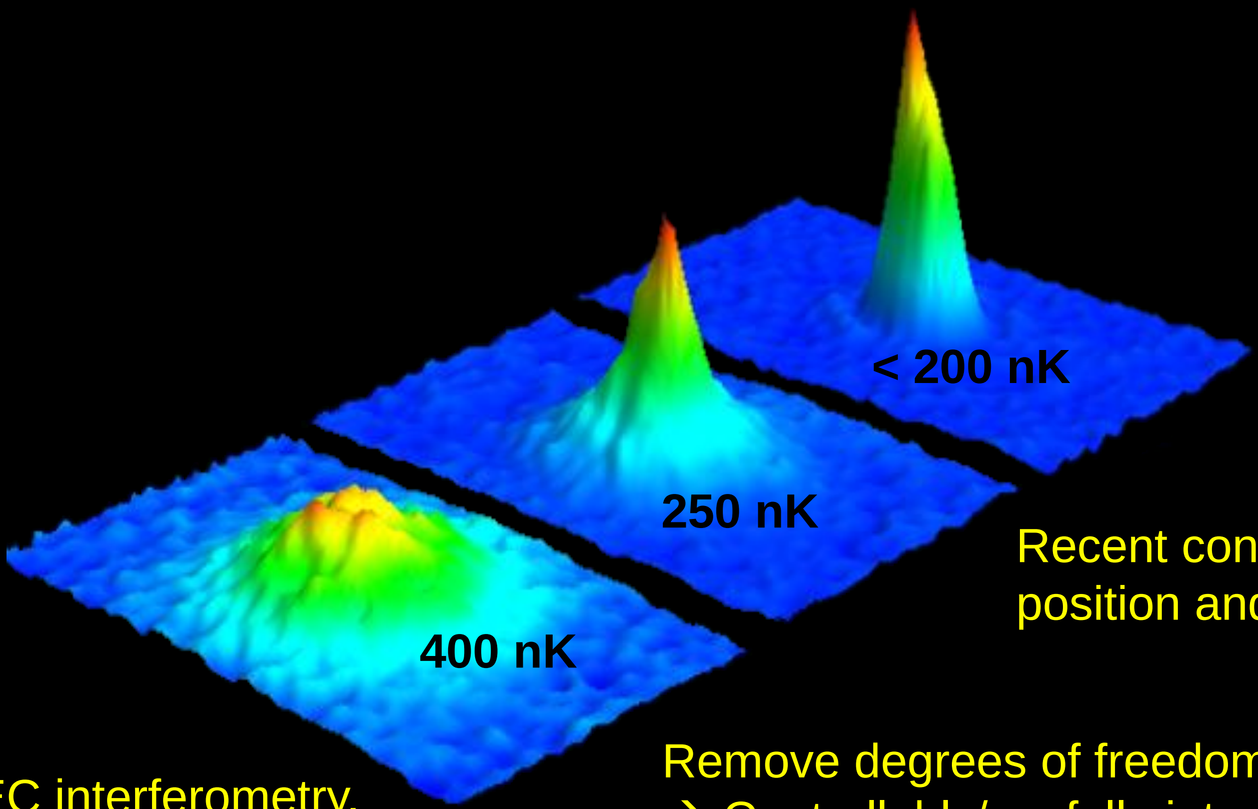
NanoKelvin Quantum Engineering

Subhadeep Gupta
UW NSF-INT Phys REU, 28th July 2014

NanoKelvin Quantum Engineering
with Ultracold Atoms



Recent control of atomic position and momentum.

Our group:
Precision BEC interferometry.
Ultracold Mixtures & Molecules

Remove degrees of freedom → Manipulate
→ Controllably/usefully introduce complexity

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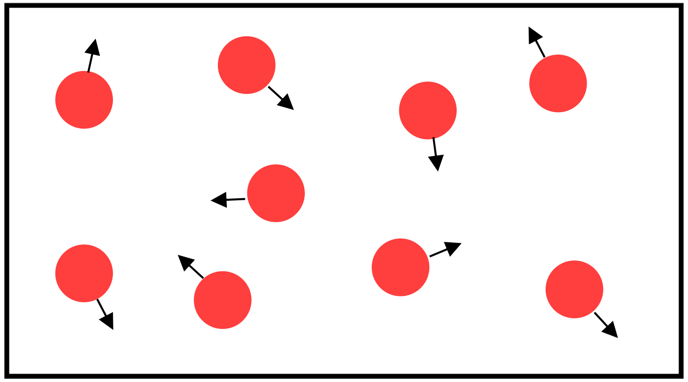
Quantum Degeneracy in a gas of atoms

1 atom per quantum state



N atoms
V volume
T temperature

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

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

Quantum Phase Space Density

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

$(n=N/V)$

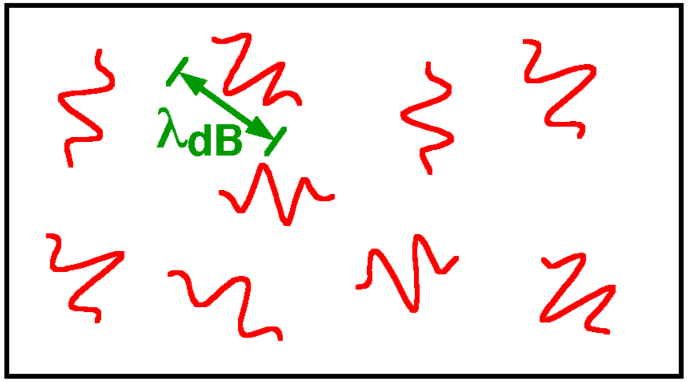
Air $n \sim 10^{19}/cm^3$, $T_c \sim 1mK$
Stuff $n \sim 10^{22}/cm^3$, $T_c \sim 0.1K$
Everything (except He) is solid

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

$T_c \sim 1\mu K$!! Ultracold !!

and ~ non-interacting

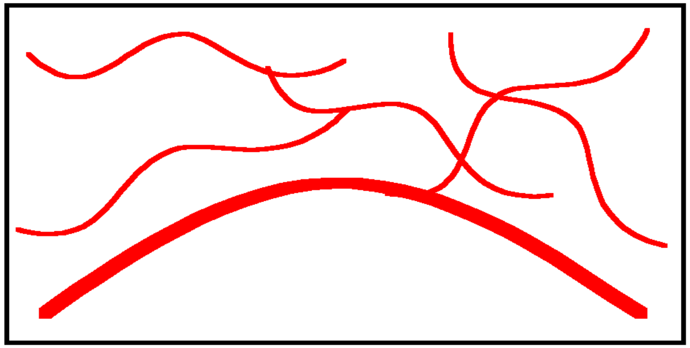
Bose-Einstein Condensation (BEC)



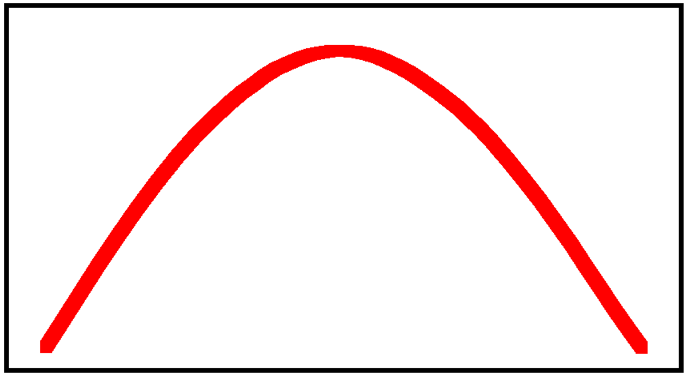
$$\lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}} \quad n = \frac{N}{V}$$

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

Quantum Phase Space Density

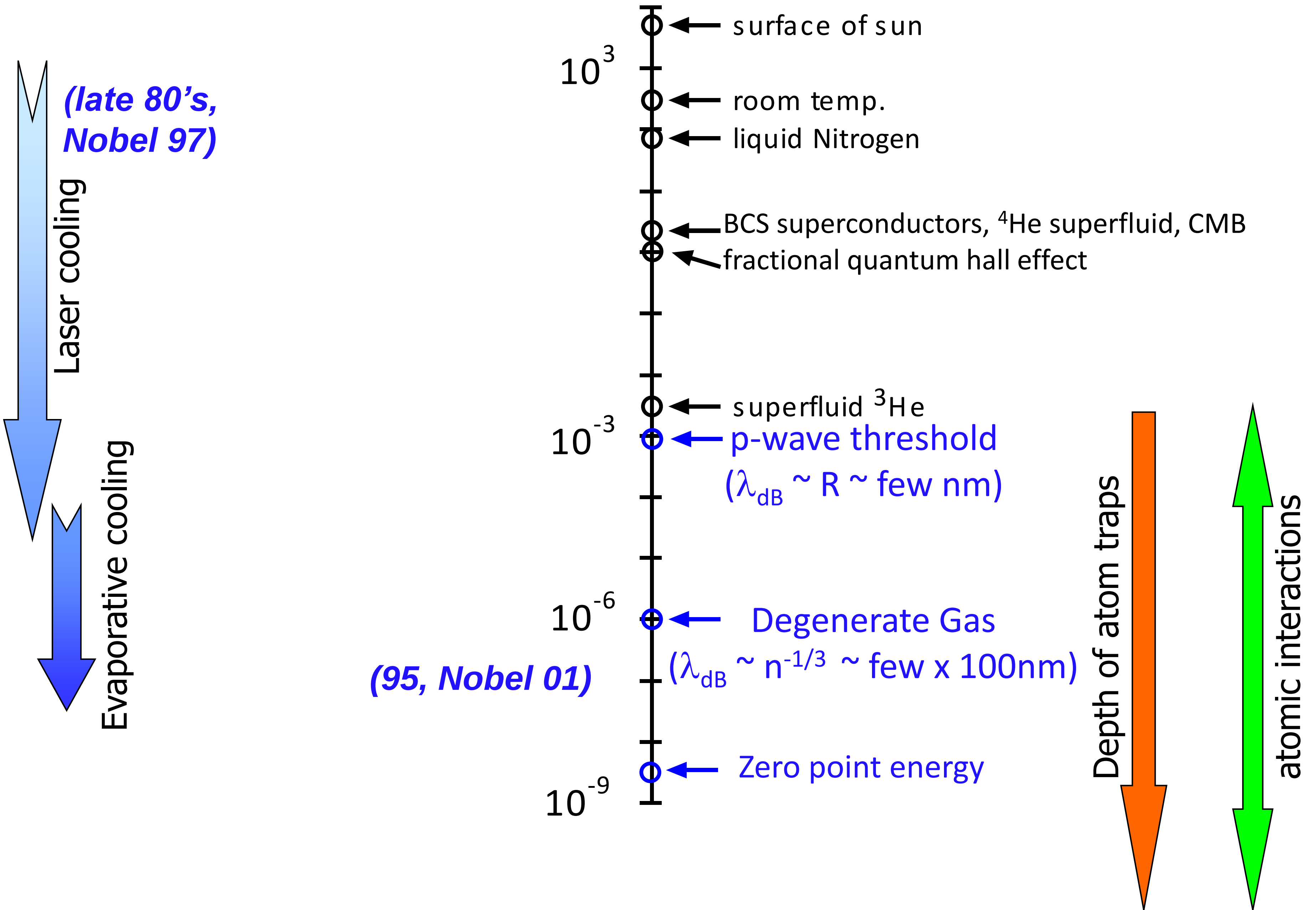


$$n\lambda_{dB}^3 \sim 1$$

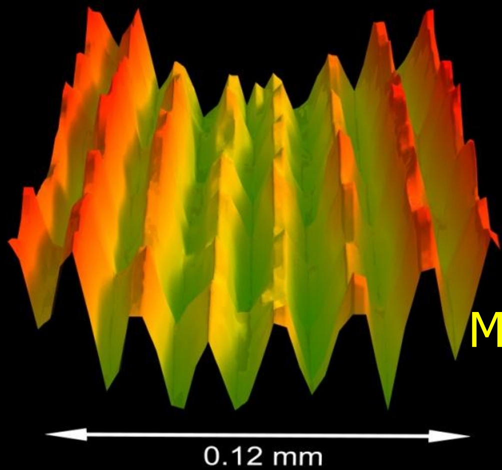


$$n\lambda_{dB}^3 >> 1$$

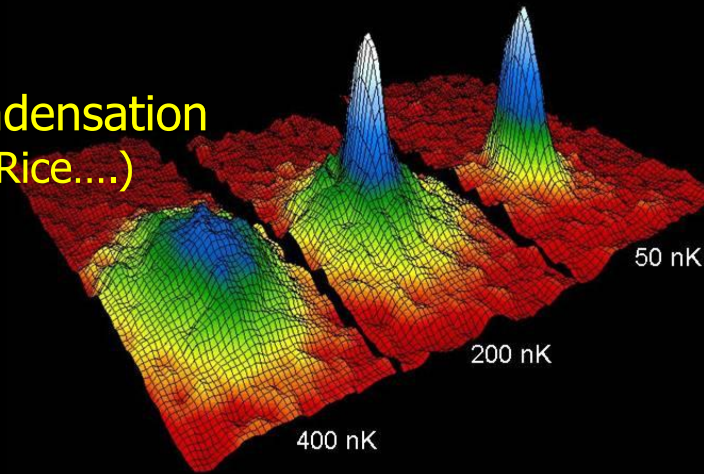
Relevant Ultracold Temperatures on the Log Kelvin Scale



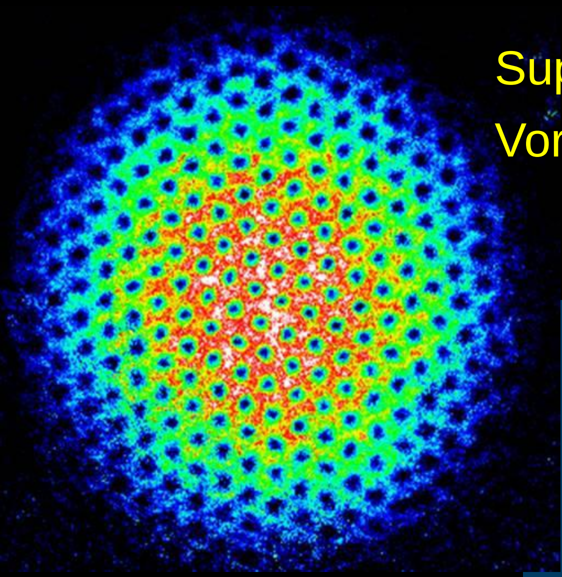
Some major achievements in ultracold atomic physics



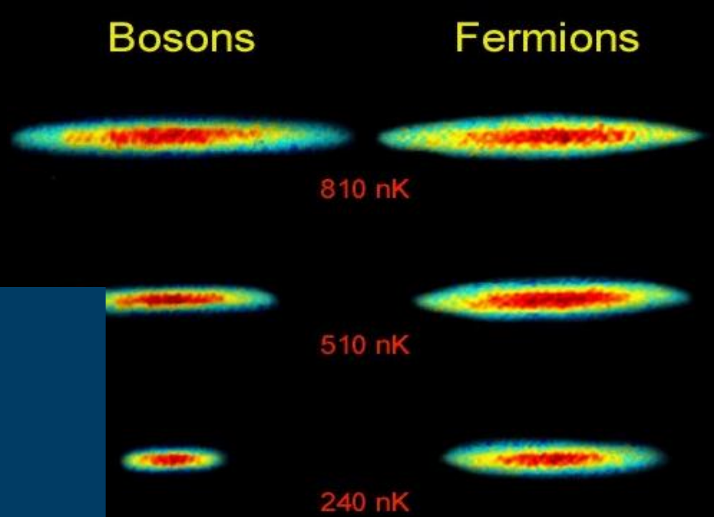
Macroscopic coherence
(97: MIT,…)



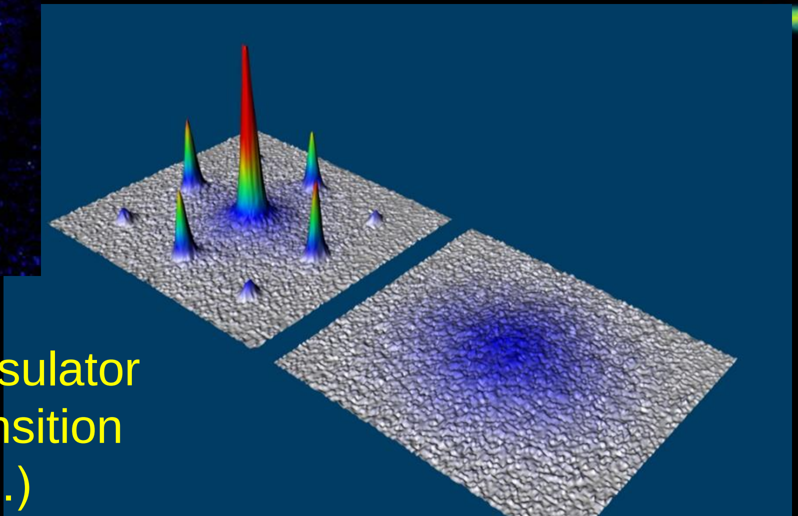
Bose-Einstein condensation
(95: JILA, MIT, Rice….)



Superfluidity,
Vortex lattice

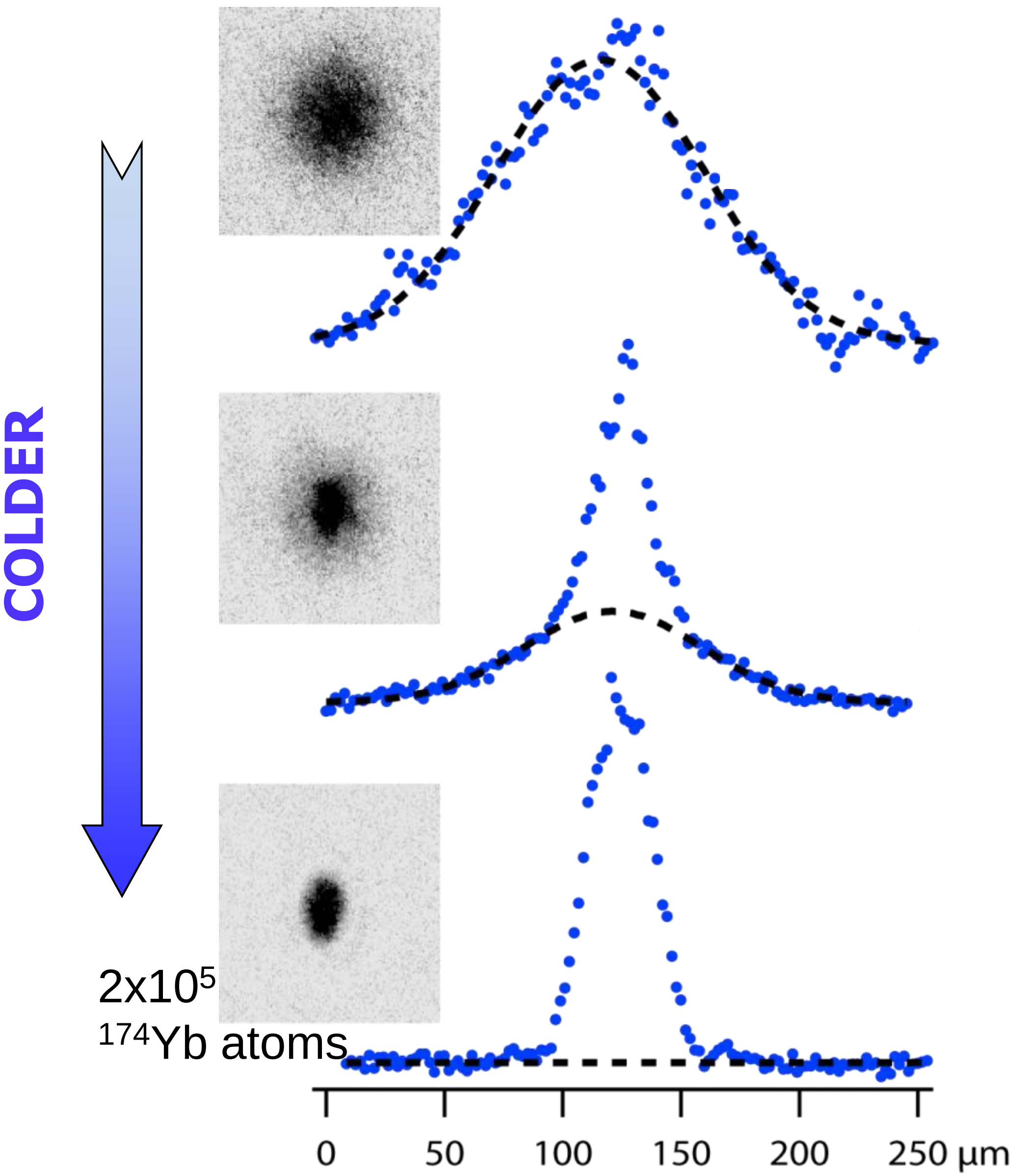


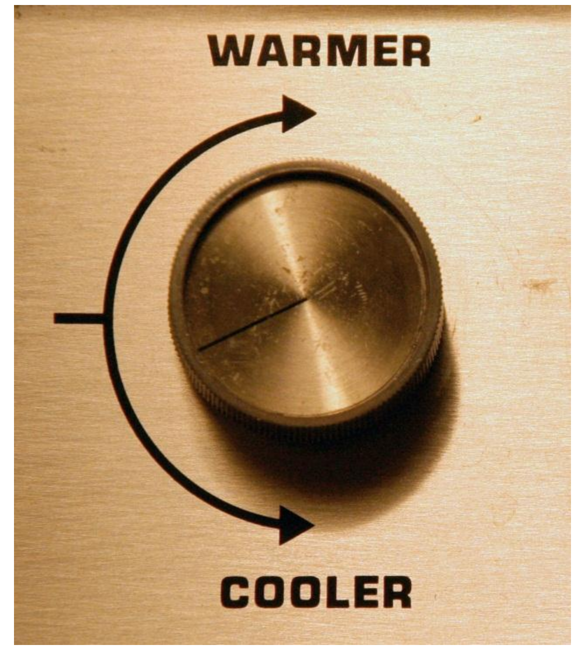
Degenerate Fermi gas
(99: JILA, Rice, ENS, Duke, MIT, Innsbruck, ….)



Superfluid to Mott-insulator quantum phase transition
(02: Munich,…..)

Ultracold Climate Control

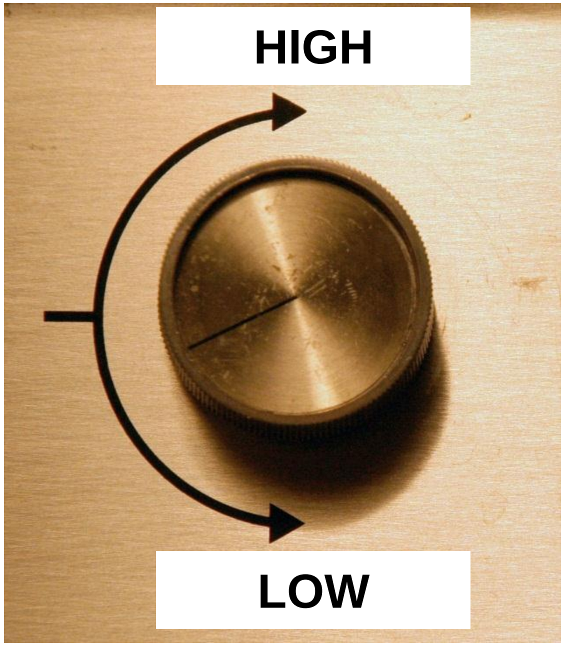




"Knobs" for Quantum Engineering

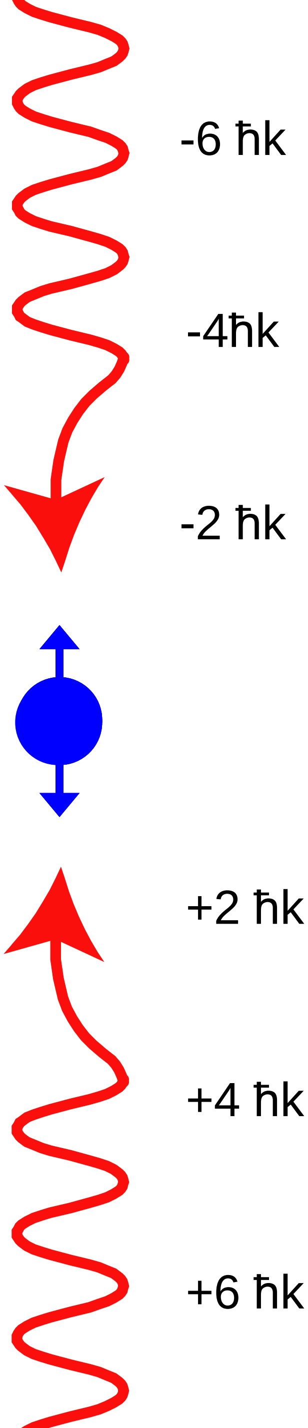
Using e-m fields, can control (relatively) easily

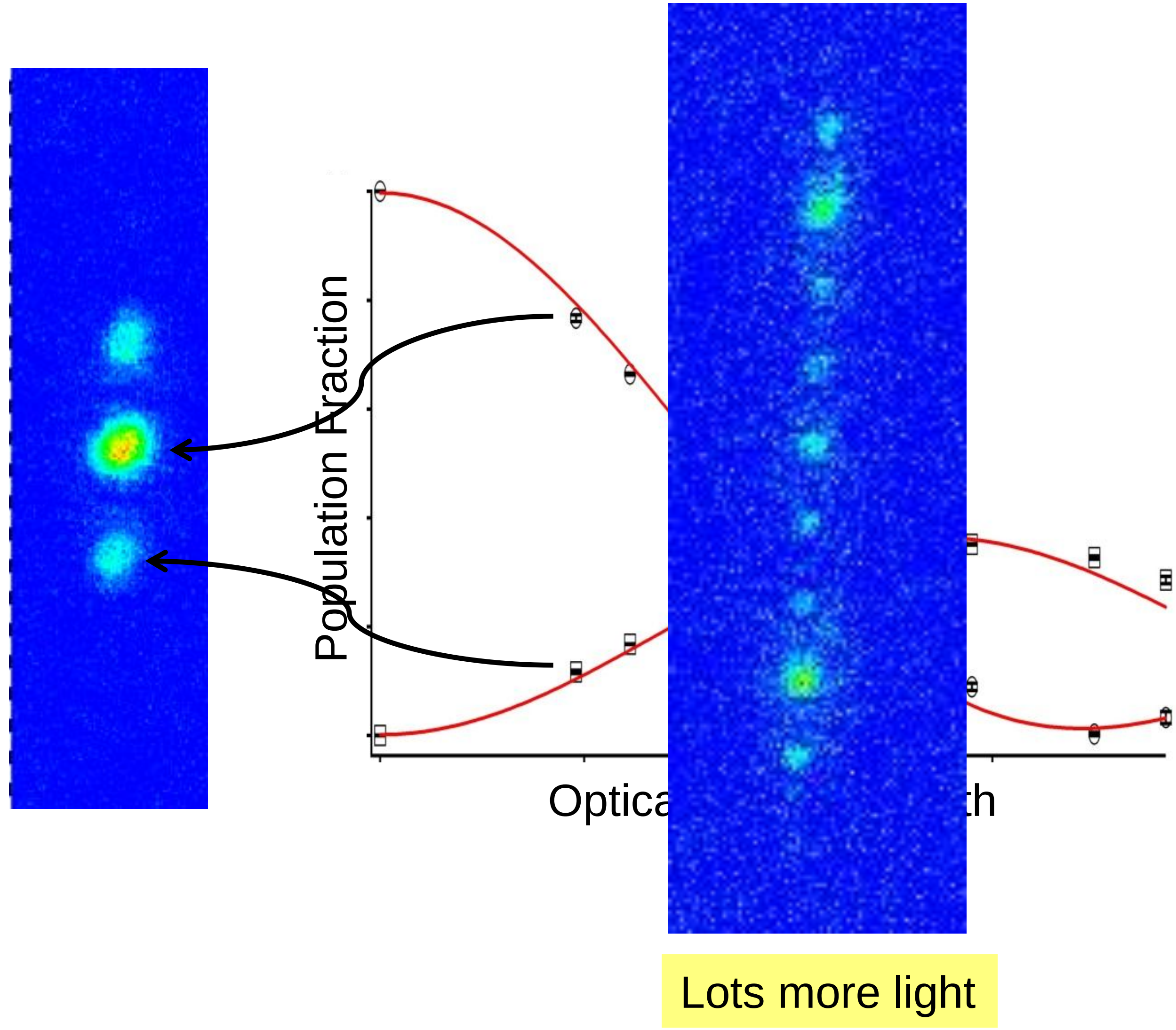
Temperature & density
Dimensionality
Crystal structure – lattices
Magnetization
Magnitude & sign of the "charge"
Chemical structure – form molecules



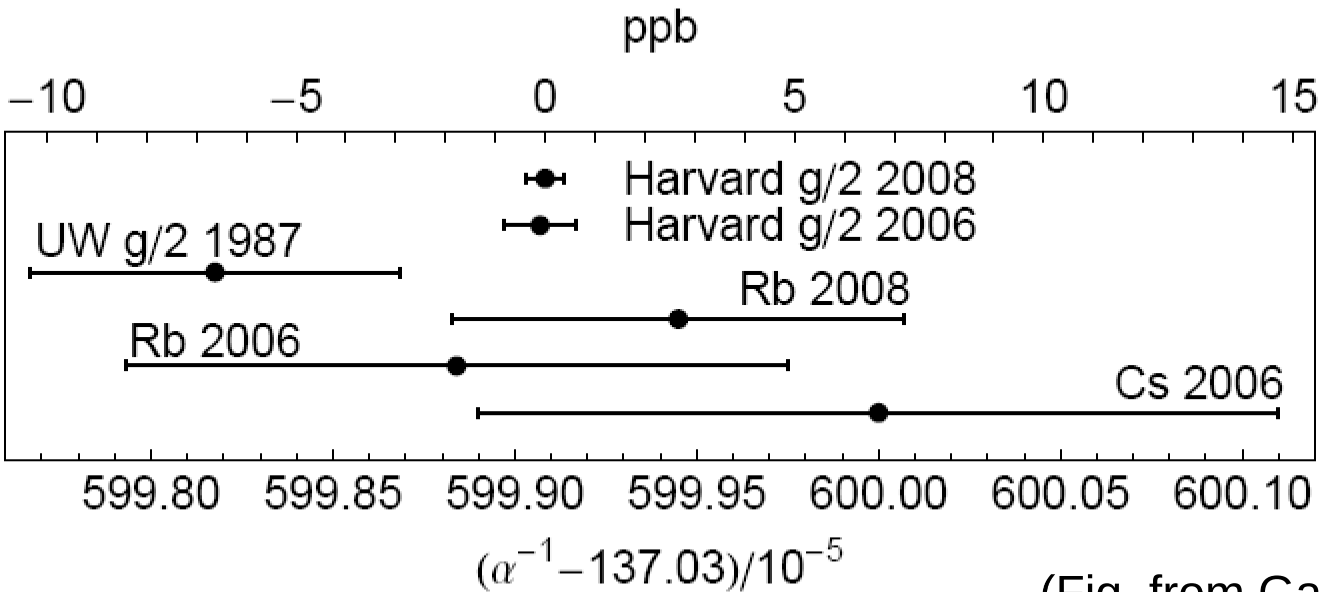
Precision BEC Interferometry

Optical Standing Wave Diffraction





Precision Measurements of the fine structure constant, α



(Fig. from Gabrielse, 2009)

g/2: α from measurement of electron magnetic moment and QED theory

Rb, Cs: Atomic Physics route to α. (Also new 2011 measurement in Rb)

Our Yb BEC route to α: Targeted at 0.1 ppb.

Atomic Physics Route to α, test of QED

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

~ 0.1 ppb: penning trap mass spectr.
(Bradley et al.,1999, Ed Myers 2012)

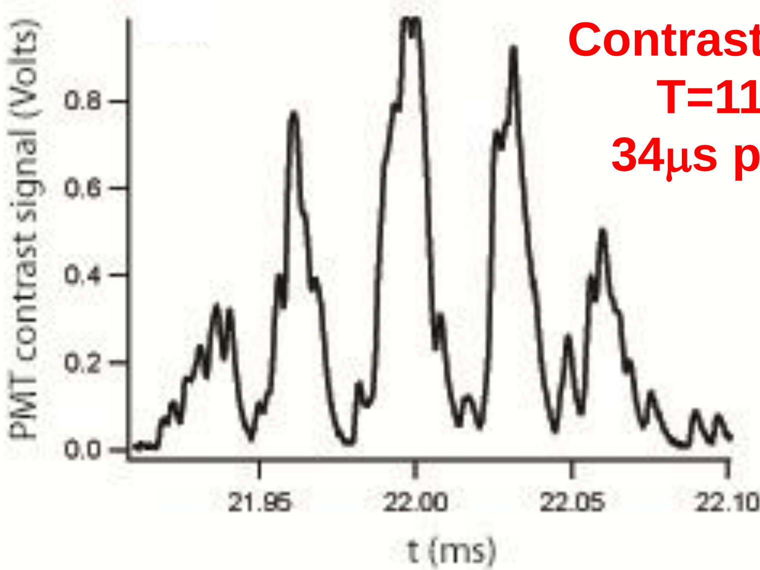
$$\alpha^2 = \left(\frac{e^2}{\hbar c}\right)^2 = \frac{2R_\infty}{c}\frac{h}{m_e} = \frac{2R_\infty}{c}\frac{M}{M_e}\frac{h}{m}$$

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

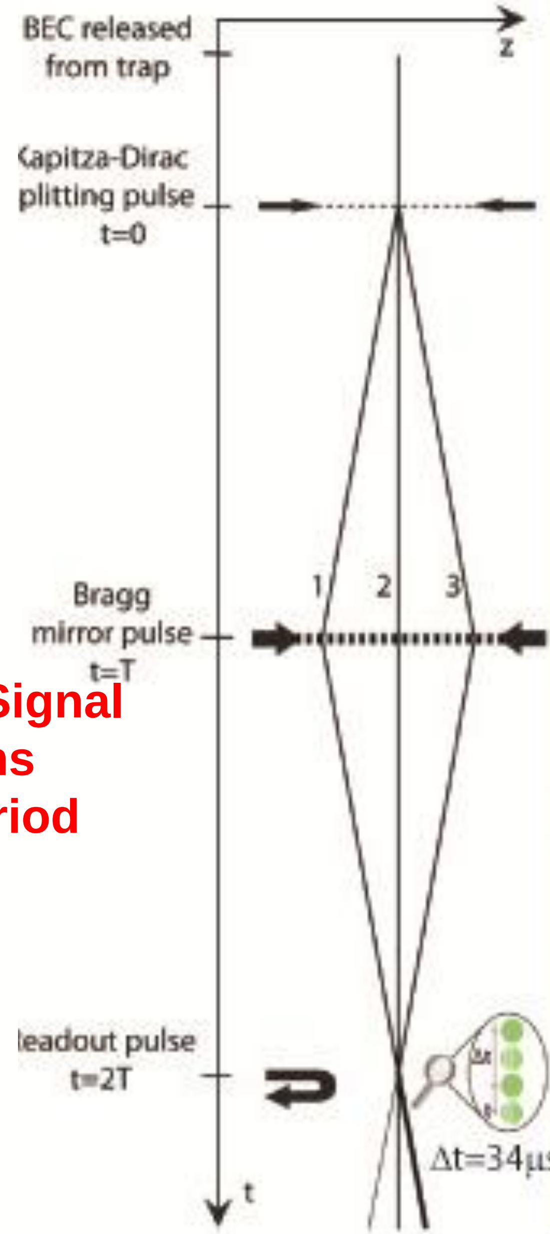
$$\omega_{\text{rec}} = \frac{1}{2}\frac{\hbar}{m}k^2$$

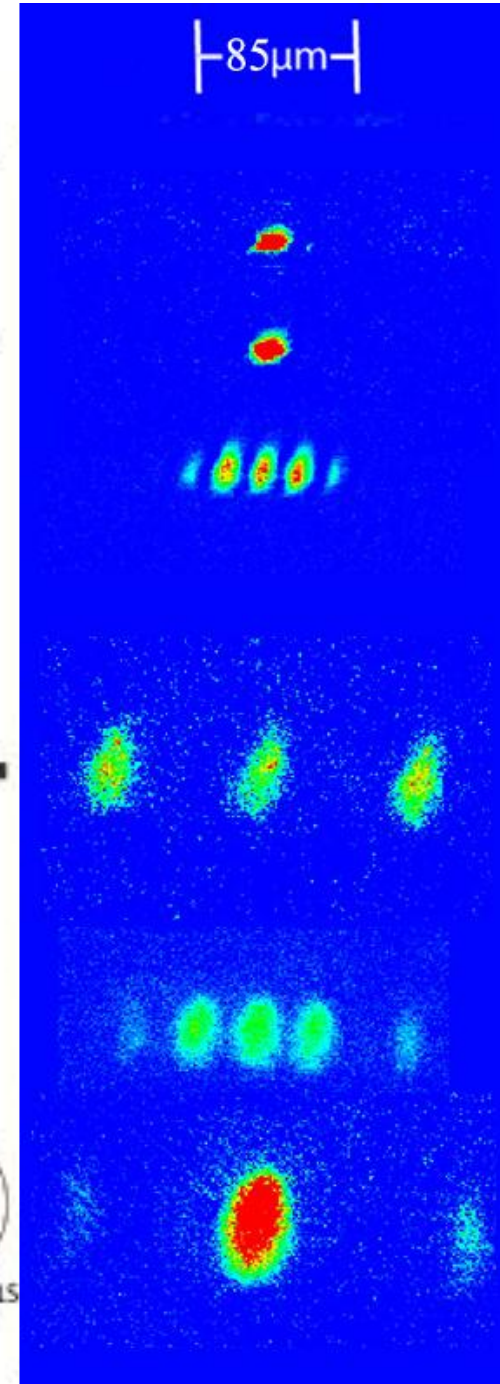
Photon Recoil Measurement
using Atomic Interferometry

Contrast Interferometer with Yb BEC



Contrast Signal
T=11ms
34μs period



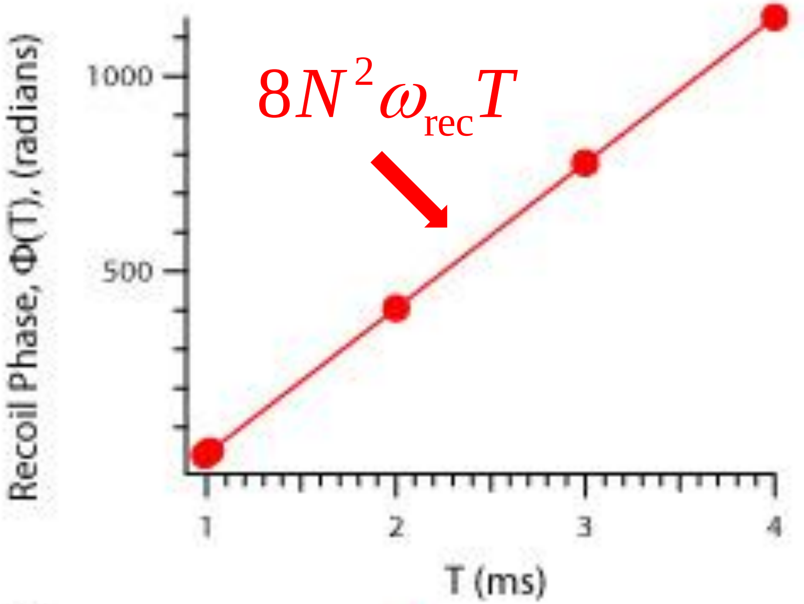


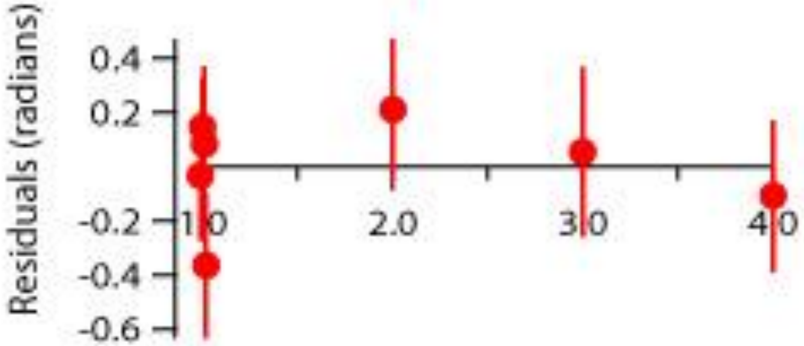
Contrast Interferometer with Yb BEC

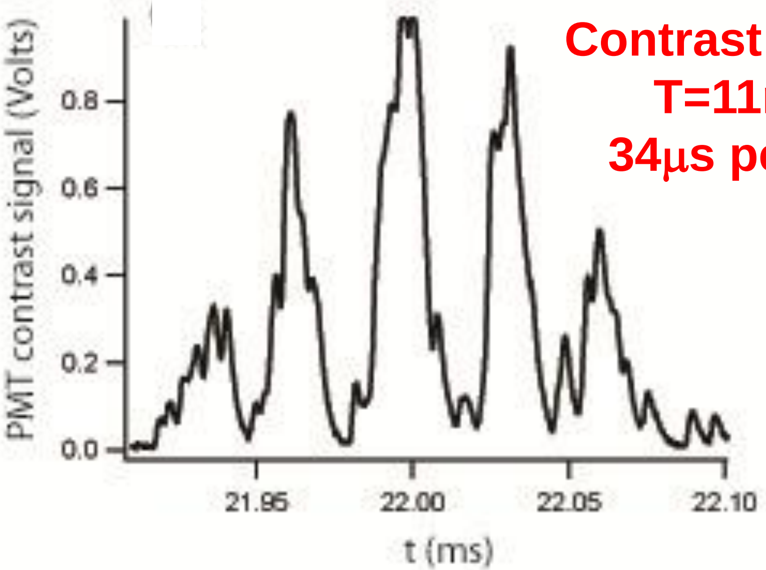
Symmetric geometry and highly coherent source

Resolving interaction and diffraction shifts at few ppm

Will install “acceleration” pulses for sub-ppb

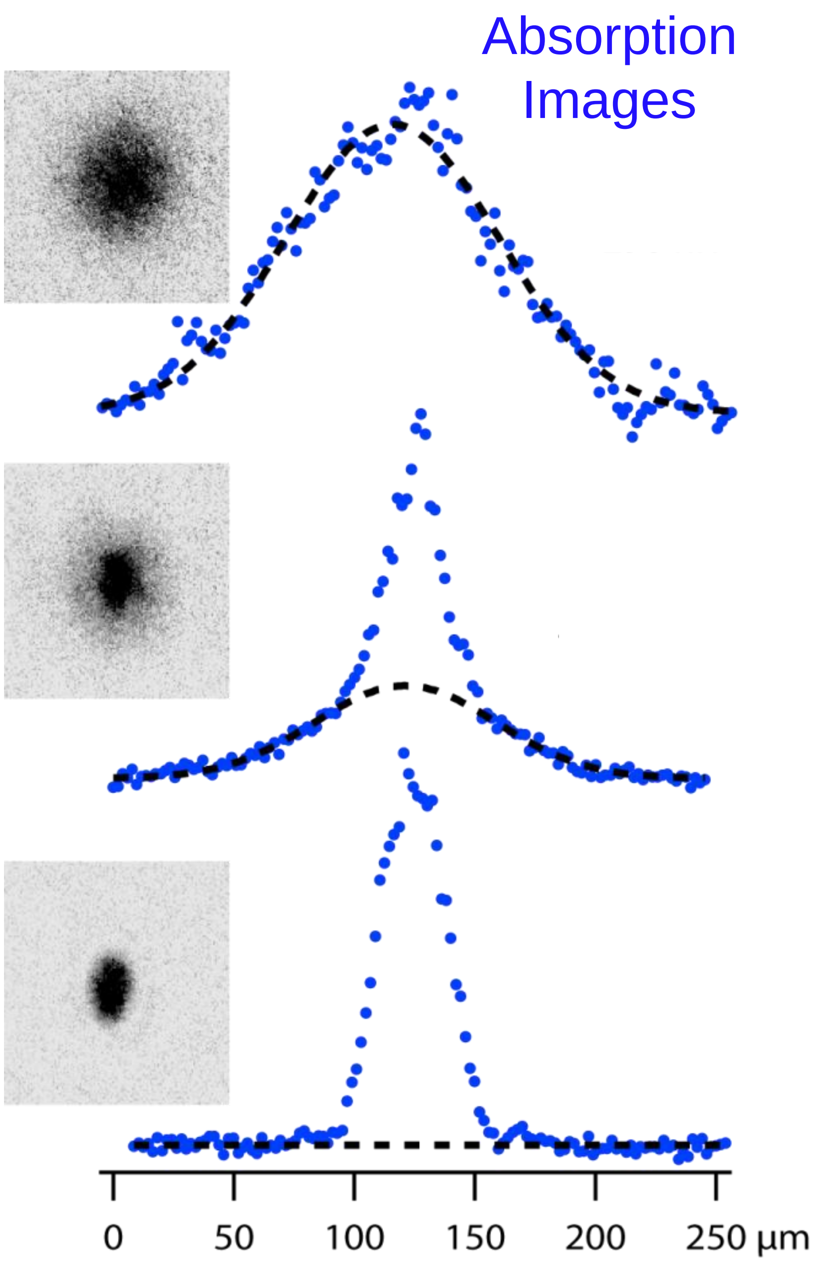


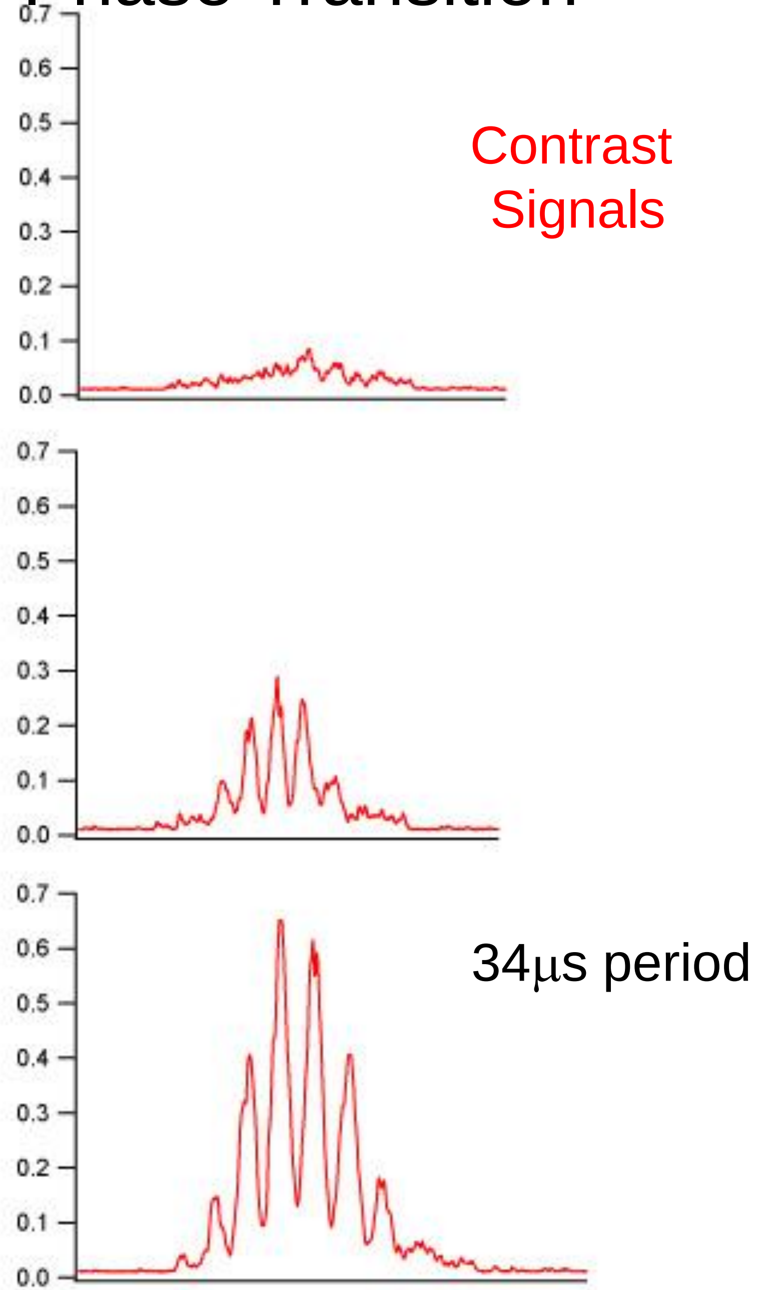




Contrast Signal
T=11ms
34μs period

Interferometric Probe of Phase Transition



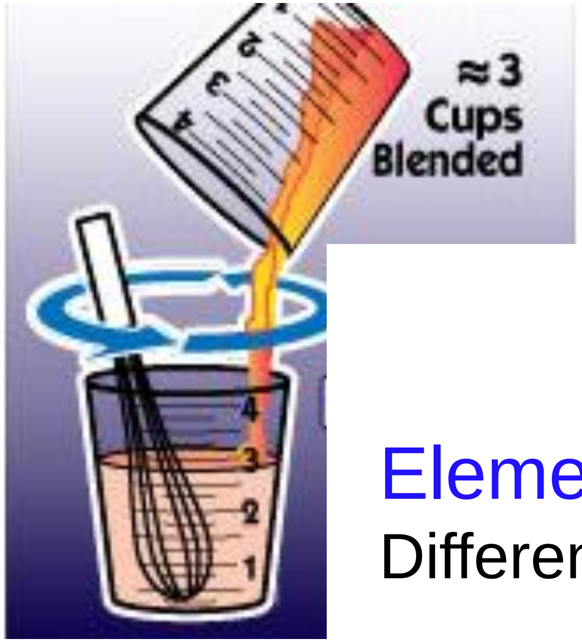


Mixtures

Spin Mixture

Same species

Eg. Realization of
fermion pairing



Elemental Mixtures

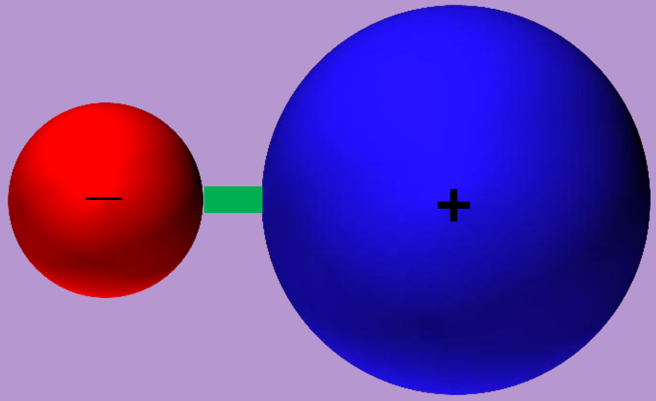
Different species

Differences in mass, valence
Fermi/Bose
Species/selective tools
Bath or Probe
Ultracold Polar molecules

Ultracold Polar Molecules

Long-range interactions
($1/r^3$ vs $1/r^6$)

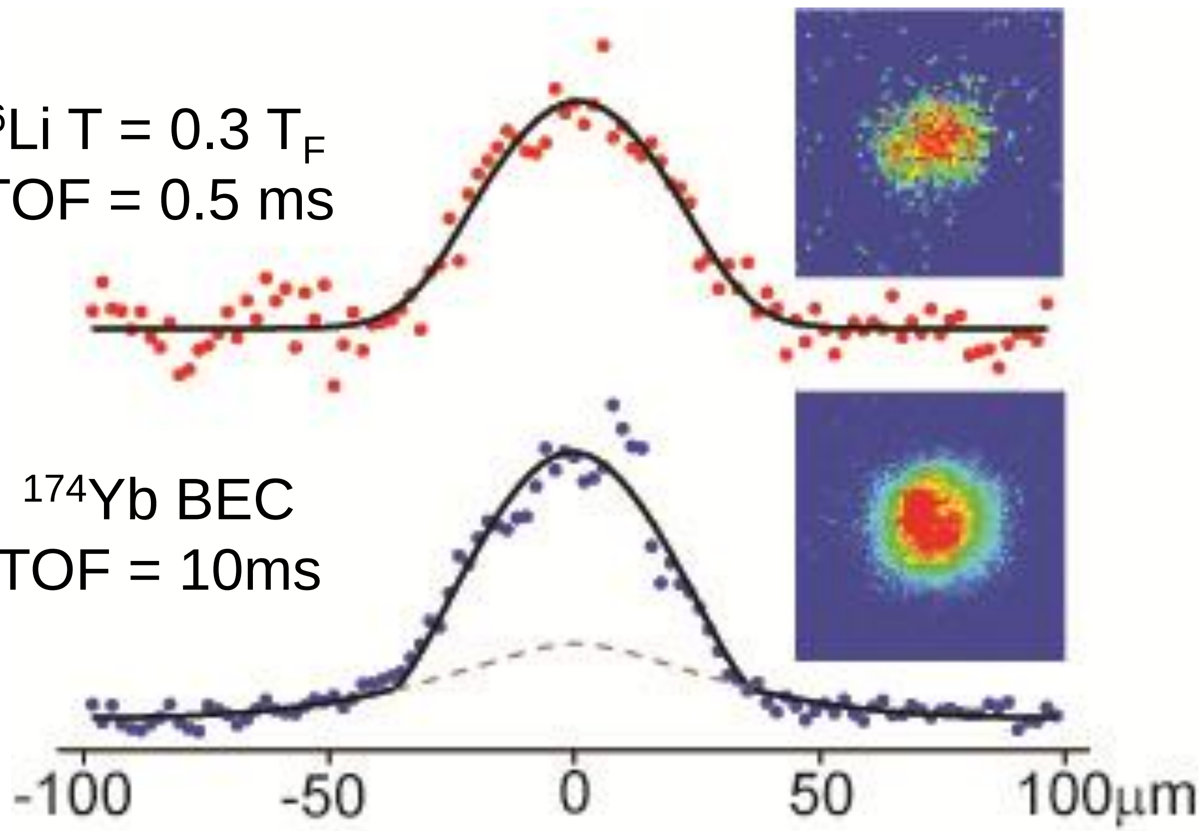
Precision Spectroscopies
for m_p/m_e time variation



Candidate for scale-able quantum information processing

Controlled ultracold chemical reactions

Quantum Degenerate Li-Yb mixture



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

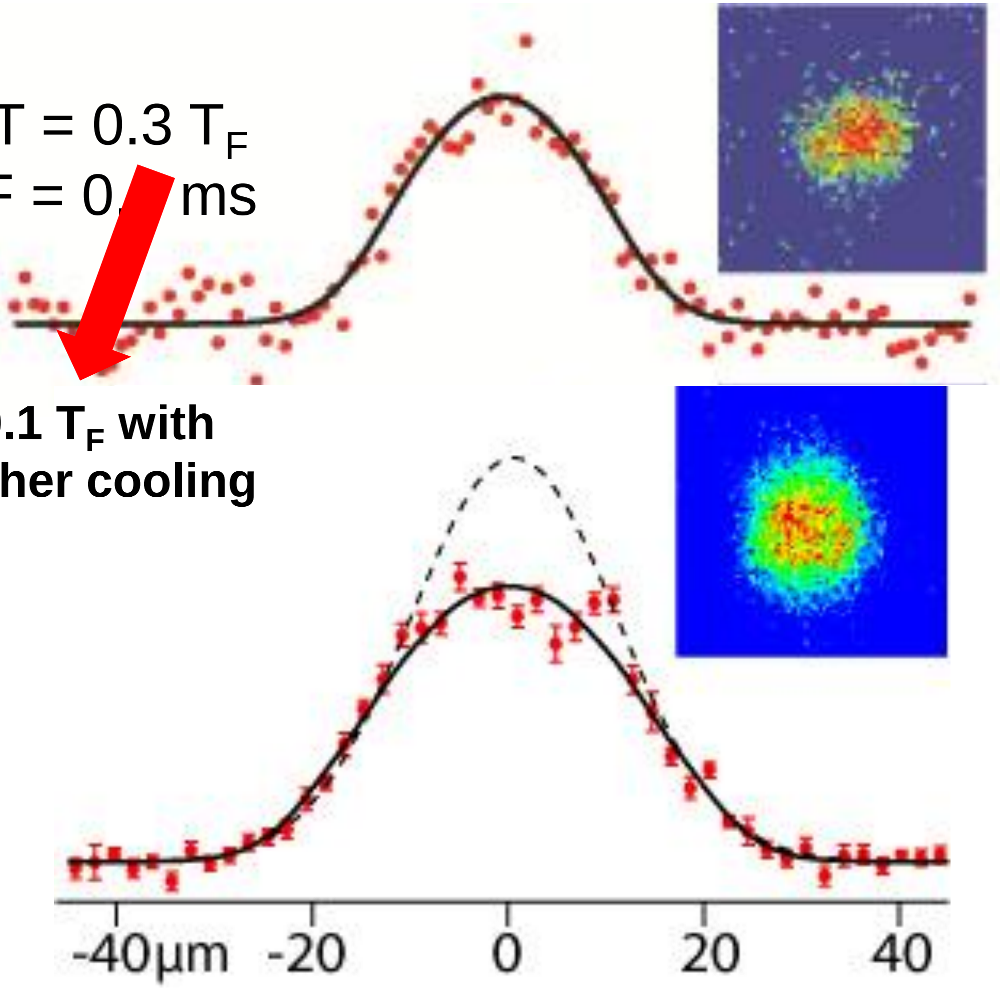
V. Ivanov et al.
PRL **106**, 053201 (2011)

A. Hansen et al.
PRA **84**, 011606(R) (2011)

Quantum Degenerate Li-Yb mixture

^{6}Li T = 0.3 T_F
TOF = 0. ms

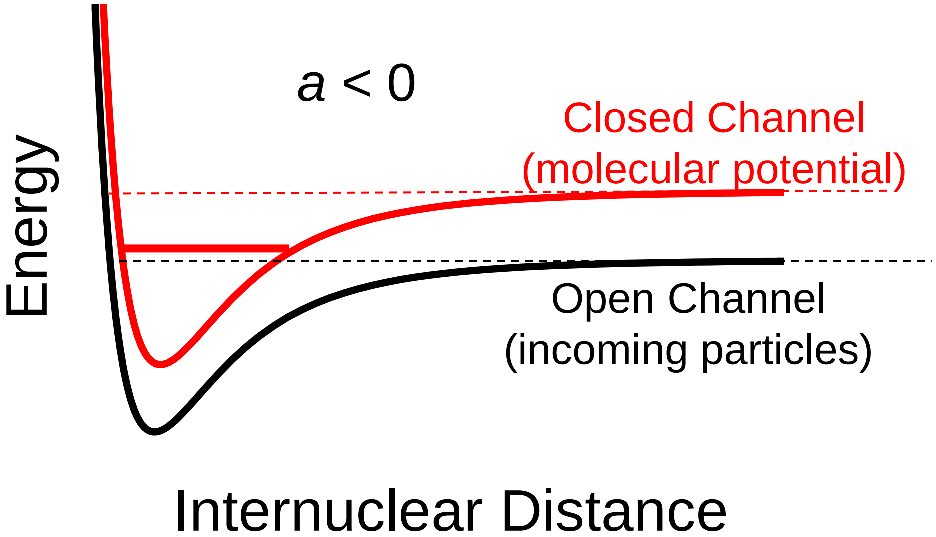
<0.1 T_F with further cooling



A. Hansen et al.
PRA **87**, 013615 (2013)

Feshbach Resonance:

Knob for Strong Interactions and Ultracold Molecules

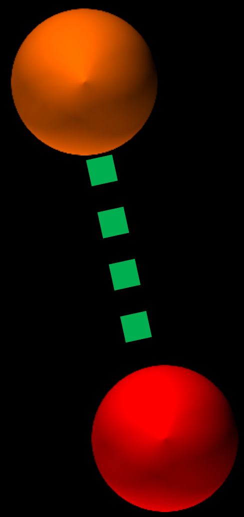


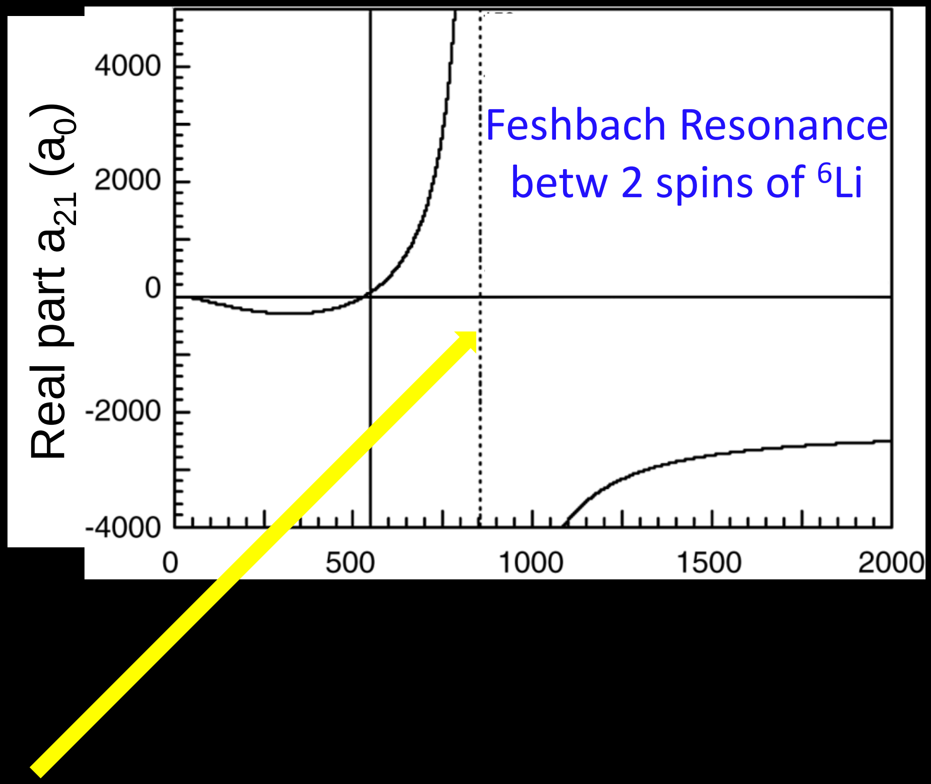
a tuned by external magnetic field

For large a > 0,
Feshbach molecule binding energy

$$\varepsilon_B = \frac{\hbar^2}{ma^2}$$

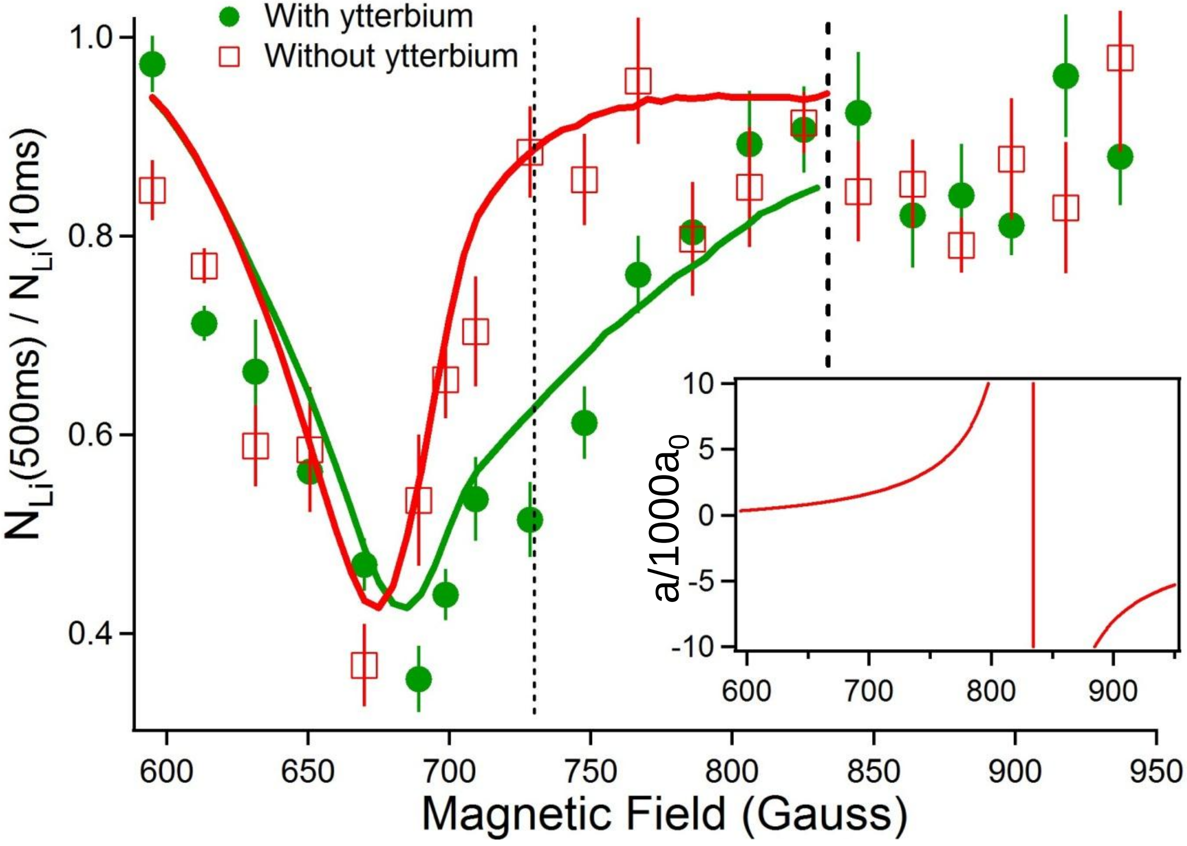
Feshbach Resonance in Lithium





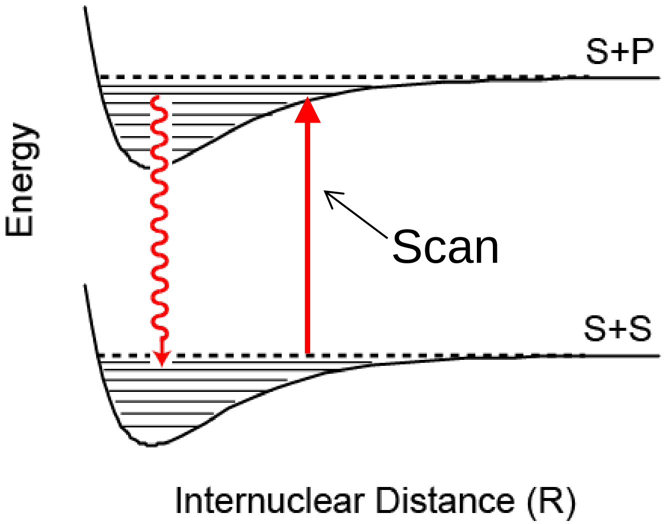
Fermi gas physics; High Tc Fermi superfluid; BEC/BCS crossover; Unitary fermions; Universal few-body physics.

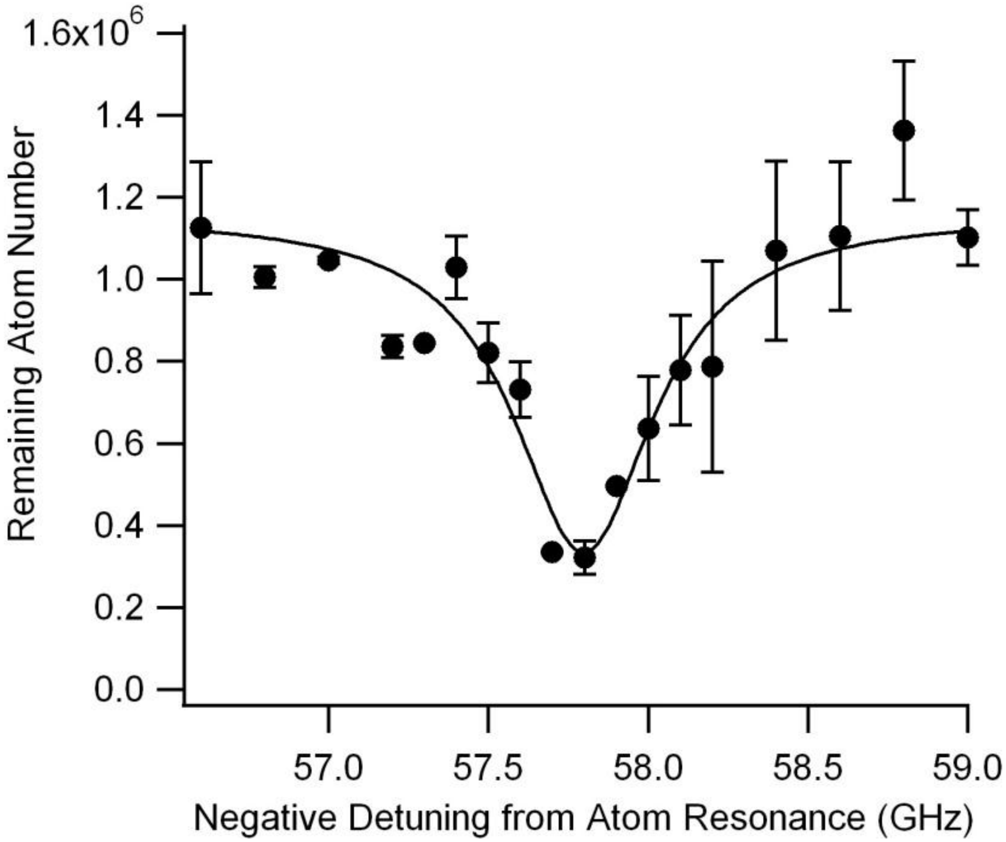
Yb + Feshbach resonant Li



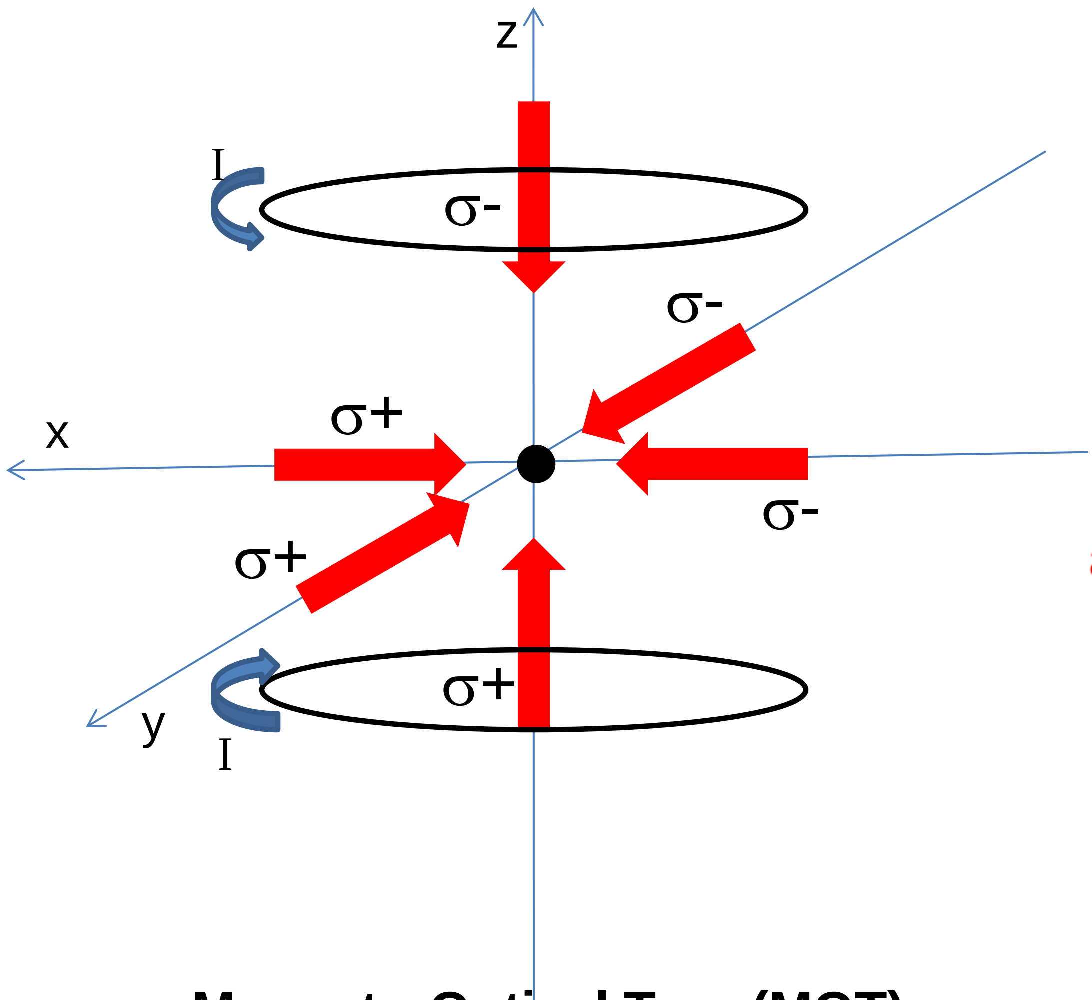
A. Khramov et al, PRA **86**, 032705 (2012)

Photoassociation Resonance



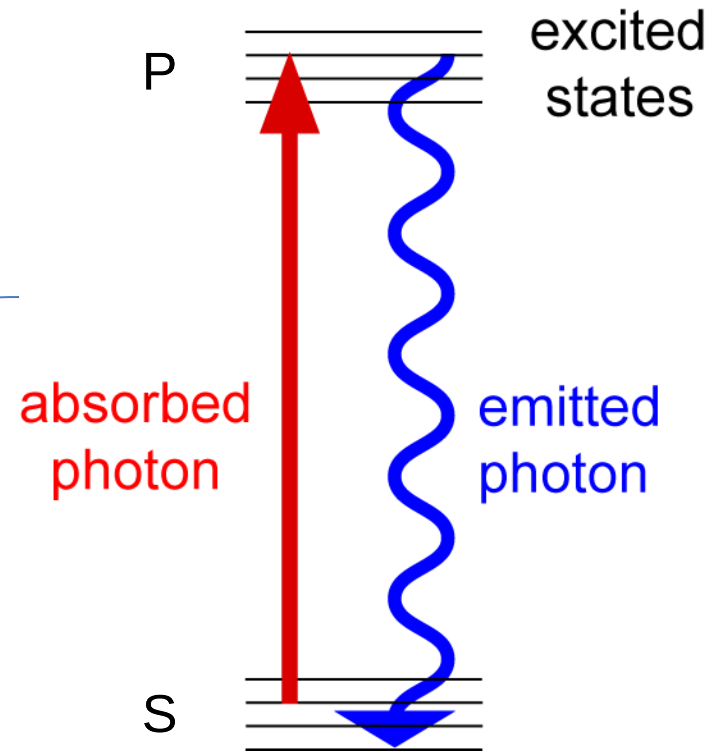


Laser Cooling



Magneto-Optical Trap (MOT)
"Workhorse" of laser cooling

Atom Source ~ 600 K; UHV environment

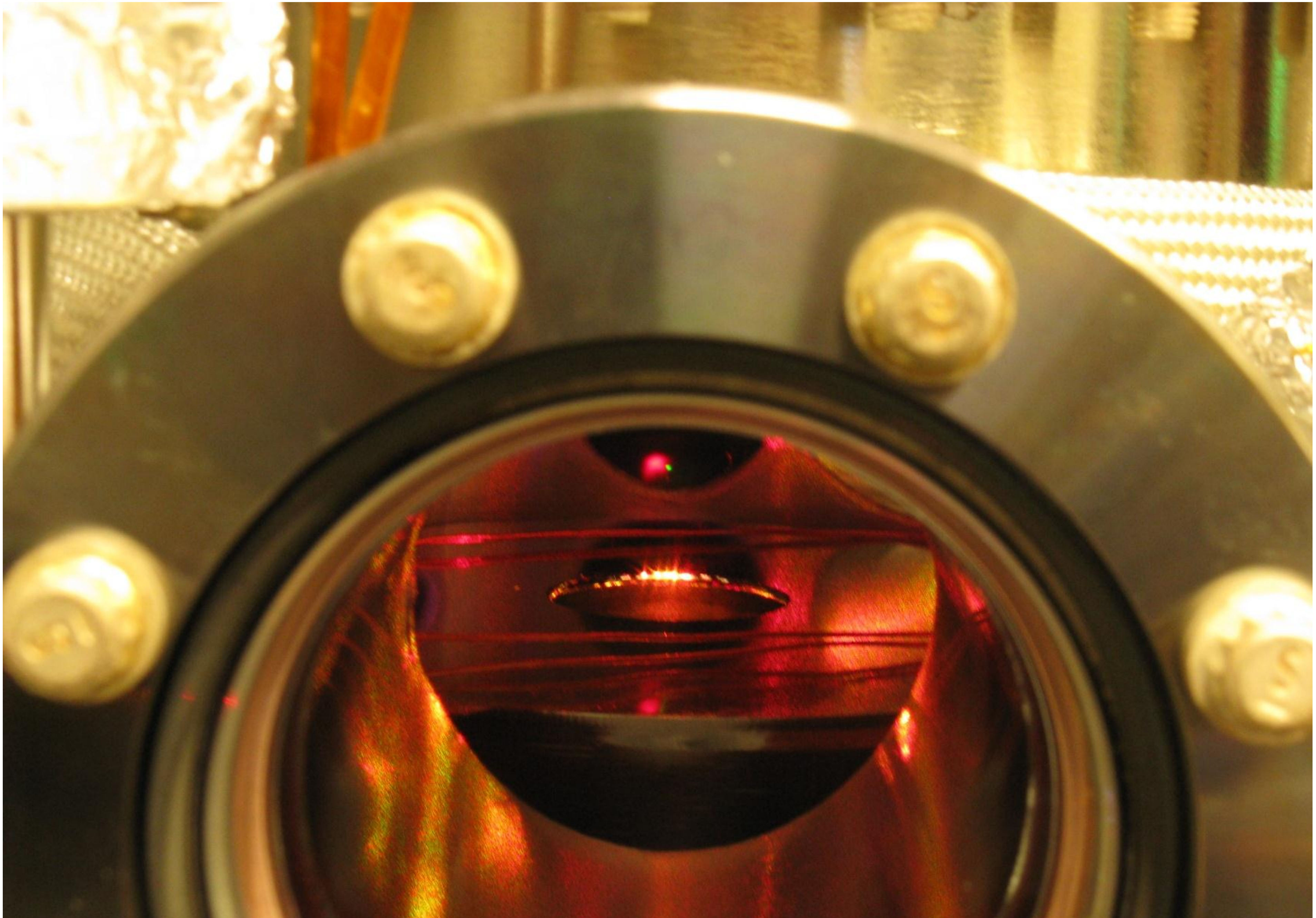


$$\hbar\omega_{\text{abs}} < \hbar\omega_{\text{em}}$$

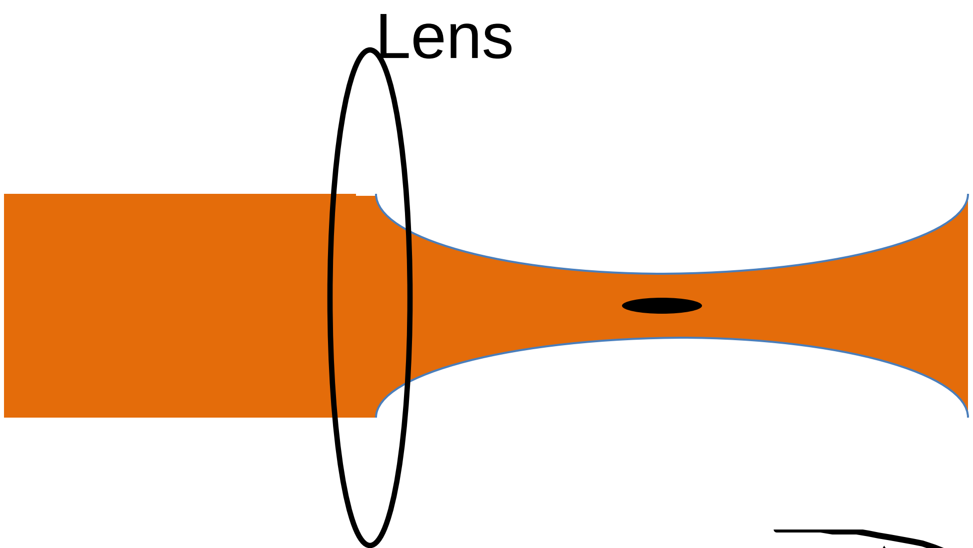
=> COOLING !

(Need a 2 level system)

Magneto-Optical Trapping

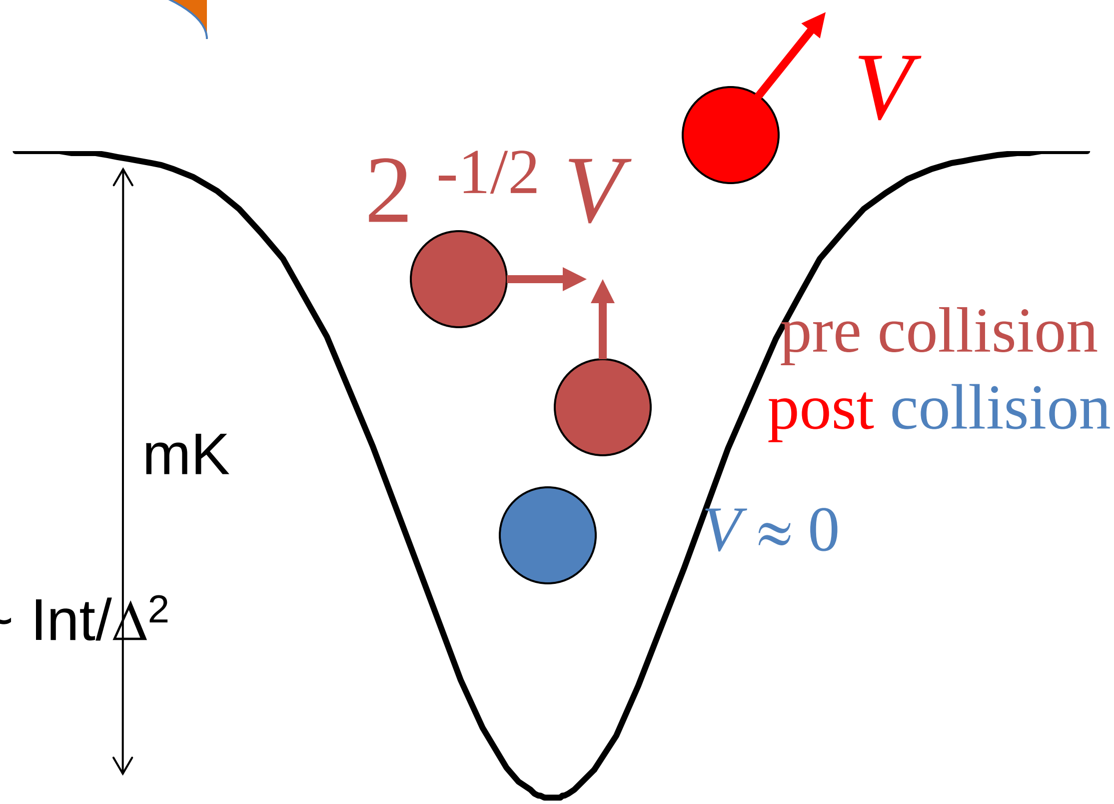


Evaporative Cooling in a Conservative Trap



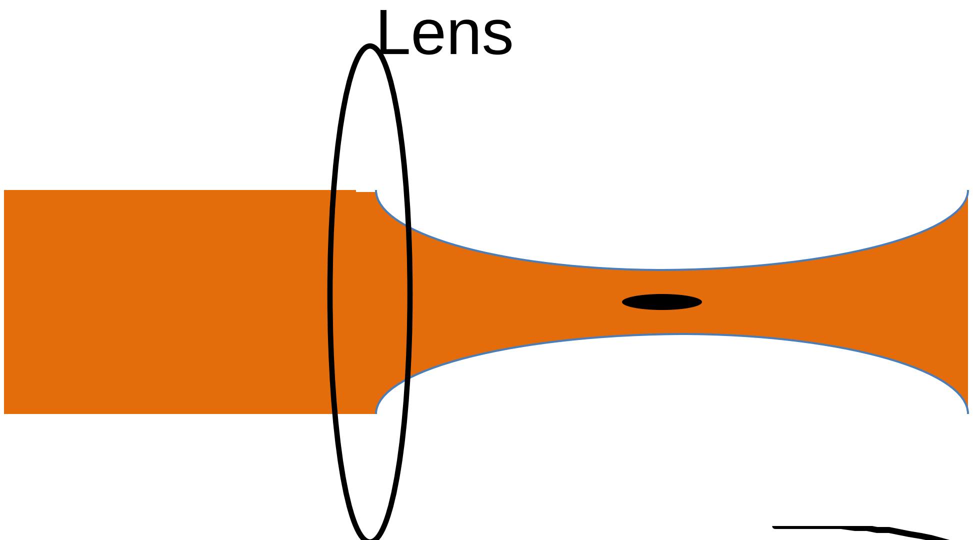
Optical Dipole Trap

$\omega_L << \omega_{res}$



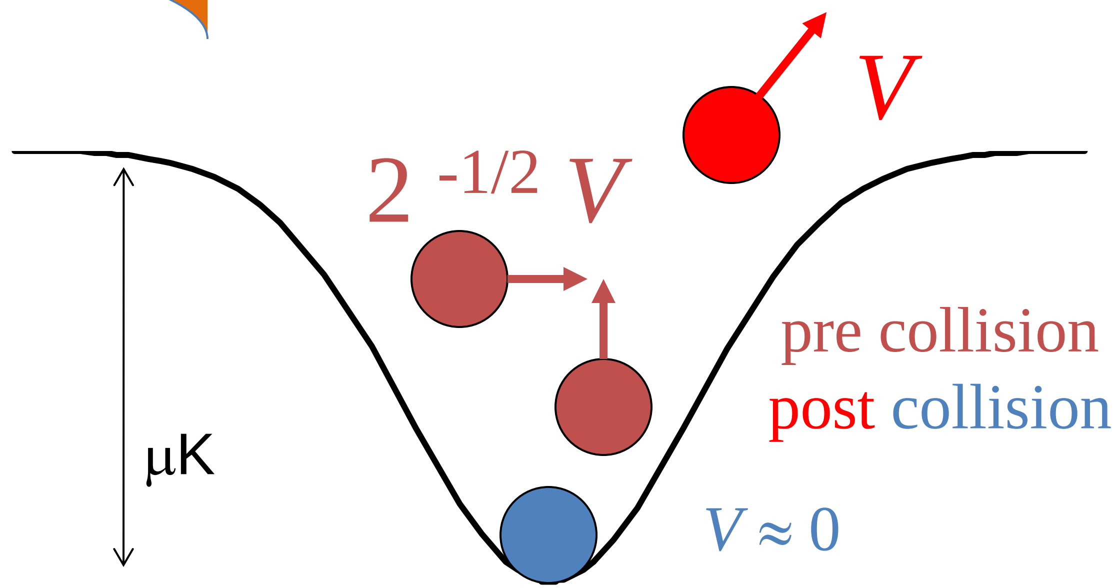
Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

Evaporative Cooling in a Conservative Trap



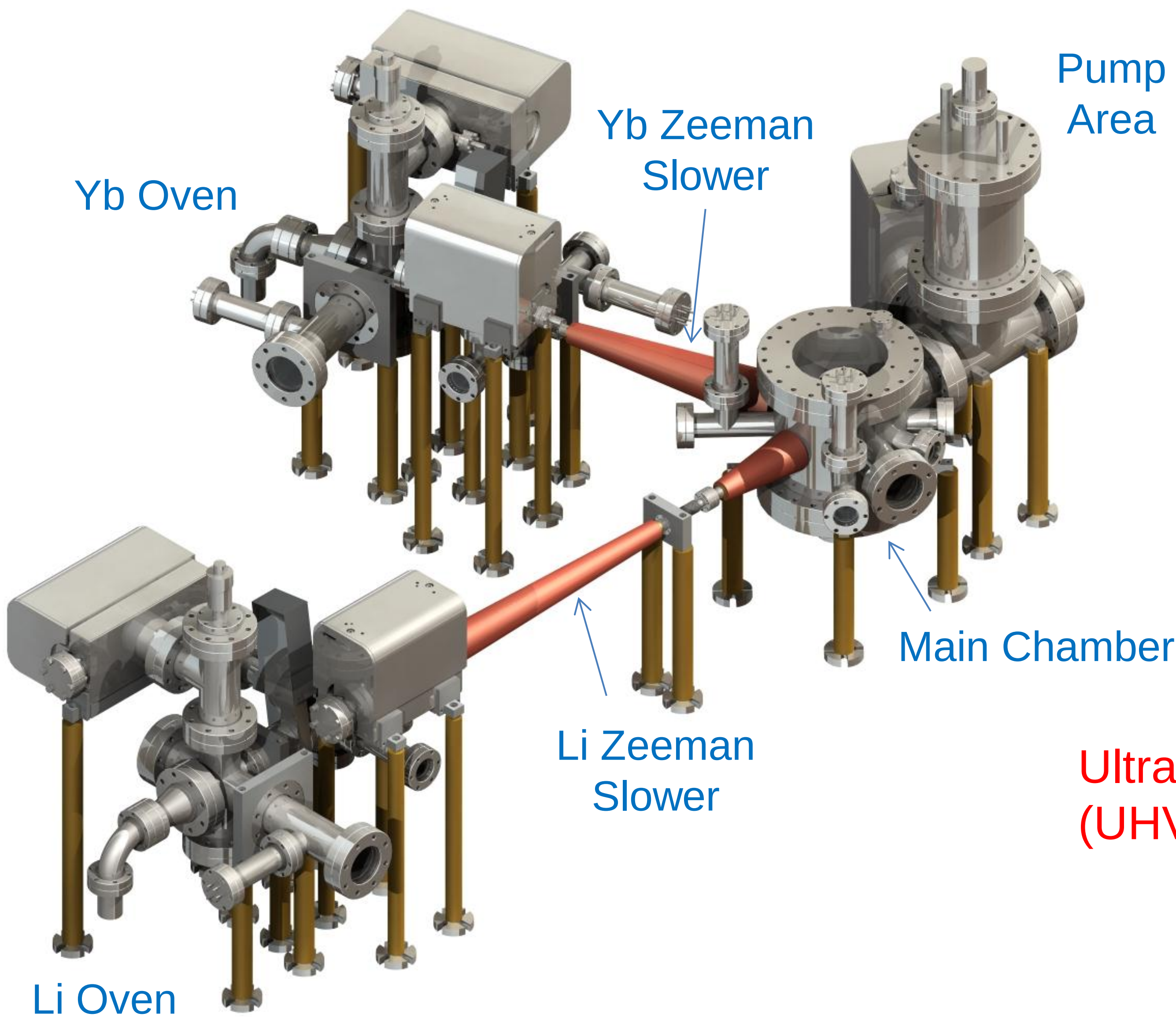
Optical Dipole Trap

$\omega_L << \omega_{res}$



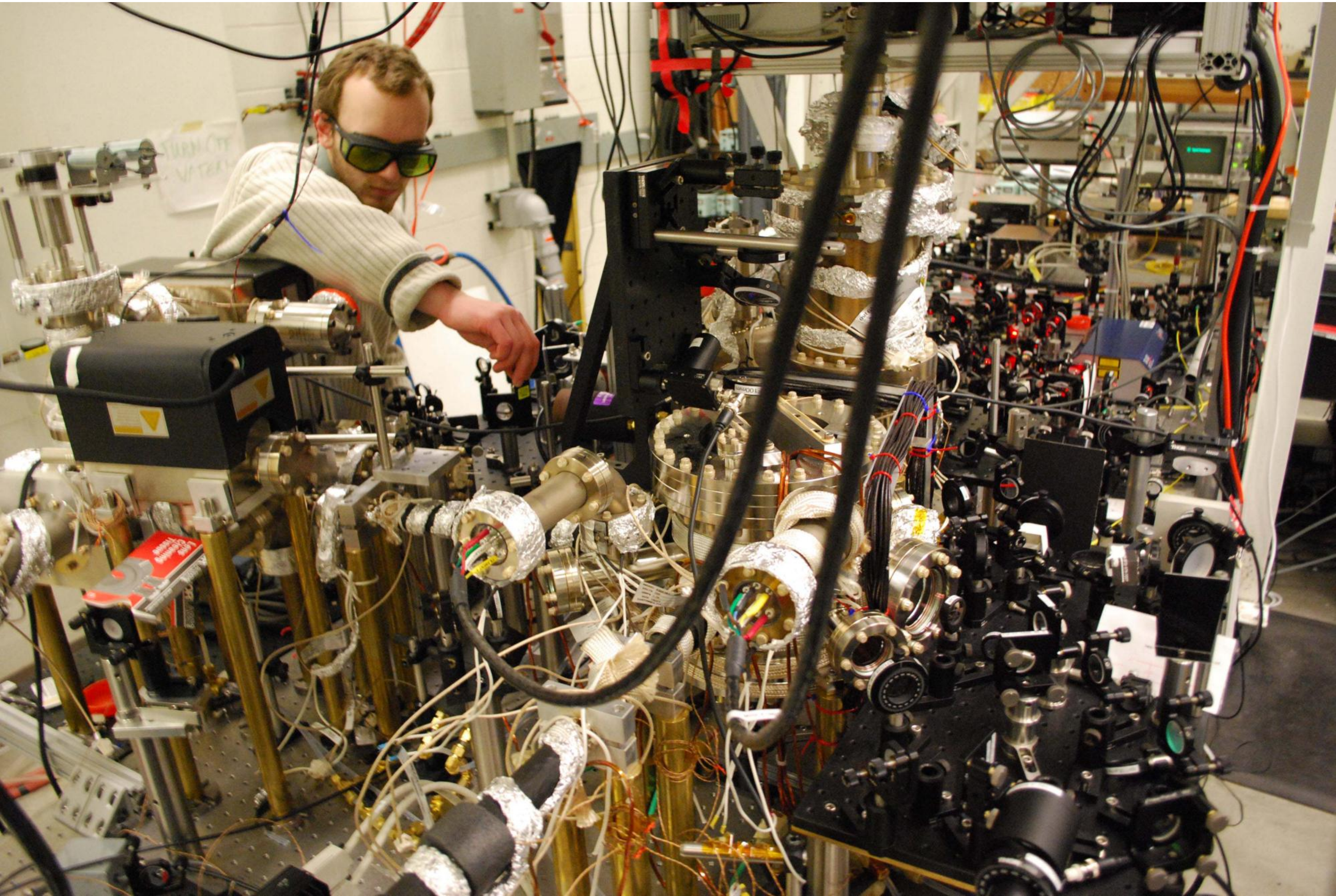
Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

Dual Species Apparatus

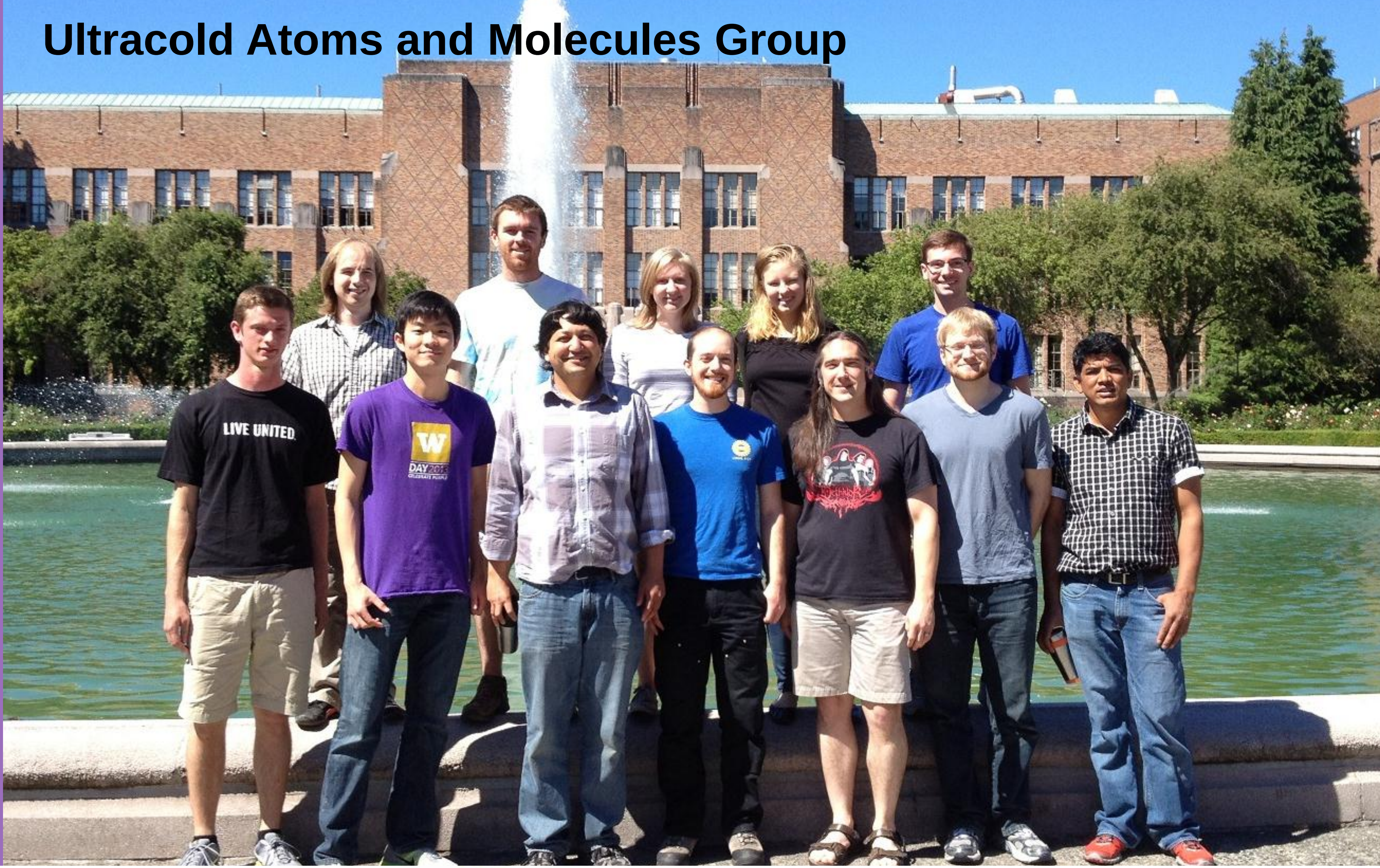


Ultrahigh Vacuum
(UHV < 10^{-10} Torr)

Apparatus I



Ultracold Atoms and Molecules Group



AFOSR

Army: MURI

Anders Hansen, *Alex Khramov*, Alan Jamison, Will Dowd,
Ben Plotkin-Swing, Ricky Roy, Alaina Green, Katie MacAlpine,
Dan Gochnauer, *Frank Munchow, Kalista Smith, Lee Willcockson*

Raj Shrestha, Anupriya Jayakumar, *Vlad Ivanov*

Stephen Di'Iorio, Chow Yi Chao, Brendan Saxberg,
Dan Gochnauer, Ben Schwyn, Charlie Fieseler, Jiawen Pi,
Eric Lee-Wong, Jason Grad, Dane Odekirk, Ryan Weh,
Billy English, Ryne Saxe, Carson Teale, N. Maloney

http://www.phys.washington.edu/users/deepg/

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