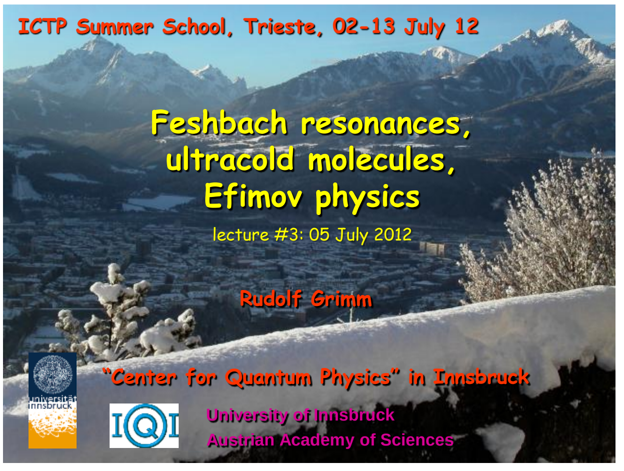


Habsburg Empire [edit]

See also: Austrian Empire and Austro-Hungarian Empire

Trieste in the 17th century, in a contemporary image by the Carniolan historian Johann Weikhard von Valvasor

After two centuries of war against the nearby major power, the Republic of Venice (which occupied it briefly from 1369 to 1372), the main citizens of Trieste petitioned Leopold III of Habsburg, Duke of Austria to become part of his domains. The agreement of cessation was signed in October 1382, in St. Bartholomew's church in the village of Šiška (*apud Sisciam*), today one of the city quarters of Ljubljana. The citizens, however, maintained a certain degree of autonomy up until the 17th century.

Following an unsuccessful Habsburg invasion of Venice in the prelude to the War of the League of Cambrai, the Venetians occupied Trieste again in 1508, and under the terms of the peace were allowed to keep the city. The Habsburg Empire recovered Trieste a little over one year later, however, when conflict resumed.

Trieste became an important port and trade hub. In 1719, it was made a free port within the Habsburg Empire by Emperor Charles VI, and remained a free port until 1 July 1891. The reign of his successor, Maria Theresa of Austria, marked the beginning of a flourishing era for the city.

In 1768, the German art historian Johann Joachim Winckelmann was murdered by a robber in Trieste, while on his way from Vienna to Italy.

Trieste was occupied by French troops three times during the Napoleonic Wars, in 1797, 1805 and in 1809. Between 1809 and 1813, it was annexed to the Illyrian Provinces, interrupting its status of free port and losing its autonomy. The municipal autonomy was not restored after the return of the city to the Austrian Empire in 1813. Following the Napoleonic Wars, Trieste continued to prosper as the Free Imperial City of Trieste (*Reichsunmittelbare Stadt Triest*), a status that granted economic freedom, but limited its political self-government. The city's role as main Austrian trading port and shipbuilding centre was later emphasized with the foundation of the merchant shipping line Austrian Lloyd in 1836, whose headquarters stood at the corner of the Piazza Grande and Sanità. By 1913 Austrian Lloyd had a fleet of 62 ships comprising a total of 236,000 tons.[6] With the introduction of the constitutionalism in the Austrian Empire in 1860, the municipal autonomy of the city was restored, with Trieste became capital of the *Adriatisches Küstenland*, the Austrian Littoral region.

The particular Friulian dialect, called *Tergestino*, spoken until the beginning of the 19th century, was gradually overcome by the Triestine dialect of Venetian (a language deriving directly from vulgar Latin) and other languages, including German grammar, Slovene and standard Italian languages. While Triestine was spoken by the largest part of the population, German was the language of the Austrian bureaucracy and Slovene was predominant in the surrounding villages. From the last decades of the 19th century, Slovene language speakers grew steadily, reaching 25% of the overall population of the municipality of Trieste in 1911 (30% of the Austro-Hungarian citizens in Trieste).[7]

The Stock Exchange Square in 1854

According to the 1911 census, the proportion of Slovene speakers amounted to 12.6% in the city center, 47.6% in the suburbs, and 90.5% in the surroundings.[8] They were the largest ethnic group in 9 of the 19 urban

42 years ago

ultracold.atoms

СЛАБОСВЯЗАННЫЕ СОСТОЯНИЯ ТРЕХ РЕЗОНАНСНО ВЗАИМОДЕЙСТВУЮЩИХ ЧАСТИЦ

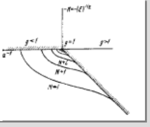
В. Н. ЕФИМОВ

ФИЗИКО-ТЕХНИЧЕСКИЙ ИНСТИТУТ им. А. Ф. ИОФФЕ АКАДЕМИИ НАУК СССР

(Поступила в редакцию 16 февраля 1970 г.)

Показано, что при достаточной резонансности парных сил у трех тождественных частиц возникает семейство связанных состояний малой энергии. Квантовые числа всех состояний одинаковы: для бесспиновых бозонов 0^+, для нуклонов $1/2^+$, $T = 1/2$. ... больше радиуса парных сил. Наиболее благоприятные условия ... уровней имеют место для трех бесспиновых нейтральных бозо- ... тные — для заряженных частиц и частиц со спином и изоспи- ... можность существования таких уровней в системе трех α-час- ... х нуклонов (H^3).

Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц. Штриховкой показана граница непрерывного спектра трех частиц. Соседние траектории уровней отличаются только преобразованием масштаба приблизительно в 22 раза. В целях наглядности это соотношение на рисунке не выдержано



42 years ago

ultracold.atoms

SOVIET JOURNAL OF NUCLEAR PHYSICS — VOLUME 12, NUMBER 5 — MAY, 1971

WEAKLY-BOUND STATES OF THREE RESONANTLY-INTERACTING PARTICLES

V. N. EFIMOV

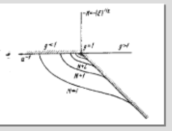
A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

Submitted February 16, 1970

Yad. Fiz. 12, 1080–1091 (November, 1970)

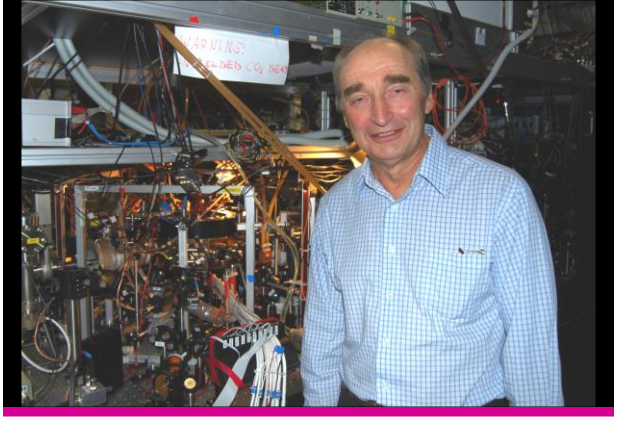
It is shown that if the pair forces of three identical particles are sufficiently resonant, a family of bound states of low energy is produced. The quantum numbers of all the states are the same: for ... leons $1/2^+$, T = 1/2. The dimension of the states is larger than the ... most favorable conditions for the appearance of a family of levels ... al bosons: the conditions are less favorable for charged particles ... spin. The possibility of existence of such levels in a system of three ... and of three nucleons (H^3) is considered.

FIG. 1. Level spectrum of three spinless neutral particles. The cross hatching denotes the boundary of the continuous spectrum of the three particles. Neighboring level trajectories differ only in a scale transformation by an approximate factor of 22. For clarity, this ratio is not maintained in the figure.



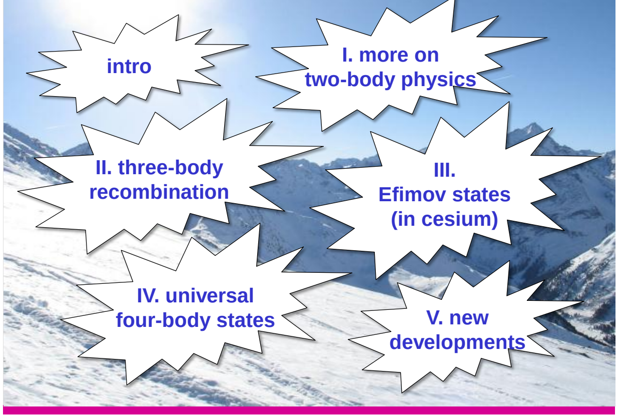
Vitaly Efimov visiting Innsbruck, 23 Oct 2009

ultracold.atoms



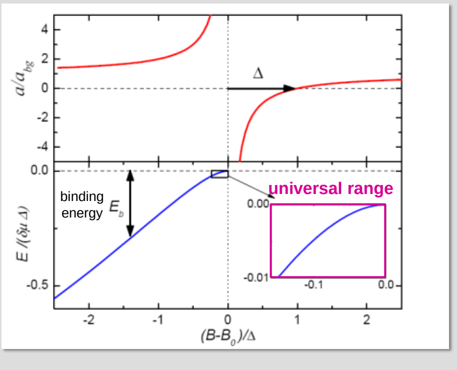
what you will here in this lecture

ultracold.atoms



I. More on two-body physics

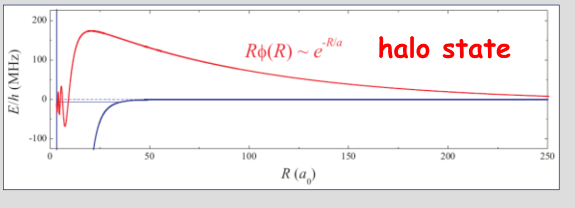
ultracold.atoms



Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

two-body universality

ultracold.atoms



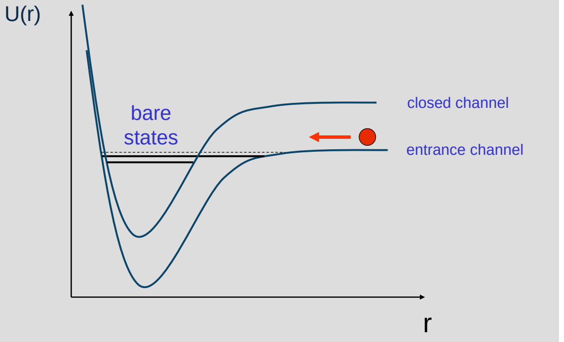
universal relation between scattering length and binding energy

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

<u>one</u> parameter tells you everything!

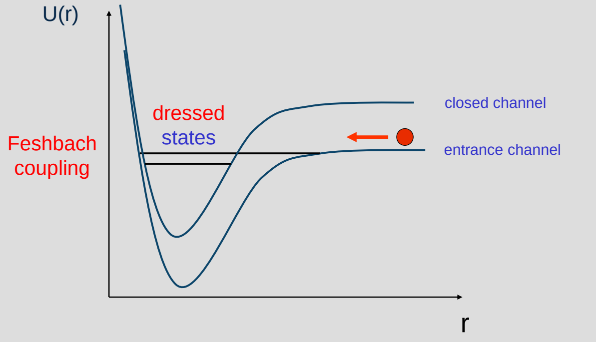
Feshbach physics in universal range

ultracold.atoms



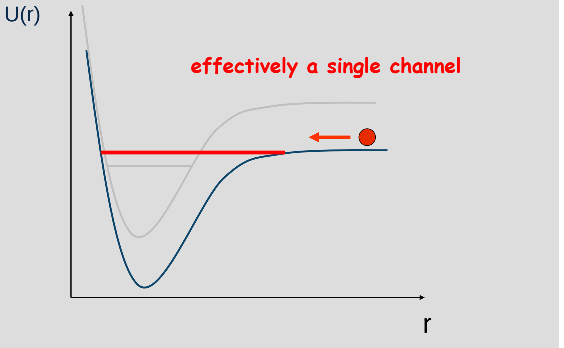
Feshbach physics in universal range

ultracold.atoms



Feshbach physics in universal range

ultracold.atoms



"broad" Feshbach resonances

ultracold.atoms

large universal range found for
"entrance-channel dominated resonances"
(often referred to as "broad" resonances)

what kind of resonances are strong ("broad") ?

resonance strength

ultracold.atoms

see review on Feshbach resonances
Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

mean scattering length of vdW potential; differential magnetic moment

strength parameter
$$s_{\rm res} = \frac{m\bar{a}}{\hbar^2}\,\delta\mu\, a_{\rm bg}\,\Delta$$

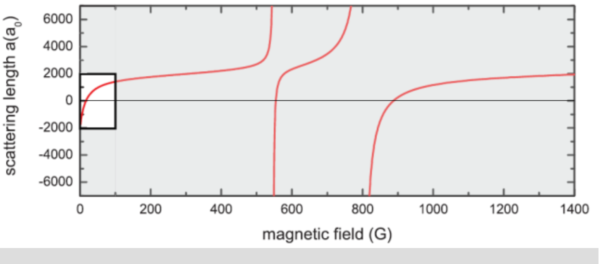
$$R^* = \bar{a}/s_{\rm res}$$
relation to Petrov parameter

entrance-channel dominated character (s_{res} >>1)
usually found for FRs with
- large background scattering length
- large width

magnetic tunability of Cs

ultracold.atoms

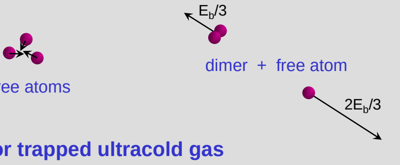
<u>three</u> broad *s*-wave FRs



plus many d- and g-wave FRs (not shown)

III. Three-body recombination

elementary process



consequences for trapped ultracold gas

large E_b / U_{trap} (for negative and moderately pos. scatt. length)

→ immediate loss of recombination products

small E_b / U_{trap} (for large positive scattering length !)

→ special situation

atom remains in trap, deposits energy into sample

dimer remains in trap, but lost by inelastic collisions with atoms

three-body recomb. theory basics

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

L_3: three-body loss coefficient [cm^6/s]

dimensional analysis

$$L_3 = 3\,C\,\frac{\hbar}{m}\,a^4$$

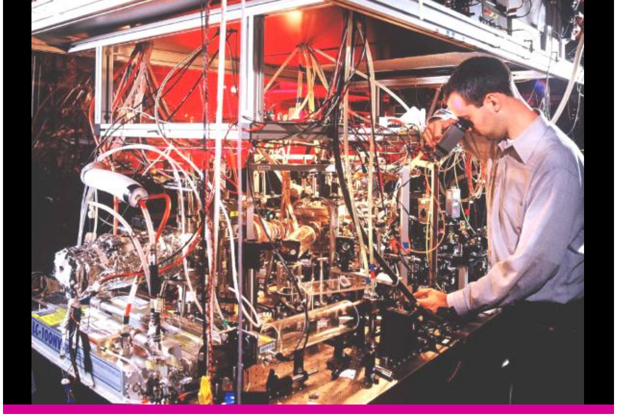
dimensionless

a^4 - scaling ! very strong dependence on scattering length

valid if a exceeds all other length scales
(vdW length of molecular potential, typ. 30 – 100a_0)

early theory paper:
Fedichev *et al.*, PRL **77**, 2921 (1996)
a^4 scaling with C = 3.9

Innsbruck Cs lab



loss and heating curves

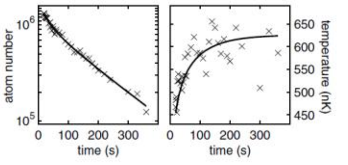


FIG. 2. Atom number and temperature as a function of time in the trap at a bias field of 56 G. The solid lines show a numerical fit to the data. The corresponding three-body loss coefficient is $L_3 = 7(2) \times 10^{-25}$ cm^6/s.

Weber et al., PRL **91**,123201 (2003)

$$\frac{dN}{dt} = -\alpha N - \gamma\frac{N^3}{T^3} \qquad \frac{dT}{dt} = \gamma\frac{N^2}{T^3}\frac{(T+T_h)}{3}$$

measured N(t) and T(t) → 3-parameter fit yields **α, $\gamma \sim L_3$, T_h**

three-body loss vs. magnetic field

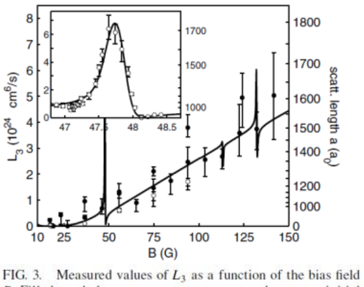


FIG. 3. Measured values of L_3 as a function of the bias field B. Filled symbols represent measurements taken at an initial temperature of 200 nK, open symbols at 450 nK. The solid line shows the calculation according to Eq. (1) with $n_l C = 225$. The scale on the right-hand side displays the corresponding scattering length values. The inset shows the region around the 48 G resonance with a model fit (see text).

Weber et al., PRL **91**,123201 (2003)

verification of general a^4-scaling

$$L_3 = n_l C\,\frac{\hbar}{m}\,a^4$$

fit yields **225**
(too large ?)

is a^4-scaling the whole story?

n_l – number of atoms lost per recombination event

often n_l=3, but not always!
can vary between 2 and 4,
in some special cases even larger

$$L_3 = n_l C \frac{\hbar}{m} a^4$$

dimensionless, but not necessarily constant !
C(a) reveals very interesting physics

Nielsen & Macek, PRL 83, 1566 (1999)
Esry et al., PRL 83, 1751 (1999)
Bedaque et al., PRL 85, 908 (2000)
Braaten & Hammer, PRL 87, 160407 (2001)

a>0:
C(a) upper limit ~70

log-periodic behavior

C(22.7 a) = C(a)

three-body physics shows
log-periodic behavior with a
discrete **scaling factor of 22.7**

smells as if there is something interesting behind it !

effective field theory for C(a)

valid for large |a|

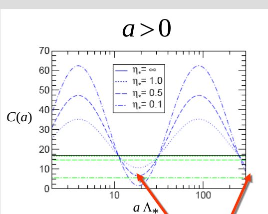
Braaten and Hammer, Phys. Rep. **428**, 259 (2006)

loss into shallow dimer

$$C(a) = 67.1\, e^{-2\eta_*}\left(\cos^2(s_0 \ln(a\Lambda_*) + 1.76) + \sinh^2 \eta_*\right) + 16.8\,(1 - e^{-4\eta_*})$$

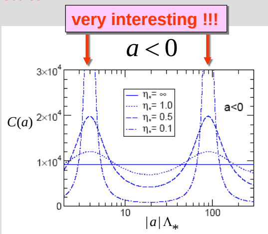
loss into deeply bound molecules

$$C(a) = \frac{4590 \sinh(2\eta_*)}{\sin^2(s_0 \ln(|a|\Lambda_*) + 1.72) + \sinh^2 \eta_*}$$



very interesting !!!

very interesting !!!



III. Efimov states

SOVIET JOURNAL OF NUCLEAR PHYSICS VOLUME 12, NUMBER 5 MAY, 1971

WEAKLY-BOUND STATES OF THREE RESONANTLY-INTERACTING PARTICLES

V. N. EFIMOV
A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

Submitted February 16, 1970
Yad. Fiz. 12, 1080–1091 (November, 1970)

It is shown that if the pair forces of three identical particles are sufficiently resonant, a family of bound states of low energy is produced. The quantum numbers of all the states are the same: for ...leons $^3\!/_2{}^+$, T = $^1\!/_2$. The dimension of the states is larger than the ... most favorable conditions for the appearance of a family of levels ...al bosons: the conditions are less favorable for charged particles ...spin. The possibility of existence of such levels in a system of three ...and of three nucleons (H^3) is considered.

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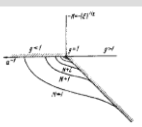
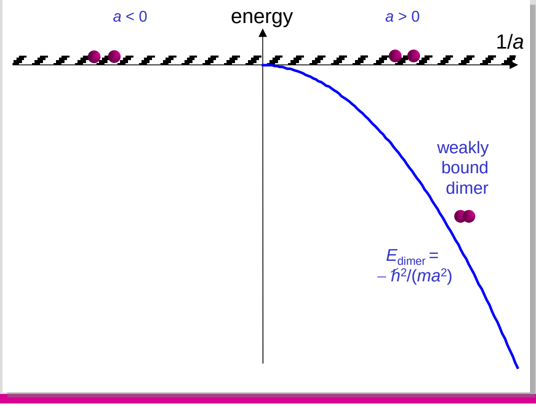
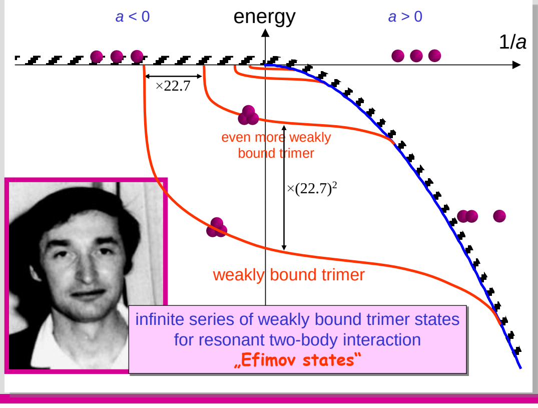
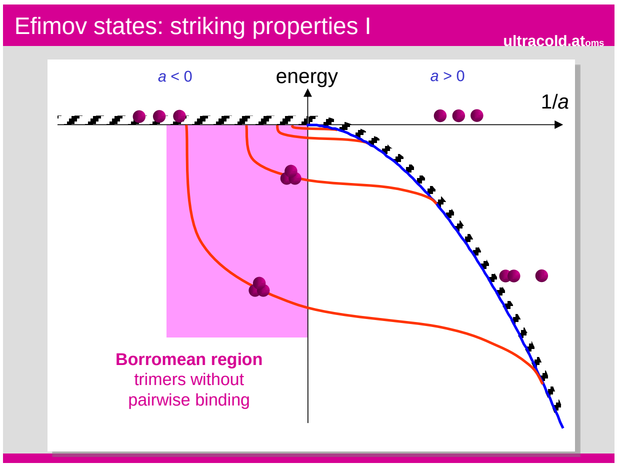


quantum states near two-body resonance



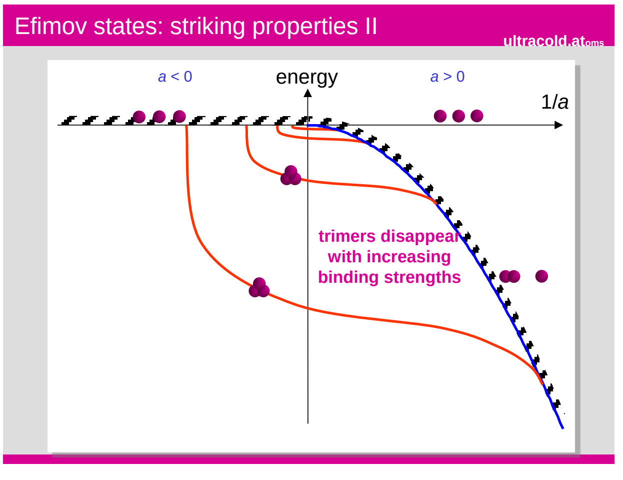
quantum states near two-body resonance



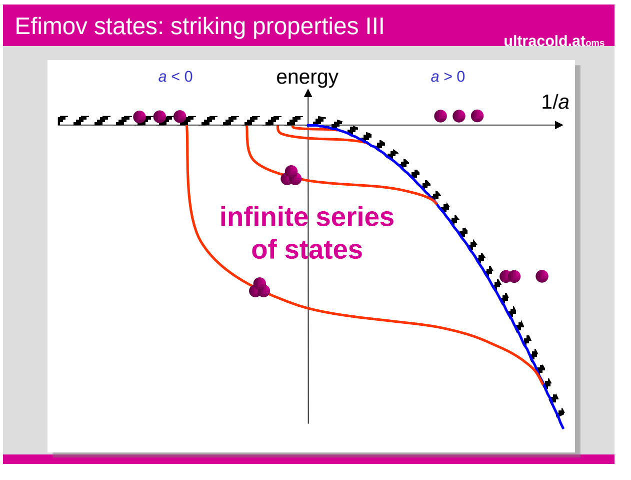


Efimov states: striking properties I
ultracold.atoms
a < 0
energy
a > 0
1/a
Borromean region
trimers without
pairwise binding

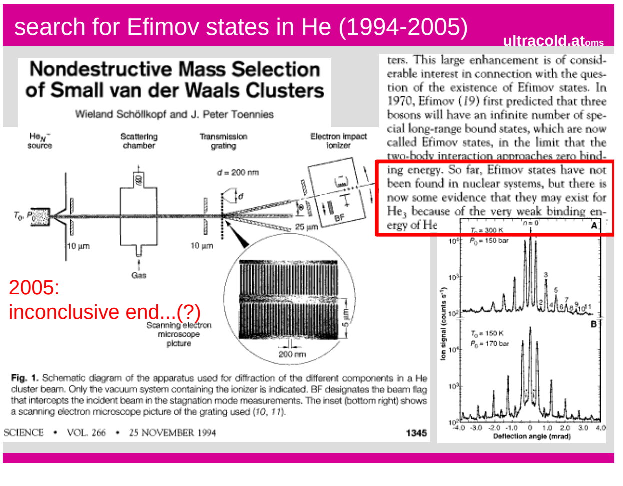
ultracold.atoms
Borromean rings
(symbol of Borromeo family, Northern Italy)



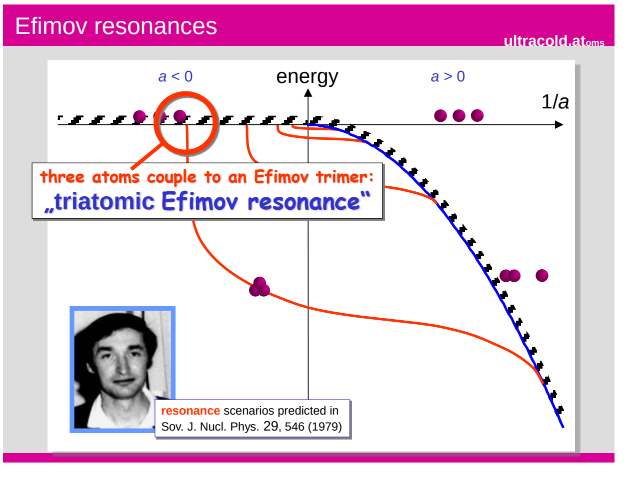
Efimov states: striking properties II
ultracold.atoms
a < 0
energy
a > 0
1/a
trimers disappear
with increasing
binding strengths



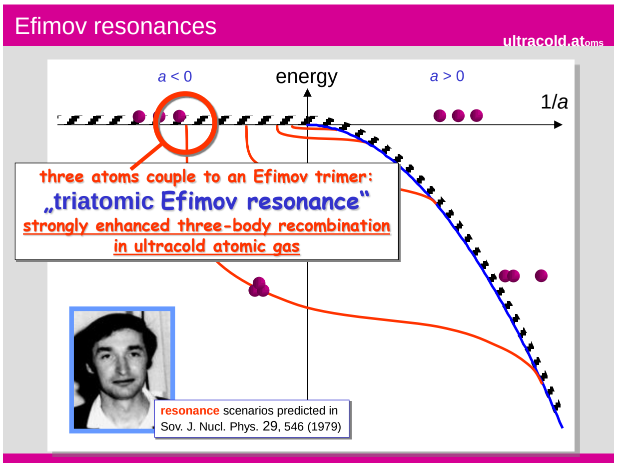
Efimov states: striking properties III
ultracold.atoms
a < 0
energy
a > 0
1/a
infinite series
of states

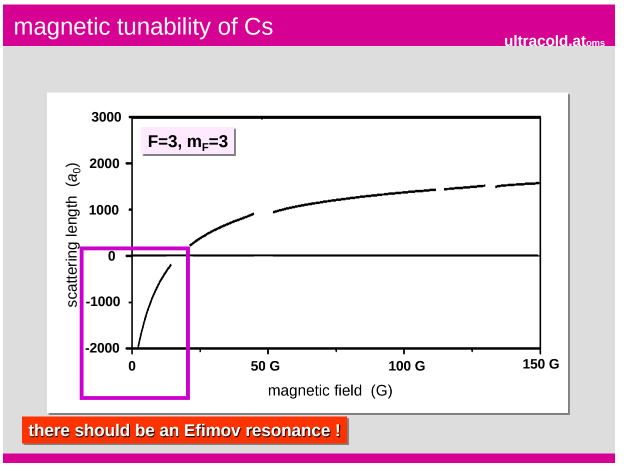


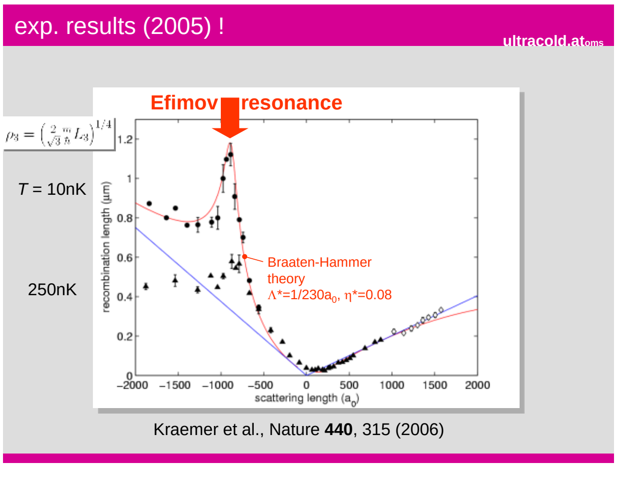
search for Efimov states in He (1994-2005)
ultracold.atoms
Nondestructive Mass Selection of Small van der Waals Clusters
Wieland Schöllkopf and J. Peter Toennies
ters. This large enhancement is of considerable interest in connection with the question of the existence of Efimov states. In 1970, Efimov (19) first predicted that three bosons will have an infinite number of special long-range bound states, which are now called Efimov states, in the limit that the two-body interaction approaches zero binding energy. So far, Efimov states have not been found in nuclear systems, but there is now some evidence that they may exist for He_3 because of the very weak binding energy of He
He_N^- source
Scattering chamber
Transmission grating
Electron impact ionizer
d = 200 nm
10 µm
10 µm
25 µm
BF
Gas
Scanning electron microscope picture
200 nm
5 µm
2005:
inconclusive end...(?)
Fig. 1. Schematic diagram of the apparatus used for diffraction of the different components in a He cluster beam. Only the vacuum system containing the ionizer is indicated. BF designates the beam flag that intercepts the incident beam in the stagnation mode measurements. The inset (bottom right) shows a scanning electron microscope picture of the grating used (10, 11).
SCIENCE • VOL. 266 • 25 NOVEMBER 1994
1345
T_0 = 300 K
P_0 = 150 bar
T_0 = 150 K
P_0 = 170 bar
Ion signal (counts s⁻¹)
Deflection angle (mrad)

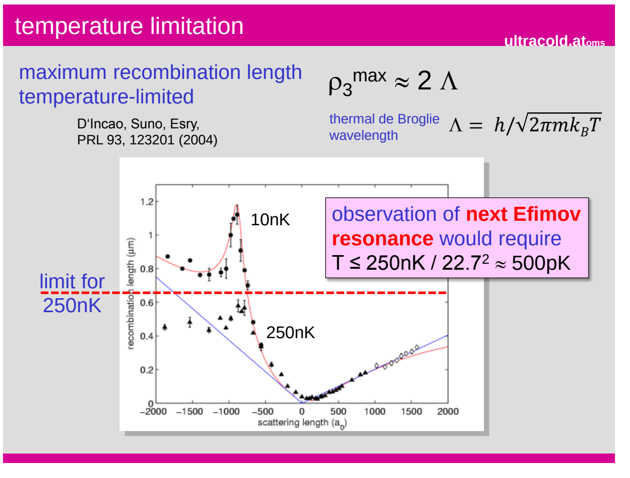


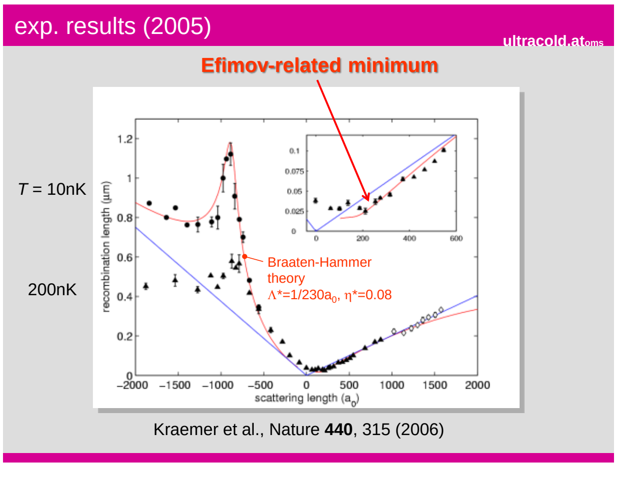
Efimov resonances
ultracold.atoms
a < 0
energy
a > 0
1/a
three atoms couple to an Efimov trimer:
„triatomic Efimov resonance"
resonance scenarios predicted in
Sov. J. Nucl. Phys. 29, 546 (1979)

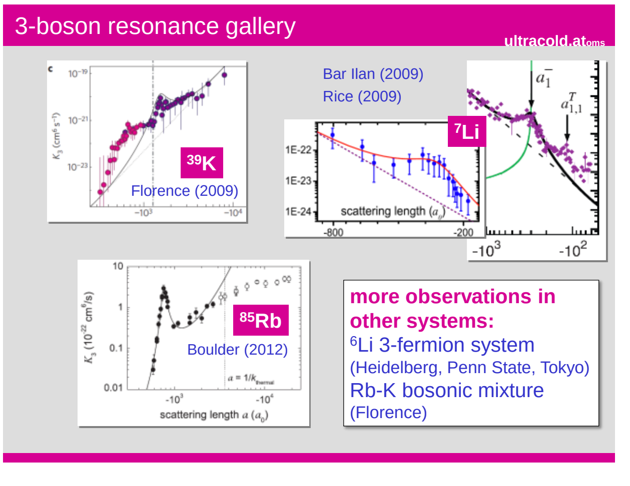

Efimov resonances
ultracold.atoms
a < 0
energy
a > 0
1/a
three atoms couple to an Efimov trimer:
„triatomic Efimov resonance"
strongly enhanced three-body recombination
in ultracold atomic gas
resonance scenarios predicted in
Sov. J. Nucl. Phys. 29, 546 (1979)


magnetic tunability of Cs
ultracold.atoms
F=3, m_F=3
scattering length (a0)
3000
2000
1000
0
-1000
-2000
0
50 G
100 G
150 G
magnetic field (G)
there should be an Efimov resonance !


exp. results (2005) !
ultracold.atoms
Efimov resonance
T = 10nK
250nK
recombination length (μm)
Braaten-Hammer
theory
Λ*=1/230a0, η*=0.08
scattering length (a0)
Kraemer et al., Nature 440, 315 (2006)

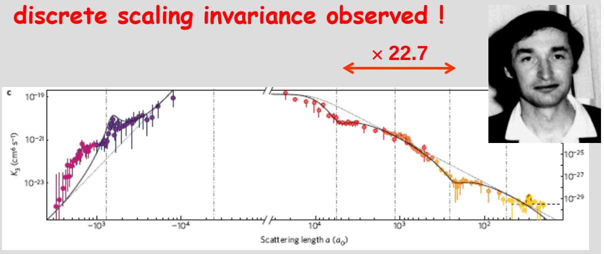

temperature limitation
ultracold.atoms
maximum recombination length
temperature-limited
D'Incao, Suno, Esry,
PRL 93, 123201 (2004)
ρ3max ≈ 2 Λ
thermal de Broglie
wavelength
Λ = h/√(2πmkBT)
10nK
observation of next Efimov resonance would require
T ≤ 250nK / 22.7² ≈ 500pK
limit for
250nK
250nK
recombination length (μm)
scattering length (a0)


exp. results (2005)
ultracold.atoms
Efimov-related minimum
T = 10nK
200nK
recombination length (μm)
Braaten-Hammer
theory
Λ*=1/230a0, η*=0.08
scattering length (a0)
Kraemer et al., Nature 440, 315 (2006)


3-boson resonance gallery
ultracold.atoms
39K
Florence (2009)
Bar Ilan (2009)
Rice (2009)
7Li
scattering length (a0)
85Rb
Boulder (2012)
scattering length a (a0)
more observations in
other systems:
6Li 3-fermion system
(Heidelberg, Penn State, Tokyo)
Rb-K bosonic mixture
(Florence)

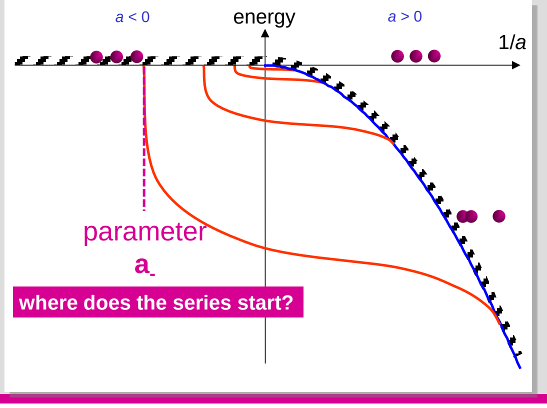
^{39}K experiments in Florence ultracold.atoms

discrete scaling invariance observed !



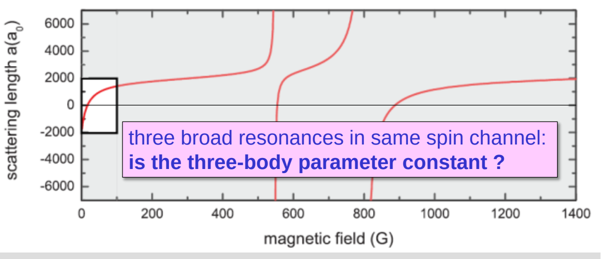
Zaccanti et al., Nature Phys. **5**, 586 (2009)

three-body parameter ultracold.atoms

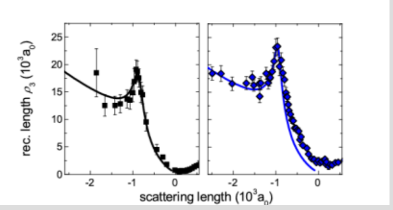


magnetic tunability of Cs (high-field range) ultracold.atoms

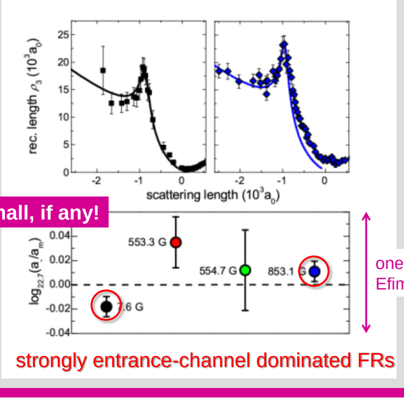
three broad s-wave FRs



variations of the three-body parameter? ultracold.atoms



variations of the three-body parameter? ultracold.atoms

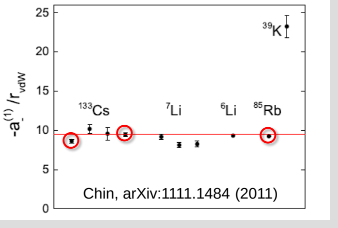


can this be an accidental coincidence? ultracold.atoms

experiments on **^{6}Li, ^{7}Li, ^{85}Rb, ^{133}Cs** show

$a_- \approx -9\, R_{vdW}$ $\quad R_{vdW} = \frac{1}{2}\left(\frac{2\mu C_6}{\hbar^2}\right)^{1/4}$

van der Waals length



only ^{39}K does not fit into the picture...
... quite interesting, indeed!

three answers from theory

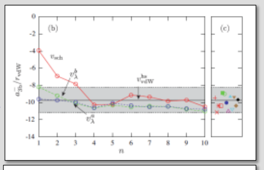
Chin, **arXiv:1111.1484**

"quantum reflection of the Efimov wavefunction"

analytical model:
$|a_-|/R_{vdW} = 9.48$

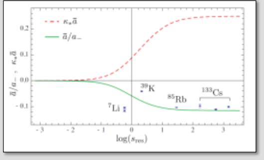
Wang, D'Incao, Esry, Greene,
arXiv:1201.1176

"A sharp cliff of attraction in the two-body interactions produces a strongly repulsive universal barrier in the effective three-body interaction potential."



Schmidt, Rath, Zwerger,
arXiv:1201.4310

solution of a two-channel model incl. character of the Feshbach resonance (open vs. close-channel dominated)



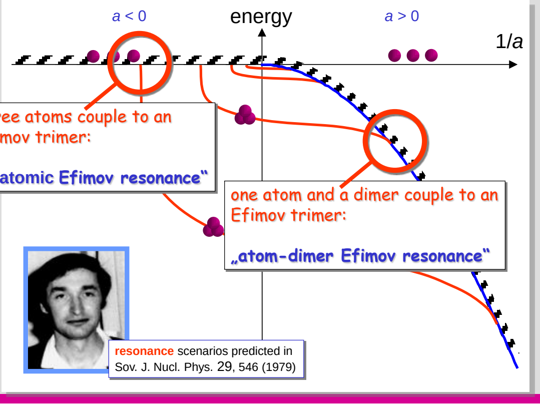
conclusions on 3BP

"3BP universality"

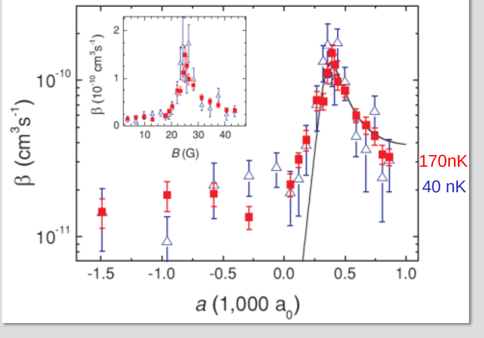
exists for interacting atoms with vdW potentials
(not for other particles, like nuclei)
and entrance-channel dominated resonances (^{133}Cs, ^{85}Rb)

situation of intermediate cases (^{39}K, ^{7}Li) still needs more investigations

Efimov resonances



atom-dimer "Efimov" resonance



Knoop et al., Nature Phys. **5**, 227 (2009)

new insights from theory

Hammer and Platter, EPJA **32**,113 (2007)

conjecture of two universal four-body states attached to an Efimov state

von Stecher, D'Incao, and Greene
Nature Phys. 5, 417 (2009)

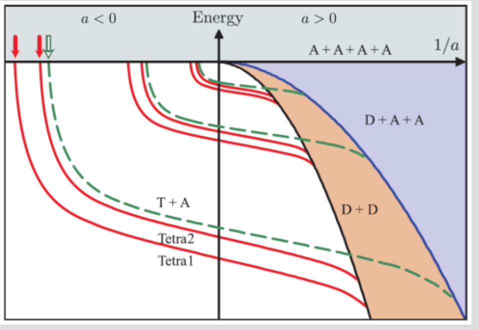
confirmation and extension of Hammer-Platter conjecture

prediction of universal relations

suggesting 4-body recombination as a probe

extended Efimov scenario (4 bosons)

ultracold.atoms



Efimov states and **universal 4-body states**

Hammer and Platter, EPJA (2007)

von Stecher, D'Incao, and Greene, Nature Phys. (2009)

trios and quartetts

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http://www.musik-base.de/images/groups/Alpentrio-Tirol.jpg

http://www.volksmusikfan.com/var/.../Alpentrio-Tirol_fullscreen.jpg

where do the 4-body resonances occur?

ultracold.atoms

universal predictions

$$a^*_{4b1} \approx 0.43 a^*_{3b}\,, \quad \text{and} \quad a^*_{4b2} \approx 0.90 a^*_{3b}\,.$$

von Stecher, D'Incao, Greene, Nature Phys. 5, 417 (2009)

-375 a_0 **-783 a_0**

expectations for Cs

(3-body resonance at -870(20) a_0)

exp. results revisited by C. Greene et al. (2008)

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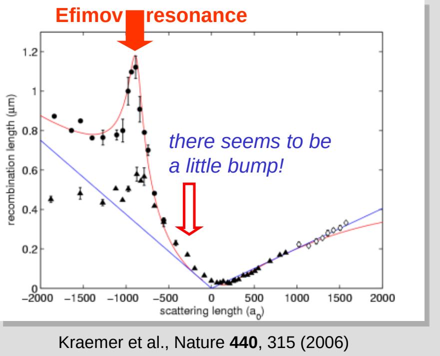
T = 10nK

200nK



Kraemer et al., Nature **440**, 315 (2006)

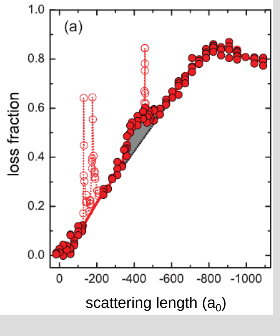
new set of experiments

ultracold.atoms

prepare sample very close to BEC

Ferlaino et al., PRL **102**, 140401 (2009)

T = 50nK, hold time 250ms



new set of experiments

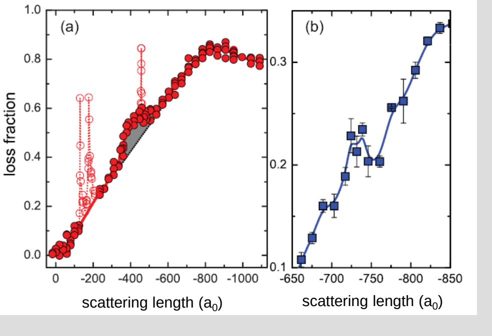
ultracold.atoms

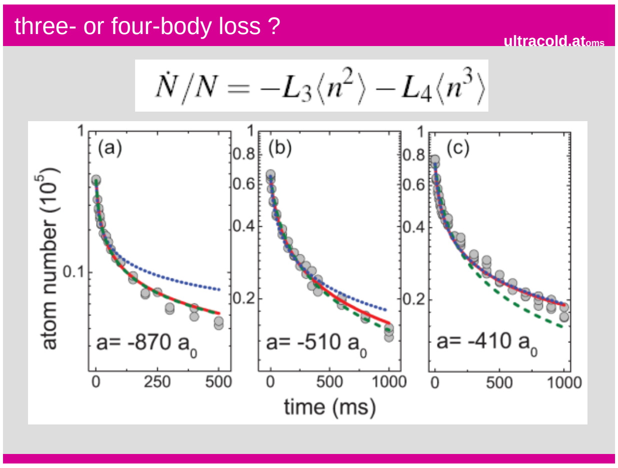
prepare sample very close to BEC

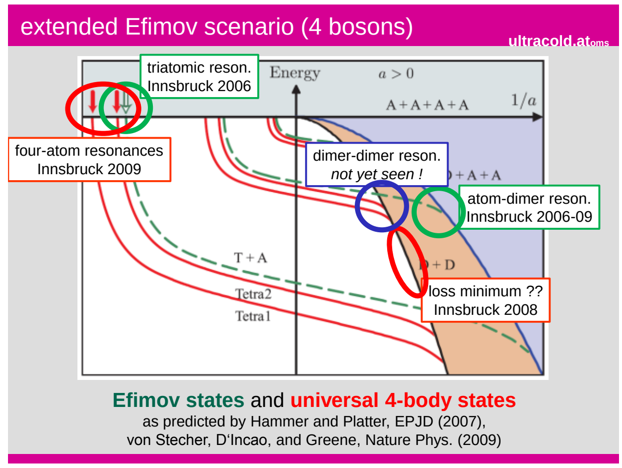
Ferlaino et al., PRL **102**, 140401 (2009)

T = 50nK, hold time 250ms

T = 30nK, hold time 8ms




three- or four-body loss ?
ultracold.atoms
$\dot{N}/N = -L_3\langle n^2\rangle - L_4\langle n^3\rangle$
atom number (10^5)
(a)
(b)
(c)
a= -870 a_0
a= -510 a_0
a= -410 a_0
time (ms)


extended Efimov scenario (4 bosons)
ultracold.atoms
triatomic reson. Innsbruck 2006
four-atom resonances Innsbruck 2009
dimer-dimer reson. not yet seen !
atom-dimer reson. Innsbruck 2006-09
loss minimum ?? Innsbruck 2008
Energy
$a > 0$
$1/a$
A+A+A+A
T+A
Tetra2
Tetra1
Efimov states and universal 4-body states
as predicted by Hammer and Platter, EPJD (2007),
von Stecher, D'Incao, and Greene, Nature Phys. (2009)


4


5


6


7

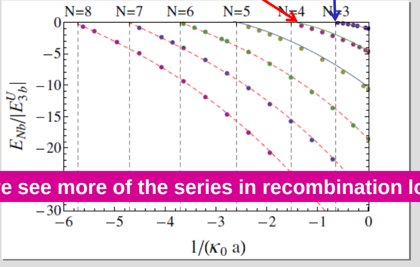
prediction of bosonic cluster states

ultracold.atoms

J. von Stecher, JPB 43, 101002 (2010)

universal four-body state (expt. confirmed, 2009)

Efimov state (expt. confirmed, 2005)



only ground states shown

can we see more of the series in recombination loss?

5-body recombination

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Resonant Five-Body Recombination in an Ultracold Gas

A. Zenesini, B. Huang, M. Berninger, S. Besler, H.-C. Nägerl, F. Ferlaino, and R. Grimm
Institut für Experimentalphysik and Zentrum für Quantenphysik, Universität Innsbruck, and Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria

Chris H. Greene and J. von Stecher*
Department of Physics and JILA, University of Colorado, Boulder, CO 80309, USA

(Dated: May 10, 2012)

arXiv:1205.1921

We combine theory and experiment to investigate five-body recombination in an ultracold gas of atomic cesium. A refined theoretical model, in combination with extensive laboratory tunability of the scattering length, enables the five-body resonant recombination rate to be calculated and measured. The position of the new observed recombination maximum agrees with a recent theoretical prediction and strongly supports the prediction of a family of universal cluster states tied to an Efimov trimer.

very challenging for <u>both</u> theory and experiment

N>4 not tractable with standard numerical tools

background from 3- and 4-body processes

encouraging observations at <u>high</u> B-fields

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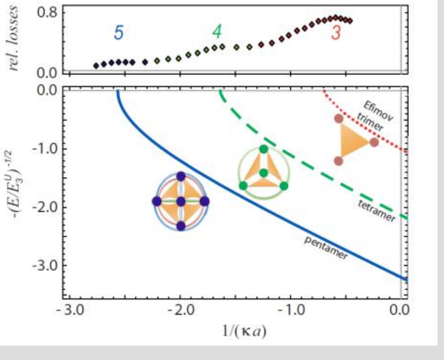

loss rate equations

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sum of all losses (L_1=L_2=0)

$$\dot{\mathcal{N}}/\mathcal{N} = -\sum_{N=1}^{+\infty} L_N \langle n^{N-1}\rangle,$$

$$\dot{T}/T = \sum_{N=1}^{+\infty} \varepsilon_N L_N \langle n^{N-1}\rangle,$$

anti-evaporation heating $2\varepsilon_N \equiv 1 - 1/N$

our expt. L_1=L_2=0, L_3 from eff. field theory

strong evidence for 5-body state

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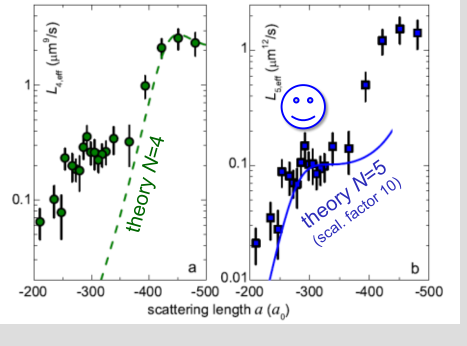

N>5 ?

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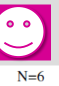
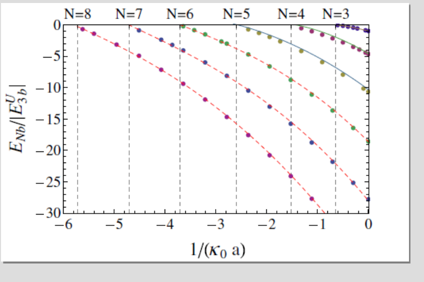
enough confidence to trust in theory



observations in Cs
2009
2012 2005/6



outlook

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reduced dimensionality (optical lattices) ←→ heteronuclear mixtures

mixed-D

some new directions

strong dipolar interactions

our first step into low-D

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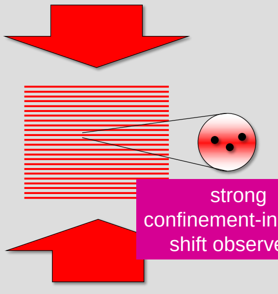
1D lattice



strong confinement-induced shift observed !

lattice depth $35E_{rec}$

harm. osc. length $\mathbf{a_{ho} = 1350\ a_0}$

extreme heavy-light mixtures

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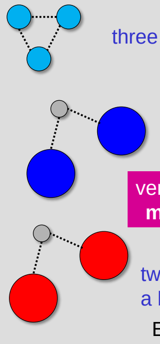


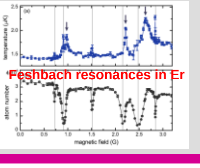
three bosons: Efimov factor 22.7

two *bosons* and a boson/fermion   Efimov factor ≈4

very interesting for experimental realizations:
mixtures of Li with lanthanides (Er,Dy...)

two *fermions* and a boson/fermion

Efimov factor ≈8



Innsbruck few-body team

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