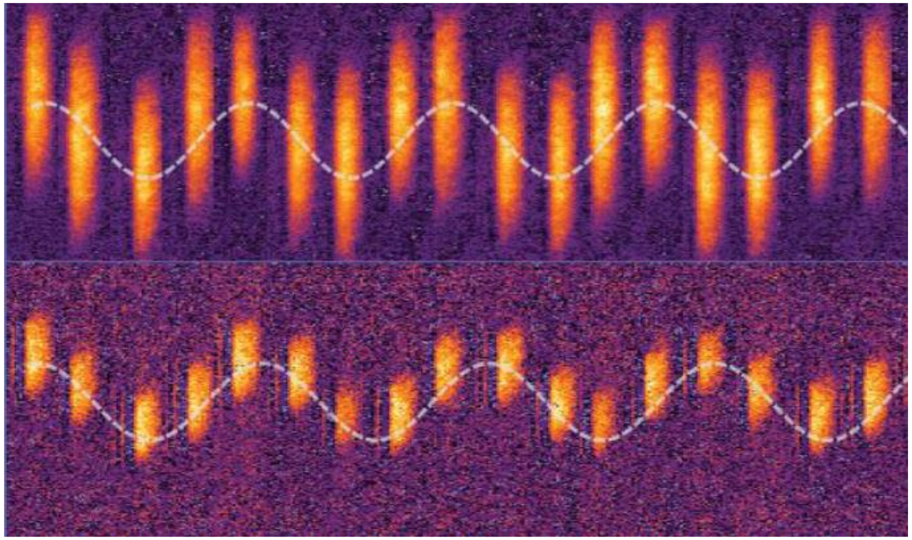
An impurity in
a strongly interacting Fermi gas



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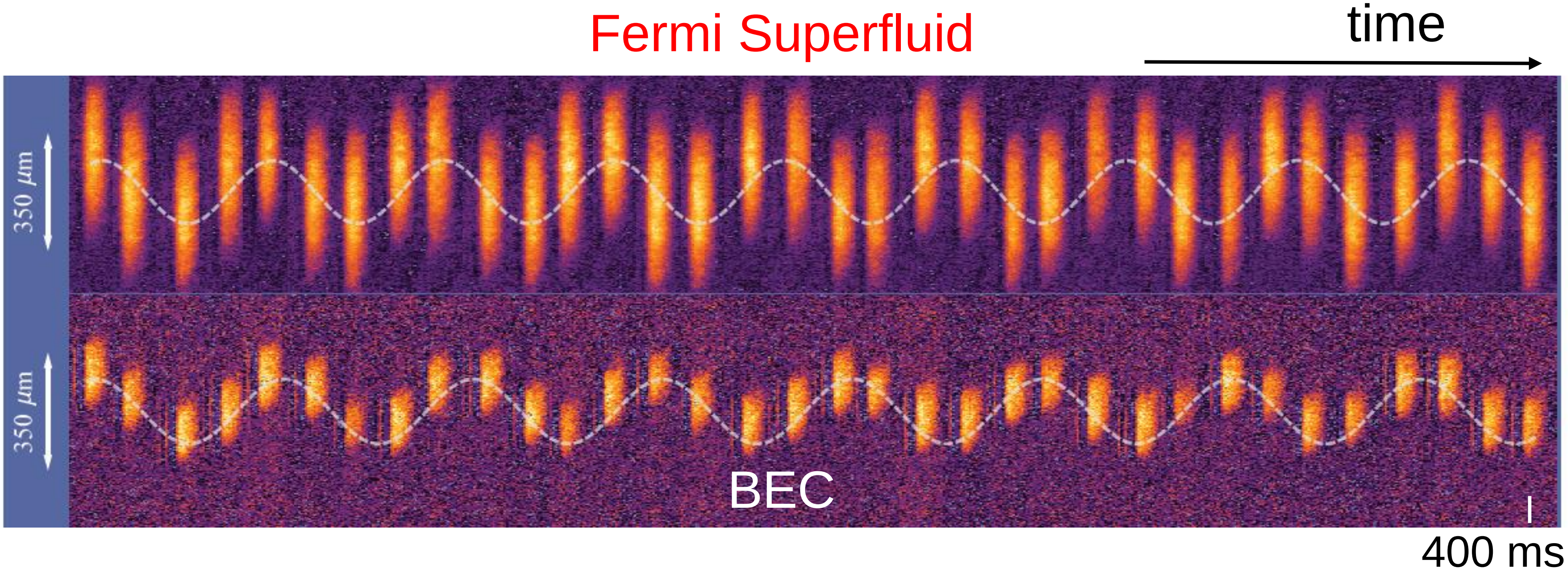
Physique quantique et applications

Institut Pascal,
Quantum 2021
September 1^{rst}, 2021

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



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

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

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

Outline

- Three-body recombination in quantum gases

- Lifetime of Bose-Fermi mixture
  Theory: a simple formula !

- Tan’s two-body contact

- Experiments with with ^{6}Li-^{7}Li isotopes

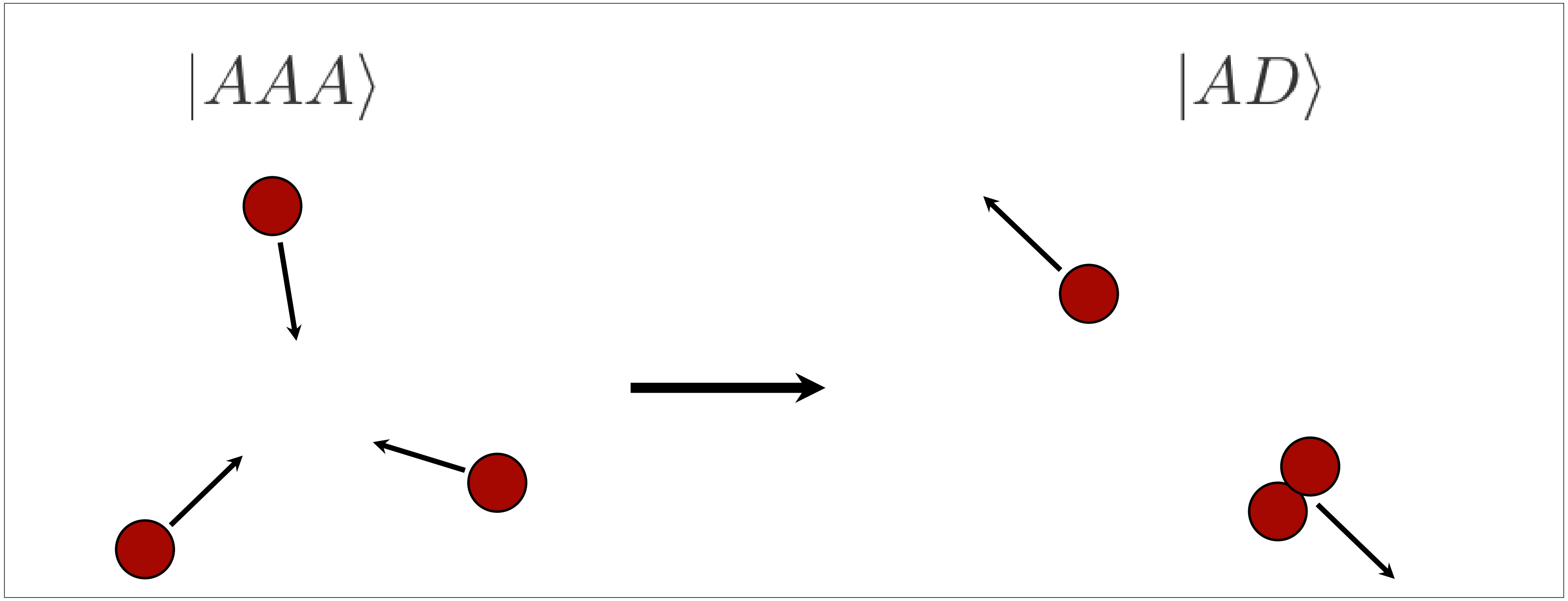
S. Laurent, M. Pierce, M. Delehaye, T. Yefsah, F. Chevy, C. Salomon
Phys. Rev. Lett., **118**, 103403, 2017

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

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

Three-body recombination
(1) Bose gas

- Three-body loss for Bose gases with scattering length a



$$\dot{n} = -L_3 n^3$$

Rate constant : $\gamma_3 = -\frac{\dot{n}}{n} = n^2 L_3(a, T, E_t)$

Two-body rate constant : $\gamma_2 = n\sigma v$

Bosons: three-body loss rate as a probe of few–body physics

For na^3 <<1 and at low enough temperature

L_3 scales as a^4 modulated by Efimov features

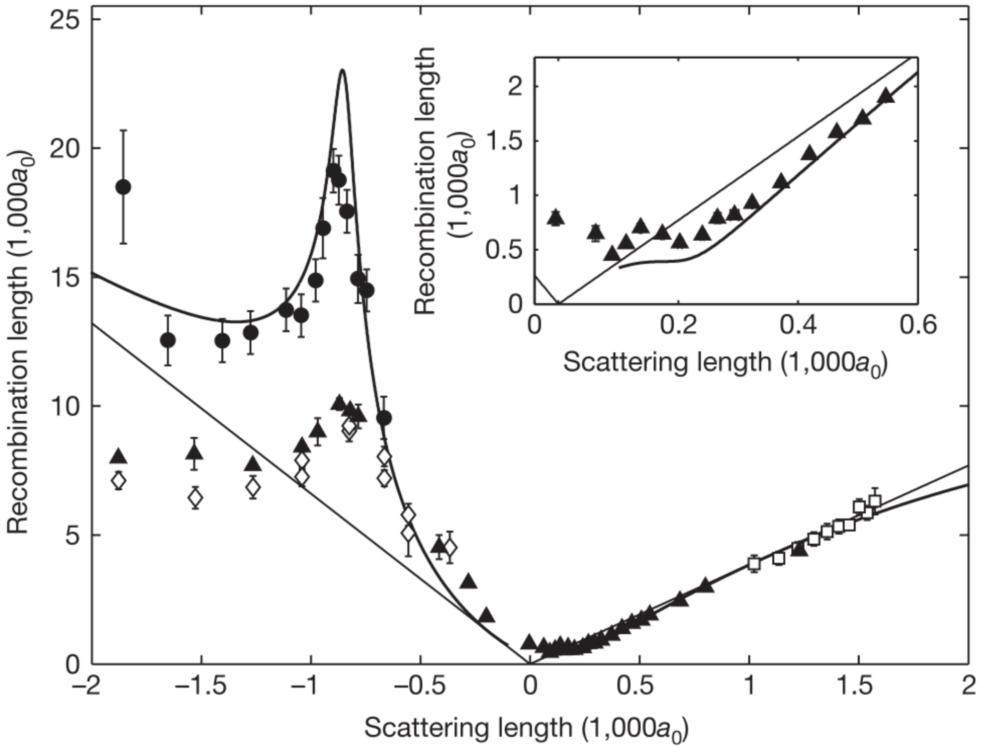
Fedichev et al., PRL 77, (1996)
D’Incao et. al., PRL **93**, 123201 (2004),
Braaten and Hammer, PRA (2008)

Universal Efimov trimers:

infinite set of weakly bound states

Kraemer *et al.*, *Nature*, **440**, (2006)

^{7}Li: Pollack *et al.*, *Science*, **326**, (2009)
^{7}Li: N. Gross et al., PRL **103**, (2009)
^{7}Li: B. Rem et al. PRL **110**, (2013)
^{39}K: Zaccanti *et al.*, *Nat. Phys.* **5**, (2009)
^{85}Rb: Wild *et al.*, *PRL*, **108**, (2012)



Universality of Efimov trimers: discrete scale invariance

Innsbruck: B. Huang et al., PRL 112, 190401 (2014)
Chicago: S. Tung et al., PRL 113, 240402 (2014)

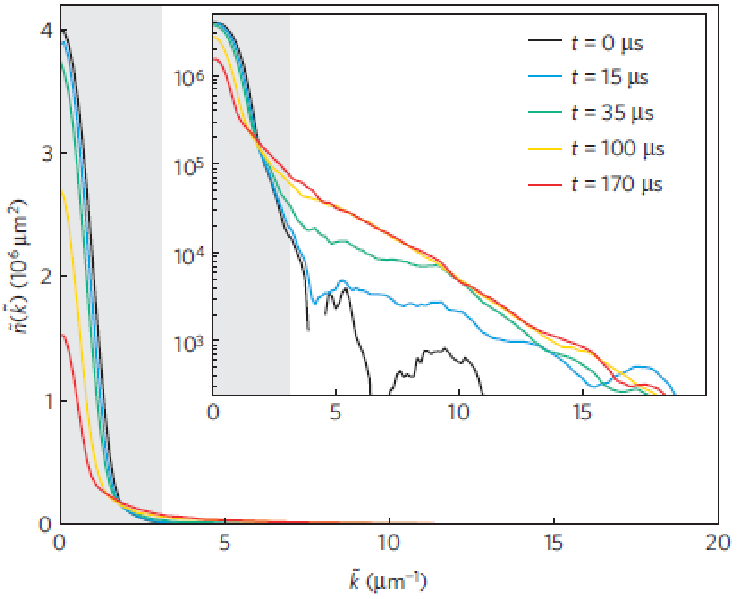
3-body loss as a probe of many-body physics

JILA: E. A. Burt, R. W. Ghrist, C. J. Myatt, M. J. Holland, E. A. Cornell, and C. E. Wieman, PRL 1997

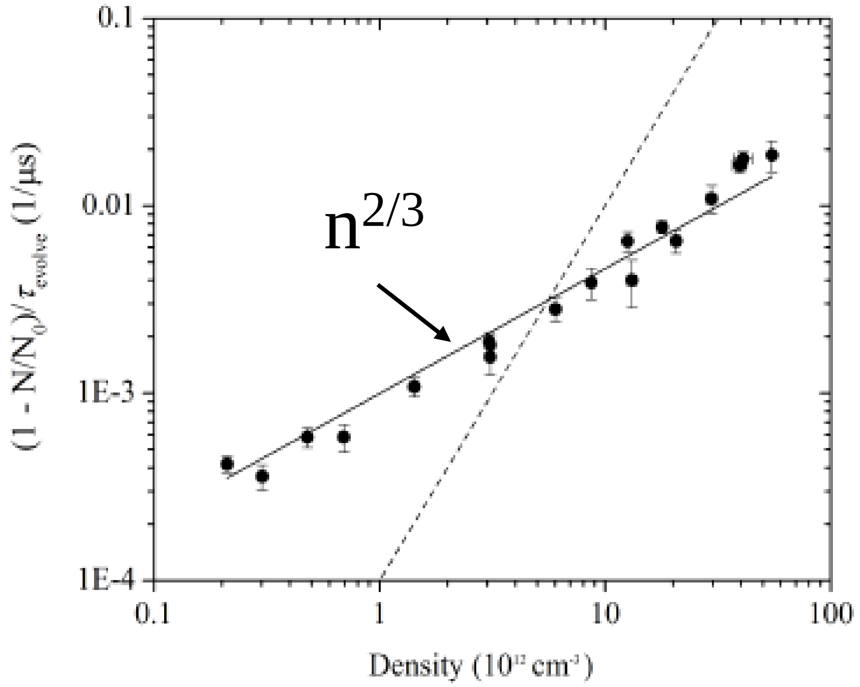
Third-order coherence of BEC matter wave field:

density density density correlations reduced by 3! in a BEC compared to thermal gas at same density (Kagan, Svistunov, Shlyapnikov)

^{85}Rb unitary Bose gas



P. Makotyn, C. E. Klauss, D. L. Goldberger, E. A. Cornell and D. S. Jin, Nat. Physics 2014

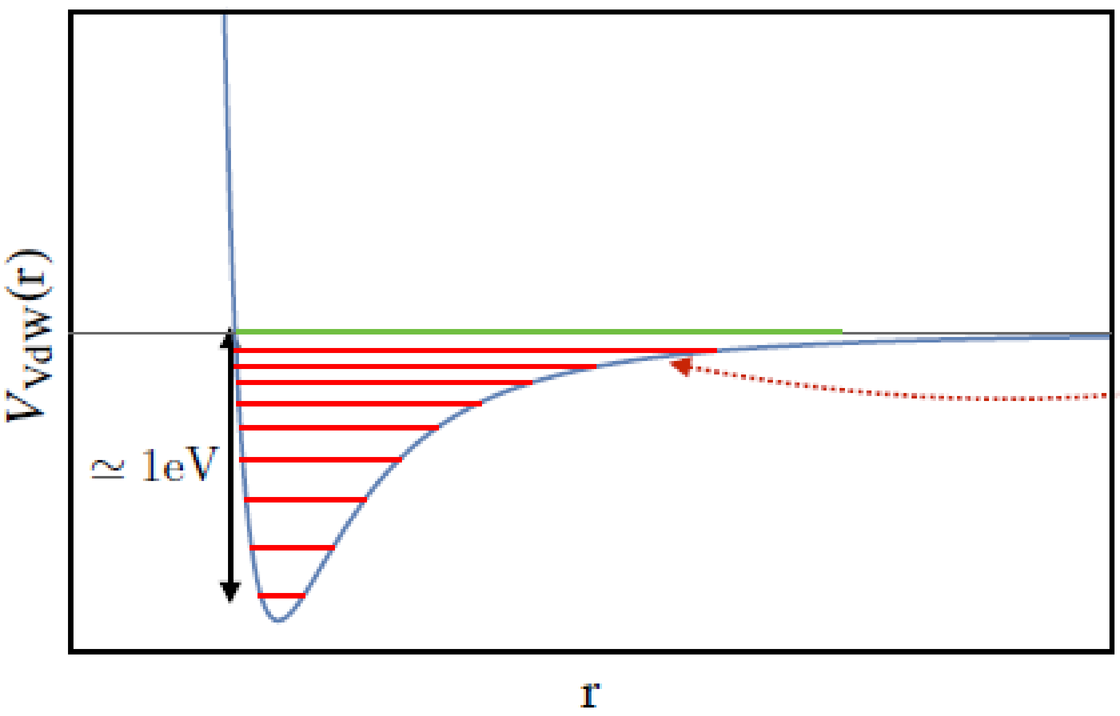


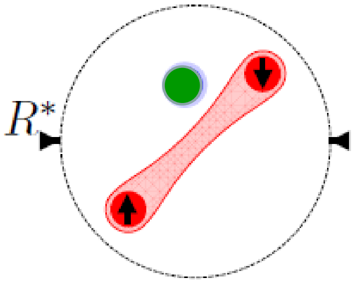
C. E. Klauss et al. ArXiv 1704.01206

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, ↓ , ↑





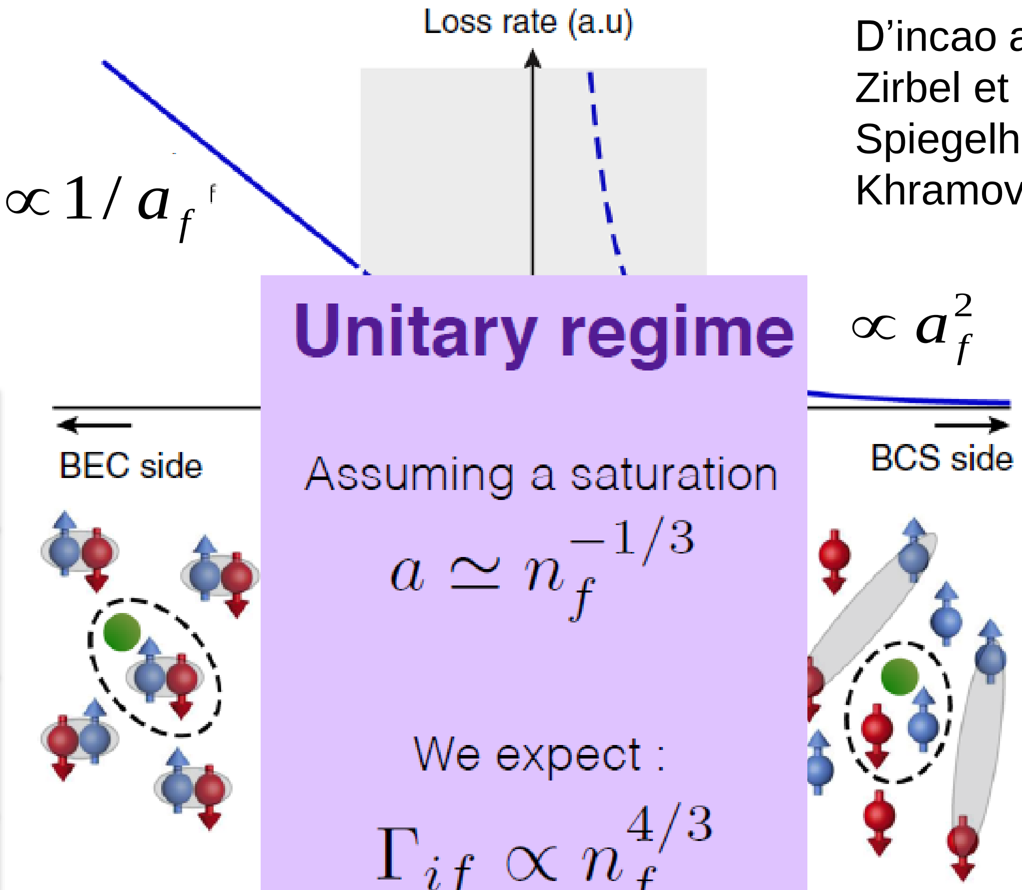
$R^* \sim 30a_0$

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

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

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



Unitary regime

Assuming a saturation

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

We expect :

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

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

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

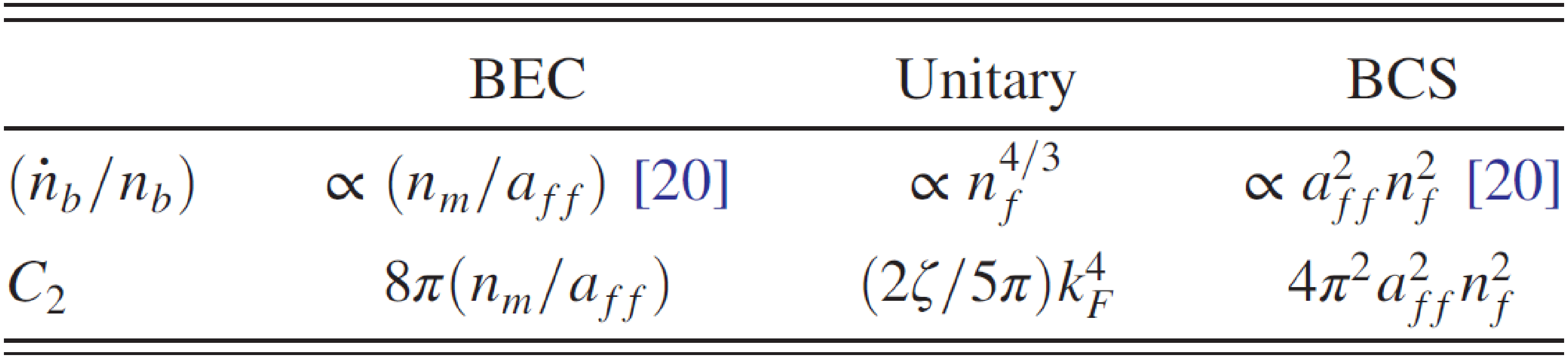
S. Tan, 2008

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

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



	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	$8\pi(n_m/a_{ff})$	$(2\zeta/5\pi)k_F^4$	$4\pi^2 a_{ff}^2 n_f^2$

$$\varsigma = 0.87(3)$$

Tan's two-body Contact

n_1: density of spin up particles = N_1/V
n_2: density of spin down particles = N_2/V

Contact density : density-density correlator when $r_1 - r_2 \to 0$

$$\langle n_1(R + r_1)\, n_2(R + r_2)\rangle \longrightarrow \frac{1}{16\pi^2 |r_1 - r_2|^2} \mathcal{C}(R).$$

Take a small sphere with radius s<<a and volume 4/3 πs^3
integrate over r_1 and r_2 and make s $\longrightarrow$ 0

$$N_{\text{pair}}(R, s) \longrightarrow \frac{s^4}{4} \mathcal{C}(R).$$

$C(R)$ has dimension $(\text{length})^{-4}$

and not N_1N_2/V^2 that scales as s^6

Local pair density is the small volume limit of $N_1N_2/V^{4/3}$

Because of the strong correlations there are many more pairs in a small volume

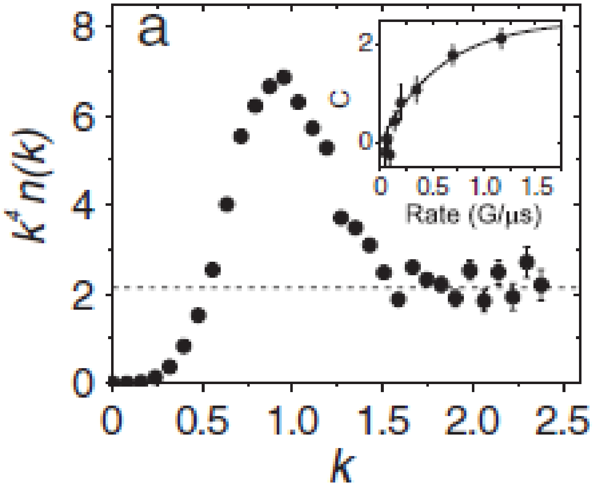
Shina Tan, Annals of Physics **323** (2008) 2952-2990;

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



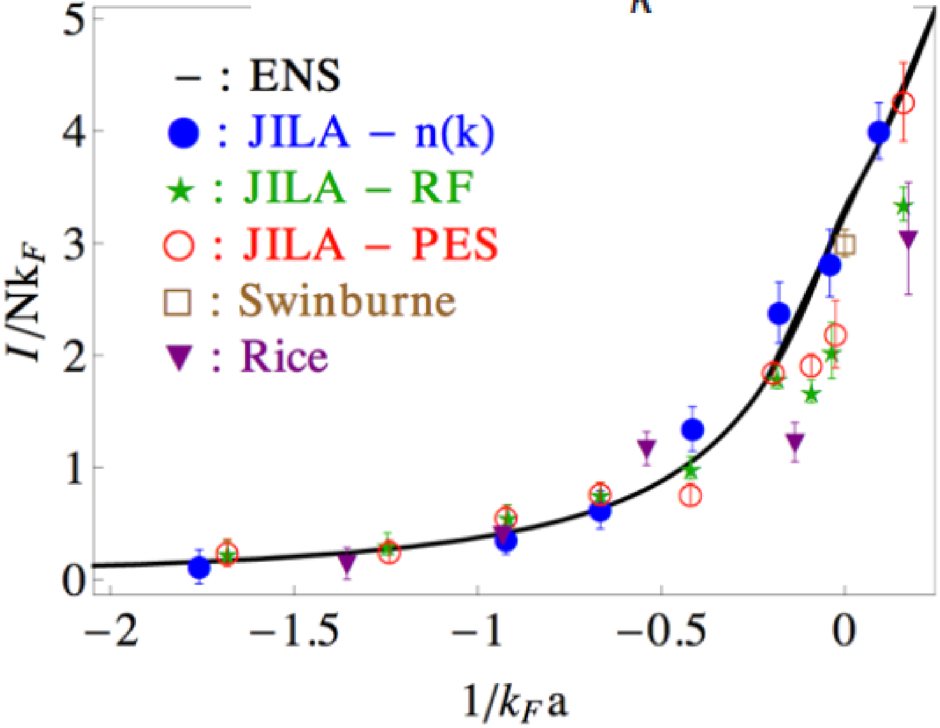
Adiabatic energy relation

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

at constant entropy

From equation of state measurements

ENS, Navon et al., Science, 2010



Tan’s Contact

Molecule photo-association

Rice University: G. Partridge et al., PRL 2005
ENS interpretation: Werner et al.,E PJ B 2009

Radio-frequency spectroscopy

JILA: Stewart et al., PRL 2010
MIT: B. Mukherjee et al., PRL 2019

Equation of state and adiabatic energy relation

JILA: Stewart et al., PRL 2010
ENS: Nascimbène et al., Nature 2010

Bragg spectroscopy

Swinburne: S. Hoinka et al., PRL 2013
C. Carcy et al., PRL 2019

Loss rate of impurity gas

ENS: Laurent et al., PRL 2017

2-body and 3-body Contact for bosons

Cambridge, Fletcher et al., 2018

Theory: *Hausmann, Punk, Zwerger, Strinati, Perali, Rossi, Kosik, Werner, Svistunov, Prokofiev, Hu, Liu, Drummond,….*

Bose/Fermi Decay and Contact

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

$$\gamma \sim a_{bf}^2$$

is the only parameter that contains short range physics

$$E_{\text{dim}er} = -\frac{\hbar^2}{m a_f^2}$$

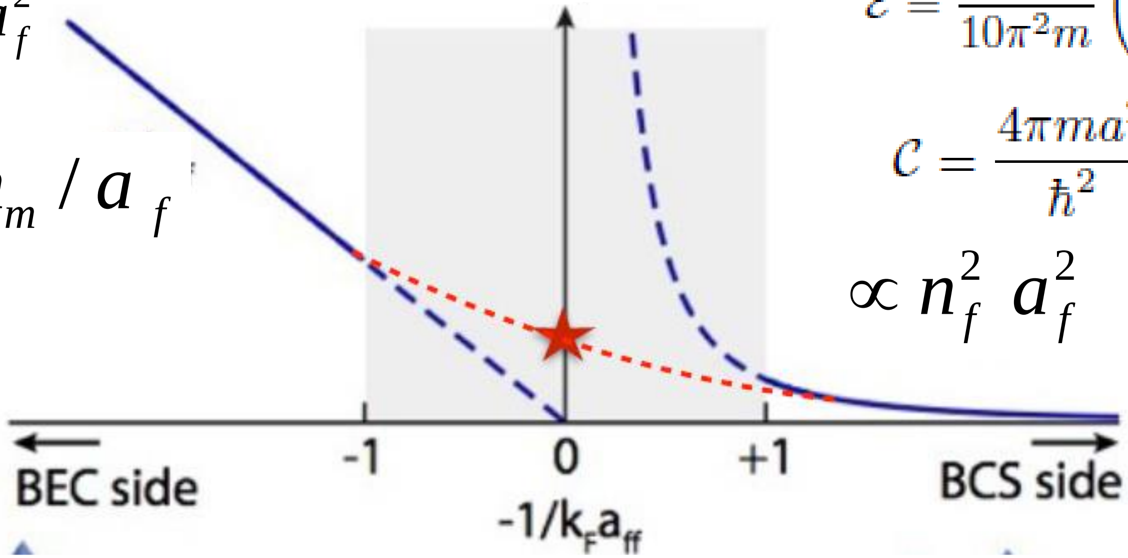
$$\Gamma_{bf}$$

$$\mathcal{E} = \frac{\hbar^2 k_F^5}{10\pi^2 m}\left(1 + \frac{10}{9\pi} k_F a + \ldots\right)$$

$$C_2 \propto n_m / a_f$$

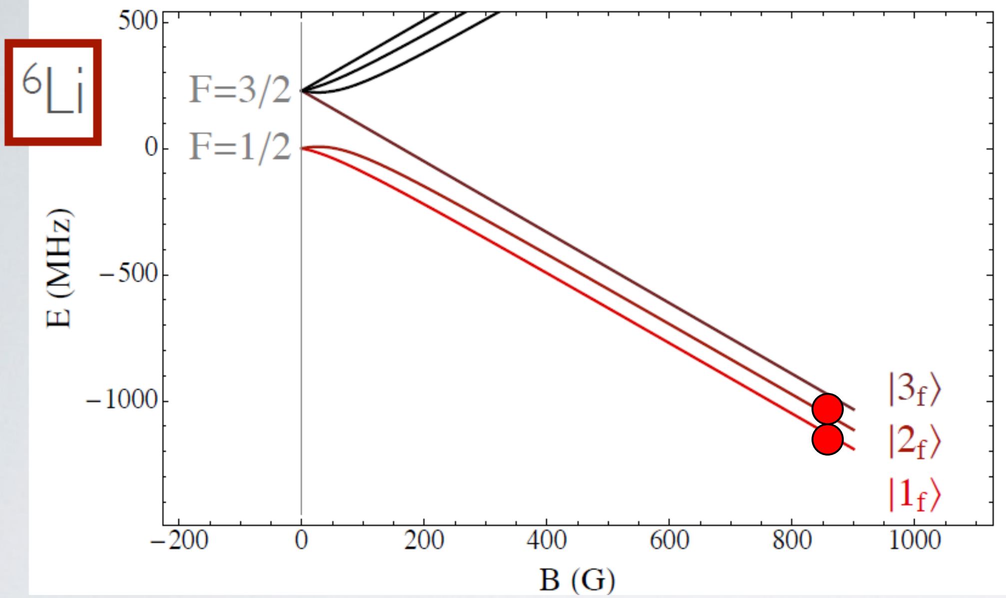
$$\mathcal{C} = \frac{4\pi m a^2}{\hbar^2} \frac{\mathrm{d}\mathcal{E}}{\mathrm{d}a}$$

$$\propto n_f^2 \; a_f^2$$

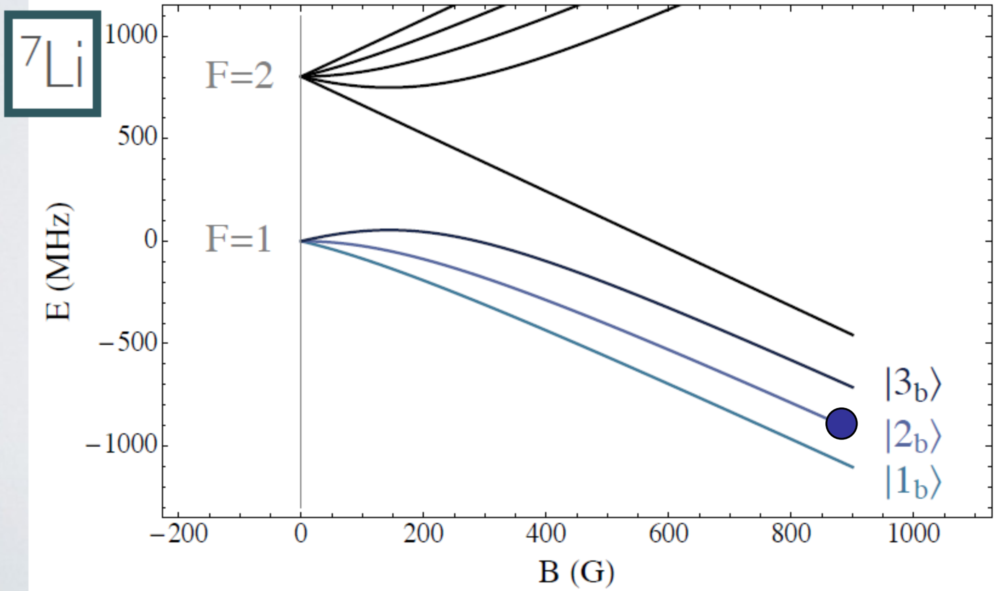


^{7}Li and ^{6}Li isotopes

^{6}Li



^{7}Li



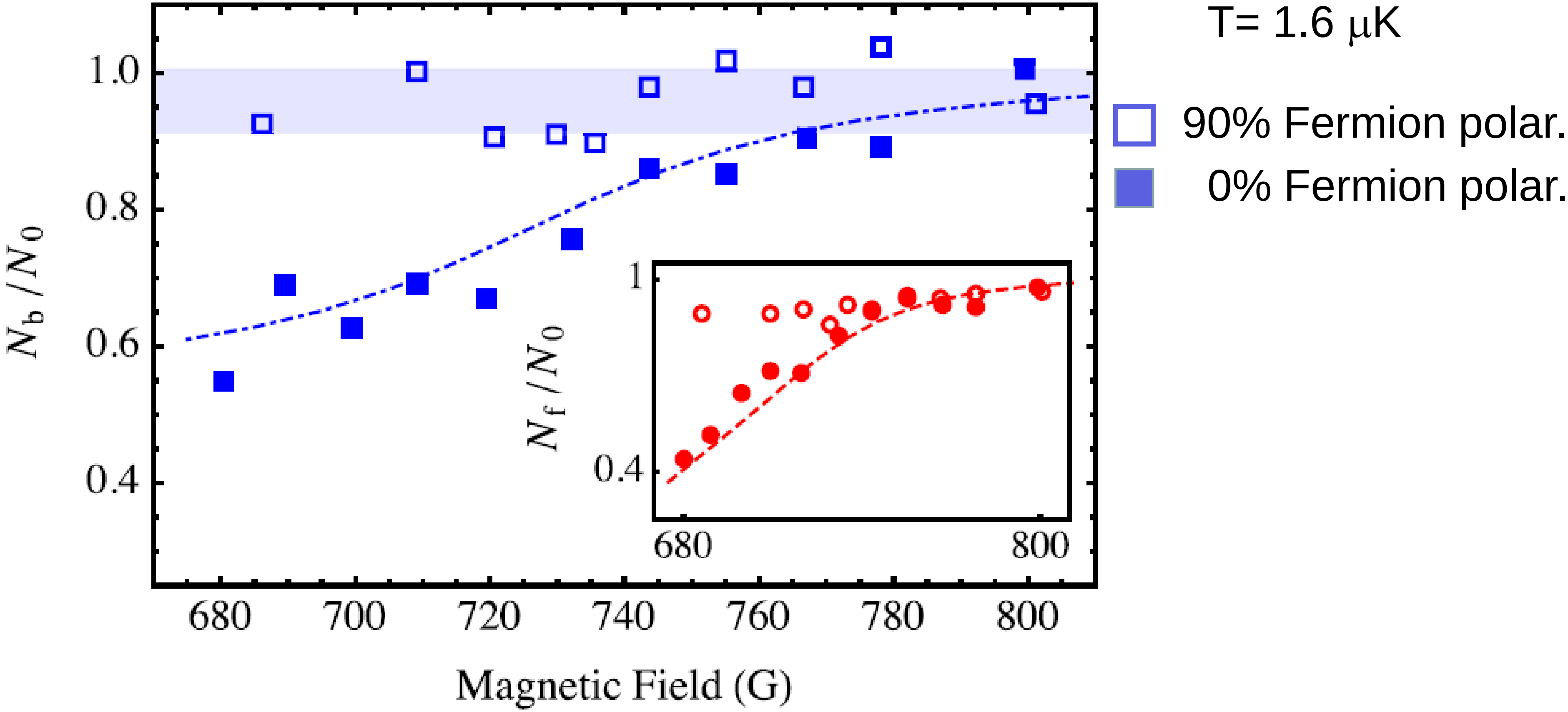
Experiments ^{6}Li/^{7}Li   BEC side

Remaining fraction of Bosons after wait time of 1 s

$N_{0,b} = 1.5\ 10^5$

$N_{0,f} = 3\ 10^5$

T= 1.6 μK

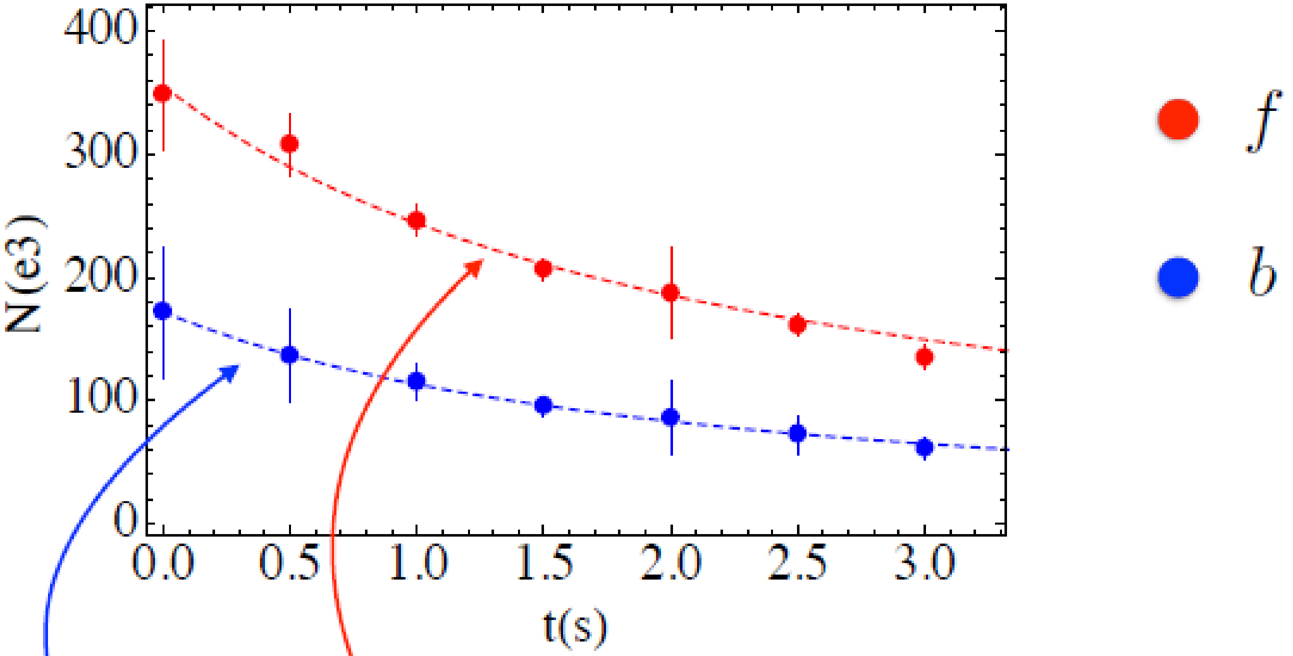


Far on BEC side, Fermions can also decay: inelastic dimer-dimer collisions

rate prop. to $a_f^{-2.55}$

D. Petrov, C.S., G. Shlyapnikov, PRL 2004

Extracting the loss rate



$$N_f(t) = \frac{N_0}{1+\alpha t}$$

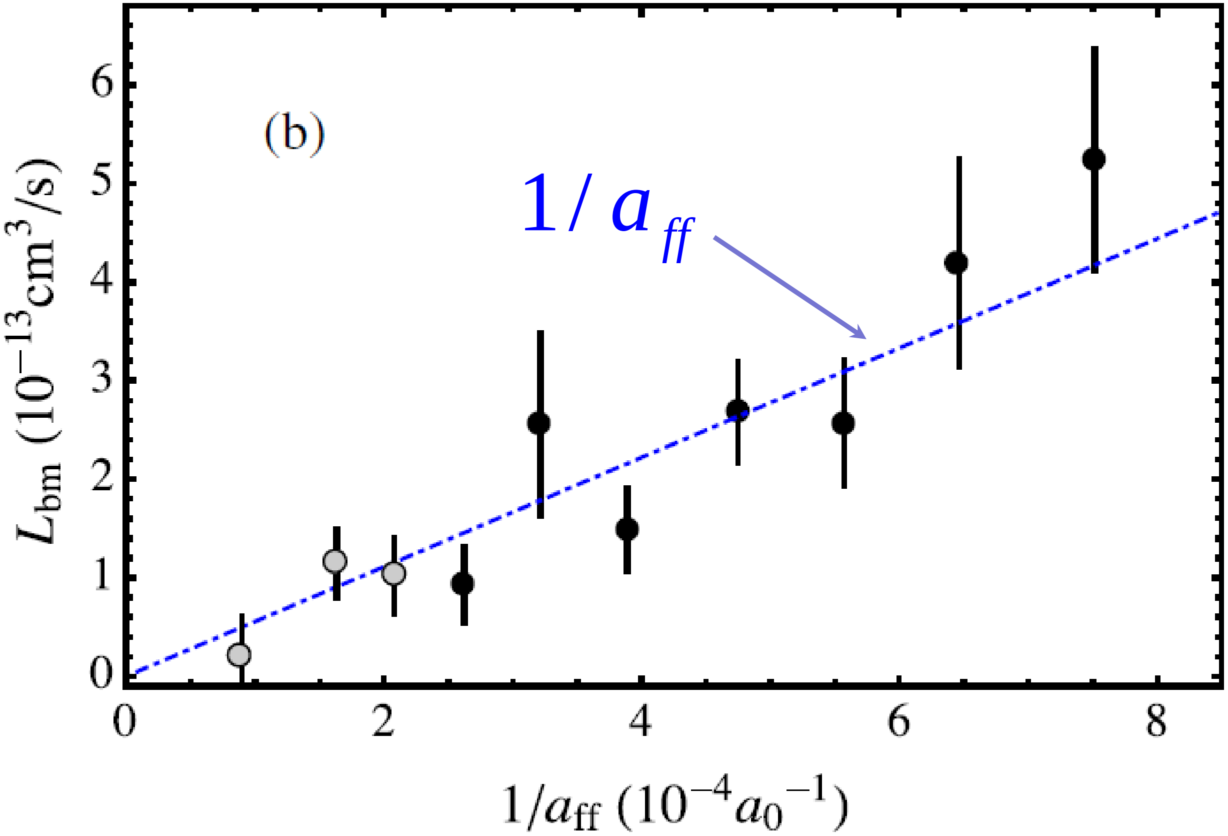
$$\dot{N}_b = -L_{bf} < n_f > N_b - \Gamma_v N_b$$

BEC side: test of *1/a$_f$ law*

$$\dot{N}_b = L_{bm} < n_m > N_b - \Gamma_v N_b$$

$$L_{bm} < n_m > = \gamma C_2 = \gamma\, 8\pi < n_m > / a_{ff} = \alpha < n_m > / a_{ff}$$

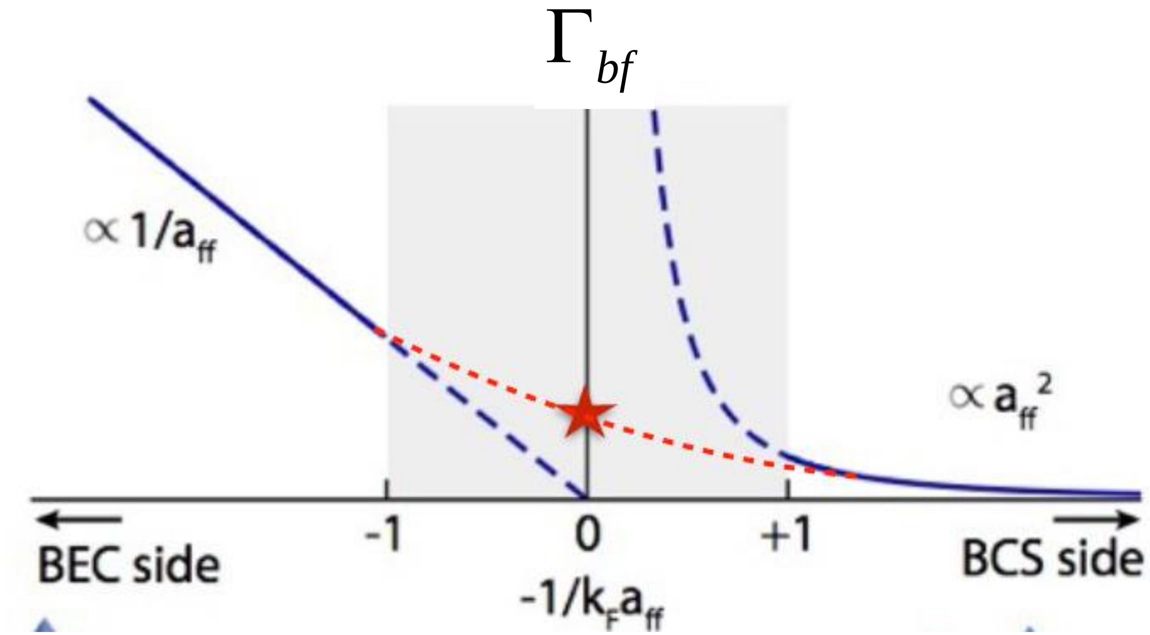
$$\gamma = \alpha / 8\pi = 1.17(11) 10^{-27} m^4 s^{-1}$$



B: 690-800 Gauss

Bose/Fermi decay in strongly interacting regime

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

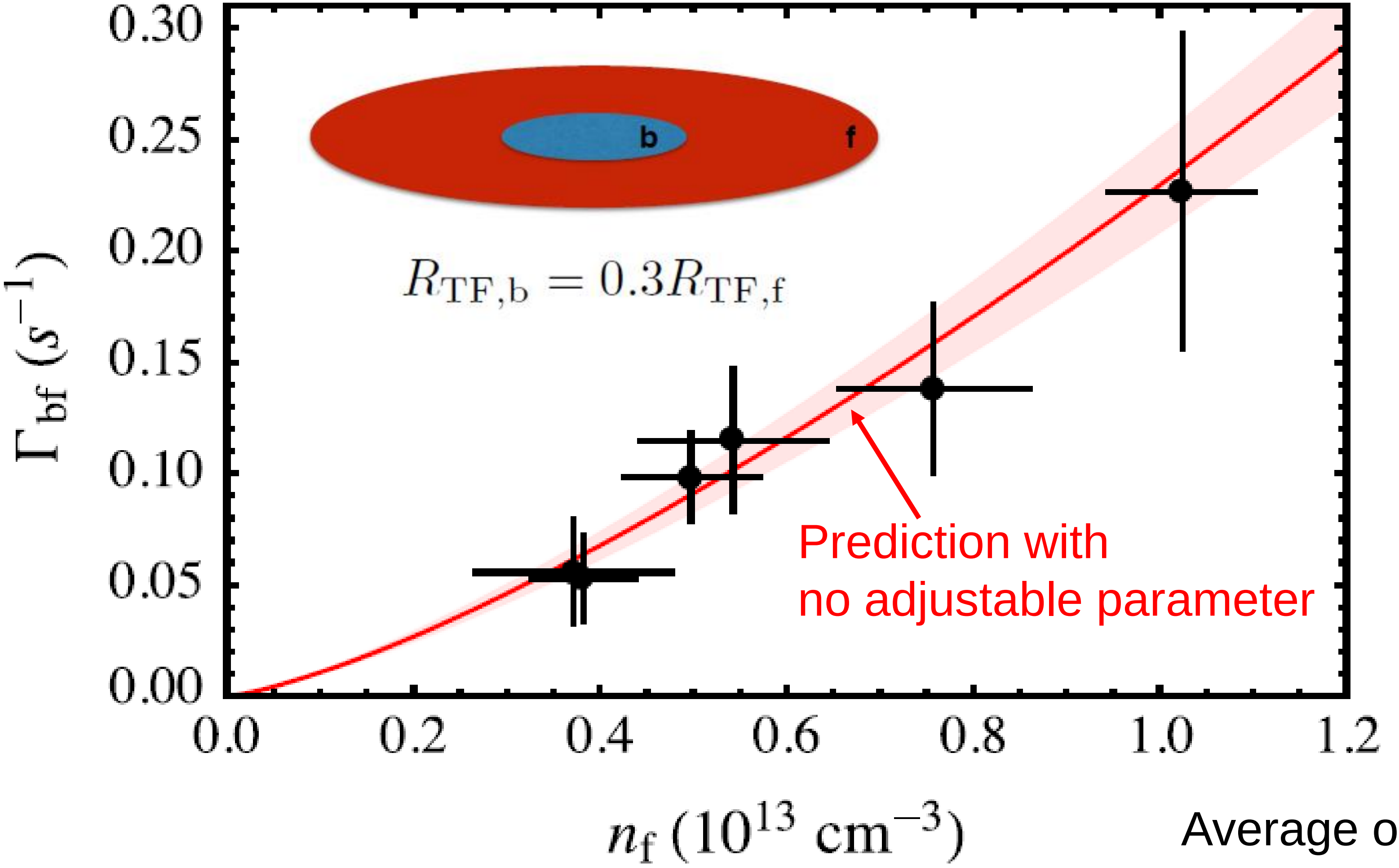


BEC + Fermi Superfluid

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

Small complication:
three-body losses of the ^{7}Li BEC at 832 Gauss

Probing the local unitary Contact

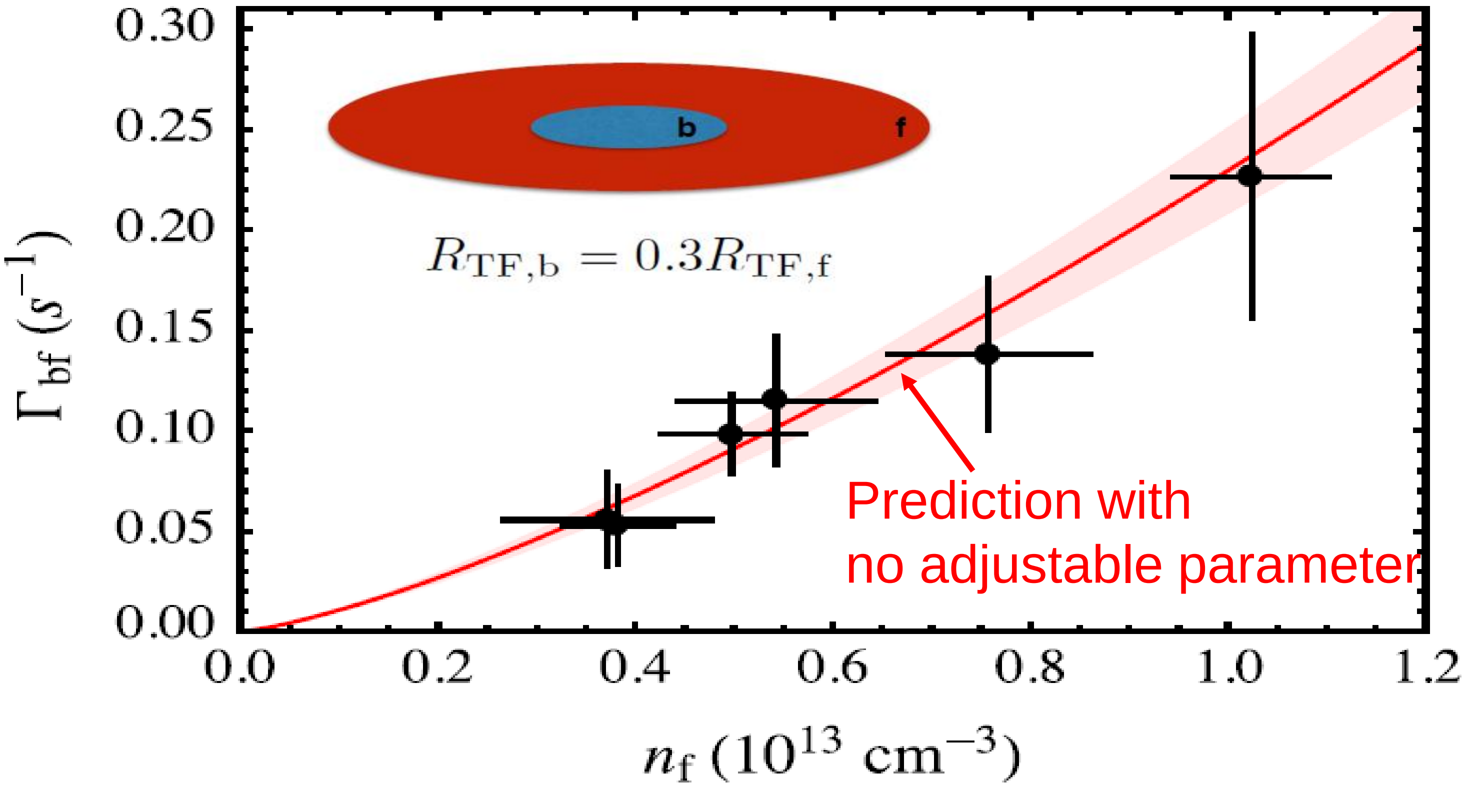


Prediction with
no adjustable parameter

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

Average over BEC
TF profile

Probing the local unitary Contact

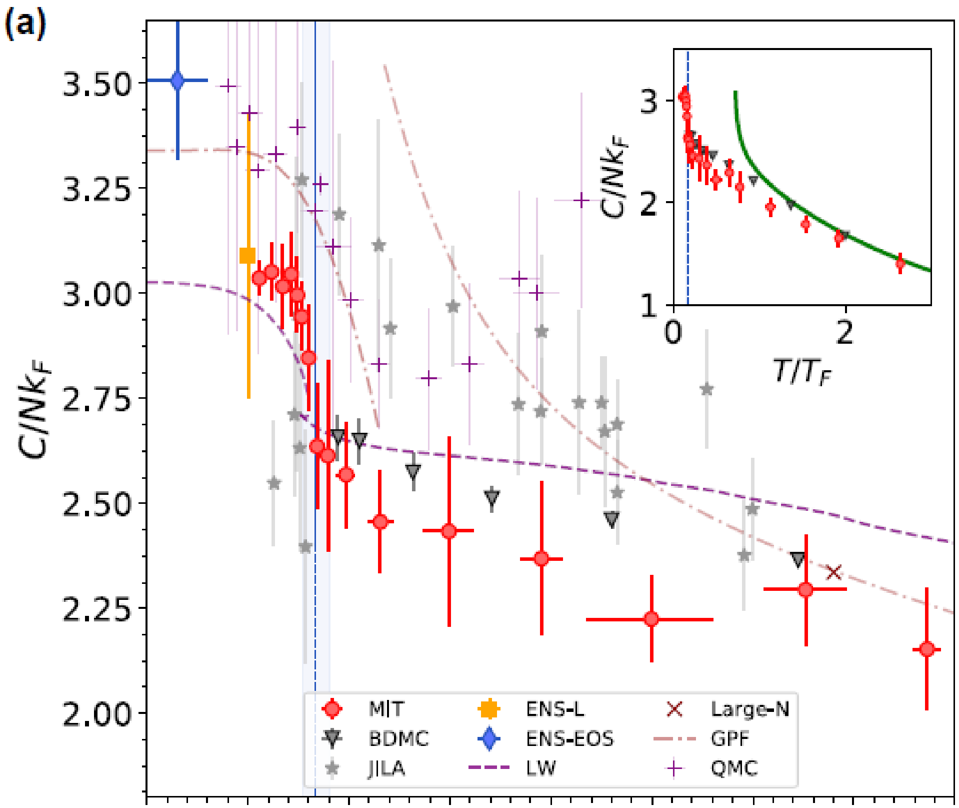


Power law fit: A n^p gives p = 1.36 (15) close to 4/3

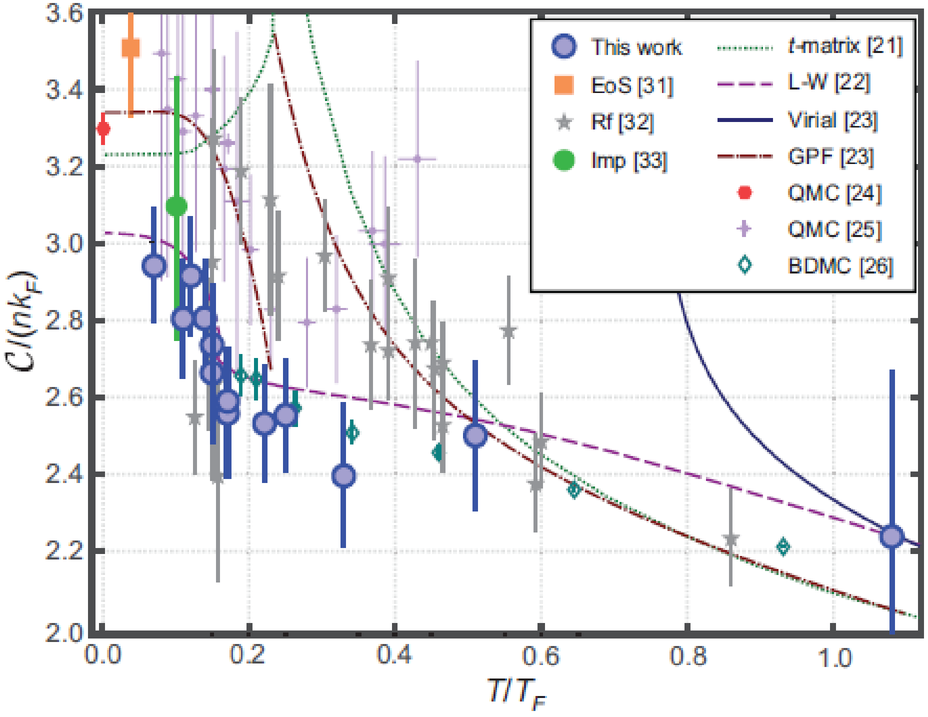
Fit: A $n^{4/3}$ gives A and local contact $C_2(0)$

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

Temperature dependence of Tan’s Contact



MIT: B. Mukherjee et al.,
PRL 122, 203402 (2019)



Swinburne, C. Carcy et al.
PRL 122, 203401 (2019)

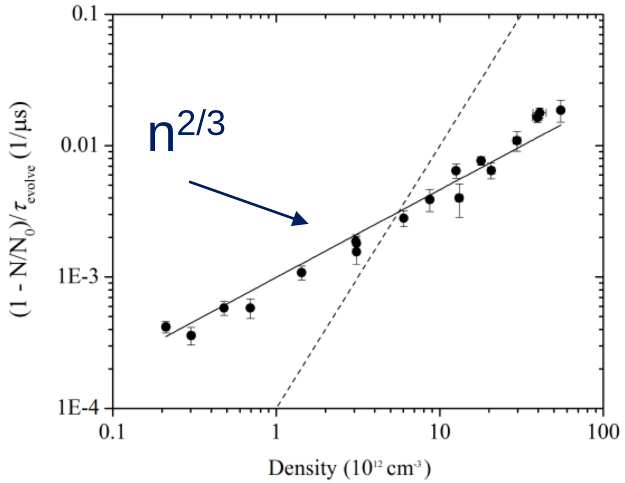
Summary

- Lifetime of Bose-Fermi mixture is governed by Tan's contact
- Theory applies to ^{174}Yb/^{6}Li, ^{40}K/^{6}Li, ^{87}Rb/^{40}K, assumes small a_{bf}
- What happens when a_{bf} increases ?

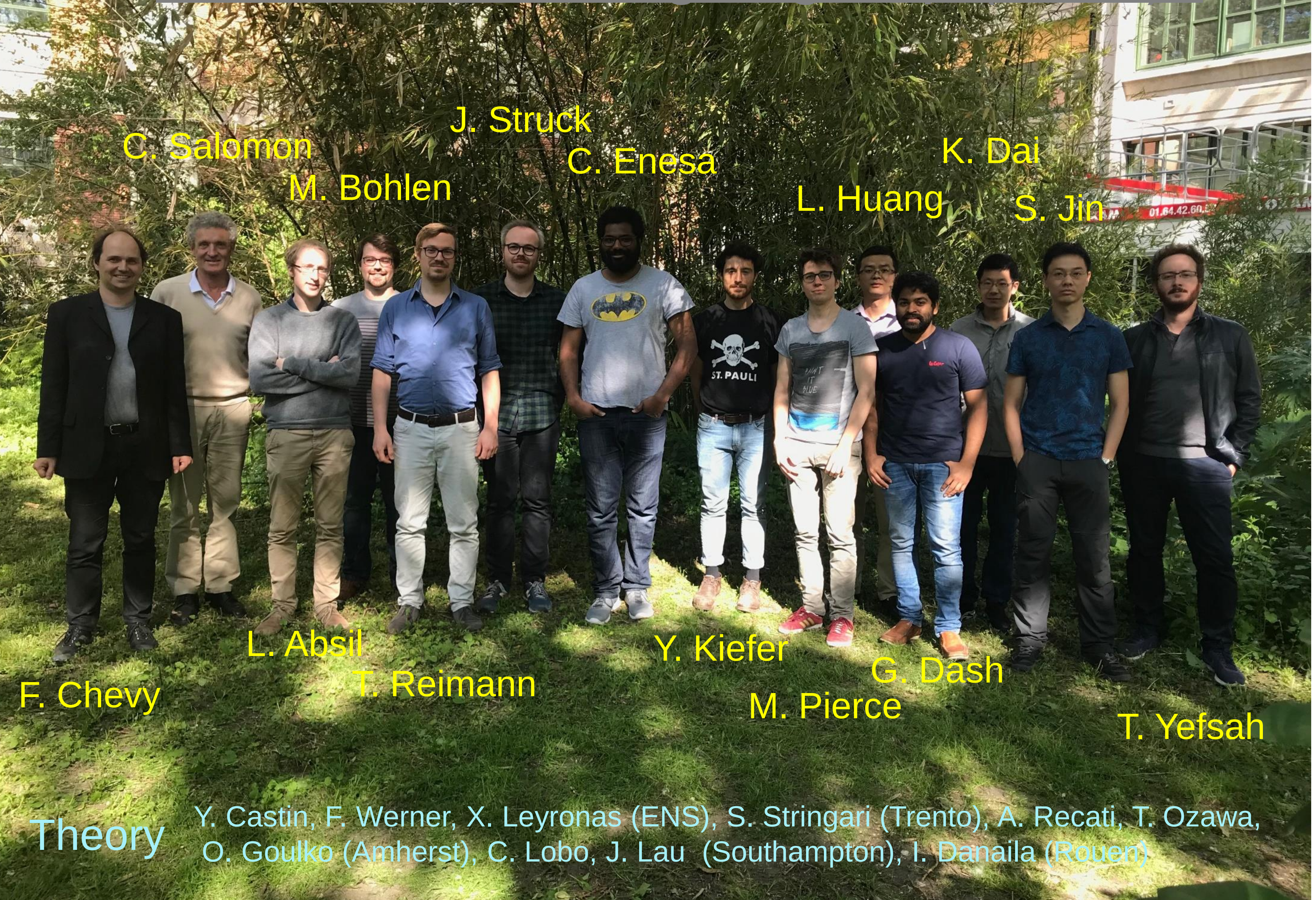
  Beyond mean field corrections: M. Pierce, X. Leyronas, F. Chevy, PRL 123, 080403, 2019, ArXiv 1903.01110, and Efimov effect
- Two-body and three-body contact in unitary Bose gas

  R. Fletcher et al., Science 2017, Cambridge

C. E. Klauss et al., PRL '17



The ENS Fermi gas group (2018)



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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)