~~From Cold Atoms to~~ Halo Nuclei

An EFT description of three-body physics

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In collaboration with
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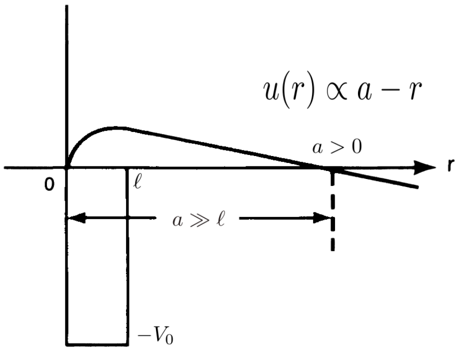
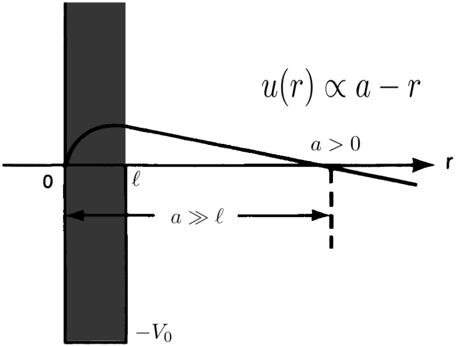
INT workshop, May 12-16, 2014

- **Separation of scales:**
  $a \gg \ell$
- **2-body universality:**
  $B_2 = 1/ma^2$



Universal features at low energies

- **Separation of scales:**
  $a \gg \ell$
- **2-body universality:**
  $B_2 = 1/ma^2$
- physics at $r \sim a$ is insensitive to physics at $r \sim \ell$
- large-a physics is studied in ℓ/a expansion
- effects from SR-dynamics can be included as perturbation

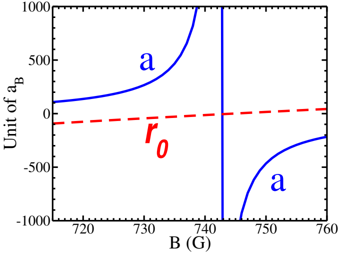


Large-a physics

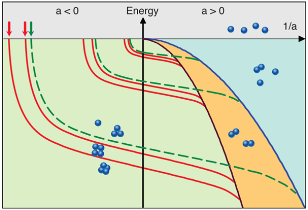
universal physics exists in systems with $\ell \ll a$

- atomic physics
  - **cold atomic gases (^{133}Cs, ^{7}Li, ^{39}K):** $\ell \ll a$ varies near Feshbach resonance

^{7}Li atoms [Gross *et al.* '09]



Efimov physics [pic:Esry '09]



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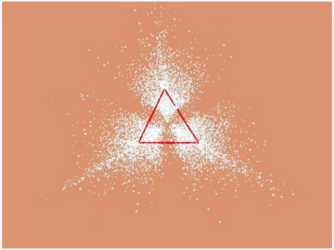
  - **^{4}He atomic clusters:**
    $\ell_{vdw} \sim 7\text{Å}$, $a \sim 100\text{Å}$

^{4}He trimer

[pic: Blume@physics.wsu.edu]



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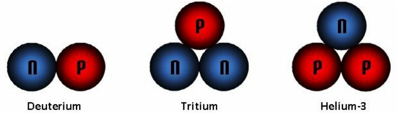
    $\ell^{t}_{np} \sim 1.7$ fm, $a^{t}_{np} \sim 5.4$ fm



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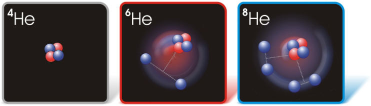
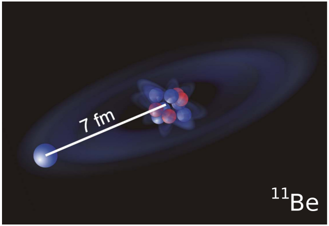


- nuclear physics
  - **few-nucleon systems (^{3}H, ^{3}He, ^{4}He):**
    $\ell^{t}_{np} \sim 1.7$ fm, $a^{t}_{np} \sim 5.4$ fm
  - **halo nuclei** (core + valence N)



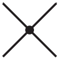
^{6}He: $S_{2n} \approx 1$ MeV $E^{*}_{c} \approx 20$ MeV

$$Q \sim \sqrt{m_N S_{2n}} \approx 30 \text{ MeV} \qquad \Lambda \sim \sqrt{m_N E^{*}_{c}} \approx 140 \text{ MeV}$$

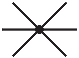
Effective field theory

- **EFT is an approach to systems with a separation of scales**
    - atomic systems $\rightarrow$ zero-range EFT
    - few-nucleon systems $\rightarrow$ pionless EFT
    - halo nuclei $\rightarrow$ halo EFT
  - **study physics in expansion of ℓ/a or Q/Λ**

- **EFT with contact interactions**
  - **2-body contact (LO)**

     $= -iC_0$

    C_0 determined by a 2-body observable
  - **3-body contact (LO)**

     $= -iD_0$

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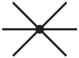
- **EFT with contact interactions**
  - **2-body contact (LO)** introduce a dimer field

 $= -iC_0$ $\xrightarrow{C_0=g^2/\Delta}$  $= -i\sqrt{2}g$

C_0 determined by a 2-body observable

  - **3-body contact (LO)**

 $= -iD_0$ $\xrightarrow{D_0=-3hg^2/\Delta^2}$  $= ih$

D_0 determined by a 3-body observable Bedaque, Hammer, van Kolck '99

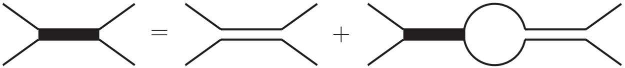
A general EFT for 3-body systems

- **EFT Lagrangian for 3 identical bosons at LO**

$$\mathcal{L} = \psi^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m} \right) \psi - d^\dagger \left(i\partial_0 + \frac{\nabla^2}{4m} - \Delta \right) d - \frac{g}{\sqrt{2}} \left(d^\dagger \psi\psi + \mathrm{h.c} \right) + h d^\dagger d \psi^\dagger \psi + \cdots$$

  - terms with more derivatives are at higher orders

- **Non-perturbative features at LO**
  - particle-particle scattering (tune g)

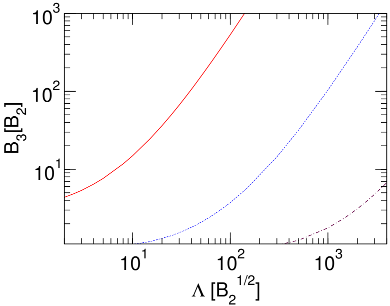


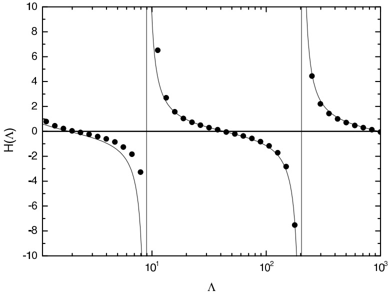
$\propto \frac{1}{1/a+ik}$

  - particle-dimer scattering (tune h)

LO renormalization

- **Without 3BF:**
  - 3-body spectrum:
    cutoff dependent ($\Lambda \sim 1/\ell$)
    Platter '09
- **LO 3BF h:**
  - tune $H(\Lambda) = \Lambda^2 h / 2mg^2$:
    fix one 3-body observable
  - limit cycle:
    $H(\Lambda)$ periodic for $\Lambda \to \Lambda(22.7)^n$
    Bedaque *et al.* '00
  - $\to$ Efimov physics





Range corrections to Efimov physics

- with perturbation theory:
  - study effective-range corrections (r_0/a) to 3-atom systems
  - NLO $(\sim r_0/a)$ range effects in 3body Efimov spectrum
    Platter, C.J., Phillips, PRA 79, 022702 (2009)
  - NLO $(\sim r_0/a)$ range effects in cold-atom recombination
    C.J., Platter, Phillips, EPL. 92, 13003 (2010)
    C.J., Phillips, Platter, Ann. Phys. 327, 1803 (2012)
  - N^2LO $(\sim r_0^2/a^2)$ range effects on Helium-4 trimer
    C.J., Phillips, Few Body Syst. 54, 2317 (2013)

EFT in halo nuclei

- include core + valence nucleon d.o.f. e.g., ^{6}He$\rightarrow n+n+{}^{4}$He; ^{11}Be$\rightarrow n+{}^{10}$Be
- include spin & isospin d.o.f.

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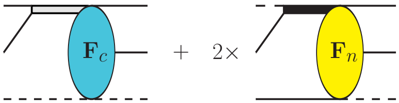
- include spin & isospin d.o.f.
- 2n-halo wave functions:

$\Psi_x(p, q) =$ 

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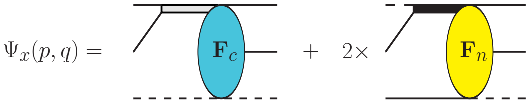
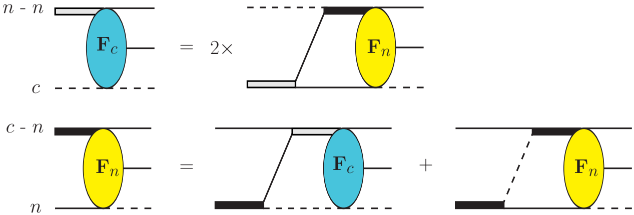


- Faddeev equation



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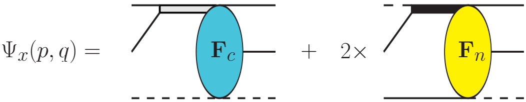
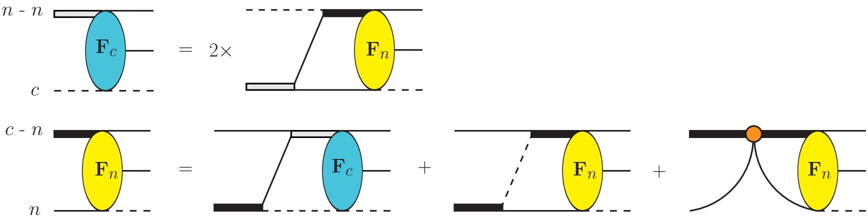
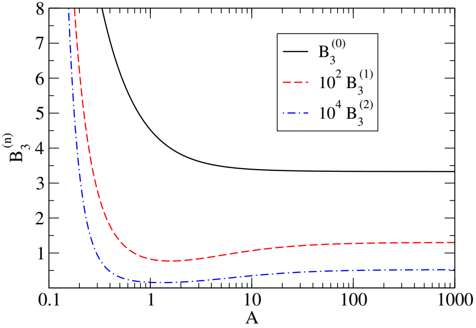


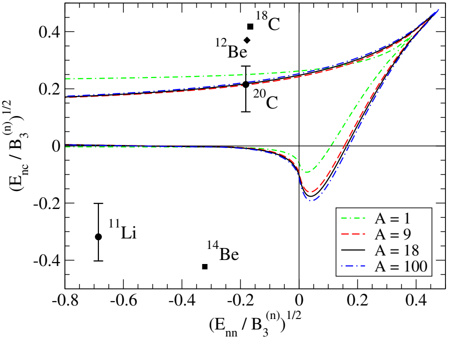
- Faddeev equation + 3-body force



- Efimov states in $a_{nn}, a_{nc} \to \infty$



- Implication of excited Efimov halo



Canham, Hammer EPJA 2008

EFT in halo nuclei

- **$1n$ halo and resonant state**
  - p-wave resonance:
    ^{5}He [Bertulani *et al.* '02, Bedaque *et al.* '02]

$1n$ halo and resonant state

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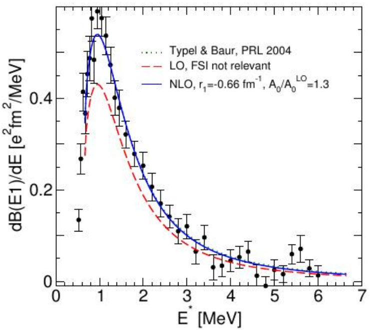
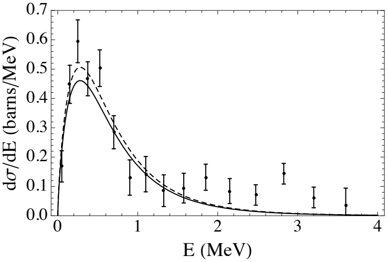
- E1 transition:
  ^{11}Be photo-dissociation



[Hammer, Phillips '11]

^{19}C photo-dissociation



Data: Nakamura *et al*, RIKEN ('99,'03);
Calculation: Acharya, Phillips ('13)

EFT in halo nuclei

- **1p halo**
  - ^{17}F [Ryberg, Forssén, Platter '13]
  - p-α scattering [Higa, Bertulani, van Kolck '14]

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  ^{17}F [Ryberg, Forssén, Platter '13]
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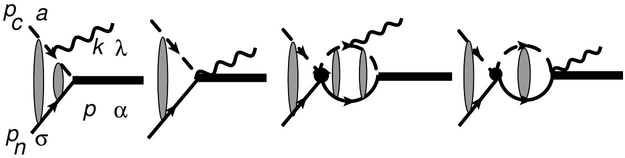
- **radiative nucleon captures**
  $^{7}\mathrm{Li} + n \to {}^{8}\mathrm{Li} + \gamma$ [Rupak, Higga '11, Zhang, Nollett, Phillips '13]
  $^{14}\mathrm{C} + n \to {}^{1}5\mathrm{C} + \gamma$ [Rupak, Fernando, Vaghani '12]
  $^{7}\mathrm{Be} + p \to {}^{8}\mathrm{B} + \gamma$ [Zhang, Nollett, Phillips '14]

proton capture



- **2-neutron halo:**
  - n-core in s-wave virtual/real bound state:
    ^{11}Li, ^{12}Be, ^{20}C [Canham, Hammer '08, '10]
    ^{22}C [Yamashita, Carvalho, Frederico, Tomio '11]
    ^{22}C Acharya, C.J., Phillips PLB 723 (2013)

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  - ^{6}**He:** n-α in p-wave resonance
    - EFT + Gamow shell model [Rotureau, van Kolck '12]
    - EFT + Faddeev Equations C.J., Elster, Phillips arXiv:1405.2394 (2014)

^{20}C, ^{21}C & ^{22}C

	^{20}C	^{21}C	^{22}C
bound/unbound	bound		
ground state	0^+		
binding/virtual energy	S_{2n}=4.76 MeV Ozawa et al. '11		
matter radius r_m	2.97(5) fm Ozawa et al. '01		

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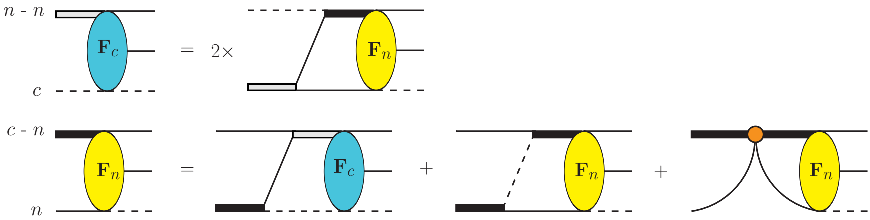
- Halo EFT: use measured ^{22}C r_m to put constraints on:
  - E_{nc} of ^{21}C $(a < 0)$
  - S_{2n} of ^{22}C

$n - n -{}^{20}$C Faddeev equations



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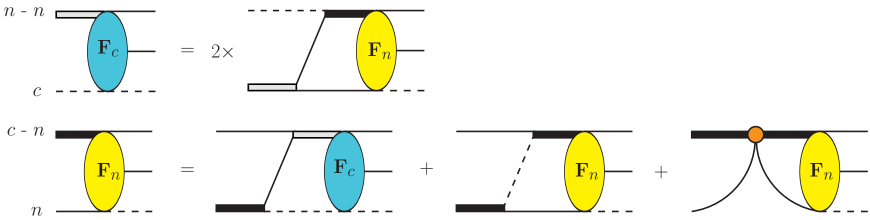
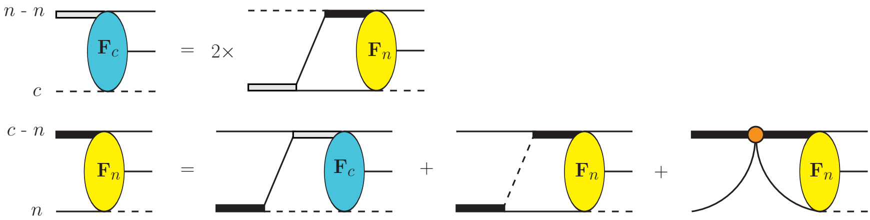


- parameterize $n - n$ and $n - {}^{20}$C interactions:
  - 2body virtual energies: $E_{nn} = 1/(M_n a_{nn}^2)$, E_{nc}

$n - n -{}^{20}$C Faddeev equations



- parameterize $n - n$ and $n -{}^{20}$C interactions:
  - 2body virtual energies: $E_{nn} = 1/(M_n a_{nn}^2)$, E_{nc}
- parameterize $n -{}^{21}$C 3body contact term
  - fix $r_m[^{22}\mathrm{C}]$

Matter radii of 2n s-wave halos

- two-body form factor

$$\mathcal{F}(k^2) = \int d\boldsymbol{p} \int d\boldsymbol{q} \Psi^\dagger(\boldsymbol{p},\boldsymbol{q})\Psi(\boldsymbol{p}-\boldsymbol{k},\boldsymbol{q}) \approx 1 - \frac{1}{6}\, r_{2b}^2\, k^2$$

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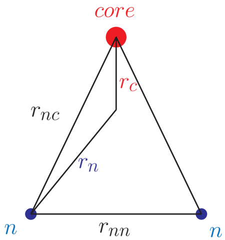
- matter radius (with point-like core)

$$R = \sqrt{A\, r_c^2 + 2\, r_n^2} \,/\, (A+2)$$



Universality and matter radii

- Define a dimensionless quantity:

$$M_n B_3 \cdot R^2 \equiv f\left(\frac{E_{nn}}{B_3}, \frac{E_{nc}}{B_3}; A\right)$$

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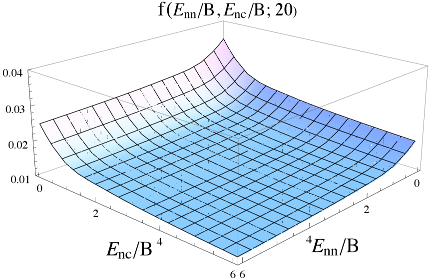
- At $A = 20$:
  - a function of E_{nn}/B_3 and E_{nc}/B_3



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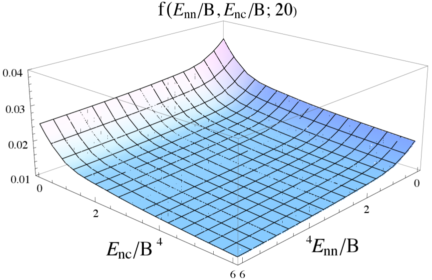
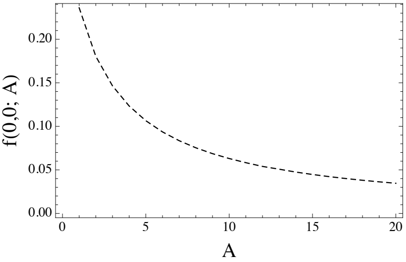


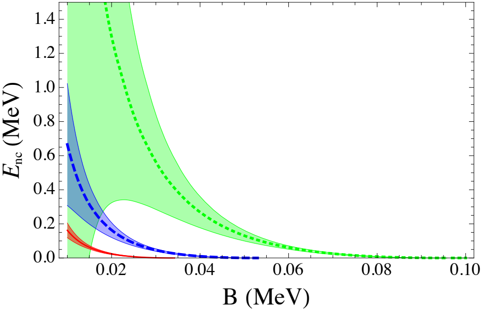
- Unitary limit $E_{nn} = E_{nc} = 0$:
  - a function of A



Acharya, C.J., Phillips PLB 2013

- Include finite size of $^{20}\mathrm{C}$

$$R^2 = r_m^2[^{22}\mathrm{C}] - \frac{20}{22}\, r_m^2[^{20}\mathrm{C}] = \left(5.4^{+0.9}_{-0.9}\right)^2 - \frac{20}{22}(2.97 \pm 0.05)^2\ \mathrm{fm}^2$$



bands: EFT power counting

Constraints on ^{21}C and ^{22}C

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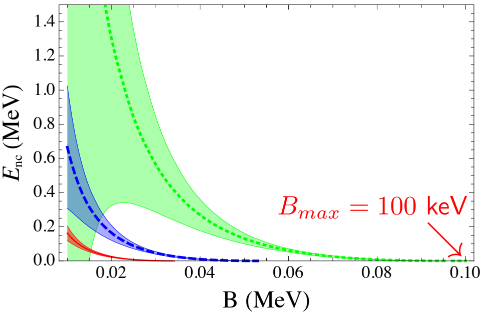

bands: EFT power counting

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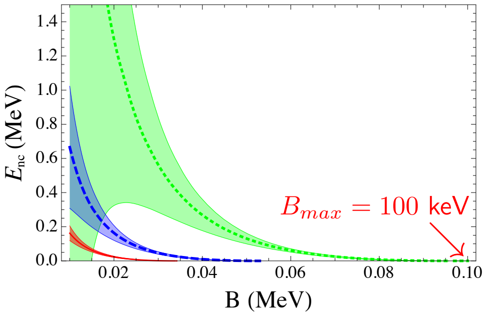

c.f. Yamashita et al. '11
$\rightarrow B_{max} \sim 120$ keV

Fortune & Sherr '12
$\rightarrow B_{max} \sim 220$ keV

Gaudefroy et al. '12
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TRIUMF

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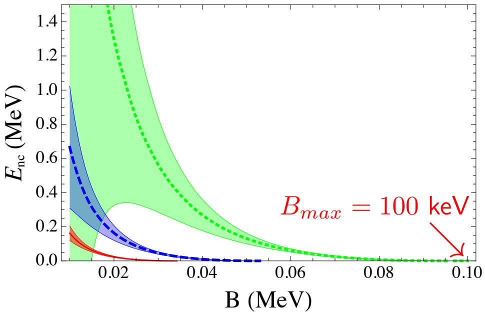

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Mosby et al. '13

$a_{nc} < 2.8$ fm $\Longleftrightarrow E_{nc} > 2.9$ MeV

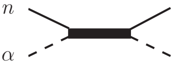
$\rightarrow B_{max} < 20$ keV

inconsistency in measurements?

Studies of ^{6}He

- **experiment in ^{6}He**
  - matter radius Tanihata *et al.* '92, Alkhazov *et al.* '97, Kislev *et al.* '05
  - charge radius Wang *et al.* '04, Mueller *et al.* '07
  - ^{6}He mass Brodeur *et al.* '12
- **cluster model**
  - separable potential Ghovanlou, Lehman '74
  - density-dependent nn contact interaction Esbensen *et al.* '97
- *ab intio* **calculation**
  - no-core shell model Navrátil *et al.* '01
  - hyperspherical harmonics Bacca *et al.* '12
  - Green's function Monte Carlo Pieper *et al.* '01
- **halo EFT**
  - explore **universal physics** in halo nuclei
  - compare **predictions** with experiments and other theories

- $n\alpha$ interaction is dominated by the $^2P_{\frac{3}{2}}$ state



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$a_1 = -62.95$ fm^3, $r_1 = -0.8819$ fm^{-1} Ardnt et al. '73

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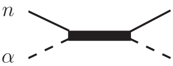

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- $r_1 \not\to 0$ Nishida '12

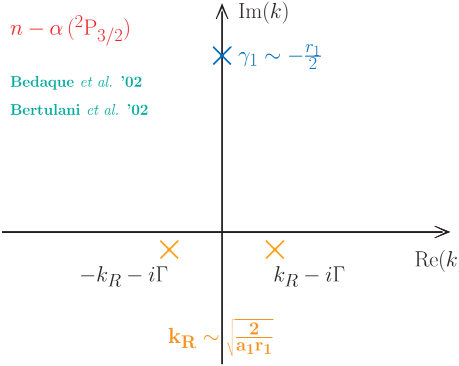
- $n\alpha$ EFT power counting: Bedaque, Hammer, van Kolck '02
  - $a_1 \sim 1/(Q^2\Lambda) \quad r_1 \sim \Lambda$
  - $Q/\Lambda \sim 0.15$

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

  shallow resonance:

  $$k_R \sim Q, \quad \Gamma \sim Q^2/\Lambda$$

  deep bound state: $\gamma_1 \sim \Lambda$



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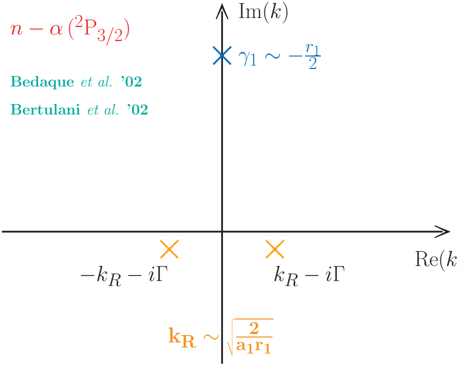

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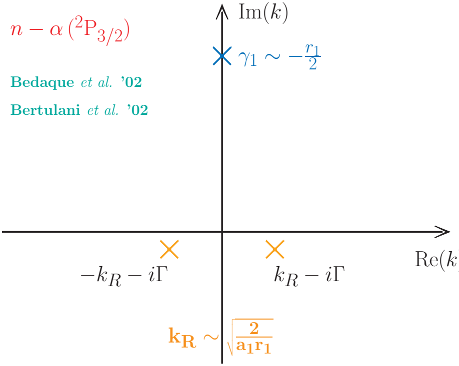
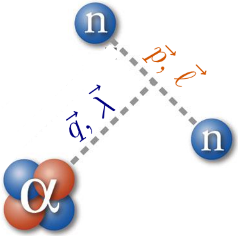


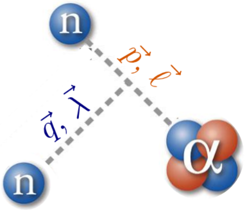
$n - \alpha\ {}^1S_{\frac{1}{2}}$ and ${}^2P_{\frac{1}{2}} \to$ beyond LO

- **Jacobi-momentum**

α spectator



n spectator



spin-orbit coupling for ^{6}He ($J = 0^{+}$)

<table>
<tr><th>pair, spec</th><th>pair</th><th>spectator</th><th>total L, S</th><th>total J</th></tr>
<tr><td>nn, α</td><td>$\ell = 0,\ s_1 = 0$</td><td>$\lambda = 0,\ s_2 = 0$</td><td>$L = 0,\ S = 0$</td><td rowspan="3">$J = 0^{+}$</td></tr>
<tr><td rowspan="2">$n\alpha$, n</td><td rowspan="2">$\ell = 1,\ s_1 = \frac{1}{2}$</td><td rowspan="2">$\lambda = 1,\ s_2 = \frac{1}{2}$</td><td>$L = 0,\ S = 0$</td></tr>
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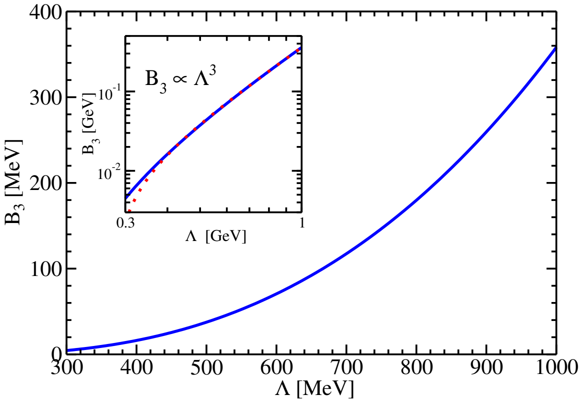
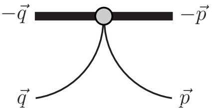
</table>

Cutoff dependence

- **without $nn\alpha$ 3-body force:**
  - S_{2n} is strongly cutoff dependent: $S_{2n} \sim \Lambda^3$ $\leftarrow$ need 3body force!

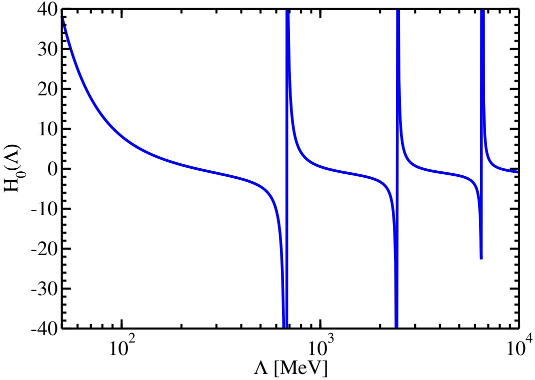


- **p-wave 3BF:**



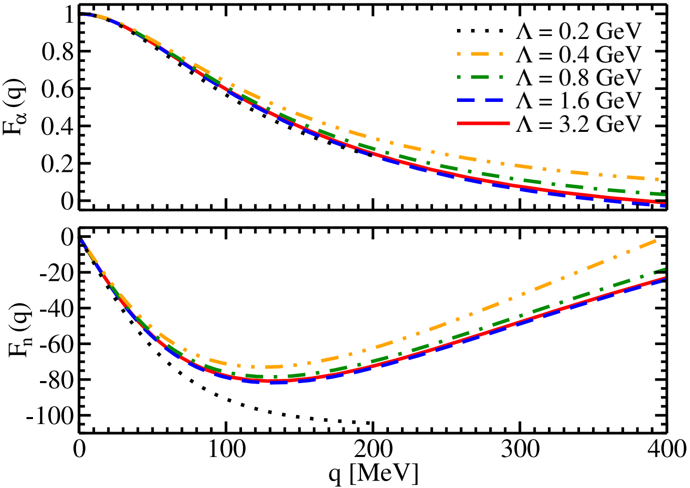
$$= M_n\, qp\, \frac{H(\Lambda)}{\Lambda^2}$$

- reproduce $S_{2n} = 0.973\text{MeV}$
- log oscillation
- No limit cycle (c.f. 3-body in S-wave)



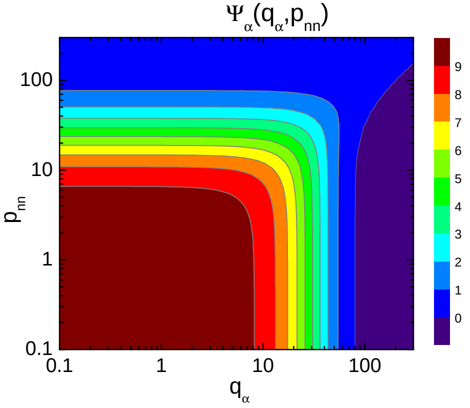
Renormalized Faddeev Components

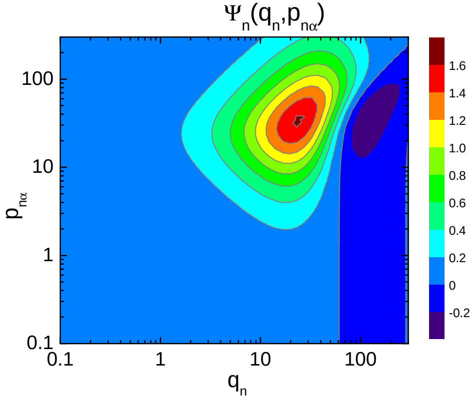
$F_\alpha(\alpha, nn)$ and $F_n(n, \alpha n)$: Λ independent



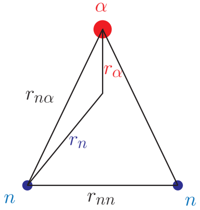
C.J., Elster, Phillips arXiv:1405.2394 (2014)

- $|\Psi\rangle$ in $\alpha - nn$ basis
- $|\Psi\rangle$ in $n - \alpha n$ basis





momenta in units of MeV



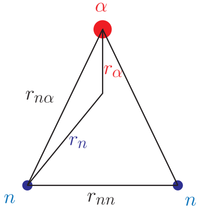
[Preliminary]

$r_{nn} = 3.77$ fm $\pm 20\%$

$r_{n\alpha} = 4.33$ fm $\pm 20\%$

- $\pm 20\%$ uncertainty is from higher-order EFT

		EFT [fm]	Exp [fm]
He-4	$r_{pp}[\alpha]$	—	1.455(1)
	$r_m[\alpha]$	—	1.455(1)
He-6			



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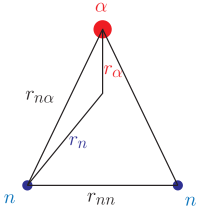
	r_n	3.21(64)	—



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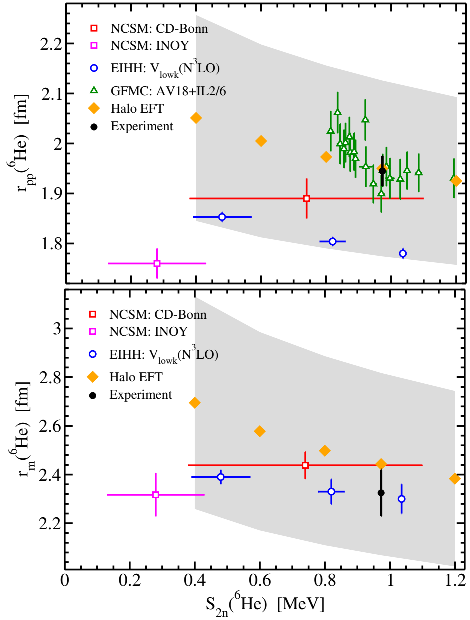
He-6	r_α	1.30(26)	—
	r_n	3.21(64)	—
	$r_{pp}[^6\text{He}] = \sqrt{r_\alpha^2 + r_{pp}^2[\alpha]}$	1.95(17)	1.938(23), 1.953(22)
	$r_m[^6\text{He}] = \sqrt{\frac{1}{3}\left(2r_\alpha^2 + r_n^2 + 2r_m^2[\alpha]\right)}$	2.44(37)	2.33(4), 2.30(7), 2.37(5)



[Preliminary]

- He-6 point-proton radius
- He-6 matter radius

c.f. Bacca, Barnea & Schwenk, '12

Conclusion and Outlook

- Halo nuclei are ideal places to study universal physics
  - ^{22}C: n-core in s-wave resonance
  - ^{6}He: n-core in p-wave resonance

- with halo EFT analysis:
  - s- / p-wave 3body force is needed for proper renormalization
  - predict probability density distribution, matter radii, point-proton radii
  - use universality to constrain experiments & other theories

- further work
  - study ^{6}He 2^{+} resonance state
  - extension to ^{11}Li
  - higher-order effects: range corrections, more partial waves, ...