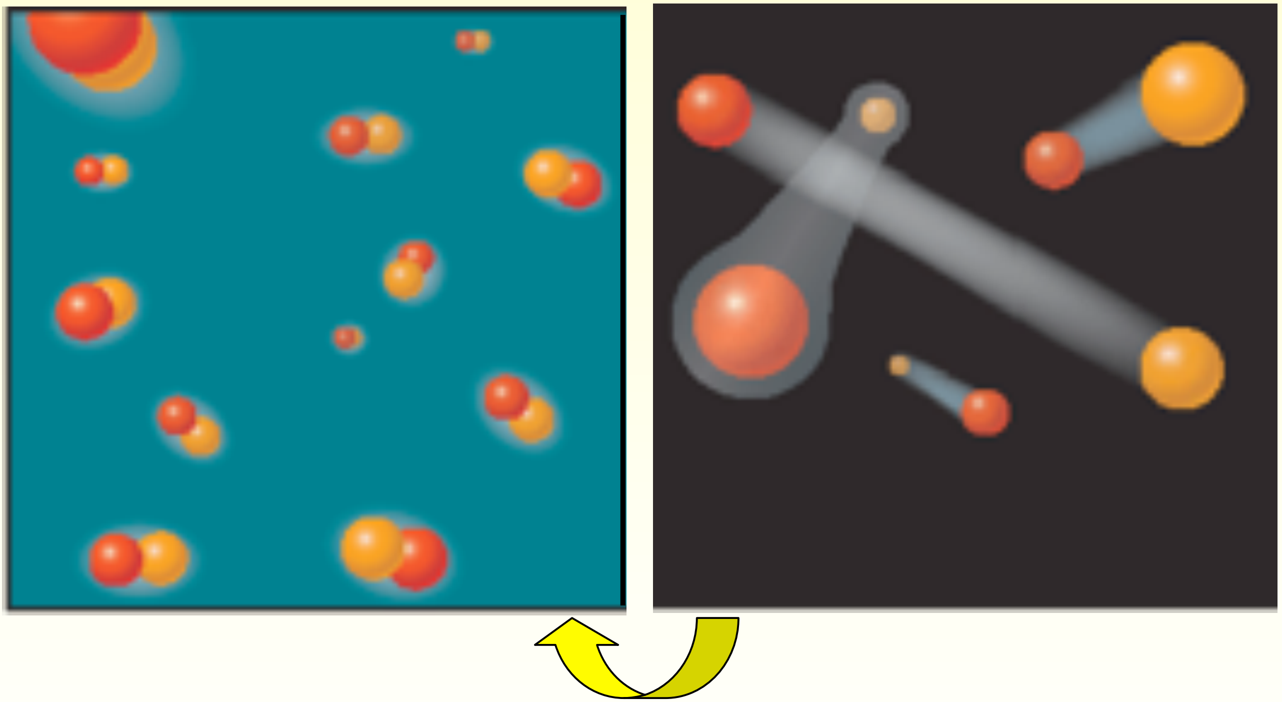
Superfluidity in interacting Fermi gases

Quantum many-body system in attractive interaction

Molecular condensate

BEC



Cooper pairs

BCS

Thomas Bourdel, J. Cubizolles, L. Khaykovich, J. Zhang, S. Kokkelmans, M. Teichmann, L. Tarruell, J. McKeever, F. Chevy, C. Salomon

Laboratoire Kastler Brossel, Ecole Normale Supérieure

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

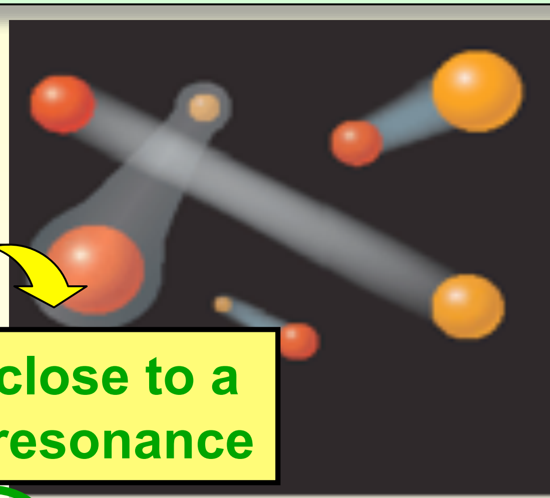
1530

Collège de France

Superfluidity in interacting Fermi gases

Molecular condensate

BEC



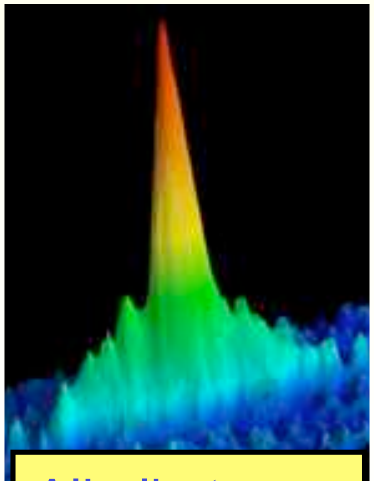
Cooper pairs

BCS

Fermions close to a Feshbach resonance

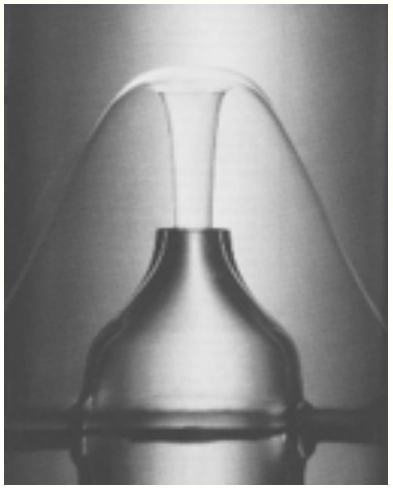
Pair binding energy [E_F]

10^{10} — 10^{5} — 1 — 10^{-1} — 10^{-4}



Alkali atom condensates

Superfluid ^{4}He



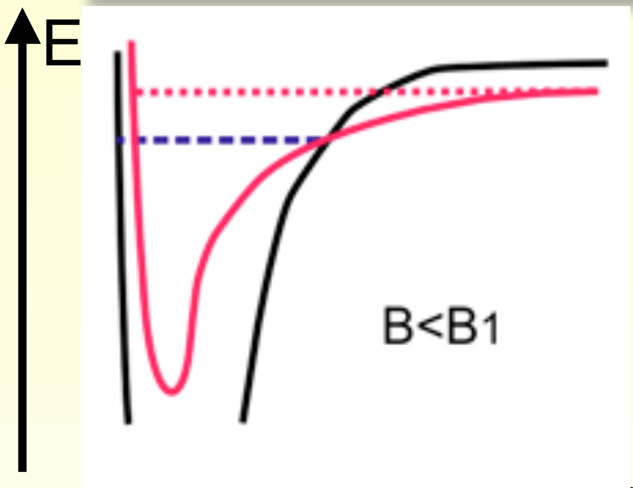
HTc Supra.

Std supra.

Outlook

- **Molecule** Formation
  - Interaction control: **Feshbach** resonance
  - **Reversible process**
- Bose-Einstein **Condensation** of molecules
  - Measurement of $a_{mol\text{-}mol}$
- **BEC-BCS** Crossover
  - Decription
  - Expansion of the gas

Feshbach resonance: |1/2,-1/2>+|1/2,1/2>

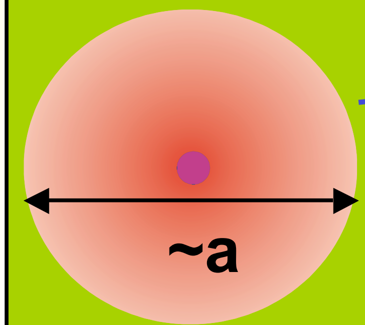


Open channel: triplet potential

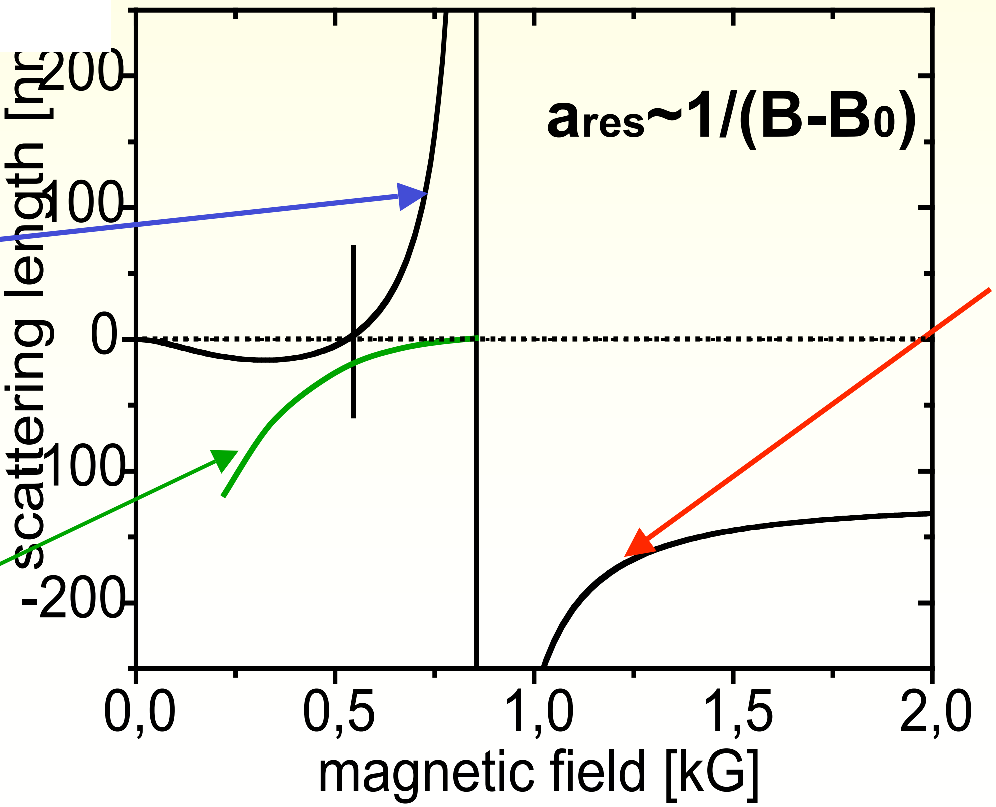
Closed channel: singlet potential

Different magnetic moments

Bound state:



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



No bound state

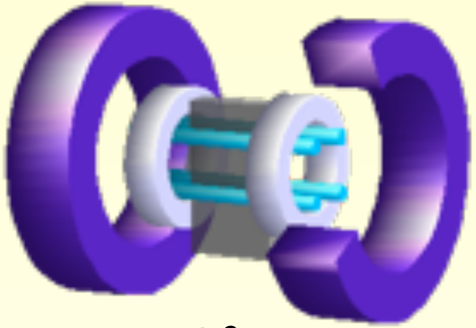
Experimental approch

Glass cell

2 isotopes
MOT

T=1 mK

Ioffe-
Pritchard
Magnetic trap

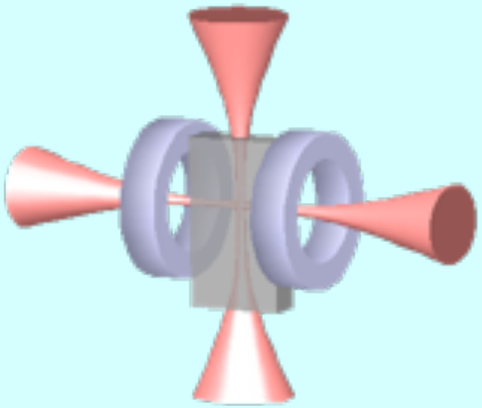


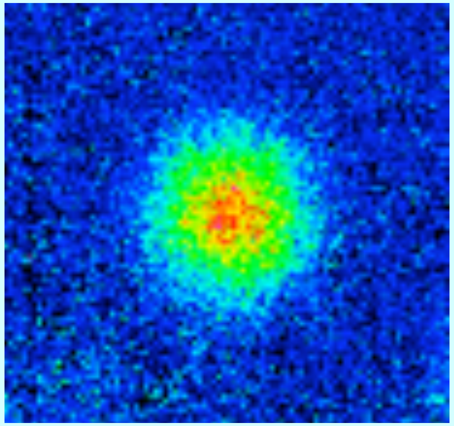
Sympathetic cooling of ^{6}Li
by evaporation of ^{7}Li

T=10 μK

Optical trap
power: 3W
waists ~25 μm

RF tranfers:
50-50 mixture





at 1060 G:

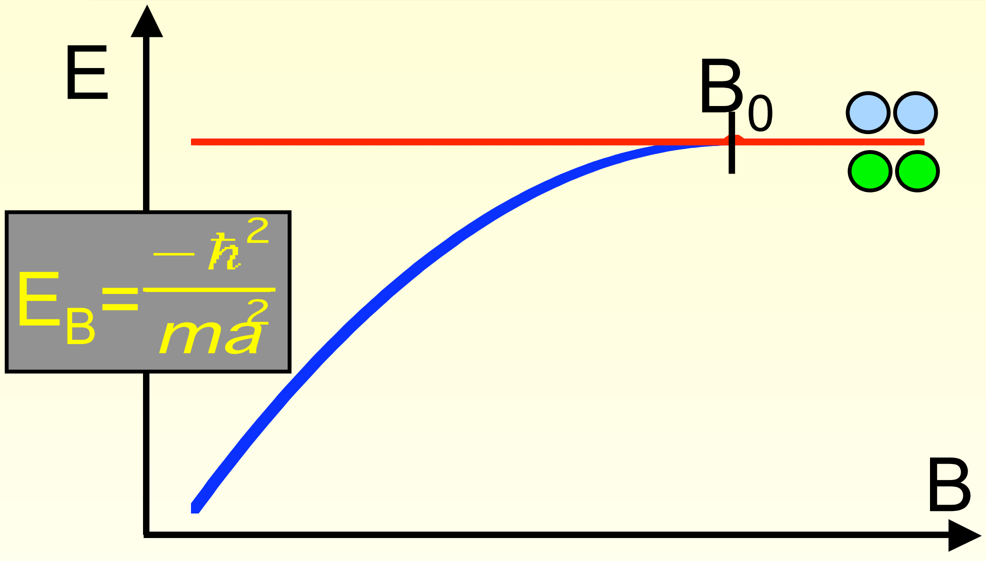
$T < 1\ \mu K$

$T_F = 5\ \mu K$

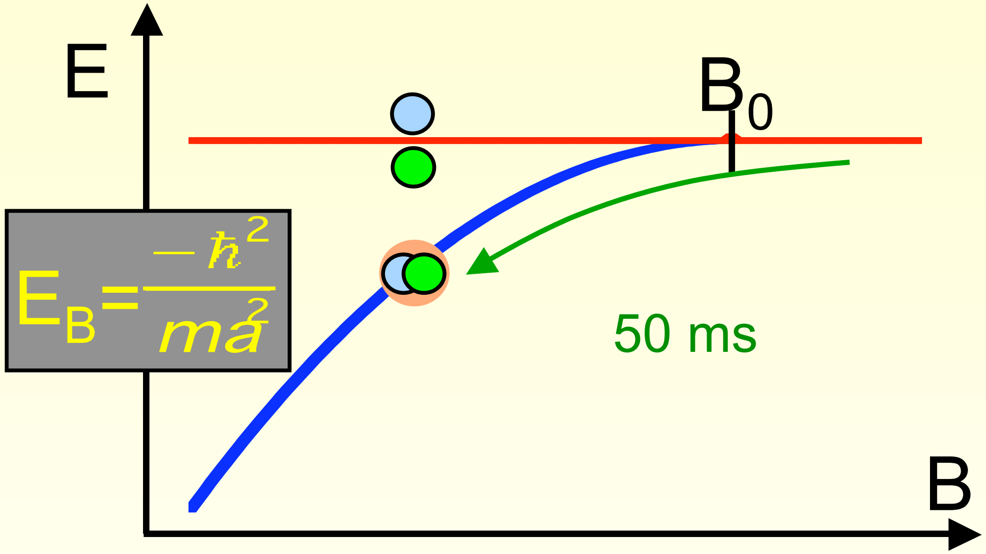
$T/T_F < 0.2$

$N_{total} = 1\ 10^5$

Formation and detection of molecules

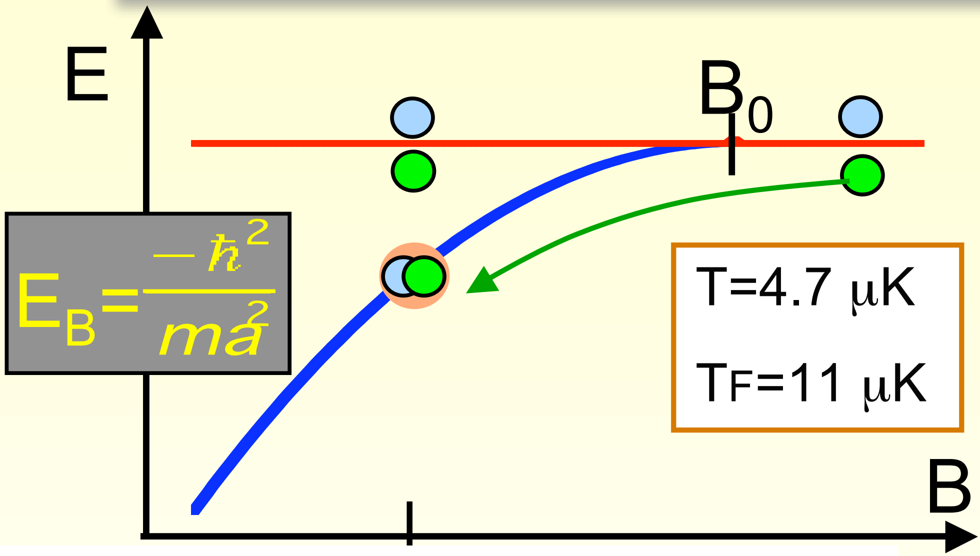


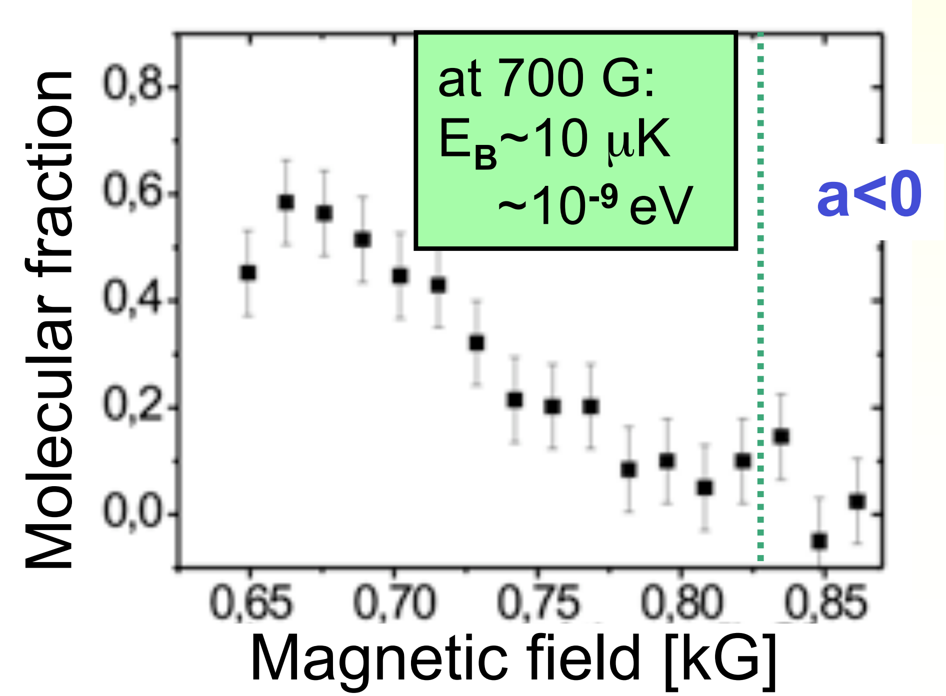
Formation and detection of molecules



Formation of molecules is energetically favorable

Formation and detection of molecules





-Conversion efficiency close to **100%** **(10%)**

-Lifetime: ~ 1 s **(1ms)**

- **slow** sweep though resonance **(fast)**

Reversing the ramp:
back to initial conditions

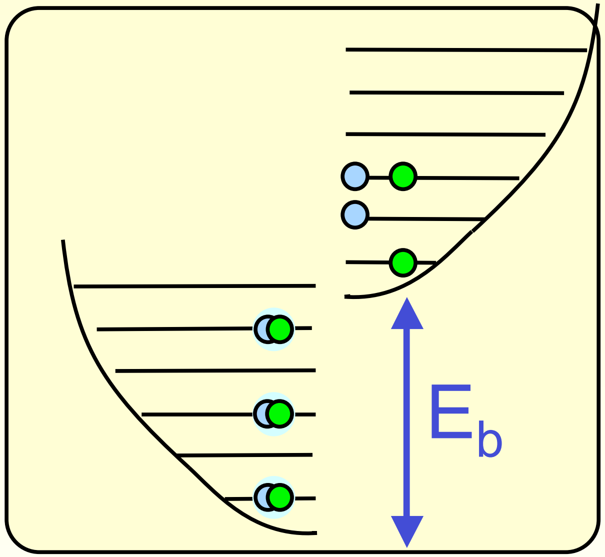
Process is **reversible**

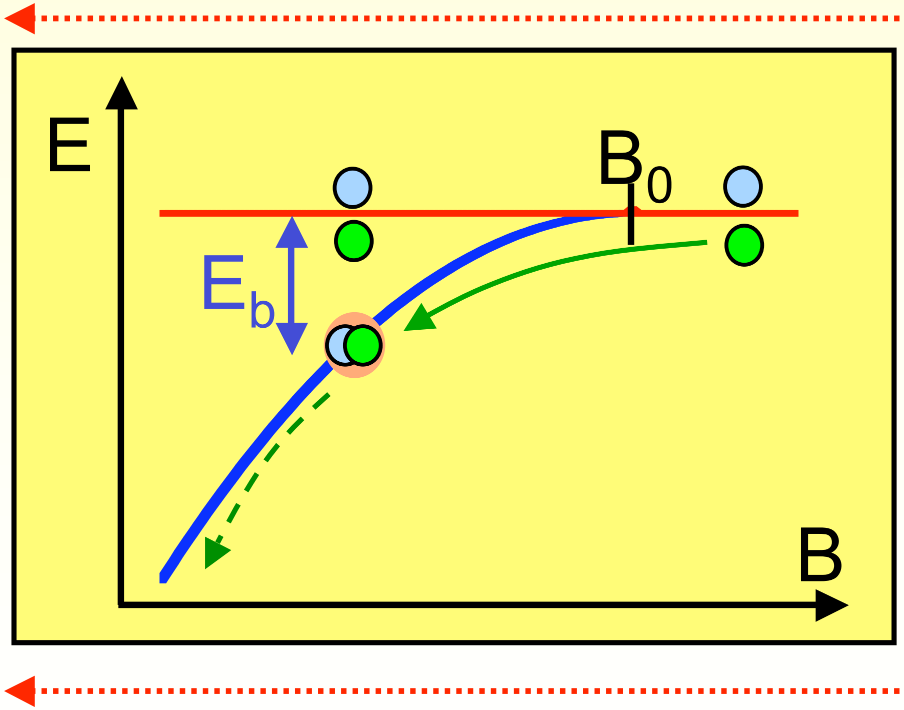
Quasi-static thermodynamic equilibrium between atoms and molecules during the ramp

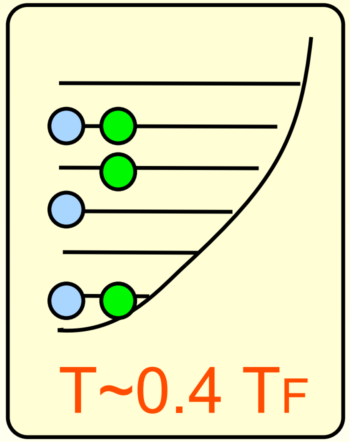
A simple thermodynamic model

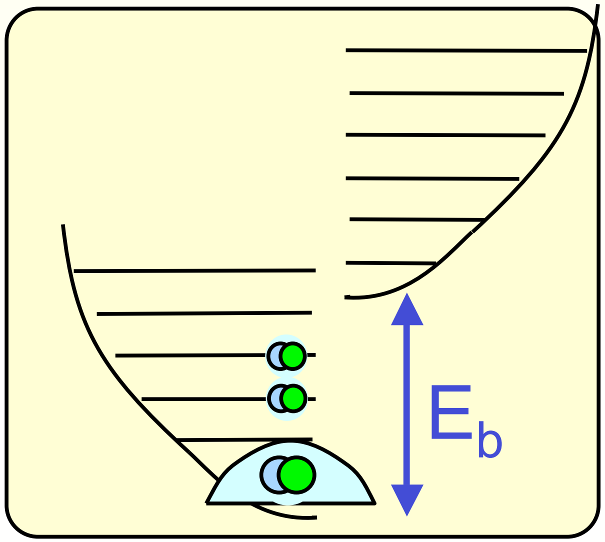
No heat transfert, reversible

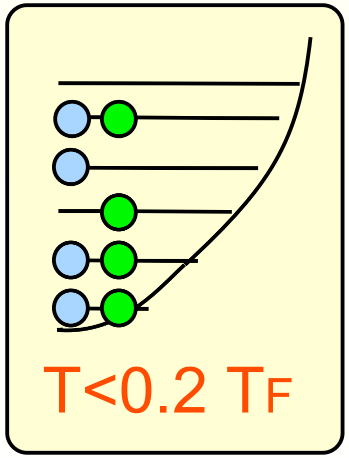
→ Entropy conservation





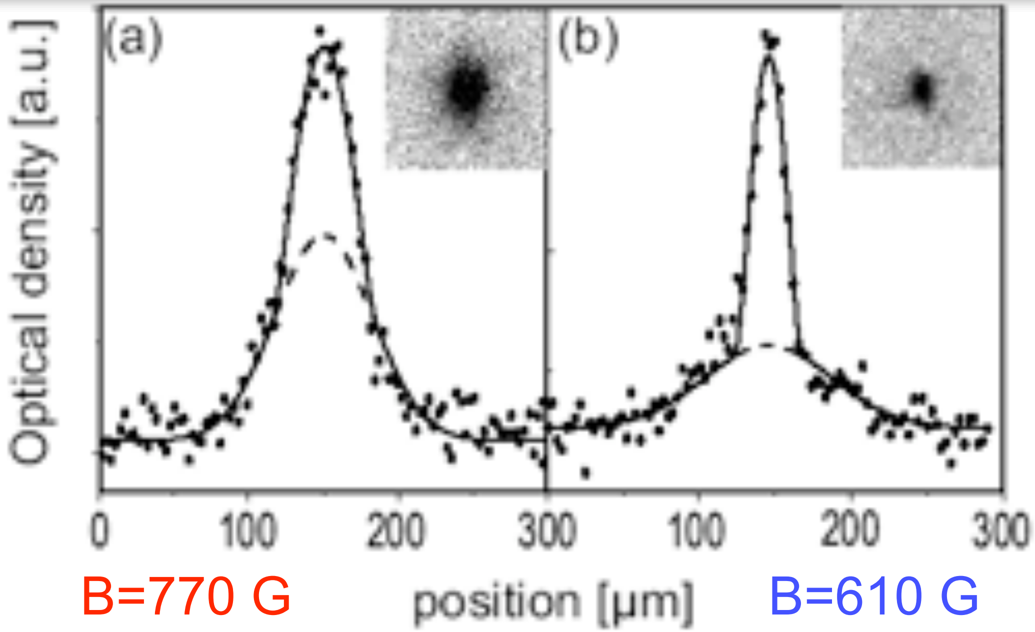






Bose-Einstein condensate of $^6Li_2$ molecules

$^6Li_2$



^7Li

B=770 G
N=2 10^4 molecules

B=610 G
N=2 10^4 atoms

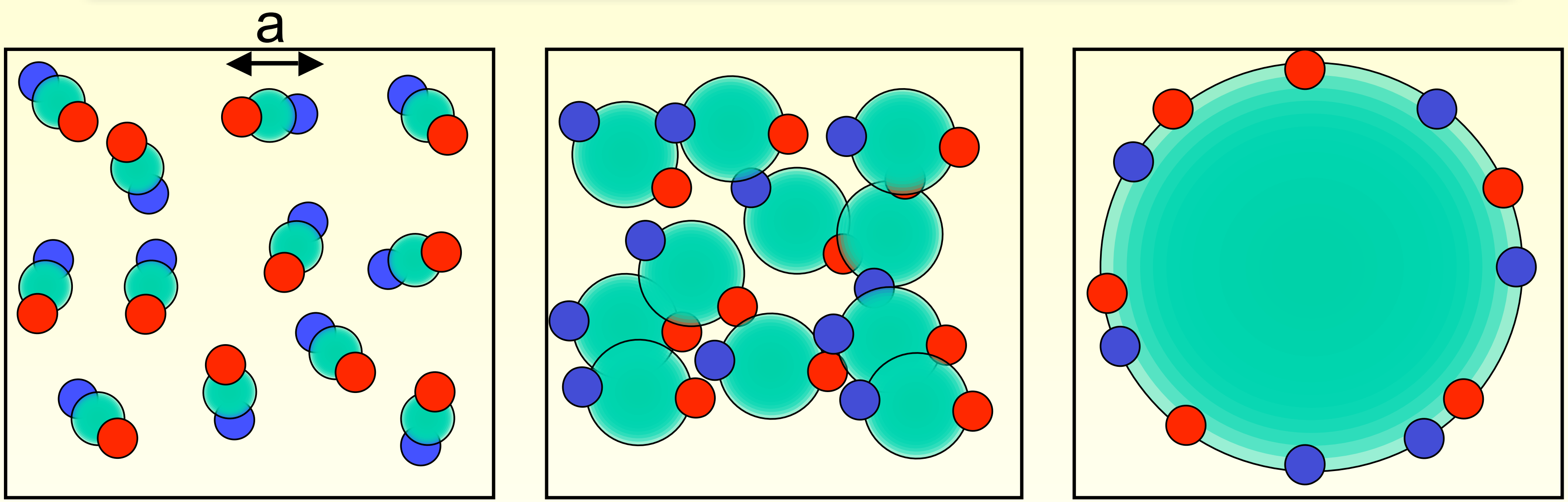
From pure condensates: Scattering length measurement

at 770 G:

In agreement with $a_{mm}=0.6\ a$

(Petrov, Salomon, Shlyapnikov, PRL, 2004)

BEC-BCS Crossover



Molecular condensate
Size a << $n^{-1/3}$
$n^{-1/3}$: mean interparticule distance

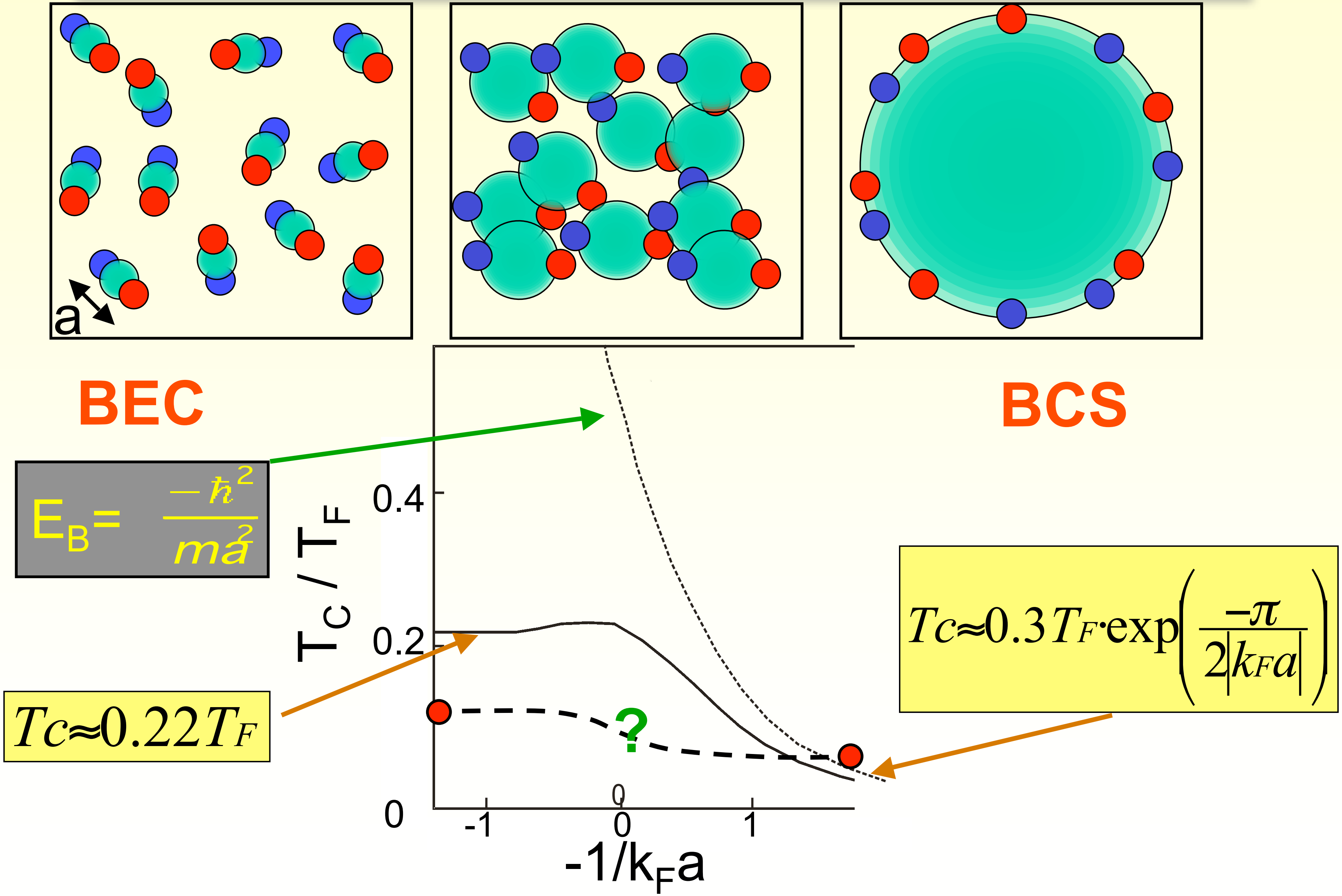
Close to resonance
$na^3 > 1$ or $k_F a > 1$
Paires are overlapping
They are stabilized by the Fermi sea

BCS Regime:
$k_F|a|<<1$
Cooper pairs: k, -k
Large compared to interparticule distance

a>0

a<0

BEC-BCS Crossover



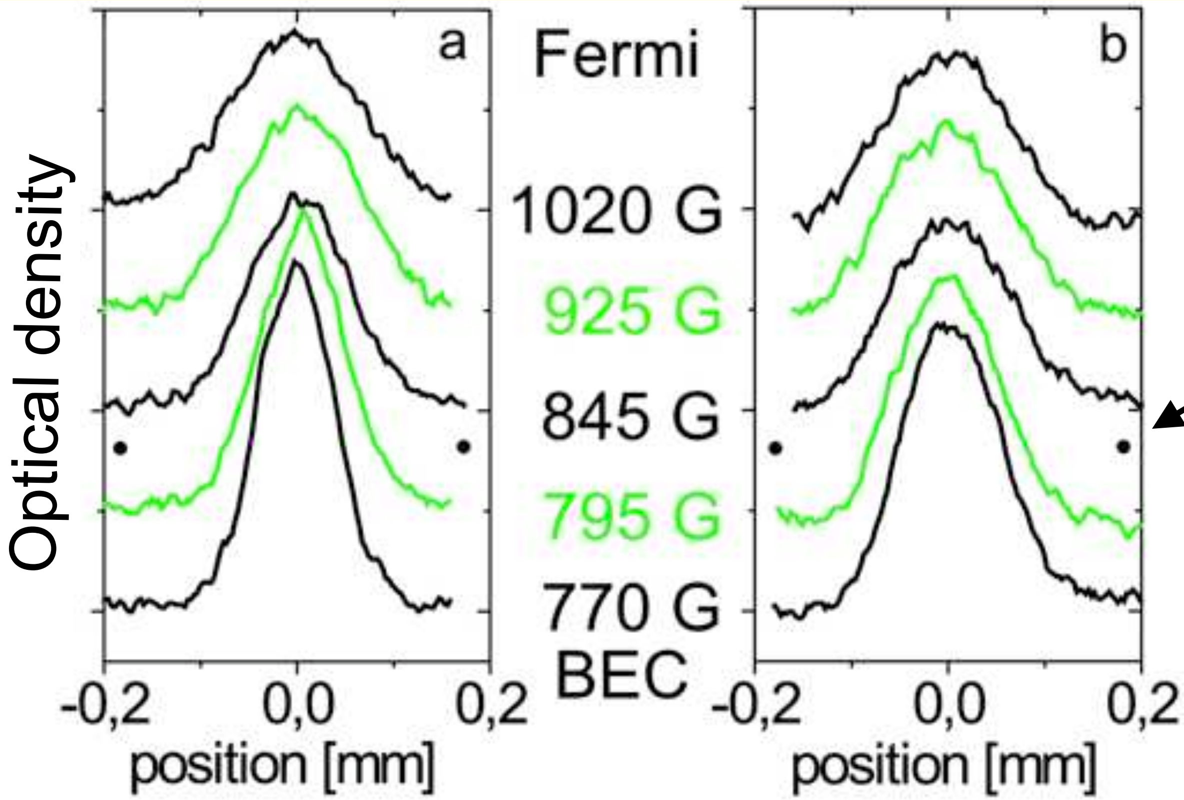
BEC-BCS Crossover: images after expansion

Condensate @770G: 4 10^4 mol., $N_0/N \geq 60\%$
Slow change of B: 1-2 G/ms
Images after time of flight

a < 0

a > 0

Aspect ratio: λ =0.3



a < 0

a > 0

Feshbach resonance peak 834 G

Axial: X

Radial:Y

BEC-BCS Crossover: images after expansion

Condensate @770G: 4 10^4 mol., $N_0/N \geq 60\%$
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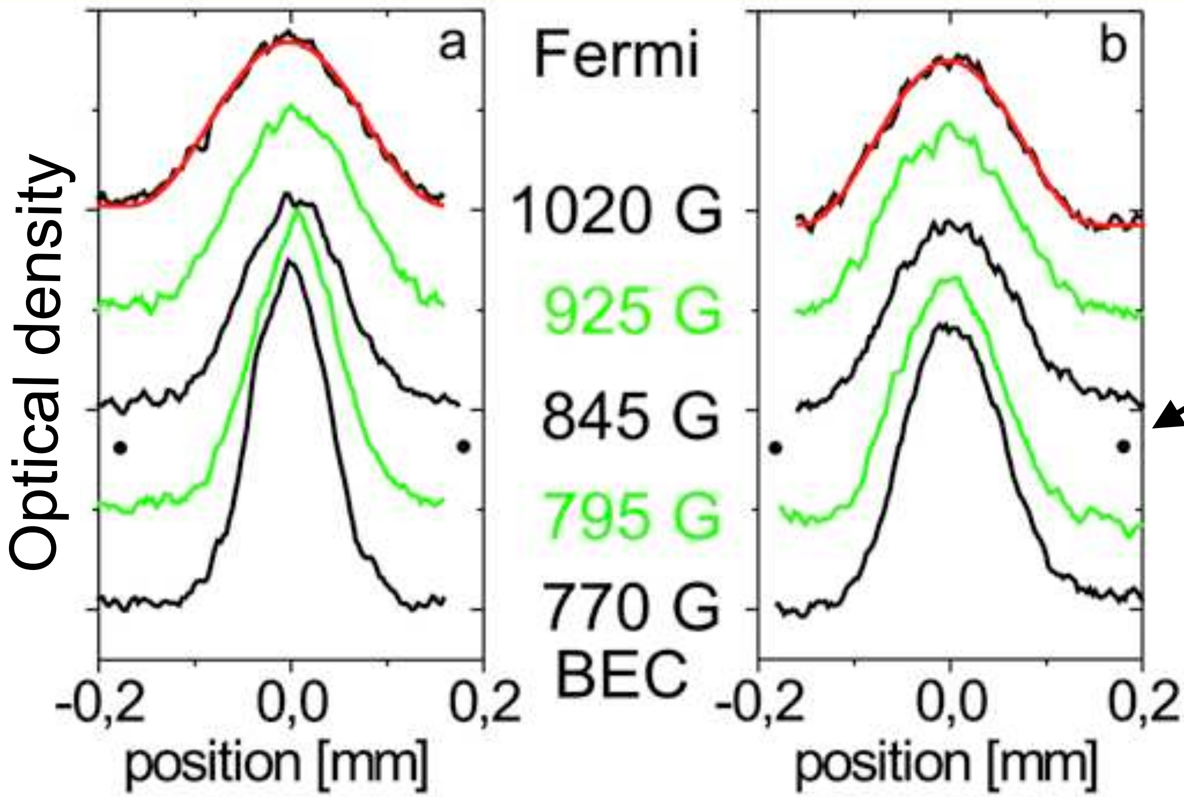


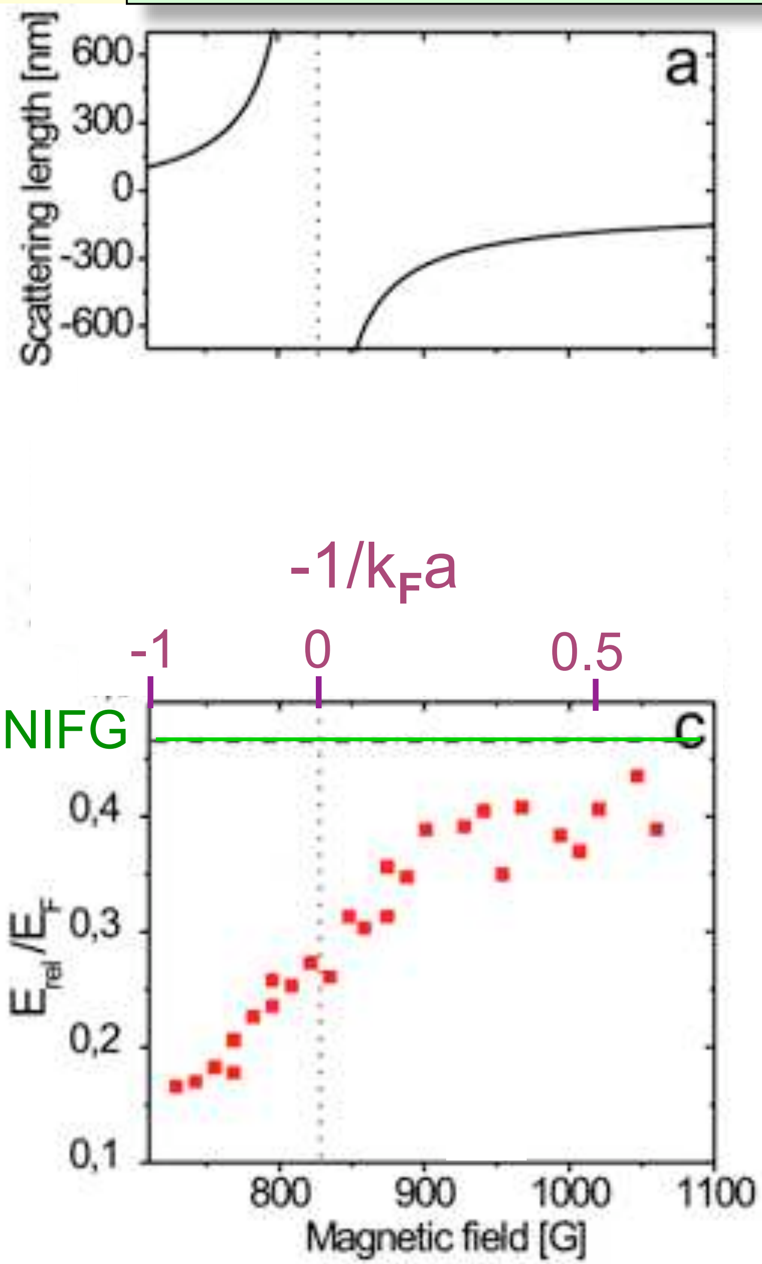
a < 0

Feshbach resonance peak 834 G

a > 0

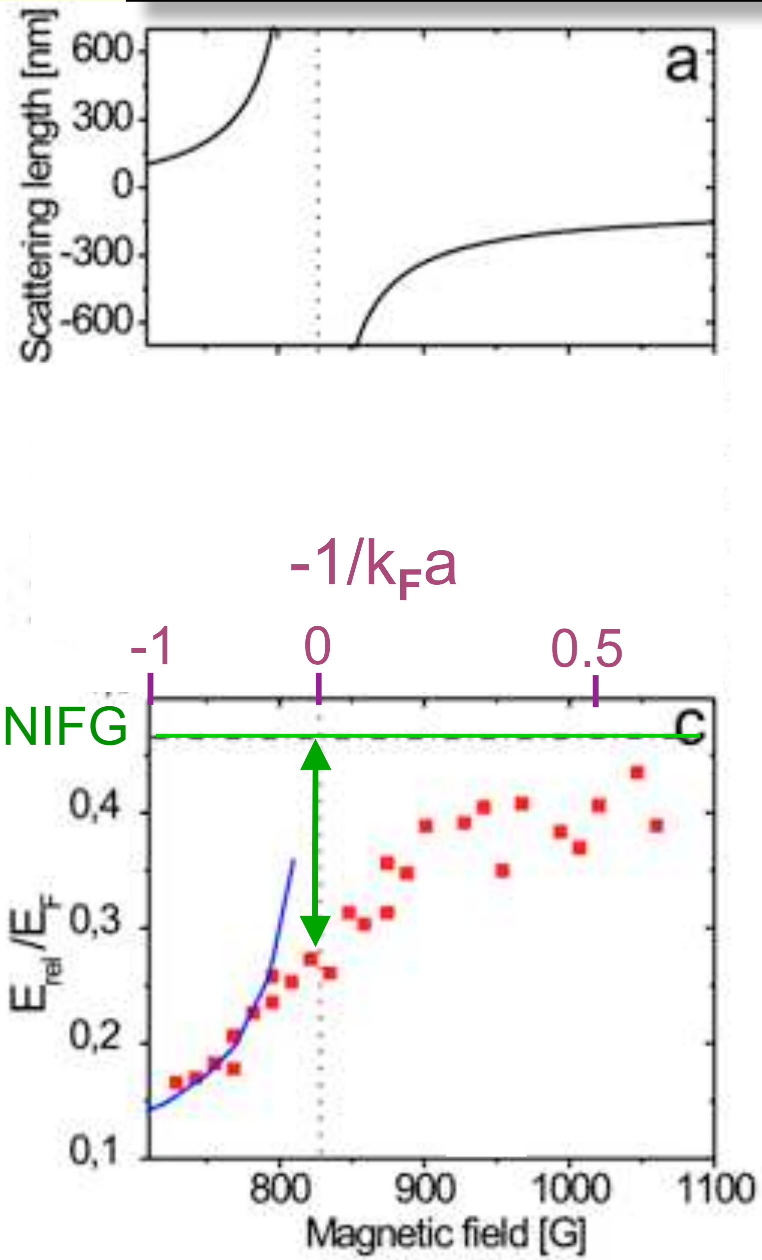
Axial: X **Radial:Y**

BEC-BCS Crossover: release energy



From Gaussian fits:

BEC-BCS Crossover: release energy



From Gaussian fits:

at resonance: unitarity limit

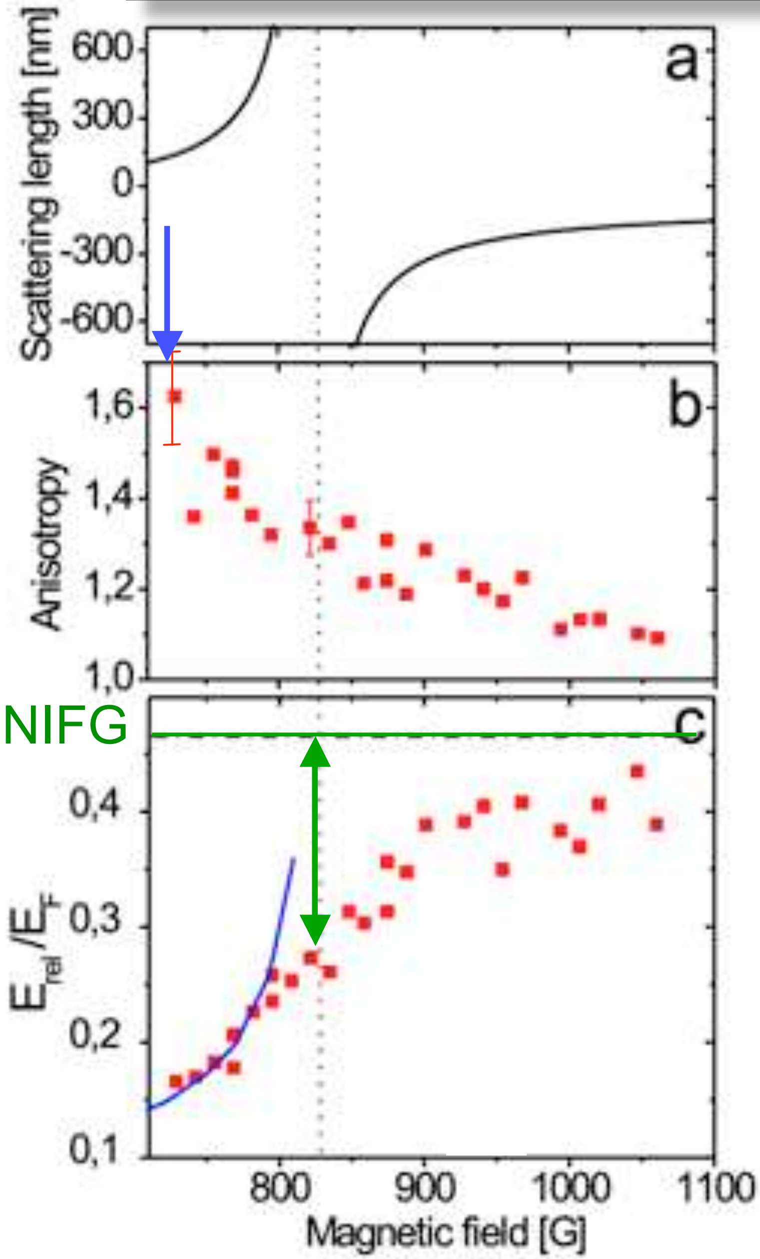
$$\mu=(1+\beta)E_F$$

We find:

In agreement with quantum Monte-Carlo calculations (Carlson 02, Giorgini 04): -0.56(1)

and with R.Gimm's experiment in Innsbruck.

BEC-BCS Crossover: Anisotropy



Superfluid or highly collisionnal

→ hydrodynamic expansion

$\eta = 1.7$

At 730 G, on the BEC side, $n_m a_m^3 << 1$

Measured anisotropy:

$\eta = \sigma_Y / \sigma_X = 1.6\ (1)$

Going toward a<0, the gas losses its hydrodynamic behavior

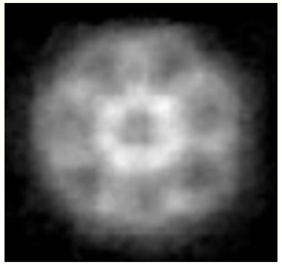
Decrease of the superfluid fraction

Another explaination: rapide loss of the superfluid character in the expansion

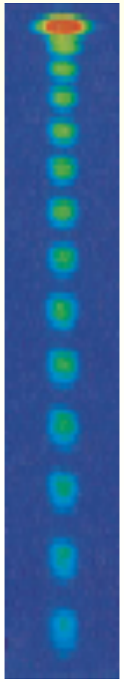
Perspectives: BEC-BCS Crossover

- Numerous experimental studies
  - Expansion measurement (ENS)
  - Collective modes (Duke, Innsbruck)
  - Pair binding energy (Innsbruck, JILA)
  - Condensation of fermionic pairs (JILA, MIT)
  - Theory (Holland, Kokkelmans, Levin, Ohashi, Griffin, Strinati, Stoof, Bruun, Pethick, Combescot, Stringari, Shlyapnikov, Giorgini, …)

- Direct proof of superfluidity (vortex)



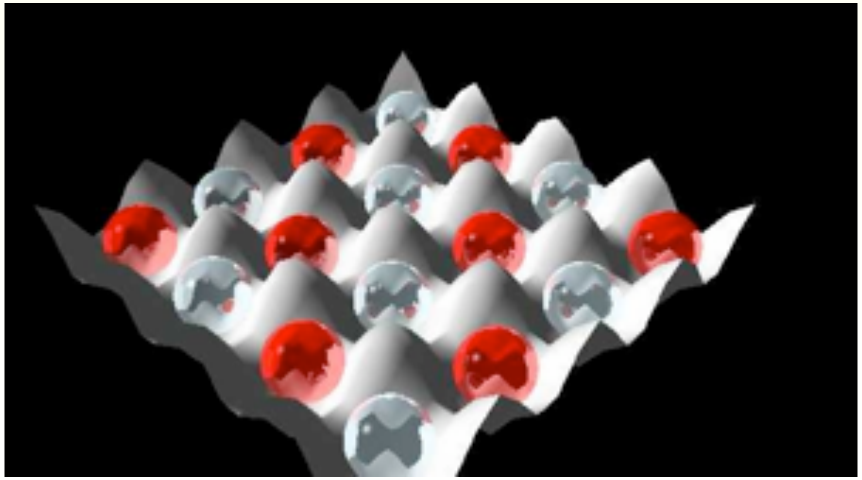
- Long range order, interference experiment



Perspectives

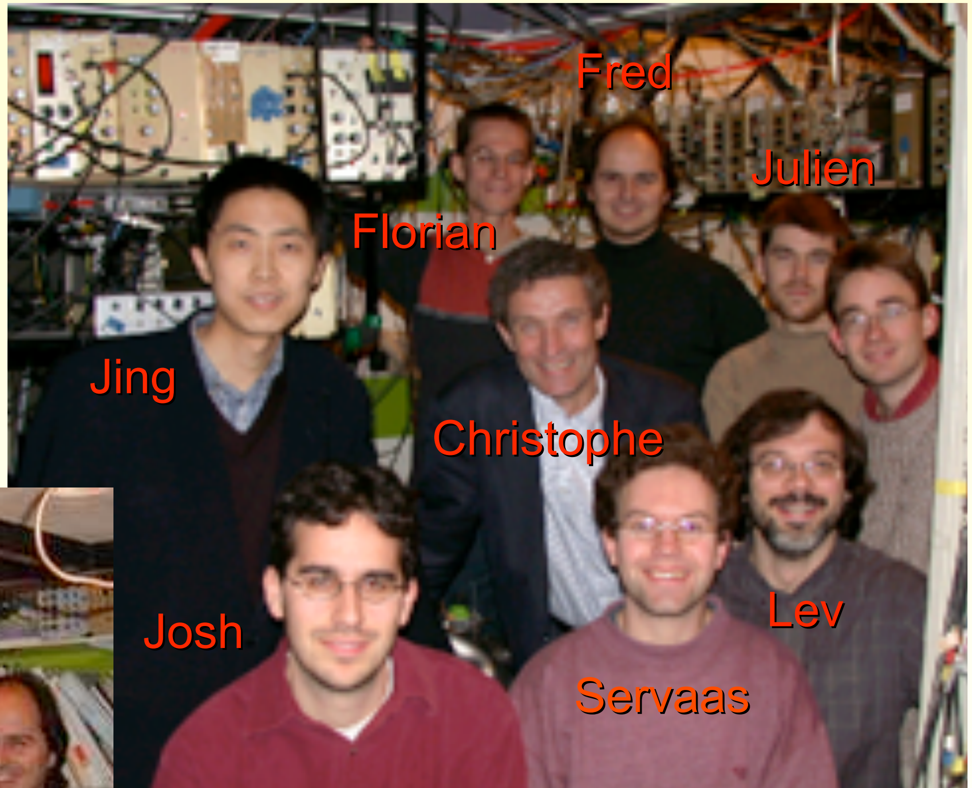
- *p*-wave pairing (^{3}He)
- Heteronuclear molecules
  - Fermionic molecules
  - Polar molecules (long range interaction)

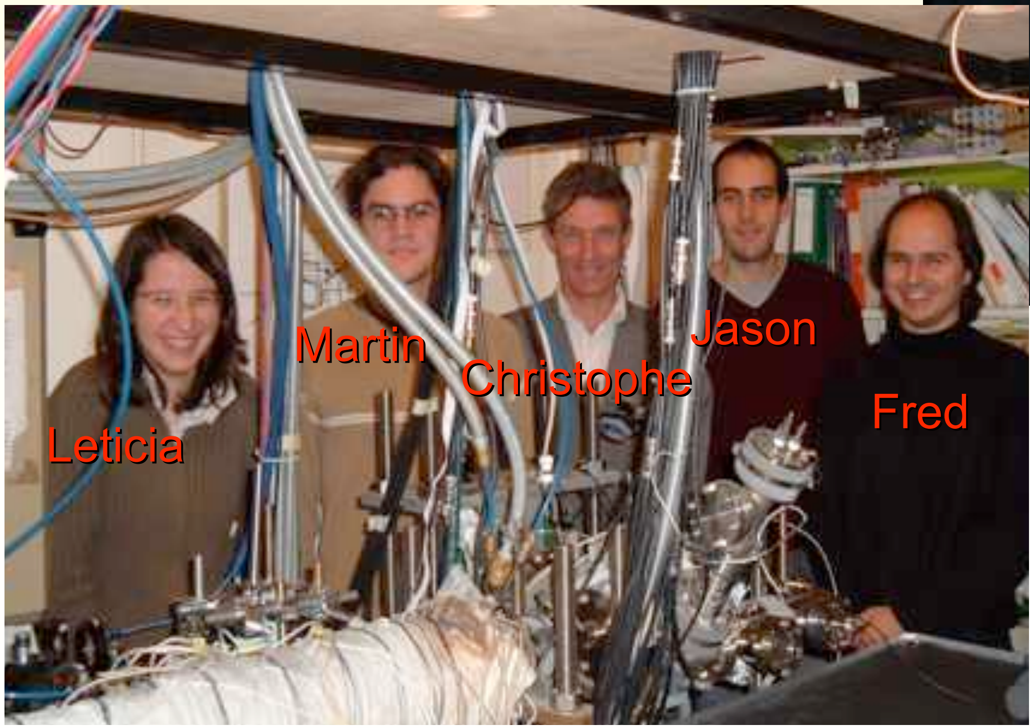
- Simulation of hamiltonians from condensed matter (Fermions in an optical lattice)



Thanks

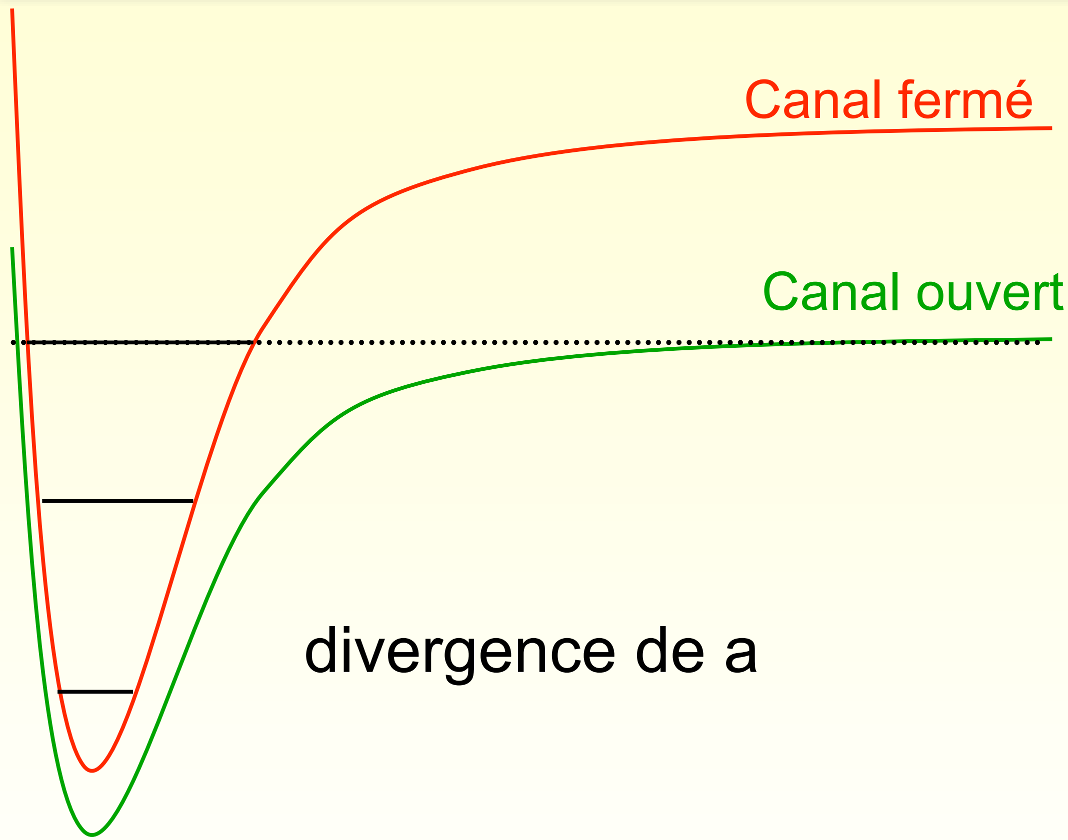
Merci





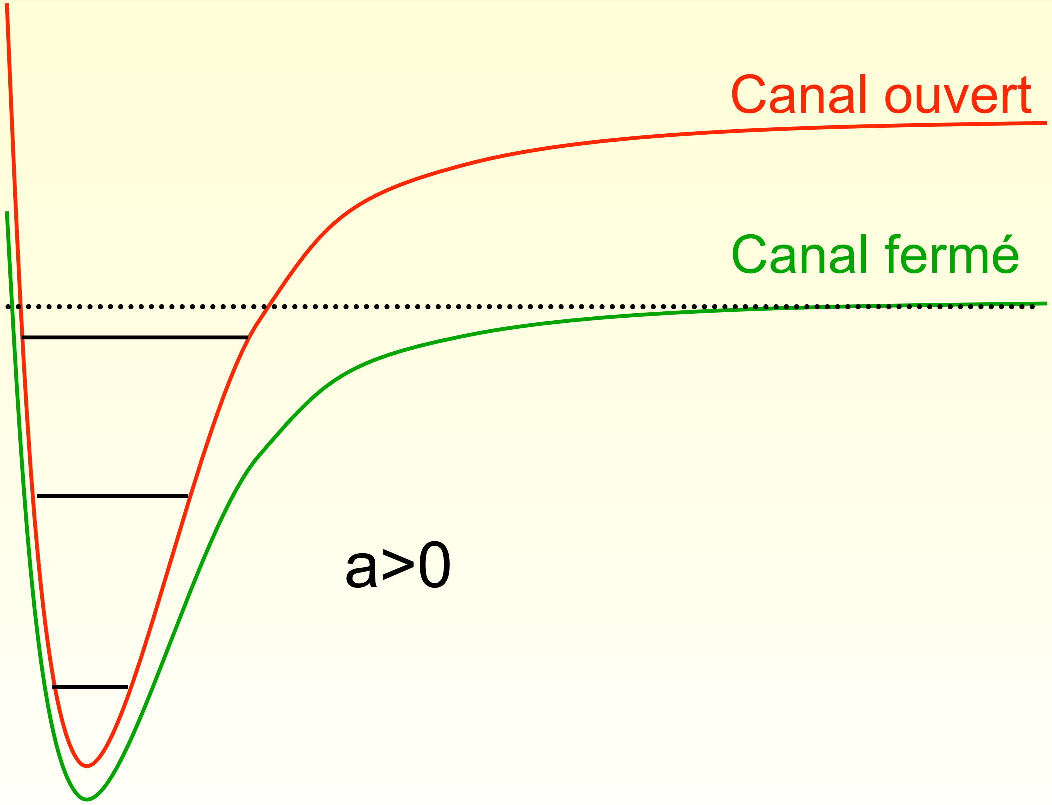
à tous

Feshbach resonance

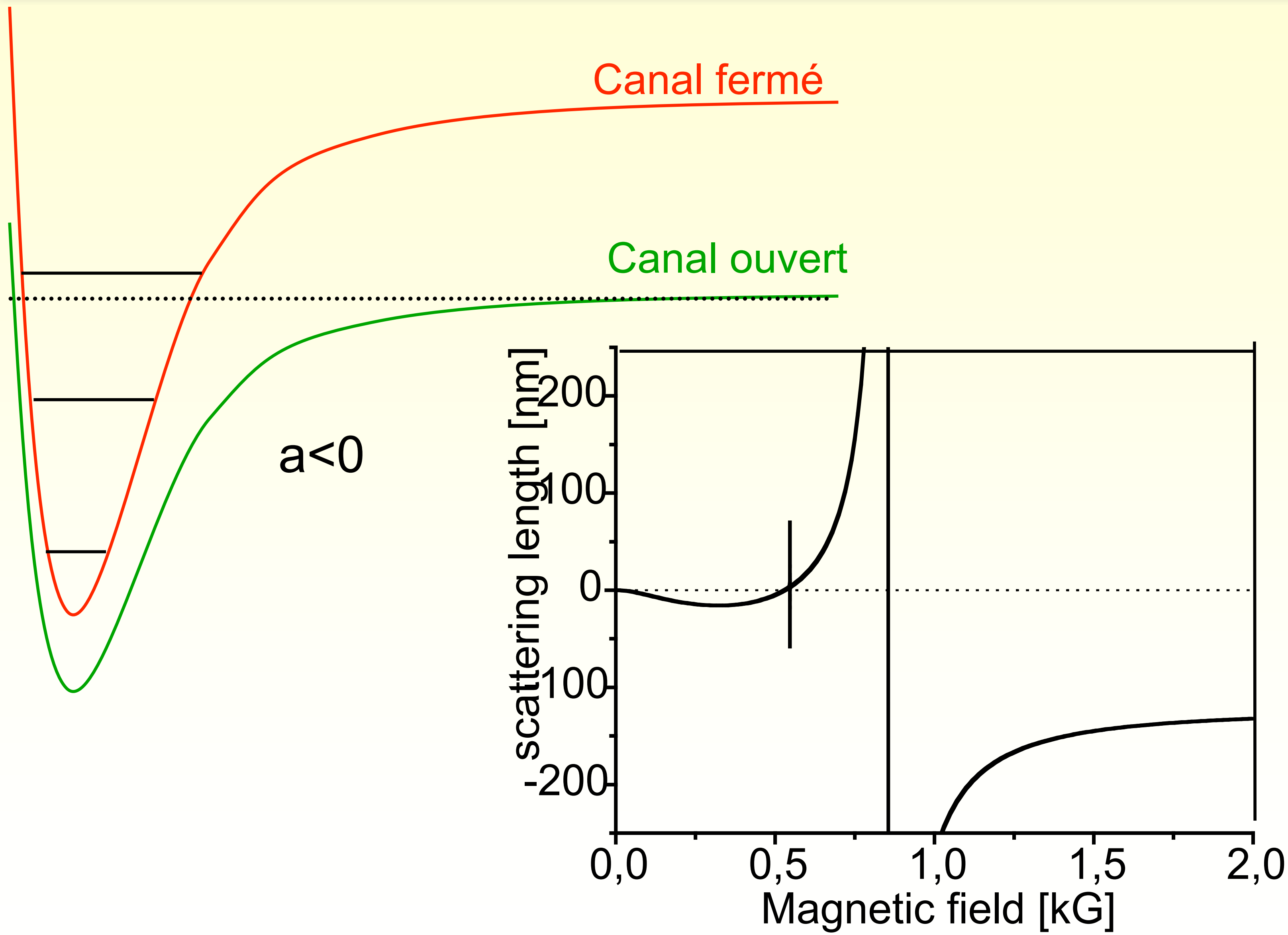


divergence de a

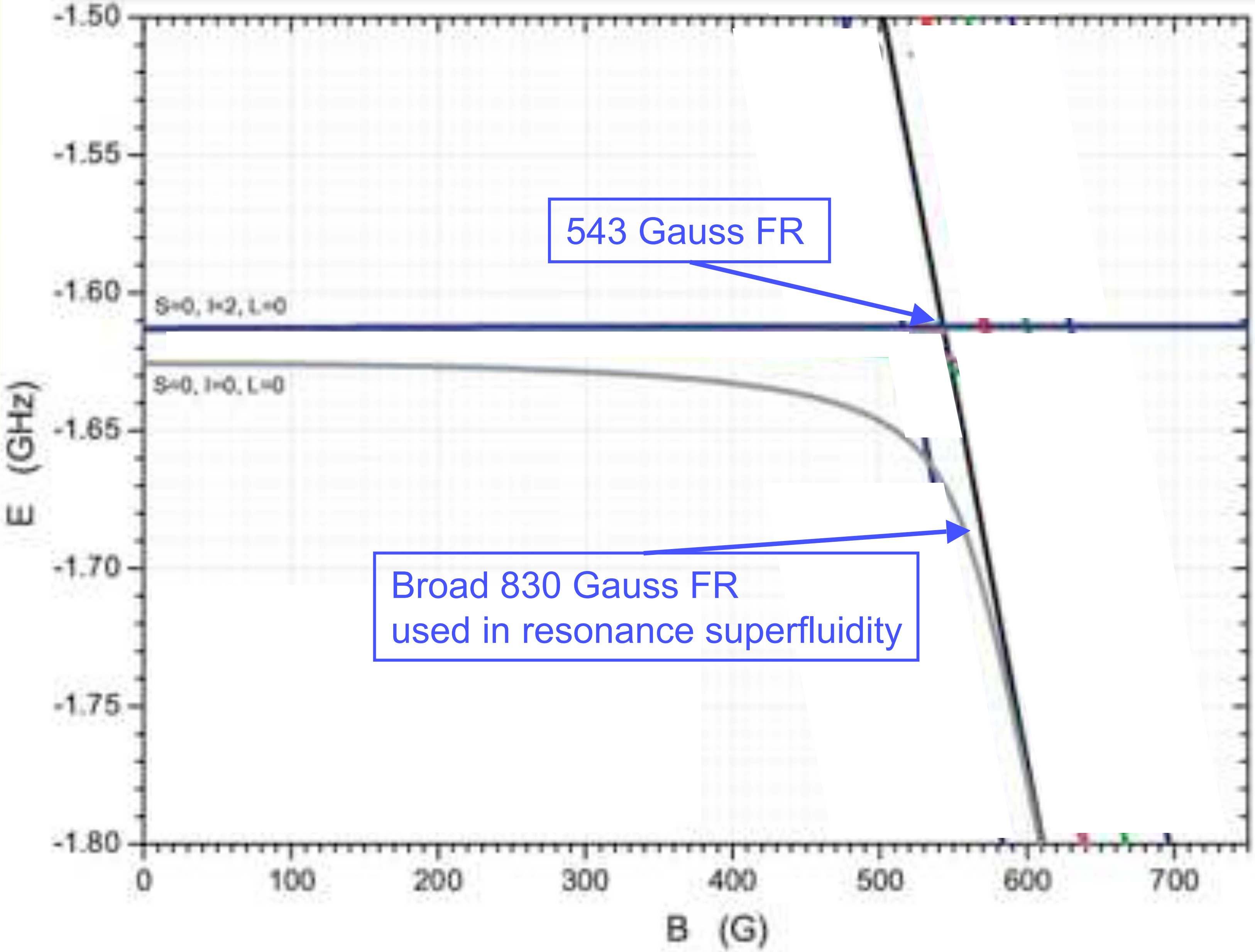
Feshbach resonance



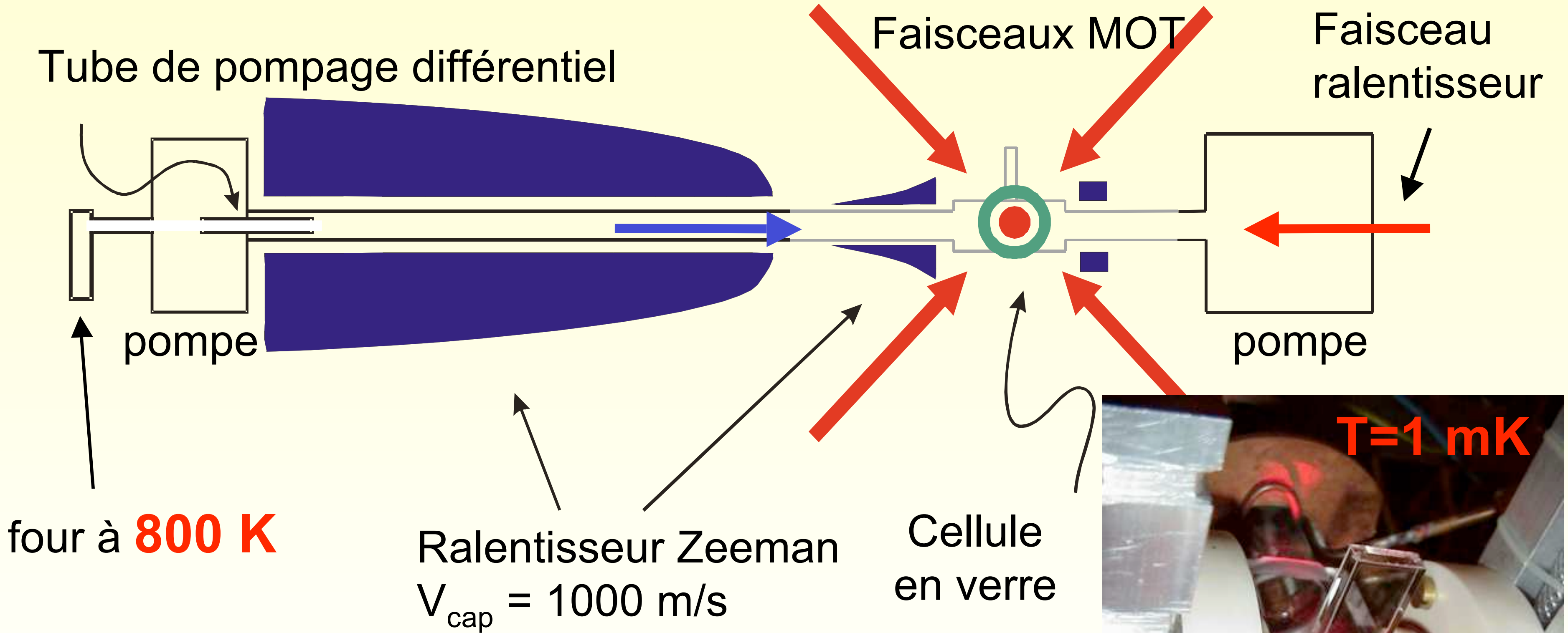
Feshbach resonance

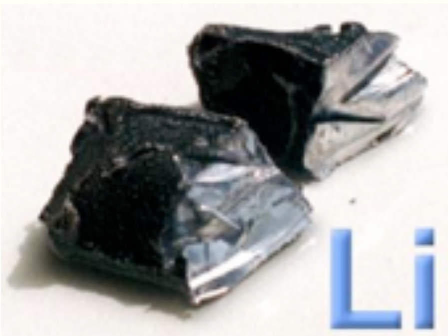


Molecular states



Dispositif expérimental



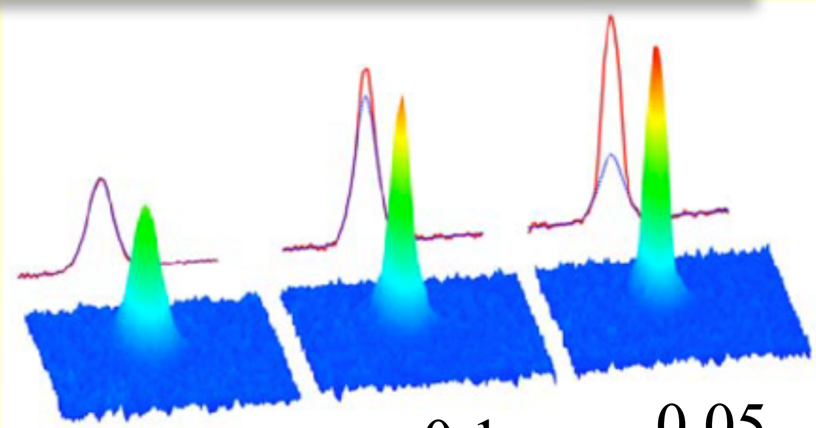


MOT

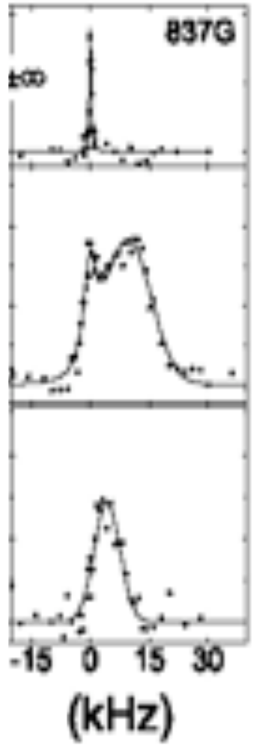
T=1 mK

Transition BEC-BCS: Autres Résultats

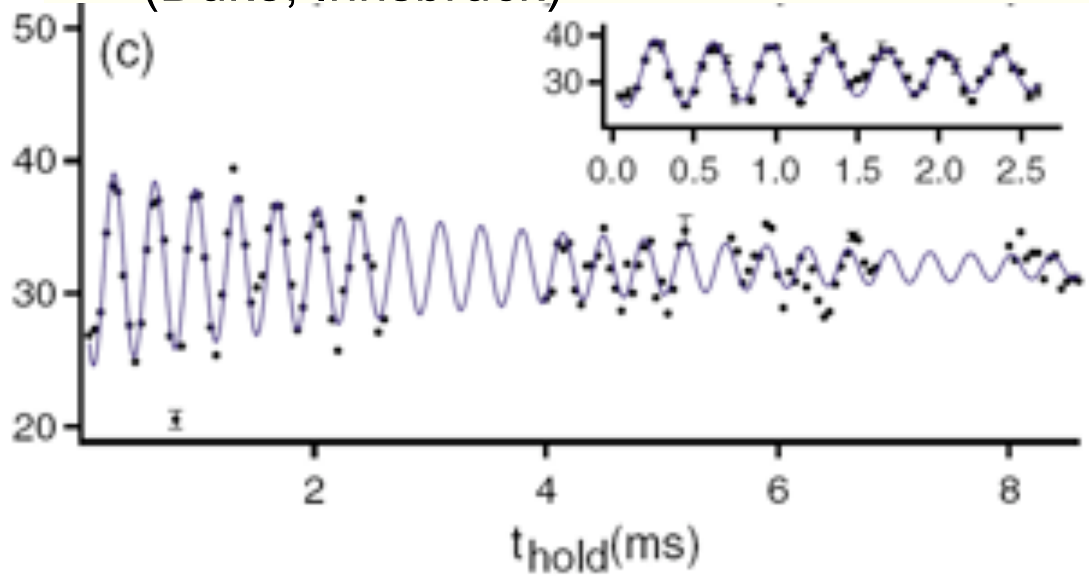
Condensation des paires de Fermions:
(JILA, MIT)



Mesure de l'énergie des paires (Innsbruck, JILA)

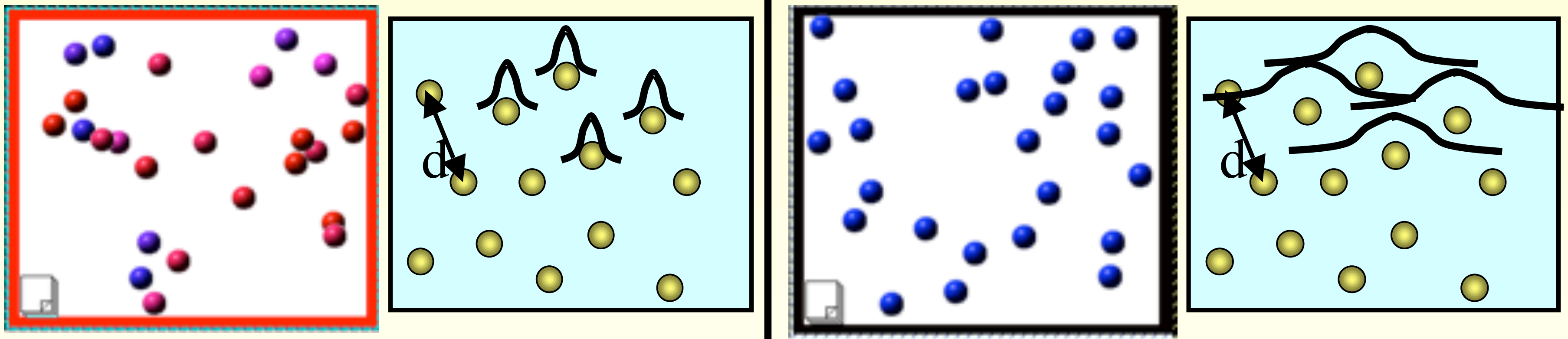


Étude des modes d'oscillation:
(Duke, Innsbruck)



Quantum gases

cooling



300 K ⇔ 1000 m/s

1 μK ⇔ 5 cm/s

atom → wave-function of size $\lambda_{dB} = h/(2\pi m k_B T)^{1/2}$

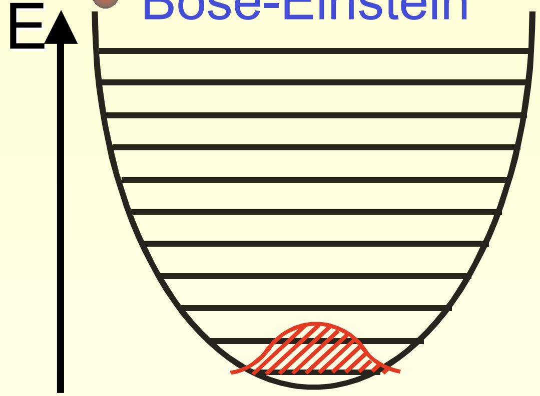
Quantum regime in a **dilute** gas: $n \sim 10^{13}$ cm^{-3}

«Very clean» **quantum many-body** System

Difference between **bosons** et **fermions**

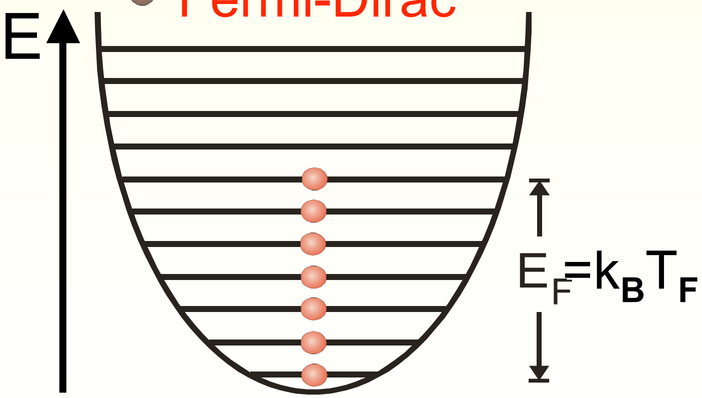
Quantum statistics

- Bose-Einstein

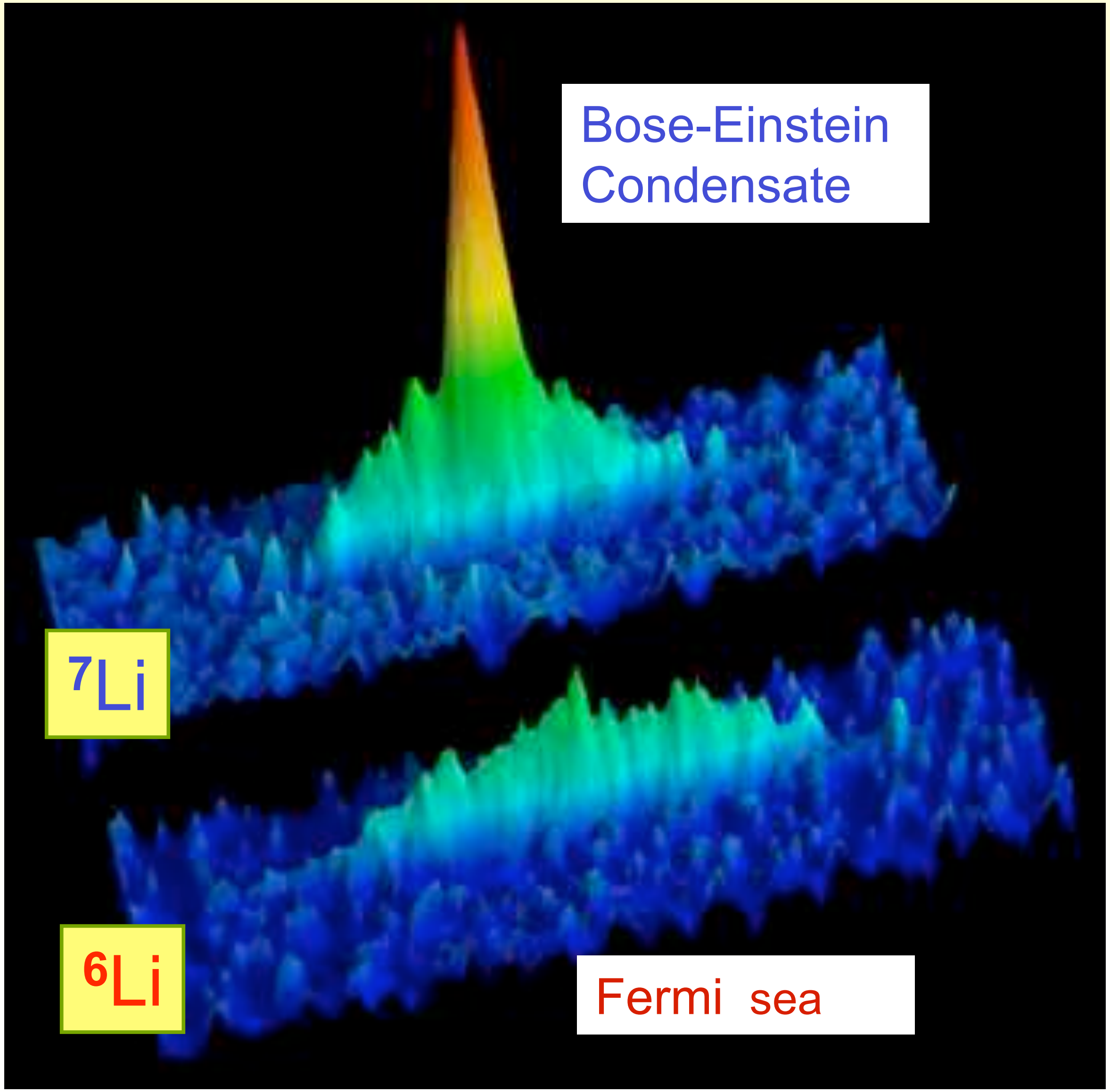


$$T_C = \frac{\hbar\omega}{k_B}(0.83\,N)^{1/3}$$

- Fermi-Dirac

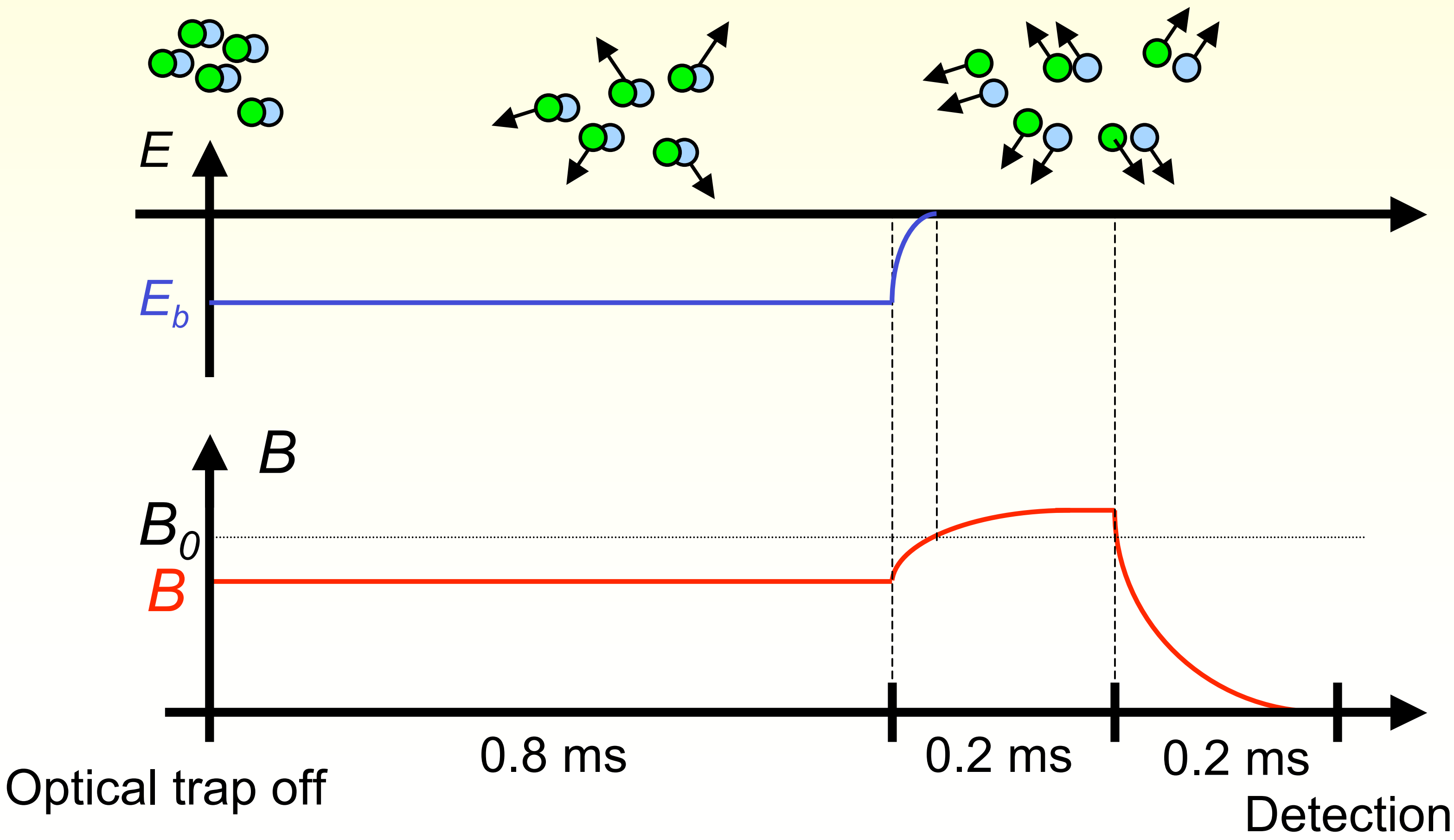


$$T \ll T_F = \frac{\hbar\omega}{k_B}(6N)^{1/3}$$



Molecules velocity distribution

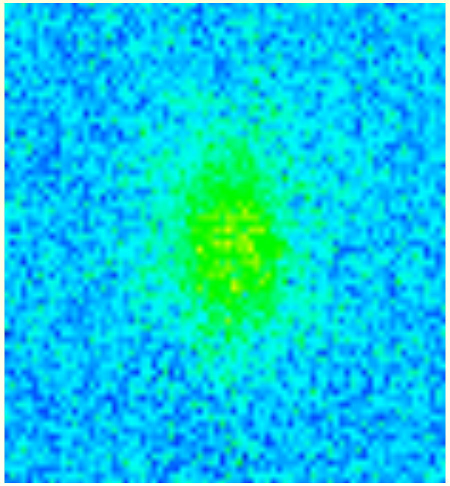
- Optical trap off: expansion of the molecular gas
- At the end of the time of flight: dissociation of pairs



Pure Condensates: measurement of a_{mm}

By lowering the trap power, we optain a pure condensate

Thomas-Fermi fit, no thermal cloud



TOF=1.2 ms

Hydrodynamic expansion
Ellipticity:
-mesured: 2.0 (1)
-theory: 1.98

Scattering length measurement

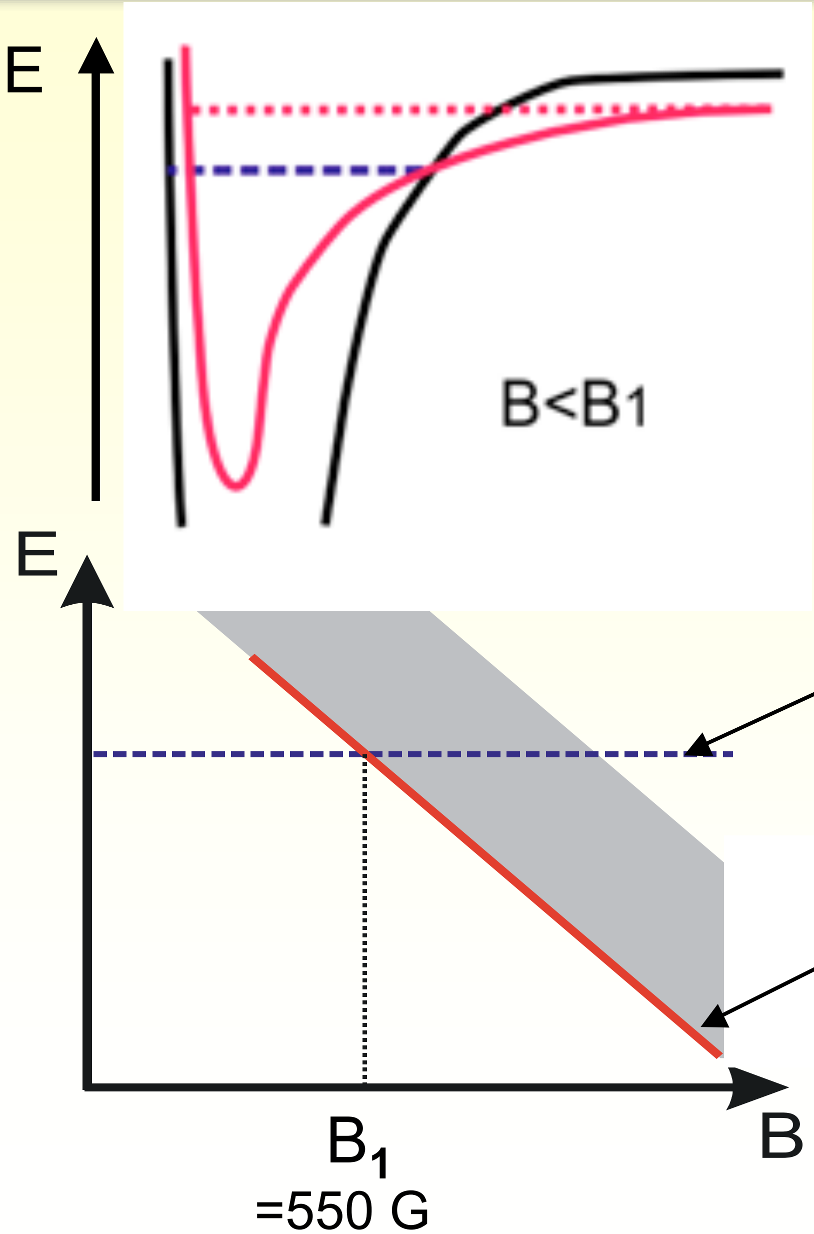
$T<T_c/3$
$\lambda=0.1$
$N=4\times10^4$ atoms

à 770 G:

In agreement with $a_{mm}=0.6\ a$

(Petrov, Salomon, Shlyapnikov, PRL, 2004)

Interaction control: Feshbach Resonance



Closed channel: singlet potential

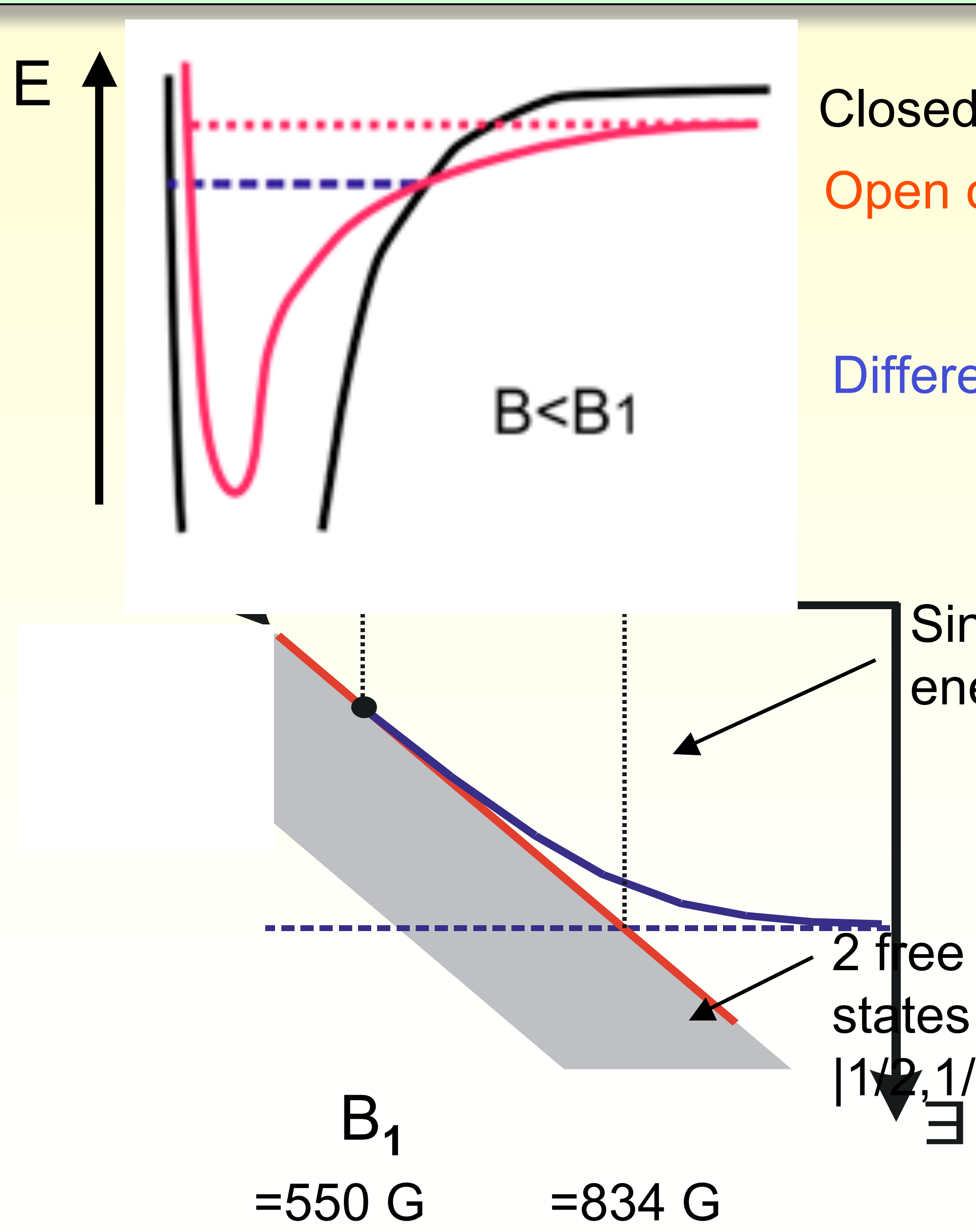
Open channel: triplet potential

Different magnetic moments

Singlet bound state energy

2 free atoms in states :
|1/2,1/2>+|1/2,-1/2>

Feshbach resonance



Closed channel: singlet potential

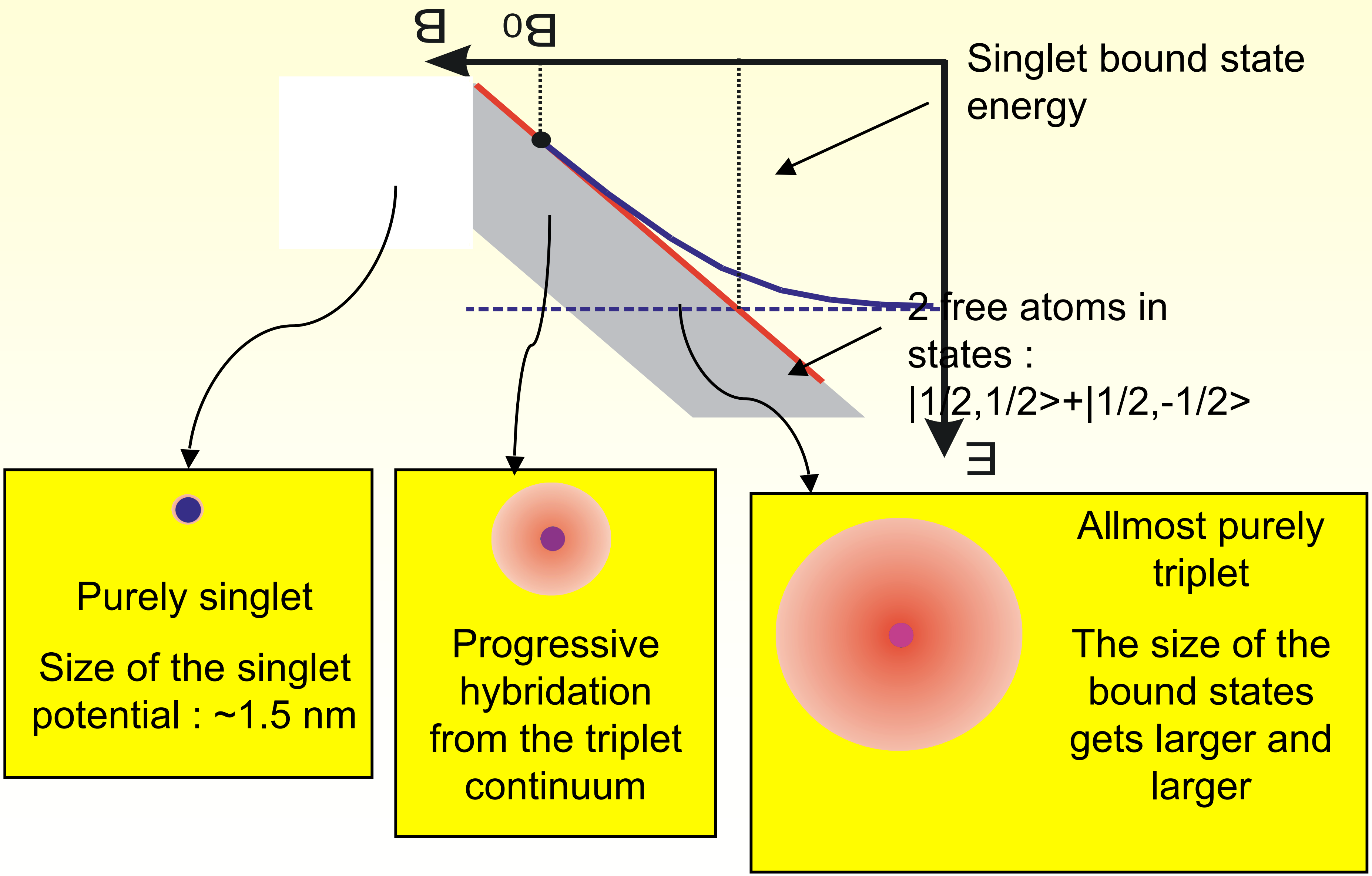
Open channel: triplet potential

Different magnetic moments

Singlet bound state energy

2 free atoms in states : |1/2,1/2>+|1/2,-1/2>

2 body bound state



Fermonic Superfluid

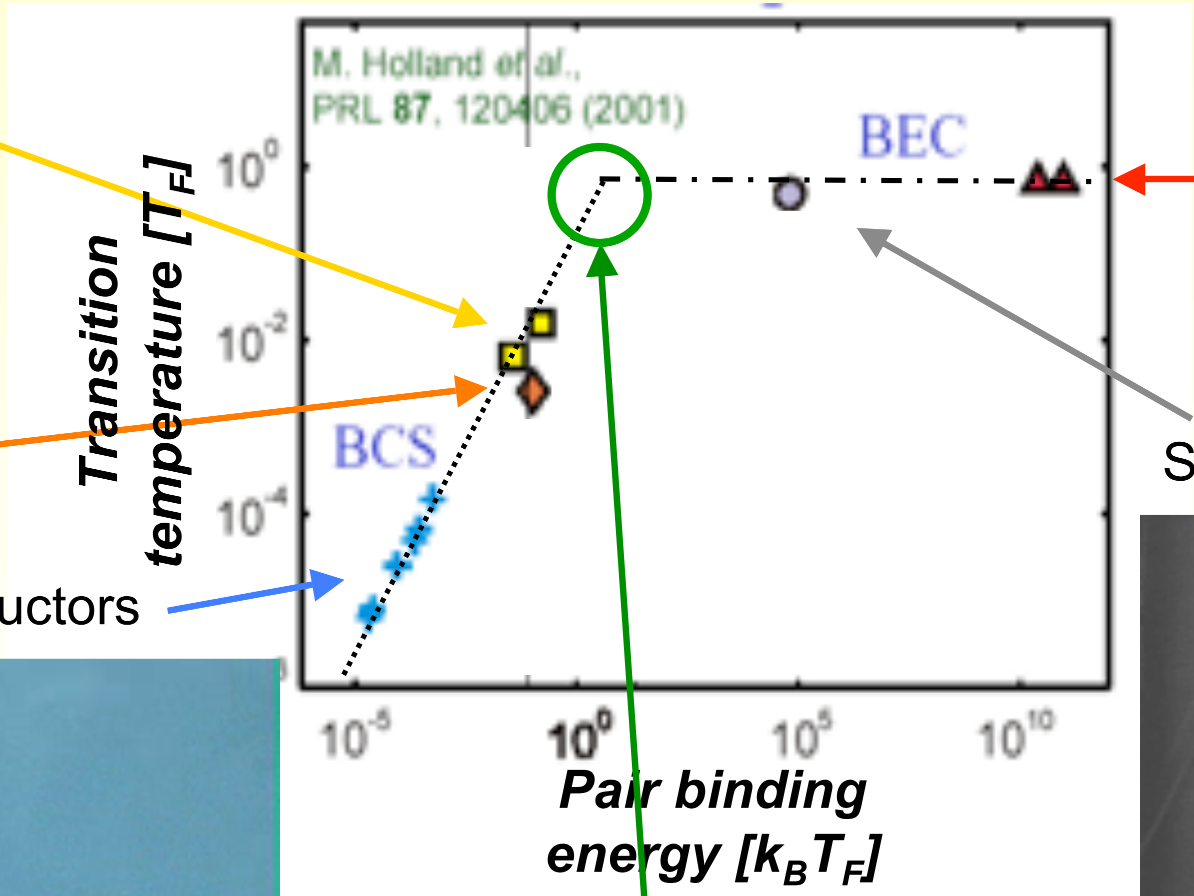
Two types of superfluidity

BCS

HTc Super.

superfluid ^{3}He

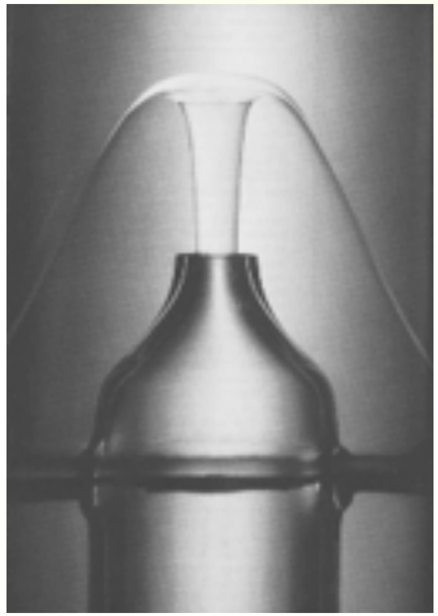
Superconductors



BEC

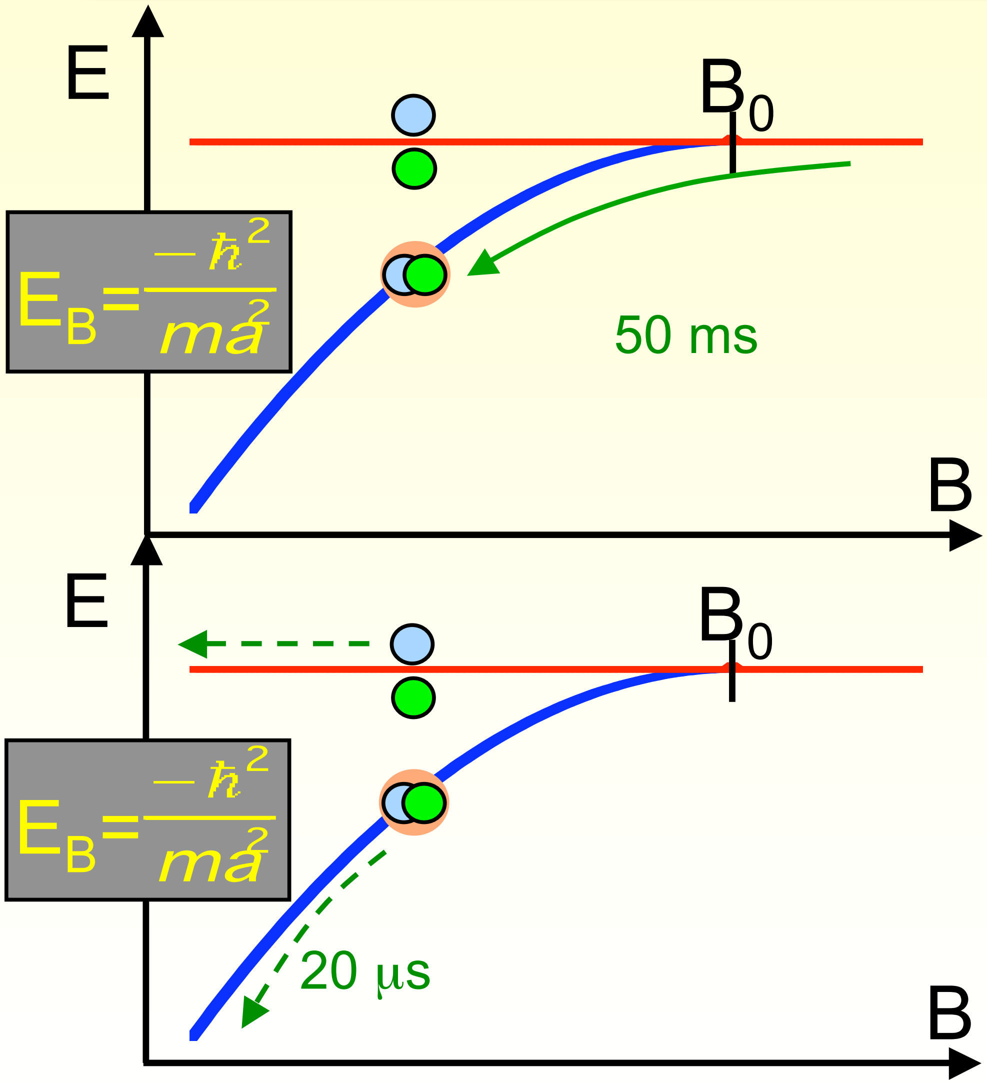
Alkali atom condensates

Superfluid ^{4}He



Fermions au voisinage d'une résonance de Feshbach

Formation and detection of molecules

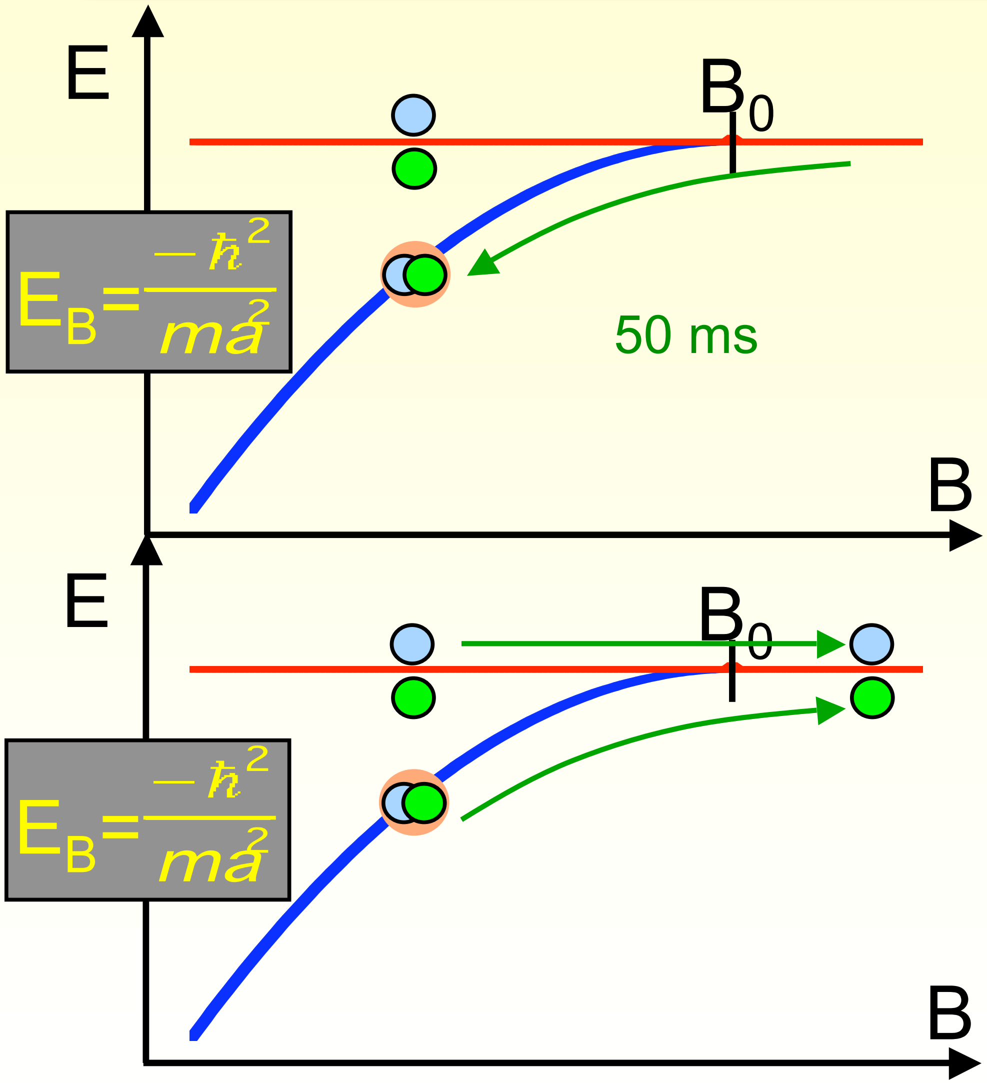


Formation of molecules is energetically favorable

Only free atoms are detected

Presence of **molecules** is detected by a **diminution of atomic signal**

Formation and detection of molecules



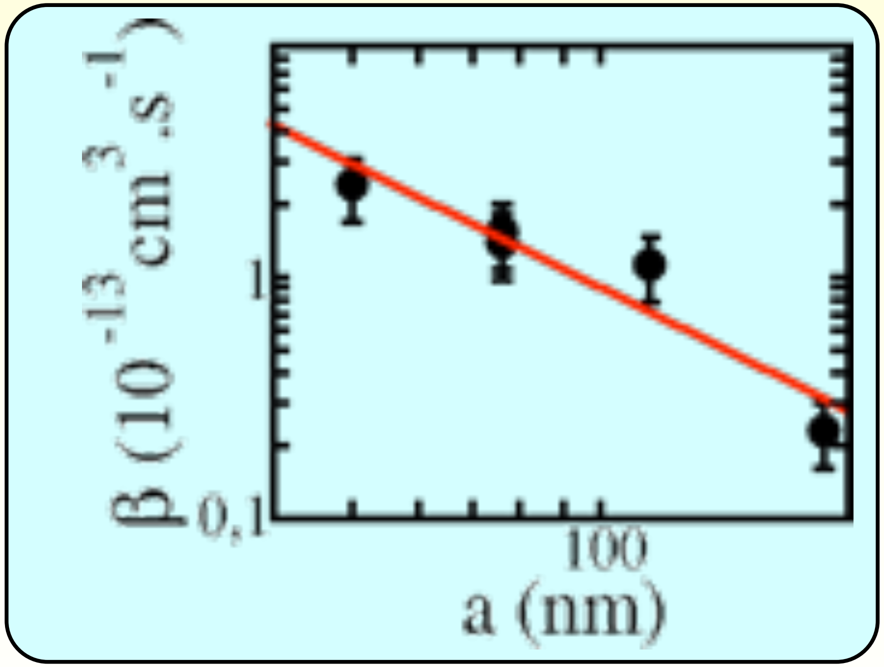
Only free atoms are detected

Presence of **molecules** is detected by a **diminution of atomic signal**

This is not due to losses

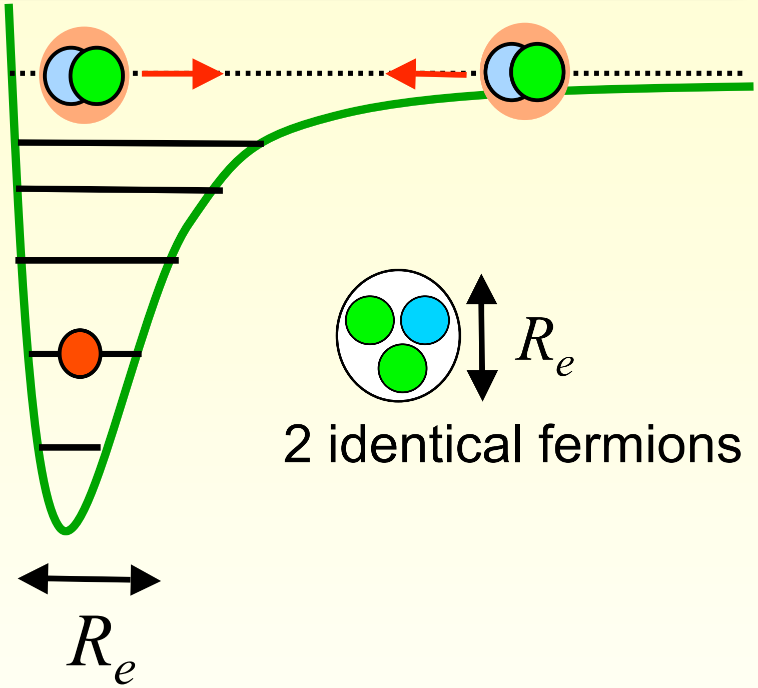
Molecular condensate lifetime

Relaxation toward deeply bound states



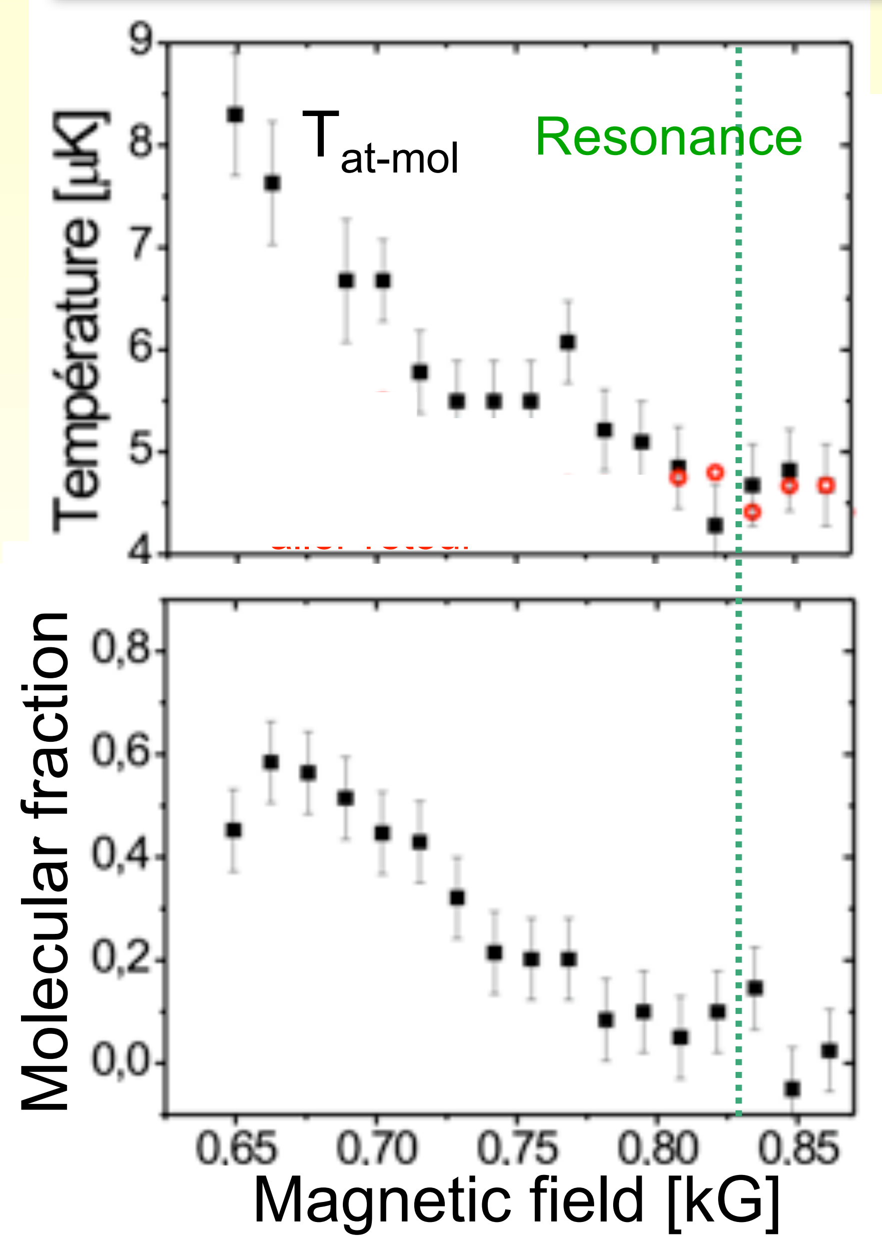
Experimentally

$\beta \sim a^{-1.9\pm0.8}$



Fermions: $\beta \sim a^{-2.55}$

Temperature of atom-molecule mixture

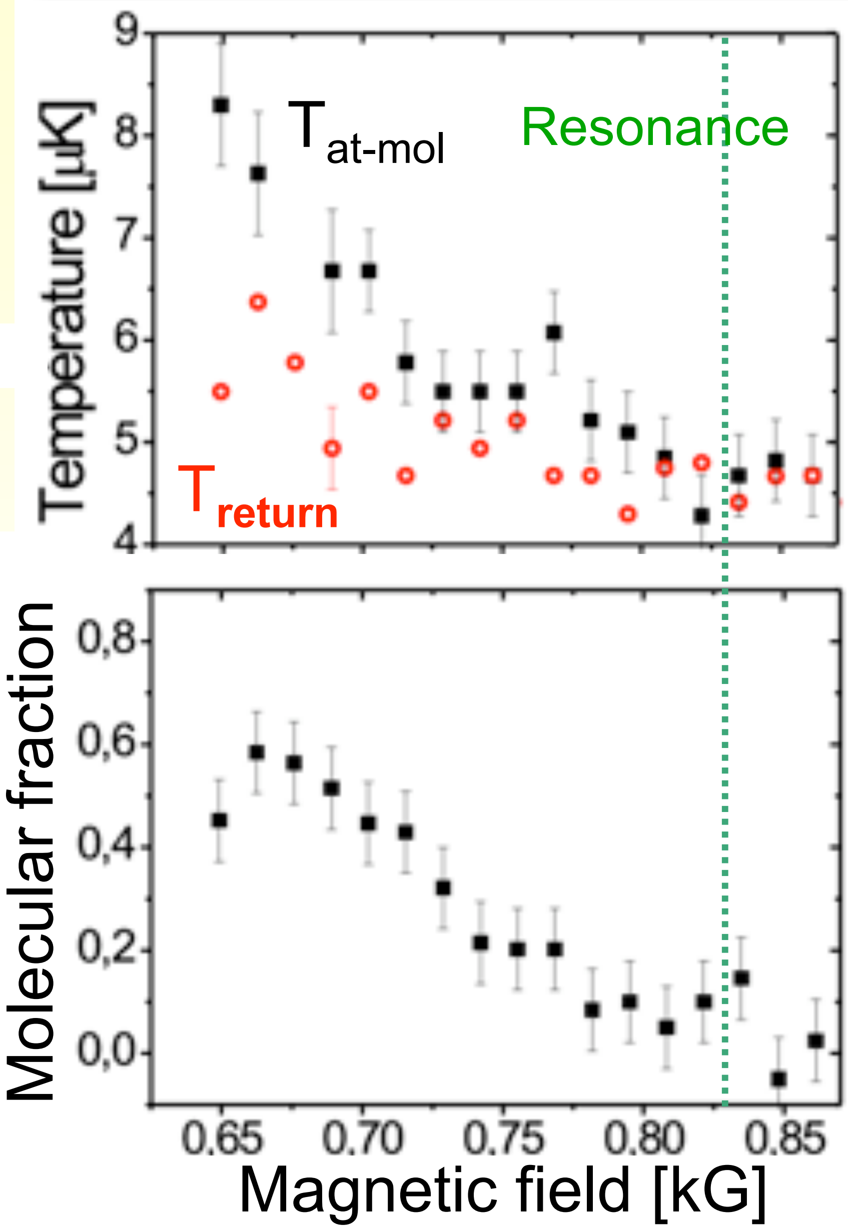


Atoms → Molecules : heating

3 body recombinaison:

$|E_B| \longrightarrow E_C$

Temperature of atom-molecule mixture



Atoms → Molecules : heating

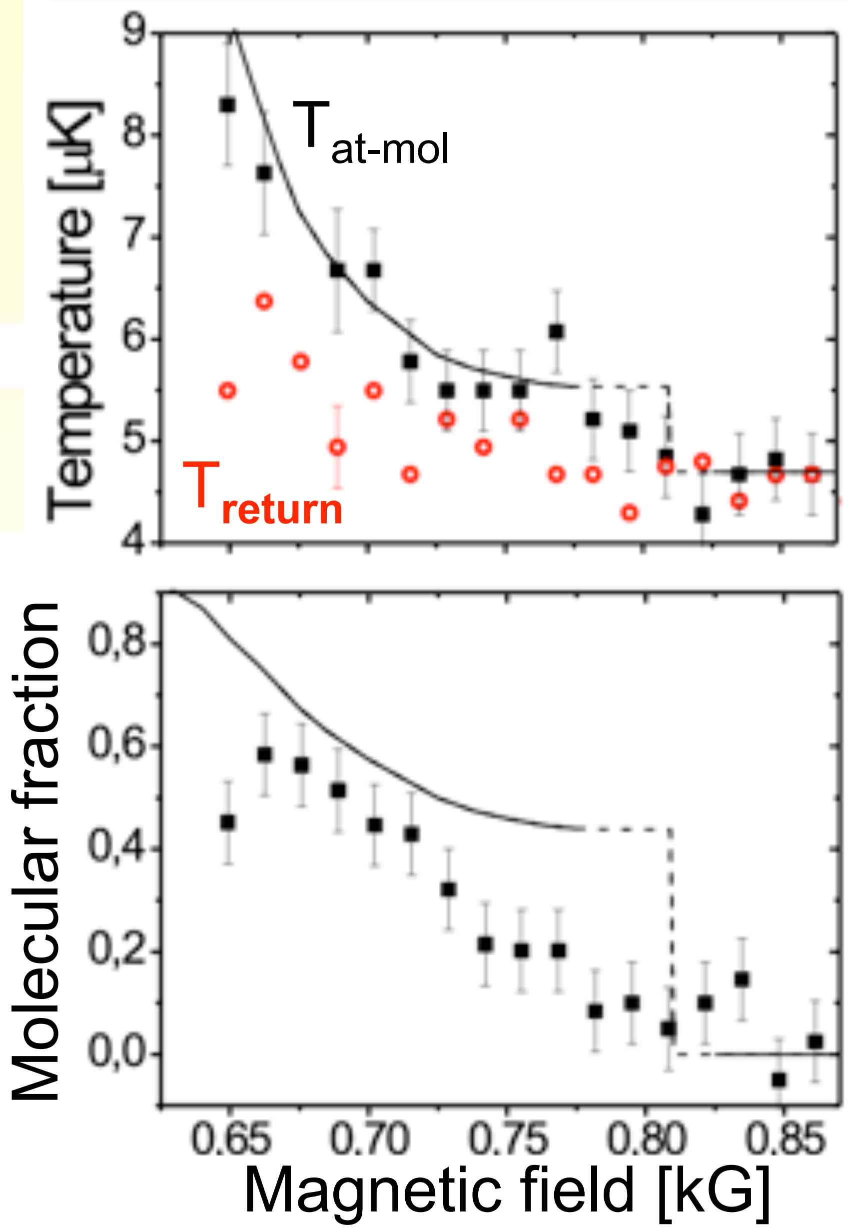
3 body recombinaison:

$|E_B| \longrightarrow E_C$

Molecules → atoms : Cooling

Process is **reversible**
Entropie conservation

Temperature of atom-molecule mixture



Atoms → Molecules : heating

3 body recombinaison:

$|E_B| \rightarrow E_C$

Molecules → atoms : Cooling

Process is **reversible**
Entropy conservation

Quasi-static thermodynamic equilibrium between atoms and molecules during the ramp