Efimov Physics in Li-6 Atoms

Daekyoung Kang

Eric Braaten, H.-W. Hammer, and Lucas Platter

The Ohio State University

Outline

- Efimov effect
- Li-6 atoms
- Effective Field Theory at low energy
- Efimov physics in Li-6 atoms
  - Trimer energy spectrum
  - Scattering properties
- Summary

Efimov effect in identical bosons

In 1970 Efimov predicted
an infinite sequence of loosely bound 3-body states as $a \to \pm\infty$

- **Unitary limit** $a \to \pm\infty$

  $E^{(n+1)}/E^{(n)} \approx 1/22.7^2$

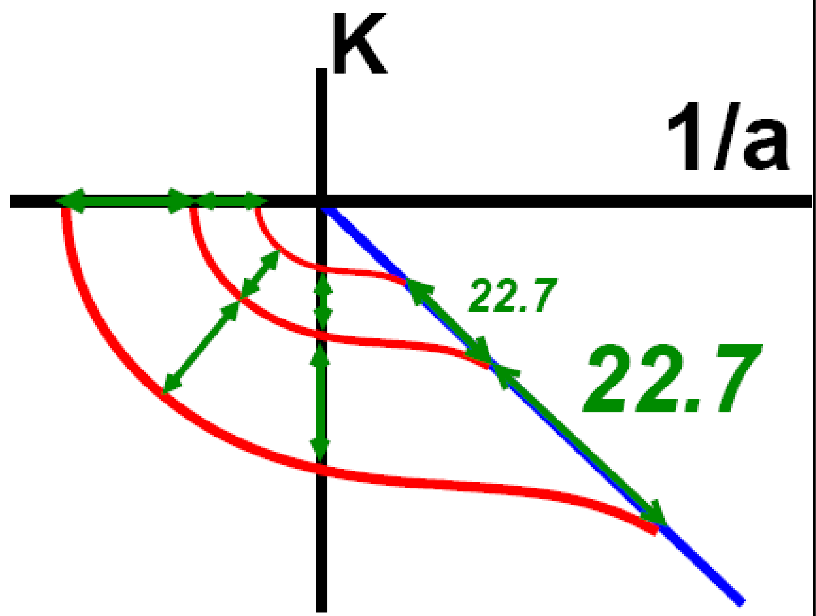
=> *discrete scaling* with
scaling factor λ=22.7

- **For finite** a

  discrete scaling is exact
  when *range-> 0*

- **Scattering of atoms**

  Log-periodic behavior in *a*
  Resonances differ by 22.7



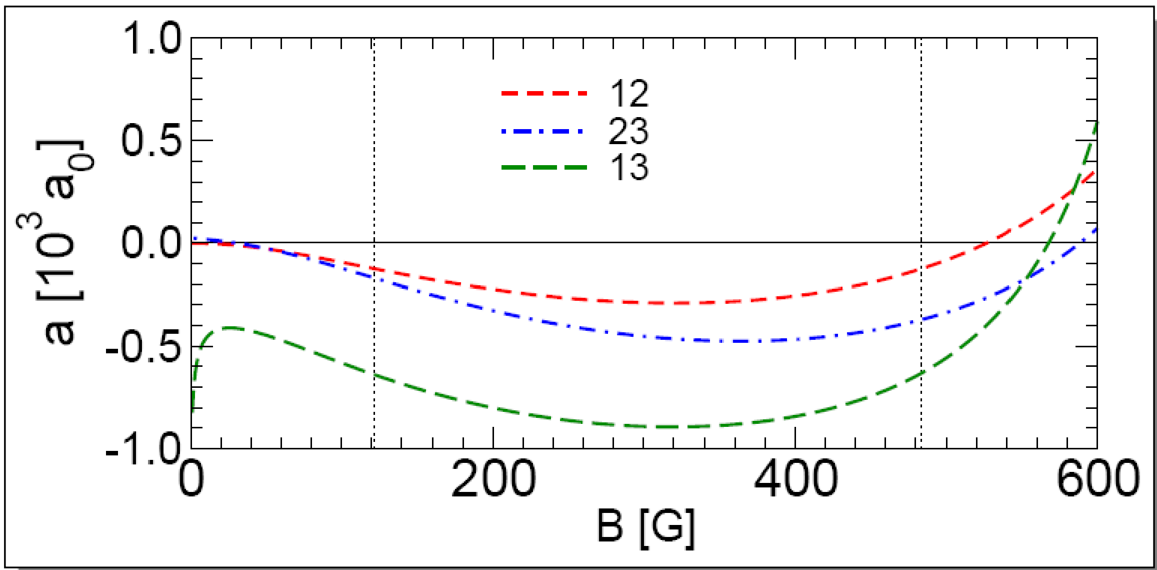
2 or 3-component System

- 3 scattering lengths (a_{ij}) in 3-body system
  - For identical bosons 3 a_{ij} are equal.
  - For 2-component system 2 a_{ij} are equal.
- Scaling factor λ depends on ratios of masses and bosonic or fermionic nature.
- Equal-mass atoms (hyperfine states)
  - λ=22.7 when 3 a_{ij} are large
  - λ=1989 when 2 a_{ij} are large (except for 2 identical fermions)
- Near Feshbach resonances, a_{ij} and ratios vary dramatically.
- ***Nature could provide a greater variety of Efimov features.***

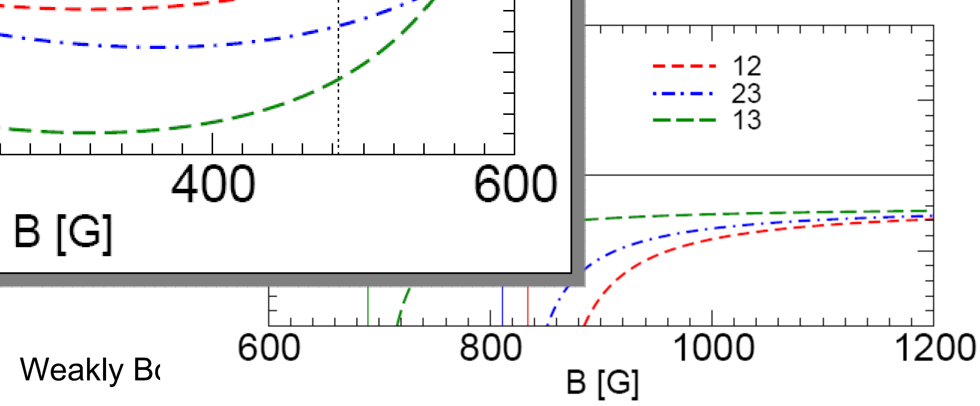
3-component Li-6 atoms

Heidelberg [Ottenstein et al, PRL (08)]
Penn state [Huckans et al, PRL(09)]

- Fermions with 3 lowest hyperfine states labeled |1>,|2>, and |3>
- Interactions: $a_{11}=a_{22}=a_{33}=0$, a_{12}, a_{23}, and a_{13}
- Wide universal regions ($|a_{ij}| >> l_{VdW} \approx 63a_0$)



Provided by P.S. Julienne

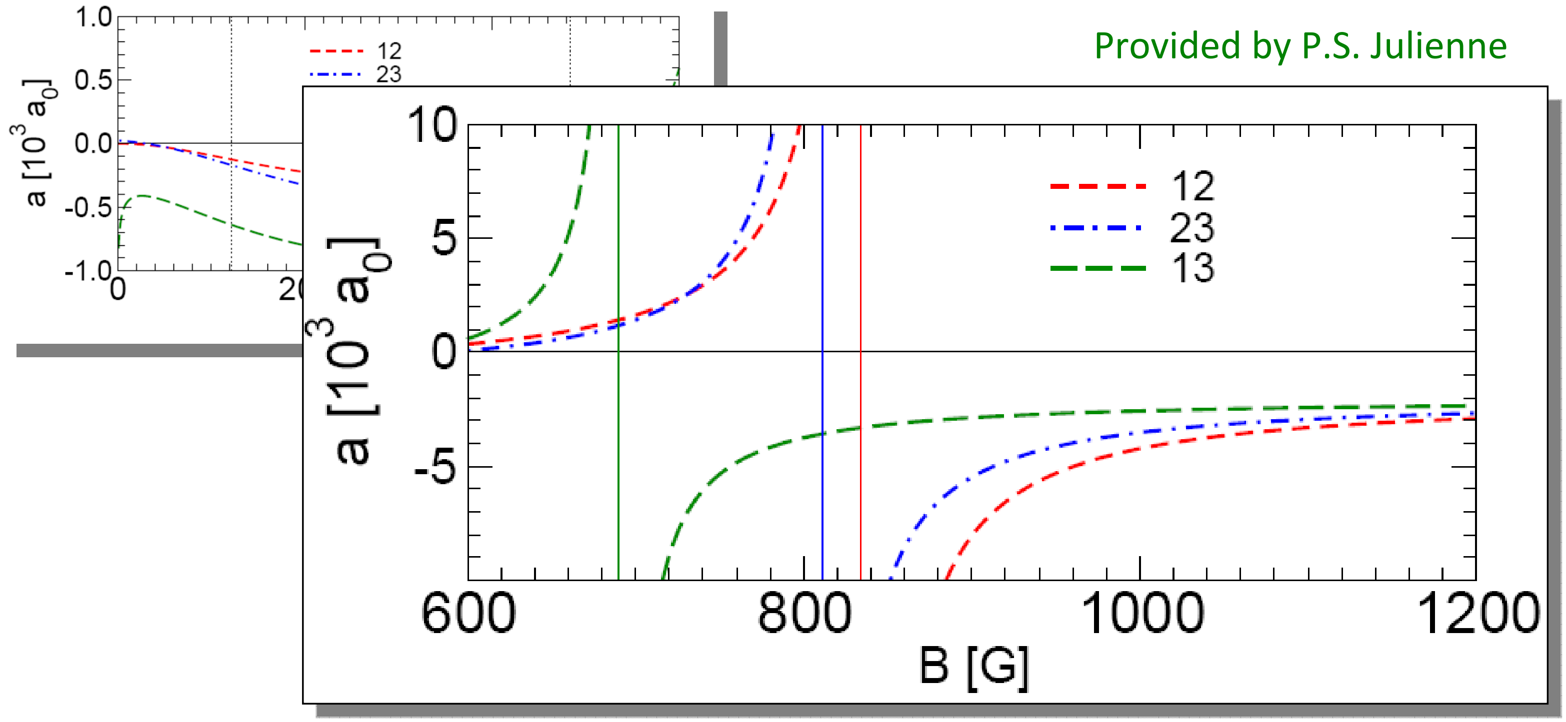


3-component Li-6 atoms

Heidelberg [Ottenstein et al, PRL (08)]
Penn state [Huckans et al, PRL(09)]

- Fermions with 3 lowest hyperfine states labeled |1>,|2>, and |3>
- Interactions: $a_{11}=a_{22}=a_{33}=0$, a_{12}, a_{23}, and a_{13}
- Wide universal regions ($|a_{ij}| >> l_{VdW} \approx 63a_0$)

Provided by P.S. Julienne



Effective Field Theory

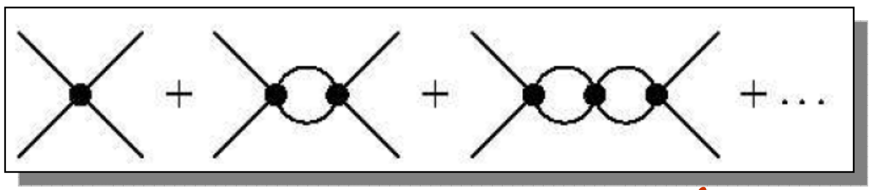
- 2-body amplitude at low energy

$$f_{ij}(k) = -\frac{1}{1/a_{ij}+ik}$$

- EFT strategy for 2-body system

construction of effective Hamiltonian that reproduces $f_{ij}(k)$

  - Interaction Hamiltonian $\frac{g_{ij}}{m}\psi_j^\dagger\psi_i^\dagger\psi_i\psi_j$
  - Sum over all possible 2-body diagrams



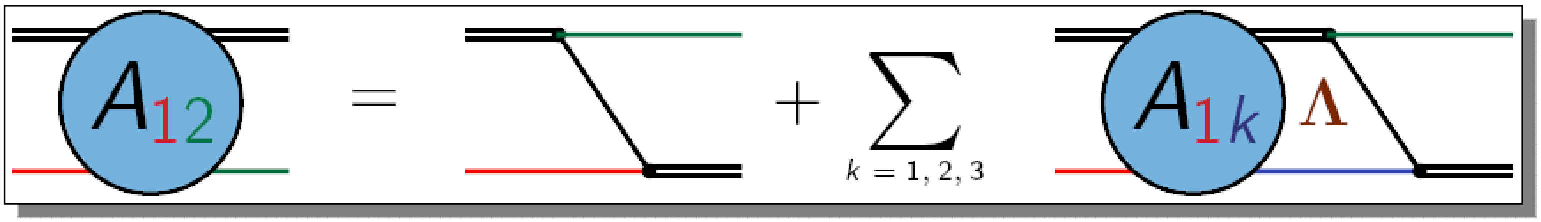
Amplitude depends on cutoff Λ

  - Renormalization of coupling g_{ij} that reproduces $f_{ij}(k)$

$$g_{ij} = 4\pi[1/a_{ij} - 2\Lambda/\pi]^{-1}$$

Effective Field Theory

- EFT strategy for 3-body system
  - Sum over all possible diagrams gives coupled integral equations



  - 3-body amplitudes $\mathbf{A_{ij}}$ depend on cutoff Λ *log- periodically*

  => fix cutoff Λ such that amplitudes $\mathbf{A_{ij}}$ reproduce a 3-body observable

- More formal strategy for 3-body system [Bedaque et al, PRL (1999)]
  - Introduce 3-body interaction
  - Renormalize 3-body coupling to eliminate the cutoff dependence

Energy spectrum

- 2-body amplitude $\mathbf{f_{ij}}$ near a dimer binding energy (a_{ij}>0)

$$f_{ij}(E) \to \frac{-2/(ma_{ij})}{E+E_{D_{ij}}} \quad \text{where} \quad E_{D_{ij}} = \frac{1}{ma_{ij}^2}$$

- 3-body amplitude $\mathbf{A_{ij}}$ near a trimer binding energy

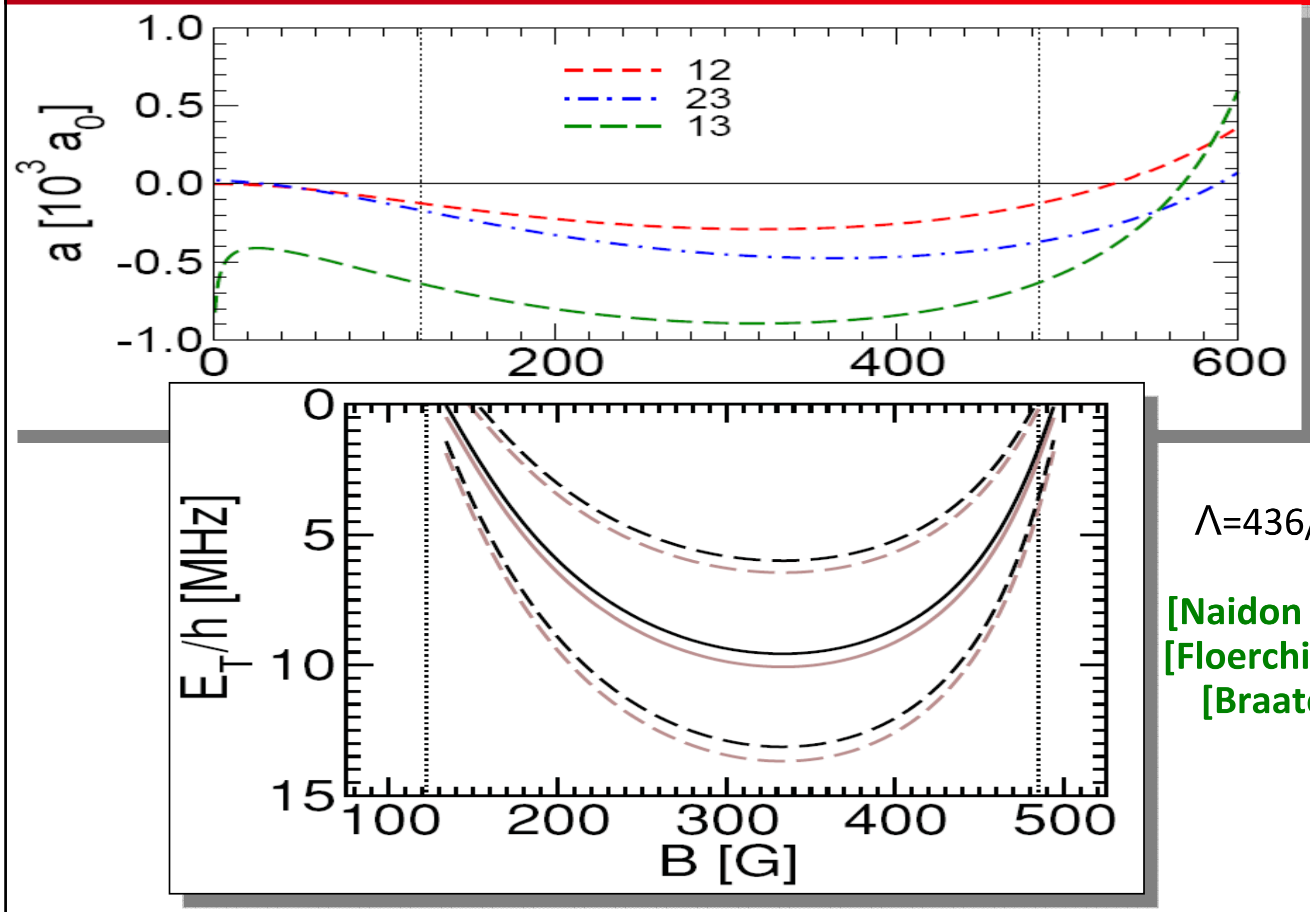
$$A_{ij}(E) \to \frac{Z}{E+E_T^{(n)}}$$

$\Rightarrow$ *Find energies that make the amplitudes diverge*

- In unitary limit ($\mathbf{a_{ij}} \to \pm\infty$)
  - trimer energy: $E_T^{(n)} = 0.031\,\lambda^{-2n}\,\frac{\Lambda^2}{m}$
  - finite width : $\Lambda \to \Lambda\, e^{i\eta^*/s_0}$

$(\lambda = e^{\pi/s_0} = 22.7)$

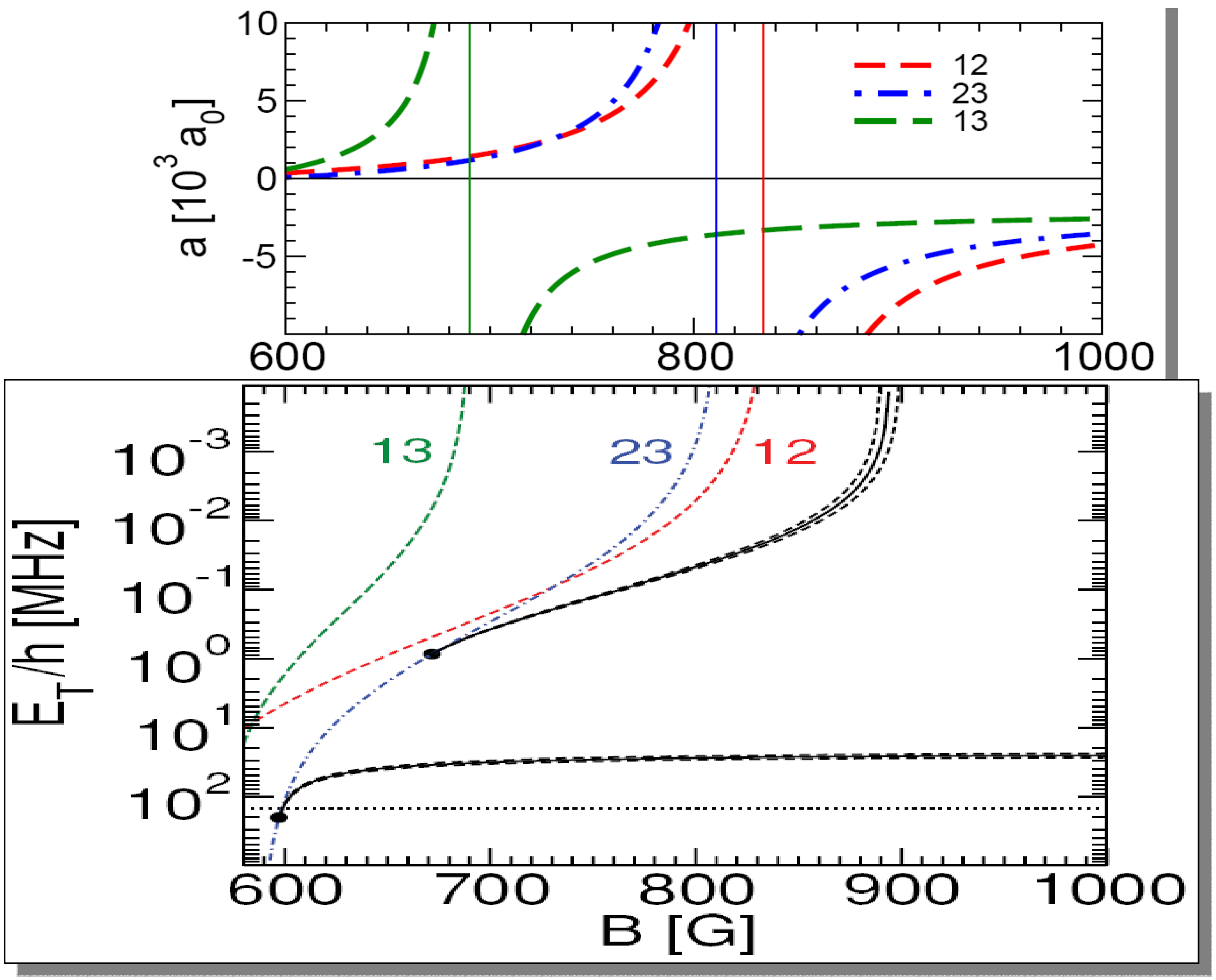
Energy Spectrum in Li-6 atoms



$\Lambda=436/a_0$ and $\eta^*=0.11$

[Naidon and Ueda, PRL(09)]
[Floerchinger et al, PRA(09)]
[Braaten et al, PRA(10)]

Energy Spectrum in Li-6 atoms



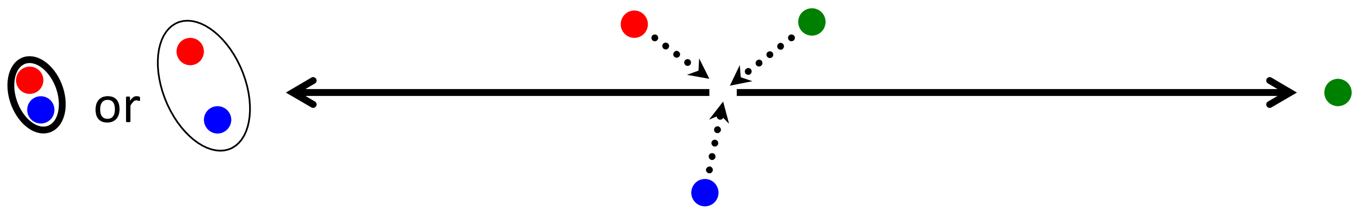
Λ=458/a0

η*=0.016

Braaten et al PRA(10)

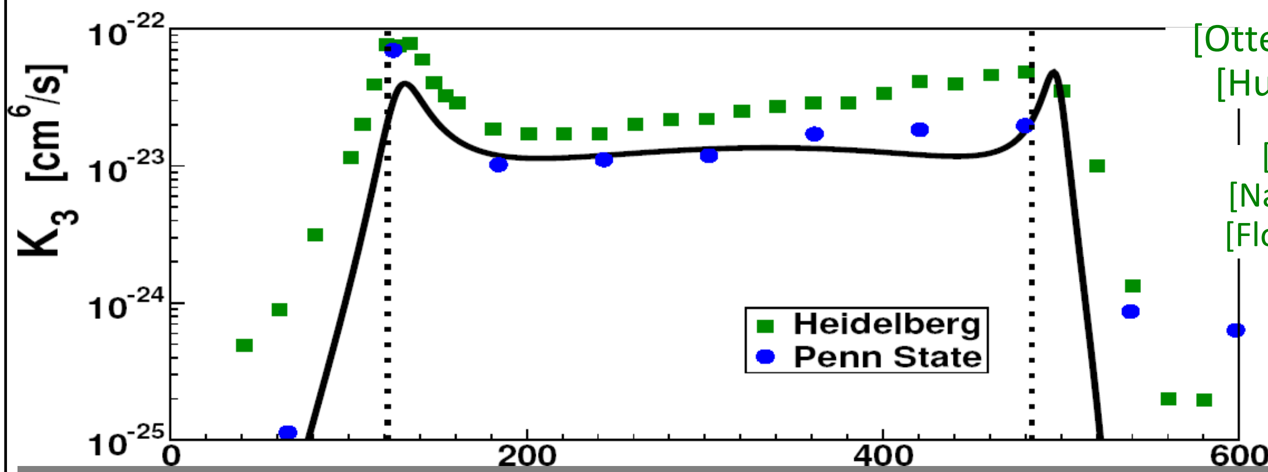
3-body Recombination

- Recombination process : AAA$\rightarrow$ A+D



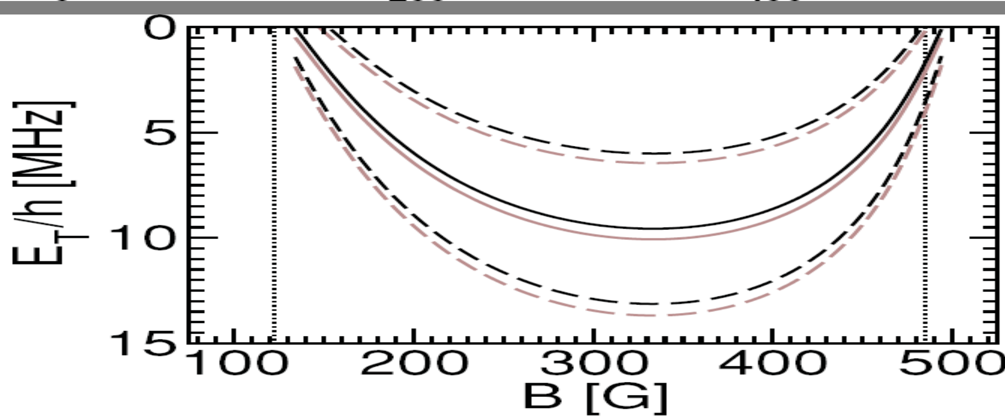
  - Shallow dimer energy=1/(m a_{ij}^2), Deep dimer energy~1/(m l_{VdW}^2)
  - ***Resonant* when timer appears at 3 atom threshold**
- Rate constant : $$\frac{dn_i}{dt} = -K_3\, n_1 n_2 n_3$$
  - Total rate (Optical theorem) : $K_3 = \frac{32\pi^2}{m}\sum_{ij} a_i a_j \mathrm{Im} A_{ij} \quad (a_i = a_{jk})$
  - Partial rate into shallow dimer : $K_3^{ij} = \frac{512\pi^2}{3\sqrt{3}ma_k^2}|\sum_l a_l A_{lk}|^2$
  - Rate into deep dimer : $K_3^{deep} = K_3 - (K_3^{12} + K_3^{23} + K_3^{13})$

Recombination at low field



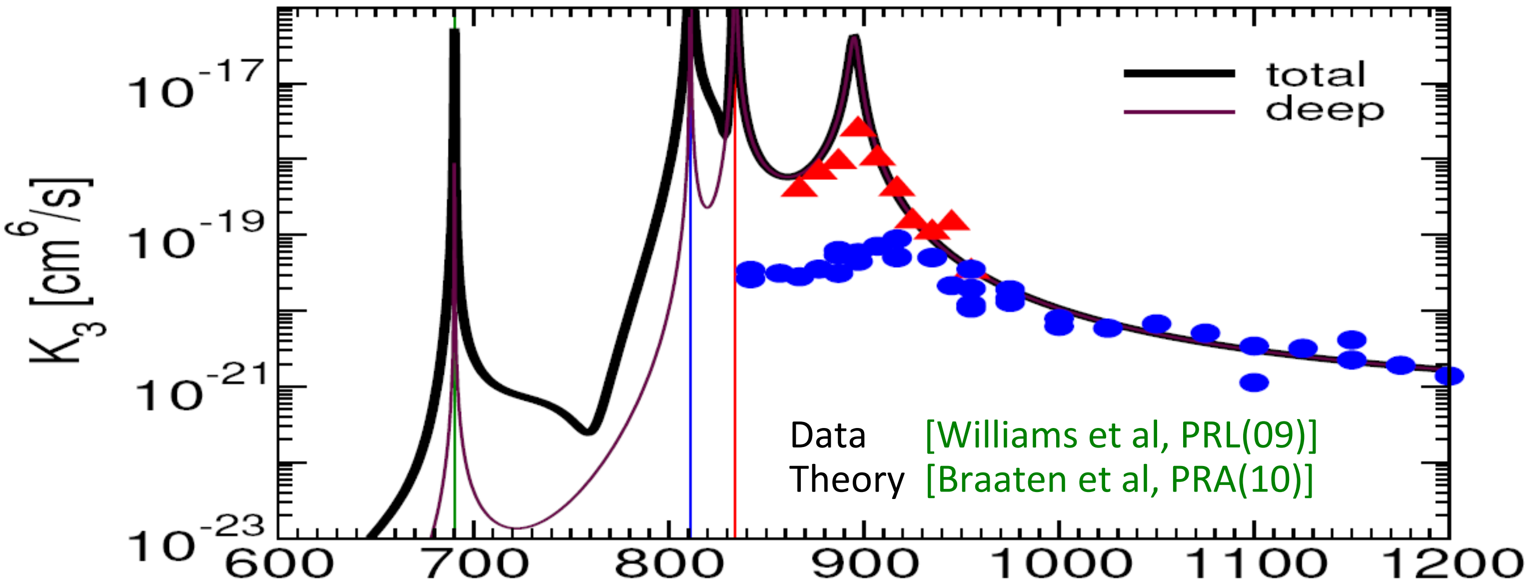
[Ottenstein et al, PRL (08)]
[Huckans et al, PRL(09)]

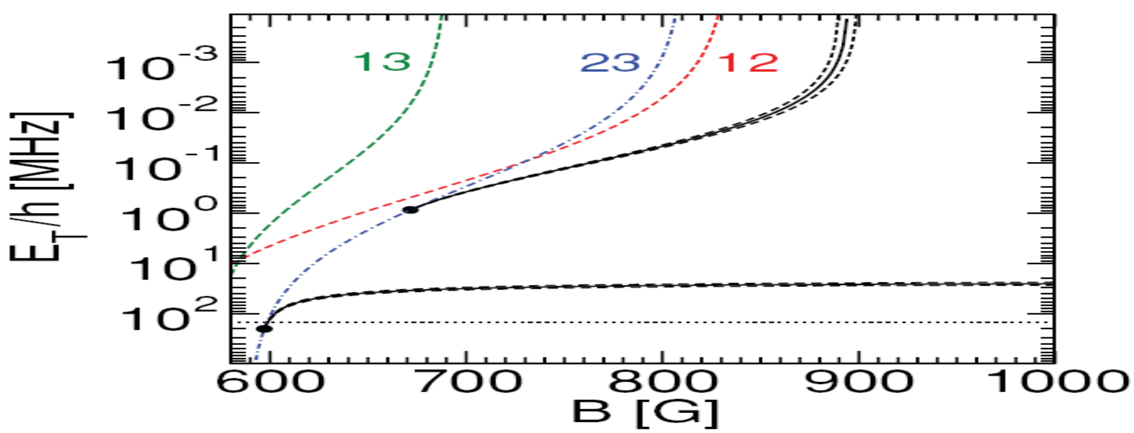
[Braaten et al, PRL(09)]
[Naidon and Ueda, PRL(09)]
[Floerchinger et al, PRA(09)]



- **narrow and broad resonances** =>trimers at threshold
- deep dimer running to threshold broadens 2nd resonance

Recombination at high field

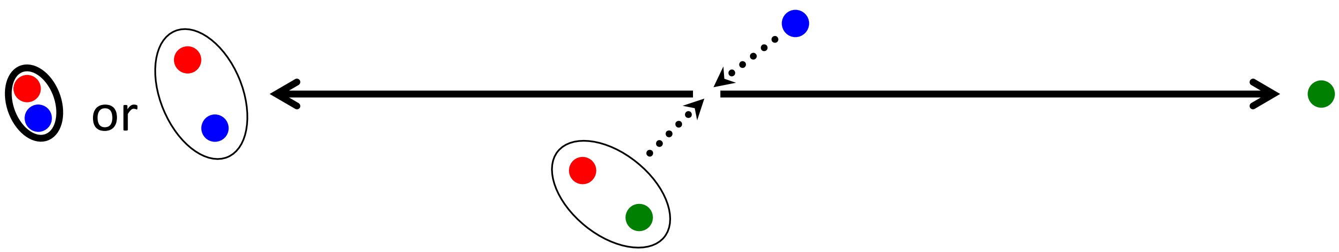




- 3 peaks at Feshbach resonances
- **Resonance at 895G**
  => trimer at threshold
  => height should decrease as temperature increases
- Interference minima at 759G, 829G

Atom-dimer Relaxation

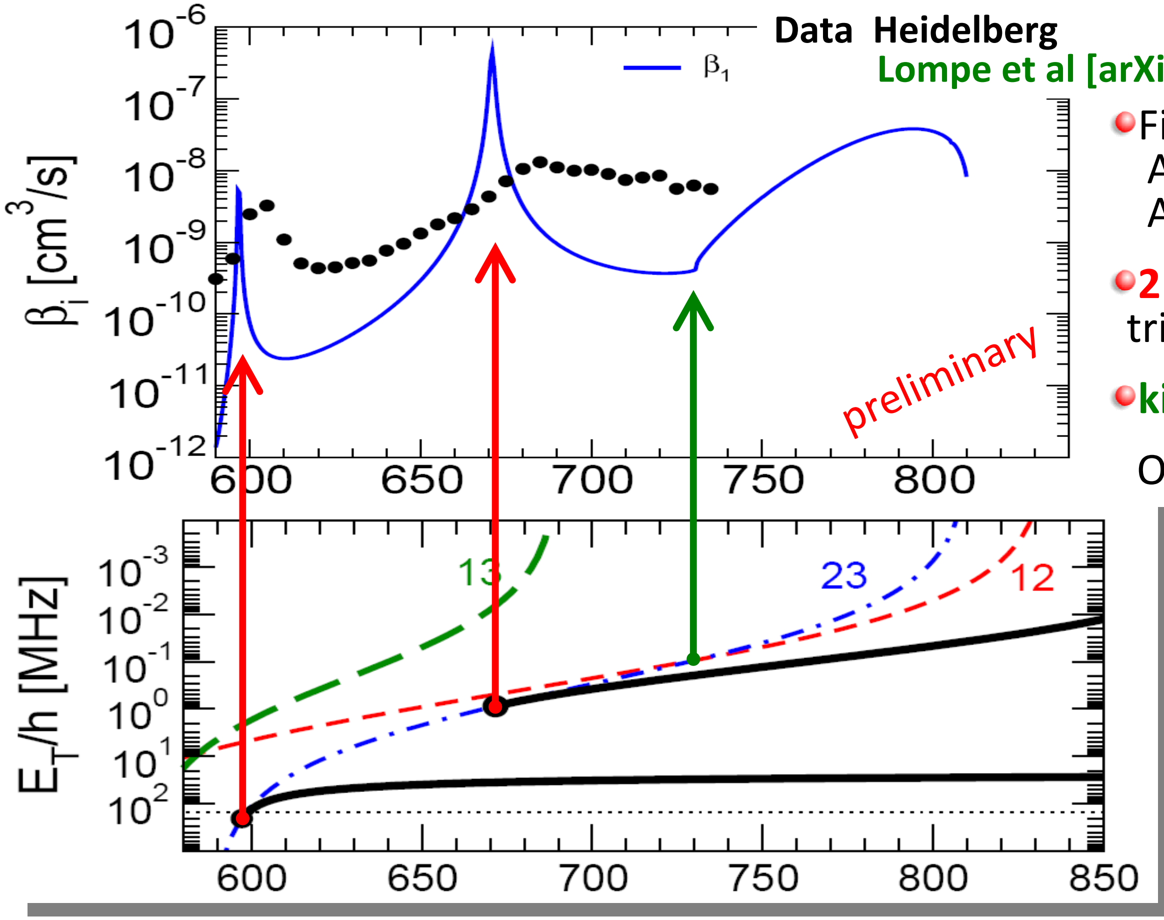
- Relaxation process : A+D →A+ (shallow Dimer)
  →A+ (deep Dimer)



  - *Resonant when trimer appears at AD threshold*

- Rate constant $\frac{dn_i}{dt} = \frac{dn_D}{dt} = -\beta_i n_i n_D$
  - Total rate (Optical theorem) : $\beta_i = \frac{16\pi}{m a_{jk}} \mathrm{Im} A_{ii}$

Relaxation for A1 + D23



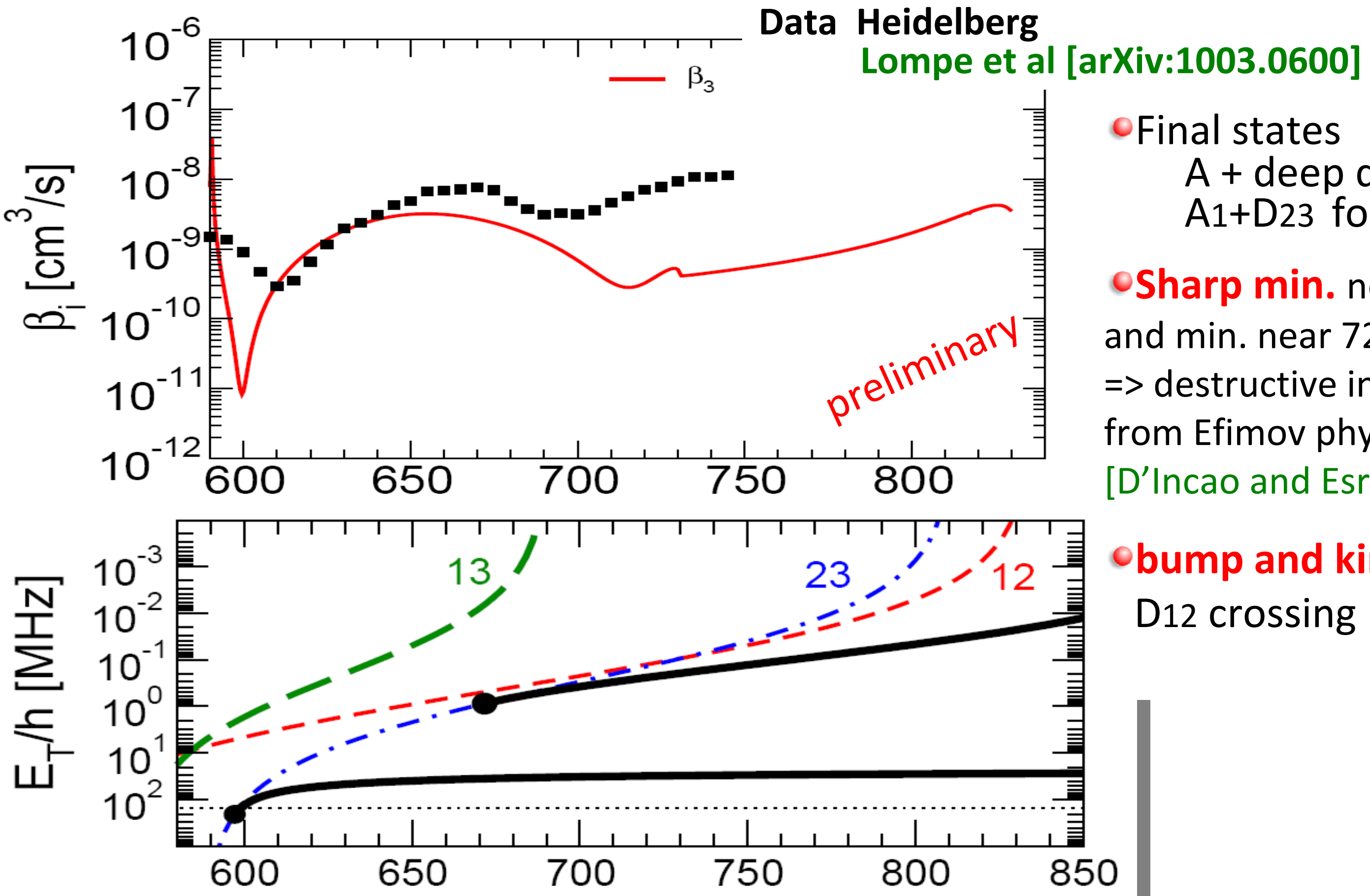
Data Heidelberg

Lompe et al [arXiv:1003.0600]

- Final states
  A + deep dimer
  A3+D12 for B>730 G
- **2 resonances** related to trimers at A1D23 threshold
- **kink** at D12 crossing D23

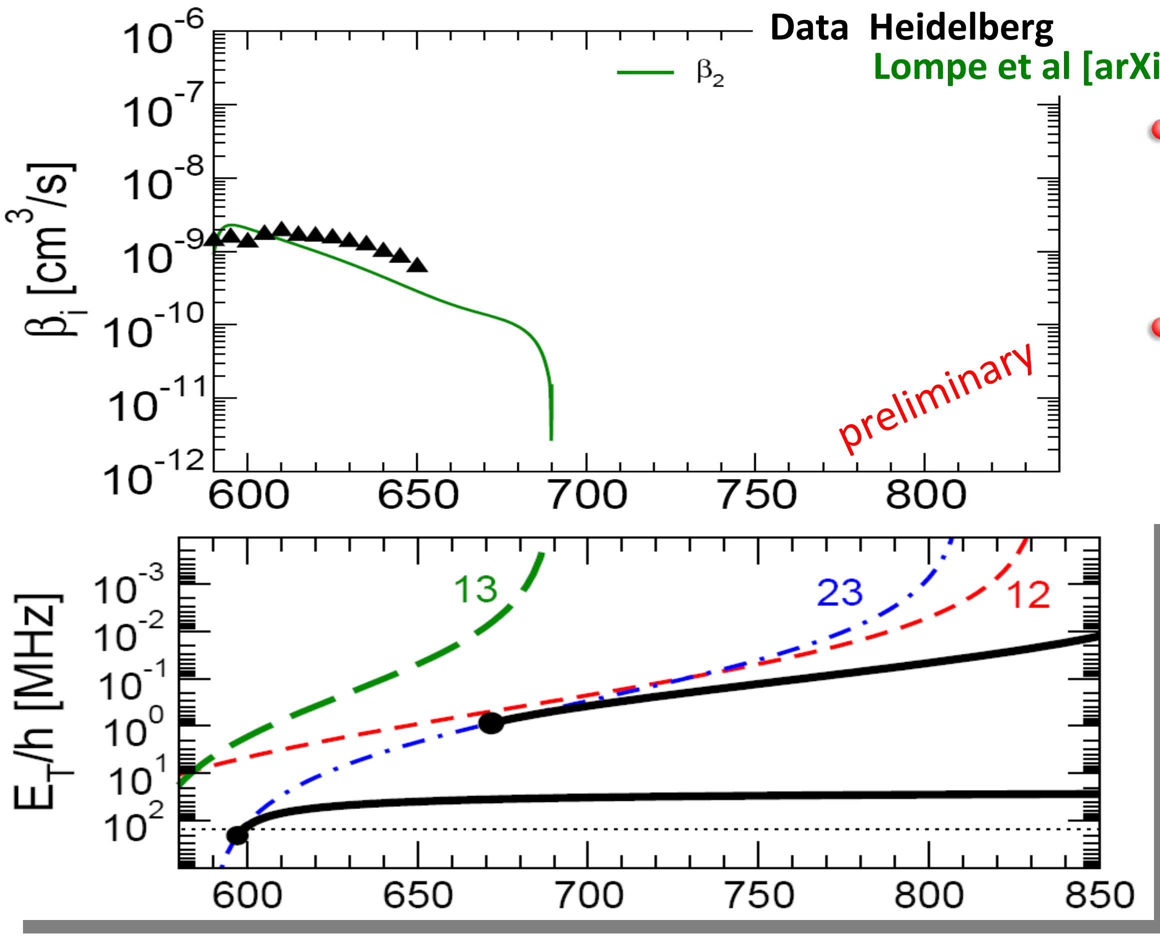
Opening A3+D12 channel

Relaxation for A3 + D12



- Final states
  A + deep dimer
  A1+D23 for B<730 G
- **Sharp min.** near 600G and min. near 720G => destructive interference from Efimov physics ?? [D'Incao and Esry PRL(09)]
- **bump and kink** at 730G
  D12 crossing D23

Relaxation for A2 + D13



- Final states
  - A + deep dimer
  - A3+D12
  - A1+D23
- **No dramatic structure**

Summary

- 3-component Li-6 system displays interesting Efimov physics
  - 1 trimer at low field and 2 trimers at high field
  - Resonances and interference minima
    in both recombination and AD relaxation
  - Kink in AD relaxation when two dimers cross
- This study has been carried at zero temperature
  - Finite temperature effect might give a better understanding of
    measurements.