TRIUMF

No-core shell model for hypernuclei

Workshop on ^{208}Pb (e,e'K) and neutron stars

May 11, 2020

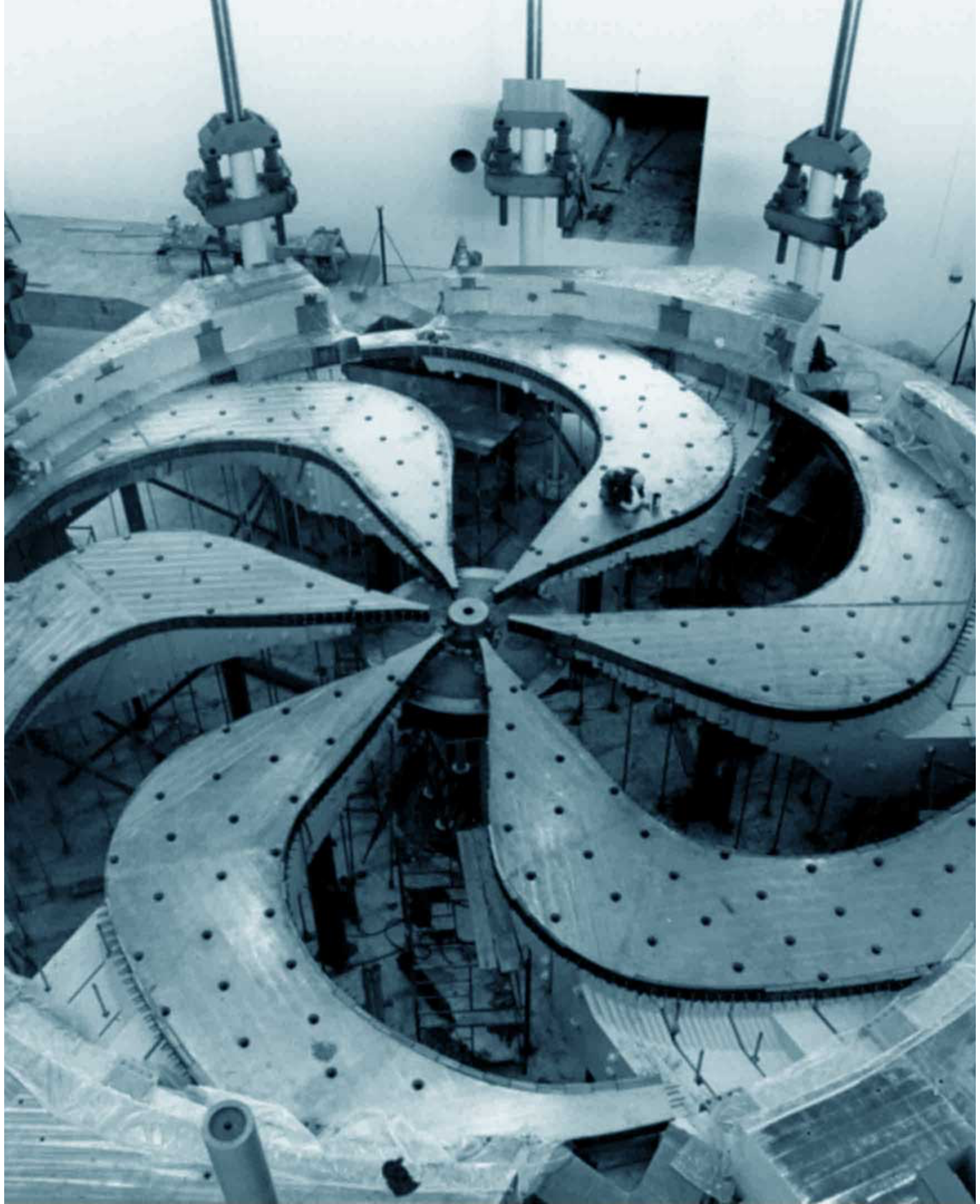
Petr Navratil

TRIUMF

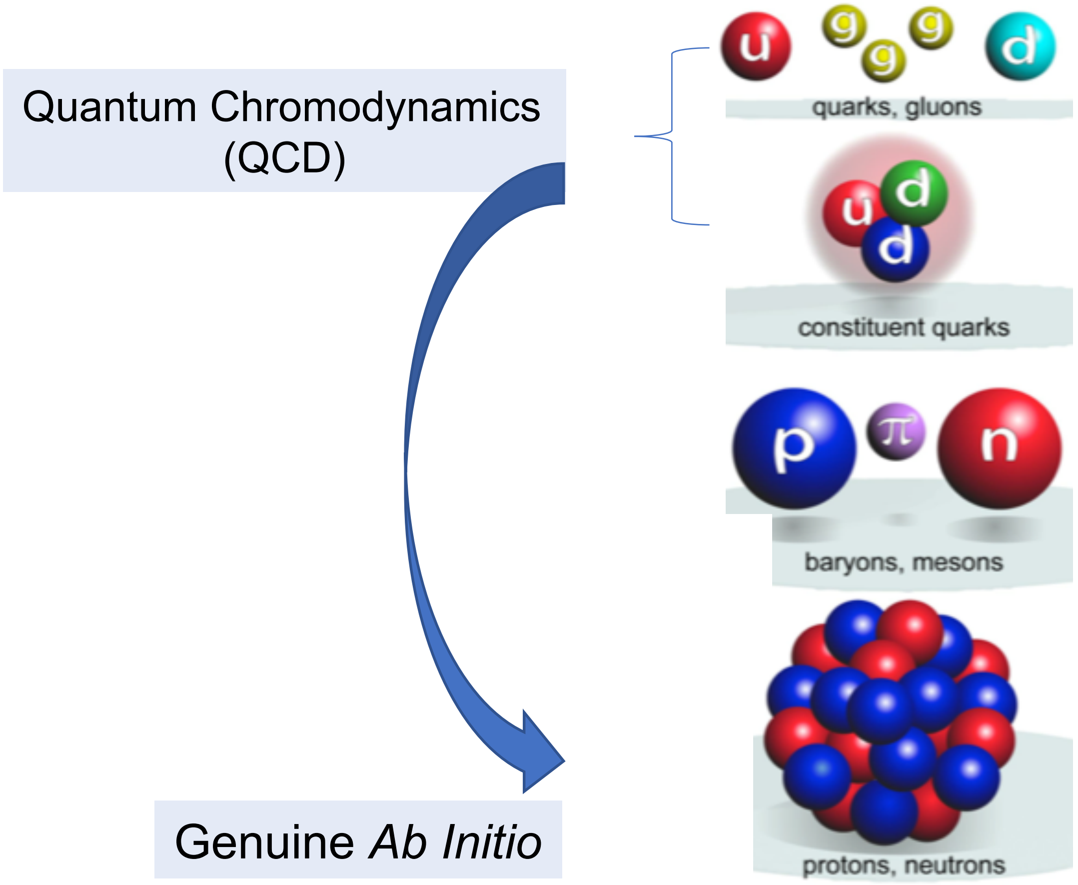
Collaborators:

D. Gazda (NPI Rez), R. Roth (TU Darmstadt), R. Wirth (MSU), Takayuki Miyagi (TRIUMF)

2020-05-12



First principles or *ab initio* nuclear theory



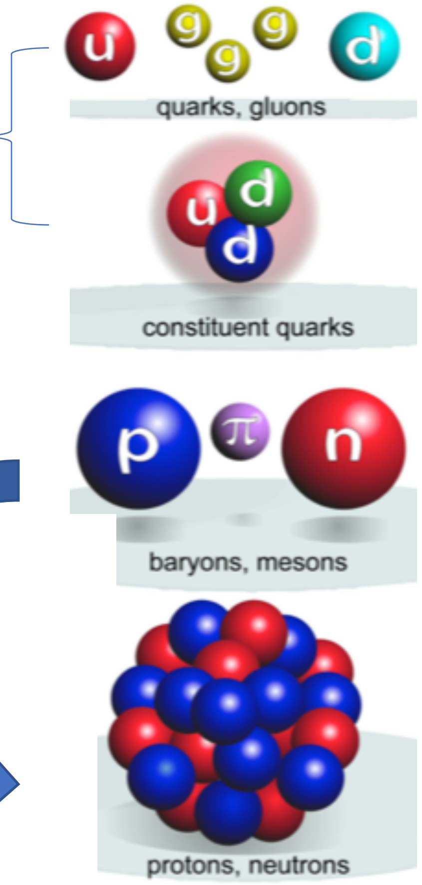
First principles or *ab initio* nuclear theory – what we do at present

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab anitio* nuclear theory

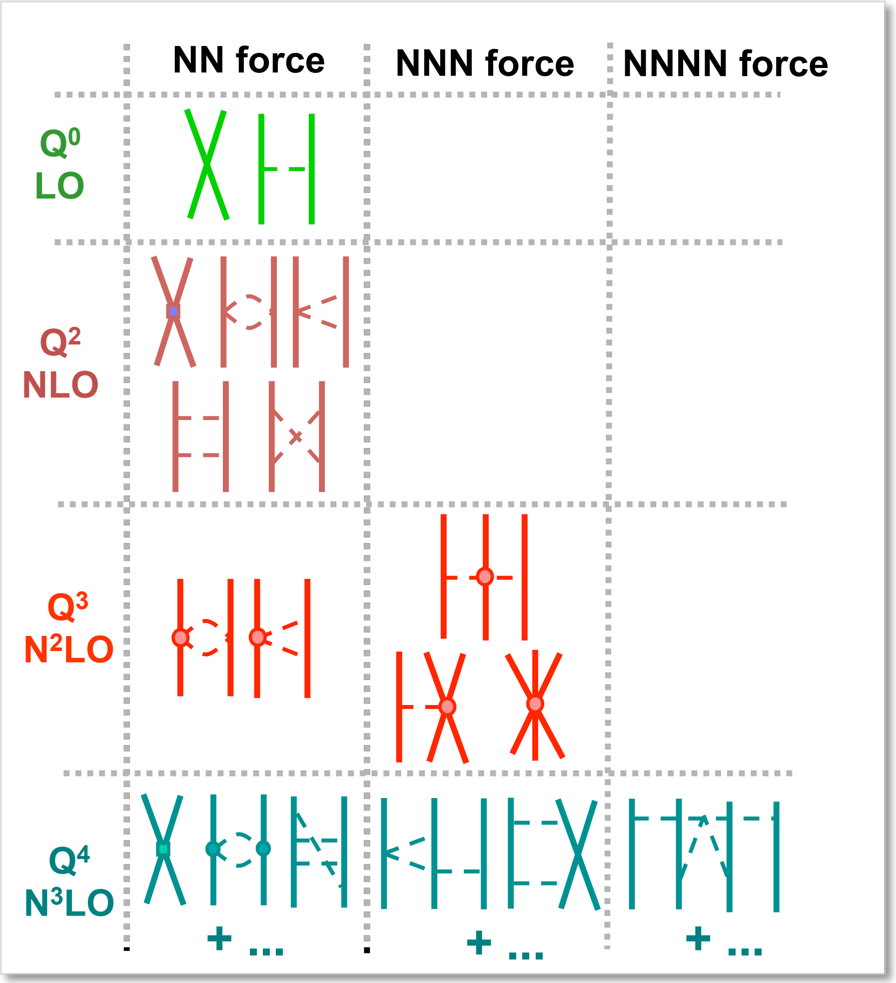
$$H\,\Psi^{(A)} = E\,\Psi^{(A)}$$



- *Ab initio*
- ✧ Degrees of freedom: Nucleons
- ✧ All nucleons are active
- ✧ Exact Pauli principle
- ✧ Realistic inter-nucleon interactions
  - ✧ Accurate description of NN (and 3N) data
- ✧ Controllable approximations

Chiral Effective Field Theory

- Inter-nucleon forces from chiral effective field theory
  - Based on the symmetries of QCD
    - Chiral symmetry of QCD ($m_u \approx m_d \approx 0$), spontaneously broken with pion as the Goldstone boson
    - Degrees of freedom: nucleons + pions
  - Systematic low-momentum expansion to a given order (Q/Λ_χ)
  - Hierarchy
  - Consistency
  - Low energy constants (LEC)
    - Fitted to data
    - Can be calculated by lattice QCD



Λ_χ~1 GeV :
Chiral symmetry breaking scale

Nucleon-Hyperon Interaction in chiral EFT

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Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics A 779 (2006) 244–266
NUCLEAR PHYSICS A

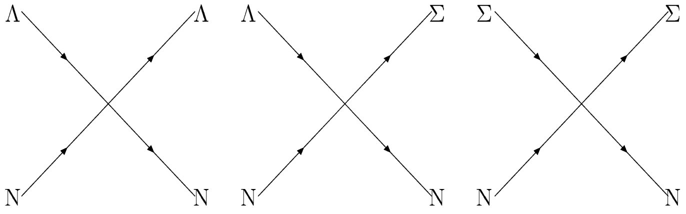
Hyperon–nucleon interactions—a chiral effective field theory approach

Henk Polinder[a,*], Johann Haidenbauer[a], Ulf-G. Meißner[a,b]

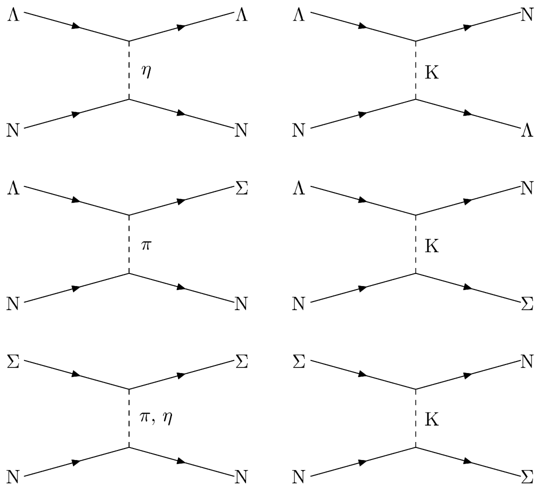
Hyperon–nucleon interaction at next-to-leading order in chiral effective field theory

J. Haidenbauer[a], S. Petschauer[b], N. Kaiser[b], U.-G. Meißner[c,a,*], A. Nogga[a], W. Weise[b,d]

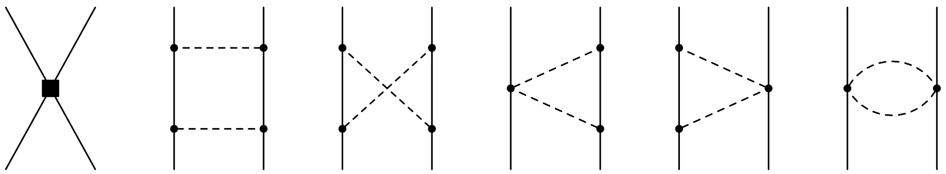
LO contacts



LO one-boson exchange



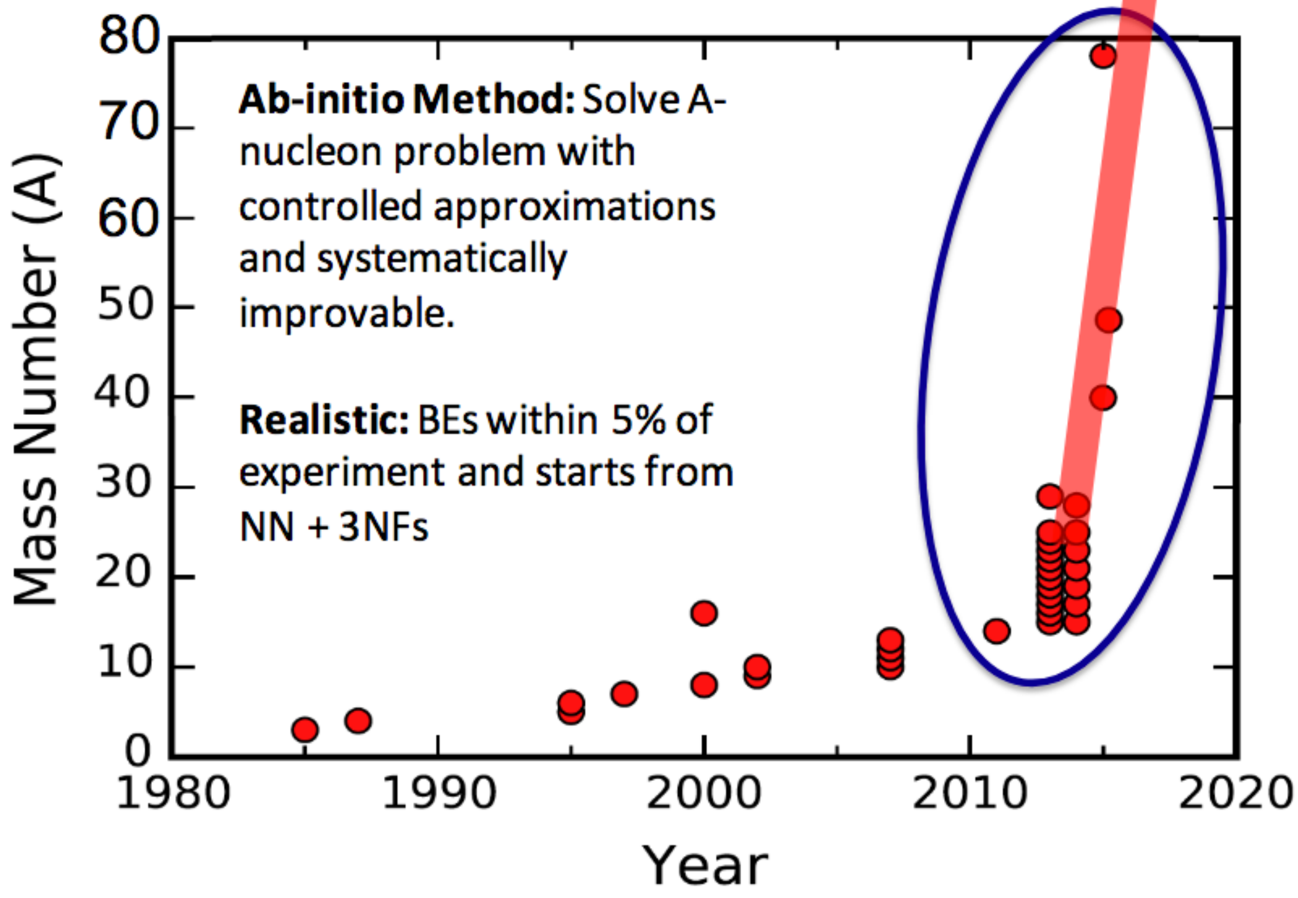
NLO



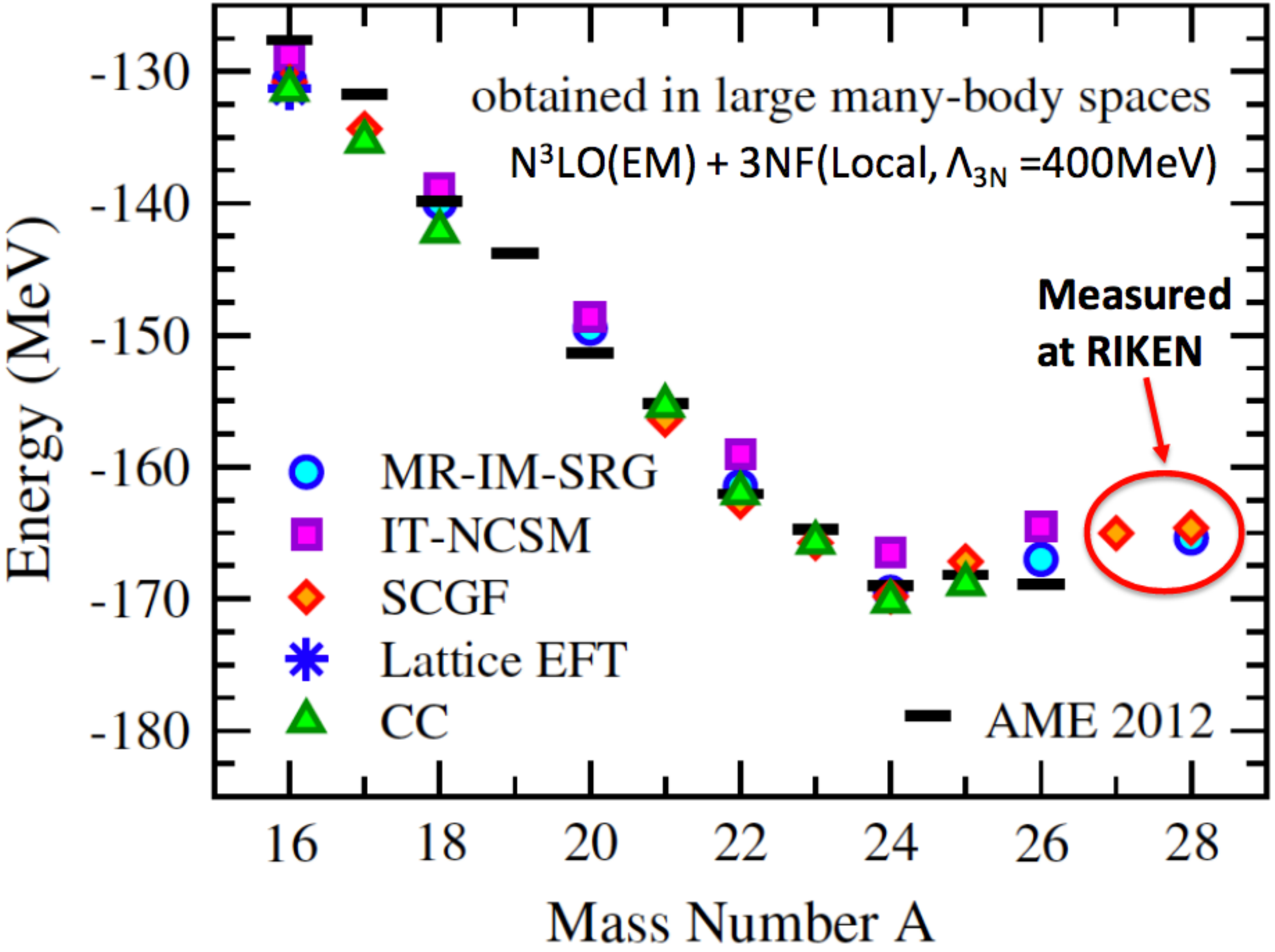
Rapid developments in nuclear *ab initio* calculations

Explosion of many-body methods (Coupled clusters, Green's function Monte Carlo, In-Medium SRG, Lattice EFT, MCSM, No-Core Shell Model, Self-Consistent Green's Function, UMOA, …)

Application of ideas from EFT and renormalization group (V_{low-k}, Similarity Renormalization Group, …)



Oxygen chain with interactions from chiral EFT

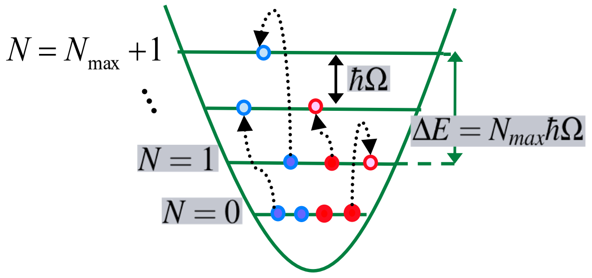


Hebeler, Holt, Menendez, Schwenk, Annu. Rev. Nucl. Part. Sci. 65, 457 (2015)

Conceptually simplest *ab initio* method: No-Core Shell Model (NCSM)

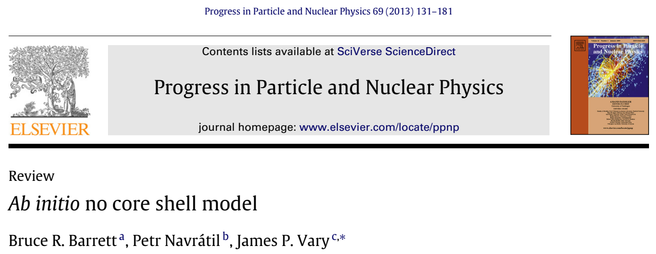
NCSM

- Basis expansion method
  - Harmonic oscillator (HO) basis truncated in a particular way (N_{max})
  - Why HO basis?
    - Lowest filled HO shells match magic numbers of light nuclei (2, 8, 20 – ^{4}He, ^{16}O, ^{40}Ca)
    - **Equivalent description in relative(Jacobi)-coordinate and Slater determinant basis**
- Short- and medium range correlations
- Bound-states, narrow resonances



$$(A)\quad \Psi^{A} = \sum_{N=0}^{N_{max}} \sum_{i} c_{Ni}\, \Phi^{HO}_{Ni}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$

$$(A)\quad \Psi^{A}_{SD} = \sum_{N=0}^{N_{max}} \sum_{j} c^{SD}_{Nj}\, \Phi^{HO}_{SD\,Nj}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^{A}\, \varphi_{000}(\vec{R}_{CM})$$


Progress in Particle and Nuclear Physics 69 (2013) 131–181

Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

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

ELSEVIER

Review

Ab initio no core shell model

Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

Physics Reports 621 (2016) 165–222
Contents lists available at ScienceDirect
Physics Reports
journal homepage: www.elsevier.com/locate/physrep

The In-Medium Similarity Renormalization Group: A novel *ab initio* method for nuclei

H. Hergert[a,b,c,*], S.K. Bogner[a,b], T.D. Morris[b,a], A. Schwenk[d,e], K. Tsukiyama[f]

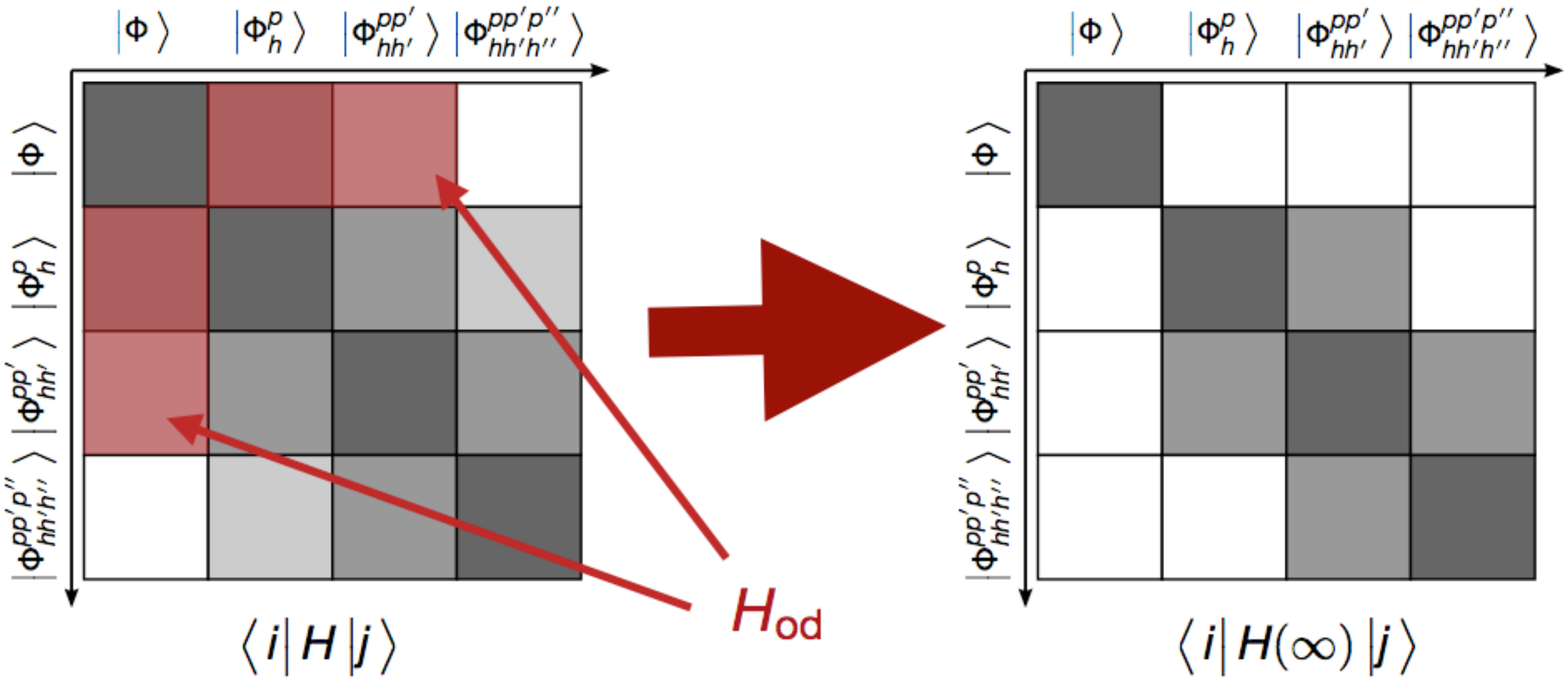
In-Medium Similarity Renormalization Group – Flow equation

Annual Review of Nuclear and Particle Science

Nonempirical Interactions for the Nuclear Shell Model: An Update

S. Ragnar Stroberg,[1,2,3] Heiko Hergert,[4] Scott K. Bogner,[4] and Jason D. Holt[1]

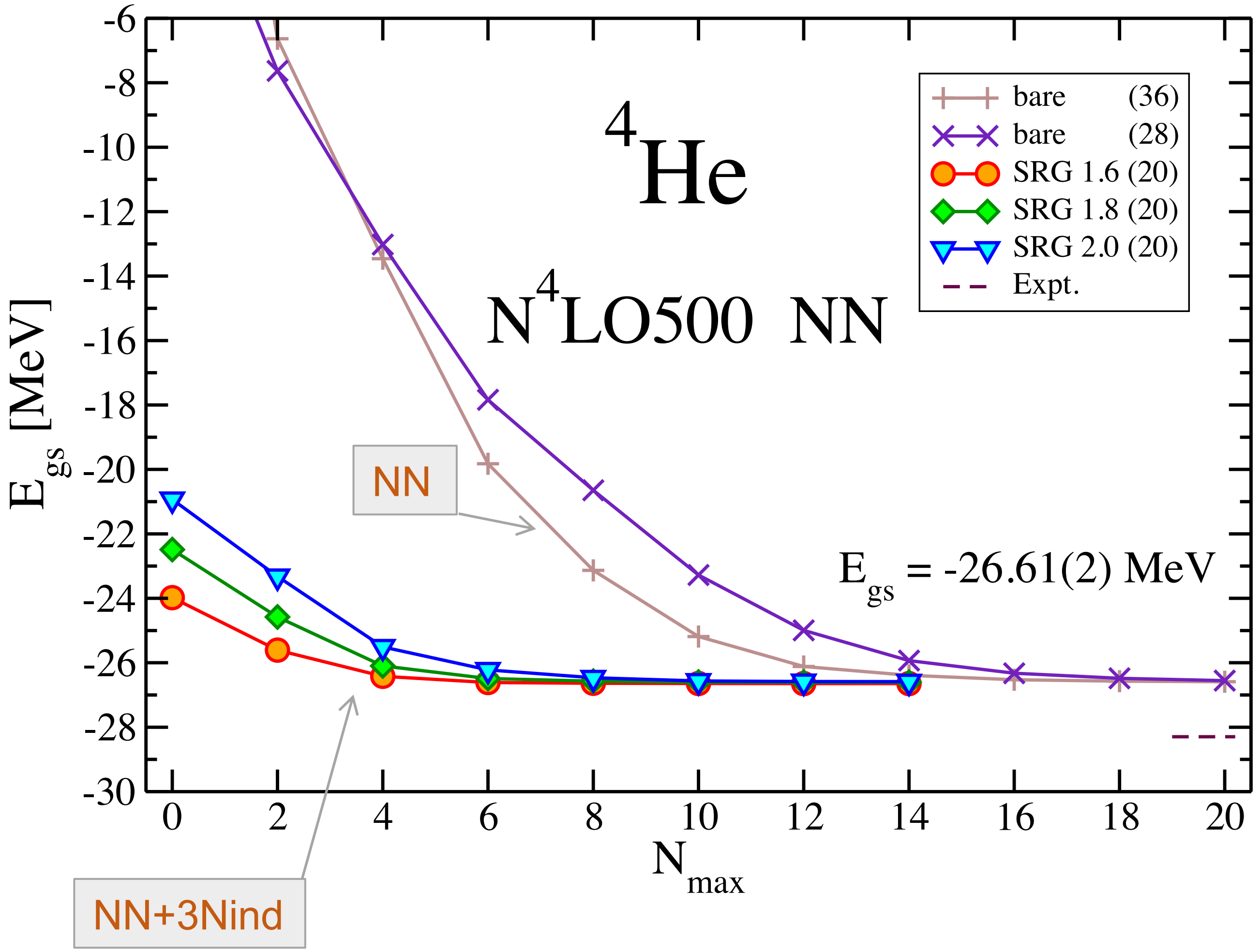
Annu. Rev. Nucl. Part. Sci. 2019. 69:307–62

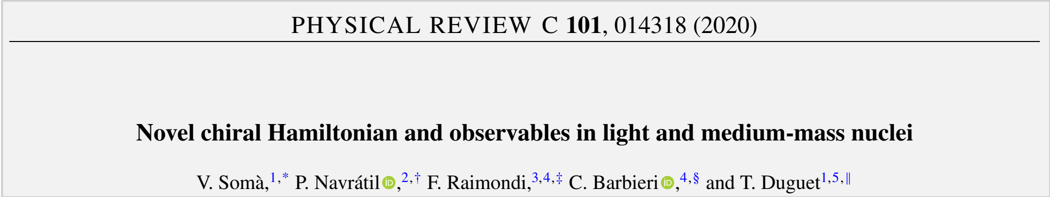


The Hamiltonian matrix is never constructed explicitly!

$$\frac{d}{ds}H(s) = \left[\eta(s), H(s)\right], \quad \text{e.g.,} \quad \eta(s) \equiv \left[H_d(s), H_{od}(s)\right]$$

SRG transformations of nuclear forces speed up convergence




PHYSICAL REVIEW C **101**, 014318 (2020)

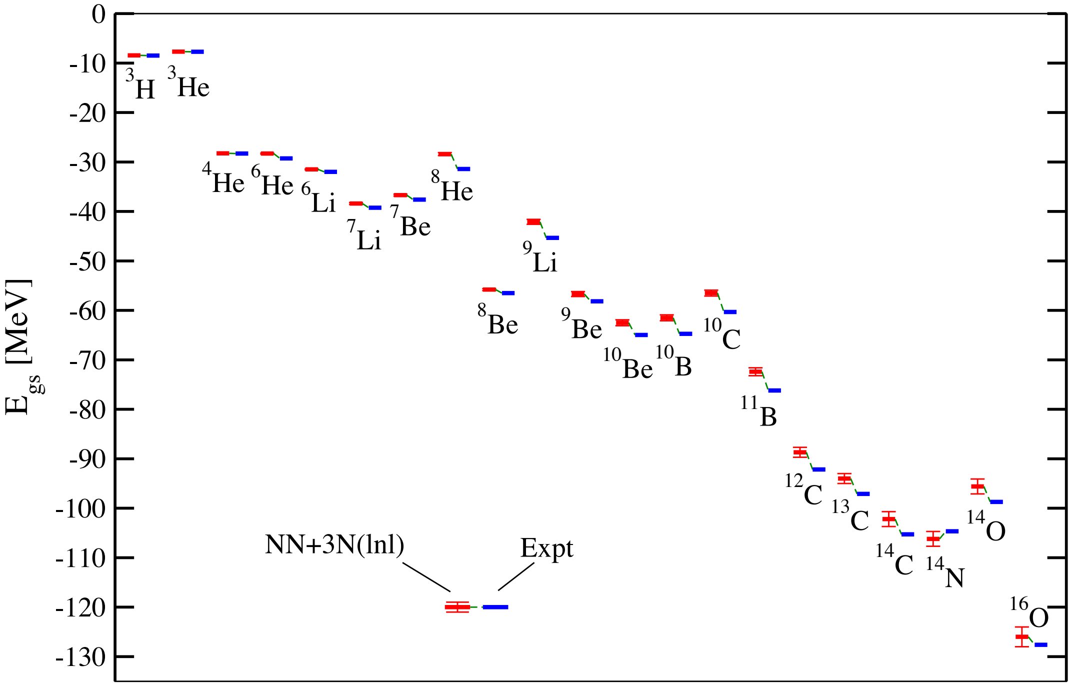
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

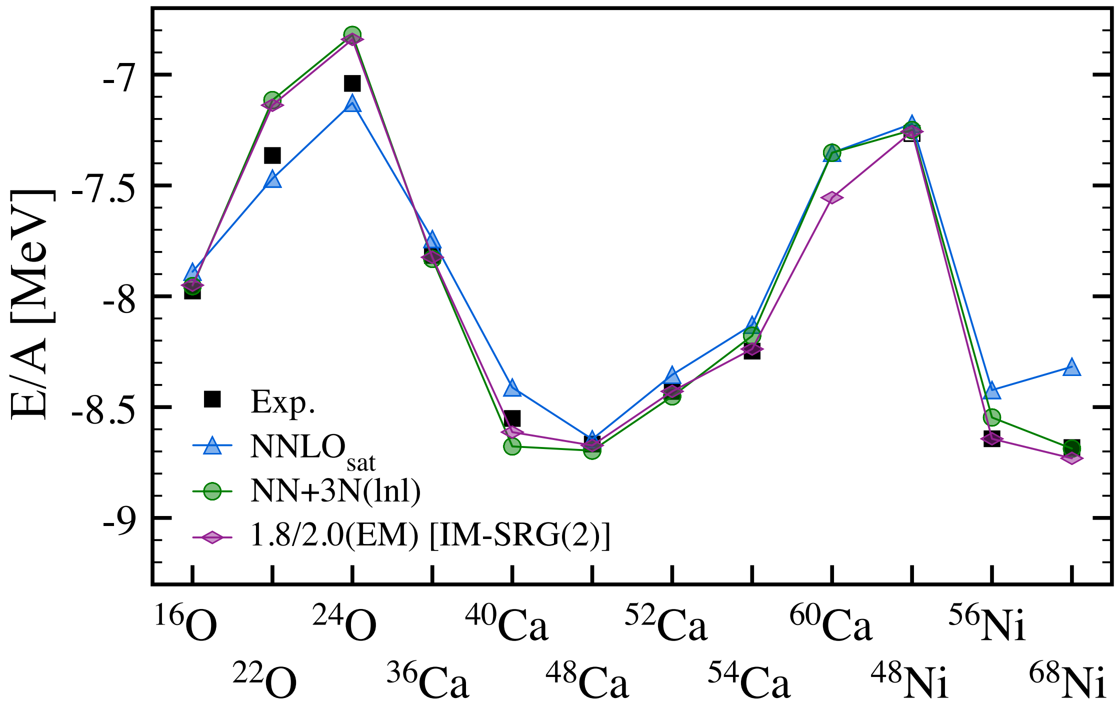
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

Binding energies of light and selected medium mass nuclei from chiral NN+3N forces

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Medium mass nuclei – Self-Consistent Green's Function method

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator





1.8/2.0 (EM) results: J. Simonis, S. R. Stroberg, K. Hebeler, J. D. Holt, and A. Schwenk, Phys. Rev. C 96, 014303 (2017).

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  - Light nuclei – NCSM
  - Medium mass nuclei – MBPT(3) – Takayuki Miyagi

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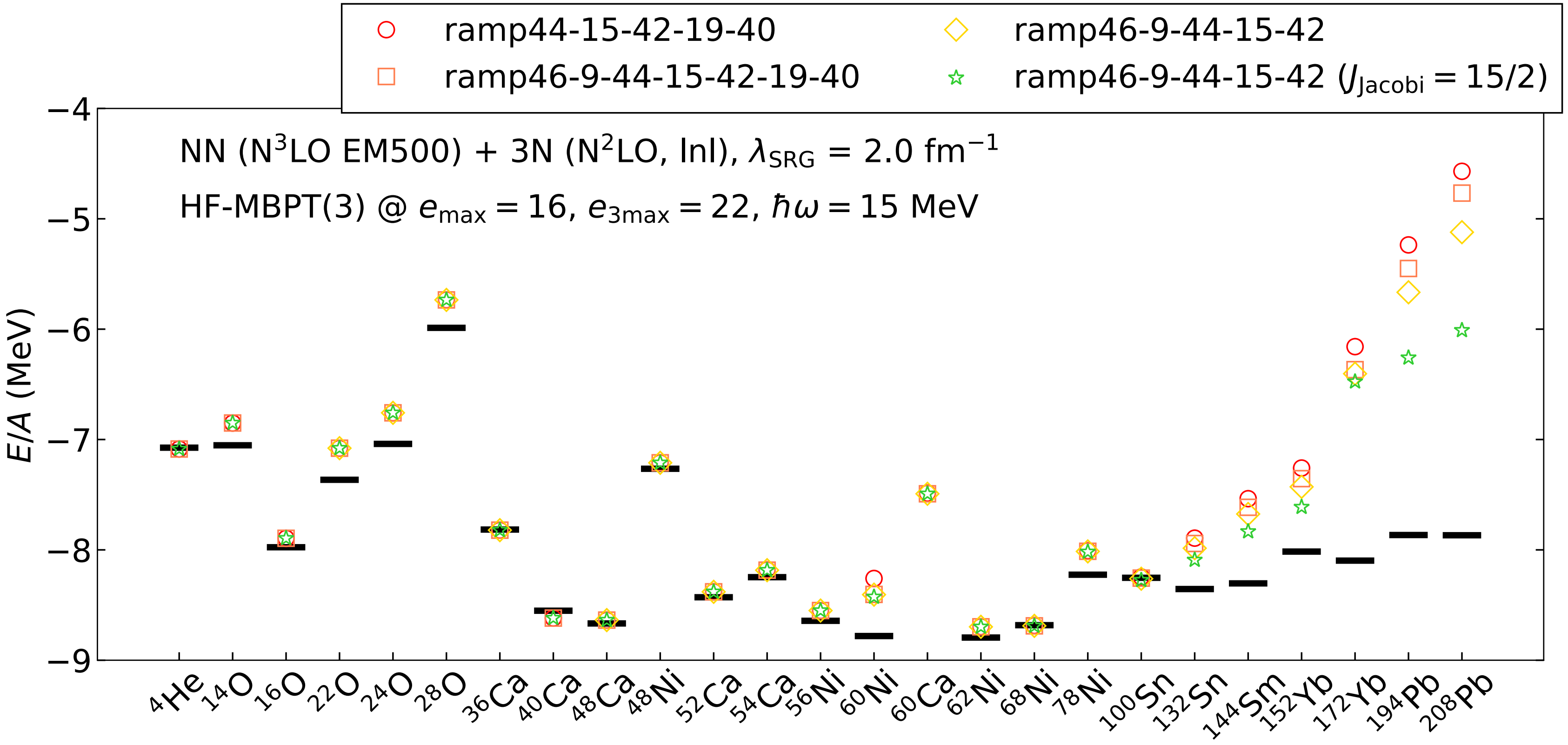


NCSM calculations for light *hypernuclei*

- Flexible approach capable performing exact calculations for few-nucleon systems and accurate calculations for nuclei & **hypernuclei** with A≤25

PHYSICAL REVIEW LETTERS

Ab Initio **Description of *p*-Shell Hypernuclei**

Roland Wirth,[1,*] Daniel Gazda,[2,3] Petr Navrátil,[4] Angelo Calci,[1] Joachim Langhammer,[1] and Robert Roth[1,†]

PHYSICAL REVIEW C **97**, 064315 (2018)

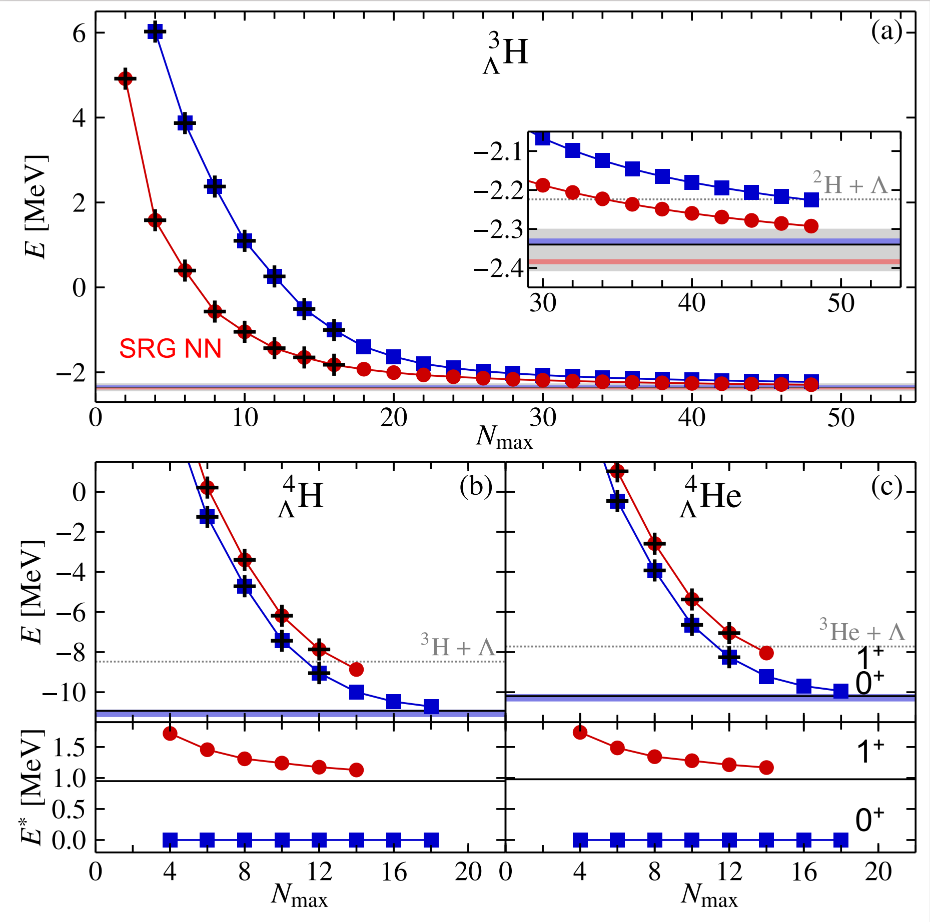
Hypernuclear no-core shell model

Roland Wirth,[1,*] Daniel Gazda,[2,3] Petr Navrátil,[4] and Robert Roth[1,†]

Testing chiral LO NY potentials with Λ-Σ mixing included

…outperform the Julich '04 YN potential

Chiral N^{3}LO NN+ N^{2}LO 3N



Jacobi-NCSM vs. Slater-Determinant basis NCSM

p (uud): m_p=938.3 MeV; ***n*** (udd): m_n=939.6 MeV, ***Λ*** (uds): m_Λ=1115.7 MeV; ***Σ*** (uus,uds,dds): m_Σ=1189.4 MeV

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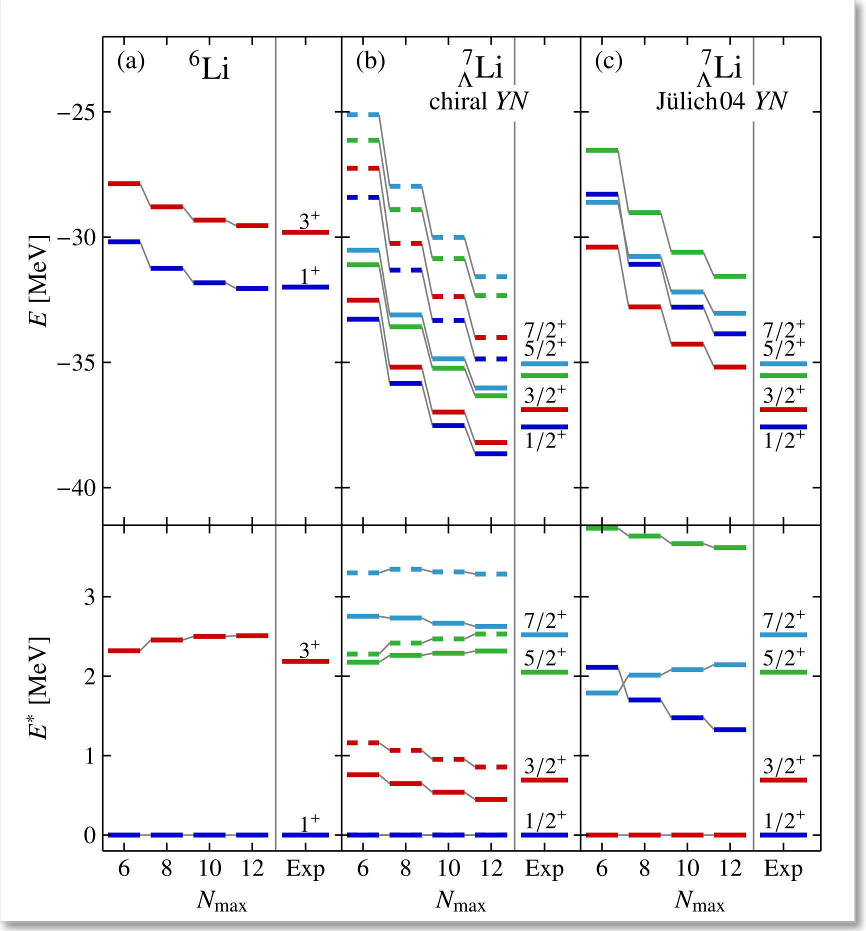

Slater-Determinant basis NCSM

SRG NN+3N

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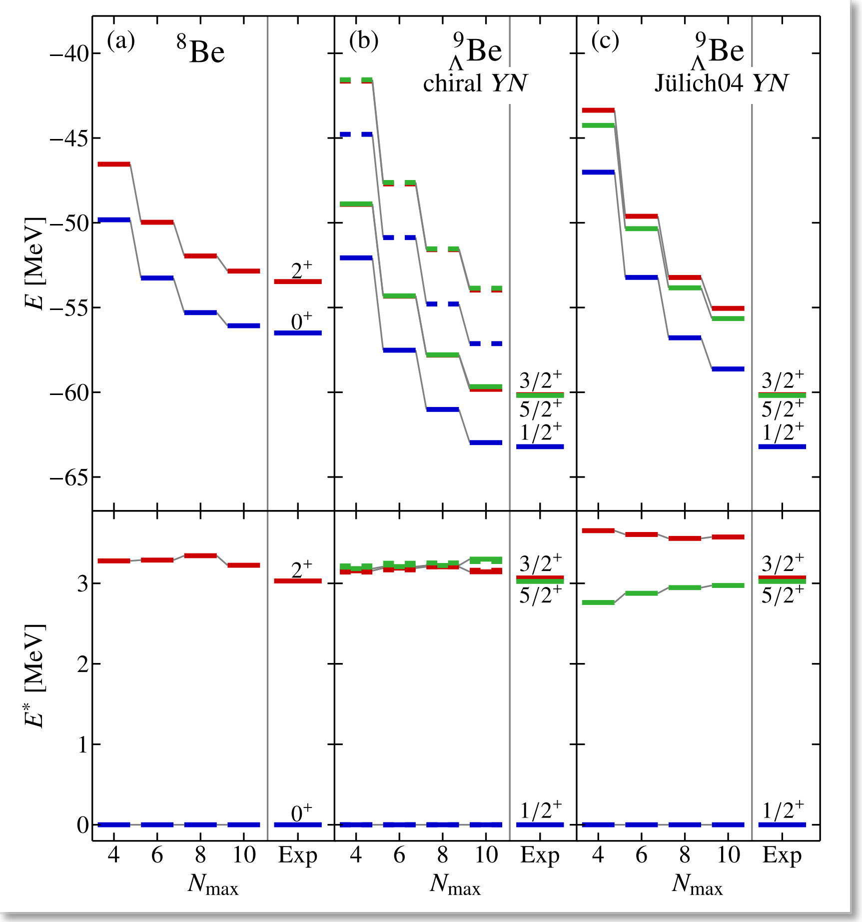

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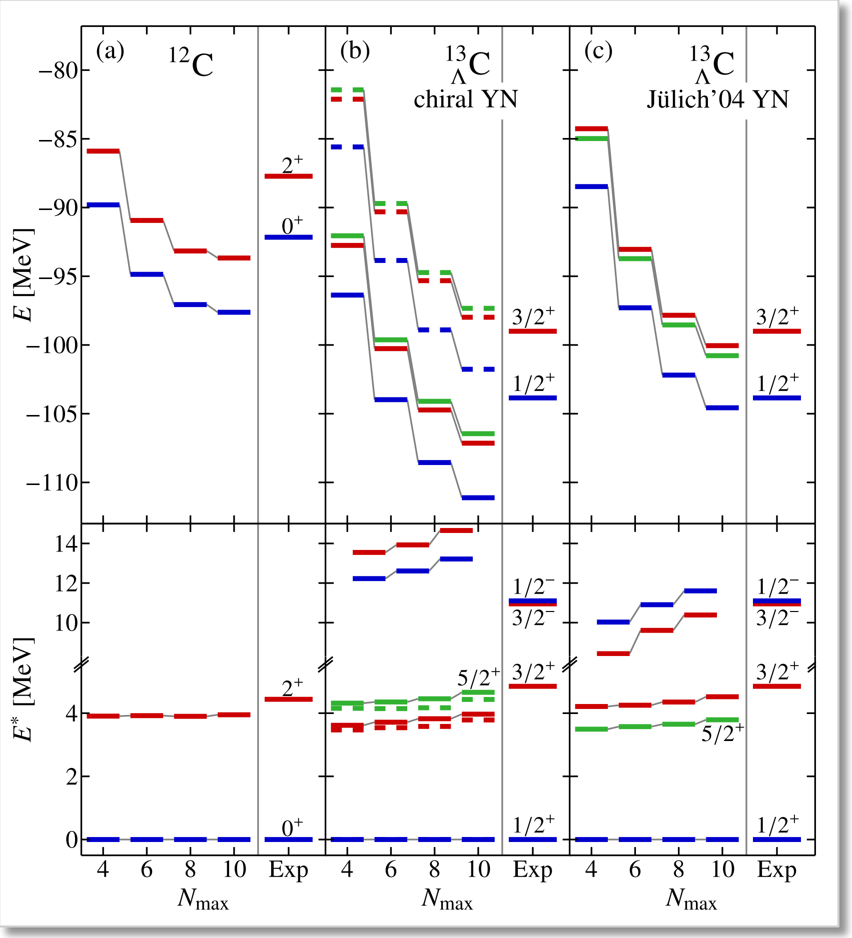

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NCSM calculations for light *hypernuclei*

PHYSICAL REVIEW C **100**, 044313 (2019)

Similarity renormalization group evolution of hypernuclear Hamiltonians

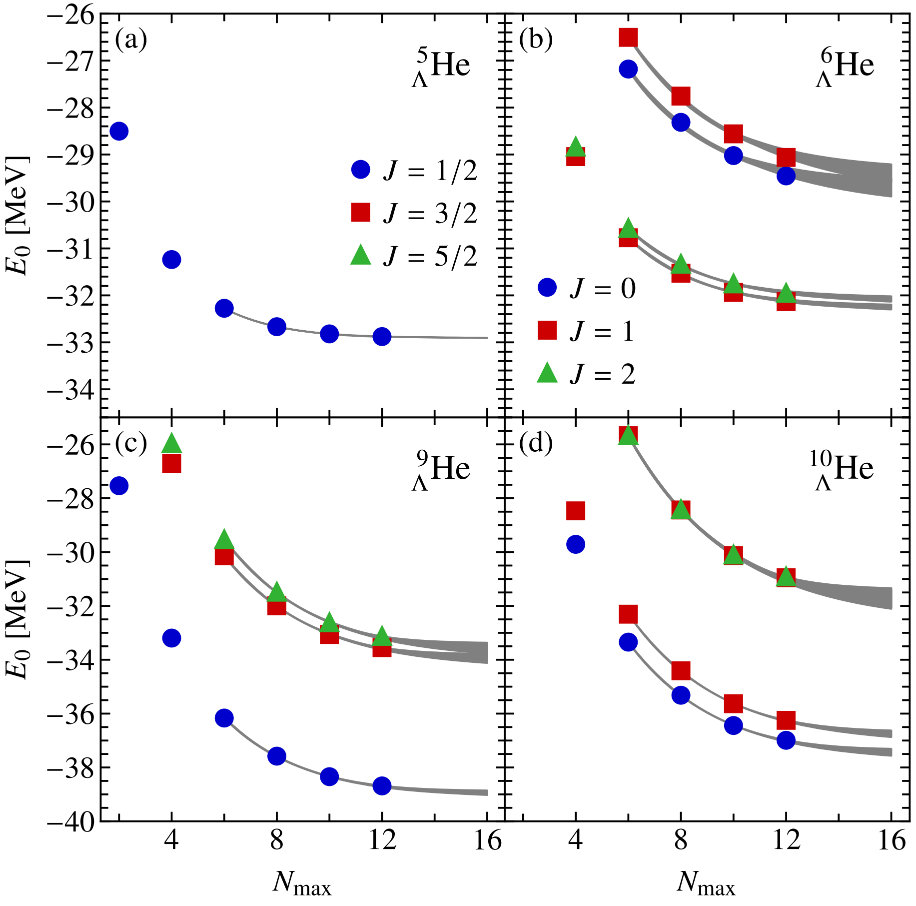
Roland Wirth[1,2,*] and Robert Roth[1,†]

Physics Letters B 779 (2018) 336–341
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Light neutron-rich hypernuclei from the importance-truncated no-core shell model

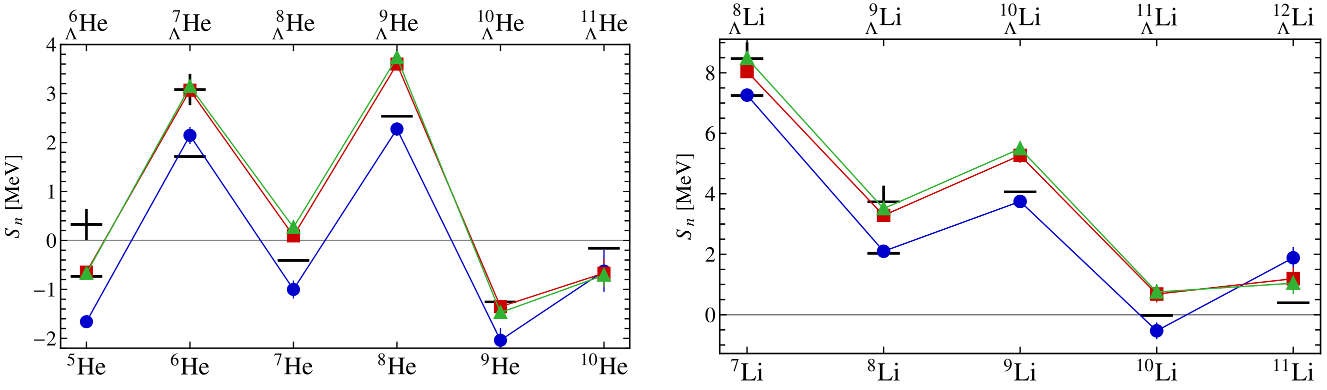
Roland Wirth*, Robert Roth

Similarity renormalization group transformation applied consistently up to the three-baryon level to improve the model-space convergence



Chiral N^{3}LO NN+ N^{2}LO 3N + LO YN

Slater-Determinant basis NCSM

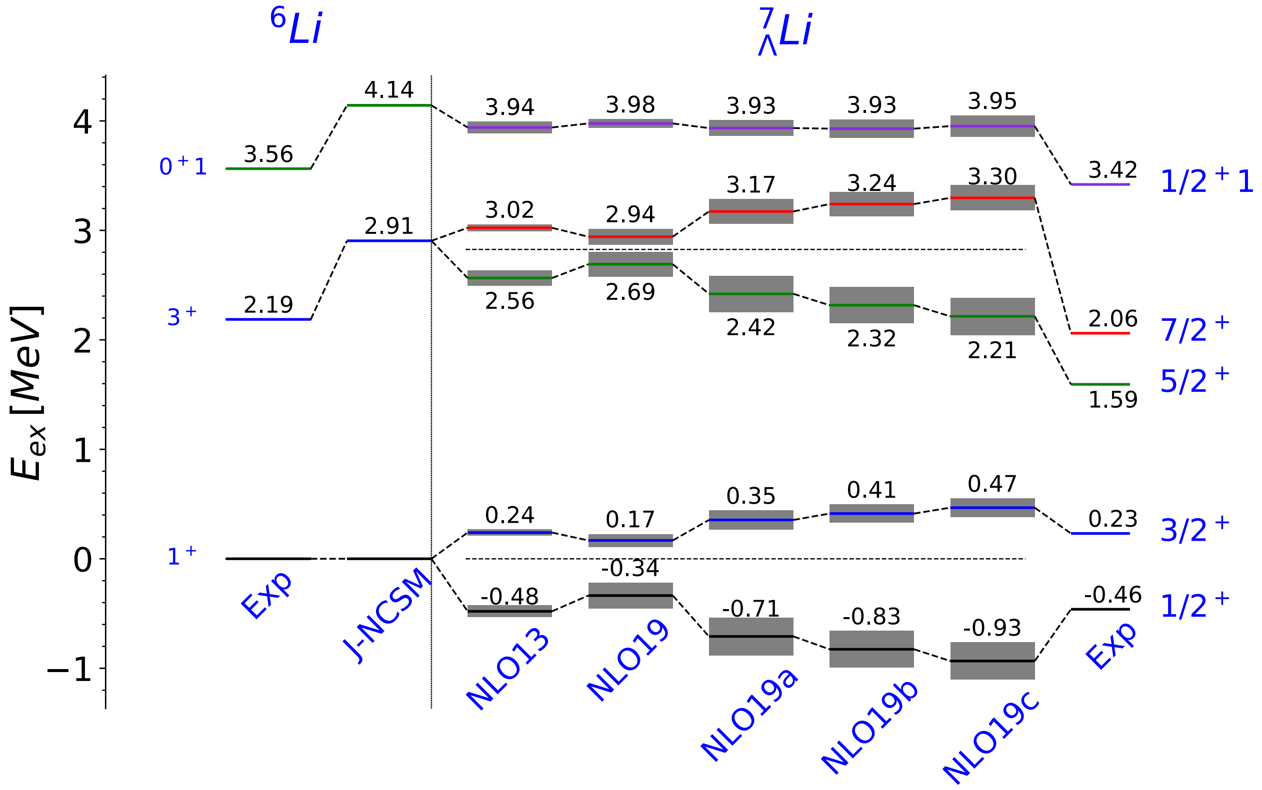


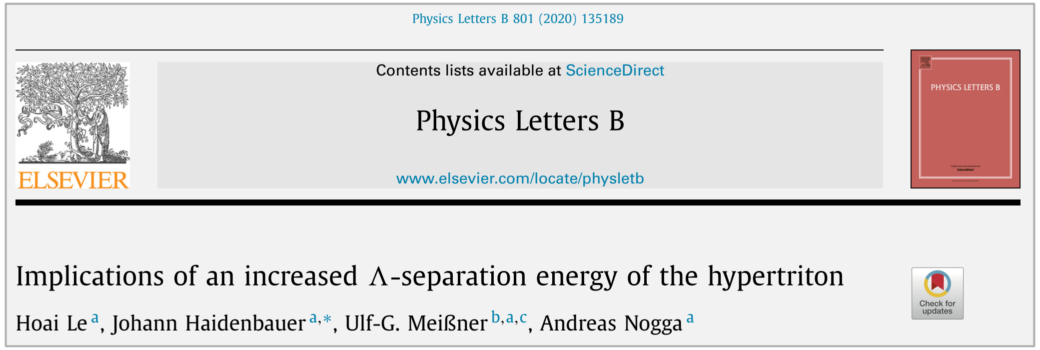
- Neutron separation energies stable and in good agreement with available data for both nucleonic parents and their daughter hypernuclei
- Neutron drip lines in the helium and lithium isotopic chains not changed by the addition of a hyperon

NCSM calculations for light *hypernuclei*

Chiral N^{4}LO NN + NLO YN
SRG transformed at two-baryon level

Jacobi-coordinate NCSM





Physics Letters B 801 (2020) 135189

Contents lists available at ScienceDirect

Physics Letters B

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Implications of an increased Λ-separation energy of the hypertriton

Hoai Le[a], Johann Haidenbauer[a,*], Ulf-G. Meißner[b,a,c], Andreas Nogga[a]

STAR collaboration -
larger $^3H_\Lambda$ binding energy (0.13 -> 0.41 MeV)

YN NLO19a,b,c fitted to obtain the larger value

$^4He_\Lambda(0^+)$, $^4He_\Lambda(1^+)$ and $^7Li_\Lambda$ still well described

Conclusions

- *Ab initio* calculations of nuclear structure and reactions becoming feasible beyond the lightest nuclei
  - Make connections between the low-energy QCD, many-body systems, and nuclear astrophysics

- *Ab initio* nuclear theory essential for precision applications such as tests of fundamental symmetries
  - Quenching of g_A
  - Double beta decay matrix elements
  - Isospin mixing correction δ_C
  - …

- Initial applications of *ab initio* methods to *p*-shell hypernuclei

- It is feasible to extend the reach and precision of *ab initio* hypernuclei calculations in a near future

In synergy with experiments, *ab initio* nuclear theory is the right approach to understand low-energy properties of atomic nuclei

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Thank you!
Merci!

Discovery, accelerated