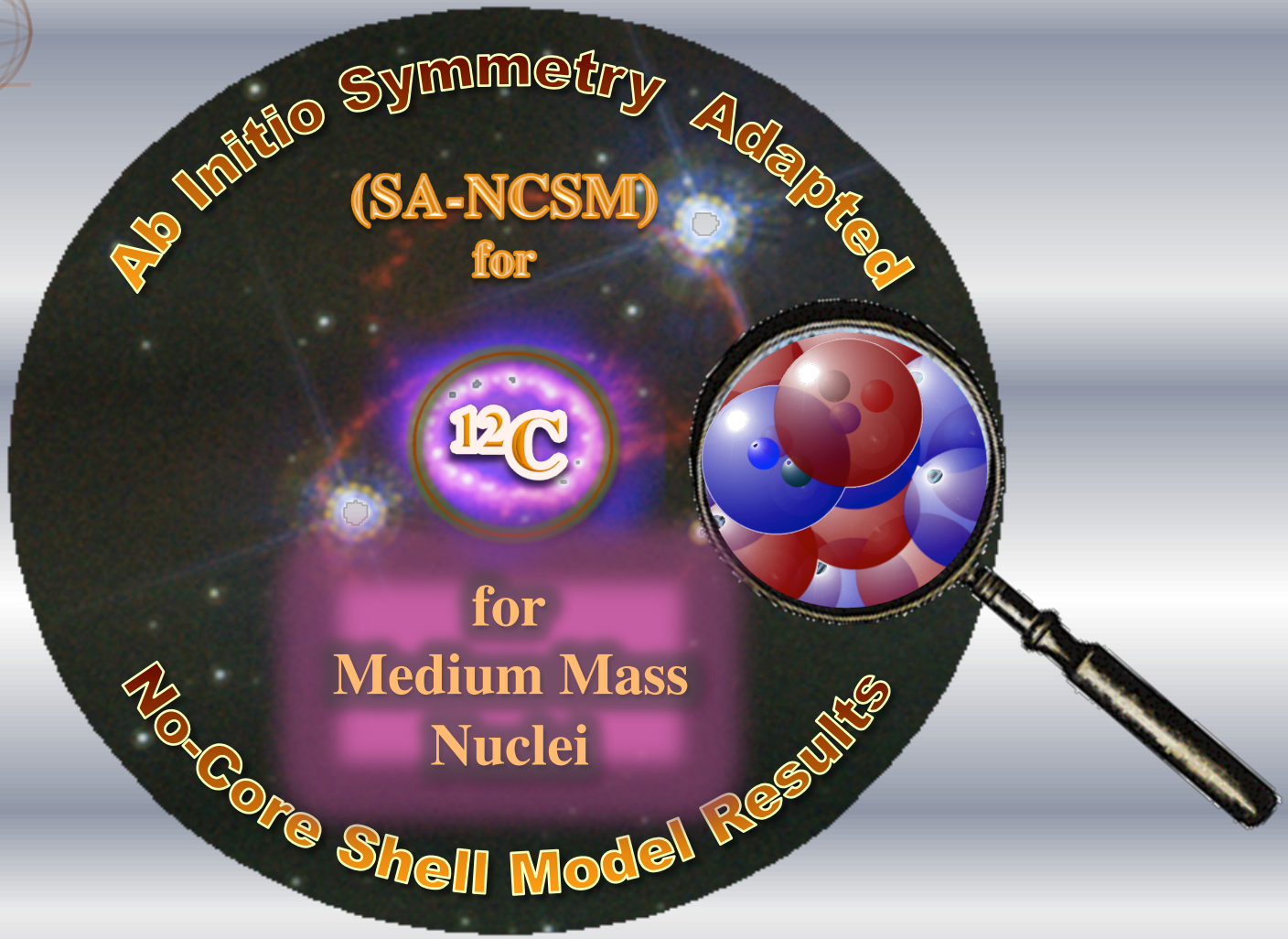
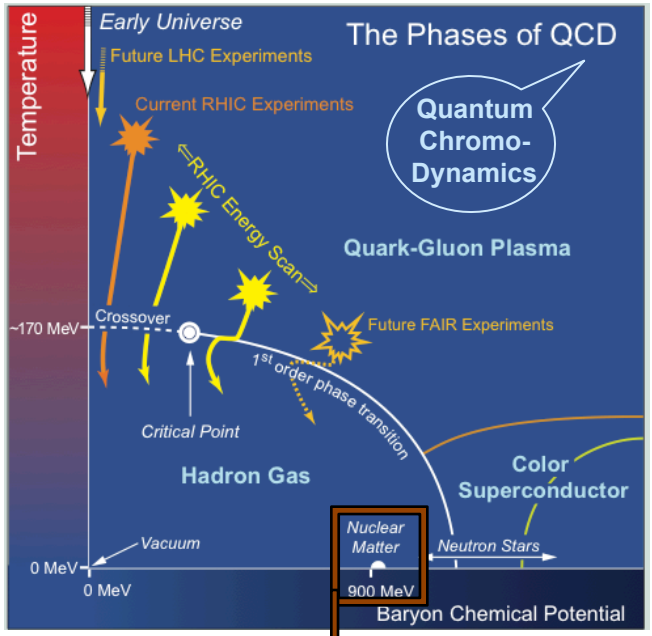


PIs: Jerry P. Draayer, Kristina D. Launey, Tomas Dytrych; Post-Doc Alexis Mercenne
Graduate Students: Alison C. Dreyfuss, Robert Baker, Grigor Sargsyan & David S. Kekejian

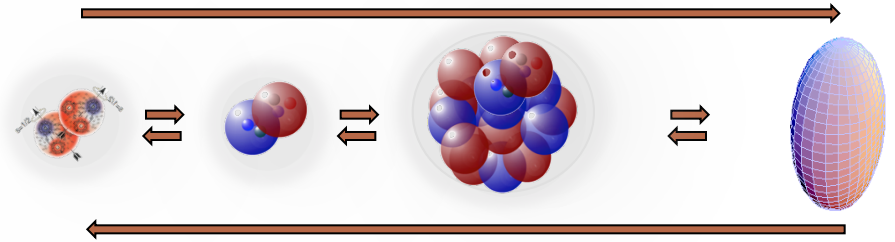
U.S. NSF & DOE Sponsored Research

… Overarching Framework …

… quarks and gluons …



"Condensed Matter Nuclear Physics"



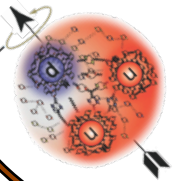
Fundamental Principles

Many-body Dynamics … "*ab initio*" …

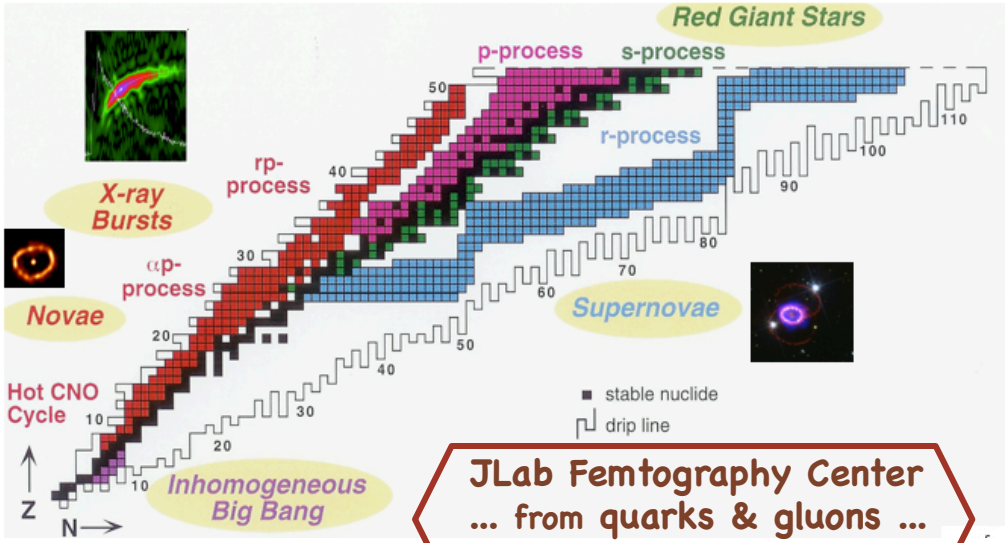
Collective Properties

… Surprises …

- Quark masses ~1% mass of a nucleon …
- Magnetization does not track charge distribution …
- Quark motion account for ~30% of total nucleon spin …

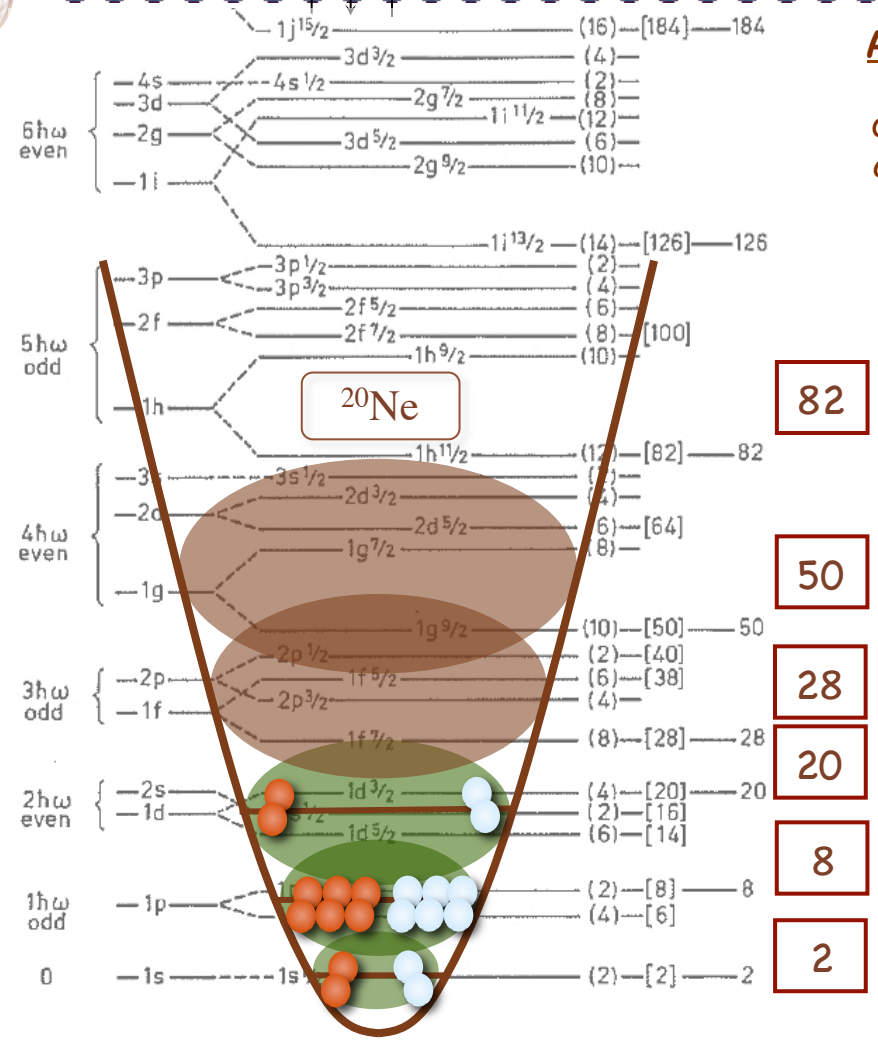


JLab 12GeV GlueX



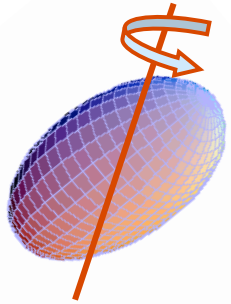
JLab Femtography Center
… from quarks & gluons …
… to nucleons & nuclei …

Shell Model Legacy Collective Model

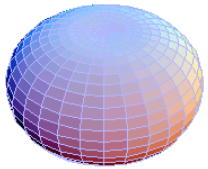


Maria Goeppert-Mayer & J. Hans D. Jensen (early 50s)
"...for their discoveries concerning nuclear shell structure ..."
(1963 Nobel Prize)

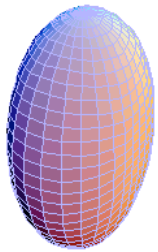
A.N. Bohr, B.R. Mottelson & J. Rainwater (late 50s)
"... for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection ..."
..." (1975 Nobel Prize)



rotations

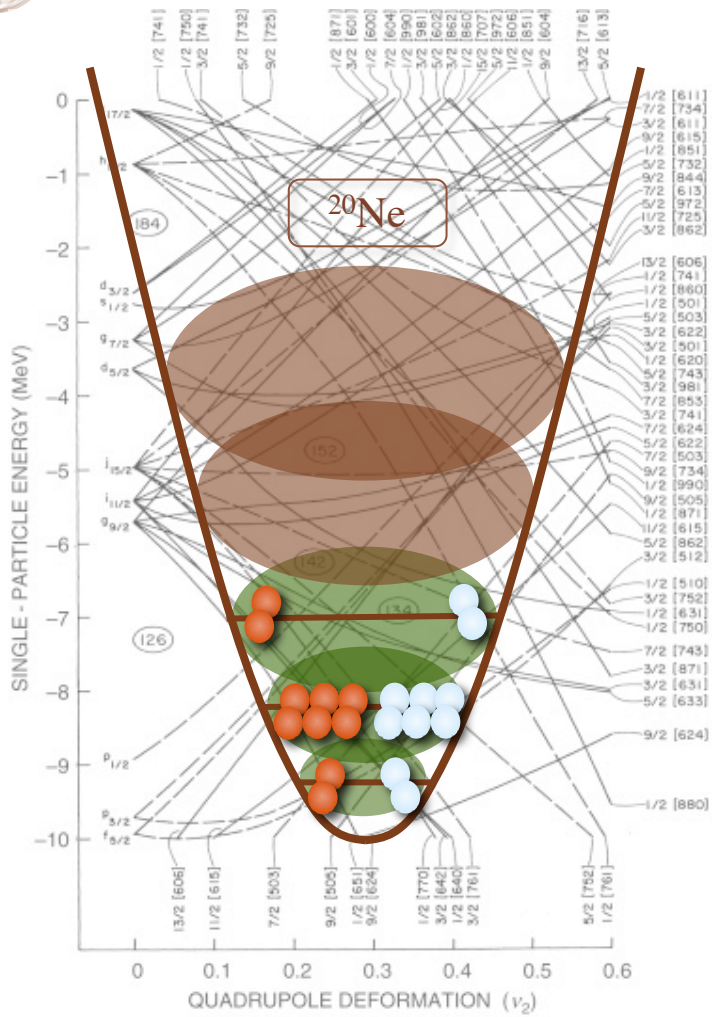


β vibrations

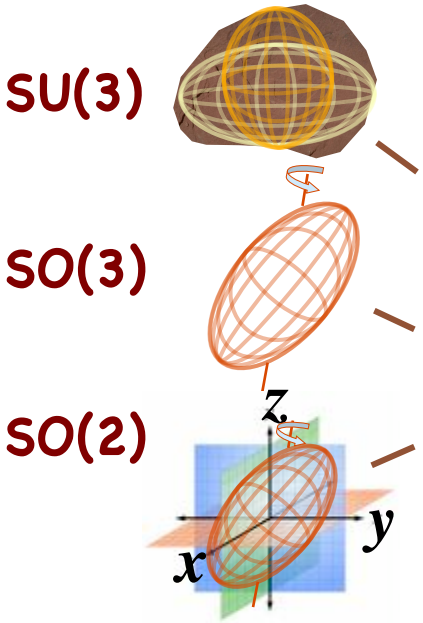


γ vibrations

Shell Model — Hybrid — Collective Model



Nilsson Model (1955)
- independent particles
- deformation <-> mean field

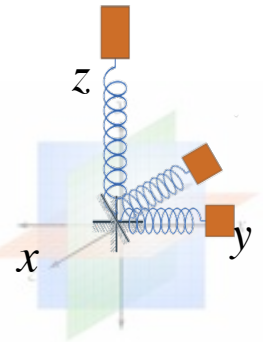


Elliott's SU(3) Model (1958)
- SU(3): symmetry of 3D H.O.
- SU(3)-adapted basis
- Valence shell

Deformation

Rotations

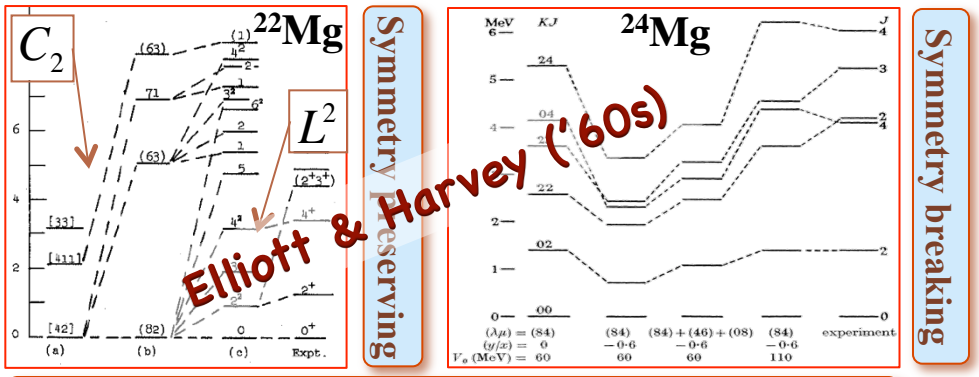
Space-Spin



Algebraic Methods

$$H = H_{HO} - \chi/_2\, Q \cdot Q$$

Gaussian Central Force

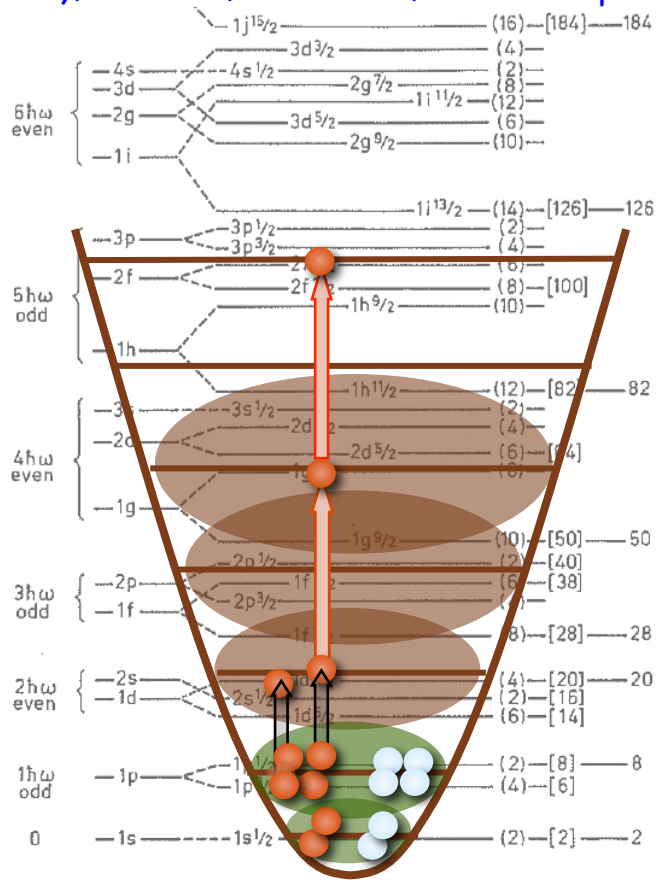


Dominance of few most deformed configurations

Shell Model — No-Core — Collective Model

No-Core Shell Model (NCSM)*

(Vary, Navratil, & Barrett, ~2000 to present)



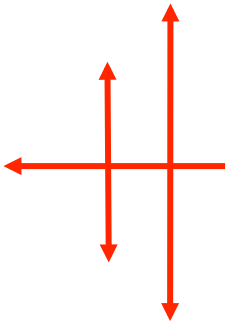
Symplectic Model (Sp-NCSM)*

(Rowe & Rosensteel, ~1980s to present)

- Sp(3,R) group structure
- SU(3) – symmetry adapted basis
- Schematic interactions

Typical Vertical Symplectic Slice

(monopole/quadrupole excitations, including 2p2h, 4p4h, …)



$0\hbar\Omega$ Elliott's SU(3)

*Realistic interaction (local or not; NN, NNN,…)

- *In principle,* exact solutions, up to N_{max}
- Successful description up through ^{16}O

*Multi-shell generalization of Elliott …

- No spurious center-of-mass motion
- Fully microscopic, equals NCSM if all symplectic slices included
- Reproduces rotational bands & B(E2) rates without effective charge

High Performance Computing Era*

Shell Model

NCSM

Coupled Cluster Theory

Monte Carlo Methods

.....

DOE

Edison (Berkeley)

Titan (Oak Ridge)

Aurora (Argonne)

... upgrades ...

HPC Era ...

NSF

Stampede, Wrangler } (TACC)

Blue Waters (NCSA)

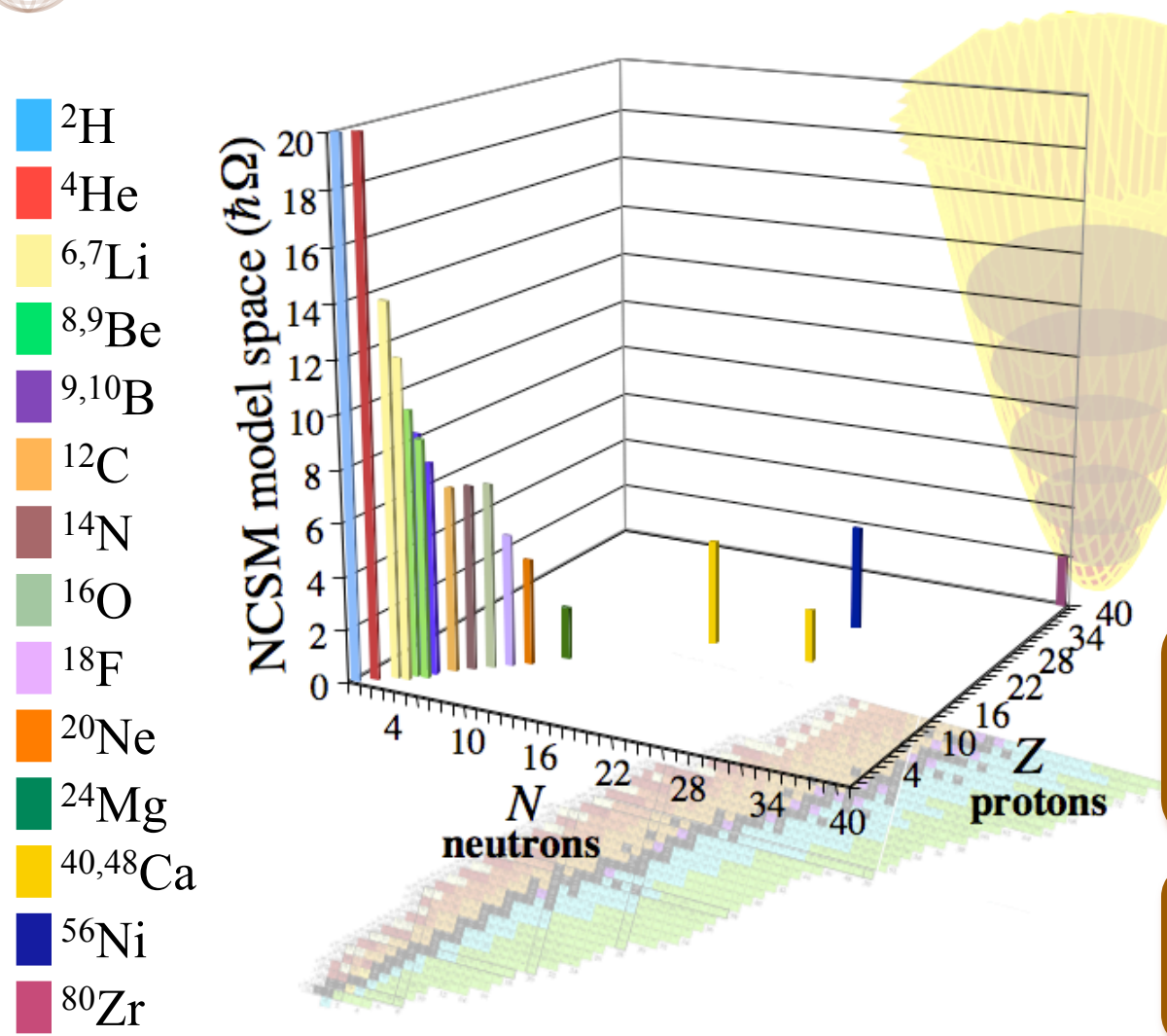
... upgrades ...

Collective Model

NCSM	SO(3)
SA-NCSM	SU(3)
NCSpM	Sp(3,R)
.....	

*21st Century – *Ab Initio* – Nuclear Physics

NCSM* / Applicability



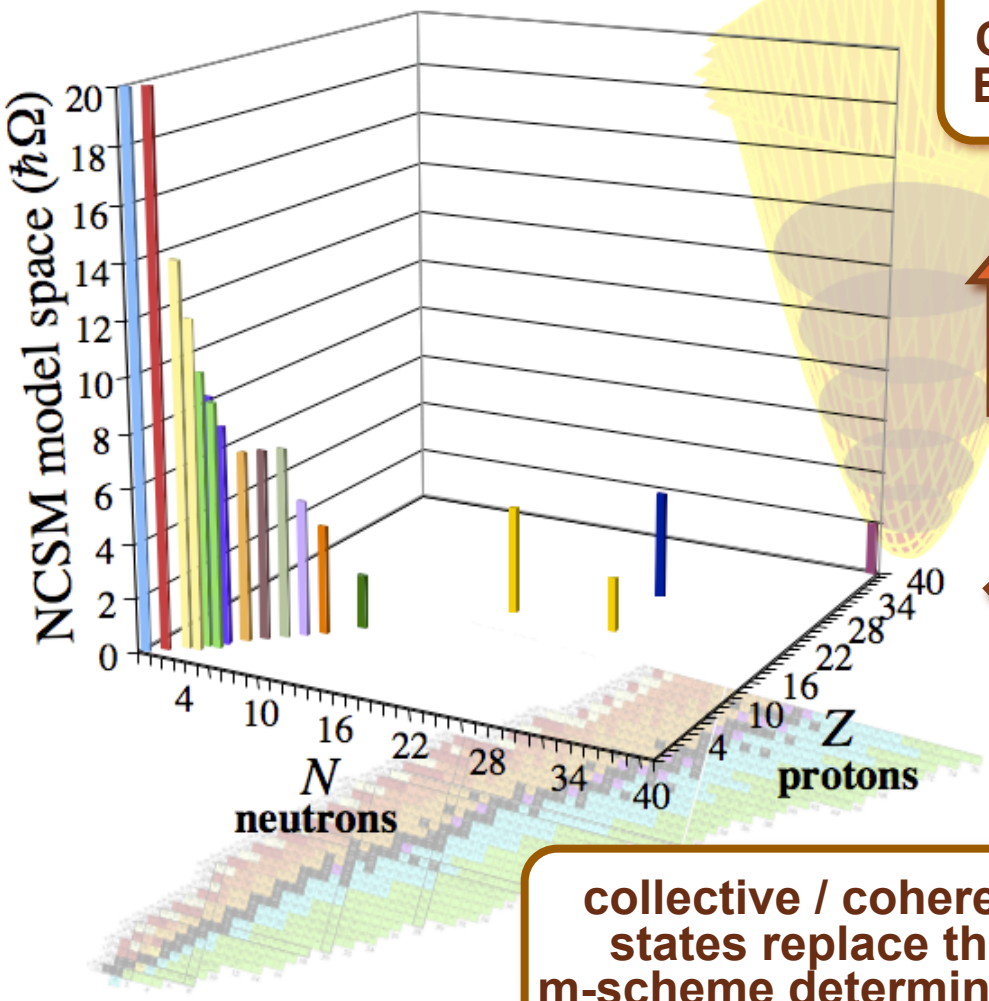
HPC
"WALL"
~10^{10}

Range of applicability limited by combinatorial growth in # of basis states (m-scheme "arithmetic")

*No-Core Shell Model
J. P. Vary, P. Navratil
& B. R. Barrett ~ 2000

SA-NCSM* / Extended Applicability

^{2}H
^{4}He
^{6,7}Li
^{8,9}Be
^{9,10}B
^{12}C
^{14}N
^{16}O
^{18}F
^{20}Ne
^{24}Mg
^{40,48}Ca
^{56}Ni
^{80}Zr



Highly deformed modes, Cluster-like configurations, B(E2) w/o effective charges

'higher' spaces

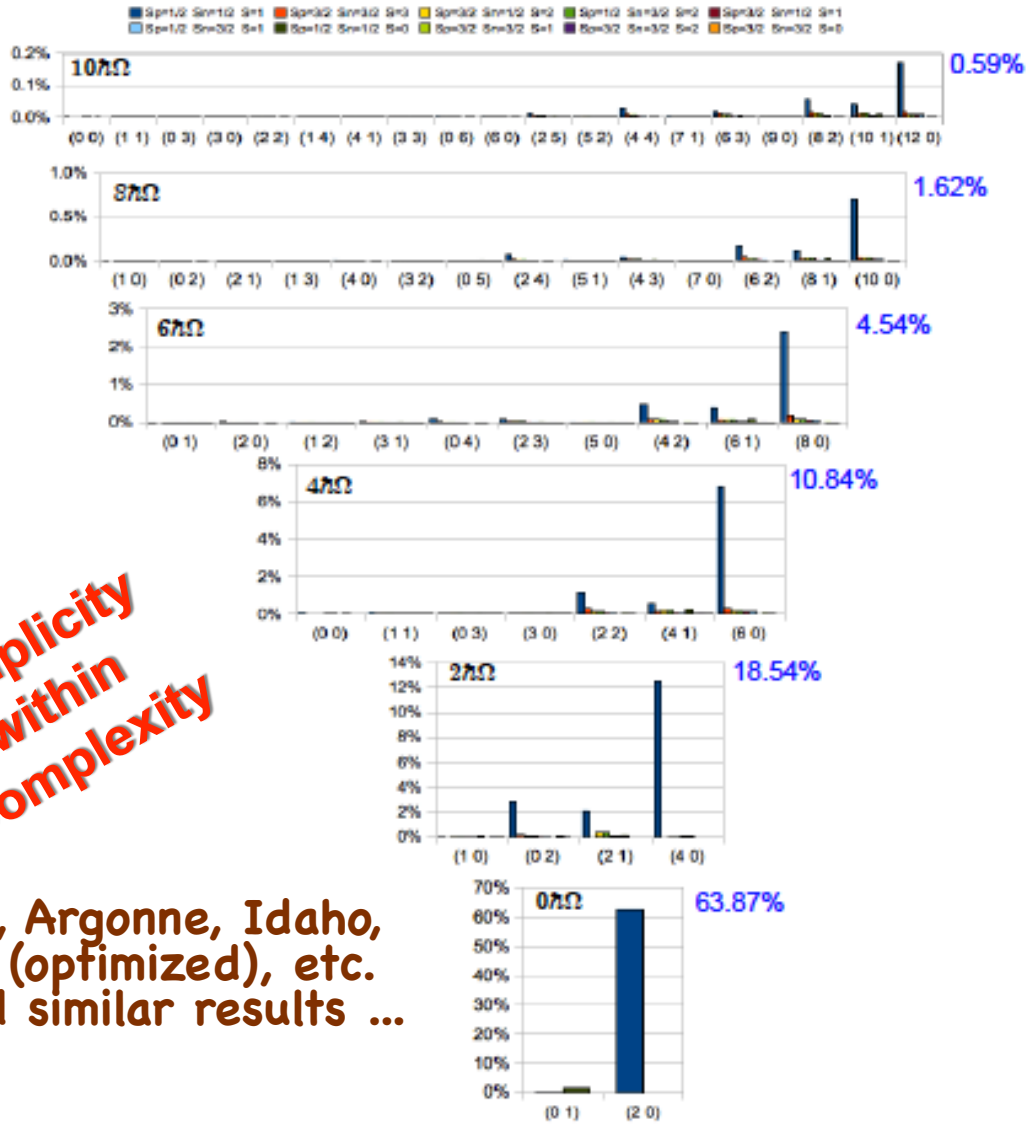
'heavier' nuclei

… enables …

*Symmetry Adapted NCSM ~2005

collective / coherent states replace the m-scheme determinants

First Results for ^{6}Li with N_{max} = 10



Simplicity within Complexity

*Bonn, Argonne, Idaho, N3LO (optimized), etc. … yield similar results …

… Proof of Principle …

> 99% of Physics In < 1% of the "reorganized" space

JISP16* bare interaction in Nmax = 10 space with $\hbar\Omega$ = 20 MeV

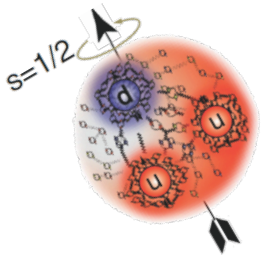
… Team Work …

Many "helps" along the way … e.g., James Vary making his NCSM available to us, Mark Caprio (ND) visiting LSU on a sabbatical, along with quality input from Anna Hayes of LANL, various collaborators from Bulgaria, China, Mexico, and so on. Also to NSF for a PetaApps award, and DOE for an EPSCoR grant, plus SURA for release time and financial assistance with postdoc team!

Simple Picture

$| \Psi_{total} > = | \Psi_{space} > x | \Psi_{spin} >$ (or $| \Psi_{total} > = | \Psi_{space} > x | \Psi_{spin-isospin} >$)

Usually consider "point particles" with spin, or spin-isospin, or SU(4) -> $SU_{spin}(2)$ x $SU_{isospin}(2)$; ignore $SU_{color}(3)$, or input these features through chiral effective interactions of a specific particle rank, namely 0-body + 1-body + 2-body + 3-body + 4-body etc.)



QCD Connection

$| \Psi_{space} > \rightarrow | \Psi_{slater-determinate} >$ (typical m-schemes LS or jj coupling)

$| \Psi_{algebraic-models} >$ (approximate boson/fermion symmetries)

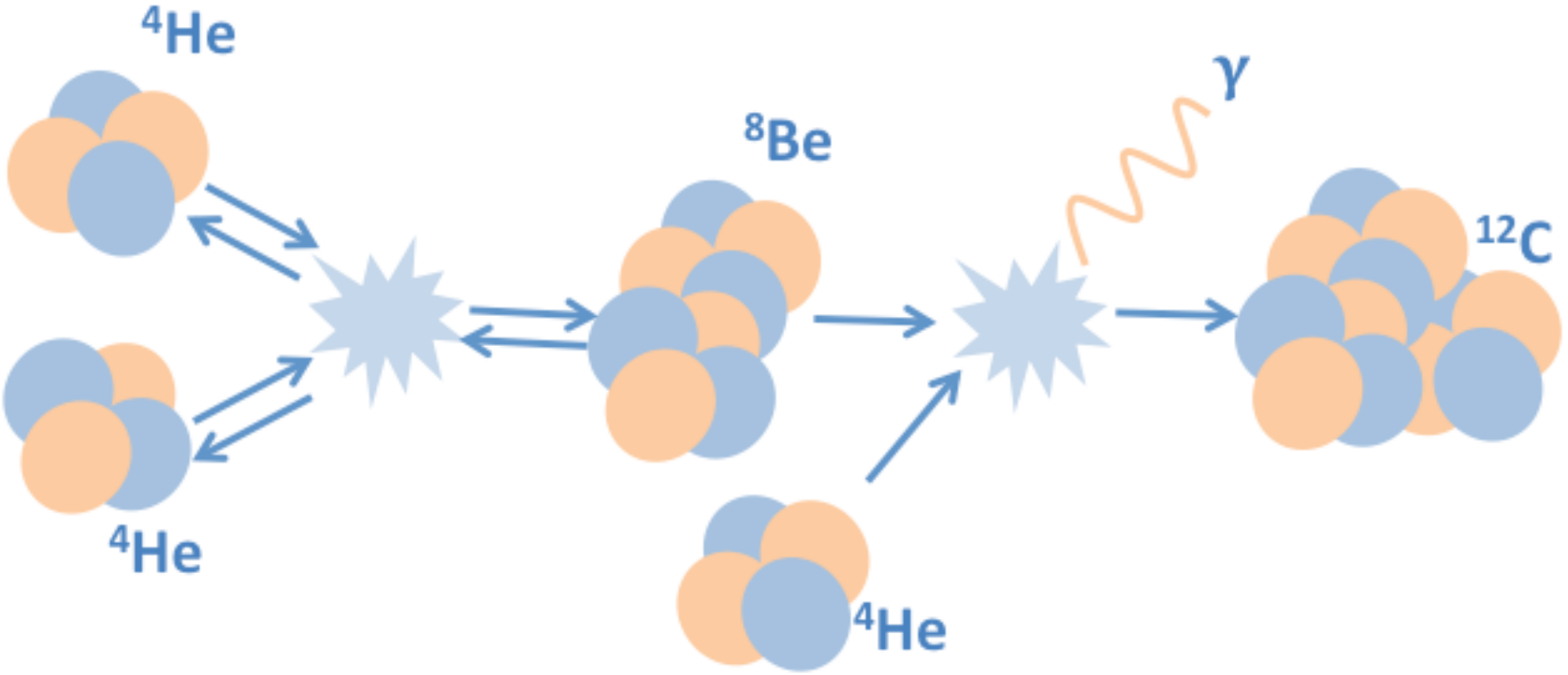
$| \Psi_{collective-state-modes} >$ (collective configuration dominance)

Next demonstrate (via many examples / results) that a collective state representation for $| \Psi_{space} >$ is a smart and wise choice for basis states!

Looking ahead to work with HE/LE NP communities to integrate the symmetry adapted *ab initio* features of strong interaction in $| \Psi_{spin} >$?

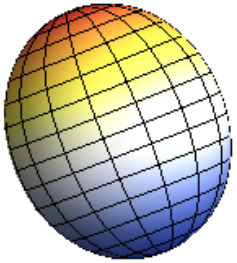
Pushing NC-Shell / Cluster Connection

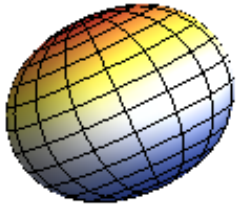
Creation of ^{12}C in hot stars



… The elusive Hoyle state …

Three Slice Scenario (legacy / modern)





^{12}C

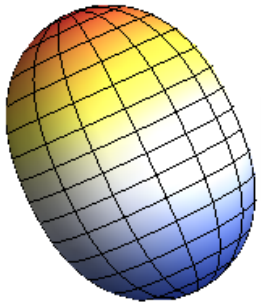
0*p*-0*h*

2*p*-2*h*

4*p*-4*h*

(6 2) *Bandhead*
(*Triaxial*)

(0 4) *Bandhead*
(*Oblate*)



(12 0) *Bandhead*
(*More Prolate*)

Main contribution to the 0_3^+

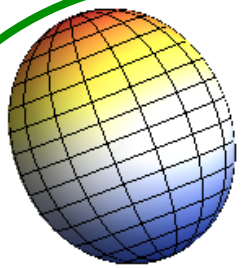
Main contribution to ground state rotational band ($0_{g.s.}^+$, 2_1^+, 4_1^+)

Main contribution to Hoyle state (0_2^+)

'Back to the Future'
– *déjà vu* –
Engeland & Ellis '67s

Choose Three Slices (NCSpM View)

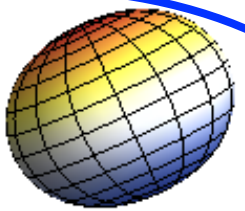
^{12}C



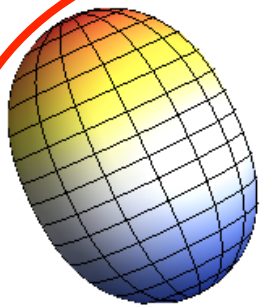
2p-2h

(6 2) Bandhead
(Prolate)

0p-0h



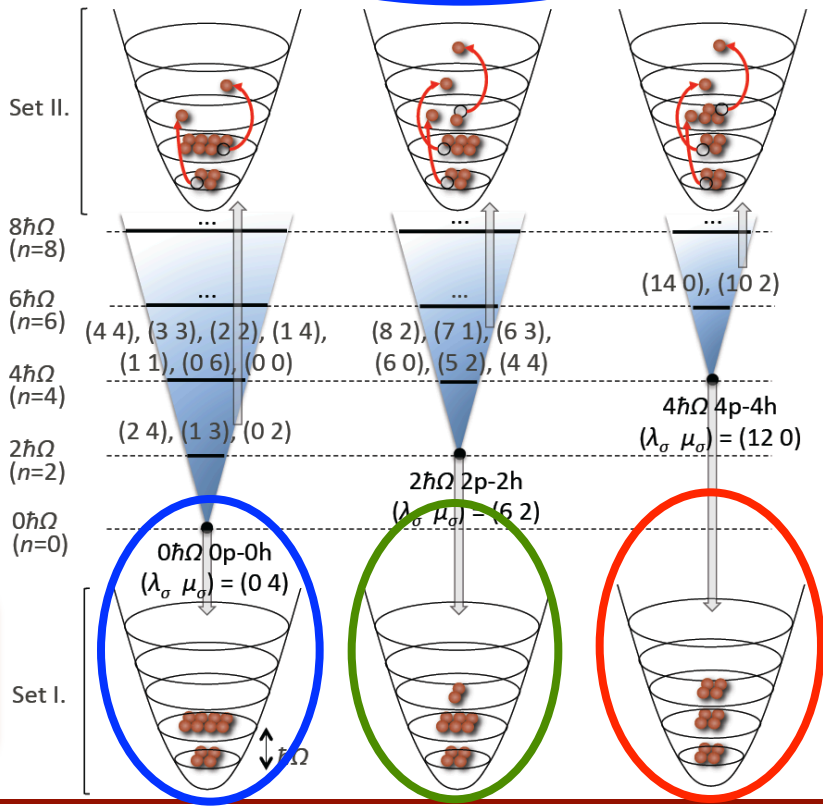
(0 4) Bandhead
(Oblate)



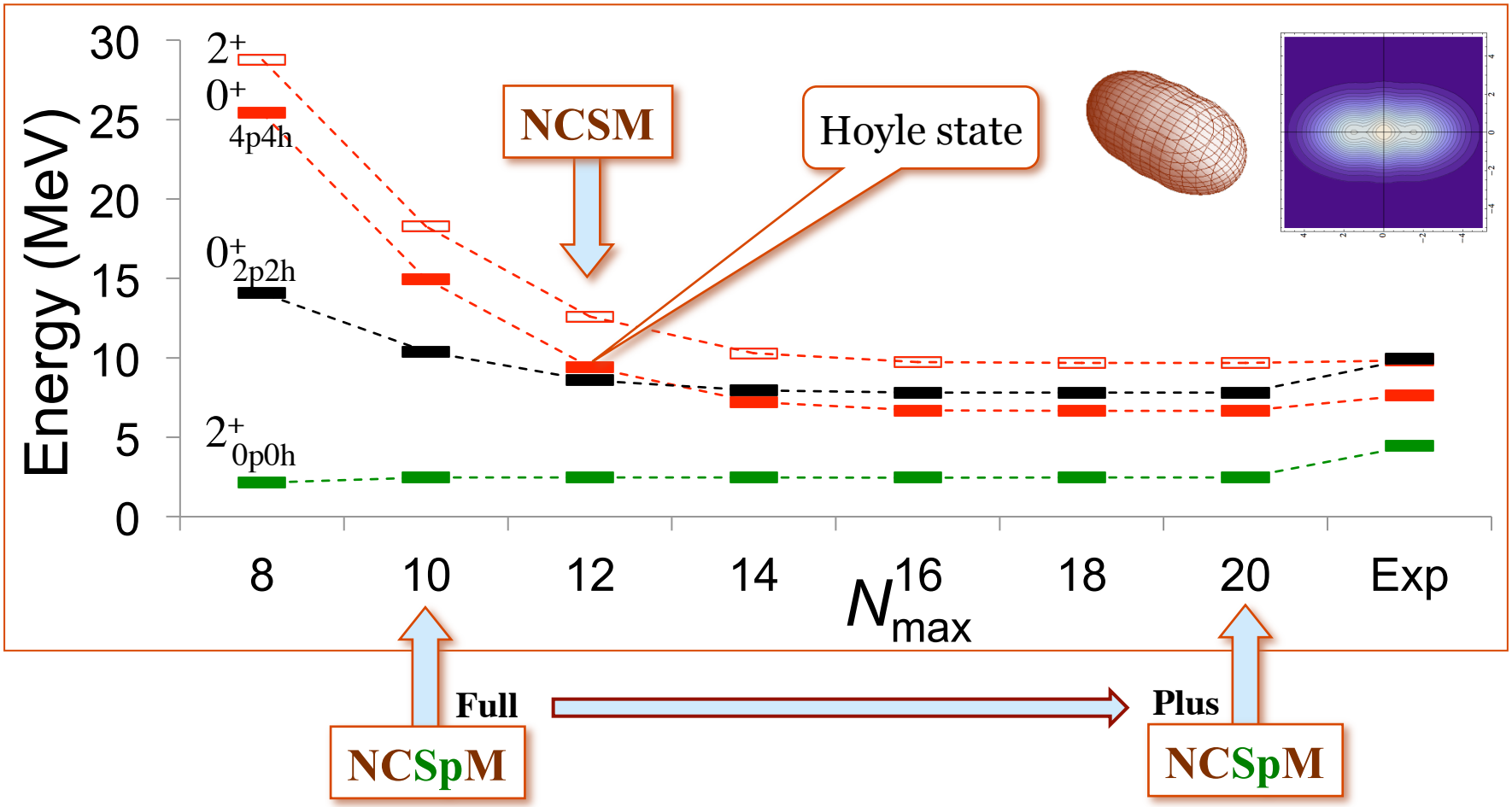
4p-4h

(12 0) Bandhead
(More Prolate)

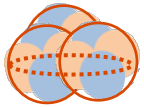
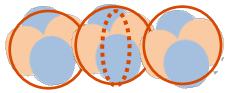
Intertwining Shell & Alpha Cluster Picture

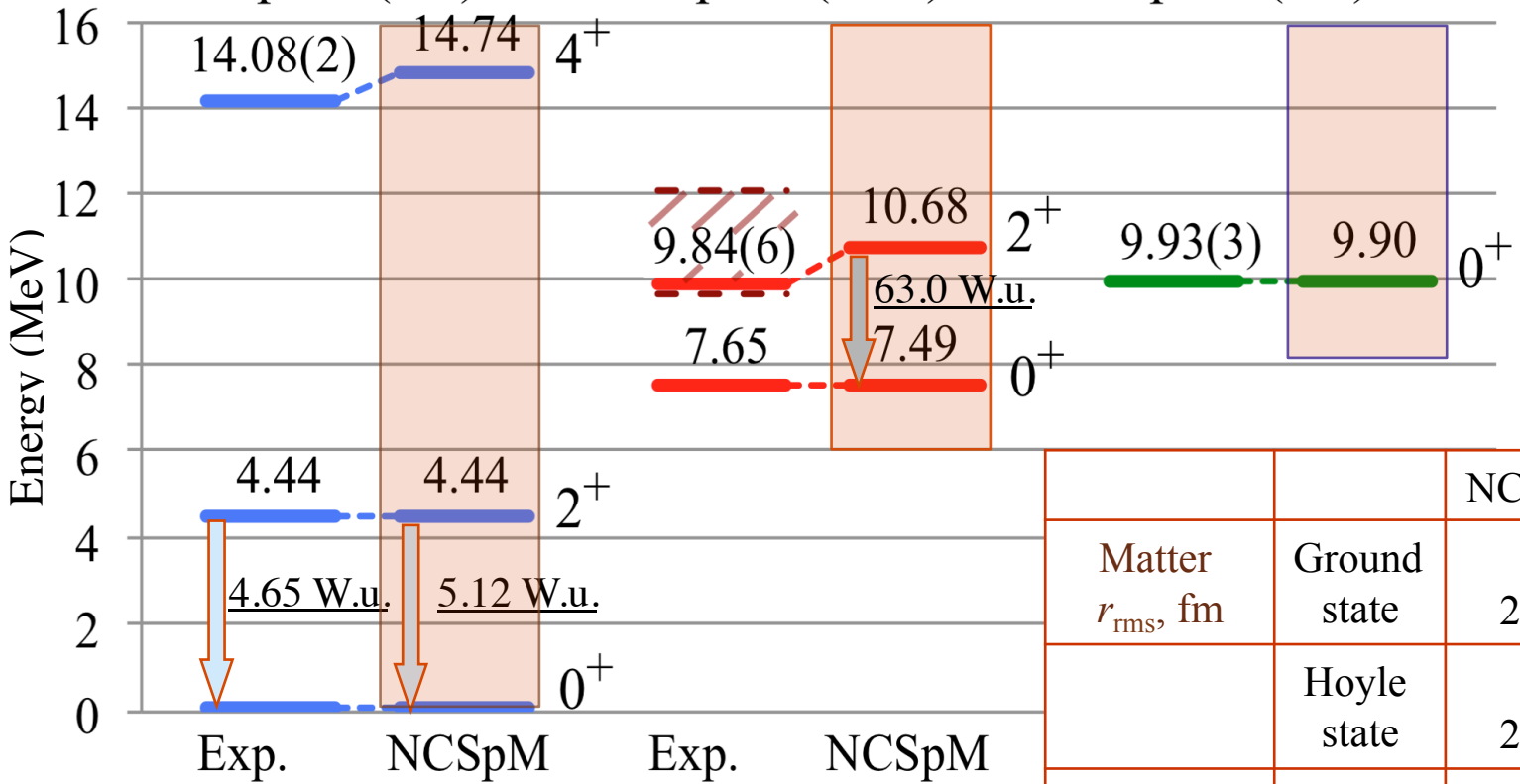


^{12}C: Systematics (Function of N_{max})



^{12}C Observables – Negative Parity

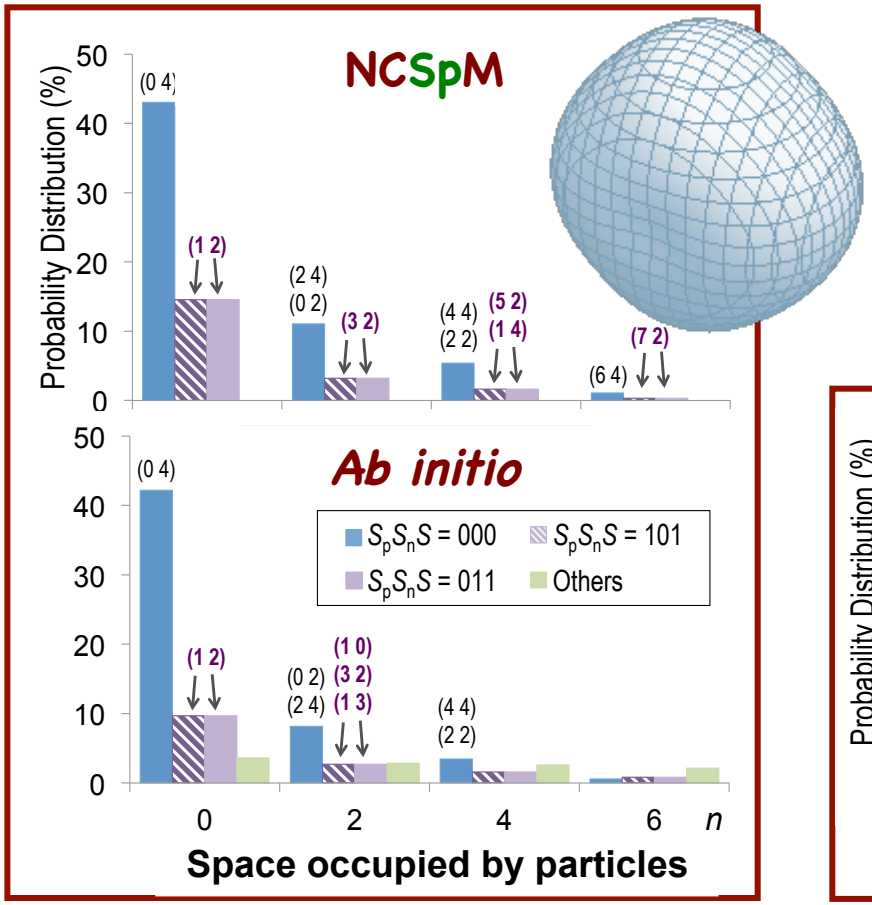


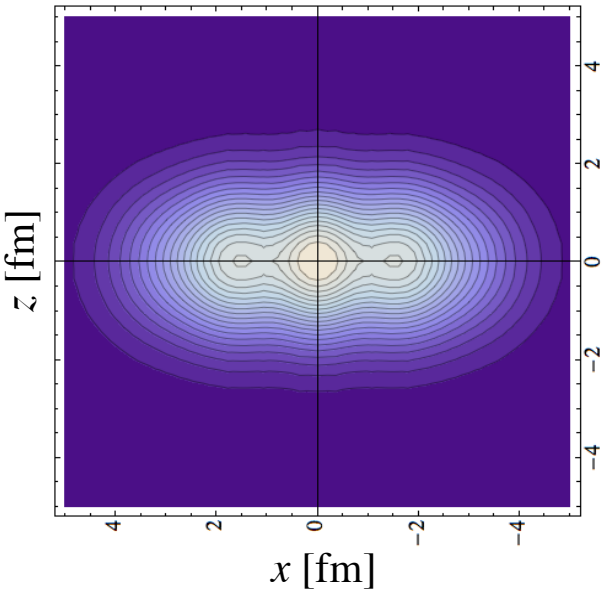
		NCSpM	Exp
Matter r_{rms}, fm	Ground state	2.44	2.43(2)
	Hoyle state	2.93	N/A
Q, e fm^2	2_1^+	+6.62	+6(3)
	2_2^+	–20.61	N/A

Formation of Clusters!

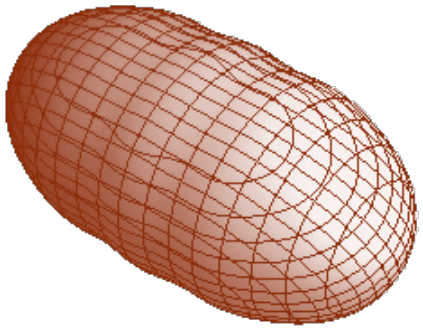
Ground state

Agrees with first-principle results in smaller spaces

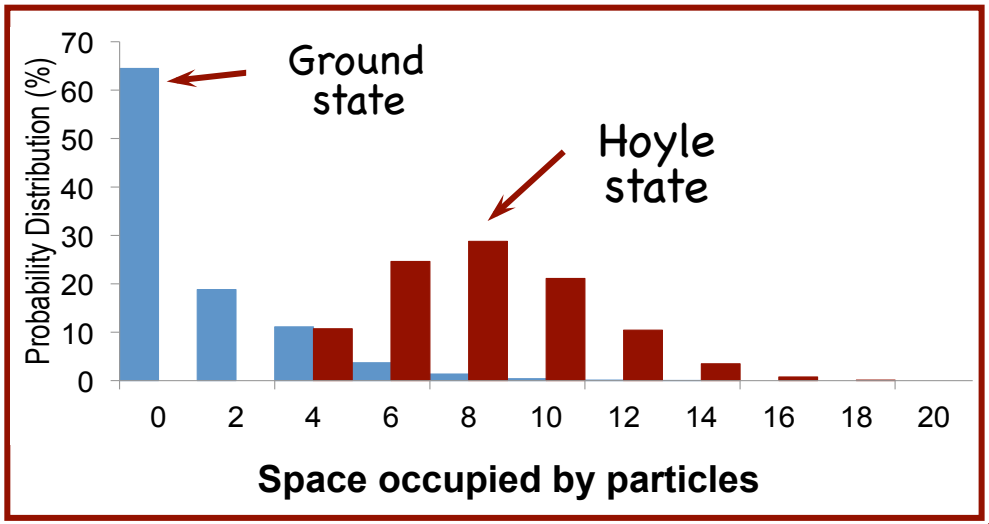




Hoyle state

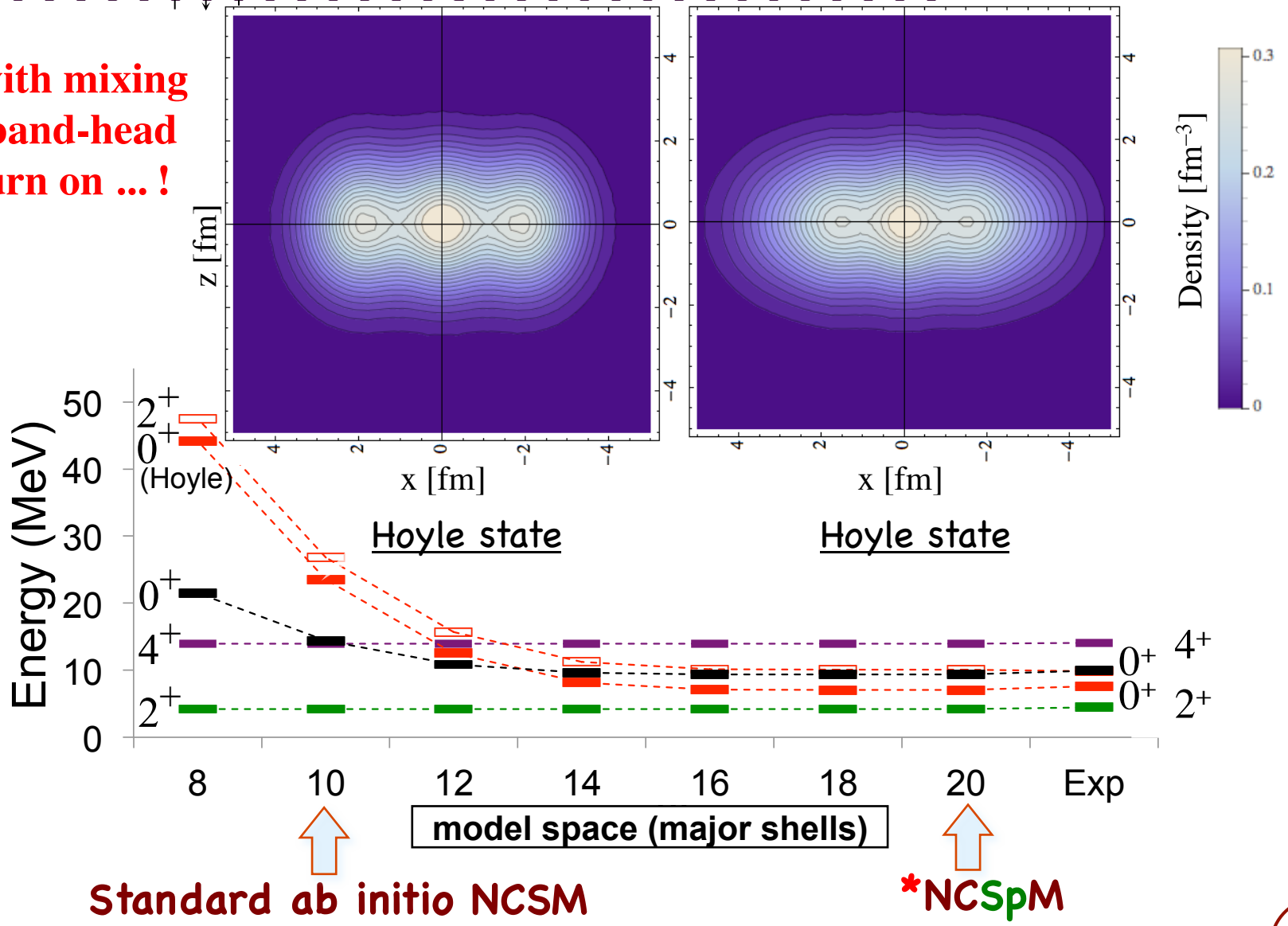


Needs at least 18-20 shells



Formation of Clusters!

*Now with mixing at the band-head level turn on ... !



Review Article – PPNP 89 (2016) 101-136

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journal homepage: www.elsevier.com/locate/ppnp

Review

Symmetry-guided large-scale shell-model theory

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Clusters
Hoyle state
Orderly patterns in nuclei from first principles

ABSTRACT

In this review, we present a symmetry-guided strategy that utilizes exact as well as partial symmetries for enabling a deeper understanding of and advancing *ab initio* studies for determining the microscopic structure of atomic nuclei. These symmetries expose physically relevant degrees of freedom that, for large-scale calculations with QCD-inspired interactions, allow the model space size to be reduced through a very structured selection of the basis states to physically relevant subspaces. This can guide explorations of simple patterns in nuclei and how they emerge from first principles, as well as extensions of the theory beyond current limitations toward heavier nuclei and larger model spaces. This is illustrated for the *ab initio* symmetry-adapted no-core shell model (SA-NCSM) and two significant underlying symmetries, the symplectic Sp(3, ℝ) group and its deformation-related SU(3) subgroup. We review the broad scope of nuclei, where these symmetries have been found to play a key role—from the light *p*-shell systems, such as ^{6}Li, ^{8}B, ^{8}Be, ^{12}C, and ^{16}O, and *sd*-shell nuclei exemplified by ^{20}Ne, based on first-principle explorations; through the Hoyle state in ^{12}C and enhanced collectivity in intermediate-mass nuclei, within a no-core shell-model perspective; up to strongly deformed species of the rare-earth and actinide regions, as investigated in earlier studies. A complementary picture, driven by symmetries dual to Sp(3, ℝ), is also discussed. We briefly review symmetry-guided techniques that prove useful in various nuclear-theory models, such as Elliott model, *ab initio* SA-NCSM, symplectic model, pseudo-SU(3) and pseudo-symplectic models, *ab initio* hyperspherical harmonics method, *ab initio* lattice effective field theory, exact pairing–plus–shell model approaches, and cluster models, including the resonating-group method. Important implications of these approaches that have deepened our understanding of emergent phenomena in nuclei, such as enhanced collectivity, giant resonances, pairing, halo, and clustering, are discussed, with a focus on emergent patterns in the framework of the *ab initio* SA-NCSM with no *a priori* assumptions.

... Also ...

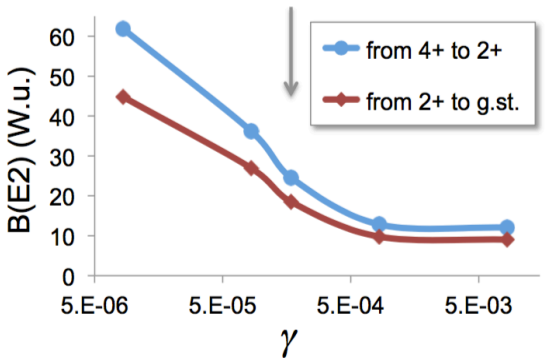
– Kristina Launey –
"State of the Art in Nuclear Cluster Physics"
(**SOTANCP3**)
Yokohama, Japan
May 26-30, 2014

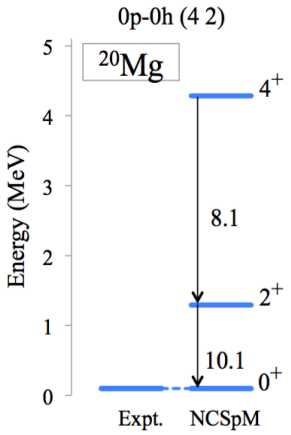
&

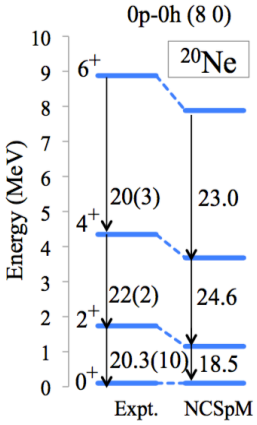
– Kristina Launey –
"State of the Art in Nuclear Cluster Physics"
(**SOTANCP4**)
Galveston, Texas, USA
May 13-18, 2018

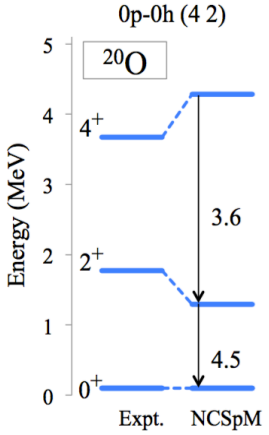
Medium Mass Nuclei (Gregory Tobin / REU)

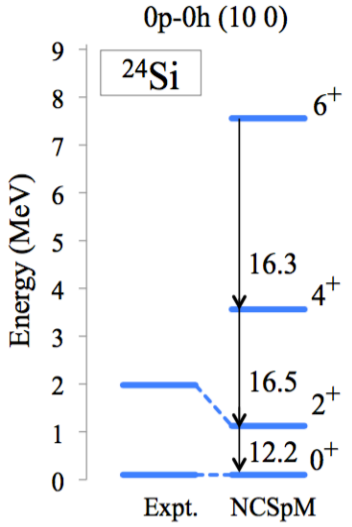
Ne-20: grey arrow is gamma used

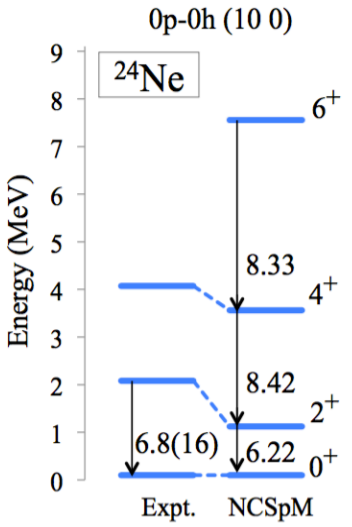


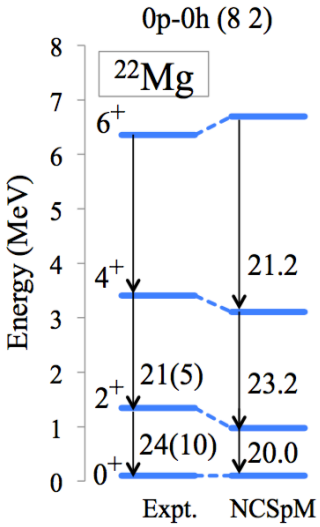


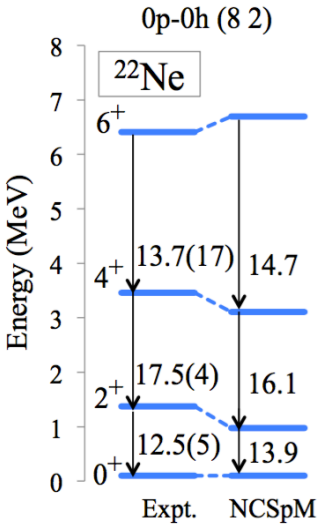






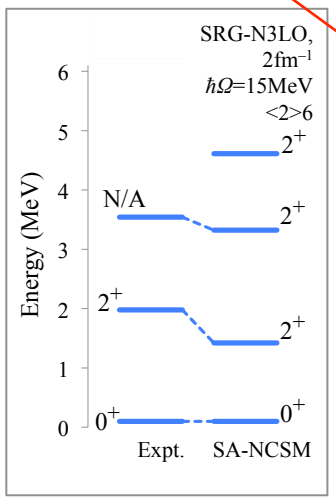


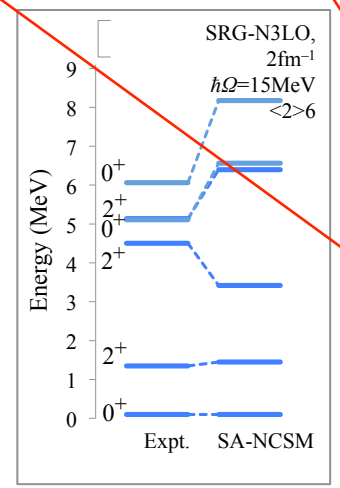


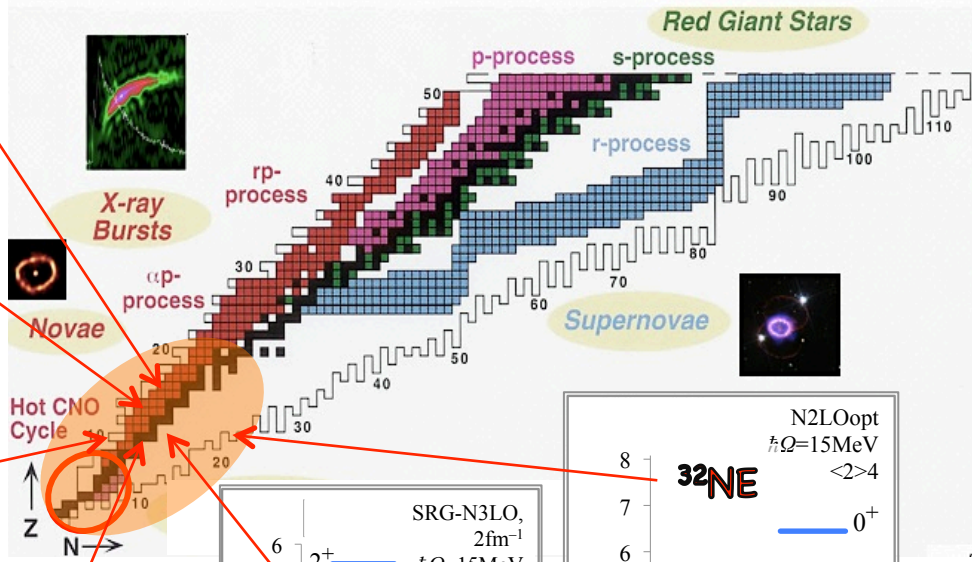


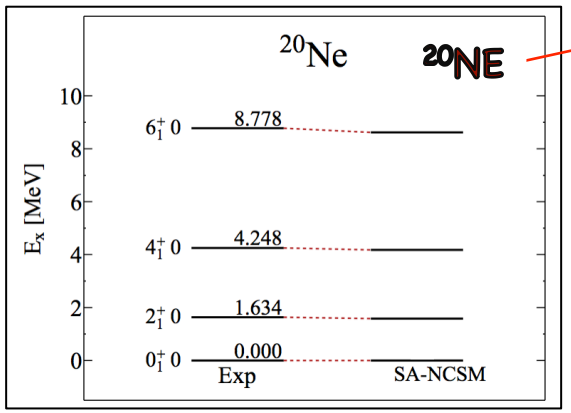
Further sd-shell Results (Robert Baker / GS)

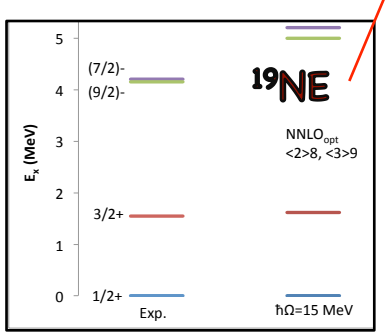
Selected (pre-thesis) Examples (Now onto Beta Decay)

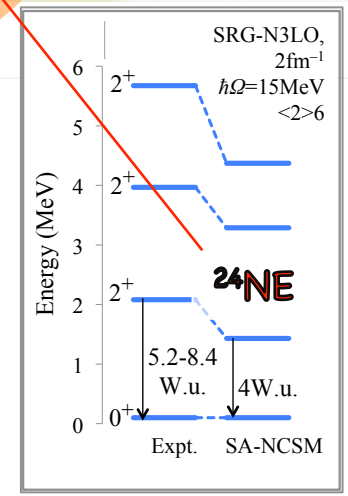


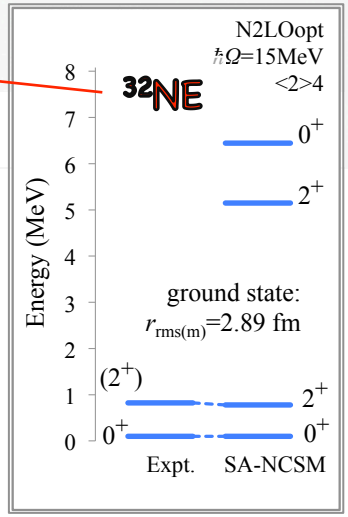








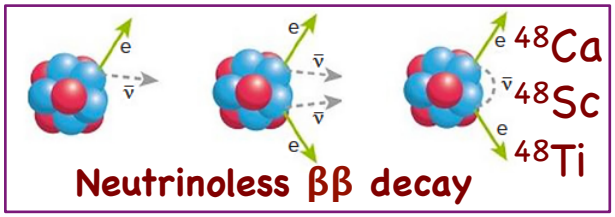




Ab initio description (converged selected spaces) (NNLO$_{opt}$, ħΩ=15 MeV, 13 HO shells)

Plus fp-shell Results (Grigor Sargsyan / GS)

^{48}Ca



Neutrinoless ββ decay

^{48}Ti

8 shells, N2LOopt

0^+

SA-NCSM (selected): 966,152

Complete model space: 3,162,511,819

2^+

SA-NCSM (selected): 3,055,554

Complete model space: ... 14,522,234,982

8 shells, N2LOopt

0^+

SA-NCSM (selected): 602,493

Complete model space: 24,694,678,414

2^+

SA-NCSM (selected): 1,178,834

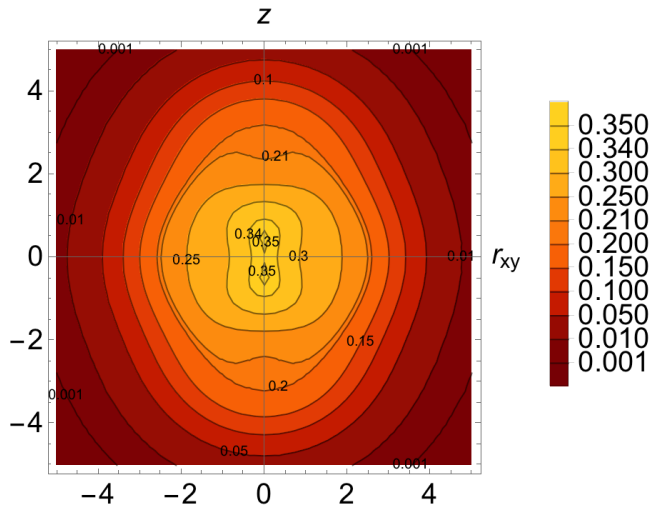
Complete model space: 113,920,316,658

^{48}Ti, Q(2^+) [e fm^2]

Experiment ..... -17.7

8 shells ..... -19.3

(no effective charges)



Reaction Theory (Alexis Mercenne / PDoc)

Nucleosynthesis: Type I X-Ray Burst

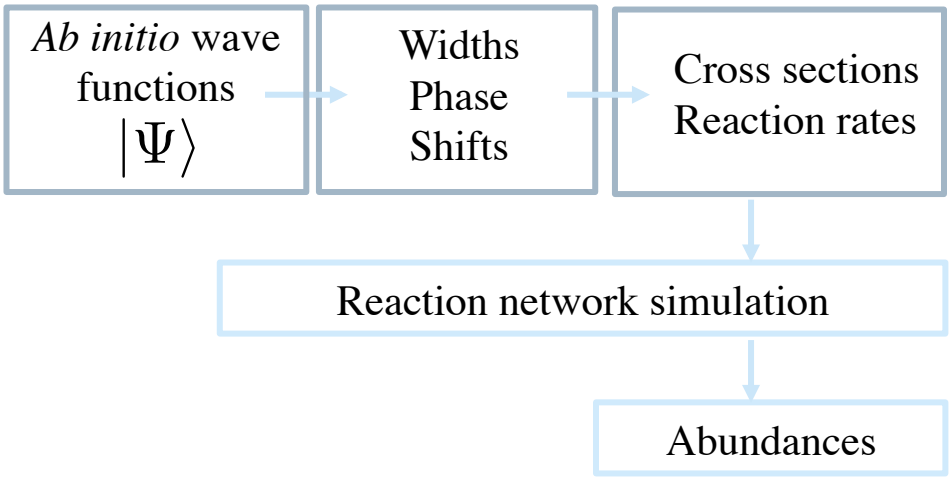
TABLE 2
REACTIONS THAT IMPACT THE BURST LIGHT CURVE IN THE MULTI ZONE X-RAY BURST MODEL.

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha,\gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha,p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p,\gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p,\gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha,p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha,p)^{17}F$	D	5.8	1
7	$^{23}Al(p,\gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha,p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p,\alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha,\gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha,p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha,p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha,\gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p,\gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha,p)^{63}Ga$	U	1.1	2
17	$^{17}F(p,\gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p,\gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p,\gamma)^{49}Mn$	D	1.2	2

[a] Up (U) or down (D) variation that has the largest impact
[b] $M_{LC}^{(i)}$ in units of 10^{38}ergs/s

Simulations for XRB are sensitive to certain reaction rates

- $^{23}Al(p,\gamma)^{24}Si$
- improve rate precision to improve simulations

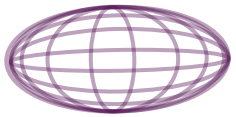


Scattering Theory (Alexis Mercenne / PDoc)

SA-NCSM + RGM

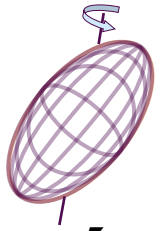
$[(\lambda_1\mu_1) \times (\lambda_r 0) \times (\lambda_2\mu_2)] \rightarrow (\lambda,\mu)$

$N_1 \rightarrow N_2$ Relative motion



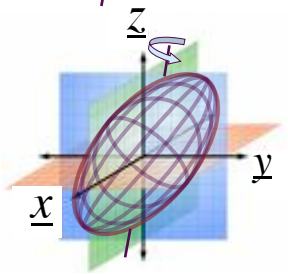
Deformation

L



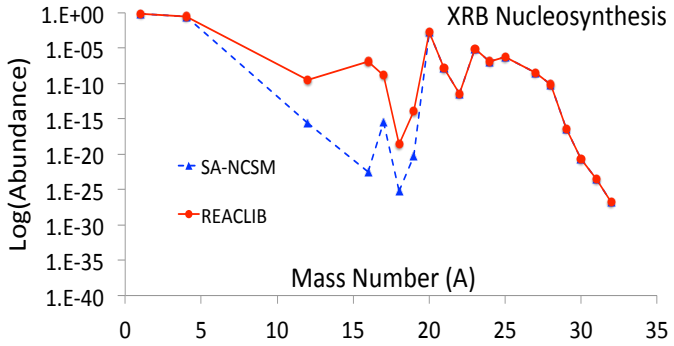
Rotations

M

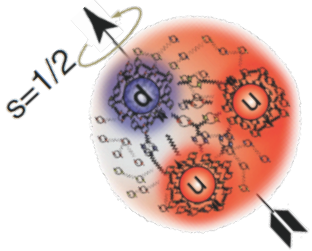


Spatial Orientation

- Deformation is the only relevant information
- All calculations prior to R-matrix use the SA basis/deformation, that is the SU(3) symmetry and corresponding Wigner-Eckart theorem:
  - Norm and Hamiltonian Kernel
  - CM treatment
  - Inversion of the Norm Kernel
- Dependence on orbital momentum (and partial waves) needed to compute cross section, which is introduced at the last step



Future Considerations



Jefferson Lab 12GeV Era

- Excited States of the Nucleon
- Electric Charge vs Magnetic Distribution
- Total Spin -> Angular Momentum plus Quark Spin

"Femtography of Nucleon"

"Normal Concept" versus "Pseudo Concept"

$$\bar{L} + \bar{S} = \bar{J} = \tilde{L} + \tilde{S}$$

"Collusion within & among Nucleons"

2nd Decade (& Beyond) of 21st Century

- Robust stand-alone SA-NCSM code, publicly available
  (… tunable to available computational resources …)

- Designed to handle up to 3-body & 4-body interactions
  (… important for alpha-particle type correlations …)

- Push forward on the Sp-NCSM – Hybrid model $N^{plus}[N_{full}]$
  (… importance of generating symmetry mixing…)

- Continue development with applications - laptop version
  (^{6}Li, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg … odd-A too & heavier …)

Next Up ... Deformed Versions ... DSA-NCSM & DSp-NCSM

... Future is Golden ...

The End

&

The Beginning

"Back to the Future"

... Déjà-vu ...

(armed with new ideas)