The heteronuclear Efimov scenario in an ultracold Bose-Fermi mixture

**Juris Ulmanis,
Stephan Häfner,
Rico Pires, Eva Kuhnle,
and Matthias Weidemüller**

http://physi.uni-heidelberg.de/Forschung/QD

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HEFEI NATIONAL LABORATORY
FOR PHYSICAL SCIENCES
AT THE MICROSCALE

Efimov's scenario

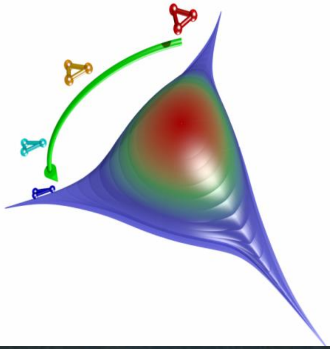
ENERGY LEVELS ARISING FROM RESONANT TWO-BODY FORCES IN A THREE-BODY SYSTEM

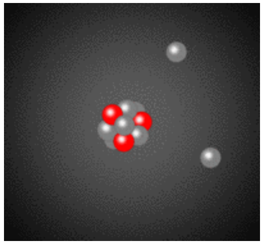
V. EFIMOV
A.F.Ioffe Physico-Technical Institute, Leningrad, USSR

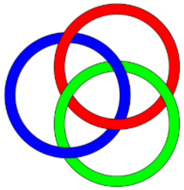
Received 20 October 1970

Resonant two-body forces are shown to give rise to a series of levels in three-particle systems. The number of such levels may be very large. Possibility of the existence of such levels in systems of three α-particles (^{12}C nucleus) and three nucleons (^{3}H) is discussed.

Phys. Lett. B **33**, 563–564 (1970)





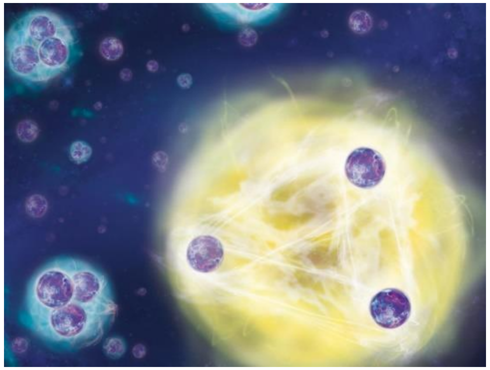


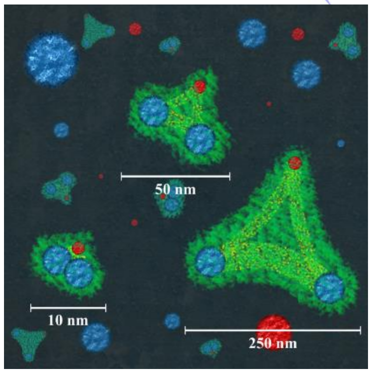
universal trimers with relevance for

nuclear physics

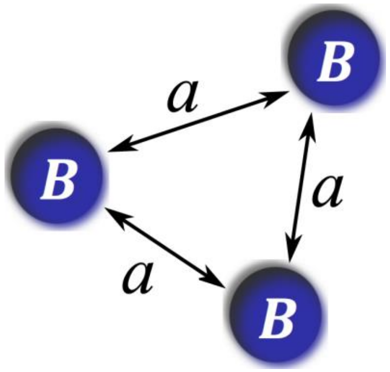
molecular physics

atomic physics





Efimov's scenario



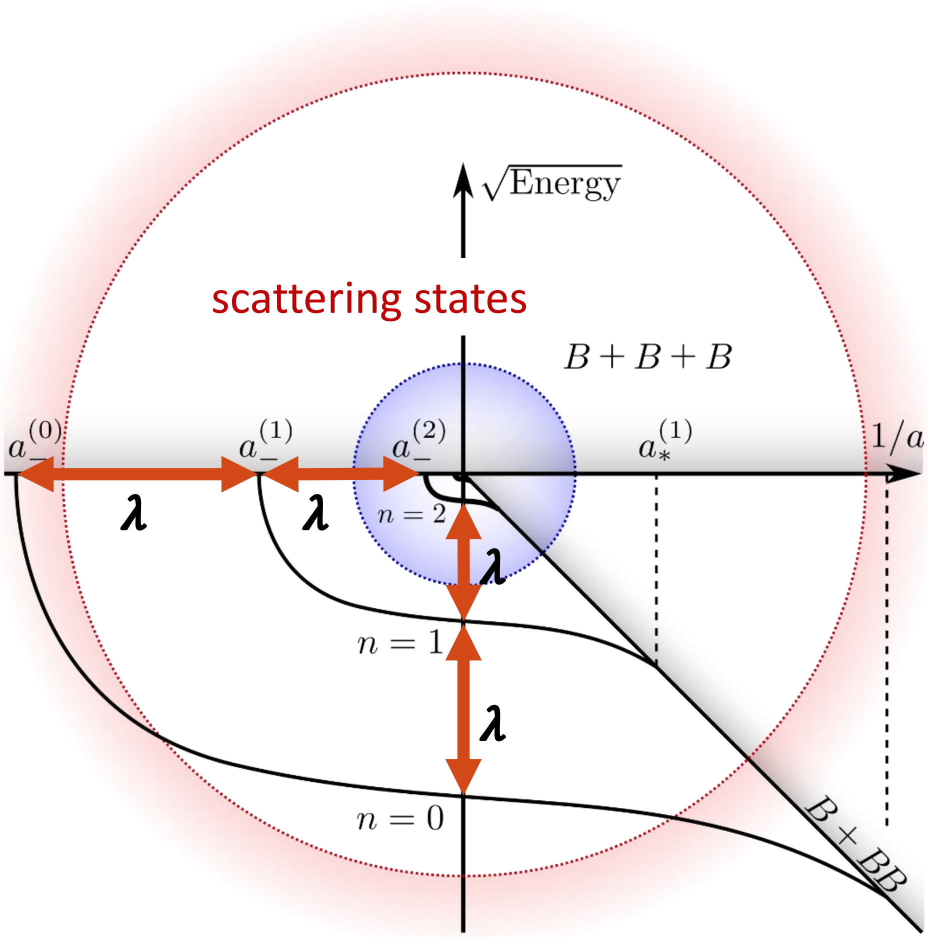
$a \to \pm\infty \qquad a \gg r_0$

$\lambda = 22.7$

effective $1/R^2$ potential
- infinite number of bound states
- discrete scaling symmetry

$$\psi_n(R) = \psi_{n-1}(\lambda R)$$

$$E_n = \lambda^{-2} E_{n-1}$$



***1/a* < 0:**
only trimers

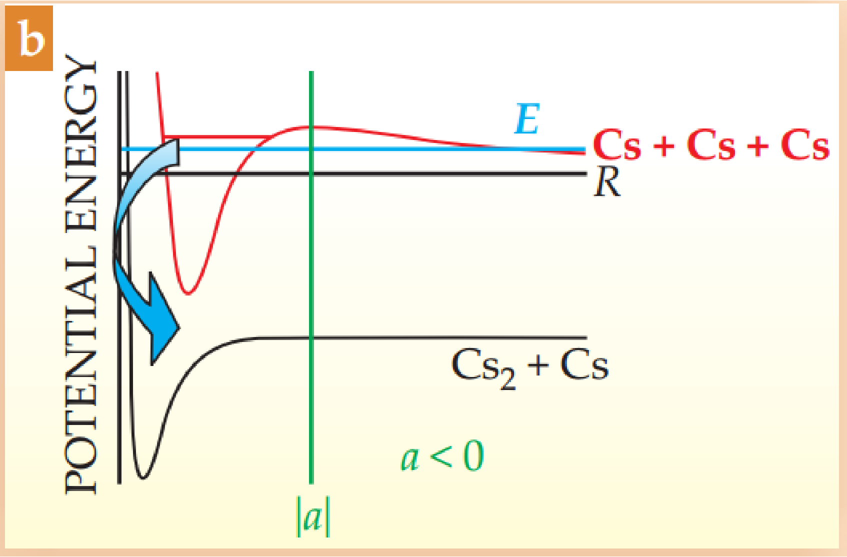
***1/a* > 0:**
universal threshold *BB*+*B*

Experimental observation in ultracold gases

Universal insights from few-body land

Chris H. Greene

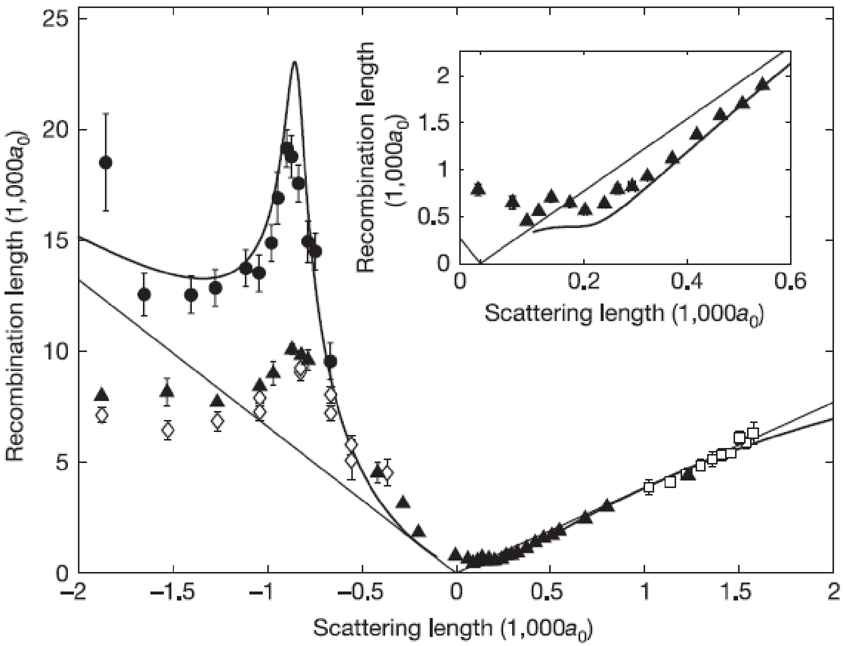
Physics Today **63**, 40 (2010)



NATURE|Vol 440|16 March 2006

Evidence for Efimov quantum states in an ultracold gas of caesium atoms

T. Kraemer[1], M. Mark[1], P. Waldburger[1], J. G. Danzl[1], C. Chin[1,2], B. Engeser[1], A. D. Lange[1], K. Pilch[1], A. Jaakkola[1], H.-C. Nägerl[1] & R. Grimm[1,3]



Recent experiments

NATURE|Vol 440|16 March 2006

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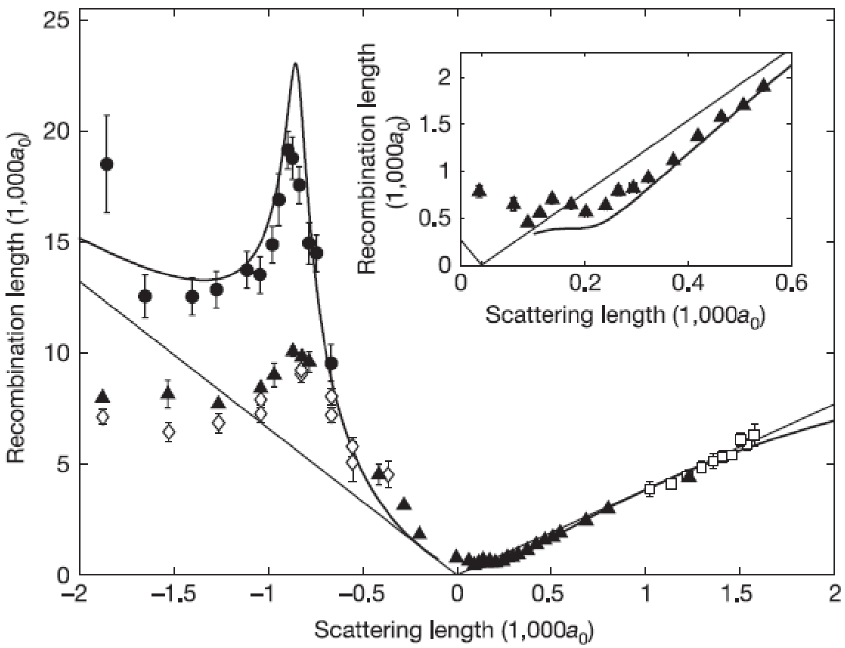
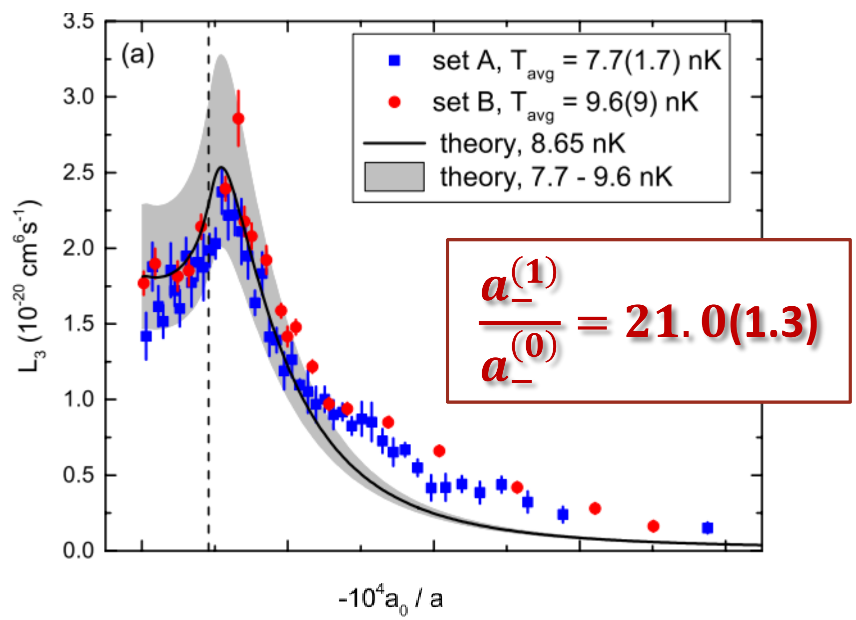


Selected for a Viewpoint in *Physics*
PRL **112,** 190401 (2014) PHYSICAL REVIEW LETTERS week ending 16 MAY 2014

Observation of the Second Triatomic Resonance in Efimov's Scenario

Bo Huang (黄博),[1] Leonid A. Sidorenkov,[1,2] and Rudolf Grimm[1,2]
[1]*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*
[2]*Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*

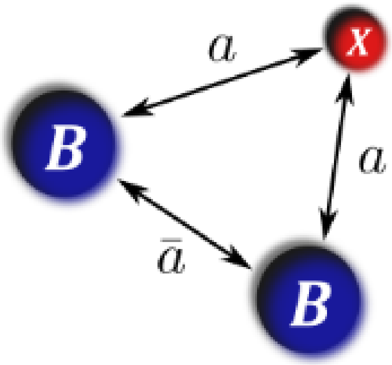
Jeremy M. Hutson
Joint Quantum Centre (JQC) Durham/Newcastle, Department of Chemistry, Durham University, South Road, Durham DH1 3LE, United Kingdom
(Received 26 February 2014; published 12 May 2014)



$$\frac{a_-^{(1)}}{a_-^{(0)}} = 21.0(1.3)$$

More experiments at (homo- and heteronuclear):
Aarhus, Chicago, ENS, Heidelberg, Houston, JILA, LENS, Pennsylvania, Ramat-Gan, Tokio, Tübingen …

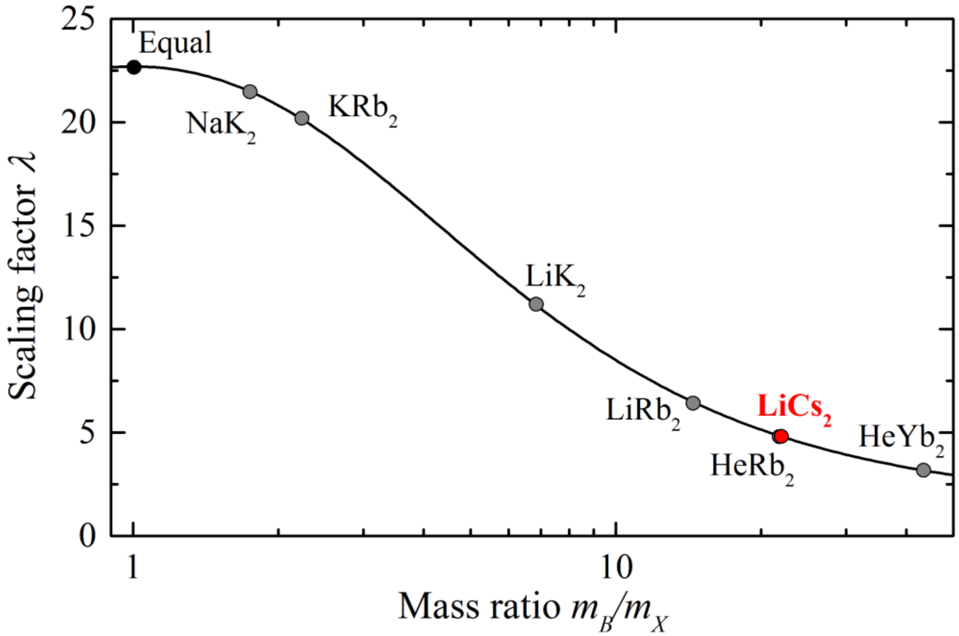
Enhancing observability of Efimov's scenario



$$a \to \pm\infty \qquad a \gg r_0$$

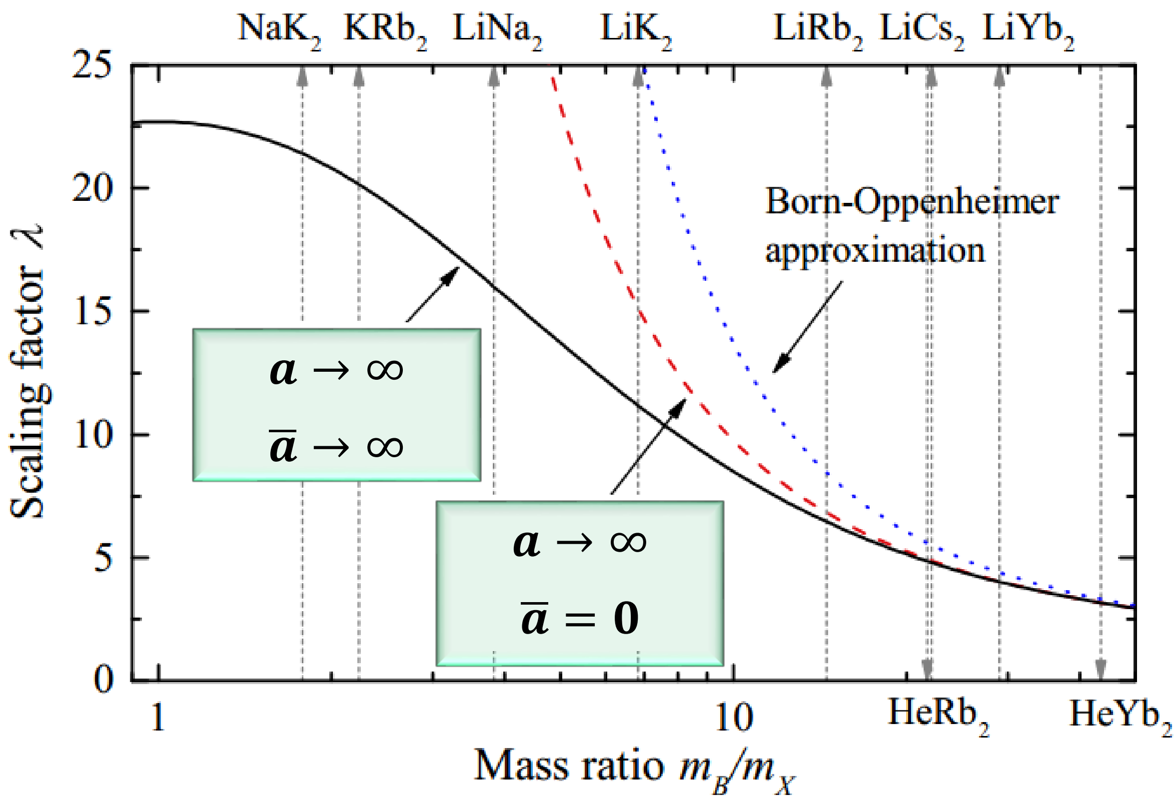
$$\bar{a} \to \pm\infty \qquad \bar{a} \gg \bar{r}_0$$

$$\lambda = \lambda\left(\frac{m_B}{m_X}\right)$$



System	λ
^6Li - Cs_2	**4.877**
^6Li - Rb_2	6.83
Equal masses	22.7

Finite intraparticle scattering lengths



Li-Cs system:

$\boldsymbol{a} \sim -\mathbf{3}\, \boldsymbol{r}_{\mathbf{0}}$

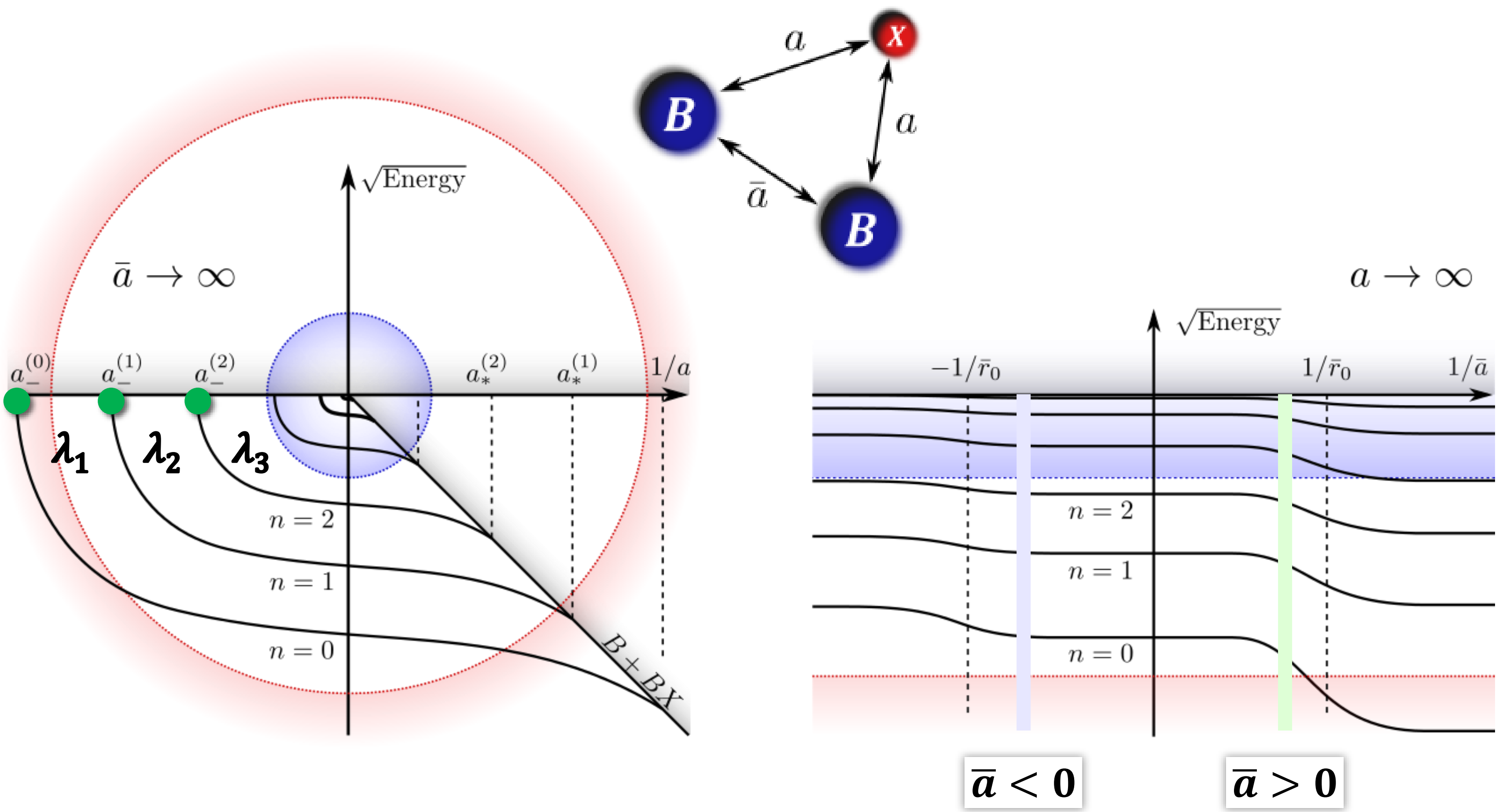
$\bar{\boldsymbol{a}} \sim -\mathbf{15}\, \bar{\boldsymbol{r}}_{\mathbf{0}}$

$\lambda =$ **?**

Short-range effects

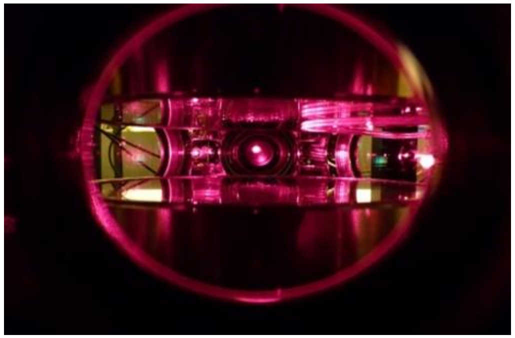
Finite intraspecies scattering lengths

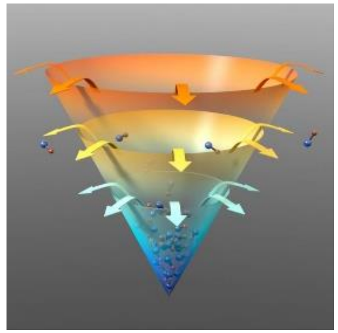
Heteronuclear Efimov scenario

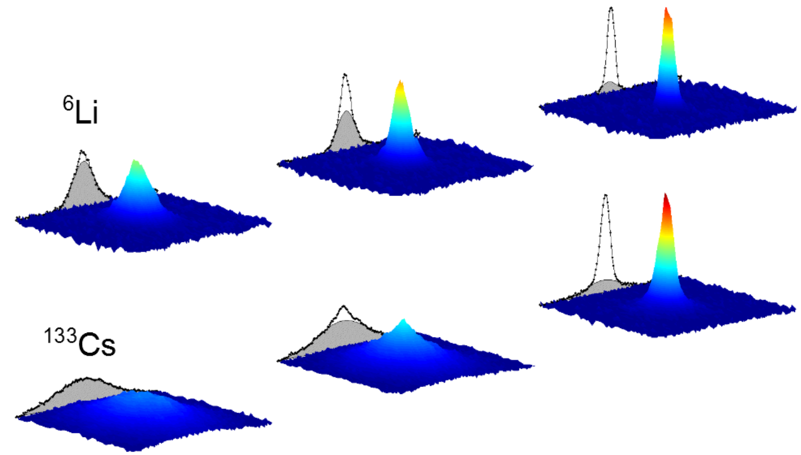


Initial concept with vdW potentials: *Wang et al., Phys. Rev. Lett.* 109 243201 (2012)

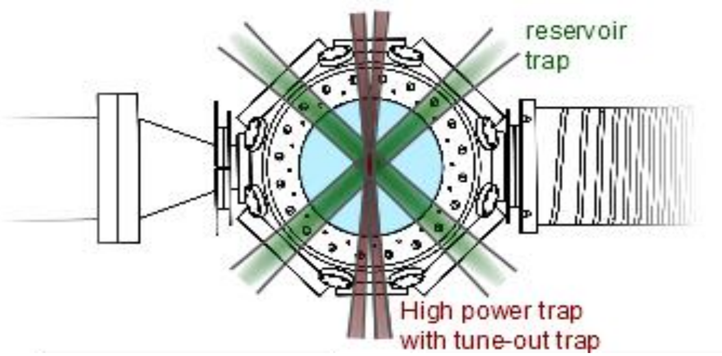
Mixing Li and Cs at nK temperatures

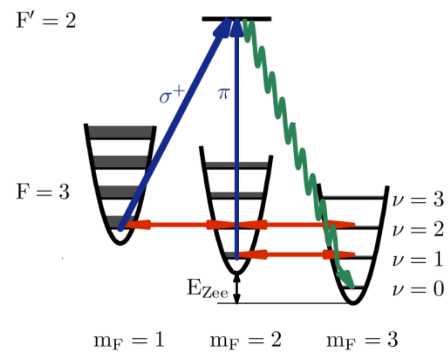


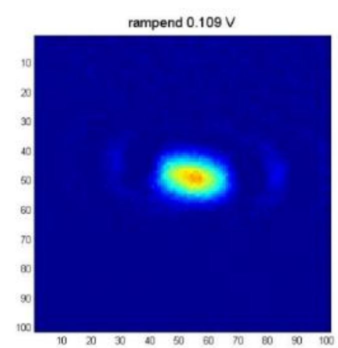




Li MOT → Loading in an optical dipole trap → Forced evaporative cooling → Cs MOT → Degenerate Raman sideband cooling → Mixing of Li and Cs in the ODT



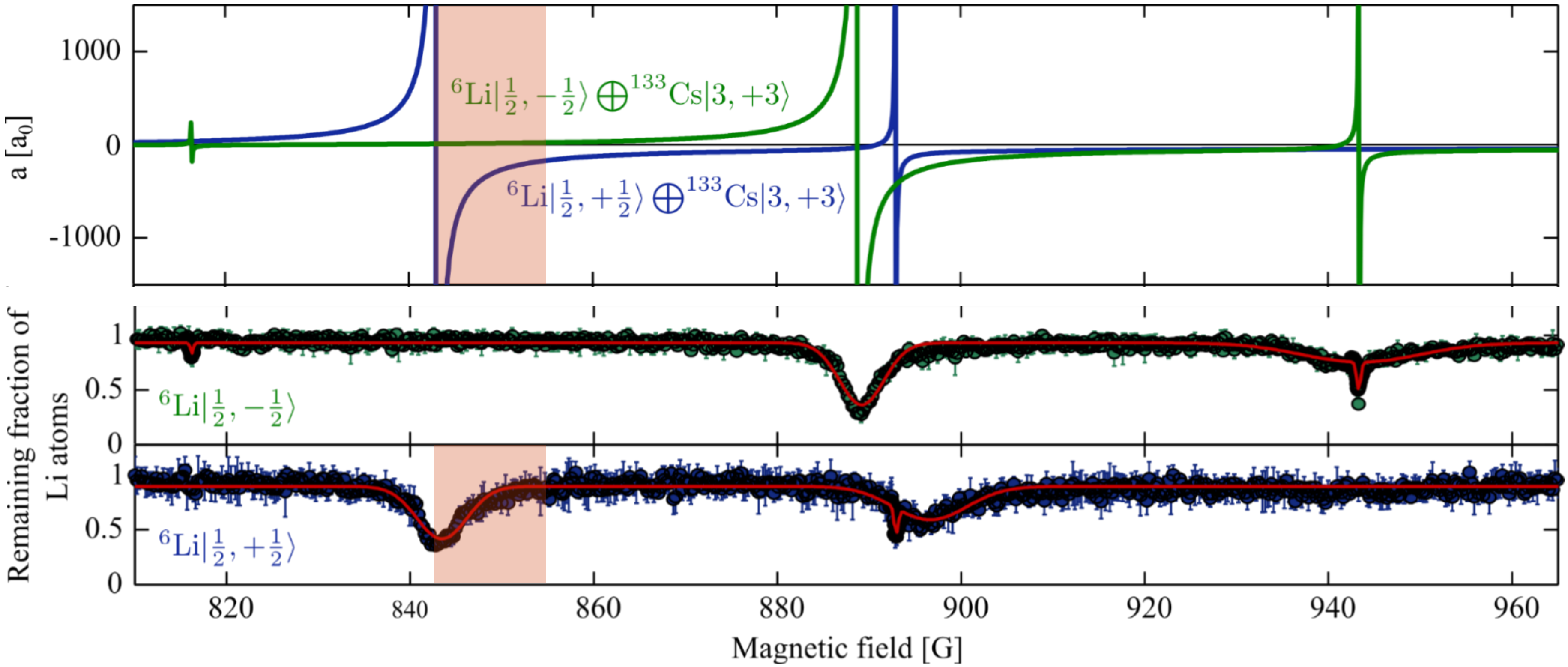




Tuning scattering length in Li-Cs

Feshbach resonances:

coupled-channels calculations by Eberhard Tiemann



Repp *et al.,* Phys. Rev. A **87**, 010701(R) (2013); see also: Tung *et al., ibid.,* 010702(R)
Pires *et al.,* Phys. Rev. A **90**, 012710 (2014)

Three-body loss rate coefficient

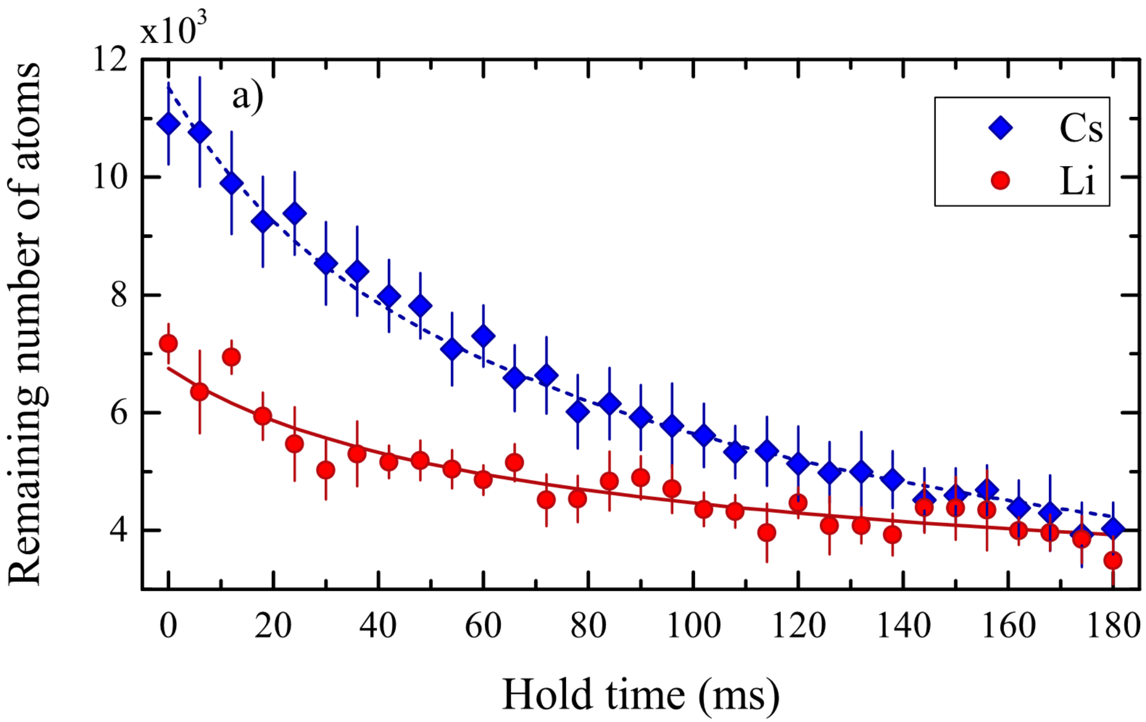
Rate equations:

$$\dot{n}_{Cs} = -L_1^{Cs} n_{Cs} - 2L_3\, n_{Li} n_{Cs}^2 \cancel{- 2L_3^{LiLiCs} n_{Li}^2 n_{Cs}} - L_3^{Cs} n_{Cs}^3$$

$$\dot{n}_{Li} = -L_1^{Li} n_{Li} - L_3\, n_{Li} n_{Cs}^2 \cancel{- 2L_3^{LiLiCs} n_{Li}^2 n_{Cs} - L_3^{Li} n_{Li}^3}$$

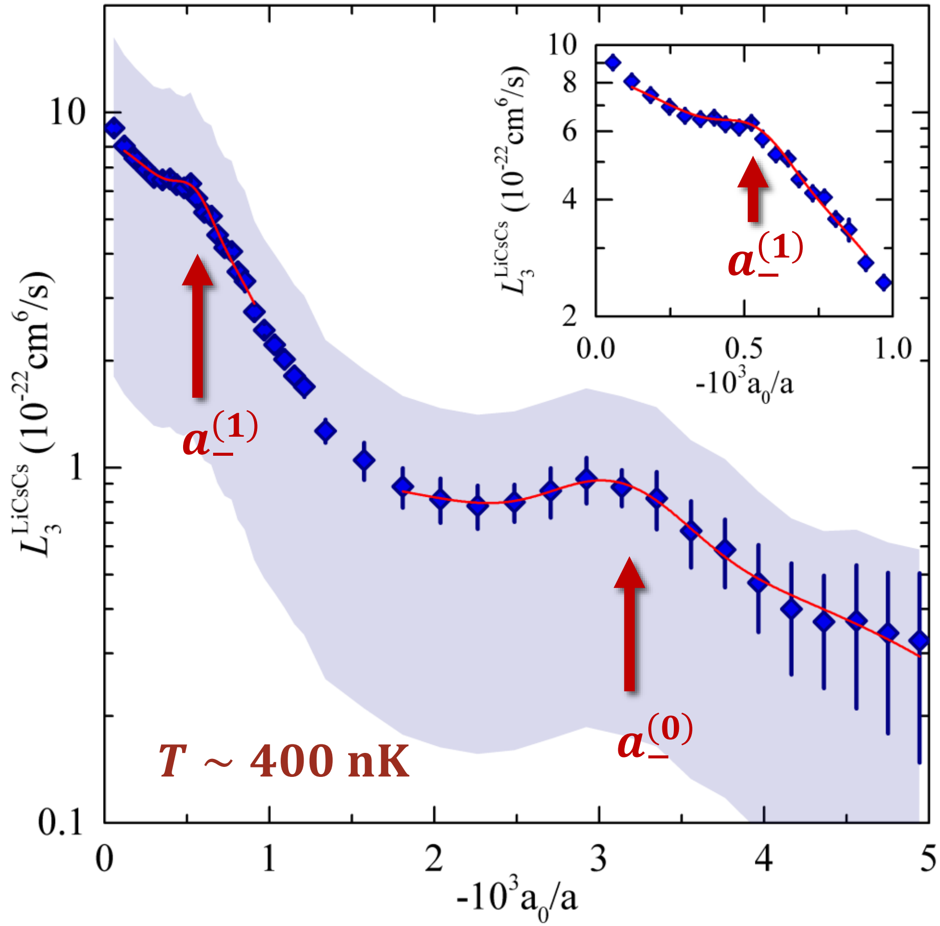
Assumptions:

- Fermionic Li
  → suppression of L_3^{LiLiCs} and L_3^{Li}
- constant temperature
- L_3^{Cs} → constant



Li+Cs+Cs→ { $Li+Cs_2$; LiCs+Cs }

Successive Efimov resonances



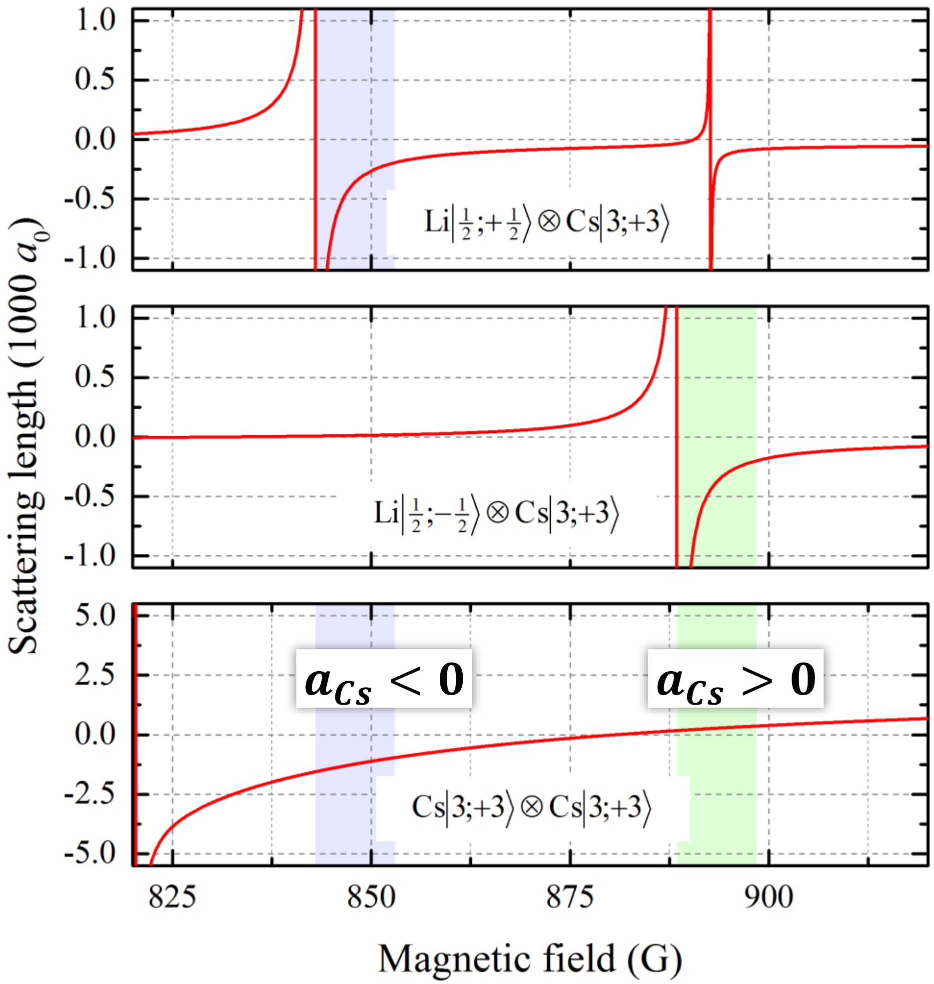
$$\frac{a_-^{(1)}}{a_-^{(0)}} = 5.8(0.1)_{\mathrm{stat}}(0.2)_{\mathrm{sys}}(1.0)_{\mathrm{rf}}$$

$$\approx 4.88\ ?$$

R. Pires *et al.*, PRL **112**, 250404 (2014); see also: S. Tung *et al.* (Chin group), PRL **113**, 240402 (2014)
Single Efimov resonance in Li-Rb: R.A.W. Mayer *et al.*, PRL **115**, 043201 (2015)

Tuning scattering length in Li-Cs

Feshbach resonances:



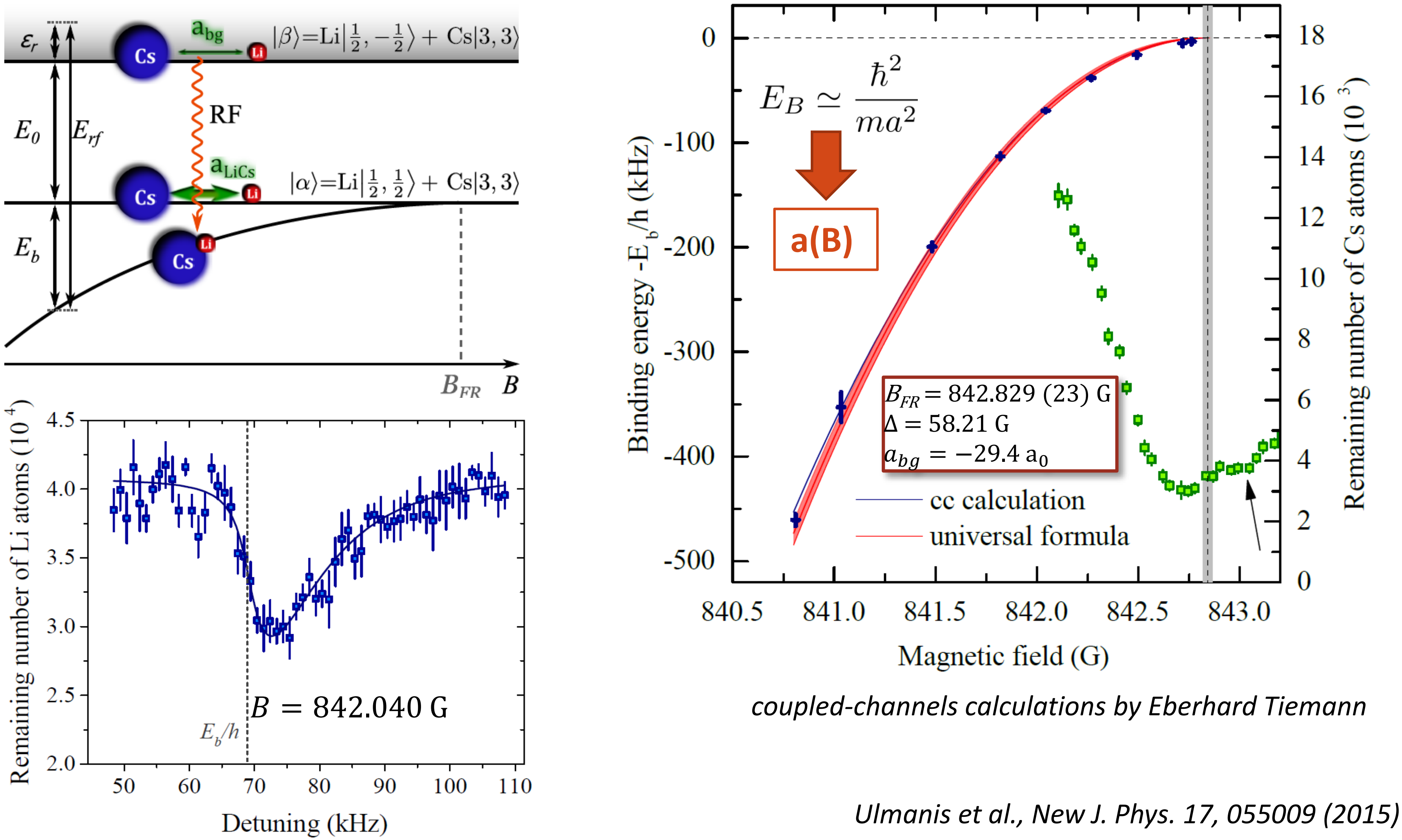
Mapping a_{LiCs}(B) and a_{Cs}(B)

Cs-Cs interactions (Grimm group):
Berninger et al., Phys. Rev. A 87, 032517 (2013)

Li-Cs interactions (our work):
Repp et al., Phys. Rev. A 87, 010701(R) (2013)
Pires et al., Phys Rev. A 90, 012710 (2014)
Ulmanis et al., New J. Phys. 17, 055009 (2015)

Li-Cs interactions (Chicago):
Tung et al., Phys. Rev. A 87, 010702(R) (2013)

rf association of (universal) LiCs dimers



coupled-channels calculations by Eberhard Tiemann

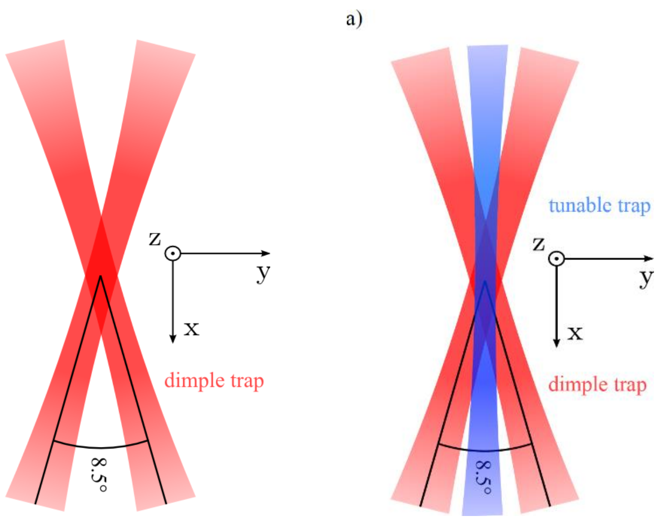
Ulmanis et al., New J. Phys. 17, 055009 (2015)

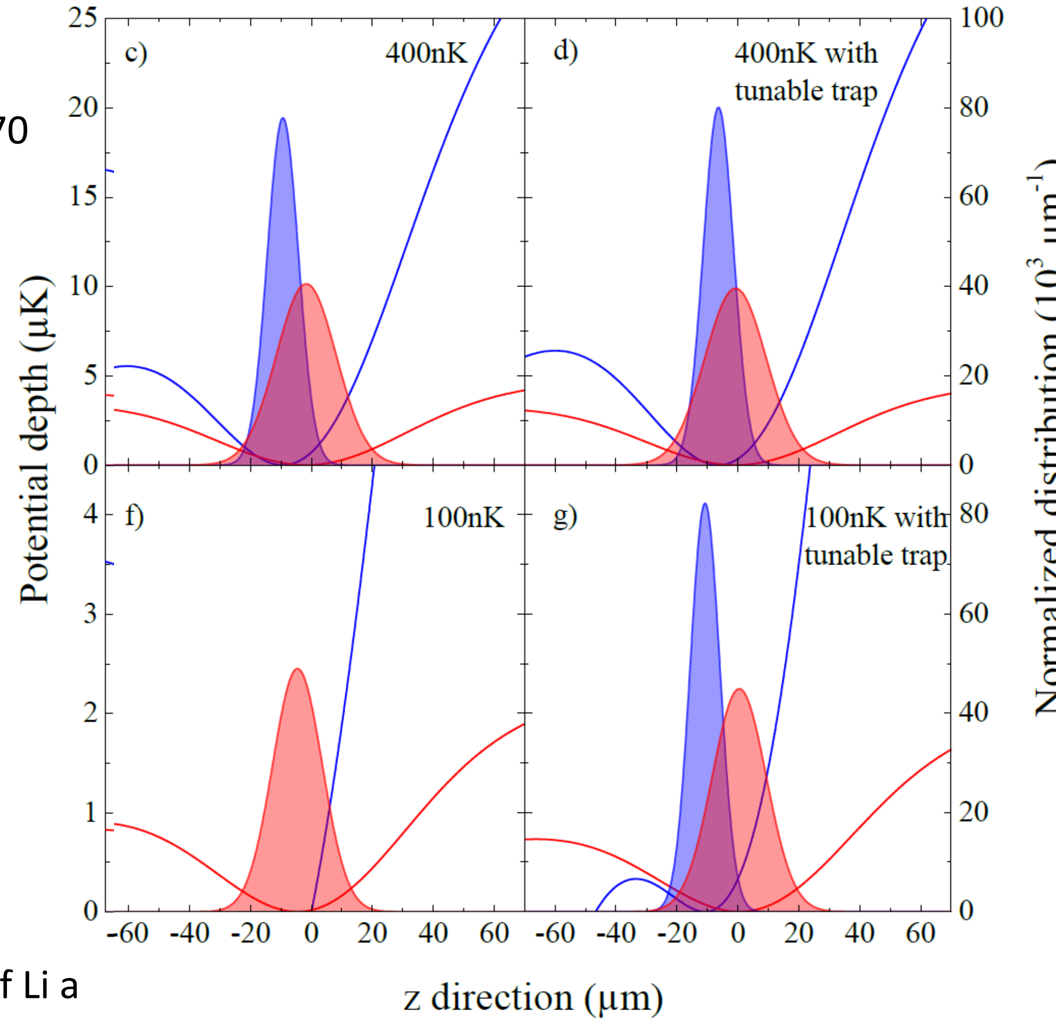
Reaching lower temperatures

Mixed species condensation

- Gravitional sag due to large Cs mass
- Factor of 4 difference in polarizability at 1070 nm

→ Solution: bichromatic dipole trap

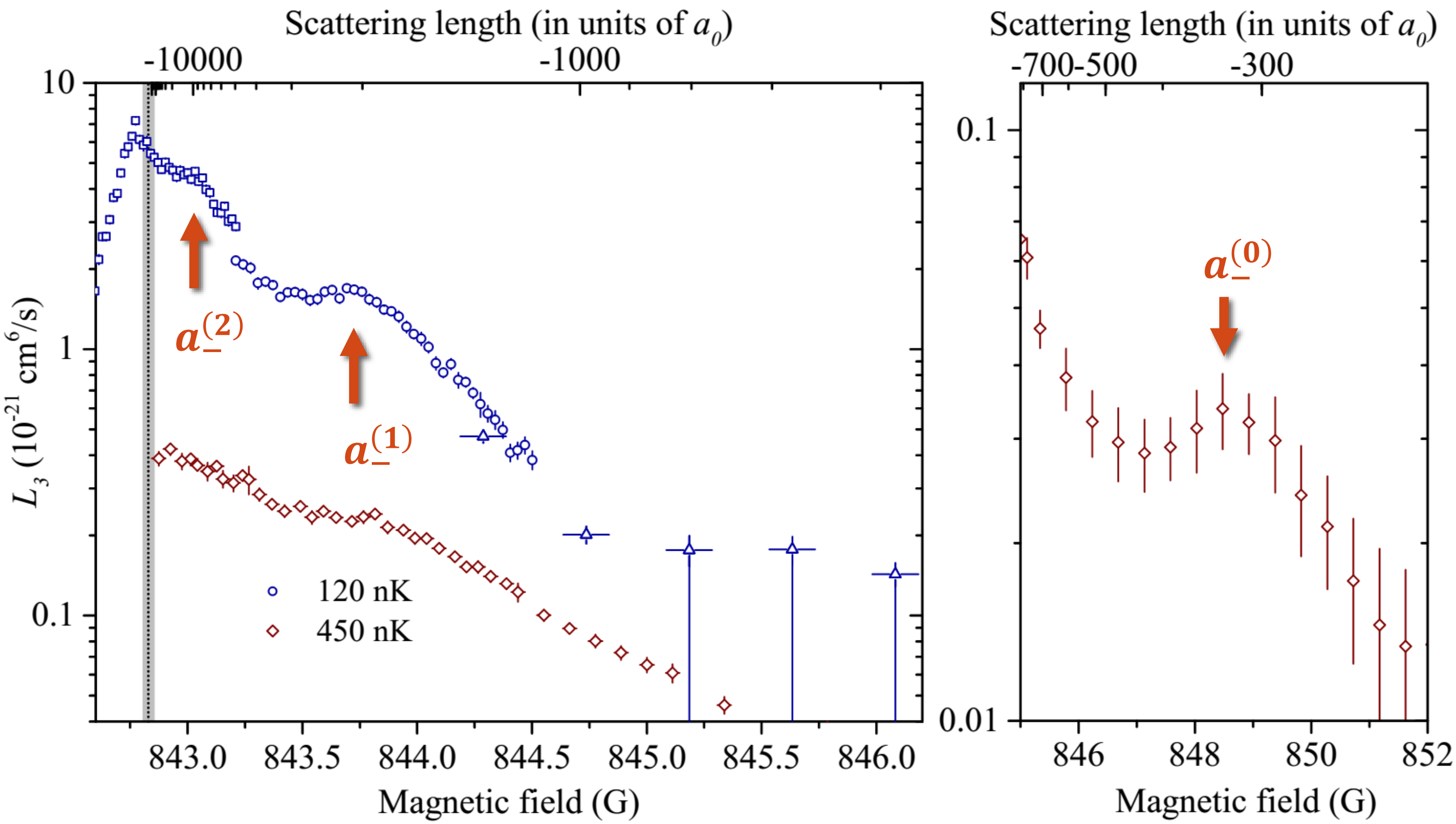




Tunable optical dipole trap @ 921 nm

- Polarizability $\boldsymbol{\alpha_{Cs} = 12 \times \alpha_{Li}}$
- Almost independent spatial control of Li a
- Compensation of gravitational sag

Observation of three Efimov resonances



J. Ulmanis *et al.,* PRA **93**, 022707 (2016)

Zero-range model

zero-range finite temperature model: ***D. Petrov and F. Werner, PRA 92, 022704 (2015)***

- *S-Matrix* formalism

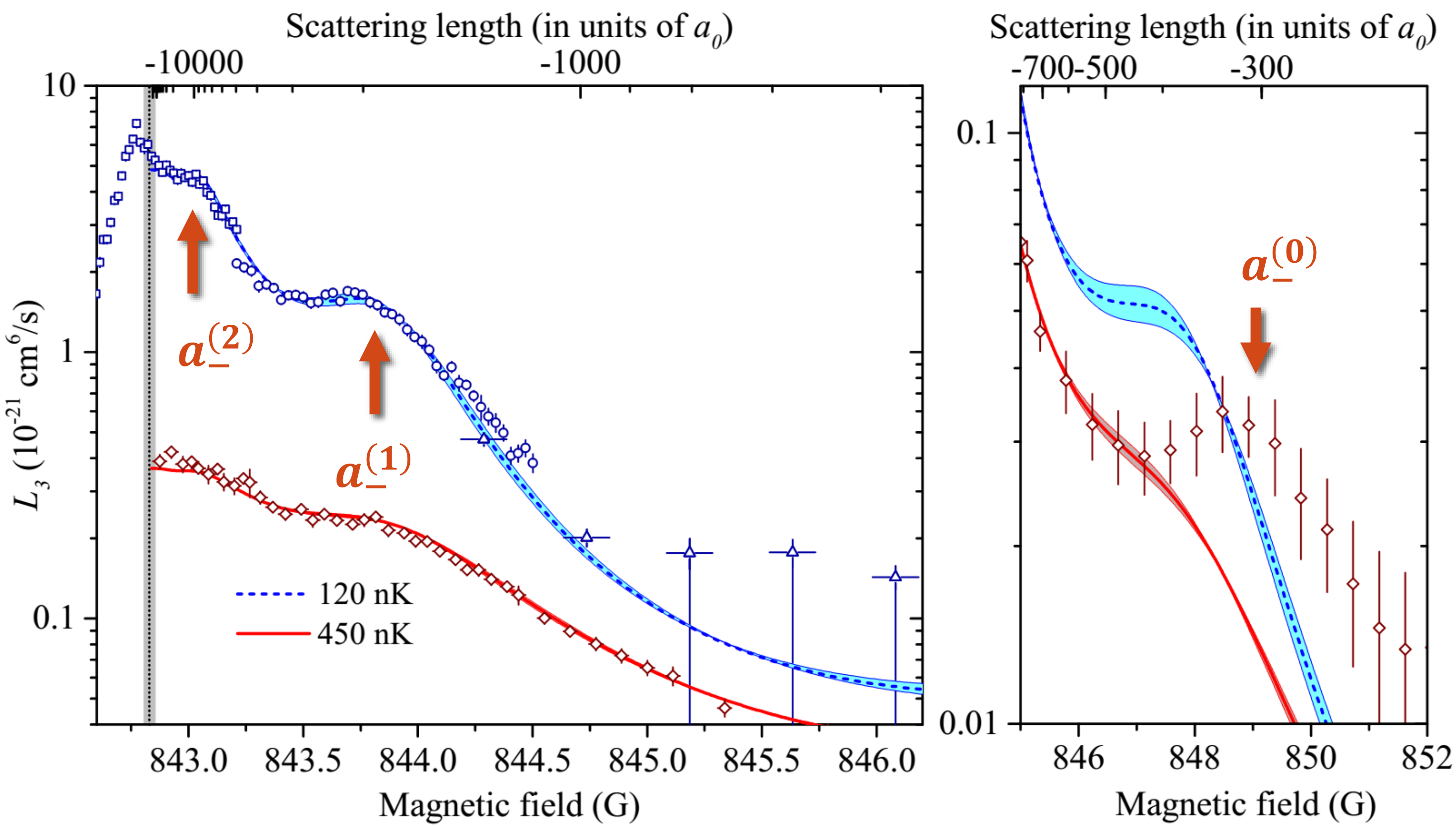
$$L_3 = 4\pi^2 \cos^3\phi \frac{\hbar^7}{\mu^4 (k_\mathrm{B} T)^3}(1 - e^{-4\eta})$$

$$\times \int_0^\infty \frac{1 - |s_{11}|^2}{|1 + (kR_0)^{-2is_0} e^{-2\eta} s_{11}|^2} e^{-\hbar^2 k^2 / 2\mu k_\mathrm{B} T} k dk$$

- Parameters:
  - $\boldsymbol{s_{11}}$ dependent on $\boldsymbol{ka_{LiCs}}$, $\boldsymbol{ka_{Cs}}$ and mass ratio
  - Scaling factor $\mathbf{exp}(\boldsymbol{\pi}/\boldsymbol{s_0})$
  - Temperature $\boldsymbol{T}$
  - Inelasticity parameter $\boldsymbol{\eta}$
  - Three-body parameter $\boldsymbol{R_0}$

Alternative method using optical potentials: M. Mikkelsen et al, J. Phys. B. 48, 085301 (2015)

Comparison with zero-range model

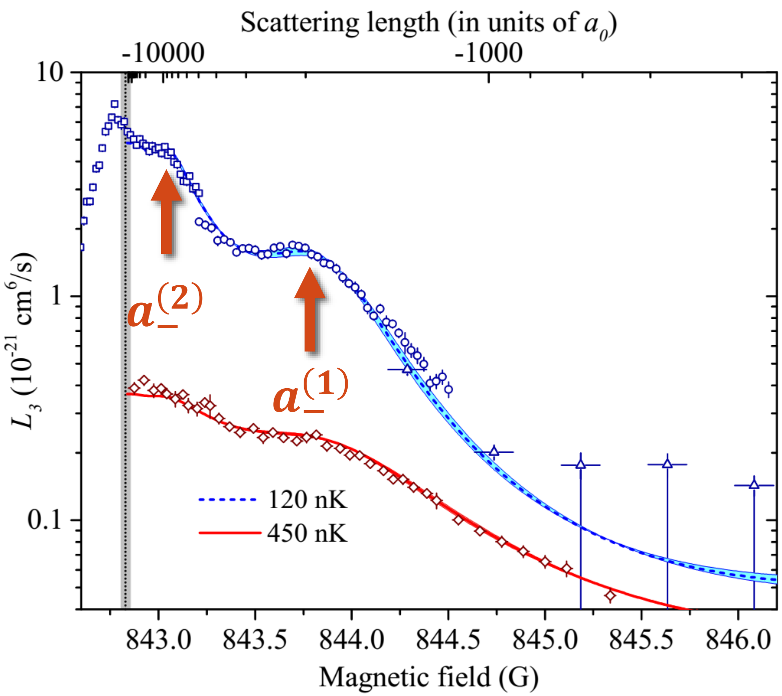


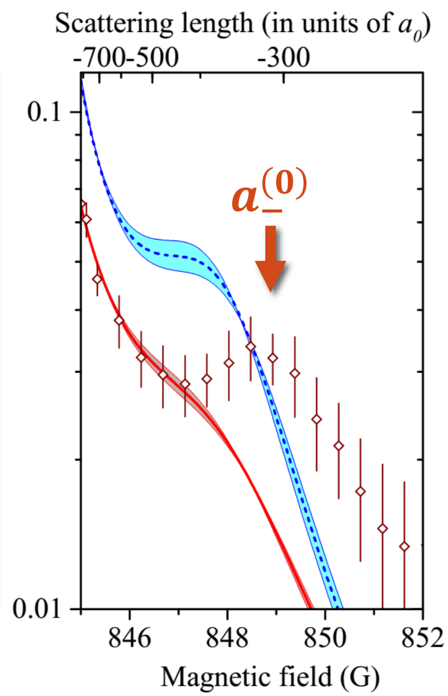
Fit of zero-range theory

- Resonance width $\boldsymbol{\eta = 0.6 - 0.8}$
- Three-body parameter $\boldsymbol{R_0 = 125\ a_0}$
- Absolute loss-rate

J. Ulmanis *et al.,* PRA **93**, 022707 (2016)

Comparison with zero-range model





Extraction of resonance positions and scaling factors from zero-range theory by setting $T \to 0,\ \eta \to 0$:

$$\lambda_1 = \frac{a_-^{(1)}}{a_-^{(0)}} = \frac{-1777\,a_0}{-350\,a_0} = 5.08$$

$$\lambda_2 = \frac{a_-^{(2)}}{a_-^{(1)}} = \frac{-9210\,a_0}{-1777\,a_0} = 5.18$$

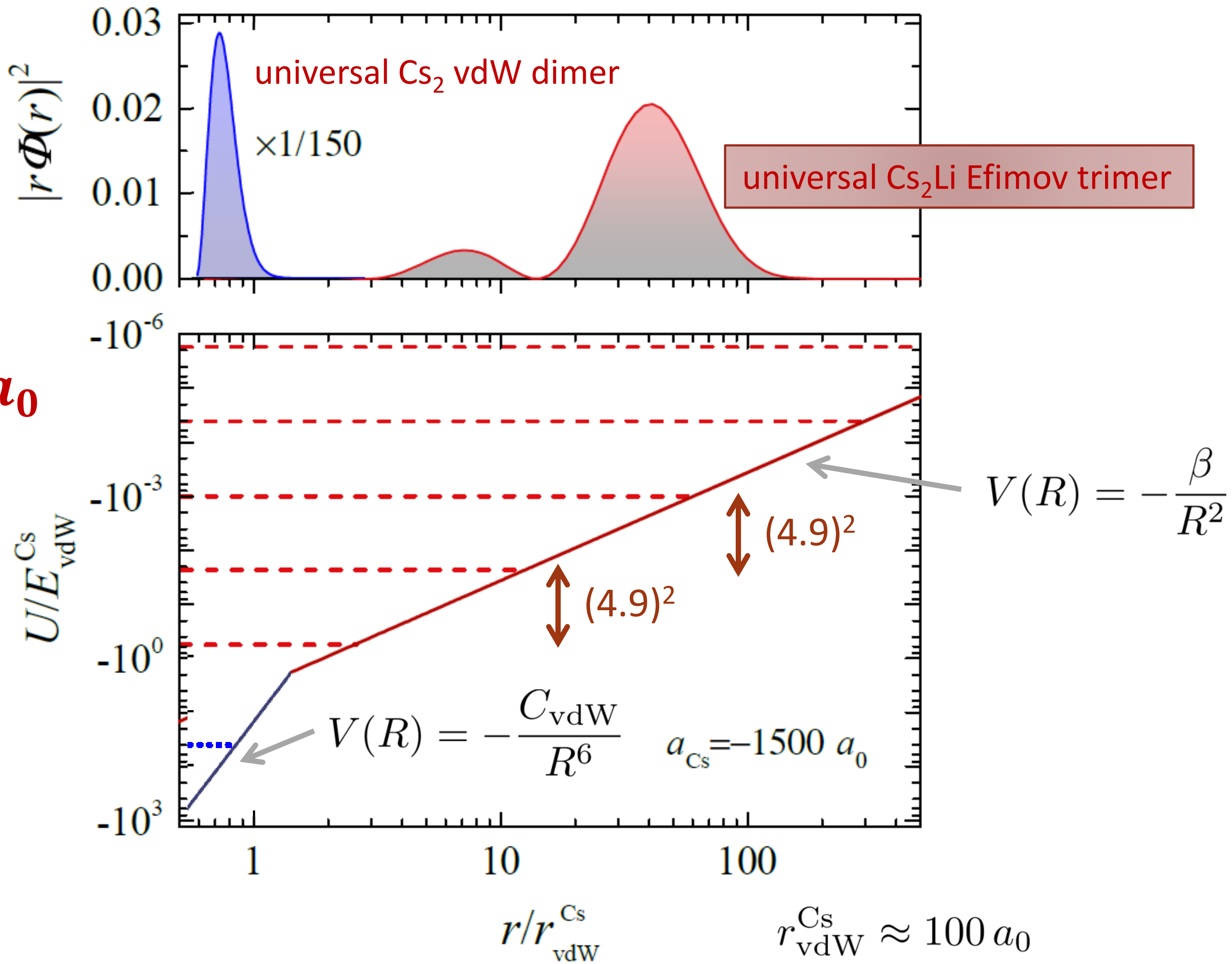
- Consistent description of excited state recombination resonances
- Deviation from universal scaling factor of 4.877
- Non-universal ground state resonance $\boldsymbol{a_-^{(0)}}$

J. Ulmanis *et al.,* PRA **93**, 022707 (2016)

Simplistic Born-Oppenheimer picture

$\boldsymbol{a \to \pm\infty}$

$\boldsymbol{a_{Cs} = -1500\, a_0}$



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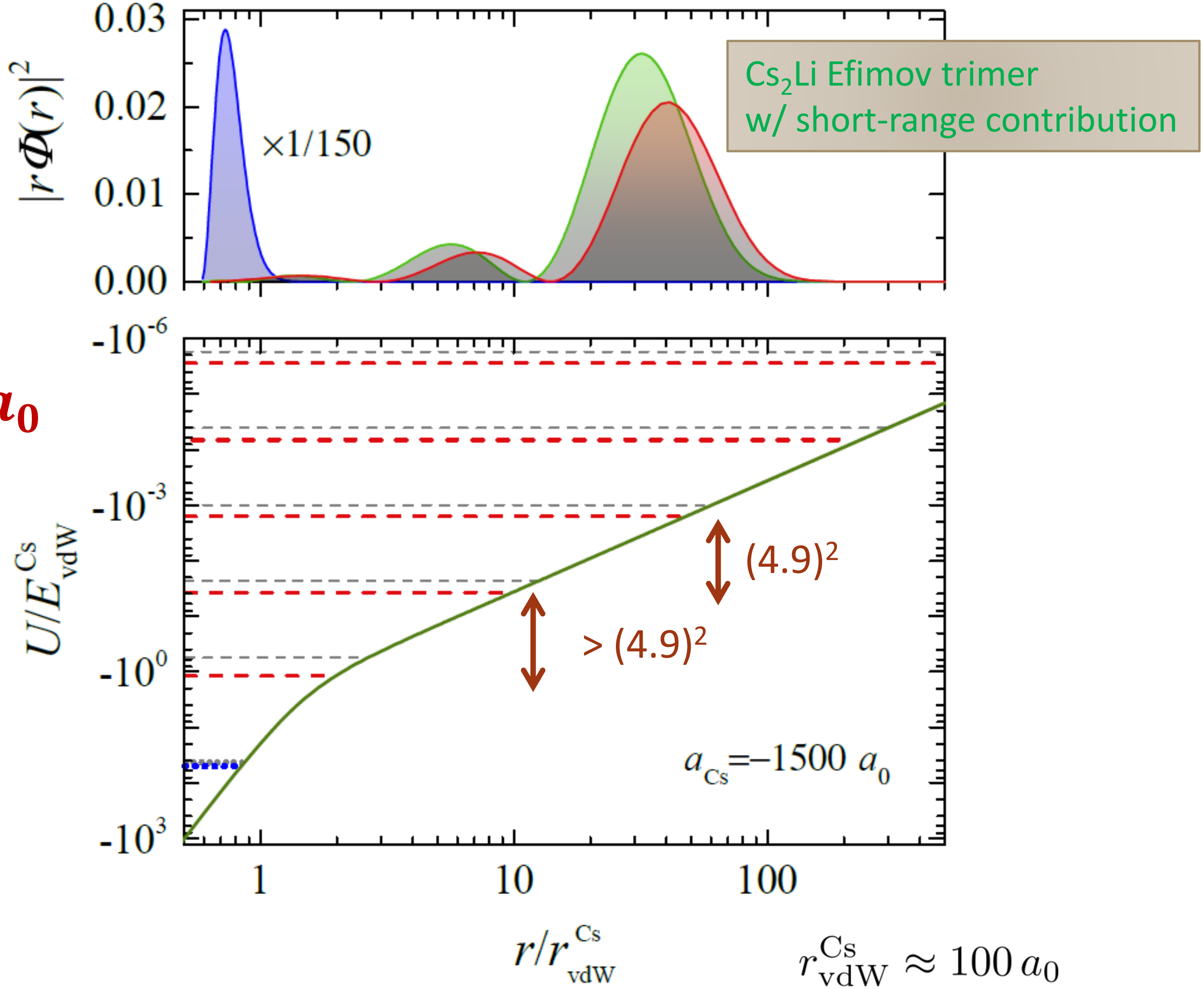
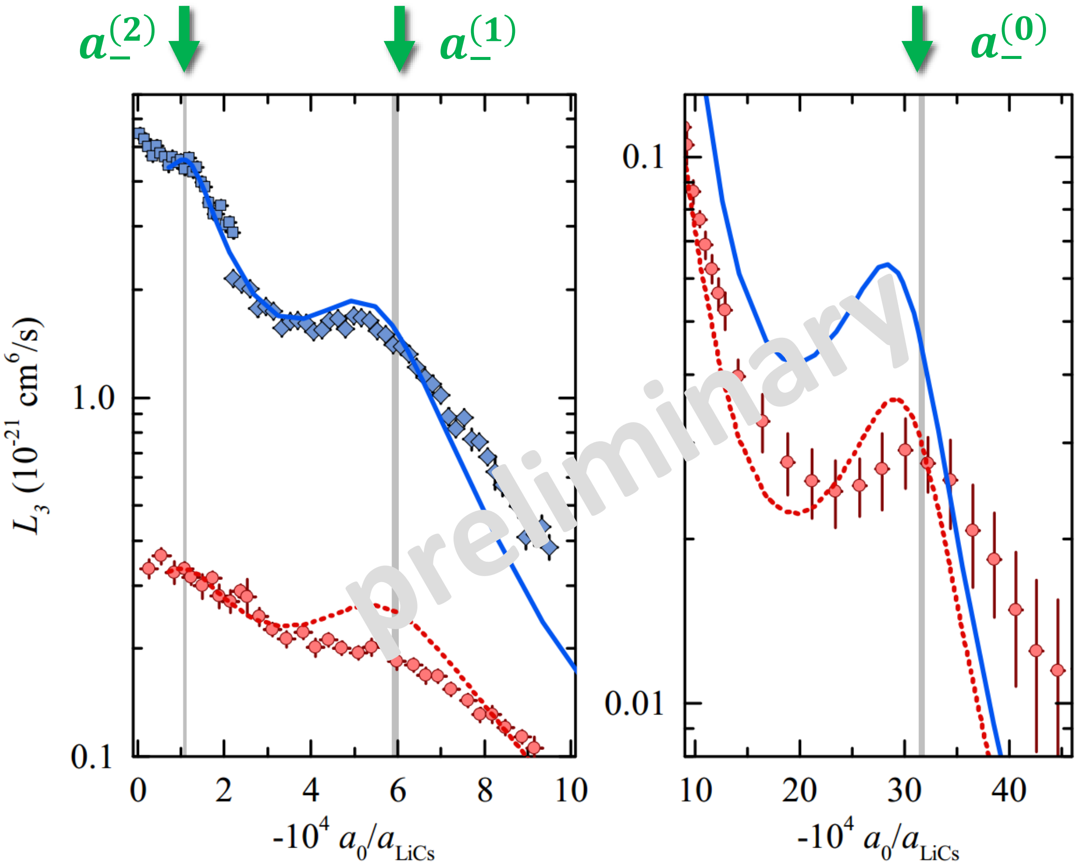


$r_{\mathrm{vdW}}^{\mathrm{Cs}} \approx 100\, a_0$

Three-body recombination: $\bar{a} < 0$



vdW scaling factors:

$$\lambda_1 = 5.3 \pm 0.1$$

$$\lambda_2 = 5.1 \pm 0.2$$

Universal zero-range theory:

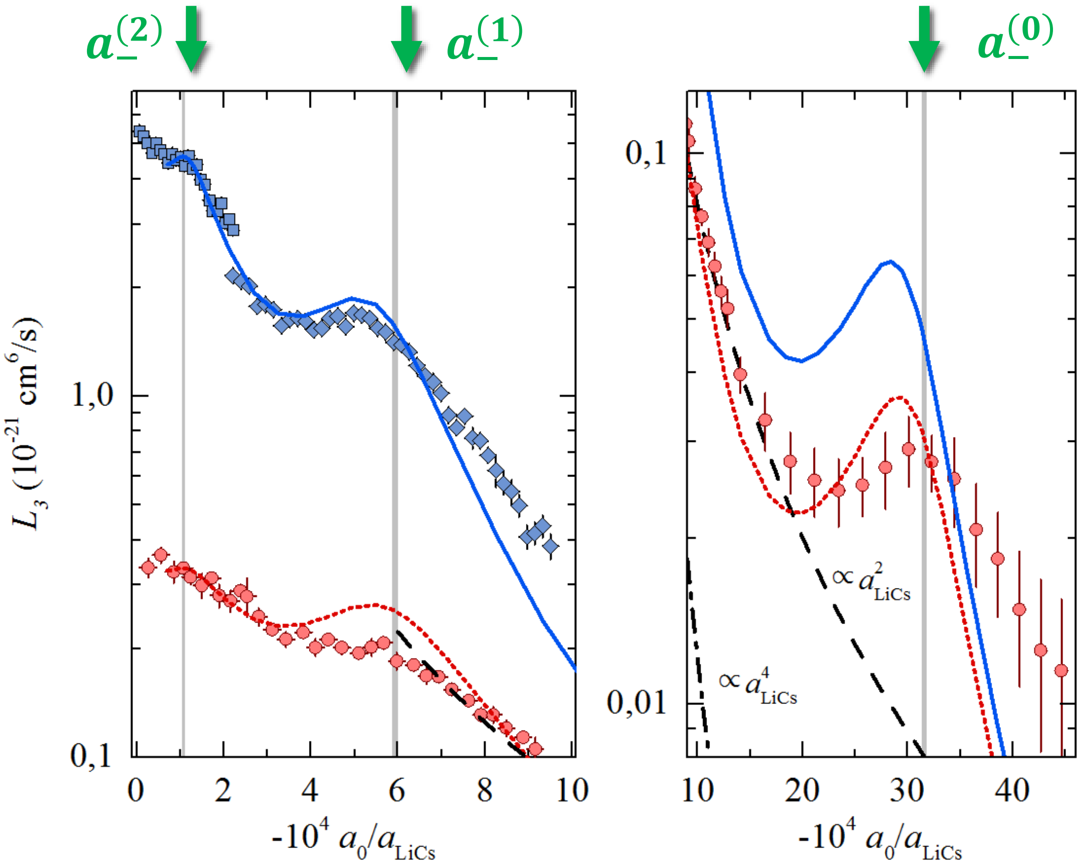
$$\lambda_1 = 5.08$$

$$\lambda_2 = 5.18$$

Universal van der Waals model: Yujun Wang and Chris Greene

Wang et al., Phys. Rev. Lett. 109 243201 (2012)

Three-body recombination: $\bar{a} < 0$



Power law for $|a_{LiCs}| \ll |a_{Cs}|$

$$L_3 \propto a_{LiCs}^2 a_{Cs}^2$$

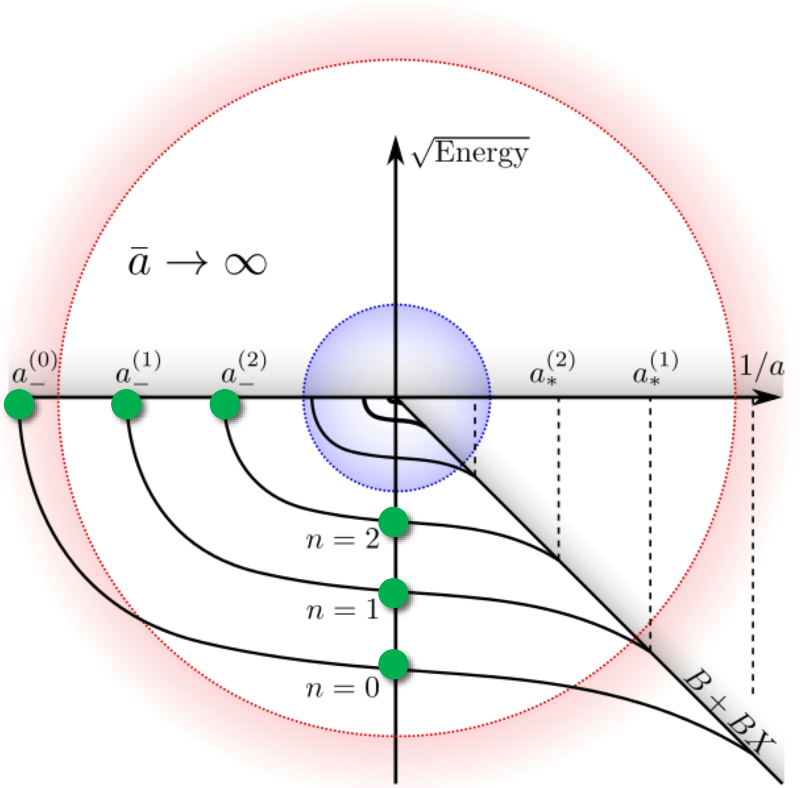
Here: $a_{Cs} \approx -1500\ a_0$

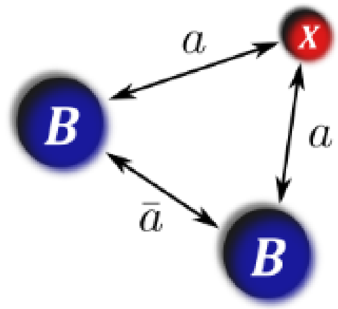
preliminary

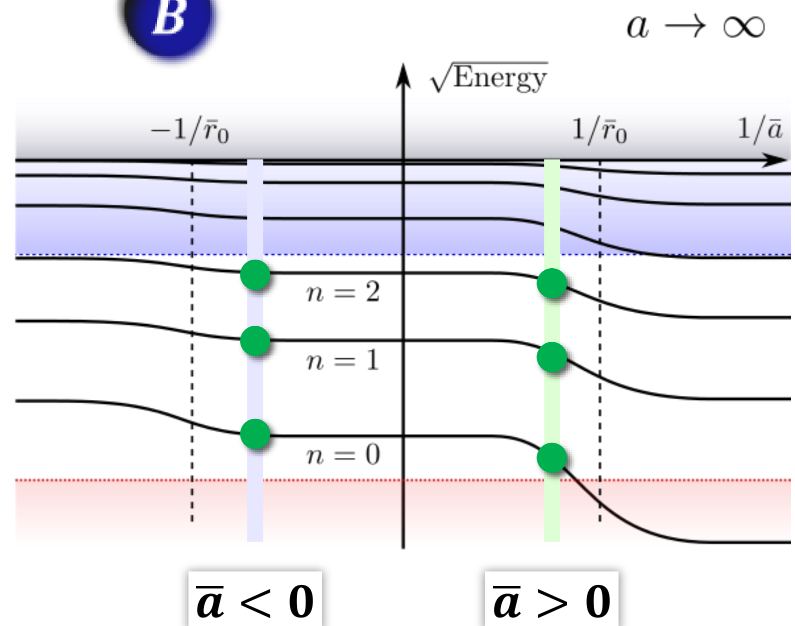
Power laws for XXY and XYZ systems:

J. D'Incao and B. Esry, Phys. Rev. Lett. 103, 083202 (2009)

Efimov's universal function





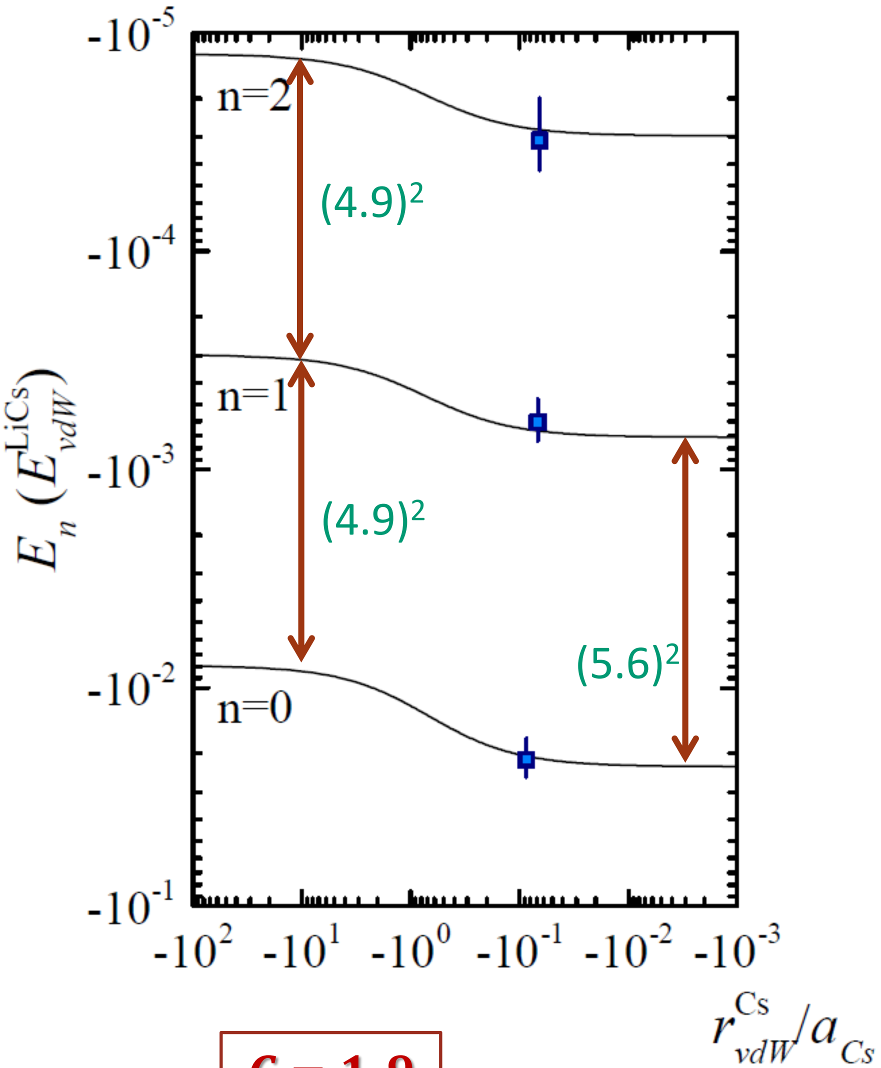


Trimer energies at the unitarity are universally related to the recombination

$$E_T = \frac{\hbar^2 k_*^2}{m} \qquad a_- = C\, k_* \qquad C = 1.56$$

E. Braaten and H. W. Hammer, *Physics Reports* ***428***, 259 (2016)

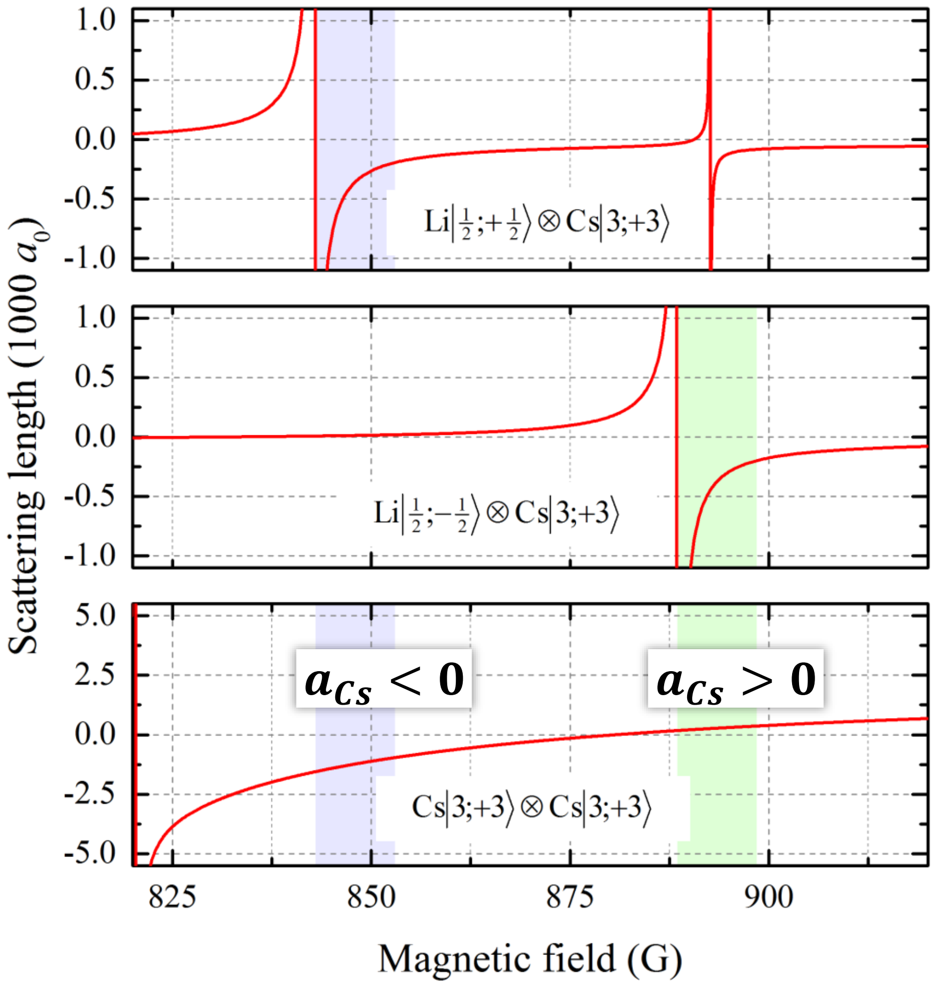
Simplistic Born-Oppenheimer picture



$C = 1.9$

Tuning scattering length in Li-Cs

Feshbach resonances:



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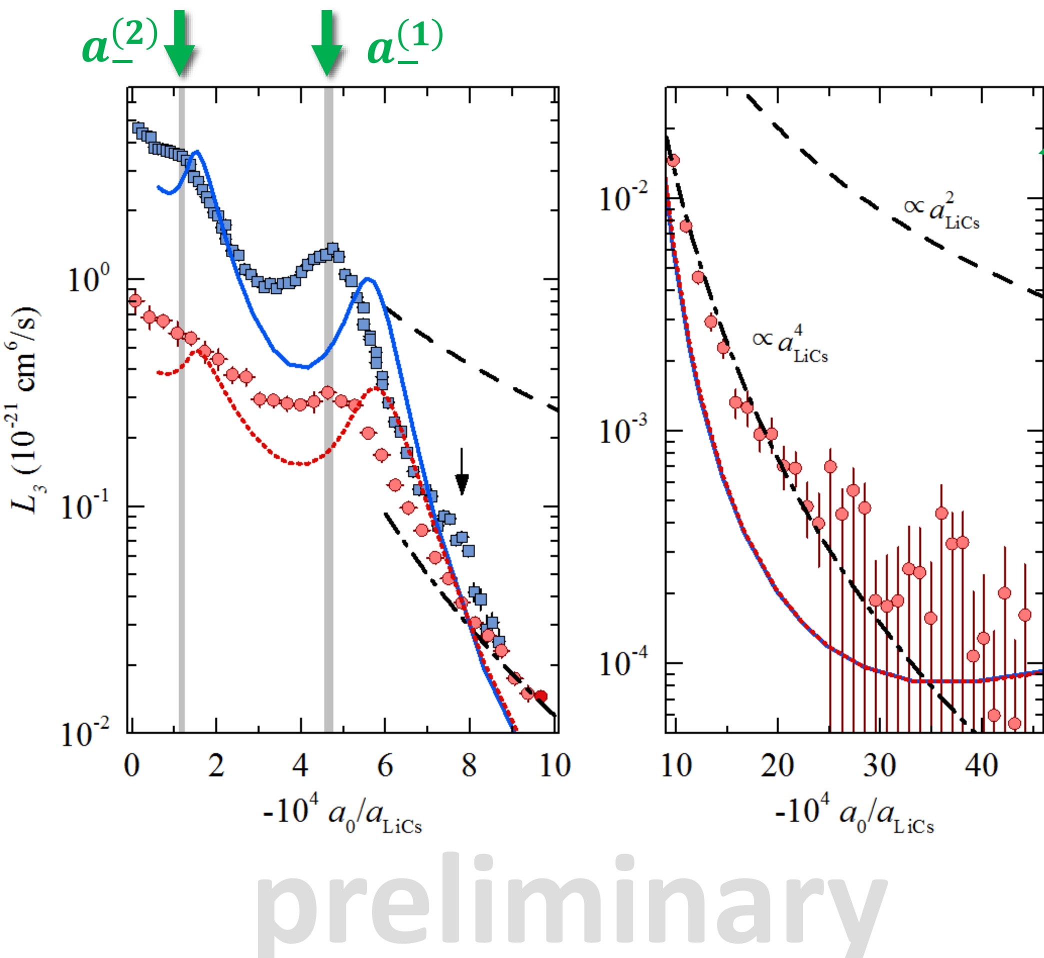
Ulmanis et al., New J. Phys. 17, 055009 (2015)

Li-Cs interactions (Chicago):
Tung et al., Phys. Rev. A 87, 010702(R) (2013)

Three-body recombination: $\bar{a} > 0$



Ground state resonance missing!

vdW scaling factor:

$$\lambda_2 = 4.3^{+0.5}_{-0.4}$$

Power law for $|a_{LiCs}| \gg a_{Cs}$

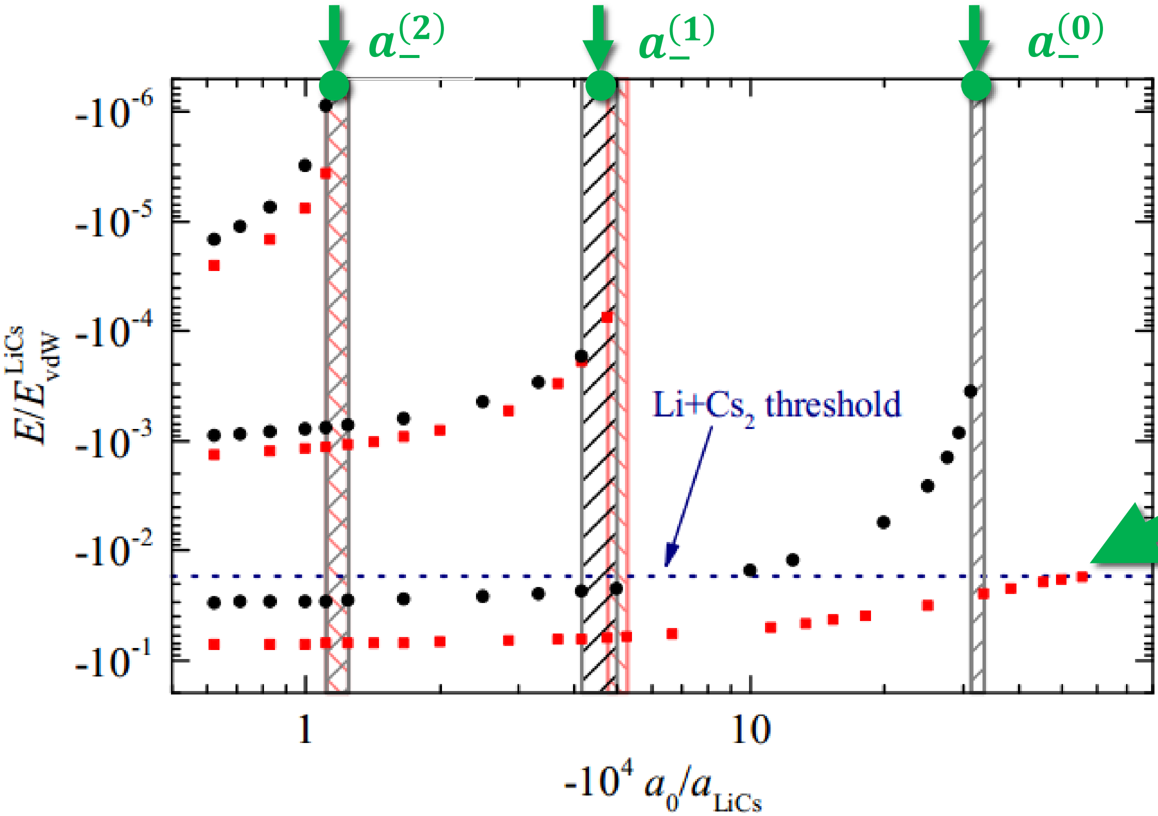
$$L_3 \propto a_{LiCs}^4$$

Here: $a_{Cs} \approx 200\ a_0$

Efimov spectrum for Li-Cs-Cs

Three-body energy spectrum for attractive Li-Cs interactions ($a_{LiCs} < 0$)

Universal van der Waals model: Y. Wang et al., *Phys. Rev. Lett.* 109 243201 (2012)



$a_{Cs} < 0$

$a_{Cs} > 0$

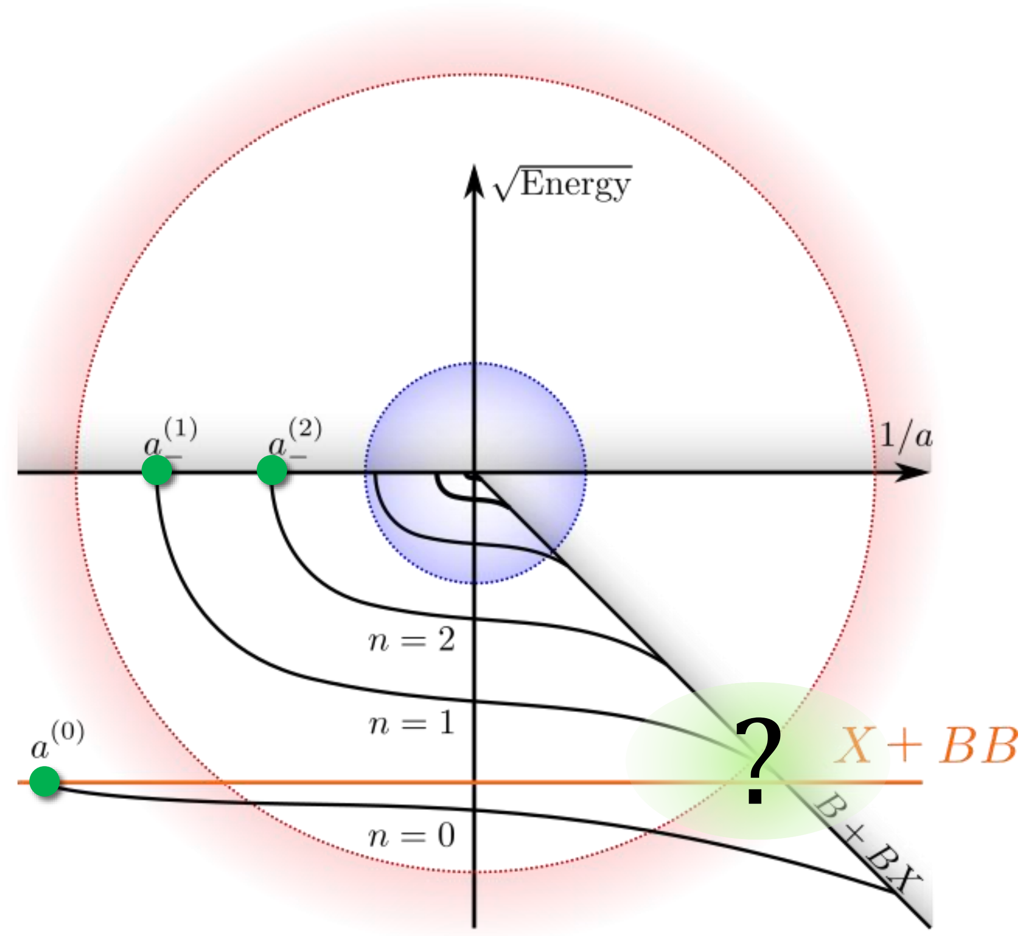
Ground state merges with the $\mathbf{Li + Cs_2}$ threshold!

Calculations with the hyperspherical formalism by Chris Greene and Yujun Wang

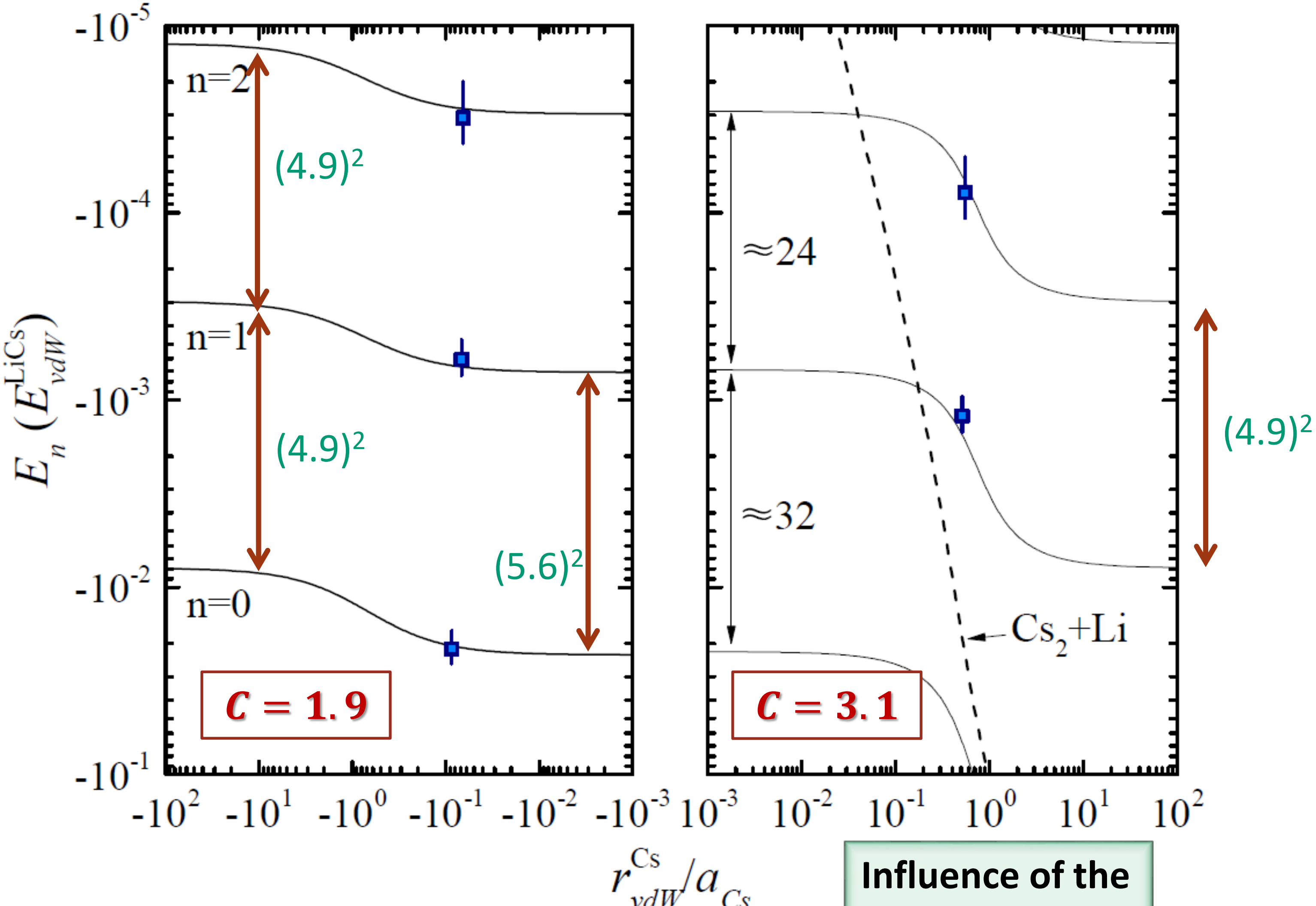
Dissappearance of the resonance

$a \to \pm\infty$

$\bar{a} \approx 200\ a_0$



Simplistic Born-Oppenheimer picture



Influence of the dimer state?

Summary

- Heteronuclear Efimov physics with large mass imbalance
- Observation of a series of 3 consecutive heteronuclear Efimov resonances in three-body losses for negative Cs scattering length
- Observation of two Efimov resonances and missing lowest resonance for positive Cs scattering length
- Role of short-range interactions (universal and nonuniversal regimes)
- Influence of the heavy-heavy scattering length

Repp *et al.,* Phys. Rev. A **87**, 010701(R) (2013)
Pires *et al.*, PRL **112**, 250404 (2014)
Pires *et al.,* Phys. Rev. A **90**, 012710 (2014)
Ulmanis *et al.,* New J. Phys.**17**, 055009 (2015)
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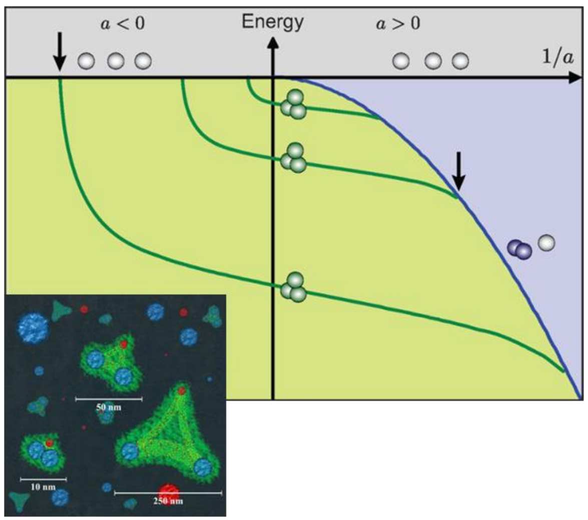
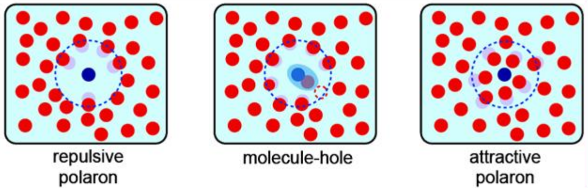
Ulmanis *et al.*, National Science Reviews, in press
Ulmanis *et al.*, to be published

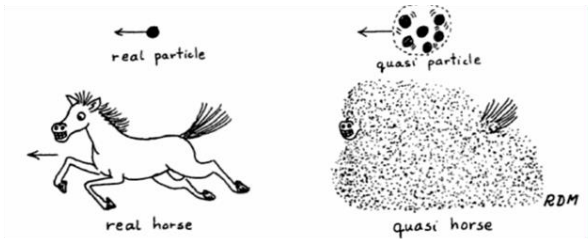
Outlook

Few-to many bound states: Efimov effect, N-body states …

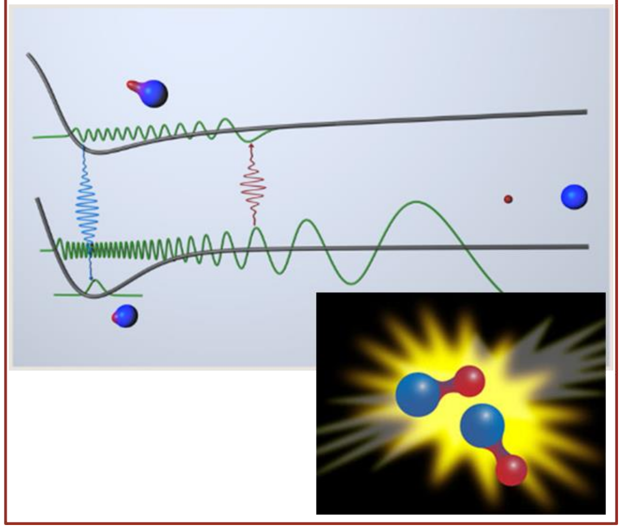


Impurity in a bath:
Polarons, simulation of solid-state systems …





Polar ground state molecules:
Dipolar interactions, ultracold chemistry …



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Quantum Dynamics of Atomic and Molecular Systems

Center for Quantum Dynamics