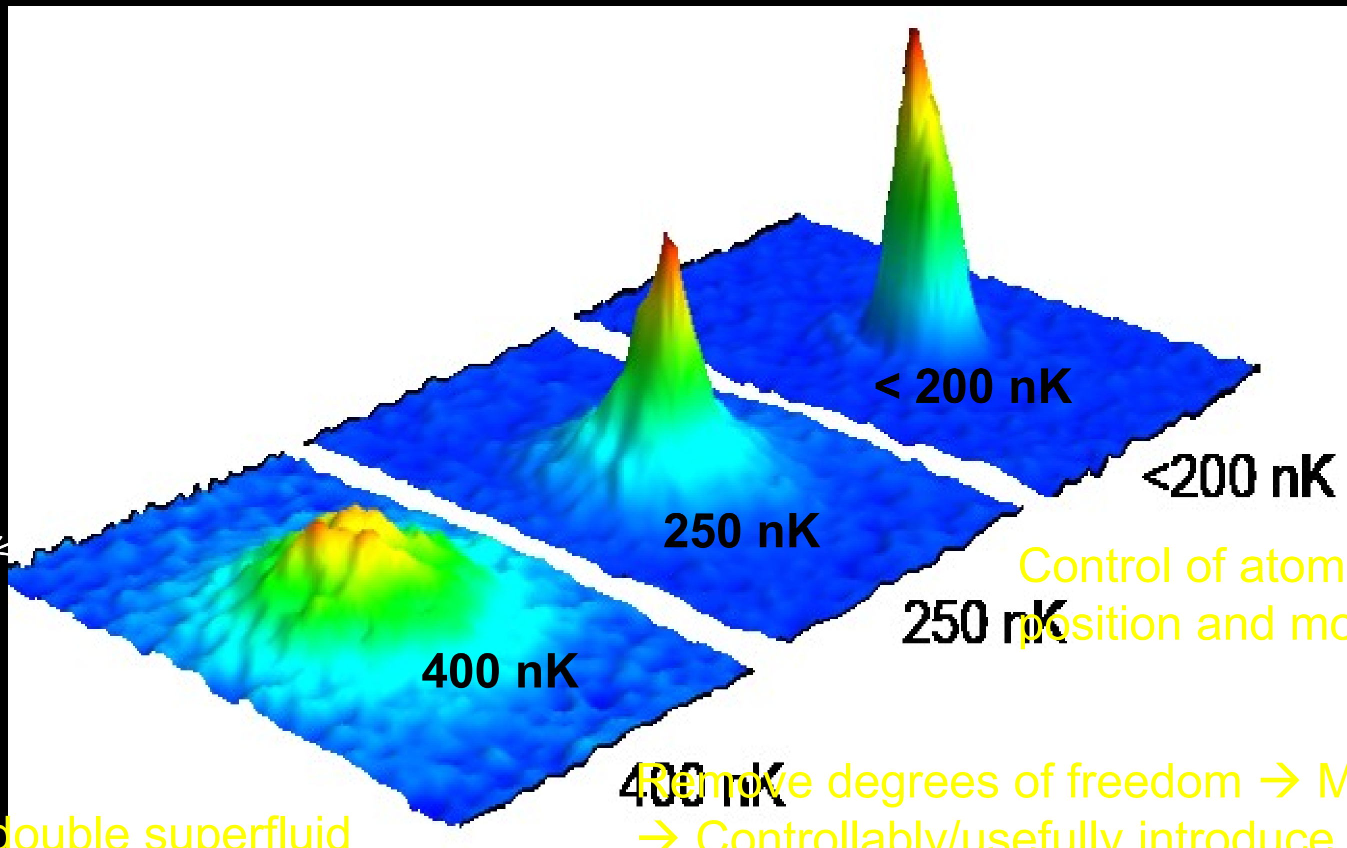
Quantum Engineering with Ultracold Atoms



Control of atomic c.m. position and momentum.

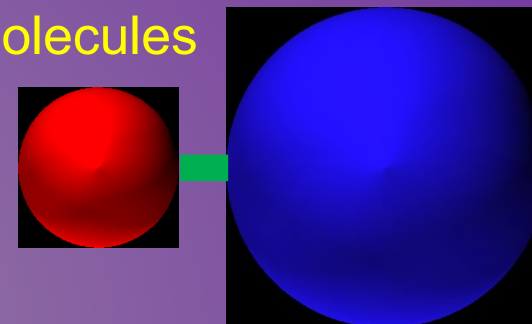
Today:
Bose-Fermi double superfluid
Ultracold Molecules
Precision BEC interferometry

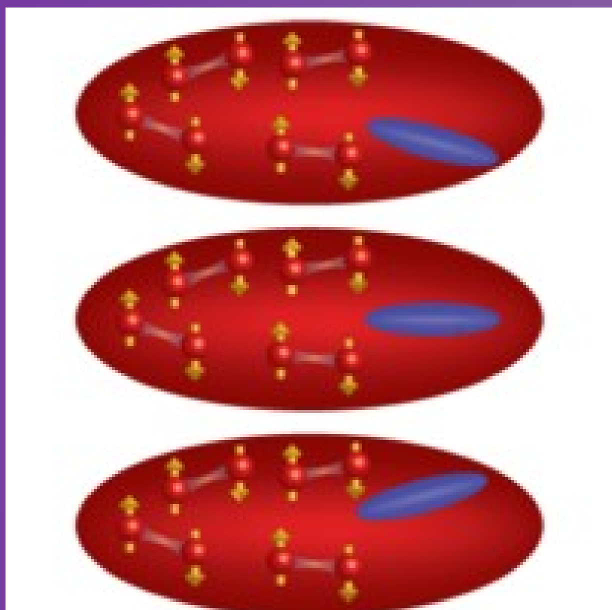
Remove degrees of freedom → Manipulate
→ Controllably/usefully introduce complexity
→ Address Q's in AMO, CM, nuclear, particle

Subhadeep Gupta
UW NSF-INT Phys REU, 12th August 2019

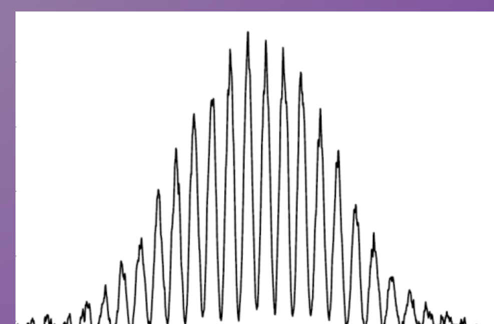
NanoKelvin Quantum Engineering

Ultracold
Molecules



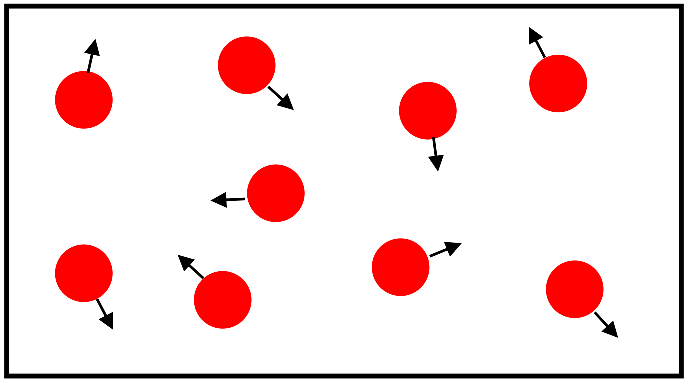


Two-Element
Bose-Fermi double superfluid



Precision BEC
interferometry

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

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

$(n=N/V)$

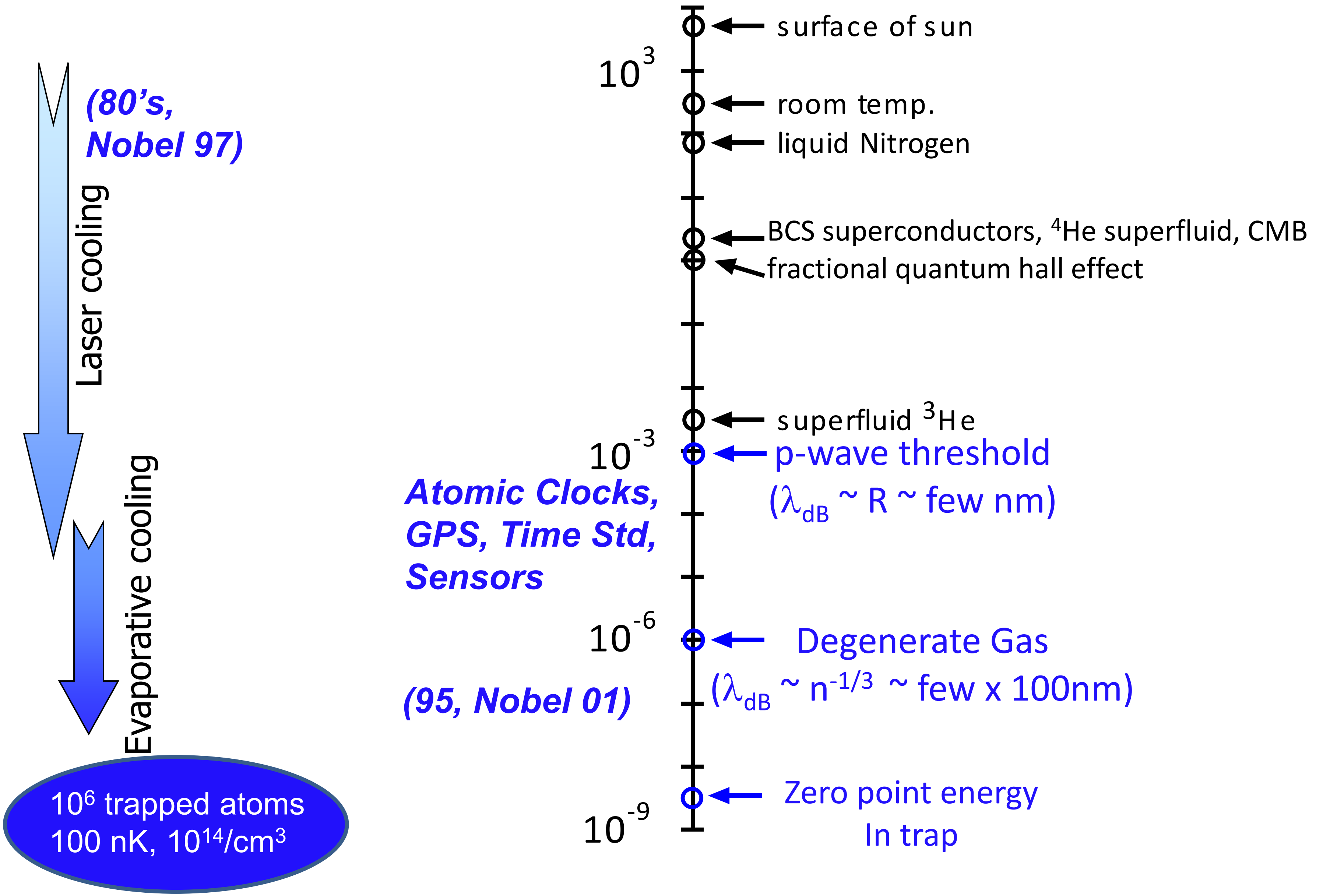
Air $n \sim 10^{19}/cm^3$, $T_c \sim 1mK$
Stuff $n \sim 10^{22}/cm^3$, $T_c \sim 0.1K$
Everything (except He) is solid

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

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

and ~ non-interacting

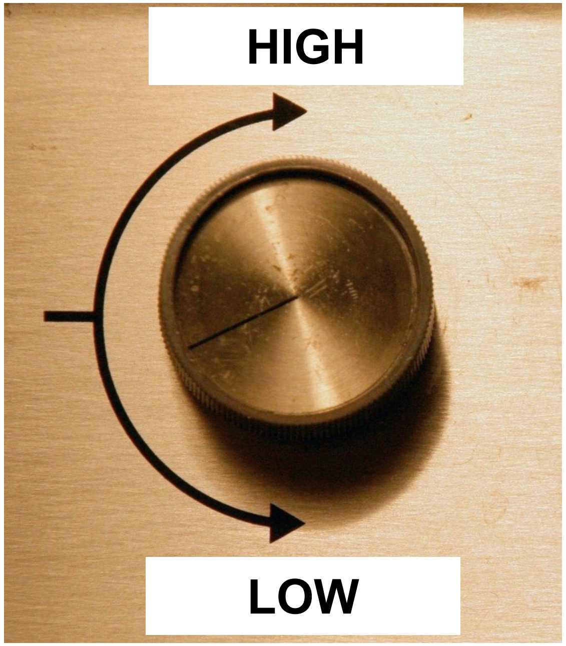
Relevant Ultracold Temperatures on the Log Kelvin Scale



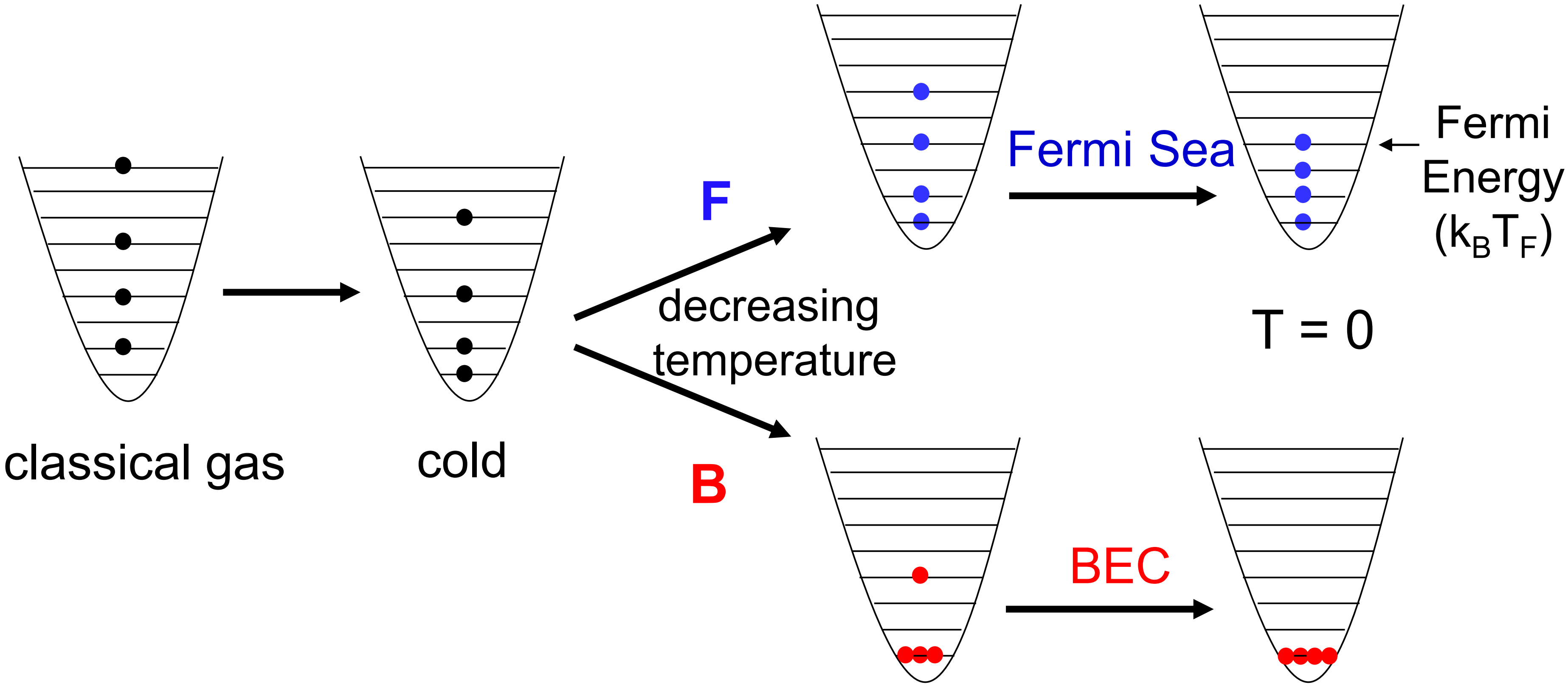
“Knobs” for Quantum Engineering

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

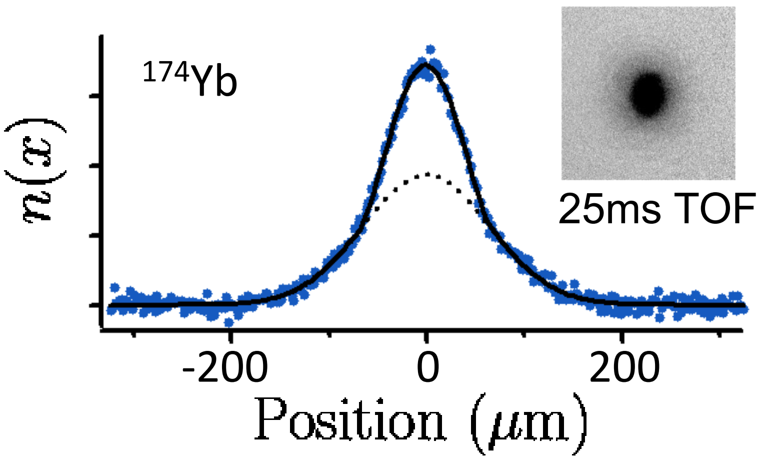


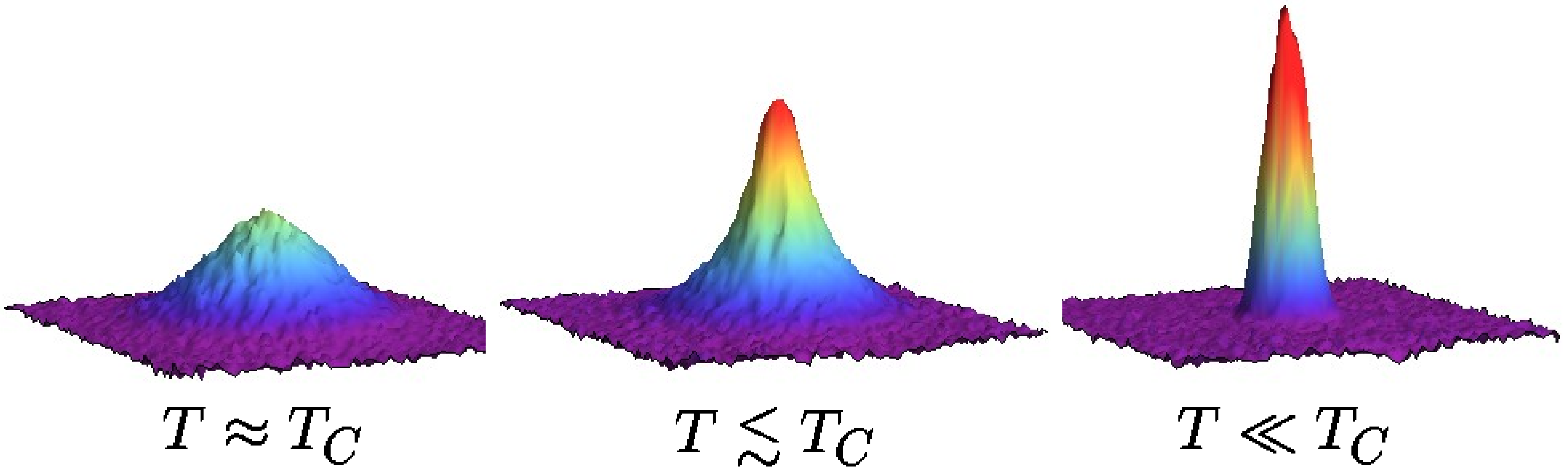
Different Quantum Matters



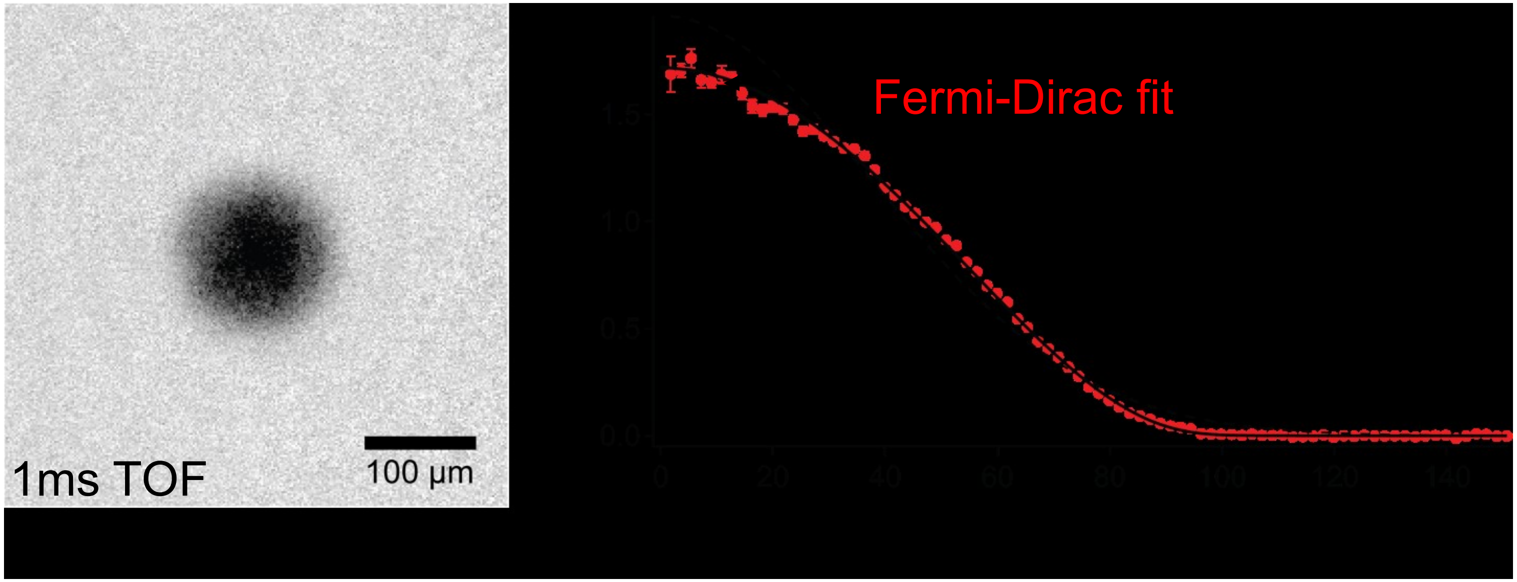
Boson degeneracy: Bose-Einstein condensate

$$n(\vec{r}) = n_{\text{BEC}}(\vec{r}) + n_{\text{th}}(\vec{r})$$





Fermion Degeneracy

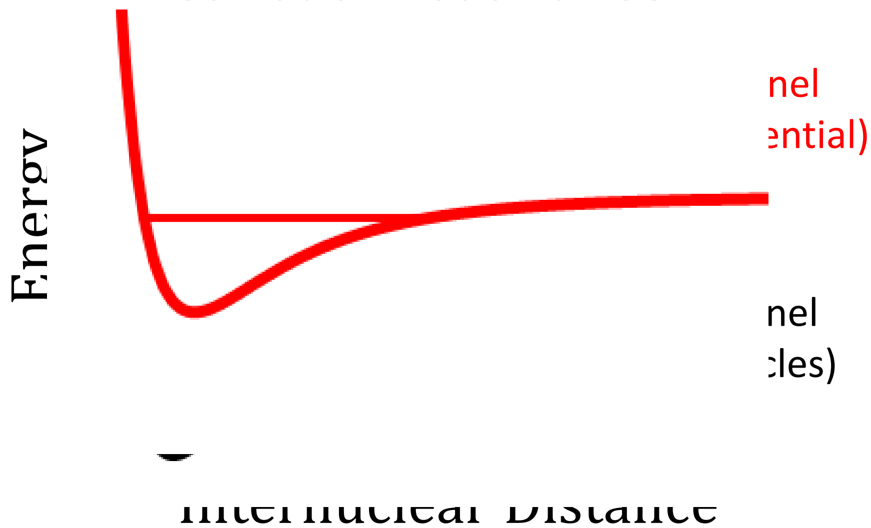


Fermi pressure due to Pauli Exclusion principle

Quantum Degeneracy: $n\lambda_{dB}^{3} \sim 1$ => $T_F \sim 1\mu K$

Controlling interactions

Feshbach resonance



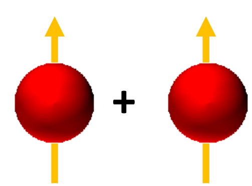
Resonance between two free atoms and a molecule

Control with external magnetic field

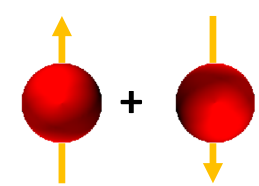
- Example

[redacted]

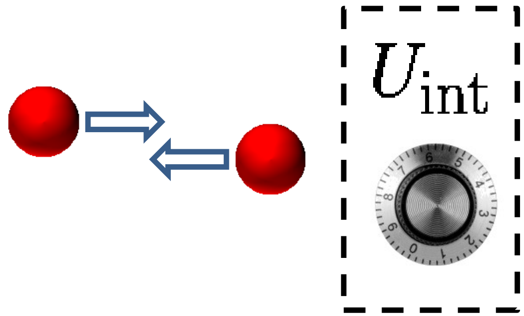
<u>Entrance channel</u>

Triplet: 

<u>Closed channel</u>

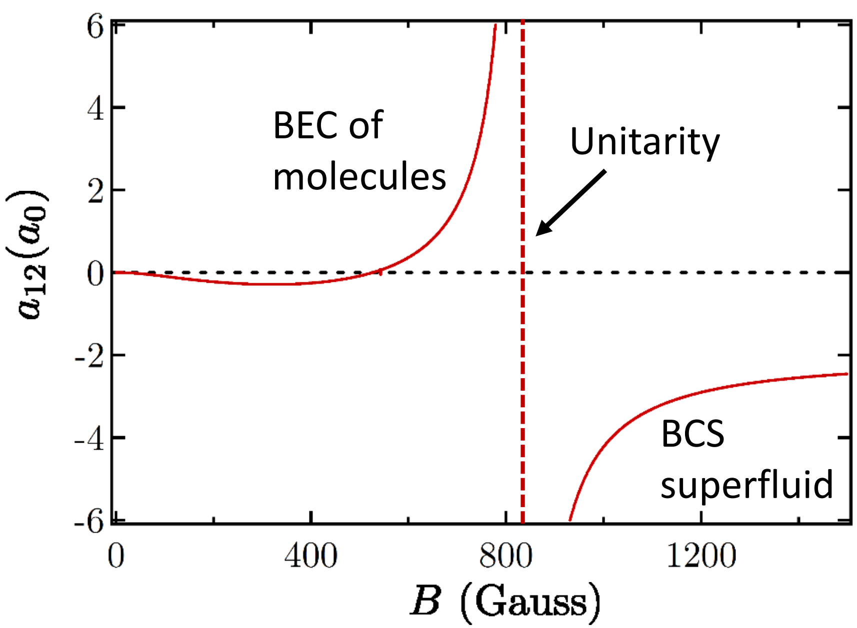
Singlet: 

Strongly interacting Fermi gases



[redacted]

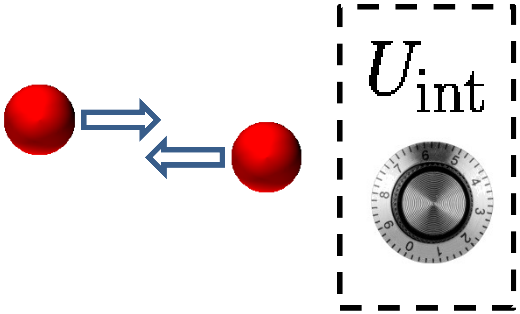
$$a(B) = a_{\text{bg}}\left(1 + \frac{\Delta}{B - B_0}\right)$$

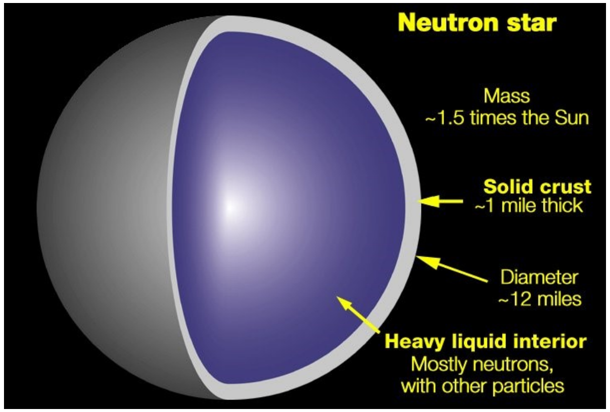


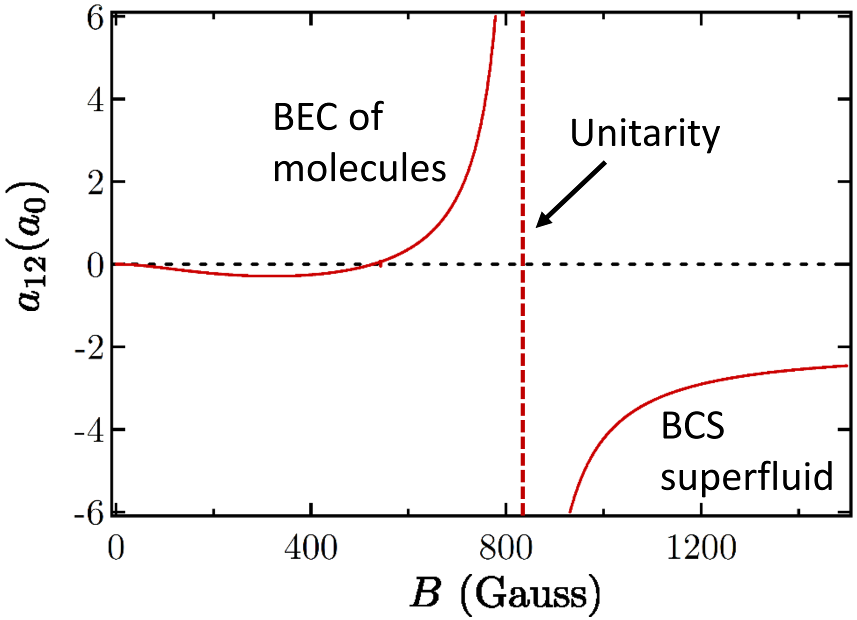
Strong interactions
$|k_F\ a| > 1$
betw. 2 spin states

Unitary Fermi Gas ($\frac{1}{k_F\,a} = 0$):
"Hydrogen Atom"
"Harmonic Oscillator"
of many-body physics

Strongly interacting Fermi gases







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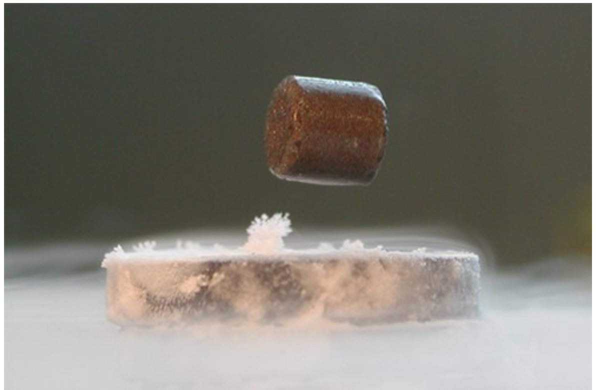
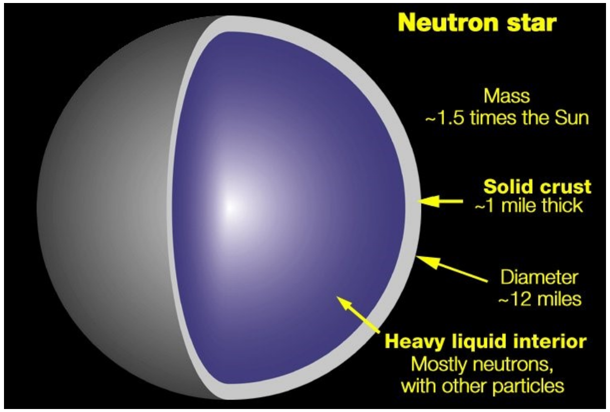
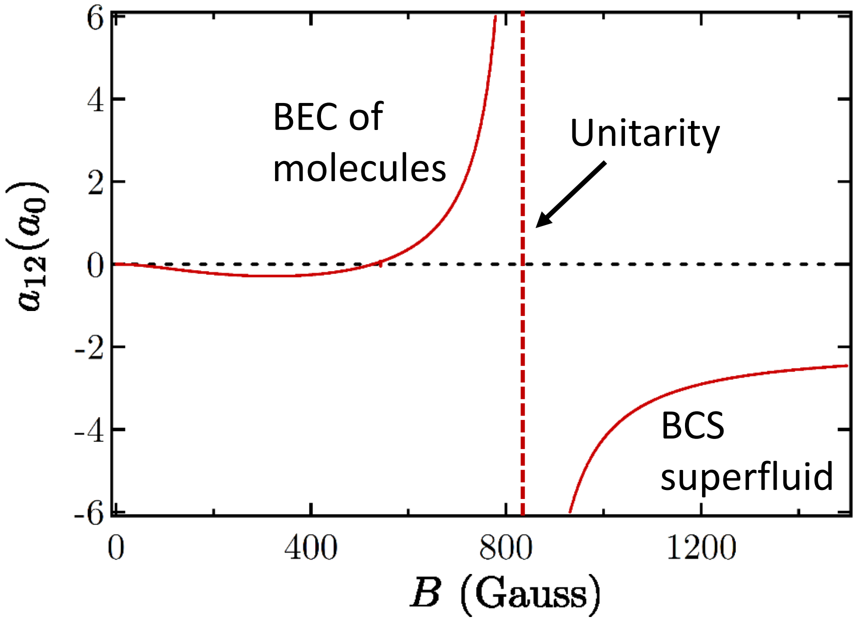


Source: http://www.wou.edu/~rmiller09/superconductivity/





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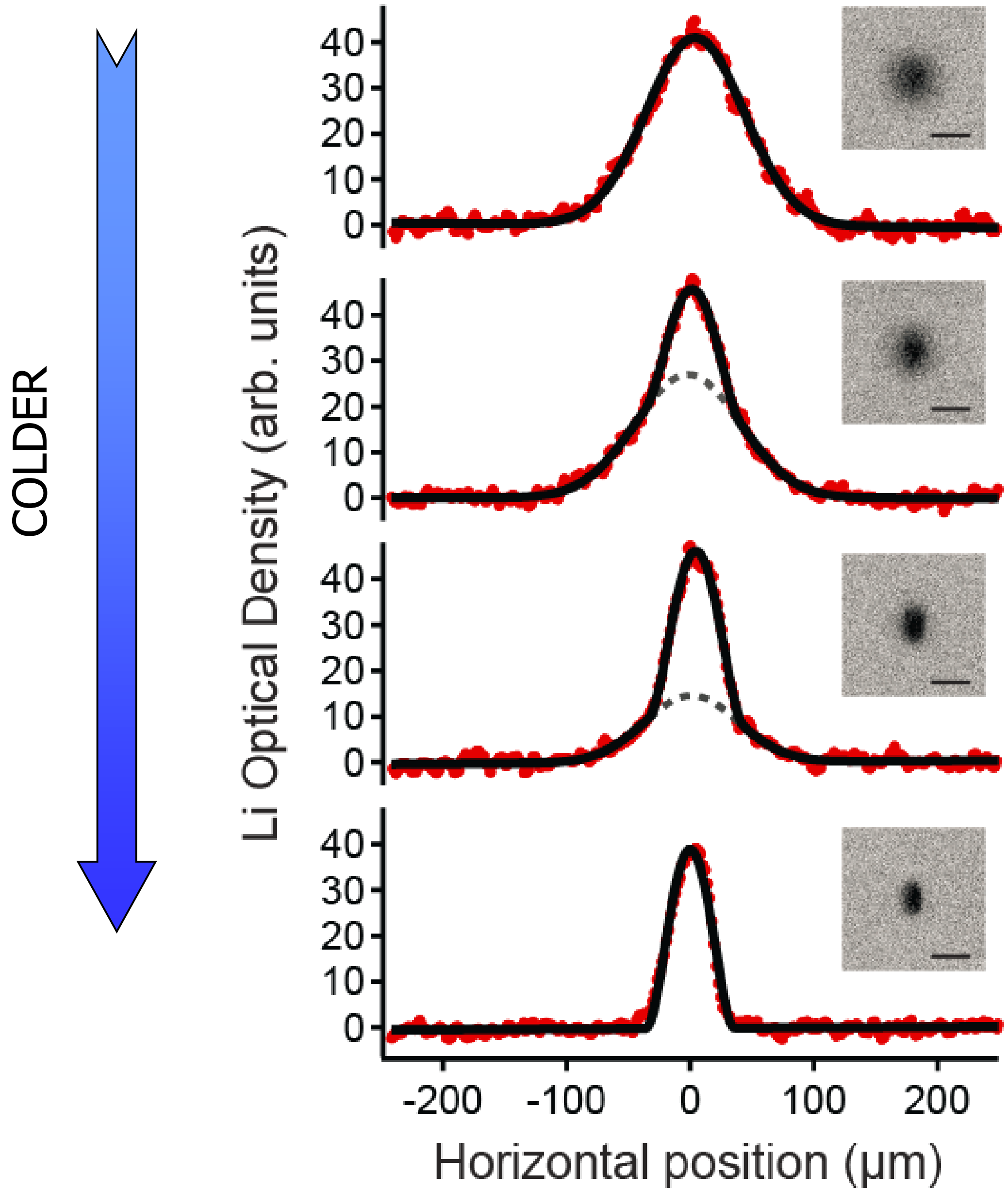
of many-body physics

Fermionic Superfluidity



Final Cooling at unitarity

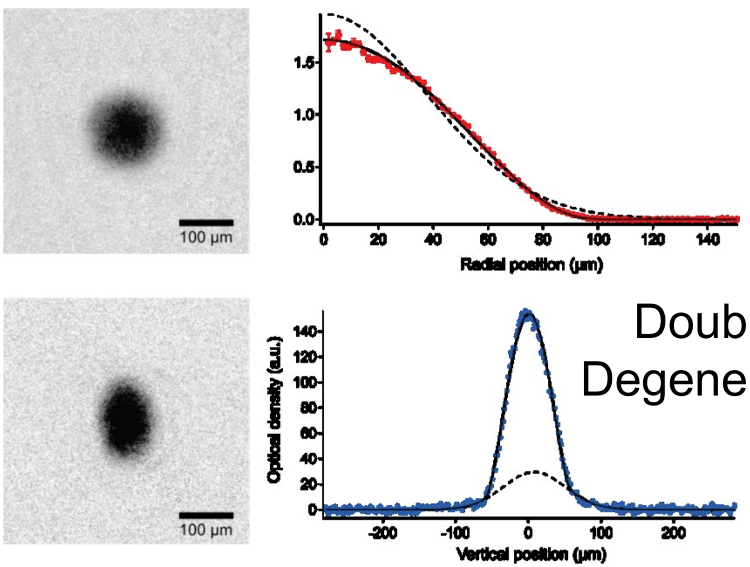
Observe condensation in TOF on the molecular side

(adiabatic transfer from unitarity to BEC side 832G → 690G)

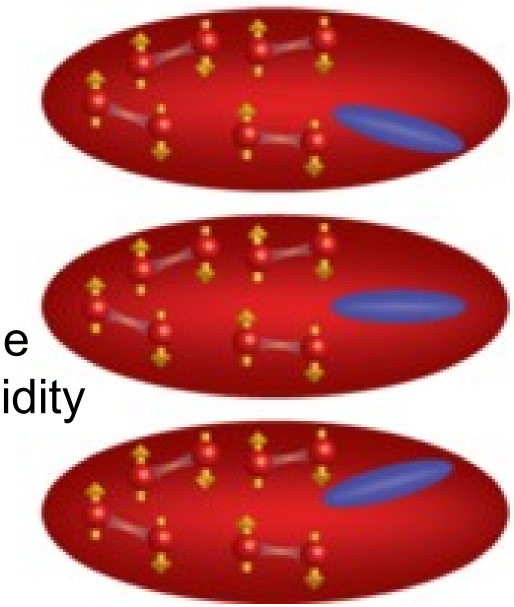
Condensation of paired fermions ($T_c \sim 0.17\ T_F$)

Paired Fermi superfluid of ^{6}Li at $T/T_c = 0.55$

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



Double Degeneracy → Double Superfluidity



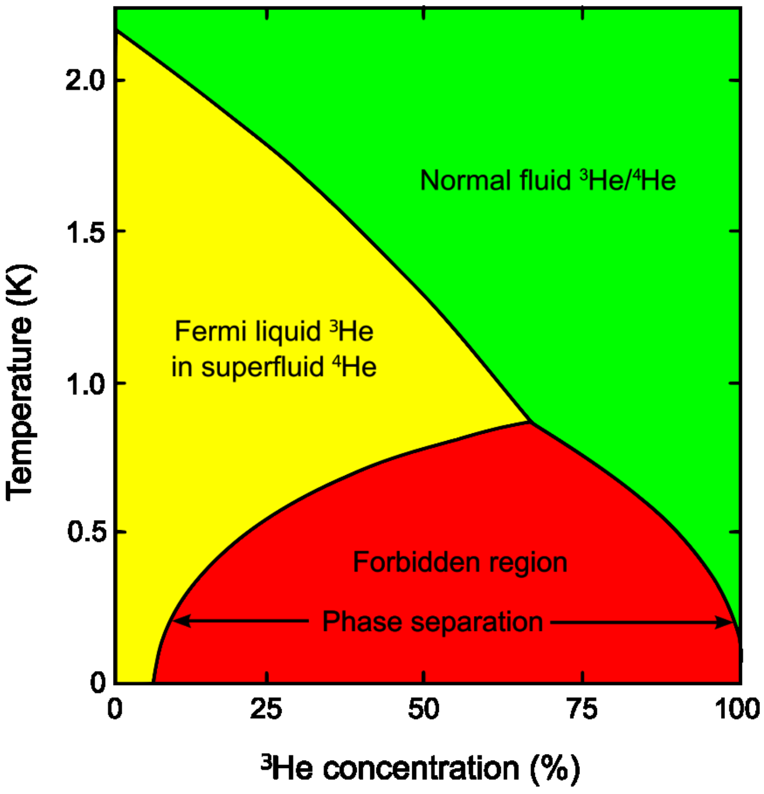
Preparing and observing the double superfluid

Demonstration of Elastic Coupling between superfluids

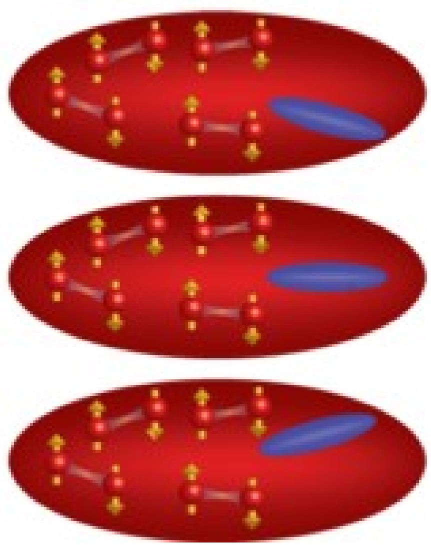
Angular Momentum Exchange between superfluids

Bose-Fermi Double Superfluid

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



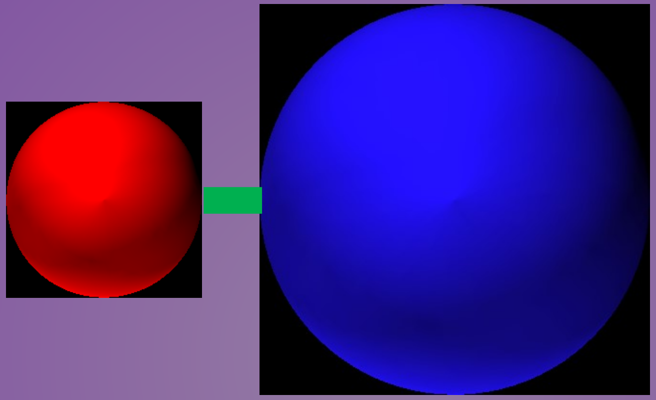
Recently B-F superfluids in atomic systems in ^7Li-^6Li, ^{174}Yb-^6Li, ^{41}K-^6Li
NEW QUANTUM SYSTEM!



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

Diatomic Molecules

(One atom too many?)



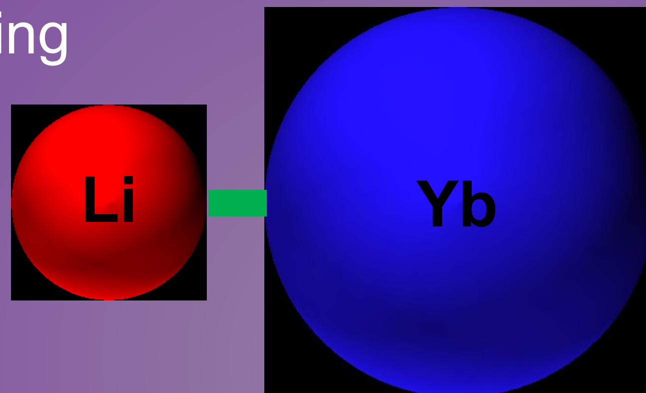
New degrees of freedom:

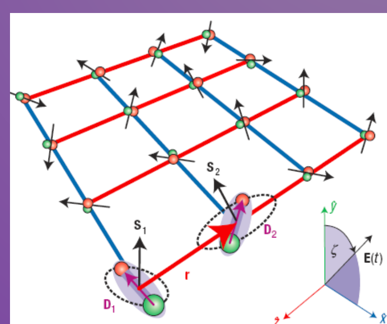
Scientific Advantages & Technical Challenges

Can cool individual atomic species first and then combine them into ultracold molecules

Ultracold Polar Molecules

Long range (d^2/r^3) interaction for quantum Information processing





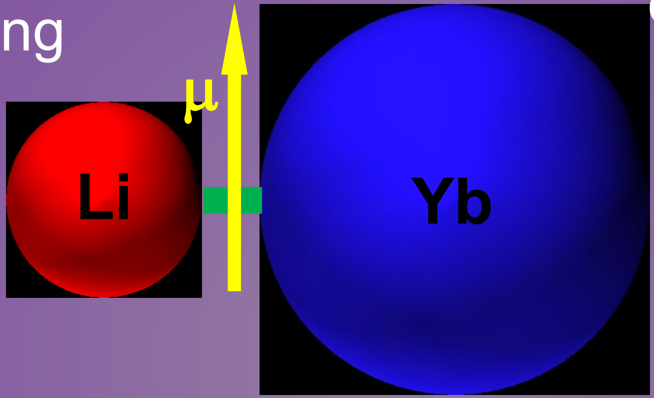
1 Debye dipoles, 0.5μm lattice interact ~ d^2/r^3 ~ hx1kHz, k_Bx50nK.

LiYb: low (0.2 D) and high (5 D) EDM calculated in different electronic states.

Ultracold Polar Molecules

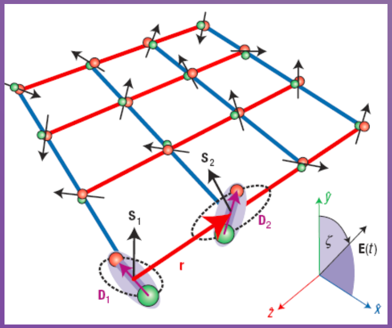
Long range (d^2/r^3) interaction for quantum Information processing

Precision Spectroscopies eg. m_p/m_e time variation



Dipolar superfluids

Quantum controlled chemical reactions



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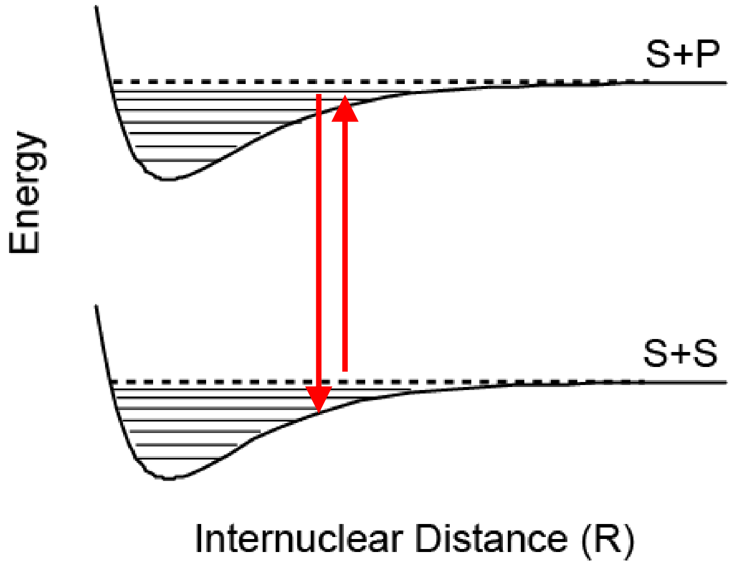
Micheli et al. Nat. Phys. **2**, 341
Rev: Carr et al. New Jrnl Phys. **11**, 055049

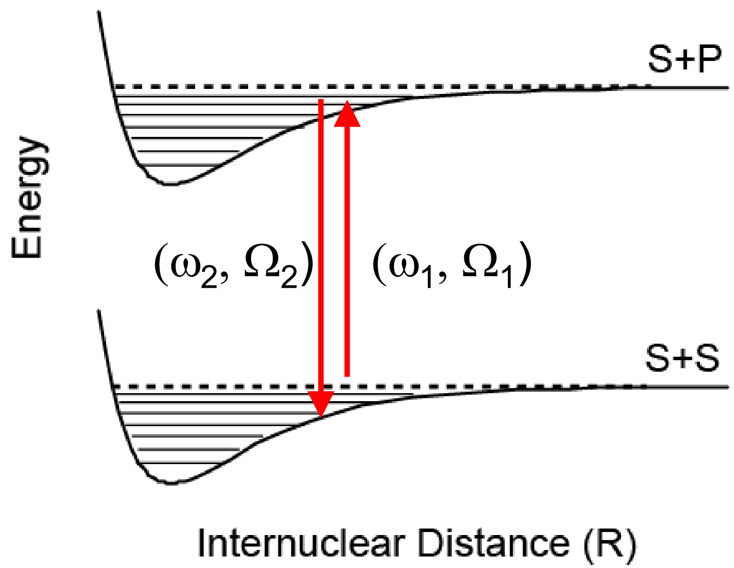
Pursued by several groups worldwide

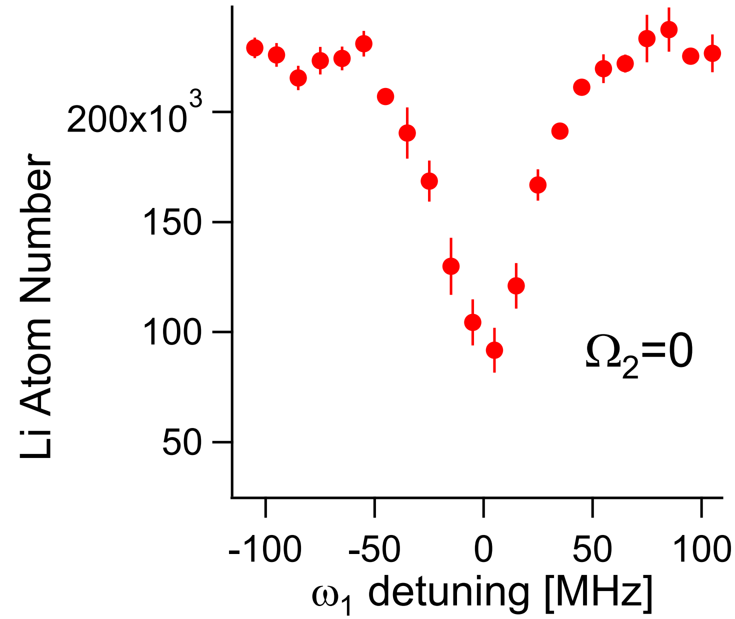
Optical Feshbach Resonance

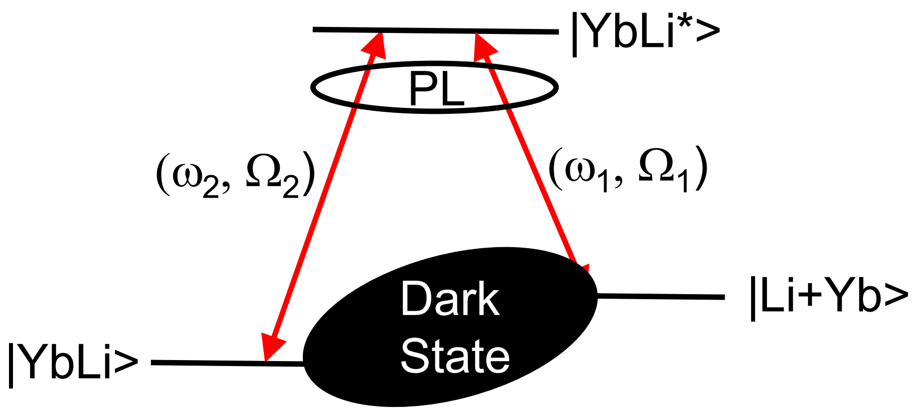


Couple (ultracold) free atoms and molecules using a coherent 2-photon Raman process

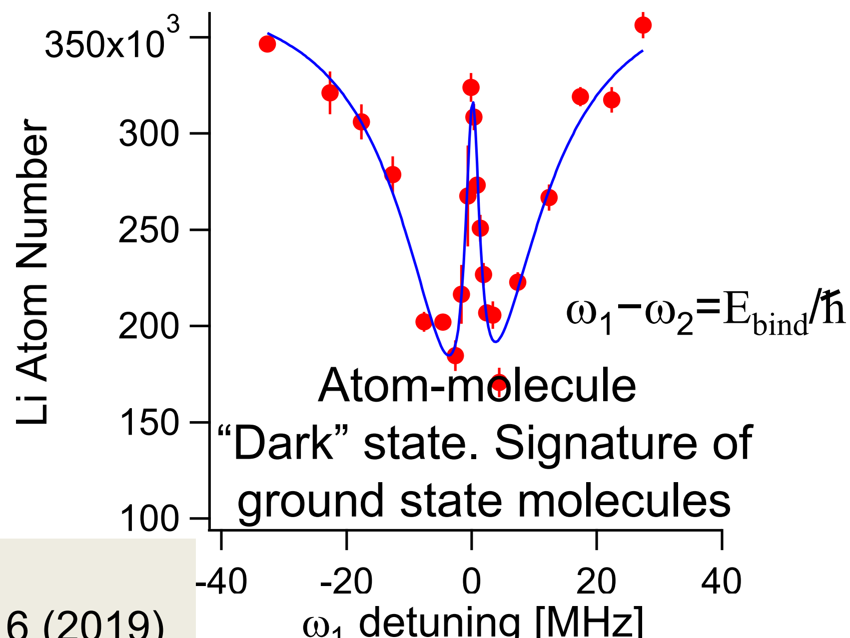
Atom-Molecule Coherence







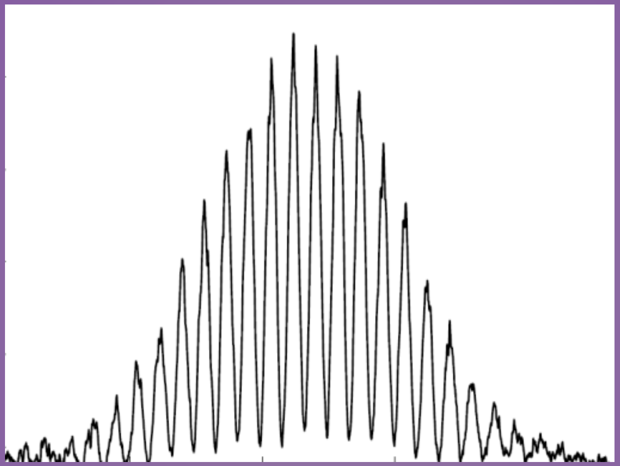
3 level Λ–system



Alaina Green et al.
Phys Rev A **99**, 063416 (2019)

Precision Contrast Interferometry with Yb BECs:

α and Development of BEC-based precision sensors



"Scaling up" Yb BEC CIFM
to large momentum separation

Photon Recoil for the Fine-Structure Constant, α

Test of QED and Standard Model

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)

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

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

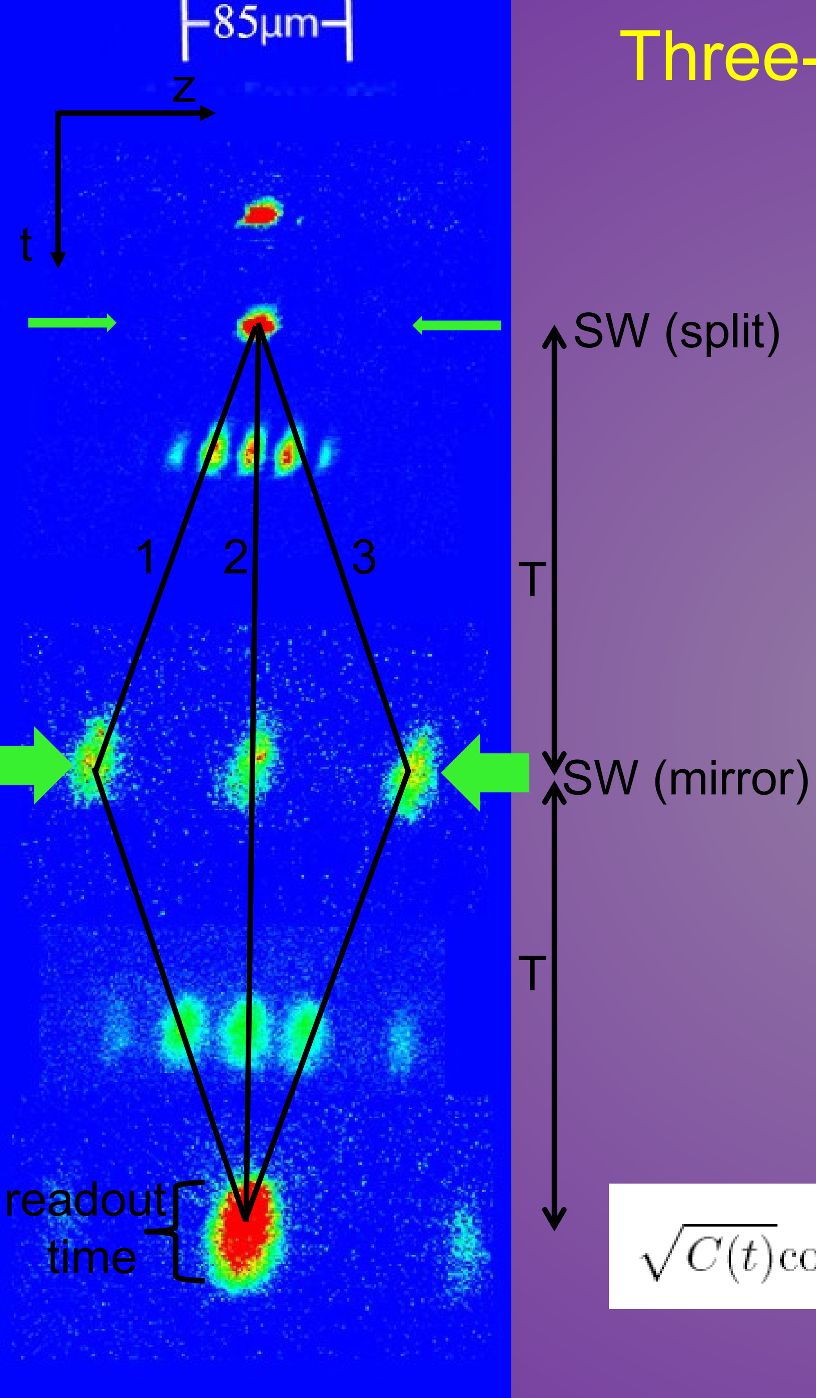
$$\omega_{\mathrm{rec}} = \frac{1}{2}\,\frac{\hbar}{m}\,\kappa$$

α at 0.25 ppb (2008, 2012)
Penning trap @ Harvard (Gabrielse)
QED calculations by Kinoshita group

Photon Recoil Measurement by light-pulse Atom Interferometry
Rb (Paris 2011) 1.3 ppb
Cs (Berkeley 2018) 0.4 ppb

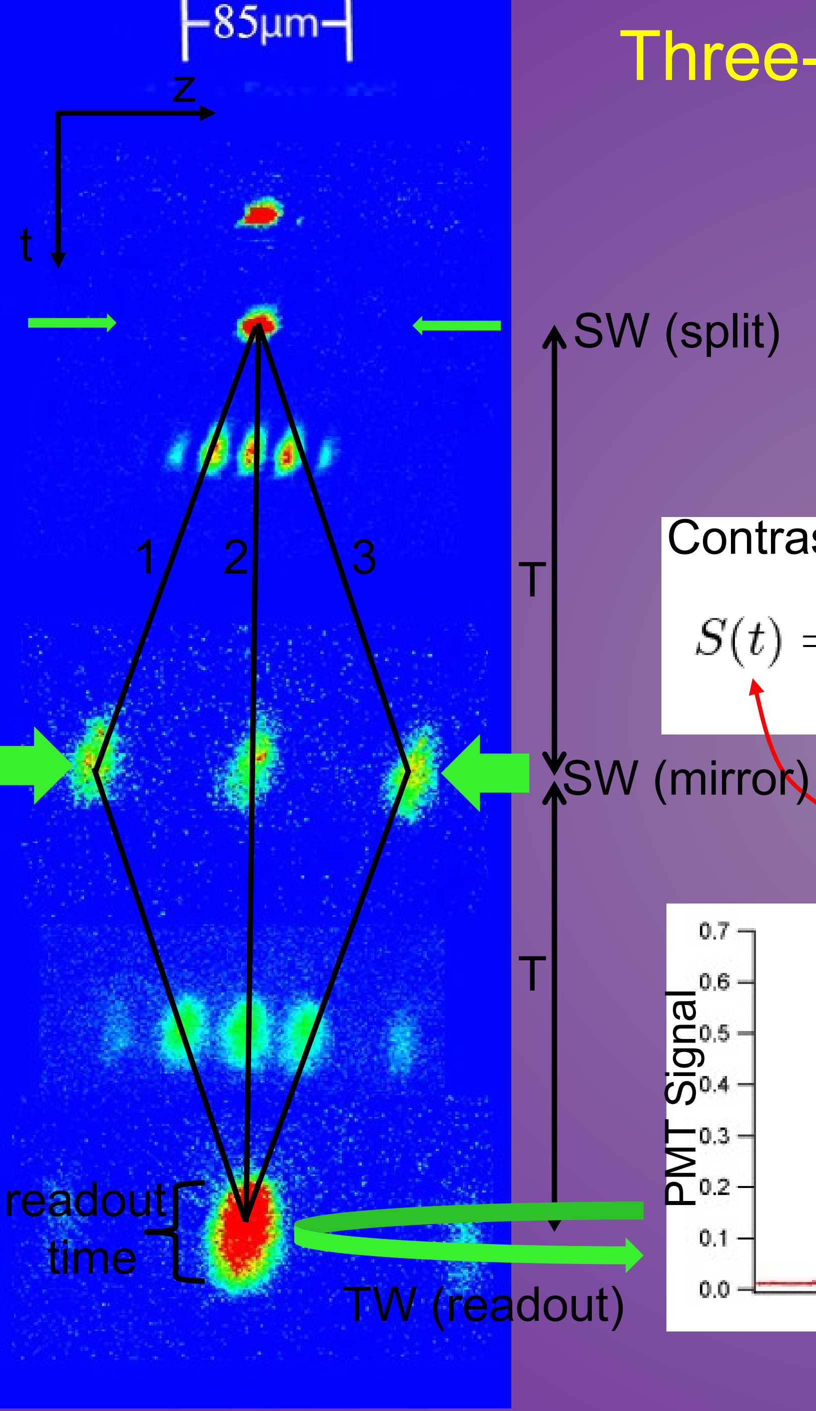
Our target with Yb BEC is < 0.1 ppb in α

Three-Path Atom Interferometry



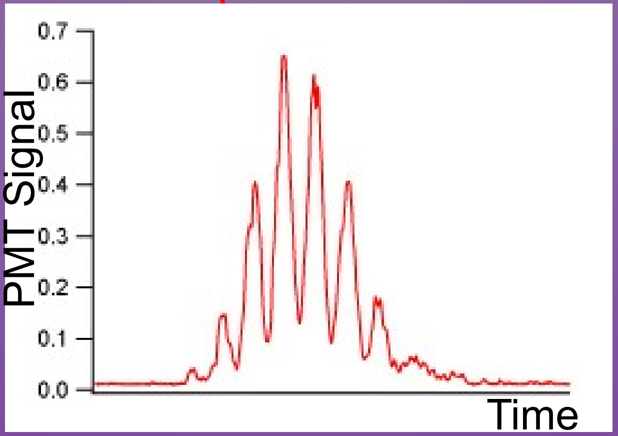
$$\sqrt{C(t)}\cos\left(\frac{\phi_1(t)+\phi_3(t)}{2}-\phi_2(t)\right)\cos\left(2kz+\frac{\phi_1(t)-\phi_3(t)}{2}\right)$$

Three-Path Contrast Atom Interferometry



Contrast Signal:

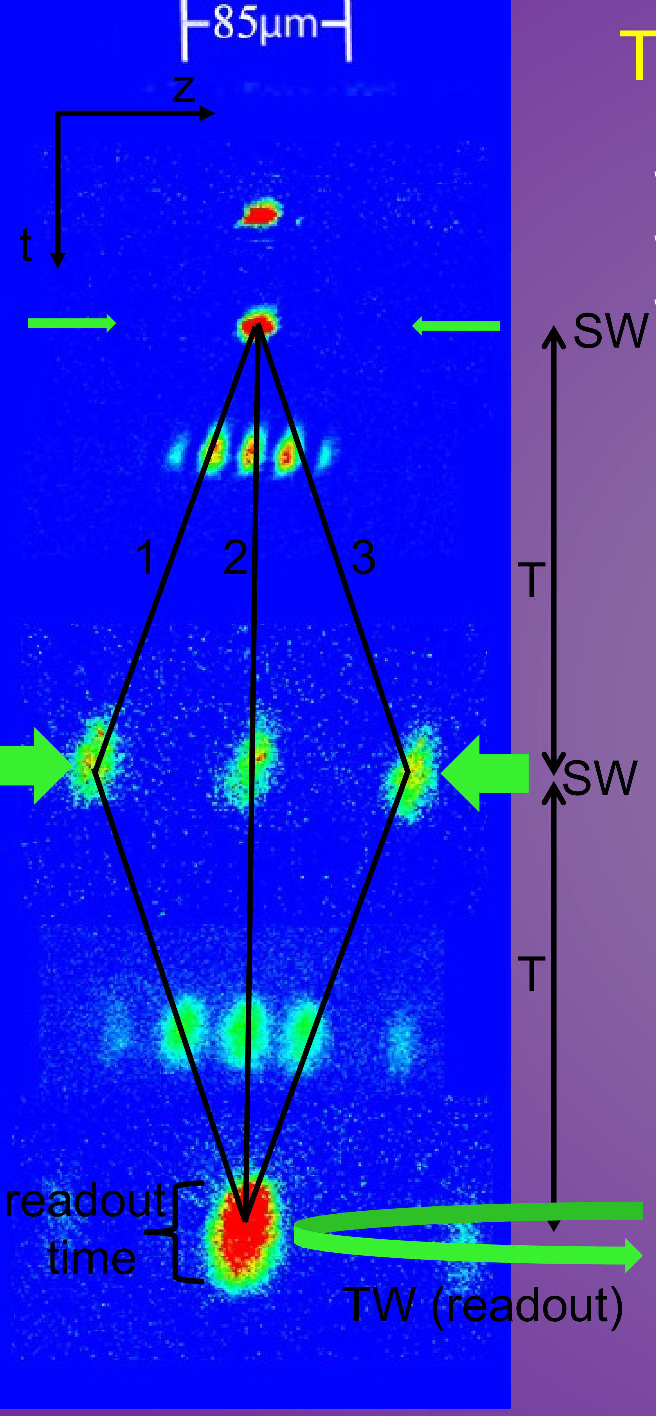
$$S(t) = C(t)\cos^2\left(\frac{\phi_1(t)+\phi_3(t)}{2} - \phi_2(t)\right)$$



S. Gupta et al. PRL **89**, 140401 (2002)

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

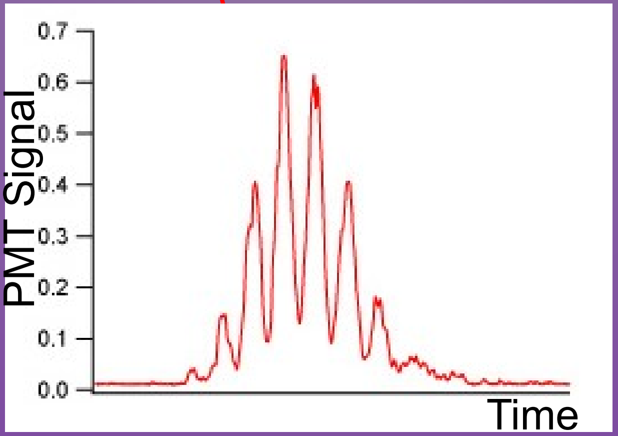
Three-Path Contrast Atom Interferometry



Sensitive to photon recoil, α
Symmetric geometry suppresses various systematics
Sensitive to gravity gradients

Contrast Signal:

$$S(t) = C(t)\cos^2\left(\frac{\phi_1(t)+\phi_3(t)}{2} - \phi_2(t)\right)$$



S. Gupta et al. PRL **89**, 140401 (2002)
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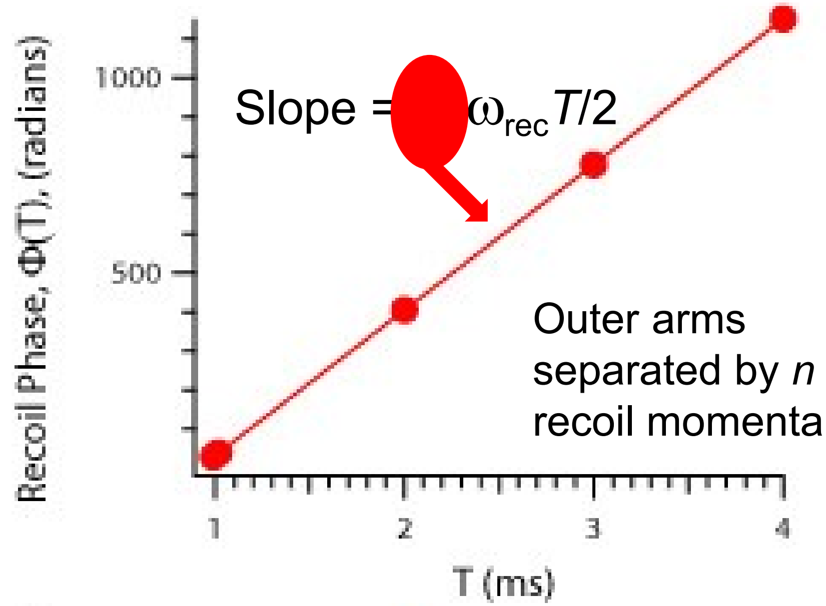
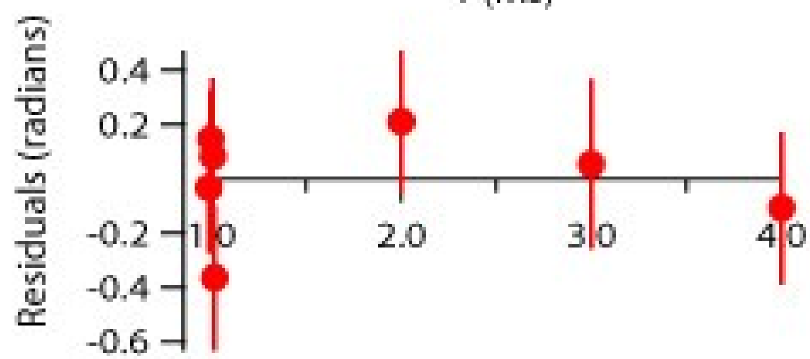
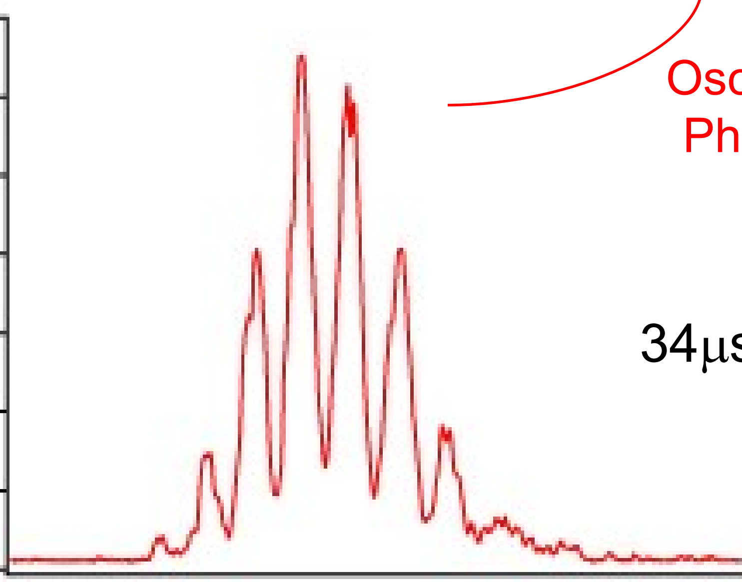
Contrast Interferometer with Yb BEC

$$\frac{\delta\omega_{rec}}{\omega_{rec}} = \frac{\delta\Phi}{\Phi} = \frac{\delta\Phi}{\frac{1}{2}\,\omega_{rec}\Delta T\sqrt{M}}$$





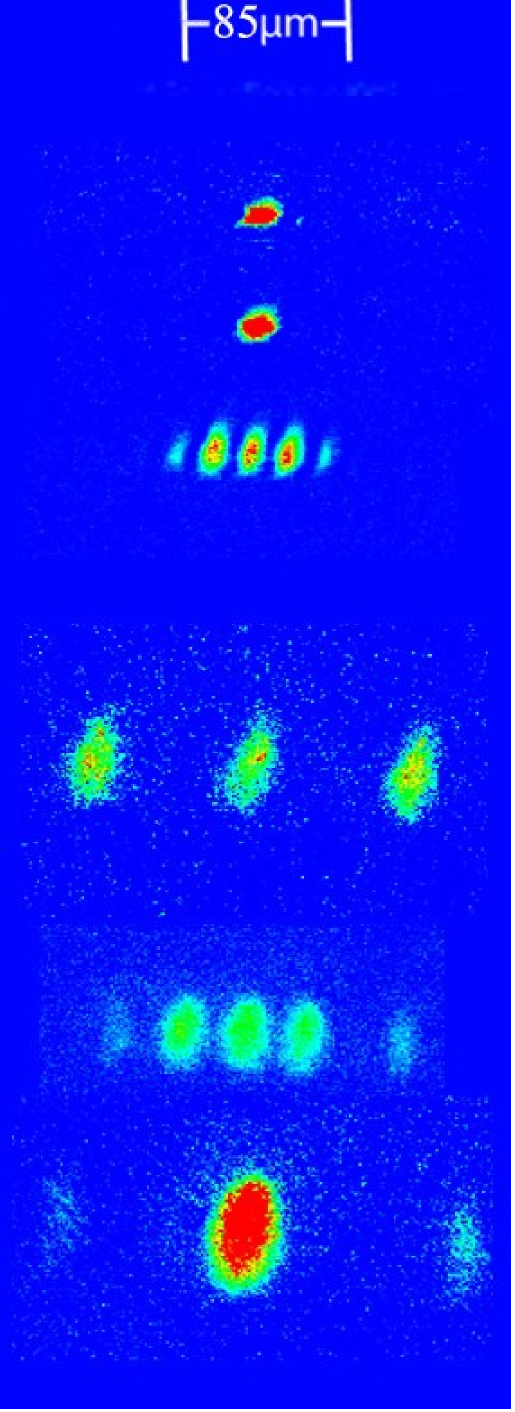


Oscillation Phase Φ

34µs period

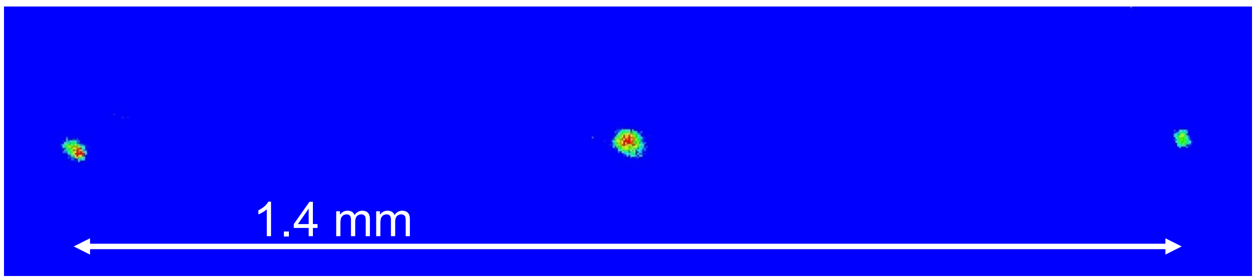
“Scaling-up” Contrast Interferometer

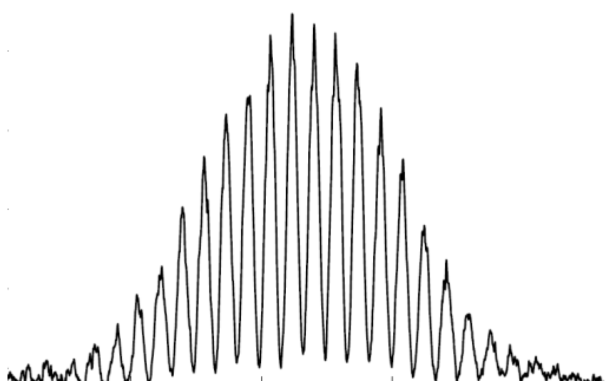
to large momentum separation



4 photons
(between outer paths)

76 photons
(between outer paths)



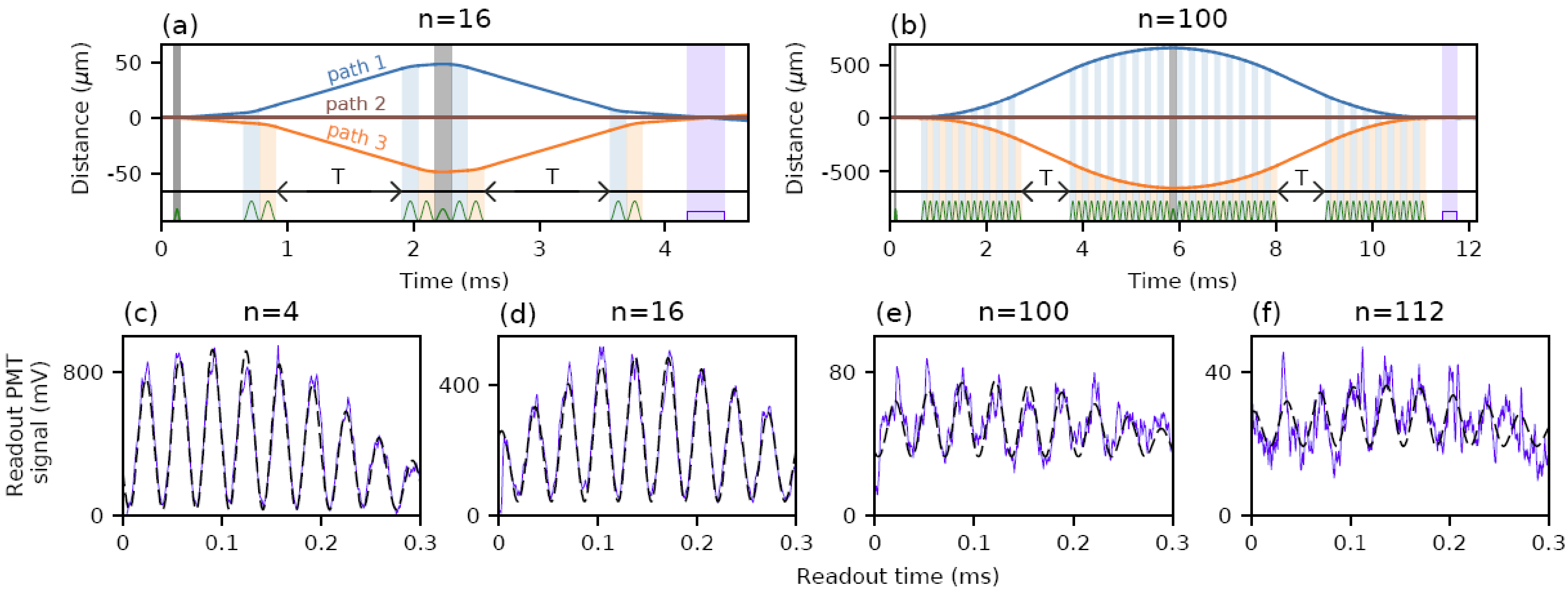


Improved readout

Use sequence of 3^{rd} order (6 recoil) Bragg pulses for acceleration

Three-Path contrast interferometer with large momentum separation

High Visibility for > 100 photon recoils



n = # photon recoils between path 1 and path 3

Signals are averages of between 20 and 100 shots

Stability acquired from:

- Interferometer symmetry
- Atom-optics pulse control

Largest momentum separation phase-stable interferometer

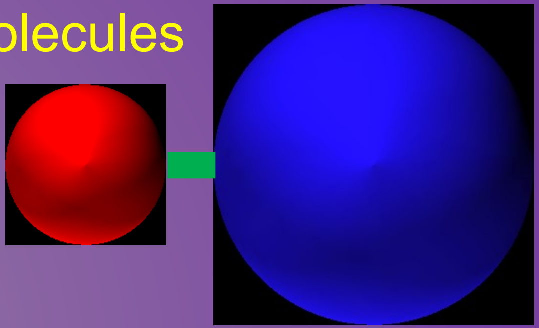
Scaling promising for competitive α measurement

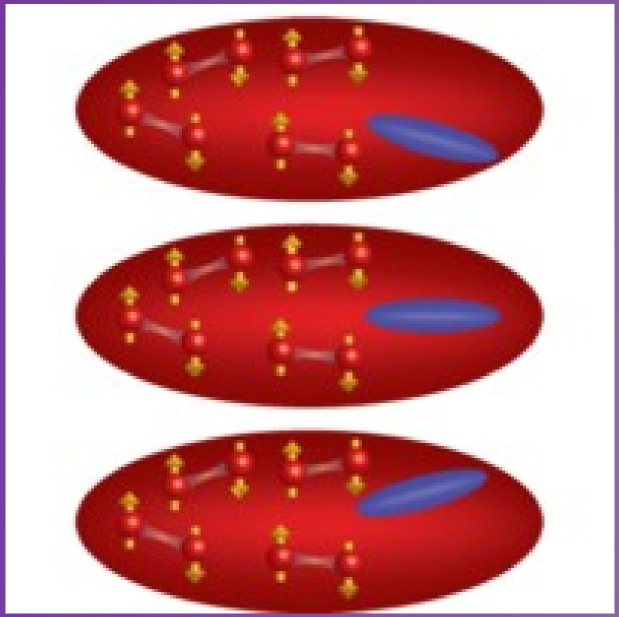
Related large LMT works:
Kasevich, Rasel, Muller groups

Ben Plotkin-Swing et al.
Phys. Rev. Lett. **121**, 133201 (2018)

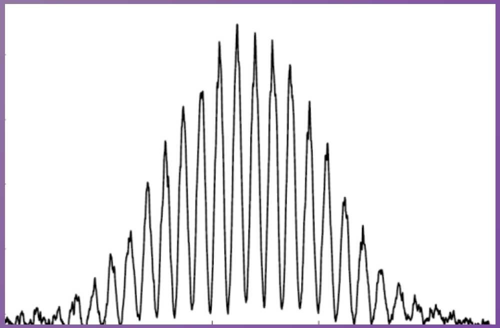
NanoKelvin Quantum Engineering

Ultracold
Molecules



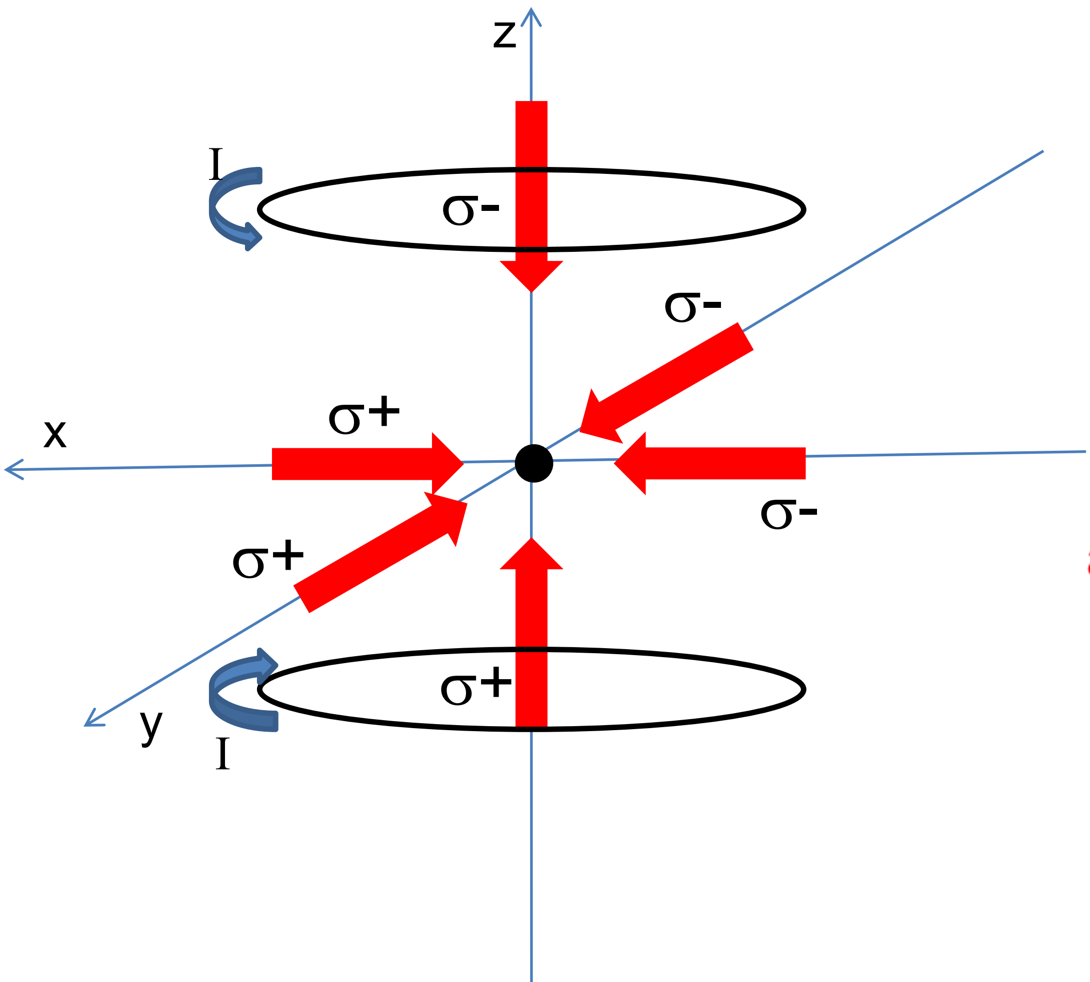


Two-Element
Bose-Fermi double superfluid

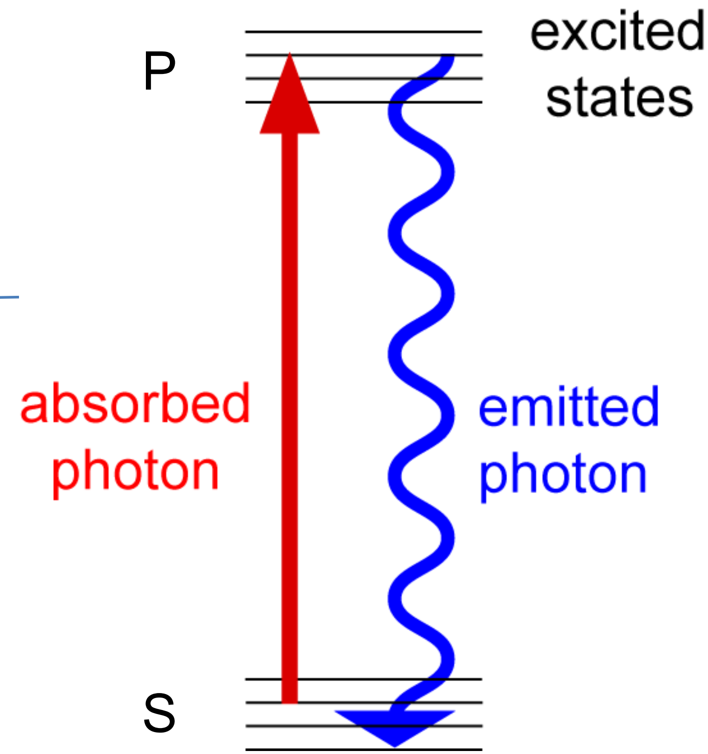


Precision BEC
interferometry

Laser Cooling



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



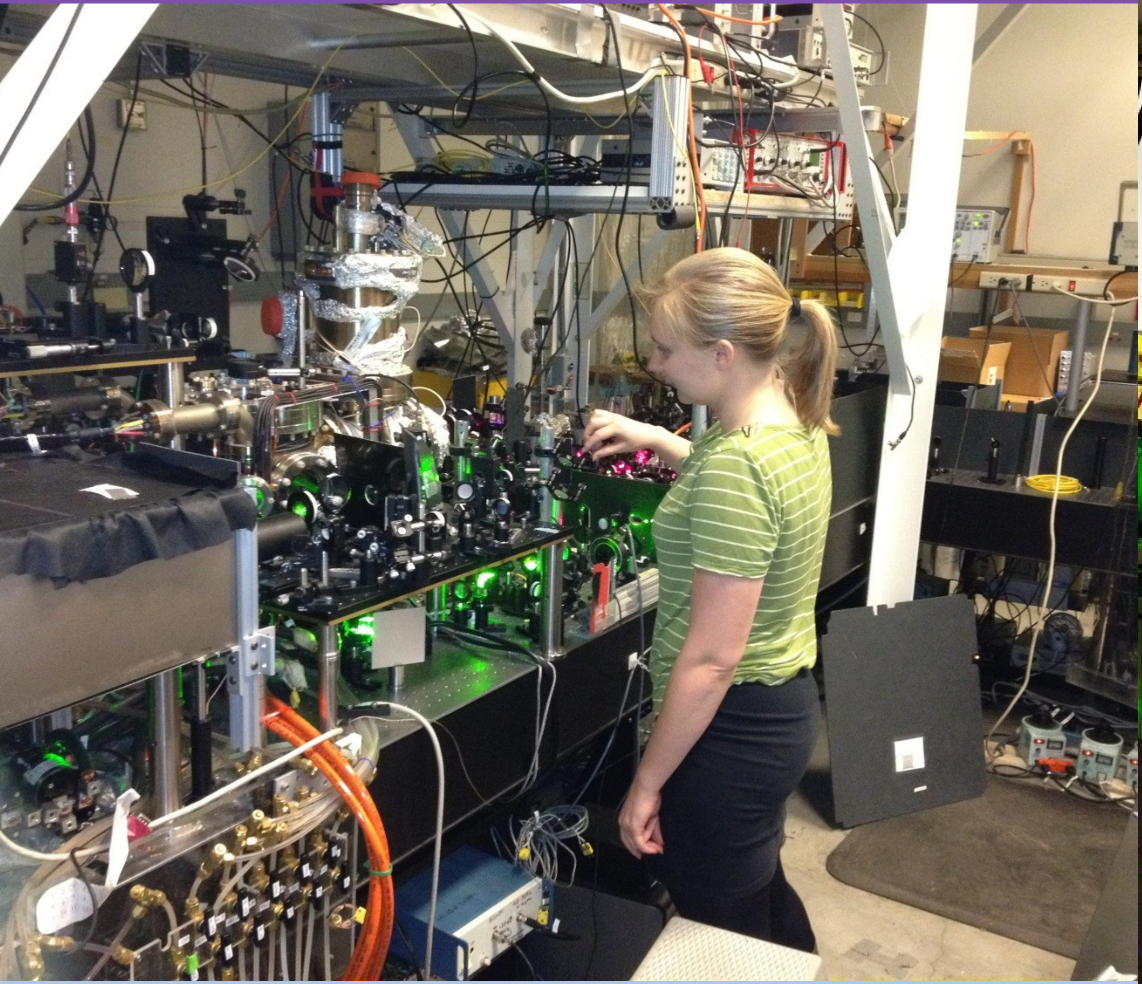
$\hbar$ $\hbar$

Atom Source ~ 600 K; UHV environment

=> COOLING !

(Need a 2 level system)

UW Ultracold Atoms Labs



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