Chiral effective field theory and neutron-rich matter

Achim Schwenk

Block Course “Aspects of QCD at Finite Density”
University of Bielefeld, Sept. 22/23, 2011
Outline

Chiral effective field theory for nuclear forces

3N forces and neutron-rich nuclei

3N forces and neutron matter, impact on neutron stars

3N forces and electroweak currents

Contact: schwenk@physik.tu-darmstadt.de
The nuclear forces frontier
Λ / Resolution dependence

with high-energy probes: quarks+gluons

at low energies: complex QCD vacuum

lowest energy excitations:
  pions, nearly massless, $m_\pi = 140$ MeV
  ‘phonons’ of QCD vacuum
Resolution dependence of nuclear forces

with high-energy probes: quarks + gluons

at low energies: complex QCD vacuum

lowest energy excitations: pions, nearly massless, \( m_\pi = 140 \text{ MeV} \)

‘phonons’ of QCD vacuum

\( \Lambda \) _{chiral} \n
momenta \( Q \sim \lambda^{-1} \sim m_\pi \)

\( \Lambda \) _{pionless} \n
momenta \( Q \ll m_\pi \)
Λ / Resolution dependence of nuclear forces

Λ_{pionless}

momenta $Q \ll m_\pi$: pionless effective field theory

large scattering length physics and corrections
Λ / Resolution dependence of nuclear forces

Λ_{chiral} momenta $Q \sim \lambda^{-1} \sim m_\pi$: chiral effective field theory
neutrons and protons interacting via pion exchanges and shorter-range contact interactions

Λ_{pionless} momenta $Q << m_\pi$

typical momenta in nuclei $\sim m_\pi$
Effective theory for NN, 3N, many-N interactions and electroweak operators: resolution scale/Λ-dependent
\[ H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + V_{4N}(\Lambda) + \ldots \]

\( \Lambda_{\text{chiral}} \) momenta \( Q \sim \lambda^{-1} \sim m_\pi \): chiral effective field theory

\( \Lambda_{\text{pionless}} \) momenta \( Q \ll m_\pi \)
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta \( \frac{1}{\Lambda} = Q \ll \Lambda_b \), breakdown scale \( \sim 500 \text{ MeV} \)

Limited resolution at low energies, can expand in powers \((Q/\Lambda_b)^n\)

<table>
<thead>
<tr>
<th>Order</th>
<th>( \mathcal{O} )</th>
<th>NN</th>
<th>3N</th>
<th>4N</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>( \mathcal{O}(\frac{Q^0}{\Lambda_b^0}) )</td>
<td>X</td>
<td>H</td>
<td>-</td>
</tr>
<tr>
<td>NLO</td>
<td>( \mathcal{O}(\frac{Q^2}{\Lambda_b^2}) )</td>
<td>X</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>N^2LO</td>
<td>( \mathcal{O}(\frac{Q^n}{\Lambda_b^n}) )</td>
<td>X</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>N^3LO</td>
<td>( \mathcal{O}(\frac{Q^3}{\Lambda_b^3}) )</td>
<td>X</td>
<td>H</td>
<td>X</td>
</tr>
</tbody>
</table>

Expansion parameter \( \sim 1/3 \)

(compare to multipole expansion for a charge distribution)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner, …
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\Lambda} = Q \ll \Lambda_b$ breakdown scale $\sim 500$ MeV

<table>
<thead>
<tr>
<th>LO $\mathcal{O}(\frac{Q^0}{\Lambda_0})$</th>
<th>NLO $\mathcal{O}(\frac{Q^2}{\Lambda^2})$</th>
<th>N$^2$LO $\mathcal{O}(\frac{Q^3}{\Lambda^3})$</th>
<th>N$^3$LO $\mathcal{O}(\frac{Q^4}{\Lambda^4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN</td>
<td>3N</td>
<td>4N</td>
<td>limited resolution at low energies, can expand in powers $(Q/\Lambda_b)^n$</td>
</tr>
</tbody>
</table>

LO, $n=0$ - leading order,
NLO, $n=2$ - next-to-leading order,…

Question: Why is there no $n=1$ contribution?

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda$, breakdown scale $\sim 500$ MeV

include long-range pion physics

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner, …
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta \( \frac{1}{\Lambda} = Q \ll \Lambda_b \), breakdown scale \( \sim 500 \text{ MeV} \)

include long-range pion physics
details at short distance not resolved
capture in few short-range couplings, fit to experiment once, \( \Lambda \)-dependent

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta \( \frac{1}{\lambda} = Q \ll \Lambda_b \) breakdown scale \( \sim 500 \text{ MeV} \)

Question: What is \( V(r) \) for NN interactions at LO?

Hint: One-pion exchange + contact interaction but with resolution scale \( \Lambda \sim 500 \text{ MeV} \) (cutoff on momenta)
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta \( \frac{1}{\lambda} = Q \ll \Lambda_b \) breakdown scale \( \sim 500 \text{ MeV} \)

- \( NN \)
- \( 3N \)
- \( 4N \)

LO \( \mathcal{O}\left(\frac{Q^0}{\Lambda_0}\right) \)

large scattering length physics

\( ^6\text{Li} \) fermions
2 spin states
|1\rangle
|2\rangle

neutrons with same density and temperature have the same properties!

from M. Zwierlein
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV

$pion \ tensor/dipole\ interactions + \ldots$

→ compare to cold polar molecules

Ni et al., Nature (2010)
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\Lambda} = Q \ll \Lambda$ breakdown scale $\sim 500$ MeV

systematic: can work to desired accuracy and obtain error estimates from truncation order and $\Lambda$ variation

accurate reproduction of low-energy NN scattering at $N^3$LO

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…
Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs Bogner, Kuo, AS, Furnstahl,...

\[ H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + V_{4N}(\Lambda) + \ldots \]
Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs Bogner, Kuo, AS, Furnstahl,…

\[ H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + V_{4N}(\Lambda) + \ldots \]

for NN interactions (preserves NN observables)

red = short-range repulsion
Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs Bogner, Kuo, AS, Furnstahl,…

\[ H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + V_{4N}(\Lambda) + \ldots \]

for NN interactions (preserves NN observables)

low-momentum interactions \( V_{low k}(\Lambda) \)

RG decouples low-momentum physics from high momenta
Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs

\[ H(\Lambda) = T + V_{\text{NN}}(\Lambda) + V_{3\text{N}}(\Lambda) + V_{4\text{N}}(\Lambda) + \ldots \]

Bogner, Kuo, AS, Furnstahl, …

\[ \Lambda = 2 \text{ fm}^{-1} (400 \text{ MeV}) \]

\[ \Lambda = 5.0 \text{ fm}^{-1} \]

\[ \Lambda = 5.0 \text{ fm}^{-1} \]

\[ \Lambda = 2 \text{ fm}^{-1} \]

low-momentum interactions \( V_{\text{low}}(k,k) \)

RG decouples low-momentum physics from high momenta

low-momentum universality from different chiral N\(^3\)LO potentials
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\Lambda} = Q \ll \Lambda_b$ breakdown scale $\sim 500$ MeV

Limited resolution at low energies, can expand in powers $(Q/\Lambda_b)^n$

- **LO** $O\left(\frac{Q^0}{\Lambda^0}\right)$
  - NN
  - 3N
  - 4N

  LO, $n=0$ - leading order,
  NLO, $n=2$ - next-to-leading order, …

  Expansion parameter $\sim 1/3$

  (compare to multipole expansion for a charge distribution)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner, …
Why are there three-body forces?

Tidal effects lead to 3-body forces in earth-sun-moon system.
Why are there three-nucleon (3N) forces?

Nucleons are finite-mass composite particles, can be excited to resonances

dominant contribution from $\Delta(1232\text{ MeV})$

+ many shorter-range parts

in chiral EFT (Delta-less): $\pi + \pi + \pi + \text{shorter-range parts}$

in pionless EFT: + higher-order parts

tidal effects lead to 3-body forces in earth-sun-moon system
### Chiral Effective Field Theory for nuclear forces

**Separation of scales: low momenta**

\[
\frac{1}{\Lambda} = Q \ll \Lambda_b \text{breakdown scale} \sim 500 \text{ MeV}
\]

Limited resolution at low energies, can expand in powers \((Q/\Lambda_b)^n\)

<table>
<thead>
<tr>
<th>LO (\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right))</th>
<th>NN</th>
<th>3N</th>
<th>4N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram 1" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NLO (\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right))</th>
<th>NN</th>
<th>3N</th>
<th>4N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image2.png" alt="Diagram 2" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N^2LO (\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right))</th>
<th>NN</th>
<th>3N</th>
<th>4N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Diagram 3" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N^3LO (\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right))</th>
<th>NN</th>
<th>3N</th>
<th>4N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4.png" alt="Diagram 4" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Question:** Why do 3N forces start at \(n=3\) (without explicit Deltas)?

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta \( \frac{1}{\lambda} = Q \ll \Lambda_b \) breakdown scale \( \sim 500 \text{ MeV} \)

consistent **NN-3N** interactions

**3N,4N:** only 2 new couplings to \( N^3\text{LO} \)

\[ c_i \text{ from } \pi N \text{ and } NN \quad \text{Meissner et al. (2007)} \]

\[ c_1 = -0.9^{+0.2}_{-0.5}, \quad c_3 = -4.7^{+1.2}_{-1.0}, \quad c_4 = 3.5^{+0.5}_{-0.2} \]

single-\( \Delta \): \( c_1 = 0, \ c_3 = -c_4/2 = -3 \text{ GeV}^{-1} \)

\( c_D, c_E \) fit to \( ^3\text{H} \) binding energy and \( ^4\text{He} \) radius (or \( ^3\text{H} \) beta decay half-life)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\Lambda} = Q \ll \Lambda_b$, breakdown scale $\sim 500$ MeV

consistent NN-3N interactions

3N,4N: only 2 new couplings to N$^3$LO

Question: Why are the next order 3N forces (n=4) parameter-free (without new 3N contact interactions)?

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…
Subleading chiral 3N forces


One-loop contributions:
2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange
decrease \( c_i \) strengths comparable to N^2LO uncertainty

\[
\delta c_1 = -\frac{g_A^2 M_\pi}{64 \pi F_\pi^2}, \quad \delta c_3 = -\delta c_4 = \frac{g_A^4 M_\pi}{16 \pi F_\pi^2} \quad \delta c_3 = -\delta c_4 = 1 \text{ GeV}^{-1}
\]

1/m corrections: spin-orbit parts, interesting for A_y puzzle
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale $\sim 500$ MeV

- **LO** $O(Q^0)$
- **NLO** $O(Q^2)$
- **N^2LO** $O(Q^3)$
- **N^3LO** $O(Q^4)$

**First perturbative estimate of 4N forces** Nogga et al. (2010)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,...
Outline

Chiral effective field theory for nuclear forces

3N forces and neutron-rich nuclei

3N forces and neutron matter, impact on neutron stars

3N forces and electroweak currents

Contact: schwenk@physik.tu-darmstadt.de
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\Lambda} = Q \ll \Lambda_b$ breakdown scale $\sim 500$ MeV

consistent **NN-3N** interactions

3N,4N: only 2 new couplings to $N^3LO$

<table>
<thead>
<tr>
<th>LO $\mathcal{O} \left( \frac{Q^0}{\Lambda^0} \right)$</th>
<th>3N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NLO $\mathcal{O} \left( \frac{Q^2}{\Lambda^2} \right)$</th>
<th>3N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N$^2$LO $\mathcal{O} \left( \frac{Q^3}{\Lambda^3} \right)$</th>
<th>3N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N$^3$LO $\mathcal{O} \left( \frac{Q^4}{\Lambda^4} \right)$</th>
<th>3N</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
</tbody>
</table>

$c_i$ from πN and NN Meissner et al. (2007)

$$c_1 = -0.9^{+0.2}_{-0.5}, \quad c_3 = -4.7^{+1.2}_{-1.0}, \quad c_4 = 3.5^{+0.5}_{-0.2}$$

**single-Δ:** $c_1 = 0, \quad c_3 = -c_4/2 = -3$ GeV$^{-1}$

$c_D, c_E$ fit to $^3$H binding energy and $^4$He radius (or $^3$H beta decay half-life)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…
Towards the limits of existence - the neutron drip-line
The oxygen anomaly
The oxygen anomaly

Nature 459, 1069-1070 (25 June 2009)
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

Nuclei with a ‘magic’ number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope $^{24}$O has been found to be one such nucleus — yet it lies just at the limit of stability.
The oxygen anomaly - not reproduced without 3N forces

Without 3N forces, NN interactions too attractive

Many-body theory based on two-nucleon forces: drip-line incorrect at $^{28}$O

(a) Forces derived from NN theory

(b) Phenomenological forces

$^{16}$O core

$^{16}$O

$^{24}$O

$^{28}$O

Fit to experiment

Single-Particle Energy (MeV)
The oxygen anomaly - impact of 3N forces

include ‘normal-ordered’ 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons

contributions from residual three valence-nucleon

interactions suppressed by

\[ \frac{E_{\text{ex}}}{E_F} \sim \frac{N_{\text{valence}}}{N_{\text{core}}} \]

The oxygen anomaly - impact of 3N forces

include ‘normal-ordered’ 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons

contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{\text{valence}}/N_{\text{core}}$


d$_{3/2}$ orbital remains unbound from $^{16}$O to $^{28}$O

microscopic explanation of the oxygen anomaly Otsuka et al., PRL (2010)
Oxygen spectra focused on bound excited states

NN only too compressed
3N contributions and extended valence space are key to reproduce excited states

CC theory:
0.35 MeV
Evolution to neutron-rich calcium isotopes

repulsive 3N contributions also key for calcium ground-state energies

Holt et al., arXiv:1009:5984

mass measured to $^{52}\text{Ca}$
shown to exist to $^{58}\text{Ca}$
Evolution to neutron-rich calcium isotopes

repulsive 3N contributions also key for calcium ground-state energies
Holt et al., arXiv:1009:5984

mass measured to $^{52}\text{Ca}$ shown to exist to $^{58}\text{Ca}$
predict drip-line around $^{60}\text{Ca}$, continuum contributions will be key
Three-body forces and magic numbers

no N=28 magic number from microscopic NN forces

Zuker, Poves,…
Three-body forces and magic numbers

3N mechanism important for shell structure
Holt et al., arXiv:1009:5984

N=28 shell closure due to 3N forces and single-particle effects ($^{41}$Ca)

N=34: predict high $2^+$ excitation energy in $^{54}$Ca at 3-5 MeV
Outline

Chiral effective field theory for nuclear forces

3N forces and neutron-rich nuclei

3N forces and neutron matter, impact on neutron stars

3N forces and electroweak currents

Contact: schwenk@physik.tu-darmstadt.de
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta \( \frac{1}{\lambda} = Q \ll \Lambda_b \) breakdown scale \( \sim 500 \) MeV

consistent **NN-3N** interactions

3N, 4N: only 2 new couplings to \( N^3\text{LO} \)

\[
\begin{array}{c|c|c}
\text{LO} & \mathcal{O}(Q^0) & \text{3N} \\
\hline
\text{NLO} & \mathcal{O}(Q^2) & - \\
\hline
\text{N^2LO} & \mathcal{O}(Q^3) & - \\
\hline
\text{N^3LO} & \mathcal{O}(Q^4) & - \\
\end{array}
\]

\( c_i \) from \( \pi N \) and NN \cite{Meissner2007}

\[
\begin{align*}
    c_1 &= -0.9^{+0.2}_{-0.5} \\
    c_3 &= -4.7^{+1.2}_{-1.0} \\
    c_4 &= 3.5^{+0.5}_{-0.2}
\end{align*}
\]

single-\( \Delta \): \( c_1 = 0, c_3 = -c_4/2 = -3 \) GeV\(^{-1} \)

\( c_D, c_E \) fit to \( ^3\text{H} \) binding energy and \( ^4\text{He} \) radius (or \( ^3\text{H} \) beta decay half-life)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,...
The oxygen anomaly - impact of 3N forces

include ‘normal-ordered’ 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons

contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$

\[ _{16}O \text{ core} \]


d$_{3/2}$ orbital remains unbound from $^{16}O$ to $^{28}O$

microscopic explanation of the oxygen anomaly Otsuka et al., PRL (2010)
Extreme neutron-rich matter in stars
Convergence with low-momentum interactions leads to flipped-potential bound states, even for small $-\lambda V$ requires nonperturbative expansion, leads to slow convergence for nuclei.
Convergence with low-momentum interactions

large cutoffs lead to flipped-potential bound states, even for small $-\lambda V$
requires nonperturbative expansion, leads to slow convergence for nuclei

Weinberg eigenvalue analysis: two-body scattering becomes perturbative
after RG evolution, except in channels with bound states

EFT and RG leads to improved convergence for nuclei and nuclear matter
Advances in nuclear matter theory

Is nuclear matter perturbative with chiral EFT and RG evolution?

exciting: empirical saturation with theoretical uncertainties
improved 3N treatment see also Holt, Kaiser, Weise (2010)

input to develop a universal energy density functional for all nuclei

UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional
Impact of 3N forces on neutron matter

Hebeler, AS (2010); Tolos, Friman, AS (2007)

only long-range parts of 3N forces contribute to neutron matter ($c_1$ and $c_3$)

neutron matter: many-body forces are predicted to N$^3$LO!

\[ V_{\text{low } k} \text{ NN from N}^3\text{LO (500)} \]

\[ 3\text{NF fit to } E_{3\text{H}} \text{ and } r_{4\text{He}} \]

\[ 0 < \Lambda_{3\text{NF}} < 2.5 \text{ fm}^{-1} \]
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta \( \frac{1}{\lambda} = Q \ll \Lambda_b \) breakdown scale \( \sim 500 \text{ MeV} \)

consistent **NN-3N** interactions

3N,4N: only 2 new couplings to \( N^3\text{LO} \)

Question: Why do the \( c_D \) and \( c_E \) terms not contribute to neutron matter?
Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\Lambda} = Q \ll \Lambda_b$ breakdown scale $\sim 500$ MeV

consistent NN-3N interactions

3N,4N: only 2 new couplings to $N^3\text{LO}$

$\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$

$\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$

$\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$

$\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$

$c_i$ from $\pi N$ and $NN$ Meissner et al. (2007)

$\begin{align*}
    c_1 &= -0.9^{+0.2}_{-0.5}, \\
    c_3 &= -4.7^{+1.2}_{-1.0}, \\
    c_4 &= 3.5^{+0.5}_{-0.2}
\end{align*}$

single-$\Delta$: $c_1=0$, $c_3=-c_4/2=-3 \text{ GeV}^{-1}$

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Meissner,…
Impact of 3N forces on neutron matter

Hebeler, AS (2010); Tolos, Friman, AS (2007)

only long-range parts of 3N forces contribute to neutron matter ($c_1$ and $c_3$)

uncertainties dominated by $c_3$ coupling
Impact of 3N forces on neutron matter

Hebeler, AS (2010); Tolos, Friman, AS (2007)

only long-range parts of 3N forces contribute to neutron matter ($c_1$ and $c_3$)

uncertainties dominated by $c_3$ coupling

microscopic calculations within band
Symmetry energy and neutron skin

Hebeler et al. (2010)

Neutron matter band predicts range for symmetry energy 30.1-34.4 MeV

<table>
<thead>
<tr>
<th>$c_1$ [GeV$^{-1}$]</th>
<th>$c_3$ [GeV$^{-1}$]</th>
<th>$\overline{S}_2$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.7</td>
<td>−2.2</td>
<td>30.1</td>
</tr>
<tr>
<td>−1.4</td>
<td>−4.8</td>
<td>34.4</td>
</tr>
</tbody>
</table>

NN-only EM          26.5
NN-only EGM         25.6

and neutron skin of $^{208}$Pb to 0.17±0.03 fm

Compare to ±0.05 fm future PREX goal
first result: 0.34+0.15-0.17 fm
from complete E1 response
0.156+0.025-0.021 fm Tamii et al., PRL (2011).
direct measurement of neutron star mass from increase in signal travel time near companion J1614-2230
most edge-on binary pulsar known (89.17°) + massive white dwarf companion (0.5 M_{\text{sun}})
heaviest neutron star with 1.97±0.04 M_{\text{sun}}
Neutron star structure determined by Tolman-Oppenheimer-Volkov eqn
\[
\frac{dP}{dr} = -\frac{GM\epsilon}{r^2} \left[ 1 + \frac{P}{\epsilon c^2} \right] \left[ 1 + \frac{4\pi r^3 P}{Mc^2} \right] \left[ 1 - \frac{2GM}{c^2r} \right]^{-1}
\]
with equation of state/pressure for neutron-star matter

\[\rho \sim P^{\Gamma}\]

pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included
extend uncertainty band to higher densities using piecewise polytropes

Impact on neutron stars
Hebeler et al., (2010)
Pressure of neutron star matter by Hebeler et al. (2010) constrain polytropes by causality and require to support 1.97 $M_{\text{sun}}$ star.

Low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state.
Neutron star radius constraints by Hebeler et al. (2010) constrain polytropes by causality and require to support $1.97 \, M_{\odot}$ star. Low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state.

Constrains neutron star radius: $10.9 - 13.9 \, \text{km for } M=1.4 \, M_{\odot}$ ($\pm 12\%$ !)
Neutron star radius constraints

constrain polytropes by causality and require to support 1.97 $M_{\odot}$ star

low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

constrains neutron star radius: 10.9-13.9 km for $M=1.4 \ M_{\odot}$ ($\pm 12\%$ !)
Comparison to astrophysics

constrain polytropes by causality and require to support 1.97 $M_{\text{sun}}$ star

constrains neutron star radius: $10.9-13.9$ km for $M=1.4$ $M_{\text{sun}}$ ($\pm 12\%$ !)


provides important constraints for EOS for core-collapse supernovae
Chiral EFT for electroweak transitions  

Menendez, Gazit, AS (2011).

two-body currents lead to important contributions in nuclei (Q~100 MeV) especially for Gamow-Teller transitions

two-body currents determined by NN, 3N couplings to N^3LO

Park et al., Phillips,…

explains part of quenching of g_A (dominated by long-range part)

+ predict momentum dependence (weaker quenching for larger p)
Chiral EFT for electroweak transitions Menendez, Gazit, AS (2011).

two-body currents lead to important contributions in nuclei ($Q \sim 100$ MeV) especially for Gamow-Teller transitions

two-body currents determined by NN, 3N couplings to N$^3$LO
Park et al., Phillips,…

extains part of quenching of $g_A$

+ predict mom. dependence

+ nuclear matrix elements for 0νββ decay based on chiral EFT operator
Thanks to collaborators!

T. Krüger, J. Menendez, V. Soma, I. Tews
S.K. Bogner
R.J. Furnstahl,
K. Hebeler
A. Nogga
J.D. Holt
T. Otsuka
T. Suzuki
Y. Akaishi
C.J. Pethick
J.M. Lattimer
D. Gazit
Summary

Exciting era with advances on many fronts: development of effective field theory and the renormalization group enables a unified description from nuclei to matter in astrophysics.

3N forces are a frontier for neutron-rich nuclei/matter:
key to explain why $^{24}$O is the heaviest oxygen isotope.

Ca isotopes and N=28 magic number, key for neutron-rich nuclei.

Dominant uncertainty of neutron (star) matter below nuclear densities, constraints on neutron star radii.

Exciting interactions with experiments and observations!