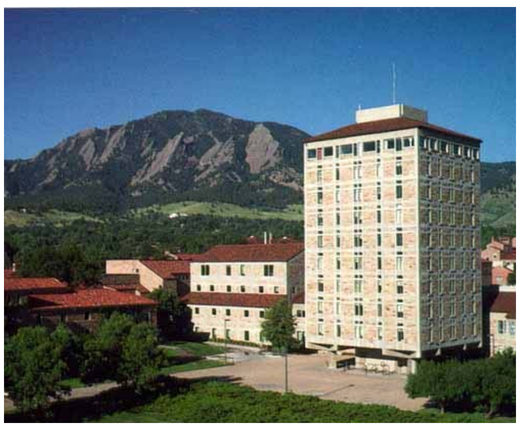
Cold fermions, Feshbach resonance, and molecular condensates (II)

D. Jin JILA, NIST and the University of Colorado



I. Cold fermions

II. Feshbach resonance

III. BCS-BEC crossover

(Experiments at JILA)

$$ NSF, NIST, Hertz

I. Cold Fermions

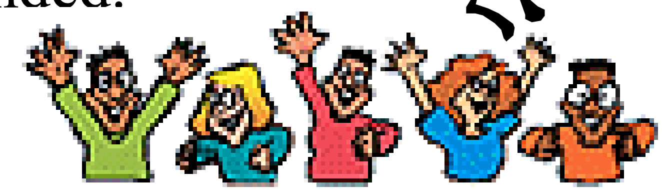
Quantum Particles

- There are two types of quantum particles found in nature - bosons and fermions.

  Bosons like to do the same thing.

  Fermions are independent-minded.

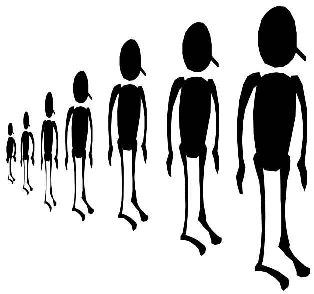
  

- Atoms, depending on their composition, can be either.

  bosons: ^{87}Rb, ^{23}Na, ^{7}Li, H, ^{39}K, ^{4}He*, ^{85}Rb, ^{133}Cs

  fermions: ^{40}K, ^{6}Li

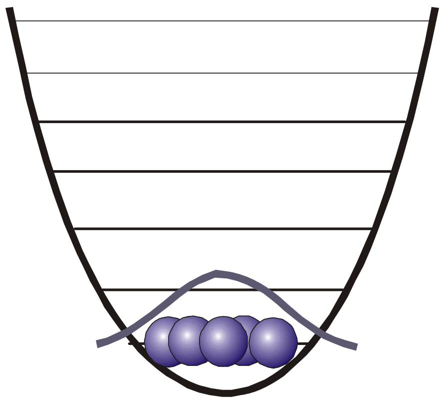
Bosons



😐 integer spin

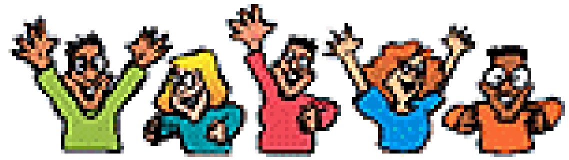
😐 $\Psi_{1,2} = \Psi_{2,1}$

Atoms in a harmonic potential.



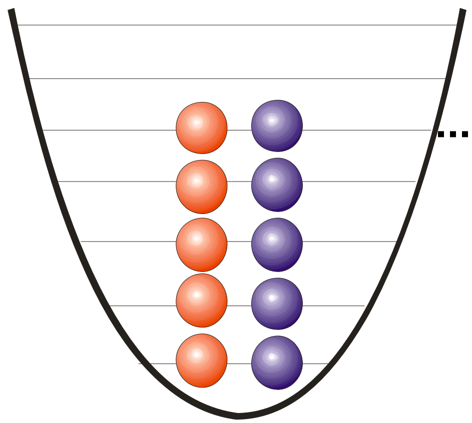
Bose-Einstein condensation 1995

<u>other bosons</u>: photons, liquid ^{4}He

Fermions 

- ☹ half-integer spin
- ☹ $\Psi_{1,2} = - \Psi_{2,1}$ (Pauli exclusion principle)

$T = 0$



$E_F = k_b T_F$

spin ↑

spin ↓

Fermi sea of atoms 1999

<u>other fermions</u>: protons, electrons, neutrons

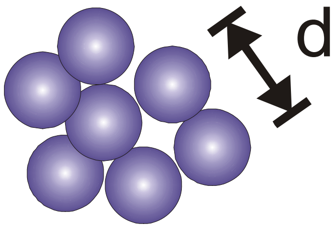
Quantum gases

Bosons

T_C BEC phase transition

Fermions

T_F Fermi sea of atoms gradually emerges for $T<T_F$



$$\lambda_{deBroglie} \sim d$$

ultralow T

Fermionic atoms

^{40}K **Jin, JILA**
Inguscio, LENS

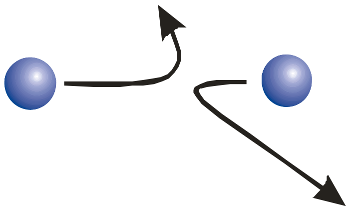
^{6}Li Hulet, Rice
Salomon, ENS
Thomas, Duke
Ketterle, MIT
Grimm, Innsbruck

others in progress…

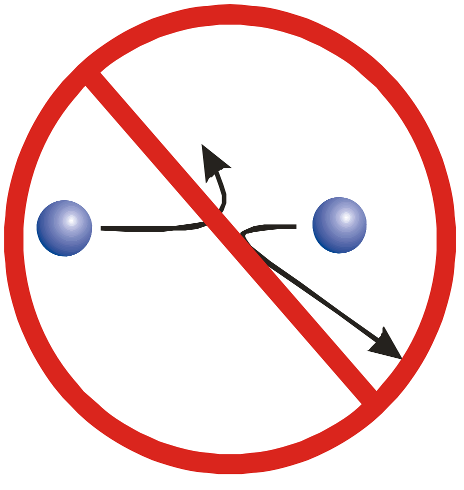
Future: Cr, Sr, Yb,
radioactive isotopes Rb,
metastable *He, *Ne
…

Cooling fermions

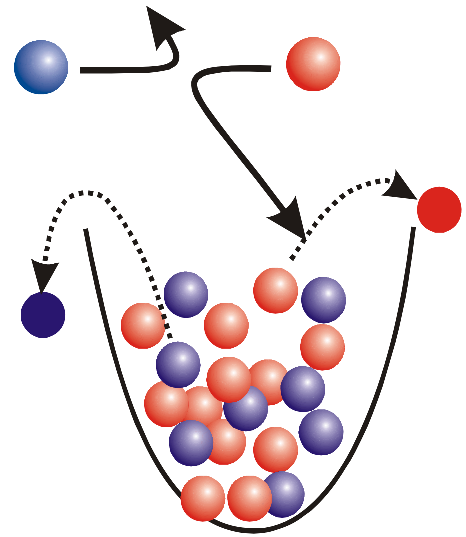
Evaporative cooling requires collisions,



but at low T identical fermions
stop colliding .



Cooling strategies for fermions

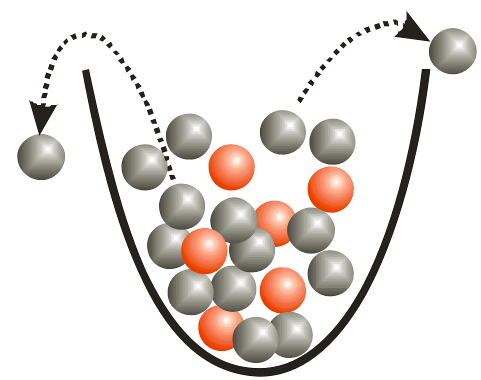


Simultaneous cooling

evaporate atoms in two spin-states

- magnetic trap ^{40}K
- optical trap ^{6}Li

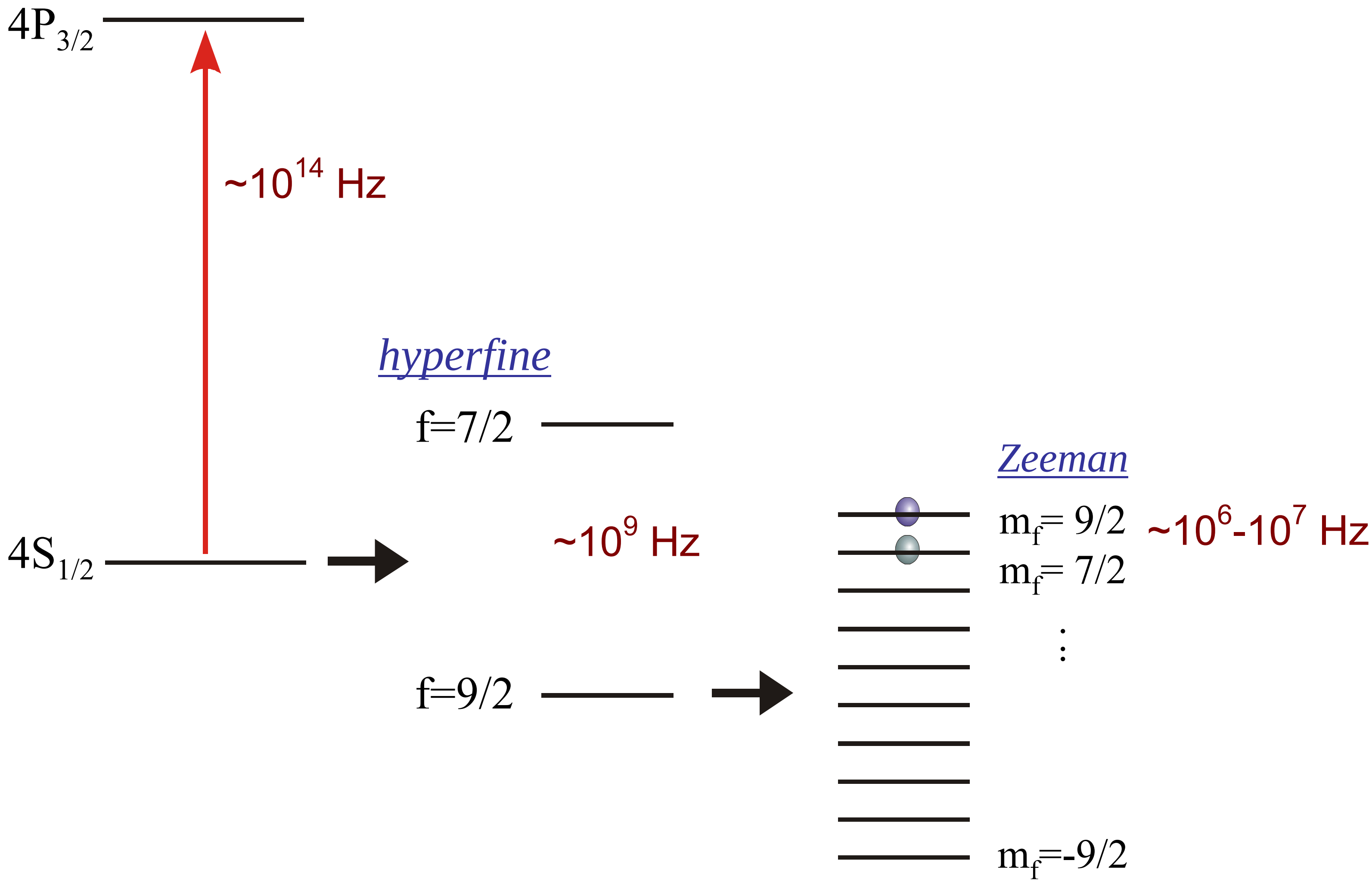
Sympathetic cooling



evaporate bosonic atoms and cool fermionic atoms via thermal contact

- two isotopes $^{7}Li + {}^{6}Li$
- two species $^{87}Rb + {}^{40}K$
  $^{23}Na + {}^{6}Li$

^{40}K spin-states



More on spin-states

spin "↑"

spin "↓"

Energy splitting is 10's MHz.

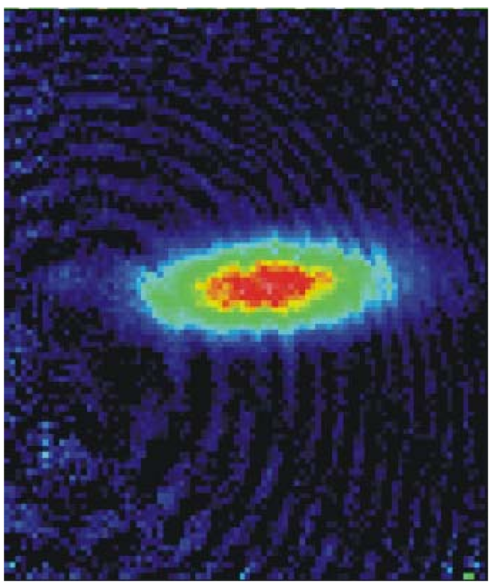
T = 1 μK corresponds to 20 kHz.

- spin degree of freedom is frozen

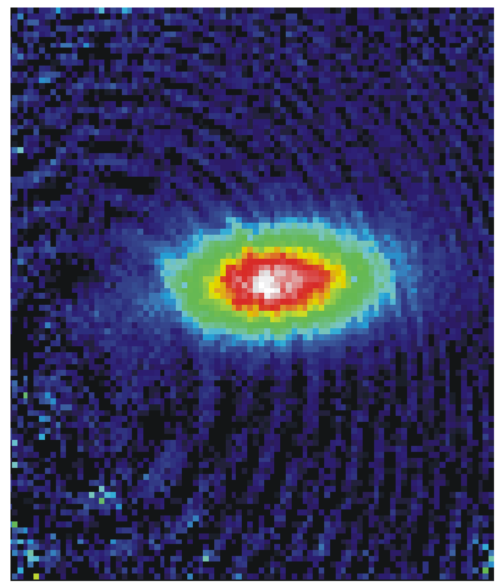
Collision measurement

1. Add energy in one dimension of trap
2. Watch thermal relaxation

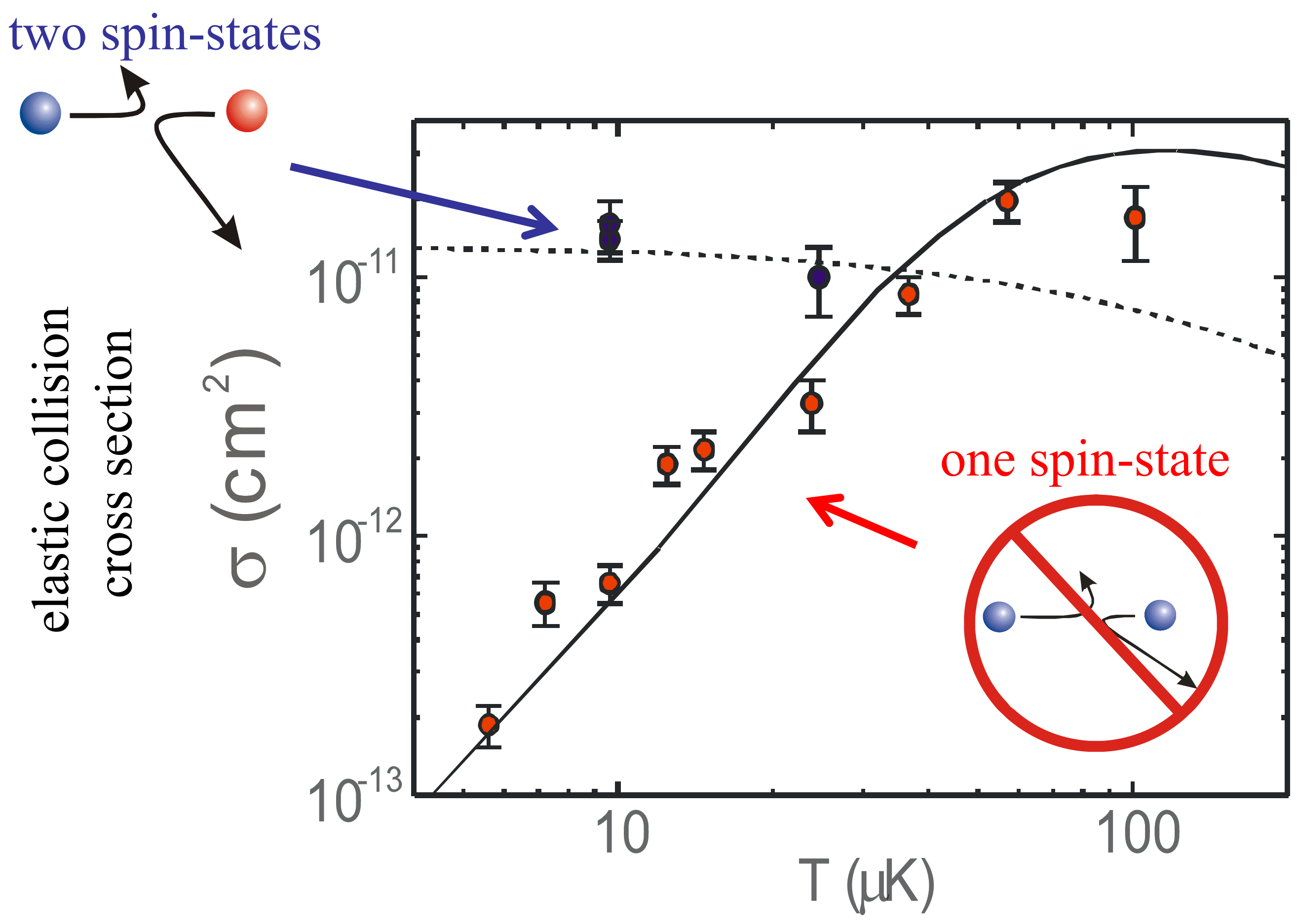
before



after relaxation



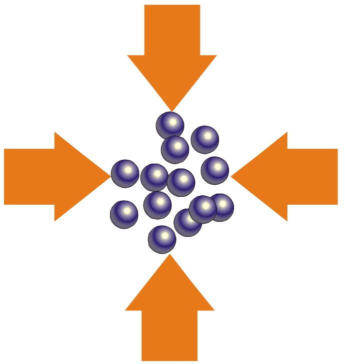
Collisions and Fermions



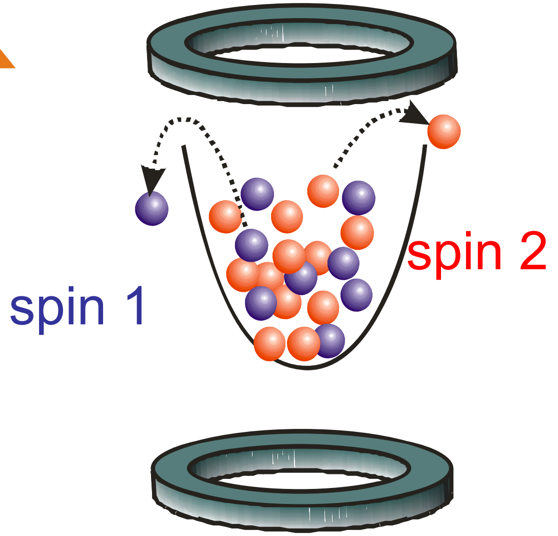
Cooling a gas of ^{40}K atoms

1. Laser cooling and trapping

300 K to 1 mK, ~10^9 atoms

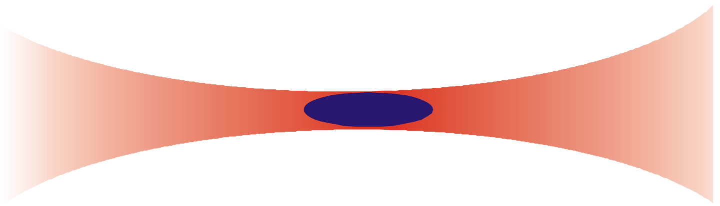


1 mK to 1 μK, ~$10^8 \rightarrow 10^6$ atoms



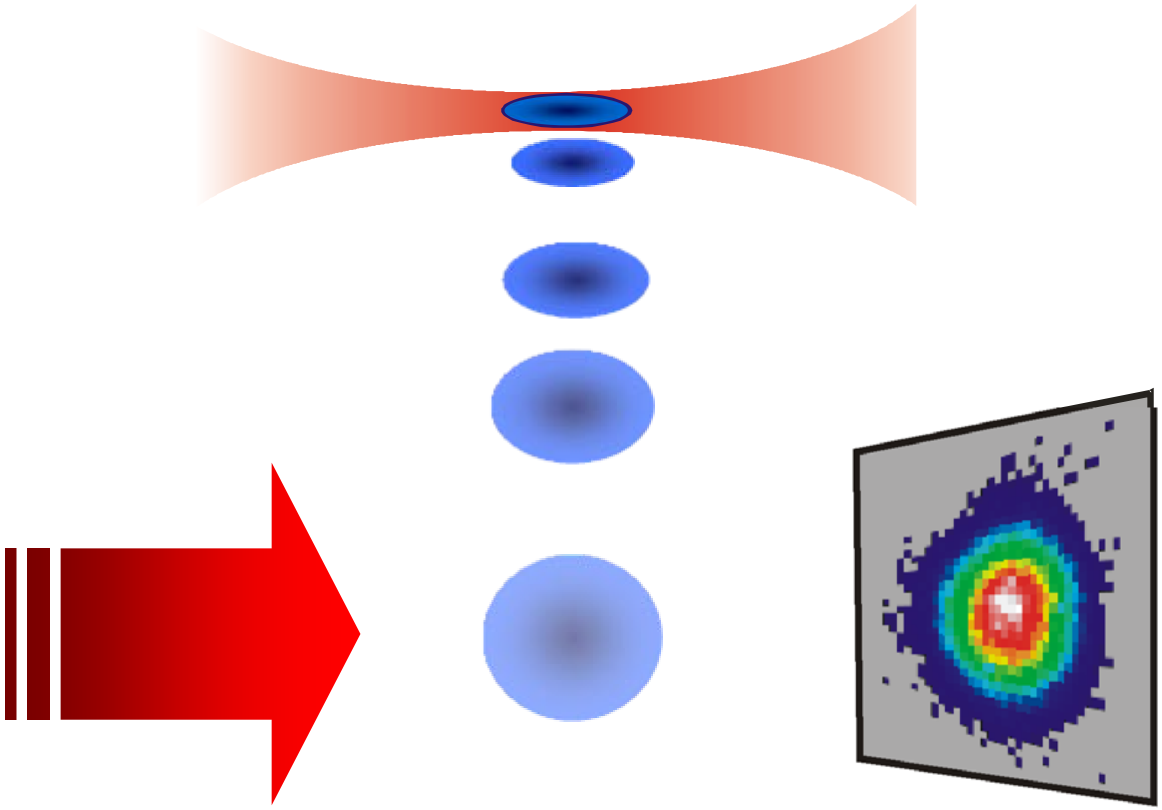
1 μK to 50 nK, $10^6 \rightarrow 10^5$ atoms

- can confine any spin-state
- can apply arbitrary B-field



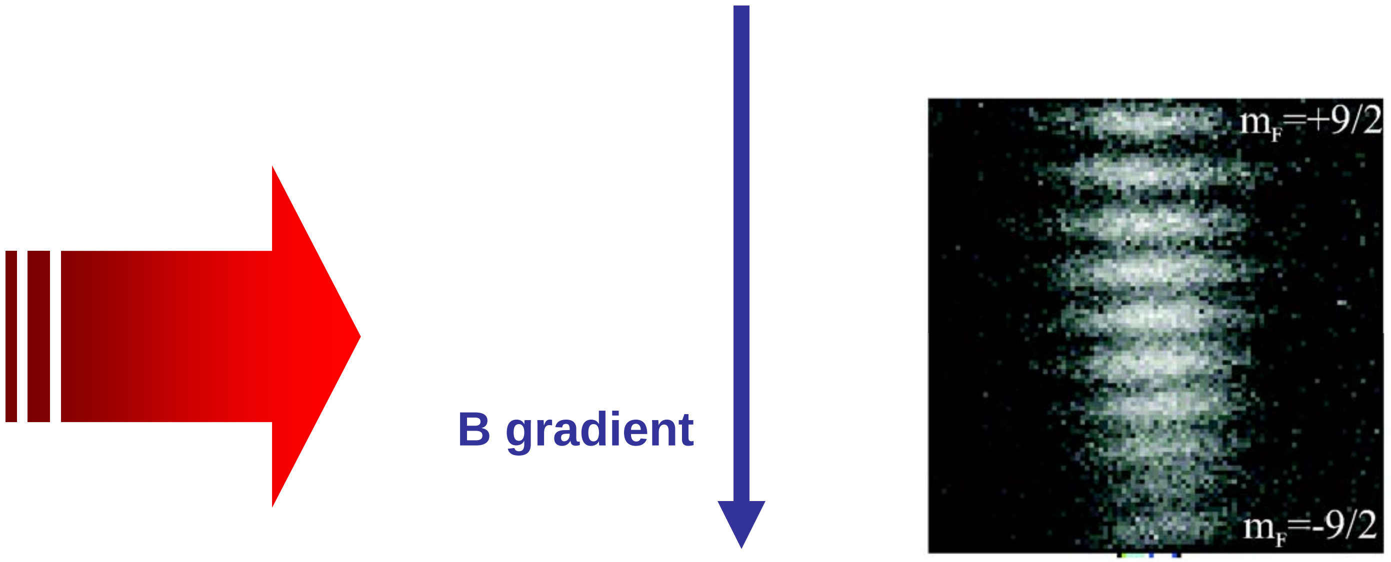
Probing the ultracold gas

Time-of-flight absorption imaging



Stern-Gerlach imaging

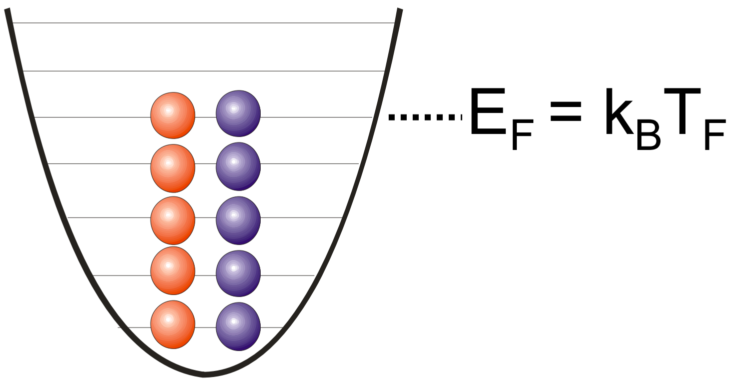
Time-of-flight absorption imaging



Quantum degenerate atomic Fermi gases

1999: ^{40}**K** JILA

^{6}**Li** - Rice, Duke, ENS, MIT, Innsbruck; ^{40}**K** - LENS, ETH Zurich

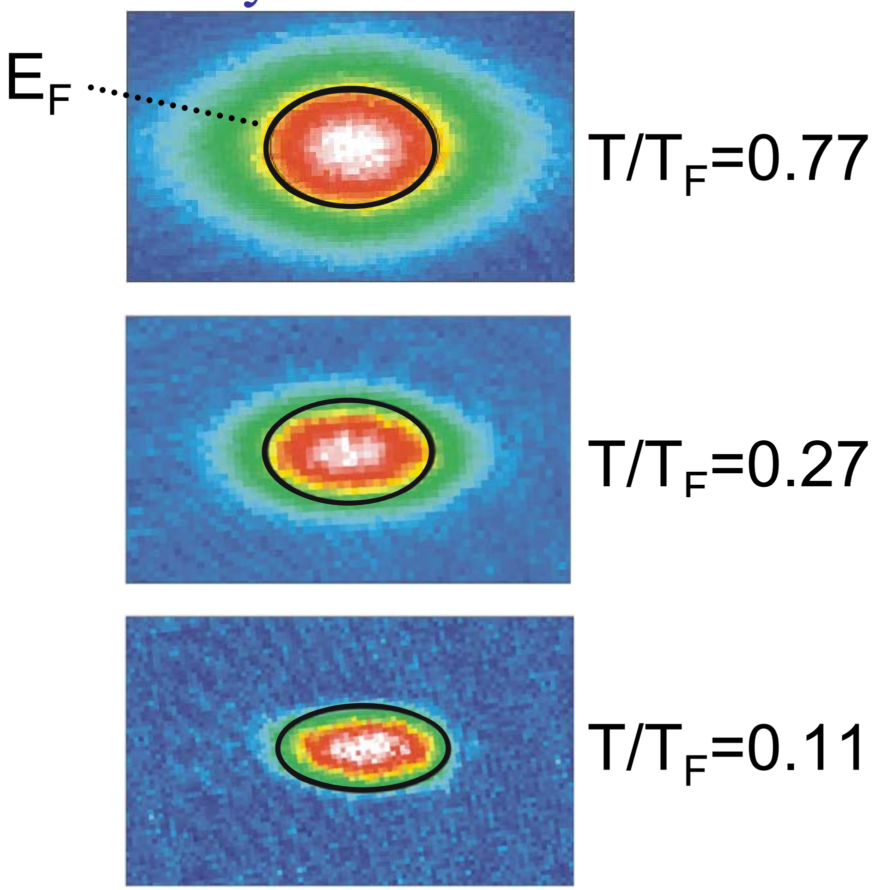


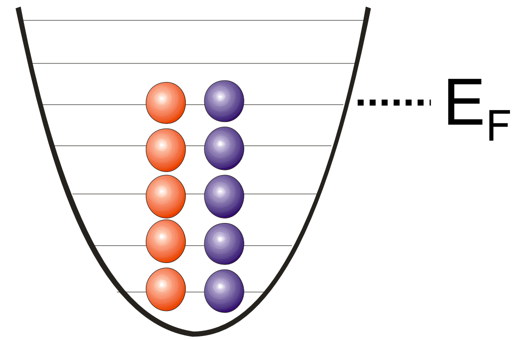
Fermi sea of atoms

- $T \sim 0.05\ T_F$
- low temperature, low density:
  $T \sim 100$ nK, $n \sim 10^{13}$ cm^{-3}

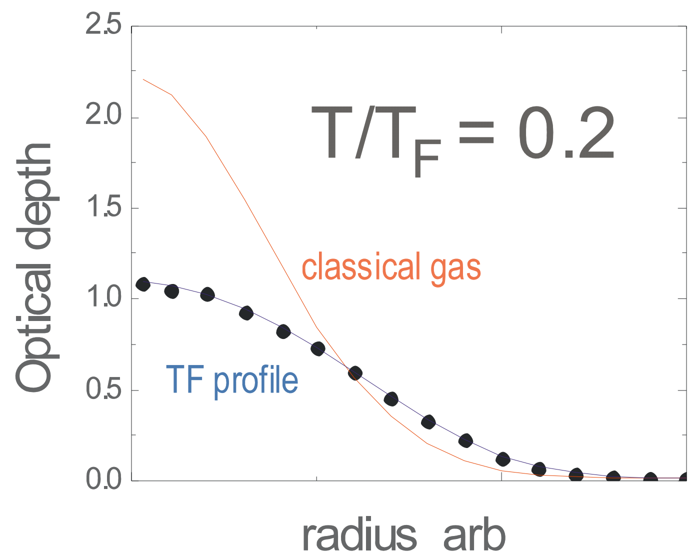
Quantum degeneracy

velocity distributions

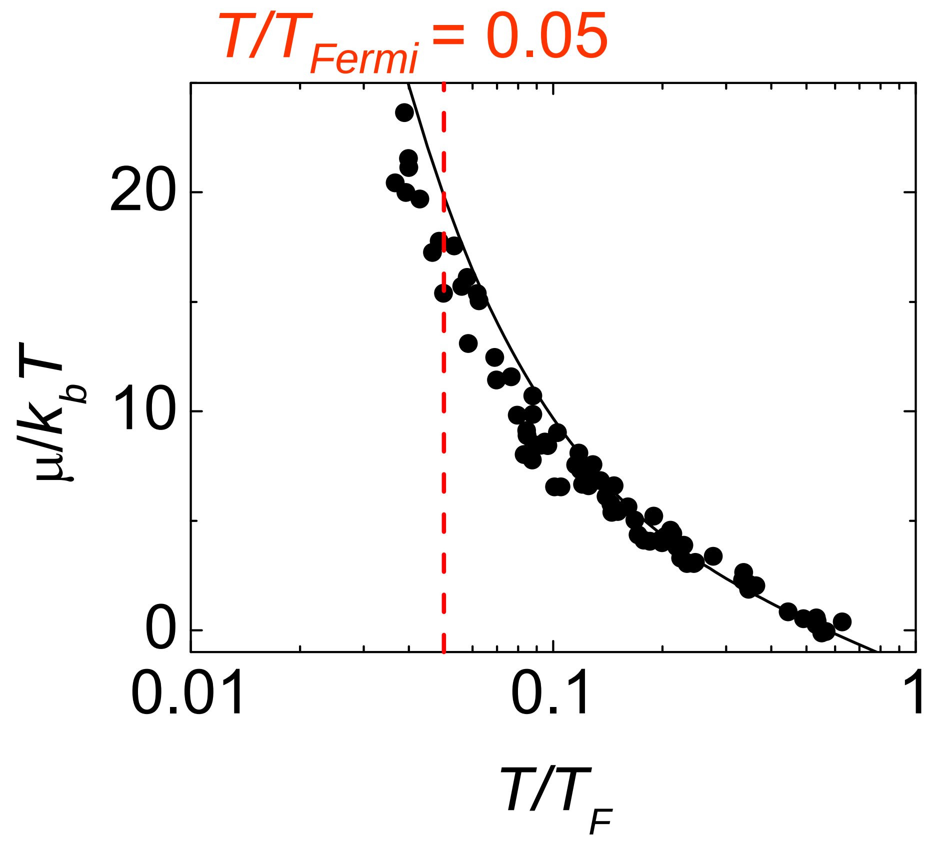




Fermi sea of atoms

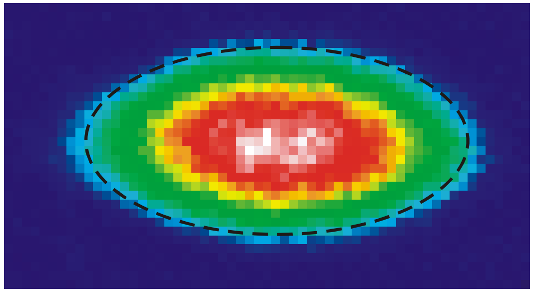


Quantum degeneracy



N = 4 ·10^5 , T = 16 nK

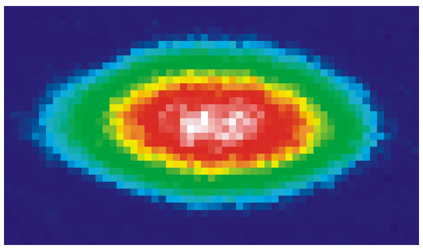
T/T_{Fermi} = 0.05

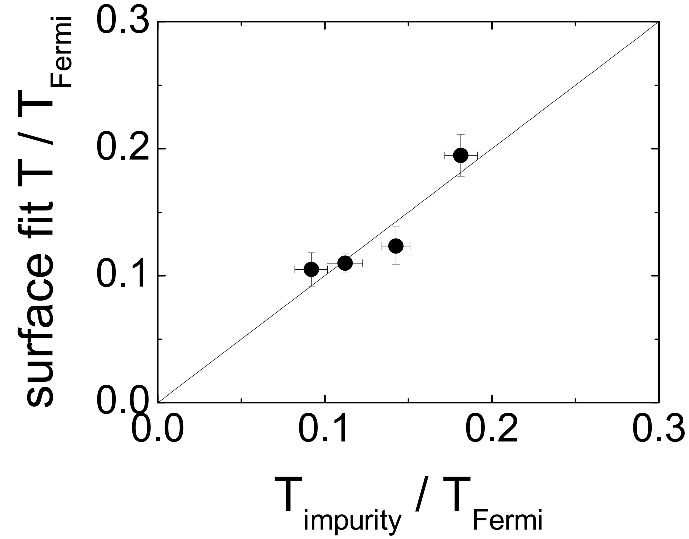


Fermi gas thermometry

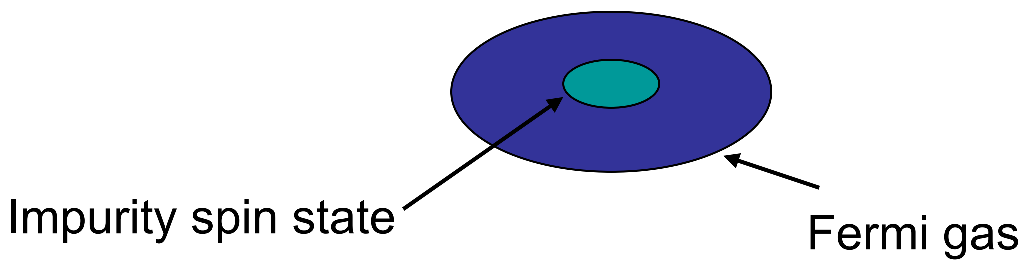
Determine temperature from

(1) surface fit to expanded cloud





(2) an embedded non-degenerate gas



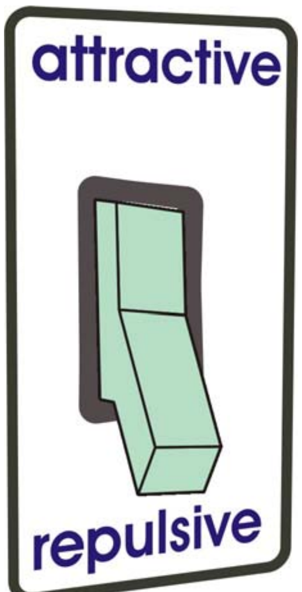
II. Feshbach resonance

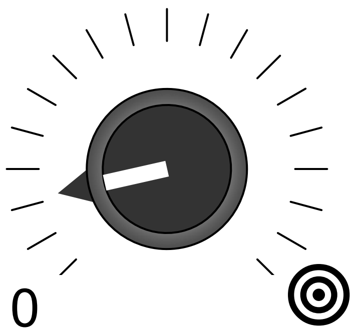
Interactions

- Interactions are characterized by the s-wave scattering length, a

  $a > 0$ repulsive, $a < 0$ attractive
  Large $|a| \rightarrow$ strong interactions

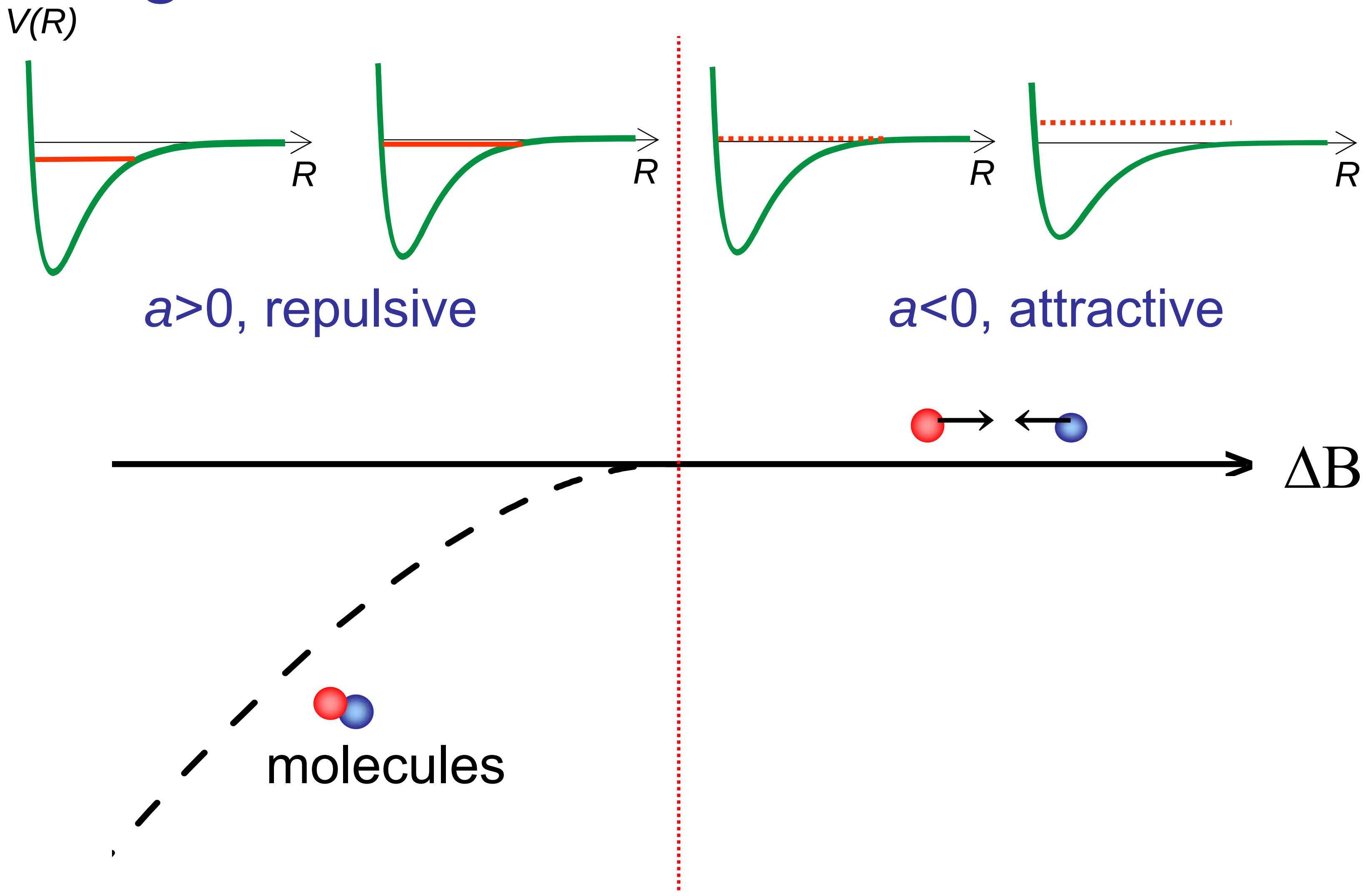
- In an ultracold atomic gas, we can control a!



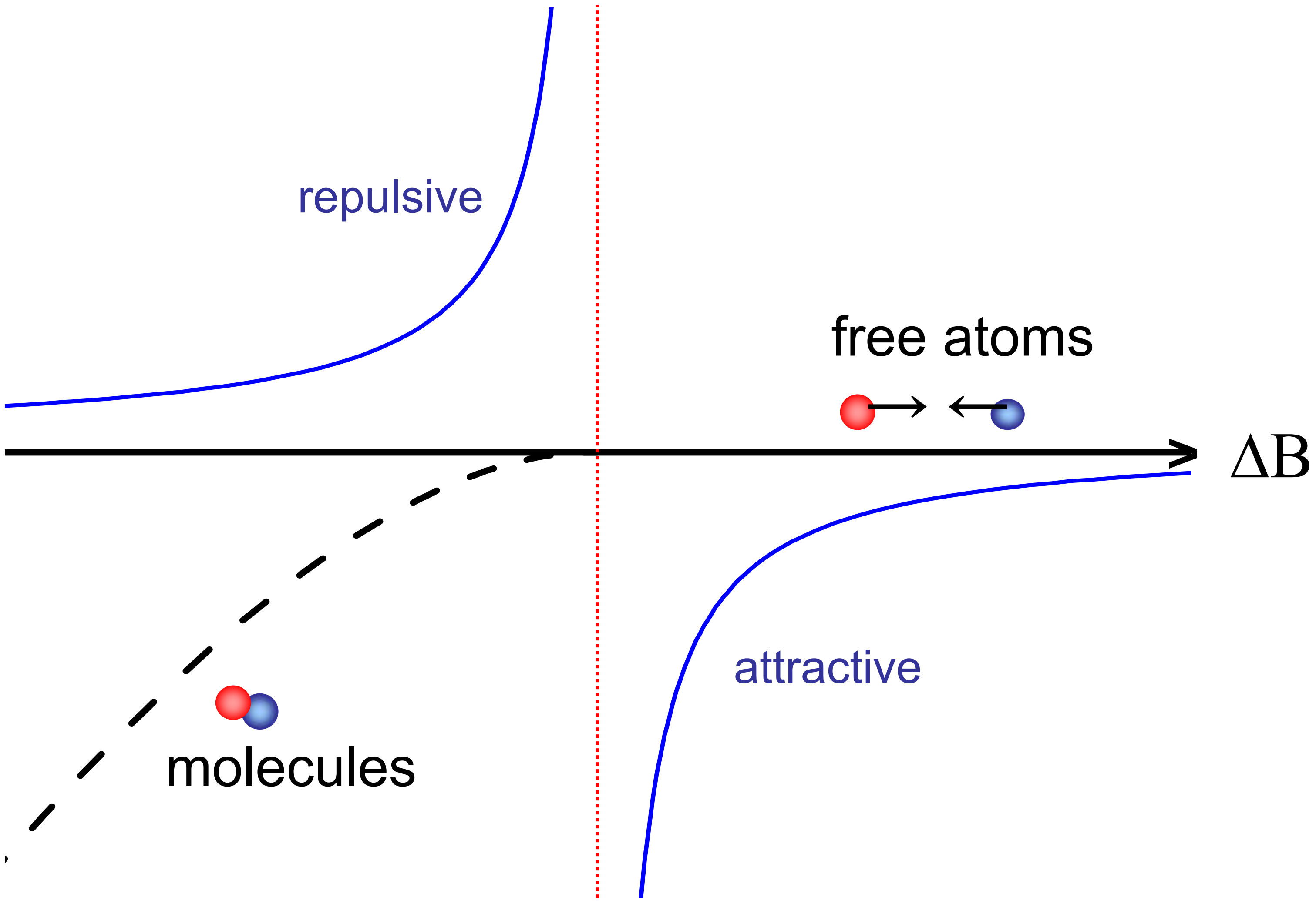


scattering length

Magnetic-field Feshbach resonance



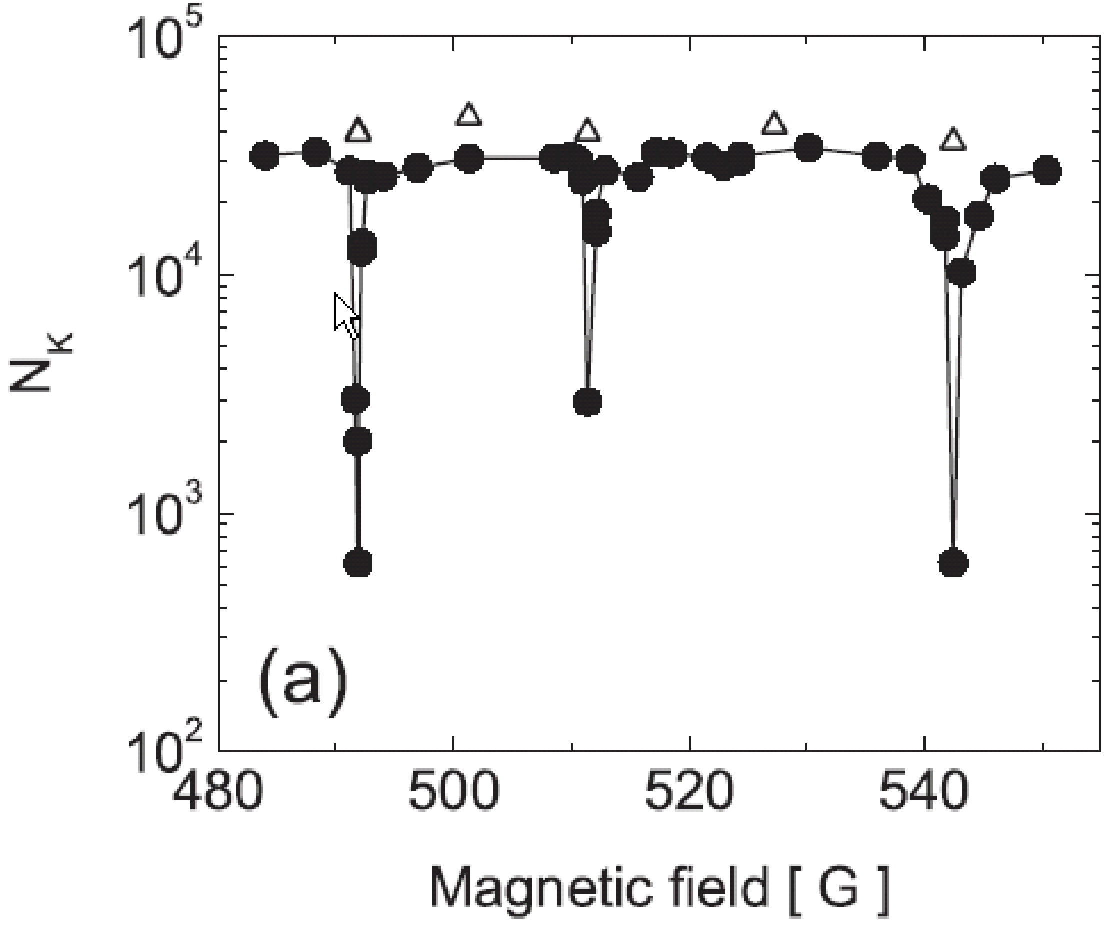
Magnetic-field Feshbach resonance



Experimental observation

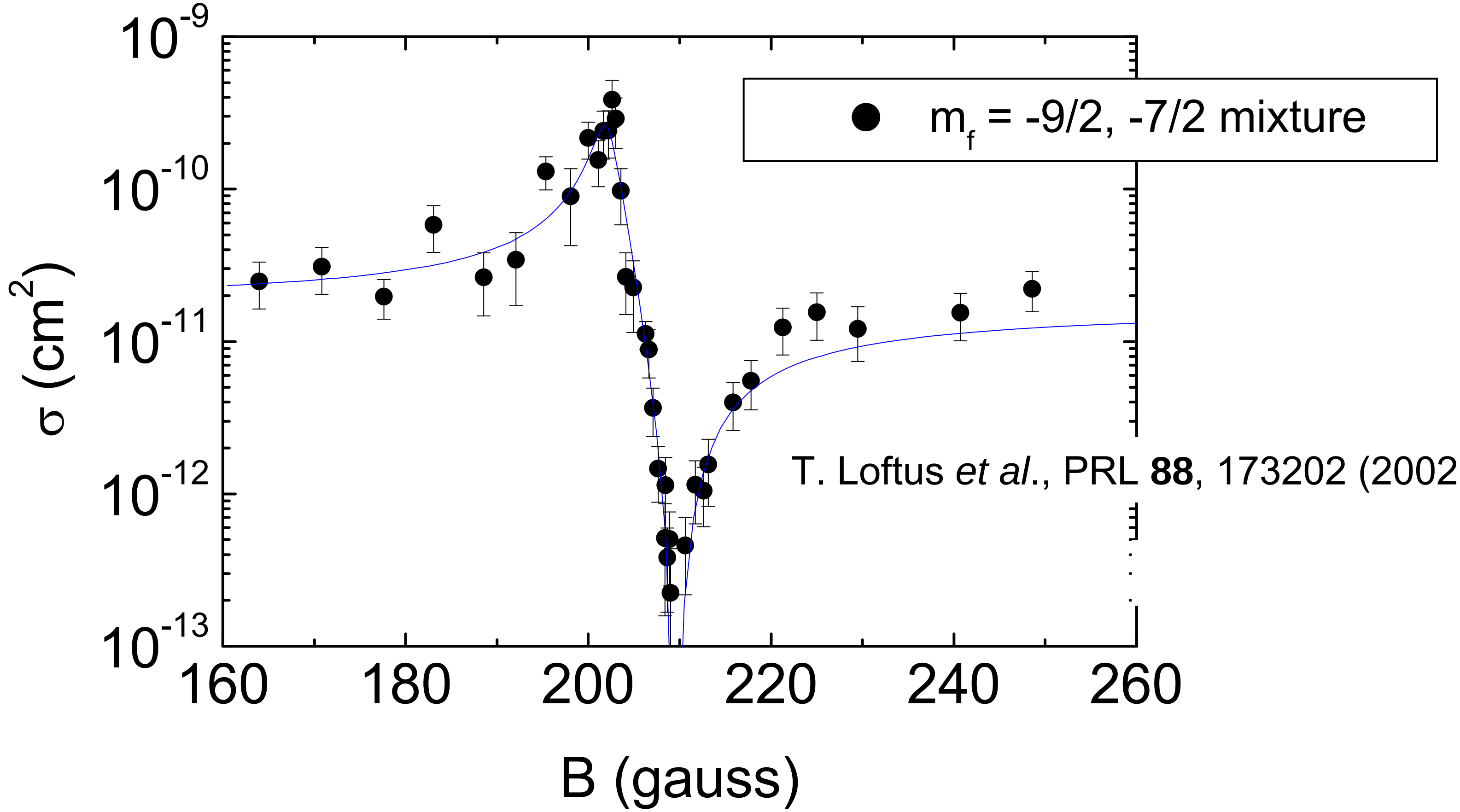
1. Trap Loss (3-body inelastic collisions)

three ^{87}Rb-^{40}K Feshbach resonances:



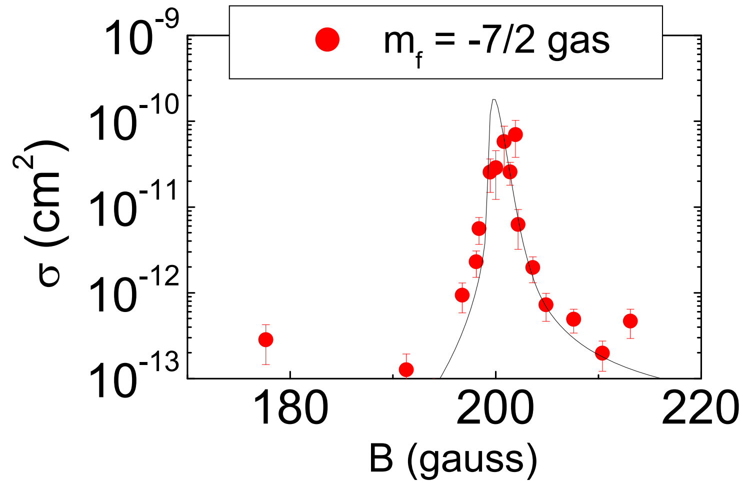
S. Inouye et al., cond-mat, 2004.

Experimental observation
2. Elastic collision rate ($\sigma = 4\pi a^2$)



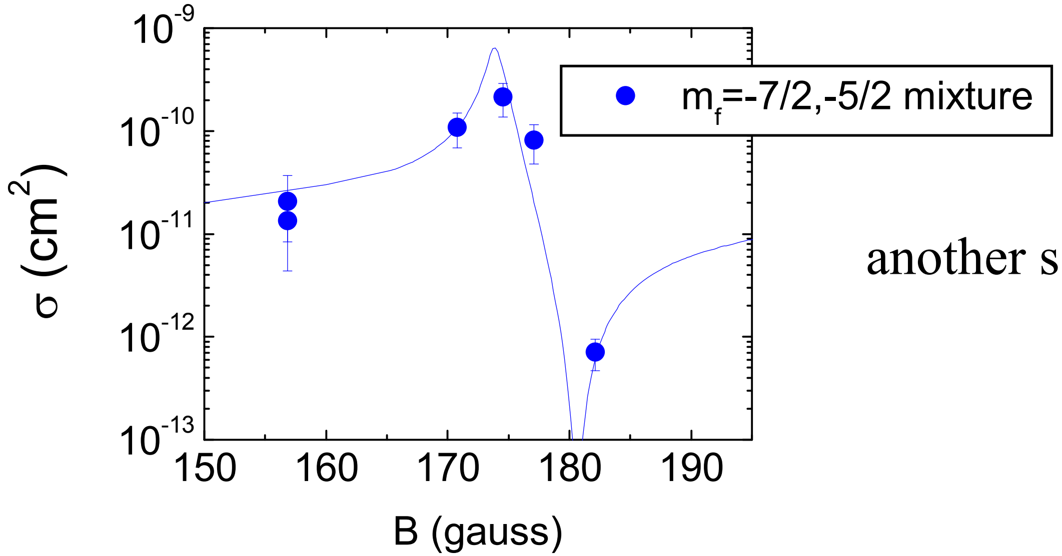
T. Loftus *et al*., PRL **88**, 173202 (2002).

More ^{40}K resonances



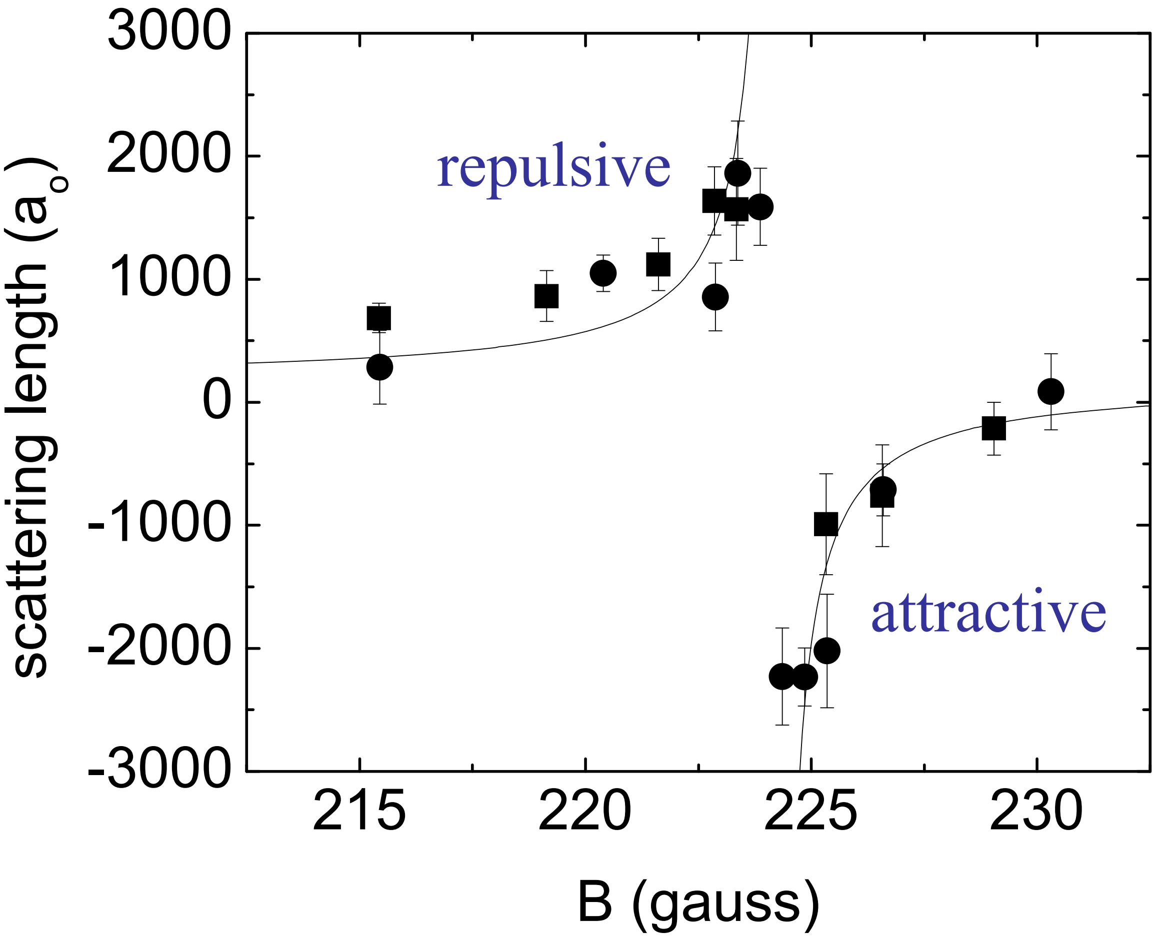
a p-wave resonance!

C. A. Regal *et al.*, PRL **90**, 053201 (2003)



another s-wave resonance

Experimental observation
3. Interaction energy (RF spectroscopy)



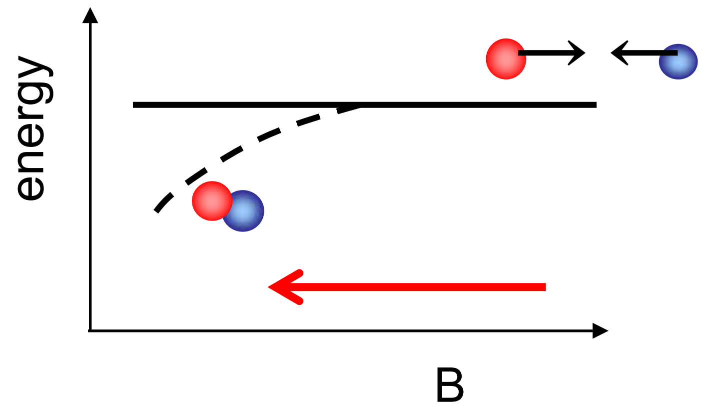
Feshbach resonance between m_f=-9/2,-5/2

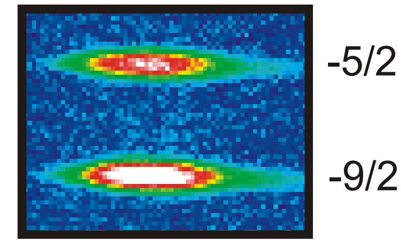
Use $\Delta\nu \sim n_9 a_{59}$

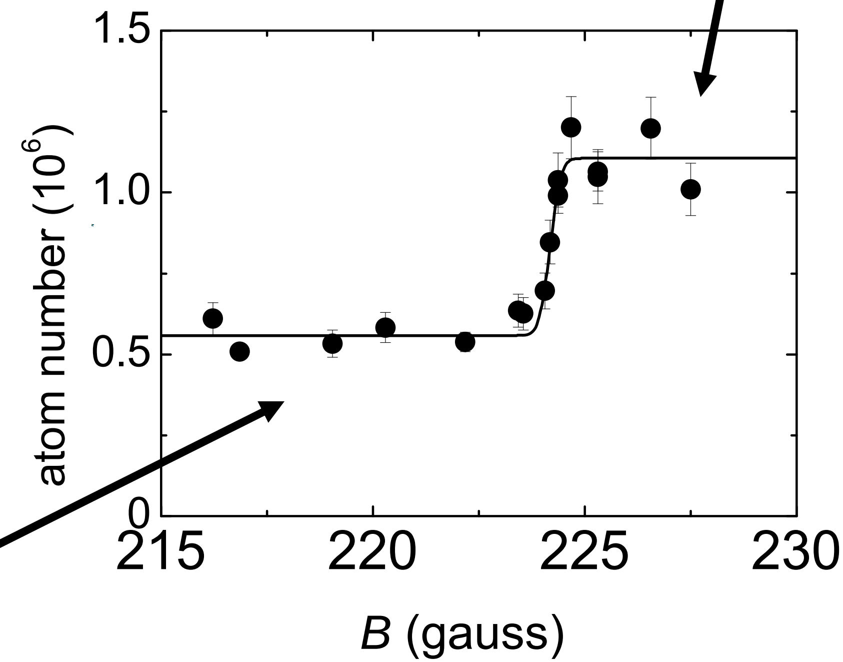
C. A. Regal and D. S. Jin, PRL, (2003)

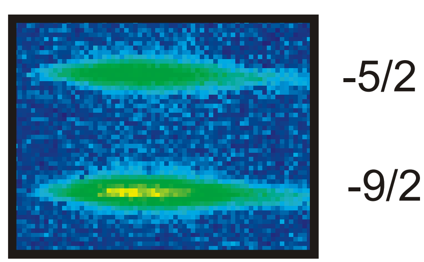
Experimental observation
4. Molecule creation

Ramp across Feshbach resonance from high to low B





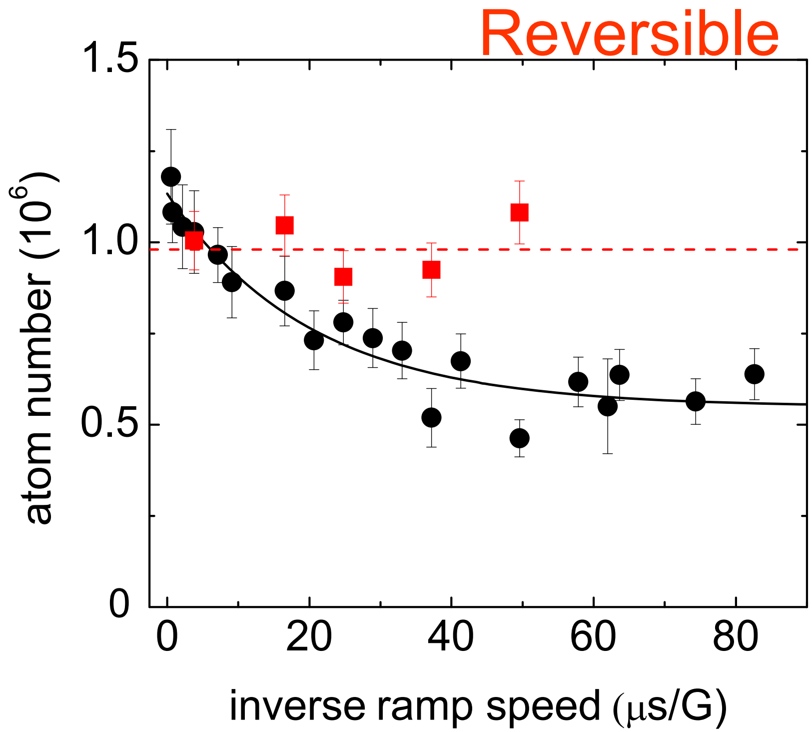


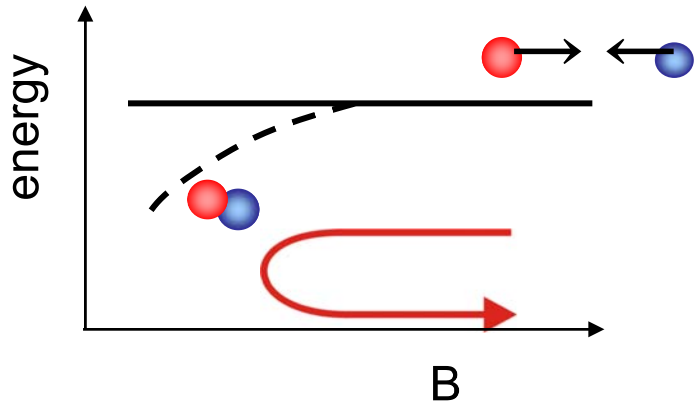


C. A. Regal et al., Nature 424, 47 (2003).

Motivation: E. A. Donley et al., *Nature* 417, 529 (2002)

Magnetic field sweep rate



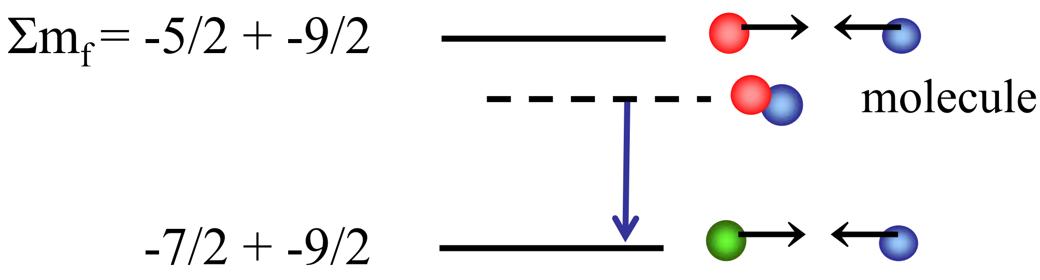


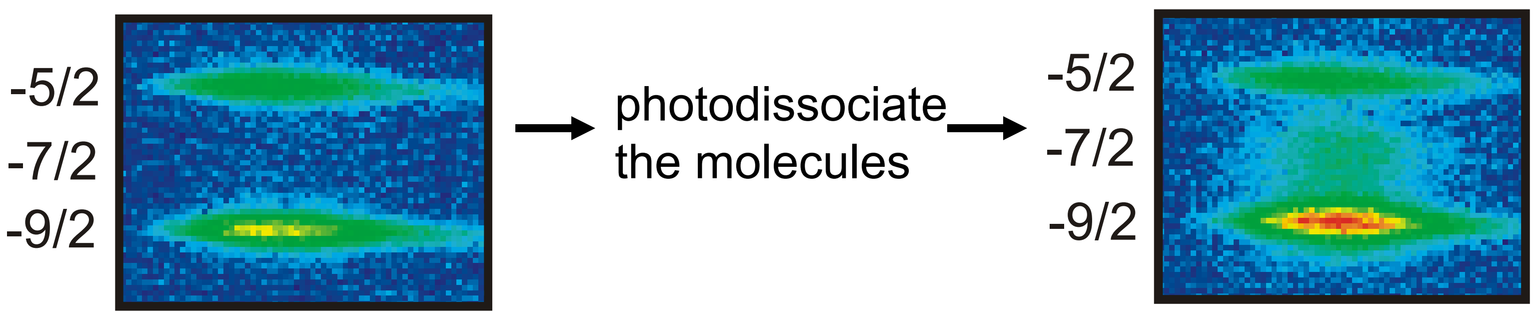
Similar experiments:

Bosons	Fermions
Innsbruck	Rice
Garching	ENS
JILA	Innsbruck

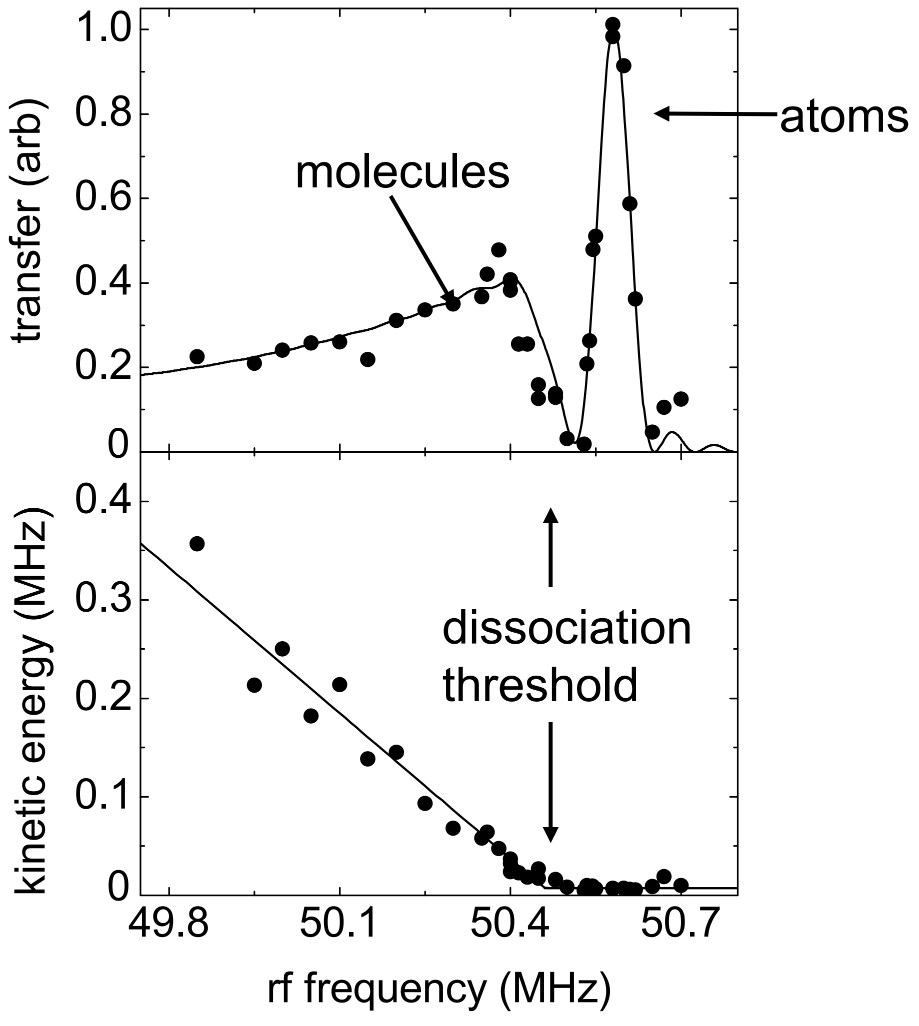
Molecule detection

- Apply RF near the atomic m_f=-5/2 to m_f=-7/2 transition

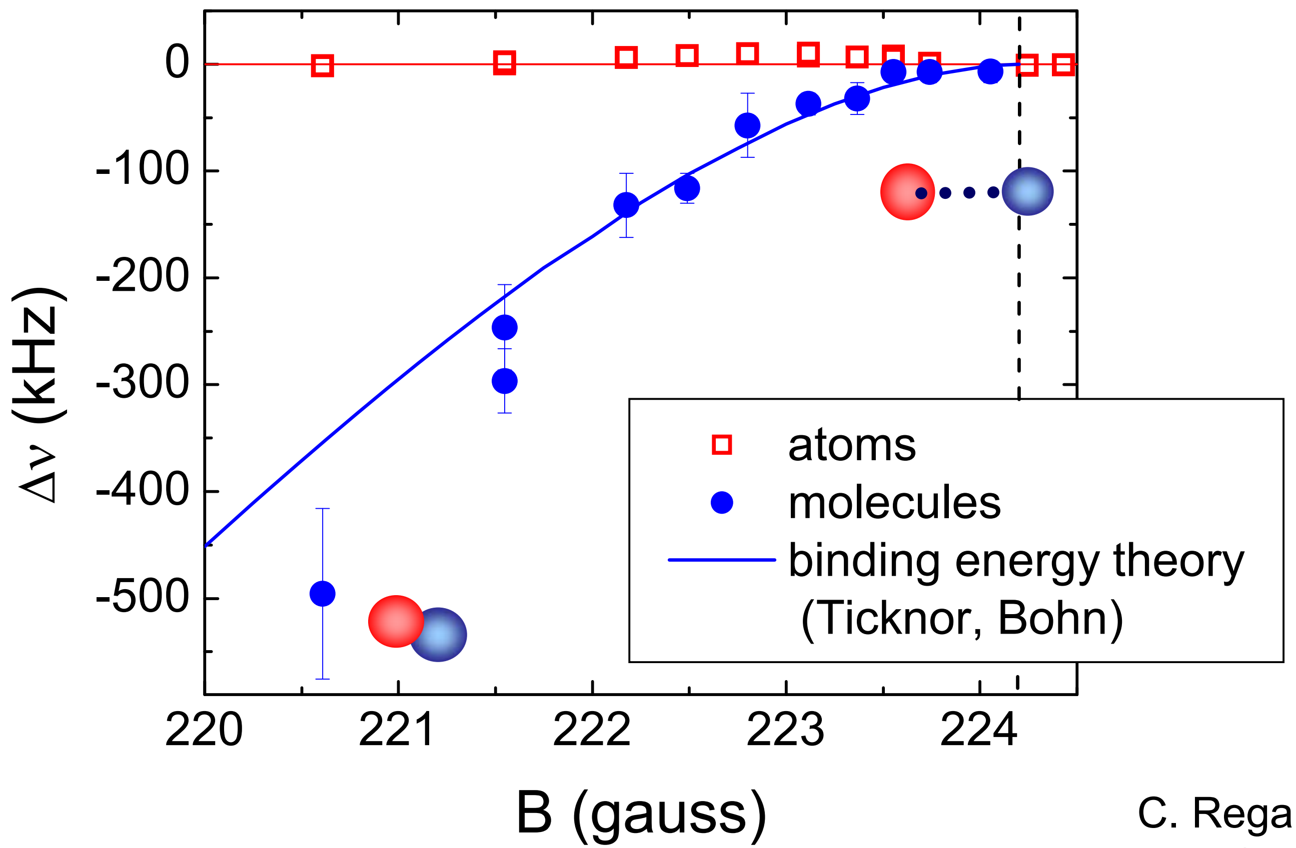




Molecule detection



Molecule binding energy

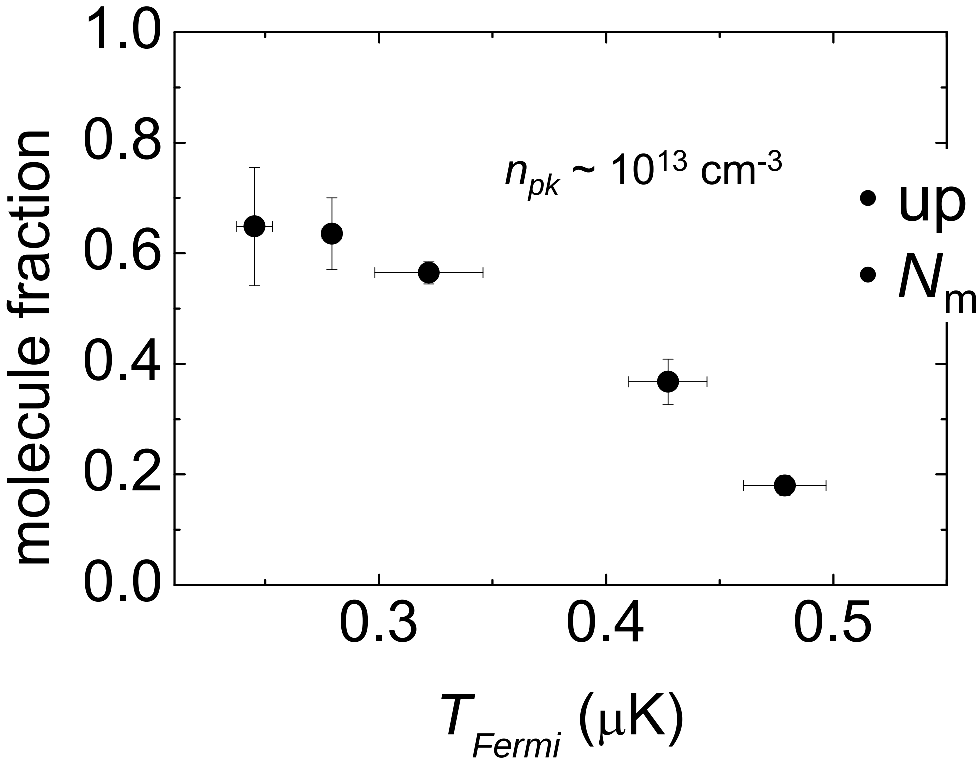


C. Regal *et al.*
Nature 424, 47 (2003)

- extremely weakly bound !

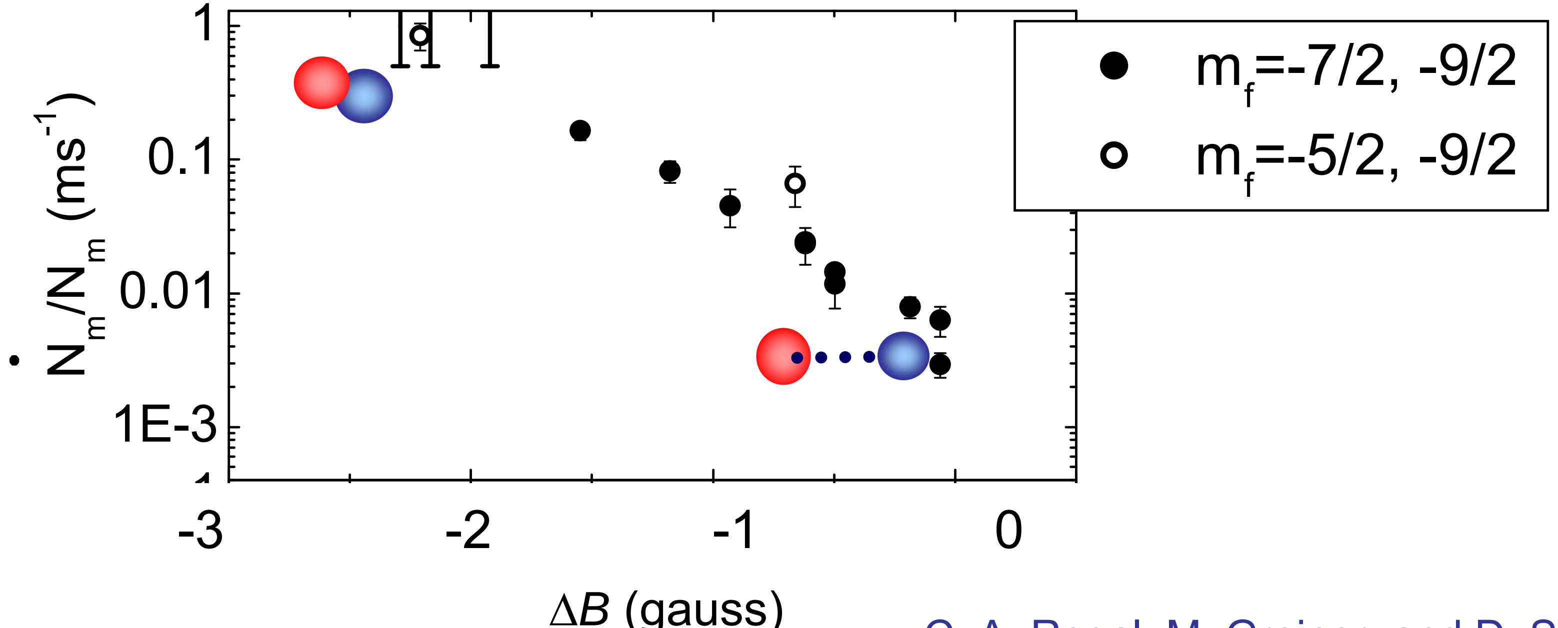
Molecule conversion efficiency

- depends strongly on energy of Fermi gas



- up to 70% conversion
- $N_{molecule}$ > 250,000

Molecule decay rate



C. A. Regal, M. Greiner, and D. S. Jin, PRL **92**, 083201 (2004)

Theory prediction: D.S. Petrov, C. Salomon, G.V. Shlyapnikov, cond-mat/0309010 (2003)
Expts: Rice, ENS, Innsbruck, JILA

Cold fermions, Feshbach resonance, and molecular condensates (II)

D. Jin JILA, NIST and the University of Colorado

I. Cold fermions

II. Feshbach resonance

III. BCS-BEC crossover

(Experiments at JILA)

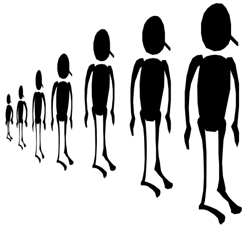
$$ NSF, NIST, Hertz

III. BCS-BEC crossover

Bose-Einstein condensation

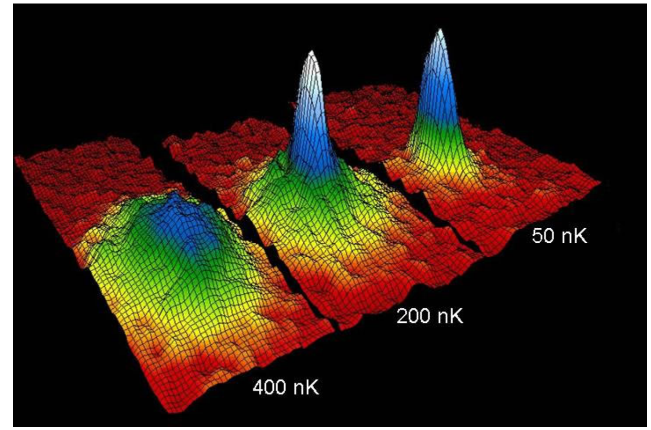
BEC shows up in condensed matter, nuclear physics, elementary particle physics, astrophysics, and atomic physics.

- Cooper pairs of electrons in superconductors
- ^{4}He atoms in superfluid liquid He
- Excitons, biexcitons in semiconductors
- Alkali atoms in ultracold atom gases
- ^{3}He atom pairs in superfluid ^{3}He-A,B
- Neutron pairs, protron pairs in nuclei And neutron stars
- Mesons in neutron star matter



Bosons and Fermions

- Condensation requires bosons.
- Material bosons are composite particles, made up of fermions.



➢ For a gas of bosonic atoms, the underlying fermion degrees of freedom are not accessible.

^{87}Rb, ^{23}Na, …

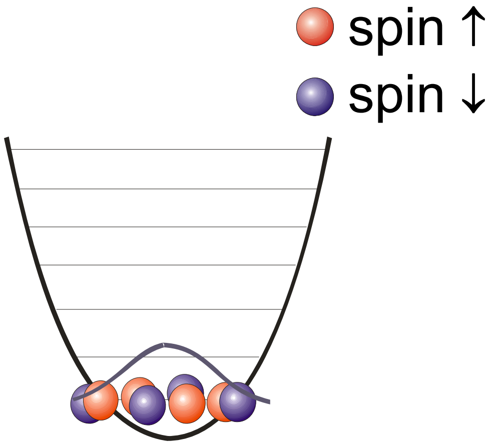
➢ By starting with a gas of fermionic atoms we can explore how bosonic degrees of freedom emerge.

^{40}K, ^{6}Li, …

Making condensates with fermions

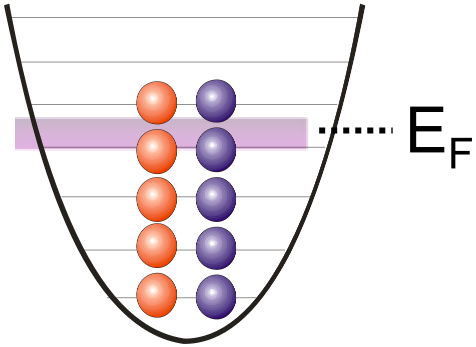
- BEC of diatomic molecules

1. Bind fermions together.
2. BEC



- BCS superconductivity/superfluidity

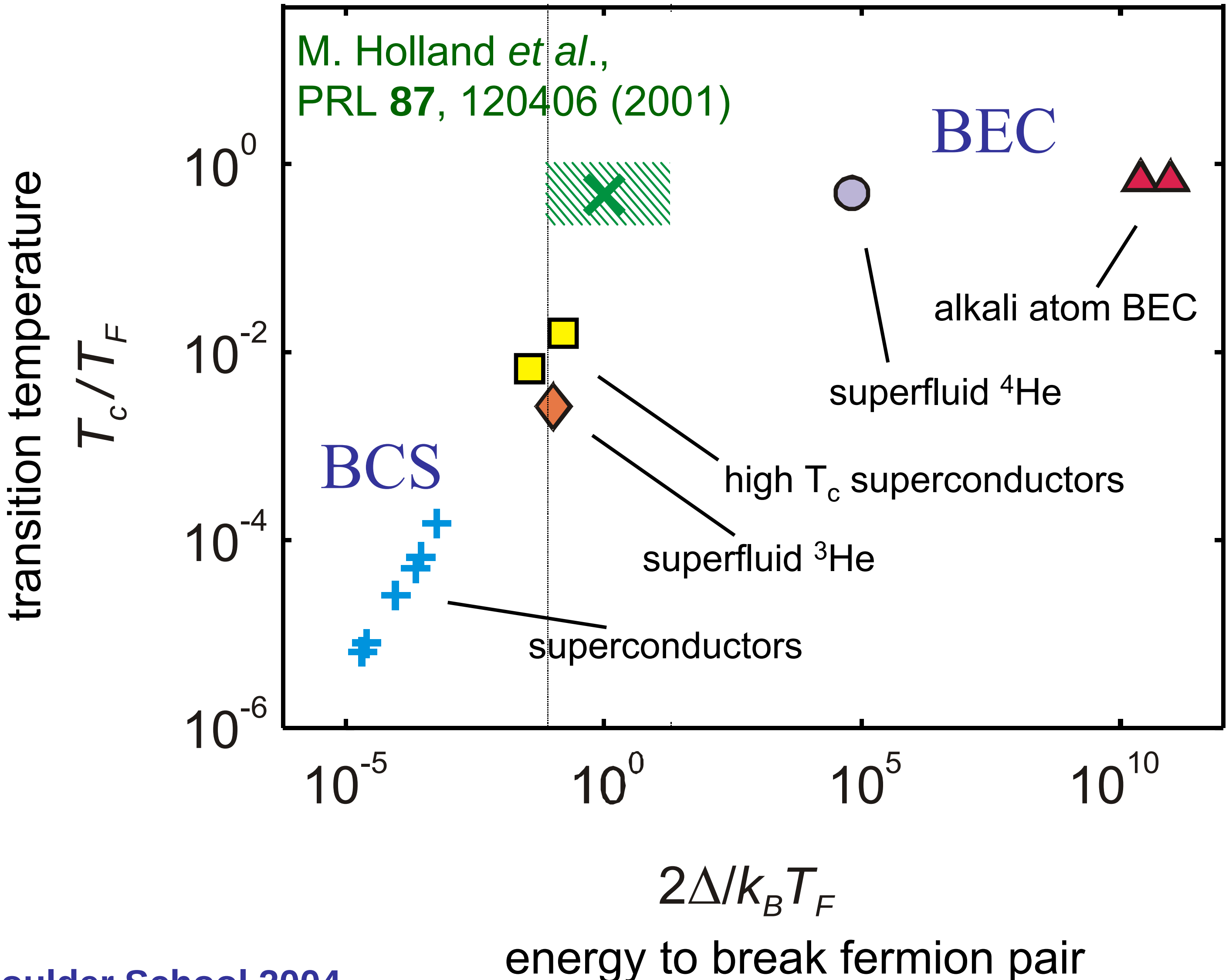
Condensation of Cooper pairs of atoms
(pairing in momentum space,
near the Fermi surface)



- Something in between?

BCS-BEC crossover

BCS-BEC landscape

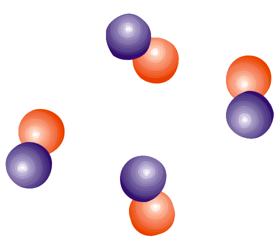
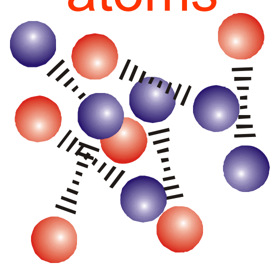
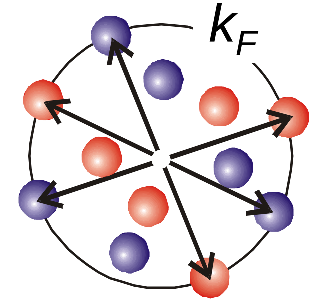


Pairing and Superfluidity

→ Spin is additive: Fermions can pair up and form effective bosons:

$$\Psi(1,\ldots,N) = \hat{A}\,[\,\phi(1,2)\,\phi(3,4)\,\ldots\,\phi(N\text{-}1,N)\,]$$

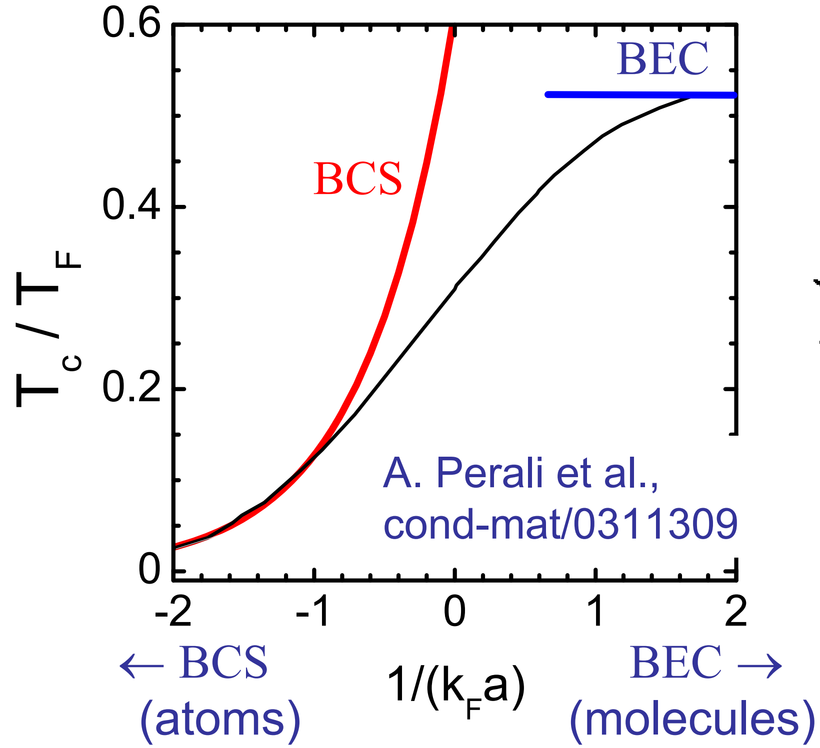
spin ↑
spin ↓

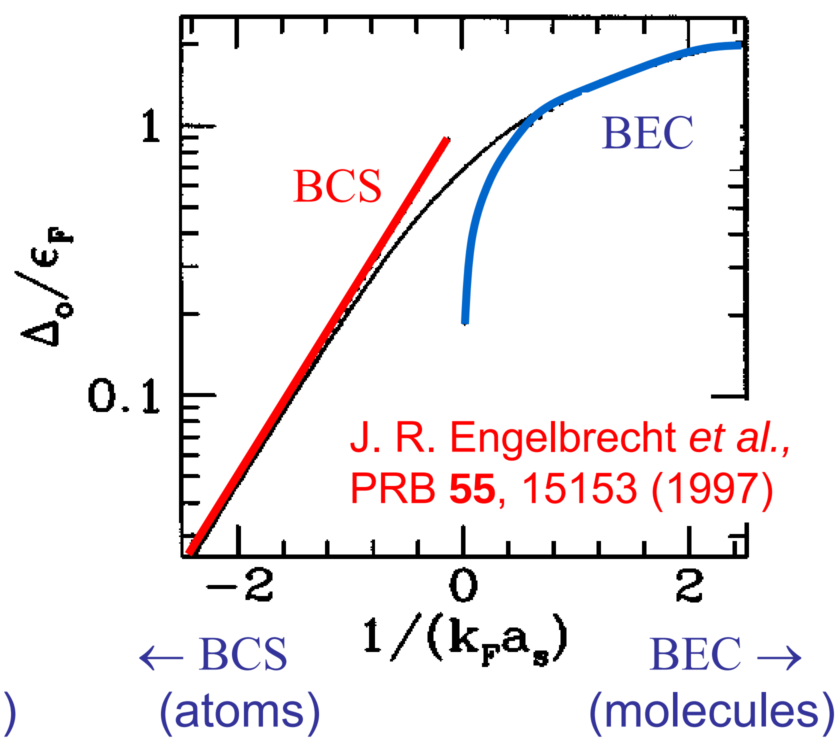
Molecules of fermionic atoms	Generalized Cooper pairs of fermionic atoms	Cooper pairs
		
BEC of weakly bound molecules	**BCS - BEC crossover**	**BCS** superconductivity Cooper pairs: correlated momentum-space pairing

BCS-BEC crossover for example:
Eagles, Leggett, Nozieres and Schmitt-Rink, Randeria, Strinati, Zwerger, Holland, Timmermans, Griffin, Levin …

BCS-BEC crossover

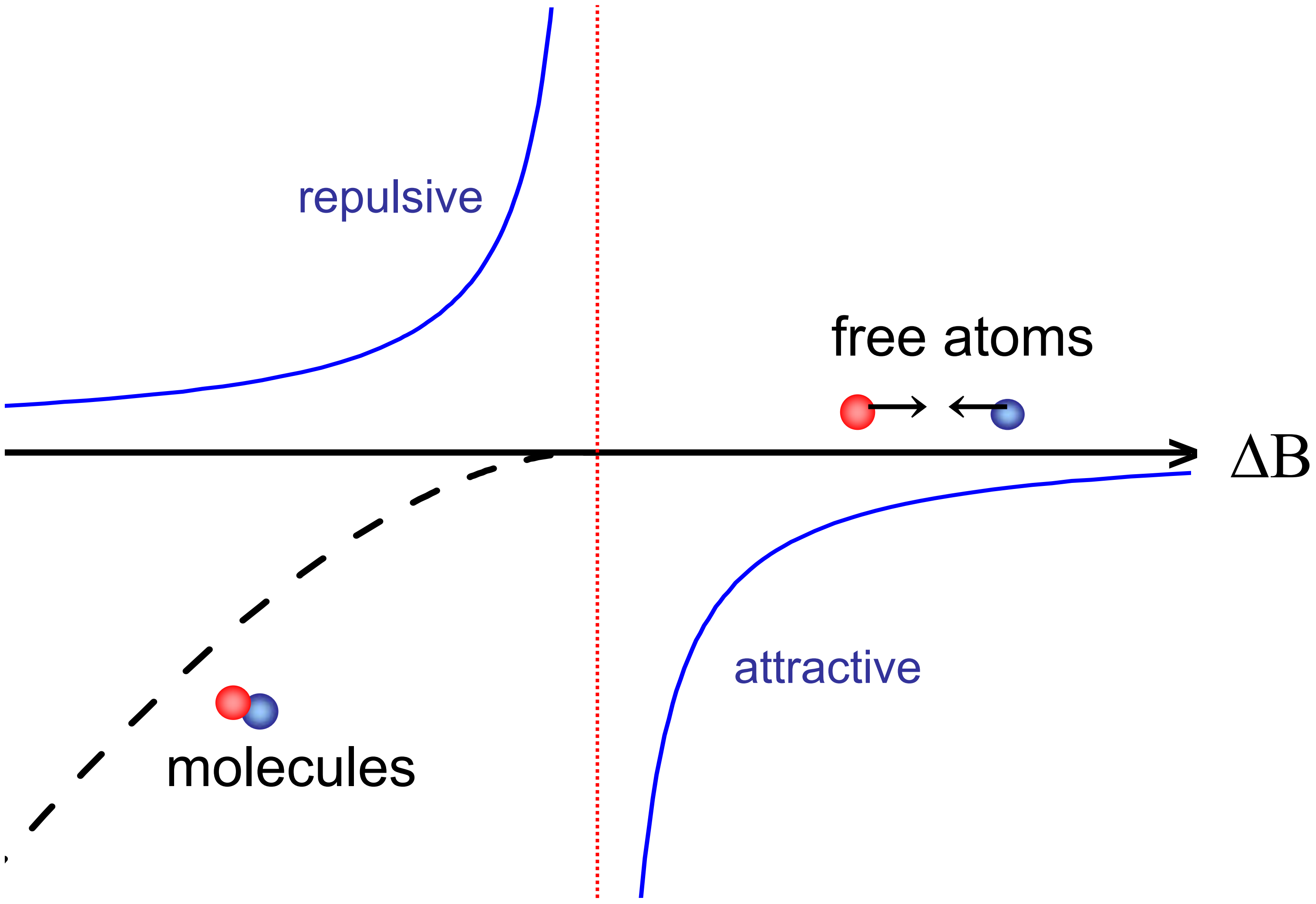
Predict a smooth connection between BCS and BEC



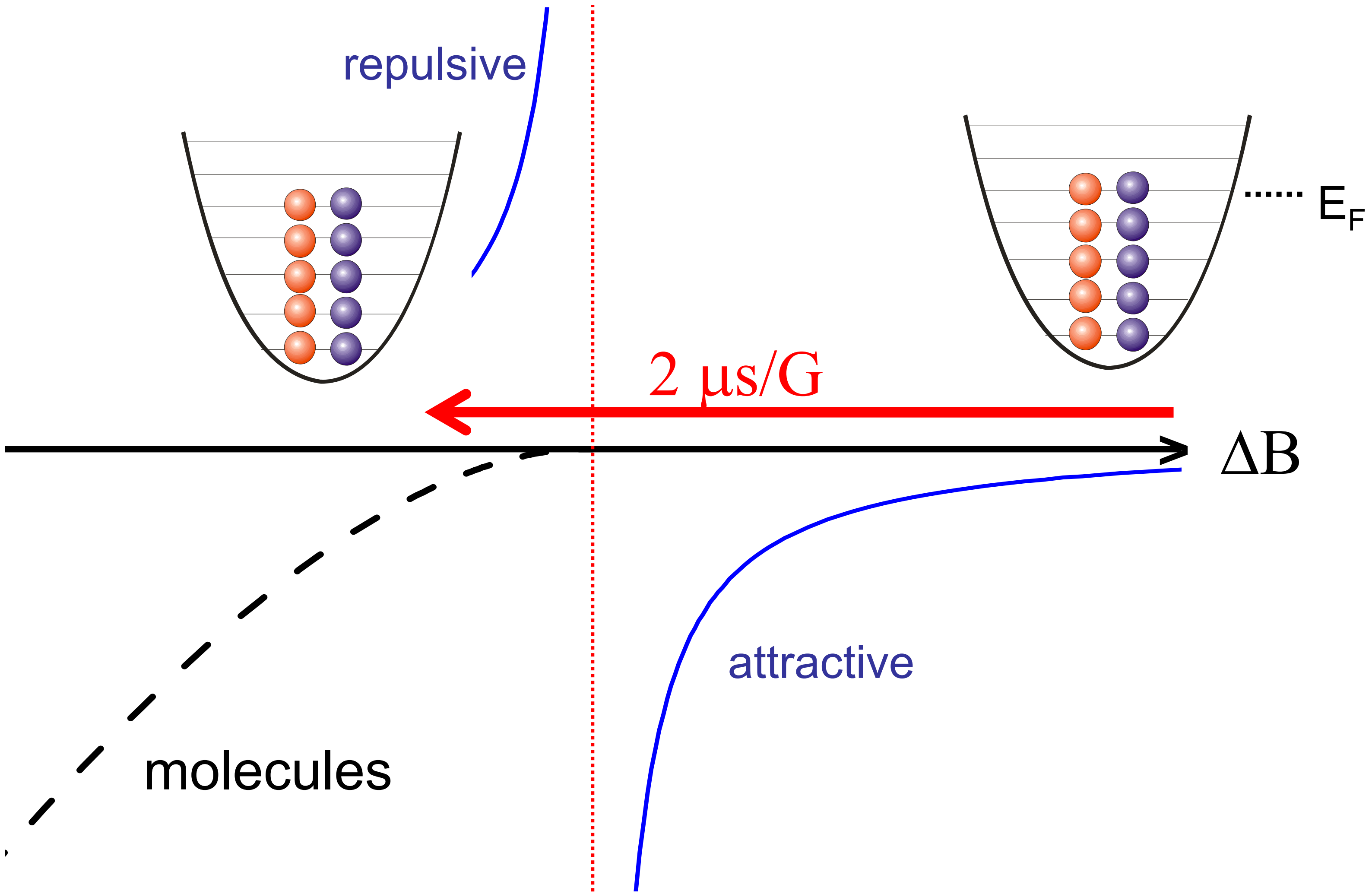


partial list: Eagles, Leggett, Nozieres and Schmitt-Rink, Randeria, Haussman, Strinati, Holland, Timmermans, Griffin, Levin, …

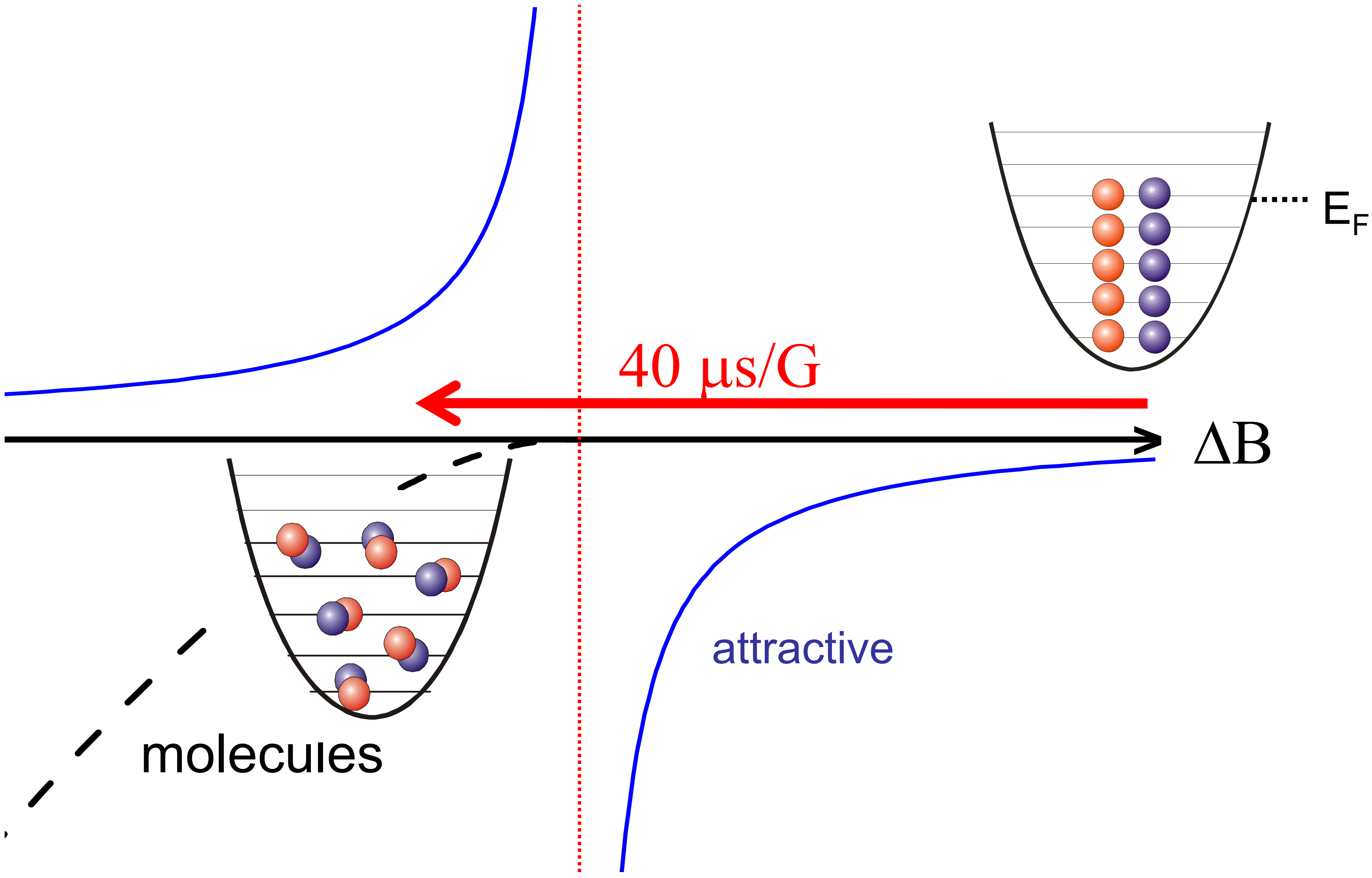
Magnetic-field Feshbach resonance



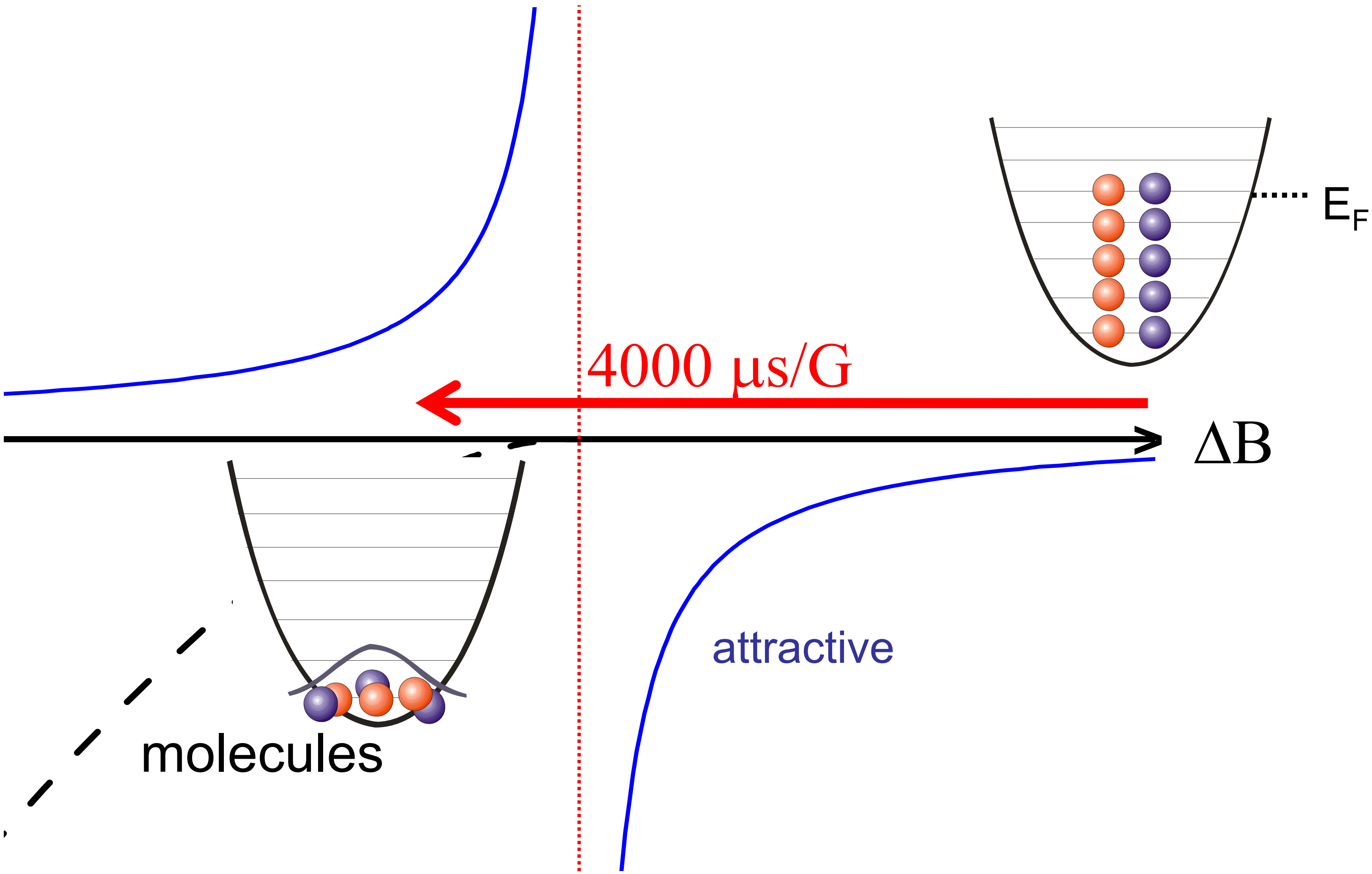
Changing the interaction strength in real time: FAST



Changing the interaction strength in real time: SLOW



Changing the interaction strength in real time: SLOWER

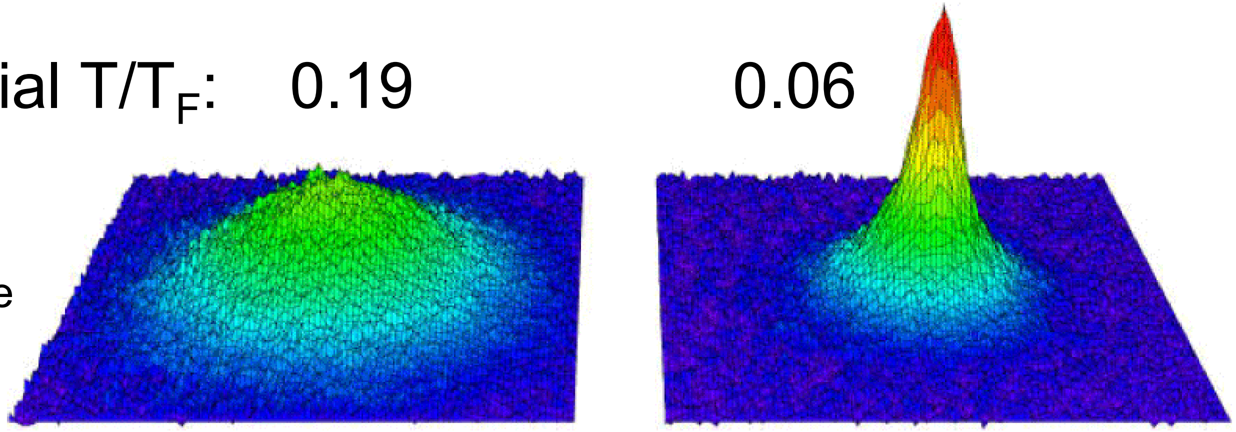


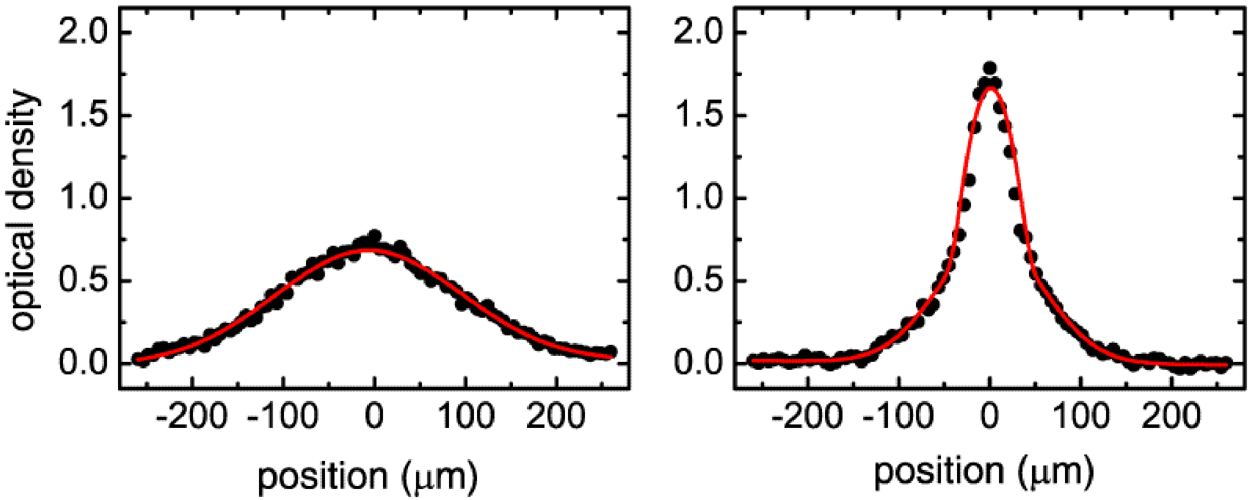
Cubizolles *et al*., PRL **91**, 240401 (2003); L. Carr *et al.,* cond-mat/0308306

Molecular Condensate

initial T/T_F: 0.19 0.06

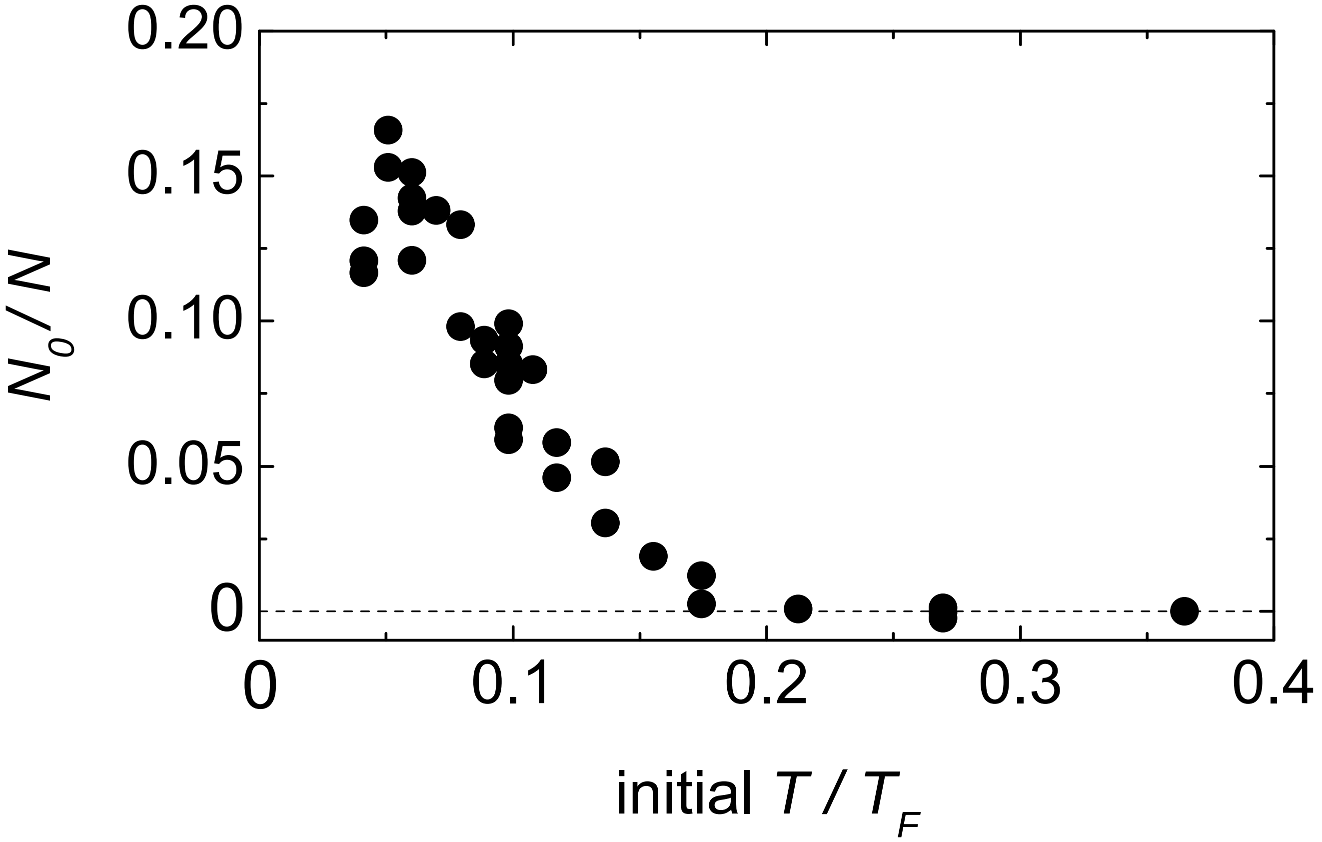
Time of flight absorption image





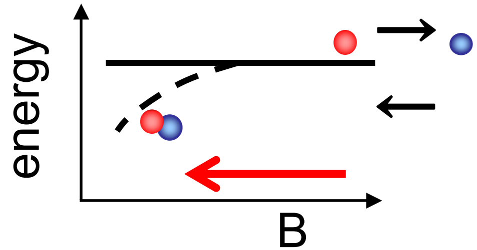
M. Greiner, C.A. Regal, and D.S. Jin, Nature **426**, 537 (2003).

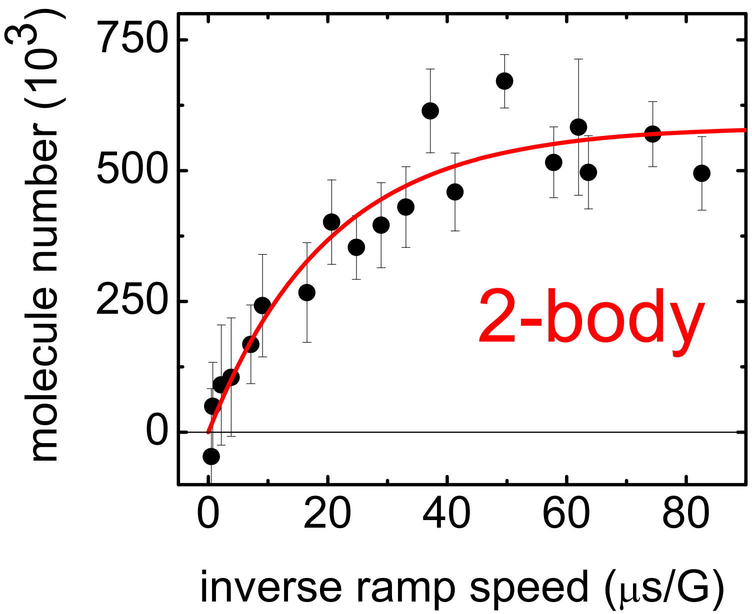
A BEC from a Fermi Sea!



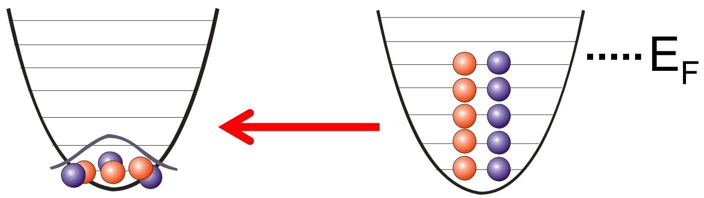
Timescales

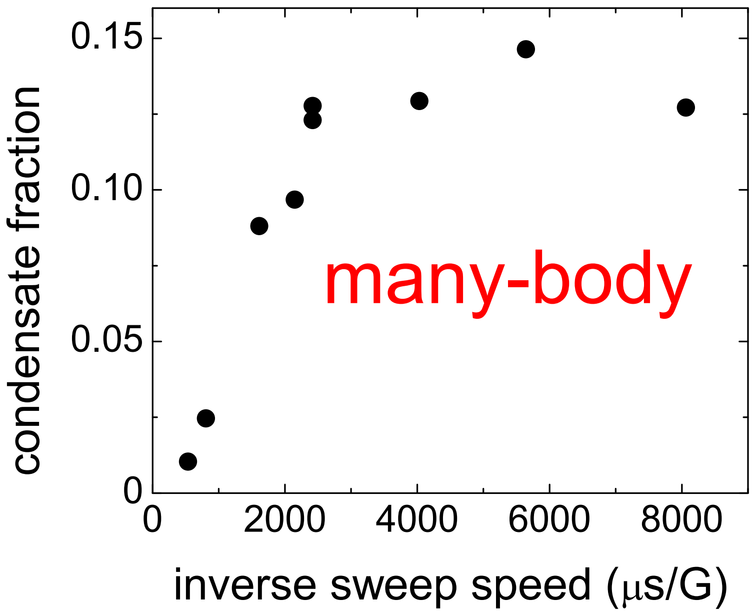
Creating molecules





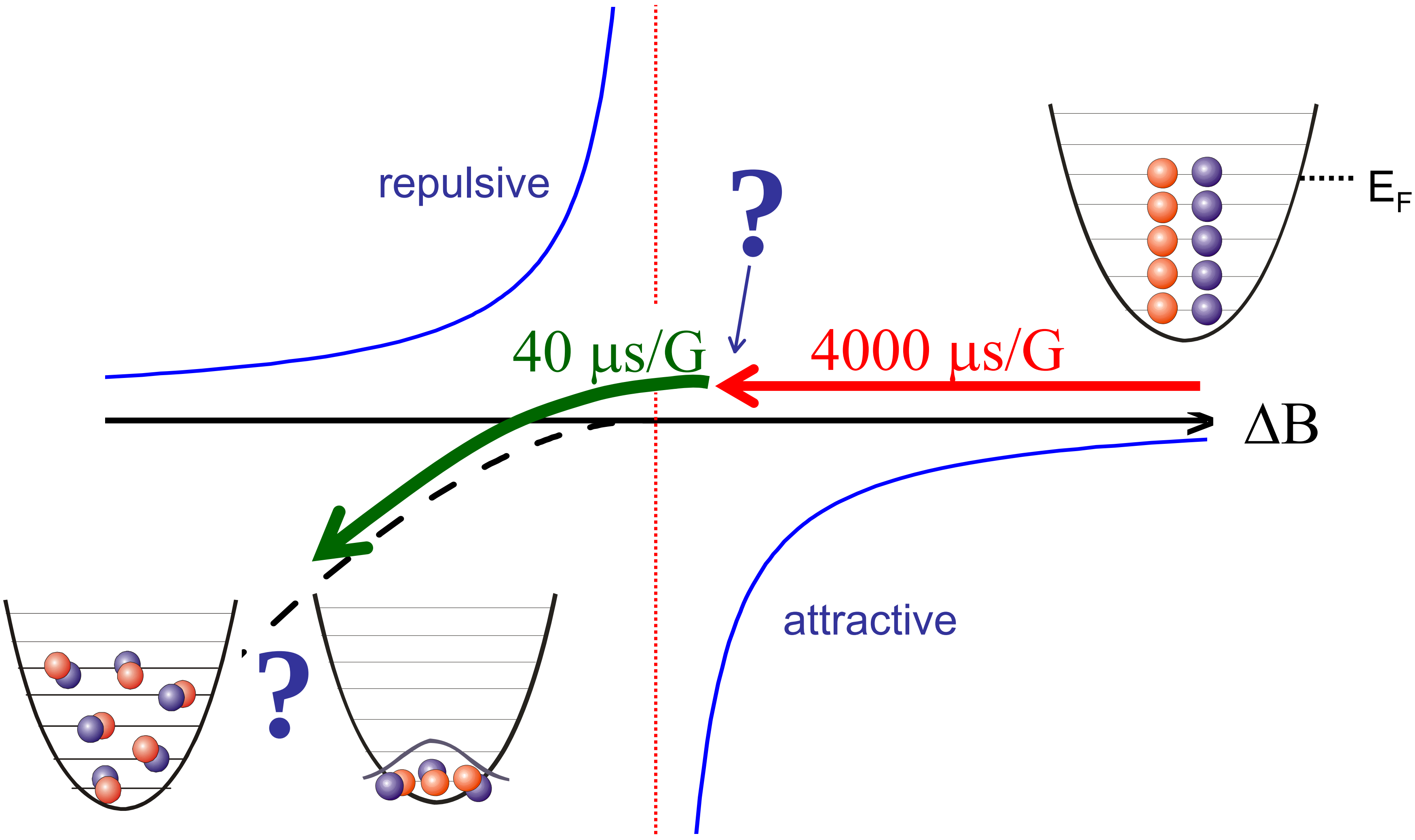
Creating molecular BEC



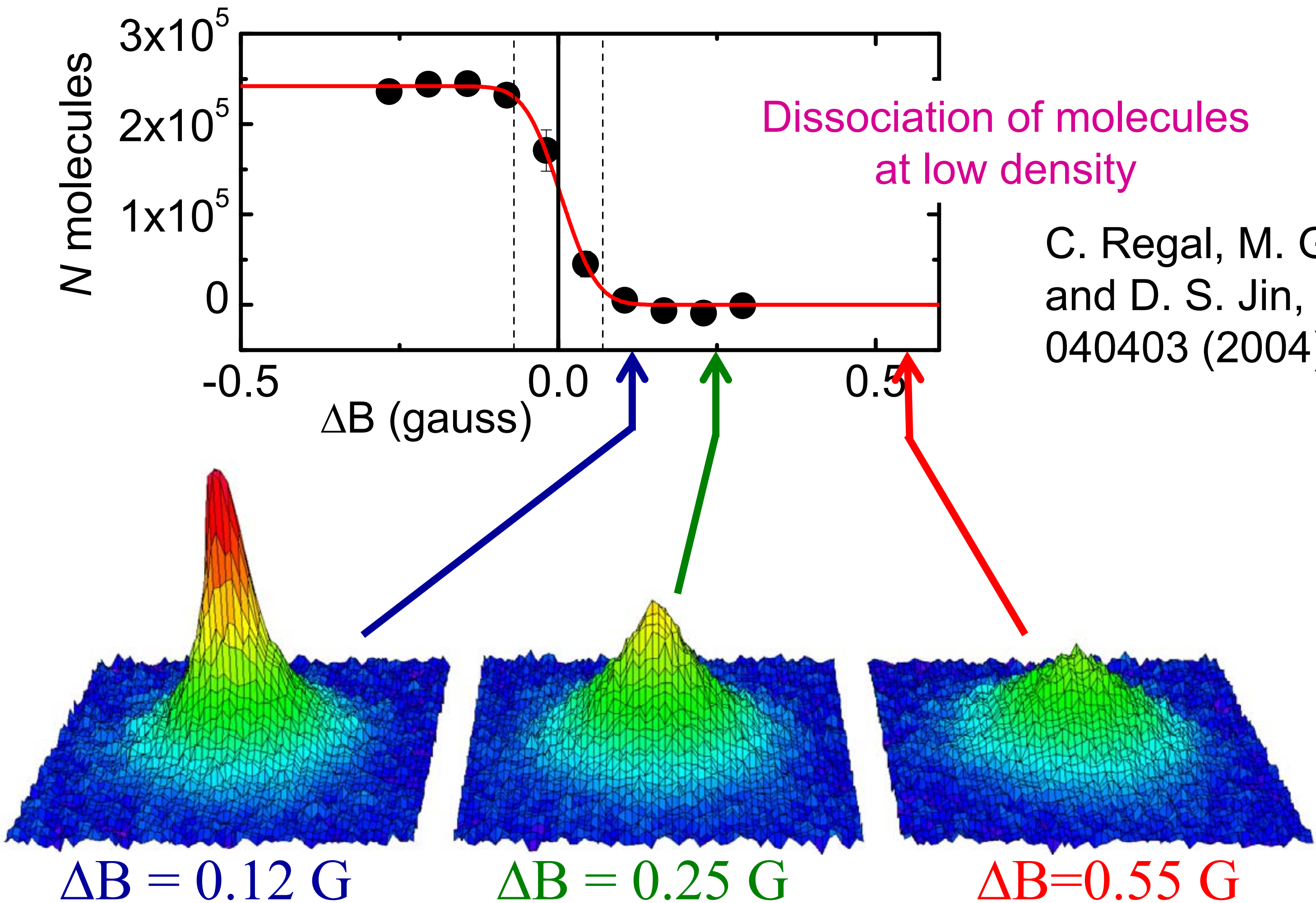


➢ two orders of magnitude difference in timescales!

Observing a Fermi condensate



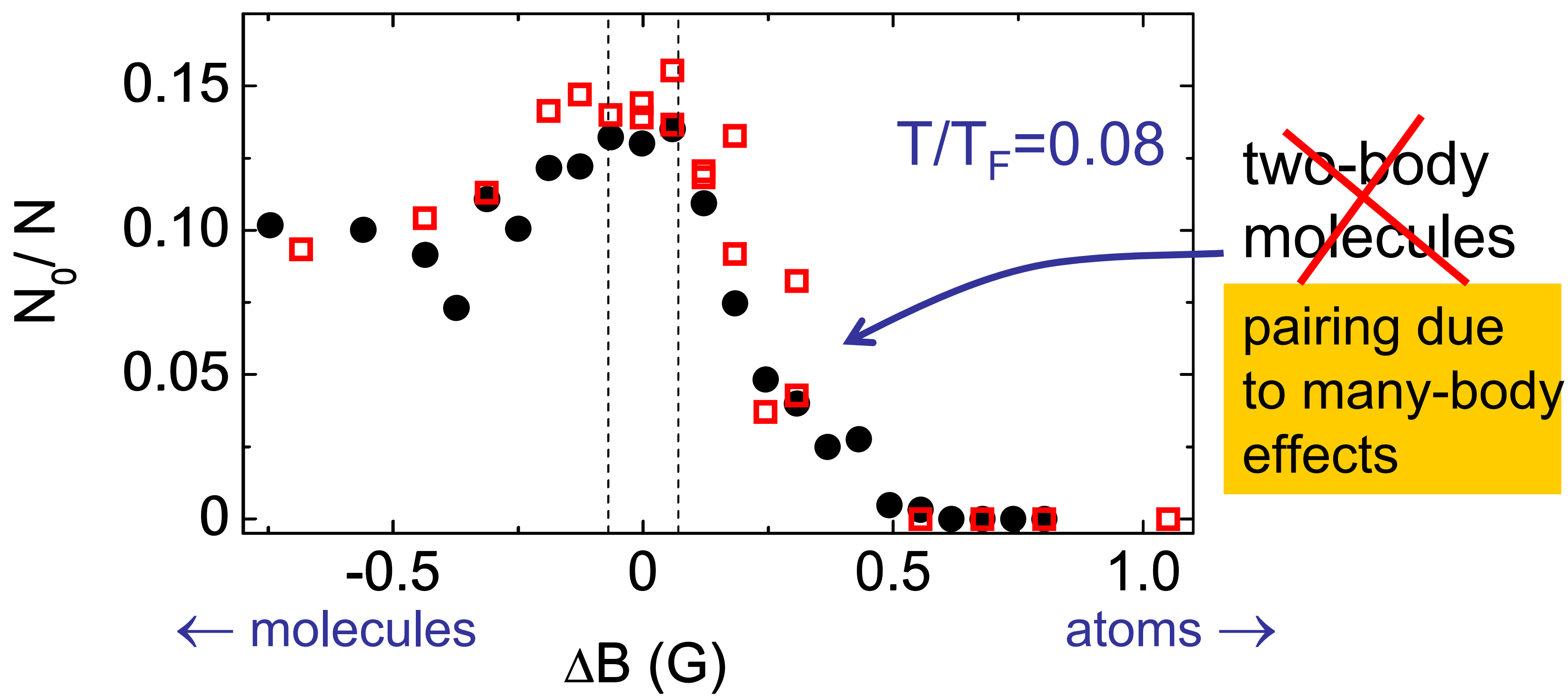
Condensates w/o a two-body bound state



C. Regal, M. Greiner, and D. S. Jin, PRL **92**, 040403 (2004)

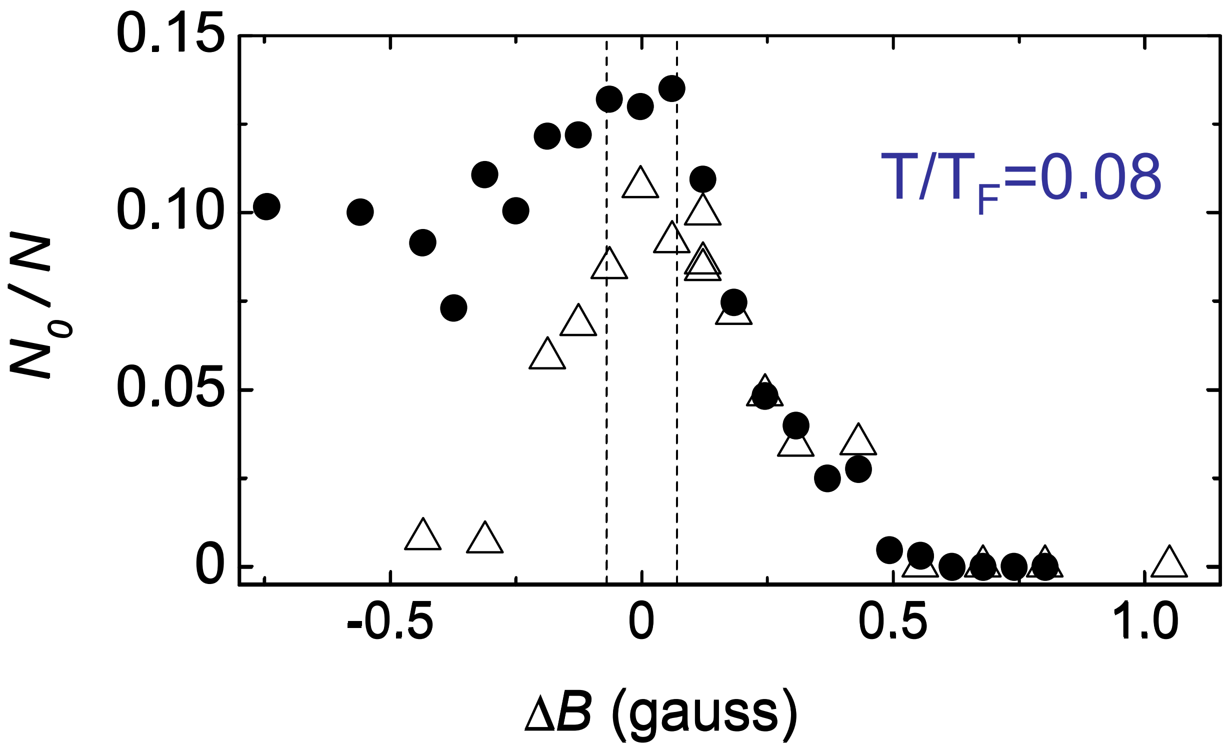
$T/T_F = 0.08$

Fermionic condensate



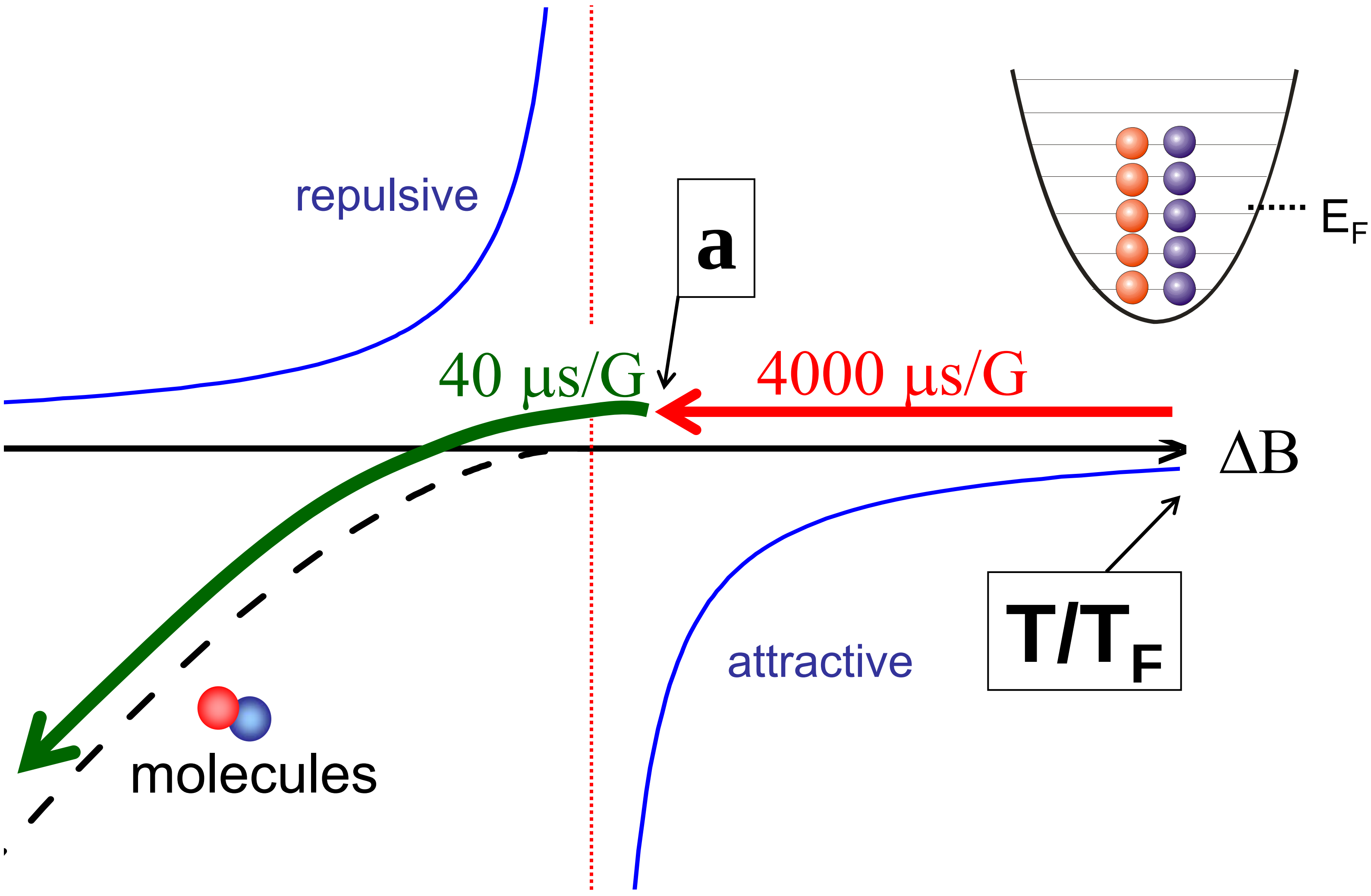
➢ Clearly see condensation on the "atom-side" of the resonance!

Fermionic condensate

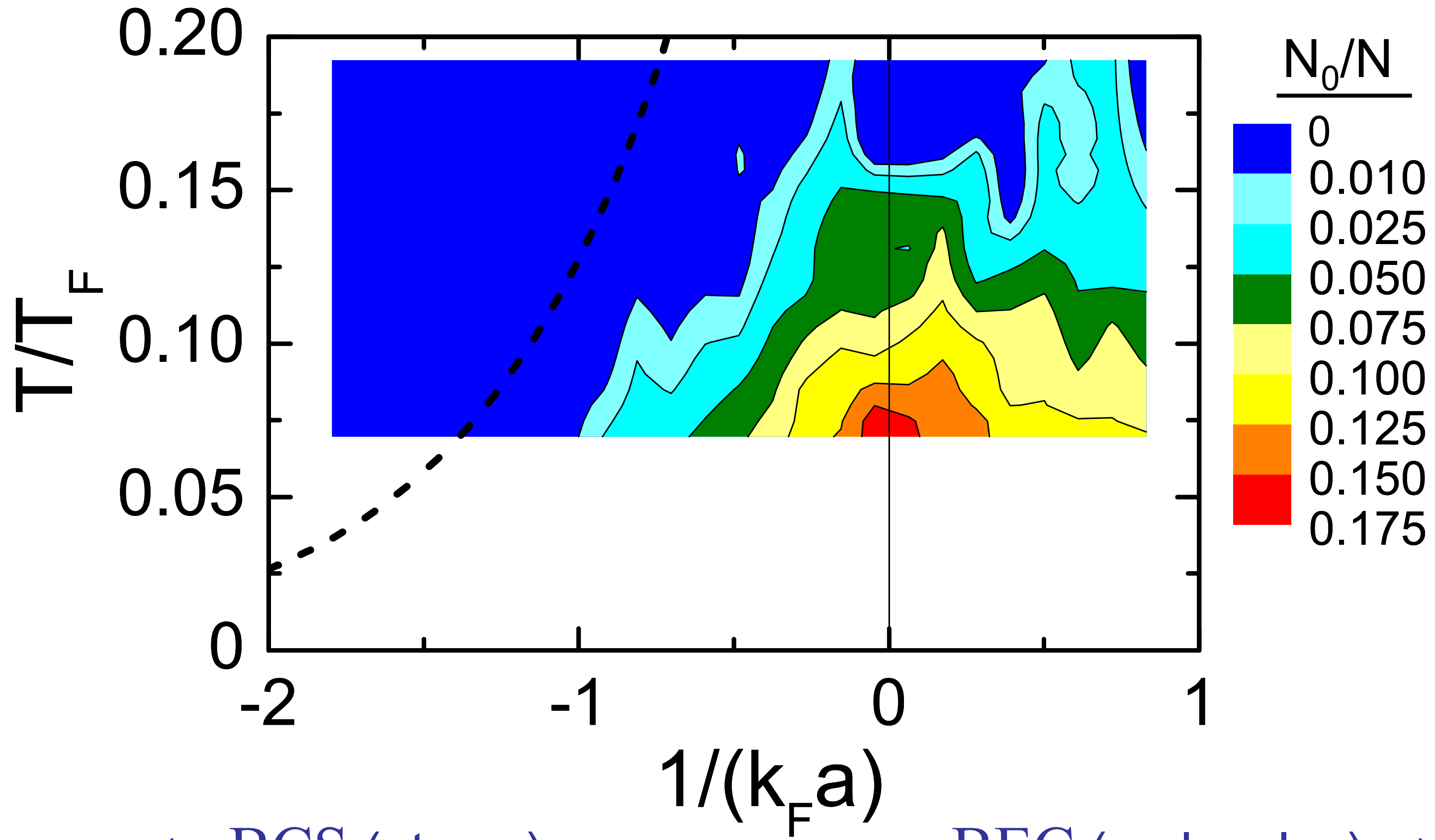


- Clearly see condensation on the "atom-side" of the resonance!
- Condensate lives much longer near resonance than in BEC limit.

Mapping out a phase diagram



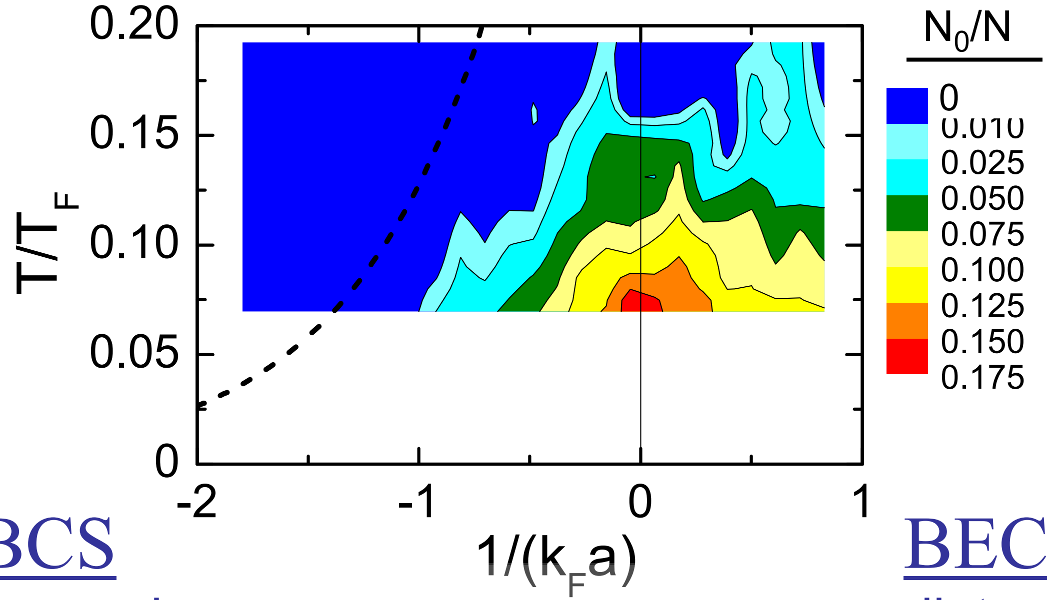
BCS-BEC Crossover



← BCS (atoms) BEC (molecules) →

C. Regal, M. Greiner, and D. S. Jin, PRL **92**, 040403 (2004)

BCS-BEC Crossover



←BCS

Cooper pairs:

- collective, many-body effect
- weakly bound
- (pairing in momentum-space)
- pair size >> $n^{-1/3}$

$T_c/T_F \ll 1$

$T_{pairing} = T_c$

Fermion excitations

BEC→

diatomic molecules:

- two-body effect
- tightly bound
- (pairing in real space)
- pair size << $n^{-1/3}$

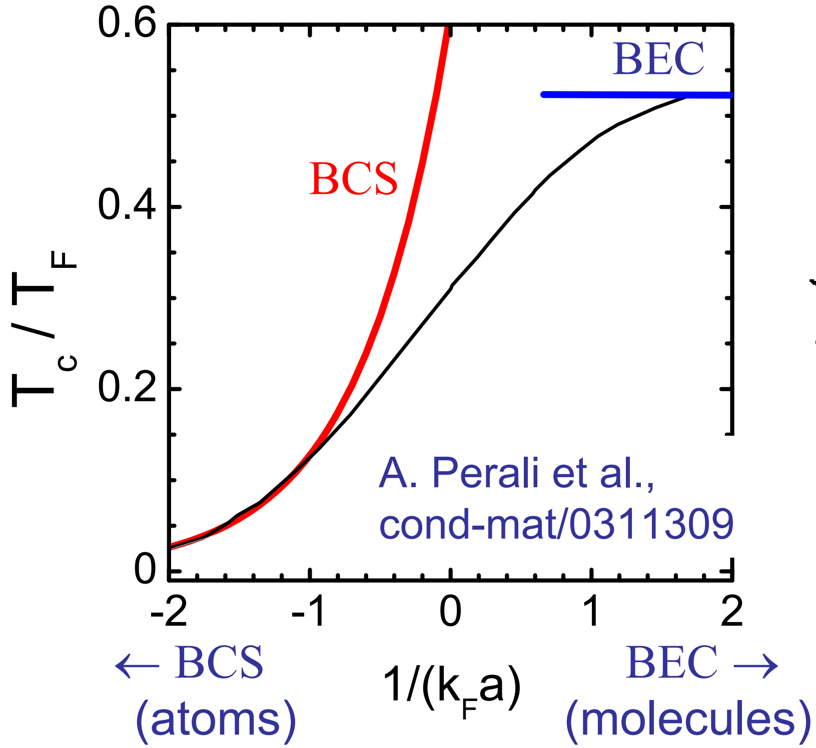
$T_c/T_F \sim 1$

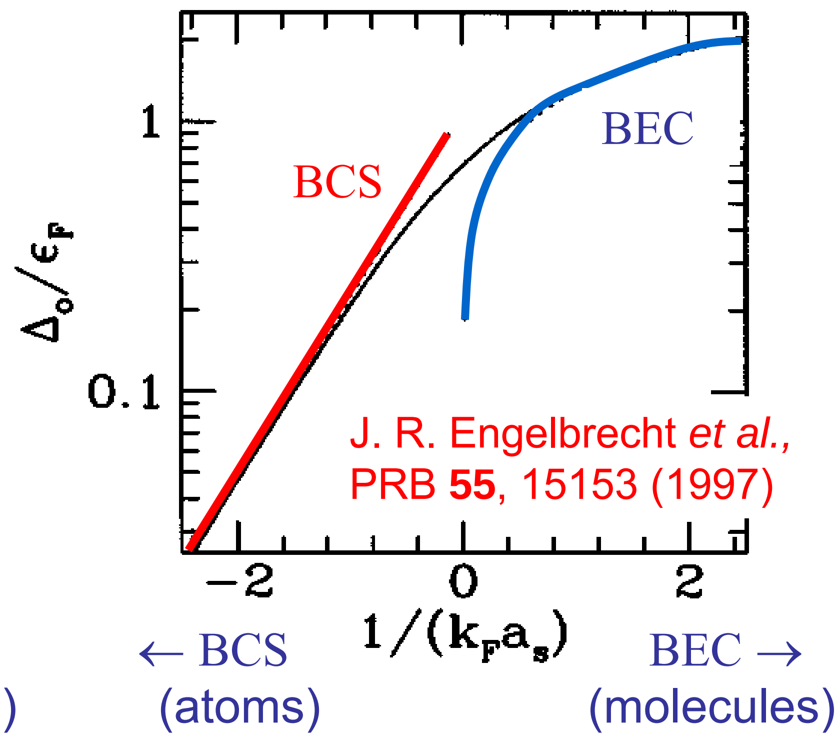
$T_{pairing} \gg T_c$

Boson excitations

BCS-BEC crossover

Predict a smooth connection between BCS and BEC



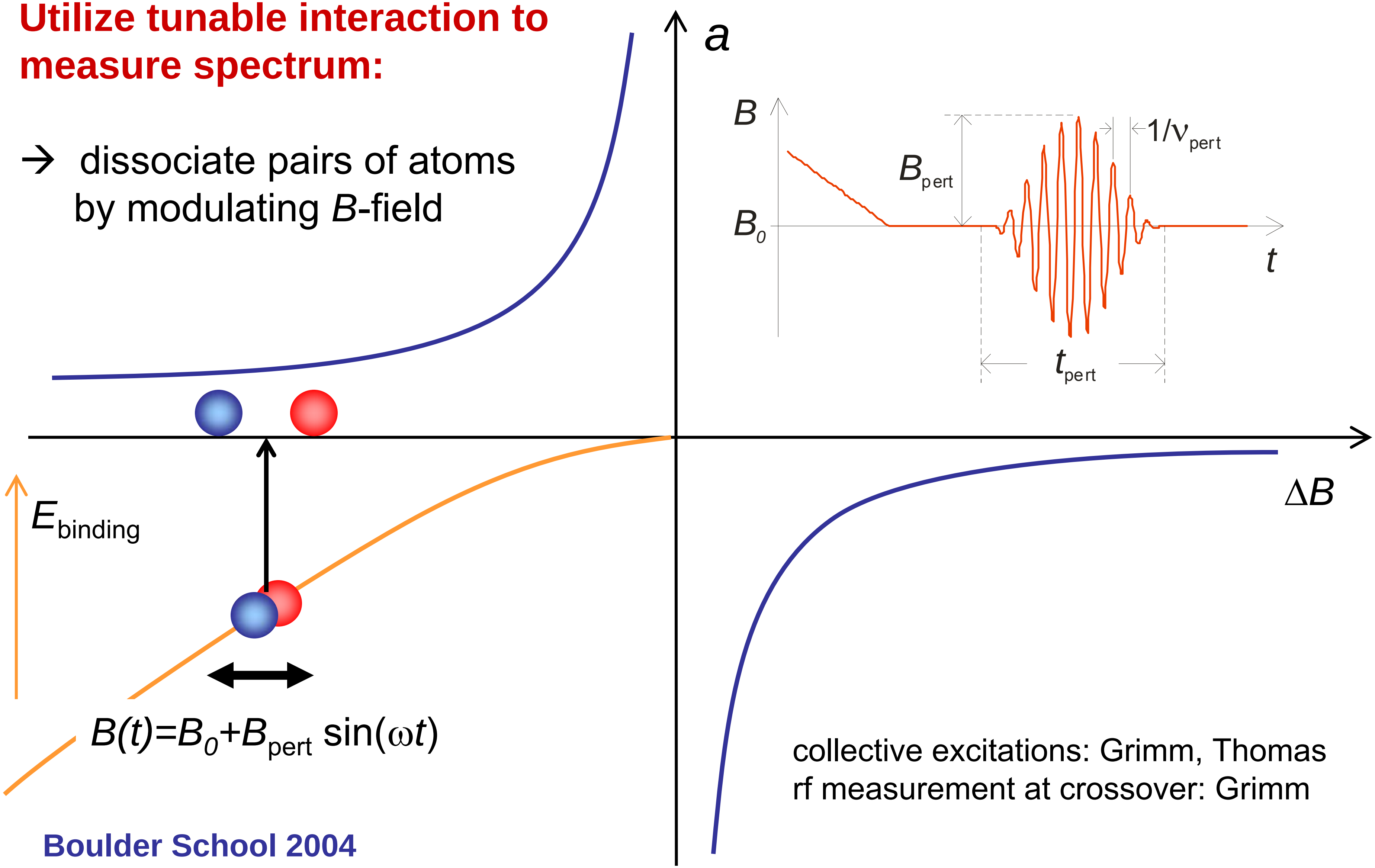


partial list: Eagles, Leggett, Nozieres and Schmitt-Rink, Randeria, Haussman, Strinati, Holland, Timmermans, Griffin, Levin, …

Measuring the excitation spectrum

Utilize tunable interaction to measure spectrum:

→ dissociate pairs of atoms by modulating *B*-field

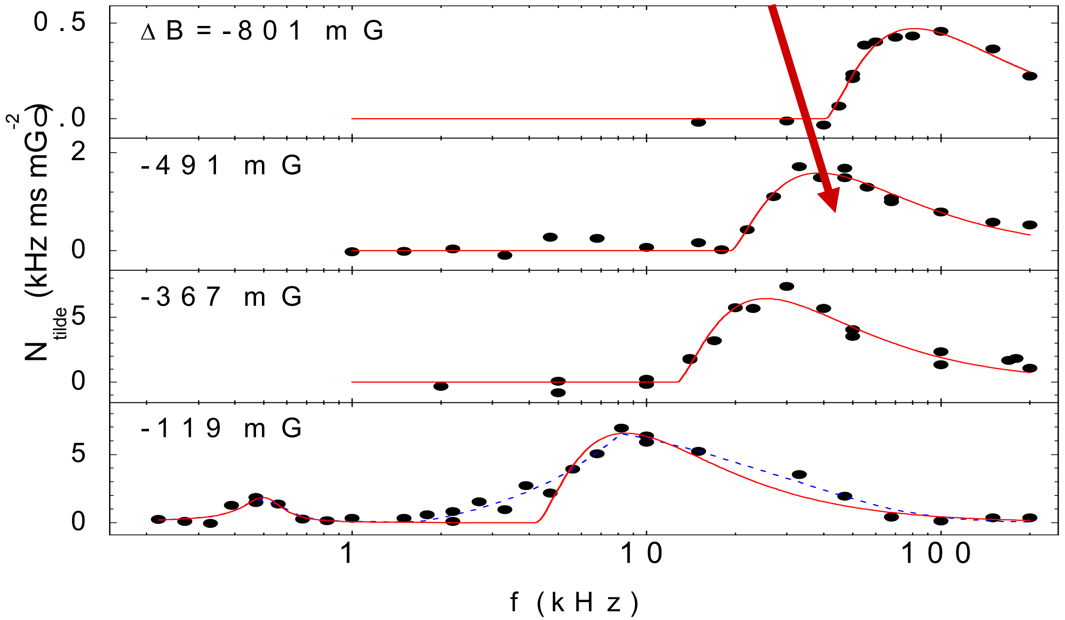


$B(t)=B_0+B_{pert}\sin(\omega t)$

collective excitations: Grimm, Thomas
rf measurement at crossover: Grimm

Excitation spectrum: BEC side

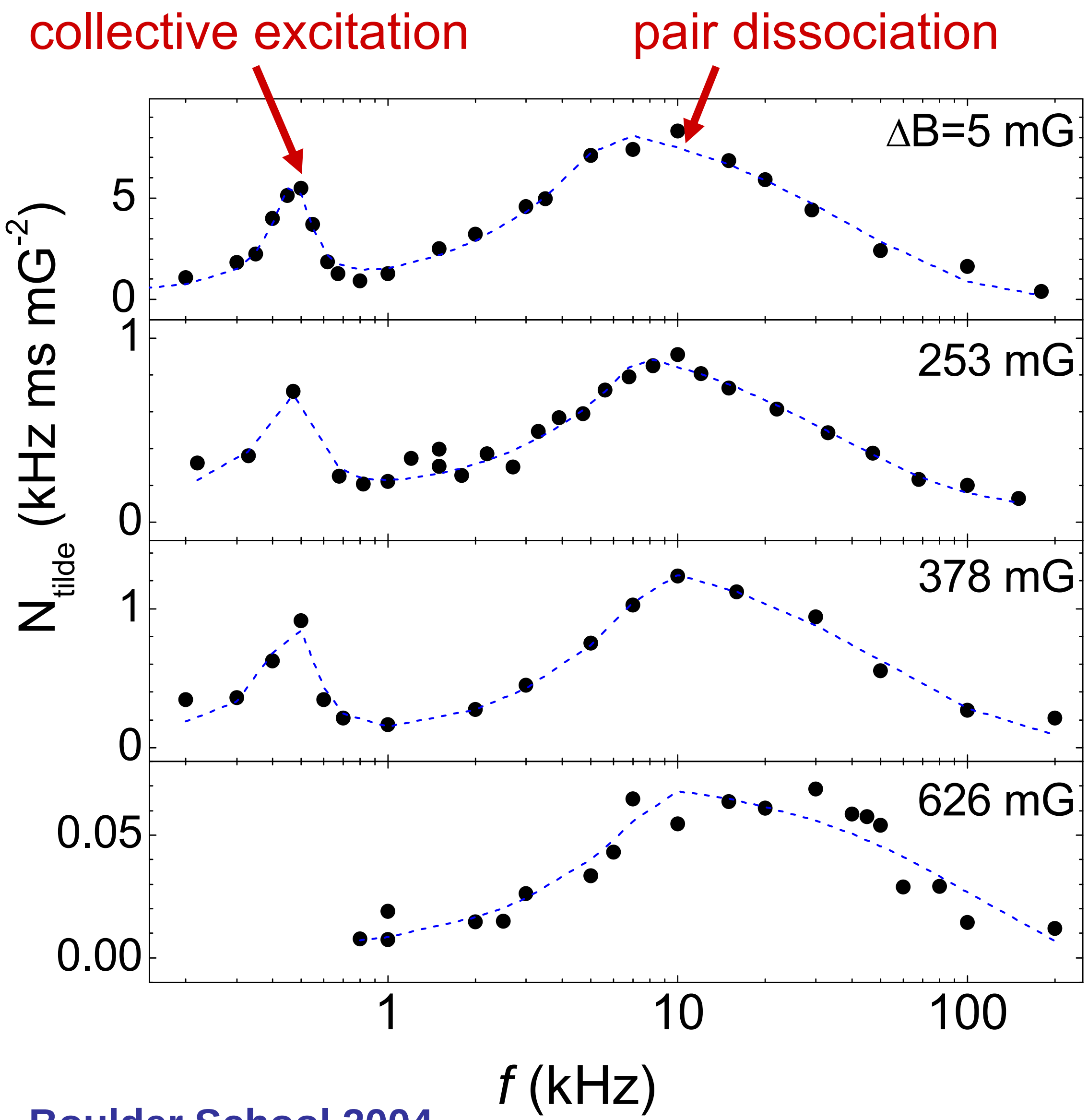
dissociation threshold: molecule binding energy E_B/h



single particle excitation spectrum:

- molecule dissociation

Excitation spectrum: BCS side

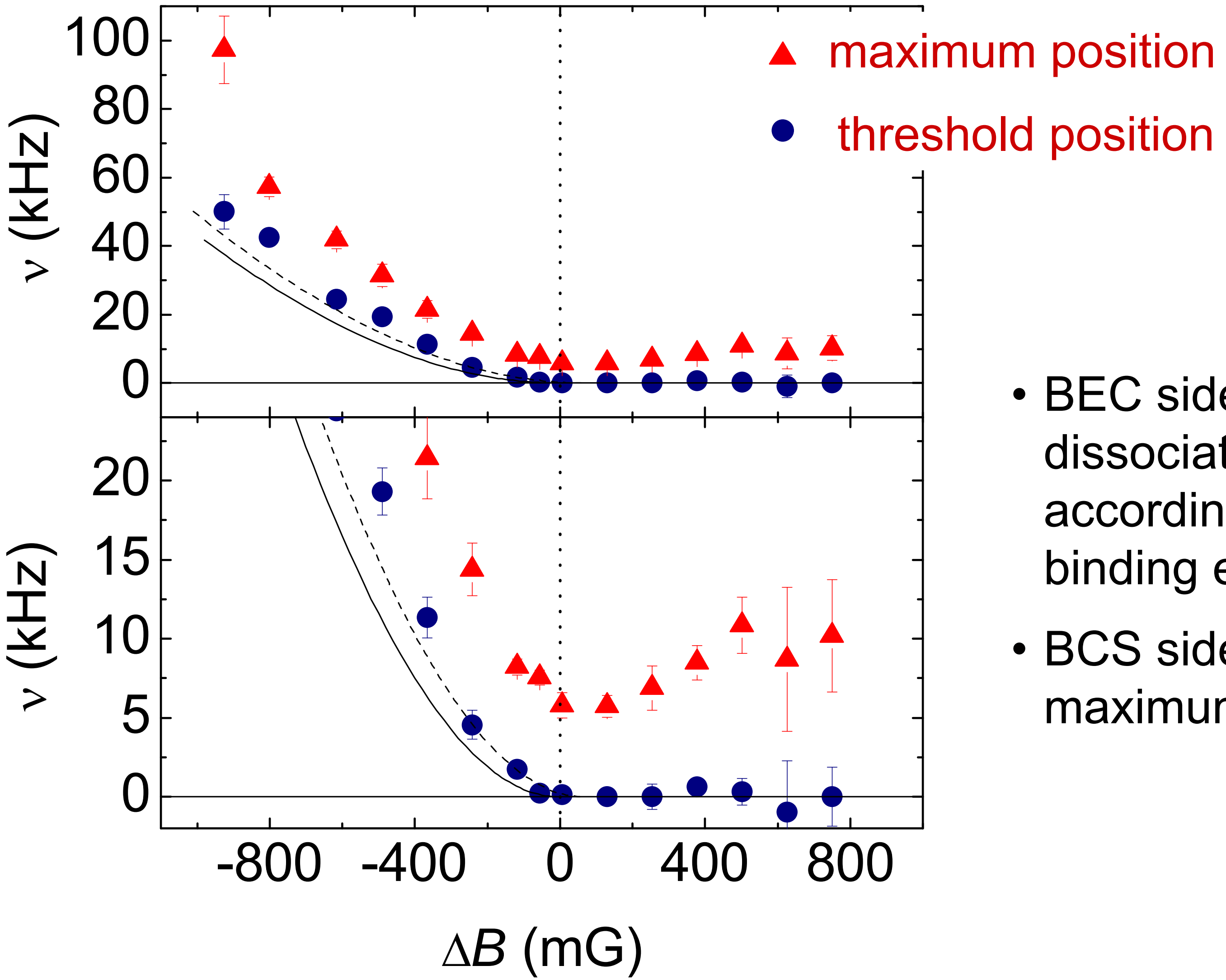


excitation spectrum

→ shows pairing

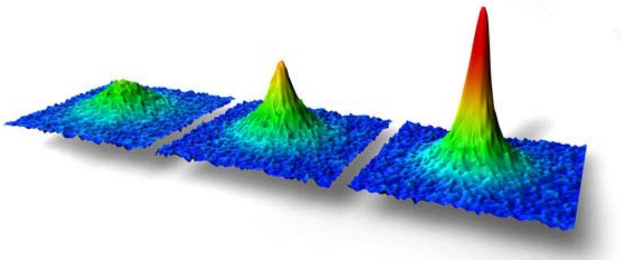
→containing information about crossover regime, no theoretical model available yet

Exctitation spectrum



- BEC side: dissociation threshold according to molecule binding energy
- BCS side: nonzero maximum → pairing

Conclusion



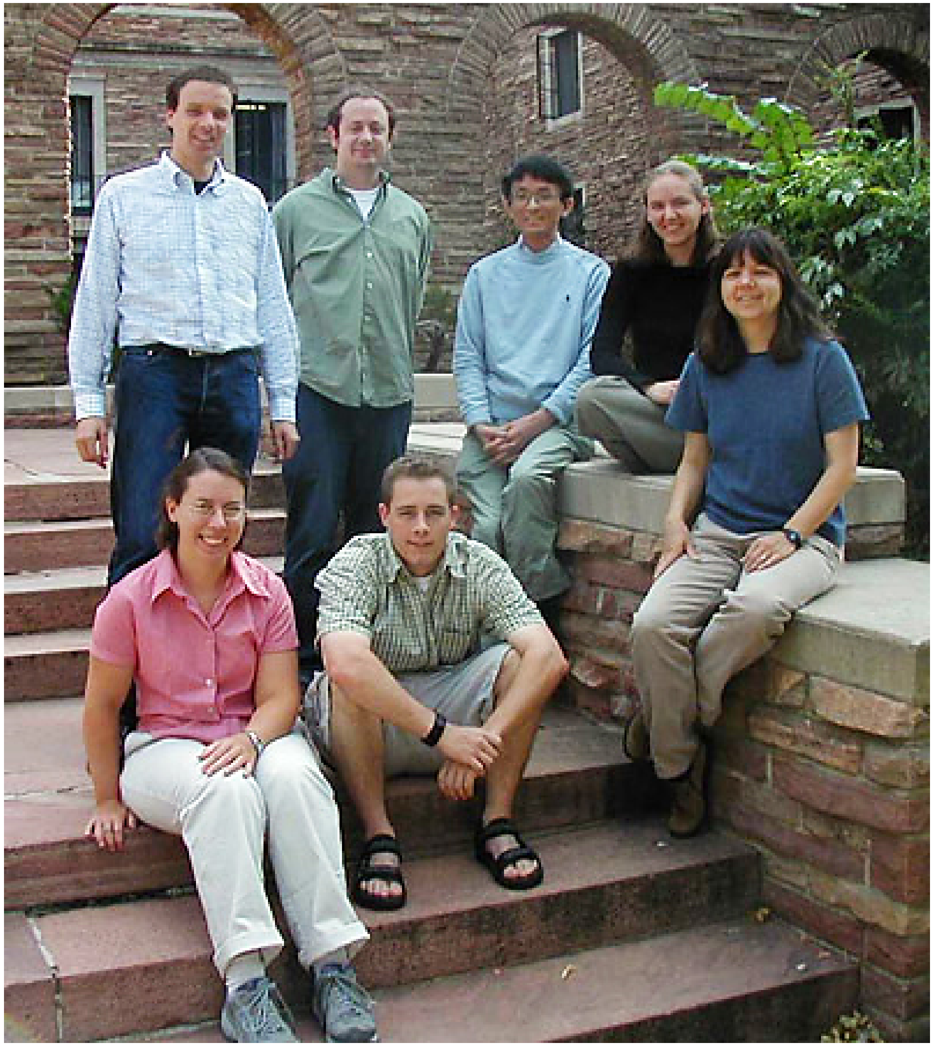
- An atomic Fermi gas provides experimental access to the BCS-BEC crossover region.
  - Fermi gas ↔ molecular BEC interconversion has been explored.
  - Condensates of fermionic atom pairs have been achieved !
    - “Cooper pairs” with strong interactions
    - “BEC” with extremely weakly bound molecules

Next…

Many opportunities for further experimental and theoretical work ...

Current group members:

M. Greiner
J. Goldwin
S. Inouye
C. Regal
J. Smith
M. Olsen



The End.