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BEC of $^6Li_2$ molecules:
Exploring the BEC-BCS crossover

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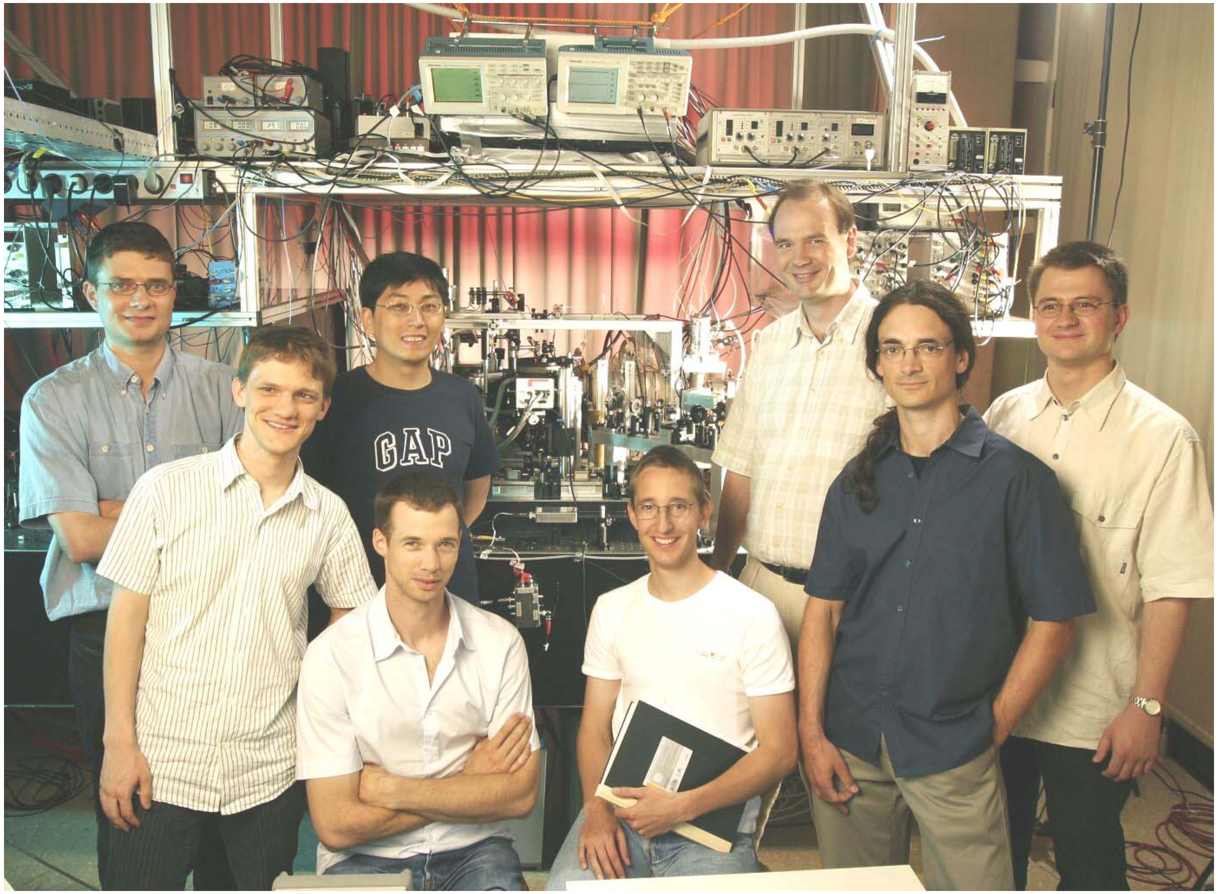
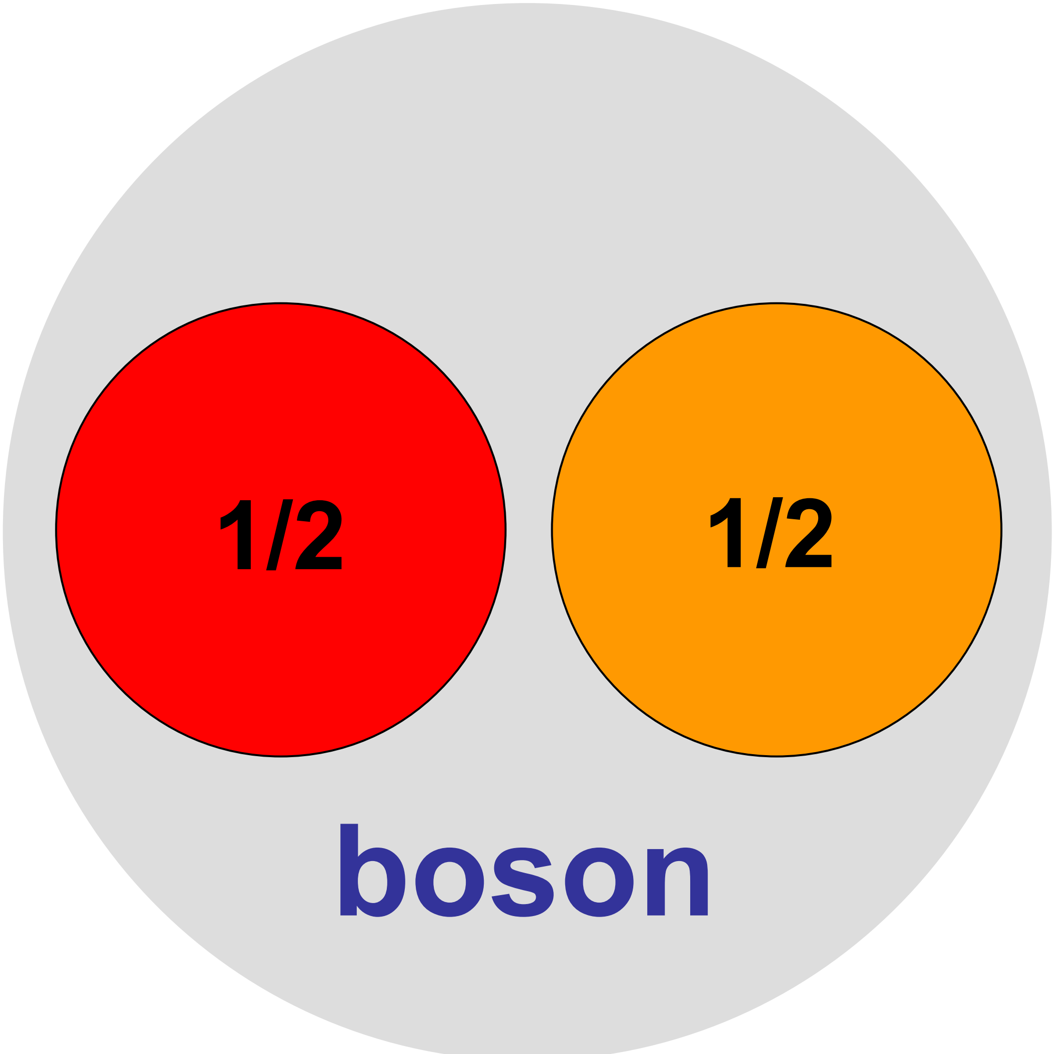


FWF Der Wissenschaftsfonds.

RTN *Cold Molecules*

fermion + fermion = boson

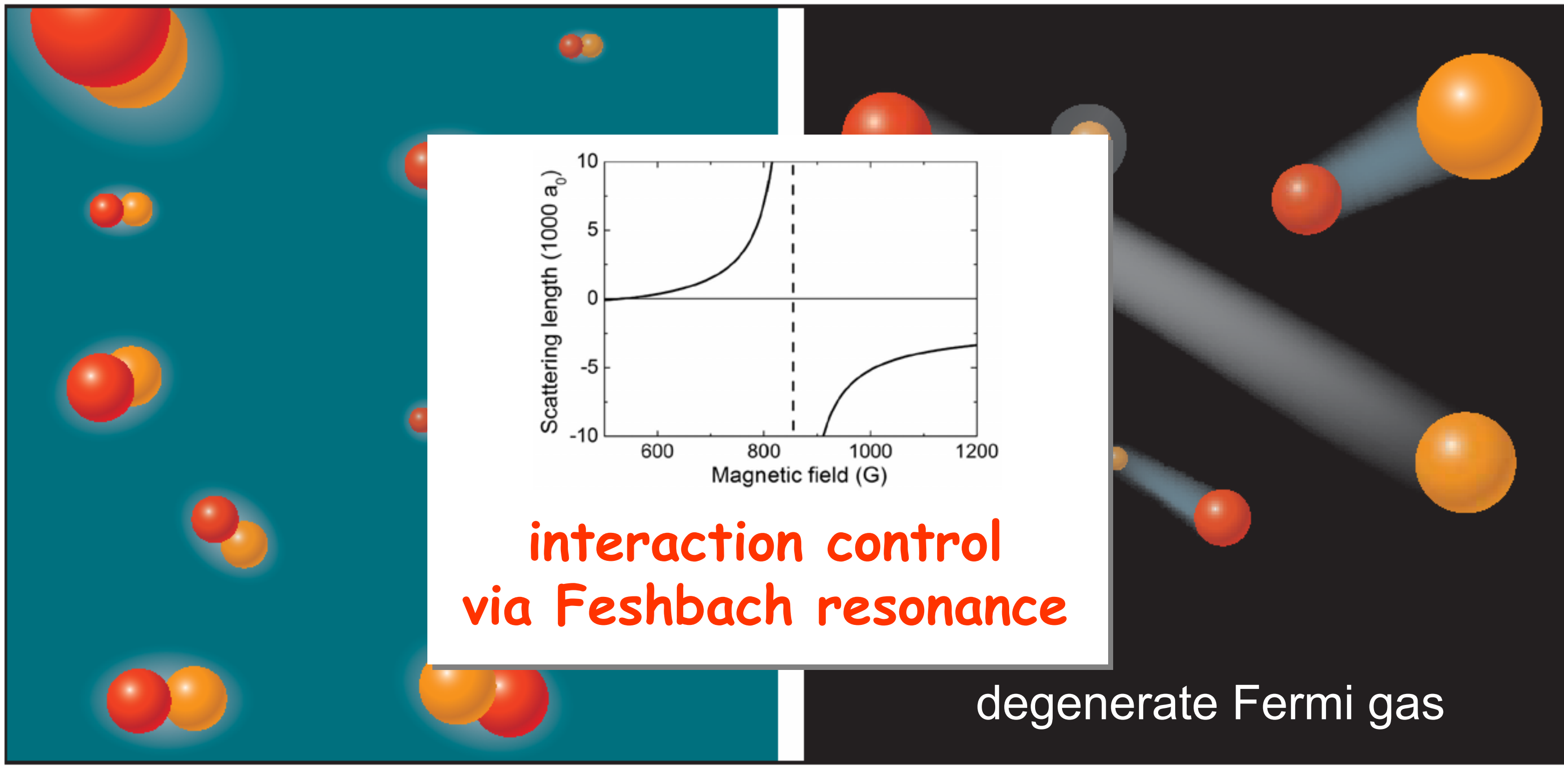


BEC – BCS crossover

molecules
strong coupling

crossover

Cooper pairs
weak coupling



high T_C superconductivity, neutron stars,
^{3}He superfluidity, nuclear physics

^{6}Li in Innsbruck

Bose-Einstein Condensation of $^6Li_2$

- production of molecules
- cooling to condensation

Exploring the BEC-BCS cross-over

(varying particle interaction)

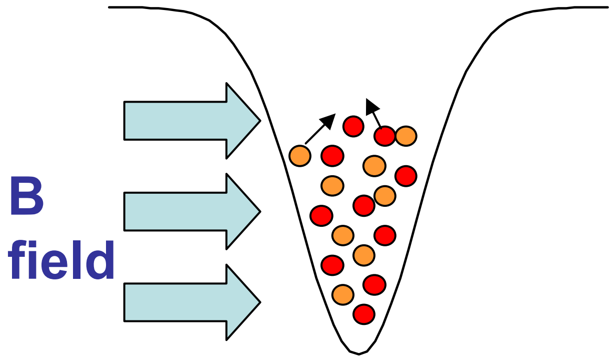
- studied cloud size
- excitation of collective oscillations
- pairing gap --- pairing of fermions

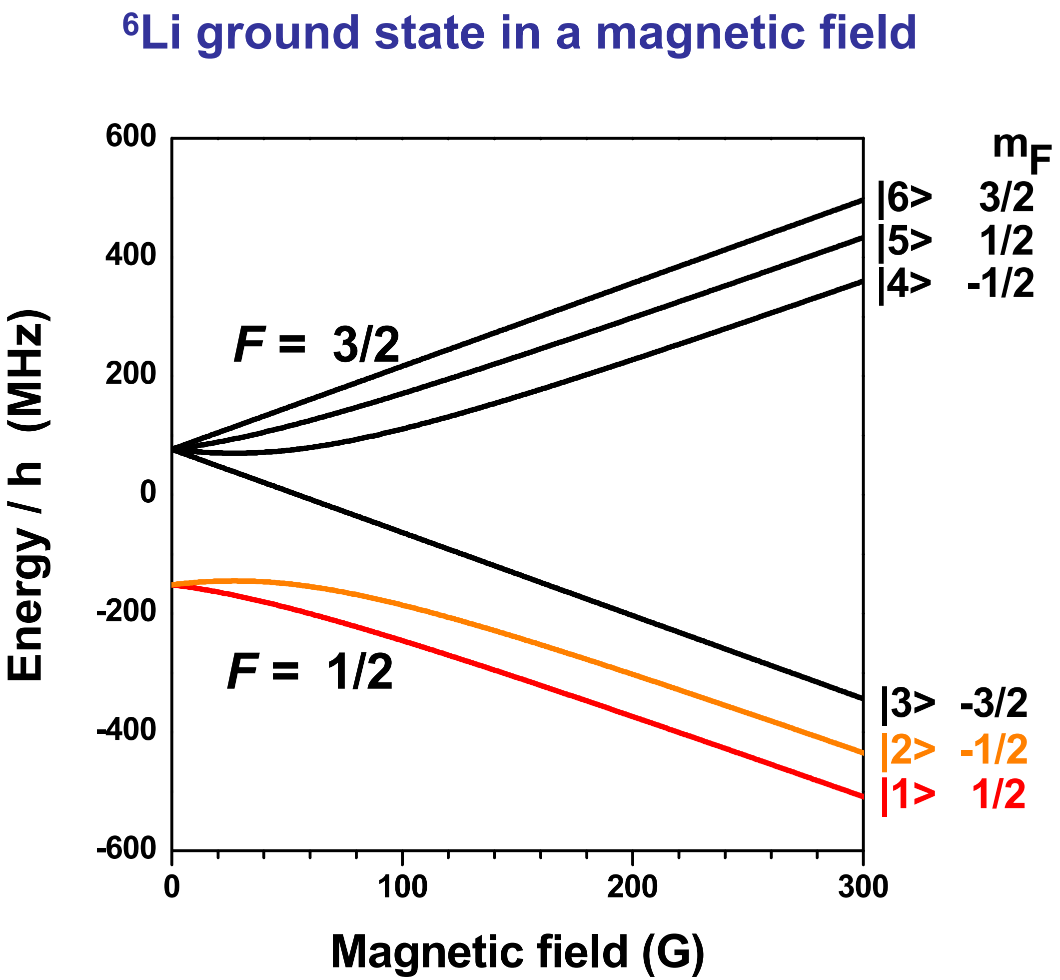
Location of the Feshbach resonance

- rf spectroscopy

Two Component Ultracold Li Atoms

• 50% - 50% mixture of ^{6}Li atoms in the lowest two ground states



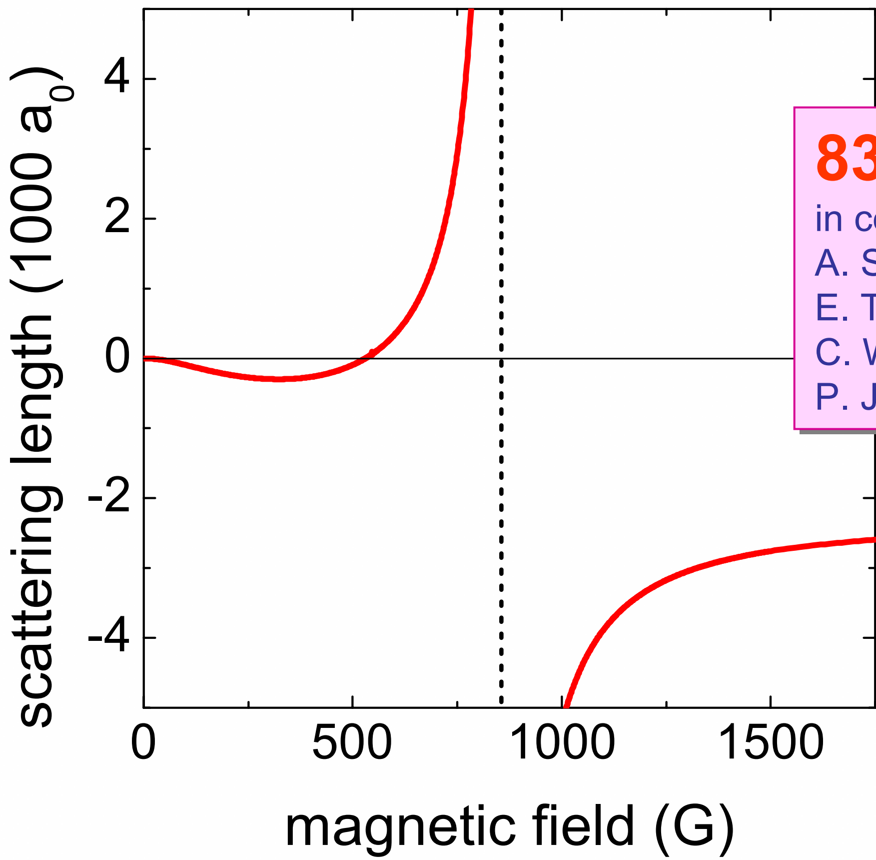


Special features:

•Stable against two-body decay

• Feshbach resonance ⇒ tunable interaction

Feshbach Resonance



834.1(1.5) G

in collab. with
A. Simoni,
E. Tiesinga,
C. Williams,
P. Julienne

prediction:
M. Houbiers et al.,
PRA 57, R1497 (1998).

weakly bound state (molecule)

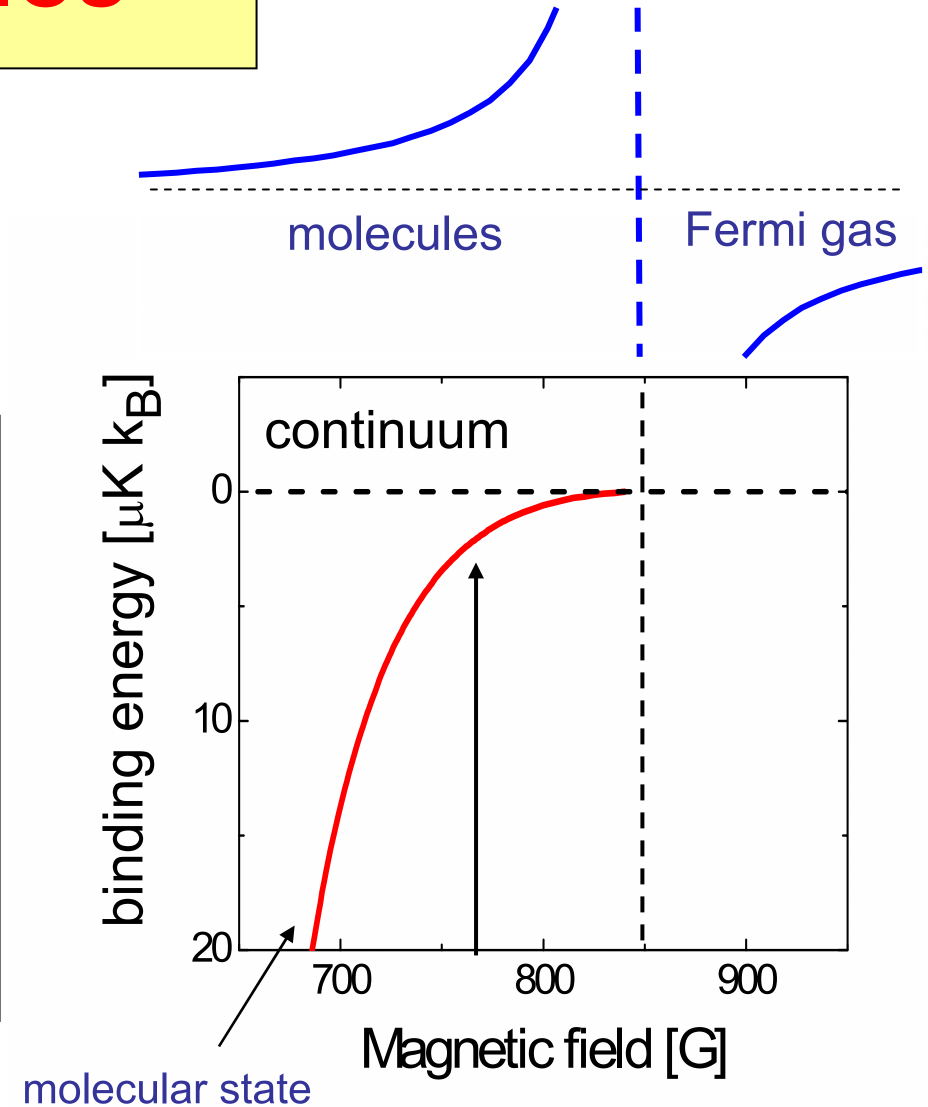
no bound state, only Fermi gas

$^6Li_2$ molecules

$$E_B = \frac{\hbar^2}{ma^2}$$

binding energy at 764G ~ k_B **2μK**

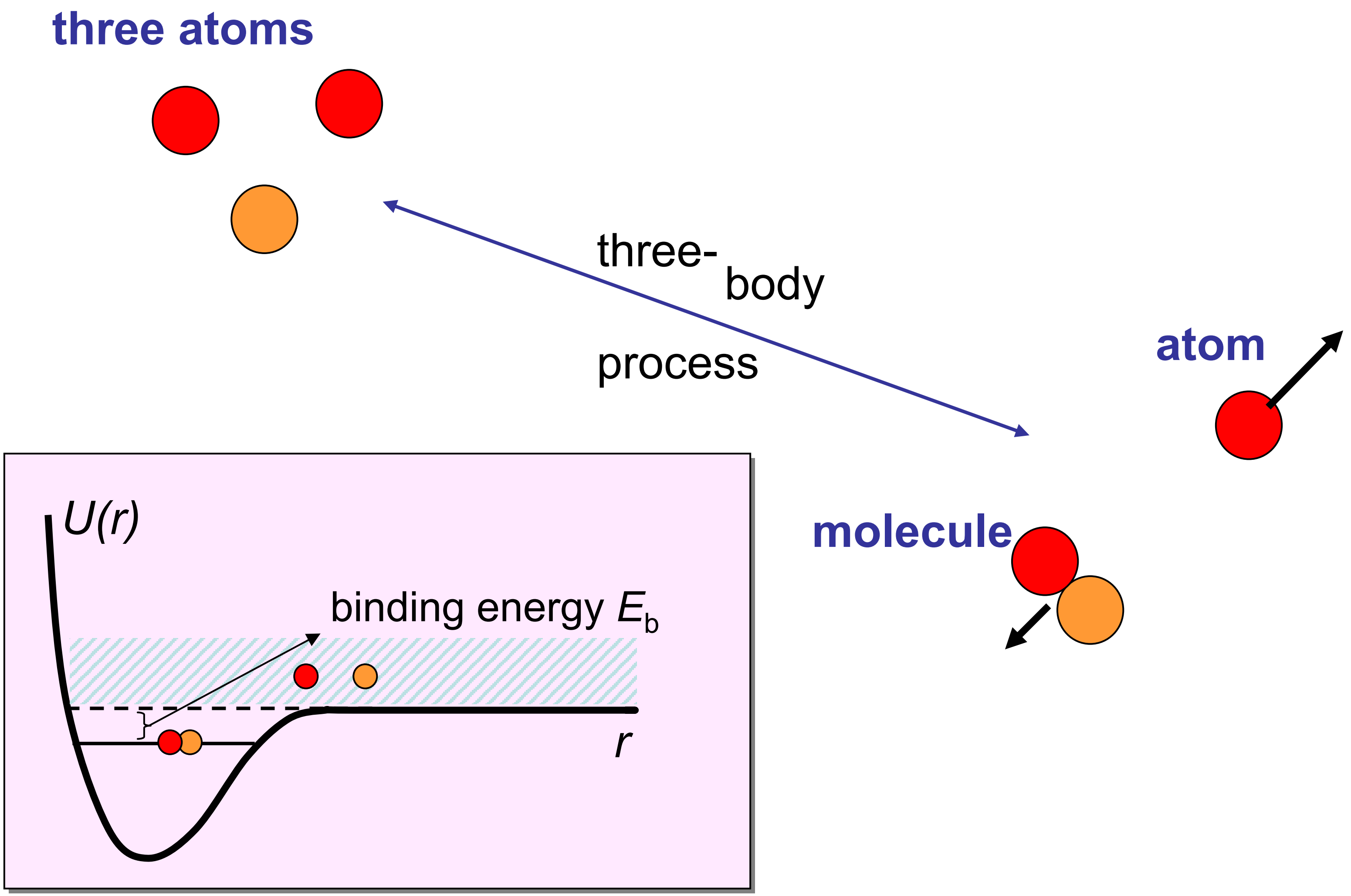
Size of the molecules ~ ***a***



10 billion times weaker than normal molecules

three-body recombination

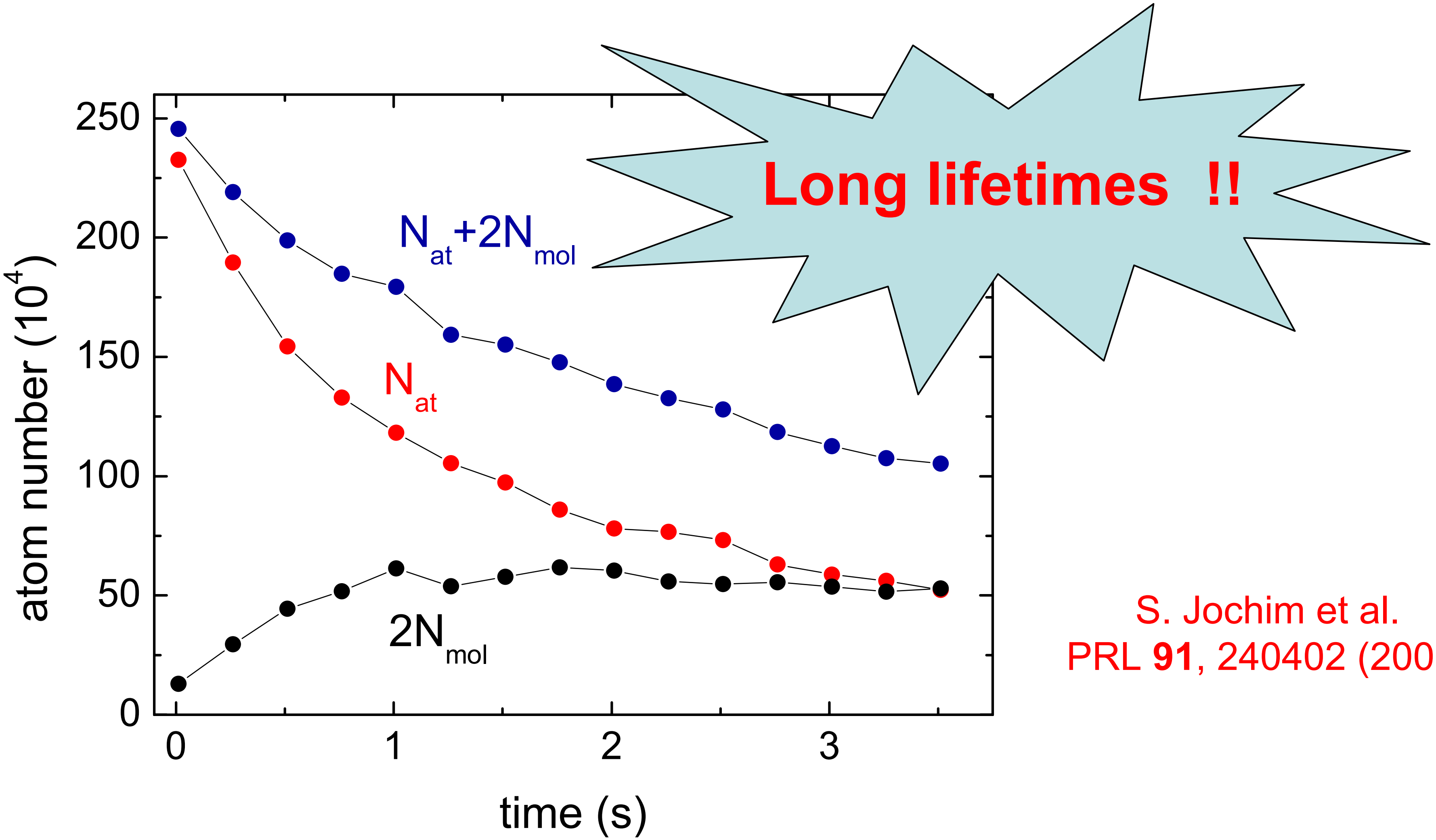
molecules made by collisions



molecule formation

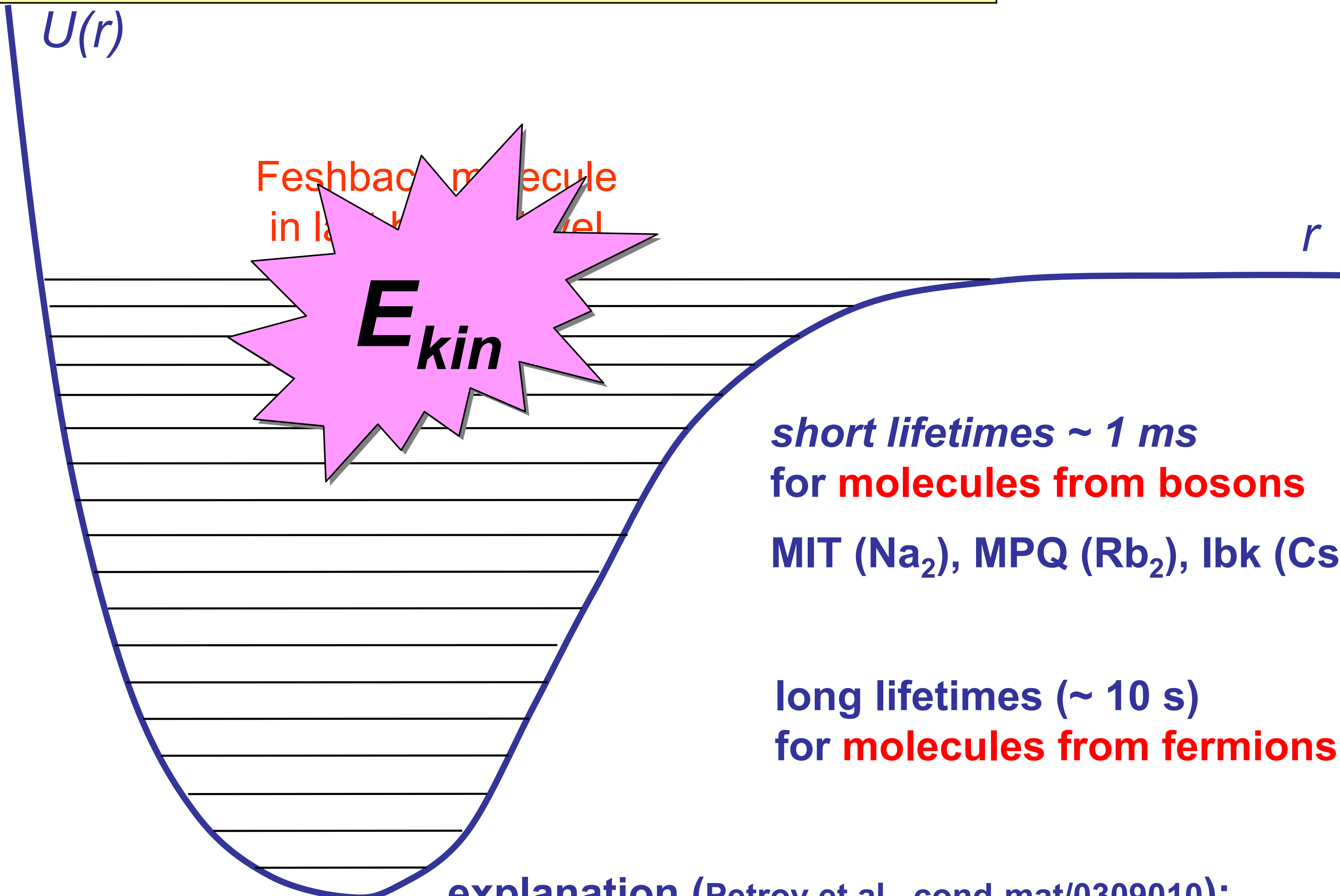
***B* = 690 G**:

mol. bind. energy $E_b = k_B \cdot 18\mu K$ >> therm. energy $k_B T = k_B \cdot 2.5\mu K$



S. Jochim et al.
PRL **91**, 240402 (2003)

molecule-molecule collisions



short lifetimes ~ 1 ms
for molecules from bosons

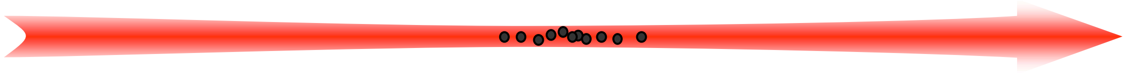
MIT (Na_2), MPQ (Rb_2), Ibk (Cs_2)

long lifetimes (~ 10 s)
for molecules from fermions

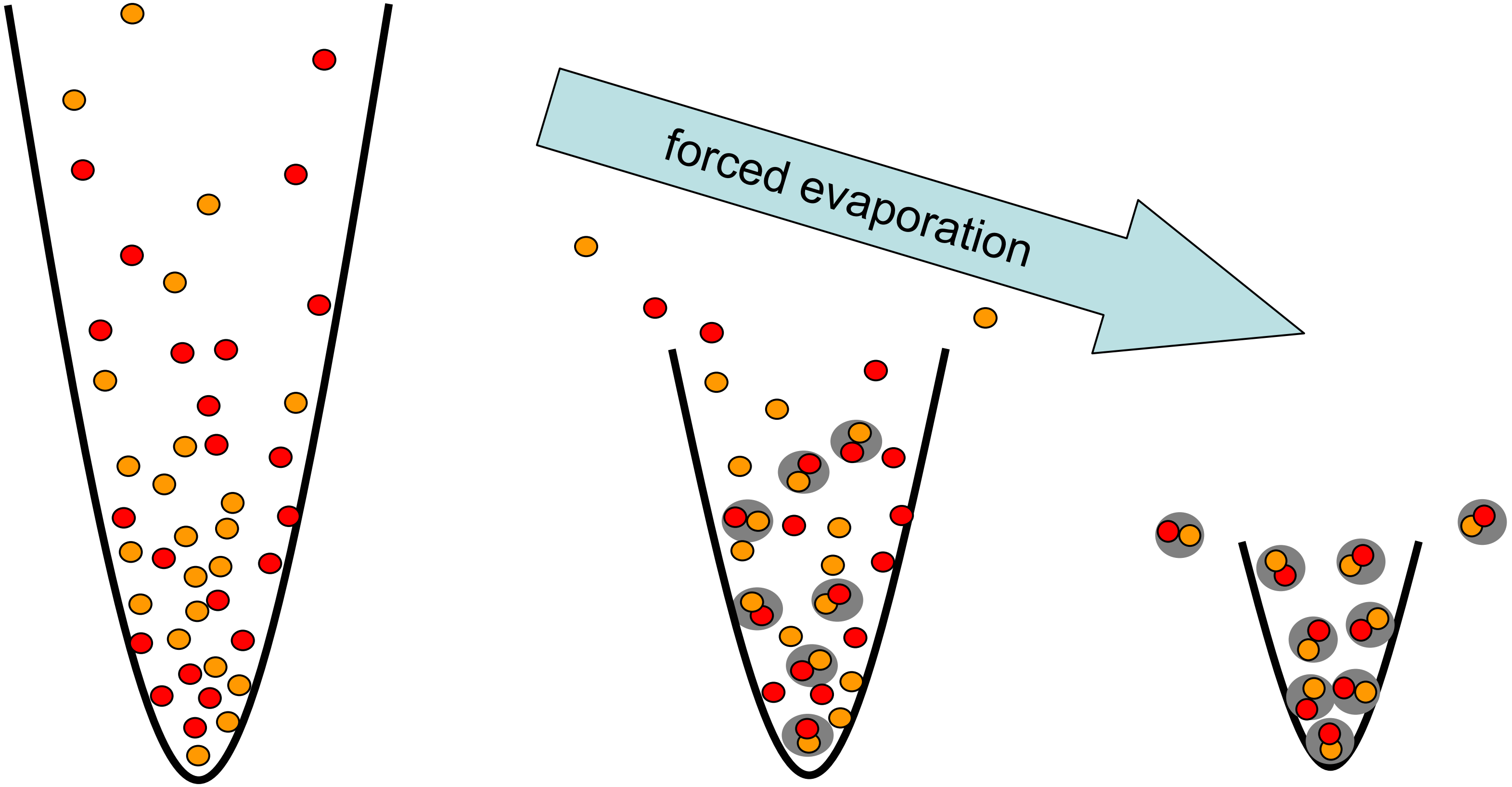
explanation (Petrov et al., cond-mat/0309010):
Pauli blocking in inelastic molecule-molecule collisions

Get BEC with evaporative cooling !!!

optical dipole trap

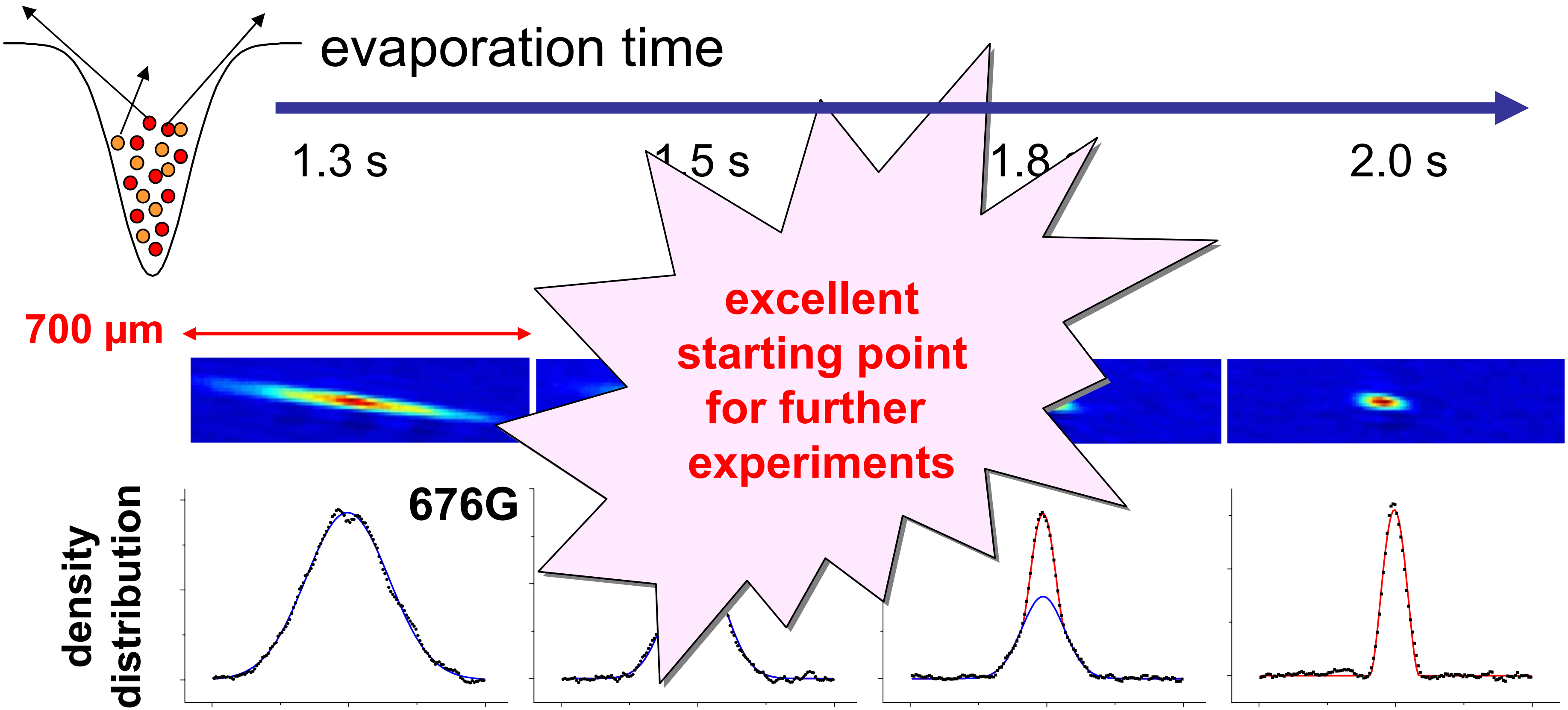


precise control
of laser power
10 W → few 100µW



Evaporative cooling

reduce trap depth in 2s by four orders of magnitude !

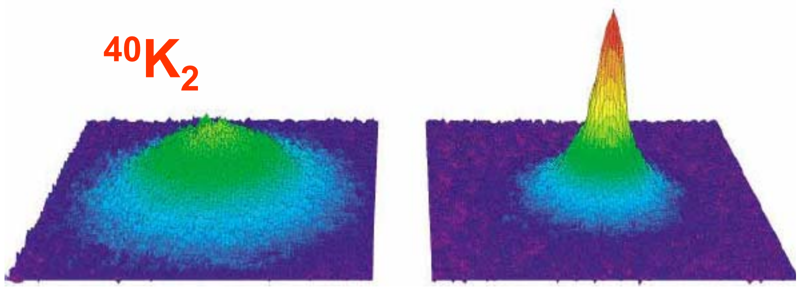


final trap power	3.8mW
number of molecules	200.000
temperature	few 10nK
condensate fraction	>90%

lifetime 40s !

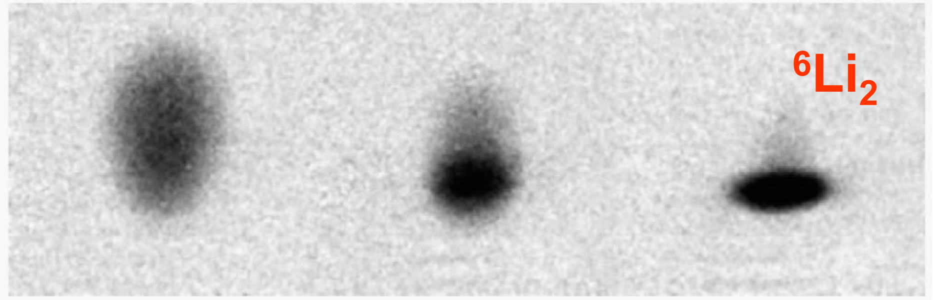
S. Jochim et al., Science ´03

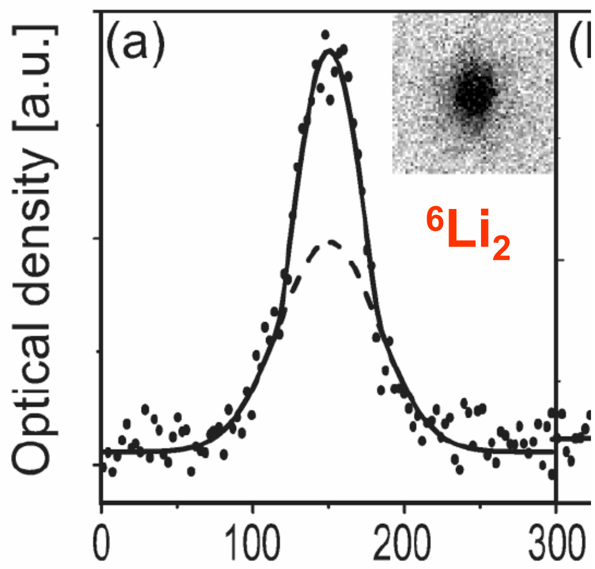
molecular BEC gallery



JILA, Jin et al.

MIT, Ketterle et al.





ENS Paris, Salomon et al.

Rice Univ., Hulet et al.

$^{6}Li_2$

Bose-Einstein Condensation of $^6Li_2$

- Production of molecules
- Cooling to condensation

Exploring the BEC-BCS cross-over
(varying particle interaction)

- studied cloud size
- excitation of collective oscillations
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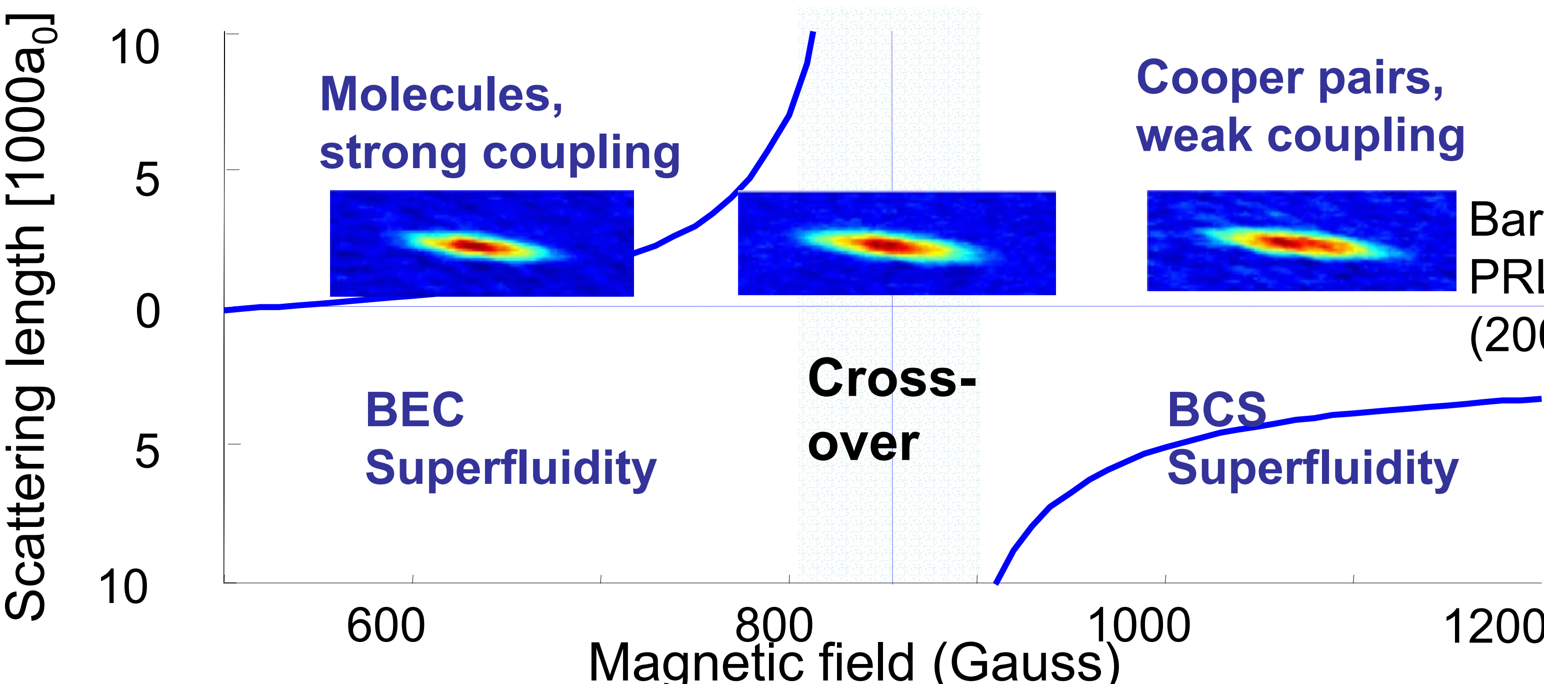
Location of the Feshbach resonance

- rf spectroscopy

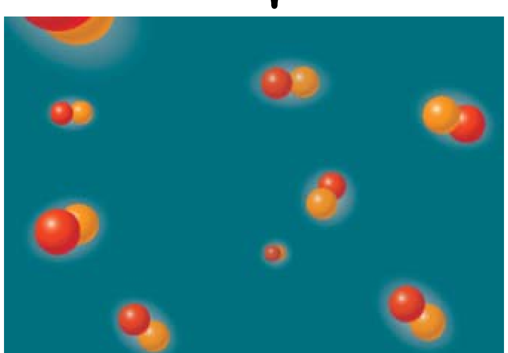
The BEC-BCS crossover

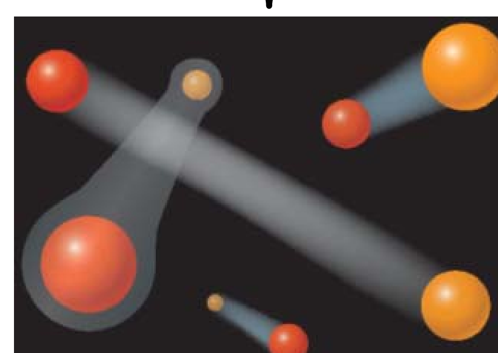
smooth! reversible! lossless!



Bartenstein et al., PRL 92, 120401 (2004)

BEC side





„Cooper pairs“

BCS side

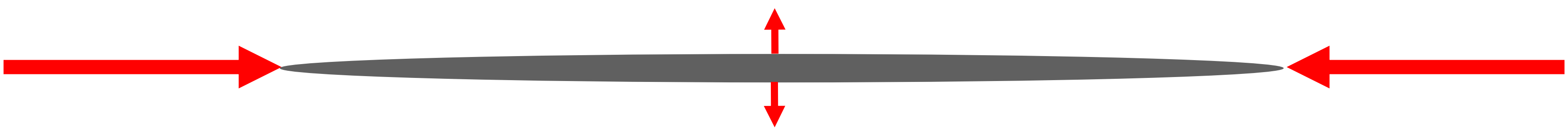
collective modes

S. Stringari, Europhys. Lett. **65**, 749 (2004):
interesting behavior of collective oscillation modes in the crossover !!!

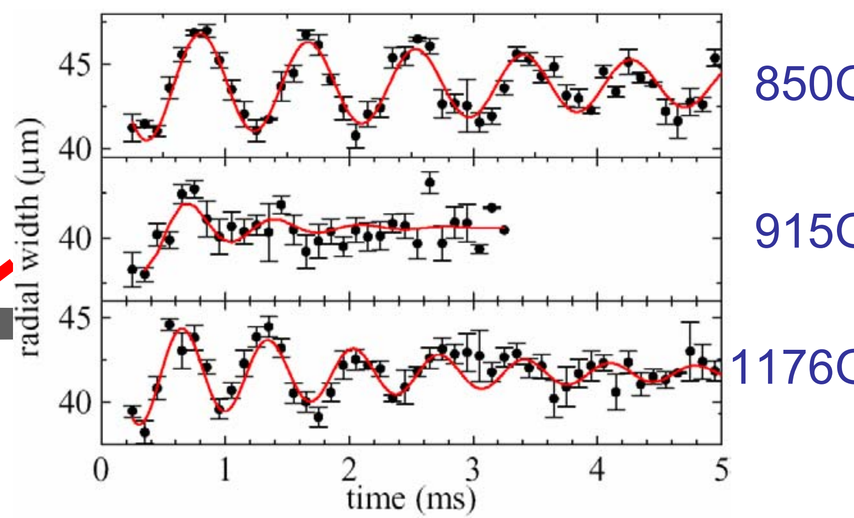
our cigar-shaped trap

$\nu_r = 755(10)$ Hz, $\nu_z \approx 22$ Hz

axial



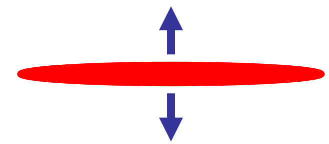
radial



Bartenstein et al., PRL `04   similar work also by J. Kinast et al. PRL `04

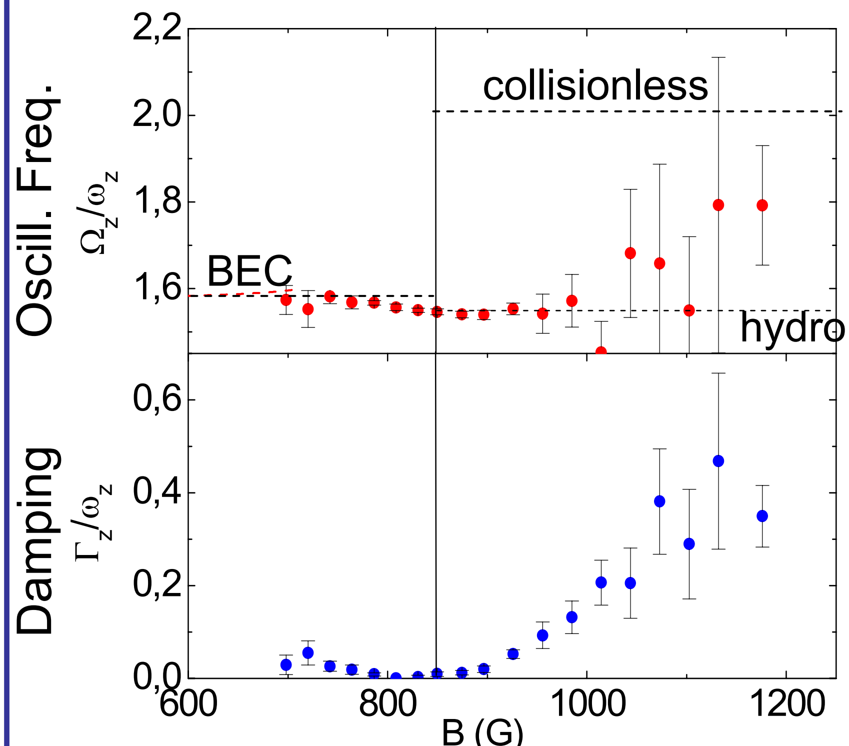
Collective Quadrupolar Excitation

$\omega_z = 2\pi$ **22Hz**



$\omega_r = 2\pi$ **755Hz**

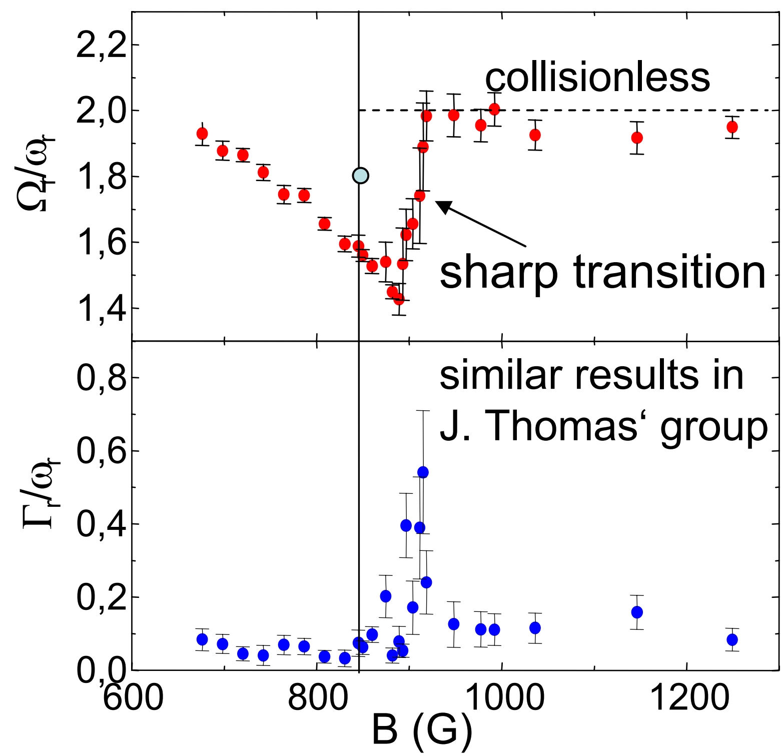
Axial Excitation



BEC

Fermi gas

Radial Excitation

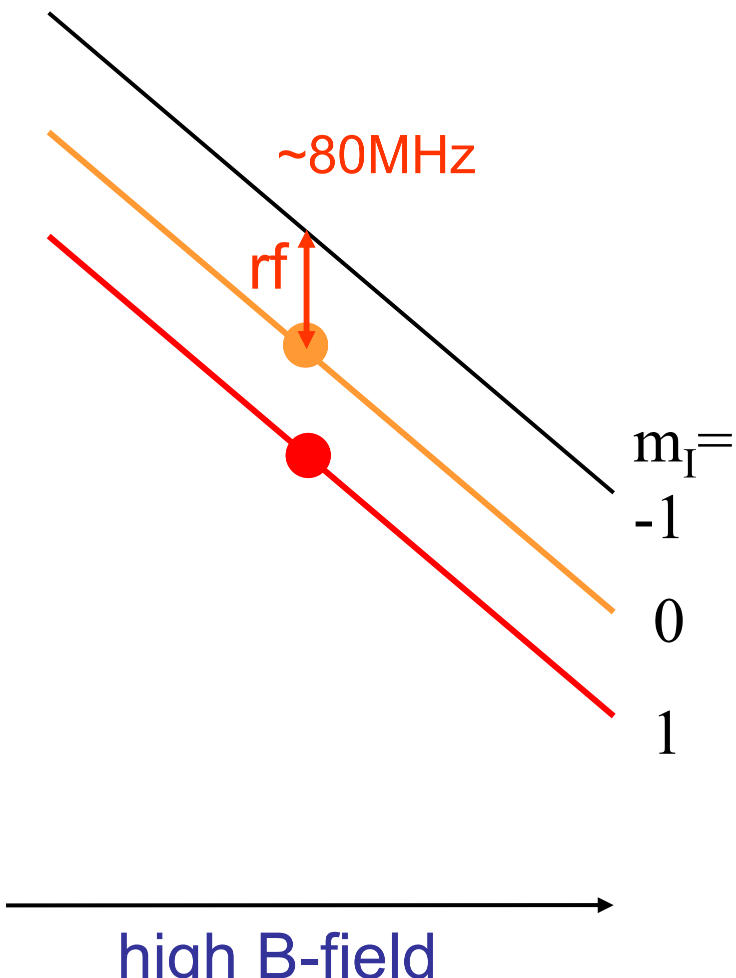


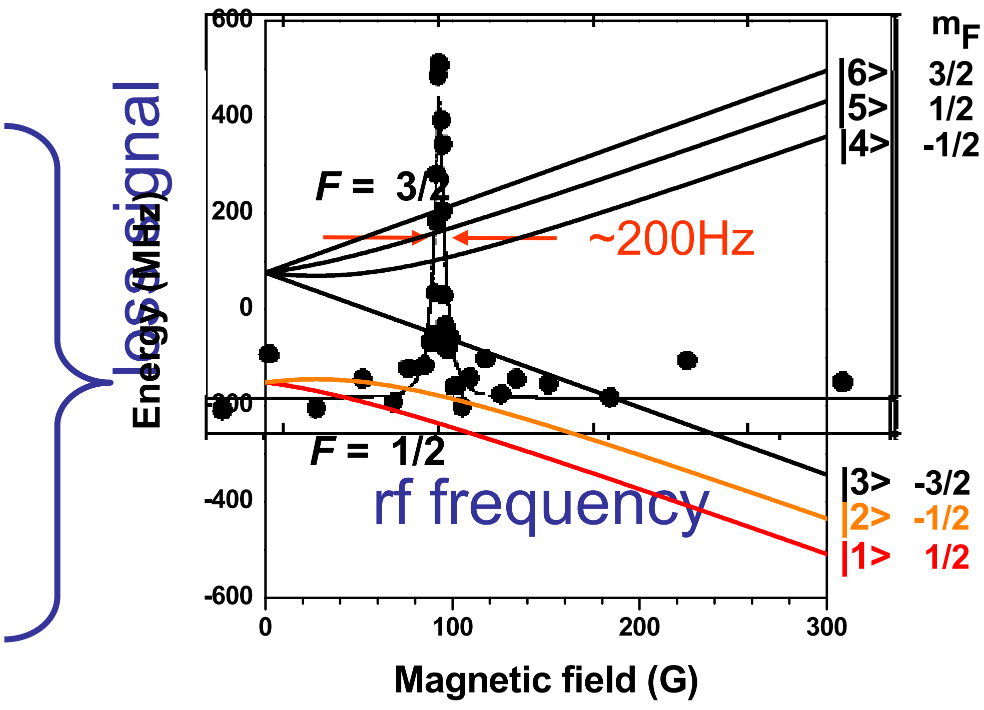
Theory: Stringari `97-`03, Vichi `01, Baranov `01, Heiselberg `04

radio-frequency spectroscopy

meas. of mol. bind. energy in ^{40}K
Regal *et al.*, Nature **424**, 47 (2003)

rf spectroscopy of ^{6}Li:
Gupta *et al.*, Science **300**, 1723 (2003)





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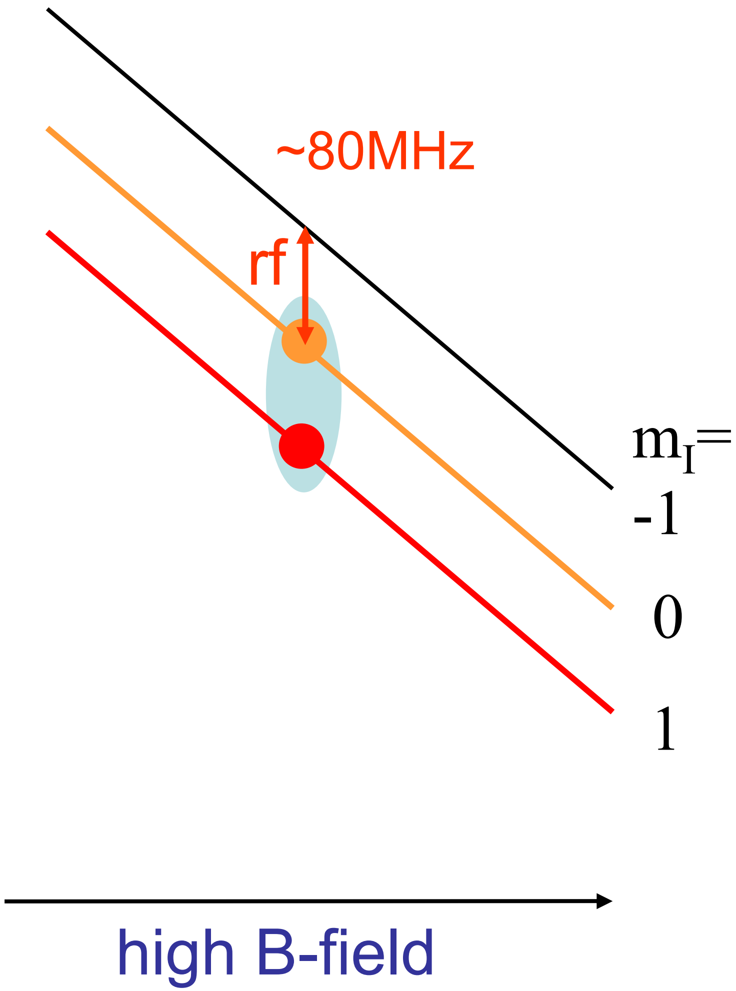

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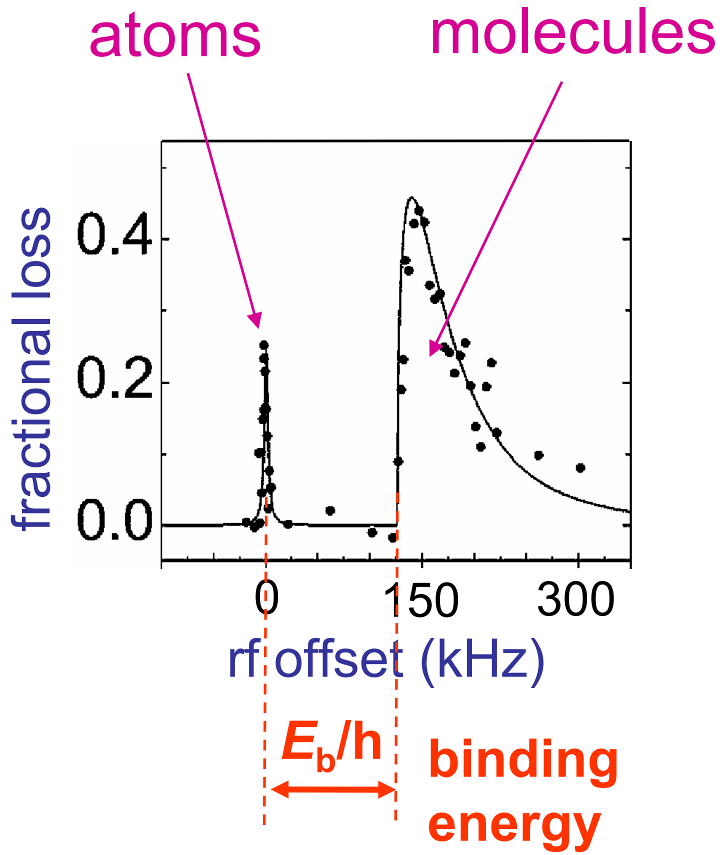
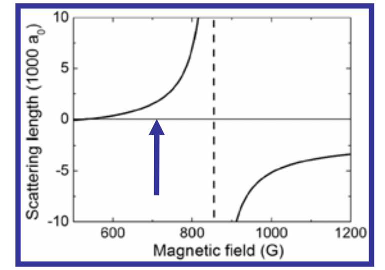
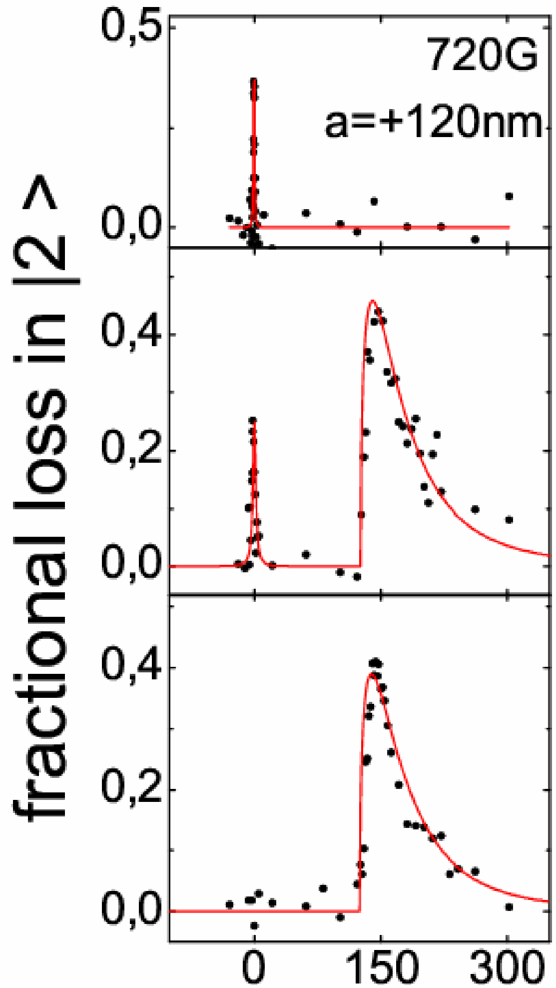


rf spectra in crossover regime



evaporation at 764G, then ramp field to 720G



rf offset (kHz)

no evaporation
$T \gg T_c$

atoms only

evaporation to
$T \approx T_c$

atom-molecule mixture

molecular signal:
two-body physics !!

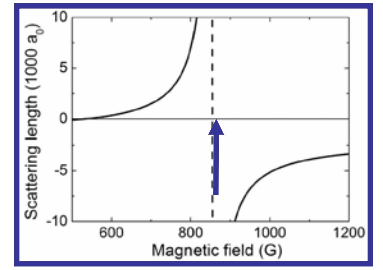
evaporation to
$T < 0.4\ T_c$

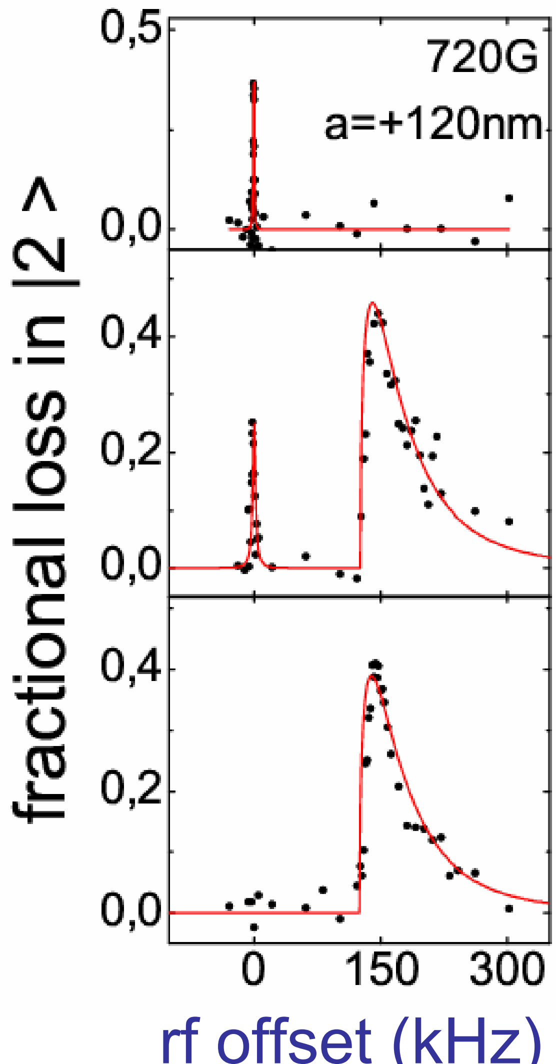
pure molecular sample
(BEC)

Chin et al., Science ´04

rf spectra in crossover regime

evaporation at 764G, then ramp field into crossover





837 G:
≈ **on resonance !**

$T \approx 0.2\ T_F$
double-peak structure:
atoms and ***pairs***

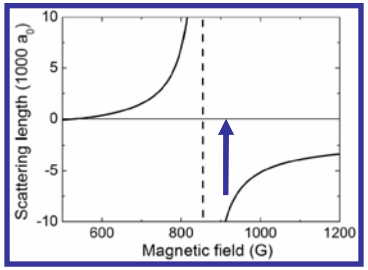
$T = 0.0?\ T_F$
pairs only !

pair signal shifts with E_F !
many-body physics

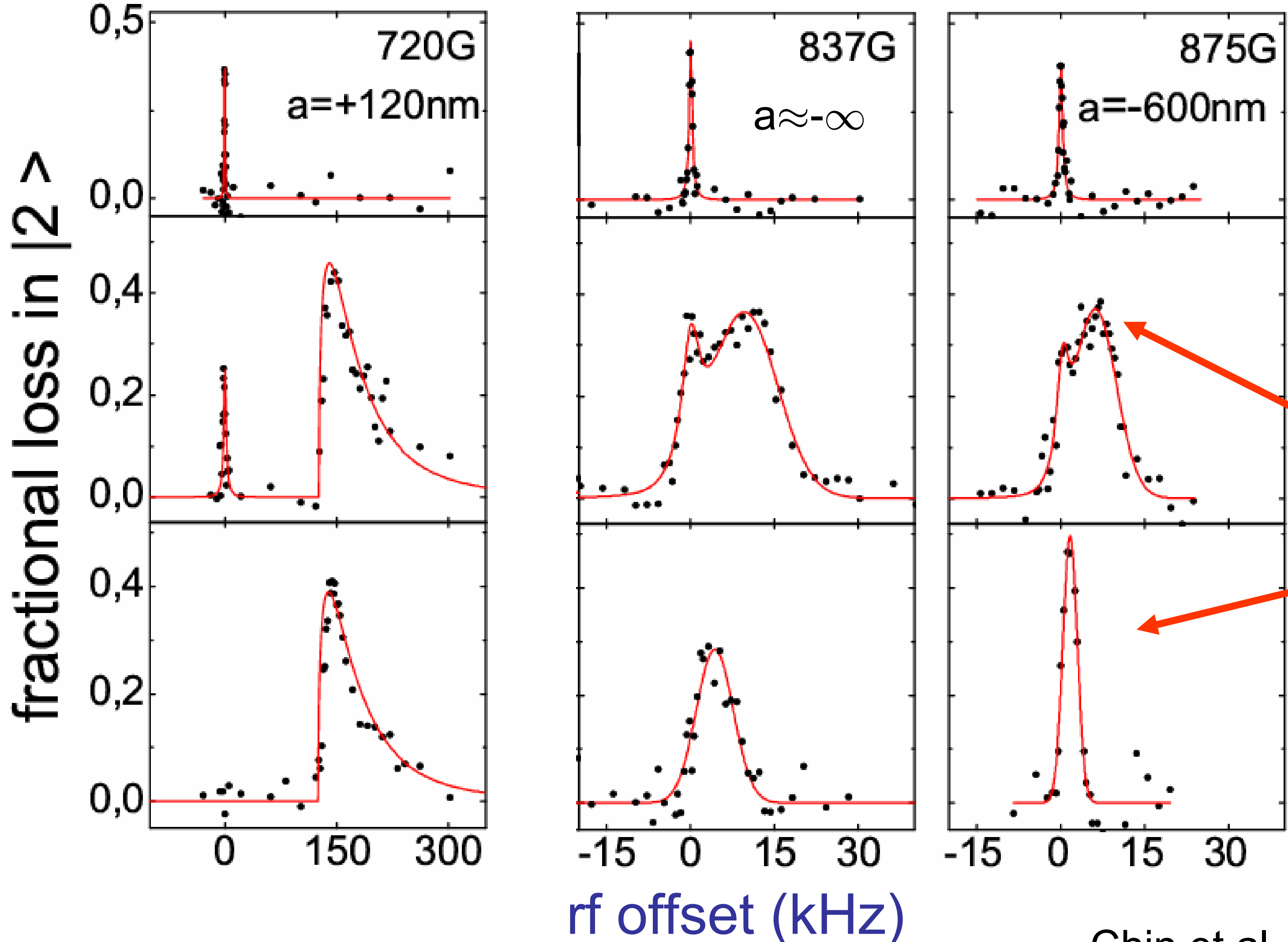
Chin et al., Science ´04

rf spectra in crossover regime

evaporation at 764G, then ramp field into crossover



large neg. sc. length



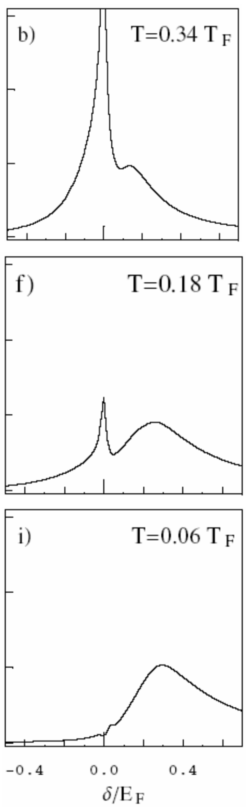
pairing gap
in
strongly
interacting
Fermi gas

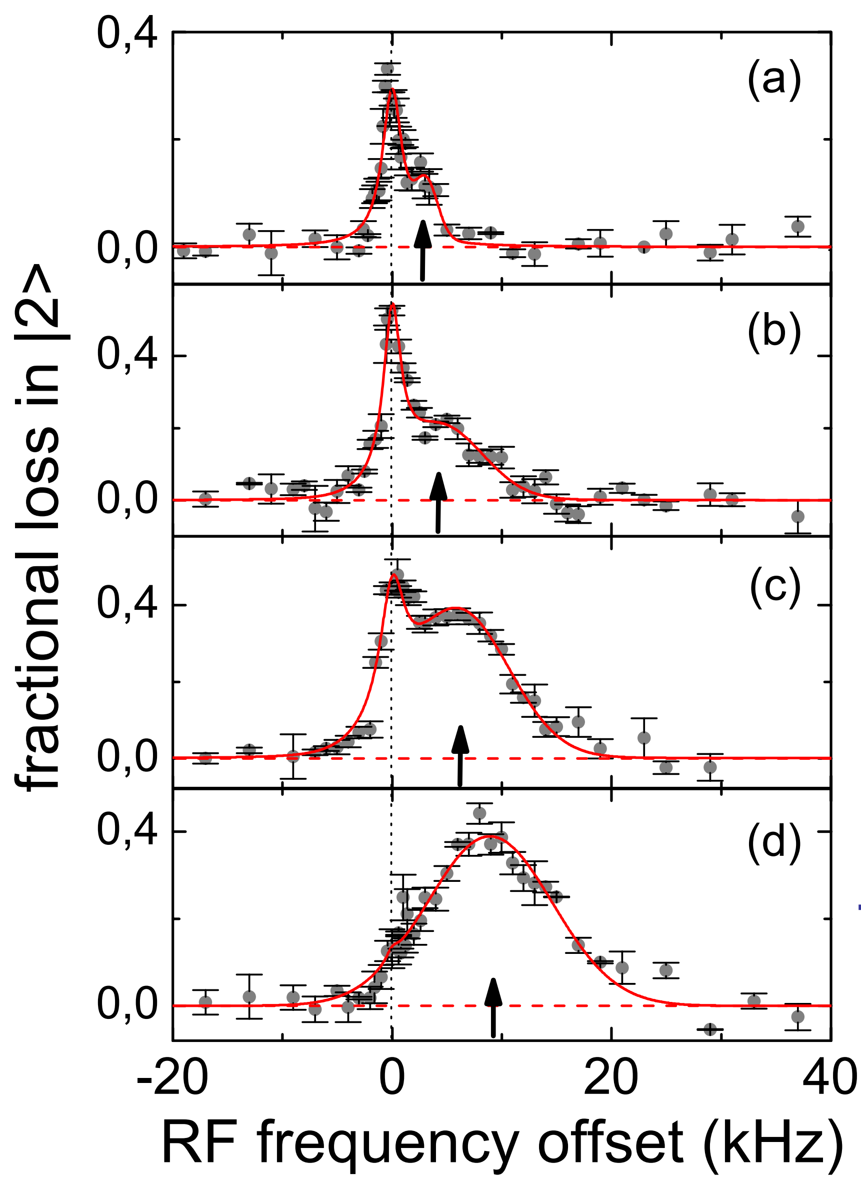
Chin et al., Science ´04

temperature dependence of pairing

theory

Kinnunen
Rodriguez
Törmä
Science Express
21 July 04





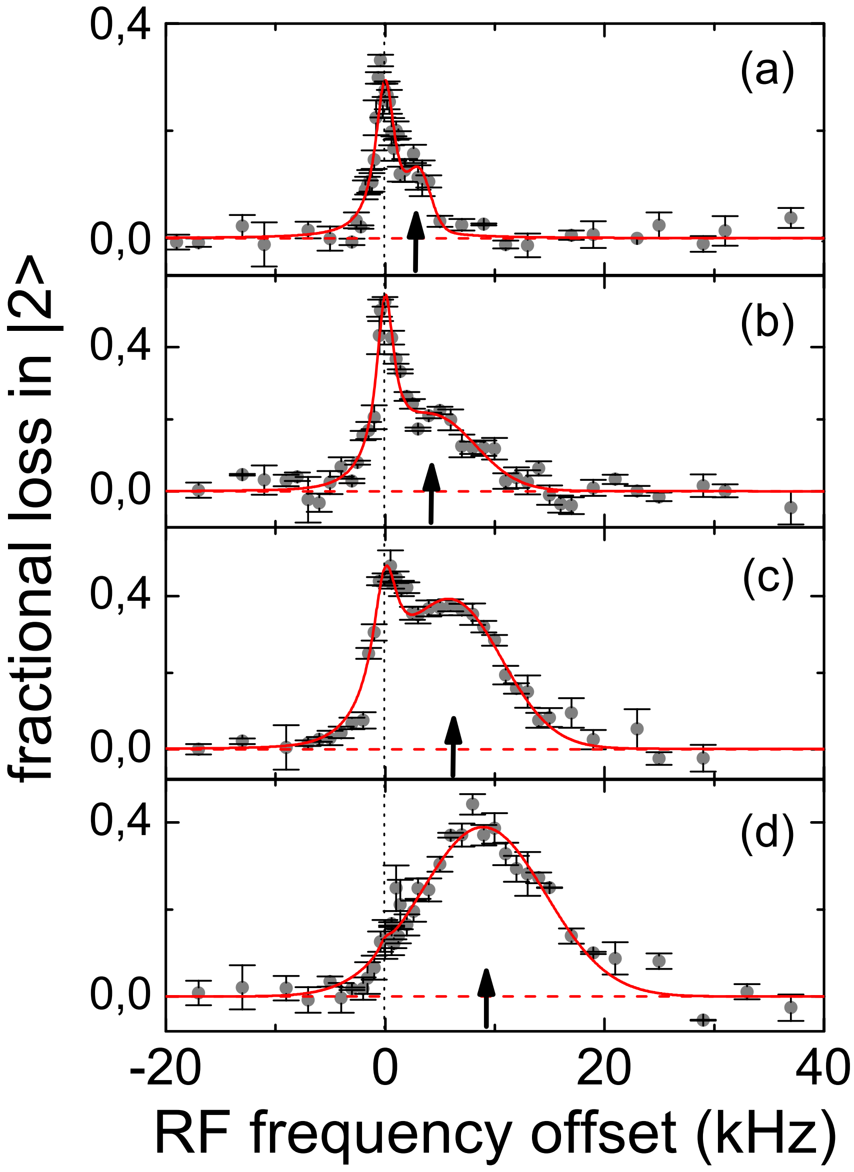
$\approx 0.5\ T_F$

$\approx 0.4\ T_F$

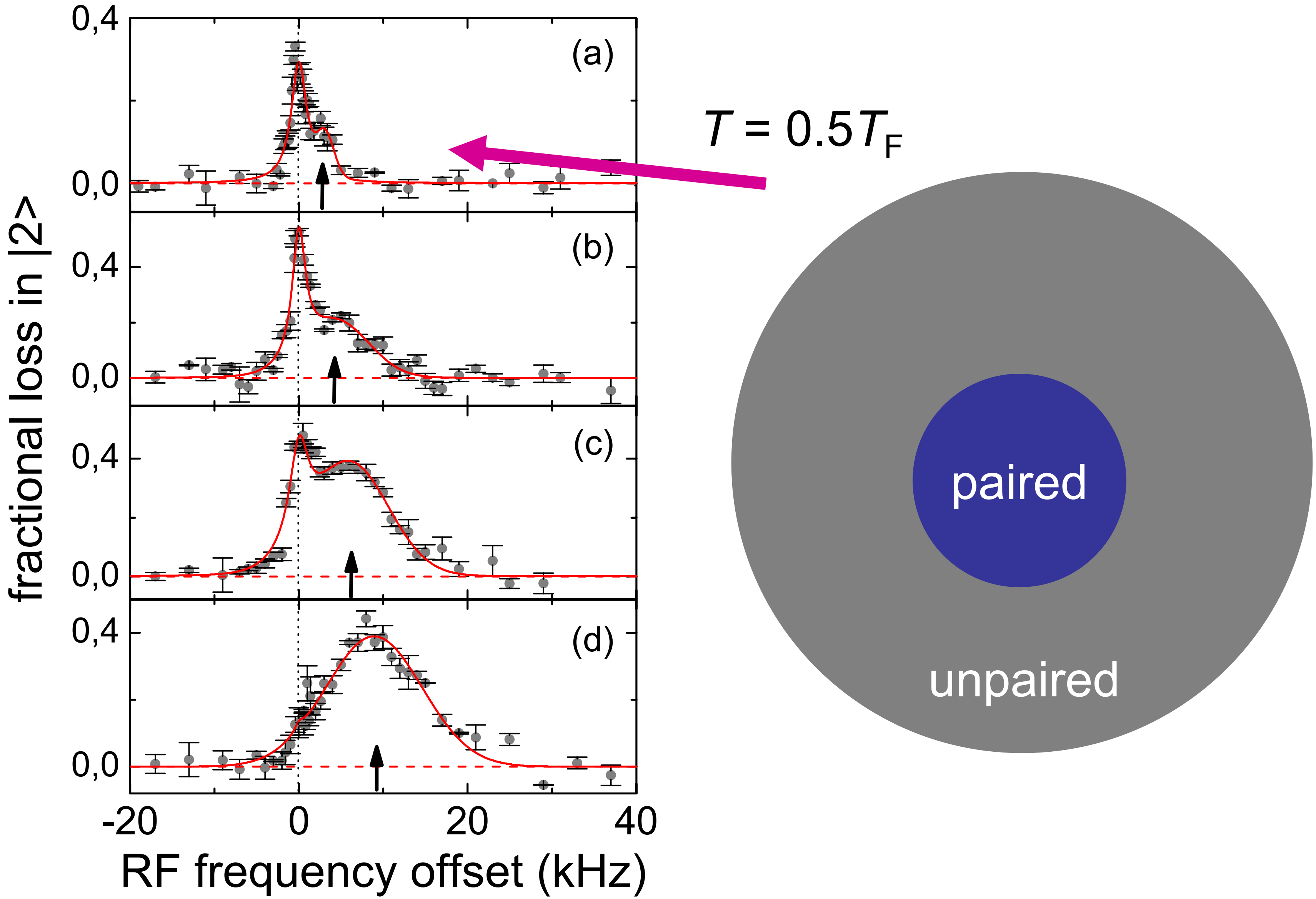
$\approx 0.2\ T_F$

$T < 0.1\ T_F$

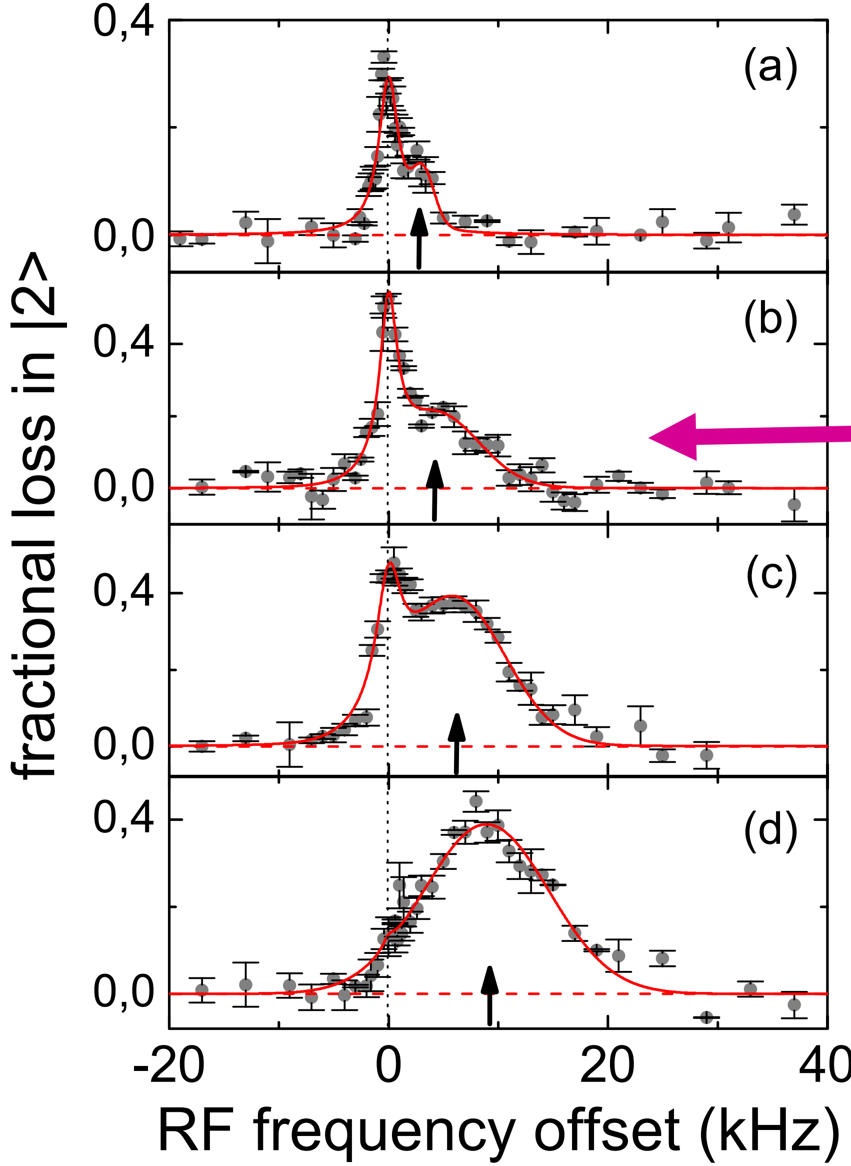
temperature dependence of pairing



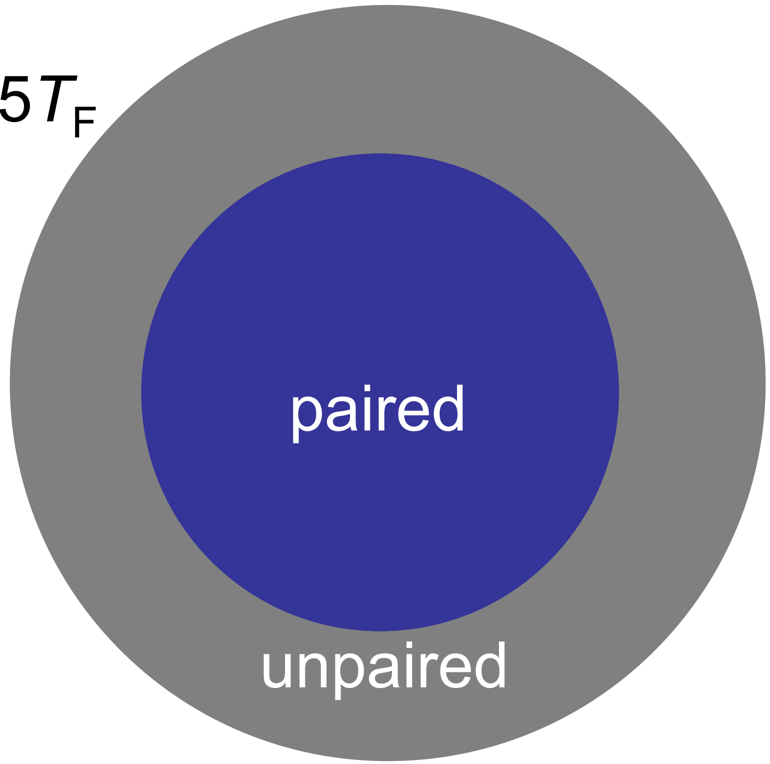
temperature dependence of pairing



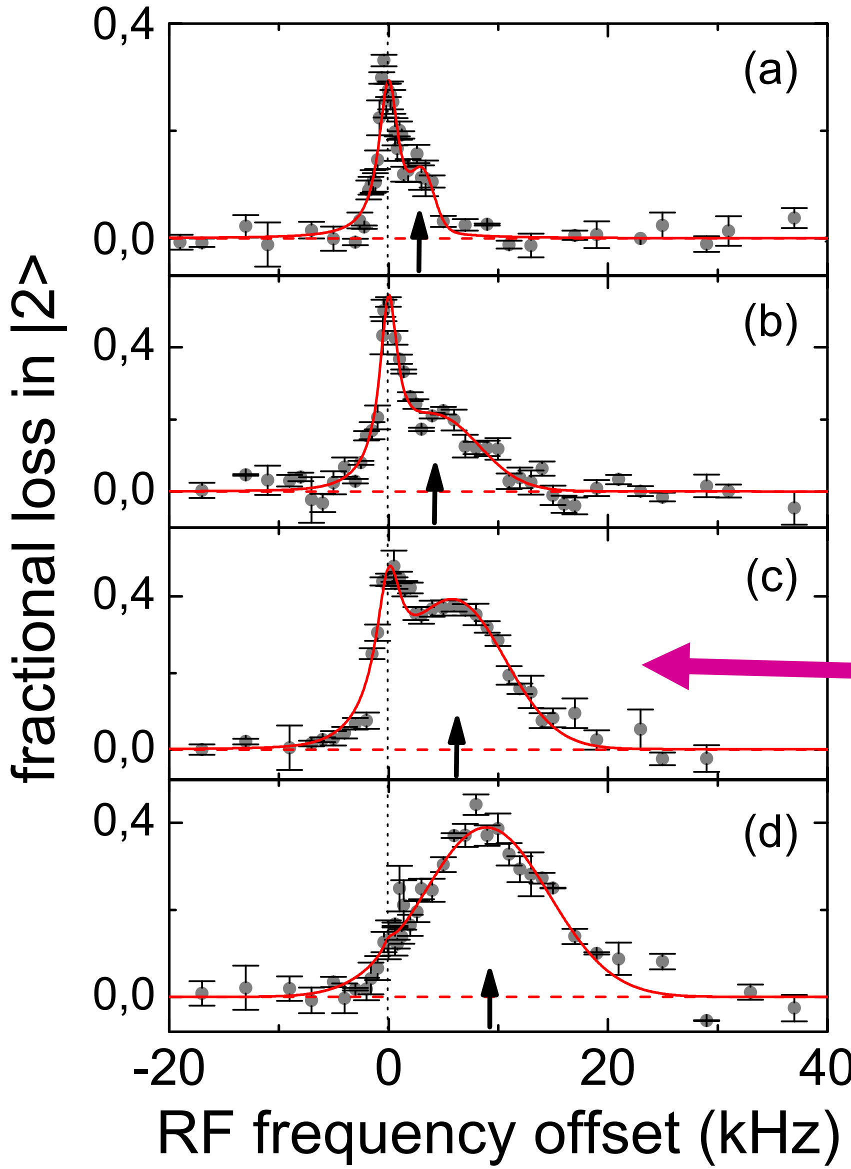
temperature dependence of pairing



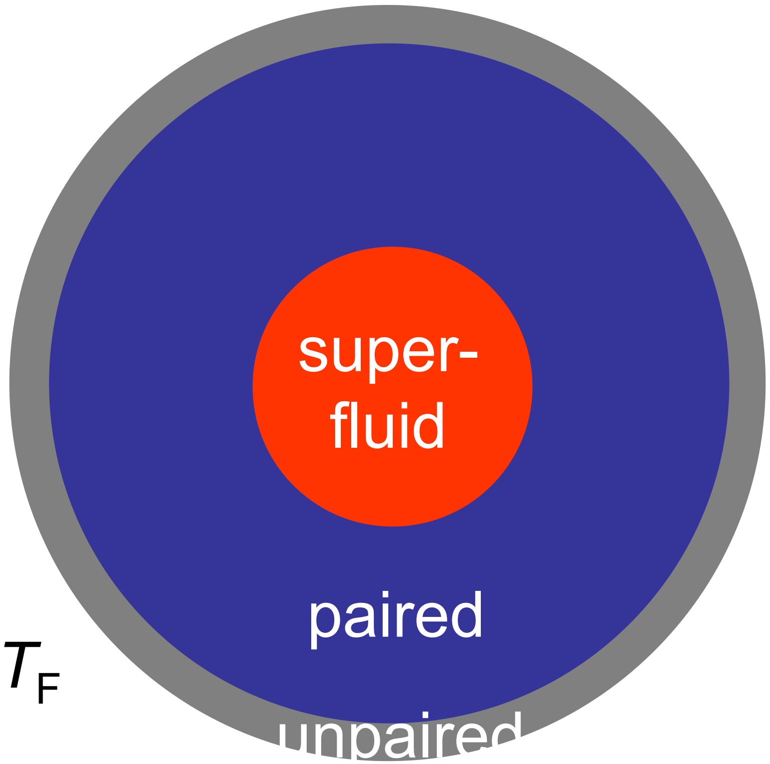
$T = 0.35 T_F$



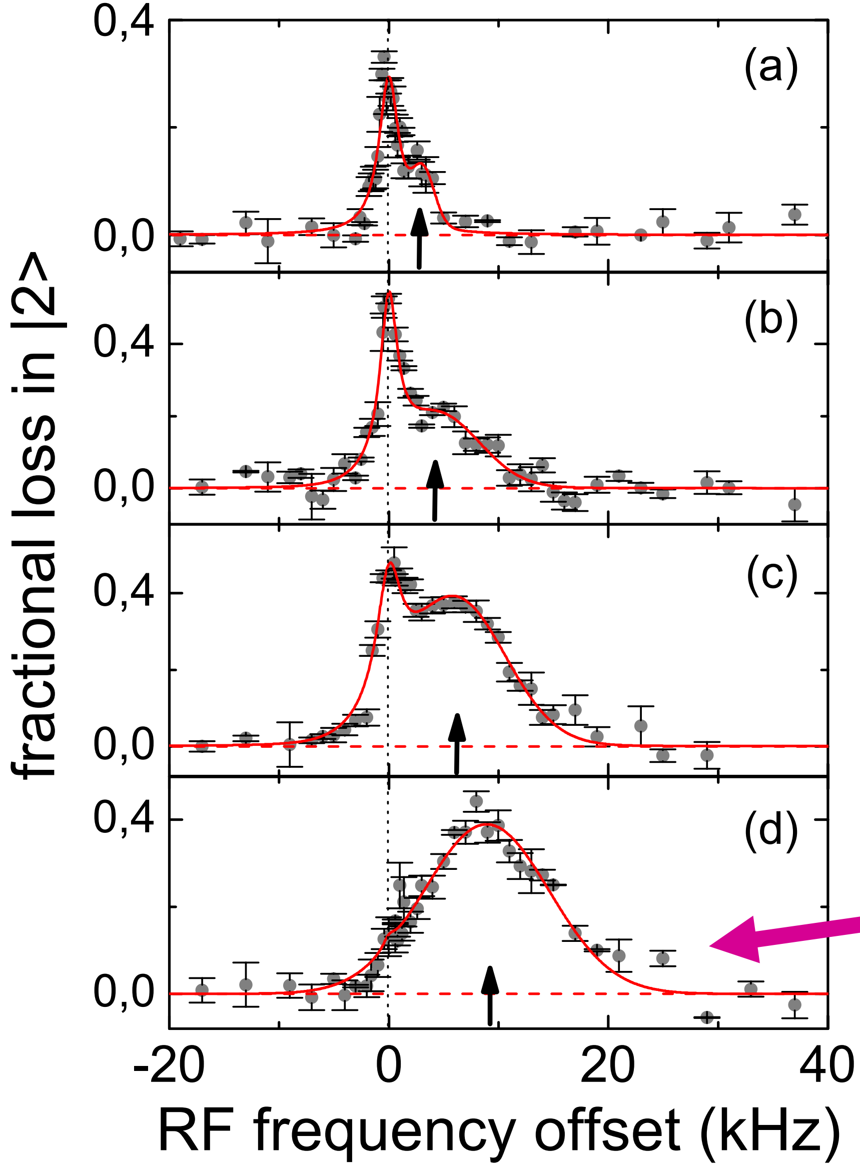
temperature dependence of pairing

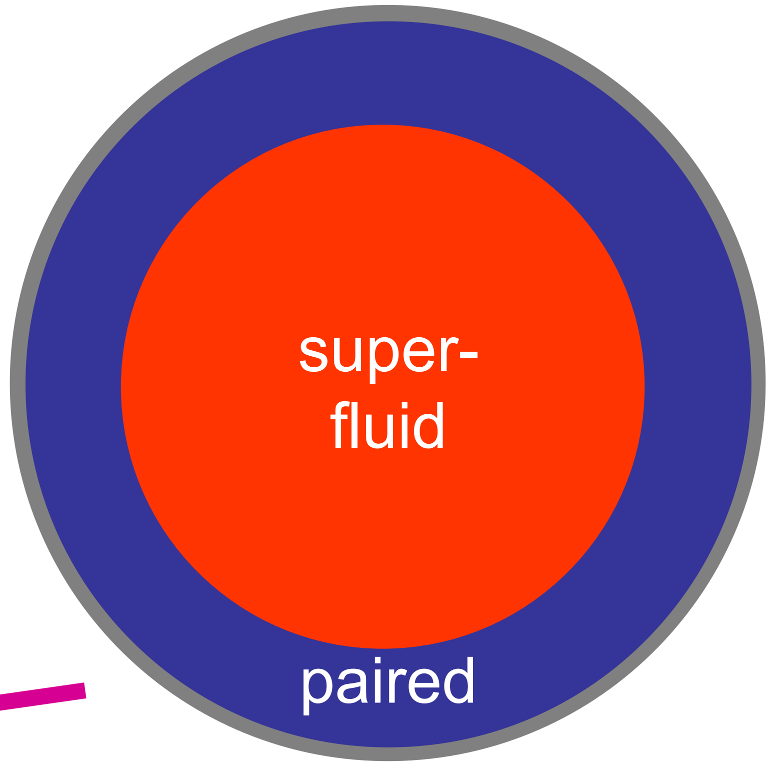


$T = 0.2 T_F$



temperature dependence of pairing





$T \approx 0.05 T_F$

Bose-Einstein Condensation of $^6Li_2$

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Location of the Feshbach resonance

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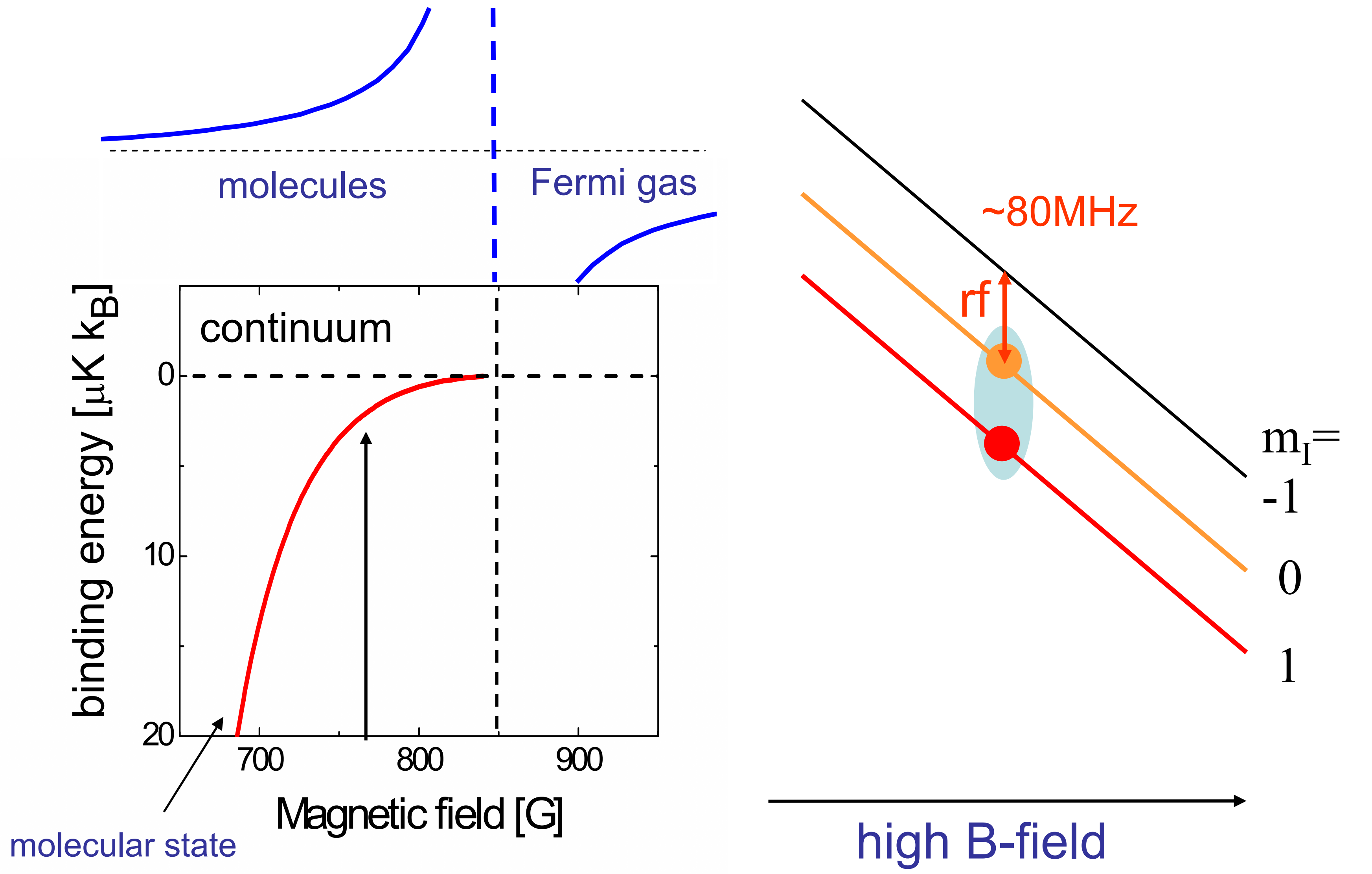
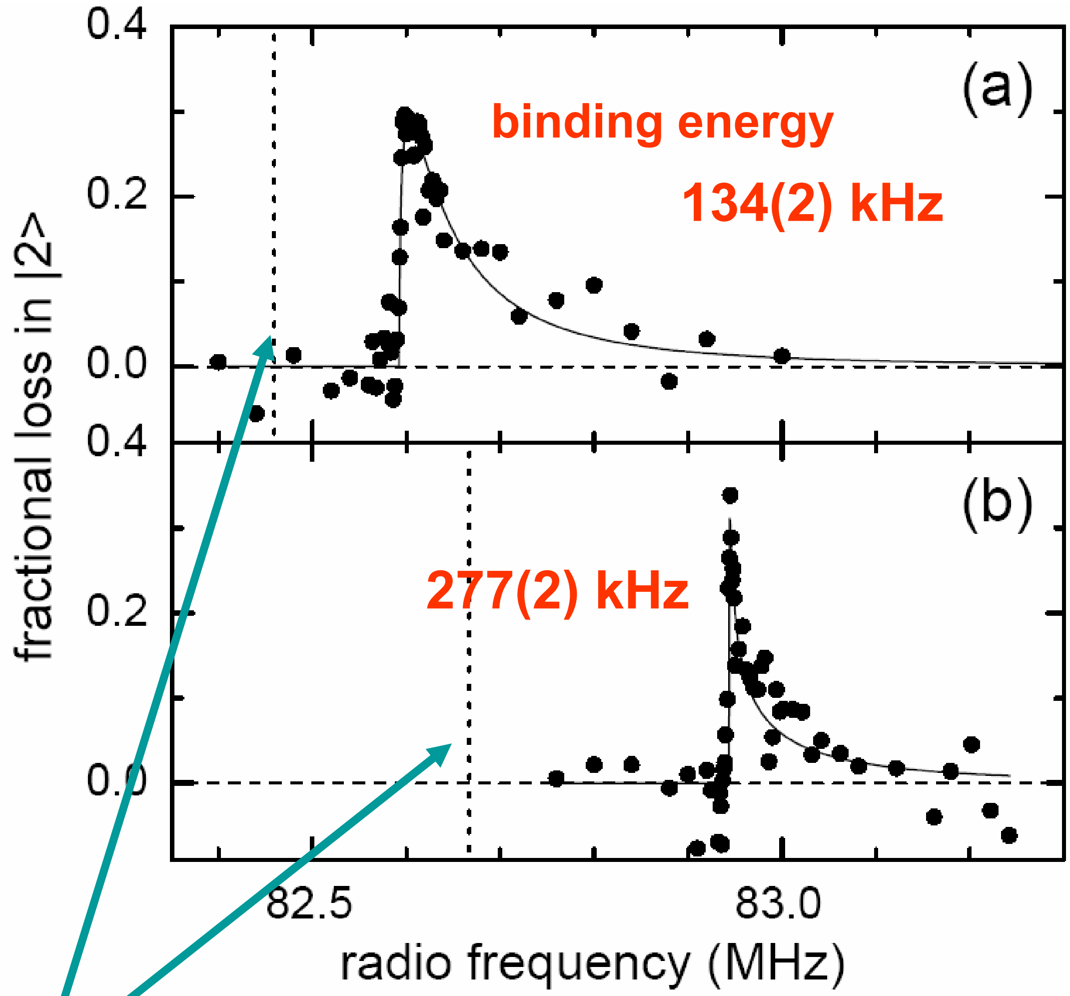
Location of the Feshbach resonance



bound-free dissociation spectra

720.13(4) G

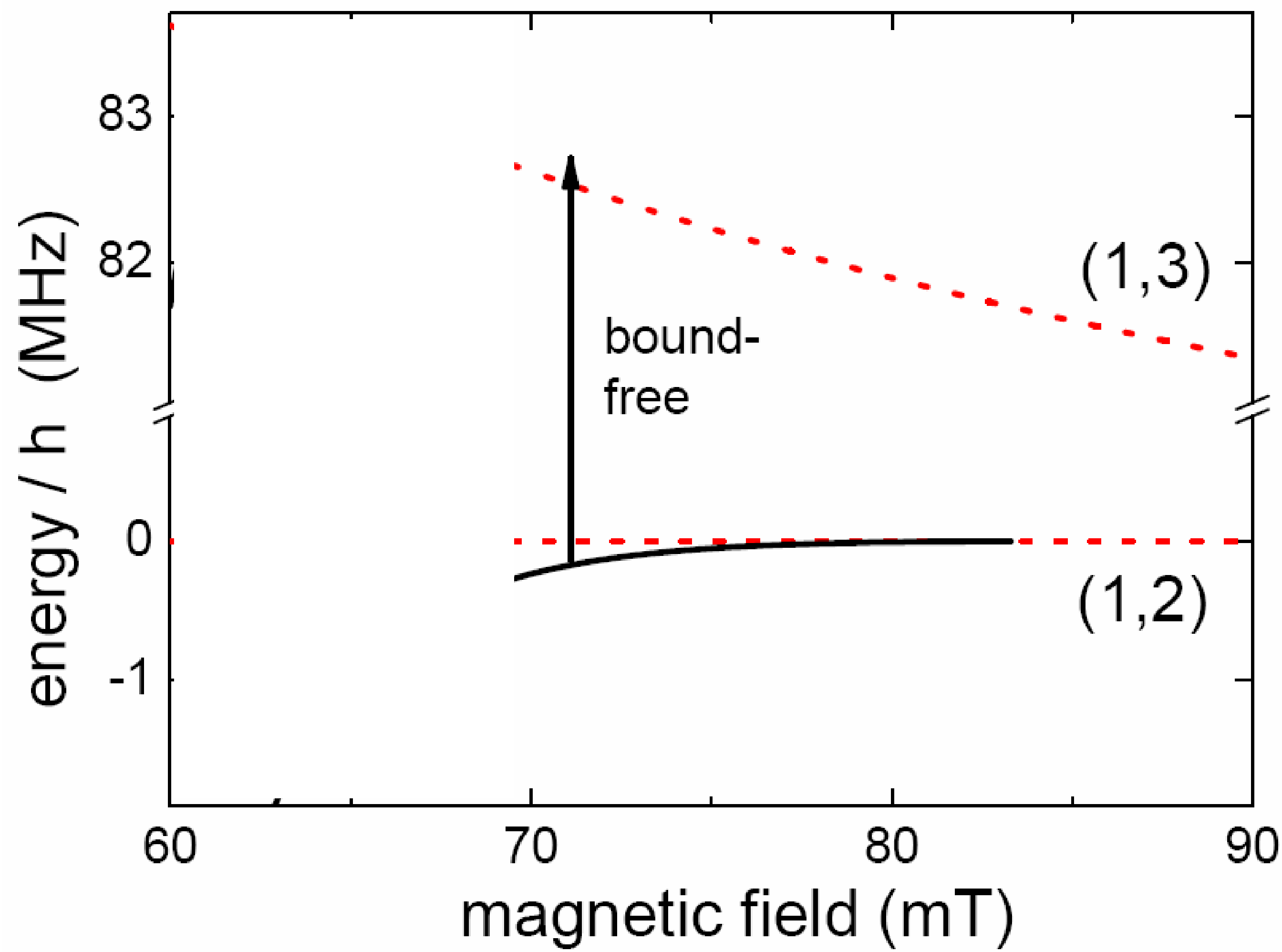
694.83(4) G



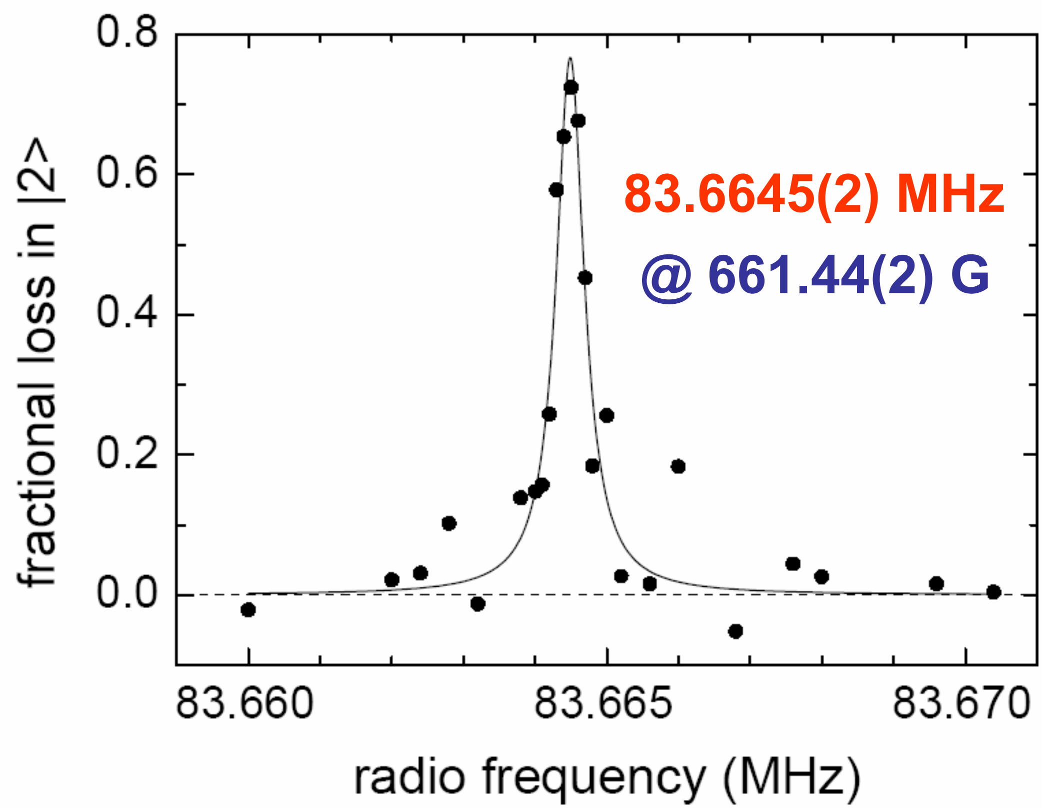
lineshape
of dissociation
signal:
C. Chin and
P. Julienne
cond-mat/0408254

Free atoms transitions

rf spectroscopy on $^6Li_2$



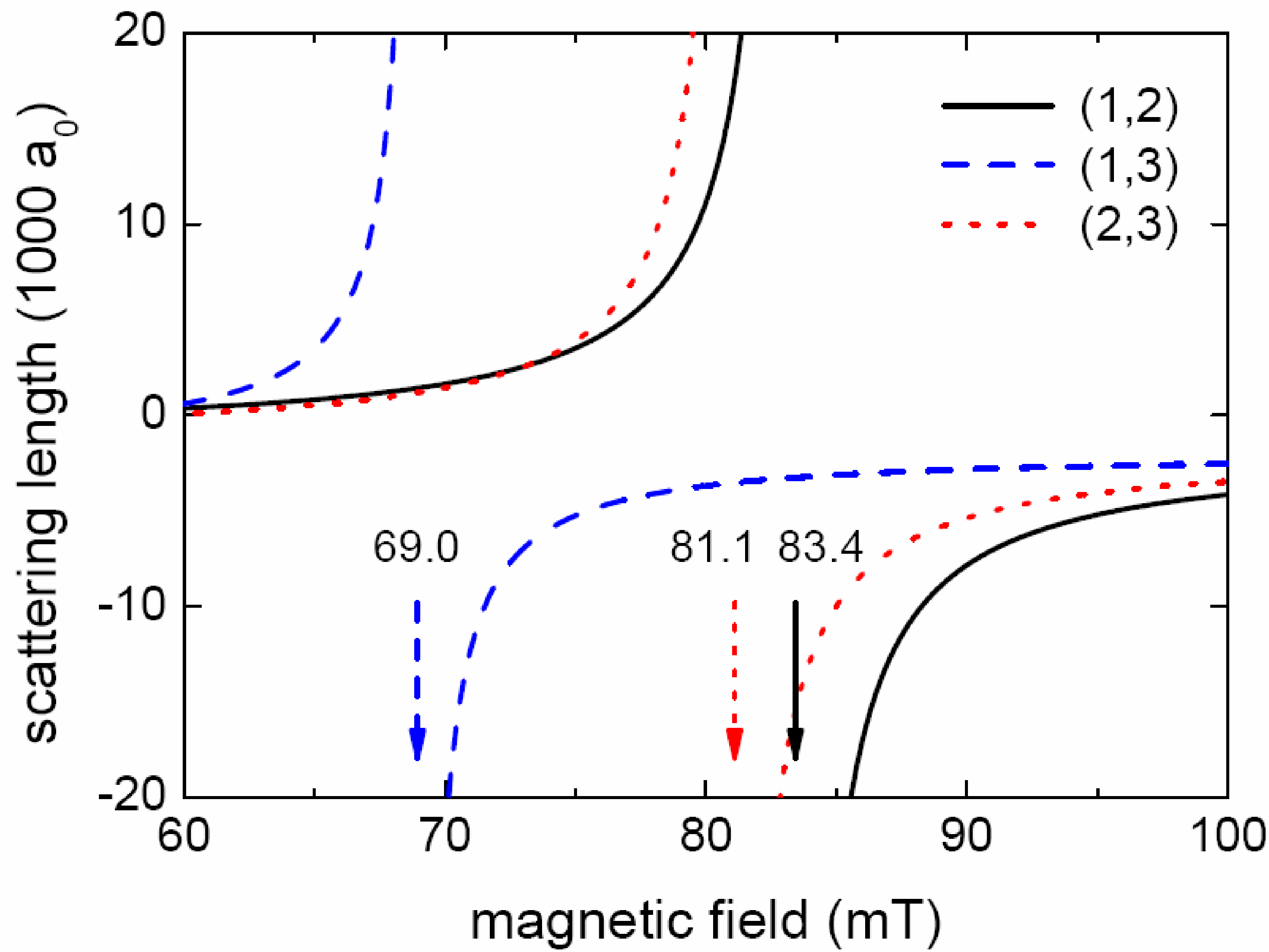
bound-bound transition



exp. data → NIST theory group: multi-channel quantum scattering model → $a_s = 45.167(8)\ a_0$

$a_t = -2140(18)\ a_0$

s-wave scattering lengths



Bartenstein et al., cond-mat/0408673

conclusion

Precise determination of Feshbach position

BEC of $^6Li_2$ molecules

- **surprisingly simple to make it**
- **essentially pure and very long lifetimes**
- **excellent starting point**

BEC-BCS cross-over

- **conversion into Fermi gas reversible**
- **cloud size**
- **collective excitation**
- **pairing gap**
- **universality scaling laws**

interesting effects,
e.g. pair breaking

… smoking gun for superfluidity?