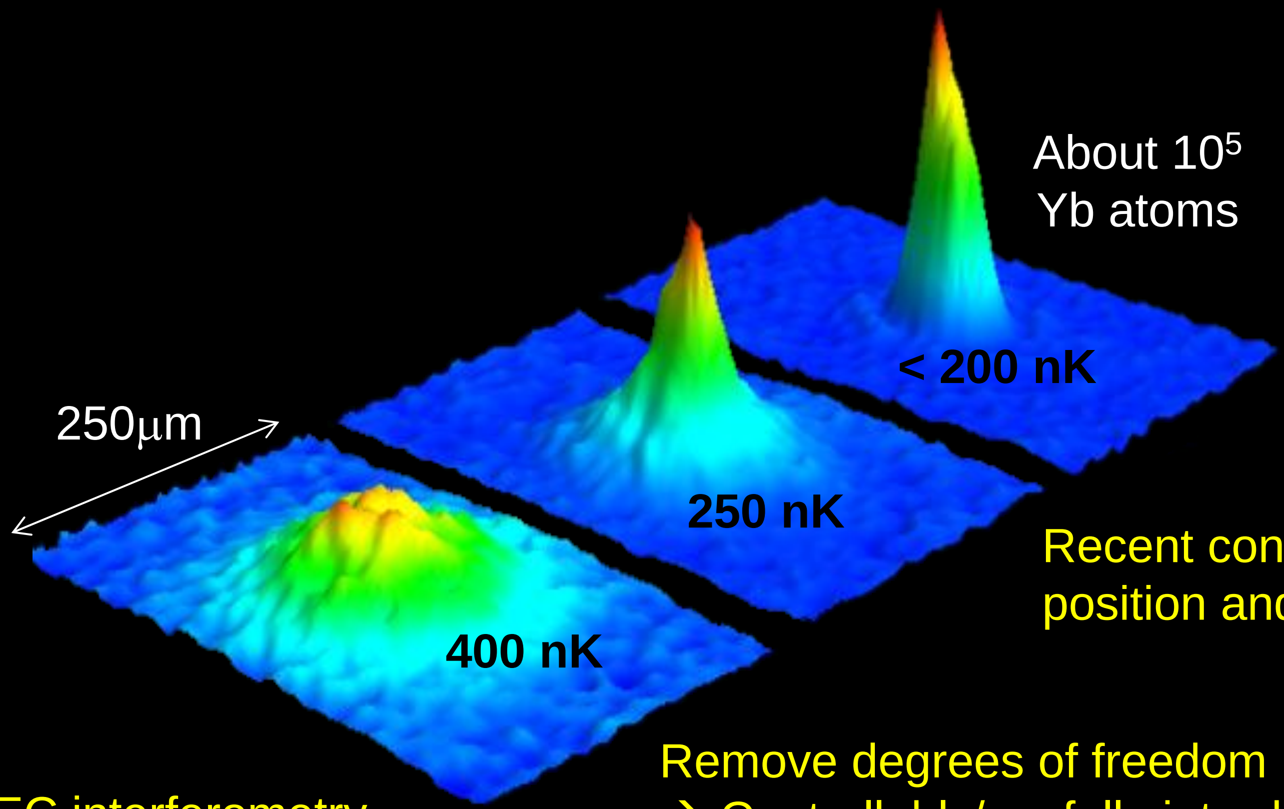
Chilling Tales about Quantum Gases



Recent control of atomic position and momentum.

Today:
Precision BEC interferometry
Bose-Fermi superfluids

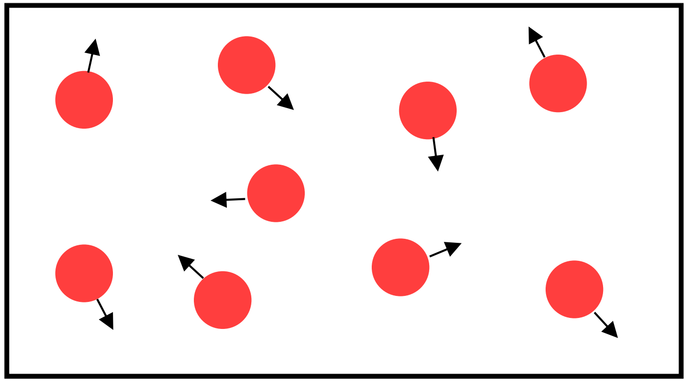
Remove degrees of freedom → Manipulate
→ Controllably/usefully introduce complexity
→ Address Q's in AMO, CM, nuclear, particle

Subhadeep Gupta

UW NSF-INT Phys REU, 8th August 2016

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

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

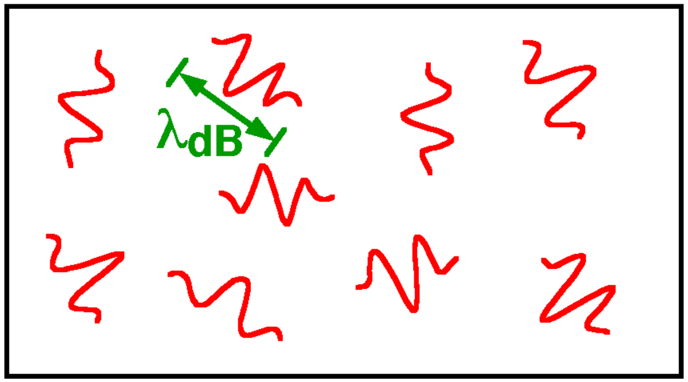
Air $n \sim 10^{19}/\text{cm}^3$, $T_c \sim 1\text{mK}$
Stuff $n \sim 10^{22}/\text{cm}^3$, $T_c \sim 0.1\text{K}$
Everything (except He) is solid

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

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

and ~ non-interacting

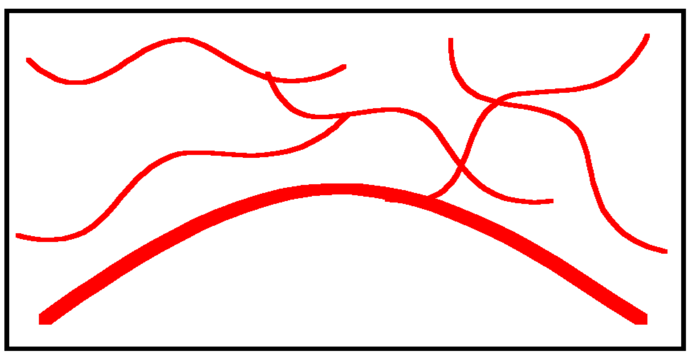
Bose-Einstein Condensation (BEC)



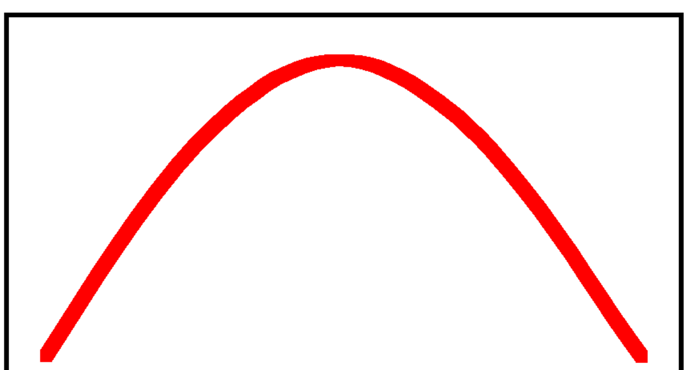
$$\lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}} \qquad n = \frac{N}{V}$$

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

Quantum Phase
Space Density

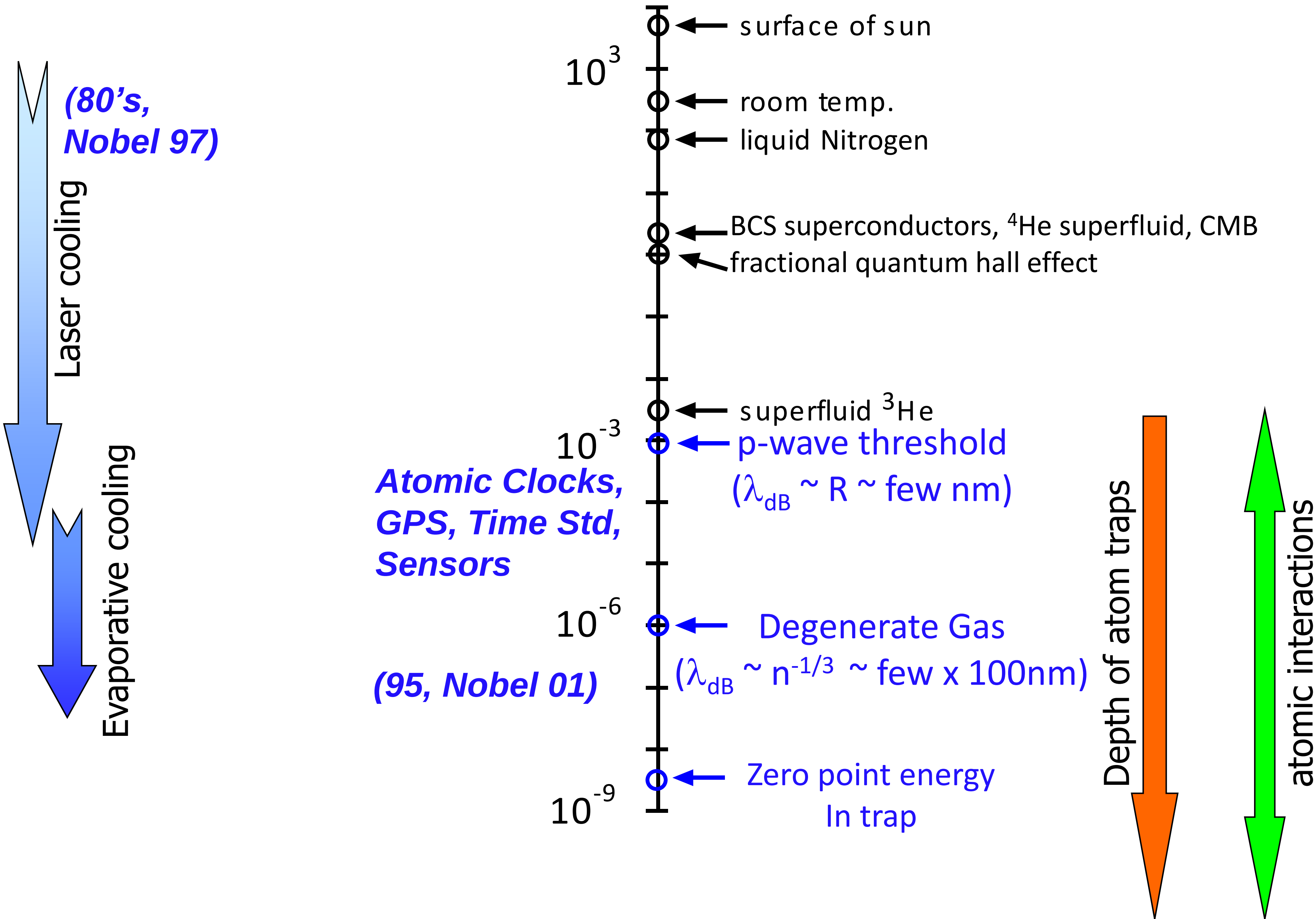


$$n\lambda_{dB}^3 \sim 1$$



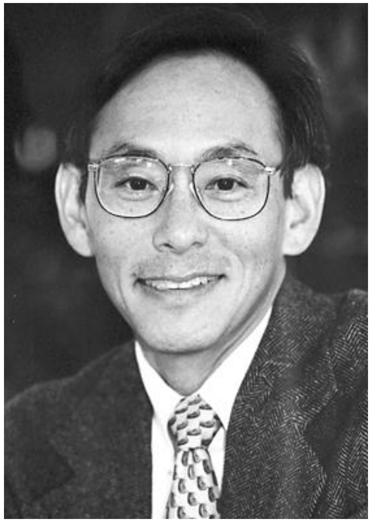
$$n\lambda_{dB}^3 >> 1$$

Relevant Ultracold Temperatures on the Log Kelvin Scale



1997 NOBEL

LASER COOLING



Steven Chu

Claude Cohen-Tannoudji

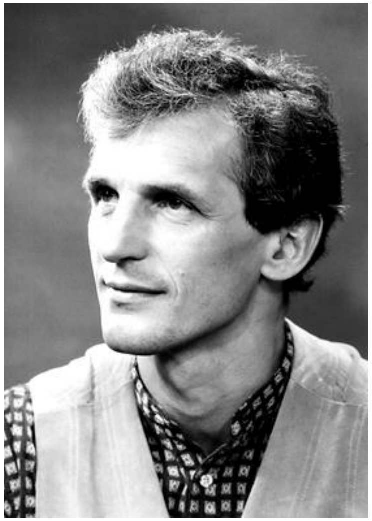
William D. Phillips

"for development of methods to cool and trap atoms with laser light"

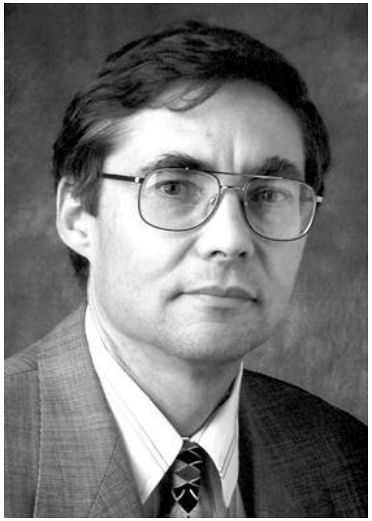
2001 NOBEL

BEC

Eric A. Cornell



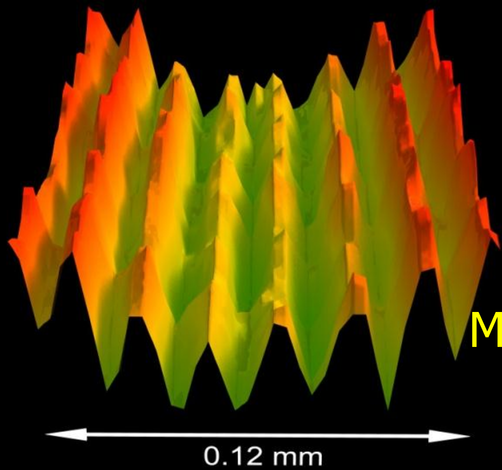
Wolfgang Ketterle



Carl E. Wieman

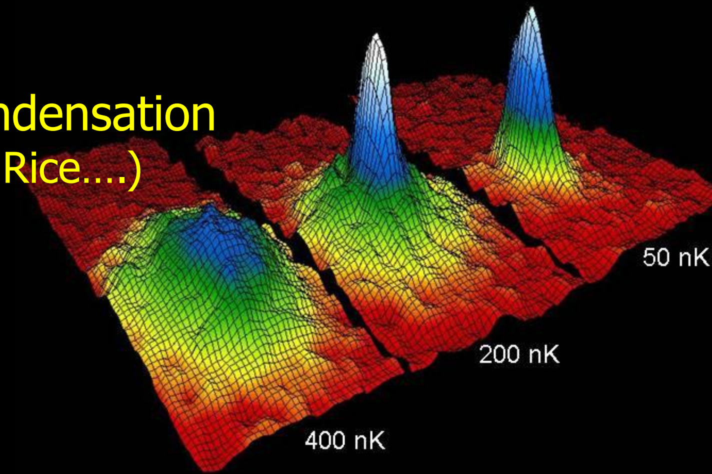
"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

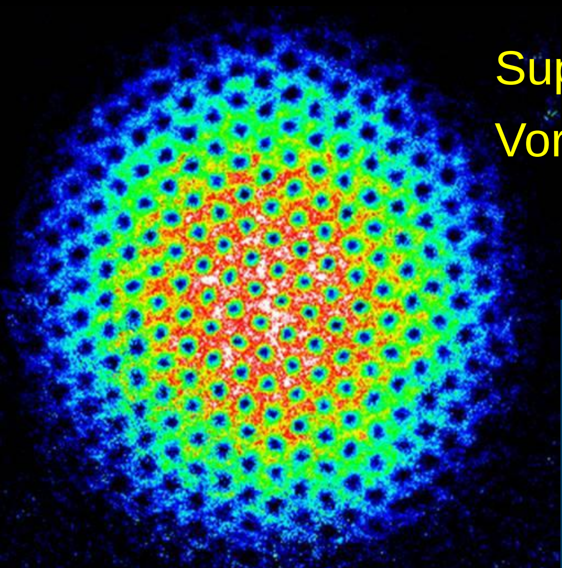
Some major achievements in ultracold atomic physics



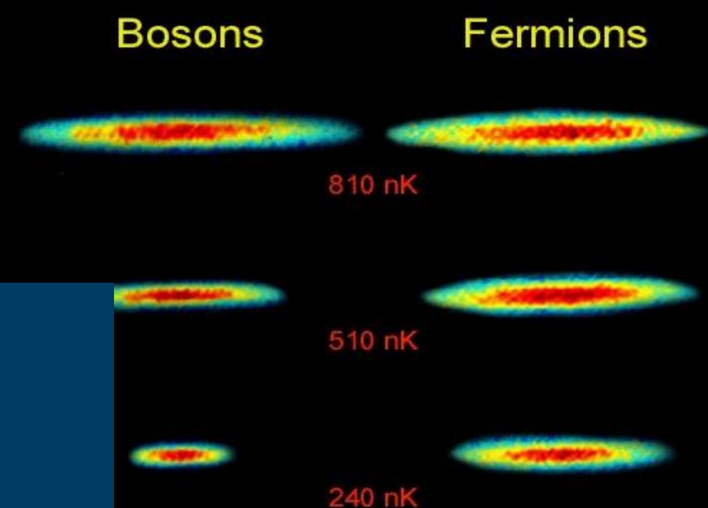
Macroscopic coherence
(97: MIT,…)

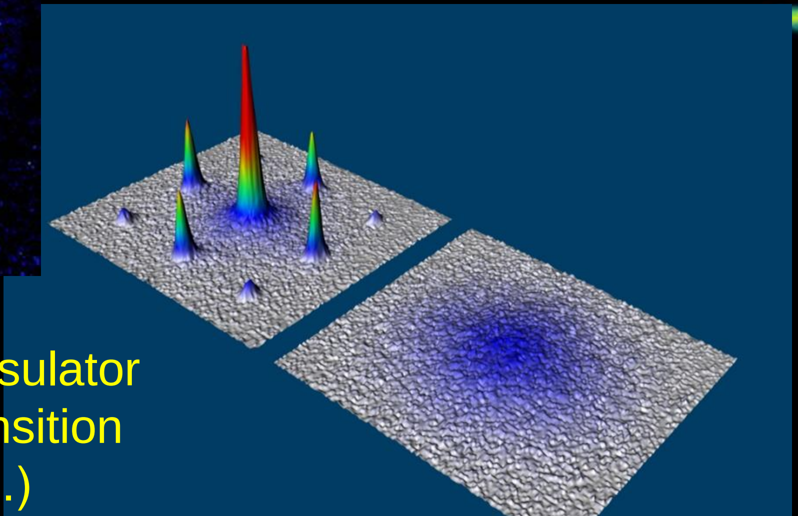
Bose-Einstein condensation
(95: JILA, MIT, Rice….)





Superfluidity,
Vortex lattice



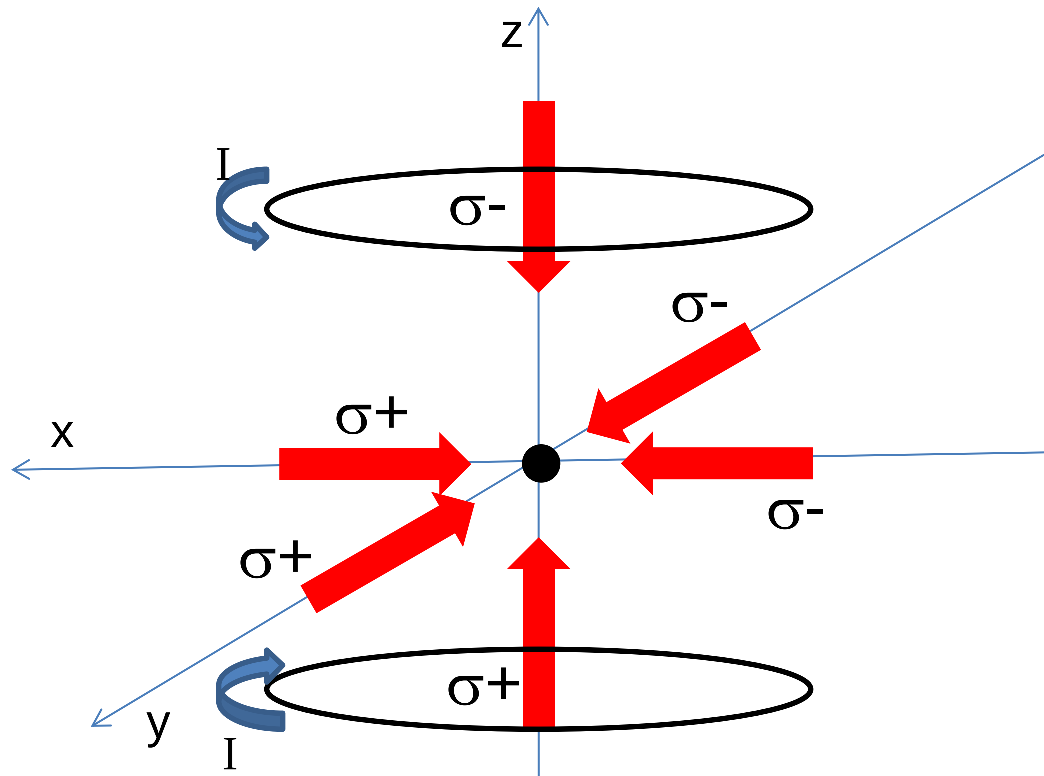


Superfluid to Mott-insulator
quantum phase transition
(02: Munich,…..)

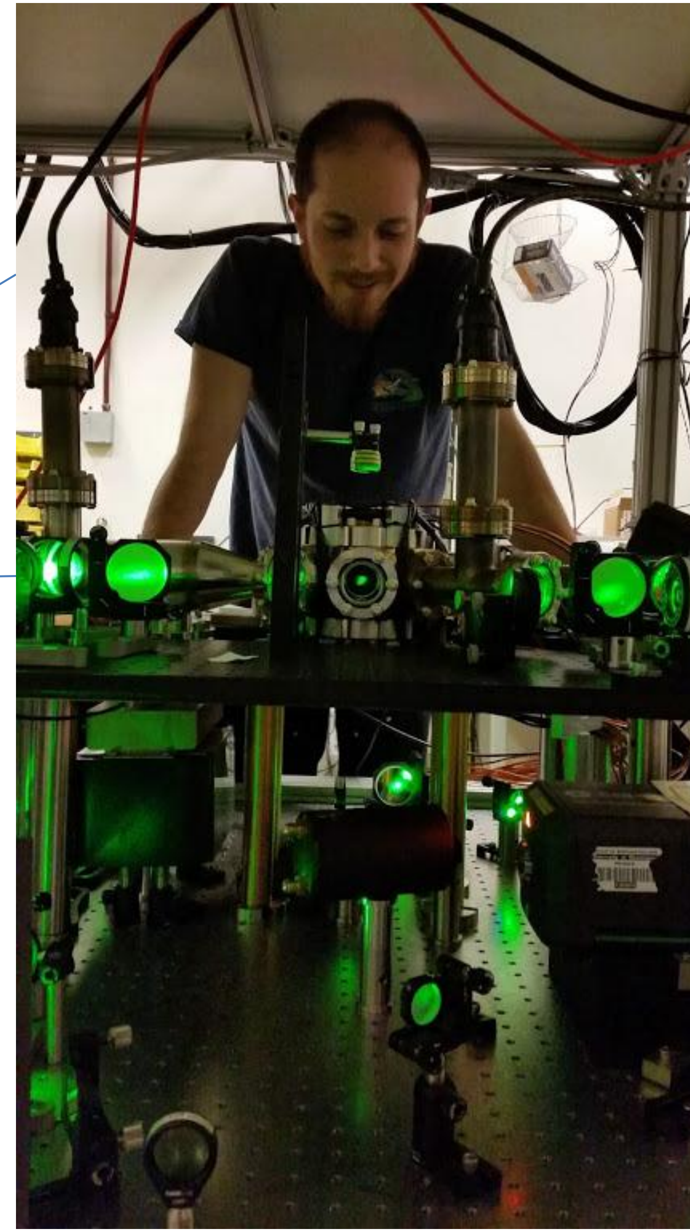
Degenerate Fermi gas
(99: JILA, Rice, ENS,
Duke, MIT, Innsbruck, ….)

Laser Cooling???

Laser Cooling



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

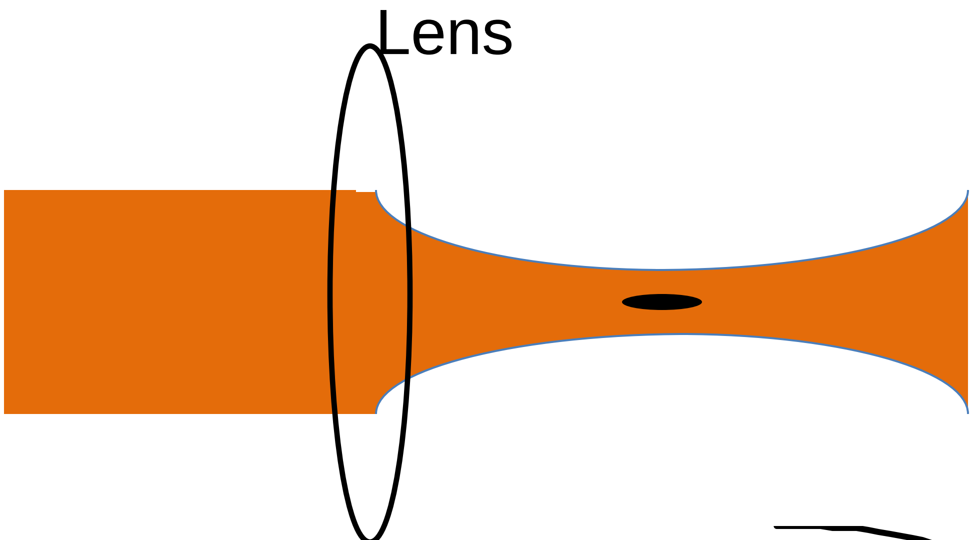


Atom Source ~ 600 K; UHV environment

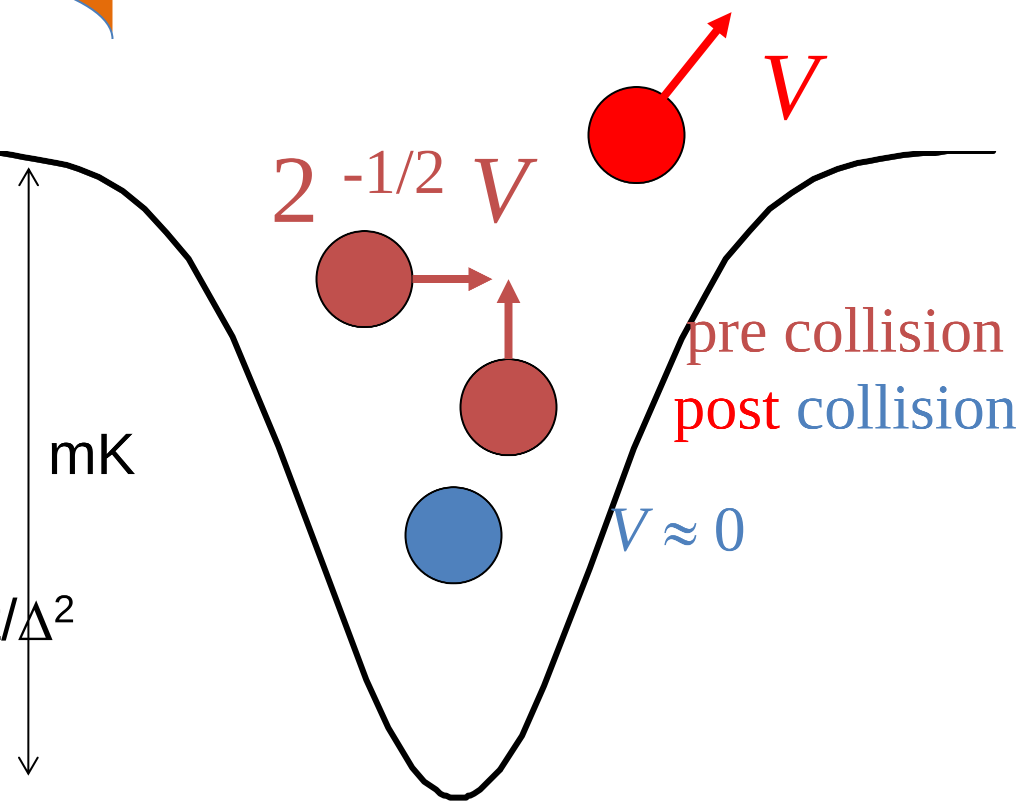
=> COOLING !

(Need a 2 level system)

Evaporative Cooling in a Conservative Trap

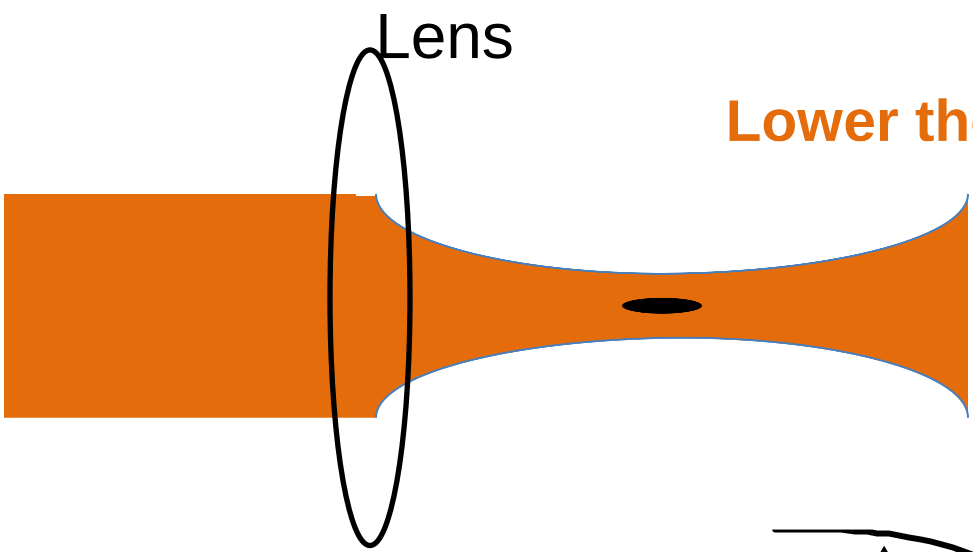


Optical Dipole Trap $\omega_L << \omega_{res}$

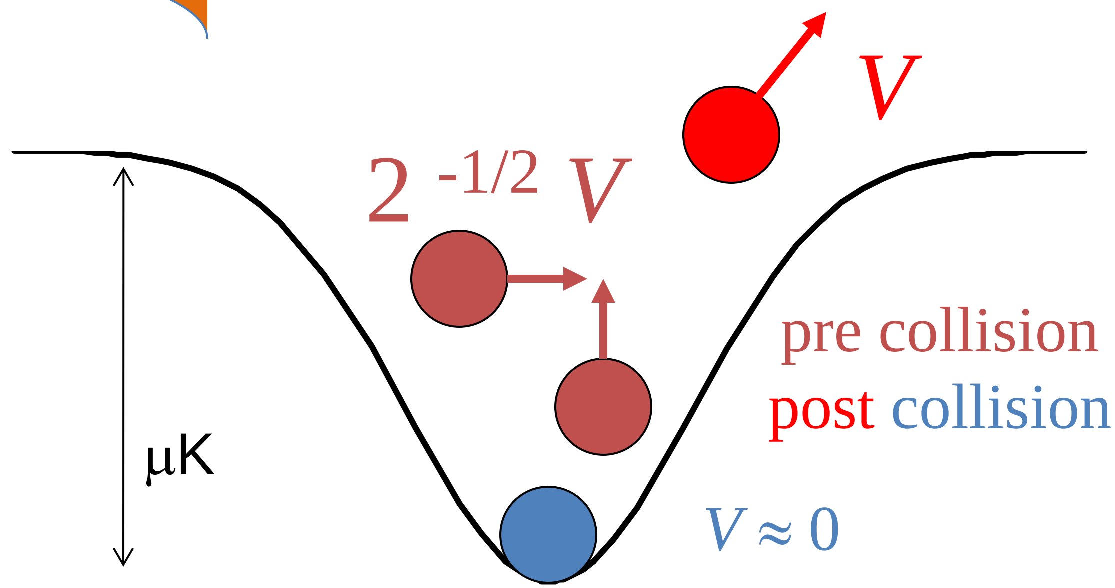


Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

Evaporative Cooling in a Conservative Trap



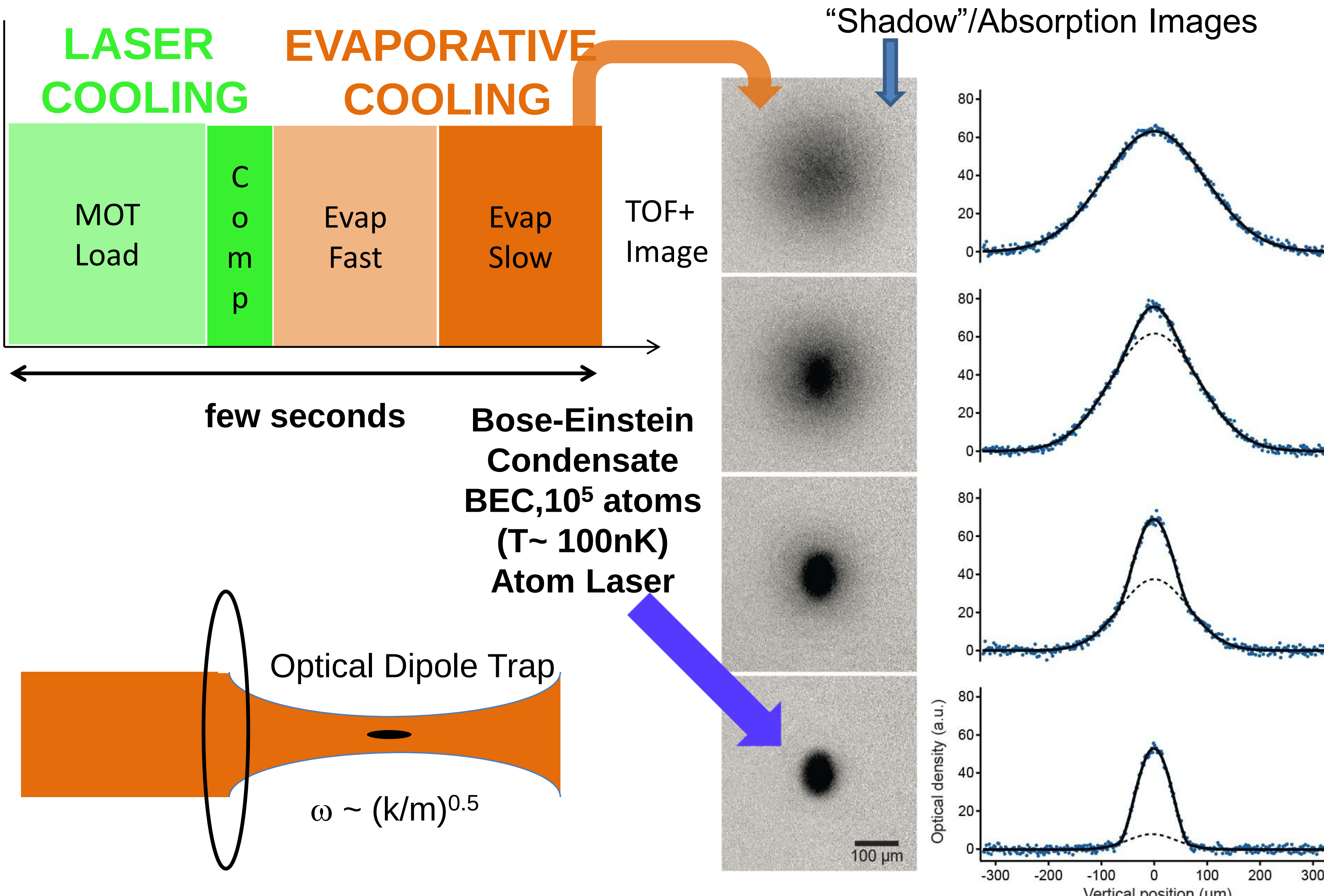
Lower the Power



Optical Dipole Trap $\omega_L << \omega_{res}$

Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

Making a Quantum Gas

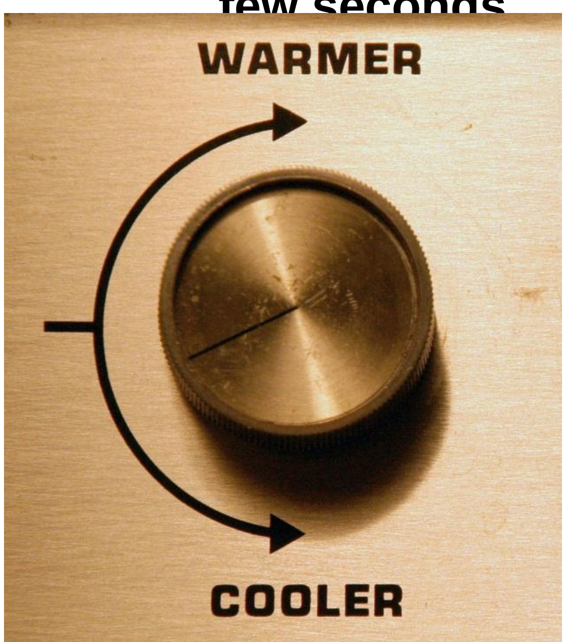


Making a Quantum Gas

LASER COOLING | **EVAPORATIVE COOLING**

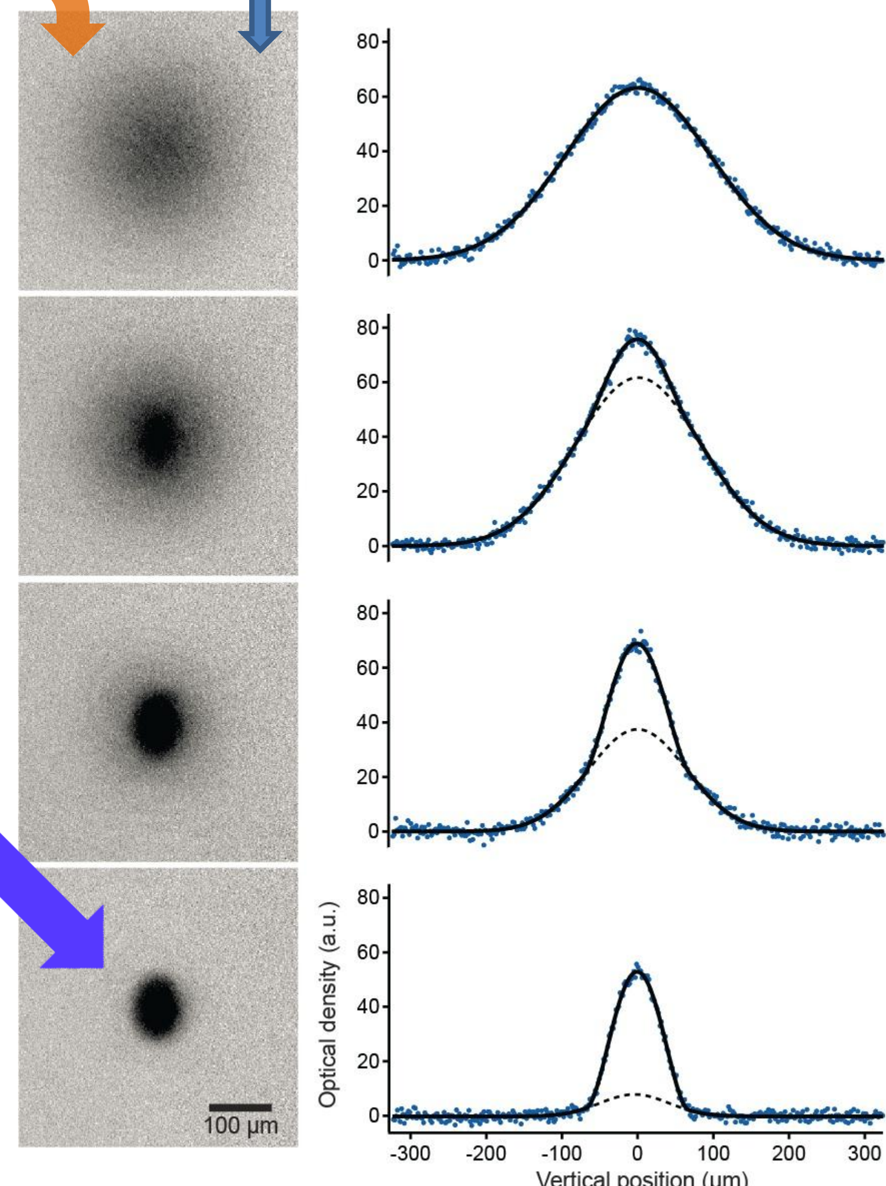
MOT Load | Comp | Evap Fast | Evap Slow | TOF+ Image

few seconds



Bose-Einstein Condensate
BEC,10^5 atoms
(T~ 100nK)
Atom Laser

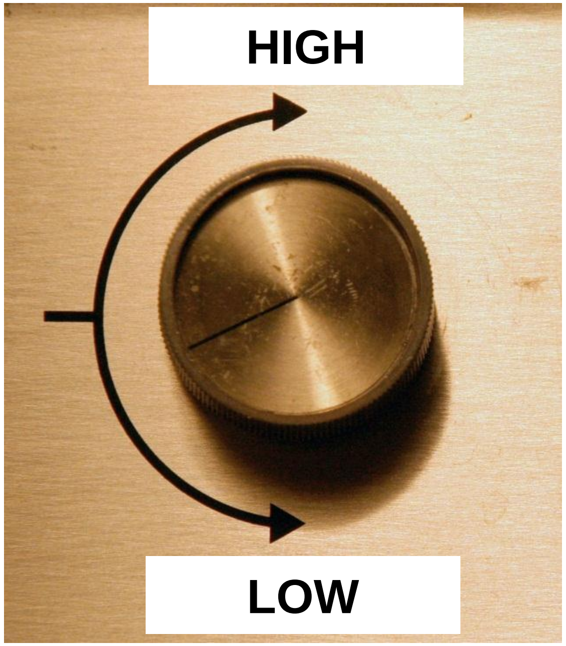
"Shadow"/Absorption Images



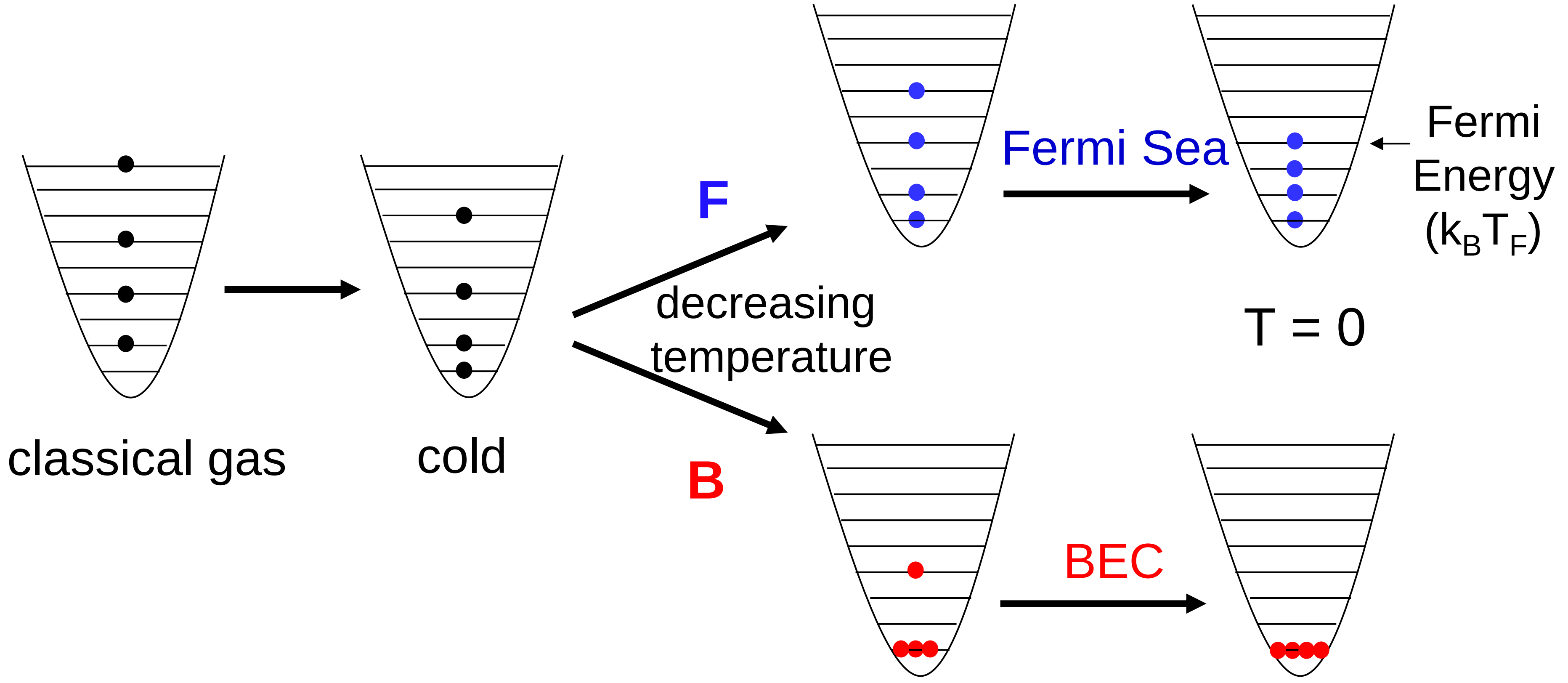
"Knobs" for Quantum Engineering

In ultracold, dilute gases,
using e-m fields, can control
(relatively) easily

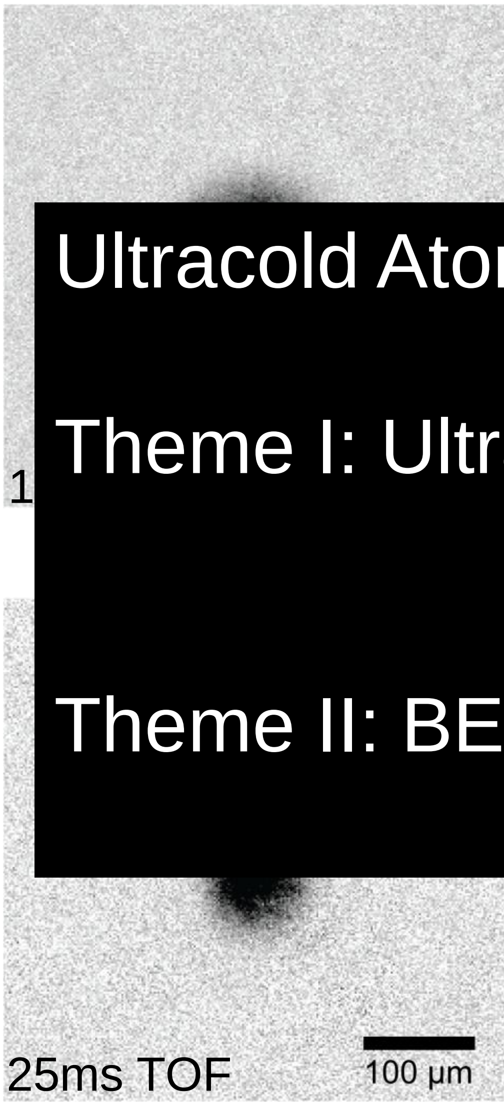
Temperature & density
Dimensionality
Magnetization
Magnitude & sign of the "charge"
Optical crystals (tunnel/on-site),
CM models, new systems
Chemical structure – form molecules

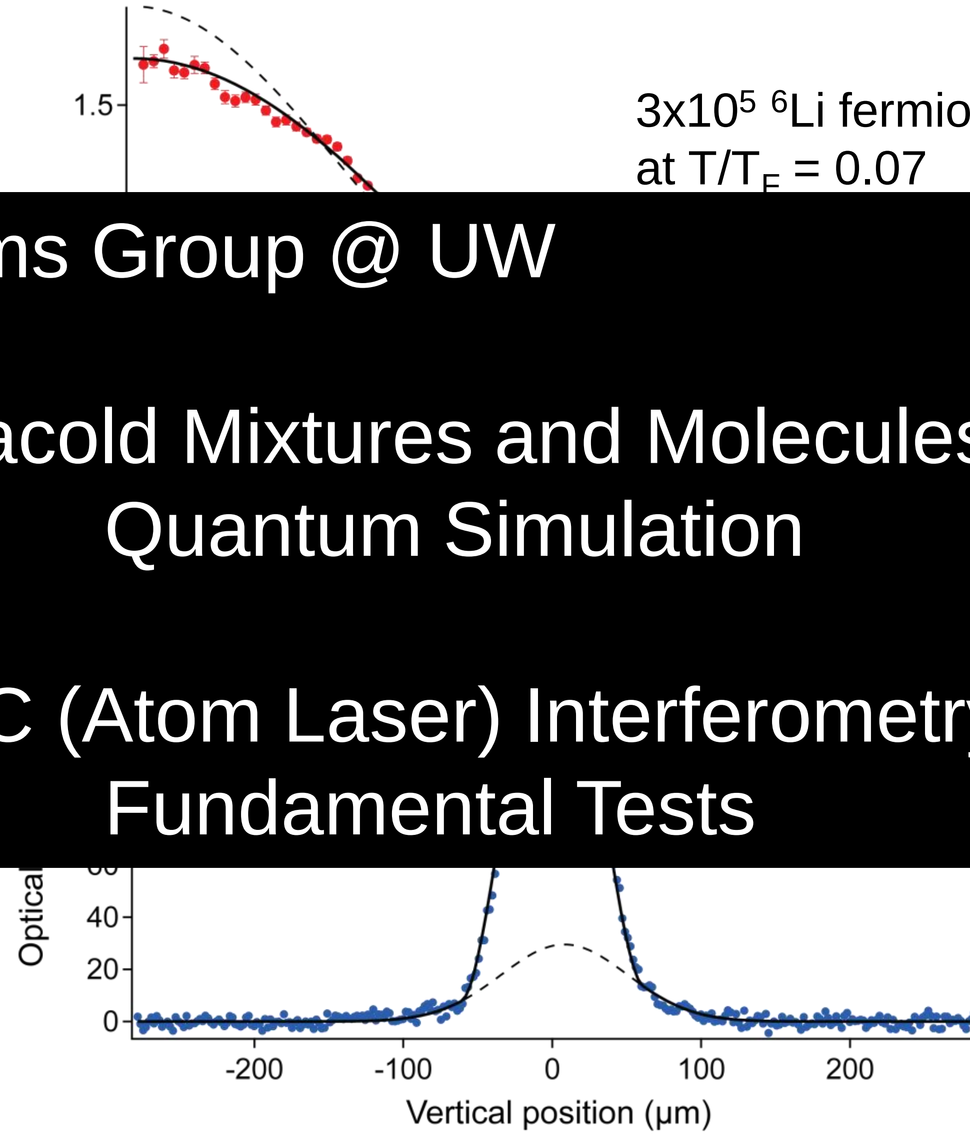


Different Quantum Matters



Quantum degenerate Fermi & Bose Gases





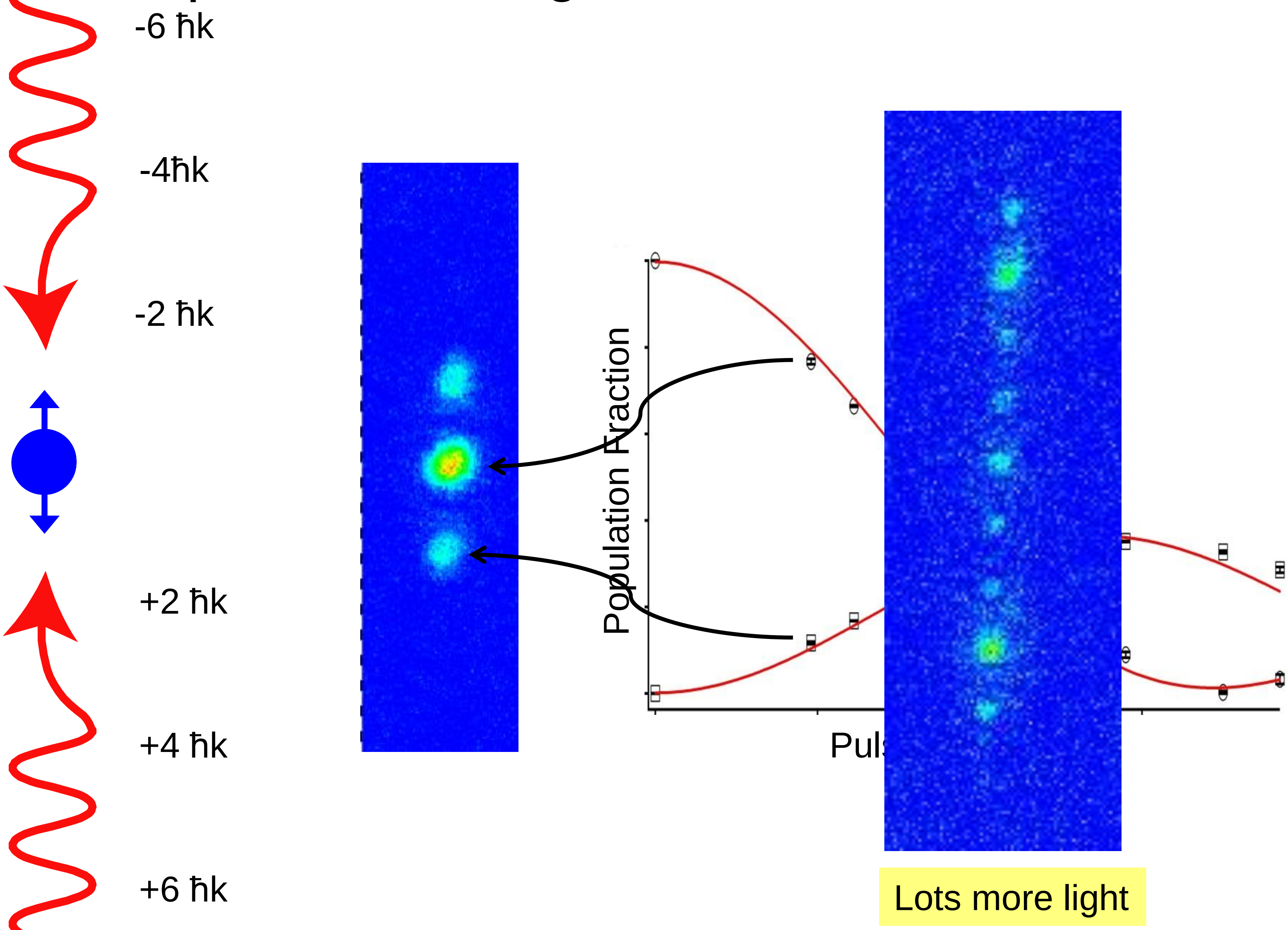
3×10^5 ^{6}Li fermions
at $T/T_F = 0.07$

Ultracold Atoms Group @ UW

Theme I: Ultracold Mixtures and Molecules
Quantum Simulation

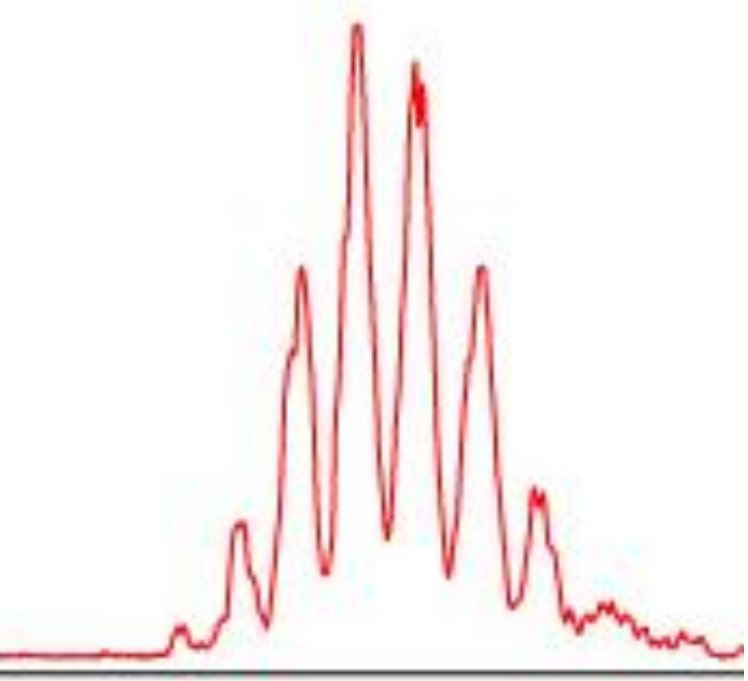
Theme II: BEC (Atom Laser) Interferometry
Fundamental Tests

Optical Standing Wave Diffraction of BEC

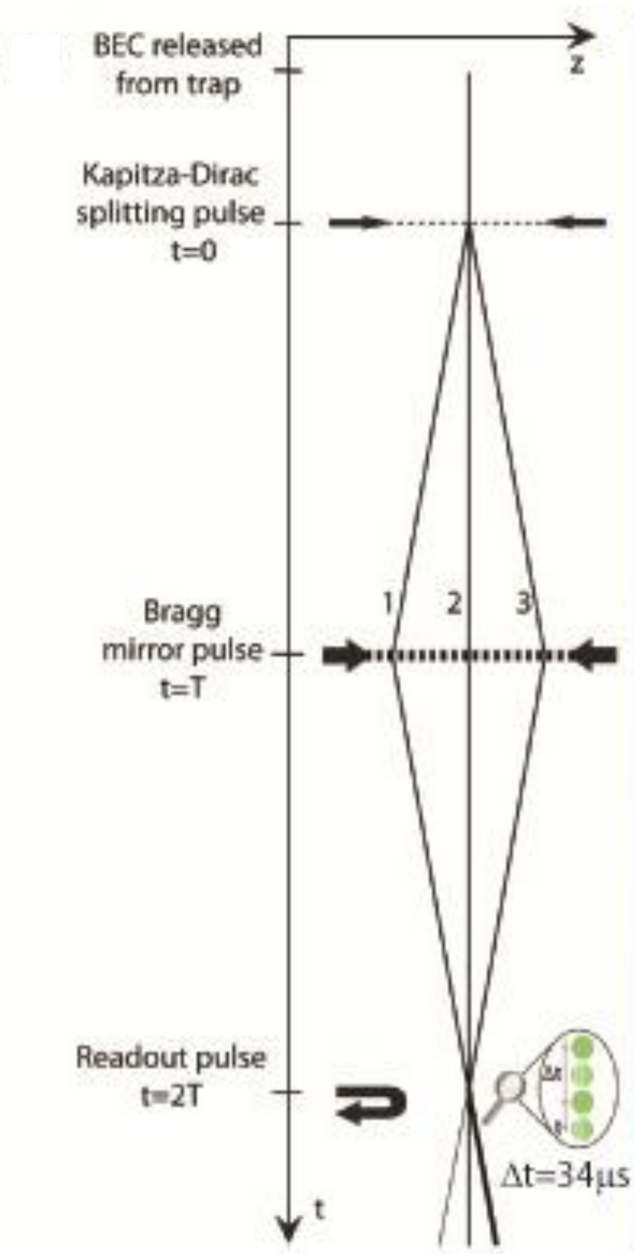


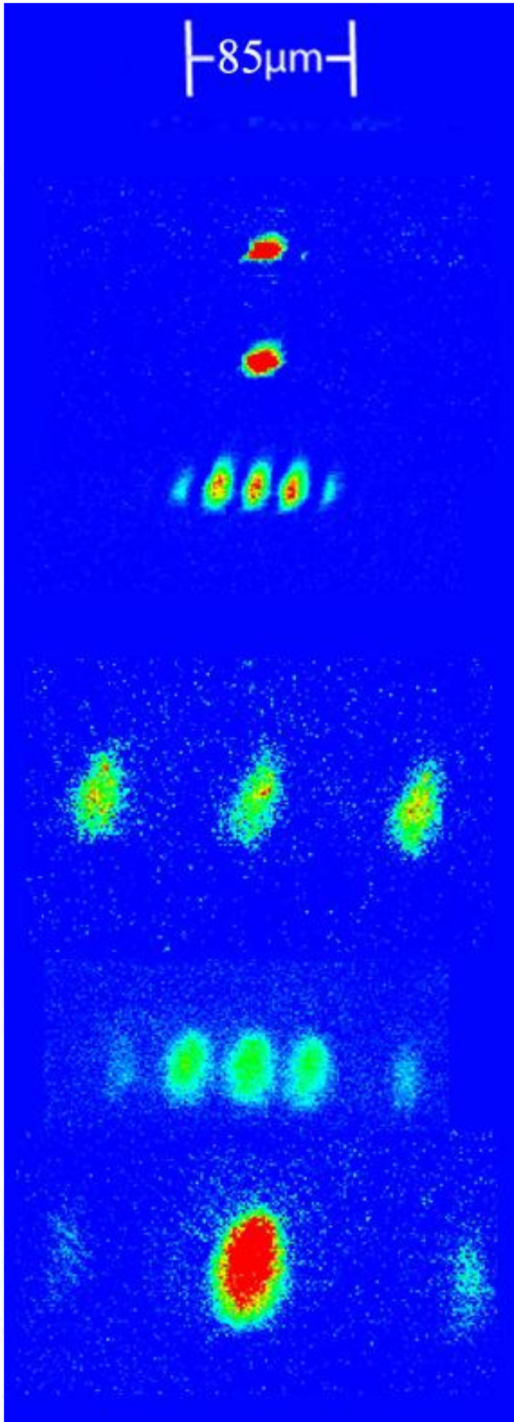
Contrast Interferometer with Yb BEC

Contrast Signal
T=11ms
34μs period



Time



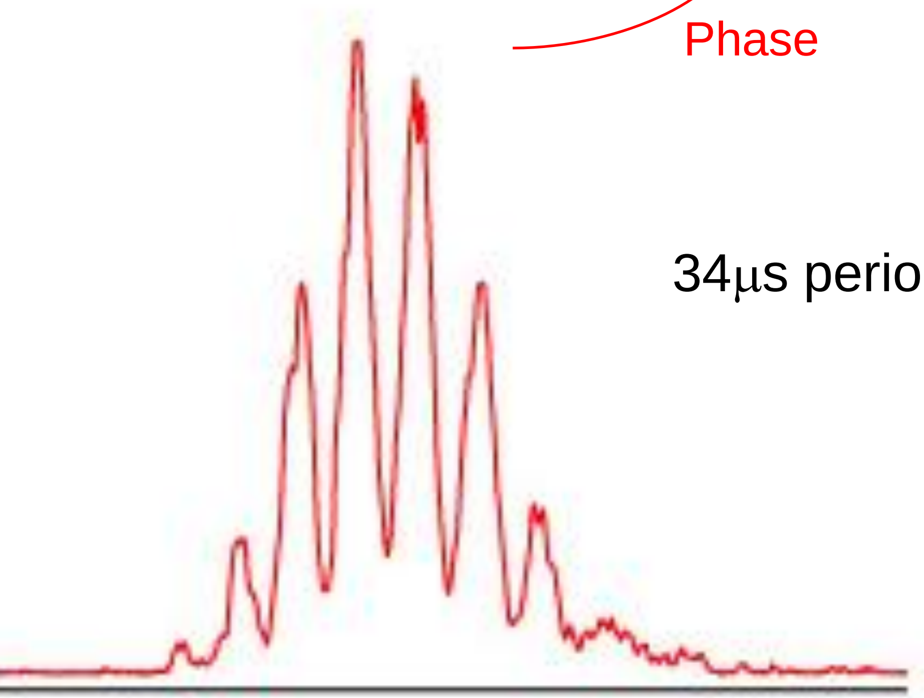


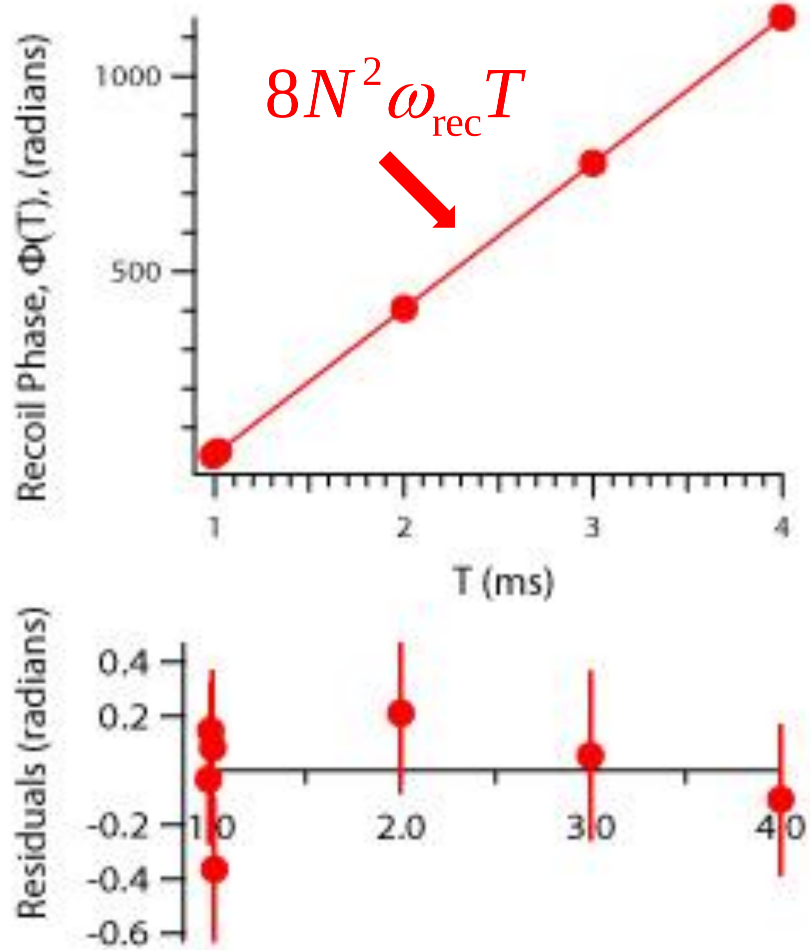
Contrast Interferometer with Yb BEC

"Acceleration"
pulses for sub-ppb

Oscillation
Phase

34μs period





A. Jamison et al. PRA **90**, 063606 (2014)
A. Jamison et al. PRA **84**, 043643 (2011)

Photon Recoil for the Fine Structure Constant, α

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

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

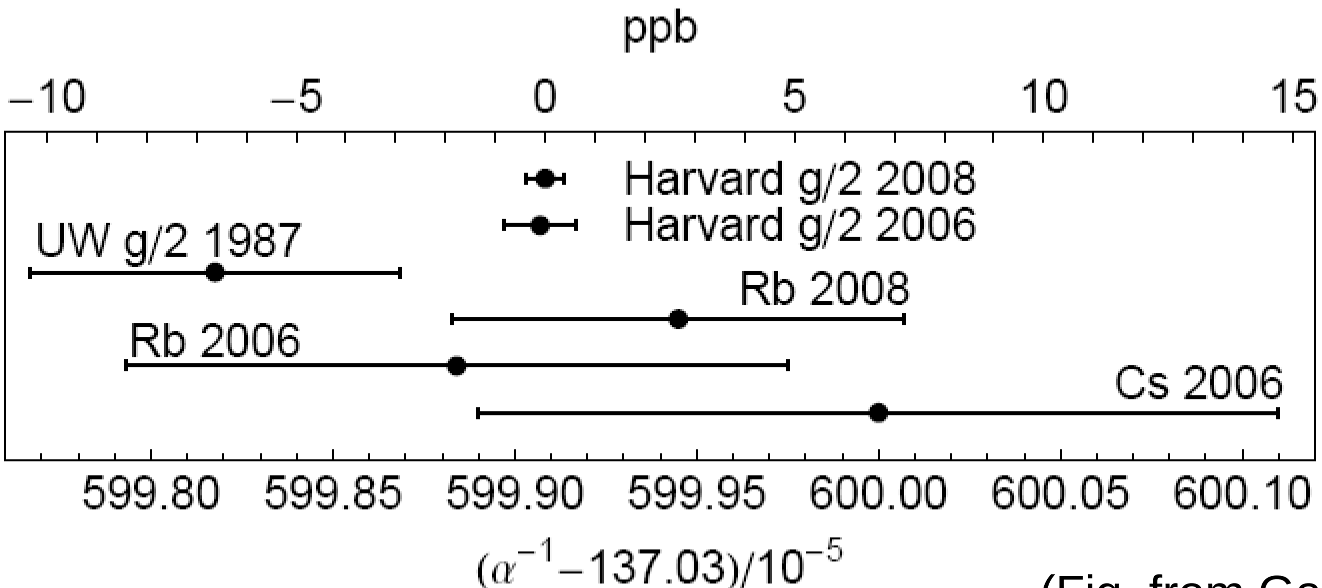
$$\alpha^2 = \left(\frac{e^2}{\hbar c}\right)^2 = \frac{2R_\infty}{c}\frac{h}{m_e} = \frac{2R_\infty}{c}\frac{M}{M_e}\frac{h}{m}$$

0.03 ppb: penning trap mass spec.
(Sturm et al., 2014)

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

Photon Recoil Measurement
using Atomic Interferometry
(currently x10 worse)

Precision Measurements of the fine structure constant, α



(Fig. from Gabrielse, 2009)

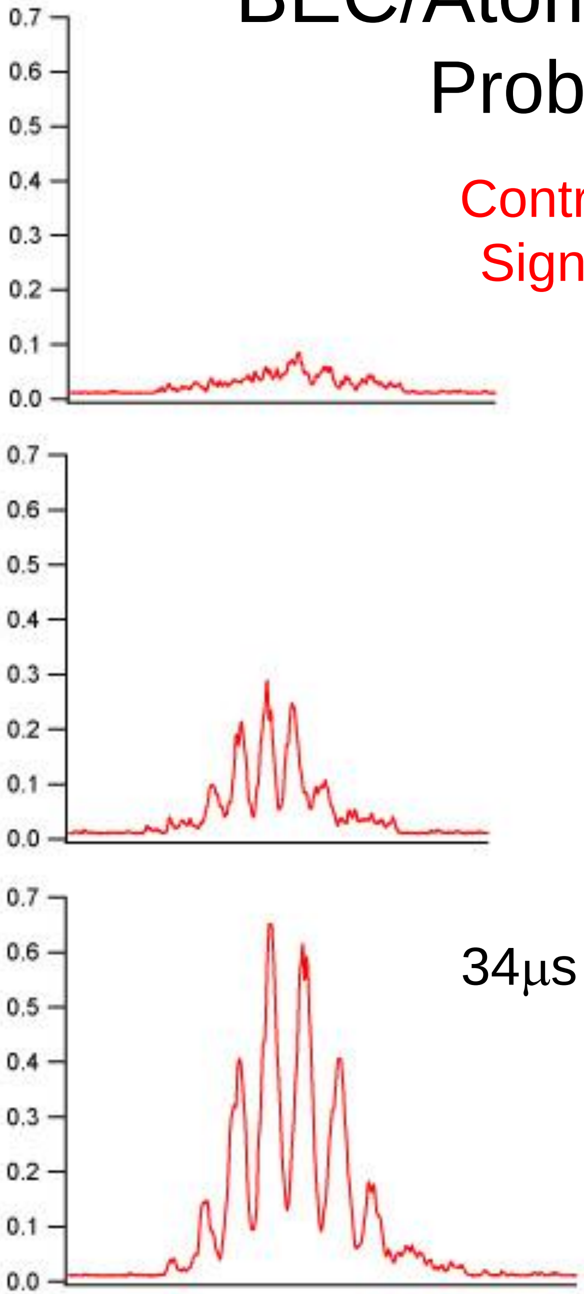
g/2: α from measurement of electron μ and *complex* QED theory
Rb, Cs: Atomic Physics route to α. (Also 2011 meas. in Rb at 0.7ppb)
α in CM: quantum Hall conductance, Josephson junction frequency
α comparison test of QED, sensitive to hadronic contribs, new physics

Our Yb BEC route to α: Targeted at < 0.1 ppb.
(High source coherence, high symmetry of interferometer)

BEC/Atom Laser for interferometry

Probe of Phase Transition

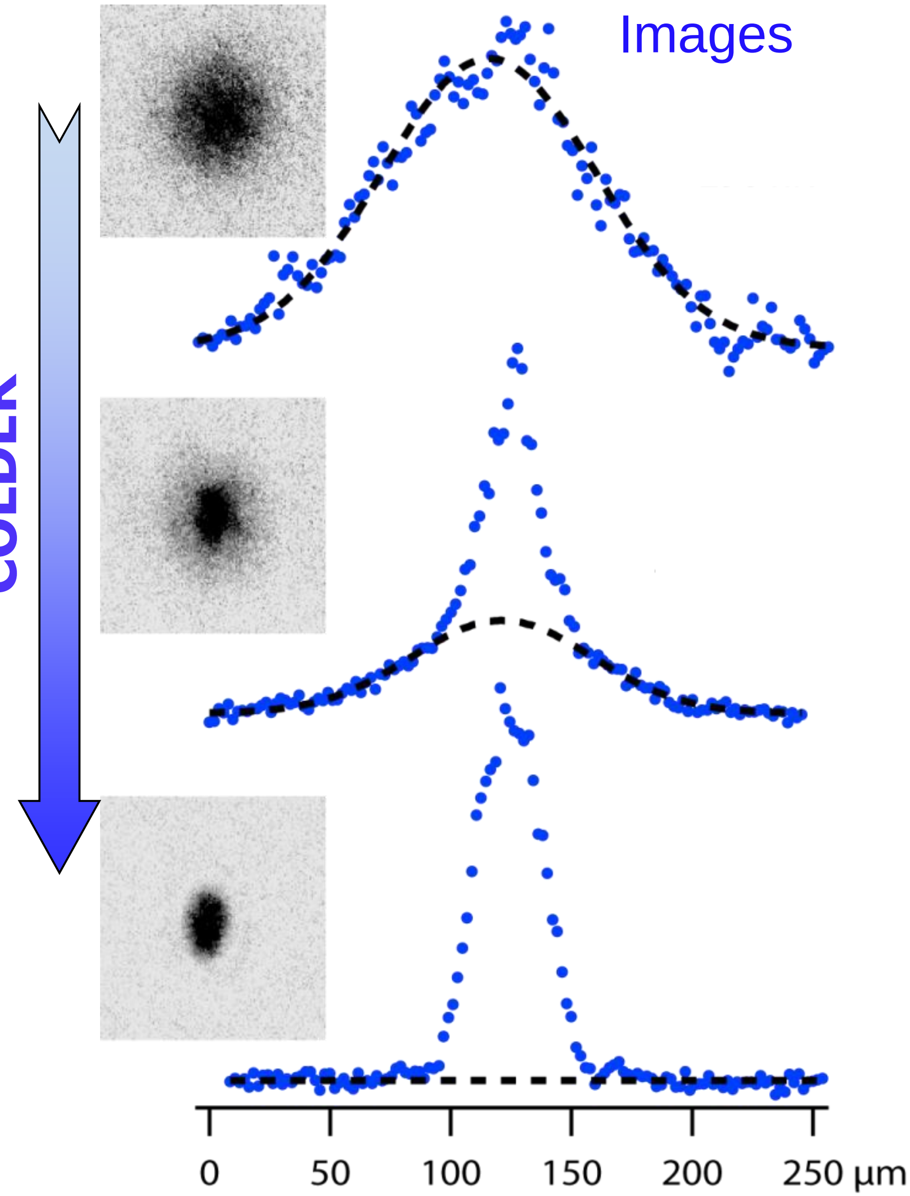
Contrast Signals



Time

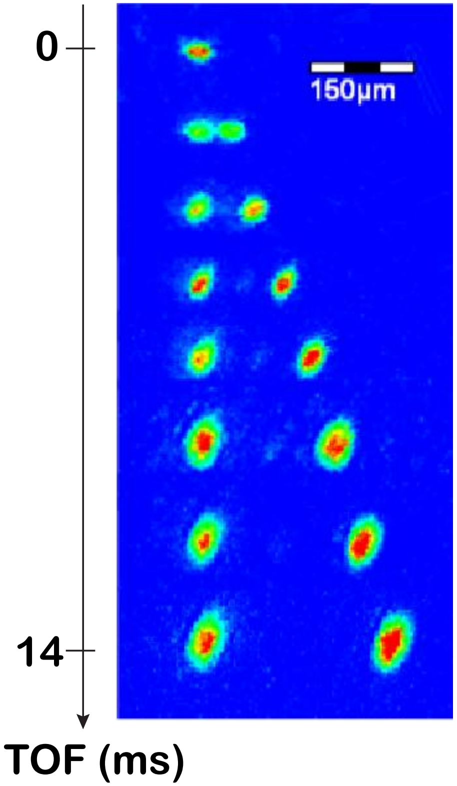
34μs period

Absorption Images

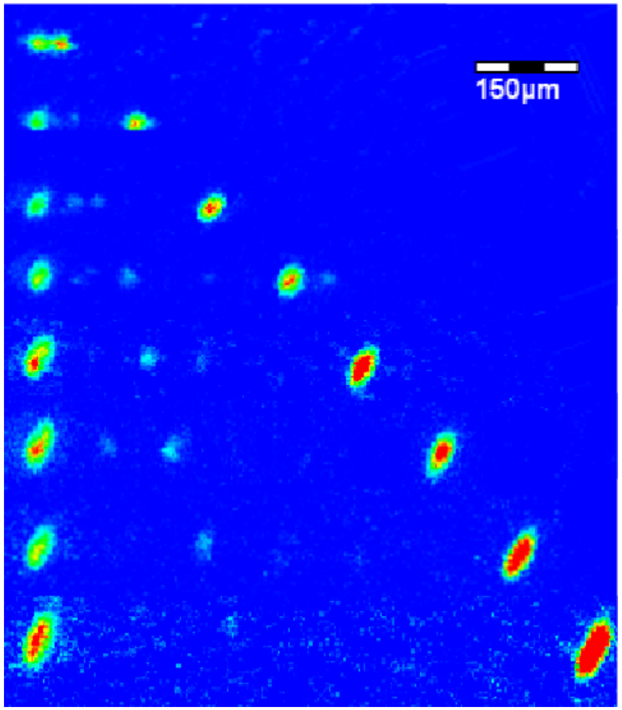


Acceleration by Bloch Oscillation

2 photon recoils



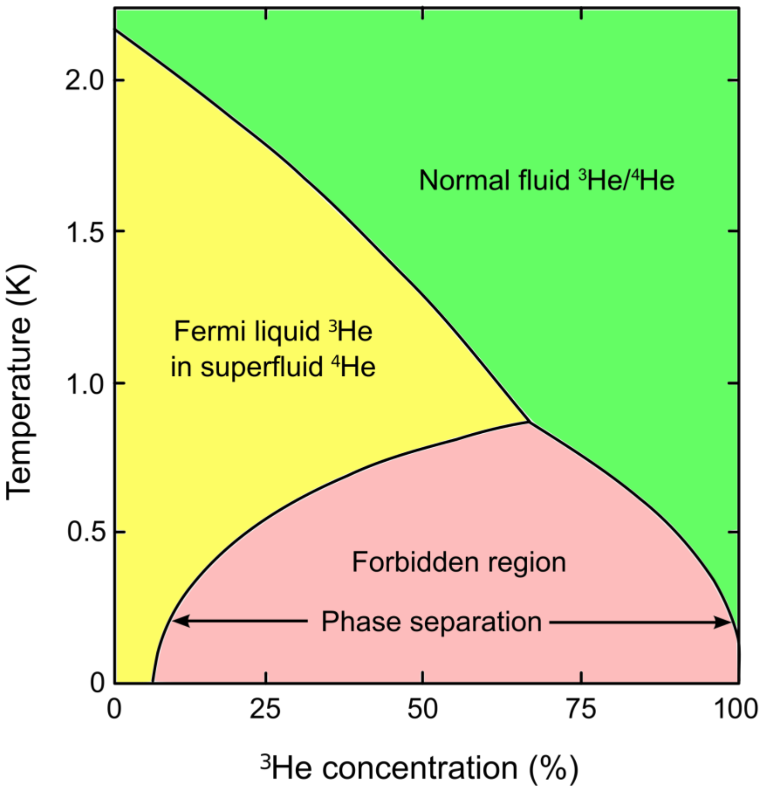
12 photon recoils

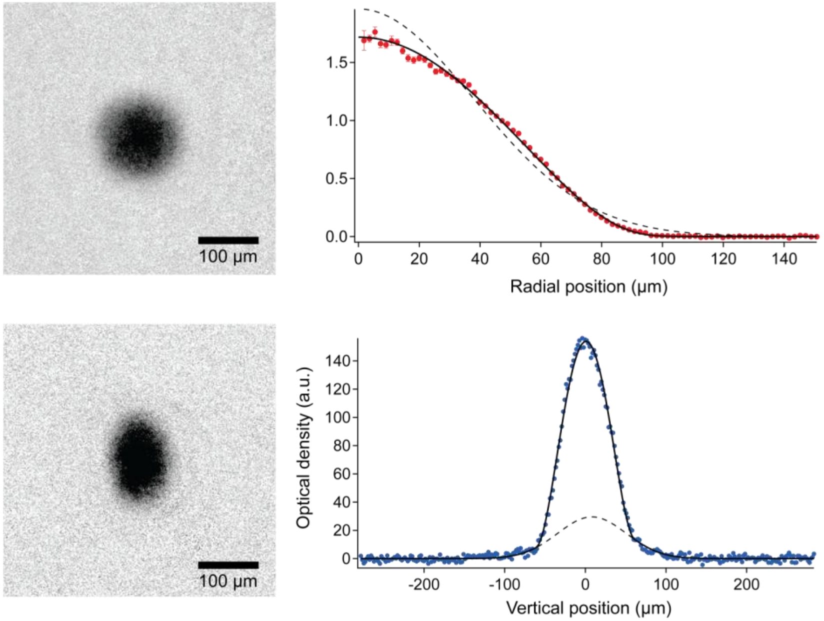


200 photon recoils observed

Bose-Fermi Mixtures

^{4}He-^{3}He mixtures.
Strong B-F repulsion.
B-F superfluid not yet realized

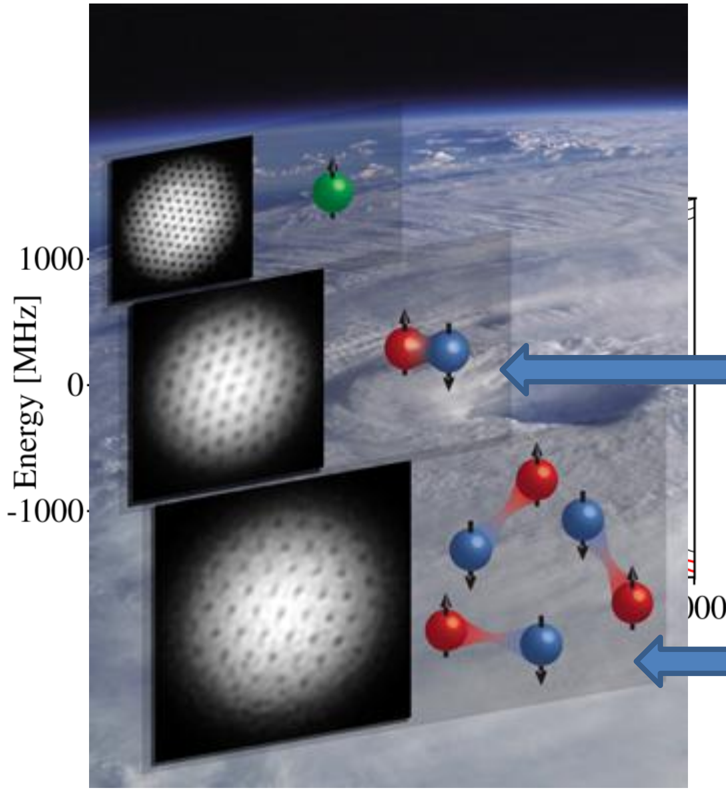




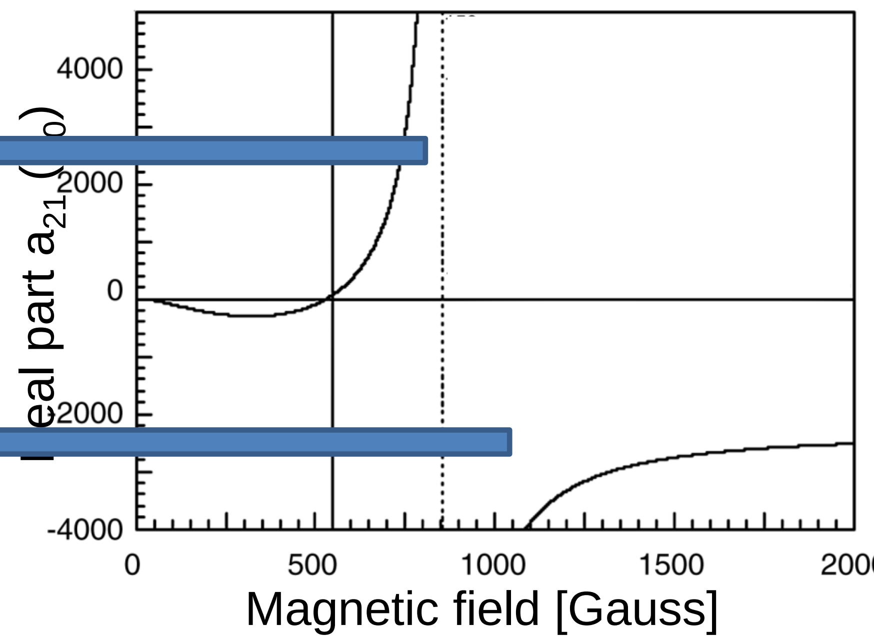
Several degenerate B-F ultracold gas mixtures:
{^{7}Li,^{23}Na,$^{85,87}Rb$,^{41}K,^{133}Cs,^{174}Yb}-^{6}Li
{^{23}Na,^{87}Rb,^{41}K}-^{40}K
2-isotope Yb, Sr, Dy,Cr; ^{87}Rb-^{173}Yb

Very recently B-F superfluids in atomic systems in ^{7}Li-^{6}Li, ^{174}Yb-^{6}Li, ^{41}K-^{6}Li
NEW QUANTUM SYSTEM!

Strong Interactions in the ^{6}Li Fermi system

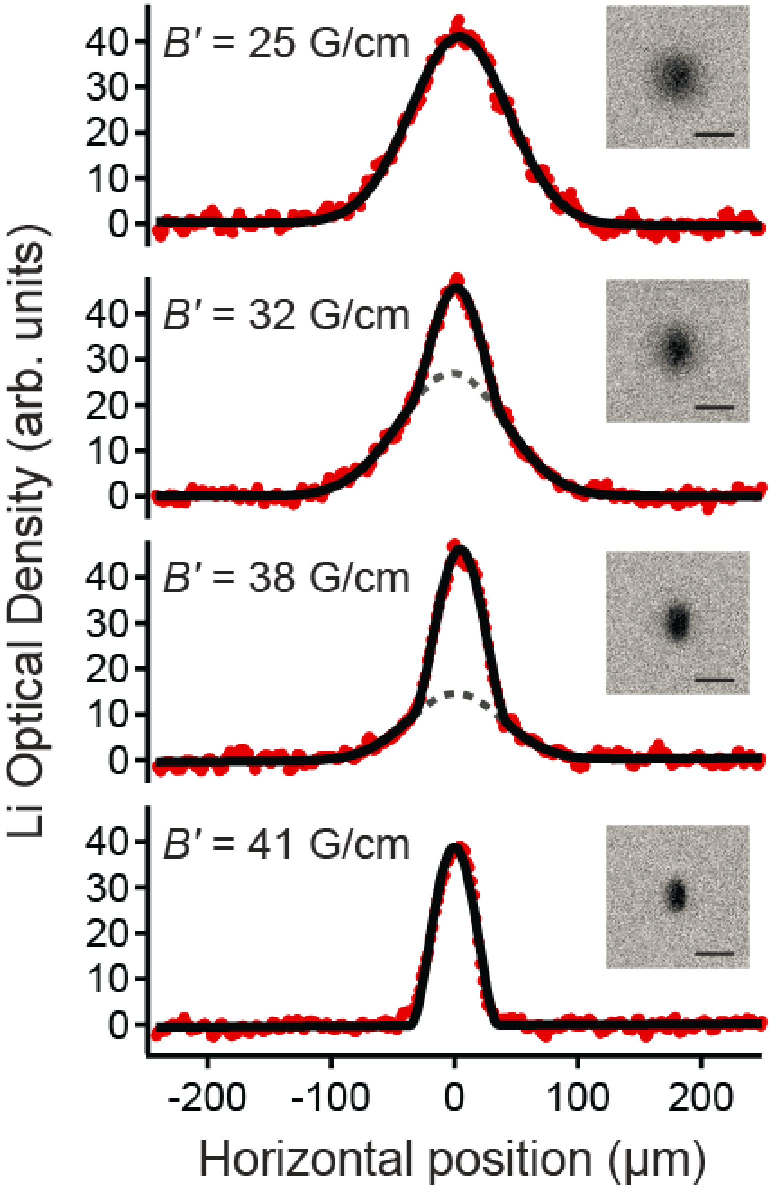


Magnetic Feshbach Resonance (MFR)

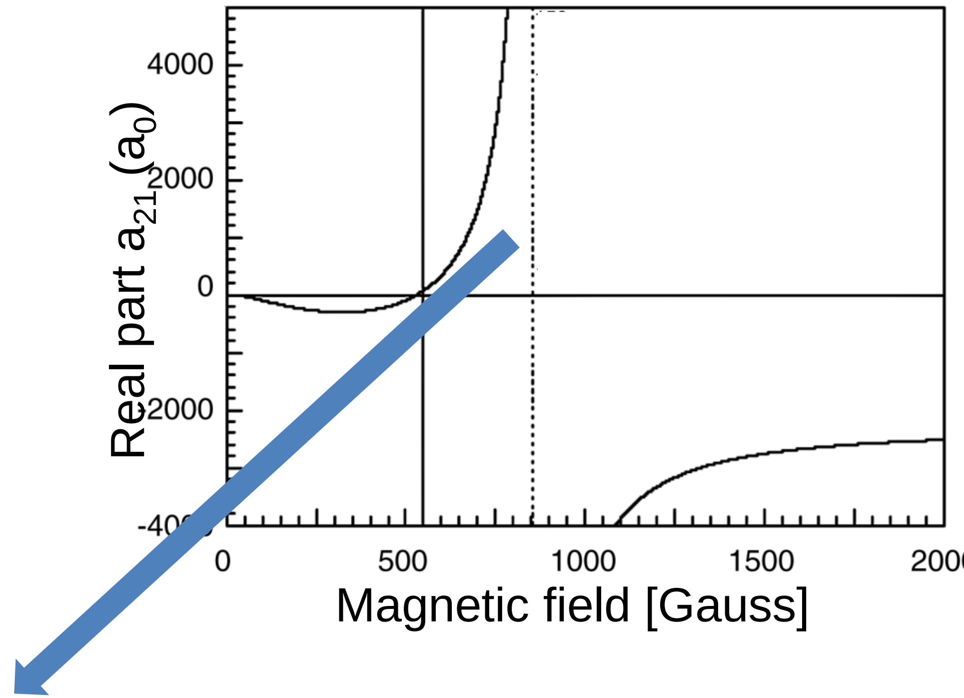


Fermi gas physics; High Tc Fermi superfluid;
BEC/BCS crossover across wide Feshbach resonance;
Unitary Fermi Gas. Universal Physics

Li_2 Fermionic Superfluidity



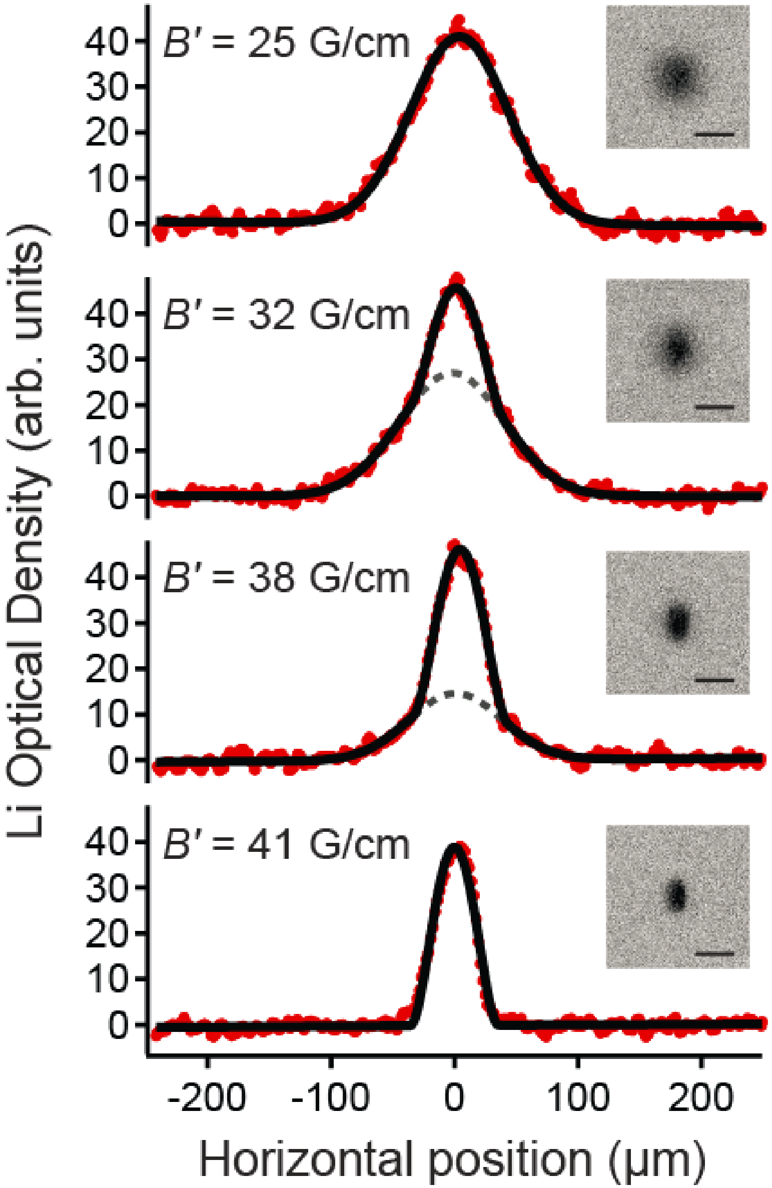
Magnetic Feshbach Resonance (MFR)

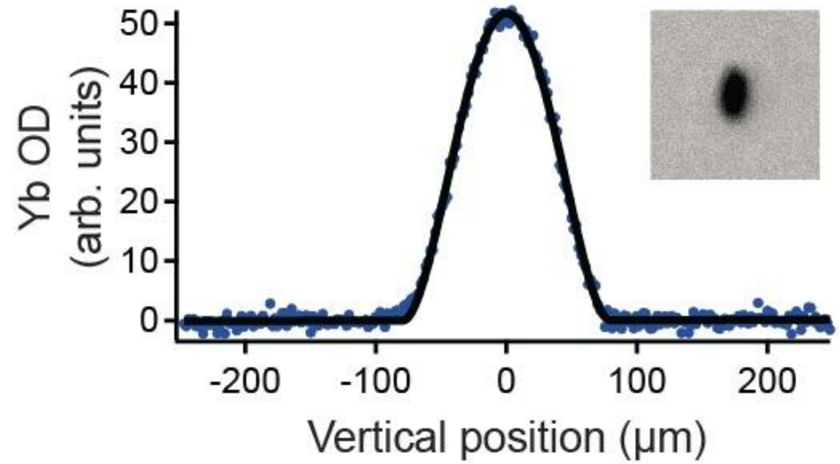


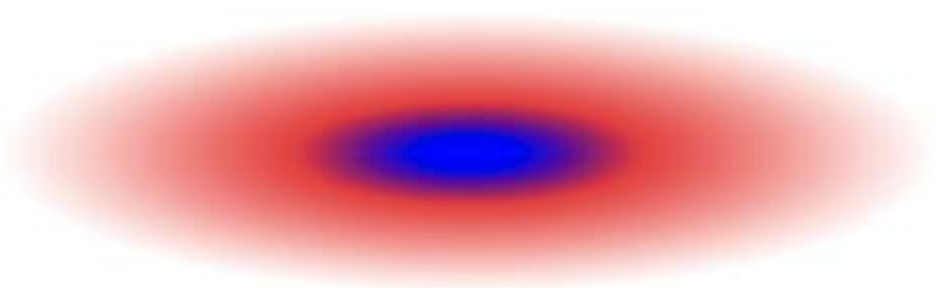
Formation of molecular BEC

(Fermionic SF T_c ~ $0.18T_F$)

^{174}Yb-^{6}Li Bose-Fermi Dual-Superfluid

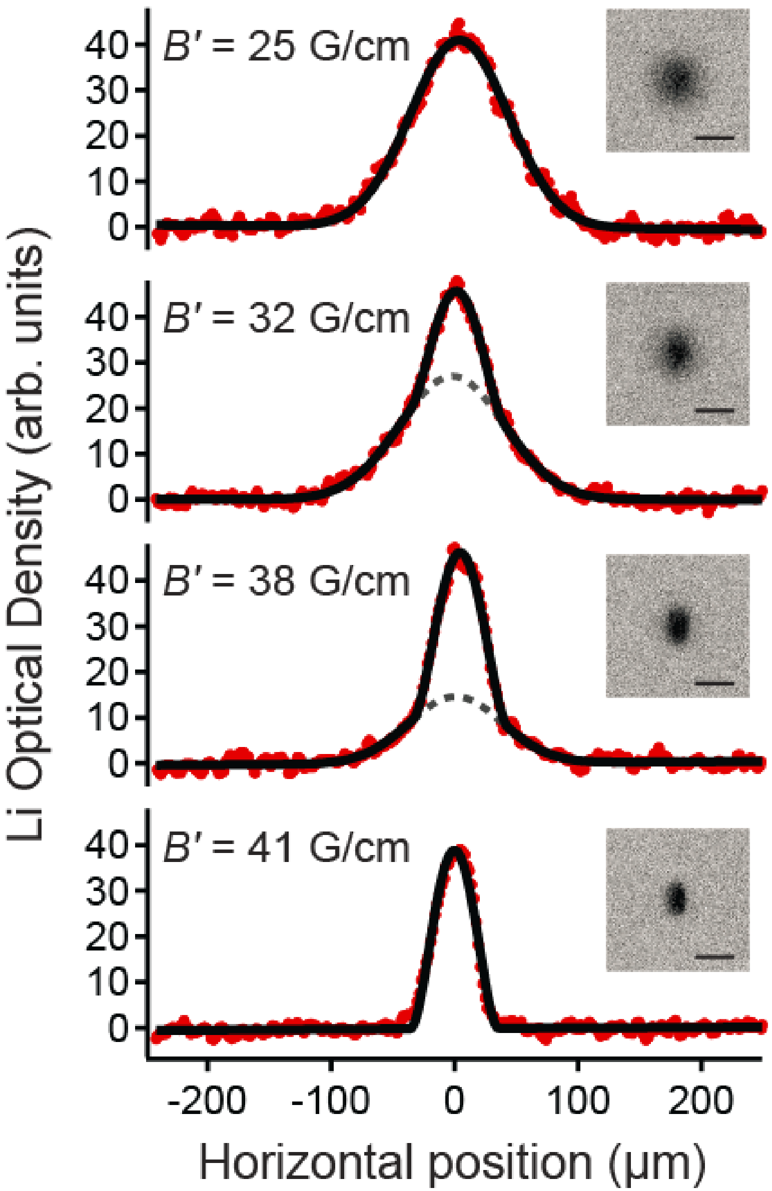


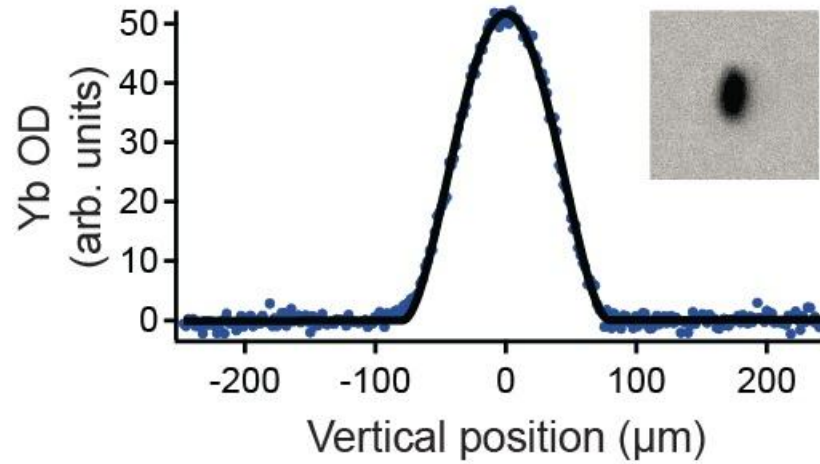




R.J. Roy et al. arXiv:1607.03221 (2016)

^{174}Yb-^{6}Li Bose-Fermi Dual-Superfluid





Characteristics at Unitarity (832G)

$N_{Li}=8\times10^4$ $N_{Yb}=1.1\times10^5$

T/Tc < 0.5 for bosons and fermions

Dual-superfluid lifetime ~ 1 sec

"Pancake": $\omega_{Yb}/2\pi = (26,388,59)$; $\omega_{Li}=8\omega_{Yb}$

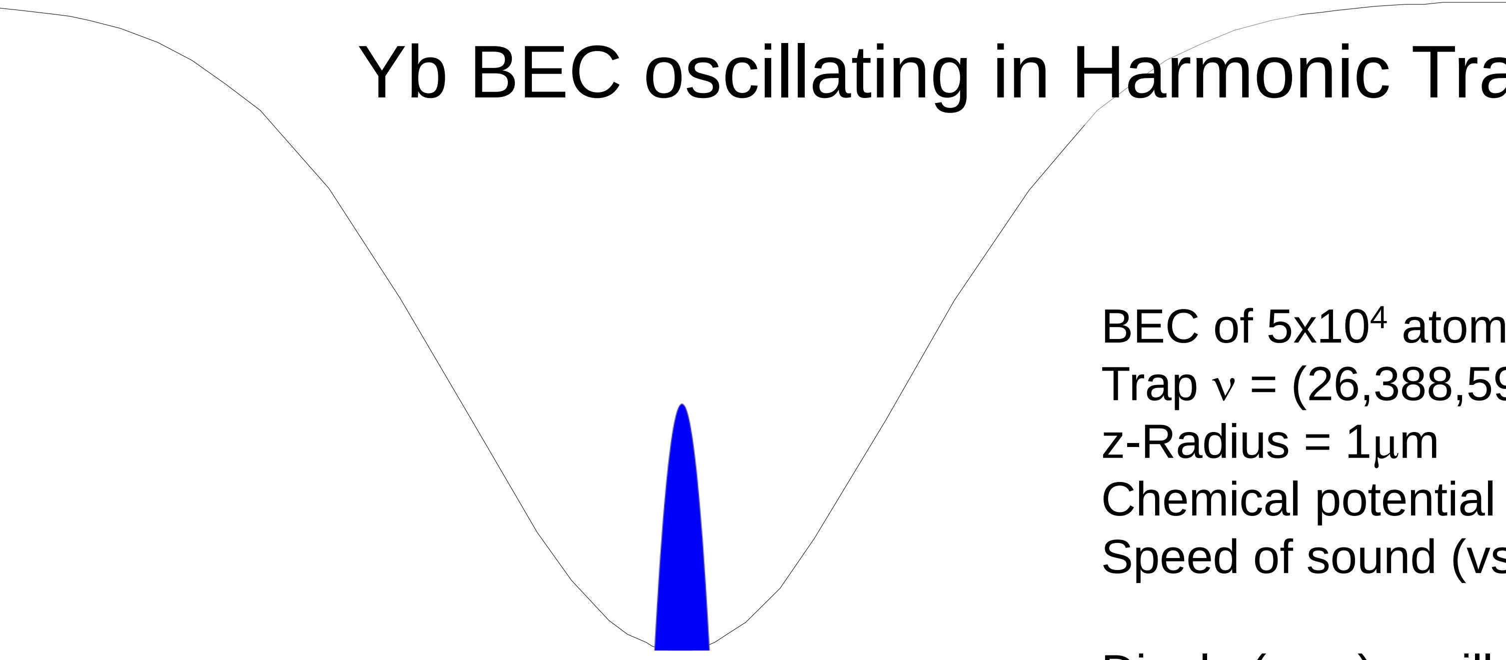
$R_{Li}/R_{Yb} = 3$

$n_{Li} = 1.4\times10^{13}/cm^3$, $n_{Yb} = 3\times10^{14}/cm^3$

Interspecies MF ~ 0.1 of μ_B, μ_F

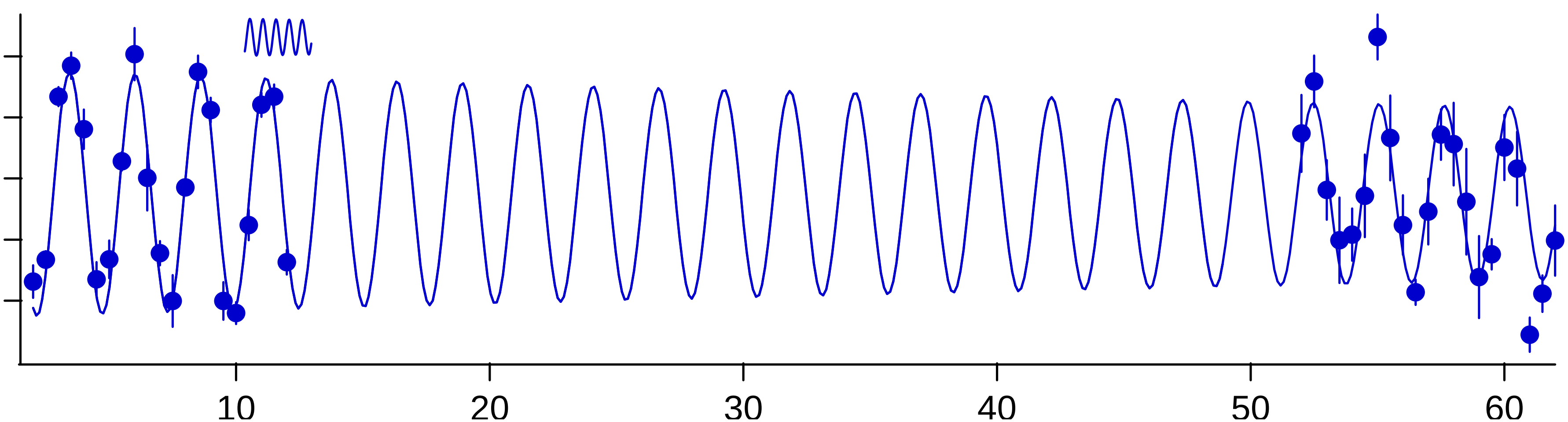
R.J. Roy et al. arXiv:1607.03221 (2016)

Yb BEC oscillating in Harmonic Trap

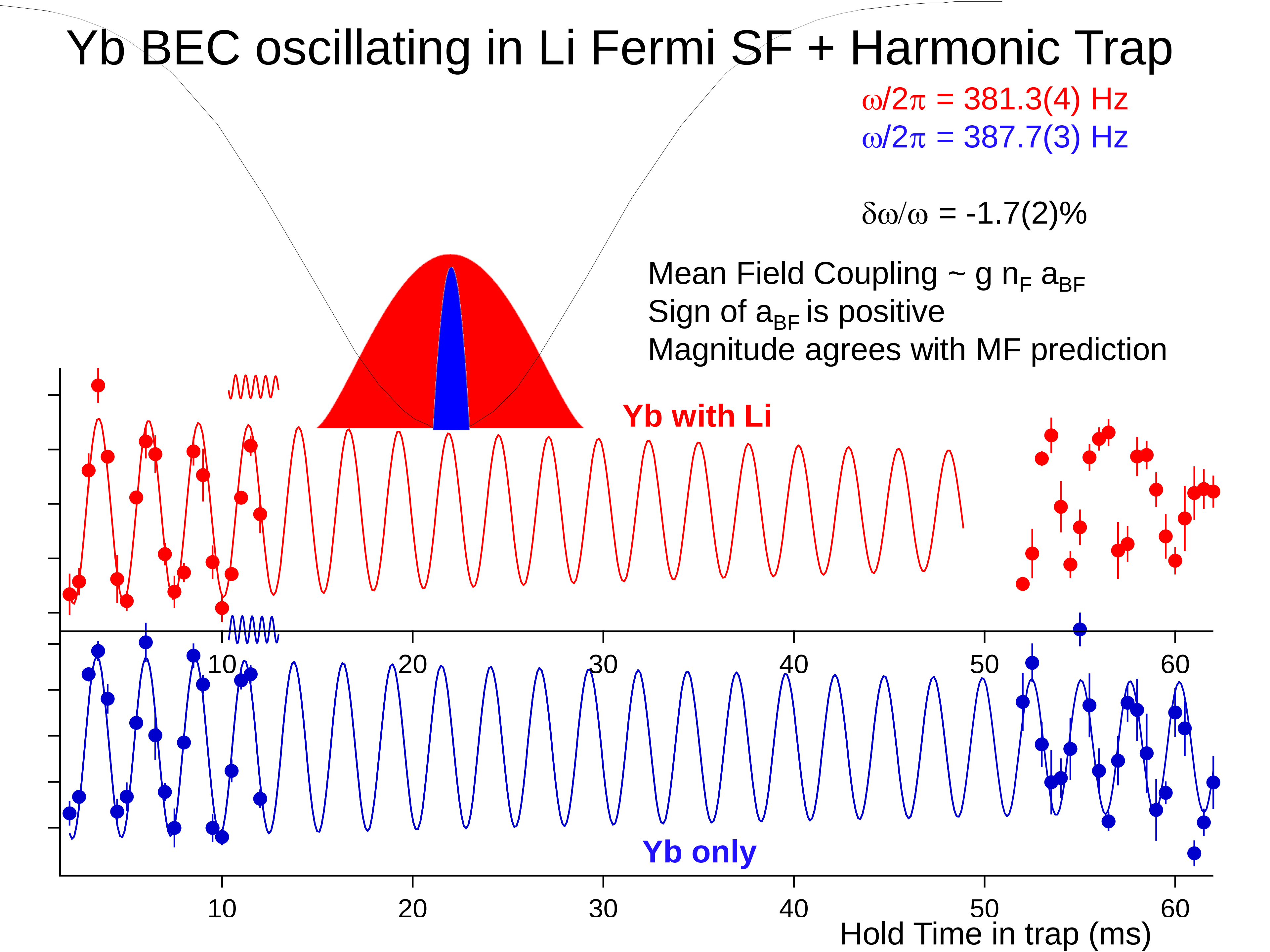


BEC of 5×10^4 atoms
Trap ν = (26,388,59) Hz
z-Radius = 1μm
Chemical potential (μ) = 60nK
Speed of sound (vs) = 2.4 mm/s

Dipole (c.m.) oscillation:
frequency = 388 Hz,
amplitude = 0.5 μm,
max velocity = 1.3 mm/s << $v_{crit,BF}$



Yb BEC oscillating in Li Fermi SF + Harmonic Trap



Summary & Prospects with Yb-Li

Yb-Li B-F superfluid, Dipole and Scissors Osc.
Elastic coupling, angular momentum exchange

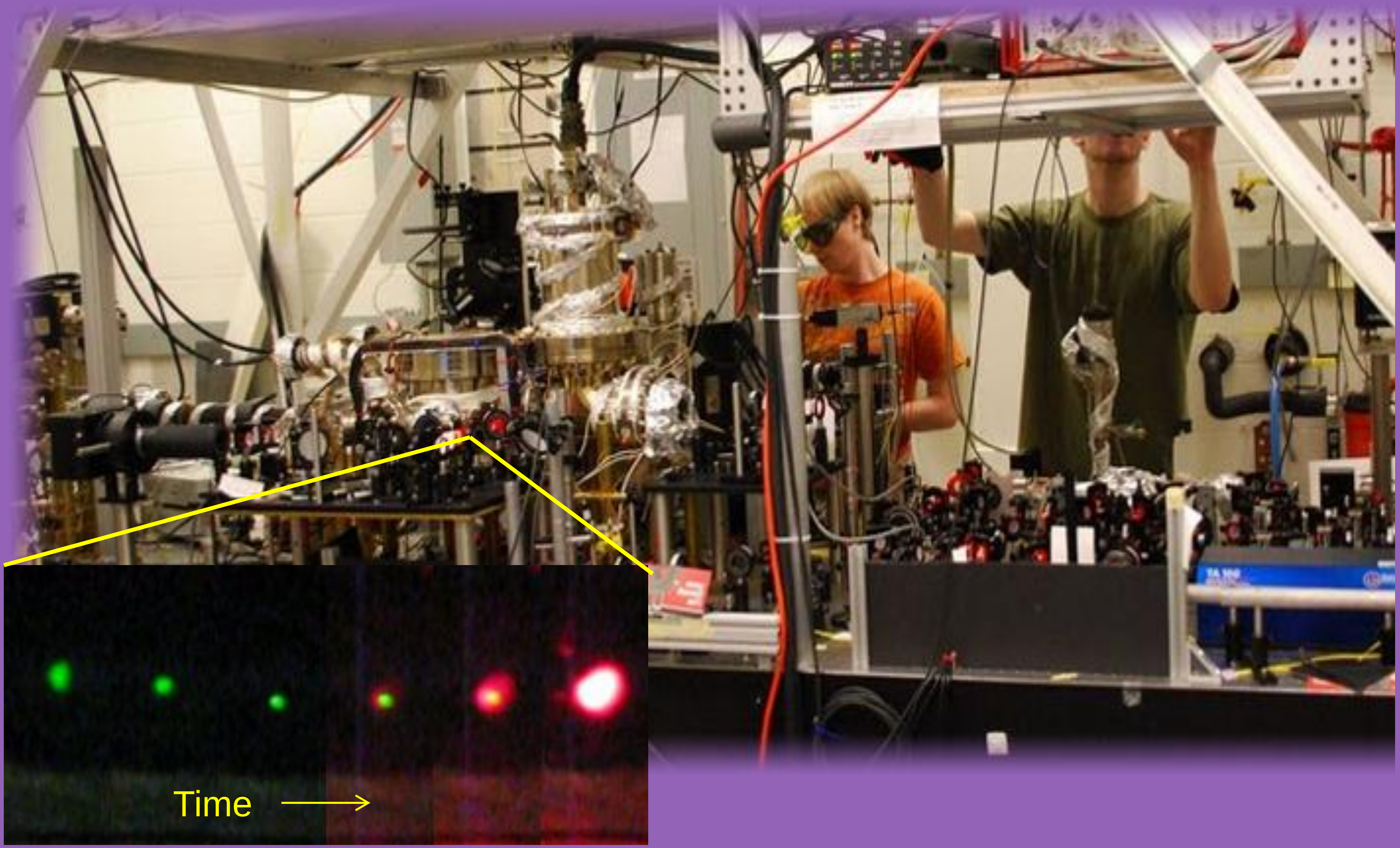
Further collective modes, damping, sound,
exotic states

Mixed SF Phase Diagram in Optical Lattice

Impurity Probe and Thermometry ($\omega_{Li}/\omega_{Yb} \sim 8$)

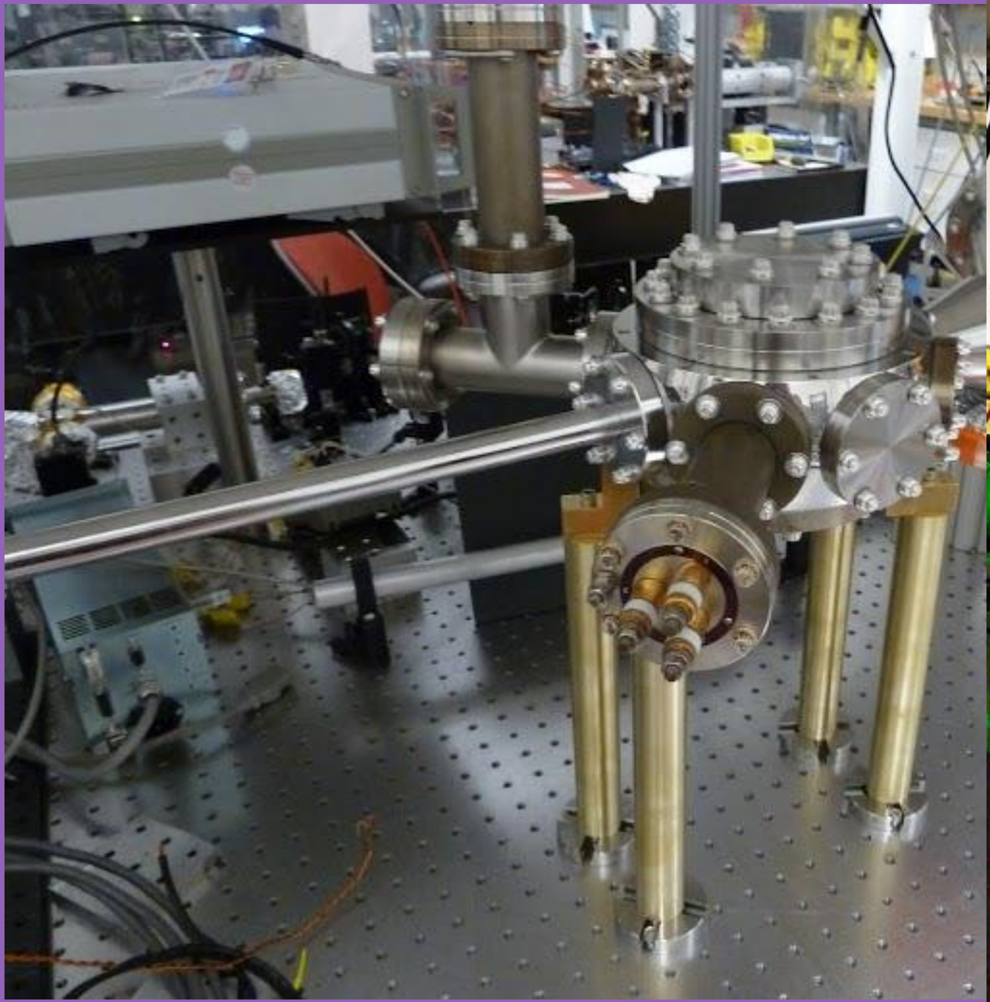
Controllable Interspecies Overlap
YbLi molecules in a 3D optical lattice

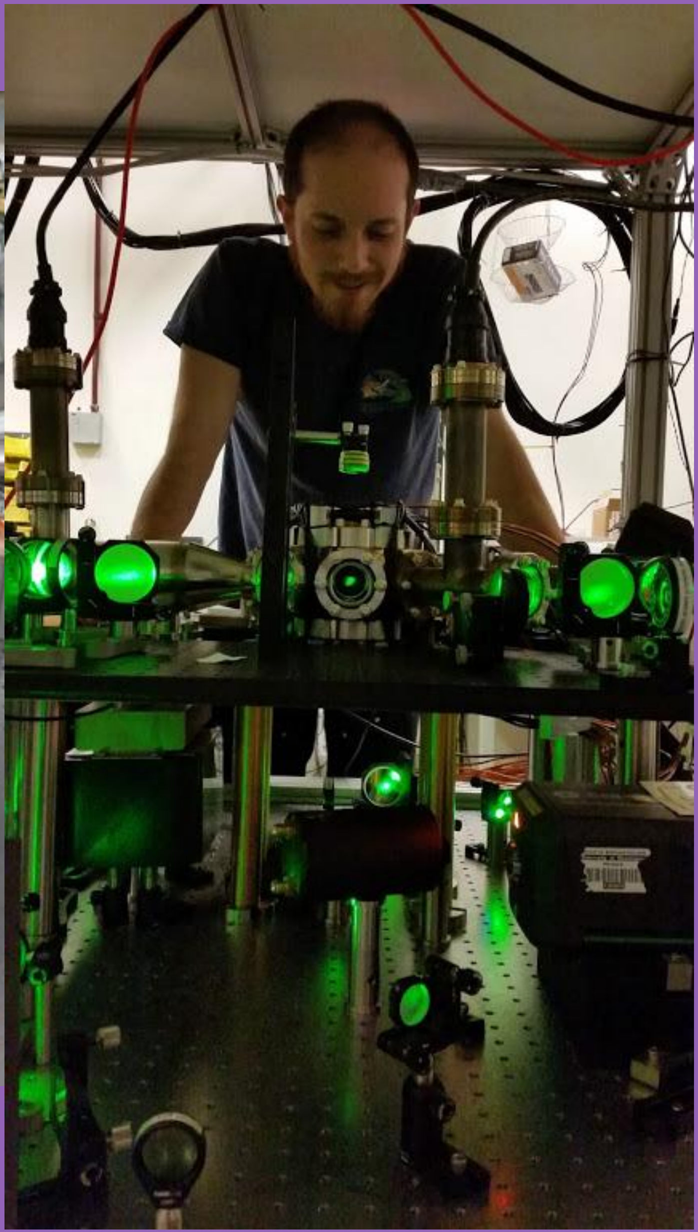
UW Ultracold Atoms Lab I



2-species Magneto-Optical Trap
(**Ytterbium** and **Lithium**)

LAB II





UW Ultracold Atoms Group (summer 2015)

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