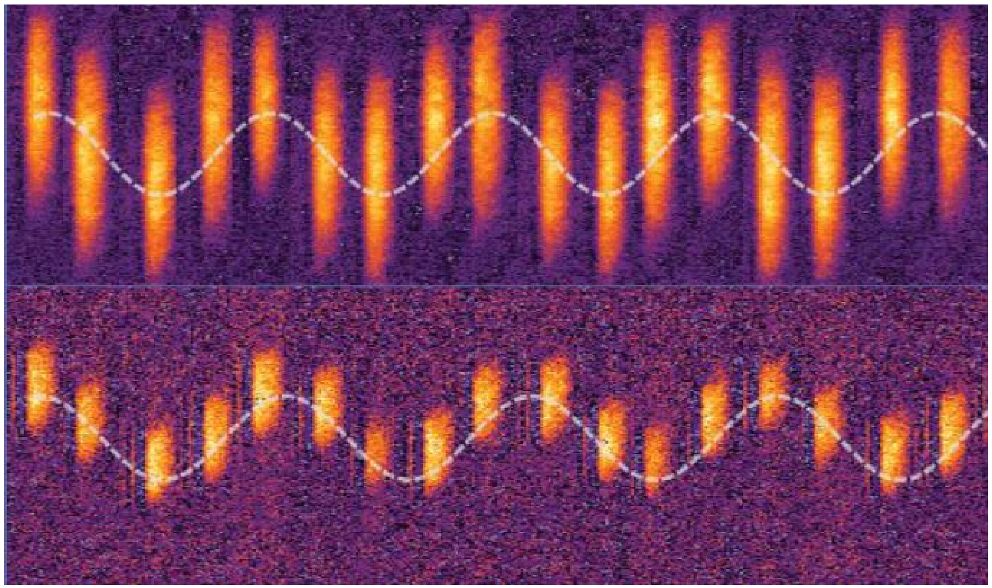
Dual Bose-Fermi Superfluids



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Physique quantique et applications

ICQSIM, Paris, November 13-17, 2017

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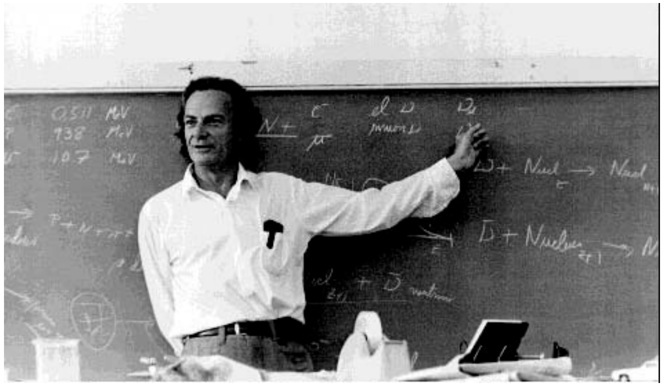
Alexander von Humboldt Stiftung/Foundation

Theory: Y. Castin, F. Werner, X. Leyronas (ENS), S. Stringari (Trento), A. Recati, T. Ozawa, O. Goulko (Amherst), C. Lobo, J. Lau (Southampton), I. Danaila (Rouen)



The goals of quantum simulation

- Obtain results on a quantum system that cannot be reached by standard methods or numerical simulations
- Explore novel geometries, parameters, or configurations that are not available in the initial system
- Invent novel situations or devices based on the acquired knowledge

Cold atoms are good quantum simulators

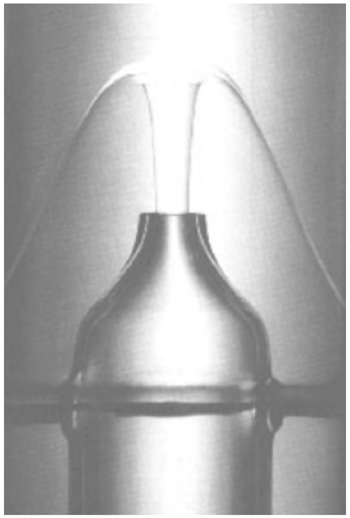
Non-trivial questions:

How to verify the simulation results ?
How to detect and correct errors ?

106 years of quantum fluids

Bose Einstein condensate

^{4}He

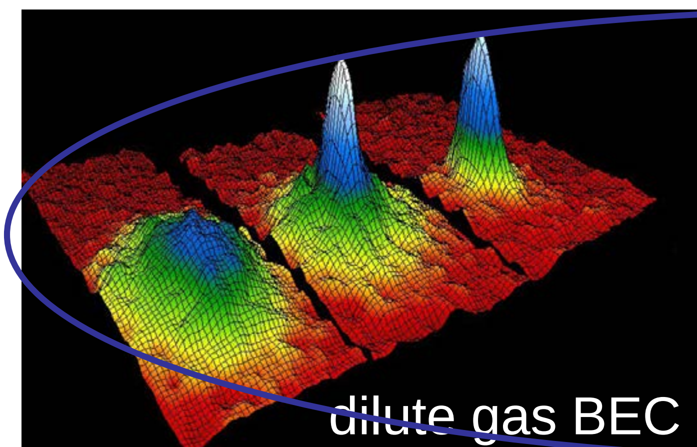


T~ 2.2 K

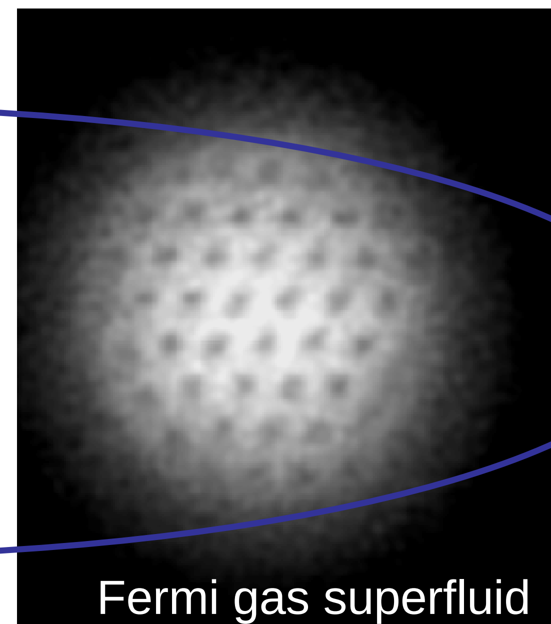
Superconductivity

High T_c
77 K

^{3}He
2.5 mK



100 nK
BCS-BEC
Crossover



+ polaritons and BEC of light

Outline

- Equation of state of fermions with tunable interaction
- Dual Bose-Fermi superfluid recipe
- The critical velocity for superfluid Bose-Fermi counterflow
- Lifetime of the Bose Fermi mixture: a simple formula !

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

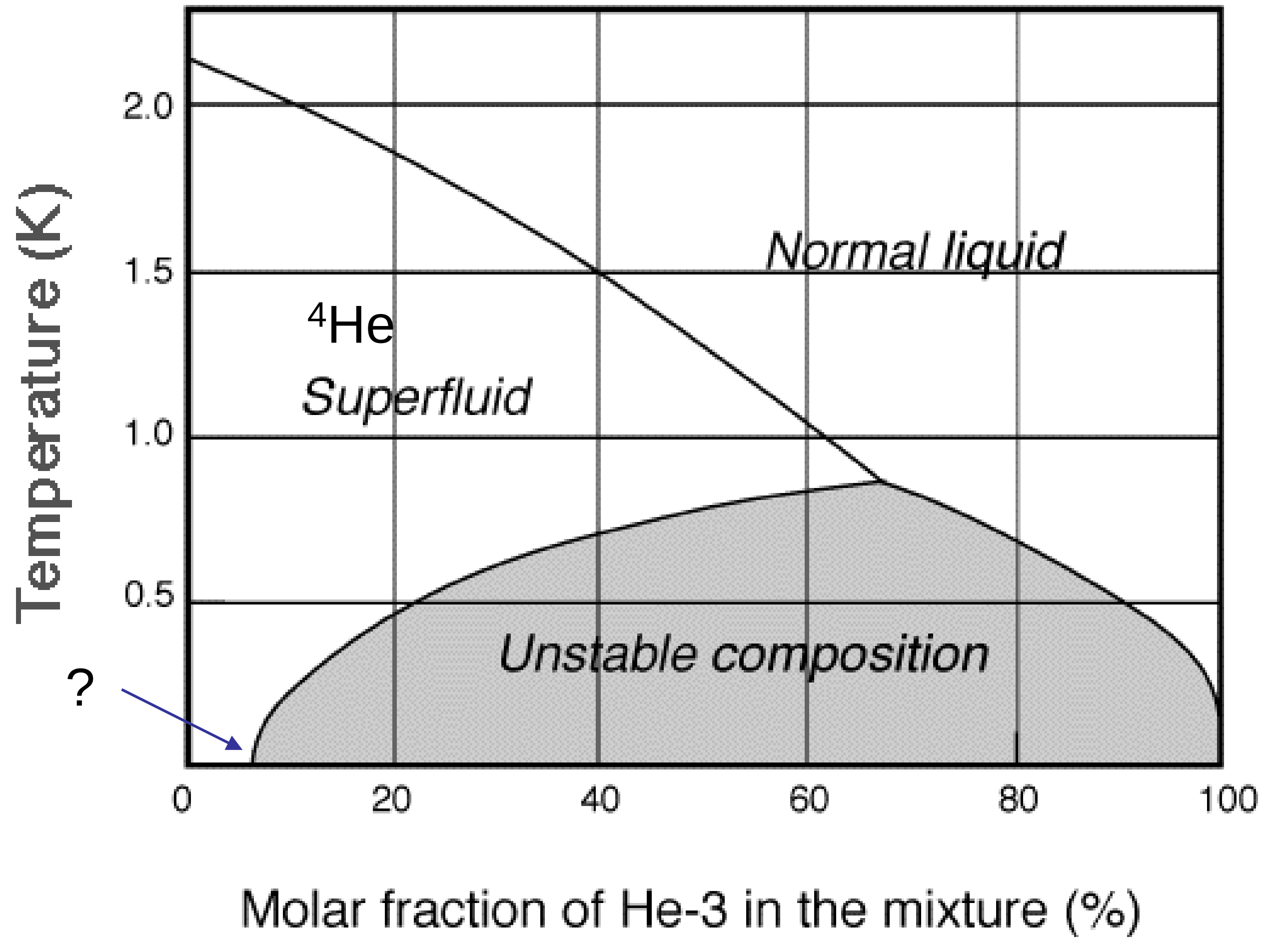
3) Y. Castin, I. Ferrier-Barbut and C. Salomon Comptes-Rendus Acad. Sciences, Paris, **16**, 241, 2015

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

5) M. Abad, A. Recati, S. Stringari, F. Chevy, EPJD, 69, 2015

6) P-P. Crépin, X. Leyronas, F. Chevy, ArXiv:1607.00218

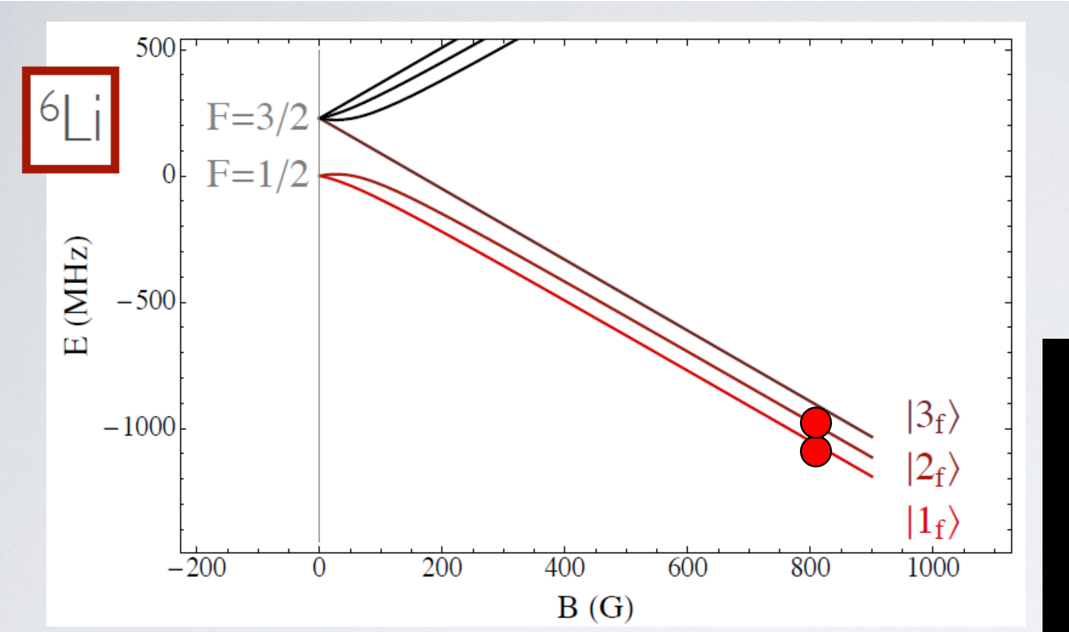
Searching for superfluid Bose-Fermi systems: ^{4}He - ^{3}He mixture

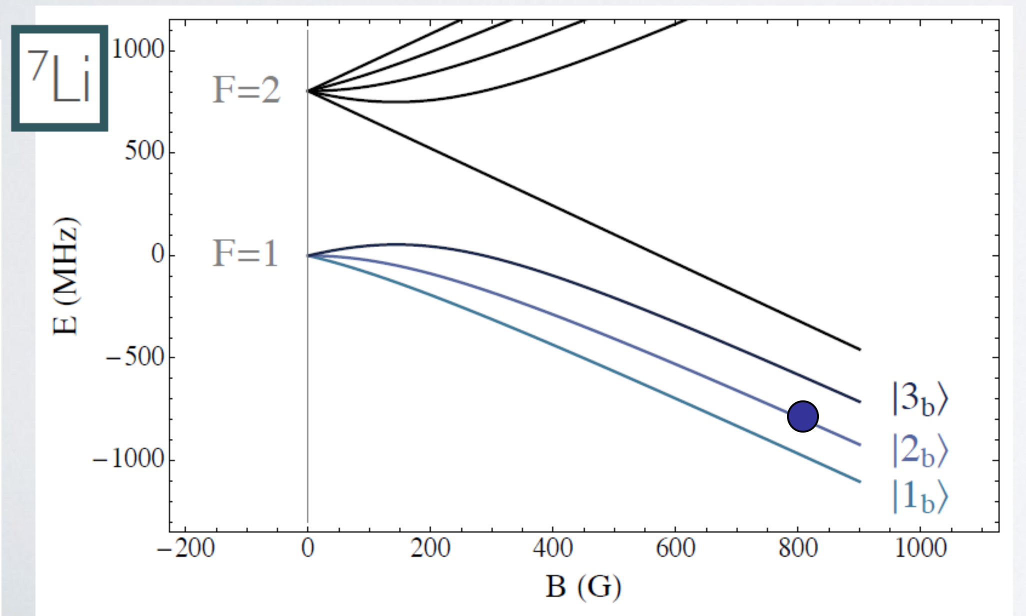


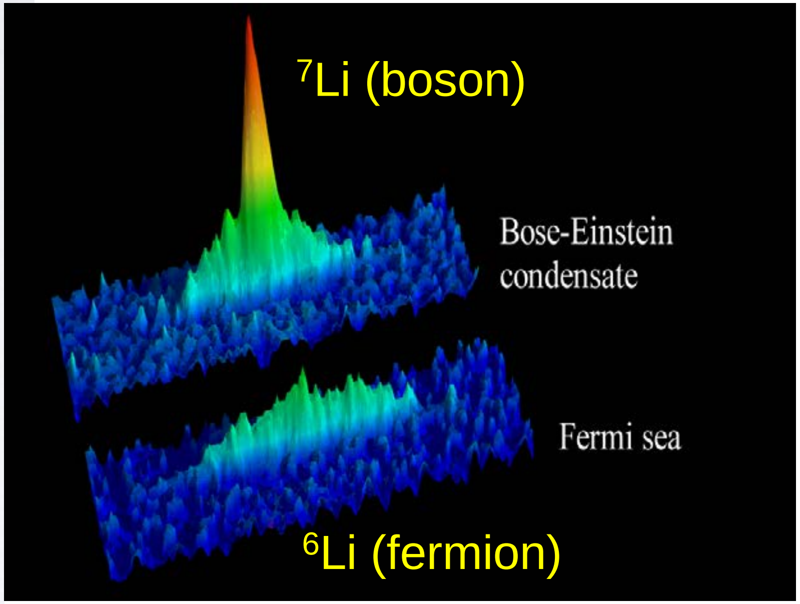
Volovik, Mineev, Khalatnikov, JETP, 42, 342 (1975): Fermi liquid theory of mixture

Expected T_c ~ 1 to 20 μK ?

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

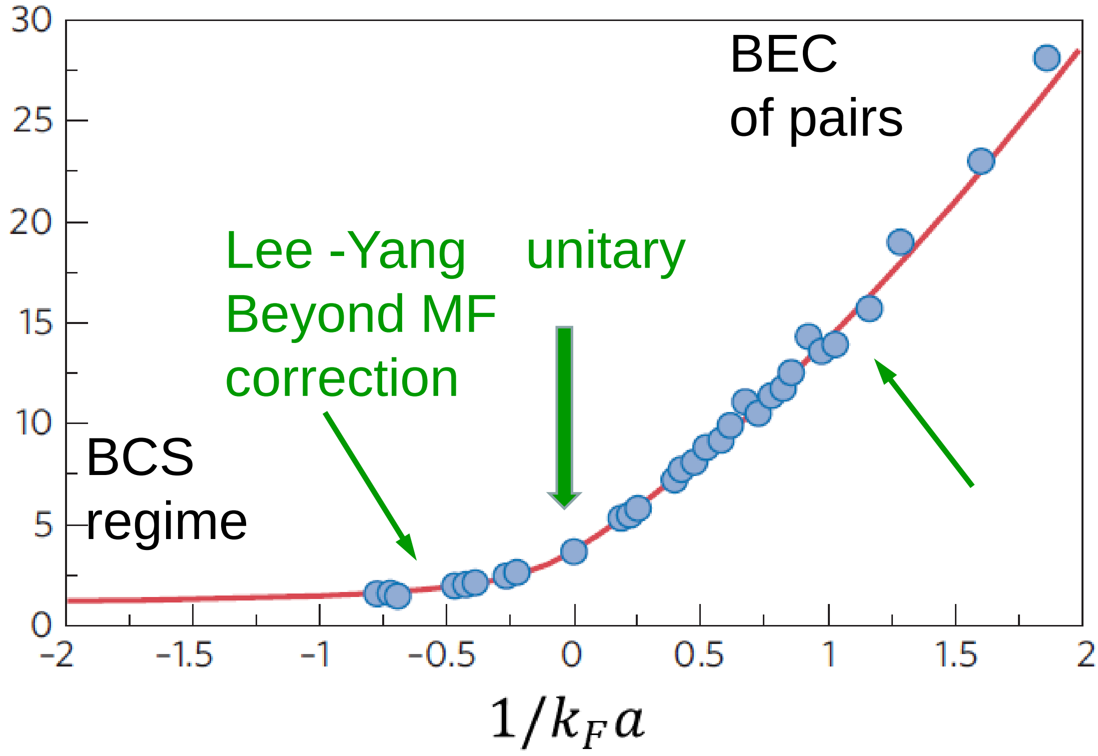






Equation of State of Fermi gas in the BEC-BCS crossover

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

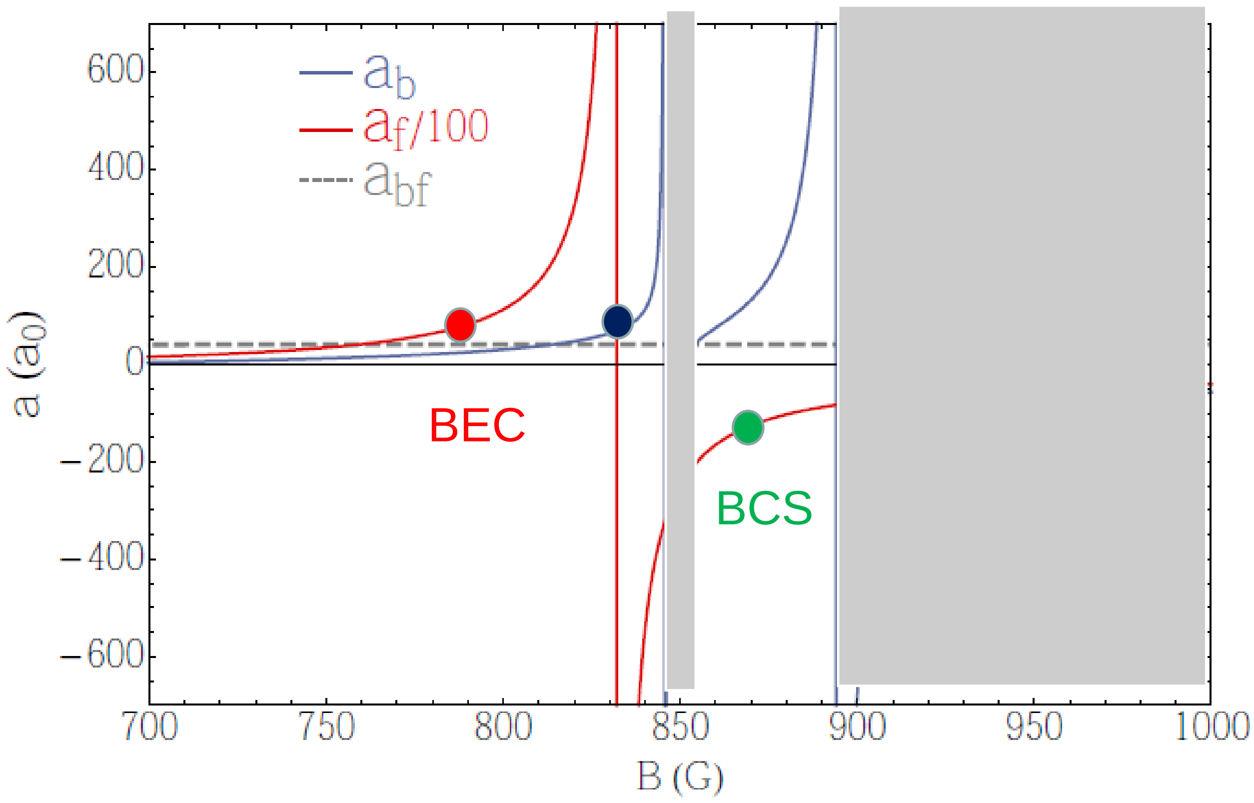
N. Navon, S. Nascimbène, F. Chevy, C. Salomon, *Science* **328**, 729-732 (2010)

Bose-Fermi superfluidity recipe

Requirements:

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

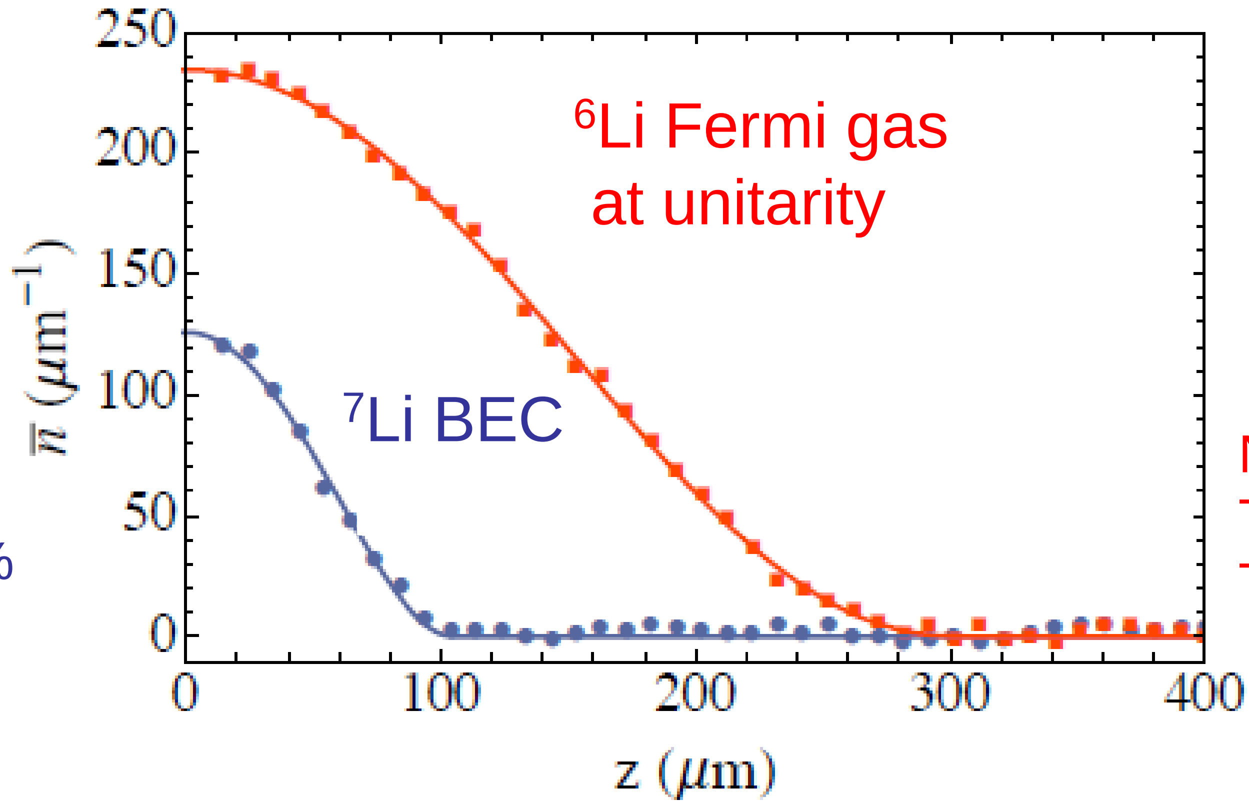
^{6}Li – ^{7}Li mixture in the $|1\rangle_f$, $|2\rangle_f$ and $|2\rangle_b$



$a_{bf} = 40.8\ a_0$

In situ density profiles

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

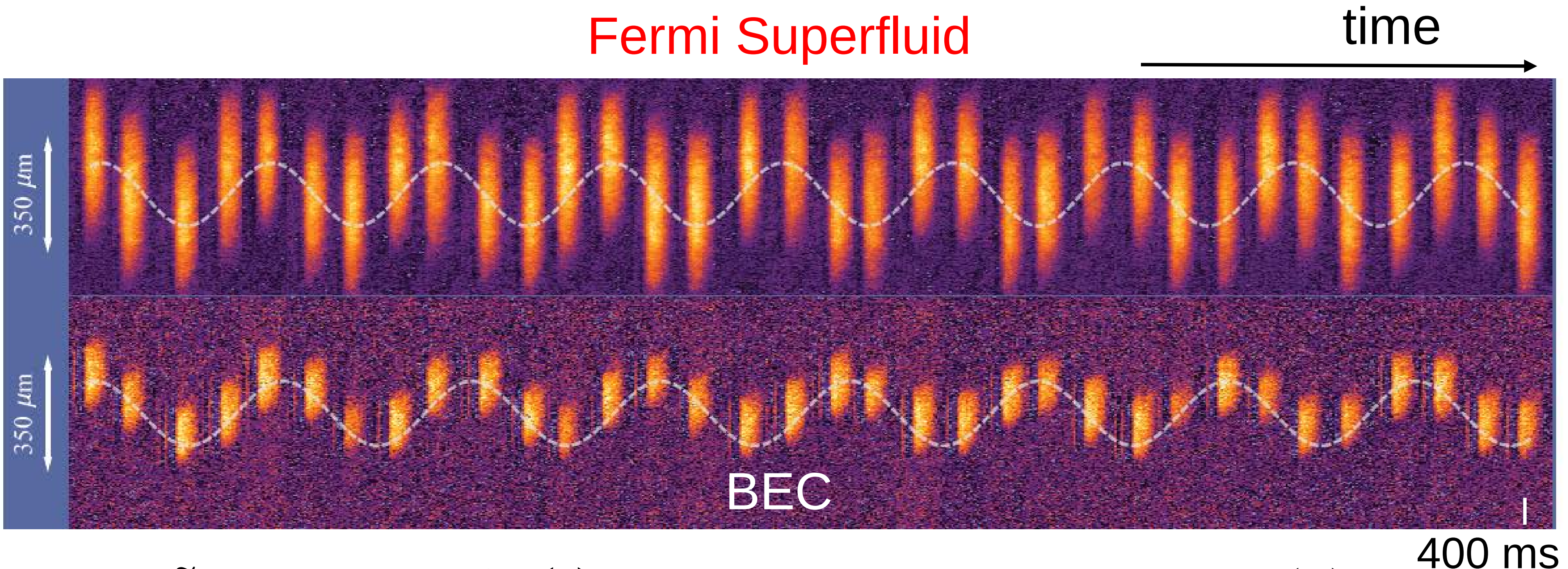


N_F= 2 10^5
T= 80 nK ~ T_c/2
T_F= 800 nK

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

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
Cool molecules to quantum regime ?

Long-lived Oscillations of both Superfluids



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

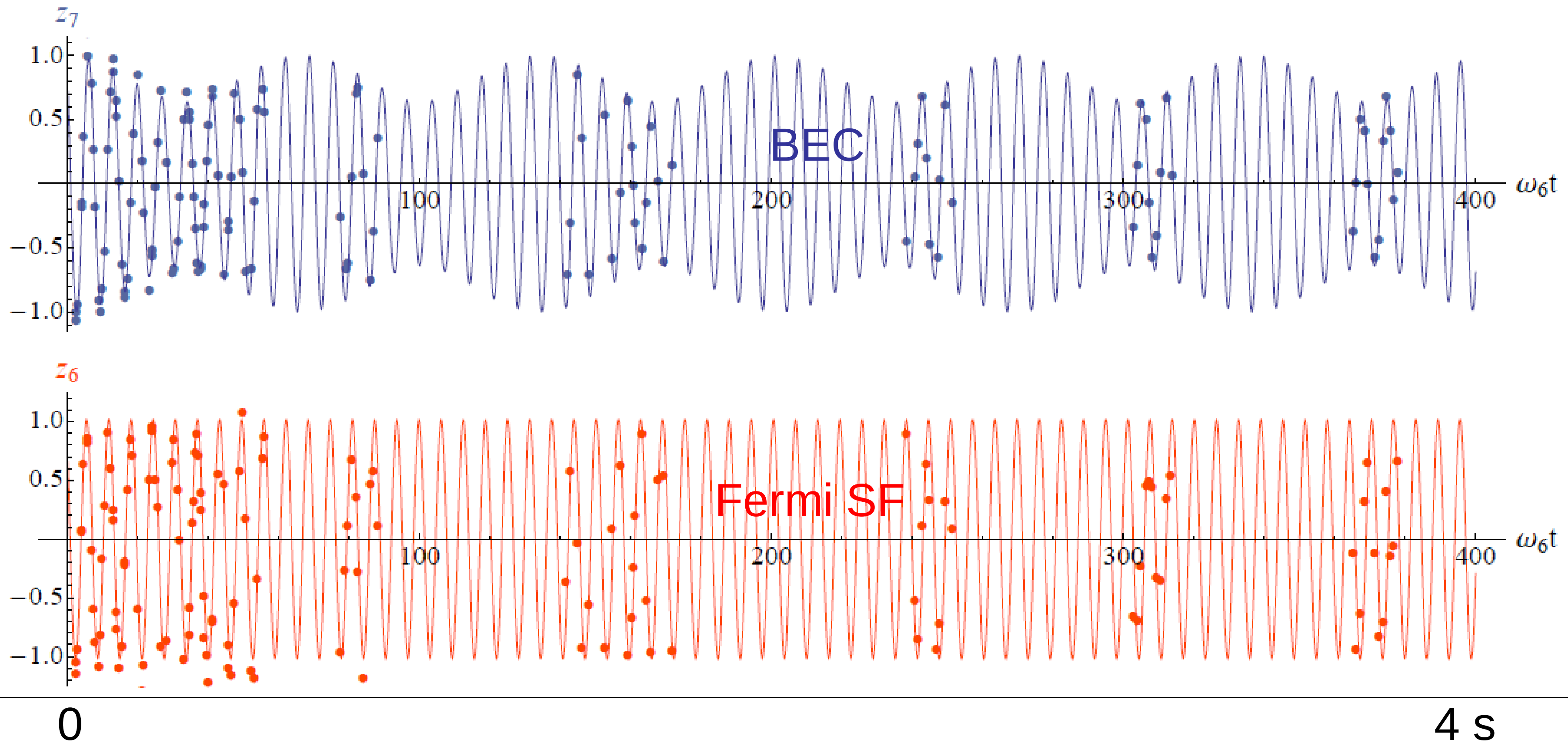
$$\tilde{\omega}_7 = 2\pi \times 15.40(1) Hz \qquad \omega_7 = 2\pi \times 15.63(1) Hz$$

Coupled Superfluids

Single Superfluid

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

Oscillations of both superfluids

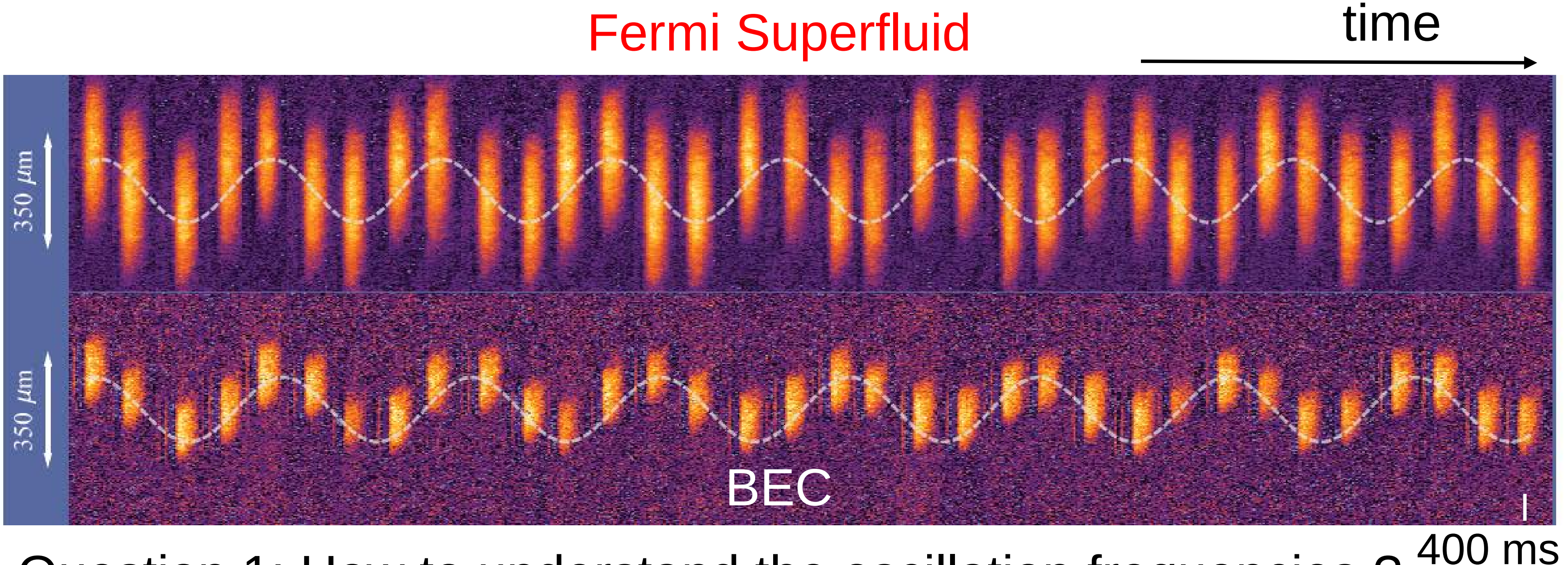


Very small damping !

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

Dual Bose-Fermi superfluids with ^{6}Li-^{7}Li isotopes



Question 1: How to understand the oscillation frequencies ?

Question 2: what is the critical velocity for superfluid counterflow ?

Question 3: what is the lifetime of the Bose-Fermi mixture ?

At unitarity, the lifetime is 7 seconds in shallow optical trap

How does it vary with $1/k_f a_f$, with a_{bf} , and with density ?

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

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

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

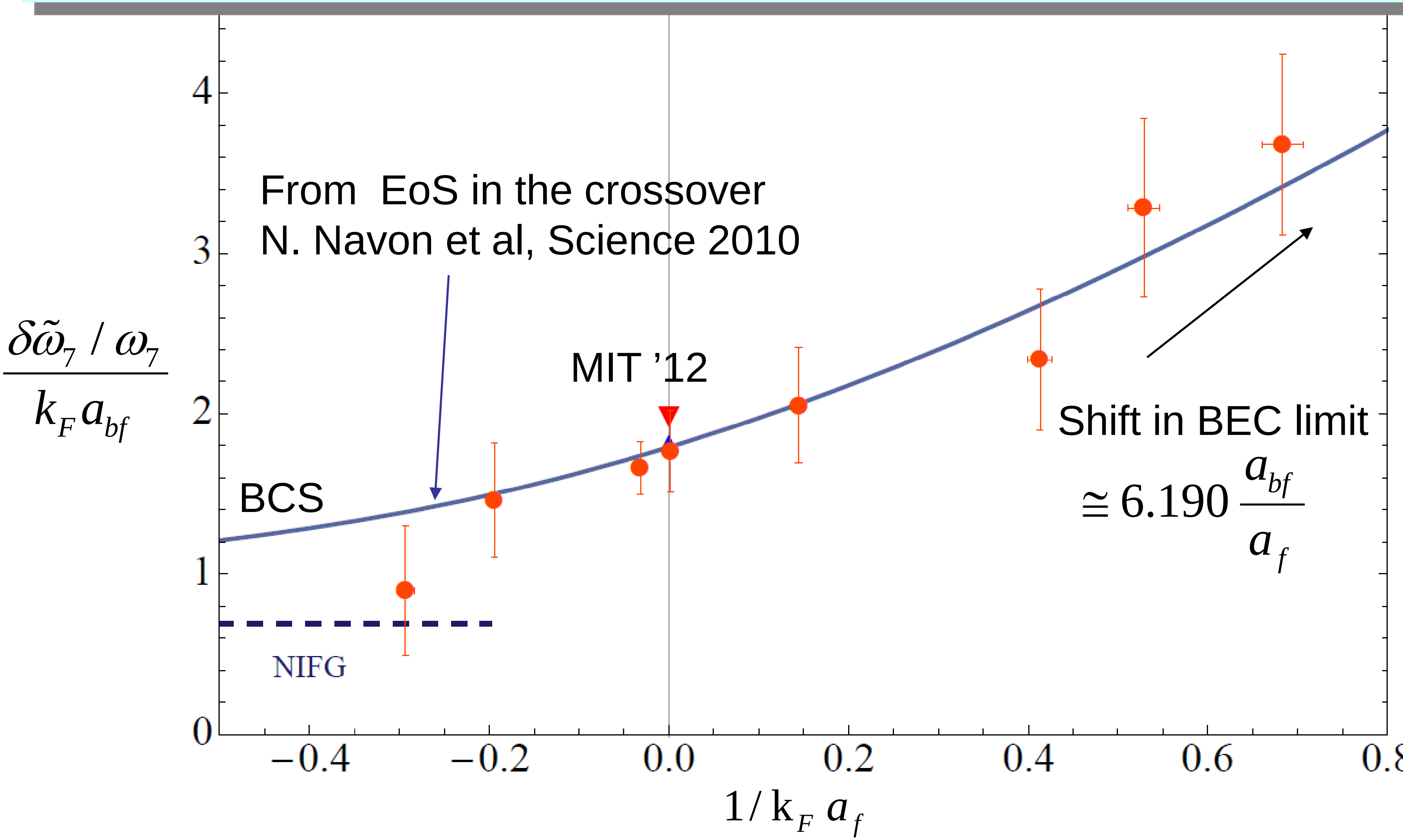
A new means to access properties of the EoS !

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

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



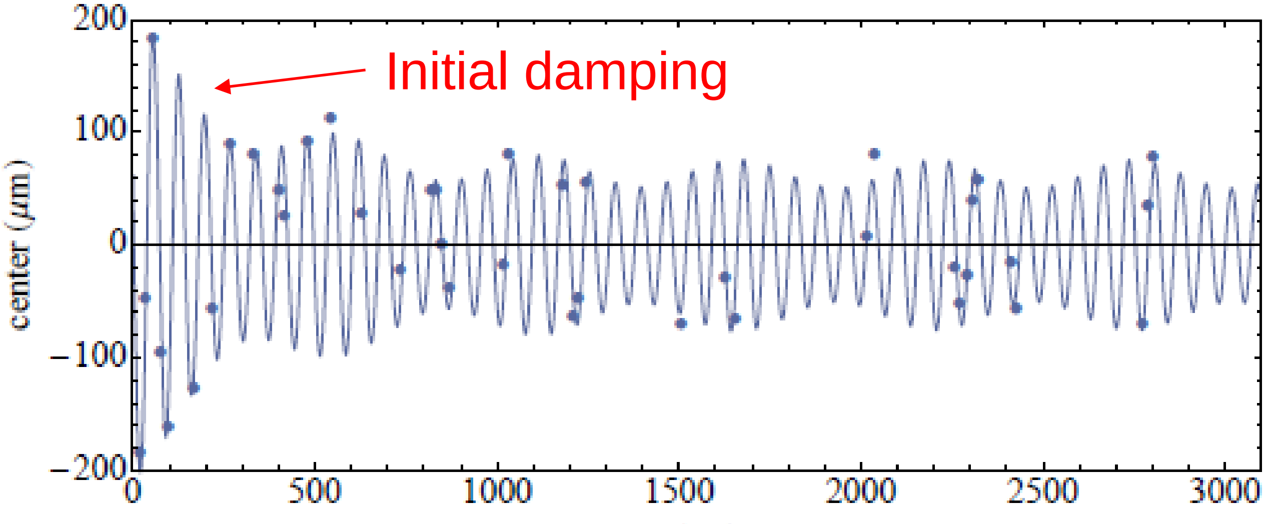
What is the critical velocity for superfluid counterflow ?

Increase initial displacement

↓

Increase relative velocity

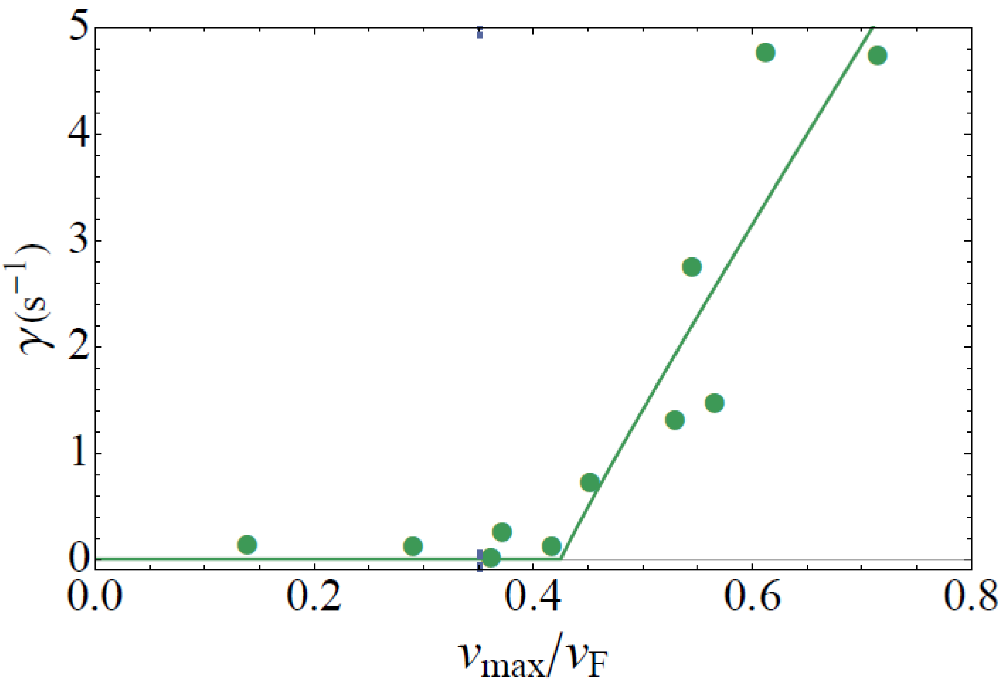
Critical velocity for superfluid counterflow



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

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

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

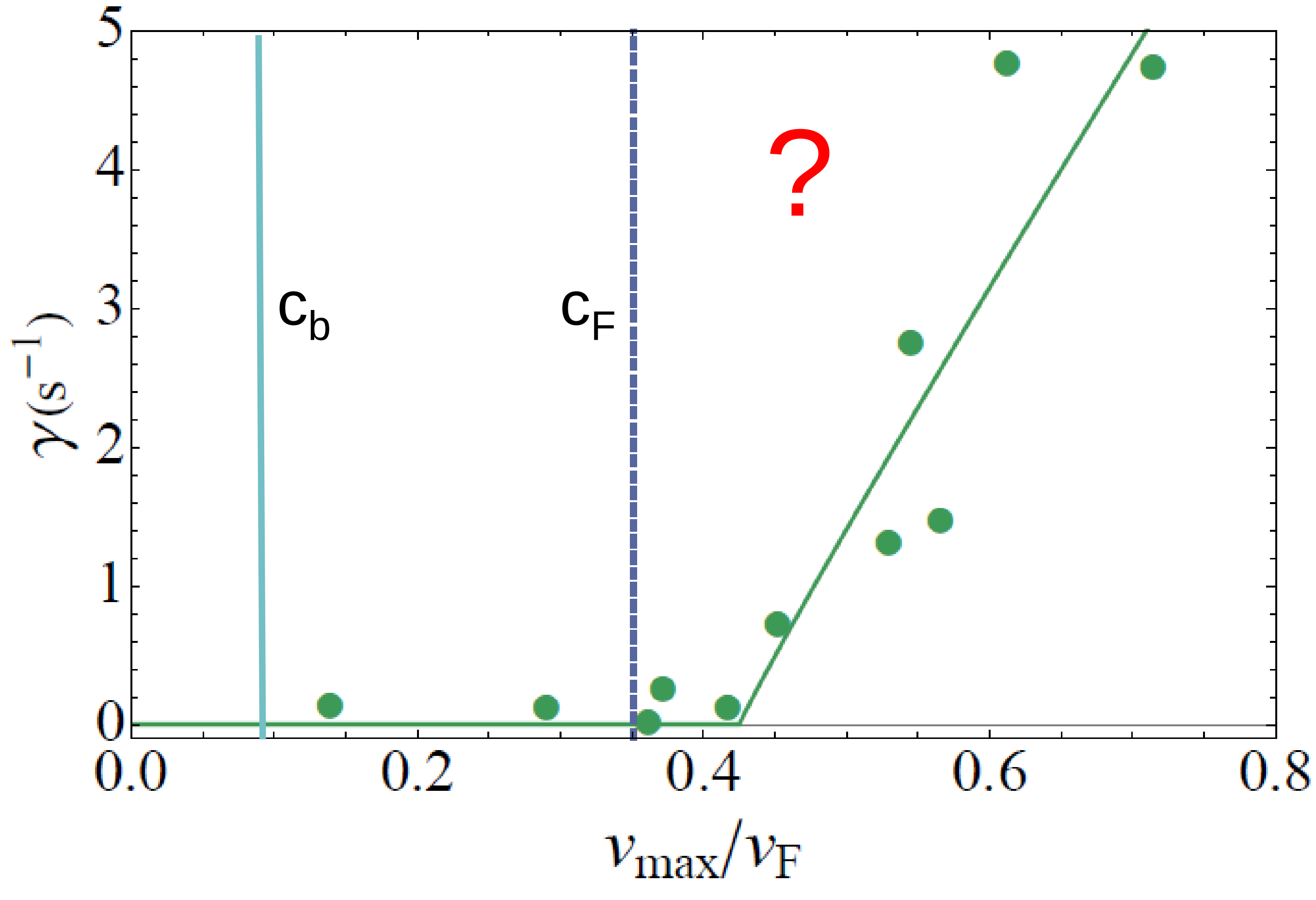
$$\hbar kV \geq \hbar\mathbf{k}.\mathbf{V} = \varepsilon_k + \hbar^2 k^2/2M \geq \varepsilon_k$$

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

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

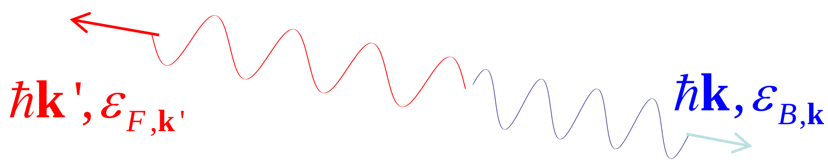
For a linear excitation spectrum $\varepsilon_k = \hbar k c$, $V_c = c$, the sound velocity

Critical velocities



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 $E_{\mathrm{B},\mathbf{k}} = \varepsilon_{\mathrm{B},\mathbf{k}} + \hbar\mathbf{k}\cdot\mathbf{V}_{\mathrm{B}}$

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

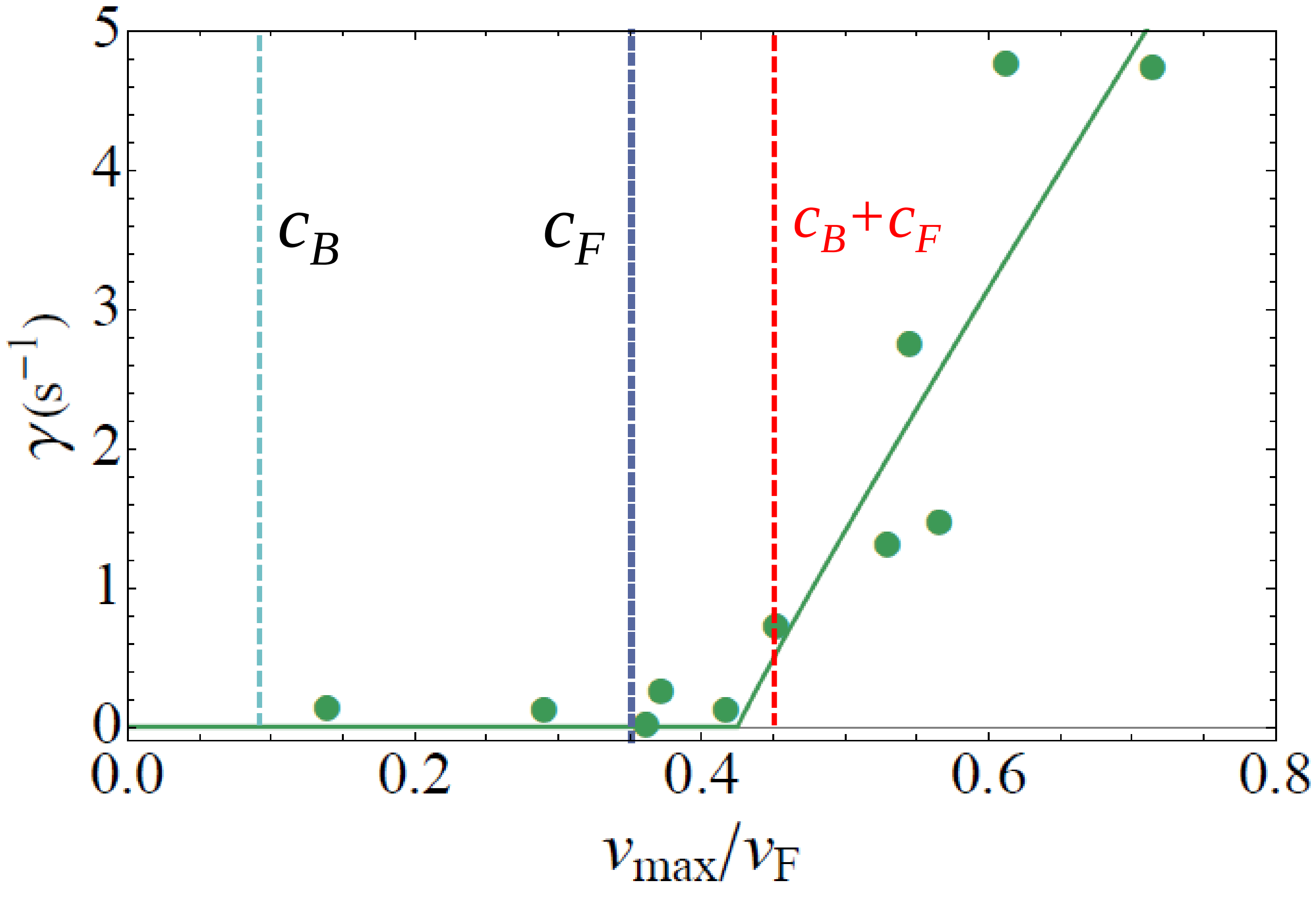
Energy-momentum conservation: $E_{\mathrm{B},\mathbf{k}} + E_{\mathrm{F},\mathbf{k}'} = 0 \quad \mathbf{k} + \mathbf{k}' = 0$

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

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)

Counterflow critical velocity



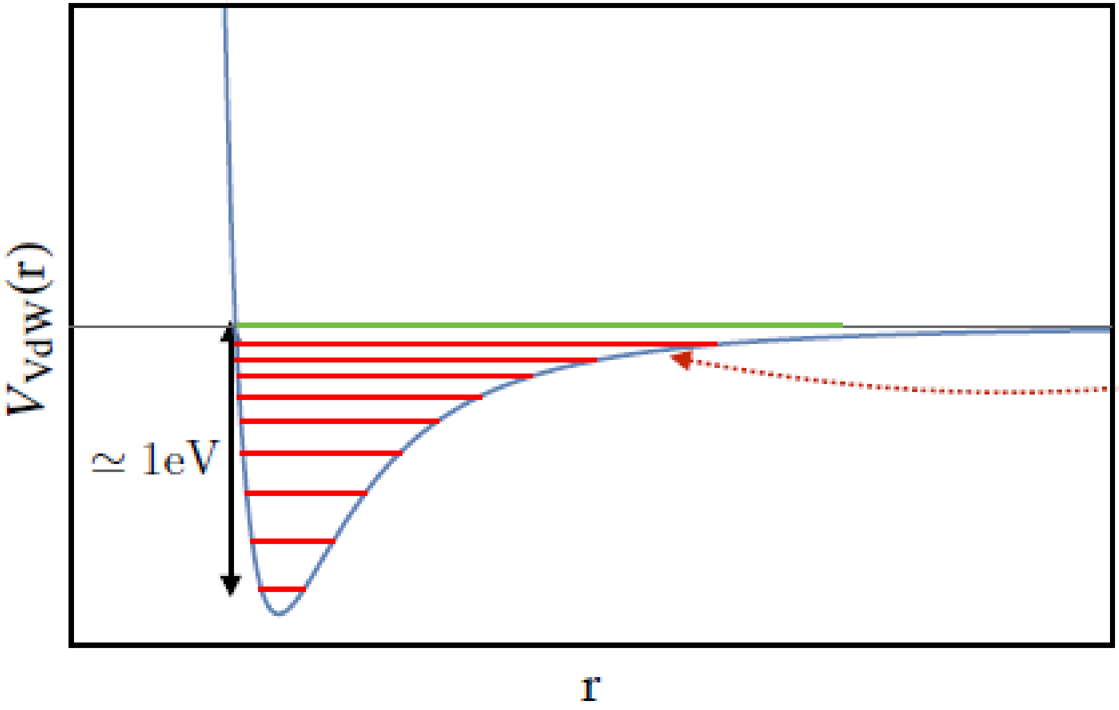
Question 3:
What is the lifetime of the Bose-Fermi mixture ?

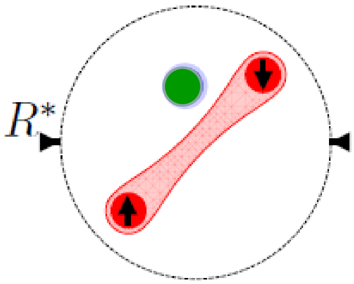
Three-body recombination as a probe of
quantum correlations in a strongly interacting system

Three-body recombination in Bose-Fermi mixture

As a_{bf} is small, bosons act as a weakly coupled impurity i immersed in a Fermi gas with large a_f

Three-body recombination: i, ↓ , ↑



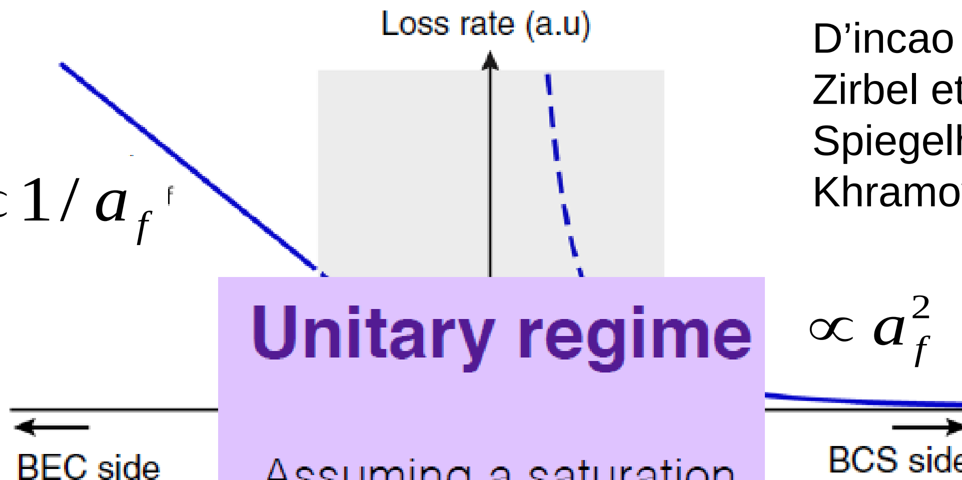


$$R^* \sim 30\, a_0$$

$$\psi \sim \frac{1}{r\sqrt{2\pi a_f}} e^{-r/a_f}$$

Decay to a deeply bound molecular state
Binding energy transferred to kinetic energy of collision partners
Atom and molecule leave the trap

A weakly coupled impurity in a resonant Fermi gas

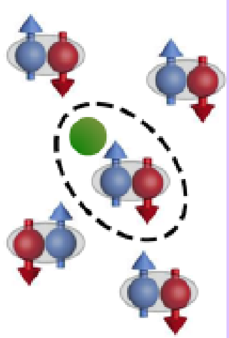


$\propto 1/a_f$

$\propto a_f^2$

D'incao and Esry, PRL 2008
Zirbel et al., PRL 2008
Spiegelhalder et al., PRL 2009
Khramov et al., PRA 2012

BEC Side
« Two » body Dimer-impurity losses
$\dot{n}_i = -L_{di} n_d n_i$
$L_{di} \propto 1/a_f$



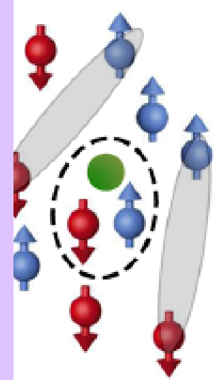
Unitary regime

Assuming a saturation

$$a \simeq n_f^{-1/3}$$

We expect :

$$\Gamma_{if} \propto n_f^{4/3}$$



BCS Side
Three body losses
$\dot{n}_i = -L_{ffi} n_i n_f^2$
$L_{ffi} \propto a_f^2$

JILA: Zirbel et al.,
PRL 100, 143201 (2008)

Unitarity: ?

A weakly coupled impurity in a resonant Fermi gas

Kagan, Svistunov, Shlyapnikov, JETP, 1985

$$P(R<R^*) = \int_{R<R^*} d^3\boldsymbol{r}_1 d^3\boldsymbol{r}_2 d^3\boldsymbol{r}_3 \left\langle \hat\Psi_1^\dagger(\boldsymbol{r}_1)\,\hat\Psi_2^\dagger(\boldsymbol{r}_2)\,\hat\Psi_i^\dagger(\boldsymbol{r}_3)\hat\Psi_i(\boldsymbol{r}_3)\hat\Psi_2(\boldsymbol{r}_2)\hat\Psi_1(\boldsymbol{r}_1)\right\rangle$$

Weak coupling between the impurity and the resonant fermions

$$\Downarrow$$

$$P(R<R^*) = \int_{R<R^*} d^3\boldsymbol{r}_1 d^3\boldsymbol{r}_2 d^3\boldsymbol{r}_3 \underbrace{\left\langle \hat\Psi_1^\dagger(\boldsymbol{r}_1)\,\hat\Psi_2^\dagger(\boldsymbol{r}_2)\,\hat\Psi_2(\boldsymbol{r}_2)\hat\Psi_1(\boldsymbol{r}_1)\right\rangle \left\langle \hat\Psi_i^\dagger(\boldsymbol{r}_3)\hat\Psi_i(\boldsymbol{r}_3)\right\rangle}_{g_{\uparrow\downarrow}(r_2,r_1)\times n_i}$$

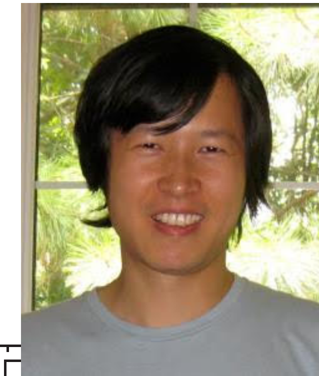
With :

$$g_{\uparrow\downarrow}(r_2,r_1) \underset{|r_2-r_1|\to 0}{\sim} \frac{1}{\Omega}\frac{C_2}{4\pi^2|r_2-r_1|^2}$$

S. Tan, 2008

Therefore the impurity decay rate Γ_{if}
should be proportional to Tan’s two-body contact C_2

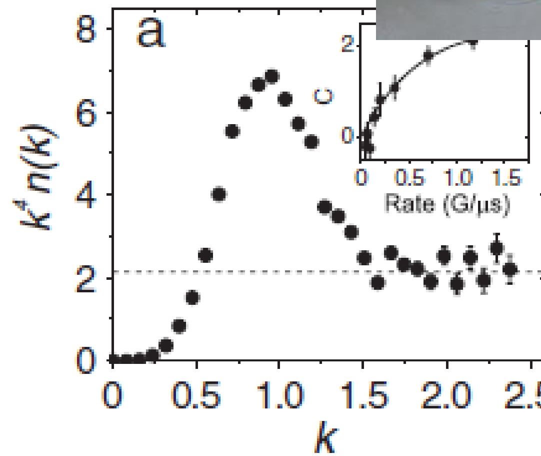
Tan's Contact



Tail of the momentum distribution at large k

$$k^4 n_\sigma(k) \to C_2 \quad when\; k \to \infty$$

JILA: Stewart et al., Jin's group, PRL, 2010

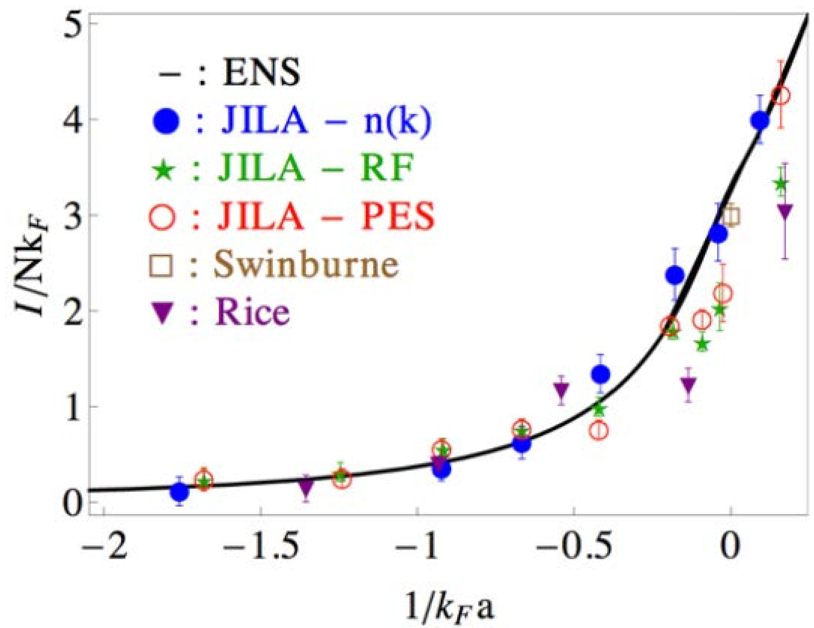


Adiabatic energy relation

$$C_2 = -\frac{4\pi m_f}{\hbar^2}\frac{\partial E}{\partial(1/a)}$$

at constant entropy

From equation of state measurements:



ENS, Navon et al., Science, 2010

Bose/Fermi decay and Tan's Contact

$$\dot{n}_b = -\gamma C_2 n_b = -\Gamma_{bf} n_b$$

$\gamma \propto a_{bf}^2$ is the only parameter that contains short range physics easily measured at high temperature on BEC side

	BEC	Unitary	BCS
$(\dot{n}_b/n_b)$	$\propto (n_m/a_{ff})$ [20]	$\propto n_f^{4/3}$	$\propto a_{ff}^2 n_f^2$ [20]
C_2	$8\pi(n_m/a_{ff})$	$(2\zeta/5\pi)k_F^4$	$4\pi^2 a_{ff}^2 n_f^2$

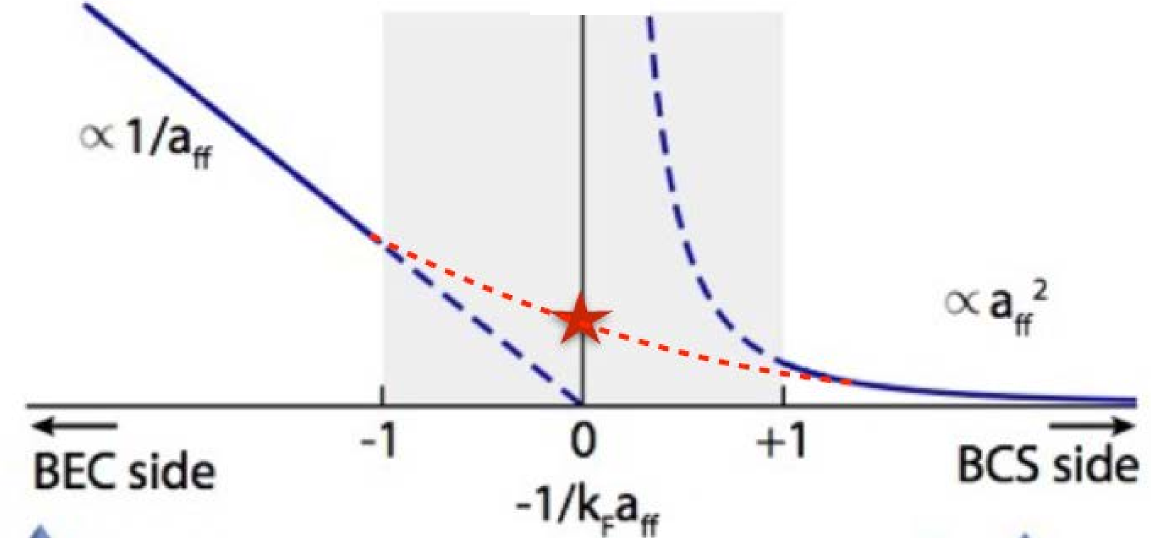
$$\varsigma = 0.87(3)$$

C. Vale, Swinburne

Bose/Fermi decay in strongly interacting regime

$$\dot{n}_b = -\gamma C_2 n_b = -\Gamma_{bf} n_b$$

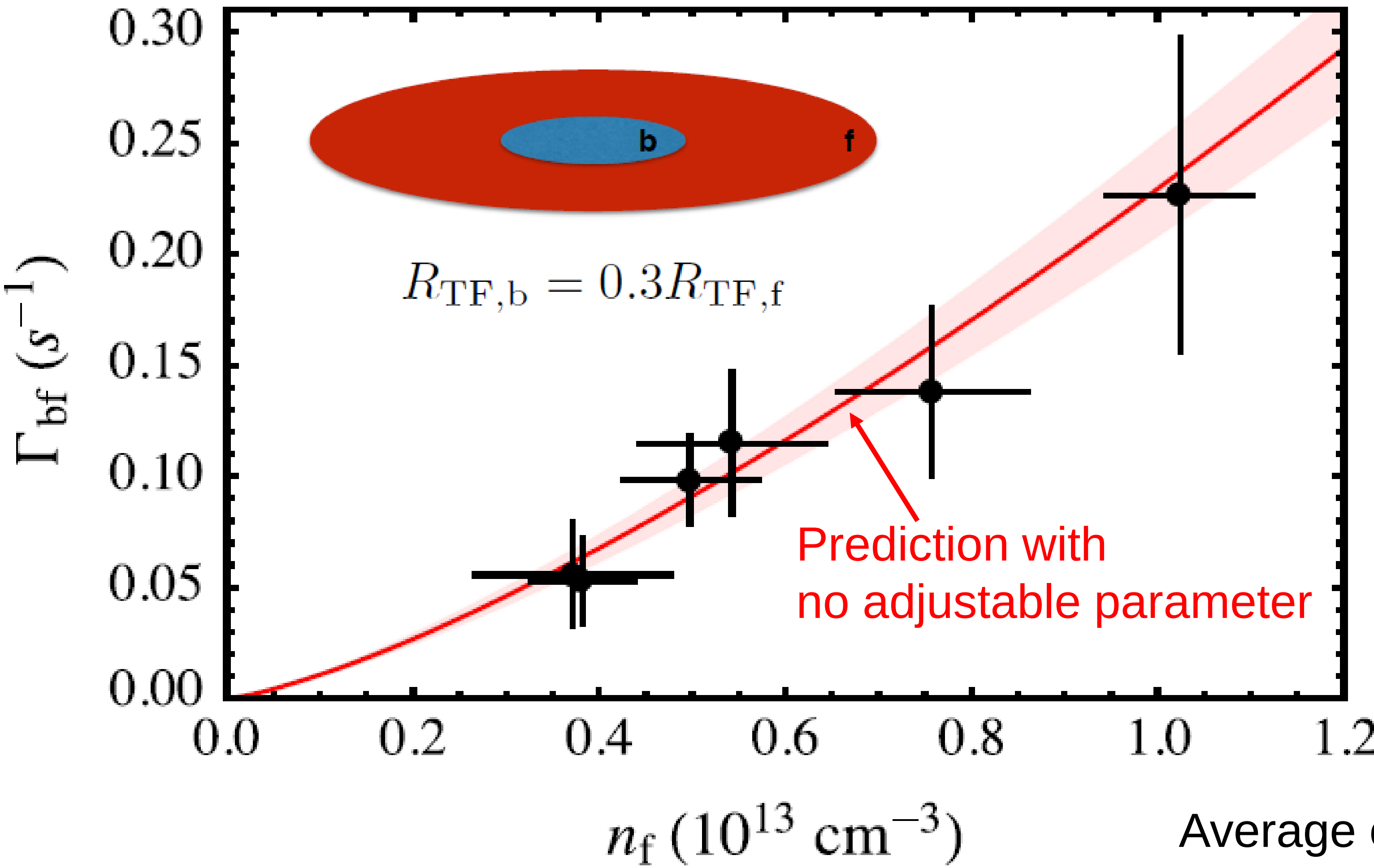
$$\Gamma_{bf}$$



BEC + Fermi Superfluid

$$\Gamma_{bf} \propto n_f^{4/3}$$

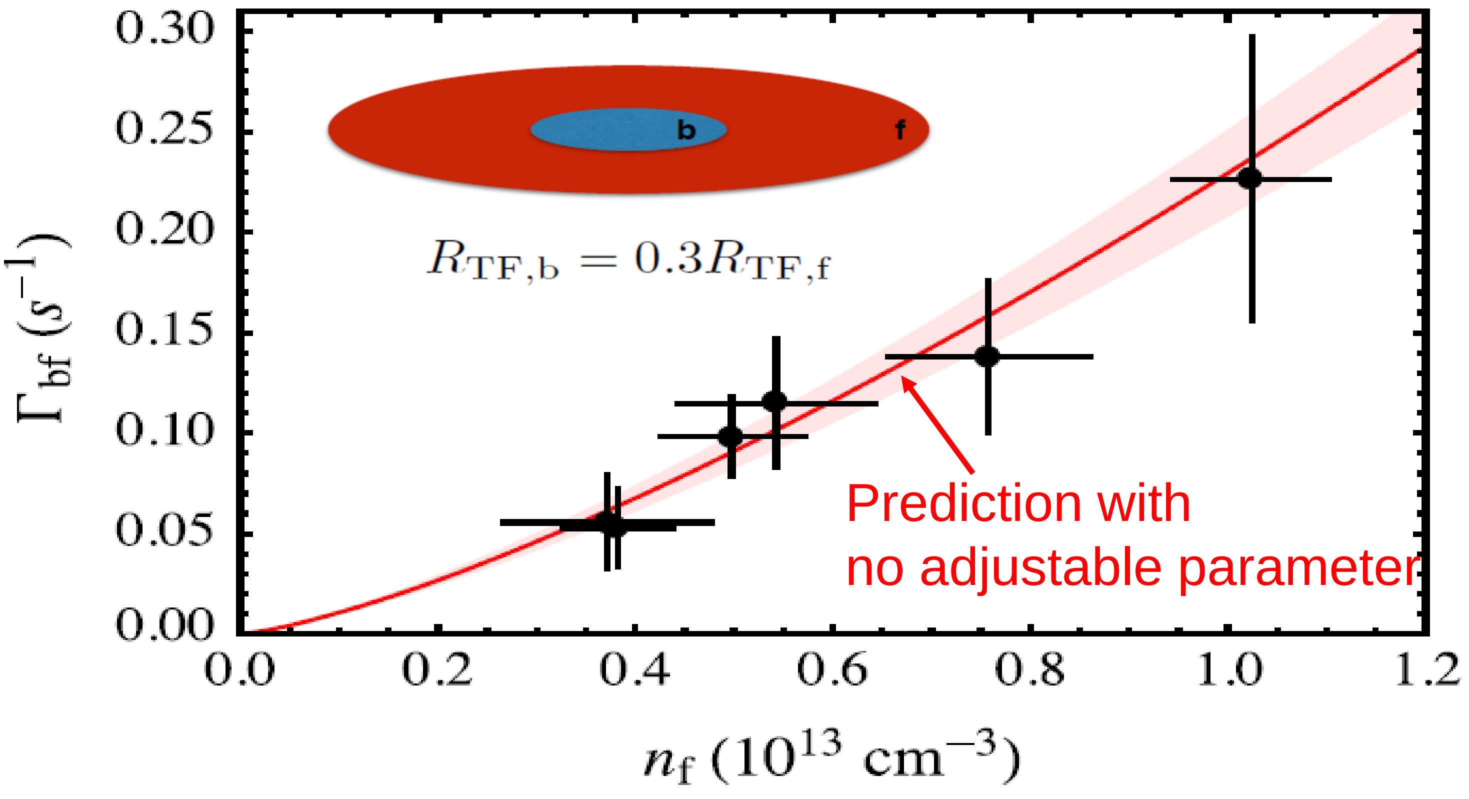
Probing the local unitary Contact



$$\Gamma_{bf} = \gamma C_2 = \frac{2\varsigma}{5\pi}\left(3\pi^2 n_f^{4/3}\right)\times 0.9$$

Average over BEC TF profile

Probing the local unitary Contact



Power law fit: A n^p gives p = 1.36 (15) close to 4/3

Fit: A $n^{4/3}$ gives A and local contact $C_2(0)$

Impurity decay is a local probe of quantum correlations in a many-body system

Summary

- Dual Bose-Fermi superfluids have intriguing novel properties
- Lifetime of Bose-Fermi mixture is governed by Tan's contact
- Theory applies to Yb/^{6}Li, K/^{6}Li, Rb/^{40}K,…..assumes small a_{bf}
- What happens when a_{bf} increases ? Efimov effect
- Measure three-body contact of Fermi gas
- Two-body and three-body contact in unitary Bose gas

R. Fletcher et al., Science 2017, Cambridge

Link with lifetime measured at JILA

C. E. Klauss et al., ArXiv 1704.01206