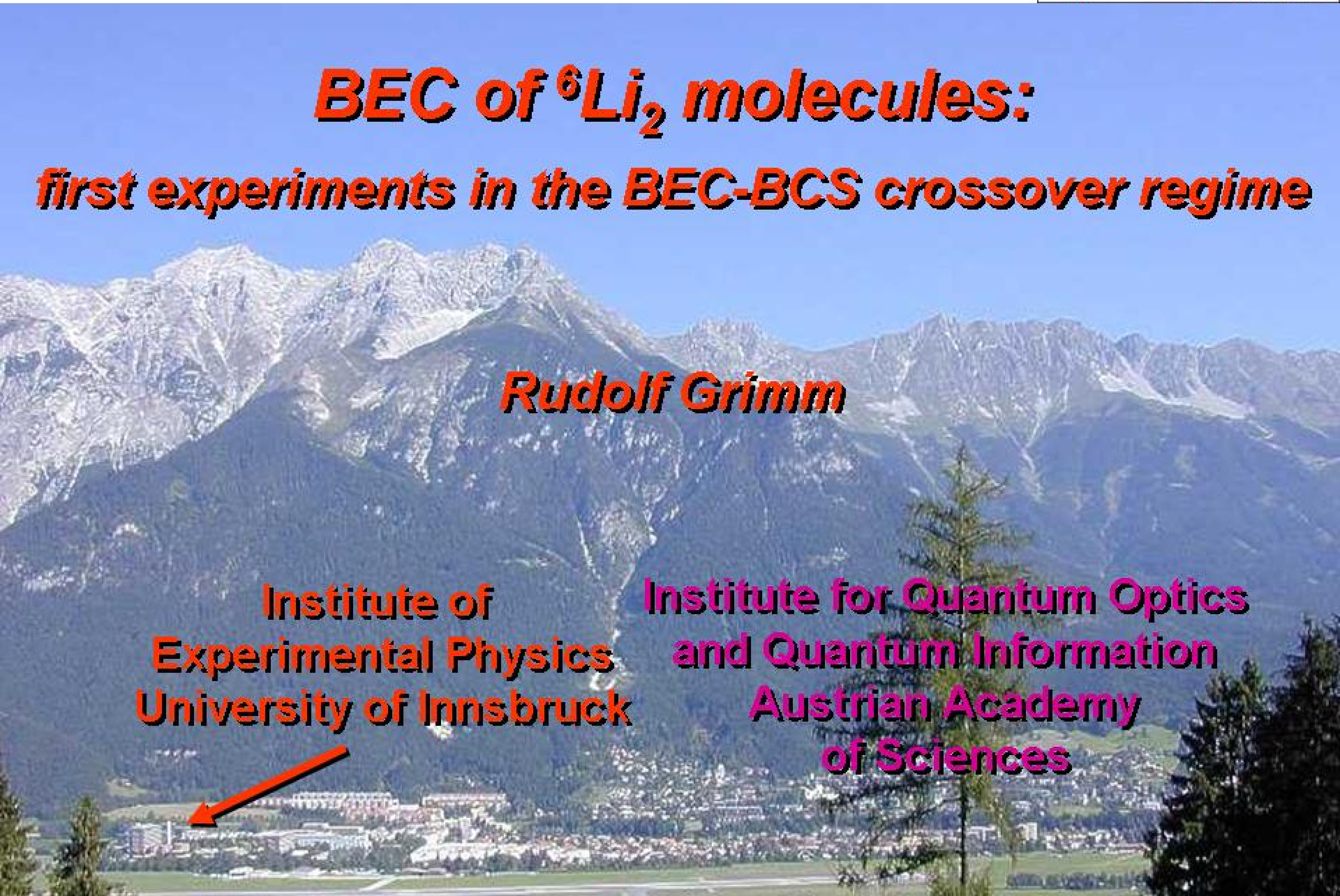
Levico, 04 Mar 2004

Ultracold atoms
quantum gases



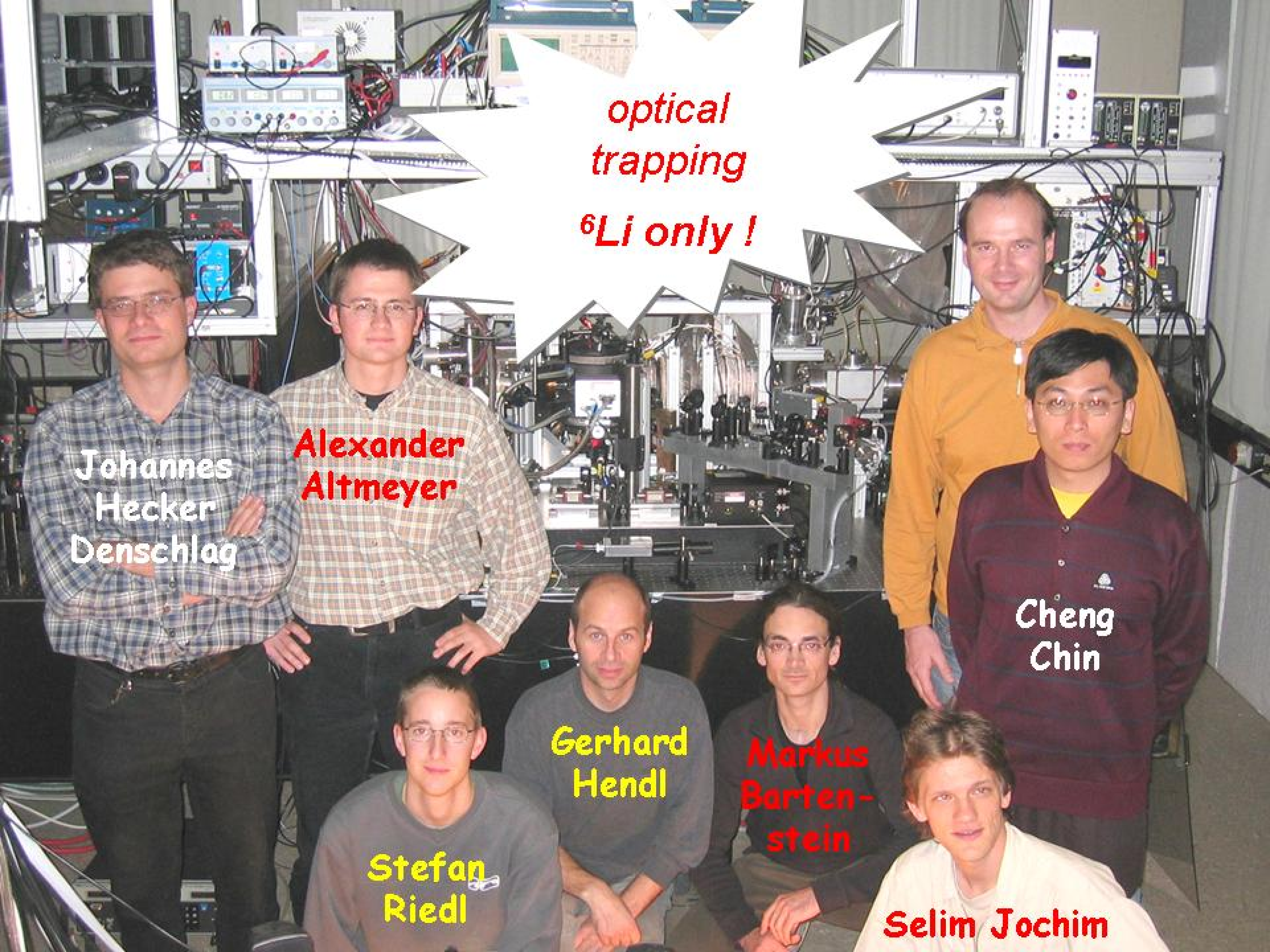
BEC of $^6Li_2$ molecules:

first experiments in the BEC-BCS crossover regime

Rudolf Grimm

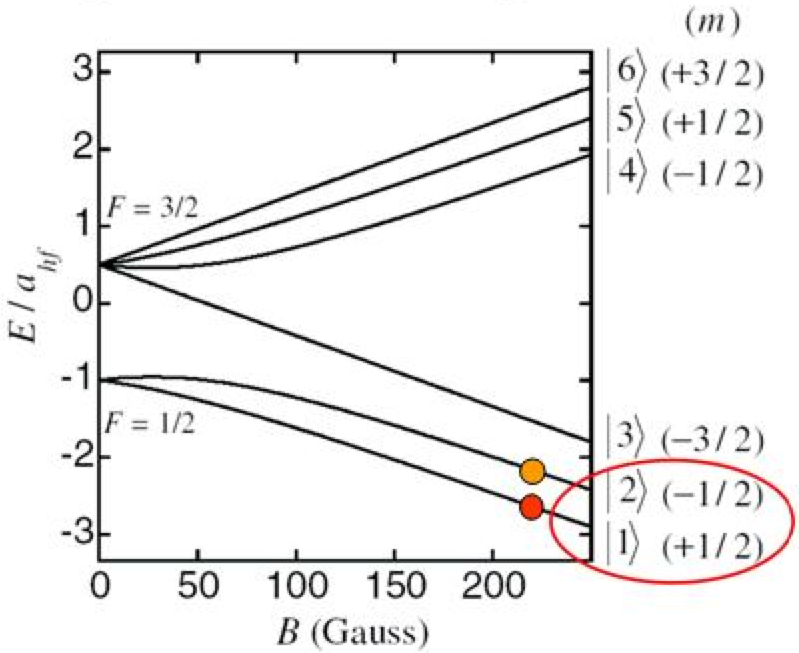
Institute of
Experimental Physics
University of Innsbruck

Institute for Quantum Optics
and Quantum Information
Austrian Academy
of Sciences


optical
trapping
^{6}Li only !
Johannes
Hecker
Denschlag
Alexander
Altmeyer
Cheng
Chin
Gerhard
Hendl
Markus
Barten-
stein
Stefan
Riedl
Selim Jochim

^{6}Li spin mixture

^{6}Li ground state in a magnetic field



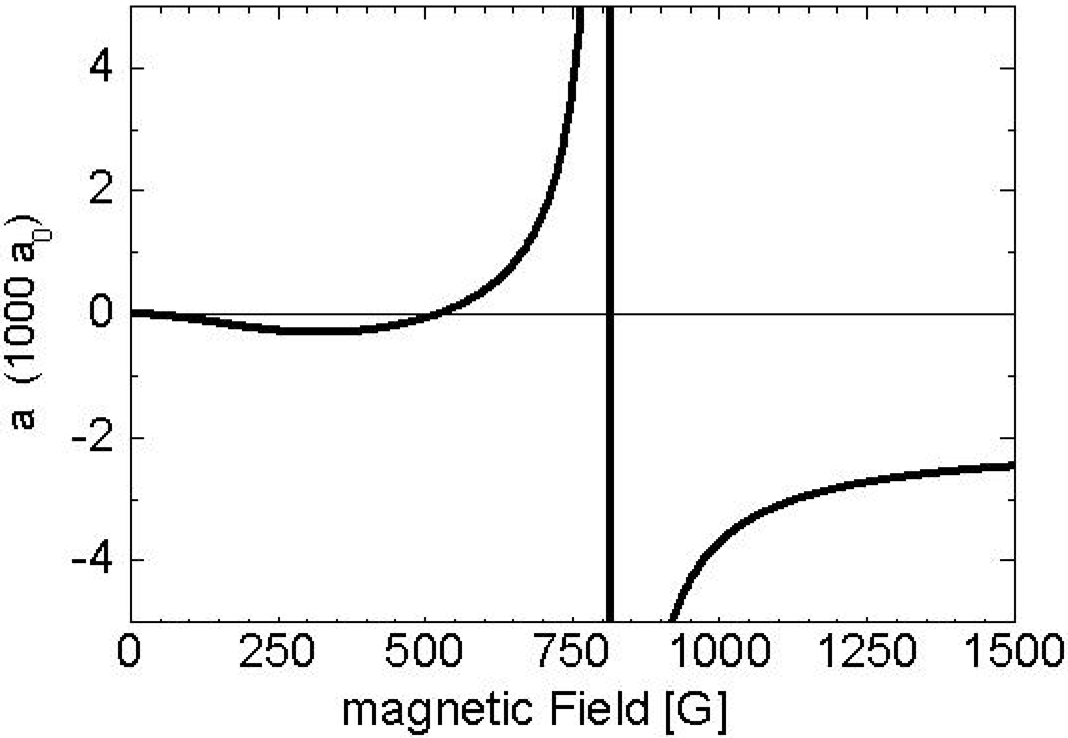
spin mixture of two lowest states

stable against two-body decay

Feshbach resonance

prediction:

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



Innsbruck ^{6}Li story

$^6Li_2$ molecules in a thermal gas

how to condense these molecules

reversible crossover to a degenerate Fermi gas

where exactly is the Feshbach resonance ?

collective excitation surprises

Innsbruck ^{6}Li story

Ultracold atoms quantum gases

<u>$^6Li_2$ molecules in a thermal gas</u>

Jochim et al., PRL 240402 (2003)

how to condense these molecules

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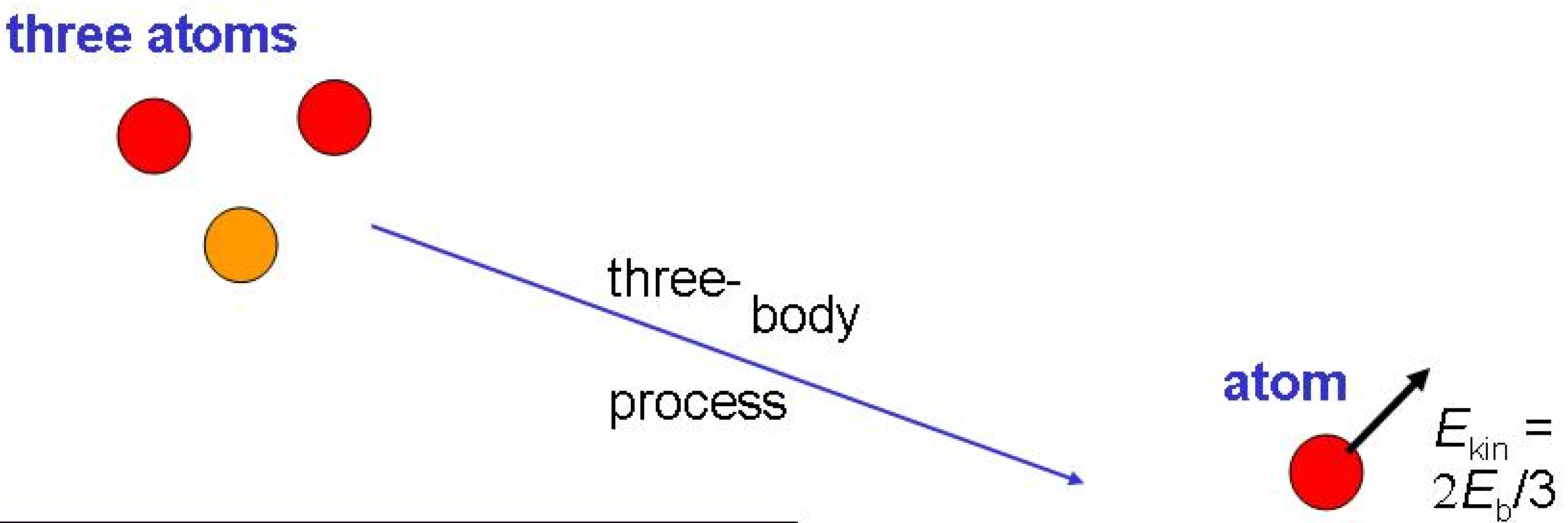
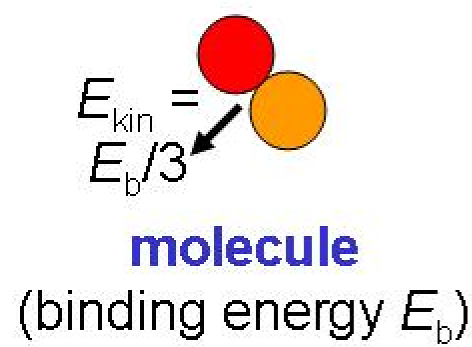
collective excitation surprises

three-body recombination

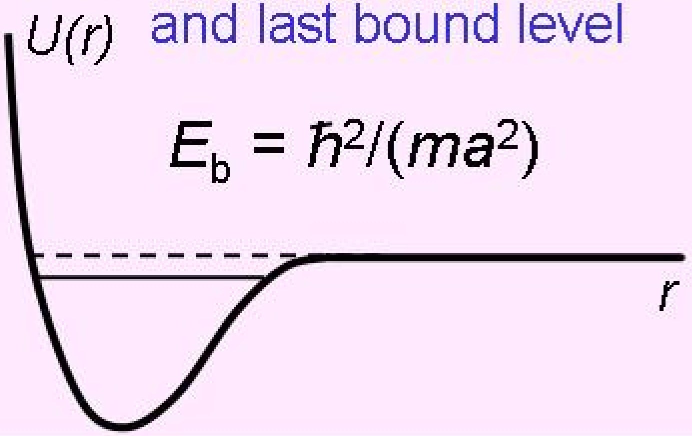
molecules made by collisions





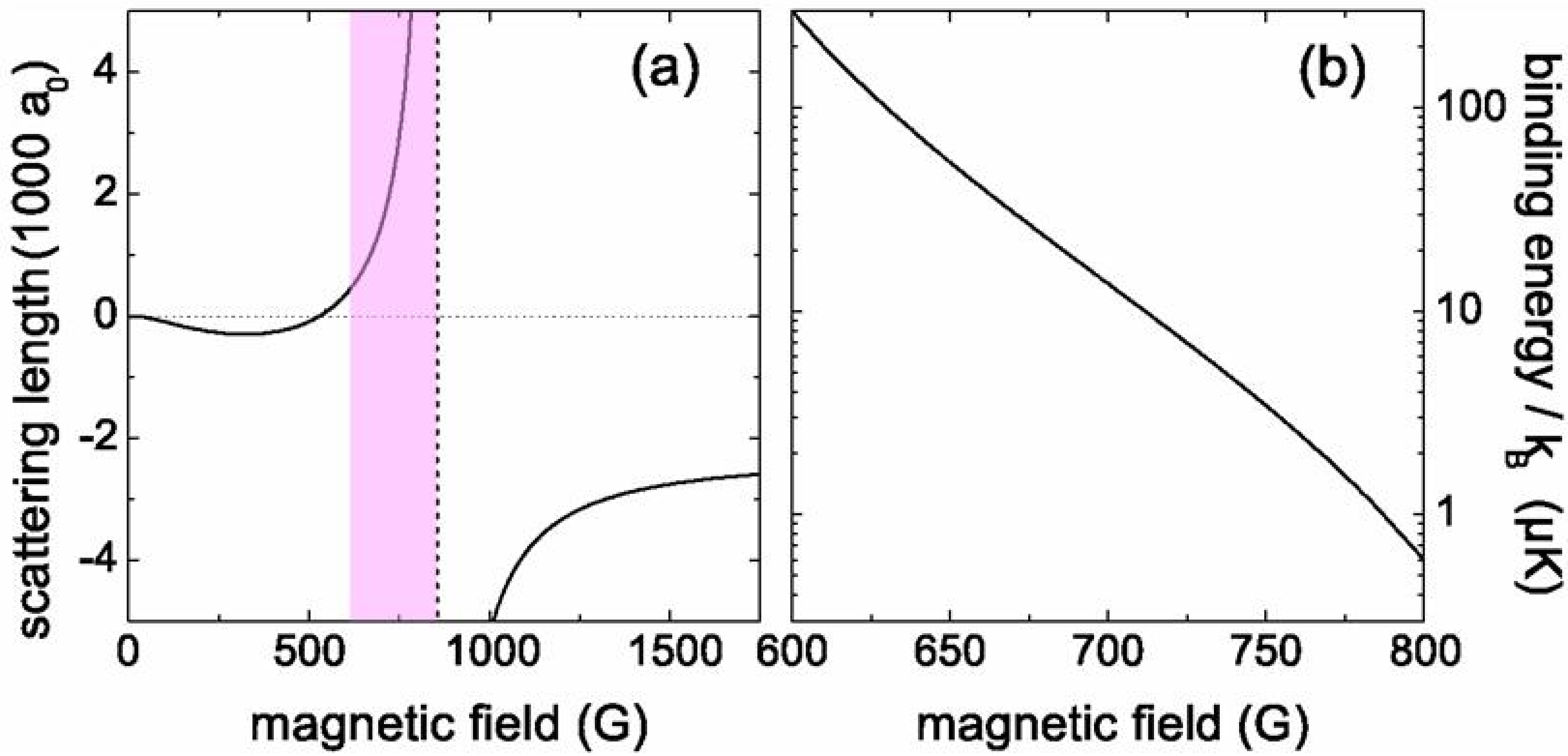
large positive scattering length and last bound level

$$E_b = \hbar^2/(ma^2)$$



weakly bound level

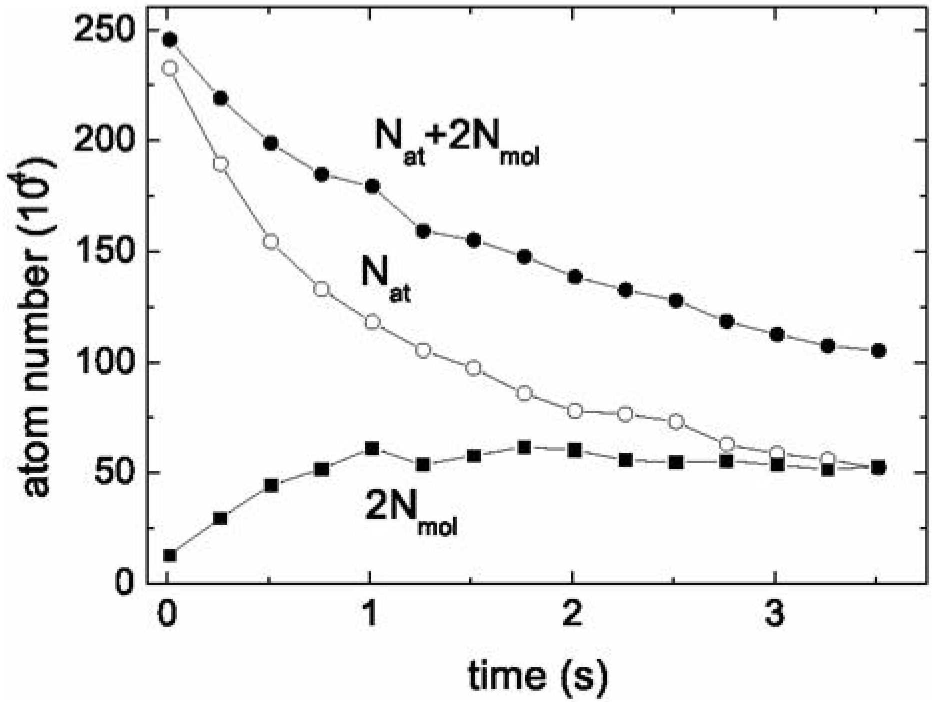
large positive scattering length   weakly bound molecular state



molecule formation

***B* = 690 G**:

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



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

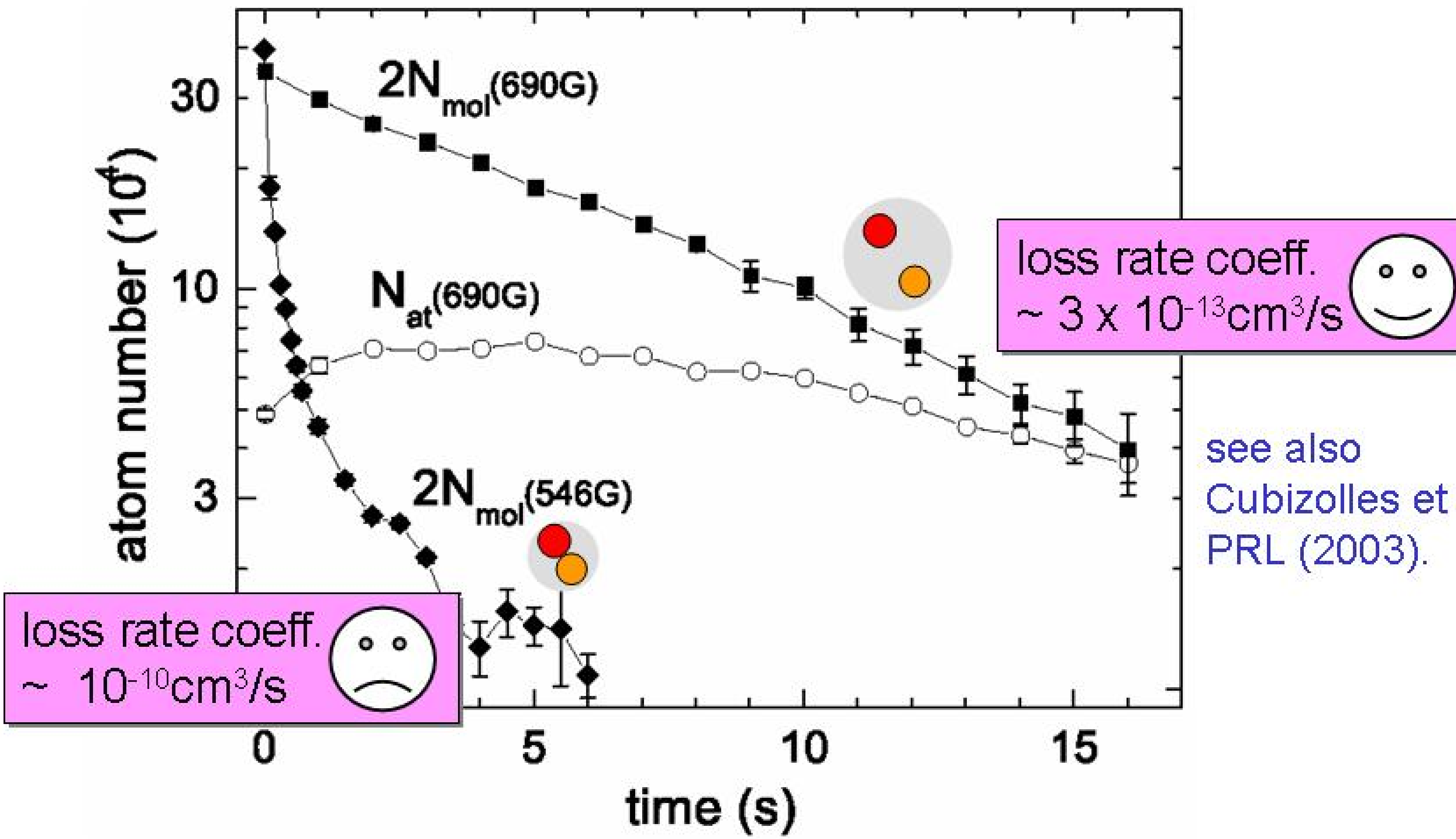
chemical atom-molecule equilibrium

$$\boxed{\Phi_{mol} = \Phi_{at}^2 e^{k_B T / E_b}}$$

atomic molecular
phase-space density

C. Chin & RG
cond-mat/0309078
(classical gas)

long lifetimes !!!



see also
Cubizolles et al.
PRL (2003).

explanation (Petrov, Salomon, Shlyapnikov, cond-mat/0309010):
Pauli blocking in inelastic molecule-molecule collisions

Innsbruck ^{6}Li story

Ultracold atoms quantum gases

$^6Li_2$ molecules in a thermal gas

<u>how to condense these molecules</u>

Jochim et al., Science 302, 2101 (2003)

reversible crossover to a degenerate Fermi gas

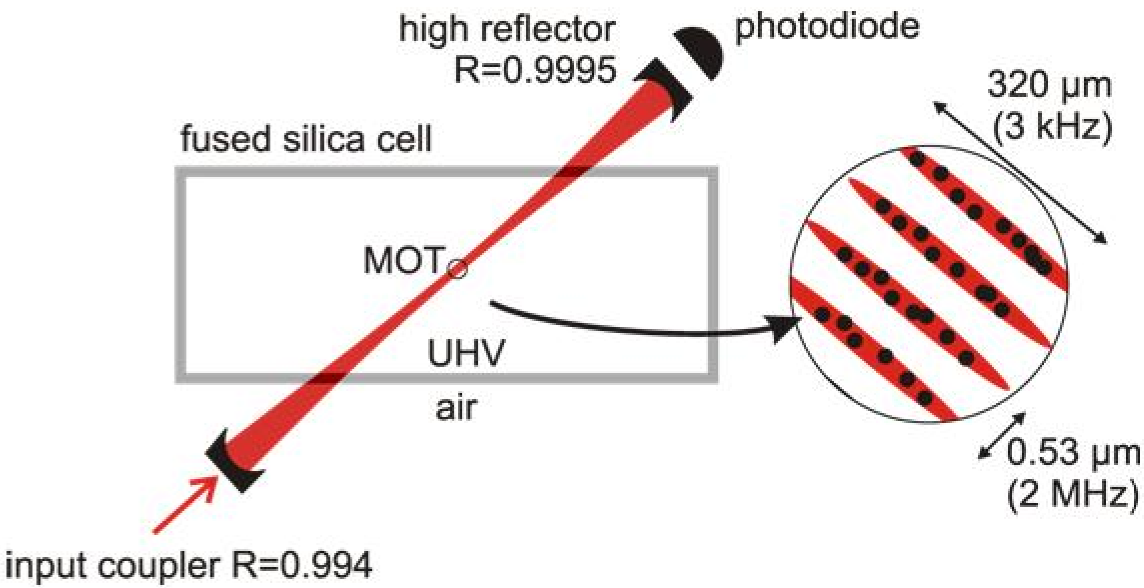
where exactly is the Feshbach resonance ?

collective excitations

resonator-enhanced dipole trap

efficient loading needs large-volume deep trap

- resonator set up at Brewster's angle
- 130x enhancement of a 2 W Nd:YAG laser (1064 nm)
- 1 mK trap depth for Li



Mosk et al. Opt. Lett 26, 1837-1839 (2001)

Far off resonance:

Li	670 nm
trap	1064 nm

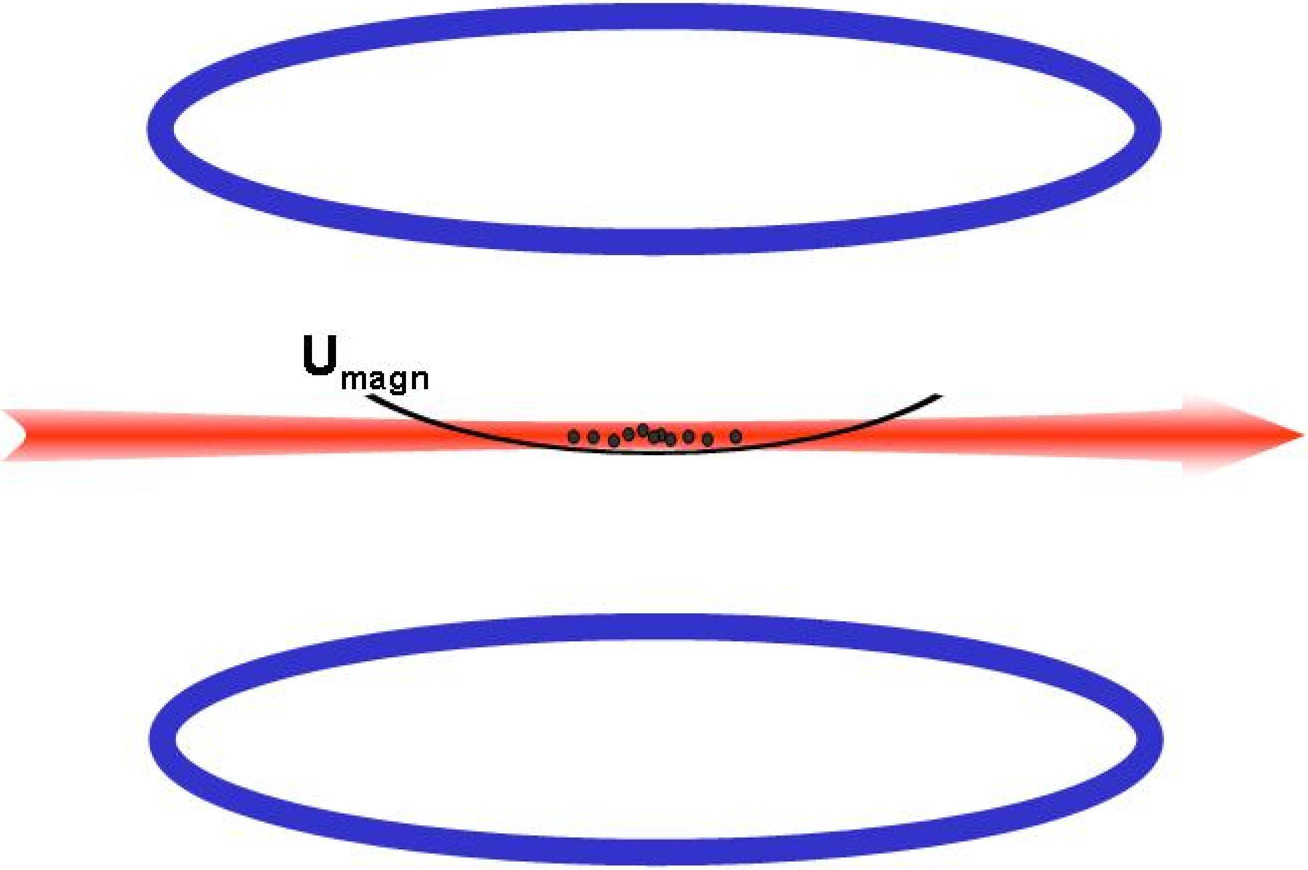
-> only ~0.5 photon scattered per second

load up to ~10^7 atoms

(~10^4 per well)

optical trap for evaporative cooling

Ultracold atoms quantum gases



special feature #1
precise control
of laser power
10 W $\rightarrow$ few 100μW

special feature #2: axial magnetic confinement
- spatial compression at very weak optical traps
- perfectly harmonic !!
- precisely known trap frequency for weak optical trap

ν_z =
24.5 Hz @ 1kG

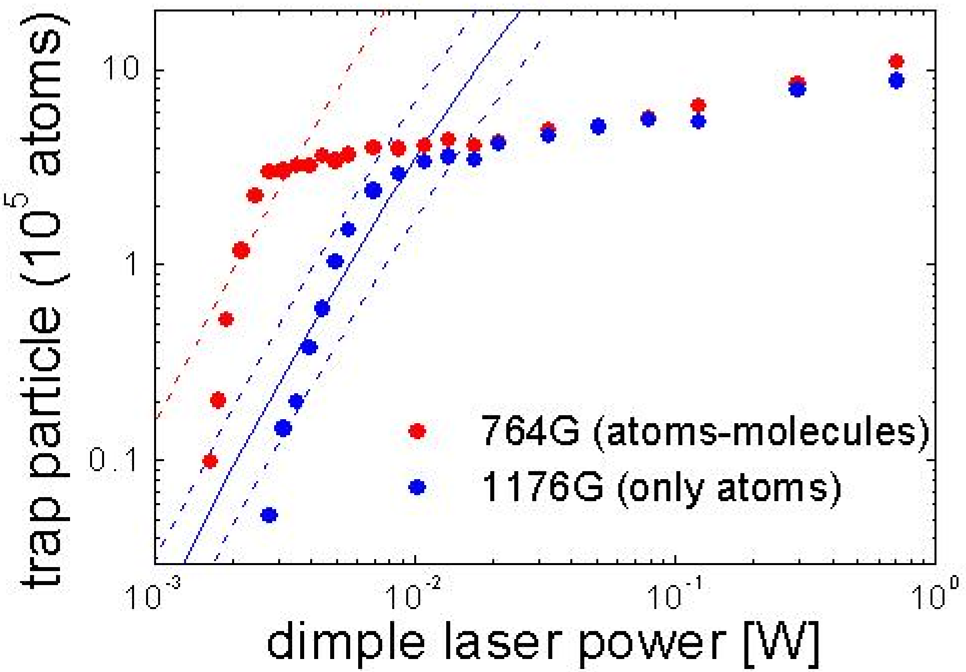
first evidence of BEC

Ultracold atoms
quantum gases

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

number of quantum states for molecules

number of quantum state for atoms



quantum degeneracy !

very long lifetime of (~20s)
→
thermalization

BEC

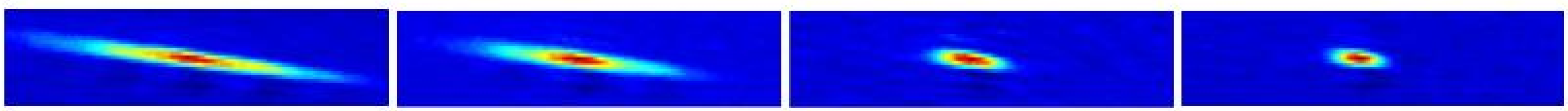
S. Jochim et al., Science Express, 13 Nov 03

in-situ images of the molecules

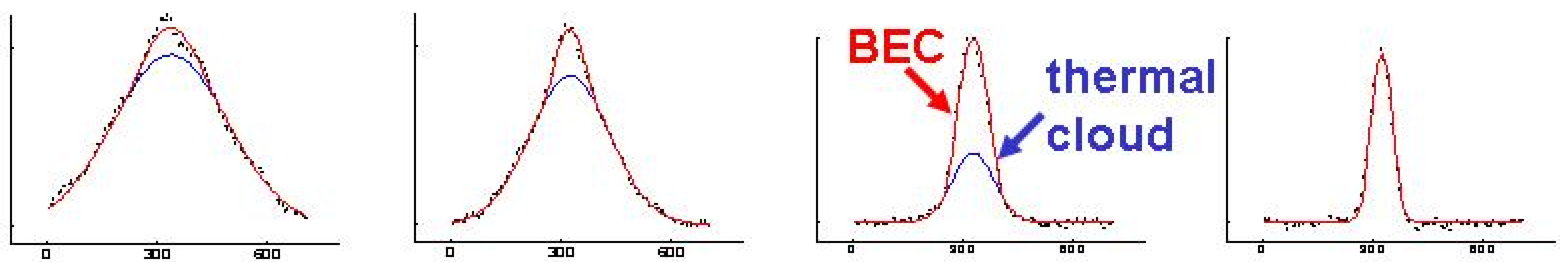
evaporation time

1.3 s 1.5 s 1.8 s 2.0 s

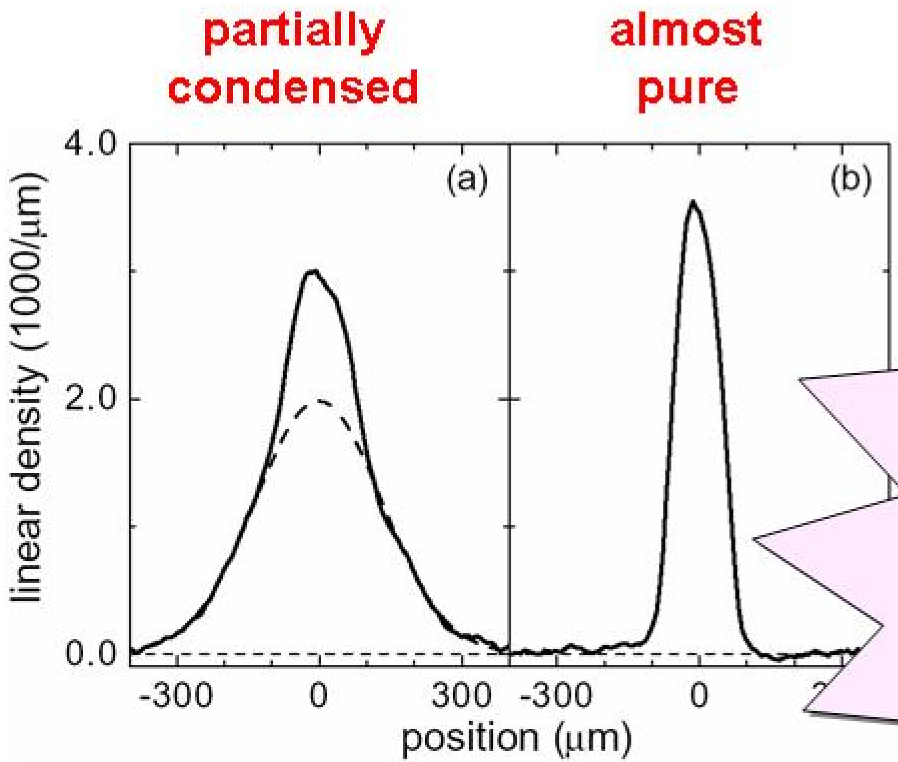
700 µm

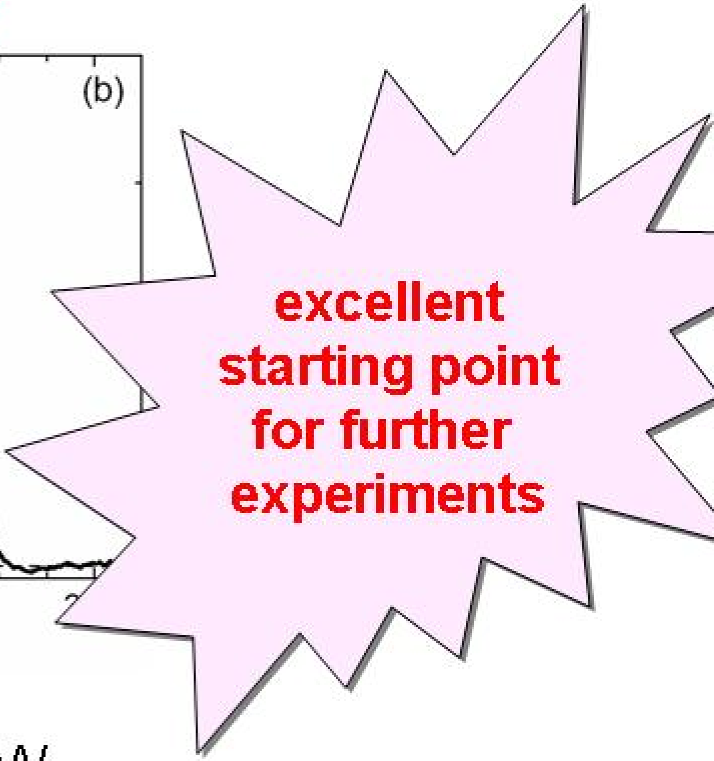


density distribution



axial profiles → phase transition





final trap power	28mW	3.8mW
number of molecules	400.000	200.000
temperature	430nK	few 10nK
condensate fraction	~20%	**>90%**

lifetime 40s !

Innsbruck ^{6}Li story

$^6Li_2$ molecules in a thermal gas

how to condense these molecules

<u>reversible crossover to a degenerate Fermi gas</u>

Bartenstein et al., cond-mat/0401109

where exactly is the Feshbach resonance ?

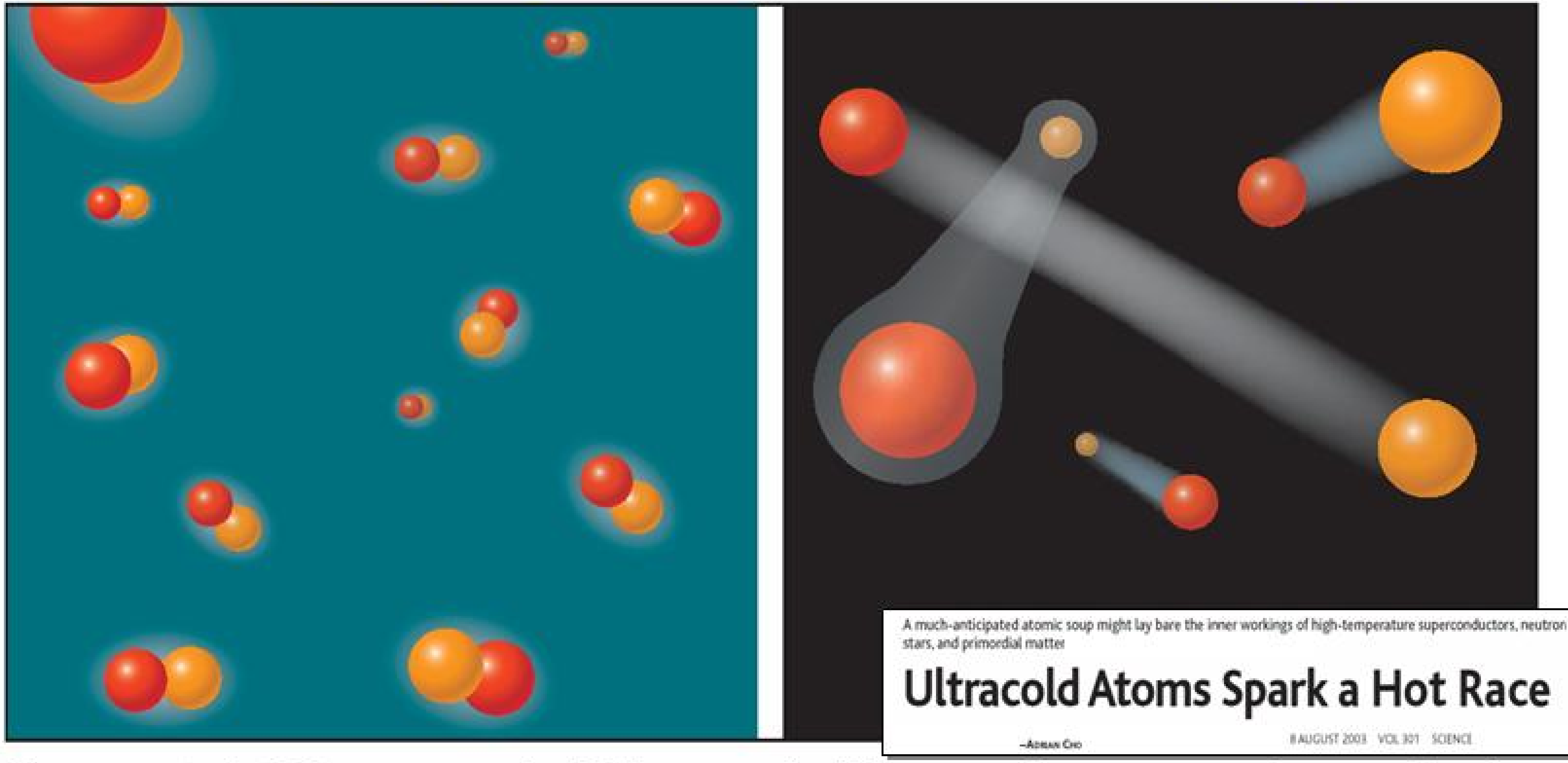
collective excitations

BEC – BCS crossover

molecules
strong coupling

crossover

Cooper pairs
weak coupling



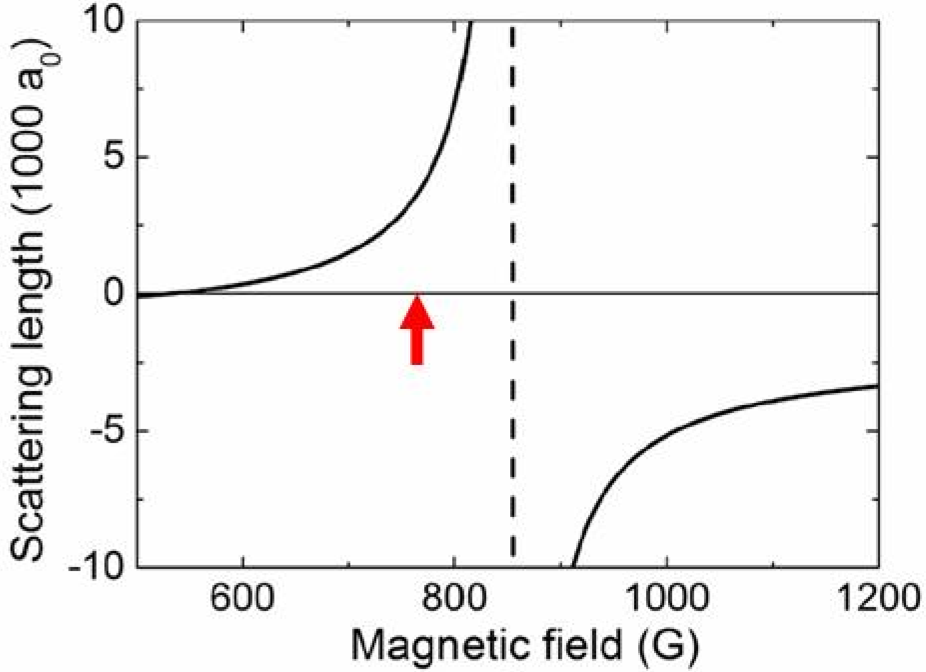
Tango or twist? In a magnetic field, atoms in different spin states can form molecules (*left*). Vary the field, and they might also form loose-knit Cooper pairs.

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

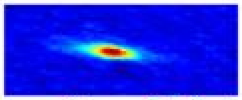
exploring the crossover

Ultracold atoms
quantum gases

Bartenstein et al., cond-mat/0401109

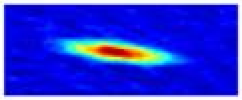


molecular
BEC

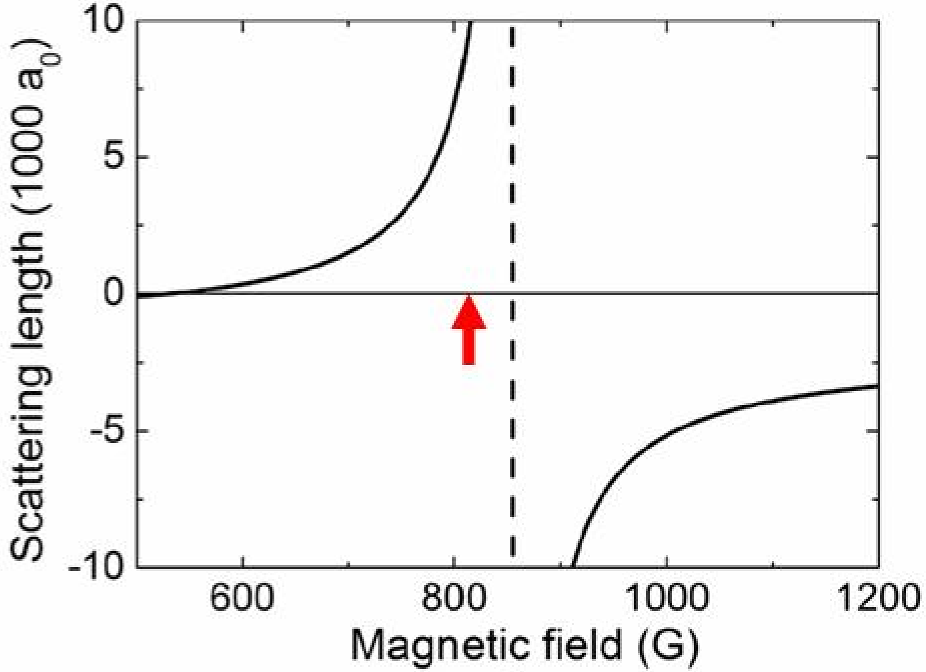


$na^3 = 0.04$

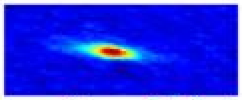
exploring the crossover



$na^3 = 0.28$



molecular
BEC

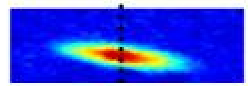


$na^3 = 0.04$

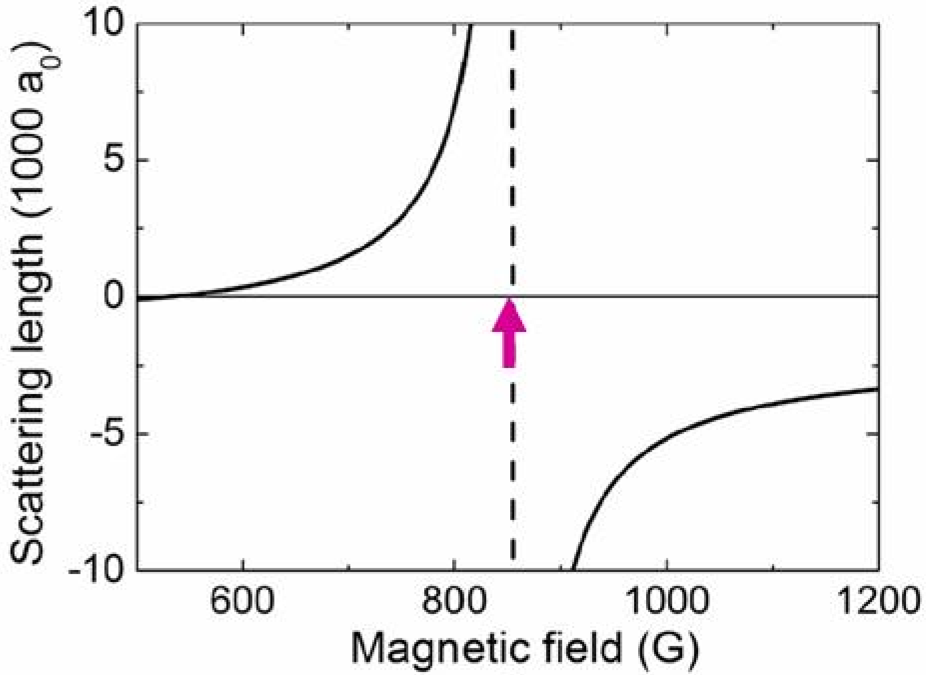
exploring the crossover

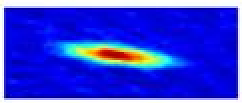
Bosons

Fermions



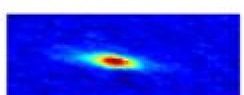
$na^3, k_F|a| = \infty$





$na^3 = 0.28$

molecular BEC

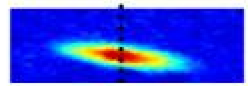


$na^3 = 0.04$

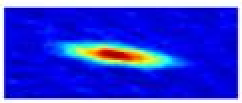
exploring the crossover

Bosons

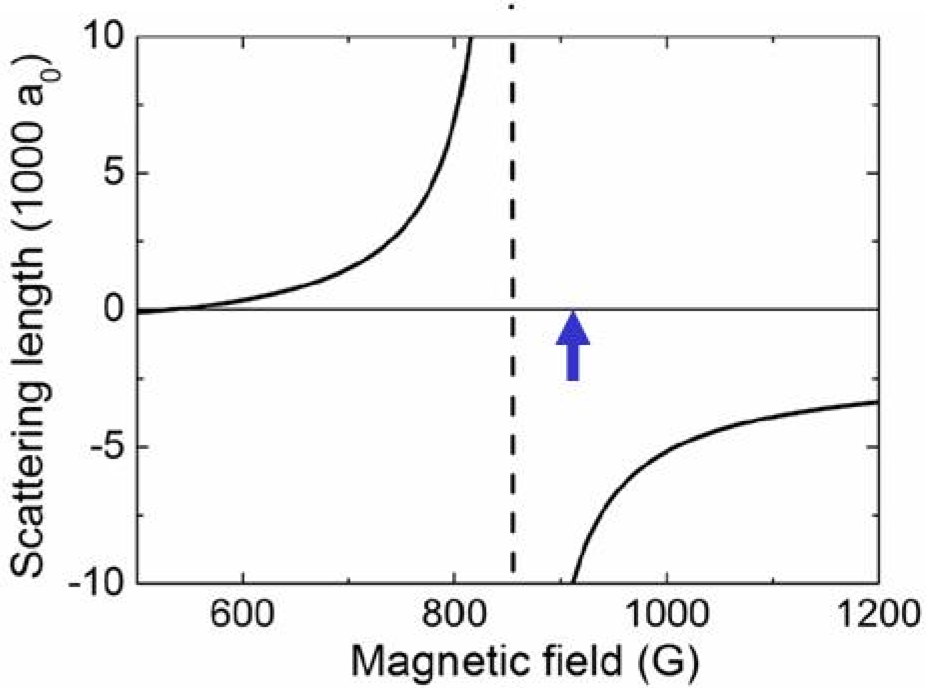
Fermions

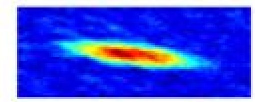


$Na^3, k_F|a| = \infty$



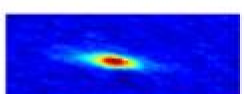
$na^3 = 0.28$





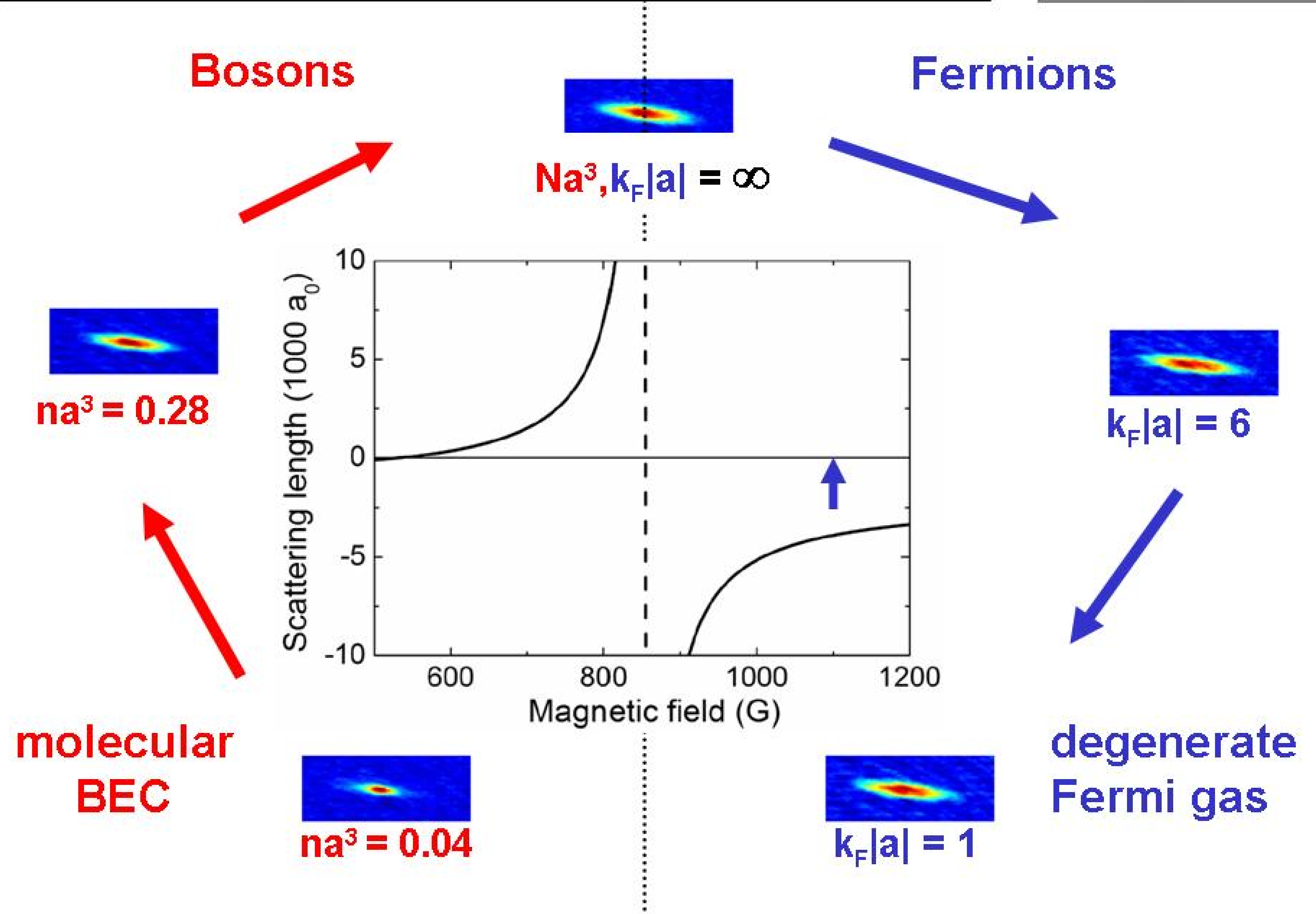
$k_F|a| = 6$

molecular BEC

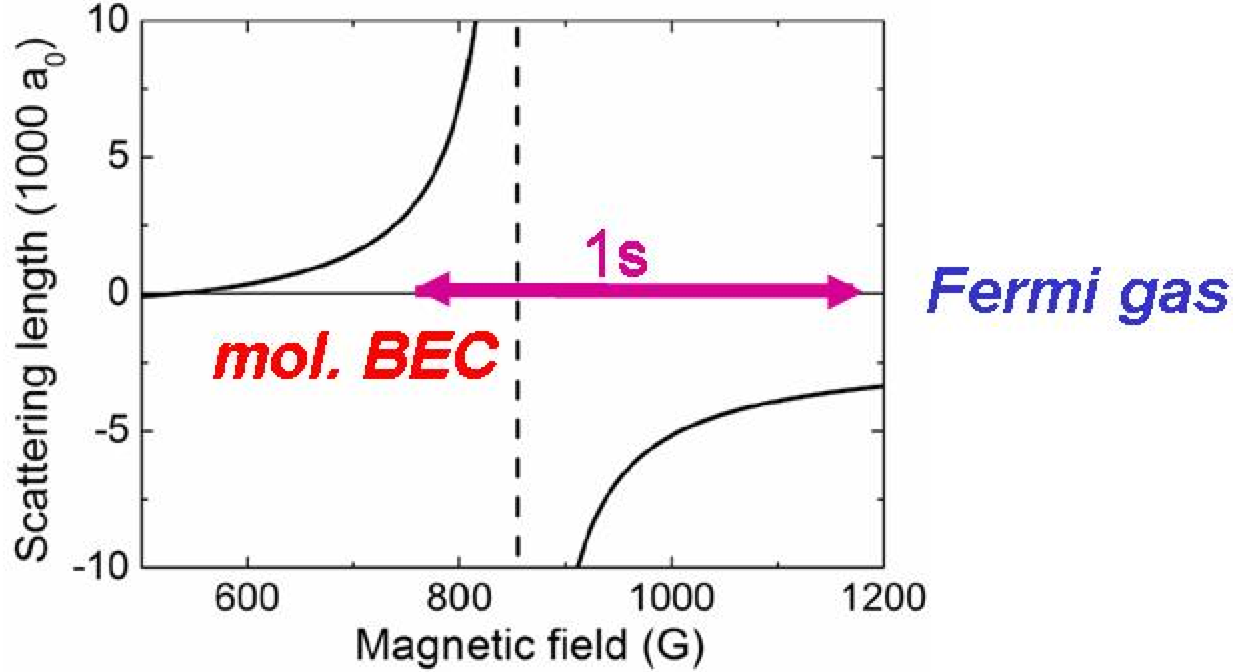


$na^3 = 0.04$

exploring the crossover

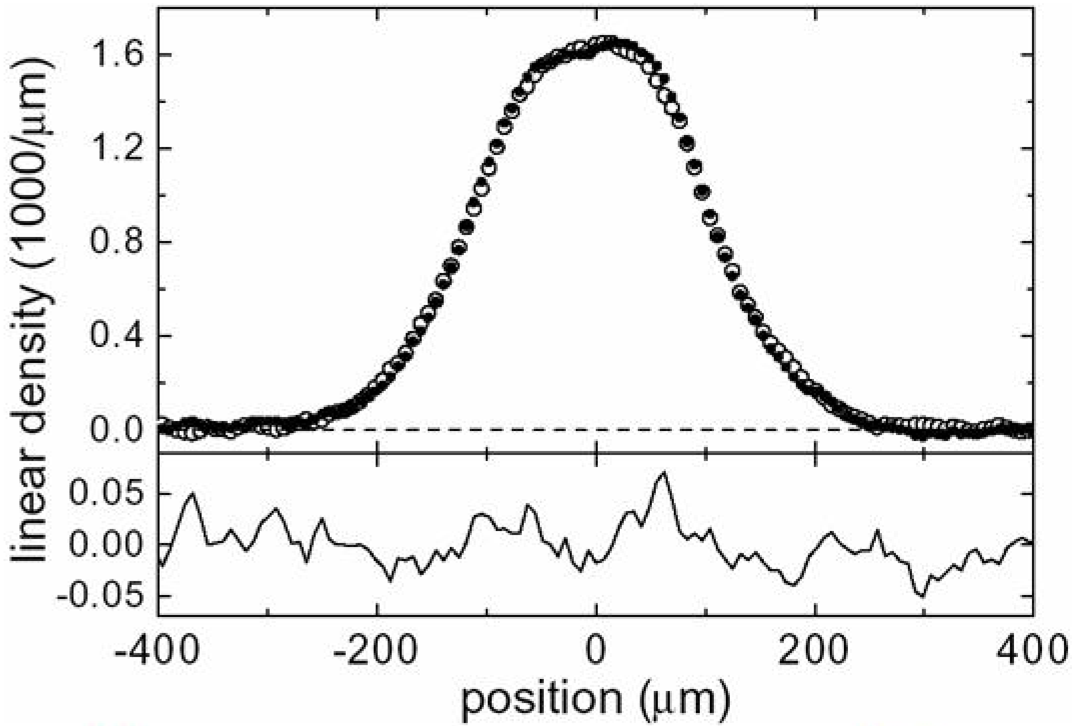


loss, reversibility ?



reversibility

- BEC →1s→ Fermi gas →1s→ BEC
- ○ BEC after 2s



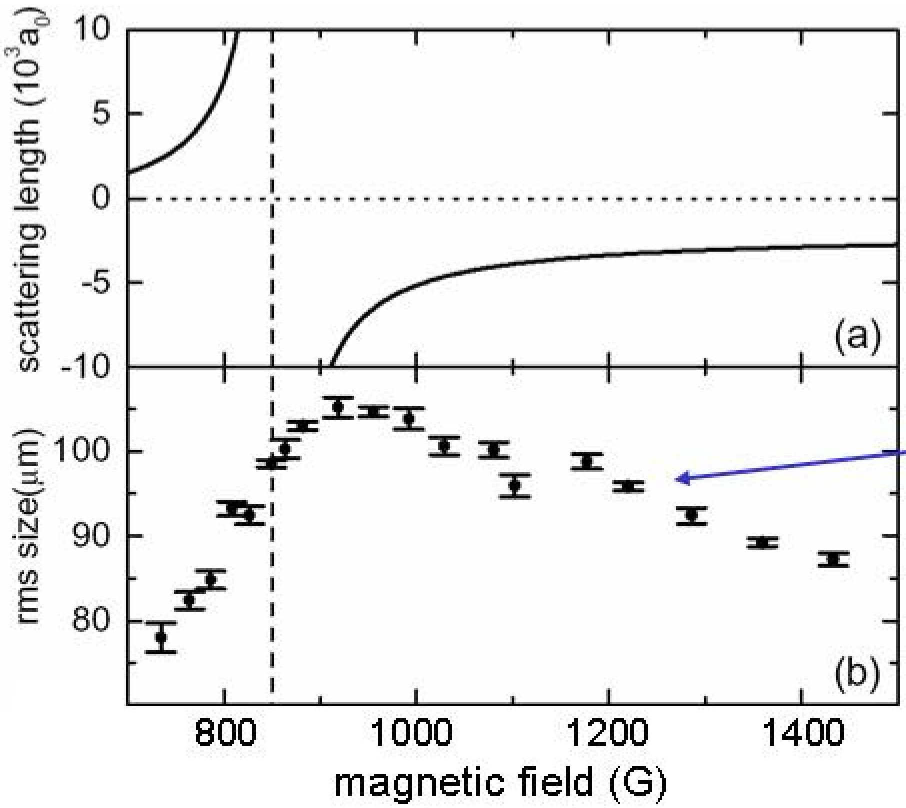
very good news: crossover reversible and lossless !

$T/T_F \approx 0.04$ in Fermi gas limit

for 90% condensate fraction in BEC limit

Carr et al.,cond-mat/0308306

cloud size → interaction energy

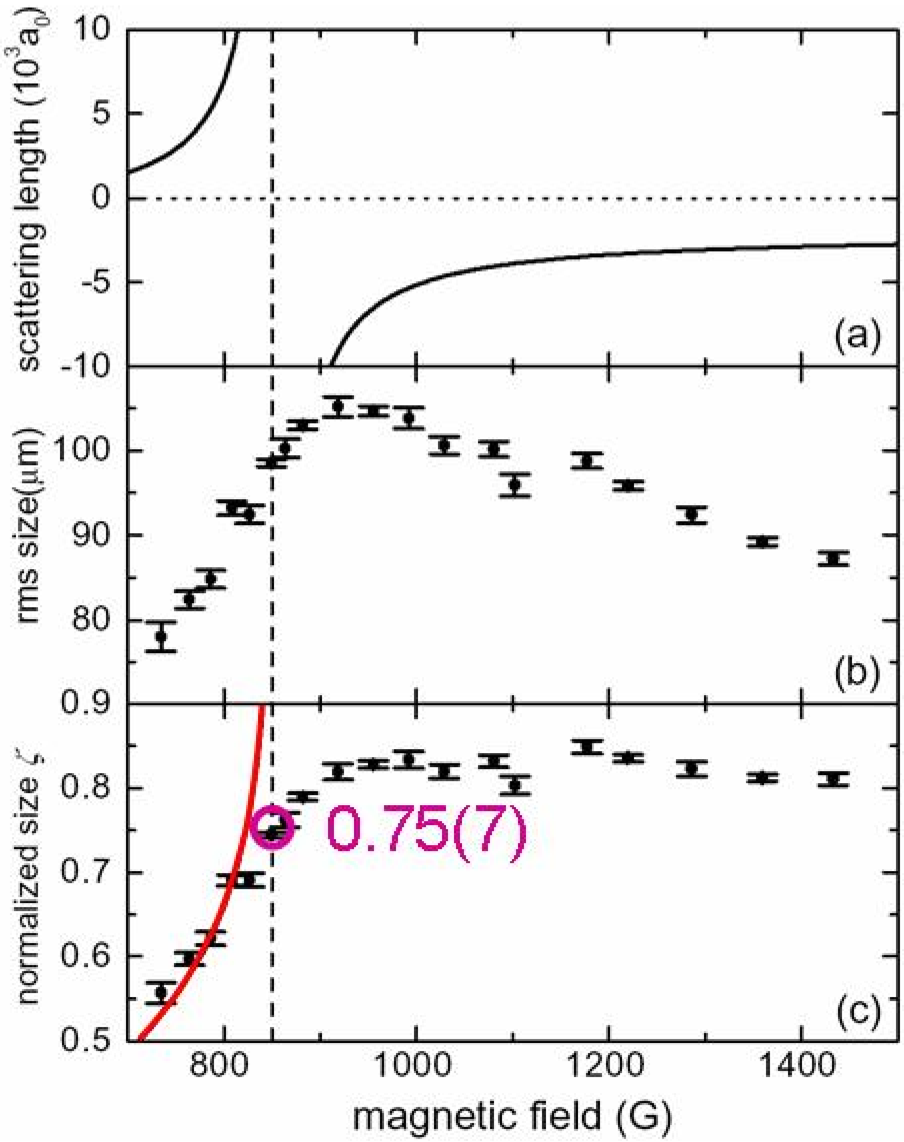


axial confinement
increases with
magnetic field
$\omega_z \propto B^{1/2}$

cloud size → interaction energy

BEC limit
with
$a_{\text{mol}} = 0.6a$
(Shlyapnikov prediction)

universal many-body interaction



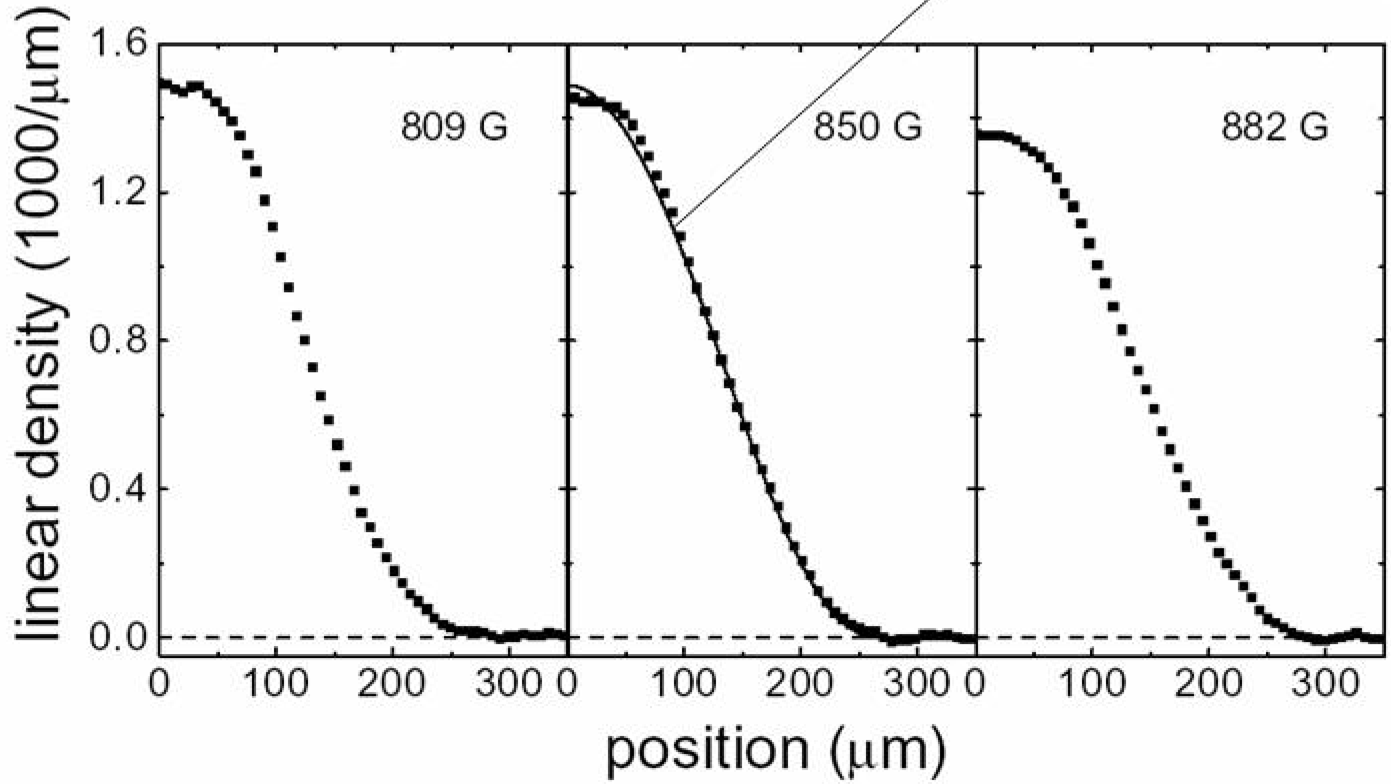
normalized to non-interacting Fermi gas

spatial profiles

integrated over *x* and *y*

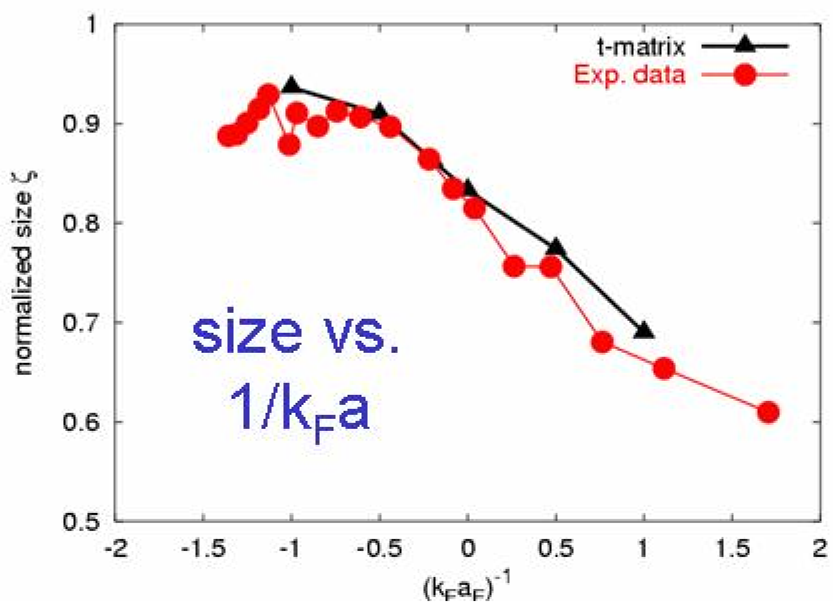
TF profile in unitarity limit (Fermi gas)

$$\rho(z) = \rho_0 (1 - z^2 / z_{TF}^2)^{5/2}$$



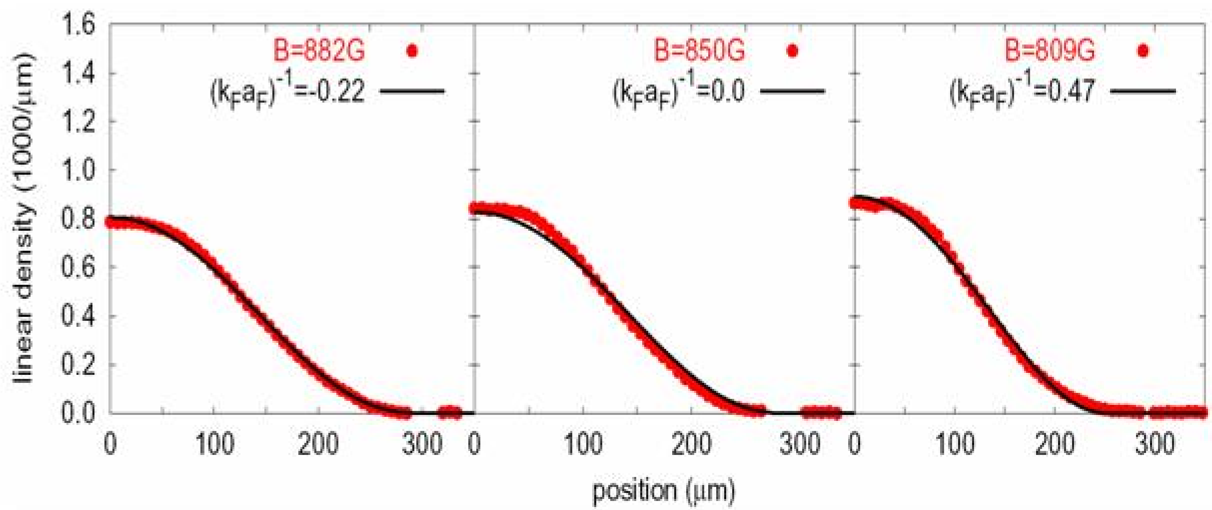
comparison with theory

Ultracold atoms quantum gases



theoretical data from Camerino group Pieri, Strinati et al.

excellent agreement for $N = 2.3 \times 10^5$ atoms (instead of 4×10^5)



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$^6Li_2$ molecules in a thermal gas

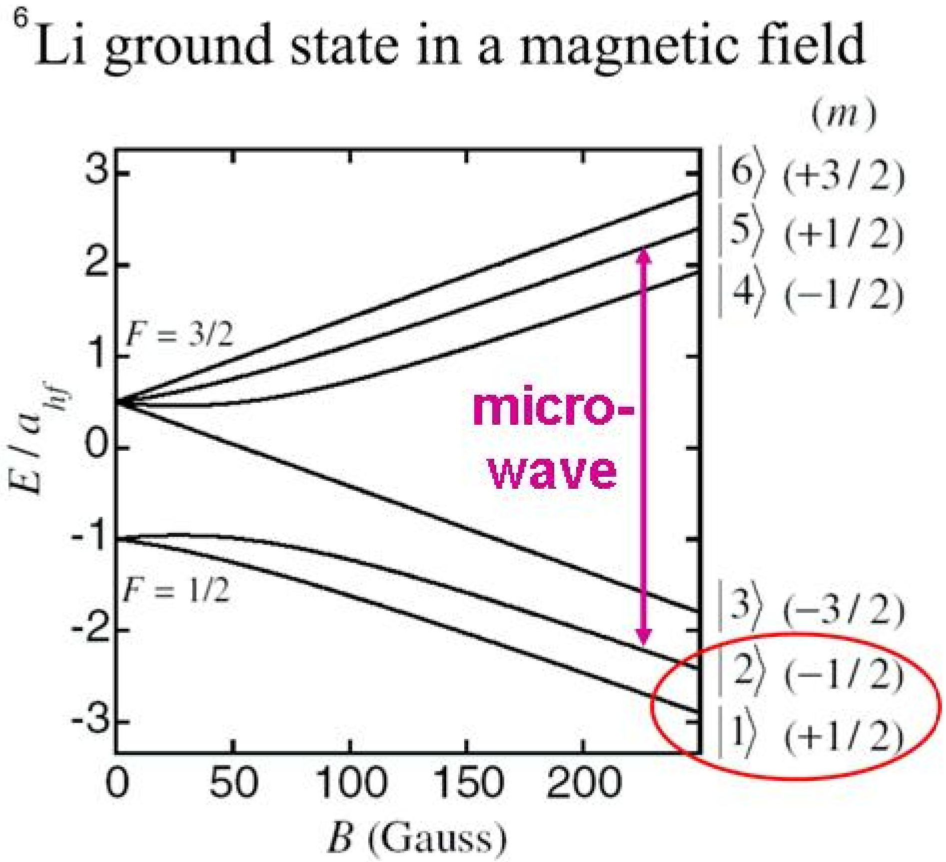
how to condense these molecules

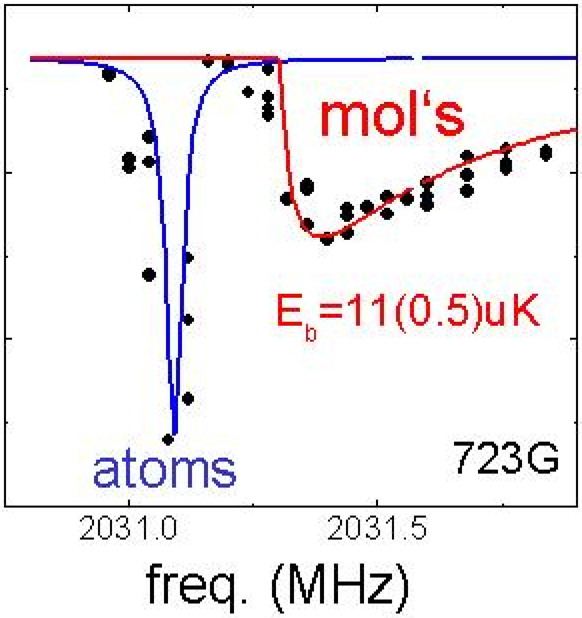
reversible crossover to a degenerate Fermi gas

where exactly is the Feshbach resonance ?

collective excitation surprises

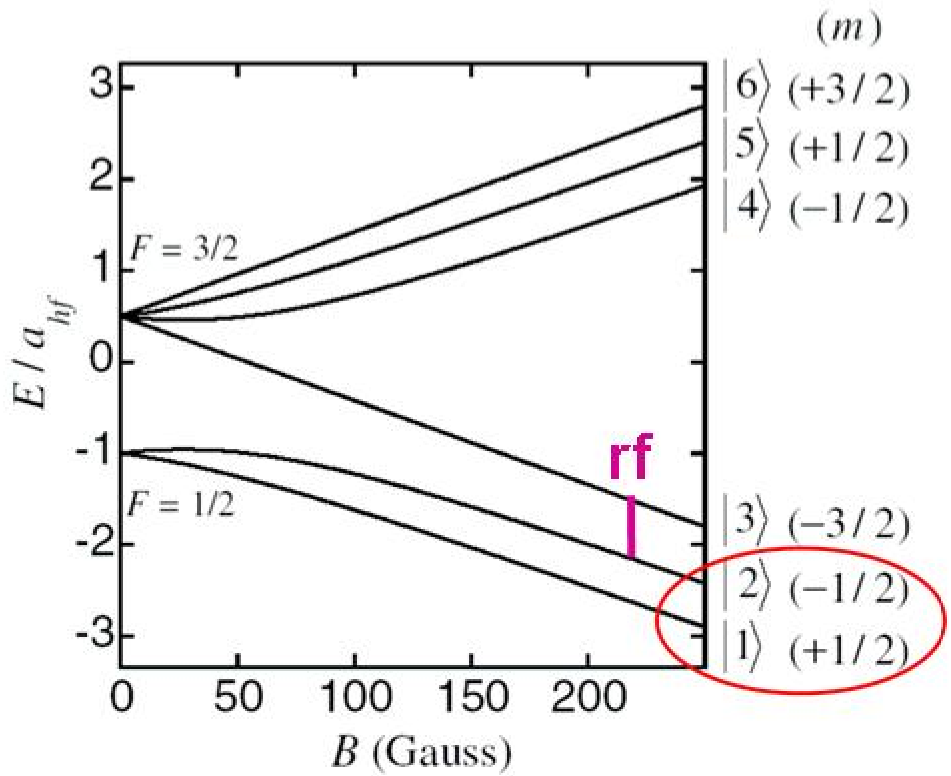
microwave / rf spectroscopy

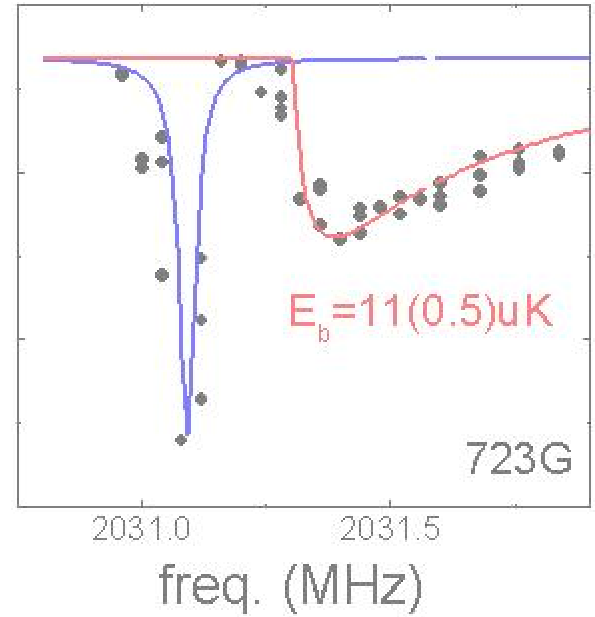


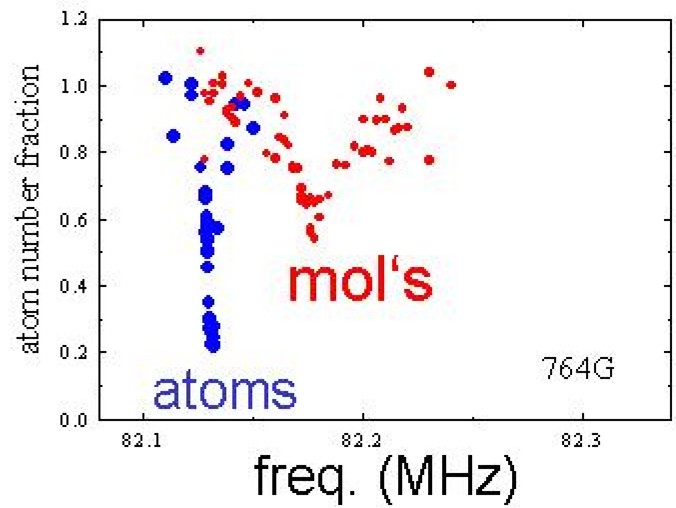


microwave / rf spectroscopy

^{6}Li ground state in a magnetic field



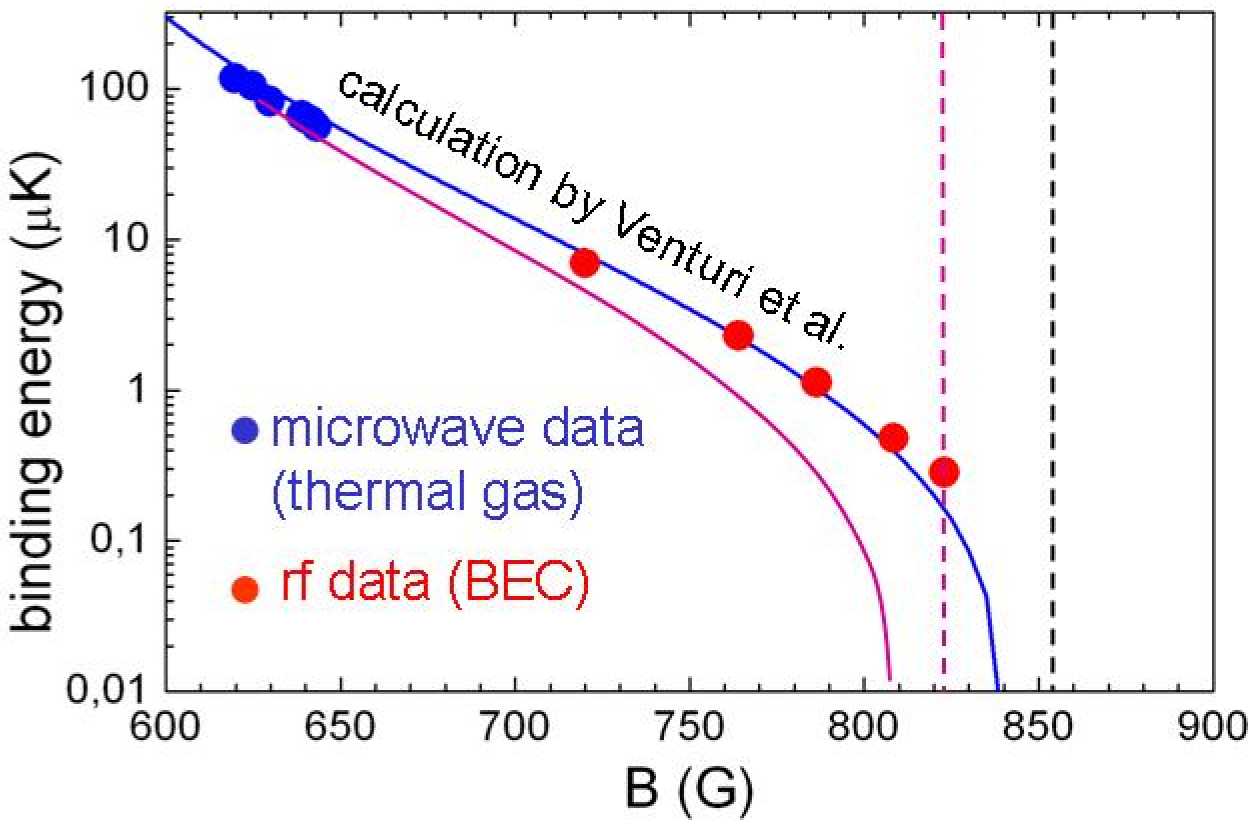




binding energy

preliminary

Feshbach resonance data published in O'Hara et al., PRA 66, 041401 (2002)



binding energy curve modified according to MIT resonance position (cond-mat/0403049)

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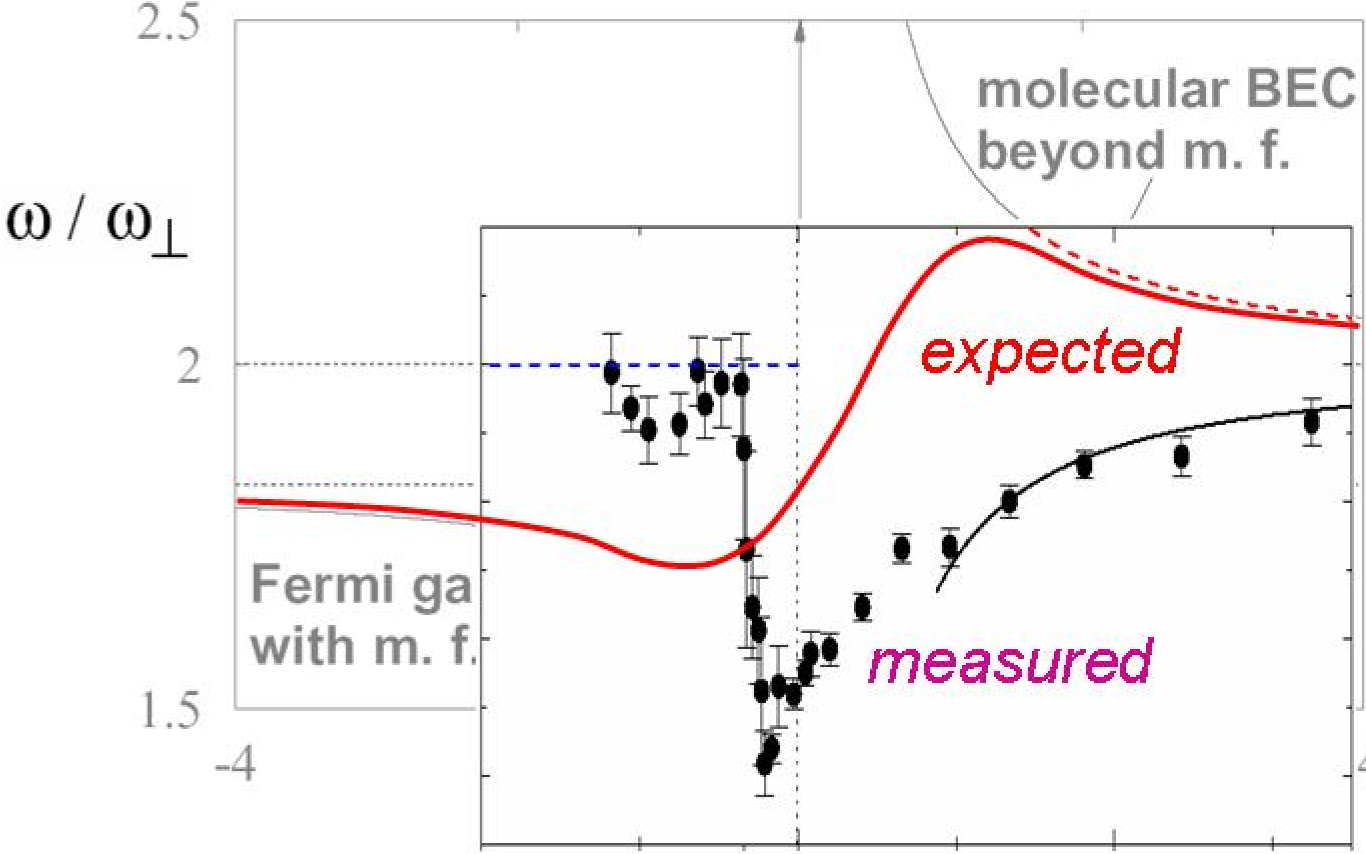
collective excitation surprises

theoretical expectations

Stringari (cond-mat/0312614)

radial compression mode expected to show very interesting behavior !

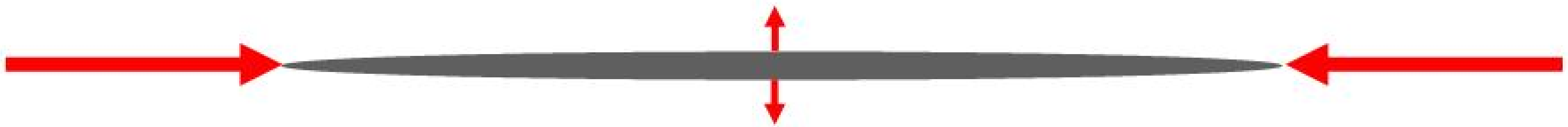


collective modes

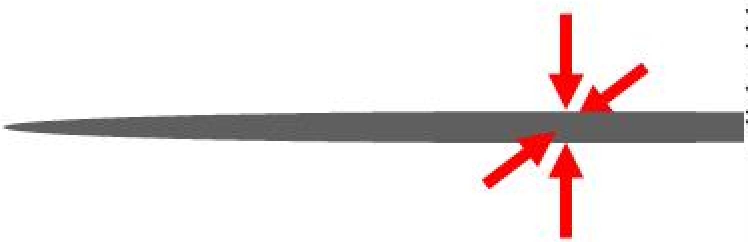
cigar-shaped trap

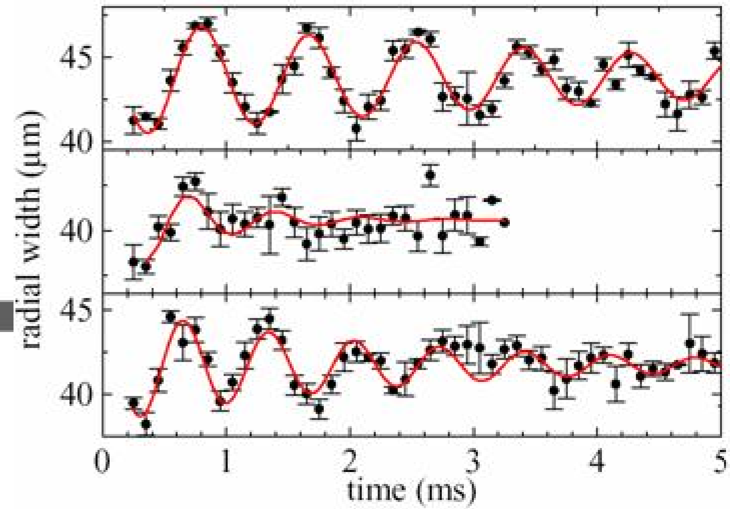
$\nu_r = 755(10)$ Hz, $\nu_z \approx 22$ Hz

axial



radial





radial mode 5× more sensitive to eq. of states

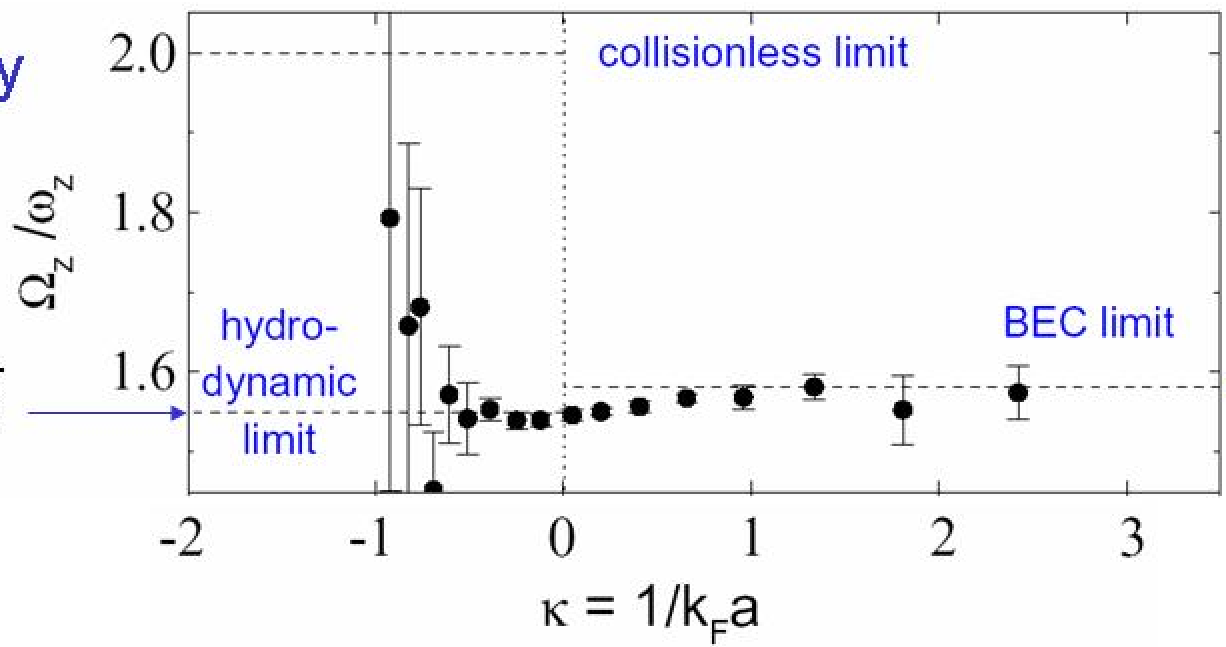
Pitaevski & Stringari, PRL 1999

axial coll. excitation

Ultracold atoms quantum gases

frequency

$\sqrt{12/5}$



$\sqrt{5/2}$

resonant

Fermi ***Bose***

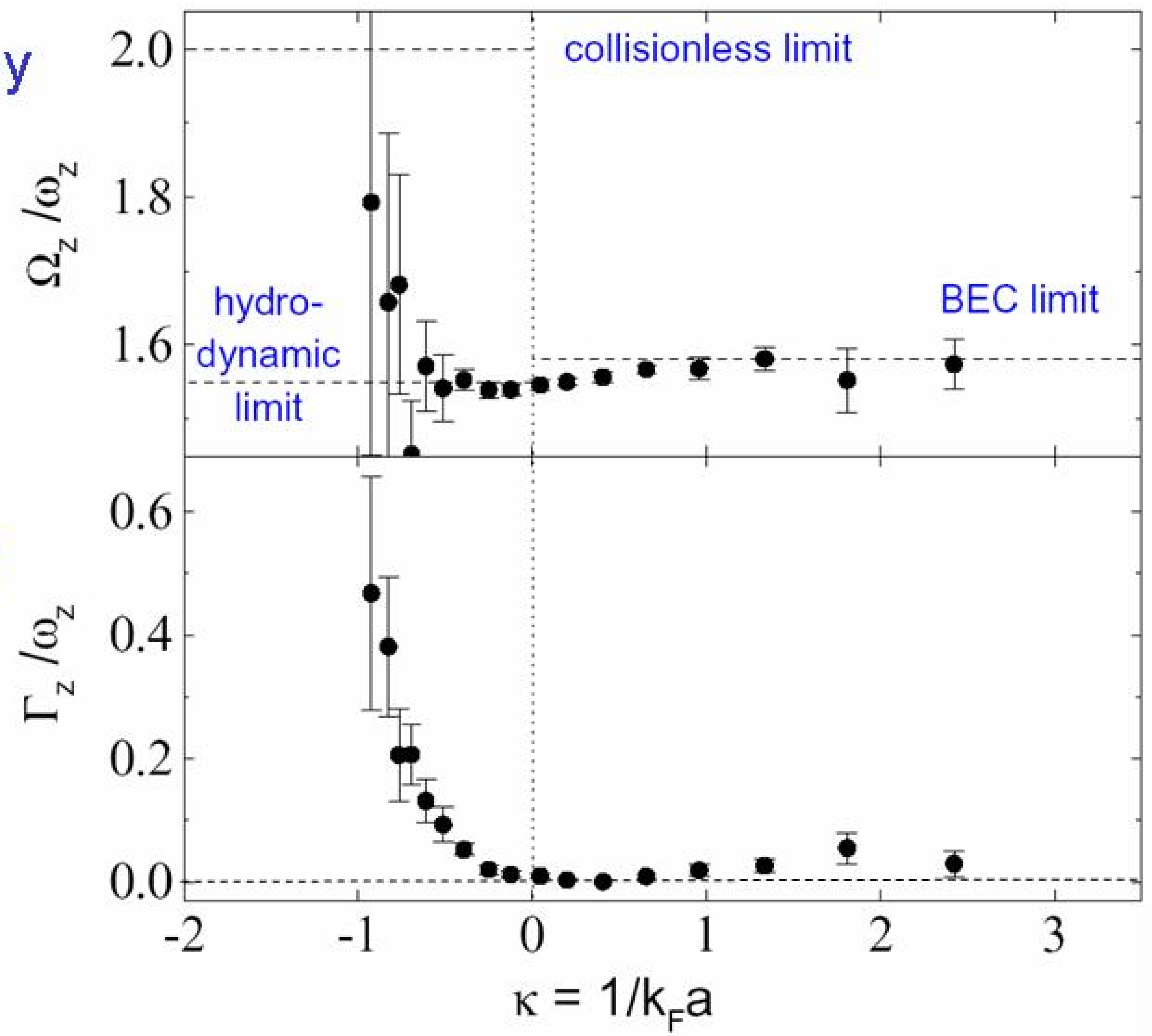
B ←

850 G

axial coll. excitation

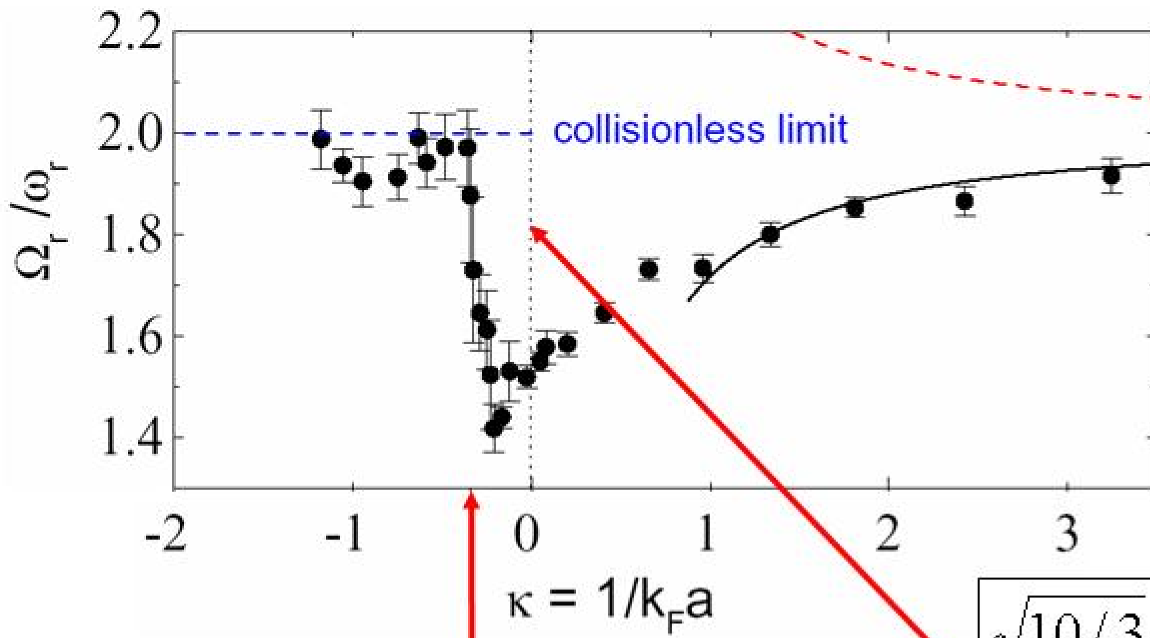
frequency

damping



radial coll. excitation

frequency



beyond m.f. correction

opposite sign ???

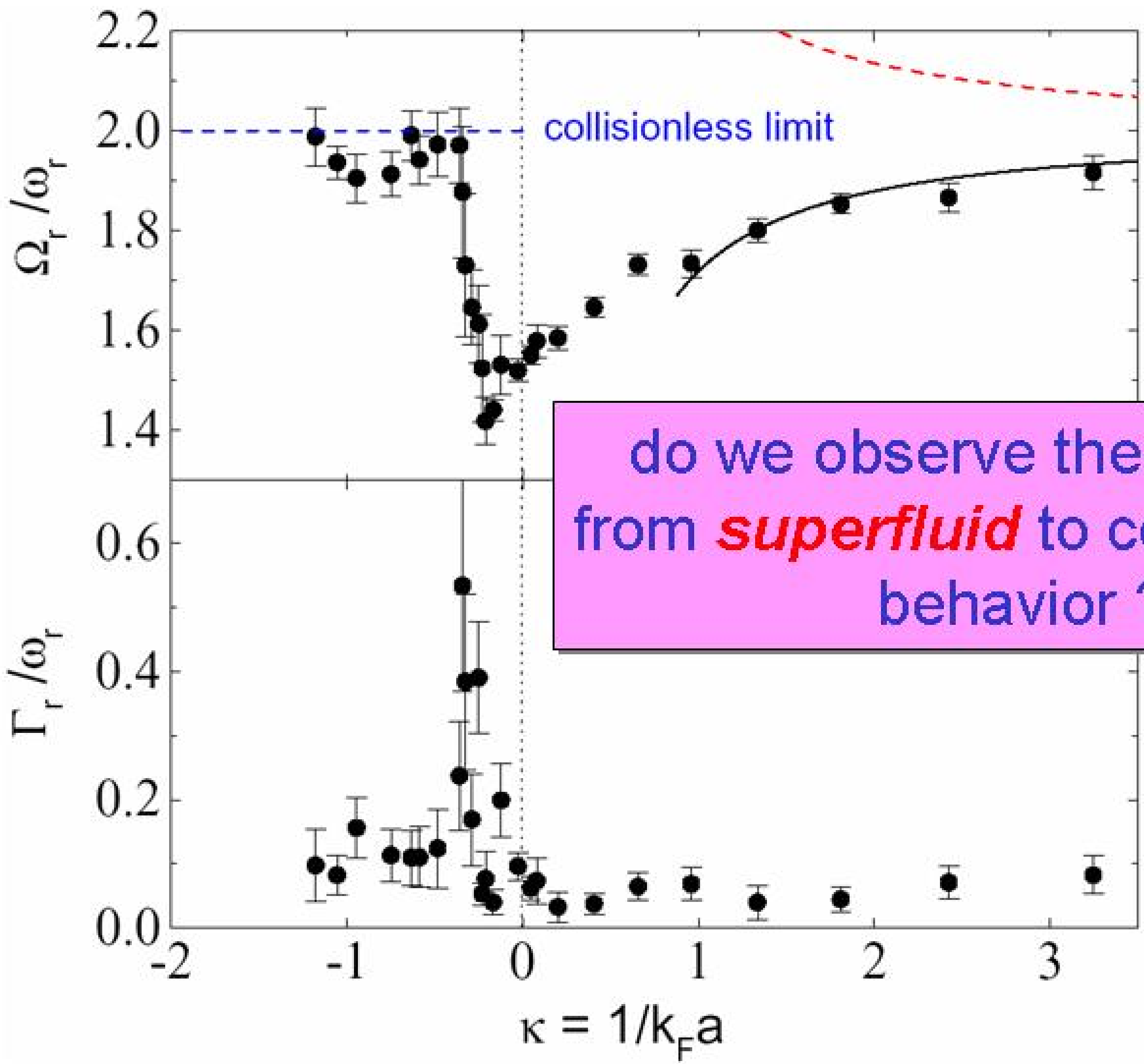
$\sqrt{10/3} = 1.83$
expected in unitarity limit

sharp transition to collisionless

radial coll. excitation

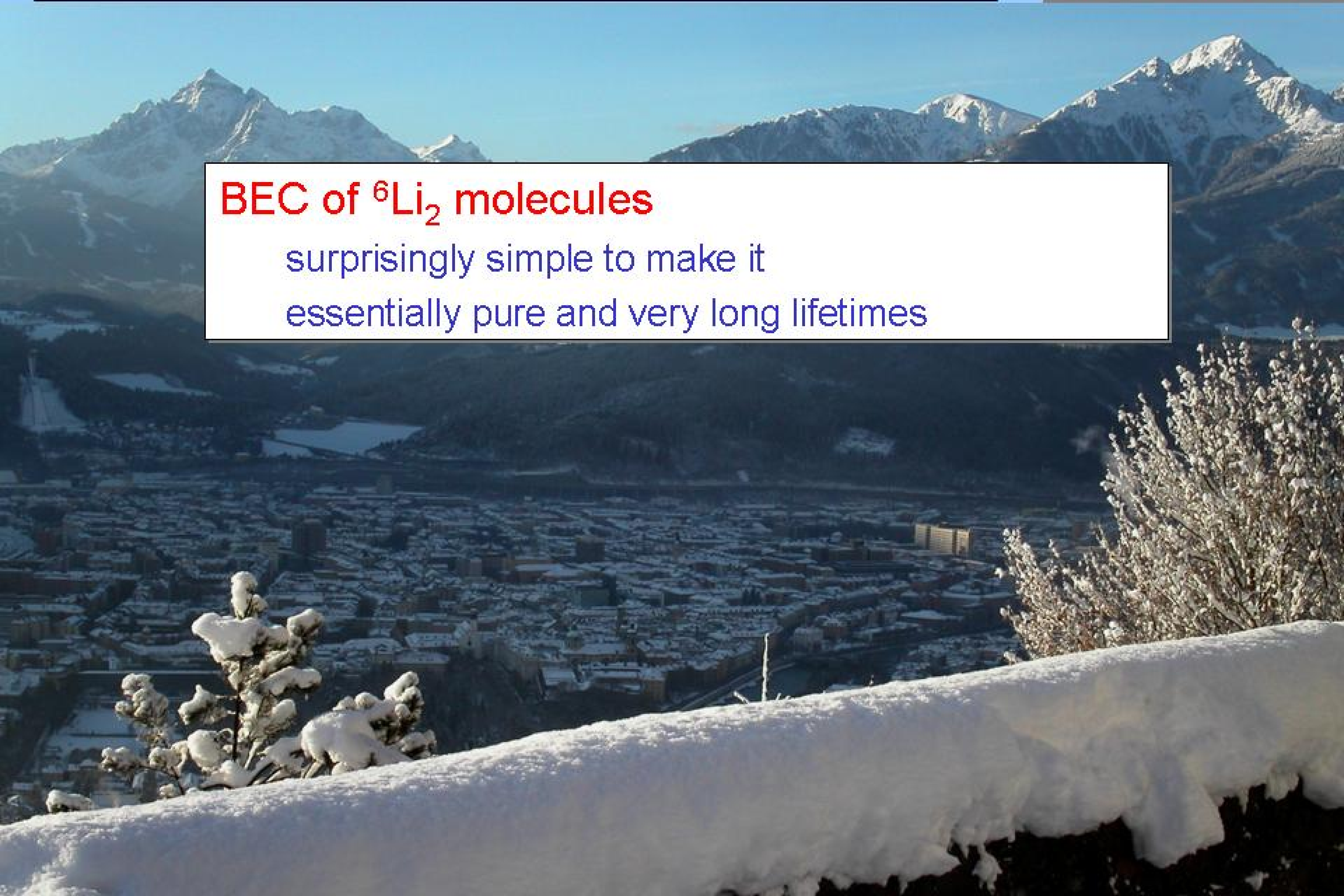
frequency

damping



do we observe the transition from ***superfluid*** to collisionless behavior ?

conclusion



BEC of $^6Li_2$ molecules

- surprisingly simple to make it
- essentially pure and very long lifetimes

conclusion

BEC of $^{6}Li_2$ molecules

- surprisingly simple to make it
- essentially pure and very long lifetimes

excellent starting point for BEC-BCS crossover

- conversion into Fermi gas reversible
- size measurements of strongly interacting cloud

conclusion

BEC of $^{6}Li_2$ molecules

- surprisingly simple to make it
- essentially pure and very long lifetimes

excellent starting point for BEC-BCS crossover

- conversion into Fermi gas reversible
- size measurements of strongly interacting cloud

Feshbach resonance position ?

- rf spectroscopy yields interesting data

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Ultracold atoms
quantum gases

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collective excitation surprises

beyond mean field correction – opposite sign ?

transition from superfluid to collisionless ?