Exotic Nuclei and Beyond

- An Ab Initio Theory Perspective -

Robert Roth

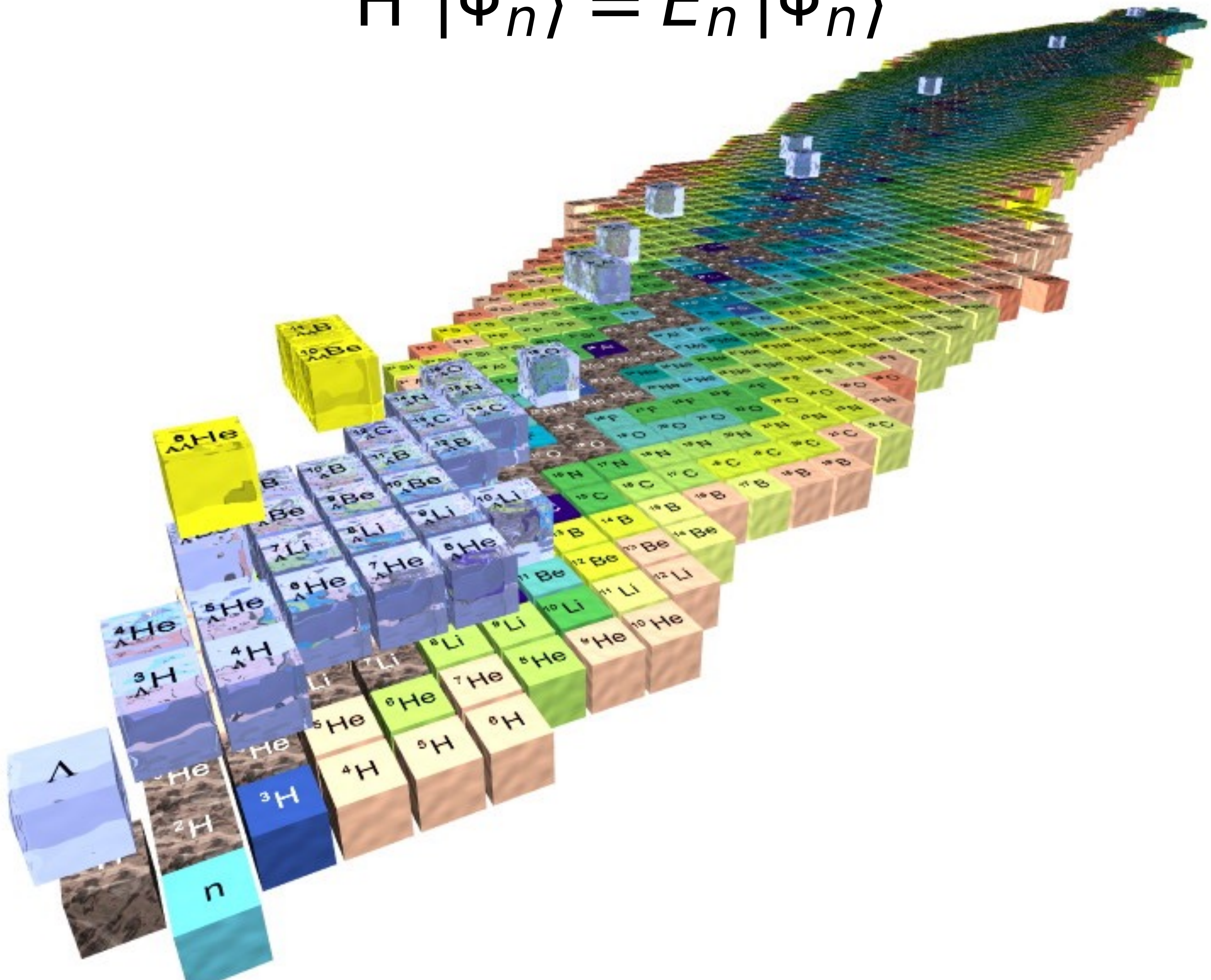
SFB 1245

TECHNISCHE UNIVERSITÄT DARMSTADT

HIC for FAIR
Helmholtz International Center

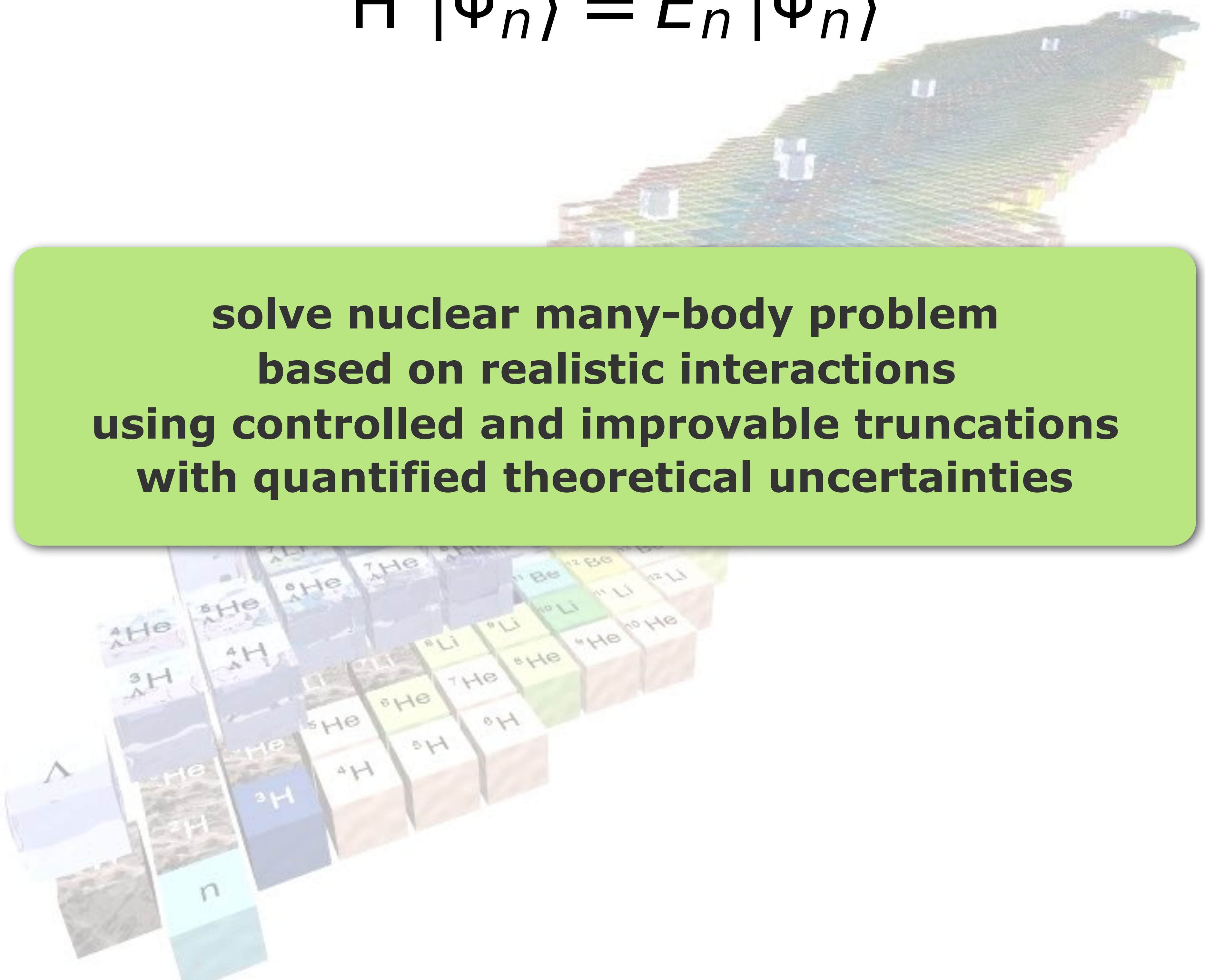
Ab Initio Nuclear Structure Theory

$$\mathrm{H}\,|\Psi_n\rangle = E_n\,|\Psi_n\rangle$$



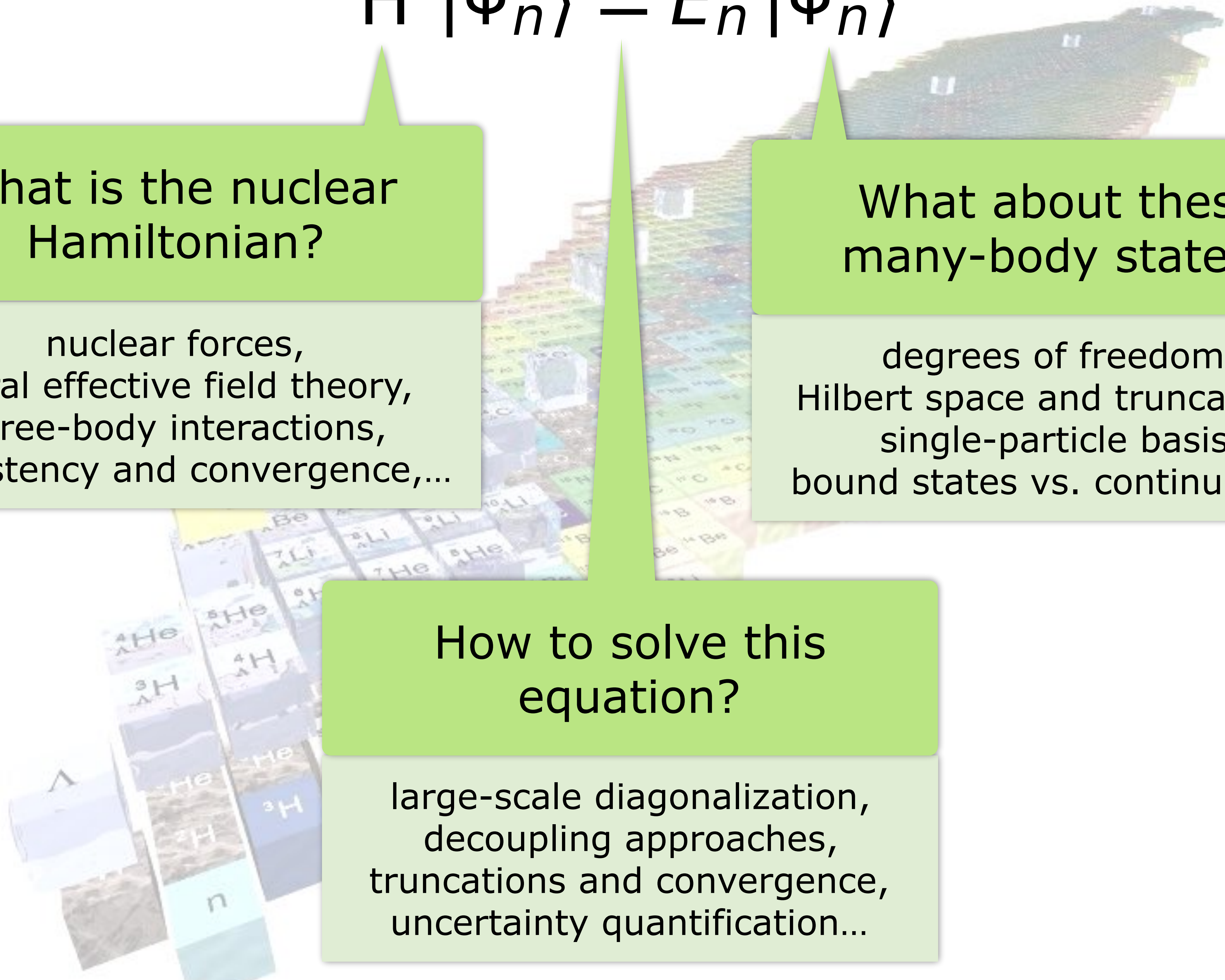
Ab Initio Nuclear Structure Theory

$$H\ |\Psi_n\rangle = E_n\,|\Psi_n\rangle$$



solve nuclear many-body problem
based on realistic interactions
using controlled and improvable truncations
with quantified theoretical uncertainties

Ab Initio Nuclear Structure Theory



$$H\ |\Psi_n\rangle = E_n\,|\Psi_n\rangle$$

What is the nuclear Hamiltonian?

nuclear forces,
chiral effective field theory,
three-body interactions,
consistency and convergence,...

What about these many-body states?

degrees of freedom,
Hilbert space and truncations,
single-particle basis,
bound states vs. continuum,...

How to solve this equation?

large-scale diagonalization,
decoupling approaches,
truncations and convergence,
uncertainty quantification...

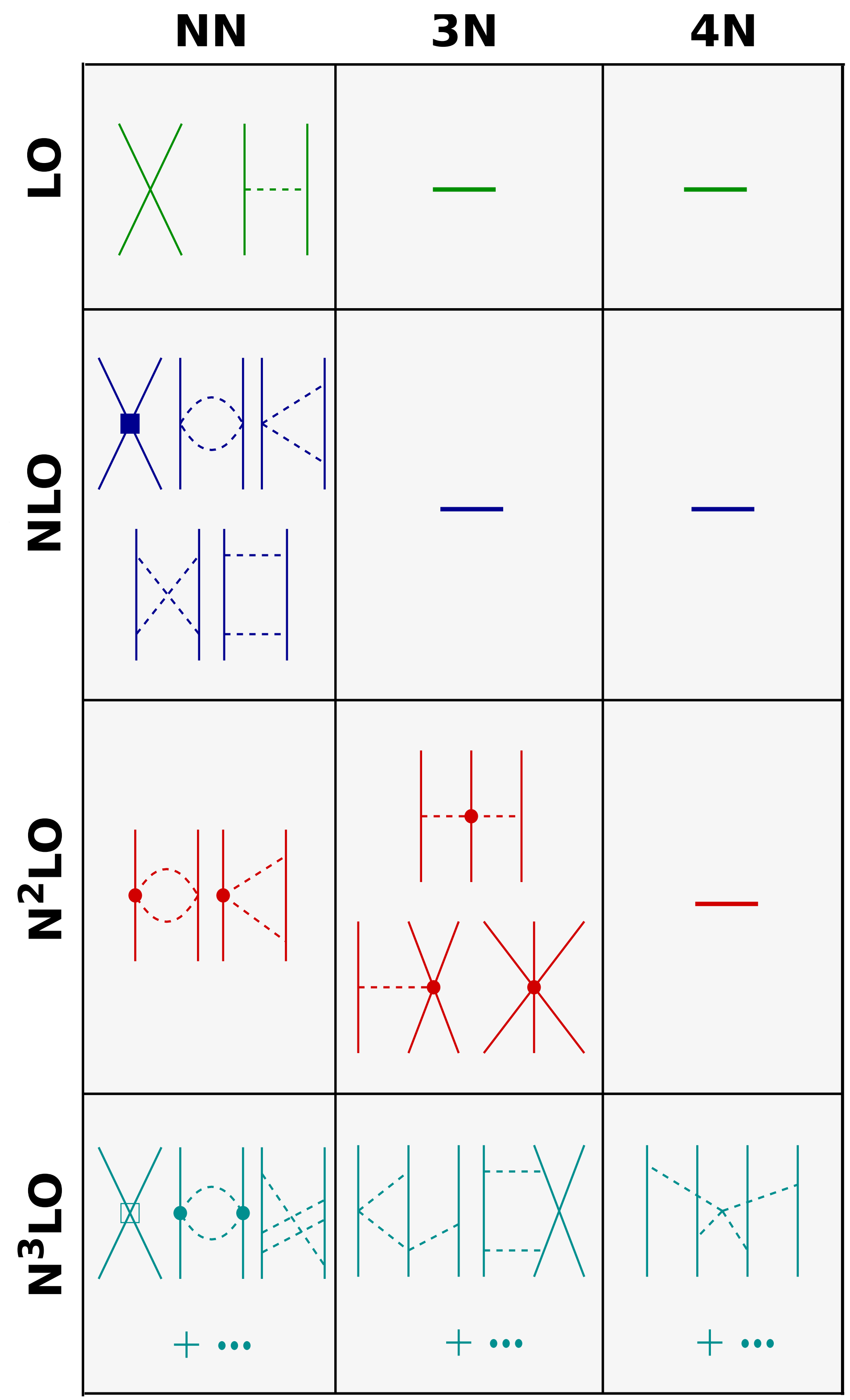
Hamiltonian

$$H = T - T_{cm} + V_{NN} + V_{3N} + \cdots$$

Nuclear Interactions from Chiral EFT

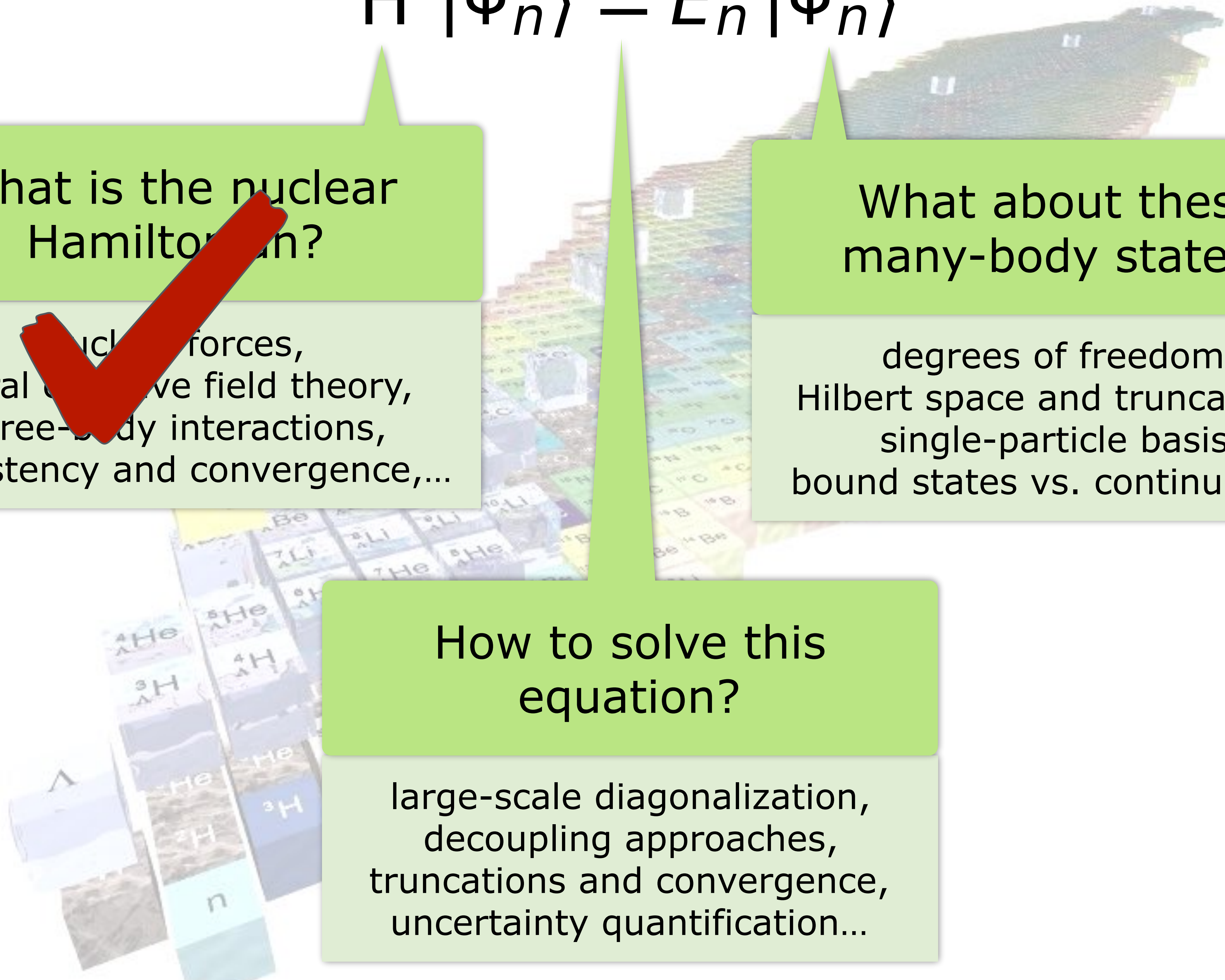
Weinberg, van Kolck, Machleidt, Entem, Meißner, Epelbaum, Krebs, Bernard,...

- low-energy **effective field theory** for relevant degrees of freedom (π,N) based on symmetries of QCD
- explicit long-range **pion dynamics**
- unresolved short-range physics absorbed in **contact terms**, low-energy constants fit to experiment
- hierarchy of **consistent NN, 3N, 4N,...** interactions and electroweak operators
- many **recent developments**
  - improved NN up to N4LO+
  - 3N interaction up to N3LO
  - 4N interaction at N3LO
  - improved fits and error analysis
  - order-by-order uncertainty quantification



Ab Initio Nuclear Structure Theory

$$\mathrm{H}\,|\Psi_n\rangle = E_n\,|\Psi_n\rangle$$



What is the nuclear Hamiltonian?

nuclear forces,
chiral effective field theory,
three-body interactions,
consistency and convergence,...

What about these many-body states?

degrees of freedom,
Hilbert space and truncations,
single-particle basis,
bound states vs. continuum,...

How to solve this equation?

large-scale diagonalization,
decoupling approaches,
truncations and convergence,
uncertainty quantification...

Unitary Transformations

ELSEVIER

NUCLEAR PHYSICS A

Nuclear Physics A 632 (1998) 61–95

A unitary correlation operator method

H. Feldmeier [1], T. Neff [2], R. Roth [3], J. Schnack [4]

Gesellschaft für Schwerionenforschung mbH, Postfach 110 552, D-64220 Darmstadt, Germany
Technische Universität Darmstadt, Darmstadt, Germany

Received 22 September 1997; accepted 12 December 1997

Abstract

The short range repulsion between nucleons is treated by a unitary correlation operator which shifts the nucleons away from each other whenever their uncorrelated positions are within the repulsive core. By formulating the correlation as a transformation of the relative distance between particle pairs, general analytic expressions for the correlated wave functions and correlated op-

Unitary Transformations

- eigenvalue problem of H and expectation value of observable O

$$\mathrm{H}\,|\Psi_n\rangle = E_n\,|\Psi_n\rangle \qquad\qquad O_n = \langle\Psi_n|\,\mathrm{O}\,|\Psi_n\rangle$$

- invent a **unitary operator U** with $\mathrm{U}\,\mathrm{U}^\dagger = 1$ and use it

$$\mathrm{U}^\dagger\mathrm{H}\,\mathrm{U}\,\mathrm{U}^\dagger\,|\Psi_n\rangle = E_n\,\mathrm{U}^\dagger\,|\Psi_n\rangle \qquad\qquad O_n = \langle\Psi_n|\,\mathrm{U}\,\mathrm{U}^\dagger\mathrm{O}\,\mathrm{U}\,\mathrm{U}^\dagger\,|\Psi_n\rangle$$

- identify **transformed operators and states** and rewrite equations

$$|\tilde{\Psi}_n\rangle = \mathrm{U}^\dagger\,|\Psi_n\rangle\,, \qquad \tilde{\mathrm{H}} = \mathrm{U}^\dagger\mathrm{H}\,\mathrm{U}\,, \qquad \tilde{\mathrm{O}} = \mathrm{U}^\dagger\mathrm{O}\,\mathrm{U}$$

$$\tilde{\mathrm{H}}\,|\tilde{\Psi}_n\rangle = E_n\,|\tilde{\Psi}_n\rangle \qquad\qquad O_n = \langle\tilde{\Psi}_n|\,\tilde{\mathrm{O}}\,|\tilde{\Psi}_n\rangle$$

Unitary Transformations

- eigenvalue problem of H and expectation value of observable O

$$\mathrm{H}\,|\Psi_n\rangle = E_n\,|\Psi_n\rangle$$

$$O_n = \langle\Psi_n|\,\mathrm{O}\,|\Psi_n\rangle$$

- i… 1 and use it

$$\ldots = \langle\Psi_n|\,\mathrm{U}\,\mathrm{U}^\dagger \mathrm{O}\,\mathrm{U}\,\mathrm{U}^\dagger\,|\Psi_n\rangle$$

unitary transformations
change the structure of the Hamiltonian
and the many-body states without
changing the observables

design a unitary
transformation that simplifies the
solution of the many-body
problem

- identify **transformed operato…**

$$|\tilde\Psi_n\rangle = \mathrm{U}^\dagger\,|\Psi_n\rangle\,, \qquad \tilde{\mathrm{H}} = \mathrm{U}^\dagger \mathrm{H}\,\mathrm{U}\,, \qquad \tilde{\mathrm{O}} = \mathrm{U}^\dagger \mathrm{O}\,\mathrm{U}$$

$$\tilde{\mathrm{H}}\,|\tilde\Psi_n\rangle = E_n\,|\tilde\Psi_n\rangle$$

$$O_n = \langle\tilde\Psi_n|\,\tilde{\mathrm{O}}\,|\tilde\Psi_n\rangle$$

early
1996

Bohrloch – 14

Korrelierte Wellenfunktion (Index ℓm weggelassen)

$$r\,\chi(x) = \left(\frac{dR_-}{dx}\right)^{1/2} R_-(x)\, \varphi(R_-(x))$$

$$\left.\begin{aligned} R_-(x) &:= R(Y(x)-1) \\ R_+(r) &:= R(Y(r)+1) \end{aligned}\right\} \rightsquigarrow \left\{\begin{aligned} R_-(R_+(r)) &= r \\ R_+(R_-(x)) &= x \end{aligned}\right.$$

R_+ invers zu R_-

$$\left.\begin{aligned} R_-'(x) &:= \frac{dR_-(x)}{dx} = \frac{S(R_-(x))}{S(x)} \\ R_+'(r) &:= \frac{dR_+(r)}{dr} = \frac{S(R_+(r))}{S(r)} \end{aligned}\right\} \rightsquigarrow R_-'(x) = \frac{1}{R_+'(r)}$$

wobei $r = R_-(x)$

Koordinatentransformation:

$r = R_-(x)$

$x = R_+(r)$ $\qquad dx = R_+'(r)\,dr$; $\quad \frac{d}{dx} = \frac{1}{R_+'(r)} \frac{d}{dr}$

Unitary Correlation Operator Method

Feldmeier, Neff, Roth, Schnack,...

unitary transformation designed to imprint central and tensor correlations into nuclear many-body states

- **explicit ansatz for unitary operator** with central and tensor correlations

$$\mathrm{U} = \mathrm{C}_\Omega \mathrm{C}_r = \exp\Big(-i \sum_{j<k} \mathrm{g}_{\Omega,jk}\Big) \exp\Big(-i \sum_{j<k} \mathrm{g}_{r,jk}\Big)$$

- **central correlations**: generated by distance-dependent shift in the relative coordinate of a nucleon pair

$$\mathrm{g}_r = \tfrac{1}{2}\big[s(\mathrm{r})\,\mathrm{q}_r + \mathrm{q}_r\,s(\mathrm{r})\big] \qquad \mathrm{q}_r = \tfrac{1}{2}\big[\tfrac{\vec{\mathrm{r}}}{\mathrm{r}} \cdot \vec{\mathrm{q}} + \vec{\mathrm{q}} \cdot \tfrac{\vec{\mathrm{r}}}{\mathrm{r}}\big]$$

- **tensor correlations**: alignment of spatial orientation of nucleon pair depending on spin direction and orientation

$$\mathrm{g}_\Omega = \tfrac{3}{2}\vartheta(\mathrm{r})\,\big[(\vec{\sigma}_1 \cdot \vec{\mathrm{q}}_\Omega)(\vec{\sigma}_2 \cdot \vec{\mathrm{r}}) + (\vec{\mathrm{q}}_\Omega \leftrightarrow \vec{\mathrm{r}})\big] \qquad \vec{\mathrm{q}}_\Omega = \vec{\mathrm{q}} - \tfrac{\vec{\mathrm{r}}}{\mathrm{r}}\mathrm{q}_r$$

Similarity Renormalization Group

Glazek, Wilson, Wegner, Perry, Bogner, Furnstahl, Hergert, Roth,...

continuous unitary transformation of Hamiltonian towards diagonal form with respect to uncorrelated basis

- **consistent unitary transformation** of Hamiltonian and observables

$$H_\alpha = U_\alpha^\dagger H\, U_\alpha \qquad O_\alpha = U_\alpha^\dagger O\, U_\alpha$$

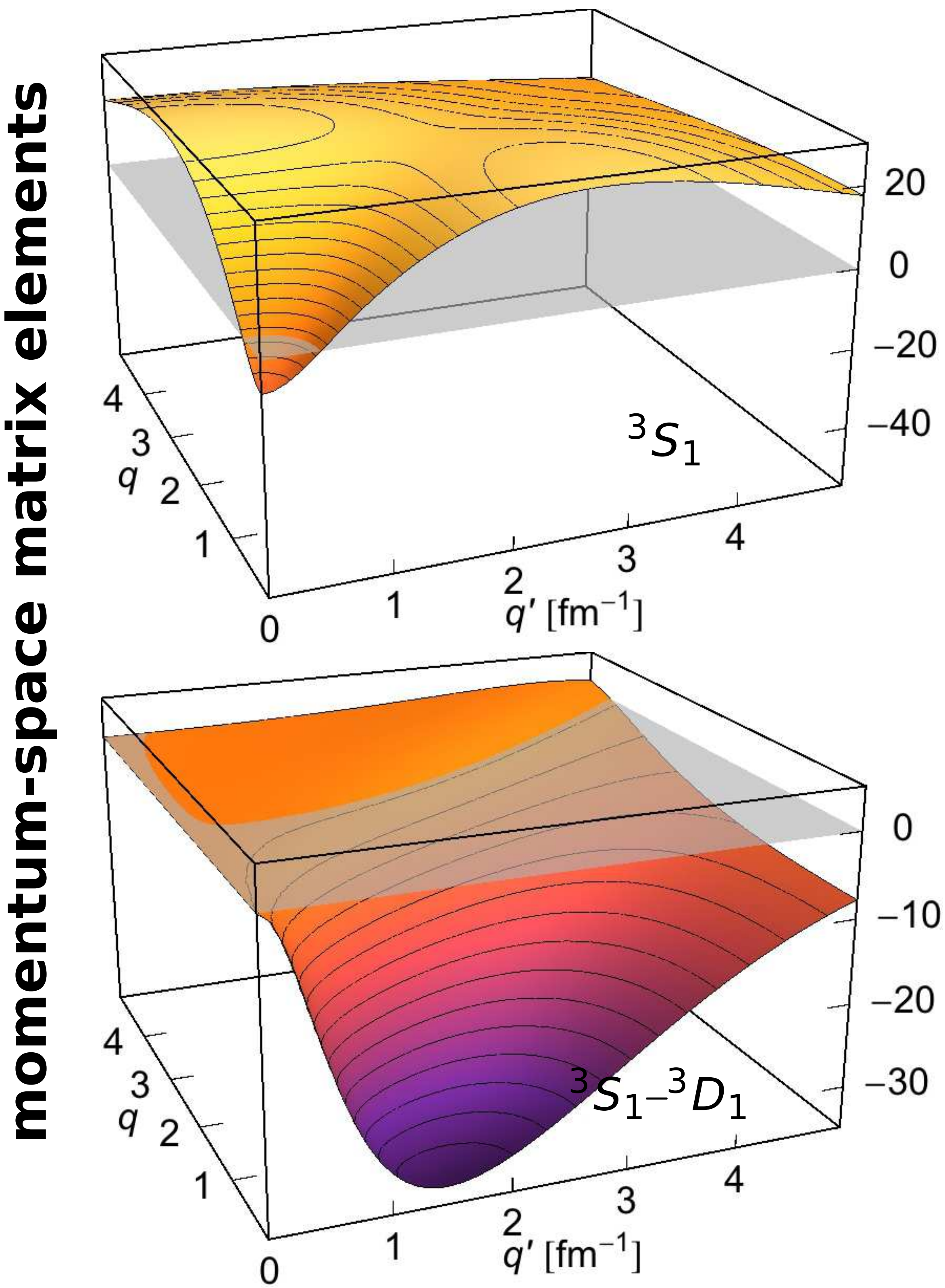
- evolution equations for H_α and U_α with continuous **flow parameter α**

$$\frac{d}{d\alpha} H_\alpha = [\eta_\alpha, H_\alpha] \qquad \frac{d}{d\alpha} O_\alpha = [\eta_\alpha, O_\alpha] \qquad \frac{d}{d\alpha} U_\alpha = -U_\alpha \eta_\alpha$$

- physics-guided choice **dynamic generator η_α**, e.g. for momentum pre-diagonalization

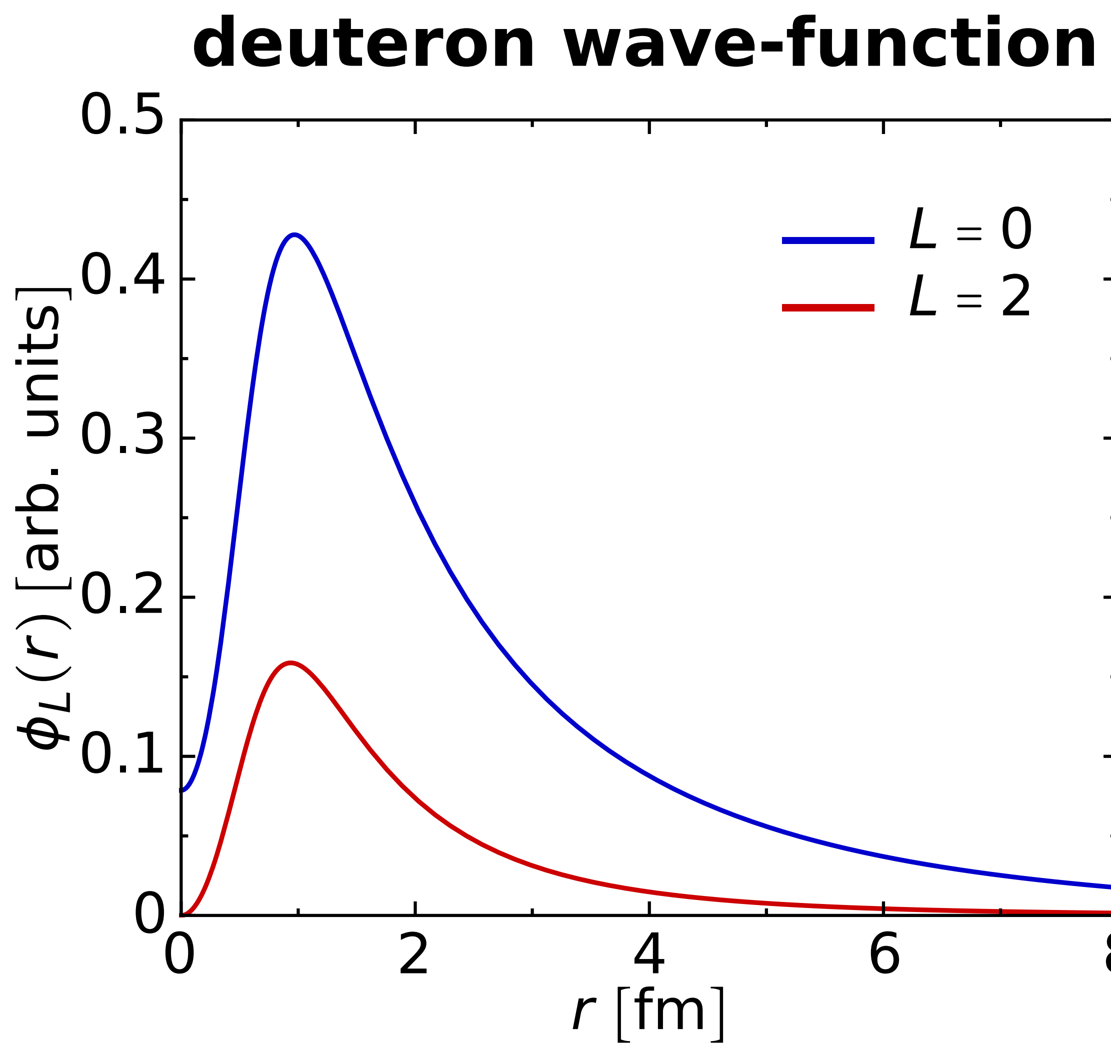
$$\eta_\alpha = (2\mu)^2\, [T_{\text{int}}, H_\alpha]$$

SRG Evolution in Two-Body Space

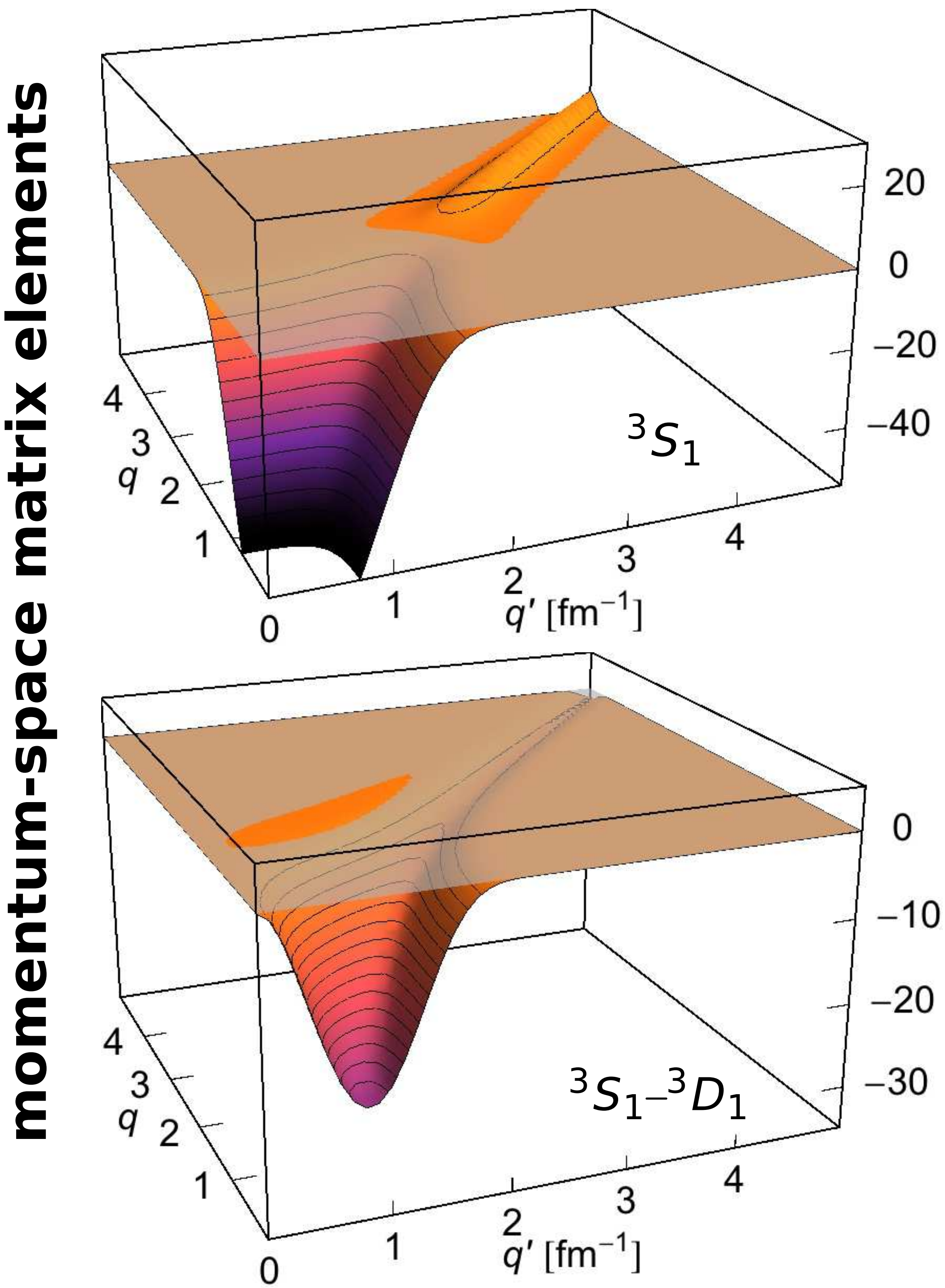


Argonne V18

$J^\pi = 1^+, T = 0$



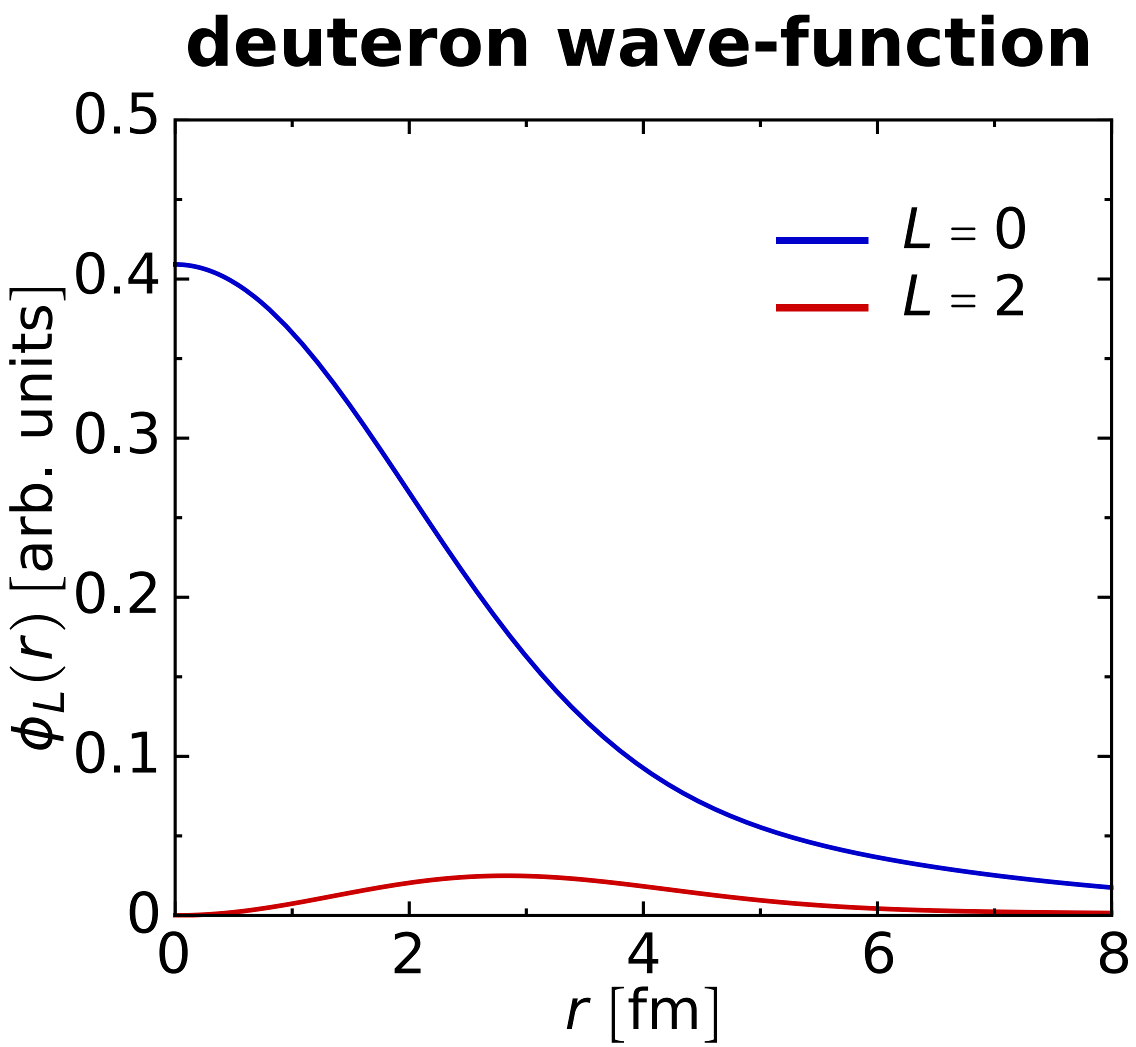
SRG Evolution in Two-Body Space



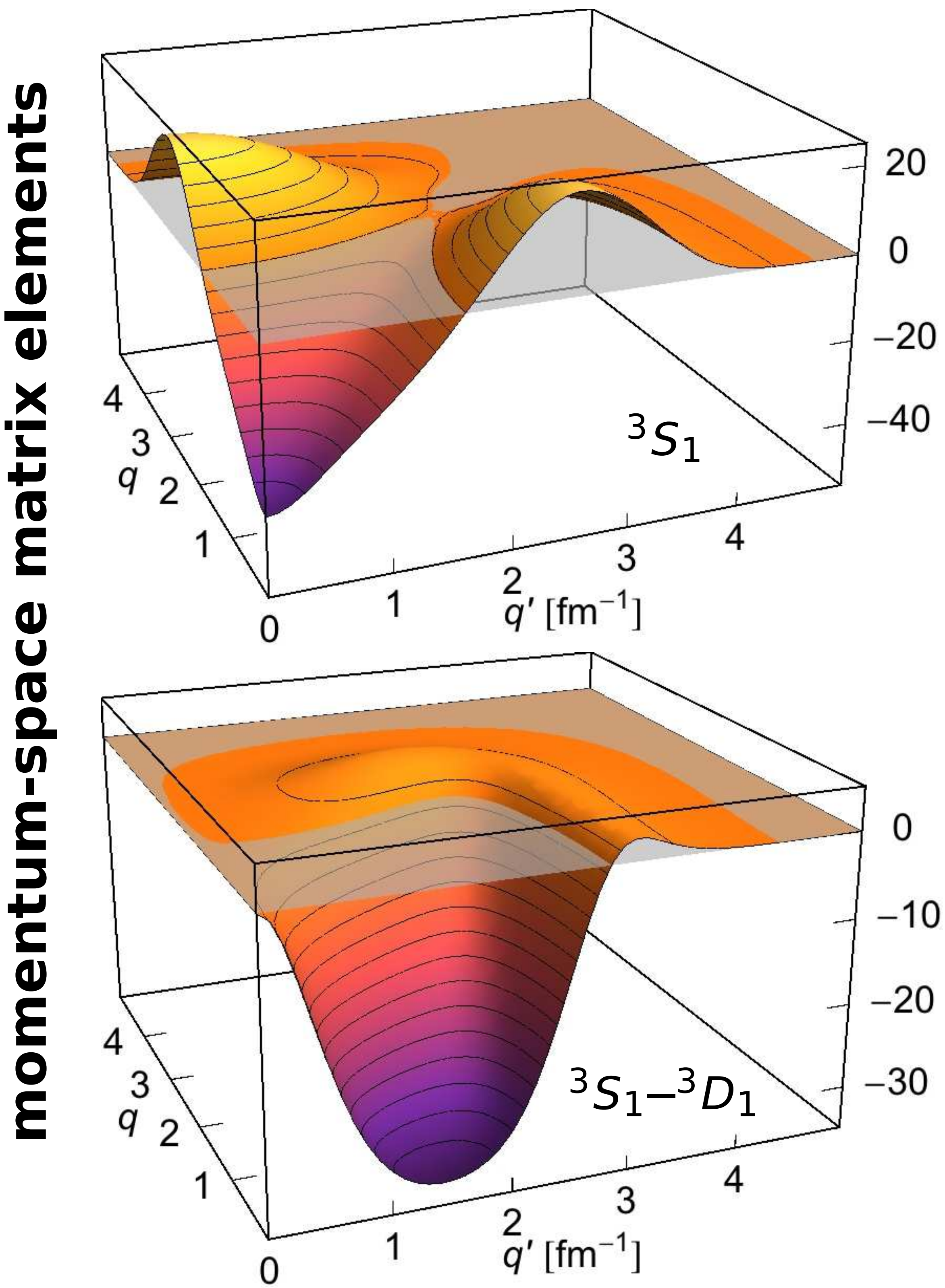
$\alpha = 0.320\,\text{fm}^4$

$\Lambda = 1.33\,\text{fm}^{-1}$

$J^\pi = 1^+, T = 0$



SRG Evolution in Two-Body Space

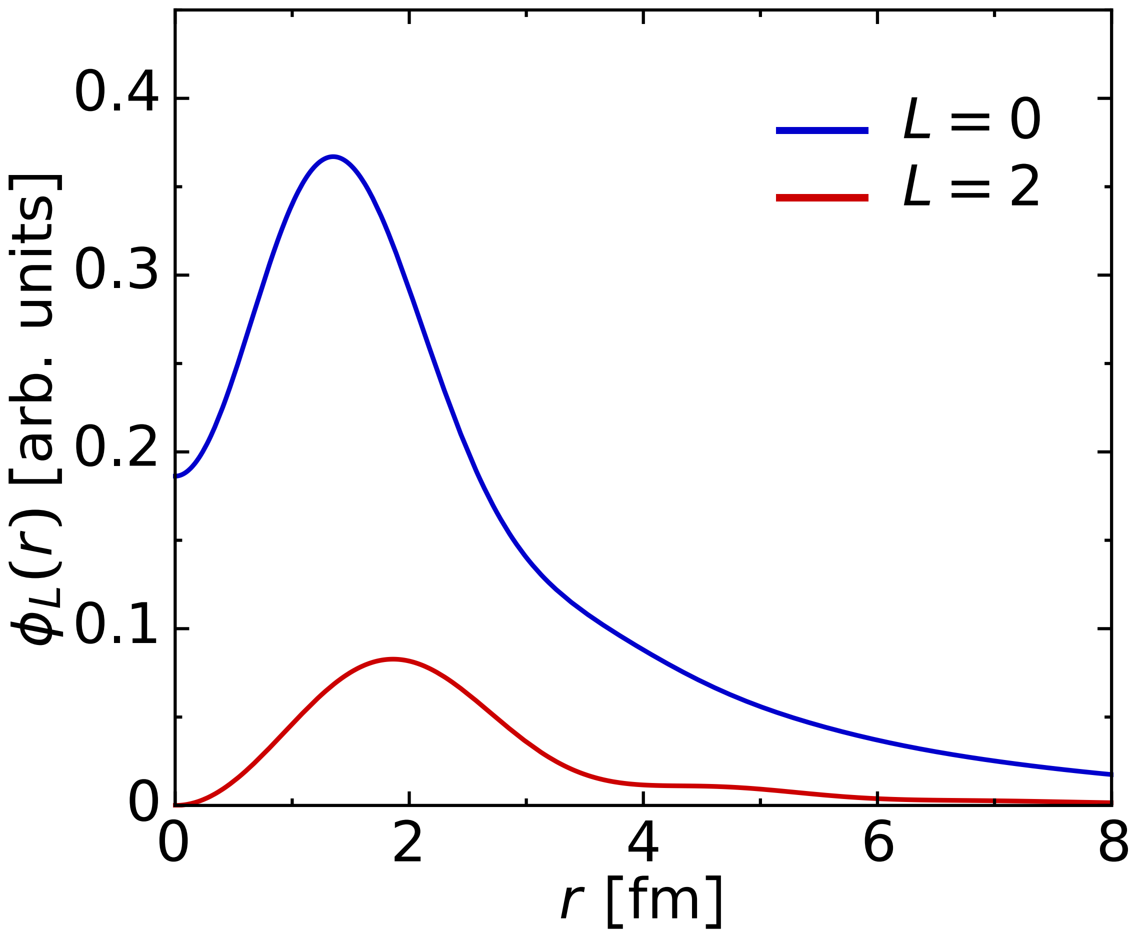


chiral NN

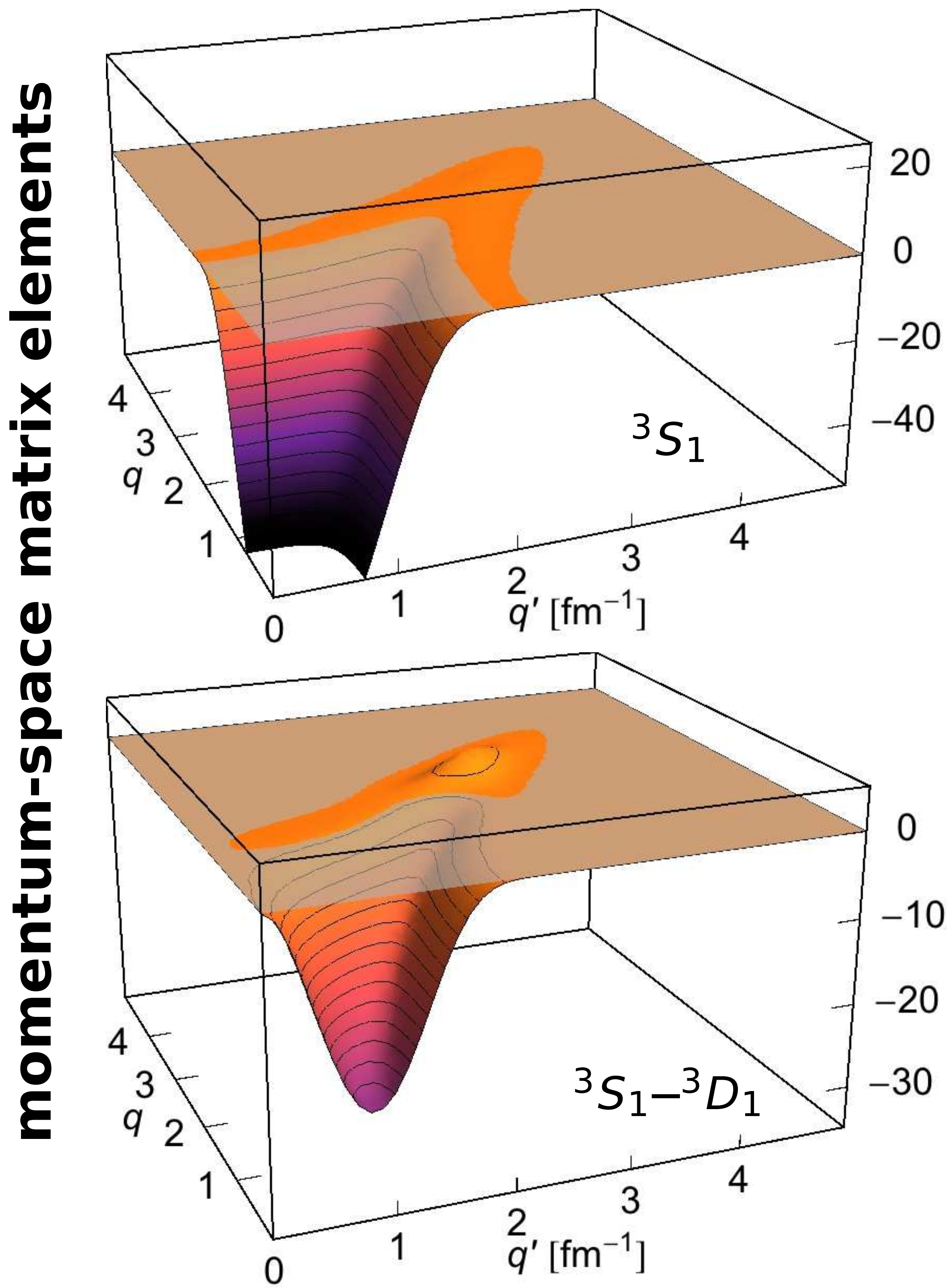
Entem & Machleidt. N^{3}LO, 500 MeV

$J^\pi = 1^+, T = 0$

deuteron wave-function



SRG Evolution in Two-Body Space

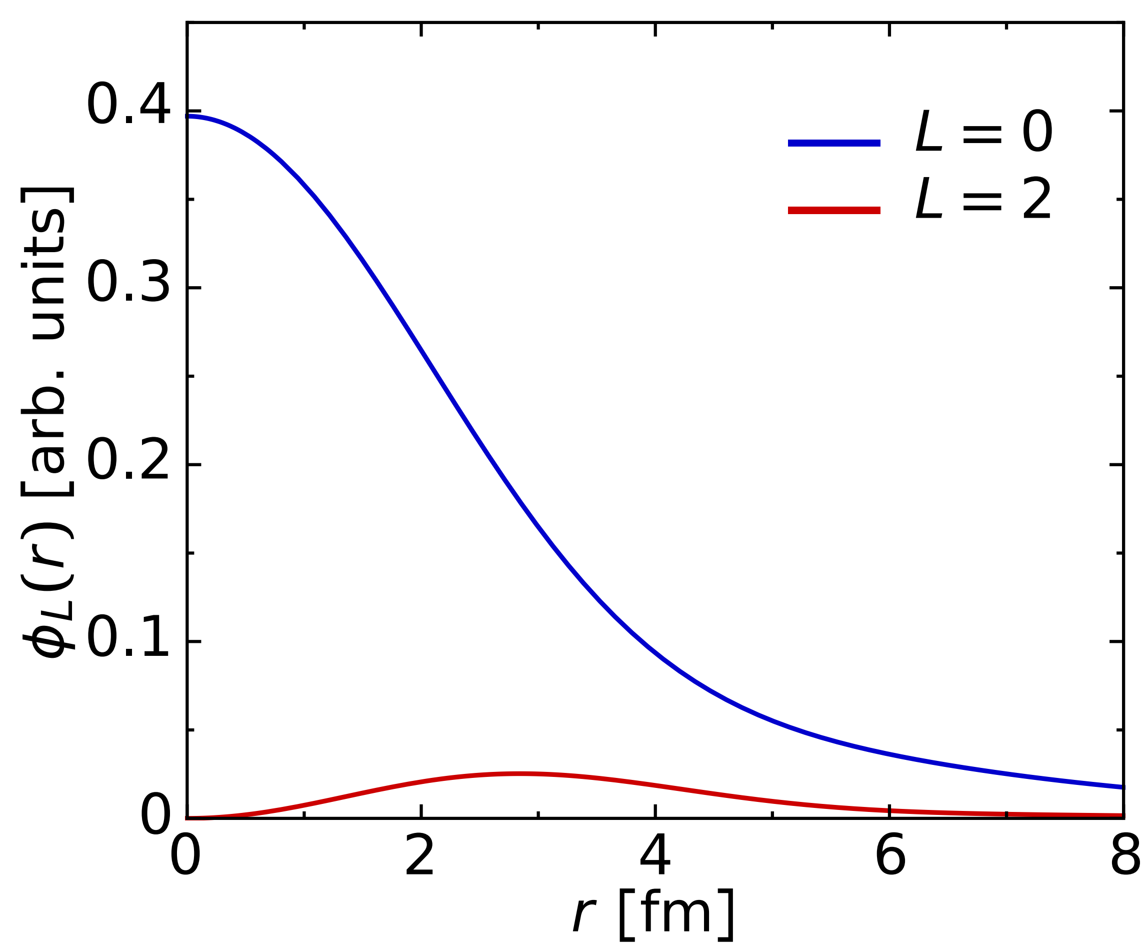


$\alpha = 0.320\,\mathrm{fm}^4$

$\Lambda = 1.33\,\mathrm{fm}^{-1}$

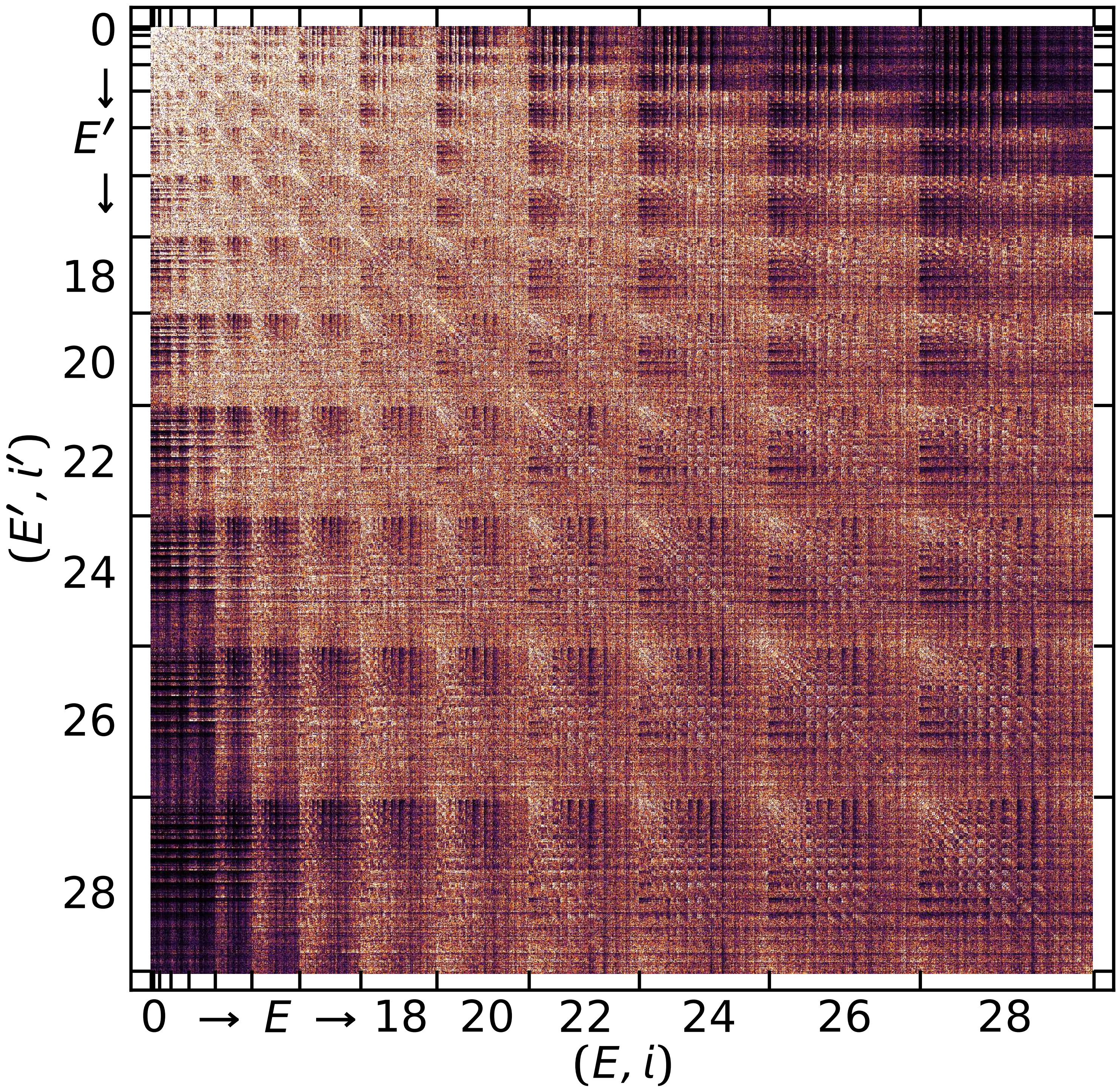
$J^\pi = 1^+, T = 0$

deuteron wave-function



SRG Evolution in Three-Body Space

3B-Jacobi HO matrix elements

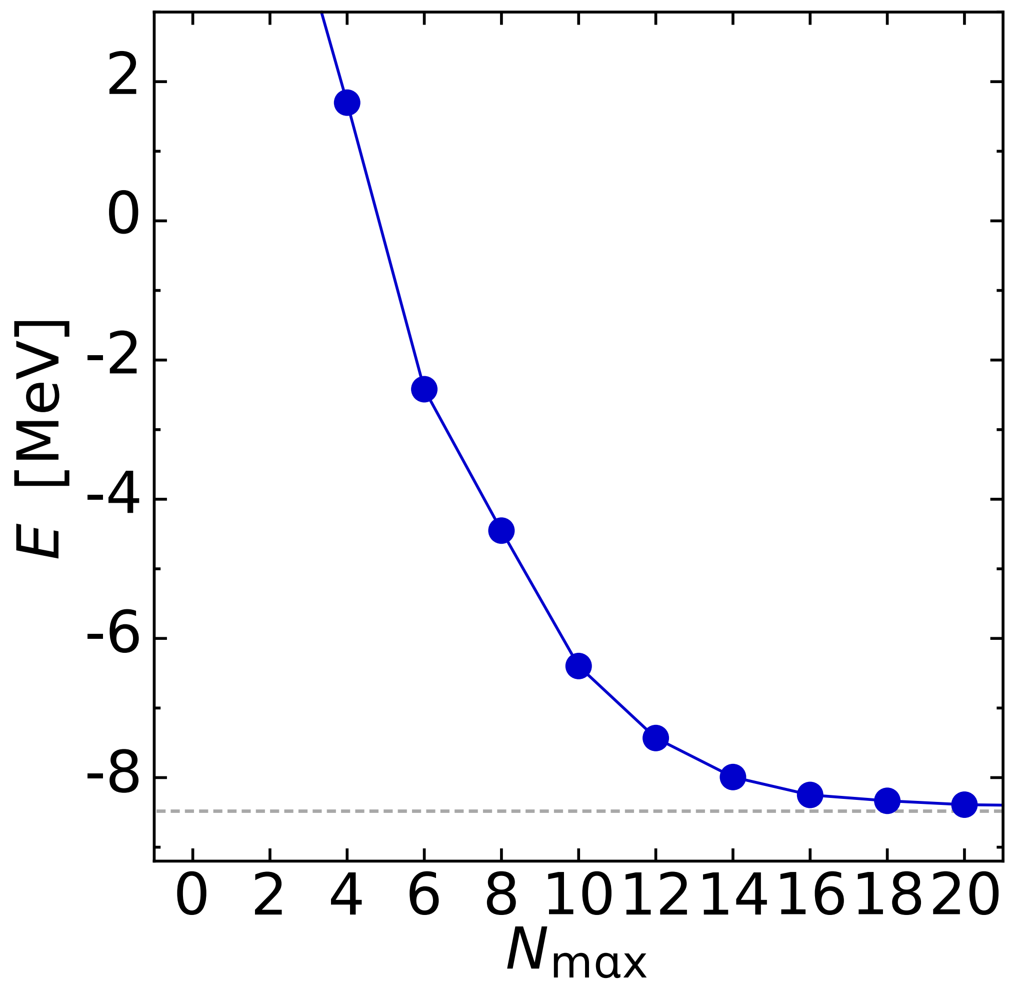


chiral NN+3N

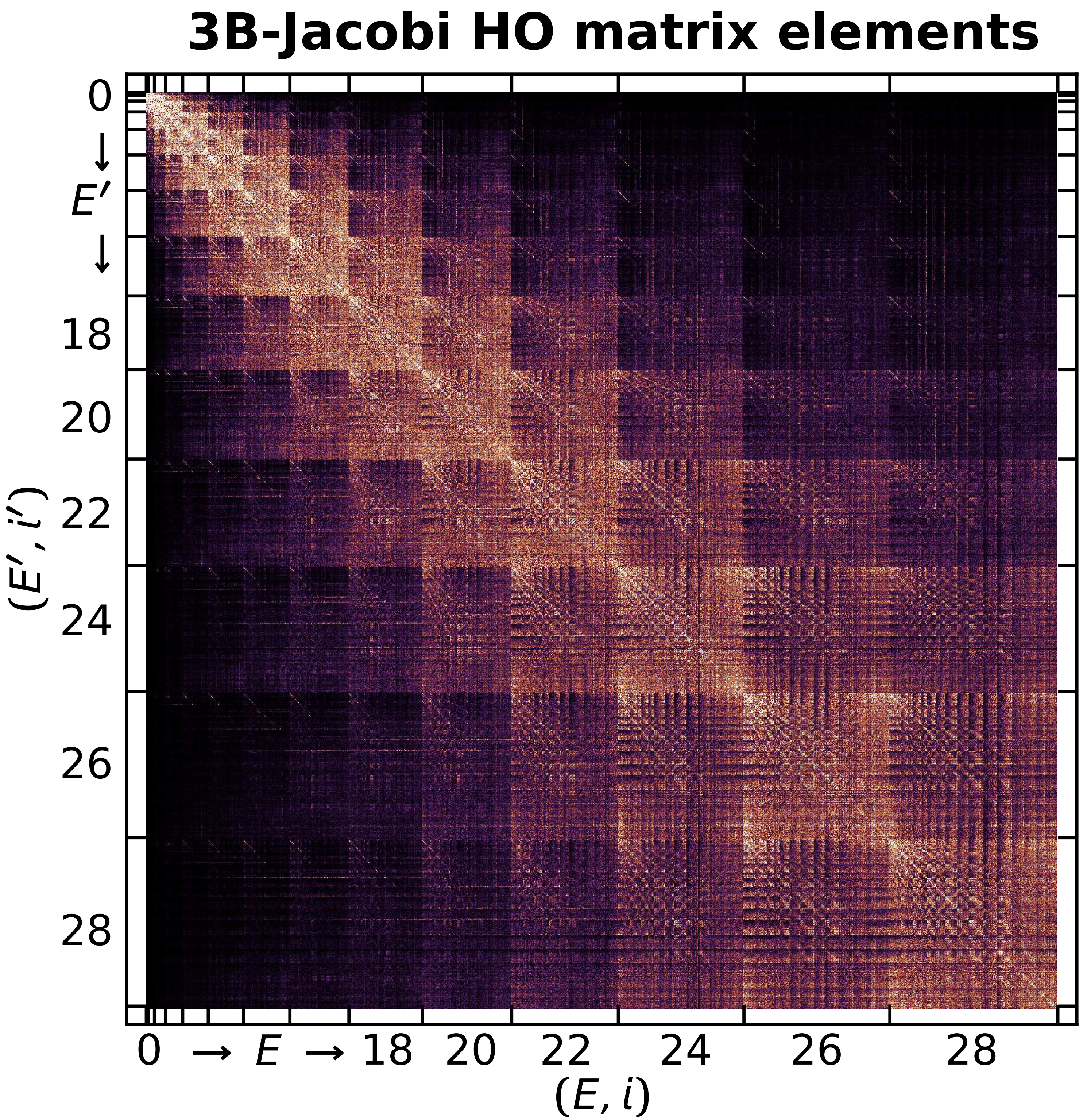
$N^3LO + N^2LO$, triton-fit, 500 MeV

$J^\pi = \frac{1}{2}^+, T = \frac{1}{2}, \hbar\Omega = 28\,\mathrm{MeV}$

NCSM ground state ^3H



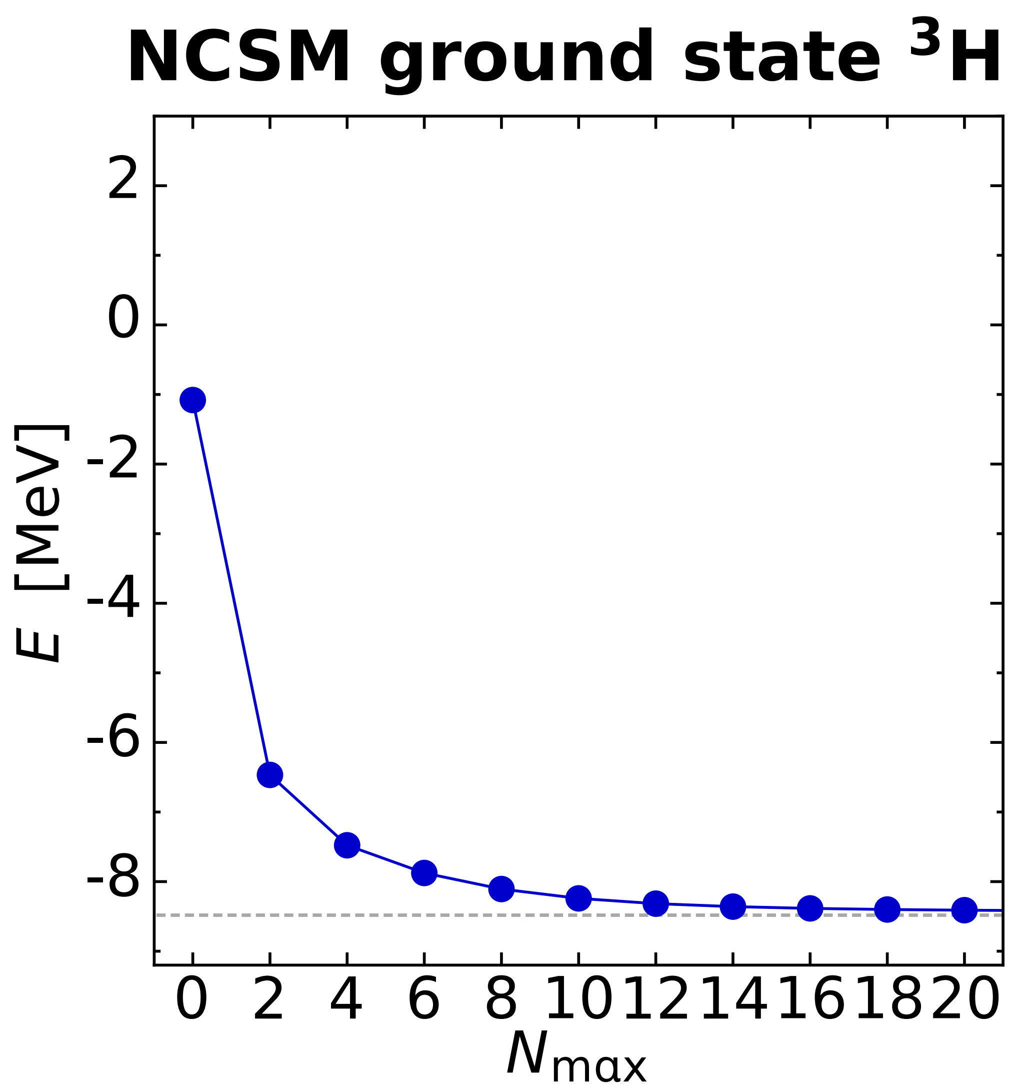
SRG Evolution in Three-Body Space



$\alpha = 0.320\,\mathrm{fm}^4$

$\Lambda = 1.33\,\mathrm{fm}^{-1}$

$J^\pi = \frac{1}{2}^+, T = \frac{1}{2}, \hbar\Omega = 28\,\mathrm{MeV}$



CE - 1

12. 3. 96
U. F.

CLUSTER - ENTWICKLUNG

Versuchszustand: $|Q\rangle = e^{-i\underset{\sim}{S}} |Q_0\rangle$

↑ Slaterdeterminante

$\underset{\sim}{S} = \underset{\sim}{S}^+$ teilchenzahlerhaltend

Effektiver Operator:

$$\underset{\sim}{O}_{eff} := e^{i\underset{\sim}{S}} \underset{\sim}{O} e^{-iS}$$

Erwartungswert:

$$\langle Q | \underset{\sim}{O} | Q \rangle = \langle Q_0 | e^{i\underset{\sim}{S}} \underset{\sim}{O} e^{-i\underset{\sim}{S}} | Q_0 \rangle = \langle Q_0 | \underset{\sim}{O}_{eff} | Q_0 \rangle$$

Cluster Entwicklung von $\underset{\sim}{O}_{eff}$

$$\underset{\sim}{O}_{eff} = \sum_{n=0}^{\infty} \underset{\sim}{O}_{eff}^{(n)}$$

Produktzustände

$$\underset{\sim}{O}_{eff}^{(n)} := \frac{1}{n!} \sum_{k_1 k_2 \cdots k_n} \langle k_1 k_2 \cdots k_n | \underset{\sim}{O}_{eff} - \sum_{m=0}^{n-1} \underset{\sim}{O}_{eff}^{(m)} | l_1 l_2 \cdots l_n \rangle a^+_{k_1} a^+_{k_2} \cdots a^+_{k_n} a_{l_n} \cdots a_{l_2} a_{l_1}$$

Hamiltonian in A-Body Space

- evolution **induces *n*-body contributions $H_\alpha^{[n]}$** to Hamiltonian

$$H_\alpha = H_\alpha^{[1]} + H_\alpha^{[2]} + H_\alpha^{[3]} + H_\alpha^{[4]} + \cdots$$

- **truncation of cluster series** formally destroys unitarity and invariance of observables (independence of α)

- flow-parameter variation provides **diagnostic tool** to assess neglected contributions of higher particle ranks

SRG-Evolved Hamiltonians

$\mathbf{NN_{only}}$: use initial NN, keep evolved NN

$\mathbf{NN+3N_{ind}}$: use initial NN, keep evolved NN+3N

$\mathbf{NN+3N_{full}}$: use initial NN+3N, keep evolved NN+3N

$\mathbf{NN+3N_{full}+4N_{ind}}$: use initial NN+3N, keep evolved NN+3N+4N

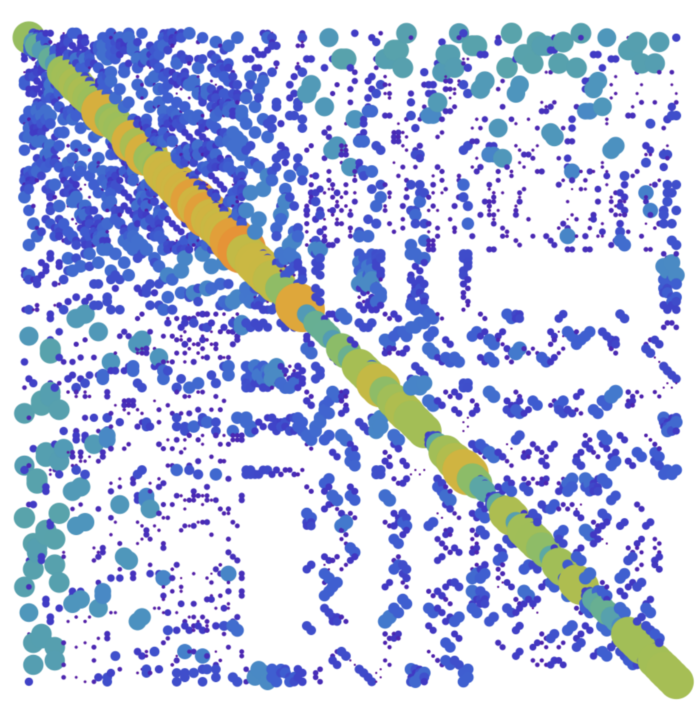
Many-Body Problem

No-Core Shell Model

Barrett, Vary, Navrátil, Maris, Nogga, Roth,...

no-core shell model is the
most universal and powerful ab initio approach for
light nuclei (up to A≈25)

- **idea**: solve eigenvalue problem of Hamiltonian represented in model space of HO Slater determinants truncated w.r.t. HO excitation energy $N_{\max}\hbar\Omega$



$$\Big(H \Big) \begin{pmatrix} \vdots \\ C_{i'}^{(n)} \\ \vdots \end{pmatrix} = E_n \begin{pmatrix} \vdots \\ C_{i}^{(n)} \\ \vdots \end{pmatrix}$$

No-Core Shell Model

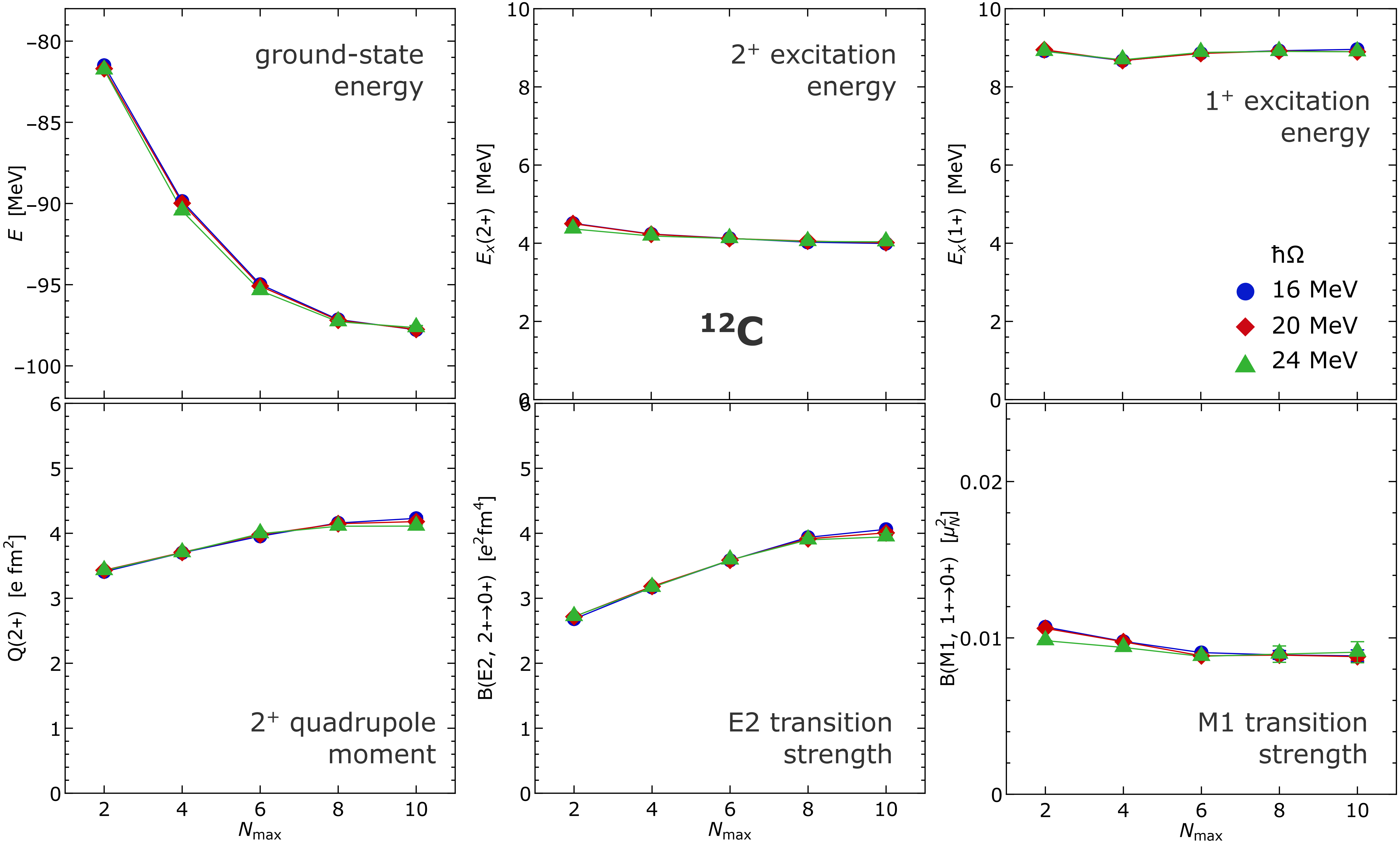
Barrett, Vary, Navrátil, Maris, Nogga, Roth,...

no-core shell model is the
most universal and powerful ab initio approach for
light nuclei (up to A≈25)

- **idea**: solve eigenvalue problem of Hamiltonian represented in model space of HO Slater determinants truncated w.r.t. HO excitation energy $N_{\max}\hbar\Omega$
  - convergence of observables w.r.t. $N_{\max}$ is the only limitation and source of uncertainty
- **importance truncation**: reduce NCSM model space to physically relevant basis states and extrapolate to full space a posteriori
  - increases the range of applicability of NCSM significantly
- **alternative basis**: optimize basis to enhance model-space convergence or to include continuum physics
  - single-particle basis: natural orbitals, Gamow states
  - many-body basis: resonating group method with binary clusters

NCSM: Convergence - Natural Orbitals

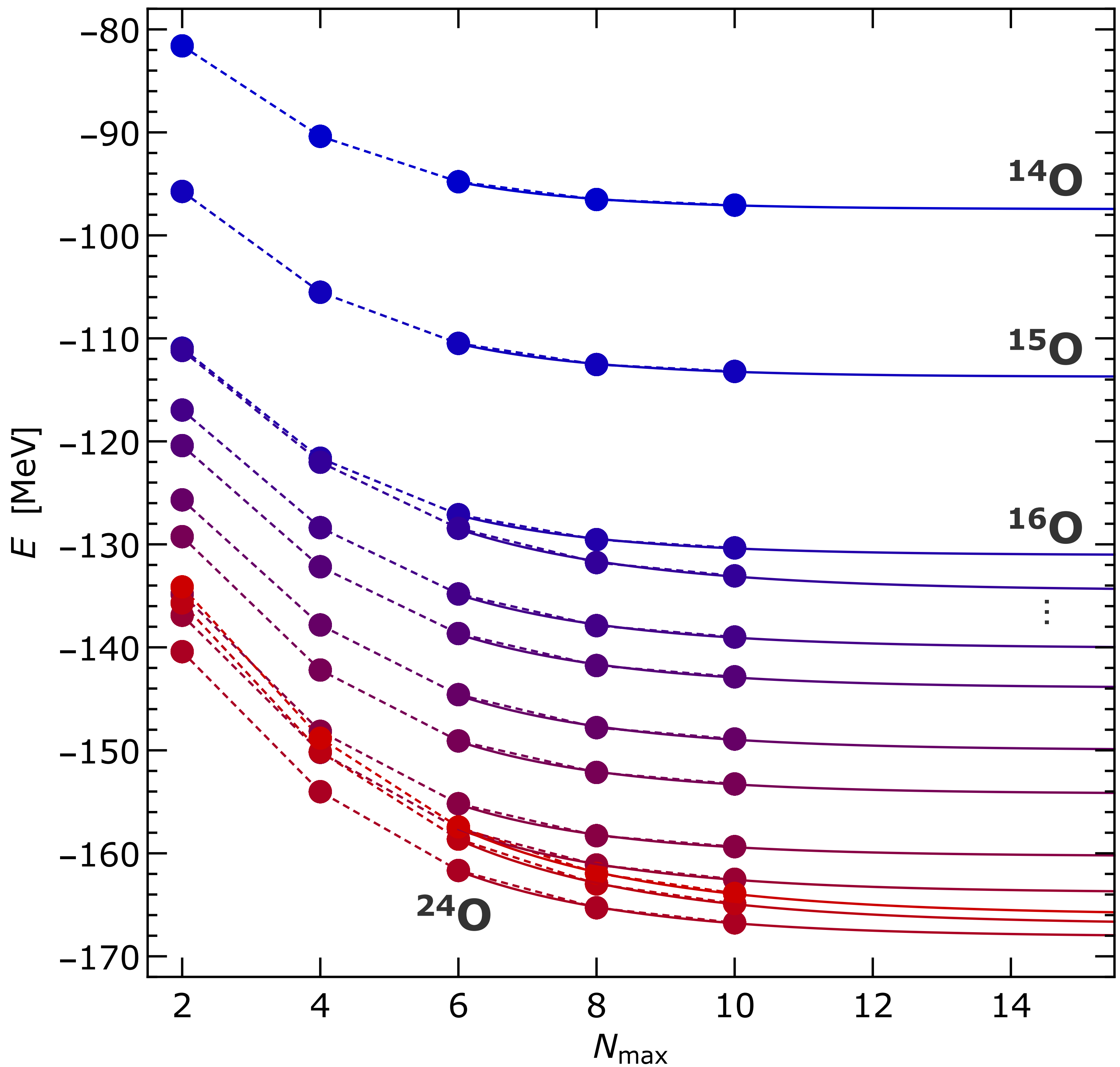
J. Müller, A. Tichai, K. Vobig, R. Roth, in prep.



NAT basis, NN+3N(500), α=0.08 fm^4, e_{max}=12

NCSM: Oxygen Isotopes

J. Müller, A. Tichai, K. Vobig, R. Roth, in prep.

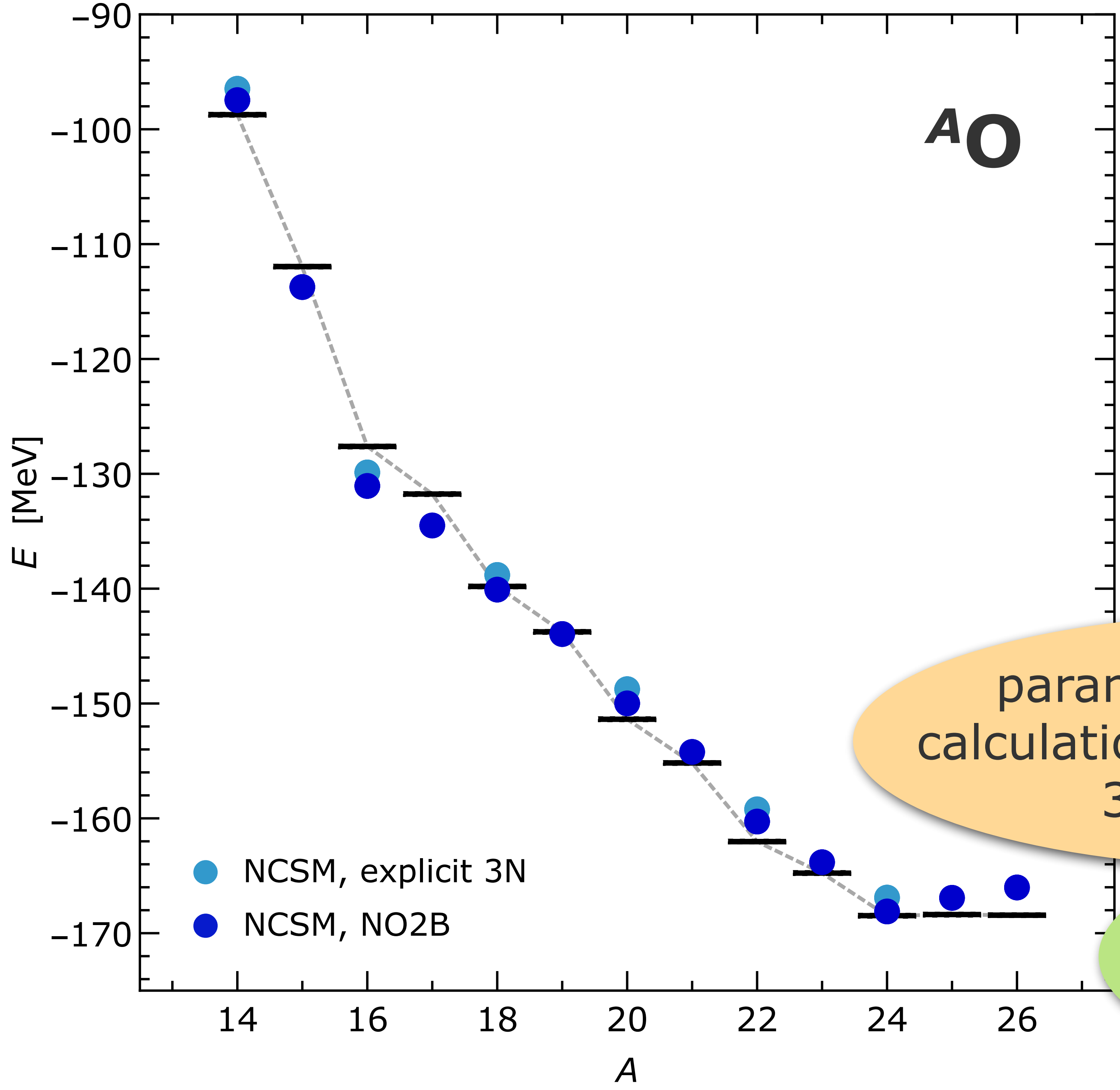


- excellent convergence with natural-orbital basis for all oxygen isotopes

chiral NN+3N
Λ_{3N}=400 MeV
α=0.08 fm^4
$\hbar\Omega$=20 MeV
e_{max}=12

NCSM: Oxygen Isotopes

J. Müller, A. Tichai, K. Vobig, R. Roth, in prep.



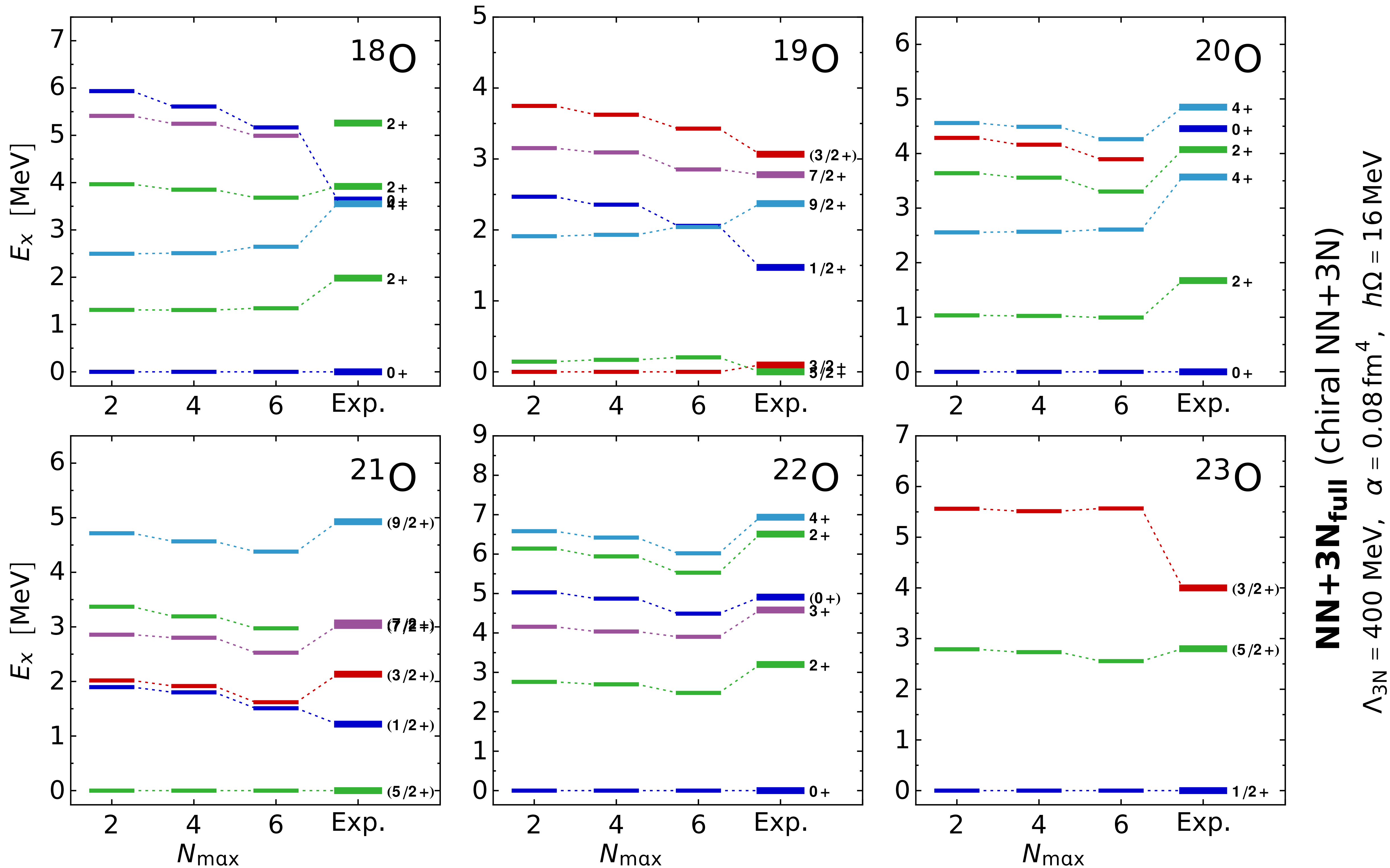
- excellent convergence with natural-orbital basis for all oxygen isotopes
- very good agreement with experimental systematics and dripline
- NO2B instead of explicit 3N causes ~1% overbinding

parameter-free ab initio calculations with explicit chiral 3N interactions

highlights predictive power of chiral NN+3N interactions

Spectra of Oxygen Isotopes

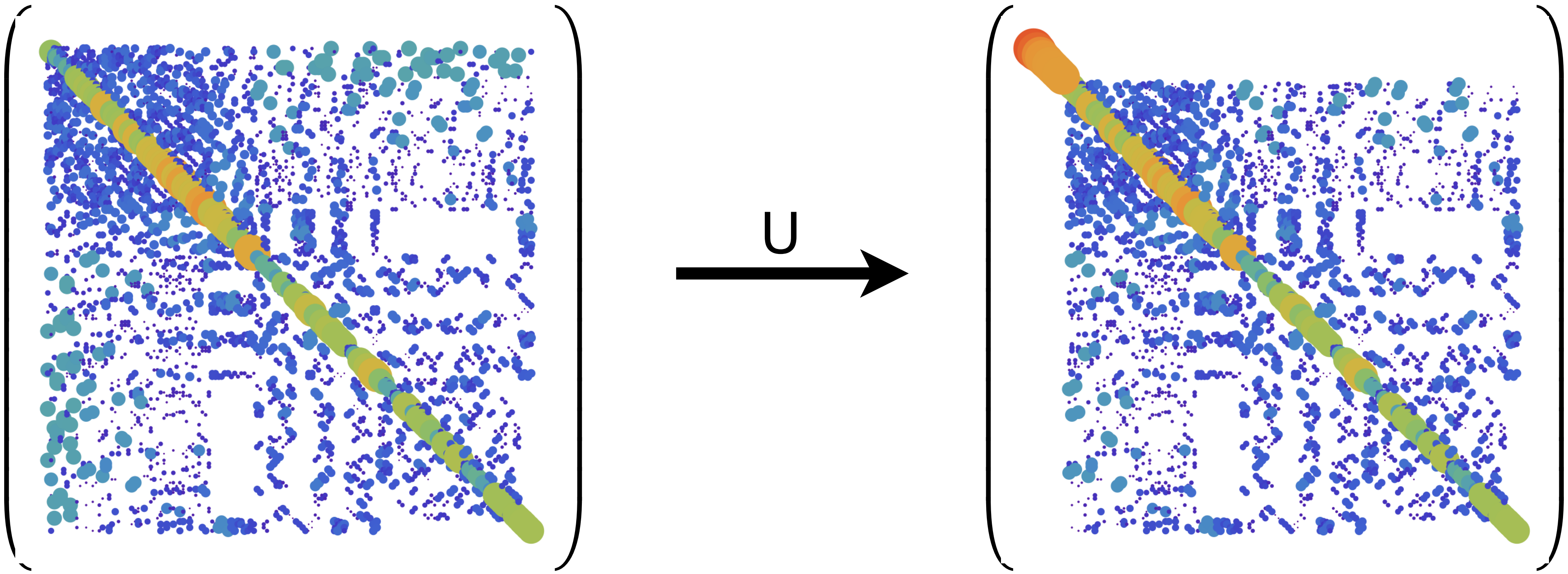
Hergert et al., PRL 110, 242501 (2013) & in prep.



Decoupling Methods

advent of novel ab initio approaches
targeting the ground state of medium-mass nuclei
very efficiently

- **idea**: decouple reference state from particle-hole excitations by a unitary or similarity transformation of Hamiltonian



Decoupling Methods

advent of novel ab initio approaches
targeting the ground state of medium-mass nuclei
very efficiently

- **idea**: decouple reference state from particle-hole excitations by a unitary or similarity transformation of Hamiltonian

Tsukiyama, Bogner, Schwenk, Hergert,...

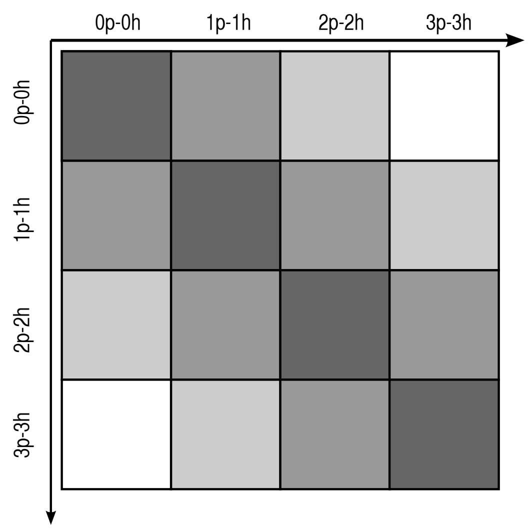
- **In-Medium Similarity Renormalisation Group**: decouple many-body reference state from particle-hole excitations by SRG transformation
  - normal-ordered A-body Hamiltonian truncated at the two-body level
  - open and closed-shell nuclei can be targeted directly

Hagen, Papenbrock, Dean, Piecuch, Binder,...

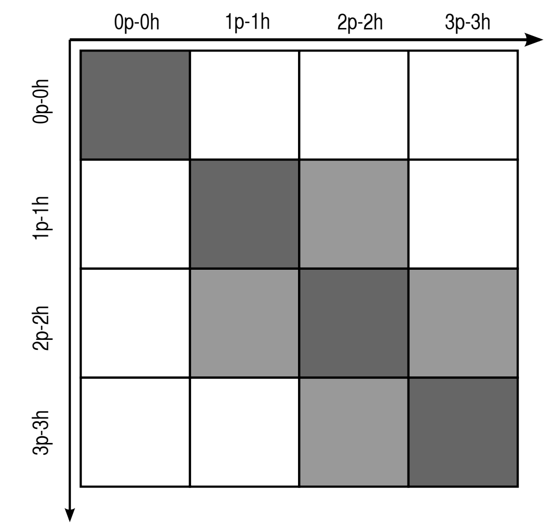
- **Coupled-Cluster Theory**: ground-state is parametrised by exponential wave operator acting on single-determinant reference state
  - truncation at doubles level (CCSD) with corrections for triples contributions
  - directly applicable for closed-shell nuclei, equations-of-motion methods for open-shell

In-Medium SRG

Tsukiyama, Bogner, Schwenk, Hergert,…



use SRG flow equations for normal-ordered Hamiltonian to decouple many-body reference state from excitations



$$\frac{d}{ds}H(s) = \left[\eta(s), H(s)\right]$$

- Hamiltonian and generator in normal order with respect to single or multi-determinant reference state, omit residual three-body piece

$$H(s) = E(s) + \sum_{ij} f^i_j(s)\,\tilde{A}^i_j + \frac{1}{4}\sum_{ijkl}\Gamma^{ij}_{kl}(s)\,\tilde{A}^{ij}_{kl} + \frac{1}{36}\sum_{ijklmn} W^{ijk}_{lmn}(s)\,\tilde{A}^{ijk}_{lmn}$$

- define generator to suppress off-diagonal contributions that couple reference state to ph excitations

$$\eta(s) = \left[H(s), H^{\mathrm{d}}(s)\right] = \left[H^{\mathrm{od}}(s), H^{\mathrm{d}}(s)\right]$$

In-Medium NCSM

Gebrerufael, Vobig, Hergert, Roth,...

NCSM
Reference State

- ground-state from NCSM at small N_{max} as reference state for multi-reference IM-SRG
- access to all open-shell nuclei and systematically improvable

IM-SRG
Many-Body Decoupling

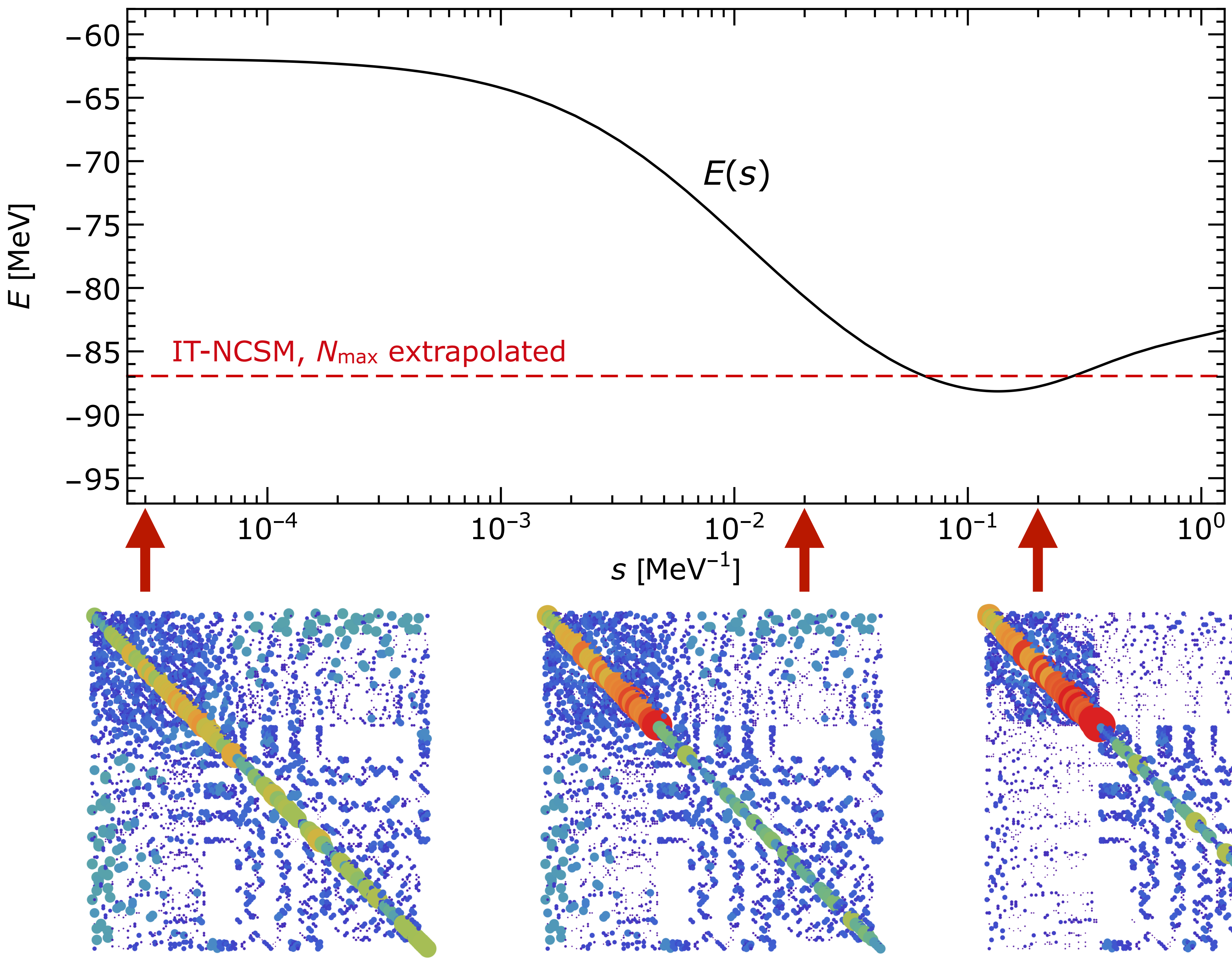
- IM-SRG evolution of multi-reference normal-ordered Hamiltonian (and other operators)
- decoupling of particle-hole excitations, i.e., pre-diagonalization in A-body space

NCSM
Observables

- use in-medium evolved Hamiltonian for a subsequent NCSM calculation
- access to ground and excited states and full suite of observables

In-Medium NCSM

Gebrerufael, et al.; PRL 118, 152503 (2017)



^{12}C

chiral NN+3N

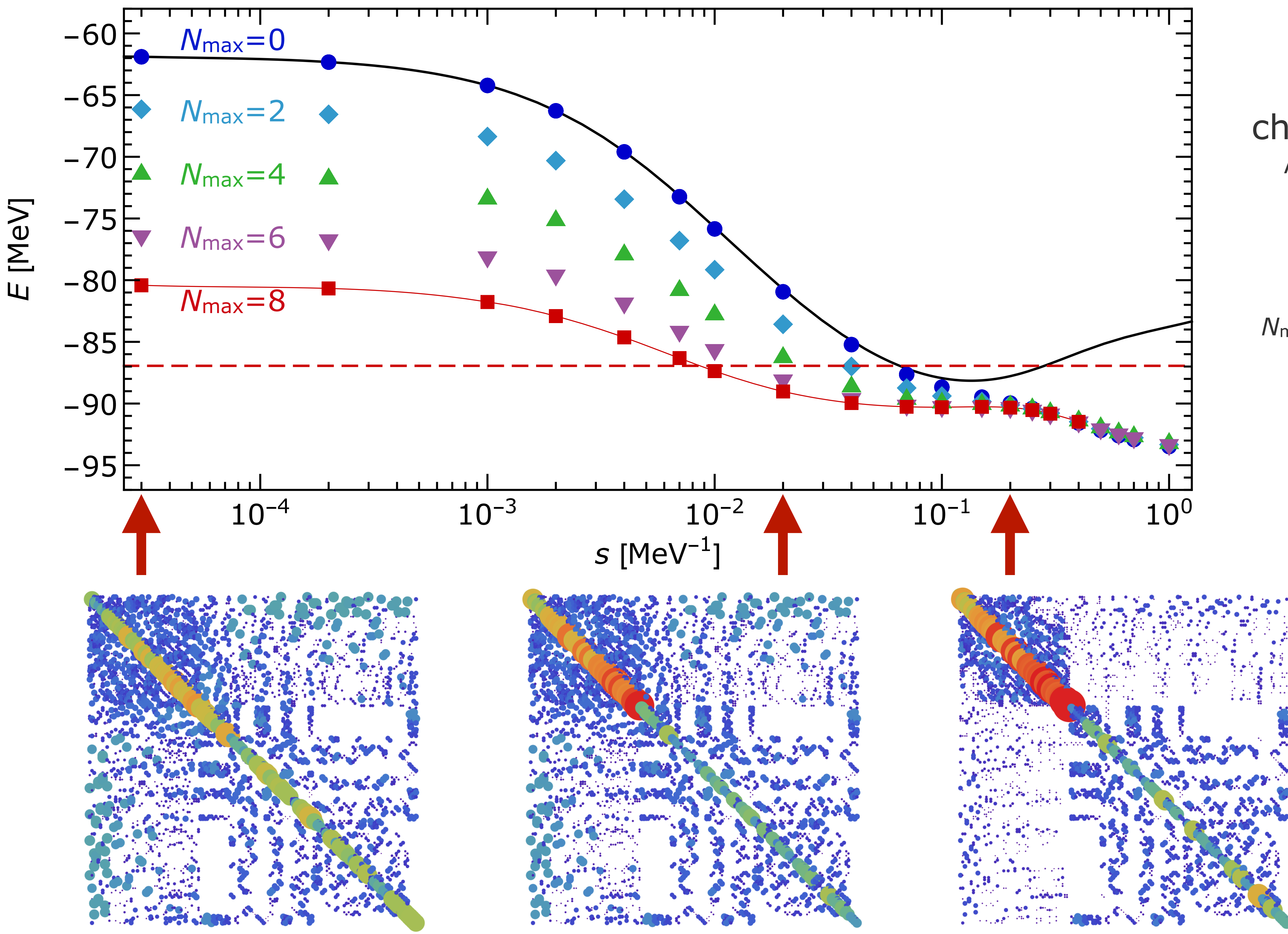
Λ_{3N}=400 MeV
α=0.08 fm^4
$\hbar\Omega$=20 MeV
e_{max}=12

N_{max}=0 reference
HF basis

Hamilton matrix in N_{max}=2 space

In-Medium NCSM

Gebrerufael, et al.; PRL 118, 152503 (2017)



^{12}C

chiral NN+3N

Λ_{3N}=400 MeV

α=0.08 fm^4

ħΩ=20 MeV

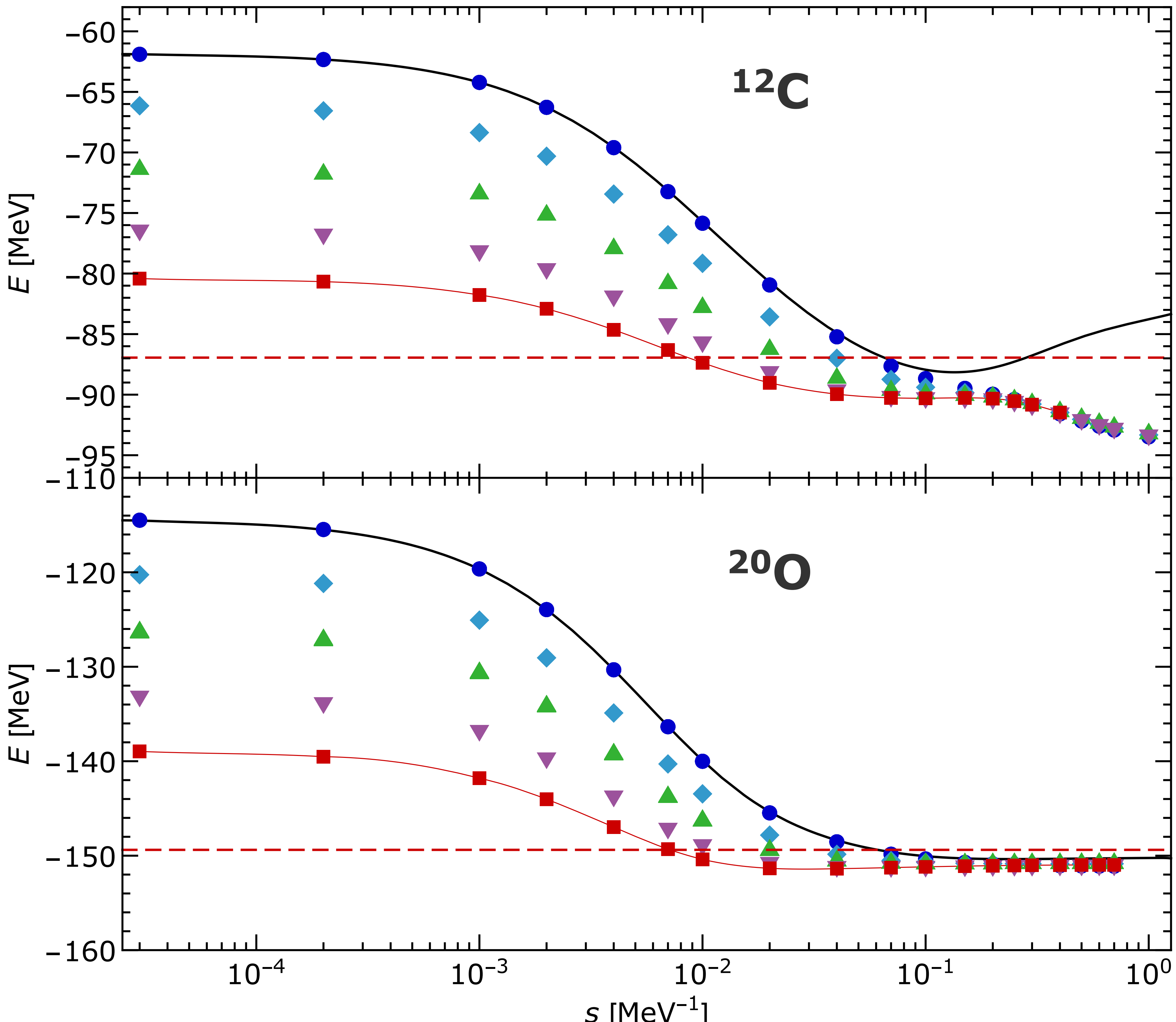
e_{max}=12

N_{max}=0 reference HF basis

Hamilton matrix in N_{max}=2 space

In-Medium NCSM

Gebrerufael, et al.; PRL 118, 152503 (2017)



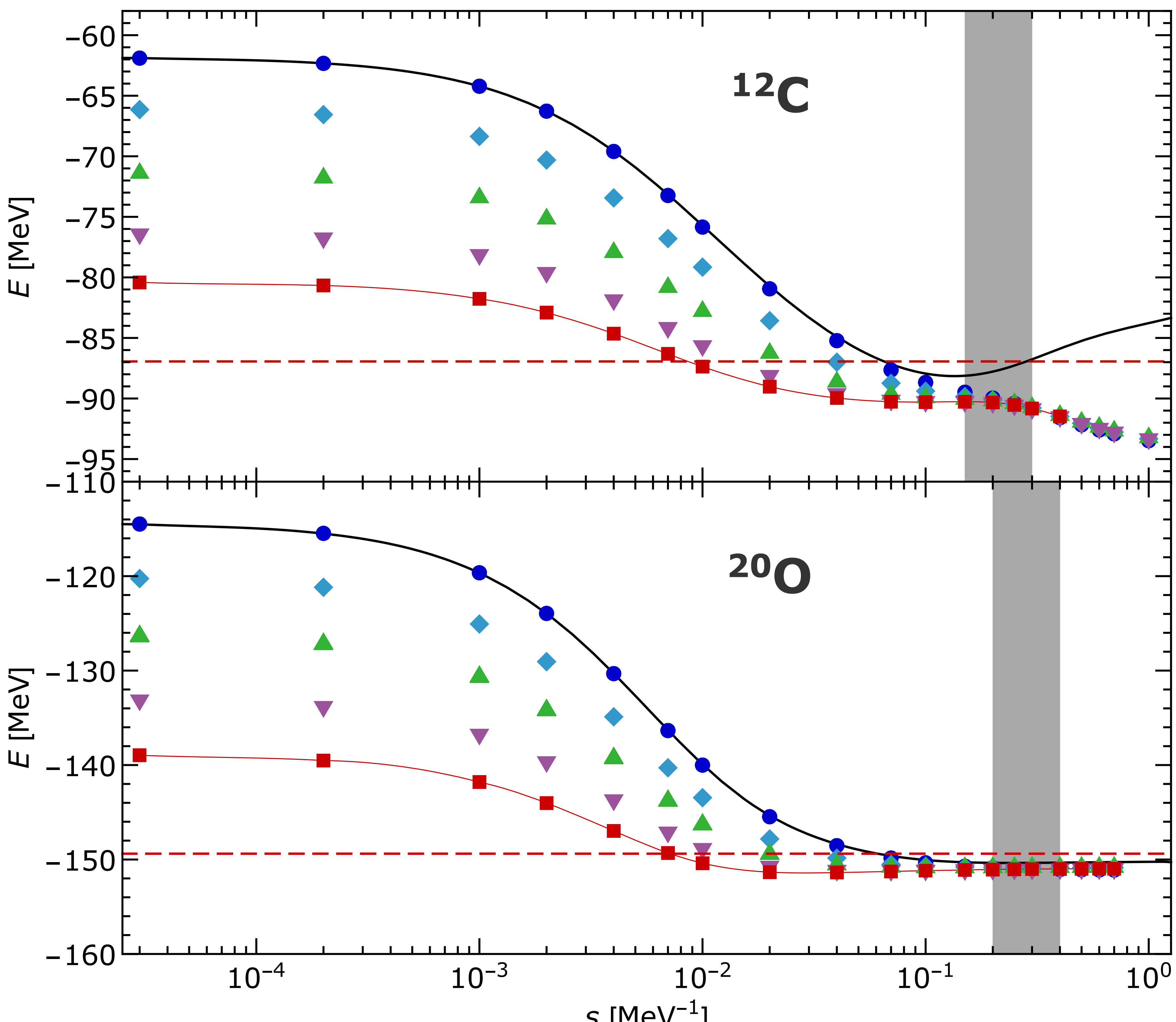
- NCSM convergence is drastically improved
- N_{max}=0 eigenvalues deviated from $E(s)$
- identify plateau in s before induced terms blow up

chiral NN+3N
Λ_{3N}=400 MeV
α=0.08 fm^4
$\hbar\Omega$=20 MeV
e_{max}=12

HF basis
N_{max}=0 reference state
N_{max}=0,2,4,6,8

In-Medium NCSM

Gebrerufael, et al.; PRL 118, 152503 (2017)



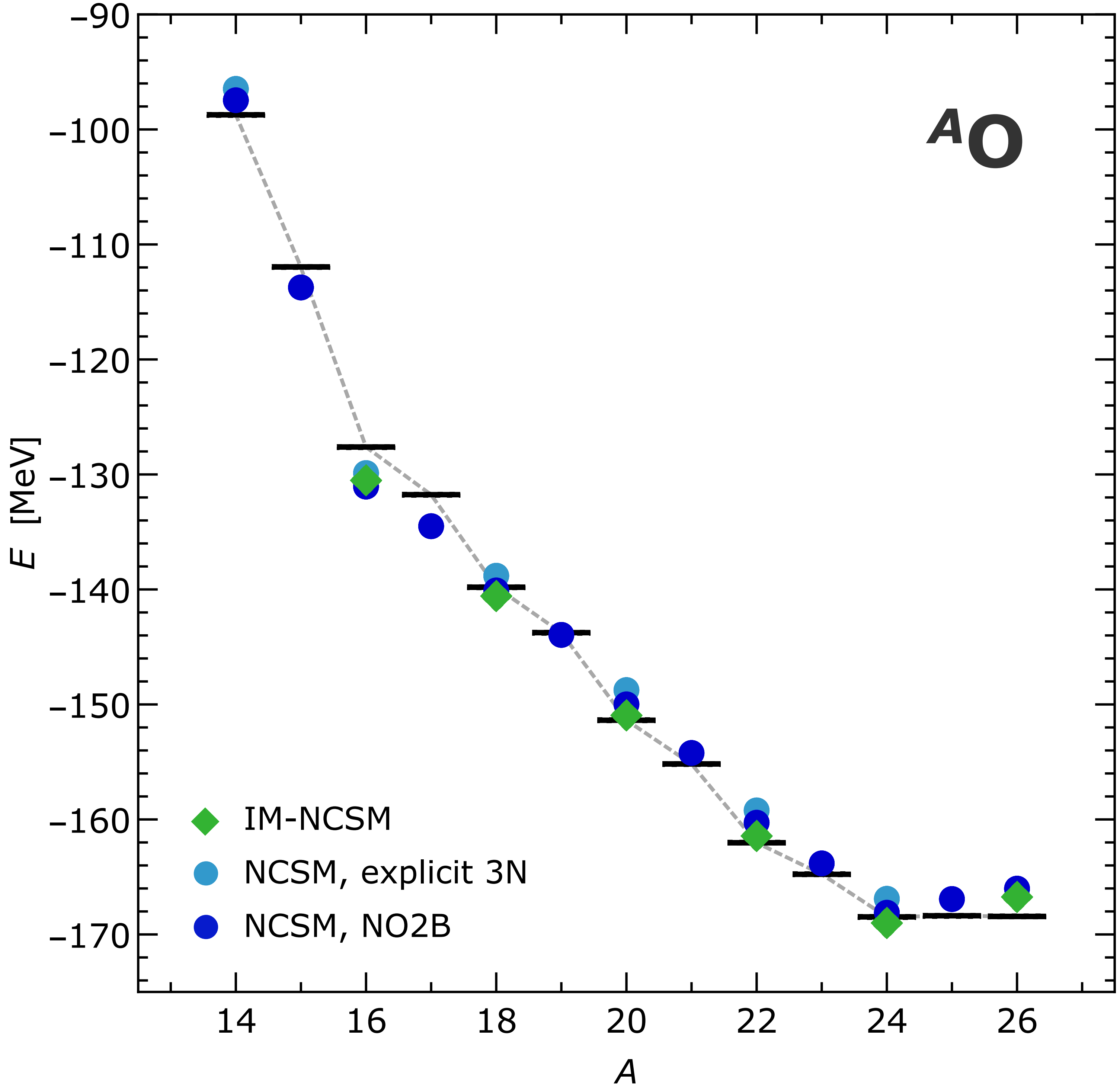
- NCSM convergence is drastically improved
- N_{max}=0 eigenvalues deviated from $E(s)$
- identify plateau in s before induced terms blow up

chiral NN+3N
Λ_{3N}=400 MeV
α=0.08 fm^4
$\hbar\Omega$=20 MeV
e_{max}=12

HF basis
N_{max}=0 reference state
N_{max}=0,2,4,6,8

IM-NCSM: Oxygen Isotopes

Gebrerufael, et al.; PRL 118, 152503 (2017)



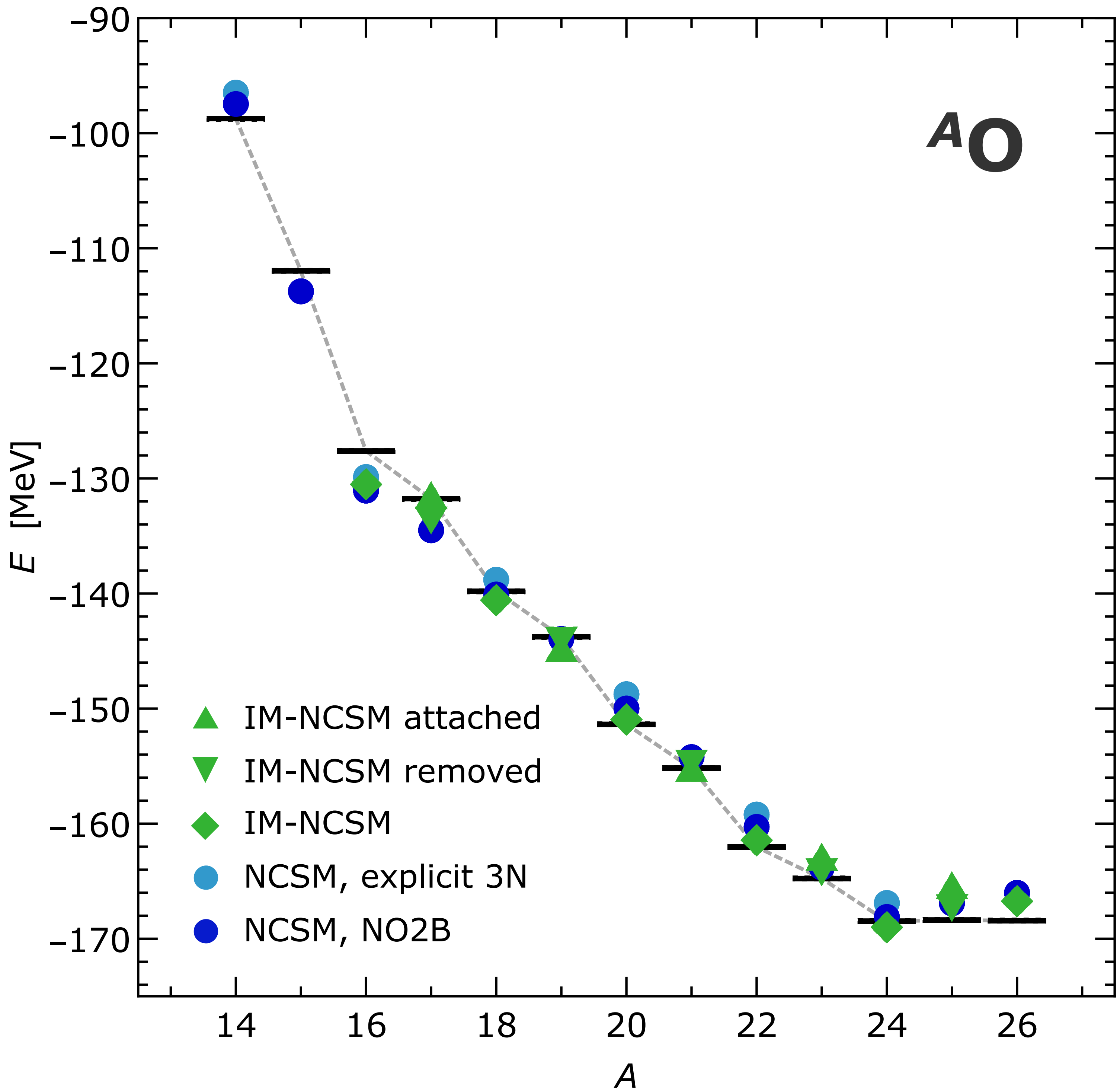
- excellent agreement with direct NCSM
- IM-SRG evolution limited to J=0 reference states and thus even-mass isotopes

chiral NN+3N
Λ_{3N}=400 MeV
α=0.08 fm^4
$\hbar\Omega$=20 MeV
e_{max}=12

HF basis
N_{max}=0 reference

IM-NCSM: Oxygen Isotopes

Vobig, Gebrerufael, Roth; in prep.



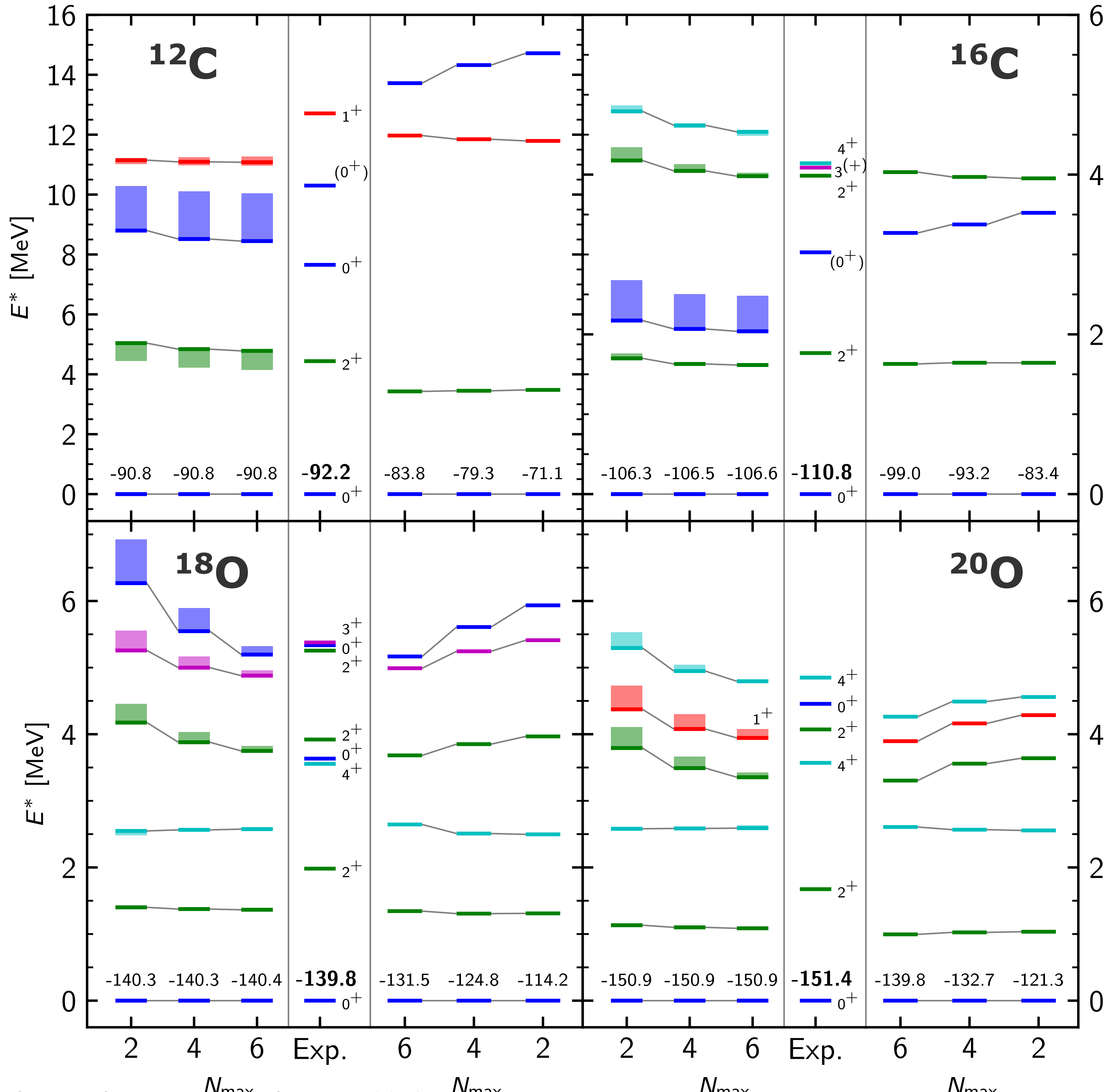
chiral NN+3N
Λ_{3N}=400 MeV
α=0.08 fm^4
$\hbar\Omega$=20 MeV
e_{max}=12

HF basis
N_{max}=0 reference

- excellent agreement with direct NCSM
- IM-SRG evolution limited to *J*=0 reference states and thus even-mass isotopes
- odd-mass nuclei via simple particle attachment or removal in final NCSM run

IM-NCSM: Excitation Spectra

Gebrerufael, et al.; PRL 118, 152503 (2017)

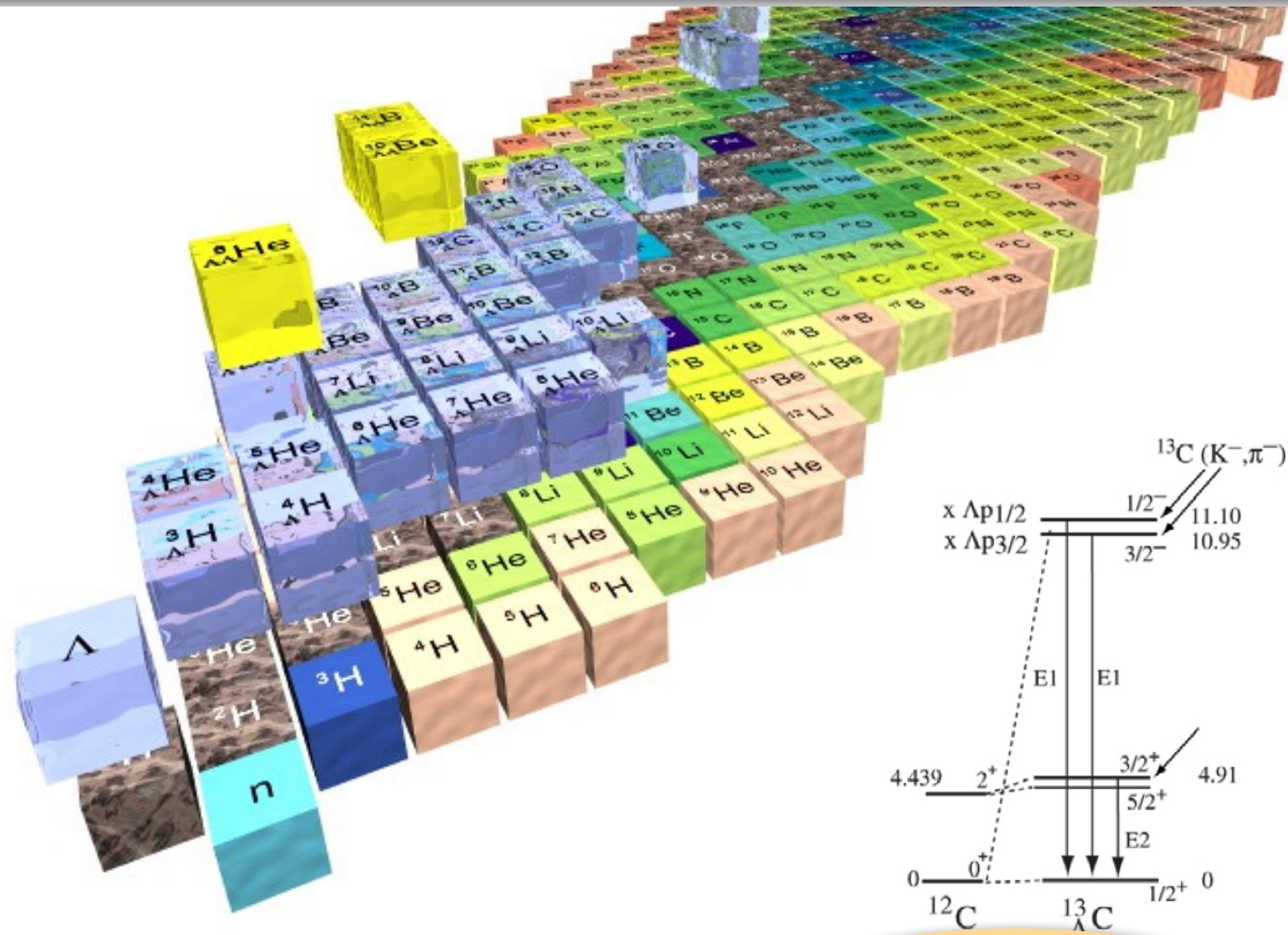


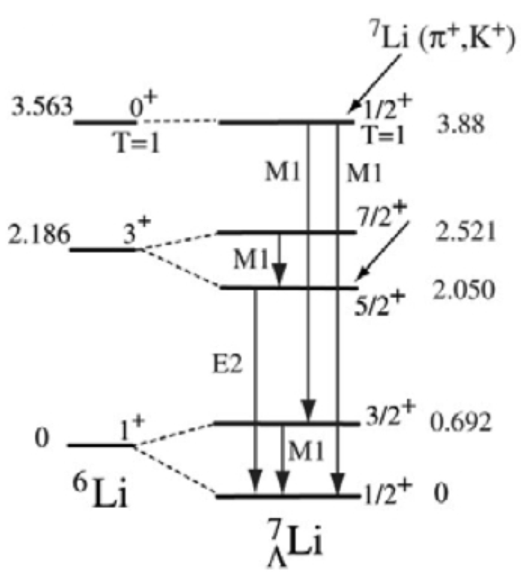
- IM-NCSM and direct NCSM in excellent agreement for converged states
- first excited 0^+ states in ^{12}C and ^{16}C differ

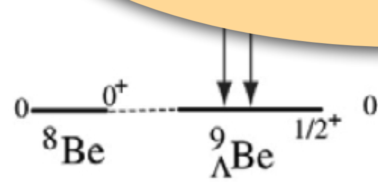
chiral NN+3N
Λ_{3N}=400 MeV
α=0.08 fm^4
ħΩ=16 MeV
e_{max}=12
HF basis

Hypernuclei

Ab Initio Hypernuclear Structure







- precise data on ground states & spectroscopy of hypernuclei
- ab initio few-body and phenomen. shell-model, mean-field or cluster-model calculations done so far
- chiral YN & YY interactions at (N)LO are available

constrain YN interactions with hypernuclear spectroscopy

time to transfer ab initio toolbox to hypernuclei

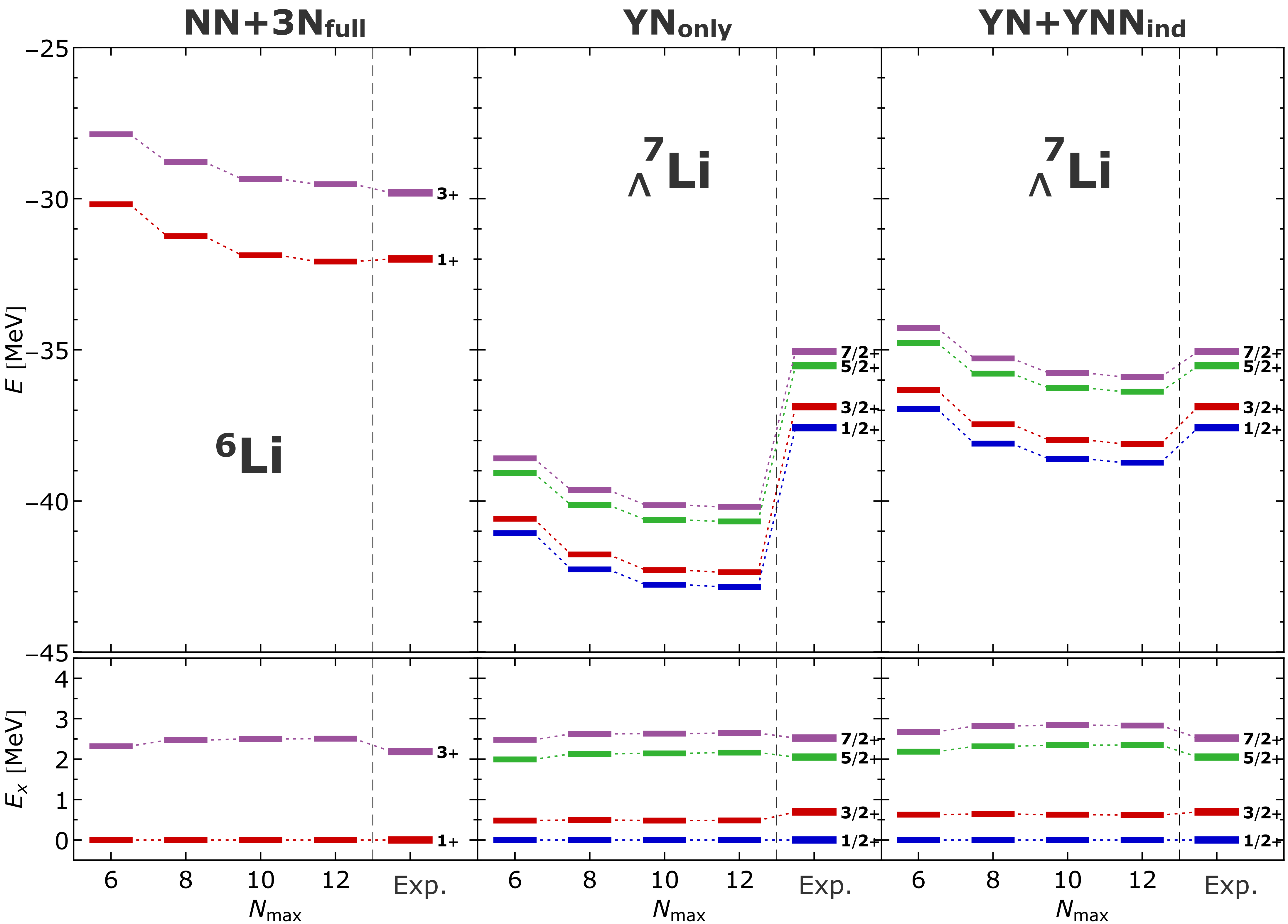
Ab Initio Toolbox for Hypernuclei

Wirth et al.; PRL 113, 192502 (2014); PRL 117, 182501 (2016)

- **Hamiltonian from chiral EFT**
  - NN+3N: standard chiral Hamiltonian (Entem&Machleidt, Navrátil)
  - YN: LO chiral interaction (Haidenbauer et al.), NLO in progress
- **Similarity Renormalization Group**
  - consistent SRG-evolution of NN, 3N, YN interactions
  - using particle basis and including ΛΣ-coupling (larger matrices)
  - Λ-Σ mass difference and $p\Sigma^{\pm}$ Coulomb included consistently
- **Importance Truncated No-Core Shell Model**
  - include explicit $(p, n, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-)$ with physical masses
  - larger model spaces easily tractable with importance truncation
  - all p-shell single-Λ hypernuclei are accessible

Application: ${}^{7}_{\Lambda}$Li

Wirth et al.; PRL 113, 192502 (2014); PRL 117, 182501 (2016)



NCSM

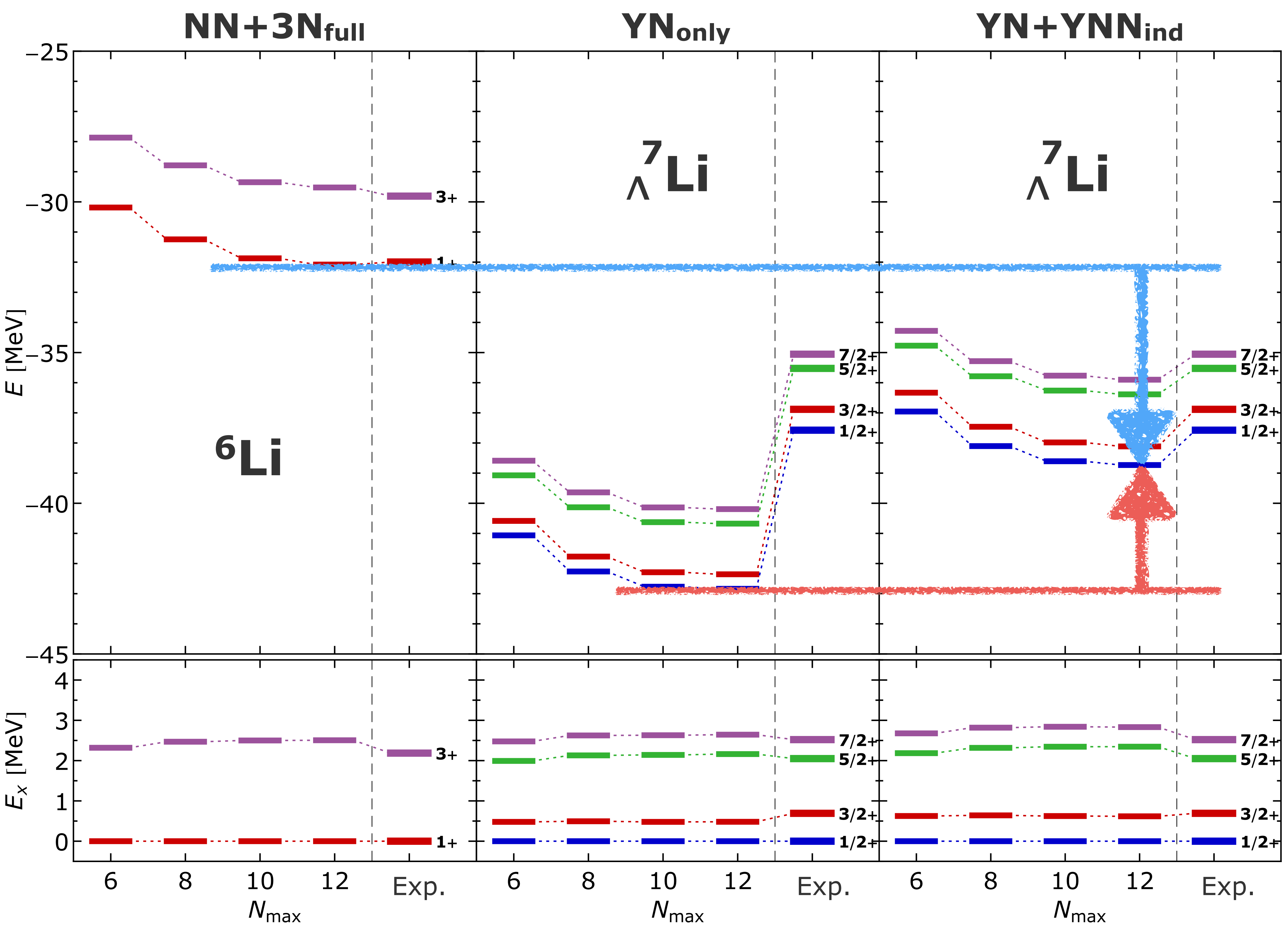
chiral NN+3N
standard
N3LO+N2LO
Λ_{3N}=500 MeV
α=0.08 fm^4

chiral YN
LO
Λ_{YN}=700 MeV
α=0.08 fm^4

$\hbar\Omega$=20 MeV

Application: $^{7}_{\Lambda}$Li

Wirth et al.; PRL 113, 192502 (2014); PRL 117, 182501 (2016)



NCSM

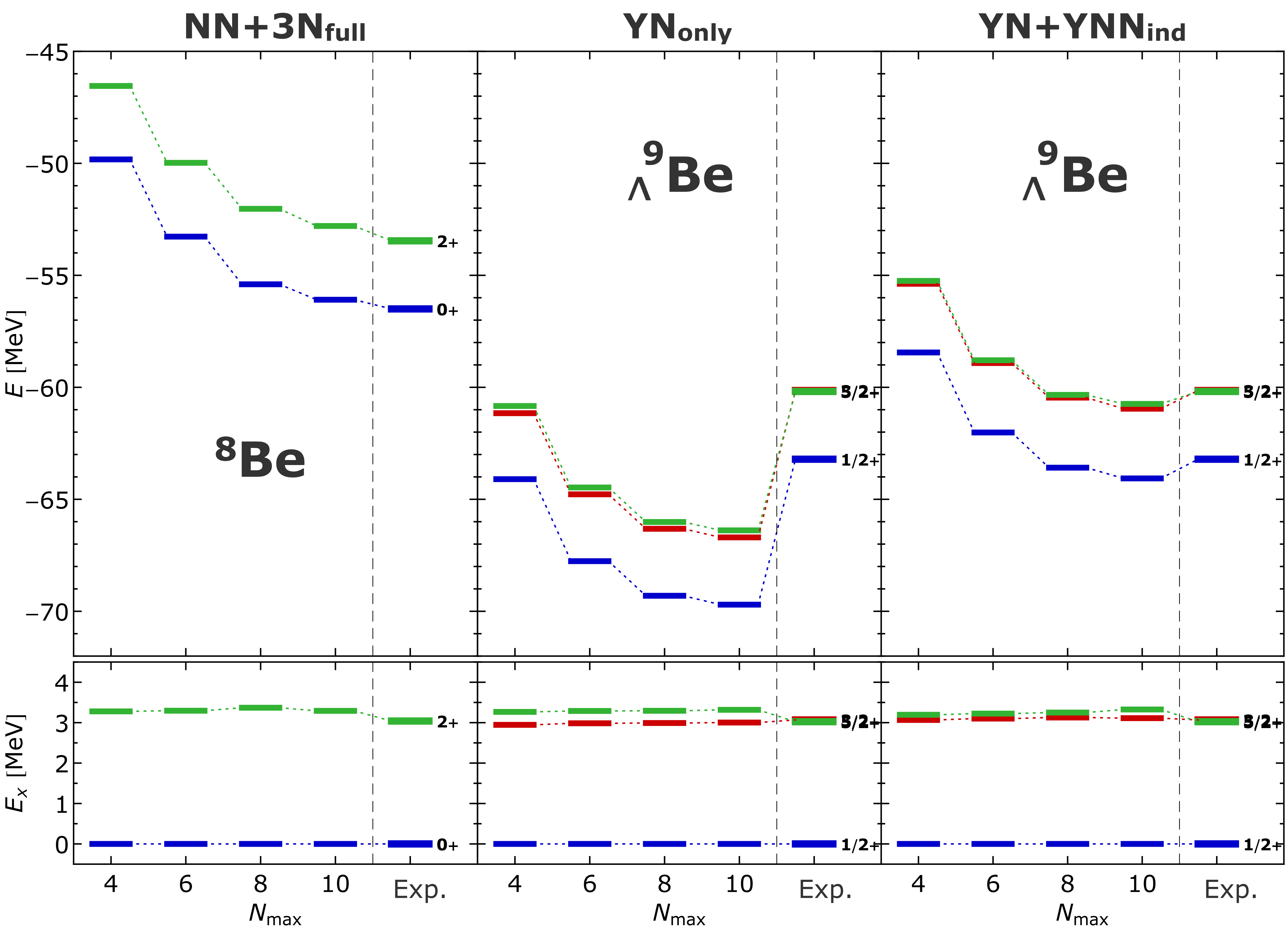
chiral NN+3N
standard
N3LO+N2LO
Λ_{3N}=500 MeV
α=0.08 fm^4

chiral YN
LO
Λ_{YN}=700 MeV
α=0.08 fm^4

$\hbar\Omega$=20 MeV

Application: $^{9}_{\Lambda}$Be

Wirth et al.; PRL 113, 192502 (2014); PRL 117, 182501 (2016)



NCSM

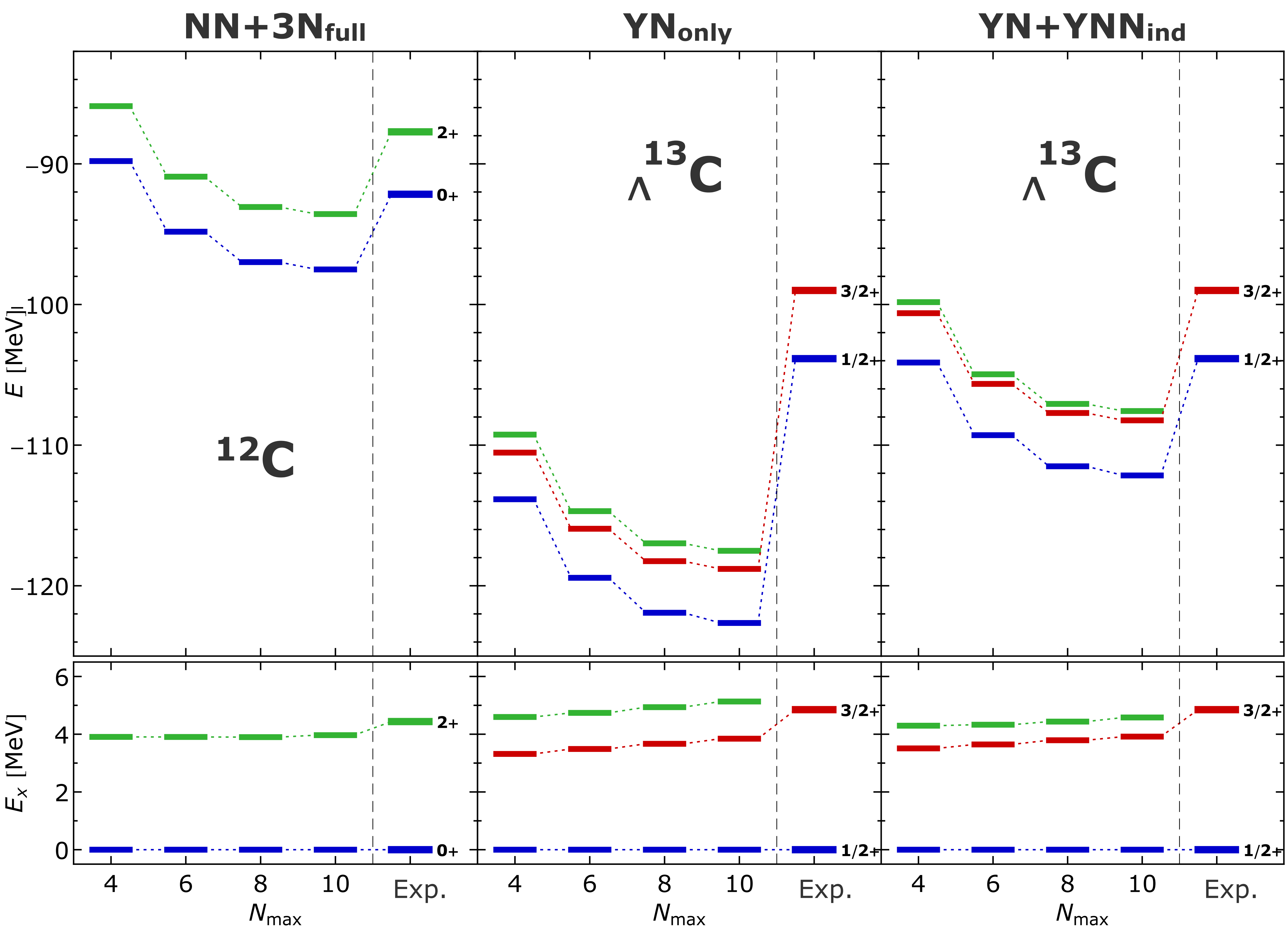
chiral NN+3N
standard
N3LO+N2LO
Λ_{3N}=500 MeV
α=0.08 fm^4

chiral YN
LO
Λ_{YN}=700 MeV
α=0.08 fm^4

ħΩ=20 MeV

Application: ${}^{13}_{\Lambda}C$

Wirth et al.; PRL 113, 192502 (2014); PRL 117, 182501 (2016)



NCSM

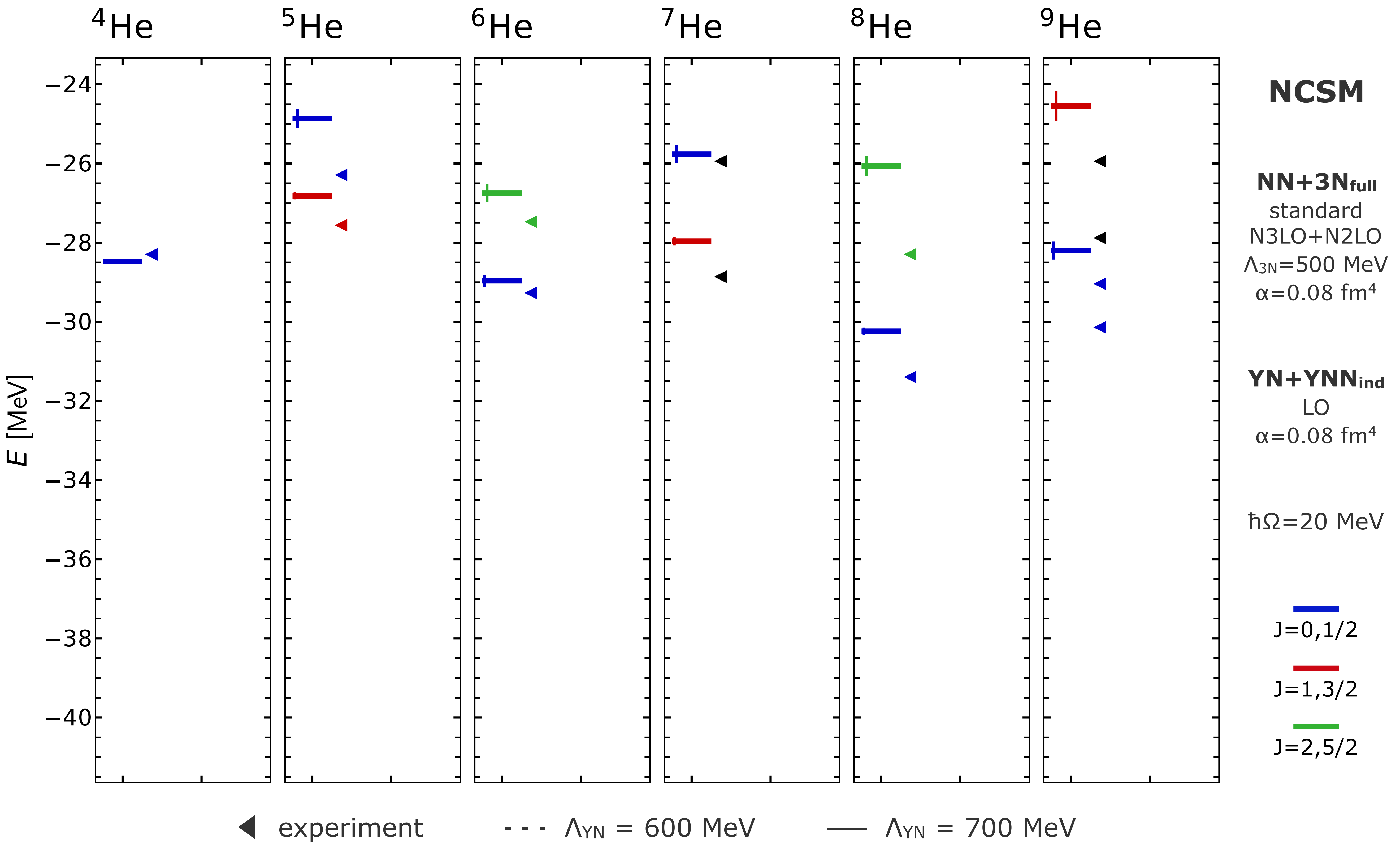
chiral NN+3N
standard
N3LO+N2LO
Λ_{3N}=500 MeV
α=0.08 fm⁴

chiral YN
LO
Λ_{YN}=700 MeV
α=0.08 fm⁴

ħΩ=20 MeV

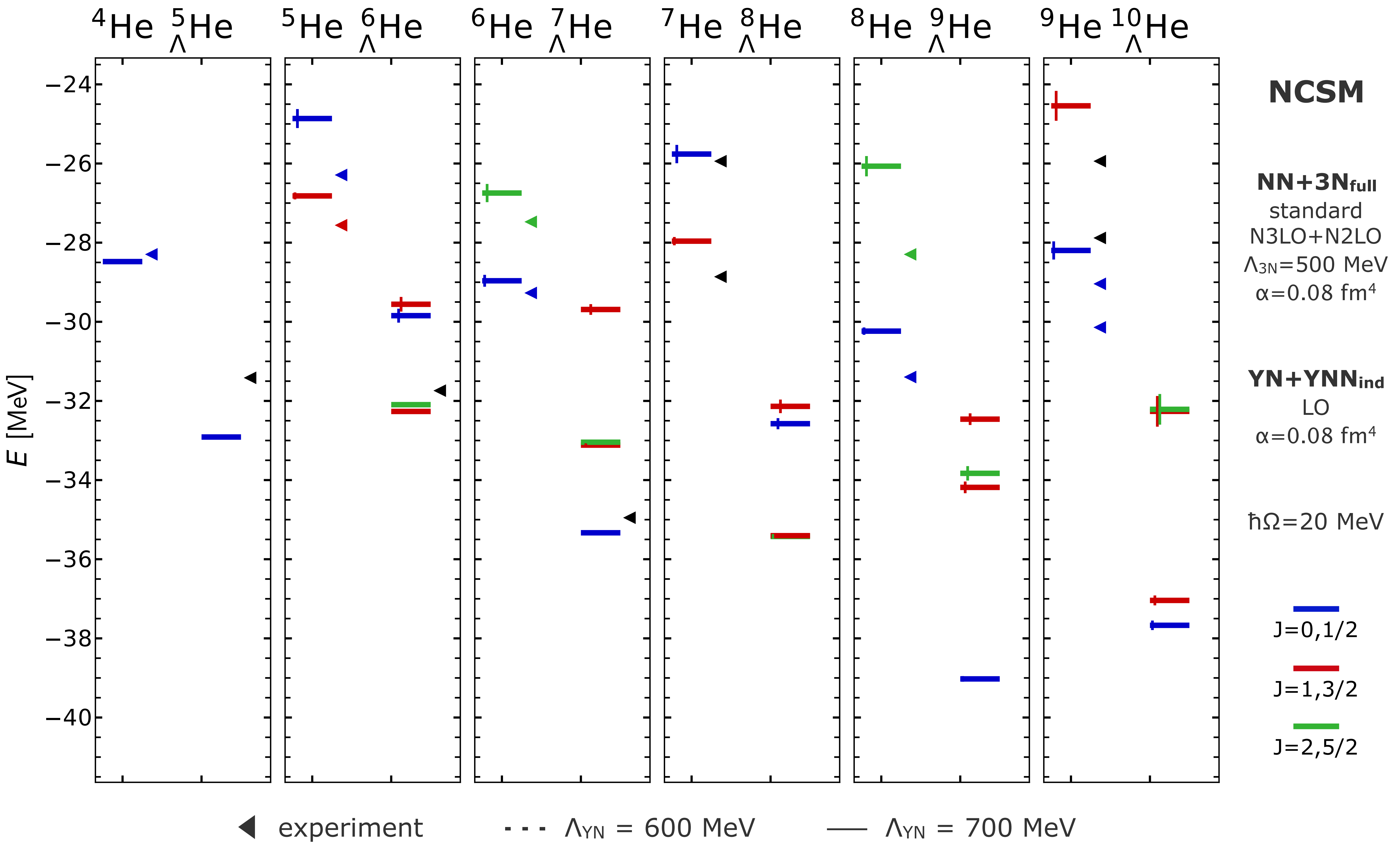
Light Neutron-Rich Hypernuclei

Wirth et al.; PLB 779, 336 (2018)



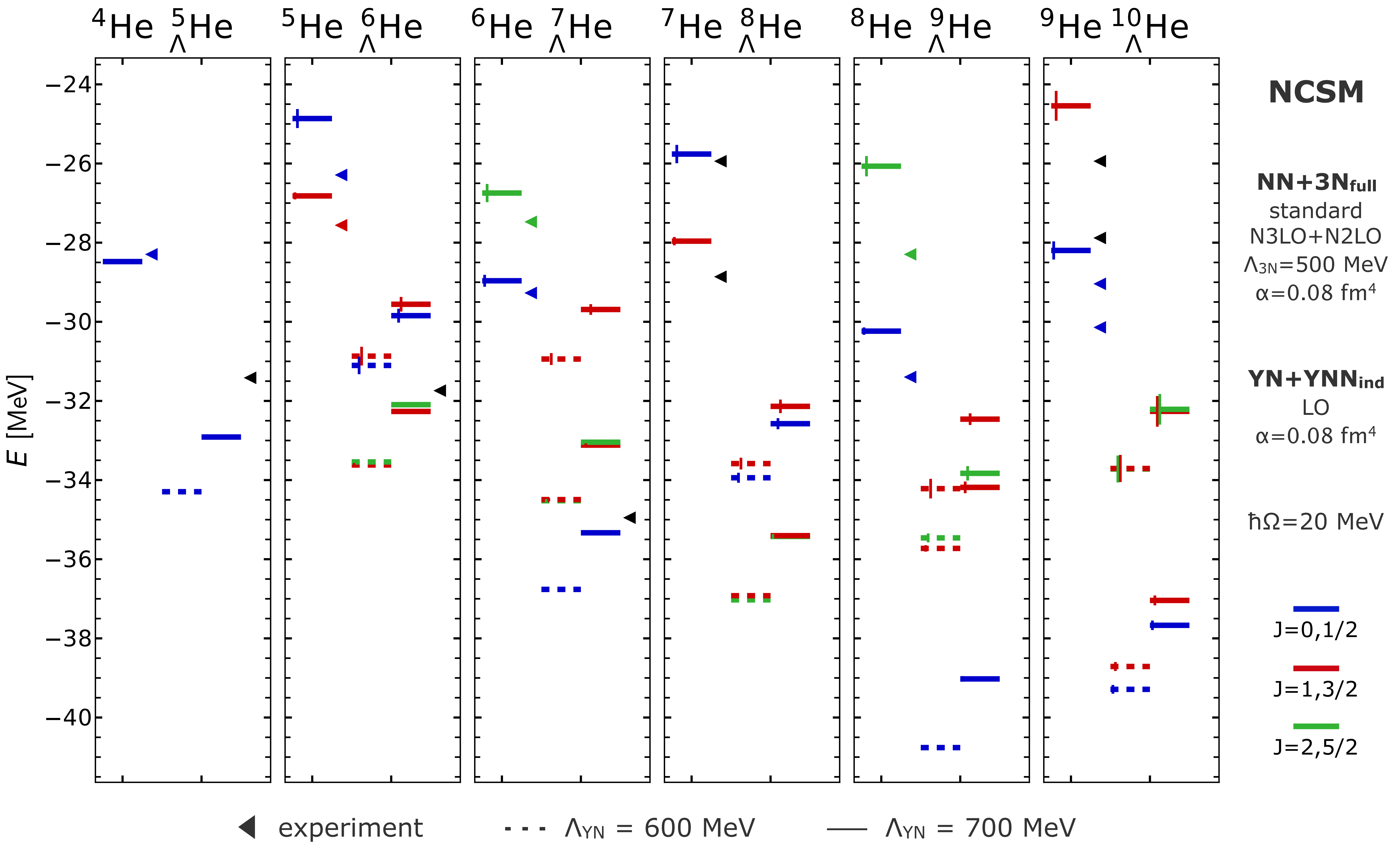
Light Neutron-Rich Hypernuclei

Wirth et al.; PLB 779, 336 (2018)



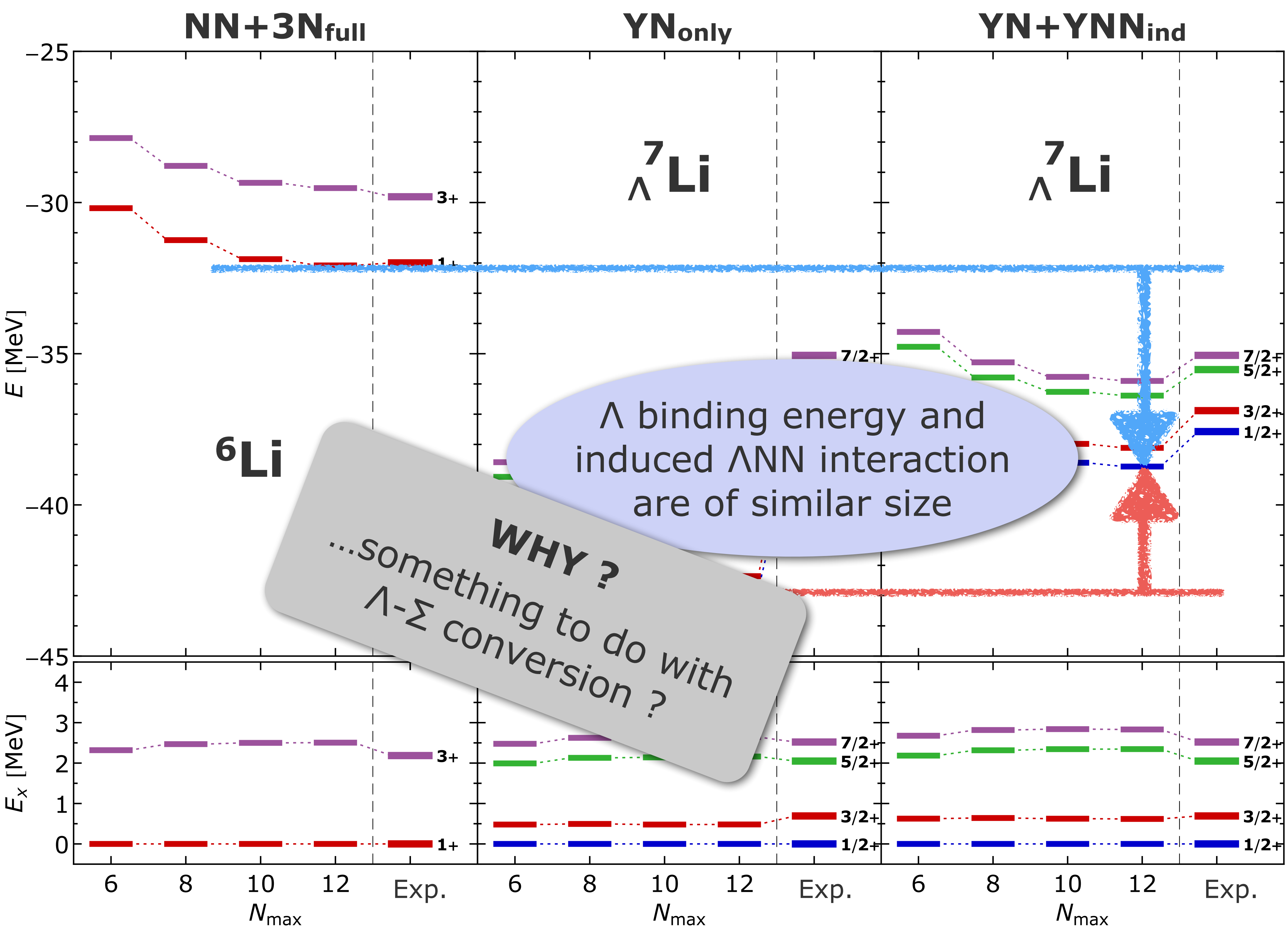
Light Neutron-Rich Hypernuclei

Wirth et al.; PLB 779, 336 (2018)



Application: $^{7}_{\Lambda}$Li

Wirth et al.; PRL 113, 192502 (2014); PRL 117, 182501 (2016)



NCSM

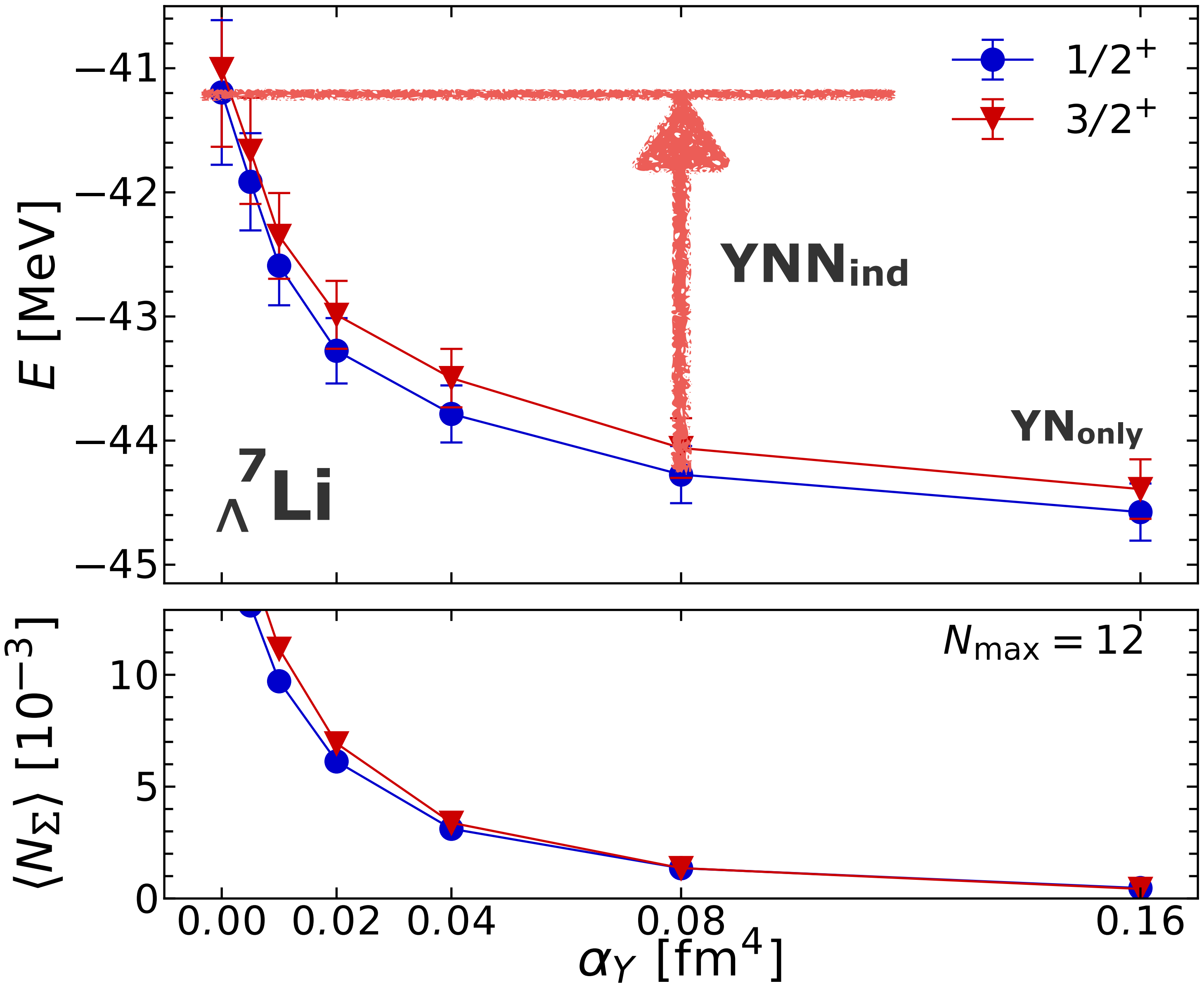
chiral NN+3N
standard
N3LO+N2LO
Λ_{3N}=500 MeV
α=0.08 fm⁴

chiral YN
LO
Λ_{YN}=700 MeV
α=0.08 fm⁴

ħΩ=20 MeV

Suppression of Λ-Σ Conversion

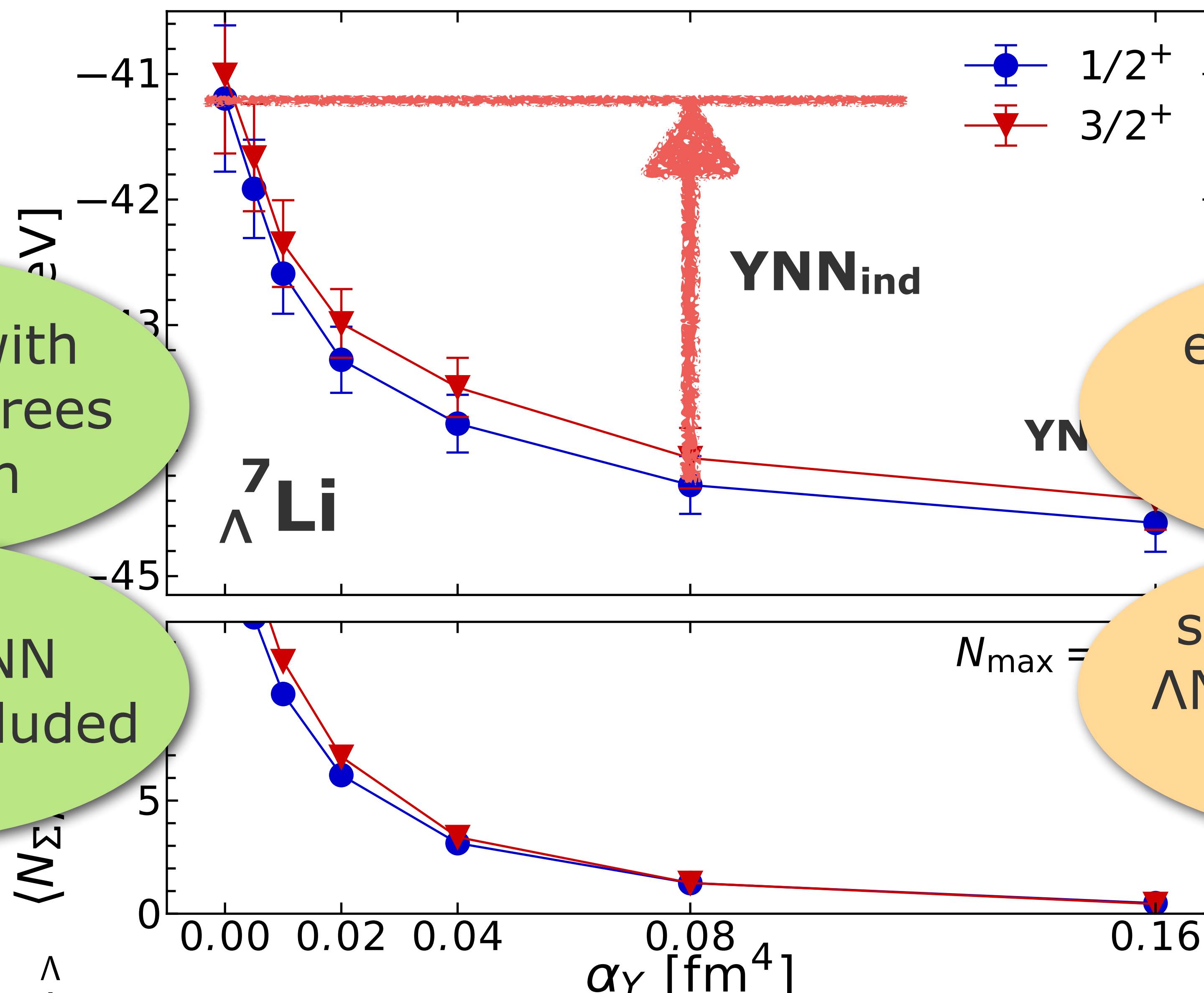
Wirth et al.; PRL 117, 182501 (2016)



- design SRG-generator that **suppresses the Λ-Σ conversion** exclusively
- Σ admixture in the wave functions eliminated or “integrated out”
- same large induced YNN interactions as in standard SRG

Suppression of Λ-Σ Conversion

Wirth et al.; PRL 117, 182501 (2016)

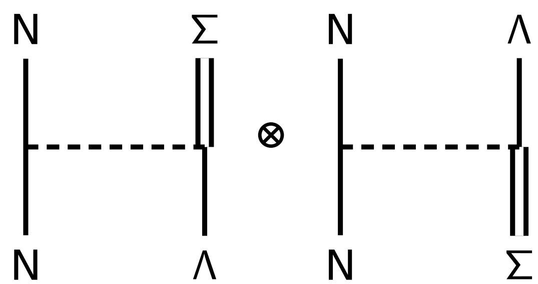


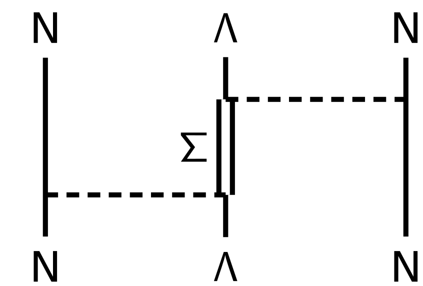
full theory with explicit Σ degrees of freedom

no initial YNN interaction included

effective Λ-only theory, Σ fully decoupled

strong repulsive ΛNN interaction is induced

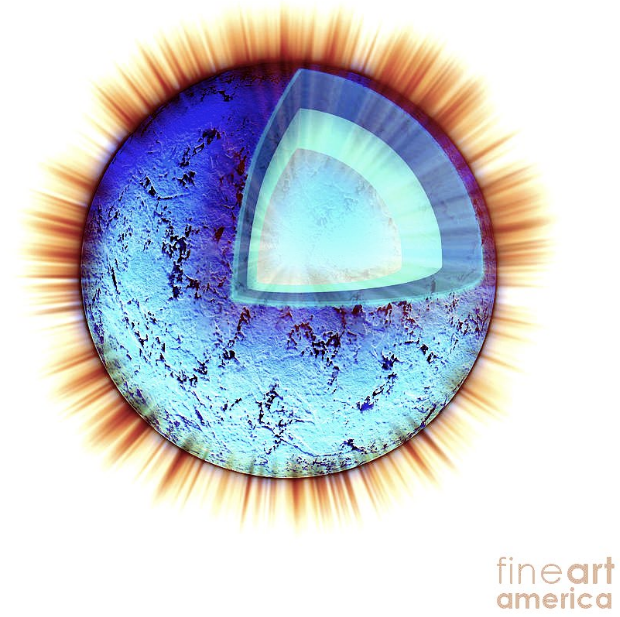


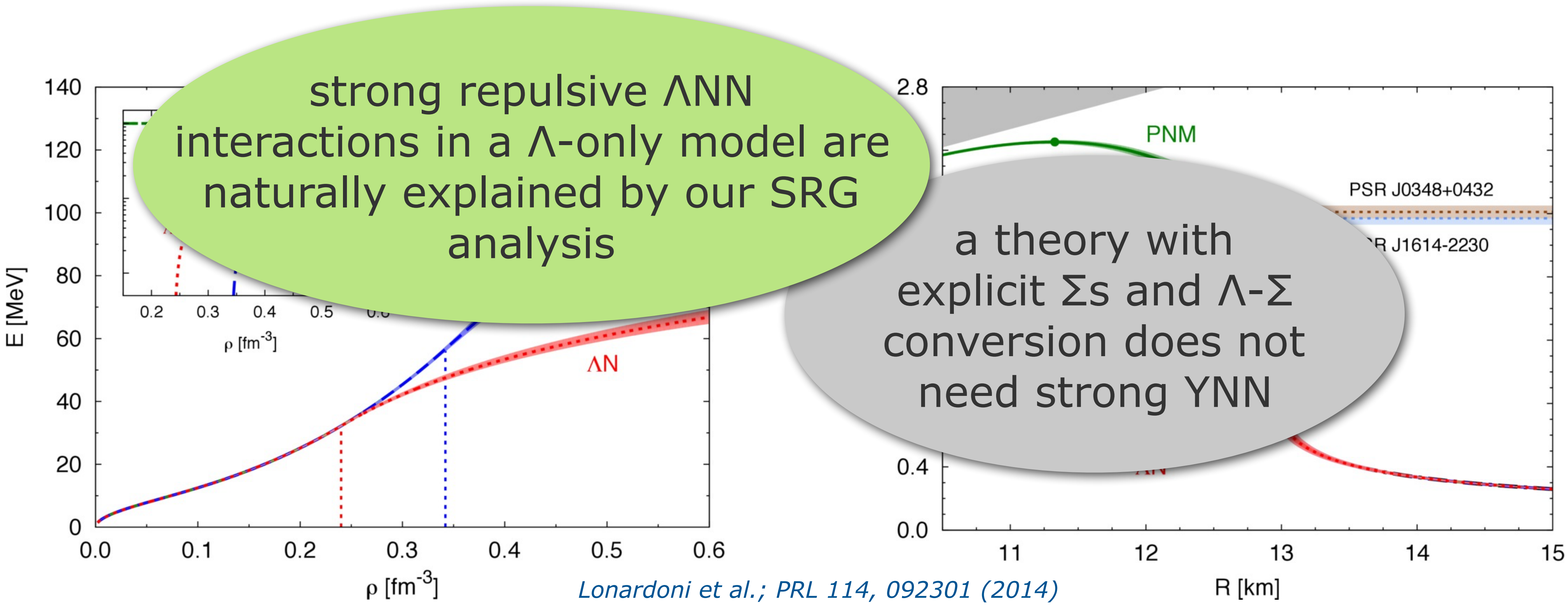


SRG evolves full coupled-channel theory to effective Λ-only theory

Implications for the Hyperon Puzzle

- neutron stars reach densities, where hyperon production should be energetically favorable
- including explicit Λs with ΛN interaction softens EOS - does not support 2M⊙ neutron star
- phenomenological fix: introduce strongly repulsive ΛNN interaction





Lonardoni et al.; PRL 114, 092301 (2014)

Conclusions

A Look Back…

- past 20 years have seen dramatic progress in ab initio many-body methods for nuclear structure and reactions

...extensions of NCSM, coupled-cluster theory, in-medium SRG,
self-consistent Green's function, many-body perturbation theory

- a number of important developments are in progress

...spectroscopy of open-shell nuclei, merging NCSM and IM-SRG,
derivation of valence-space interactions, broad range of observables

- the reach of ab initio methods has grown tremendously

...medium-mass and heavy nuclei,
low-lying and collective excitations,
continuum effects and reaction observables,
resonances, hypernuclei

A Look Ahead...

- for the next few years the focus will move towards improvements of the chiral interactions

  ...consistent higher orders, systematic study of order-by-order convergence, inclusion of consistent currents, improved fitting strategies

- rigorous quantification of theoretical uncertainties will play an important role

  ...propagation of uncertainties from chiral EFT inputs to nuclear structure observables, full quantification of many-body uncertainties

- lots of relevant physics predictions...

All My Best Wishes to...

... and special thanks
for so many things

GSI Theory Excursion
2002

Epilogue

- **thanks to my group and my collaborators**
  - S. Alexa, T. Hüther, M. Knöll, L. Mertes, J. Müller, C. Stumpf, A. Tichai, K. Vobig, C. Walde, R. Wirth, T. Wolfgruber
    Technische Universität Darmstadt
  - P. Navrátil
    TRIUMF, Vancouver
  - A. Tichai, T. Duguet
    CEA Saclay
  - H. Hergert
    NSCL / Michigan State University
  - J. Vary, P. Maris
    Iowa State University
  - E. Epelbaum, H. Krebs & the LENPIC Collaboration
    Universität Bochum, …

SFB 1245
Deutsche Forschungsgemeinschaft
DFG
HIC for FAIR
Helmholtz International Center
LOEWE
Exzellente Forschung für Hessens Zukunft
HELMHOLTZ GEMEINSCHAFT
Bundesministerium für Bildung und Forschung