EFB22, Krakow, Sept. 12, 2013

Universal aspects of neutron halos in light exotic nuclei

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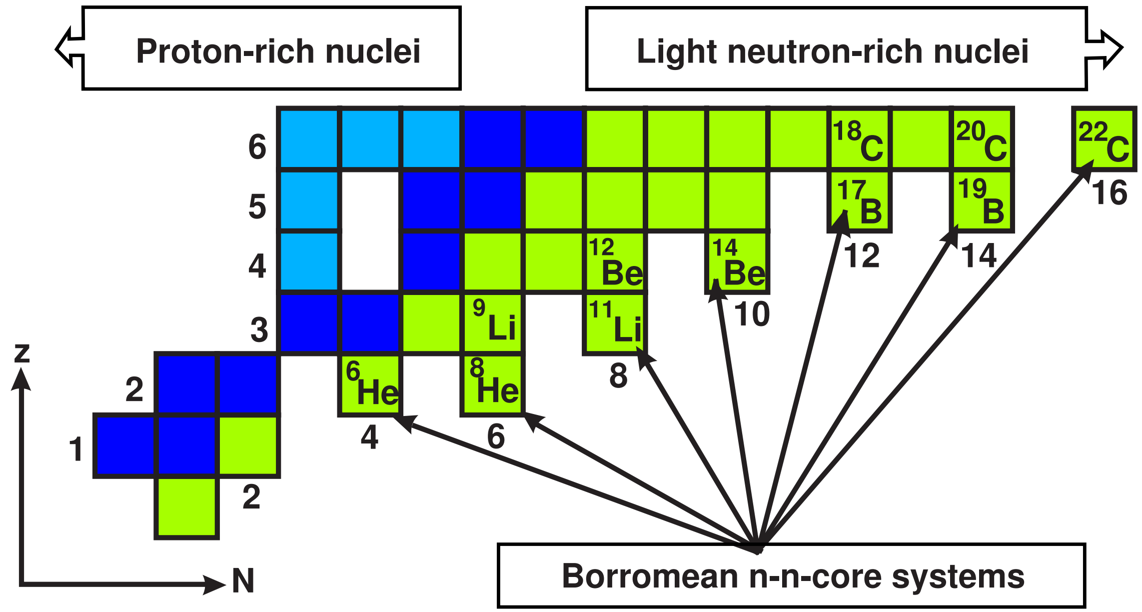
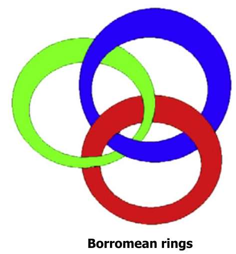
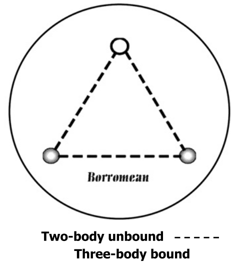
Light-neutron rich nuclei







^{11}Li, ^{14}Be, ^{20}C, ^{22}C

C.A. Bertulani, Nuclear Physics in a Nutshell, Princeton University Press, 2007.

TF, Delfino, Tomio, Yamashita, “Universal aspects of light halo nuclei
Prog. Part. Nucl. Phys. 67 (2012) 939”

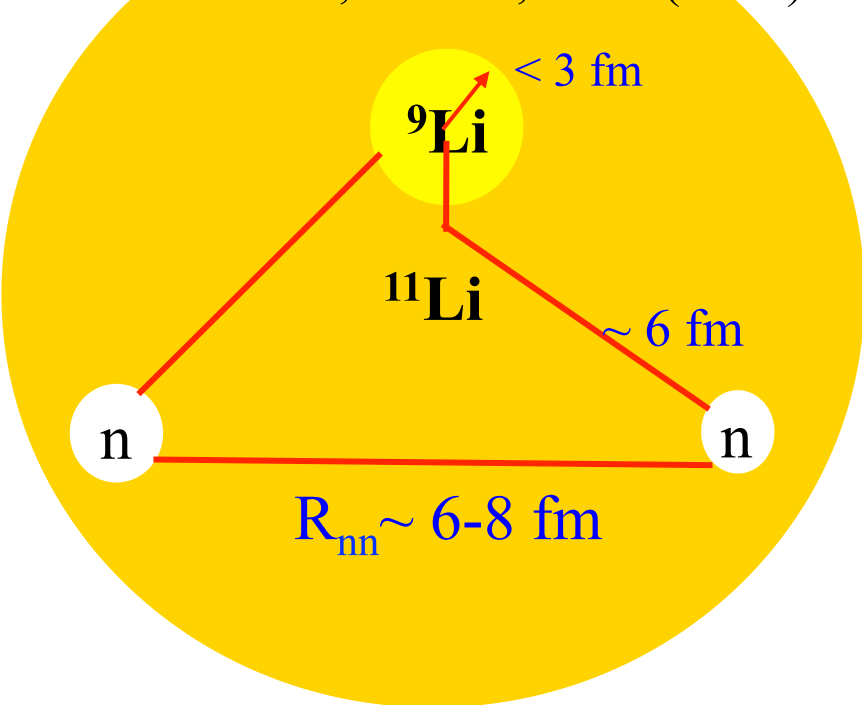
Tanihata,Savajols Kanungo. “Recent experimental progress in nuclear halo structure studies Prog. Part. Nucl. Phys. 68 (2012) 215”

Zinner, Jensen. ”Comparing and contrasting nuclei and cold atomic gases”. J. Phys. G: Nucl. Part. Phys. 40 (2013) 053101

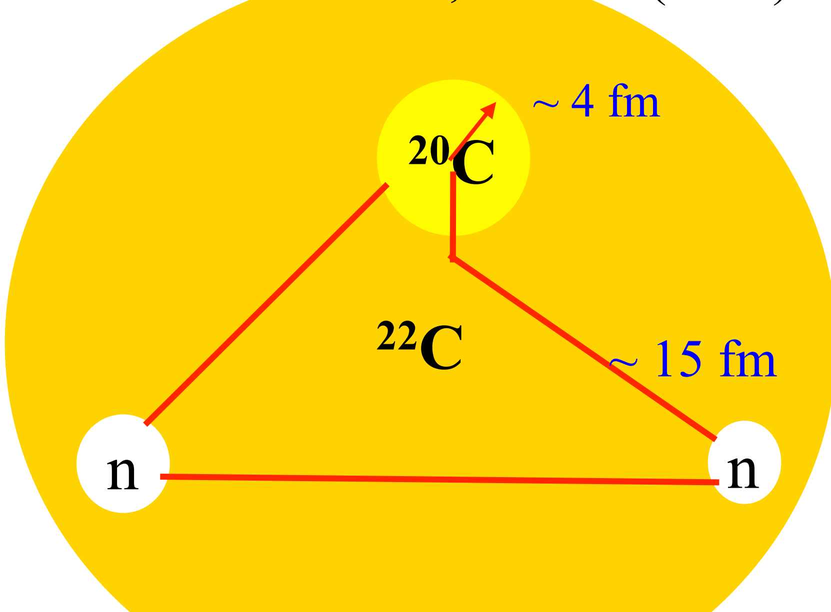
Two-neutron weakly bound s-wave three-body halo nuclei

S_{2n} **= 369 keV -** Smith et al. PRL101, 202501 (2008)

Tanihata et al., PRL**55**, 2676 (1985)



Tanaka et al. PRL104, 062701 (2010)



S_{2n} **< 70 keV** Mosby et al. NPA 909, 69 (2013)

Weakly bound quantum systems

$$(E - H_0)\psi = 0$$

- Almost everywhere the wf is an eigenstate of H_0 - short-range force
- Physics: symmetry, scales and dimension (& mass ratios)

→ Universality (model independence)

Generalization: "The few scales of nuclei and nuclear matter"
Delfino, TF, Timóteo, Tomio. PLB 634 (2006) 185

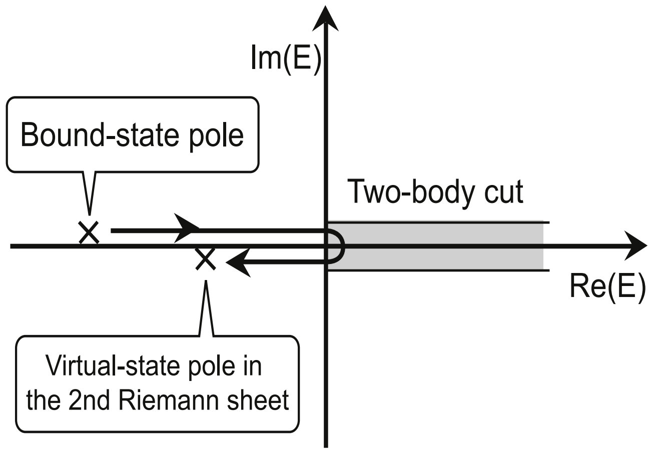
Two-body s-wave:

$$k \cot(\delta) = -\frac{1}{a} + \frac{r_0}{2} k^2 + \cdots$$

$$|a| >> r_0$$

$a > 0$

$a < 0$



- $^1S_0$ nn state $E_{virtual}$= -143 keV (a = -17fm)
- S n-core virtual (^{10}Li ~ -25 keV) or bound (^{19}C ~ 500 keV)

Three-boson

Subtle three-body phenomenon in L=0:

Thomas collapse (1935)	**Efimov effect (1970)**
$r_o \rightarrow 0$	$\lvert a \rvert \rightarrow \infty$
Route to collapse?	infinitely many bound states condensing at E=0

Thomas-Efimov effect!

$\lvert a \rvert / r_o \rightarrow \infty$

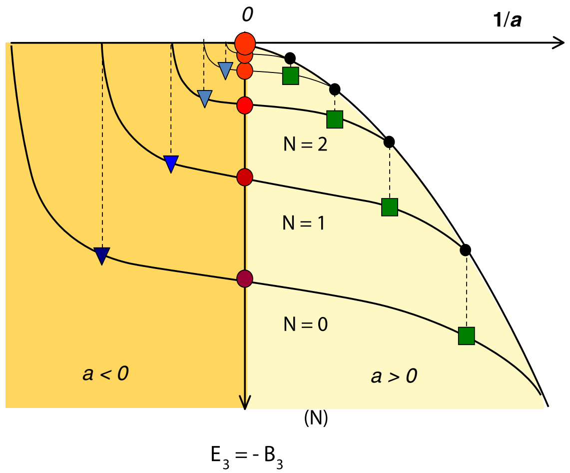
Adhikari, Delfino,TF,Goldman,Tomio, PRA37 (1988) 3666

One three-body scale is necessary to represent short-range physics !!!!
& discrete scaling

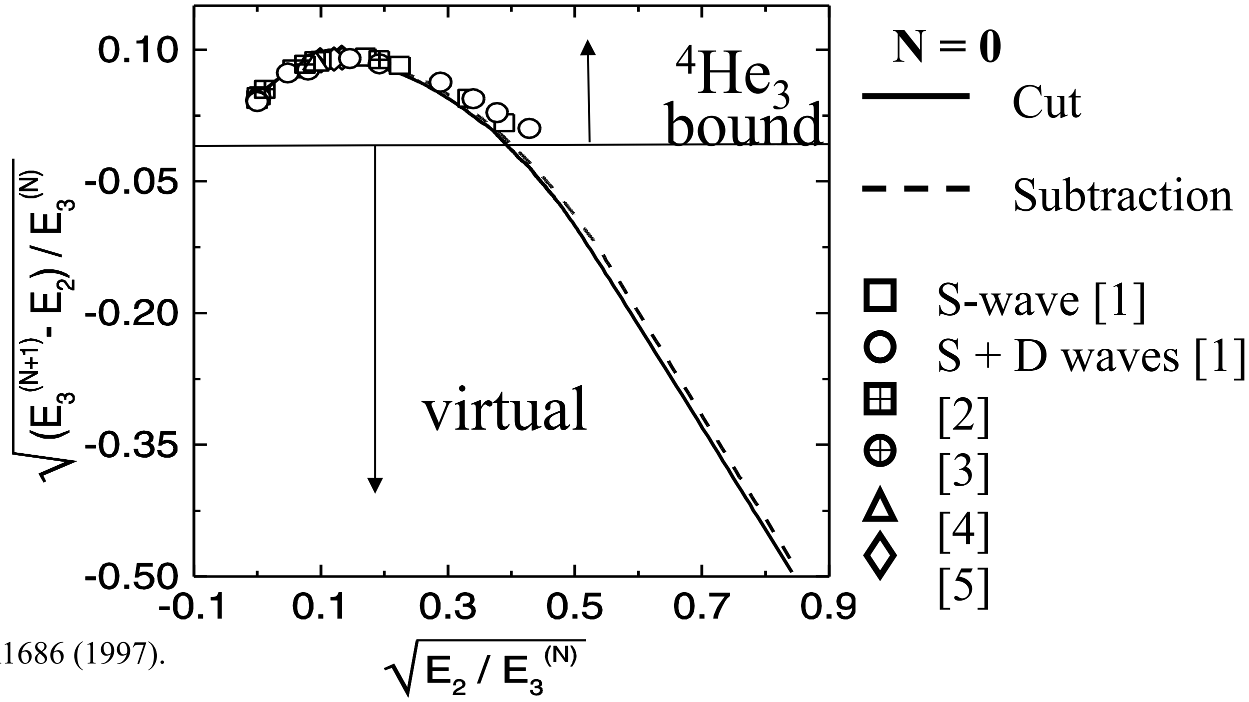
Jensen, Riisager, Fedorov, Garrido, RMP76, 215 (2004)
Braaten, Hammer Phys. Rep.428, 259 (2006)

Efimov States – Bound and virtual states (3 identical bosons)

Correlations between observables: Jensen, Fedorov, Yamashita, Hammer, Platter, Gattobigio, Kievsky, Kolganova, Van Kolck, Bedaque, Phillips,...



Scaling plot from zero range force

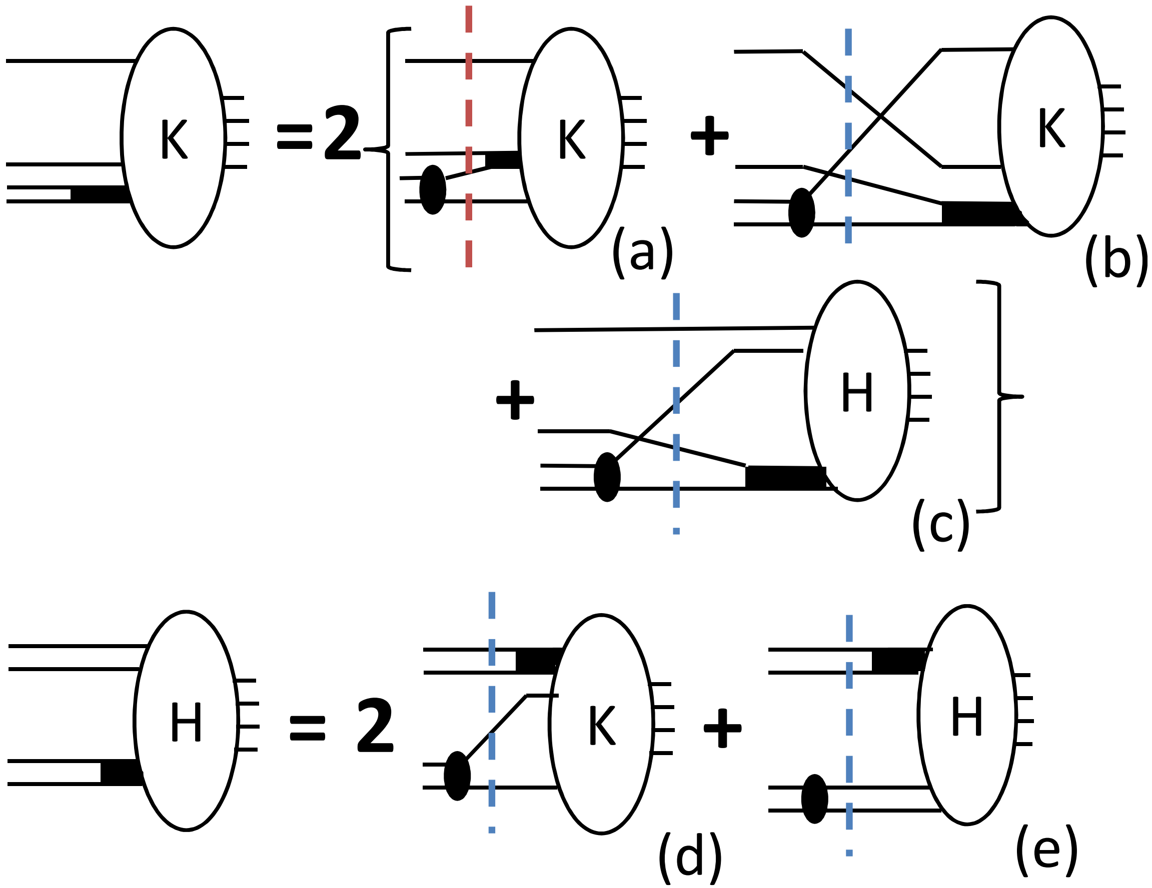


[1] Cornelius, Glöckle. *JCP* **85**, 1 (1996).
[2] Huber. *PR***A31**, 3981 (1985).
[3] Barletta, Kievsky. *PR* **A64**, 042514 (2001).
[4] Fedorov, Jensen. *JP***A34**, 6003 (2001).
[5] Kolganova, Motovilov, Sofianos. PRA **56**, R1686 (1997).

- *Scaling limit:* T. Frederico, LT, A. Delfino and E. A. Amorim, PRA**60**, R9 (1999)
- *Limit cycle*: Mohr et al Ann.Phys. 321 (2006)225
- *Correlation between observables: Phillips Plot* $^2a_{nd}$ v.s. E_{triton}

Range correction: Thogersen, Fedorov, Jensen PRA78(2008)020501(R)

Four-bosons

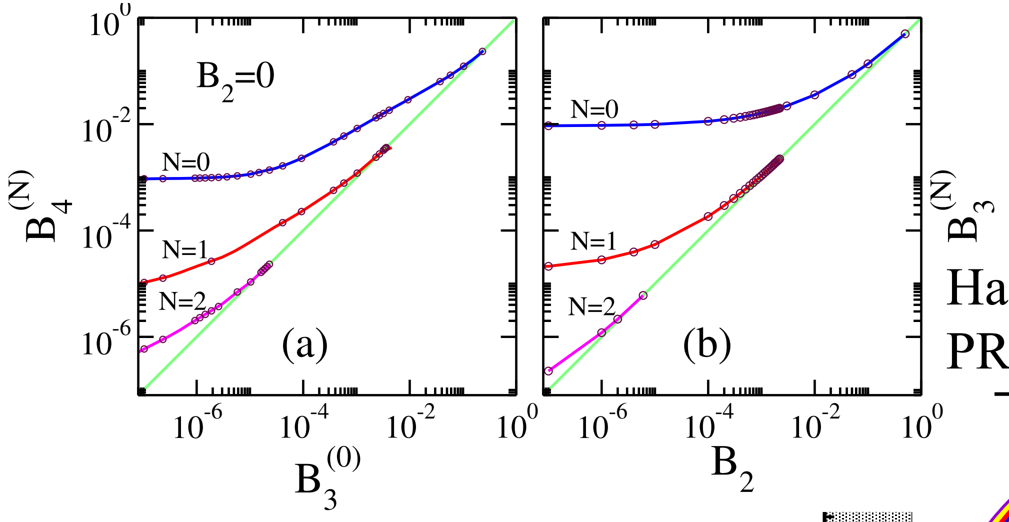


Subtracted Green's Functions: $G_0^{(N)} = \frac{1}{E - H_0} - \frac{1}{-\mu_N^2 - H_0}$

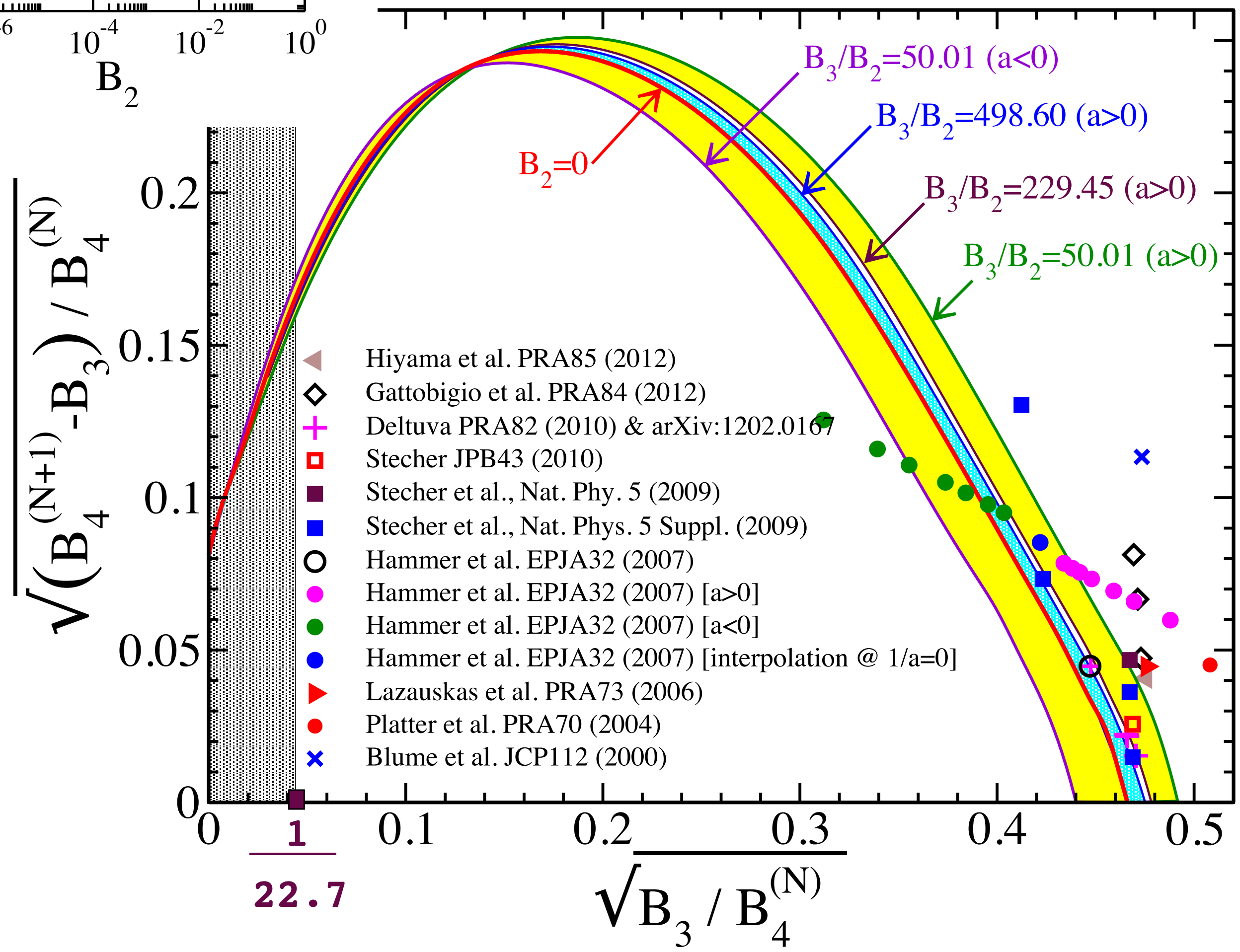
with μ_3 (RED): 3B scale & μ_4 (BLUE): 4B scale

Yamashita, Tomio, Delfino, TF, EPL 75 (2006) 555.

$a = \infty$



Hadizadeh, Yamashita,Tomio, Delfino, TF, PRL107, 135304 (2011



H.W. Hammer and L. Platter, Universal properties of the four-body system with large scattering lengths, European Physical Journal 32, 113 (2007)

- Zero-range potential - EFT
- Three-body repulsive potential to deal with the Thomas collapse

★ Repulsive interaction at short distances kills the four-body scale.
How to check the 4-boson scale? Use an attractive interaction

J. von Stecher, J.P. D'Incao , C.H. Greene, Signatures of universal four-body phenomena and their relation to the Efimov effect, Nature Physics 5, 417 (2009).

•Two-body Gaussian potential - Stochastic variational method

M. Gattobigio, A. Kievsky, M. Viviani, Energy spectra of small bosonic clusters having a large two-body scattering length, Physical Review A 86, 042513 (2012).

•Two-body Gaussian LM2M2 potentials - Hyperspherical formalism

★ How to check 4-boson scale? Disentangle the scales by a four-body potential

Experimental verification? → Technique to tune three or four-body potentials!!!!

Halo Nuclei and Efimov physics (n+n+core)

Fedorov, Jensen, Riisager, "Efimov states in halo nuclei" PRL73 (1994) 2817. ^{14}Be ^{18}C ^{20}C

Mazumdar, Bhasin, "Efimov effect in the nuclear halo 14Be nucleus" PRC 56 (1997) R5

Amorim, TF, Tomio "Universal aspects of Efimov states and light halo nuclei", PRC 56, R2378 (1997)

Mazumdar, Arora, Bhasin, "Three-body analysis of the occurrence of Efimov states in 2n halo nuclei such as ^{19}B, ^{22}C, and ^{20}C", PRC61 (2000) 051303

Halo Nuclei and EFT

Bertulani, Hammer, van Kolck, "Effective field theory for halo nuclei: shallow p-wave states", NPA712 (2002) 37

Halo Nuclei, EFT and Efimov physics

Hammer, Platter, "Efimov States in Nuclear and Particle Physics", Annu. Rev. Nucl. Part. Sci. 60 (2010) 207

[redacted]

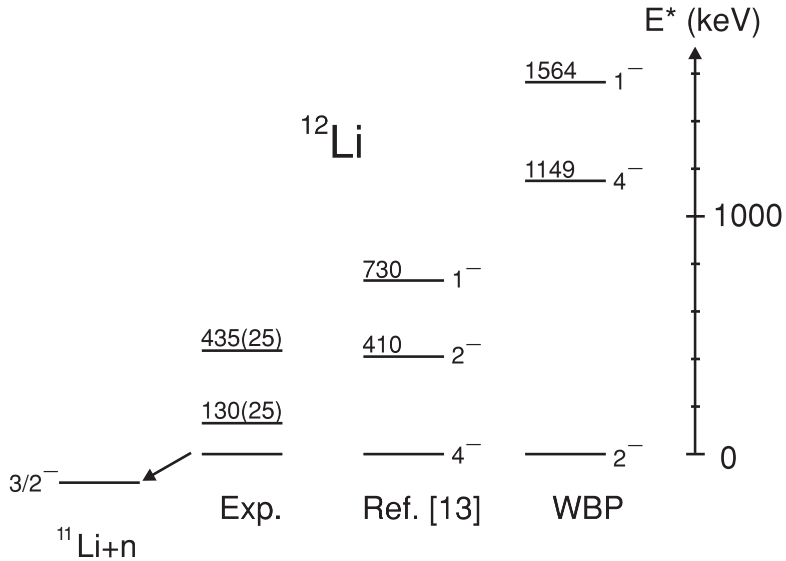
PHYSICAL REVIEW C **81**, 021302(R) (2010)

First observation of excited states in ^{12}Li

(n+n+n+core)

C. C. Hall,[1] E. M. Lunderberg,[1] P. A. DeYoung,[1,*] T. Baumann,[2] D. Bazin,[2] G. Blanchon,[3] A. Bonaccorso,[4] B. A. Brown,[2,5] J. Brown,[6] G. Christian,[2,5] D. H. Denby,[1] J. Finck,[7] N. Frank,[2,5,†] A. Gade,[2,5] J. Hinnefeld,[8] C. R. Hoffman,[9,10] B. Luther,[11] S. Mosby,[2,5] W. A. Peters,[2,5,‡] A. Spyrou,[2,5] and M. Thoennessen[2,5]

The neutron-unbound ground state and two excited states of ^{12}Li were formed by the two-proton removal reaction from a 53.4-MeV/u ^{14}B beam. The decay energy spectrum of ^{12}Li was measured with the Modular Neutron Array (MoNA) and the Sweeper dipole superconducting magnet at the National Superconducting Cyclotron Laboratory. Two excited states at resonance energies of 250 ± 20 keV and 555 ± 20 keV were observed for the first time and the data are consistent with the previously reported s-wave ground state with a scattering length of $a_s = -13.7$ fm.



$$^{12}Li =^9 Li + n + n + n$$

Pauli principle kills sensitivity to the 4-body scale!

Scales of s-wave n-n-c system: contact interaction

E_{nn} Energy of the virtual nn system

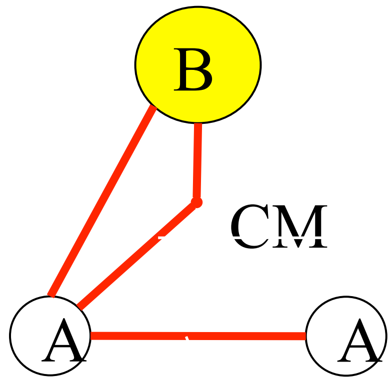
E_{nc} Energy of the bound/virtual nc system

$B_N = |E_3^{(N)}|$ Energy of the Nth state of the nnc system

A = mass of the core

Root mean square radii

Scaling functions for the radii



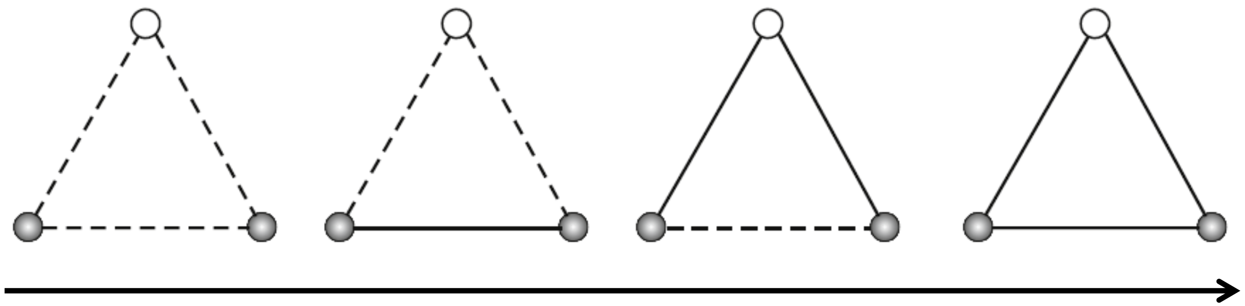
$$\sqrt{\langle r_{A\gamma}^2 \rangle |E_3|} = R_{A\gamma}\left(\pm\sqrt{\frac{E_{AA}}{E_3}}, \pm\sqrt{\frac{E_{AB}}{E_3}}, \mathrm{A}\right)$$

Build constraints!

$$\sqrt{\langle r_{\gamma}^2 \rangle |E_3|} = R_{\gamma}^{CM}\left(\pm\sqrt{\frac{E_{AA}}{E_3}}, \pm\sqrt{\frac{E_{AB}}{E_3}}, \mathrm{A}\right)$$

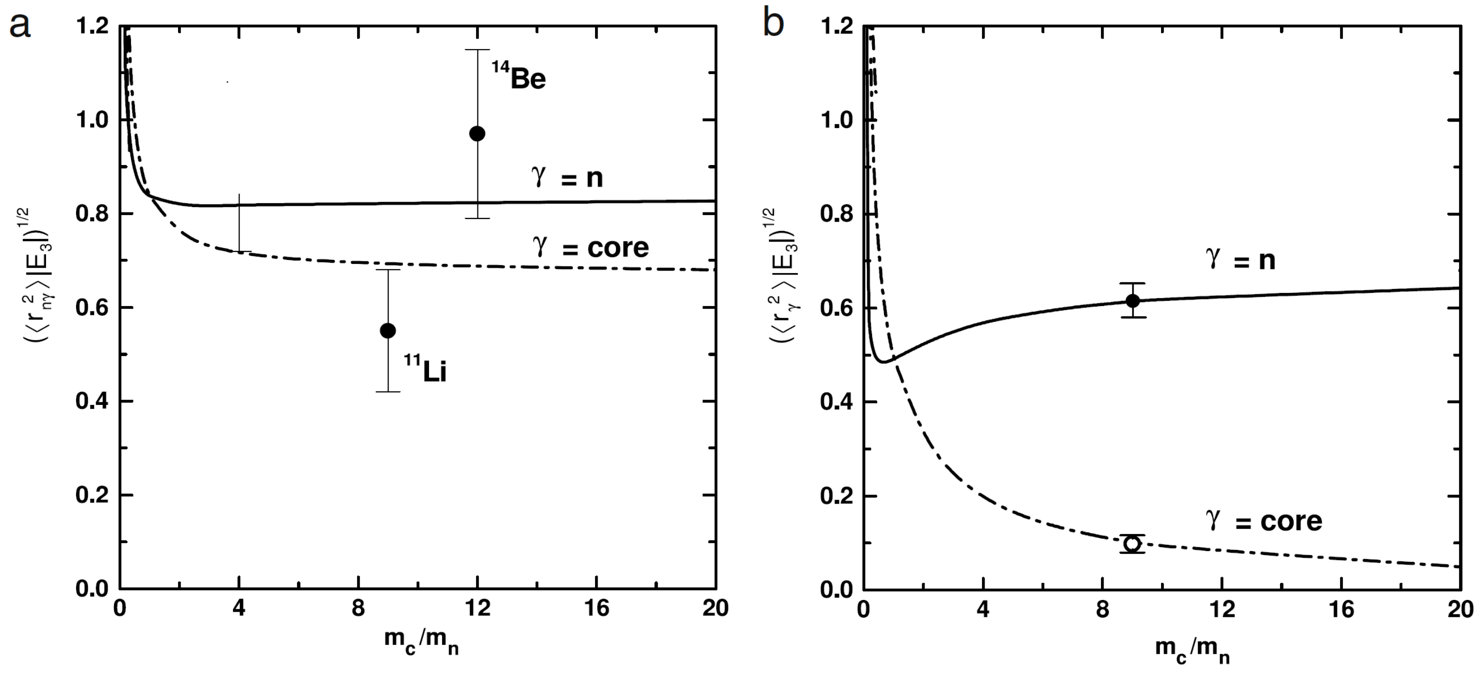
$\gamma = A$ or B

\+ two-body bound state
\- two-body virtual state



System size for fixed 3-body binding

Root mean square radii: Core+neutron+neutron



The experimental values of the charge radius of ^{9}Li and ^{11}Li are given in [4] as 2.217(35) and 2.467(37) fm, respectively, such that $\sqrt{\langle r_{ch}^2(^{11}\text{Li})\rangle - \langle r_{ch}^2(^9\text{Li})\rangle} = 1.08(11)$ fm. A neutron halo radius of 6.54(38) fm was obtained from the extracted matter radius in the experiment performed by [3]. Together with $S_{2n} = 369.15(65)$ keV, reported in [176] for ^{11}Li, the experimental value of the root-mean-square distance of ^{9}Li in respect to the center-of-mass of ^{11}Li ($\sqrt{\langle r_c^2\rangle}$) in units of $\hbar/\sqrt{m_n S_{2n}}$, is 0.10(1) and the halo radius ($\sqrt{\langle r_n^2\rangle}$) in such units is 0.617(36), these values should be compared with the theoretical results extracted from Fig. 21, of 0.10 and 0.61, respectively. The agreement with the experimental supports the model assumptions.

[3] P. Egelhof, et al., Eur. J. Phys. A 15 (2002) 27.
[4] R. Sánchez, et al., Phys. Rev. Lett. 96 (2006) 033002.
[176] M. Smith, et al., Phys. Rev. Lett. 101 (2008) 202501.

Root mean square radii: Core+neutron+neutron

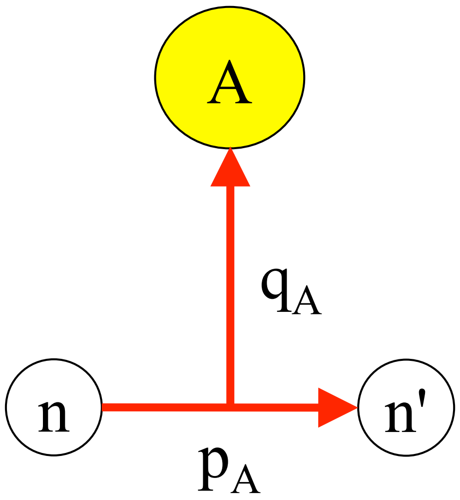
- Moriguchi et al. PRC88, 024610 (2013) - RIKEN reaction cross-section $\mathbf{r_n \sim 6.1}$ **fm**
- $\mathbf{S_{2n}}$**=369 keV** Smith et al. PRL101(2008)
- IMPROVE $E_v[^{10}Li]$!

Yamashita, Tomio and T. F.
NPA 735, 40 (2004)

Canham and Hammer
NPA 836 (2010) 275

Nucleus	B_3 [keV]	E_{nc} [keV]	r_0 [fm]	$\sqrt{\langle r_{nn}^2 \rangle}$ [fm]	$\sqrt{\langle r_{nc}^2 \rangle}$ [fm]	$\sqrt{\langle r_n^2 \rangle}$ [fm]	$\sqrt{\langle r_c^2 \rangle}$ [fm]
^{11}Li	247	-25	0.0	8.7±0.7	7.1±0.5	6.5±0.5	1.0±0.1
	247	-25	1.4	8.80±0.07	7.21±0.06	6.51±0.05	1.040±0.008
	247	-800 [48]	0.0	6.8±1.8	5.9±1.5	5.3±1.4	0.9±0.2
	247	-800 [48]	1.4	6.3±0.5	5.5±0.4	4.9±0.4	0.81±0.06
^{14}Be	1120	-200 [49]	0.0	4.1±0.5	3.5±0.5	3.2±0.4	0.40±0.05
	1120	-200 [49]	1.4	3.86±0.09	3.29±0.08	3.02±0.07	0.384±0.009
^{12}Be	3673	503	0.0	3.0±0.6	2.5±0.5	2.3±0.5	0.32±0.07
	3673	503	1.4	3.3±0.2	2.7±0.1	2.5±0.1	0.35±0.02
^{18}C	4940	731	0.0	2.6±0.7	2.2±0.6	2.1±0.5	0.18±0.05
	4940	731	1.4	2.9±0.2	2.4±0.2	2.3±0.2	0.21±0.01
^{20}C	3506	530 [45]	0.0	3.0±0.7	2.5±0.6	2.4±0.5	0.19±0.04
	3506	530 [45]	1.4	3.38±0.18	2.75±0.15	2.60±0.14	0.21±0.01
	3506	162	0.0	2.8±0.3	2.4±0.3	2.3±0.3	0.19±0.02
	3506	162	1.4	3.03±0.06	2.53±0.05	2.39±0.05	0.198±0.004
	3506	60	0.0	2.8±0.2	2.3±0.2	2.2±0.2	0.18±0.01
	3506	60	1.4	2.84±0.03	2.41±0.03	2.28±0.03	0.192±0.002
^{20}C*	65.0±6.8	60	0.0	42±3	38±3	41±3	2.2±0.2
^{20}C*	64.9±0.7	60	1.4	43.2±0.5	38.7±0.4	42.9±0.5	2.26±0.02

Neutron-neutron correlation function



$$C_{nn}(\vec{p}_A) = \frac{\int d^3 q_A \left|\Phi(\vec{q}_A, \vec{p}_A)\right|^2}{\int d^3 q_A \rho(\vec{q}_n')\rho(\vec{q}_n)}$$

$$\vec{q}_{n'} = \vec{p}_A - \frac{\vec{q}_A}{2} \qquad \vec{q}_n = -\vec{p}_A - \frac{\vec{q}_A}{2}$$

One-body density

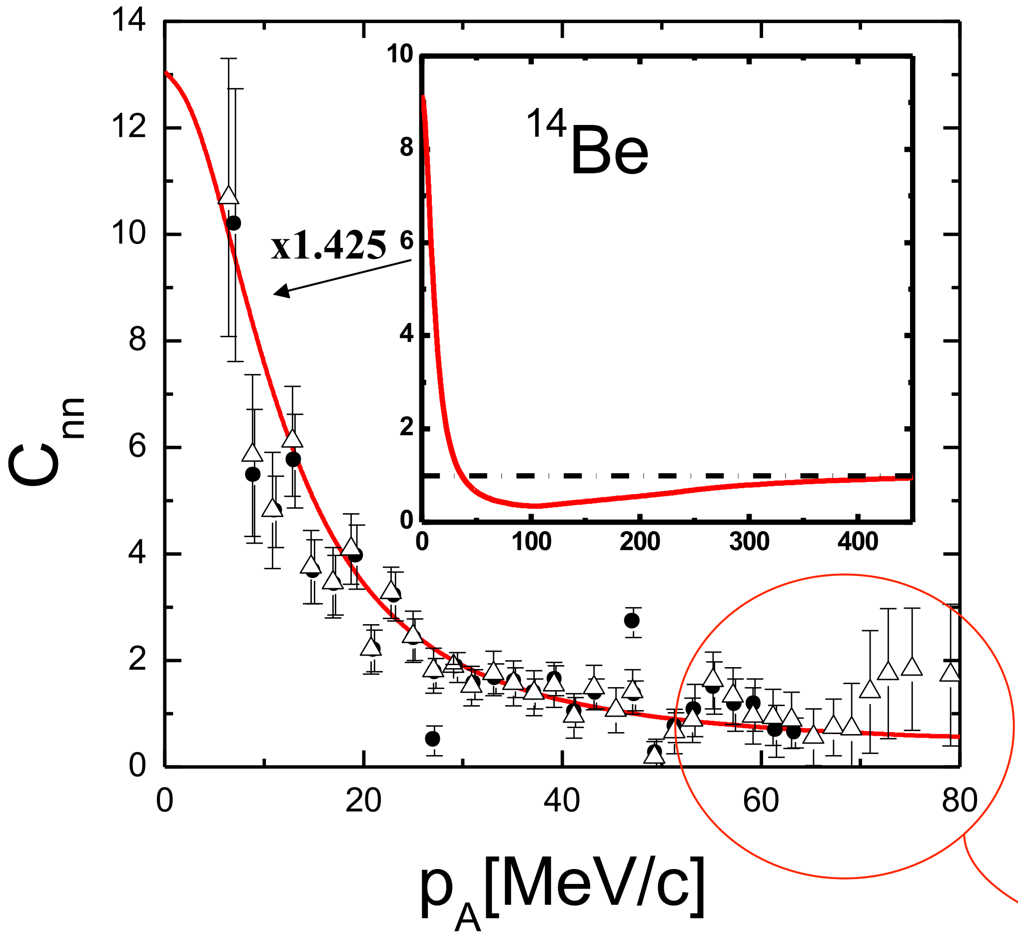
$$\rho(\vec{q}_{nA}) = \int d^3 q_{n'A} \left|\Phi\left(-\vec{q}_{nA} - \vec{q}_{n'A}, \frac{\vec{q}_{nA} - \vec{q}_{n'A}}{2}\right)\right|^2$$

$\Phi \equiv \Phi(\vec{q}_A, \vec{p}_A)$ Breakup amplitude including the FSI between the neutrons

$$\Phi = \Psi(\vec{q}_A, \vec{p}_A) + \frac{1/(2\pi^2)}{\sqrt{E_{nn}} - ip_A} \int d^3 p \frac{\Psi(\vec{q}_A, \vec{p})}{p_A^2 - p^2 + i\varepsilon}$$

Ψ is the three-body wave function

Neutron-neutron correlation function



● F. M. Marqués et al. Phys. Rev. C **64**, 061301 (2001)

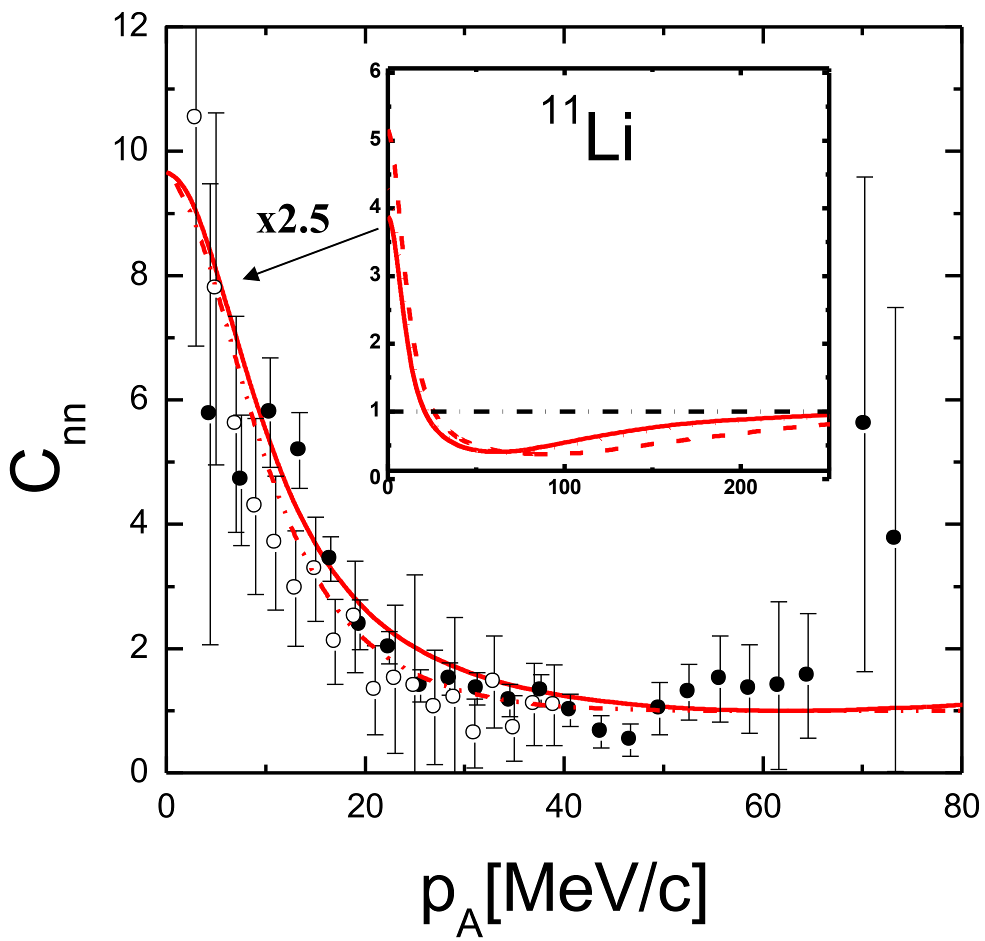
△ F. M. Marqués et al. Phys. Lett. B **476**, 219 (2000)

$E_3 = 1.337$ MeV
$E_{nA} = 0.2$ MeV
$E_{nn} = 0.143$ MeV

asymptotic region ?

Yamashita, TF, Tomio PRC 72, 011601(R) (2005)

Neutron-neutron correlation function



●

F. M. Marqués et al.
Phys. Rev. C **64**, 061301 (2001)

○ — · —

M. Petrascu et al.
Nucl. Phys. A **738**, 503 (2004)

——— E_3 = 0.29 MeV
E_{nA} = 0.05 MeV

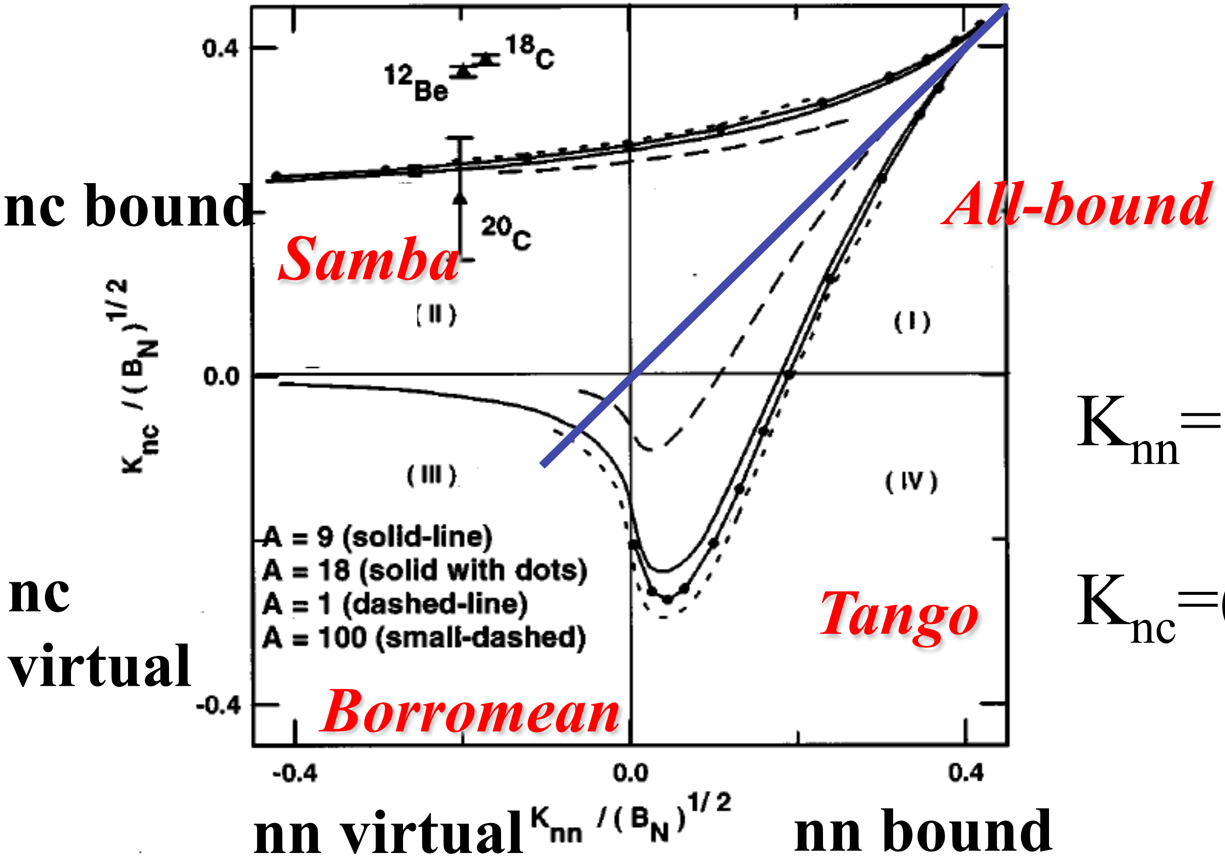
– – – E_3 = 0.37 MeV
E_{nA} = 0.8 MeV

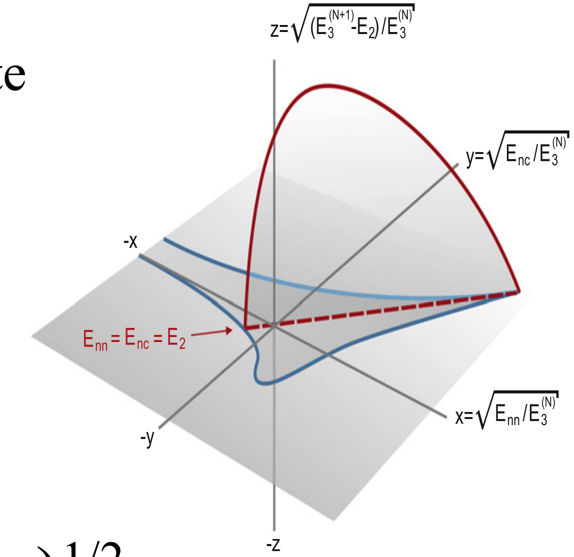
········ E_3 = 0.37 MeV
E_{nA} = 0.05 MeV

Enn = 0.143 MeV

Threshold for an excited Efimov state: Halo-nuclei

Critical condition for an excited (N+1)-th above the N-th state





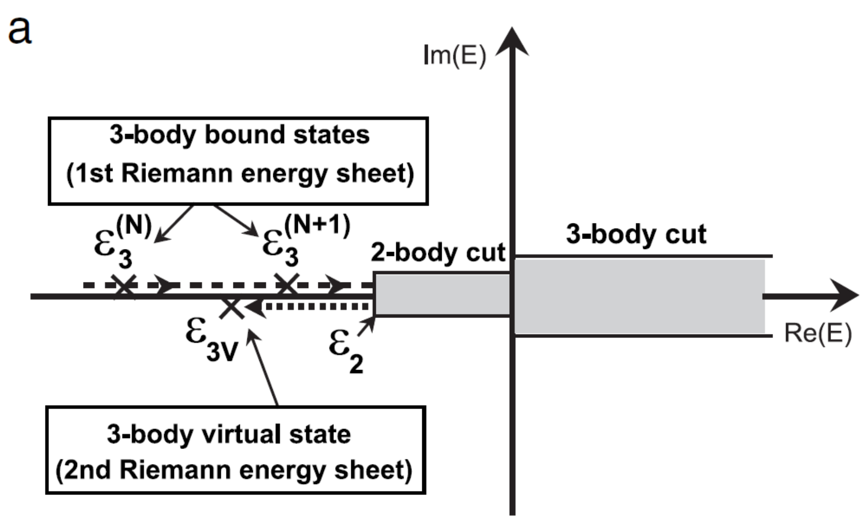
$K_{nn}=(B_{nn})^{1/2}$

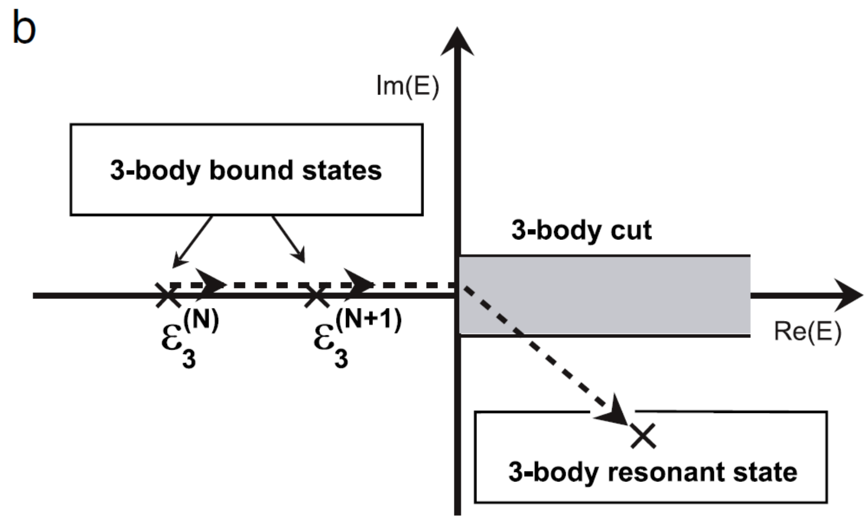
$K_{nc}=(B_{nc})^{1/2}$

Amorim,TF,Tomio PRC56(1997)2378

Canham and Hammer EPJ A 37 (2008) 367; NPA 836 (2010) 275

analytic structure & Efimov state trajectory

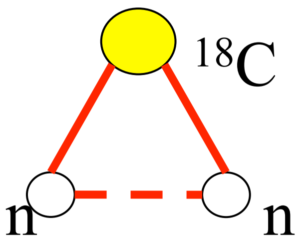




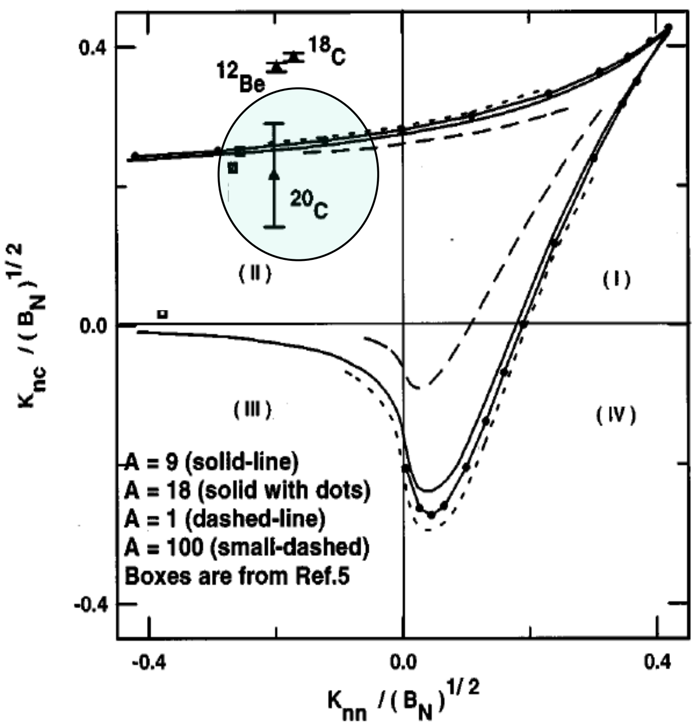
S.K. Adhikari and L. Tomio, Phys. Rev. C **26**, 83 (1982); S.K. Adhikari, A.C. Fonseca, and L. Tomio, *ibid.* **26**, 77 (1982).

F. Bringas, M.T. Yamashita and T. Frederico, Phys. Rev. A **69**, 040702(R) (2004).

^{20}C virtual Efimov state

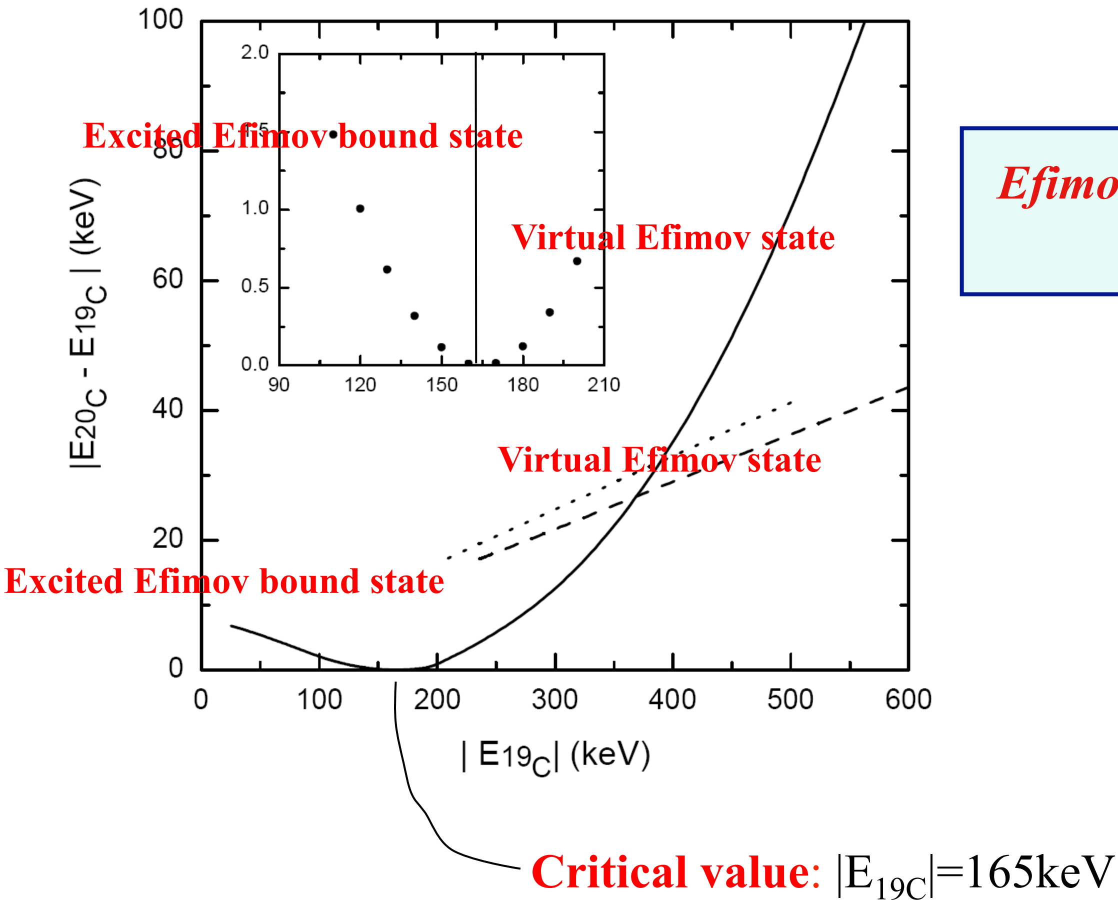


S_{2n}= 3.5 MeV
E_{nc}=160 ± 110 keV



Arora, Mazumdar, Bhasin PRC69 (2004)061301(R) Mazumdar, Rau, Bhasin PRL97(2006)062503
Efimov state→Fano resonance of n+^{19}C by changing E_{nc}

Yamashita, TF,Tomio, PRL99 (2007)269201 & PLB660(2008)339
Efimov state → virtual state by changing E_{nc}



Efimov state in ^{20}C goes to a virtual state for $|E_{19C}| >$ 165keV !

T. Nakamura, et al., Phys. Rev. Lett. 83 (1999) 1112.

$$S_n[\,^{19}C\,] = 530 \pm 130 \text{ keV}$$

n-^{19}C scattering and Efimov physics

What to expect for s-wave scattering?
Look at doublet neutron-deuteron scattering…

➡ Pole in s-wave kcot(δ) for n-d system ! Well known ~ 50 years

Delves' 60, Van oers & Seagrave' 67, Girard & Fuda' 78

$$k cot \delta_0 = -A + Bk^2 - \frac{C}{1 + Dk^2},$$

The existence of the triton virtual state was found on the basis of the effective range expansion.

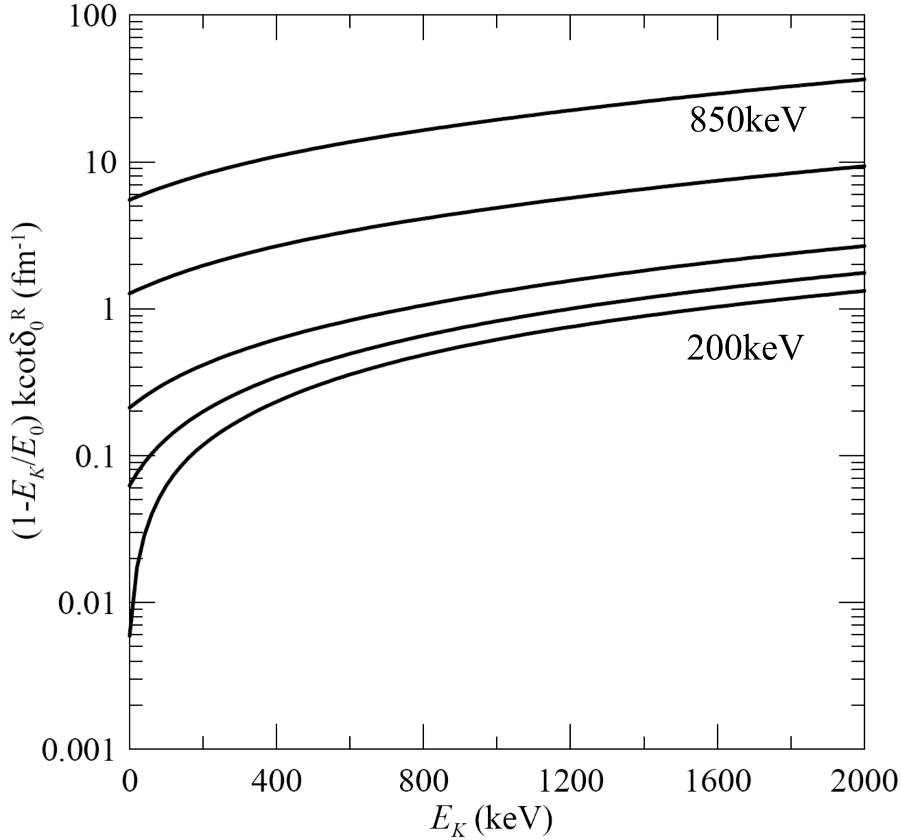
➡ Universal property!

The atom-dimer (three-boson) scattering length is approximately given in Bratten and Hammer (Phys. Rep. 428 (2006) 259):

$$a_{AD} = (1.46 - 2.15 \tan[s_0 ln(a\Lambda_*) + 0.09])a \ ,$$

where $s_0 = 1.00624$.

n-^{19}C scattering and Efimov physics

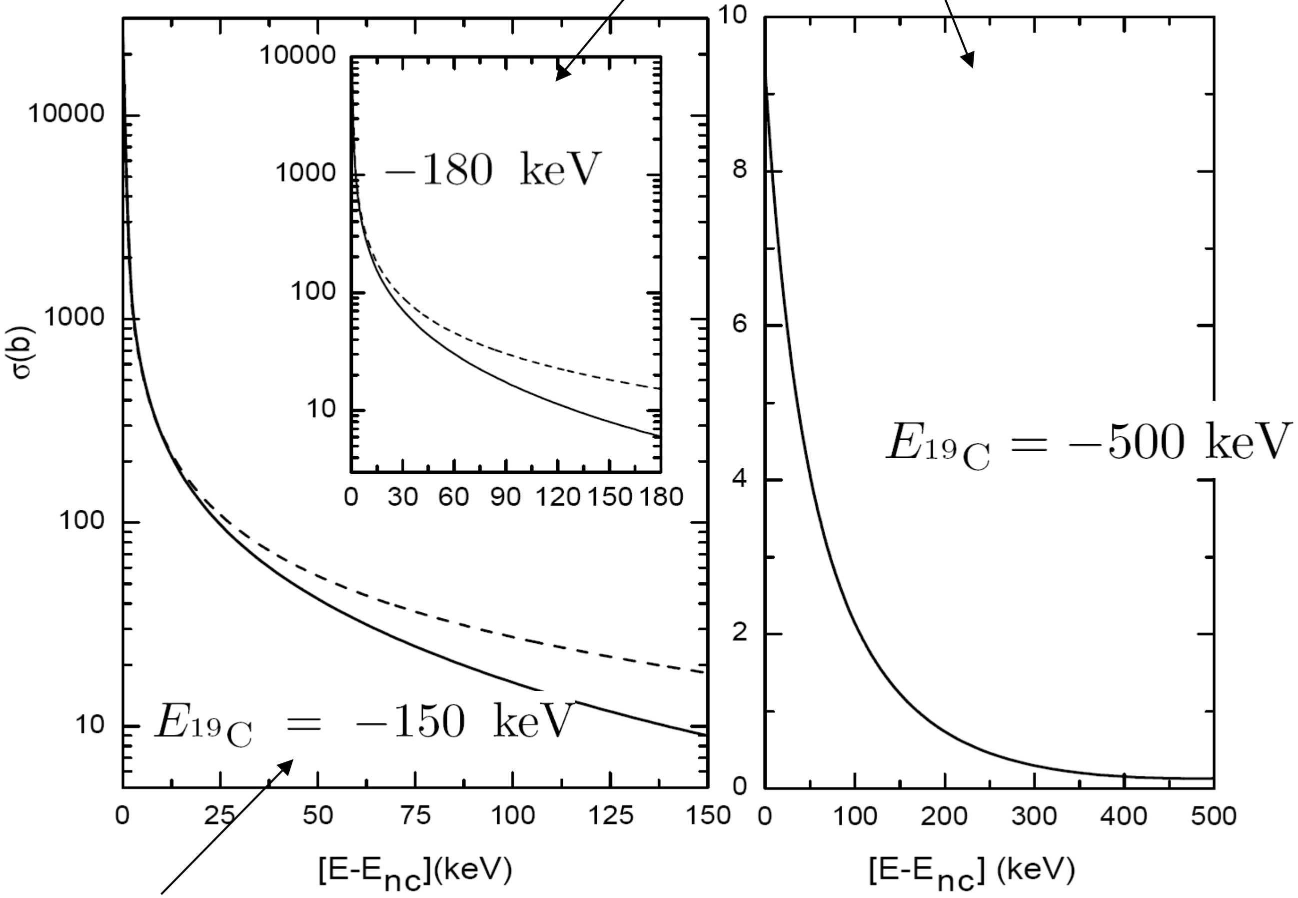


$$k\cot\delta_0^R = \frac{-a^{-1}_{n-^{19}C} + \beta\, E + \gamma\, E^2}{1 - E/E_0},$$

$\lvert E_{^{19}C}\rvert$(keV)	$(a_{n-^{19}C})^{-1}$ (fm^{-1})	β (fm.keV)$^{-1}$	γ (fm.keV^2)$^{-1}$	E_0 (keV)
200	-0.591 10^{-2}	5.685 10^{-4}	4.673 10^{-8}	1442.745
400	-0.624 10^{-1}	6.743 10^{-4}	8.821 10^{-8}	823.887
600	-2.118 10^{-1}	9.337 10^{-4}	1.464 10^{-7}	451.398
800	-1.268	3.11 10^{-3}	4.424 10^{-7}	114.976
850	-5.510	1.201 10^{-2}	1.641 10^{-6}	28.845

n-^{19}C scattering and Efimov physics

^{20}C has a virtual Efimov state

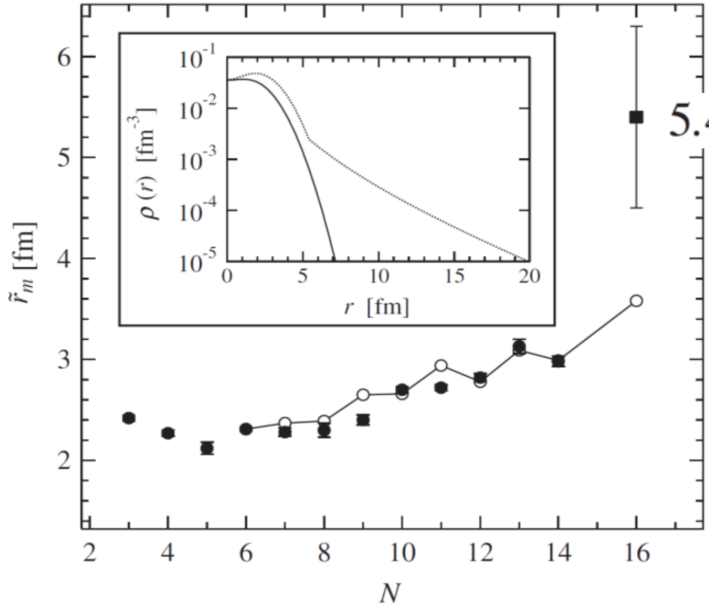


^{20}C has an excited bound Efimov state

$^{22}C = n - n - ^{20}C$

K. Tanaka *et al.*, Phys. Rev. Lett. **104** (2010) 062701

Reaction cross sections (σ_R) for ^{19}C, ^{20}C and the drip-line nucleus ^{22}C on a liquid hydrogen target have been measured at around 40A MeV by a transmission method. A large enhancement of σ_R for ^{22}C compared to those for neighboring C isotopes was observed. Using a finite-range Glauber calculation under an optical-limit approximation the rms matter radius of ^{22}C was deduced to be 5.4 ± 0.9 fm. It does not follow the systematic behavior of radii in carbon isotopes with $N \leq 14$, suggesting a neutron halo. It was found by an analysis based on a few-body Glauber calculation that the two-valence neutrons in ^{22}C preferentially occupy the $1s_{1/2}$ orbital.



$S_{2n} = 420 \pm 940$ keV

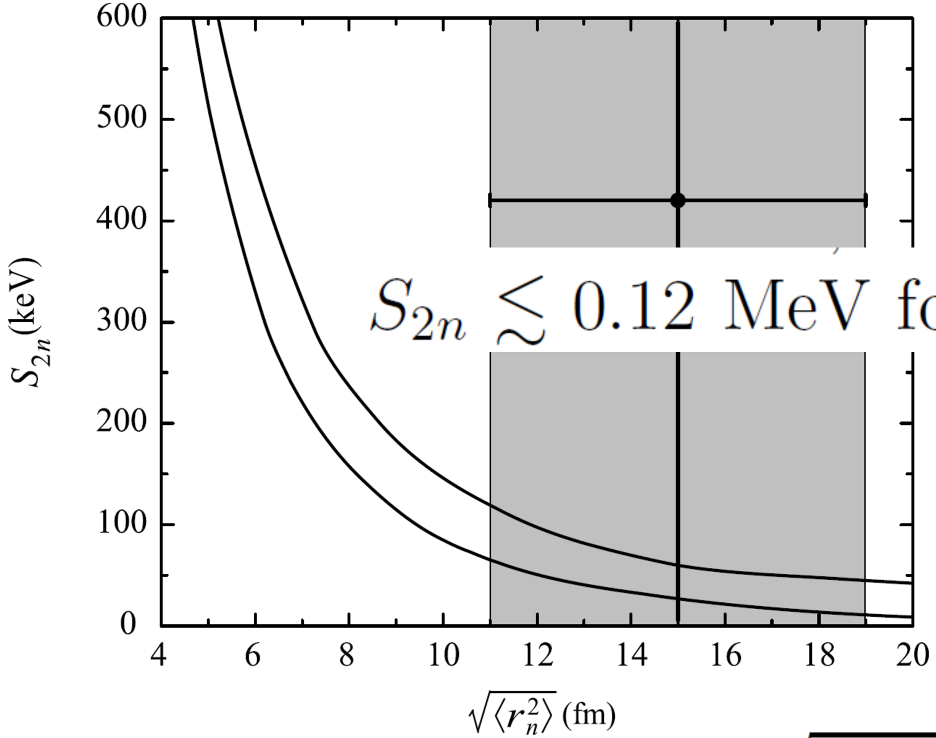
$$\tilde{r}_m^{22C} \equiv \langle (r_m^{22C})^2 \rangle^{1/2}$$

$$\tilde{r}_m^{20C} = 3\ fm$$

$$\tilde{r}_n^{22C} = \sqrt{\frac{22}{2}} \sqrt{(\tilde{r}_m^{22C})^2 - \frac{20}{22} (\tilde{r}_m^{20C})^2} \approx 15 \pm 3 fm$$

$^{22}C = n - n - {}^{20}C$

^{21}C *virtual state energy 0, -100 KeV. E_{nn}=-143KeV*



$S_{2n} = 420 \pm 940$ keV

$S_{2n} \lesssim 0.12$ MeV for ^{22}C

Yamashita, M de Carvalho, TF, Tomio,
PLB697(2011)90; A&E PLB715(2012)282

$11 \text{ fm} \leqslant \sqrt{\langle r_n^2 \rangle} \leqslant 19 \text{ fm}$

$$\sqrt{\langle r_{ch}^2(^{22}\text{C})\rangle - \langle r_{ch}^2(^{20}\text{C})\rangle} \gtrsim 0.9 \text{ fm}$$

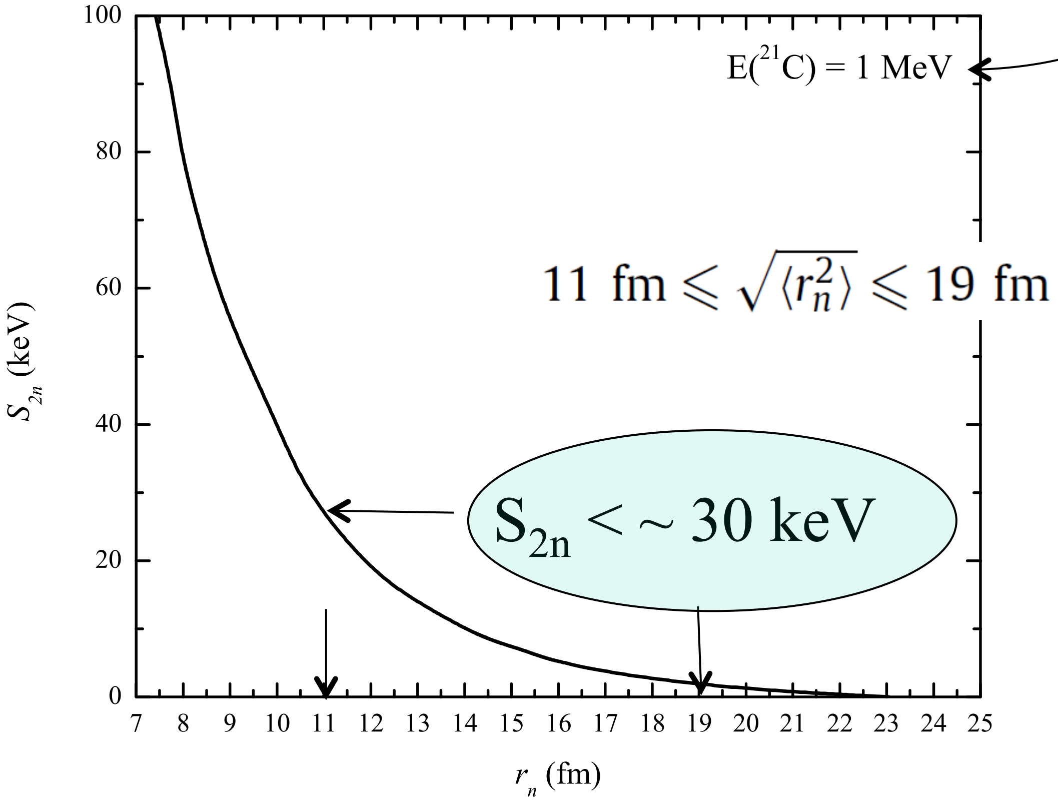
H.T. Fortune, R. Sherr, Phys. Rev. C 85 (2012) 027303.

Acharya, Ji, Phillips PLB723(2013)19 [S_{2n} < 100 keV] (EFT)

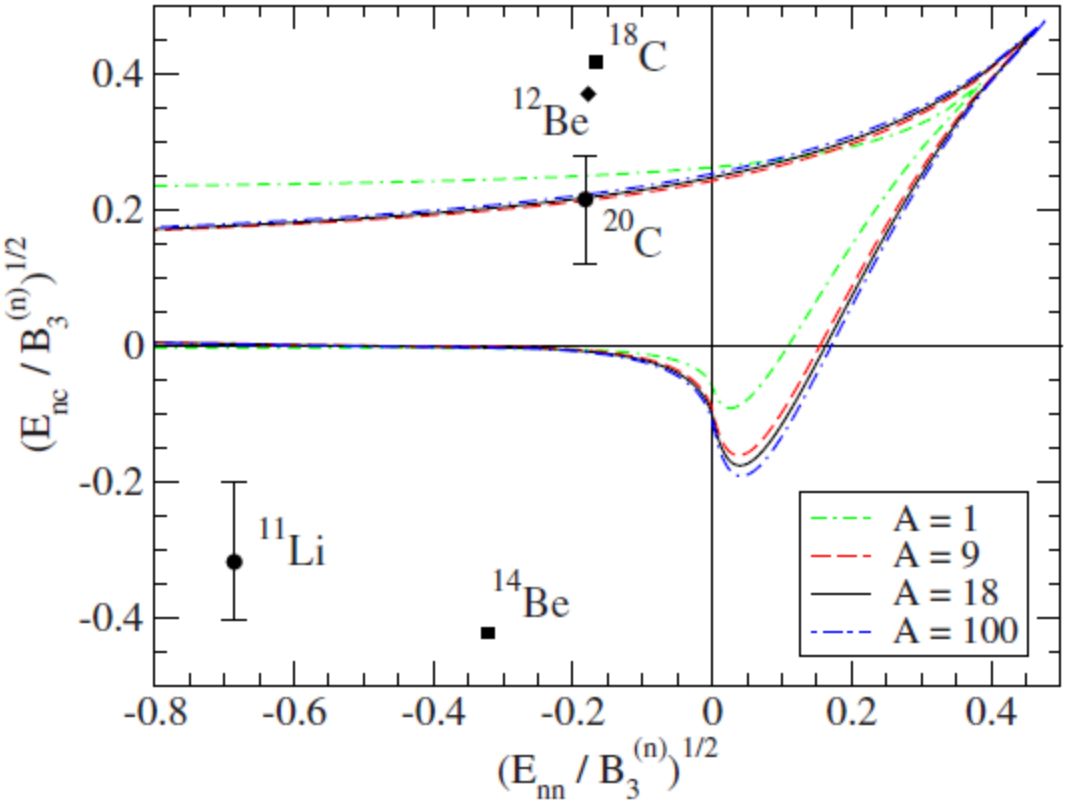
Horiuchi and Y. Suzuki, Phys. Rev. C 74, 034311 (2006)

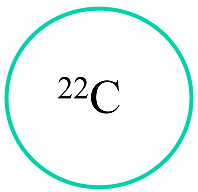
$^{22}C = n - n - {}^{20}C$

^{21}C Mosby et al. NPA 909, 69 (2013) – MSU - $|a_s| < 2.8$ fm (^{21}C virtual state)



$^{22}C = n - n - {}^{20}C$

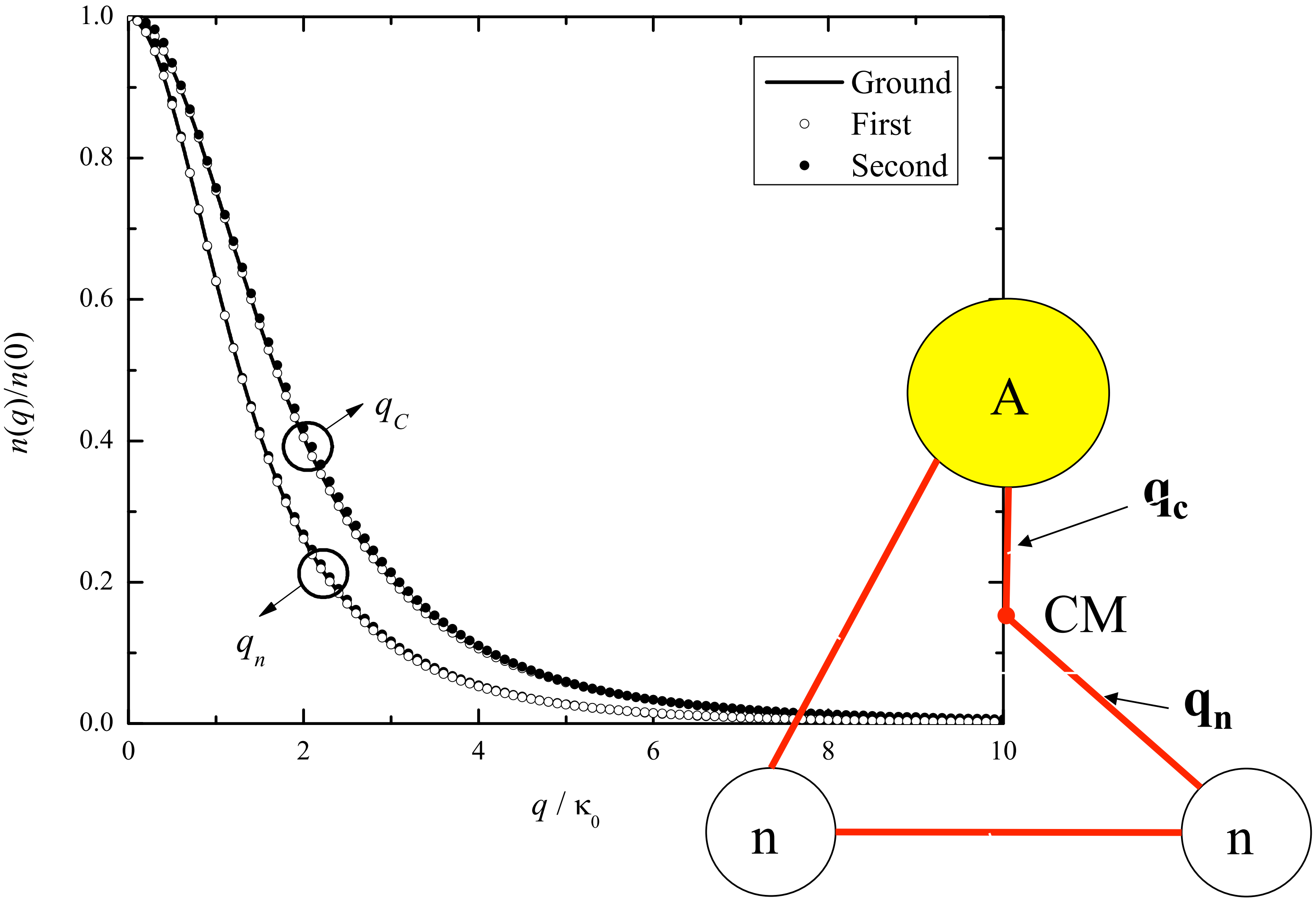




^{21}C with a virtual state with energy 1 MeV

→ It is not possible an excited Efimov state/continuum resonance

Limit cycle: one-body momentum densities n+n+A (A=20)



Halo-neutron momentum distribution in ^{22}C

If L_{total} is nonzero ?

- Virtual p-wave states of light non Borromean nn halo nuclei

$$E_{virtual} \sim 1.7\, E_{nc}$$

(Delfino et al PRC61, 051301 (2000))

- Soft dipole mode:

- M. Cubero et al, PRL 109, 262701 (2012) - $^{11}Li + ^{208}Pb$ close the Coulomb barrier → E_{res}=690 keV width=0.32 keV
- Fernandez-Garcıa et al PRL 110, 142701 (2013) - $^{11}Li + ^{208}Pb$ breakup around the Coulomb barrier
- Ershov, Vaagen, Zhukov, PRC 86 (2012) 034331 – ^{22}C

Determined by scattering lenghts only!

Summary

- Weakly bound & large systems: **few scales regime** in halo nuclei, molecules, trapped atoms
  CORRELATIONS BETWEEN OBSERVABLES→ CONSTRAINTS!

- Zero-range model n-n-c system:
  threshold conditions for excited states and resonances
  borromean configuration: **Efimov state→ resonance**
  at least one subsystem is bound: **Efimov state→ virtual state**

- Few-examples: ^{11}Li, ^{14}Be, ^{20}C, ^{22}C

- ^{20}C **Efimov state→ virtual state** $\mathbf{E_{19C} > 165}$ **keV**

- ^{22}C large nn halo $S_{2n} \sim 30$ keV with ^{21}C virtual state 1 MeV (from $|a_s|<2.8$ fm)→

  No Efimov continuum resonance/excited state (range corrections?)

Outlook

- Neutron halo > 2n (no need of a 4-body scale)...
  - $^{12}Li = {}^{10}Li+n+n+n$, $^{21}C = {}^{18}C+n+n+n$
- Exploration of universality in scattering, breakup of halo nuclei & CDCC ...
- Pigmy resonances L_{total}=1,2, 3 ...
- Fix the tail of ab-initio calculations...

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