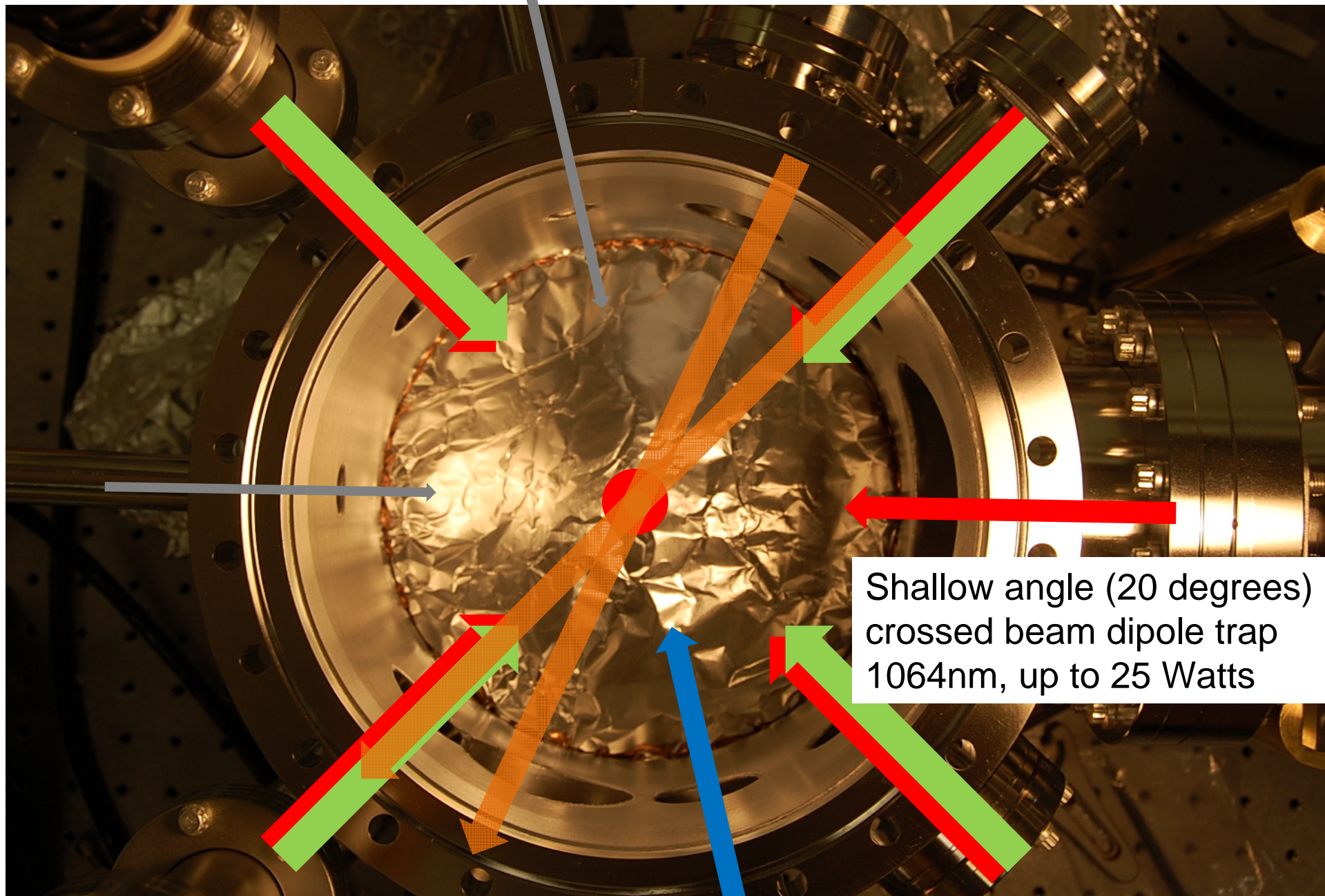


## Sequential Loading

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



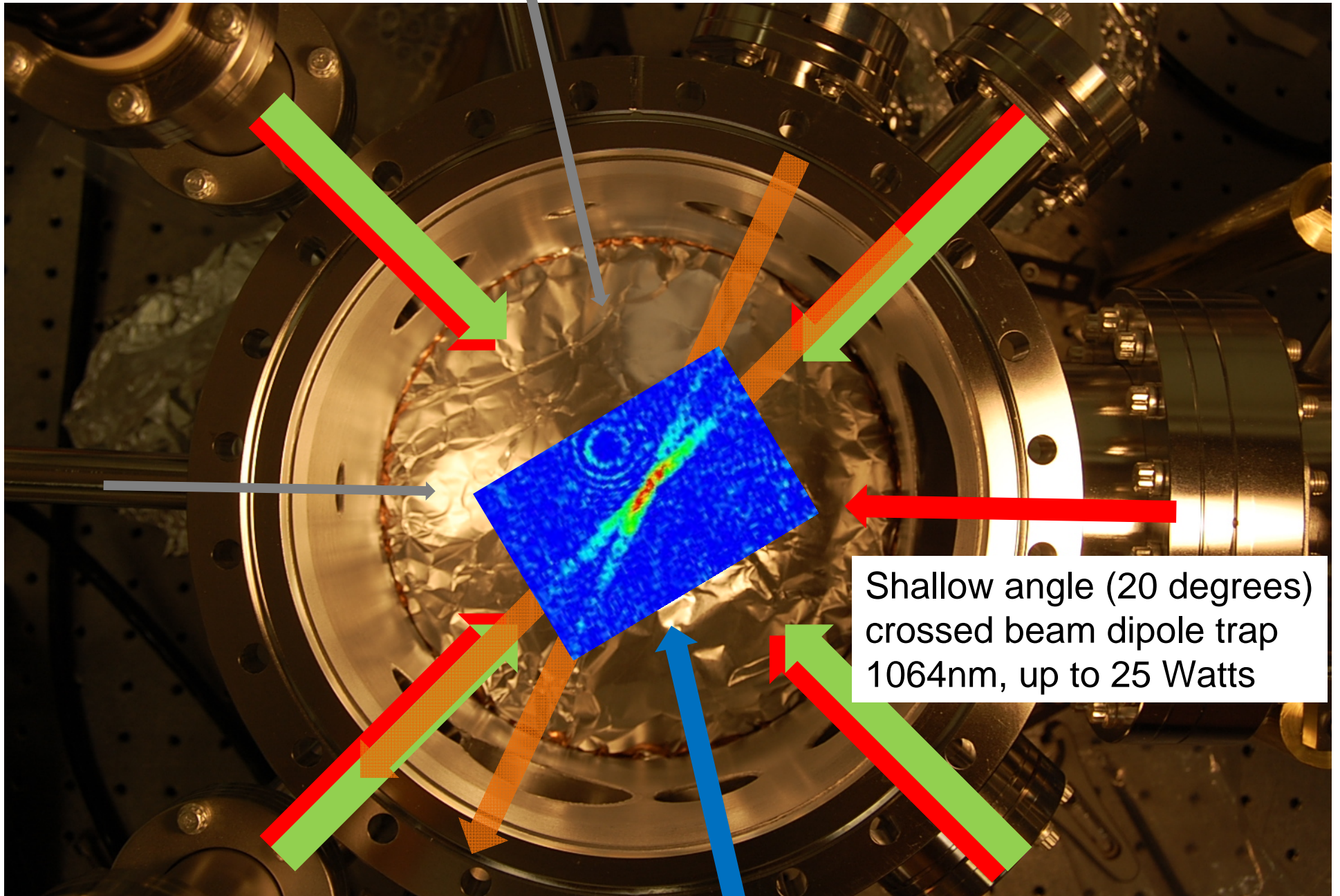
# Optical Dipole Trap



Shallow angle (20 degrees)  
crossed beam dipole trap  
1064nm, up to 25 Watts

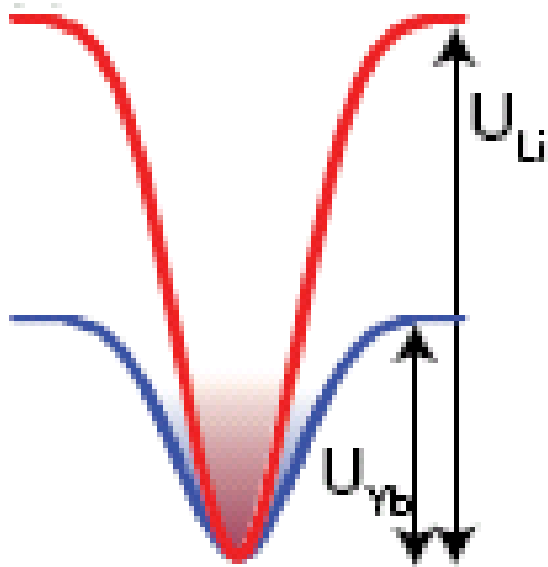


# Optical Dipole Trap





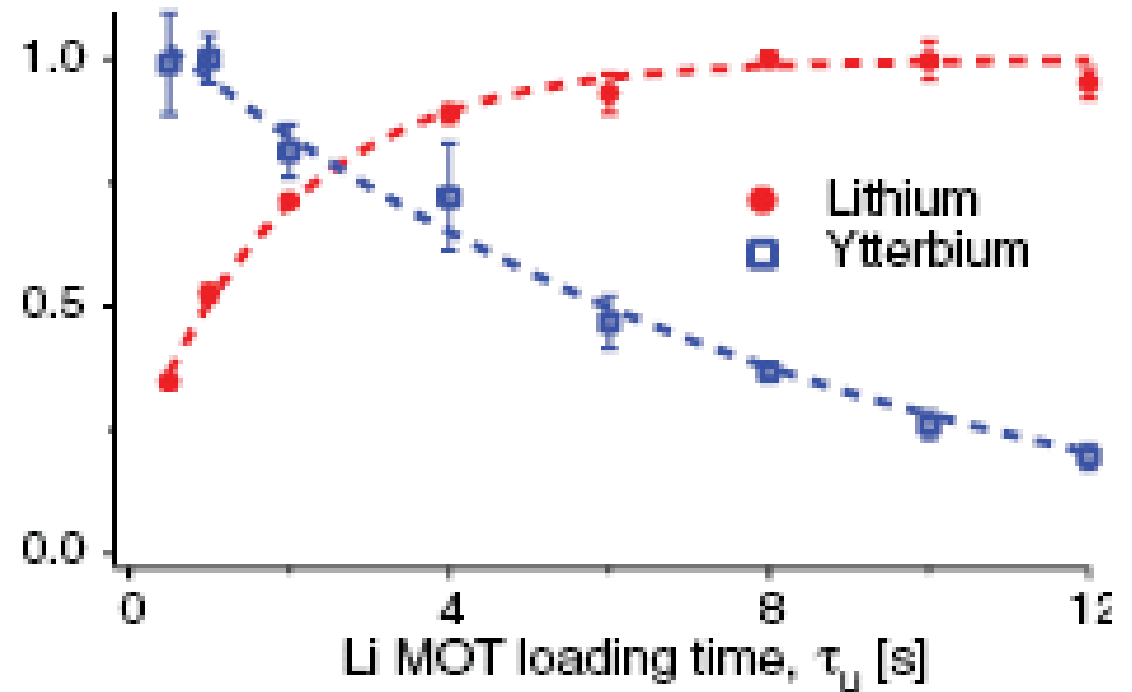
# Co-trapping of Lithium and Ytterbium



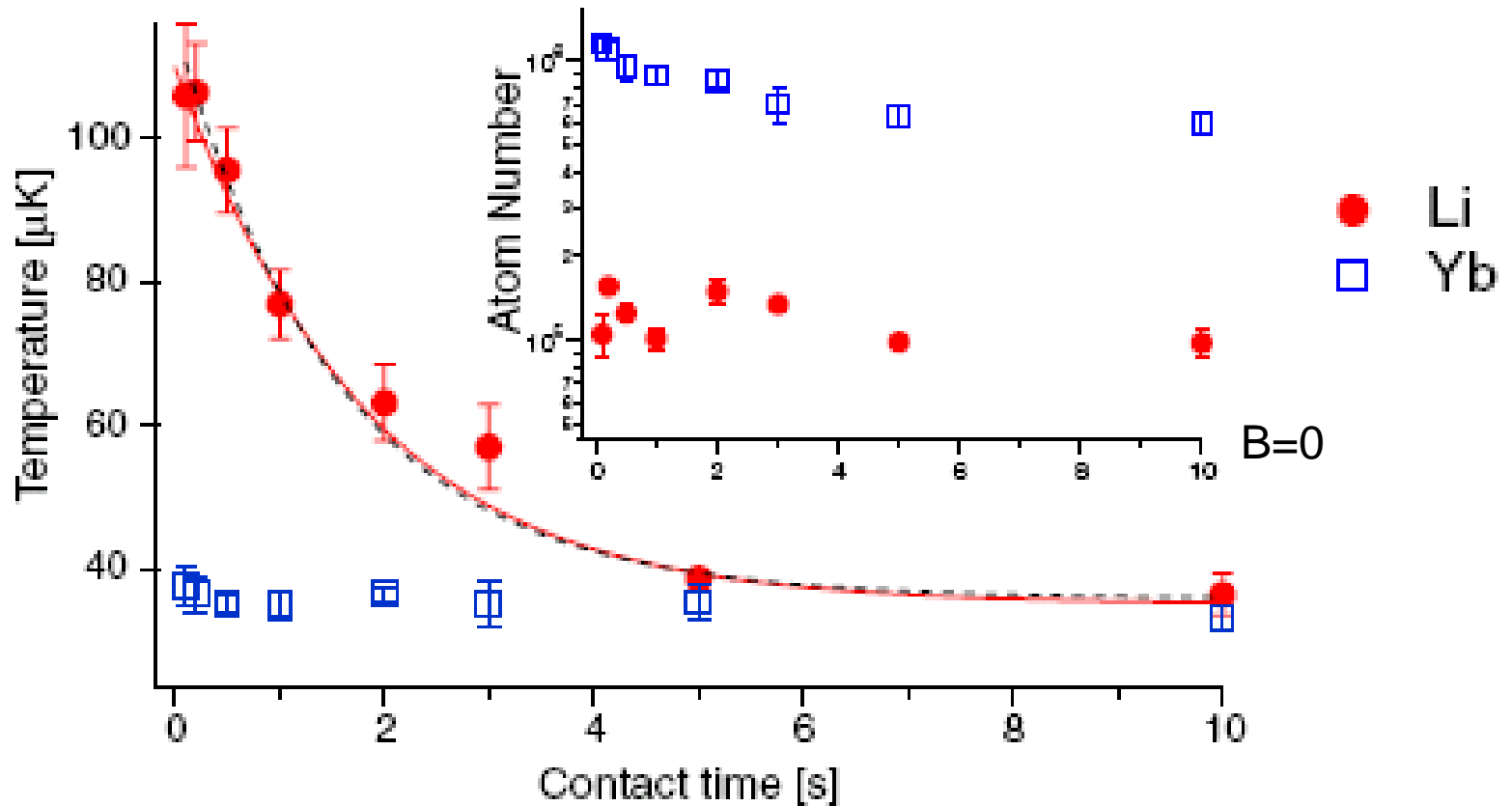
1064nm optical trapping potentials for Li and Yb.

$$\omega_{Li}/\omega_{Yb} = 8$$

Controlling the relative numbers



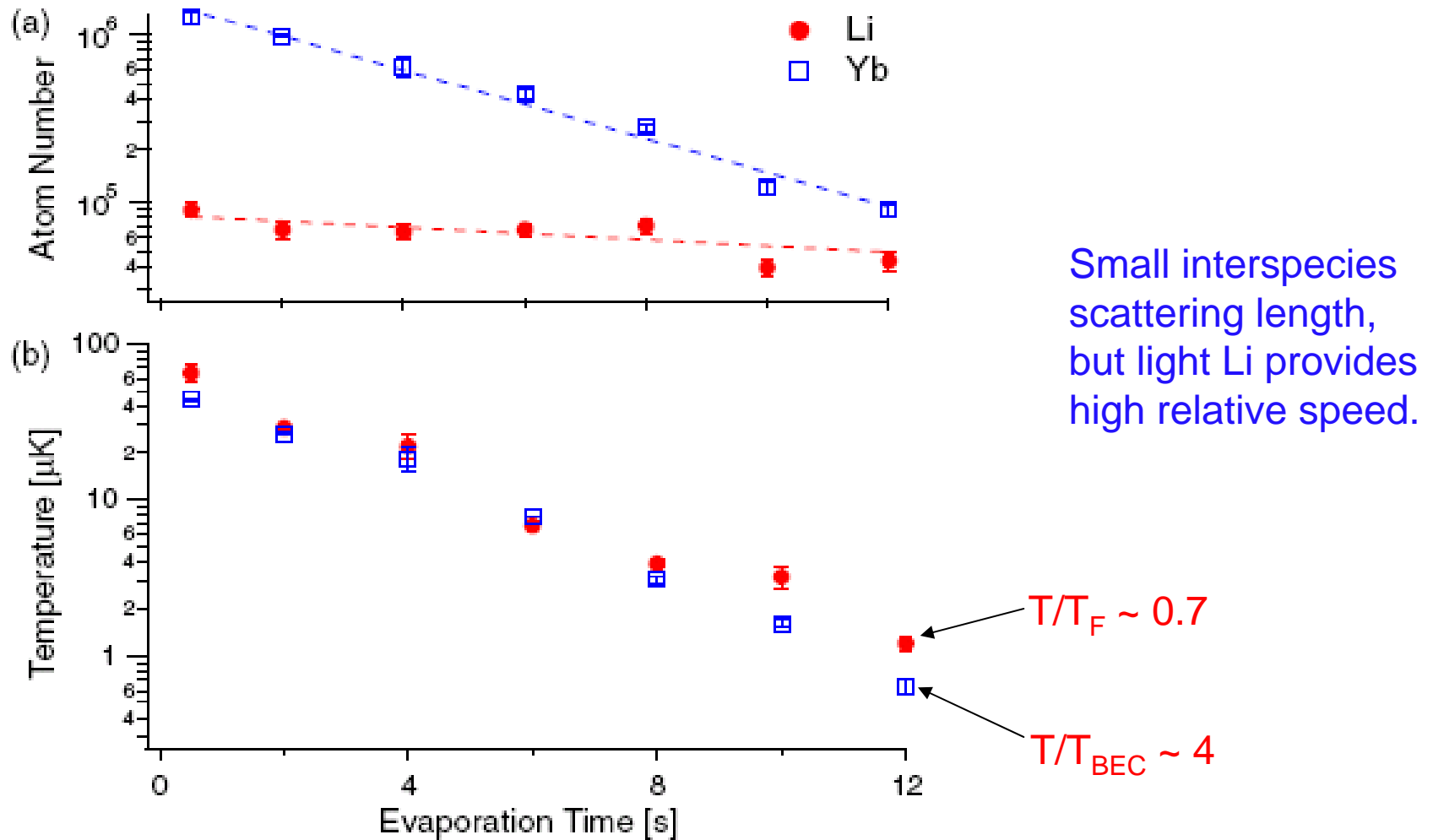
# Ground State behavior of Li-Yb mixture



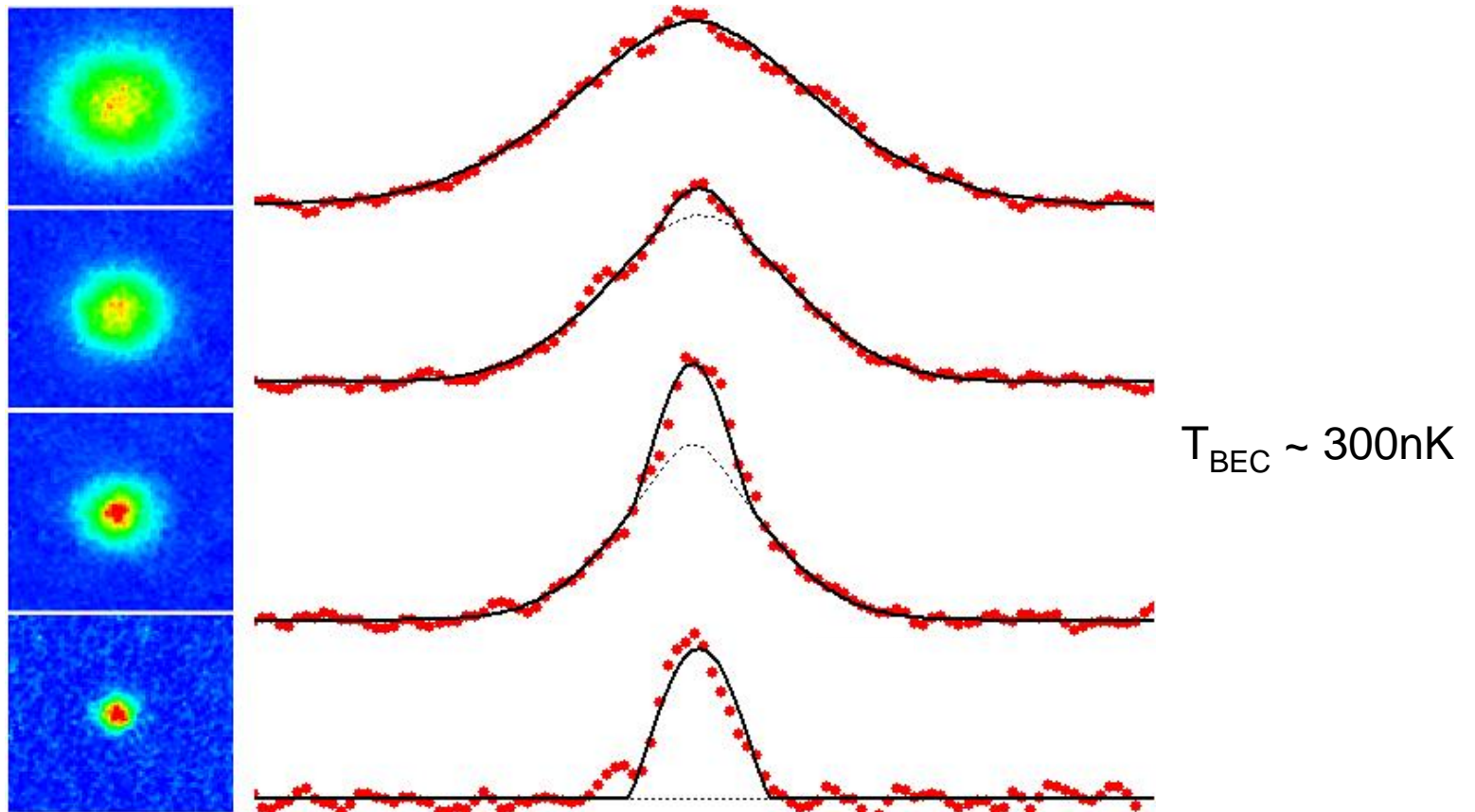
It's stable!

Extract  $|a| = (13 \pm 3) a_0$  ( $\sim 0.7 \text{ nm}$ , kind of small)

# Sympathetic Cooling to below $T_F$



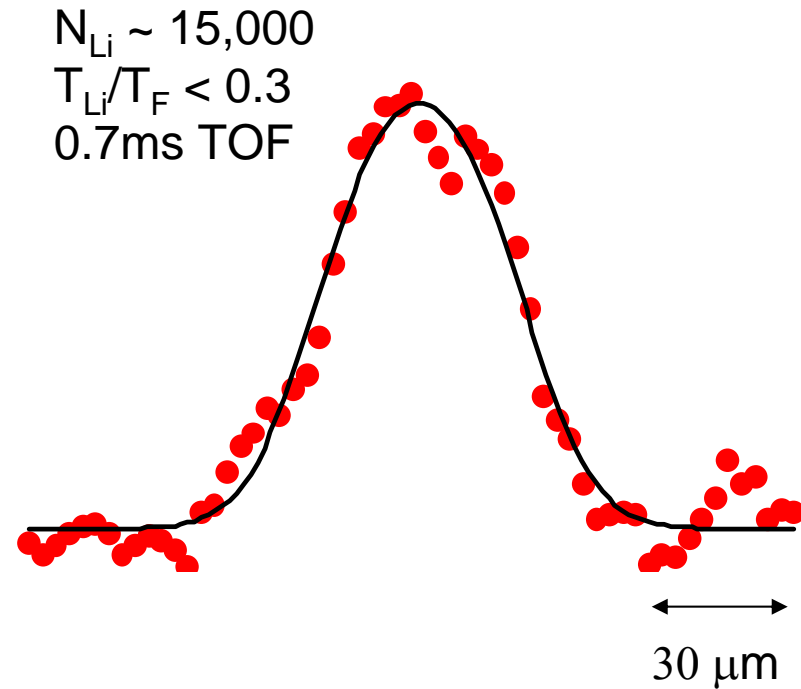
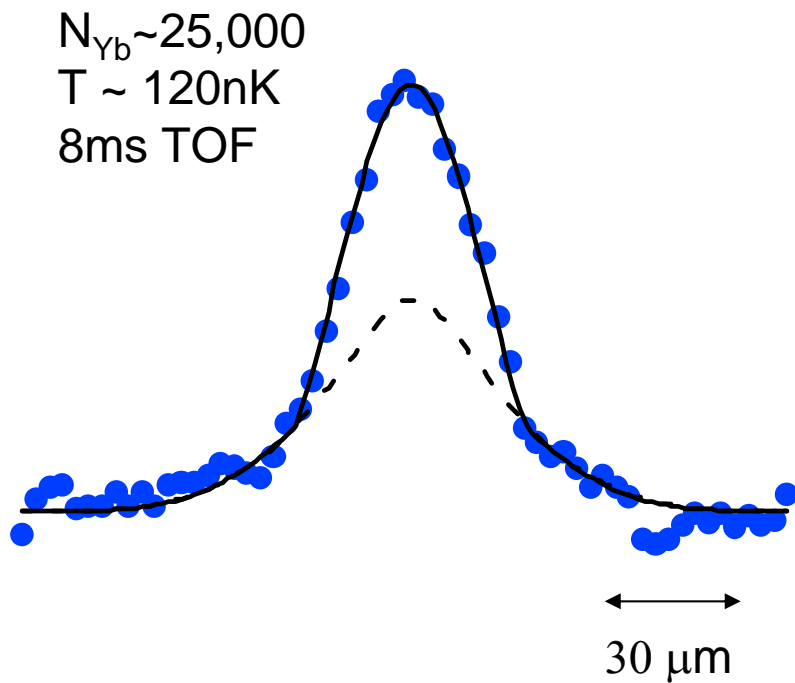
# Bose-Einstein condensation of $^{174}\text{Yb}$ in a $1.06\mu\text{m}$ trap



A straightforward method to create Yb BECs in 1064nm potential.  
Quasi-pure BECs with up to 50,000 atoms possible

Recent technical improvements: improved laser cooling, tighter optical confinement.

# Simultaneous Quantum Degeneracy in alkali + spin-zero system



Recent similar results in Takahashi/Doyle collaboration

## Implications for other Li-Yb combinations

Isotope	Natural Abundance		Nuclear spin
$^{168}\text{Yb}$	0.0013		0
$^{170}\text{Yb}$	0.0305		0
$^{171}\text{Yb}$	0.143		1/2 <b>F</b>
$^{172}\text{Yb}$	0.219		0
$^{173}\text{Yb}$	0.161	10.55nm	5/2 <b>F</b>
$^{174}\text{Yb}$	0.318	5.55nm	0
$^{176}\text{Yb}$	0.127		0

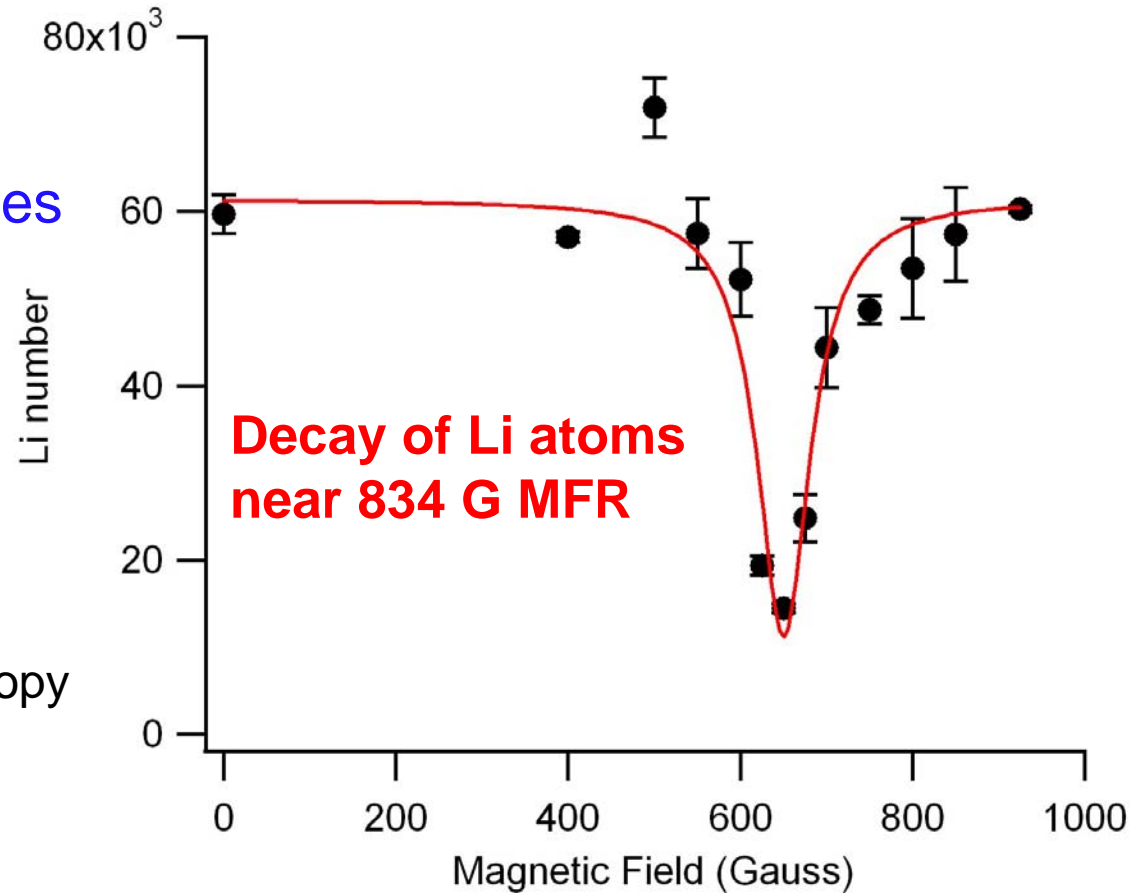
**+  $^6\text{Li}$**  Should all be stable with near identical value of scat length  
 $^{173}\text{Yb} + ^6\text{Li}$  gives most promising degenerate Fermi-Fermi mixture.

**+  $^7\text{Li}$**  Should all have near identical value of scat length, different from above.

# What Next?

Search for Magnetic Feshbach Resonances

Atom loss spectroscopy



(seen earlier in several expts.)

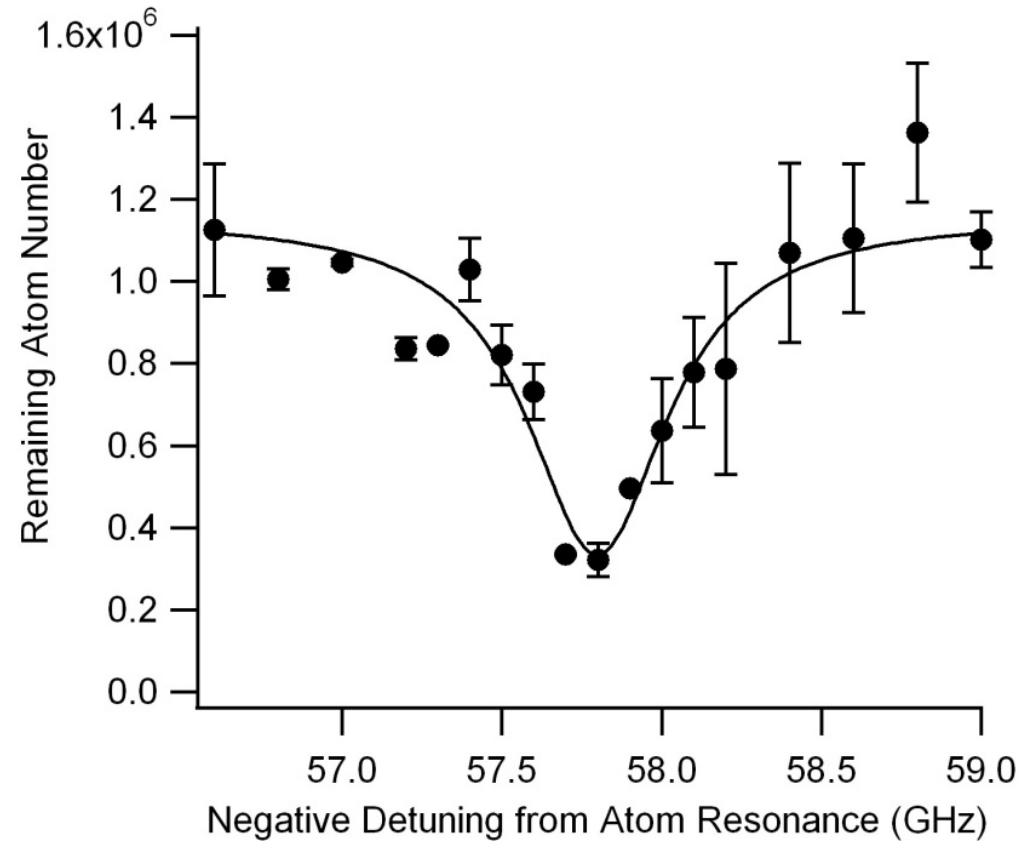
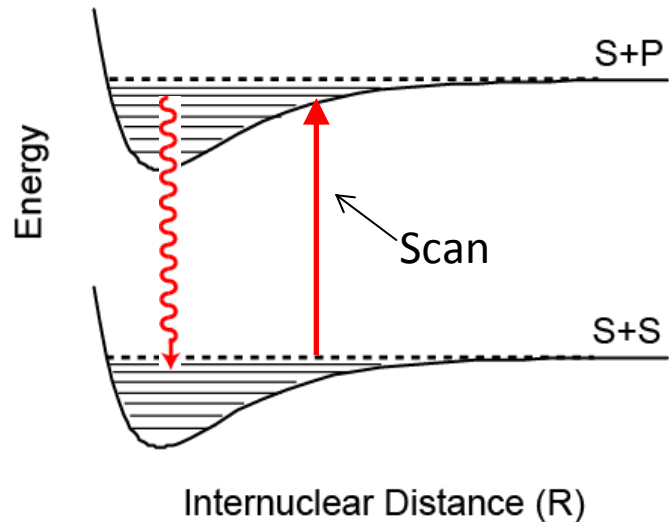
Li MFR in the presence of Yb.

Collisions with distinguishable 3<sup>rd</sup> component (heavy, boson/fermion)

Impurity/microscopic probe of  $^6\text{Li}$  superfluid

# What Next?

## Photoassociation Spectroscopy



**Trap loss measurement  
in the  ${}^6\text{Li}$  system**

Provides information on excited potential  
Key step towards LiYb molecule  
Key step towards Optical Feshbach Resonance



# UW Ultracold Atoms Team



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

Undergrad: Ben Schwyn

Post-doc: Vlad Ivanov (now at UW Madison)

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