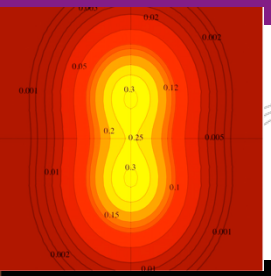
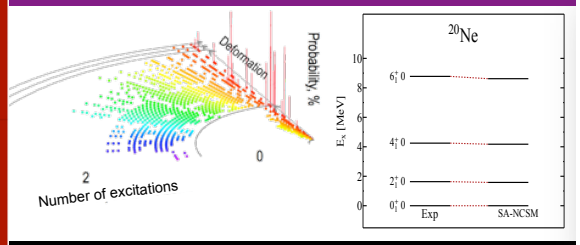
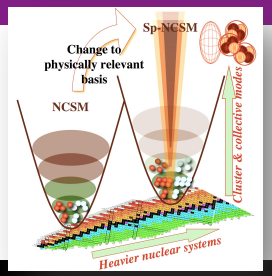
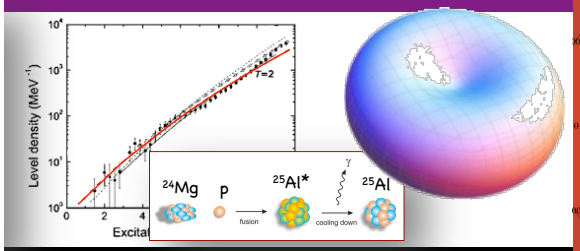
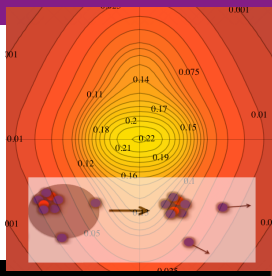









Emergent clustering phenomena in the framework of the ab initio symmetry-adapted no-core shell model

Kristina Launey **... LSU Team ...** **Jerry Draayer, Tomas Dytrych,**
Alexis Mercenne
Robert Baker, Ali Dreyfuss,
David Kekejian, Grigor Sargsyan,
Madeleine Miora

In collaboration with

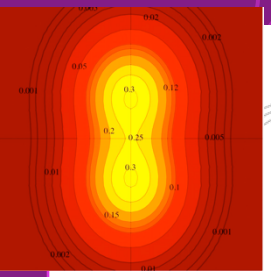
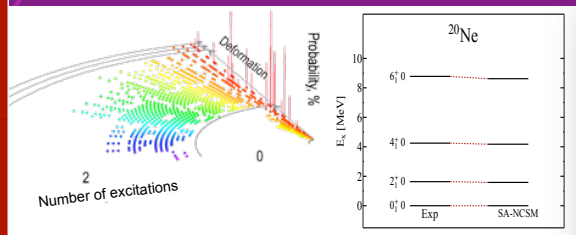
Ohio U. – Ch. Elster
LLNL – J. Escher
Czech Republic – D. Langr & T. Oberhuber
Princeton U. – W. Tang & B. Wang

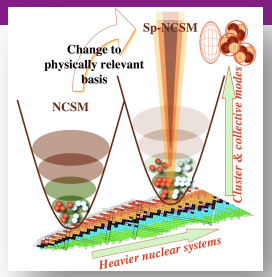
HPC Resources

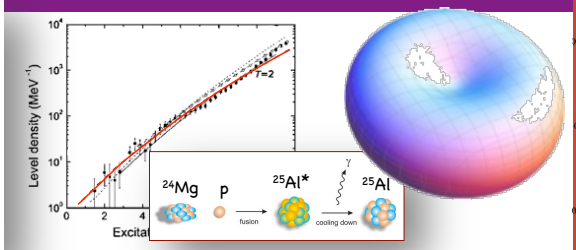
NSF/U. of Illinois ...*BlueWaters*
LSU...*SuperMike-II*

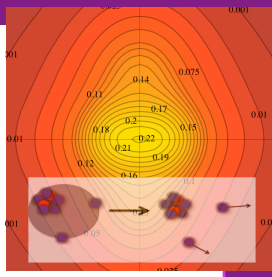
Supported by NSF & DOE

LSU







2N Force | 3N Force | 4N Force

LO $(Q/\Lambda_\chi)^0$

NLO $(Q/\Lambda_\chi)^2$

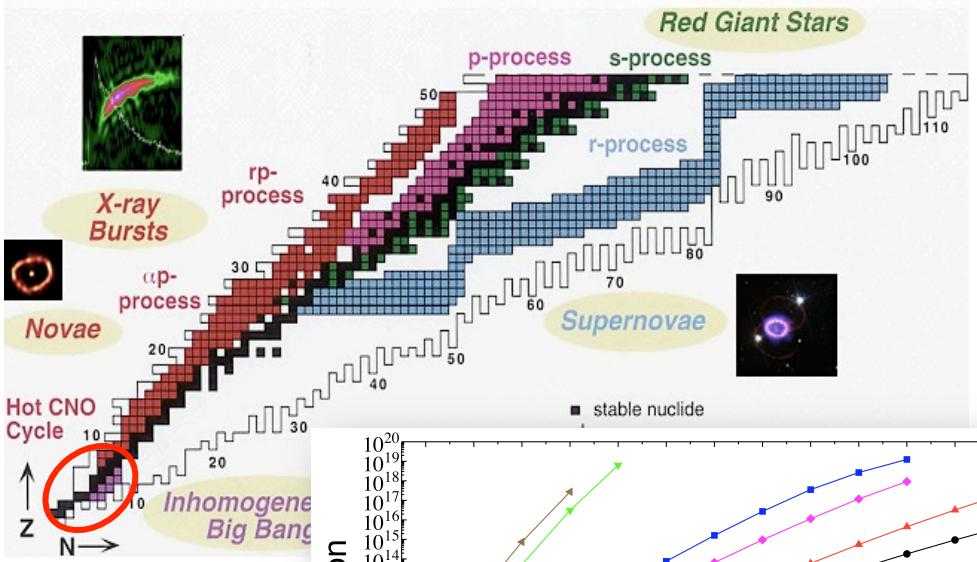
NNLO $(Q/\Lambda_\chi)^3$

N^{3}LO $(Q/\Lambda_\chi)^4$

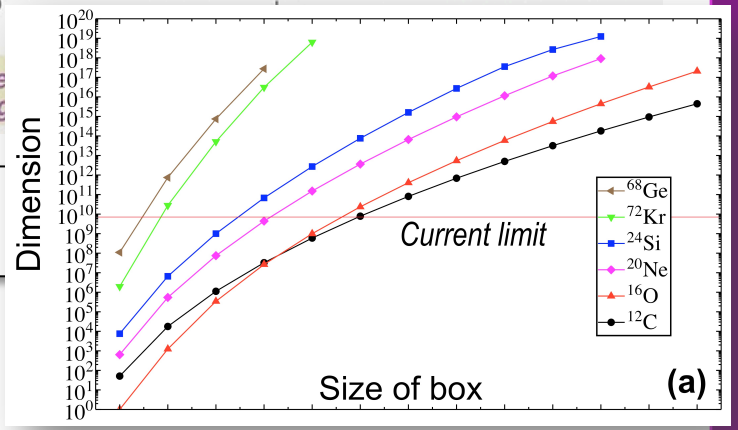
N^{4}LO $(Q/\Lambda_\chi)^5$

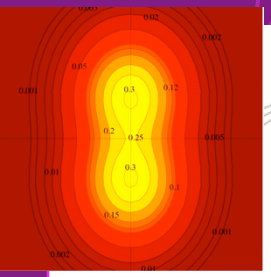
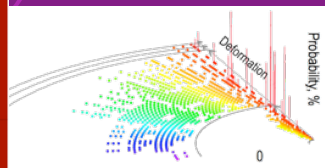
Chiral Interactions

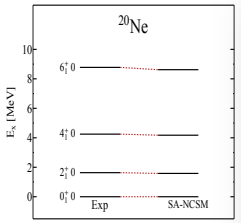
Weinberg, van Kolck, Machleidt, Entem, Meissner, Epelbaum, Krebs, Bernard,…

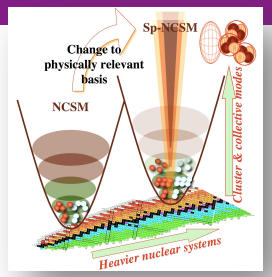


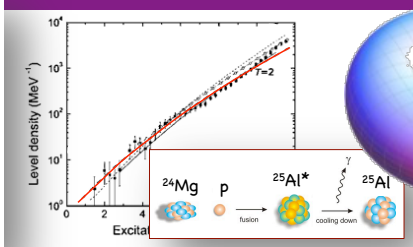
No-core Shell Model (NCSM)

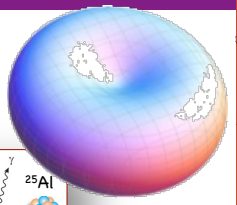
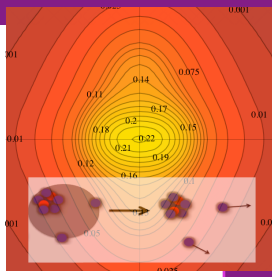


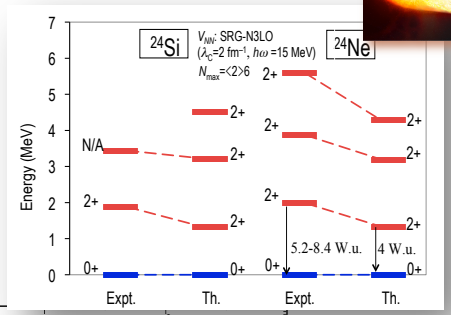


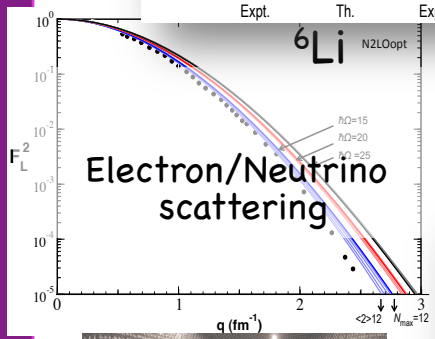


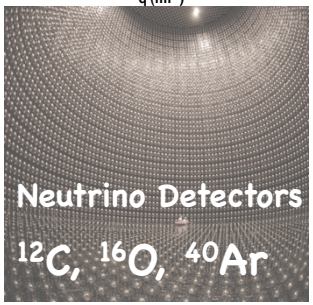


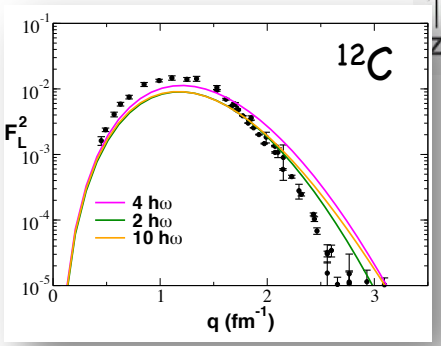




(Super)novae, X-ray bursts, nucleosynthesis

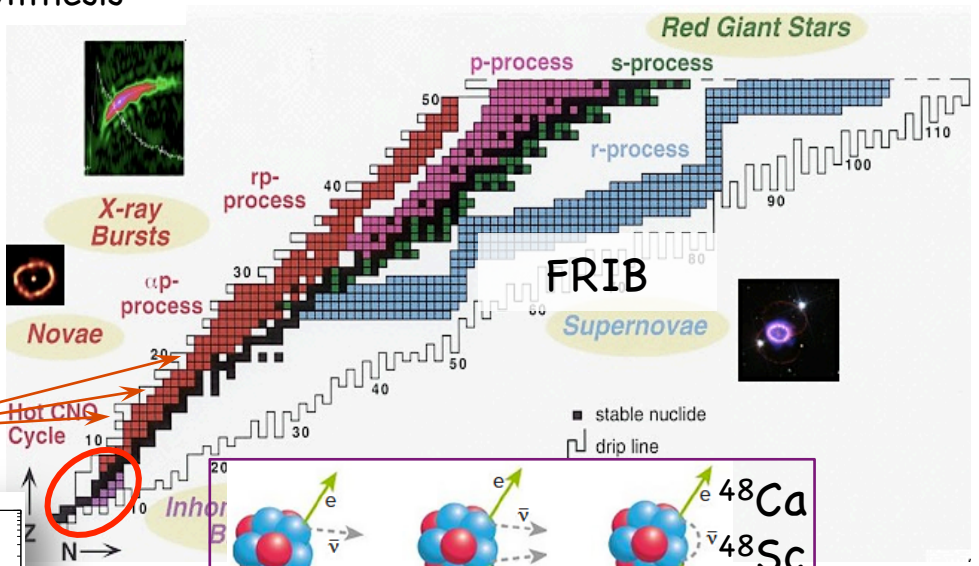


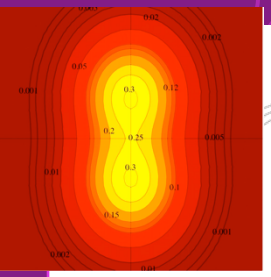
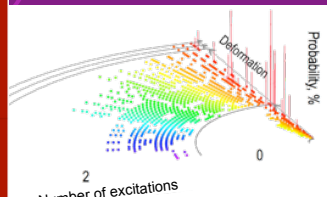


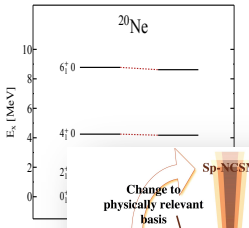


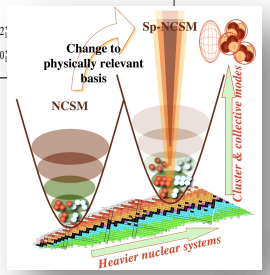


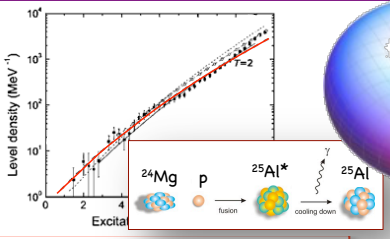
Close proximity of the drip lines

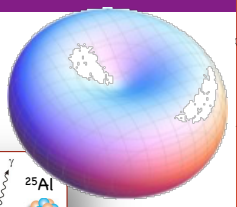
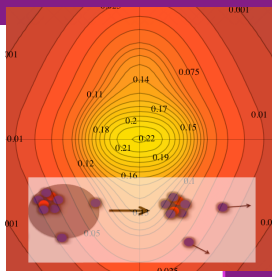


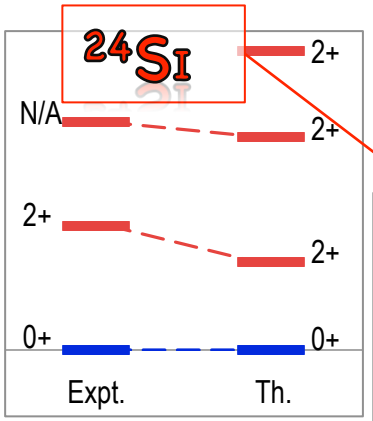


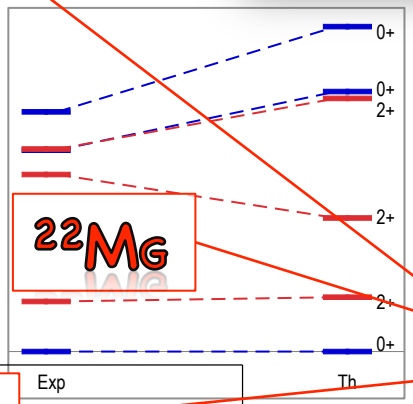


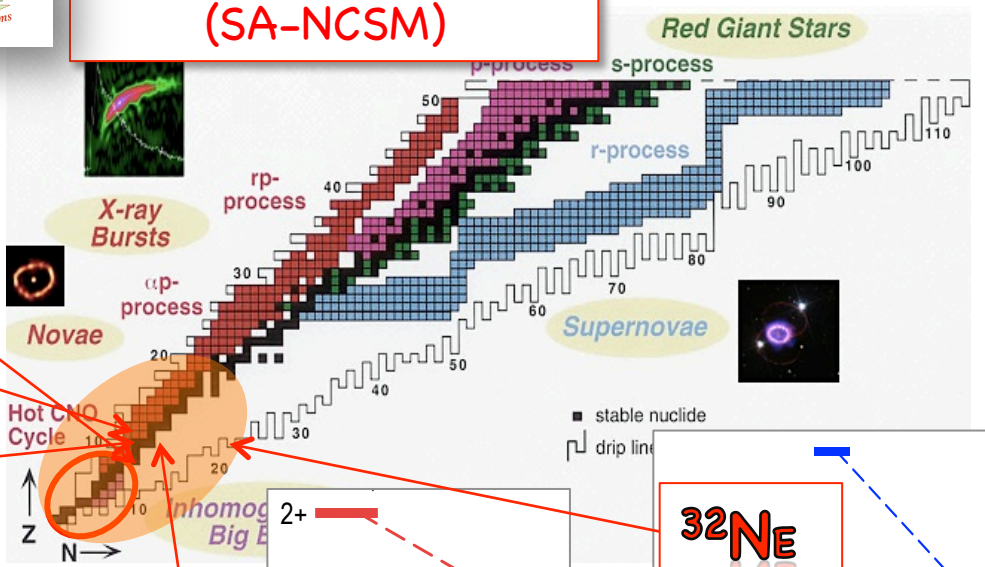


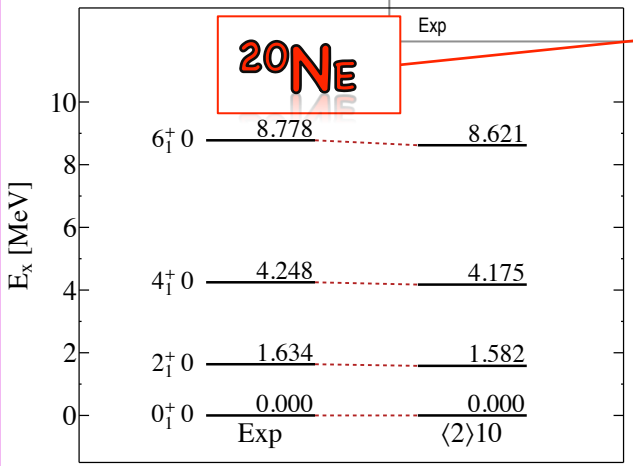



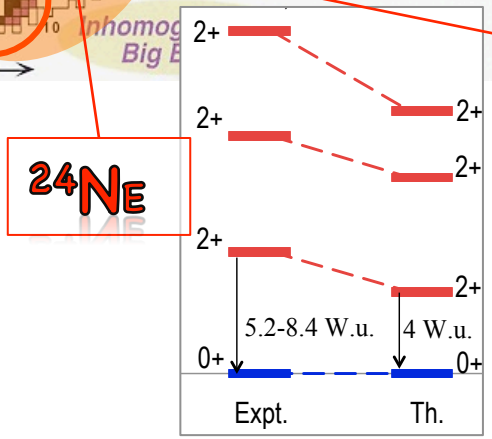
Symmetry-adapted No-core Shell Model (SA-NCSM)

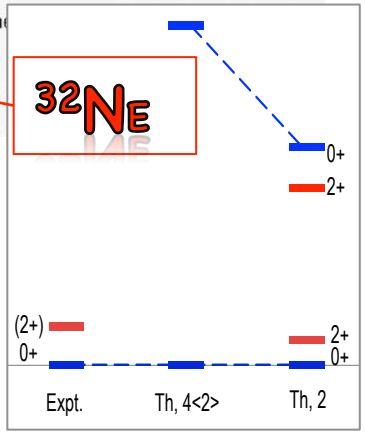


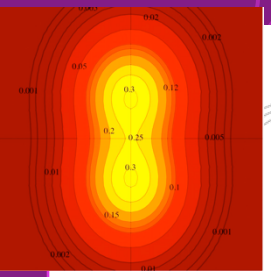


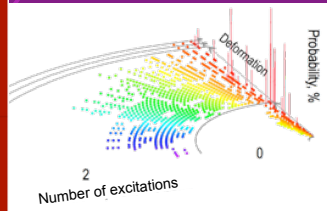


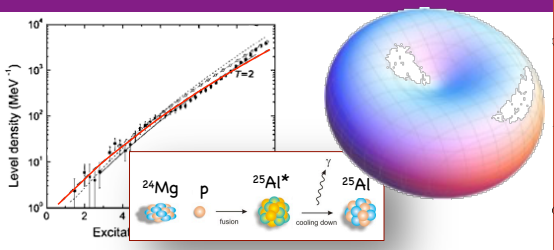


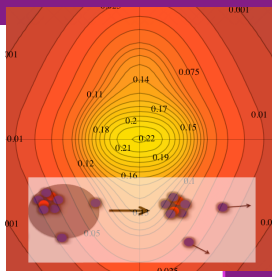


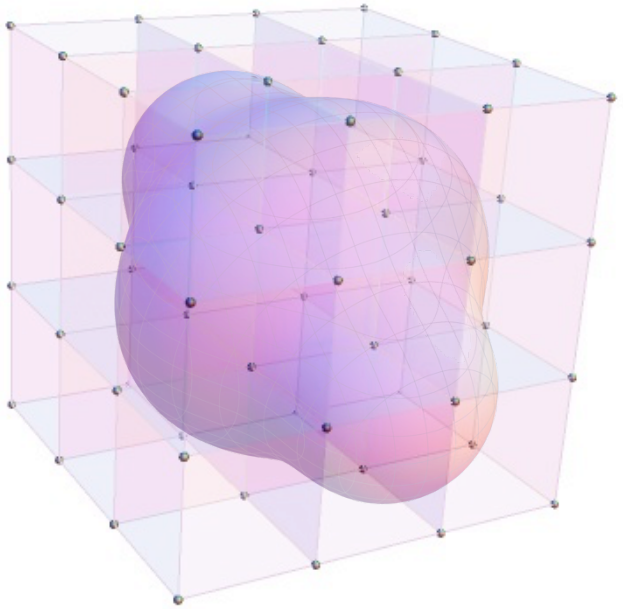






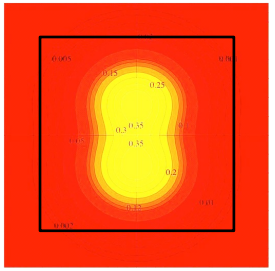






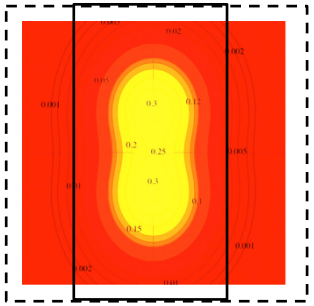
NCSM

Total HO quanta
N_{max}



SA-NCSM

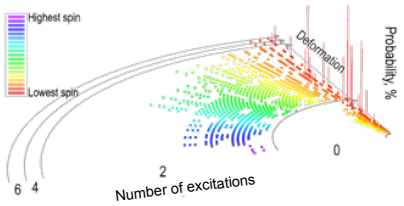
Total HO quanta
N_{max}
+
Distribution:
z, x, y

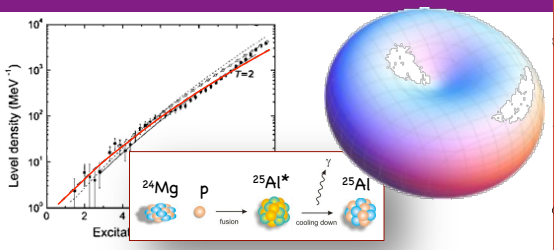


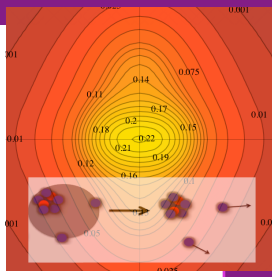
LSU code (LSU3shell): sourceforge.net/projects/lsu3shell

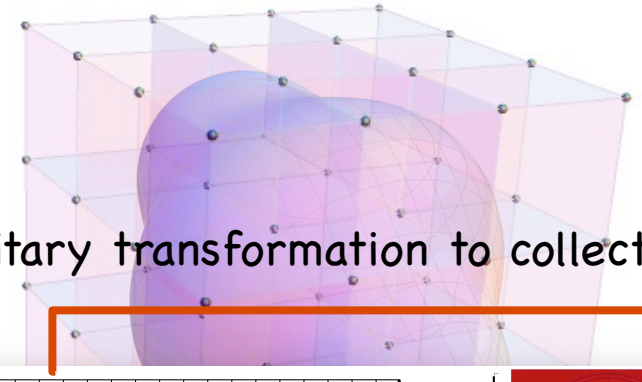
Dytrych et al., Phys. Rev. Lett. 111 (2013) 252501

Launey et al., Prog. Part. Nucl. Phys. 89 (2016) 101





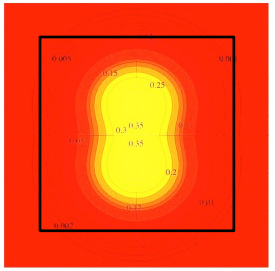




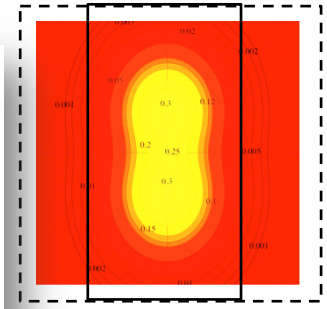
Unitary transformation to collective basis (Sp)

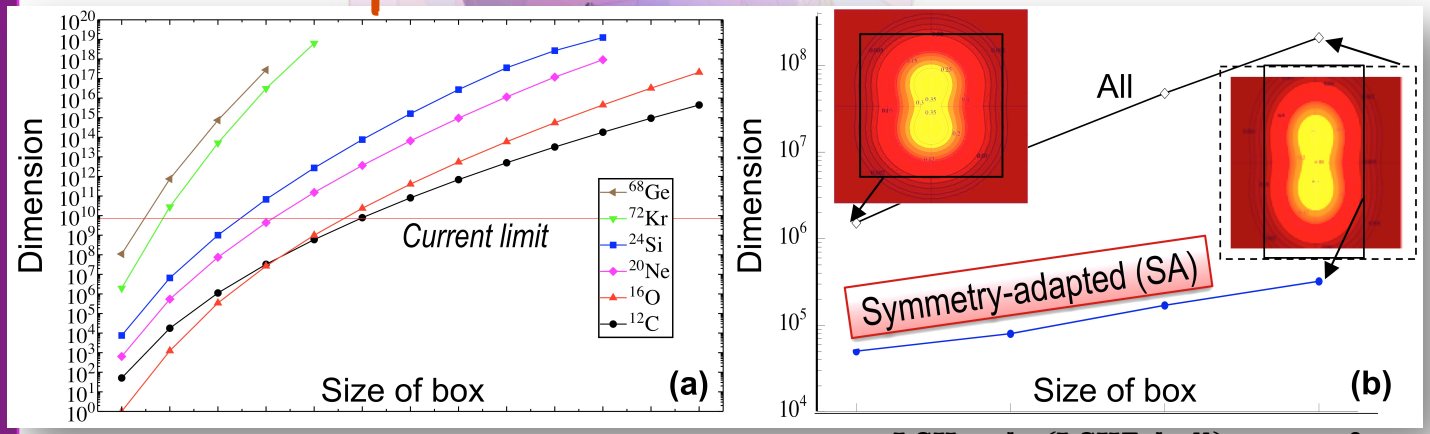
NCSM

Total HO quanta N_{max}



SA-NCSM





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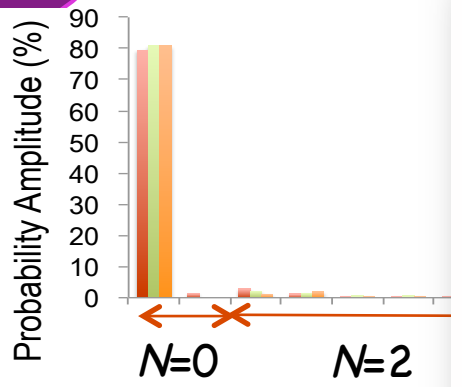
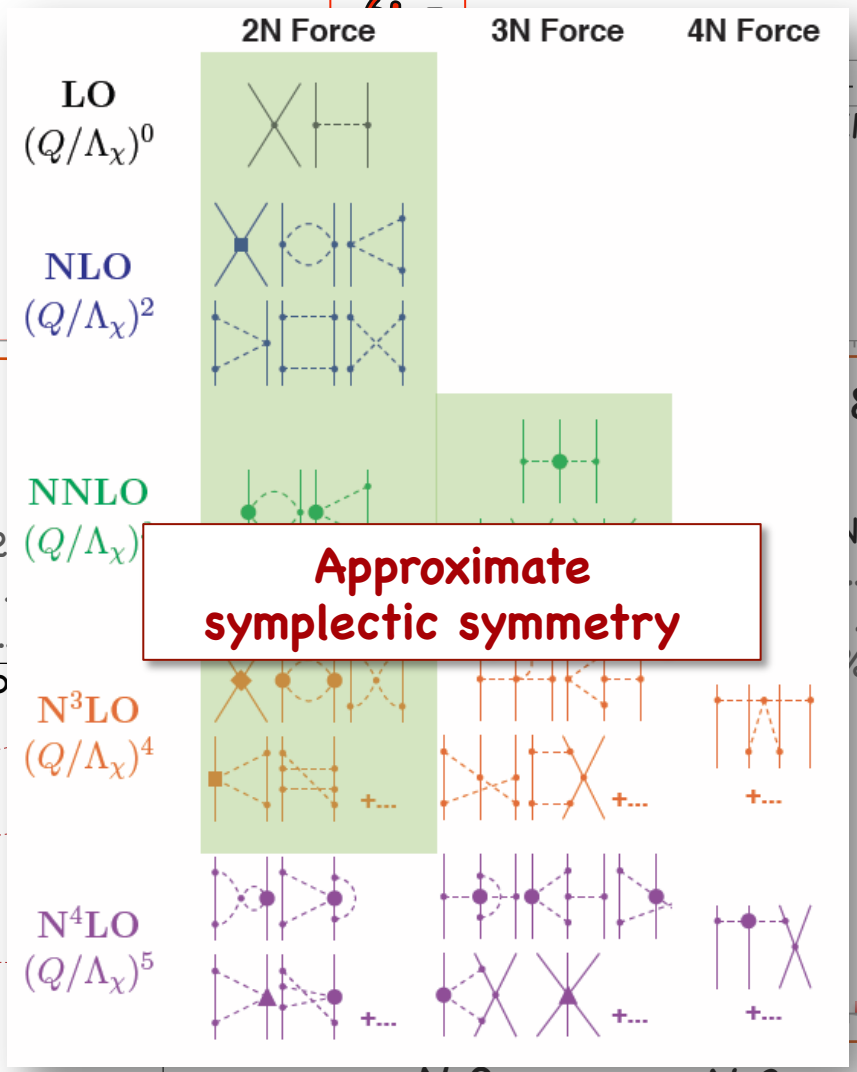
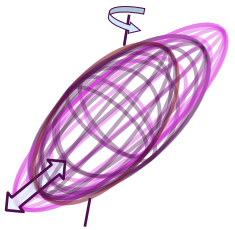
Dytrych et al., Phys. Rev. Lett. 111 (2013) 252501

Launey et al., Prog. Part. Nucl. Phys. 89 (2016) 101

Preference of Nature







2+

M (N³LO)

8 N=10

⁶Li, Nmax=12

J=1,2,3 states……2

Sp(3,R) irreps……

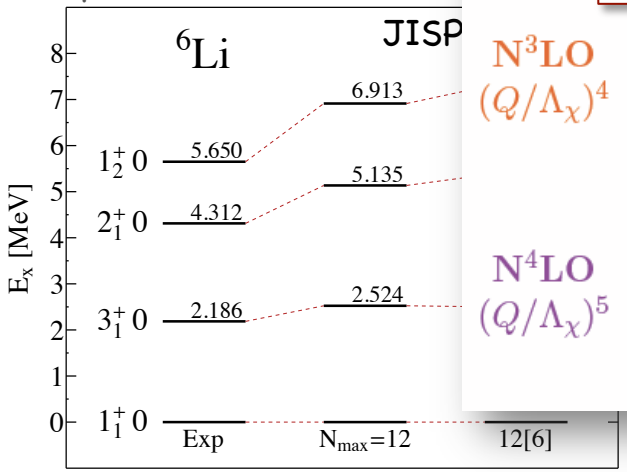
Sp(3,R) with P>0.2%……

Nmax=8

…2x10¹¹

…1,392

%: ….27



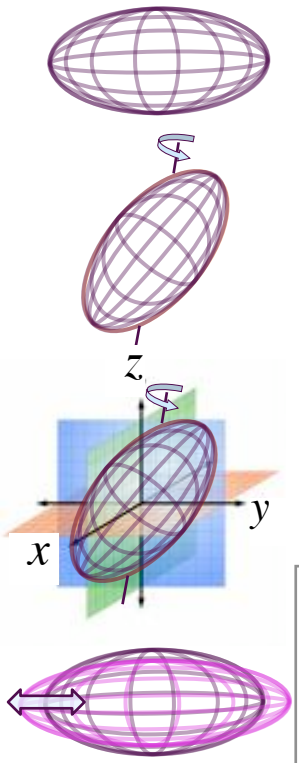
²⁰Ne

EM (N³LO)

N=4 N=6

What physics can we learn from Sp basis?

Sp (collective) basis configuration:



one equilibrium deformation (``shape")

rotations

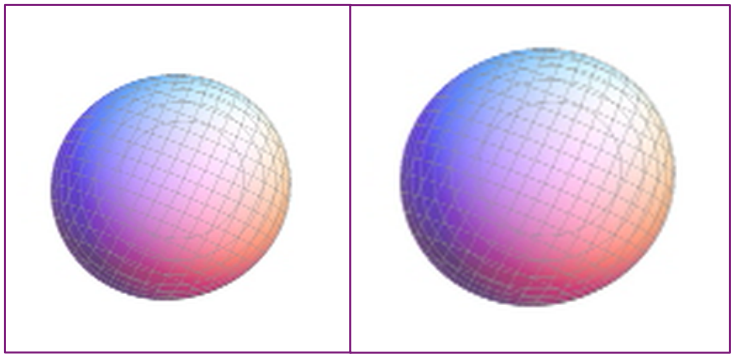
space orientation

Vibrations

(of the giant resonance monopole (r^2)/ quadrupole (Q) type)

All states preserve the equilibrium shape...

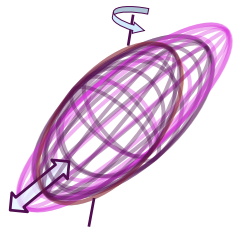
Symmetry?



Symplectic Sp(3,R) Symmetry!

Formal definition

All linear canonical transformations of the single-particle phase-space observables

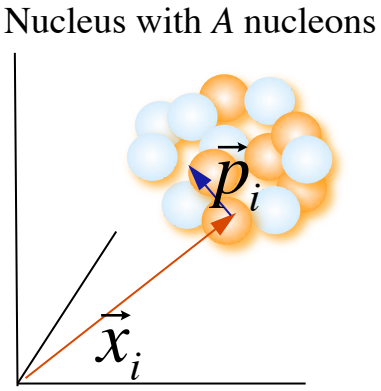


$$x_{i\alpha} \rightarrow \sum_{\beta=x,y,z} a_{\alpha\beta} x_{i\beta} + b_{\alpha\beta} p_{i\beta}$$

$$p_{i\alpha} \rightarrow \sum_{\beta=x,y,z} c_{\alpha\beta} x_{i\beta} + d_{\alpha\beta} p_{i\beta}$$

that preserve the canonical commutation relation

$$\left[x_{i\alpha}, p_{j\beta}\right] = i\hbar\delta_{ij}\delta_{\alpha\beta}$$



Generators:

$$Q_{ij} = \sum_n x_{ni} x_{nj},$$

$$S_{ij} = \sum_n (x_{ni} p_{nj} + p_{ni} x_{nj}),$$

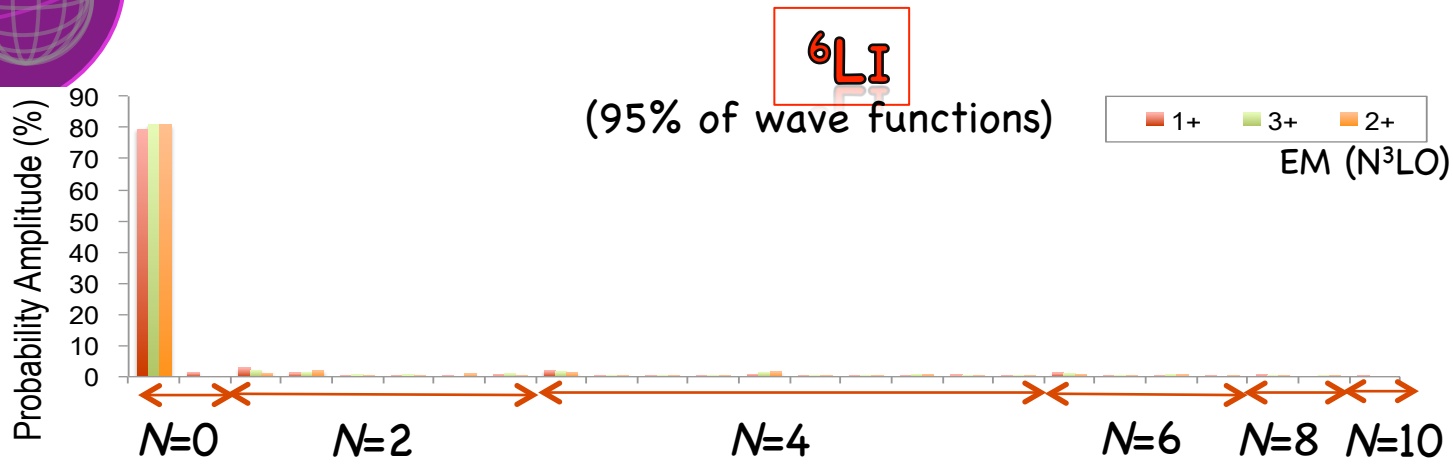
$$L_{ij} = \sum_n (x_{ni} p_{nj} - x_{nj} p_{ni}),$$

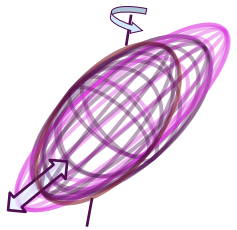
$$K_{ij} = \sum_n p_{ni} p_{nj},$$

SU(3) in a HO shell (Elliott, 1958)

Rowe, Rosensteel, Draayer, Hecht, Suzuki, Escher, Bahri, ….

SA-NCSM with Sp(3,R) basis





^{6}Li, Nmax=12

J=1,2,3 states……2x10^7

Sp(3,R) irreps……528

Sp(3,R) with P>0.2%……25

Reproducing B(E2)?

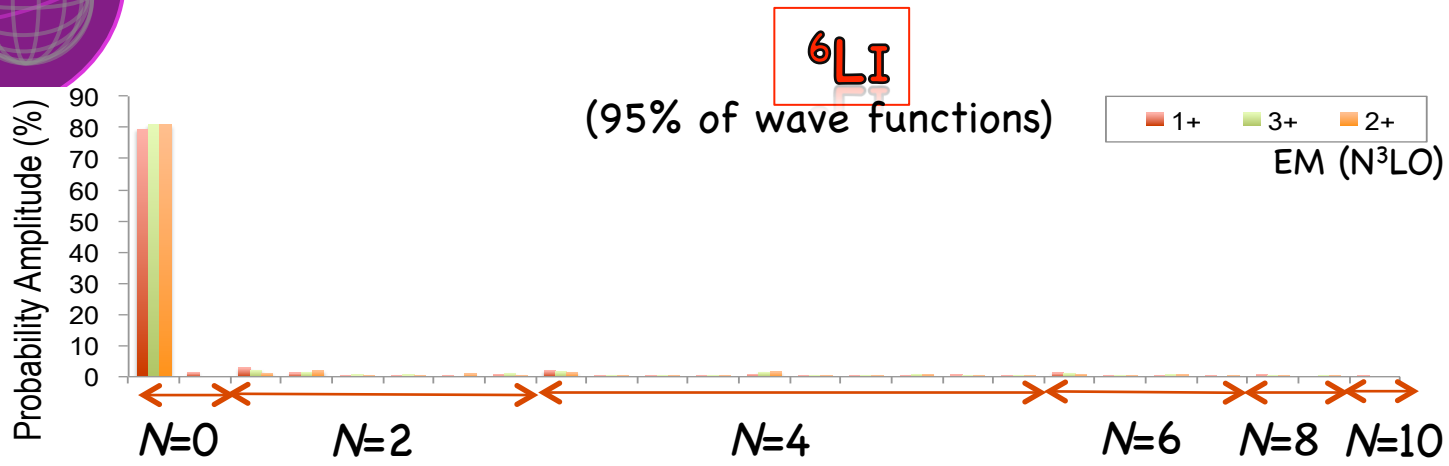
$$B(E2) = \frac{1}{2J_i+1}\frac{5}{16\pi}\left(\frac{\hbar}{m\omega}\right)^2 |\langle J_f \| Q_2 \| J_i \rangle|^2$$

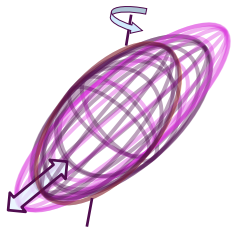
$$Q_{2M} = \sqrt{3}\left(A^{(20)}_{2M} + C^{(11)}_{2M} + B^{(02)}_{2M}\right)$$

Symplectic generators – do not mix Sp basis configurations

=> Significance of dominant Sp configuration

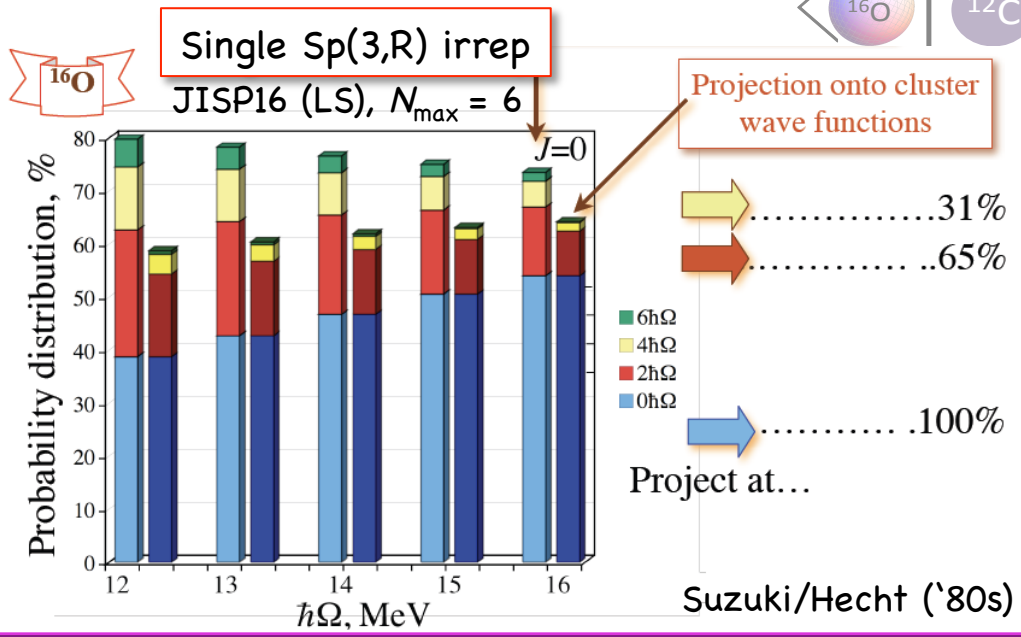
SA-NCSM with Sp(3,R) basis



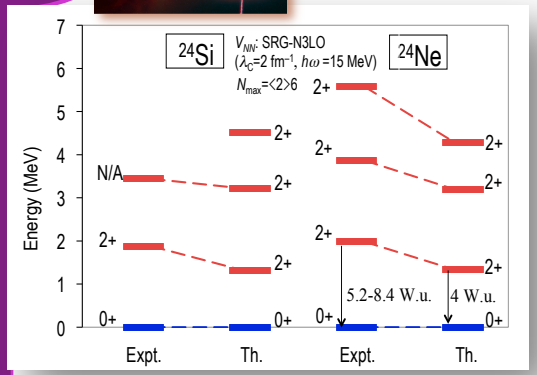


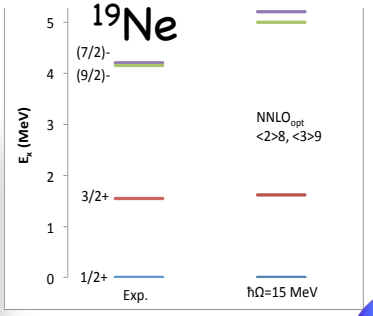
^{6}Li, Nmax=12
J=1,2,3 states……..2x10^7
Sp(3,R) irreps……..528
Sp(3,R) with P>0.2%….25

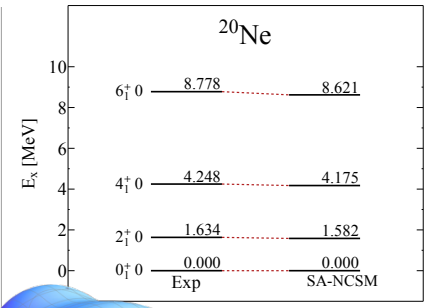
Relation to alpha clustering?



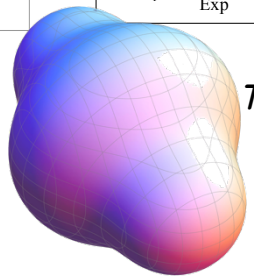
Deformed/clusters (in intrinsic frame)…





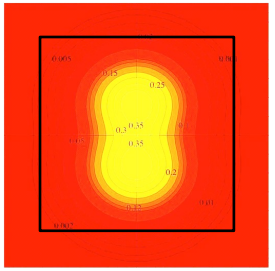


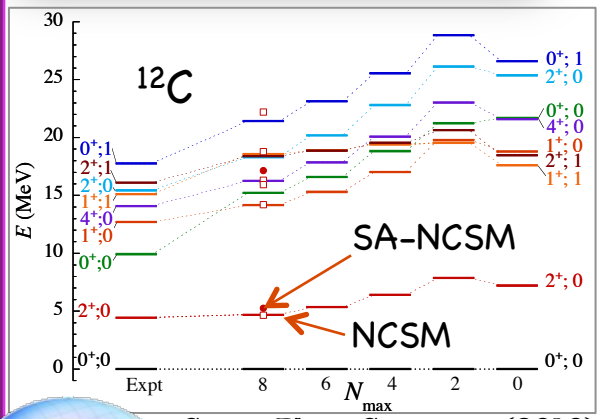
Robert Baker, PhD student, LSU



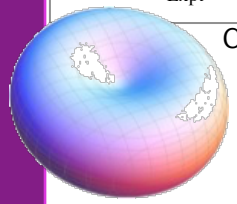
NCSM

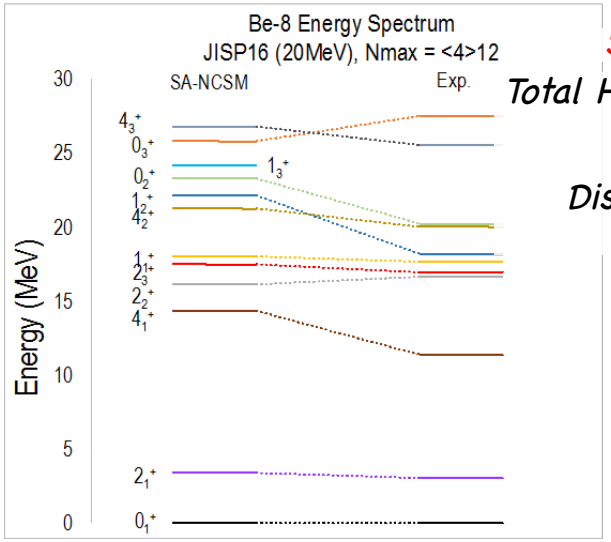
Total HO quanta N_{max}





Comp. Phys. Commun. (2016)

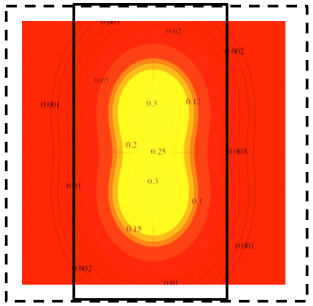




Harvey Shows, undergraduate student, LSU

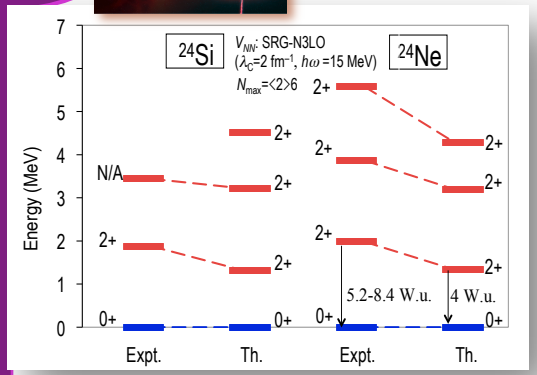
SA-NCSM

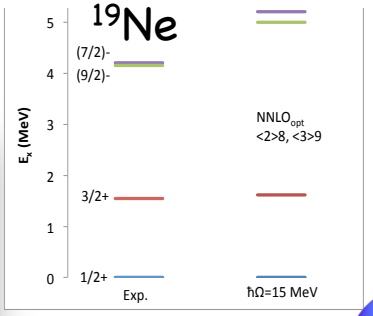
Total HO quanta N_{max} + Distribution: z, x, y

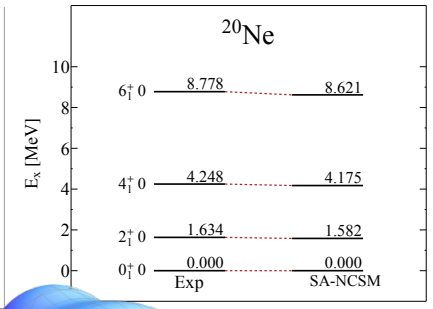


Deformation/clustering: important in nuclear wave functions

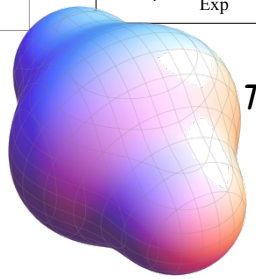
Deformed/clusters (in intrinsic frame)…





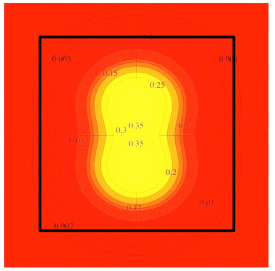


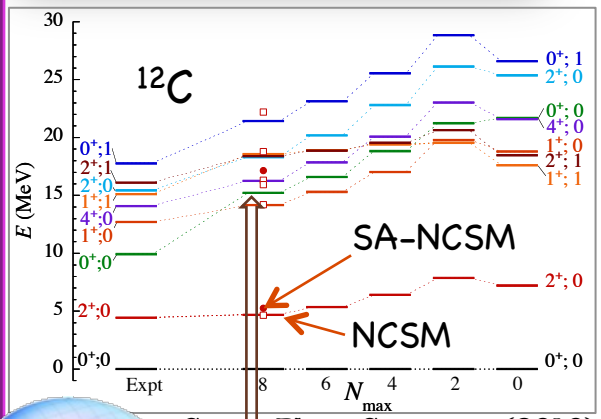
Robert Baker, PhD student, LSU



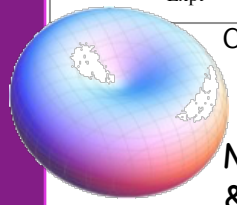
NCSM

Total HO quanta N_{max}

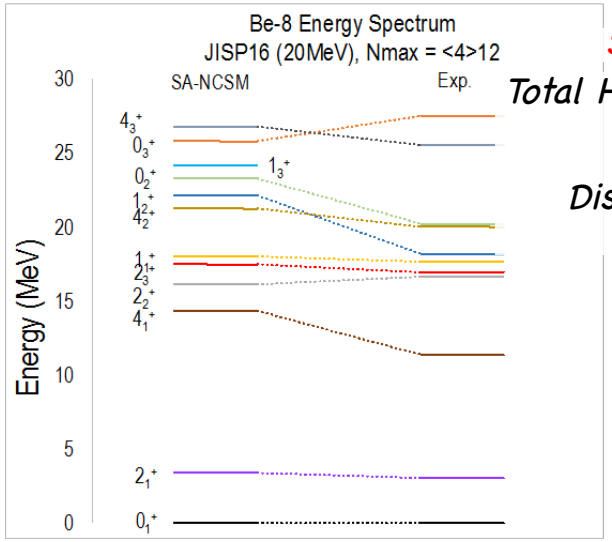




Comp. Phys. Commun. (2016)



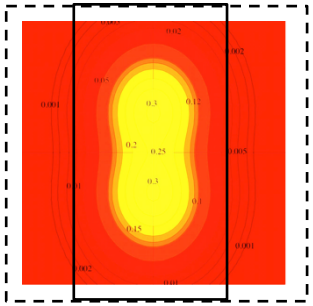
Mixture of large oblate & small prolate (spin-2); small radius



Harvey Shows, undergraduate student, LSU

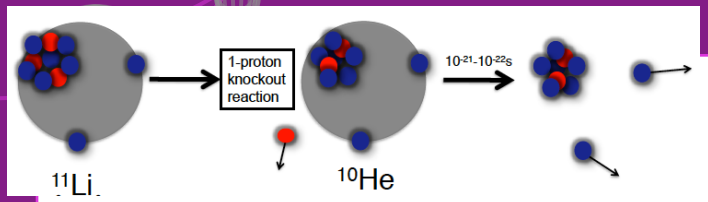
SA-NCSM

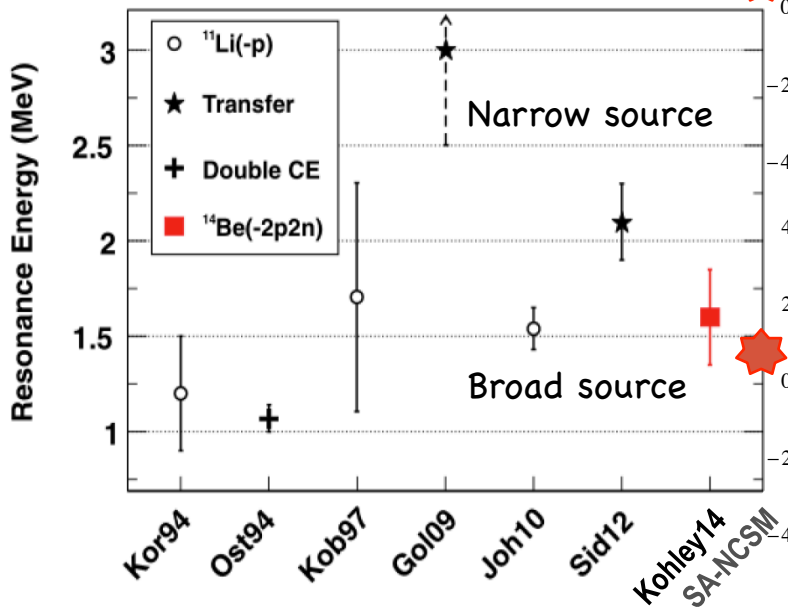
Total HO quanta N_{max} + Distribution: z, x, y

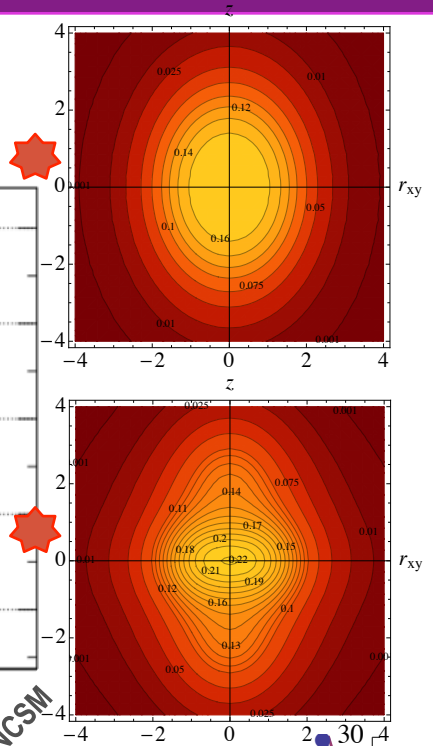


Deformation/clustering: important in nuclear wave functions

Toward the drip line

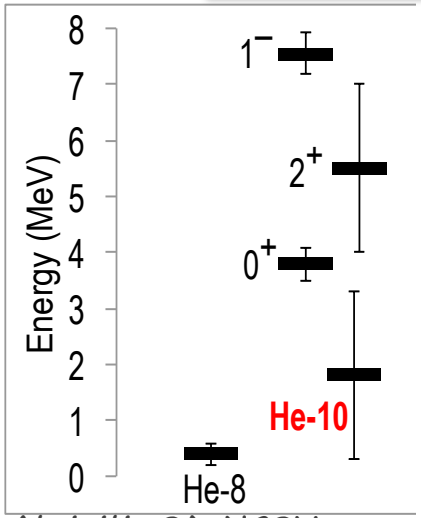




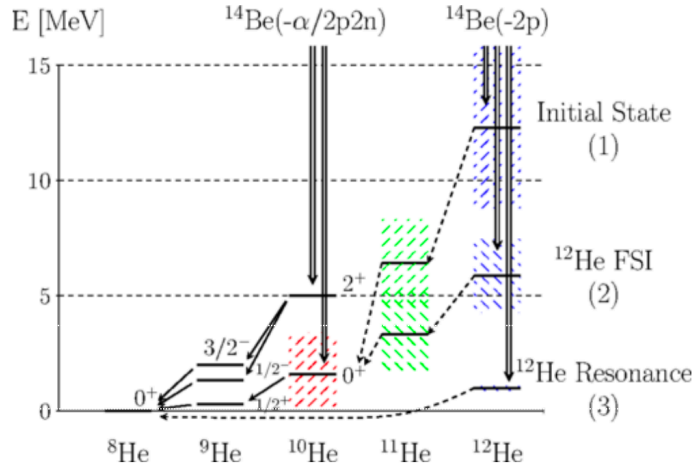


^{10}HE

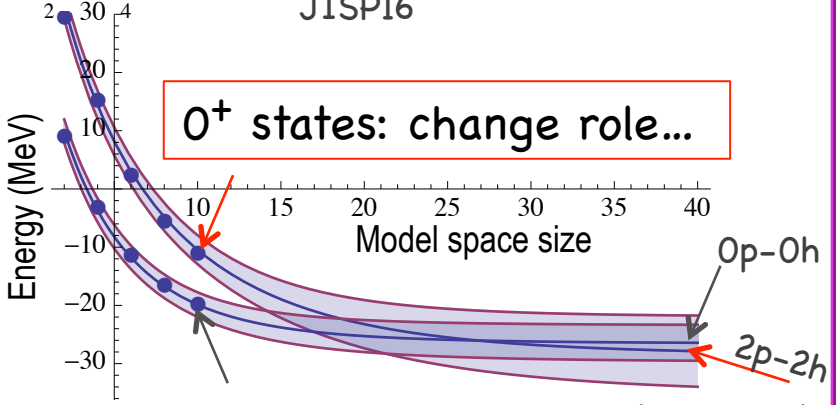
Brian Harvey (REU-14)



Ab initio SA-NCSM
JISP16

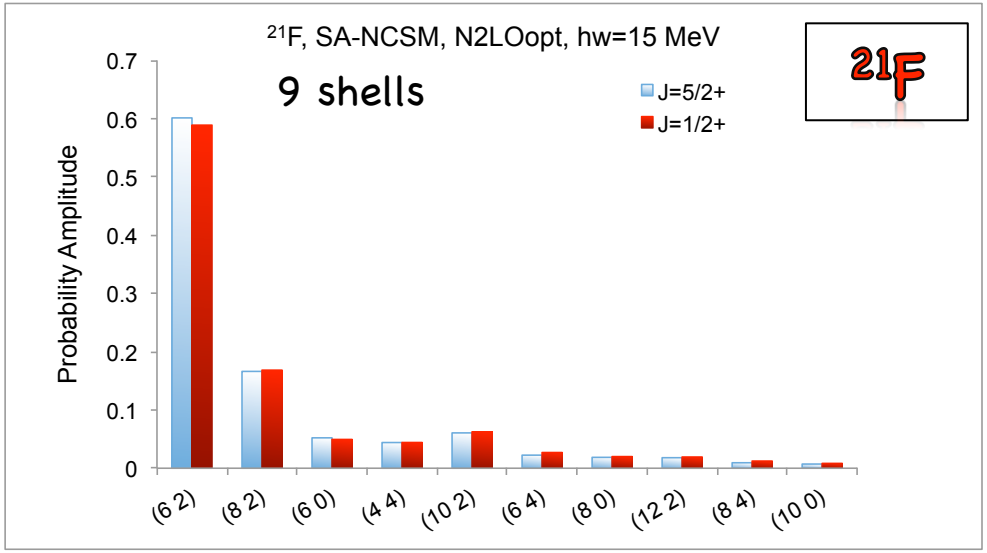


MoNA group at NSCL, M.D.Jones, Z.Kohley, et al., PRC 91, 044312 (2015)



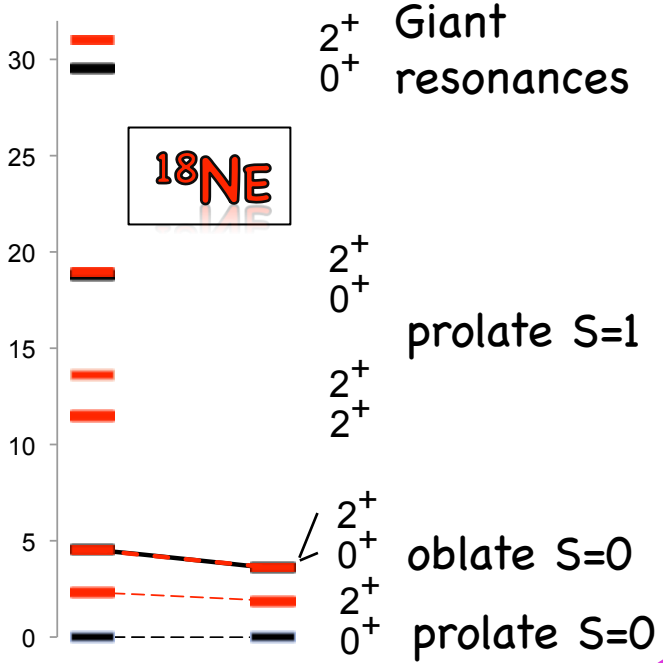
Extrapolation based on Furnstahl, Hagen, Papenbrock (PRC 2012)
+ x,y,z "SU(3) corrections"

Collectivity & clustering up to medium mass



Grigor Sargsyan, PhD student, LSU

Ne & Mg isotopes



N2LOopt; 9 shells

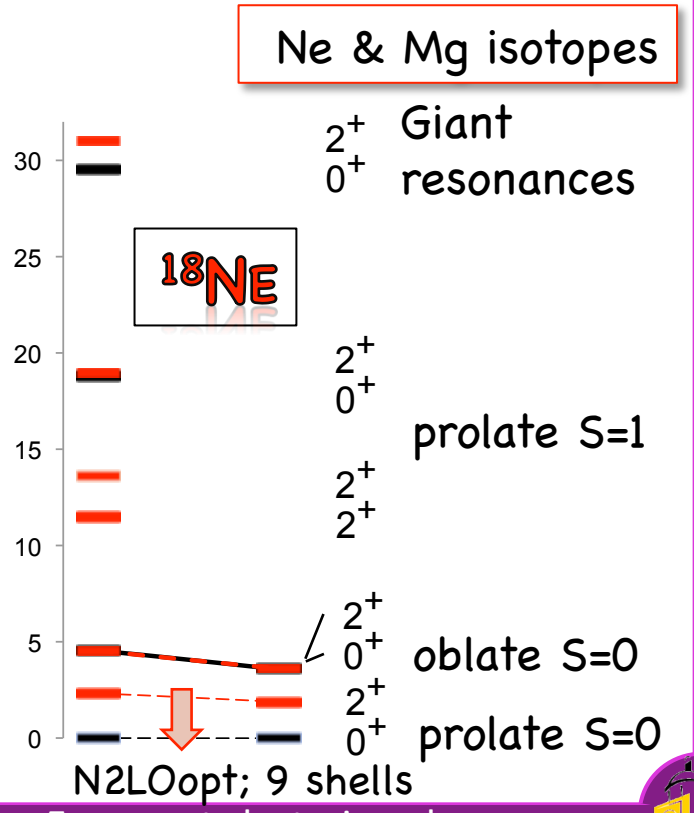
Collectivity & clustering up to medium mass

^{18}Ne, B(E2: $2^+ \rightarrow 0^+$)

Experiment…… 17.7(18) W.u.

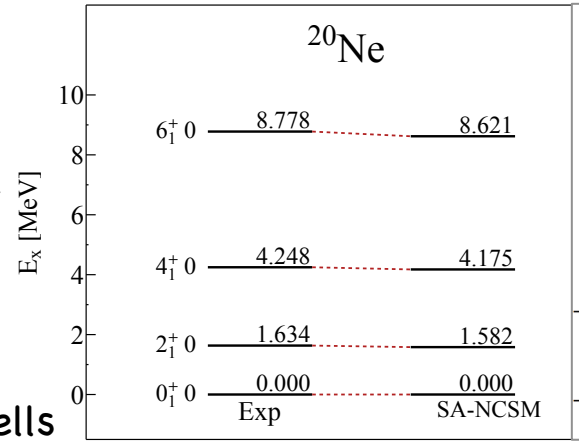
9 shells …… 1.13 W.u.

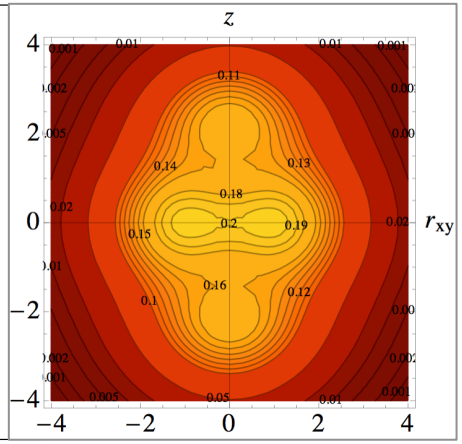
33 shells ……. 13.0(7) W.u.
(no effective charges)

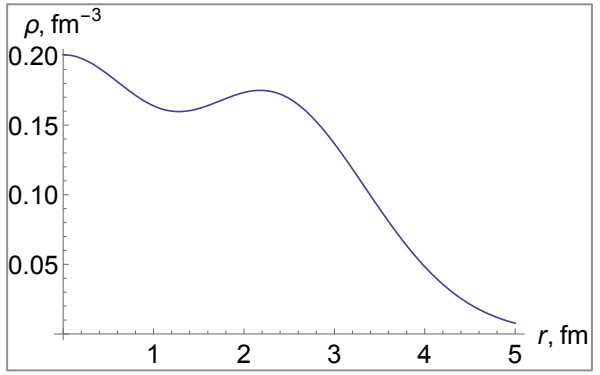


Grigor Sargsyan, PhD student, LSU

Collectivity & clustering up to medium mass







^{20}NE

13 shells

SA-NCSM (selected model space): 50 million states

Complete model space: 1000 billion states

Ne & Mg isotopes

^{18}Ne, B(E2: $2^+ \to 0^+$)

Experiment…… 17.7(18) W.u.

9 shells …… 1.13 W.u.

33 shells ……. 13.0(7) W.u.
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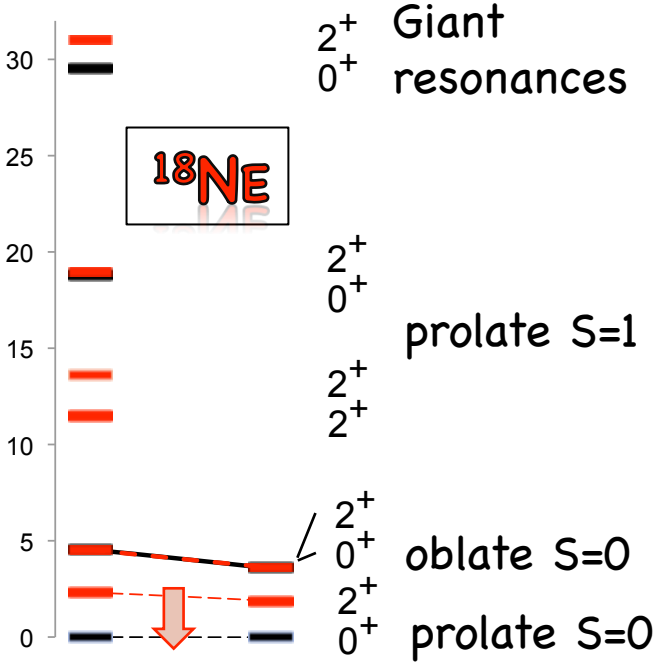
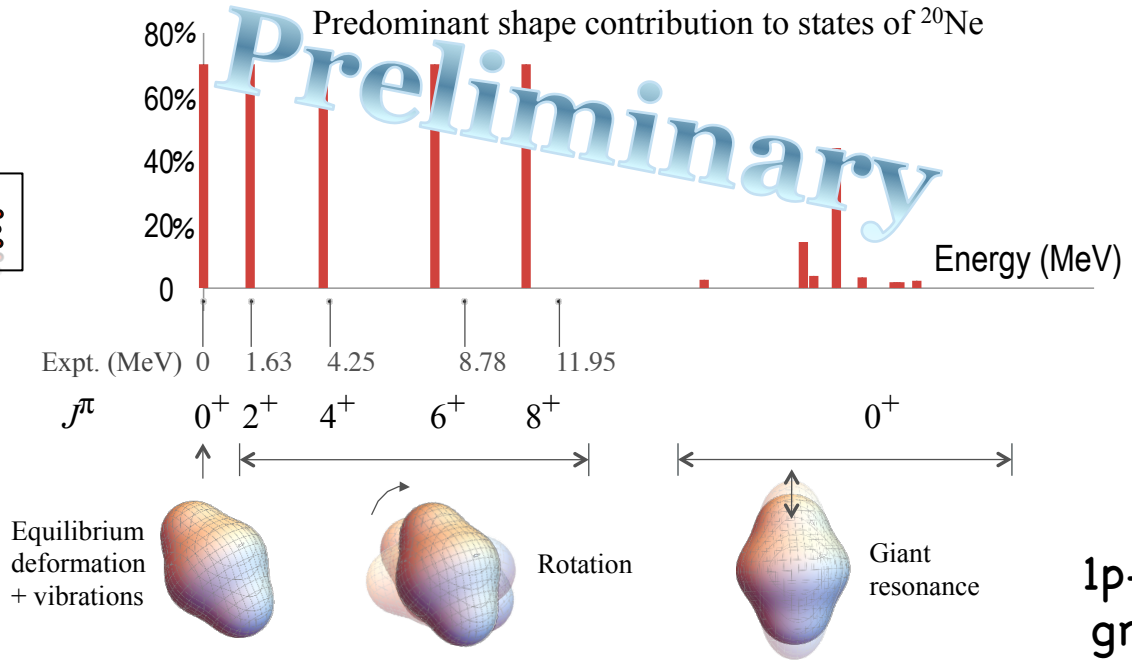


Grigor Sargsyan, PhD student, LSU

Collectivity & clustering up to medium mass

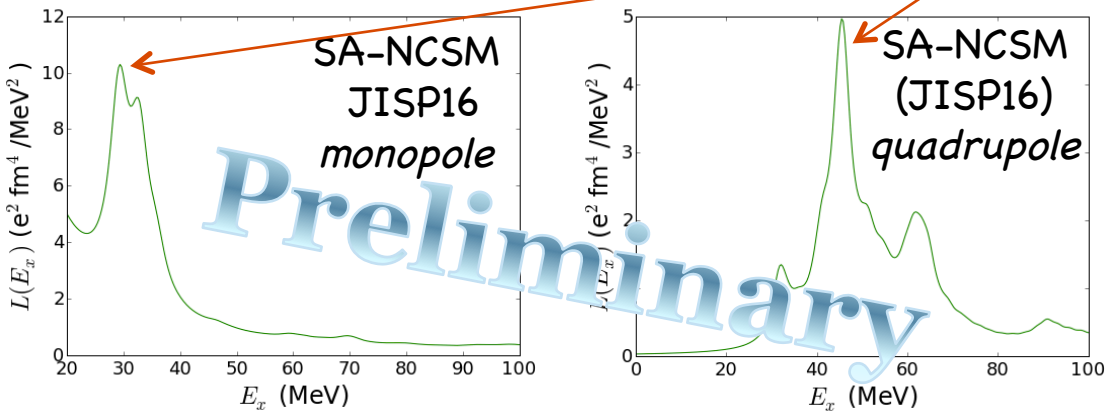
^{20}Ne



1p-1h excitations of ground-state shape

^{16}O

Response functions



Robert Baker, PhD student, LSU

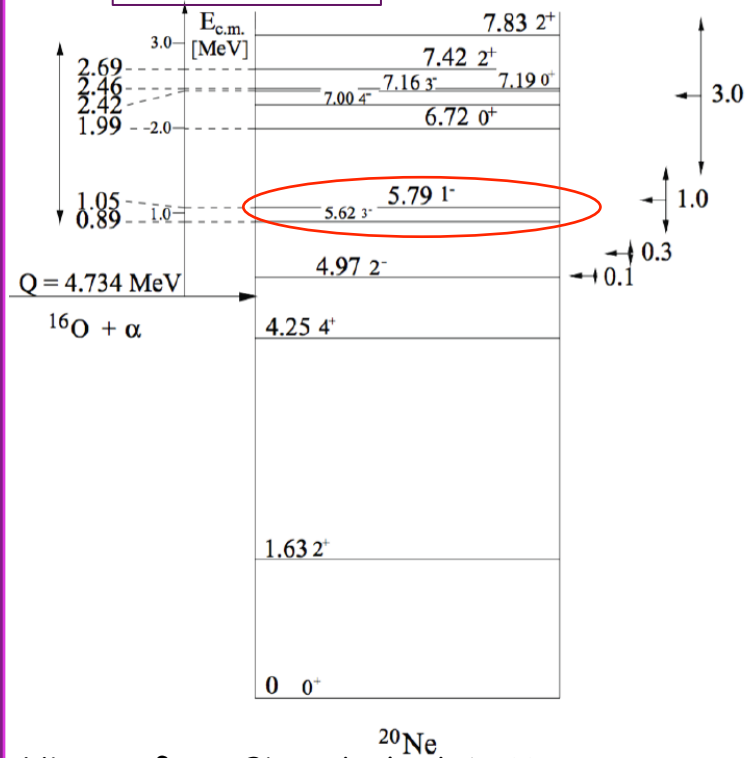
XRB nucleosynthesis abundances from *ab initio* wave functions

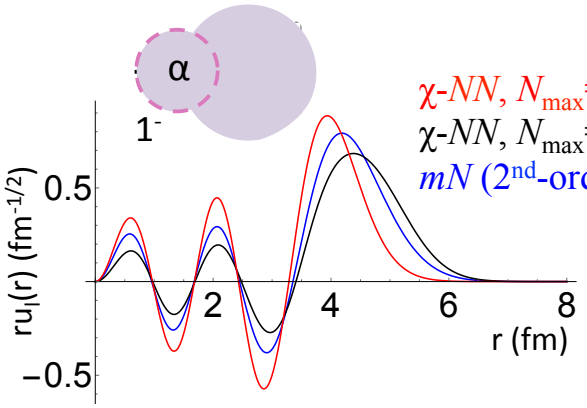
SA-NCSM, Sp(3,R) basis with:

- chiral potential ("χ-*NN*")
- microscopic potential, up to 2nd-order expansion of long-range central ("*mN*")

Alpha capture reactions

$^{16}O(\alpha,\gamma)^{20}Ne$





χ-*NN*, N_{max}=3
χ-*NN*, N_{max}=11
mN (2nd-order LR), N_{max}=13

Wave functions from *ab initio* SA-NCSM with N2LOopt

Ali Dreyfuss, PhD student, LSU

XRB nucleosynthesis abundances from *ab initio* wave functions

SA-NCSM, Sp(3,R) basis with:
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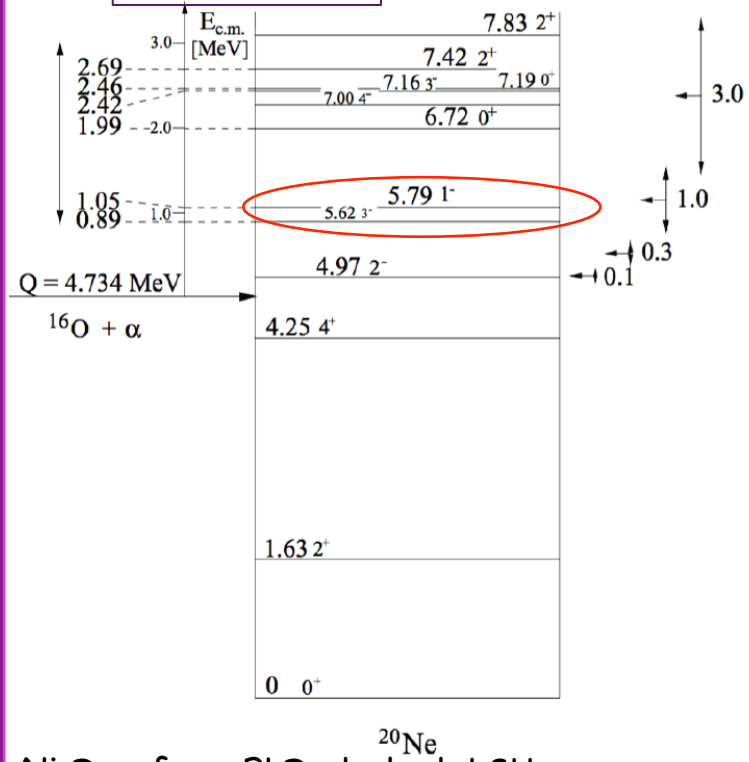
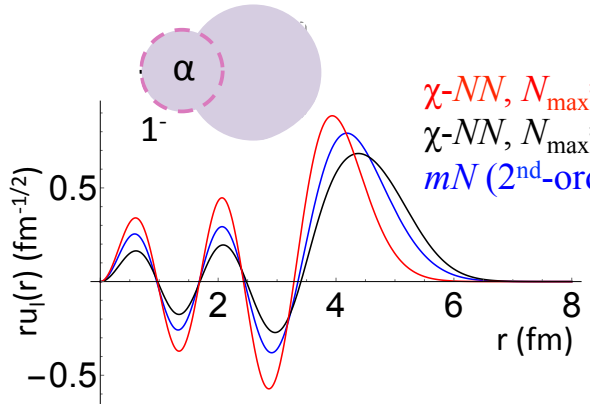


Ali Dreyfuss, PhD student, LSU



χ-*NN*, N_{max}=3
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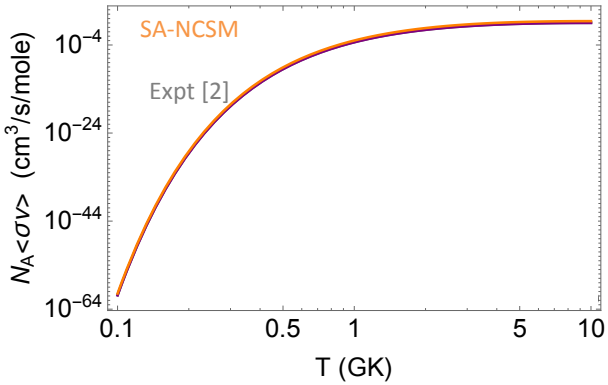
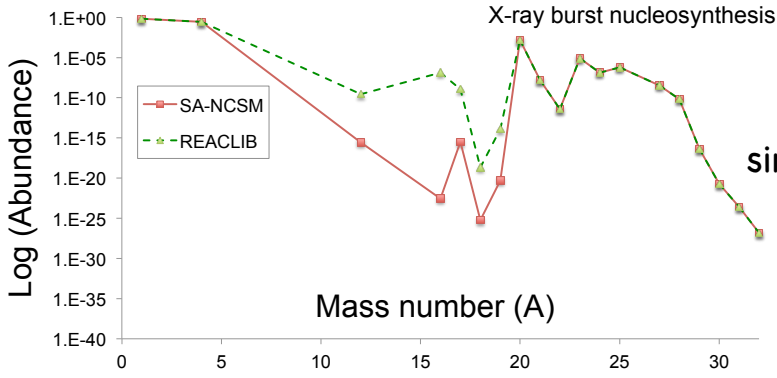
mN (2nd-order LR), N_{max}=13

Wave functions from *ab initio* SA-NCSM with N2LOopt



Γ_α width

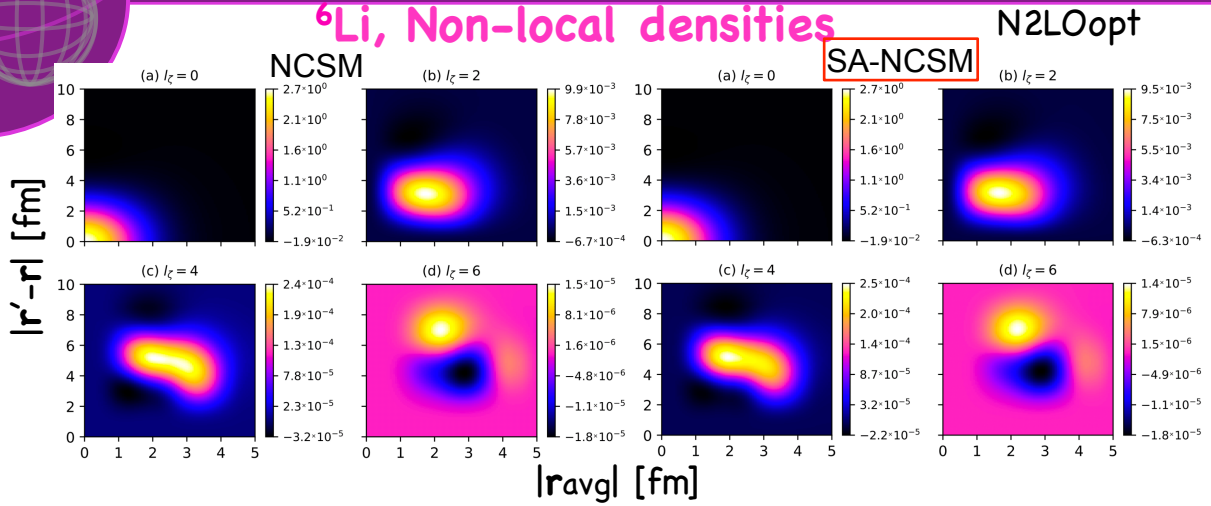
Reaction rates



Nucleosynthesis simulations (Xnet): XRB abundance pattern

Scattering observables from first principles

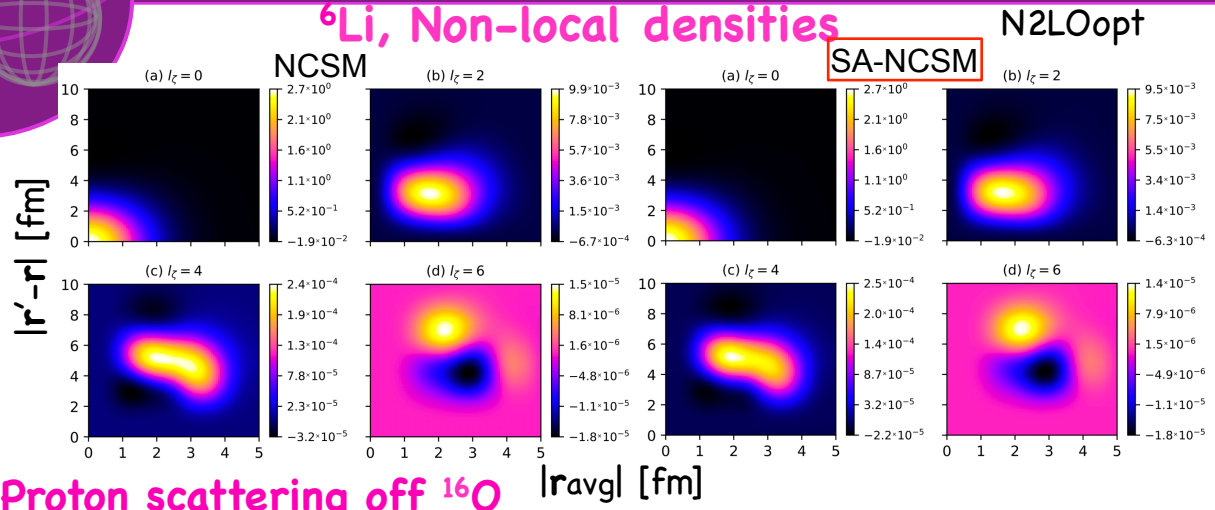
^{6}Li, Non-local densities



Burrows, Elster, Popa, Launey, Nogga, Maris, Phys. Rev. C 97 (2018) 024325

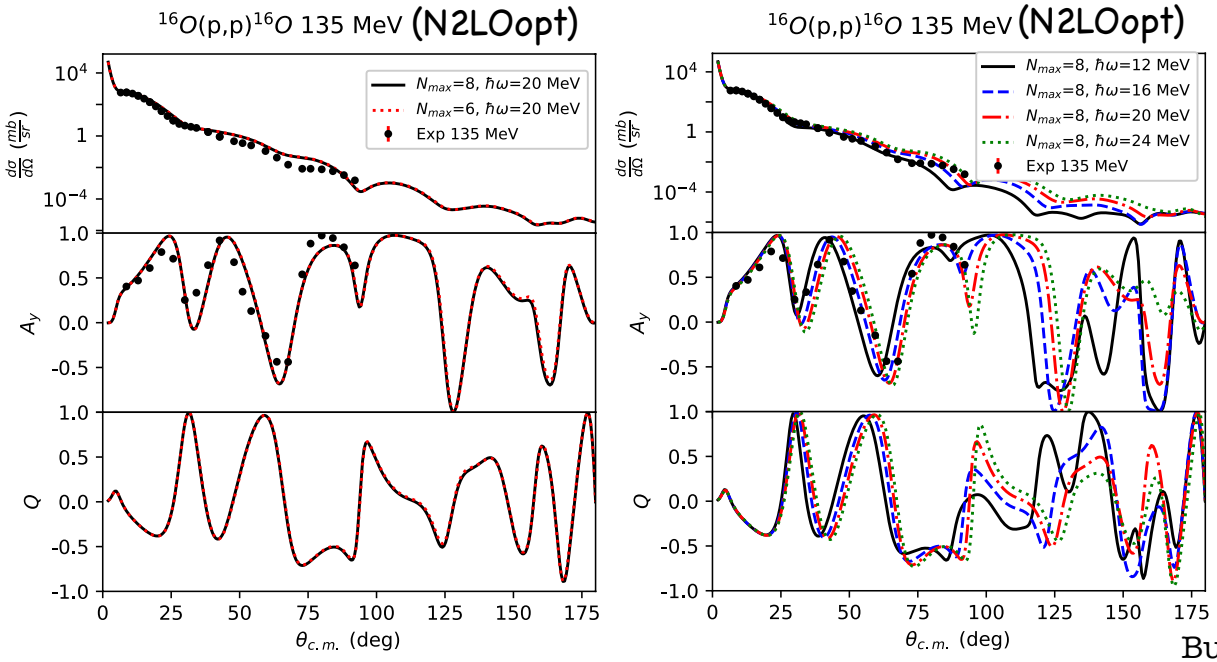
Scattering observables from first principles

^{6}Li, Non-local densities



Burrows, Elster, Popa, Launey, Nogga, Maris, Phys. Rev. C 97 (2018) 024325

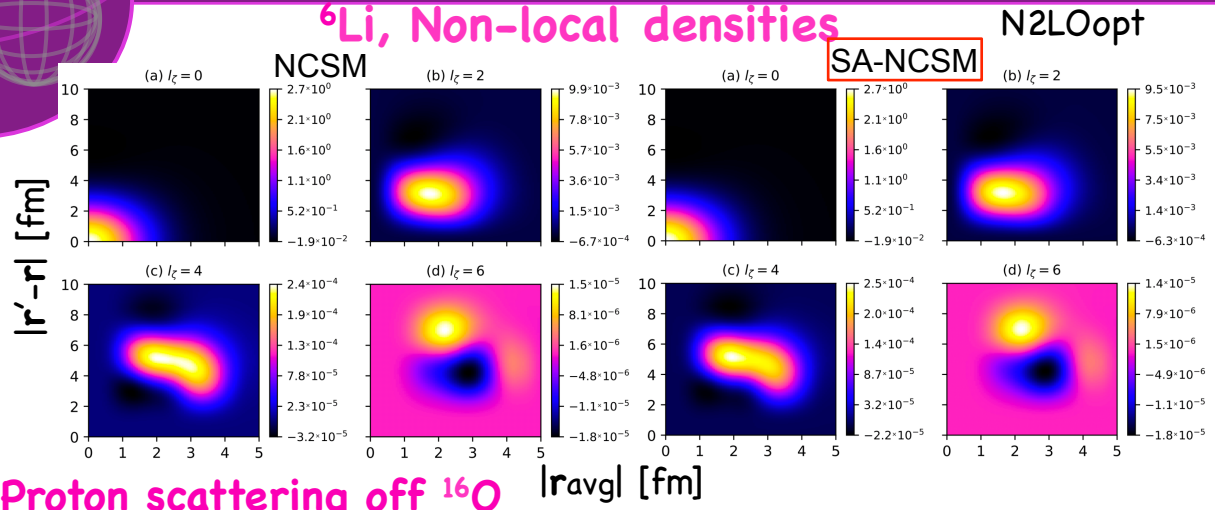
Proton scattering off ^{16}O



Burrows, et al., in preparation (2018)

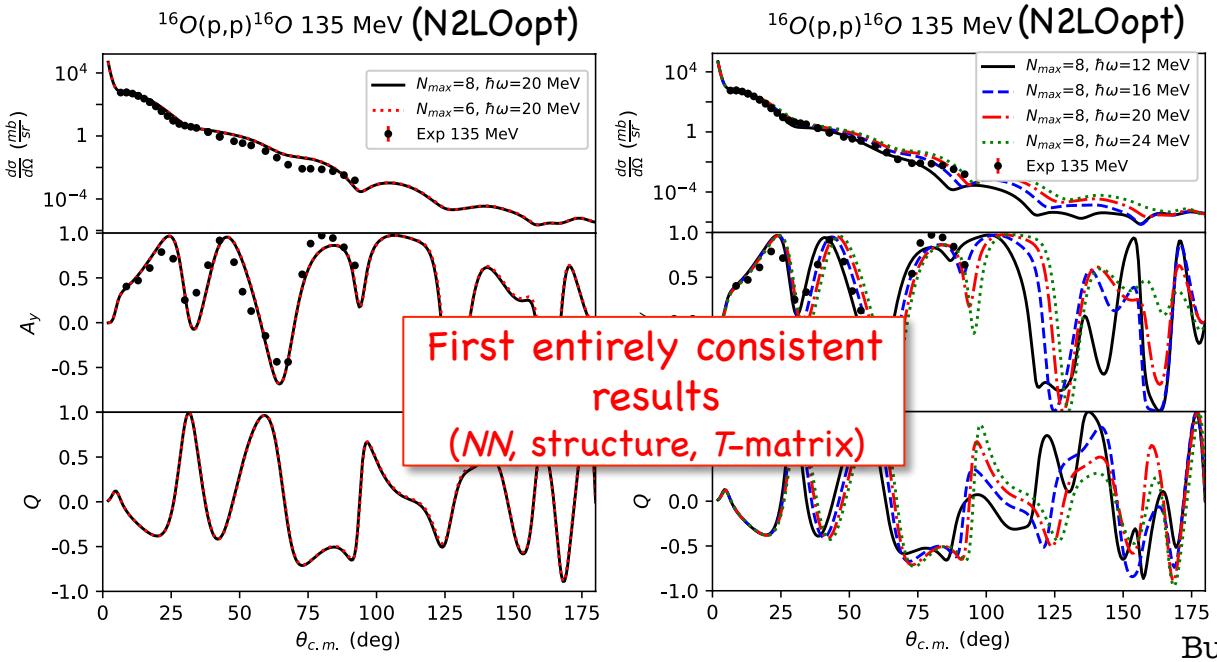
Scattering observables from first principles

^{6}Li, Non-local densities



Burrows, Elster, Popa, Launey, Nogga, Maris, Phys. Rev. C 97 (2018) 024325

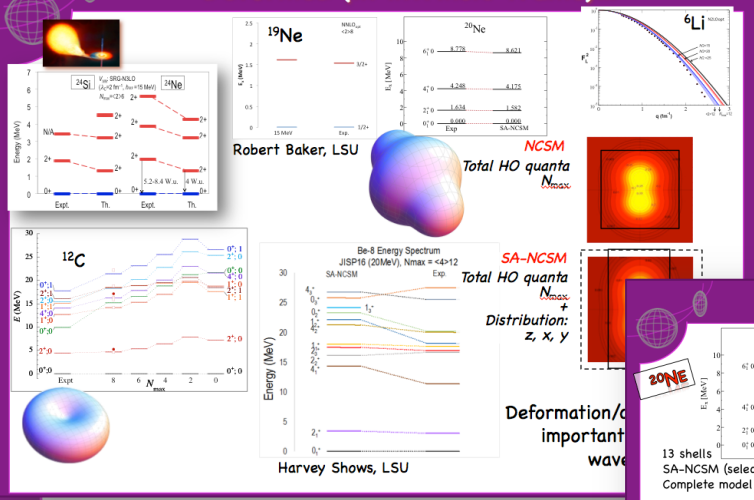
Proton scattering off ^{16}O



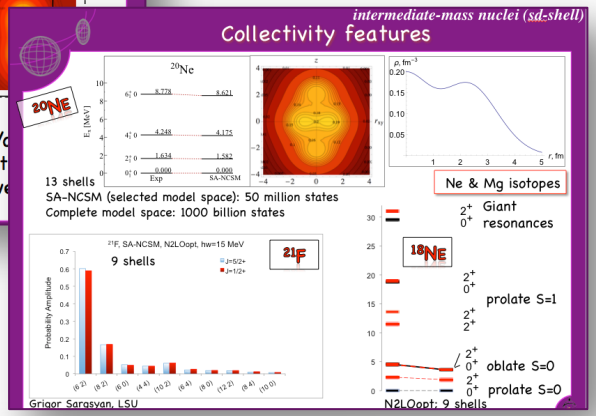
First entirely consistent results (*NN*, structure, *T*-matrix)

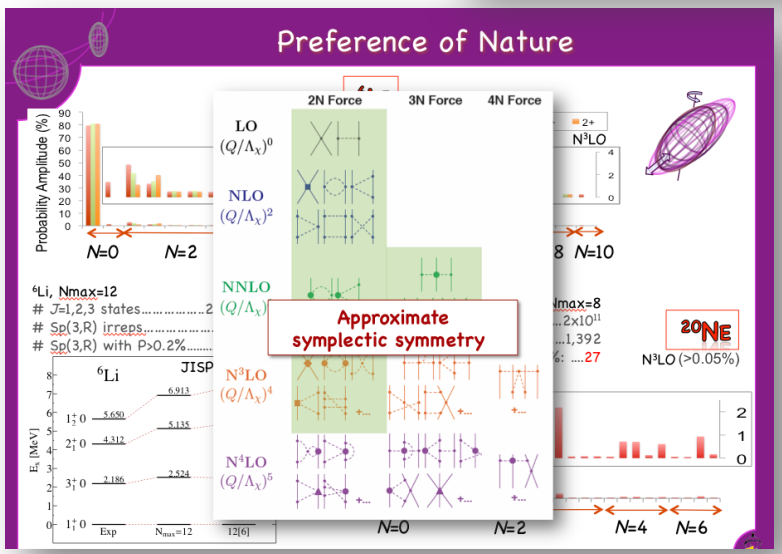
Burrows, et al., in preparation (2018)

Conclusions

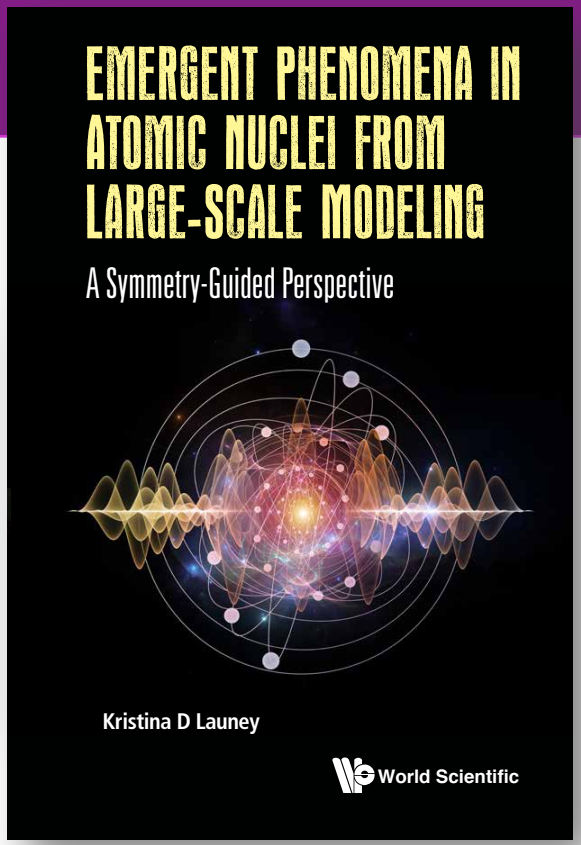


Collective/clustering features
up to medium-mass nuclei
from first principles





Simple physics: "shape" + vibrations + rotations



John L Wood
Calvin W Johnson
David J Rowe
Jutta E Escher
Thomas Luu & Andrea Shindler
Dean Lee
Yasuyuki Suzuki & Wataru Horiuchi
Jerry P Draayer & Tomas Dytrych
Yoram Alhassid
George Rosensteel
Feng Pan & Xin Guan