Fermionic Efimov States
& A New Emerging Universality

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Collaborators

Theory

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Experiment

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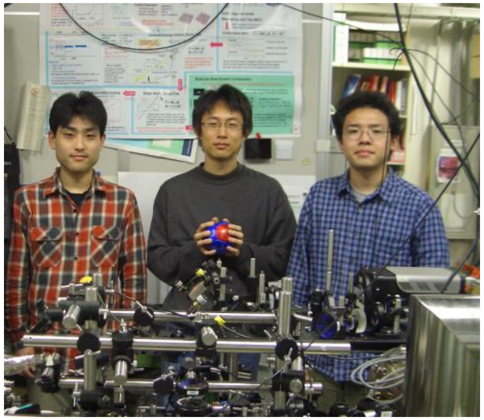
Munekazu Horikoshi (U. Tokyo)

Takashi Mukaiyama (U. Electro-Comm.)



P. Naidon, MU, PRL **103**, 073203 (2009); Compt. Rend. Phys. **12**, 13 (2011)

S. Nakajima, et al., PRL **105**, 023201 (2010); ibid. **106**, 143201 (2011)

P. Naidon, E. Hiyama, and M. U., arXiv: 1109.5807

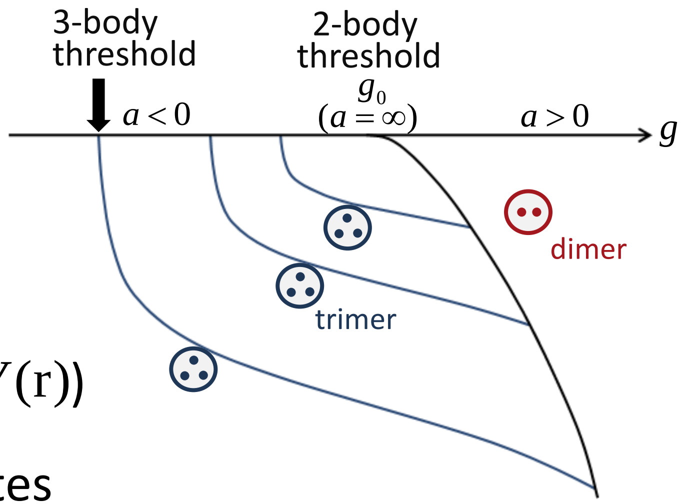
What's the Efimov Effect?

V. Efimov, Phys. Lett. **33B**, 563 (1970)
Sov. J. Nucl. Phys. **12**, 589 (1971)

3 spinless neutral particles, interacting through a potential

$$gV(\mathrm{r}), \quad V(\mathrm{r}) < 0$$

Near a 2-body threshold $(g = g_0)$, an effective 3-body force emerges:

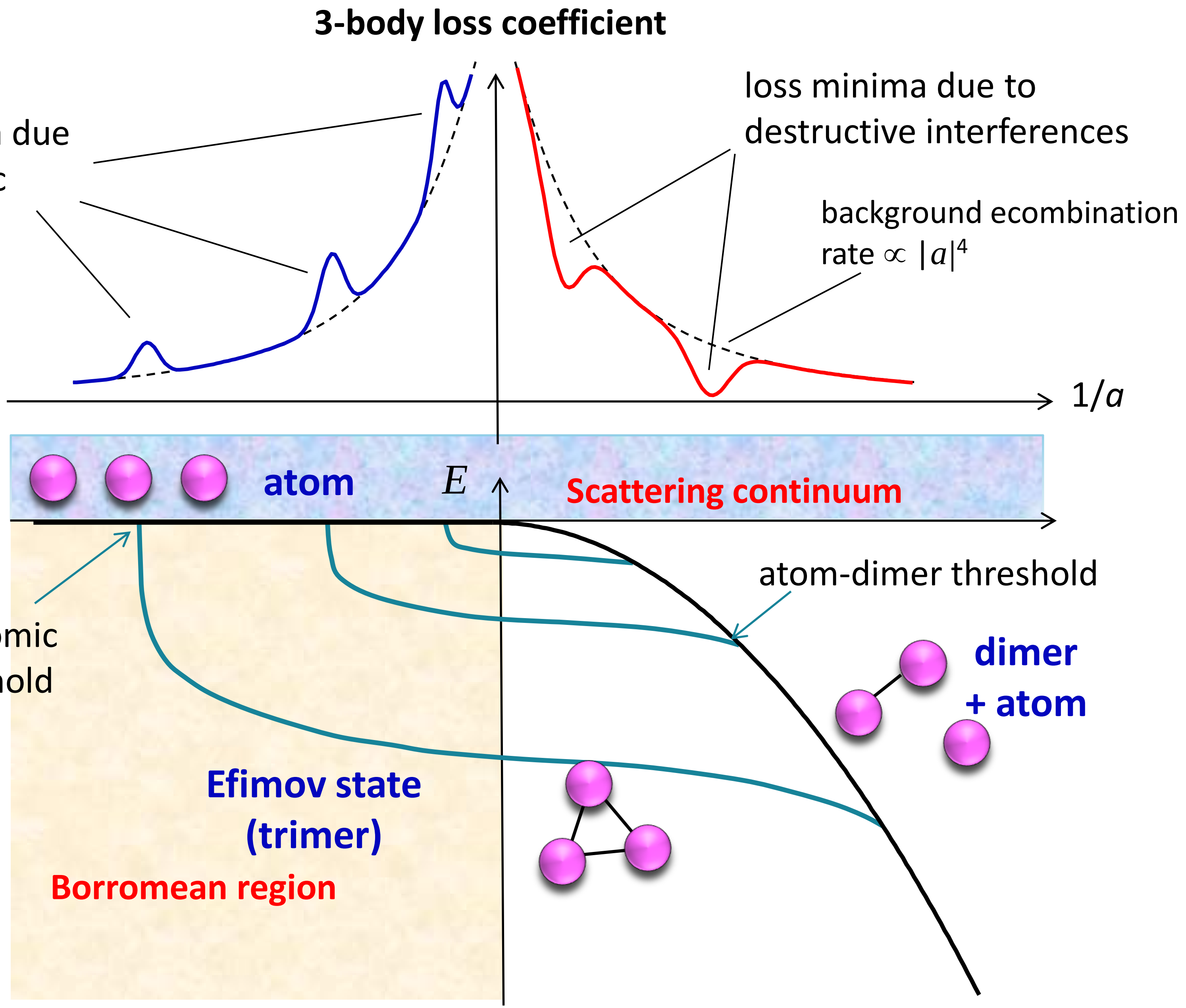


- resonant character: $a \gg r_0$ = range of forces
- universal long-range attraction $-R^{-2}$
  (independent of the detailed structure of $V(\mathrm{r})$)
- supports an infinitely many 3-body bound states
  with discrete scaling symmetry and accumulation point at $g = g_0$

$$\frac{a_{n+1}}{a_n} \approx e^{\pi/s_0} \approx 22.7, \quad s_0 = 1.00624\cdots$$ (universal scaling parameter)

"Matryoshka doll" scaling

Experimental Signatures: Loss Maxima and Minima



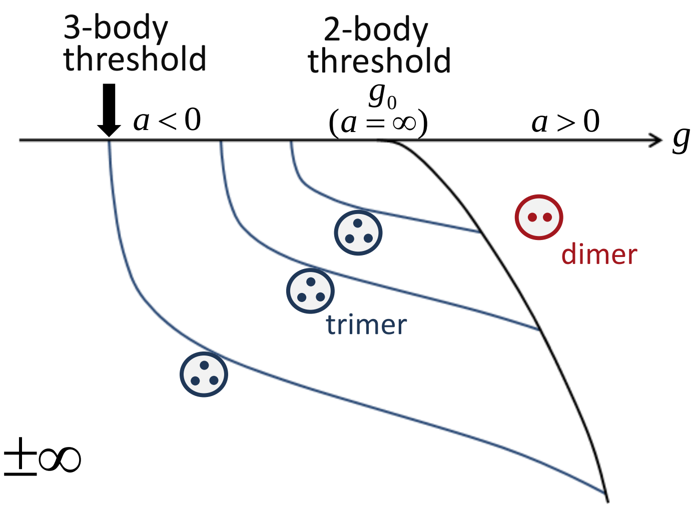
Some Remarks

- The universal attractive potential $\left(-R^{-2}\right)$ permits continuous scale invariance:

$$H=-\nabla_R^2-R^{-2}\xrightarrow{R\to\lambda R}\lambda^{-2}H$$

- However, because of the 3-body parameter κ_* only discrete scale invariance is permitted:

$$E_n\to e^{-\frac{2\pi}{s_0}(n-n_*)}\frac{\hbar^2\kappa_*^2}{M} \text{ as } n\to\infty \text{ with } a=\pm\infty$$

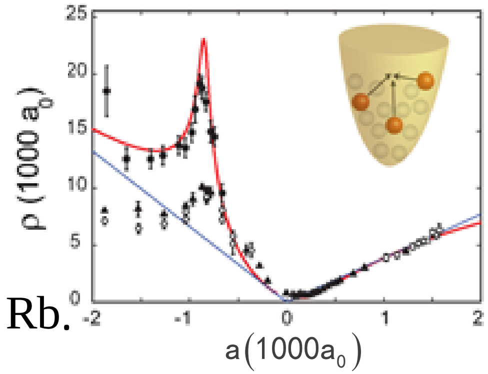


➢ The 3-body parameter is a free parameter in the Efimov theory.

➢ In principle, it can take any random value from one FBR to another, let alone from one atomic species to another.

➢ However, Nature seems to prefer otherwise! ← **main message of this talk**

Some Experimental Achievements in Ultracold Atomic Gases



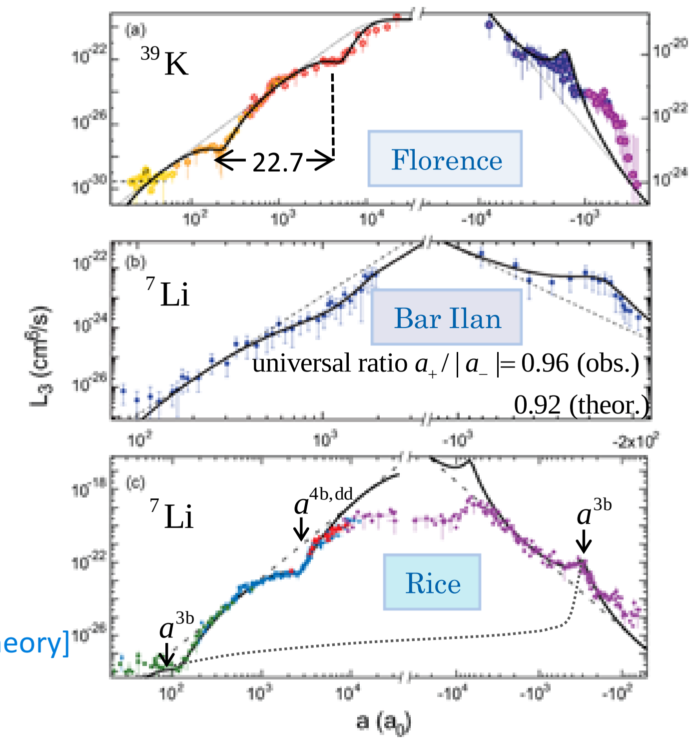
2006 Efimov trimers identified in ^{133}Cs.

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

B. D. Esry, et al., PRL **83**, 1751 (1999) [theory]

2008 Efimov trimers observed in a mass-imbalance system of ^{41}K & ^{87}Rb.

G. Barontini, et al., PRL **103**, 043201 (2009)



2009 Discrete scaling law between loss minima observed.

^{39}K M. Zaccanti, et al., Nature Phys. **5**, 586 (2009)

2009-2010 Universality across the Feshbach resonance

^{7}Li N. Gross, et al., PRL **103**, 163202 (2009)

PRL **105**, 103203 (2010)

cf. S. E. Pollack, et al., Science **326**, 1683 (2009)

M. Zaccanti, et al., ibid.

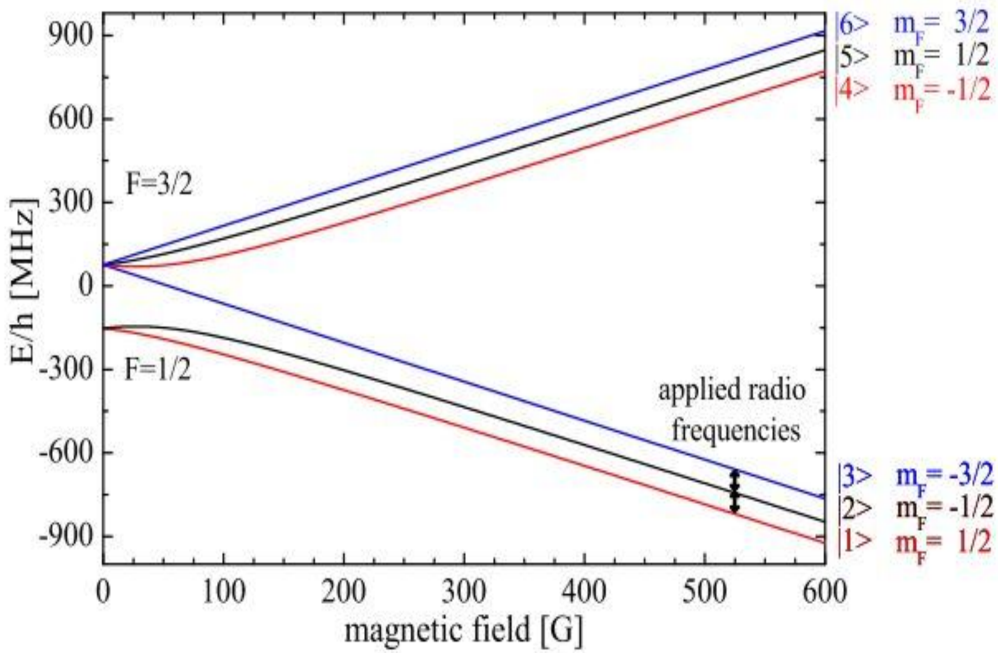
2009 A pair of universal tetramers for each Efimov trimer.

H.Hammer and L. Platter, Eur. Phys. J. A**32**, 113 (2007) [theory]

J. Von Stecher, et al., Nature Physics 5, **417** (2009) [theory]

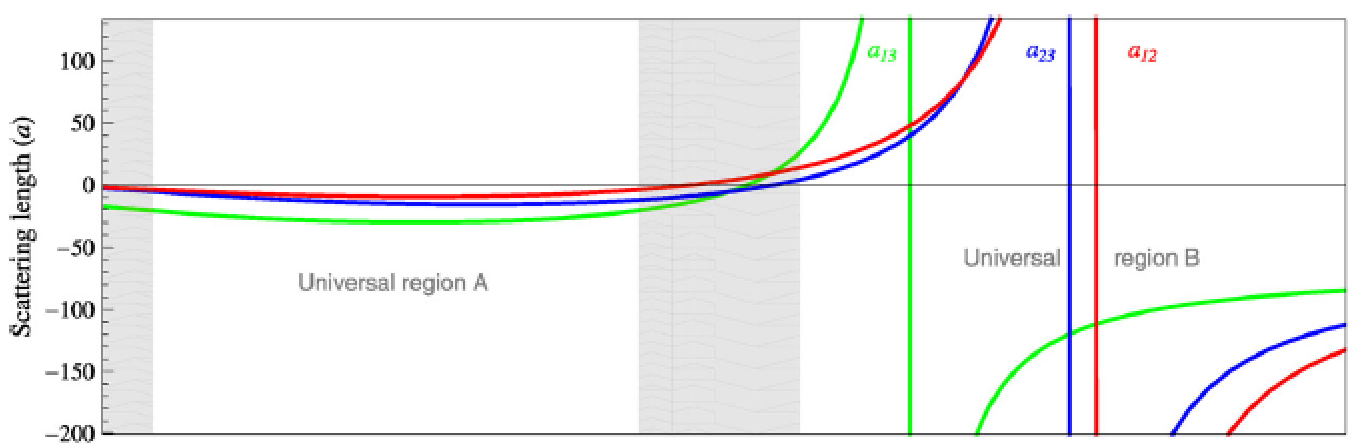
F. Ferlaino, et al., PRL **102**, 140401 (2009) [experiment]

Our System: 3-Component Fermi System of ^{6}Li



$$\frac{1}{2}\ (\text{electronic}) \otimes 1\ (\text{nuclear}) = \frac{1}{2} \oplus \frac{3}{2}\ (\text{hyperfine})$$

- **Broad FBR for each pair of states**
- **Two universal regions (A, B)**
- **Can test different aspects of Efimov physics:**
  - **tri-atomic resonance**
  - **atom-dimer resonance**

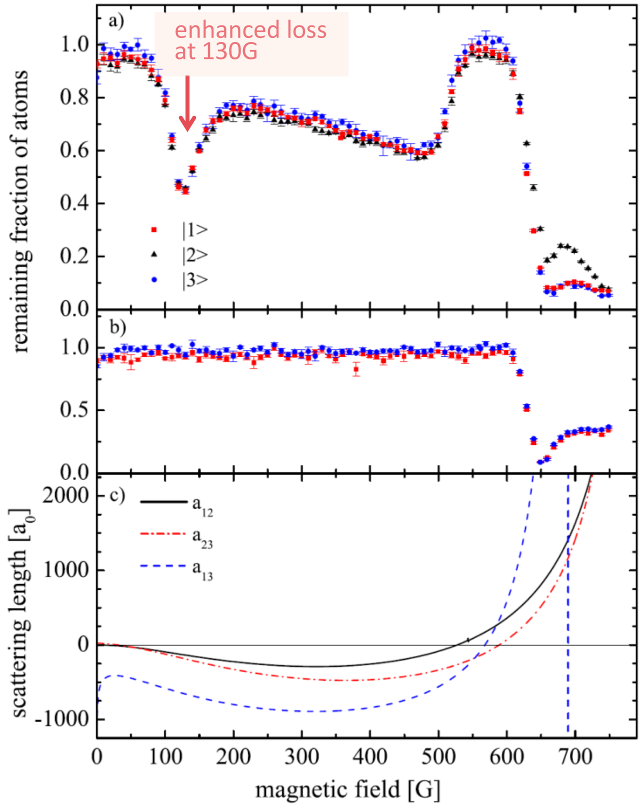


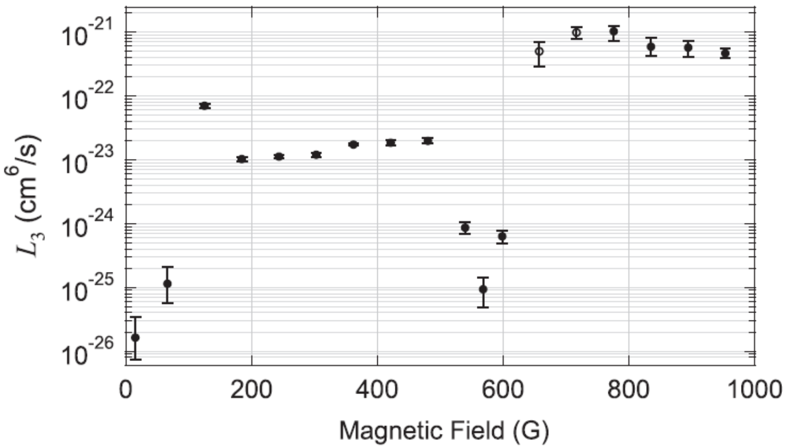
Enhanced Loss in a 3-Component Fermi System of ^{6}Li

T. B. Ottenstein, et al., PRL **101**, 203202 (2008)
J. H. Huckans, et al., PRL **102**, 165302 (2009)
J.R. Williams, et al., PRL**103**, 130404 (2009)

- ➢ **Stable if each pair of states alone is populated.**
- ➢ **Unstable at 130G only if all three states are populated.**

→ smoking gun of Efimov states





Efimov Senario confirmed by theories

effective field theory

E. Braaten, et. al., PRL **103**, 073202 (2009)

hyperspherical analysis

P. Naidon and MU, PRL **103**, 073203 (2009)

functional renormalization group theory

S. Floerchinger, et al., PRA **79**, 053633 (2009)

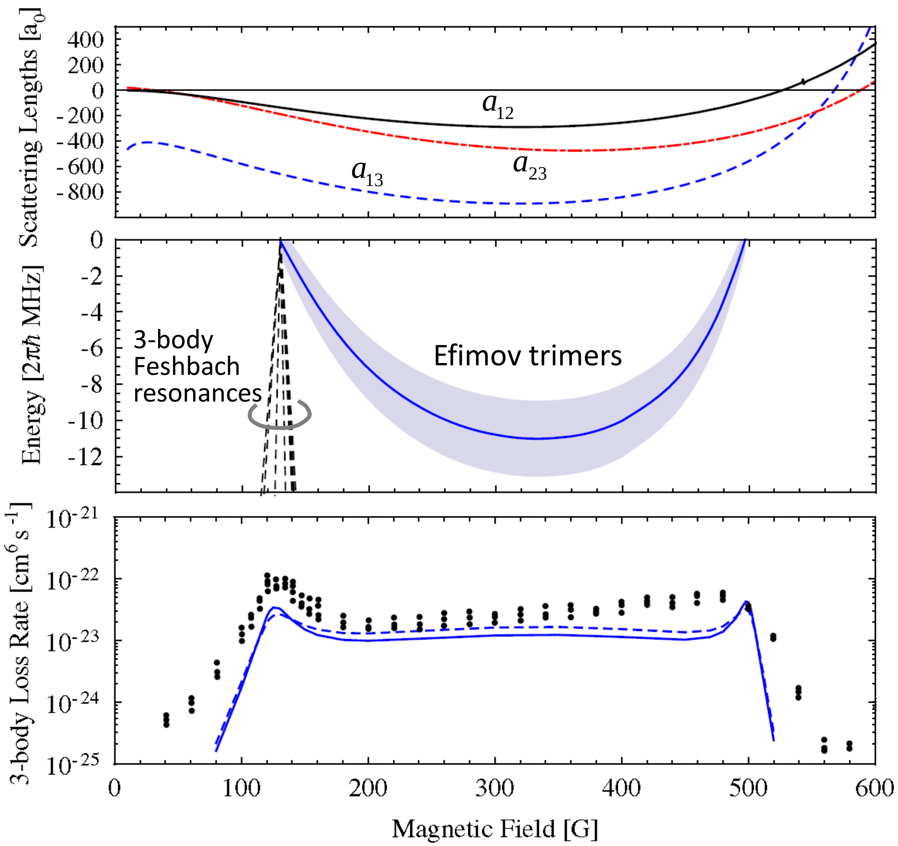
semiclassical approach

Seth T. Rittenhouse, PRA **81**, 040701 (R) (2010)

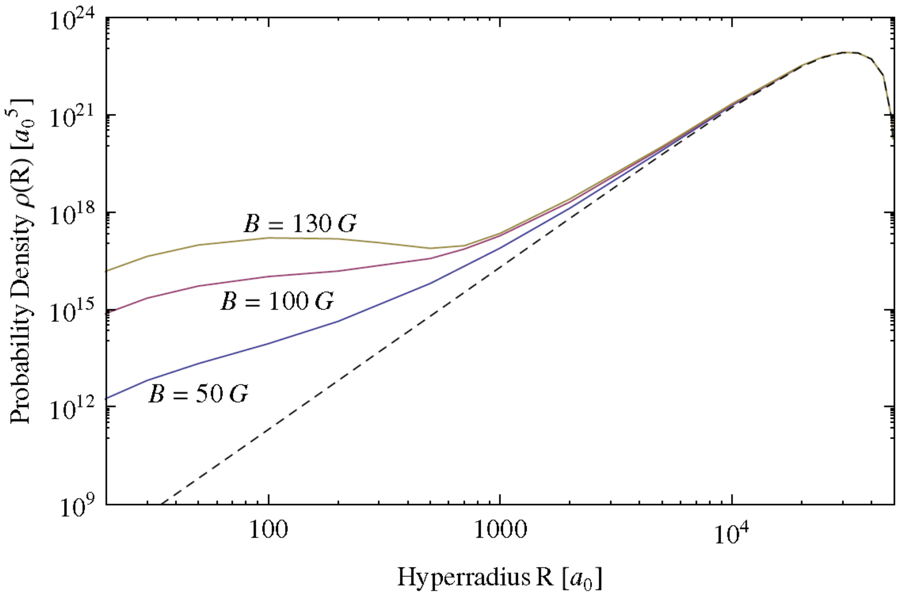
Efimov Trimer vs. Feshbach Senarios

P. Naidon, MU, PRL **103**, 073203 (2009)

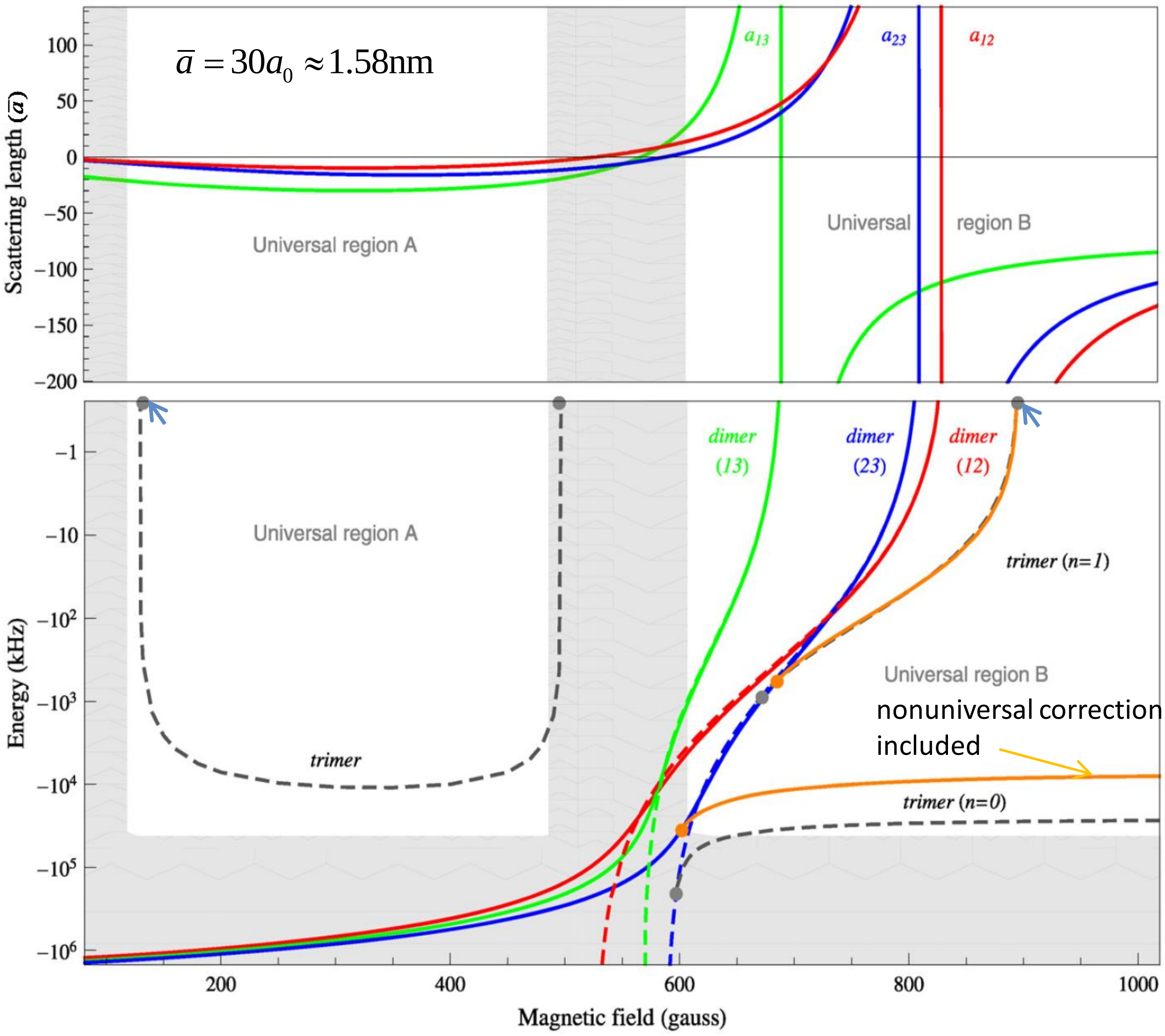
Theory confirms that the loss peak corresponds to a tri-atomic association threshold of Efimov trimers.



Physics: presence of an Efimov state enhances the probability density for 3 atoms to be found at short distance, which leads to an enhanced 3-body recombination.



A Possible Unification?



O'Hara group observed another 3-atom threshold at 895G and determined

$$\kappa_* = 6.9(2)\times 10^{-3} a_0^{-1}$$

This value is very close to

$$\kappa_* = 6.9(2)\times 10^{-3} a_0^{-1}$$

which was obtained in a different universal region A at 100G. [Braaten et al. PRL 103, 073202 (2010)]

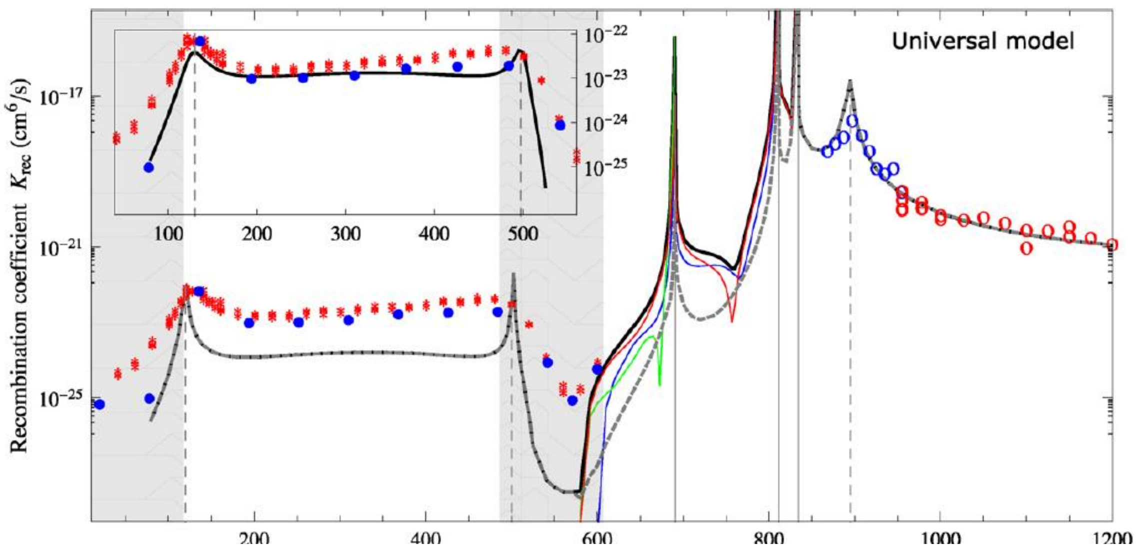
↓

Suggests a possible unification of the two universal regions A and B.

cf. Innsbruck exp. on Cs
M. Berninger, et al., PRL **107**, 120401 (2011)

Single-Channel Model

P. Naidon, MU, C. R. Physique **12**, 13 (2011)



Data taken from

* J. H. Huckans, et al.,
PRL **102**, 165302 (2009)

• T. B. Ottenstein, et al.,
PRL **101**, 203202 (2008)

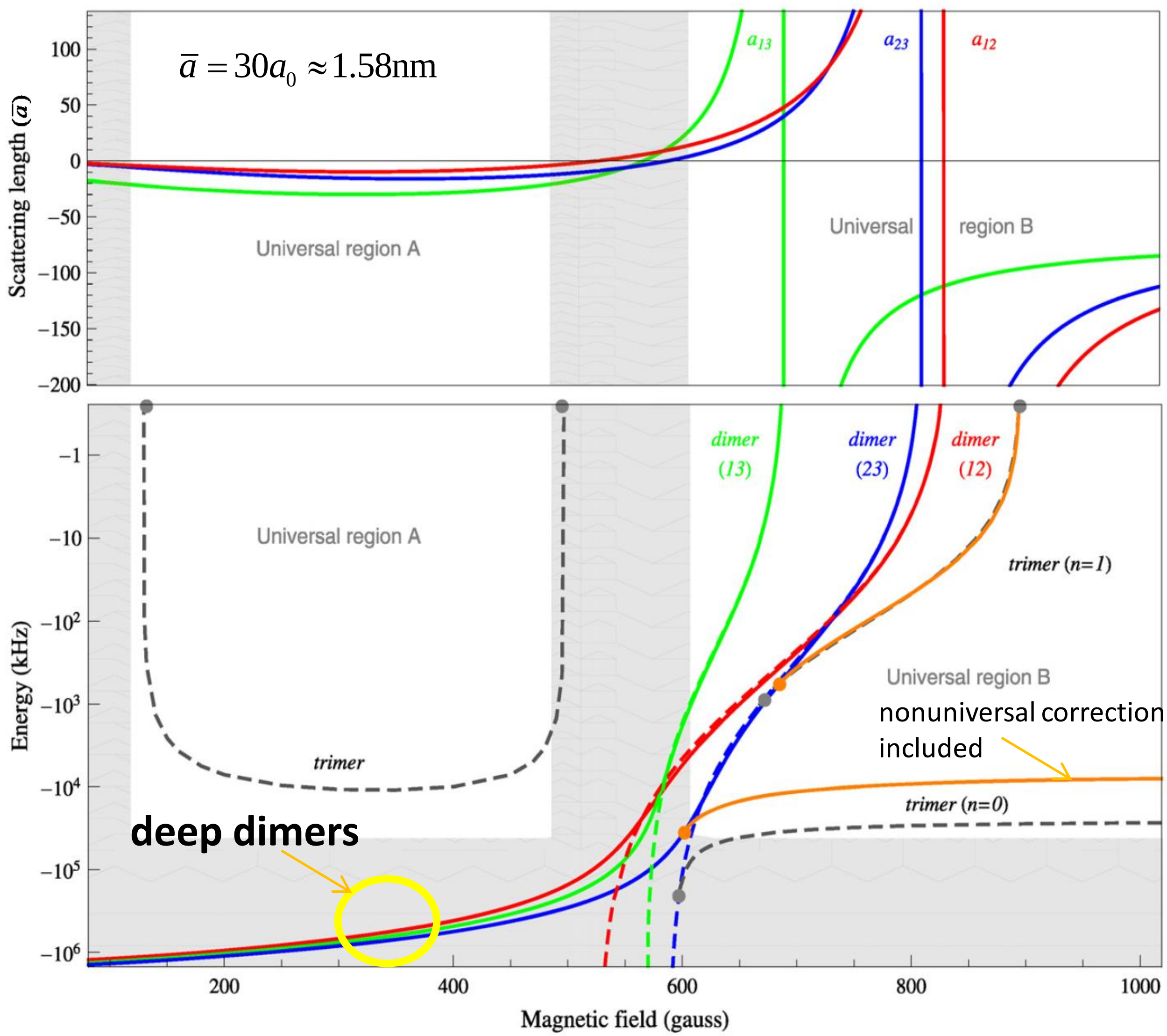
○ J.R. Williams, et al.,
PRL **103**, 130404 (2009)

- **The single-channel model with energy-dependent scattering lengths and a fixed three-body parameter qualitatively reproduces an overall feature of the entire region.**

- **But not quite good for universal region A.**

Why?

Qualitative Deviation from Universal Theory



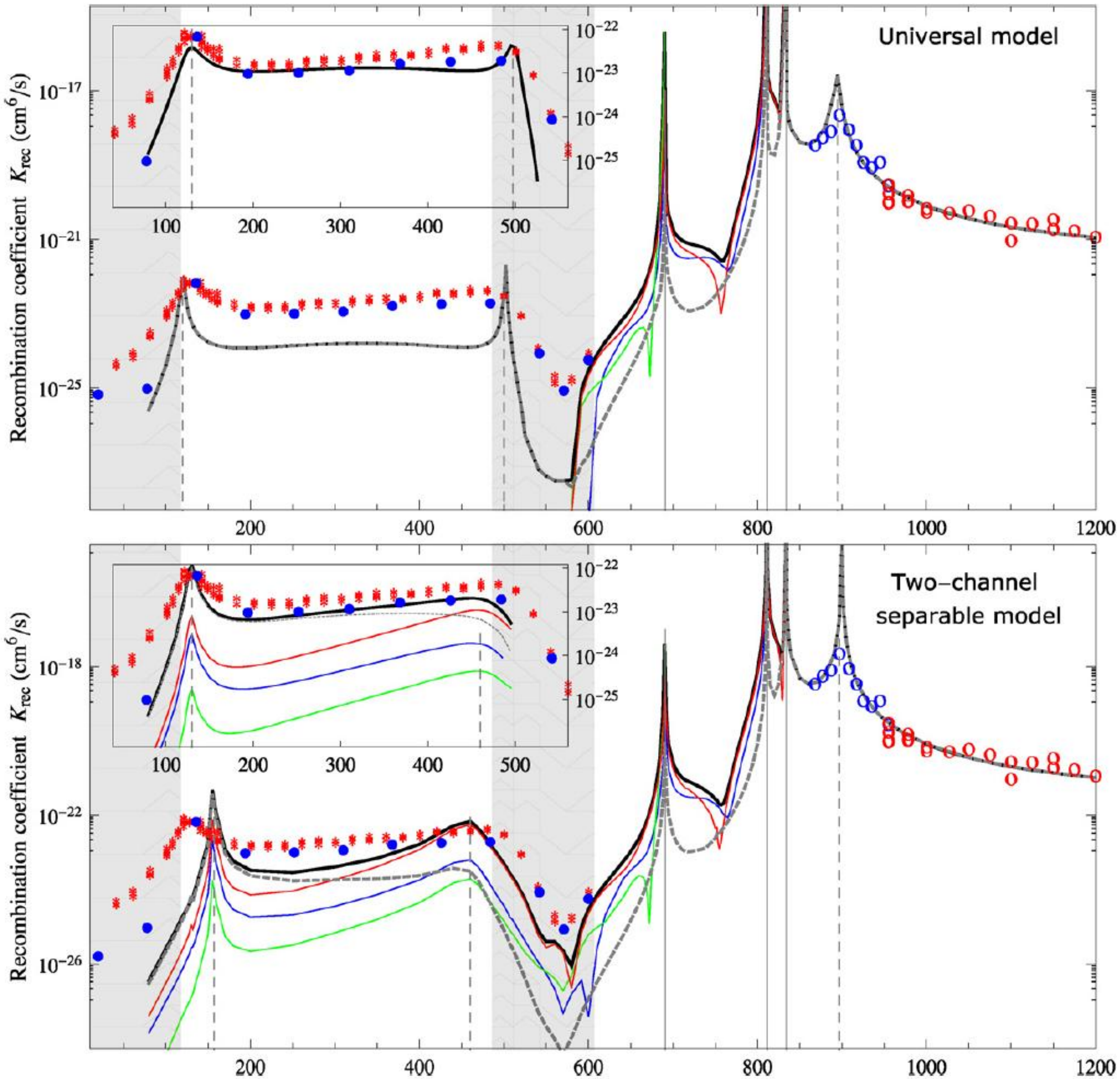
Deep dimers, which are not taken into account in the universal model, introduce effective-range correations.

↓

The coupled-channel nature matters!

Two-Channel Model

P. Naidon, MU, C. R. Physique **12**, 13 (2011)



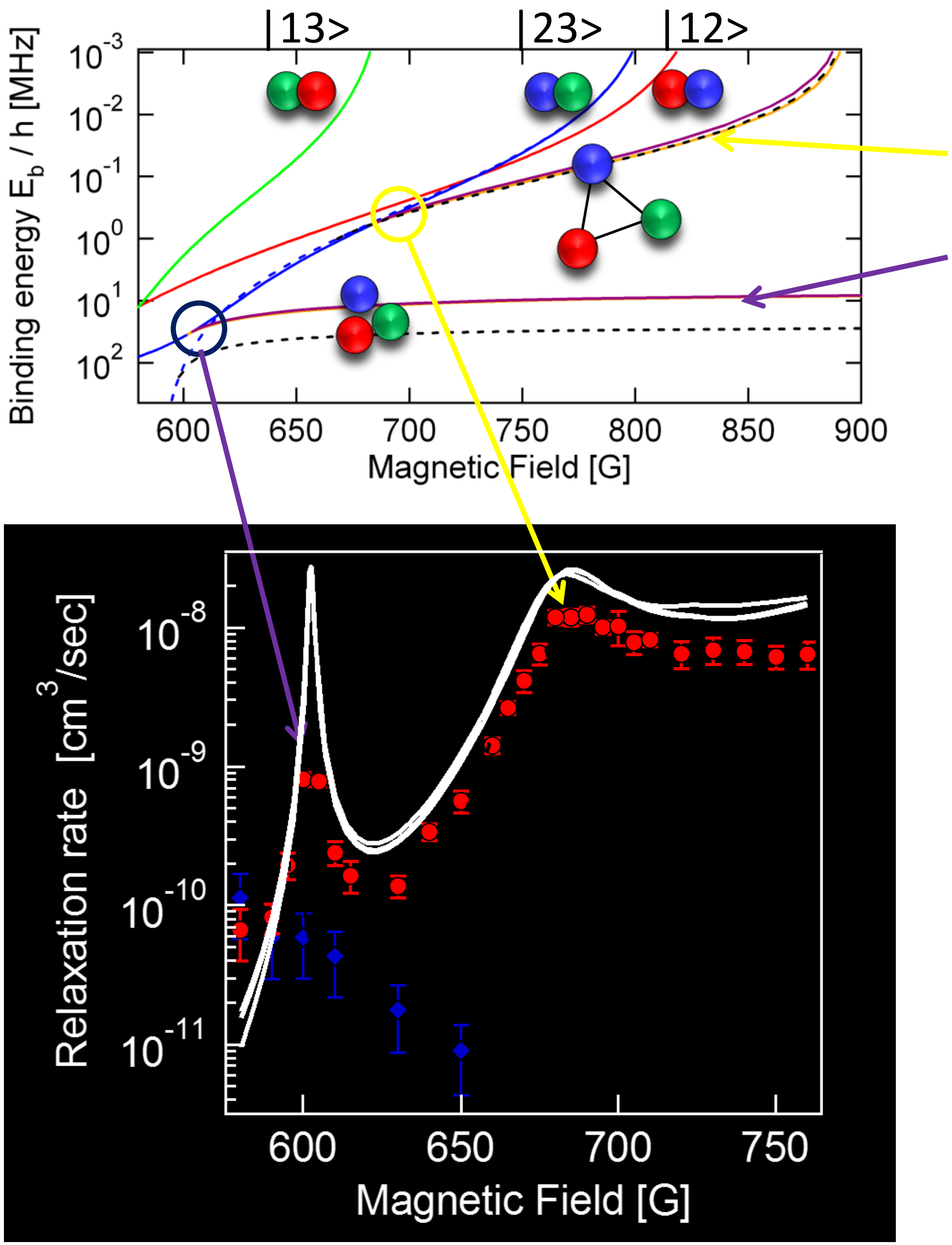
* J. H. Huckans, et al., PRL **102**, 165302 (2009)
• T. B. Ottenstein, et al., PRL **101**, 203202 (2008)
o J.R. Williams, et al., PRL **103**, 130404 (2009)

➢ Two-channel model captures a global feature in the entire region.

➢ Zero-energy Efimov physics well described by a two-channel model with energy-dependent scattering length and finite-range corrections.

Atom-Dimer-Efimov Resonance

S. Nakajima *et.al.*, PRL **105**, 023201 (2010)
T. Lompe, *et al.*, PRL **105**, 103201 (2010)



1st excited Efimov state

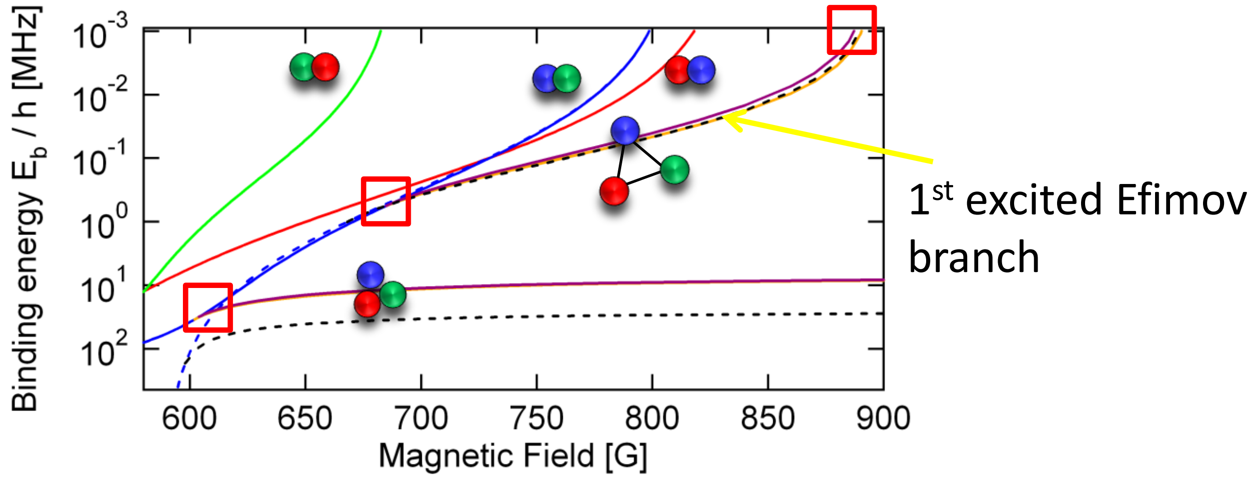
Ground-state Efimov state

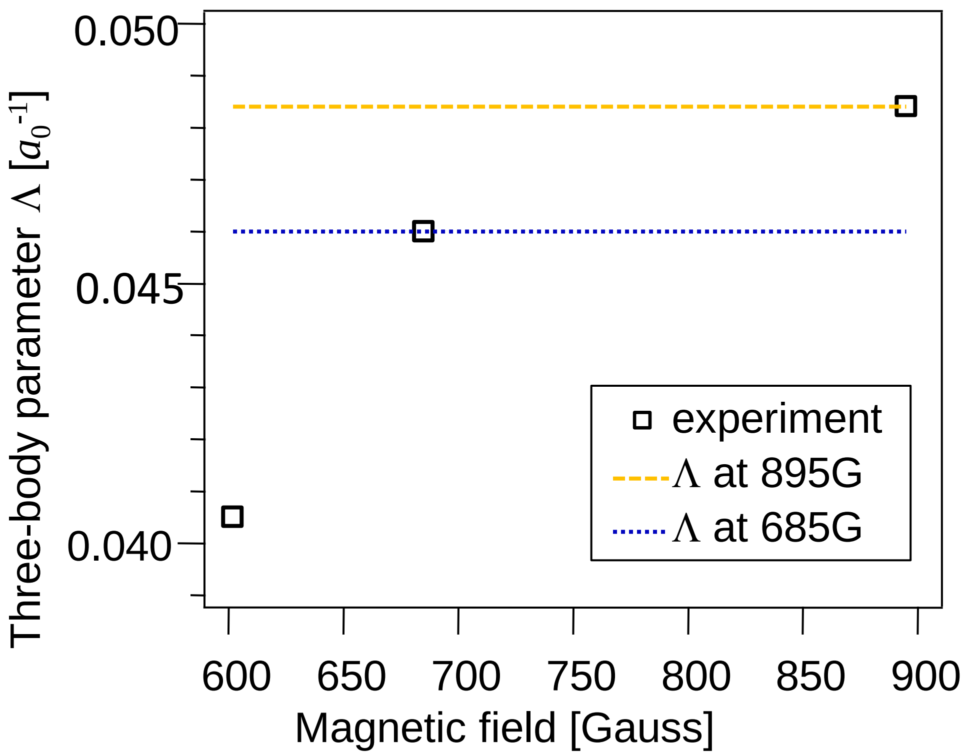
Two loss peaks associated with atom(1)+dimer (23) ↔ trimer For the ground and first excited state trimers observed.

↓

New pieces of information on the three-body parameter for nonzero energy Efimov trimers

Three-Body Parameter





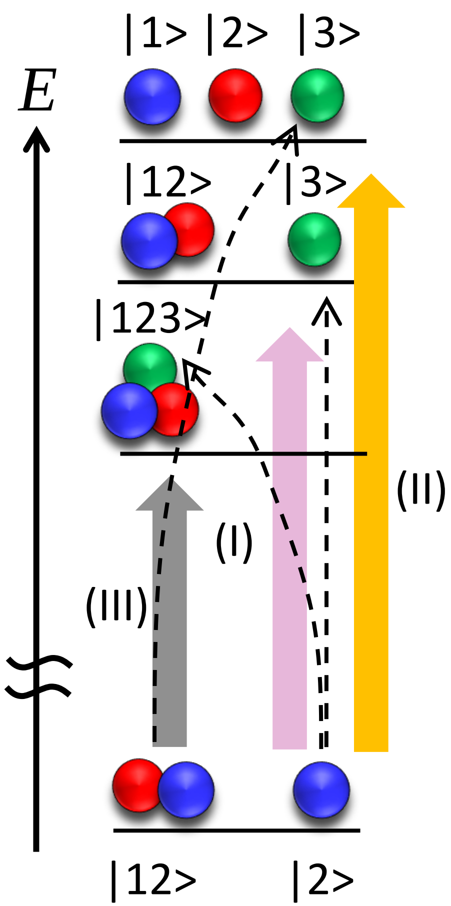
The 3-body parameter measured at different points do not agree.

How does the 3-body parameter change along the 1st excited Efimov branch?

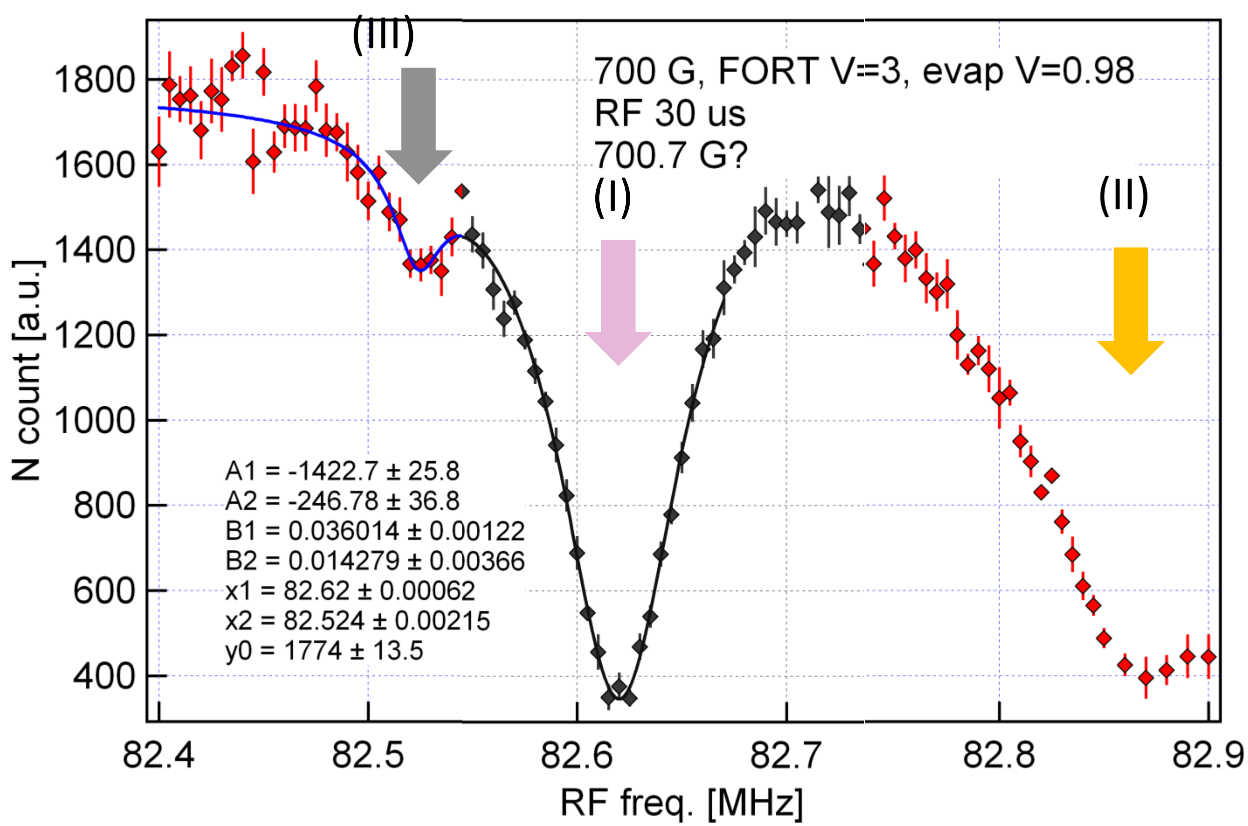
RF Association of Efimov Trimers

S. Nakajima, *et al.*, Phys. Rev. Lett. 106, 143201 (2011)

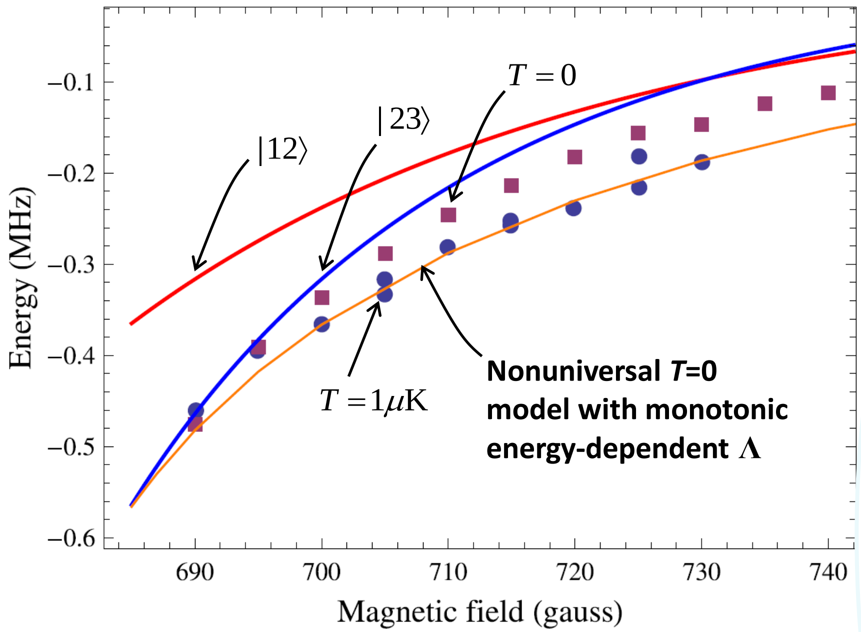
T. Lompe *et.al.*, Science **330**, 940 (2010)



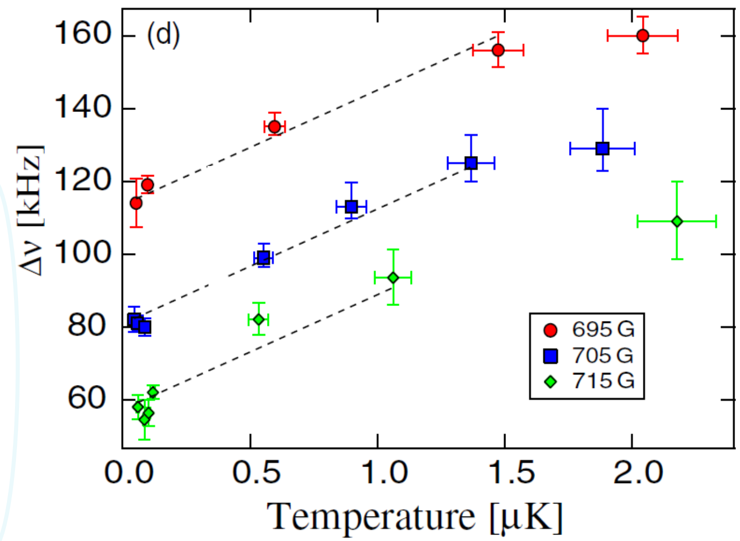
Number of atoms in state |2> vs RF frequency



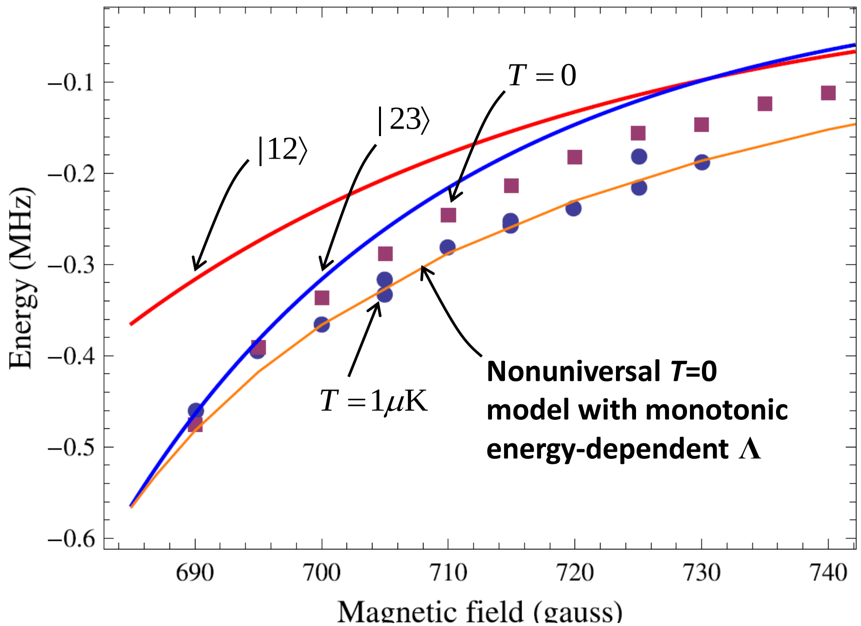
Temperature Dependence of Efimov Binding Energy



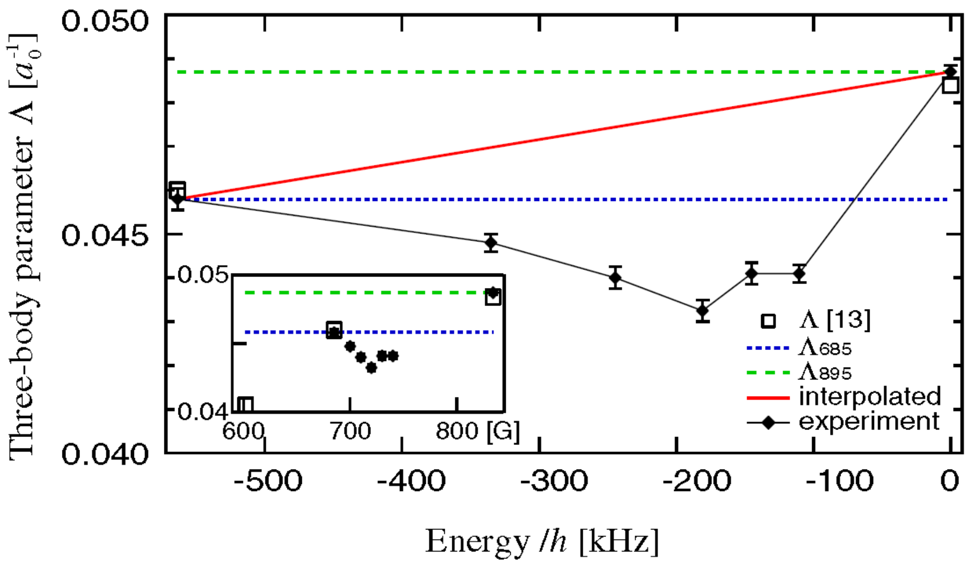
- ● S. Nakajima, et al., PRL **106**, 143201 (2011)
- ■ T. Lompe, et al., Science 330, **940** (2010)



Energy Dependence of 3-Body Parameter



- S. Nakajima, et al., PRL **106**, 143201 (2011)
- T. Lompe, et al., Science 330, **940** (2010)



- non-monotonic energy dependence of Λ as large as 15 %
  - multichannel effect?
  - finite-range effect?
  - 3-body physics?

- A small uncertainly (≤ 0.7%) in *a* can cause a large (5%) variation of Λ .

↓

Even more precise measurement of *a* is needed.

Back to Zero-Energy Efimov: Hidden Universality ?

- Evidence of near-constant (in log scale) three-body parameter in Cs (Innsbruck).
- Several alkali's (133Cs, 7Li, 85Rb) give similar values in a_{-}/a_{vdW}.
- Let's check this theoretically using a realistic potential.

Results of He-4 Trimers

- Realistic LM2M2 potential [R.A. Aziz, M.J. Slaman, J. Chem. Phys. 94, 8047 (1991)]
- Solve Shrödinger equation with the Gaussian expansion method

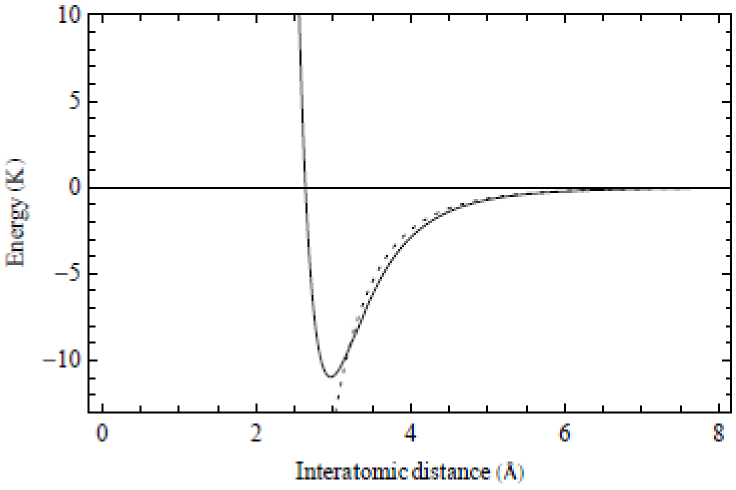
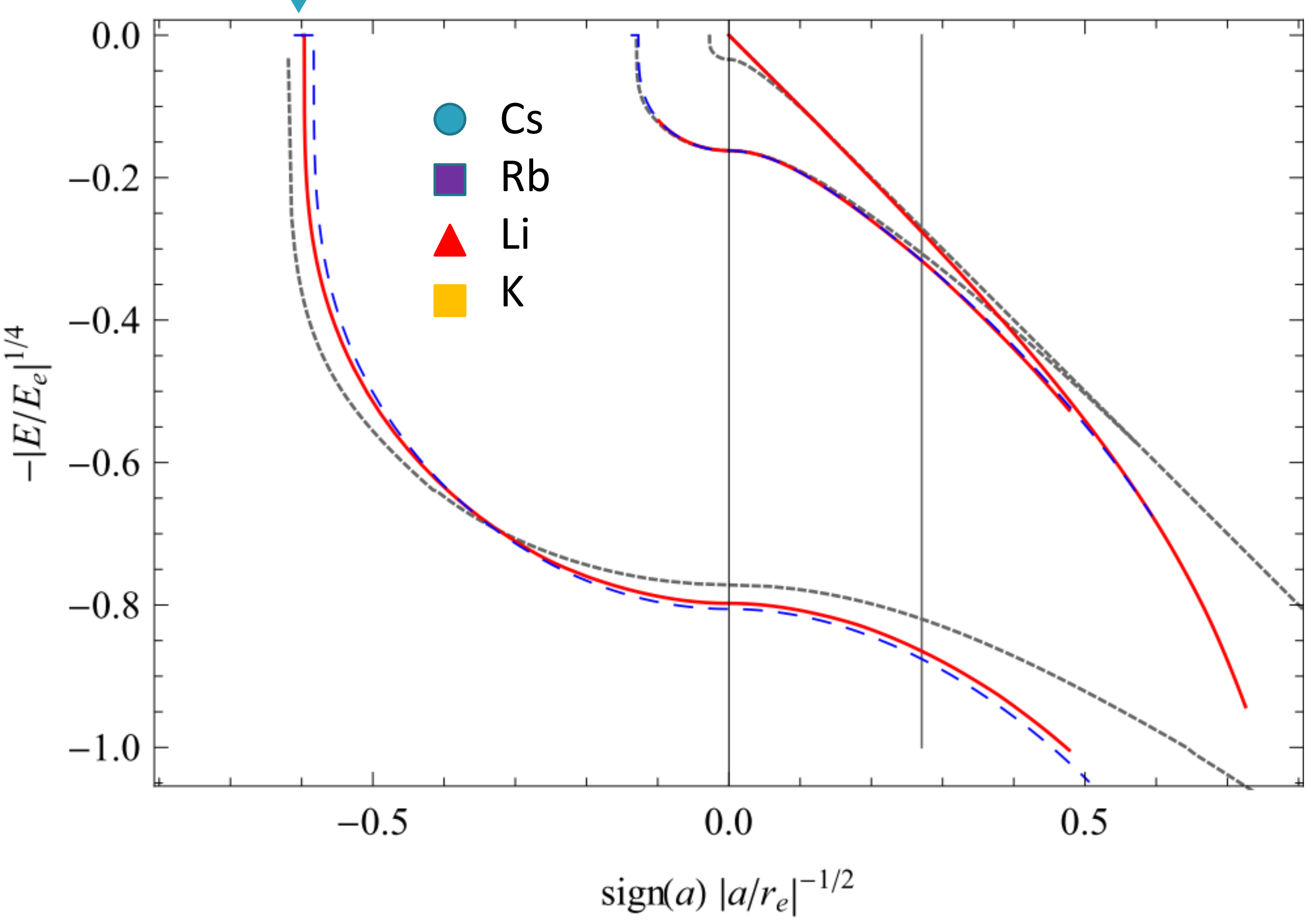


Figure 1: LM2M2 potential [25] used for the realistic calculations. The dotted curve indicates the van der Waals asymptote $-C_6/r^6$.

Let’s Compare with Cs, Rb, K, Li

Cs133	Innsbruck
Rb85	JILA
Li6	Tokyo
Li7	Bar Ilan
K39	Florence

$a = 2.7 r_e \Longleftrightarrow a = 9.7 \bar{a}$



Realistic He

Fitted Universal

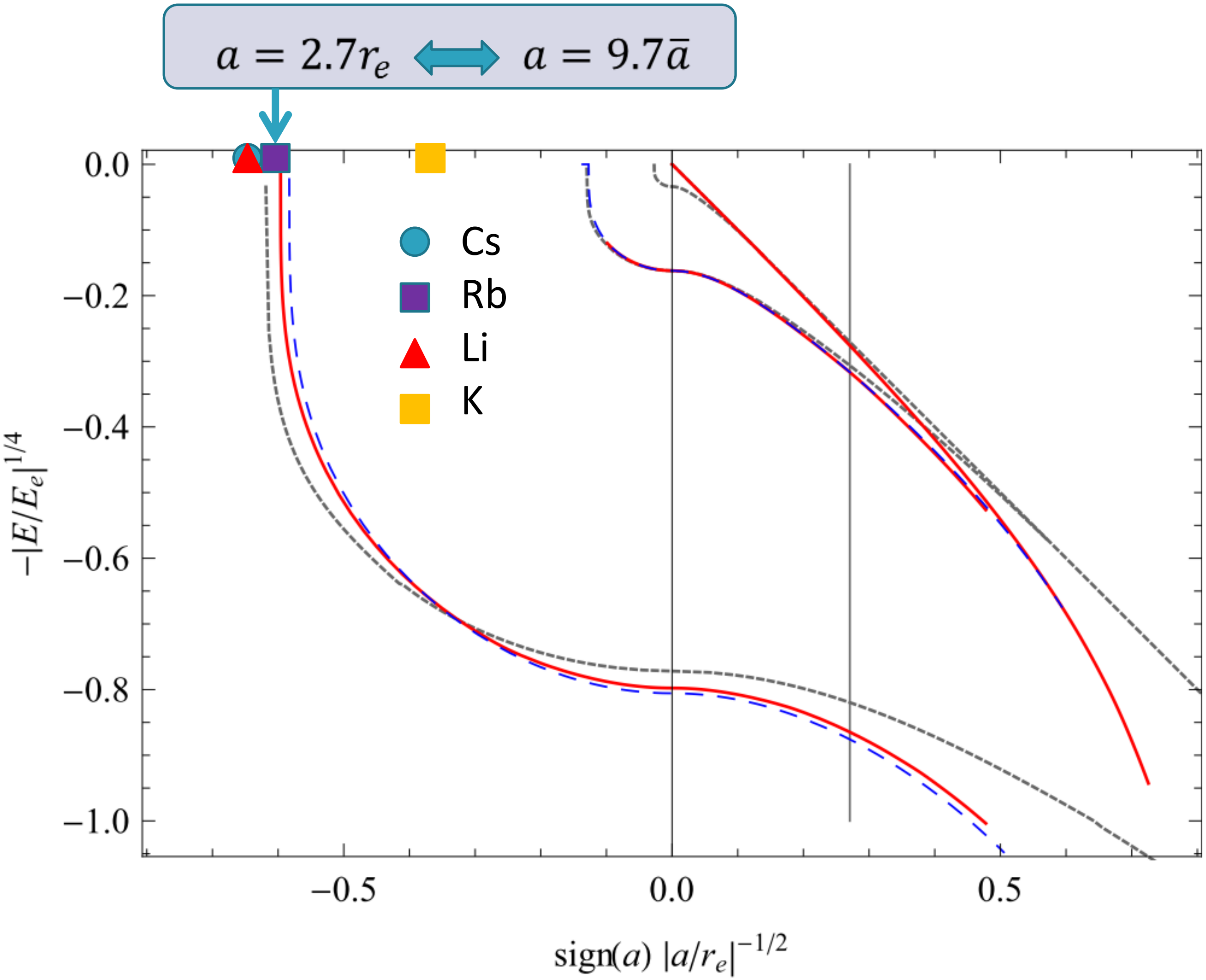
Separable Model

Calculations:

P. Naidon

E. Hiyama

He-4 Trimers: Comparison with Cs, Rb, K, Li



Calculations:

P. Naidon

E. Hiyama

Conclusions

- Fermionic Li system provides a weath of information about Efimov physics.
- a(E) and effective range capture an overall feature of two universal regions (A and B) at zero energy.
- 3-body parameter shows irregular behavior (15%) at negative energy.
- Mounting evidence of near-constant 3-body parameter at zero energy not only across different universal regimes (A, B) but also across different species.