

Universality in QCD and Halo Nuclei

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Collaborators: E. Braaten, D. Canham, D. Kang, L. Platter, R. Springer, ...

- Introduction
- Effective Field Theory for large scattering length
- Limit cycle \Leftrightarrow Efimov effect
- Halo nuclei
- Scattering properties of the $X(3872)$
- Summary and Outlook

Review article: Braaten, HWH, Phys. Rep. **428** (2006) 259

Epelbaum, HWH, Meißner, arXiv:0811.1338 (to appear in Rev. Mod. Phys.)

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Frequently asked Questions & Answers about EFT

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Introduction: To hear some people talk, one might think that one round of the EFT Basic Recipe would cure every ailment known to the human race. Just tap, tap, tap and everyone becomes peaceful—all grievances disappear, all traumas are instantly resolved and no one grows old or dies. That's a worthy thought, of course, but we're not quite there yet.

If EFT had reached such perfection, there would be nothing more to learn and this Question and Answer series would be unnecessary. But because we are always seeking greater proficiency, I am dedicating a significant part of this web site to those Questions and Answers about EFT that will allow us to move forward. The *questions* covered in this section come from both newcomers and experienced practitioners alike. The *answers* are designed to assist EFT users in the "art" of this process which, hopefully, will allow us all to approach perfection—a noble goal indeed. Let's begin.

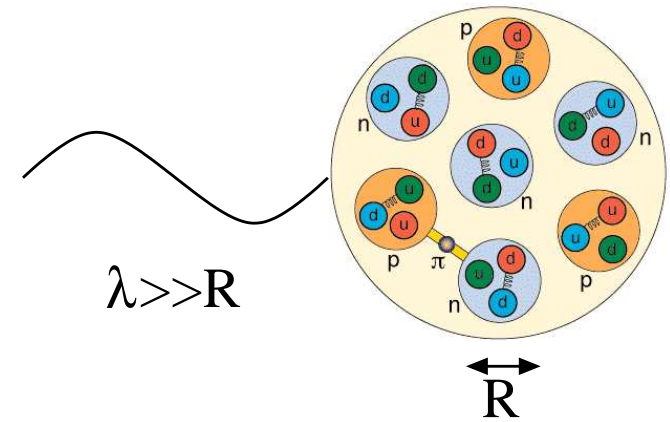
QUESTIONS & ANSWERS INDEX

- [When it doesn't work...???](#)
- [What is the EFT "open hand" policy and what rights and restrictions do I have regarding the EFT materials, workshops, certifications, credentials, organizations and the practice of EFT?](#)
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- [Can we do EFT surrogately or through intention? If so do we need permission?](#)

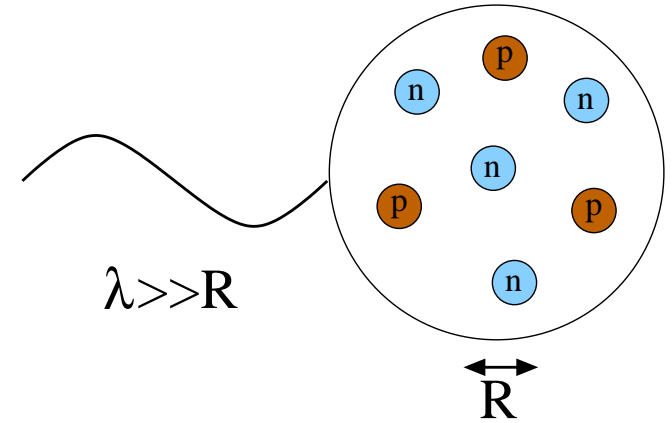
http://www.emofree.com/Articles.aspx?id=13#

thanks to D. Phillips

- Separation of scales:
 $1/k = \lambda \gg R$
- Limited resolution at low energy:
→ expand in powers of kR

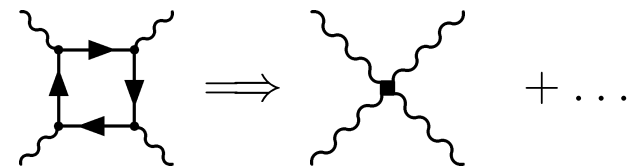


- Separation of scales:
 $1/k = \lambda \gg R$
- Limited resolution at low energy:
→ expand in powers of kR
- Short-distance physics not resolved
→ capture in low-energy constants using renormalization
→ include long-range physics explicitly
- Systematic, model independent → error estimates
- Classic example: light-light-scattering (Euler, Heisenberg, 1936)



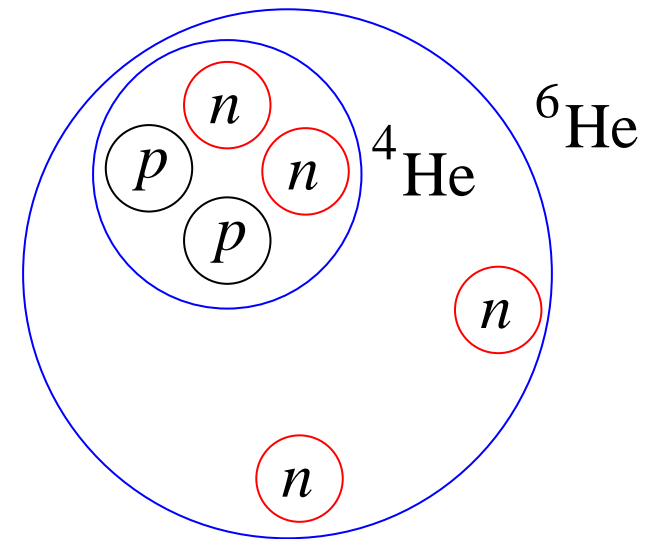
Simpler theory for $\omega \ll m_e$:

$$\mathcal{L}_{QED}[\psi, \bar{\psi}, A_\mu] \rightarrow \mathcal{L}_{eff}[A_\mu]$$



- Few-body systems
—→ fix interaction/low-energy constants for many-body calculations
- Few-body physics in many-body systems
—→ certain properties of many-body systems are determined by **effective** few-body physics
- Limited resolution at low energy —→ **cluster structure**

- Example: halo nuclei



- Strong interaction \implies large scattering length a
- Natural expansion parameter: $\ell/|a|, k\ell, \dots$ ($\ell \sim r_e, l_{vdW}, \dots$)

$$a > 0 \implies B_d \approx \frac{\hbar^2}{ma^2}$$

- Atomic physics:
 - ^4He : $a \approx 104 \text{ \AA} \gg r_e \approx 7 \text{ \AA} \sim l_{vdW} \longrightarrow B_d \approx 100 \text{ neV}$
 - Feshbach resonances \implies variable scattering length
- Nuclear physics: S -wave NN -scattering, halo nuclei, ...
 - $^1S_0, ^3S_1$: $|a| \gg r_e \sim 1/m_\pi \longrightarrow B_d \approx 2.2 \text{ MeV}$
 - ^6He : $2n$ separation energy $\approx 973 \text{ keV}$
- Particle physics:

Is the $X(3872)$ a $D^0 D^{0*}$ molecule? ($J^{PC} = 1^{++}$)

$$m_X - (m_{D^0} + m_{D^{0*}}) = (-0.3 \pm 0.4) \text{ MeV}$$

- Effective Lagrangian

(Kaplan, 1997; Bedaque, HWH, van Kolck, 1999)

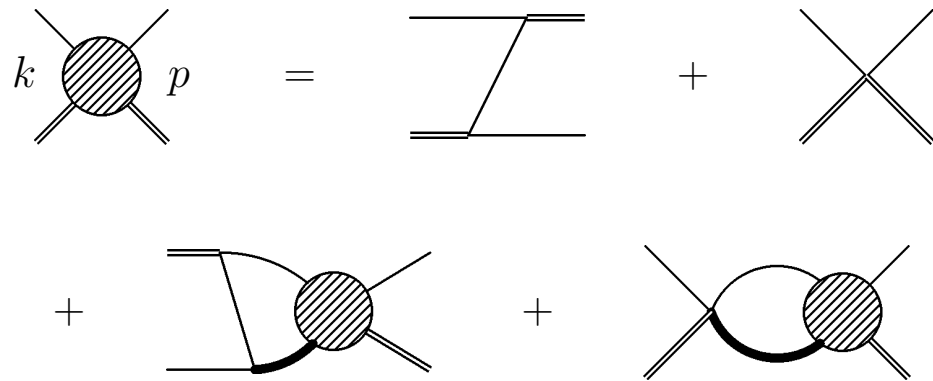
$$\mathcal{L}_d = \psi^\dagger \left(i\partial_t + \frac{\vec{\nabla}^2}{2m} \right) \psi + \frac{g_2}{4} d^\dagger d - \frac{g_2}{4} (d^\dagger \psi^2 + (\psi^\dagger)^2 d) - \frac{g_3}{36} d^\dagger d \psi^\dagger \psi + ..$$

- 2- and 3-body interaction at leading order g_2, g_3

- 2-body amplitude:



- 3-body equation:
(S -waves)



- Dimensionless coupling:

$$\frac{g_3}{9g_2^2} = \frac{H(\Lambda)}{\Lambda^2}$$

- Demand invariance of observables from Λ
- $H(\Lambda)$ periodic: **limit cycle**

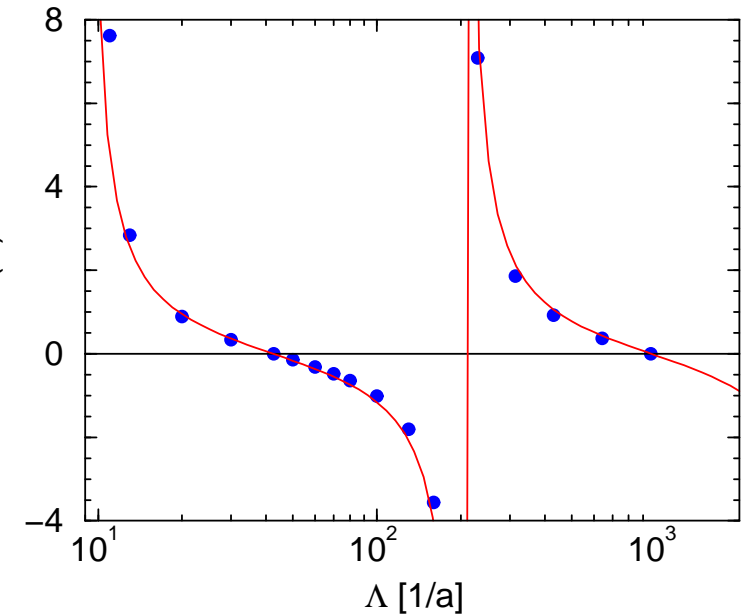
$$\Lambda \rightarrow \Lambda e^{n\pi/s_0} \approx \Lambda (22.7)^n$$

(Wilson, 1971)

- **Discrete scale invariance**

$$H(\Lambda) = \frac{\cos(s_0 \ln(\Lambda/\Lambda_*) + \arctan(s_0))}{\cos(s_0 \ln(\Lambda/\Lambda_*) - \arctan(s_0))}, \quad s_0 \approx 1.00624$$

(Bedaque, HWH, van Kolck, 1999)



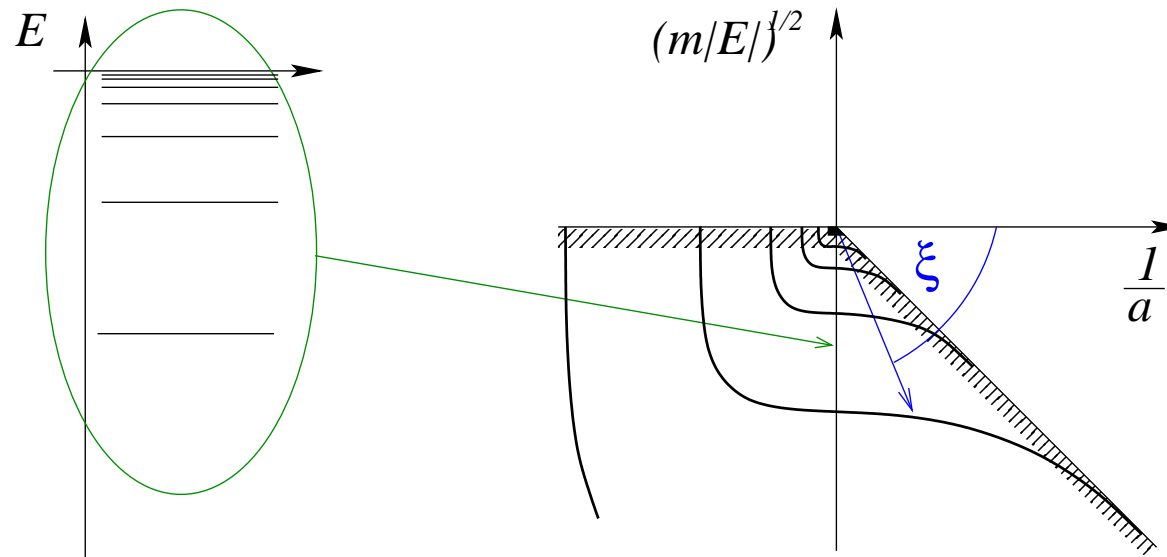
- **Observable Consequences?**

\implies Efimov effect, log-periodic dependence of observables on scattering length, limit cycle in deformed QCD?, ...

- **Renormalization group approach** (Barford, Birse, 2005)

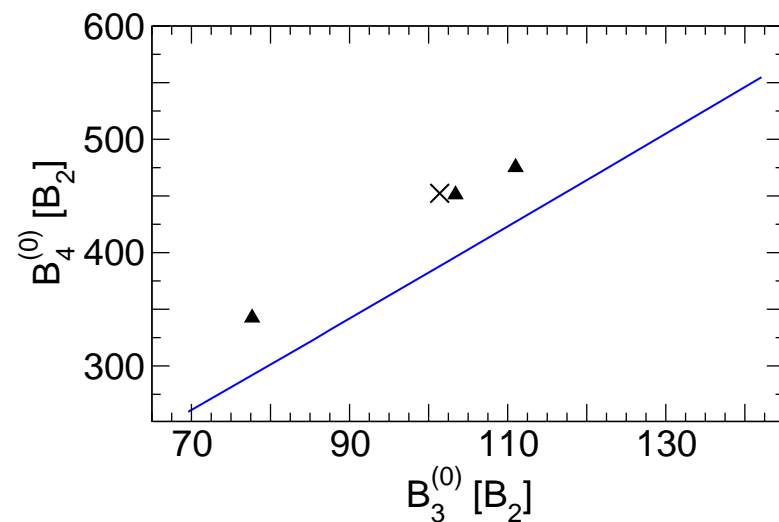
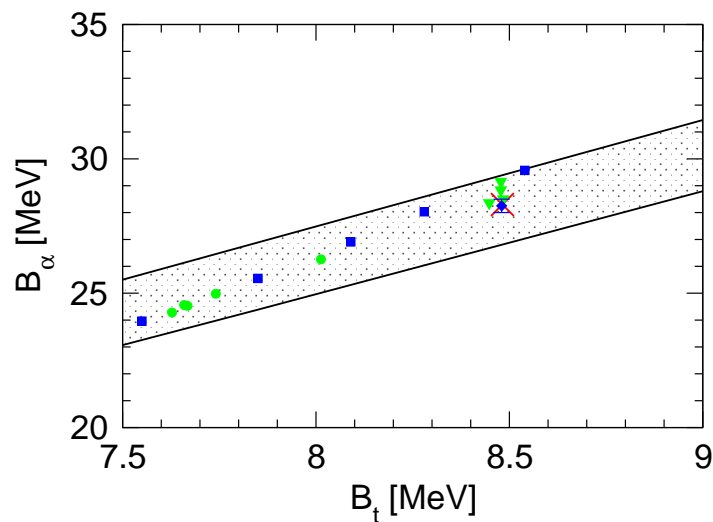
- Universal spectrum of three-body states

(V. Efimov, Phys. Lett. **33B** (1970) 563)



- Discrete scale invariance for fixed angle ξ
- **Geometrical spectrum** für $1/a \rightarrow 0$
- Manifestation in scattering observables
 - ⇒ **log-periodic dependence** on a
 - ⇒ indirect observation of the Efimov effect

- 2 Parameters at LO \Rightarrow 3-body observables are correlated
 \Rightarrow Phillips line (Phillips, 1968)
- No four-body parameter at LO (Platter, HWH, Meißner, 2004)
 \Rightarrow 4-body observables are correlated \Rightarrow Tjon line



- Variation of Λ_* parametrizes correlations
- Nuclear physics: Λ dependence of V_{low-k} (Bogner et al., 2004)

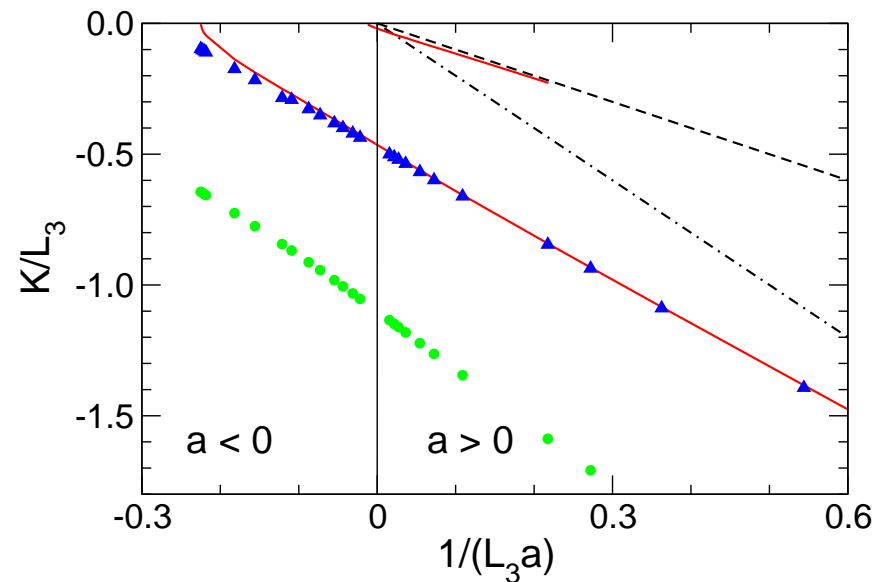
- Universal properties of 4-body system with large a
 - Bound state spectrum
 - Scattering Observables
- “Efimov-plot”: 4-body bound state spectrum as function of $1/a$

$$K = \text{sign}(E) \sqrt{m|E|}$$

$$B_4^{(0)} = 5B_3^{(0)} \quad (1/a \equiv 0)$$

$$B_4^{(1)} = 1.01B_3^{(0)}$$

(Platter, HWH, EPJA **32** (2007) 113)

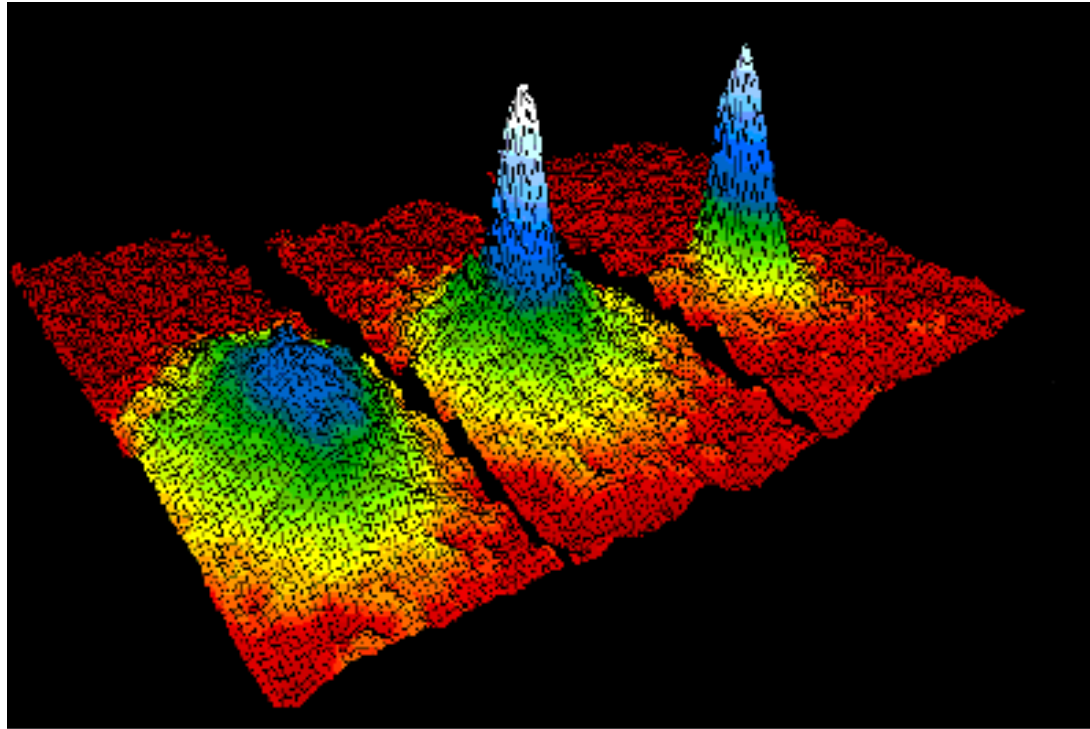


- Signature in Cs loss data

von Stecher, D’Incao, Greene, arXiv:0810.3876

Ferlaino, Knoop, Berninger, Harm, D’Incao, Nägerl, Grimm, arXiv:0903.1276

- Velocity distribution ($T = 400$ nK, 200 nK, 50 nK)



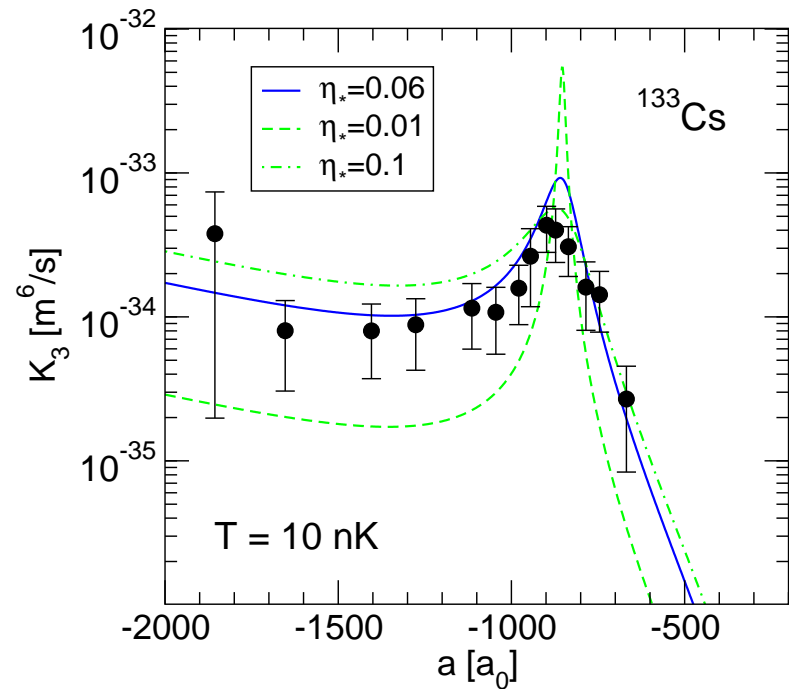
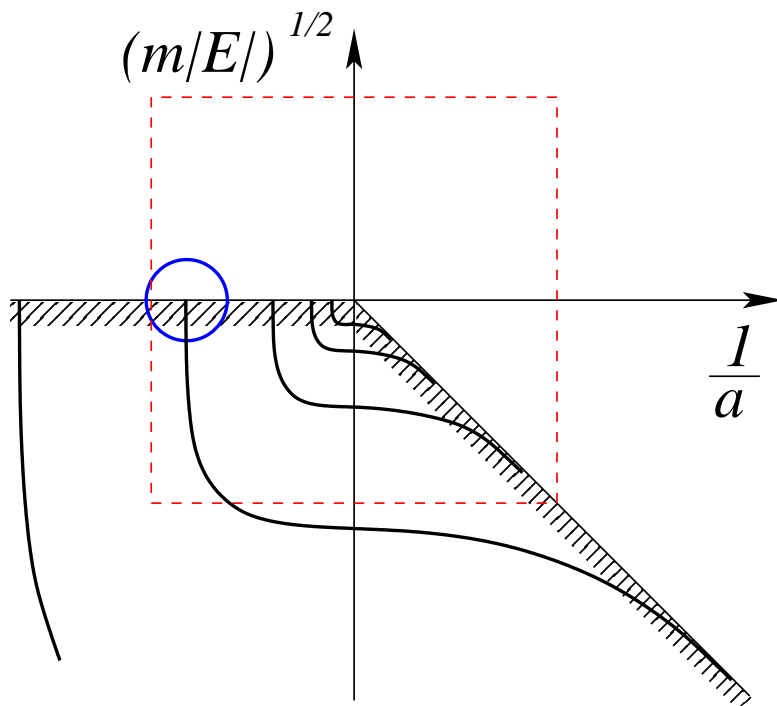
(Source: <http://jilawww.colorado.edu/bec/>)

- Variable scattering length via Feshbach resonances

- Experimental evidence for Efimov states in ^{133}Cs

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

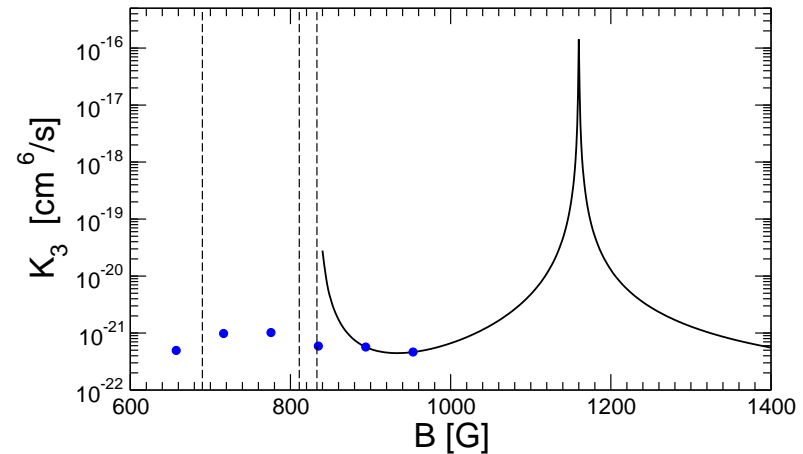
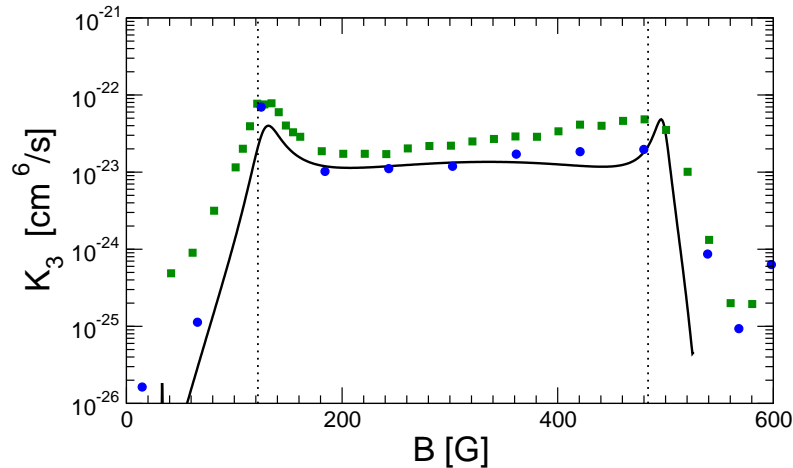
- Identification via 3-body recombination rate



$$a < 0: \quad a'_* = -875a_0$$

- Treatment of finite temperature (Braaten, HWH, Kang, Platter, 2008)

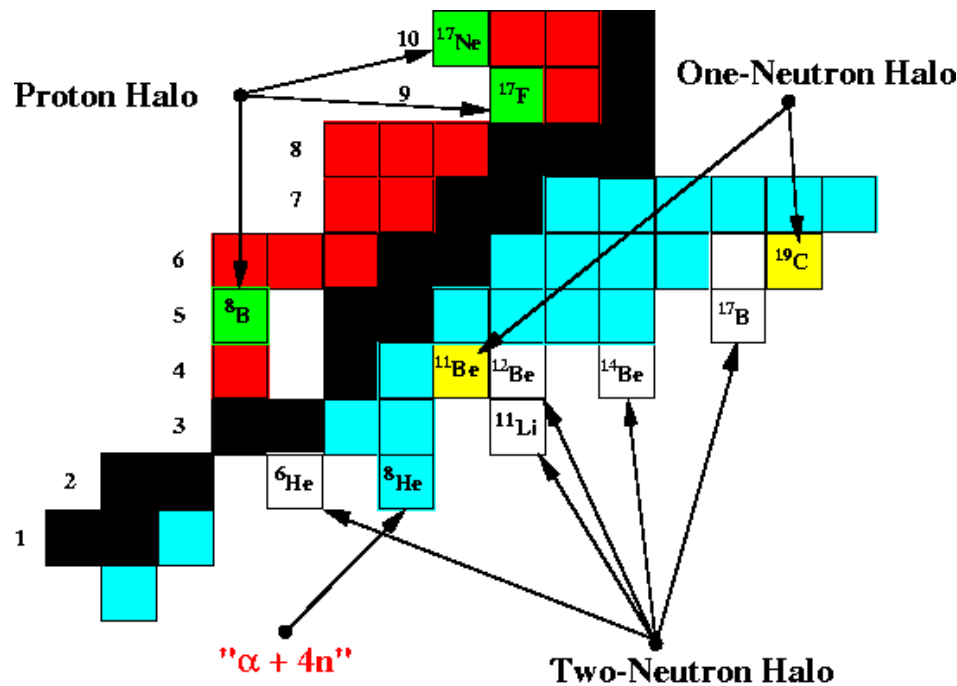
- Efimov effect for fermions $\Rightarrow \geq 3$ spin states
- Experimental evidence for Efimov states in ${}^6\text{Li}$
 - Ottenstein et al. (Heidelberg), Phys. Rev. Lett. **101** (2008) 203202
 - Huckans et al. (Penn State), arXiv:0810.3288



(Braaten, HWH, Kang, Platter, arXiv:0811.3578)

- Systematic normalization error: 70-90%
- Prediction of resonance around $B \approx 1160$ G
- Other approaches: Schmidt et al., arXiv:0812.1191; Naidon et al., arXiv:0811:4086

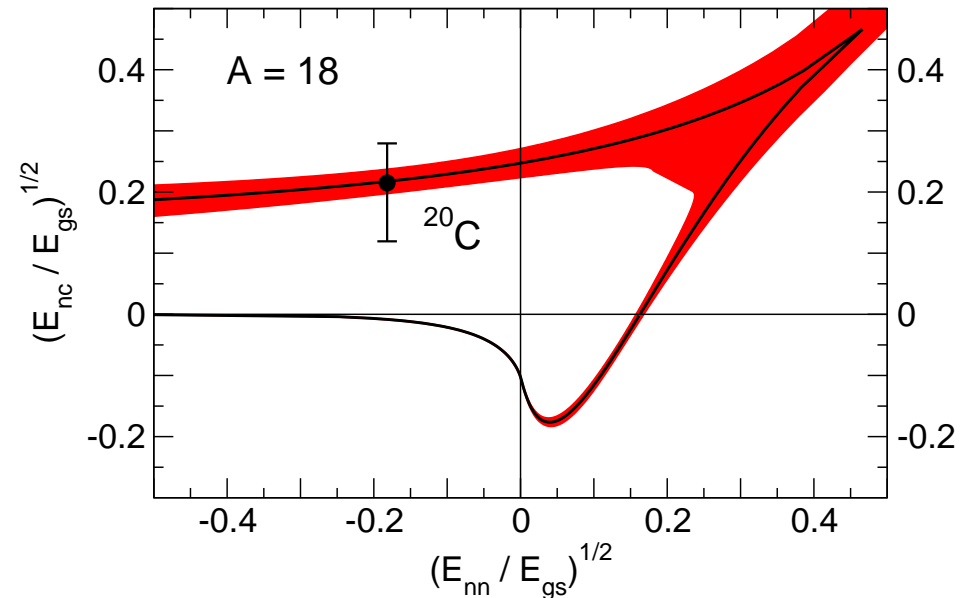
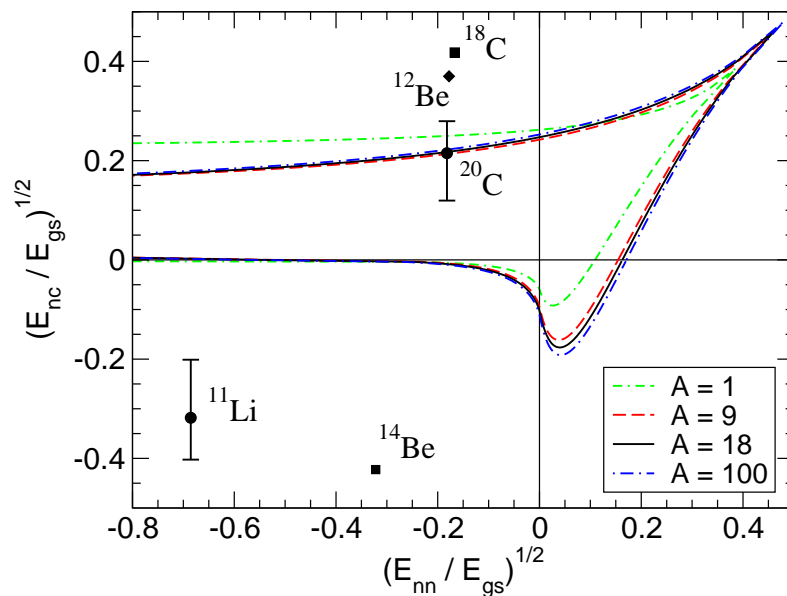
- Low separation energy of valence nucleons: $B_{valence} \ll B_{core}, E_{ex}$
 → close to “nucleon drip line” → **scale separation** → EFT



<http://www.nupecc.org>

- EFT for halo nuclei
 - $n\alpha$ -System (“ ^5He ”) (Bedaque, Bertulani, HWH, van Kolck, 2002)
 - $\alpha\alpha$ -System (“ ^8Be ”) (Higa, HWH, van Kolck, 2008)

- **Examples:** $^{14}\text{Be} \longleftrightarrow ^{12}\text{Be} + n + n$, $^{20}\text{C} \longleftrightarrow ^{18}\text{C} + n + n$
- **“Effective” 3-body system:** separation energy of valence nucleons small compared to binding energy of “core”
- **Efimov effect in halo nuclei?** \Rightarrow **excited states**



Canham, HWH, Eur. Phys. J. A **37** (2008) 367
 (cf. Amorim, Frederico, Tomio, 1997)

- Structure of halo nuclei \rightarrow matter form factors, radii

$$F(k^2) = \int d^3p d^3q \Psi(\vec{p}, \vec{q}) \Psi(\vec{p}, \vec{q} - \vec{k}) = 1 - \frac{1}{6}k^2 \langle r^2 \rangle + \dots$$

- Candidate: ^{20}C

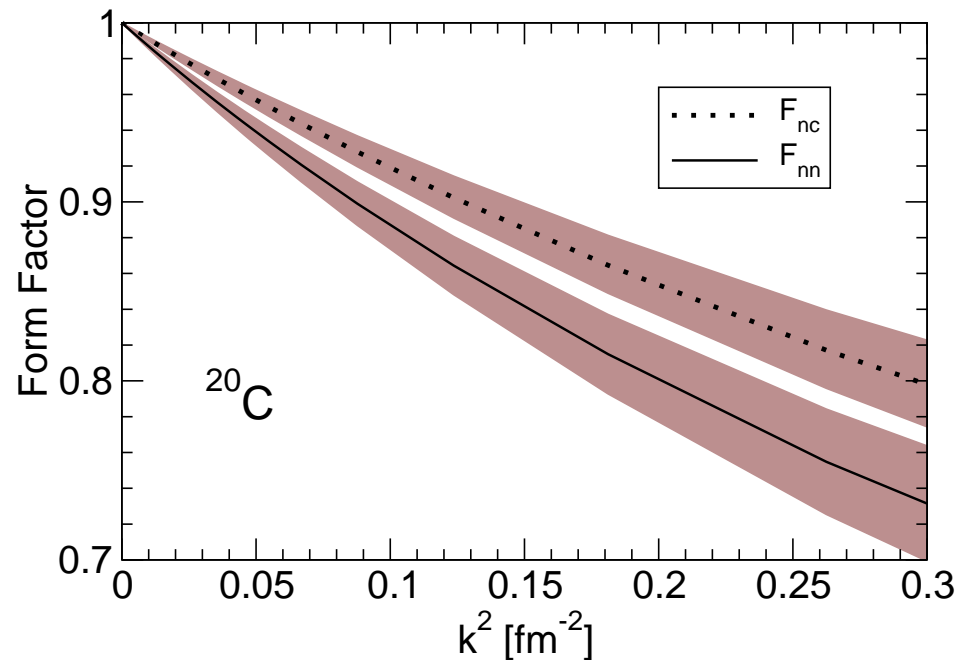
- Form factors:

F_{nn} neutron-neutron

F_{nc} neutron-core

F_n neutron-cm

F_c core-cm



Canham, HWH, Eur. Phys. J. A **37** (2008) 367

- Structure of halo nuclei → matter form factors, radii

nucleus	B_{nnc} [keV]	B_{nc} [keV]	$\sqrt{\langle r_{nn}^2 \rangle}$ [fm]	$\sqrt{\langle r_{nc}^2 \rangle}$ [fm]
^{14}Be	1120	-200.0	4.1 ± 0.5	3.5 ± 0.5
^{20}C	3506	161	2.8 ± 0.3	2.4 ± 0.3
	3506	530	3.0 ± 0.7	2.5 ± 0.6
	3506	60	2.8 ± 0.2	2.3 ± 0.2
$^{20}\text{C}^*$	65 ± 6.8	60	42 ± 3	38 ± 3

Canham, HWH, Eur. Phys. J. A **37** (2008) 367

(cf. Yamashita, Tomio, Frederico, 2004)

- Input: TUNL Nuclear data evaluation project, ...
- Experiment: $^{14}\text{Be} \rightarrow \sqrt{\langle r_{nn}^2 \rangle} = (5.4 \pm 1.0)$ fm
(Marques et al., Phys. Rev. C **64** (2001) 061301)

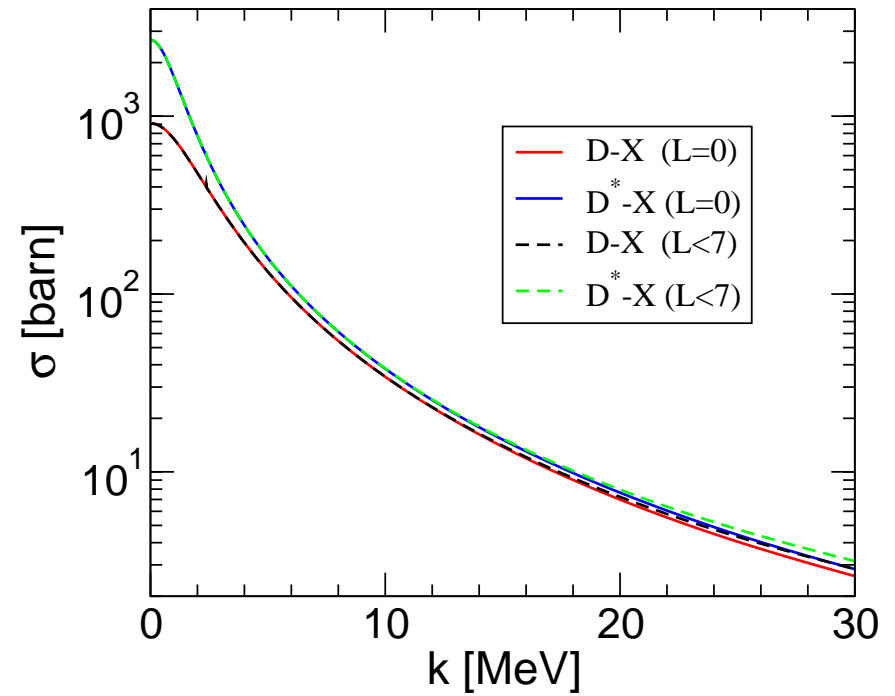
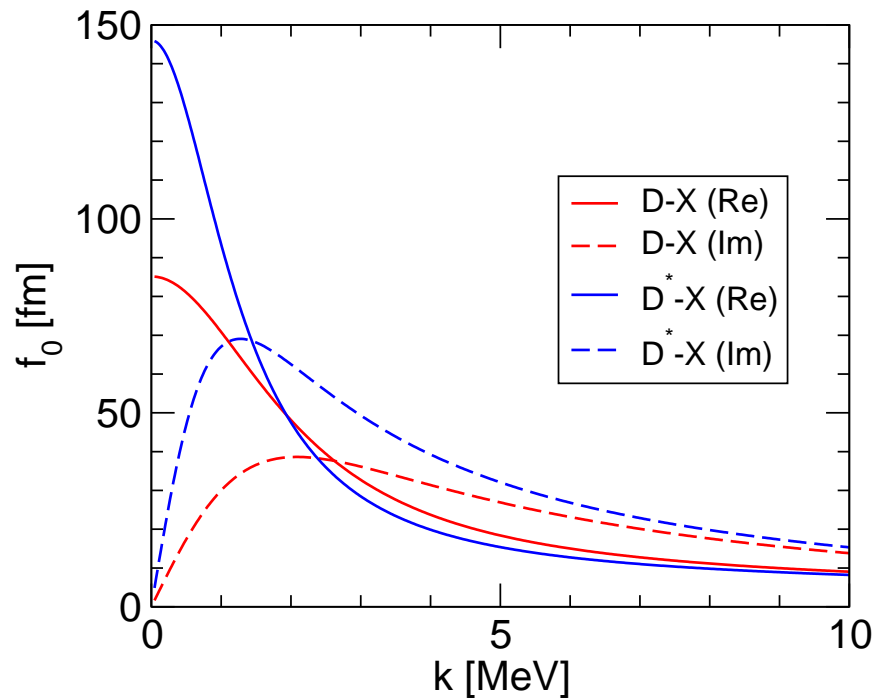
- Many new $c\bar{c}$ -mesons at B-factories: X, Y, Z
 - Challenge for understanding of QCD
 - Large scattering length physics important
- Example: $X(3872)$ (Belle, CDF, BaBar, D0)

$$m_X = (3871.55 \pm 0.20) \text{ MeV} \quad \Gamma < 2.3 \text{ MeV} \quad J^{PC} = 1^{++}$$

- No ordinary $c\bar{c}$ -state
 - Decays violate isospin
 - Measured mass depends on decay channel
- Nature of $X(3872)$?
 - $D^0 D^{0*}$ -molecule? (cf. Tornquist, 1991)
 - Tetraquark
 - Charmonium Hybrid
 - ...

- Nature of $X(3872)$ not finally resolved
- Assumption: $X(3872)$ is weakly-bound D^0 - D^{0*} -molecule
 - $\implies |X\rangle = (|D^0\bar{D}^{0*}\rangle + |\bar{D}^0D^{0*}\rangle)/\sqrt{2}$, $B_X = (0.26 \pm 0.41) \text{ MeV}$
 - \implies **universal properties** (cf. Braaten et al., 2003-2008, ...)
 - Explains isospin violation in decays of $X(3872)$
 - \implies superposition of $I = 1$ and $I = 0$
 - Different masses due to different line shapes in decay channels
- Large scattering length determines interaction of $X(3872)$ with D^0 and D^{0*}
 - \implies **no Efimov effect** \implies no X - D - and X - D^* -molecule
 - \implies parameter-free prediction of X - D -, X - D^* -scattering
- **EFT with explicit pions:** Fleming, Kusunoki, Mehen, van Kolck, 2007

- Predictions for scattering amplitude/cross section



Canham, HWH, Springer, in preparation

- Rare events at B factories ($B \rightarrow X, \bar{B} \rightarrow D, D^*$)
- Final state interaction of D, D^* mesons in B_c -decays (e.g. LHCb)

- EFT \Rightarrow (effective) few-body properties of many-body systems
- EFT for systems with large scattering length
 - Limit cycle in three-body system \Leftrightarrow Efimov effect
 - Universal correlations (Phillips, Tjon line,...)
- Applications in atomic, nuclear, and particle physics
 - cold atoms close to Feshbach resonance
 - halo nuclei
 - scattering properties of the $X(3872)$
- Future: more exciting applications
 - Halo nuclei: Structure, Reactions, ...
 - Three-nucleon system on the lattice: finite V , limit cycle, ...
 - Cold atoms: $N \geq 4$, 2d-systems, ...
 - ...