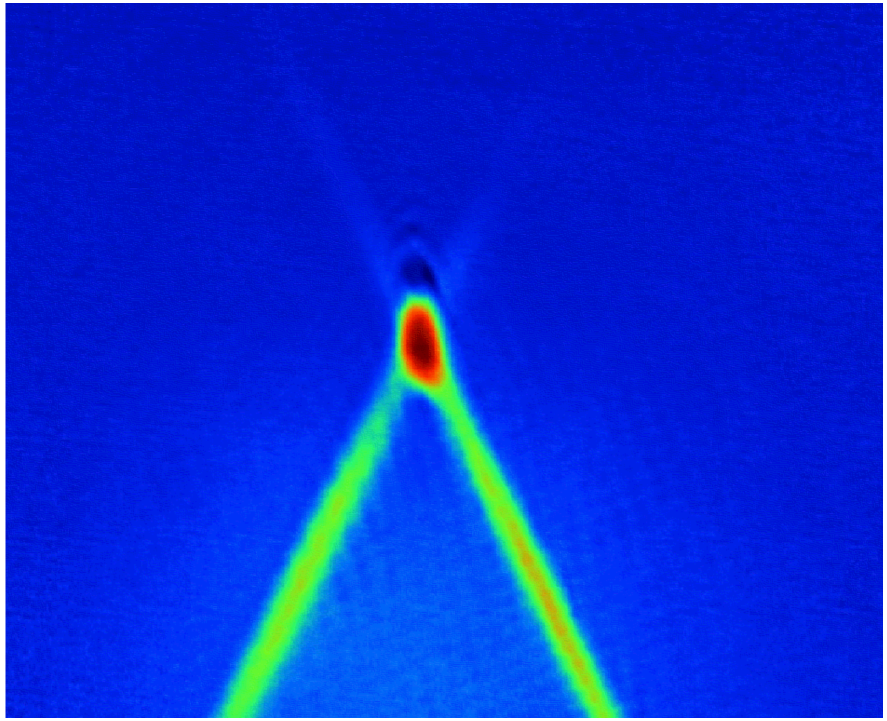
A Mixture of Bose and Fermi Superfluids



C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

INT workshop
Frontiers in quantum simulation with cold atoms
University of Washington, April 2, 2015

The ENS Fermi Gas Team

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

Lithium Exp.

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

U. Eismann
A. Bergschneider
T. Langen
N. Navon

Lithium-Potassium Exp.

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

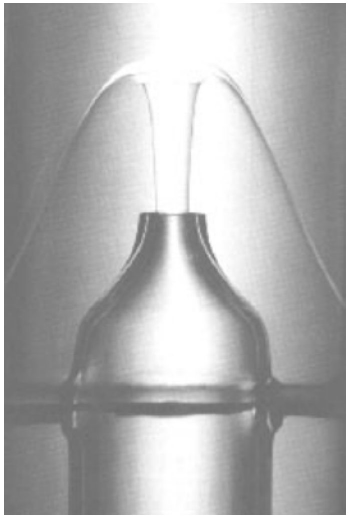
L. Khaykovich

I. Ferrier-Barbut, M. Delehaye, S. Laurent, A. T. Grier,
M. Pierce, B. S. Rem, F. Chevy, and C. Salomon
Science, **345**, 1035, 2014

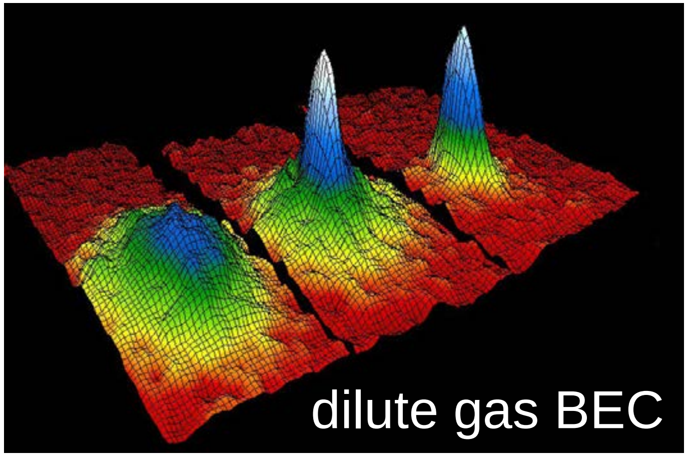
104 years of quantum fluids

Bose Einstein condensate

^4He



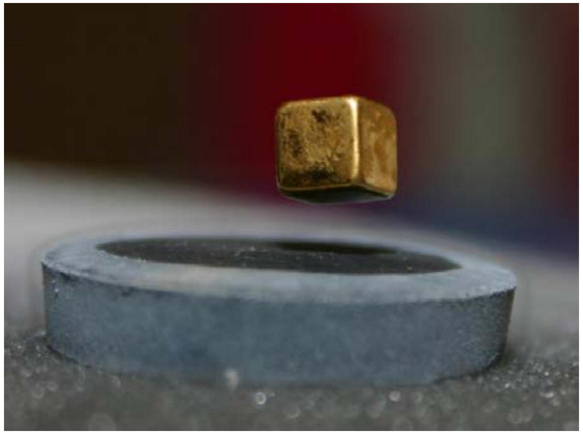
T~ 2.2 K



100 nK

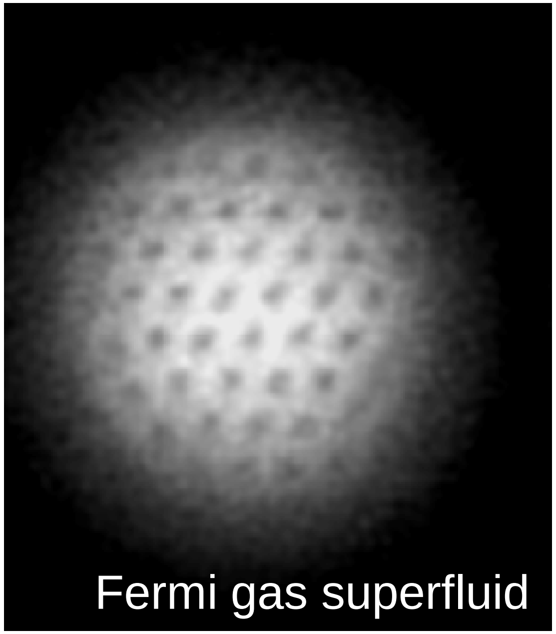
Also BEC of photons and cavity polaritons

Superconductivity



High T_c
77 K

^3He
2.5 mK

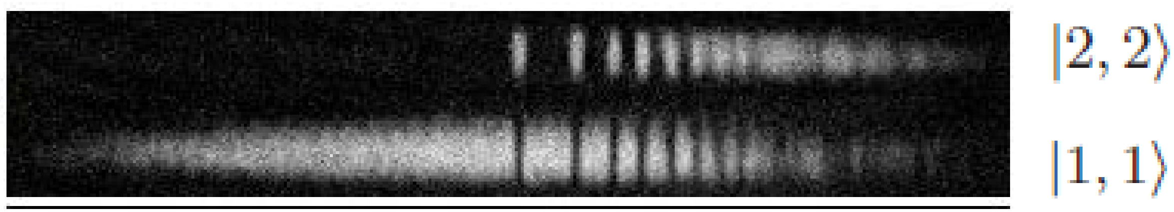


Superfluid mixtures

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

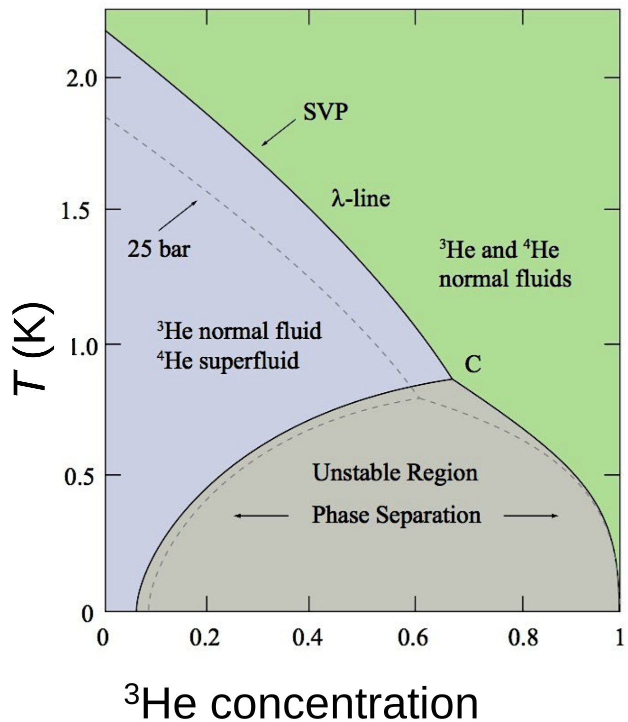


Bose-Fermi Systems

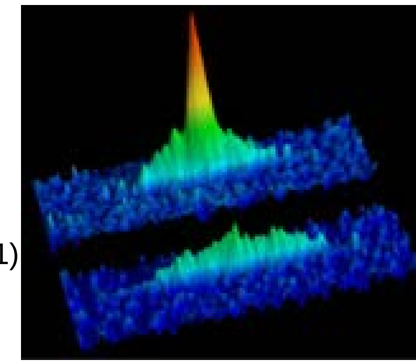
- Cooper pairing of electrons in superconductors (phonon exchange)
- High-energy physics / Meissner effect P. W. Anderson, *P.R.* **130**, 439 (1963)

- ^{4}He - ^{3}He mixtures

Strong boson - fermion repulsion prevented double SF so far



- Ultracold atom mixtures



^{6}Li - ^{7}Li (2001) ENS, Rice

Schreck *et al., PRL* **87**, 080403 (2001)
Truscott *et al., Science* **291**, 2570 (2001)

^{23}Na - ^{6}Li	(2002)
^{40}K - ^{87}Rb	(2002)
^{6}Li - ^{87}Rb	(2005)
^{3}He* - ^{4}He*	(2006)
^{6}Li - ^{40}K - ^{87}Rb	(2008)
^{6}Li - ^{85,87}Rb	(2008)
^{84,86,88}Sr - ^{87}Sr	(2010)

^{6}Li - ^{174}Yb	(2011)
^{170,174}Yb - ^{173}Yb	(2011)
^{40}K - ^{41}K - ^{6}Li	(2011)
^{161}Dy - ^{162}Dy	(2012)
^{23}Na - ^{40}K	(2012)
^{6}Li - ^{133}Cs	(2013)
^{52}Cr - ^{53}Cr	(2014)

None doubly superfluid!!

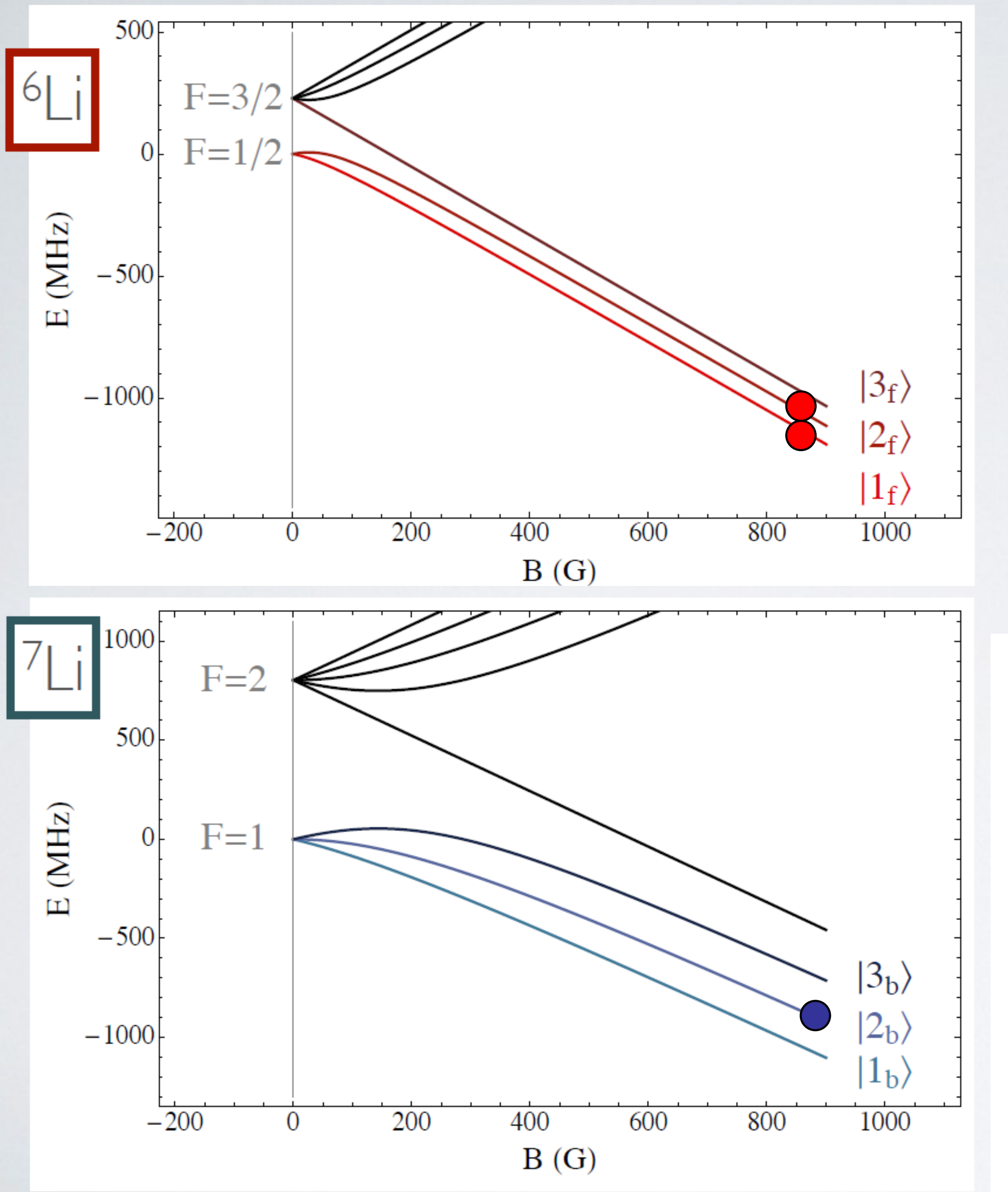
T_C ~ 50 μK?

A novel system: a double superfluid mixture of ^{6}Li and ^{7}Li

Outline

- Experiment with ^{6}Li-^{7}Li isotopes
- Excitation of center of mass modes: first sounds
- Simple model
- Critical velocity for two-superfluid counterflow
- Perspectives

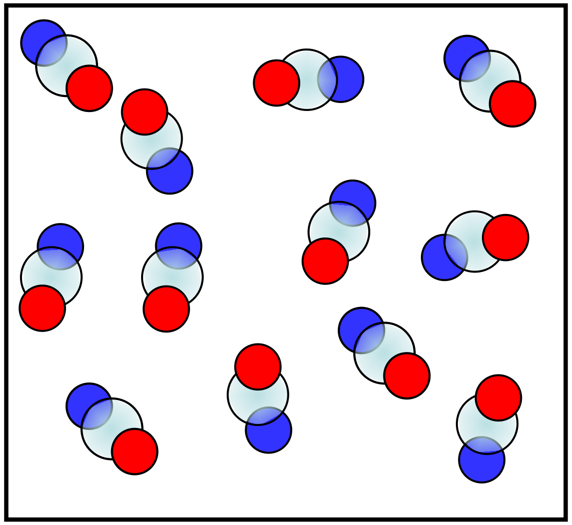
^{7}Li and ^{6}Li isotopes

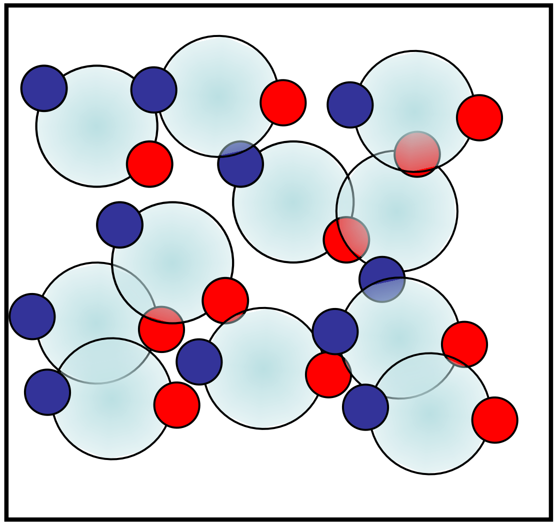


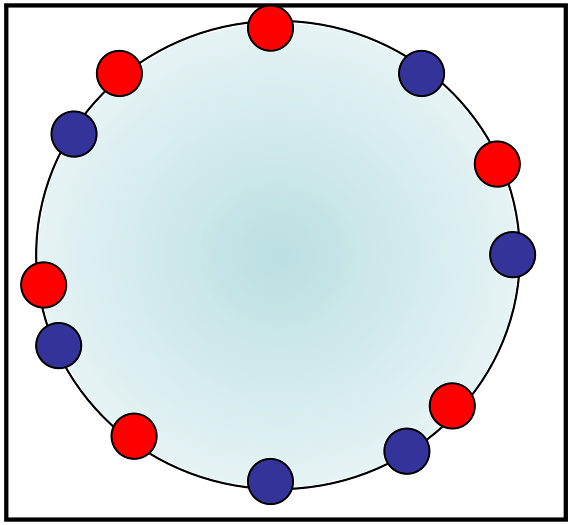
Fermi Superfluid in the BEC-BCS Crosover

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

The hydrogen atom of many-body physics !







Molecular condensate

Strongly bound

Size: $a \ll n^{-1/3}$

$n^{-1/3}$: average distance between particles

On resonance

$na^3 \gg 1$

$k_F a \geq 1$

Pairs stabilized by Fermi sea

Size of pairs $h v_F / \Delta \sim k_F^{-1}$

BCS regime:

$k_F |a| \ll 1$

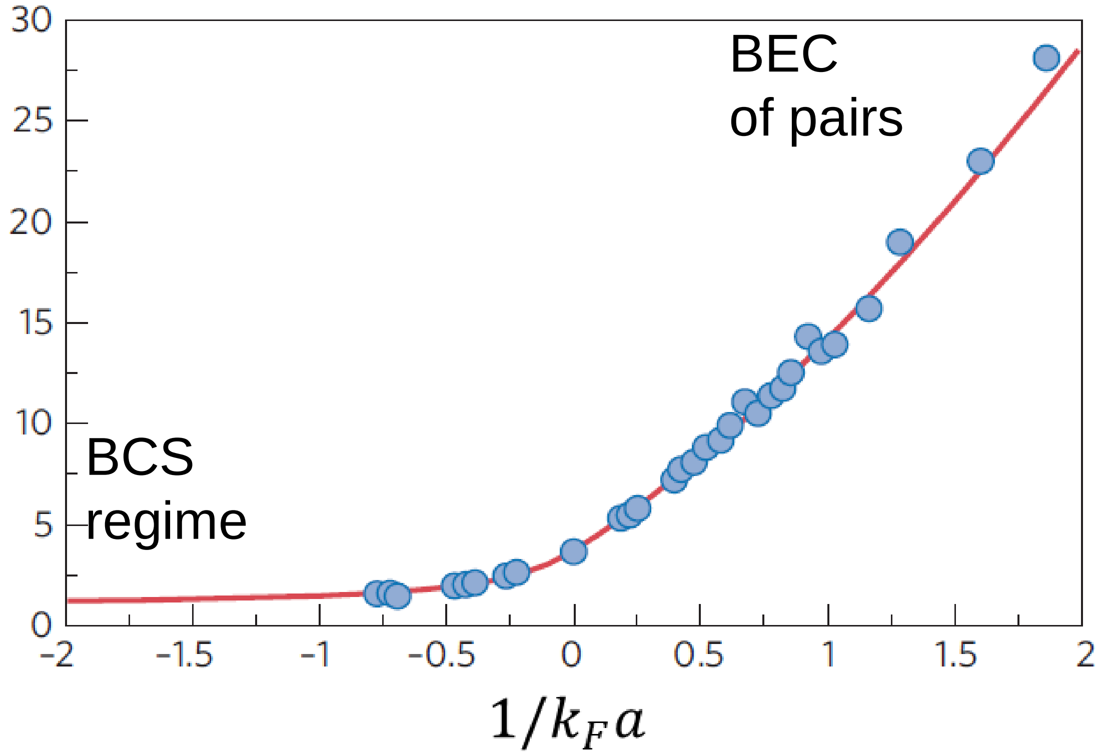
Cooper pairs $\vec{k}$, $-\vec{k}$

Well localized in Momentum: $k \sim k_F$

Delocalized in position

Equation of State in the crossover

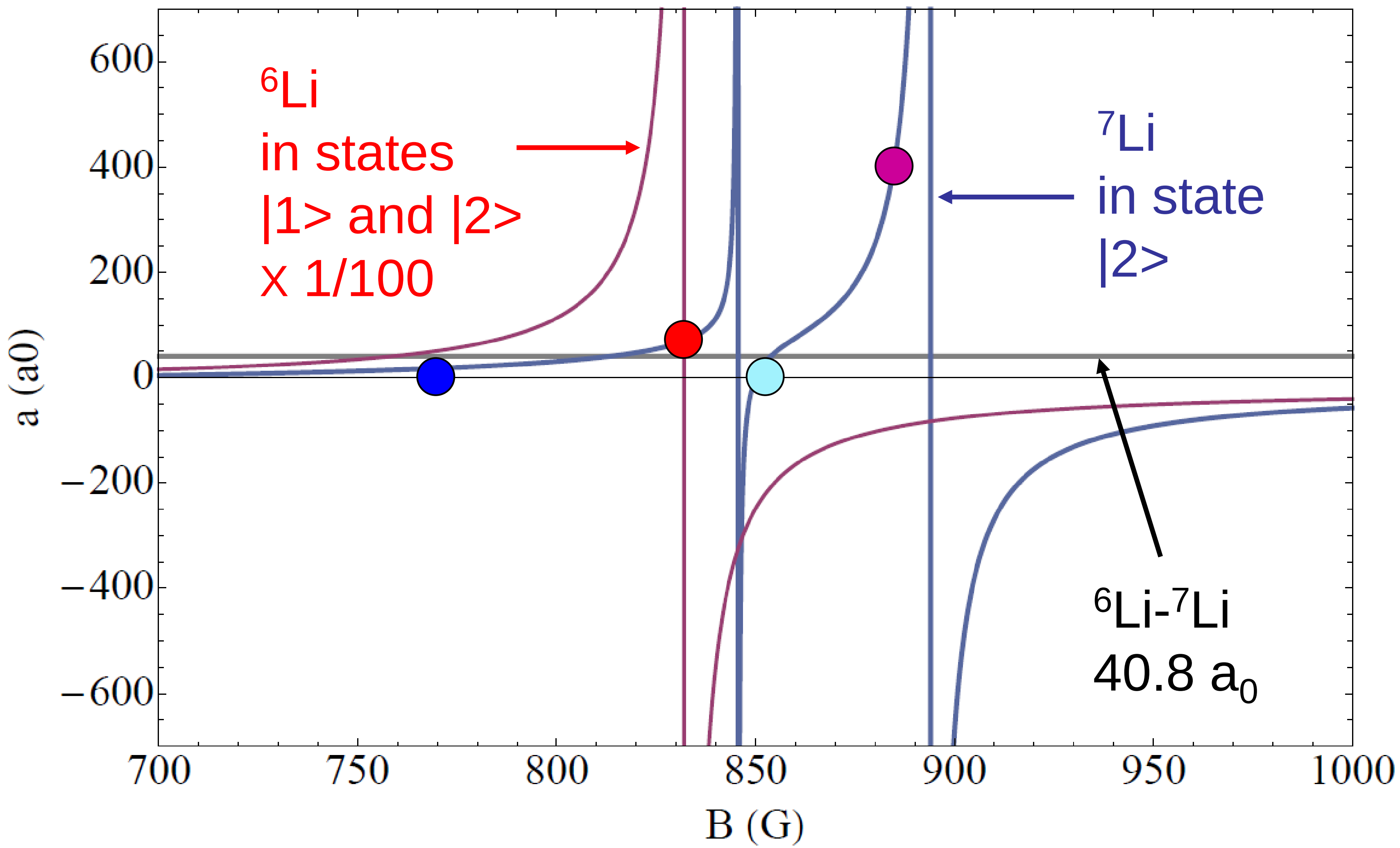
Pressure equation of state $P/P_0 = f(1/k_F a)$



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)

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



Experimental Setup

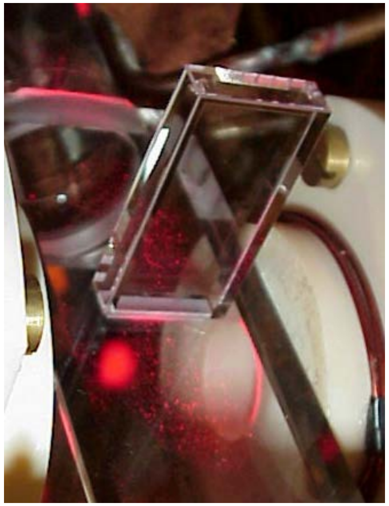
Magneto-optical trap of bosonic ^{7}Li and fermionic ^{6}Li

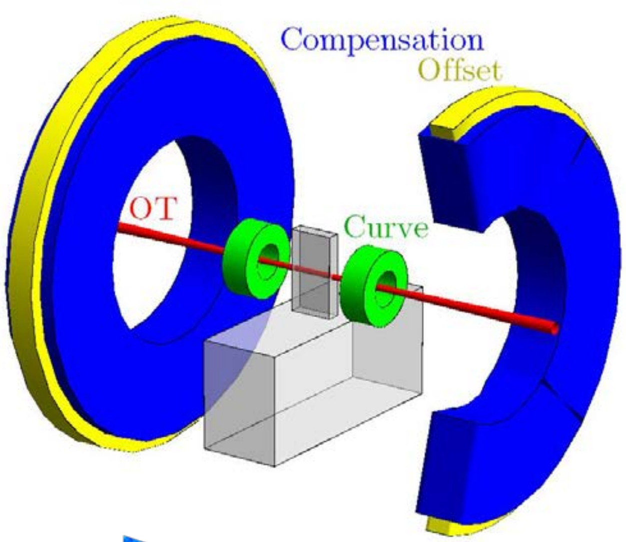
After evaporation in a magnetic trap we load the atoms in a single beam optical trap (OT) with magnetic axial confinement. T~ 40 μK

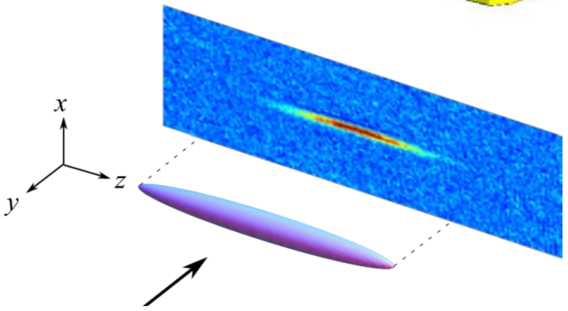
Evaporative cooling of mixture in OT

~ 4 second ramp, T~ 80 nK

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

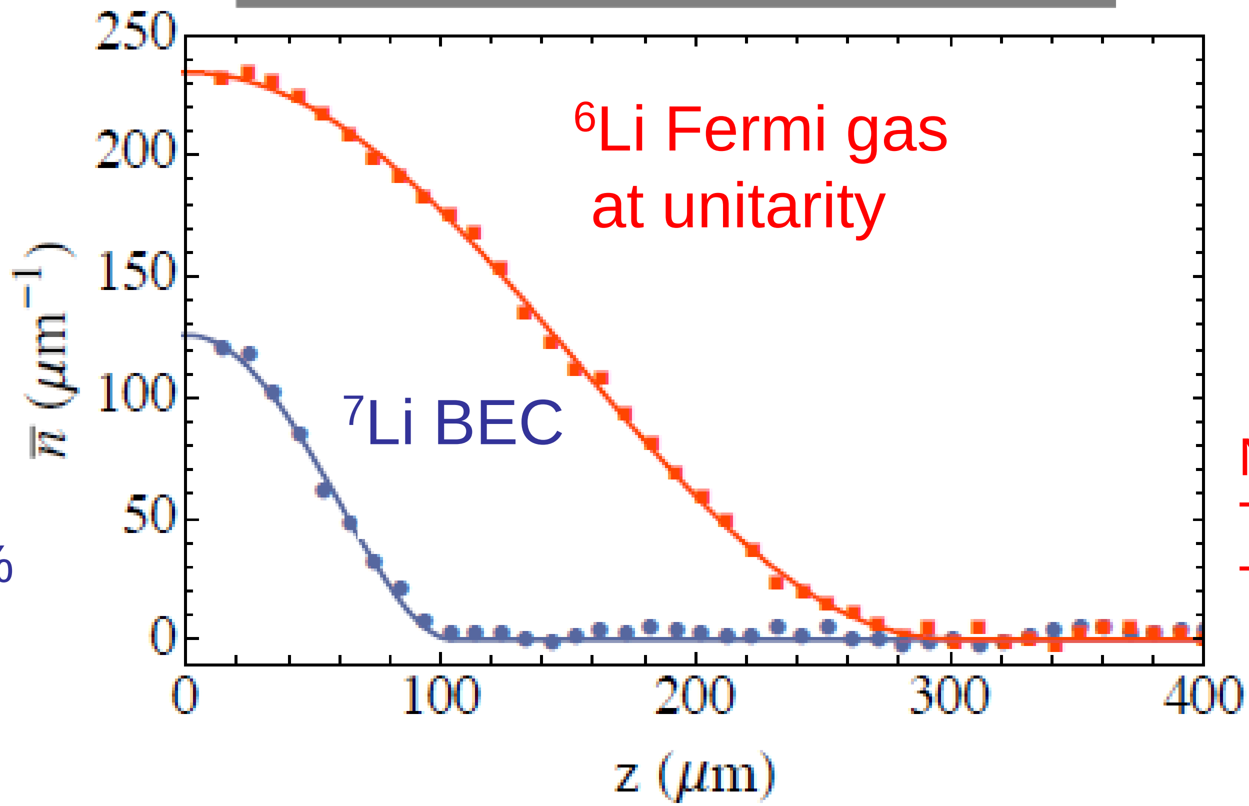






In situ Profiles

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



N_F=2 10^5
T= 80 nK ~ T_c/2
T_F= 800 nK

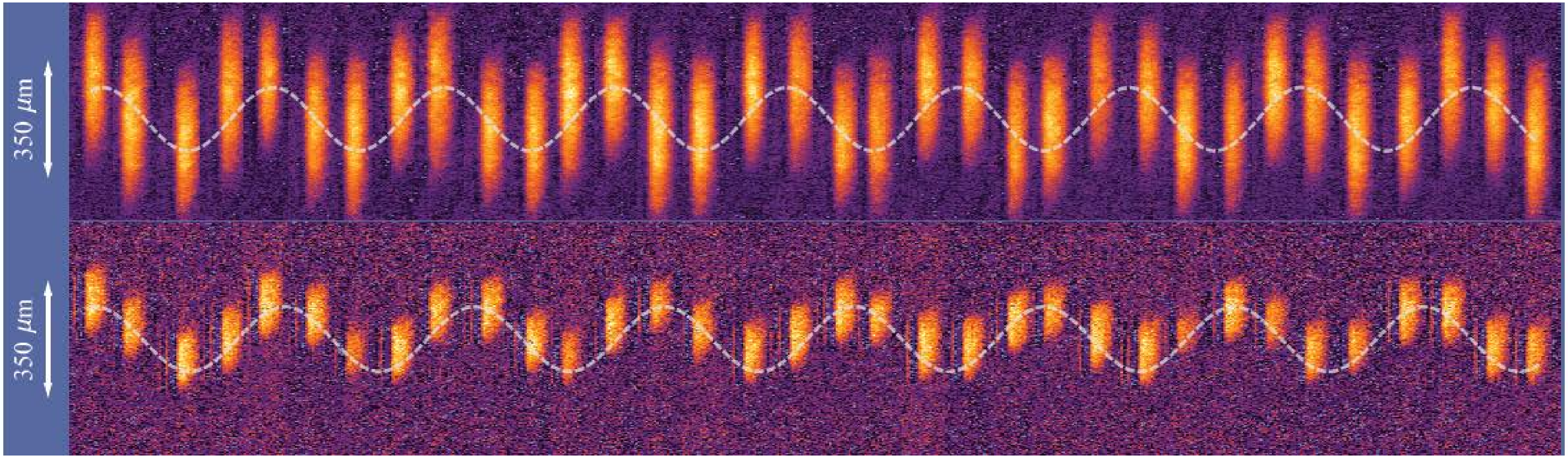
Trap frequencies: ν_z=15.6 Hz
for bosons, ν_{rad}= 440 Hz

Expected SF fractions: N_0/N_B> 0.8
N_0/N_F ~0.8

Lifetime of mixture : 7s in shallowest trap

Long-lived Oscillations of both Superfluids

Fermi Superfluid



BEC

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

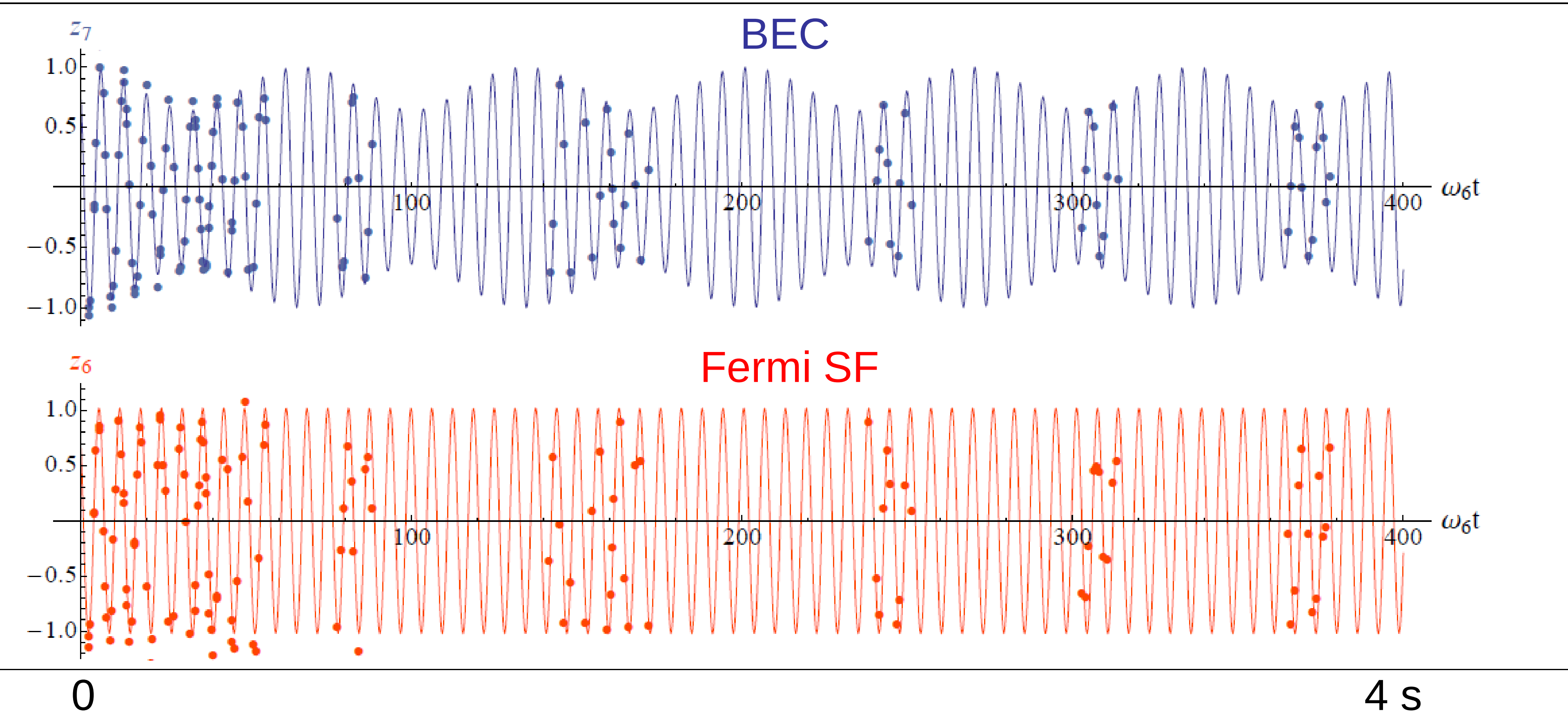
$$\tilde{\omega}_7 = 2\pi \times 15.40(1) Hz \qquad \omega_7 = 2\pi \times 15.63(1) Hz$$

Coupled Superfluids

Single Superfluid

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

Oscillations of both superfluids



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

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

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

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

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

The equation of state $n(\mu)$ is known in the BEC-BCS crossover
N. Navon et al., Science, 2010

Effective potential

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The potential remains harmonic with rescaled frequency

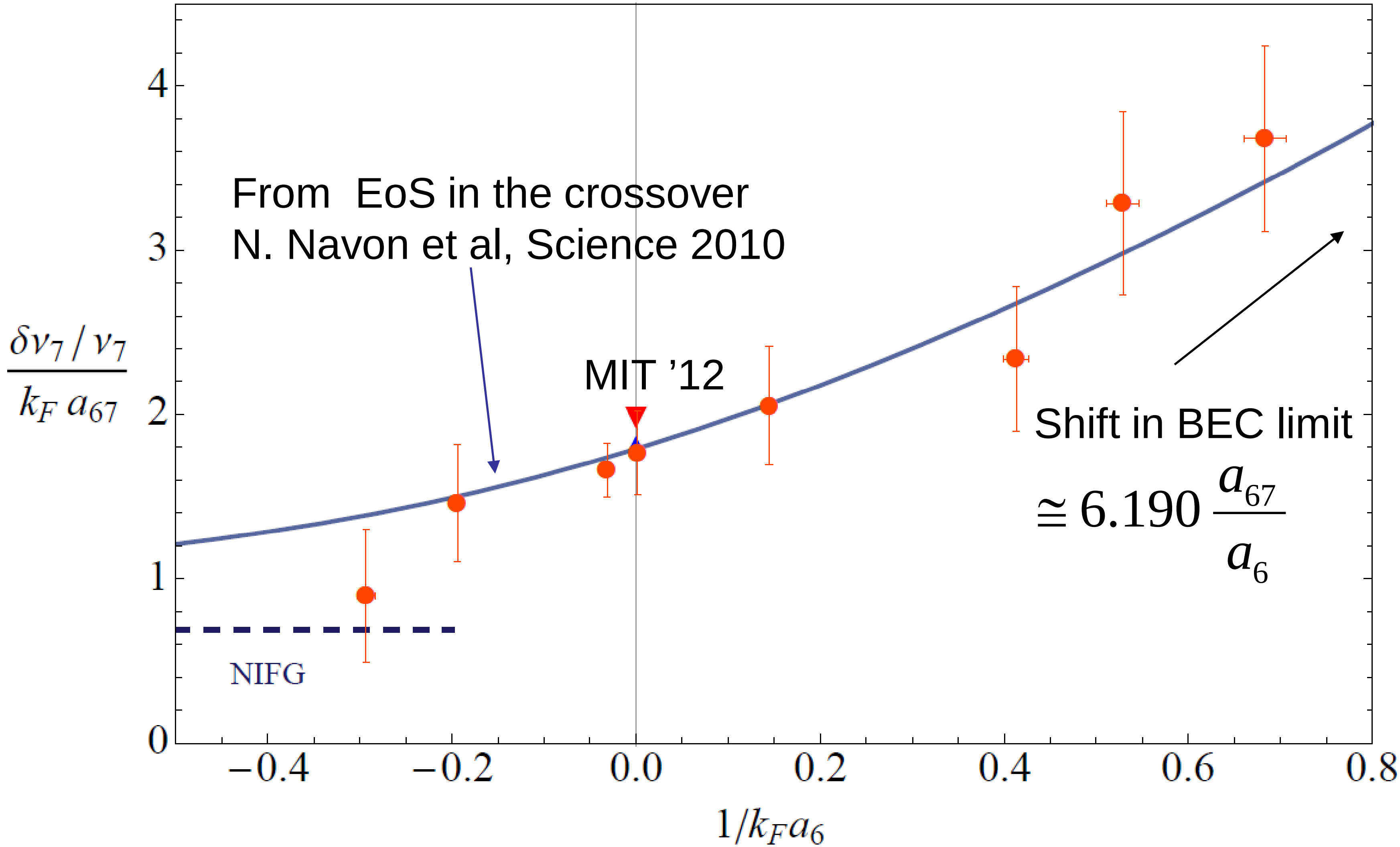
$$\tilde{\omega}_7 = \omega_7 \sqrt{1 - g_{67}\left(\frac{dn^{(0)}}{d\mu_6}\right)_0}$$

At unitarity $\mu_6 = \xi \hbar^2 (3\pi^2 n_6)^{2/3} / 2m_6 \quad with\ \xi = 0.37$ 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: $\tilde{\omega}_7 = 2\pi \times 15.40(1)\ Hz$

Bose-Fermi Coupling in BEC-BCS crossover



What is the critical velocity
for superfluid counterflow ?

Landau critical velocity

Impurity of mass M moving with velocity $\vec{v}$ inside a superfluid
Emission of an elementary excitation of momentum $\vec{p}$ and energy $\varepsilon(\vec{p})$

Energy and momentum conservation:

$$v_c = \underset{\boldsymbol{p}}{\mathrm{Min}} \left(\frac{\frac{p^2}{2M} + \varepsilon(\boldsymbol{p})}{p} \right)$$

$$M \to \infty \qquad v_c = \underset{\boldsymbol{p}}{\mathrm{Min}} \left(\frac{\varepsilon(\boldsymbol{p})}{p} \right)$$

Sound excitations
phonons

$$\varepsilon(p) = c\,p \quad \Longrightarrow \quad v_c = c$$

critical velocity

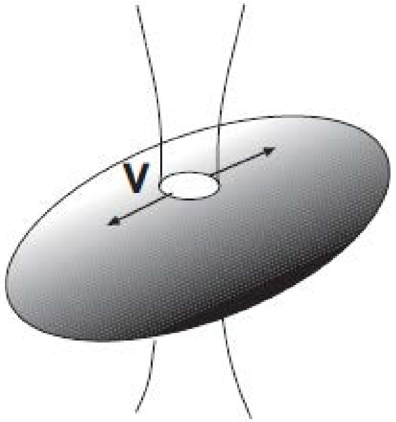
Bose gas

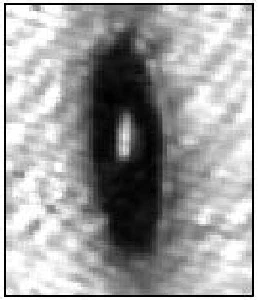
MIT: 3D geometry,
moving laser beam

v_c/c_s between 0.1 and 0.2

2D geometry: ENS 2012
Seoul Univ.

+ Many theory papers !





C. Raman et al. PRL 1999
R. Onofrio et al. PRL 2000

Fermi gas in BEC-BCS crossover

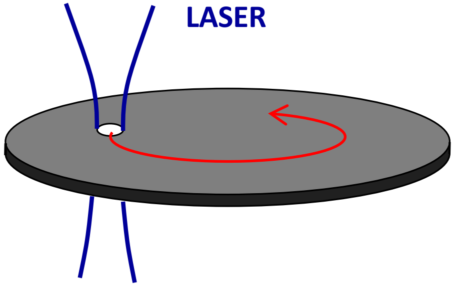
MIT: 3D geometry, moving standing wave method

Miller, PRL 2007

$v_c/c_s \sim 0.6$ $\quad v_c/v_F \sim 0.3$

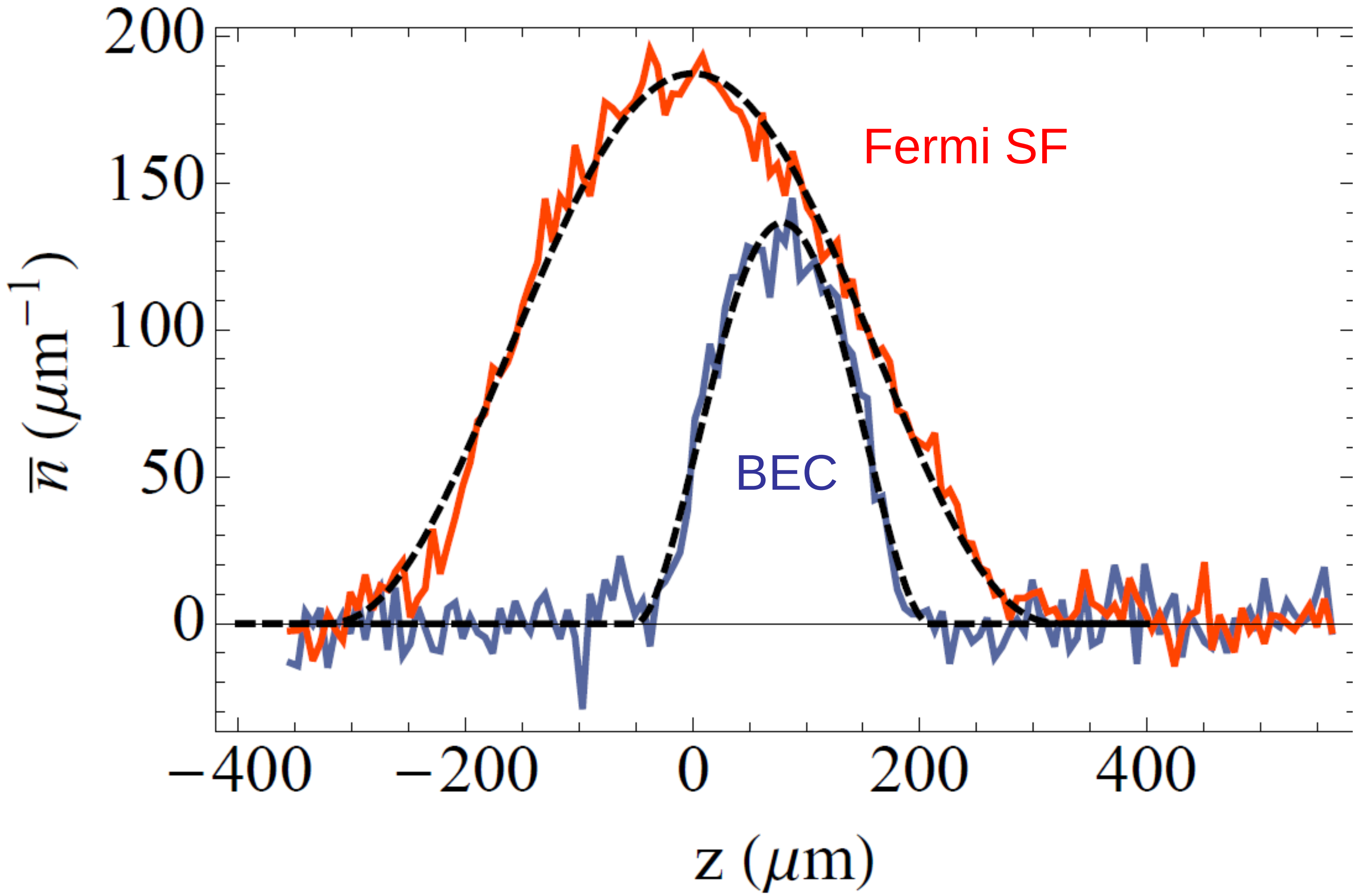
Hamburg: 3D geometry

$v_c/c_s \sim 0.68$ $\quad v_c/v_F \sim 0.3$



Weimer et al. PRL 2015

BEC: a new probe of Fermi superfluid

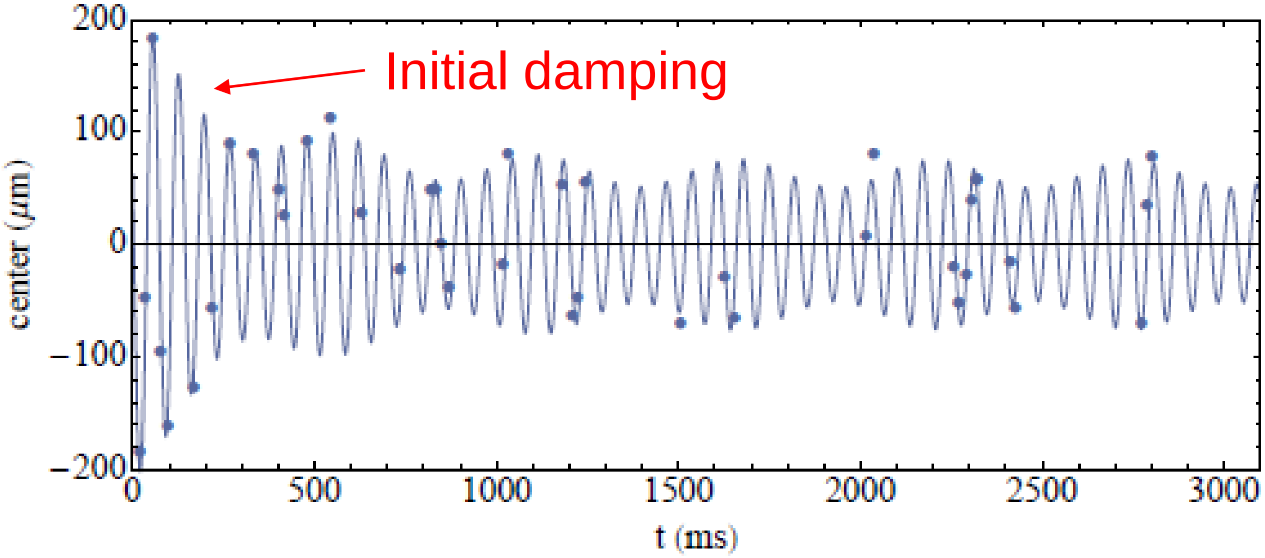


The BEC is a mesoscopic probe of the Fermi SF near its center

finite mass impurity !

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

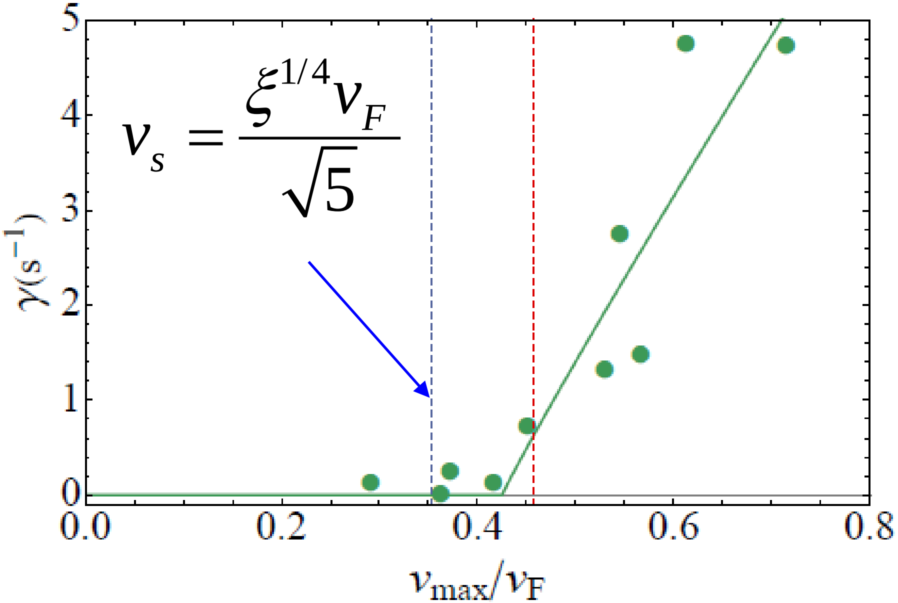
Critical velocity for superfluid counterflow



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

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

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 appears higher than the speed of sound of unitary gas in elongated trap !

Critical velocity for two superfluids @ T=0

Bose gas quasi-particles: Bogoliubov dispersion: $\varepsilon_B(\vec{k})$

$$\omega^2 = c_s^2 k^2 + (k^2 / 2m_7)^2$$

$$m_7 c_s^2 = n\frac{\partial \mu}{\partial n} = ng = \mu$$

Fermi gas quasi-particles: $\varepsilon_F(\vec{k})$

Two contributions: phonons, $\varepsilon_{ph}(\vec{k})$ and pair breaking $\varepsilon_f(\vec{k})$

Combescot
Kagan
Stringari

Bose gas moving with velocity v $\varepsilon_B(\vec{k}) + \hbar\vec{k}.\vec{v}$

Energy and momentum conservation $\varepsilon_B(-\vec{k}) - \hbar\vec{k}.\vec{v} = -\varepsilon_F(\vec{k})$

Landau critical velocity:

$$v_c = \min_k \frac{1}{\hbar|k|}\left(\varepsilon_B(k) + \varepsilon_F(k)\right)$$

Y. Castin, I. Ferrier-Barbut and C. Salomon
Comptes-Rendus Acad. Sciences, Paris, **16**, 241 (2015)

Counter-flow critical velocity

Several excitation branches in the Fermi gas

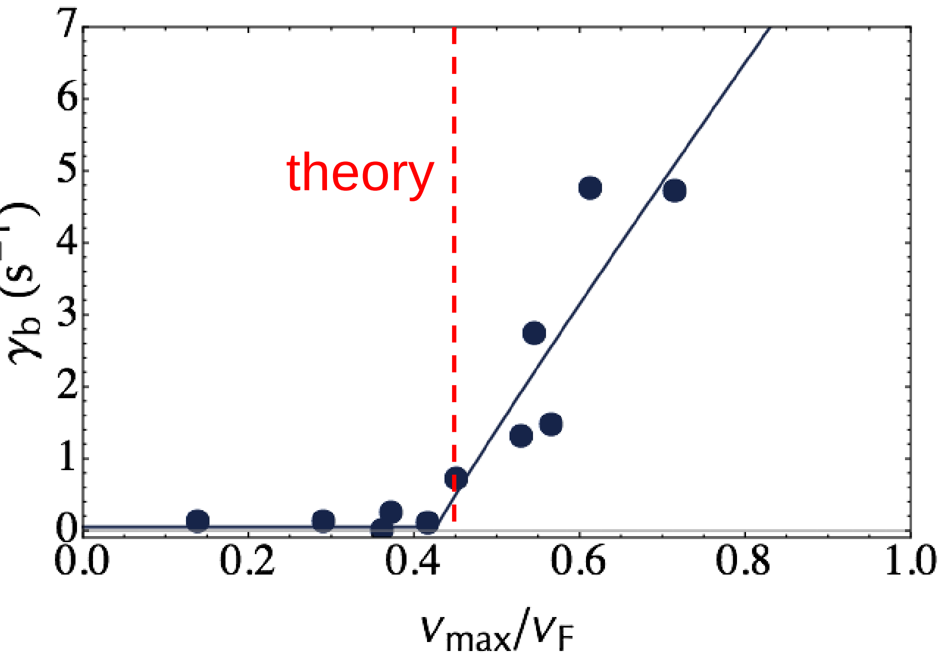
Combescot, Kagan and Stringari
PRA **74**, 042717 (2006)

At unitarity, we expect the phonon modes to dominate:

$$v_c = c_B + c_F$$

The critical velocity is the sum

of the speed of sound in Bose gas c_B and speed of sound in Fermi gas c_F



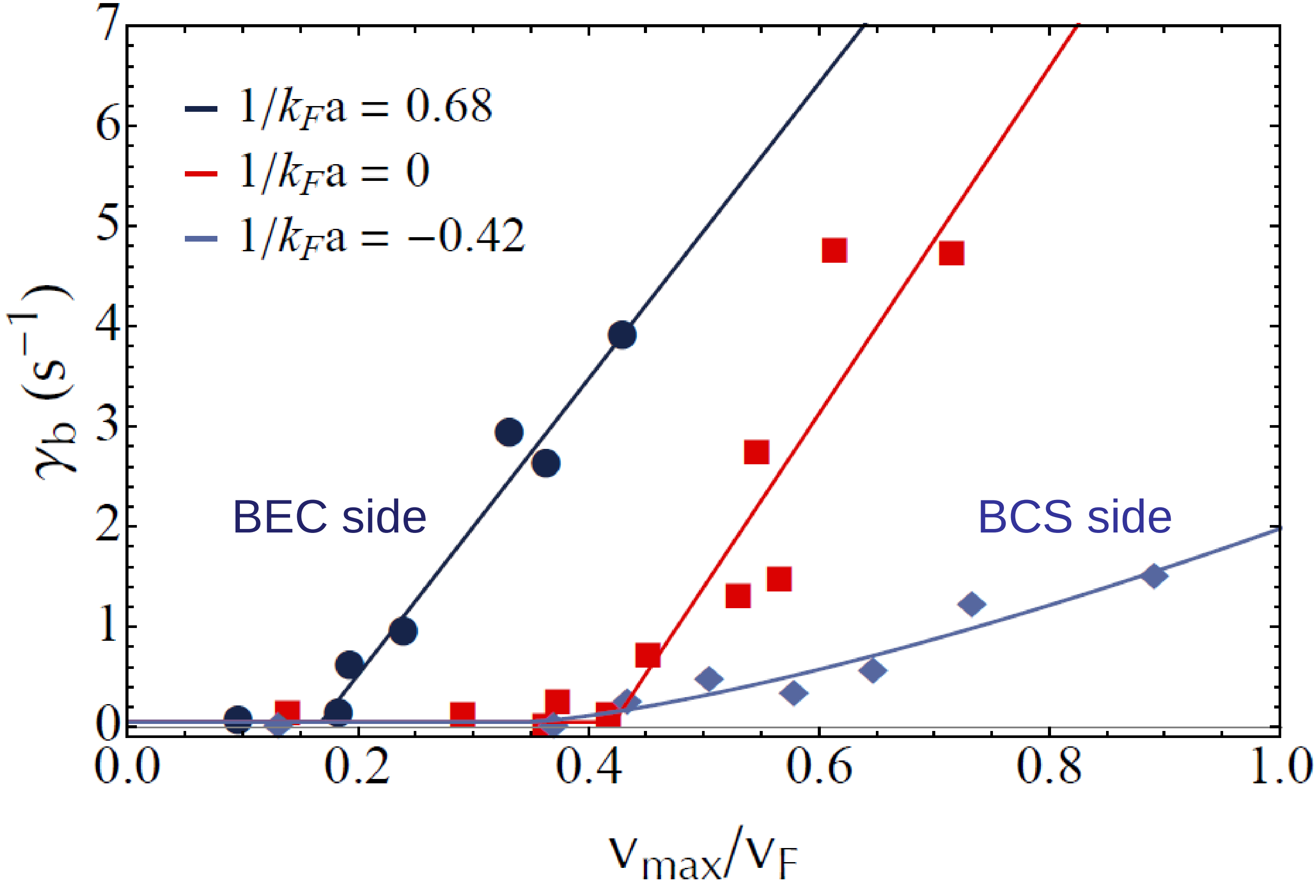
Theory

$$c_B = 0.10(2)v_F$$
$$c_F = 0.36(4)v_F$$
$$v_c = 0.46(6)v_F$$

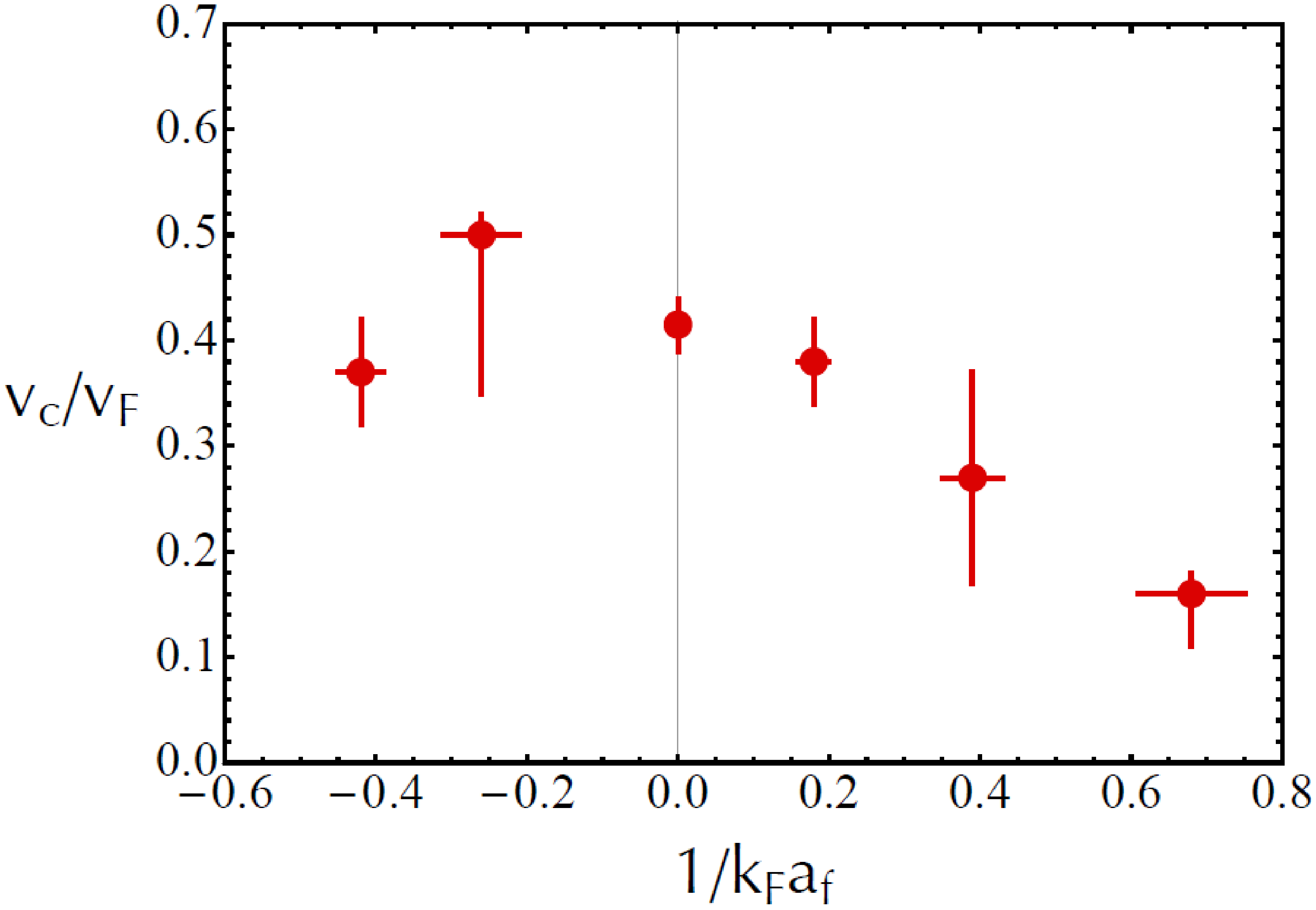
Experiment

$$v_c = 0.42(4)v_F$$
$$v_c / c_F = 1.16(20)$$

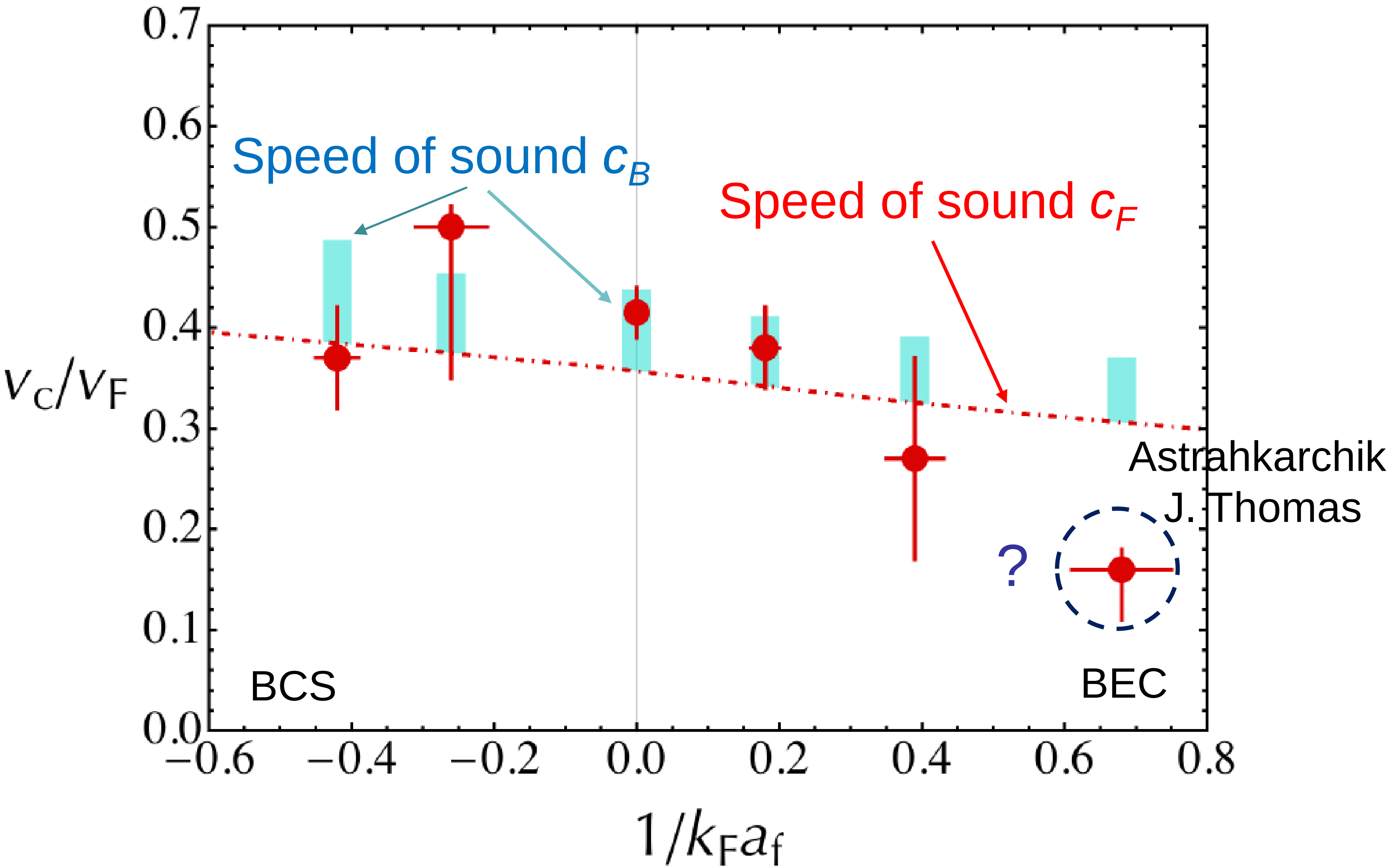
Counter-flow critical velocity in BEC-BCS crossover



Critical velocity in the BEC-BCS crossover



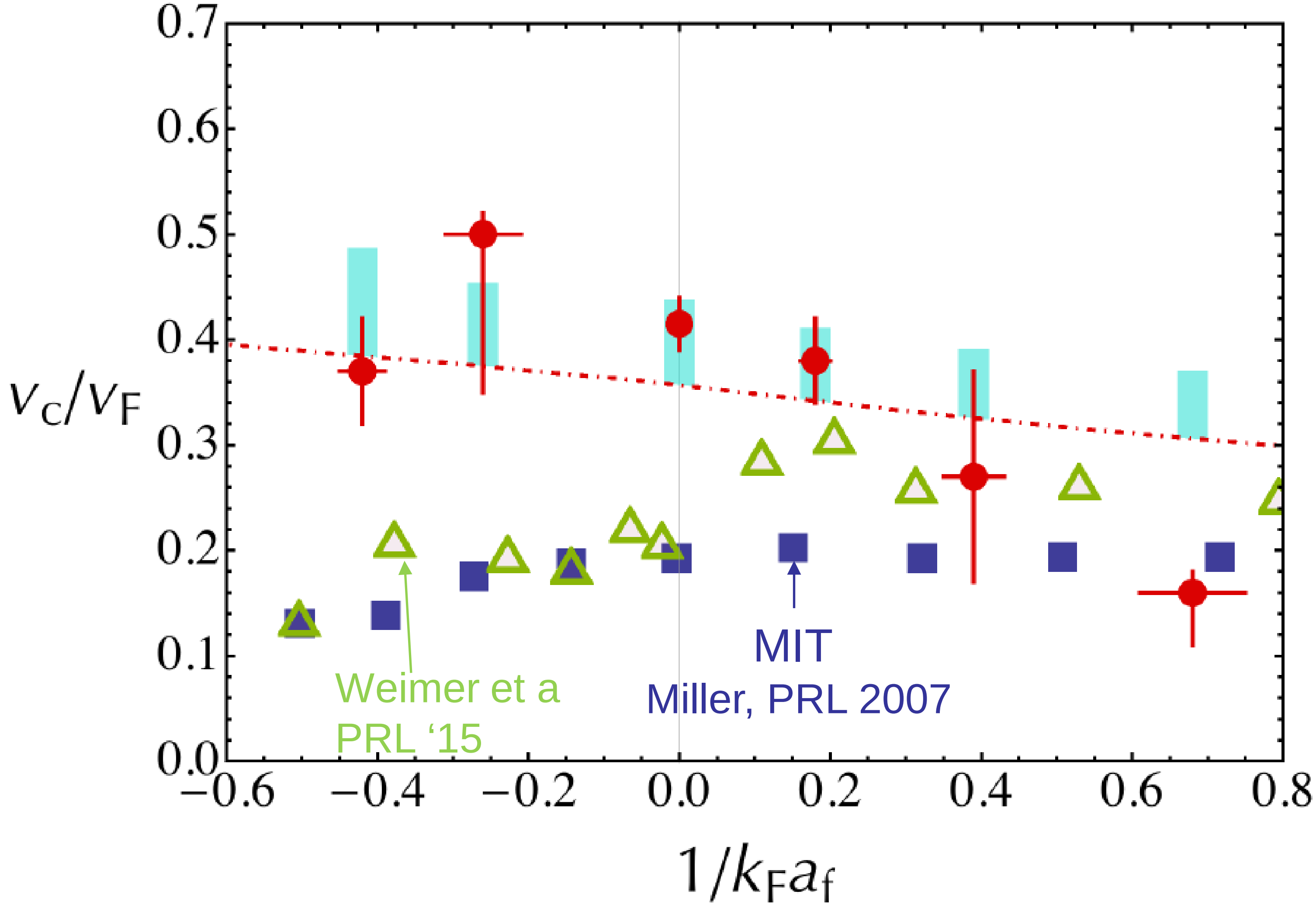
Critical velocity in the BEC-BCS crossover

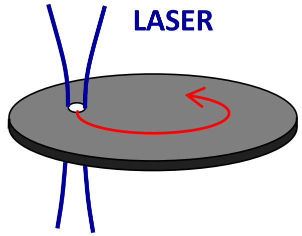


Compatible with $v_c = c_B + c_F$ around unitarity

Comparison with other measurements in pure Fermi gases

Laser excitation: moving standing wave potential (MIT) or laser stirrer (Hamburg)





Summary

- Production of a Bose-Fermi double superfluid
- First sounds in low temperature limit
- Measurement of critical velocity in BEC BCS crossover
- Theory:
  - role of Bose-Fermi interaction: M. Habad, Recati, Stringari, Chevy arXiv:1411.7560v1
  - Lifetime of excitations: W. Zheng, Hui Zhai, PRL 113, 2014
  - Influence of harmonic trap

Perspectives

Temperature effects and nature of excitations

Flat bottom trap for fermions when $a_{bb}=a_{bf}$ Ozawa et al. 2014

Search for FFLO Phase with spin imbalanced gas

Rotations, vortices, second sound, higher modes

Bose-Fermi Superfluids in optical lattices and phase diagram