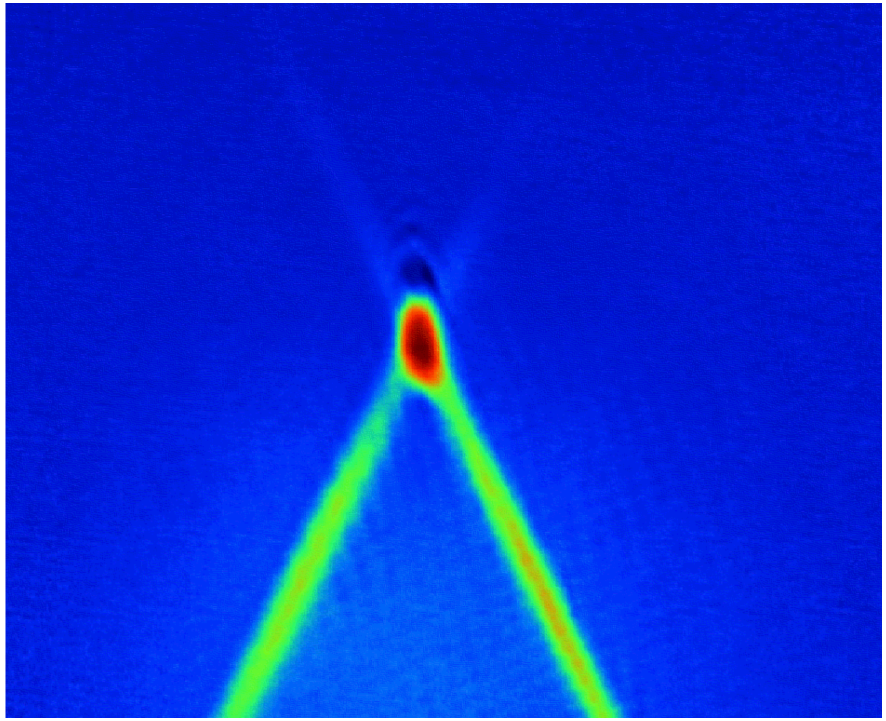
A Mixture of Bose and Fermi Superfluids



C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

Enrico Fermi School
Quantum Matter at Ultralow Temperatures
Varenna, July 8, 2014

The ENS Fermi Gas Team

F. Chevy, Y. Castin, F. Werner, C.S.

Lithium Exp.

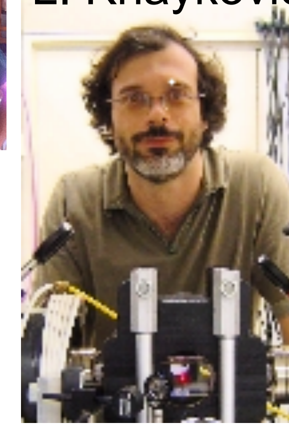
I. Ferrier-Barbut
M. Delehaye
S. Laurent
M. Pierce
A. Grier
B. Rem

U. Eismann
A. Bergschneider
T. Langen
N. Navon
S. Nascimbène
K. Jiang

Lithium-Potassium Exp.

F. Sievers,
D. Fernandes
N. Kretschmar
M. Rabinovic
D. Suchet

L. Khaykovich



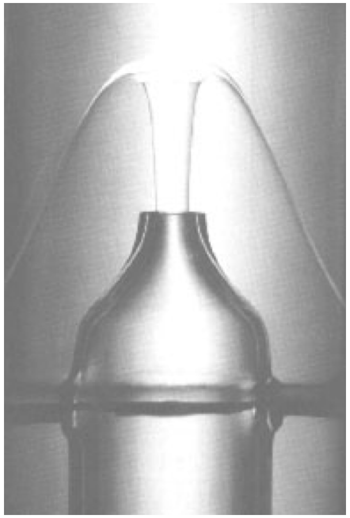
arXiv:1404.2548 To appear in Science, July 17

I. Ferrier-Barbut, M. Delehaye, S. Laurent, A. T. Grier, M. Pierce, B. S. Rem, F. Chevy, and C. Salomon

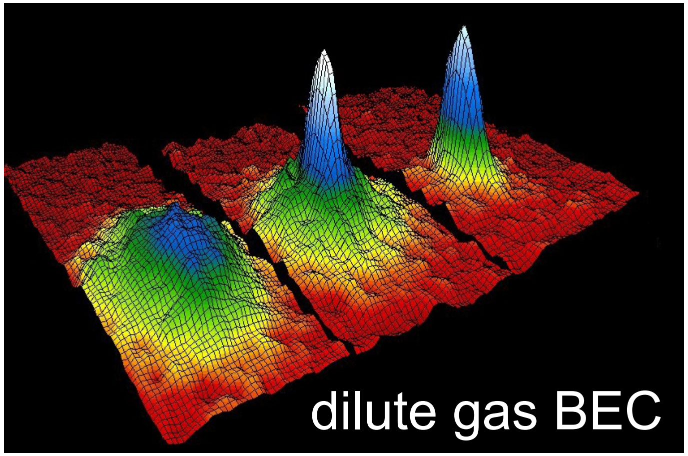
103 years of quantum fluids

Bose Einstein condensate

^4He

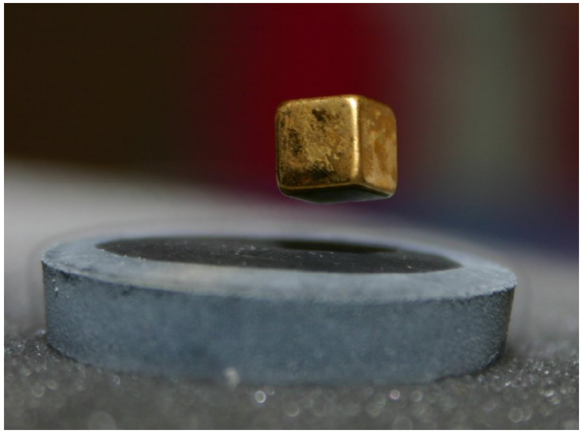


T~ 2.2 K



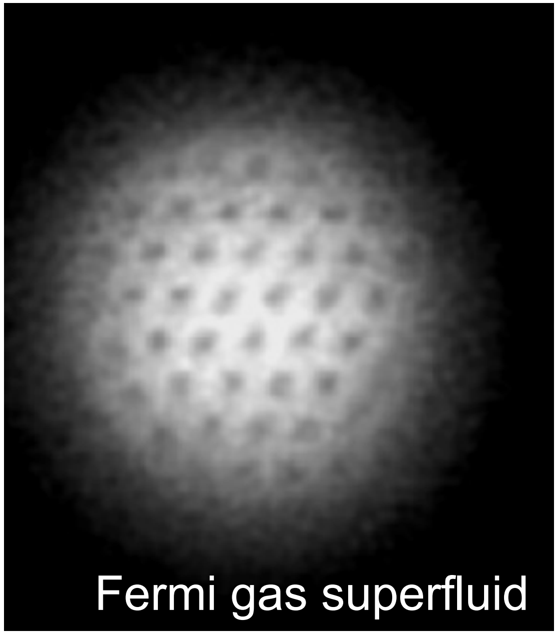
100 nK

Superconductivity



High T_c
77 K

^3He
2.5 mK

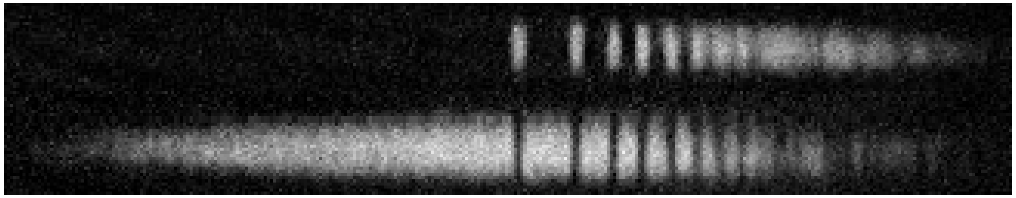


Superfluid mixtures

Bose-Bose superfluid mixtures first observed long ago:

Two hyperfine states in Rb at JILA (Myatt et al. ’97) and vortex production
Spinor condensates at MIT, Hamburg, Berkeley, ENS, ….
Dark-bright soliton production in two Rb BEC, Engels group, PRL 2011

Rb



$|2, 2\rangle$

$|1, 1\rangle$

Bose-Bose and Bose-Fermi Mixtures

Bose-Bose superfluid mixtures first observed long ago:
Two hyperfine states in Rb at JILA (Myatt et al. '97) and vortex production
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Bose-Fermi mixtures

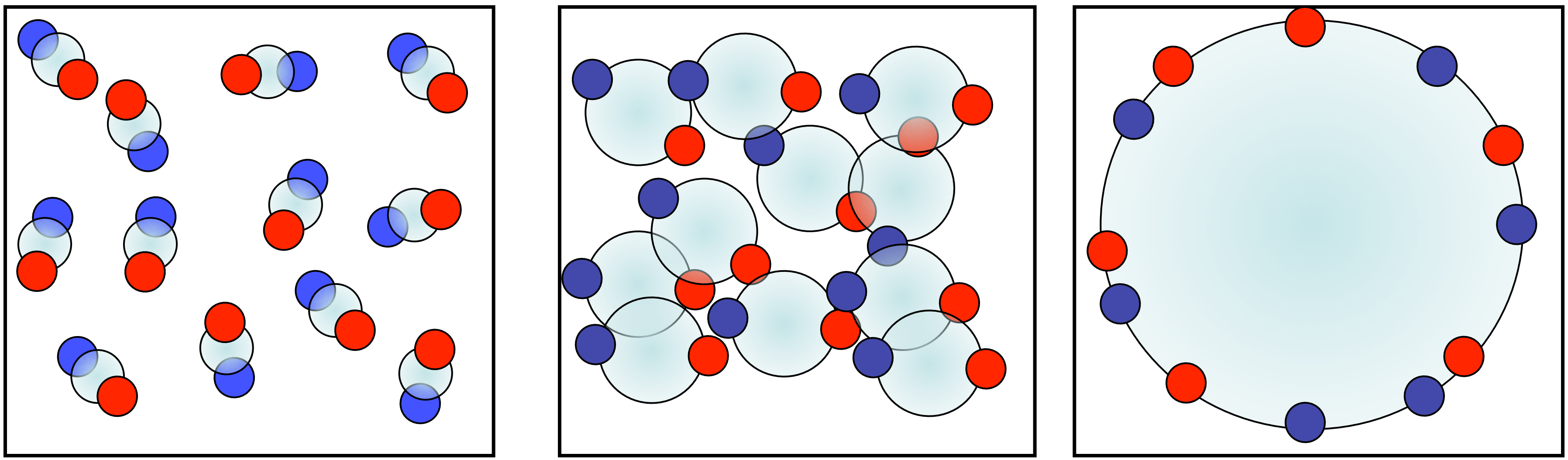
^{7}Li - ^{6}Li at ENS, Rice
^{23}Na - ^{6}Li at MIT, ^{6}Li-^{133}Cs in Chicago, Heidelberg,
^{40}K - ^{87}Rb at LENS, Hamburg, ETH, JILA, Innsbruck, Singapore,Taiyuan,…
^{23}Na-^{40}K at MIT, MPQ
Isotopes of Yb, Kyoto and Sr Innsbruck, ……

But no Bose-Fermi superfluids simultaneously !
Decades of attempts with ^{4}He and ^{3}He

- Experiment with ^{6}Li-^{7}Li
- Excitation of center of mass modes: first sounds
- Simple model
- Critical velocity and perspectives

Fermi Superfluid in the BEC-BCS Crosover
10 year anniversary !

^{6}Li Fermions with two spin states and attractive interaction



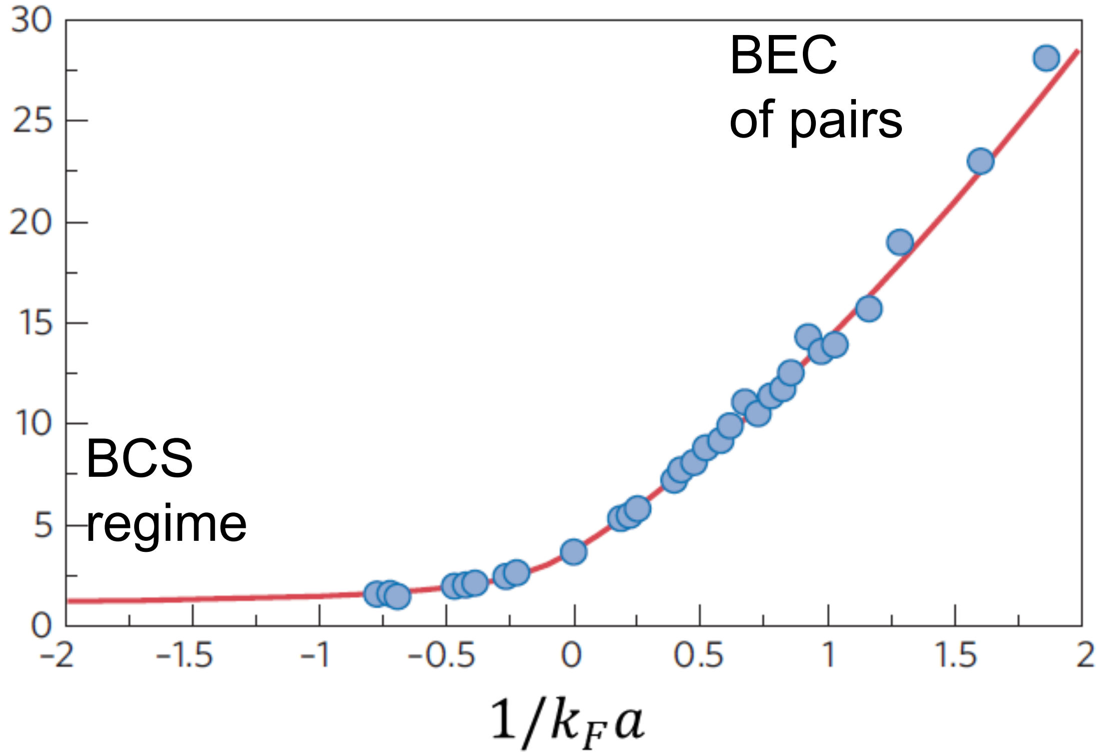
Molecular condensate
Strongly bound
Size: $a << n^{-1/3}$
$n^{-1/3}$: average distance between particles

On resonance
$na^3 >> 1$
$k_F a \geq 1$
Pairs stabilized by Fermi sea
Size of pairs
$hv_F/\Delta \sim k_F^{-1}$

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

Equation of State in the crossover

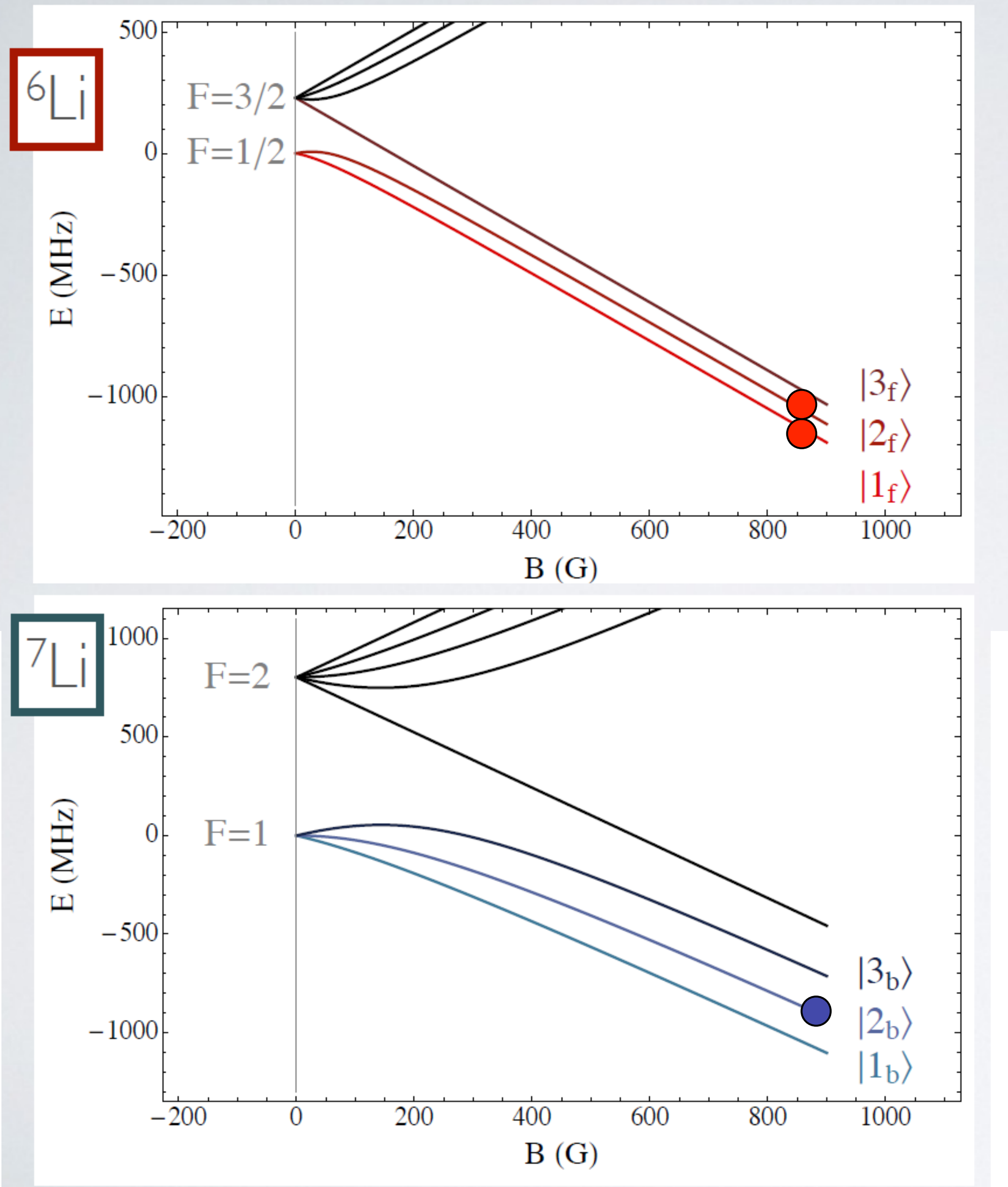
Pressure equation of state $P/P_0 = f(1/k_F a)$



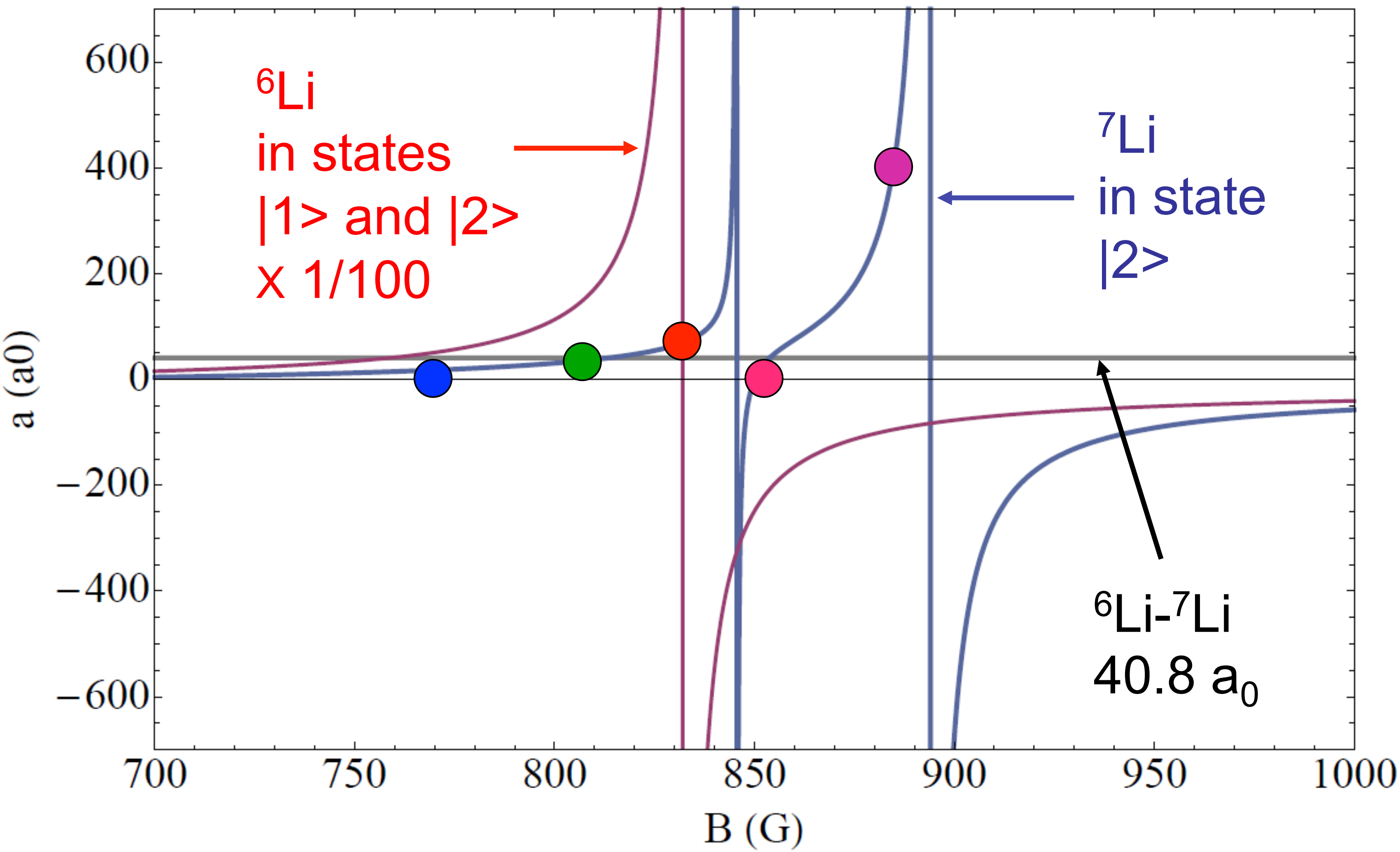
BCS-BEC crossover
at T~ 0

N. Navon, S. Nascimbène, F. Chevy, C. Salomon, *Science* **328**, 729-732 (2010)
S. Nascimbène, N. Navon, K. Jiang, F. Chevy, C. Salomon, *Nature* 463 (2010)

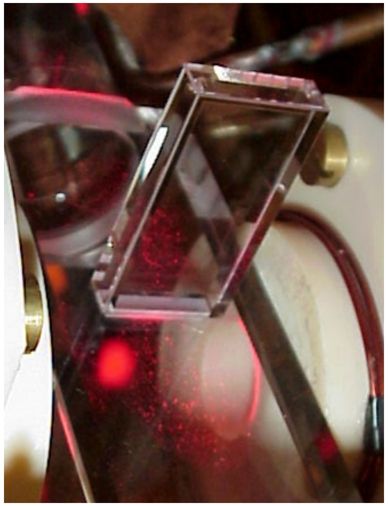
^{7}Li and ^{6}Li isotopes



Tuning interactions in ^{7}Li and ^{6}Li

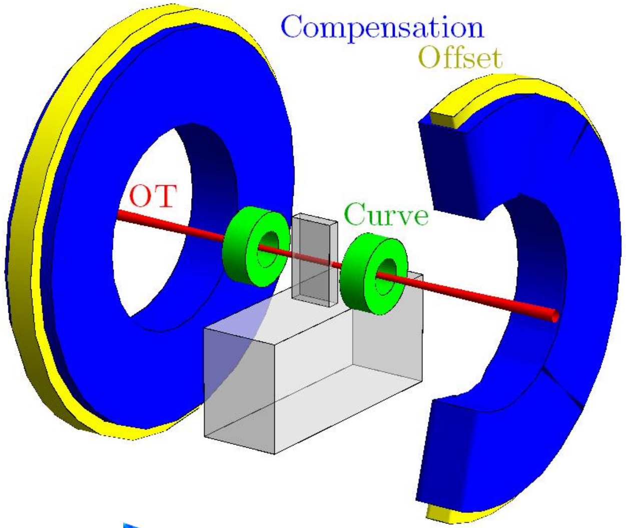


Experimental Setup



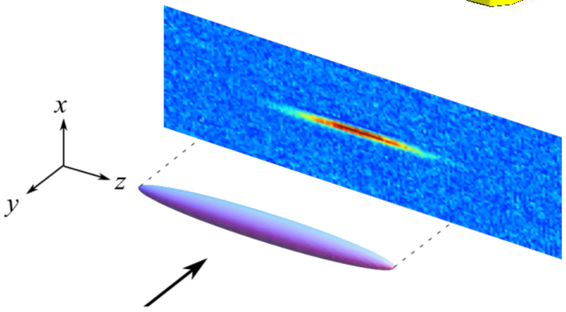
Magneto-optical trap of bosonic ^{7}Li and fermionic ^{6}Li

After evaporation in a magnetic trap we load the atoms in a single beam optical trap (OT) with magnetic axial confinement. T~ 40 μK



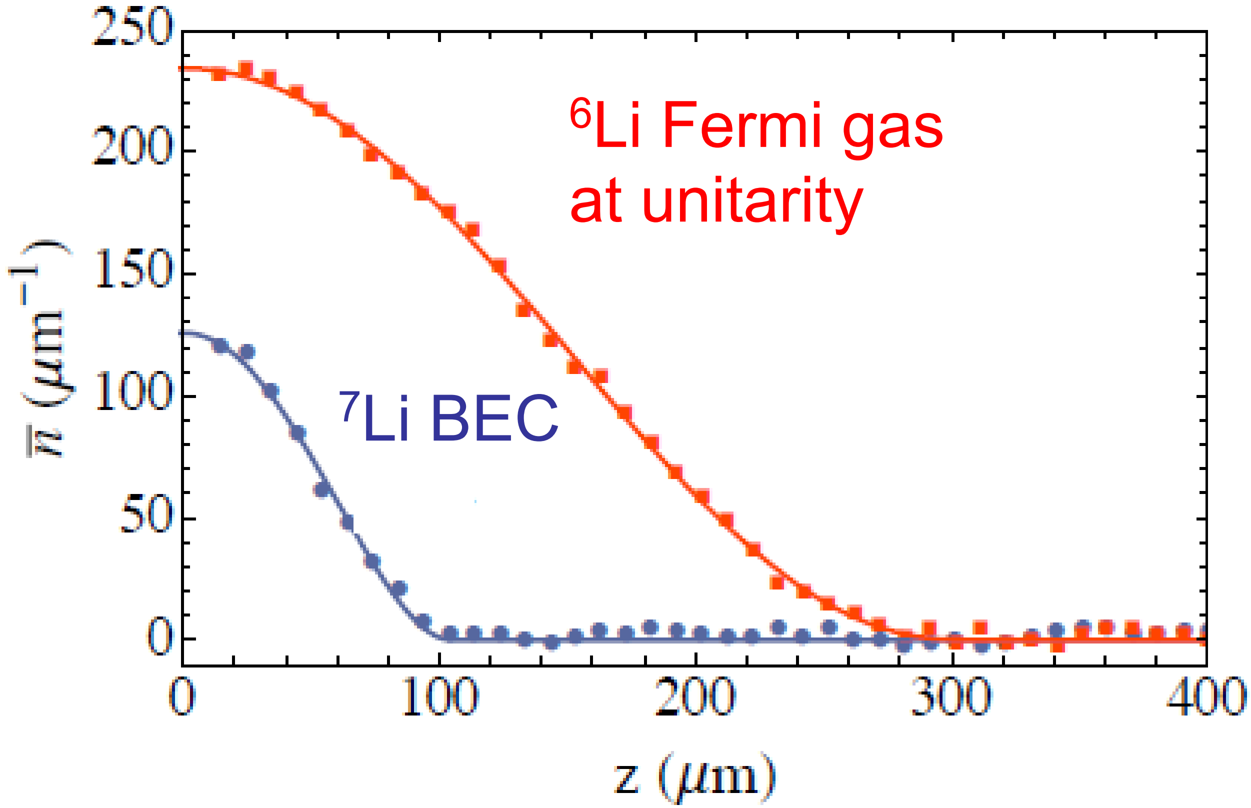
Evaporative cooling of mixture in OT

~ 4 second ramp, T~ 100 nK



Absorption imaging of the *in-situ* density distributions or Time of Flight

In situ Profiles



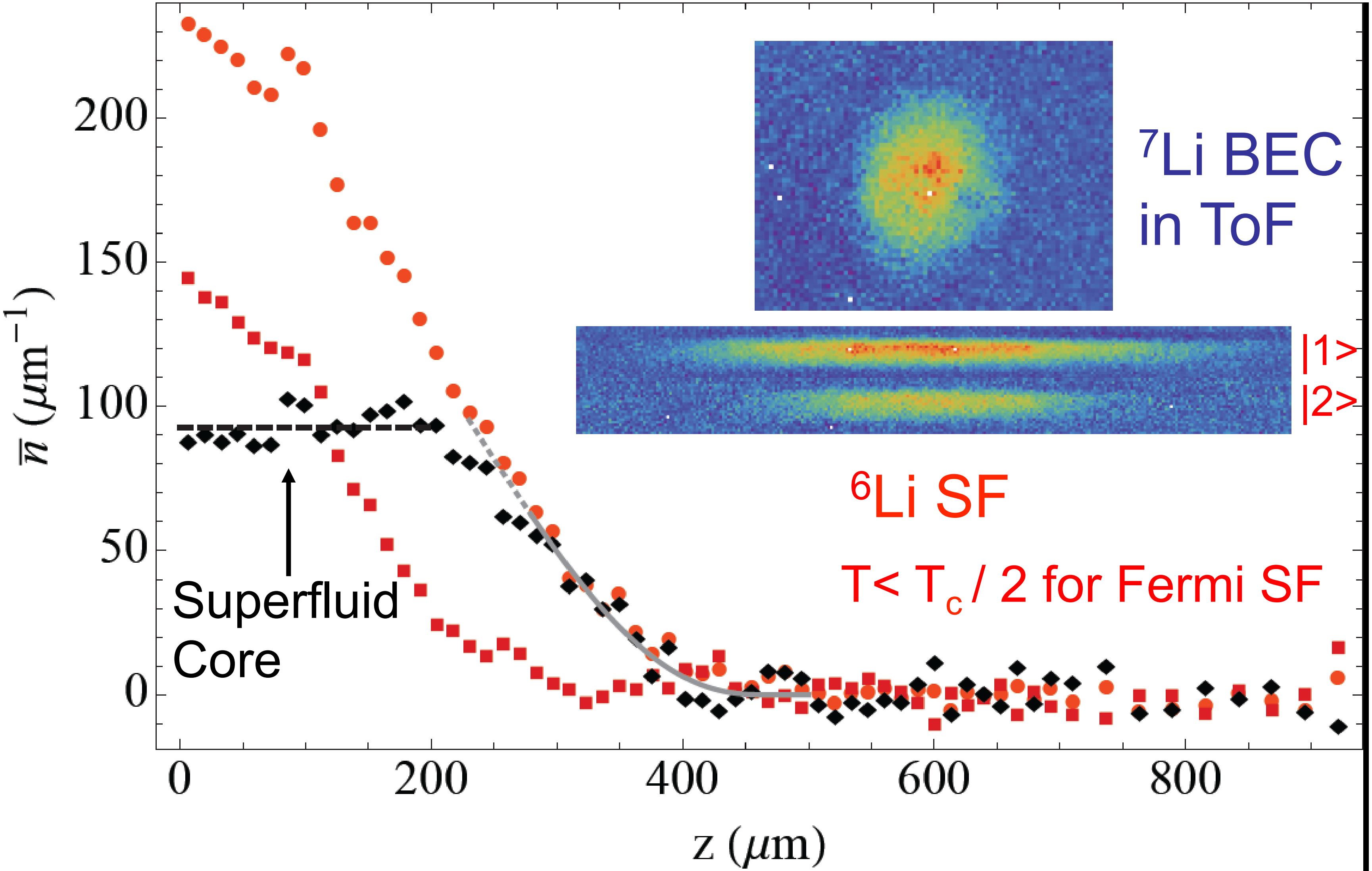
Trap frequencies: ν_z=15.6 Hz
for bosons, ν_{rad}= 440 Hz

Lifetime of mixture : 7s in shallowest trap

N_B=2 10^4
T=90 nK
N_0/N_B> 80%
$T<T_c/2$

N_F=2 10^5
T= 90 nK=$0.16T_F$
T_F= 560nK
Upper bound for T

Mixture of Bose and Fermi Superfluids



Method used at MIT ’06, Rice ’06, ENS ‘09

First sounds in mixture of superfluids

Superfluids have collective excitations

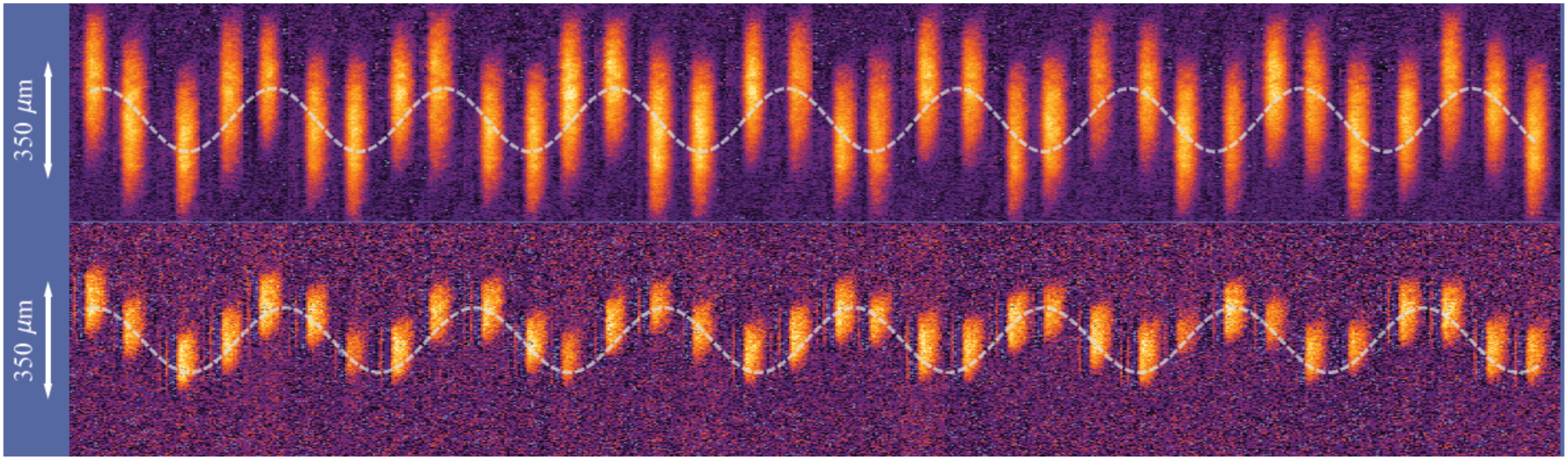
In a mixture of two superfluids, one expects
two first sound modes ie density waves excitations
Volovik, Mineev, Khalatnikov, JETP, 42, 342,(1975)

In a trap the lowest acoustic mode corresponds to
center of mass oscillations of the clouds (dipole mode)

We displace the axial position of the clouds by
having the waist of the dipole trap shifted from the
magnetic trap minimum.

Long-lived Oscillations of both Superfluids

Fermi Superfluid



BEC

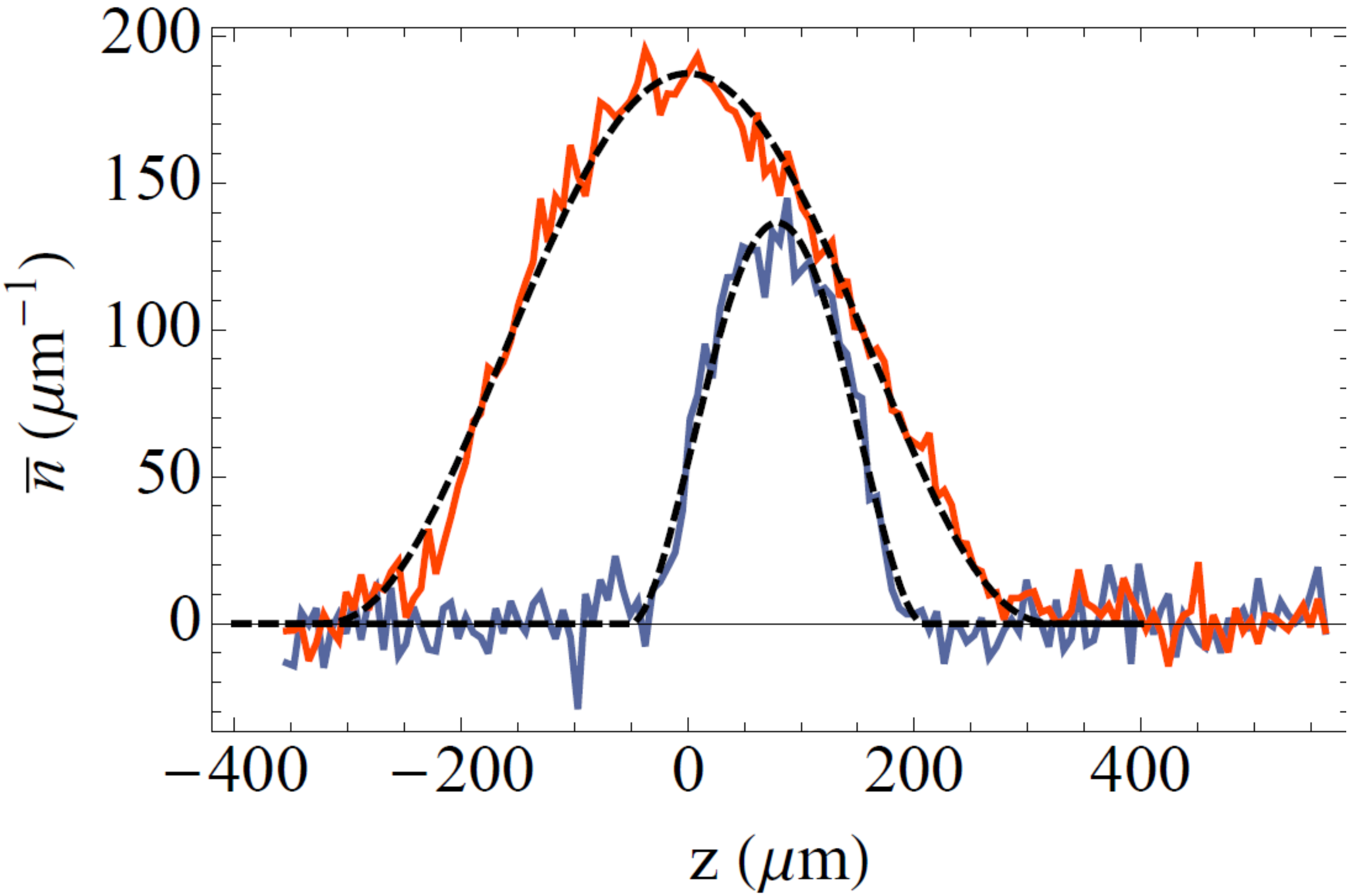
$\tilde{\omega}_6 = 2\pi \times 17.06(1) Hz$ $\omega_6 = 2\pi \times 17.14(3) Hz$

$\tilde{\omega}_7 = 2\pi \times 15.40(1) Hz$ $\omega_7 = 2\pi \times 15.63(1) Hz$

Coupled Superfluids

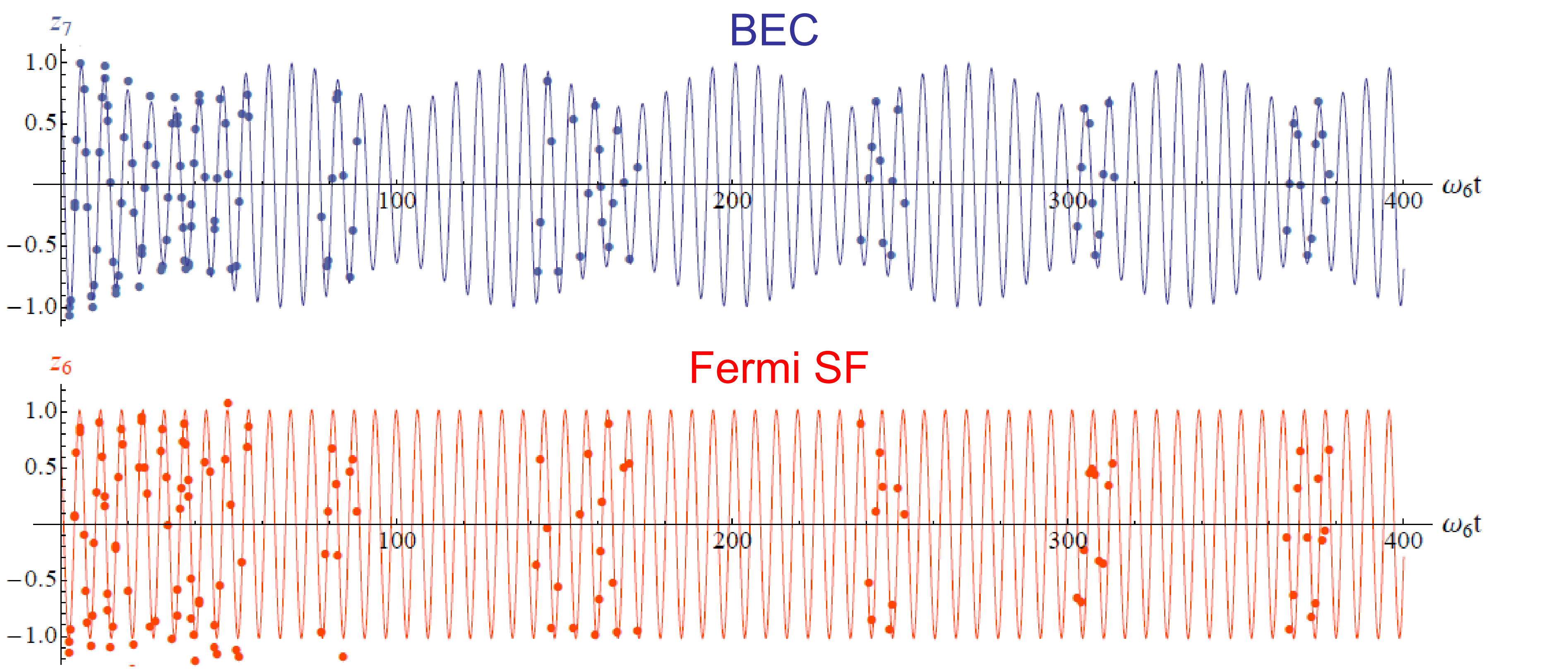
Single Superfluid
Ratio = $(7/6)^{1/2} = (m_7/m_6)^{1/2}$

Relative displacement of superfluids



No damping only when the max relative velocity < 2 cm/s

Oscillations of both superfluids



0 4 s

Very small damping !

Modulation of the ^{7}Li BEC amplitude by ~30% at $(\tilde{\omega}_6 - \tilde{\omega}_7)/2\pi$

Mean field model

1.5% down shift in ^{7}Li BEC frequency

BEC osc. amplitude beat at frequency $(\tilde{\omega}_6 - \tilde{\omega}_7)/2\pi$

Weak interaction regime: $k_F a_{67} << 1$ and $N_7 << N_6$

Boson effective potential $V_{eff} = V(r) + g_{67} n_6(r) \quad with\ g_{67} = \frac{2\pi\hbar^2 a_{67}}{m_{67}}$

$$m_{67} = m_6 m_7 / (m_6 + m_7)$$

LDA $\quad n_6(r) = n_6^0(\mu_6^0 - V(r))$

Where $n_6(\mu)$ is the Eq. of State of the stationary Fermi gas.

For the small BEC: $V(r) << \mu_6^0$

Expand $\quad n_6(r) \approx n_6^0(\mu_6^0) - V(r)\frac{dn_6^0}{d\mu_6} + ...$

Effective potential

With TF radius of BEC<< TF radius of Fermi SF, we get:

$$V_{eff} = g_{67} n_6(0) + V(r)\left[1 - g_{67}\left(\frac{dn_6^{(0)}}{d\mu_6}\right)_0\right]$$

The potential remains harmonic with rescaled frequency

$$\tilde{\omega}_7 = \omega_7 \sqrt{1 - g_{67}\left(\frac{dn^{(0)}}{d\mu_6}\right)_0}$$

At unitarity $\mu_6 = \xi\hbar^2 (3\pi^2 n_6)^{2/3} / 2m_6 \quad with\ \xi = 0.38$ Bertsch param.

We simply get $\tilde{\omega}_7 = \omega_7\left(1 - \frac{3 g_{67} n_6(0)}{4\mu_6^{(0)}}\right) = \omega_7\left(1 - \frac{13\, k_F\, a_{67}}{7\pi\,\xi^{5/4}}\right)$

From Thomas Fermi radius of ^{6}Li superfluid, we find $\tilde{\omega}_7 = 2\pi \times 15.43\ Hz$

Very close to the measured value: $\tilde{\omega}_7 = 2\pi \times 15.40(1)\ Hz$

Amplitude modulation

Include now back-action on the Fermions

Sum-rule approach: mapping onto a coupled oscillator problem

$$z_6 = (1 - \varepsilon\rho)\cos(\tilde{\omega}_6 t) + \varepsilon\rho\cos(\tilde{\omega}_7 t)$$

$$z_7 = -\varepsilon\cos(\tilde{\omega}_6 t) + (1 + \varepsilon)\cos(\tilde{\omega}_7 t)$$

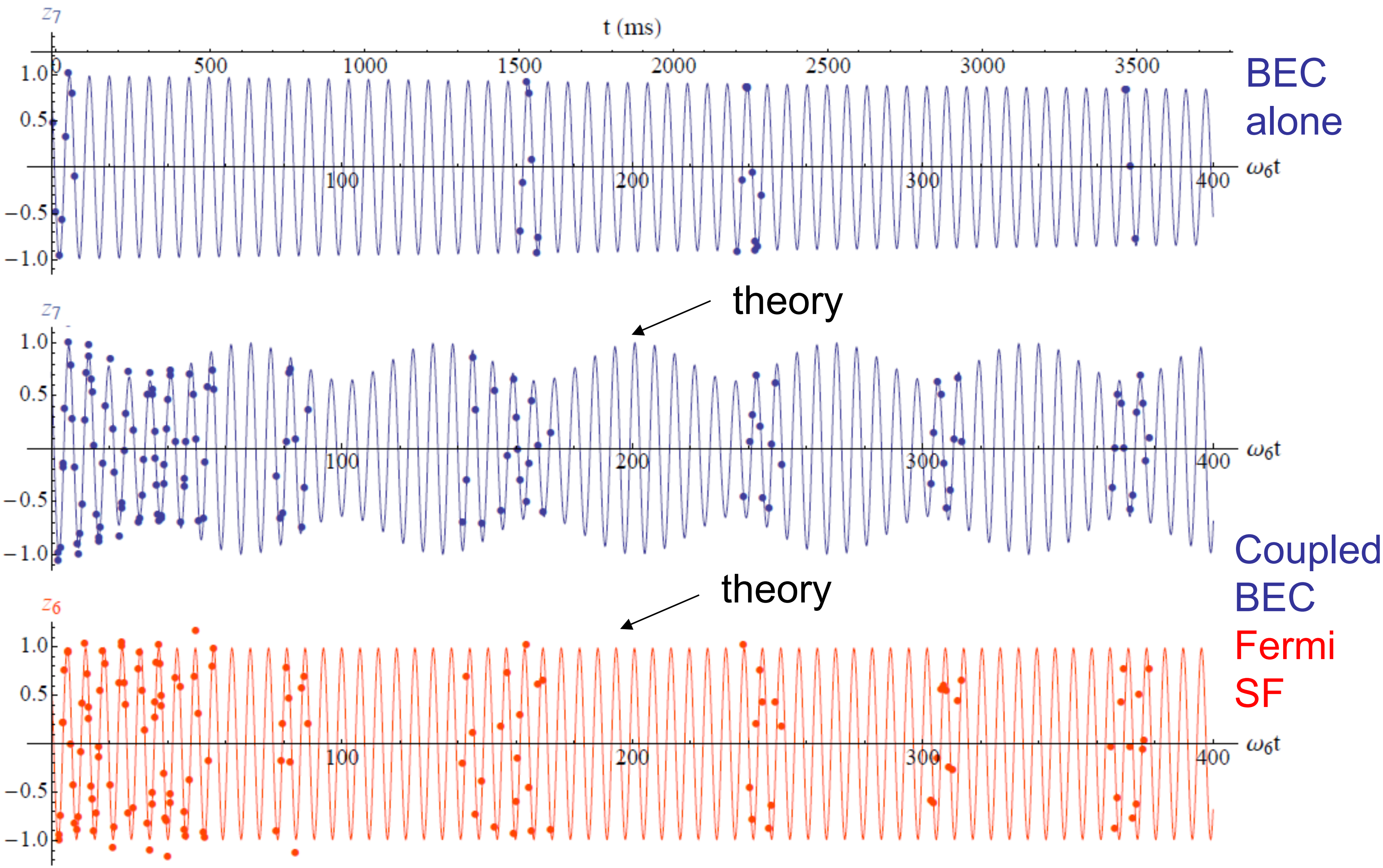
with $\rho = \frac{N_7}{N_6}$ and $\varepsilon = \frac{2m_7}{m_7 - m_6}\left(\frac{\tilde{\omega}_7 - \omega_7}{\omega_7}\right) \approx 0.3$

=14

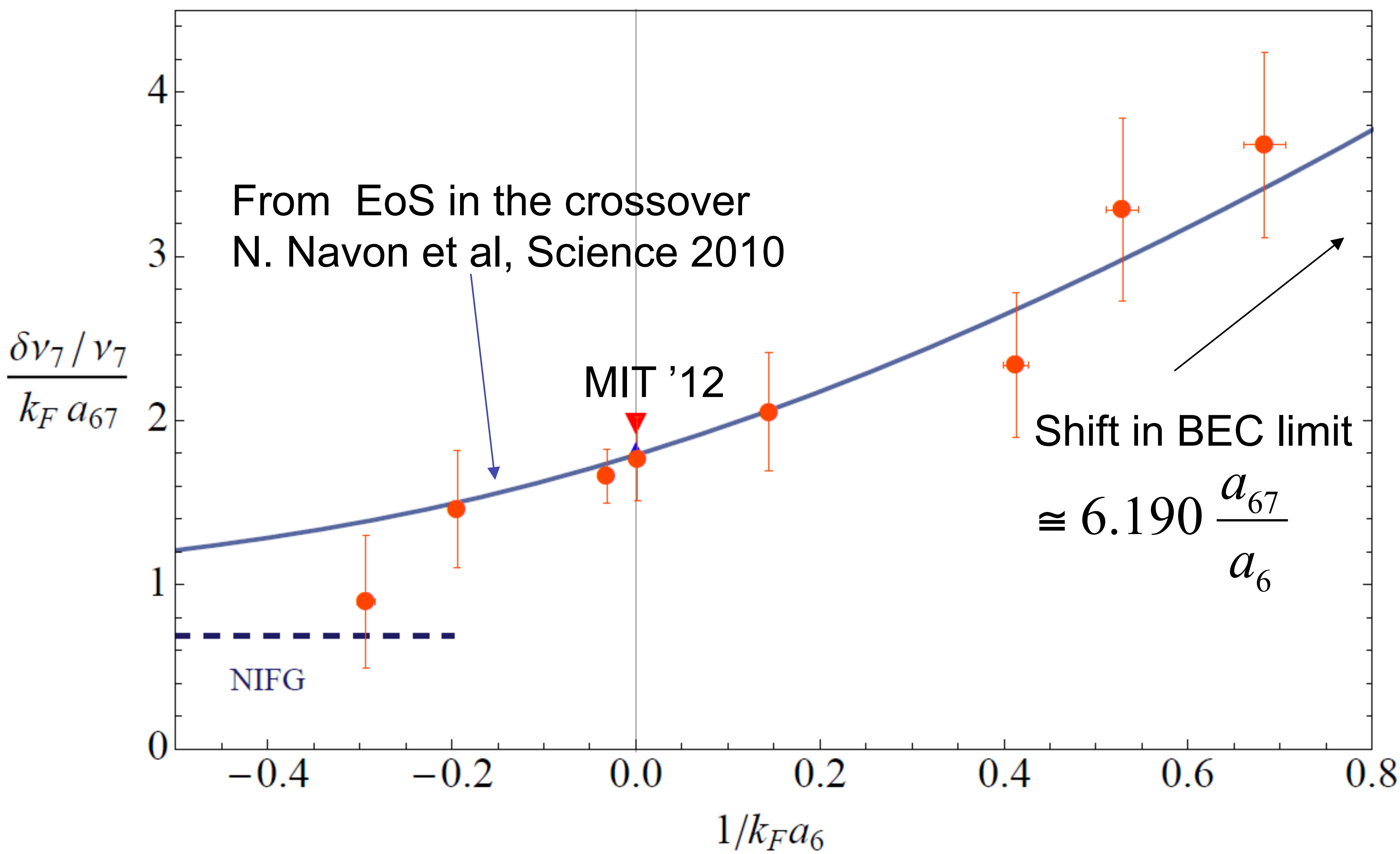
Hence a significant modulation of the amplitude of z_7 at the beat frequency $\tilde{\omega}_6 - \tilde{\omega}_7$

Coherent energy exchange between both gases amplified by quasi-degeneracy of pendulum frequencies

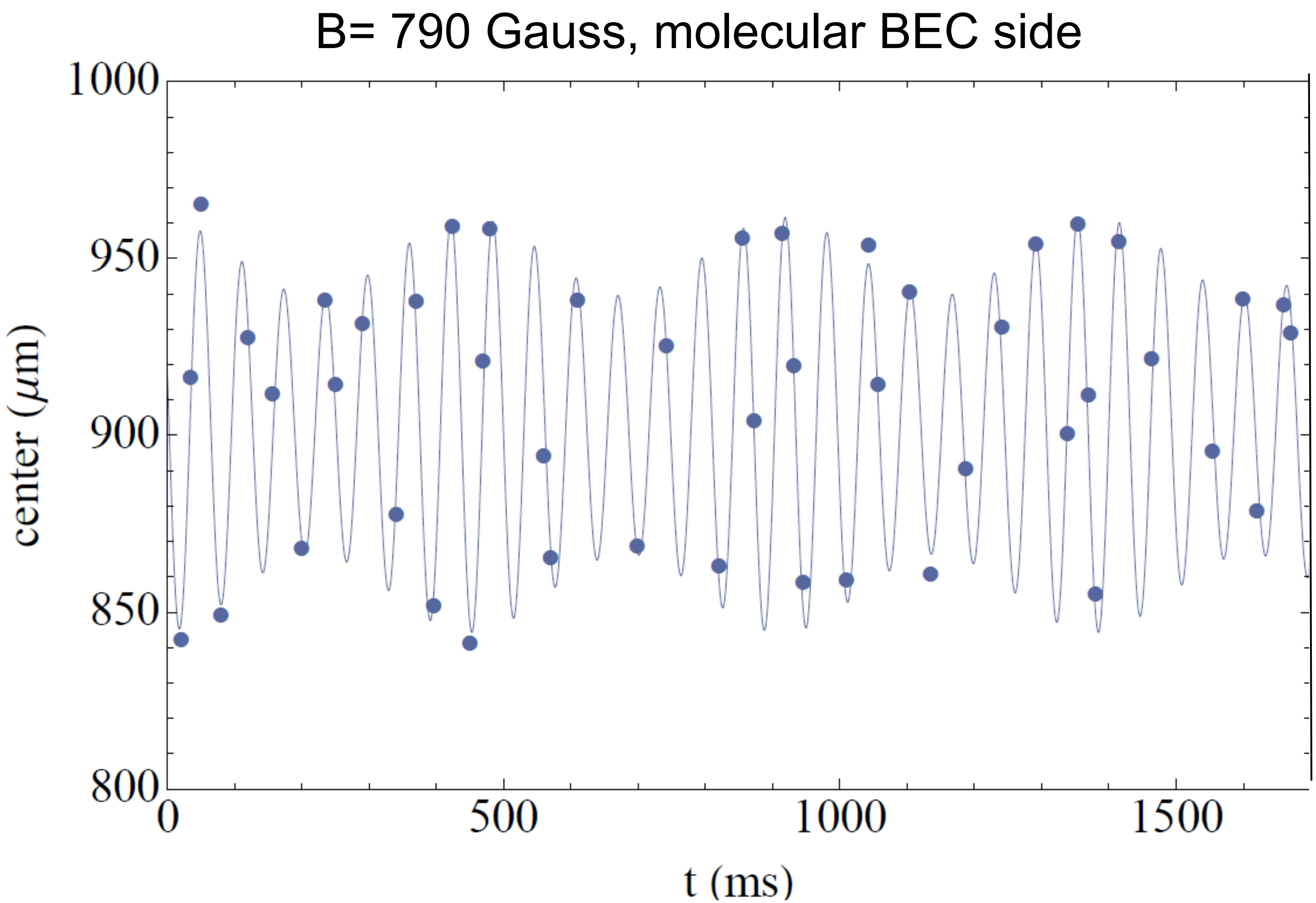
Amplitude modulation: theory vs expt



Bose-Fermi Coupling in BEC-BCS crossover



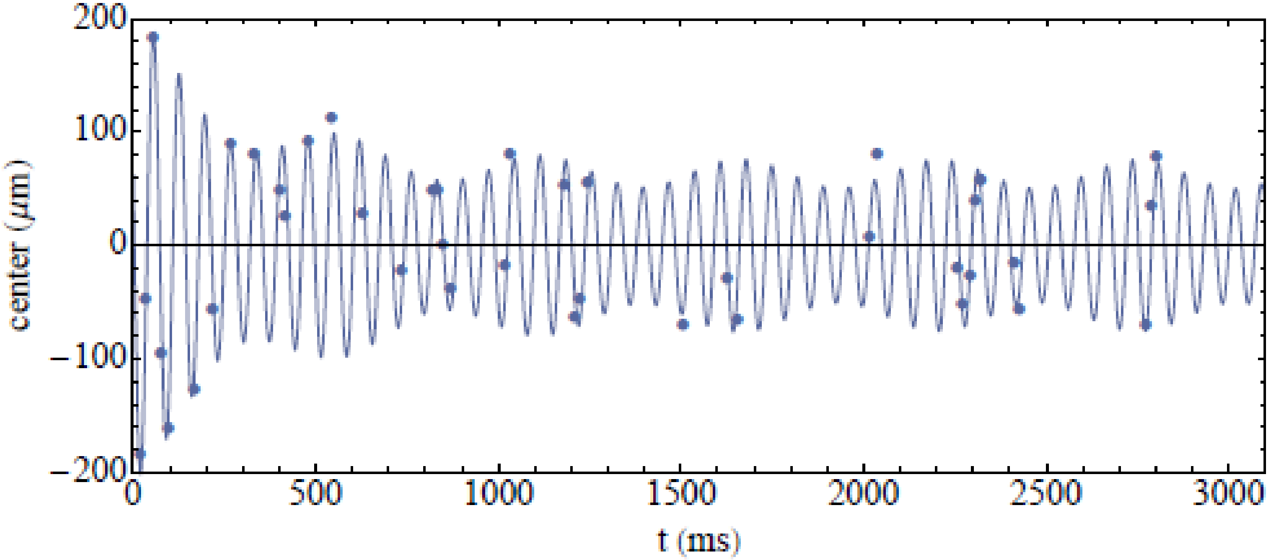
Undamped oscillations of two BEC's



Reduction of critical velocity by a factor ~2

In contrast to damping observed in Rb condensate mixtures, Myatt, PRL 1997 and dark-bright soliton trains in Engels group, PRL 2011

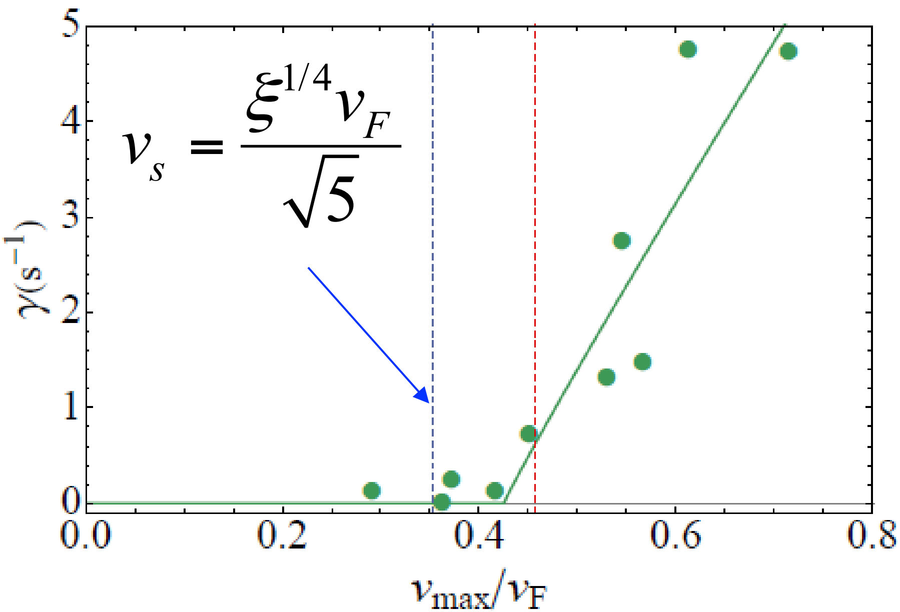
Critical velocity



$$d = d_0 \exp(-\gamma t) + d'$$

$$\gamma = 3.1\, s^{-1}$$

Time(ms)



$$\gamma(v) = \Theta(v - v_c)\, A\ ((v - v_c)/v_F)^{\alpha}$$

$$v_c = 0.42^{+0.05}_{-0.11}\, v_F$$

$$\alpha = 0.95^{+0.8}_{-0.3}$$

v_c is very close to the speed of sound of unitary gas in elongated trap

MIT experiment: $v_c = 0.32\ v_F$

Summary

- Production of a Bose-Fermi double superfluid
- Measurement of critical velocity at unitarity
- first sounds in low temperature limit
- critical velocity of SF mixture: work in progress.

  Y. Castin, S. Stringari, Hui Zhai

Perspectives

Temperature effects and nature of excitations

Flat bottom trap for fermions when $a_{bb}=a_{bf}$

Molmer 1997, Trento group, ArXiv 1405.7187

FFLO Phase with spin imbalanced gas ?

Second sound, higher modes, vortices,

Bose-Fermi Superfluids in optical lattices and counterflow