Ab Initio Nuclear Structure and Reactions in the Context of Neutron Skin

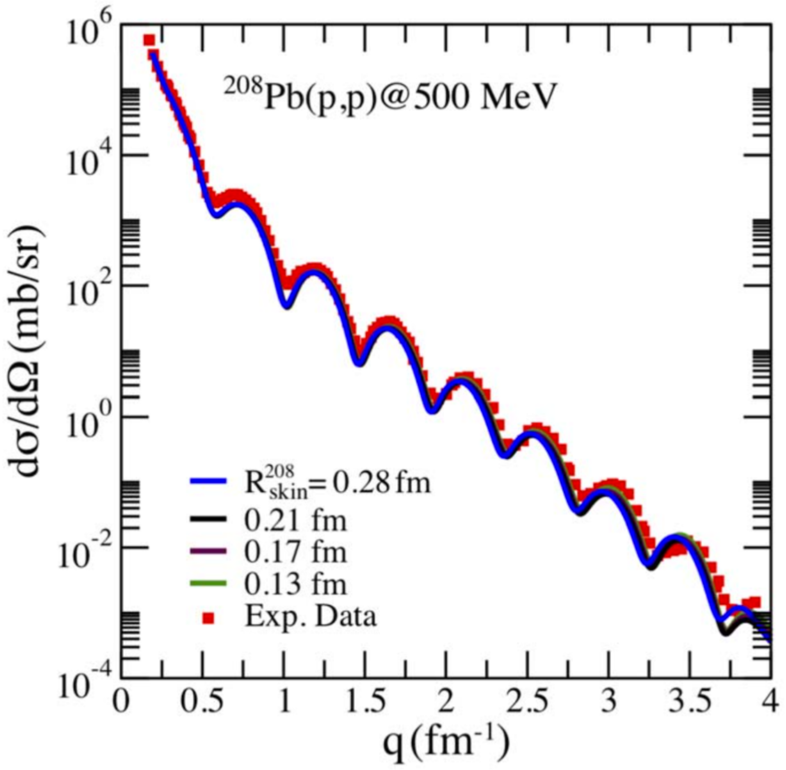
Alexis Mercenne
Louisiana State University

Constraining the Neutron Skin

Electron scattering experiments (PREX, CREX)

Provide the most accurate measurement of the nucleon distribution. Upcoming MREX for neutron radius of ^{208}Pb, but not before 2030.

M. Thiel et al. *J. Phys. G: Nucl. Part. Phys. 46 (2019) 093003*



Hadronic probes (FRIB)

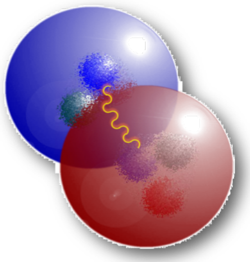
Extraction of neutron skin is model-dependent, suffers from large and uncontrolled theoretical uncertainties.

- Optical potential models fitted on experimental data.
- Models reproduce binding energies and charge radii for a variety of nuclei.
- Very accurate representation of the experimental cross sections.
- Yet, wide range of values for the neutron-skin thickness.

J. Piekarewicz, S.P. Weppner, Nucl. Phys. A 778, 10 (2006)

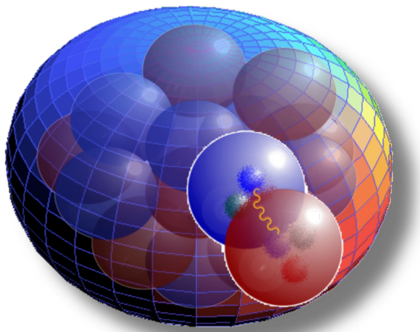
Ab Initio Calculations

First Principles



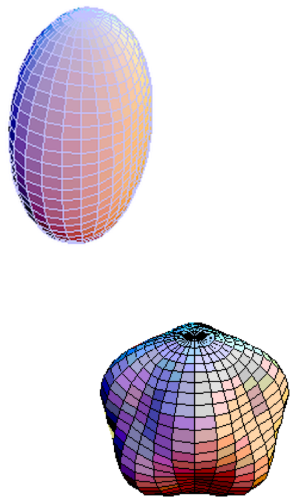
Realistic
Interactions
(χEFT)

Many-body Dynamics



Symmetry-Adapted
No-Core Shell
Model (SA-NCSM)

Properties of Nuclei

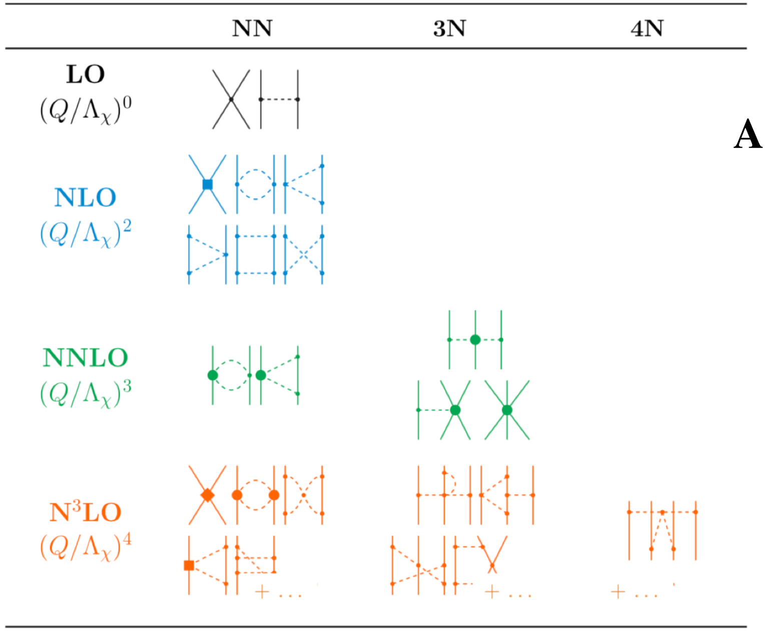


Ab Initio Low Energy Nuclear Physics

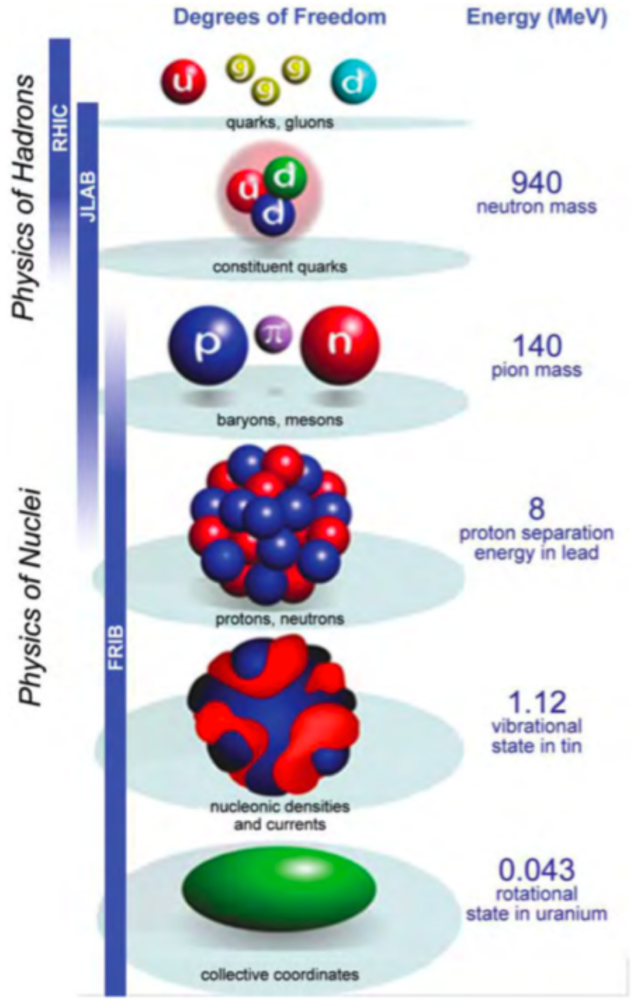
Two energy regimes:
- High energy nuclear physics (quarks, ~ GeV).
- Low energy nuclear physics (nucleons, ~ MeV).

Interactions from Chiral Effective Field Theory (χEFT) : Effective Lagrangians consistent with symmetries of QCD – expansion in Q/Λ.

Only nucleons as degree of freedom.



A plethora of many-body methods:
- In-medium Similarity Renormalization Group
- Coupled Cluster methods
- Self-consistent Green's Functions
- Configuration Interaction Approaches (No-core Shell Model, **Symmetry-adapted No-core Shell Model**)
- Quantum Monte Carlo
- Lattice Effective Field Theory



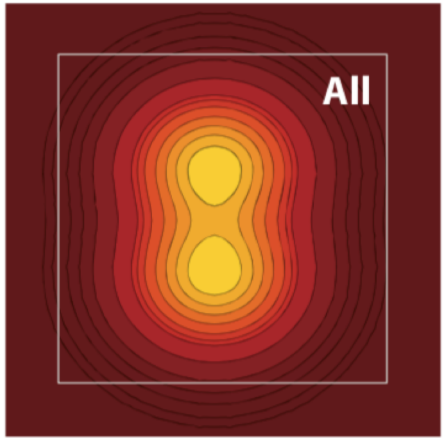
Symmetry-adapted No-core Shell Model (SA-NCSM)

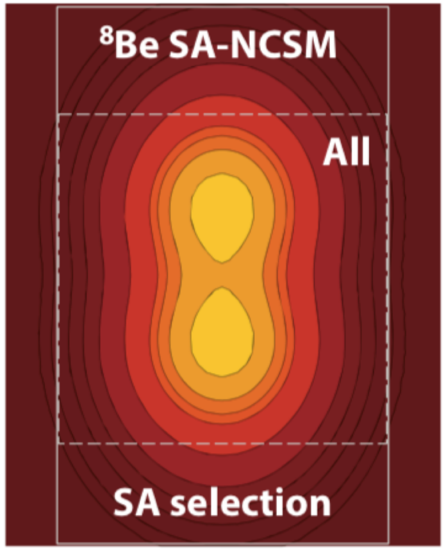
Based on traditional No-core Shell Model (NCSM):

- Spherical harmonic oscillator basis.
- Configuration interaction.
- Ab initio (no restrictions for interactions …NN, NNN, non-local,… χEFT)

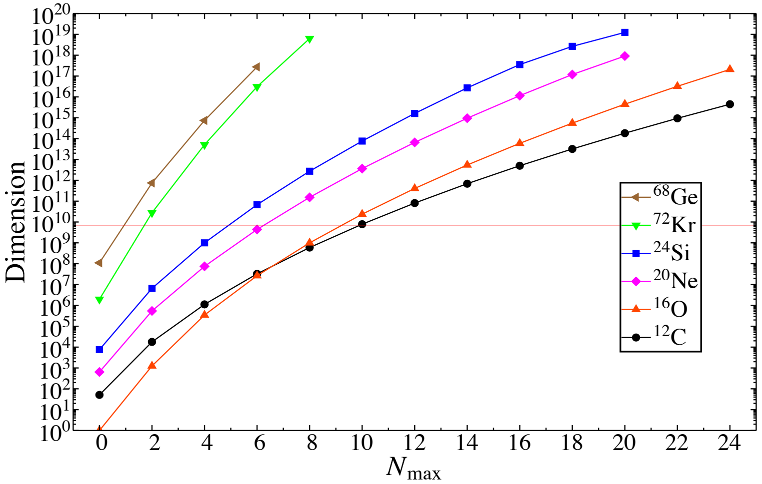
But brings new features:

- SU(3)-coupled basis states or Sp(3,R)-coupled basis states.
- Selected model space (truncation) – physically relevant + exact center-of-mass factorization!
- Equal to NCSM in complete-N_{max} model space.

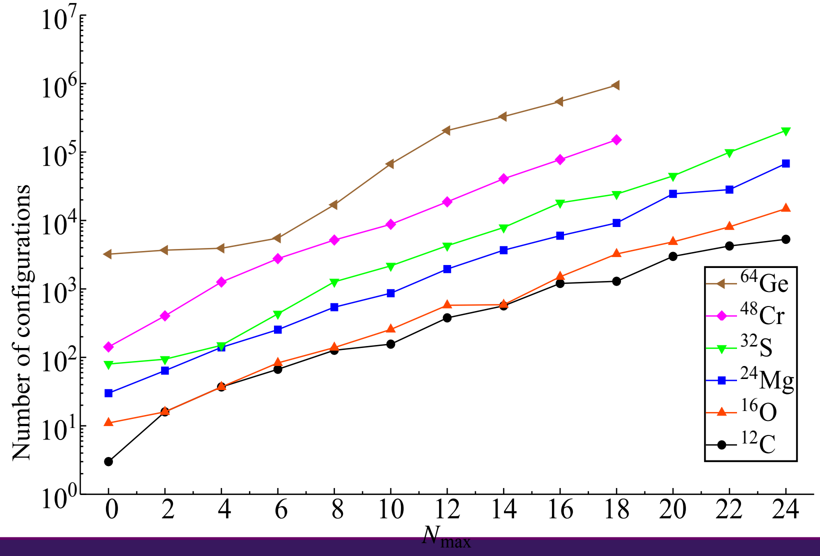




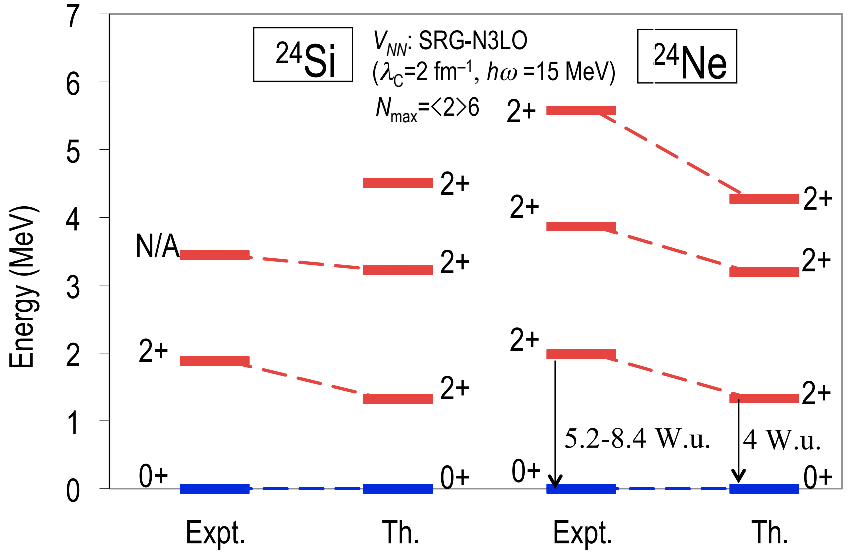
NCSM

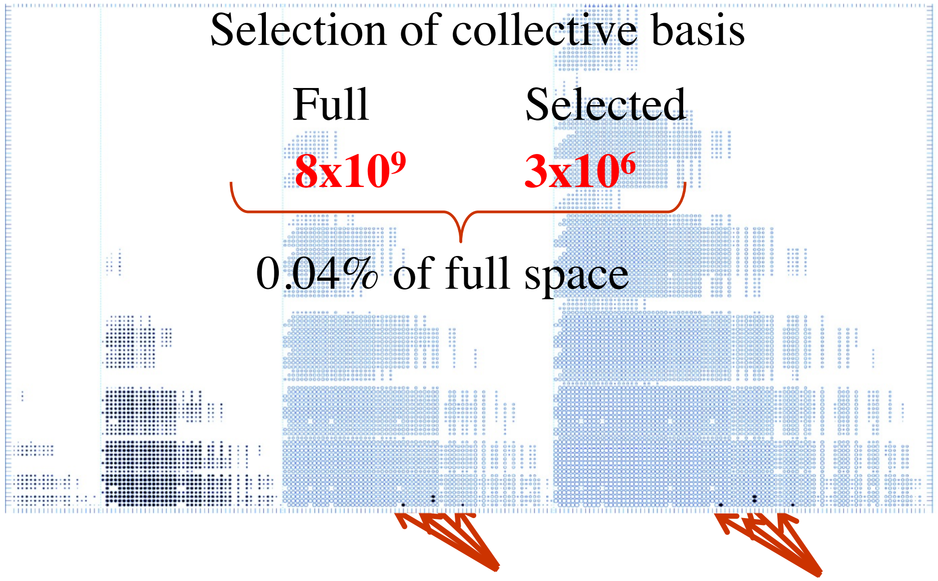


SA-NCSM

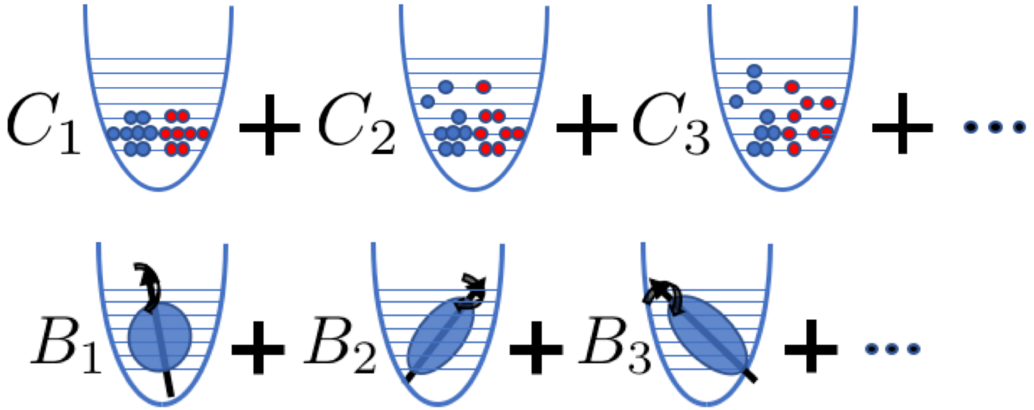


Symmetry-adapted No-core Shell Model



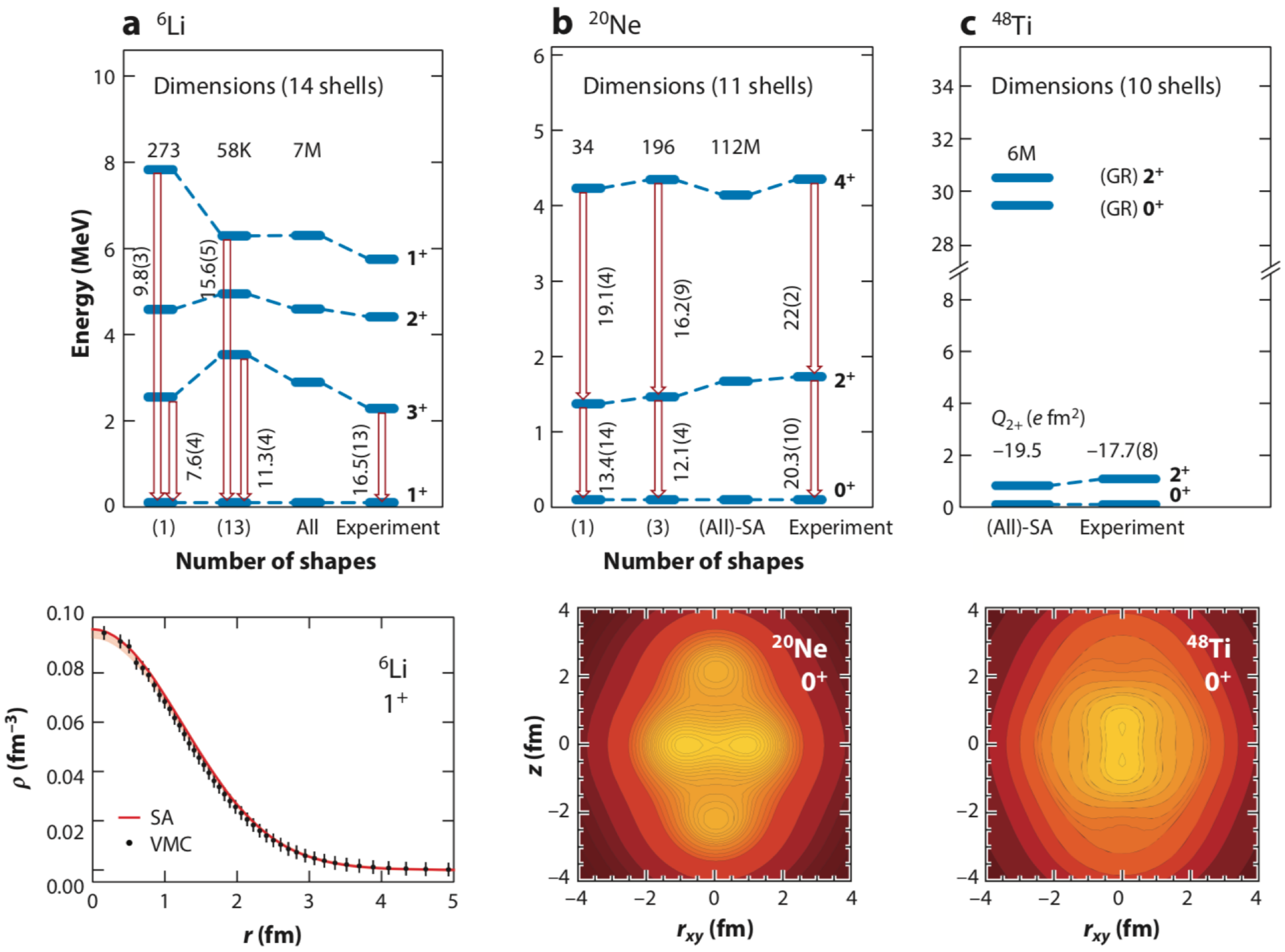


- Few basis states contribute.
- Practically exact calculations.
- Important shapes capture relevant correlations.
- Allow to keep non-negligible contributions only:
    I. Manageable model space.
    II. Center-of-mass/relative motion can be exactly factorized.

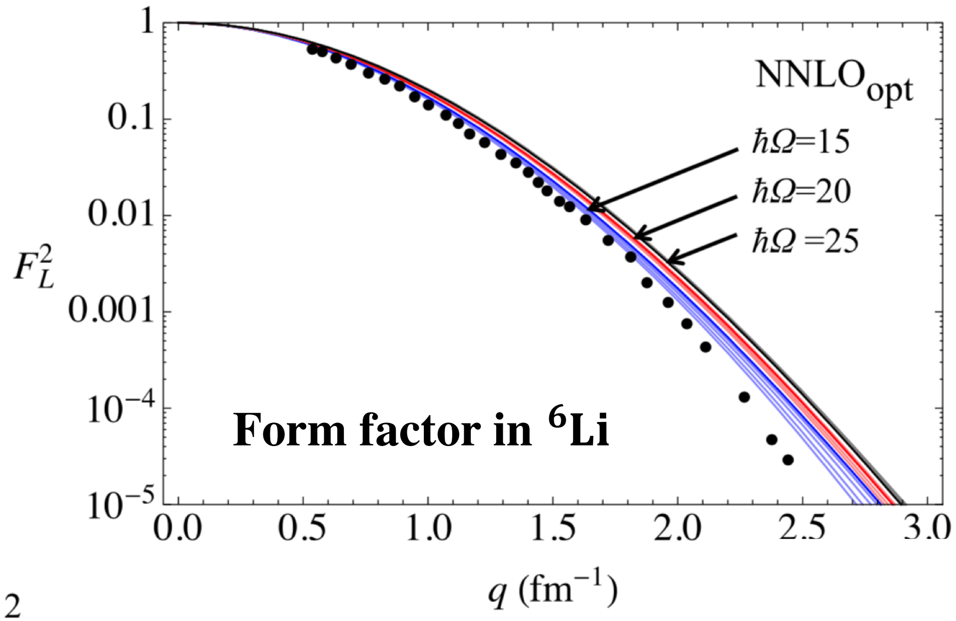


SA-NCSM Observables

Annu. Rev. Nucl. Part. Sci. 71, 253 (2021)



PRC 91, 023326 (2015)



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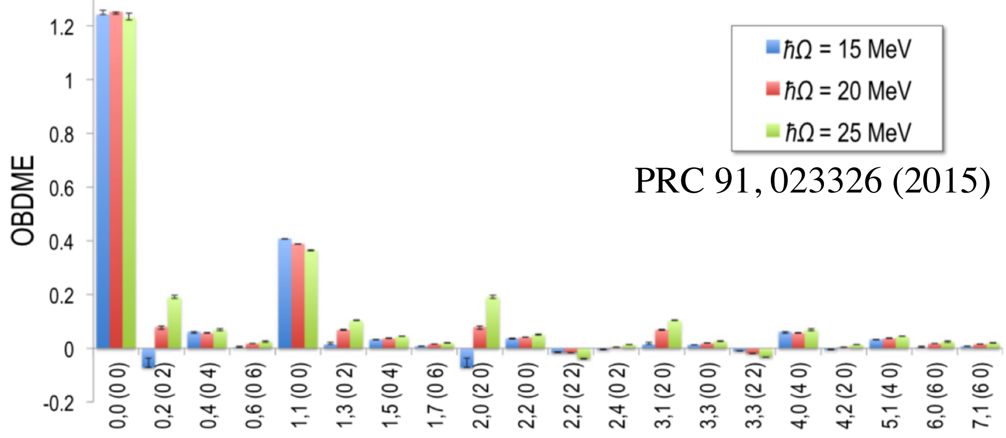

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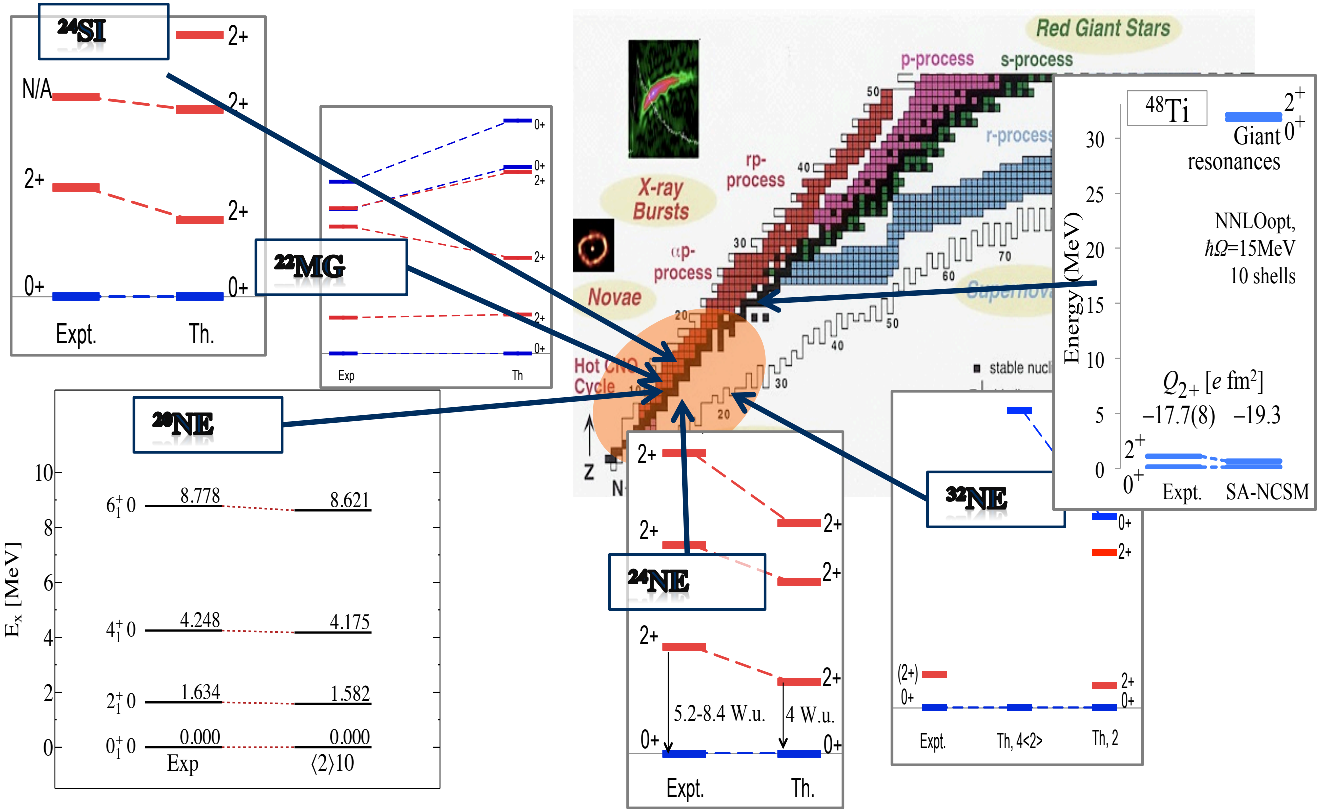
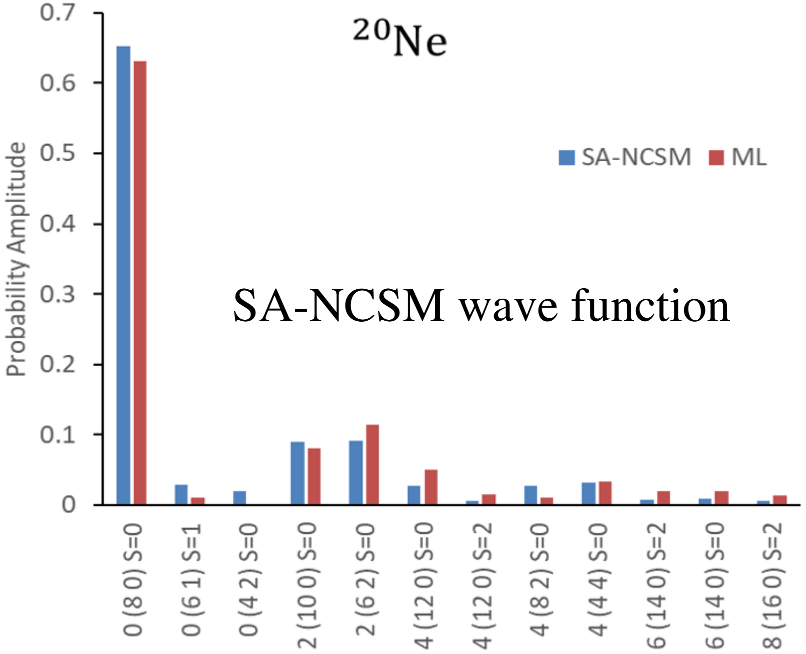
Pushing Ab Initio Calculations Up to the Calcium Region

- Applied to many nuclei up to calcium region.
- Successful in calculating: energy spectrum, rms radius, electromagnetic transitions …etc.

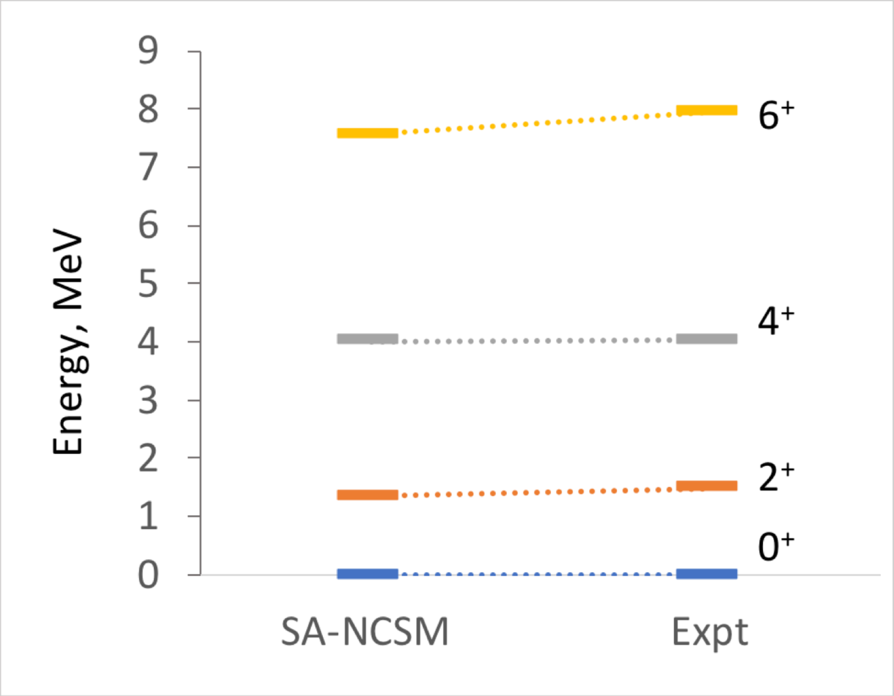


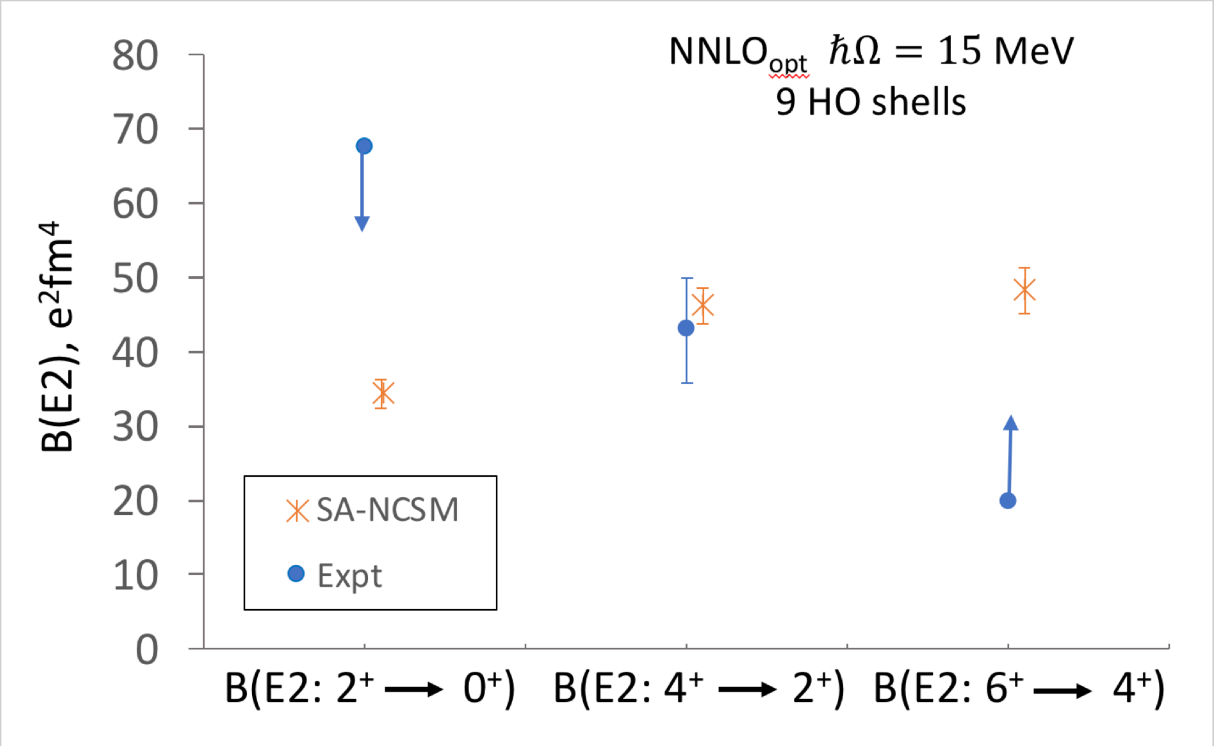


O. Molchanov et al. Phys. Rev. C **105**, 034306

SA-NCSM Results for Neutron Rich Nuclei

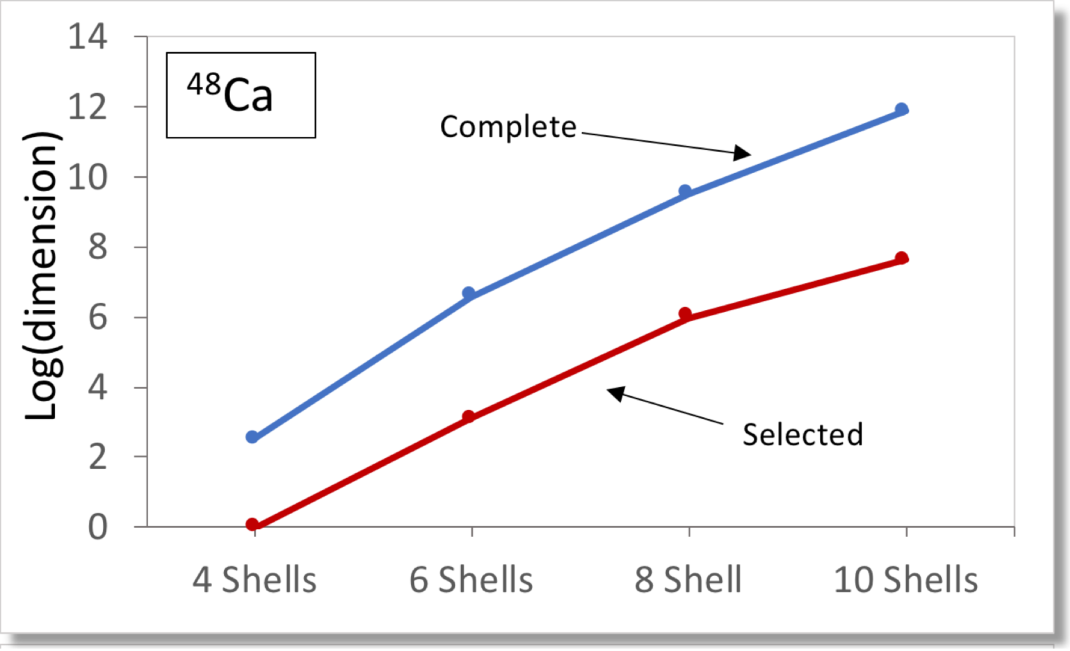
^{28}Mg yrast band

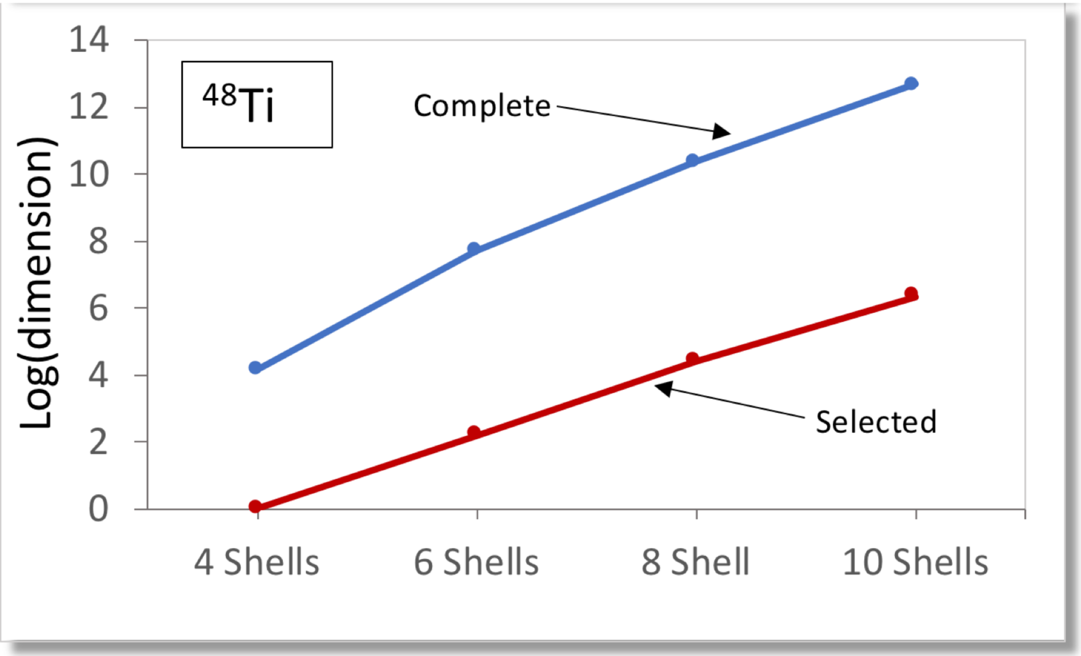




Williams et al., PRC **100,** 014322 (2019)

SA-NCSM Heaviest Systems $A = 48$





G.H. Sargsyan et al. Bulg. J. Phys. 49, 47 (2022)

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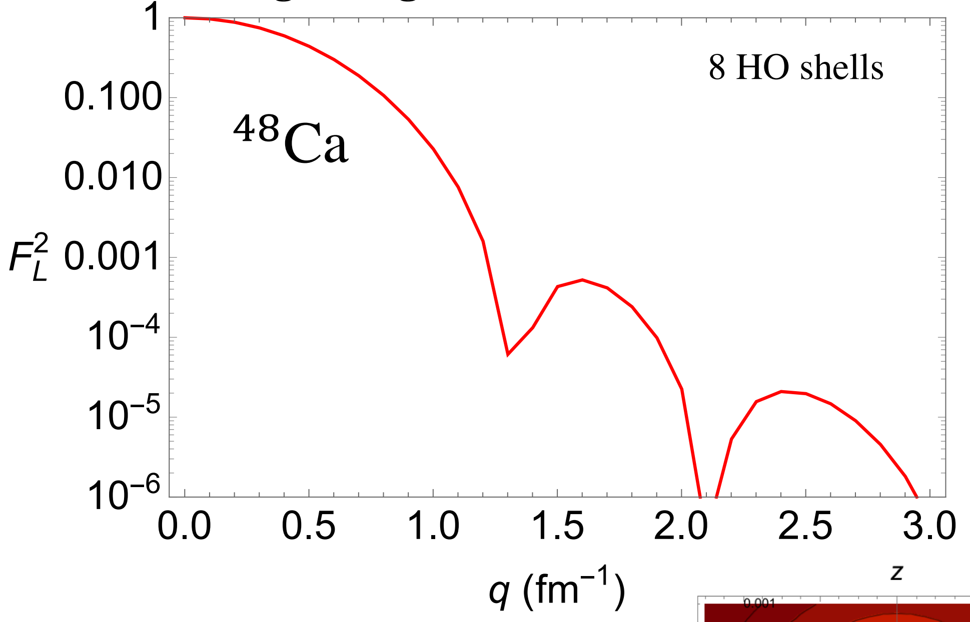
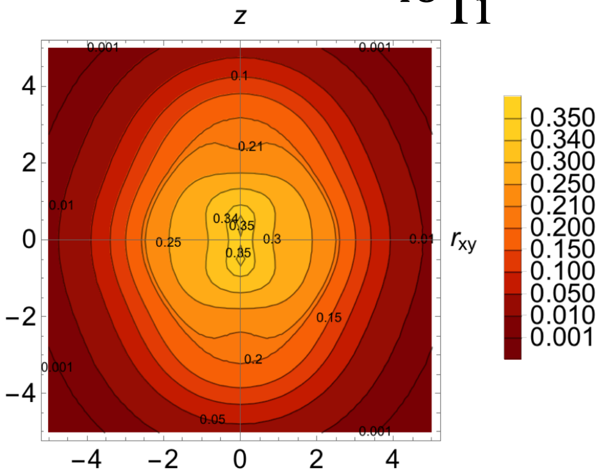
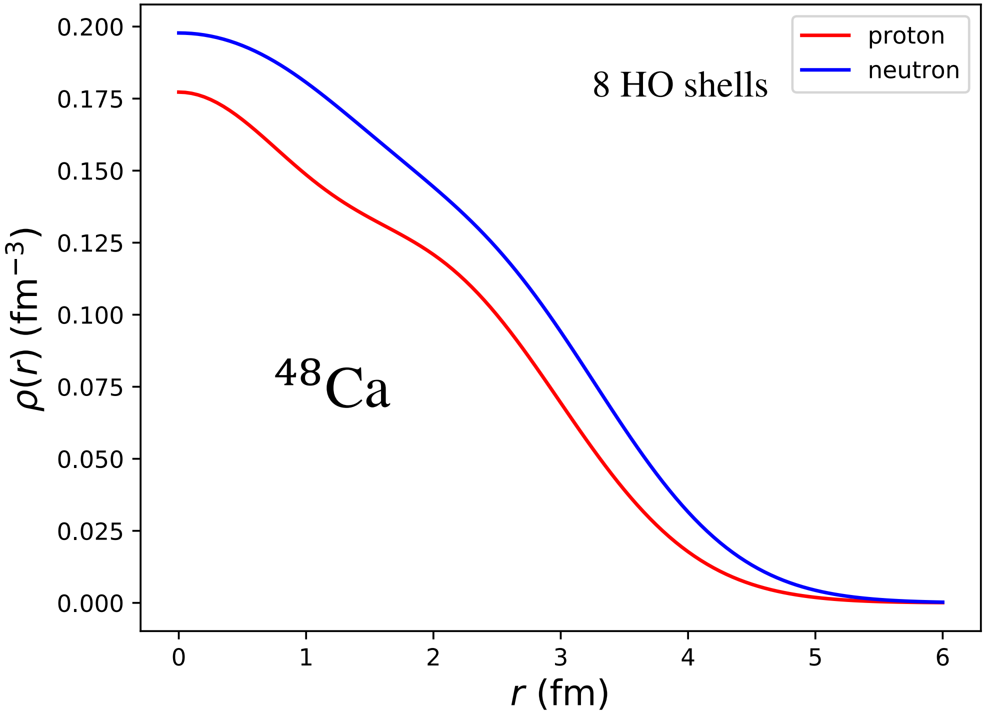




^{48}Ti, Q(2$^+$) [e fm^2]

Experiment……… -17.7

10 shells…………… -19.3



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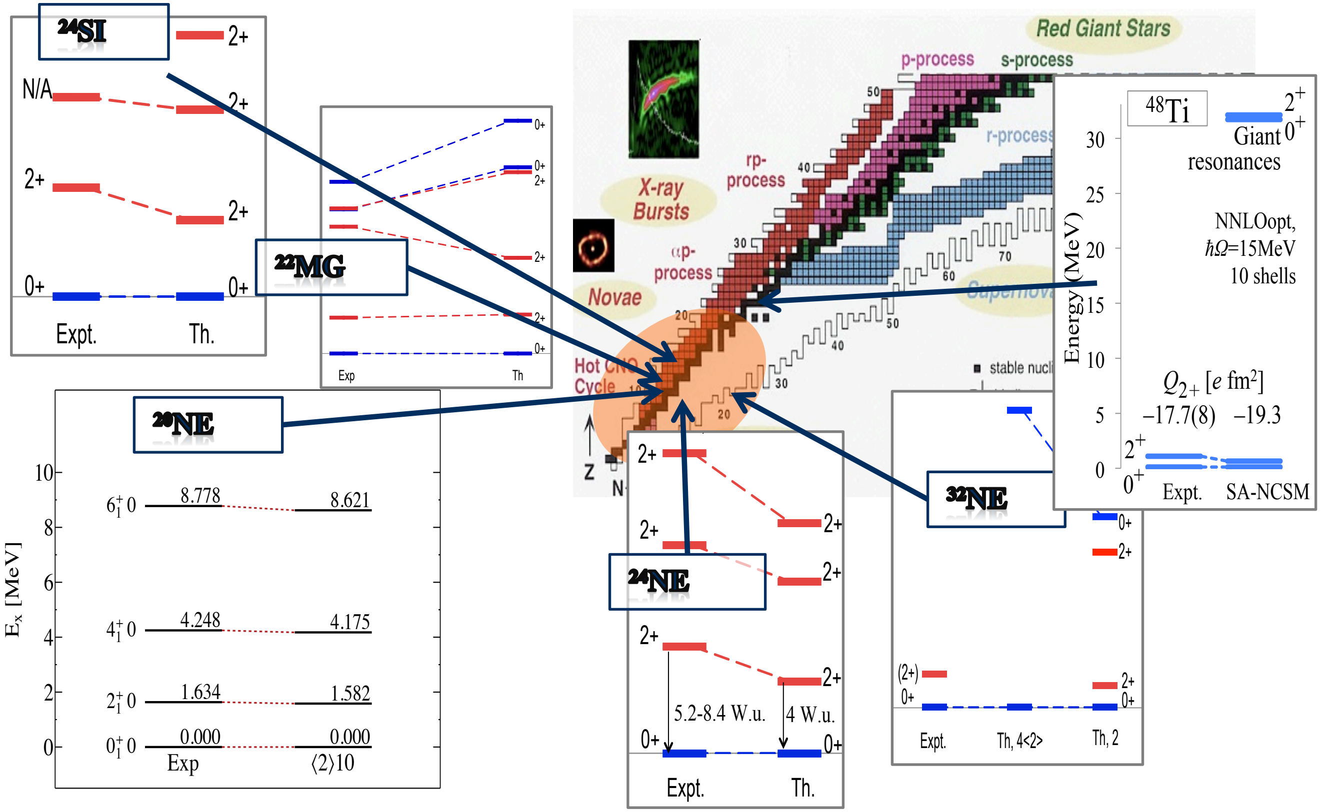
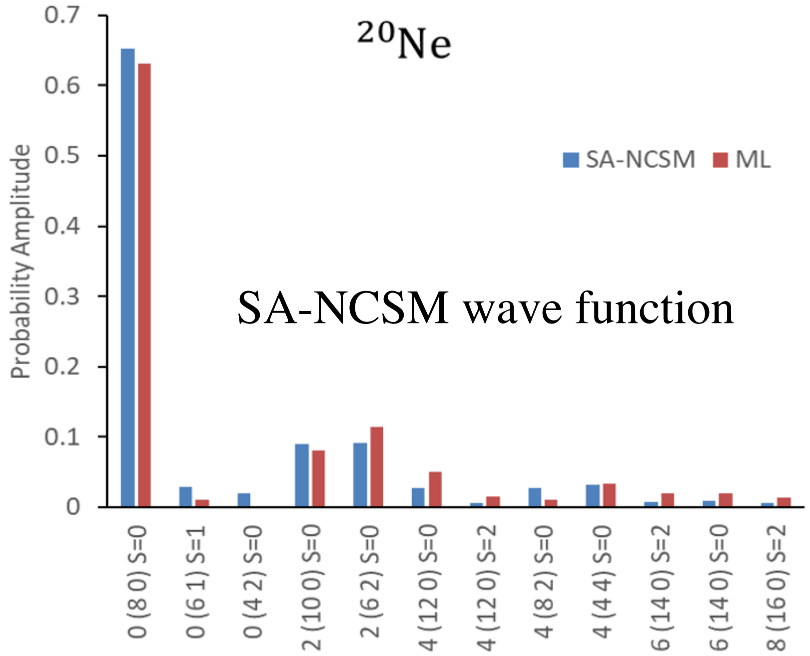




Next step: use this physically relevant many-body basis to nuclear reactions.

- Support FRIB experiments for exotic nuclei.
- Provide reliable inputs for astrophysical studies.

Plugging SA-NCSM Wavefunctions Into Reaction Calculations

Coupled-channel Framework

$$(T_c - (E - E_c))u_c(r) + \sum_{c'=1}^{N_c} \int dr' V_{cc'}(r', r) u_{c'}(r') = 0$$

Solution

Kinetic part

Scattering energy

Threshold energy

Coupling potential

Can be solved with calculable R-matrix.

a.k.a optical potential, inter-cluster interaction, nucleon-nucleus potential …etc

A basis for reactions: channel index gathers partitions, quantum numbers of projectile and target, total angular momentum of composite …etc

$$c = \{A\ I_T; a\ I_p; n\ell j; J\}$$

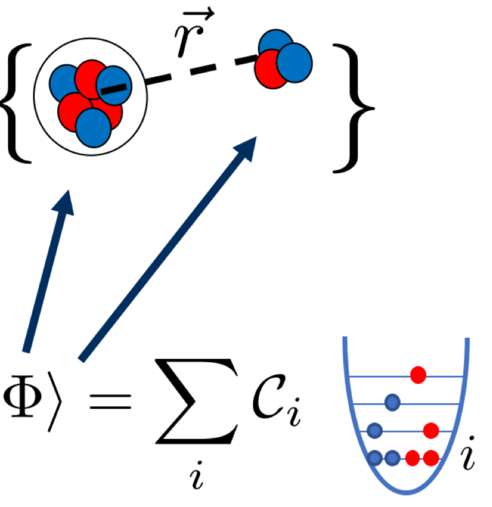
Low energies/light systems: the coupled-channel equation can be treated exactly; all thresholds are included; Non-local potential couples all channels with each other.

Higher energies/heavier systems: too many reaction thresholds; use of optical potential instead.

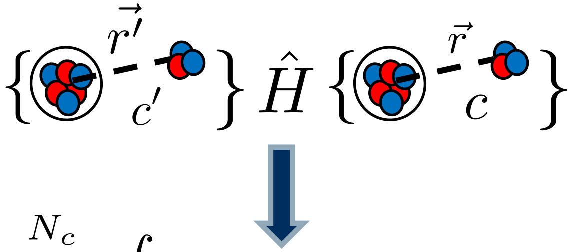
Low Energy Ab Initio Reactions With the Resonating Group Method

- $u_c(r)$ describes the relative motion between the two clusters.
- Asymptotic of $u_c(r)$ gives cross section for specific channel.
- Requires internal wave functions and NN interaction.
- Microscopic: full antisymmetrization + cluster correlations.
- Can be generalized to any number of clusters.

$$|\Psi\rangle = \sum_c \int dr \frac{u_c(r)}{r} r^2 \mathcal{A}\{\ldots\}$$



$$c = \{A\ I_T; a\ I_p; n\ell j; J\}$$



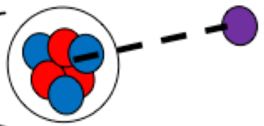
$$(T_c - (E - E_c))u_c(r) + \sum_{c'=1}^{N_c} \int dr' V_{cc'}(r', r) u_{c'}(r') = 0$$

Low Energy Ab Initio Reactions With the Resonating Group Method

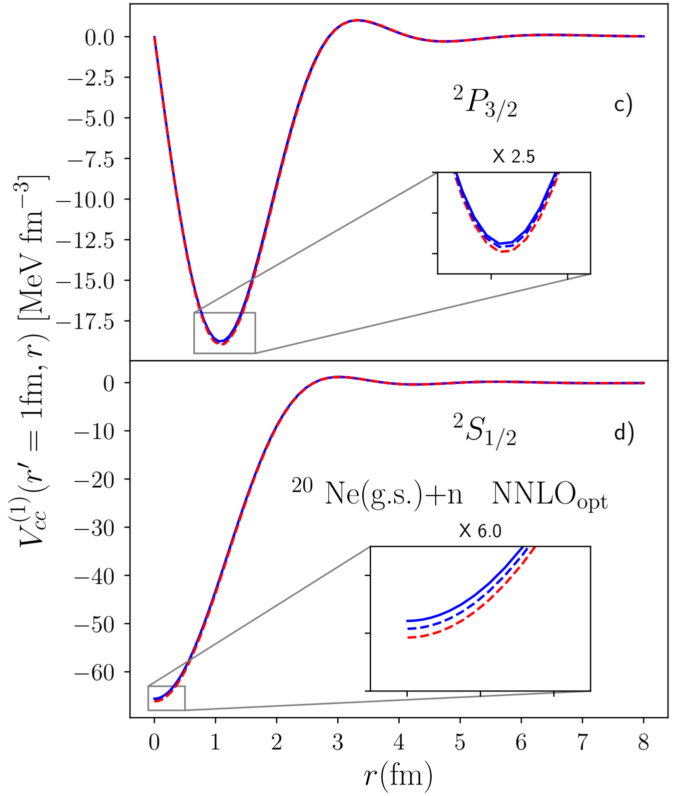
Symmetry-adapted RGM:

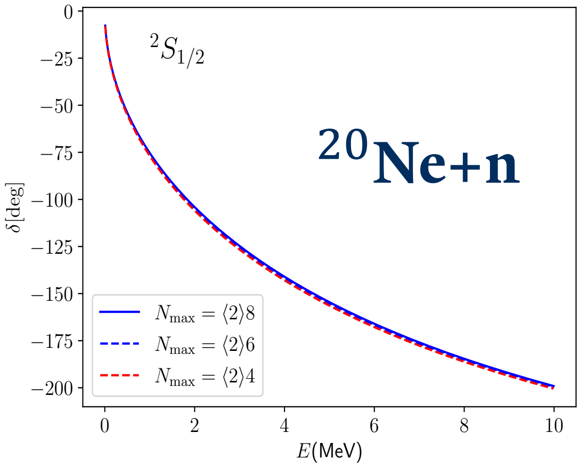
- *Ab initio* single-nucleon projectile reactions in a coupled-channel framework.
- First results studied the influence of selected model space on non-local potentials.

$$|\Psi\rangle = \sum_\nu \int dr \frac{g_\nu(r)}{r} r^2 \mathcal{A}\{\ \}$$

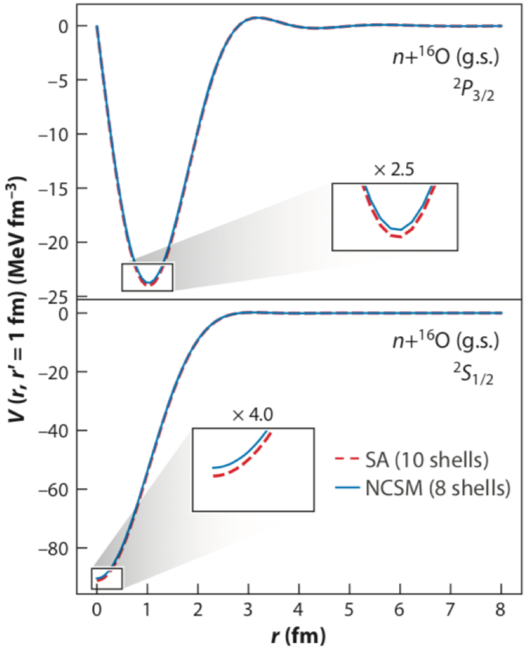


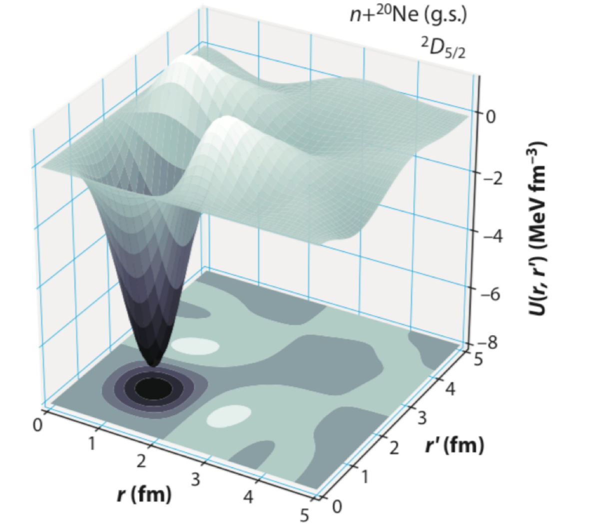
$$|\Phi\rangle = \sum_i c_i$$





AM, Launey, Dytrych, Escher, Quaglioni, Sargsyan, Draayer Comput. Phys. Comm. ***280****, 108476 (2022)*

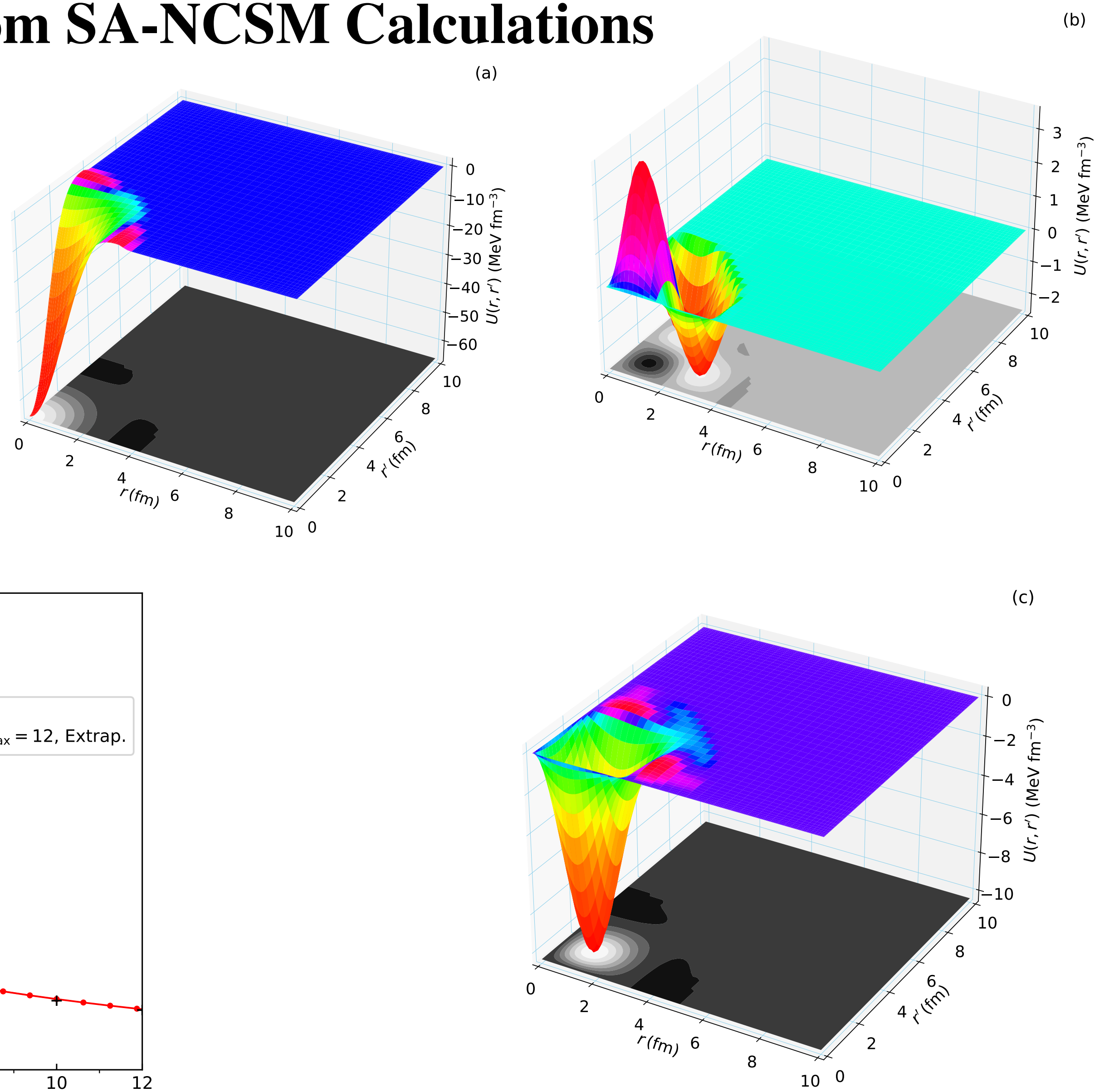




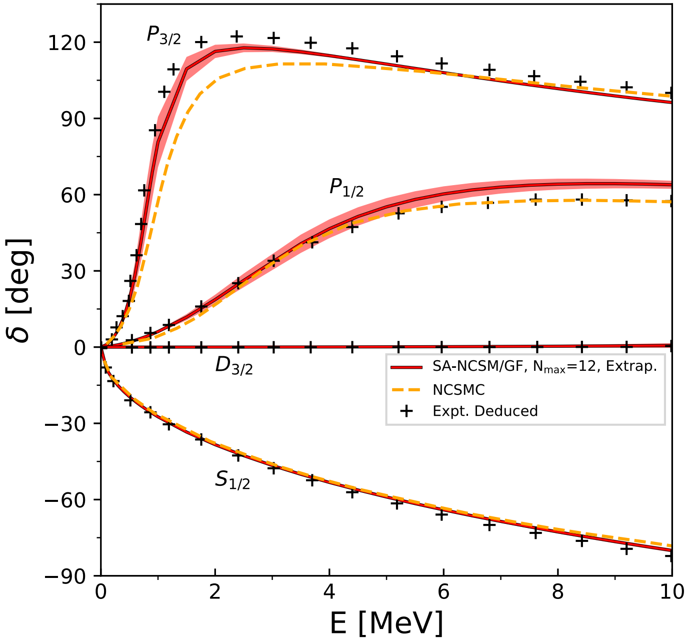
Launey, Mercenne, Dytrych Ann. Rev. Nucl. Part. Sci. ***71****, 253 (2021)*

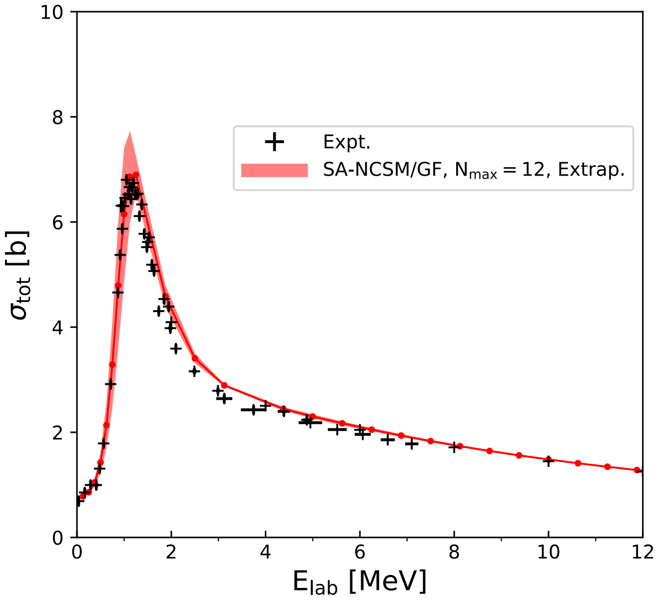
Optical Potentials Derived from SA-NCSM Calculations

- ^{4}He wave function calculated with SA-NCSM.
- Optical potential describing neutron scattering on ^{4}He constructed with Green's function method.

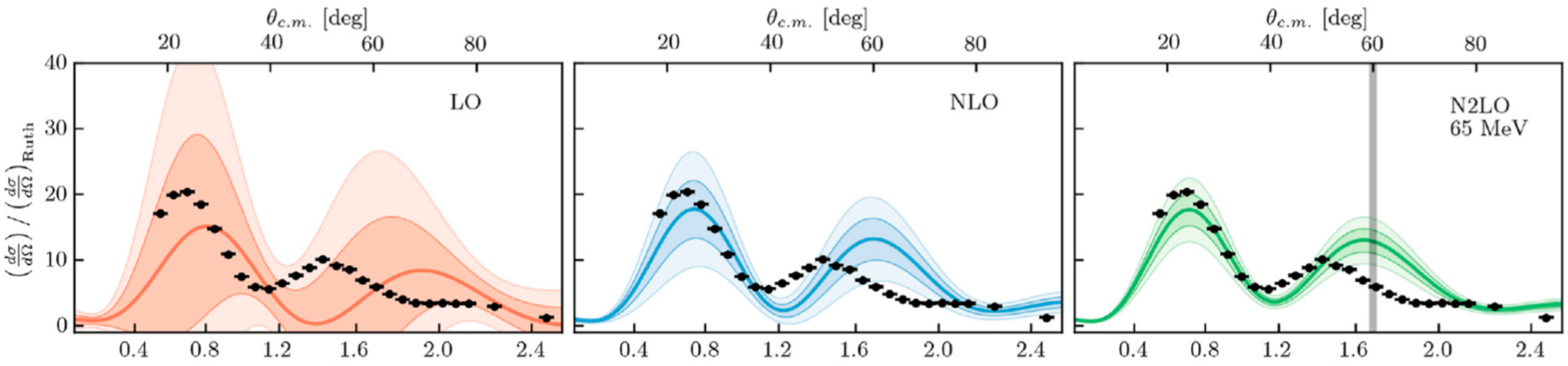


Matthew Burrows and Kristina Launey, preliminary results





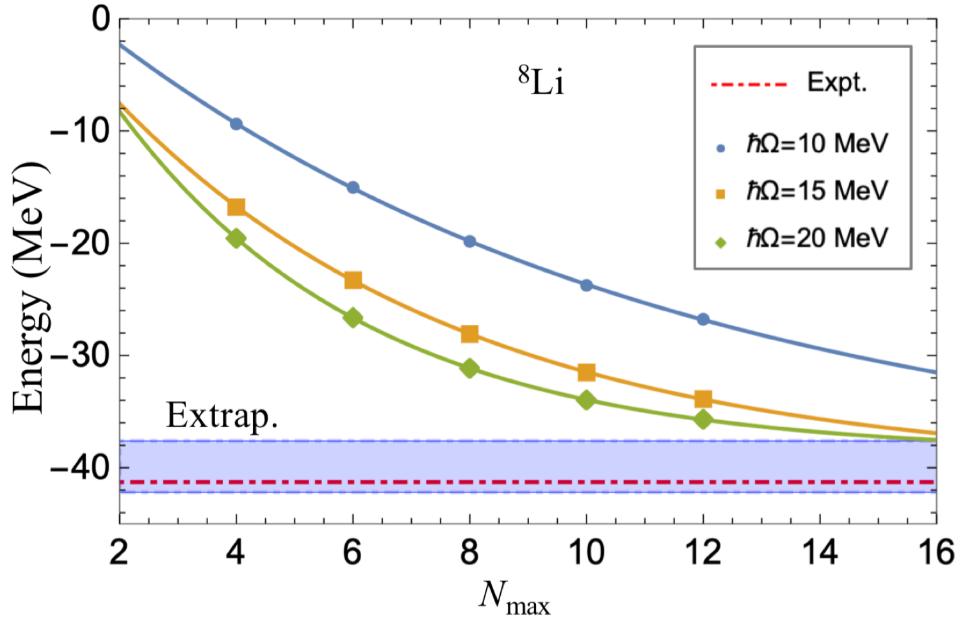
Uncertainties in Ab Initio Calculations



R. R. Baker et al. *Front. Phys. 10:1071971*

Two main sources:

- Model space truncations.
- Uncertainties from the underlying χEFT



G. H. Sargsyan et al. arxiv: 2210.08843

Summary

- Practically exact ab initio calculations are now performed up to the calcium region.

- Symmetry-adapted No Core Shell Model (SA-NCSM) makes use of a physically relevant basis that allows a good reproduction of spectra, B(E2) values, quadrupole moments, form factors …etc.

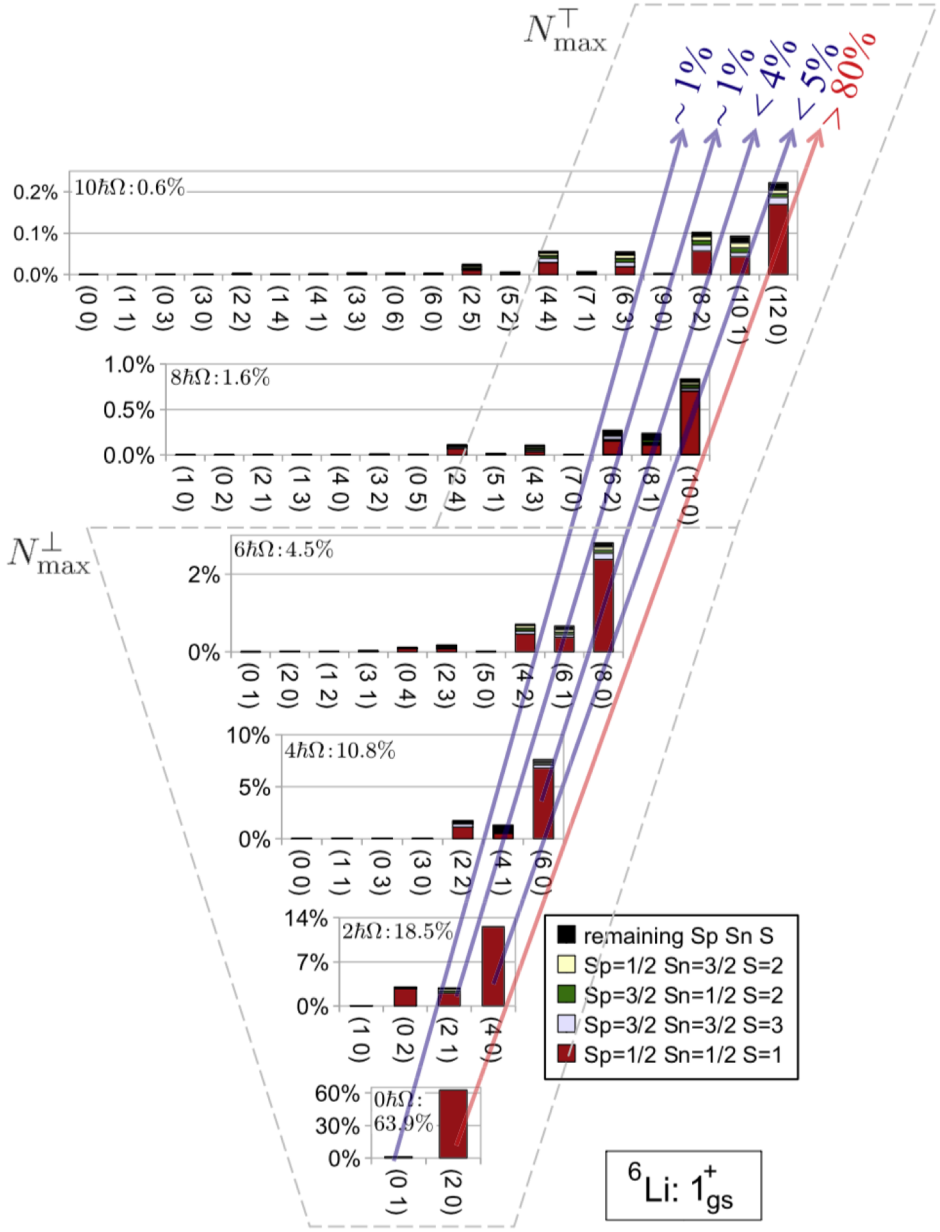
- SA-NCSM wave functions can be implemented into reaction formalisms:
  - For low-energy reactions in multiple coupled-channels framework.
  - At higher energies with the construction of effective ab initio nucleon-nucleus potentials (optical potentials).

- Applications of SA-NCSM in neutron-rich nuclei can help to evaluate the neutron skin thickness.

- Compared to traditional methods extracting R_{skin} from proton scattering, theoretical uncertainties will now be better controlled.

LSU collaborators: K. Launey, J. Draayer, T. Dytrych, G. Sargsyan, M. Burrows, K. Becker, D. Mumma, N. Thompson.

And also: M. Ploszajczak (GANIL), Y. Alhassid (Yale), J. Escher (LLNL), N. Michel (Institute of Modern Physics, Lanczhou).



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10ħΩ: 0.6%
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2ħΩ: 18.5%
0ħΩ: 63.9%
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Sp=1/2 Sn=1/2 S=1
^{6}Li: 1^{+}_{gs}