Direct association of halo dimers and trimers in ultracold atoms.

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Electroweak properties of light nuclei, INT Seattle 7/11/2012

אוניברסיטת בר-אילן Tradition of Excellence Bar-Ilan University

People

Bar-Ilan University, Israel

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Servaas Kokkelmans

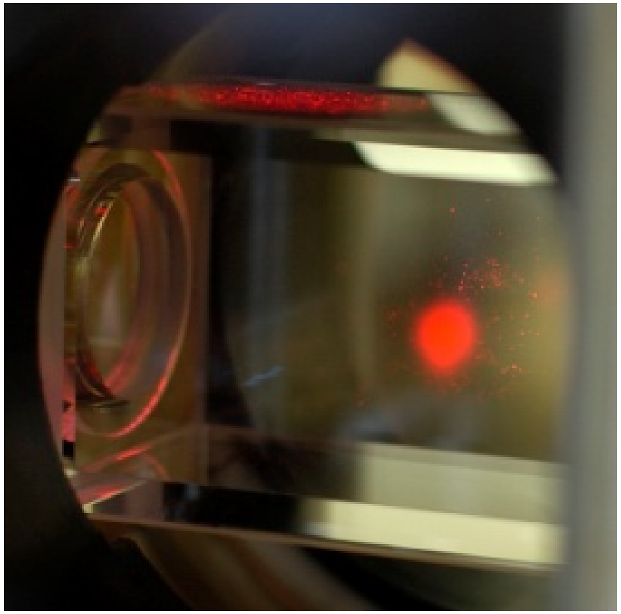
L. Kh, Eli Shwartz, Noam Gross, Zav Shotan, Olga Machtey
Not on the picture: Aviad Schori, Cornee Ravensbergen (short term visitor)

Ultracold (Li) atoms

Magneto-optical trap

Close to the resonance (orbital electronic states) visible (laser) light – 671 nm (~2 eV)

Ultrahigh vacuum environment



Magnetic fields

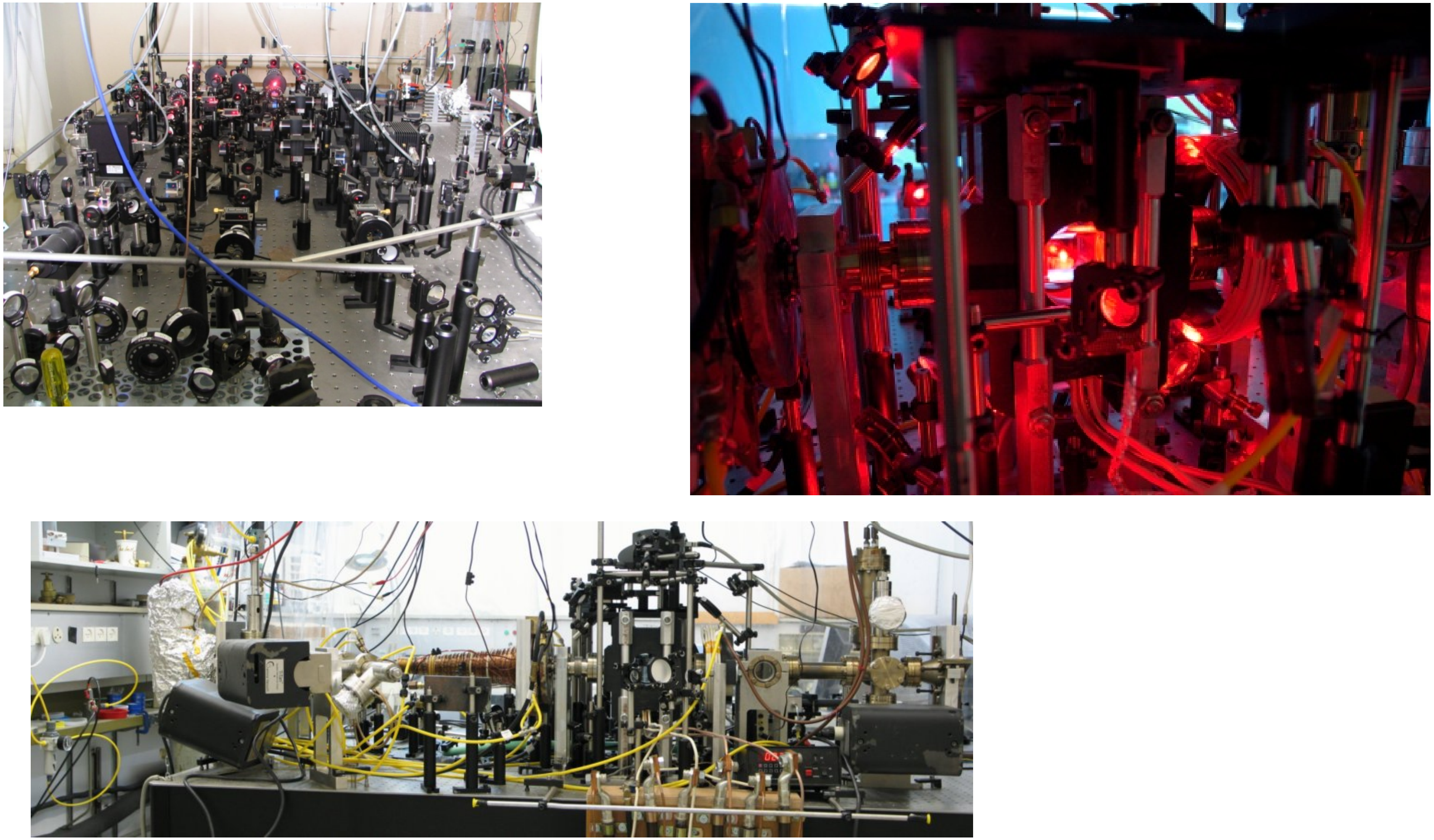
Dissipative trap

$N \sim 5\text{x}10^8$ atoms

$n \sim 10^{10}$ atoms/cm^3

$T \sim 300\ \mu K$

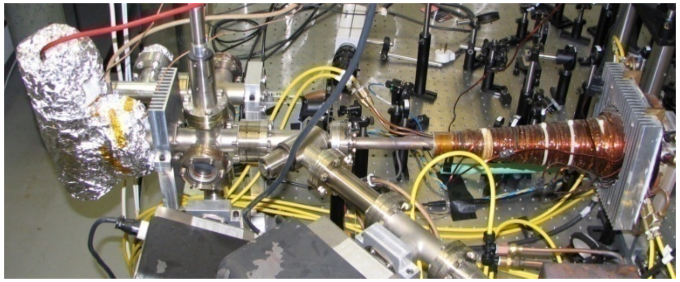
Ultracold atoms – table-top experiment



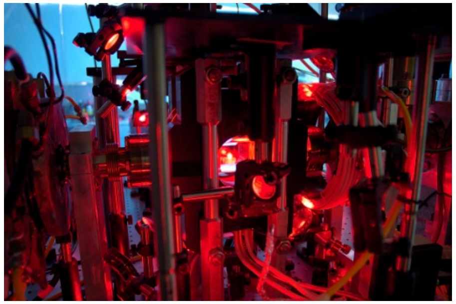
Ultracold (Li) atoms

Cooling:

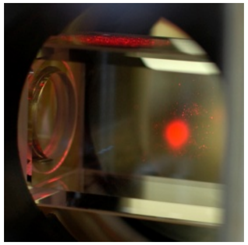
Zeeman
slower



MOT
~10^9 atoms

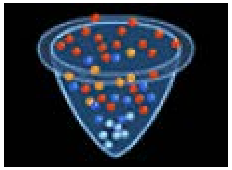


CMOT
~5×10^8 atoms
(300 μK)

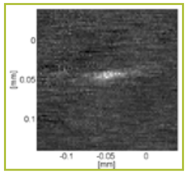


Trapping: conservative atom trap

(our case: focus of powerful infrared laser)



Crossed-beam optical trap



Evaporation:
~2×10^4 atoms
~1.5 μK

Typical numbers:

Temperature: ~ μK

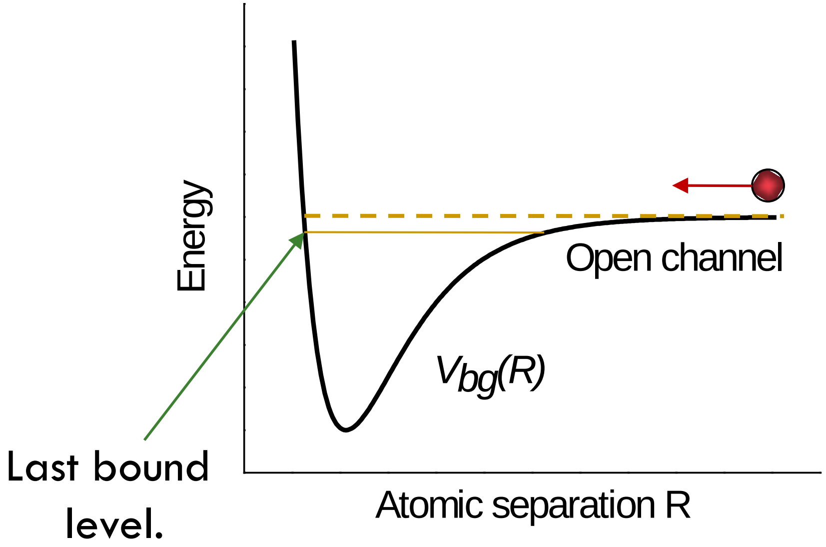
Relative velocities: few cm/sec

Collision energies: few peV

N. Gross and L. Khaykovich, PRA ***77***, 023604 (2008)

Scattering length

At low temperatures the scattering is completely s-wave dominated.



s-wave scattering length a
is determined by the last bound state

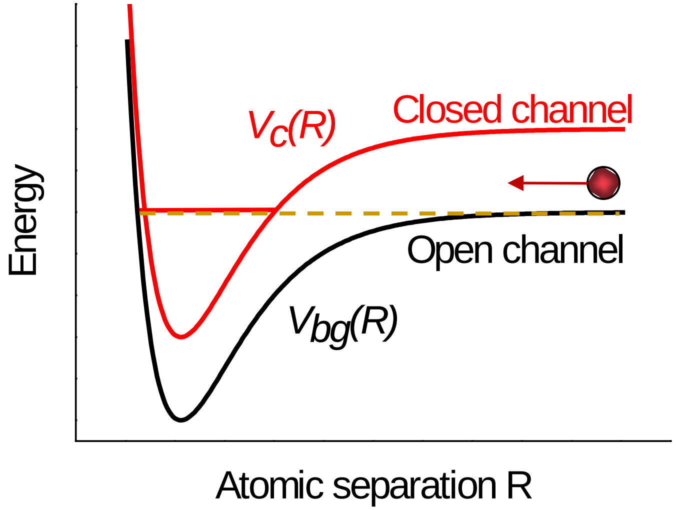
$$a = a_{bg}$$

Li atoms: $a_{bg} = 10 a_{Bohr}$

Typical size of the interatomic potential – the van der Waals length $l_{vdW} \sim 100 a_{Bohr}$

Feshbach resonance

Magnetic field tuning of the scattering length.



Closed channel: singlet potential
bound state

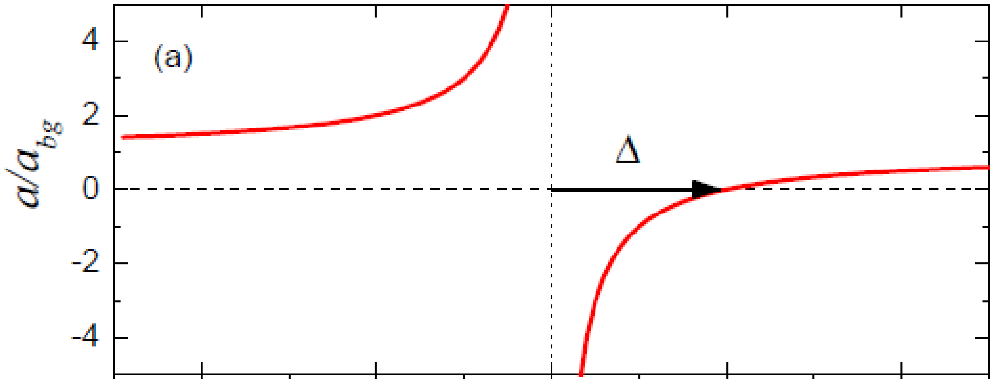
Open channel: triplet potential
free atoms

Different magnetic moments

-The thriplet potential depends on the magnetic field

- The singlet potential does not

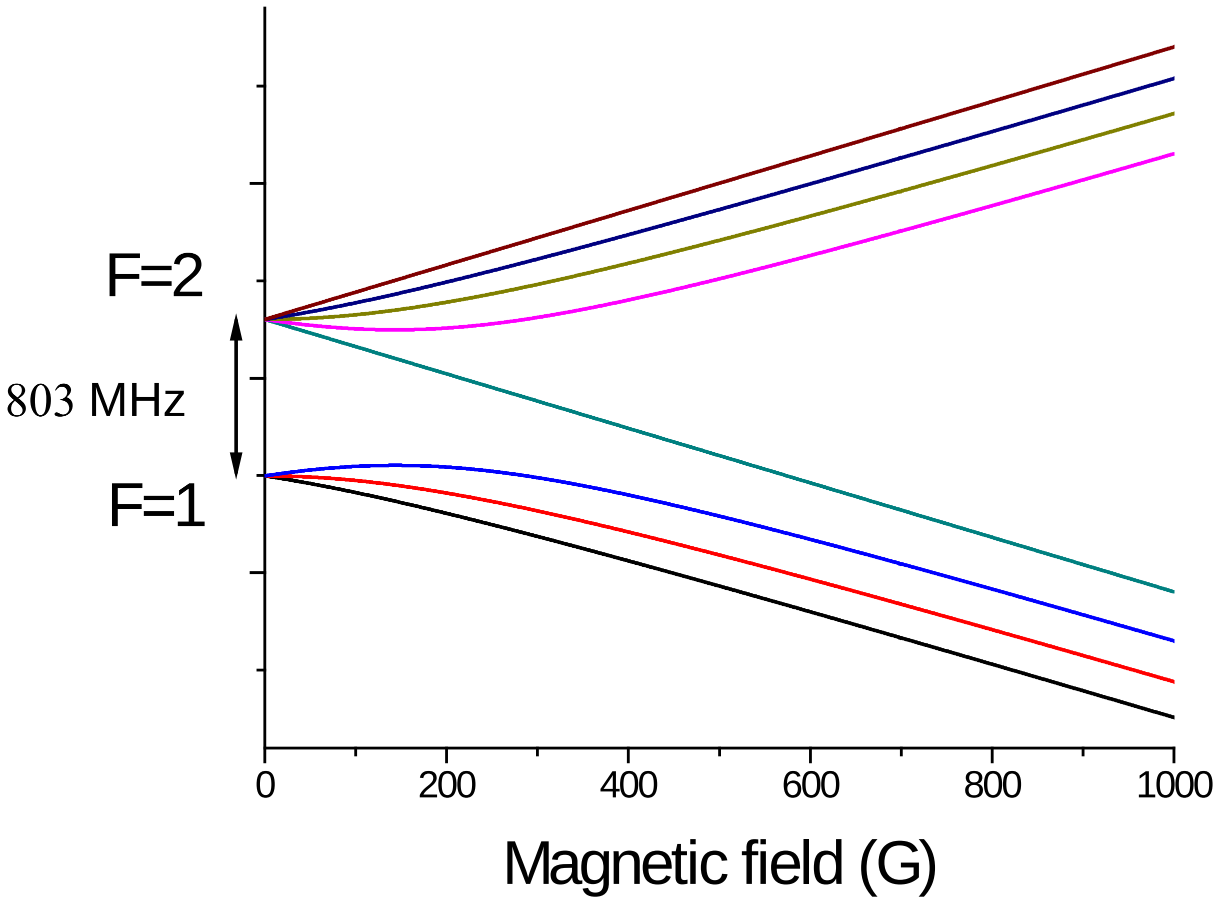
$$a = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$



EXPERIMENTAL PLAYGROUND

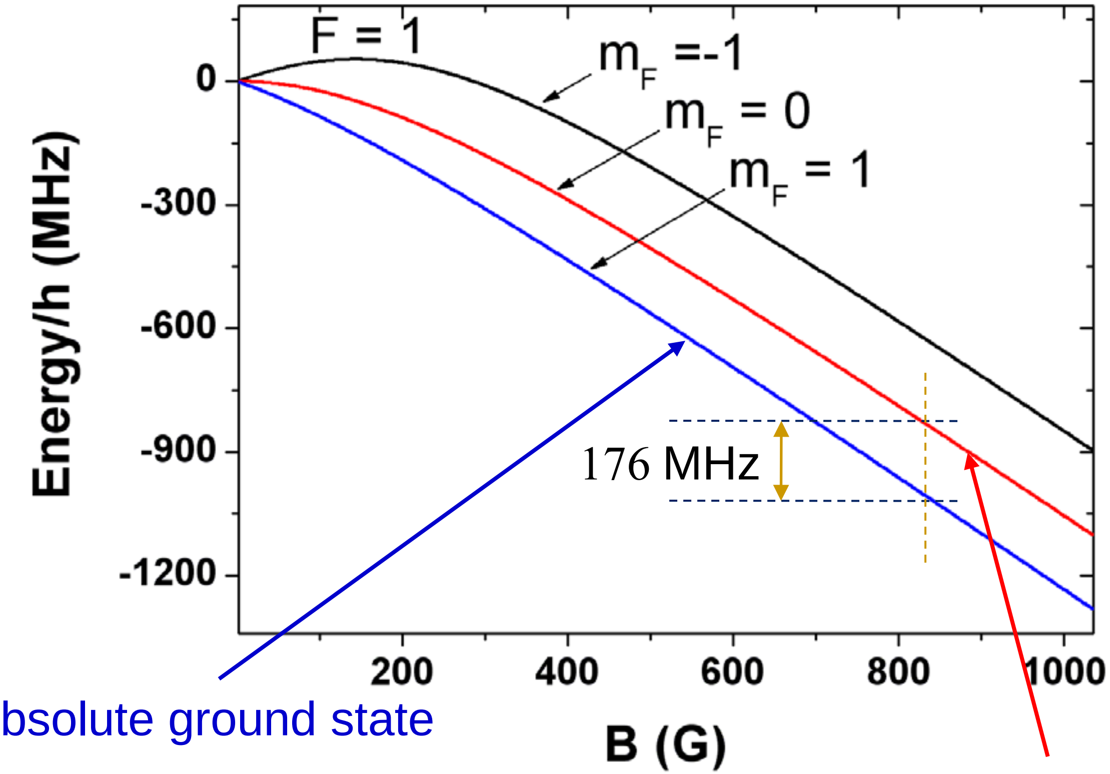
Experimental playground - ^{7}Li atoms

Hyperfine structure of the ground state.



Experimental playground - ^{7}Li

3 identical bosons on a single nuclear-spin state.



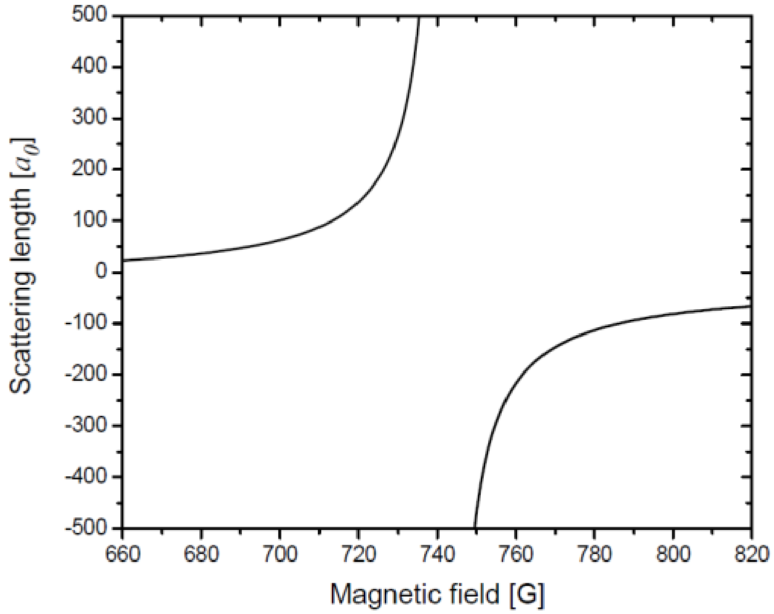
Absolute ground state

The one but lowest Zeeman state

Experimental playground - ^{7}Li

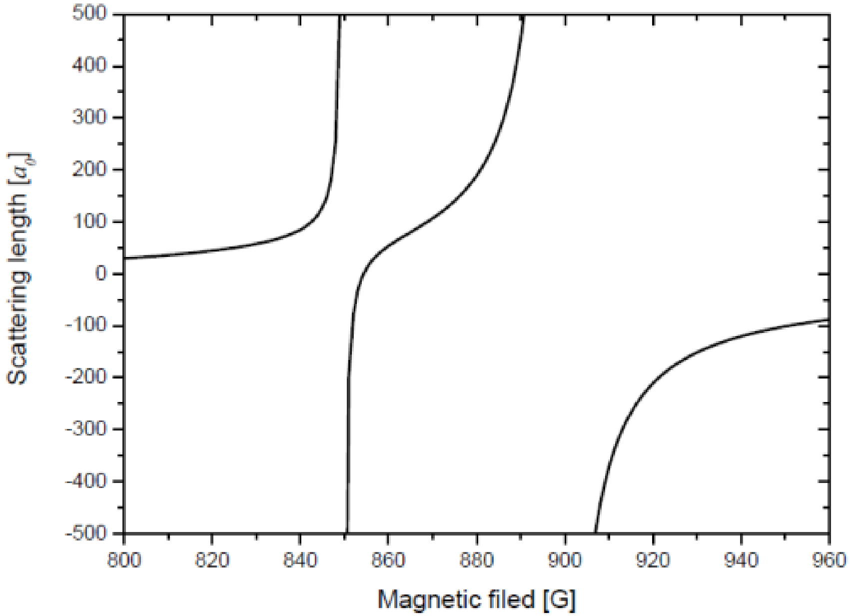
Absolute ground state

Feshbach resonance



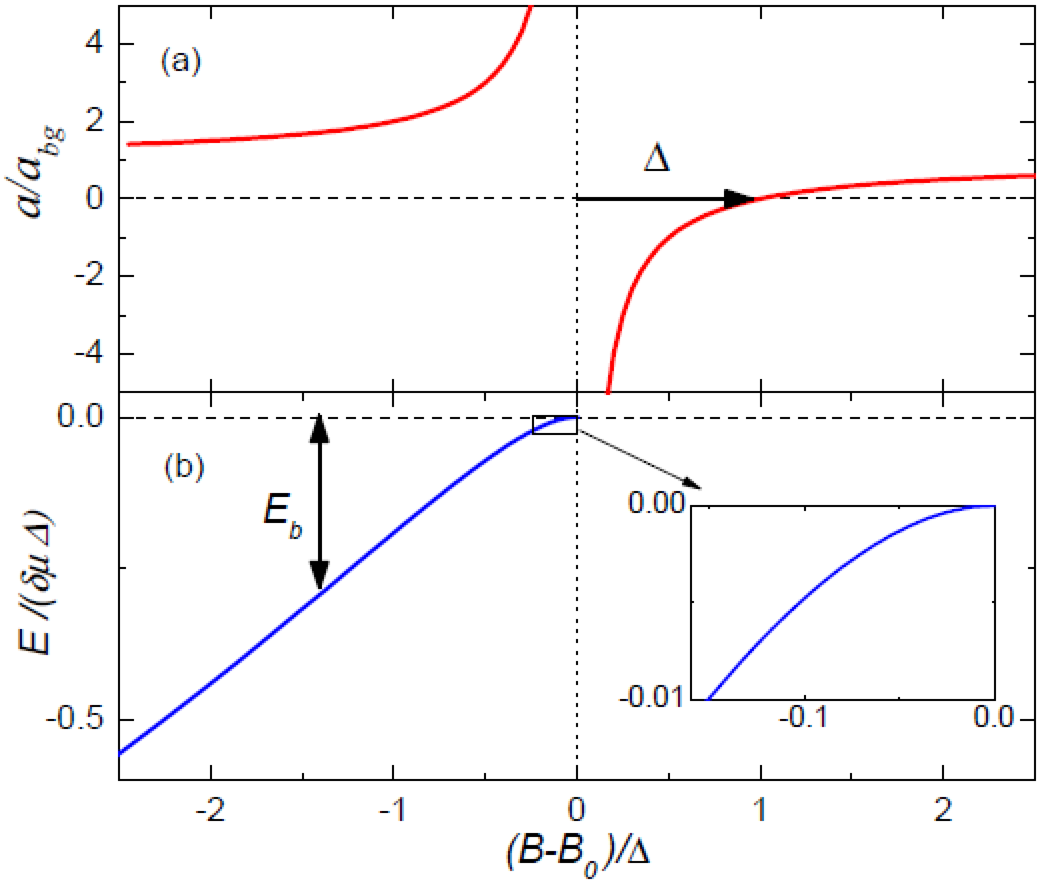
The one but lowest Zeeman state

Feshbach resonance



TWO-BODY UNIVERSALITY

Feshbach molecule (universal dimer)



Feshbach molecule (universal dimer):

$$E_b = -\frac{\hbar^2}{ma^2}$$

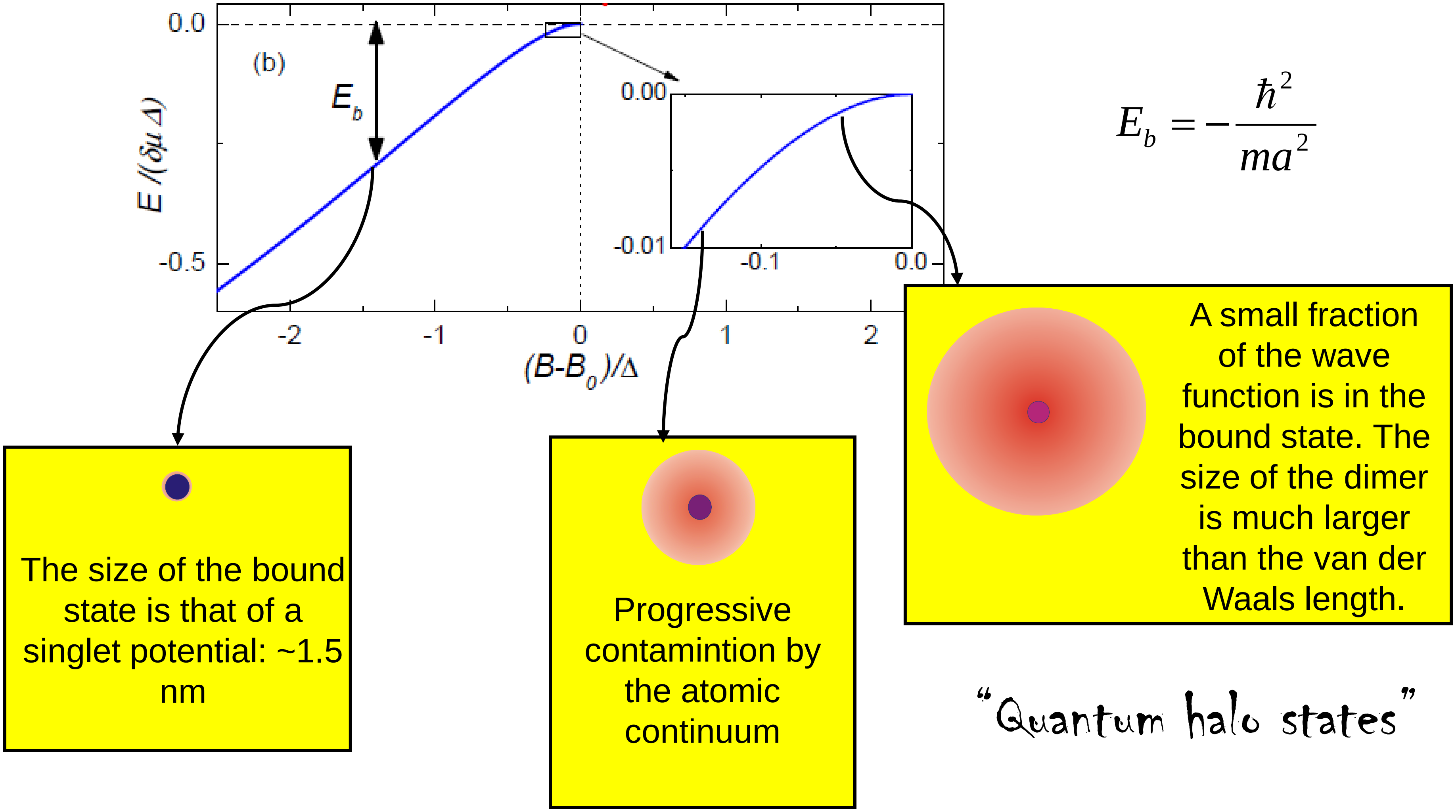
Bare state (non-universal) dimer:

$$E_b = \delta\mu\left(B - B_0\right)$$

Also: **deuteron,** He_2

Universal dimer – quantum halo state

$$E_b = -\frac{\hbar^2}{ma^2}$$



The size of the bound state is that of a singlet potential: ~1.5 nm

Progressive contamintion by the atomic continuum

A small fraction of the wave function is in the bound state. The size of the dimer is much larger than the van der Waals length.

"Quantum halo states"

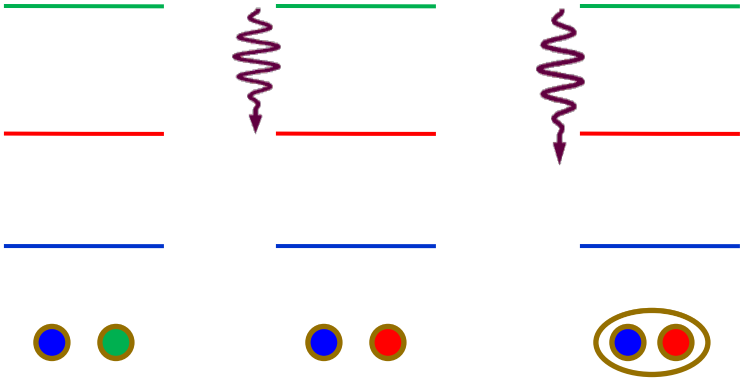
ASSOCIATION OF HALO DIMERS

Differenet systems

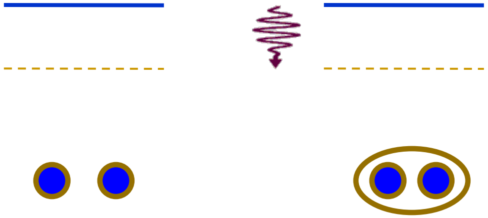
- Rf association of universal dimers (partial list only) :
  - 2005 ^{85}Rb JILA, Boulder, CO
  - 2006 ^{6}Li in Innsbruck, Austria; MIT, Cambridge MA
  - 2008 ^{41}K - ^{87}Rb in Florence, Italy
  - 2009 ^{40}K - ^{87}Rb in Hannover, Germany
  - 2010 ^{7}Li in BIU, Israel
  - …

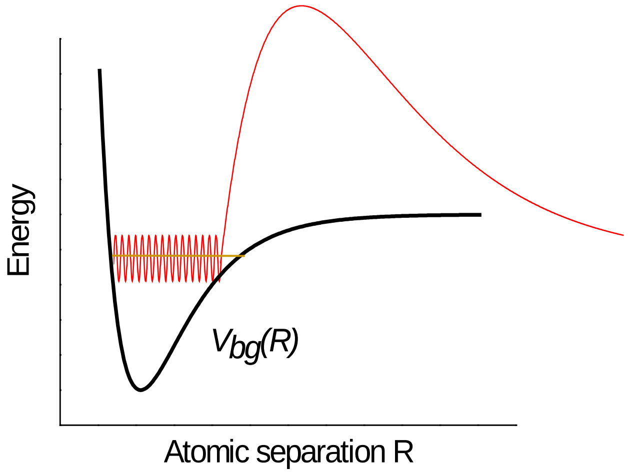
Rf association of universal dimers

-Spin flip



-Frozen spin



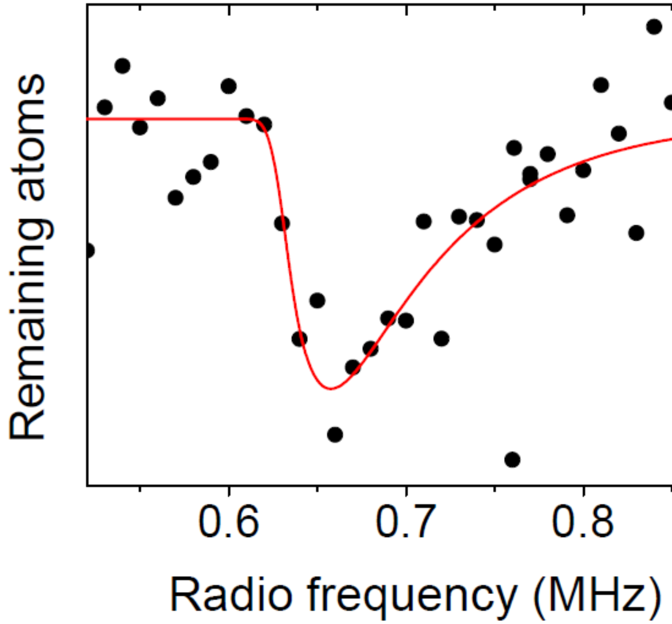


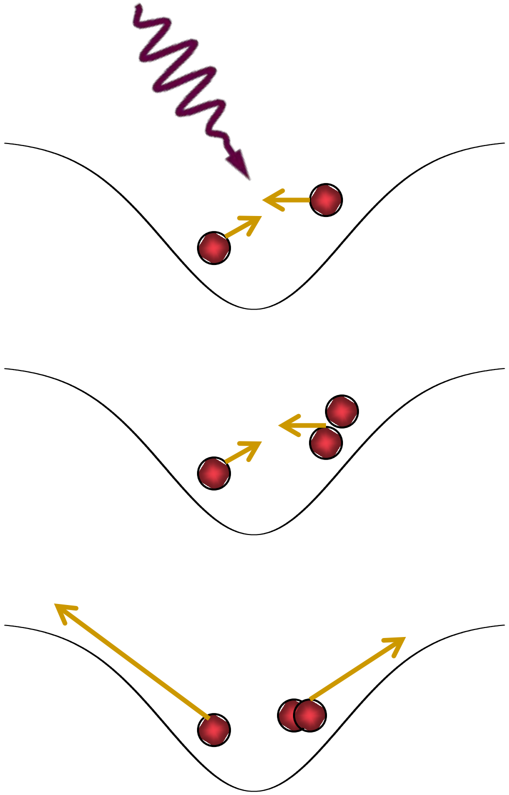
Strong overlapping
with scattering continuum

Rf association of universal dimers

Precise characterization of Feshbach resonances by rf-spectroscopy of universal dimers.

A typical RF spectrum

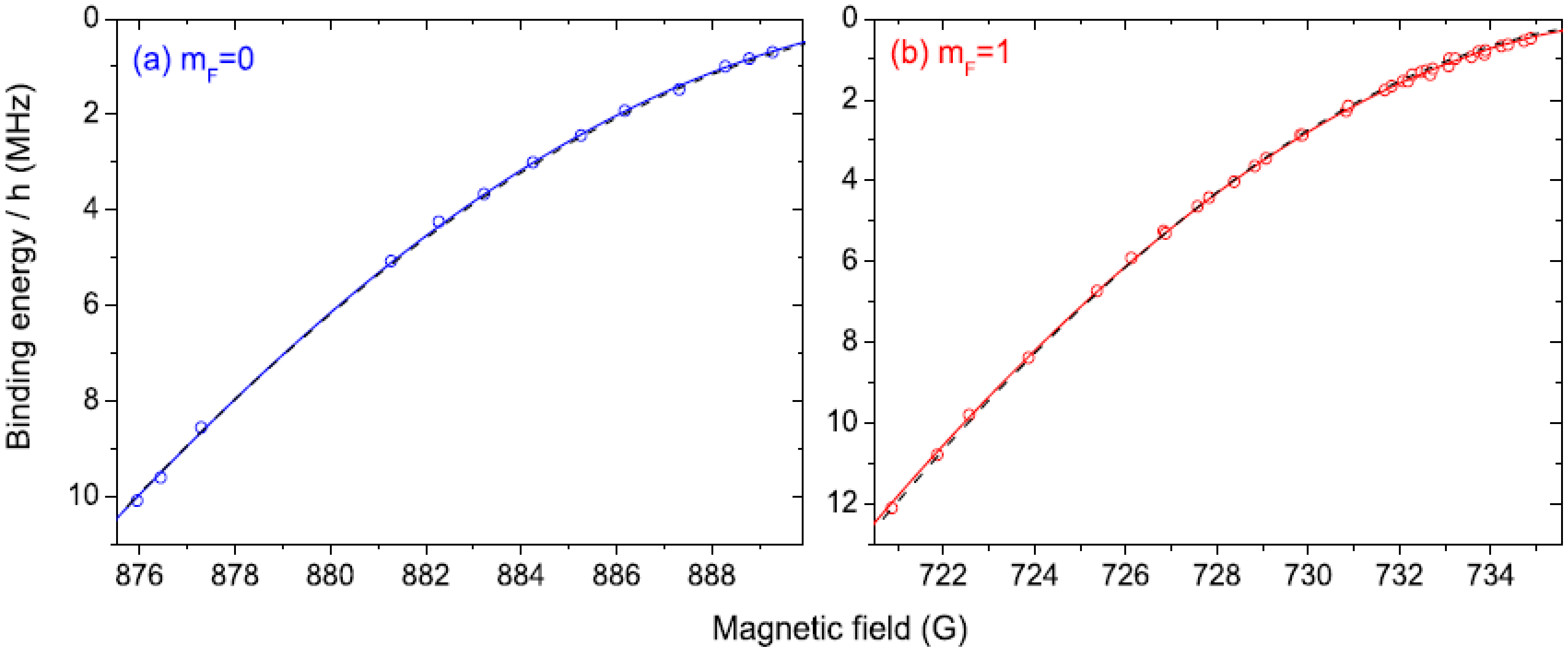




N. Gross, Z. Shotan, O. Machtey, S. Kokkelmans and L. Khaykovich, C.R. Physique 12, 4 (2011) ; arXiv:1009.0926

Rf association of universal dimers

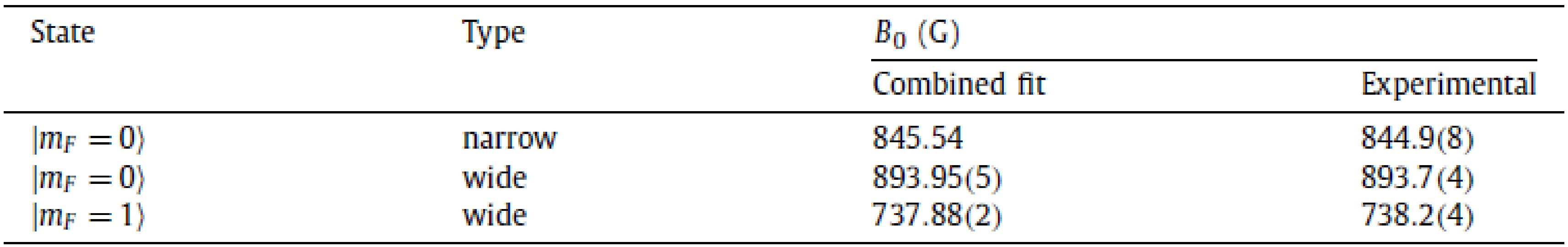
Precise characterization of Feshbach resonances by rf-spectroscopy of universal dimers.



N. Gross, Z. Shotan, O. Machtey, S. Kokkelmans and L. Khaykovich, C.R. Physique 12, 4 (2011) ; arXiv:1009.0926

Mapping between the scattering length and the applied magnetic field

Precise characterization of Feshbach resonances by rf-spectroscopy of universal dimers.



State	Type	B_0 (G)	
		Combined fit	Experimental
$\vert m_F = 0\rangle$	narrow	845.54	844.9(8)
$\vert m_F = 0\rangle$	wide	893.95(5)	893.7(4)
$\vert m_F = 1\rangle$	wide	737.88(2)	738.2(4)

Improved characterization of Li inter-atomic potential.

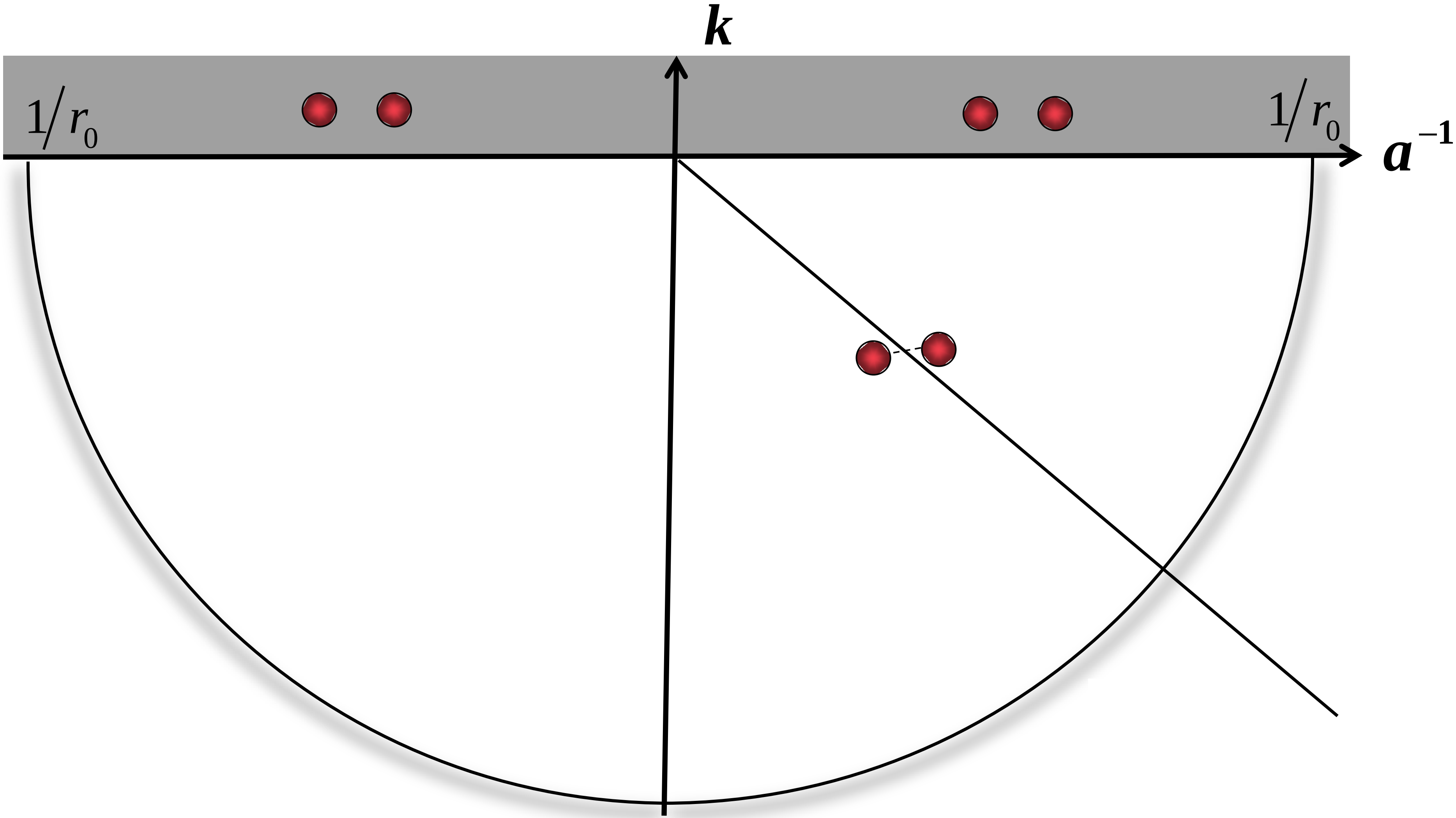
$$a_S = 34.33(2) a_0$$

$$a_T = -26.87(8) a_0$$

N. Gross, Z. Shotan, O. Machtey, S. Kokkelmans and L. Khaykovich, C.R. Physique 12, 4 (2011) ; arXiv:1009.0926

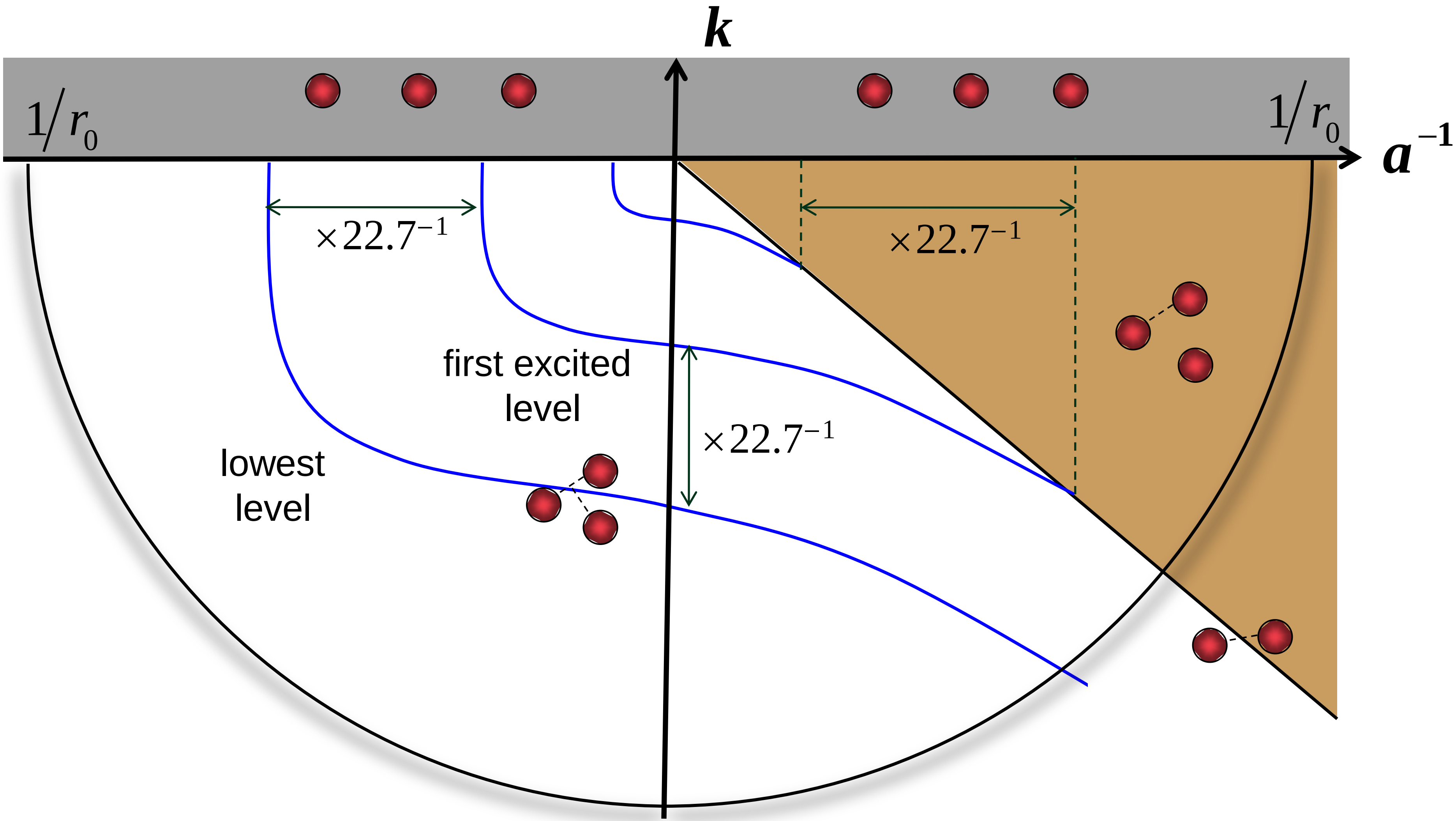
THREE-BODY UNIVERSALITY:
EFIMOV QUNATUM STATES

Quantum states near 2-body resonance



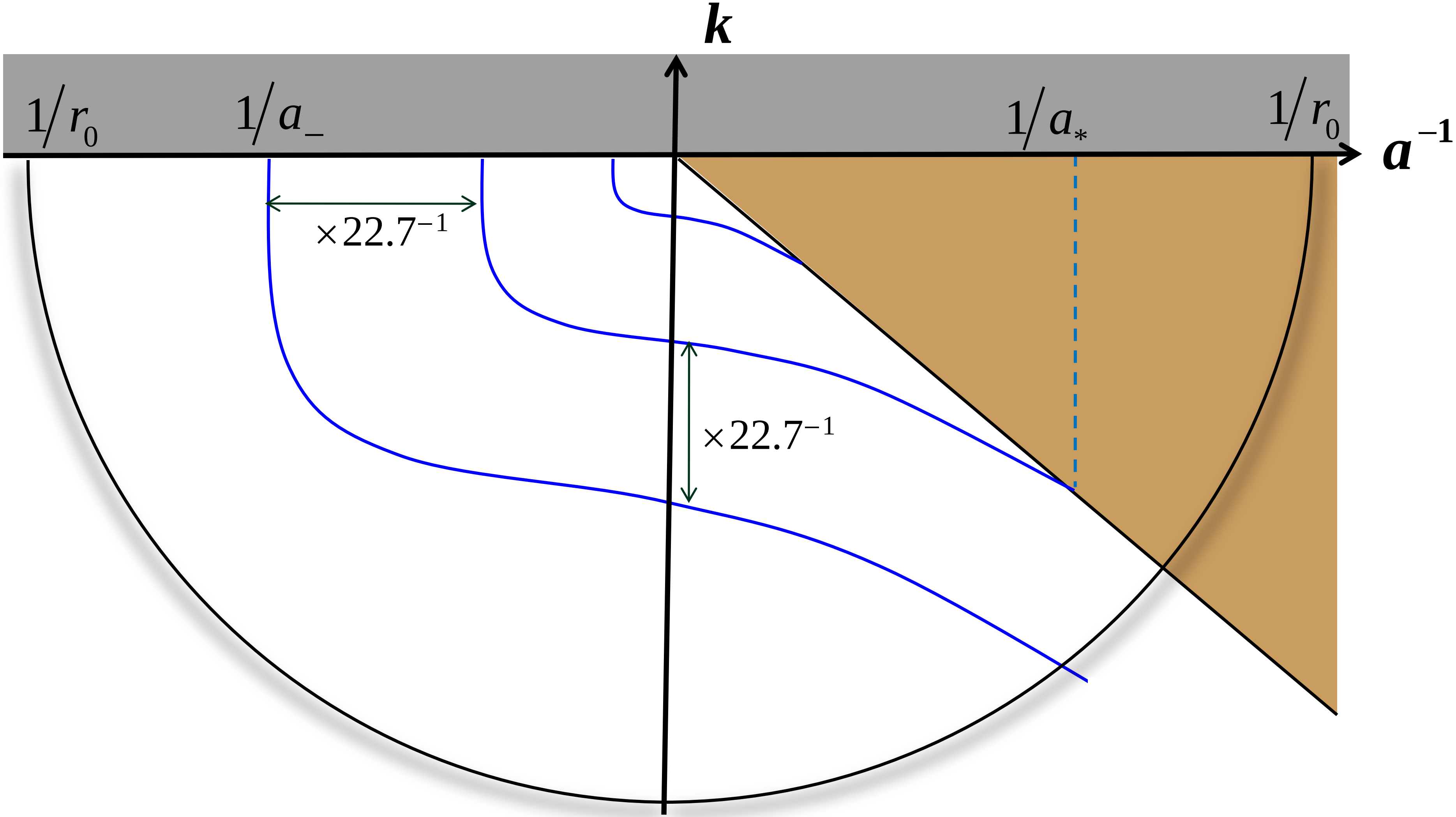
van der Waals range (^{7}Li): $r_0 = \left(\frac{mC_6}{16\hbar^2}\right)^{1/4} \approx 32.5a_0$

Efimov scenario – universality window



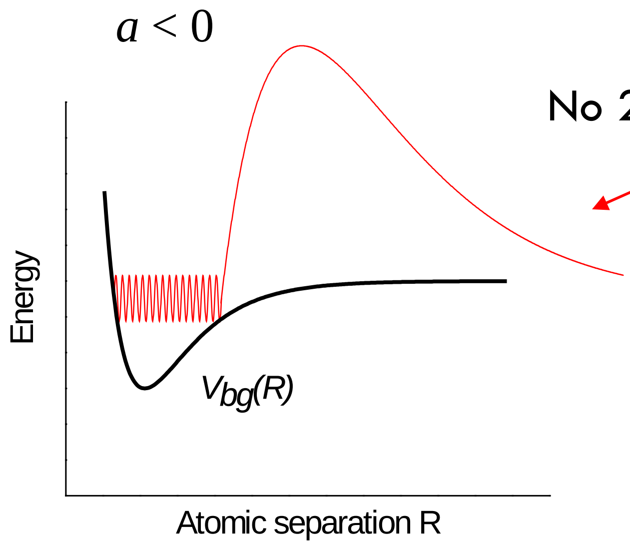
van der Waals range (^{7}Li): $r_0 = \left(\frac{mC_6}{16\hbar^2}\right)^{1/4} \approx 32.5a_0$

Efimov scenario – 3-body parameter



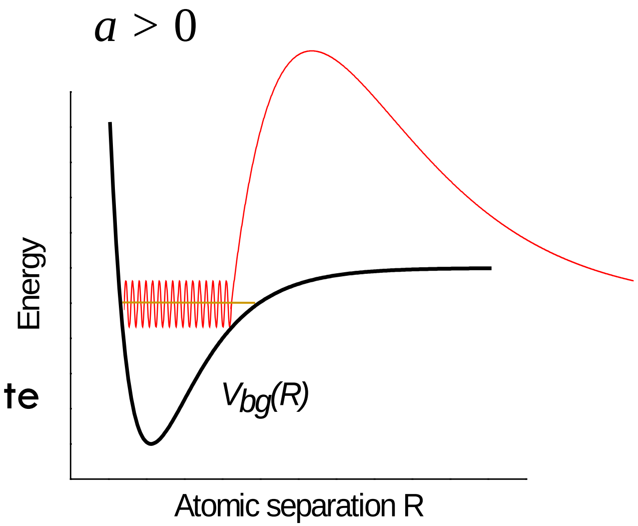
Position of a highly excited Efimov state is fixed by a 3-body parameter.

Efimov scenario and real molecules



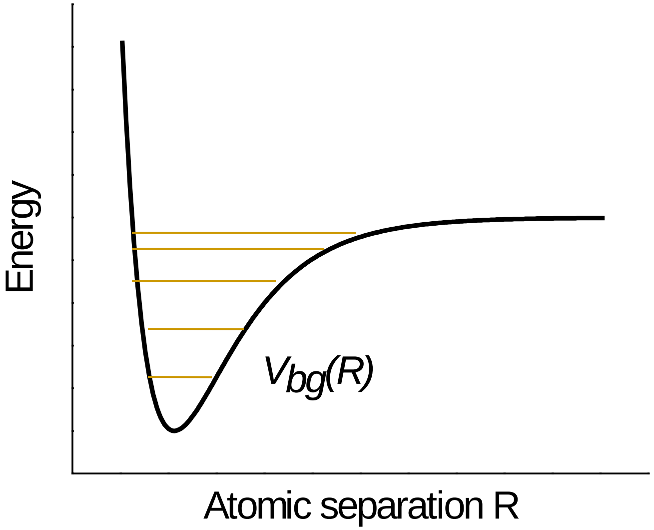
No 2-body bound states

One 2-body bound state



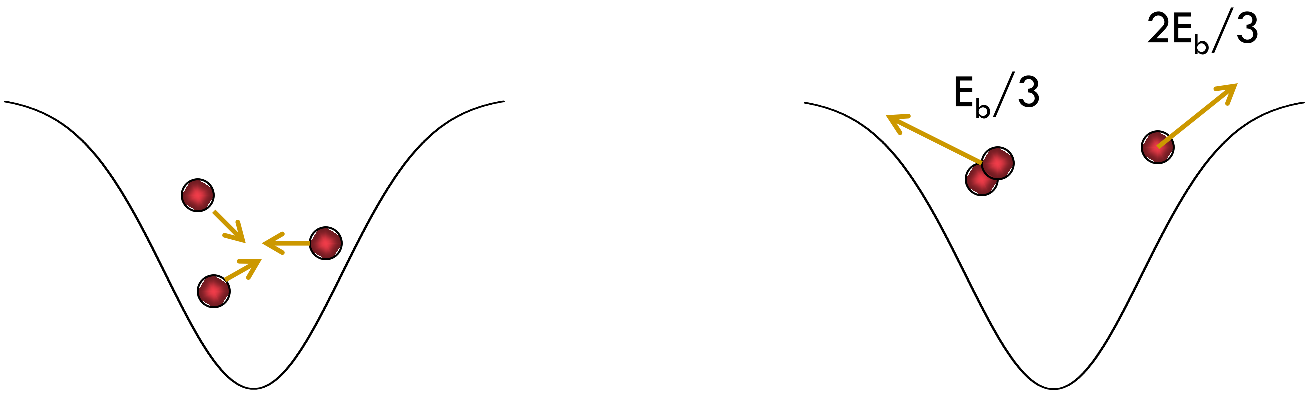
Real molecules:

many deeply bound states



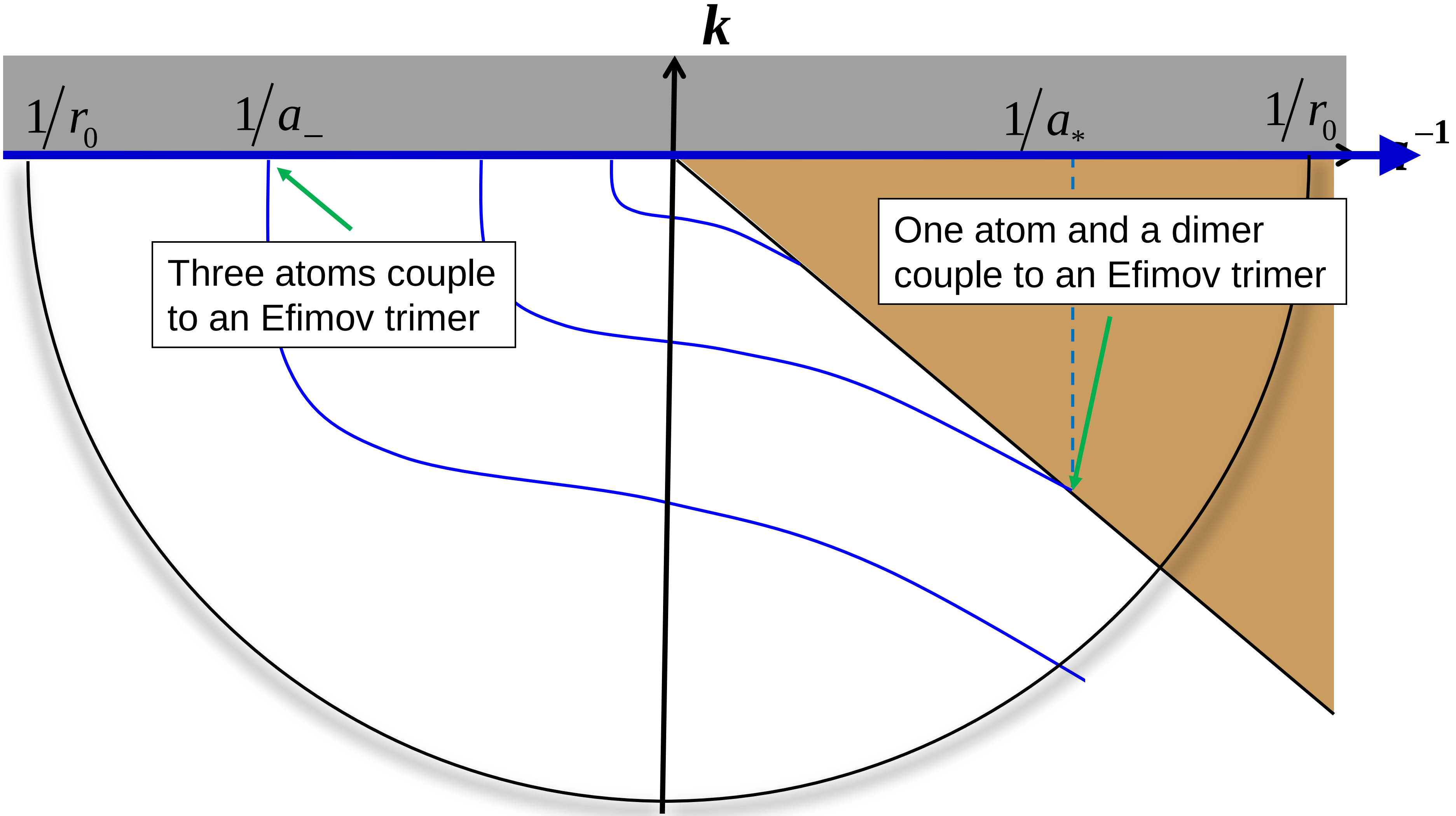
Three-body recombination

Three body inelastic collisions result in a weakly (or deeply) bound molecule.



Release of binding energy causes loss which probes 3-body physics.

Experimental observables

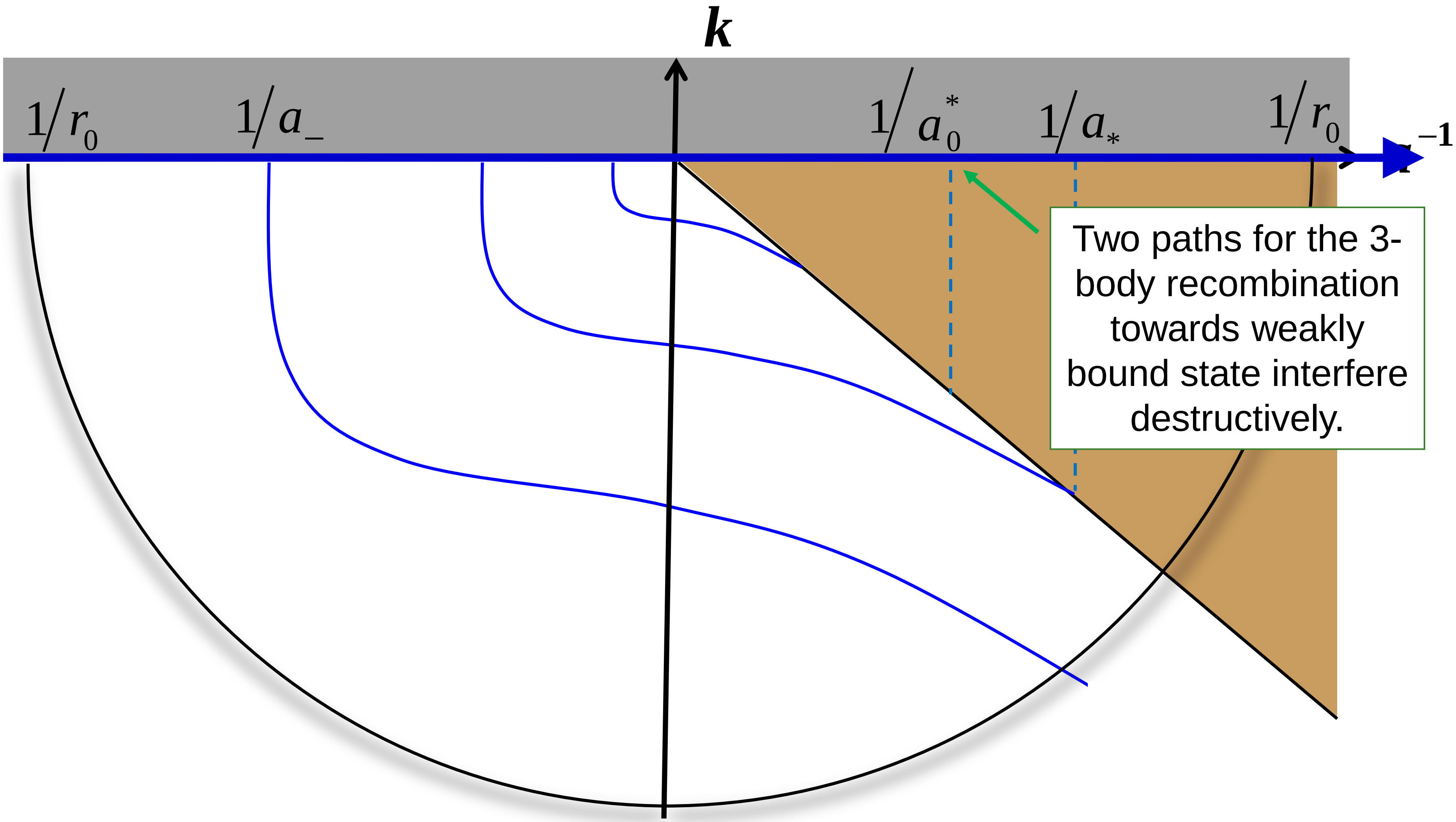


Three atoms couple to an Efimov trimer

One atom and a dimer couple to an Efimov trimer

Experimental observable - ***enhanced*** three-body recombination.

Experimental observables



Two paths for the 3-body recombination towards weakly bound state interfere destructively.

Experimental observable – recombination ***minimum***.

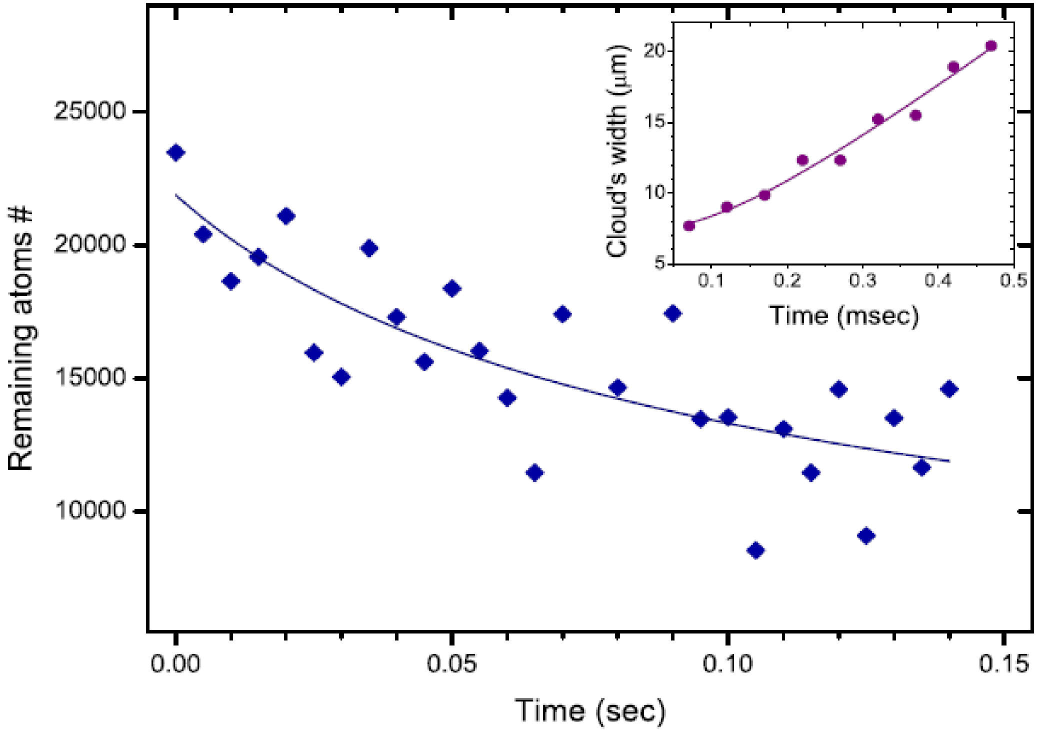
EXPERIMENTAL RESULTS

Different systems

- Efimov physics (and beyond) with ultracold atoms:
  - 2006 - … ^{133}Cs Innsbruck
  - 2008 – 2010 ^{6}Li 3-component Fermi gas in Heidelberg, Penn State and Tokyo Univ.
  - 2009 ^{39}K in Florence, Italy
  - 2009 ^{41}K - ^{87}Rb in Florence, Italy
  - 2009 ^{7}Li in Huston University, TX
  - 2009 - … ^{7}Li in BIU, Israel
  - 2012 ^{85}Rb JILA, Boulder, CO

Experimental results

Typical set of measurements - atom number decay and temperature:



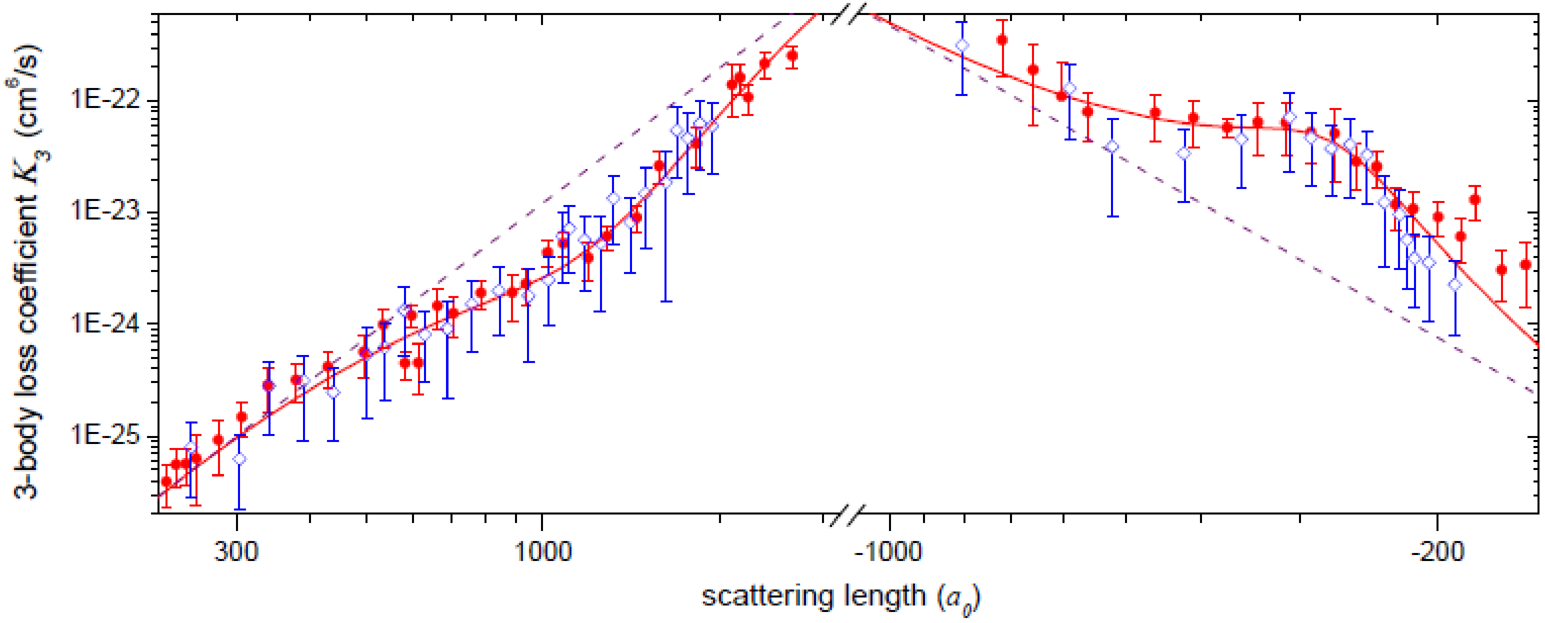
<u>Loss rate from a trap:</u>

$\dot{N} = -K_3 \langle n^2 \rangle N$ K_3 – 3-body loss coefficient [cm^6/sec]

Experimental results

a > 0: T= 2 – 3 μK

a < 0: T= 1 – 2 μK



mf = 1; Feshbach resonance ~738G.
mf = 0; Feshbach resonance ~894G.

N. Gross, Z. Shotan, S. Kokkelmans and L. Khaykovich, PRL **103**, 163202 (2009); PRL **105**, 103203 (2010).

Summary of the results

Fitting parameters to the universal theory:

State	η_+	η_-	a_+/a_0	a_-/a_0	$a_+/\lvert a_-\rvert$
$\lvert m_F = 0\rangle$	0.213(79)	0.180(48)	238(25)	−280(12)	0.85(11)
$\lvert m_F = 1\rangle$	0.170(41)	0.253(62)	265(16)	−274(12)	0.97(8)

$|a_-|/r_0 = 8.6(4)$ UT prediction:

$a_+/|a_-| = 0.96(3)$

Derived parameters:

	Position of recombination minima:	*Position of atom-dimer threshold:*	
		a_+	a_-
$\lvert m_F = 0\rangle$	$a_0^* = 1134(120)a_0$	$a_* = 262(27)a_0$	$a_* = 288(26)a_0$
$\lvert m_F = 1\rangle$	$a_0^* = 1262(76)a_0$	$a_* = 292(18)a_0$	$a_* = 282(16)a_0$

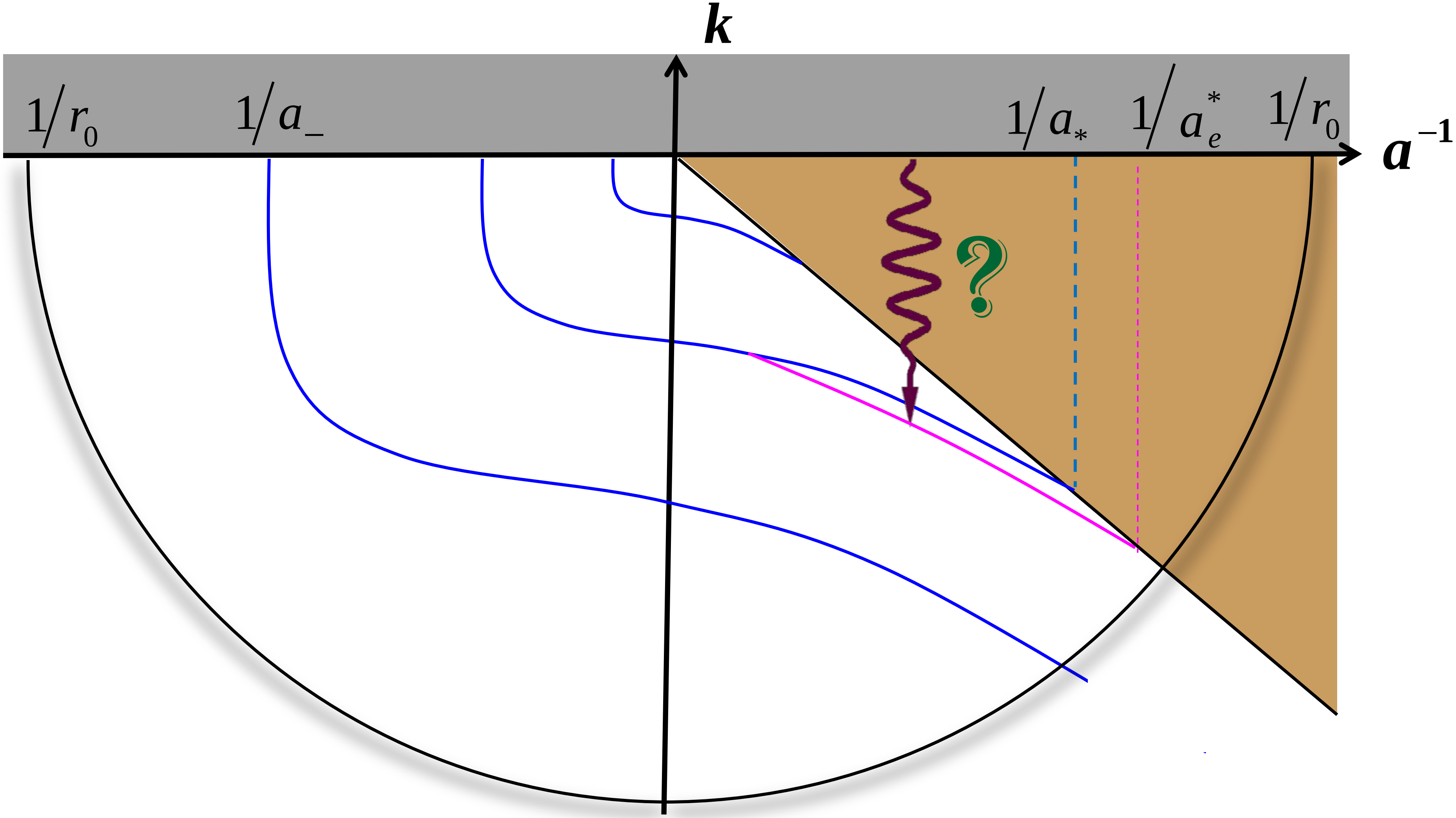
- 3-body parameter is the same across the region of $|a| \to \pm\infty$
- 3-body parameter is the same for both nuclear-spin subleves.

N. Gross, Z. Shotan, O. Machtey, S. Kokkelmans and L. Khaykovich, C.R. Physique **12**, 4 (2011).

ASSOCIATION OF HALO TRIMERS.

Rf association of Efimov trimers

Three-atom continuum to trimer transition? Can it work?

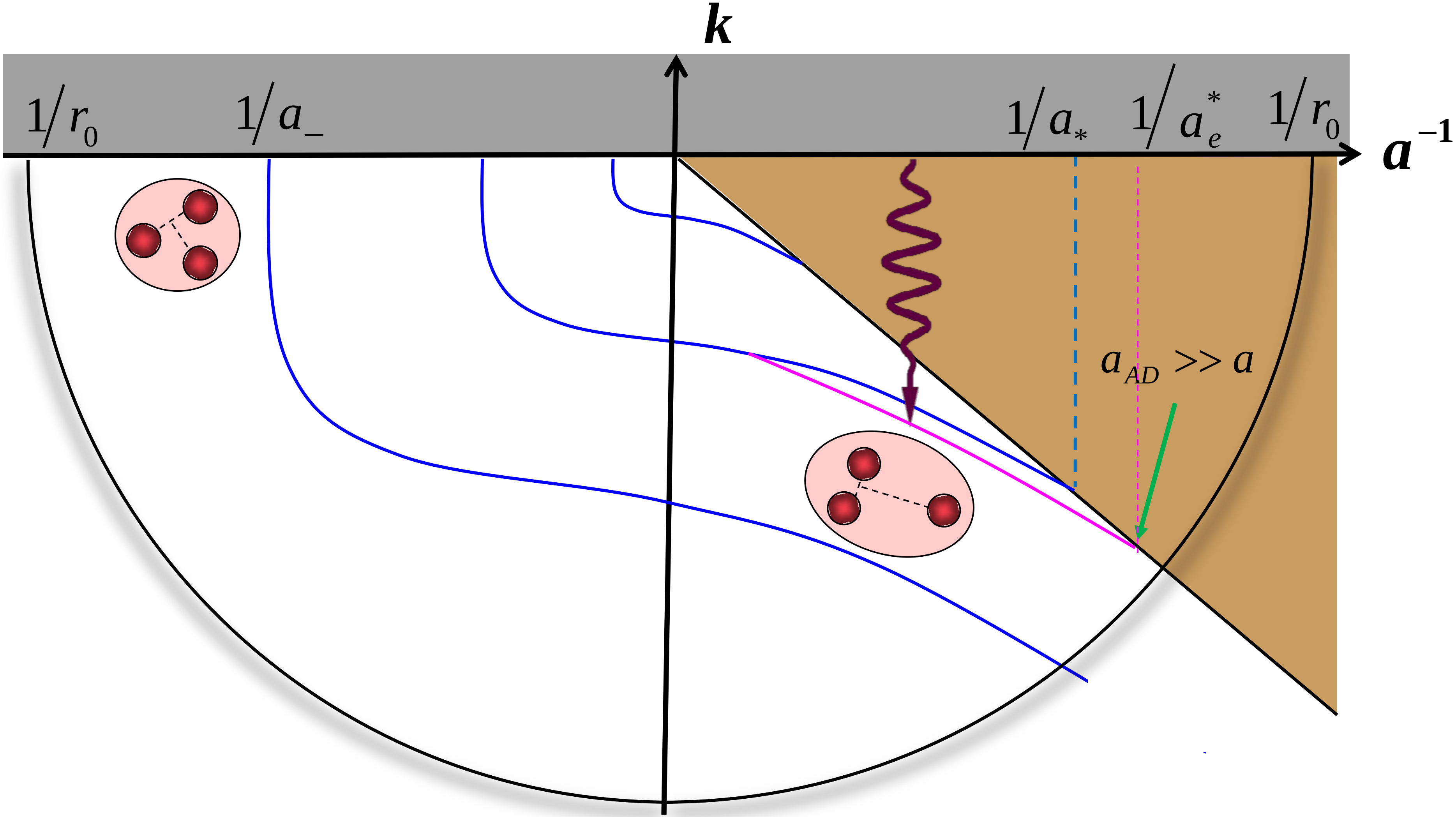


See also rf association of Efimov trimers in three-component Fermi gas:

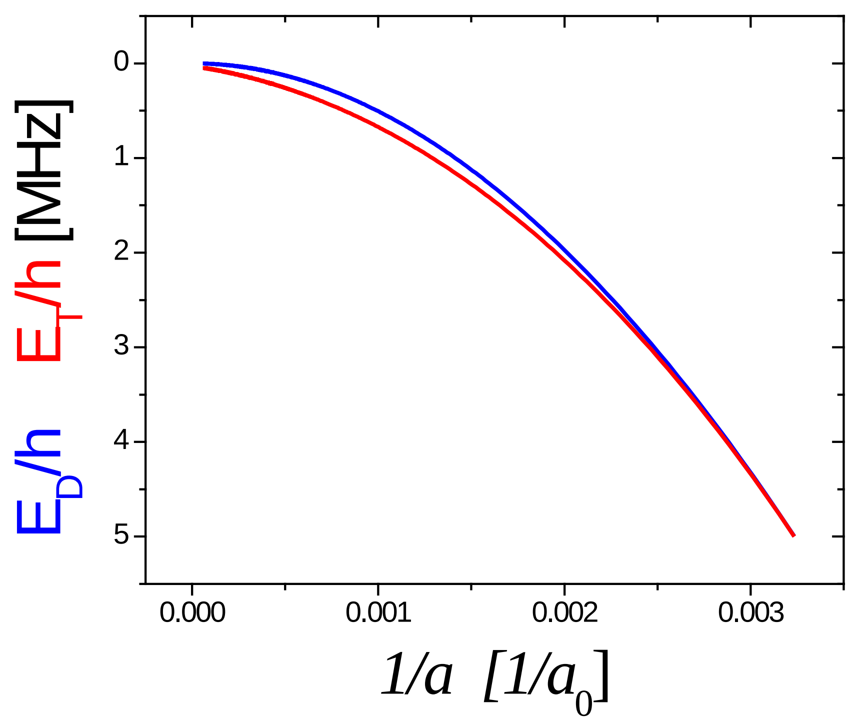
T. Lompe, T.B. Ottenstein, F.Serwane, A.N. Wenz, G. Zurn, S. Jochim , Science **330**, 940 (2010).

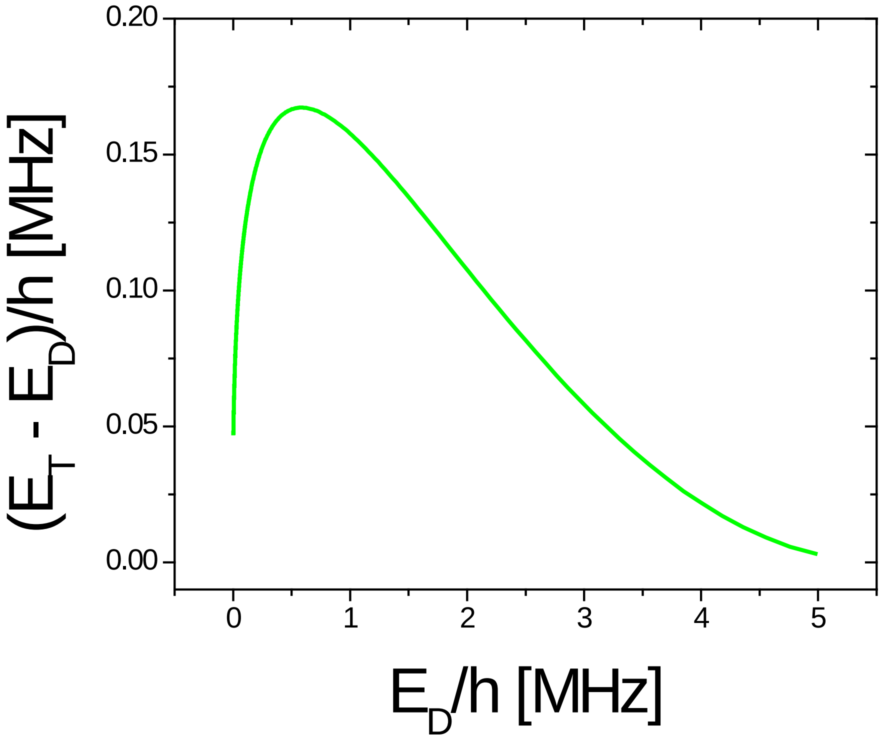
Rf association of Efimov trimers

Free-atoms to trimer transition?



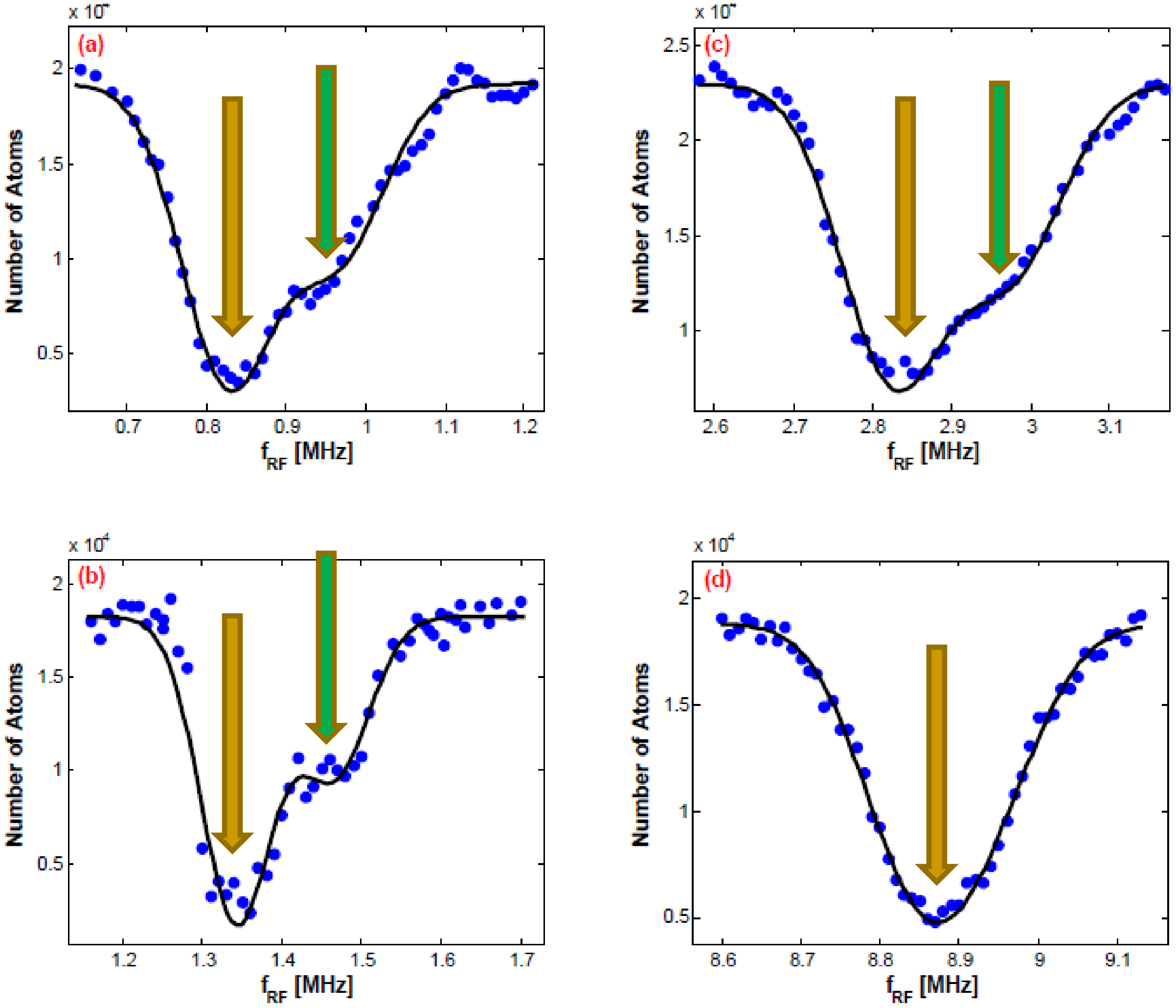
Energy levels

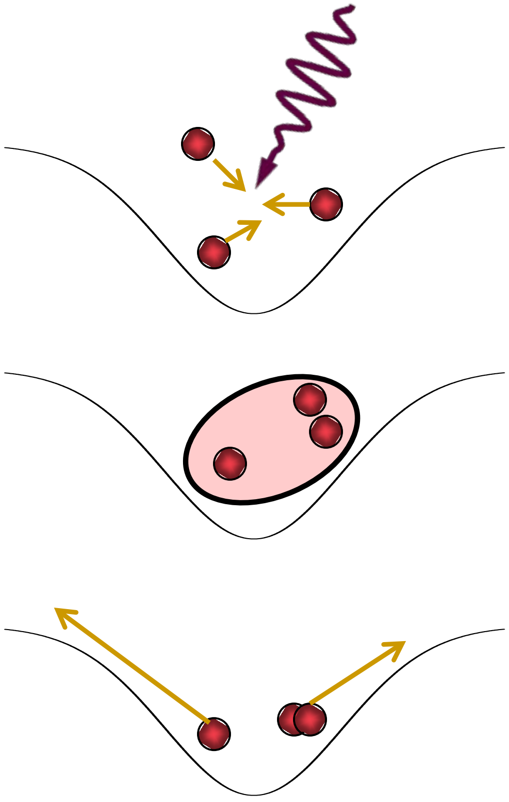




Rf scans

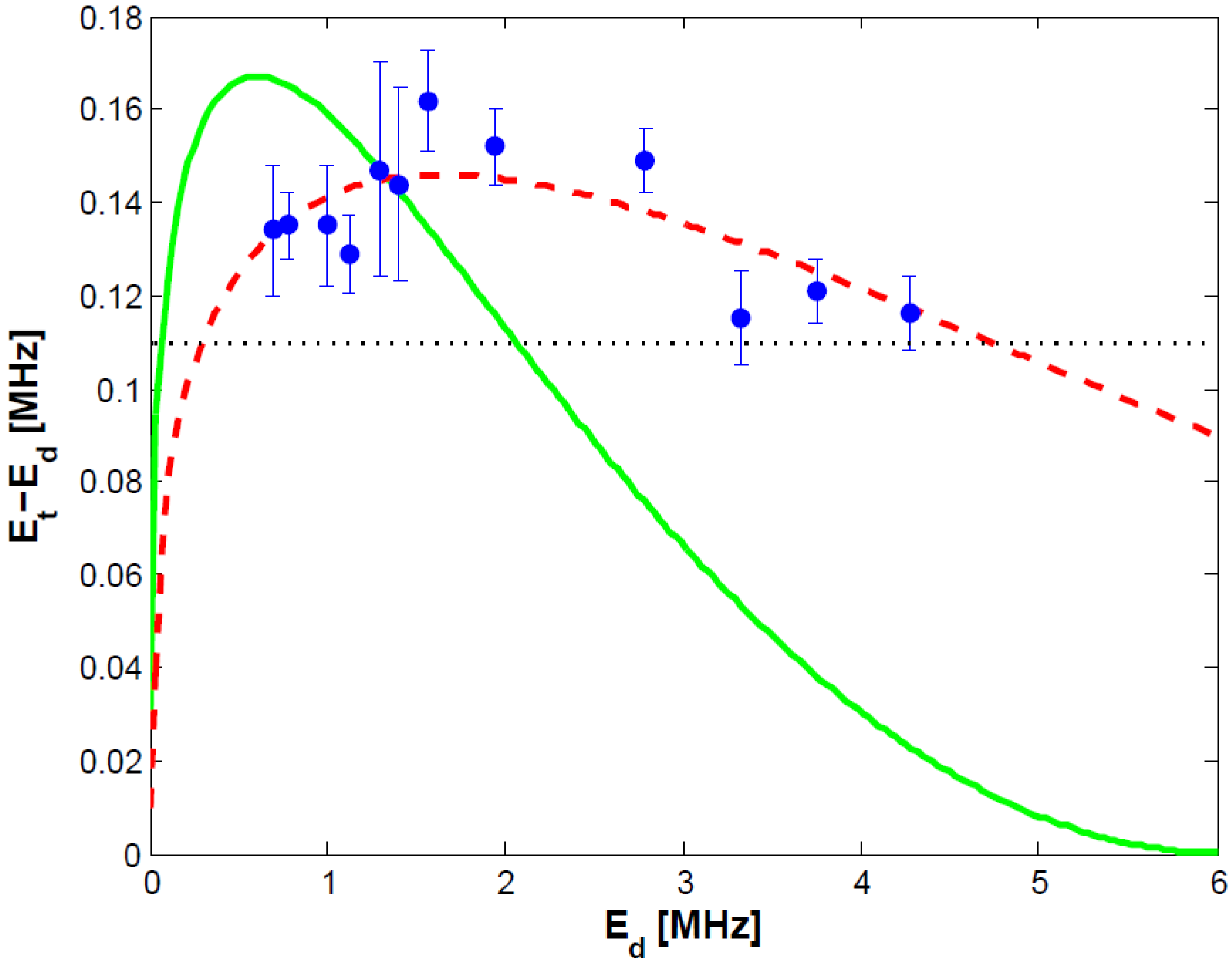
Remaining atoms after rf-pulse at different magnetic fields.





O. Machtey, Z. Shotan, N. Gross and L. Khaykovich, PRL **108**, 210406 (2012)

Trimer-dimer energy difference

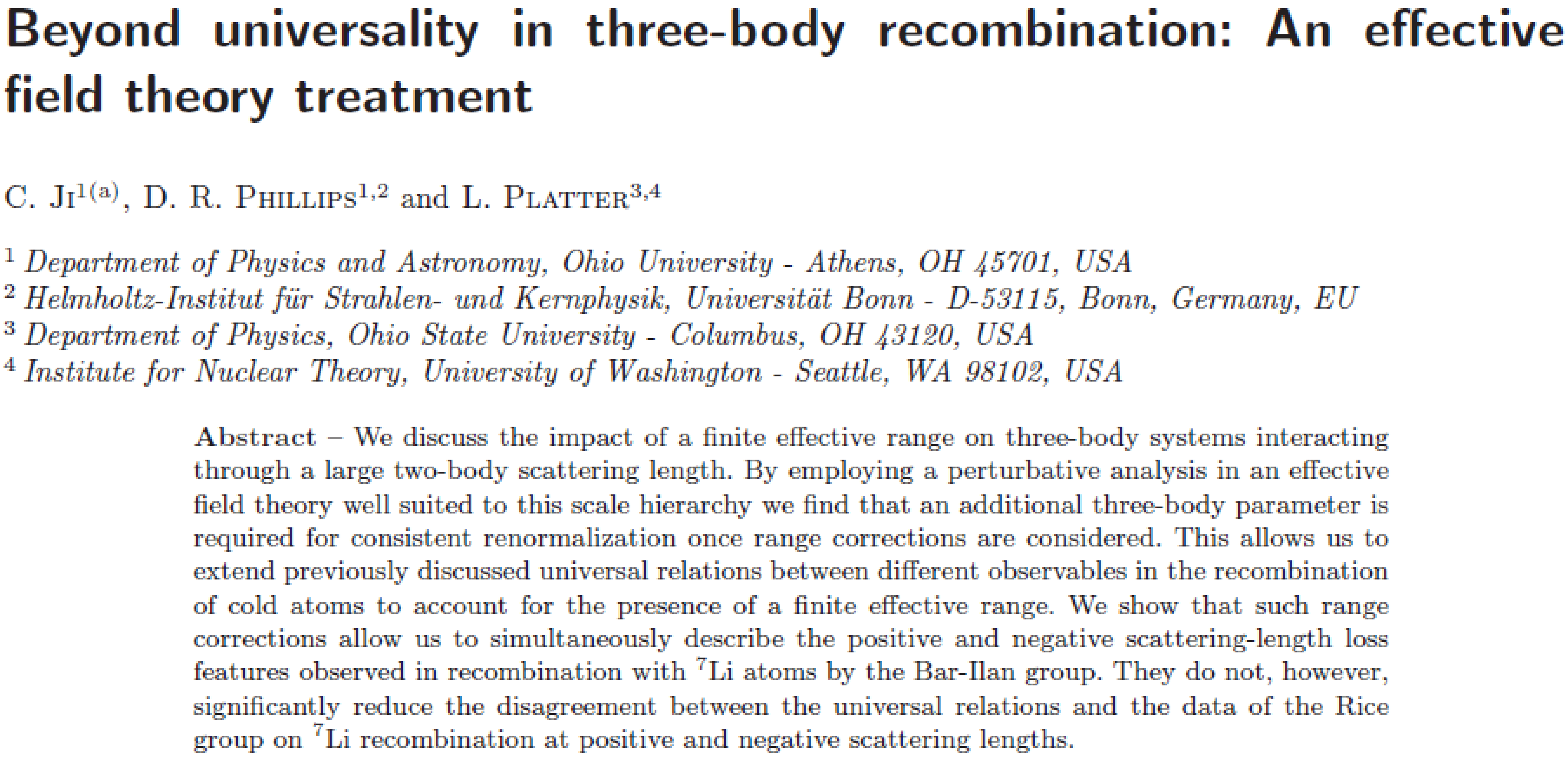


Estimation:

$a_* \sim 180 a_0$

O. Machtey, Z. Shotan, N. Gross and L. Khaykovich, PRL **108**, 210406 (2012)

Beyond universality theory



Beyond universality in three-body recombination: An effective field theory treatment

C. Ji[1(a)], D. R. Phillips[1,2] and L. Platter[3,4]

[1] *Department of Physics and Astronomy, Ohio University - Athens, OH 45701, USA*
[2] *Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn - D-53115, Bonn, Germany, EU*
[3] *Department of Physics, Ohio State University - Columbus, OH 43120, USA*
[4] *Institute for Nuclear Theory, University of Washington - Seattle, WA 98102, USA*

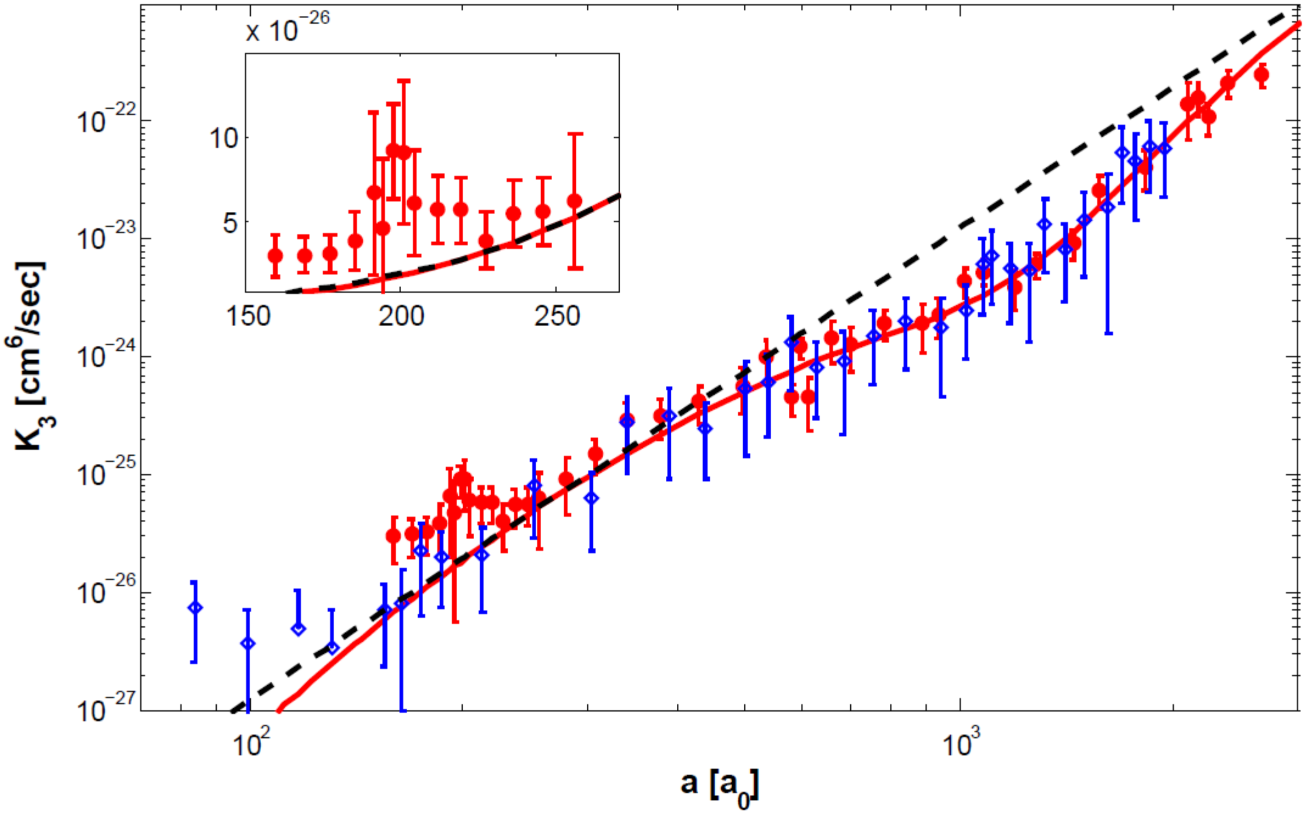
Abstract – We discuss the impact of a finite effective range on three-body systems interacting through a large two-body scattering length. By employing a perturbative analysis in an effective field theory well suited to this scale hierarchy we find that an additional three-body parameter is required for consistent renormalization once range corrections are considered. This allows us to extend previously discussed universal relations between different observables in the recombination of cold atoms to account for the presence of a finite effective range. We show that such range corrections allow us to simultaneously describe the positive and negative scattering-length loss features observed in recombination with ^{7}Li atoms by the Bar-Ilan group. They do not, however, significantly reduce the disagreement between the universal relations and the data of the Rice group on ^{7}Li recombination at positive and negative scattering lengths.

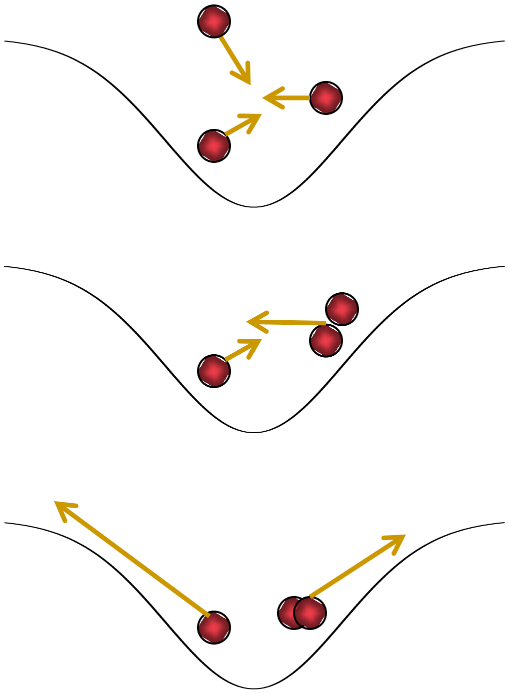
Prediction including finite effective range: $a_* = (210 \pm 44) a_B$

C. Ji, D. Phillips, L.Platter, Europhys. Lett. **92**, 13003 (2010).

3-body recombination data

Avalanche resonance.





O. Machtey, Z. Shotan, N. Gross and L. Khaykovich, PRL **108**, 210406 (2012)

Conclusions and outlook

- Ultracold atoms are extremely suitable to study few body universal physics and halo quantum states.
- Remarkable progress (experimental and theoretical) has been achieved in recent years.
- There are still many open questions to be studied.