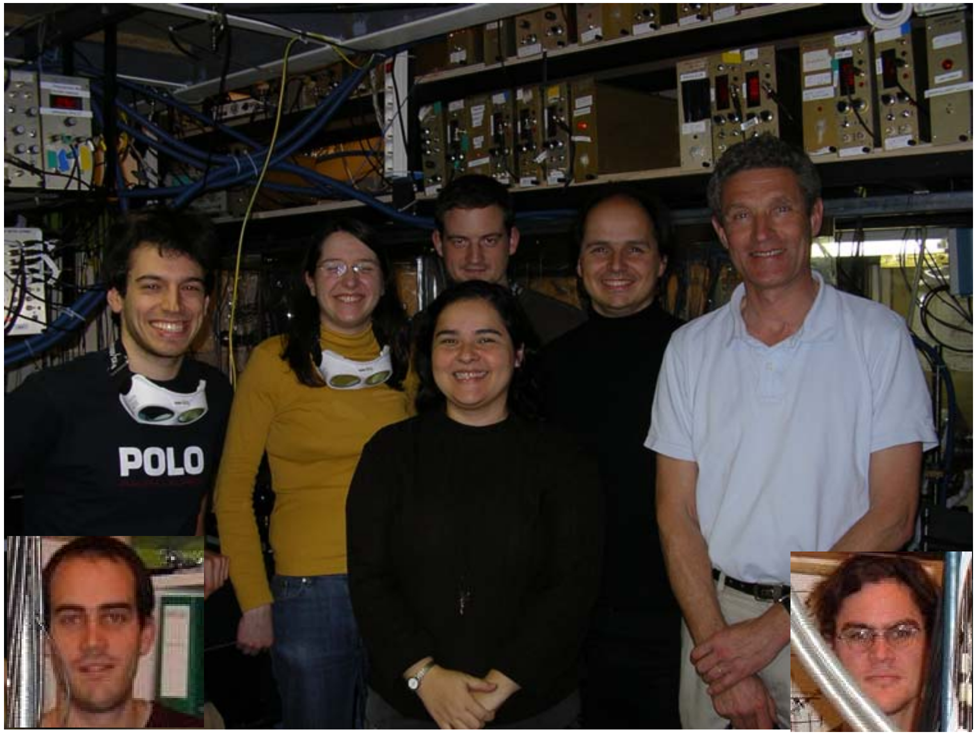
Ultracold Fermi gases
experiments in the BEC-BCS crossover



Collège de France

L. Tarruell, M. Teichmann, G. Duffy, S. Nascimbène, N. Navon, J. McKeever,
K. Magalhães, T. Bourdel, L. Khaykovich, J. Cubizolles, J. Zhang, F. Chevy, C. Salomon
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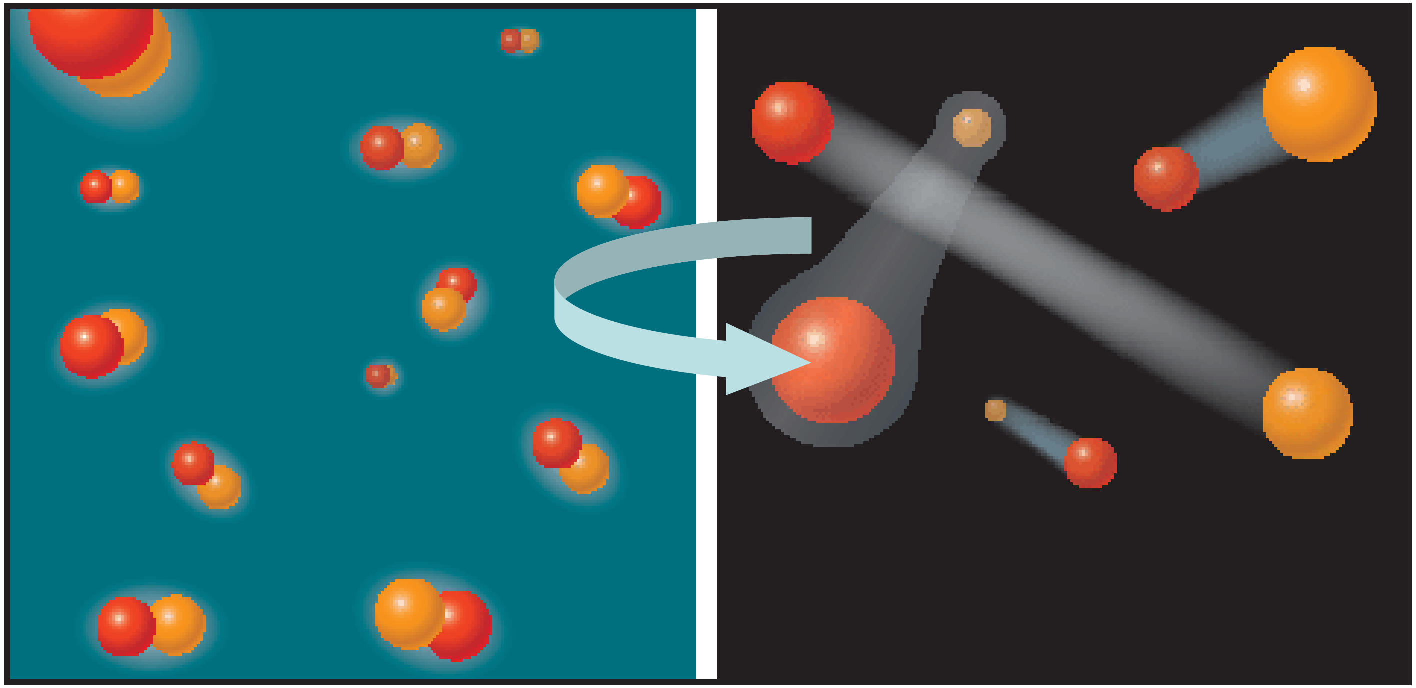
C. Lobo, A. Recati, I. Carusotto, S. Stringari, T. L Dao, A. Georges

Fermi superfluid and Bose-Einstein condensate of Molecules

Fermions with two spin states with attractive interaction



BEC of molecules ← BCS fermionic superfluid

Bound state

Interaction strength

No bound state

Leggett, Eagles, Nozières, Schmidt-Rink,… ‘80

Dilute gases: Feshbach resonance

Outline

General methods for ultracold Fermi gas manipulation

Tuning the interaction in the gas

Molecule formation and Bose-Einstein condensation of fermion dimers

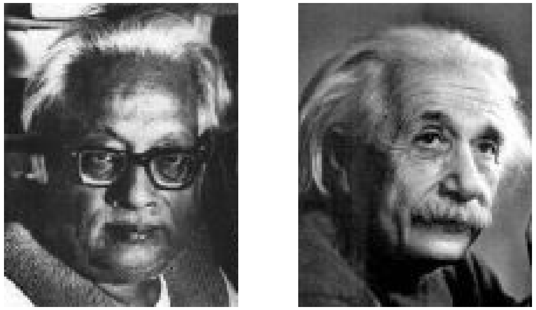
Crossover experiments and superfluidity

Superfluidity with spin population imbalance

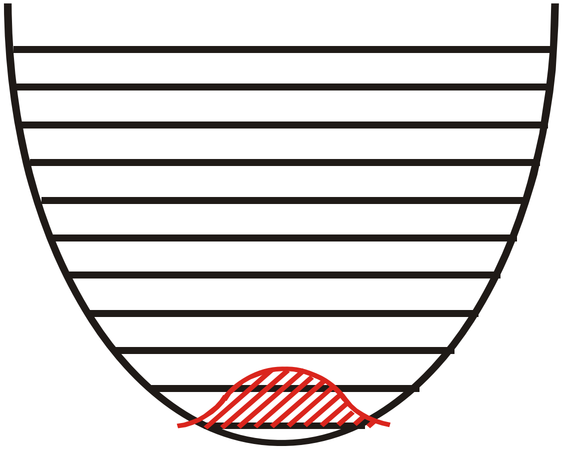
Prospects

Quantum statistics in harmonic traps

- Bose-Einstein statistics (1924)



Bose-Einstein condensate

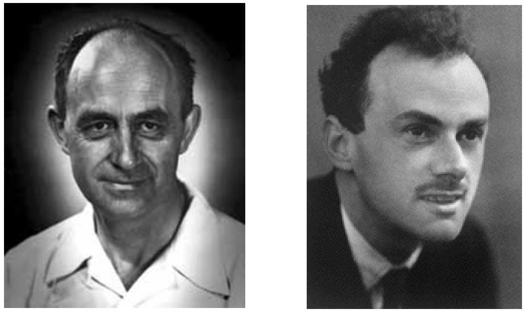


Bose enhancement

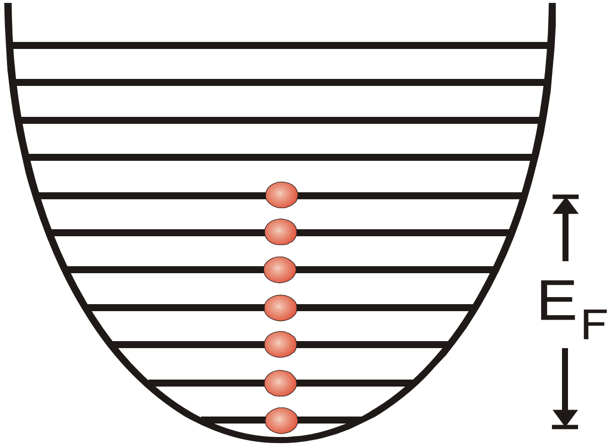
$$T_C = \frac{\hbar\omega}{k_B}(0.83\,N)^{1/3}$$

Dilute gases: 1995, JILA, MIT

- Fermi-Dirac statistics (1926)



Fermi sea

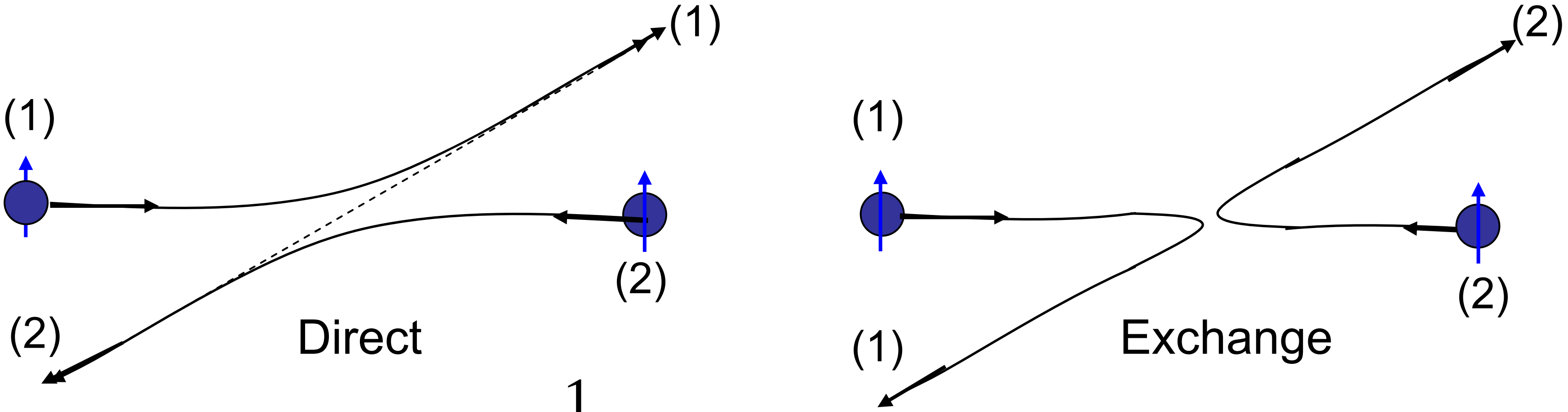


Pauli Exclusion

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

Dilute gases: 1999, JILA

Collisions between identical particles and quantum statistics



$$|\psi_f > = \frac{1}{\sqrt{2}}(1+\varepsilon P_{21})\,|1:k\,e_z, 2:-k\,e_z >$$

Scattering amplitude interfere with + sign for bosons and – for fermions

At low temperature, s-wave only

Bosons

$$\sigma = 8\pi a^2$$

Fermions $\sigma = 0$

Good for clocks: no interaction shift

But evaporation is more difficult

Sympathetic cooling

Cooling Methods

Solution 1: sympathetic cooling (with bosons)

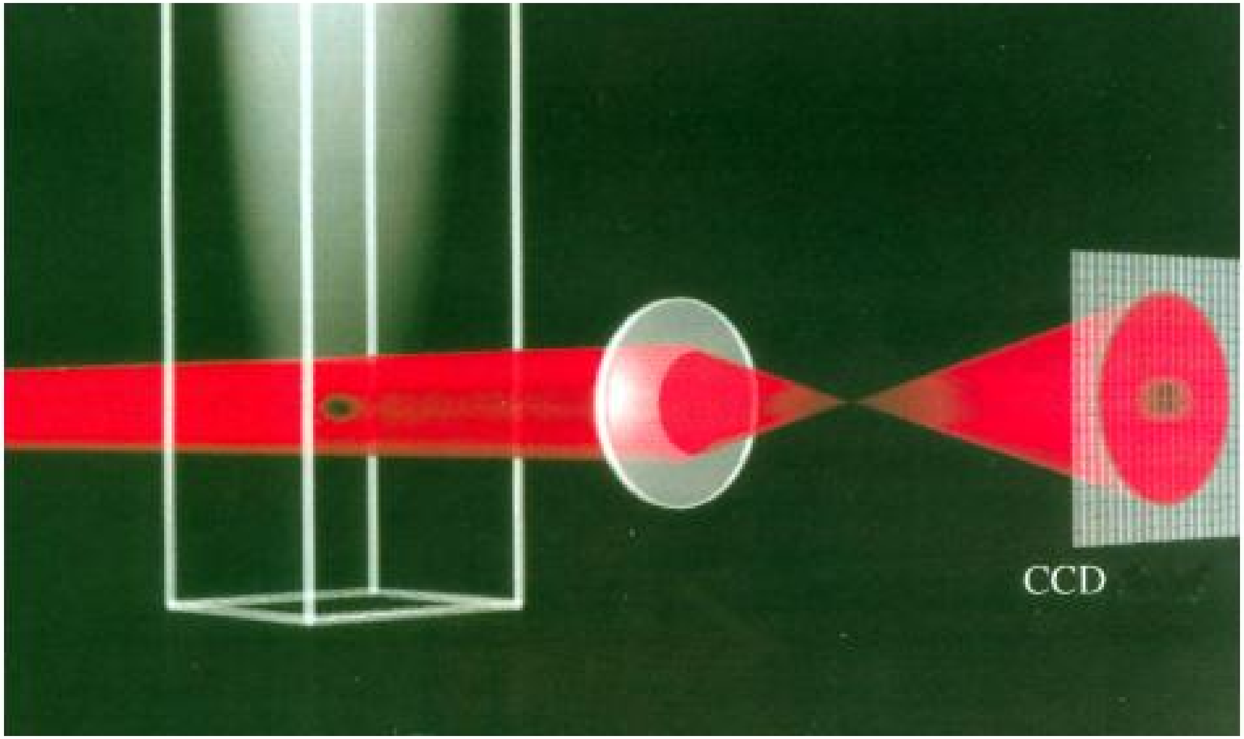
^{6}Li-^{7}Li, ^{6}Li-^{23}Na, ^{6}Li-^{87}Rb, ^{40}K-^{87}Rb,….

Solution 2: mixture of spin states in magnetic trap

Solution 3: mixture of spin states in optical trap + Feshbach resonance

^{40}K	JILA Boulder	1999	magnetic trap, spin mixture
	LENS Florence	2002	magn. trap & sympathetic cooling Rb
	ETH Zurich	2004	magn. trap & sympath. cooling Rb
	Univ. Hamburg	2005	magn. trap & sympath. cooling Rb
	Univ Toronto	2005	chip magn. trap & sympath. cooling Rb
^{6}Li	Rice univ.	2001	magn. trap, sympathetic cooling ^{7}Li
	ENS Paris	2001	magn. trap, sympathetic cooling ^{7}Li
	Duke Univ.	2001	optical dipole trap, mixt.of spin states
	MIT Boston	2002	magn. trap, sympathetic cooling ^{23}Na
	Uni. Innsbruck	2003	optical dipole trap, mixt.of spin states
	Univ. Tubingen	2005	chip magn. trap, sympathetic cooling Rb
	Uni. Swinburne	2007	optical dipole trap, mixt.of spin states
^{171}Yb	Univ. Kyoto	2006	optical dipole trap, mixt.of spin states

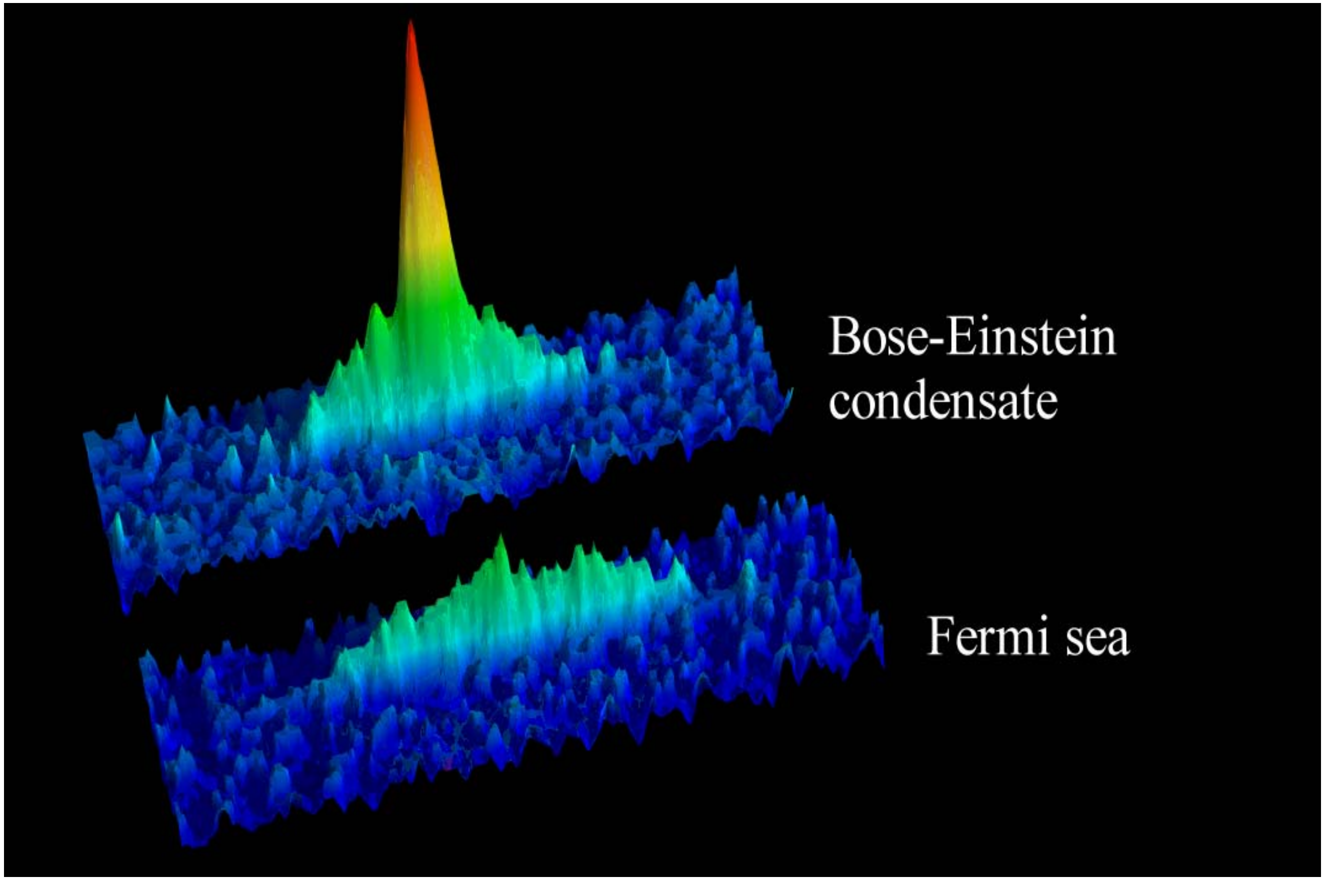
Absorption imaging



in situ: cloud size
After switching off the trap: momentum distribution

Bose-Einstein condensate and Fermi sea

2001
ENS



Lithium 7

Lithium 6

10^4 Li 7 atoms, in thermal equilibrium with
10^4 Li 6 atoms in a Fermi sea.

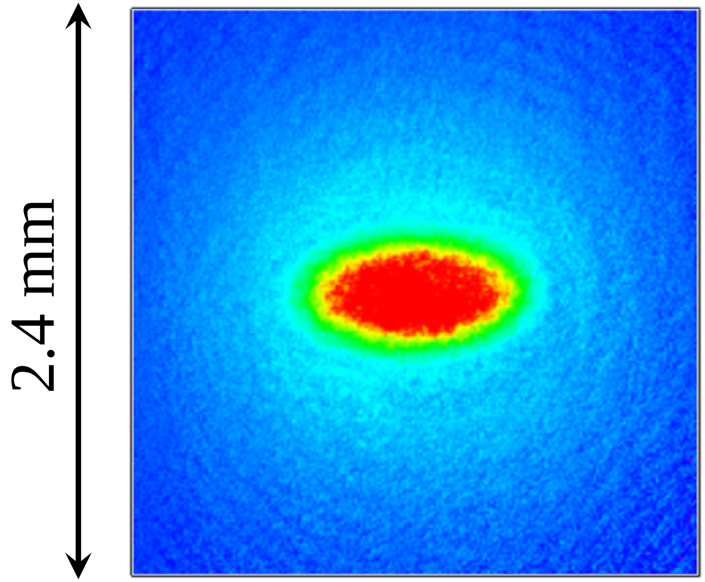
Quantum degeneracy: $T= 0.28\ \mu K = 0.2(1)\ T_C= 0.2\ T_F$

F. Schreck et al., PRL 01

Lithium-Sodium mixture (MIT)

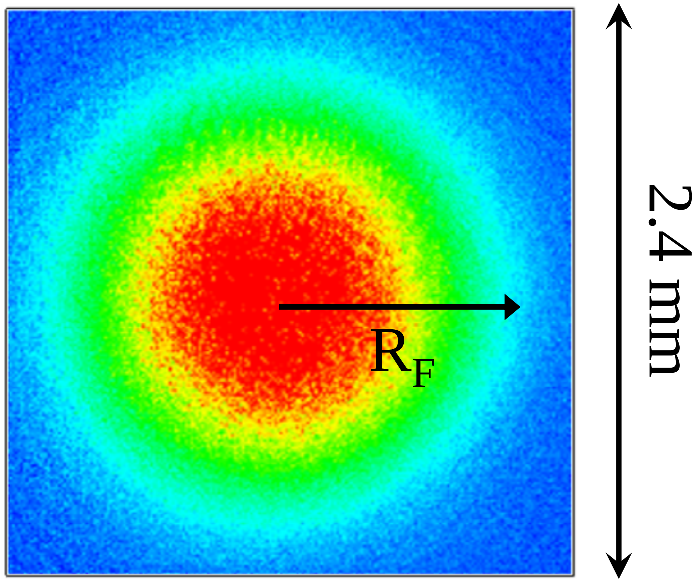
Use Sodium F = 2 as refrigerator
to cool Lithium in F = 3/2 (state $|6\rangle$) in a magnetic trap
20s forced evaporation on Na results in typically

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, and W. Ketterle, Phys. Rev. Lett. **91**, 160401 (2003)

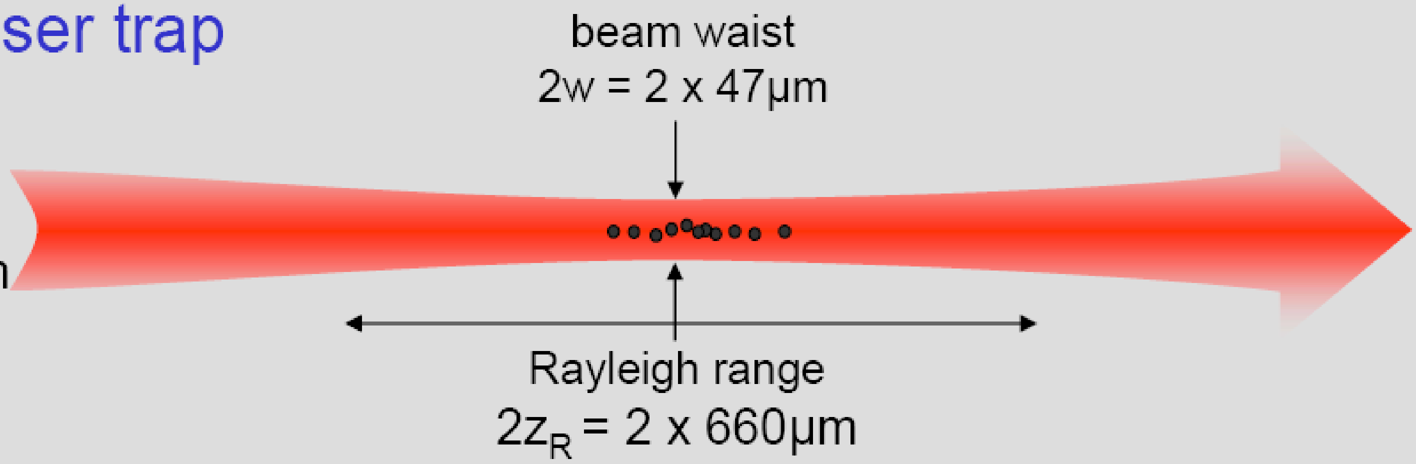
All-optical method

all-optical approach by John Thomas group at Duke Univ., Durham, NC, USA

CO_2 laser trap

65 W

λ=10.6µm



beam waist

2w = 2 x 47µm

Rayleigh range

$2z_R$ = 2 x 660µm

trap depth 690µK

loading of a few 10^6 atoms ***directly from the MOT***

after plain evaporation for 5s:

1.3 x 10^6 atoms @ 5µK, p.s.d. 8 x 10^{-3} ($T/T_F = 2.8$)

Now 2 10^5 atoms at T/T_F=0.1

Also Innsbruck Univ.

ultrastable CO_2 trapping of lithium fermions
O'Hara et al., PRL 82, 4204 (1999)

Optical Traps

Dipole force: far-off resonance laser : very low photon scattering rate
Flexible geometry,1 or several beams, adjustable aspect ratio

Decouples trapping function and magnetic tuning for Feshbach Resonances

Can be switched on and off very fast

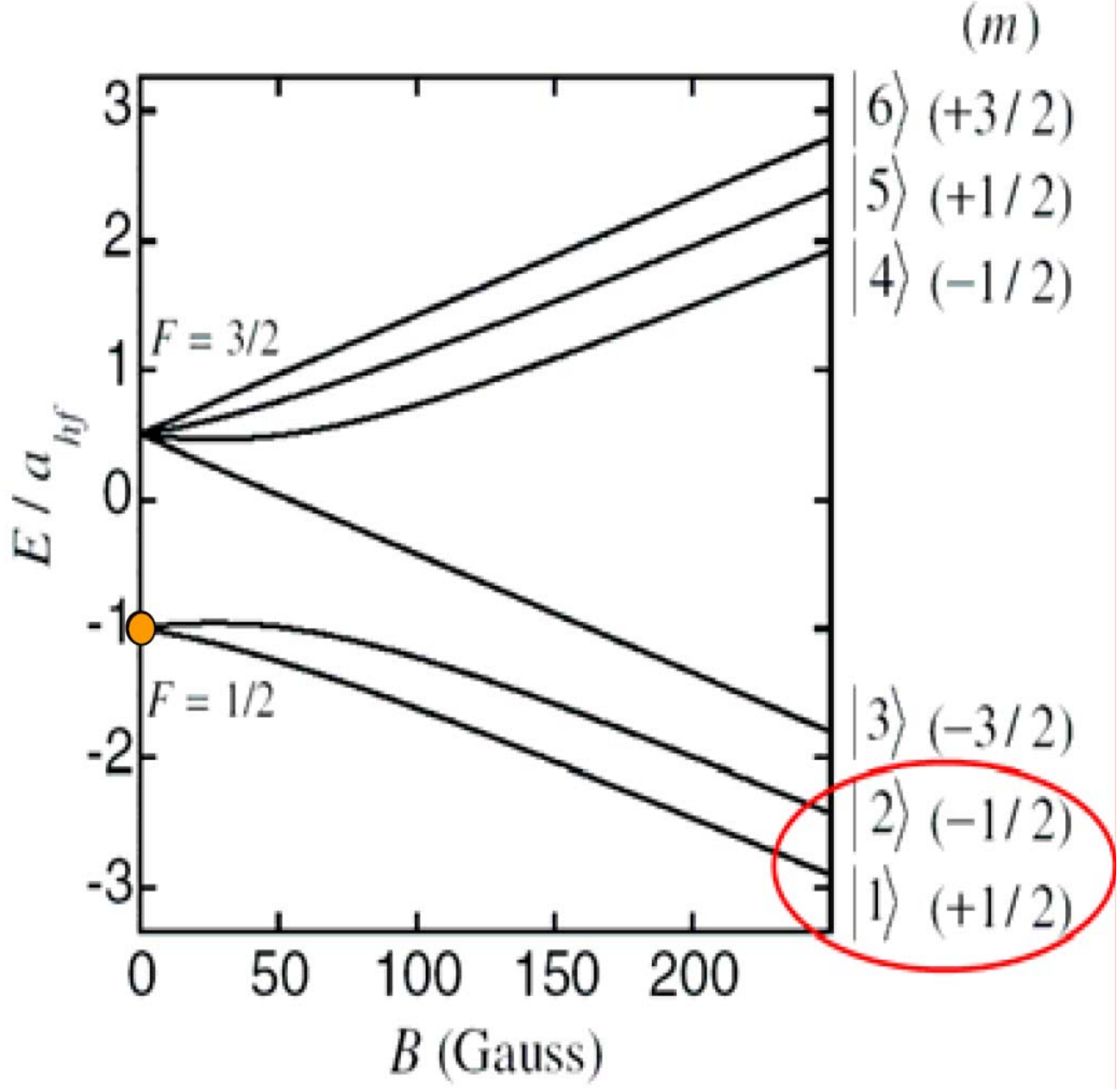
Easy modulation of trap depth or position using acousto-optic modulators
Excitation of collectives modes, rotating trap,….

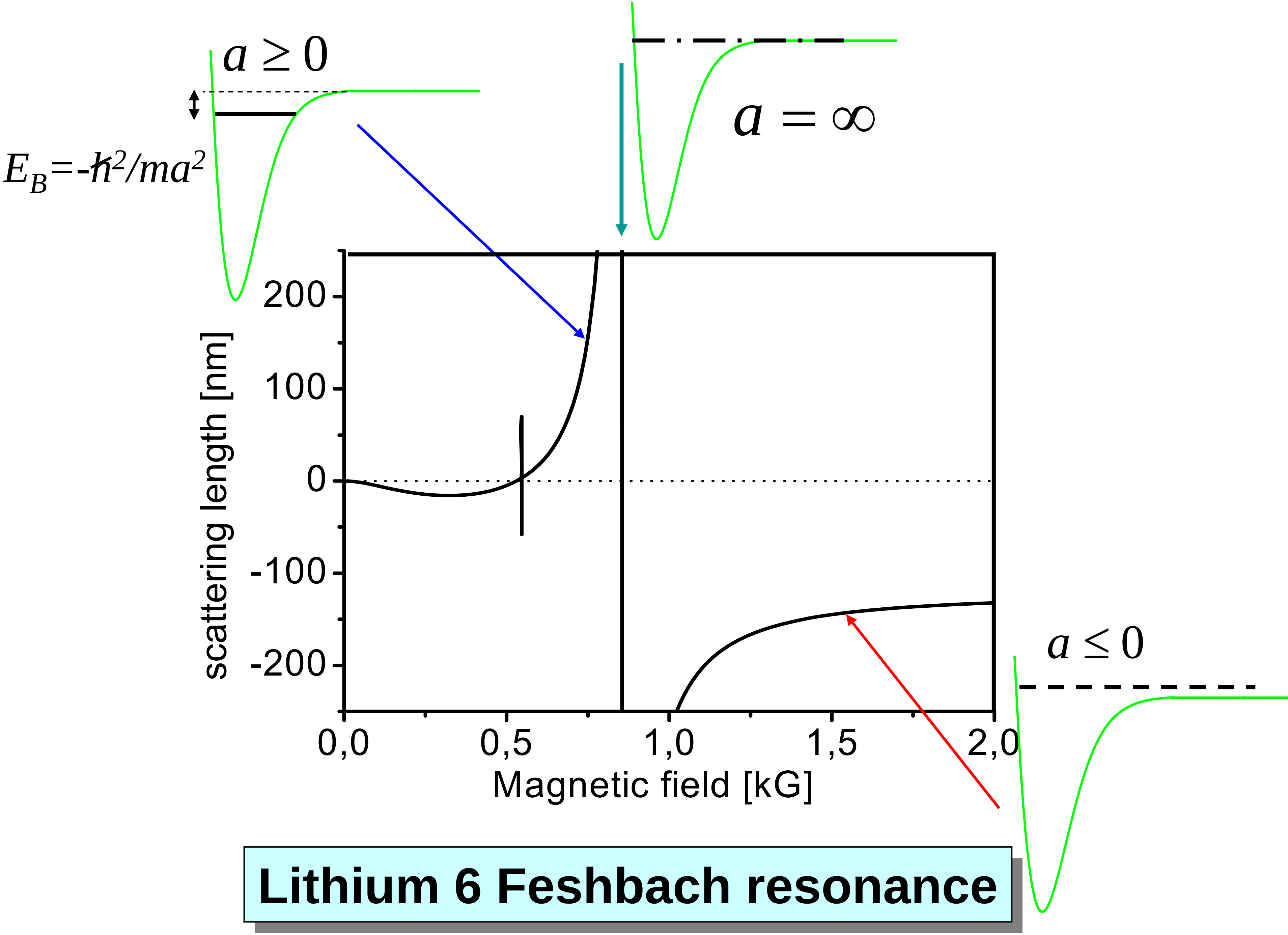
3D, 2D, 1D optical lattices by interference of several laser beams

See e.g. Proceedings of 2006 Varenna School on Cold Fermi Gases
on cond-mat, and book to appear in 2007
And R. Grimm, Ovchinikov ‘00

Tuning atom-atom interactions

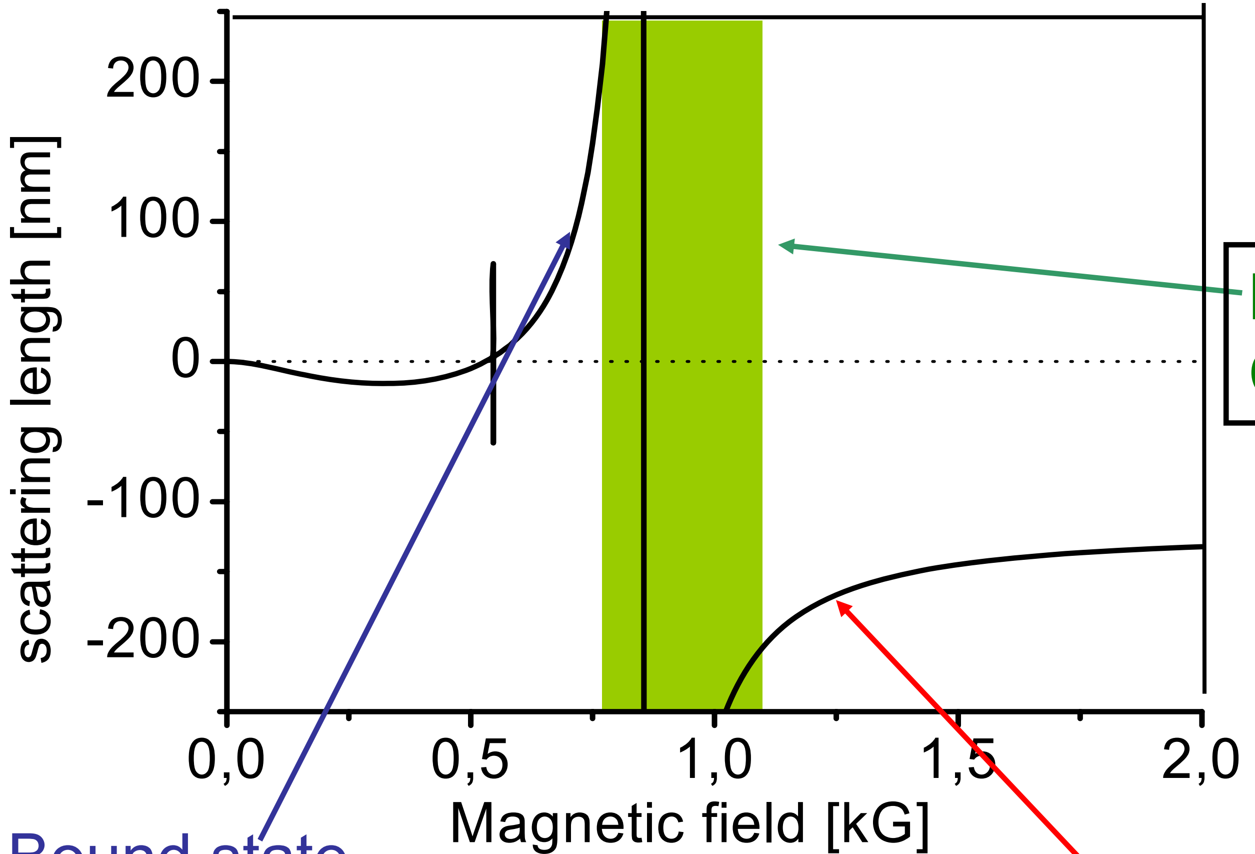
^{6}Li Ground state in magnetic field





Lithium 6 Feshbach resonance

interacting fermions



BEC-BCS Crossover

Bound state

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

condensate of molecules

No bound state

BCS phase

Experimental approach

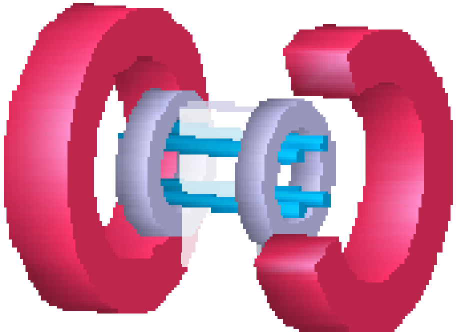
Cooling of ^{7}Li and ^{6}Li

1000 K: oven

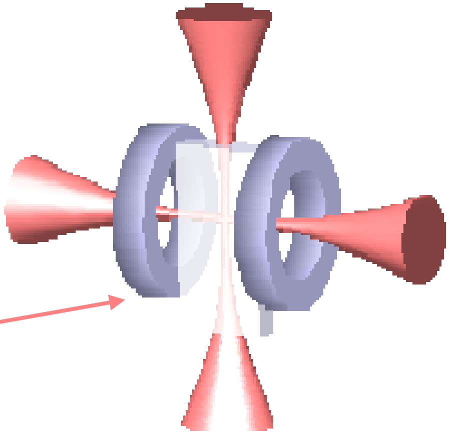
1 mK: laser cooling

10 μK: evaporative cooling
in magnetic trap

$$E = -\vec{\mu}.\vec{B} = +|\vec{\mu}||\vec{B}|$$

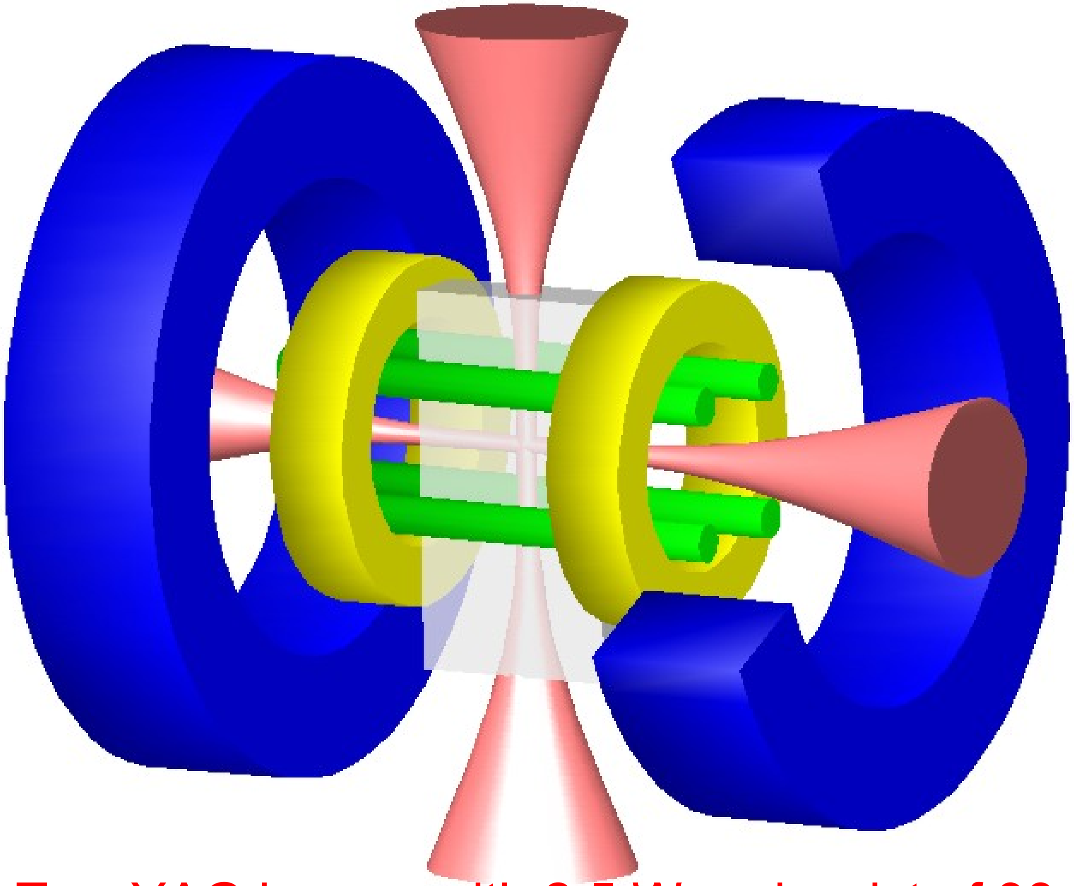


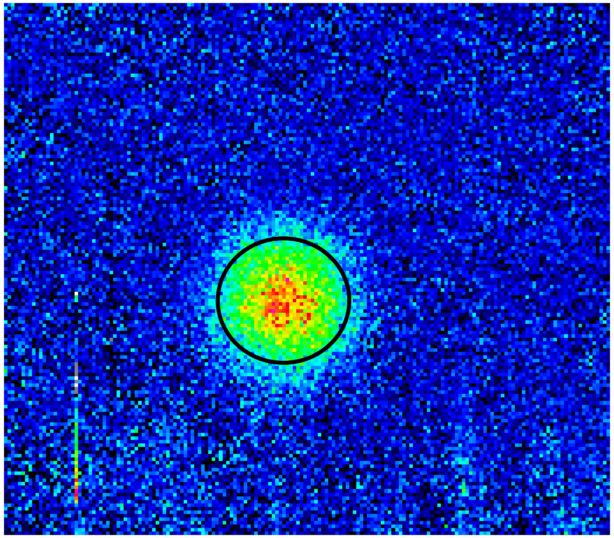
Tuning the interactions in optical trap
Final evaporation in optical trap



Optical trap

Evaporation of ^{6}Li gas in an optical trap





T_F = 5 µK

T/T_F =0.2

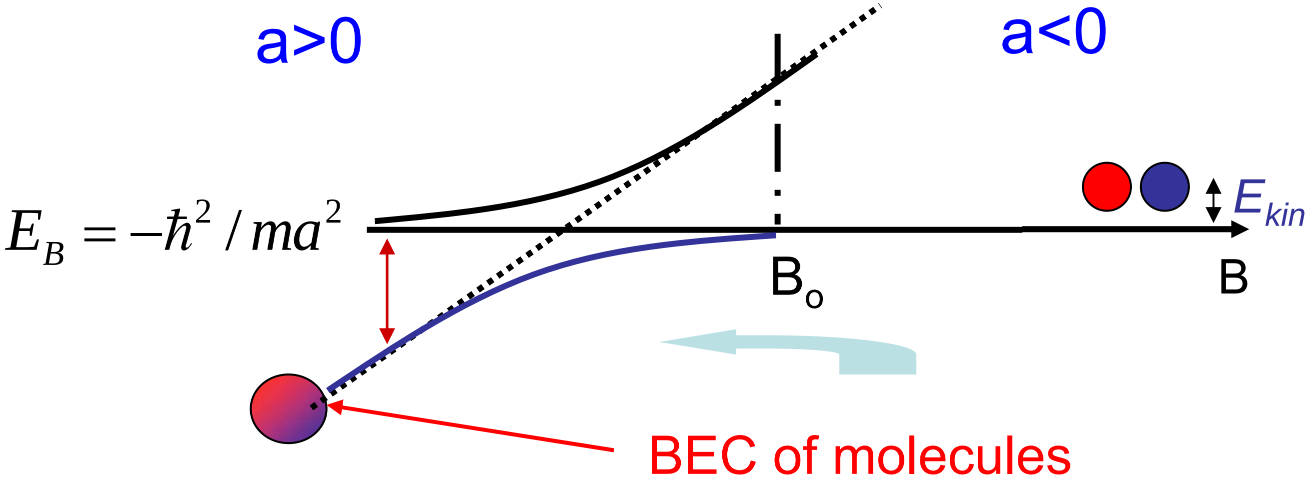
N_{total} = 1 10^5

Two YAG beams with 2.5 W and waist of 38 µm

Temperature is measured in the weakly interacting regime (B< 200 G)
by fit to the finite T Fermi distribution
Difficult to get T in the crossover region (except in imbalanced case, MIT)
Thermal fraction on molec BEC side, or universal thermodynamics at unitarity

Molecule production
Method 1

JILA 03
ENS 03

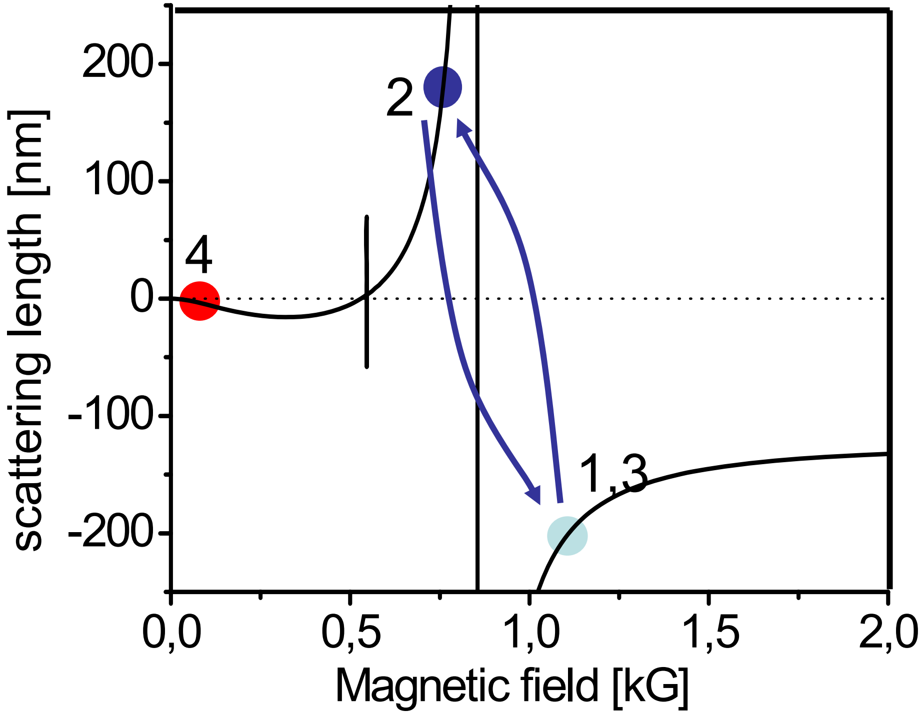


BEC of molecules

Recipe: in region a<0, cool a gas of fermions below T_F
Slowly scan across resonance towards a>0
Typically : 1000 G to 770 G in 200 ms
This produces molecules with up to 90% efficiency !
Reversible process ! Entropy is conserved.
If T< 0.2 T_F, BEC of molecules

How to detect molecules ?

Dissociate them into atoms !
For the probe laser to be on resonance, the magnetic field needs to be turned off.
Dimers follow the B field sweep and are not detected.



Double ramp method :

$$2N_{mol}=N_3-N_2$$

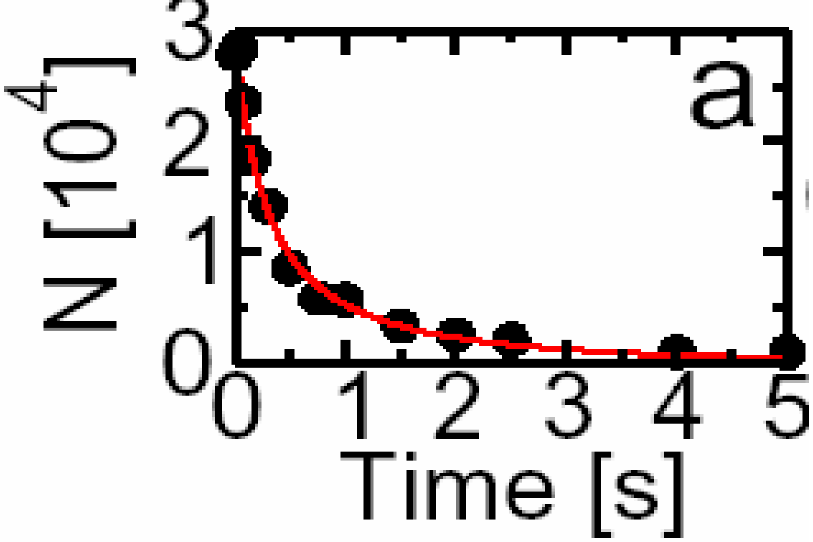
Ramp 2 to 3 dissociates molecules into atoms

Importance of the ramp speed
Adiabaticity:

$$\frac{1}{E_B}\frac{dE_B}{dt} << \frac{E_B}{\hbar}$$

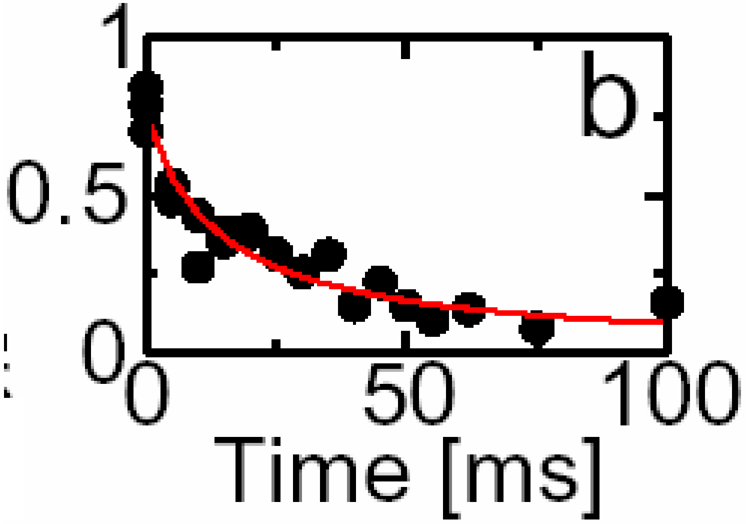
Surprise:dimers of ^{6}Li fermions live very long !

τ = 500 ms



a = 78 nm

τ = 20 ms



a = 35 nm

Two-body Loss Rate: $\beta \sim 2.4\ 10^{-13}$ cm^3/s

J. Cubizolles et al. PRL 03

^{40}K, Regal et al., PRL 03

Contrast with boson case near Feshbach Resonance

Long lifetime and large elastic collision rate

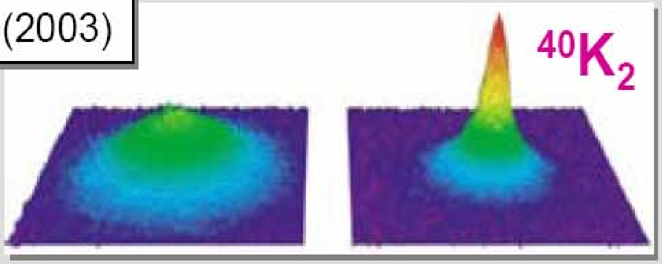
Excellent conditions for cooling of molecules to BEC

Condensates of molecules

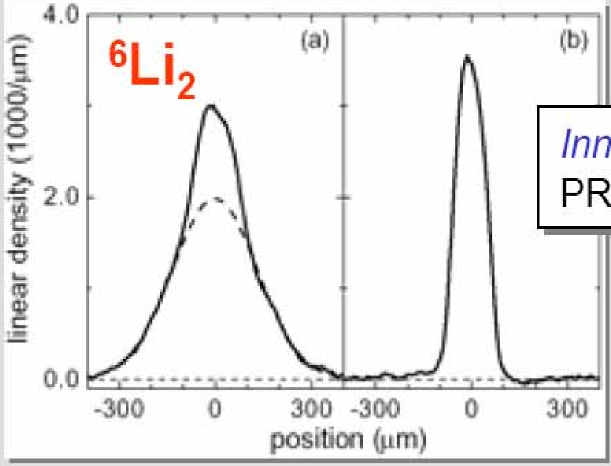
in situ

expansion

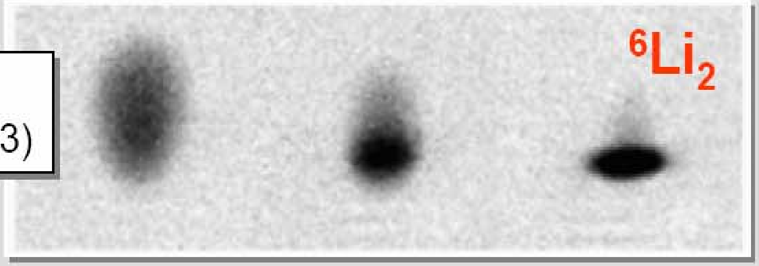
JILA Greiner et al.,
Nature 426, 537 (2003)

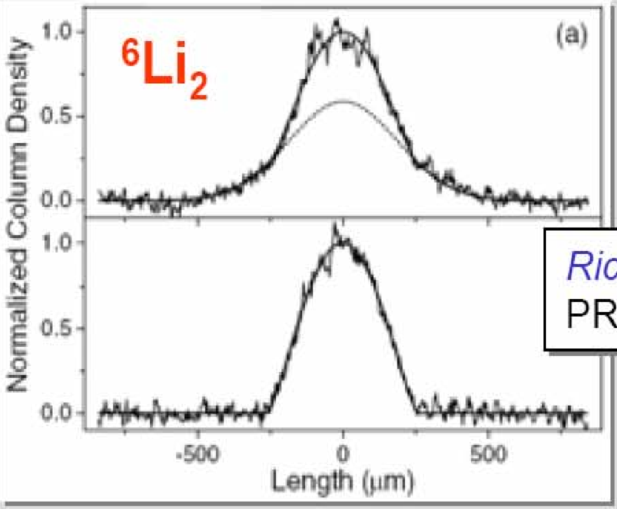


Innsbruck Bartenstein et al.,
PRL 92, 120401 (2004)



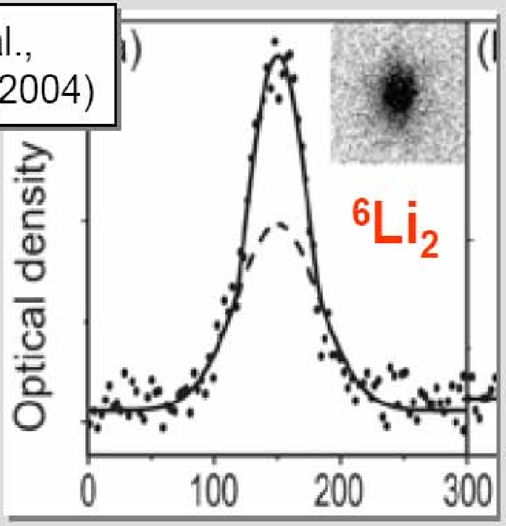
MIT Zwierlein et al.,
PRL 91, 250401 (2003)





Rice Partridge et al.,
PRL 93, 020404 (2005)

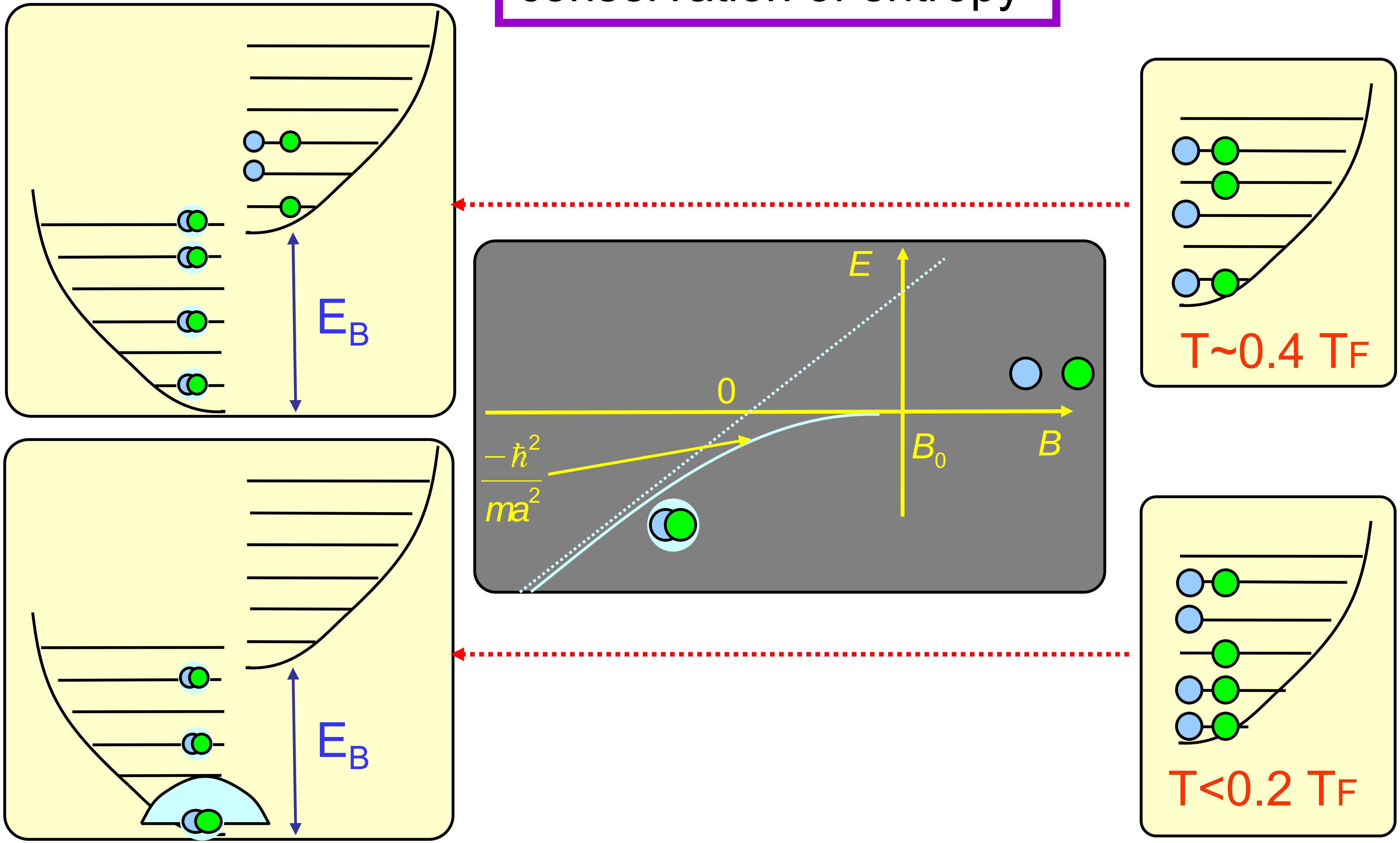
ENS Bourdel et al.,
PRL 93, 050401 (2004)



2007: Swinburne Univ

A simple thermodynamic model

conservation of entropy



Questions on BEC-BCS crossover

BEC of molecules: excellent starting point for exploring the crossover

Q1: Lifetime of molecules ?

Q2: interaction between molecules ?

Q3: What happens in strongly correlated regime: unitarity: $k_F a >> 1$?

Q4: Can we measure the excitation gap ?

Q5: How to probe superfluidity in crossover regime ?

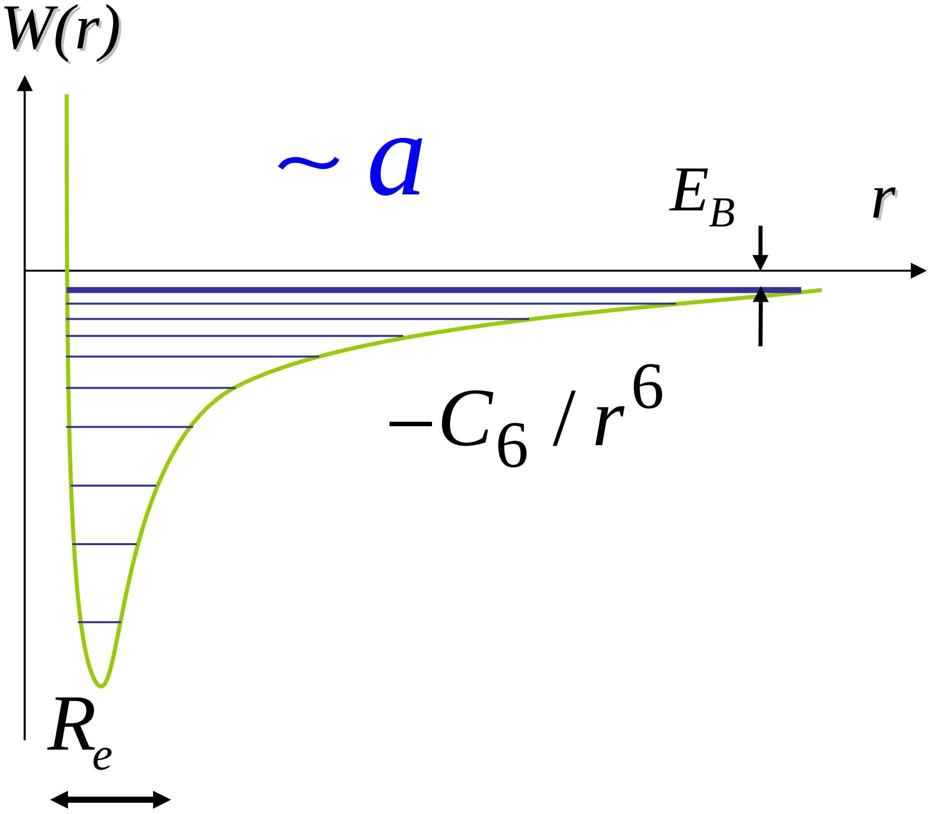
Q6: what is the momentum distribution of particles ?

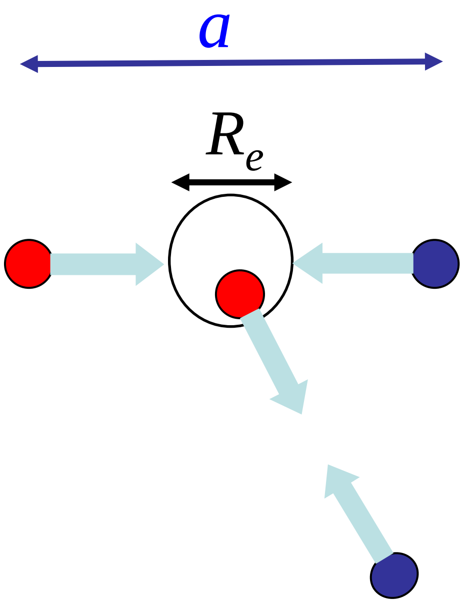
Q7: superfluidity with imbalanced spin populations ?

Q8: Which theoretical description(s) is most accurate ?

Remarkable stability of weakly bound molecules

Suppression of vibrational relaxation for fermion dimers





Pauli exclusion principle

Inhibition by factor $(a/R_e)^2 >> 1$

Binding energy: $E_B = h^2/ma^2$

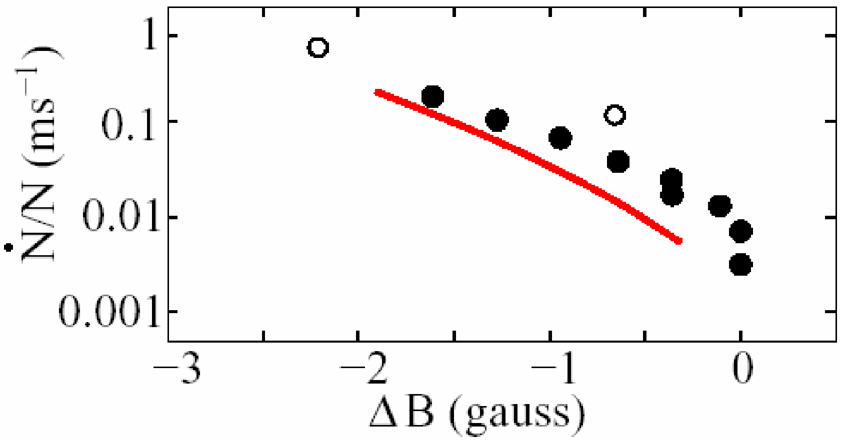
Momentum of each atom: $\hbar/a$

G~ $1/a^s$ with s = 2.55 for dimer-dimer coll.
3.33 for dimer-atom coll.

D. Petrov, C.S., G. Shlyapnikov, PRL 04

Comparison with experiments

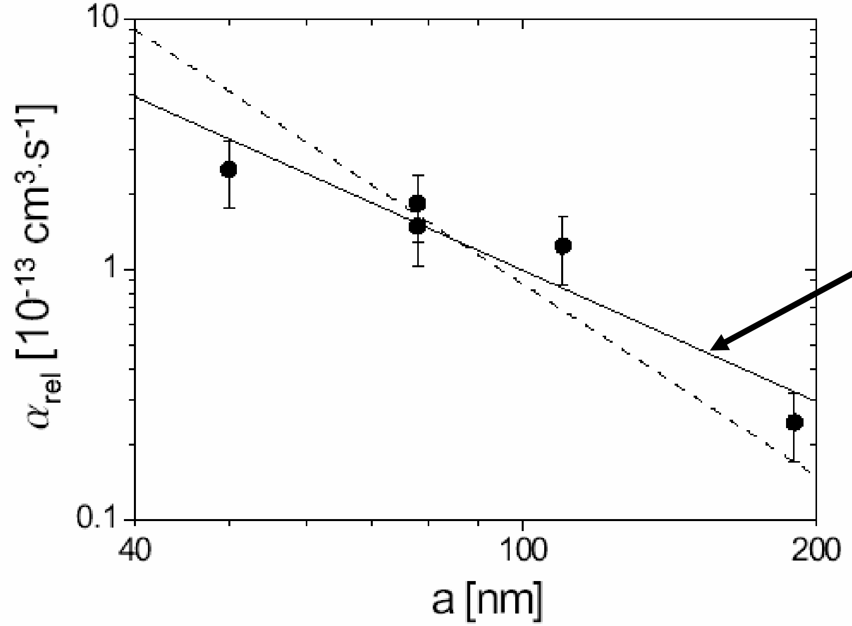
$^{40}K_2$, JILA
Regal 04



$$\beta_{\exp} \sim a^{-2.3\pm0.4}$$

$^{6}Li_2$

ENS 04



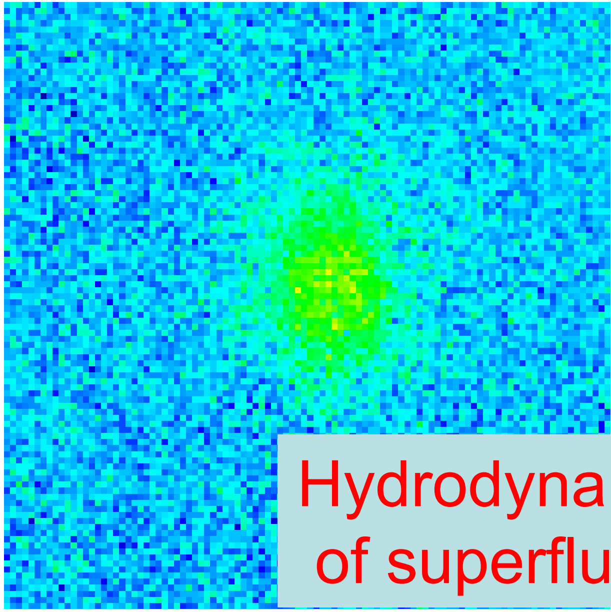
$$\beta_{\exp} \sim a^{-1.9\pm0.8}$$

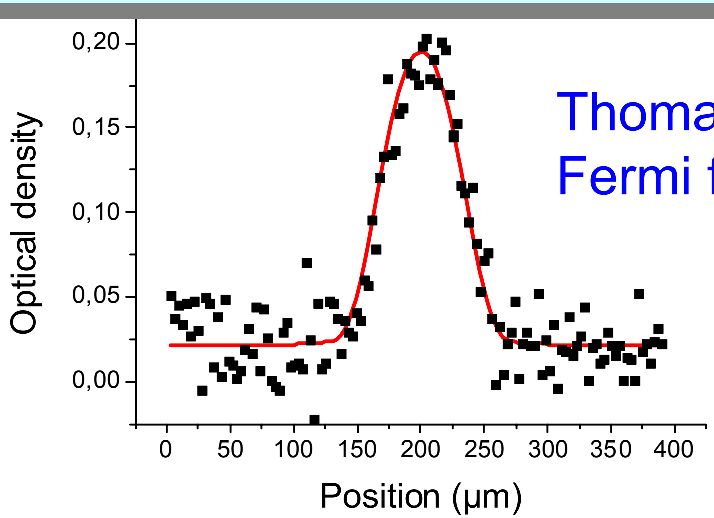
$$\beta_{th} \sim a^{-2.55}$$

On resonance, lifetime of strongly interacting gas exceeds 30 s !

Interaction between molecules measurement of a_{mm}

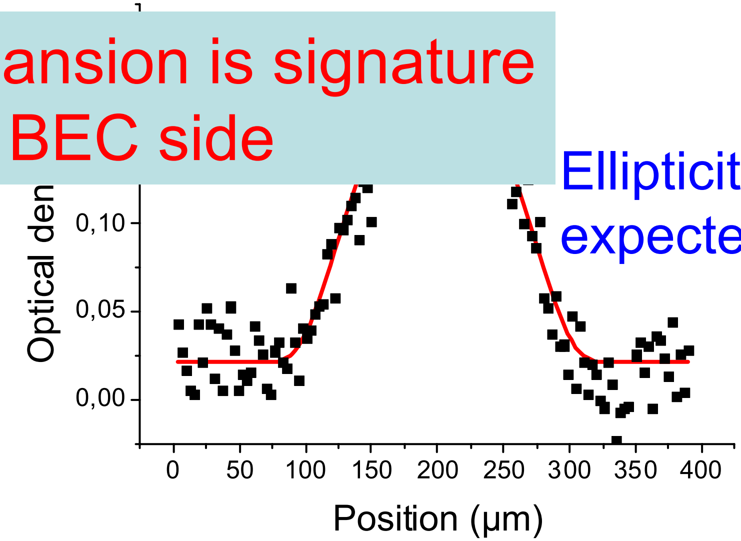
nearly pure condensate λ=0.1





Thomas Fermi fit

Hydrodynamic expansion is signature of superfluidity on BEC side



Ellipticity: 2.0
expected: 1.98

$$T \le 0.9\mu K = T_c^0 / 3$$

In trap TF radius:
R_x= 26µm, R_y= 2.75µm

Good agreement with theory:

a_{mm}=0.6 a = 0.6 x 306= 183 nm

D. Petrov, G. Shlyapnikov, C.S.

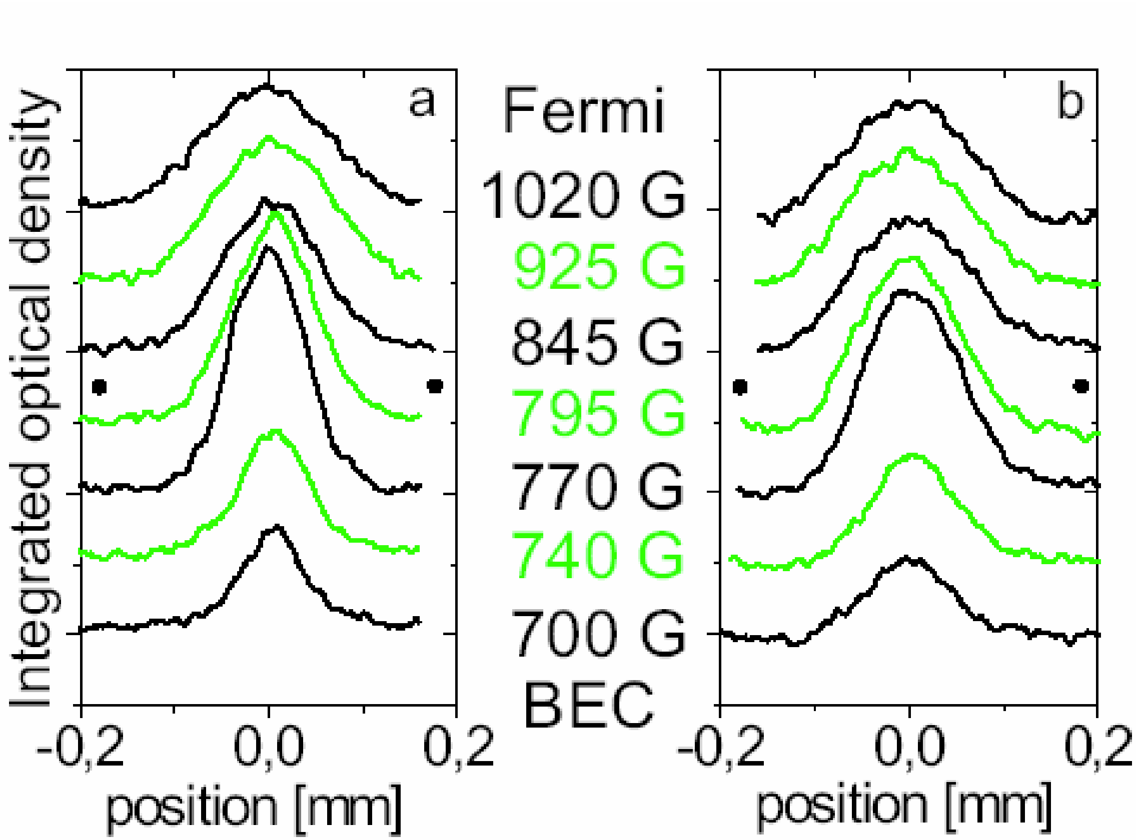
Excludes: $a_{mm} = 2a$

From hydrodynamic expansion

At 770 G: $a_{mm} = 170^{+100}_{-60}\ nm$

BEC – BCS crossover expansion images

Prepare nearly pure condensate at 770G: 4 10^4 mol., $N_0/N \geq 70\%$
Change magnetic field slowly across FR: rate: 1-2 G/ms
Take 1.4 ms TOF image



a < 0

a > 0

Trap aspect ratio: λ=0.3

a < 0

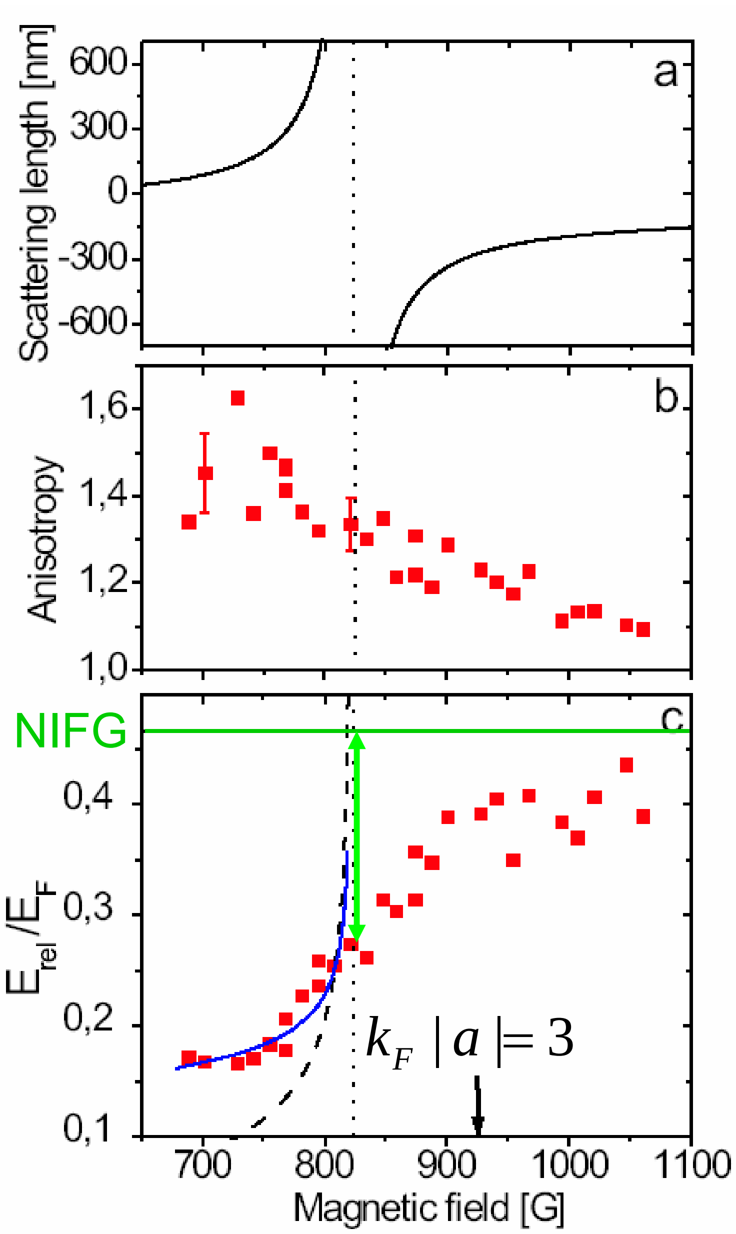
Resonance position 823 G

a > 0

Axial: X

Radial:Y

BEC – BCS crossover: on resonance



On resonance $k_Fa{>>}1$, behavior should no longer depend on a.
Equation of state should have same density dependence as ideal Fermi gas

$$\boxed{\mu = \frac{\hbar^2}{2m}(6\pi^2)^{2/3}(1+\beta)n^{2/3}}$$

$\beta = 0$: ideal Fermi gas
$\beta \neq 0$ at unitarity

On resonance: $E_R = \sqrt{1+\beta}\; E_R^0$
Where E_R^0 is the release energy of non interacting Fermi gas in harm. trap
We find: $\beta = -0.58(15)$

A fundamental quantity in many-body theories
Good agreement with QMC method (Carlson 02 Giorgini 04, UMASS-ETH coll. 05)

T. Bourdel et al., PRL 2004

Universal equation of state of the balanced Fermi gas

balanced Fermi gas ($\mu_\uparrow = \mu_\downarrow$)

$$n = \frac{1}{6\pi^2}\left(\frac{2m\mu_\uparrow}{\hbar^2}\right)^{3/2}$$ x numerical factor

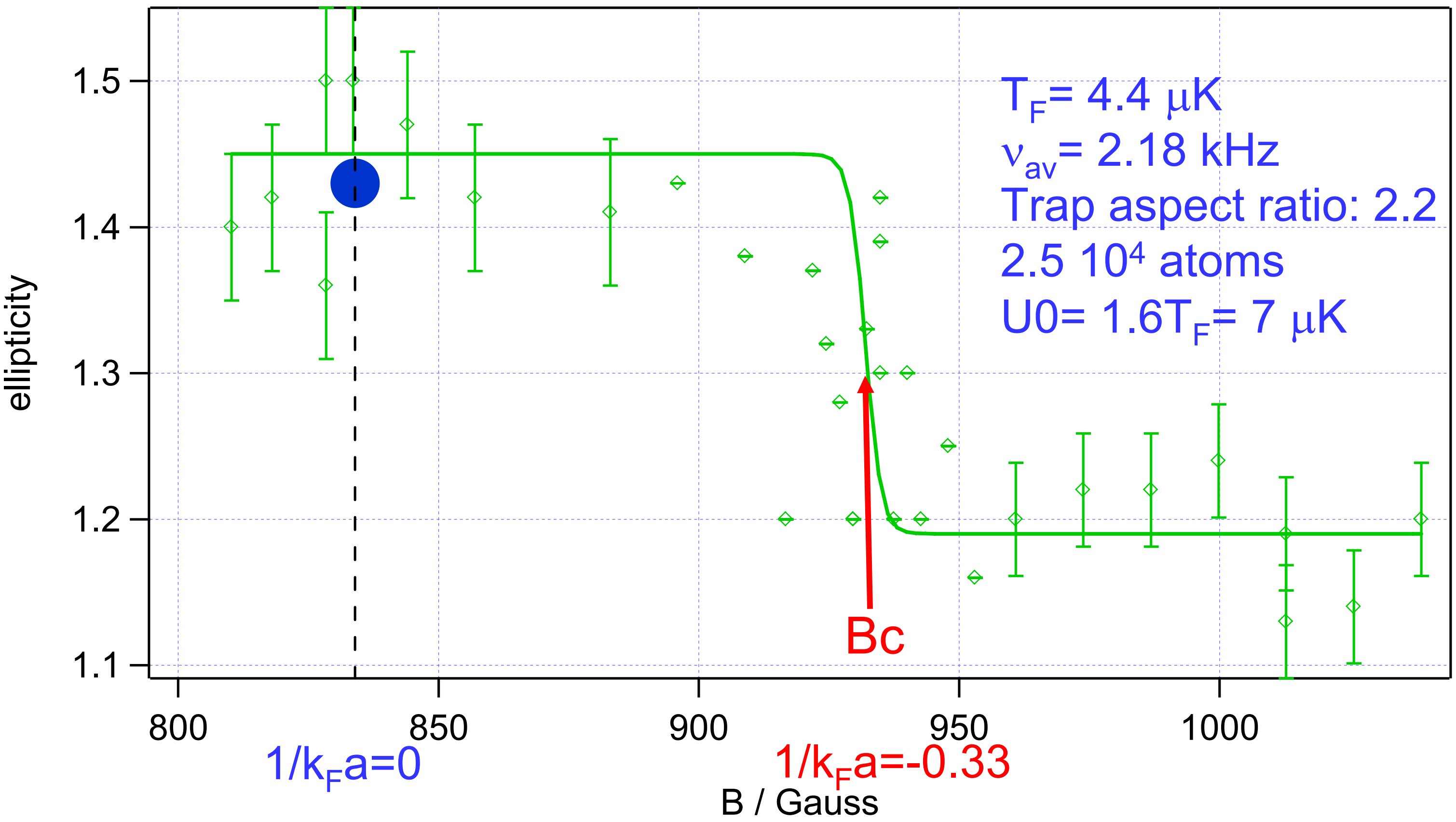
$$\mu_\uparrow = \xi \frac{\hbar^2}{2m}\left(6\pi^2 n\right)^{2/3} = \xi E_F$$

Determination of ξ

Experiment	*ENS (^{6}Li)*	0.42(15)
	Rice (^{6}Li)	0.46(5)
	JILA(^{40}K)	0.46(10)
	Innsbruck (^{6}Li)	0.27(10)
	Duke (^{6}Li)	0.51(4)

Theory	*BCS*	0.59
	Astrakharchik	0.42(1)
	Perali	0.455
	Carlson	0.42(1)
	Haussmann	0.36

Aspect ratio at low temperature



Abrupt decrease near 930 G !

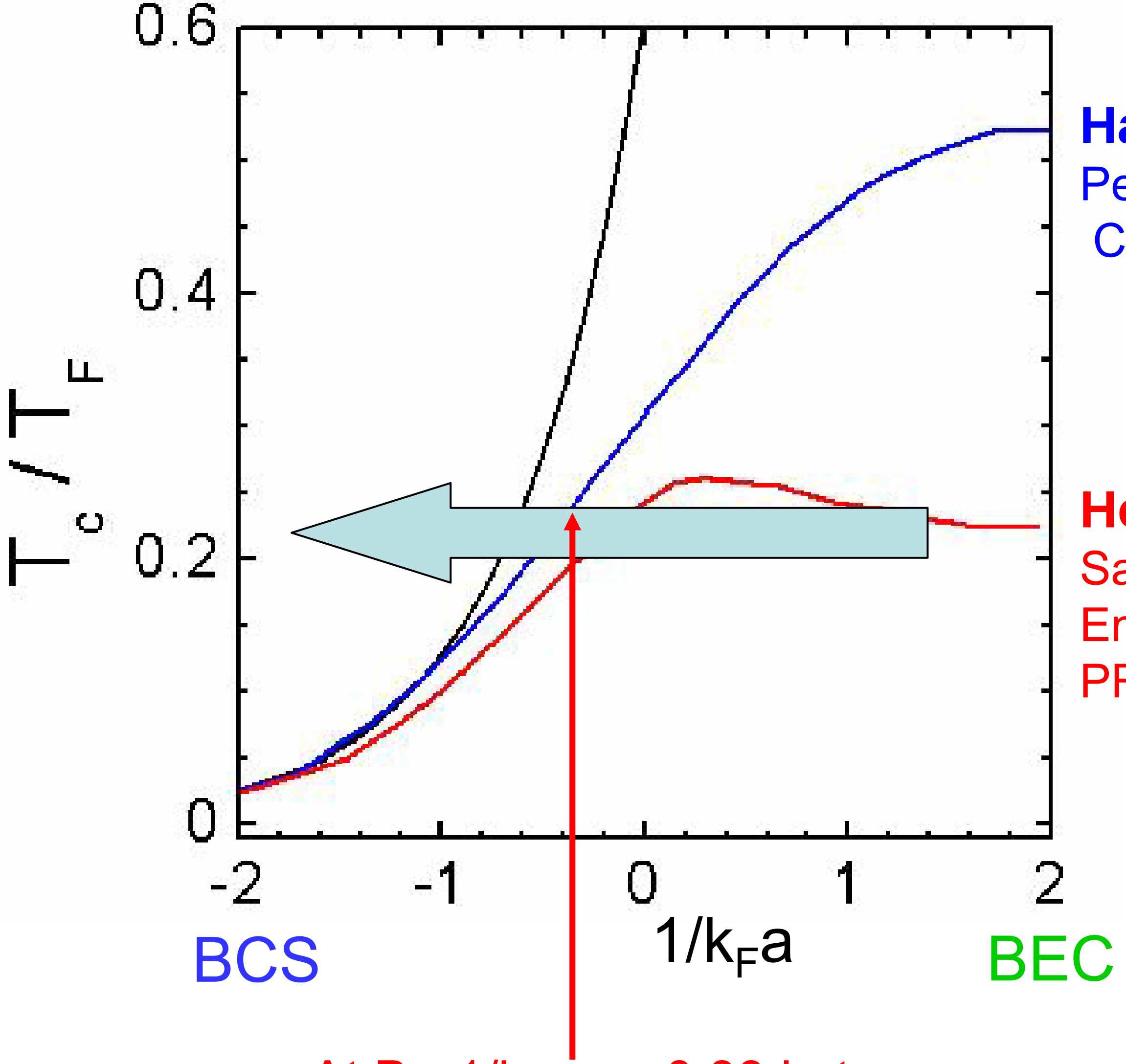
On resonance: agreement with hydrodynamic prediction

At Bc : crossing of the critical temperature near 930 Gauss.

For T >Tc, generalized Cooper pairs are broken, hence loss of superfluidity.

At higher T, the step smoothes and shifts towards smaller $1/k_F|a|$

Critical temperature in BEC- BCS crossover

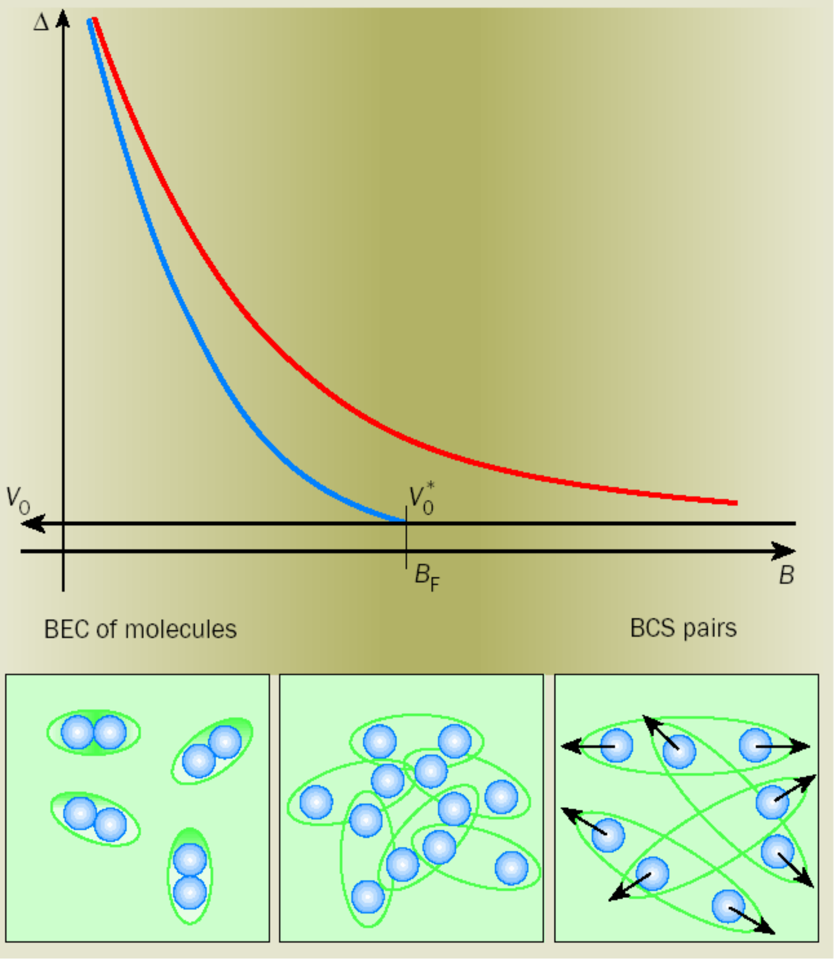


Harmonic trap
Perali et al.,
Cond-mat 0311309

Homogeneous case
Sa de Melo, Randéria,
Engelbrecht,
PRL 71, (1993)

At B_c, $1/k_F a = -0.33$ in trap

Phase diagram at T=0



F. Chevy
C.S.
Physics World
March 05

Molecular BEC
Strongly bound
Size: a << $n^{-1/3}$
$n^{-1/3}$: average dist.
between particles

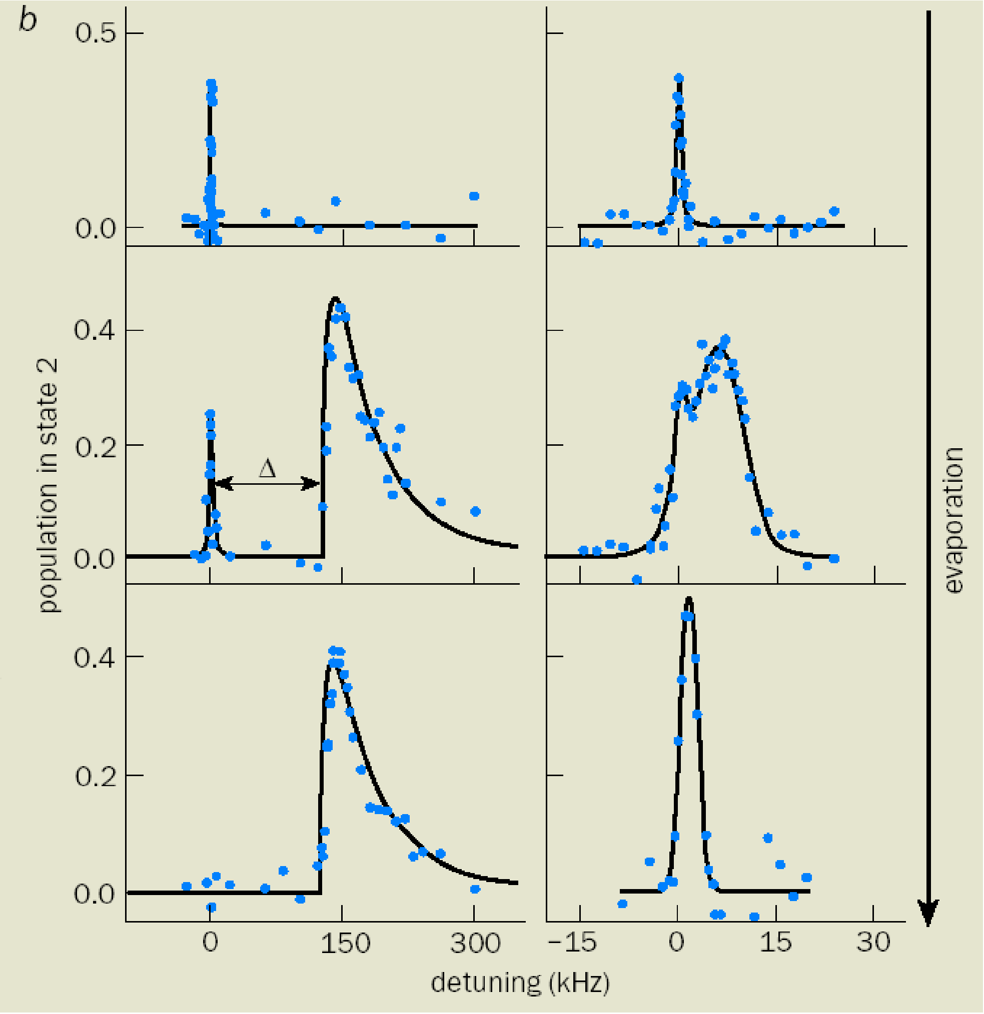
On resonance
$na^3 > 1$ or $k_F a \geq 1$
Pairs stabilized by Fermi sea

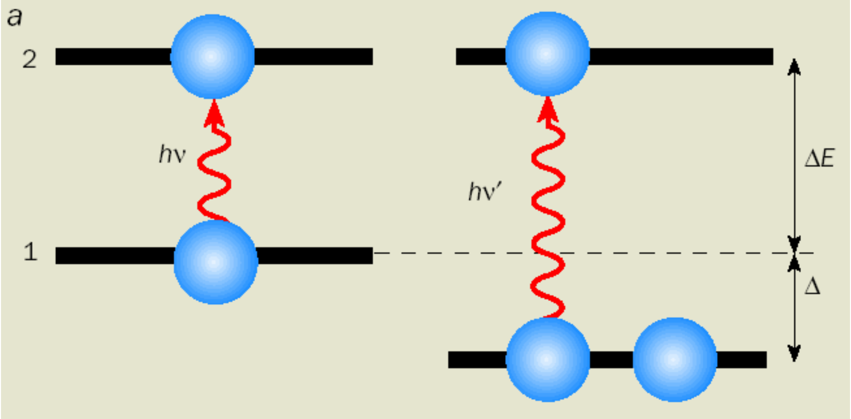
BCS regime:
$k_F|a| \ll 1$
Cooper pairs **k, -k**
Well localized in
Momentum: $k \sim k_F$
Delocalized in
position

Observation of pairing gap

Innsbruck
C. Chin et al., Science 04

$T = 5\ T_F$





RF dissociation spectroscopy

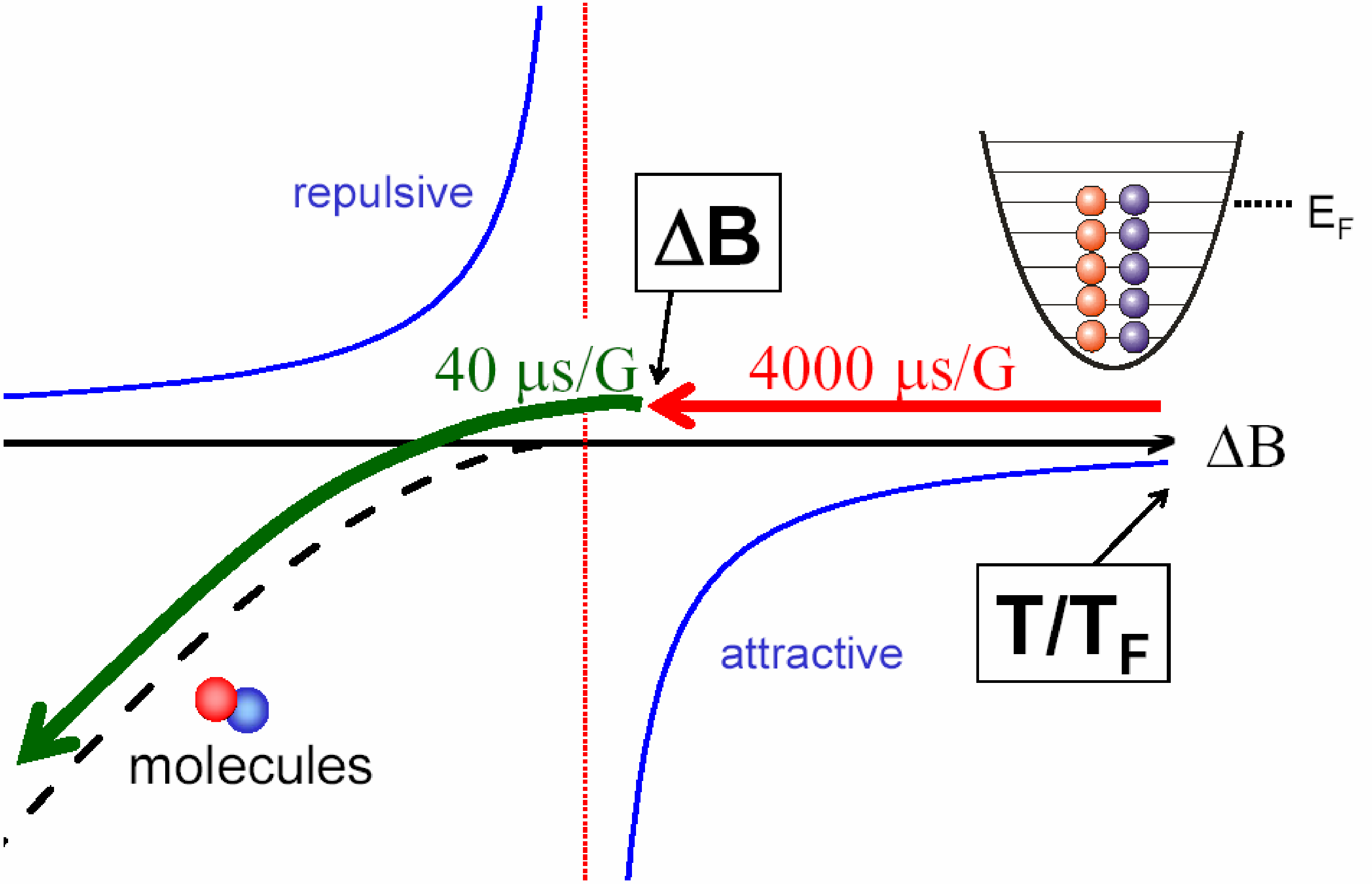
$T < 0.2 T_F$
$T_F = 1.2\ \mu K$

BEC side

BCS side

On resonance: $h\Delta \sim 0.2\ E_F$

Are fermion pairs condensed?

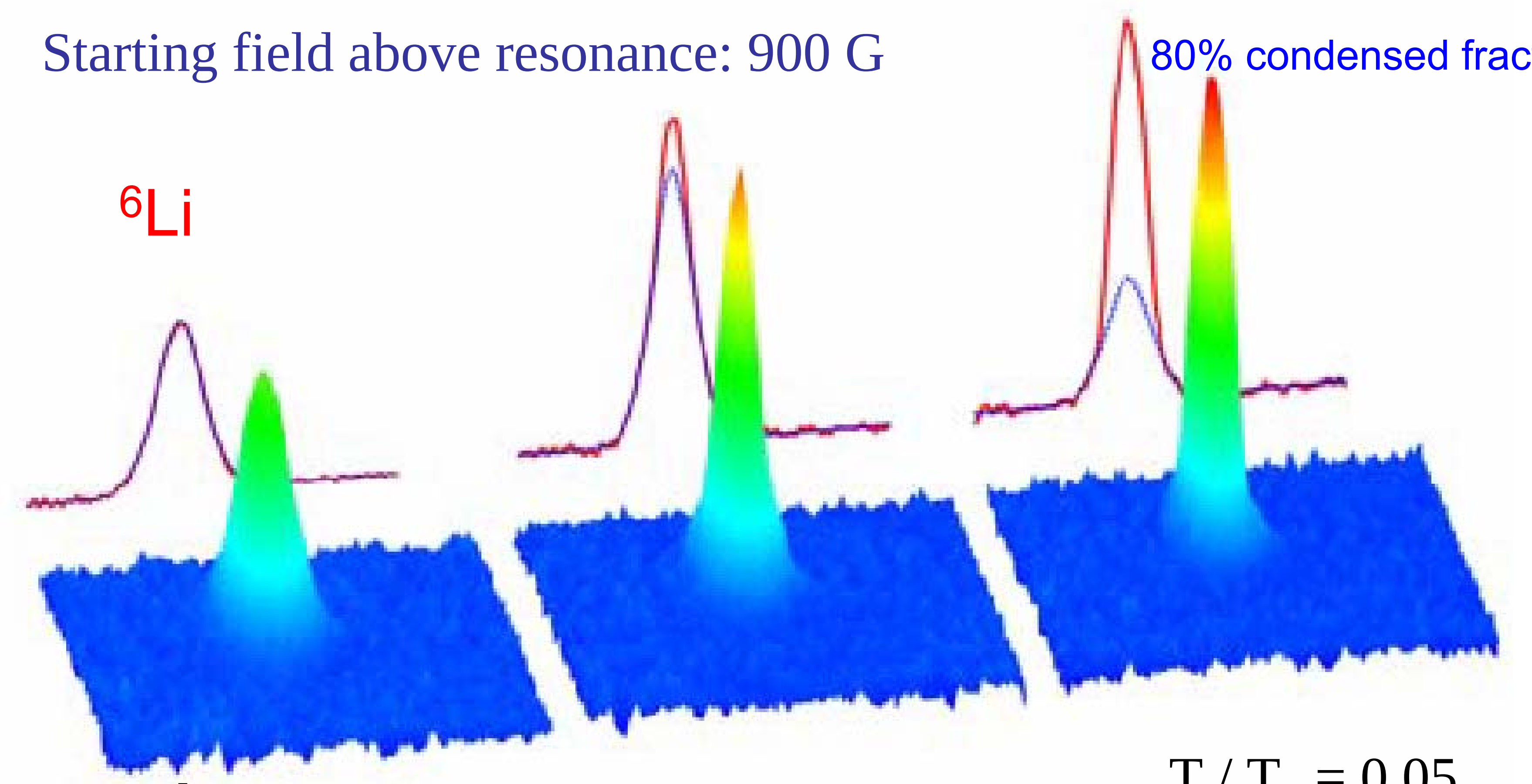


C. A. Regal et al., Phys. Rev. Lett. **92**, 040403 (2004)

Condensation of fermionic pairs: JILA, MIT

C. Regal, PRL 04
M. Zwierlein et al.,04

Starting field above resonance: 900 G



^{6}Li

80% condensed fraction

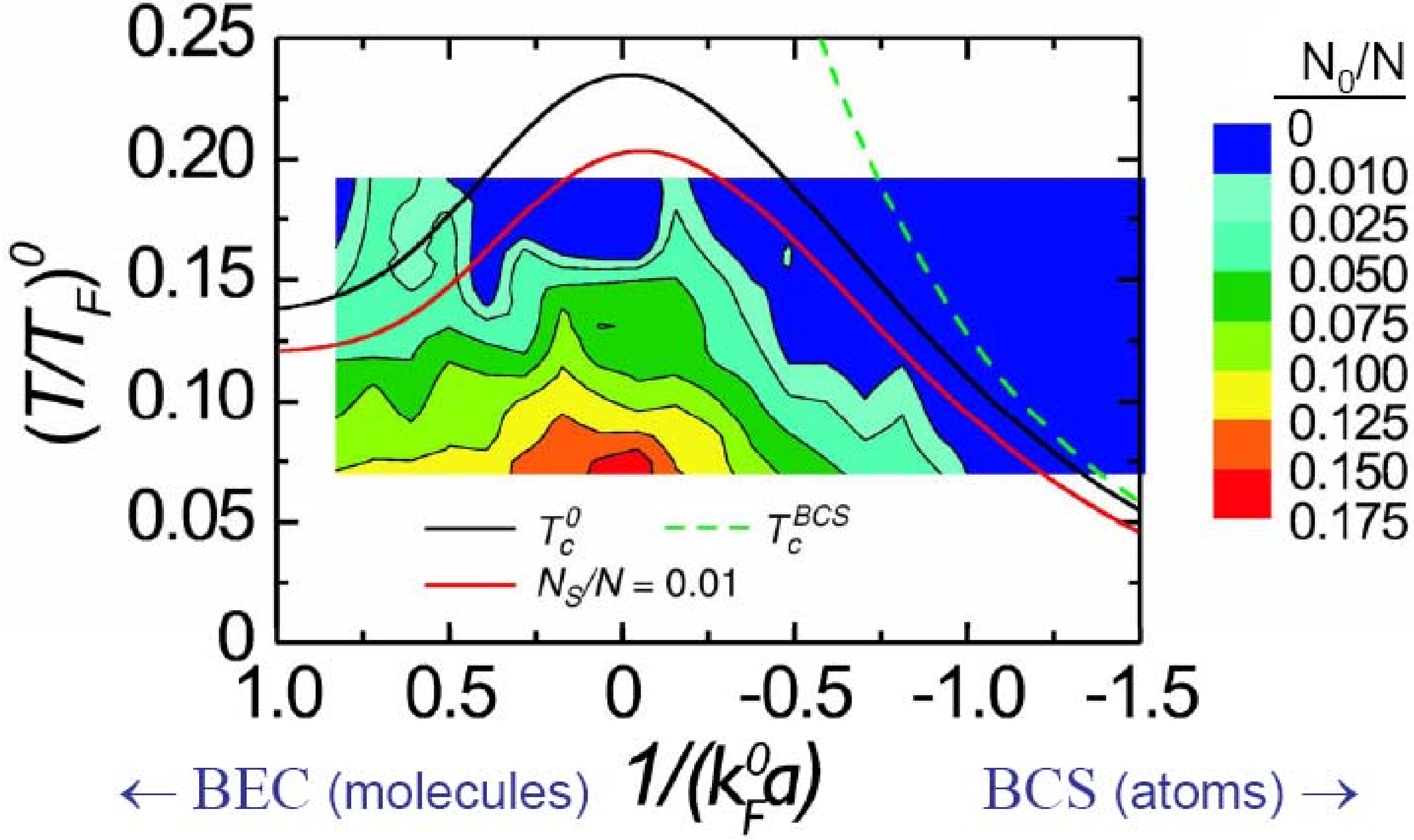
Initial temperature:T / T_F = 0.2

T / T_F = 0.1

T / T_F = 0.05

High condensate fraction indicates the presence of k, -k pairs on resonance side where no molecular bound state exists

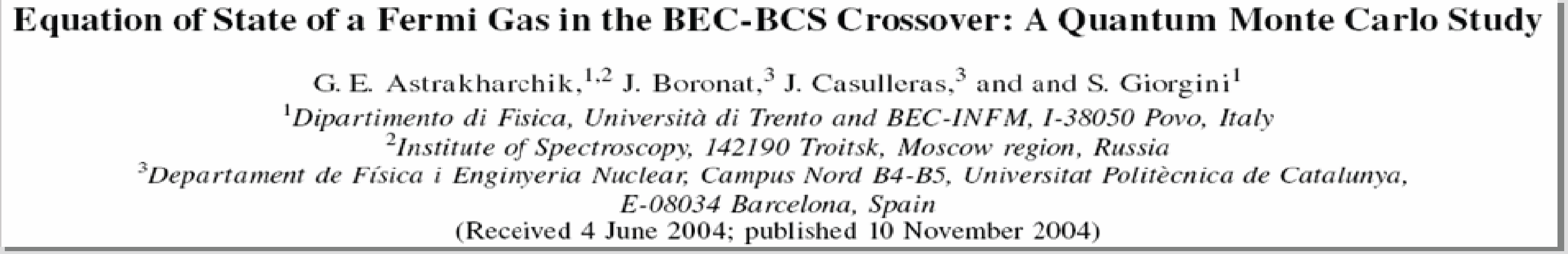
Pair condensation transition temperature: ^{40}K



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

Theory: Q. Chen *et al*., PRA **73**, 041601 (2006)

Equation of state in the crossover



Equation of State of a Fermi Gas in the BEC-BCS Crossover: A Quantum Monte Carlo Study

G. E. Astrakharchik,[1,2] J. Boronat,[3] J. Casulleras,[3] and and S. Giorgini[1]
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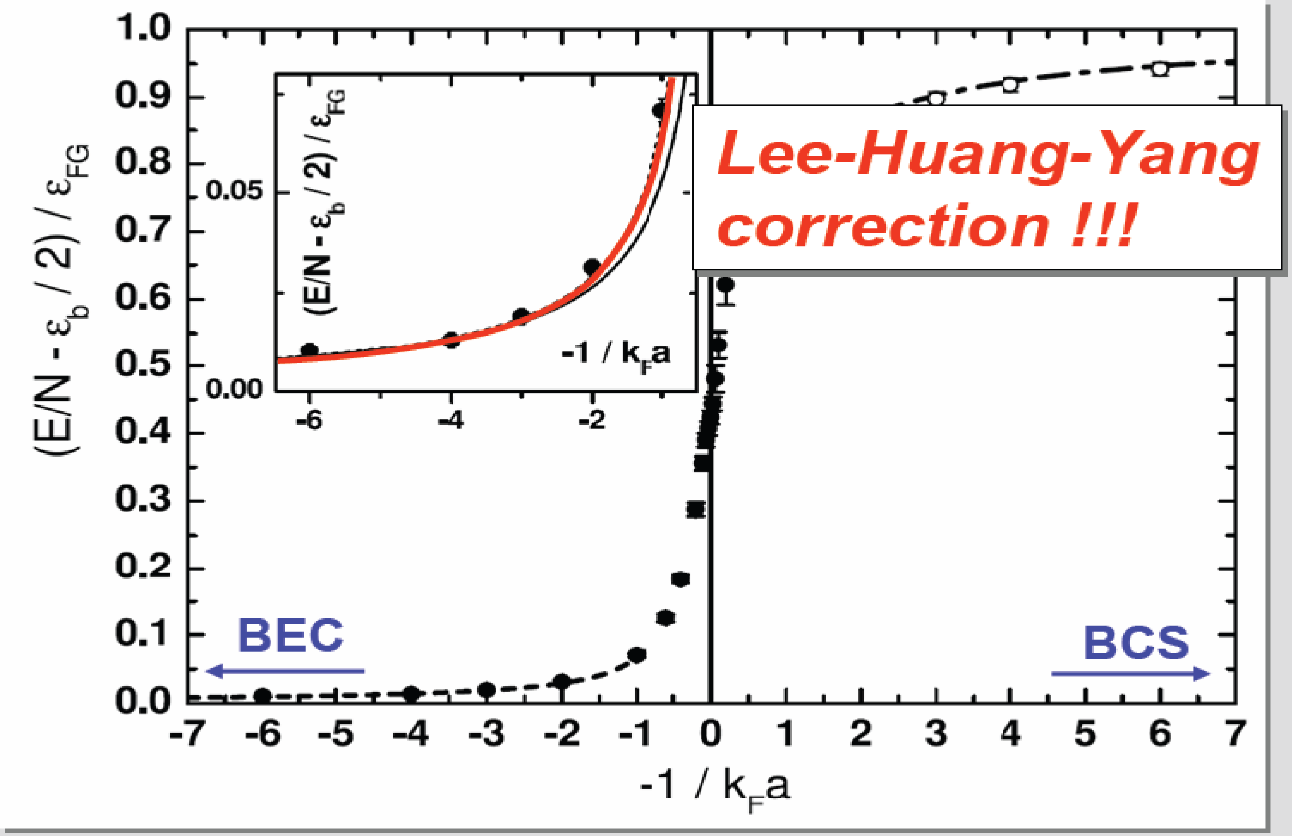
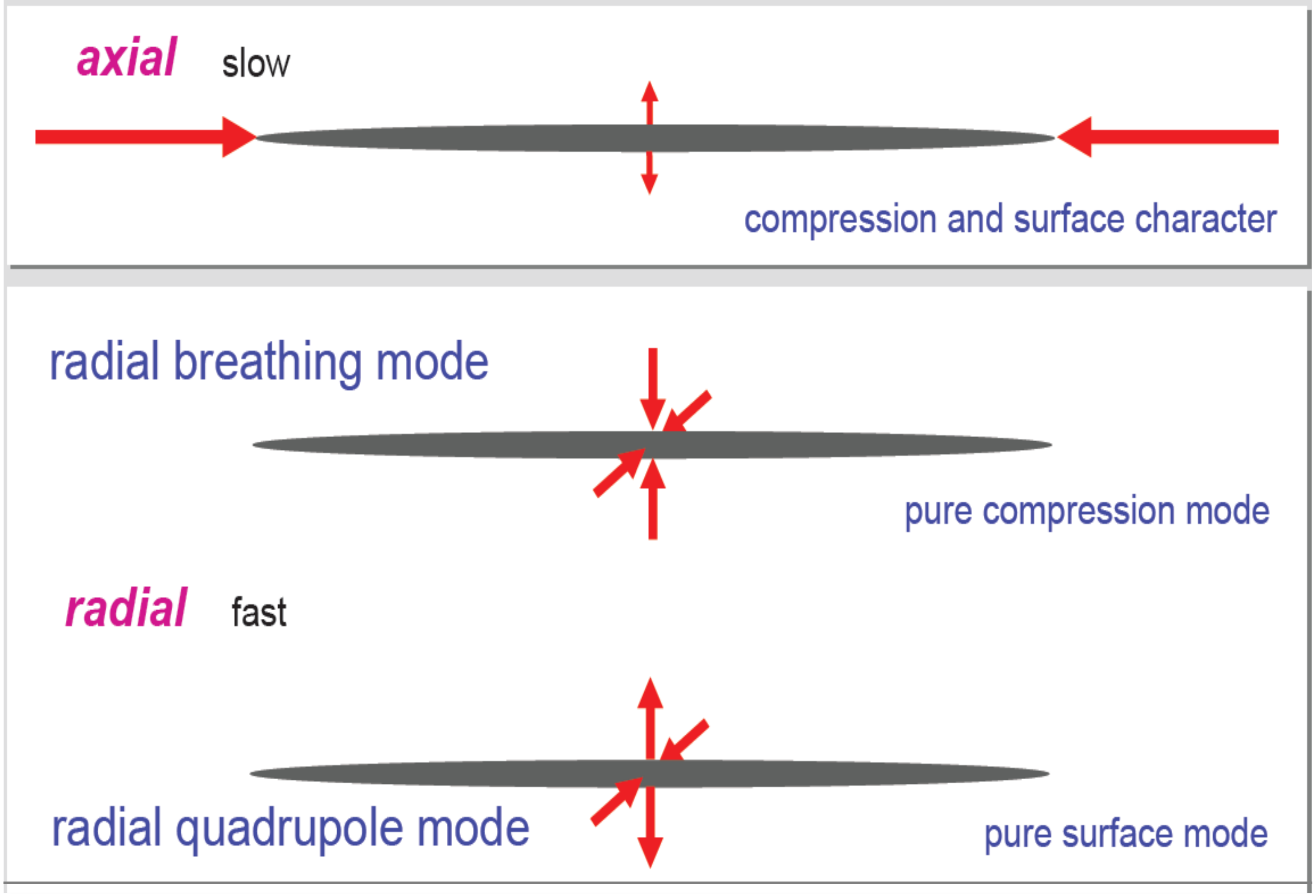
(Received 4 June 2004; published 10 November 2004)



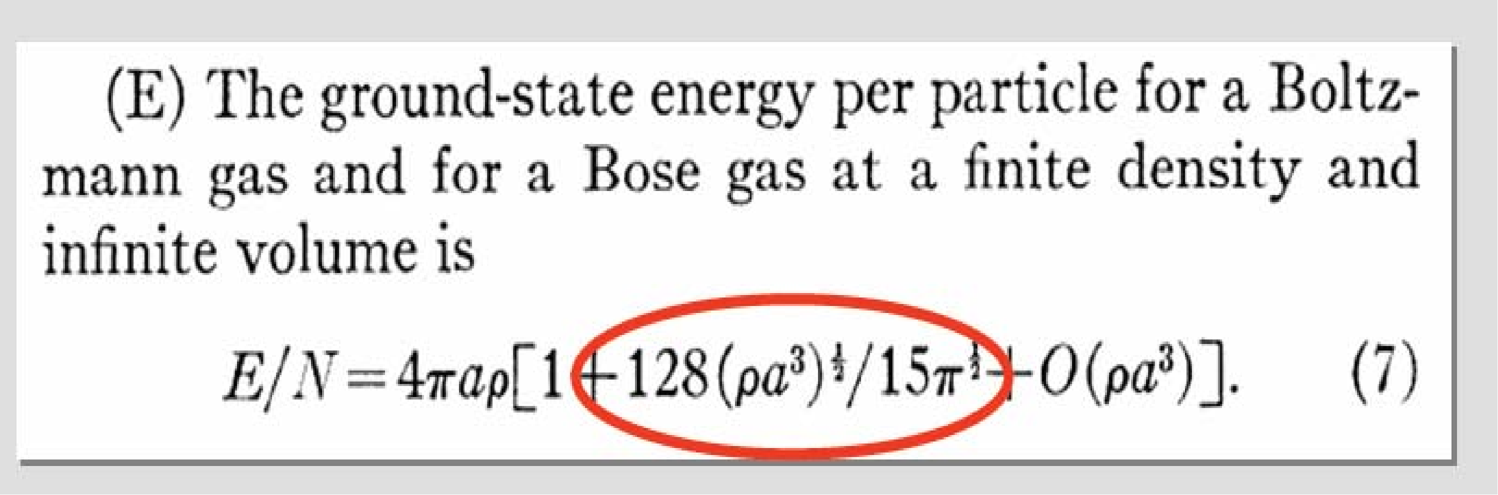
Lee-Huang-Yang correction !!!

Collective modes:
precision test of equation of state



Innsbruck and Duke univ.

Lee-Huang-Yang Correction



(E) The ground-state energy per particle for a Boltzmann gas and for a Bose gas at a finite density and infinite volume is

$$E/N=4\pi a\rho[1+128(\rho a^3)^{\frac{1}{2}}/15\pi^{\frac{1}{2}}+O(\rho a^3)]. \qquad (7)$$

Phys Rev 105, 1119 (1957)

Lee-Huang-Yang correction is positive
Up-shift in radial breathing mode frequency
on molecular BEC side

Radial breathing mode: Innsbruck expt

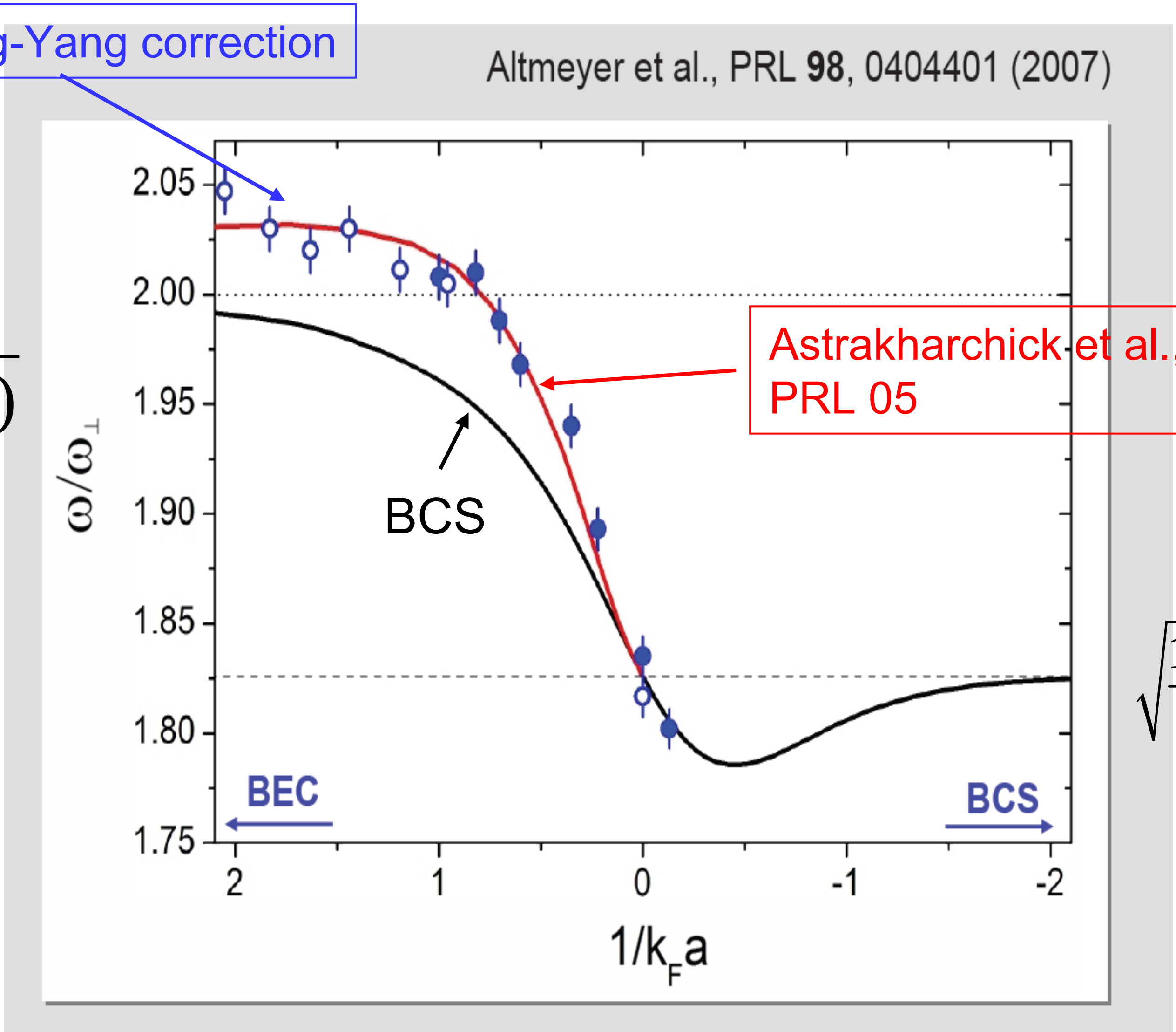
$$\mu \sim n^{\gamma}$$

$$\omega / \omega_{\perp} = \sqrt{2(\gamma + 1)}$$

BEC: 2

Unitarity and BCS:

$$\sqrt{\frac{10}{3}}$$



Lee-Huang-Yang correction

Altmeyer et al., PRL **98**, 0404401 (2007)

Astrakharchick et al., PRL 05

BCS

$$\sqrt{\frac{10}{3}}$$

Direct proof of superfluidity

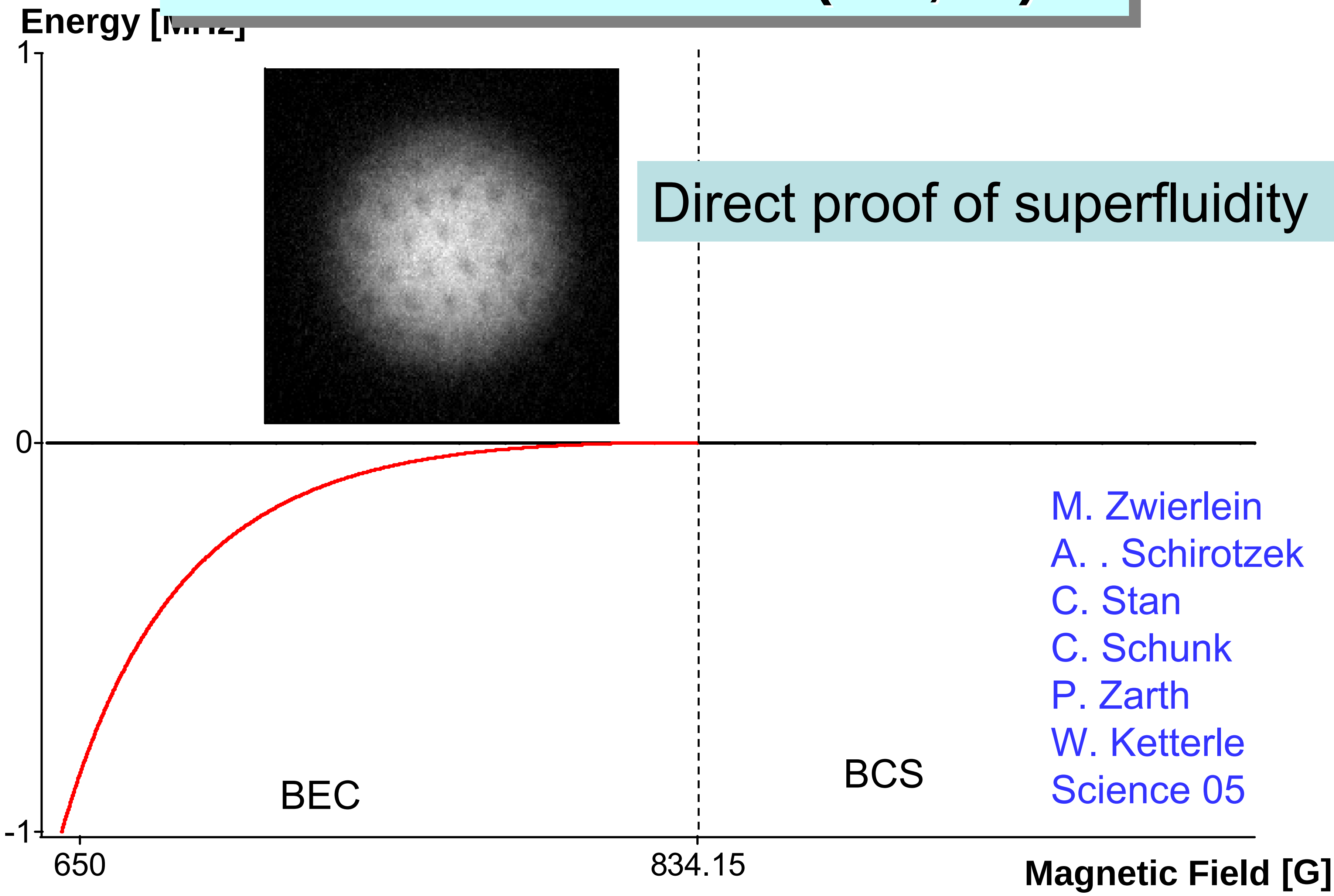
So far:
Anisotropic expansion
Collective modes
Pairing gap
Condensate fractions

are evidence for superfluid behavior

Direct proof of superfluidity in the system ?

Put the gas in rotation
In contrast to classical gas, the superfluid Fermi gas should exhibit quantized vortices, ($\hbar/2m$) (Lev Pitaevskii's lecture)

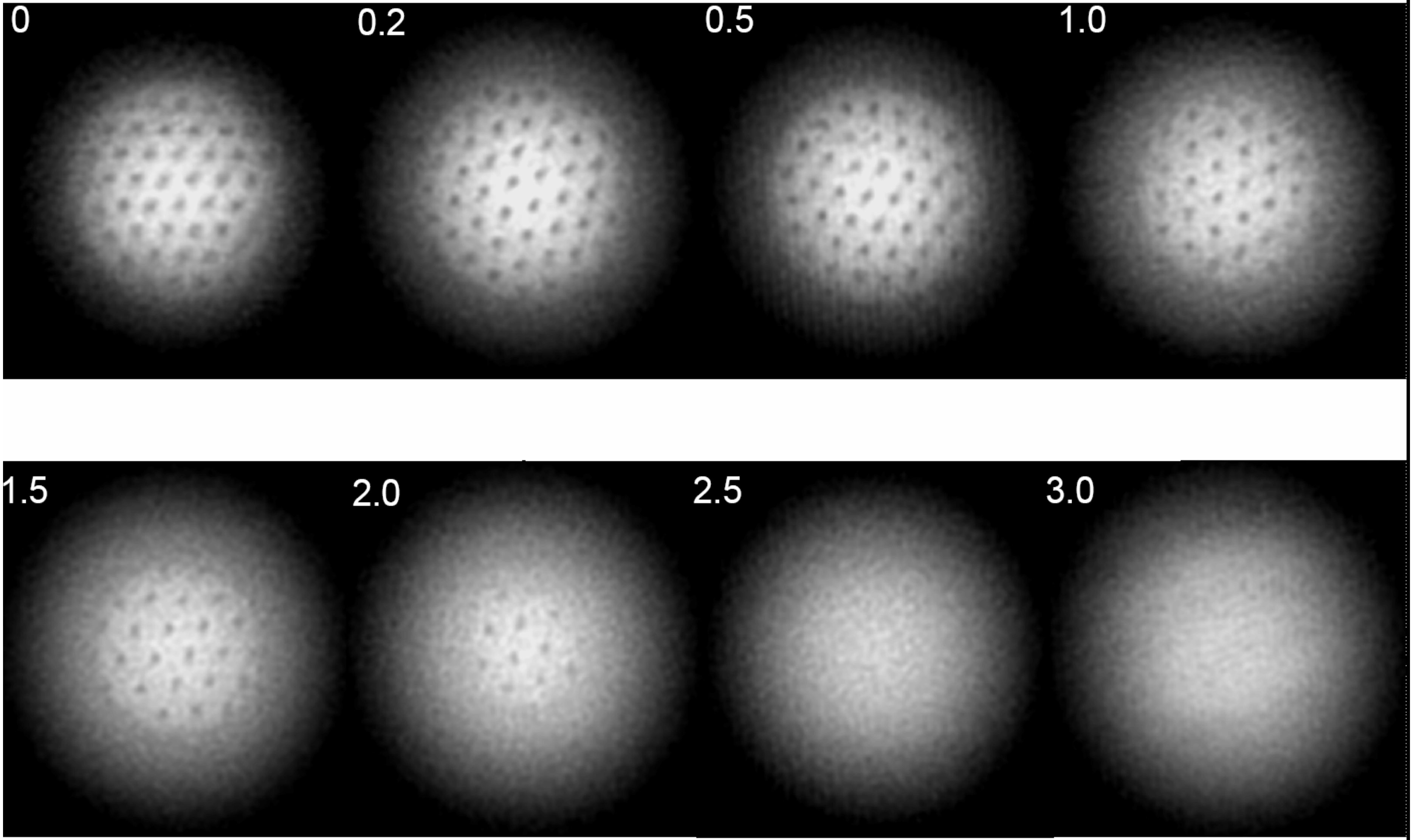
Observation of vortex lattices in the BEC-BCS crossover (MIT, 05)



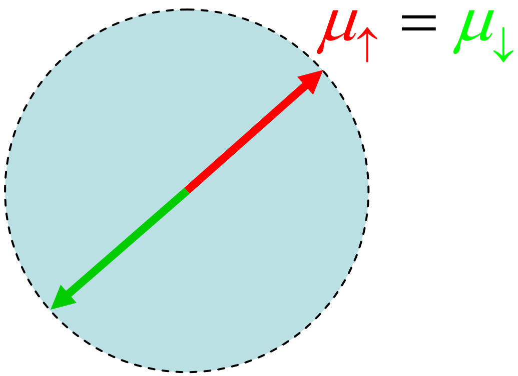
Direct proof of superfluidity

M. Zwierlein
A. . Schirotzek
C. Stan
C. Schunk
P. Zarth
W. Ketterle
Science 05

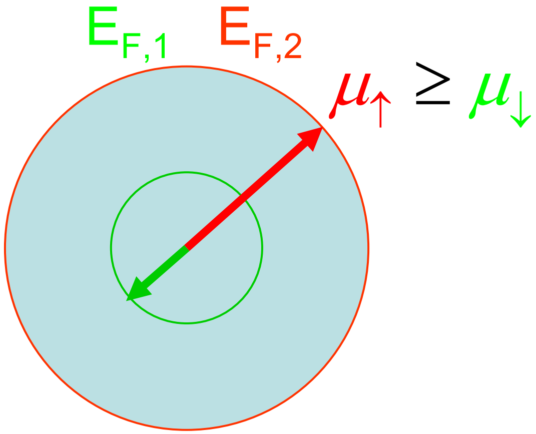
Pair breaking in TOF [ms] 930 G



Imbalanced Fermi gas: motivation



Attractive Fermi gas with equal spin population
$\Rightarrow$ BCS theory, pairing at edge of Fermi surface



What is the nature and existence of superfluidity when spin population is imbalanced ?
Mismatched density and/or pairing with different masses

Ex:
Superconductors in magnetic field or quark matter
Cold gases: Mit and Rice expt

$$E_{F,i} = \frac{\hbar^2 k_{F,i}^2}{2m_i} = \frac{\hbar^2}{2m_i}\left(6\pi^2 n_i\right)^{2/3}$$

Overview of Theoretical scenarios

Chandrasekhar and Clogston: stability of the paired state : $\mu_\uparrow > \mu_\downarrow$

Conversion of a particle: $\downarrow \to \uparrow$

Decrease the grand potential $H - \mu_\uparrow N_\uparrow - \mu_\downarrow N_\downarrow$: $\mu_\uparrow - \mu_\downarrow$

Cost of pair breaking: Δ

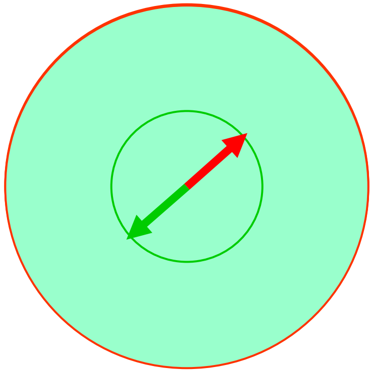
$\Rightarrow$ Paired state stable for $\mu_\uparrow - \mu_\downarrow < \Delta$

And beyond?

Polarized phase : One spin species (Carlson, PRL **95**, 060401 (2005))

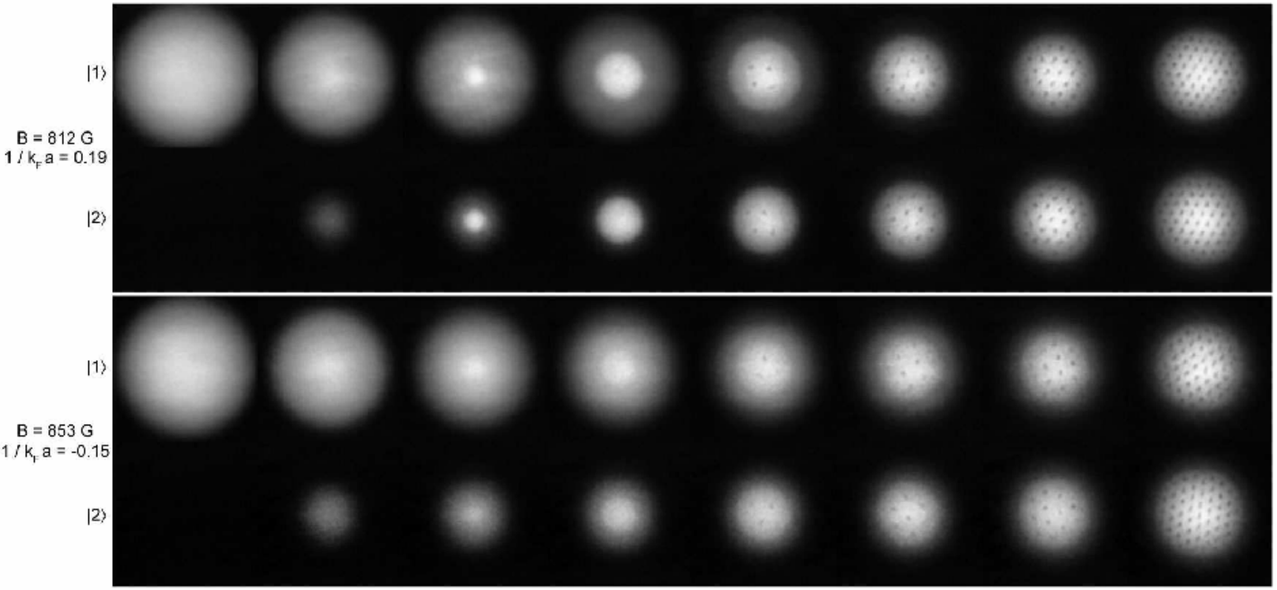
FFLO Phase (Fulde Ferrell Larkin Ovchinikov) : pairing in $\mathbf{k}_\uparrow - \mathbf{k}_\downarrow \neq 0$
(C. Mora et R. Combescot, PRB **71**, 214504 (2005))

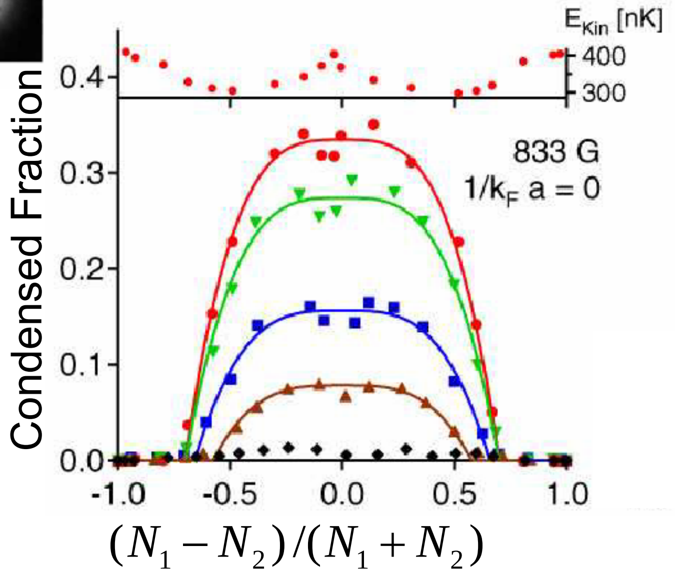
Sarma phase (internal gap) : pairing in $\mathbf{k}_\uparrow - \mathbf{k}_\downarrow = 0$
⬇opening of a gap in the Fermi sea of majority species. (Liu, PRL **90**, 047002 (2003))



MIT experiment

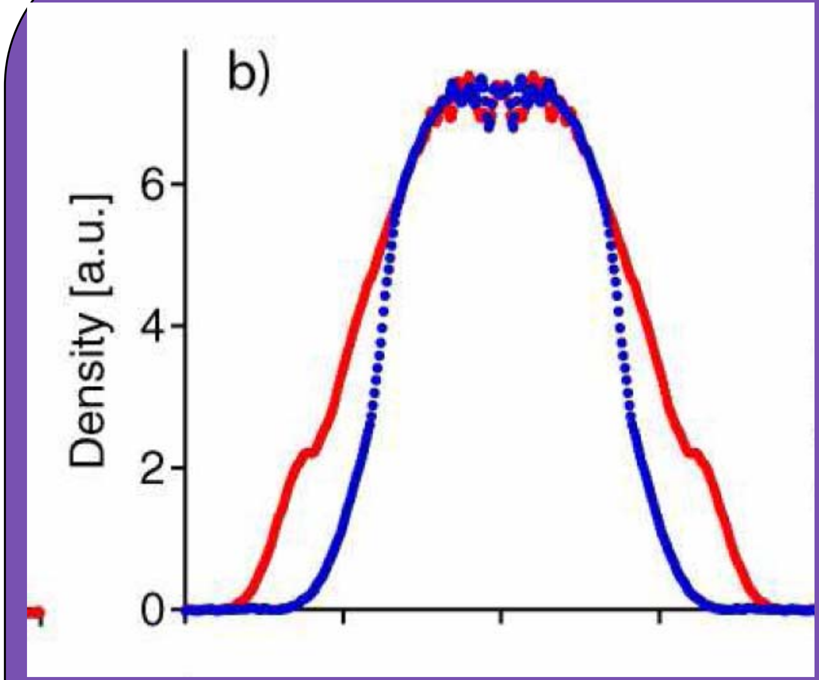
(Science Express, December 22, 2005)





Superfluidity observed in Time of flight
Loss of superfluidity for large
Spin population imbalance

Experimental results



MIT: 3 phases

- Fully paired superfluid core

-Intermediate mixture

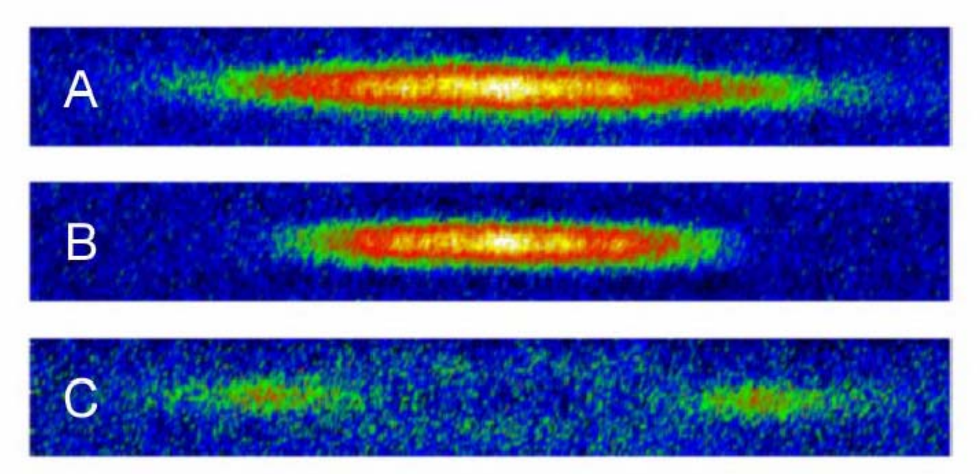
-Fully polarized rim

M.W. Zwierlein, *et al.*, Science, **311** (2006) 492.

Rice: 2 phases

Fully paired superfluid core

Fully polarized rim

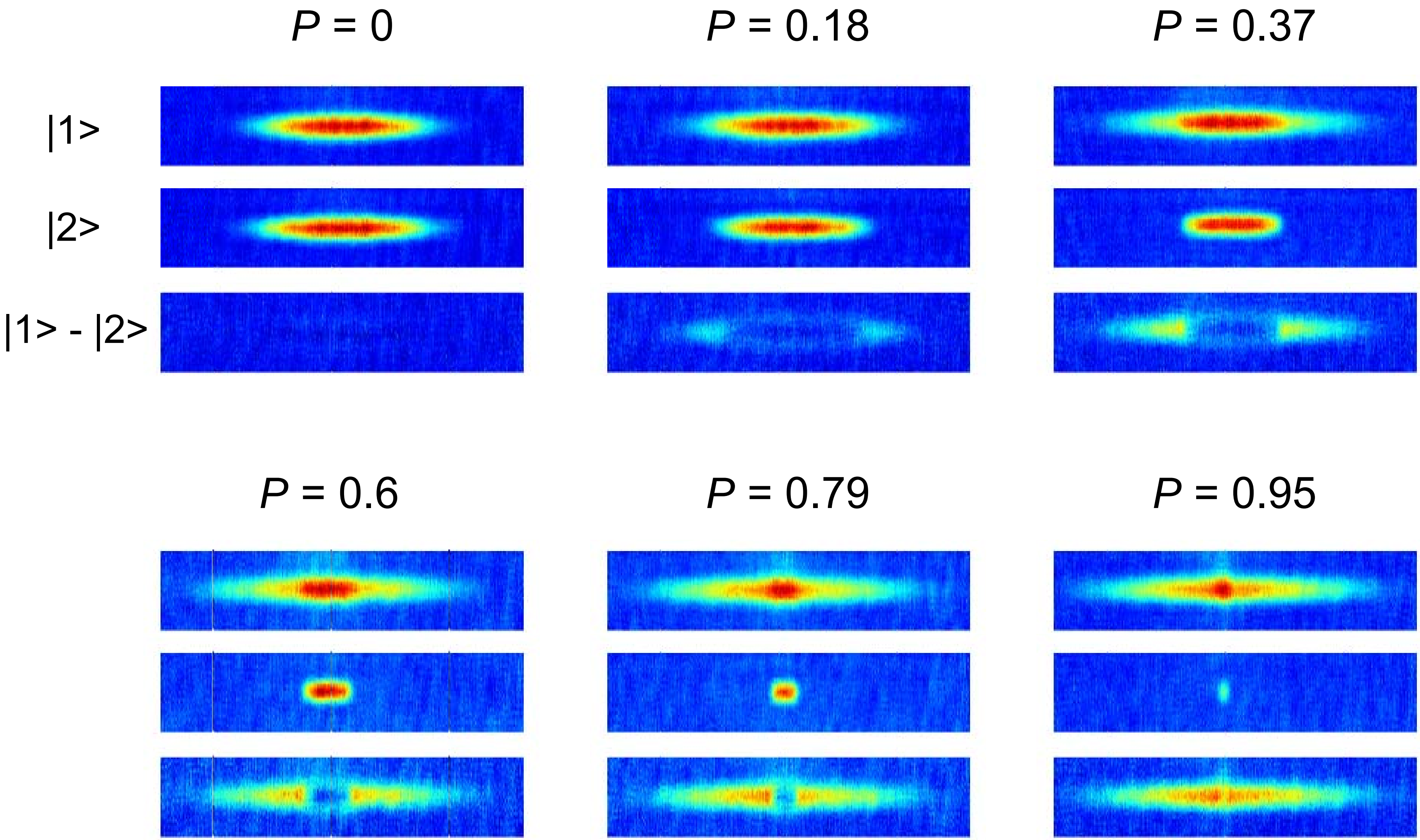


G. Partridge, W. Li , R.I. Kamar, Y.-A. Liao, R.G. Hulet, Science, **311** (2006) 503.

G. Partridge et al., Cond-mat 0608455

Rice Univ: phase separation at unitarity

$$P = (N_1 - N_2)\,/\,(N_1 + N_2)$$



Partridge *et al*., PRL **97**, 190407 (2006)

Avalanche of recent publications !

P. Pieri and G.C. Strinati cond-mat/0512354 : diagrammatic method
Extrapolation from BEC regime

W. Yi and L.-M. Duan, cond-mat/0601006 : BCS at finite temperature

M. Haque and H.T.C. Stoof, cond-mat/0601321 : BCS at T=0

T.N. de Silva and E.J. Mueller, cond-mat/0601314 : BCS at T=0

D. Sheehy, L. Radzihovsky, PRL 06
A. Bulgac, M. McNeil Forbes ’06
K. Levin et al., 06
M. Parish, Nature Physics 3 ’07

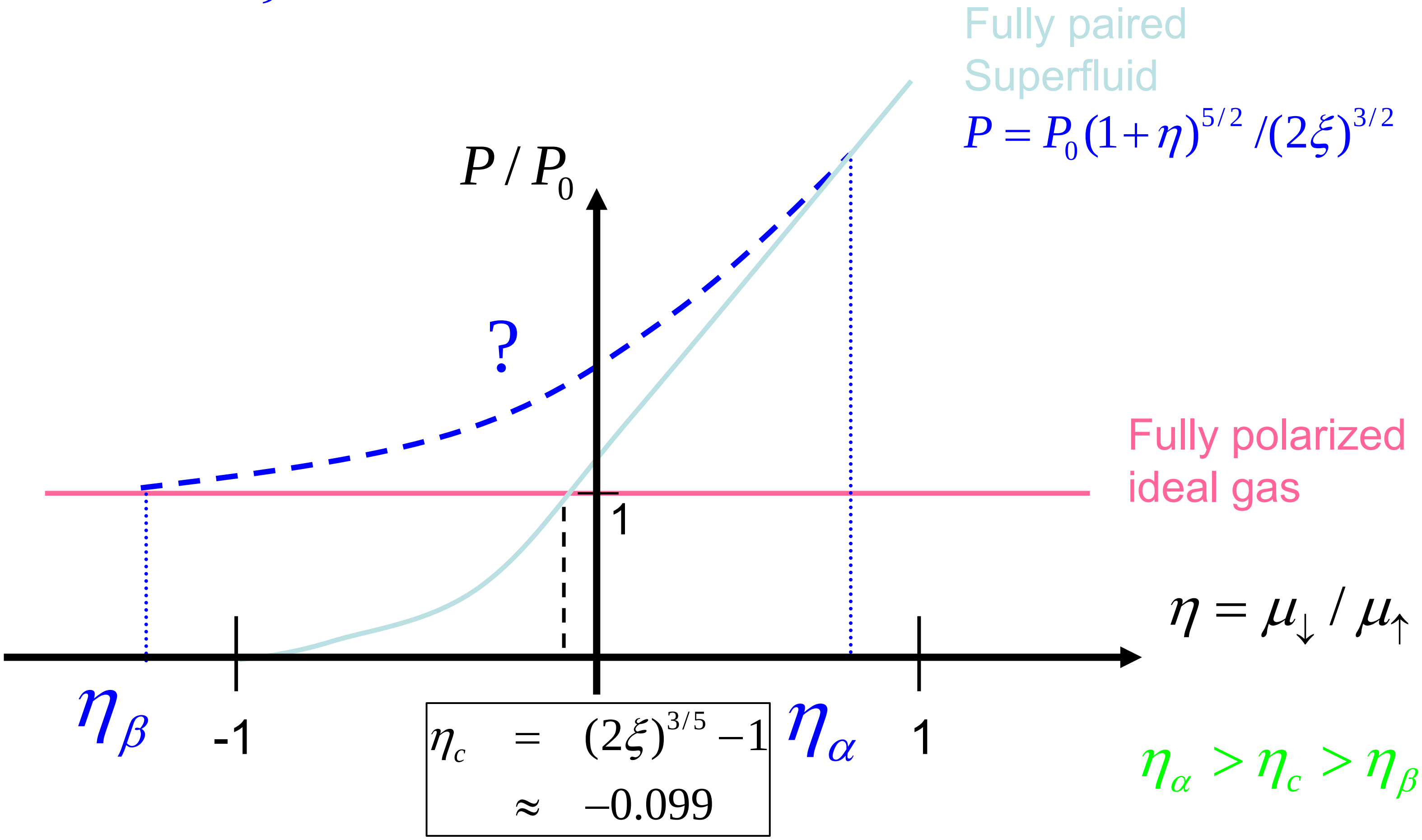
………

F. Chevy approach:
Assumptions:
1) Unitarity: universal parameter $\mu = (1+\beta)\ E_F = \xi E_F$ known
2) Grand canonical description, Local density approx,
3) T=0 approach

Universal phase diagram of the homogeneous unitary system (2)

F. Chevy, PRA 06

$$\left.\begin{aligned}\Omega &= -PV \\ dP &= \sum_{\sigma=\updownarrow} n_\sigma d\mu_\sigma\end{aligned}\right\} \Rightarrow \text{Just need to know } n(\mu)$$



$$\begin{aligned}\eta_c &= (2\xi)^{3/5} - 1 \\ &\approx -0.099\end{aligned}$$

$\eta_\alpha > \eta_c > \eta_\beta$

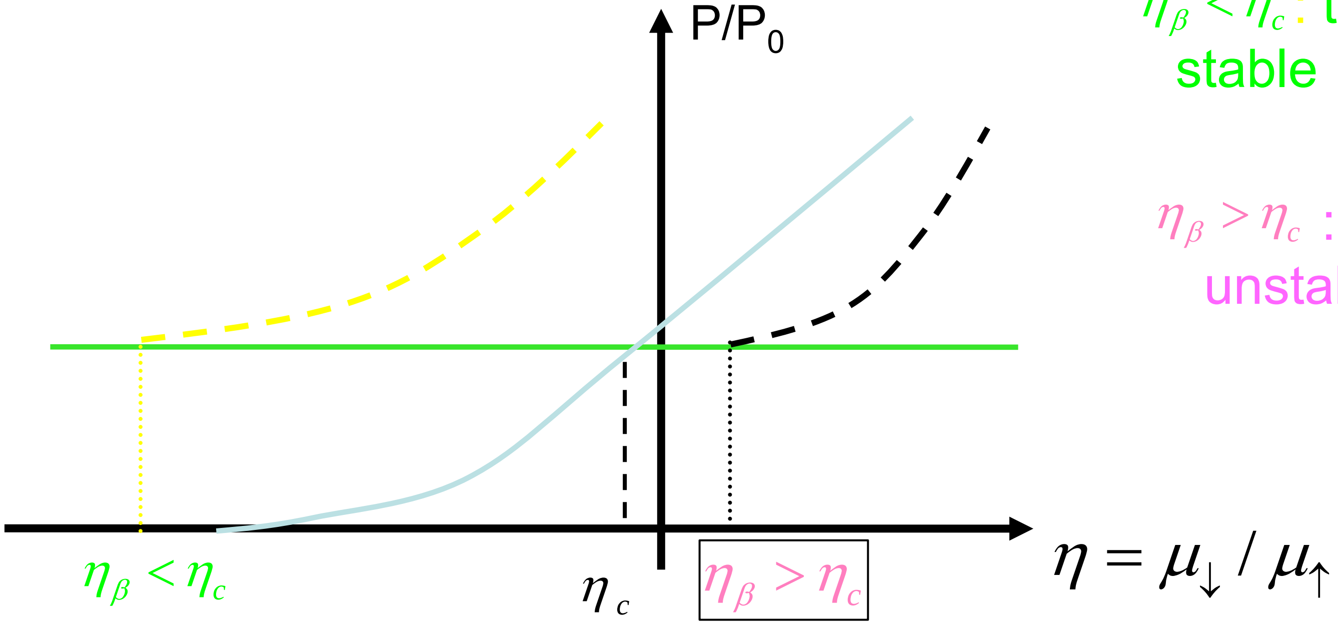
Theoretical evidence for an intermediate phase

General properties of a mixed branch?

Step 1: calculate the energy E of a single impurity atom immersed in a Fermi sea (E= $\mu_\downarrow$, with $n_\downarrow = 0^+$)

For a= ∞ , E=-0.606 E_F✸ ⬇η_β< - 0.606 < η_c~ -0.1

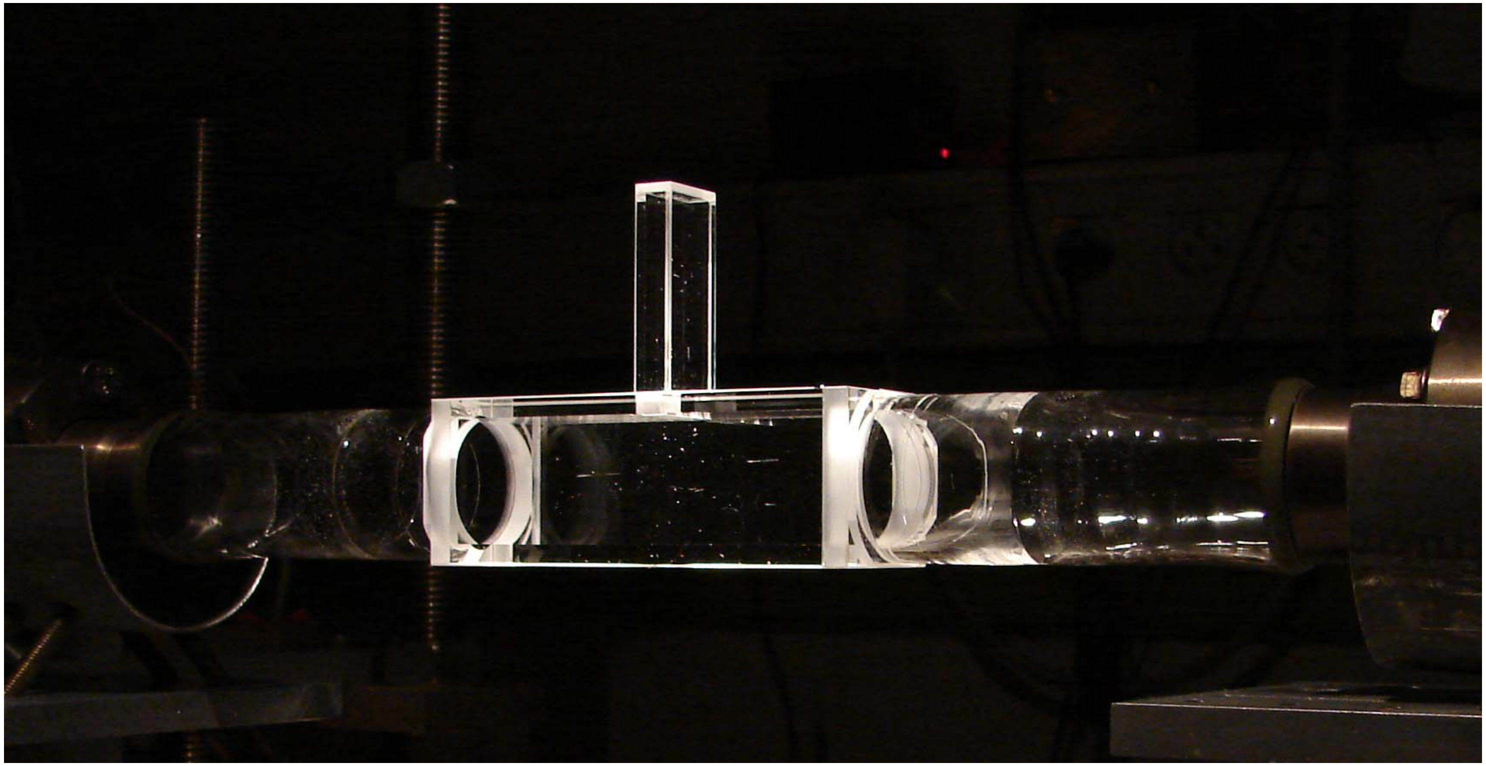
Step 2: dP/dμ_σ= n > 0



$\eta_\beta < \eta_c$: the new branch is stable

$\eta_\beta > \eta_c$: the new branch is unstable

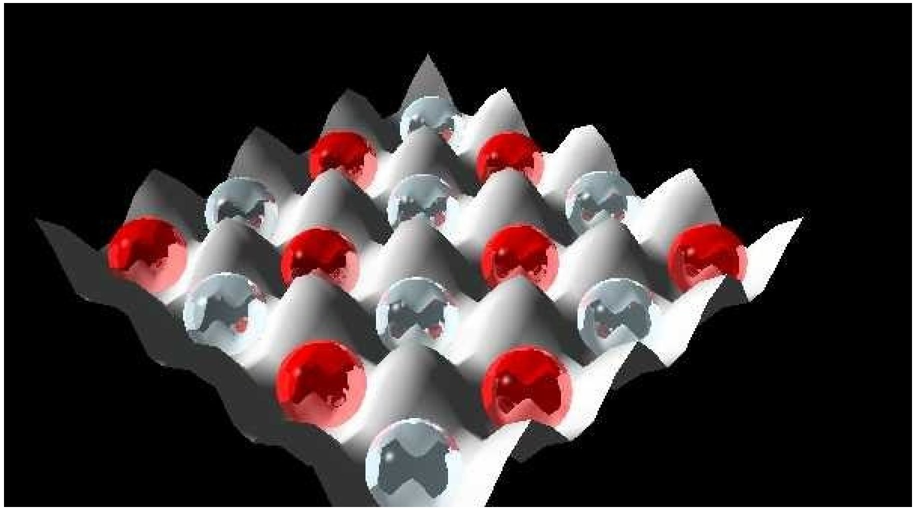
New experimental setup



Enlarged glass cell
New laser sources: 120 mW diodes operating at 75 degree C
New Zeeman slower
More stable Ioffe-Pritchard trap
120 Watt far detuned optical trap (Fiber laser)
Access for 3D optical lattice
2 10^{10} ^{7}Li atoms in MOT → expected increase of x10 in ^{6}Li number
Ongoing: Transfer into magnetic trap

Open questions and perspectives

- Imbalance of spin populations, properties of mixed phase ?, phase diagram
  phase separation, role of trap anisotropy (M. Randeria)
- Single particle excitations by Raman transitions, T.L. Dao et al., cond –mat 0611206
- p-wave pairing ?
- **Fermions in optical lattices: simulation of condensed matter Hamiltonians**
- Fermionic Hubbard model
- ^{6}Li: Transition toward antiferromagnetic order: Néel transition
- Lattices with frustration
- Fermi-Fermi mixtures : pairing with different masses
- Bose-Fermi mixtures



$T_{\text{Néel}} \sim 30$ nK

F. Werner et al., PRL 05

Thank you for your attention!

Come visit the lab at ENS !