Effective Field Theory For Halo Nuclei

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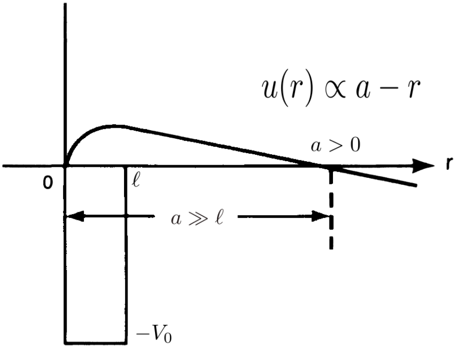
Key elements of an EFT

- separation of scales:
  - an observable's length scale is much larger than the interaction range $a \gg \ell$
  - physics at scale a is insensitive to physics at scale ℓ
- systematic expansion:
  - construct effective Lagrangian
    $\mathcal{L} = \sum c_\nu (\ell/a)^\nu$
  - calculate observables at scale a in the ℓ/a expansion
- universality:
  - separation of scales $\rightarrow$ universality
    2body universality: $B_2 = 1/ma^2$
  - a limited number of LECs enter at a given EFT order
  - observables are correlated through a limited number of parameters



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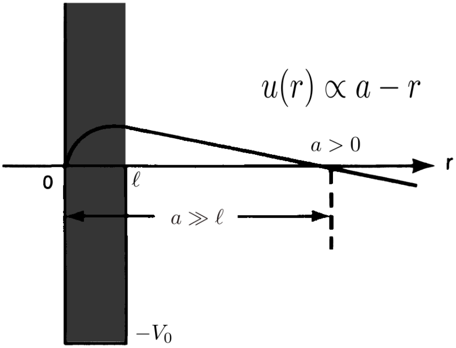


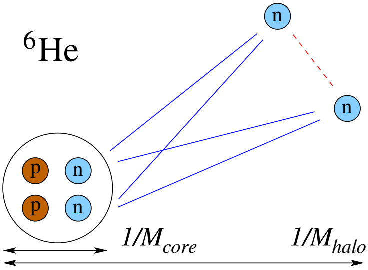
Effective Theory for Halo Nuclei

- cluster configuration:

  core + valence nucleons d.o.f.

- separation of scales:

  $M_{\text{halo}} \sim \sqrt{m_n S_{2n}}$
  $M_{\text{core}} \sim \sqrt{m_n E_c^*}$
  $M_{\text{halo}} \ll M_{\text{core}}$

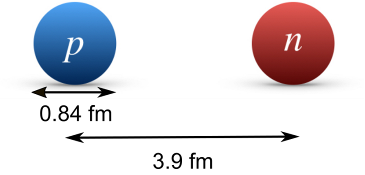


- effects from underlying theory:
  - a theory in NN/NNN interactions (pionful, pionless, realistic, ...)
  - anti-symmetrization of core neutrons is not explicit in halo EFT
  - short-range effects are embedded in LECs controlled by systematic expansions in $M_{\text{halo}}/M_{\text{core}}$

- EFT unveils universality in halo nuclei

Examples of Halo Nuclei

- ^{2}H
  - simplest neutron halo
  - pionless EFT for few-nucleon systems is a specific case of halo EFT



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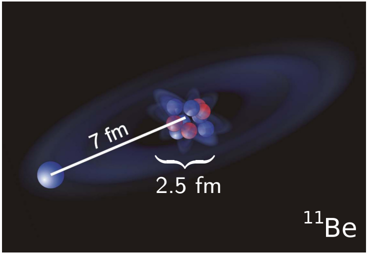
  - ^{6}He, ^{11}Be, ...



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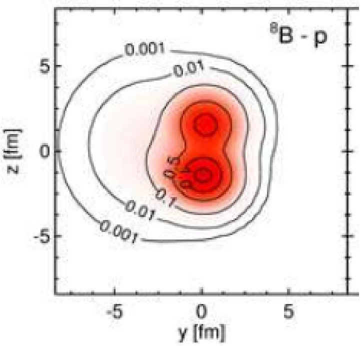
- proton halos
  - ^{17}F* (s-wave halo)
  - ^{8}B (p-wave halo):
    $E_c^* = 1.59$ MeV; $S_{1p} = 0.14$MeV
    $M_{\rm halo}/M_{\rm core} \approx 20\%$



FMD calculation (T. Neff, GSI)

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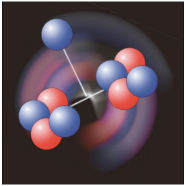
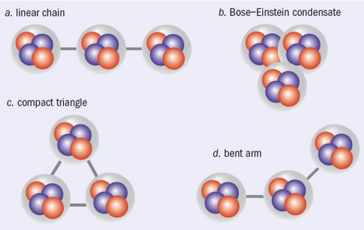
- α-clustering
  - ^{9}Be: $\alpha + \alpha + n$
  - ^{8}Be, ^{12}C*, ^{16}O*





Outline

- Halos in s-wave interactions
- Halos in p-wave interactions
- Halos with Coulomb (proton halos and α-clusters)
- Electromagnetic reactions on halo nuclei

- Discussions:
  - EFT construction and power counting
  - Universality in Halo EFT (mainly LO results)
  - Connection with underlying theory /experiments

Naturalness in EFT

“Someone” said:

There are a thousand Hamlets in a thousand people’s eyes,
so is the word “naturalness”.

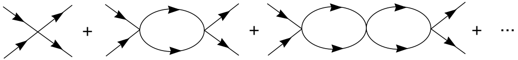
Naturalness in observables

naturalness of observables can be connected with naturalness in LECs

- a two-body system in s-wave zero-range interactions

$$\mathscr{L} = \psi^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m} \right) \psi - \frac{C_0}{2} (\psi^\dagger \psi)^2 \quad ; \text{where } \; C_0 = \frac{4\pi}{m} (-\Lambda + 1/a)^{-1}$$

- iterative sum



Kaplan, Savage, Wise, '98

- scattering amplitude at $k \sim M_{\rm halo}$: $\quad t_0(k) = \frac{2\pi}{\mu} \left(1/a + ik\right)^{-1}$
  - natural case: $a \sim 1/M_{\rm core}$
    $\to t_0 \approx C_0(\Lambda \to 0)$;
    C_0 is natural and perturbative
  - unnatural case: $a \sim 1/M_{\rm halo}$
    $\to t_0$ unnaturally enhanced by a bound/virtual pole ;
    $C_0(\Lambda \to 0)$ is unnatural, nonpertubative loop even for $\Lambda \sim p$

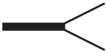
- In an ideal case, one can keep unnaturalness at LO and maintain naturalness in a perturbative expansion of $M_{\rm halo}/M_{\rm core}$ at higher orders

Halo Effective Field Theory

- We adopt EFT with contact interactions to describe clustering in halo nuclei
- introduce auxiliary dimer fields for bound/resonance states

$$
\begin{aligned}
\mathscr{L} &= \mathscr{L}_1 + \mathscr{L}_2 + \mathscr{L}_3 \\
\mathscr{L}_1 &= n^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m_n} \right) n + c^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m_c} \right) c \\
\mathscr{L}_2 &= s^\dagger \left[\eta_0 \left(i\partial_0 + \frac{\nabla^2}{4m_n} \right) + \Delta_0 \right] s + \sigma^\dagger \left[\eta_1 \left(i\partial_0 + \frac{\nabla^2}{2(m_n+m_c)} \right) + \Delta_1 \right] \sigma \\
&\quad + g_0 \left[s^\dagger (nn) + \text{h.c.} \right] + g_1 \left[\sigma^\dagger (nc) + \text{h.c.} \right], \\
\mathscr{L}_3 &= h \, (\sigma n)^\dagger \, (\sigma n)
\end{aligned}
$$

- 2-body contact (LO)



$= -i\sqrt{2}g$

$g \leftarrow$ 2-body observable

- 3-body contact (LO)

$= ih$

$h \leftarrow$ 3-body observable

One-neutron s-wave halos

- **Iterative summation**

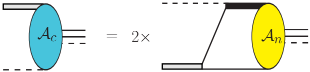
- **scattering amplitude:** $t_0(k) = \frac{2\pi}{\mu}\left(\frac{1}{a_0} - \frac{r_0}{2}k^2 + ik\right)^{-1}$
  - $a_0 \sim 1/M_{\text{halo}}$; $r_0 \sim 1/M_{\text{core}}$
  - calculation in expansion of r_0/a_0
- **tune coupling**
  - LO: $a_0 = \left(\frac{2\pi\Delta}{\mu g^2} + \Lambda\right)^{-1}$
  - NLO: $r_0 = -\eta\frac{2\pi}{\mu^2 g^2}$
- **pole expansion**: $t_0(k) = \frac{2\pi}{\mu}\frac{\mathcal{C}_\sigma^2/\mathcal{C}_{\sigma,LO}^2}{\gamma_0 + ik} + \text{regular}$
  - LO: $\mathcal{C}_{\sigma,LO} = \sqrt{2\gamma_0}$
  - NLO: $\mathcal{C}_\sigma/\mathcal{C}_{\sigma,LO} = 1/\sqrt{1-\gamma_0 r_0}$

One-neutron s-wave halos

	^{2}H	^{11}Be	^{15}C	^{19}C
EXP				
S_{1n} [MeV]	2.224573(2)	0.50164(25)	1.2181(8)	0.58(9)
E_c^* [MeV]	140	3.36803(3)	6.0938(2)	1.62(2)
$\langle r_{nc}^2 \rangle^{1/2}$ [fm]	3.936(12)	6.05(23)	4.15(50)	6.6(5)
	3.95014(156)	5.7(4)	7.2±4.0	6.8(7)
		5.77(16)	4.5(5)	5.8(3)
EFT				
$M_{\rm halo}/M_{\rm core}$	0.33	0.39	0.45	0.6
r_0/a_0	0.32	0.32	0.43	0.33
$\mathcal{C}_\sigma/\mathcal{C}_{\sigma,LO}$	1.295	1.3	1.63	1.3
$\langle r_{nc}^2 \rangle^{1/2}$ [fm]	3.954	6.16	4.93	5.72

A three-body problem in Faddeev formalism

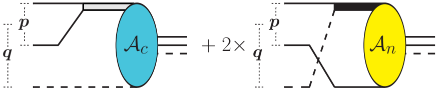
- **solving transition amplitudes $\mathcal{A}_c$ and $\mathcal{A}_n$**



- **three-body wave functions**

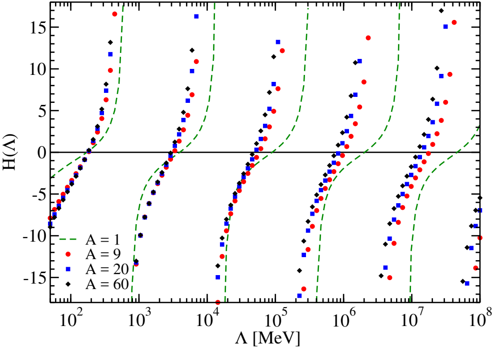
$\Psi_n(\boldsymbol{p},\boldsymbol{q}) =$

$\Psi_c(\boldsymbol{p},\boldsymbol{q}) =$



Three-body renormalization

- **running of three-body coupling**
  - tune $H(\Lambda) = \Lambda^2 h / 2mg^2$:
    reproduce one observable in a $2n$-halo
  - limit cycle:
    $H(\Lambda)$ periodic for $\Lambda \to \Lambda \exp(n\pi/s_0)$
    $A = 1$: Bedaque *et al.* '00
    discrete scale invariance $\quad\to$ Efimov physics



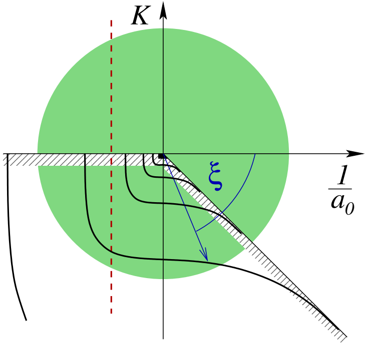
Efimov physics

- a universal spectrum of three-body bound states

$$B_3 = -\frac{1}{ma_0^2} + \left[e^{-2\pi n}\, f(\xi)\right]^{1/s_0} \frac{\kappa_*^2}{m}$$

Braaten, Hammer, Phys. Rept. '06

  - atomic physics: vary a_0 through Feshbach resonance
  - nuclear physics: fixed a_0



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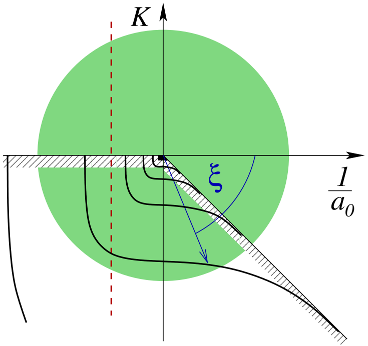
  - atomic physics: vary a_0 through Feshbach resonance
  - nuclear physics: fixed a_0

- unitary limit ($a \to \infty$):
  $B_3 = e^{-2\pi n/s_0} \frac{\kappa_*^2}{m}$
- discrete scale invariance:
  $\kappa_* \to \kappa_*, \quad a_0 \to e^{\pi n/s_0} a_0$
- exploring Efimov physics in halo nuclei is an important subject



EFT For $2n$ s-wave Halos

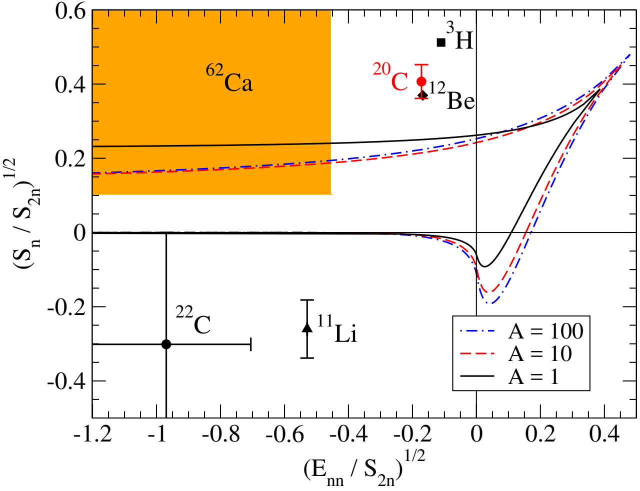
- n-core in s-wave virtual/real bound state:
  ^{11}Li, ^{12}Be, ^{20}C [Canham, Hammer, EPJA '08, NPA '10]
  ^{22}C Acharya, C.J., Phillips, PLB '13

- charge radius of 2n s-wave halos
  [Hagen, Hammer, Platter, EPJA '13]
  [Vanasse, arXiv '15, '16]

- heaviest 2n s-wave halo:
  ^{62}Ca [Hagen, Hagen, Hammer, Platter, PRL '13]
  fit n-^{60}Ca scattering length from coupled-cluster calculations

Universality in $2n$ s-wave halo

- contour constraints on ground-state energy S_{2n} if the excited-state energy $B_3^* = \max\{0, E_{nn}, S_{1n}\}$



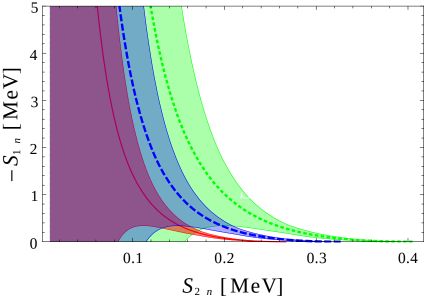
Canham, Hammer, EPJA '08; Frederico *et al.* PPNP '12

Correlations in ^{22}C

$$\langle r_m^2 \rangle_{2n-\mathrm{halo}} = \frac{1}{m_n S_{2n}} f\left(\frac{E_{nn}}{S_{2n}}, \frac{S_{1n}}{S_{2n}}; A\right)$$

Acharya, C.J., Phillips, PLB '13

Experimental input:
$\langle r_m^2 \rangle_{2n-\mathrm{halo}} - \langle r_m^2 \rangle_{\mathrm{core}} = 3.01^{+0.85}_{-0.72}$ fm
Togano *et al.* PLB '16



bands: uncertainty from NLO EFT
$\sim \max\left\{\frac{\sqrt{mE_{nn}}}{M_{\mathrm{core}}}, \frac{\sqrt{mS_{1n}}}{M_{\mathrm{core}}}, \frac{\sqrt{mS_{2n}}}{M_{\mathrm{core}}}\right\}$

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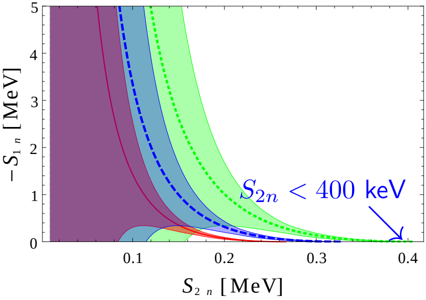

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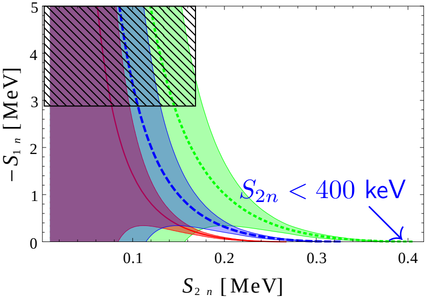


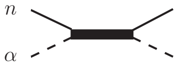
Other experimental bound:

- AME2012
  $S_{2n} < 170$ keV
- Gaudefroy et al., PRL '12
  $S_{1n} < -2.9$ MeV

bands: uncertainty from NLO EFT
$\sim \max\left\{\frac{\sqrt{mE_{nn}}}{M_{\mathrm{core}}}, \frac{\sqrt{mS_{1n}}}{M_{\mathrm{core}}}, \frac{\sqrt{mS_{2n}}}{M_{\mathrm{core}}}\right\}$

P-wave neutron halos

- nc interaction in a p-wave bound/resonance state



$$= \frac{2\pi}{\mu} \frac{\vec{p} \cdot \vec{q}}{-1/a_1 + r_1 k^2/2 - ik^3}$$

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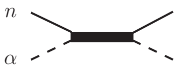


$$= \frac{2\pi}{\mu} \frac{\vec{p} \cdot \vec{q}}{-1/a_1 + r_1 k^2/2 - ik^3}$$

- causality $r_1 < 0$ and $r_1 \not\to 0$ Nishida '12
- both a_1 and r_1 enter at leading order
- p-wave power countings
  - [Bertulani, Hammer, van Kolck NPA '02] $a_1 \sim M_{\text{halo}}^{-3}$, $r_1 \sim M_{\text{halo}}$
  - [Bedaque, Hammer, van Kolck PLB '03] $a_1 \sim M_{\text{halo}}^{-2} M_{\text{core}}^{-1}$, $r_1 \sim M_{\text{core}}$
    - $a_1 > 0$: shallow bound state: ^{11}Be $(1/2^-)$
    - $a_1 < 0$: shallow resonance: ^{5}He $(3/2^-)$

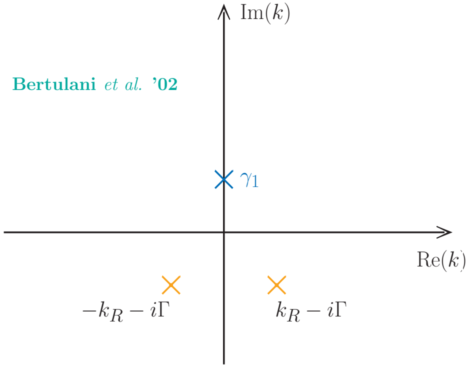
p-wave power counting (Bertulani)

- p-wave EFT power counting: Bertulani, Hammer, van Kolck NPA '02
  - $a_1 \sim 1/M_{\rm halo}^3 \quad r_1 \sim M_{\rm halo}$
  - two fine tunings at LO

shallow resonance:

$$k_R, \Gamma \sim M_{\rm halo}$$

shallow bound state: $\gamma_1 \sim M_{\rm halo}$



$n-\alpha$ p-wave power counting (Bedaque)

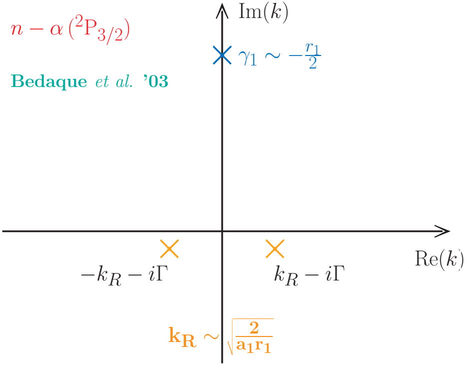
- $n\alpha$ EFT power counting: Bedaque, Hammer, van Kolck PLB '03
  - $a_1 \sim 1/(M_{\rm halo}^2 M_{\rm core})$ $\quad r_1 \sim M_{\rm core}$
  - one fine tuning at LO

- ${}^2P_{\frac{3}{2}}$:

  shallow resonance:

  $$k_R \sim M_{\rm halo},\, \Gamma \sim M_{\rm halo}^2/M_{\rm core}$$

  deep bound state: $\gamma_1 \sim M_{\rm core}$



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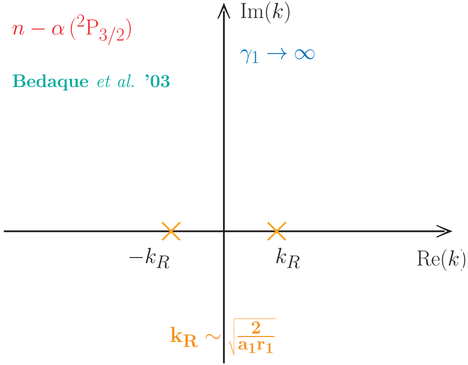

LO: drop ik^3 term; $\quad \Gamma \to 0,\ \gamma_1 \to \infty$

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  - $a_1 \sim 1/(M_{\text{halo}}^2 M_{\text{core}})$ $\quad r_1 \sim M_{\text{core}}$
  - one fine tuning at LO

- ${}^2P_{\frac{3}{2}}$:

  shallow resonance:

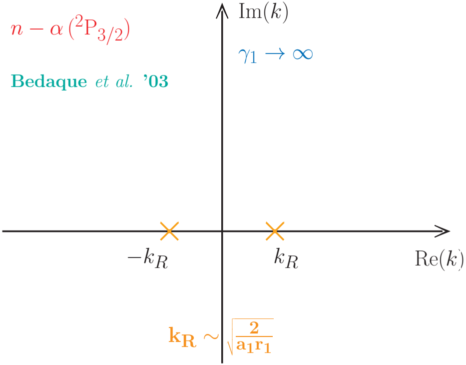
  $$k_R \sim M_{\text{halo}},\ \Gamma \sim M_{\text{halo}}^2/M_{\text{core}}$$

  deep bound state: $\gamma_1 \sim M_{\text{core}}$

- when doing expansion, avoid spurious poles in 3body calculations

  e.g., ^{6}He ground state

  e.g., ^{6}He resonance state



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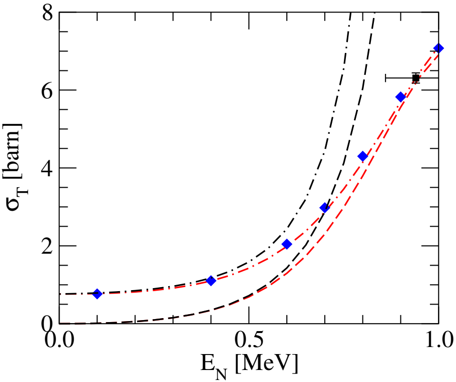
$n - \alpha$ scattering cross sections



- expansion without resumming ik^3
  $t \propto \frac{1}{r_1(k^2-k_R^2)}$
  is only valid if $|k^2 - k_R^2|$ is not small

- expansion with resumming ik^3
  is required when $k \sim k_R$

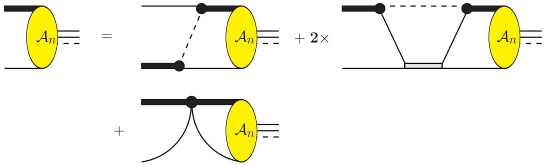
^{6}He: $2n$ Halo with p-wave nc interactions

- **cluster model**
  - separable potential Ghovanlou, Lehman '74
  - variational method Funada *et al.* '94
  - density-dependent nn contact interaction Esbensen *et al.* '97
  - Wood Saxon $n\alpha$ + GPT nn Danilin, Thompson, Vaagen, Zhukov '98

- *ab intio* **calculation**
  - no-core shell model Navrátil *et al.* '01; Sääf, Forssén '14, Romero-Redondo
  - NCSM-RGM/Continuum Romero-Redondo *et al.* '14 '16
  - Green's function Monte Carlo Pieper *et al.* '01; '08
  - hyperspherical harmonics (EIHH) Bacca *et al.* '12

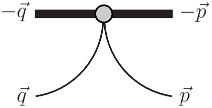
- **Halo EFT in ^{6}He ground state**
  - EFT+Gamow shell model Rotureau, van Kolck Few Body Syst. '13
  - EFT+Faddeev equation C.J., Elster, Phillips, PRC '14

Faddeev equations for ^{6}He

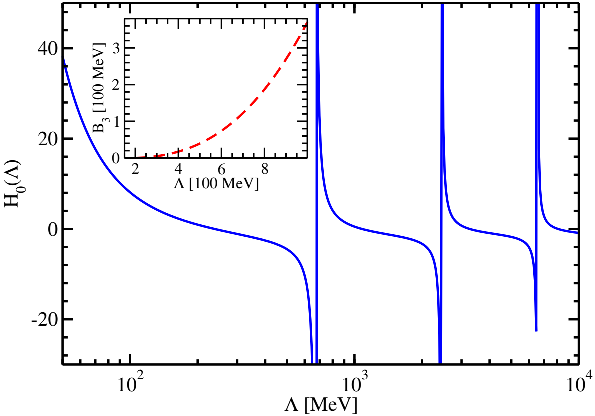


Running of 3BF Coupling

- p-wave 3BF:
  reproduce $S_{2n} = 0.973$ MeV



$$= M_n \, qp \, \frac{H(\Lambda)}{\Lambda^2}$$



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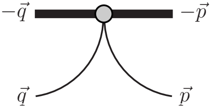
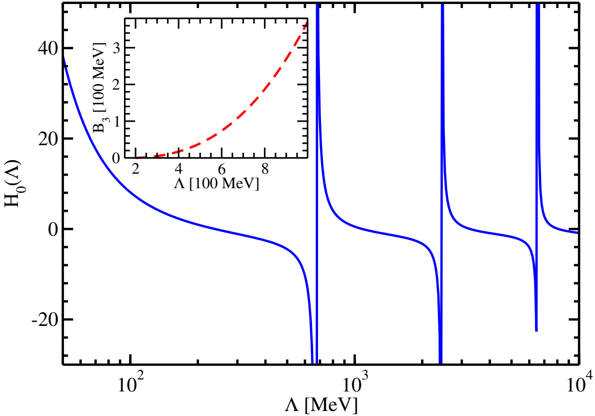


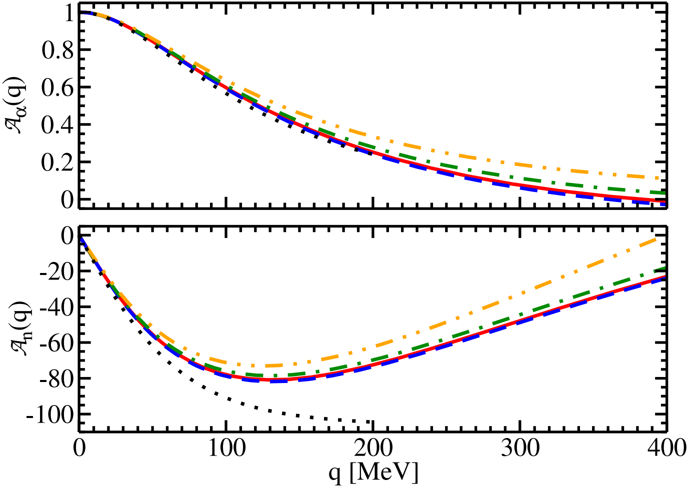
$$= M_n\, qp\, \frac{H(\Lambda)}{\Lambda^2}$$

- discrete scaling symmetry is broken due to p-wave interactions



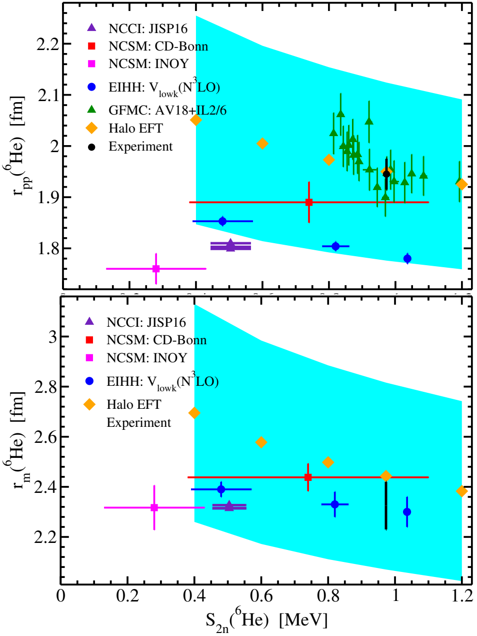
Renormalized Faddeev Components

$\mathcal{A}_\alpha$ and $\mathcal{A}_n$ are cutoff independent



C.J., Elster, Phillips, PRC '14

Universal correlations btw ^{6}He radii & S_{2n}



[Preliminary]

- He-6 point-proton radius
- He-6 point-nucleon radius

compare with

NCCI: Caprio, Maris, Vary, PRC '14

NSCM: Caurier, Navratil, PRC '06

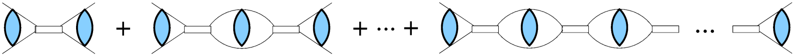
GFMC: Pieper, RNC '08

EIHH: Bacca, Barnea, Schwenk, PRC '12

Halo EFT: preliminary (uncertainty)

Halo EFT with Coulomb

- In halo/clustering systems with Coulomb interactions, a new scale $k_c = Q_c \alpha_{em} \mu$ enters
  - $k_c \gtrsim M_{\rm halo}$: Coulomb interaction is nonperturbative

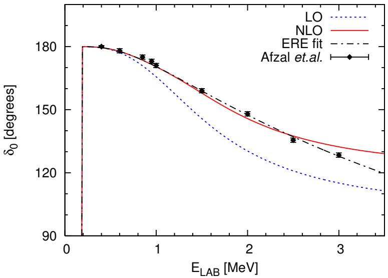


    p-p scattering [Kong, Ravndal, PLB '99; NPA '10]
    p-α and α-α scattering [Higa, Hammer, van Kolck, NPA '08; Higa, FBS '11]
    ^{17}F* [Ryberg, Forssén, Hammer, Platter, PRC '14; AnnPhys '16]

  - $k_c \ll M_{\rm halo}$: Coulomb interaction is perturbative
    ^{3}H and ^{3}He [König, Grießhammer, Hammer, van Kolck, JPG '16]

Fine tuning in α clustering and proton-halos

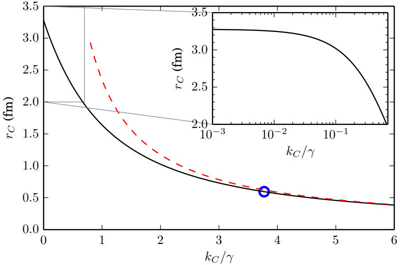
α-α narrow resonance



Higa, Hammer, van Kolck, NPA '08

- $k_c \gg k_R$
- a highly fine tuned system
- LO $k_R^2 \approx 2/(a_0 r_0)$
- NLO a_0, r_0, P_0

universality in proton halos

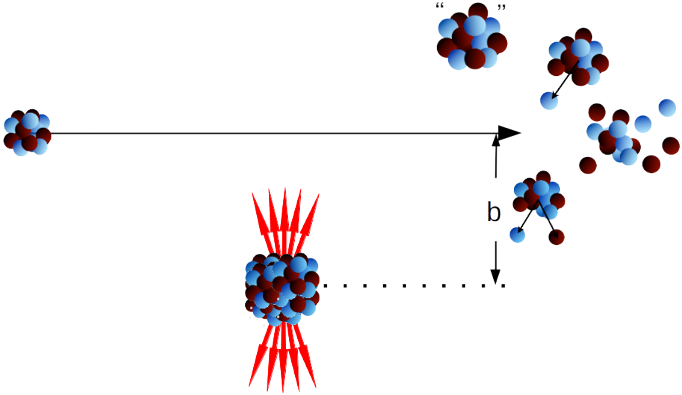


Ryberg, Forssén, Hammer, Platter, AnnPhy '16

- $k_c \gg \gamma$
- fine tuning both a_0 and r_0
- large cancelation btw Coulomb repulsion and strong interaction

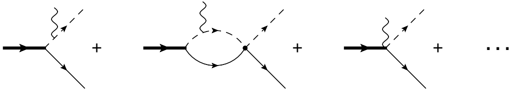
Electromagnetic reactions on halo nuclei

- Coulomb dissociation
  - breakup by colliding a halo nucleus with a high-Z nucleus
  - the halo dynamics dominates when $Q_\gamma \sim M_{\text{halo}}$

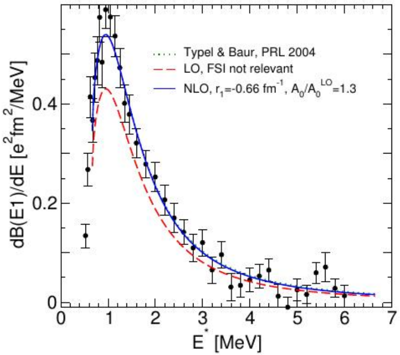


EFT on Coulomb dissociation of $1n$ halos

- **E1 transition**

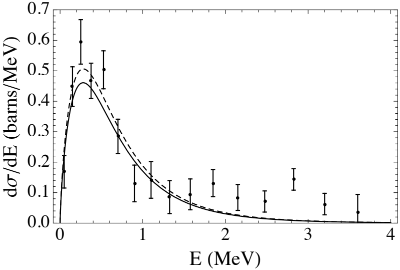


^{11}Be photo-dissociation



[Hammer, Phillips, NPA '11]

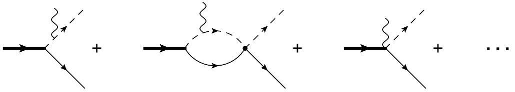
^{19}C photo-dissociation



[Acharya, Phillips, NPA '13]

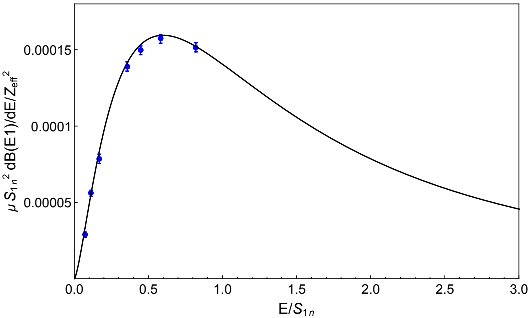
EFT on Coulomb dissociation of $1n$ halos

- **E1 transition**



universal E1 transition

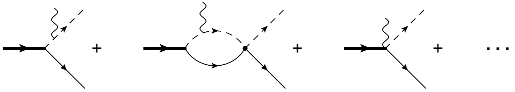
$$\frac{\mu S_{1n}^2}{Z_{eff}^2}\frac{dB(E1)}{dE} = \frac{3\alpha_{em}}{\pi^2}\frac{(E/S_{1n})^{3/2}}{(E/S_{1n}+1)^4}$$



deuteron E1 strength

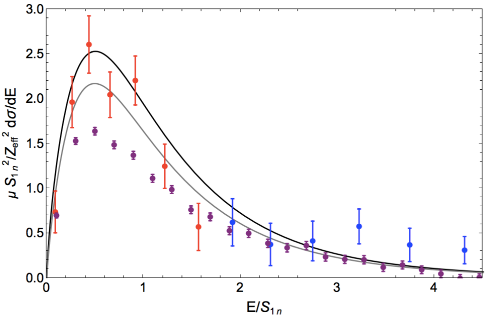
EFT on Coulomb dissociation of $1n$ halos

- **E1 transition**



LO EFT: universal E1 transition

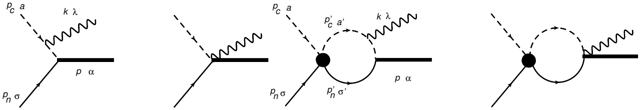
$$\frac{d\sigma}{dE} = \frac{16\pi^3}{9} N_{E1}(E, R) \frac{d\mathrm{B}(\mathrm{E1})}{dE}$$



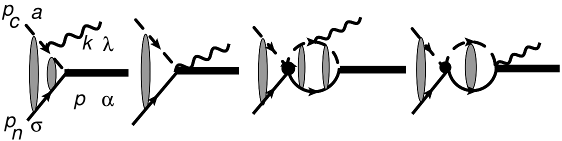
Coulomb dissociation differential cross section in ^{11}Be and ^{19}C

Radiative Nucleon Captures

neutron captures



proton captures



Radiative Nucleon Captures

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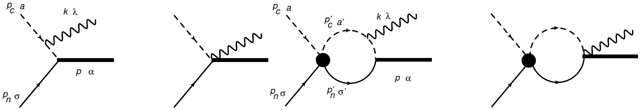

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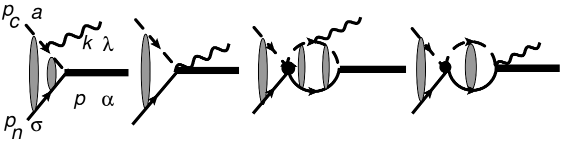


$^7\mathrm{Li} + n \to {}^8\mathrm{Li} + \gamma$

Rupak, Higga, PRL '11; Fernando, Higa, Rupak, EPJA '12; Zhang, Nollett, Phillips, PRC '14

$^{14}\mathrm{C} + n \to {}^{15}\mathrm{C} + \gamma$

Rupak, Fernando, Vaghani, PRC '12

$^7\mathrm{Be} + p \to {}^8\mathrm{B} + \gamma$

Zhang, Nollett, Phillips, PRC '14; Ryberg, *et al.* EPJA '14

$^{16}\mathrm{O} + p \to {}^{17}\mathrm{F}^*(1/2^+) + \gamma$

Ryberg, Forssén, Hammer, Platter, PRC '14; AnnPhy '16

Radiative Nucleon Captures

E1 S-factor for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$

- Zhang, Nollett, Phillips, PRC '14

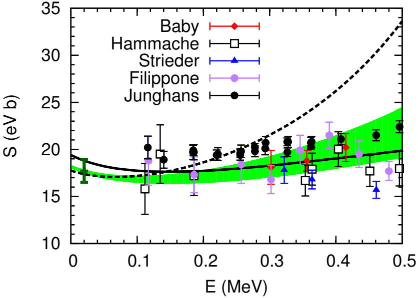
  —— NSCM-GRM result

  [Navratil, Roth, Quaglioni, PLB '11]

  - - - - LO EFT: fit to NSCM-GRM ANC

  LO EFT: fit to ANC from VMC

  VMC [Nollett, Wiringa, PRC '11]



Radiative Nucleon Captures

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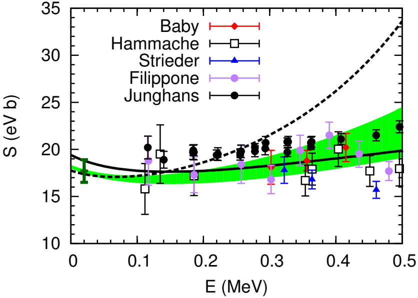
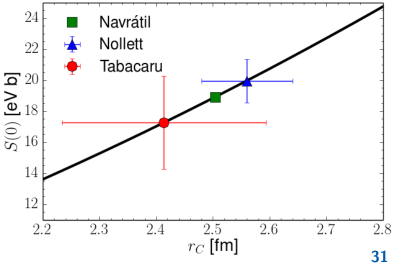


- Ryberg, Forssén, Hammer, Platter, EPJA '14

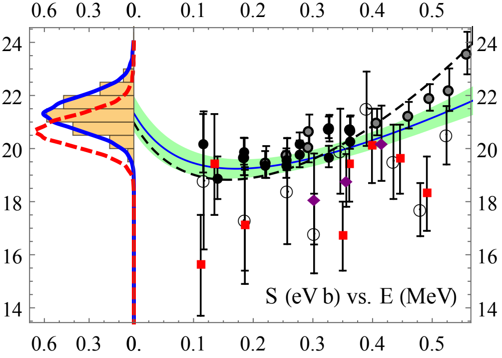
  correlation btw $S(0)$ and $r_C[^8\text{B}]$



Radiative Nucleon Captures

NLO Halo EFT calculation of E1 S-factor for $^7\text{Be}(p,\gamma)^8\text{B}$ combined with ab initio ANC and Bayesian data-error analysis

Zhang, Nollett, Phillips, PLB '15



$$S(0) = (21.3 \pm 0.7 eV b)$$

Summary

- Halo EFT describes structure/reaction in halo nuclei in a controlled expansion in $M_{\rm halo}/M_{\rm core}$

- Halo EFT rejuvenate cluster models with a systematic uncertainty estimates

- Halo EFT can be complimentary to *ab initio* calculations
    - adopt inputs from *ab initio* results
    - benchmark with *ab initio* calculations
    - explain universal correlations from observables in *ab initio* work

$n-n$ s-wave power counting

- nn EFT power counting:
  - EFT: $a_0 \sim 1/Q \quad r_0 \sim 1/\Lambda_{EFT}$
  - $Q/\Lambda_{EFT} \sim 0.15$

- ${}^1S_0$:

  LO: $r_0 \to 0$

  shallow virtual state $\gamma_0 \sim Q$

- LO nn t-matrix ($r_0 \to 0$)

$$t_{nn} = \frac{-1}{4\pi^2 \mu_{nn}} \frac{1}{1/a_0 + ik}$$