Update on QMC calculations with local chiral interactions

Ingo Tews

In collaboration with J. Carlson, S. Gandolfi, A. Gezerlis,
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JINA–CEE

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Outline

- Quantum Monte Carlo method
  - Very precise for strongly interacting systems
  - Need of local interactions (depend only on relative distance r)
- Local chiral interactions
  - Can be constructed up to N^2LO
- Artifacts for local regulators: Ambiguity for NN and 3N contact interactions
- Results for nuclei with A≤16
  - Excellent description of binding energies and charge radii
- Summary

Quantum Monte Carlo method

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Cast many-body Schrödinger equation as diffusion equation:

$$\lim_{\tau\to\infty} e^{-H\tau}|\Psi_T\rangle \to |\Psi_0\rangle$$

$$\psi(R,\tau) = \int dR'^{3N} \langle R|e^{-(T+V)\tau}|R'\rangle \psi(R',0)$$

Basic steps:

- Choose trial wavefunction which overlaps with the ground state

$$|\psi(R,0)\rangle = |\psi_T(R,0)\rangle = \sum_i c_i|\phi_i\rangle \to \sum_i c_i e^{-(E_i-E_0)\tau}|\phi_i\rangle$$

- Evaluate propagator for small timestep $\Delta\tau$, in practice only for local potentials
- Make consecutive small time steps using Monte Carlo techniques to project out ground state

$$|\psi_T(R,\tau)\rangle \to |\phi_0\rangle \quad \text{for} \quad \tau\to\infty$$

More details:
Carlson, Gandolfi, Pederiva, Pieper, Schiavilla, Schmidt, Wiringa, RMP (2015)

Quantum Monte Carlo method

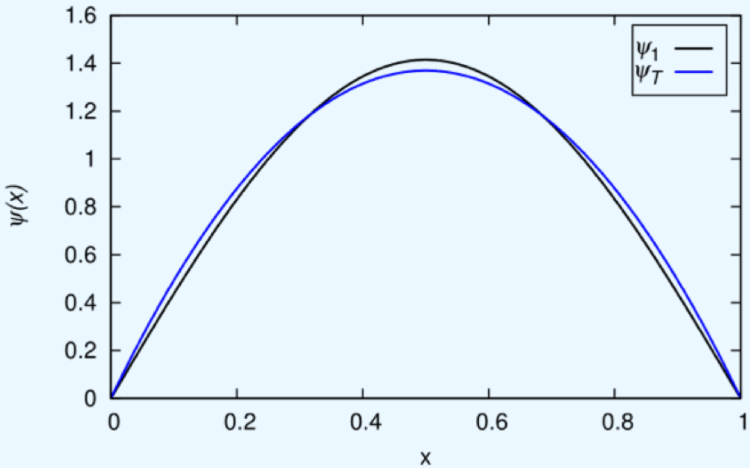
Particle in a 1D box, solution:

$$\psi_n(x) = \sqrt{2}\sin(n\,\pi\,x), \quad E_n = \frac{n^2\pi^2}{2}$$

Basic steps:

- Choose parabolic trial wavefunction which overlaps with the ground state

Animation by Joel Lynn, TU Darmstadt



Quantum Monte Carlo method

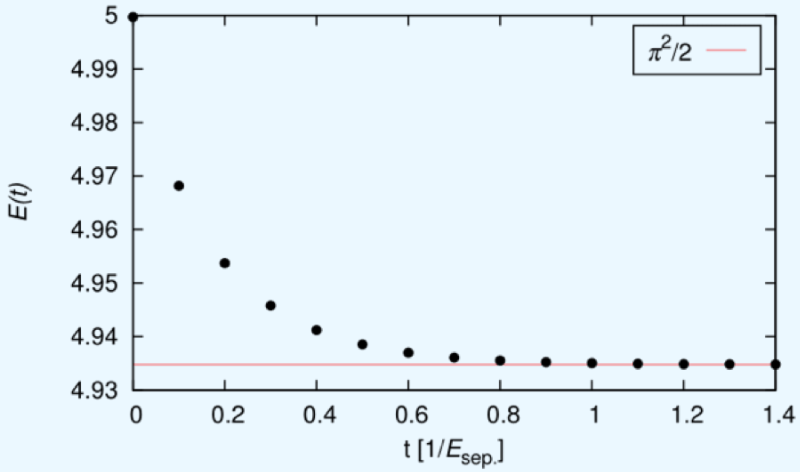
Particle in a 1D box, solution:

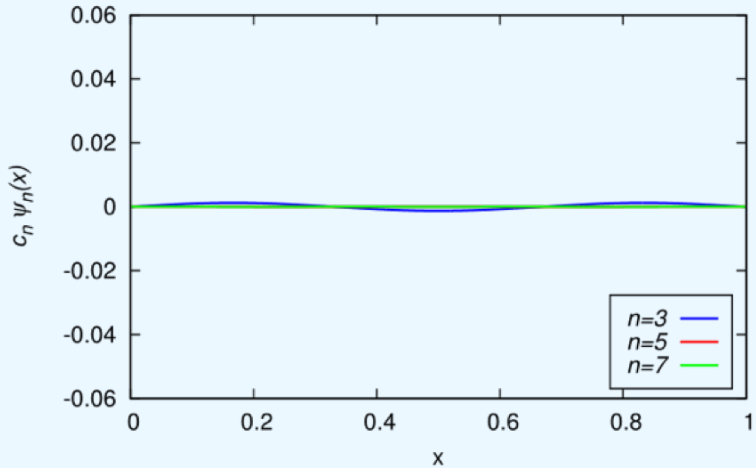
$$\psi_n(x) = \sqrt{2}\sin(n\,\pi\,x), \quad E_n = \frac{n^2\pi^2}{2}$$

Basic steps:

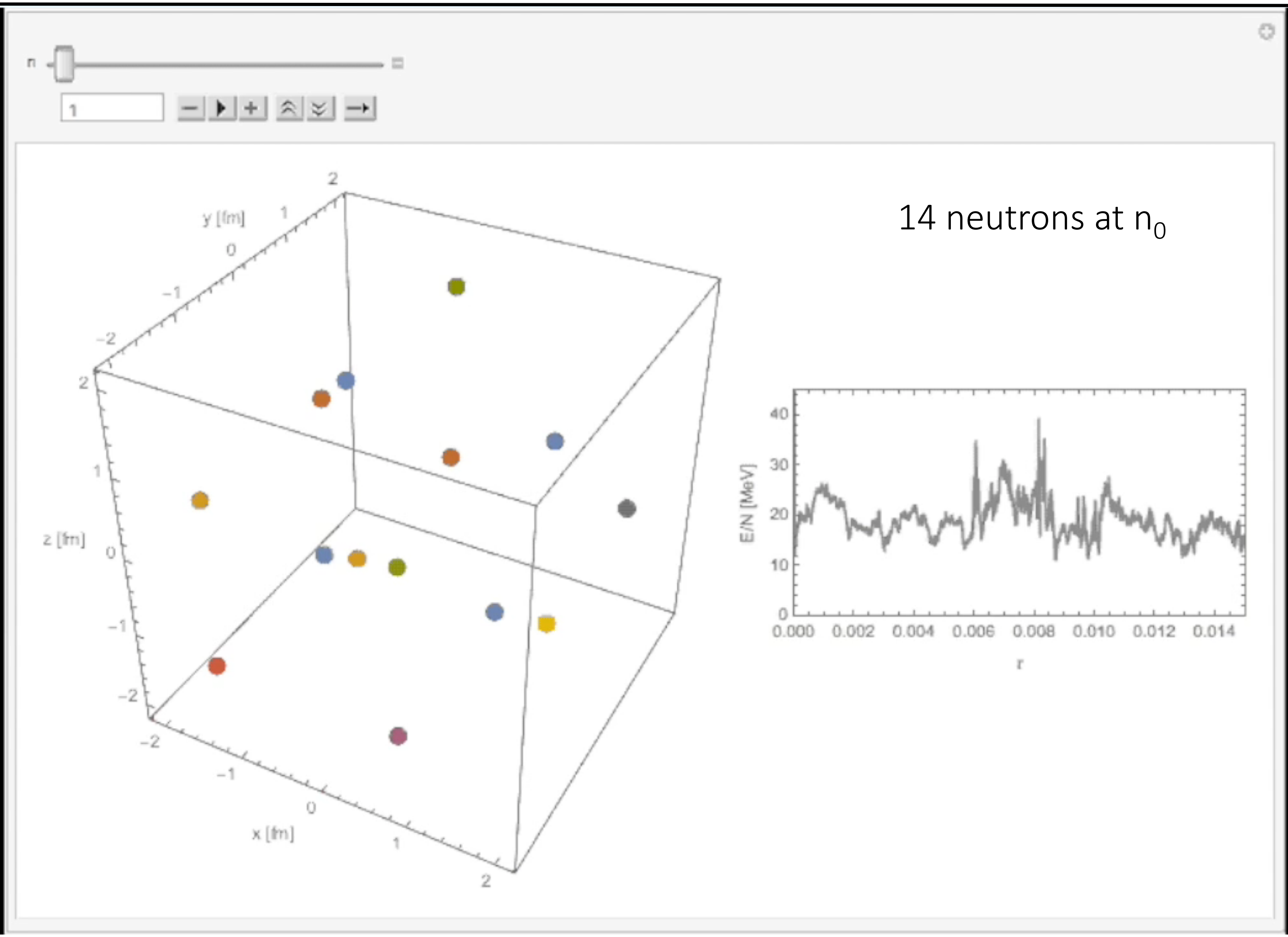
- Make consecutive small timesteps, $\tau = 1.4\left(\frac{1}{E_{\mathrm{sep}}}\right)$

Animation by Joel Lynn, TU Darmstadt





Quantum Monte Carlo method



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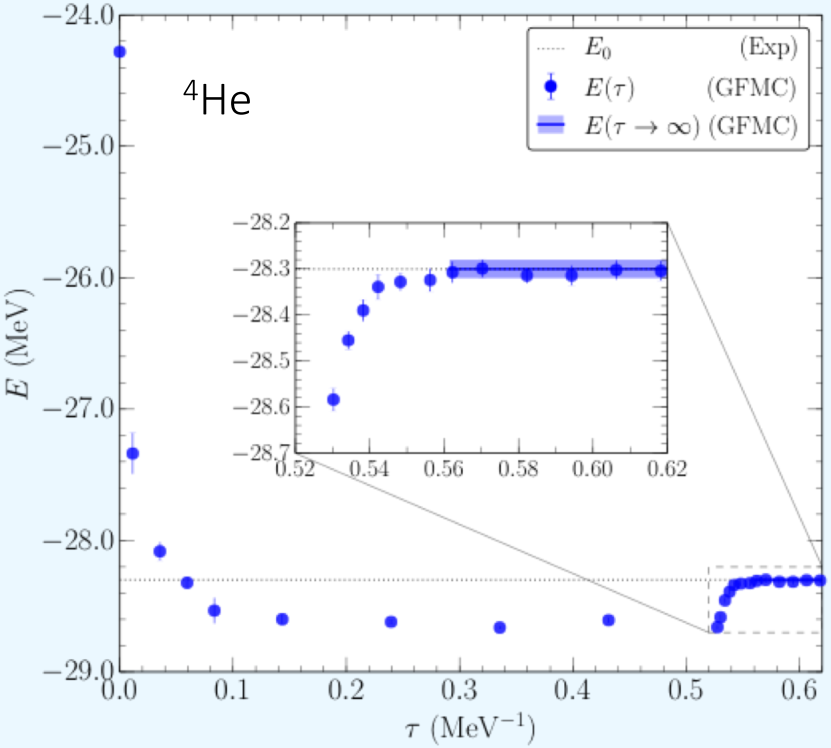
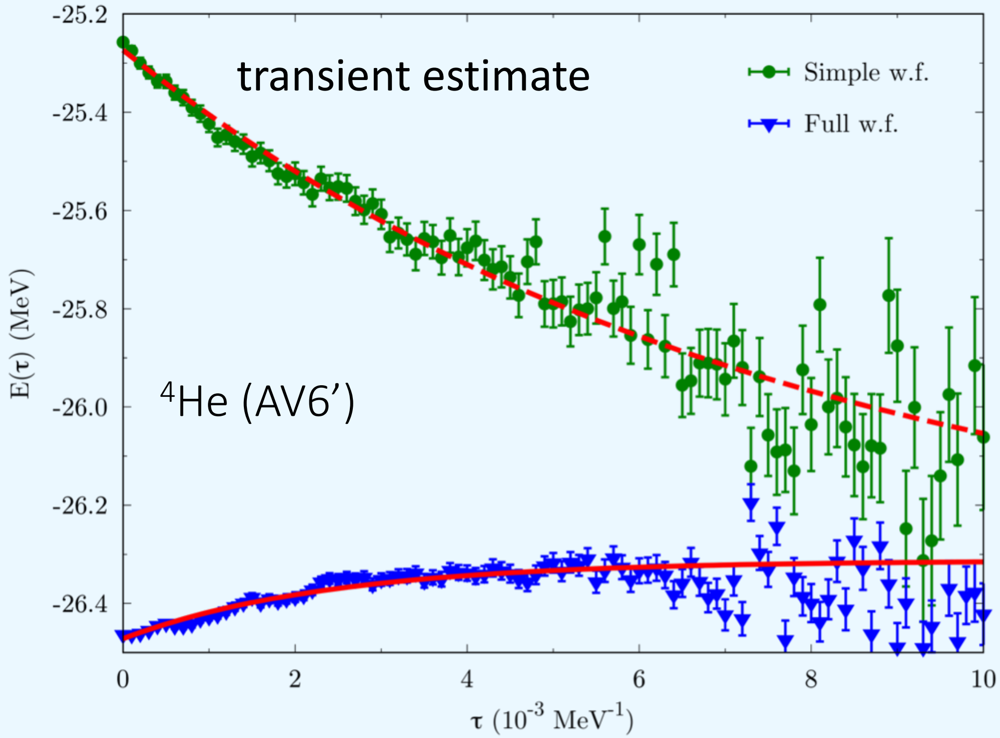


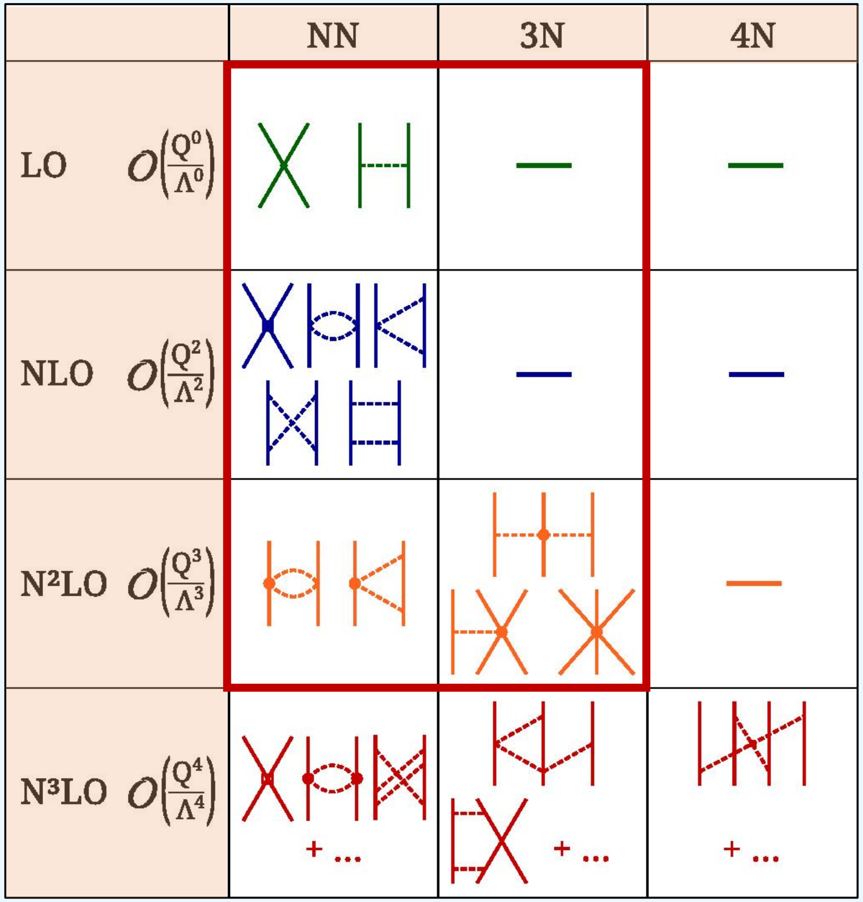
Lynn, IT, et al. PRC (2017)



Lonardoni et al., arXiv:1802.08932

- Very precise method for strongly interacting systems.
- With transient estimates, stochastically exact.
- Needs as input local interactions but chiral EFT generally nonlocal!

Local chiral interactions

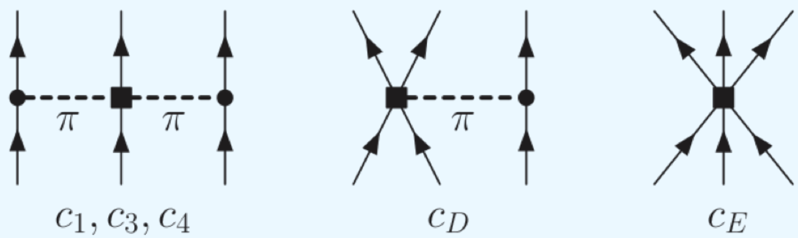


Weinberg, van Kolck, Kaplan, Savage, Wise,
Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

- Can be constructed up to N²LO
  Gezerlis, IT, Epelbaum, Gandolfi, Hebeler, Nogga, Schwenk, PRL (2013)
  Gezerlis, IT, Epelbaum, Freunek, Gandolfi, Hebeler, Nogga, Schwenk, PRC (2014)

- Two-body LECs fit to phase shifts

- Include leading 3N forces:



3N LECS fit to uncorrelated observables:

- Probe properties of light nuclei: ^{4}He E_B
- Probe spin-orbit splitting: n-α scattering

Local chiral interactions

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To evaluate the propagator for small timesteps $\Delta\tau$ we need local potentials:

$$\langle r'|V|r\rangle = \begin{cases} V(r)\delta(r-r') & \text{if local} \\ V(r',r) & \text{if nonlocal} \end{cases}$$

Chiral Effective Field Theory interactions generally nonlocal:

- Momentum transfer $\mathbf{q} = \mathbf{p}' - \mathbf{p}$
- Momentum transfer in the exchange channel $\mathbf{k} = \frac{1}{2}(\mathbf{p} + \mathbf{p}')$
- Fourier transformation: $\mathbf{q} \to \mathbf{r}$, $\mathbf{k} \to \nabla_{\mathbf{r}}$

Sources of nonlocalities:

- Usual regulator in rel. momenta

$$f(p) = e^{-(p/\Lambda)^{2n}}$$

- k-dependent contact operators

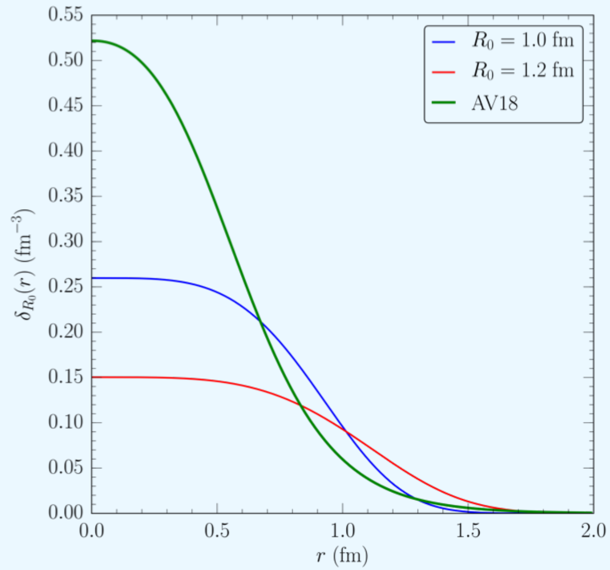
Solutions:

- Choose local regulators:

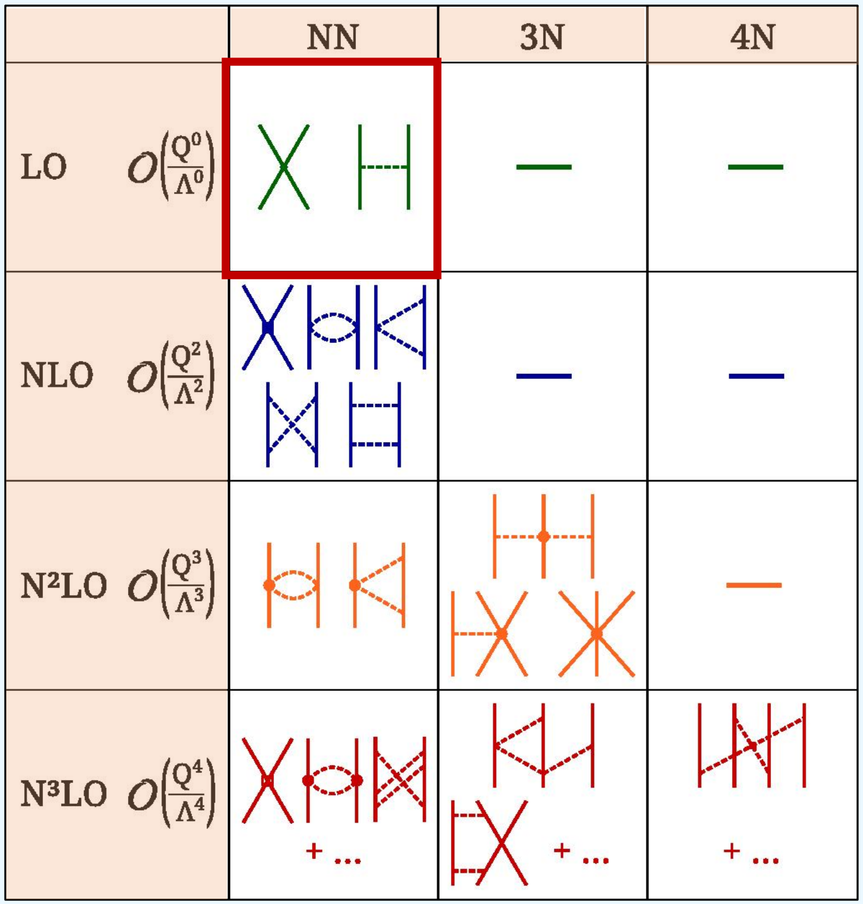
$$V_{\text{long}}(r) \to V_{\text{long}}(r)\left(1 - e^{-(r/R_0)^4}\right)$$

$$\delta(r) \to \delta_{R_0}(r) = \alpha e^{-(r/R_0)^4}$$

- Use Fierz freedom to choose local set of contact operators.



Local chiral interactions



Weinberg, van Kolck, Kaplan, Savage, Wise,
Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

- Leading order $V^{(0)} = V^{(0)}_{\text{cont}} + V^{\text{OPE}}_{\text{long}}$
- Pion exchanges local

$$V_{\text{long}}(r) = V_C(r) + W_C(r)\,\tau_1\cdot\tau_2 + \left(V_S(r) + W_S(r)\,\tau_1\cdot\tau_2\right)\sigma_1\cdot\sigma_2 + \left(V_T(r) + W_T(r)\,\tau_1\cdot\tau_2\right) S_{12}$$

→ local regulator

$$V_{\text{long}}\,(r) \;\rightarrow\; V_{\text{long}}(r)\left(1 - e^{-(r/R_0)^4}\right)$$

- Contact potential:

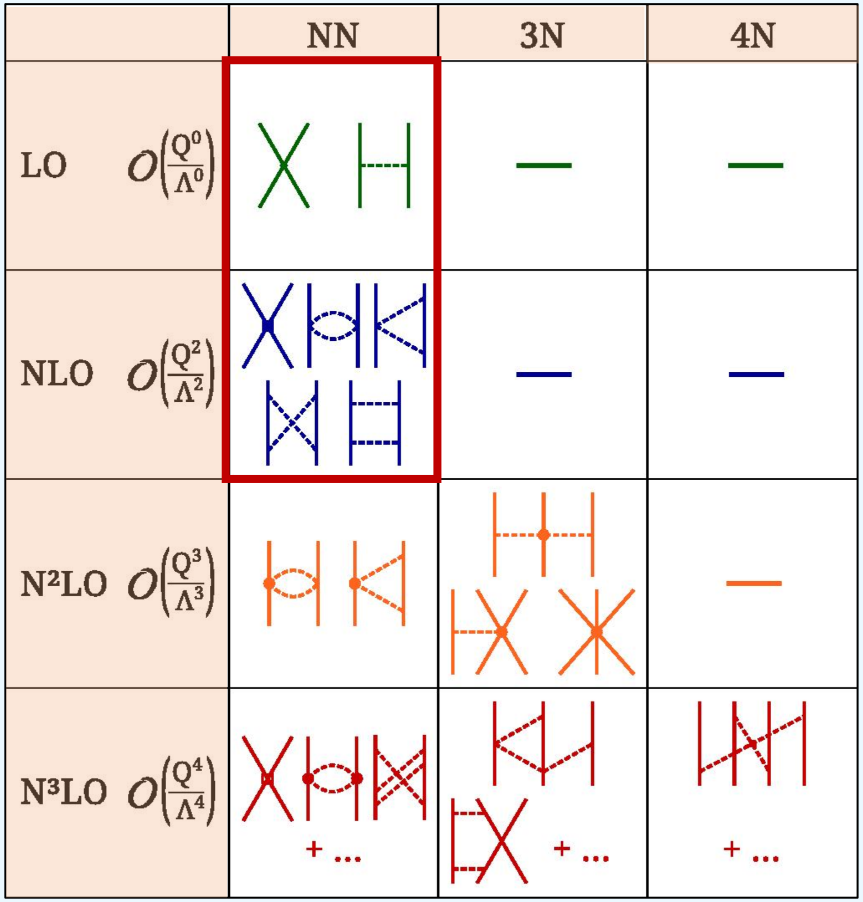
$$V^{(0)}_{\text{cont}} = \alpha_1 1 + \alpha_2\,\sigma_1\cdot\sigma_2 + \alpha_3\,\tau_1\cdot\tau_2 + \alpha_4\,\sigma_1\cdot\sigma_2\,\tau_1\cdot\tau_2$$

→ Only two independent (Pauli principle)

$$V^{(0)}_{\text{cont}} = C_S 1 + C_T\sigma_1\cdot\sigma_2$$

$$\delta(\mathbf{r}) \;\rightarrow\; \delta_{R_0}(\mathbf{r}) = \alpha e^{-(r/R_0)^4}$$

Local chiral interactions



- Choose local set of short-range operators at NLO (7 out of 14)

$$
\begin{aligned}
V_{\text{cont}}^{(2)} = \; & \gamma_1\, q^2 + \gamma_2\, q^2\, \sigma_1 \cdot \sigma_2 + \gamma_3\, q^2\, \tau_1 \cdot \tau_2 \\
& + \gamma_4\, q^2 \sigma_1 \cdot \sigma_2 \tau_1 \cdot \tau_2 \\
& + \gamma_5\, k^2 + \gamma_6\, k^2\, \sigma_1 \cdot \sigma_2 + \gamma_7\, k^2\, \tau_1 \cdot \tau_2 \\
& + \gamma_8\, k^2 \sigma_1 \cdot \sigma_2 \tau_1 \cdot \tau_2 \\
& + \gamma_9\, (\sigma_1 + \sigma_2)(\mathbf{q} \times \mathbf{k}) \\
& + \gamma_{10}\, (\sigma_1 + \sigma_2)(\mathbf{q} \times \mathbf{k}) \tau_1 \cdot \tau_2 \\
& + \gamma_{11} (\sigma_1 \cdot \mathbf{q})(\sigma_2 \cdot \mathbf{q}) \\
& + \gamma_{12} (\sigma_1 \cdot \mathbf{q})(\sigma_2 \cdot \mathbf{q}) \tau_1 \cdot \tau_2 \\
& + \gamma_{13} (\sigma_1 \cdot \mathbf{k})(\sigma_2 \cdot \mathbf{k}) \\
& + \gamma_{14} (\sigma_1 \cdot \mathbf{k})(\sigma_2 \cdot \mathbf{k}) \tau_1 \cdot \tau_2
\end{aligned}
$$

Weinberg, van Kolck, Kaplan, Savage, Wise,
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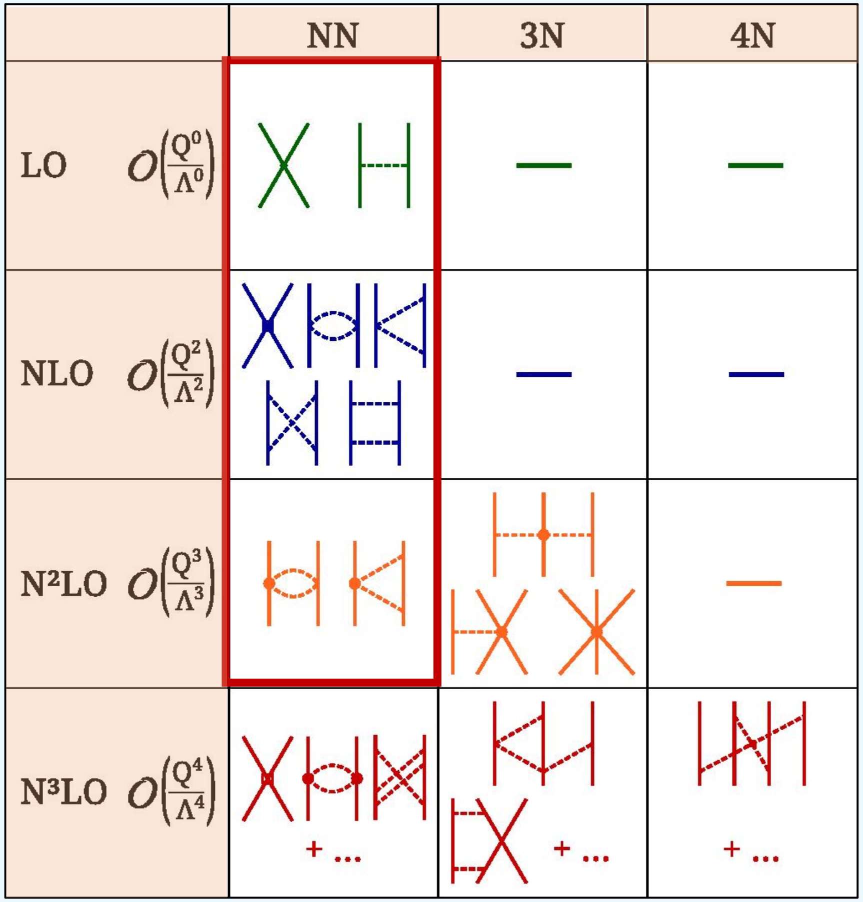
Local chiral interactions



Weinberg, van Kolck, Kaplan, Savage, Wise,
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- Choose local set of short-range operators at NLO (7 out of 14)
- Pion exchanges up to N^{2}LO are local
- This freedom can be used to remove all nonlocal operators up to N^{2}LO

  Gezerlis, IT, Epelbaum, Gandolfi, Hebeler, Nogga, Schwenk, PRL (2013)
  Gezerlis, IT, Epelbaum, Freunek, Gandolfi, Hebeler, Nogga, Schwenk, PRC (2014)
- LECs fit to phase shifts

Contact ambiguity: NN sector

- Contact potential at LO:

$$V_{\text{cont}}^{(0)} = C_{\mathbb{1}}\,\mathbb{1} + C_\sigma \sigma_{12} + C_\tau \tau_{12} + C_{\sigma\tau} \sigma_{12}\tau_{12}$$

- Construct antisymmetrized potential:

$$V_{\text{as}}(\mathbf{q},\mathbf{k}) = \frac{1}{2}\left(V(\mathbf{q},\mathbf{k}) - \mathcal{A}[V(\mathbf{q},\mathbf{k})]\right)$$

$$\mathcal{A}[V(\mathbf{q},\mathbf{k})] = \frac{1}{4}(1+\sigma_{12})(1+\tau_{12})V\left(\mathbf{q}\to -2\mathbf{k}, \mathbf{k}\to -\frac{1}{2}\mathbf{q}\right)$$

$$V_{\text{cont,as}}^{(0)} = \frac{1}{2}\left(1 - \frac{1}{4}(1+\sigma_{12})(1+\tau_{12})\right)V_{\text{cont}}^{(0)}$$

$$= \tilde{C}_S + \tilde{C}_T\sigma_{12} + \left(-\frac{2}{3}\tilde{C}_S - \tilde{C}_T\right)\tau_{12} + \left(-\frac{1}{3}\tilde{C}_S\right)\sigma_{12}\tau_{12}$$

- Only two linearly independent contact interactions!

Contact ambiguity: NN sector

True, only when regulator f behaves like

$$f(\mathbf{q},\mathbf{k}) = f\left(-2\mathbf{k}, -\frac{1}{2}\mathbf{q}\right)$$

but not for local regulator $f(\mathbf{q})$:

$$V^{(0,\mathrm{loc})}_{\mathrm{cont,as}} = \tilde{C}_S + \tilde{C}_T \sigma_{12} + \left(-\frac{2}{3}\tilde{C}_S - \tilde{C}_T\right)\tau_{12} + \left(-\frac{1}{3}\tilde{C}_S\right)\sigma_{12}\tau_{12} + V^{f}_{\mathrm{corr}}(\mathbf{p}\cdot\mathbf{p}')$$

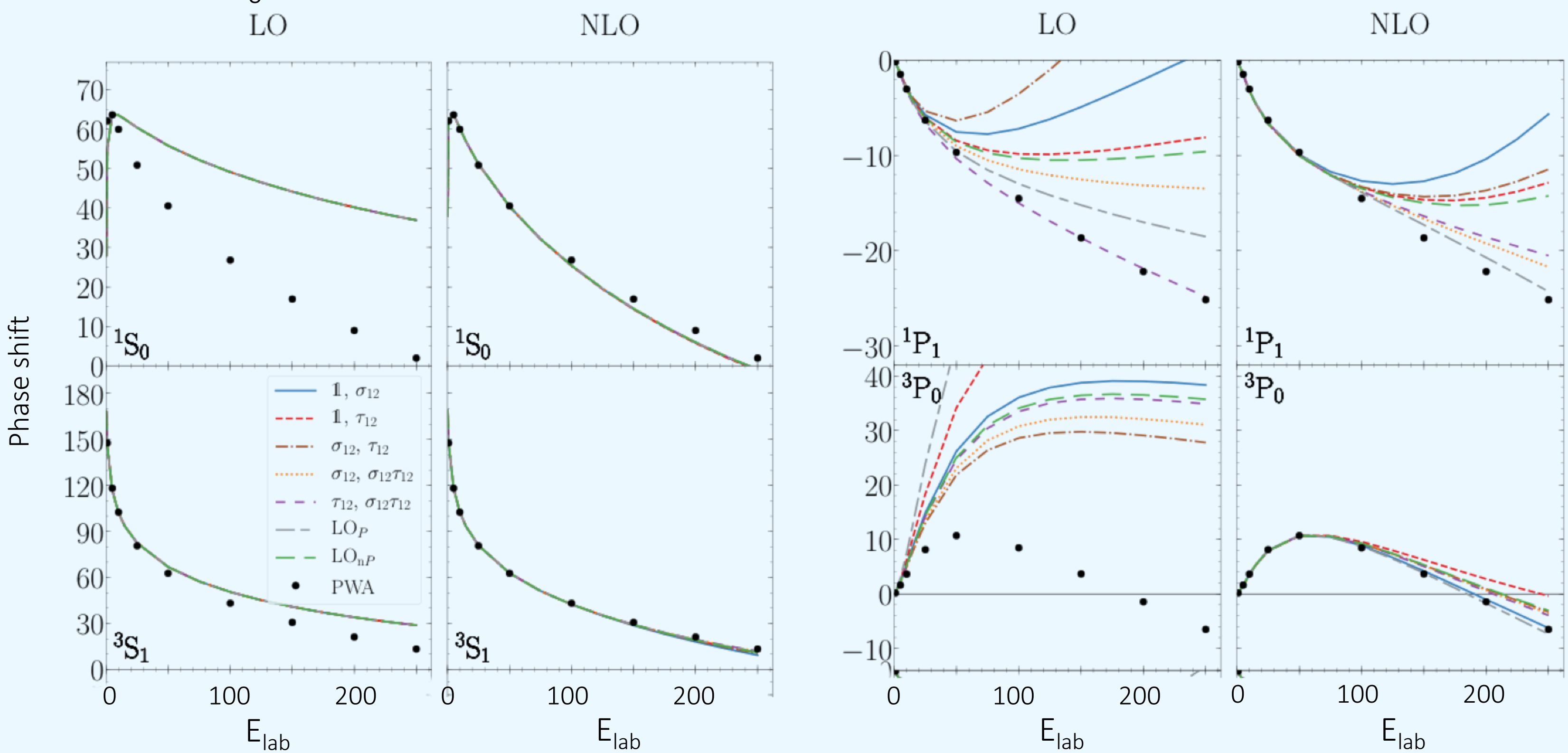
Manifestation of the fact that introducing a regulator function affects potential terms beyond the order at which one is working, and should be corrected at higher order.

But:

- Violation of Fierz ambiguity can lead to sizable contributions in 3N sector.
  Lynn, IT, et al., PRL (2016), Dyhdalo, Hebeler, Furnstahl, IT, PRC (2016)
- Leads to mixing of different partial waves.

Contact ambiguity: NN sector

Cutoff R_0 = 1.0 fm: Huth, IT, et al., PRC (2017)



- Violation of Fierz ambiguity sizable in the NN sector at LO but restored to a large extent by including subleading operators at NLO.
- In 3N sector, subleading corrections only at N^4LO.

Contact ambiguity: NN sector

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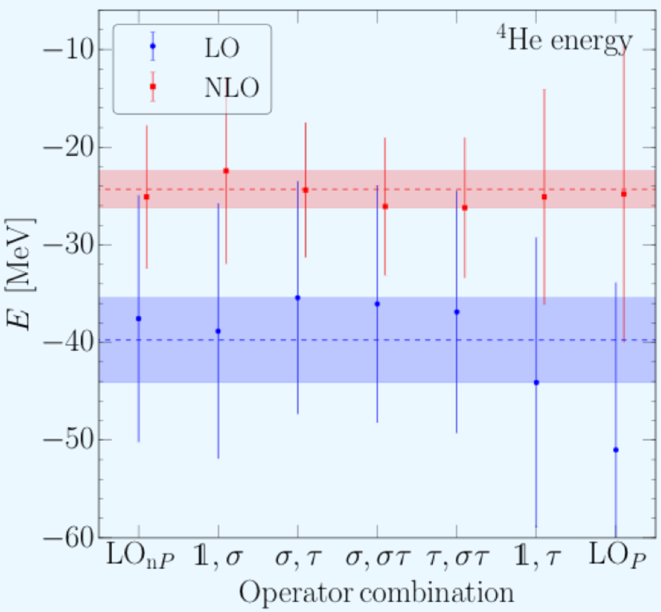

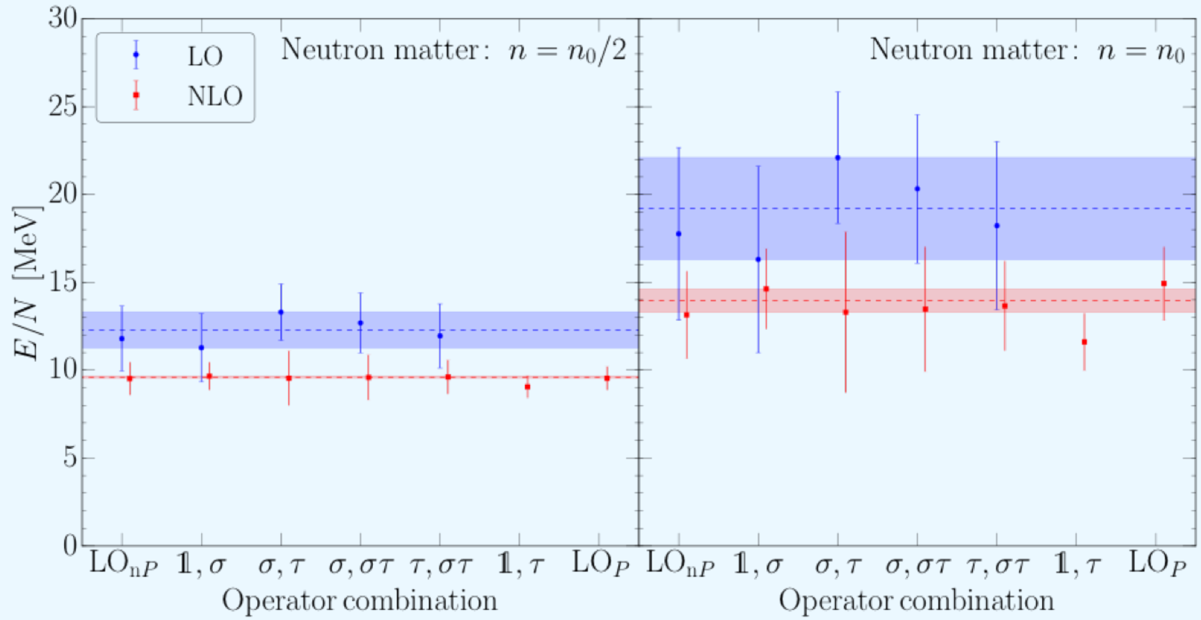

Huth, IT, et al., PRC (2017)

EKM uncertainty estimates.

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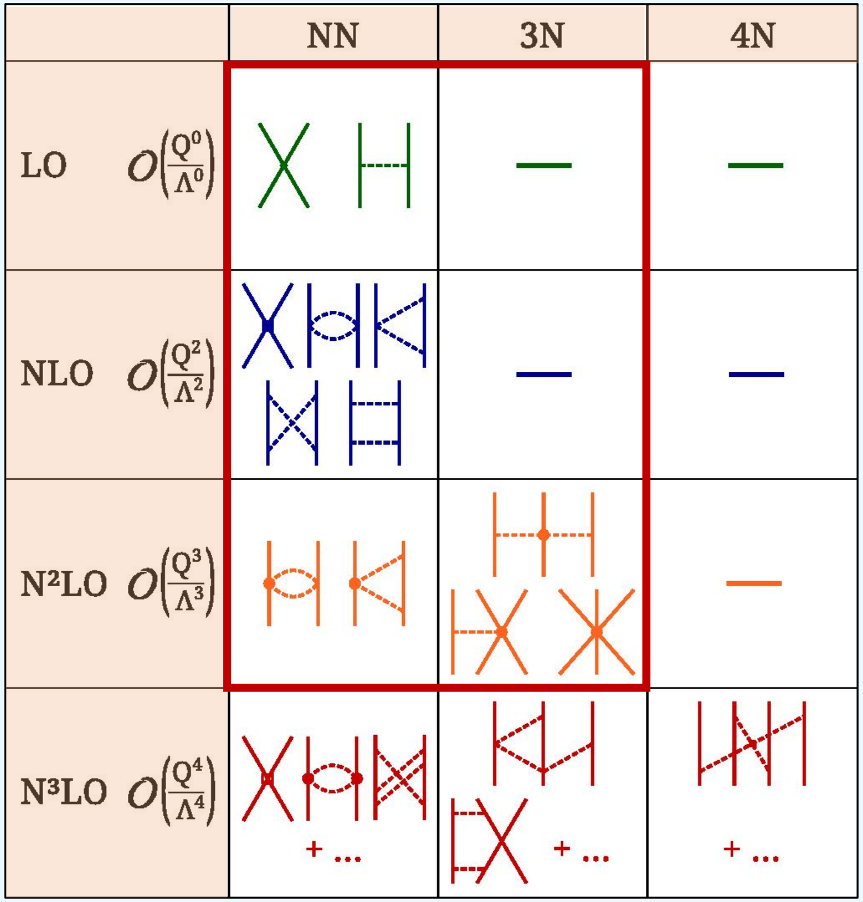
QMC with chiral 3N forces



Weinberg, van Kolck, Kaplan, Savage, Wise,
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- It is possible to remove all nonlocal operators up to N²LO
  Gezerlis, IT, Epelbaum, Gandolfi, Hebeler, Nogga, Schwenk, PRL (2013)
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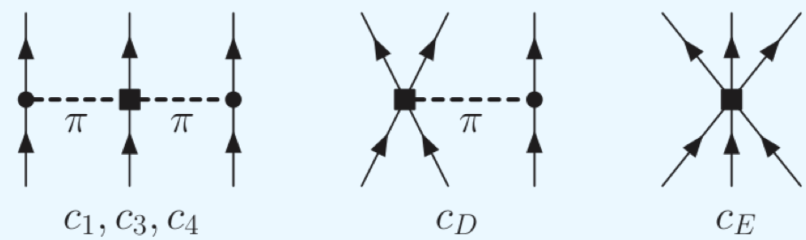
- Two-body LECs fit to phase shifts
- Include leading 3N forces:



3N LECS fit to uncorrelated observables:

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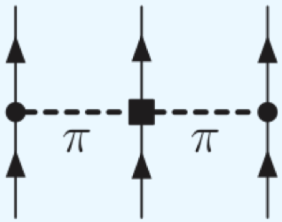
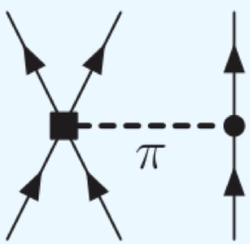
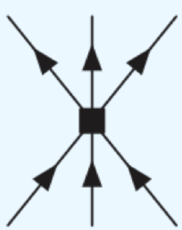
QMC with chiral 3N forces



c_1, c_3, c_4



c_D



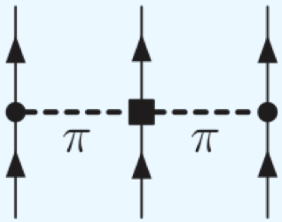
c_E

- Two-pion-exchange:
  - c_1 term: Tucson-Melbourn S-wave interaction
  - $c_{3,4}$ term: Fujita-Miyazawa interaction
- Usually only contribution to pure neutron matter.
- Usually V_D and V_E vanish in T=3/2 or S=3/2 systems:
  - V_D due to spin-isospin structure
  - V_E due to Pauli principle

  see also Hebeler, Schwenk, PRC (2010)
- Only true for regulator symmetric in particle labels like commonly used nonlocal regulators, not for local regulators!

local 3N, see also Navratil, Few Body Syst. (2007)

QMC with chiral 3N forces



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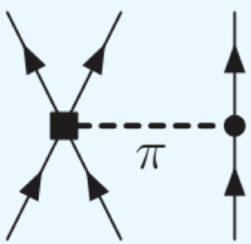
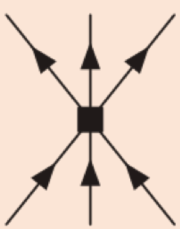


c_D



c_E

- For local regulator also V_E contributes to neutron matter:

$$V_E \sim c_E \sum_{i<j<k} \sum_{\text{cyc}} \mathcal{O}_{ijk}\, \delta_{R_{3N}}(r_{ij})\, \delta_{R_{3N}}(r_{kj})$$

- Fierz ambiguity:

$$\mathcal{O}_{ijk} = \{\mathbb{1},\, \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j,\, \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j,\, \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j,\, \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_k,\, [(\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j)\cdot\boldsymbol{\sigma}_k][(\boldsymbol{\tau}_i\times\boldsymbol{\tau}_j)\cdot\boldsymbol{\tau}_k]\}.$$

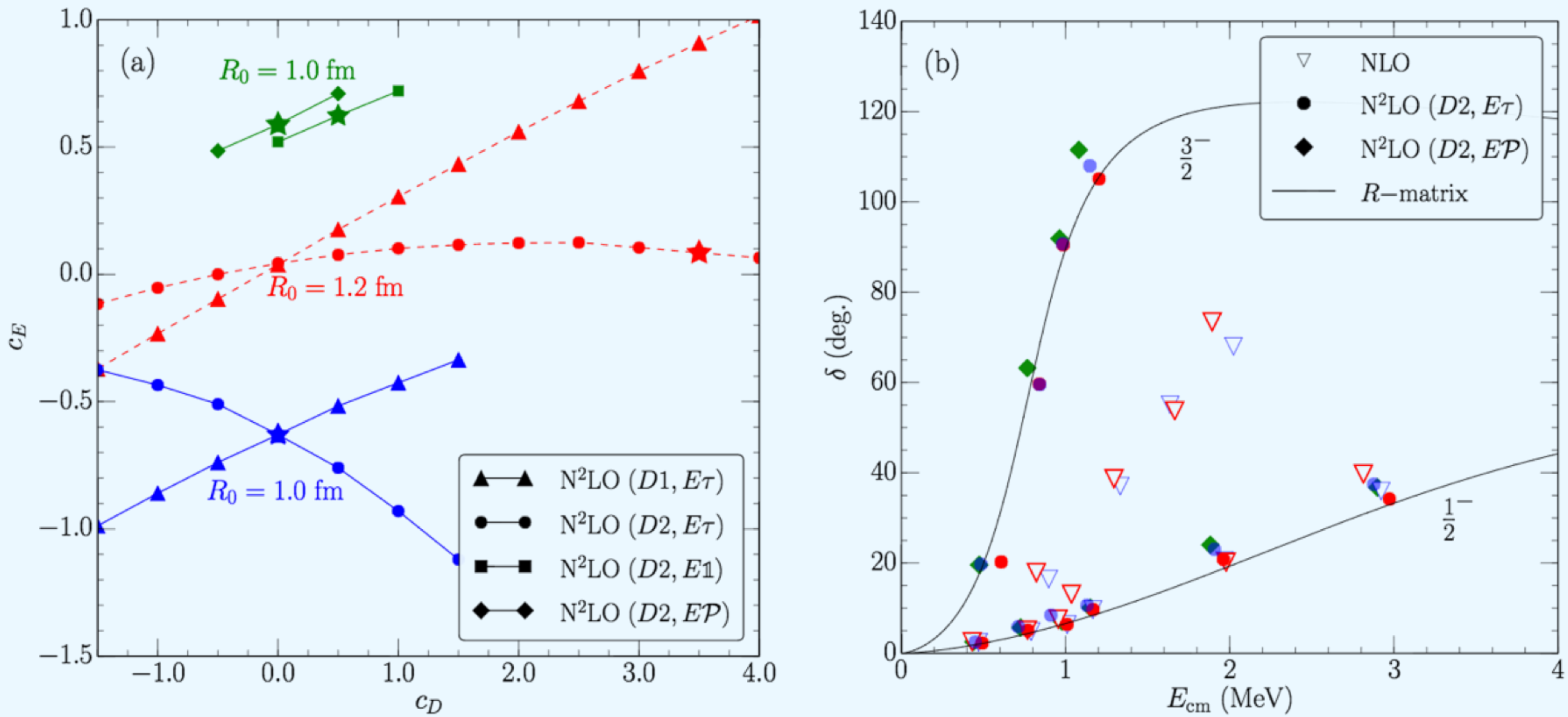
Epelbaum, Nogga, Gloeckle, Kamada, Meißner, Witala, PRC (2002)

- No Fierz rearrangement freedom for local regulators, choose different short-range structures to estimate the impact:

$$V_{E\tau} \sim \tau_i \cdot \tau_j$$
$$V_{E\mathbb{1}} \sim \mathbb{1}$$
$$V_{E\mathcal{P}} \sim \mathcal{P}_{S=1/2,\,T=1/2}$$

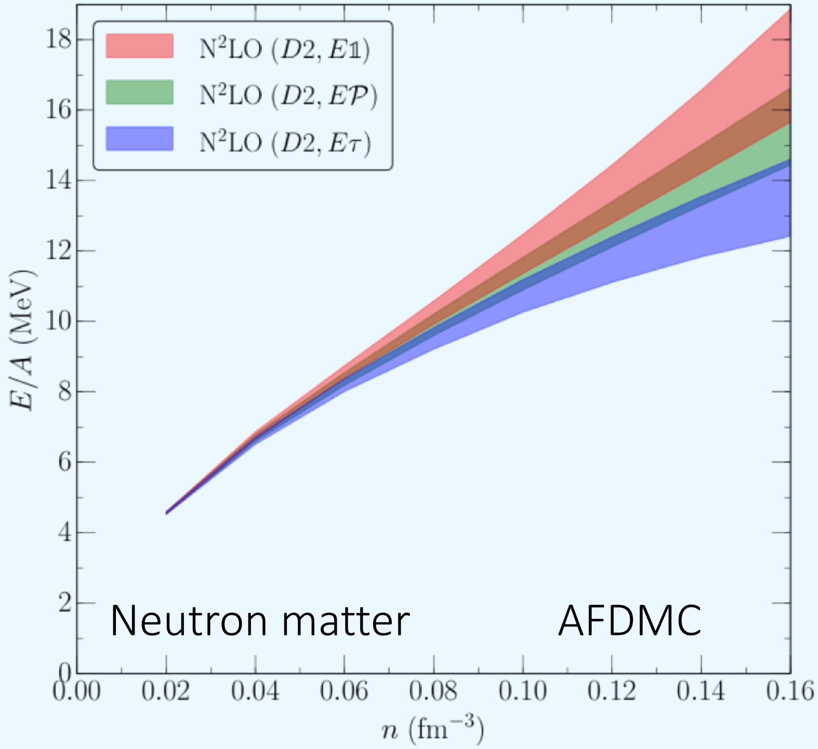
Fits of 3N LECs

- Fit c_E and c_D to ^{4}He binding energy and n-α scattering (A≤5)



Lynn, IT, et al., PRL (2016)

Results



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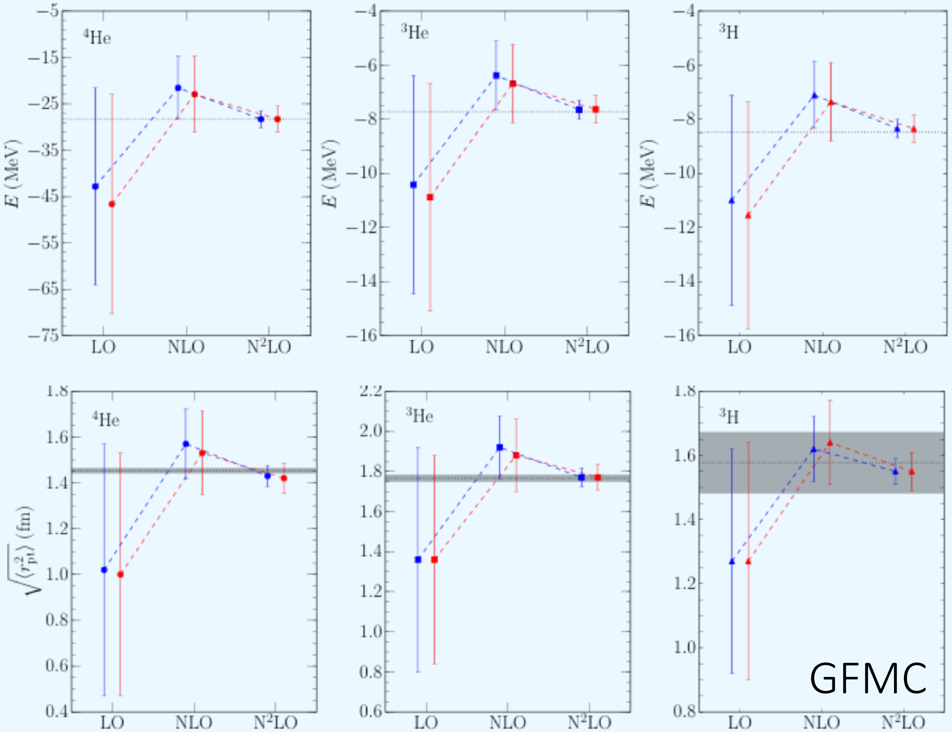

Lynn, IT, et al. PRC (2017)

- Chiral interactions at N^{2}LO simultaneously reproduce the properties of A≤5 systems and of neutron matter (uncertainty estimate as in E. Epelbaum et al, EPJ (2015)).
- Commonly used phenomenological 3N interactions fail for neutron matter. Sarsa, Fantoni, Schmidt, Pederiva, PRC (2003)

Results

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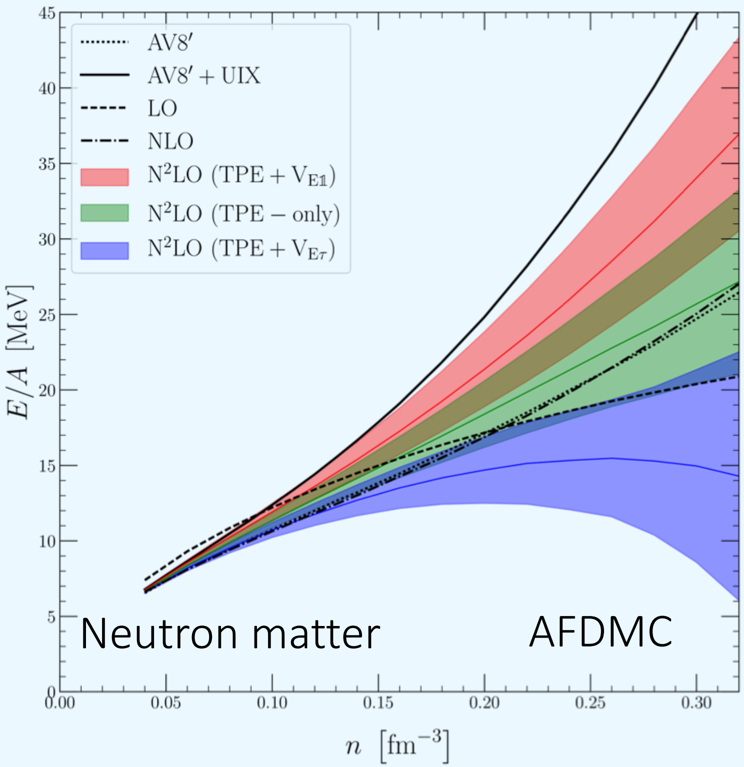
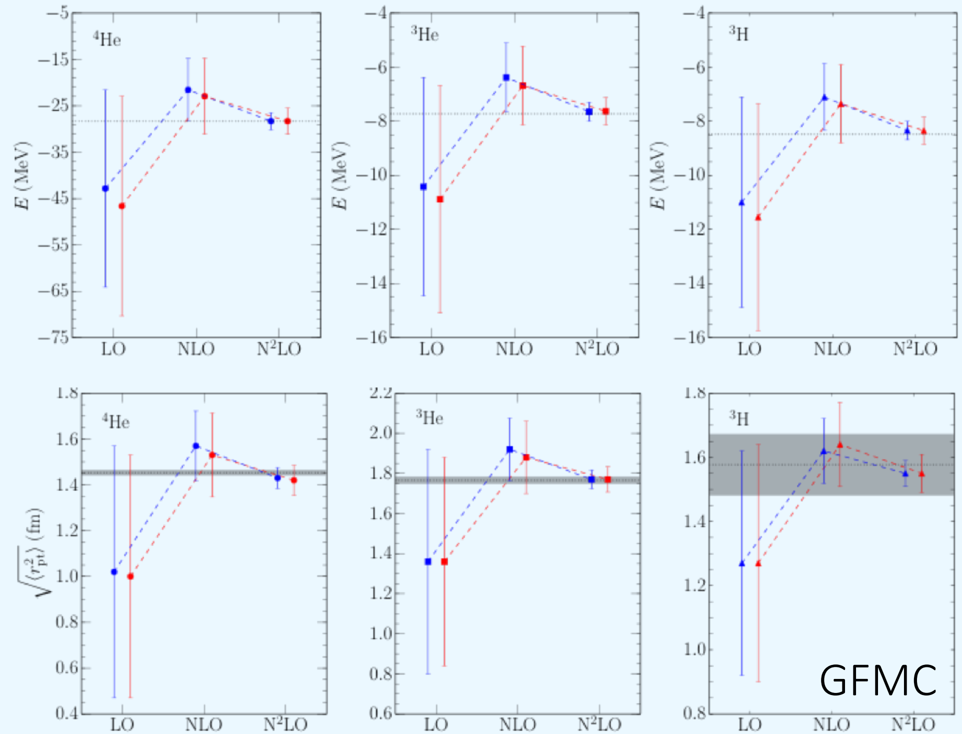


IT, Carlson, Gandolfi, Reddy, arXiv:1801.01923



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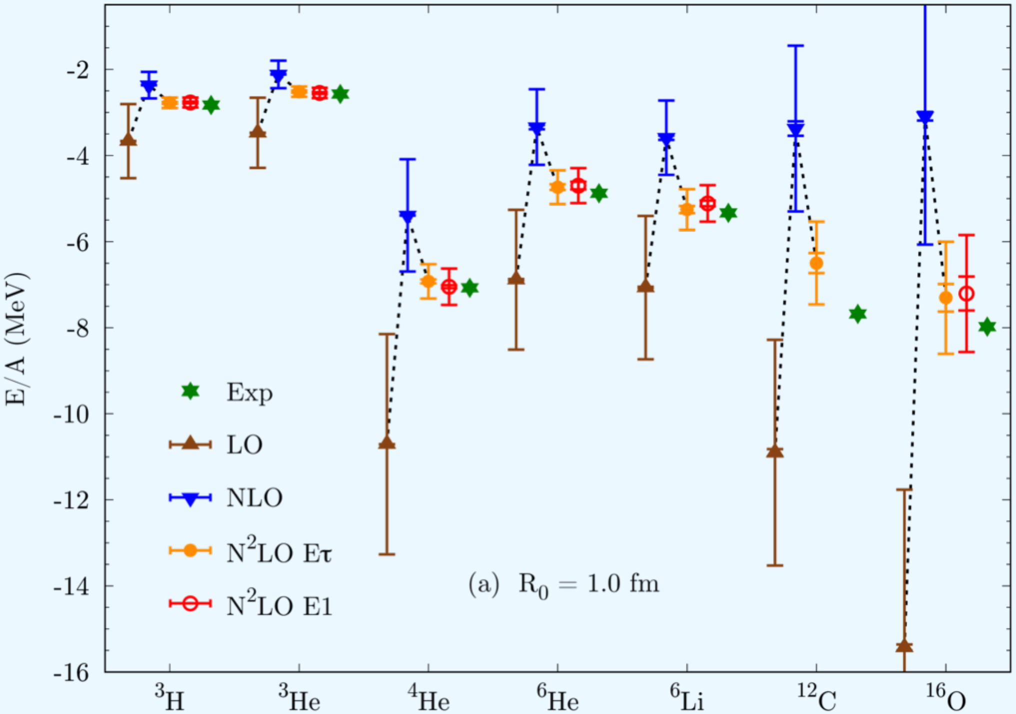
Results for heavier systems

Results for AFDMC calculations of heavier systems (R_0 = 1.0 fm):
(Using the same local chiral interactions)

Lonardoni et al., arXiv:1709.09143 and 1802.08932



$^A Z\,(J^\pi, T)$	Potential	E_C (MeV)	E (MeV)
^{6}He $(0^+, 1)$	LO	−42.1(1)	−41.3(1)(9.6)
	NLO	−18.19(7)	−20.0(3)(5.0)
	N^{2}LO *NN*	−22.24(4)	−23.1(2)(1.2)
	N^{2}LO 3*N* $E\tau$	−26.58(6)	−28.4(4)(2.0)
	N^{2}LO 3*N* $E\mathbb{1}$	−26.33(8)	−28.2(5)(1.9)
	exp		−29.3
^{6}Li $(1^+, 0)$	LO	−42.8(1)	−42.4(1)(9.9)
	NLO	−19.2(2)	−21.5(3)(4.9)
	N^{2}LO *NN*	−24.3(1)	−25.5(4)(1.1)
	N^{2}LO 3*N* $E\tau$	−28.9(1)	−31.5(5)(2.3)
	N^{2}LO 3*N* $E\mathbb{1}$	−28.9(1)	−30.7(4)(2.1)
	exp		−32.0
^{12}C $(0^+, 0)$	LO	−131.5(2)	−131(1)(31)
	NLO	−31.1(2)	−41(2)(21)
	N^{2}LO *NN*	−63.5(2.4)	−66(3)(6)
	N^{2}LO 3*N* $E\tau$	−70.2(5)	−78(3)(9)
	N^{2}LO 3*N* $E\mathbb{1}$	–	–
	exp		−92.2
^{16}O $(0^+, 0)$	LO	−251.7(2)	−247(1)(58)
	NLO	−37.3(2)	−49(2)(46)
	N^{2}LO *NN*	−72.8(2)	−87(3)(11)
	N^{2}LO 3*N* $E\tau$	−91.8(6)	−117(5)(16)
	N^{2}LO 3*N* $E\mathbb{1}$	−85.8(5)	−115(6)(15)
	exp		−127.6

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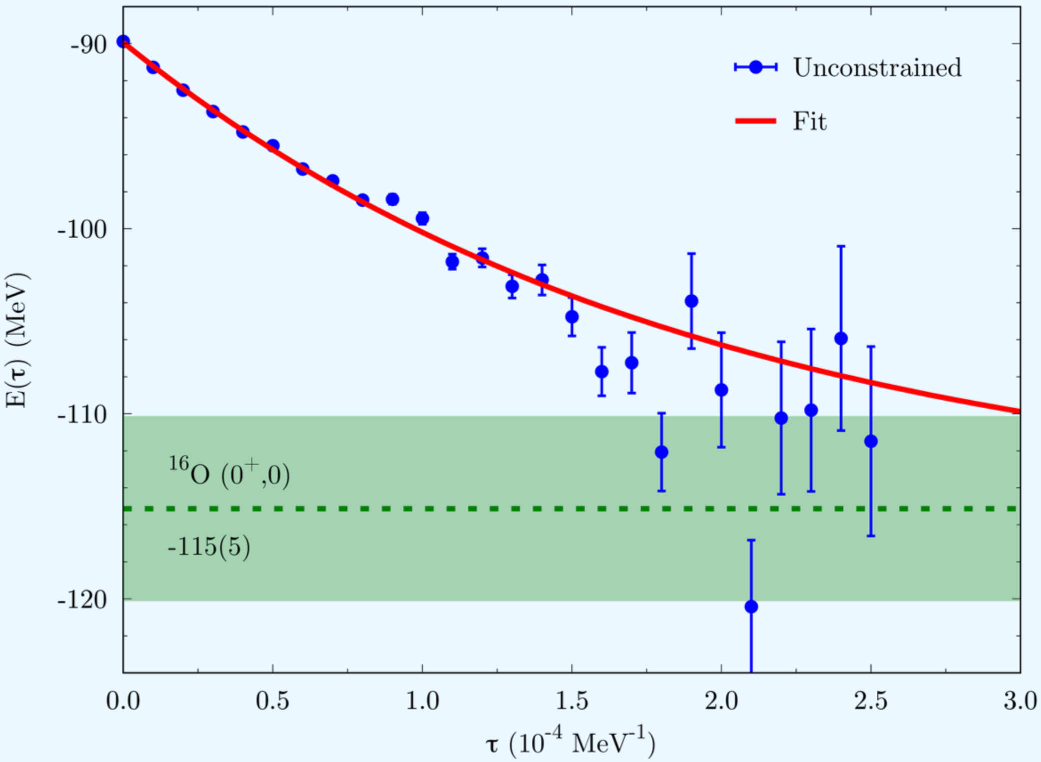
Lonardoni et al., arXiv:1709.09143 and 1802.08932

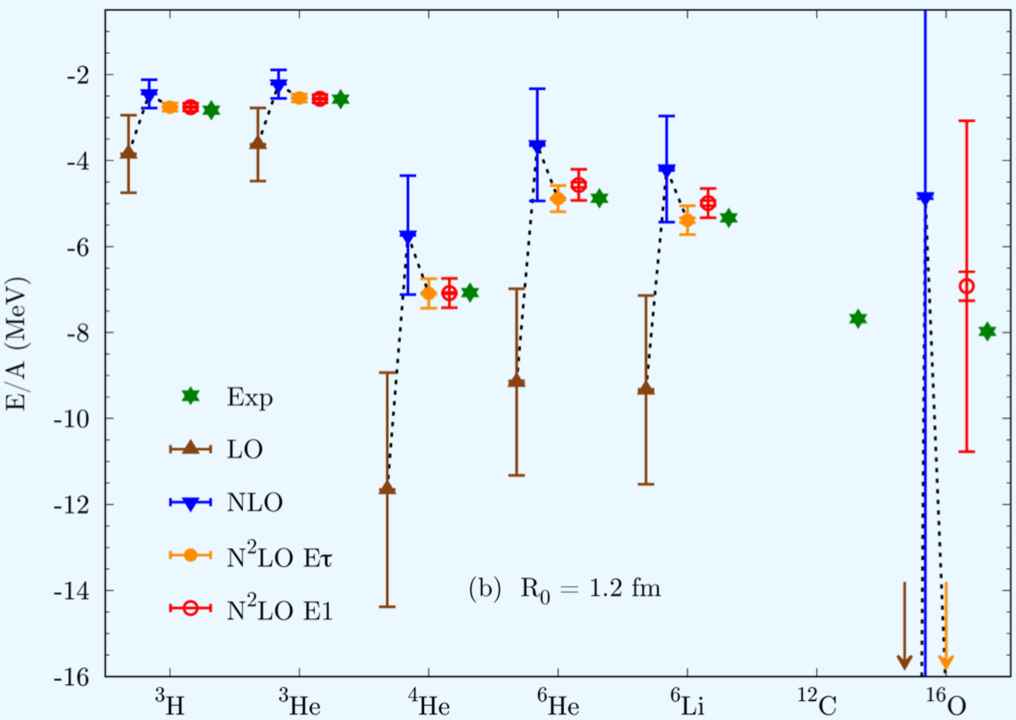


$^{A}Z\,(J^\pi, T)$	Potential	E_C (MeV)	E (MeV)
^{6}He $(0^+, 1)$	LO	−42.1(1)	−41.3(1)(9.6)
	NLO	−18.19(7)	−20.0(3)(5.0)
	N^{2}LO *NN*	−22.24(4)	−23.1(2)(1.2)
	N^{2}LO 3*N* $E\tau$	−26.58(6)	−28.4(4)(2.0)
	N^{2}LO 3*N* $E\mathbb{1}$	−26.33(8)	−28.2(5)(1.9)
	exp		−29.3
^{6}Li $(1^+, 0)$	LO	−42.8(1)	−42.4(1)(9.9)
	NLO	−19.2(2)	−21.5(3)(4.9)
	N^{2}LO *NN*	−24.3(1)	−25.5(4)(1.1)
	N^{2}LO 3*N* $E\tau$	−28.9(1)	−31.5(5)(2.3)
	N^{2}LO 3*N* $E\mathbb{1}$	−28.9(1)	−30.7(4)(2.1)
	exp		−32.0
^{12}C $(0^+, 0)$	LO	−131.5(2)	−131(1)(31)
	NLO	−31.1(2)	−41(2)(21)
	N^{2}LO *NN*	−63.5(2.4)	−66(3)(6)
	N^{2}LO 3*N* $E\tau$	−70.2(5)	−78(3)(9)
	N^{2}LO 3*N* $E\mathbb{1}$	−	−
	exp		−92.2
^{16}O $(0^+, 0)$	LO	−251.7(2)	−247(1)(58)
	NLO	−37.3(2)	−49(2)(46)
	N^{2}LO *NN*	−72.8(2)	−87(3)(11)
	N^{2}LO 3*N* $E\tau$	−91.8(6)	−117(5)(16)
	N^{2}LO 3*N* $E\mathbb{1}$	−85.8(5)	−115(6)(15)
	exp		−127.6

Results for heavier systems

Results for AFDMC calculations of heavier systems (R_0 = 1.2 fm):
(Using the same local chiral interactions)

Lonardoni et al., arXiv:1709.09143 and 1802.08932



${}^{A}Z\,(J^\pi, T)$	Potential	E_C (MeV)	E (MeV)
^{6}He $(0^+, 1)$	LO	$-55.65(6)$	$-54.9(2)(12.8)$
	NLO	$-21.41(6)$	$-21.8(1)(7.7)$
	N^{2}LO NN	$-24.25(5)$	$-24.3(1)(1.8)$
	N^{2}LO $E\tau$	$-28.37(5)$	$-29.3(1)(1.8)$
	N^{2}LO $E\mathbb{1}$	$-26.98(8)$	$-27.4(4)(1.8)$
	exp		-29.3
^{6}Li $(1^+, 0)$	LO	$-56.84(3)$	$-56.0(1)(13.1)$
	NLO	$-23.64(8)$	$-25.2(2)(7.2)$
	N^{2}LO NN	$-26.76(3)$	$-27.0(2)(1.7)$
	N^{2}LO $E\tau$	$-30.8(1)$	$-32.3(3)(1.7)$
	N^{2}LO $E\mathbb{1}$	$-29.2(1)$	$-29.9(4)(1.7)$
	exp		-32.0
^{16}O $(0^+, 0)$	LO	$-1158.8(5)$	$-1110(31)(259)$
	NLO	$-72.3(1)$	$-77.5(7)(240.8)$
	N^{2}LO NN	$-98.6(1)$	$-106(4)(56)$
	N^{2}LO $E\tau$	$-169(2)$	$-263(26)(56)$
	N^{2}LO $E\mathbb{1}$	$-99.5(4)$	$-111(5)(56)$
	exp		-127.6

Results for heavier systems

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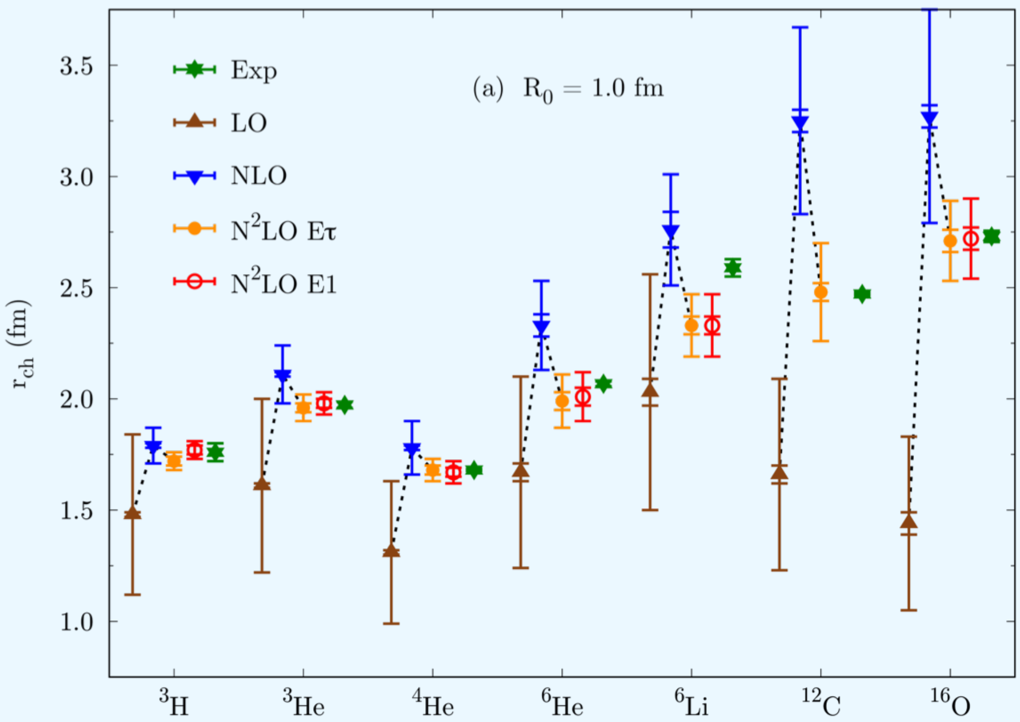
Results for AFDMC calculations of heavier systems (R_0 = 1.0 fm):
(Using the same local chiral interactions)

Lonardoni et al., arXiv:1709.09143 and 1802.08932



$^AZ\,(J^\pi, T)$	Potential	r_{ch} (fm)
^{6}He $(0^+, 1)$	LO	1.67(4)(39)
	NLO	2.33(5)(15)
	N^{2}LO NN	2.11(4)(5)
	N^{2}LO $3N$ $E\tau$	1.99(4)(8)
	N^{2}LO $3N$ $E\mathbb{1}$	2.01(4)(7)
	exp	2.068(11) [52]
^{6}Li $(1^+, 0)$	LO	2.03(6)(47)
	NLO	2.76(8)(17)
	N^{2}LO NN	2.46(4)(7)
	N^{2}LO $3N$ $E\tau$	2.33(4)(10)
	N^{2}LO $3N$ $E\mathbb{1}$	2.33(4)(10)
	exp	2.589(39) [53]
^{12}C $(0^+, 0)$	LO	1.66(4)(39)
	NLO	3.25(5)(37)
	N^{2}LO NN	2.66(4)(14)
	N^{2}LO $3N$ $E\tau$	2.48(4)(18)
	N^{2}LO $3N$ $E\mathbb{1}$	—
	exp	2.471(6) [54]
^{16}O $(0^+, 0)$	LO	1.44(3)(34)
	NLO	3.27(5)(43)
	N^{2}LO NN	2.76(5)(12)
	N^{2}LO $3N$ $E\tau$	2.71(5)(13)
	N^{2}LO $3N$ $E\mathbb{1}$	2.72(5)(11)
	exp	2.730(25) [55]

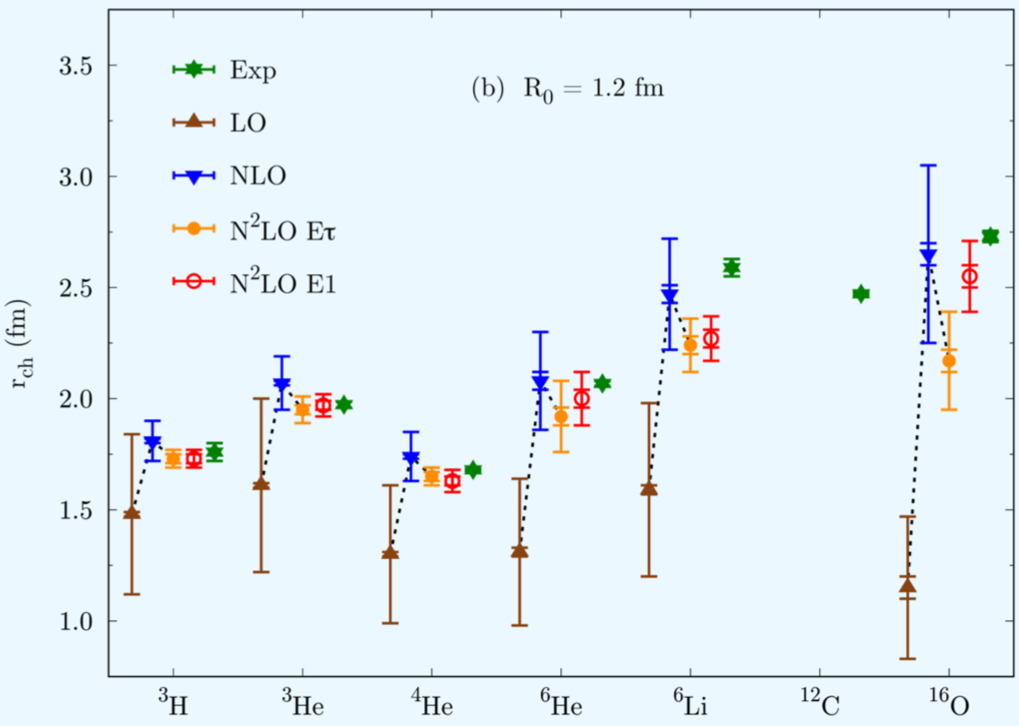
Excellent description of binding energies and charge radii for A ≤16!

Results for heavier systems

INSTITUTE for NUCLEAR THEORY

Results for AFDMC calculations of heavier systems (R_0 = 1.2 fm):
(Using the same local chiral interactions)

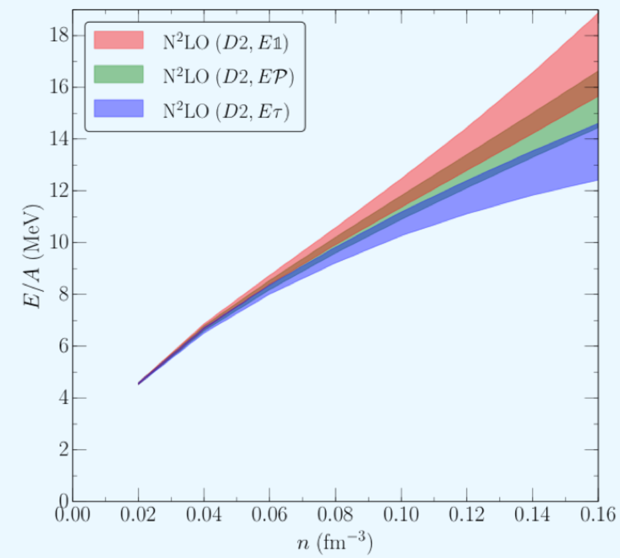
Lonardoni et al., arXiv:1709.09143 and 1802.08932

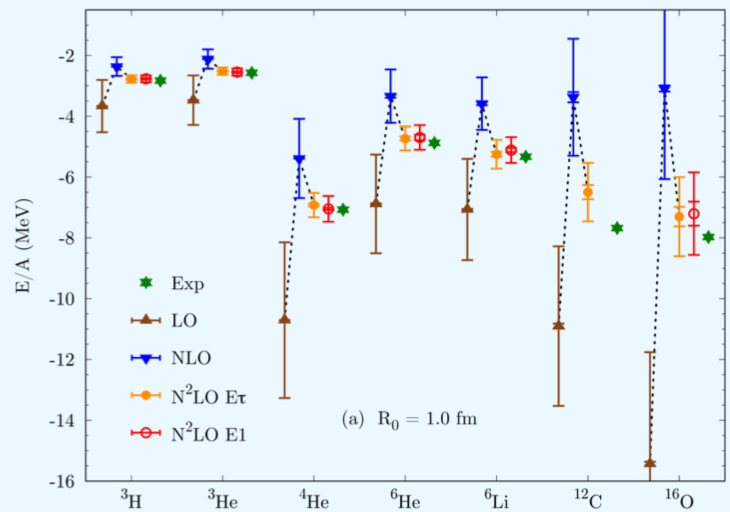


${}^{A}Z\,(J^{\pi},T)$	Potential	r_{ch} (fm)
^{6}He $(0^+,1)$	LO	1.31(2)(31)
	NLO	2.08(4)(18)
	N^{2}LO *NN*	2.02(4)(4)
	N^{2}LO $E\tau$	1.92(4)(4)
	N^{2}LO $E\mathbb{1}$	2.00(4)(4)
	exp	2.068(11) [52]
^{6}Li $(1^+,0)$	LO	1.59(2)(37)
	NLO	2.47(4)(21)
	N^{2}LO *NN*	2.41(4)(5)
	N^{2}LO $E\tau$	2.24(4)(6)
	N^{2}LO $E\mathbb{1}$	2.29(4)(5)
	exp	2.589(39) [53]
^{16}O $(0^+,0)$	LO	1.15(5)(27)
	NLO	2.65(5)(35)
	N^{2}LO *NN*	2.47(5)(8)
	N^{2}LO $E\tau$	2.17(5)(11)
	N^{2}LO $E\mathbb{1}$	2.55(5)(8)
	exp	2.730(25) [55]

Summary

- QMC calculations of neutron matter, light nuclei, and n-alpha scattering with local chiral potentials up to N^2LO including NN and 3N forces.
- QMC methods offer access to harder chiral interactions.
- Chiral interactions a t N^2LO simultaneously reproduce the properties of A≤ 16 systems and of neutron matter, commonly used phenomenological 3N interactions fail. Extension to heavier, neutron-rich systems possible.
- Important regulator effects for local interactions.
- Further improvements necessary to reduce uncertainties .





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