Quantum Monte Carlo calculations of the equation of state of neutron matter with chiral EFT interactions

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Extracting Bulk Properties of Neutron-Rich Matter with Transport Models in Bayesian Perspective,
April 4th, 2017, FRIB-MSU, East Lansing

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Outline

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- Motivation

- Chiral effective field theory e.g. Epelbaum *et al.*, PPNP (2006) and RMP (2009)
  - Systematic basis for nuclear forces, naturally includes many-body forces
  - Very successful in calculations of nuclei and nuclear matter

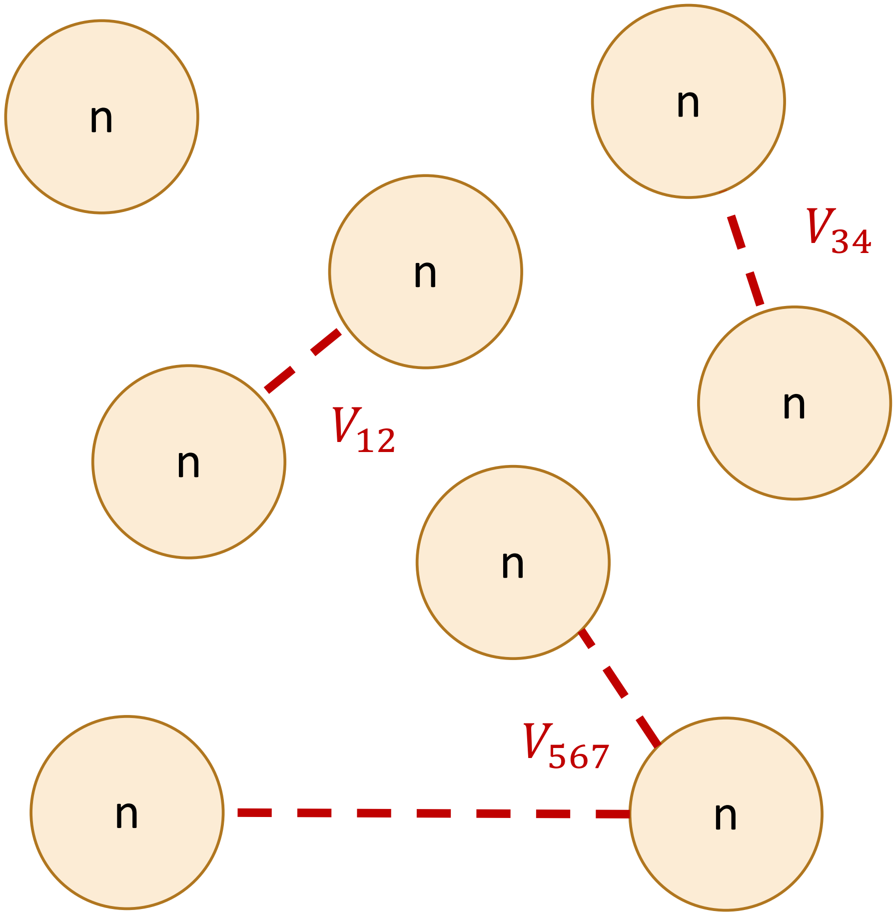
- Quantum Monte Carlo method
  - Very precise for strongly interacting systems
  - Need of local interactions (depend only on $r = |\mathbf{r}_i - \mathbf{r}_j|$)

- Local chiral interactions Gezerlis, IT, et al., PRL & PRC (2013, 2014, 2016)
  - Can be constructed up to N^2LO

- Results for neutron matter, light nuclei, and n-alpha scattering

- S and L constraints from lower bound of neutron matter

Motivation



To obtain the equation of state we need:

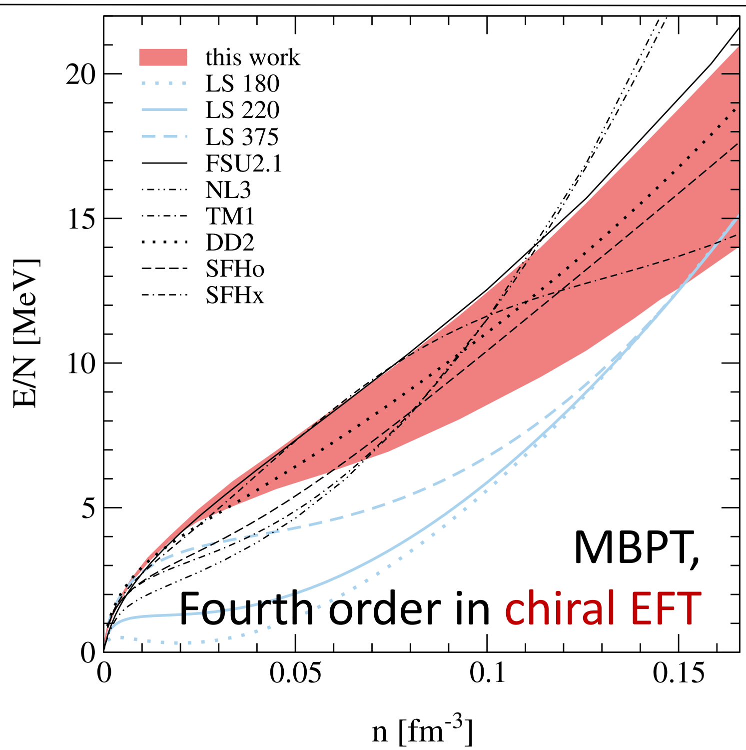
- ❑ A theory for the strong interactions among nucleons

  → Phenomenological forces or Chiral EFT

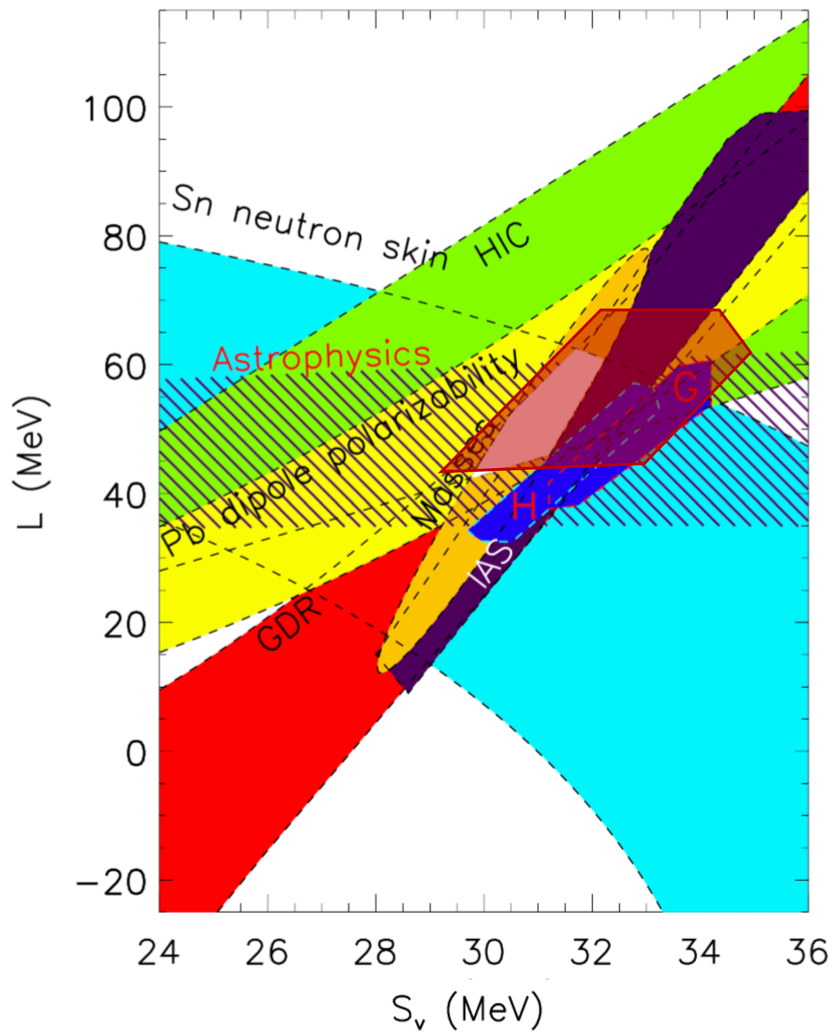
- ❑ An ab initio method to solve the many-body Schrödinger equation

  → Many-body Pert. Theory (MBPT), Quantum Monte Carlo (QMC), Coupled Cluster, …

Motivation



IT, Krüger, Hebeler, Schwenk (2013)



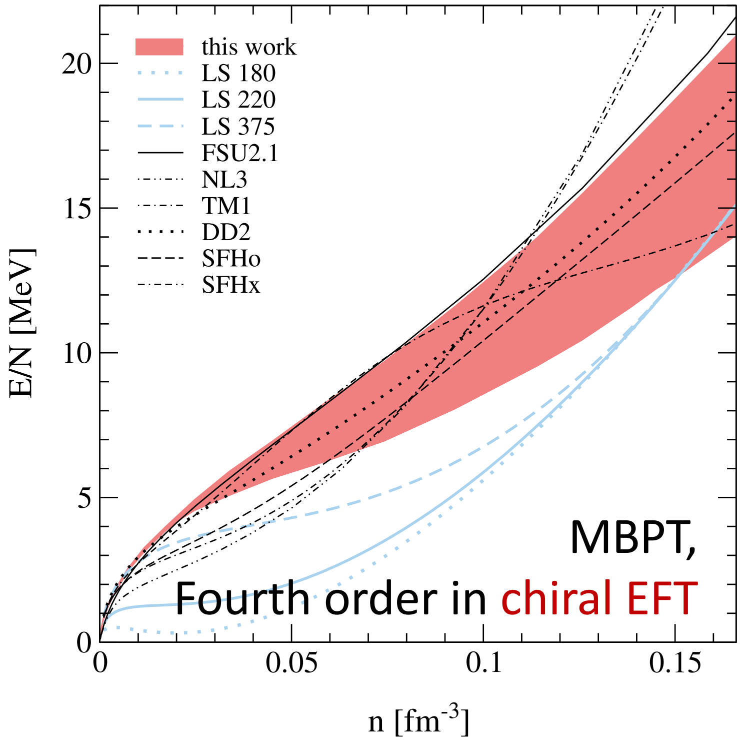
Lattimer, Lim, ApJ (2013)

Put constraints on symmetry energy and its density dependence L:

- $S_V = 28.9 - 34.9$ MeV
- $L = 43.0 - 66.6$ MeV

Good agreement with experimental constraints

Motivation



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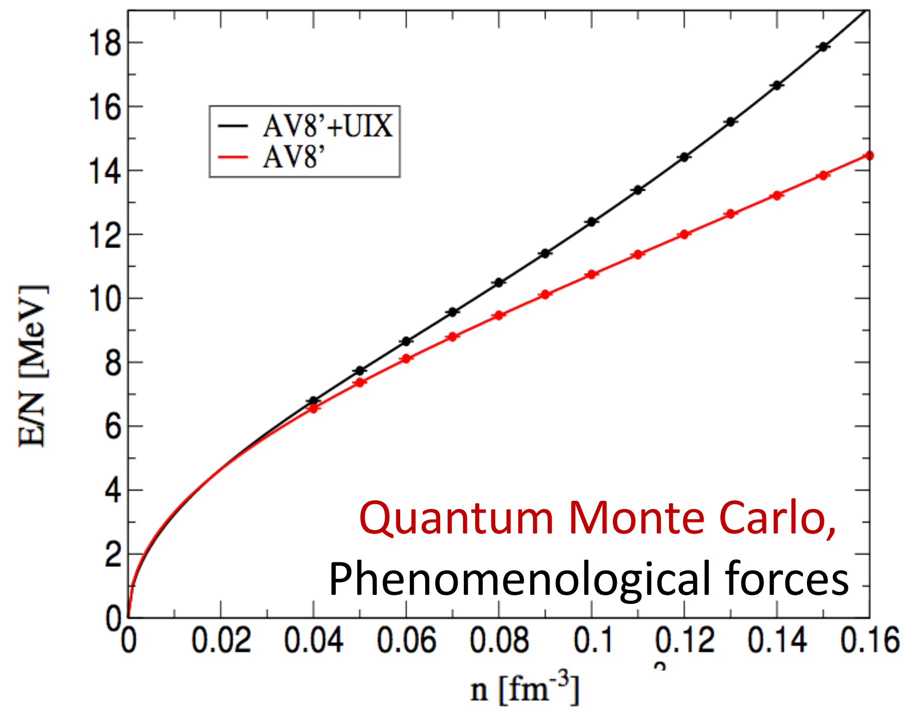


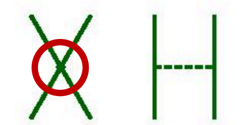
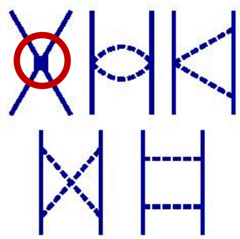
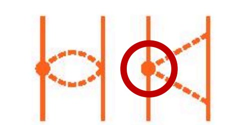
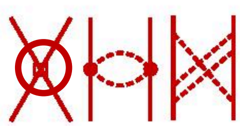
Credit: Stefano Gandolfi

Status:

- Sizeable uncertainty for chiral EFT calculations of neutron matter
- Quantum Monte Carlo: very precise method for strongly interacting systems
- Phenomenological interactions provide a good description of light nuclei and nuclear matter, but it is not clear how to systematically improve their quality, no uncertainty estimates

- QMC calculations with local chiral EFT interactions

Chiral effective field theory for nuclear forces

	NN	
LO $O\left(\frac{Q^0}{\Lambda^0}\right)$		2 LECs
NLO $O\left(\frac{Q^2}{\Lambda^2}\right)$		7 LECs
N²LO $O\left(\frac{Q^3}{\Lambda^3}\right)$		
N³LO $O\left(\frac{Q^4}{\Lambda^4}\right)$	 + ...	15 LECs

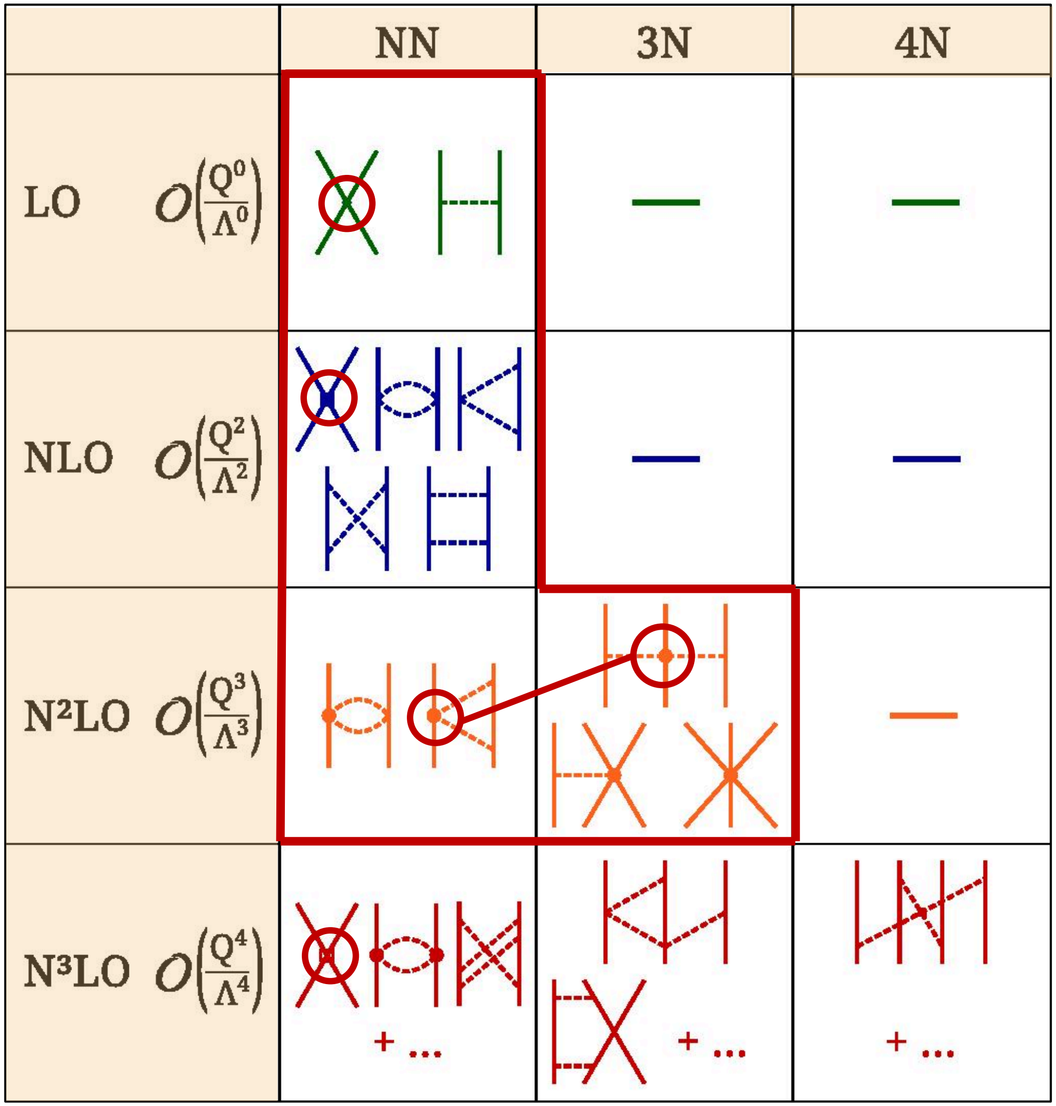
Systematic expansion of nuclear forces in low momenta Q over breakdown scale Λ_b:

- Pions and nucleons as explicit degrees of freedom
- Long-range physics explicit, short-range physics expanded in general operator basis, couplings (LECs) fit to experiment
- Separation of scales:

  Expand in powers of $\left(\frac{Q}{\Lambda_b}\right)^\nu \sim \left(\frac{1}{3}\right)^\nu$
- Power counting scheme
- Can work to desired accuracy with systematic error estimates

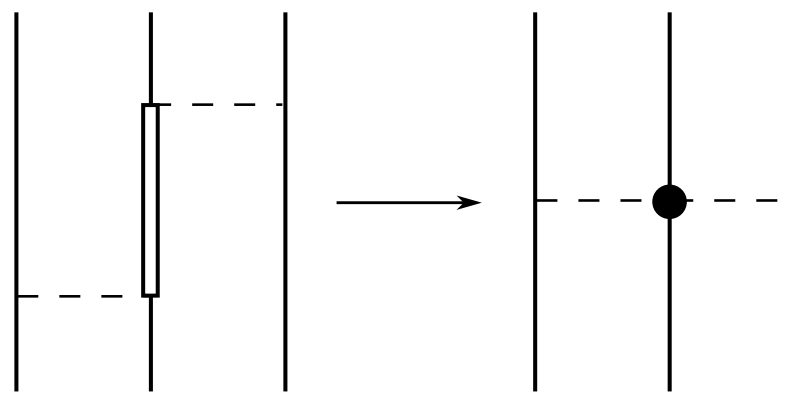
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer ...

Chiral effective field theory for nuclear forces



Many-body forces:

- Crucial for nuclear physics
- Natural hierarchy of nuclear forces
- Fitting: NN forces in NN system (NN phase shifts), 3N forces in 3N/4N system (Binding energies, radii)
- Consistent interactions: Same couplings for two-nucleon and many-body sector



Quantum Monte Carlo method

Solve the many-body Schrödinger equation

$$H|\psi\rangle = -\frac{\partial}{\partial\tau}|\psi\rangle\,, \qquad \tau = it$$

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

Basic steps:

- Choose trial wavefunction which overlaps with the ground state

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

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

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

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

Quantum Monte Carlo method

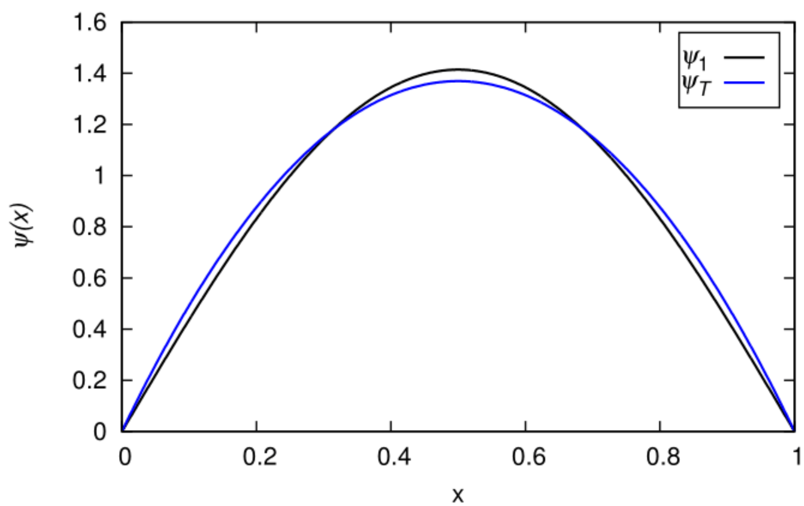
Particle in a 1D box, solution:

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

Basic steps:

- Choose parabolic trial wavefunction which overlaps with the ground state

Animation by Joel Lynn, TU Darmstadt



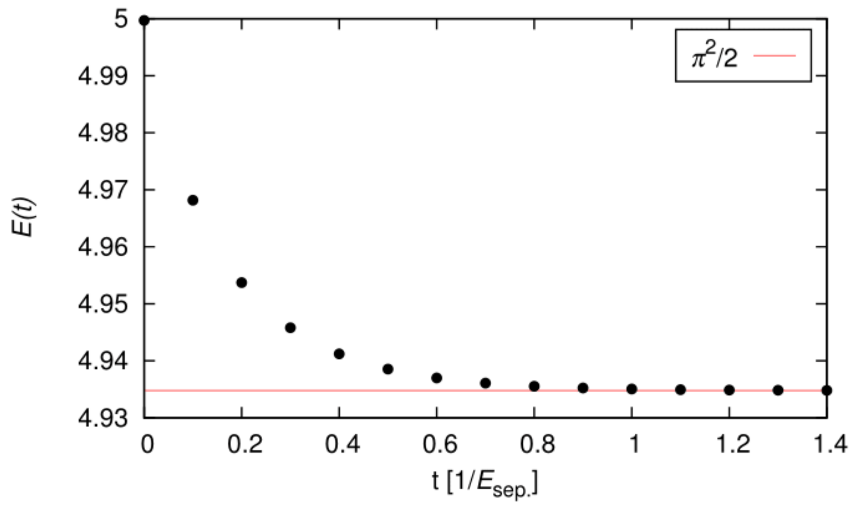
Quantum Monte Carlo method

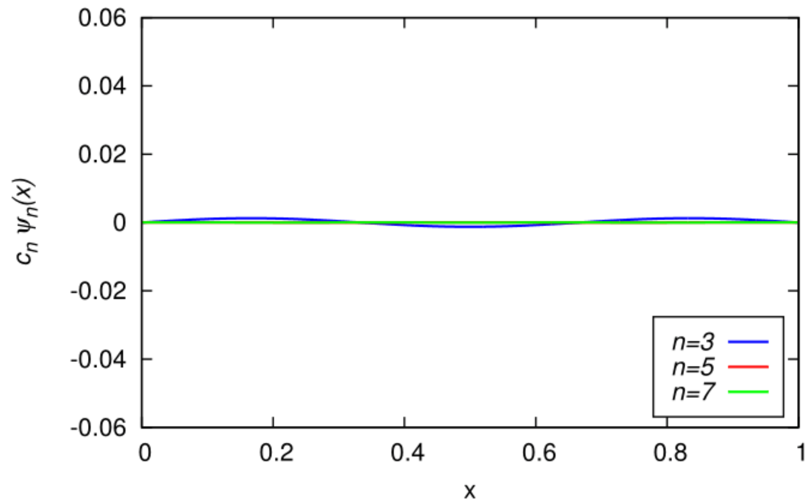
Particle in a 1D box, solution:

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

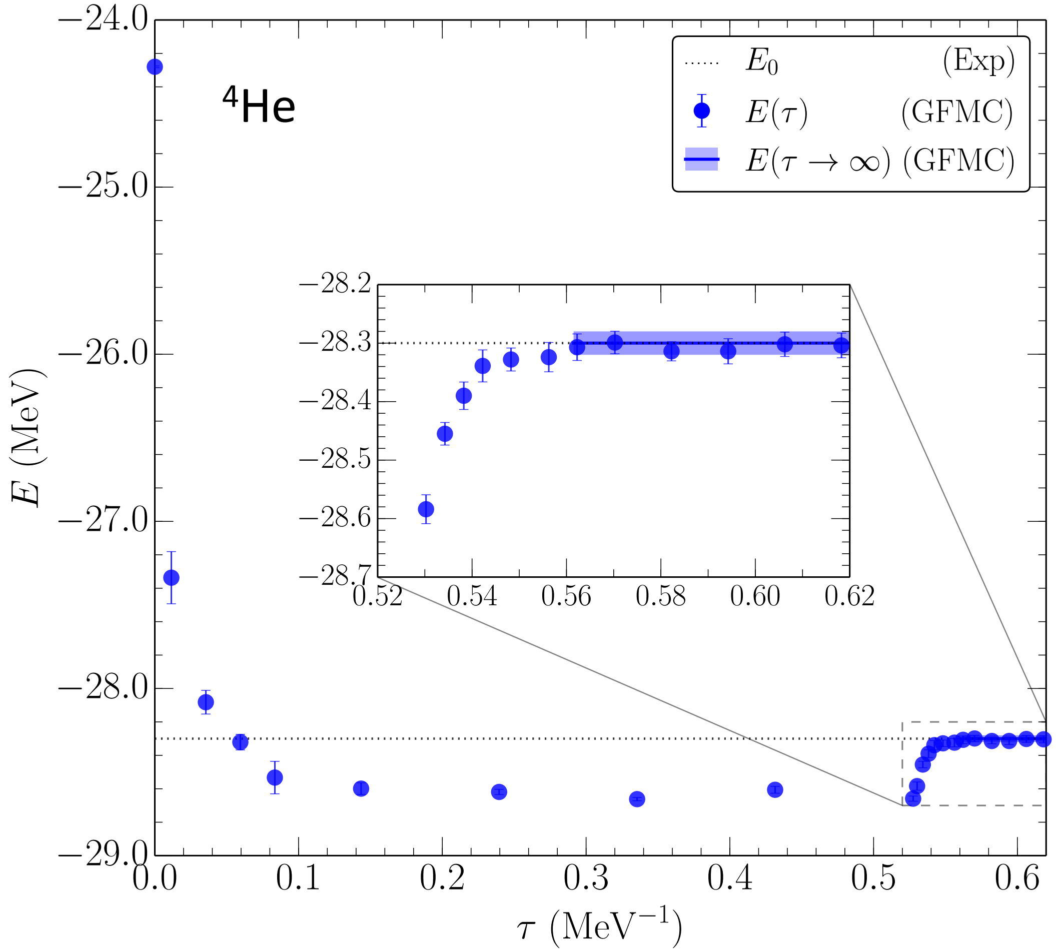
- Make consecutive small timesteps, $\tau = 1.4\left(\frac{1}{E_{\text{sep}}}\right)$

Animation by Joel Lynn, TU Darmstadt



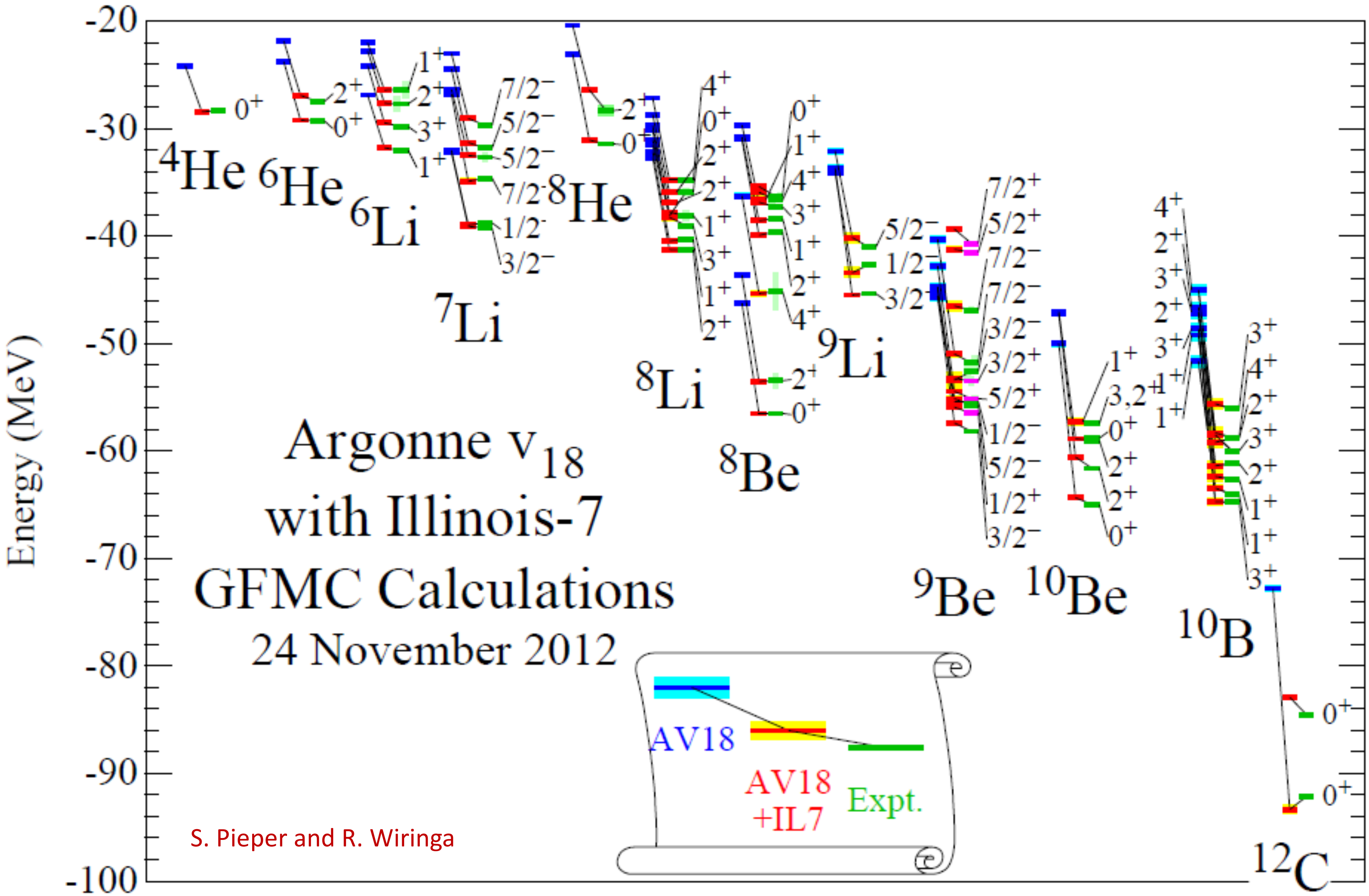


Quantum Monte Carlo method



Lynn, IT, Carlson, Gandolfi, Gezerlis, Schmidt, Schwenk, in preparation.

Quantum Monte Carlo method



Local chiral interactions

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

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

Chiral Effective Field Theory interactions generally nonlocal:

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

Sources of nonlocalities:

- Usual regulator in relative momenta

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

- k-dependent contact operators

Solutions:

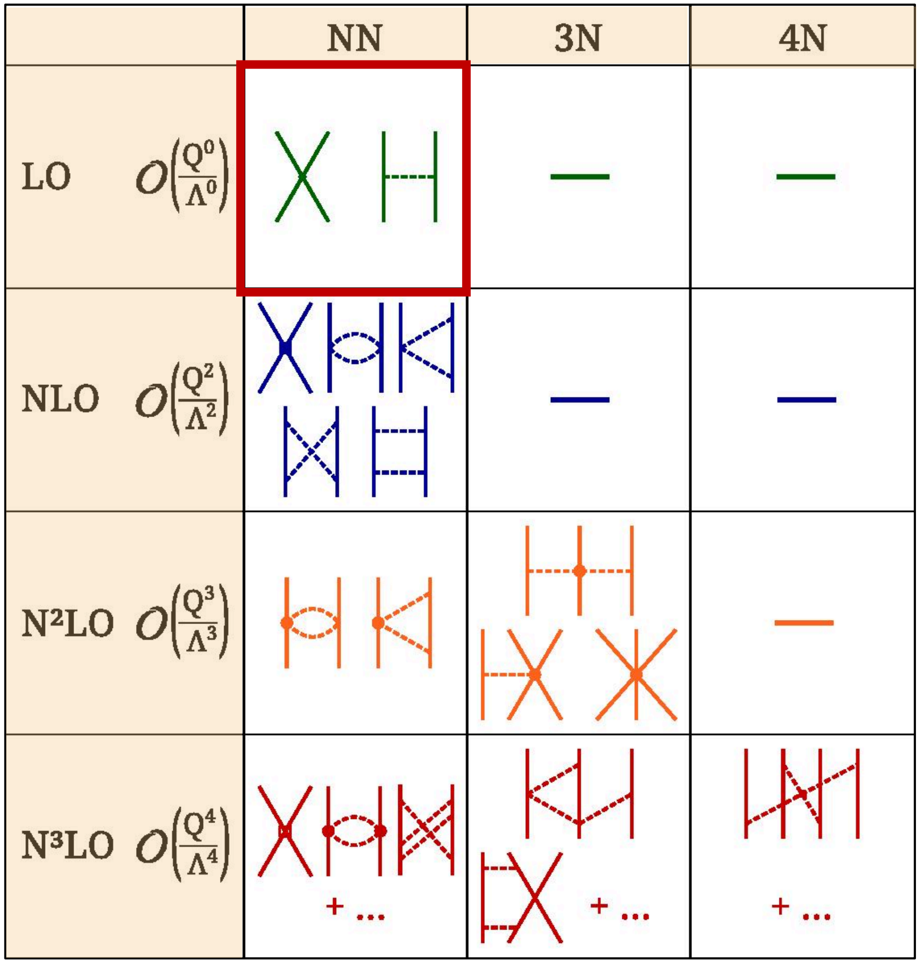
- Choose local regulators:

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

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

- 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 $V^{(0)} = V^{(0)}_{\text{cont}} + V^{\text{OPE}}$
- Pion exchange local → local regulator

$$f_{\text{long}}(r) = 1 - \exp(-r^4/R_0^4)$$

- Contact potential:

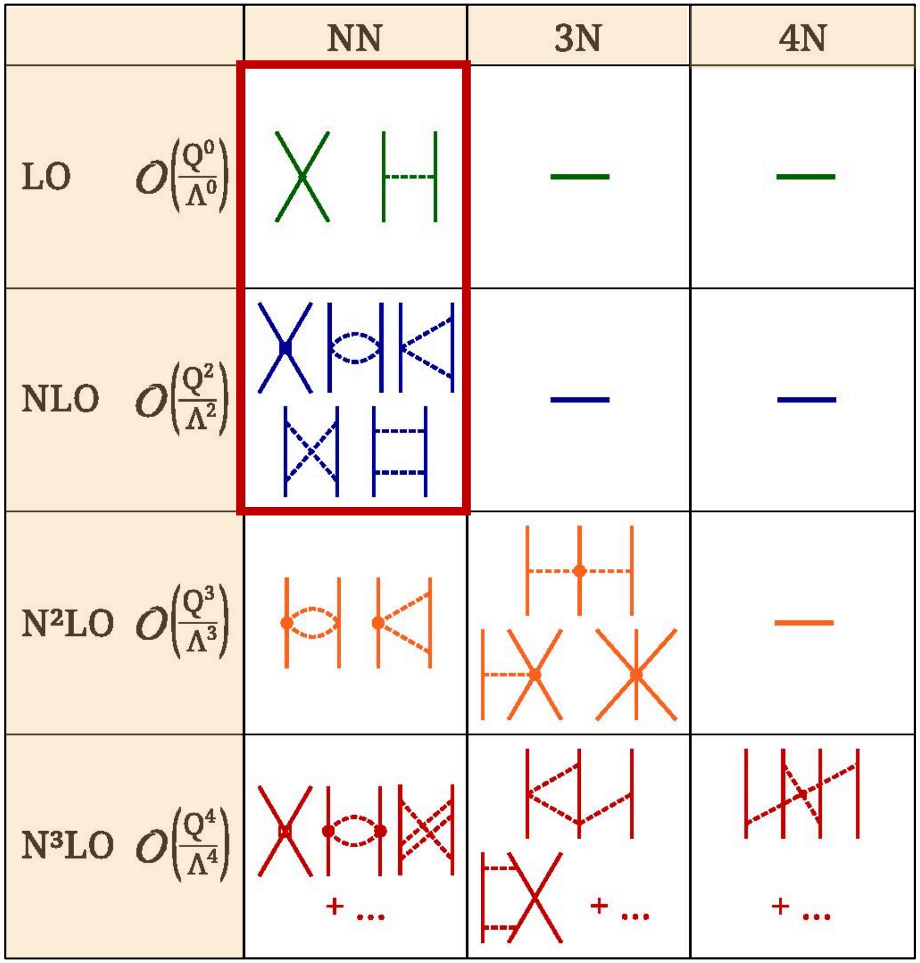
$$V^{(0)}_{\text{cont}} = \alpha_1 \mathbf{1} + \alpha_2 \sigma_1 \cdot \sigma_2 + \alpha_3 \tau_1 \cdot \tau_2 + \alpha_4 \sigma_1 \cdot \sigma_2 \tau_1 \cdot \tau_2$$

→ Only two independent (Pauli principle)

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

$$f_{\text{short}}(r) = \alpha \exp(-r^4/R_0^4)$$

Local chiral interactions

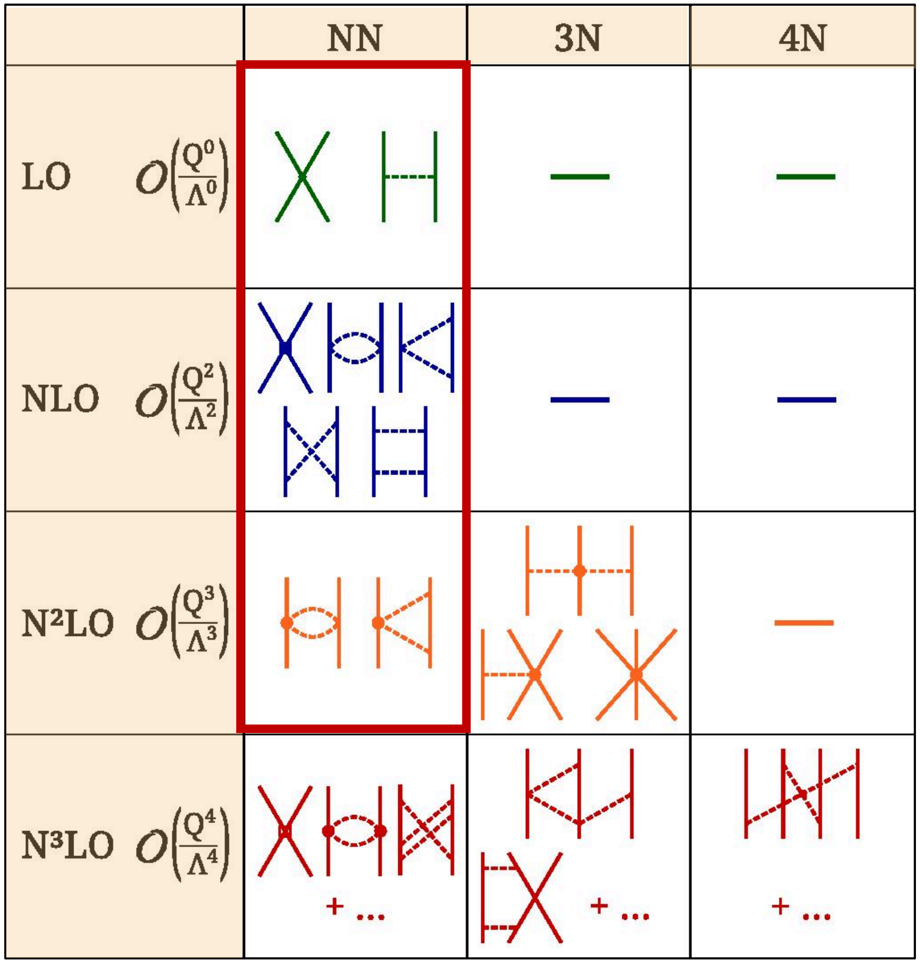


- Choose local set of short-range operators at NLO (7 out of 14)

$$
\begin{aligned}
V_{\text{cont}}^{(2)} = & \gamma_1\, q^2 + \gamma_2\, q^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \gamma_3\, q^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \gamma_4\, q^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \gamma_5\, k^2 + \gamma_6\, k^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \gamma_7\, k^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \gamma_8\, k^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \gamma_9\, (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)(\mathbf{q} \times \mathbf{k}) \\
& + \gamma_{10}\, (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)(\mathbf{q} \times \mathbf{k}) \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \gamma_{11} (\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q}) \\
& + \gamma_{12} (\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q}) \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \gamma_{13} (\boldsymbol{\sigma}_1 \cdot \mathbf{k})(\boldsymbol{\sigma}_2 \cdot \mathbf{k}) \\
& + \gamma_{14} (\boldsymbol{\sigma}_1 \cdot \mathbf{k})(\boldsymbol{\sigma}_2 \cdot \mathbf{k}) \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \,.
\end{aligned}
$$

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

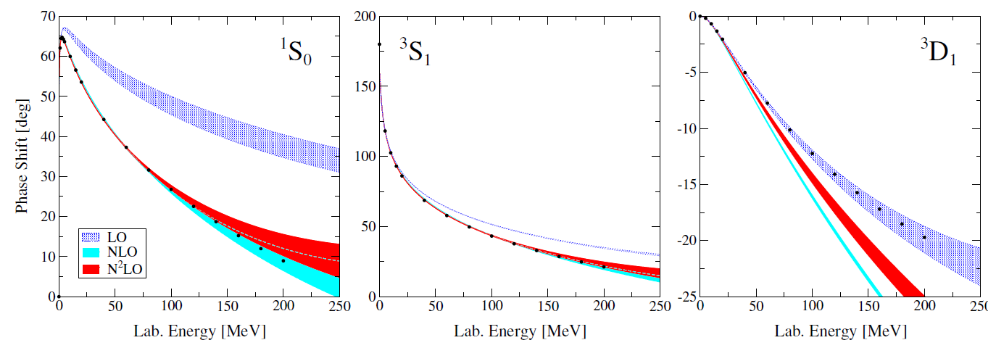
Local chiral interactions



- Choose local set of short-range operators at NLO (7 out of 14)
- Pion exchanges up to N^2LO are local
- This freedom can be used to remove all nonlocal operators up to N^2LO

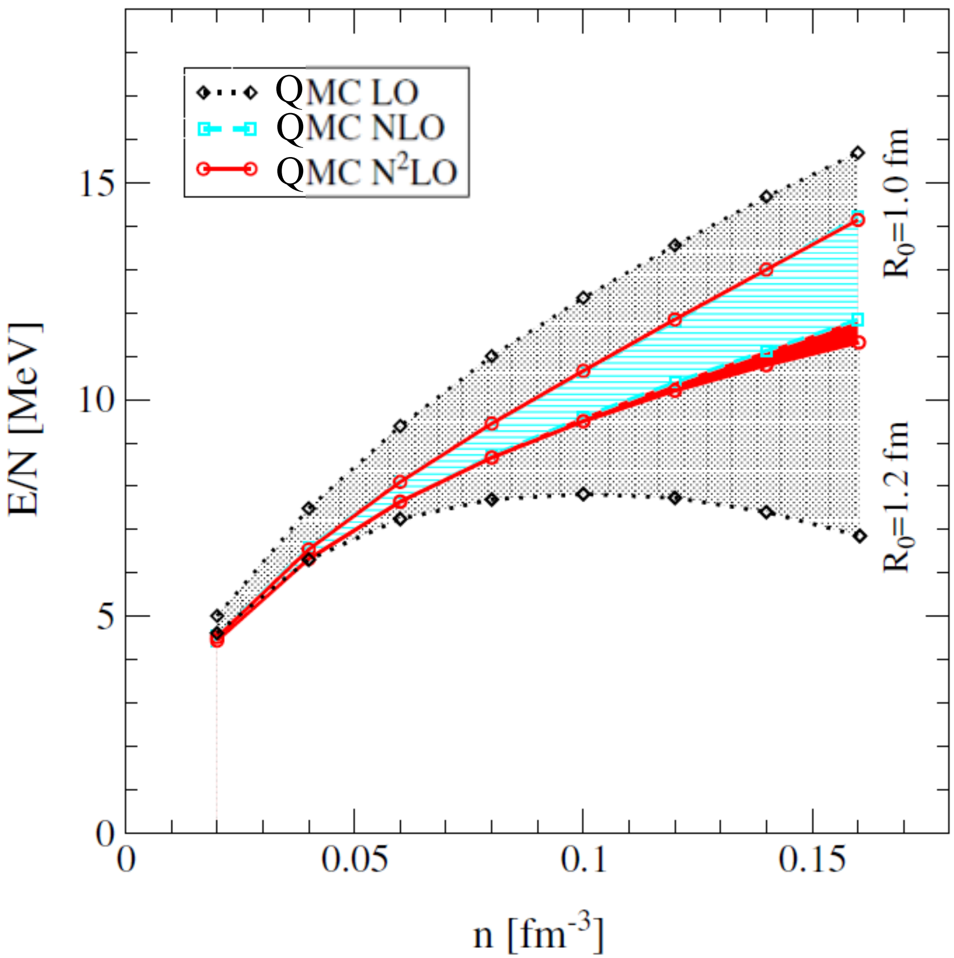
  Gezerlis, IT, Epelbaum, Gandolfi, Hebeler, Nogga, Schwenk, PRL (2013)
  Gezerlis, IT, Epelbaum, Freunek, Gandolfi, Hebeler, Nogga, Schwenk, PRC (2014)

- LECs fit to phase shifts



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

QMC results for NN forces



Gezerlis, IT, Epelbaum, Freunek, Gandolfi, Hebeler, Nogga, Schwenk, PRL (2013) and PRC (2014)

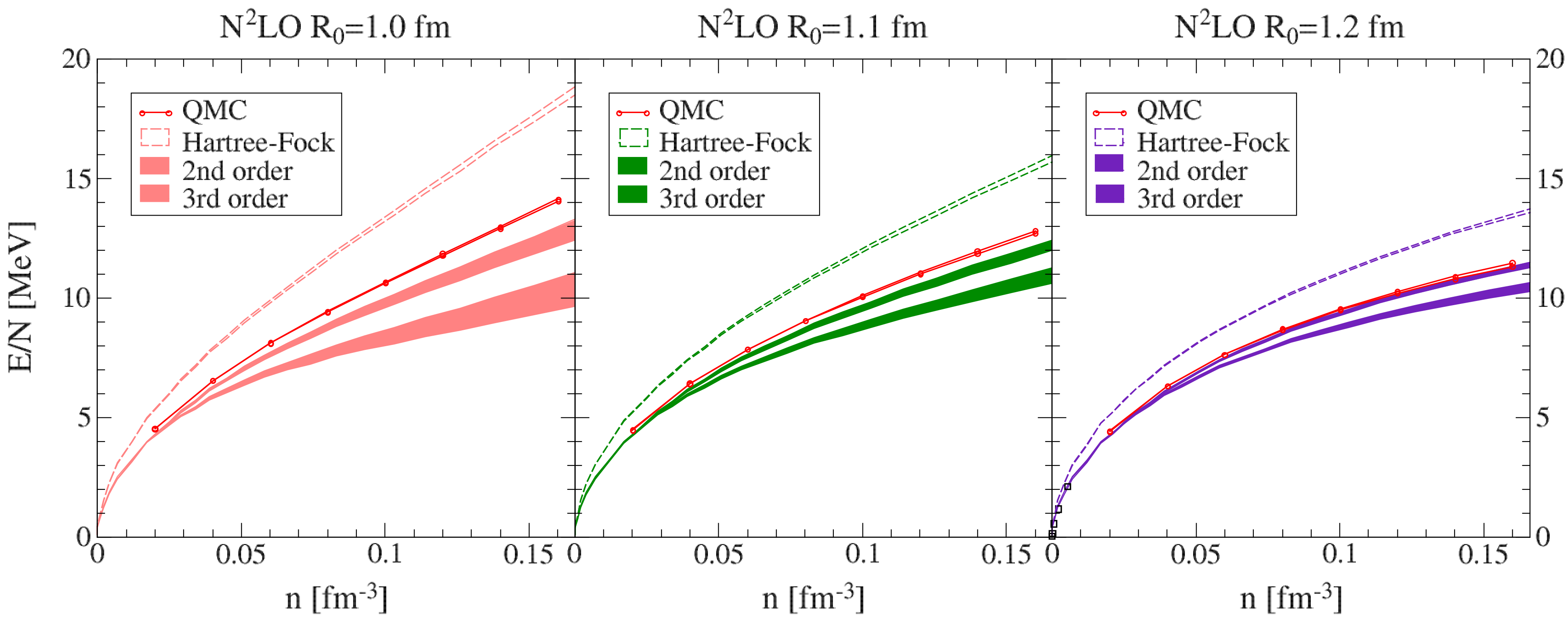
NN-only calculation:

- QMC:
  Statistical uncertainty of points negligible

- Bands include NN cutoff variation
  $R_0 = 1.0 - 1.2$ fm

- Order-by-order convergence up to saturation density

Benchmark of MBPT

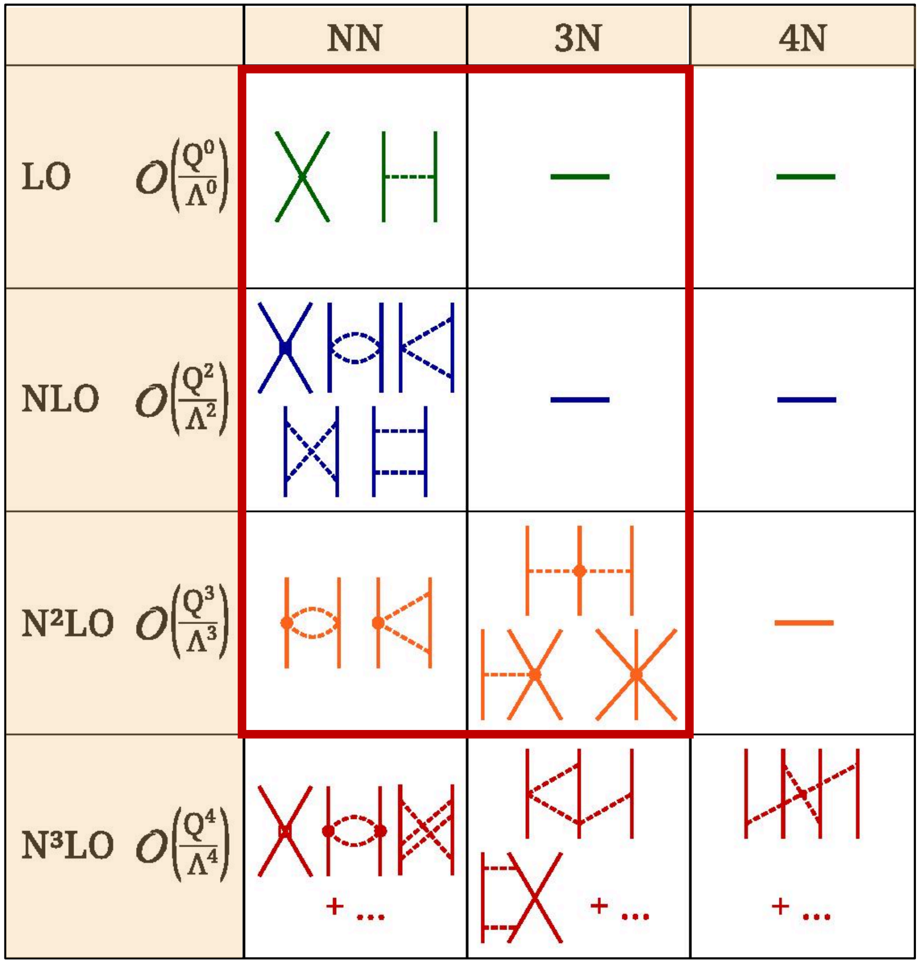


Gezerlis, IT, Epelbaum, Freunek, Gandolfi, Hebeler, Nogga, Schwenk, PRC (2014)

Many-body perturbation theory:

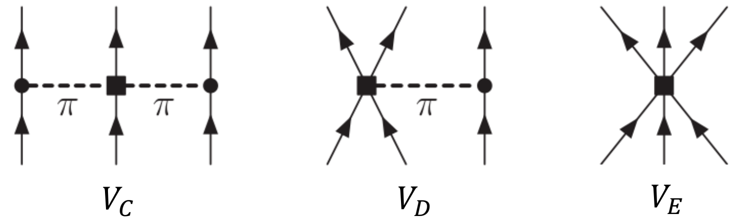
- Excellent agreement with QMC for soft potentials ($R_0 = 1.2$ fm)
- Validates perturbative calculations for those interactions

Local chiral interactions



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

Inclusion of leading 3N forces:



Three topologies:

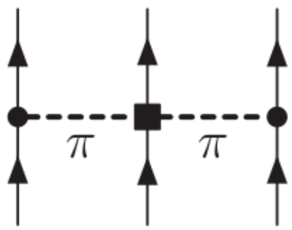
- Two-pion exchange V_C
- One-pion-exchange contact V_D
- Three-nucleon contact V_E

Only two new couplings: c_D and c_E.

Fit to uncorrelated observables:

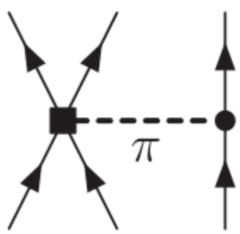
- Probe properties of light nuclei: ^{4}He E_B
- Probe T=3/2 physics: n-α scattering

QMC with chiral 3N forces



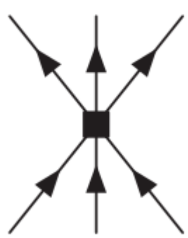
c_1, c_3, c_4

Usually Two-pion-exchange most important in PNM:
c_1 term: Tucson-Melbourn S-wave interaction
$c_{3,4}$ term: Fujita-Miyazawa interaction



c_D

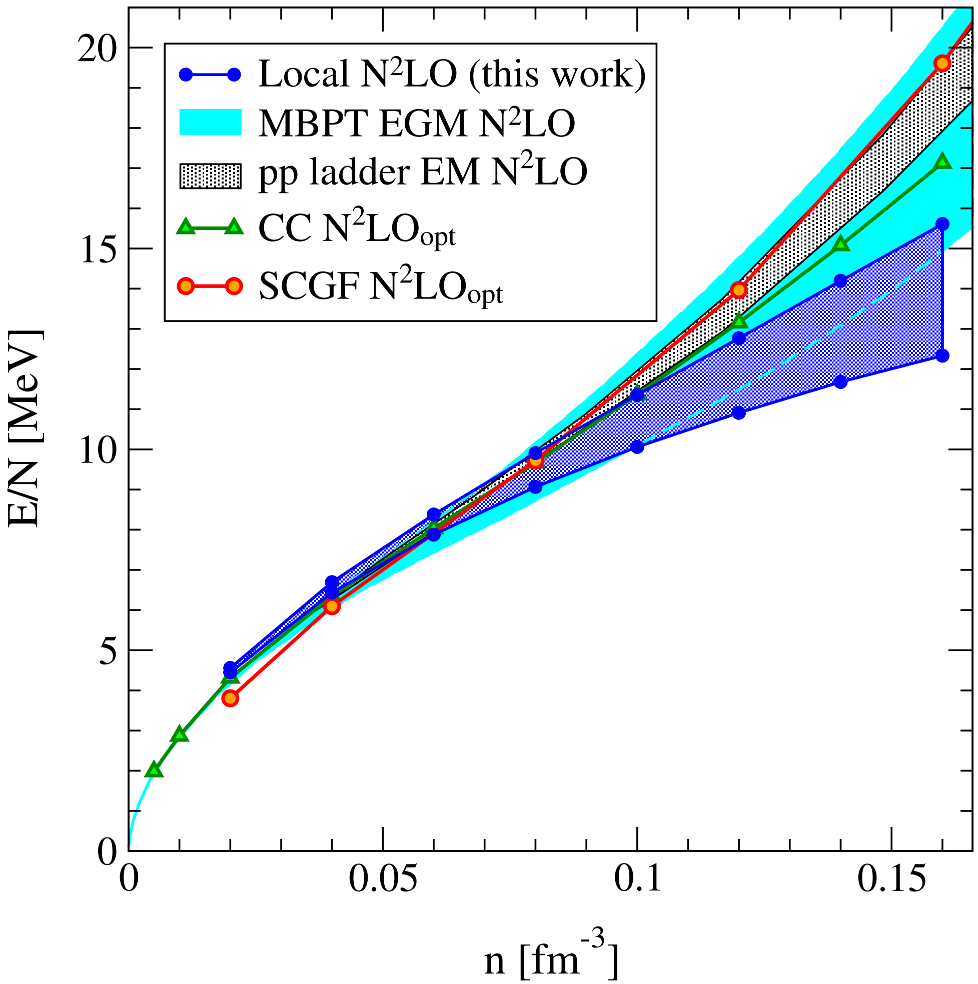
Usually V_D and V_E vanish in neutron matter:
c_D due to spin-isospin structure,
c_E due to Pauli principle
see also Hebeler, Schwenk, PRC (2010)



c_E

Only true for regulator symmetric in particle labels like commonly used nonlocal regulators, not for local regulators

QMC results with 3N TPE



IT, Gandolfi, Gezerlis, Schwenk, PRC (2016)

- Only three-nucleon two-pion exchange $\sim c_1$ and c_3
- Auxiliary-field diffusion Monte Carlo:
  - NN + 3N TPE forces
  - $R_0 = 1.0 - 1.2$ fm
  - $R_{3N} = 1.0 - 1.2$ fm
- 3N cutoff dependence small
- TPE 3N contributions ≈ 1 – 2 MeV at n_0
- smaller than for nonlocal regulators

Fits of 3N LECs

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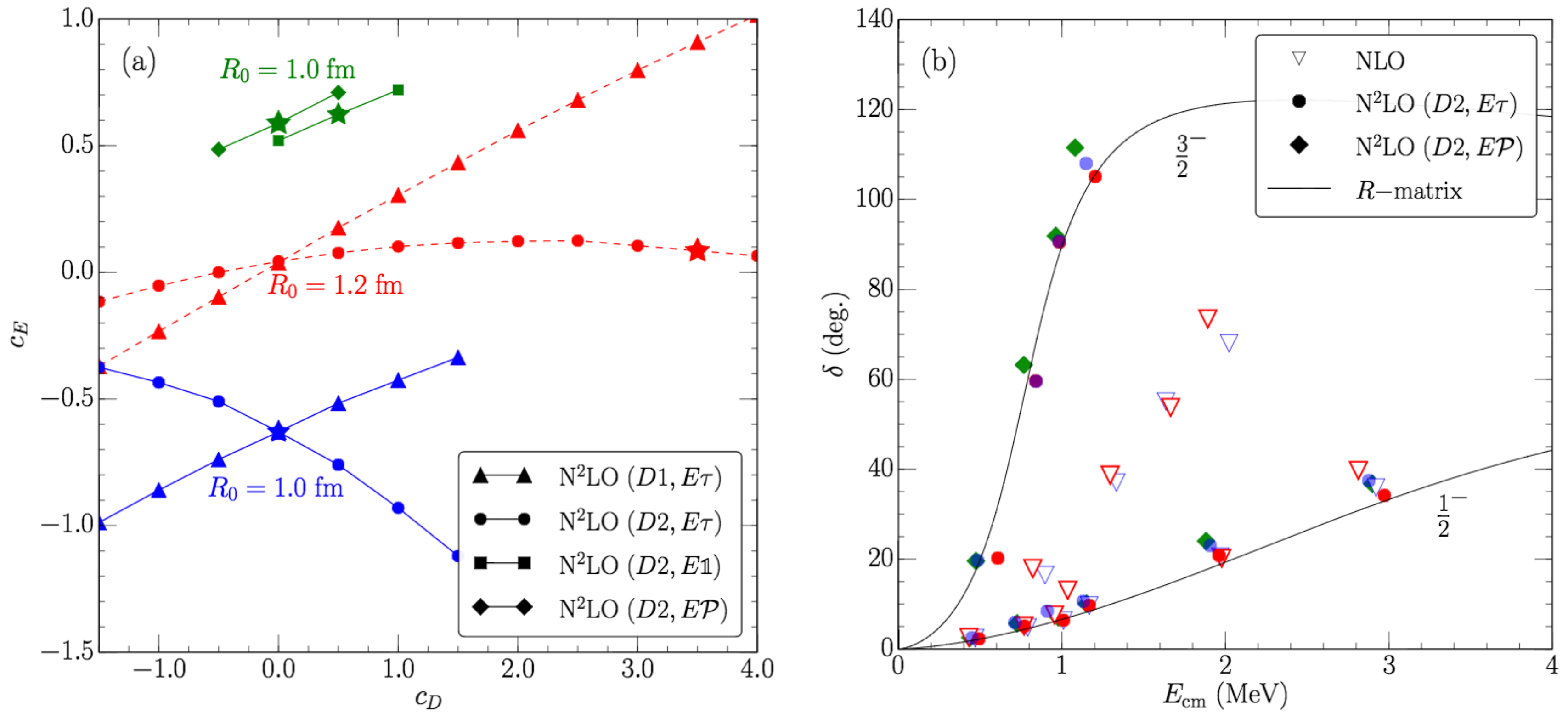
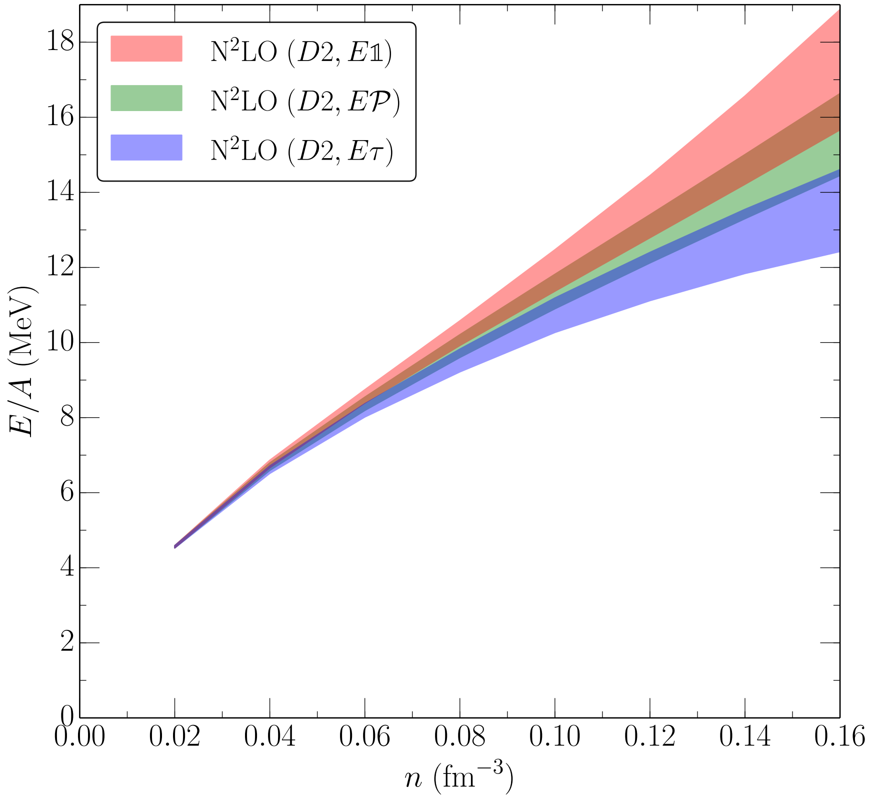
- Fit c_E and c_D to ^{4}He binding energy and n-α scattering



Lynn, IT, Carlson, Gandolfi, Gezerlis, Schmidt, Schwenk, PRL (2016)

Results



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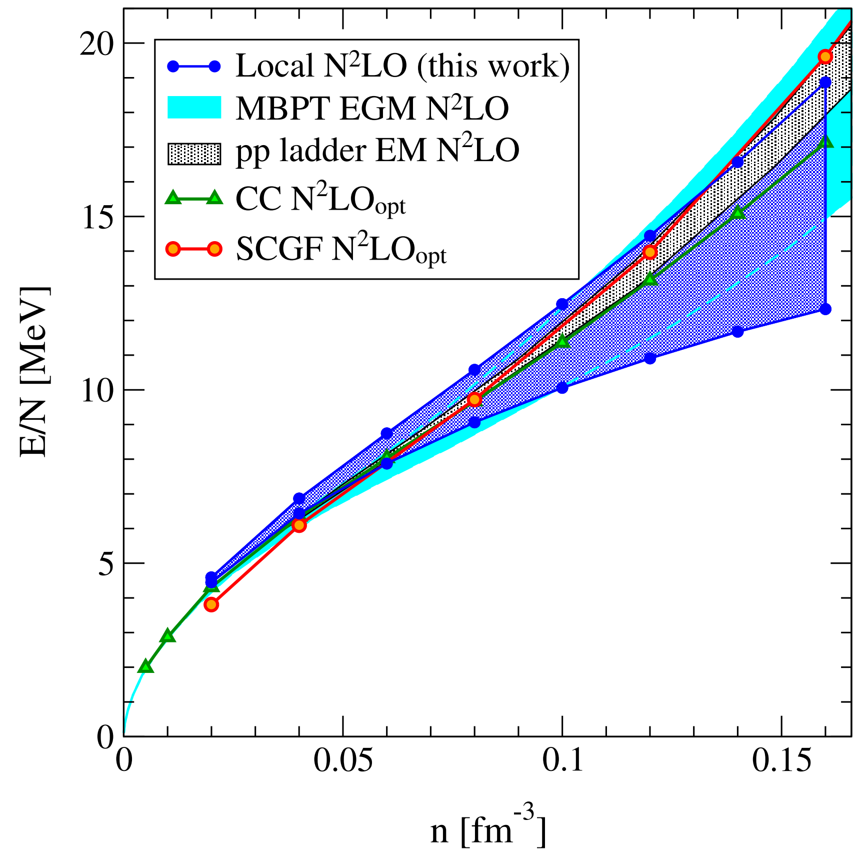
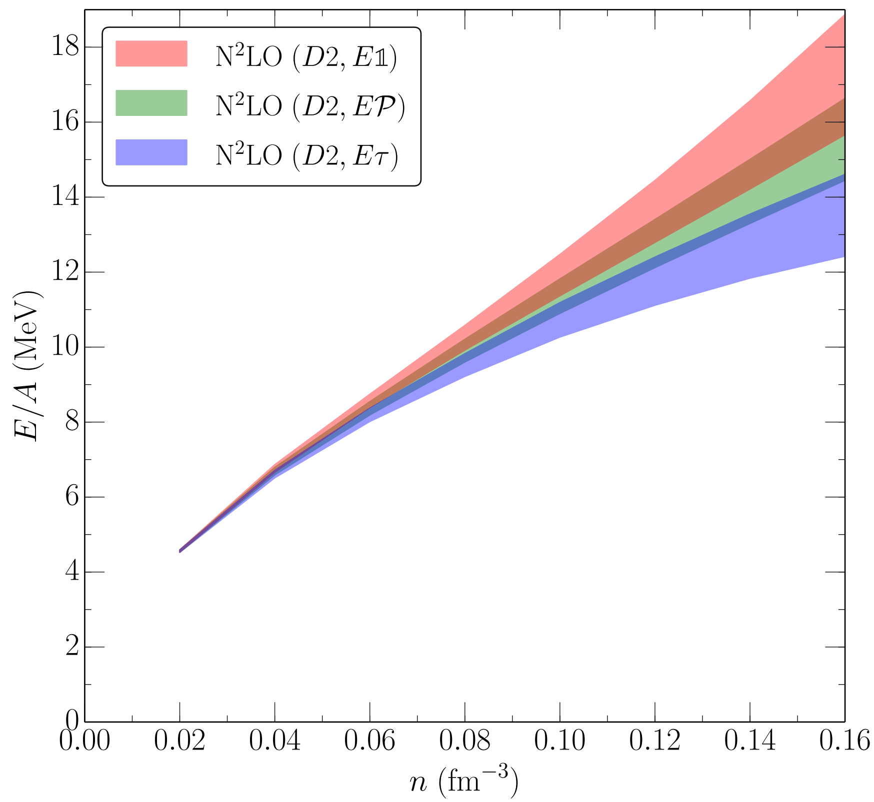


- Less repulsion from TPE, but additional contributions due to shorter-range 3N forces
- After inclusion of all contributions we find agreement of various approaches (different way of uncertainty estimate, see EKM, PRC 2015)

Results



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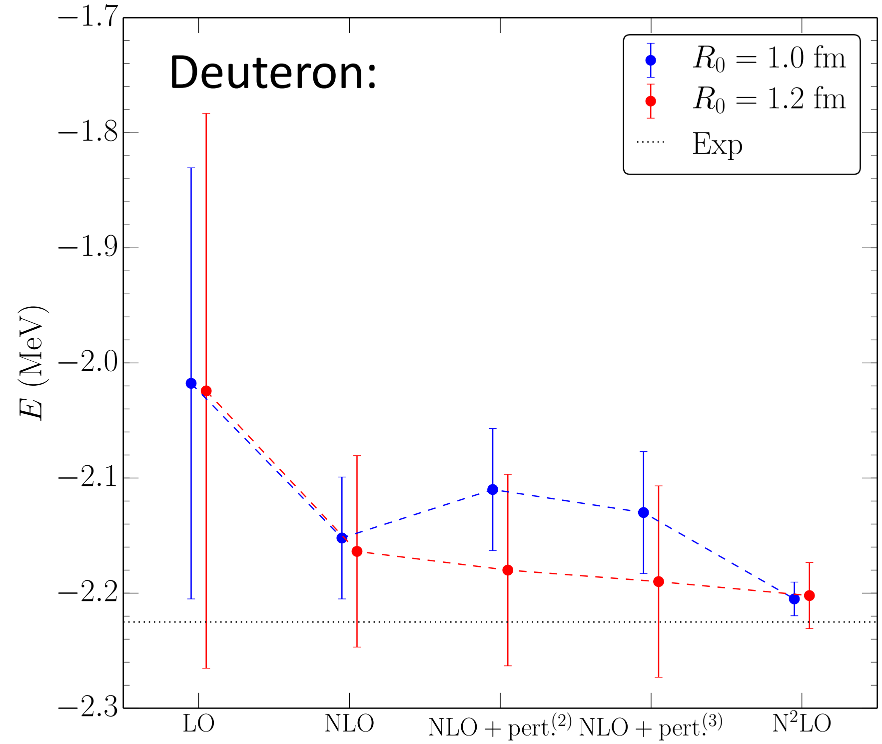
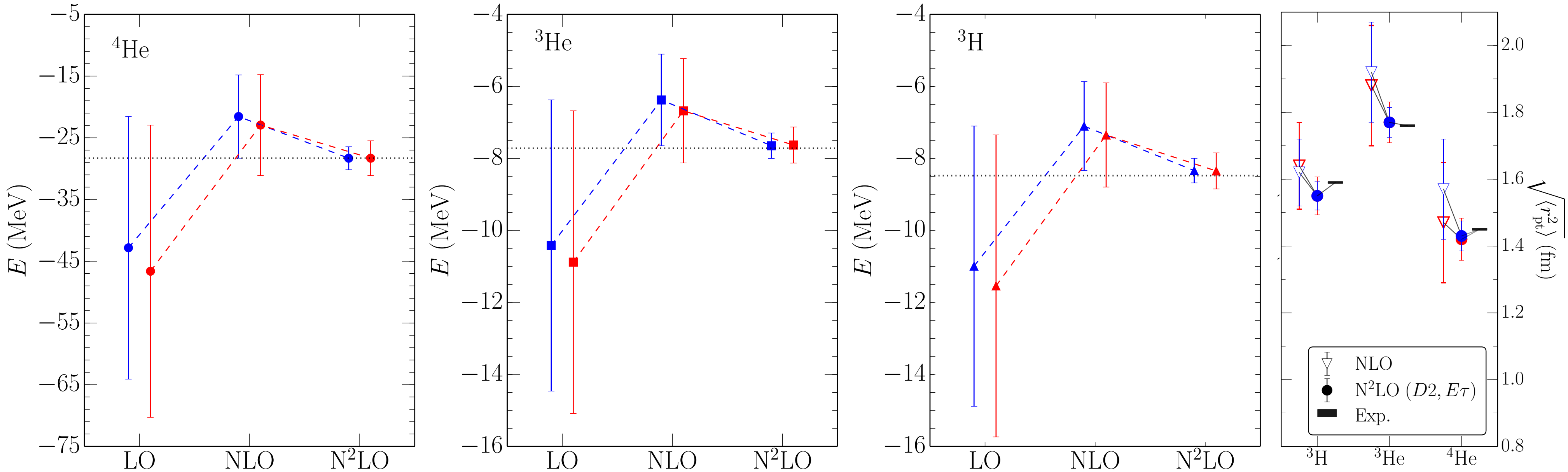


Lynn, IT, Carlson, Gandolfi, Gezerlis, Schmidt, Schwenk, in preparation.

- Chiral interactions at $\mathrm{N^2LO}$ 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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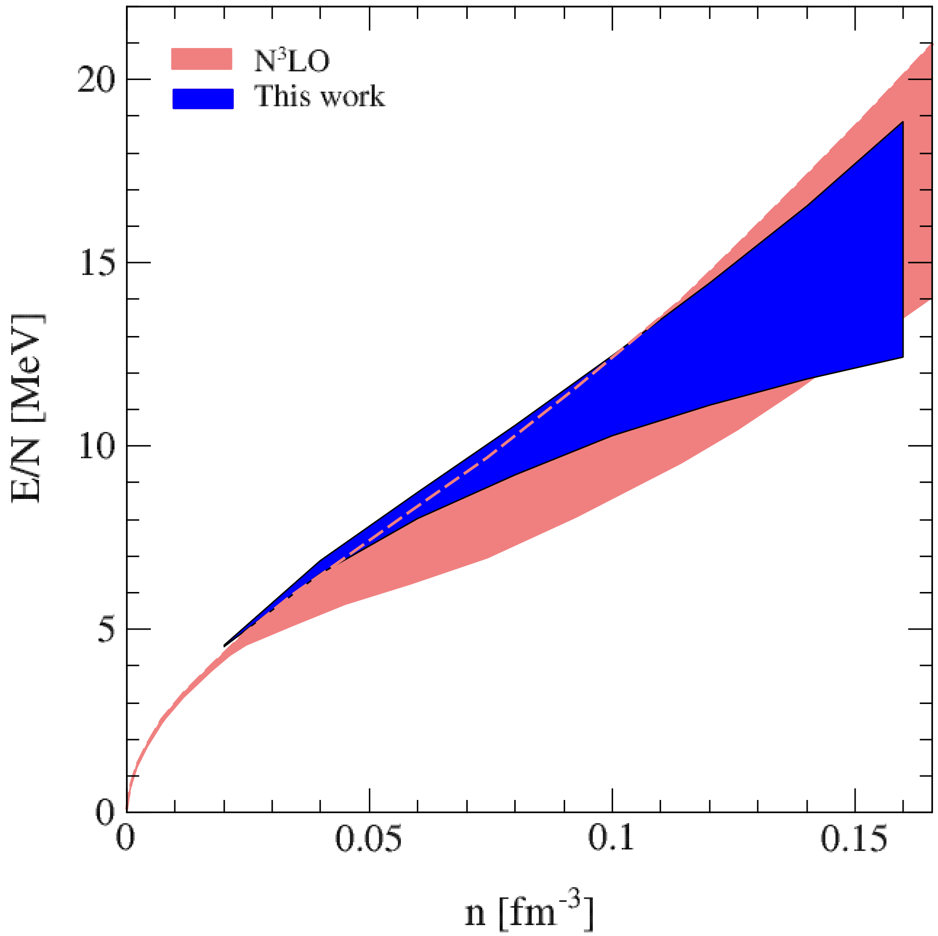
Results

Comparing to N^3LO calculation:



IT, Krüger, Hebeler, Schwenk, PRL (2013)
Lynn, IT, Carlson, Gandolfi, Gezerlis, Schmidt, Schwenk, PRL (2016)

Chiral EFT forces with the Quantum Monte Carlo method:

- Energies agree well with MBPT result within uncertainty bands
- Many-body uncertainty negligible
- uncertainties comparable but QMC band only at N^2LO and includes also hard interactions

- Improve local chiral interactions:
  - Develop N^3LO potentials

Next step: N^3LO

Improve local chiral interactions:

- Develop maximally local N^3LO potentials
- Inclusion of Delta degree of freedom

- Problem: only 8 out of 30 possible operators local

$$
\begin{aligned}
V_{\text{cont}}^{(4)} = \quad & D_1\, \boldsymbol{q}^4 + D_2\, \boldsymbol{q}^4 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + D_3\, \boldsymbol{q}^4 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + D_4\, \boldsymbol{q}^4 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_5\, \boldsymbol{k}^4 + D_6\, \boldsymbol{k}^4 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + D_7\, \boldsymbol{k}^4 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + D_8\, \boldsymbol{k}^4 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_9\, \boldsymbol{q}^2 \boldsymbol{k}^2 + D_{10}\, \boldsymbol{q}^2 \boldsymbol{k}^2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + D_{11}\, \boldsymbol{q}^2 \boldsymbol{k}^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + D_{12}\, \boldsymbol{q}^2 \boldsymbol{k}^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_{13}\, (\boldsymbol{q} \times \boldsymbol{k})^2 + D_{14}\, (\boldsymbol{q} \times \boldsymbol{k})^2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + D_{15}\, (\boldsymbol{q} \times \boldsymbol{k})^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + D_{16}\, (\boldsymbol{q} \times \boldsymbol{k})^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \frac{i}{2} D_{17}\, \boldsymbol{q}^2 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot (\boldsymbol{q} \times \boldsymbol{k}) + \frac{i}{2} D_{18}\, \boldsymbol{q}^2 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot (\boldsymbol{q} \times \boldsymbol{k}) \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + \frac{i}{2} D_{19}\, \boldsymbol{k}^2 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot (\boldsymbol{q} \times \boldsymbol{k}) + \frac{i}{2} D_{20}\, \boldsymbol{k}^2 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot (\boldsymbol{q} \times \boldsymbol{k}) \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_{21}\, \boldsymbol{q}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{q}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{q} + D_{22}\, \boldsymbol{q}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{q}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{q}\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_{23}\, \boldsymbol{k}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{q}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{q} + D_{24}\, \boldsymbol{k}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{q}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{q}\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_{25}\, \boldsymbol{q}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{k}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{k} + D_{26}\, \boldsymbol{q}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{k}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{k}\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_{27}\, \boldsymbol{k}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{k}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{k} + D_{28}\, \boldsymbol{k}^2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{k}\, \boldsymbol{\sigma}_2 \cdot \boldsymbol{k}\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
& + D_{29}\, \left((\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot (\boldsymbol{q} \times \boldsymbol{k})\right)^2 + D_{30}\, \left((\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot (\boldsymbol{q} \times \boldsymbol{k})\right)^2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \qquad (34)
\end{aligned}
$$

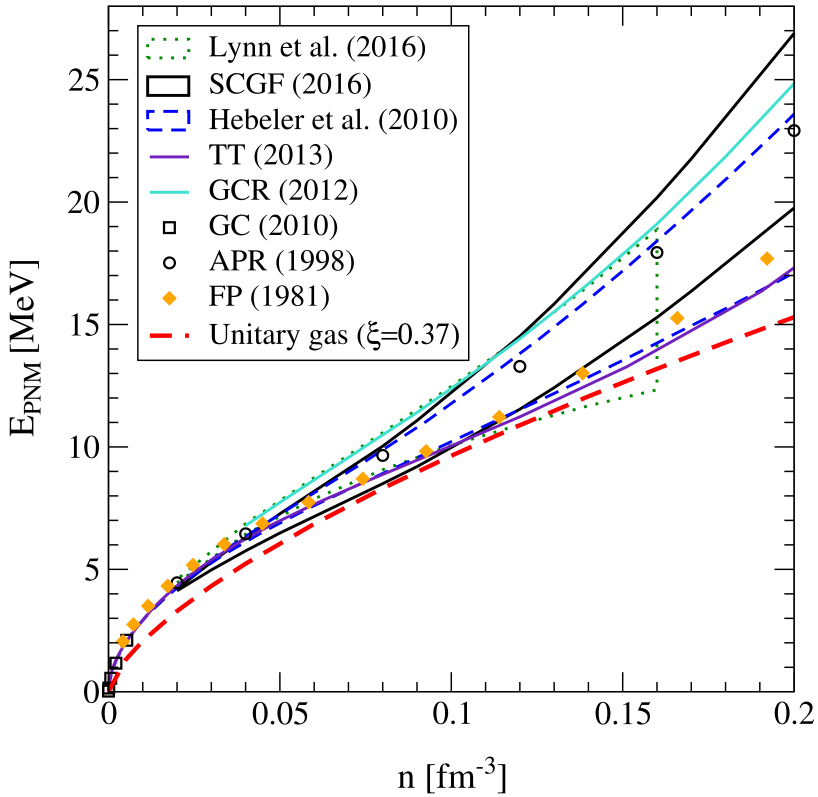
- But: work in progress!

Now: Constraints on S and L from

lower bound of neutron matter energy

Kolomeitsev, Lattimer, Ohnishi, IT, arXiv:1611.07133

S and L constraints from lower bound of neutron matter energy



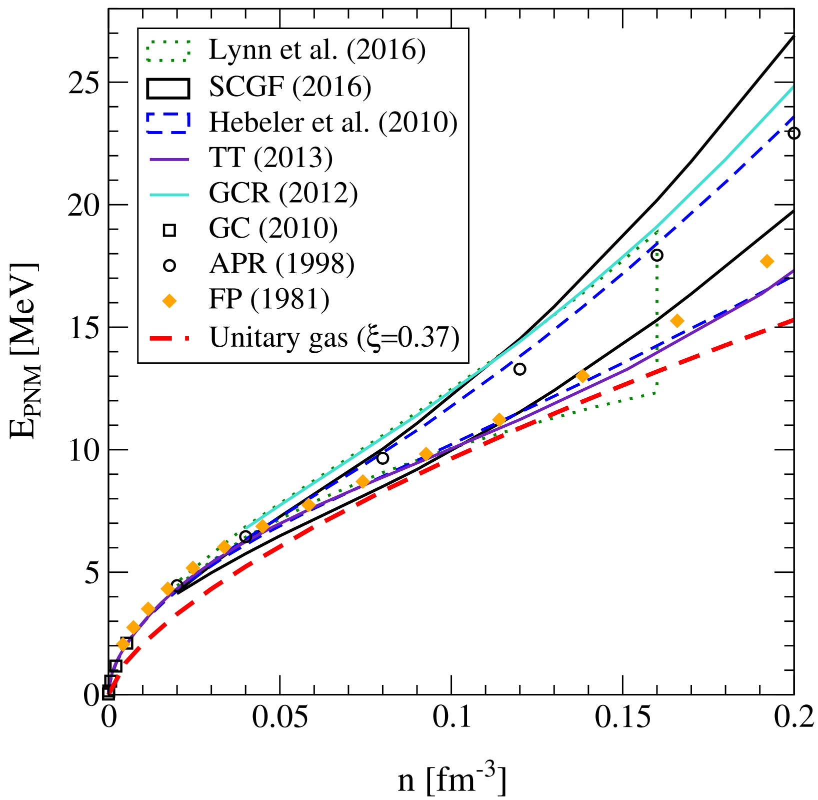
Kolomeitsev, Lattimer, Ohnishi, IT, arXiv:1611.07133

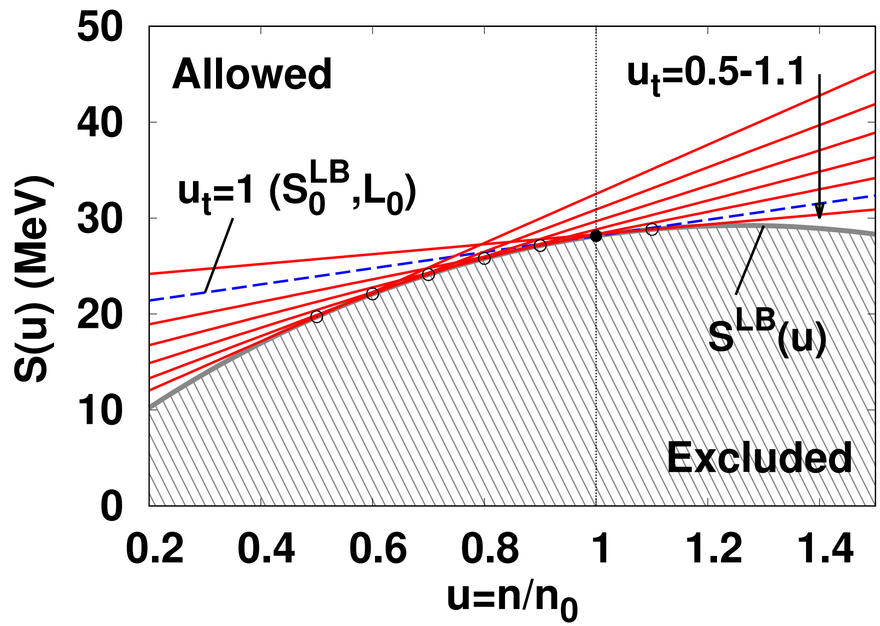
Unitary gas:

- Gas interacting via two-body interactions with infinite scattering length and vanishing effective range
- Then, system has no scale except density, and can be described by a dimensionless parameter, ξ (Bertsch parameter)
- Details of the interaction become irrelevant (universality)
- Experiment and theory: $\xi \approx 0.37$

Empirical observation:
Unitary gas energy seems to be lower bound to neutron-matter energy
- Constraints on S and L

S and L constraints from lower bound of neutron matter energy





Kolomeitsev, Lattimer, Ohnishi, IT, arXiv:1611.07133

$$S_0 + \frac{L}{3}(u-1) \geq E^0_{\mathrm{UG}} u^{2/3} - \left[E_0 + \frac{K_n}{18}(u-1)^2\right]$$

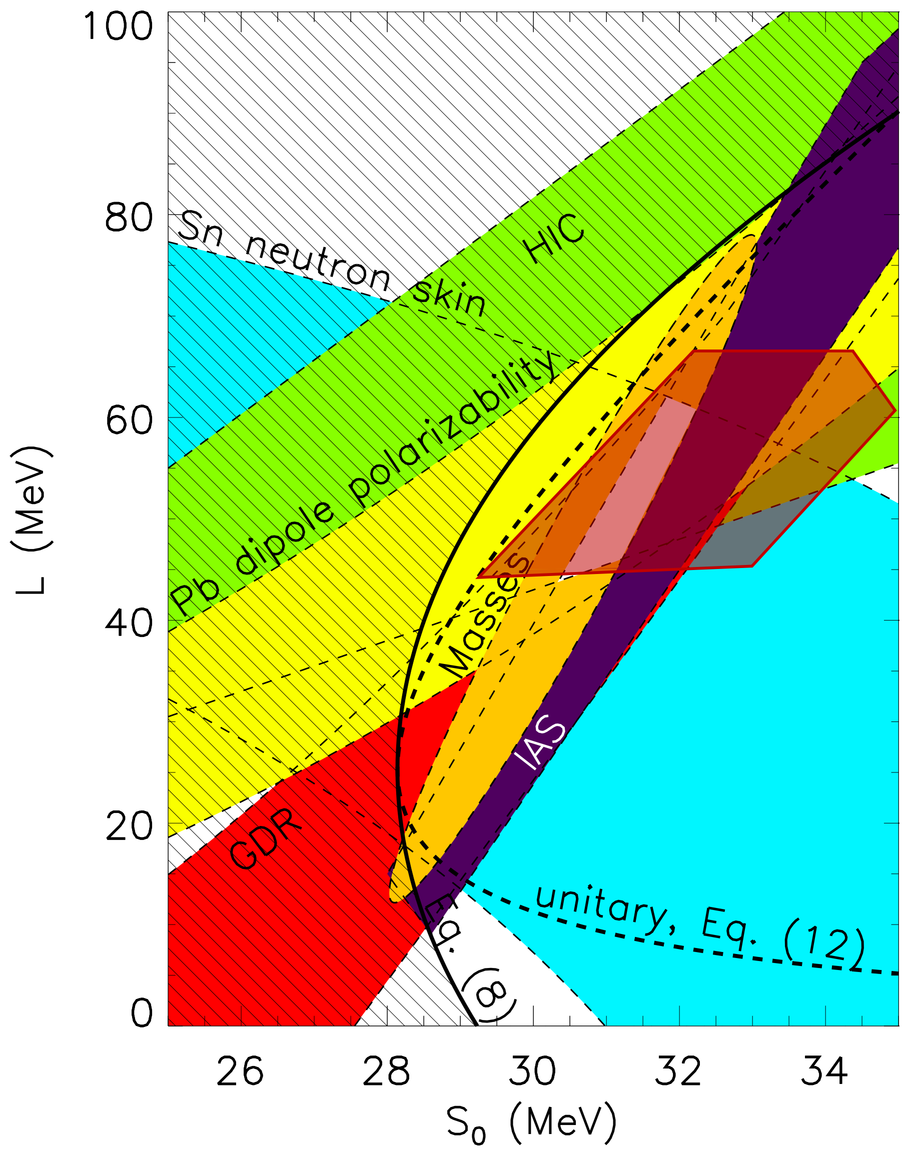
$$K_n = K + K_{\mathrm{sym}}$$

Empirical observation:

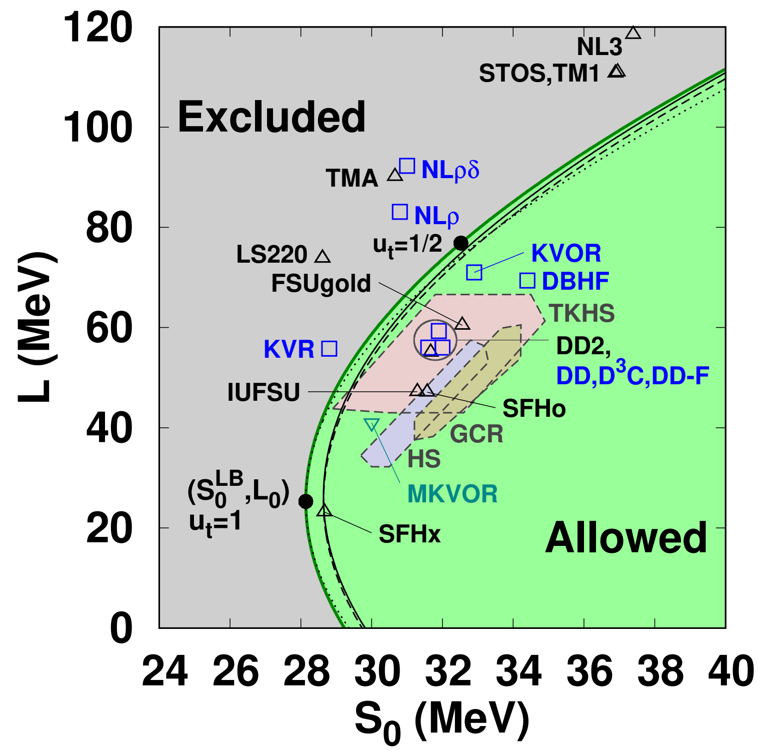
Unitary gas energy seems to be lower bound to neutron-matter energy

- ➢ Constraints on S and L

S and L constraints from lower bound of neutron matter energy



Kolomeitsev, Lattimer, Ohnishi, IT, arXiv:1611.07133



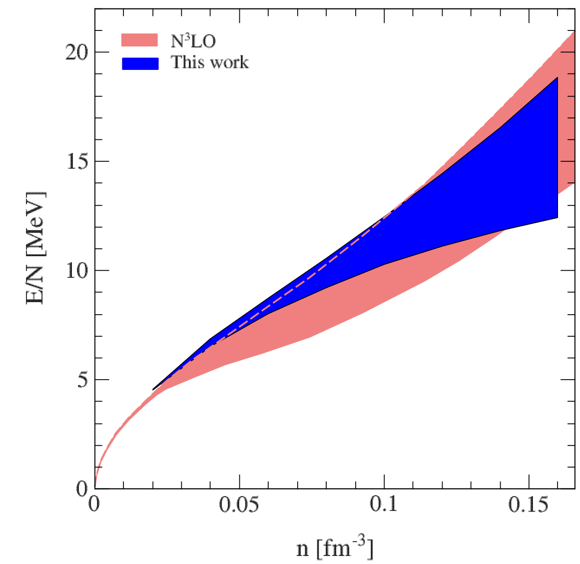
$$E_0 = -15.5\ \text{MeV},\ n_0 = 0.157\ \text{fm}^{-3},$$
$$K = 270\ \text{MeV},\ K_{\text{sym}} = 0,\ \xi = 0.365,$$
$$K_n = K$$

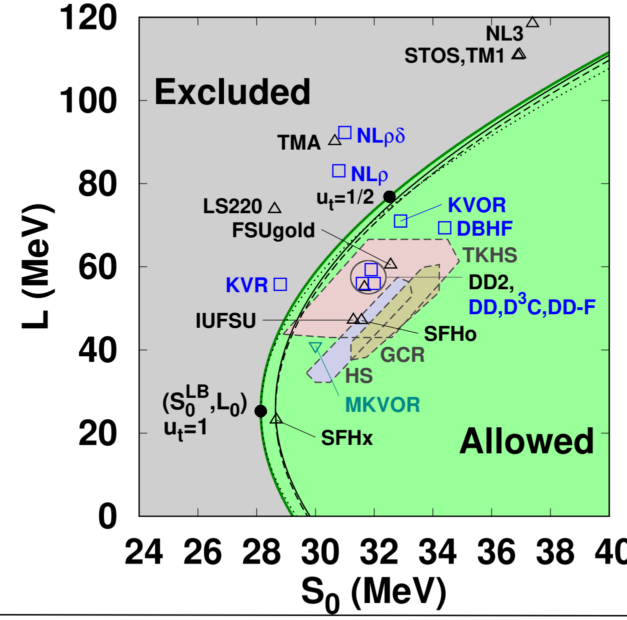
Put constraints on symmetry energy S and its density dependence L.

$$S_0^{\text{LB}} = 28.14\ \text{MeV, and } L_0 = 25.28\ \text{MeV.}$$

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 can serve as nonperturbative benchmarks.
  - Gezerlis, IT, Epelbaum, Gandolfi, Hebeler, Nogga, Schwenk, PRL (2013)
  - Gezerlis, IT, Epelbaum, Freunek, Gandolfi, Hebeler, Nogga, Schwenk, PRC (2014)
  - IT, Gandolfi, Gezerlis, Schwenk, PRC (2016)
  - Lynn, IT, Carlson, Gandolfi, Gezerlis, Schmidt, Schwenk, PRL (2016)
- Chiral interactions at $\mathrm{N}^2\mathrm{LO}$ simultaneously reproduce the properties of A≤5 systems and of neutron matter, commonly used phenomenological 3N interactions fail.
- Further improvements will allow to determine neutron-matter EOS with improved uncertainties (factor of 2).
- Constraints on symmetry energy and its slope parameter from lower bound of neutron-matter energy.
  - Kolomeitsev, Lattimer, Ohnishi, IT, arXiv:1611.07133





Thanks

INSTITUTE for NUCLEAR THEORY

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Thank you for your attention.