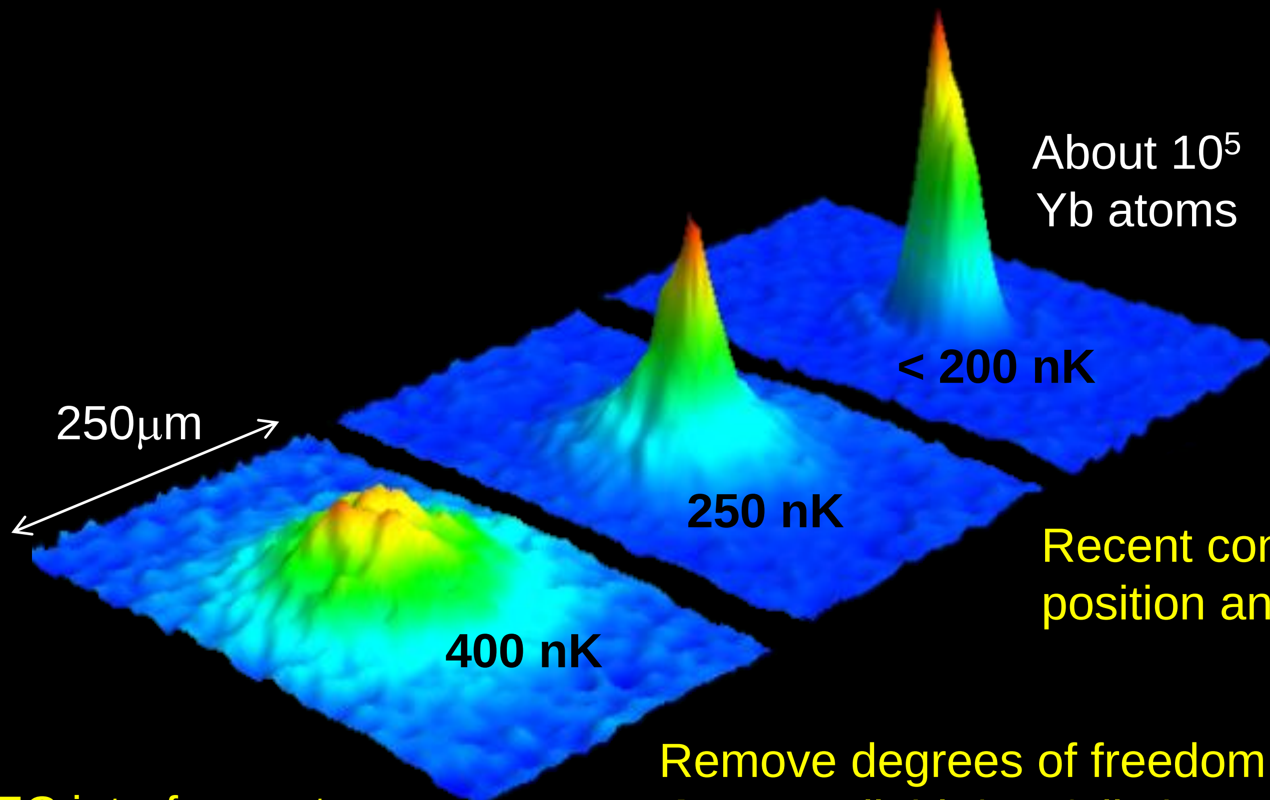
Ultracold Atoms and Quantum Gases



Recent control of atomic position and momentum.

Today:
Precision BEC interferometry
Bose-Fermi superfluids

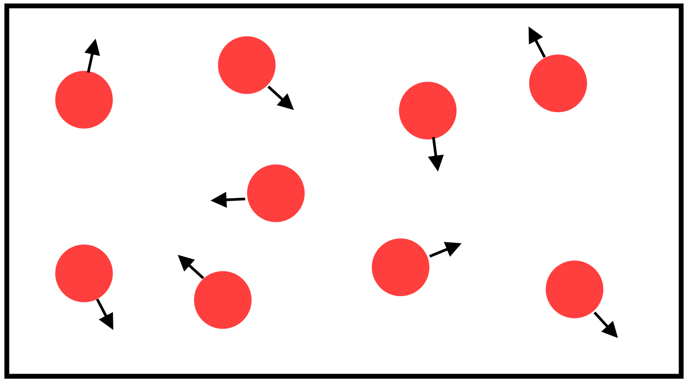
Remove degrees of freedom → Manipulate
→ Controllably/usefully introduce complexity
→ Address Q's in AMO, CM, nuclear, particle

Subhadeep Gupta

UW NSF-INT Phys REU, 26th June 2017

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

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

$(n=N/V)$

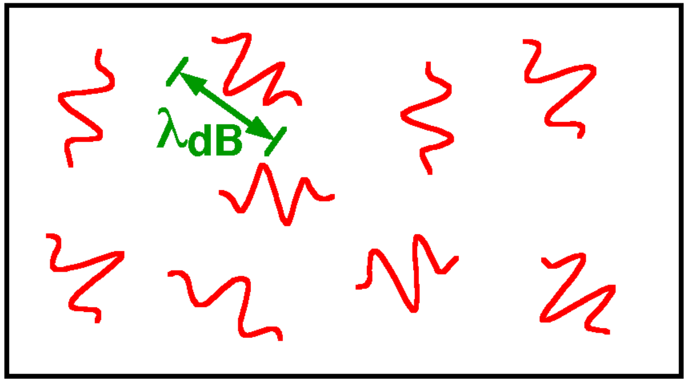
Air $n \sim 10^{19}/cm^3$, $T_c \sim 1mK$
Stuff $n \sim 10^{22}/cm^3$, $T_c \sim 0.1K$
Everything (except He) is solid

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

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

and ~ non-interacting

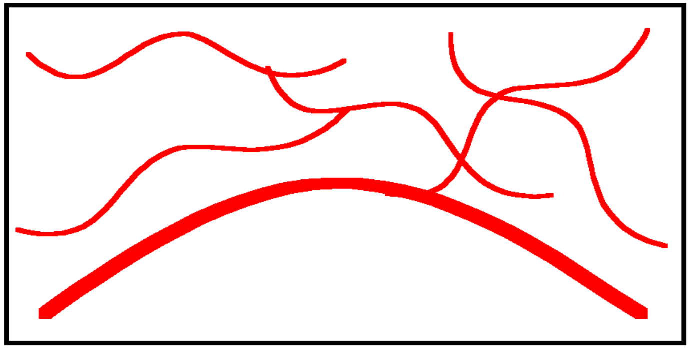
Bose-Einstein Condensation (BEC)



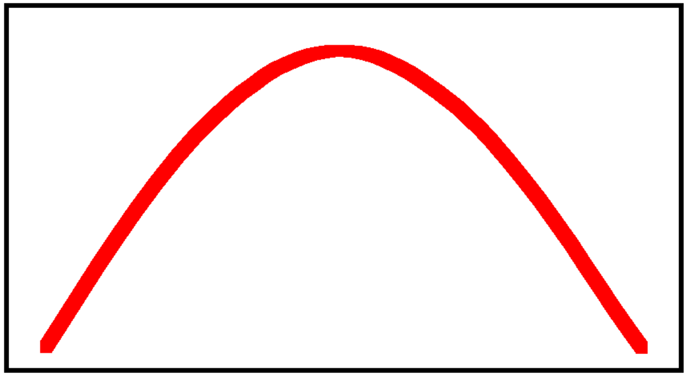
$$\lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}} \quad n = \frac{N}{V}$$

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

Quantum Phase Space Density

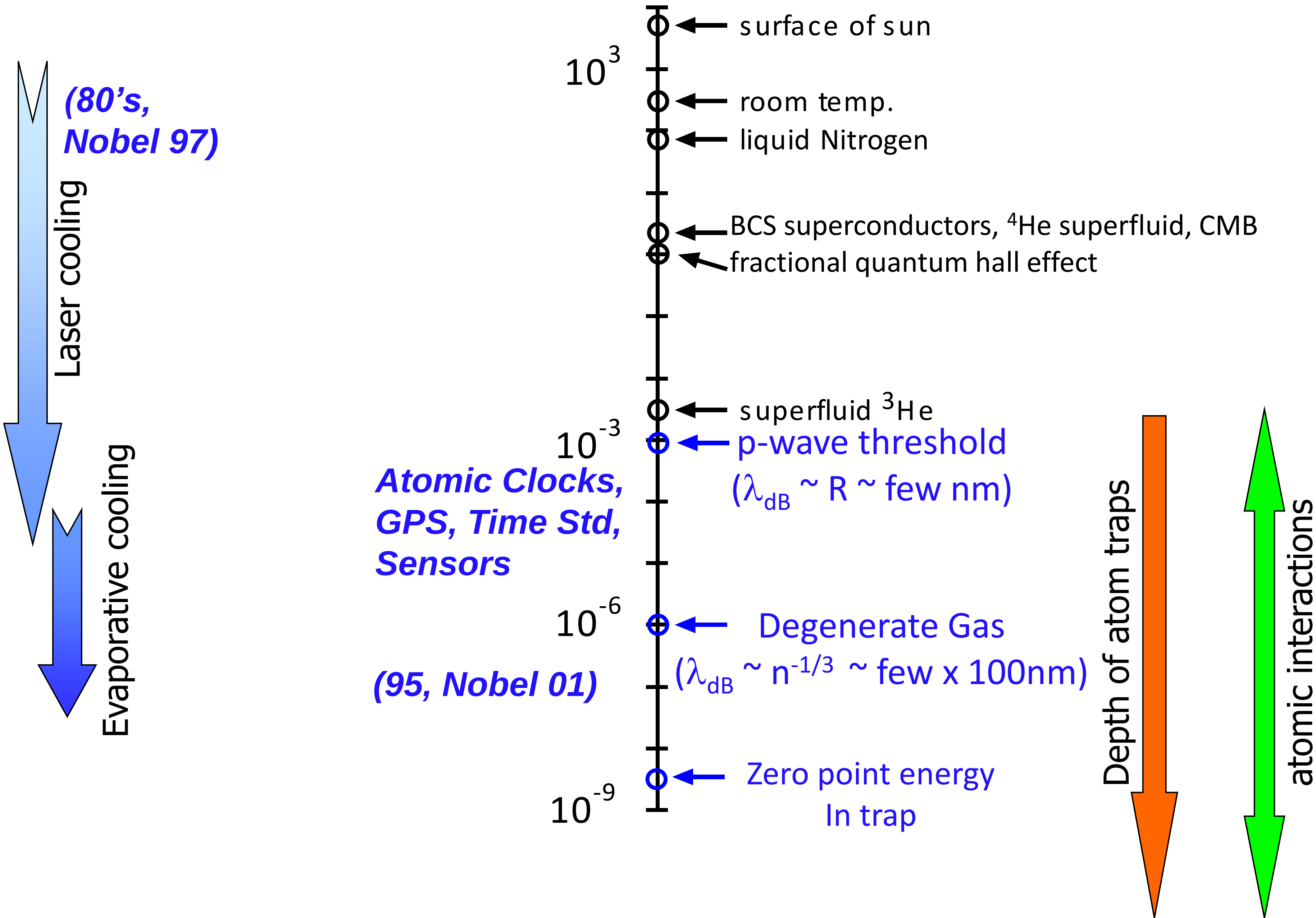


$$n\lambda_{dB}^3 \sim 1$$



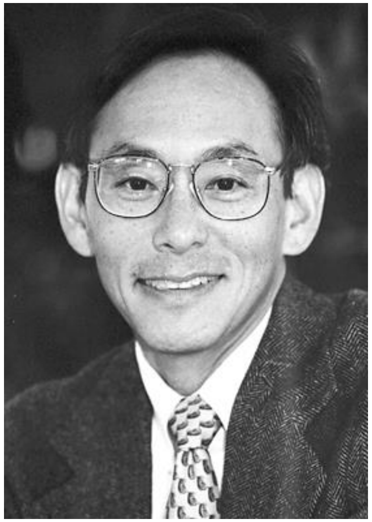
$$n\lambda_{dB}^3 >> 1$$

Relevant Ultracold Temperatures on the Log Kelvin Scale



1997
NOBEL

LASER
COOLING


Steven Chu


Claude Cohen-Tannoudji

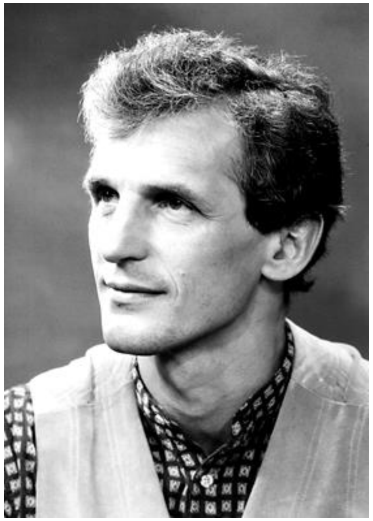

William D. Phillips

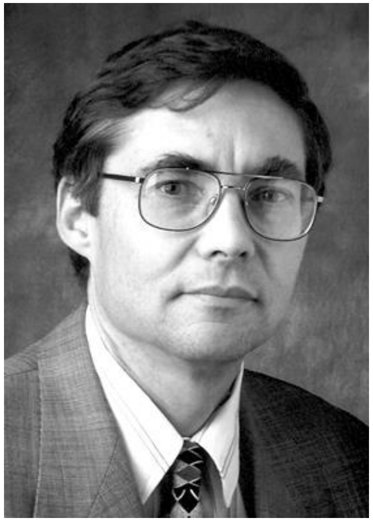
"for development of methods to cool and trap atoms with laser light"

2001
NOBEL

BEC

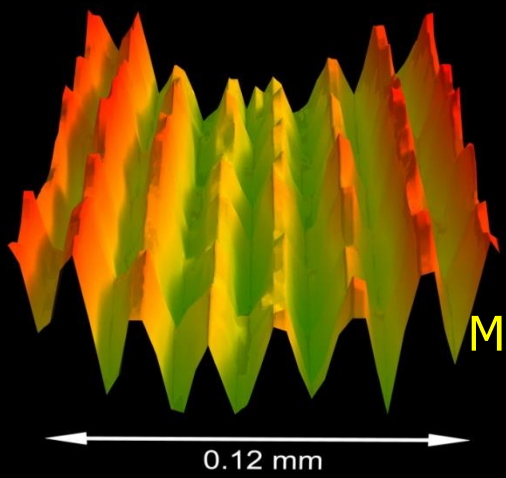

Eric A. Cornell


Wolfgang Ketterle


Carl E. Wieman

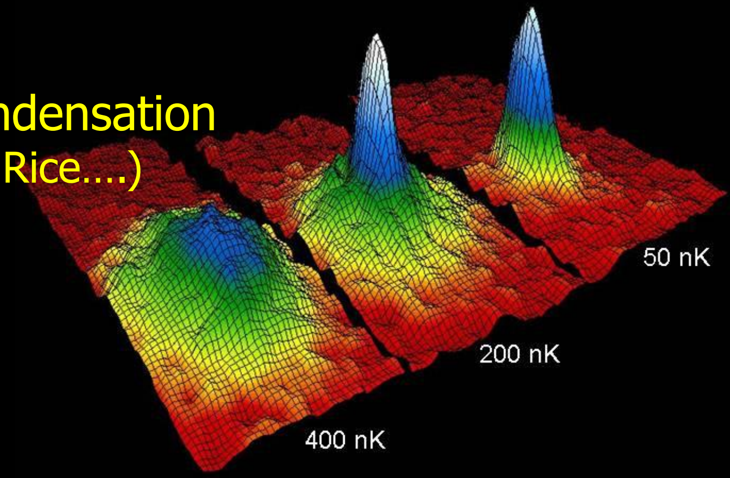
“for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

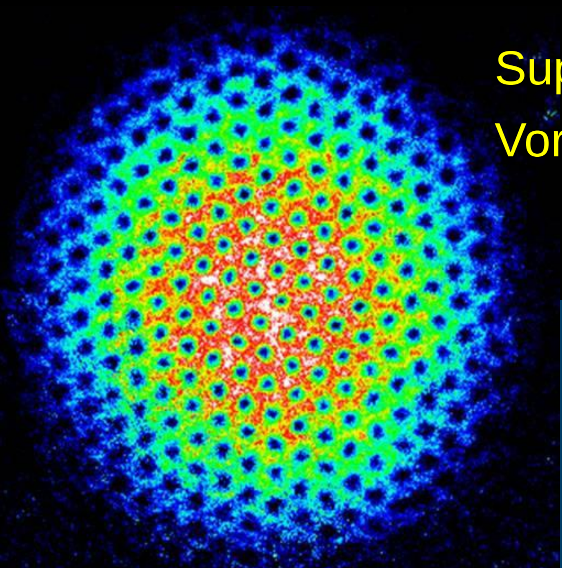
Some major achievements in ultracold atomic physics



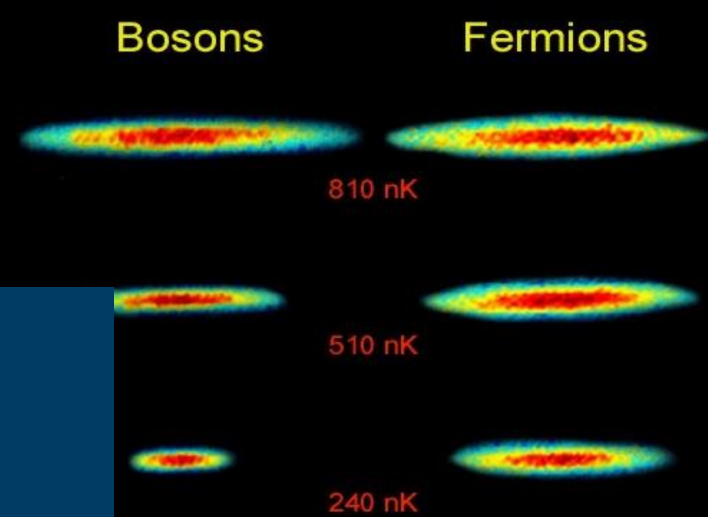
Macroscopic coherence
(97: MIT,…)

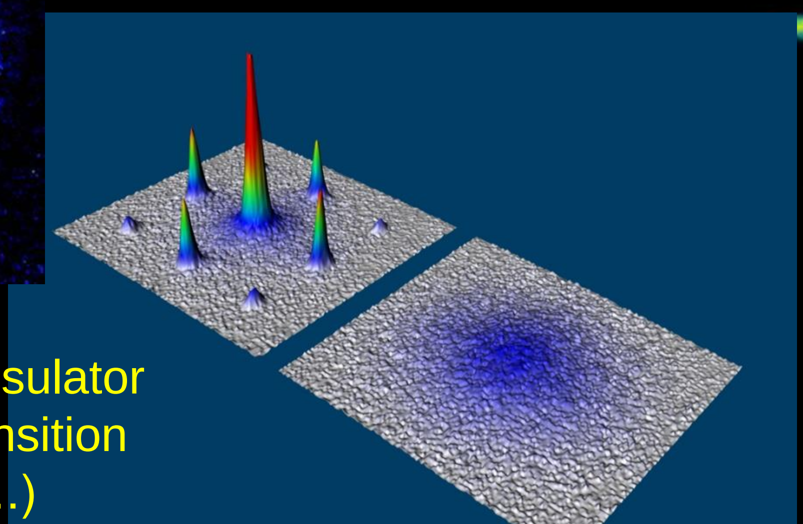
Bose-Einstein condensation
(95: JILA, MIT, Rice….)





Superfluidity,
Vortex lattice



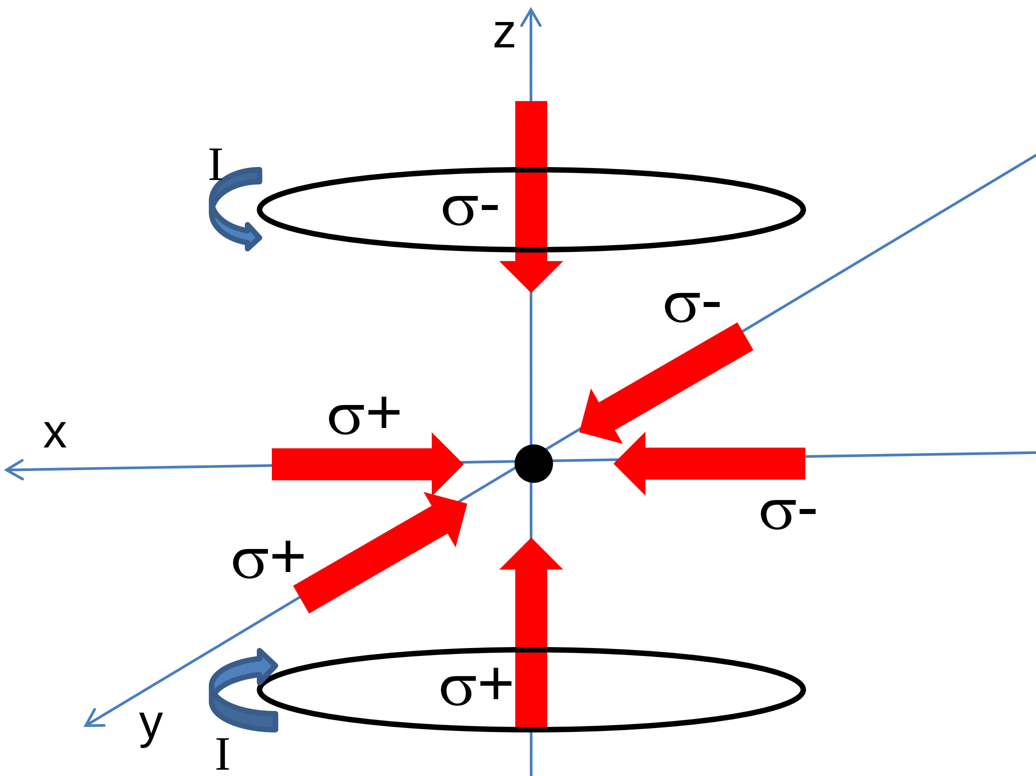


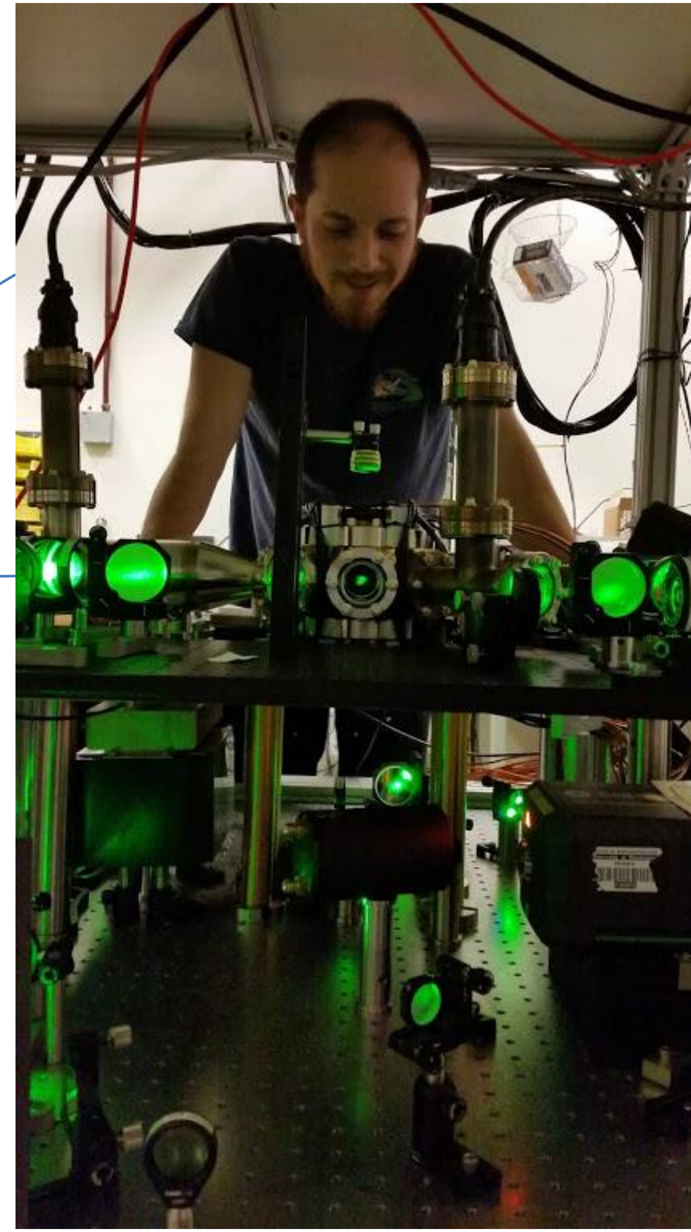
Superfluid to Mott-insulator
quantum phase transition
(02: Munich,…..)

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

Laser Cooling???

Laser Cooling





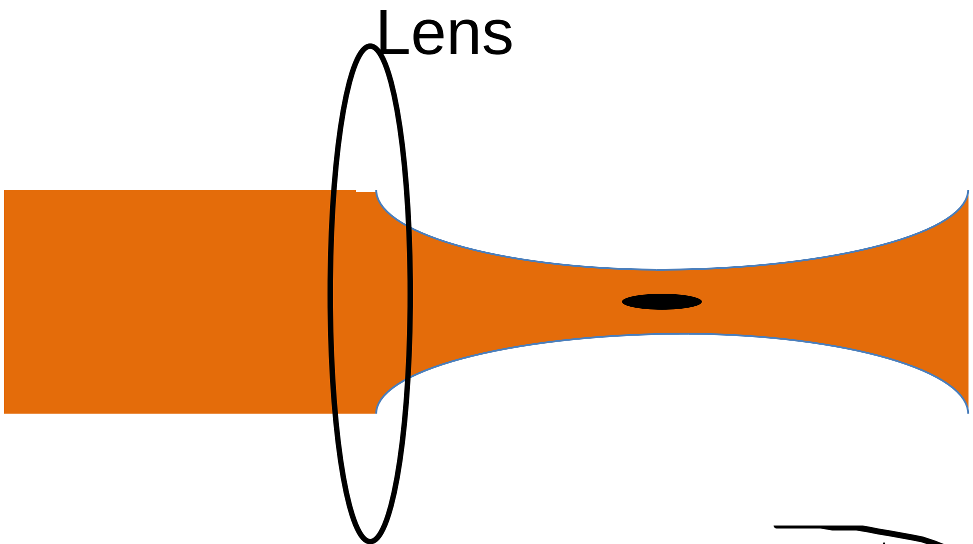
Magneto-Optical Trap (MOT)
"Workhorse" of laser cooling

Atom Source ~ 600 K; UHV environment

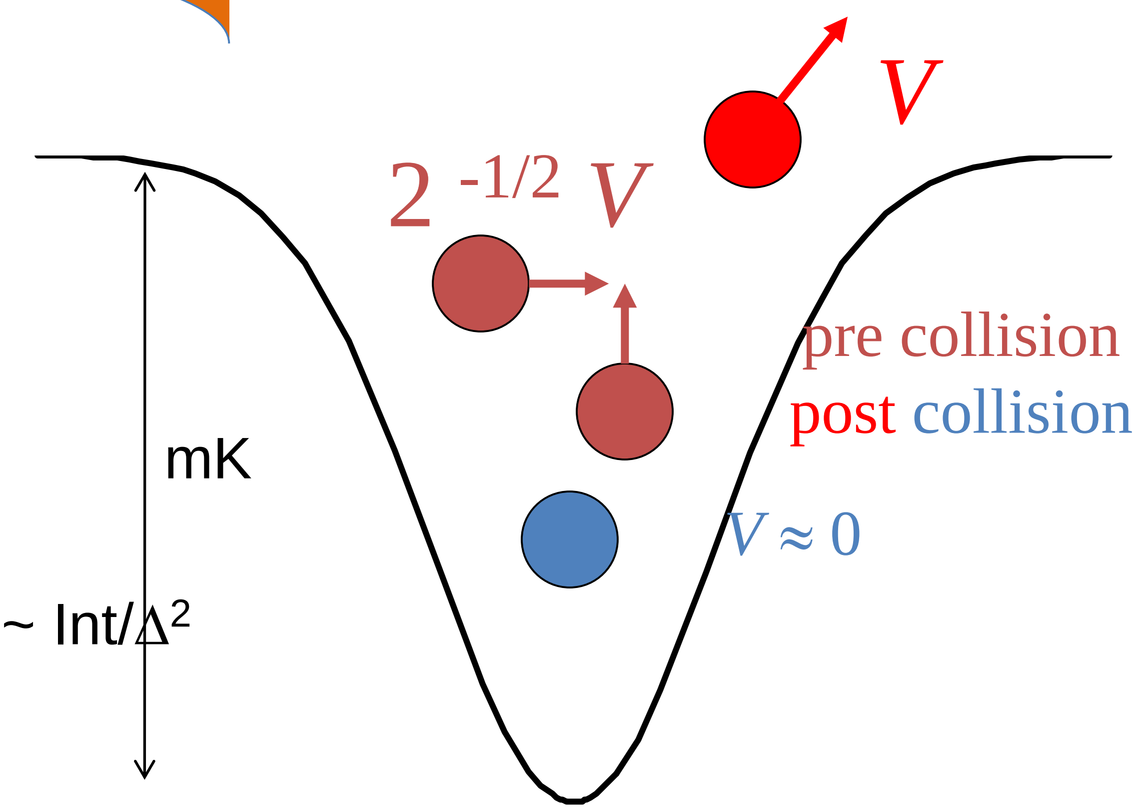
=> COOLING !

(Need a 2 level system)

Evaporative Cooling in a Conservative Trap

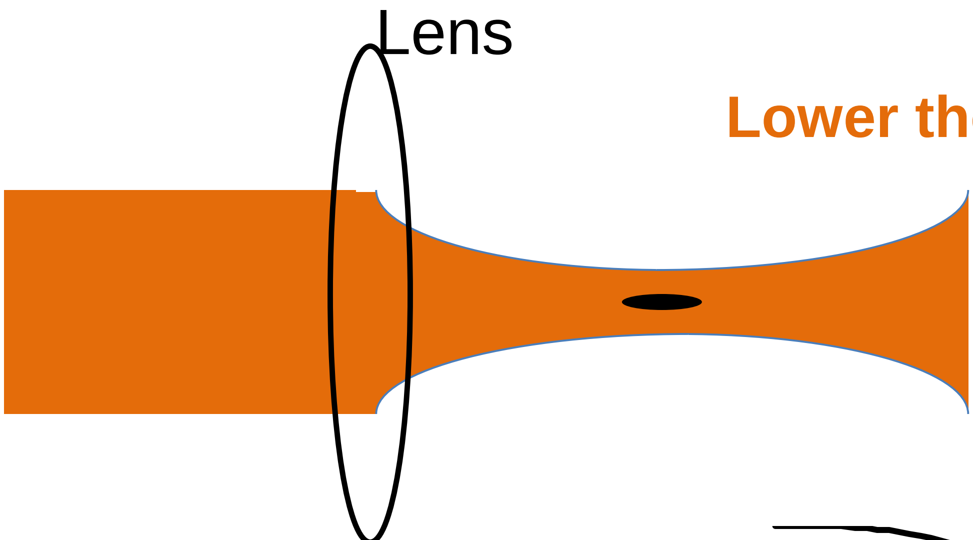


Optical Dipole Trap $\omega_L << \omega_{res}$

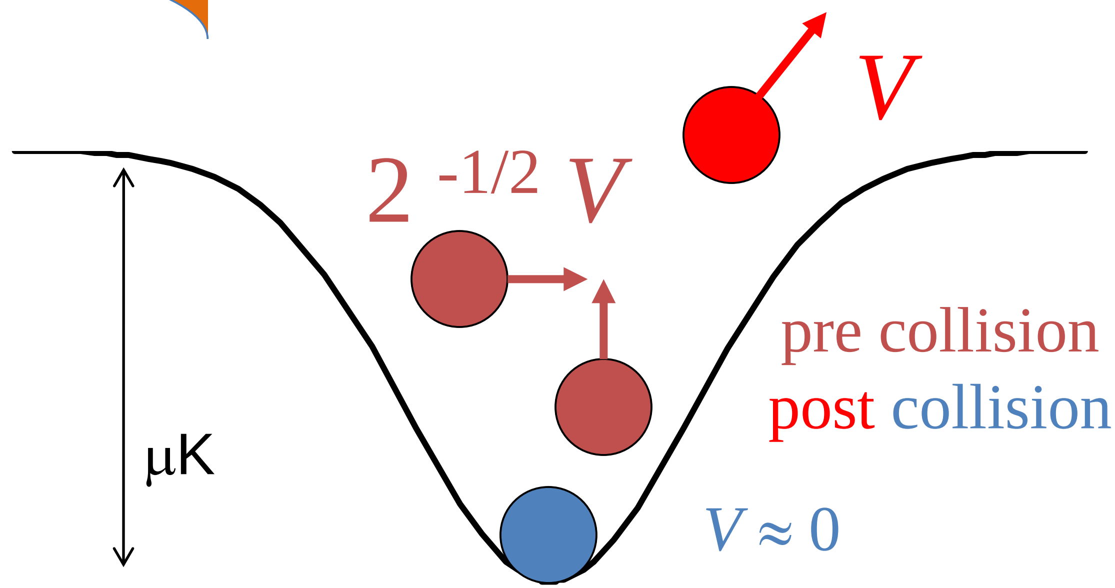


Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

Evaporative Cooling in a Conservative Trap



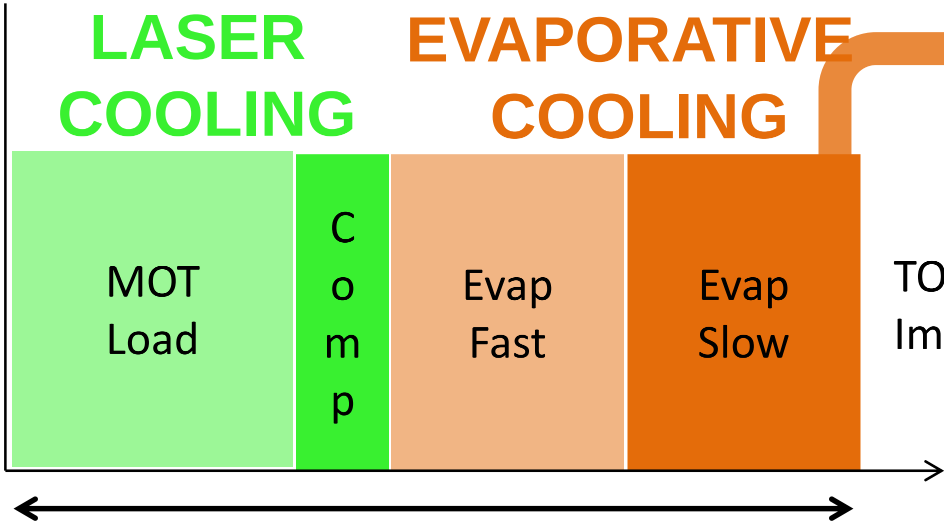
Lower the Power



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

Depth ~ Int/Δ; Heating Rate ~ Int/Δ^2

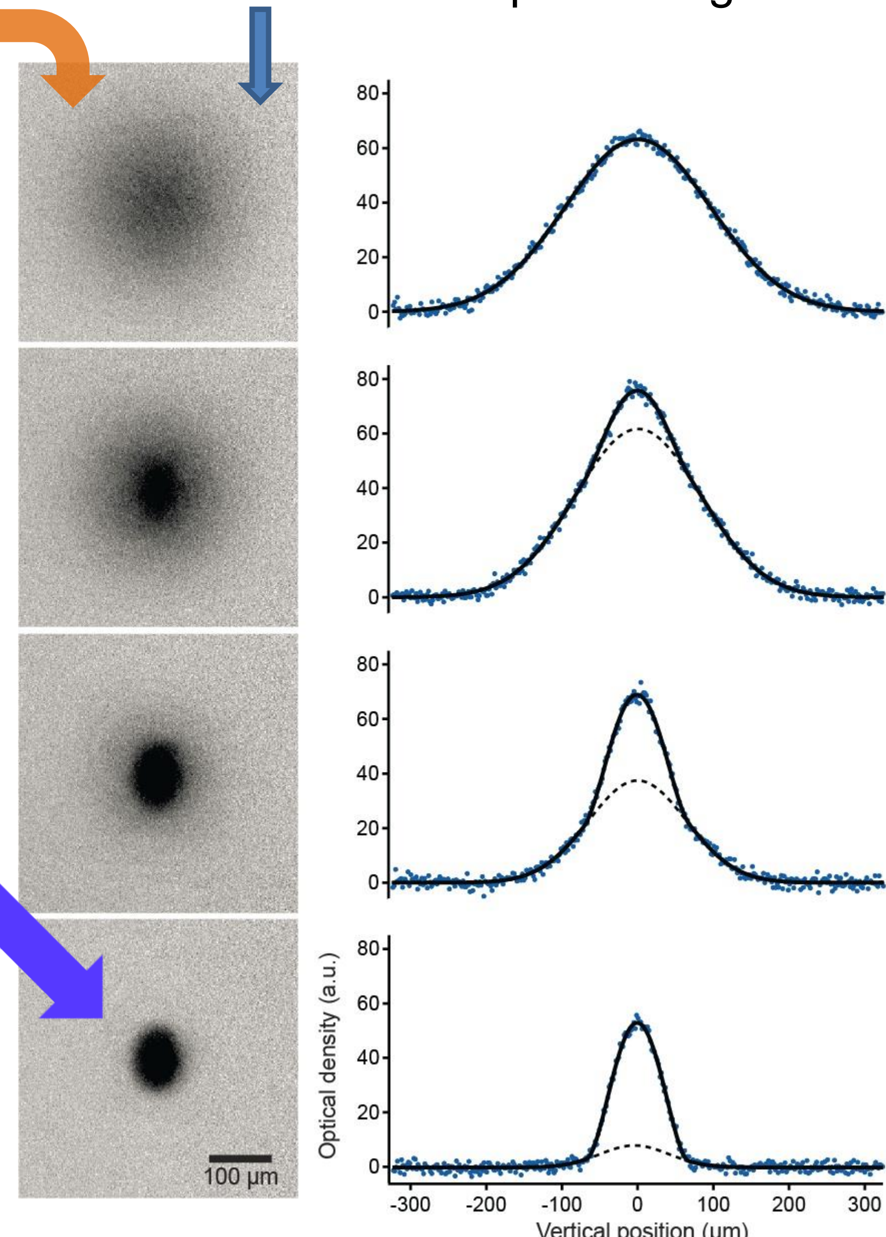
Making a Quantum Gas

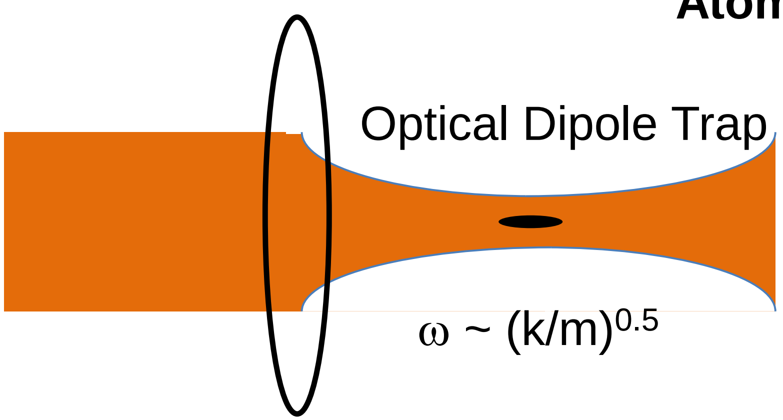


few seconds

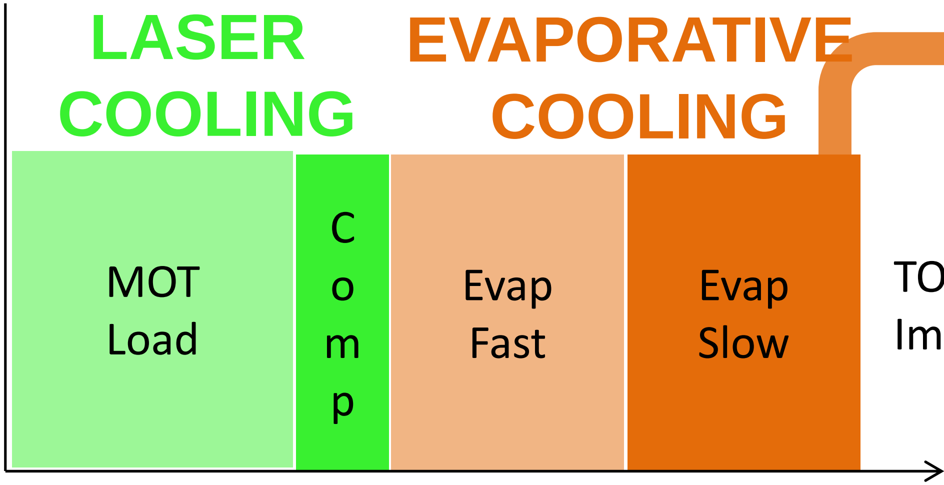
Bose-Einstein Condensate
BEC, 10^5 atoms
(T~ 100nK)
Atom Laser

"Shadow"/Absorption Images

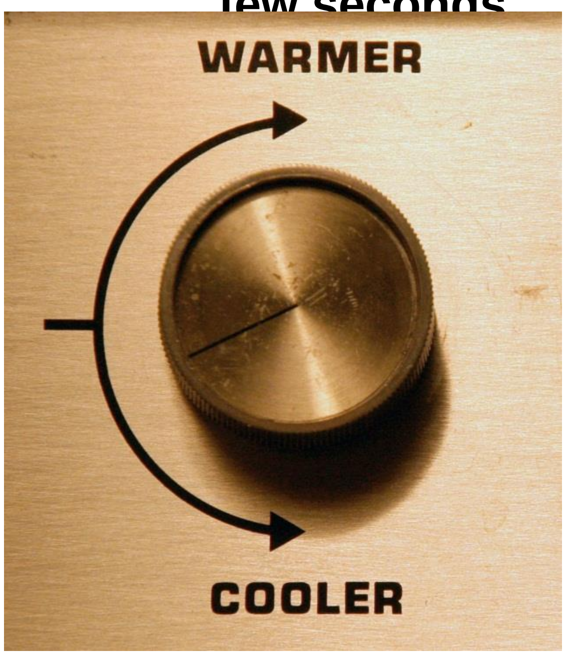




Making a Quantum Gas

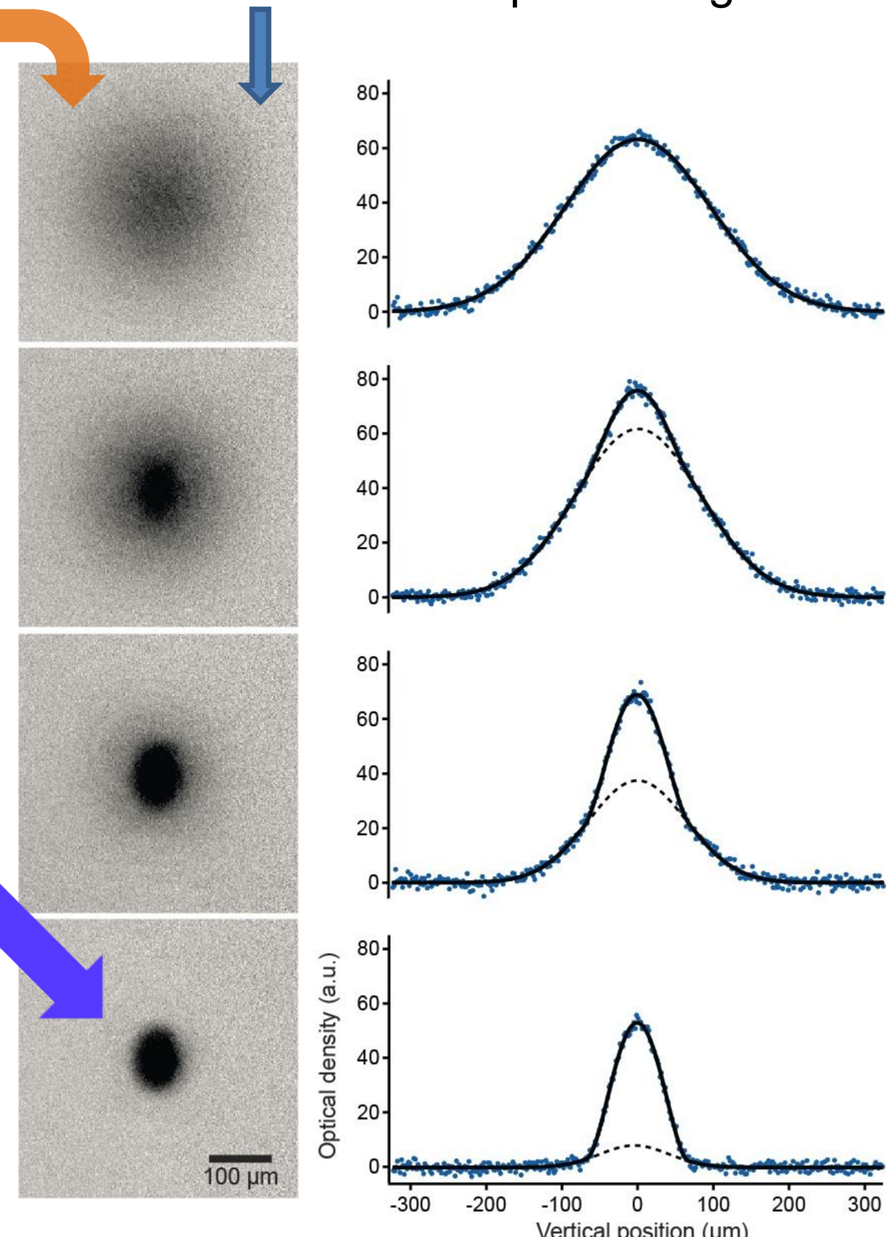


few seconds

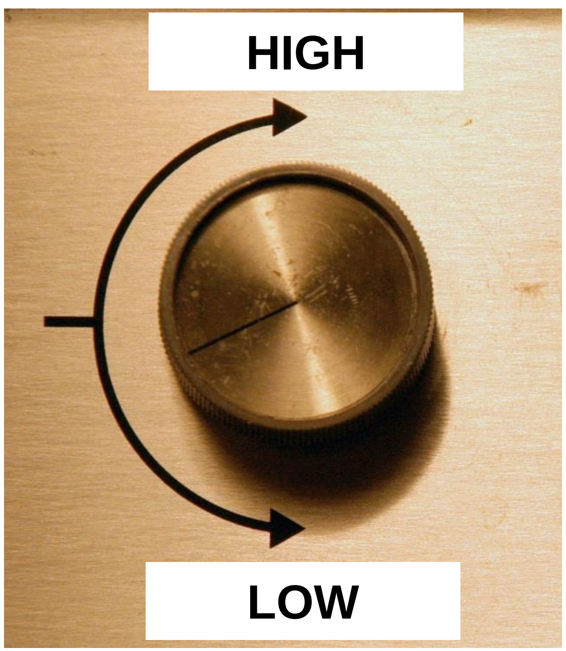


Bose-Einstein Condensate
BEC, 10^5 atoms
(T~ 100nK)
Atom Laser

"Shadow"/Absorption Images



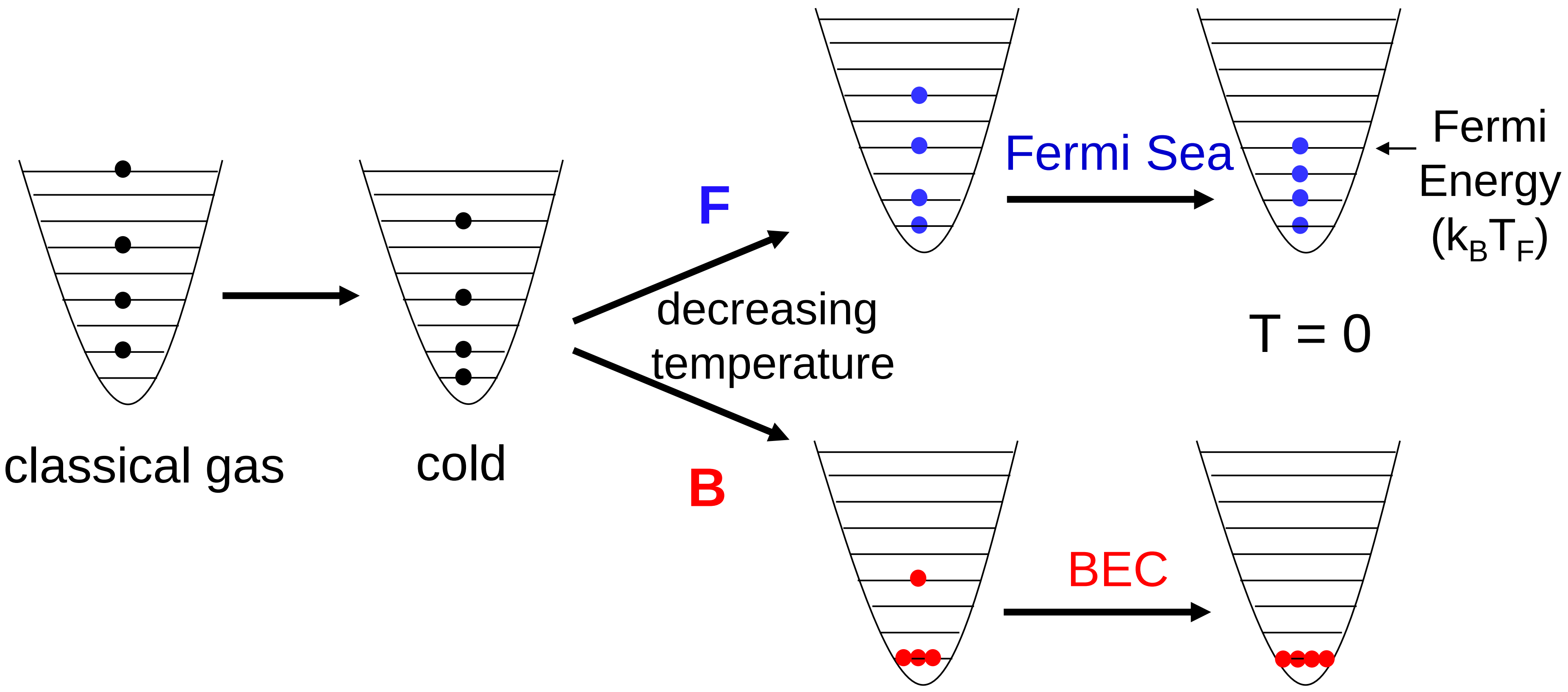
"Knobs" for Quantum Engineering



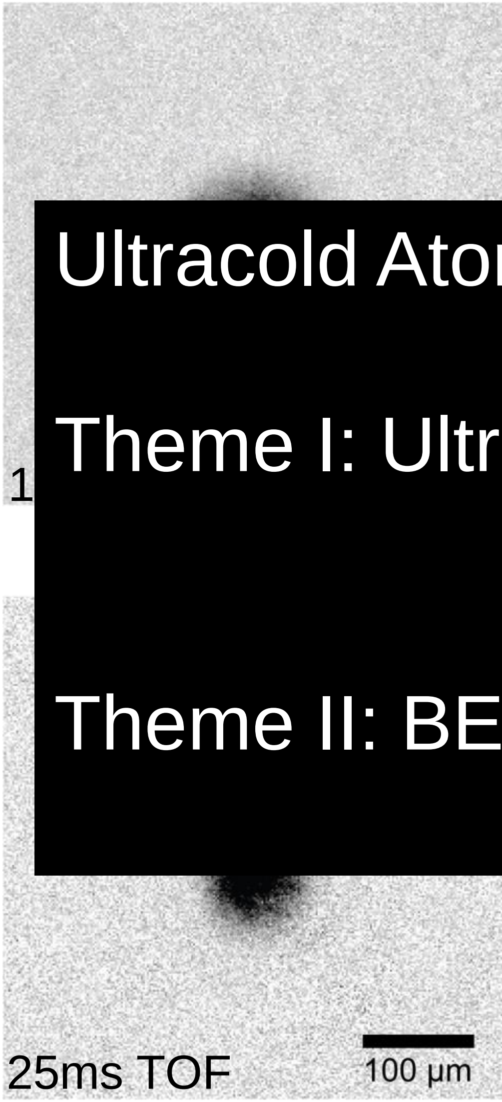
In ultracold, dilute gases, using e-m fields, can control (relatively) easily

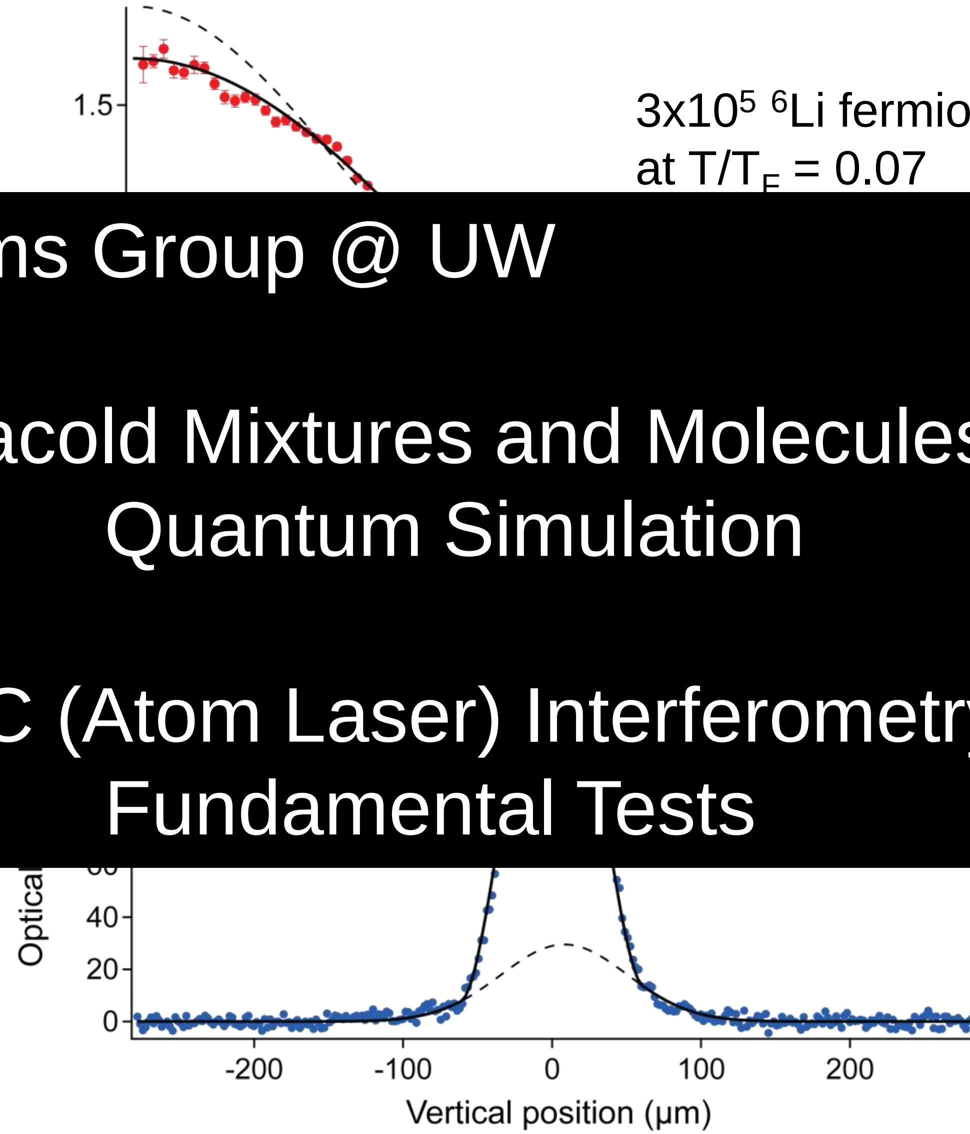
Temperature & density
Dimensionality
Magnetization
Magnitude & sign of the "charge"
Optical crystals (tunnel/on-site),
CM models, new systems
Chemical structure – form molecules

Different Quantum Matters



Quantum degenerate Fermi & Bose Gases





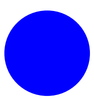
3×10^5 ^{6}Li fermions
at $T/T_F = 0.07$

Ultracold Atoms Group @ UW

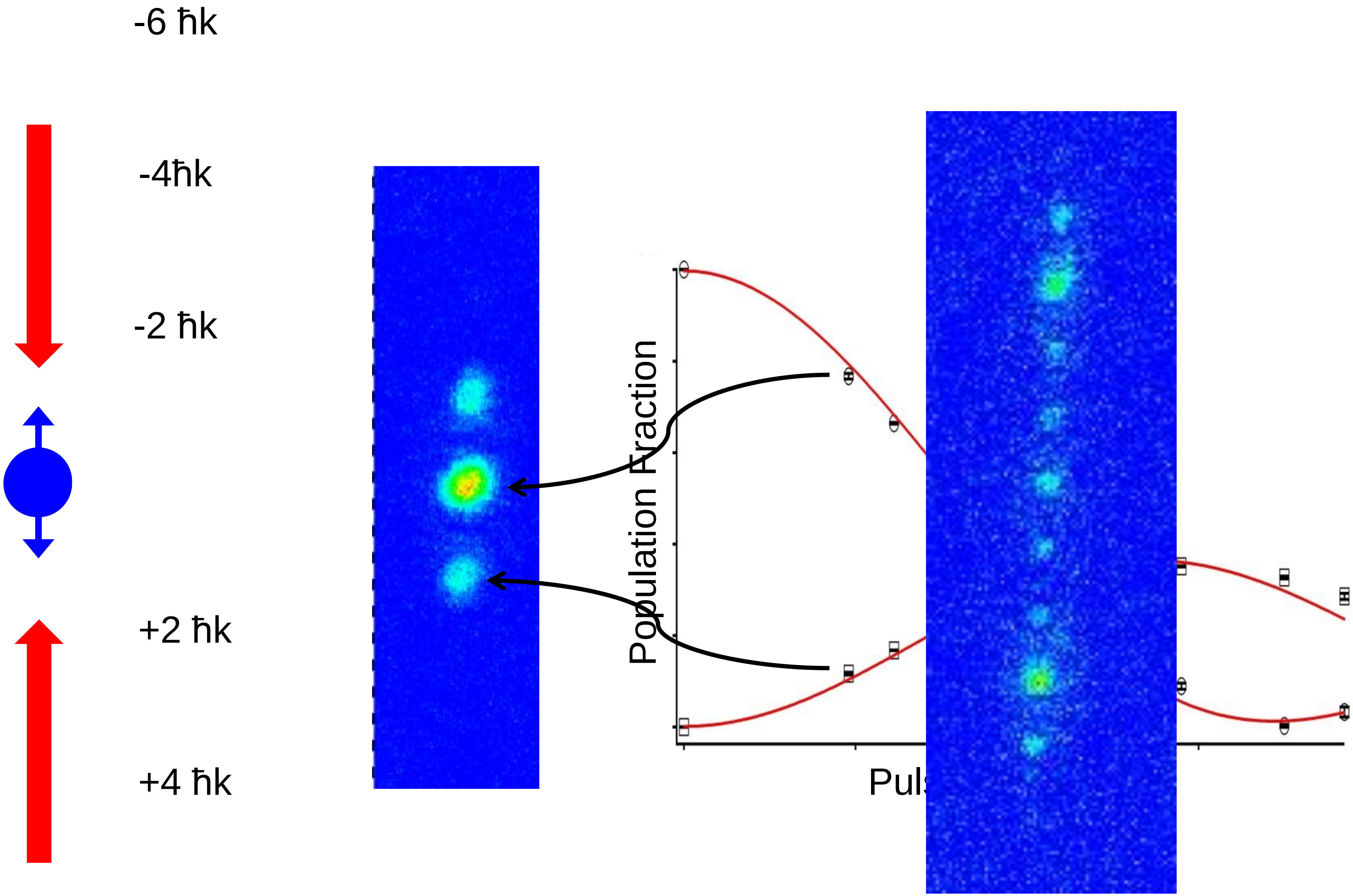
Theme I: Ultracold Mixtures and Molecules
Quantum Simulation

Theme II: BEC (Atom Laser) Interferometry
Fundamental Tests

Optical Standing Wave Diffraction of BEC



Optical Standing Wave Diffraction of BEC



Lots more light

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)

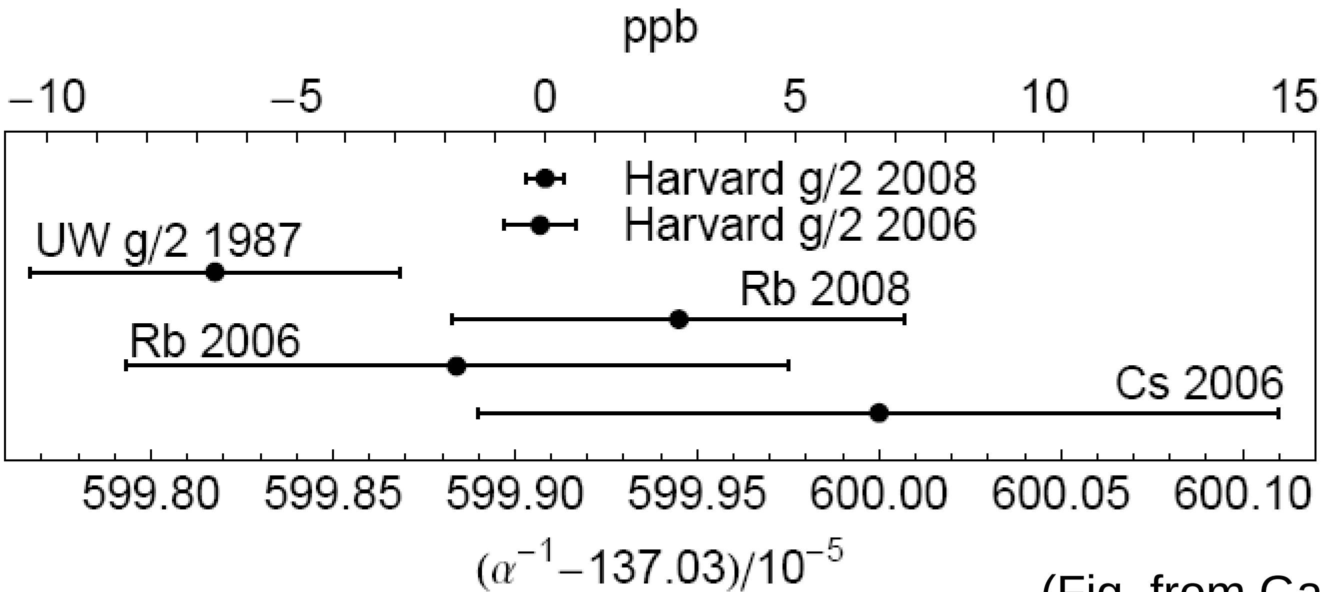
$$\alpha^2 = \left(\frac{e^2}{\hbar c}\right)^2 = \frac{2R_\infty}{c}\frac{h}{m_e} = \frac{2R_\infty}{c}\frac{M}{M_e}\frac{h}{m}$$

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

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

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

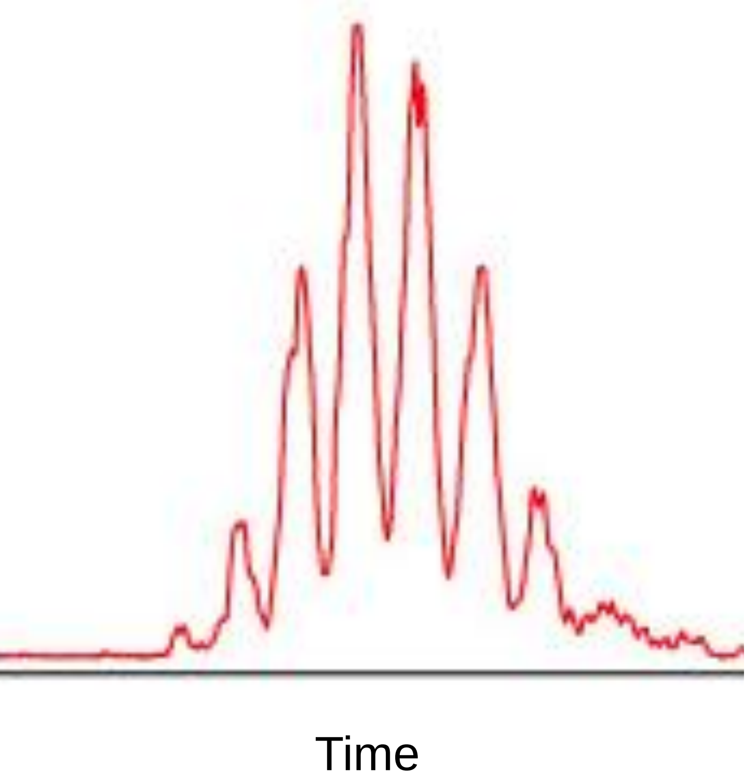
α comparison test of QED, sensitive to hadronic contribs, new physics

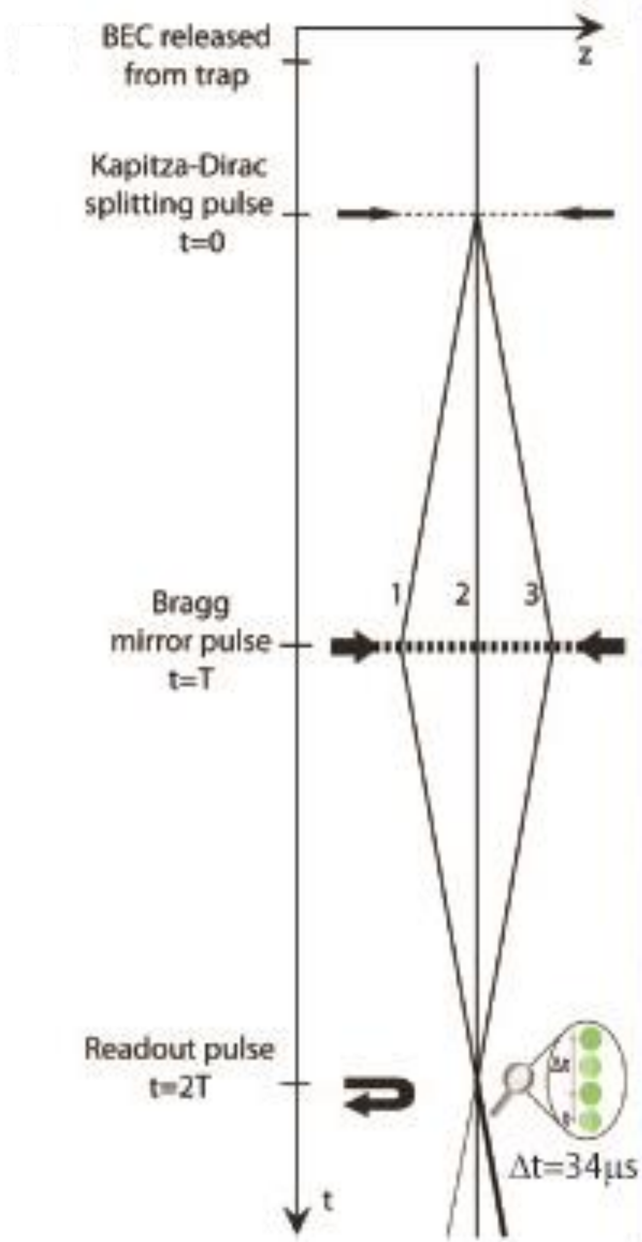
Our Yb BEC route to α: Targeted at < 0.1 ppb.

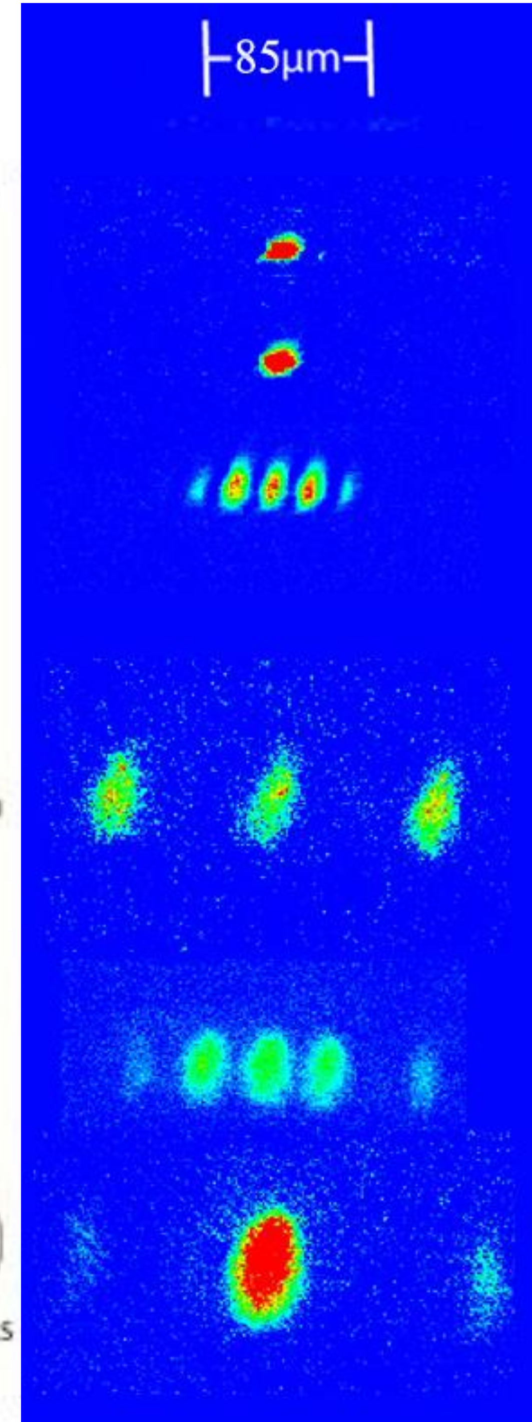
(High source coherence, high symmetry of interferometer)

Contrast Interferometer with Yb BEC

Contrast Signal
T=11ms
34μs period

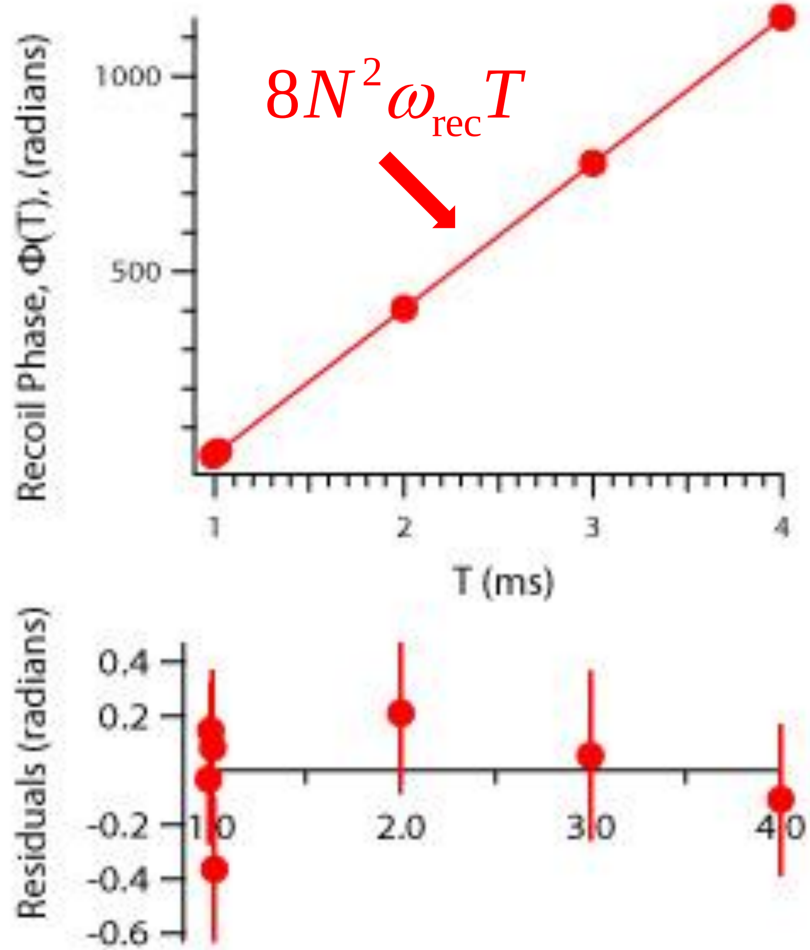






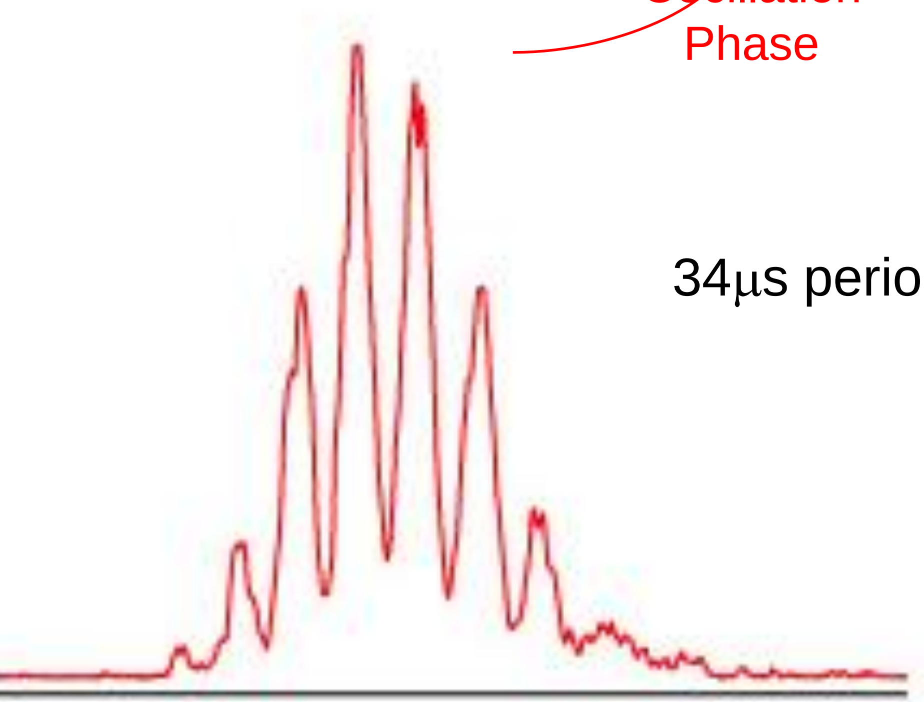
Contrast Interferometer with Yb BEC

“Acceleration”
pulses for sub-ppb



Oscillation
Phase

34μs period

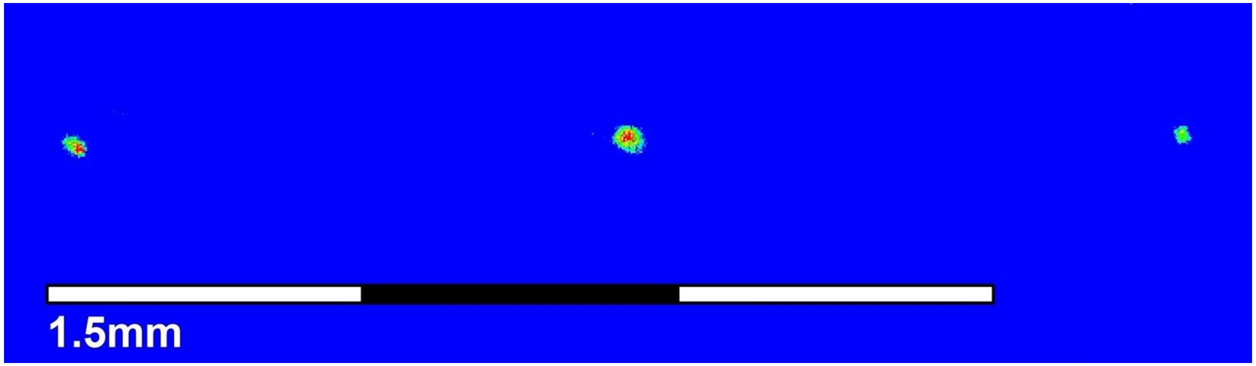


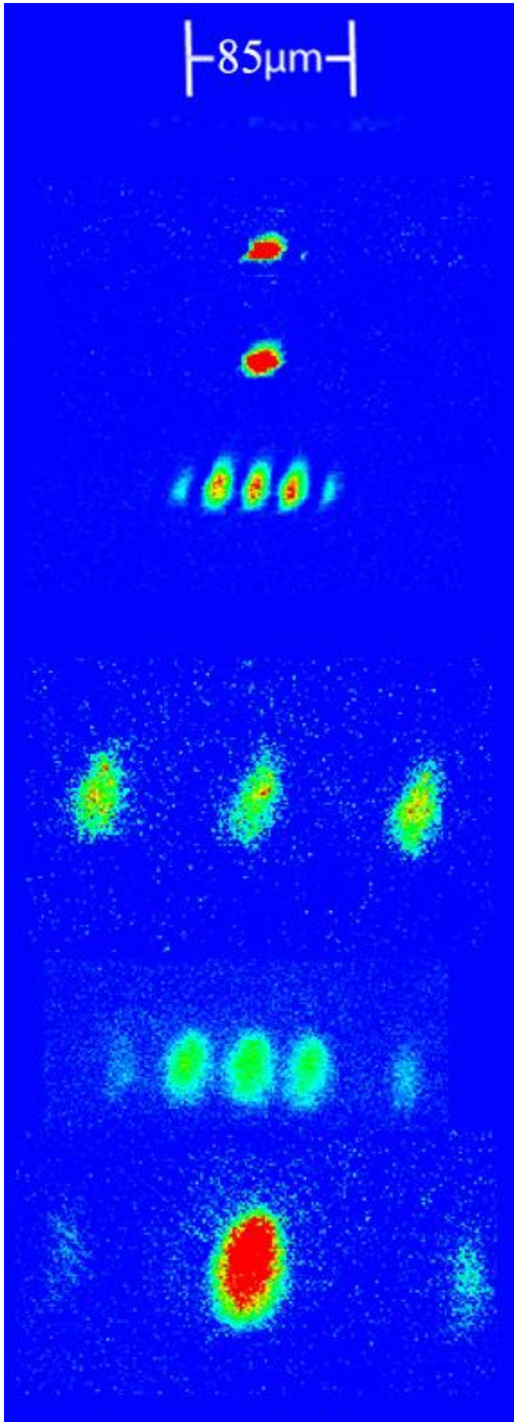
A. Jamison et al. PRA **90**, 063606 (2014)
A. Jamison et al. PRA **84**, 043643 (2011)

“Large Area” Contrast Interferometry

N = 1

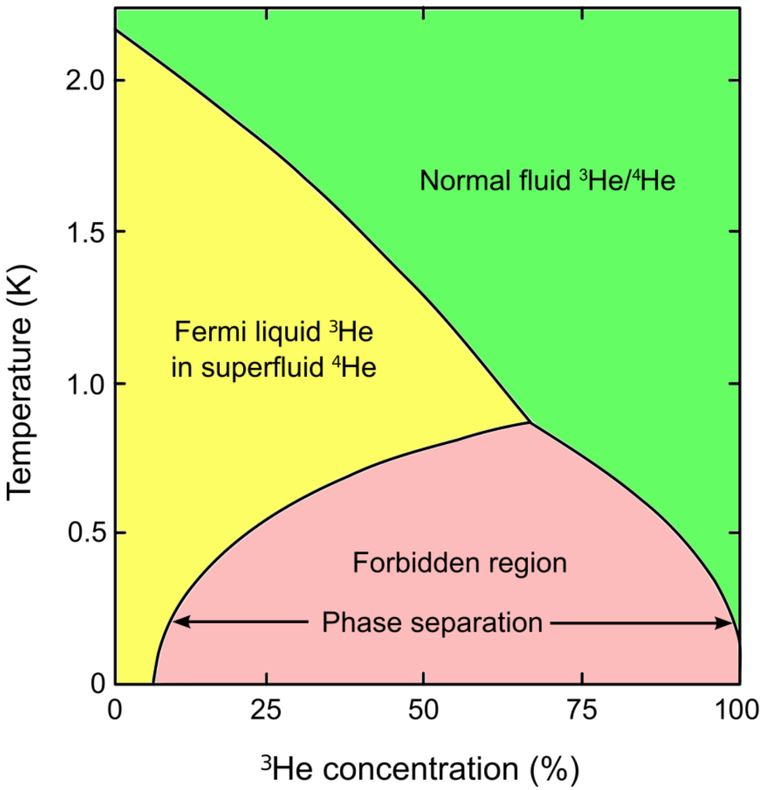
N = 19

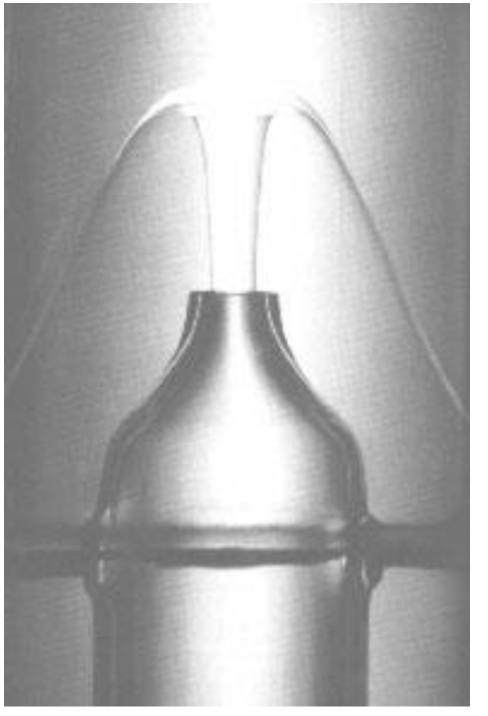




Bose-Fermi Mixtures

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



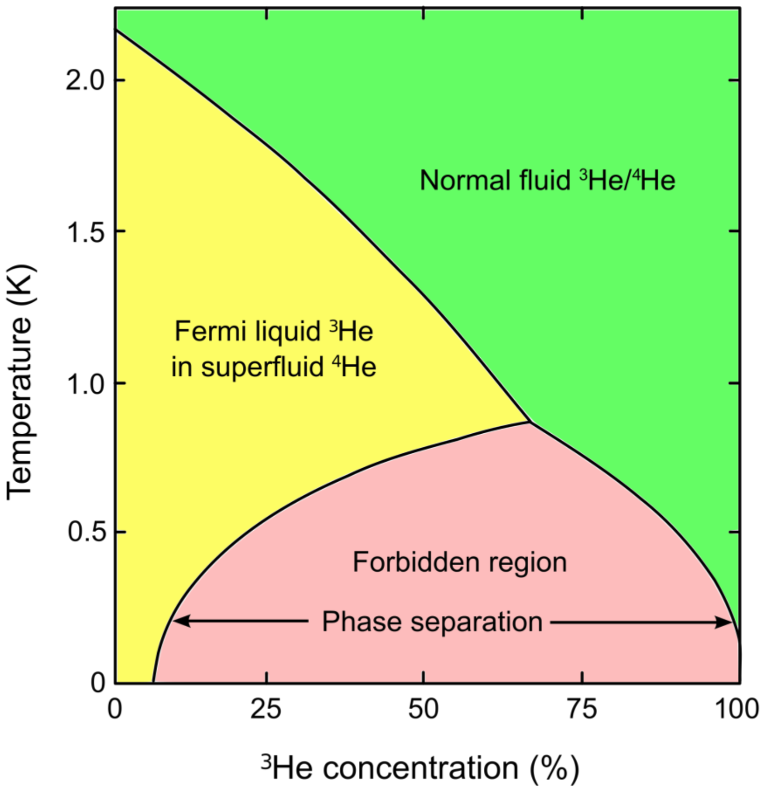


^4He-^3He double-SF challenging.
Experimental pursuit continues.
Theoretical work since 70's:
Dissipation-free drag (Andreev '75)
Higher sound modes
Exotic States (Stringari '16)

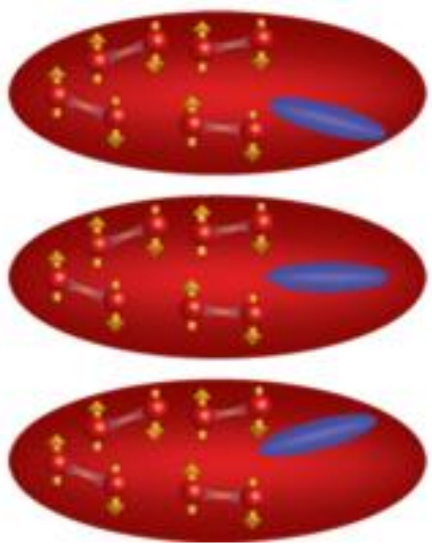
J. Tuoriniemi et al. JLTP **129,** 531 (2002), J. Rysti et al. Phys Rev B **85**, 134529 (2012)

Bose-Fermi Mixtures

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

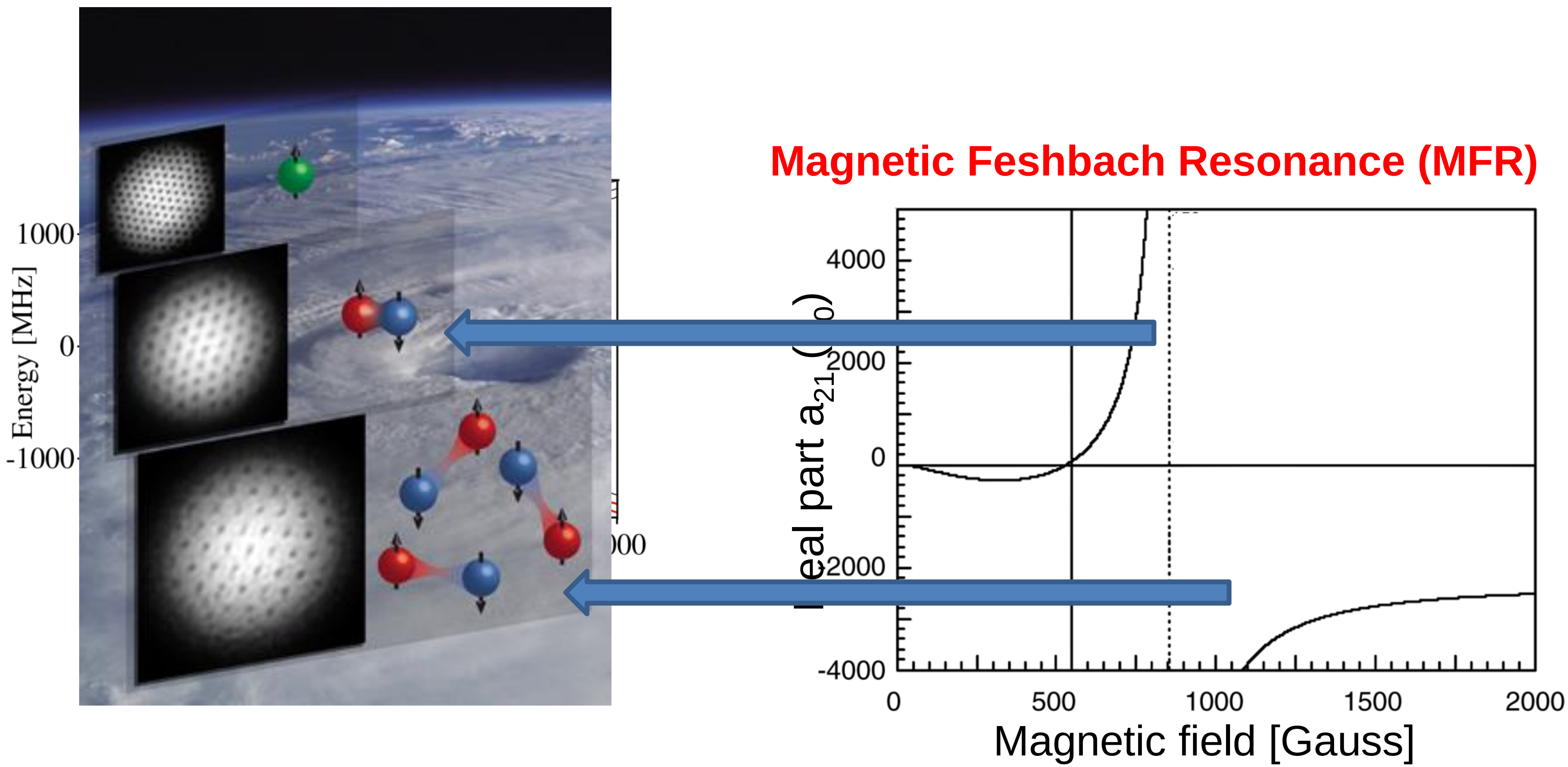


Very recently B-F superfluids in atomic systems in ^7Li-^6Li, ^{174}Yb-^6Li, ^{41}K-^6Li
NEW QUANTUM SYSTEM!



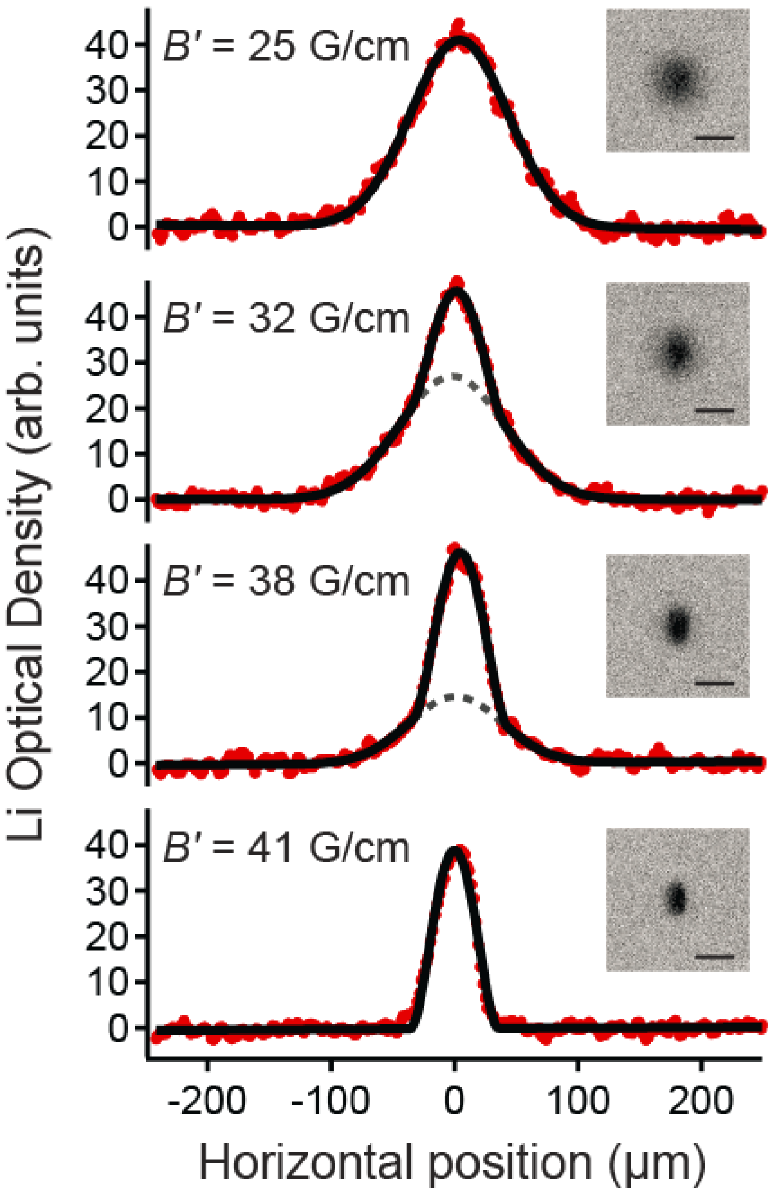
R.J. Roy et al. Phys Rev Lett **118**, 055301 (2017)

Strong Interactions in the ^{6}Li Fermi system

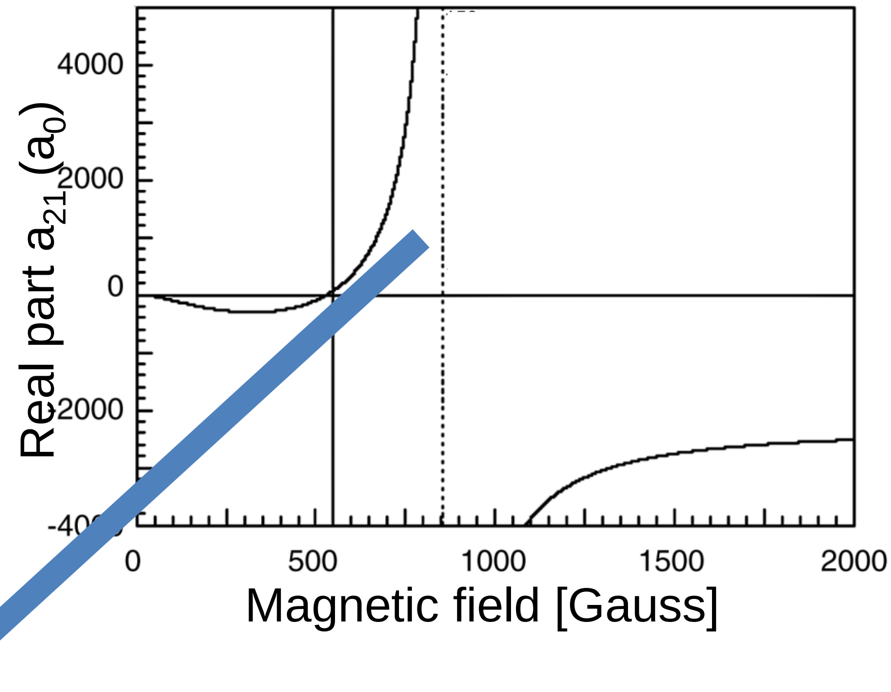


Fermi gas physics; High Tc Fermi superfluid;
BEC/BCS crossover across wide Feshbach resonance;
Unitary Fermi Gas. Universal Physics

Li_2 Fermionic Superfluidity



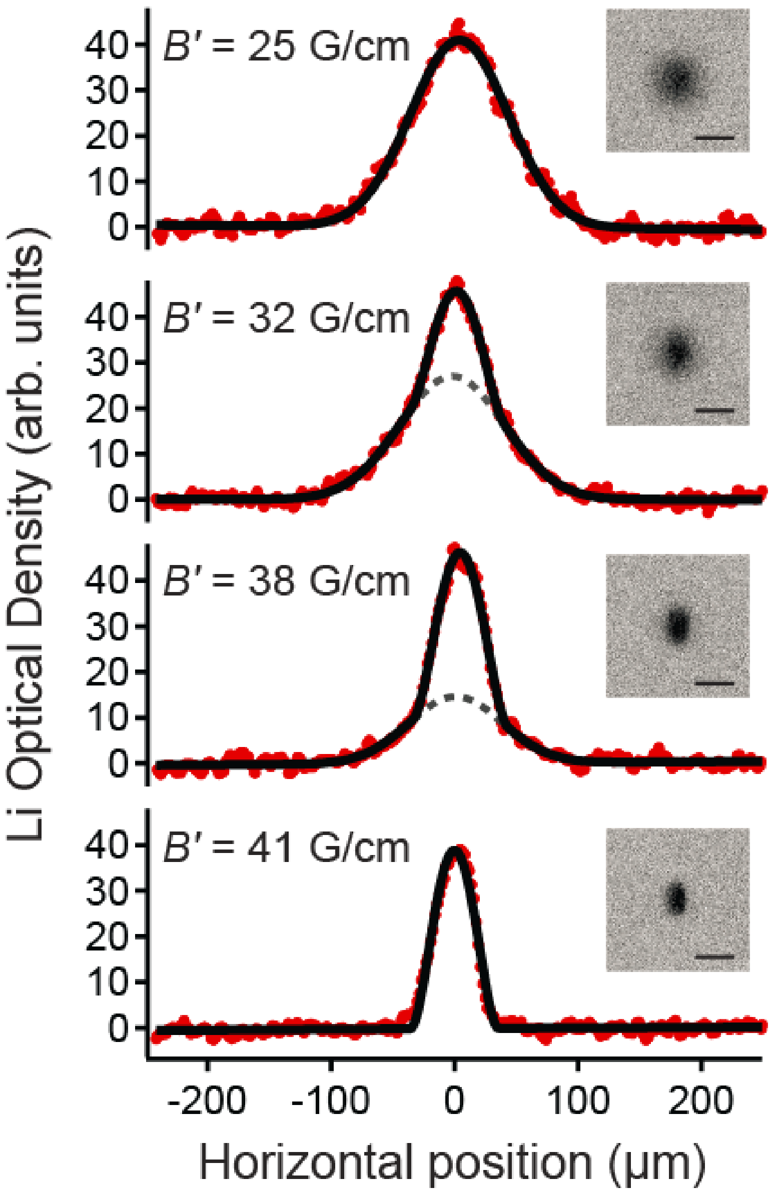
Magnetic Feshbach Resonance (MFR)

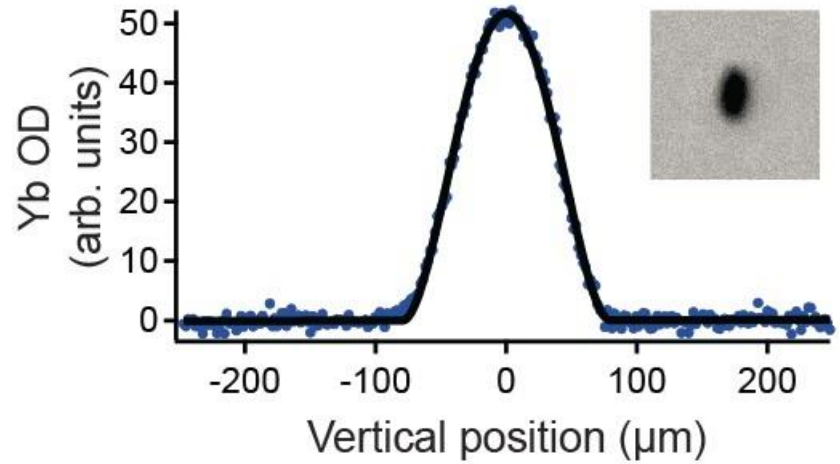


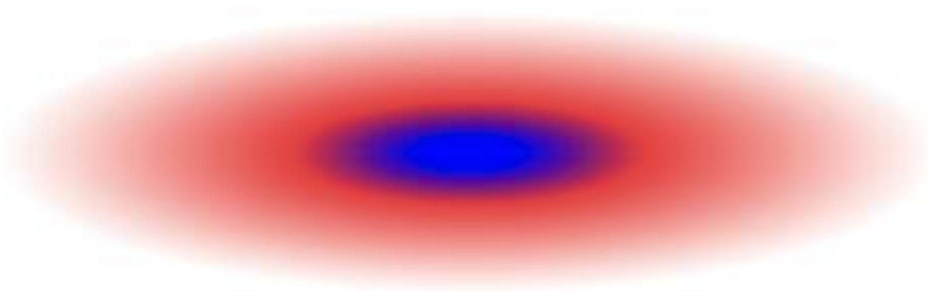
Formation of molecular BEC

(Fermionic SF $T_c \sim 0.18T_F$)

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

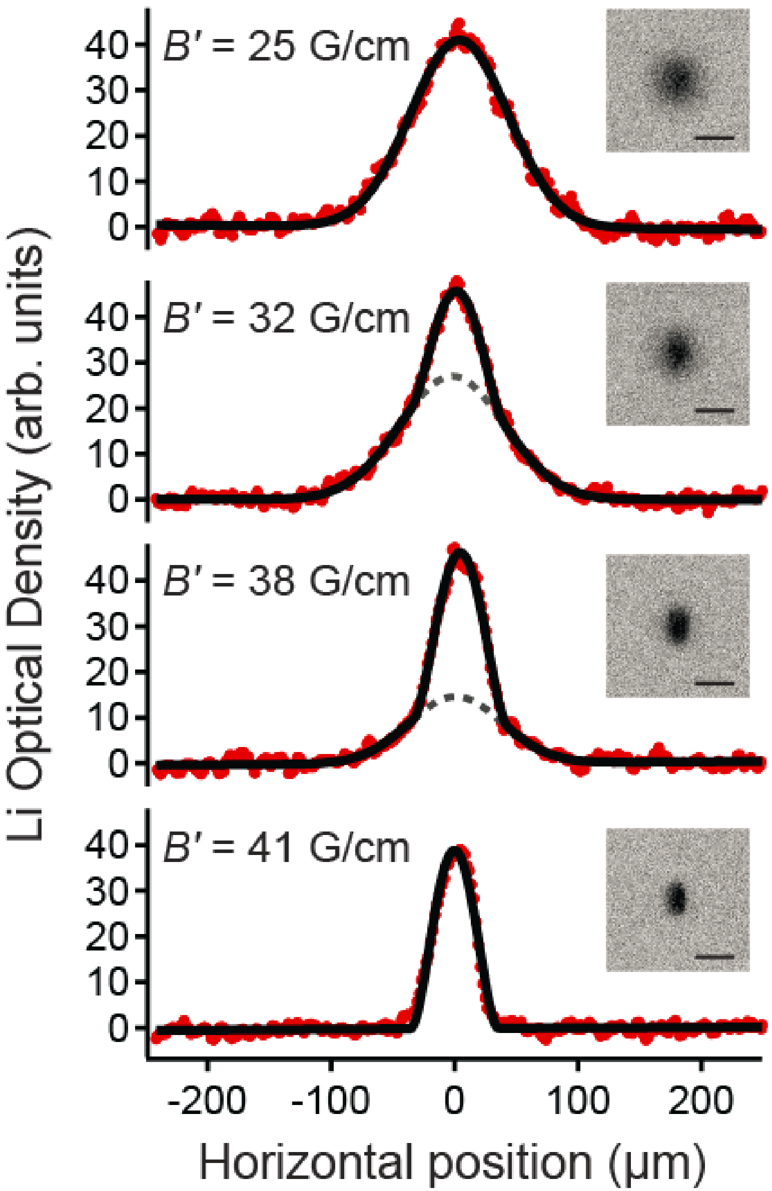


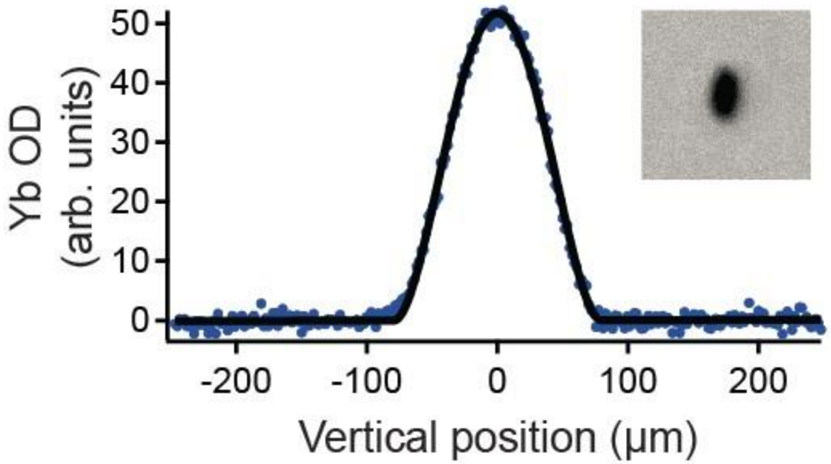




R.J. Roy et al. Phys Rev Lett **118**, 055301 (2017)

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



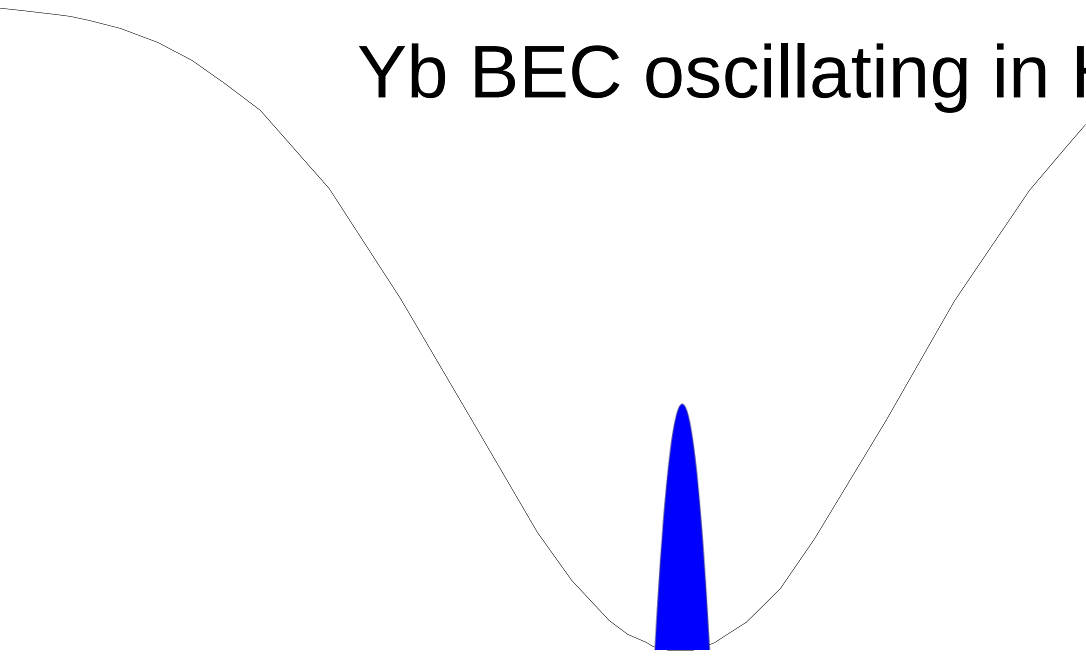


Characteristics at Unitarity (832G)

N_{Li}=8x10^4 N_{Yb}=1.1x10^5
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} = 1.4x10^{13}/cm^3 , n_{Yb}= 3x10^{14}/cm^3
Interspecies MF ~ 0.1 of μ_B, μ_F

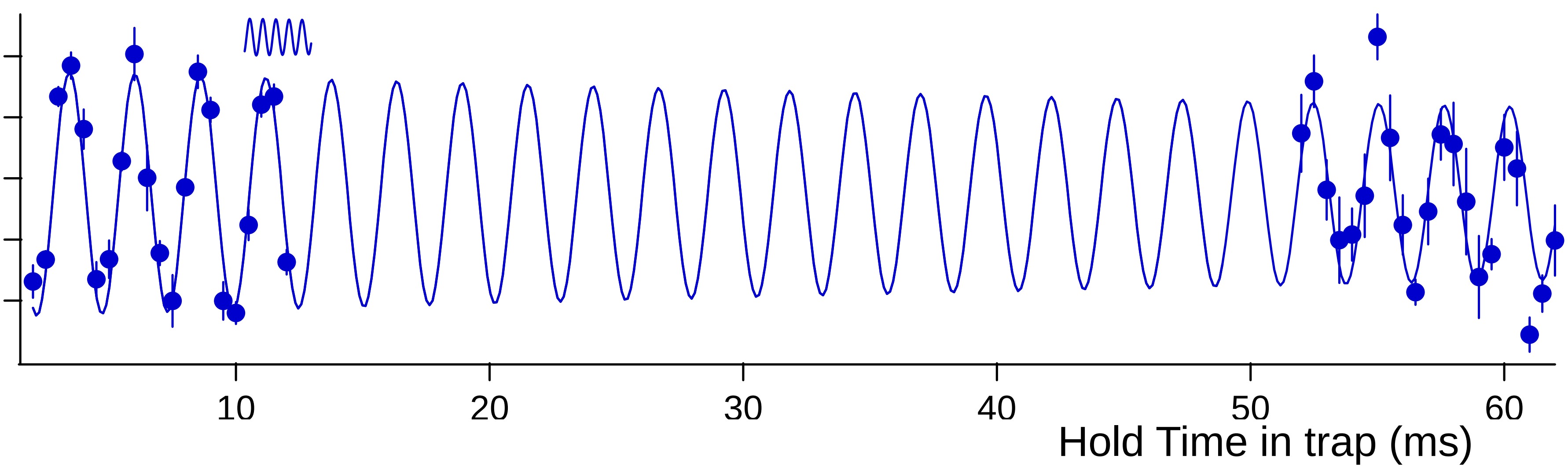
R.J. Roy et al. Phys Rev Lett **118**, 055301 (2017)

Yb BEC oscillating in Harmonic Trap



BEC of 5×10^4 atoms
Trap ν = (26,388,59) Hz
z-Radius = 1 μm
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 << $v_{crit,BF}$

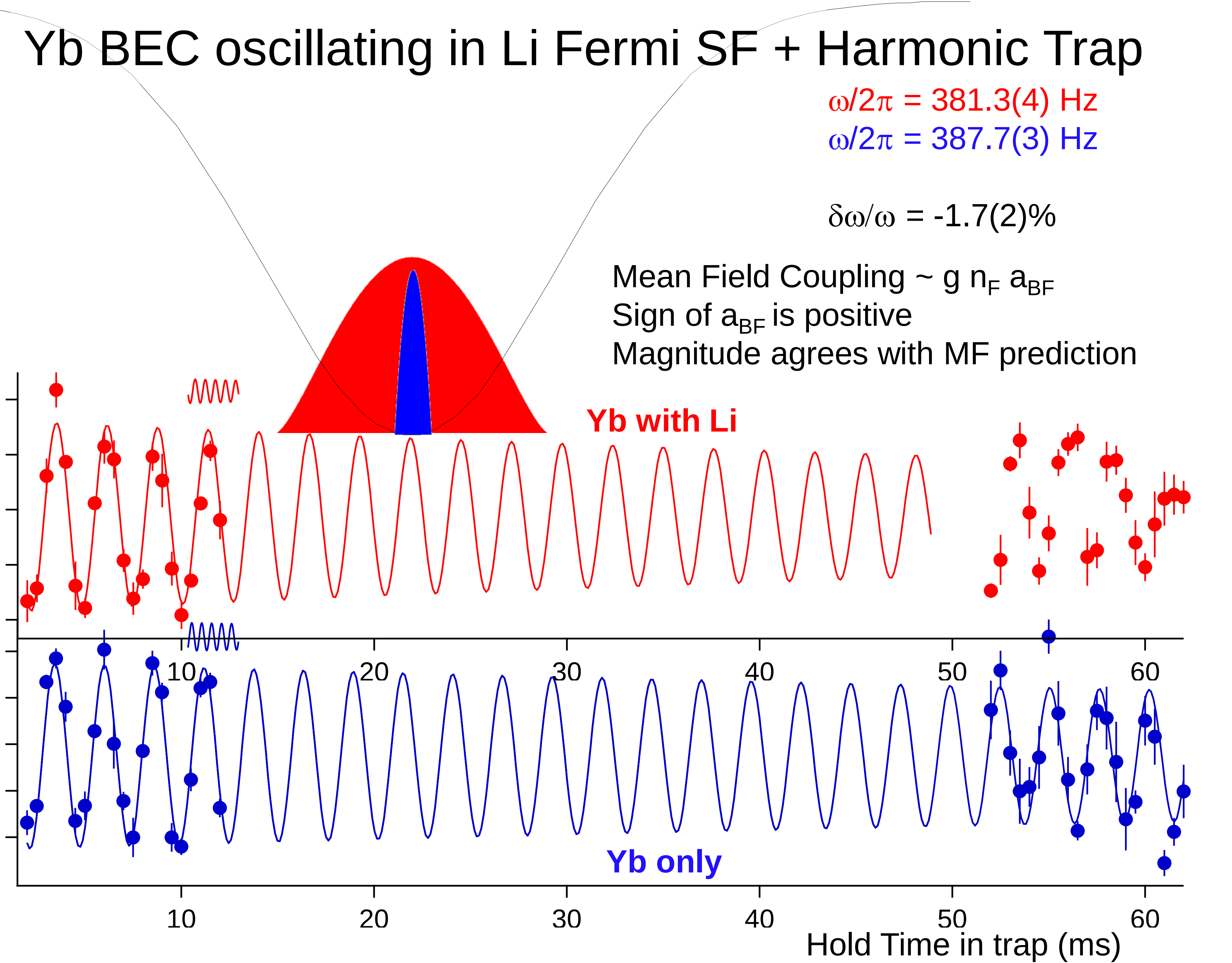


Yb BEC oscillating in Li Fermi SF + Harmonic Trap

$\omega/2\pi$ = 381.3(4) Hz
$\omega/2\pi$ = 387.7(3) Hz

$\delta\omega/\omega$ = -1.7(2)%

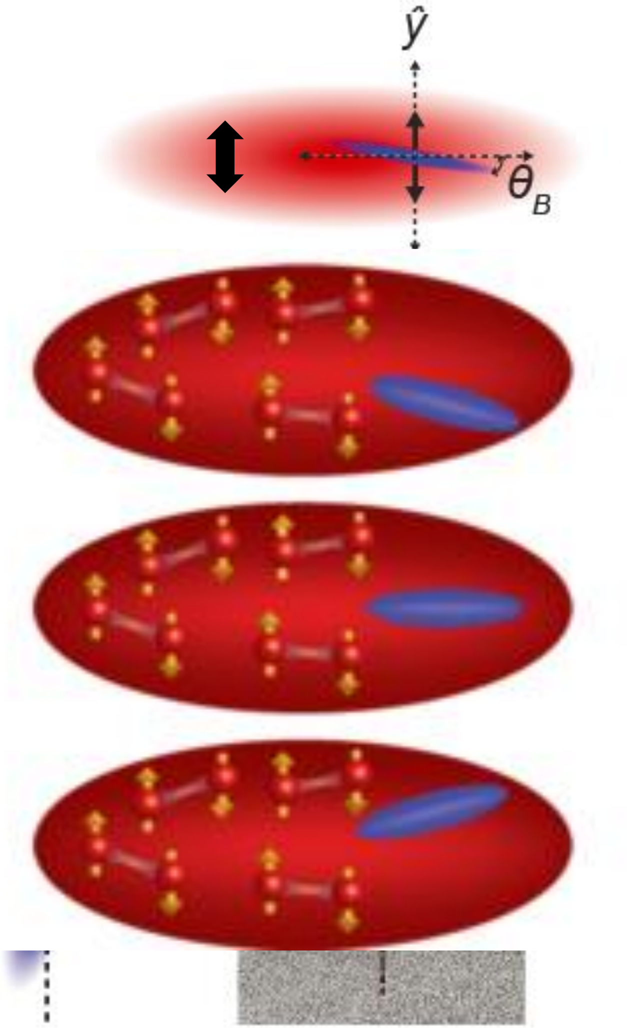
Mean Field Coupling ~ g n_F a_{BF}
Sign of a_{BF} is positive
Magnitude agrees with MF prediction

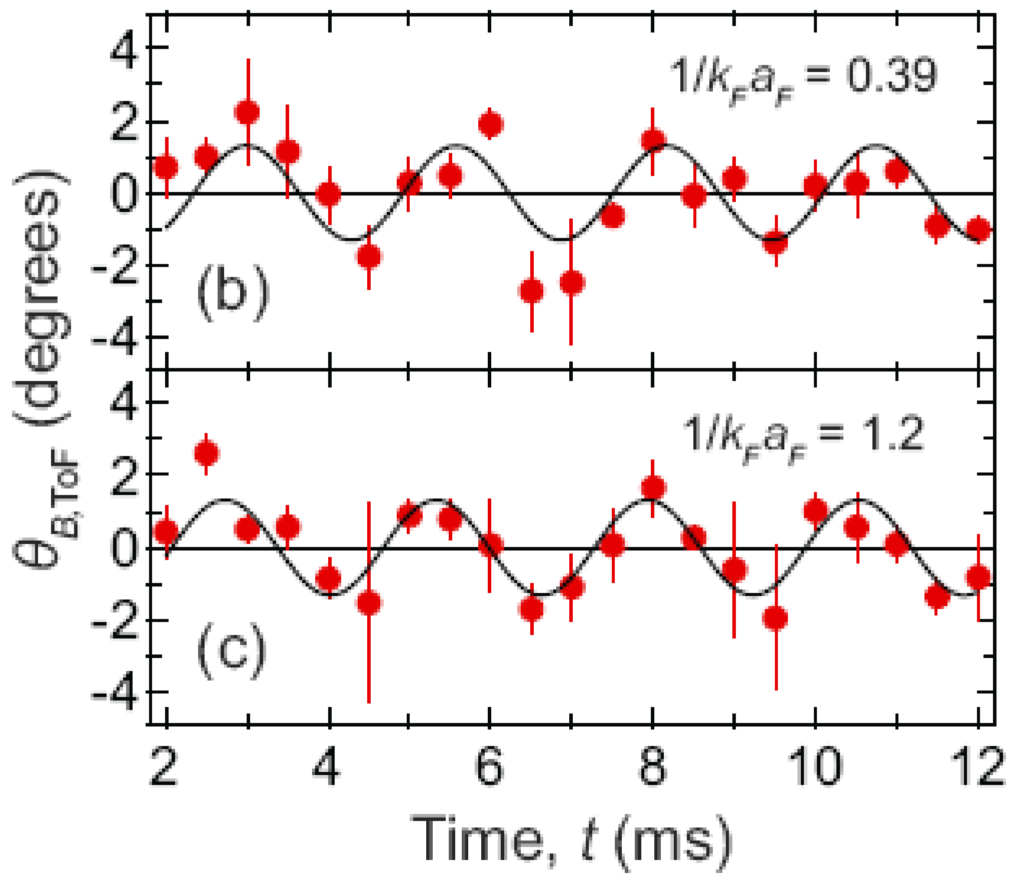


Angular Momentum Exchange between superfluids

Scissors mode of BEC driven by Fermi Superfluid

$\omega_s \sim \omega_{vert}$ $\omega_\theta/\omega_{dip}$ = 1.02(3)





R.J. Roy et al. Phys Rev Lett **118**, 055301 (2017)

Summary & Prospects with Yb-Li

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

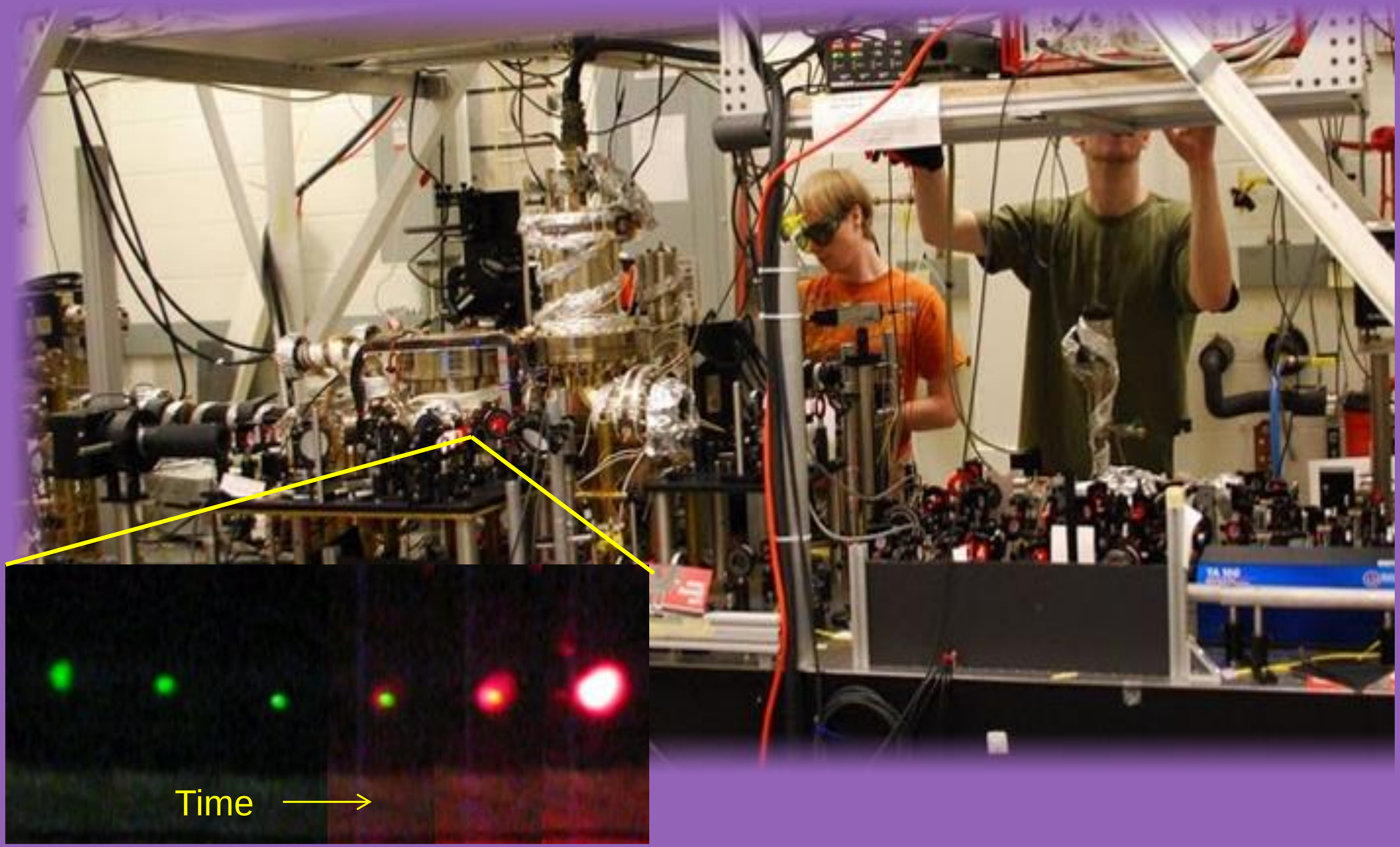
Further collective modes, damping, sound,
exotic states

Mixed SF Phase Diagram in Optical Lattice

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

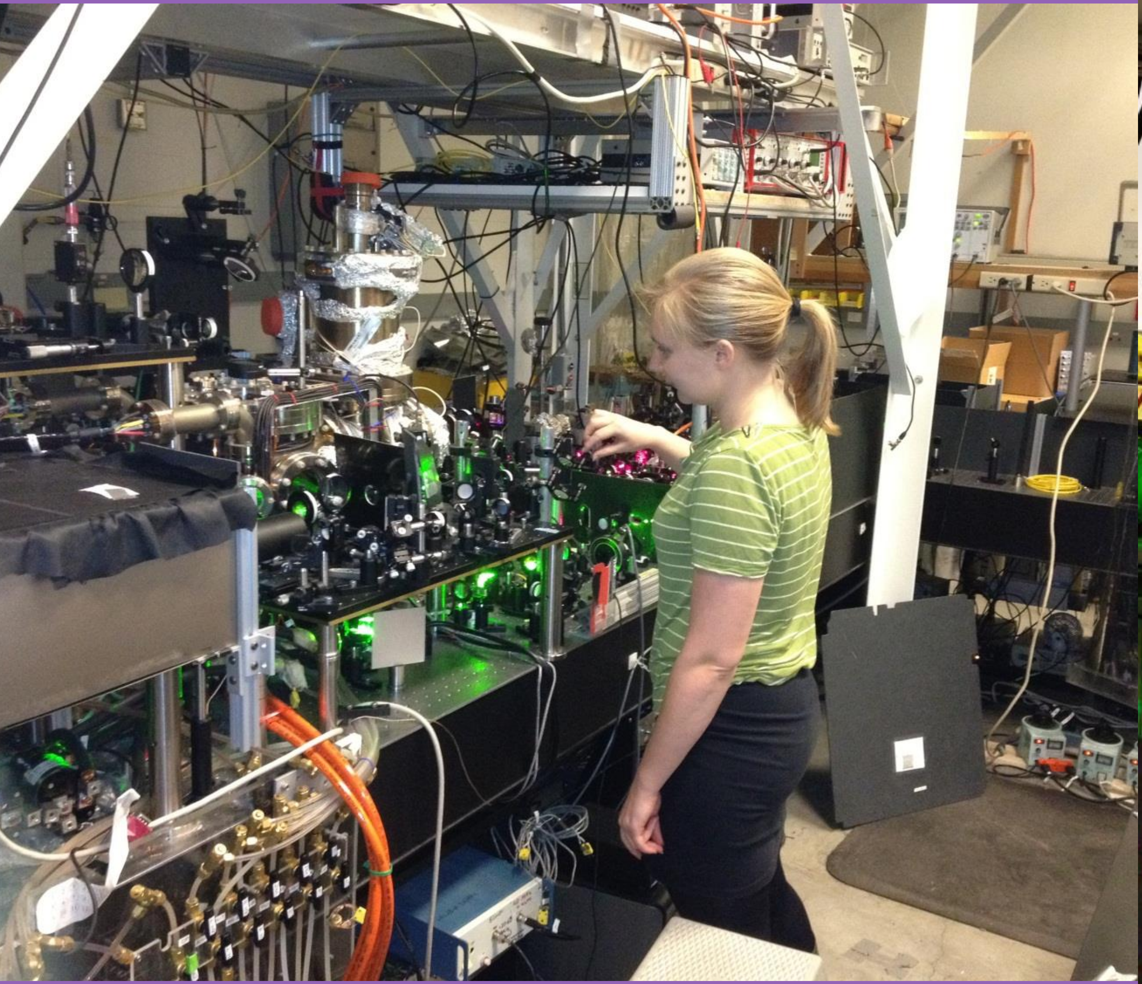
Controllable Interspecies Overlap
YbLi molecules in a 3D optical lattice

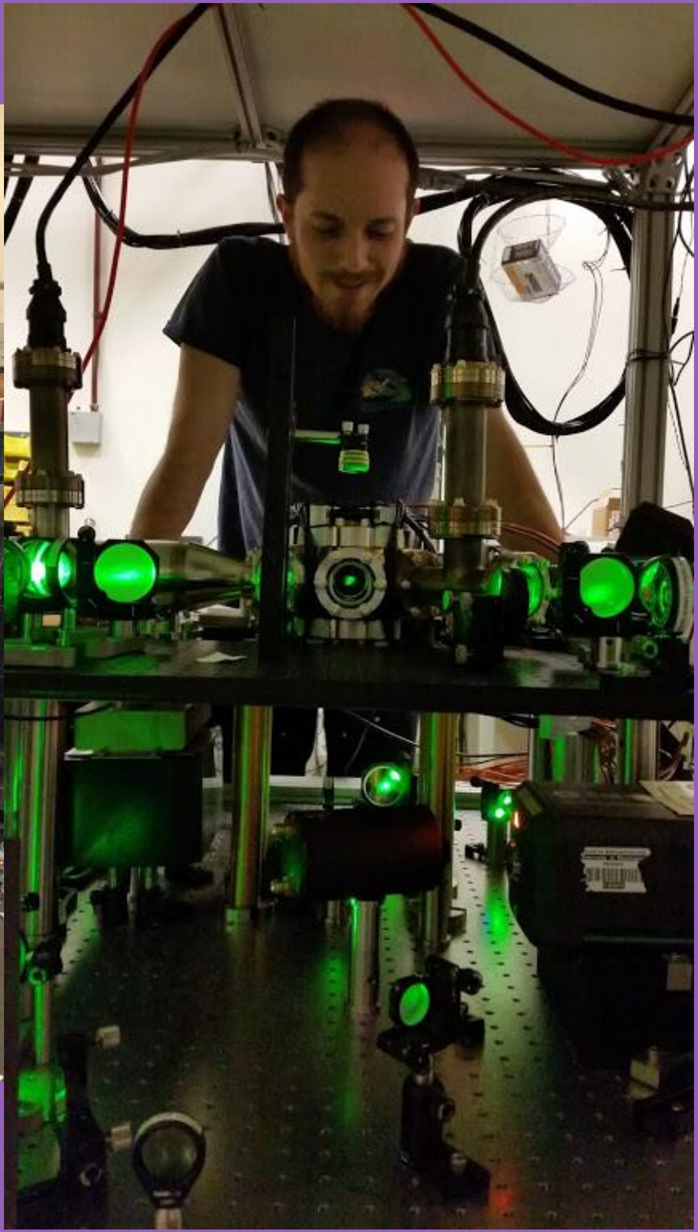
UW Ultracold Atoms Labs



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

UW Ultracold Atoms Labs





UW Ultracold Atoms Group

Ben Plotkin-Swing
Ricky Roy
Katie McAlpine
Alaina Green
Dan Gochnauer
Khang Ton
Jun Hui See Toh
Eric Cooper
DG

ARO MURI

AFOSR