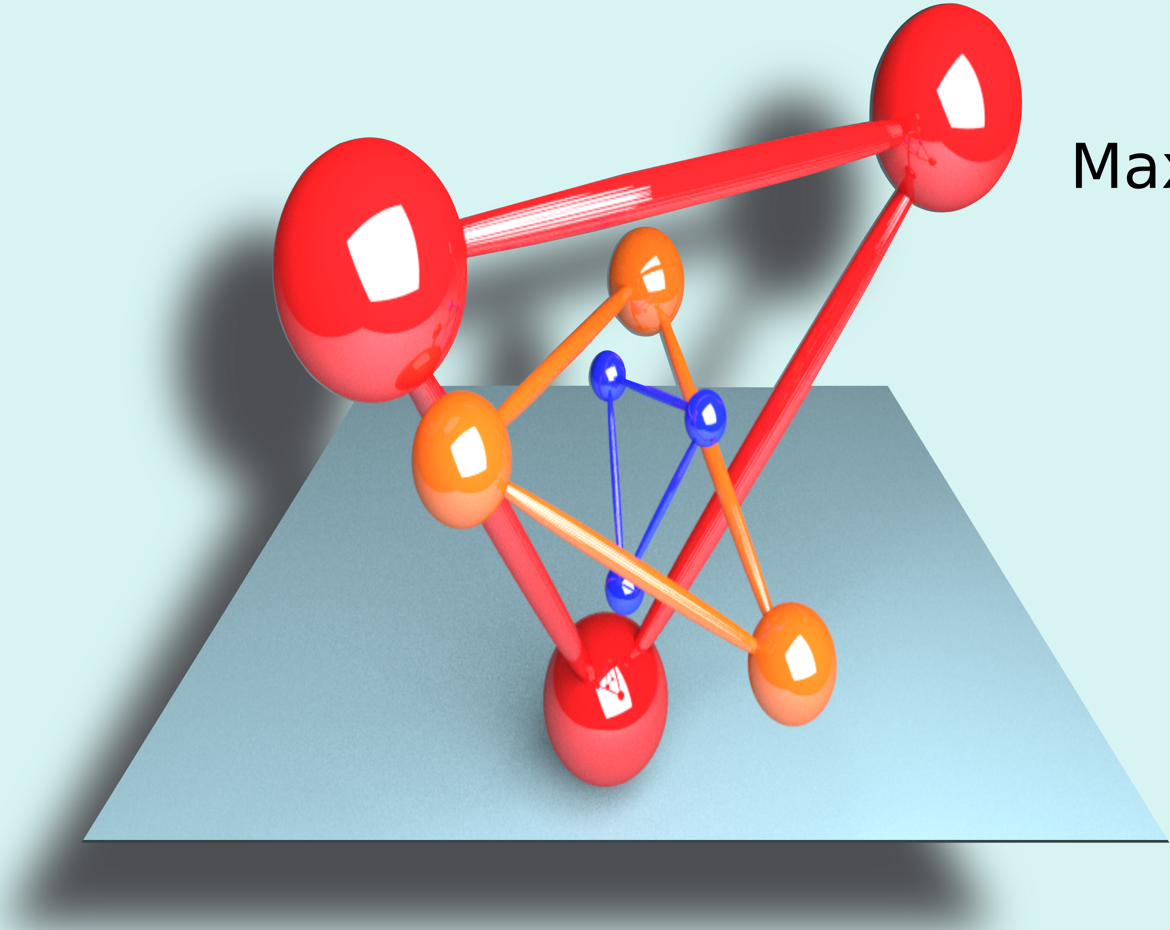
Efimov physics in strongly mass-imbalanced ultracold gases



P. Giannakeas

Max Planck Institute for the Physics of Complex Systems

CLUSHIQ 2020

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Outline

- Introduction & quick overview of Efimov physics in **ultracold gases**
- Efimov physics in mass imbalanced ultracold gases
- Three-body recombination processes
- Atom-dimer elastic and relaxation processes

Introduction

- Efimov states: An infinite progression of trimer states even when all two-body subsystems are barely bound.
- Last two decades there is a tremendous experimental and theoretical progress exploring for example
  - the discrete scaling invariance between successive Efimov states
  - universal aspects of the ground Efimovian state

REVIEWS OF MODERN PHYSICS, VOLUME 89, JULY–SEPTEMBER 2017

Universal few-body physics and cluster formation

Chris H. Greene,[*] P. Giannakeas,[†] and J. Pérez-Ríos[‡]

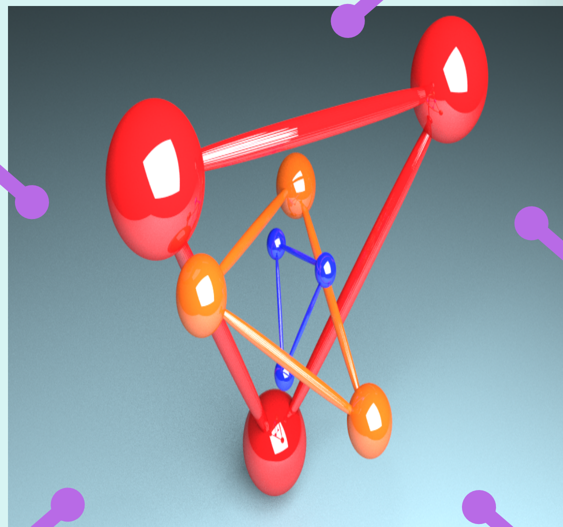
IOP Publishing — Reports on Progress in Physics

Rep. Prog. Phys. 80 (2017) 056001 (78pp) https://doi.org/10.1088/1361-6633/aa50e8

Review

Efimov physics: a review

Pascal Naidon[1] and Shimpei Endo[2]



N·H ELSEVIER — PHYSICS REPORTS

Physics Reports 347 (2001) 373–459 www.elsevier.com/locate/physrep

The three-body problem with short-range interactions

E. Nielsen[a,b], D.V. Fedorov[c], A.S. Jensen[c], E. Garrido[d,*]

ELSEVIER — Available online at www.sciencedirect.com SCIENCE @ DIRECT® — PHYSICS REPORTS

Physics Reports 428 (2006) 259–390 www.elsevier.com/locate/physrep

Universality in few-body systems with large scattering length

Eric Braaten[a], H.-W. Hammer[b,c,*]

IOP Publishing — Journal of Physics B: Atomic, Molecular and Optical Physics

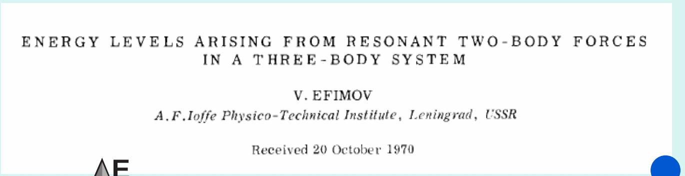
J. Phys. B: At. Mol. Opt. Phys. 51 (2018) 043001 (49pp) https://doi.org/10.1088/1361-6455/aaa116

Tutorial

Few-body physics in resonantly interacting ultracold quantum gases

José P D'Incao

Efimov Physics in ultracold gases: A quick overview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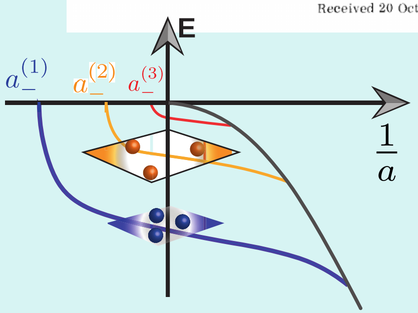

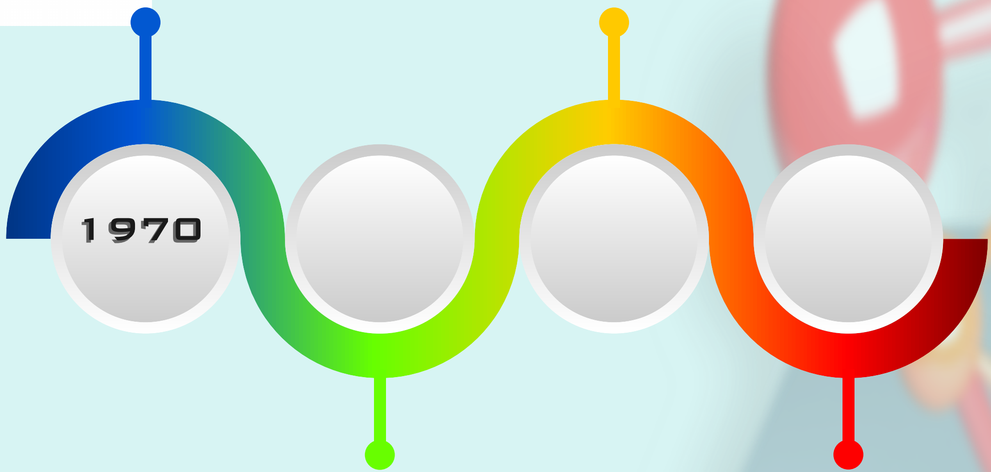

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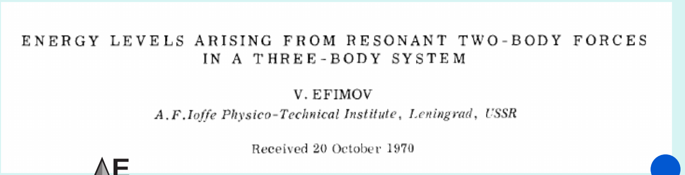
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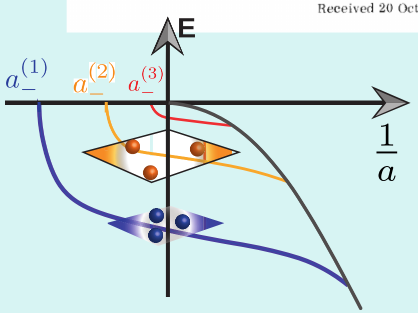

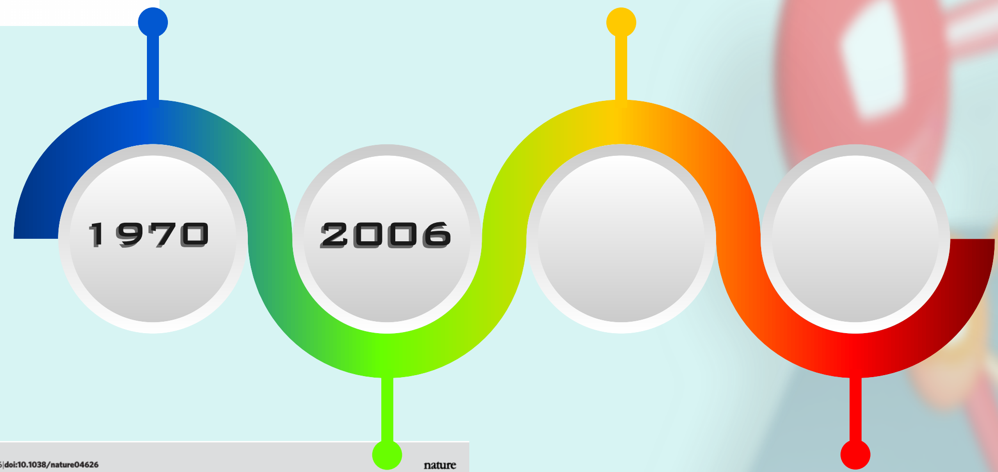

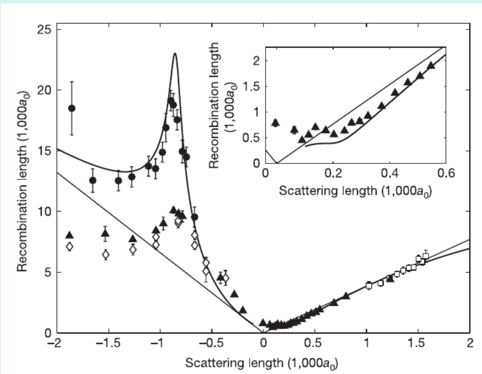


Vol 440|16 March 2006|doi:10.1038/nature04626 nature

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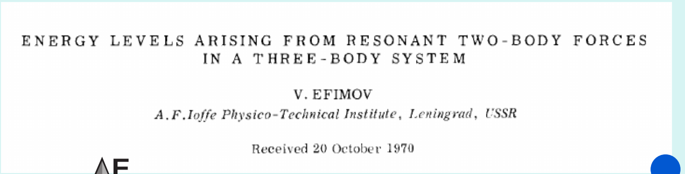

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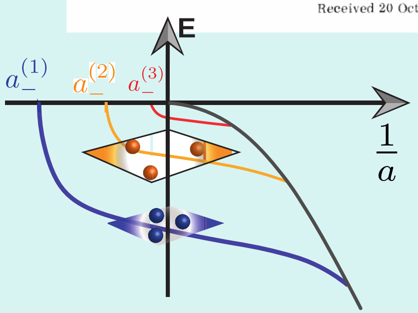

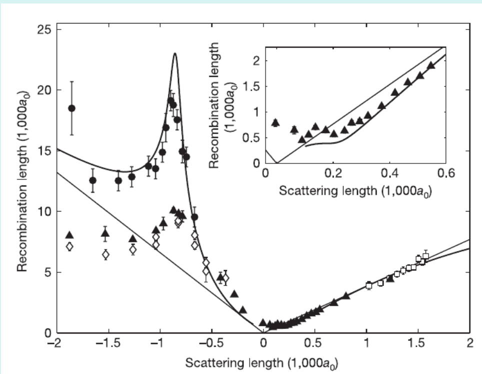

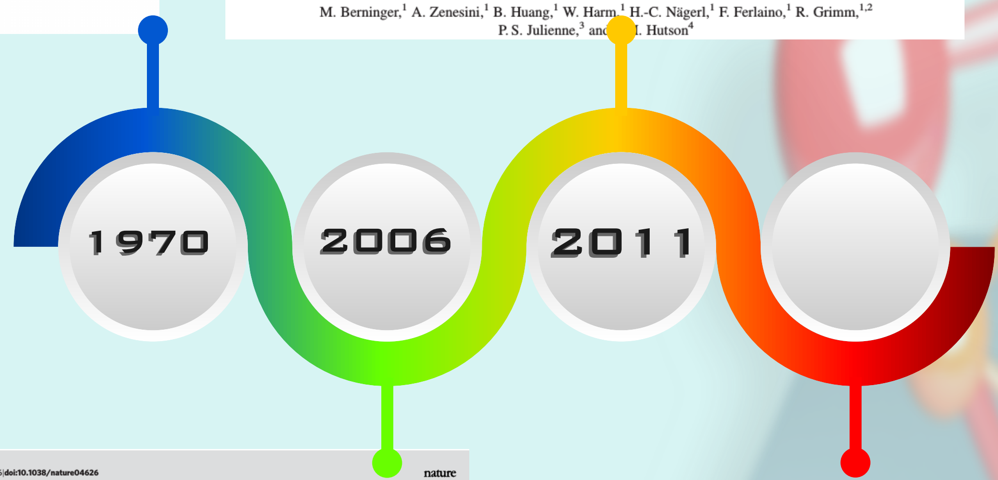

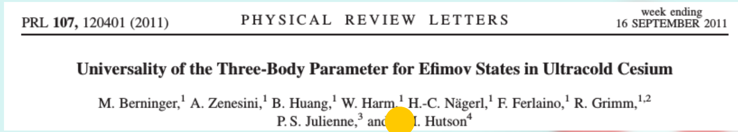

PRL 107, 120401 (2011) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2011

Universality of the Three-Body Parameter for Efimov States in Ultracold Cesium

M. Berninger,[1] A. Zenesini,[1] B. Huang,[1] W. Harm,[1] H.-C. Nägerl,[1] F. Ferlaino,[1] R. Grimm,[1,2] P. S. Julienne,[3] an… I. Hutson[4]

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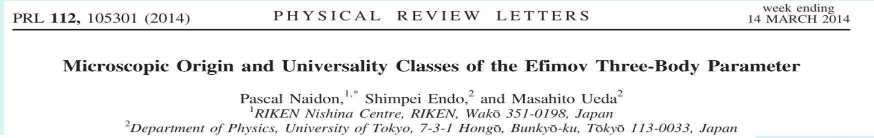
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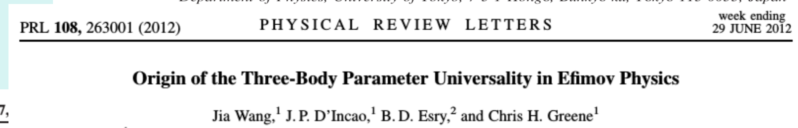
[2]Department of Physics, University of Tokyo, 7-3-1 Hongō, Bunkyō-ku, Tōkyō 113-0033, Japan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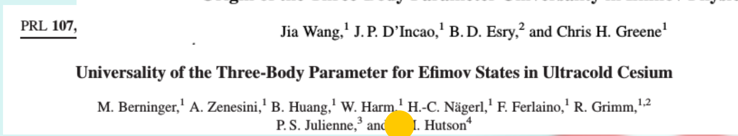
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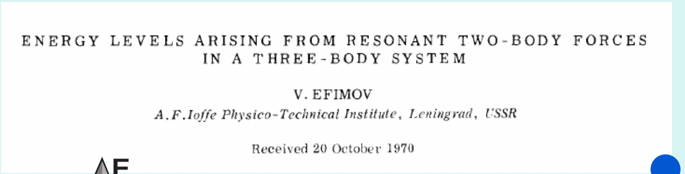
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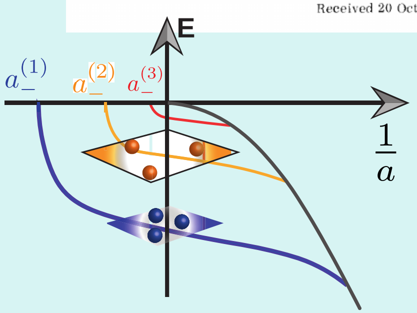

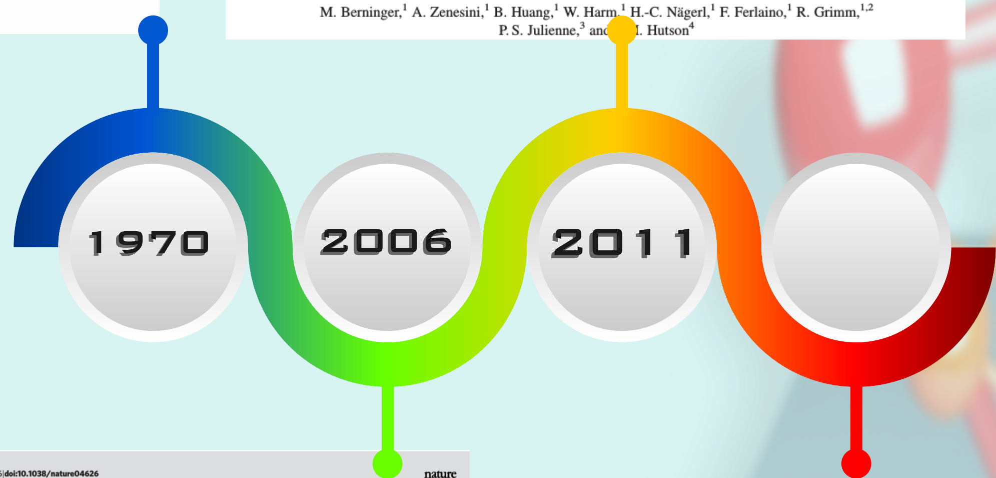

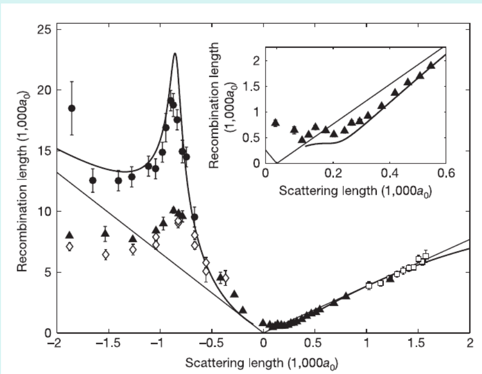

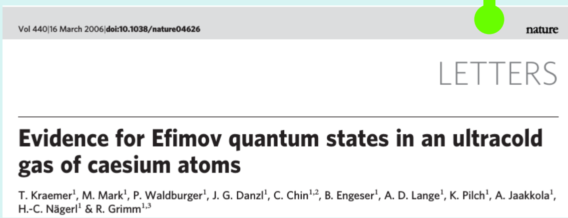
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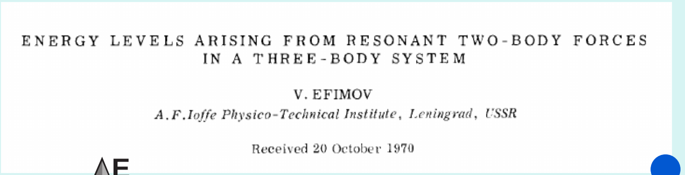
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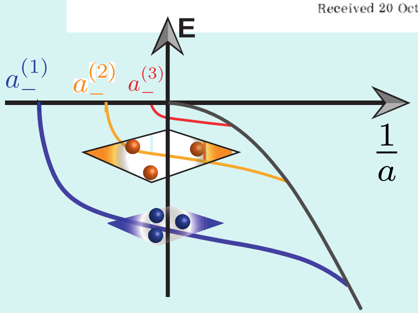

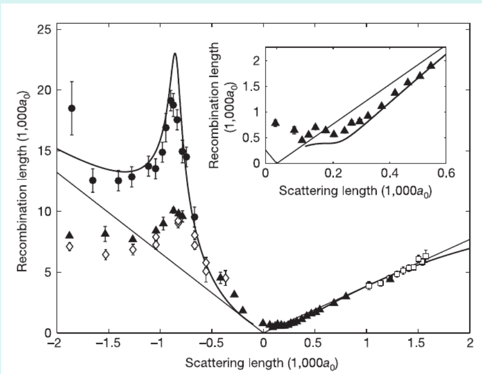

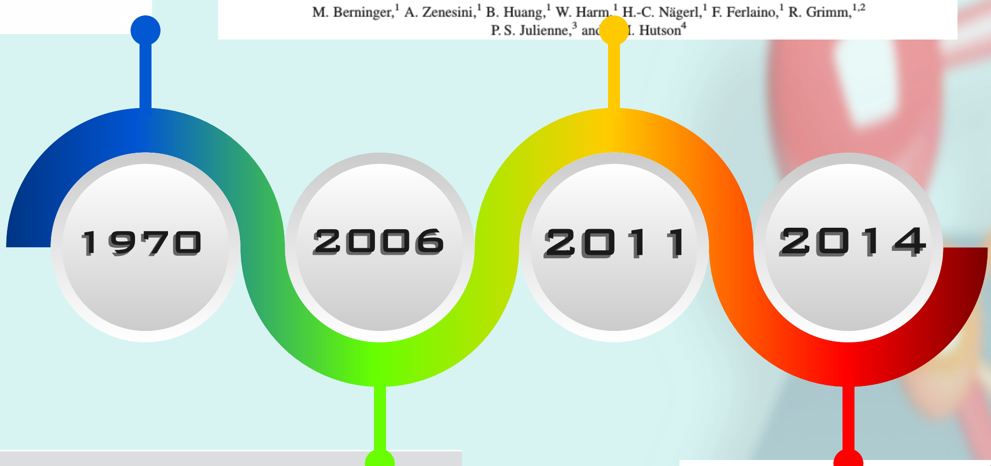


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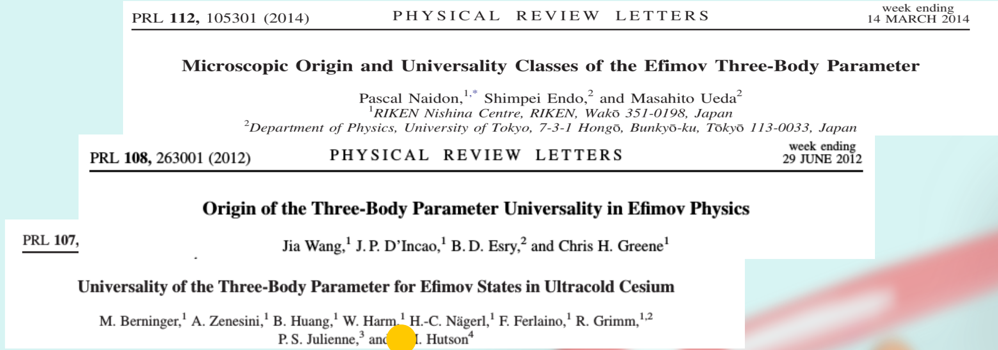
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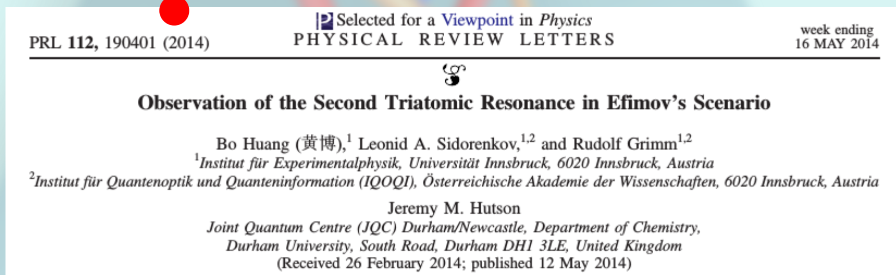
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PRL 112, 190401 (2014) PHYSICAL REVIEW LETTERS week ending 16 MAY 2014

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*

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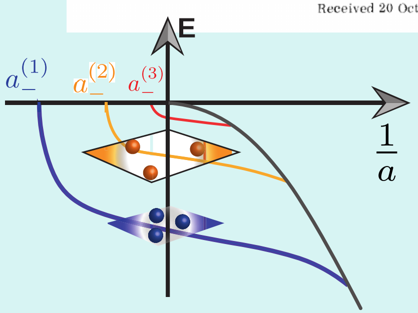

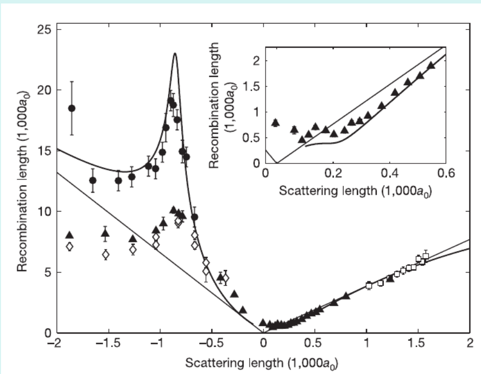

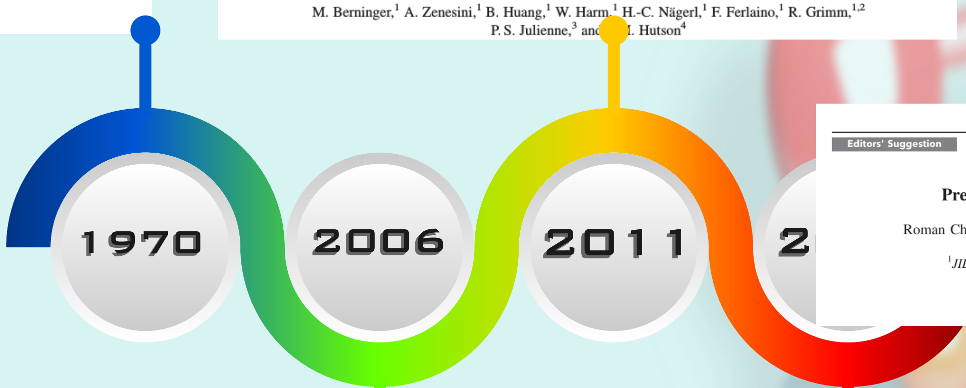

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PHYSICAL REVIEW LETTERS 123, 233402 (2019)
Editors' Suggestion Featured in Physics

Precision Test of the Limits to Universality in Few-Body Physics

Roman Chapurin,[1] Xin Xie,[1] Michael J. Van de Graaff,[1] Jared S. Popowski,[1] José P. D'Incao,[1]
Paul S. Julienne,[2] Jun Ye,[1] and Eric A. Cornell[1]
[1]*JILA, National Institute of Standards and Technology, and the University of Colorado, Department of Physics, Boulder, Colorado 80309, USA*
[2]*Joint Quantum Institute, National Institute of Standards and Technology, and the University of Maryland, College Park, Maryland 20742, USA*

Homo-vs-heteronuclear Efimov Physics

Motivation

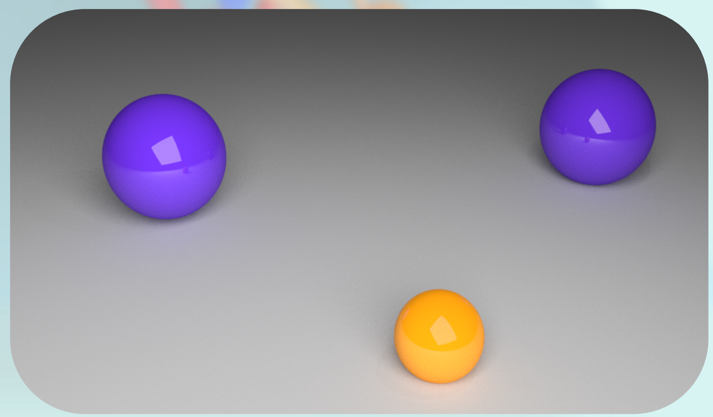
- Investigate the role of Efimov physics in collisions in systems with two heavy - one light particle
- Identify novel phenomena which govern the physics of a mass-imbalanced gas

Why mass-imbalanced systems?

- Three-body collisions in these systems possess far richer physics than in the case of equal mass particles
- Experimentally are more favorable than in the case of equal mass atoms
  - In the homonuclear case the Efimov states scale by ~ 22.7
  - In heteronuclear collisions the scaling factor is reduced

However...

- For heteronuclear systems the parameter space is larger
  - Intraspecies (heavy-heavy) scattering length, a_{HH}
  - Interspecies (heavy-light) scattering length, a_{HL}
- Both scattering lengths may vary in sign
- mass-ratio is an additional parameter



Homo-vs-heteronuclear Efimov Physics

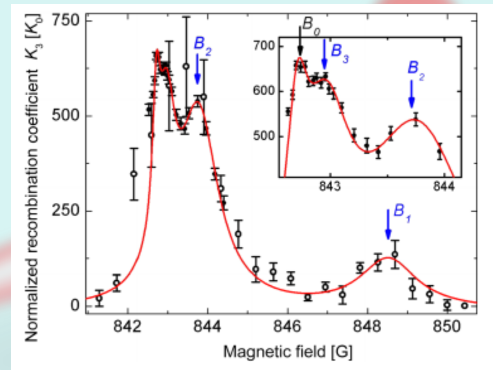
- Recent experimental evidences suggest much richer Efimov physics

- Chin's group: $a_{\mathrm{CsCs}} \gtrless 0$ & $a_{\mathrm{LiCs}} \gtrless 0$

PRL 113, 240402 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Geometric Scaling of Efimov States in a ^{6}Li-^{133}Cs Mixture

Shih-Kuang Tung, Karina Jiménez-García, Jacob Johansen, Colin V. Parker, and Cheng Chin*



nature physics LETTERS
PUBLISHED ONLINE: 15 MAY 2017 | DOI: 10.1038/NPHYS4130

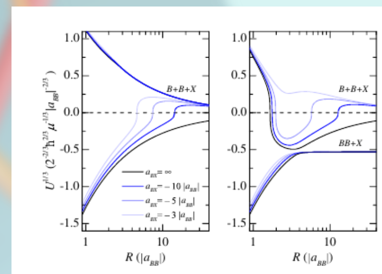
Testing universality of Efimov physics across broad and narrow Feshbach resonances

Jacob Johansen, B. J. DeSalvo, Krutik Patel and Cheng Chin*

Table 1 | Summary of Efimov resonances for the three Feshbach resonances in Li-Cs at 843 (ref. 12), 889, and 893 G.

B_0 (G)	s_{res}	a_{CsCs} (a_0)	$a_-^{(2)}$ (a_0)	$a_{th}^{(2)}$ (a_0)
888.577(10)(10)	0.66	200	−2,050(60)	−2,150
892.648(1)(10)	0.05	260	−3,330(240)	−2,200
842.750(1)(3)	0.66	−1,400	−1,635(60)	−1,680

Here, B_0 indicates the Feshbach resonance position, s_{res} the Feshbach resonance strength, a_{CsCs} the Cs-Cs scattering length, $a_-^{(2)}$ the resonance position associated with the second Efimov state, and $a_{th}^{(2)}$ the prediction from the universal theory using a single-channel model[28,29].

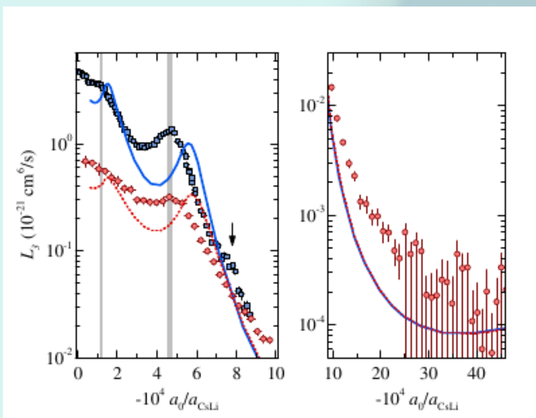


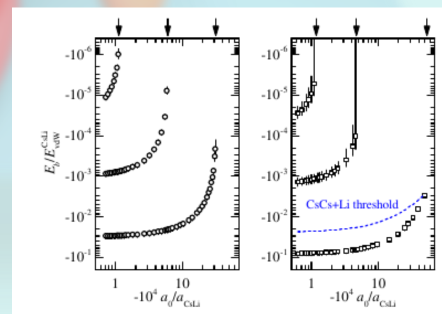
- Weidermüller's group: $a_{\mathrm{CsCs}} > 0$ & $a_{\mathrm{LiCs}} < 0$

PRL 117, 153201 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

Heteronuclear Efimov Scenario with Positive Intraspecies Scattering Length

Juris Ulmanis,[1] Stephan Häfner,[1] Rico Pires,[1] Eva D. Kuhnle,[1] Yujun Wang,[2,‡] Chris H. Greene,[3,*] and Matthias Weidemüller[1,4,†]

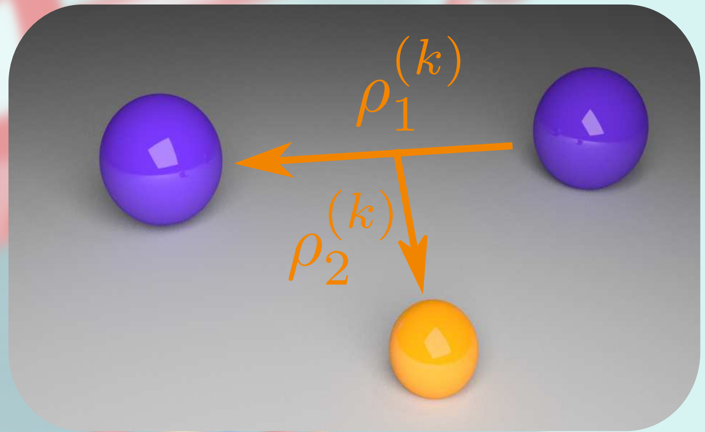




A system of mass-imbalanced atoms

- Consider a system of two heavy and one light particle

$$H_{tot} = \sum_{i=1}^{3} -\frac{\hbar^2}{2m_i}\nabla_i^2 + \sum_{i>j} V_{i,j}(r_{ij})$$



- The mutual two-body interactions are approximated via zero-range pseudopotentials

- Theoretical approach: The adiabatic hyperspherical representation

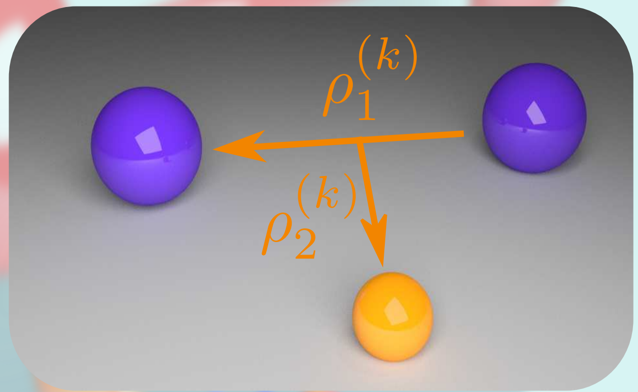
Adiabatic Hyperspherical Representation

- Hyperspherical coordinates:

$$\rho_1^{(k)} = R\sin\alpha^{(k)},\ \ \rho_2^{(k)} = R\cos\alpha^{(k)}\ \ \&\ \Omega^{(k)} = \{\omega_1^{(k)}, \omega_2^{(k)}, \alpha^{(k)}\}$$

- The total wavefunction reads:

$$\Psi(R,\Omega) = \sum_n R^{-5/2} F_n(R)\Phi_n(R;\Omega)$$



- The Hyperangular Equation for contact interactions:

$$H_{ad}(R;\Omega)\Phi_n(R;\Omega) = U_n(R)\Phi_n(R;\Omega)$$

- 1D coupled hyper-radial equations:

$$-\frac{\hbar^2}{2\mu}\frac{d^2}{dR^2}F_n(R) + (U_n(R)-E)F_n(R) = \frac{\hbar^2}{2\mu}\sum_m \left[2P_{nm}\frac{d}{dR} + Q_{nm}\right]F_m(R),$$

where $P_{nm} = \langle\Phi_n|\frac{\partial}{\partial R}|\Phi_m\rangle_\Omega$ and $Q_{nm} = \langle\Phi_n|\frac{\partial^2}{\partial R^2}|\Phi_m\rangle_\Omega$

E. Nielsen et al, Physics Reports 347, 373 (2001)

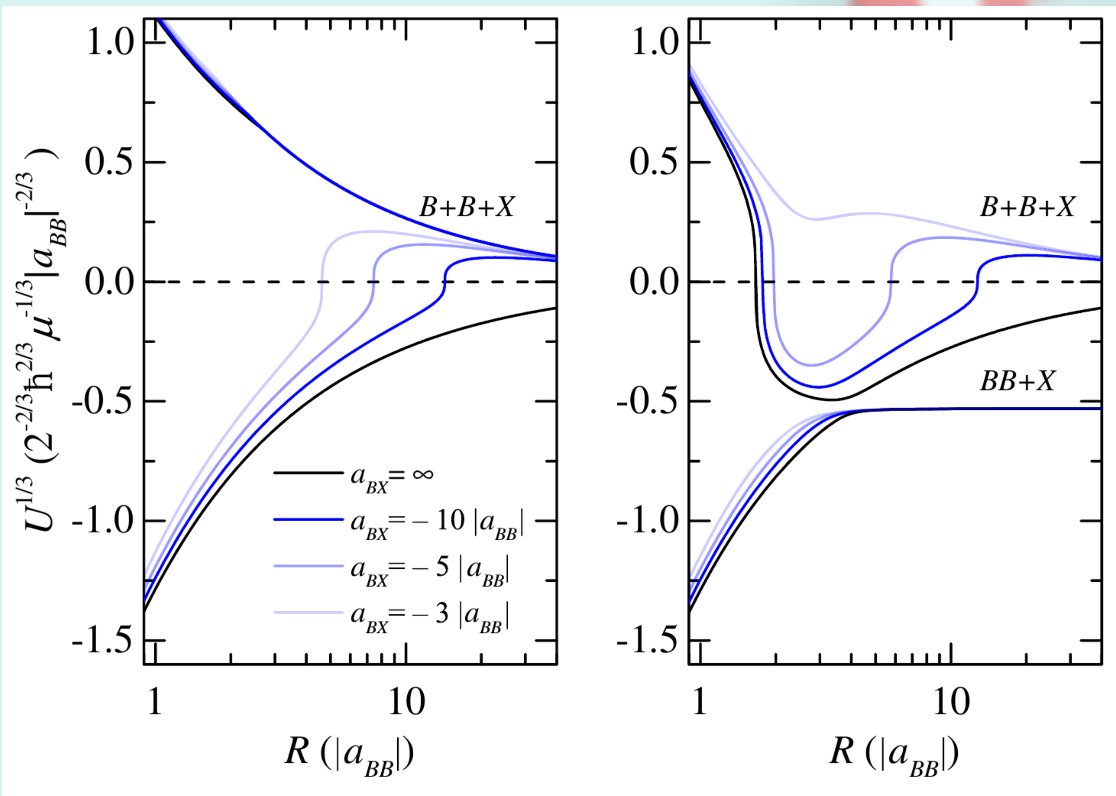
O. I. Kartavtsev and A. V. Malykh, JPB 40, 1429 (2007)

S.T. Rittenhouse et al, PRA 82, 022706 (2010)

Adiabatic Hyperspherical Representation

- Adiabatic potential curves
  - For $a_{HL} < 0$ and $a_{HH} \gtrless 0$

$a_{HH} < 0$ $\qquad\qquad$ $a_{HH} > 0$



Ulmanis et al, PRL 117, 153201 (2016)

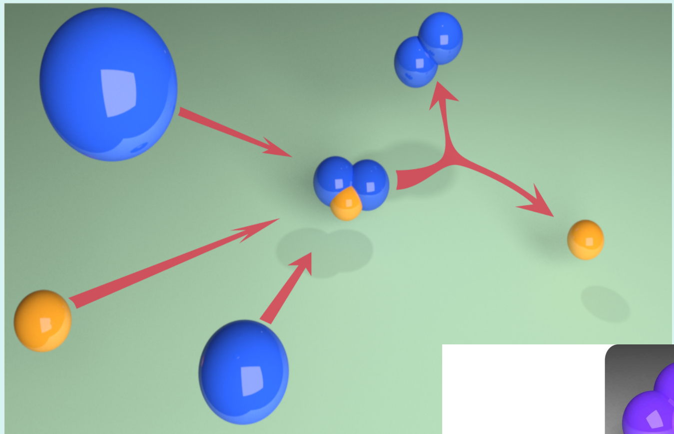
Three-body recombination into shallow dimers

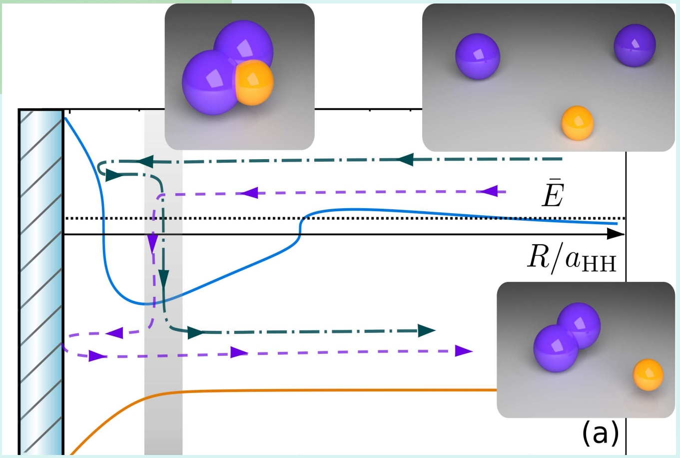
- Rich topology: Efimov resonances + Stückelberg minima
- A unique property of HHL systems

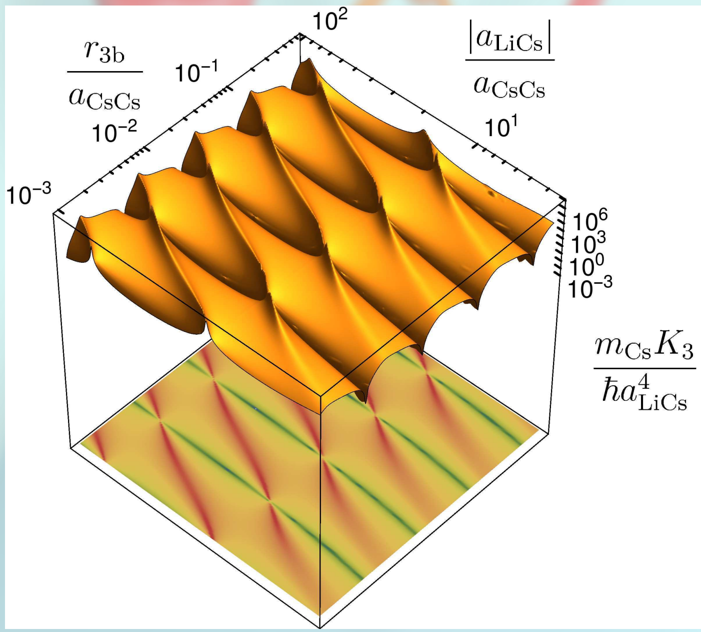
PHYSICAL REVIEW LETTERS **120,** 023401 (2018)

Ultracold Heteronuclear Three-Body Systems: How Diabaticity Limits the Universality of Recombination into Shallow Dimers

P. Giannakeas[1,2,*] and Chris H. Greene[1,†]

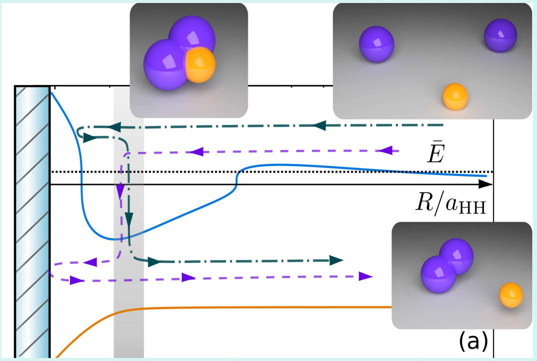


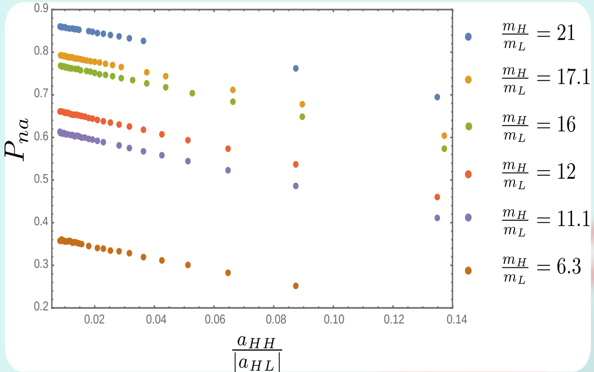




Three-body recombination into shallow dimers

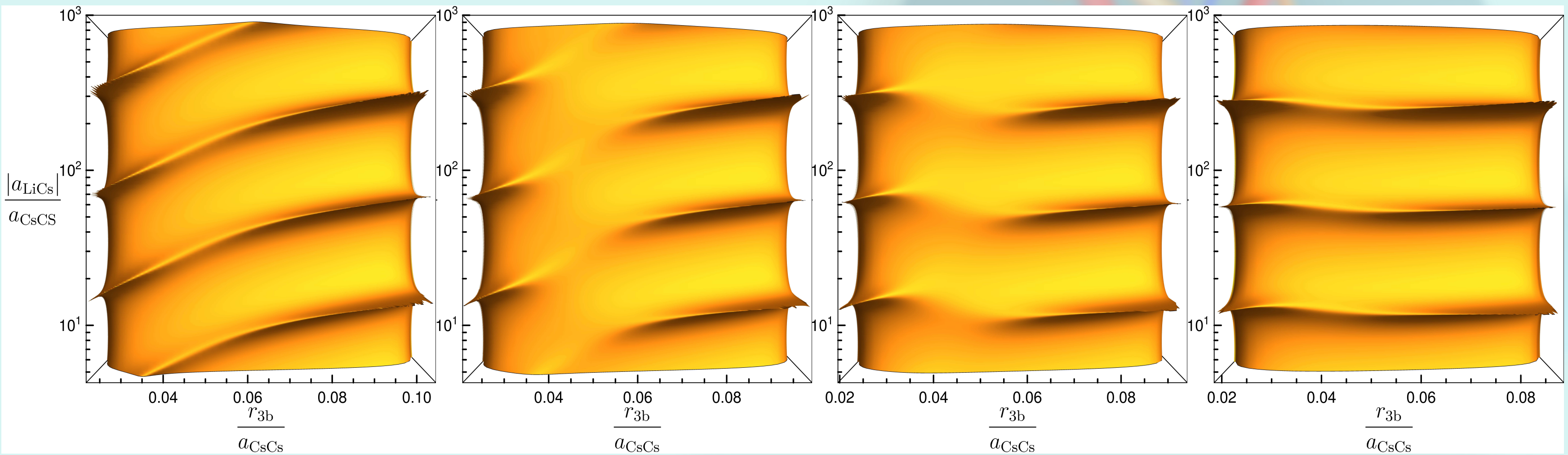
- How the "diabaticity" affects the resonant structure?





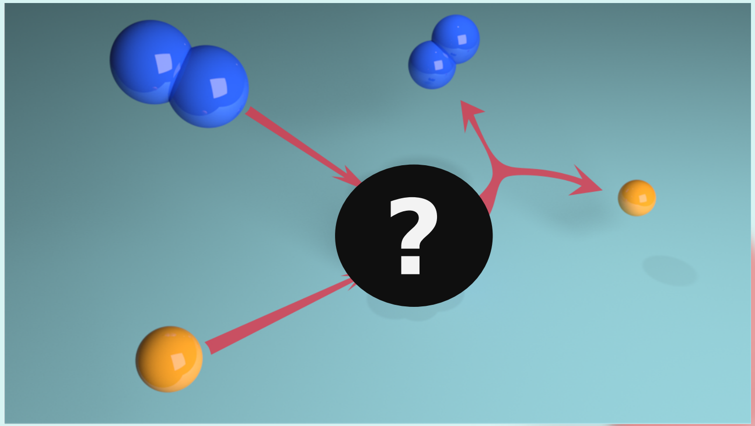
- Vary the Landau-Zener probability: Diabatic $\rightarrow$ Adiabatic

- The less diabatic are the collisions the more universal are the Efimov resonances

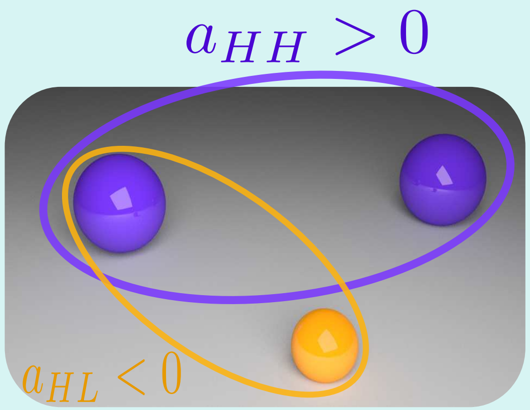


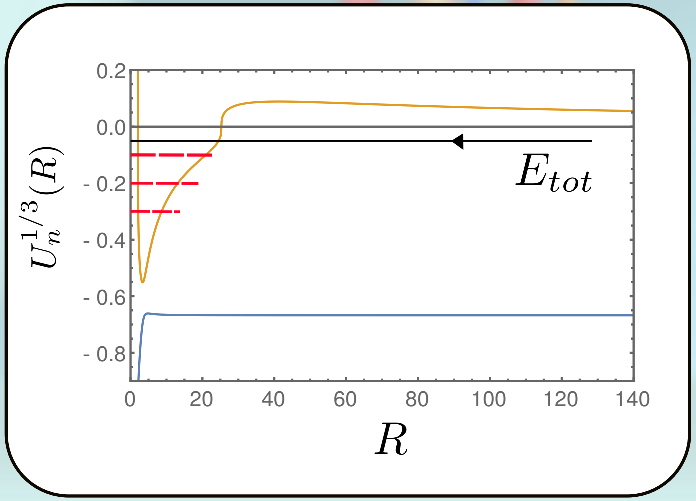
Atom-dimer collisions in mass-imbalanced gases

Physical system



- Consider a heavy-heavy dimer colliding with a light atom
- The energy regime of interest lies below the break-up threshold





Atom-dimer collisions in mass-imbalanced gases

- Atom-dimer collisions are treated with Faddeev equations
- The pairwise interactions are modeled via Yamaguchi potentials
- Naidon's type of Yamaguchi potential $\rightarrow$ successfully captures the physics of Van der Waals interactions ($\sim 1/r^6$)

PHYSICAL REVIEW A **90**, 022106 (2014)

Physical origin of the universal three-body parameter in atomic Efimov physics

Pascal Naidon,[1,*] Shimpei Endo,[2,†] and Masahito Ueda[2]

PRL **112**, 105301 (2014) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2014

Microscopic Origin and Universality Classes of the Efimov Three-Body Parameter

Pascal Naidon,[1,*] Shimpei Endo,[2] and Masahito Ueda[2]

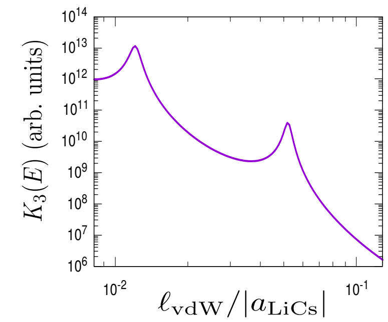
- Focus on ^{6}Li-^{133}Cs-^{133}Cs
- Using the Li-Cs Feshbach resonance at $B = 889$ G, where $a_{\mathrm{CsCs}} = 190\ a_0$
- Parameters are relevant to the experiments:

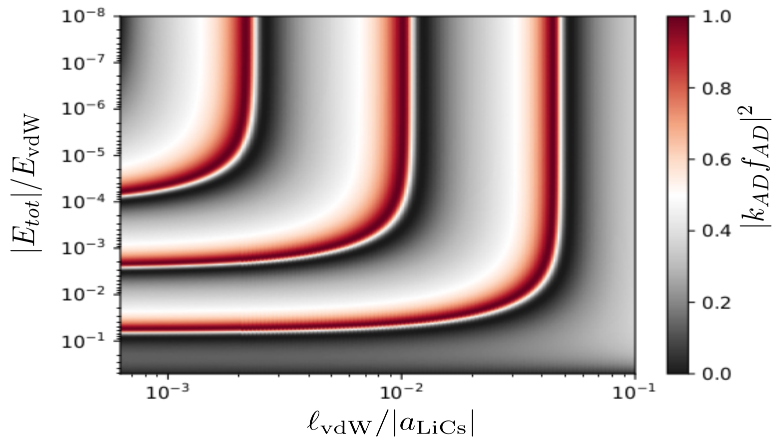
PRL **117**, 153201 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

Heteronuclear Efimov Scenario with Positive Intraspecies Scattering Length

Juris Ulmanis,[1] Stephan Häfner,[1] Rico Pires,[1] Eva D. Kuhnle,[1] Yujun Wang,[2,‡] Chris H. Greene,[3,*] and Matthias Weidemüller[1,4,†]

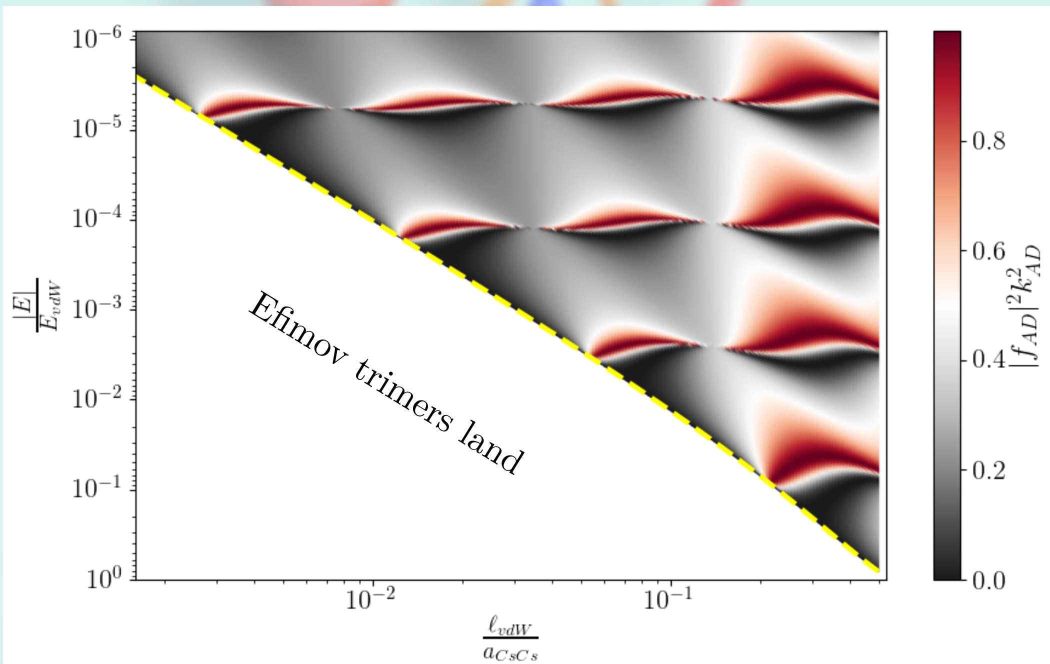
- K_3 and atom-dimer resonances near the break-up threshold are in agreement





Atom-dimer collisions in mass-imbalanced gases

- Atom-dimer collisions near unitarity $|a_{HL}| \to \infty$
- Collisions are more diabatic close to the unitarity limit
- Emerging Stückelberg physics in the atom-dimer spectra



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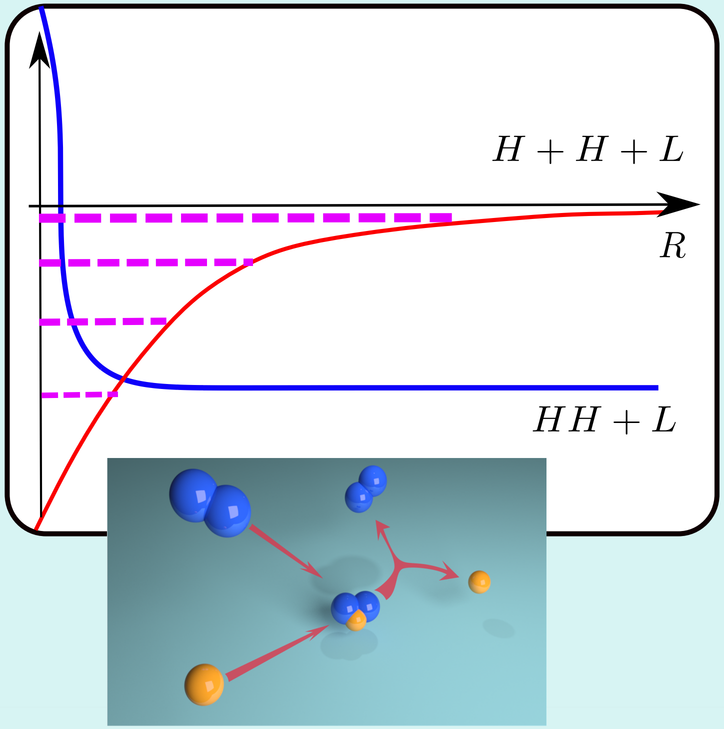
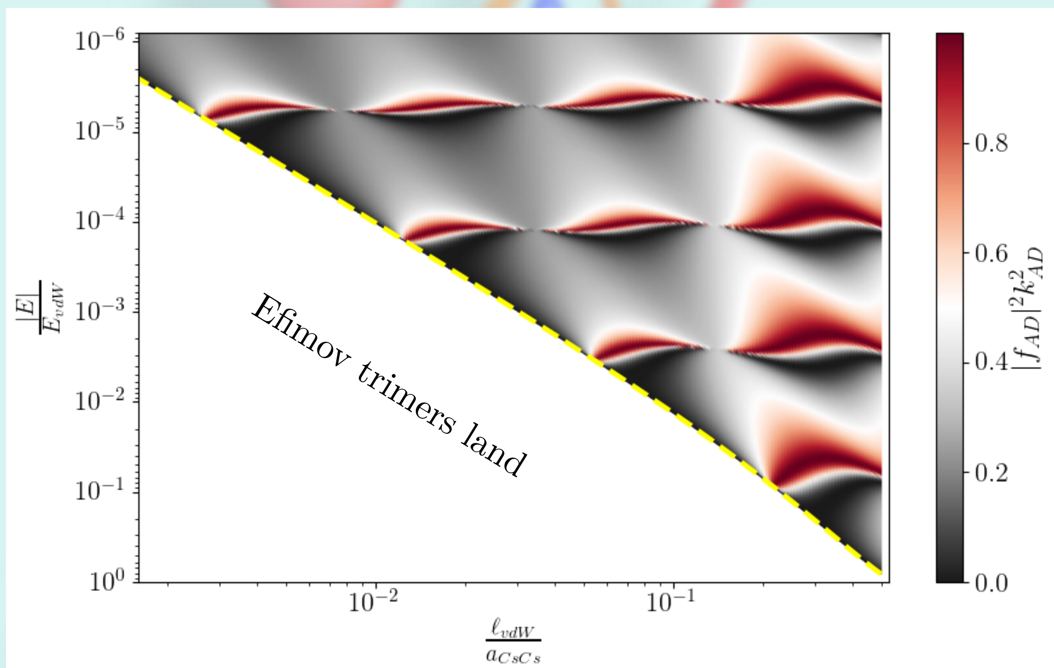
Intuitive Picture: **Diabatized** Hyperspherical potential curves





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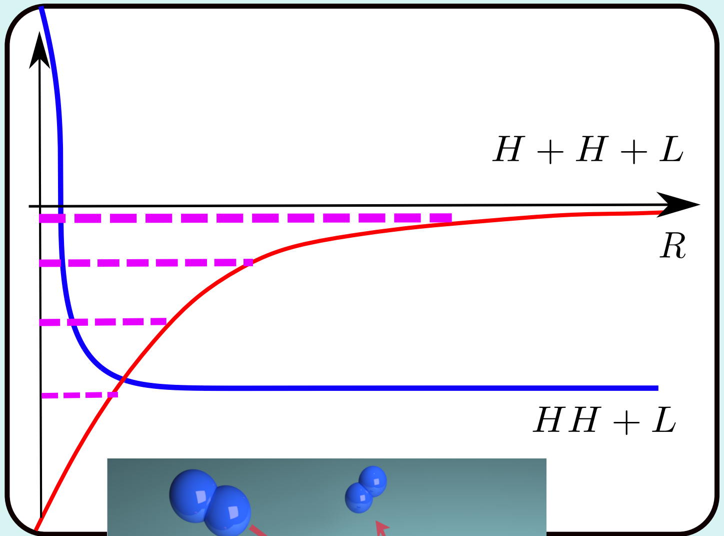
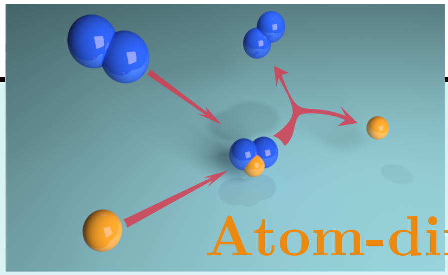
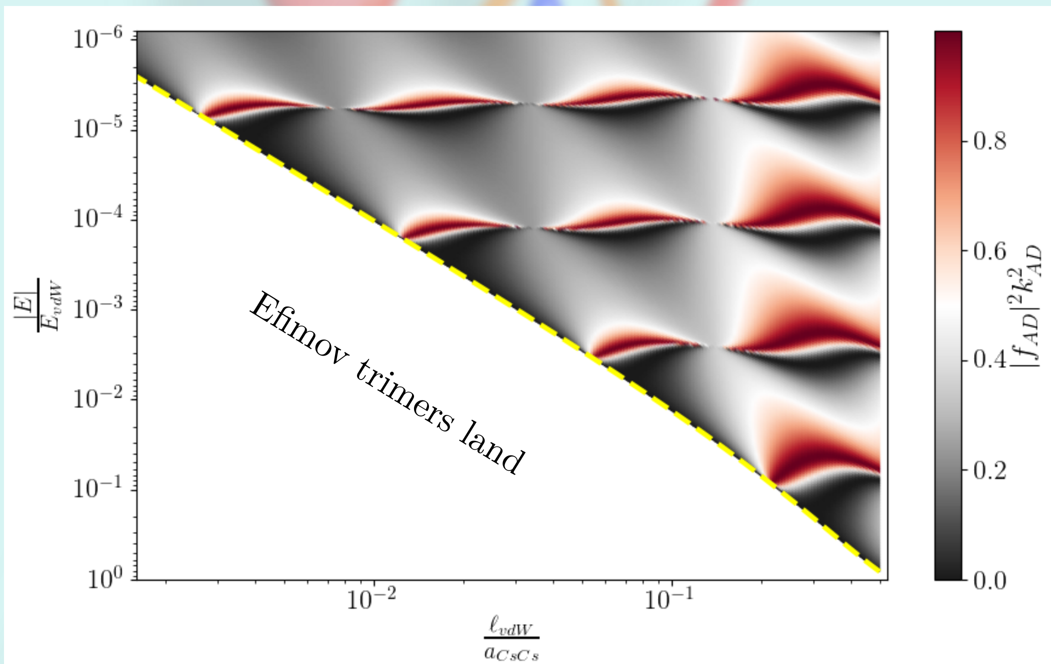
Intuitive Picture: **Diabatized**
Hyperspherical potential curves



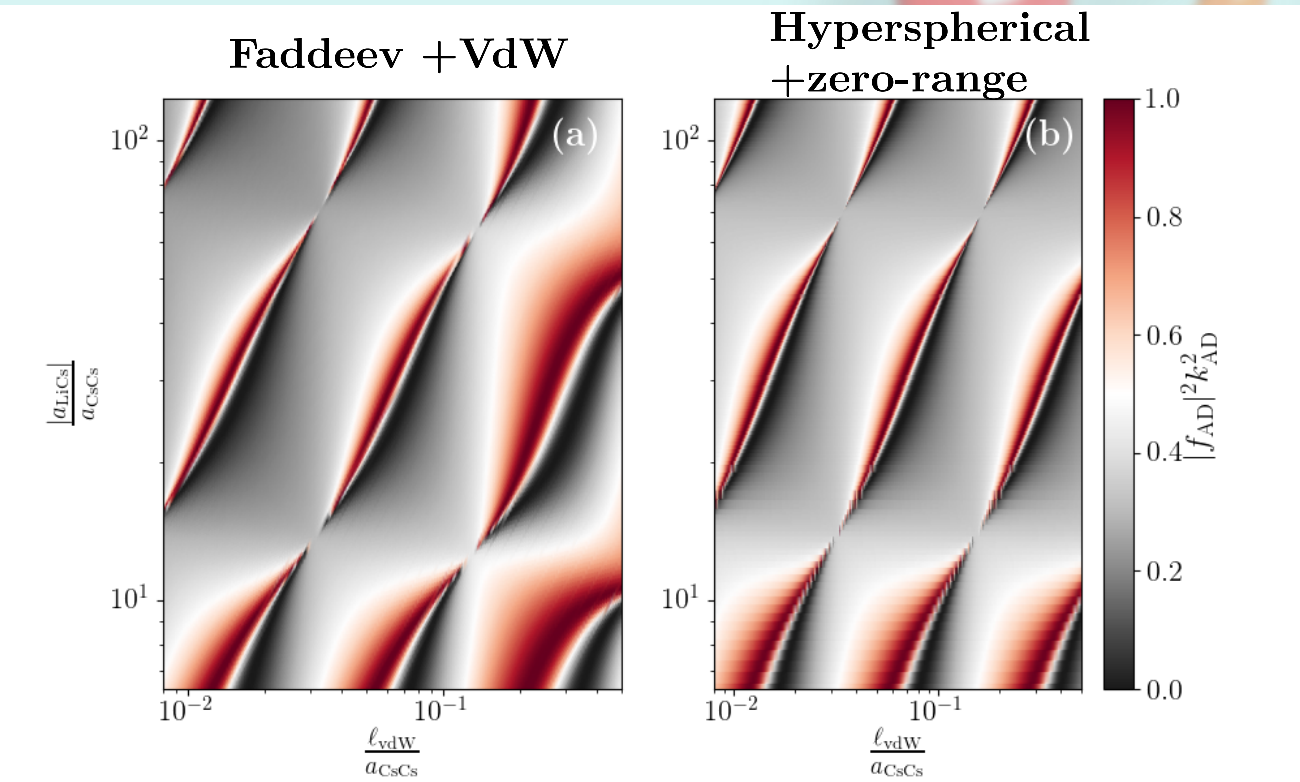




Atom-dimer resonances $\to$ **Fano-Feshbach mechanism**

Atom-dimer collisions in mass-imbalanced gases

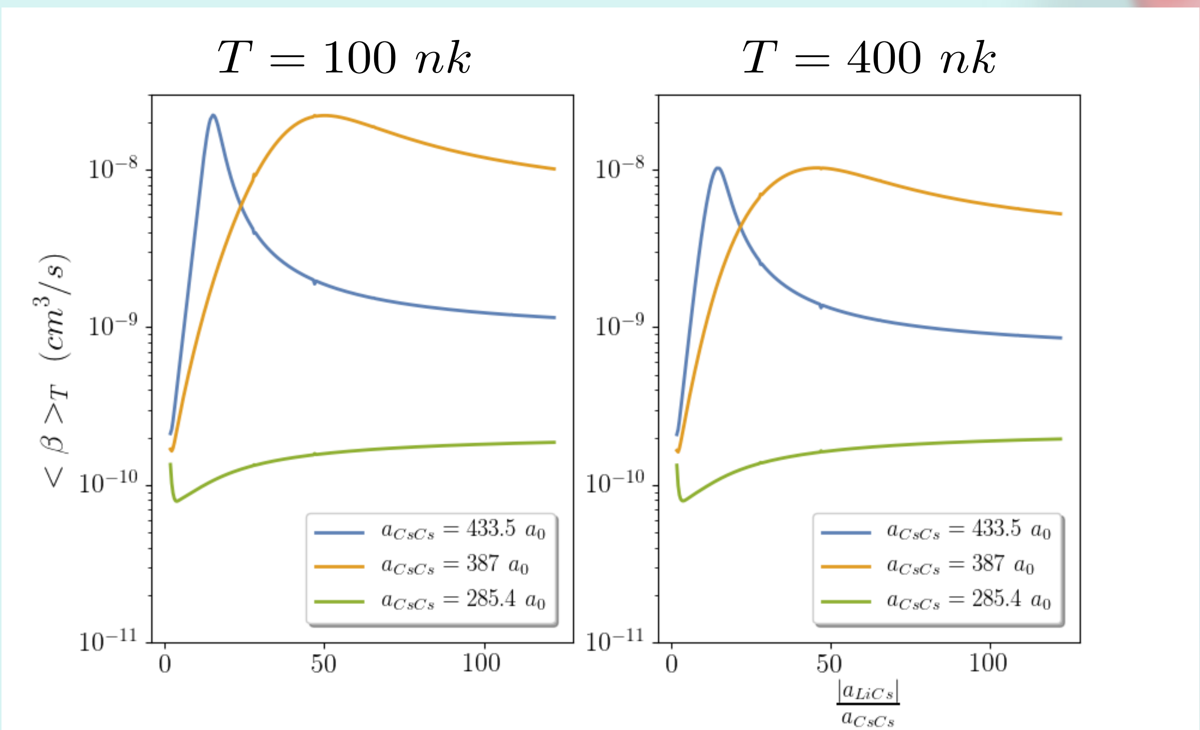
- **Probing** the regime of univerality at near break-up threshold energies
- Comparing **zero-range Hyperspherical coordinates treatment** with **Faddeev approach**
- Van der Waals physics is important for $a_{CsCs} < 10^3\ a_0$

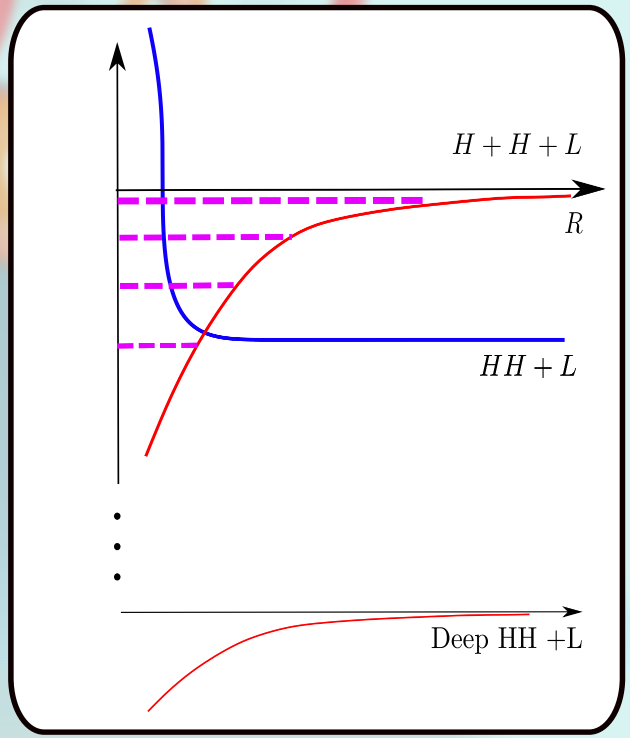


Atom-dimer collisions in mass-imbalanced gases

- Considering inelastic processes, i.e. **atom-dimer relaxation**
- Atom-dimer collisions can go to a deeply dimer+ a recoiling atom
- Quantity of interest: **Thermally averaged atom-dimer relaxation coefficient**

For ^{6}Li-^{133}Cs-^{133}Cs:



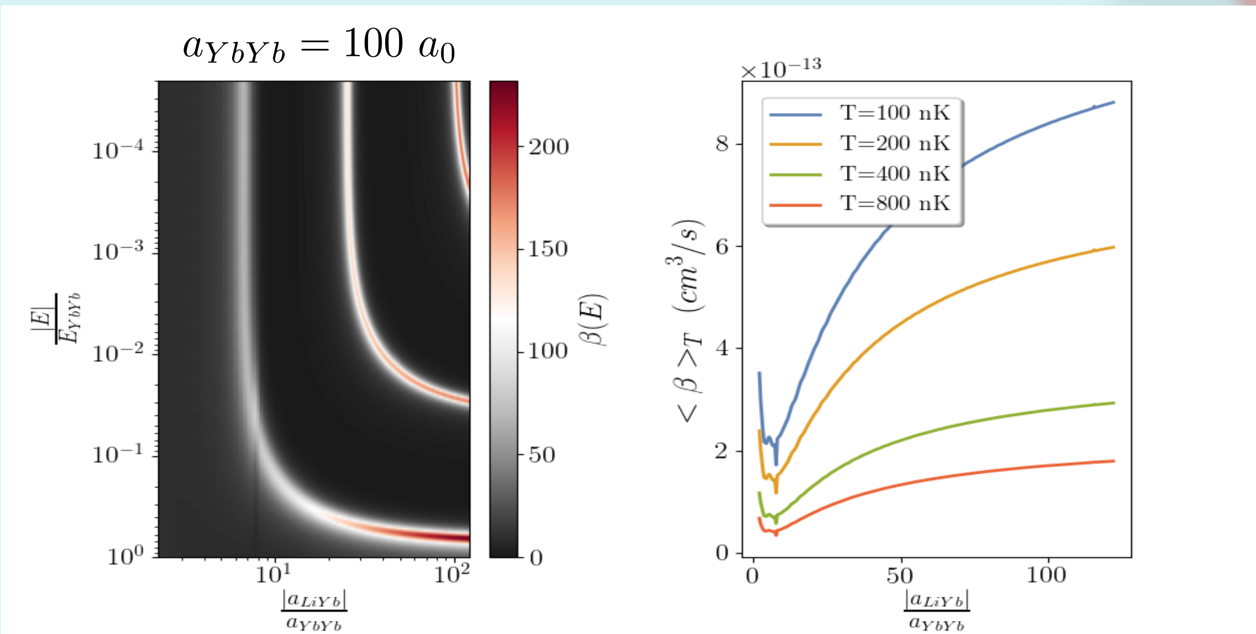


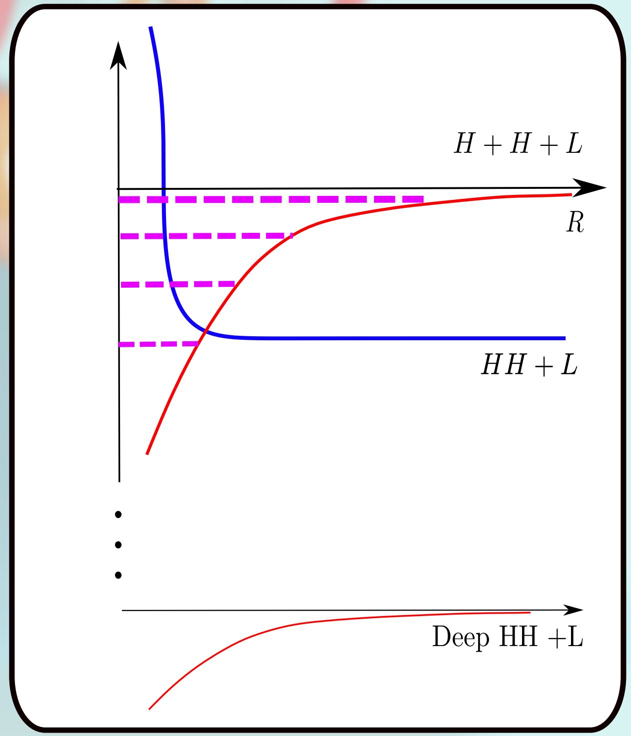
Atom-dimer collisions in mass-imbalanced gases

- Large mass ratio are more favorable to observe the Fano-Feshbach atom-dimer resonances via deep dimer relaxation processes

- Available ranges of heavy-heavy scattering lengths is a nessecity

For ^{6}Li-^{174}Yb-^{174}Yb:





Conclusions

- Efimov physics possesses unique feautures in mass-imbalanced ultracold gases
- **Three-body recombination** processes to shallow dimers exhibit intertwined Efimov resonances + **Stückelberg minima**
- **Atom-dimer** resonances fulfill Fano-Feshbach scenario due to **Efimov trimer states**