"Condensation of pairs of fermionic lithium atoms"

Wolfgang Ketterle
Massachusetts Institute of Technology
MIT-Harvard Center for Ultracold Atoms

CUA

5/10/04
KITP workshop, Santa Barbara

Optical lattices
Superradiance
N_0(Rb) > 50 million

BEC I

Ultracold fermions

Claudiu Stan
Martin Zwierlein
Christian Schunck
Jamie Kerman
Sebastian Raupach

BEC II

Na_2 molecules
Condensed matter physics with BECs

Jamil Abo-Shaeer
Kaiwen Xu
Jit Kee Jin
Daniel Miller
Takashi Mukaiyama

BEC III

Atom chips, surface atom optics

Yong-Il Shin
Tom Pasquini
Michele Saba
Andre Shirotzek
Christian Sanner
D.E. Pritchard

BEC IV

Atom optics and lower dimensions

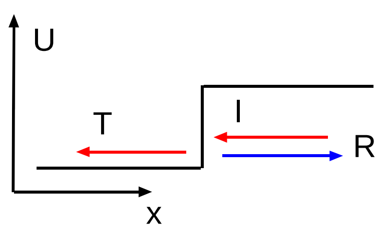
Micah Boyd
Erik Streed
Gretchen Campbell
Jongchul Mun
Dominik Schneble
Aaron Leanhardt
D.E. Pritchard

$$
NSF
ONR
ARO
NASA
DARPA

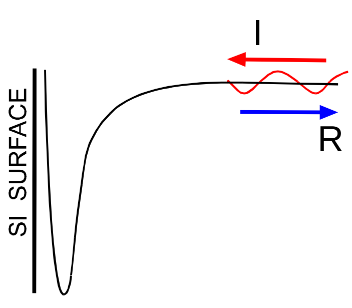
Quantum Reflection of Ultracold Atoms

T.A. Pasquini, Y. Shin, C. Sanner, M. Saba, A. Schirotzek,
D.E. Pritchard, W.K.

Quantum Reflection



- Quantum mechanical turning point without classical analogue.
- Reflection coefficient determined by matching condition.



- Long range, attractive Casimir-Polder potential.

$$U = -C_4 / r^4$$

- Reflection occurs far from surface at effective “step”.

$$R \approx \sqrt{1-2\beta_4 k}$$

$$C_4 = \beta_4^2 \hbar^2 / 2m$$

Mody et. al., PRB 2001; Friedrich et. al. PRA 2002

Reflection of cold atoms from surfaces

Extremely weak interactions

Normal incidence: Hydrogen on helium 1 K
(Walraven 1986; Greytak/Kleppner 1991)

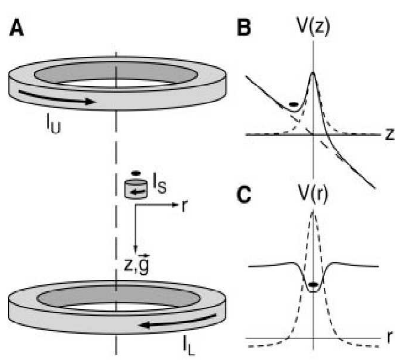
Grazing incidence: Helium on helium (Masuhara 1983)

All other atoms

Normal incidence 10 nK

Grazing incidence Cesium (Hinds 1986), Ne* (Shimizu 2001)

Gravito-magnetic Trap



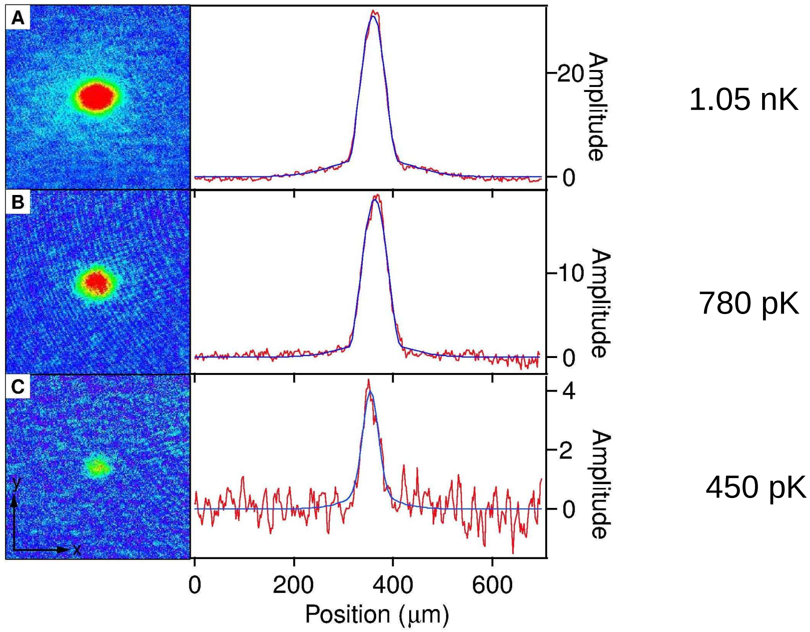
- Ultra-dilute condensates
- Easily adjustable trap position
- Long, slow dipole oscillation
- Very long lifetime

<u>Trap Parameters:</u>

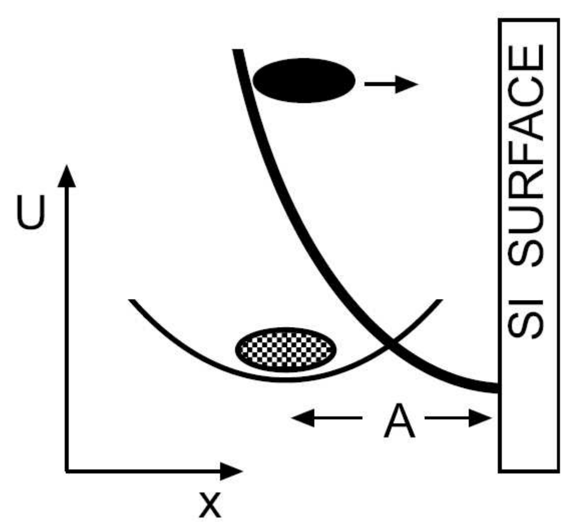
$N = 10^4$ - 10^5 $n=10^{11}\ cm^{-3}$ ◆$_{HO}$ = 1 – 10Hz   ◆$_{LIFE}$ ~ 1 min

T_C = 1 nK v_{TH} = 1 mm/s v_S = 1 mm/s

Condensation of pairs of fermionic lithium atoms

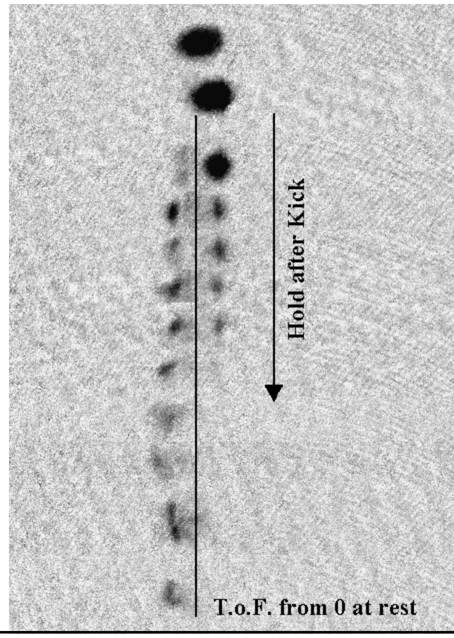


A.E. Leanhardt, T.A. Pasquini, M. Saba, A. Schirotzek, Y. Shin, D. Kielpinski, D.E. Pritchard, and W. Ketterle, Science **301**, 1513 (2003).

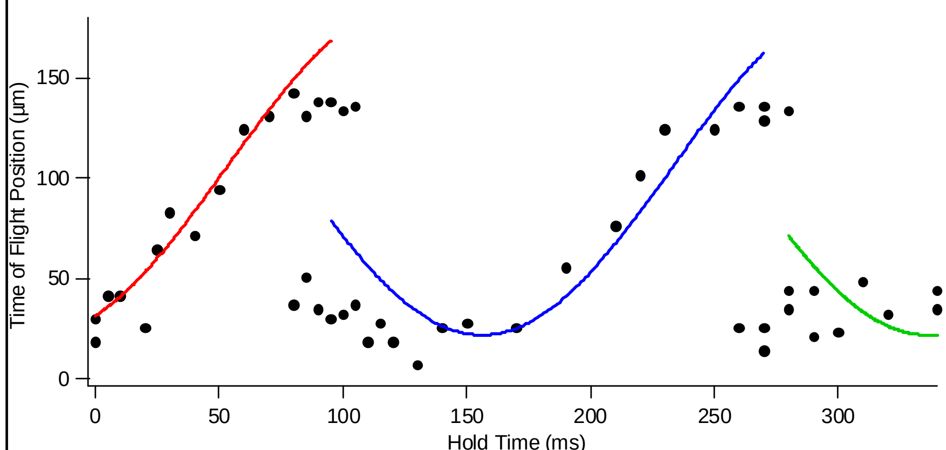


Condensation of pairs of fermionic lithium atoms

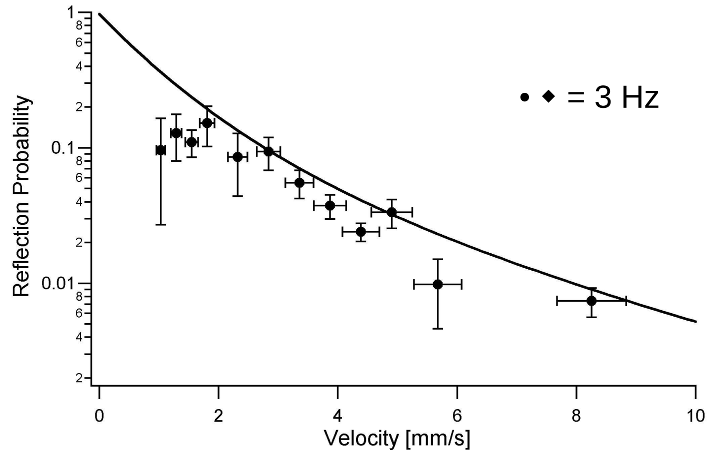
Interrupted Dipole Oscillations



Interrupted Dipole Oscillations

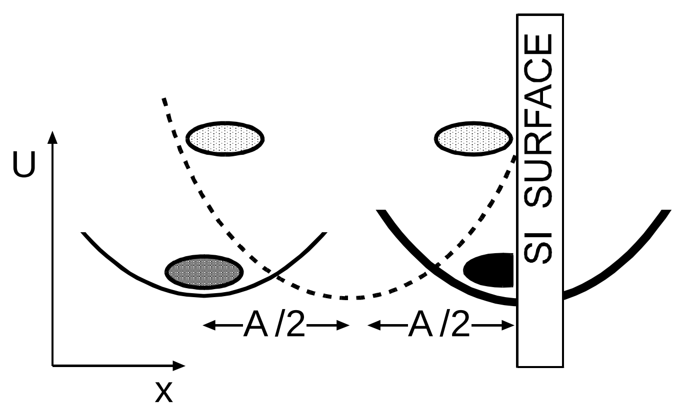


Reflection Probability



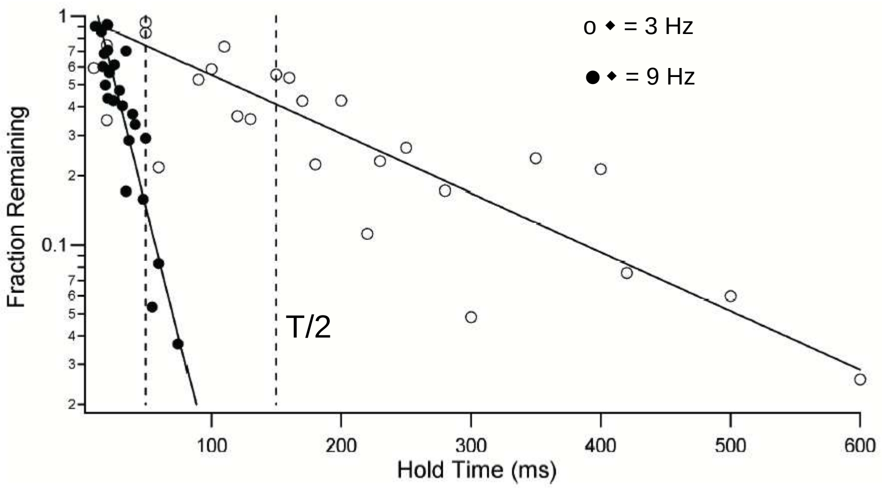
• Good agreement with theory above 2 mm/s.
• Theoretical curve determined by numerical solution with van der Waals/Casimir potential

Surface Reflection Trap



• Half magnetic and half surface confinement
• Trap center "inside" surface
• Load trap at zero velocity by using an intermediate trap

Surface Reflection Trap



Lifetime imply R > 50 %

Outlook

- Enhance reflection coefficient
  - Membrane surfaces or spongy materials
- New atomic mirrors and atom optics
- Confinement in surface trap
  - Condensates in a “cup”
- Study density dependent effects
  - Collective behavior

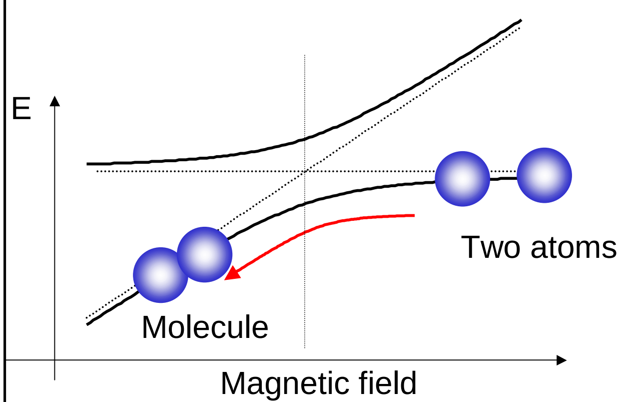
Condensation of pairs of fermionic lithium atoms

Pairs of bosonic atoms

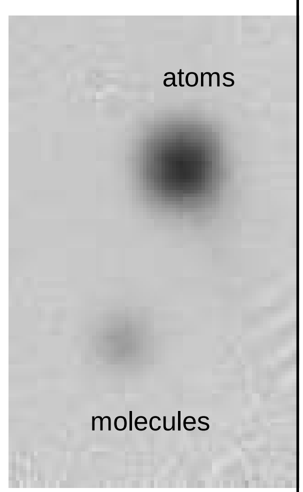
Quantum degenerate Na_2 molecules

Takashi Mukaiyama, Kaiwen Xu, Jamil Abo-Shaeer, Jit Kee Chin, Daniel Miller, W.K.
Phys. Rev. Lett. **91**, 210402 (2003)
Phys. Rev. Lett., in print; cond-mat/0311558.

The new cold frontier: molecules



Feshbach resonance

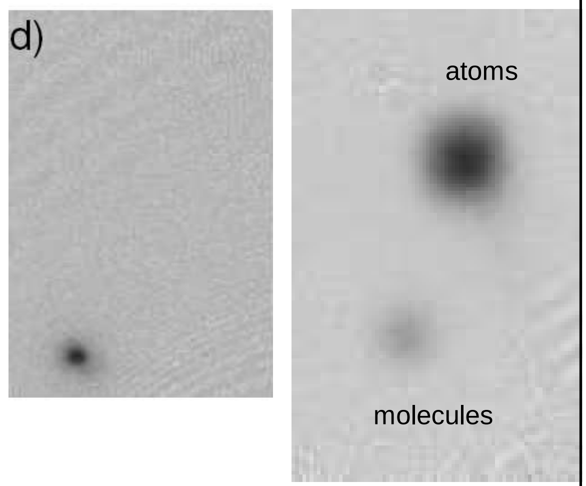


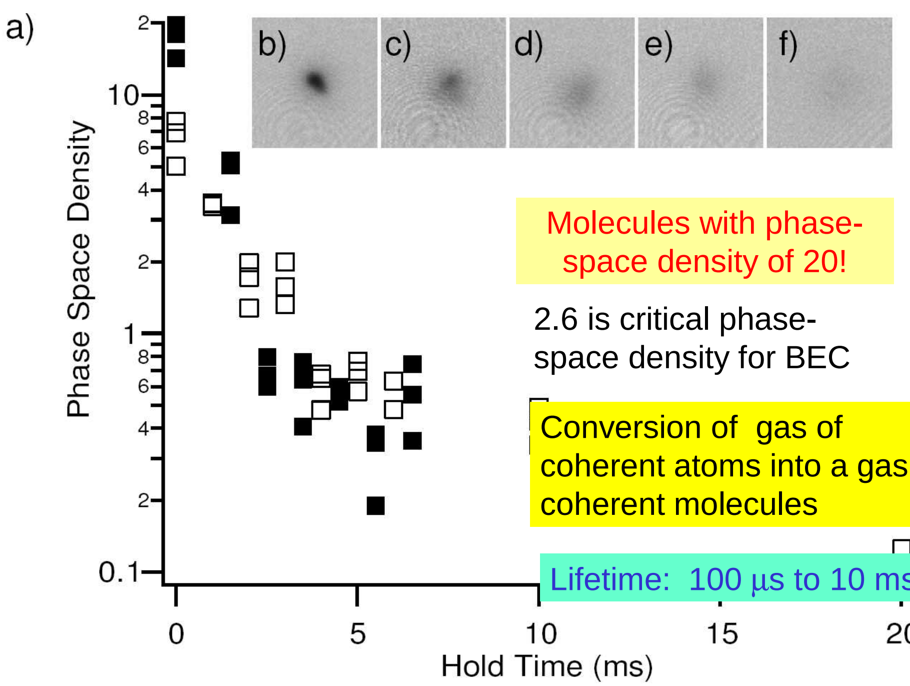
Bosons: Boulder, Garching, Innsbruck, MIT
Fermions: Boulder, Rice, Paris, Innsbruck, MIT

Condensation of pairs of fermionic lithium atoms

Blast away the atoms

Colder molecules!





Molecules with phase-space density of 20!

2.6 is critical phase-space density for BEC

Conversion of gas of coherent atoms into a gas of coherent molecules

Lifetime: 100 µs to 10 ms

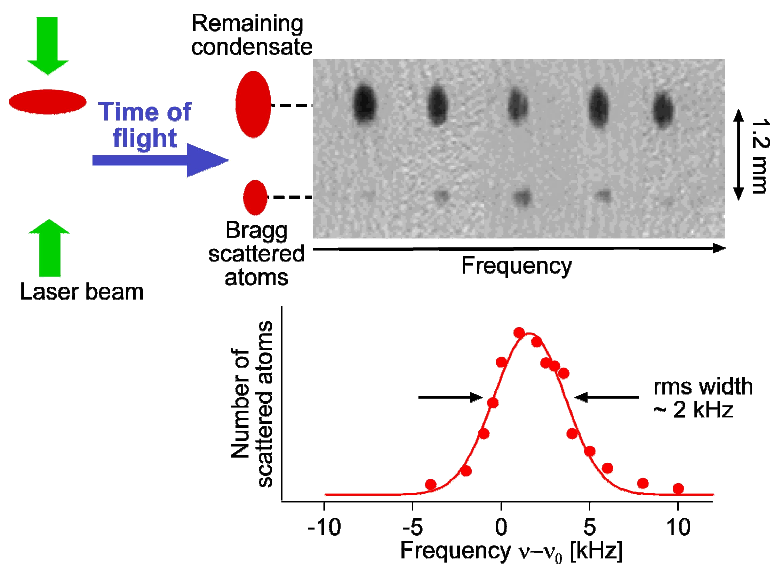
Condensation of pairs of fermionic lithium atoms

Frequency doubling of coherent matter waves

$$a_{2m}^{+} a_m a_m$$

$$\hbar\omega = E = mc^2$$

Bragg spectroscopy



J. Stenger, S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, D.E. Pritchard, W.K., PRL **82**, 4569 (1999)

Bragg resonance

transition $\mathbf{p}_i \rightarrow \mathbf{p}_f = \mathbf{p}_i + \mathbf{q}$

change of optical energy = change of kinetic energy

$$\hbar\omega_2 - \hbar\omega_1 = (q^2/2m) + \mathbf{q}\cdot\mathbf{p}_i/m$$

recoil energy

Doppler shift $\mathbf{q}\cdot\mathbf{v}$

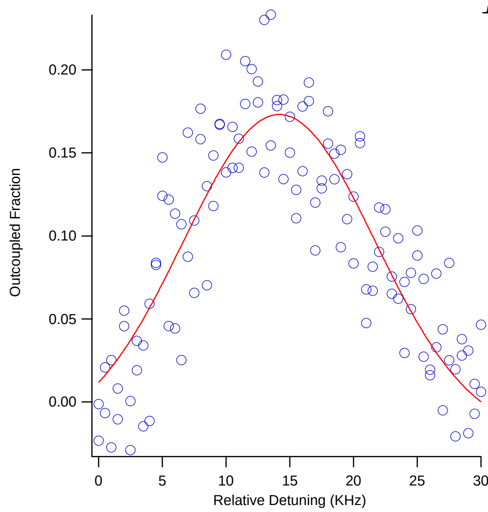
Doppler broadening
⇒ momentum distribution of the condensate

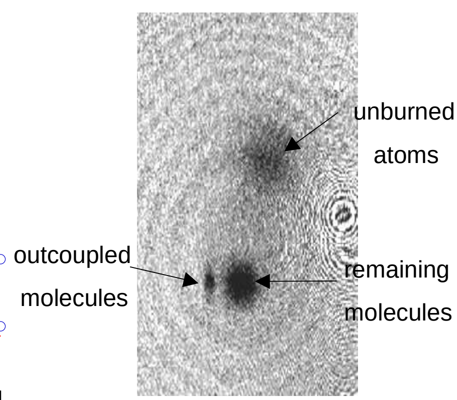
Coherence length ∝ (Doppler broadening)$^{-1}$

Bragg Spectrum

Molecule optics!

$$T = \frac{m}{2k_B}\left(\frac{\Delta\omega}{k}\right)^2 \approx 50\ nK$$





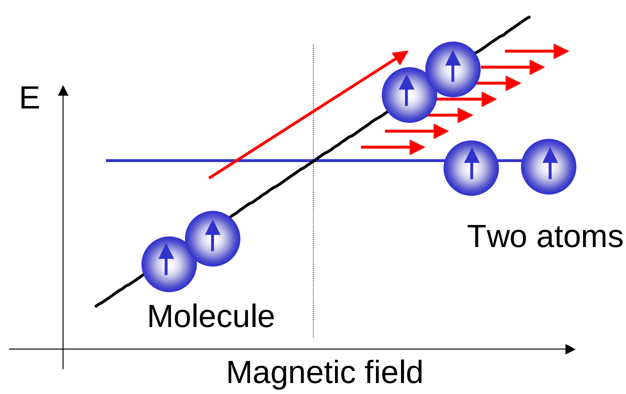
Width of Bragg spectrum $\propto$ (coherence length)$^{-1}$

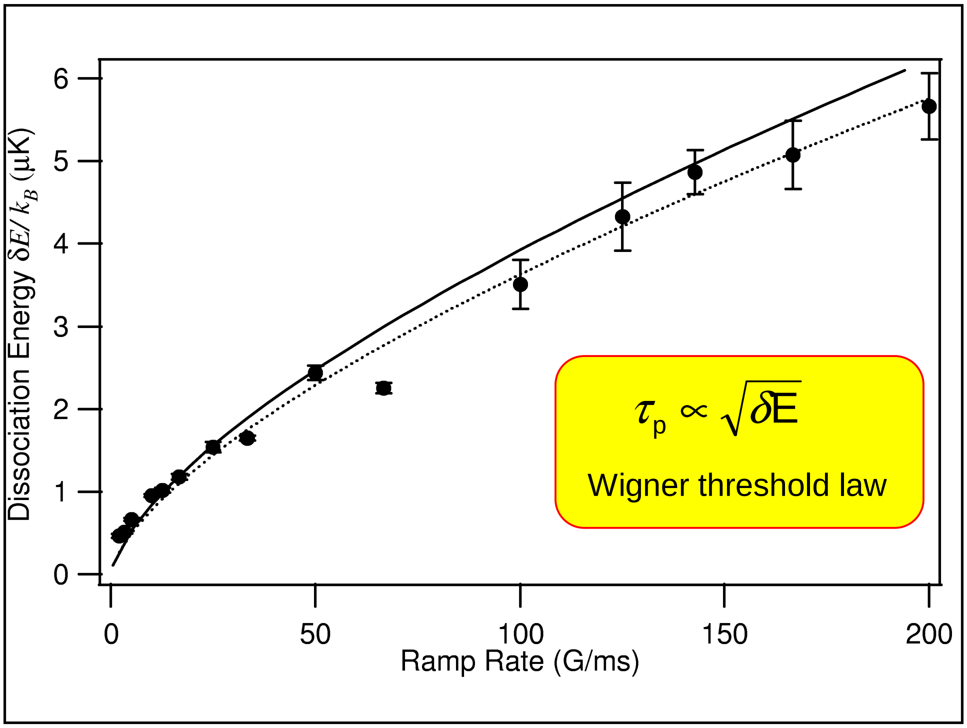
De Broglie Wavelength: 1.1 um

Interparticle spacing: 0.86 um

Phase space density: ~ 5

Possibly other contributions to the width:
- random motion
- excitations





Quantum degeneracy in fermions

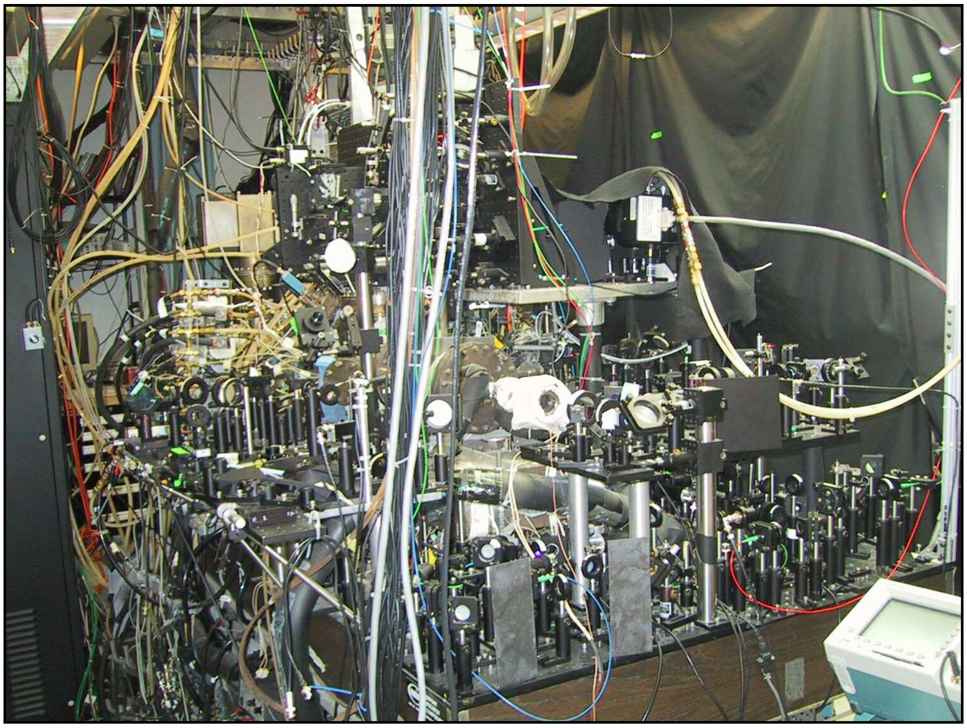
Evaporative cooling of fermions

No s-wave collisions in single-component fermionic cloud

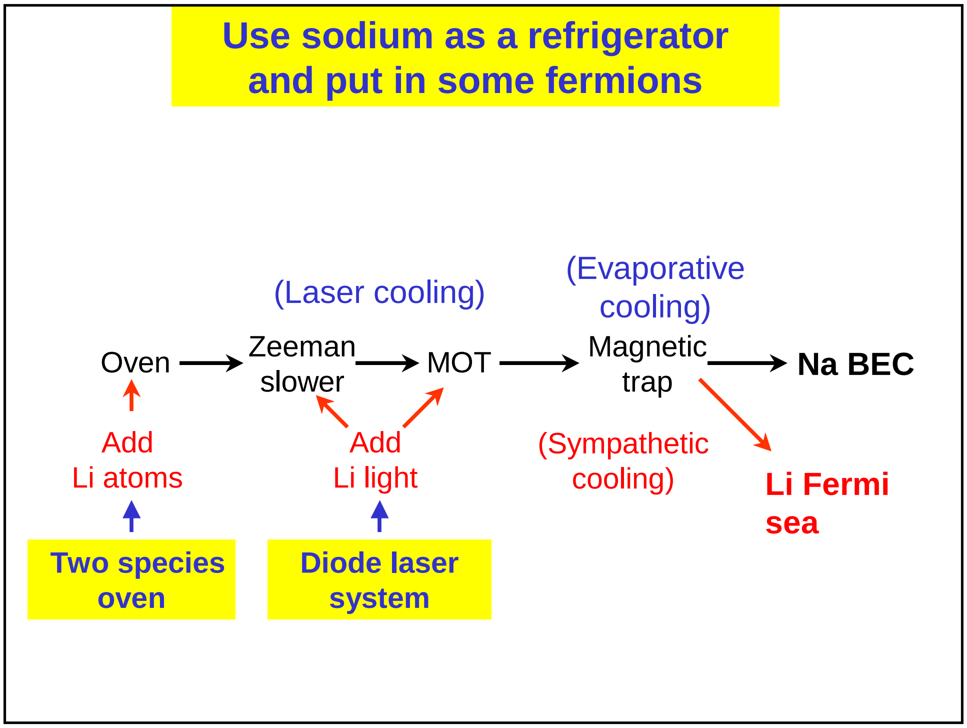
⇒ use mixtures

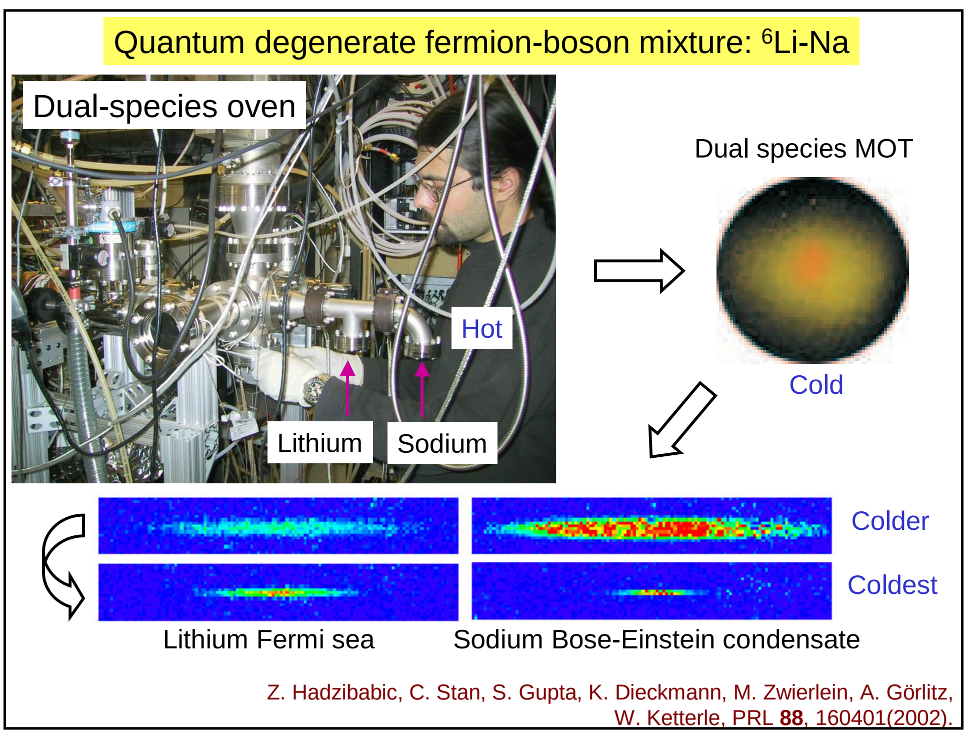
Fermion-Fermion
- Two hyperfine states of ^{40}K (Boulder, 1999)
- Two HFS of ^{6}Li (Duke, 2001; Innsbruck 2003)

Fermion-Boson
- ^{6}Li-^{7}Li (Rice, 2001; Paris, 2001)
- ^{6}Li-^{23}Na (MIT, 2001)
- ^{40}K-^{87}Rb (Florence, 2002; Boulder, 2002; Zürich, 2004)



Condensation of pairs of fermionic lithium atoms

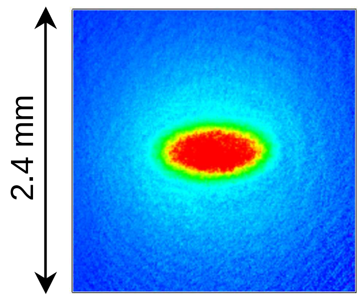




Sodium - Lithium Mixture

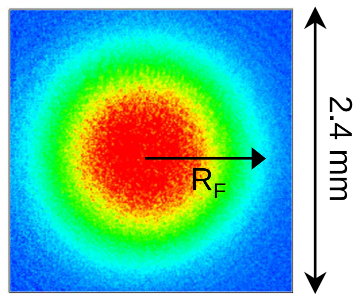
Na F = 2 condensate as refrigerator
cool Li F = 3/2 (state $|6\rangle$) in a magnetic trap -
20s forced evaporation

10^7 atoms in BEC (w/o Li)



50 ms time of flight
ω = 2π × (72,72,18) Hz

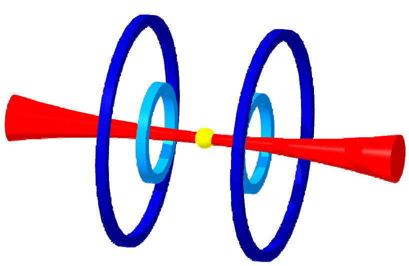
50 10^6 Li atoms at $\frac{T}{T_F} < 0.3$

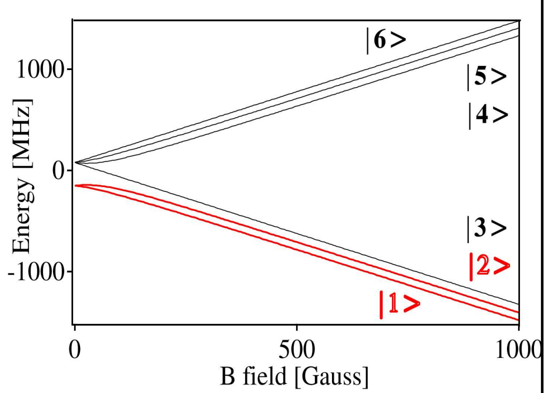


12 ms time of flight
ω = 2π × (142,142,36) Hz

Z. Hadzibabic, S. Gupta, C. A. Stan, C. H. Schunck, M.W. Zwierlein, K. Dieckmann, W. K., Phys. Rev. Lett. **91**, 160401 (2003)

Preparation of an interacting Fermi system in ^{6}Li





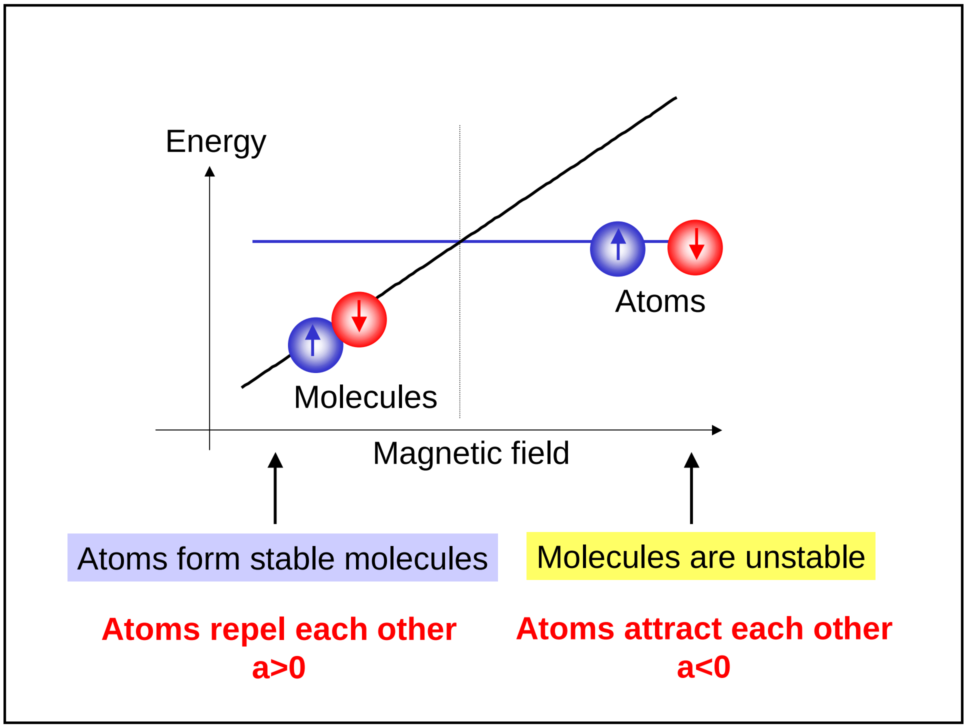
Setup:

Optical trapping:
9 W @ 1064 nm

ω = 2π × (16,16, 0.19) kHz
E_{trap} = 800 μK

States |1> and |2> correspond to |↑> and |↓>

Condensation of pairs of fermionic lithium atoms

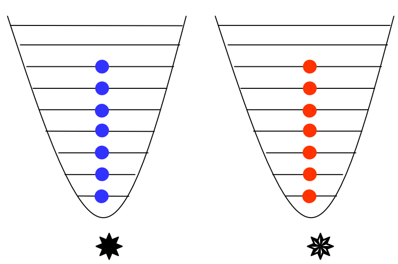


Interacting Fermions

Spin-mixture of Spin ✸ and ❈

Without interaction:

$a = 0$

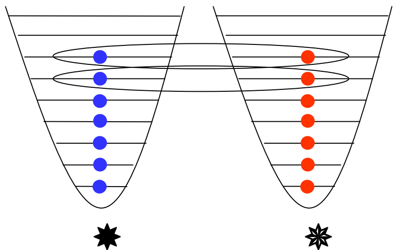


Interacting Fermions

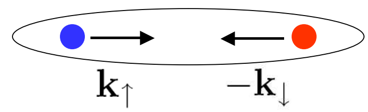
Spin-mixture of Spin ✸ and ❊

With attractive interaction:

a < 0



BCS-Transition
Condensation of
long-range Cooper pairs



$$T_C \approx 0.5\, T_F e^{-\frac{\pi}{2k_F\,|a|}}$$

⇒ We want a large and negative scattering length

T_c/T_F is predicted to be as high as 0.2

Many theorists: Eagles, Nozières, Schmitt-Rink, Holland, Zwerger, Timmermans, Levin, Strinati, Combescot, Griffin, Stoof, Randeira

Interacting Fermions

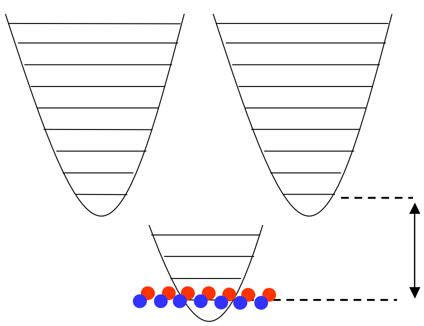
Spin-mixture of Spin ✸ and ❊

With repulsive interaction:

a > 0

BEC-Transition
Condensation of
tightly bound Fermion pairs

$$\begin{aligned} T_C &= 0.91\,\hbar\bar{\omega}\,N_{\rm mol}^{1/3} \\ &= 0.5\,T_F \end{aligned}$$

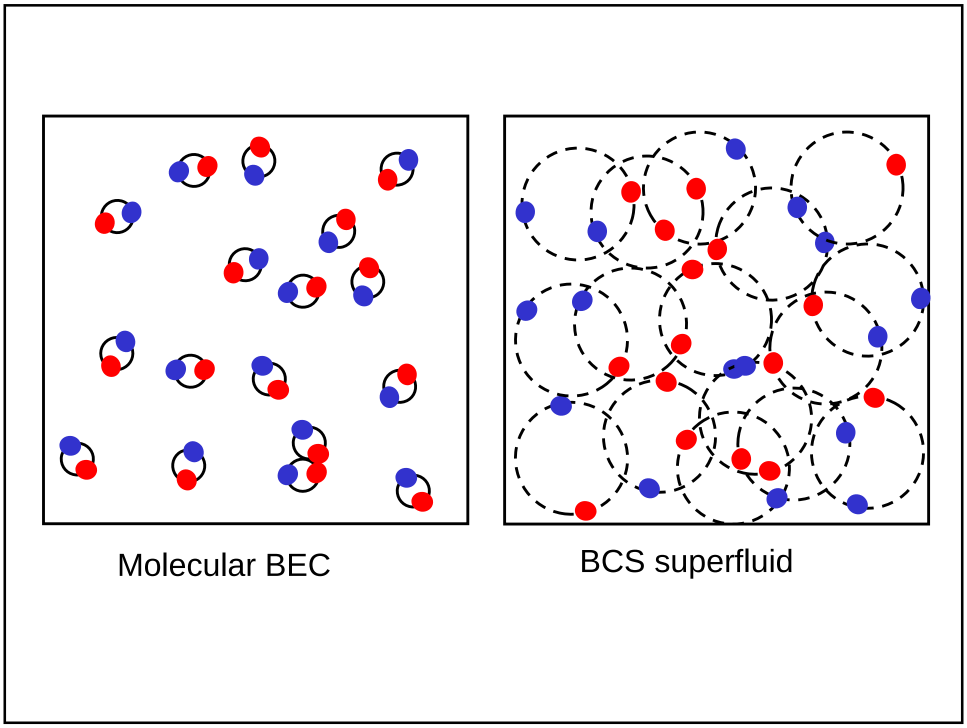


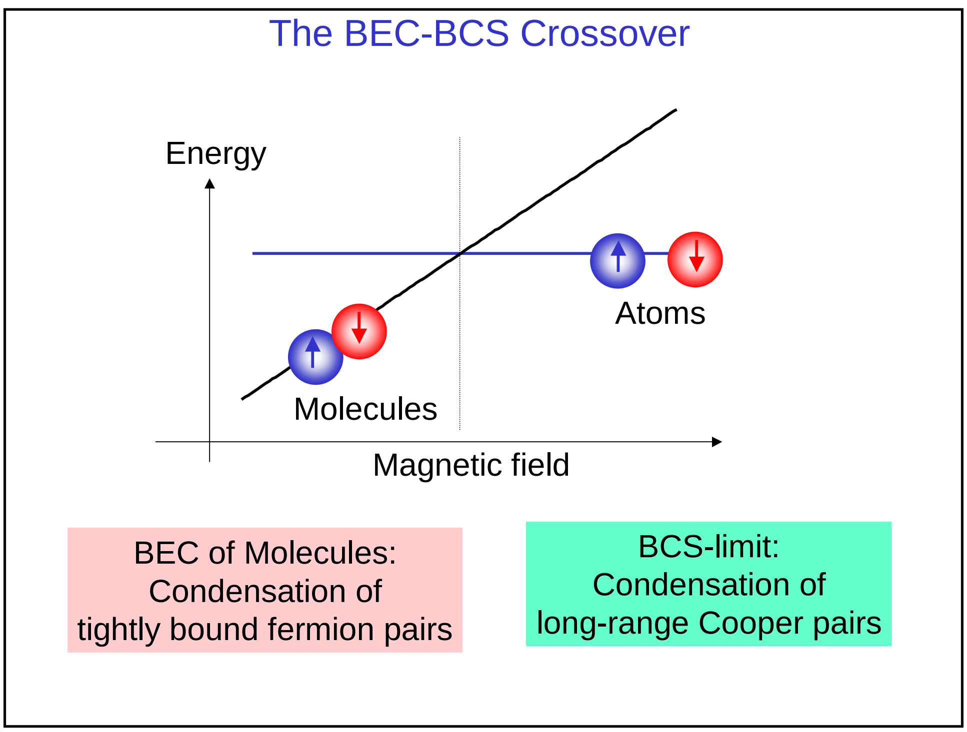
$$E_B = -\frac{\hbar^2}{2ma^2}$$

per atom

A bound state appears!

Condensation of pairs of fermionic lithium atoms





Condensation of pairs of fermionic lithium atoms

BCS

$$\frac{\text{Binding energy of pairs}}{\text{Fermi energy}} \approx \frac{\text{Transition termperature}}{\text{Fermi temperatue}} \approx$$

$10^{-5} \ldots 10^{-4}$	normal superconductors
10^{-3}	superfluid ^3He
10^{-2}	high T_c superconductors

BEC

$$\frac{\text{Binding energy of bosons}}{k_B \text{ BEC transition temperature}} \approx$$

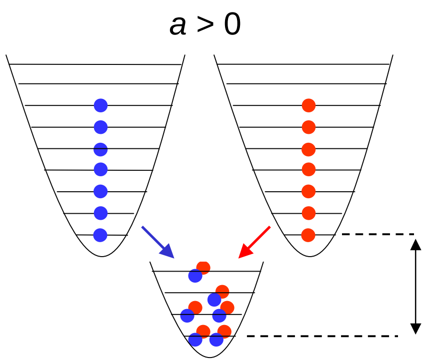
10^{5}	superflluid ^4He
10^{10}	alkali BEC

$$\frac{\text{Binding energy of composite boson}}{k_B \text{ degeneracy temperature}} \approx$$

$10^{-5} \ldots 10^{-4}$	normal superconductors
10^{-3}	superfluid ^3He
10^{-2}	high T_c superconductors
1	BEC-BCS crossover
10^{5}	superflluid ^4He
10^{10}	alkali BEC

Direct evaporation of ^{6}Li molecules

Long lifetime of Lithium molecules! (ENS, Rice)
⇒ Directly evaporate at large and positive *a*
⇒ Form molecules by three-body recombination when kT ⑥ E_B



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

Direct evaporation of ^{6}Li molecules

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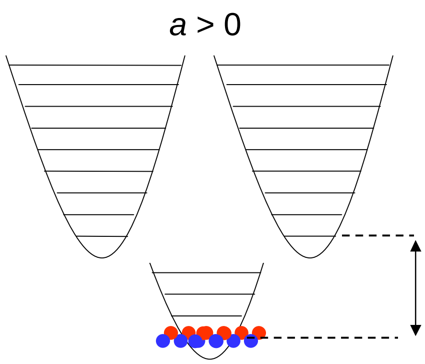
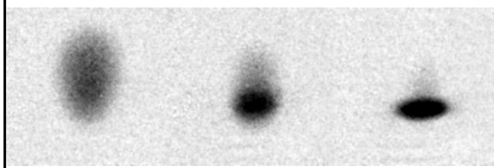


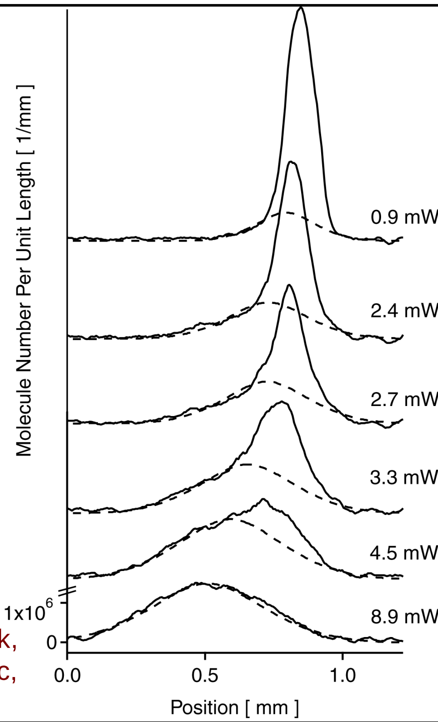
Cool further
⇒ BEC of molecules!

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

Condensation of pairs of fermionic lithium atoms

BEC of Molecules

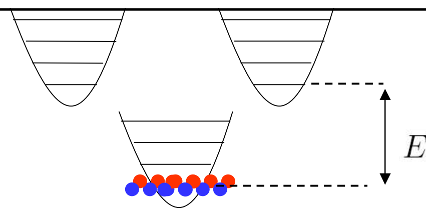




Up to 3 million condensed molecules

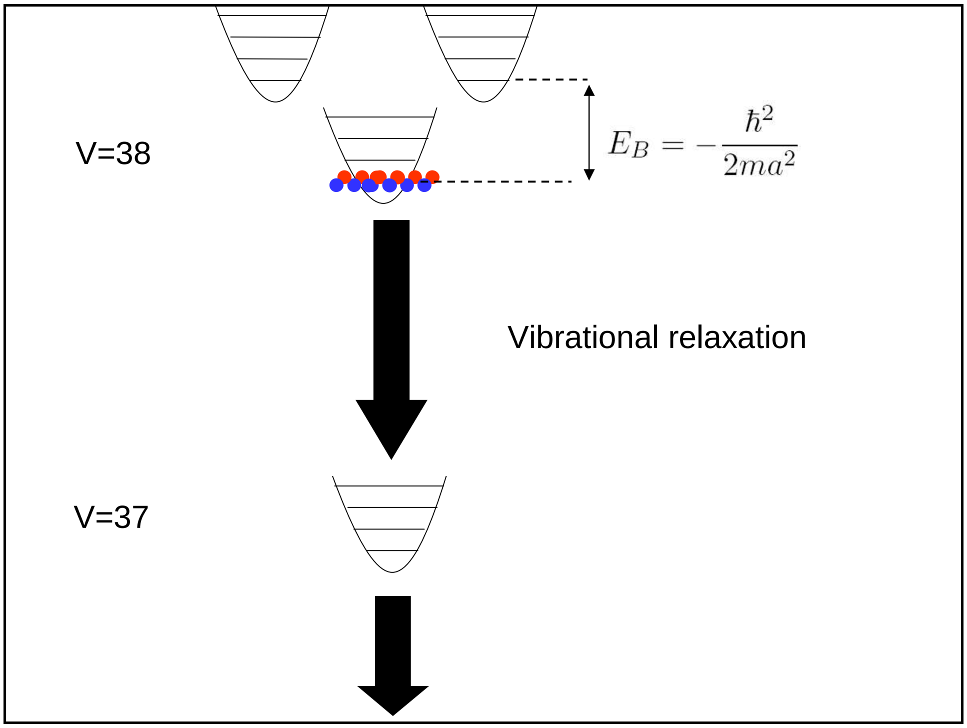
Boulder	Nov ‘03
Innsbruck	Nov ‘03, Jan ’04
MIT	Nov ’03
Paris	March ‘04

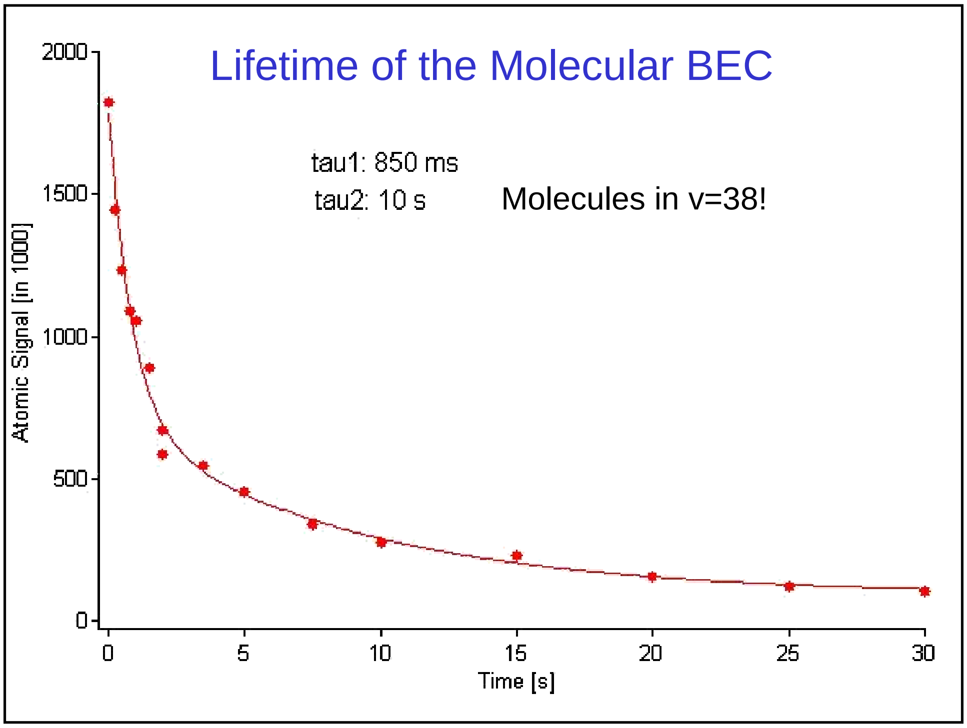
M.W. Zwierlein, C. A. Stan, C. H. Schunck, S.M. F. Raupach, S. Gupta, Z. Hadzibabic, W.K., Phys. Rev. Lett. 91, 250401 (2003)



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

Condensation of pairs of fermionic lithium atoms

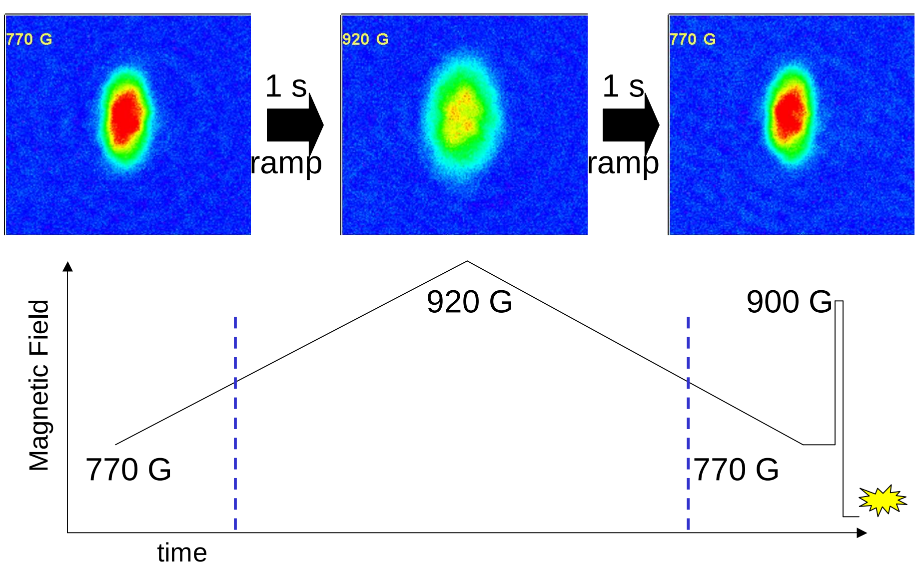




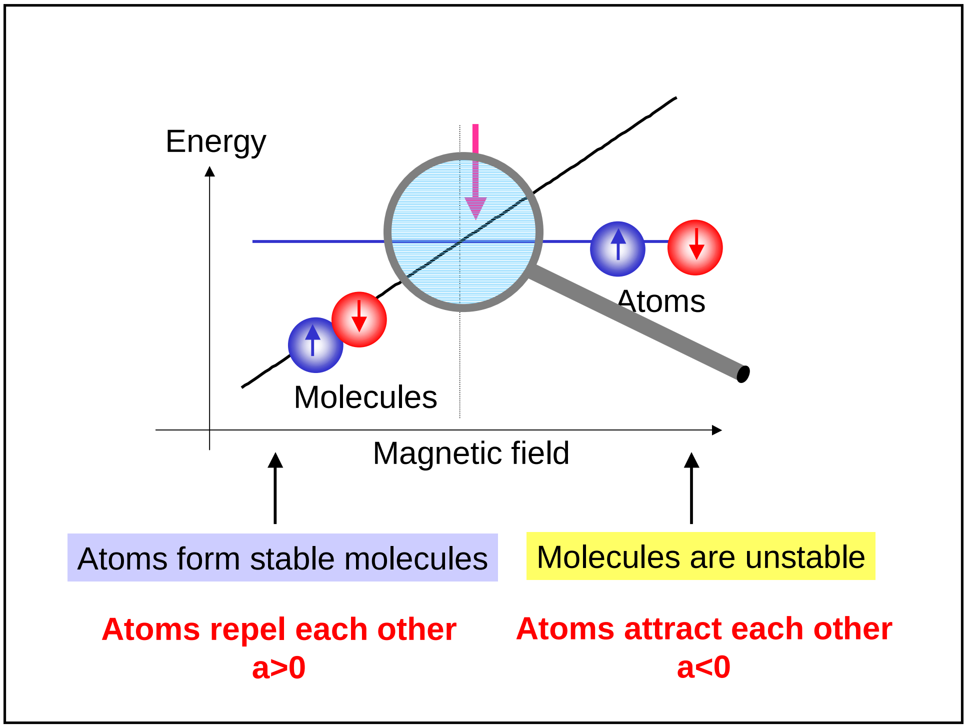
Crossover from a Degenerate Fermi Gas to a BEC of molecules

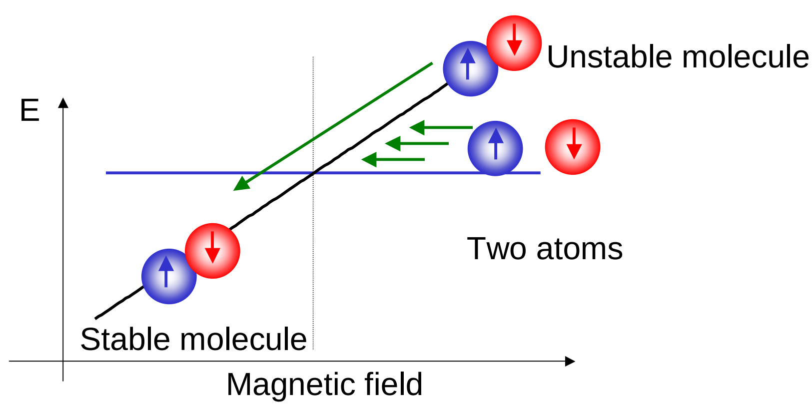
Recent results of the last few months:
- Innsbruck
- Boulder
- MIT
- Paris
- Duke

Crossover from a BEC to a Degenerate Fermi Gas …and back



Condensation of pairs of fermionic lithium atoms

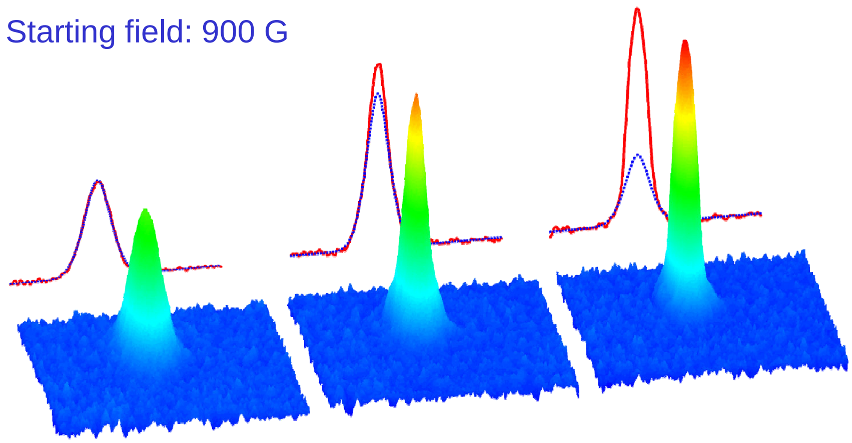




Momentum distribution of stable molecules at $B<B_0$ reflects distribution of center-of-mass momentum of atom pairs or quasi-molecules at $B>B_0$

Observation of Condensates!

Starting field: 900 G



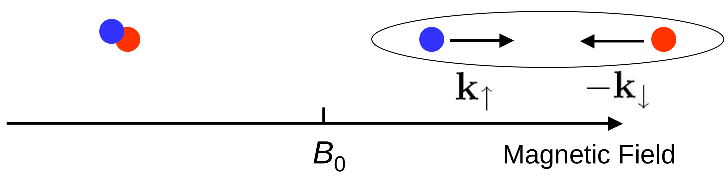
Initial temperature: $T / T_F = 0.2$ $T / T_F = 0.1$ $T / T_F = 0.05$

Also : C. A. Regal et al., Phys. Rev. Lett. **92**, 040403 (2004)

M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman, W.K. Phys. Rev. Lett. **92**, 120403 (2004).

How to detect Condensates of Pairs of Fermions?

$a > 0$	$a < 0$
Stable molecule	Quasi-molecules Long-range pair

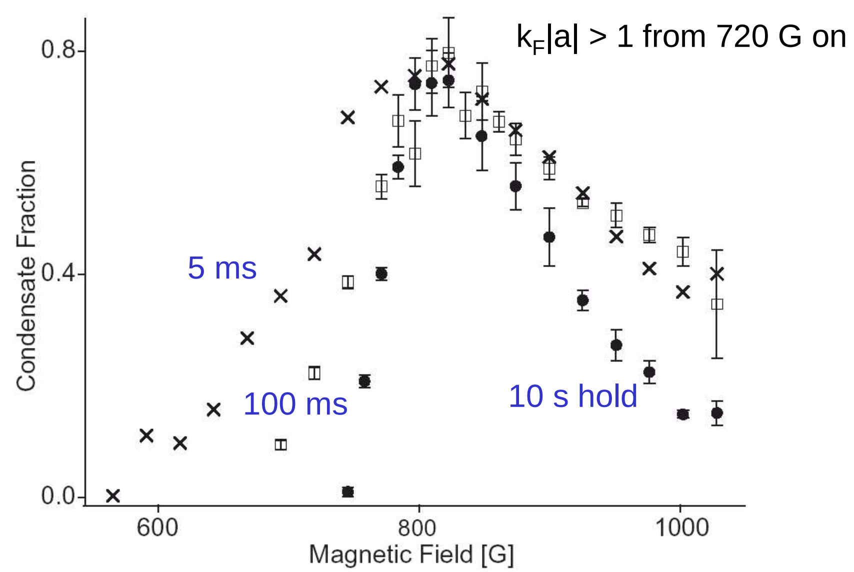


Idea: Quickly ramp over resonance to rapidly transfer fermionic atom pairs into stable molecules

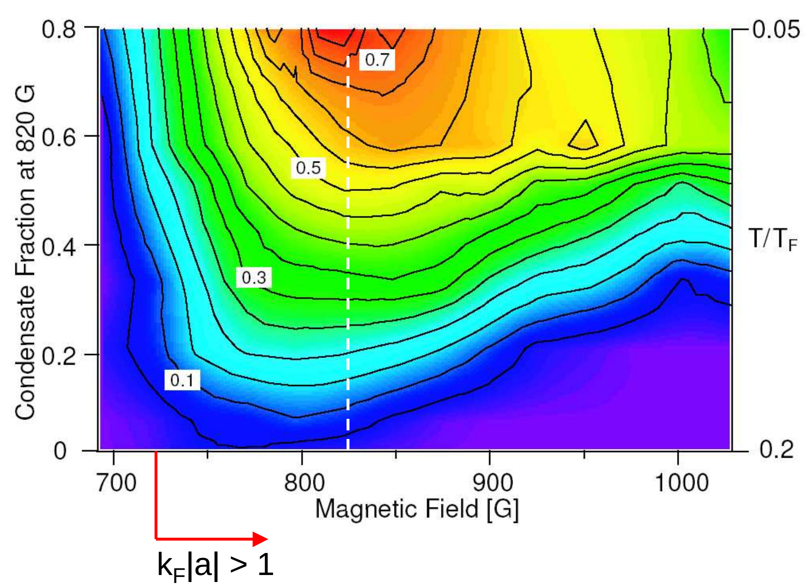
Limitation: probably works only for next neighbors
Can only detect “molecular” pairs, not long-range Cooper pairs

Condensation of pairs of fermionic lithium atoms

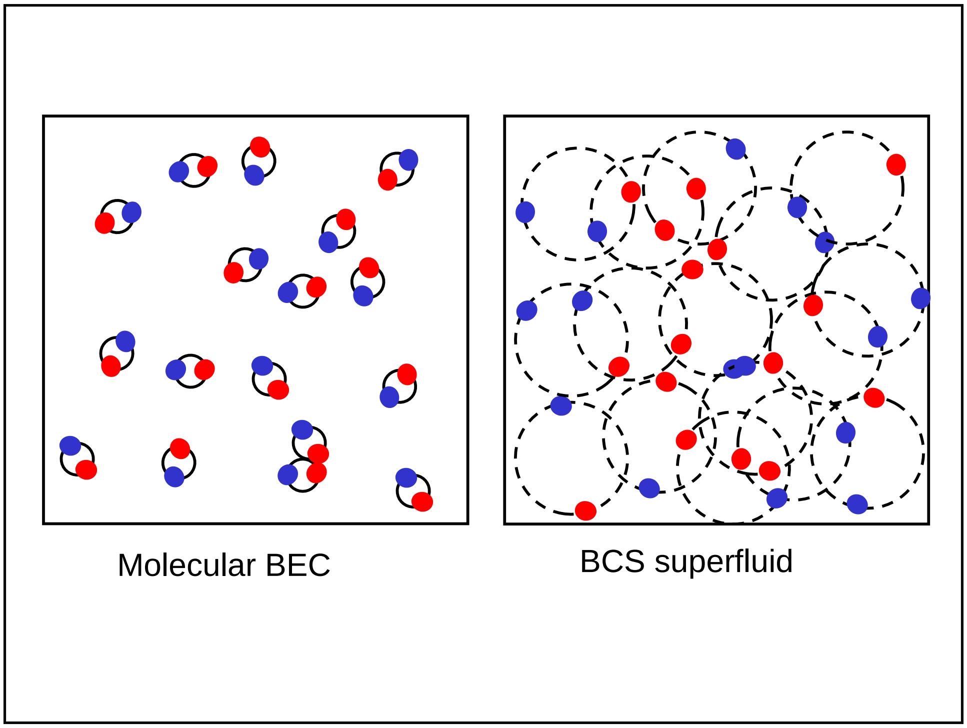
Condensate Fraction vs. hold time

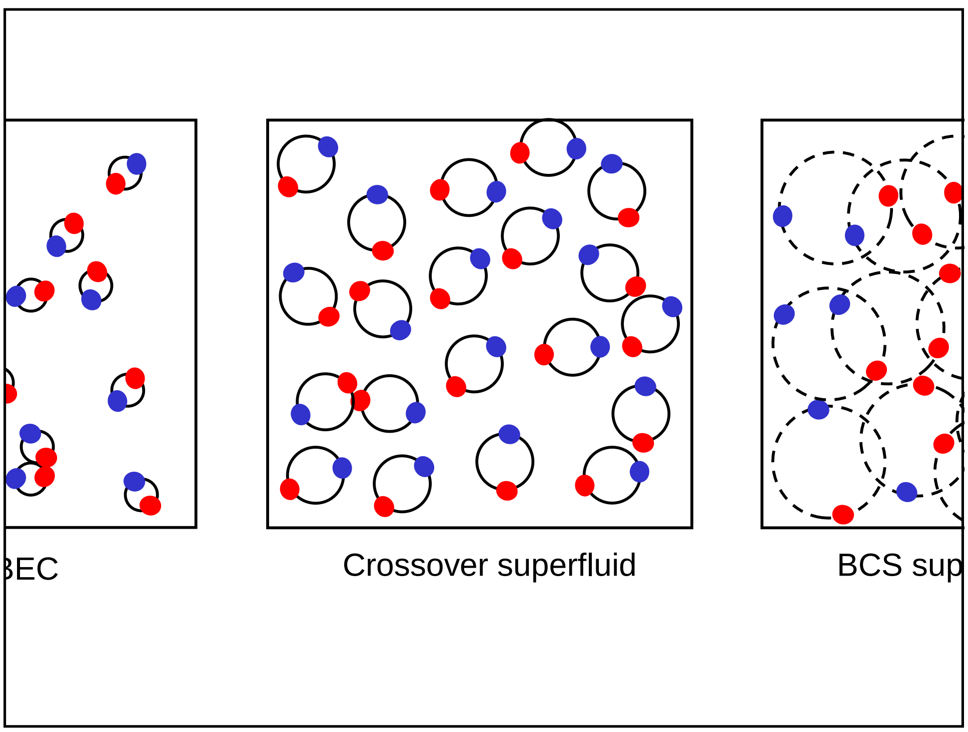


„Phase diagram" for pair condensation



Condensation of pairs of fermionic lithium atoms





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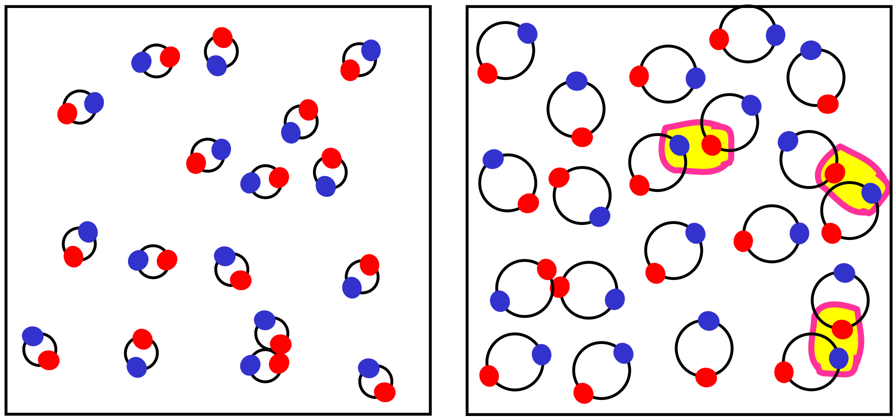


Molecular BEC

Crossover superfluid

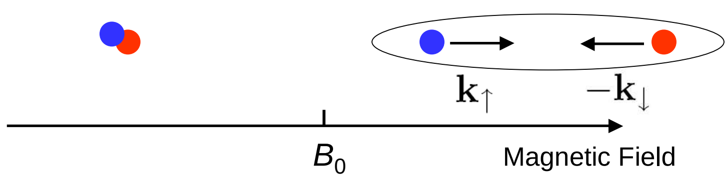
How to detect Condensates of Pairs of Fermions?

$a > 0$

Stable molecule

$a < 0$

Quasi-molecules
Long-range pair

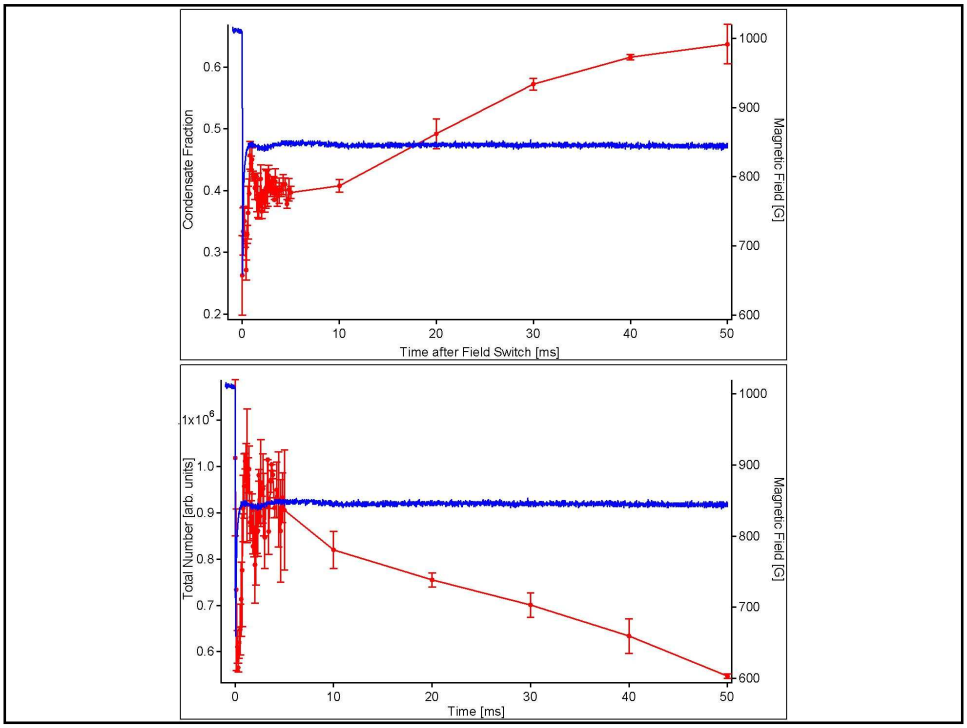


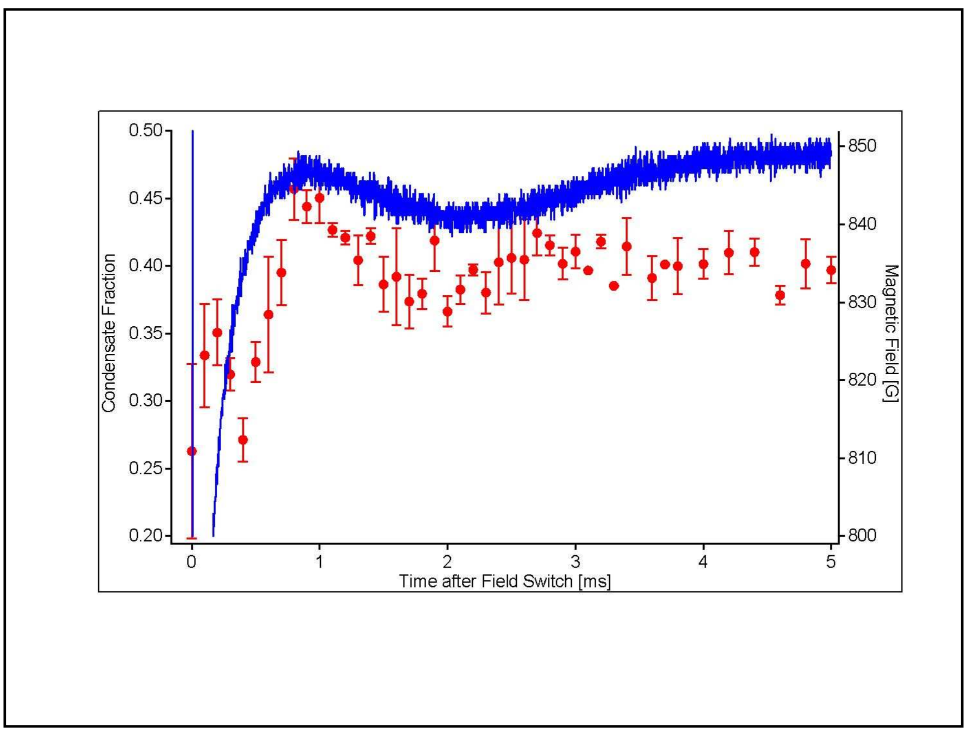
Idea: Quickly ramp over resonance to rapidly transfer fermionic atom pairs into stable molecules

Limitation: probably works only for next neighbors
Can only detect “molecular” pairs, not long-range Cooper pairs

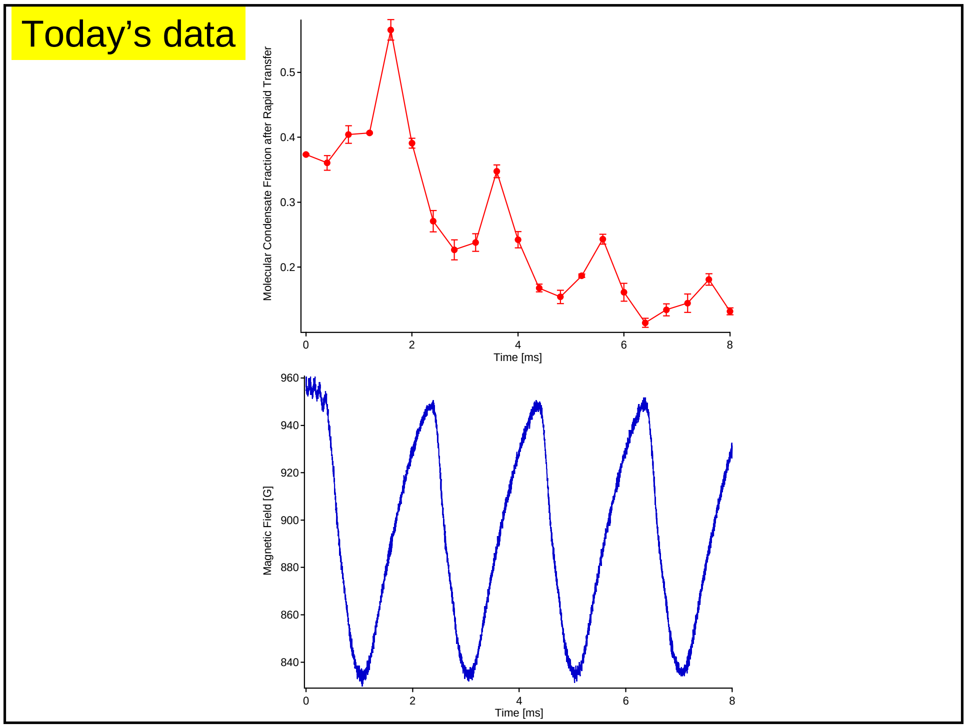
Is the ramp fast enough to neglect collisions or other dynamics?

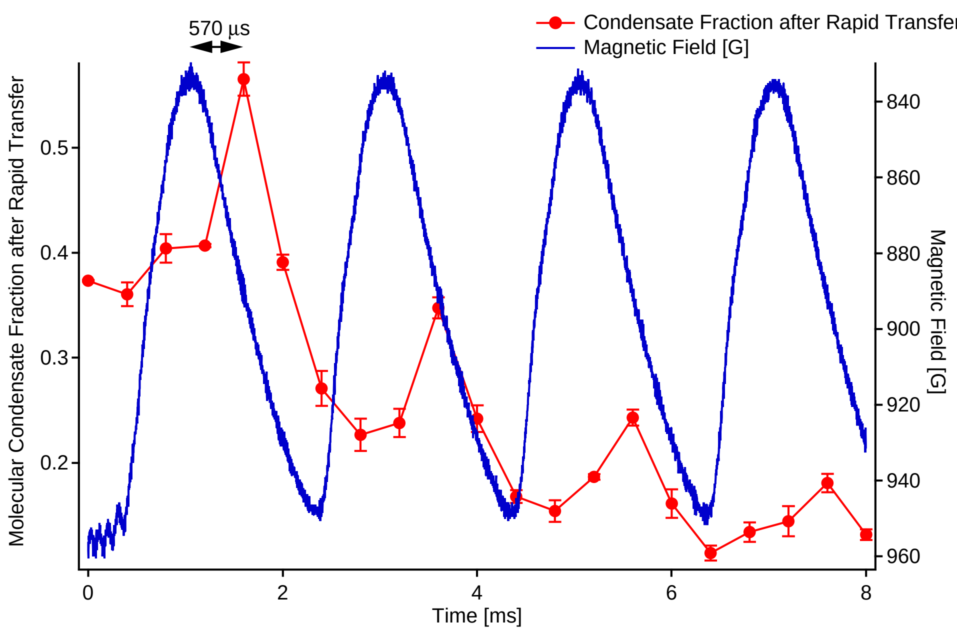
Condensation of pairs of fermionic lithium atoms





Condensation of pairs of fermionic lithium atoms

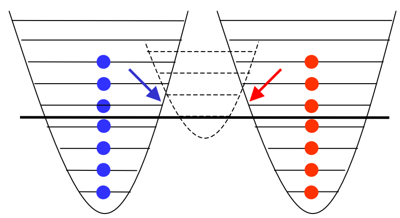




What‘s going on?

Tentative interpretation:
High condensate fraction implies pre-existing molecules above the two-body resonance position – stabilized by the Fermi sea

Simple model, neglecting interactions



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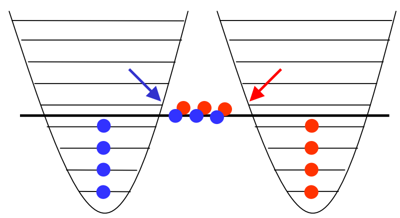
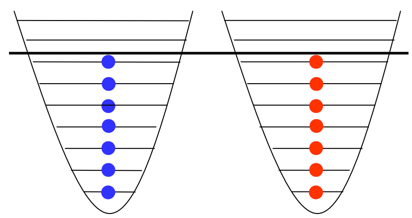


What‘s going on?

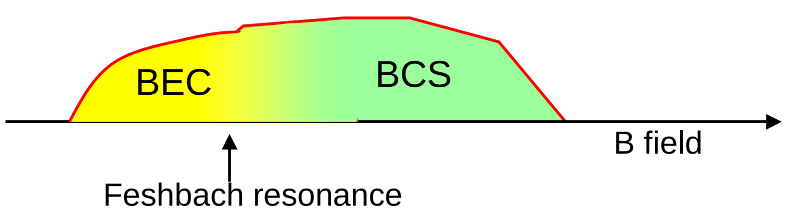
Tentative interpretation:
High condensate fraction implies pre-existing molecules above the two-body resonance position – stabilized by the Fermi sea

„Cooper pairs“ become delocalized only when
E_{Mol} ♦ $2 E_F$ or equivalently k_F | a | ⓪ 1

Simple model, neglecting interactions



Also: H. T. C. Stoof, preprint cond-mat/0402xxx

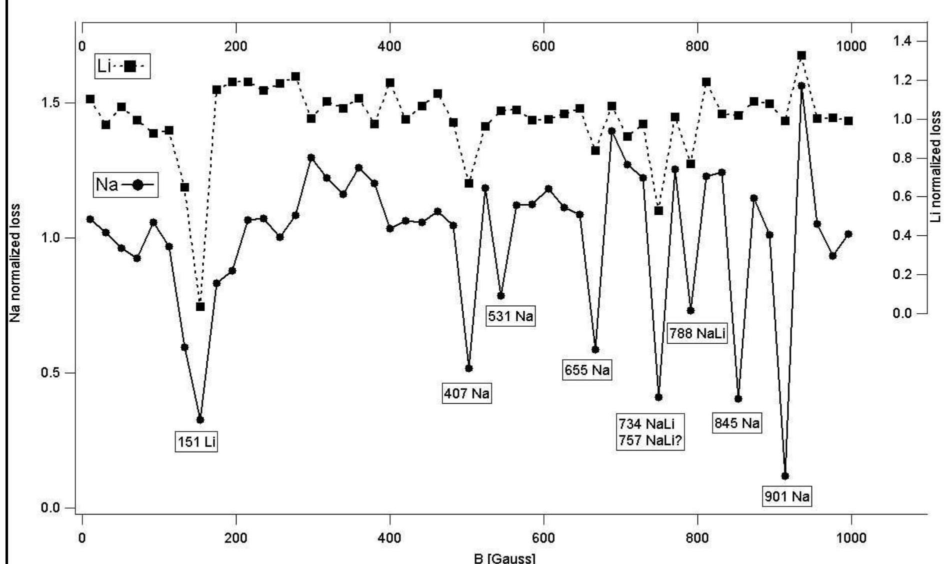


All experimental results are consistent with the existence of a molecular condensate above the Feshbach resonance

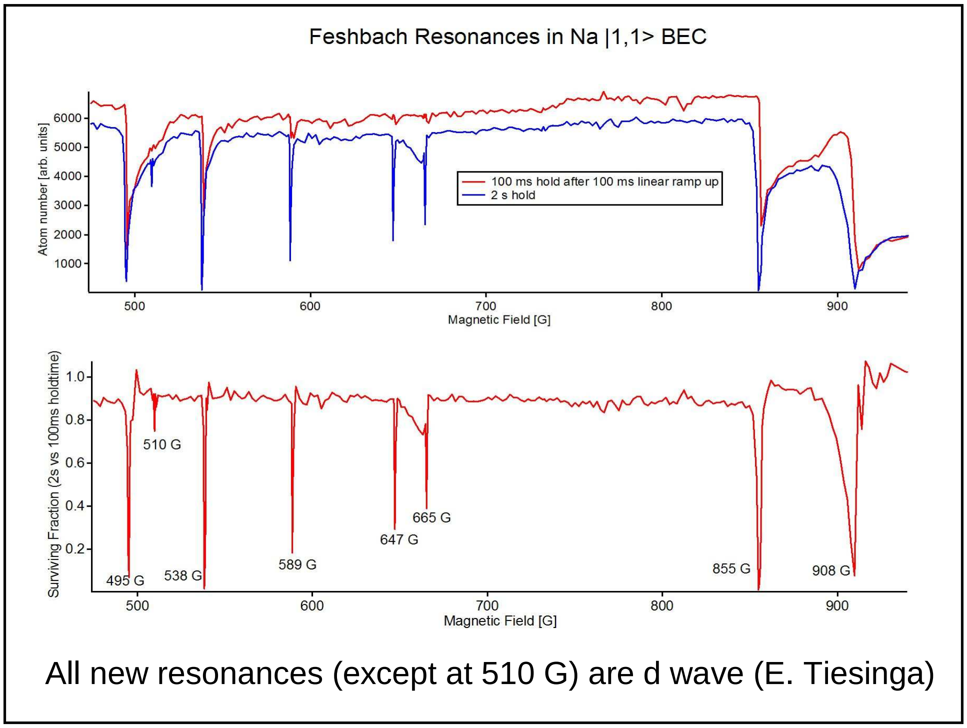
Molecules above the Feshbach resonance and tightly bound Cooper pairs are probably the same

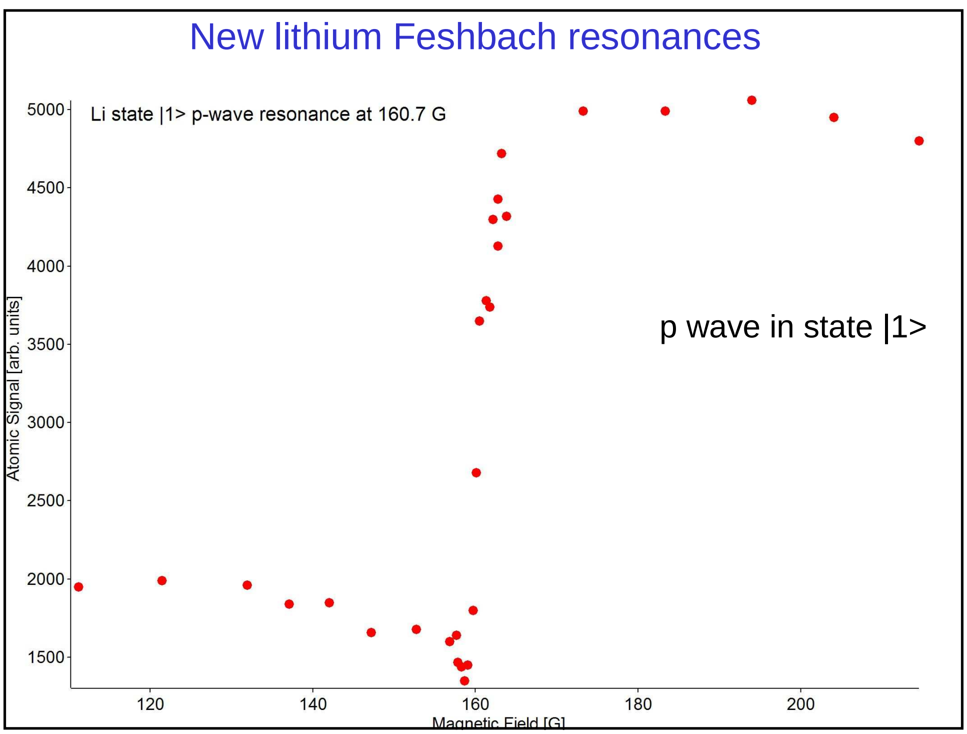
Heteronuclear fermionic molecules

Li – Na Feshbach scan

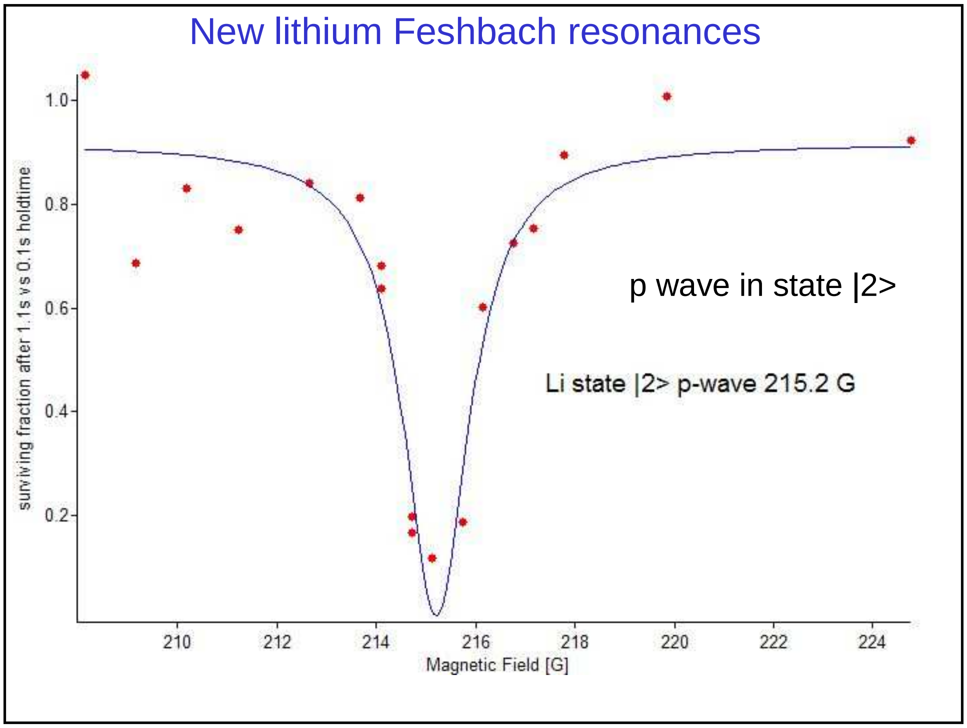


Condensation of pairs of fermionic lithium atoms



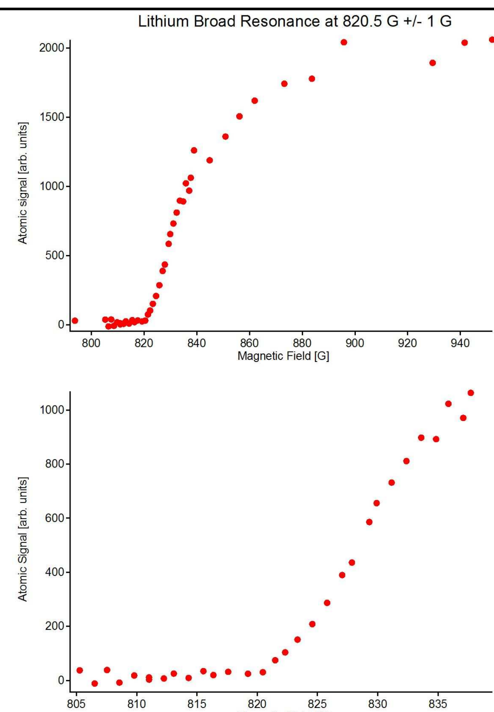


Condensation of pairs of fermionic lithium atoms

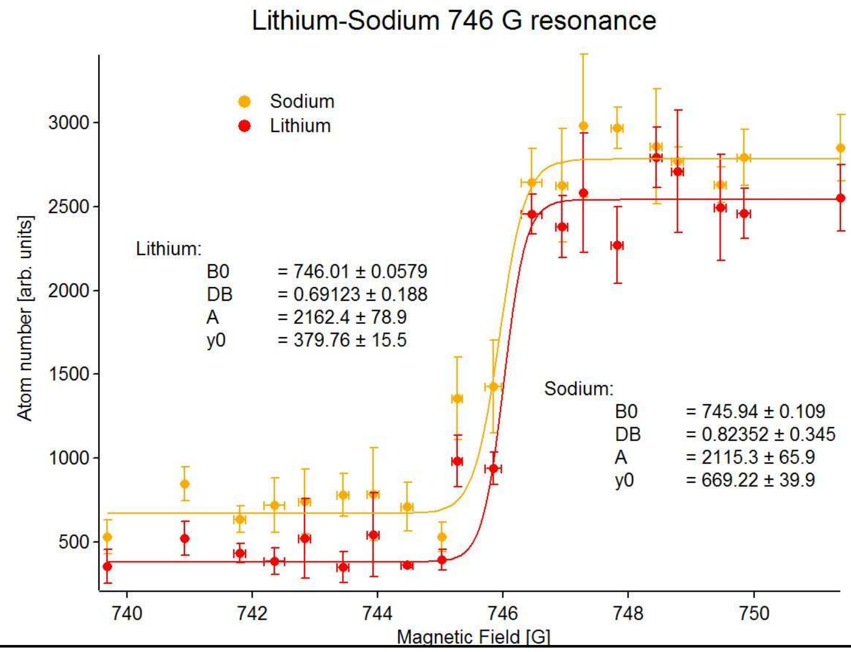


Broad Li Feshbach resonance at 821 G

(previously 822 +/- 3 G)



Li – Na Feshbach resonances



Li – Na Feshbach resonances

at 746, 760, 795 G

Stable LiNa molecules?

Should be stable after blasting Li and Na away
and outside the Feshbach resonance, when fermionic nature suppresses collisions

The Lithium Team

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Christian H. Schunck, Martin W. Zwierlein, Andrew J. Kerman

Not shown: Subhadeep Gupta, Zoran Hadzibabic