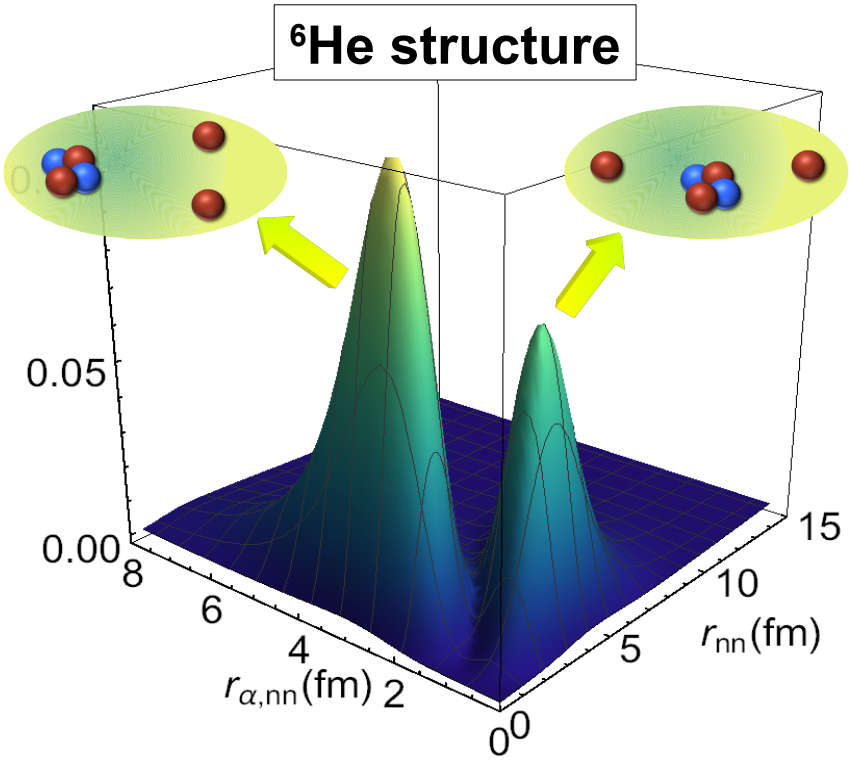
Ab initio NCSMC for three-cluster dynamics

Carolina Romero-Redondo

Progress in Ab Initio Techniques in Nuclear Physics, TRIUMF
Vancouver. February 25th, 2016

Lawrence Livermore National Laboratory

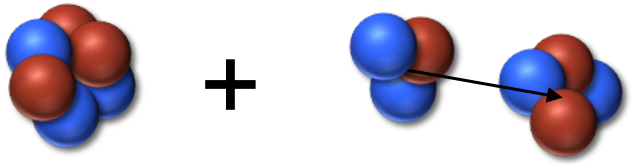


Collaborators:
S. Quaglioni, P. Navrátil, G. Hupin

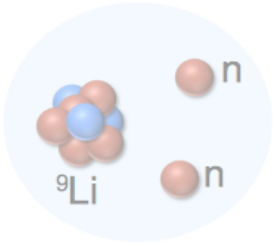
LLNL-PRES-684340
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Outline

No-core shell model with continuum

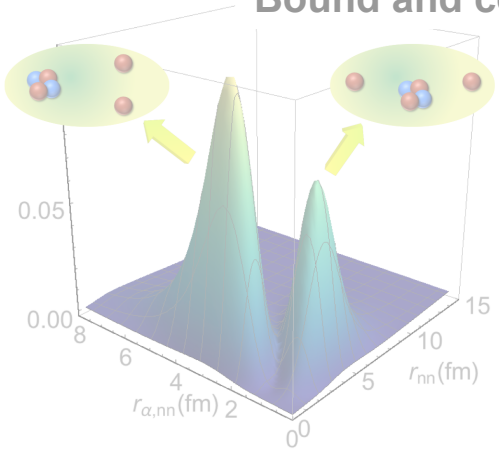


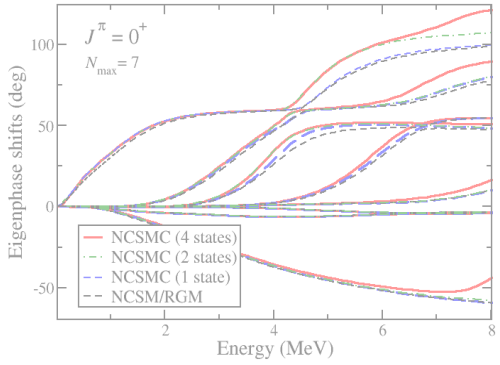
Three-cluster systems



^{6}He

Bound and continuum states





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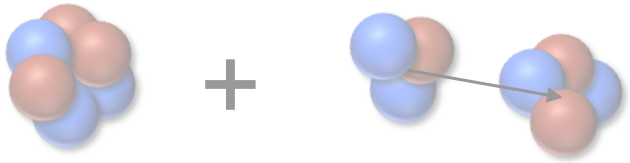

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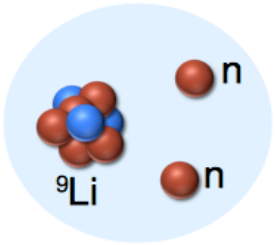

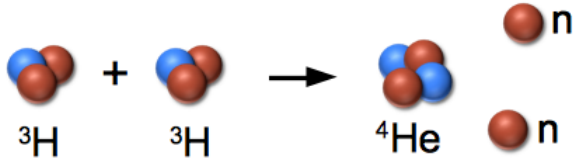

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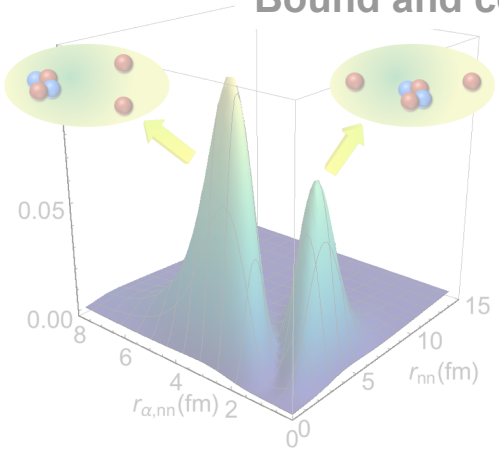

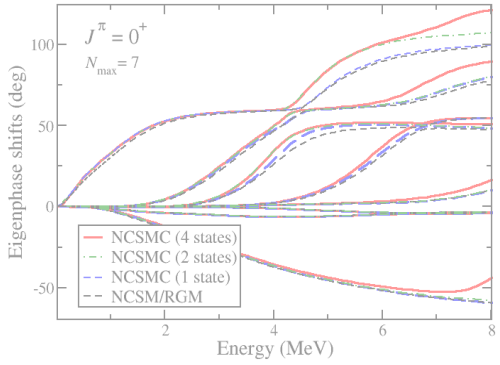

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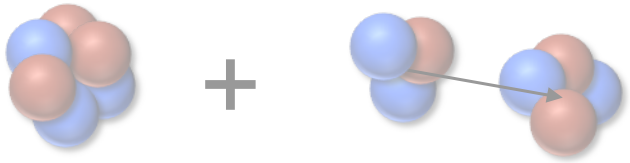

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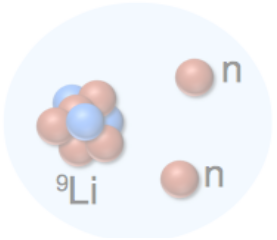

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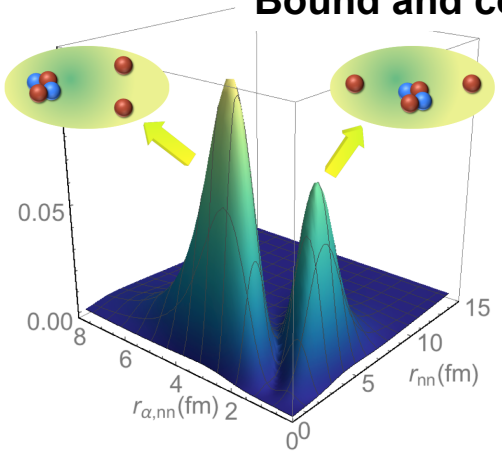
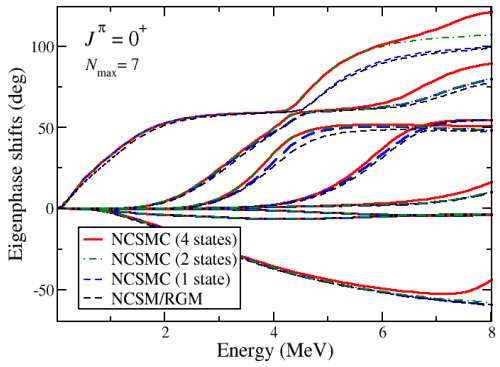
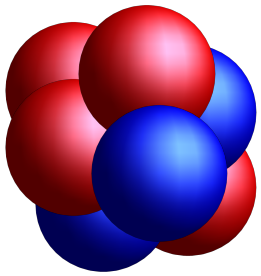
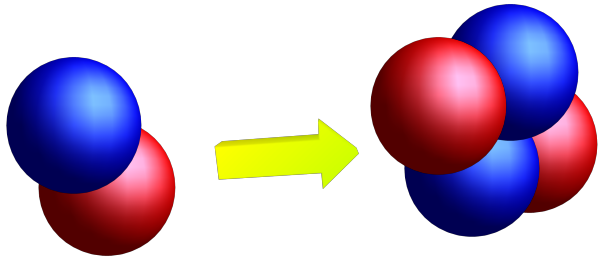




The **No core shell model with continuum (NCSMC)** provides a unified description of bound and continuum states



Bound states

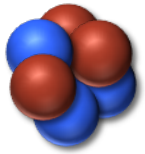


Continuum

S. Baroni, P. Navrátil and S. Quaglioni
PRL **110**, 022505 (2013); PRC **87**, 034326 (2013)

The **No core shell model with continuum (NCSMC)** provides a unified description of bound and continuum states

NCSM
Short range description



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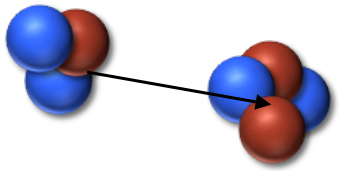
NCSM/RGM
Long range description



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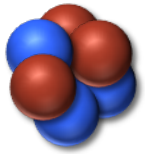

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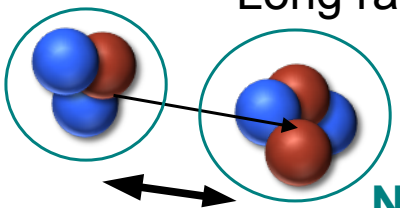
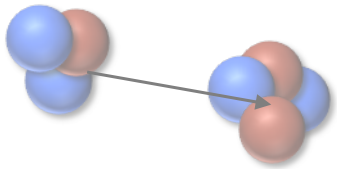
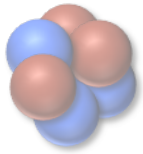


NCSM
wave functions

The **No core shell model with continuum (NCSMC)** provides a unified description of bound and continuum states

NCSM/RGM
Long range description





NCSM
Short range description

NCSM eigenstates

NCSM/RGM channel states

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} \, , \lambda \right\rangle + \sum_{\nu} \int d\vec{r} \, \gamma_{\nu}(\vec{r}) \, \hat{A}_{\nu} \left| {}_{(A-a)} \, \vec{r} \, {}_{(a)} \, , \nu \right\rangle$$

Unknowns

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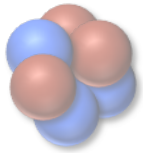
NCSM/RGM
Long range description



NCSM
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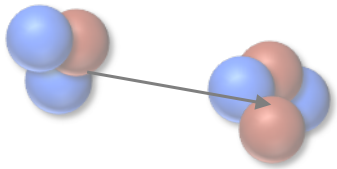

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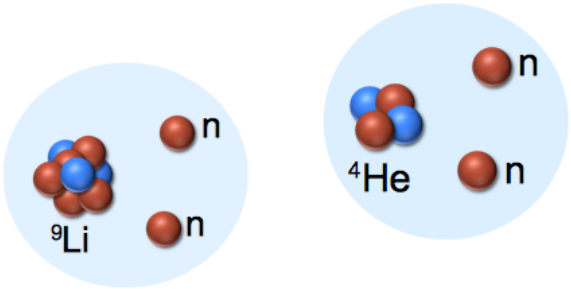
Unknowns

Intercluster antisymmetrizer

Three-cluster structures appear in many nuclear systems

Three-cluster structures appear in many nuclear systems

Bound and resonant states:
2n Halo nuclei



3-body continuum states:
Reactions

The **NCSMC** can be applied to three-cluster systems, providing a unified description of bound and continuum states

NCSM
Short range description

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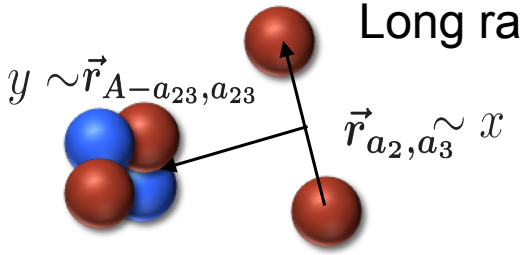
NCSM/RGM-3B
Long range description



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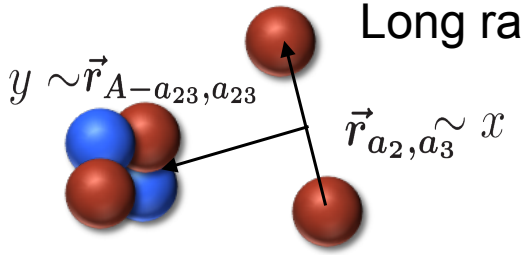

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Unknowns

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NCSM
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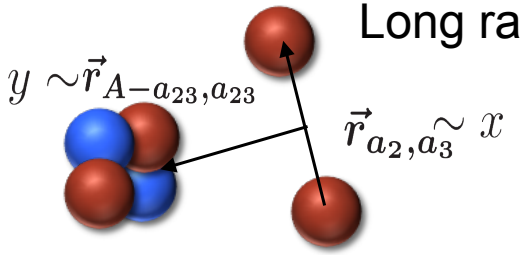

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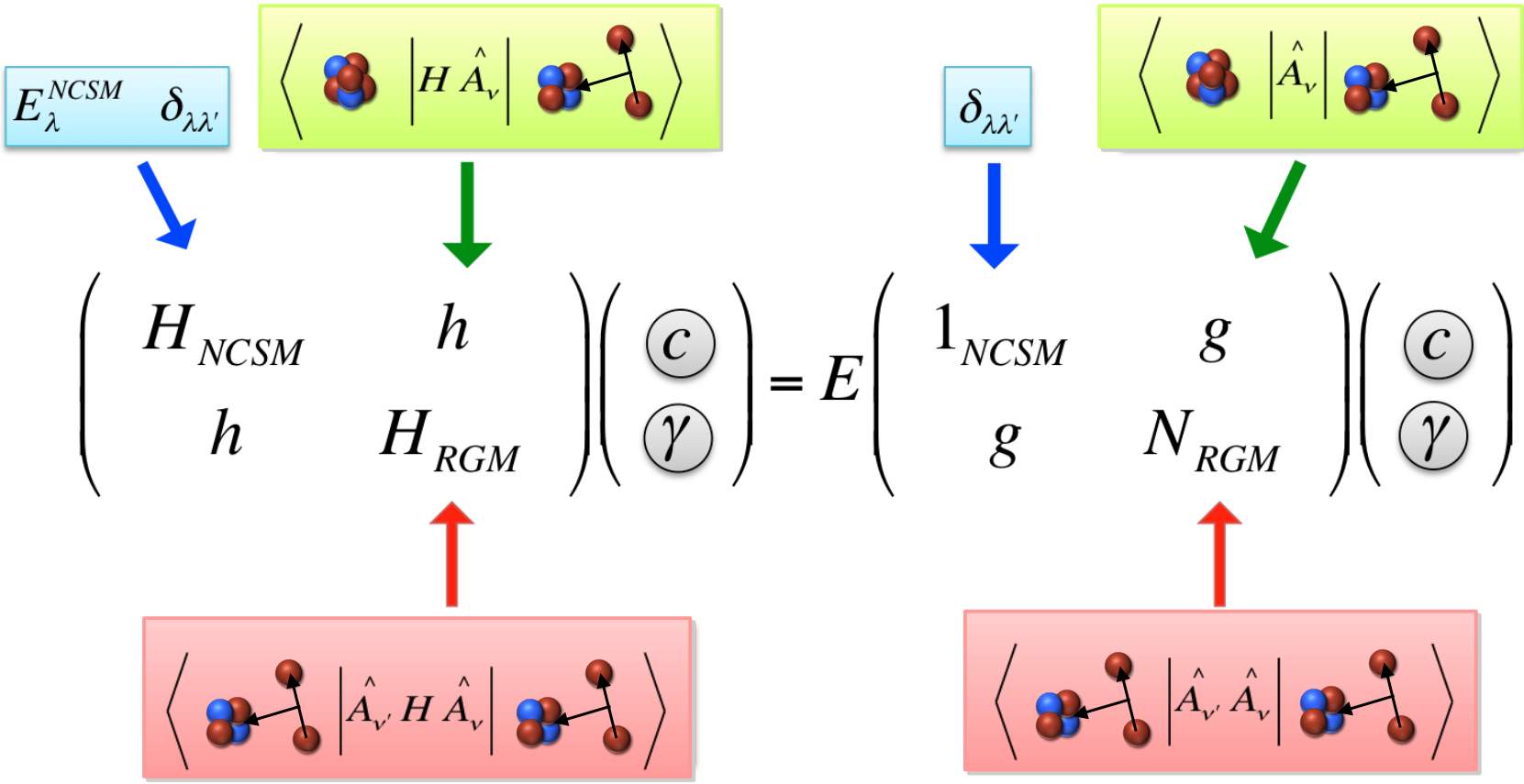
Unknowns

Intercluster antisymmetrizer

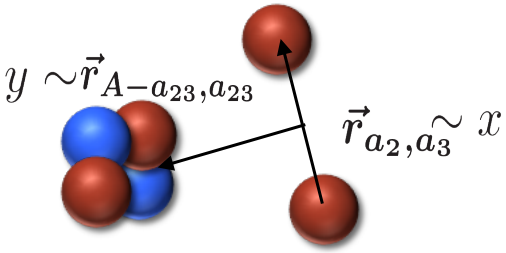
The **NCSMC** can be applied to three-cluster systems, providing a unified description of bound and continuum states

$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

The **NCSMC** can be applied to three-cluster systems, providing a unified description of bound and continuum states



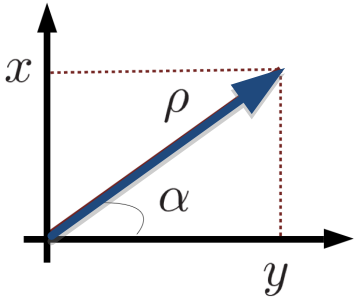
Solving the **NCSMC** equations for three-cluster systems



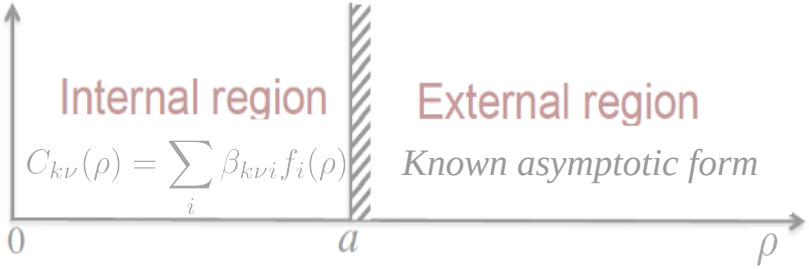
Expansion in hyperspherical basis

$$\chi_\nu^{J^\pi T}(x,y) = \sum_k C_{k\nu}(\rho)\phi_k^{\ell_x \ell_y}(\alpha)$$

Hyperspherical coordinates



(x,y) → (ρ,α)



R-matrix on Lagrange mesh*

*M. Hesse, J.-M. Sparenberg, E Van Raemdonck, D. Baye. Nuclear Physics A 640 (1998) 37-51

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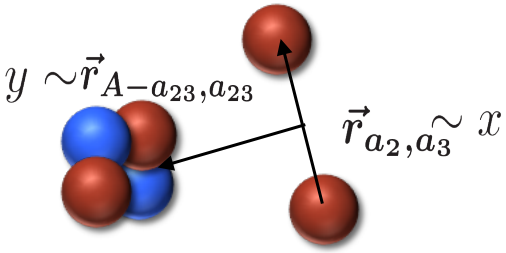

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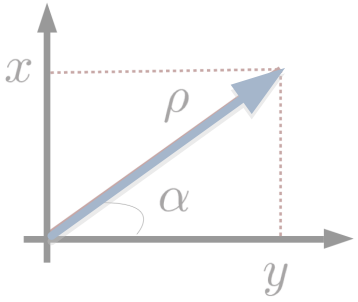

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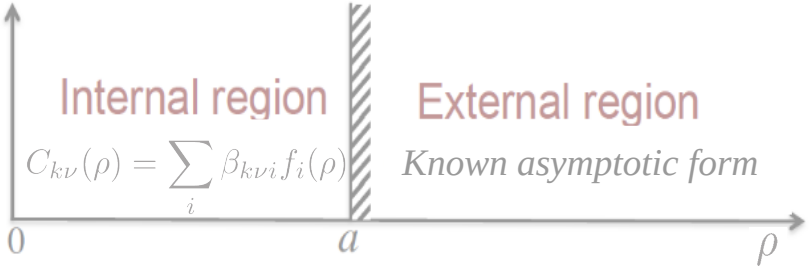

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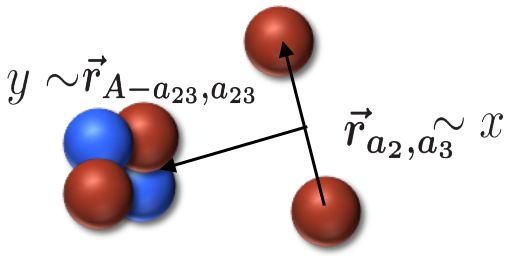

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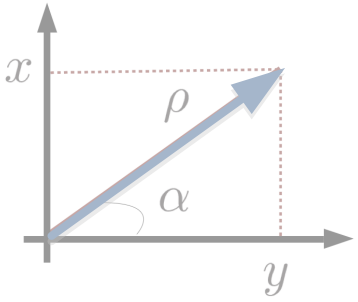

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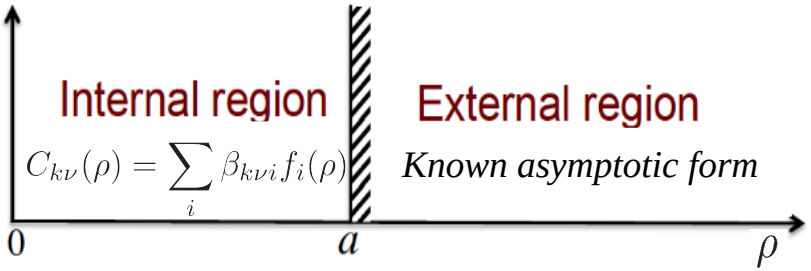

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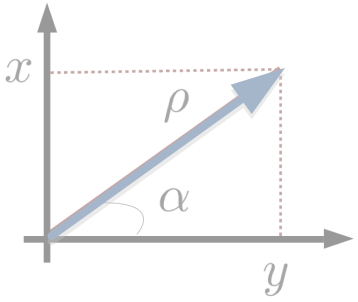
Solving the **NCSMC** equations for three-cluster systems

External region: known asymptotic behavior (ρ > a)

* Bound state: $C_{k\nu}(\rho) = A_{k\nu}\sqrt{\kappa\rho}K_{k+2}(\kappa\rho)$

* Continuum state: $C_{k\nu}(\rho) = A_{k\nu}\left[H_k^-(\kappa\rho)\delta_{\nu,\nu'}\delta_{k,k'} - S_{\nu k,\nu' k'}H_k^+(\kappa\rho)\right]$

Hyperspherical coordinates



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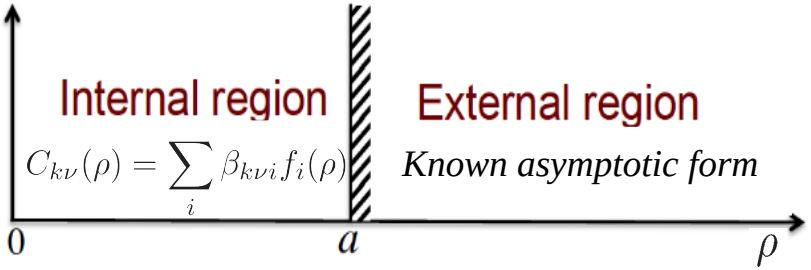
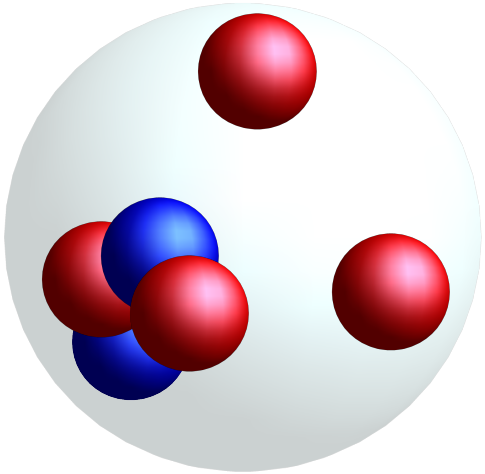


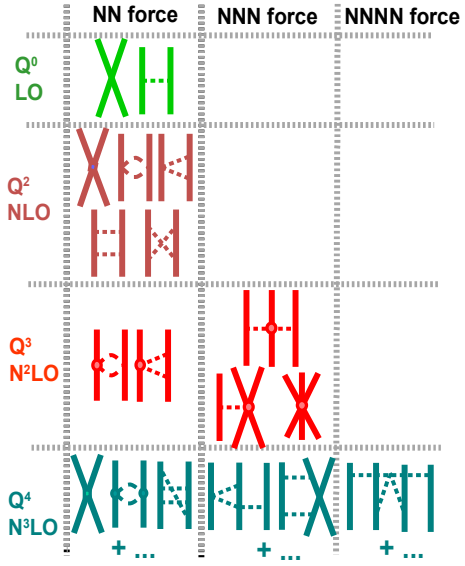
R-matrix on Lagrange mesh*

*M. Hesse, J.-M. Sparenberg 1, E Van Raemdonck, D. Baye. Nuclear Physics A 640 (1998) 37-51

^{6}He is a two-neutron halo, therefore presenting an extended three-cluster configuration

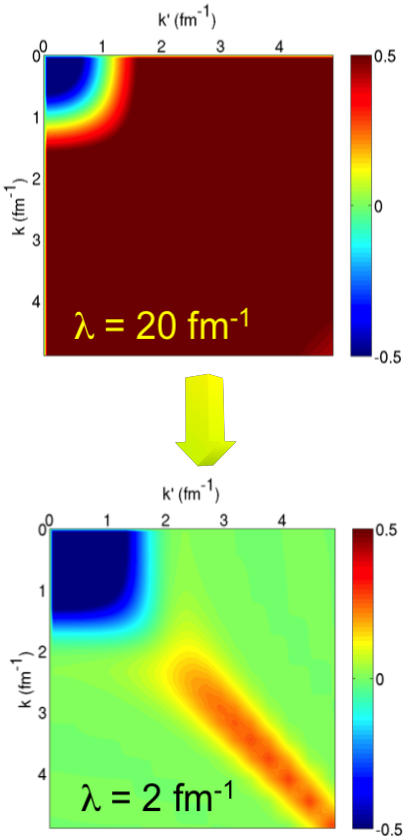


Interaction used as input



Realistic interactions

chiral N^{3}LO NN (Entem-Machleidt)

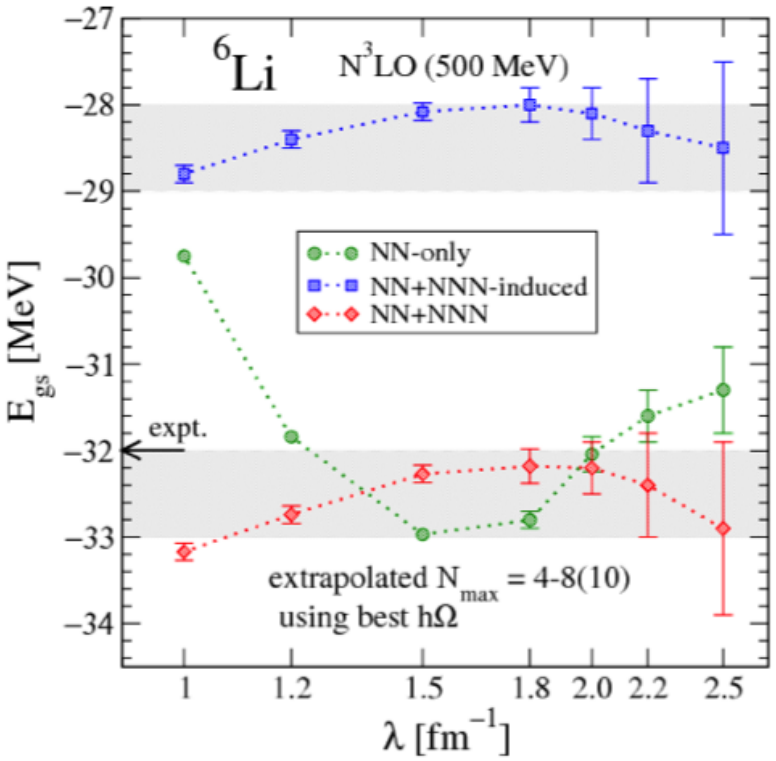


SRG

Decouples low and high momenta

Induces many-body forces of higher order

There are special values λ for which omitted induced 3N forces "compensate" for the lack of inclusion of real 3N forces



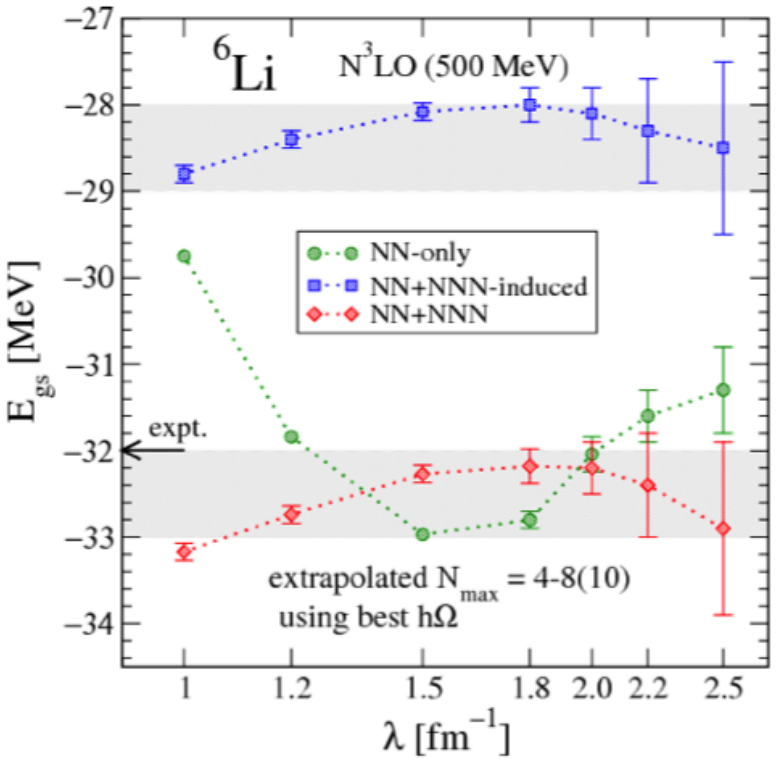
Complete NN force

NN only

Complete 3N force

PRL 103, 082501 (2009)

There are special values λ for which omitted induced 3N forces "compensate" for the lack of inclusion of real 3N forces



Complete NN force

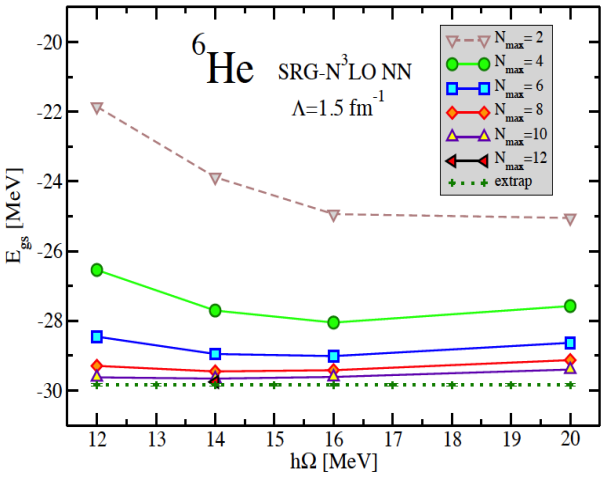
NN only

Complete 3N force

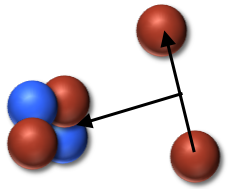
We will use both λ=1.5 and 2.0 fm^{-1}

^{6}He is a two-neutron halo, therefore presenting an extended three-cluster configuration

^{6}He ground state, NCSM



NCSM



^{4}He (g.s.)

+

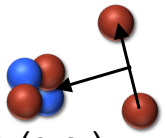
^{6}He (up to 10 eigenstates)

The **NCSM** 6-nucleon eigenstate compensates for the missing many-body correlations

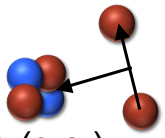
Experimental value
-29.269 MeV

λ=1.5 fm^{-1}

Energy of 0$^+$ g.s.



^{4}He (g.s.)



^{4}He (g.s.) + ^{6}He (g.s.)

N_{max}	NCSM	NCSM/RGM	NCSMC (0^+_1)
4	-27.70	-27.14	-28.29
6	-27.98	-28.91	-30.02
8	-28.95	-28.61	-29.69
10	-29.45	-28.70	-29.86
12	-29.66	-28.70	-29.86
Extrapolation	-29.84(4)	---	---

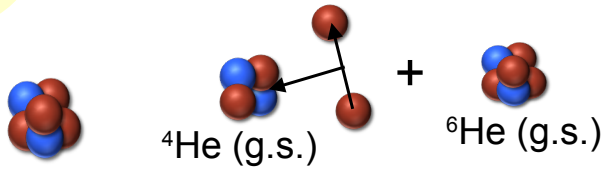
CRR, S. Quaglioni, P. Navrátil. ***In progress***

The **NCSM** 6-nucleon eigenstate compensates for the missing many-body correlations

λ= 2.0 fm^{-1}

Experimental value
-29.269 MeV

Energy of 0$^+$ g.s.



N_{max}	NCSM	NCSMC (0^+_1)
8	-26.44	-28.81
10	-27.70	-28.97
12	-28.37	-29.17
Extrapolation	-29.20(11)*	---

*D. Sääf, C. Forssén, PRC **89** 011303 (2014)

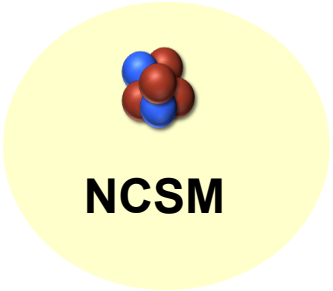
CRR, S. Quaglioni, P. Navrátil. ***In progress***

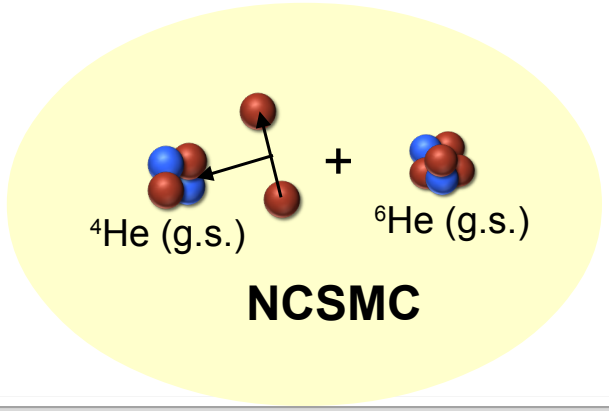
The **NCSM** 6-nucleon eigenstate compensates for the missing many-body correlations

Matter radius

N_{max}	Λ_{SRG}=1.5 fm^{-1}		Λ_{SRG}=2.0 fm^{-1}	
	NCSM	NCSMC (0^+_1)	NCSM	NCSMC (0^+_1)
8	2.18	2.28	2.06	2.30
10	2.22	2.33	2.10	2.35
12	2.25	2.34	2.15	2.36

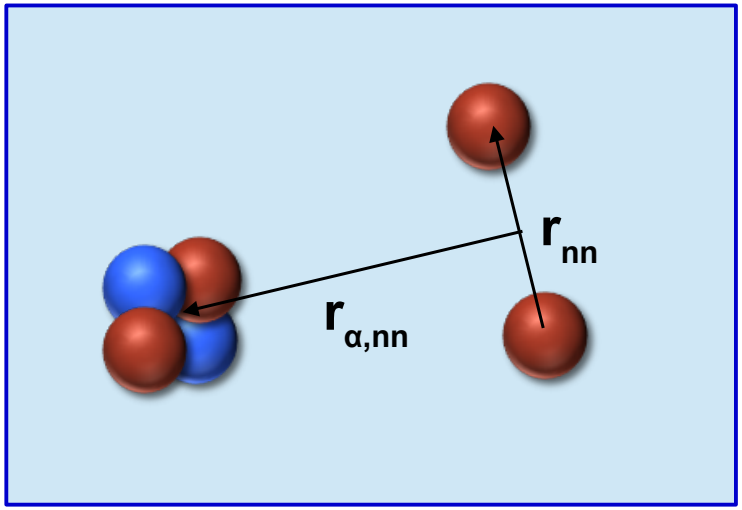
Experiments
2.33 ± 0.04 fm, PLB **289**, 261 (1992)
2.30 ± 0.07 fm, PRL **78**, 2313 (1997)
2.37 ± 0.05 fm, EurPhys J A**25** 215 (2005)

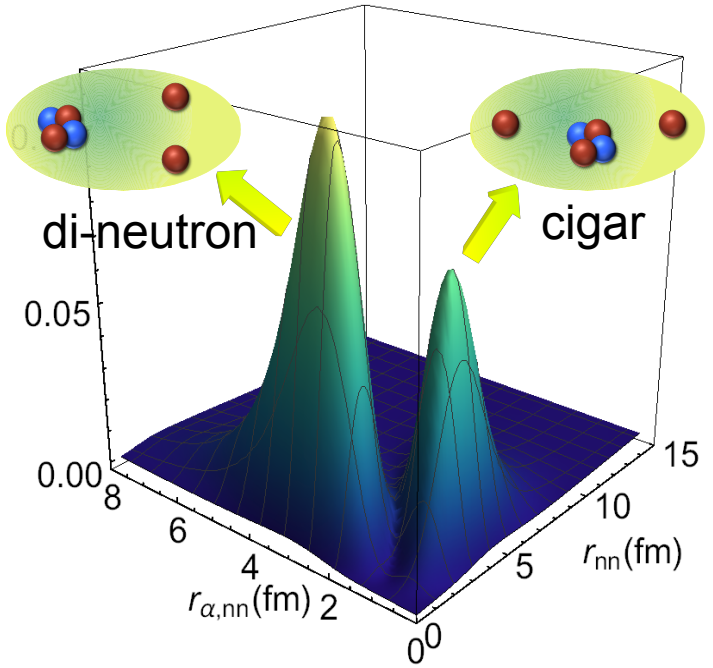


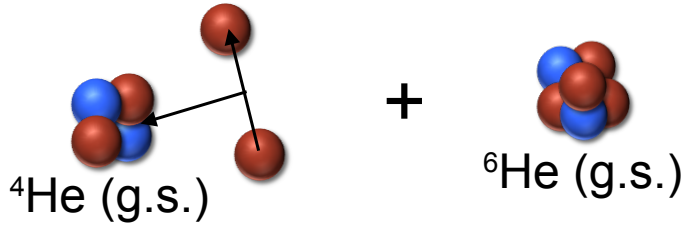


CRR, S. Quaglioni, P. Navrátil. ***In progress***

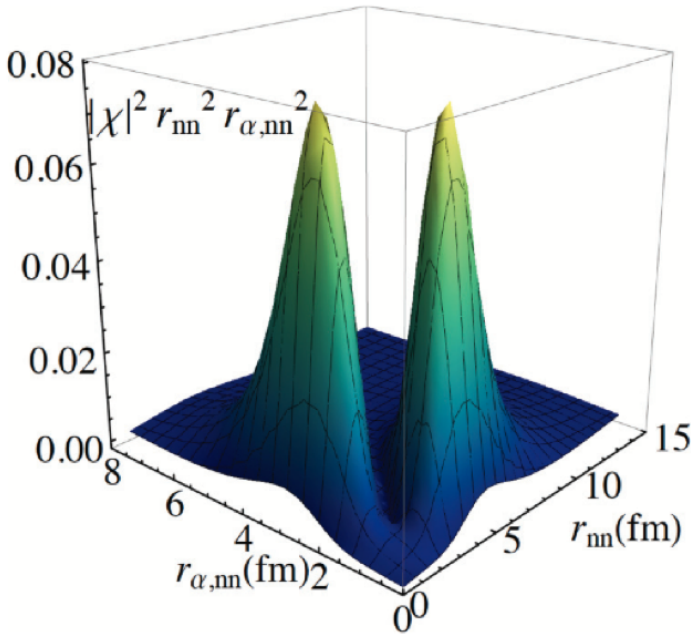
The probability distribution of the ^{6}He ground state presents two peaks corresponding to the di-neutron and cigar configurations

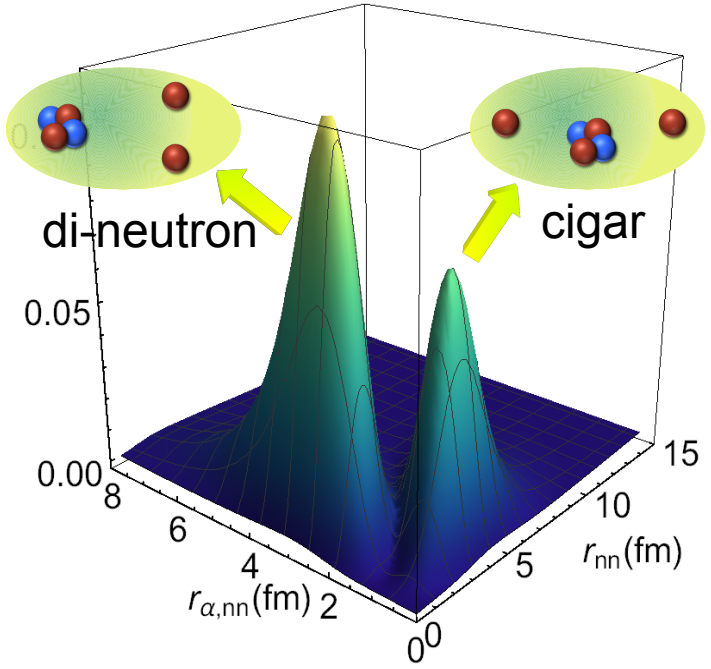


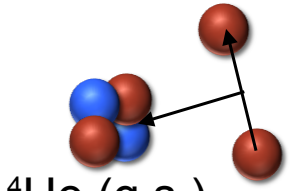




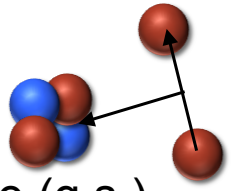
The probability distribution of the ^{6}He ground state presents two peaks corresponding to the di-neutron and cigar configurations







^{4}He (g.s.)

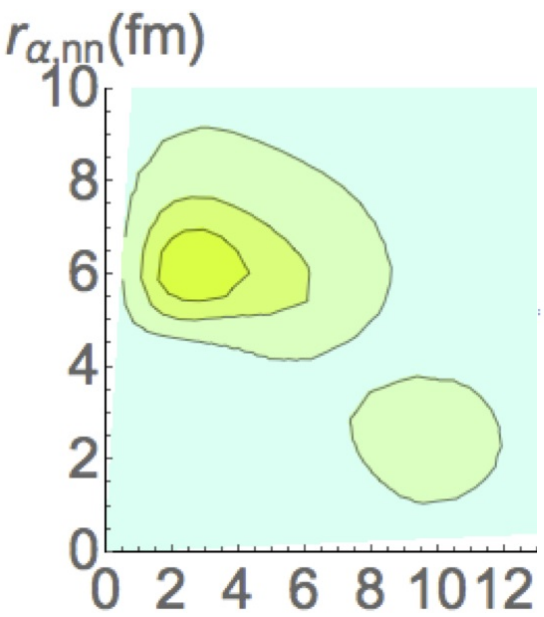


^{4}He (g.s.)

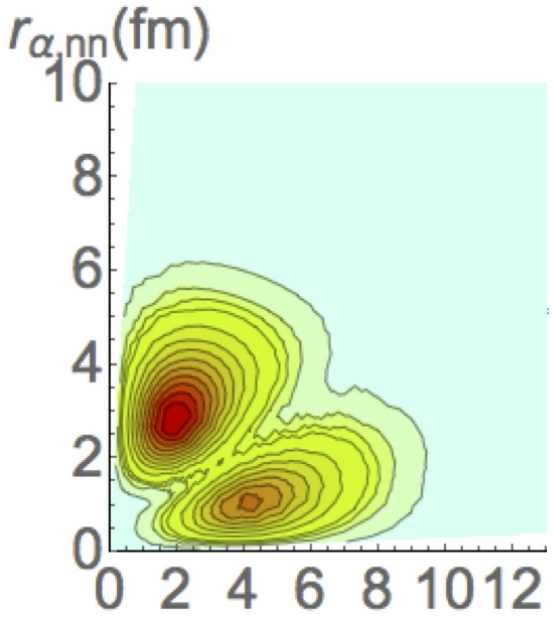
+

^{6}He (g.s.)

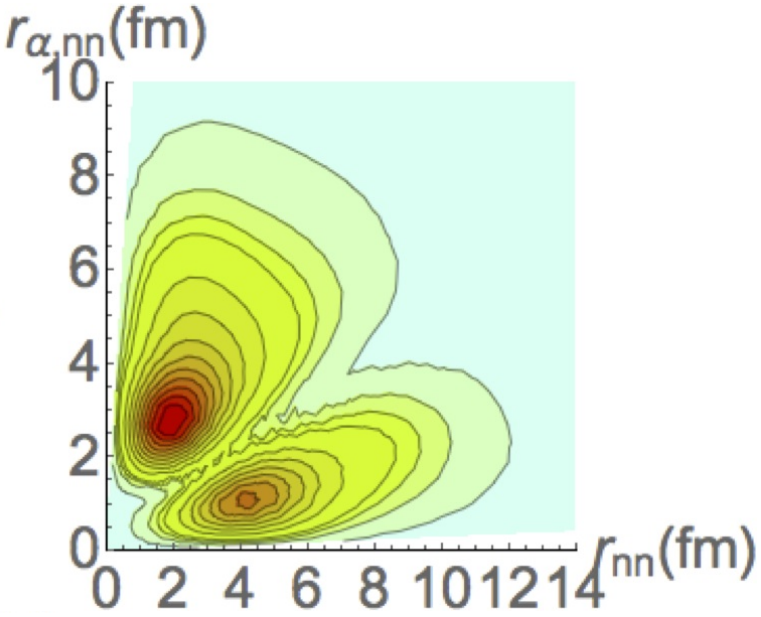
Within the NCSMC, we can see how the RGM part of the basis contributes to the tail of the probability distribution



RGM contribution

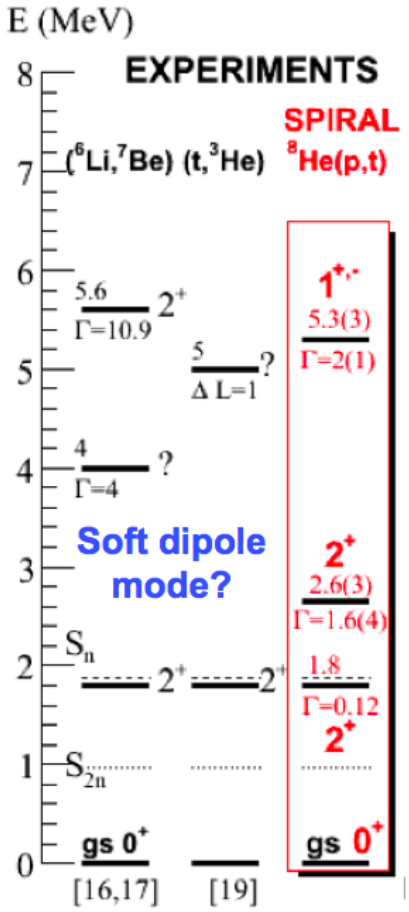


NCSM contribution

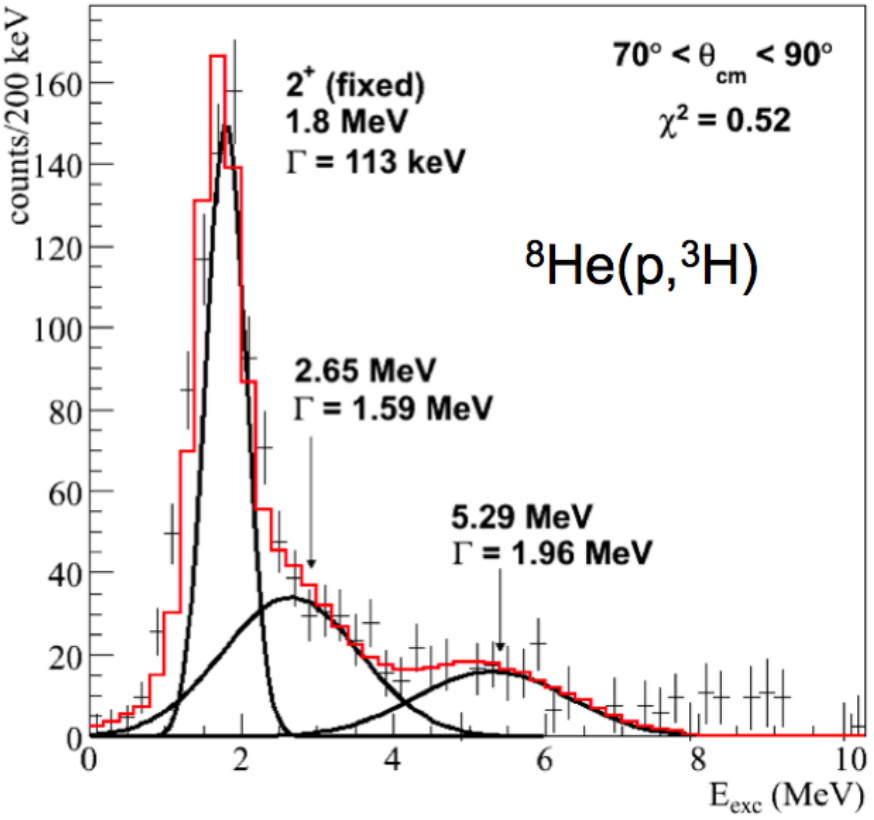


Total NCSMC

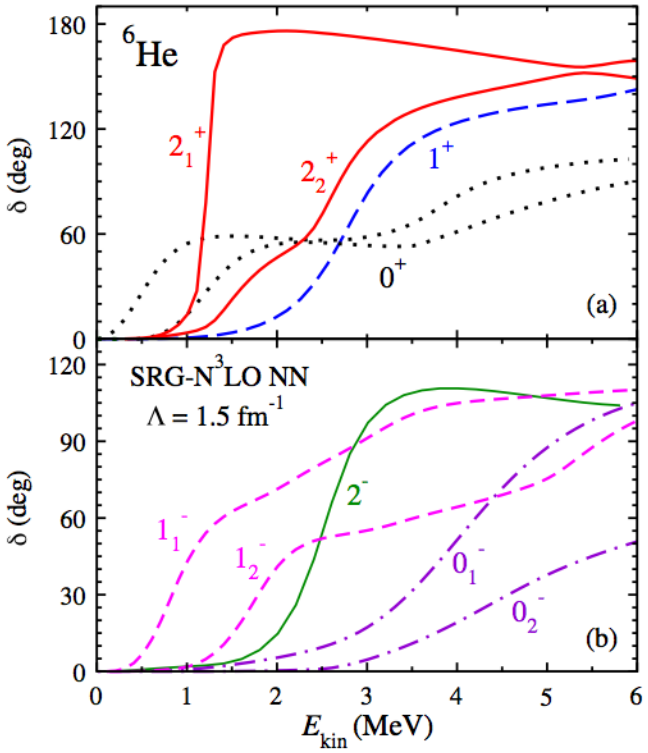
The spectrum of ^{6}He has been remeasured in 2012

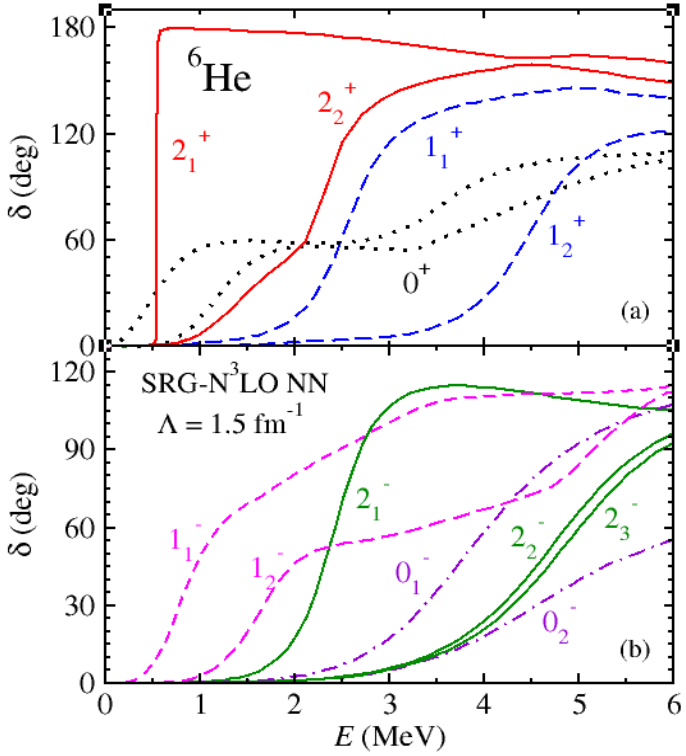


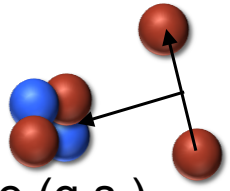
Recent expt. @SPIRAL, GANIL: PLB **718** (2012) 441



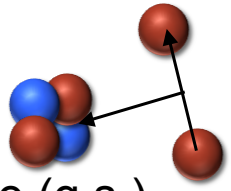
The continuum spectrum can be extracted from the phase shifts





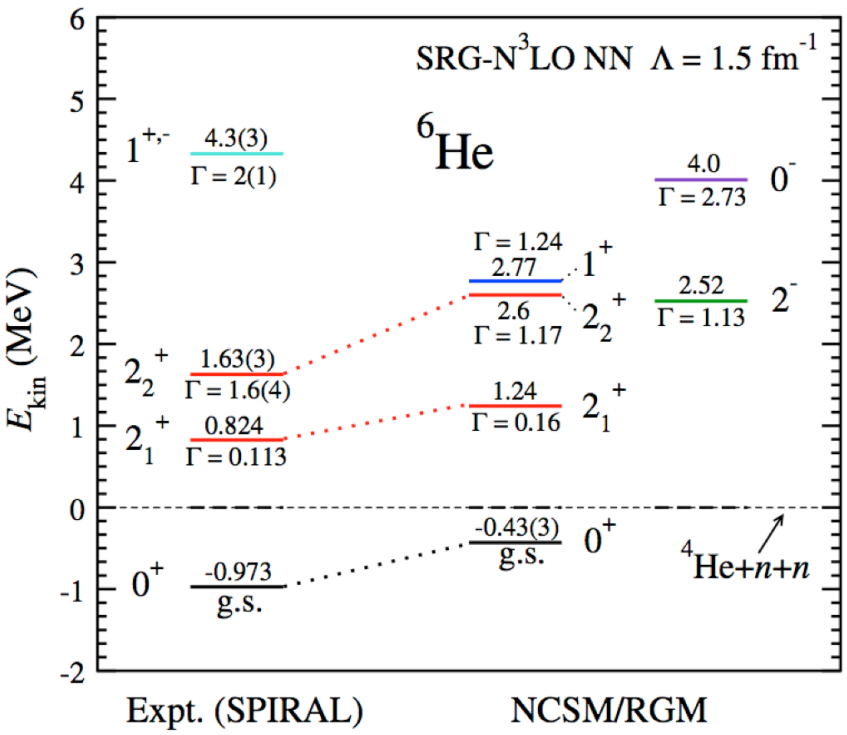


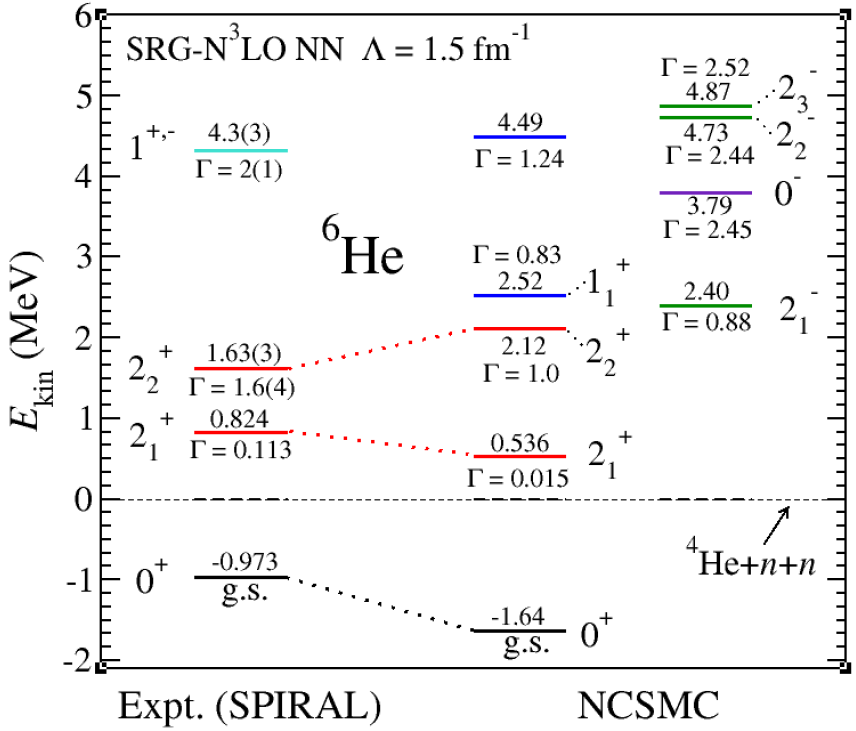
^{4}He (g.s.)

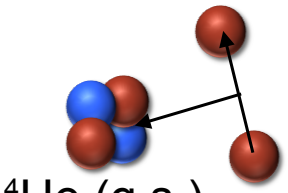


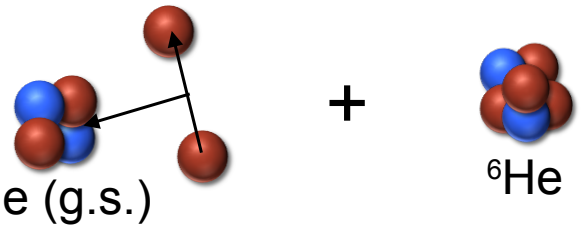
^{4}He (g.s.) + ^{6}He

The continuum spectrum can be extracted from the phase shifts

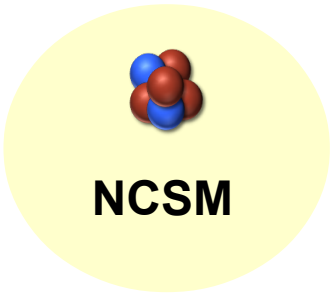




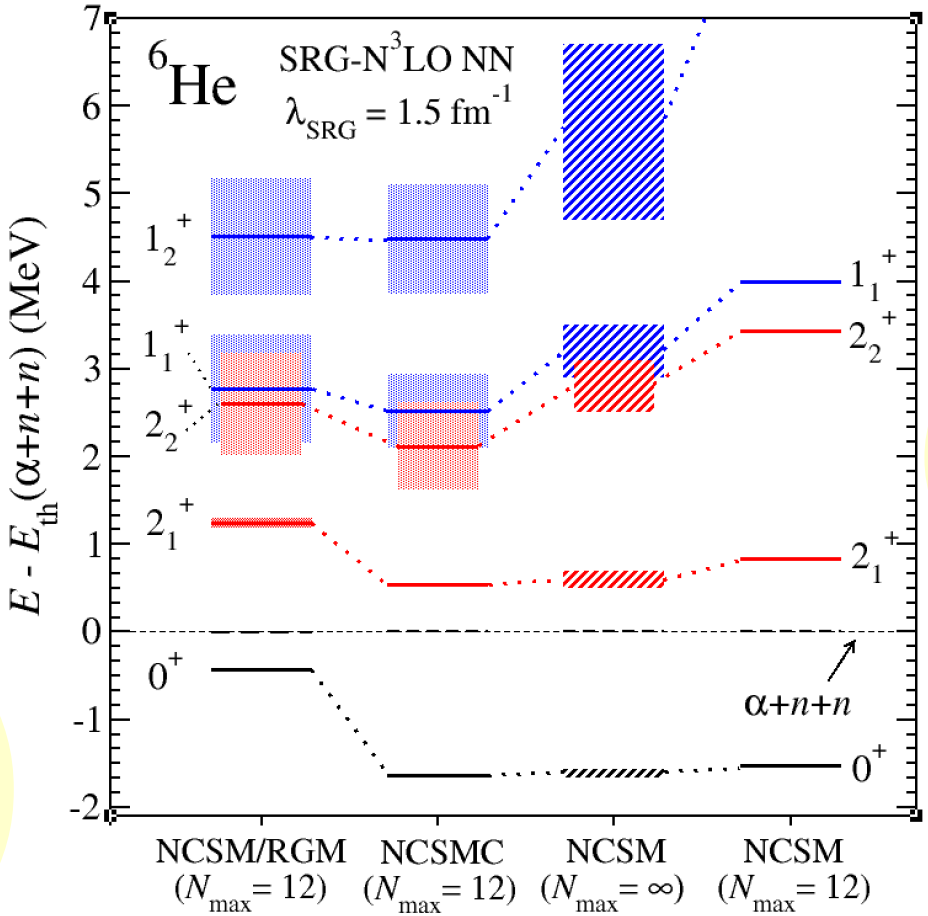


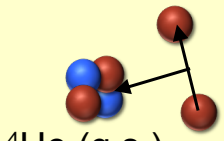


We can compare the spectrum given by the different formalisms



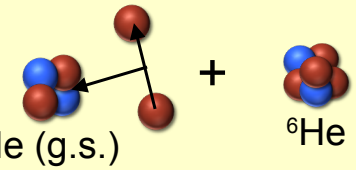
NCSM





^{4}He (g.s.)

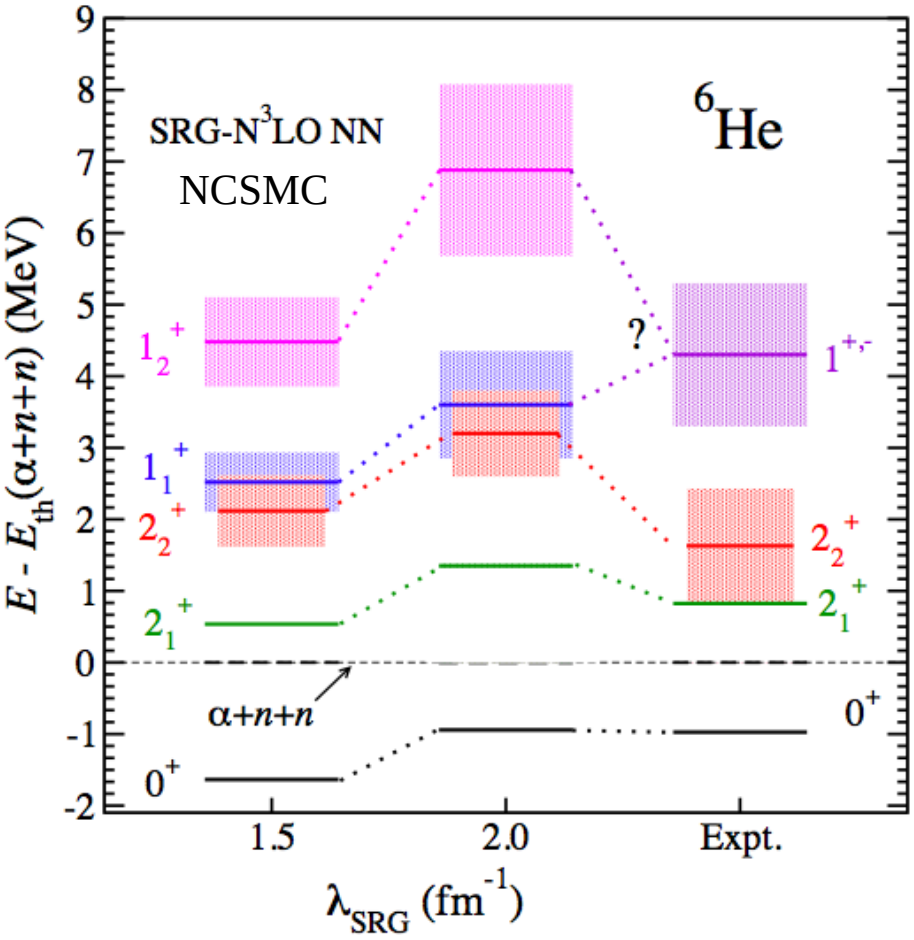
NCSM/RGM

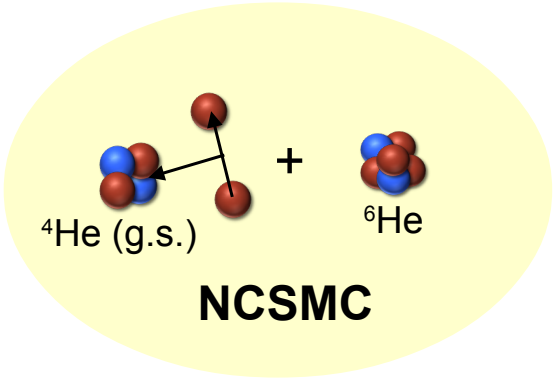


^{4}He (g.s.) + ^{6}He

NCSMC

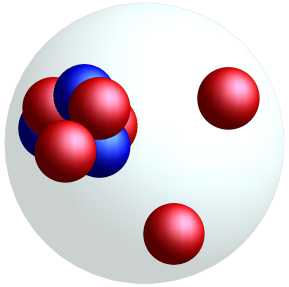
We can also study the dependence in the evolution parameter λ_{SRG}



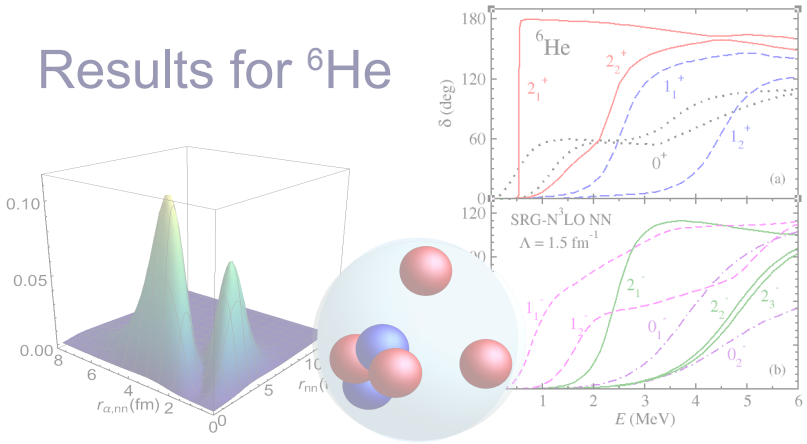


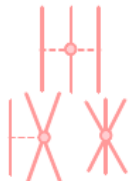
Summary and outlook

NCSMC for
3-cluster problems

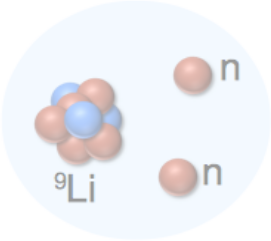


Results for ^{6}He





3-nucleon force

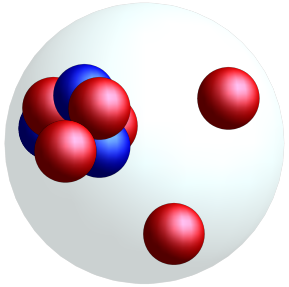


Heavier halo

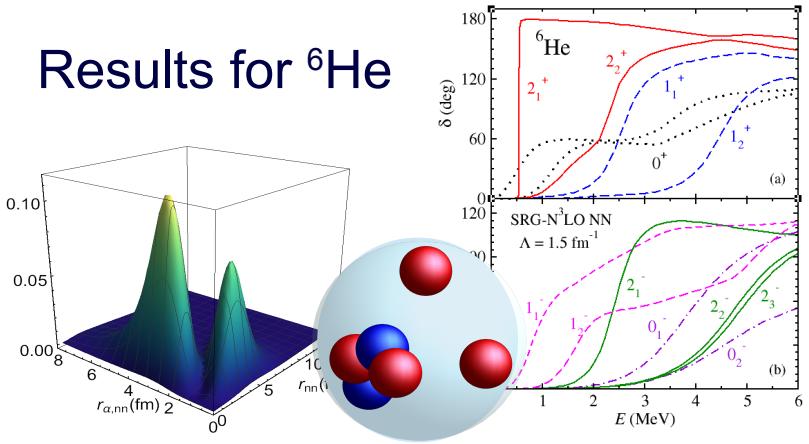
Reactions with 3-body channels

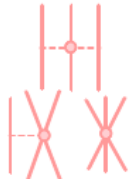
Summary and outlook

NCSMC for
3-cluster problems

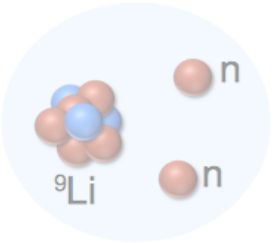


Results for ^{6}He





3-nucleon force

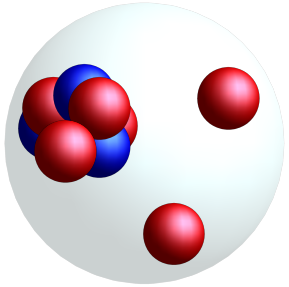


Heavier halo

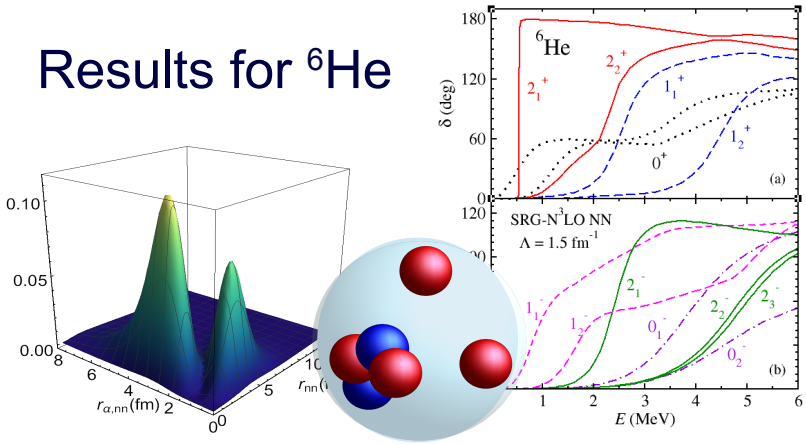
Reactions with 3-body channels

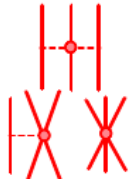
Summary and outlook

NCSMC for
3-cluster problems

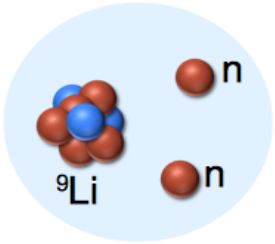


Results for ^{6}He

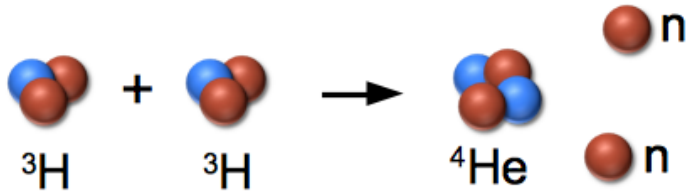




3-nucleon force



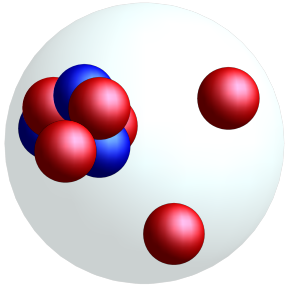
Heavier halo



Reactions with 3-body channels

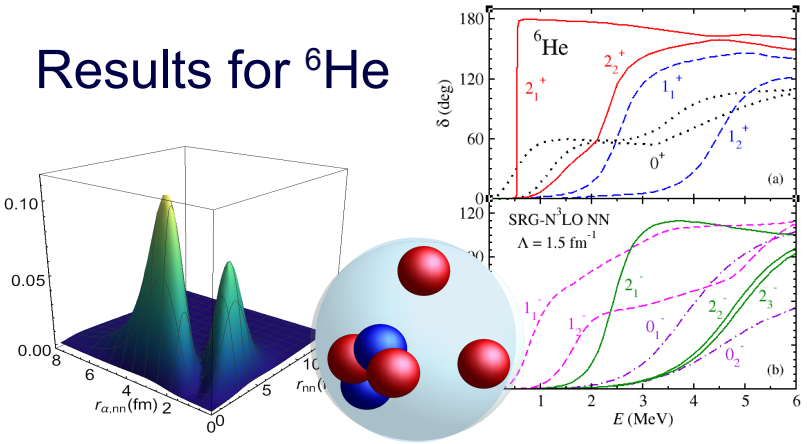
Summary and outlook

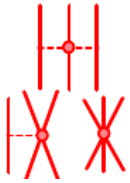
NCSMC for
3-cluster problems



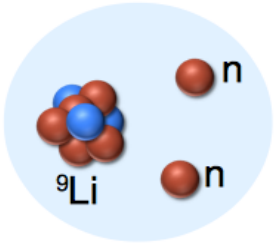
Thank you!!!

Results for ^{6}He

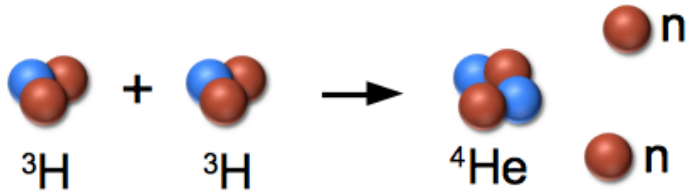




3-nucleon force



Heavier halo



Reactions with 3-body channels

Thank you!

Lawrence Livermore
National Laboratory