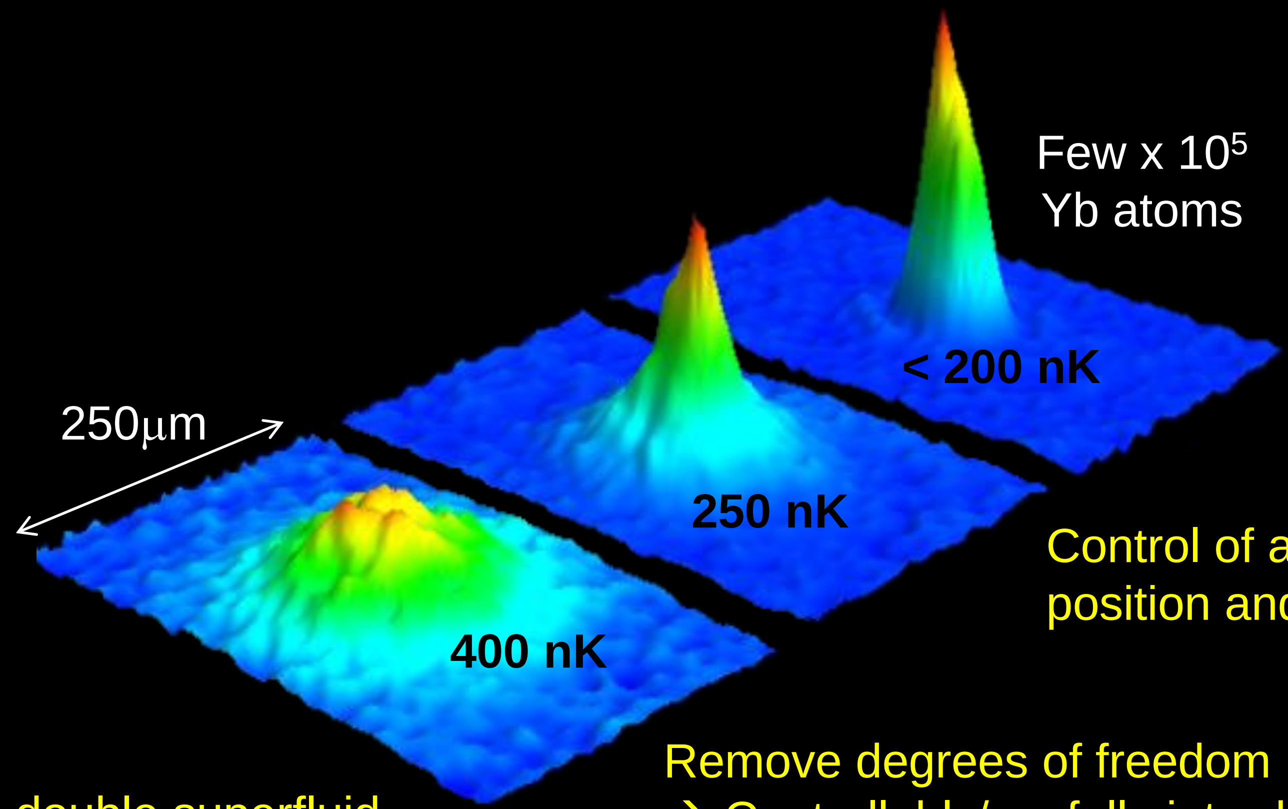
NanoKelvin Quantum Engineering



Control of atomic c.m.
position and momentum.

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

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

Subhadeep Gupta

UW NSF-INT Phys REU, 2nd July 2018

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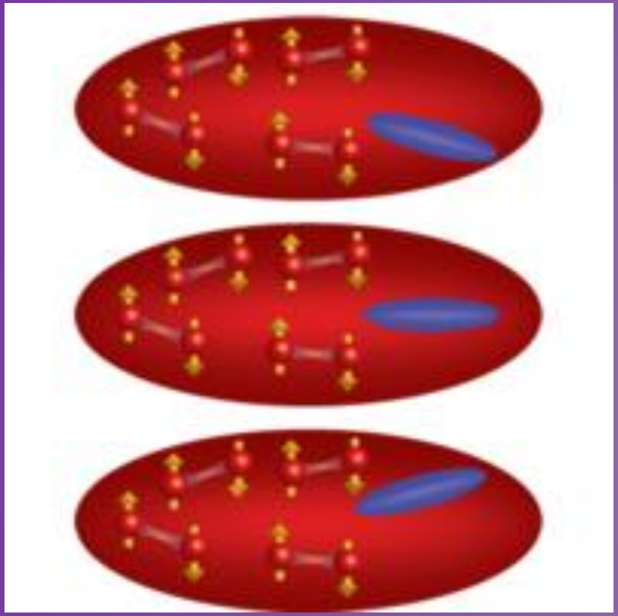
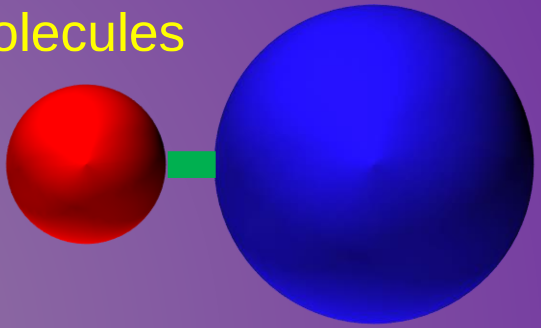
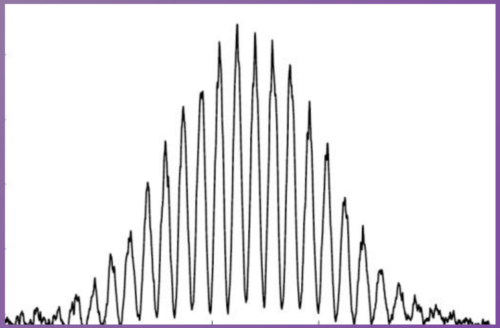


Two-Element
Bose-Fermi double superfluid

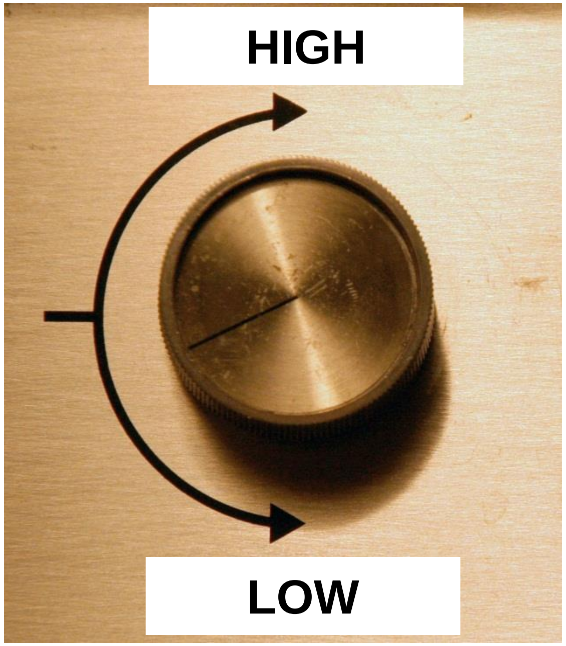
Ultracold
Molecules





Precision BEC
interferometry

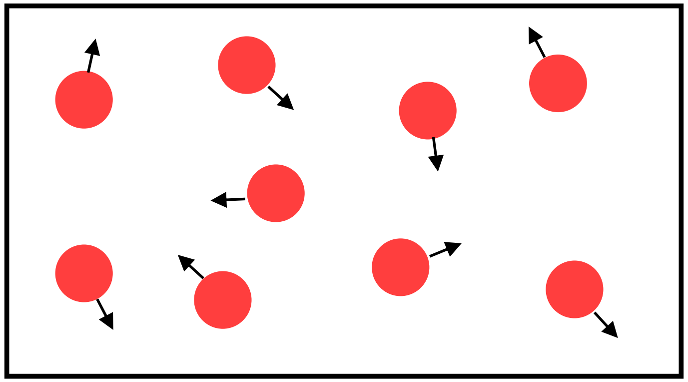
“Knobs” for Quantum Engineering



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

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

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

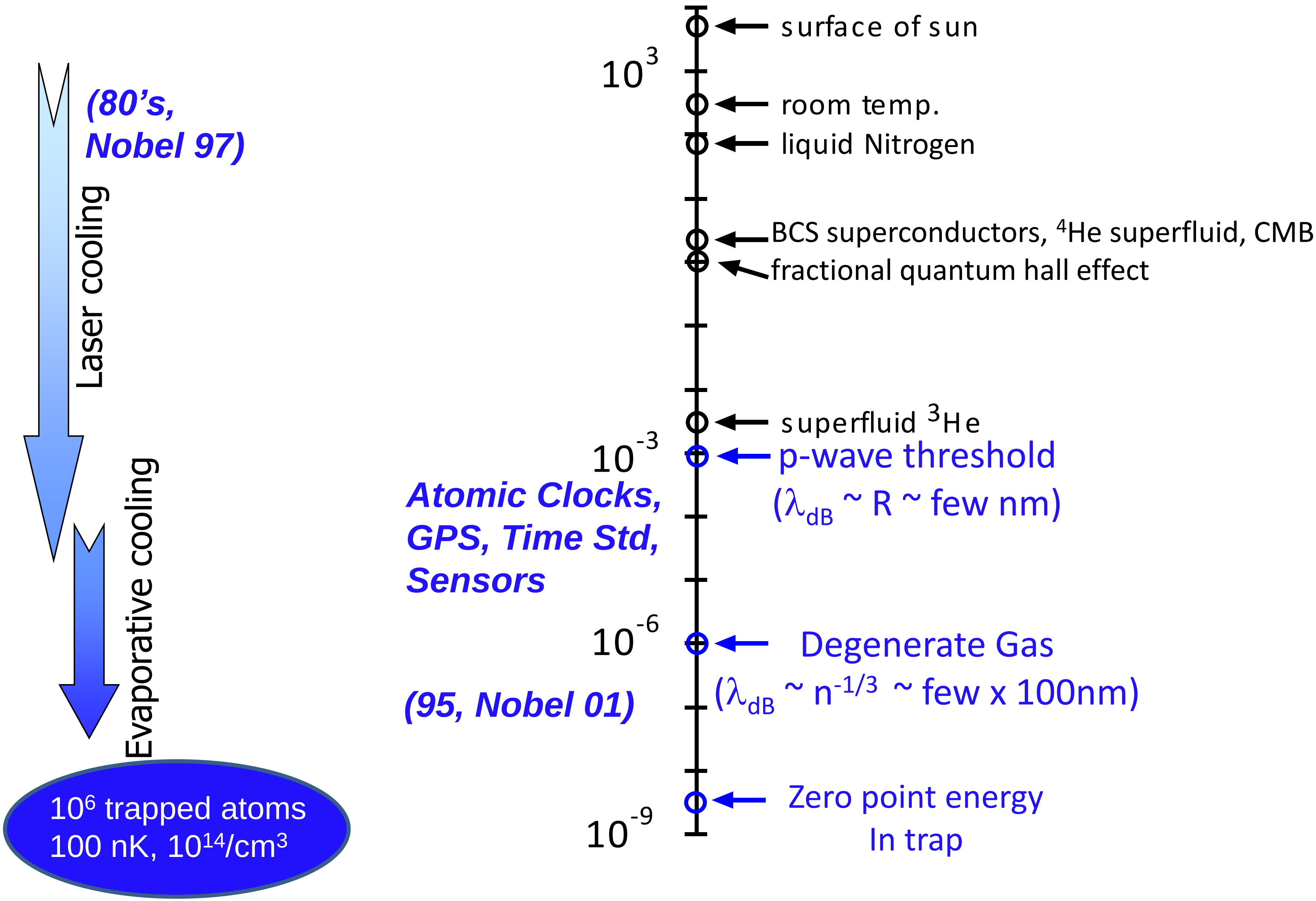
Air $n \sim 10^{19}/\text{cm}^3$, $T_c \sim 1\text{mK}$
Stuff $n \sim 10^{22}/\text{cm}^3$, $T_c \sim 0.1\text{K}$
Everything (except He) is solid

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

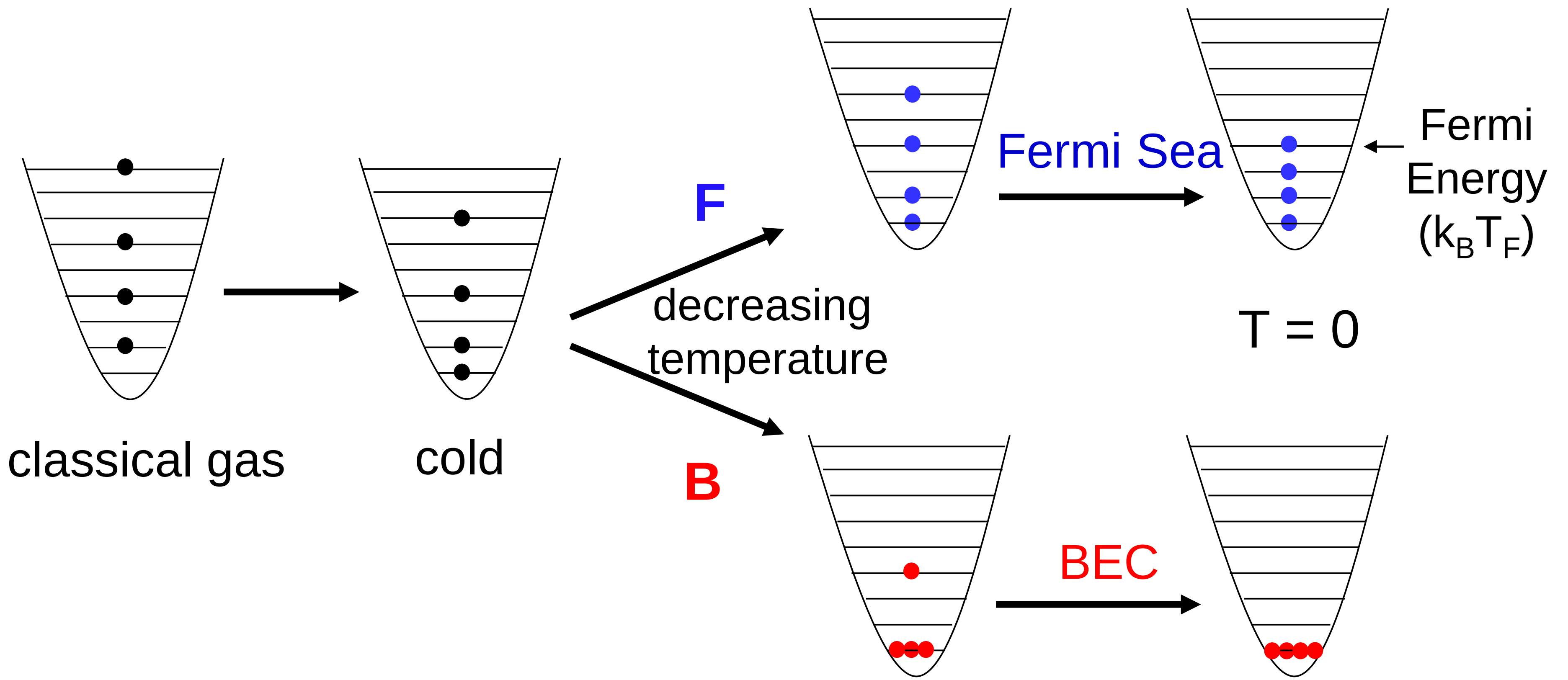
$T_c \sim 1\mu\text{K}$!! Ultracold !!

and ~ non-interacting

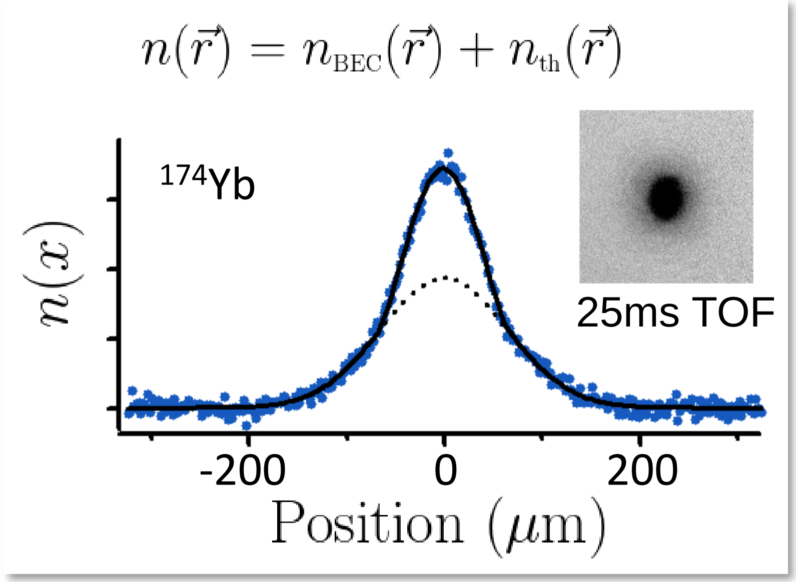
Relevant Ultracold Temperatures on the Log Kelvin Scale

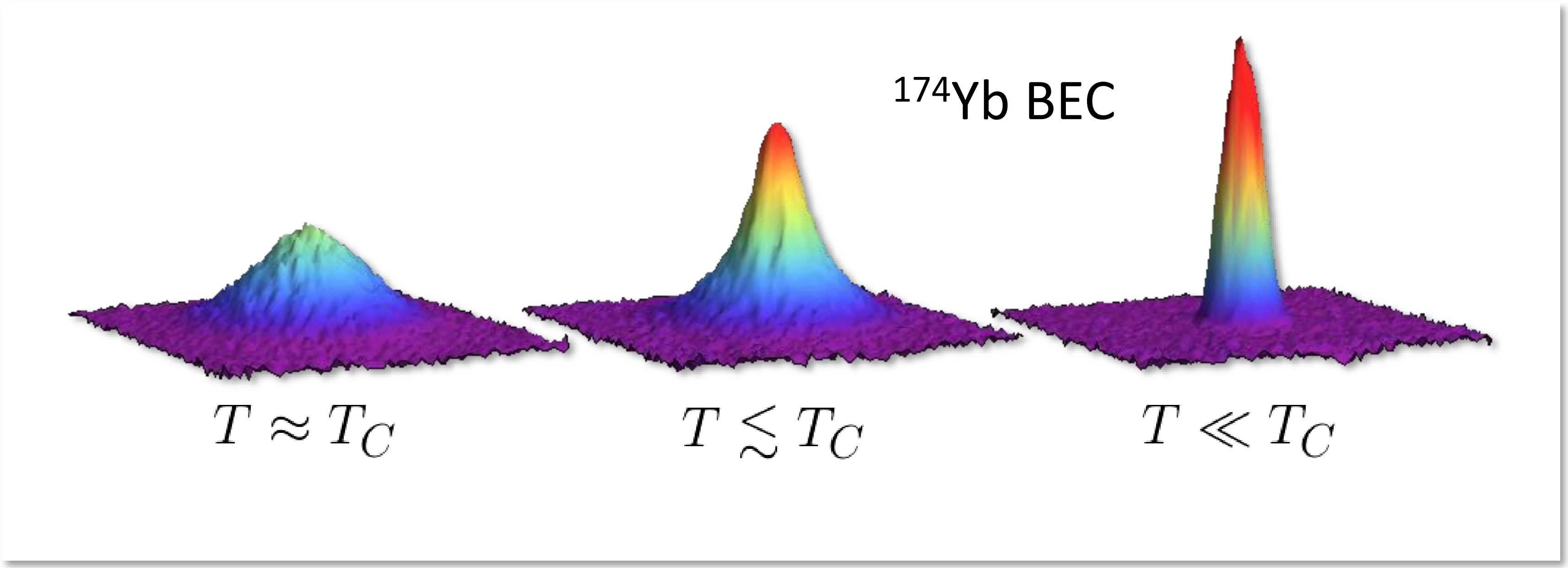


Different Quantum Matters

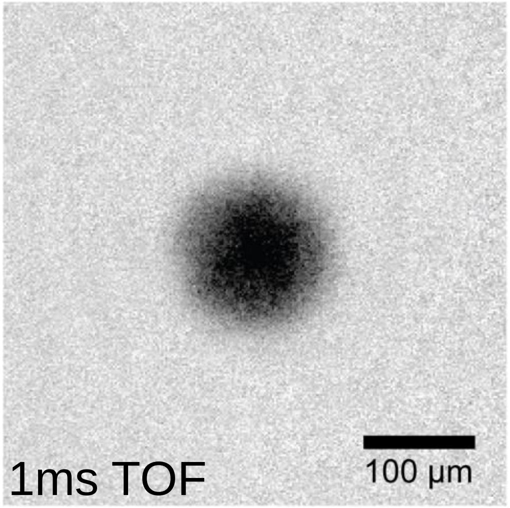


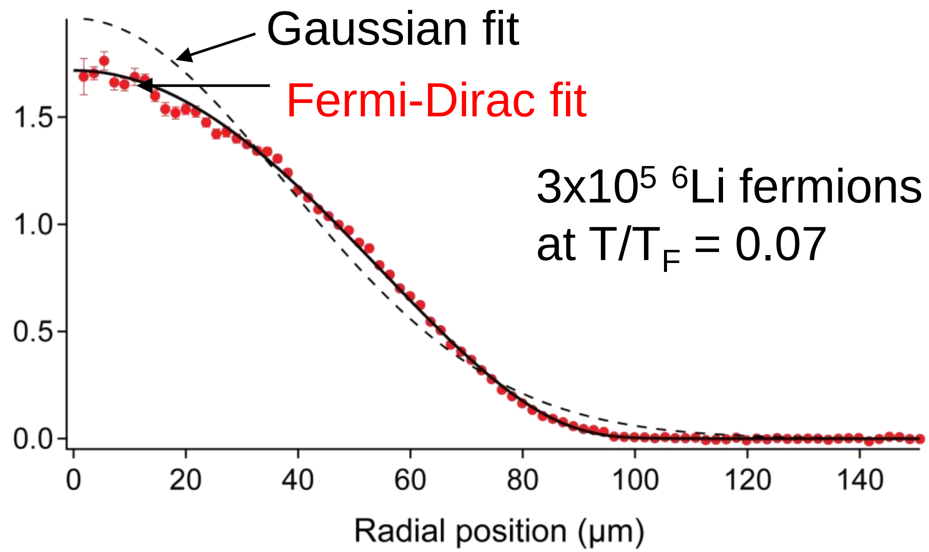
Boson degeneracy: Bose-Einstein condensate





Fermion Degeneracy

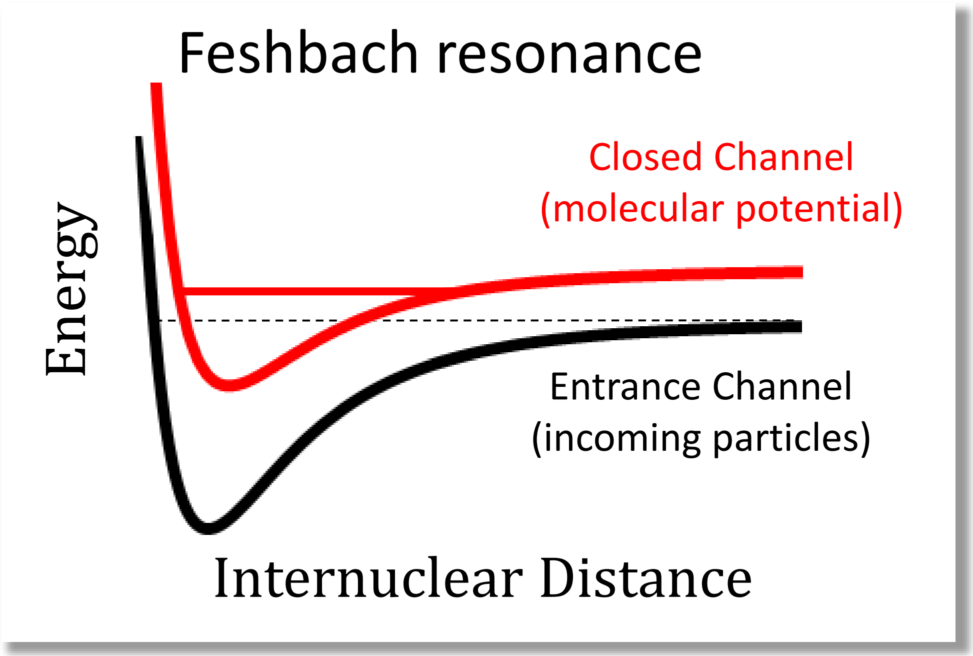




Fermi pressure due to Pauli Exclusion principle

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

Controlling two-body interactions



Resonance between two free atoms and a molecule

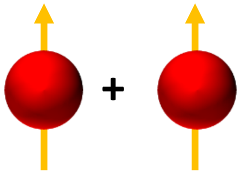
Control with external magnetic field

- Example

$^6\mathrm{Li} + {}^6\mathrm{Li}$

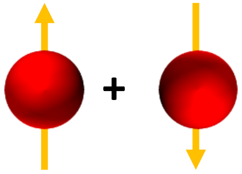
<u>Entrance channel</u>

Triplet:

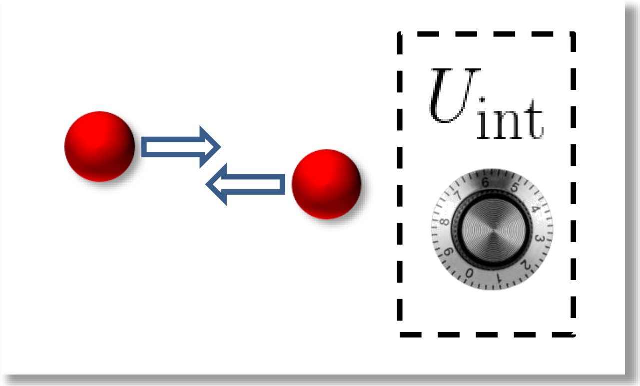


<u>Closed channel</u>

Singlet:

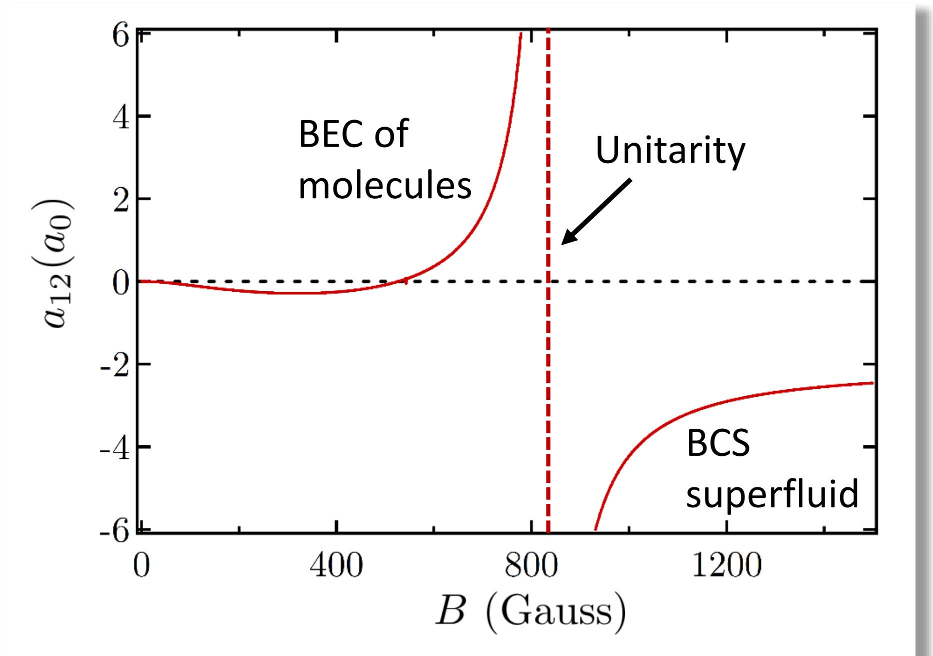


Strongly interacting Fermi gases



$$U_{\text{int}} \propto a$$

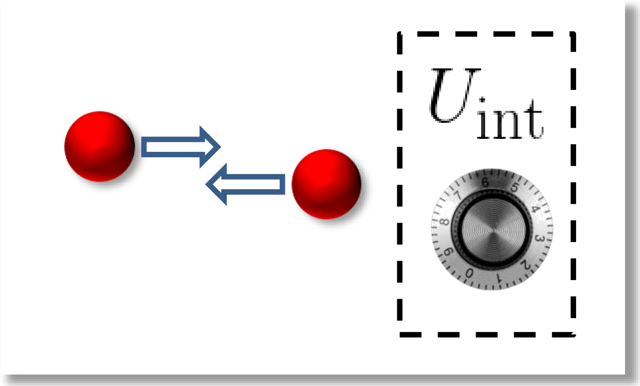
$$a(B) = a_{\text{bg}}\left(1 + \frac{\Delta}{B - B_0}\right)$$

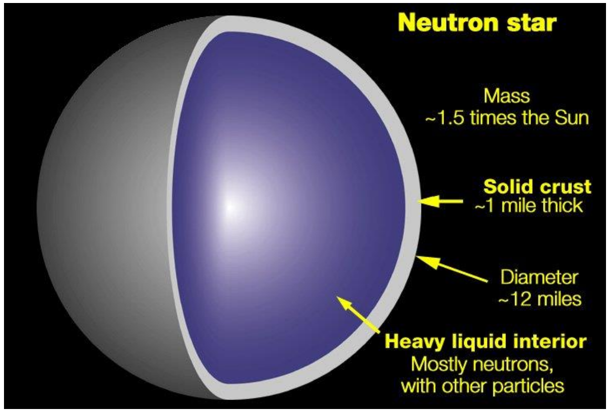


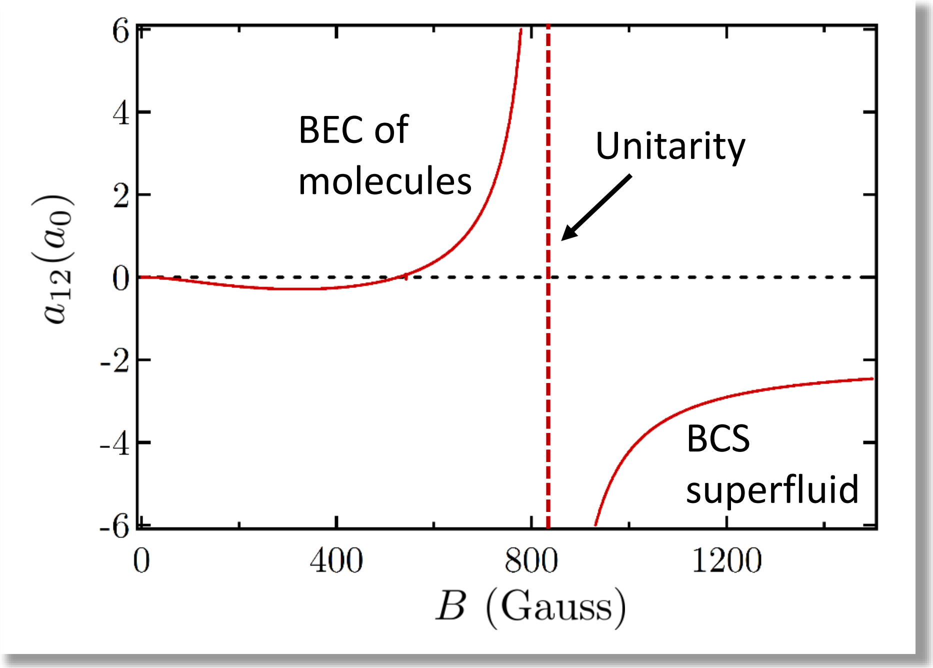
Strong interactions
$|k_F\, a| > 1$
betw. 2 spin states

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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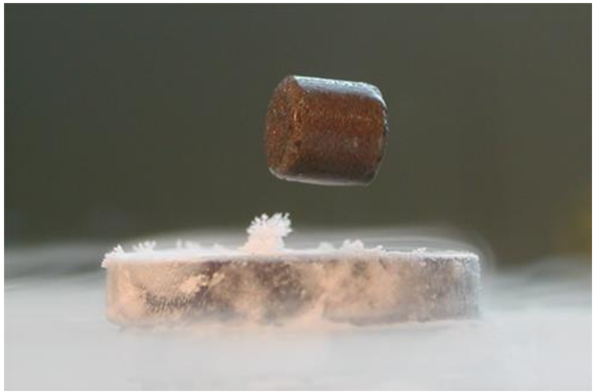
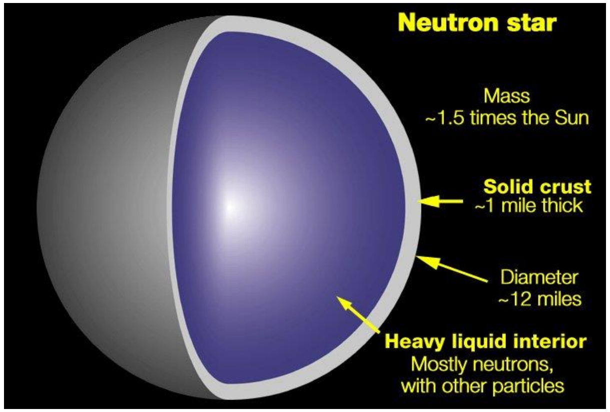
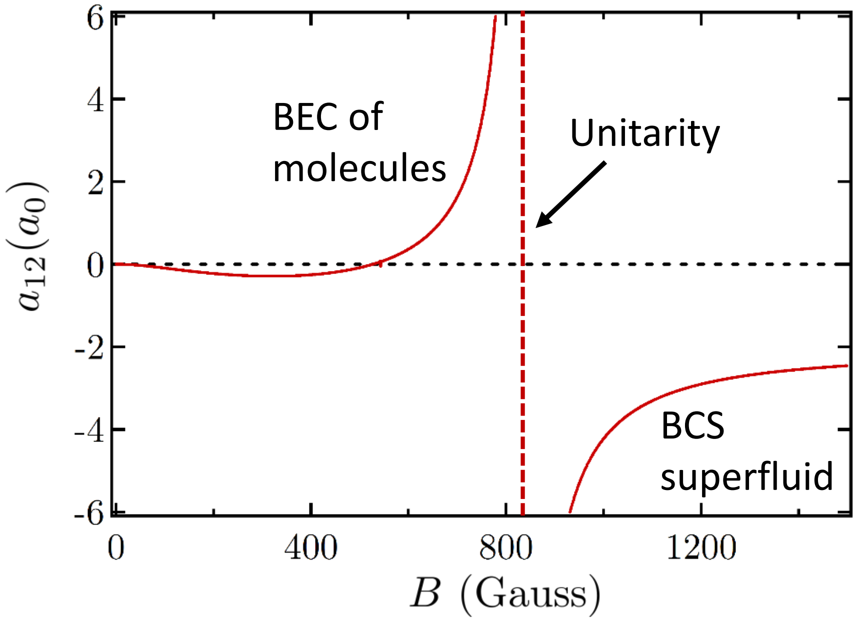


Source: http://www.wou.edu/~rmiller09/superconductivity/





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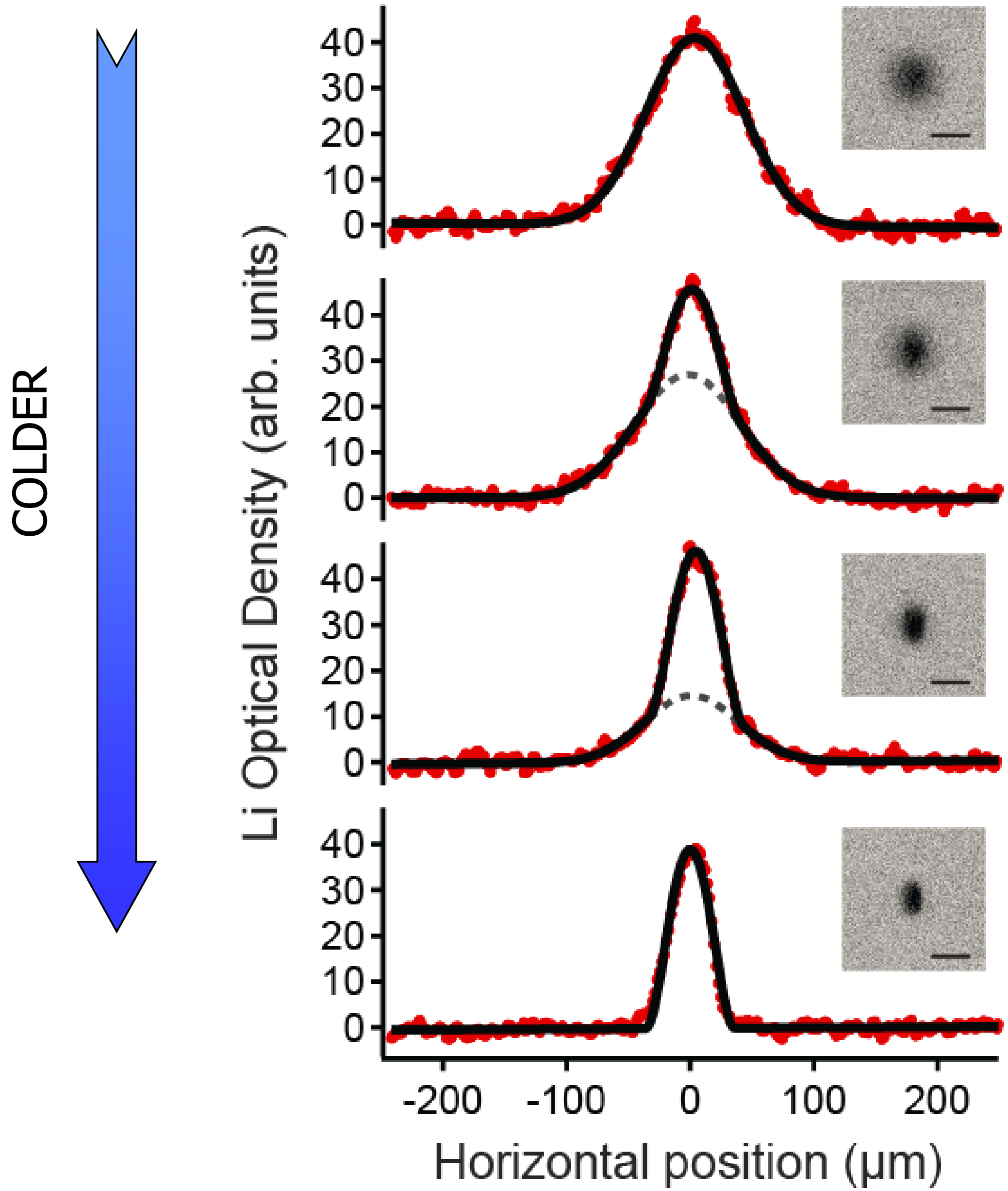
Fermionic Superfluidity



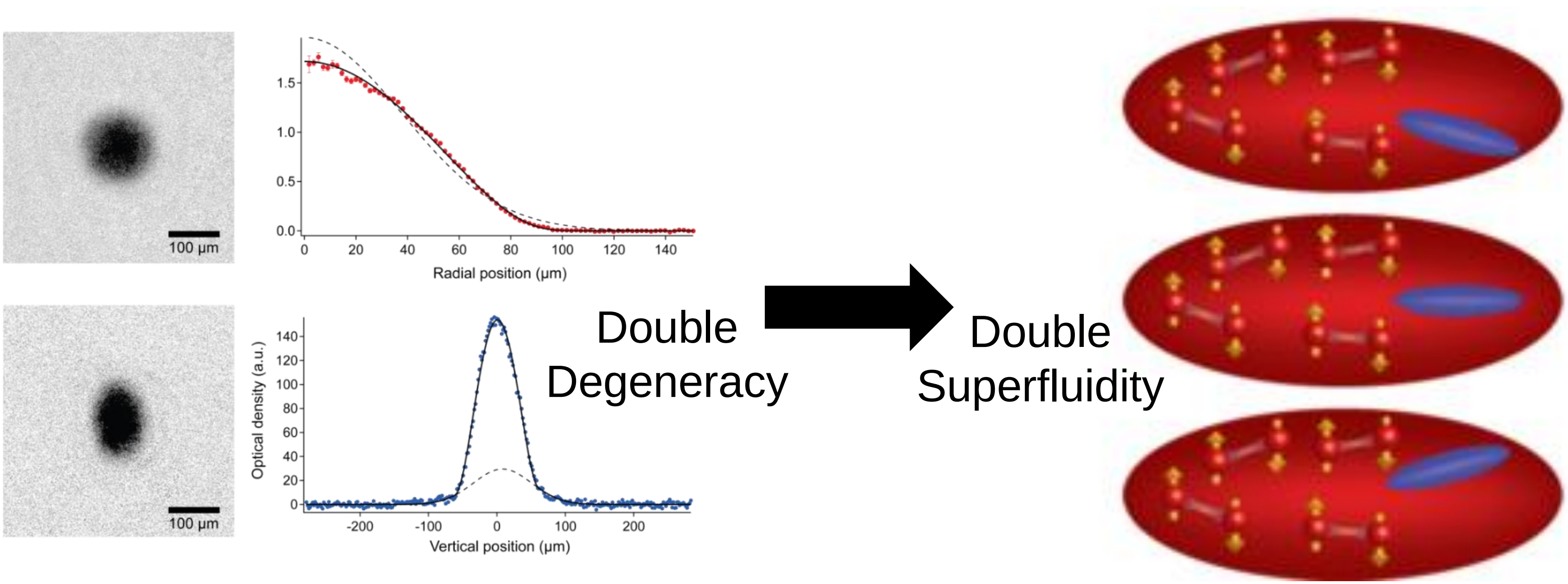
Final Cooling at unitarity

Observe condensation in TOF on the molecular side
(adiabatic transfer from unitarity to BEC side 832G → 690G)

Condensation of paired fermions
(T_c ~ 0.17 T_F)

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

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



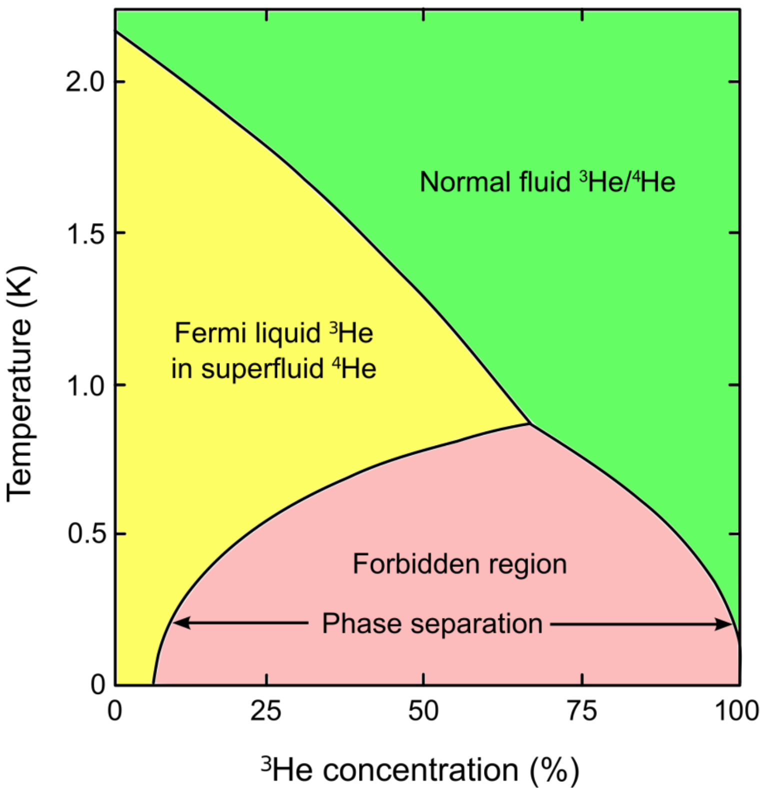
Preparing and observing the double superfluid

Demonstration of Elastic Coupling between superfluids

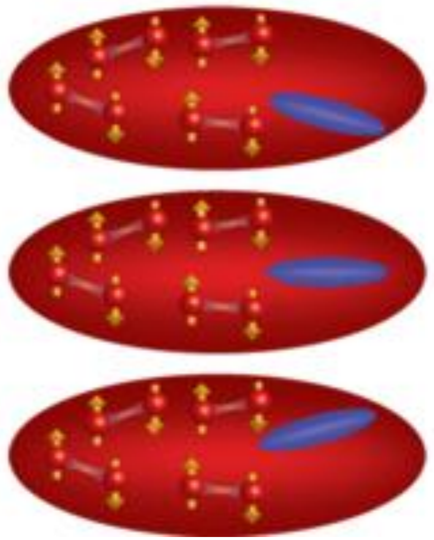
Angular Momentum Exchange between superfluids

Bose-Fermi Double Superfluid

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

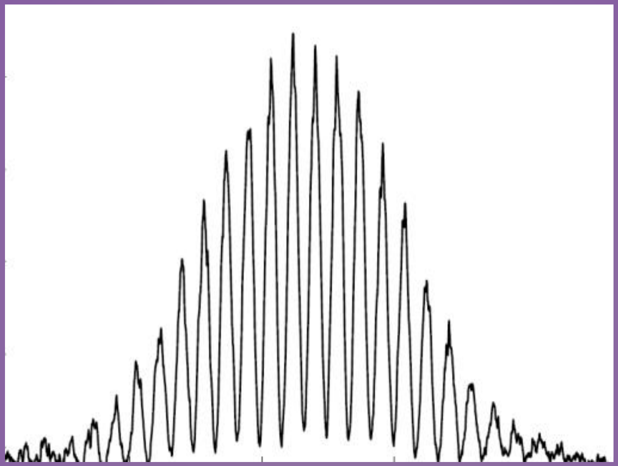


Recently B-F superfluids in atomic systems in ^7Li-^6Li, ^{174}Yb-^6Li, ^{41}K-^6Li
NEW QUANTUM SYSTEM!



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

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)

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

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

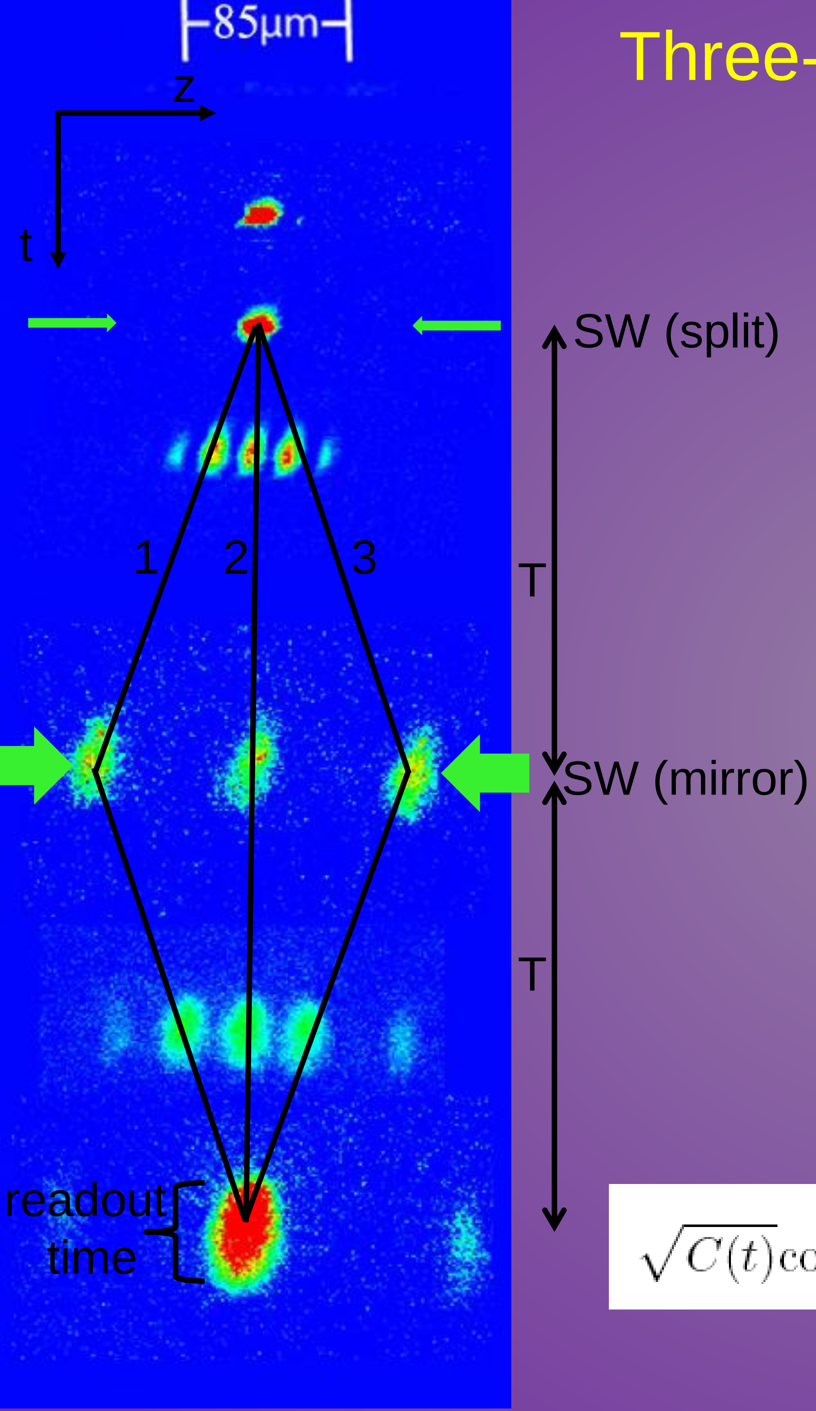
$$\omega_{\text{rec}} = \frac{1}{2}\frac{\hbar}{m}k^2$$

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) < 0.5 ppb

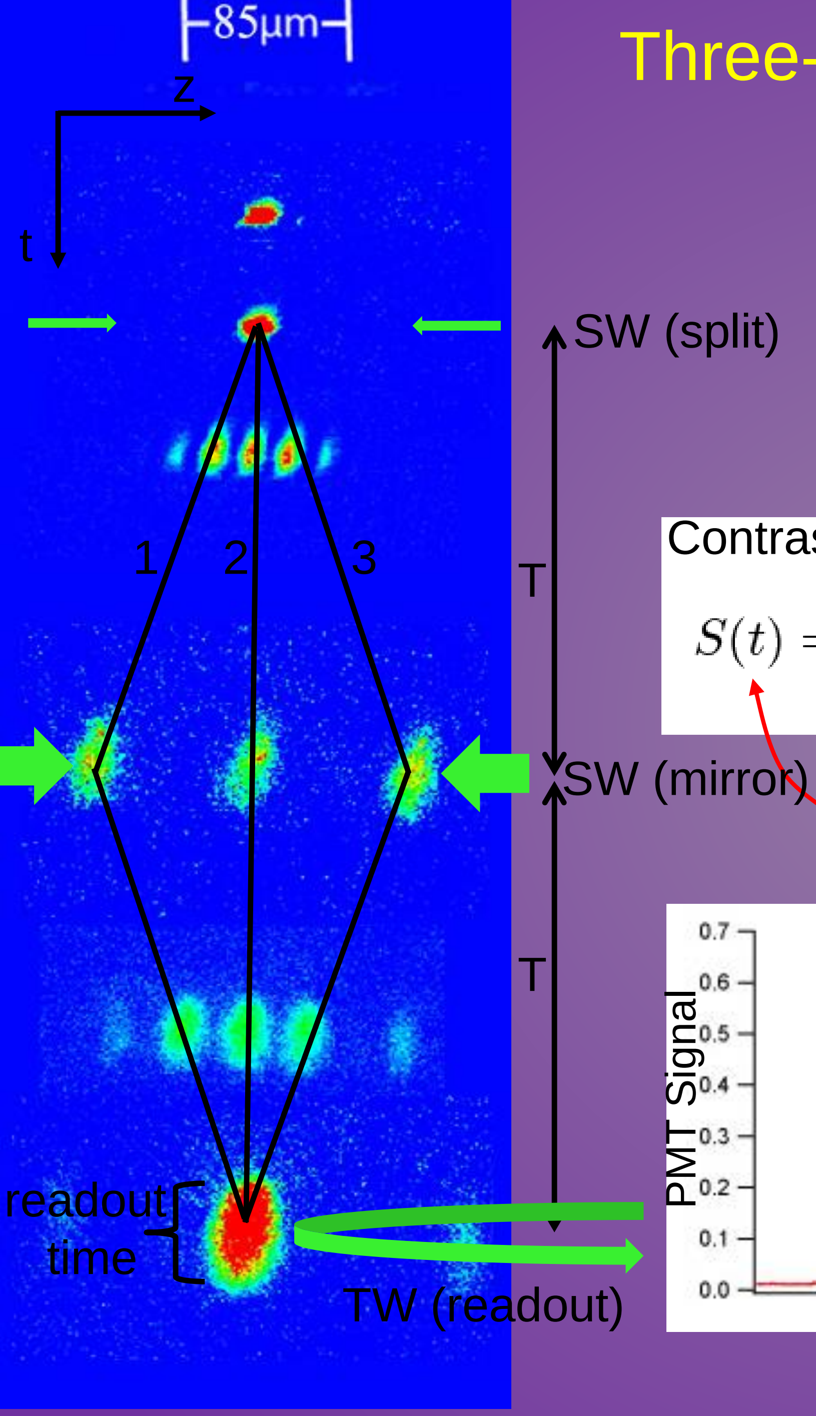
Our target with Yb BEC is < 0.1 ppb in α

Three-Path Atom Interferometry



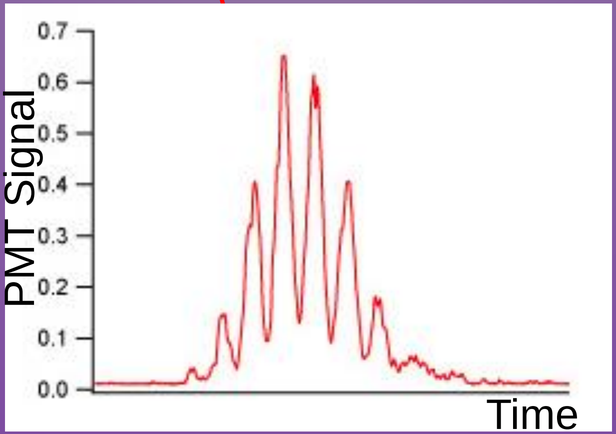
$$\sqrt{C(t)}\cos\left(\frac{\phi_1(t)+\phi_3(t)}{2}-\phi_2(t)\right)\cos\left(2kz+\frac{\phi_1(t)-\phi_3(t)}{2}\right)$$

Three-Path Contrast Atom Interferometry



Contrast Signal:

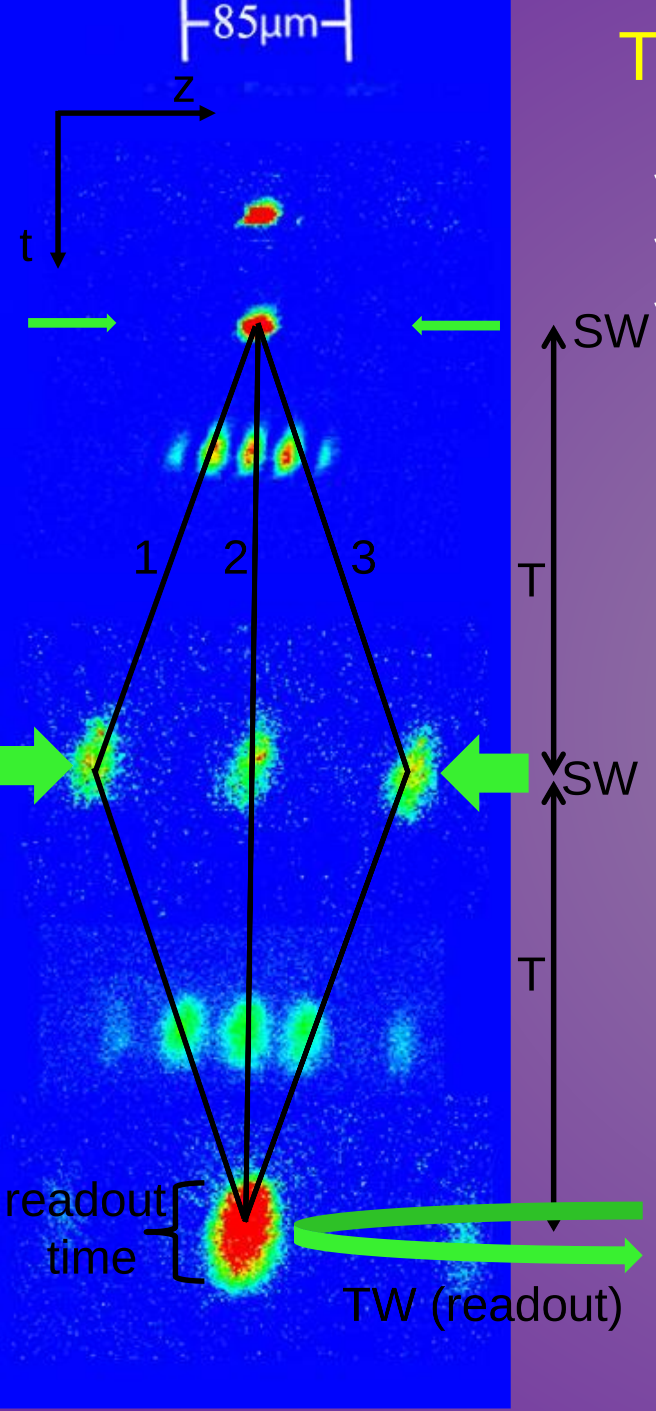
$$S(t) = C(t)\cos^2\left(\frac{\phi_1(t) + \phi_3(t)}{2} - \phi_2(t)\right)$$



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



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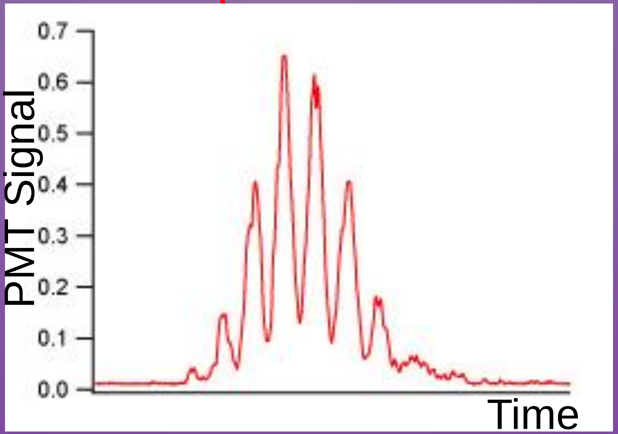

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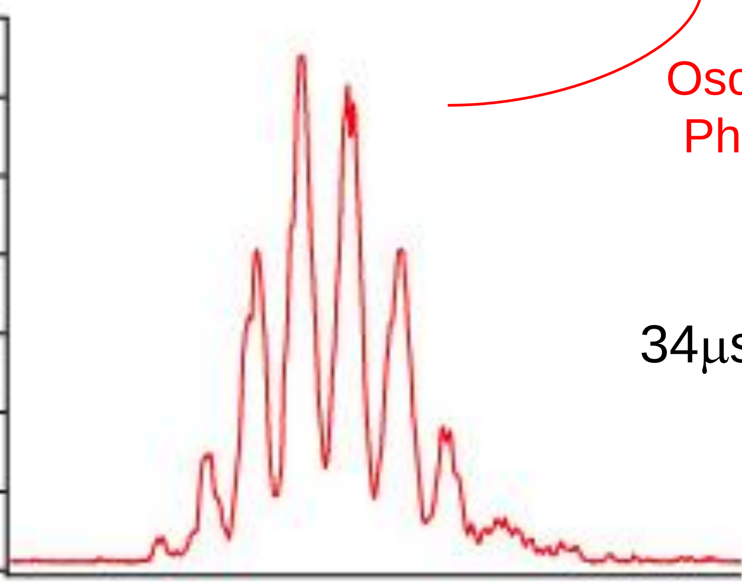
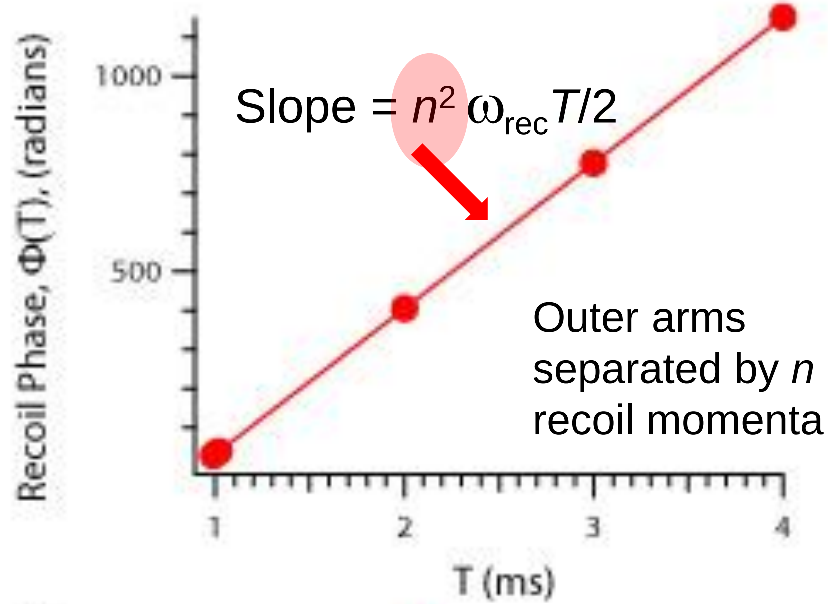
Contrast Interferometer with Yb BEC

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



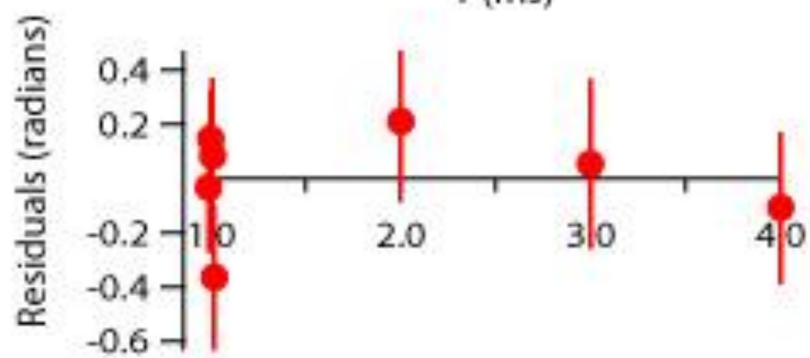
Oscillation Phase Φ

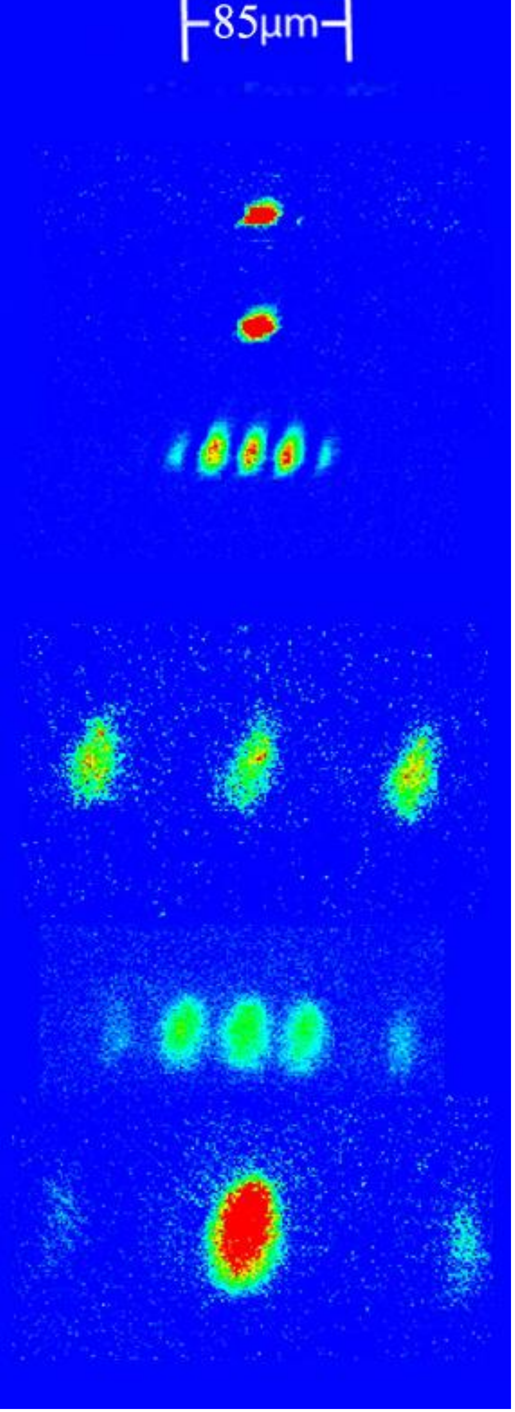
34μs period



Slope = $n^2\,\omega_{\mathrm{rec}}T/2$

Outer arms separated by n recoil momenta



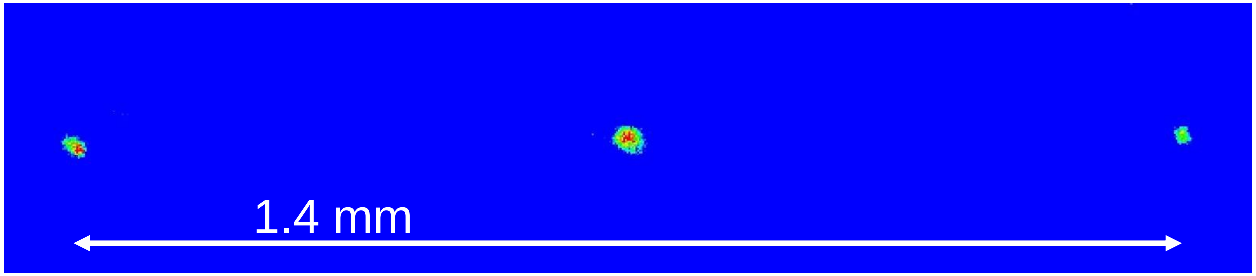


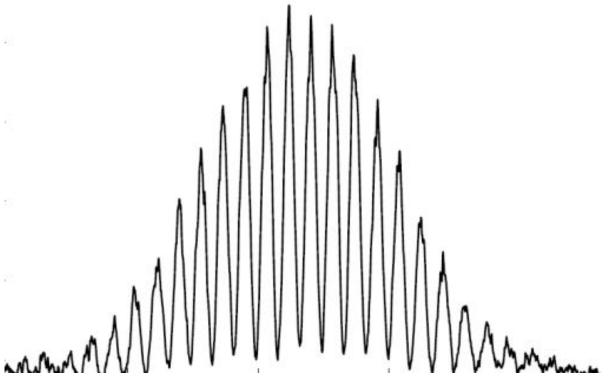
"Scaling-up" Contrast Interferometer

to large momentum separation

4 photons
(between outer paths)

76 photons
(between outer paths)



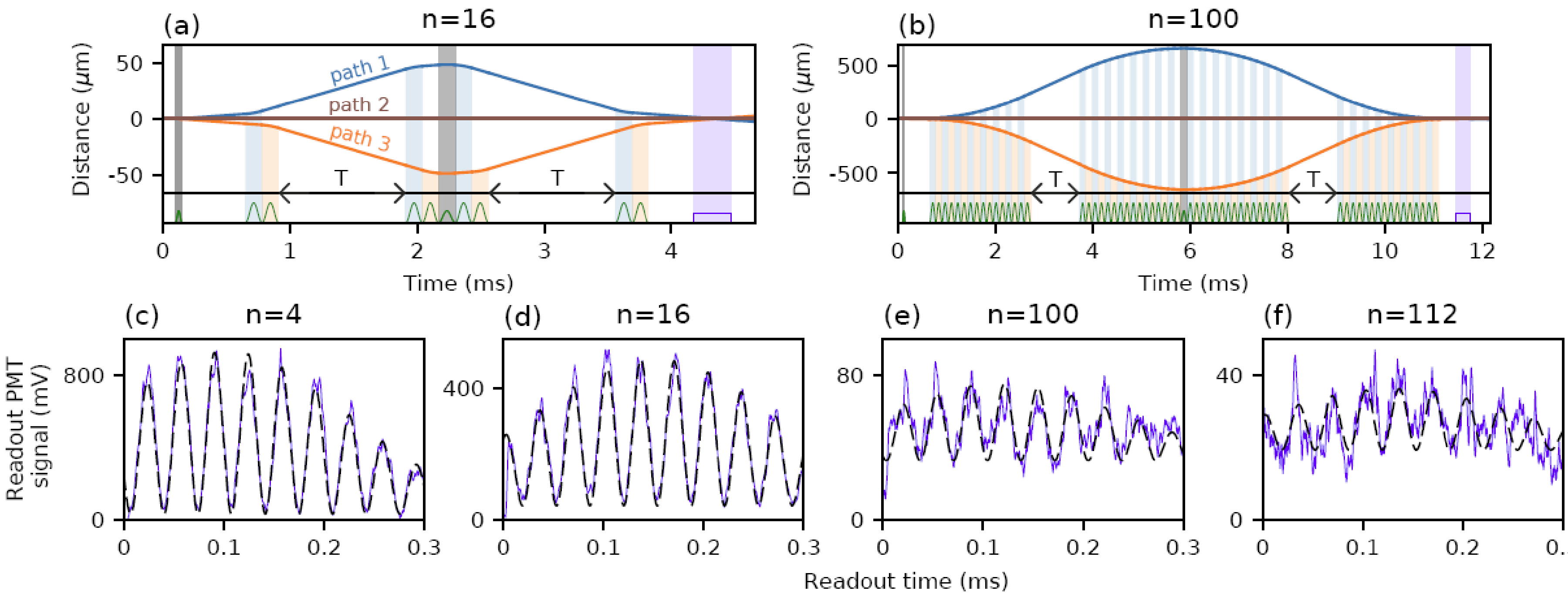


Improved readout

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

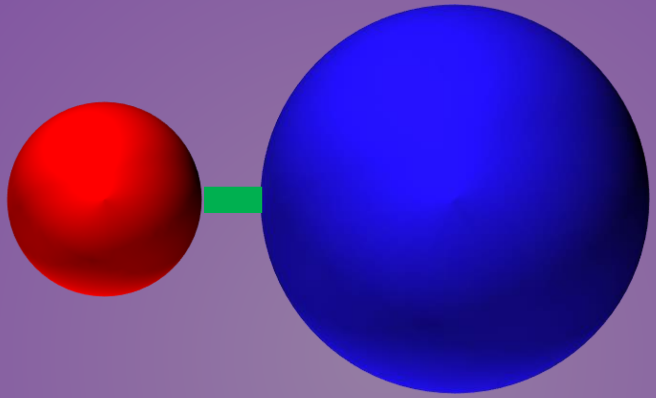
Largest momentum separation phase-stable interferometer
Scaling promising for competitive α measurement

Related large LMT works:
Kasevich, Rasel, Muller groups

Ben Plotkin-Swing et al. (arXiv:1712.06738)

Diatomic Molecules

(One atom too many?)



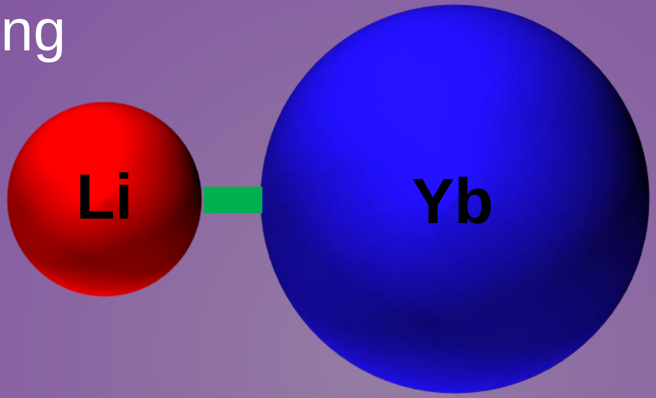
New degrees of freedom:

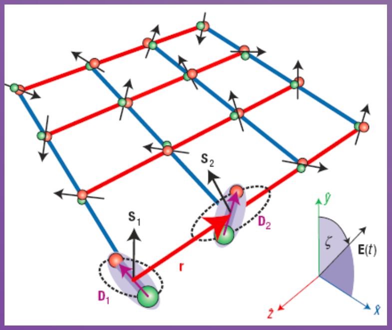
Scientific Advantages & Technical Challenges

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





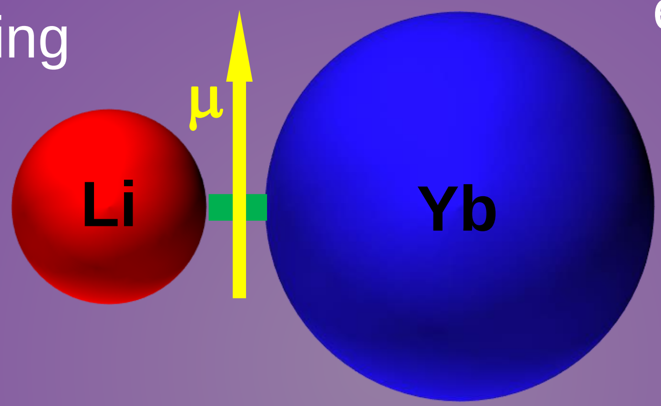
1 Debye dipoles, 0.5μm lattice interact ~ d^2/r^3 ~ hx1kHz, k_Bx50nK.

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

Ultracold Polar Molecules

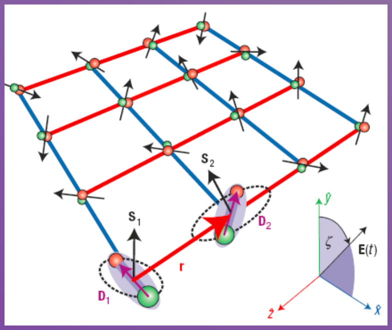
Long range (d^2/r^3) interaction for quantum Information processing

Precision Spectroscopies eg. m_p/m_e time variation



Dipolar superfluids

Quantum controlled chemical reactions



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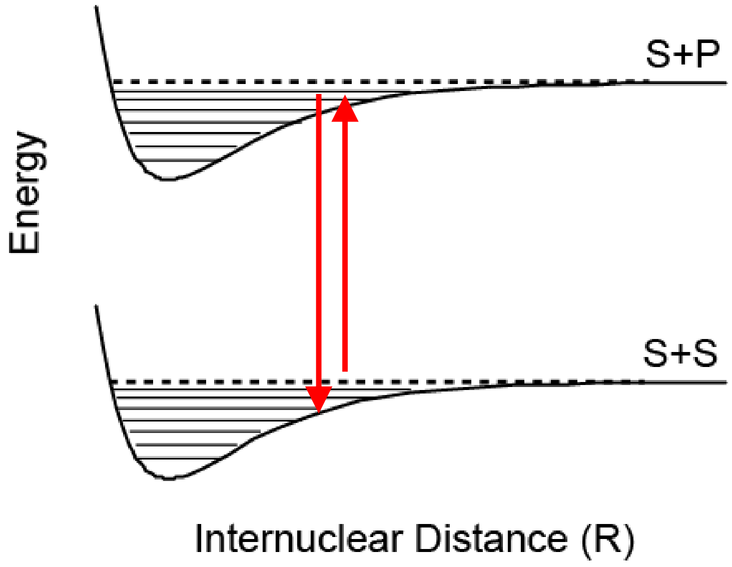
Micheli et al. Nat. Phys. **2**, 341
Rev: Carr et al. New Jrnl Phys. **11**, 055049

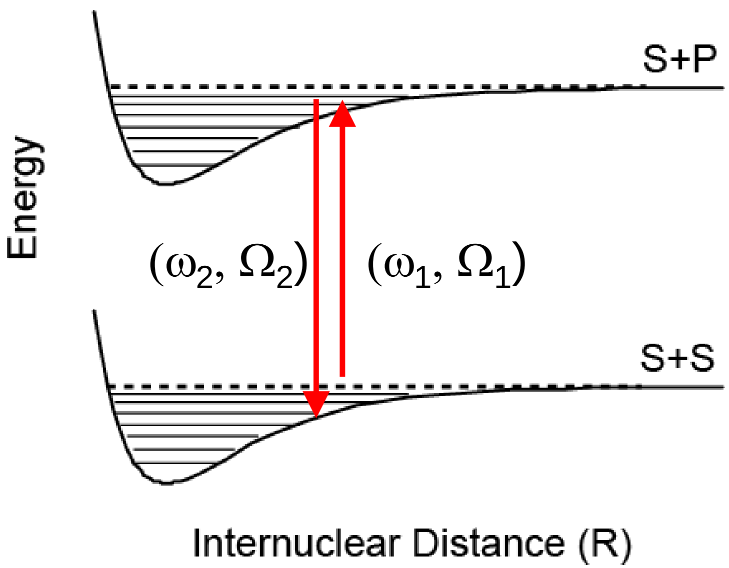
Pursued by several groups worldwide

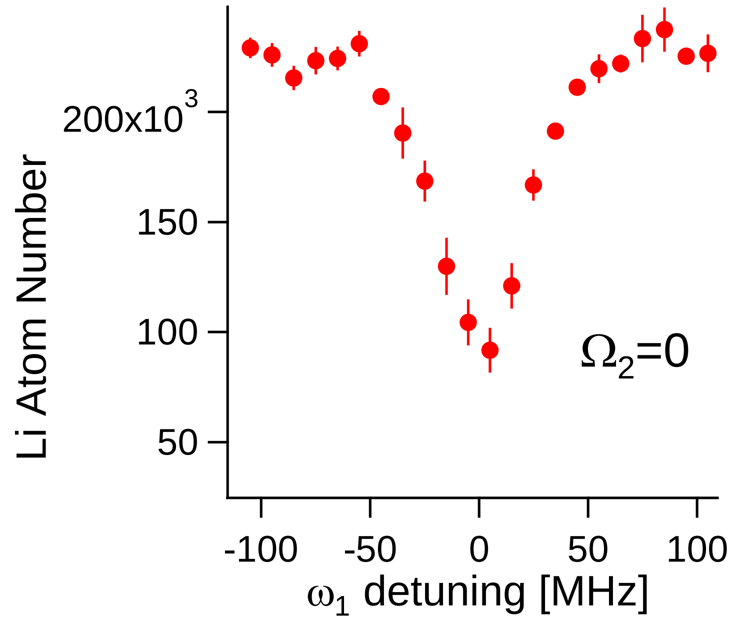
Optical Feshbach Resonance

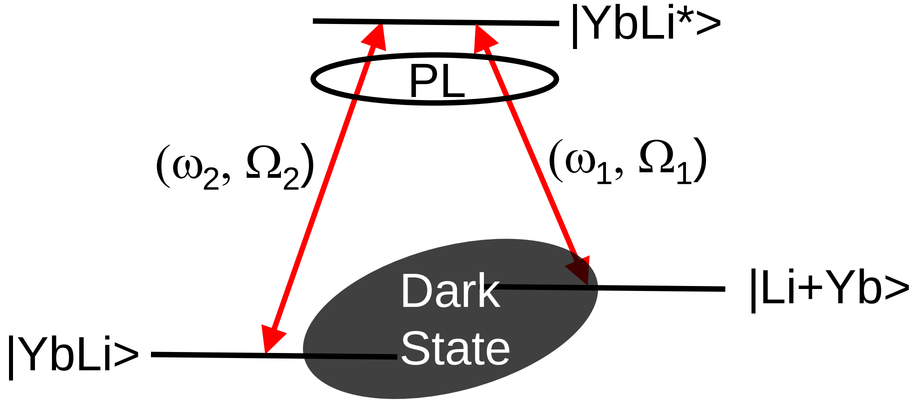


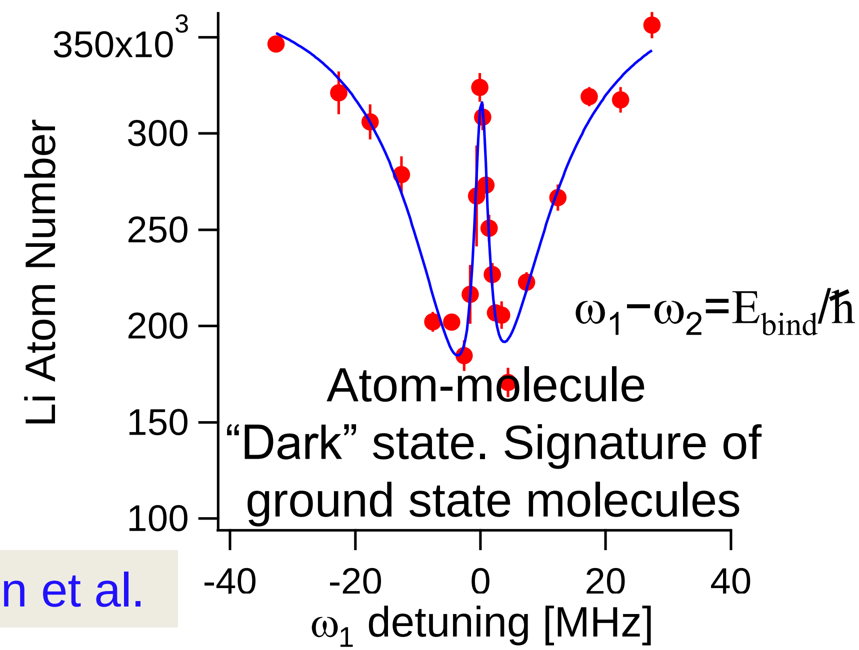
Couple free atoms and molecules using
a coherent 2-photon Raman process

Atom-Molecule Coherence





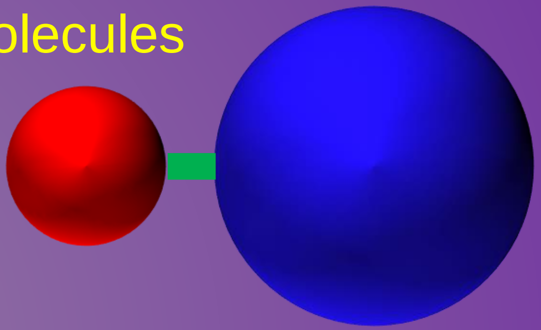




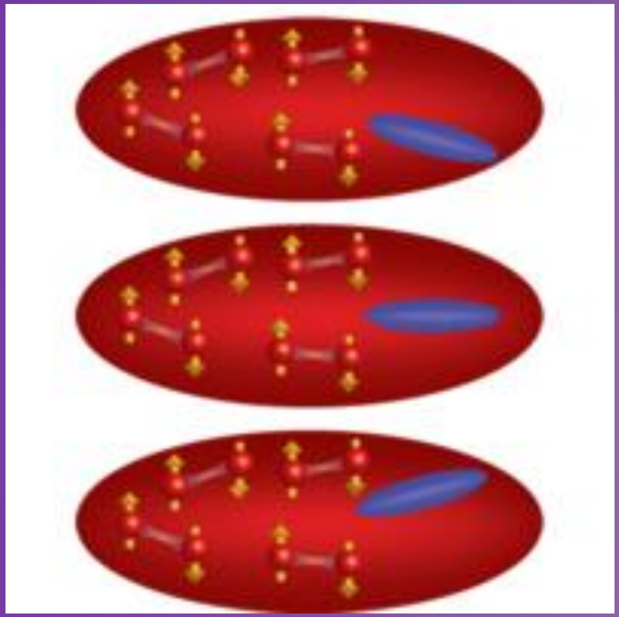
3 level Λ–system

Alaina Green et al.

NanoKelvin Quantum Engineering



Ultracold
Molecules



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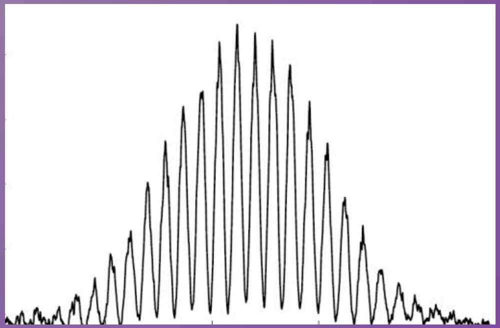
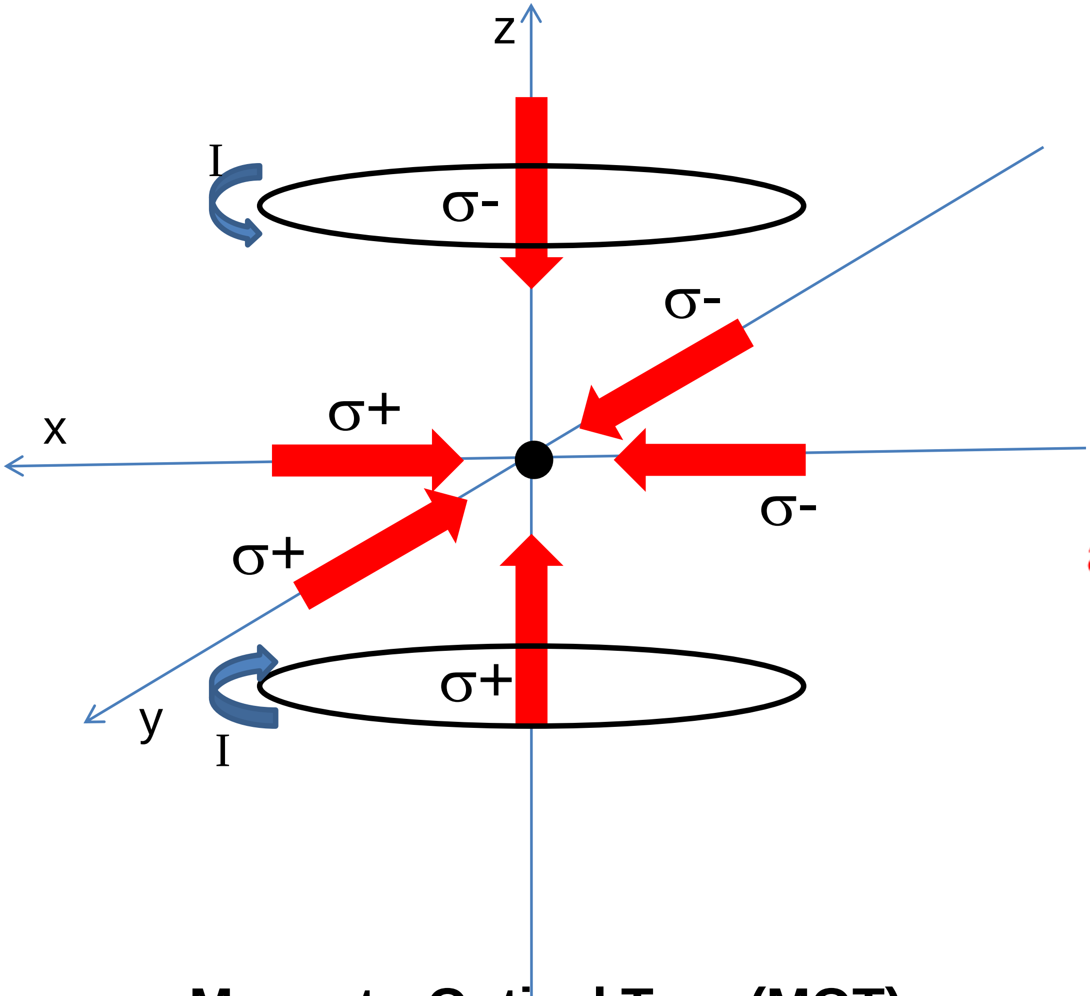
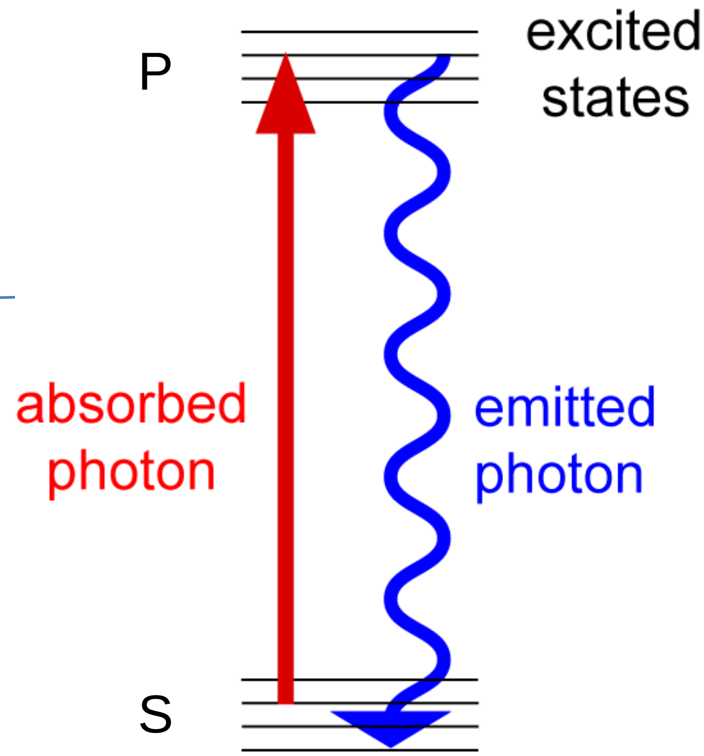


Precision BEC
interferometry

Laser Cooling



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



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

=> COOLING !

Atom Source ~ 600 K; UHV environment

(Need a 2 level system)

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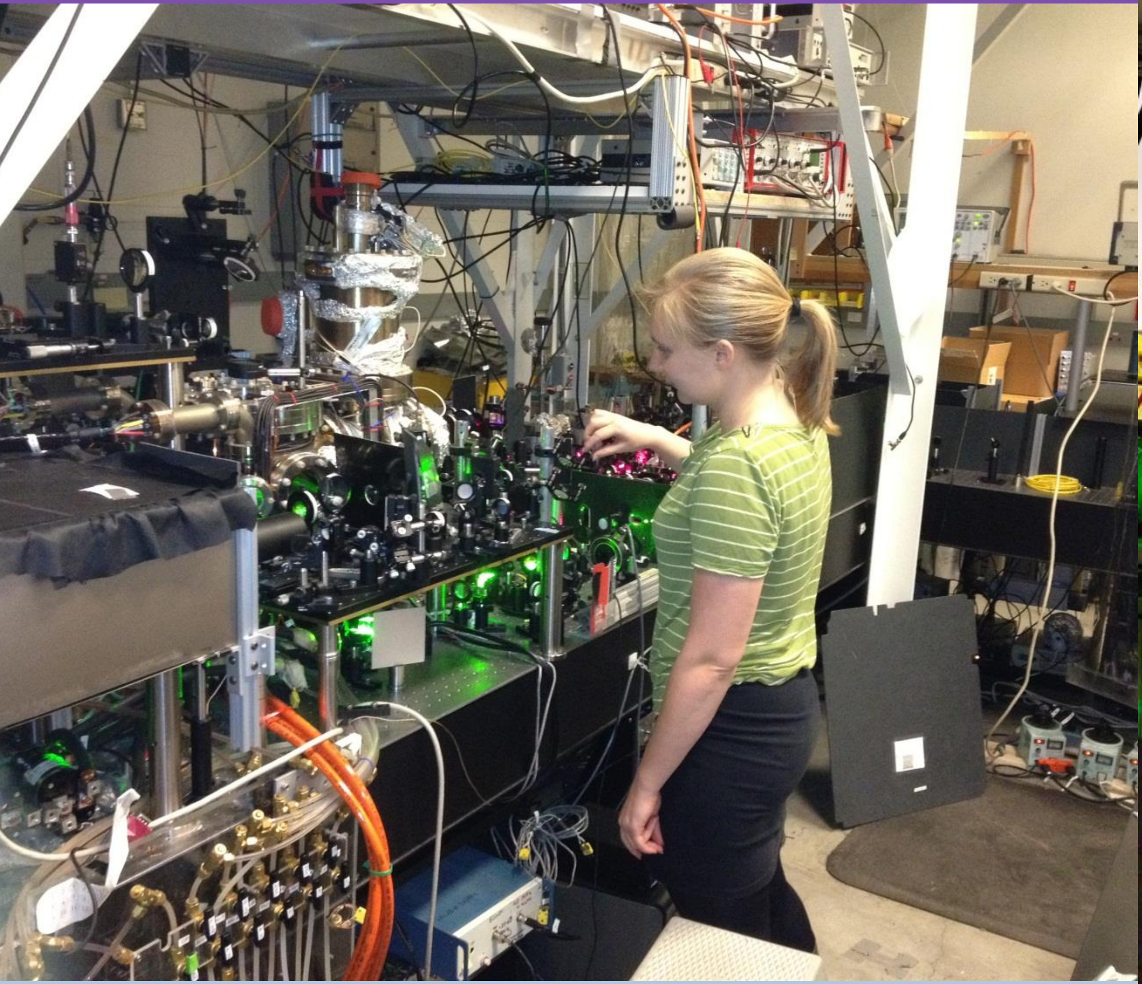

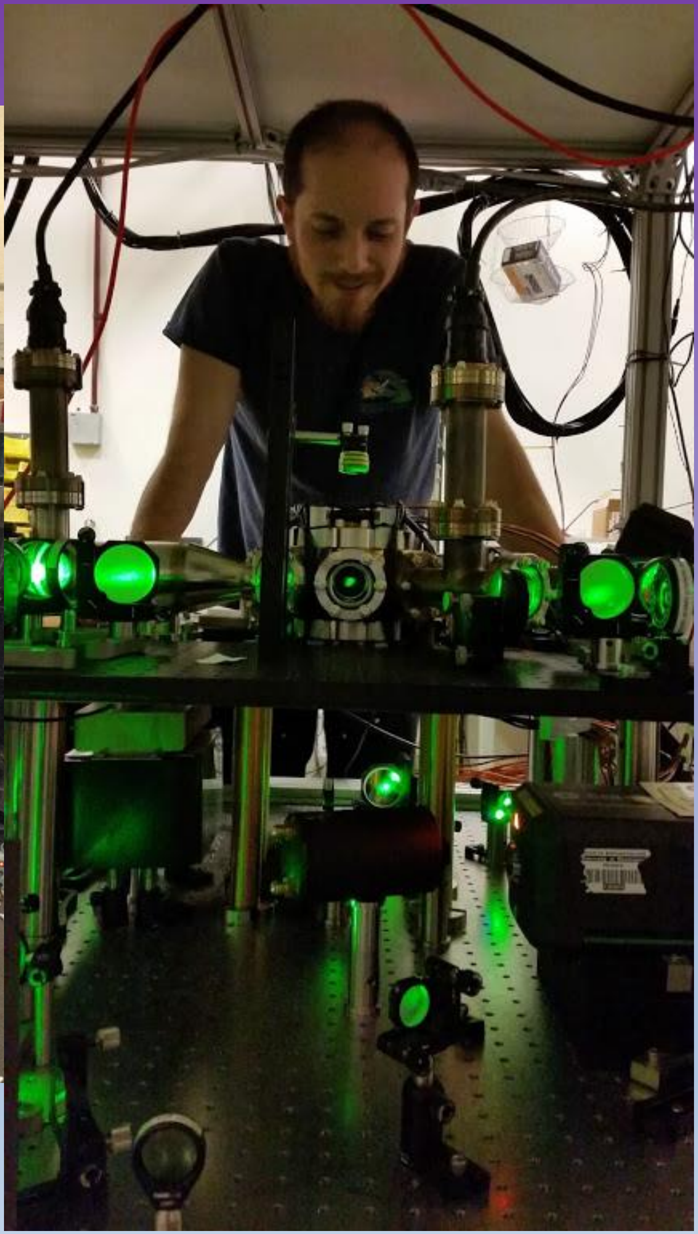

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