Cold Atoms Experiments

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JILA, NIST and the University of Colorado

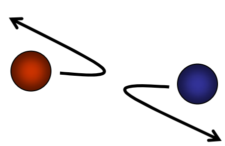
$ NSF, NIST

Why study atomic gases?

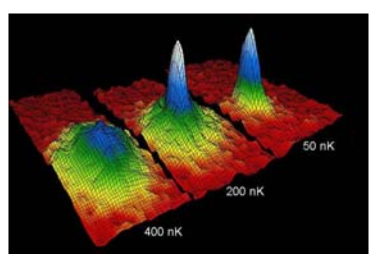
Investigate many-body quantum physics
with a model system

- low density, low temperature
  - well understood microscopics

$n \sim 10^{13}\ \text{cm}^{-3}$, $T \sim 100$ nK

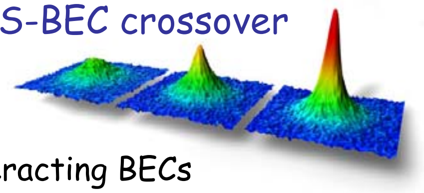


- unique experimental tools
  - controllable interactions

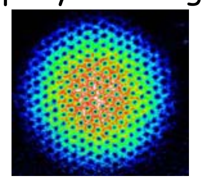


Lots of exciting experiments:

* Fermi gas and BCS-BEC crossover

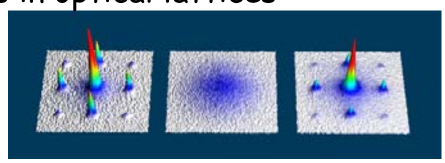


Rapidly rotating BECs



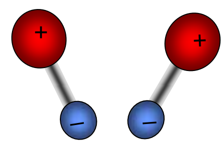
Strongly interacting BECs

Atoms in optical lattices



1d and 2d gases

Cold molecules



Outline:

I. Introduction

II. Controlling Interactions

III. BCS-BEC Crossover

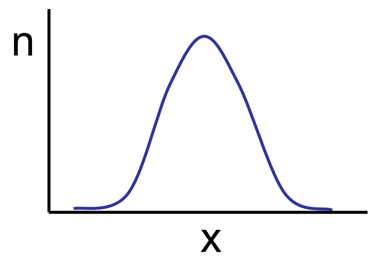
IV. Recent Experiments at JILA

Some Numbers

Numbers:

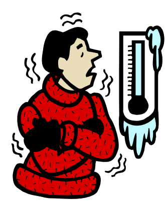
atoms	electrons
$n = 10^{13}$	10^{23} cm^{-3}
$d = 10^{-7}$	10^{-10} m
$N = 10^{5}$	∞
$m = 7\times10^{-26}$	9×10^{-31} kg
$T_F = 10^{-6}$	10^{5} K
$v_F = 10^{-2}$	10^{6} m/s
$T/T_F = 0.05$	<0.001

Trap ⇨ inhomogeneous density



Important properties

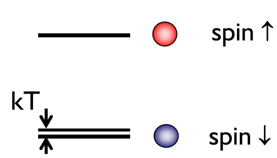
Ultracold (100 nK!) gas :



1. Meta-stable.

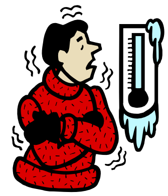
   True ground state is a solid.

2. Spin degree of freedom is frozen out.

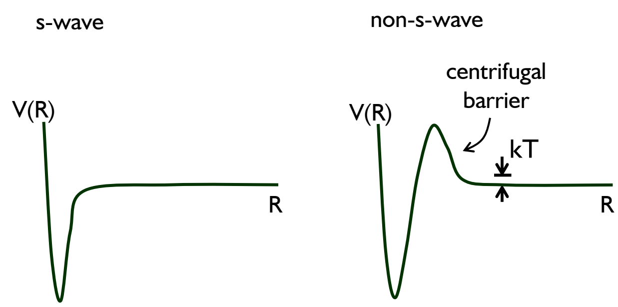


3. Contact interactions (collisions) are s-wave.

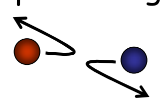
Contact Interactions

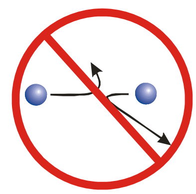


Collisions/interactions are only s-wave.



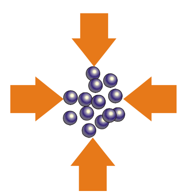
Spin-polarized fermions stop colliding.



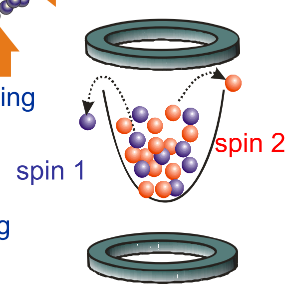


Techniques

1. Laser cooling and trapping

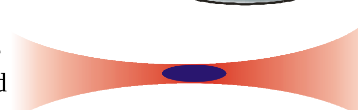


2. Magnetic trapping & evaporative cooling



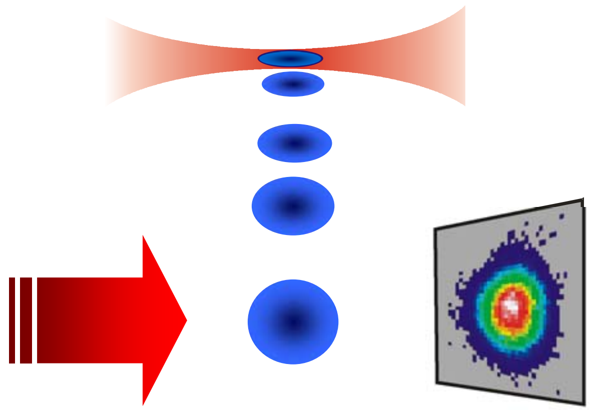
3. Optical trapping & evaporative cooling

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



Probing the ultracold gas

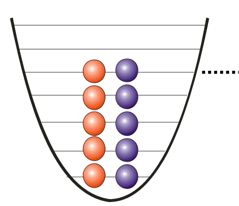
Time-of-flight absorption imaging



Fermi gas of atoms

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

many experimental groups: ^{40}K, ^{6}Li, ^{173}Yb, ^{3}He*



$E_F = k_B T_F$

$E_F = hf_{trap}(6N)^{1/3}$

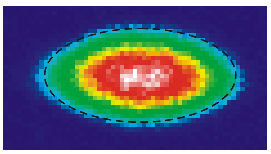
Fermi sea of atoms

$T \sim 0.05\ T_F$

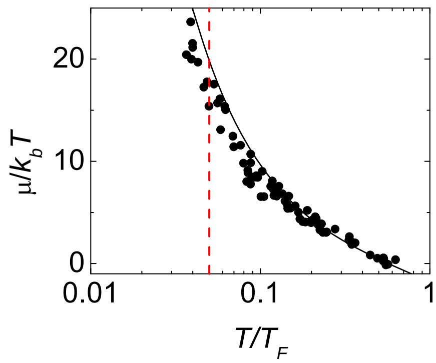
Quantum degeneracy

Get T from the measured velocity distribution.

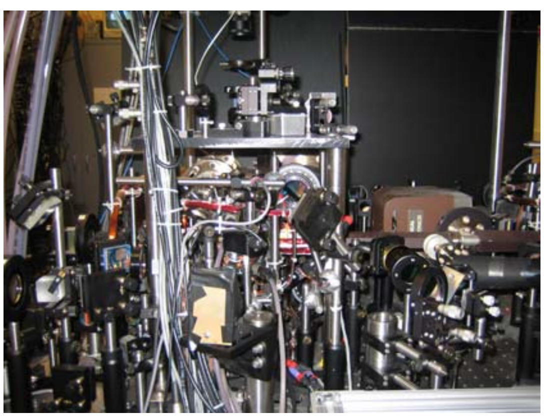
N = 4 ·10^5 , T = 16 nK
T/T_{Fermi} = 0.05

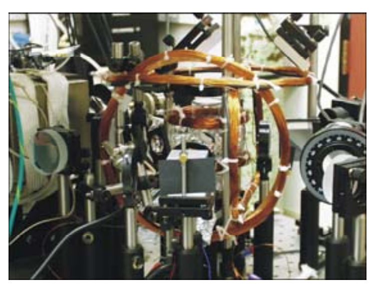


reach T/T_{Fermi} ~ 0.05



Apparatus

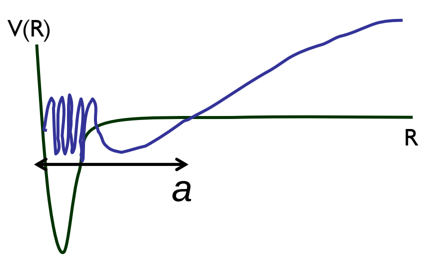




II. Controlling Interactions

Interactions

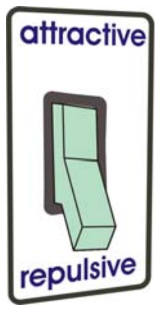
s-wave scattering length, a

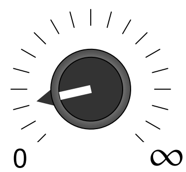


a > 0 repulsive, *a* < 0 attractive
Large |*a*| → strong interactions

Controlling interactions

a > 0 repulsive, *a* < 0 attractive
Large |*a*| → strong interactions



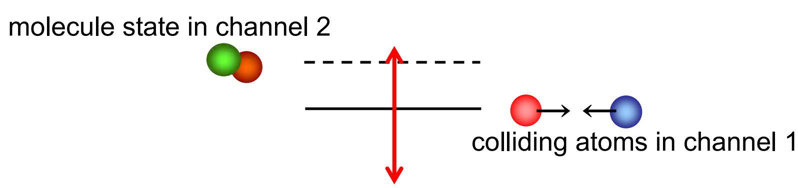


scattering length, a

^{40}K

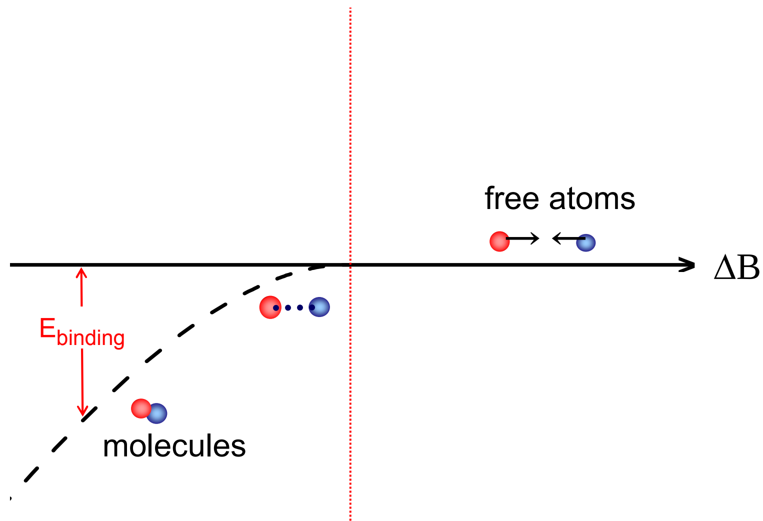
Magnetic-field Feshbach resonance

A magnetic-field tunable atomic scattering resonance

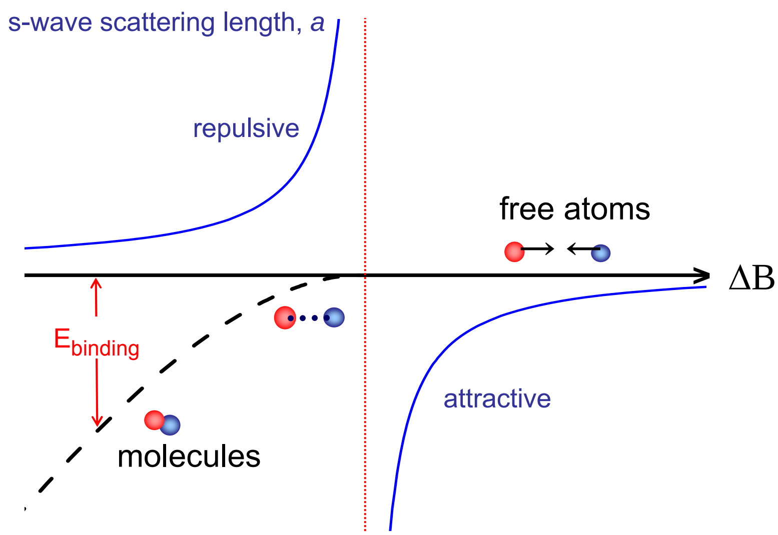


Channels are coupled by the hyperfine interaction.

Magnetic-field Feshbach resonance

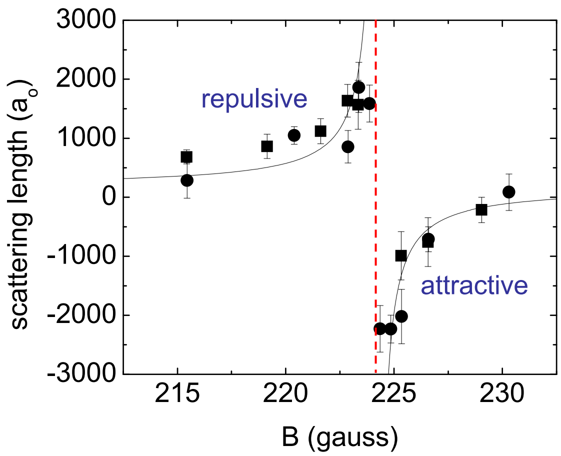


Magnetic-field Feshbach resonance



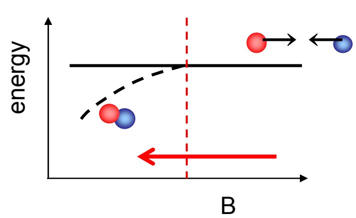
Magnetic-field Feshbach resonance

- spectroscopic measurement of the mean-field energy shift

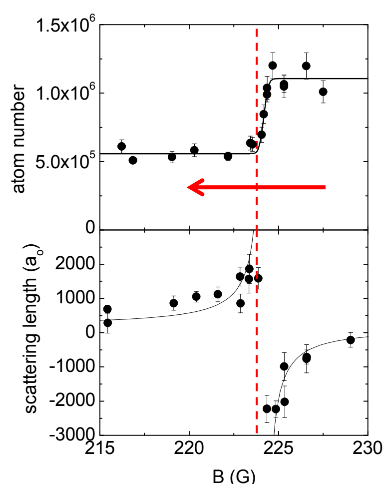


C. A. Regal and D. S. Jin, PRL **90**, 230404 (2003)

Turning atoms into molecules

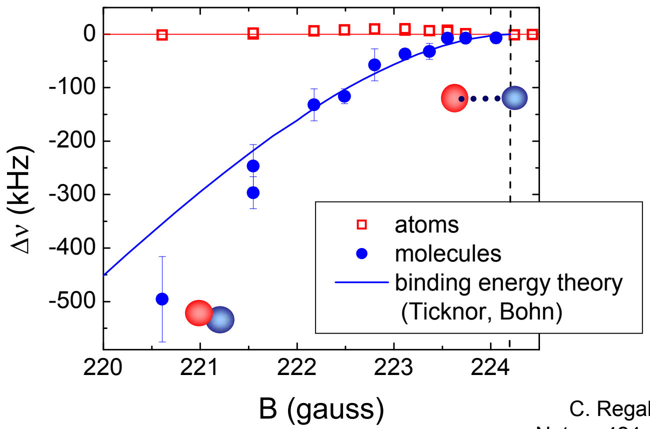


Ramp across Feshbach resonance from high to low B



The atoms reappear if we sweep back to high B.

Molecule binding energy

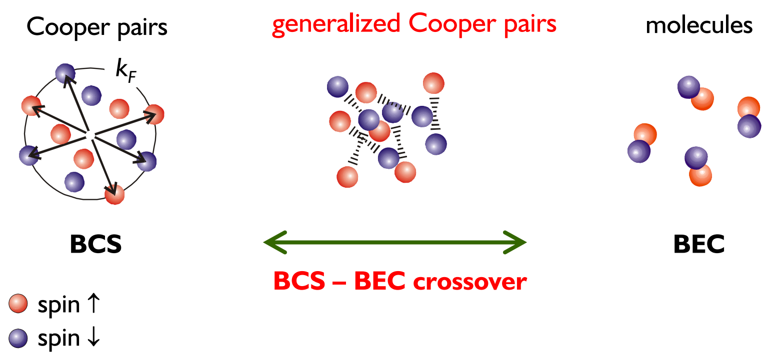


C. Regal *et al.*
Nature 424, 47 (2003)

- extremely weakly bound !
- long lifetime

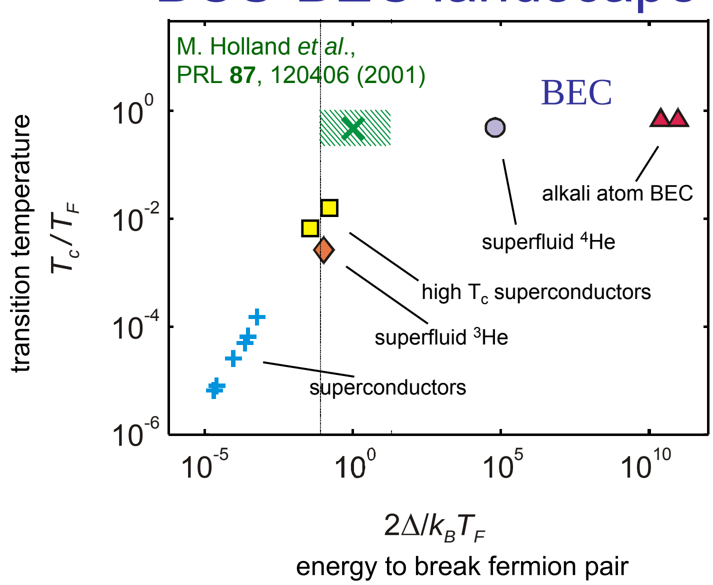
III. BCS-BEC crossover

Making condensates with fermions

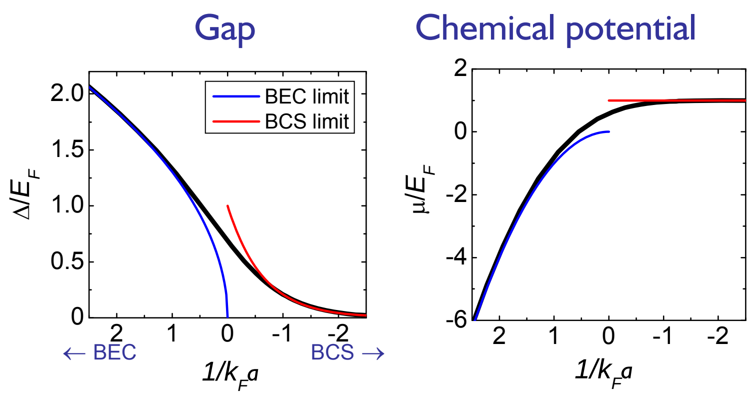


BCS-BEC crossover theory (partial list):
Eagles, Leggett, Nozieres and Schmitt-Rink, Randeria, Strinati, Haussman, Holland, Timmermans, Griffin, Levin …

BCS-BEC landscape



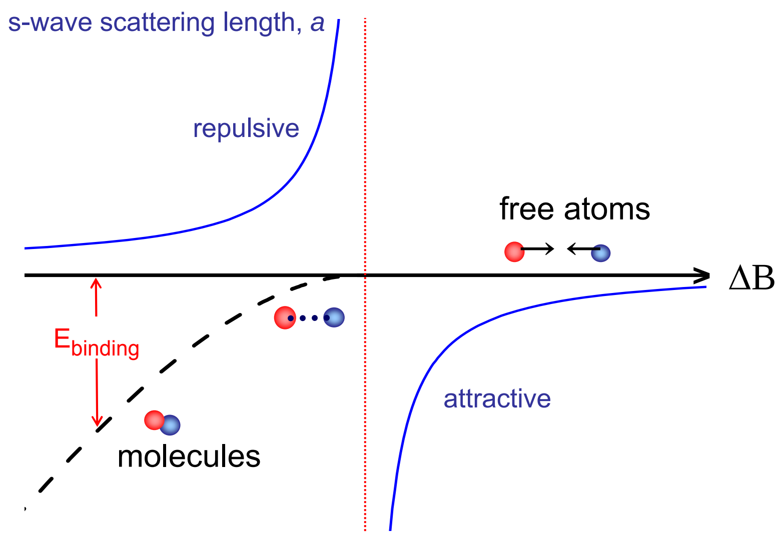
BCS-BEC Crossover



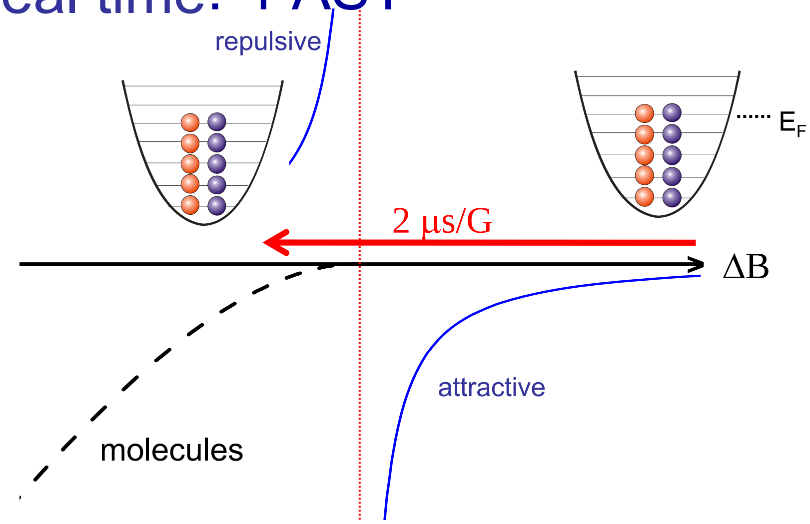
$1/k_F a$ characterizes interactions in BCS-BEC crossover

M. Marini, F. Pistolesi, and G.C. Strinati, Europhys. J. B **1**, 151 (1998)

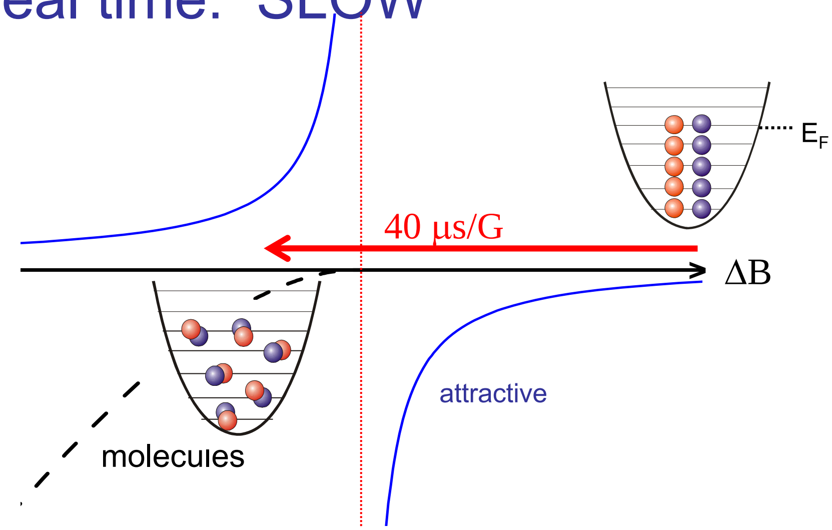
Magnetic-field Feshbach resonance



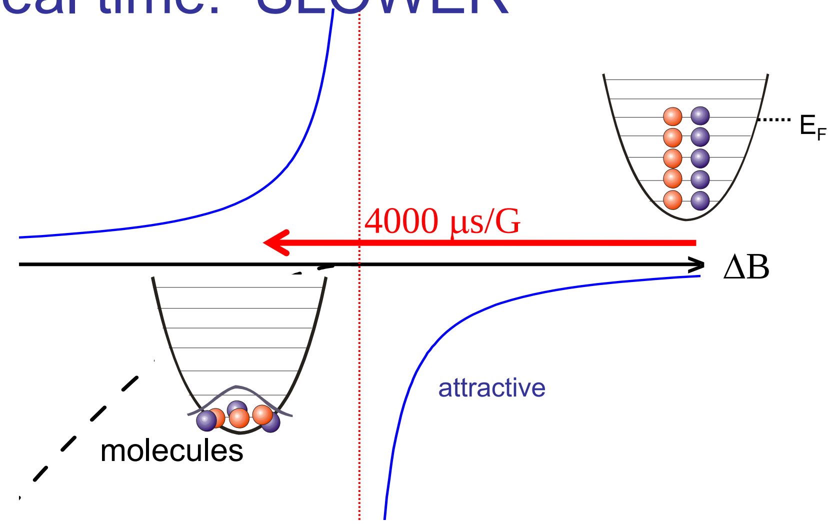
Changing the interaction strength in real time: FAST



Changing the interaction strength in real time: SLOW

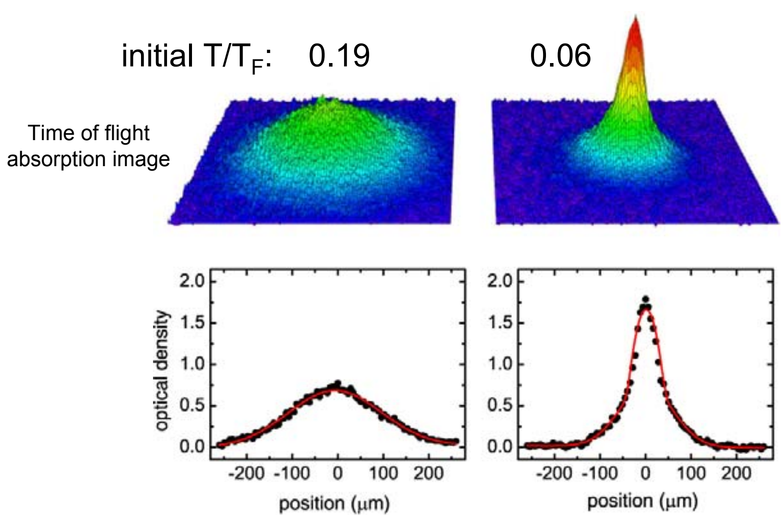


Changing the interaction strength in real time: SLOWER



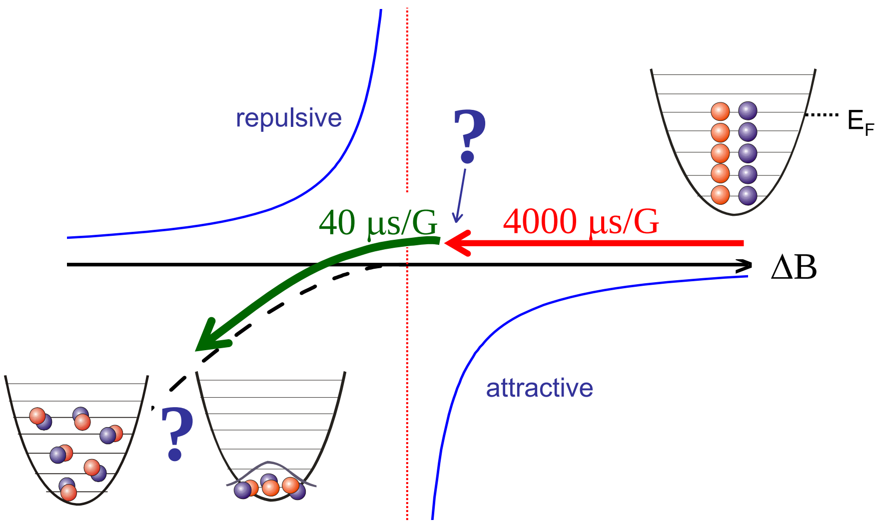
Cubizolles *et al*., PRL **91**, 240401 (2003); L. Carr *et al.*, PRL **92**, 150404 (2004)

Molecular Condensate

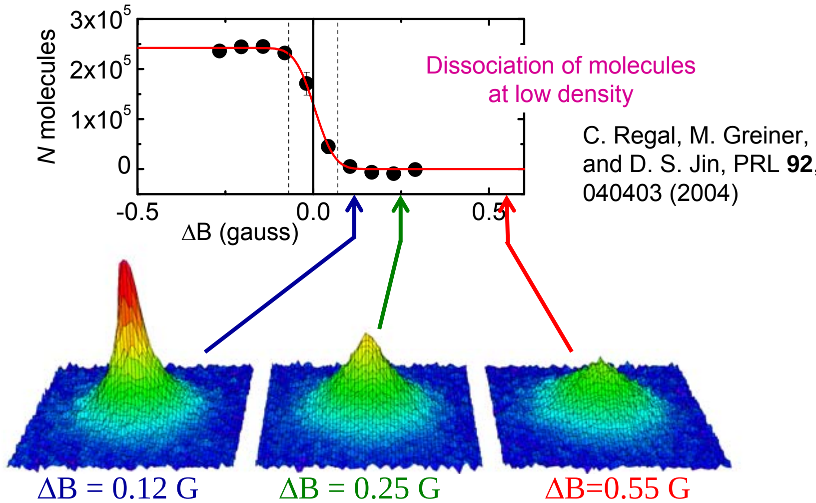


M. Greiner, C.A. Regal, and D.S. Jin, Nature **426**, 537 (2003).

Observing a Fermi condensate



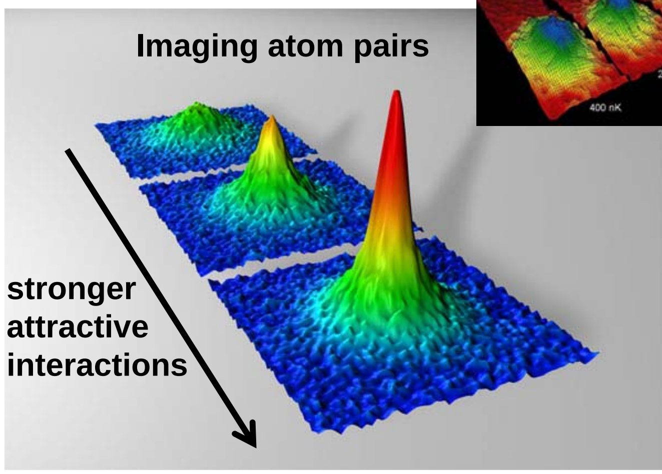
Condensates without a two-body bound state



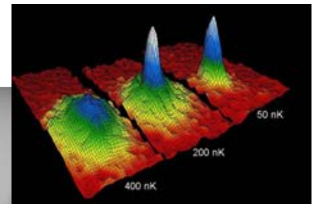
T/T_F=0.08

Fermi Condensate

2004

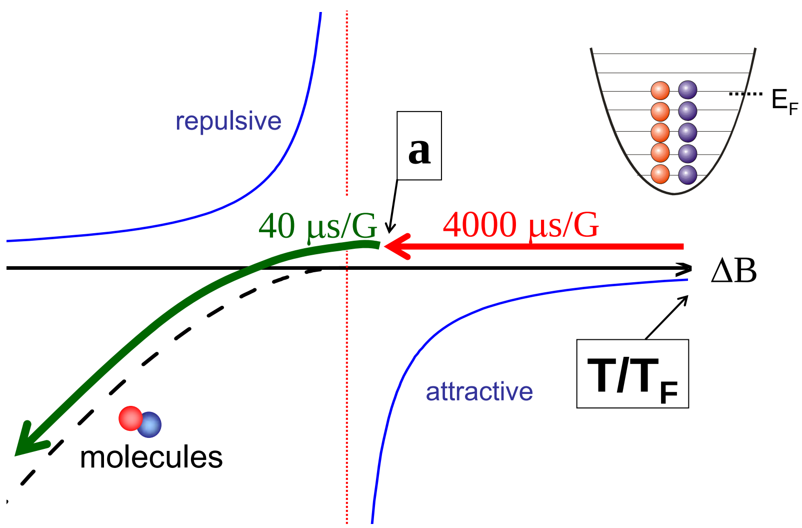


Bose-Einstein Condensate

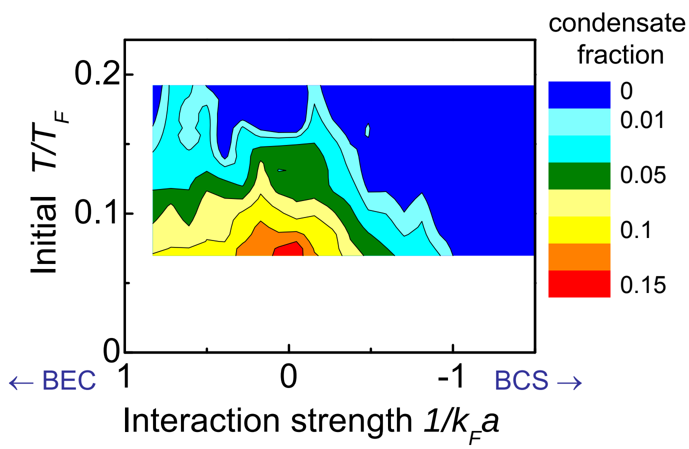


C. A. Regal, M. Greiner, and D. S. Jin, PRL 92, 040403 (2004)

Mapping out a phase diagram

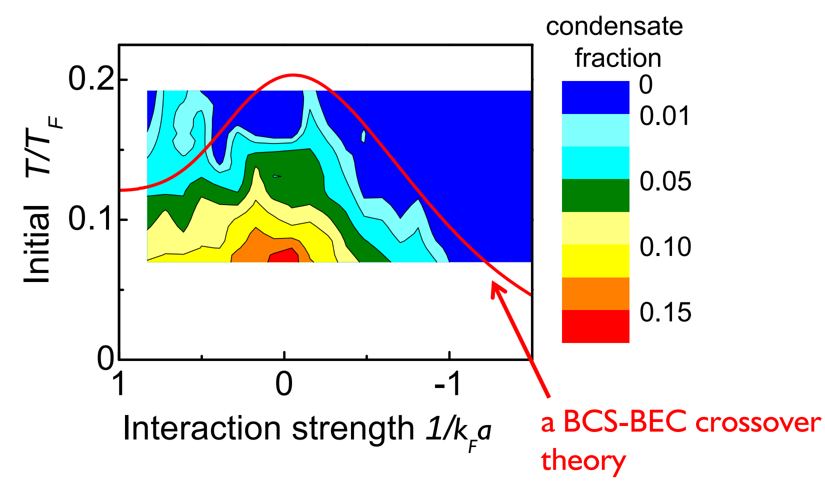


BCS-BEC Crossover



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

BCS-BEC Crossover



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

Q. Chen, C.A. Regal, M. Greiner, D.S. Jin & K. Levin, PRA **73**, 041601 (2006).

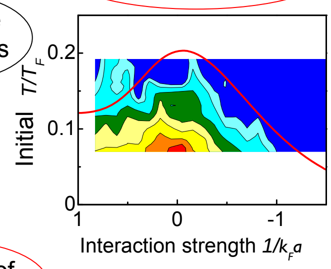
Probing the BCS-BEC crossover

Condensate fraction

Collective excitations

Unbalanced spin population

Vortices



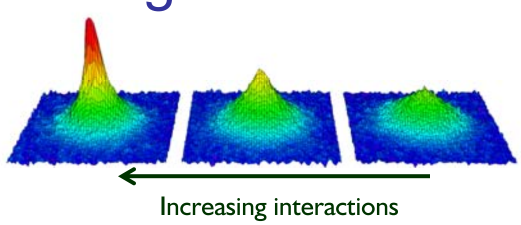
Unitarity and Universality

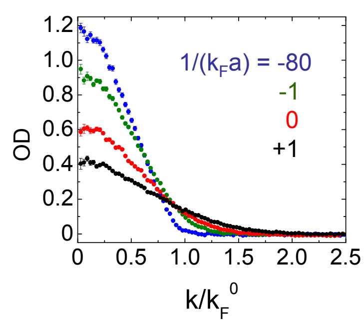
Probes of pairing

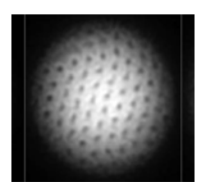
Thermodynamic measurements

Correlations in atom shot noise

Probing the BCS-BEC crossover







(Ketterle, MIT)

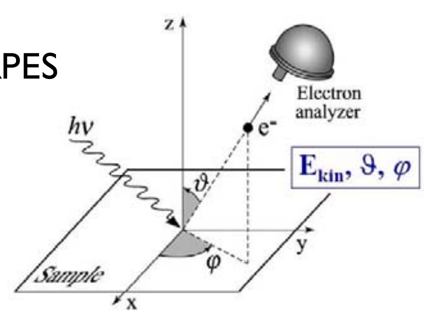
IV. Recent experiments at JILA

1. Photoemission spectroscopy for ultracold atoms

2. Exploring a p-wave Feshbach resonance

Photoemission spectroscopy for ultracold atoms

Like ARPES

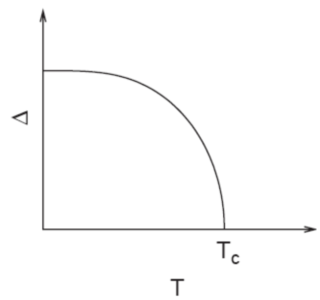


Look at the BCS-BEC crossover (s-wave)

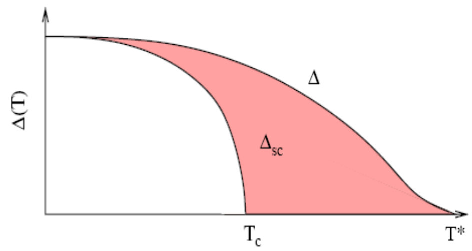
The gap

2Δ is the energy to break a pair

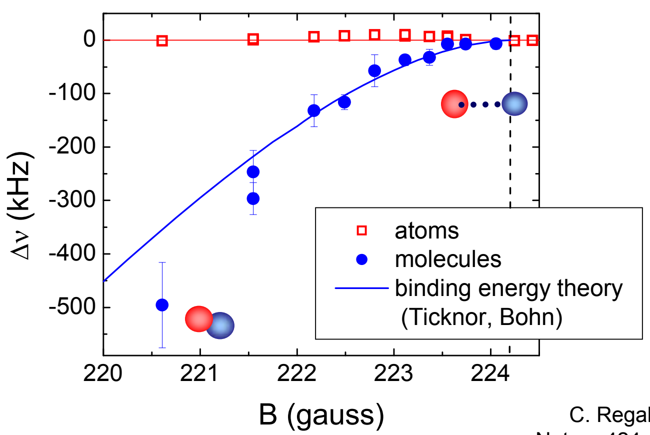
BCS superconductivity



BCS-BEC crossover



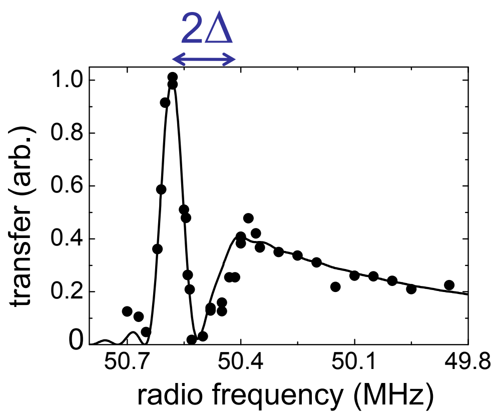
rf spectroscopy: A brief history

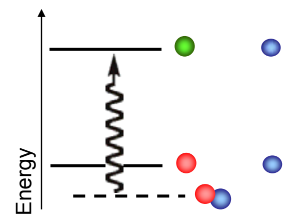


C. Regal *et al.*
Nature 424, 47 (2003)

rf spectroscopy: A brief history

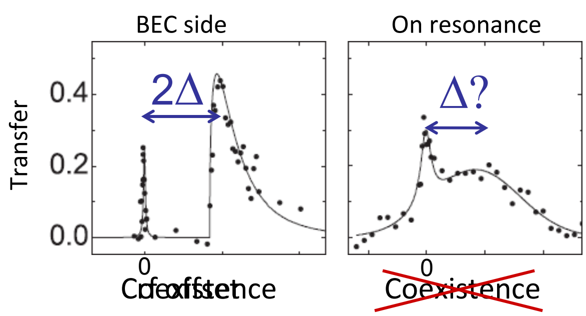
Molecule dissociation ^{40}K

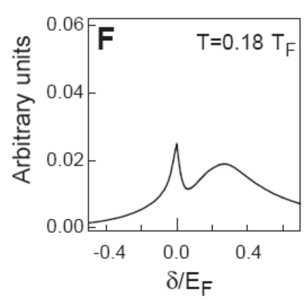




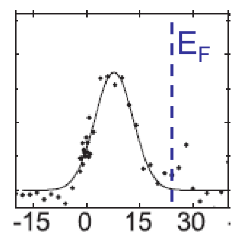
C.A. Regal, C. Ticknor, J. L. Bohn, & D.S. Jin, Nature **424**, 48 (2003)

Measuring the gap? ^{6}Li





C. Chin *et al.*, Science **305**, 1128 (2004)



J. Kinnunen, M. Rodrıguez, & P. Torma, Science **305**, 1131 (2004)

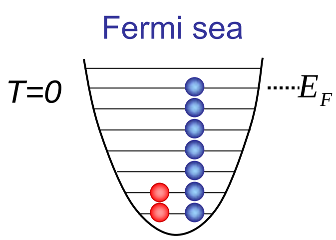
Controversy…

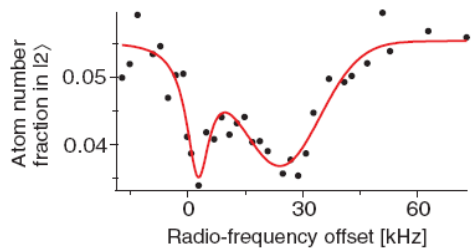
Pairing Without Superfluidity: The Ground State of an Imbalanced Fermi Mixture

C. H. Schunck,* Y. Shin, A. Schirotzek, M. W. Zwierlein,† W. Ketterle

^6Li

C. H. Schunck *et al.*,
Science **316**, 867 (2007)



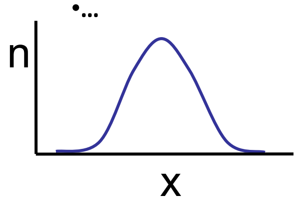


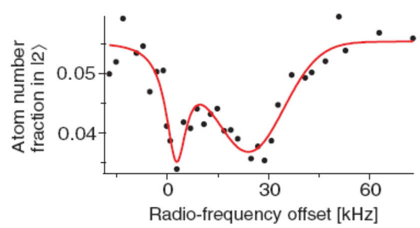
Issues

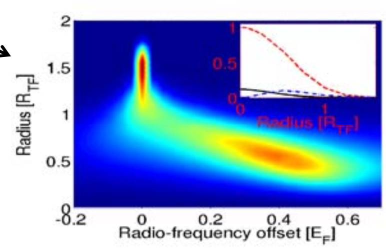
Theory papers

Trap inhomogeneity:

- •Torma, Science 2004
- •Levin, PRA 2005
- •Griffin, PRA 2005
- •Stoof, PRA 2008
- •Levin, PRA 2008
- •Mueller, preprint 2007
- •…







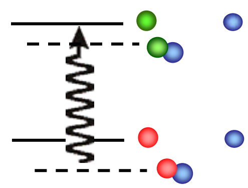
Issues

Theory papers

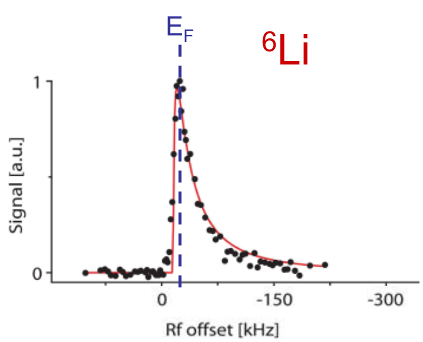
^{6}Li

Final-state effects:

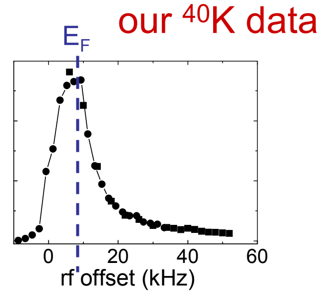
•Chin & Julienne, PRA 2005
•Yu & Baym, PRA 2006
•Baym, PRL 2007
•Perali & Strinati, PRL 2008
•Punk & Zwerger, PRL 2007
•Basu & Mueller, preprint 2007
•Veillette *et al.,* preprint 2008
•Levin, preprint 2008
•…



RF spectroscopy without final-state effects



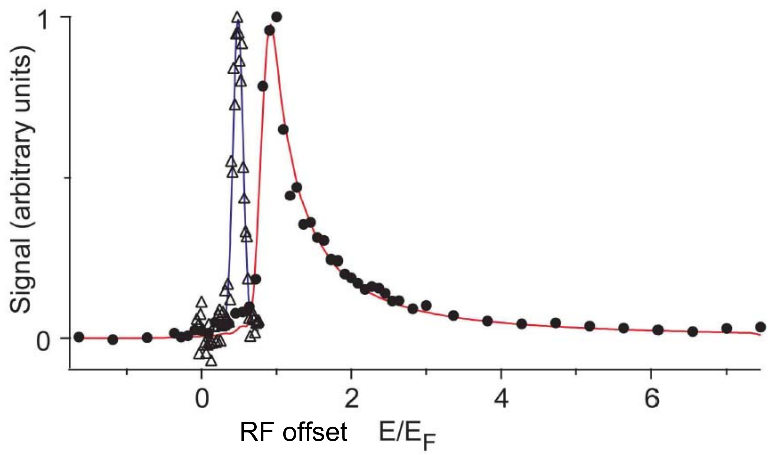
C. H. Schunck *et al.*, arXiv:0802.0341v1



Final-state effects

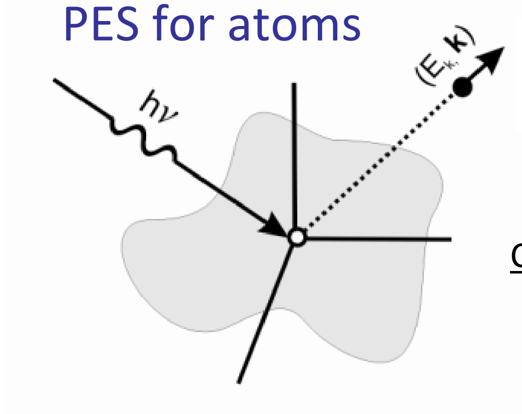
^6Li

C. H. Schunck *et al.*, arXiv:0802.0341v2



Momentum-resolved rf spectroscopy

PES for atoms



$$\epsilon_k = \frac{\hbar^2 k^2}{2m}$$

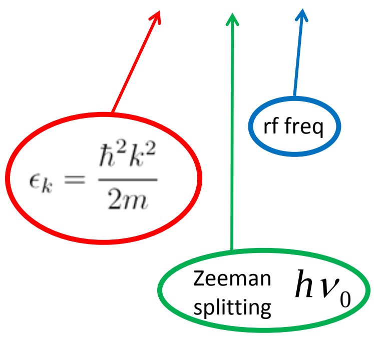
Conservation of energy

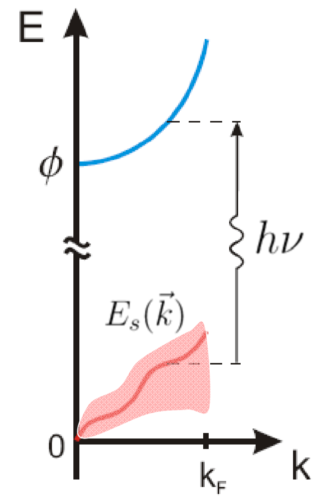
$$E_s(\vec{k}) = \epsilon_k + \phi - h\nu$$

Photoemission spectroscopy for atom gases

Conservation of energy

$$E_s(\vec{k}) = \epsilon_k + \phi - h\nu$$



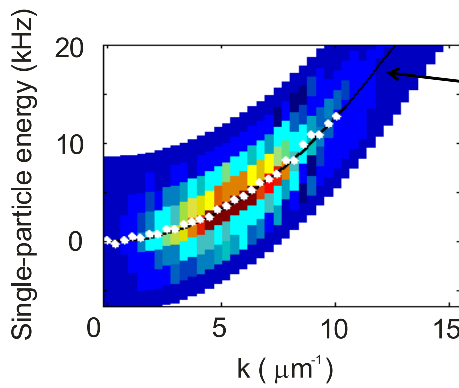


Momentum-resolved rf spectroscopy

1. Apply rf pulse.
2. Turn off trap.
3. Selectively image transferred atoms after expansion.
4. Perform an inverse Abel transform to get N(k) from the image.
5. Repeat for a different rf frequencies.

$$E_s(\vec{k}) = \epsilon_k + \phi - h\nu$$

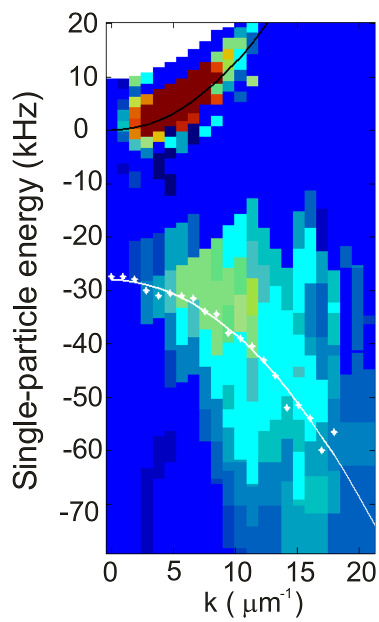
Weakly-interacting Fermi gas



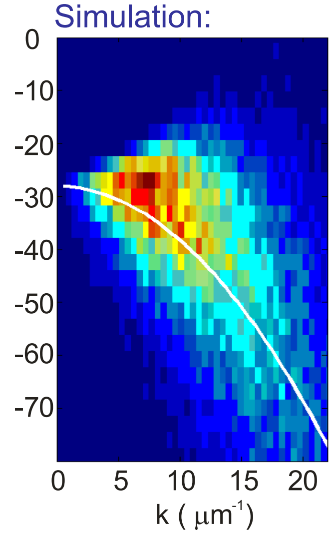
$$\epsilon_k = \frac{\hbar^2 k^2}{2m}$$

$T/T_F = 0.18$

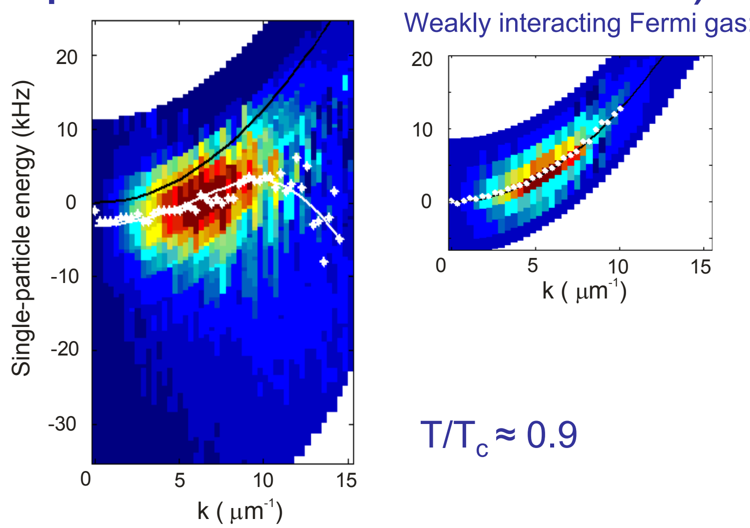
Molecules



Simulation:

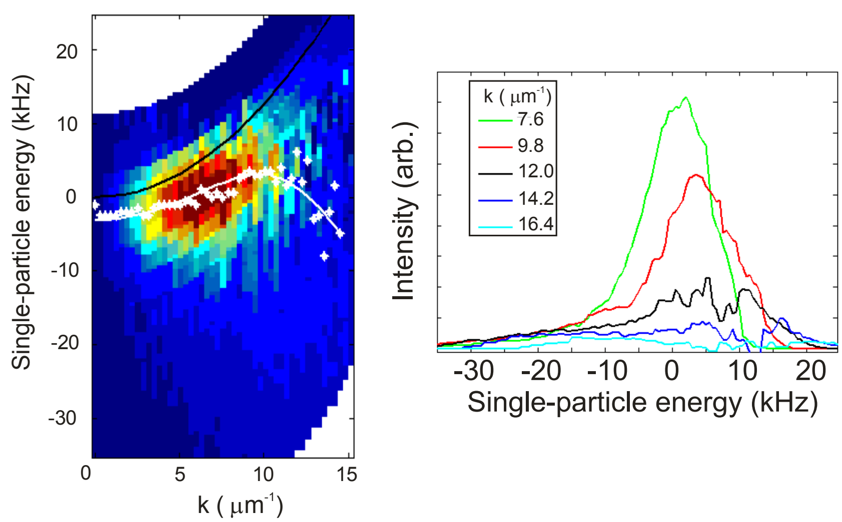


Strongly interacting Fermi gas (cusp of BCS-BEC crossover)

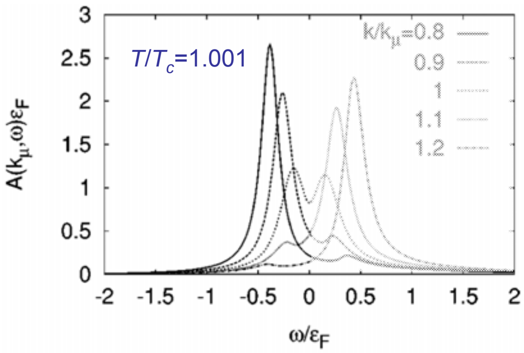


T/T$_c$ ≈ 0.9

Curves at fixed k



Theory: The Spectral Function



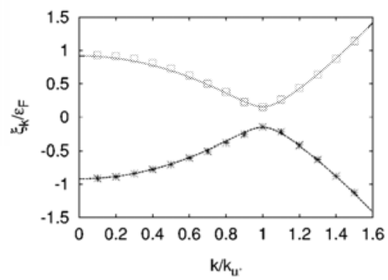
A. Perali, P. Peiri, G. C. Strinati, & C. Castellani, PRB 66, 024510 (2002)

pseudogap

Renormalized μ

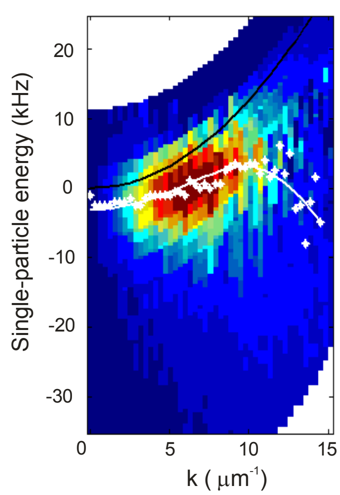
BCS-like dispersion

$$\omega(k) = \pm\sqrt{\left(\frac{\hbar^2 k^2}{2m} - \mu\right)^2 + \Delta^2}$$



Theory: Randeria, Levin, Yanase & Yamada, Strinati, Bruun & Baym, Bulgac, Barnea,…

Evidence of a pseudogap



Fit centers to

$$E_s = \mu - \sqrt{(\varepsilon_k - \mu)^2 + \Delta^2}$$

$\mu = 12.6 \pm 0.7$ kHz

$\Delta = 9.5 \pm 0.6$ kHz

E_F^0 = 10.4 kHz

But the ramp to resonance increases the density

Next?

Probe the BCS-BEC crossover

Temperature

Interaction strength

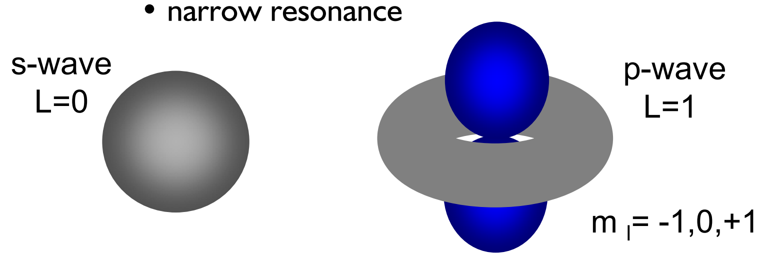
Spin-imbalance

This technique could be used more generally.

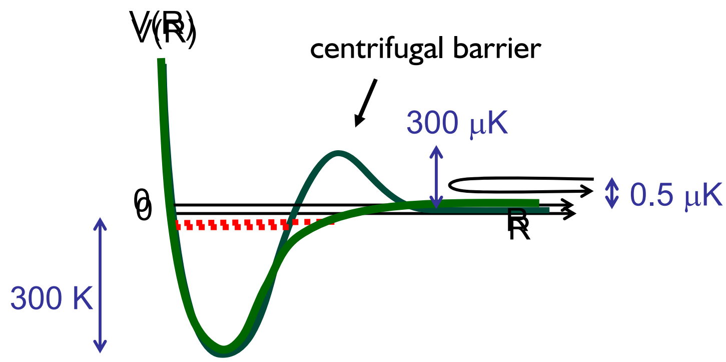
P-wave Pairing?

Fermi condensates with non-s-wave pairing?

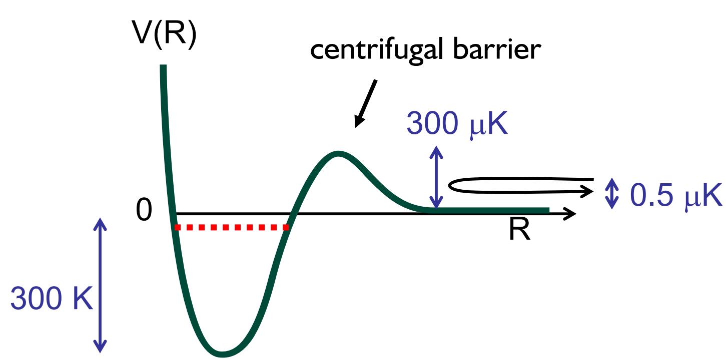
- Examples:
  - superfluid ^3He (p-wave)
  - high Tc superconductors (d-wave)
- Novel features:
  - anistropic gap
  - multiple superfluid phases,
  - narrow resonance



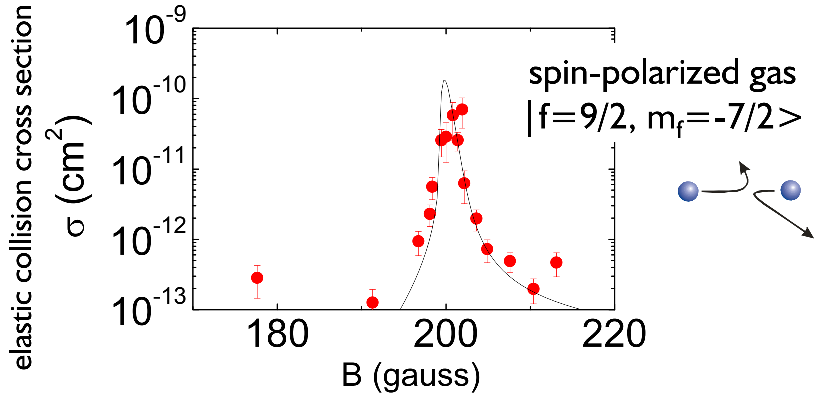
S-wave resonance



P-wave resonance

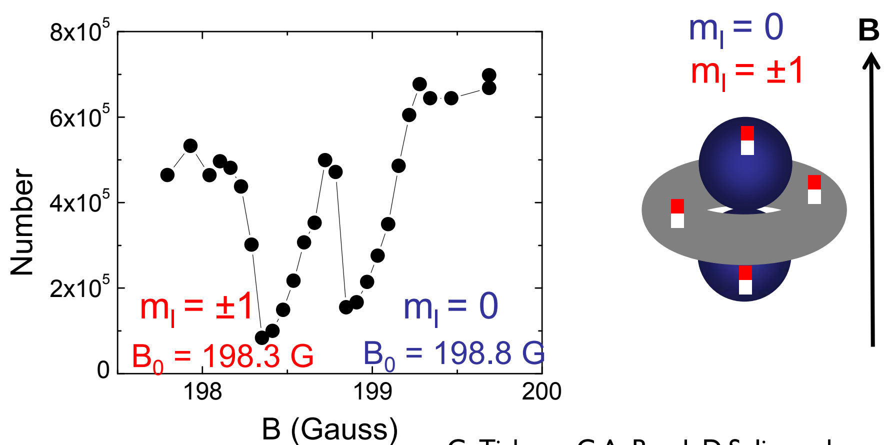


p-wave resonance ^{40}K



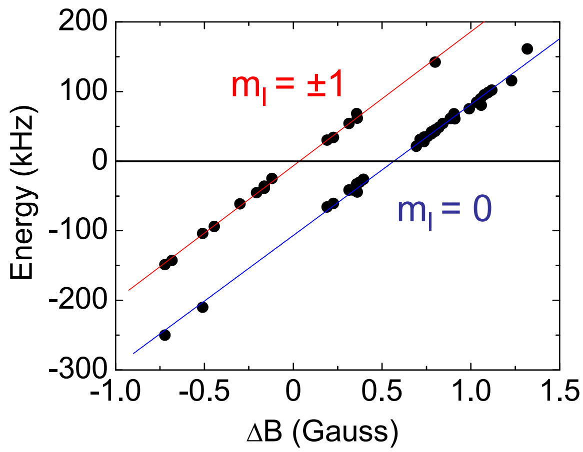
C.A. Regal, C. Ticknor, J.L. Bohn, & D.S. Jin, PRL **90**, 053201 (2003)

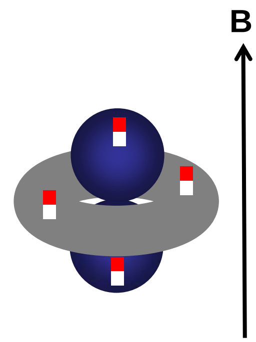
Multiplet structure



C. Ticknor, C.A. Regal, D.S. Jin, and J.L. Bohn, PRA 69, 042712 (2004).

P-wave molecule energy

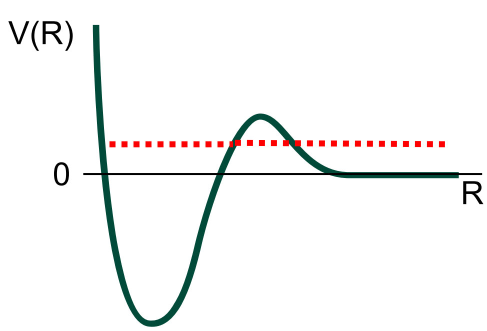




J.P. Gaebler, J.T. Stewart, J.L. Bohn, & D.S. Jin, PRL 98, 200403 (2007)

A way to "see" molecules

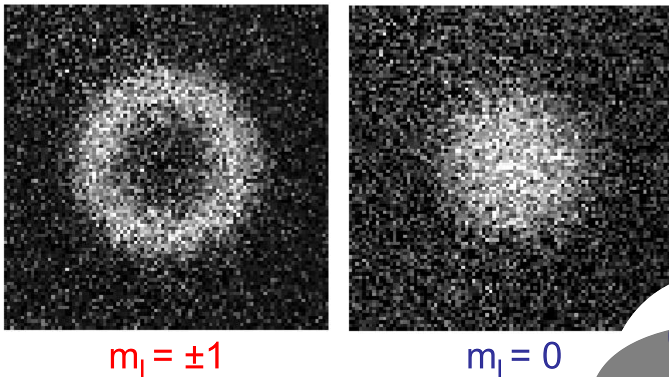
Create molecules

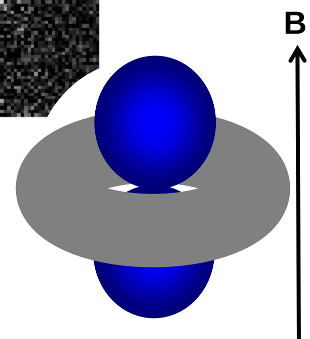


Look for energetic atoms created by tunneling

P-wave Feshbach molecules

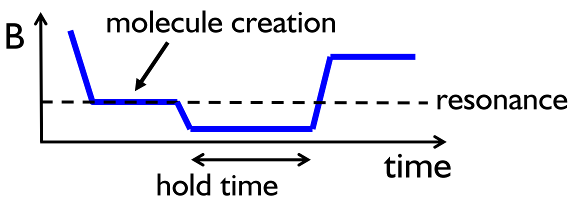
^{40}K

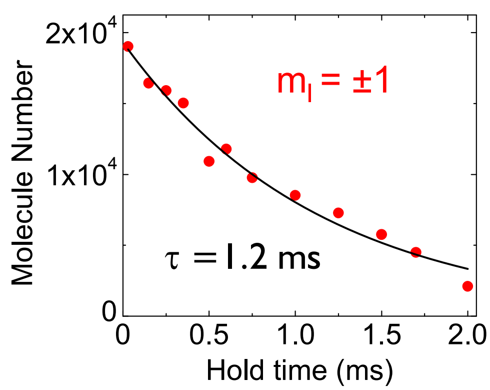




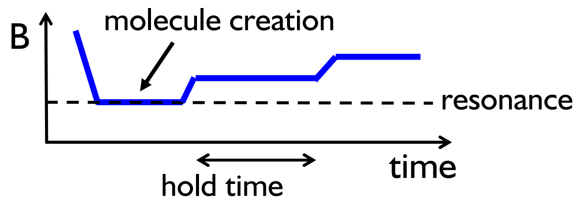
J.P. Gaebler, J.T. Stewart, J.L. Bohn, & D.S. Jin, PRL 98, 200403 (2007)

Molecule lifetime

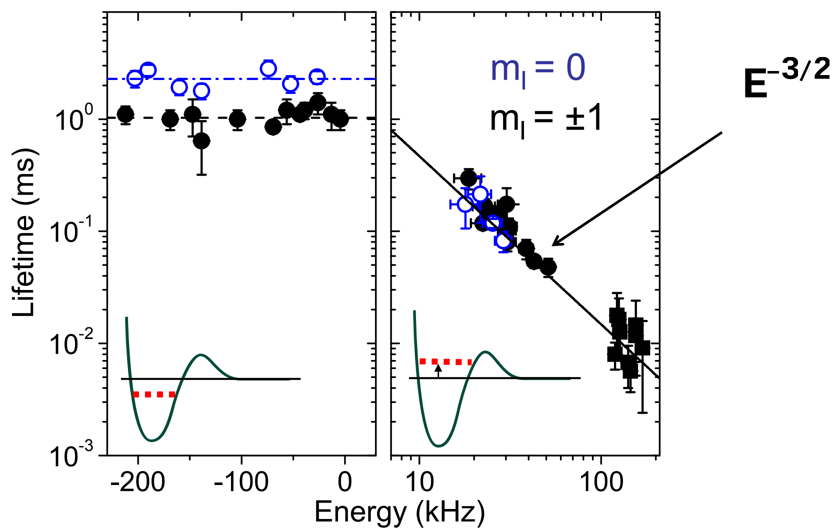




Quasi-bound molecule lifetime



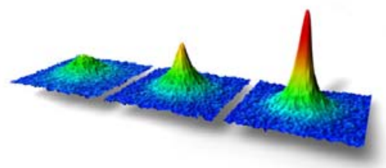
P-wave molecule lifetimes



J.P. Gaebler, J.T. Stewart, J.L. Bohn, & D.S. Jin, PRL 98, 200403 (2007)

Conclusion:

Ultracold atoms gases provide a unique model system for exploring quantum, many-body phenomena.



People

Jayson Stewart, John Gaebler

Brian DeMarco

Cindy Regal

Markus Greiner