Beyond Ultracold Atoms: Halo Nuclei and Hadronic Molecules

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Agenda

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1. EFT for Ultracold Atoms I: Effective Field Theories & Universality
2. EFT for Ultracold Atoms II: Cold Atoms & the Unitary Limit
3. EFT for Ultracold Atoms III: Weak Coupling at Finite Density
4. EFT for Ultracold Atoms IV: Few-Body Systems in the Unitary Limit
5. Beyond Ultracold Atoms: Halo Nuclei and Hadronic Molecules

Literature

G.P. Lepage, TASI Lectures 1989, arXiv:hep-ph/0506330

D.B. Kaplan, arXiv:nucl-th/9506035

E. Braaten, HWH, Phys. Rep. **428** (2006) 259 [arXiv:cond-mat/0410417]

Effective Theory

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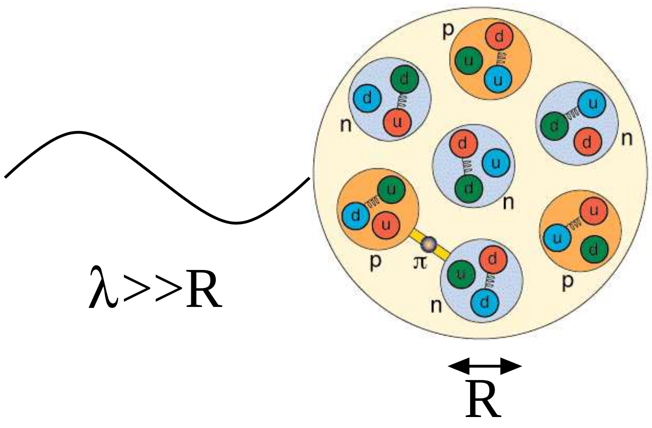
- Separation of scales:
  $1/k = \lambda \gg R$
- Limited resolution at low energy:
  $\longrightarrow$ expand in powers of kR



Effective Theory

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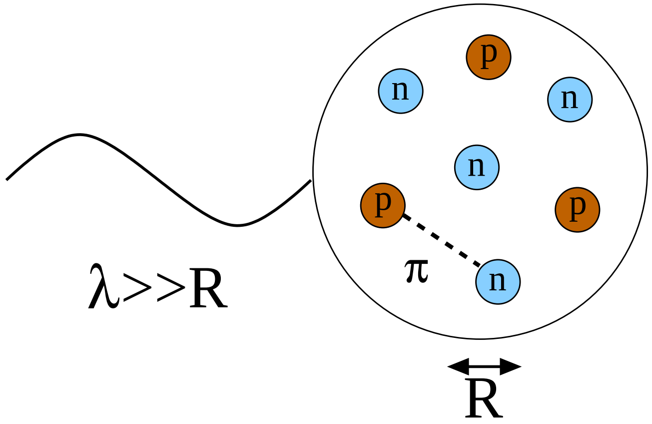

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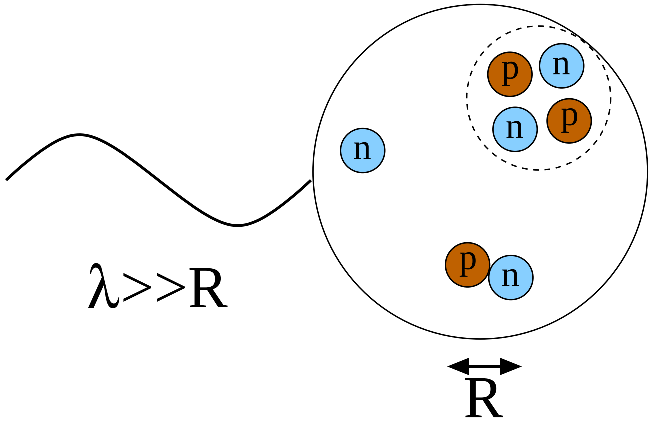
  $\longrightarrow$ capture in low-energy constants using renormalization
  $\longrightarrow$ include long-range physics explicitly
- Systematic, model independent

Effective Theory



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- Short-distance physics not resolved
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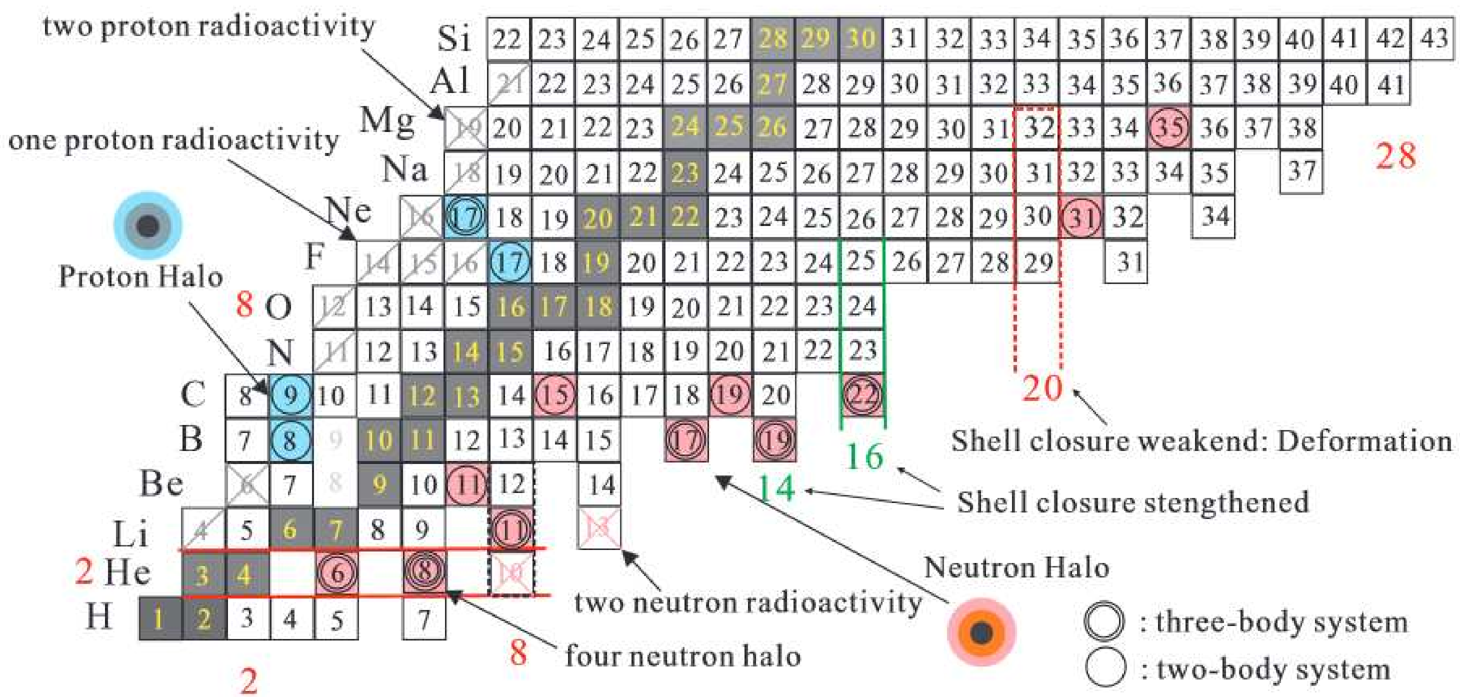
- Systematic, model independent
- Very low energies: only short range interactions
- Exploit cluster substructures $\Longrightarrow$ Halo EFT
- Universal properties

Halo Nuclei

- Low separation energy of valence nucleons: $B_{valence} \ll B_{core}, E_{ex}$

  $\longrightarrow$ close to “nucleon drip line” $\longrightarrow$ scale separation $\longrightarrow$ EFT



C.-B. Moon, Wikimedia Commons

- EFT for halo nuclei

  (Bertulani, HWH, van Kolck, 2002; Bedaque, HWH, van Kolck, 2003; ...)

Scales and Antisymmetrization

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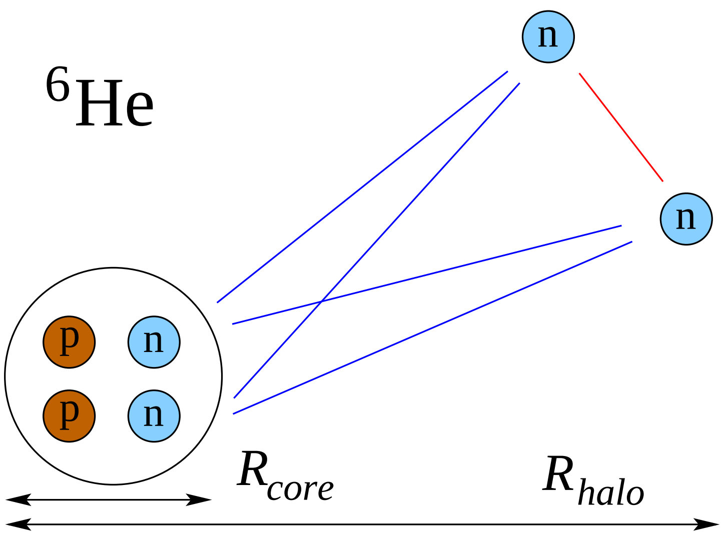
- Scales: $R_{halo} \gg R_{core} \sim \ell$
- Antisymmetrization with respect to neutrons in core?
- Core neutrons not active dof in halo EFT



- Physics: exchange of core nucleon and halo nucleon only contributes to observables if there is spatial overlap between wave functions of core and halo nucleon

$$\Longrightarrow \quad \text{small for } R_{core} \ll R_{halo}$$

- Effects subsumed in low-energy constants, included perturbatively in expansion in R_{core}/R_{halo}

Two-Neutron Halo Nuclei

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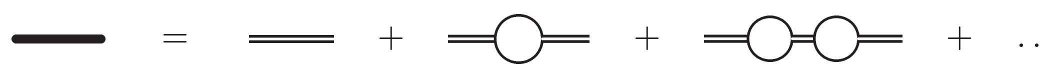
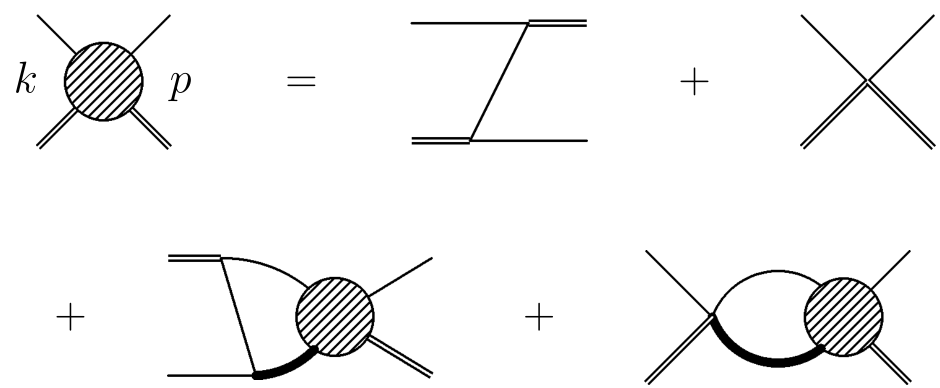
- Effective Lagrangian (schematically)

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

- 2- and 3-body interaction at leading order: g_2, g_3 enhanced!
- 2-body amplitude:



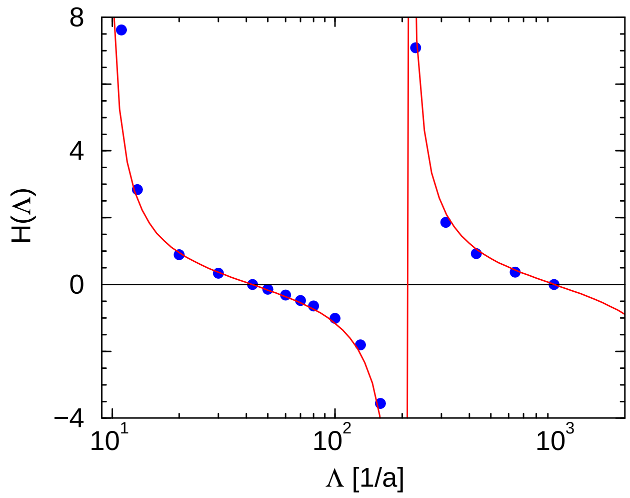
- 3-body amplitude:



- Structure of 2-neutron halo nuclei $\rightarrow$ energies, matter form factors, radii

Renormalization

- Observables are independent of regulator/cutoff Λ

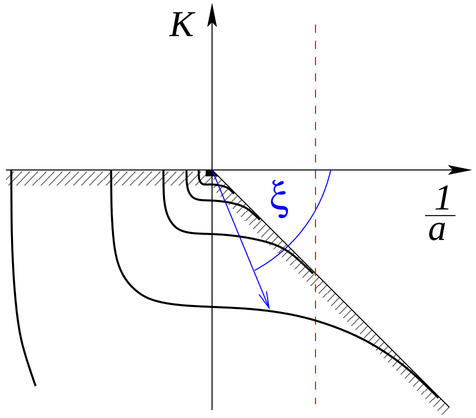


$\Rightarrow$ Running coupling $H(\Lambda) \propto \Lambda^2 g_3(\Lambda)$

- $H(\Lambda)$ periodic: limit cycle

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

- Discrete scale invariance



- Efimov effect (Efimov, 1970)
- Observed in ultracold atoms (Krämer et al., 2006; ...)
- Relevant in halo nuclei?

Efimov Physics in Halo Nuclei

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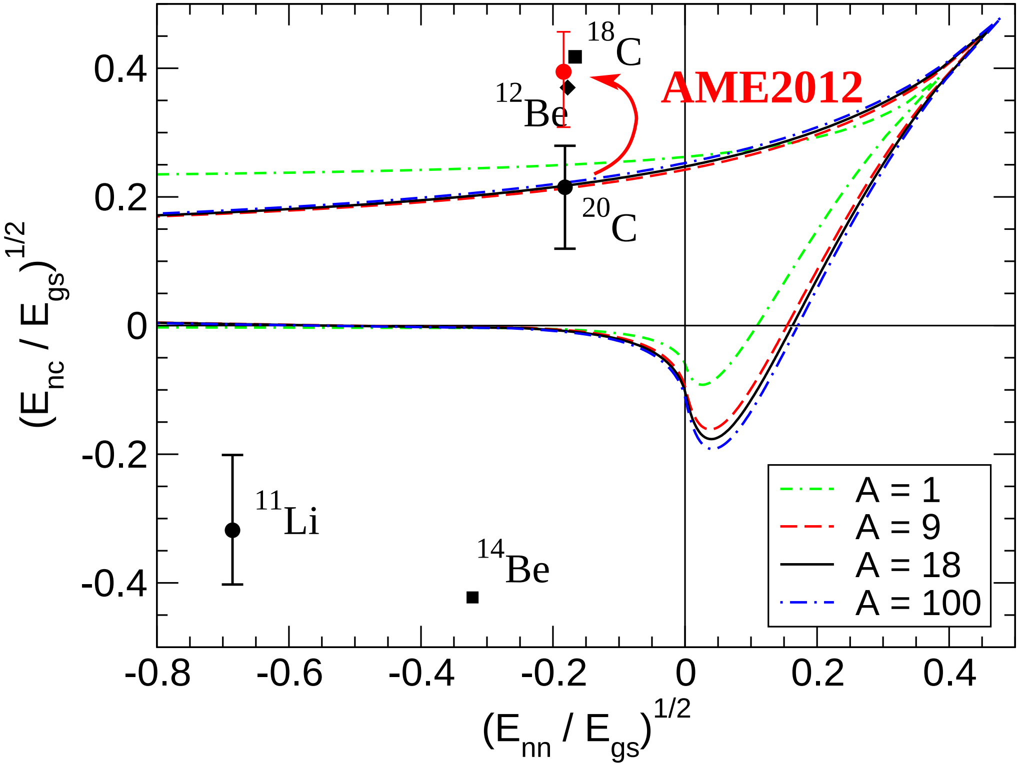
- Efimov effect in halo nuclei? (Fedorov, Jensen, Riisager, 1994)

  $\Longrightarrow$ excited states obeying scaling relations
- Correlation plot: $E_{nn} \leftrightarrow E_{nc}$ (Amorin, Frederico, Tomio, 1997)



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

Efimov Physics in ^{22}C

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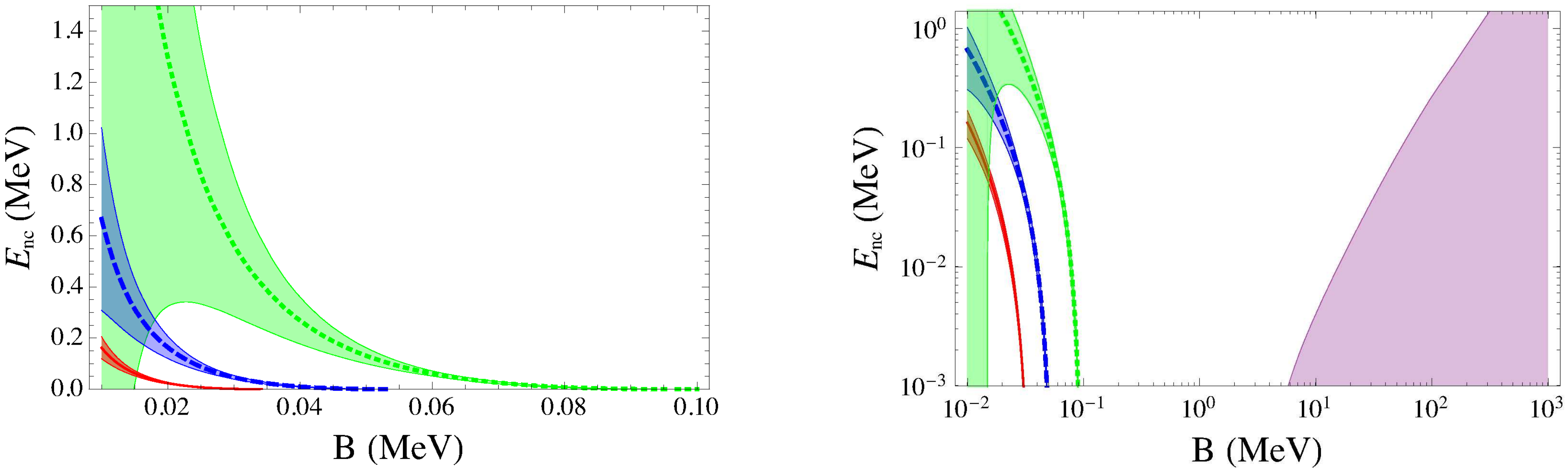
- Matter radius from ^{22}C + p & Glauber: $\langle r_0^2 \rangle^{1/2} = 5.4(9)$ fm
  (Tanaka et al., Phys. Rev. Lett. **104** (2010) 062701)
- Halo EFT analysis of impact on other observables in ^{22}C
  (Acharya, Ji, Phillips, Phys. Lett. B **723** (2013) 196)



Plots for $\langle r_0^2 \rangle^{1/2} = 4.5,\ 5.4,\ 6.3$ fm

- Excited Efimov states in ^{22}C appear to be ruled out

Efimov Physics in ^{62}Ca

(G. Hagen, P. Hagen, HWH, Platter, Phys. Rev. Lett. **111** (2013) 132501)

- The Many and the Few: emergence of effective halo degrees of freedom
- Coupled cluster calculations of ^{60}Ca and ^{61}Ca using chiral N2LO two-body force and schematic three-body force:

  ^{61}Ca is a weakly bound S-wave state (or virtual state)

- Quantitative estimate: $S_n = B_{nc} = 5...8$ keV
- Scattering Parameters:

  $a_{cn} = 54(1)$ fm, $r_{cn} = 9.0(2)$ fm $\Longrightarrow$ $r_{cn}/a_{cn} \approx 1/6$

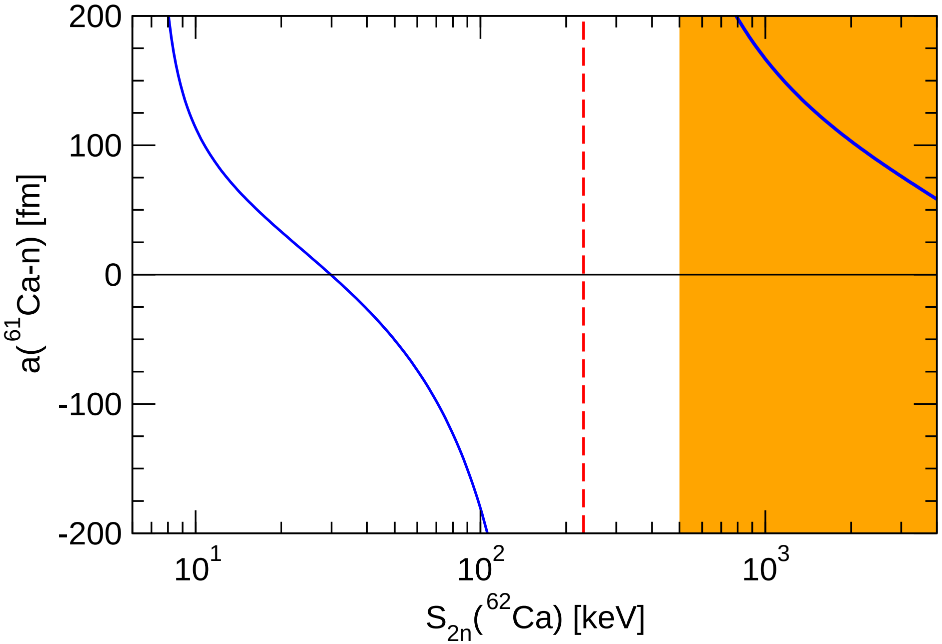
- Investigate consequences for ^{62}Ca using halo EFT
- Prospects for excited Efimov states in ^{62}Ca:

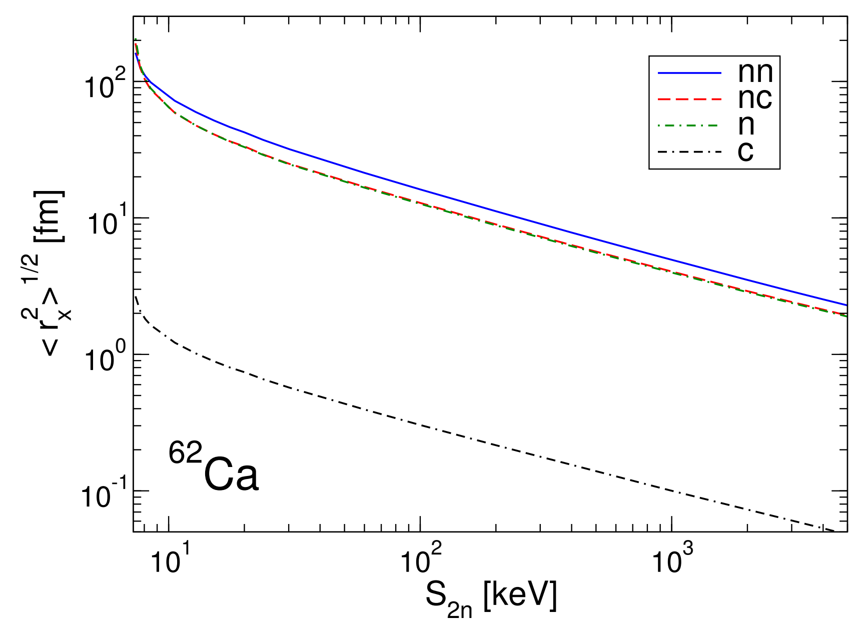
  $S_{\rm deep} = 1/(\mu_{cn} r_{cn}^2) \approx 500$ keV, scaling factor $\lambda_0 \approx 16$

  $\Longrightarrow$ possible if $S_{2n} \gtrsim 230$ keV

Efimov Physics in ^{62}Ca

- Universal correlations between S_{2n}, ^{61}Ca-n scattering length, ^{62}Ca matter, and charge radii





(G. Hagen, P. Hagen, HWH, Platter, Phys. Rev. Lett. **111** (2013) 132501)

- Excited Efimov state appears around $S_{2n} \approx 230$ keV
- Matter radii of order tens of Fermi possible

Production of Excited Efimov States

- How to study excited Efimov states experimentally?
  (A. Macchiavelli, Few-Body Syst. **56**, 773 (2015)
- Consider transfer reactions for candidate nucleus $^{A}Z_{N}$
  (a) One-neutron transfer: $^{(A-1)}Z_{(N-1)}(d,p)^{A}Z_{N}$
  (b) Two-neutron transfer: $^{(A-2)}Z_{(N-2)}(t,p)^{A}Z_{N}$
- Back-of-the-envelope estimate $\Longrightarrow$ (a) is most promising
- Reaction calculation in Halo EFT would be useful

Hadronic Molecules

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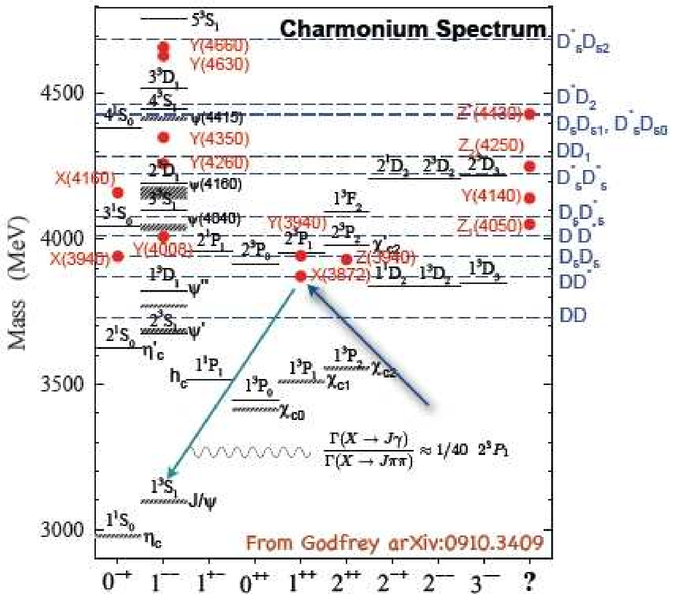
- New $c\bar{c}$ states at B factories: X, Y, Z
- Example: $X(3872)$ (Belle, CDF, BaBar, D0)
- No ordinary $c\bar{c}$-state
  - Decays violate isospin
  - Measured mass depends on decay channel



$m_X = (3871.69 \pm 0.17)$ MeV $\qquad \Gamma < 1.2$ MeV $\qquad J^{PC} = 1^{++}$

- Nature of $X(3872)$?
  $\bar{D}^0 D^{0*}$-molecule, tetraquark, charmonium hybrid, ...
- Molecular nature $\Rightarrow$ interaction of $X(3872)$ with D^0, $\bar{D}^0$, D^{0*}, $\bar{D}^{0*}$ determined by large scattering length

Nature of $X(3872)$

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- Nature of $X(3872)$ not finally resolved
- Assumption: $X(3872)$ is weakly-bound D^0-$\bar{D}^{0*}$-molecule

$\Longrightarrow |X\rangle = (|D^0 \bar{D}^{0*}\rangle + |\bar{D}^0 D^{0*}\rangle)/\sqrt{2}\,, \qquad B_X = (0.11 \pm 0.21)$ MeV

$\Longrightarrow$ universal properties (cf. Braaten et al., 2003-2008, ...)

  - Explains isospin violation in decays of $X(3872) \Rightarrow$ superposition of $I = 1$ and $I = 0$
  - Different masses due to different line shapes in decay channels

- Large scattering length to LO determines interaction of $X(3872)$ with D^0 and D^{0*}
- Higher orders: EFT with perturbative pions $\Rightarrow$ XEFT

(Fleming, Kusunoki, Mehen, van Kolck, 2007; Fleming, Mehen, 2008)

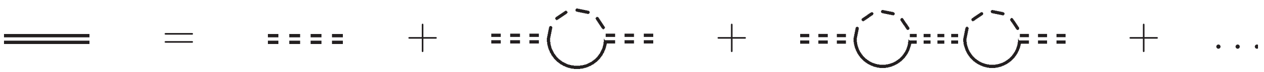
(Braaten, HWH, Mehen, 2010; ...)

EFT for $X(3872)$

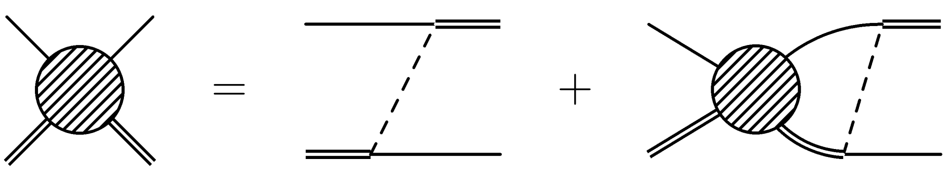
- Effective Lagrangian

$$
\begin{aligned}
\mathcal{L} \;=\; & \sum_{j=D^0,D^{*0},\bar{D}^0,\bar{D}^{*0}} \psi_j^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_j} \right) \psi_j + \Delta X^\dagger X \\
& -\frac{g}{\sqrt{2}} \left(X^\dagger (\psi_{D^0}\psi_{\bar{D}^{*0}} + \psi_{D^{*0}}\psi_{\bar{D}^0}) + \text{ H.c. } \right) + \ldots ,
\end{aligned}
$$

- Propagator of the $X(3872)$

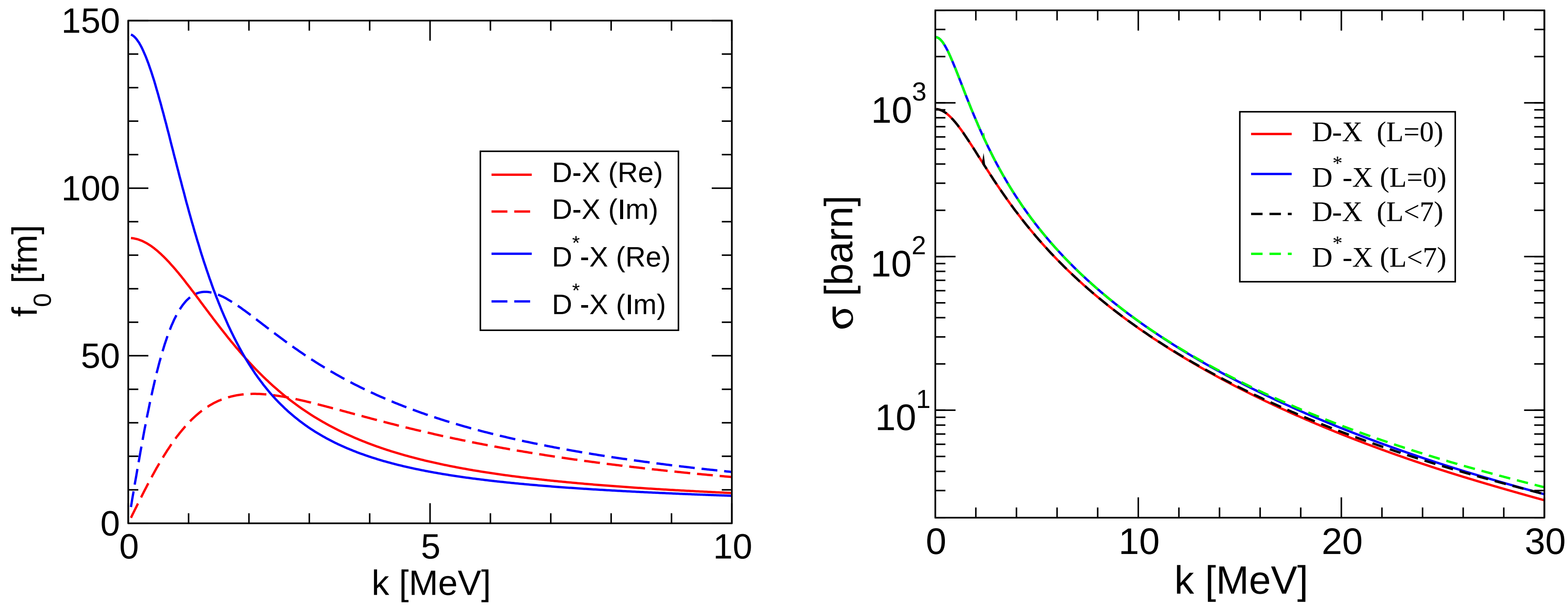


- Three-body integral equation



X-D- and X-D^*-Scattering

- Predictions for scattering amplitude/cross section

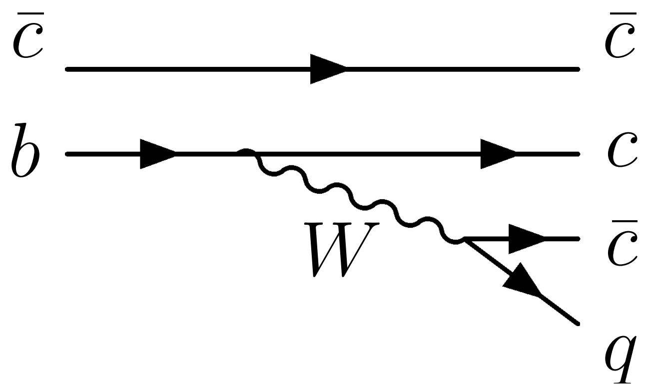


Canham, HWH, Springer, Phys. Rev. D **80**, 014009 (2009)

- Three-body scattering lengths: $a_{D^0X} = -9.7a \approx -85$ fm
  $a_{D^{*0}X} = -16.6\,a \approx -146$ fm

Experimental Observation ?

- Behavior of $X(3872)$ produced in isolation should be distinguishable from its behavior when in the presence of $D^0, D^{*0}, \bar{D}^0, \bar{D}^{*0}$
- Final state interaction of D, D^* mesons in B_c-decays
- Example: quark-level B_c decay yielding three charmed/anticharmed quarks in final state



- Process in principle accessible at the LHC

Summary

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- Cluster EFT for halo nuclei

  $\Longrightarrow$ large scattering length/shallow states
  - Controlled, systematic approach $\Longrightarrow$ error estimates
  - Straightforward inclusion of external currents
- Universal theory has applications in atomic, nuclear, and particle physics
- Universality predicts correlations between observables

  $\Longrightarrow$ input from theory or experiment
- Excited Efimov state possible in ^{62}Ca
- Calculations of EM structure and reactions