Light-nuclei spectra from chiral dynamics

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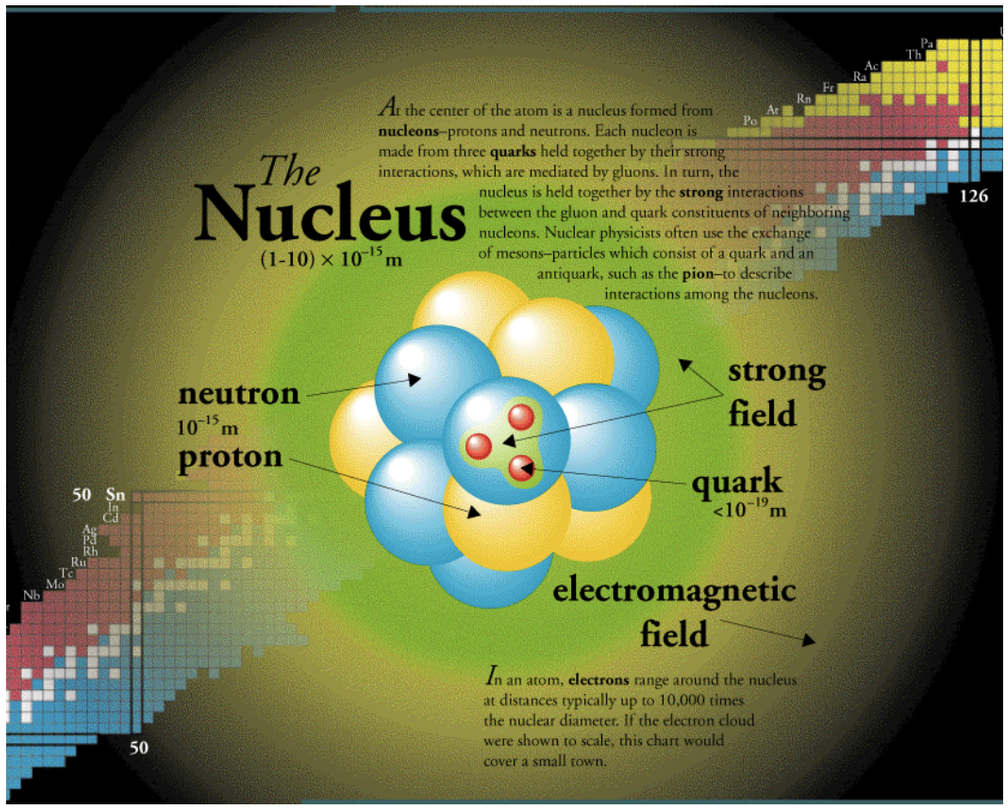
WORK NOT POSSIBLE WITHOUT EXTENSIVE COMPUTER RESOURCES
Argonne Laboratory Computing Resource Center (Blues, Bebop)
Argonne Leadership Computing Facility (Theta)

Nuclear Physics in a Nutshell:



- Atomic nuclei are complex quantum many-body systems of strongly interacting fermions (nucleons) displaying interesting properties: shell structure, pairing, deformation, strong clustering, etc

- QCD is the underlying theory of the strong interaction but nucleons are the relevant degree of freedom for the low-energy nuclear physics nuclear interactions

Nuclear forces: very complicated problem to derive in terms of quarks and gluons

- Historically research on the nuclear force has proceeded along different ways for example:

Phenomenological approach:

use the general form of a potential allowed by the symmetries (rotation, translation, isospin, etc);
potential terms are responsible to describe various phenomena remarked in NN interactions: for example the tensor term is important for the long-range part of potential and arises naturally from pion-exchange
In these potentials, the IR and SR parts are usually determined in a fully phenomenological way while for the LR part, an OPEP is often used

χEFT approach:

pions, nucleons, Δ's as degrees of freedom
construct their interactions consistently with the symmetries of the underlying theory, low-energy QCD

Atomic nuclei:

Collection of point-like particles whose dynamics is dictated by:

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots.$$

- v_{ij} : 2NF fitted on NN scattering data, deuteron BE, nn scattering length
- V_{ijk} : 3NF fitted on properties of light nuclei
- 2NF > 3NF > 4NF >...
- Calculations of the properties of light nuclei based upon the bare nuclear forces shown that 3NFs are important

Models of nuclear interactions:
- phenomenological: Argonne (NN) + Urbana-Illinois (NNN)
- local, chiral effective field theory: χEFT (NN+NNN+...)

Numerical methods:
- Ab initio approaches are aimed at solving the many-body Schrödinger equation associated with the nuclear Hamiltonian

$$H\,\Psi(\mathbf{R}; s_1, .., s_A; t_1, .., t_A) = E\,\Psi(\mathbf{R}; s_1, .., s_A; t_1, .., t_A)$$

- Our many-body method of choice is Quantum Monte Carlo (in particular VMC and GFMC) which allows for solving the nuclear Schrödinger equation with the required 1-2% accuracy level for both the ground- and the low-lying excited states of A ≤ 12 nuclei

Nuclear Models: NN phenomenological potentials

2NF Argonne V18 (AV18):

Wiringa. Stoks, Schiavilla
PRC **51**, 38 (1995)

- is a r-space potential controlled by ~4300 np and pp scattering data below 350 MeV of the Nijmegen database with a total $\chi^2 \cong 1$
- it is expressed as a sum of EM and OPE terms and phenomenological intermediate- and short-range parts

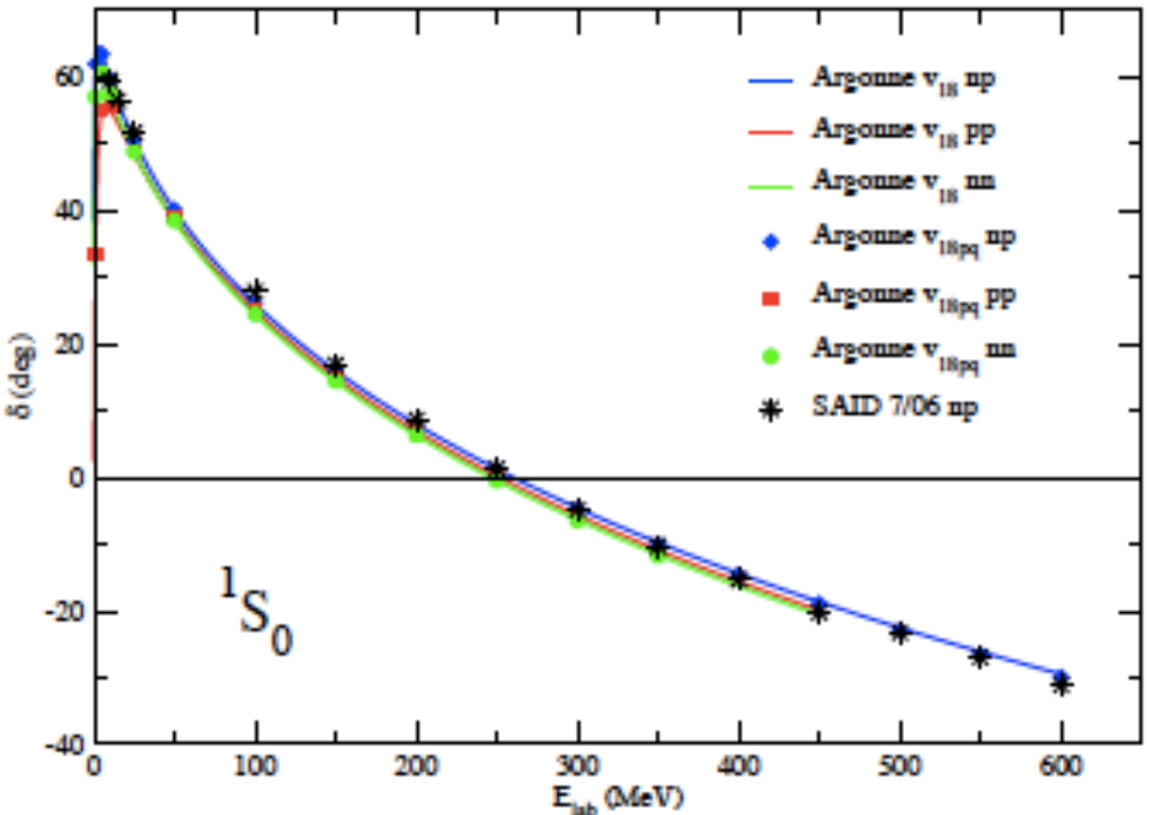
$$v_{18}(r_{12}) = v_{12}^{\gamma} + v_{12}^{\pi} + v_{12}^{I} + v_{12}^{S} = \sum_{p=1}^{18} v^{p}(r_{12}) O_{12}^{p}$$

Static part: $O_{12}^{l=1,\ldots,6} = [\mathbf{1}\,,\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\,,\, S_{12}] \otimes [\mathbf{1}\,,\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$

Spin-orbit, (Spin-orbit)^2, L^2 part: $O_{12}^{l=7,\ldots,14} = [\mathbf{L}\cdot\mathbf{S},\, (\mathbf{L}\cdot\mathbf{S})^2] \otimes [\mathbf{1},\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$

$$[\mathbf{L}^2,\, \mathbf{L}^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2] \otimes [\mathbf{1},\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$$

Charge-dependent part: $O_{12}^{l=15,\ldots,18} = [\mathbf{1},\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2,\, S_{12}] \otimes T_{12},\, \tau_1^z + \tau_2^z$



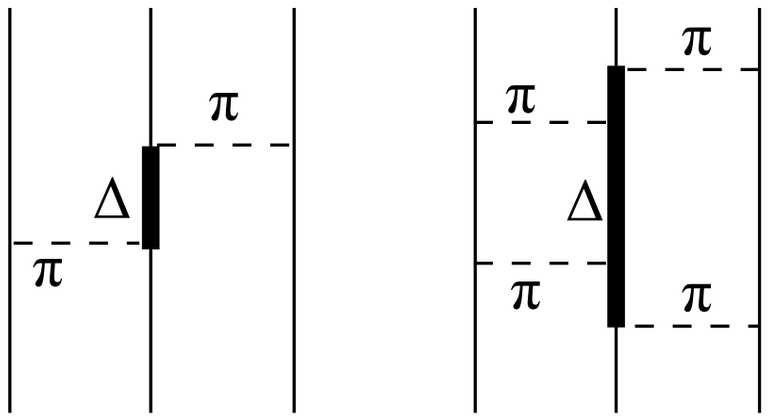
$$S_{12} = 3\,\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}}\,\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \qquad T_{12} = 3\,\tau_{1z}\tau_{2z} - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

- The AV18 model has a total of 42 independent parameters. While the fit was made up to 350 MeV, the phase shifts are qualitatively good up to much larger energies ≥ 600 MeV

Nuclear Models: NNN phenomenological potentials

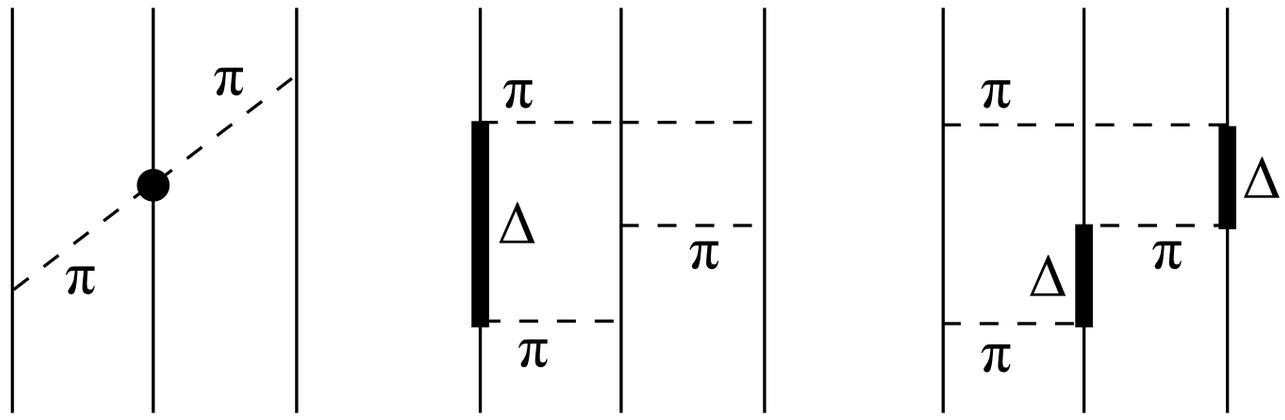
3NF Urbana-Illinois (UIX-IL7): • an Hamiltonian which only includes AV18 does not provide enough binding in the light nuclei

Urbana IX: J. Carlson et al. NP **A401**, 59 (1983) contains the attractive Fujita and Miyazawa two-pion exchange interaction and a phenomenological repulsive term; the two parameters were obtained by fitting the binding energy of ^{3}H and the density of nuclear matter in conjunction with the AV18



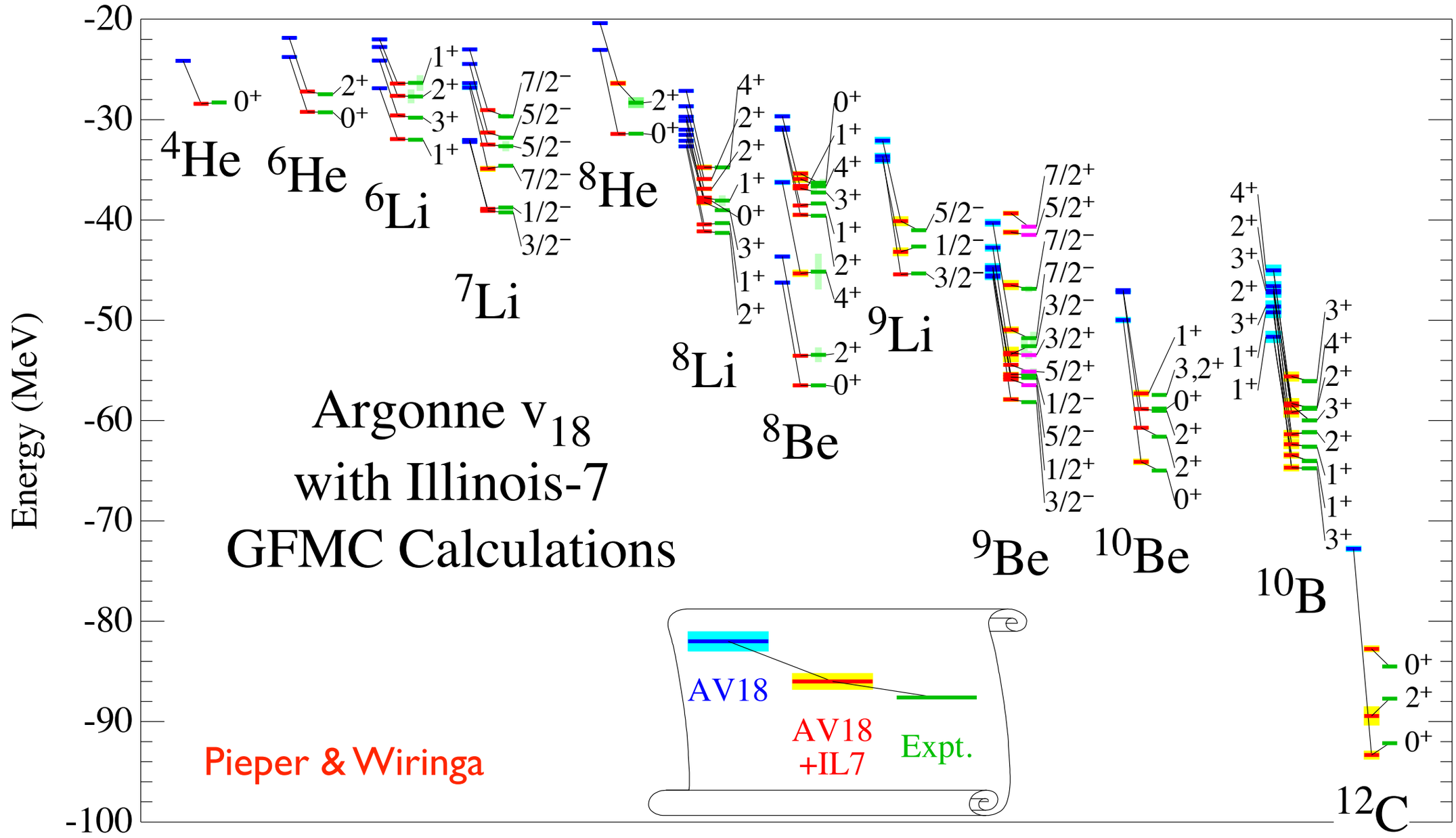
Good description for s-shell nuclei (A=3,4); inadequate description of the absolute binding energies and spin-orbit splitting of heavier nuclei

Illinois 7: S. Pieper et al. PRC **64**, 014001 (2001) also includes terms originating from three-pion rings containing one or two Δs and the two-pion S-wave contribution; the four parameters were searched to obtain a best fit, in conjunction with the AV18, for energies of about 20 nuclear ground and low-lying excited states in A≤10 nuclei



Good description for light nuclei up to A=12; inadequate description of the neutron star matter equation of state

AV18/IL7: the structure of light nuclei



Pros: • Very good description of several nuclear binding energies using AV18+IL7 (GFMC ground-state: uncertainties within 1-2%)

Cons: • Phenomenological interactions are phenomenological, not clear how to improve their quality
• They do not provide rigorous schemes to consistently derive 2N and 3N forces and compatible electroweak currents

The nuclear χEFT approach:

S. Weinberg, Phys. Lett. **B251**, 288 (1990); Nucl. Phys. **B363**, 3 (1991); Phys. Lett **B295**, 114 (1992)

- In χEFT, the symmetries of quantum chromodynamics (QCD), including its approximate chiral-symmetry, are employed to constrain the interactions of pions (π) among themselves, with baryons (N and Δ-isobars) or with external fields (such as electroweak)

- In particular, π's couple to baryons by powers of its momentum Q, and the Lagrangian ($\mathcal{L}_{eff}$) can be expanded systematically in powers of Q/Λ (according to a power counting scheme); ($Q << \Lambda \approx 1$ GeV is the chiral-symmetry breaking scale and $Q \sim m_\pi$)

$$\mathcal{L}_{eff} = \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + \ldots$$

- χEFT allows for a perturbative treatment in terms of powers of a Q- as opposed to a coupling constant- expansion

- The unknown coefficients in this perturbative expansion are called LEC's and are fixed by comparison with experimental data

- The χ-expansion provides a practical calculation scheme to construct two- and many-body potential as well as external currents, capable (in principle) of systematic improvements

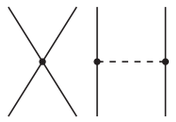
Chiral 2N

Δ-less

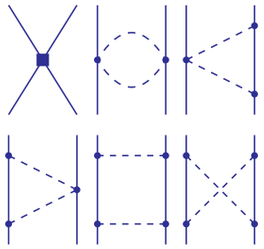
Additional in Δ-full

$\Delta = m_\Delta - m_N \sim 300\,\mathrm{MeV} \sim 2m_\pi$

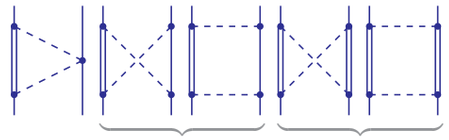
LO $(Q/\Lambda_\chi)^0$



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



Kaiser et al.'97
Entem & Machleidt '02

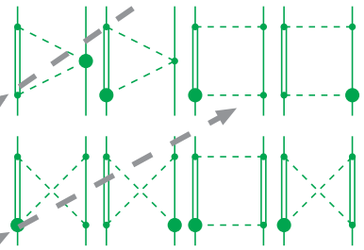


Ordonez et al.'96;Kaiser et al.'98;
Krebs et al. '07

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

+...

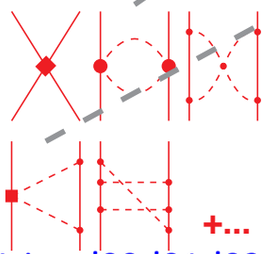
Kaiser et al.'97



+...

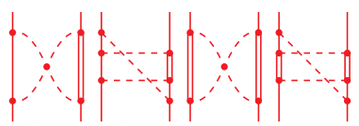
Krebs et al.'07

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



+...

Kaiser '00-'01-'02;
Entem & Machleidt '02



+...

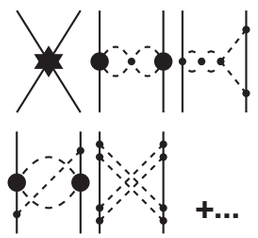
Kaiser '15

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

+...

Entem et al.'15, Epelbaum et al.'15

N^{5}LO $(Q/\Lambda_\chi)^6$



+...

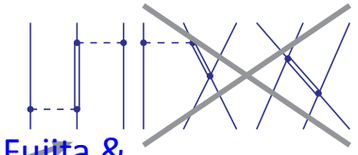
Entem et al.'15

Chiral 3N

Δ-less

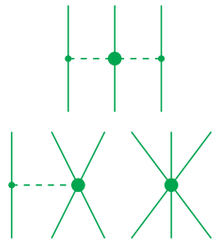
Additional in Δ-full

$\Delta = m_\Delta - m_N \sim 300\,\mathrm{MeV} \sim 2m_\pi$

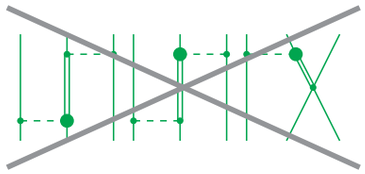


Fujita &
Miyazawa '57

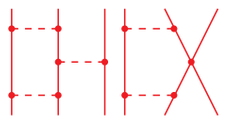
van Kolck'96;
Epelbaum'08



U. van Kolck '94; Epelbaum et al.'02;
Nogga et al.'05; Navratil et al.'07



Epelbaum et al. '08



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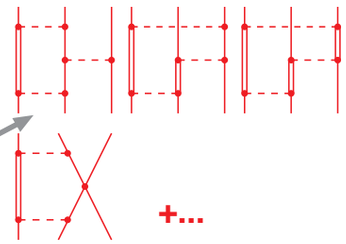
Bernard at al. '08;
Ishikawa & Robilotta '07



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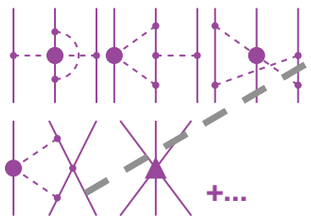
Epelbaum et al. '08



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Krebs at al. '12-'13;
Girlanda et.al '11

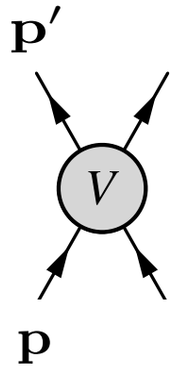
Entem & Machleidt '11
Machleidt & Sammarruca '16

Chiral 2N potentials: some recent developments

- First generation of chiral NN potential up to N3LO:
  Entem-Machleidt PRC **68**, 041001 2003; Epelbaum-Gloeckle-Meissner JNP **A747**, 362 2005
- Optimized N2LO NN potential (πN LECs are tuned to NN peripheral scattering):
  Ekström et al. PRL **110**, 192502 2013; JPG **42**, 034003 2015
- N2LO potential: a simultaneous fit of NN and 3N forces to low NN data (E_{lab}=35 MeV), deuteron BE, BE and CR of hydrogen, helium, carbon and oxygen isotopes;
  Carlsson et al. PRC **91**, 051301(R) 2015
- New generation of chiral NN potentials up to N4LO: improved choice of the regulator, no SFR;
  Epelbaum et al. PRL **112**, 102501 2014; EPJ **A51**, 53 2015; PRL **115**, 122301 2015
- Chiral 2π and 3π exchange up to N4LO and up to N5LO in NN peripheral scattering;
  Entem et al. PRC **91**, 014002 2015; PRC **92**, 064001 2015, arXiv:1703.05454 2017
- The LENPIC collaboration arXiv: 1705.01530v1
- .....

Note: Many of the available versions of chiral potentials are formulated in momentum-space and are strongly nonlocal: ⇨ $\mathbf{p} \to -i\boldsymbol{\nabla}$ hard to use in QMC methods

Nonlocalities due to contact interactions and to regulator functions



Nonlocal regulator

$$V_{\rm NN}(\mathbf{p},\mathbf{p}') \to \exp\left[-[(\mathbf{p}^2+\mathbf{p}'^2)/\Lambda^2]^n\right] V_{\rm NN}(\mathbf{p},\mathbf{p}')$$

Local regulator

$$V_{\rm NN}(\mathbf{p},\mathbf{p}') \to \exp\left[-[(\mathbf{p}'-\mathbf{p})^2/\Lambda^2]^n\right] V_{\rm NN}(\mathbf{p},\mathbf{p}')$$

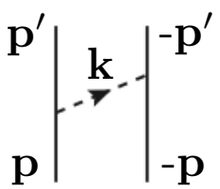
- Local NN potentials up to N2LO:
  Gezerlis et al. PRL **111**, 032501 2013; PRC **90**, 054323 2014; Lynn et al. PRL **113**, 192501 2014
- Minimally nonlocal/local NN potentials including N2LO Δ contributions;
  Piarulli et al. PRC **91**, 024003 2015; PRC **94**, 054007 2016

Local chiral NN potential:

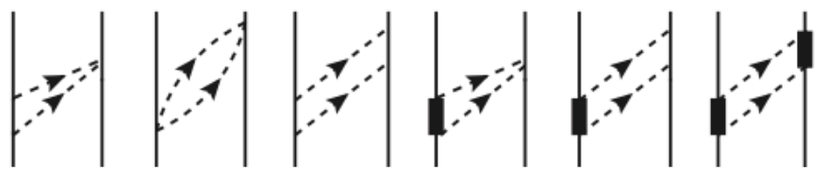
The local chiral NN potential we designed can be written as: $v_{12} = v_{12}^{\rm EM} + v_{12}^{\rm L} + v_{12}^{\rm S}$

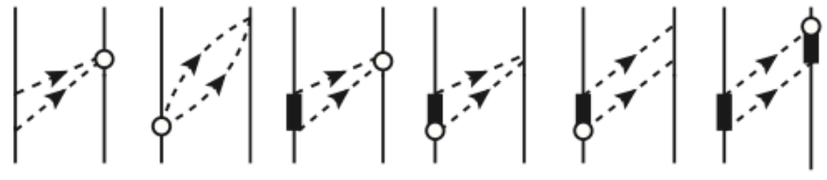
$v_{12}^{\rm EM}$: EM component including Coulomb, DF, VP and MM interactions

$v_{12}^{\rm L}$: long-range component including

LO : Q^0 

• dependence only on the momentum transfer **k**=**p**′-**p**

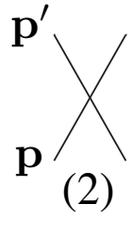
NLO : Q^2 

N2LO : Q^3 

• known LECs: $g_A, F_\pi, h_A = 3\,g_A/\sqrt{2}$

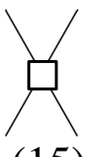
• unknown LECs: $c_1,\ c_2,\ c_3,\ c_4$ $(\mathcal{L}_{\pi N}^{(2)})$
$b_3 + b_8$ $(\mathcal{L}_{\pi N\Delta}^{(2)})$ taken from π-N scattering
(Krebs at al. EPJ **A32,** 127 2007)

$v_{12}^{\rm S}$: short-range component including

LO : Q^0 

(2)

NLO : Q^2 
(7)

N3LO : Q^4 
(15)

At NLO and N3LO strongly nonlocal contact terms: proportional to K^2 and K^4 where **K**=(**p**′+**p**)/2; we use Fierz rearrangements to remove these nonlocalities (see also Gezerlis et al. PRL **111**, 032501 2013; PRC **90**, 054323 2014)

Contact terms of type **k**×**K** or k^2 K^2 still persist: they can not Fierz-transformed away

Coordinate-space $v_{12}^{\rm L}$:

In coordinate-space the long-range part of the interaction can be written as

$$v_{12}^{\rm L} = \left[\sum_{l=1}^{6} v_{\rm L}^{l}(r)\, O_{12}^{l}\right] + v_{\rm L}^{\sigma T}(r)\, O_{12}^{\sigma T} + v_{\rm L}^{tT}(r)\, O_{12}^{tT}$$

- Charge-independent part: $O_{12}^{l=1,\ldots,6} = [\mathbf{1}\,,\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\,,\, S_{12}] \otimes [\mathbf{1}\,,\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$

- Charge-dependent part: $O_{12}^{\sigma T} = \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\, T_{12}$

  $O_{12}^{tT} = S_{12} T_{12}$

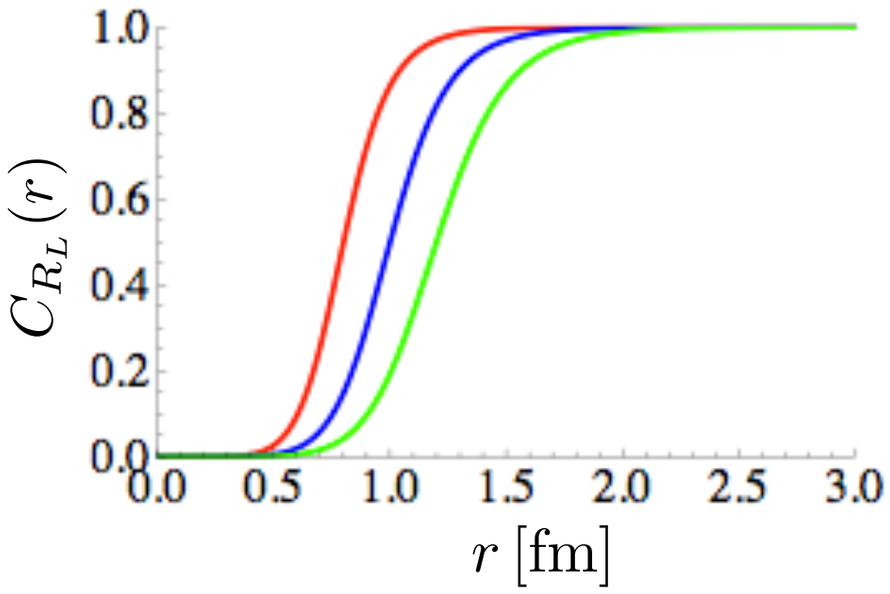
  $T_{12} = 3\,\tau_{1z}\tau_{2z} - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$

The radial functions have divergencies of type $1/r^n$, $1 \le n \le 6$; we need a regulator function which ensures that the short-distance part of the long-range potential at *r* smaller than $R_{\rm L}$ are smoothly cut off

- $C_{R_{\rm L}}(r) = 1 - \dfrac{1}{(r/R_{\rm L})^6\, e^{(r-R_{\rm L})/a_L} + 1}$

$$R_L = (0.8, 1.0, 1.2)\ \text{fm}$$

$$a_L = R_L/2$$



Coordinate-space $v_{12}^{\rm S}$:

In coordinate-space the short-range part of the interaction can be written as

$$v_{12}^{\rm S} = \sum_{l=1}^{16} v_{\rm S}^{l}(r)\, O_{12}^{l}$$

- Static part: $O_{12}^{l=1,\ldots,6} = [\mathbf{1}\,,\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\,,\,S_{12}]\otimes[\mathbf{1}\,,\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2]$
- Spin-orbit, (Spin-orbit)^2, L^2 part: $O_{12}^{l=7,\ldots,11} = \mathbf{L}\cdot\mathbf{S}\,,\,\mathbf{L}\cdot\mathbf{S}\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\,,\,(\mathbf{L}\cdot\mathbf{S})^2\,,\,\mathbf{L}^2\,,\,\mathbf{L}^2\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2$
- Charge-dependent part: $O_{12}^{l=12,\ldots,16} = T_{12}\,,\,(\tau_1^z+\tau_2^z)\,,\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\,T_{12}\,,\,S_{12}\,T_{12}\,,\,\mathbf{L}\cdot\mathbf{S}\,T_{12}$

In order to a have a fully nonlocal interaction, we are neglecting $\mathbf{p}^2$-terms of type

- $\{\, v_{\rm S}^{p}(r) + v_{\rm S}^{p\sigma}(r)\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + v_{\rm S}^{pt}(r)\,S_{12} + v_{\rm S}^{pt\tau}(r)\,S_{12}\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\;,\;\mathbf{p}^2\,\}$

The FT of the single contact terms is carried out with a Gaussian regulator, depending only on the momentum transfer *k,* such that

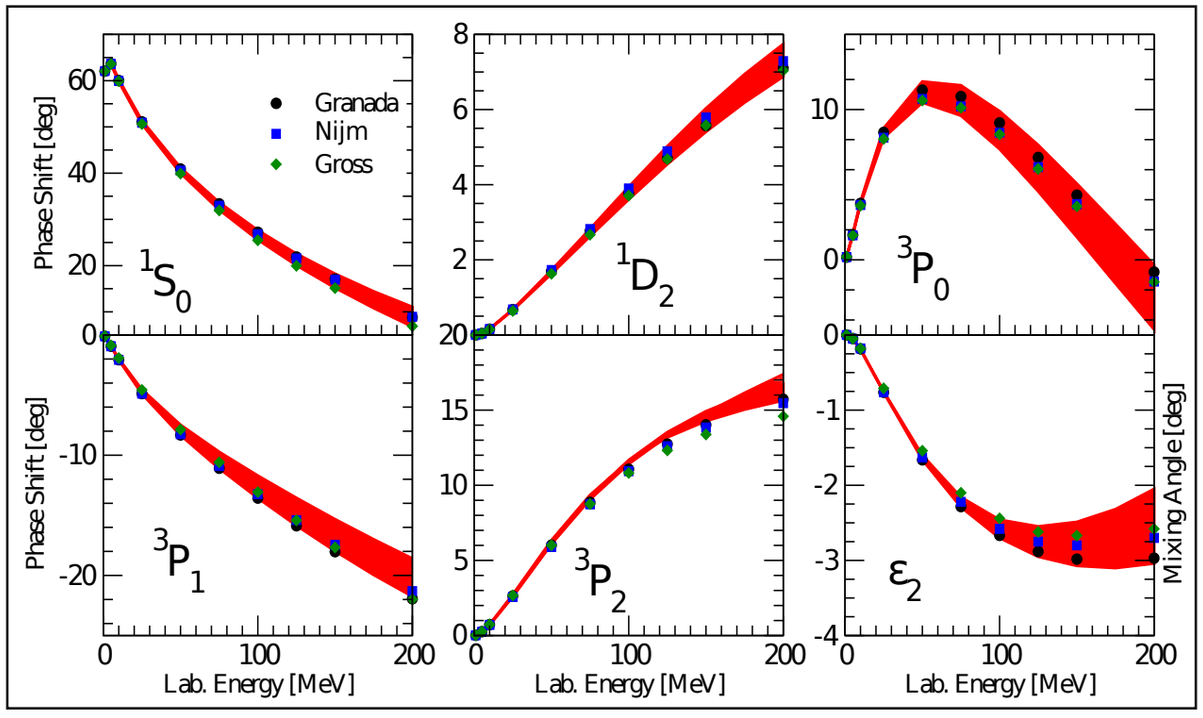
- $\widetilde{C}_{R_{\rm S}}(k) = e^{-R_{\rm S}^2 k^2/4} \longrightarrow C_{R_{\rm S}}(r) = \dfrac{1}{\pi^{3/2}R_{\rm S}^3}\, e^{-(r/R_{\rm S})^2}$

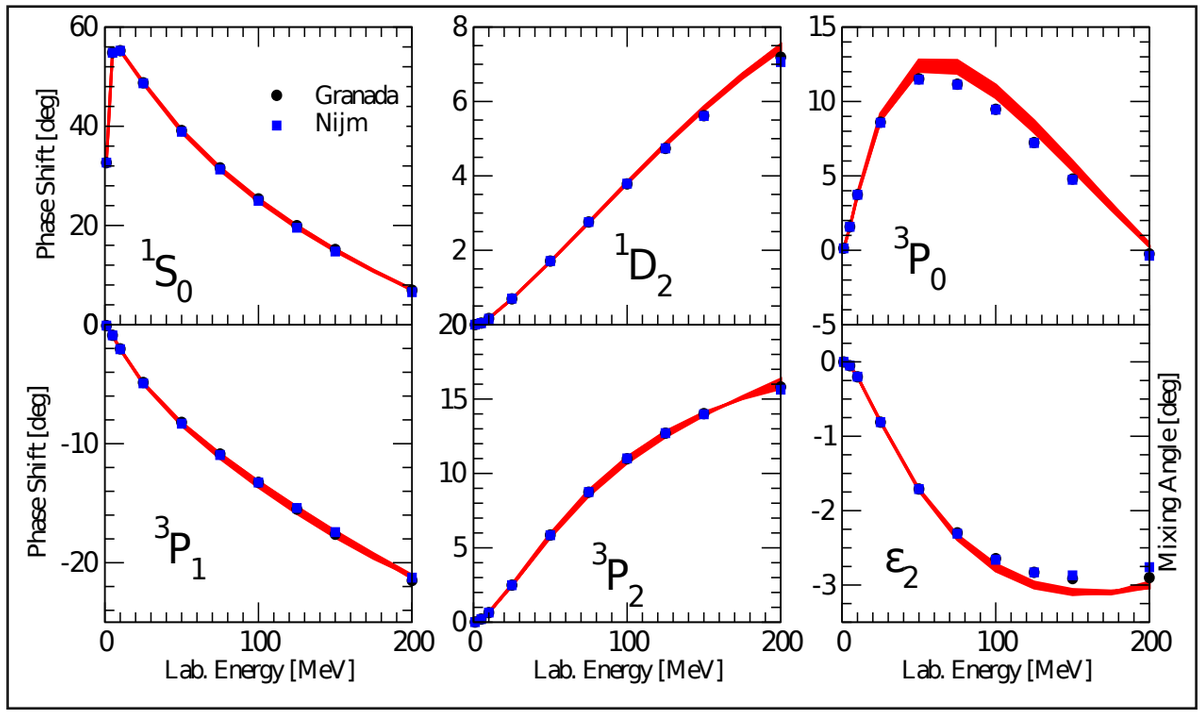
In combination with $R_L = (0.8, 1.0, 1.2)$ fm we consider $R_S = (0.6, 0.7, 0.8)$ fm corresponding to typical momentum-space cutoff $\Lambda_{\rm S} = 2/R_{\rm S}$ $(700, 600, 500)$ MeV

Fitting procedure:

The LECs fixed by fitting the pp and np Granada database up to two ranges of E_{lab} = 125 MeV and 200 MeV, the deuteron BE and the nn scattering length: we first fit the phase shifts then we refine the fit with a direct comparison with the database

To minimizing χ^2 the we use the Practical Optimization Using No Derivatives (for Squares), POUNDers (M. Kortelainen, PRC **82**, 024313 2010)





model	order	$R_{\rm L}$ (fm)	$R_{\rm S}$ (fm)	$E_{\rm LAB}$ (MeV)	χ^2/datum
Model b	LO	1.0	0.7	125	59.88
Model b	NLO	1.0	0.7	125	2.18
Model b	N2LO	1.0	0.7	125	2.32
Model b	N3LO	1.0	0.7	125	1.07
Model a	N3LO	1.2	0.8	125	1.05
Model c	N3LO	0.8	0.6	125	1.11
Model $\widetilde{a}$	N3LO	1.2	0.8	200	1.37
Model $\widetilde{b}$	N3LO	1.0	0.7	200	1.37
Model $\widetilde{c}$	N3LO	0.8	0.6	200	1.40

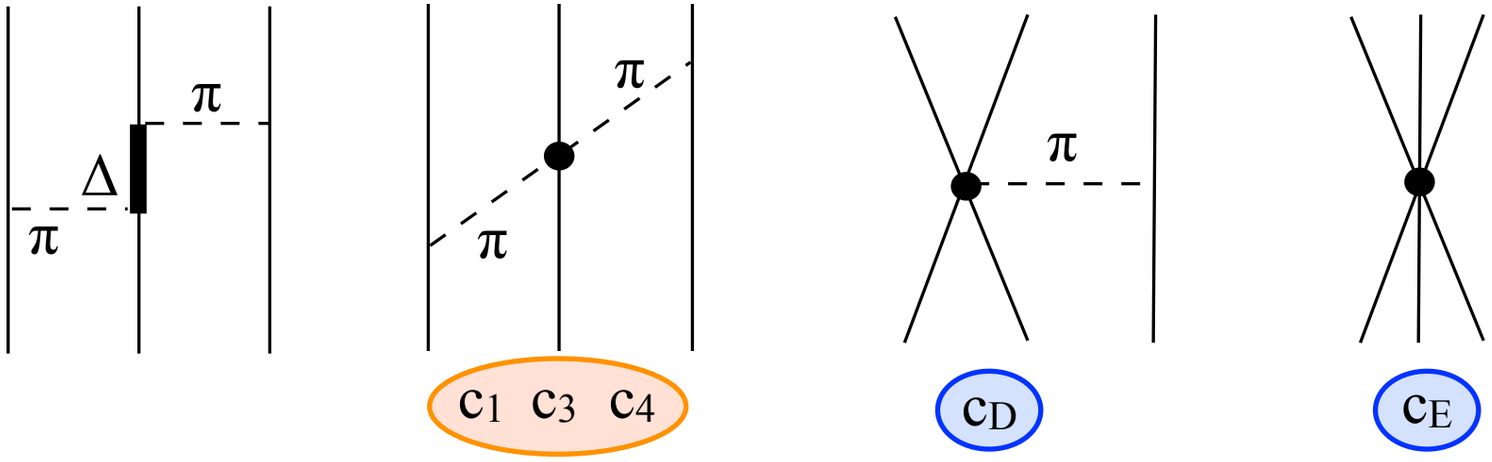
Model a : $(R_L, R_S) = (1.2, 0.8)$

Model b : $(R_L, R_S) = (1.0, 0.7)$

Model c : $(R_L, R_S) = (0.8, 0.6)$

Local chiral 3N potential:

Inclusion of 3N forces at N2LO:



same as NN interaction need to be fixed

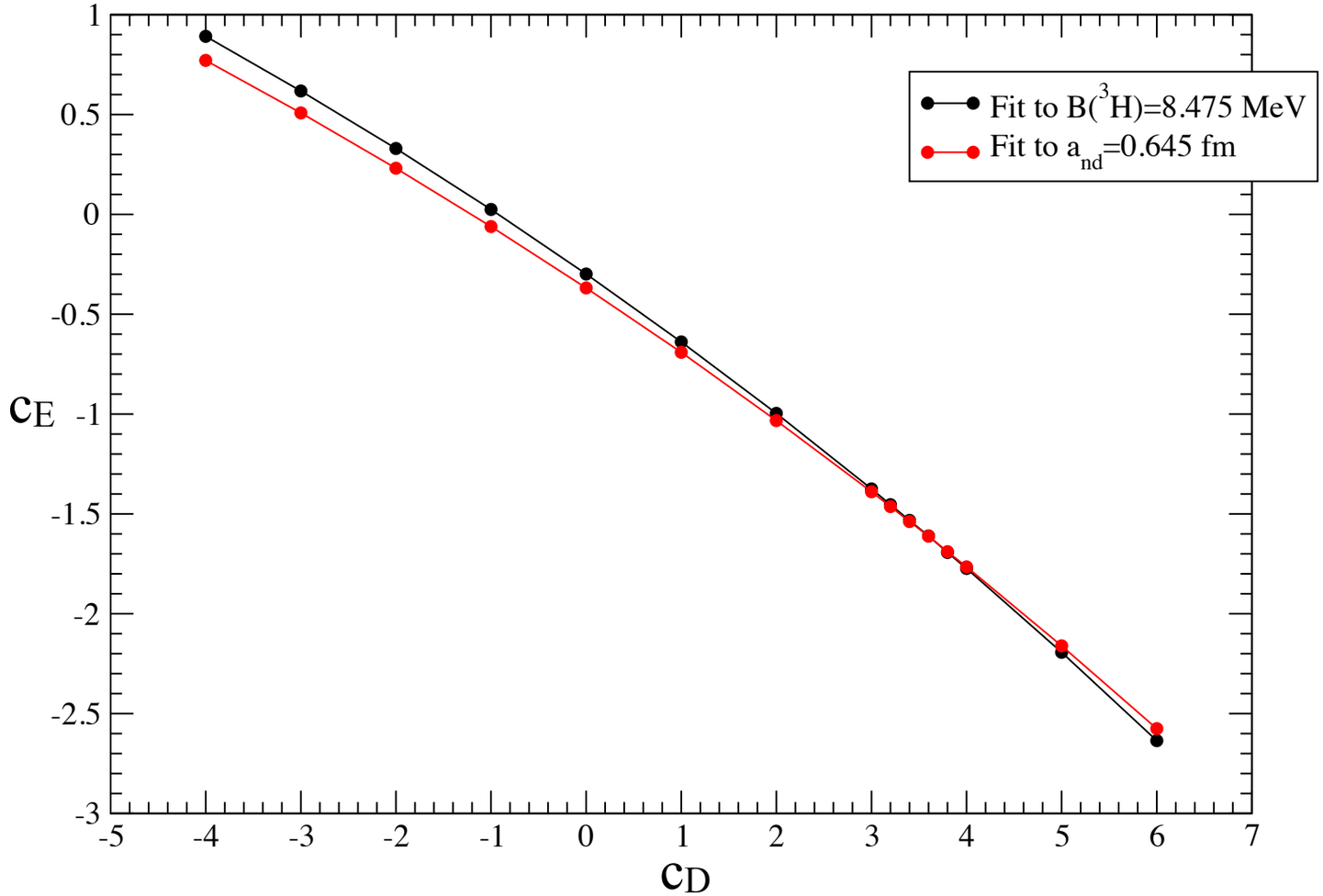
Note:
same regulator functions and cutoff used in the NN interaction

courtesy of Laura E. Marcucci (Universita' di Pisa)

Fit to:

- ^{3}H binding energy
- nd scattering length

Model	c_D	c_E
Ia	3.666	–1.638
Ib	–2.061	–0.982
IIa	1.278	–1.029
IIb	–4.480	–0.412



Quantum Monte Carlo (QMC) methods:

- Encompasses a large family of computational methods whose common aim is the study of complex quantum systems
- Provide a reliable solution (or an accurate approximation) of the quantum many-body problem

VMC, GFMC: sampling in coordinate space

→ limited number of nucleons A=12

R.B. Wiringa, PRC **43**, 1585 (1991)
Carlson, *et al.*, Rev. Mod. Phys. **87**, 1067 (2015)

AFDMC: sampling in coordinate space + spin-isospin coordinate

→ larger nuclei A~50 & nuclear matter

Smith and Fantoni, Phys. Lett. B **446**, 99 (1999)
Carlson, *et al.*, Rev. Mod. Phys. **87**, 1067 (2015)

CVMC: sampling in coordinate space + cluster expansion

→ closed shell nuclei (+/- 1): A=40

Pieper, *et al.*, Phys. Rev. C **46**, 1741 (1992)
Lonardoni, *et al.*, arXiv:1705.04337

QMC: Variational Monte Carlo (VMC)

R.B. Wiringa, PRC **43**, 1585 (1991)

- Minimize the expectation value of H:

$$E_T = \frac{\langle \Psi_T | H | \Psi_T \rangle}{\langle \Psi_T | \Psi_T \rangle} \geq E_0$$

- Trial wave function (involves variational parameters):

$$|\Psi_T\rangle = \left[1 + \sum_{i<j<k} U_{ijk}\right] \left[S \prod_{i<j} (1 + U_{ij})\right] |\Psi_J\rangle$$

$|\Psi_J\rangle = \left[\prod_{i<j} f_c(r_{ij})\right] |\Phi(JMTT_z)\rangle$ (s-shell nuclei): Jastrow wave function, fully antisymmetric

$S \prod_{i<j}$: represents a symmetrized product

$U_{ij} = \sum_{p=2,6} u_p(r_{ij})\, O_{ij}^p$: pair correlation operators

$U_{ijk} = \sum_x \epsilon_x\, V_{ijk}^x$: three-body correlation operators

$|\Psi_T\rangle$ are spin-isospin vectors in 3A dimension with $2^A \begin{pmatrix} A \\ Z \end{pmatrix}$

- The search in the parameter space is made using COBYLA (Constrained Optimization BY Linear Approximations) algorithm available in NLopt library
- The typical number of variational parameters for s-shell nuclear wave functions is about two dozen for a two-body potential; four to six parameters are added if a three-body potential is included in the Hamiltonian

QMC: Green's function Monte Carlo (GFMC)

J. Carlson et al., Rev. Mod. Phys. **87**, 1067 (2015)

• The diffusion Monte Carlo (DMC) method such as GFMC, overcomes the limitation of VMC calculation by using a projection technique to enhance the true ground-state component of a starting trial wave function

• The method relies on the observation that the trial wave function can be expanded in the complete set of eigenstates of the Hamiltonian according to

$$|\Psi_T\rangle = \sum_n c_n |\Psi_n\rangle \qquad\qquad H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

which implies

$$\lim_{\tau\to\infty} |\Psi(\tau)\rangle = \lim_{\tau\to\infty} e^{-(H-E_0)\,\tau}\,|\Psi_T\rangle = c_0|\Psi_0\rangle \qquad\qquad |\Psi(\tau=0)\rangle = |\Psi_T\rangle$$

where τ is the imaginary time. The GFMC projects out lowest energy state from the best variational trial wave function

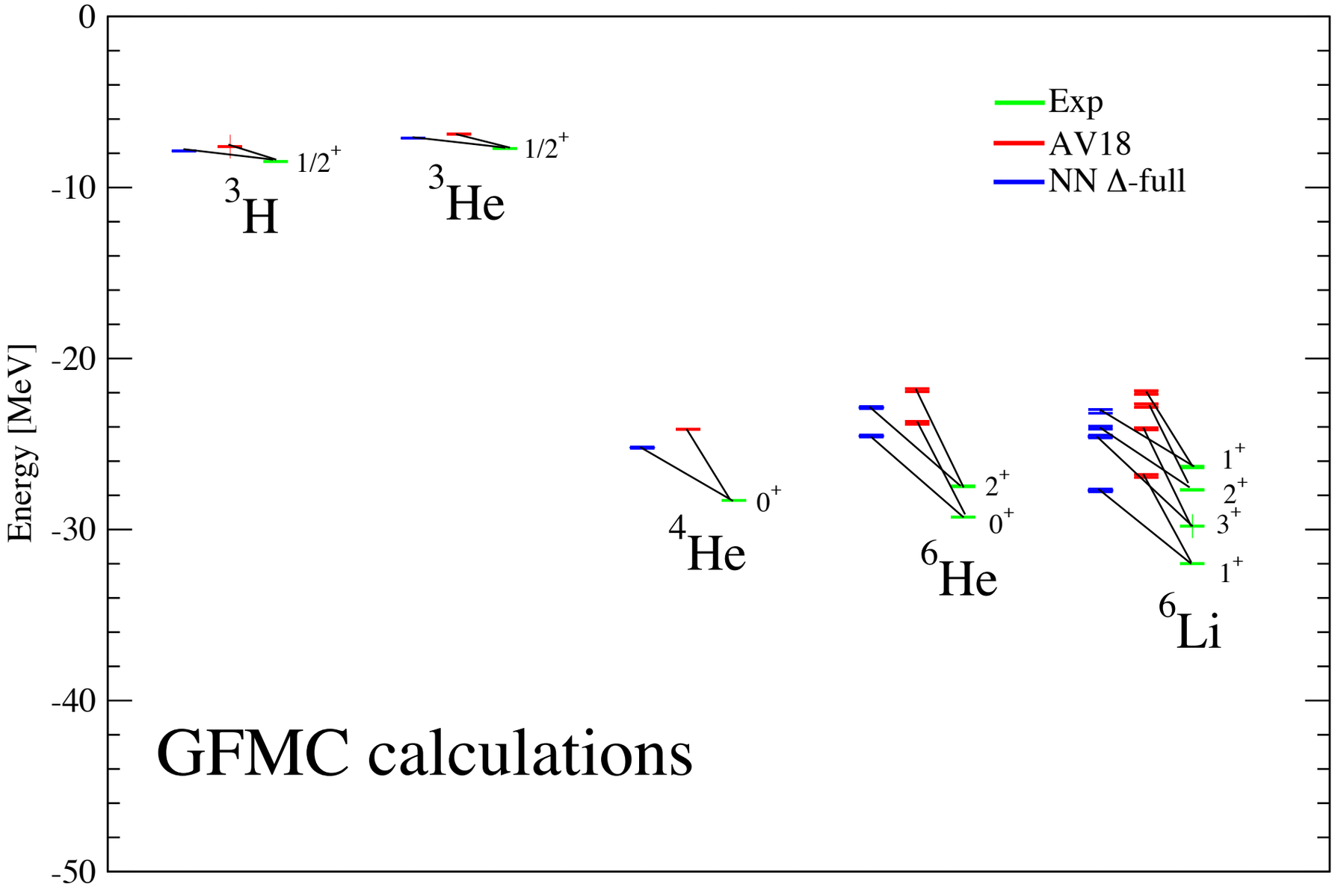
• The evaluation of Ψ(τ) is done stochastically in small time steps Δτ (τ = n Δτ) using a Green's function formulation

Propagator does not contain p^2 , L^2, $(\mathbf{L}\,.\,\mathbf{S})^2$

• it is carried out with a simplified version H' of the full Hamiltonian H; H' is a projection of H on the first eight-operator preserving the potential in all S and P waves as well as the deuteron channel; the remaining terms are calculated perturbatively

QMC for A≤6 with only local NN interaction

- The A≤6 ground- and excited state energies with only local NN chiral interaction compared with the corresponding GFMC results obtained with AV18 and experimental values



3N interactions are needed!!

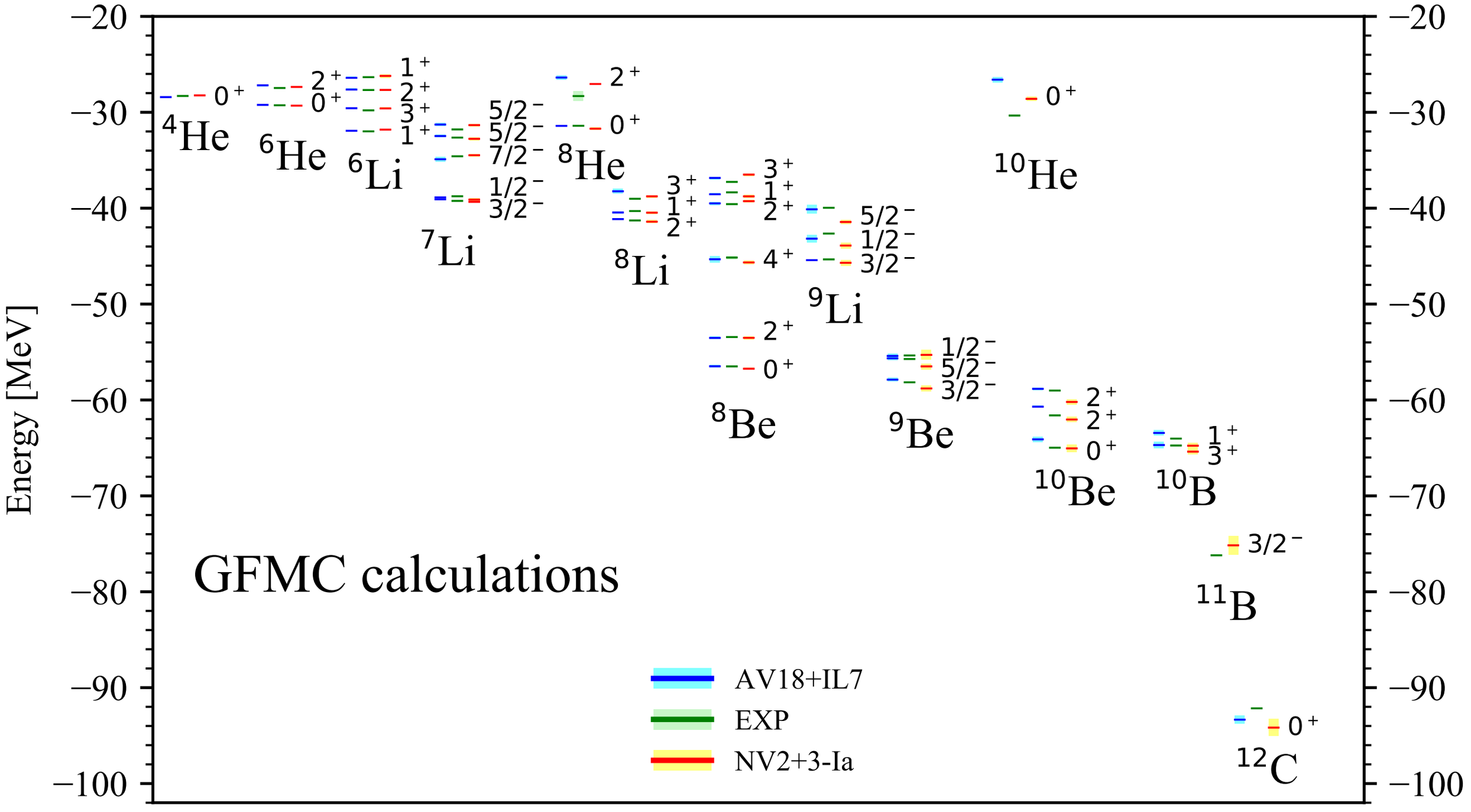
Piarulli et al. PRC **94**, 054007 20016

- For A=3, 4 benchmark with the HH calculations

- For A=3, 4, and 6 the energies differ by about 0.2-0.3, 1.0, and 0.5-1.3 MeV, respectively, from the corresponding ones obtained using the AV18

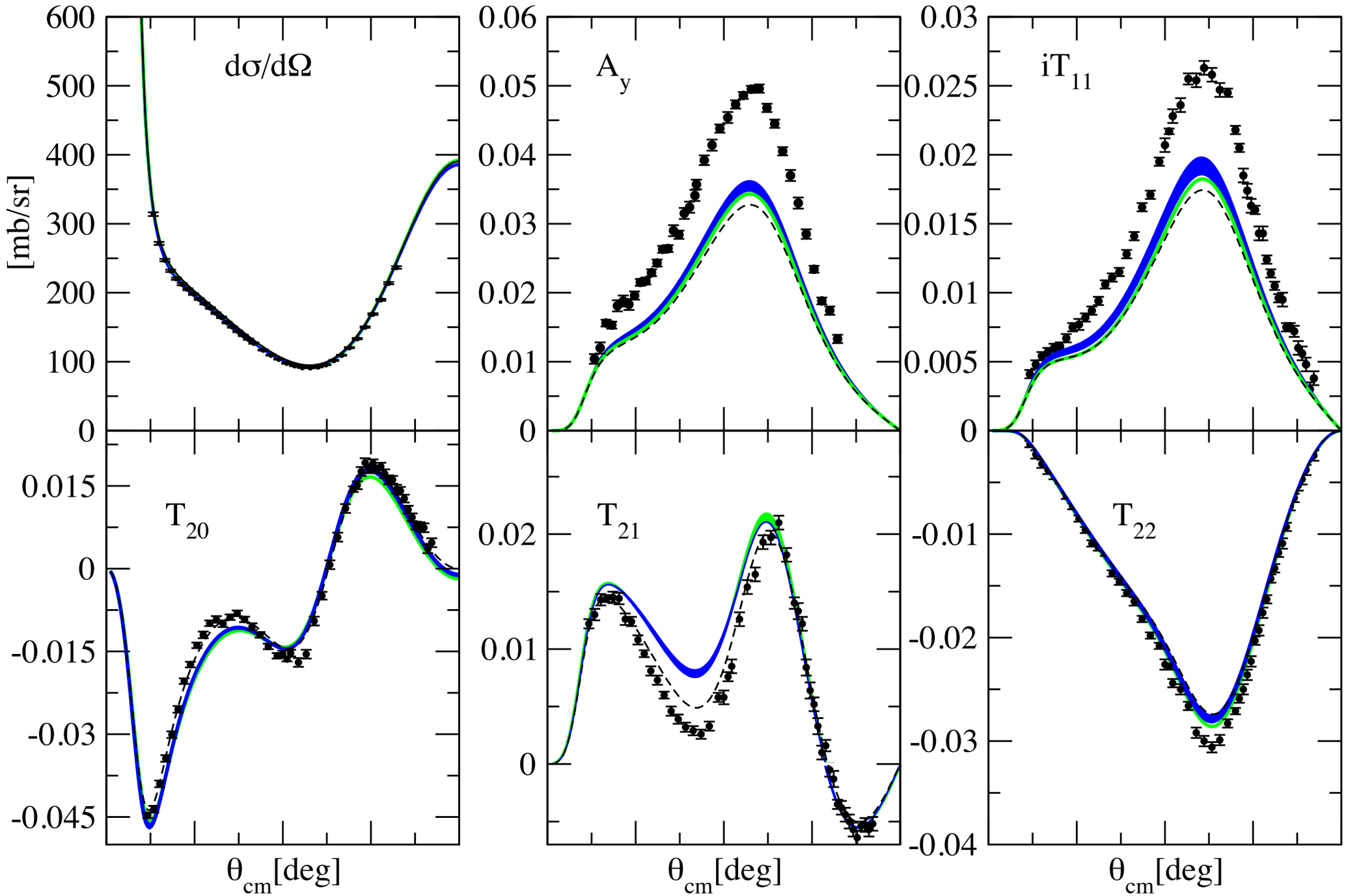
QMC for A≤12 with local NN+NNN interactions

- The A≤12 ground- and excited state energies with local NN+NNN chiral interaction, AV18+IL7, and the corresponding experimental values



- Compared to the AV18+UIX, these local chiral potentials give better description for absolute binding energies and spin-orbit splitting for p-shell nuclei

• Polarization observables in pd elastic scattering at 3 MeV, obtained in HH calculations with the NV2+3 models Ia-Ib (IIa-IIb), are shown by the green (blue) band. The black dashed line are results obtained with only the two-body interaction NV2-Ia



subleading contact terms in 3N interaction??? Additional 10 LECs

Conclusions:

- We have constructed a family of local NN potential with chiral TPE including Δ-isobar up to N2LO and contact interactions up to N3LO in the chiral expansion

- Three versions of this NN chiral potential for three different cutoff values have been developed with good fits to np and pp Granada database

- Corresponding local NNN chiral interaction up N2LO have been also developed; they involve two new LECs fixed by fitting the binding energy of ^{3}H and nd scattering length

- A subset of these local NN and NN+NNN chiral interactions have been used to in HH and QMC calculations of binding energies and rms proton radii for some nuclei with A≤12

Plans:

- Test other versions of NV2+3 with different energy fits and regulators and compare
- Studies of the effect of subleading 3N contact interactions in light nuclei
- Different strategies to fit 3NI
- Comprehensive treatment of radii, moments, electroweak transitions in VMC/GFMC including exchange currents