Chiral EFT Expansion in Light Nuclei

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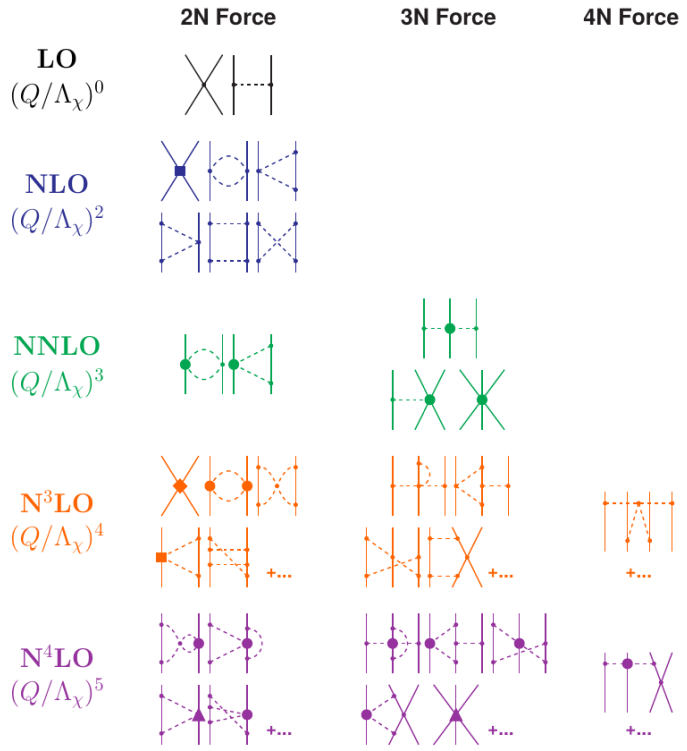
Outline

Motivation

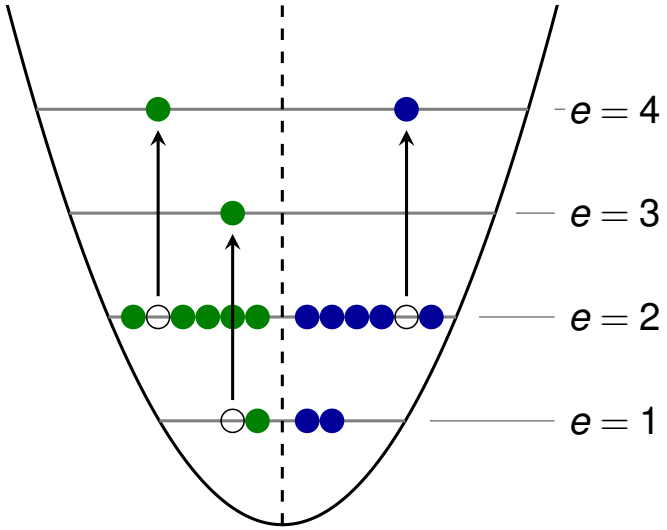
- ab initio nuclear structure
  - solving the nuclear many-body problem with realistic interactions
  - use controlled and improvable truncations
  - quantification of theoretical uncertainties
  - convergence with respect to truncations
- chiral effective field theory (EFT)
  - systematic and improvable
  - full quantification of theory uncertainties



arXiv:1703.05454[nucl-th](2017)

No-Core Shell Model

- model space constructed out of antisymmetric harmonic-oscillator states
- total excitation energy is truncated by $N_{\max}\,\hbar\omega$
- solve eigenvalue problem
- exact solution for $N_{\max} \to \infty$



example basis configuration for ^{16}O with $N_{\max} \geq 6$

Similarity Renormalization Group

- SRG aims to decouple low- and high-momentum states
- accelerate the convergence of many-body calculations with model-space size
- continuous unitary transformation via flow equation approach

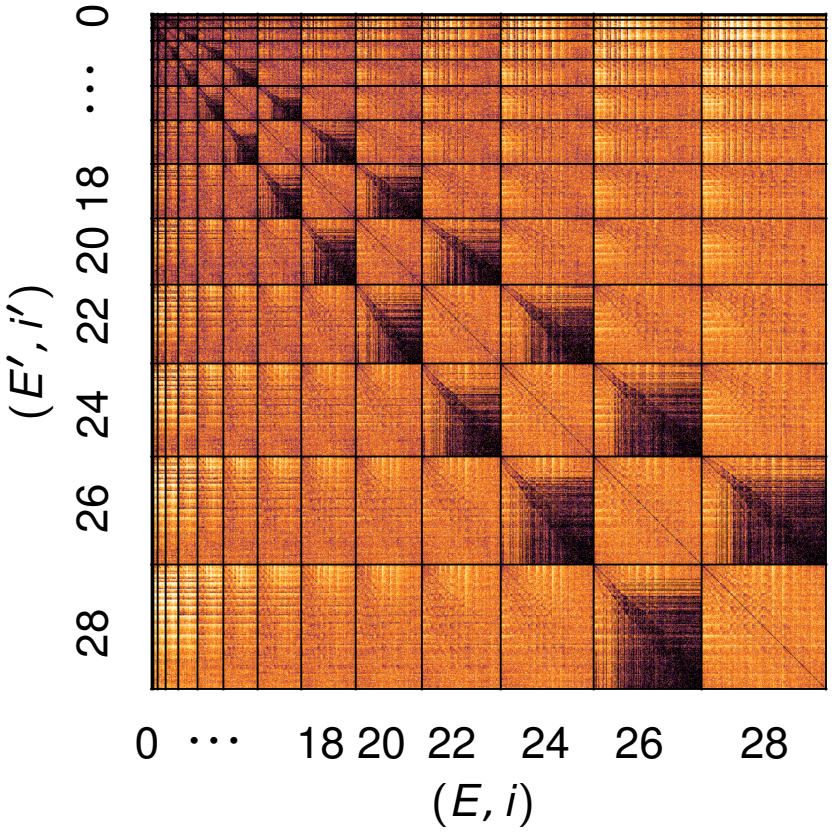
$$\boldsymbol{H}_\alpha = \boldsymbol{U}_\alpha^\dagger \boldsymbol{H}_0 \boldsymbol{U}_\alpha \qquad \Rightarrow \qquad \frac{\mathrm{d}\boldsymbol{H}_\alpha}{\mathrm{d}\alpha} = [\boldsymbol{\eta}_\alpha, \boldsymbol{H}_\alpha]$$

- antihermitian dynamic generator

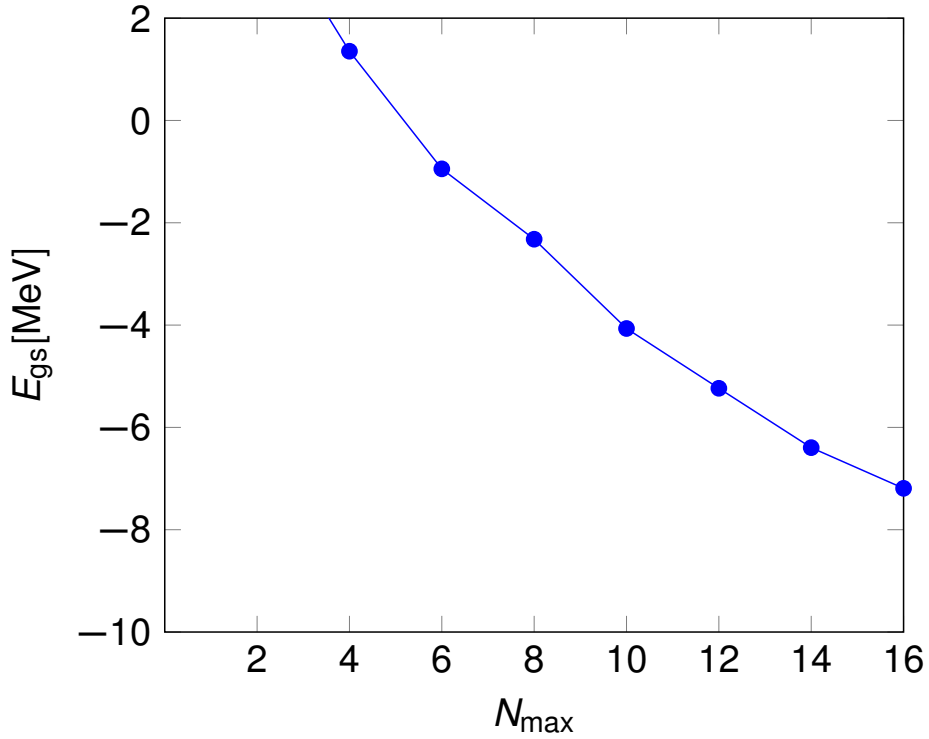
$$\boldsymbol{\eta}_\alpha = (2\mu)^2 [\boldsymbol{T}_{\mathrm{int}}, \boldsymbol{H}_\alpha]$$

- SRG induces forces with higher particle rank
- solve flow equations in two- and three-body space

^{3}H SRG Evolution with α =0.0 fm^4

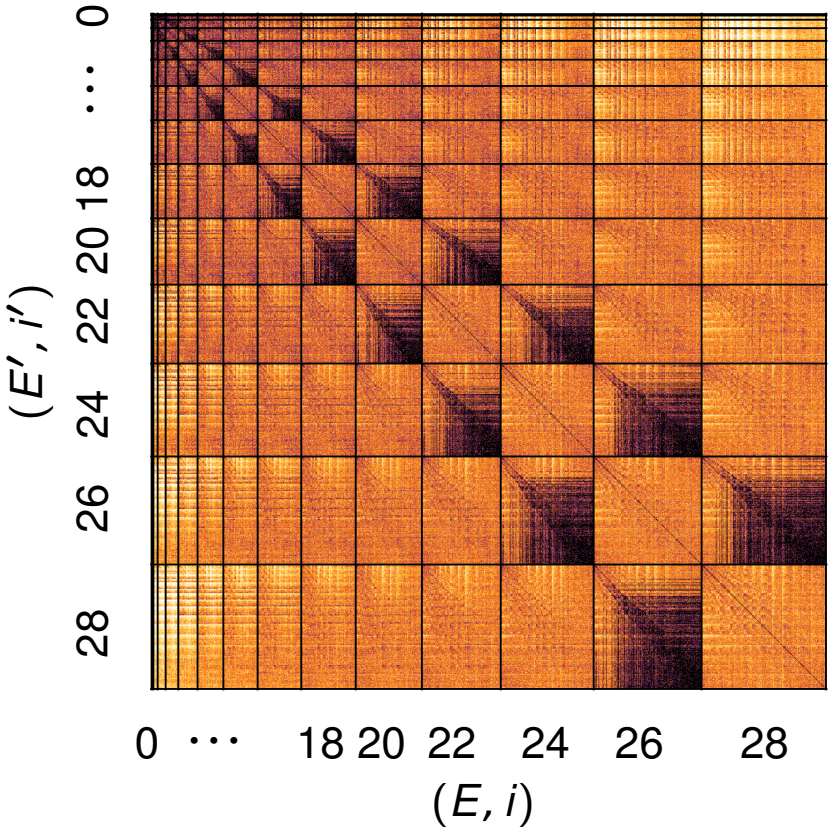


^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis

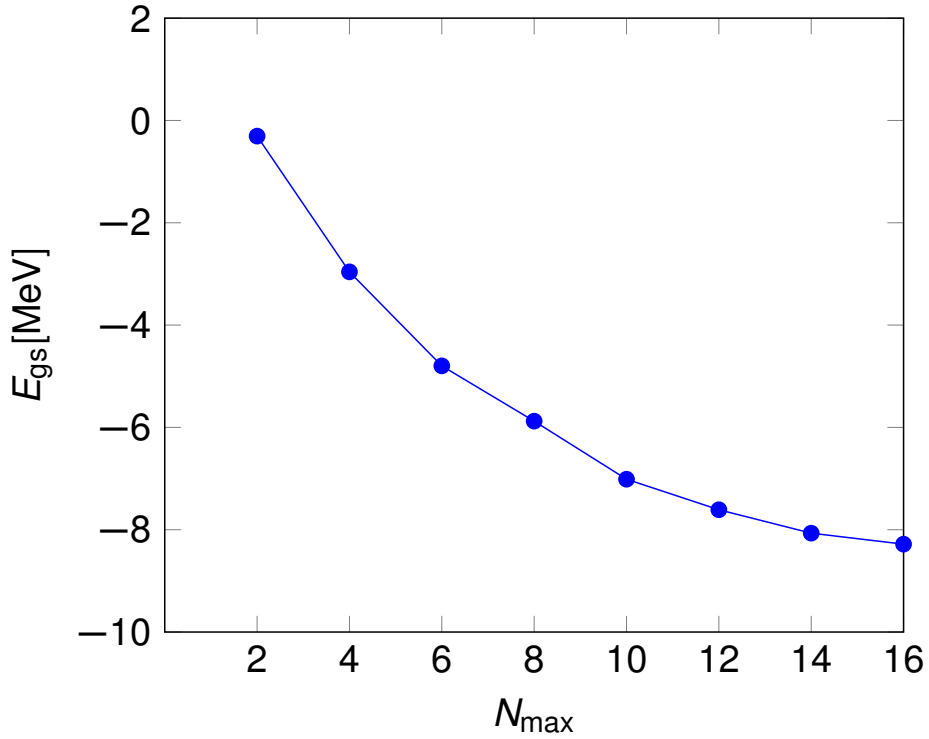


^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

^{3}H SRG Evolution with α =0.01 fm^4

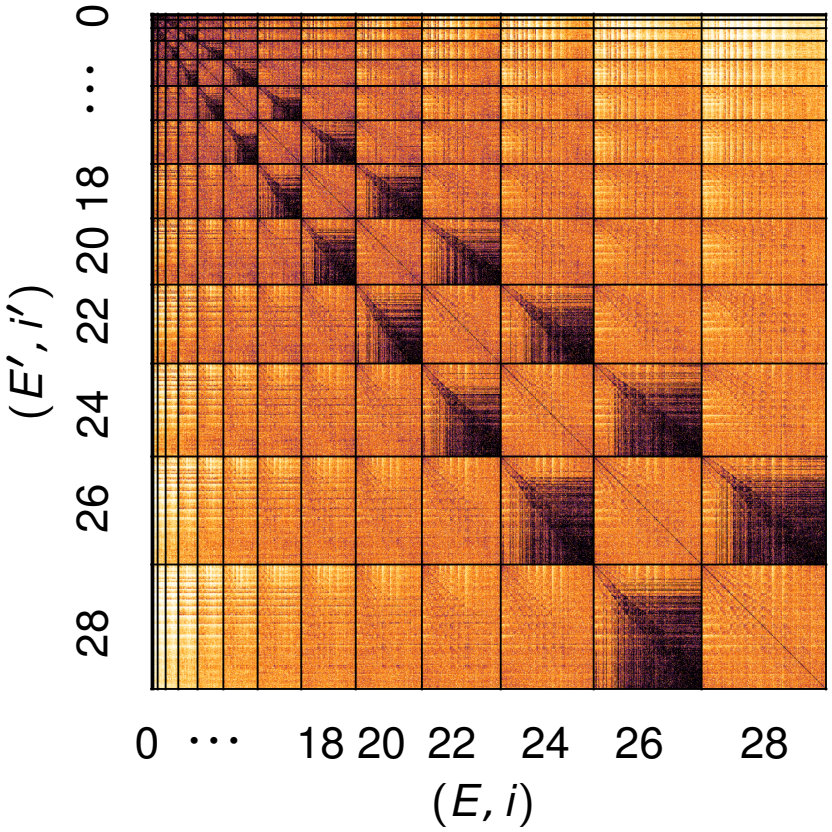


^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis

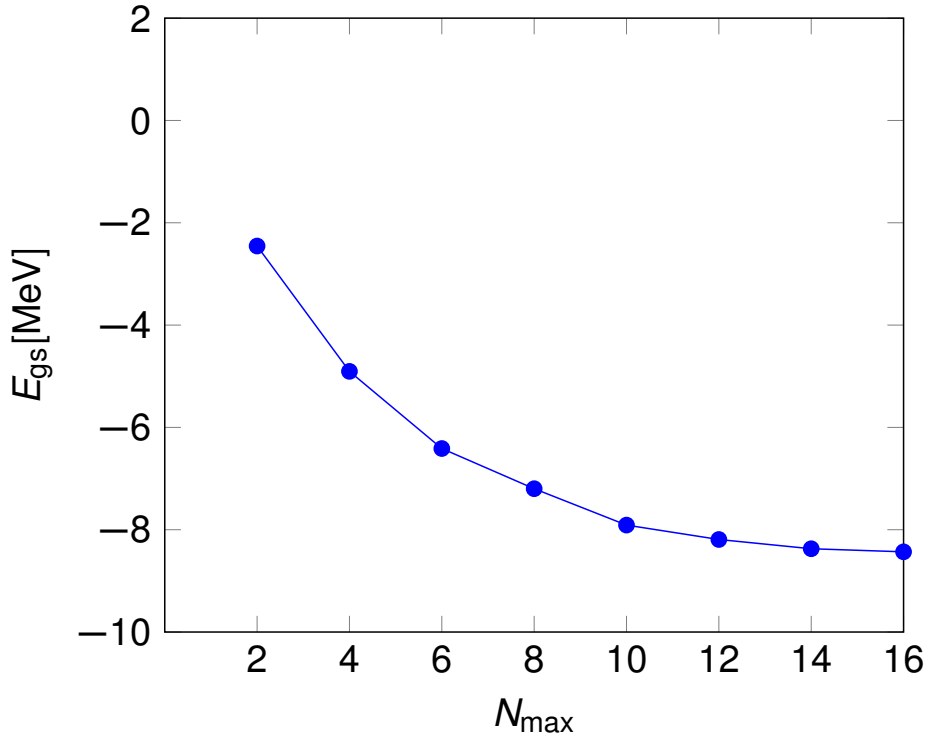


^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

^{3}H SRG Evolution with α =0.02 fm^4

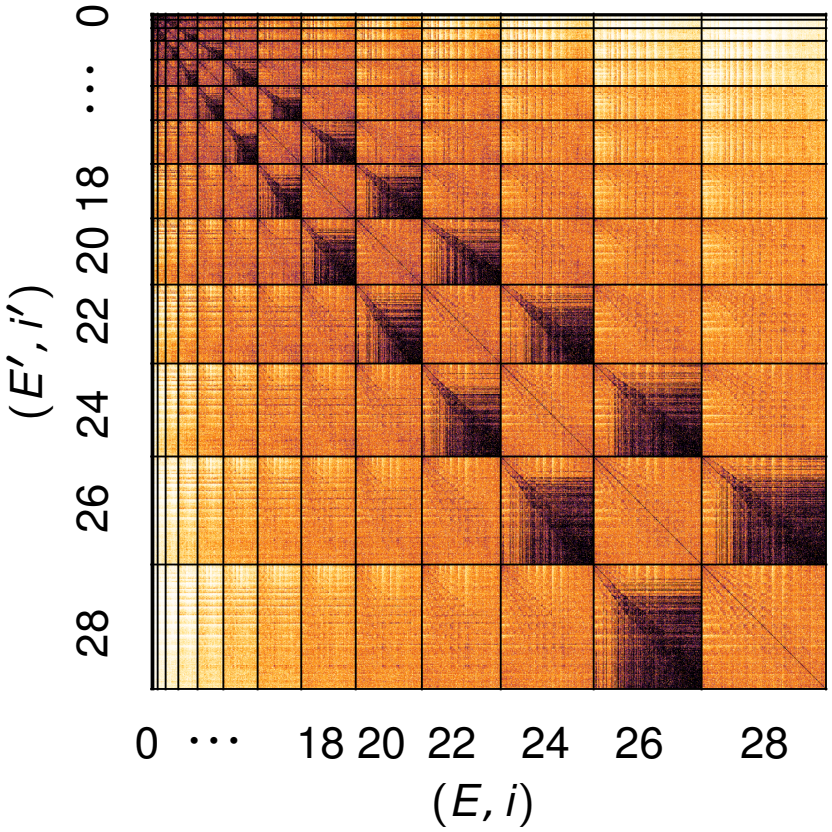


^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis

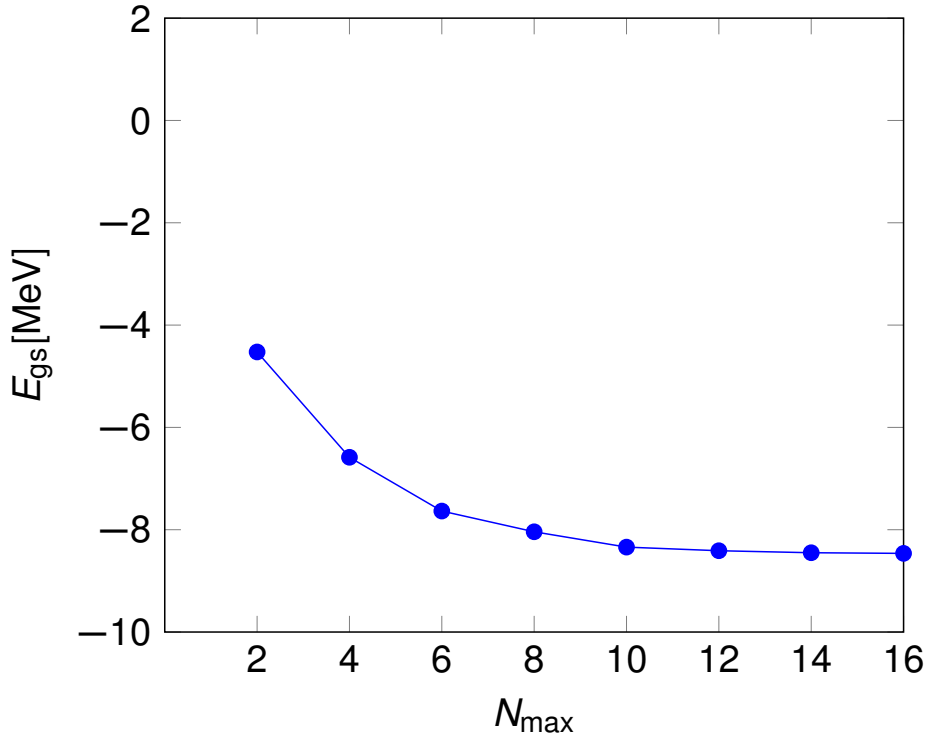


^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

^{3}H SRG Evolution with α =0.04 fm^4

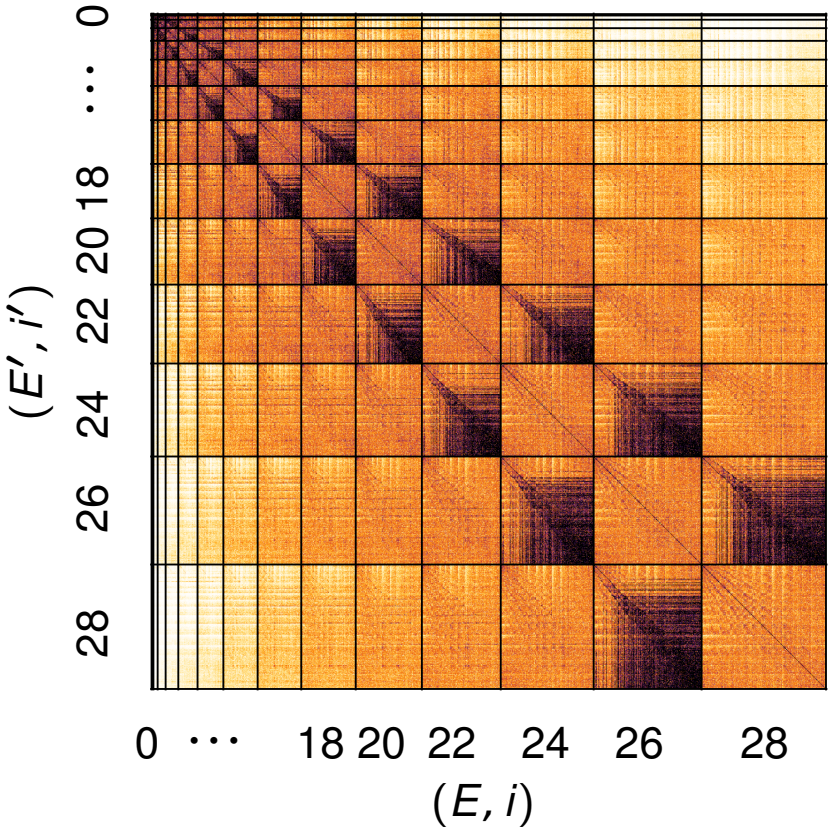


^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis

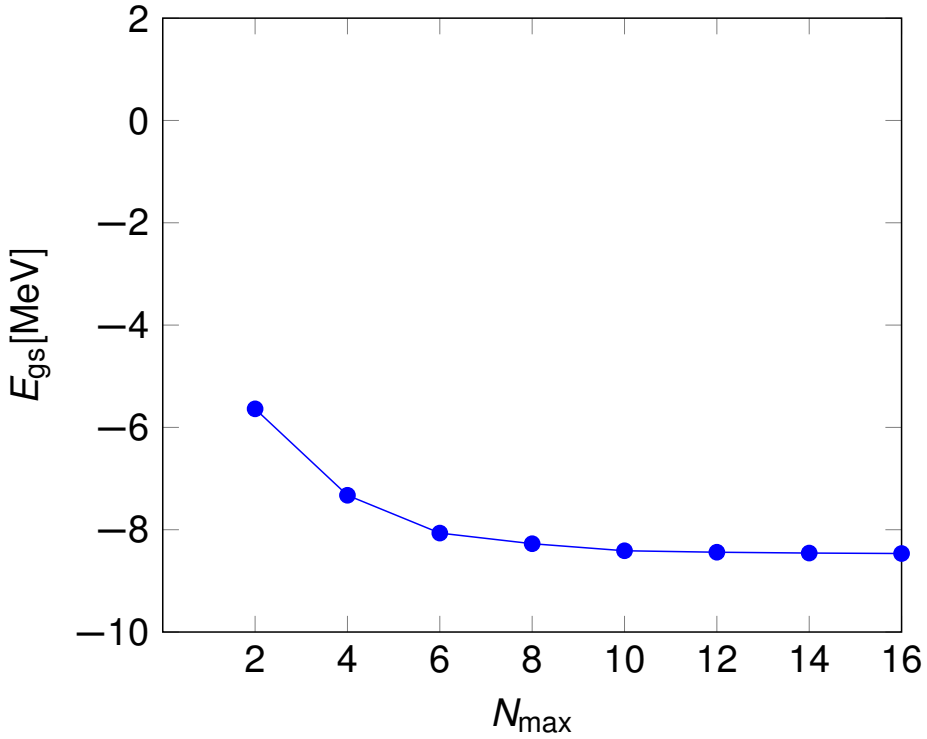


^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

^{3}H SRG Evolution with α =0.0625 fm^4

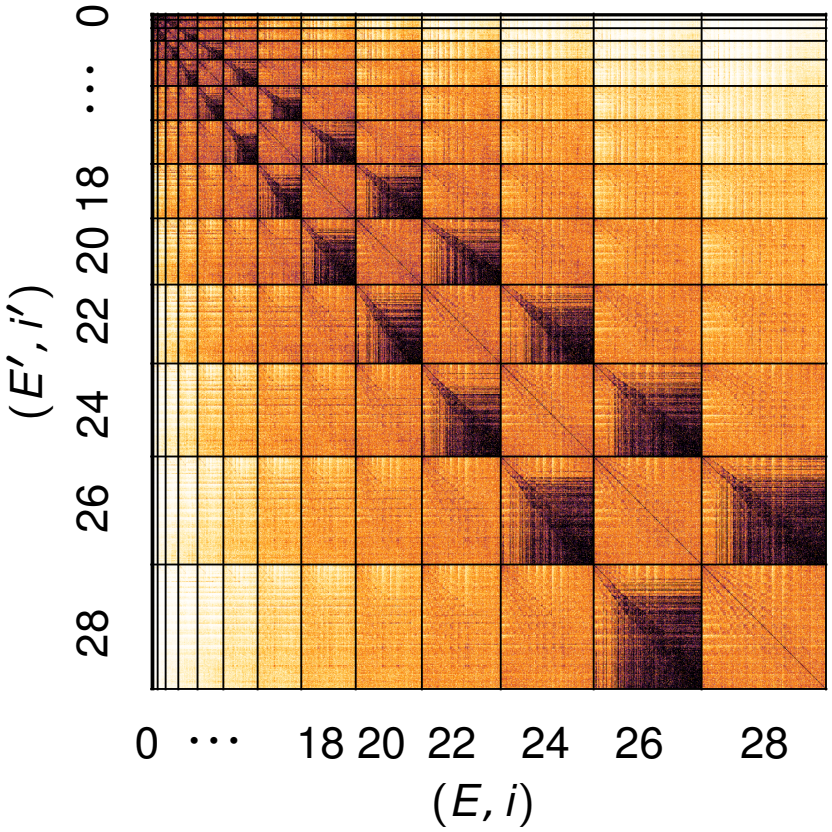


^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis

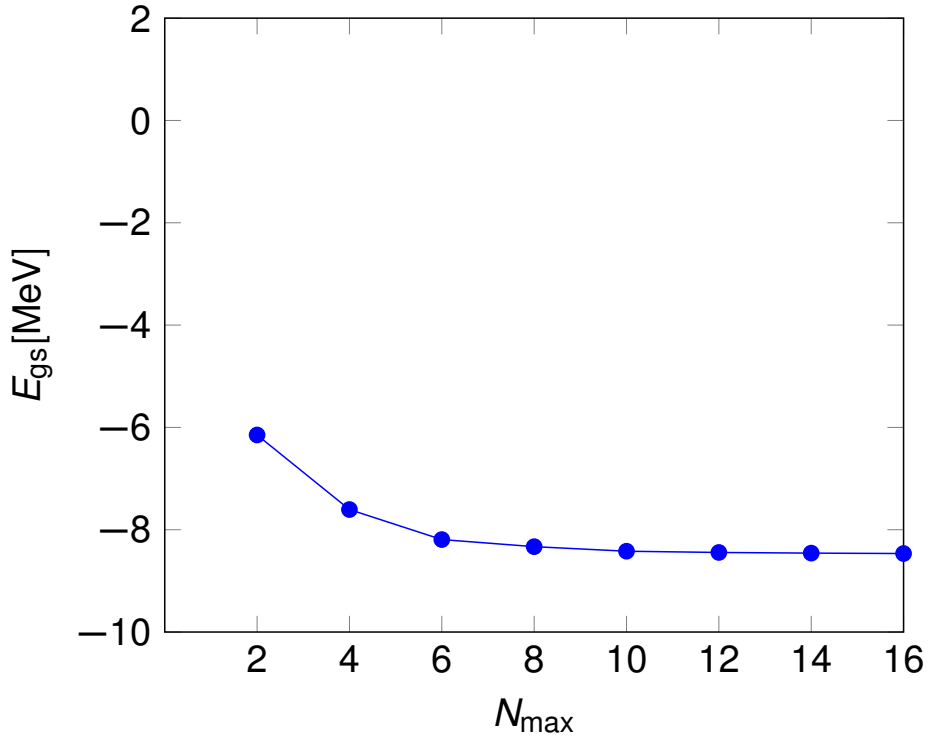


^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

^{3}H SRG Evolution with α =0.08 fm^4

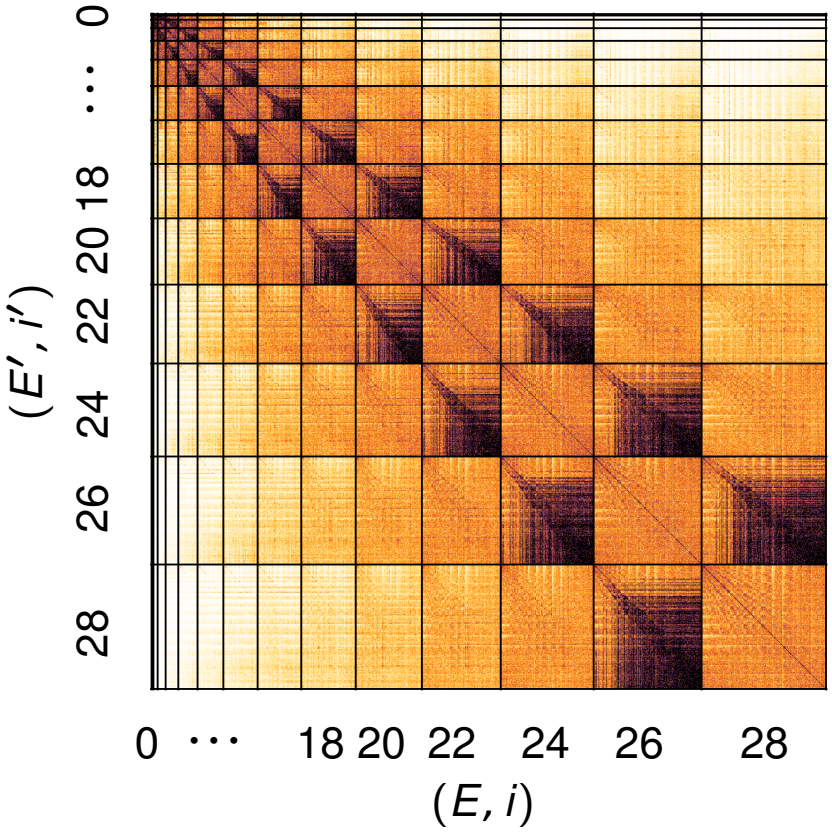


^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis

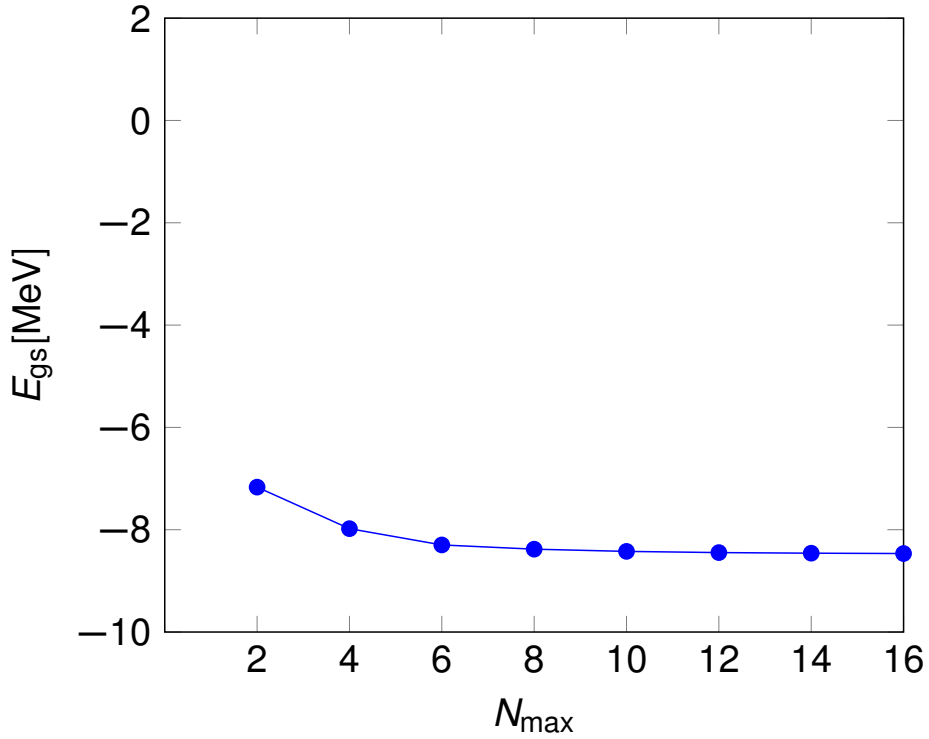


^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

^{3}H SRG Evolution with α =0.16 fm^4

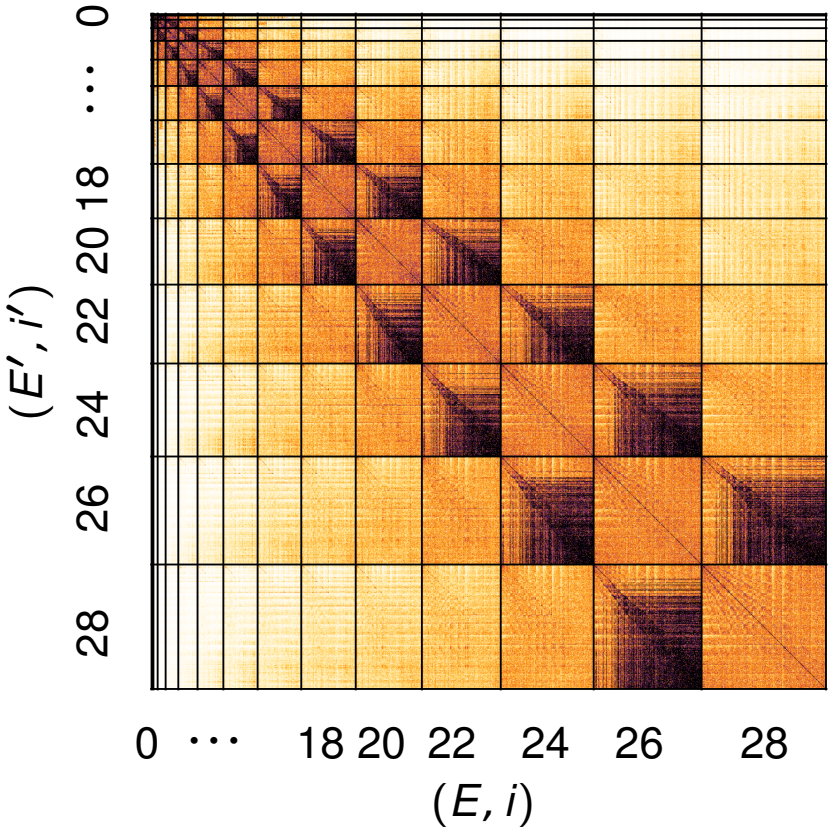


^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis

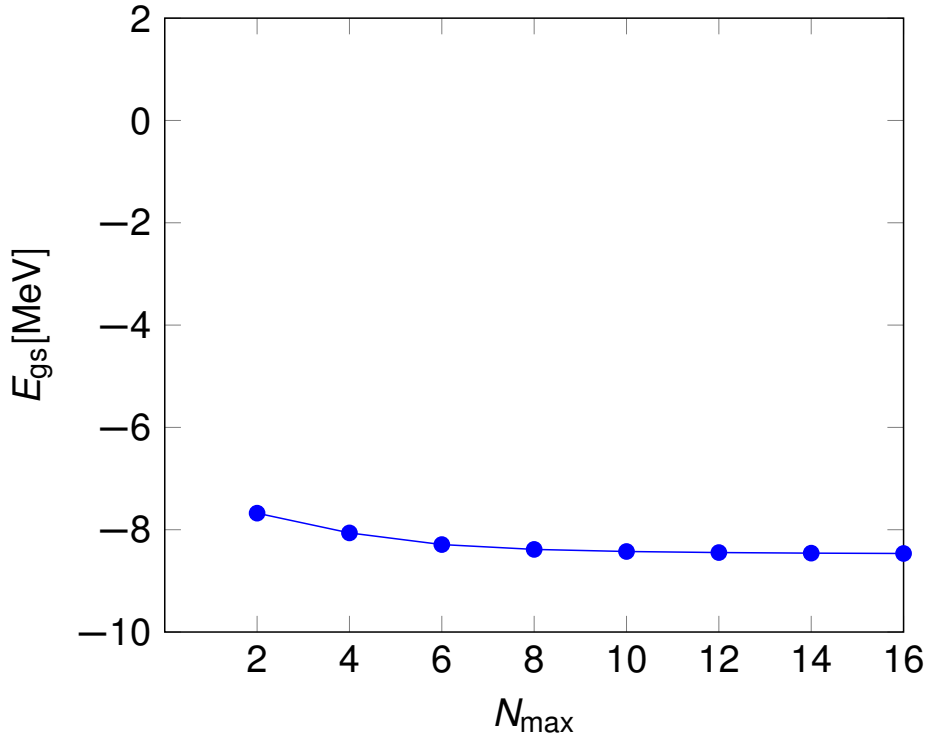


^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

^{3}H SRG Evolution with α =0.32 fm^4



^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis



^{3}H NCSM calculation
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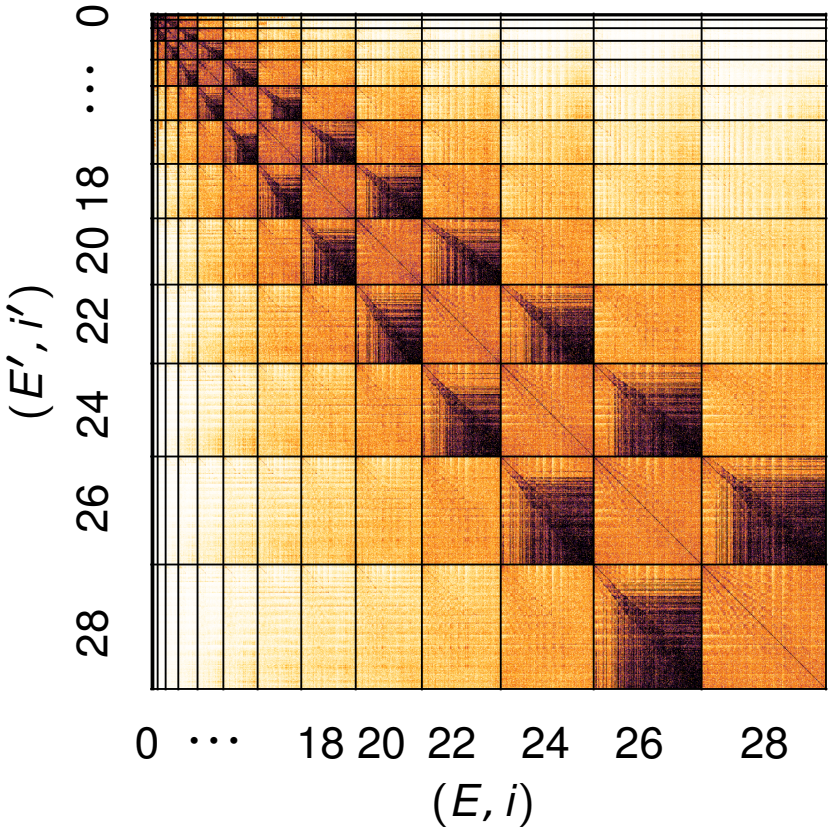
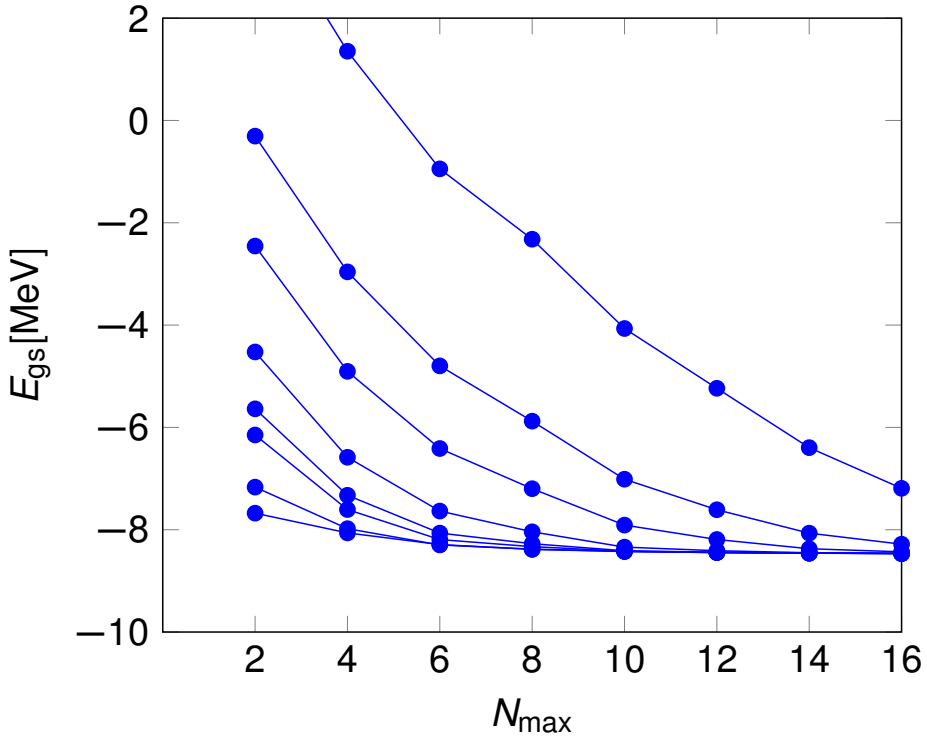
^{3}H SRG Evolution with α =0.32 fm^4



^{3}H channel (T=1 J=1 P=1) in antisymmetrized Jacobi HO basis



^{3}H NCSM calculation
$\hbar\omega = 20$ MeV

Chiral Interactions

Improved Epelbaum /LENPIC

Entem and Machleidt (EM)

Chiral Interactions

Improved Epelbaum /LENPIC

- semi-local regularization
- five cutoffs $R = 0.8, 0.9, 1.0, 1.1$ and 1.2 fm
- NN force up to N4LO
- consistent 3N force at N2LO and N3LO in construction

Eur.Phys.J.A(2015)51:53, PRL115.122301(2015)

Entem and Machleidt (EM)

Chiral Interactions

Improved Epelbaum /LENPIC

- semi-local regularization
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- NN force up to N4LO
- consistent 3N force at N2LO and N3LO in construction

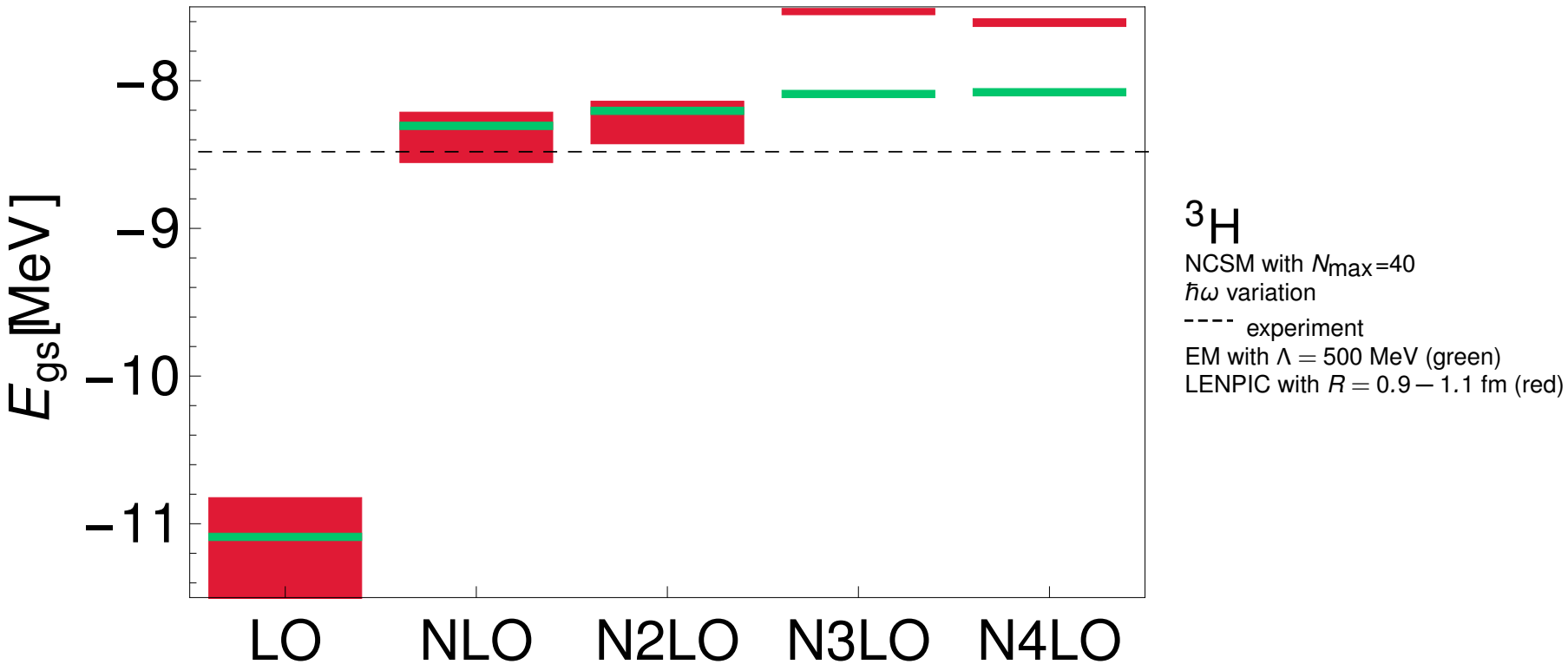
Eur.Phys.J.A(2015)51:53, PRL115.122301(2015)

Entem and Machleidt (EM)

- non-local regularization
- three cutoffs $\Lambda = 450, 500$ and 550 MeV
- NN force up to N4LO
- added consistent regularized N2L0 3N force

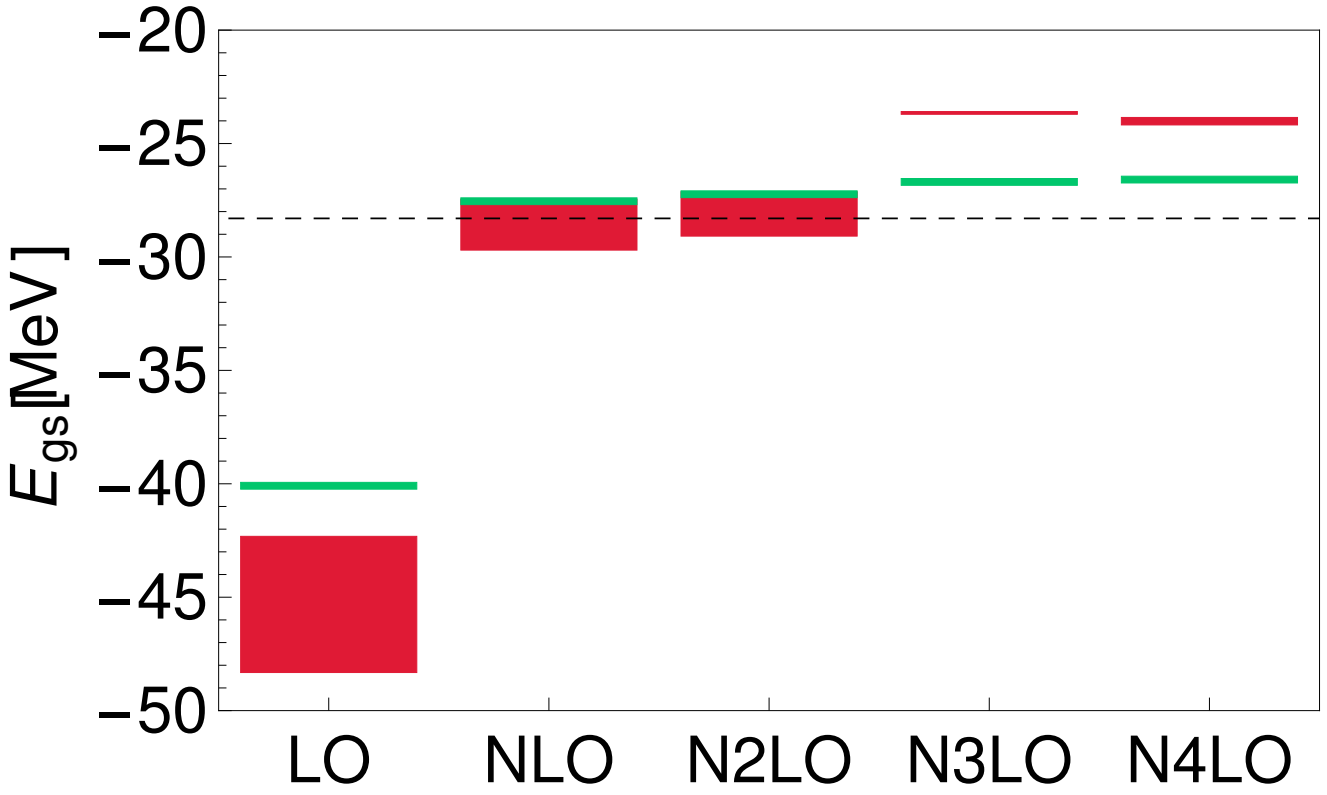
arXiv:1703.05454[nucl-th](2017)

^{3}H with NN Interactions



- uncertainty due to cutoff variation decreases with increasing order
- 3N force necessary for reproducing ^{3}H ground-state energy

^{4}He with NN Interactions

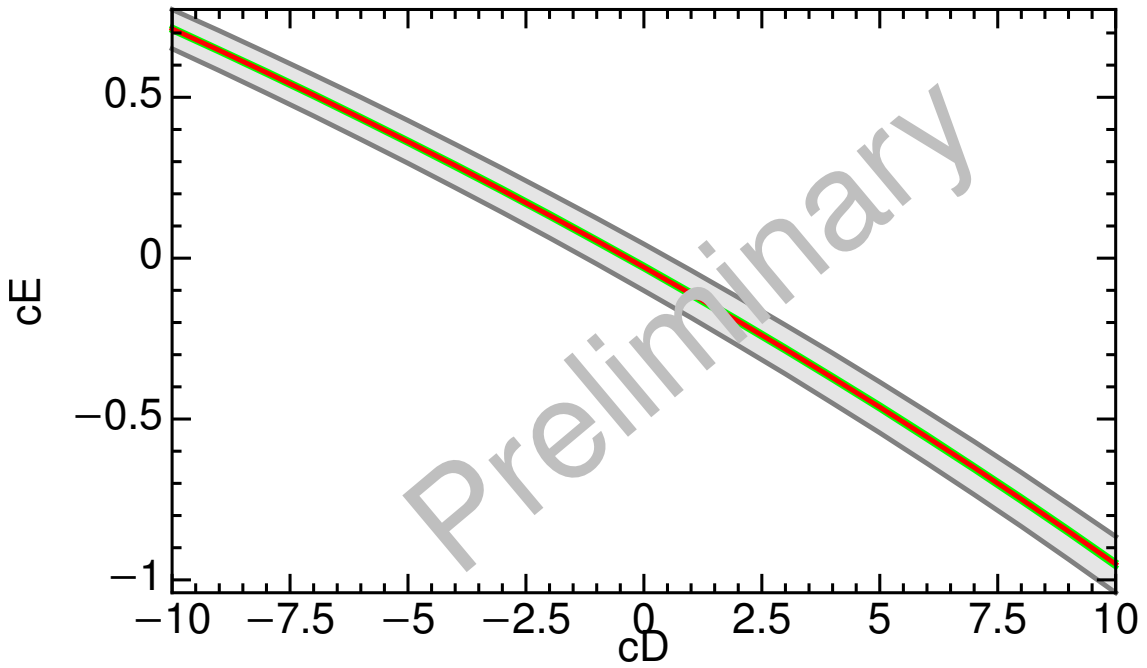


^{4}He
NCSM with N_{max}=20
$\hbar\omega$ variation
---- experiment
EM with $\Lambda = 500$ MeV (green)
LENPIC with $R = 0.9 - 1.1$ fm (red)
SRG used for LENPIC at N3LO and N4LO

- similar to ^{3}H ground-state results

Fitting additional 3N LECs

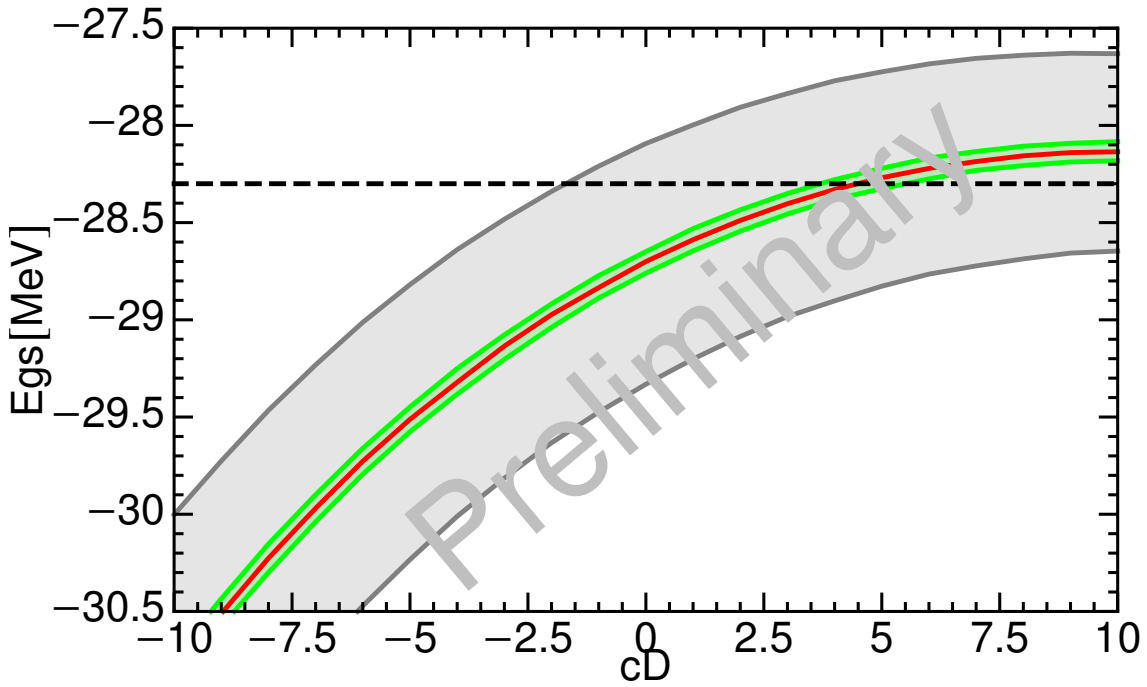
- adding 3N force at N2LO gives rise of 2 additional LECs
- correlation between c_D and c_E by fitting ^{3}H ground-state energy



c_D and c_E correlation
LENPIC N2LO with R=1.0 fm
NCSM with N_{max}=40
$\hbar\omega$ variation

	$\Delta E_{^3\mathrm{H}gs}$
red	2 keV
green	10 keV
grey	100 keV

Sensitivity of c_D and c_E

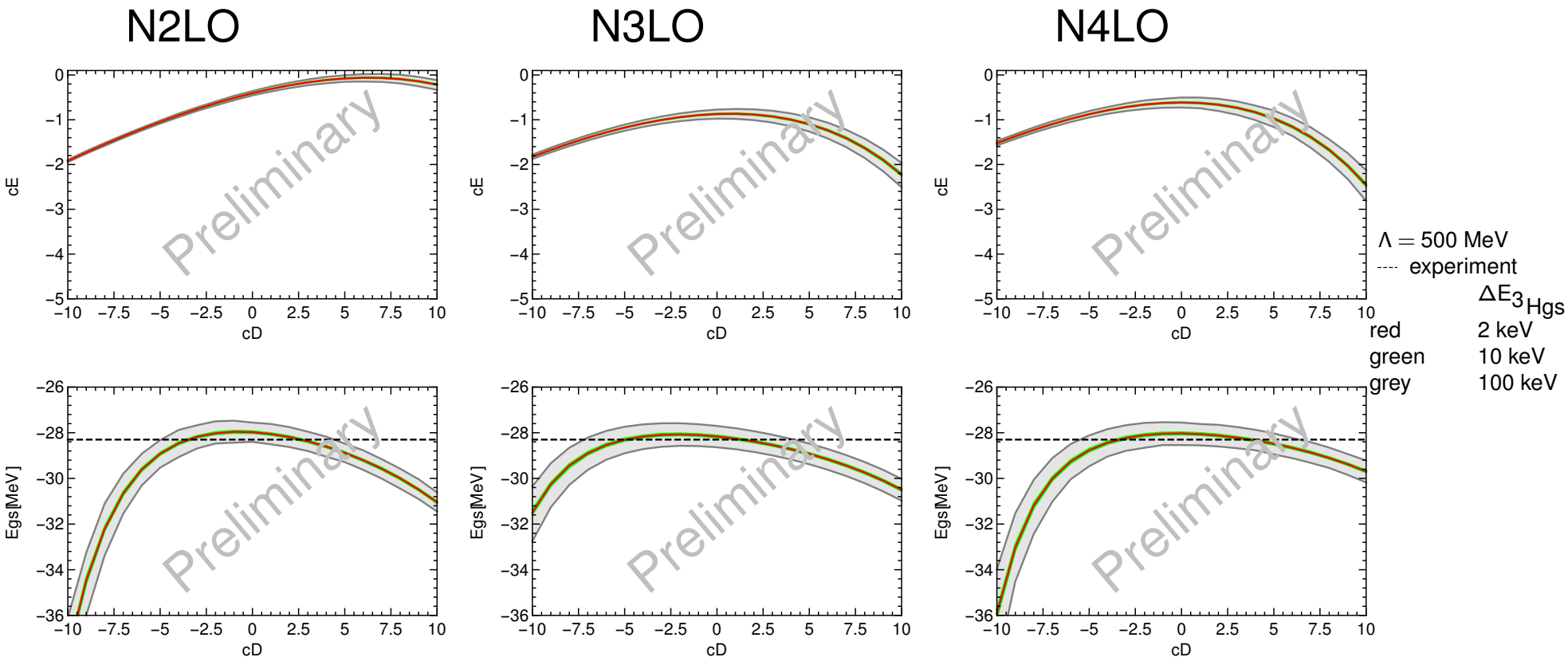


^{4}He
LENPIC N2LO with R=1.0 fm
NCSM with N_{max}=20
$\hbar\omega$=40 MeV
---- experiment

	$\Delta E_{3_{Hgs}}$
red	2 keV
green	10 keV
grey	100 keV

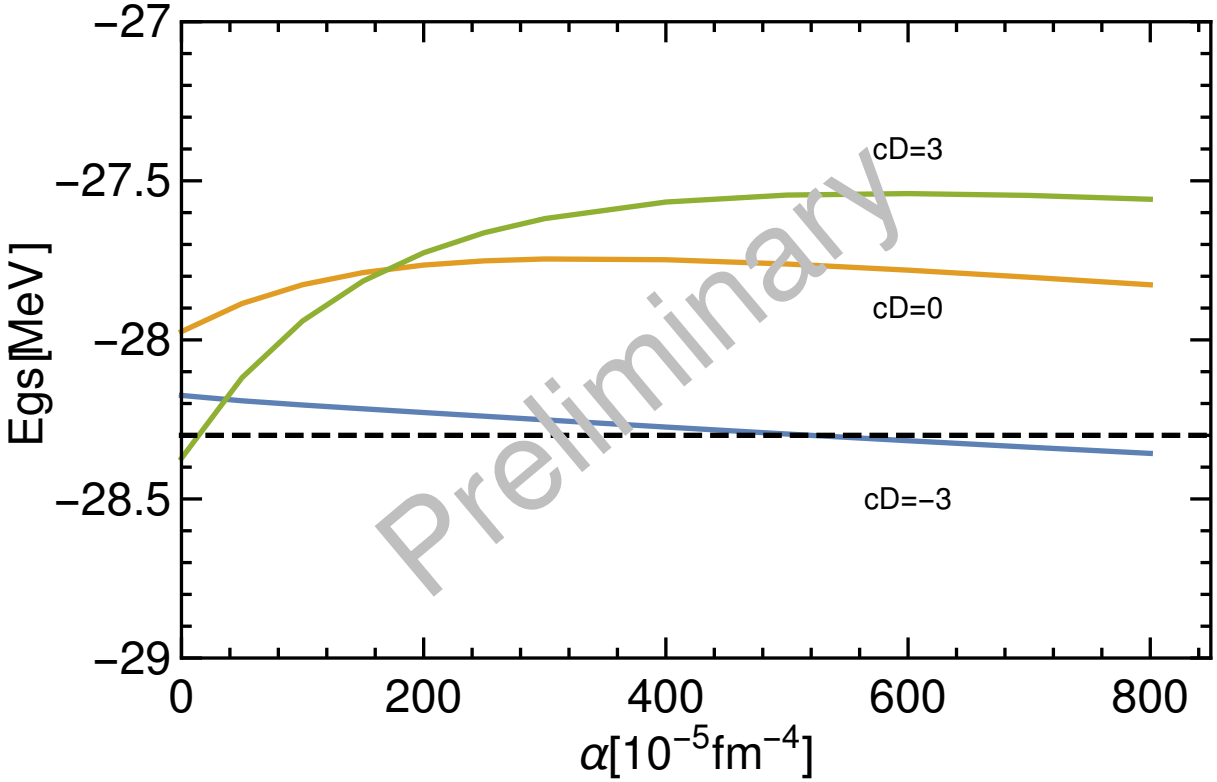
- ground-state energy of ^{4}He can be reproduced within uncertainty range
- fix c_D with scattering data

Fitting additional 3N LECs of EM Interactions



- broad range of cD and cE pairs reproduce ^{4}He ground-state energy

SRG evolved NN+3N Hamiltonian



^{4}He
EM N2LO with $\Lambda = 500$ MeV
NCSM with N_{max}=20
$\hbar\omega$=36 MeV
---- experiment

- strong flow parameter α dependence → induced four-body force
- how to resolve this problem?

Summary and Outlook

- LENPIC and EM interactions allow order-by-order analysis
- full quantification of theory uncertainties possible

- finalize cD and cE pairs
- add N3LO 3N interaction
- resolve problem with SRG
- have fun with chiral interactions

Thank You

Thank you for your attention!