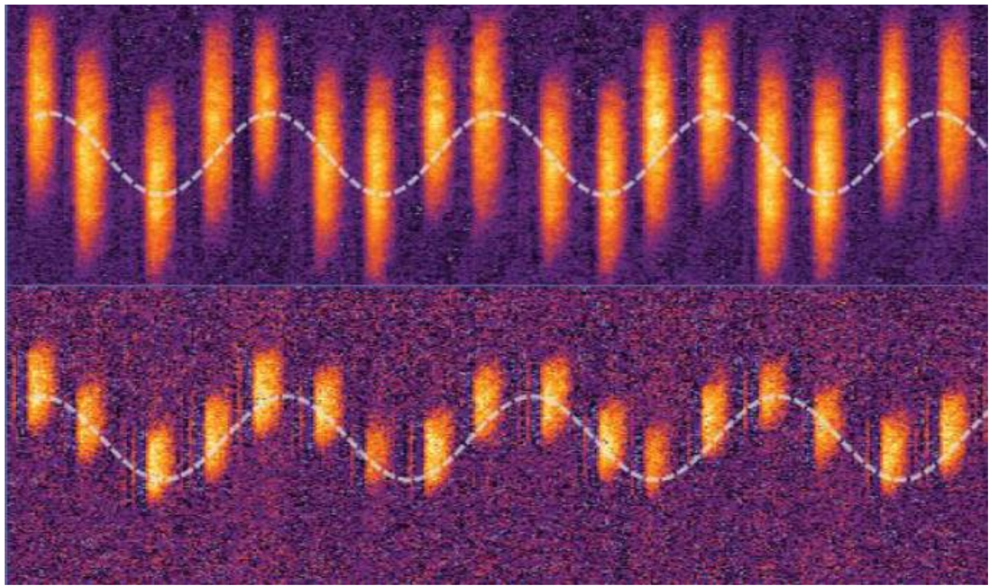
Dual Bose-Fermi Superfluids

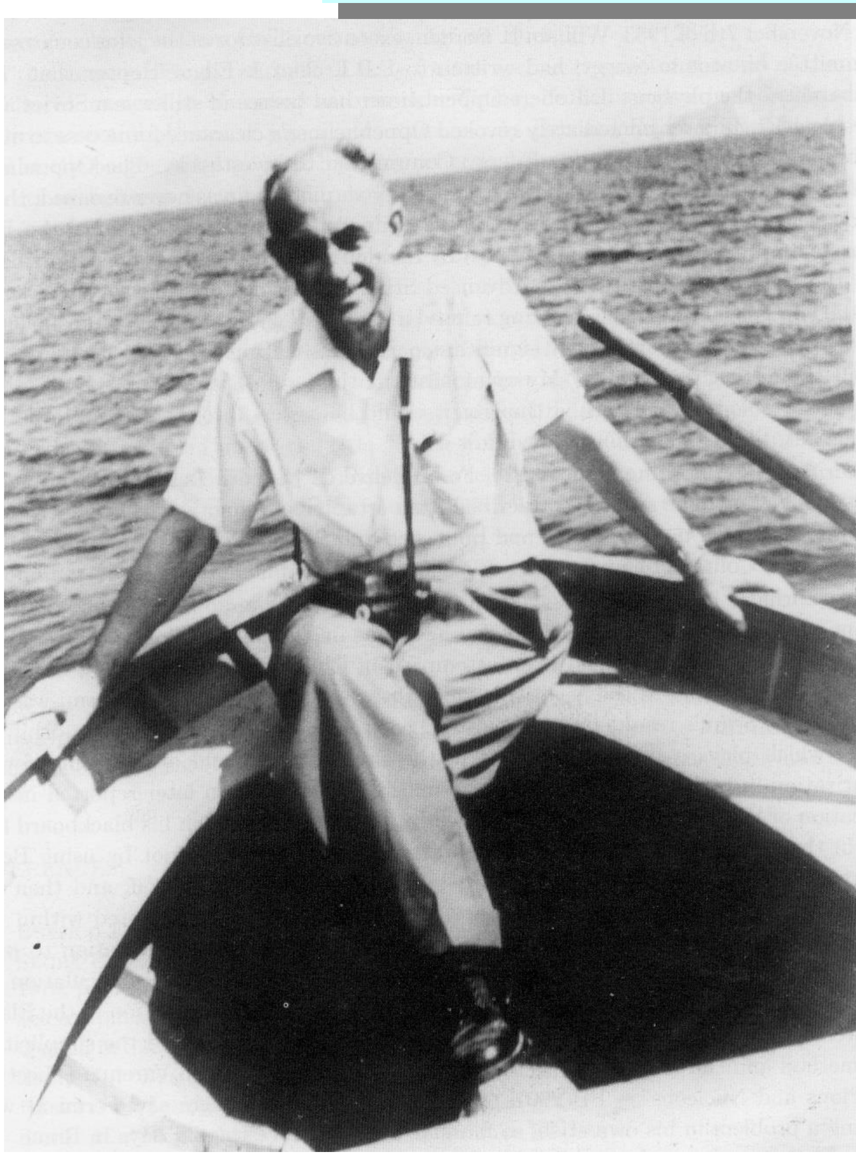


C. Salomon

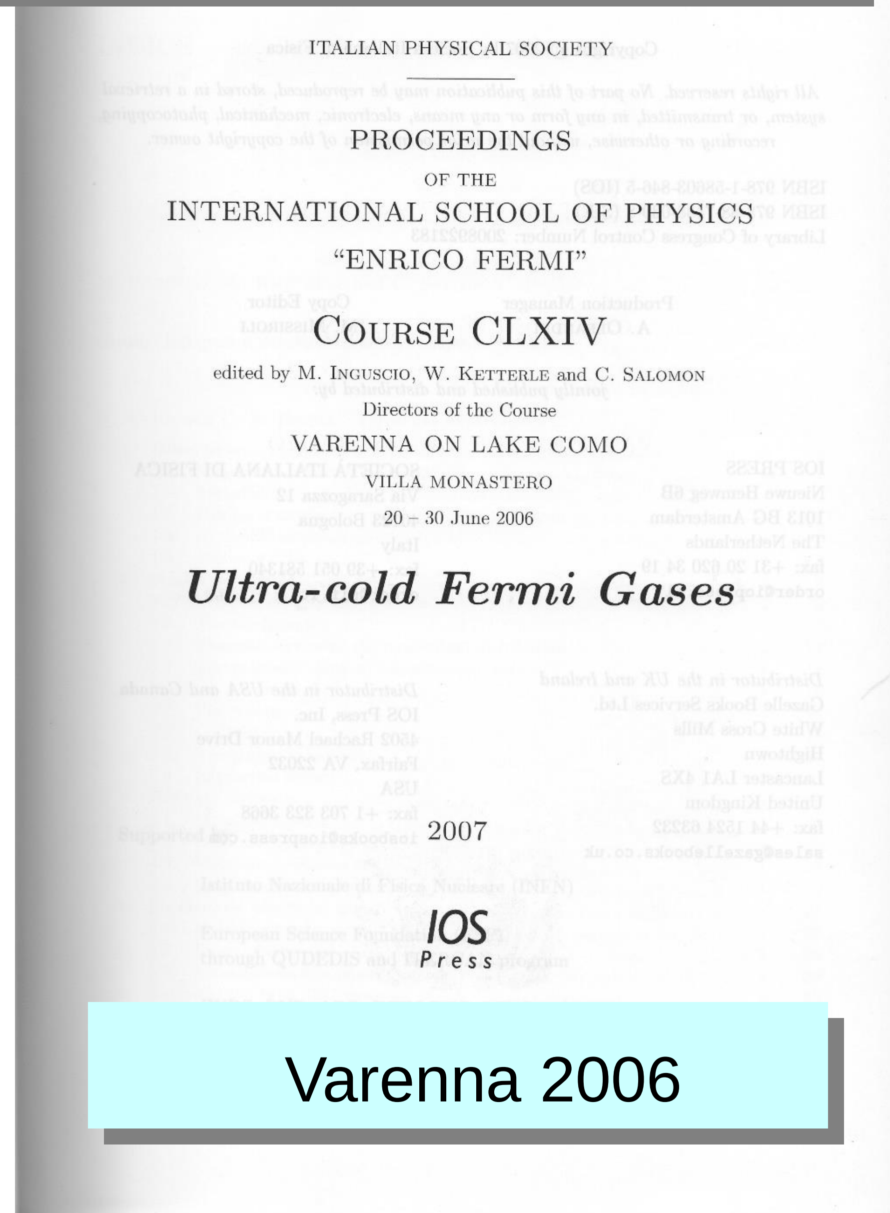
Laboratoire Kastler Brossel
Physique quantique et applications

Enrico Fermi School on Mixtures of Quantum Gases
Varenna, July 18,2022

Bose and Fermi Statistics



Enrico Fermi on lake Como



ITALIAN PHYSICAL SOCIETY

PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF PHYSICS

"ENRICO FERMI"

COURSE CLXIV

edited by M. INGUSCIO, W. KETTERLE and C. SALOMON

Directors of the Course

VARENNA ON LAKE COMO

VILLA MONASTERO

20 – 30 June 2006

Ultra-cold Fermi Gases

2007

IOS Press

Varenna 2006

Outline of the two lectures

- Dual Bose-Fermi superfluid with ^{6}Li-^{7}Li isotopes
- Center of mass modes and link with Equation of State
- Measurement of critical velocity for superfluid counterflow
- Lifetime of the Bose Fermi mixture: a simple formula !
- Link with Tan's contact

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

2) M. Delehaye, S. Laurent, I. Ferrier-Barbut, S. Jin, F. Chevy, C. Salomon, PRL, 115, 265303, 2015

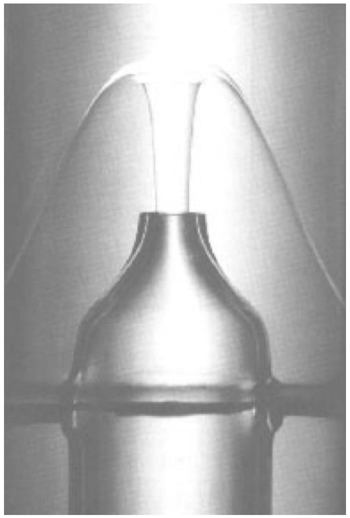
3) Y. Castin, I. Ferrier-Barbut and C. Salomon Comptes-Rendus Acad. Sciences, Paris, **16**, 241, 2015

4) S. Laurent, M. Pierce, M. Delehaye, T. Yefsah, F. Chevy, C. Salomon Phys. Rev. Lett., **118**, 103403, 2017

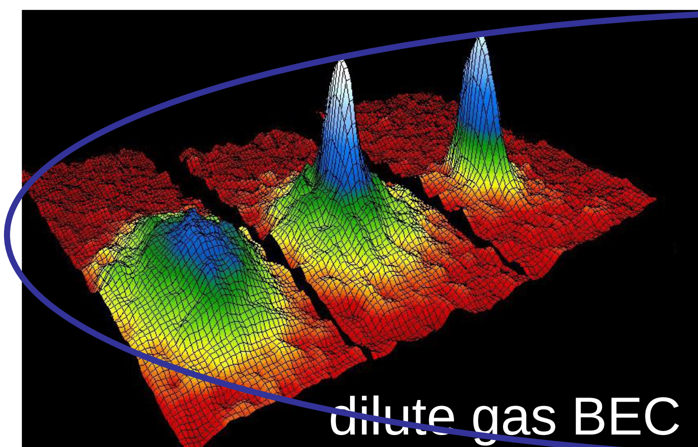
111 years of quantum fluids

Bose Einstein condensate

^{4}He



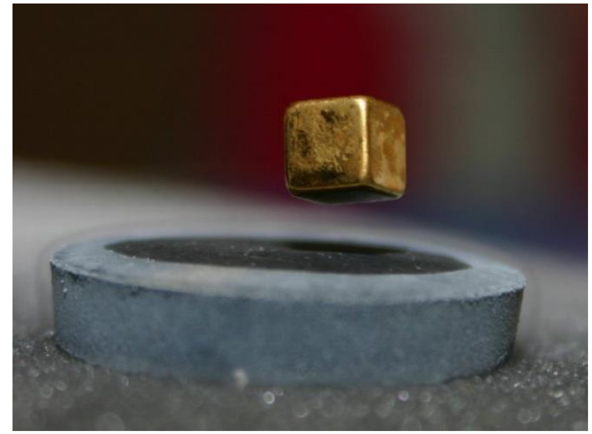
T~ 2.2 K



100 nK

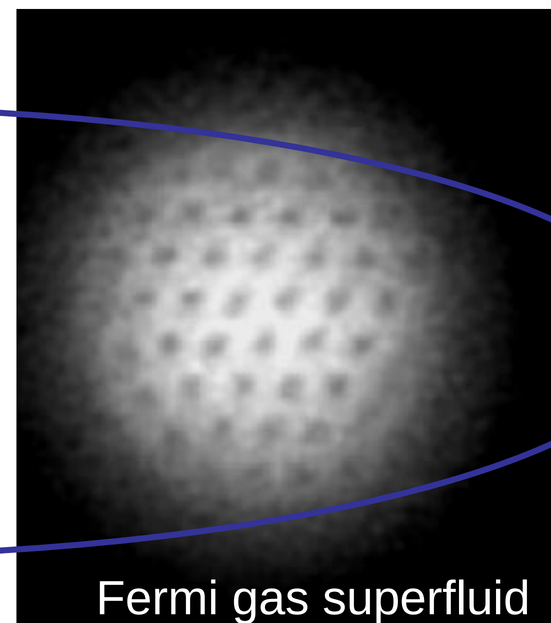
+ BEC of light and polaritons

Superconductivity



High T_c
77 K

^{3}He
2.5 mK



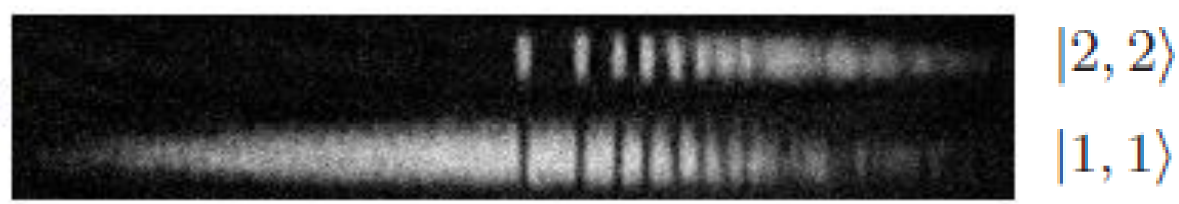
Mixtures of Superfluids

Bose-Bose superfluid mixtures first observed long ago !

Two hyperfine states in Rb at JILA (Myatt et al. ’97) and vortex production
Mixtures of BEC’s at LENS, Hamburg,….
Spinor condensates at MIT, Hamburg, Berkeley, ENS, ….

Dark-bright soliton production in two Rb BEC, Engels group, PRL 2011

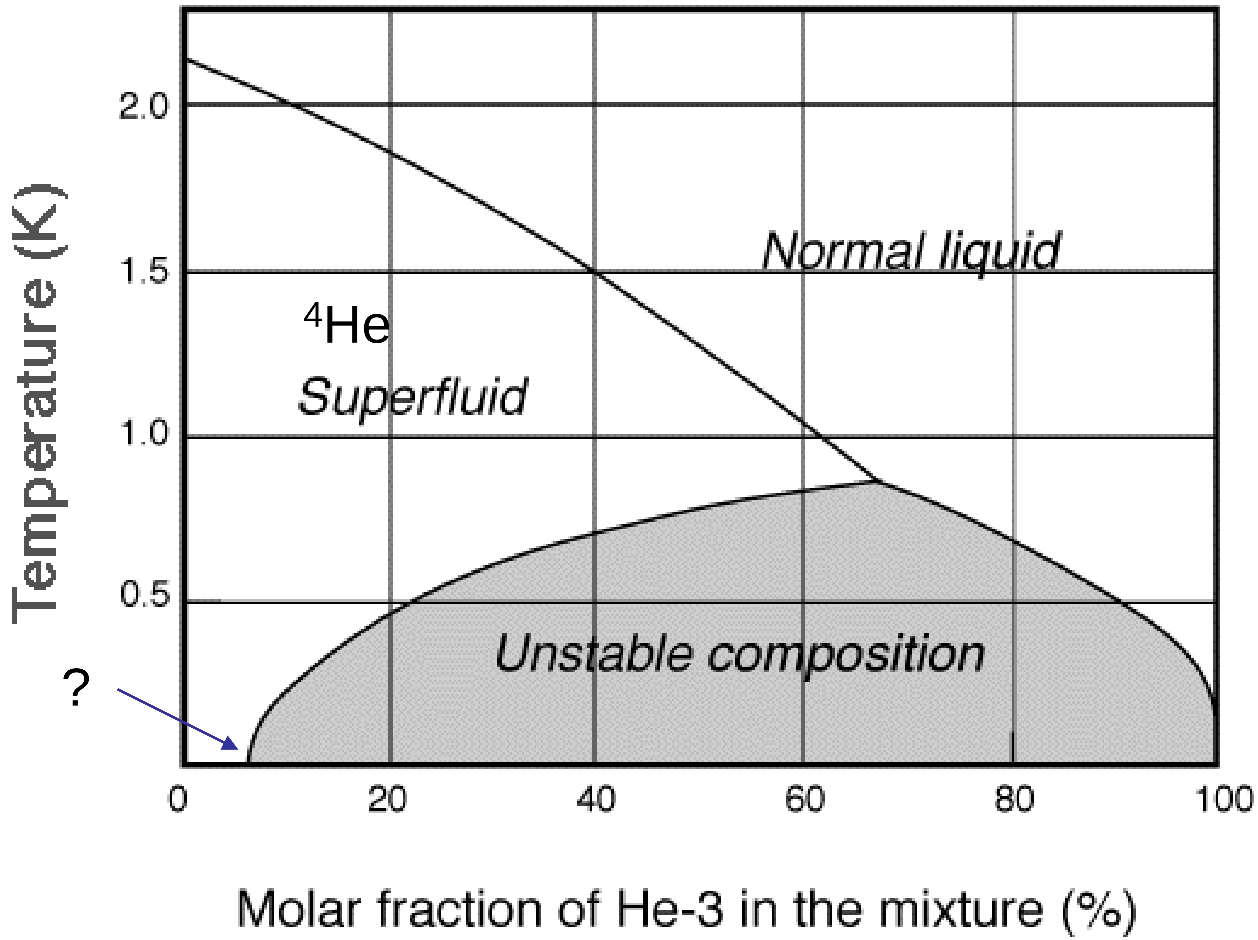
Rb



Many groups are studying Bose-Fermi mixtures but
until 2014 none had achieved double Bose-Fermi superfluidity

Today at least 3 examples, ^{6}Li-^{7}Li at ENS (2014)
^{6}Li-^{41}K at USTC, ^{6}Li-^{174}Yb at Washington Univ., (2016)
….

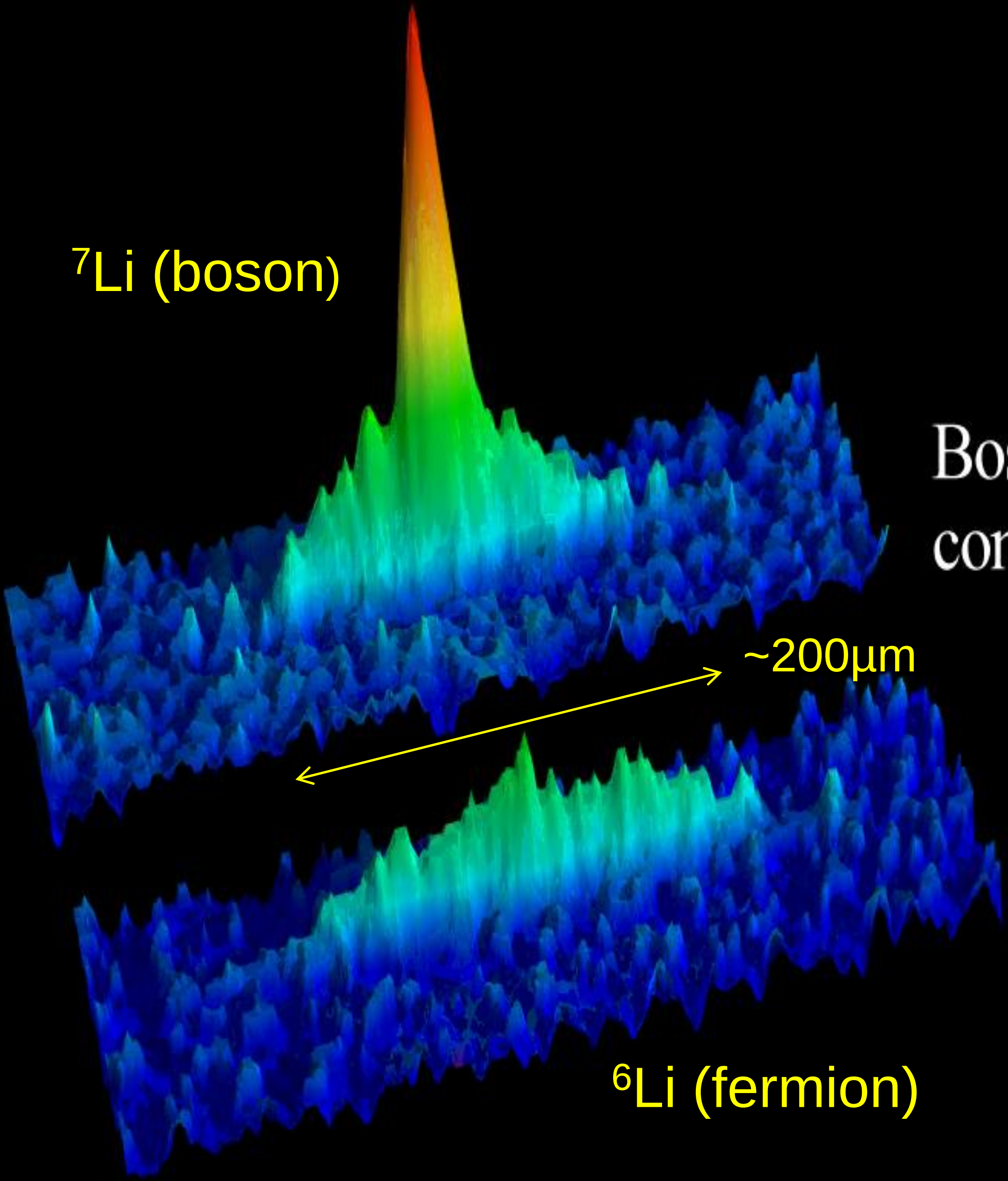
Searching for superfluid Bose-Fermi systems: ^{4}He - ^{3}He mixture



Volovik, Mineev, Khalatnikov, JETP, 42, 342 (1975): Fermi liquid theory of mixture

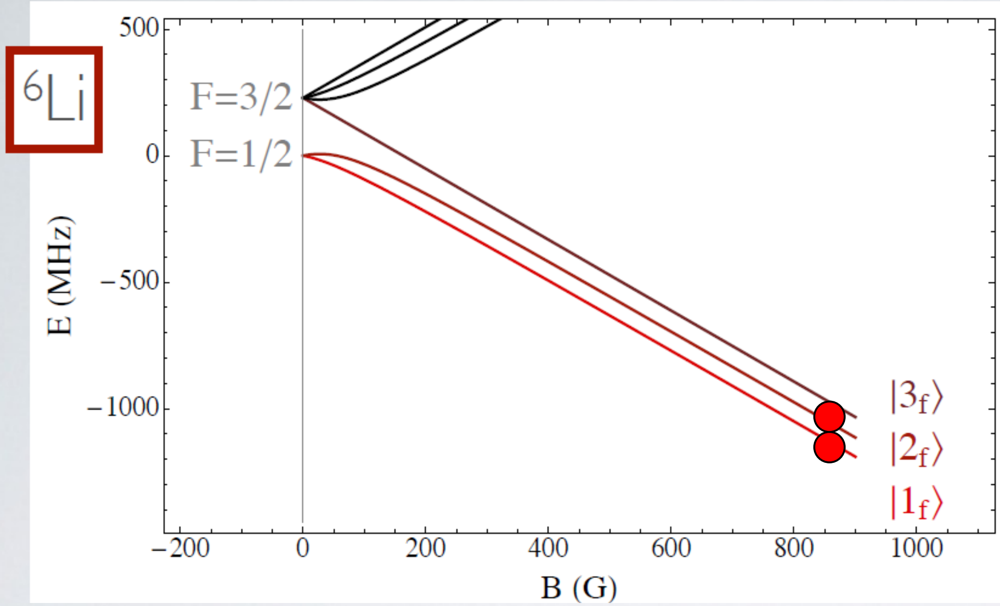
Expected $T_c \sim 1$ to 20 μK ?

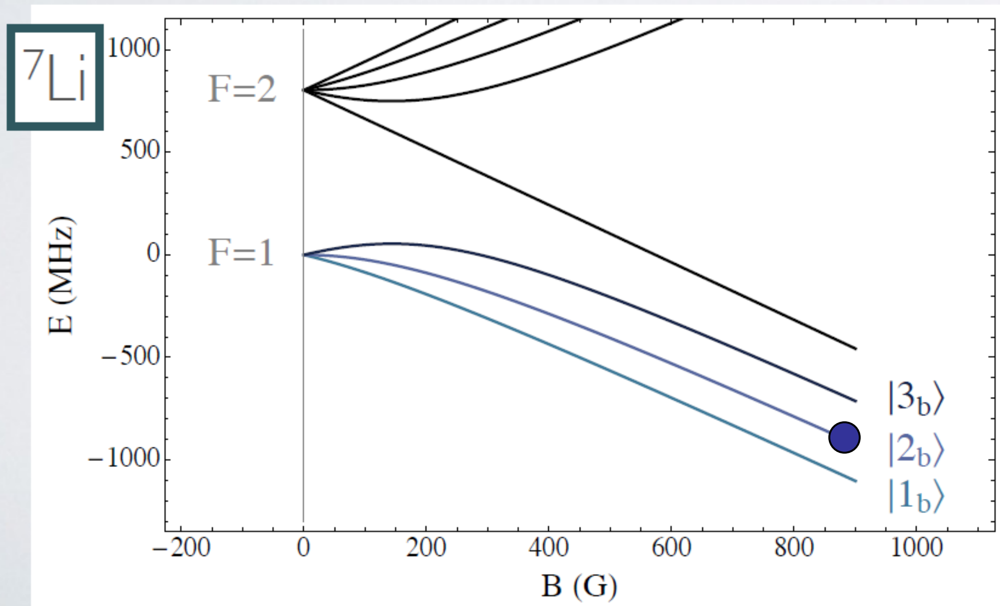
ENS 2001



Bose-Einstein condensate

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



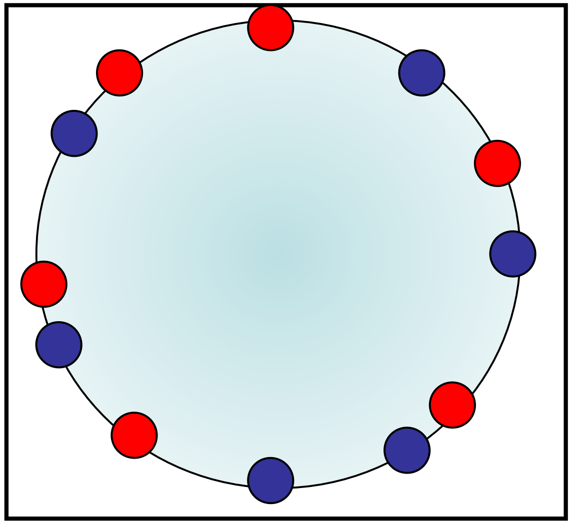


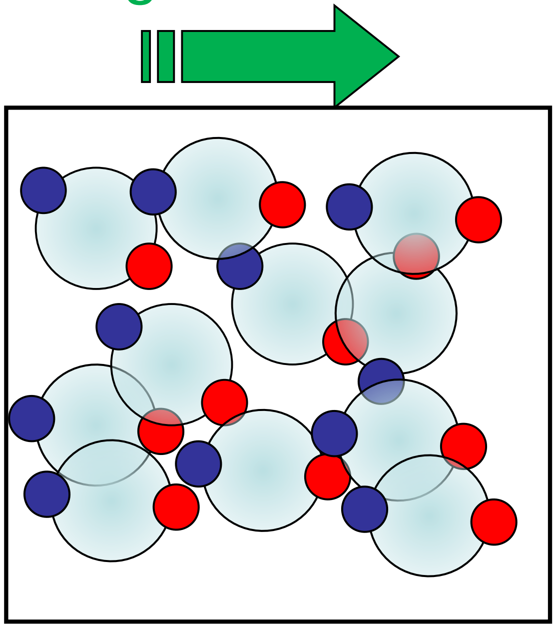
Fermions with two spin states and attractive interaction the BCS-BEC Crossover

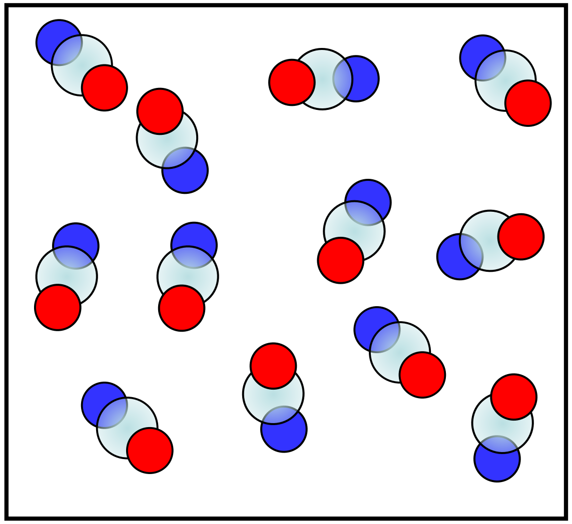
Leggett, Nozières, schmidt-Rink,.. '80

Increasing attraction strength

$$T_c \approx T_F \; e^{-\pi/2k_F|a|}$$





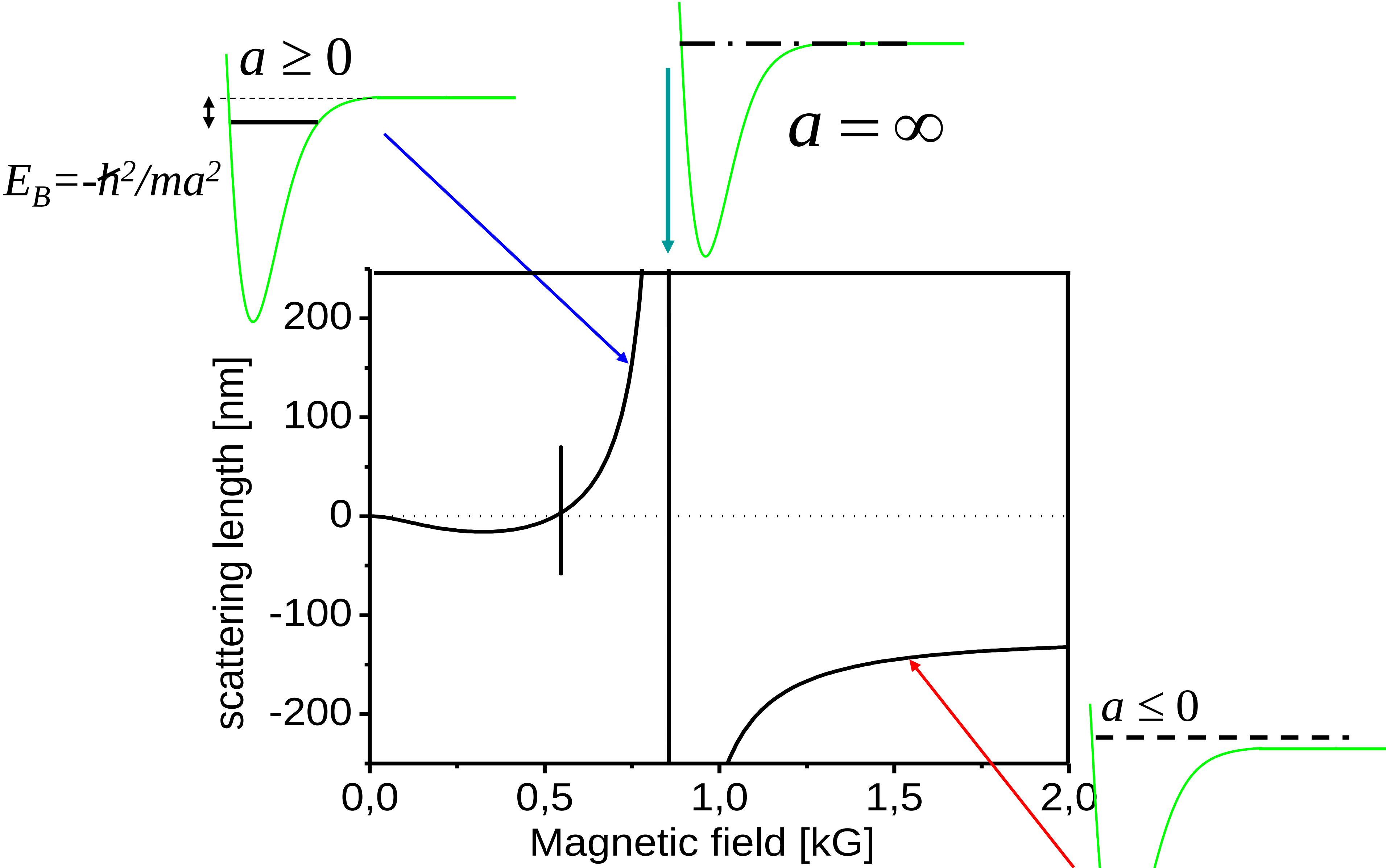


BCS regime:
$k_F|a| << 1$
Cooper pairs $\vec{k}$, $-\vec{k}$
Well localized in
Momentum: $k \sim k_F$
Delocalized in position

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

a Molecular Condensate

A two-body bound state
strongly bound molecules
Size: $a << n^{-1/3}$
$n^{-1/3}$: average distance
between particles



Tuning interactions:

Fano-Feshbach resonance. Ex: Lithium 6

Fermi Superfluid in the BEC-BCS Crossover

Fermions with two spin states $\uparrow\downarrow$ and tunable attractive interaction

M. Greiner, C. Regal & D. Jin, Nature 2003 with potassium 40
Emergence of a molecular Bose–Einstein condensate from a Fermi gas

S. Jochim et al., Science 2003, with Lithium 6
Bose-Einstein condensation of molecules

Followed by large number of studies of BCS-BEC crossover, both theory and experiment, see book edited by W. Zwerger

Equation of State of Quantum Gases

$$PV = Nk_B T$$

is a useful but incomplete equation of state !

Complete information is given by thermodynamic potentials:

Grand potential $$\Omega = -PV = E - TS - \mu N$$

Pressure

Volume

Internal energy

Temperature

Entropy

Chemical potential

Atom number

$P(\mu, T)$ is an equation of state of the gas

S. Nascimbène et al., Nature, **463**, 1057, (2010) temperature dependence and spin imbalance.

See also:

M. Horikoshi et al., Science, 327, 442 (2010), M. Zwierlein et al., MIT (2012)

The Equation of State of a Cold Gas

Q. Zhou, T.L. Ho,
Nature Physics, 09

C. Cheng, S.Yip,
PRB (2007)

The pressure is obtained from *in situ* images

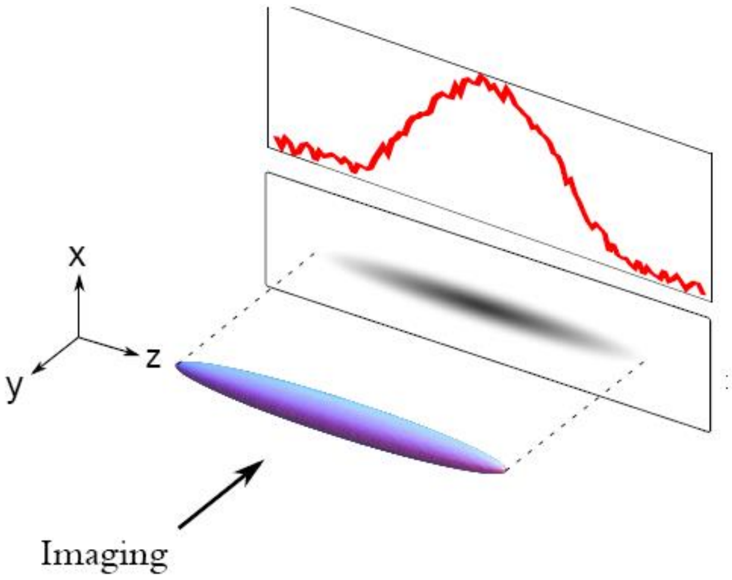
$$P(\mu_z, T) = \frac{m\omega_r^2}{2\pi}\bar{n}(z)$$

$$\bar{n}(z) = \int dxdy\, n(x, y, z)$$

Doubly-integrated density profile

Local density approx.

$$\mu(r) = \mu_0 - V(r)$$



$P(\mu_z, T)$ is an Equation of State of the locally homogeneous gas

Universal Equation of State at unitarity

$$1/k_F\, a = 0$$

Thermodynamics is universal

T. L.Ho, E. Mueller, '04

The system has continuous scale invariance

Pressure depends only on $\boldsymbol{\mu / k_B T}$

Critical temperature $T_c = 0.16\ T_F$ is universal

At very low Temp.

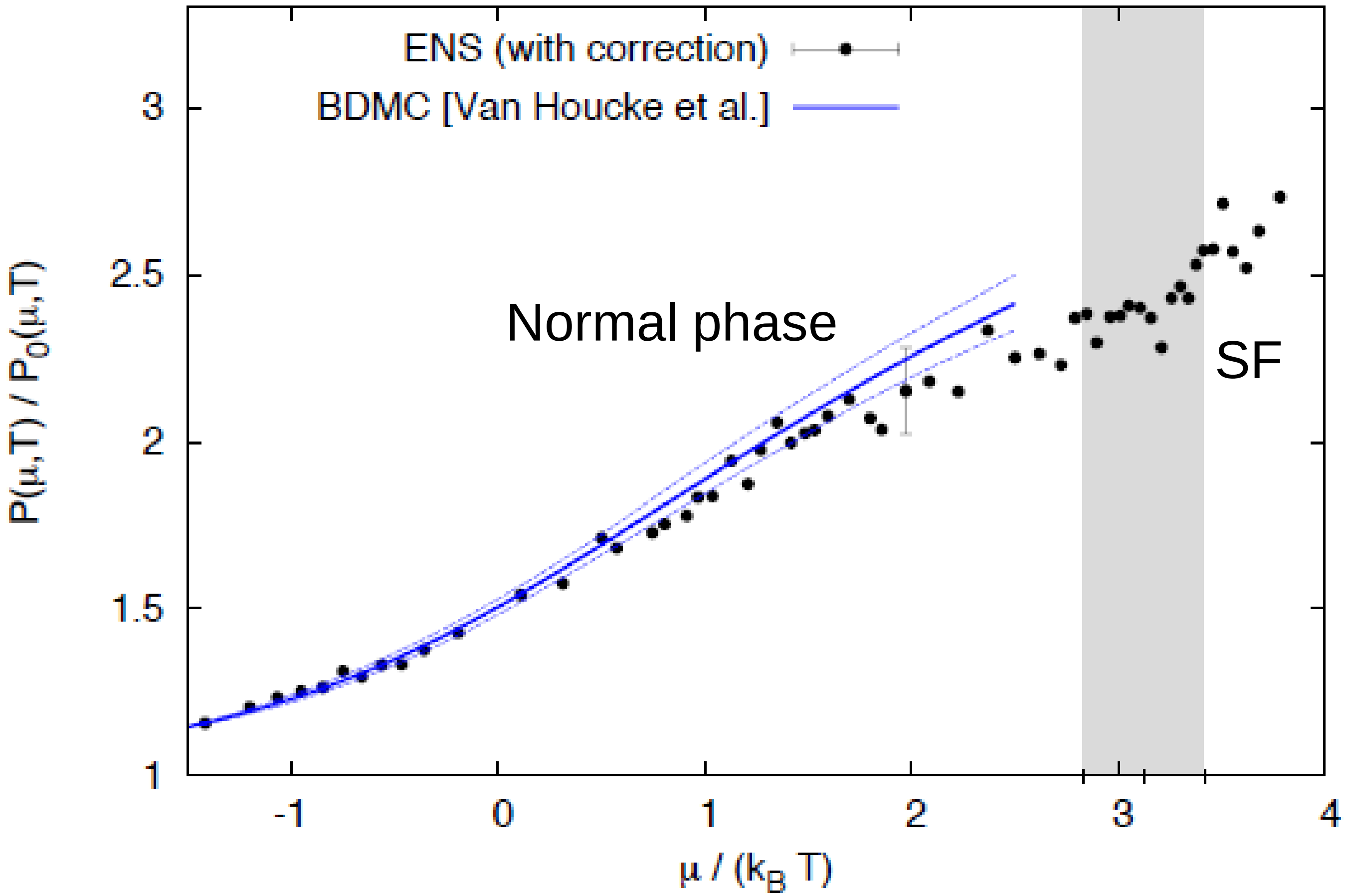
$$\mu = \xi E_F$$

$$\xi = 0.37 E_F$$

Carlson, Hausmann, ……
MIT, Ku et al.,
Science 2012

Universal Equation of State at Unitarity
Comparison with Bold Diagrammatic Monte-Carlo

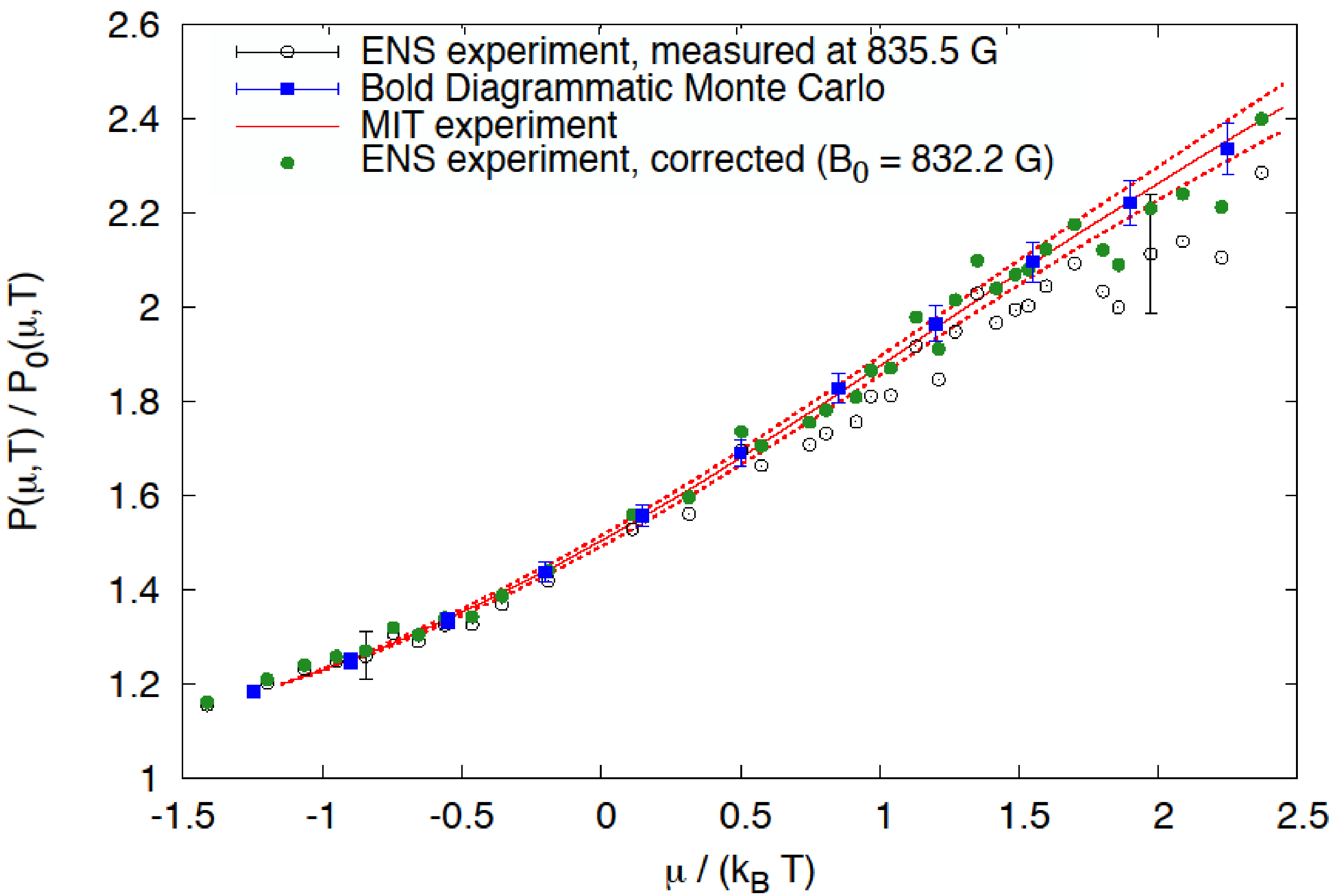
S. Nascimbène, N. Navon, K. Jiang, F. Chevy, C. Salomon, Nature 2010



Theory:
Van Houcke,
Werner,
Kosik, Prokof'ev,
Svistunov,
Ku, Sommer
Cheuk, Schirotzek
Zwierlein
Nature Phys.,
2012

5% agreement with a Many-Body theory in strongly interacting regime

Comparison with Bold Diagrammatic Monte-Carlo and MIT (2012)



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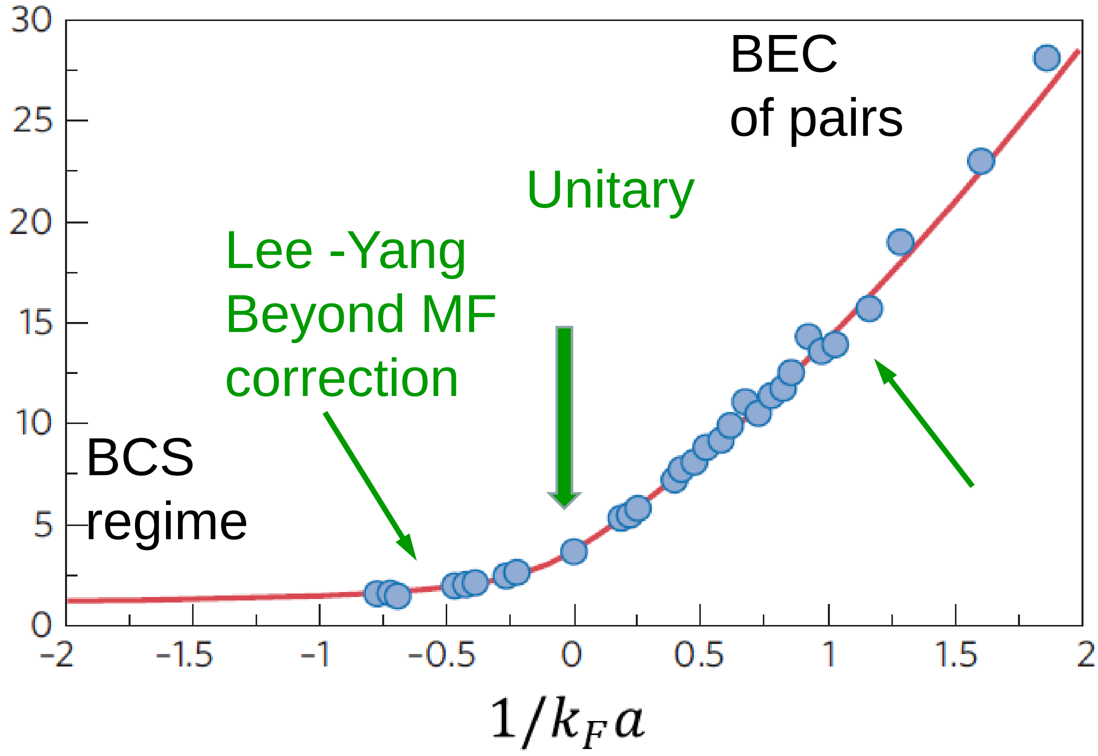
Kosik, Prokof'ev,
Svistunov,
Ku, Sommer
Cheuk, Schirotzek
Zwierlein
Nature Phys.,
2012

5% agreement with a Many-Body theory in strongly interacting regime

Equation of State of Fermi gas in the BEC-BCS crossover

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



BCS-BEC crossover at T~0

Lee-Huang-Yang Beyond MF correction

An example of quantum simulation in the strongly correlated regime

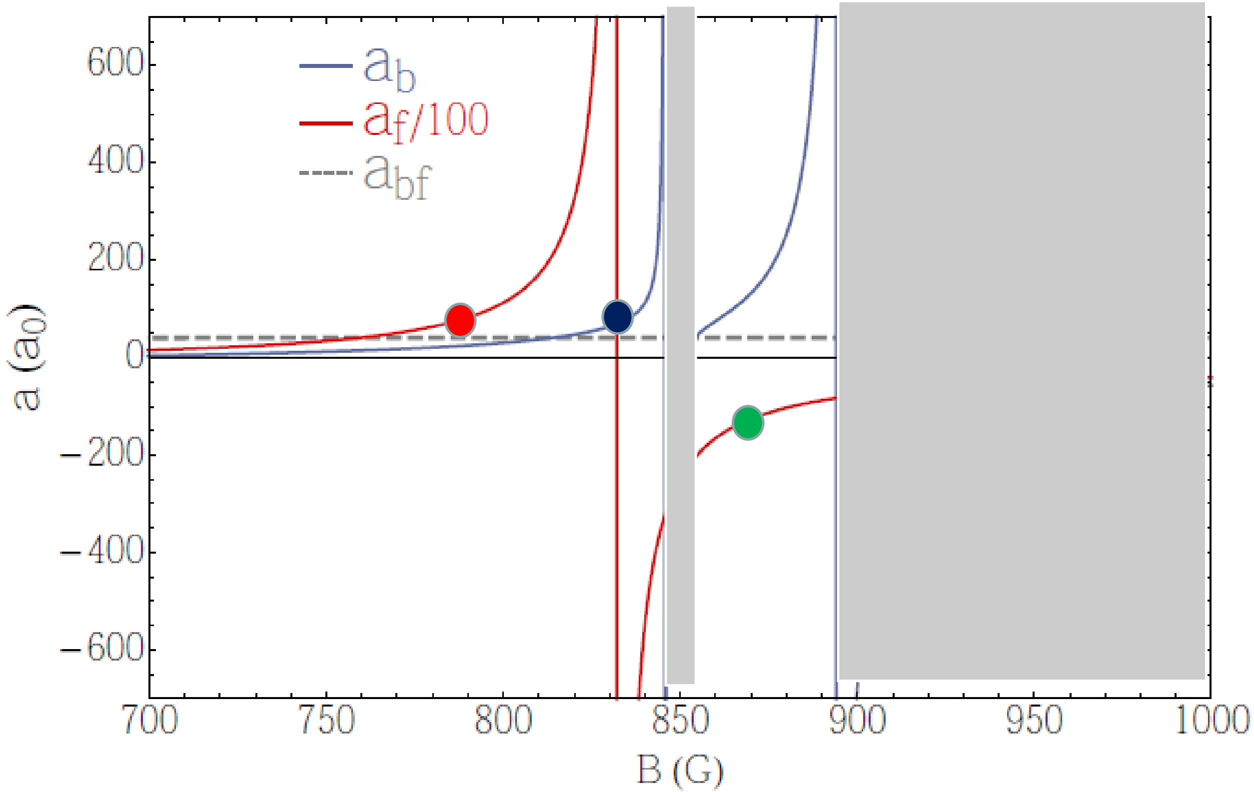
N. Navon, S. Nascimbène, F. Chevy, C. Salomon, *Science* **328**, 729-732 (2010)

Bose-Fermi superfluidity recipe

Requirements:

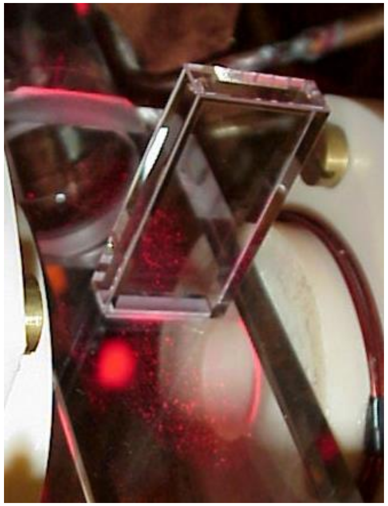
- Low a_{bf} (no interspecies demixing)
- High $|a_f|$(high fermionic superfluid T_c)
- Positive a_{bb} (stable BEC)

^{6}Li – ^{7}Li mixture in the |1>$_f$, |2>$_f$ and |2>$_b$



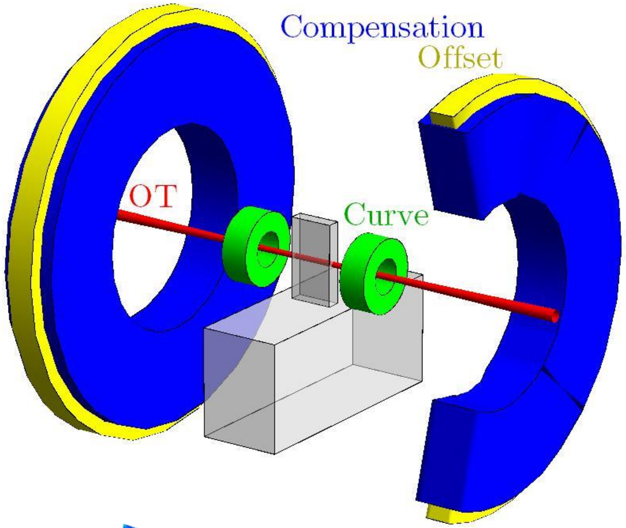
$a_{bf} = 40.8\ a_0$

Experimental Setup



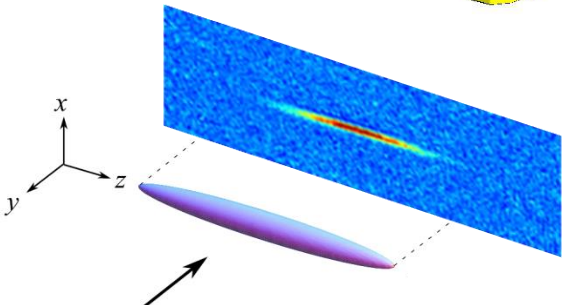
Magneto-optical trap of bosonic ^{7}Li and fermionic ^{6}Li

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

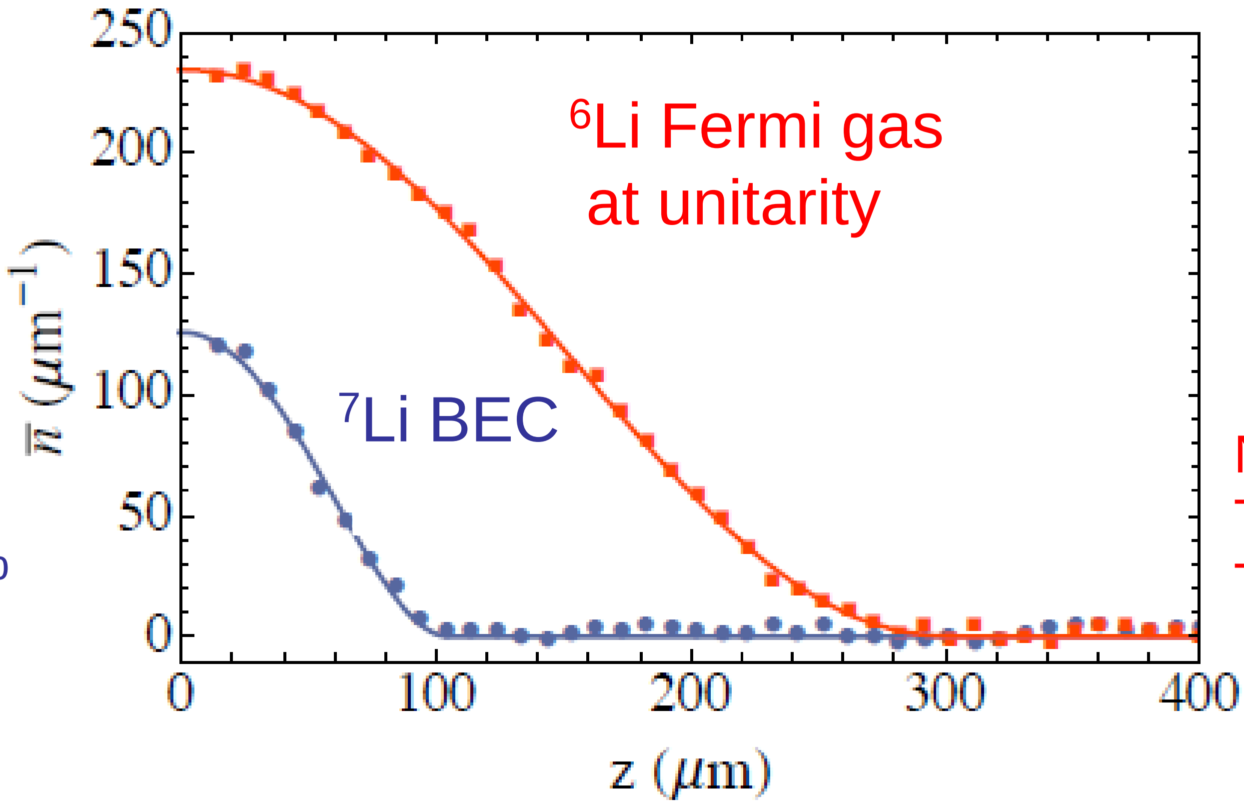
~ 4 second ramp, T~ 50-80 nK



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

In situ density profiles

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



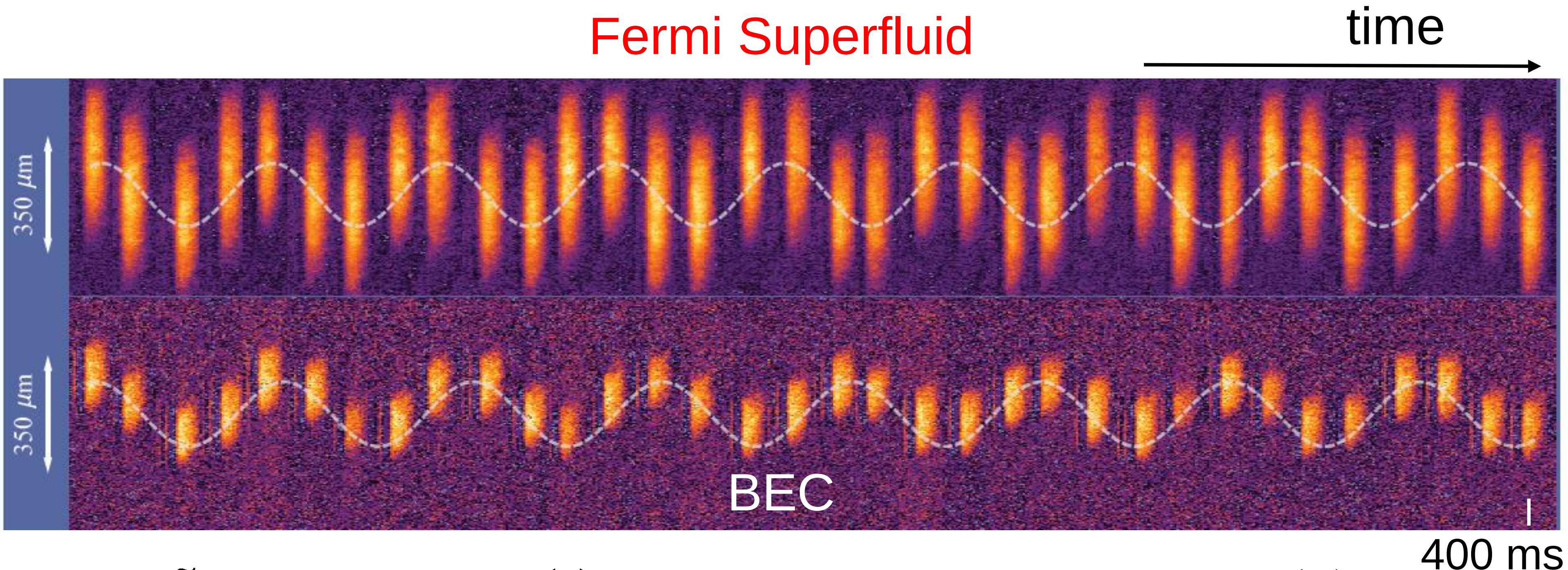
$N_F= 2\ 10^5$
T= 80 nK ~ $T_c/2$
T_F= 800 nK

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

Lifetime of mixture: 7s in shallowest trap

Unitary ^{6}Li Fermi gas can cool any species fulfilling the requirements to BEC
See also ^{6}Li-^{41}K, USTC, China, PRL '16, and ^{6}Li-^{173}Yb, UWash, PRL'17

Long-lived Oscillations of both Superfluids



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

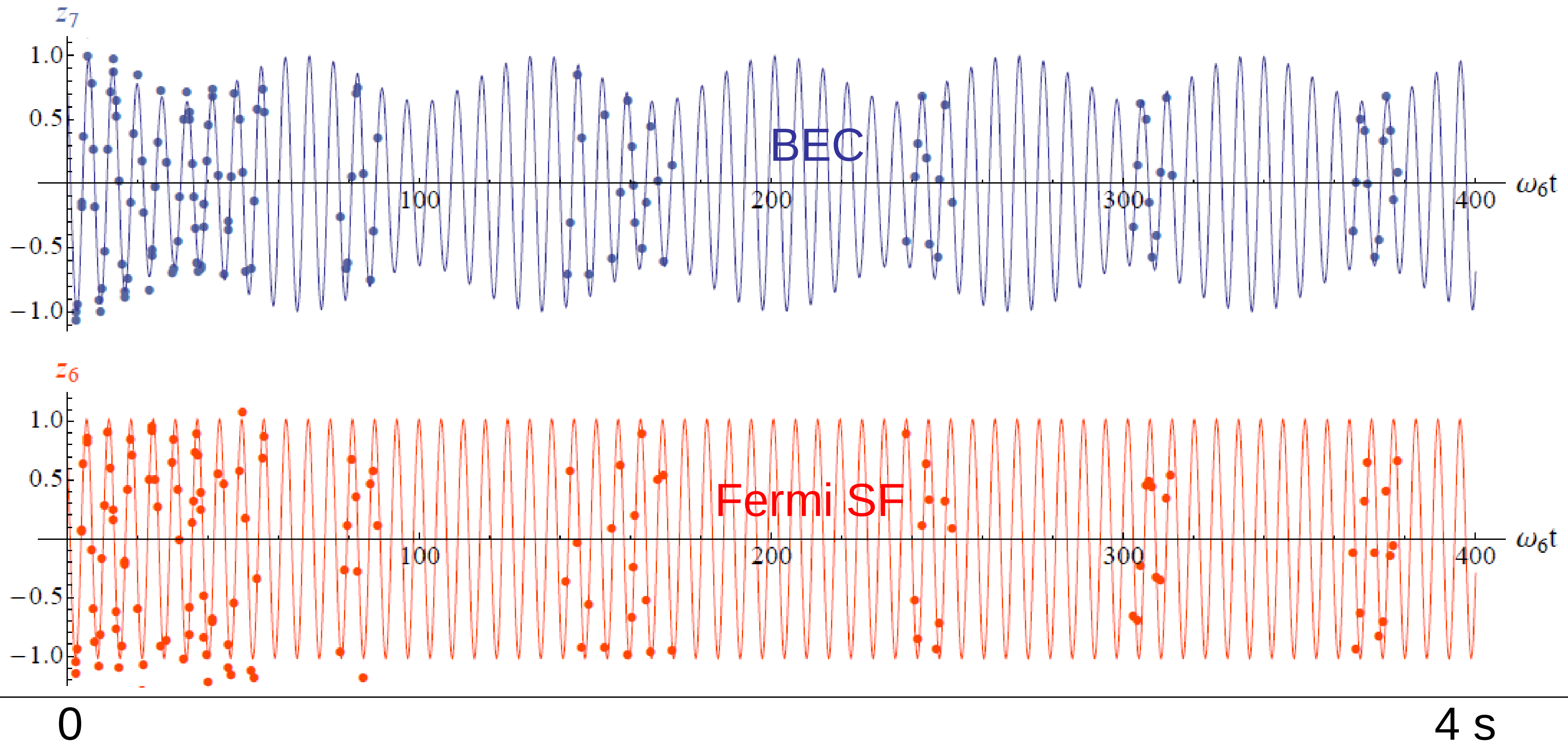
$$\tilde{\omega}_7 = 2\pi \times 15.40(1) Hz \qquad \omega_7 = 2\pi \times 15.63(1) Hz$$

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 $(\tilde{\omega}_6 - \tilde{\omega}_7)/2\pi$

Coherent energy exchange between the two oscillators

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: $k_F a_{bf} << 1$ and $N_7 << N_6$

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

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

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

Boson effective potential and link with Equation of State

Thomas Fermi radius of BEC<< TF radius of Fermi Superfluid:

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

The potential remains harmonic with rescaled frequency

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

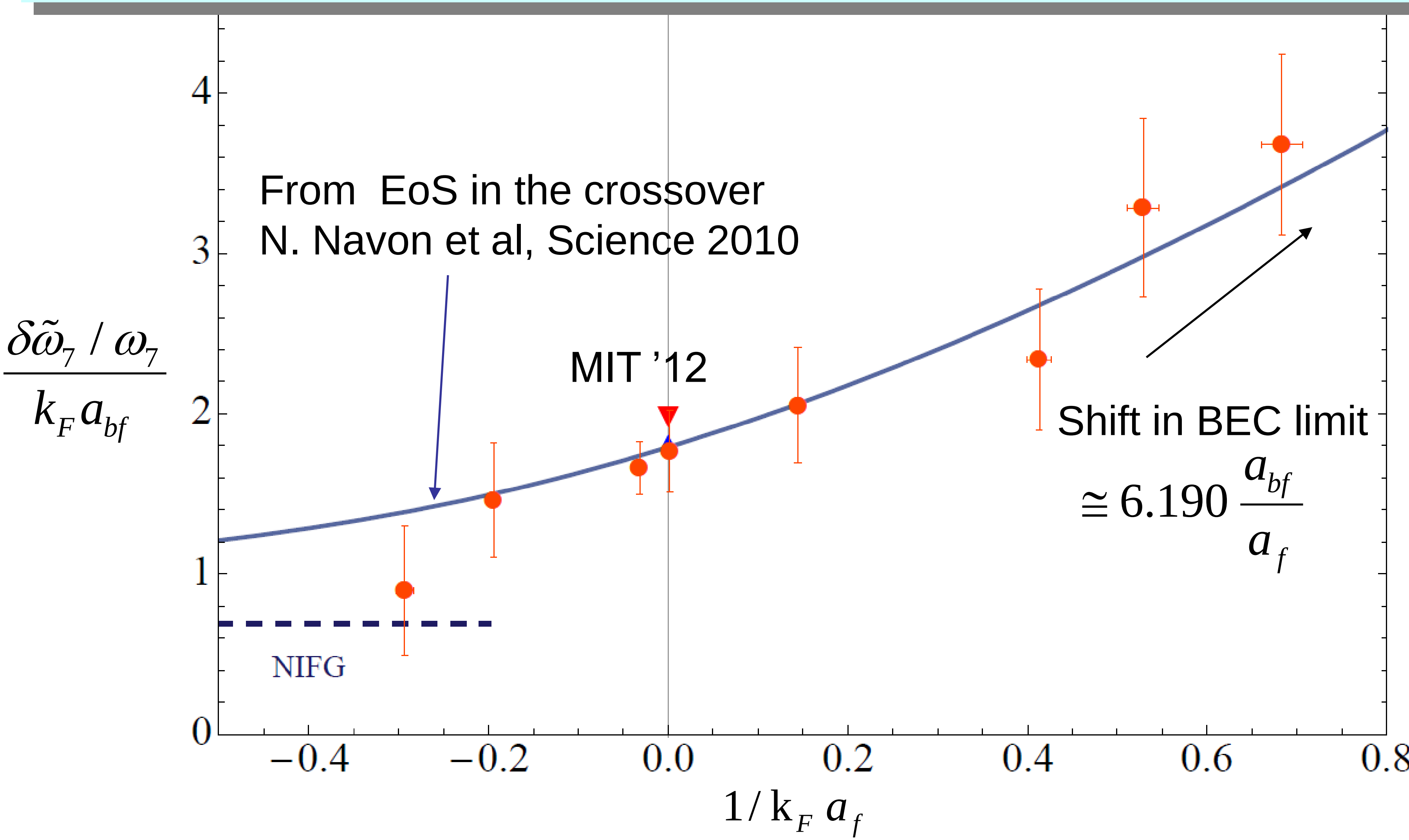
A new means to access properties of the EoS !

The equation of state $n(\mu)$ at low T is known in the BEC-BCS crossover
N. Navon et al., Science, 2010, M. Ku et al., Science 2012

Example: at unitarity, 1/a=0

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

Equation of State and Bose-Fermi Coupling in BEC-BCS crossover



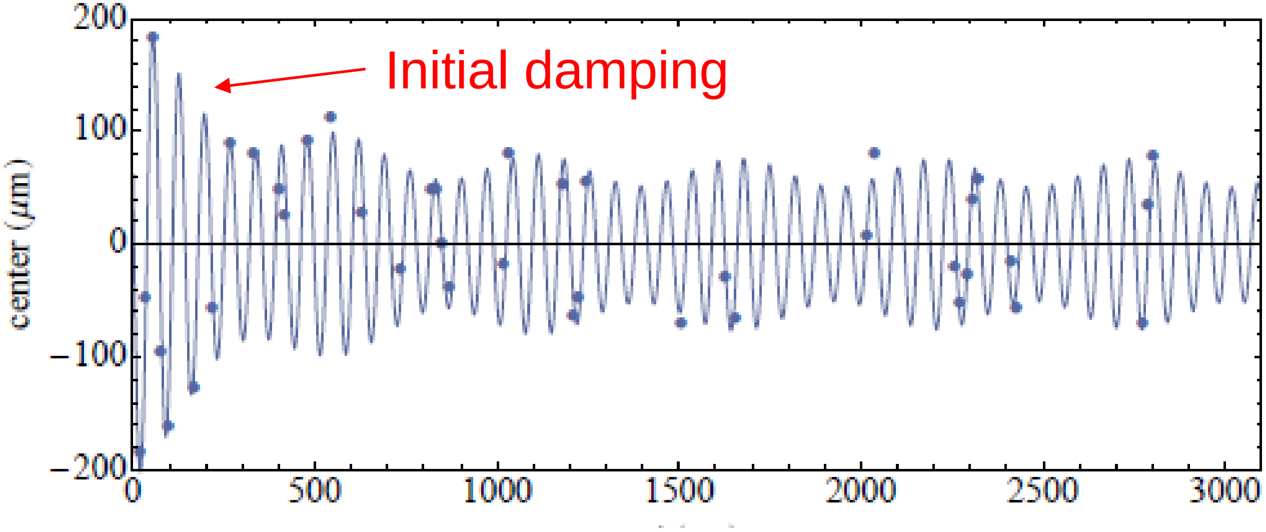
What is the critical velocity for superfluid counterflow ?

Increase initial displacement

↓

Increase relative velocity

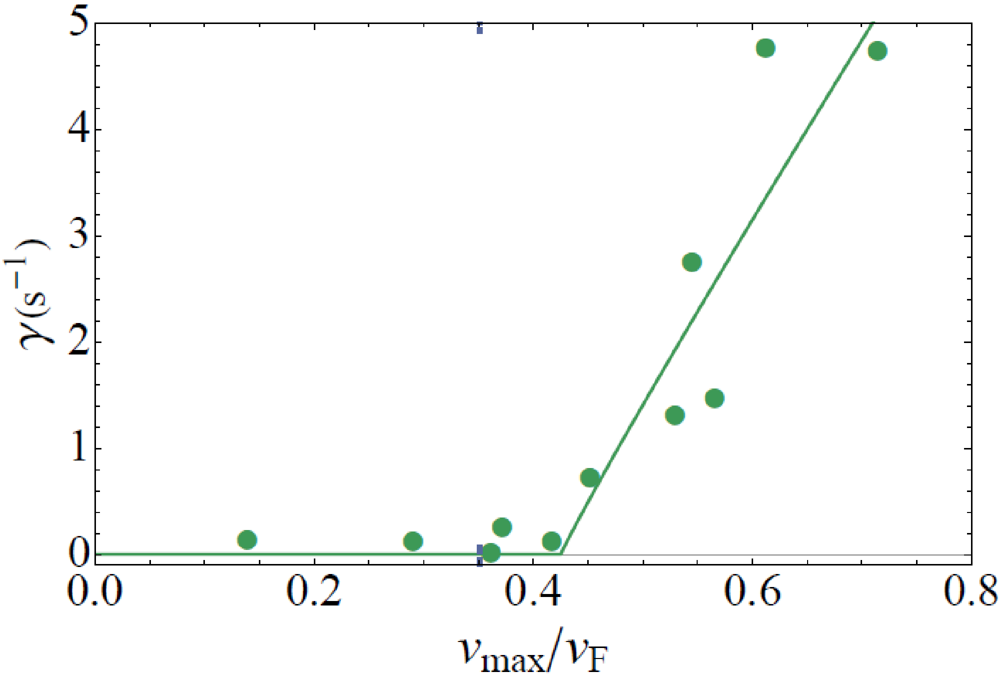
Critical velocity for superfluid counterflow



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

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

Time(ms)



V_c = 2 cm/s
is quite high !

Landau criterion

Momentum Conservation : $M\mathbf{V} = M\mathbf{V}' + \hbar\mathbf{k}$

Energy Conservation : $MV^2/2 = MV'^2/2 + \varepsilon_{\mathbf{k}}$

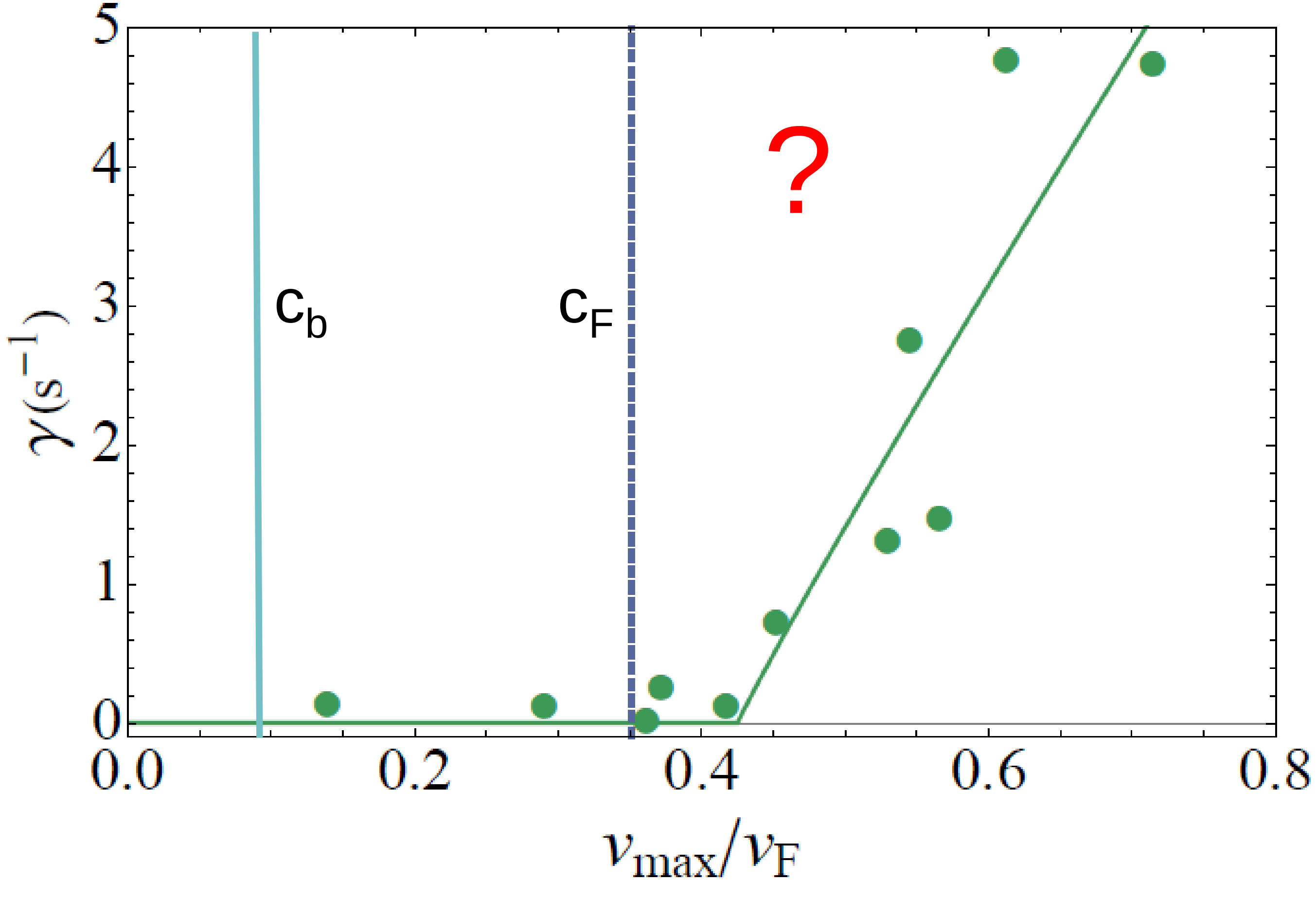
$$\hbar k V \geq \hbar\mathbf{k}.\mathbf{V} = \varepsilon_k + \hbar^2 k^2/2M \geq \varepsilon_k$$

Motion of impurity is damped by the creation of elementary excitations if:

$$V \geq V_c = \min_k \left(\frac{\varepsilon_k}{\hbar k} \right)$$

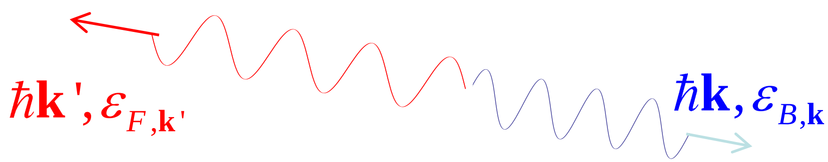
For a linear excitation spectrum $\varepsilon_k \sim kc$, $V_c = c$, the sound velocity

Critical velocities



Revisiting Landau criterion for a Bose-Fermi mixture @ T=0

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



1 Excitation in the bosonic superfluid $\quad E_{\mathrm{B},\mathbf{k}} = \varepsilon_{\mathrm{B},\mathbf{k}} + \hbar\mathbf{k}\cdot\mathbf{V}_{\mathrm{B}}$

1 Excitation in the fermionic superfluid $\quad E_{\mathrm{F},\mathbf{k}'} = \varepsilon_{\mathrm{F},\mathbf{k}'} + \hbar\mathbf{k}'\cdot\mathbf{V}_{\mathrm{F}}$

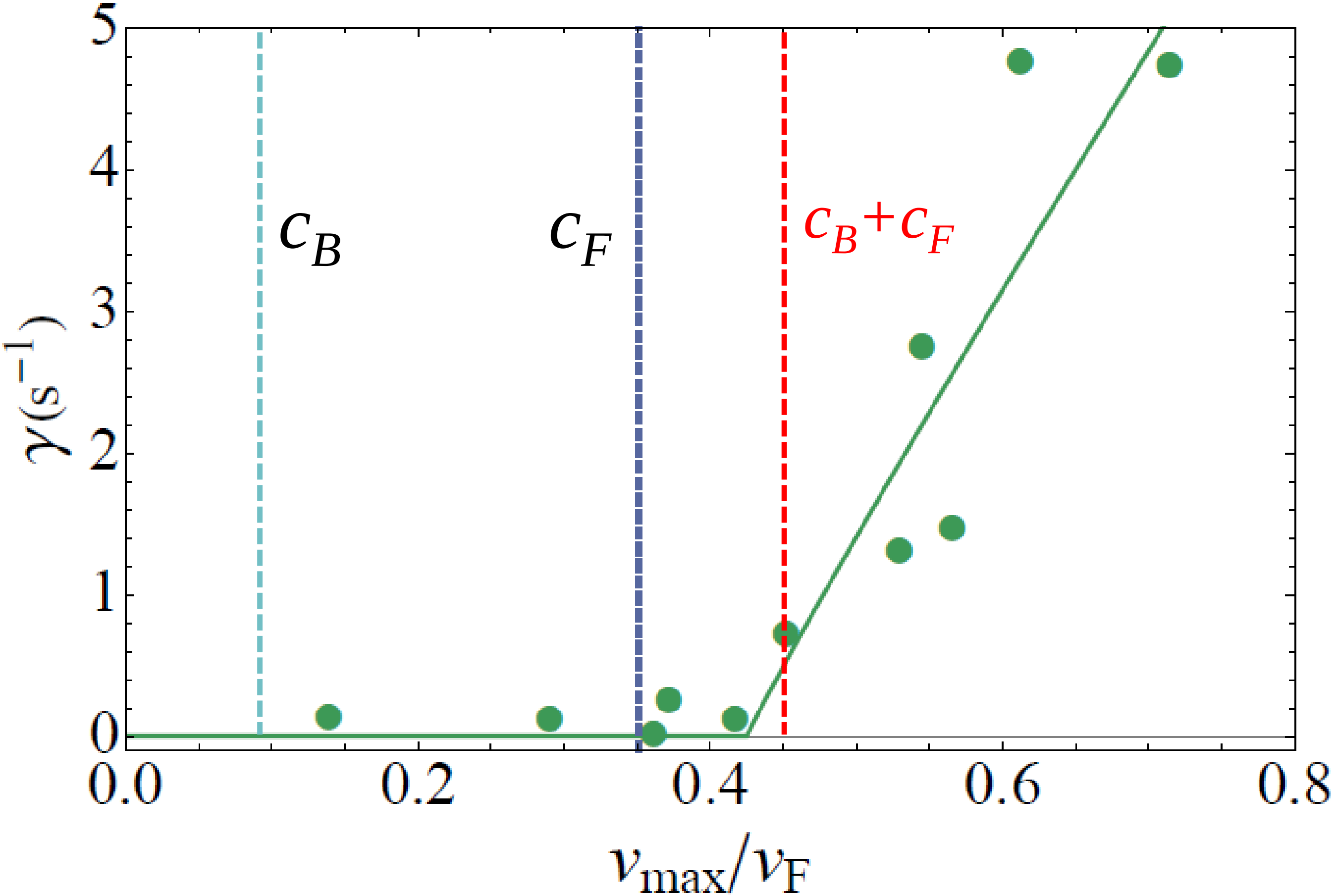
Energy-momentum conservation: $\quad E_{\mathrm{B},\mathbf{k}} + E_{\mathrm{F},\mathbf{k}'} = 0 \qquad \mathbf{k}+\mathbf{k}'=0$

$$|\mathbf{V}_B - \mathbf{V}_F| \geq \min_k \left(\frac{\varepsilon_{B,k} + \varepsilon_{F,-k}}{\hbar k} \right)$$

Sound Modes: $V_{\mathrm{c}} = c_{\mathrm{B}} + c_{\mathrm{F}}$

See also Abbad et al. EPJD 69, 126 (2015), F. Chevy, PRA **91**, 063606 (2015), W. Zheng and H. Zhai, Phys. Rev. Lett. 113, 265304 (2014)

Counter-flow critical velocity



Next lecture

What is the lifetime of the Bose-Fermi mixture ?

Three-body recombination as a probe of quantum correlations in a strongly interacting system