Non-empirical energy functionals from low-momentum interactions

II. Low-momentum interactions from renormalization group methods

T. Duguet[1,2]

[1]DSM/Irfu/SPhN, CEA Saclay, France

[2]National Superconducting Cyclotron Laboratory,
Department of Physics and Astronomy, Michigan State University, USA

Ecole Joliot-Curie, Lacanau, Sept. 27th - Oct 3rd, 2009

Lecture series

Outline

1. Introduction to energy density functional methods
2. Low-momentum interactions from renormalization group methods
   - Ideas underlying the renormalization group approach
   - Low-momentum interactions in the NN and NNN sectors
   - Ab-initio calculations of light nuclei
3. The building of non-empirical energy functionals

Outline

Outline

1. Introduction
   - Non-empirical energy functional
   - Nuclear Hamiltonian
   - Ideas underlying the renormalization group approach
2. Low-momentum interactions
   - Low-momentum interactions in the NN sector
   - Advantages for light-nuclei calculations
   - Low-momentum interactions in the NNN sector
3. Conclusions
4. Bibliography

Outline

Performance of empirical EDFs

Performance of existing EDFs

- Tremendous successes for known nuclei
- "Asymptotic freedom" as one enters "the next major shell"

Crucial undergoing works

- Enrich the analytical structure of empirical functionals
  1. Tensor terms, e.g. [T. Lesinski et al., PRC76, 014312]
  2. Higher-order derivatives [B. G. Carlsson et al., PRC78, 044326]
  3. $\rho_n - \rho_p$ dependence to $C_{qq}^{\tilde{\rho}\tilde{\rho}}(\vec{r})$, e.g. [J. Margueron *et al.*, PRC77, 054309]
- Improve fitting protocols = data, algorithm and post-analysis

One can also propose a complementary approach...

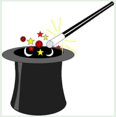
- Data not always constrain unambiguously non-trivial characteristics of EDF
- Interesting not to rely entirely on trial-and-error and fitting data

Constructing non-empirical EDFs for nuclei

Long term objective

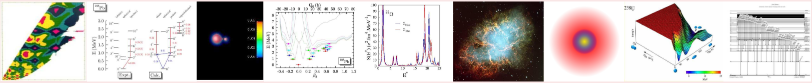
Build non-empirical EDF in place of existing models

Empirical



Predictive?

Finite nuclei and extended nuclear matter

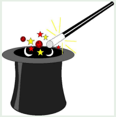


Constructing non-empirical EDFs for nuclei

Long term objective

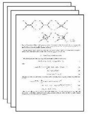
Build non-empirical EDF in place of existing models

Empirical



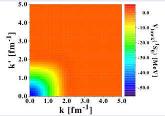
Predictive?

Non-empirical

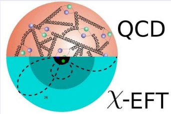


Predictive...

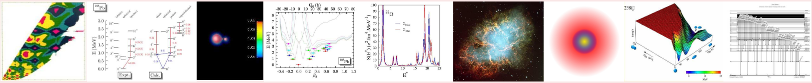
Low-k NN+NNN



QCD / χ-EFT



Finite nuclei and extended nuclear matter



Long term project and collaboration

Design *non-empirical* Energy Density Functionals

- Bridge with *ab-initio* many-body techniques
- Calculate properties of heavy/complex nuclei from NN+NNN
- Controlled calculations with theoretical error bars

SPhN	T. Duguet, J. Sadoudi, V. Soma
IPNL	K. Bennaceur, J. Meyer
TRIUMF	A. Schwenk, K. Hebeler, S. Baroni
NSCL	S. K. Bogner, B. Gebremariam
OSU	R. J. Furnstahl, L. Platter
ORNL	T. Lesinski
JULICH	A. Nogga

Take-away message

Renormalization group methods

1. "The" nuclear Hamiltonian H is a low-energy effective theory of QCD
2. H is characterized by an intrinsic "resolution scale" in energy/momentum Λ
3. One can optimize Λ of $H(\Lambda)$ to suit a certain purpose

Low momentum interactions

1. Obtained by lowering the "resolution scale" Λ of conventional potentials
2. Softer than conventional potentials
3. Simplify tremendously A-body calculations
4. Good starting point to build non-empirical energy functionals

Outline

Matrix elements representation of V^{NN}

Coordinates

$$\vec{k} \equiv \frac{\vec{k}_1 - \vec{k}_2}{2}$$
$$\vec{K} \equiv \vec{k}_1 + \vec{k}_2$$

Two-body (iso)spin

$|SM_S\rangle$ with $S = 0, 1$ and $-S \leq M_S \leq +S$

$|TM_T\rangle$ with $T = 0, 1$ and $-T \leq M_T \leq +T$

Two-body momentum $\otimes$ spin $\otimes$ isospin basis (no CIB/CSB)

$$\langle \vec{k}_1 \vec{k}_2 \,; SM_S \,; TM_T | V^{NN} | \vec{k}'_1 \vec{k}'_2 \,; SM_S \,; TM_T \rangle \equiv \langle \vec{k} | V_{ST} | \vec{k}' \rangle \, (2\pi)^3 \, \delta^3(\vec{K} - \vec{K}')$$

Main points

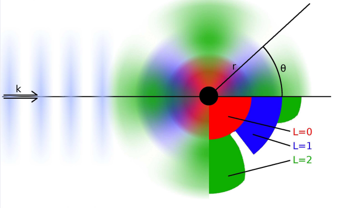
- V^{NN} decomposes in four spin-isospin channels (S, T)
- Focus on relative motion $\langle \vec{k} | V_{ST} | \vec{k}' \rangle$

Matrix elements representation of V^{NN}

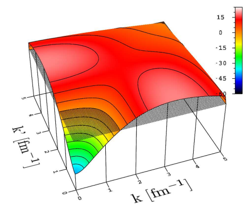
Partial-wave expansion of $\langle \vec{k} | V_{ST} | \vec{k}' \rangle$

$$\langle \vec{r} | \vec{k} \rangle = e^{i\mathbf{k}\cdot\mathbf{r}} = 4\pi \sum_{LM_L} i^L \, Y^{L*}_{M_L}(\hat{k}) \, Y^L_{M_L}(\hat{r}) \, j_L(kr) = 4\pi \sum_{LM_L} i^L \, Y^{L*}_{M_L}(\hat{k}) \, \langle \vec{r} | k\, L\, M_L \rangle$$

$$\mathcal{Y}^M_{(LS)J}(\hat{k}) \equiv \sum_{M_L M_S} \langle (LS) M_L M_S | JM \rangle \, Y^\ell_m(\hat{k}) \, |SM_S\rangle$$



$V^{JST}_{LL}(k,k')$ for ${}^{2S+1}L_J = {}^1S_0$

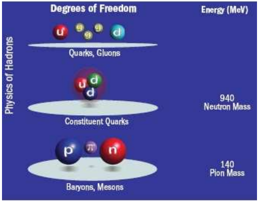


$$\langle \vec{k} | V_{ST} | \vec{k}' \rangle = \frac{\pi}{2} (4\pi)^2 \sum_{LL'JM} i^{L'-L} \mathcal{Y}^{M}_{(L'S)J}{}^{*} (\hat{k}') \mathcal{Y}^M_{(LS)J}(\hat{k}) \, V^{JST}_{LL'}(k,k')$$

Degrees of freedom, energy scales and nuclear Hamiltonian

Any $H(\Lambda) = T + V^{NN}(\Lambda) + V^{NNN}(\Lambda) + \ldots$

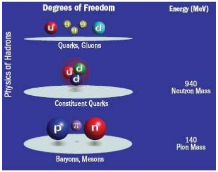
1. Describing point-like nucleons is *effective*
2. Includes a resolution scale Λ that cut-offs $k \gtrsim \Lambda$
3. Has necessarily up to A-body components



Degrees of freedom, energy scales and nuclear Hamiltonian

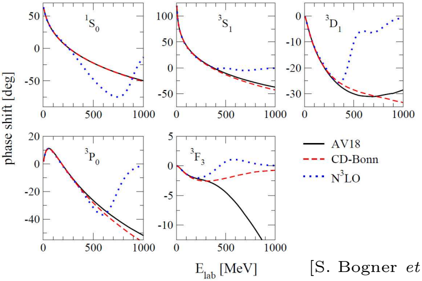
Any $H(\Lambda) = T + V^{NN}(\Lambda) + V^{NNN}(\Lambda) + \ldots$

1. Describing point-like nucleons is *effective*
2. Includes a resolution scale Λ that cut-offs $k \gtrsim \Lambda$
3. Has necessarily up to A-body components



High-momentum/short-range physics explicitly encoded characterized by Λ

- Most $H(\Lambda)$ have $\Lambda \gg \Lambda_{\text{data, physics}} \approx 2.1\ \text{fm}^{-1} \Leftrightarrow E_{lab} \approx 350$ MeV

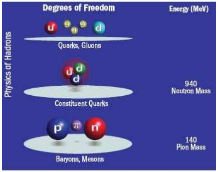


[S. Bogner *et al.*, PLB649, 488]

Degrees of freedom, energy scales and nuclear Hamiltonian

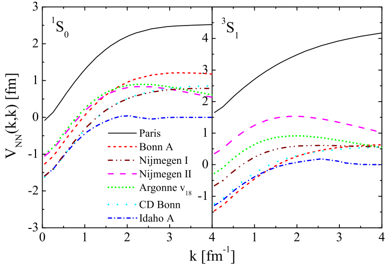
Any $H(\Lambda) = T + V^{NN}(\Lambda) + V^{NNN}(\Lambda) + \dots$

1. Describing point-like nucleons is *effective*
2. Includes a resolution scale Λ that cut-offs $k \gtrsim \Lambda$
3. Has necessarily up to A-body components

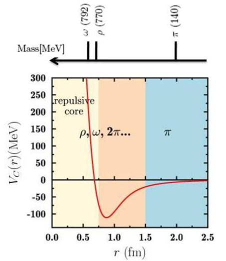


High-momentum/short-range physics explicitly encoded characterized by Λ

- Short-range modeling is essentially arbitrary!



[S. Bogner *et al.*, PR386, 1]



From [D. Lacroix]

Outline

Renormalization group considerations

I. If interested in low-energy observable $\langle O \rangle$

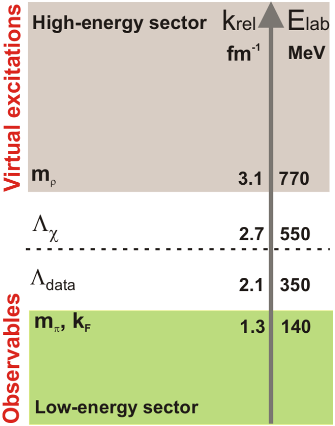
- Insensitive to high-k details of $H(\Lambda_{\text{high}})$

II. Use arbitrarily "simple" short-r/high-k model

- Only in relevant region $k, k' \leq \Lambda$
- Must not distort relevant long-r physics
- e.g. keep π-exchanges from χ-EFT untouched

III. $\partial_\Lambda \langle O \rangle \neq 0$ signals missing pieces

- Omitted V^{NNN},... in A-body calculation
- Incomplete A-body calculation



Renormalization group considerations

I. If interested in low-energy observable $\langle O \rangle$

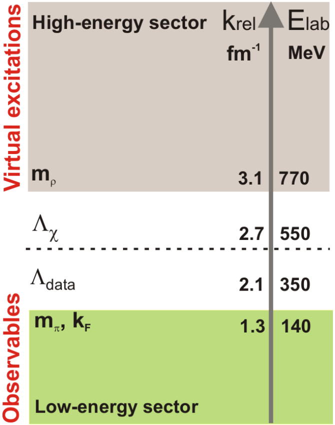
- Insensitive to high-k details of $H(\Lambda_{\text{high}})$

II. Use arbitrarily "simple" short-r/high-k model

- Only in relevant region $k, k' \leq \Lambda$
- Must not distort relevant long-r physics
- e.g. keep π-exchanges from χ-EFT untouched

III. $\partial_\Lambda \langle O \rangle \neq 0$ signals missing pieces

- Omitted $V^{NNN}, \ldots$ in A-body calculation
- Incomplete A-body calculation



Renormalization group considerations

I. If interested in low-energy observable $\langle O \rangle$

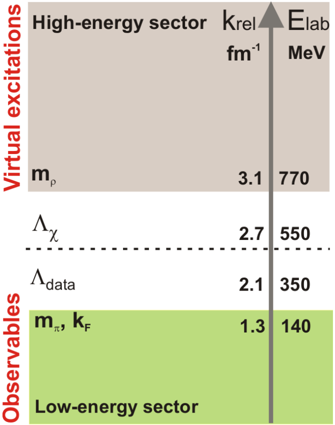
- Insensitive to high-k details of $H(\Lambda_{\text{high}})$

II. Use arbitrarily "simple" short-r/high-k model

- Only in relevant region $k, k' \leq \Lambda$
- Must not distort relevant long-r physics
- e.g. keep π-exchanges from χ-EFT untouched

III. $\partial_\Lambda \langle O \rangle \neq 0$ signals missing pieces

- Omitted $V^{NNN}, \ldots$ in A-body calculation
- Incomplete A-body calculation



Renormalization group considerations

I. If interested in low-energy observable $\langle O \rangle$

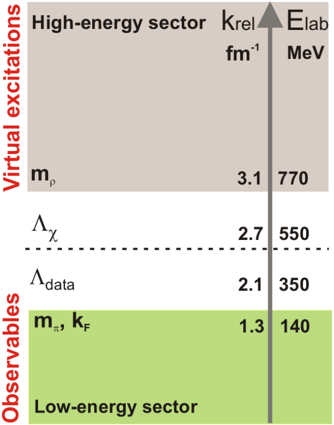
- Insensitive to high-k details of $H(\Lambda_{\text{high}})$

II. Use arbitrarily "simple" short-r/high-k model

- Relevant info encoded in Λ-dependent couplings
- Must not distort relevant long-r physics
- e.g. keep π-exchanges from χ-EFT untouched

III. $\partial_\Lambda \langle O \rangle \neq 0$ signals missing pieces

- Omitted $V^{NNN}, \ldots$ in A-body calculation
- Incomplete A-body calculation



Conclusion: run down Λ to $\sim \Lambda_{\text{data}}$

- Take $\Lambda < \Lambda_\chi$ to further decouple unconstrained/irrelevant high-k modes
- Keep $\Lambda > m_\pi$ to maintain χ-EFT hierarchy $V^{NN} \gg V^{NNN} \gg V^{NNNN} \gg \ldots$
- Huge by-product: $H(\Lambda_{\text{low}})$ is softer and makes A-body calculations simpler

Outline

Outline

Renormalization-group flow equation in the NN sector

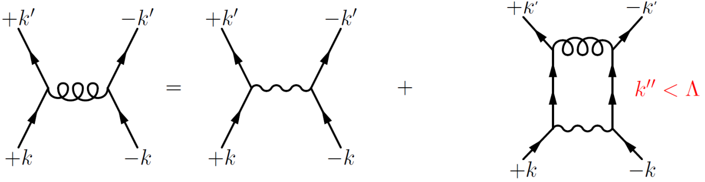
Phase-shifts at given Λ (uncoupled partial-wave)

- Lipmann-Schwinger equation for the T-matrix with $k, k' \leq \Lambda$

$$T_L^{JST}(k,k';E;\Lambda) = \frac{m}{\hbar^2} V_{LL}^{JST}(k,k';\Lambda) + \frac{2}{\pi}\mathcal{P}\int_0^\Lambda k''^2\,\mathrm{d}k''\,\frac{V_{LL}^{JST}(k,k'';\Lambda)\,T_L^{JST}(k'',k;E;\Lambda)}{E-\hbar^2\,k''^2/m}$$

- Phase-shifts obtained from the "fully-on-shell" T-matrix

$$\tan\delta_L^{JST}(k;\Lambda) \equiv -k\,T_L^{JST}(k,k;\hbar^2\,k^2/m;\Lambda)$$



Renormalization-group flow equation in the NN sector

Lower Λ of V^{NN} (uncoupled partial-wave)

- Maintain $\delta_L^{JST}(k;\Lambda)$ for $k \leq \Lambda$ and $E_{\mathrm{Deuteron}} = 2.2$ MeV invariant

$$\frac{\mathrm{d}\, T_L^{JST}(k,k';\hbar^2\, k^2/m;\Lambda)}{\mathrm{d}\,\Lambda} = 0$$

- This leads to a RG flow equation for $V_{LL}^{JST}(k,k';\Lambda)$ with $k,k' \leq \Lambda$

$$\frac{\mathrm{d}}{\mathrm{d}\,\Lambda} V_{LL}^{JST}(k',k;\Lambda) = \frac{2}{\pi} \frac{V_{LL}^{JST}(k',k;\Lambda)\, T_{LL}^{JST}(\Lambda,k;\hbar^2\,\Lambda^2/2m;\Lambda)}{1-(k/\Lambda)^2}$$

- Keeping $\delta_L^{JST}(k;\Lambda)$ independent of Λ implies $\partial_\Lambda V^{NN}(k,k';\Lambda) \neq 0$

Boundary conditions to solve RG flow equation

1. Start from an existing model $V^{NN}(k,k';\Lambda_{\mathrm{high}})$ (0 for k or $k' \geq \Lambda_{\mathrm{high}}$)

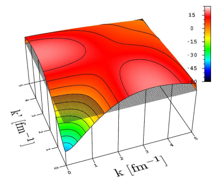
$$V_{LL}^{JST}(k,k';\Lambda_0) \equiv V_{LL}^{JST}(k,k';\Lambda_{\mathrm{high}})$$

2. Run down Λ down to $\sim \Lambda_{\mathrm{data}}$

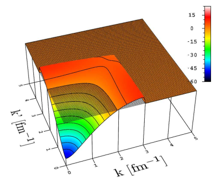
Renormalization-group flow equation in the NN sector

Example of (non-unitary) RG flow in $^1S_0$ channel

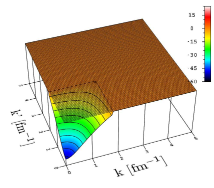
- Evolution performed through Lee-Suzuki transformation in practice
- Start from AV18 NN potential



$\Lambda = 5.0\ \text{fm}^{-1}$



$\Lambda = 3.0\ \text{fm}^{-1}$



$\Lambda = 1.8\ \text{fm}^{-1}$

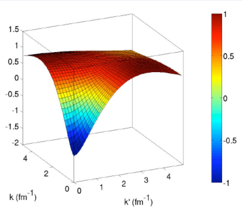
Results

1. $V^{NN}(k', k; \Lambda)$ changes because $H(\Lambda)$ is not observable; $\langle\Psi(\Lambda)|H(\Lambda)|\Psi(\Lambda)\rangle$ is
2. Non-unitary evolution but not a trivial cut of matrix elements beyond Λ!
   - Matrix elements beyond Λ are renormalized onto those below Λ
   - No off-diagonal matrix element coupling low-k and high-k left

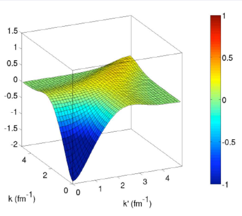
Renormalization-group flow equation in the NN sector

Example of (unitary) RG flow in $^1S_0$ channel

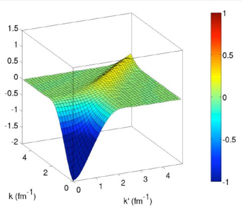
- It exists a unitary RG method: the Similarity Renormalization Group (SRG)
- Start from AV18 NN potential



$\Lambda = 10.0\ \mathrm{fm}^{-1}$



$\Lambda = 3.0\ \mathrm{fm}^{-1}$



$\Lambda = 2.0\ \mathrm{fm}^{-1}$

[S. Bogner, private communication]

Comparison with non-unitary evolution

1. Unitary evolution only adds diagonal band to keep $\delta_L^{JST}(k)$ unchanged at all k
2. Low-energy sector + decoupling of low- and high-k modes the same

Renormalization-group flow equation in the NN sector

Dependence on Λ_0

- Start from various $V^{NN}(\Lambda_{\mathrm{high}})$
- Universal $V^{NN}(\Lambda \approx 2) \equiv V_{\mathrm{low\ k}}$
- Model-dependence screened-out

Phase shifts $\delta_L^{JST}(k)$

- Unchanged for $k \leq \Lambda$ at all Λ

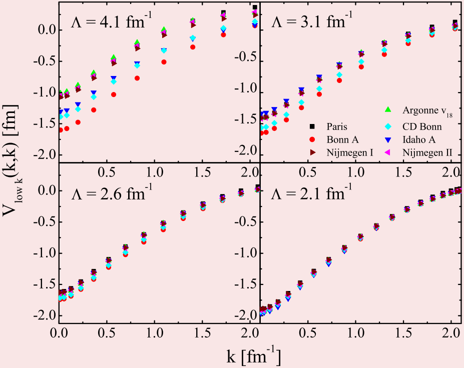
Deuteron properties

- Binding energy invariant
- Wave-function unchanged

$V^{NN}(\Lambda)$ = vacuum interaction

- Energy/density independent
- It is not a G-matrix in disguise!
- Low/high k not decoupled by G

Convergence of the RG flow in $^3S_1$ channel



[S. Bogner *et al.*, PR386, 1]

Renormalization-group flow equation in the NN sector

Dependence on $V^{NN}(\Lambda_0)$

- Start from various $V^{NN}(\Lambda_{\text{high}})$
- Universal $V^{NN}(\Lambda \approx 2) \equiv V_{\text{low k}}$
- Model-dependence screened-out

Phase shifts $\delta_L^{JST}(k)$

- Unchanged for $k \leq \Lambda$ at all Λ

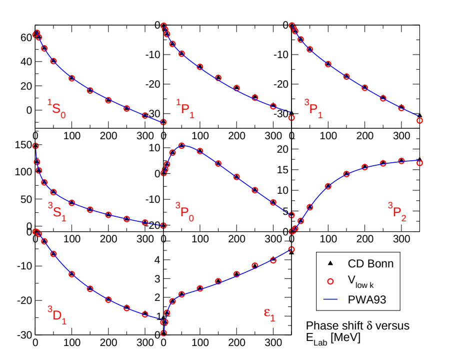
Deuteron properties

- Binding energy invariant
- Wave-function unchanged

$V^{NN}(\Lambda)$ = vacuum interaction

- Energy/density independent
- It is not a G-matrix in disguise!
- Low/high k not decoupled by G

Phase shifts in various partial waves



[S. Bogner, private communication]

Renormalization-group flow equation in the NN sector

Dependence on $V^{NN}(\Lambda_0)$

- Start from various $V^{NN}(\Lambda_{\text{high}})$
- Universal $V^{NN}(\Lambda \approx 2) \equiv V_{\text{low k}}$
- Model-dependence screened-out

Phase shifts $\delta_L^{JST}(k)$

- Unchanged for $k \leq \Lambda$ at all Λ

Deuteron properties

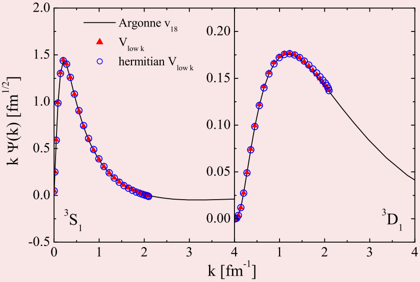
- Binding energy invariant
- Wave-function unchanged

$V^{NN}(\Lambda)$ = vacuum interaction

- Energy/density independent
- It is not a G-matrix in disguise!
- Low/high k not decoupled by G

Deuteron binding energy and wave function

V^{NN}	E_{Deuteron} [MeV]
Arg. v_{18}	-2.2247
$V_{\text{low k}}(2.1)$	-2.2247



[S. Bogner *et al.*, PR386, 1]

Renormalization-group flow equation in the NN sector

Dependence on $V^{NN}(\Lambda_0)$

- Start from various $V^{NN}(\Lambda_{\text{high}})$
- Universal $V^{NN}(\Lambda \approx 2) \equiv V_{\text{low k}}$
- Model-dependence screened-out

Phase shifts $\delta_L^{JST}(k)$

- Unchanged for $k \leq \Lambda$ at all Λ

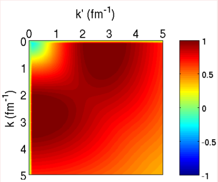
Deuteron properties

- Binding energy invariant
- Wave-function unchanged

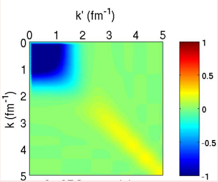
$V^{NN}(\Lambda)$ = vacuum interaction

- Energy/density independent
- It is not a G-matrix in disguise!
- Low/high k not decoupled by G

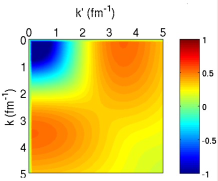
Comparison with G-matrix in $^3S_1$ channel



$\Lambda = \Lambda_{\text{high}}$



$\Lambda = 2.0\ \text{fm}^{-1}$



G matrix

[S. Bogner, private communication]

Outline

Advantage to use Λ_{low} for nuclear structure calculations

Why bother if things like $\delta_L^{JST}(k)$ and E_{Deuteron} remain unchanged?

- Because non-observable features are Λ-dependent
  1. Correlations in wave-functions $|\Psi(\Lambda)\rangle$
  2. Convergence in calculations, e.g. of $E = \langle\Psi(\Lambda)|H(\Lambda)|\Psi(\Lambda)\rangle$
- Take advantage to perform technically simpler calculations!

Advantage to use Λ_{low} for nuclear structure calculations

Why bother if things like $\delta_L^{JST}(k)$ and E_{Deuteron} remain unchanged?

- Non-observable features are Λ-dependent
  - Correlations in wave-functions $|\Psi(\Lambda)\rangle$
  - Convergence in calculations, e.g. of $E = \langle\Psi(\Lambda)|H(\Lambda)|\Psi(\Lambda)\rangle$
- Take advantage to perform technically simpler calculations!

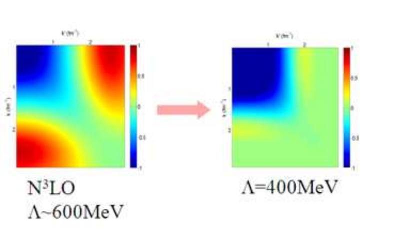
In NN sector

- $V^{NN}(\Lambda_{\text{low}})$ smoother in k-space
- $V^{NN}(\Lambda_{\text{low}})$ smoother in HO basis

In NNN sector

- Λ_{low} provides better convergence
- Same for larger A-body system
- What about Λ-dependence of $E_{^3\text{H}}$?

Softening of V^{NN} in k-space



[S. Bogner, private communication]

Advantage to use Λ_{low} for nuclear structure calculations

Why bother if things like $\delta_L^{JST}(k)$ and E_{Deuteron} remain unchanged?

- Non-observable features are Λ-dependent
  - Correlations in wave-functions $|\Psi(\Lambda)\rangle$
  - Convergence in calculations, e.g. of $E = \langle\Psi(\Lambda)|H(\Lambda)|\Psi(\Lambda)\rangle$
- Take advantage to perform technically simpler calculations!

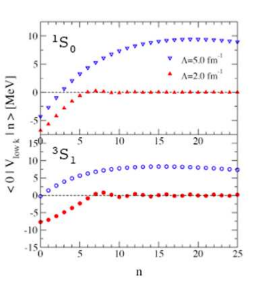
In NN sector

- $V^{NN}(\Lambda_{\text{low}})$ smoother in k-space
- $V^{NN}(\Lambda_{\text{low}})$ smoother in HO basis

In NNN sector

- Λ_{low} provides better convergence
- Same for larger A-body system
- What about Λ-dependence of $E_{^3\text{H}}$?

Softening of V^{NN} in HO basis



[A. Schwenk, private communication]

Advantage to use Λ_{low} for nuclear structure calculations

Why bother if things like $\delta_L^{JST}(k)$ and E_{Deuteron} remain unchanged?

- Non-observable features are Λ-dependent
  - Correlations in wave-functions $|\Psi(\Lambda)\rangle$
  - Convergence in calculations, e.g. of $E = \langle\Psi(\Lambda)|H(\Lambda)|\Psi(\Lambda)\rangle$
- Take advantage to perform technically simpler calculations!

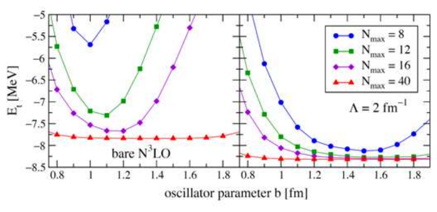
In NN sector

- $V^{NN}(\Lambda_{\text{low}})$ smoother in k-space
- $V^{NN}(\Lambda_{\text{low}})$ smoother in HO basis

In NNN sector

- Λ_{low} provides better convergence
- Same for larger A-body system
- What about Λ-dependence of $E_{^3\text{H}}$?

NCSM calculation of ^{3}H



[P. Navratil *et al.*, private communication]

Outline

Induced many-body forces

RG evolution induces up to A-body forces in A-body system

1. Well known from Lee-Suzuki effective-interaction theory
2. Most easily seen from SRG [S. Bogner *et al.*, AP323, 1478]

$$\frac{\mathrm{d}H(\Lambda)}{\mathrm{d}\Lambda} = -\frac{4}{\Lambda^5}\Big[\Big[T, H(\Lambda)\Big], H(\Lambda)\Big] \propto \Big[\Big[\sum c^\dagger c, \sum_{\text{2-body}} c^\dagger c^\dagger c\, c\Big], \sum_{\text{2-body}} c^\dagger c^\dagger c\, c\Big]$$

$$\propto \ldots + \sum_{\text{3-body}} c^\dagger c^\dagger c^\dagger c\, c\, c + \ldots$$

3. Is it a problem?
   - Not if remain of "natural size", i.e. follow χ-EFT power counting
   - Λ-dependence of A-body observables used to assess truncation errors
4. A-body forces are a priori present at Λ_0 anyway
   - Might as well develop (S)RG machinery to make them soft
   - Recently achieved through SRG method [E. D. Jurgenson *et al.*, PRL103, 082501]
5. What are the results?

Induced many-body forces in three- and four-body systems

For V^{NN} only

1. Tjon line suggests missing V^{NNN}
2. $\Delta E_{^3\mathrm{H}} \sim 0.6$ MeV for $\Lambda \in [2, \infty]$
3. Non-negligible but $\ll \langle V^{NN}(\Lambda)\rangle_\Lambda$

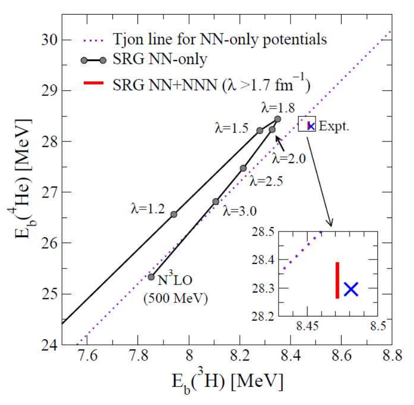
Including induced V^{NNN}

1. Break away from Tjon line
2. $\partial_\Lambda E_{^3\mathrm{H}} = 0$ for all Λ
3. $\langle V^{NNN}(\Delta\Lambda)\rangle_\Lambda \sim \langle V^{NNN}(\Lambda_0)\rangle_{\Lambda_0}$
4. But net $V^{NNN}(\Lambda_{\mathrm{low}})$ much softer!

Induced V^{NNNN}?

1. $\partial_\Lambda E_{^4\mathrm{He}} \approx 0$ for $\Lambda \in [2, \infty]$
2. Negligible in ^{4}He
3. To be monitored in heavier nuclei!

Tjon line: $E_{^3\mathrm{H}}$ versus $E_{^4\mathrm{He}}$



[E. D. Jurgenson *et al.*, PRL103, 082501]

Induced many-body forces in three- and four-body systems

For V^{NN} only

1. Tjon line suggests missing V^{NNN}
2. $\Delta E_{^3\mathrm{H}} \sim 0.6$ MeV for $\Lambda \in [2, \infty]$
3. Non-negligible but $\ll \langle V^{NN}(\Lambda)\rangle_\Lambda$

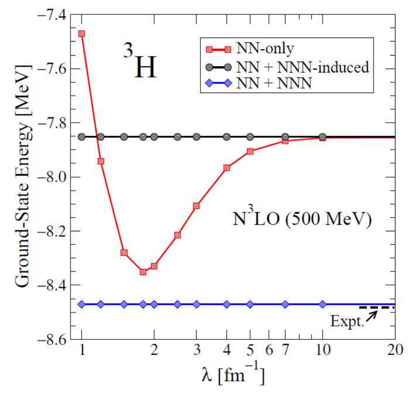
Including induced V^{NNN}

1. Break away from Tjon line
2. $\partial_\Lambda E_{^3\mathrm{H}} = 0$ for all Λ
3. $\langle V^{NNN}(\Delta\Lambda)\rangle_\Lambda \sim \langle V^{NNN}(\Lambda_0)\rangle_{\Lambda_0}$
4. But net $V^{NNN}(\Lambda_{\mathrm{low}})$ much softer!

Induced V^{NNNN}?

1. $\partial_\Lambda E_{^4\mathrm{He}} \approx 0$ for $\Lambda \in [2, \infty]$
2. Negligible in ^{4}He
3. To be monitored in heavier nuclei!

NCSM calculation of ^{3}H



[E. D. Jurgenson *et al.*, PRL103, 082501]

Induced many-body forces in three- and four-body systems

For V^{NN} only

1. Tjon line suggests missing V^{NNN}
2. $\Delta E_{^3\mathrm{H}} \sim 0.6$ MeV for $\Lambda \in [2, \infty]$
3. Non-negligible but $\ll \langle V^{NN}(\Lambda)\rangle_\Lambda$

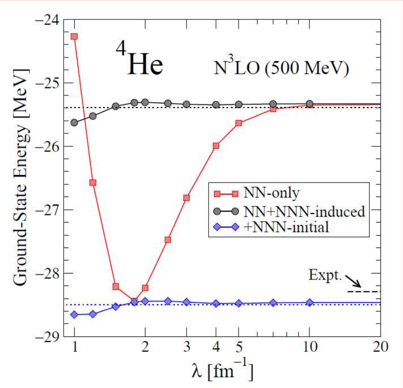
Including induced V^{NNN}

1. Break away from Tjon line
2. $\partial_\Lambda E_{^3\mathrm{H}} = 0$ for all Λ
3. $\langle V^{NNN}(\Delta\Lambda)\rangle_\Lambda \sim \langle V^{NNN}(\Lambda_0)\rangle_{\Lambda_0}$
4. But net $V^{NNN}(\Lambda_{\mathrm{low}})$ much softer!

Induced V^{NNNN}?

1. $\partial_\Lambda E_{^4\mathrm{He}} \approx 0$ for $\Lambda \in [2, \infty]$
2. Negligible in ^{4}He
3. To be monitored in heavier nuclei!

NCSM calculation of ^{4}He



[E. D. Jurgenson *et al.*, PRL103, 082501]

Outline

Conclusions

New paradigm for nuclear interactions

1. The "hard core" is not an absolute feature of $H(\Lambda)$
2. $H(\Lambda_{\text{high}})$ models hurt, i.e. A-body is highly non-perturbative
3. As the doctor says "if it hurts, just don't do it!"

Use $H(\Lambda_{\text{low}})$ for low-energy studies

1. Keep $m_\pi, k_F < \Lambda_{\text{low}} \leq \Lambda_{\text{data}}$
2. Simplifies tremendously ab-initio calculations of light-nuclei
3. V^{NNN} unavoidable
   - What about V^{NNNN} in heavy nuclei?
   - What about the power counting at finite density?

What about EDF calculations now?

1. See how low-momentum interactions do for infinite nuclear matter EOS
2. Build EDF from many-body perturbation theory
3. Approximate such still-too-complicated EDF
   - Constrain Skyrme- or Gogny-like energy functionals

Conclusions

New paradigm for nuclear interactions

1. The "hard core" is not an absolute feature of $H(\Lambda)$
2. $H(\Lambda_{\text{high}})$ models hurt, i.e. A-body is highly non-perturbative
3. As the doctor says "if it hurts, just don't do it!"

Use $H(\Lambda_{\text{low}})$ for low-energy studies

1. Keep $m_\pi, k_F < \Lambda_{\text{low}} \leq \Lambda_{\text{data}}$
2. Simplifies tremendously ab-initio calculations of light-nuclei
3. V^{NNN} unavoidable
   - What about V^{NNNN} in heavy nuclei?
   - What about the power counting at finite density?

What about EDF calculations now?

1. See how low-momentum interactions do for infinite nuclear matter EOS
2. Build EDF from many-body perturbation theory
3. Approximate such still-too-complicated EDF
   - Constrain Skyrme- or Gogny-like energy functionals

Conclusions

New paradigm for nuclear interactions

1. The "hard core" is not an absolute feature of $H(\Lambda)$
2. $H(\Lambda_{\mathrm{high}})$ models hurt, i.e. A-body is highly non-perturbative
3. As the doctor says "if it hurts, just don't do it!"

Use $H(\Lambda_{\mathrm{low}})$ for low-energy studies

1. Keep $m_\pi, k_F < \Lambda_{\mathrm{low}} \leq \Lambda_{\mathrm{data}}$
2. Simplifies tremendously ab-initio calculations of light-nuclei
3. V^{NNN} unavoidable
   - What about V^{NNNN} in heavy nuclei?
   - What about the power counting at finite density?

What about EDF calculations now?

1. See how low-momentum interactions do for infinite nuclear matter EOS
2. Build EDF from many-body perturbation theory
3. Approximate such still-too-complicated EDF
   - Constrain Skyrme- or Gogny-like energy functionals

Outline

Selected bibliography

S. Kehrein,
The flow equation approach to many-particle systems, 2006, Springer-Verlag, Berlin

S. D. Glazek, K. G. Wilson,
Phys. Rev. D48 (1993) 5863

S. K. Bogner, T. T. S. Kuo, A. Schwenk,
Phys. Rept. 386 (2003) 1

S. K. Bogner, R. G. Furnstahl, R. J. Perry,
Phys. Rev. C75 (2007) 061001

S. K. Bogner, R. G. Furnstahl, R. J. Perry, A. Schwenk,
Phys. Lett. B649 (2007) 488

S. K. Bogner, R. G. Furnstahl, R. J. Perry,
Ann. Phys. 323 (2008) 1478

E. D. Jurgenson, P. Navratil, R. G. Furnstahl,
Phys. Rev. Lett. 103 (2009) 082501