PHYSIKALISCHES INSTITUT

RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

University of Excellence

Quantum Dynamics of Atomic and Molecular Systems

Center for Quantum Dynamics

Observation of Efimov resonances in a mixture with extreme mass imbalance

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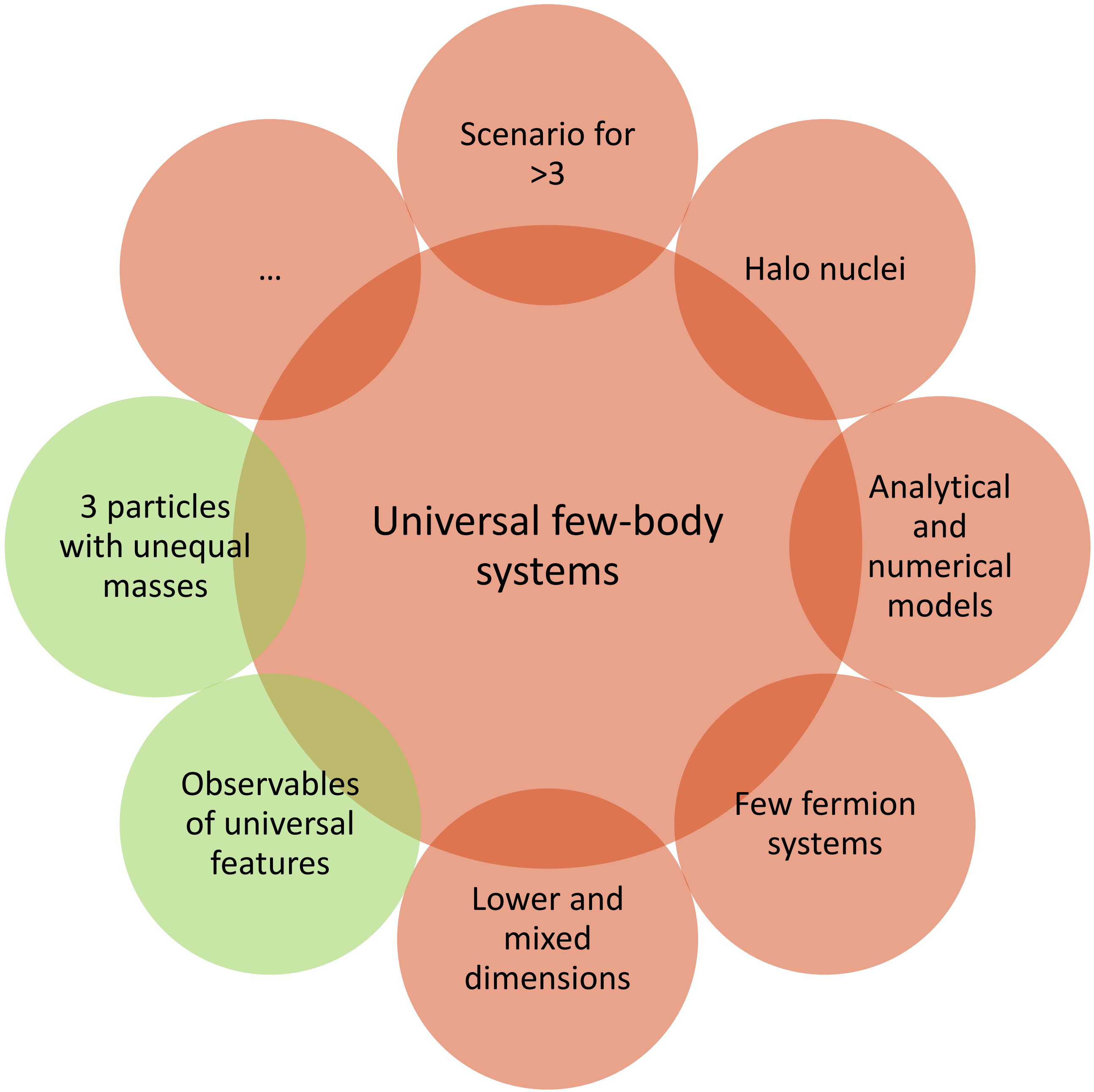
Seattle, May 13, 2014, „Few-body Universality in Atomic and Nuclear Physics: Recent Experimental and Theoretical Advances "



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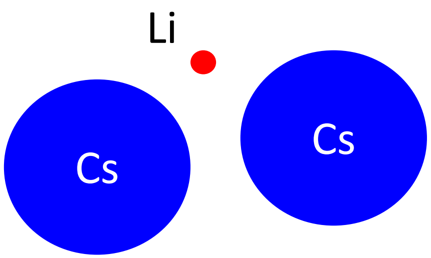
Efimov physics with mass imbalance



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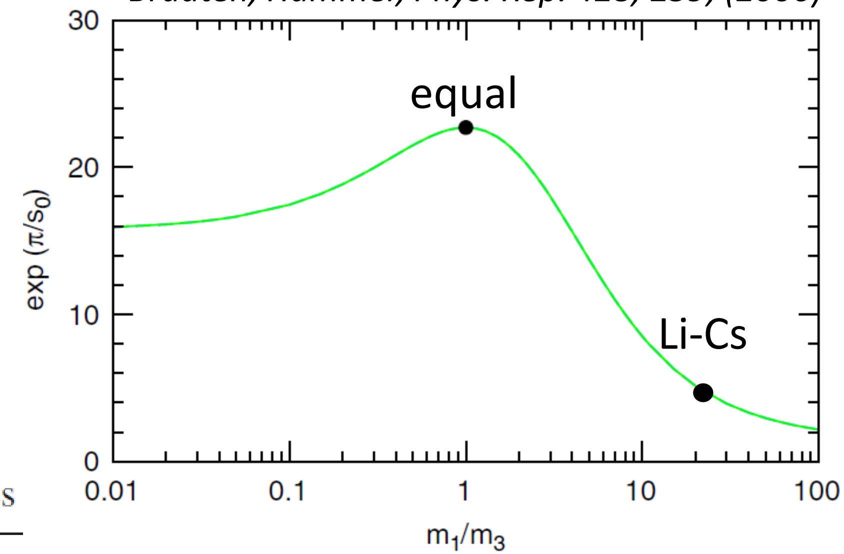
Braaten, Hammer, Phys. Rep. 428, 259, (2006)



		Two features		Three features	
B-F	e^{π/s_0}	$\lvert a_{min}\rvert$	E_{max}(nK)	$\lvert a_{min}\rvert$	E_{max}(nK)
^{133}Cs-^{6}Li	4.877	3×10^3	1500	2×10^4	60.0
^{87}Rb-^{6}Li	6.856	8×10^3	230	6×10^4	5.00
^{23}Na-^{6}Li	36.28	9×10^5	$\leqslant 0.1$	3×10^7	$\leqslant 0.1$
^{7}Li-^{6}Li	$>10^2$	$\geqslant 10^8$	$\leqslant 0.1$	$\geqslant 10^8$	$\leqslant 0.1$
^{133}Cs-^{40}K	47.02	2×10^6	$\leqslant 0.1$	9×10^7	$\leqslant 0.1$
^{87}Rb-^{40}K	$>10^2$	$\geqslant 10^8$	$\leqslant 0.1$	$\geqslant 10^8$	$\leqslant 0.1$

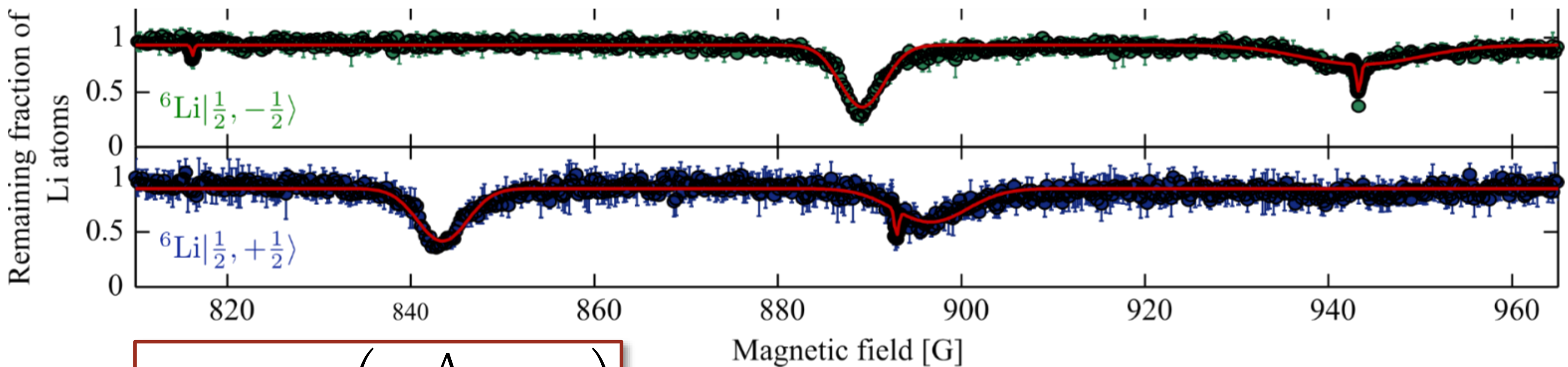
D'Incao et al., Phys. Rev. A 73, 030703(R) (2006)

Barontini et al., *Phys. Rev. Lett.* 103, 043201 (2009); Bloom et al., *Phys. Rev. Lett*. 111, 105301 (2013)

1) Atom loss
2) Three-body loss rate

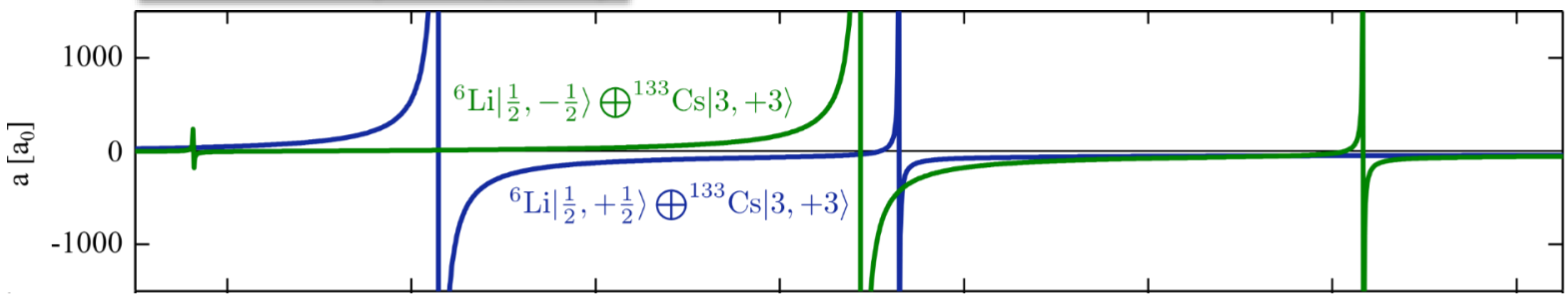
Feshbach resonances in Li-Cs

Repp et al., *Phys. Rev. A* 87, 010701(R) (2013)
Tung et al., *Phys. Rev. A* 87, 010702(R) (2013)



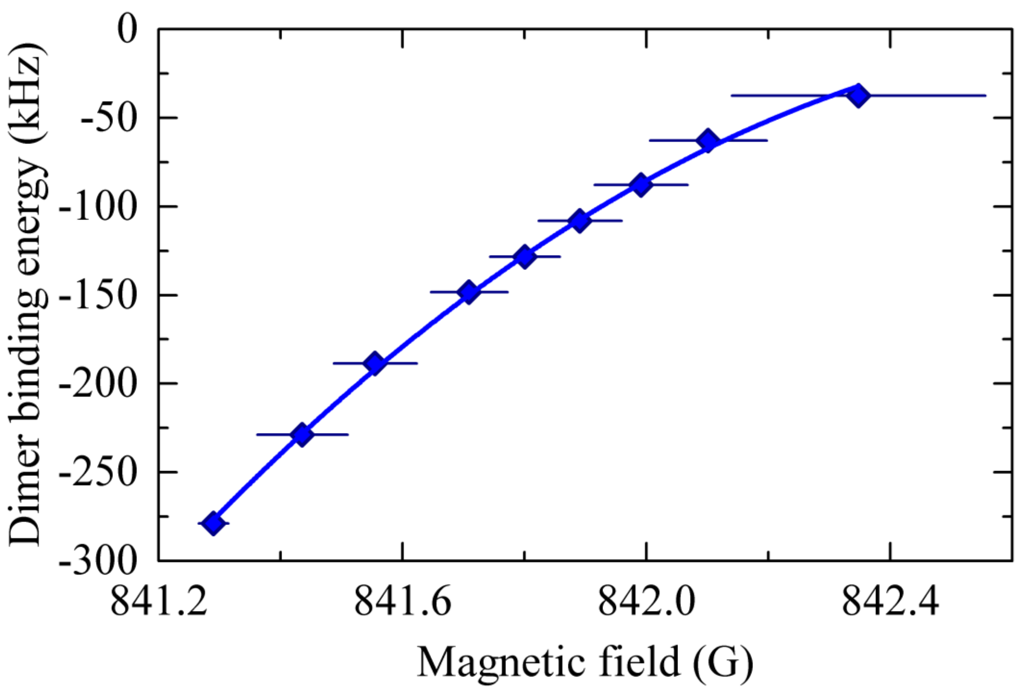
$$a(B) = a_{bg}\left(\frac{\Delta}{B - B_{FR}} + 1\right)$$

B_{FR} = 842.99(4) G Δ = 60.4 G



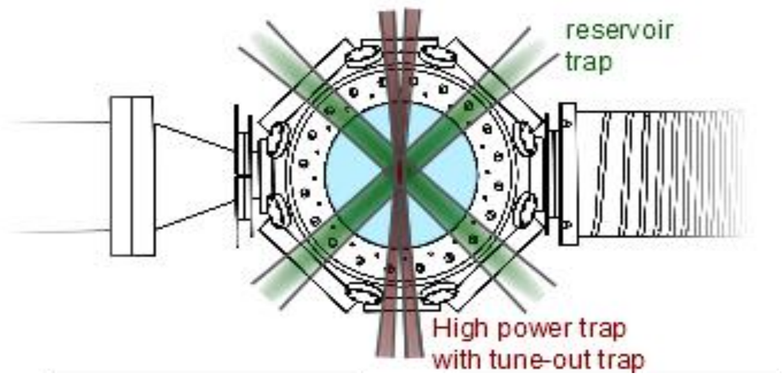
coupled-channels calculations by Eberhard Tiemann

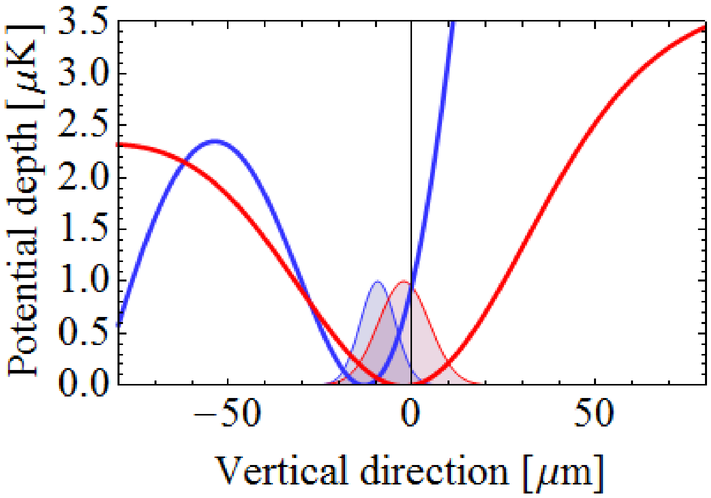
Rf spectroscopy of dimers at 843 G



B_{FR} = 842.90(20) G
Δ = 61.4(7) G
with rf spectroscopy of dimers

Experimental conditions



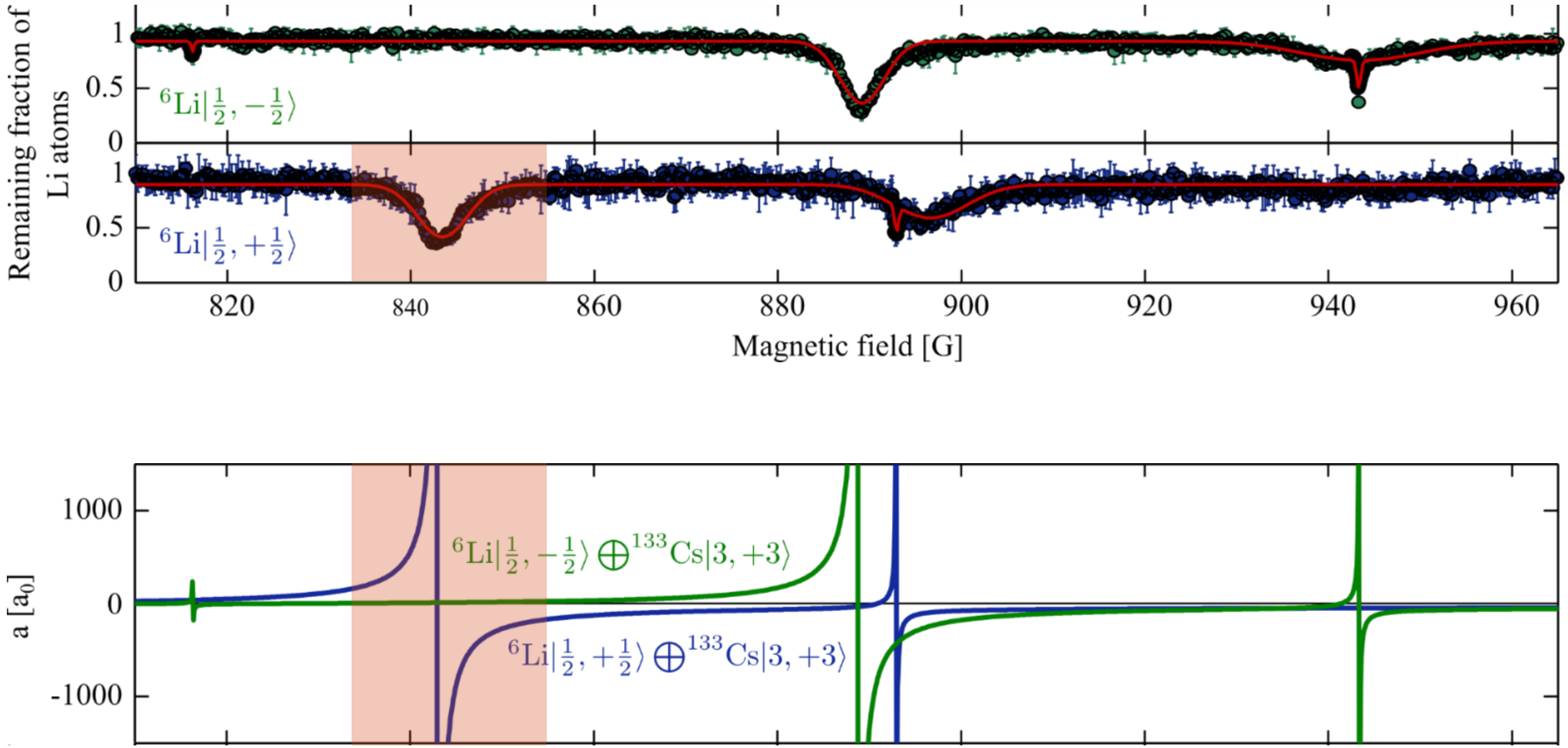


	frequencies	atom numbers	density	temperature
Cs	2 π 54 Hz	1.6×10^4	4×10^{11} cm^{-3}	0.4 μK
Li	2 π 141 Hz	4×10^4	0.8×10^{11} cm^{-3}	0.4 μK

→ at these temperatures: overlap ≈ 80 % and gravitational sag ≈ 10 μm

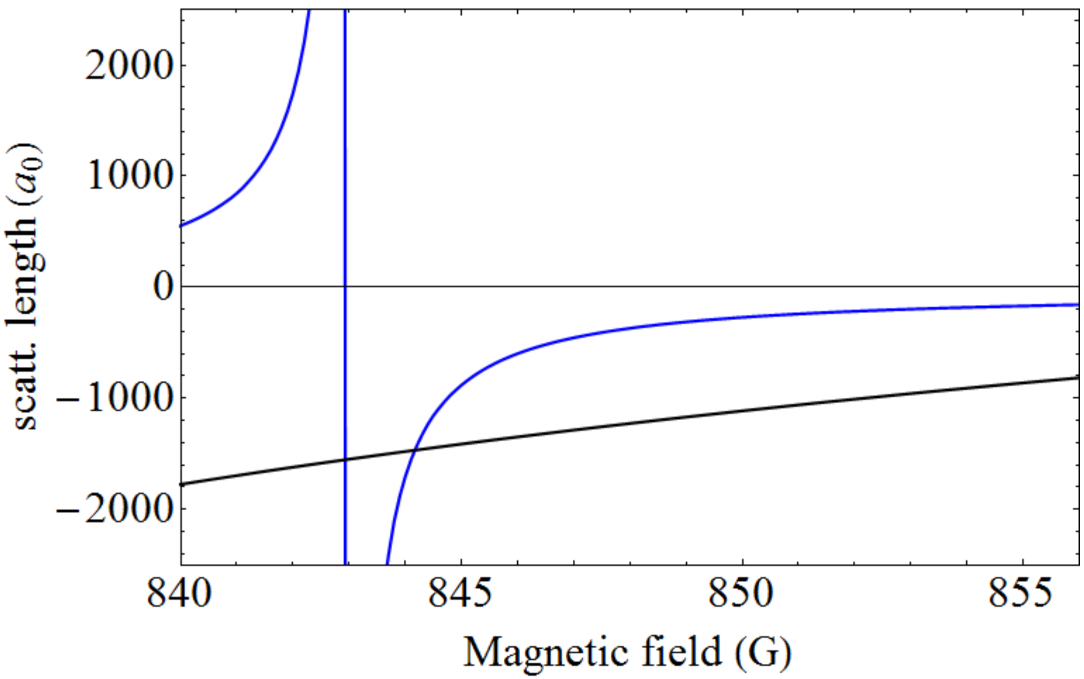
Feshbach resonances in Li-Cs

Repp et al., Phys. Rev. A 87, 010701(R) (2013)
Tung et al., Phys. Rev. A 87, 010702(R) (2013)



coupled-channels calculations by Eberhard Tiemann

Interaction around 843 G



^{133}Cs|3,+3⟩ ⊕ ^{133}Cs|3,+3⟩

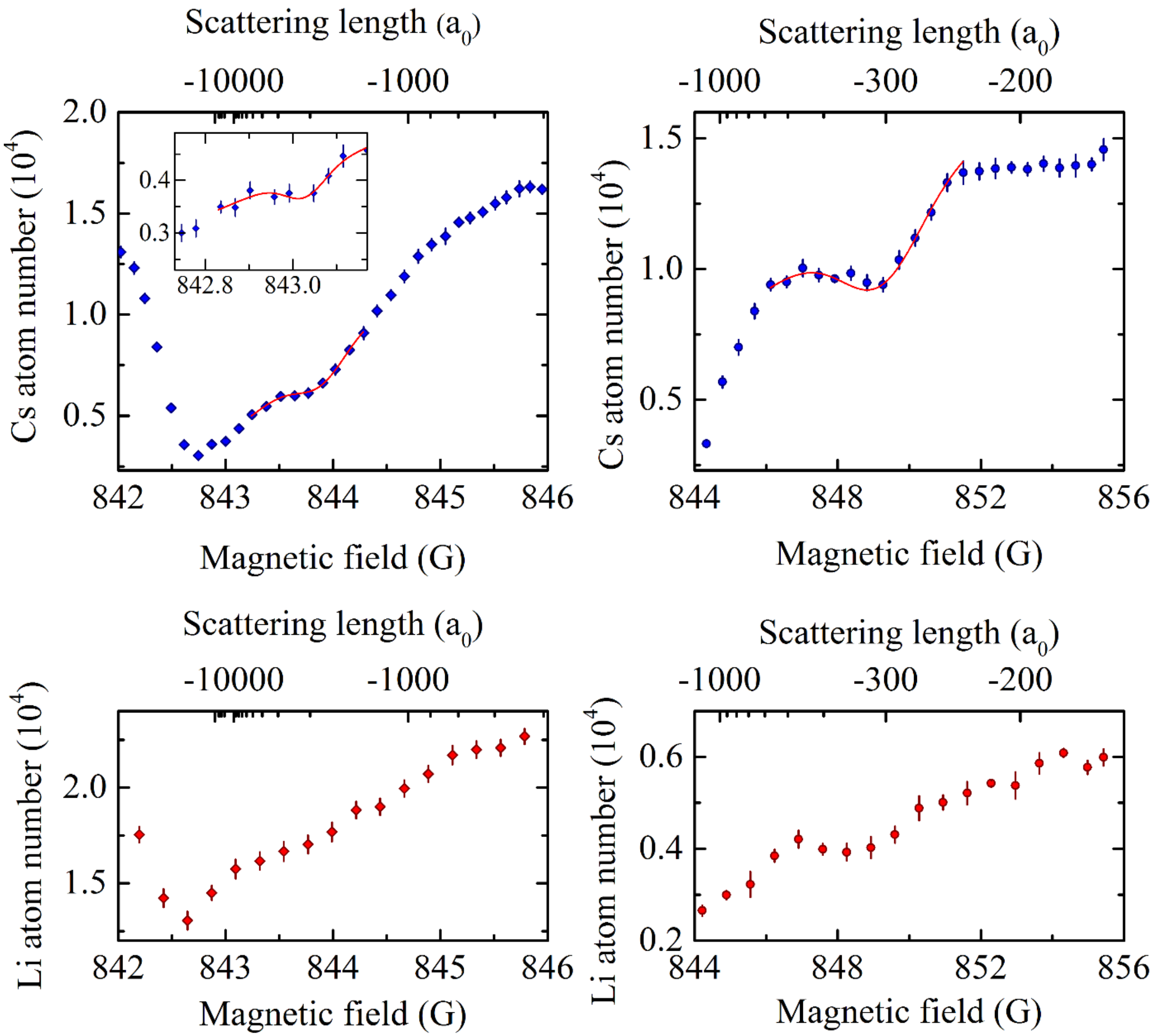
^{6}Li|1/2,+1/2⟩ ⊕ ^{133}Cs|3,+3⟩

Van der Waals

$r_0^{LiCs} = 45\ a_0$

$r_0^{Cs} = 101\ a_0$

Atom loss



Observation for $a < 0$:
Enhanced loss
$B_0 = 849.12(6)_{stat}(3)_{sys}$ G
$B_1 = 843.89(1)_{stat}(3)_{sys}$ G
$B_2 = 843.03(5)_{stat}(3)_{sys}$ G

Chin group, Tung et al., arXiv:1402.5943v1 (2014)

Grimm group, *Phys. Rev. Lett*. 112, 190401 (2014)

Three-body loss rate

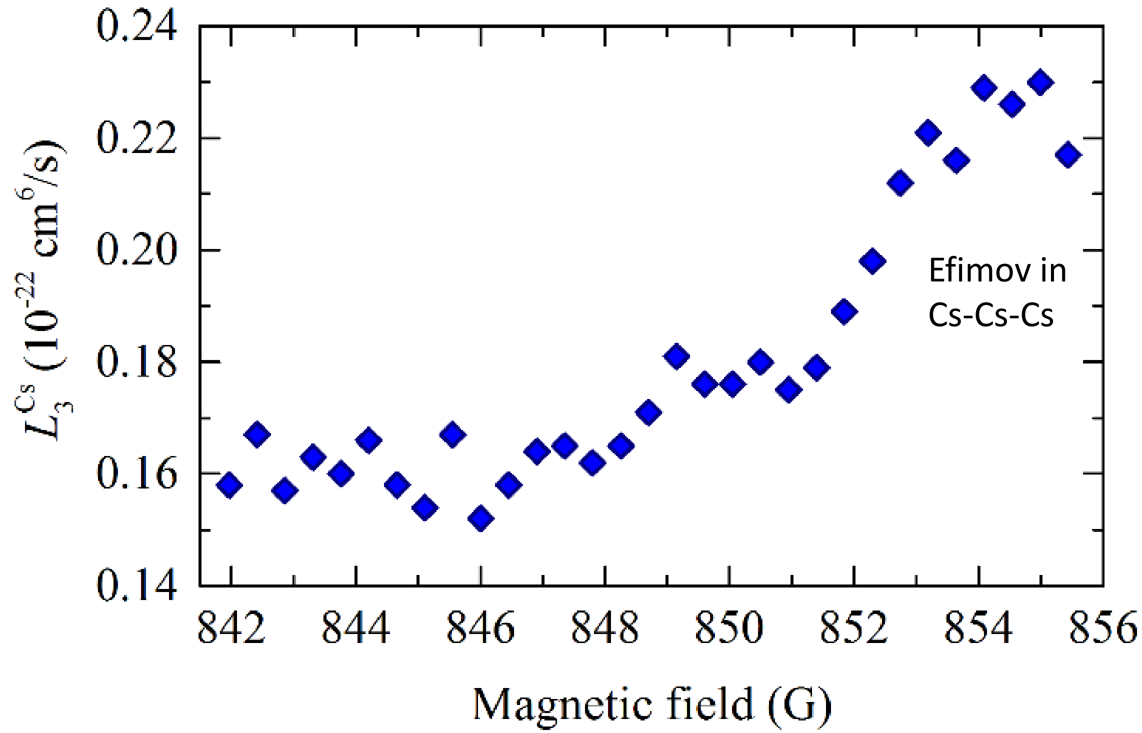
$$\dot{n}_{Cs} = -L_1^{Cs} n_{Cs} - 2L_3^{LiCsCs} n_{Li} n_{Cs}^2 - L_3^{Cs} n_{Cs}^3$$

$$\dot{n}_{Li} = -L_1^{Li} n_{Li} - L_3^{LiCsCs} n_{Li} n_{Cs}^2$$

Assumptions:

- Fermionic Li → suppression of L_3^{LiLiCs} and L_3^{Li}
- Recompression of the trap stops residual evaporation → constant temperature

Three-body loss coefficient L_3^{Cs}



L_3^{Cs} is roughly constant in the relevant field range 840 G to 852 G

Berninger et al., *Phys. Rev. Lett*. 107, 120401 (2011)

Three-body loss rate

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

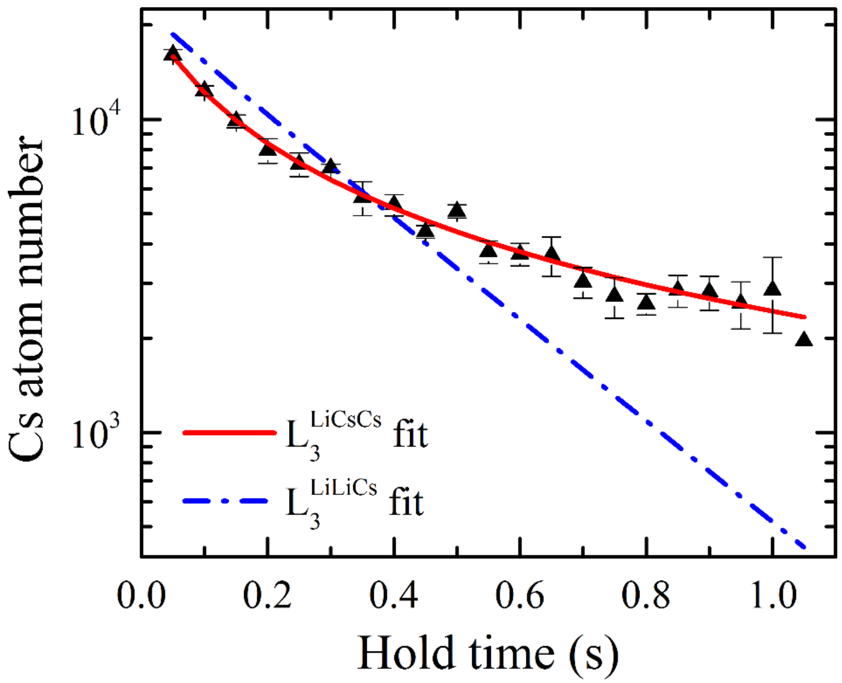
$$\dot{n}_{Li} = -L_1^{Li} n_{Li} - L_3^{LiCsCs} n_{Li} n_{Cs}^2$$

Assumptions:

- Fermionic Li → suppression of L_3^{LiLiCs} and L_3^{Li}
- Recompression of the trap stops residual evaporation → constant temperature
- L_3^{Cs} → constant
- More $N_{Li} = 3 \times 10^4$ than $N_{Cs} = 2 \times 10^4$, after wait time the loss of Li atoms ≈ 30% but all Cs atoms are lost → constant n_{Li}

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

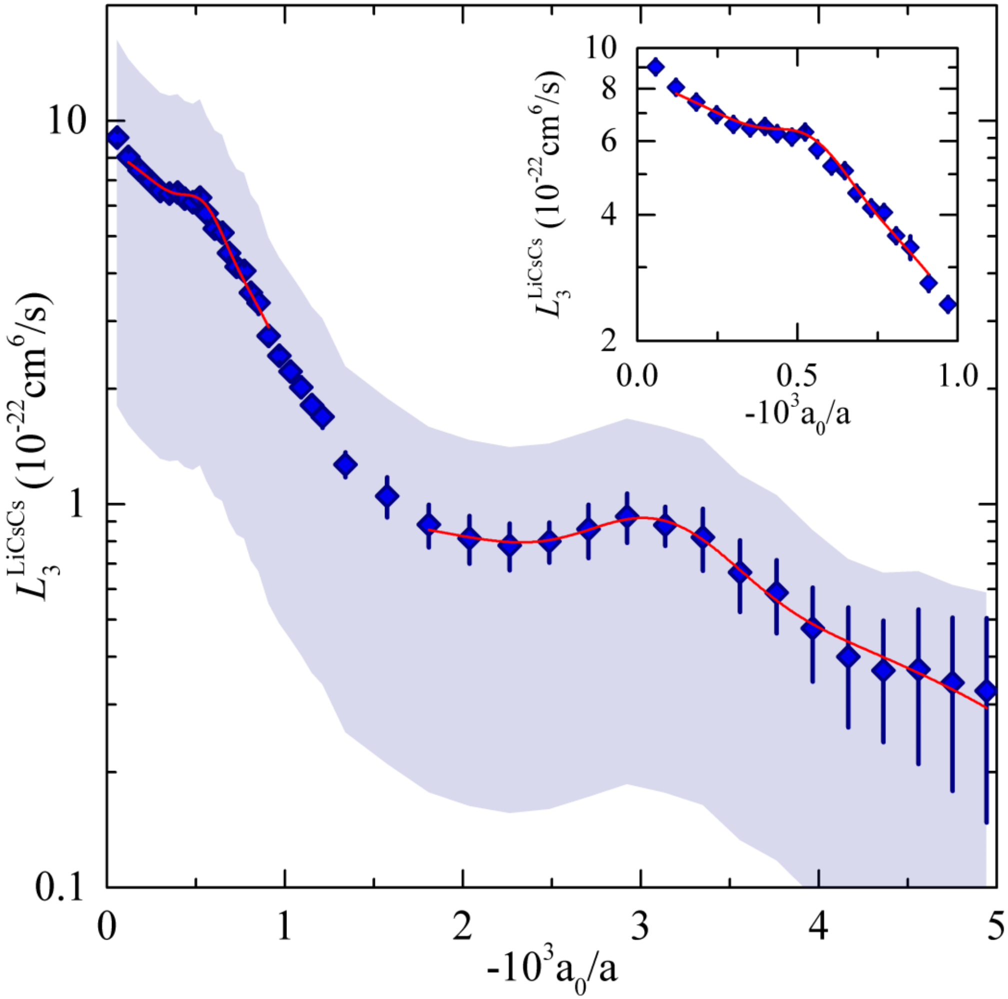
Three-body loss coefficient L_3^{LiCsCs}



Conversion $N_{Cs} \rightarrow n_{Cs}$ depends on trap frequencies and temperatures of Li and Cs as well as on overlap

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

Three-body loss coefficient L_3^{LiCsCs}

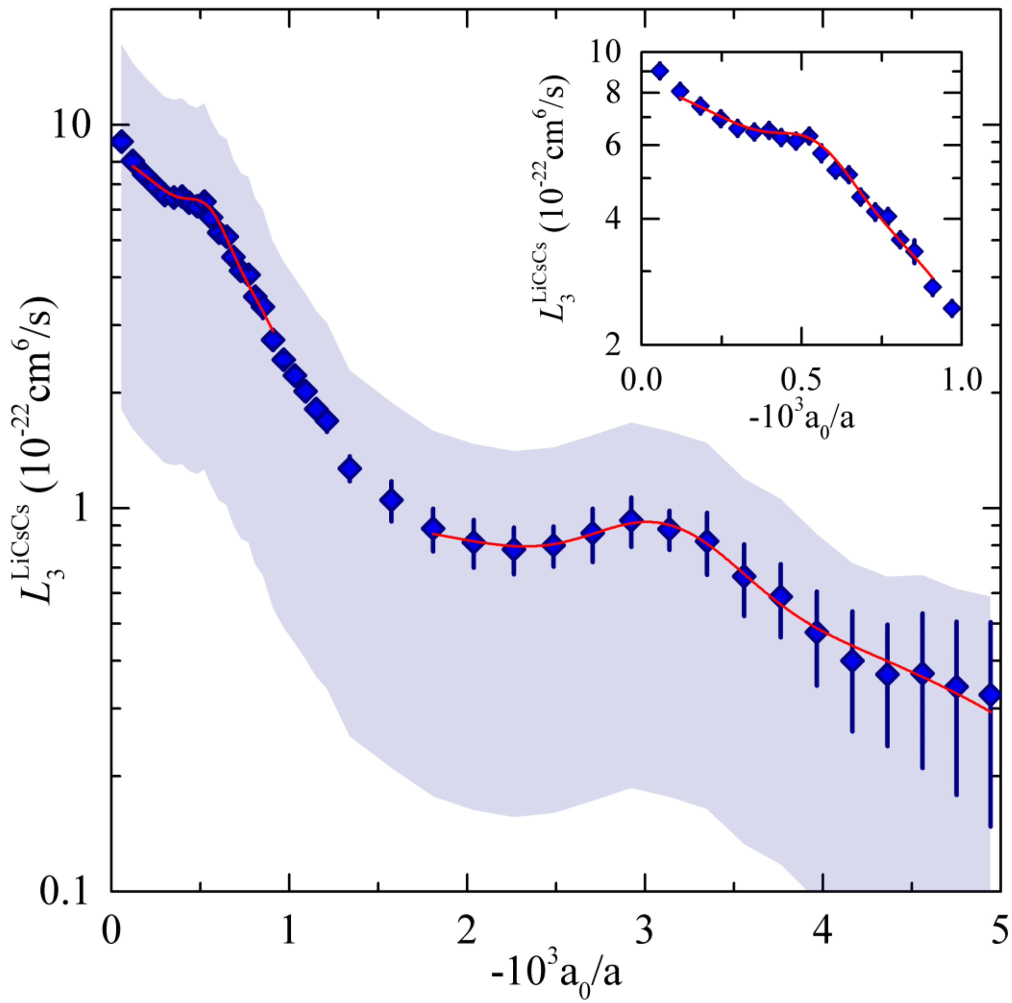


Observation:
$B_0 = 848.90(6)_{stat}(3)_{sys}$ G
$B_1 = 843.85(1)_{stat}(3)_{sys}$ G

Comparison with atom loss
$B_0 = 849.12(6)_{stat}(3)_{sys}$ G
$B_1 = 843.89(1)_{stat}(3)_{sys}$ G

included: reduction due to 80 % overlap

Three-body loss coefficient L_3^{LiCsCs}



Observation:
B_0 = 848.90(6)$_{stat}$(3)$_{sys}$ G
B_1 = 843.85(1)$_{stat}$(3)$_{sys}$ G

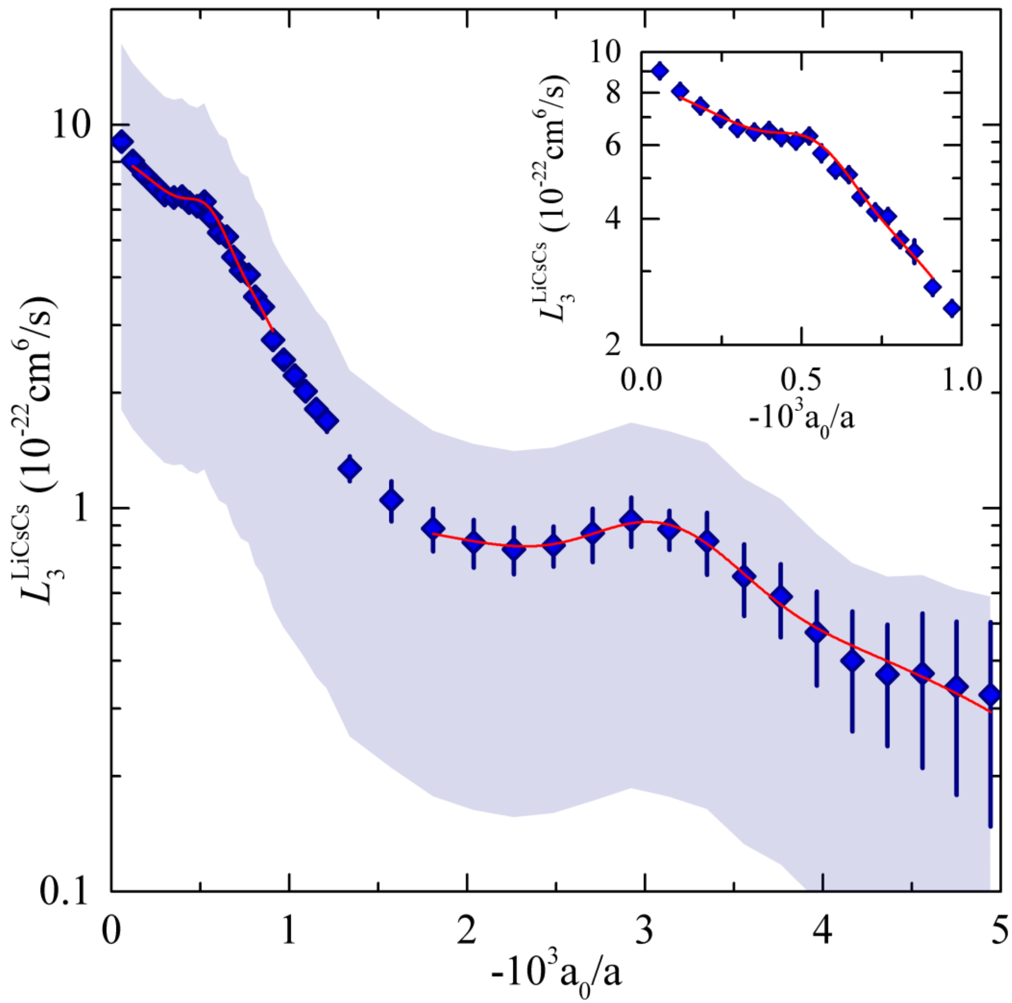
$$a(B) = a_{bg}\left(\frac{\Delta}{B - B_{FR}} + 1\right)$$

$$a_-^{(0)} = -320(3)_{stat}(2)_{sys}(10)_{rf}\, a_0$$

$$a_-^{(1)} = -1871(19)_{stat}(58)_{sys}(388)_{rf}\, a_0$$

B_{FR} = 842.90(20) G
Δ = 61.4(7) G
with rf spectroscopy of dimers

Three-body loss coefficient L_3^{LiCsCs}



$$a_-^{(0)} = -320(3)_{stat}(2)_{sys}(10)_{rf}\, a_0$$

$$a_-^{(1)} = -1871(19)_{stat}(58)_{sys}(388)_{rf}\, a_0$$

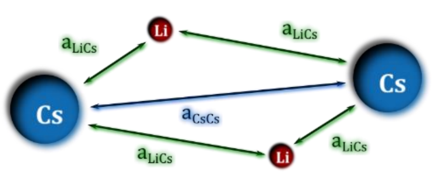
$$\frac{a_-^{(1)}}{a_-^{(0)}} = 5.8(0.1)_{stat}(0.2)_{sys}(1.0)_{rf}$$

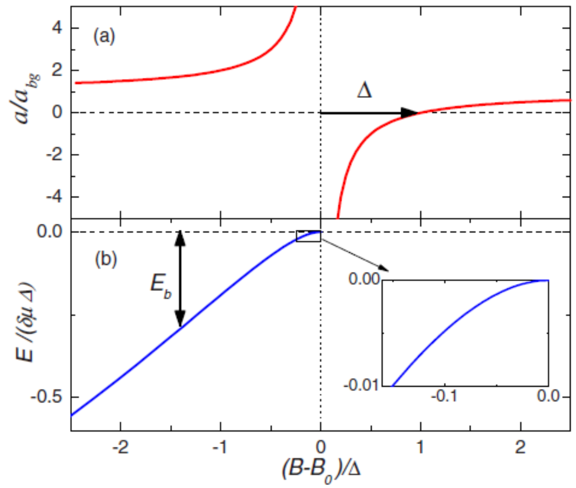
Summary

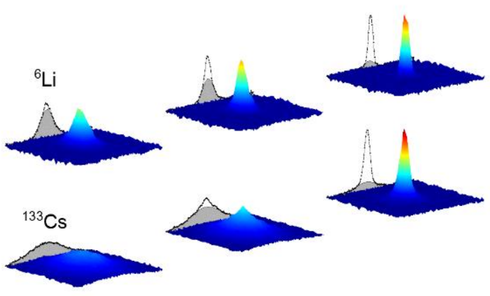
- Feshbach resonances in Li-Cs
- Atomic loss curves show loss features associated with Efimov states
- These features are measurable in both species
- Third resonance is in the deep universal regime
- Measurement of L_3^{LiCsCs}
- The first two resonances leads to a scaling $\frac{a_-^{(1)}}{a_-^{(0)}} = 5.8(0.1)_{\text{stat}}(0.2)_{\text{sys}}(1.0)_{\text{rf}}$

Outlook

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







- Binding energies of Feshbach dimers
- Mixture at lower temperatures: L_3 of the third resonance
- … or need a finite-range correction?
- Binding energies of Efimov states
- …

Li-Cs team

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Robert Heck (former master student)
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