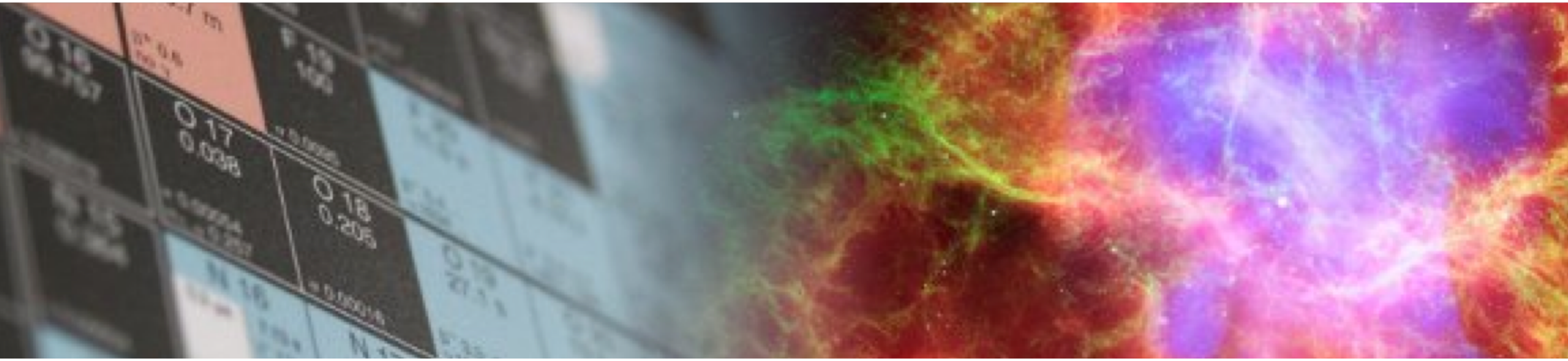
Chiral interactions for nuclear matter and medium-mass nuclei

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT



TRIUMF ab initio workshop, Feb. 26, 2019

DFG
SFB 1245
erc
Bundesministerium für Bildung und Forschung
HELMHOLTZ ASSOCIATION

Outline

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Nuclear landscape based on a chiral NN+3N interaction including uncertainties with **R. Stroberg,** J.D. Holt, J. Simonis

Improved nuclear matter calculations and
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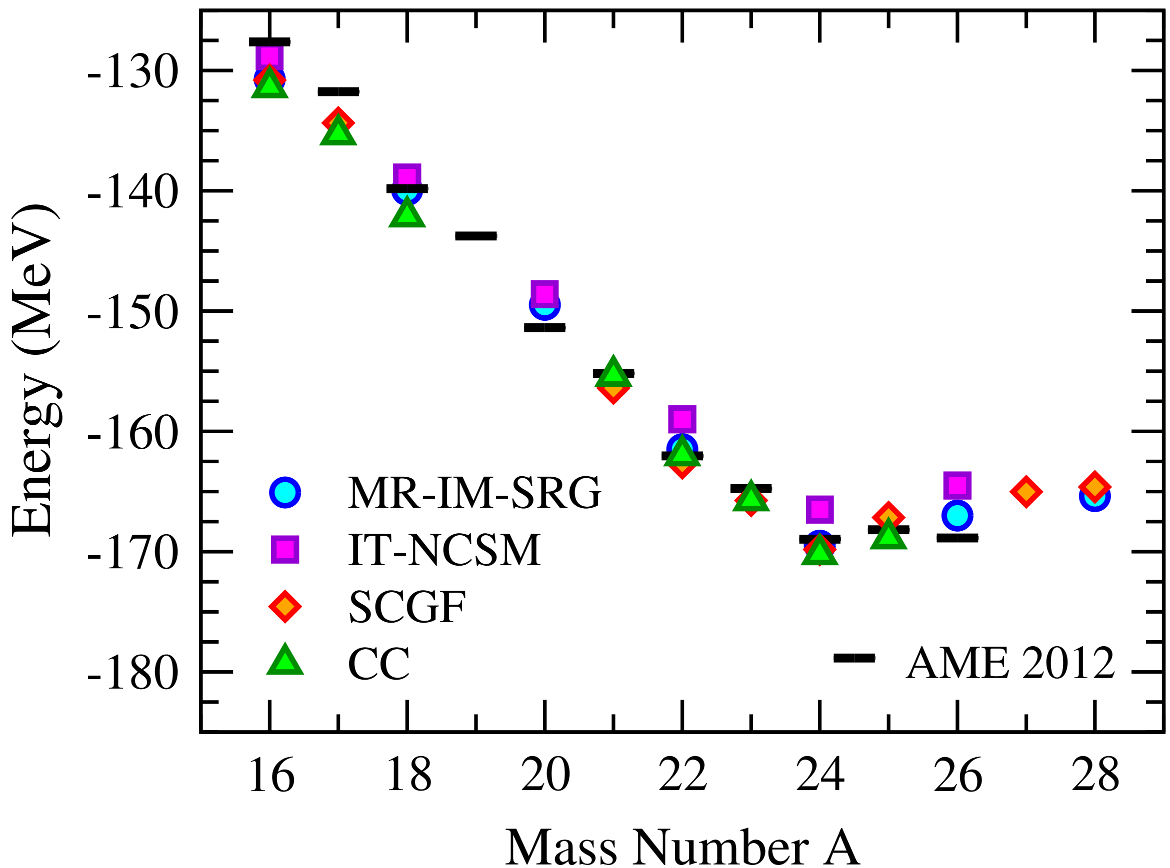
Ab initio calculations of neutron-rich oxygen isotopes

based on same NN+3N interactions with different many-body methods

CC theory/CCEI
Hagen et al., PRL (2012),
Jansen et al., PRL (2014)

Multi-Reference
In-Medium SRG
and IT-NCSM
Hergert et al., PRL (2013)

Self-Consistent
Green's Functions
Cipollone et al., PRL (2013)

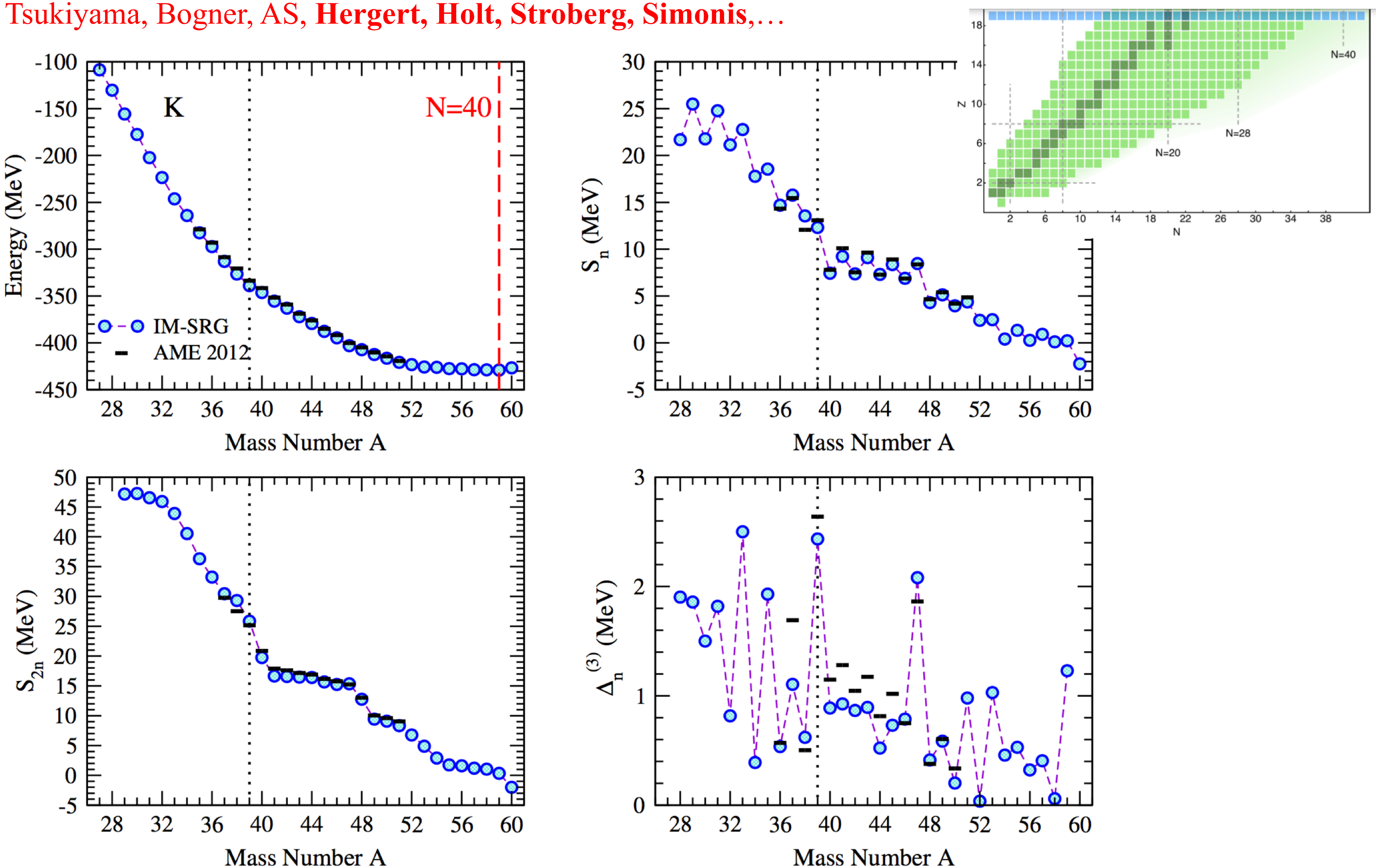


Many-body calculations of medium-mass nuclei have smaller uncertainty compared to uncertainties in nuclear forces

Great progress from medium to heavy nuclei

VS-IMSRG with ensemble normal ordering from NN+3N 1.8/2.0 (EM)

Tsukiyama, Bogner, AS, **Hergert, Holt, Stroberg, Simonis**,…



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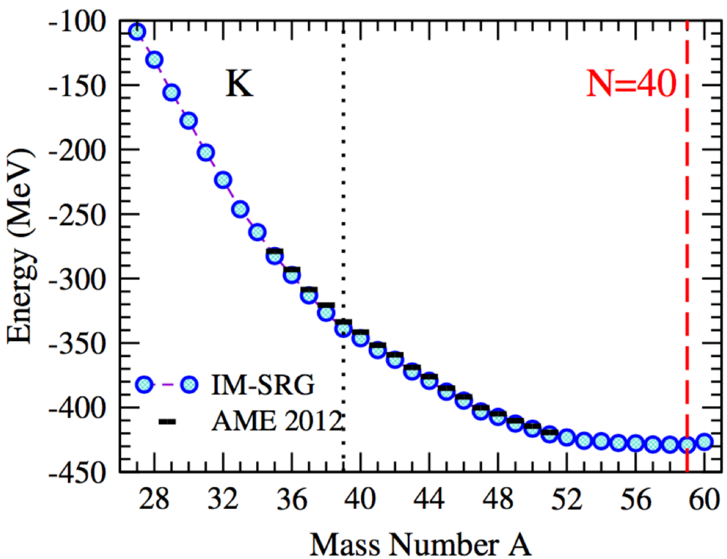
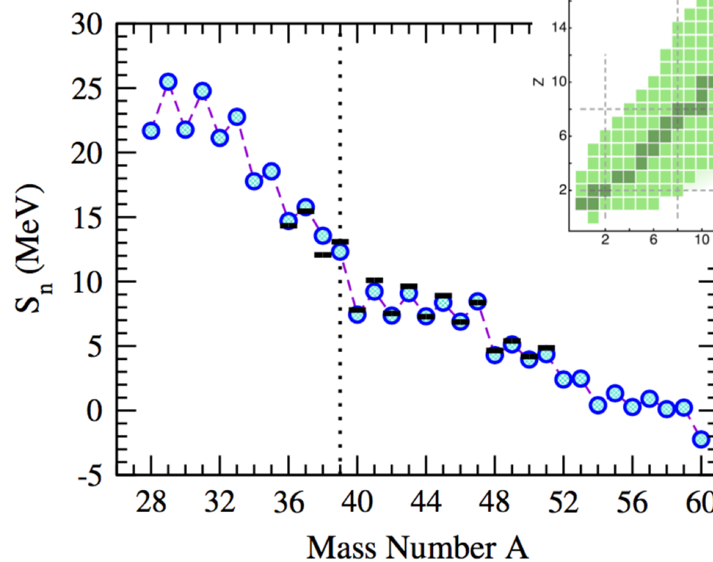
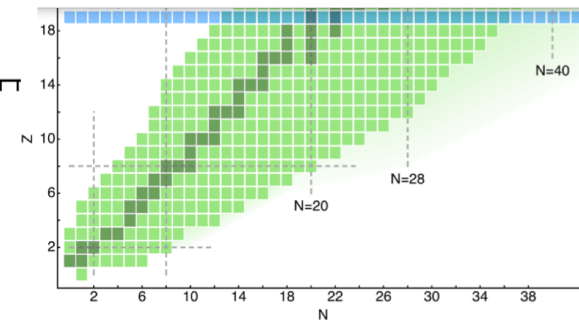






Important for medium-mass nuclei:

Consider nuclear forces with good (nuclear matter) saturation properties

N^2LO_{sat} fit to selected nuclei up to A=24 Ekström et al. (2015)

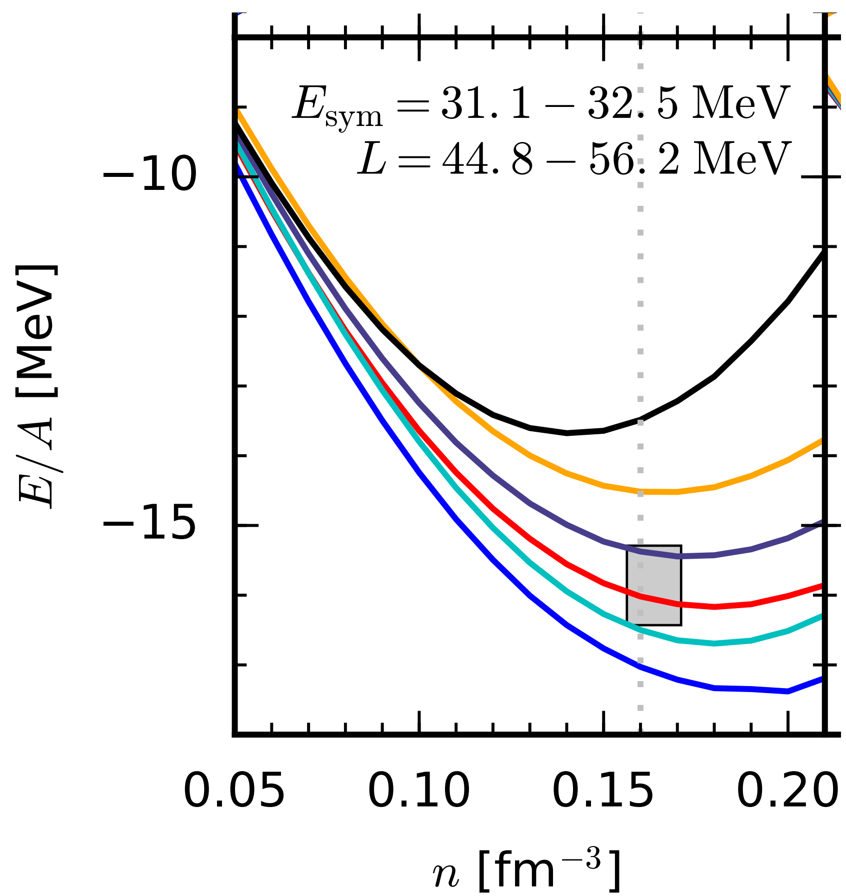
NN evolved + 3N fit to ^{3}H, ^{4}He Hebeler et al. (2011)

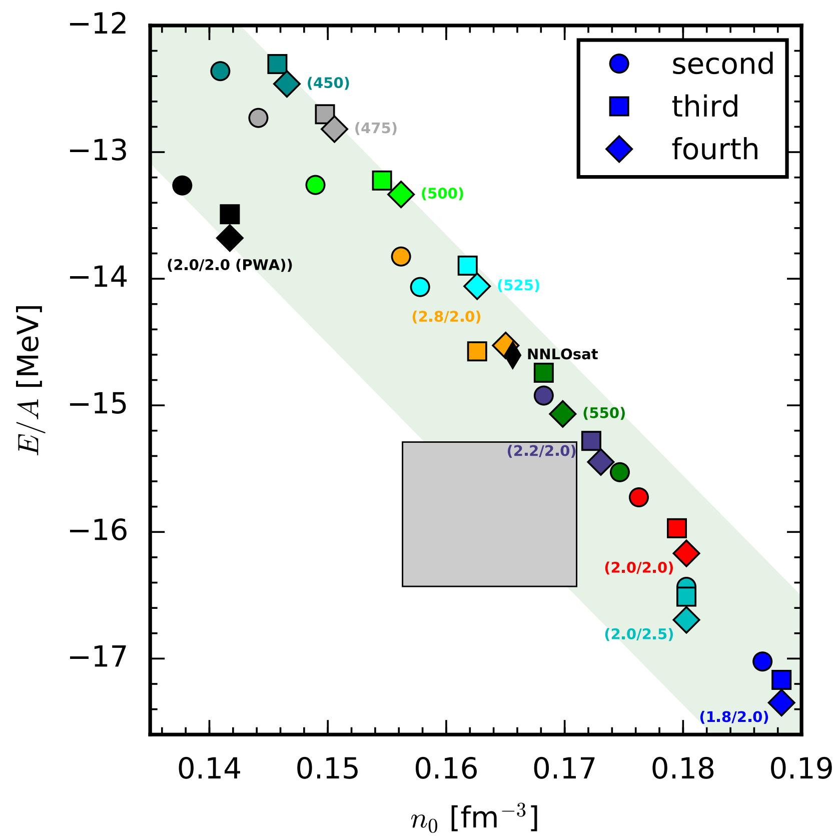
Nuclear forces and nuclear matter

Monte-Carlo calculation of all energy diagrams up to 4th order in MBPT

Drischler, Hebeler, AS, PRL (2019), automated 5th and 6th order calculation, Drischler et al.

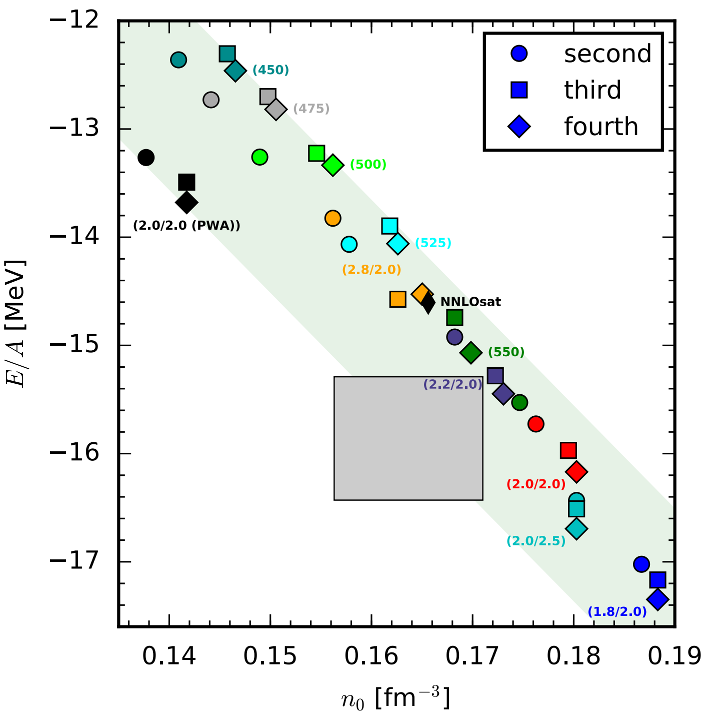
chiral order	Λ/c_D	second order NN-only	second order NN+3N	second order 3N res.	third order NN+3N	fourth order NN-only	fourth order NN+3N[a]
N^3LO/N^2LO	$\lambda/\Lambda = 1.8/2.0\ \mathrm{fm}^{-1}$	-2.30	-2.24	-0.40	-0.10	-0.20	-0.07

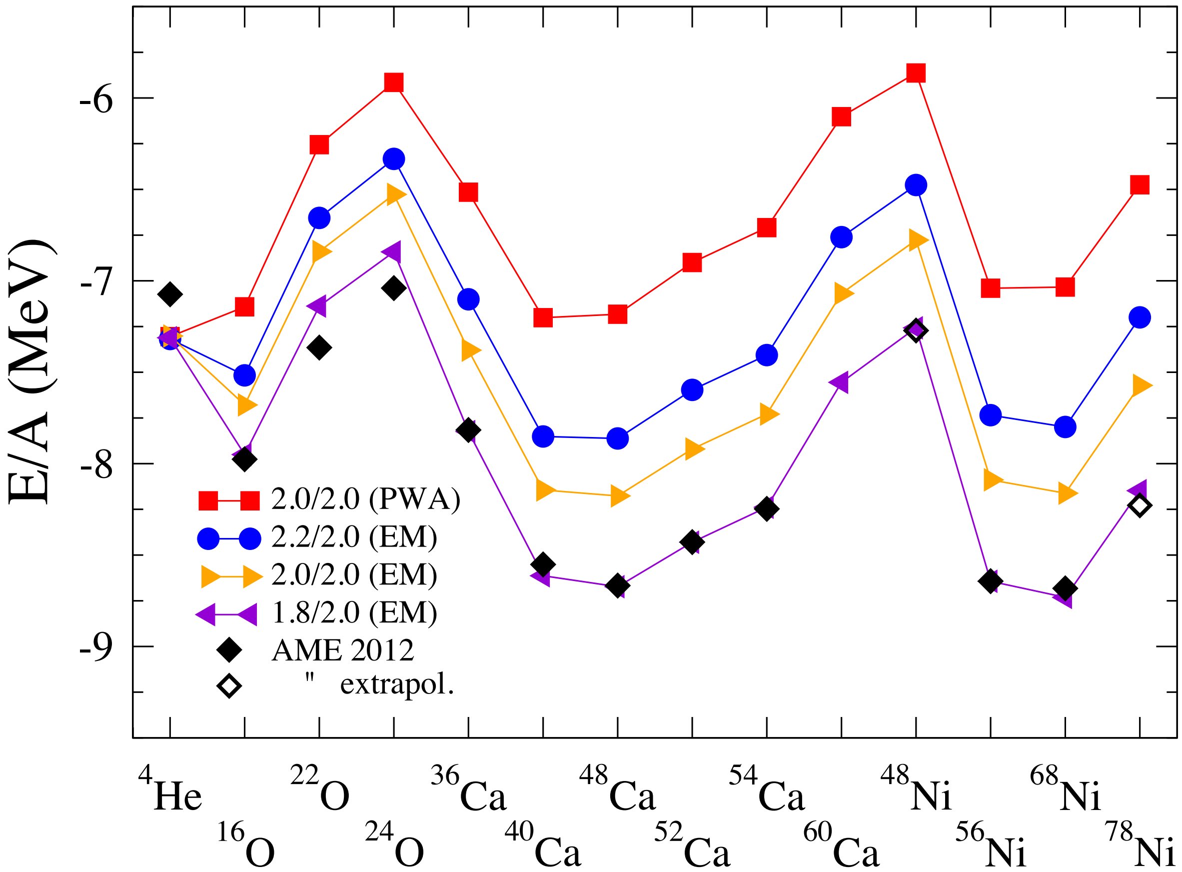




Importance of saturation for nuclear forces Simonis, Stroberg et al. (2017)

IM-SRG calculations of closed shell nuclei follow nuclear matter saturation trends





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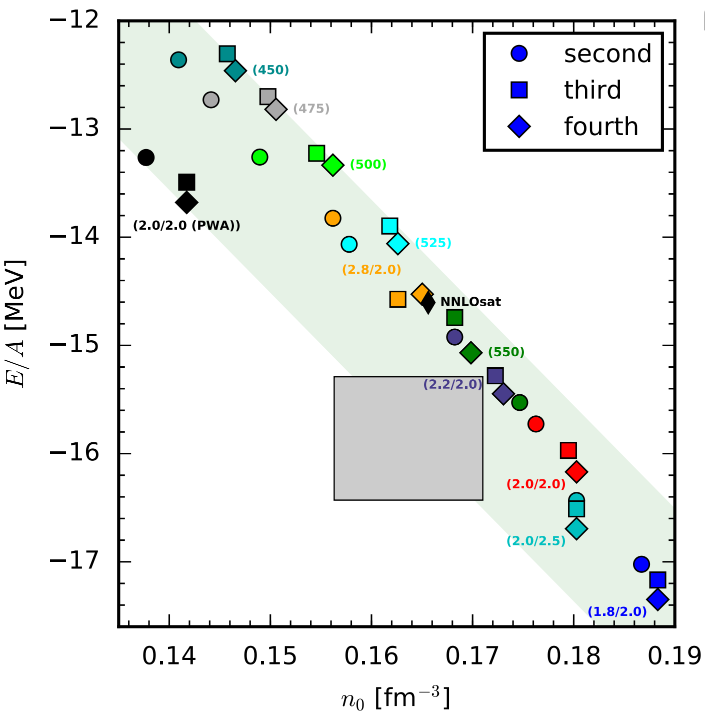

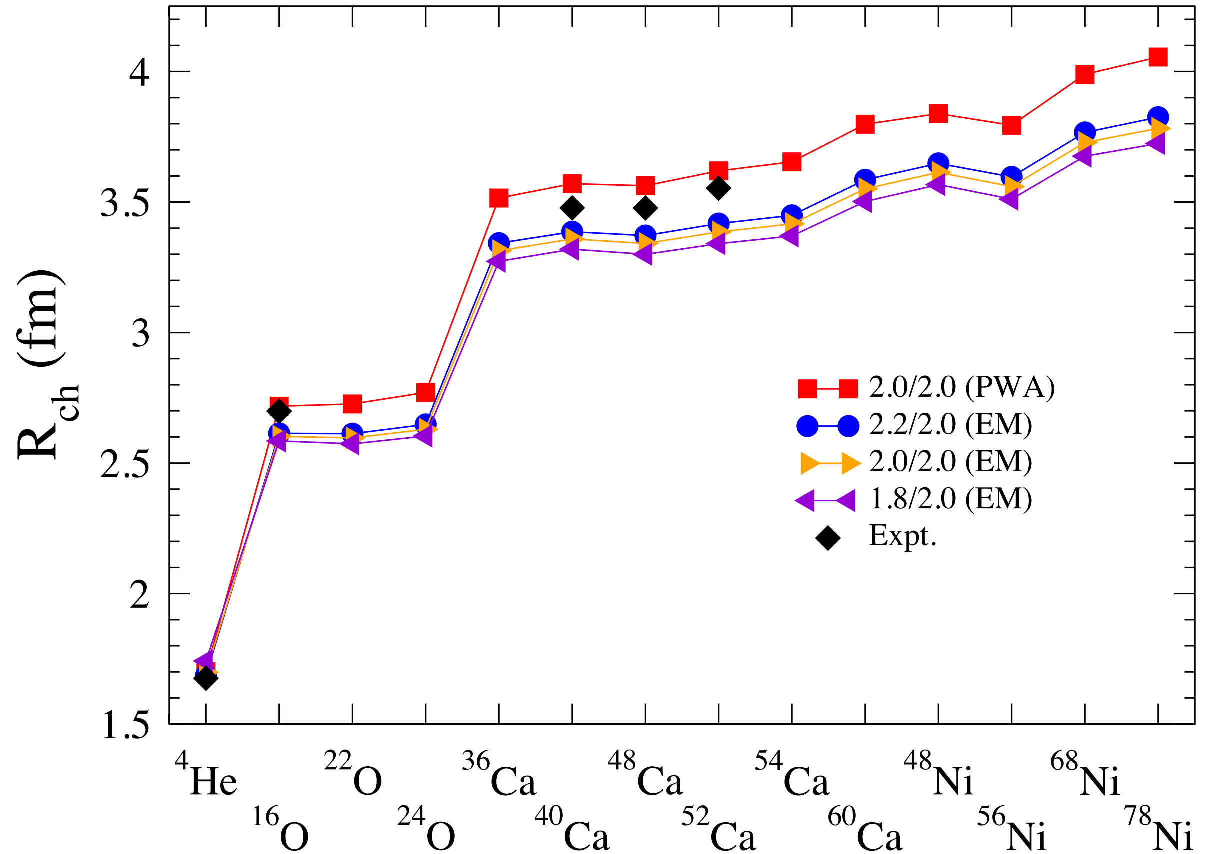

too small radii for 1.8/2.0 (EM), provides too much Coulomb repulsion

see liquid drop analysis Stroberg et al., in prep.

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Simple uncertainty estimates

NN+3N interaction 1.8/2.0 (EM) fit to A=3,4 only, remarkably well for energies

calculated all nuclei to Fe in VS-IMSRG, global comparison of S_{1n} with experiment shows Gaussian dist with $\sigma_{1n} \sim 1$ MeV, similar for S_{2n}, S_{1p}, S_{2p}

Stroberg, Holt, Simonis, AS, in prep.

predictions for isotope chains (here Cl) assuming same pdf for unknown nuclei

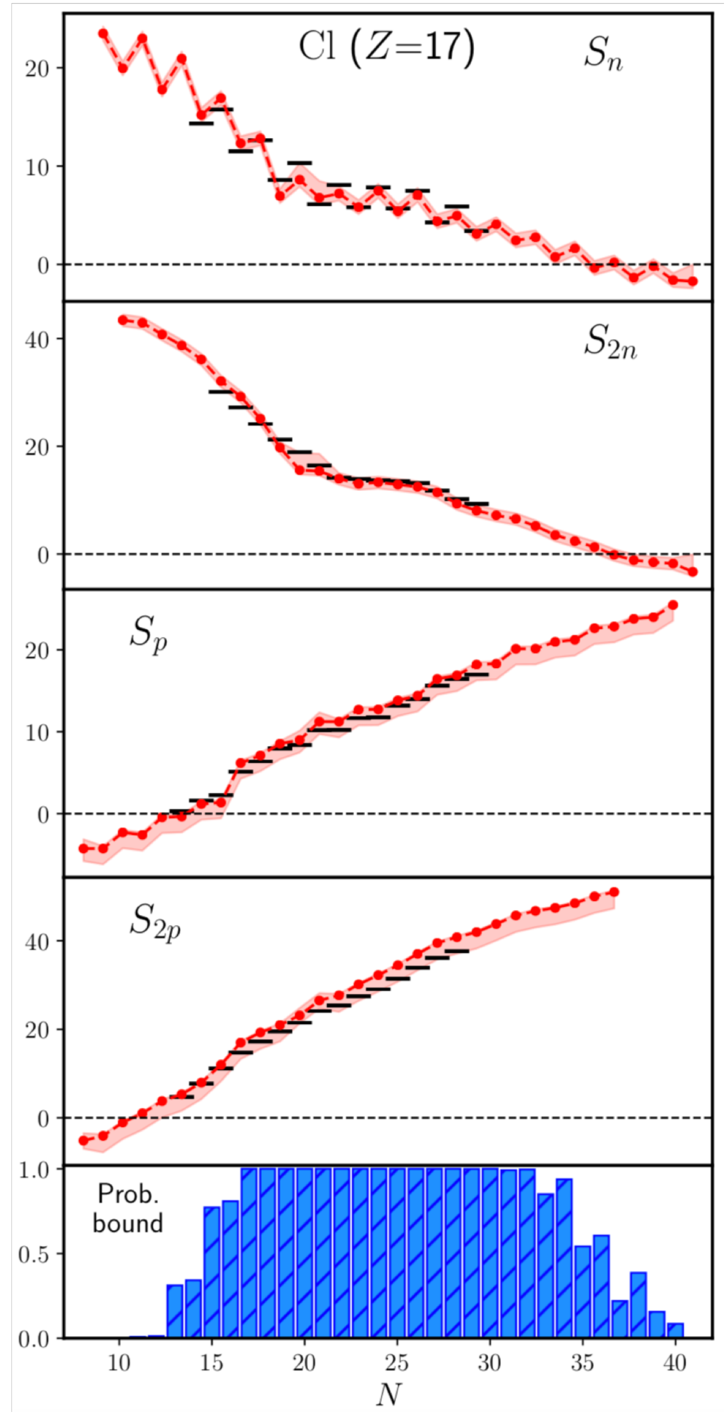
probability for being bound to 1n emission

$$\mathcal{P}_{1n} = \frac{1}{2}\left(\text{Erf}\left[S_n^{(th)}(N,Z)/\sqrt{2}\sigma_{1n}\right] + 1\right)$$

and prob. bound to 1n+2n: $\mathcal{P}_{1n}\mathcal{P}_{2n} - \delta_{\text{corr}}$

more sophisticated stat. modeling

see EDF based work of Neufcourt et al., PRL (2019)



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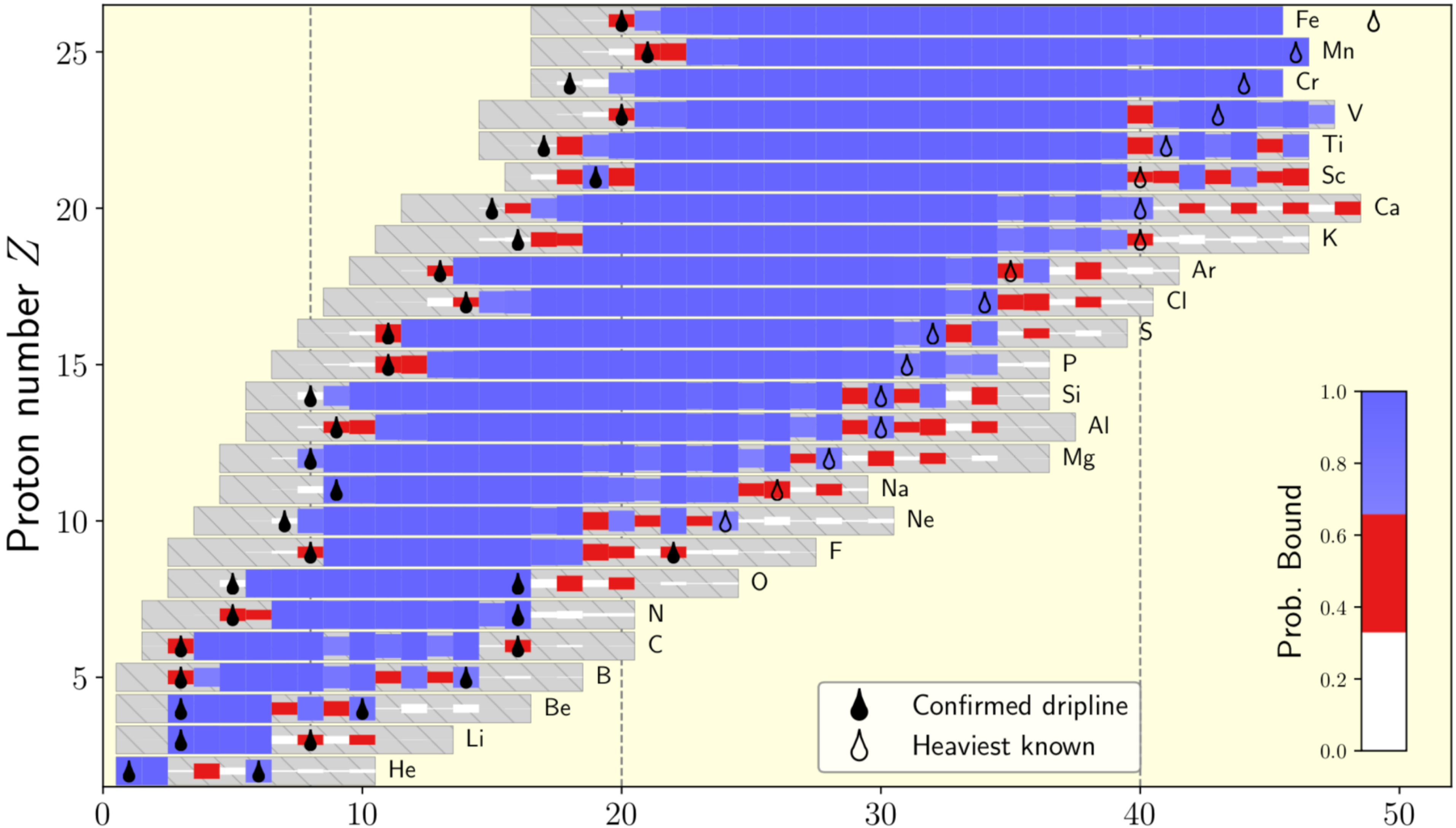

Stroberg, Holt, Simonis, AS, in prep.

ab initio is advancing to global theories, limitations due to input NN+3N

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Monte-Carlo calculation of all energy diagrams up to 4th order in MBPT

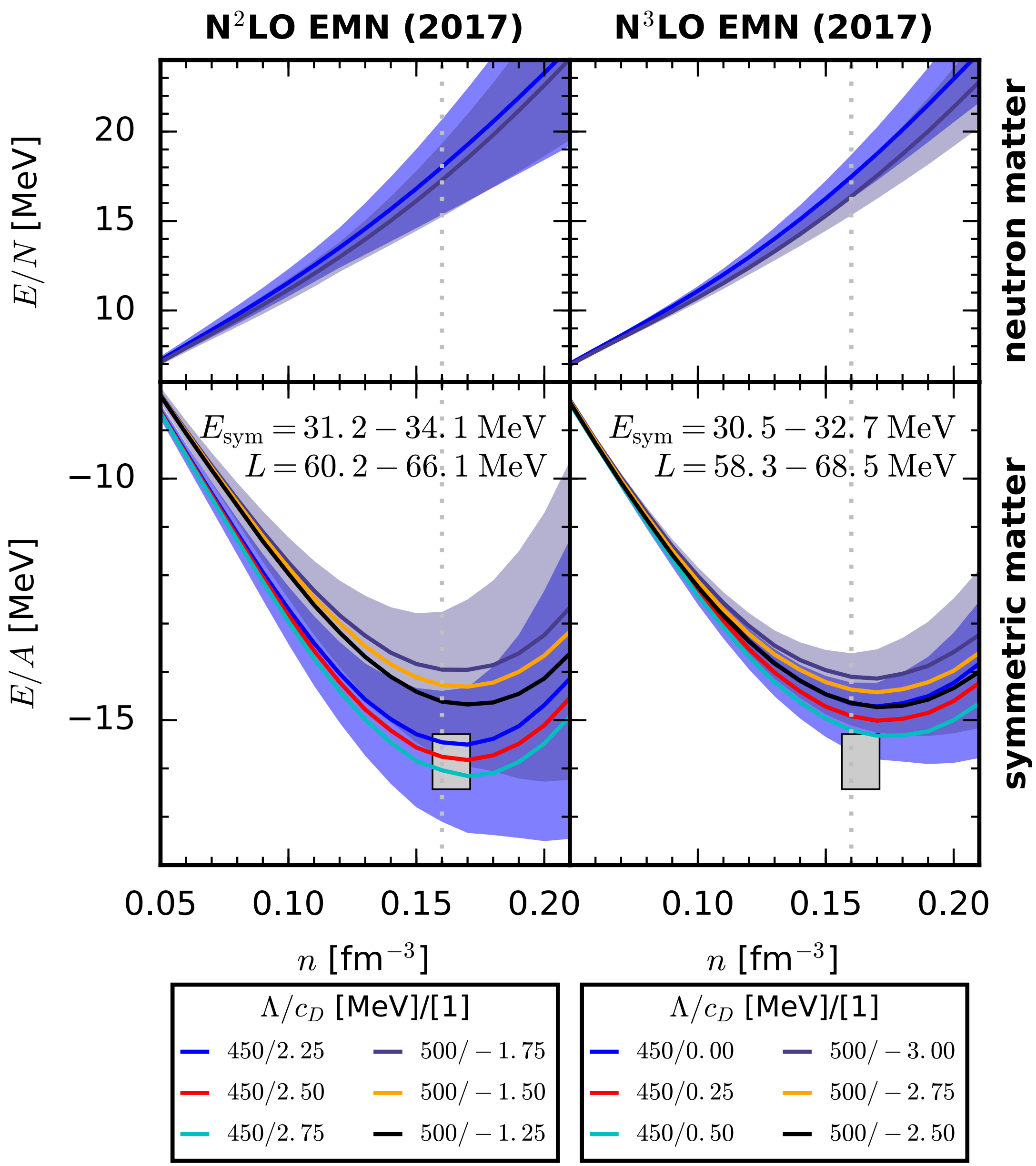
Drischler, Hebeler, AS, PRL (2019)

including NN, 3N, 4N

3N fit to ^{3}H and saturation

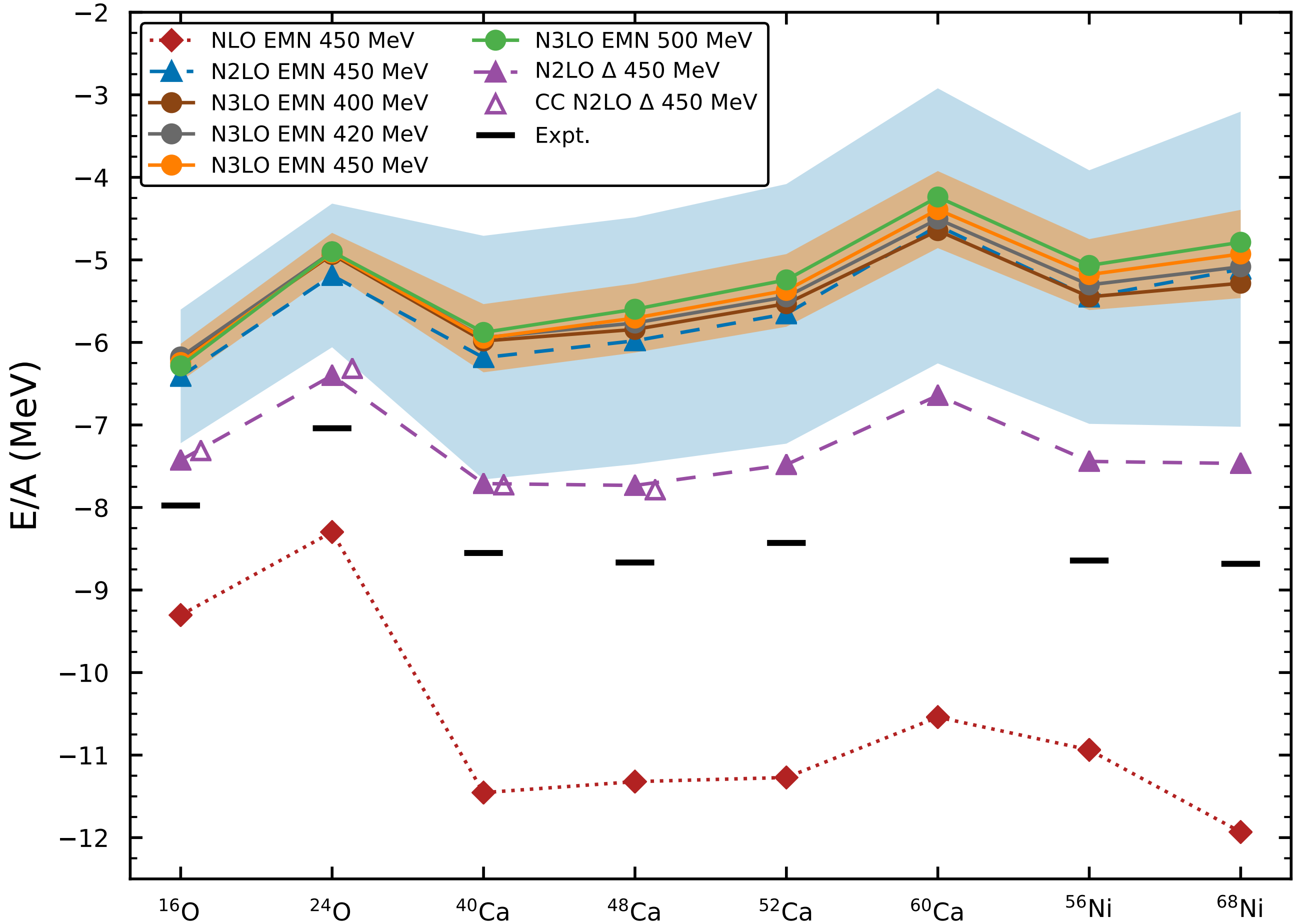
systematic improvement from N^{2}LO to N^{3}LO

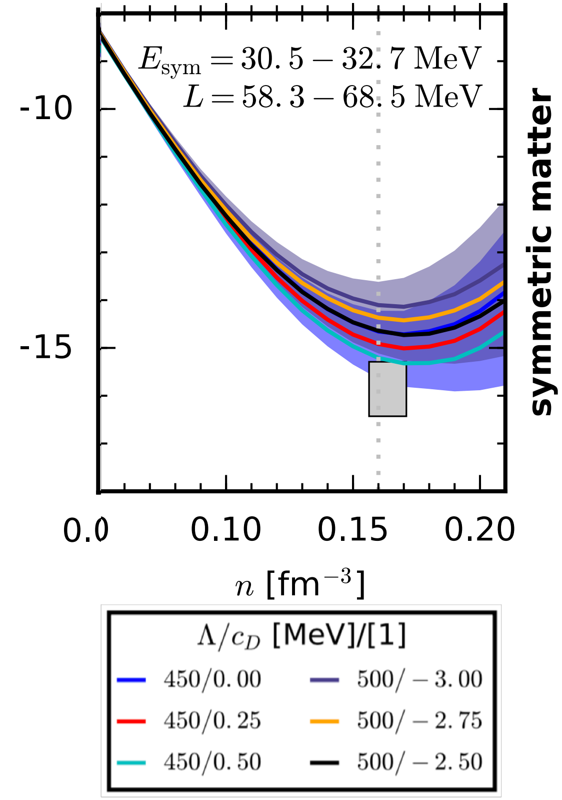
first full N^{3}LO Hamiltonians for use in nuclear structure and EOS calculations



First N^{3}LO results for medium-mass nuclei Hoppe, Simonis et al.

NLO, N^{2}LO, N^{3}LO (EMN 450) with EFT uncertainty bands





bands overlap and at N^{3}LO cutoff variation is within band

underbinding expected from saturation point

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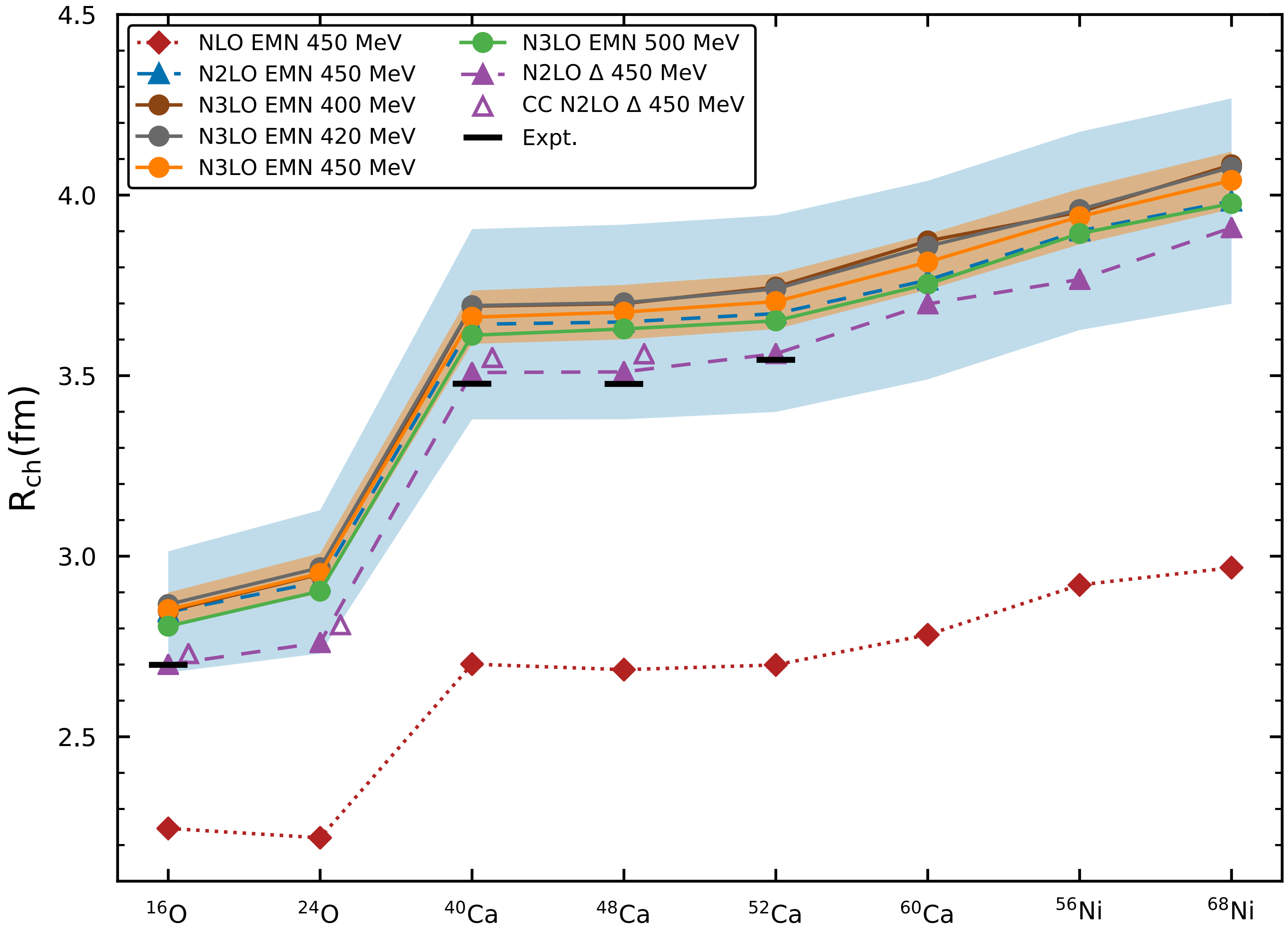
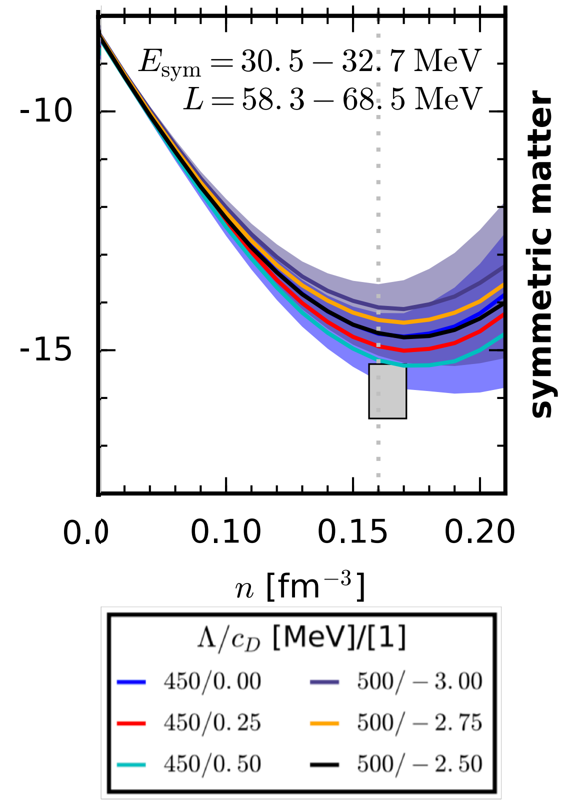


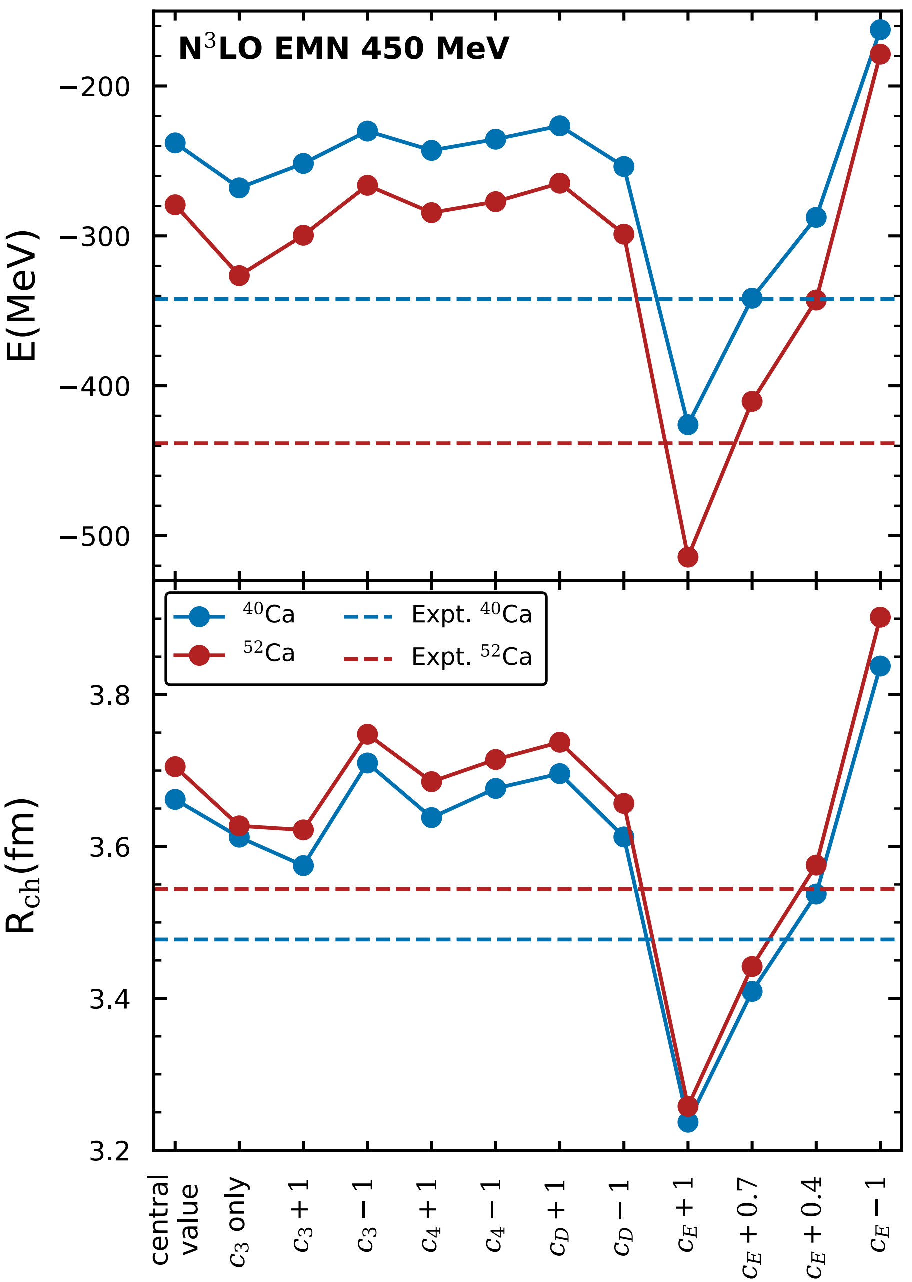


bands overlap and at N^{3}LO cutoff variation is within band

radii in better agreement, larger than expected from saturation point

Exploring sensitivities to 3N force couplings Hoppe, Simonis et al.

vary all LECs by ± 1 for ^{40,52}Ca
largest sensitivity to c_E
(but c_E variation breaks ^{3}H fit)



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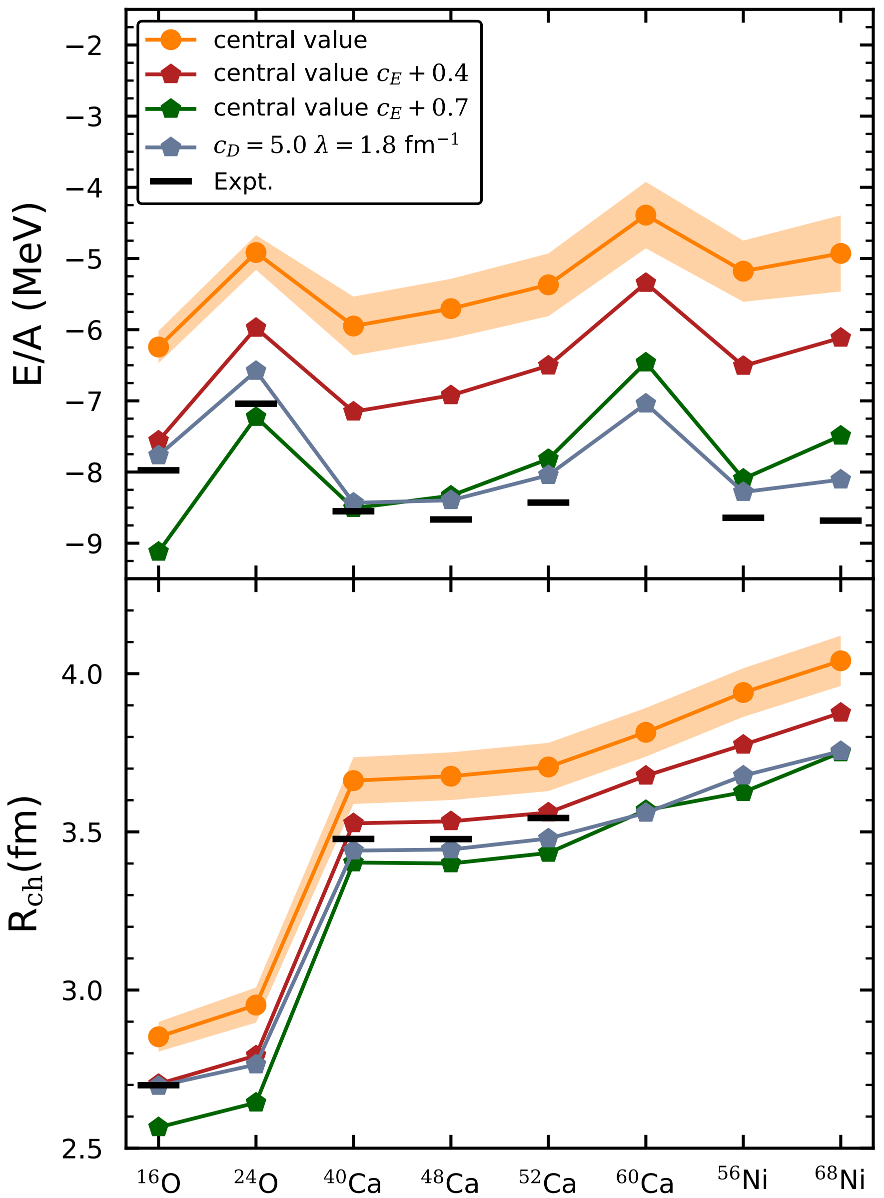
explore for closed shell nuclei,
also promising results for
SRG evolved interaction



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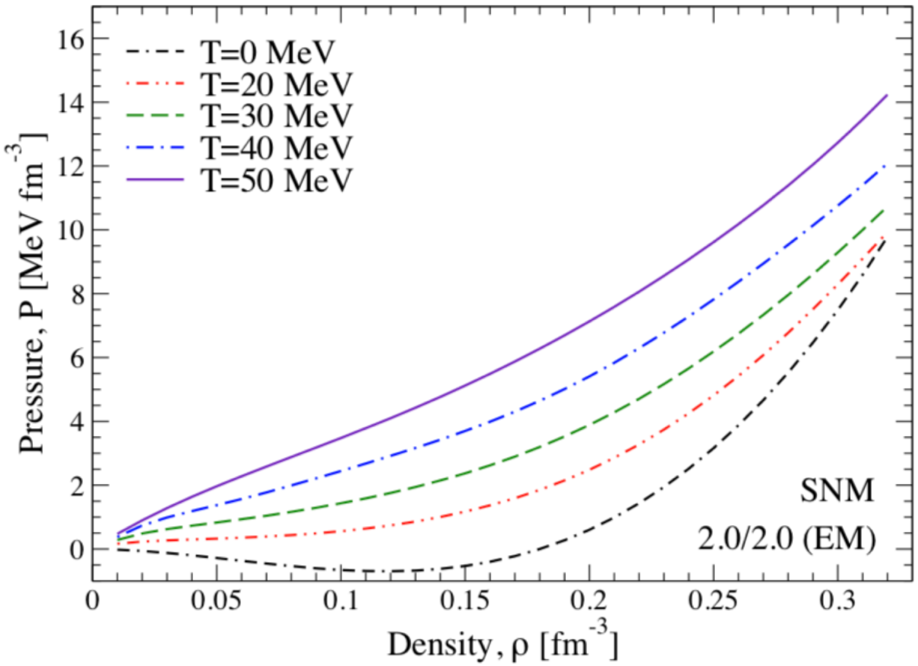
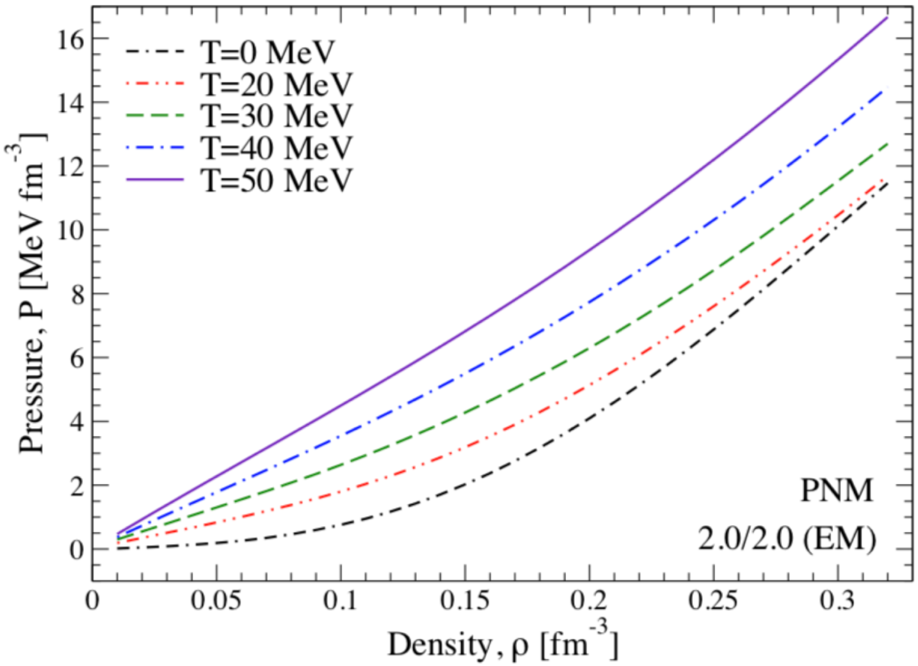
ab initio calcs of EOS at finite T **Carbone**, Rios, Polls,… Holt, Wellenhofer, Weise,…





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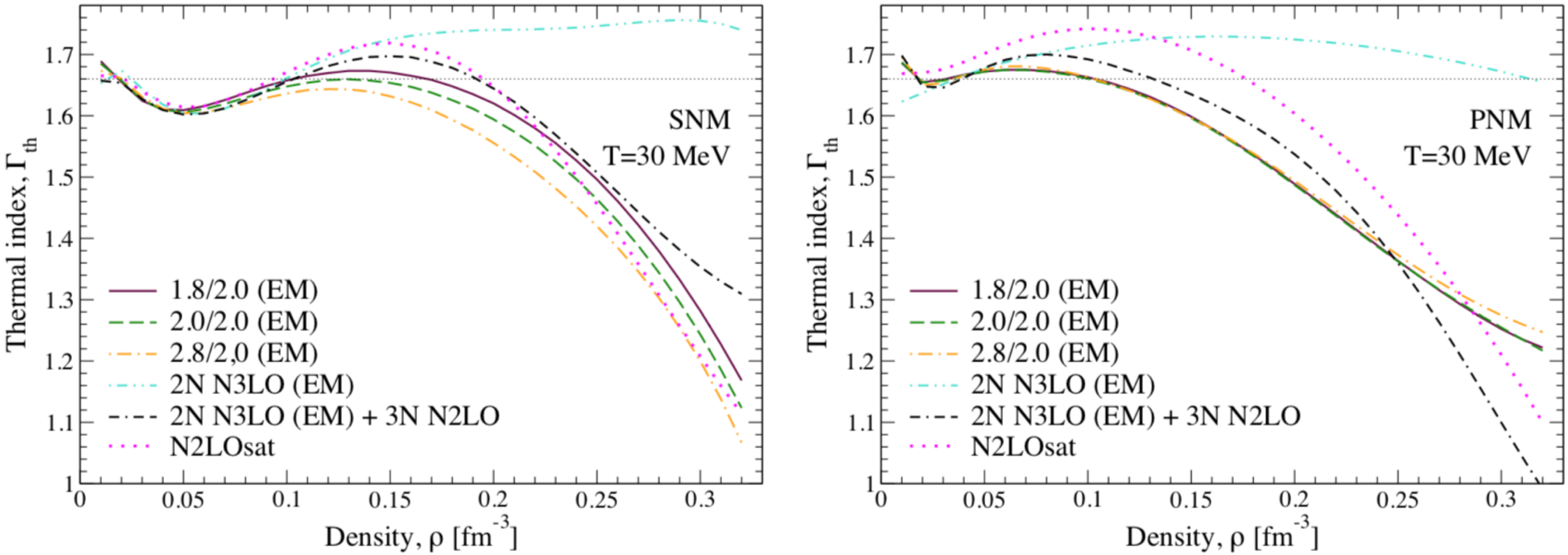
thermal contributions: thermal index (dominated by nucleon m*)

$$\Gamma_{\mathrm{th}} = 1 + \frac{P_{\mathrm{th}}}{\varepsilon_{\mathrm{th}}} = 1 + \frac{P - P_{\mathrm{cold}}}{\varepsilon - \varepsilon_{\mathrm{cold}}}$$



Impact on core-collapse supernova simulations

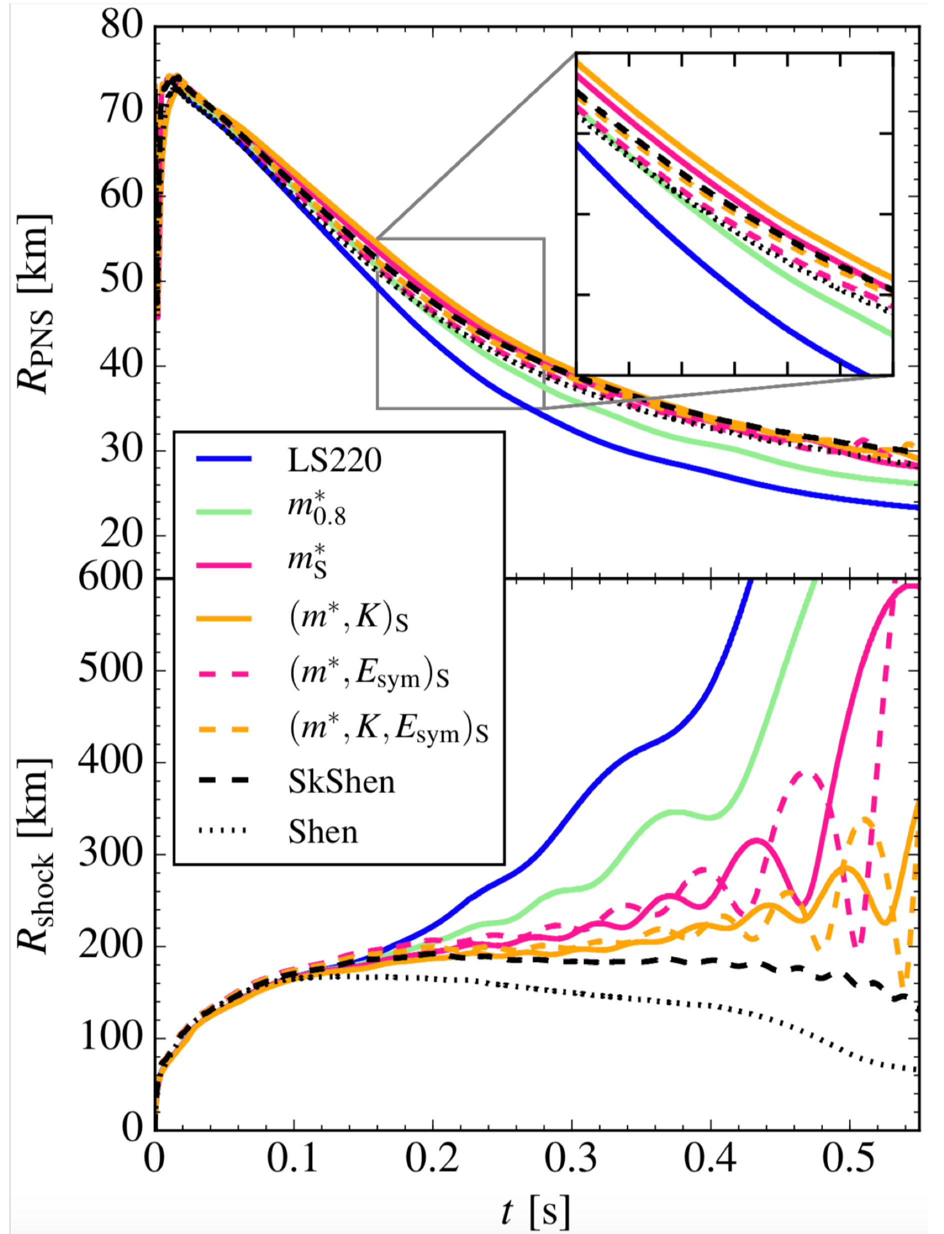
Yasin, Schäfer, Arcones, AS, 1812.02002

constructed EOS that systematically vary nuclear matter properties between LS and Shen et al. EOS

	m^*/m	K	$E_{\rm sym}$	L	n_0	B
LS220	1.0	220	29.6	73.7	0.155	16.0
Shen	0.634	281	36.9[a]	110.8	0.145	16.3
Theo.	0.9(2)	215(40)	32(4)	51(19)	0.164(7)	15.86(57)

thermal contributions/m* are key for proto-neutron star contraction

faster contraction aids supernova shock to more successful explosion



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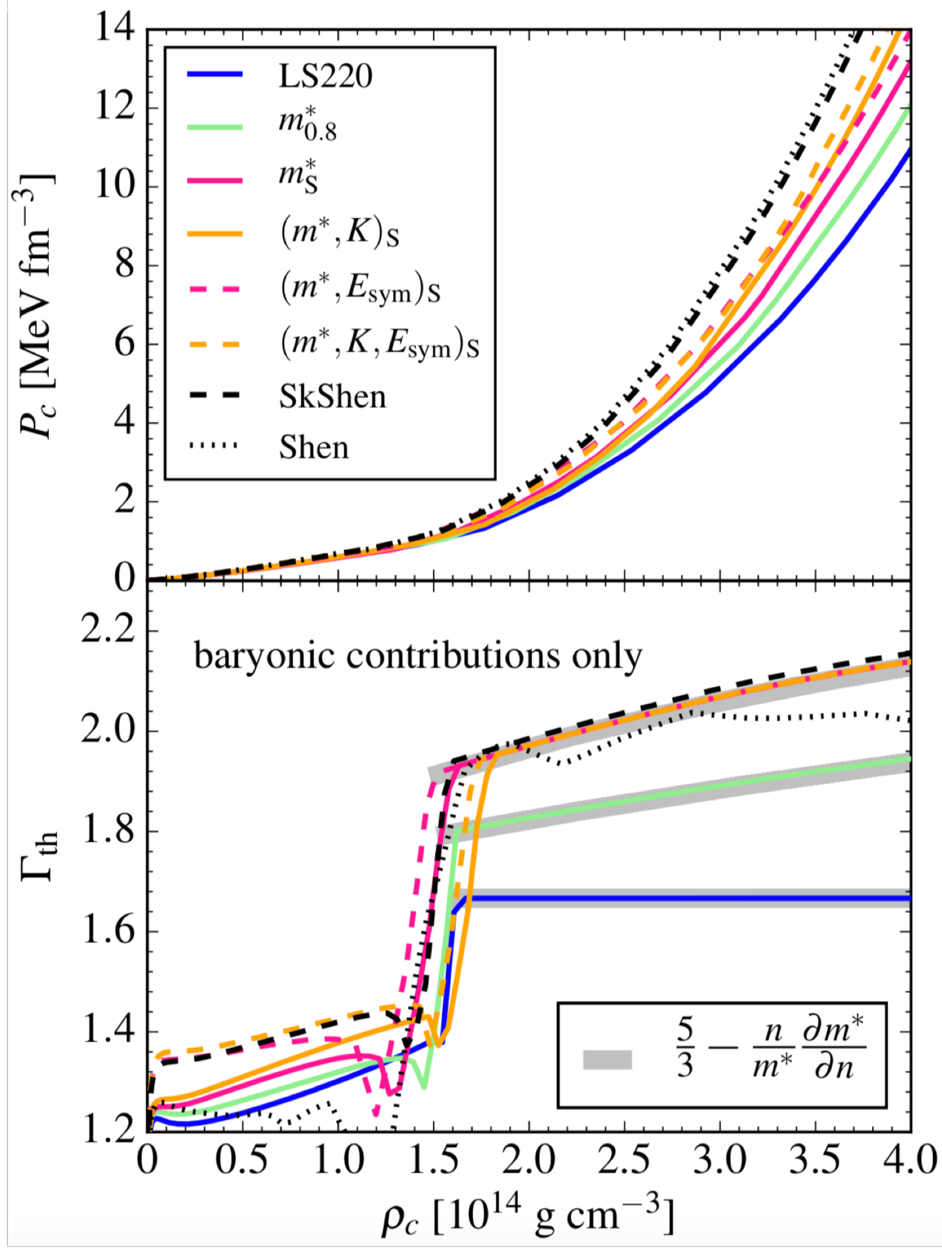
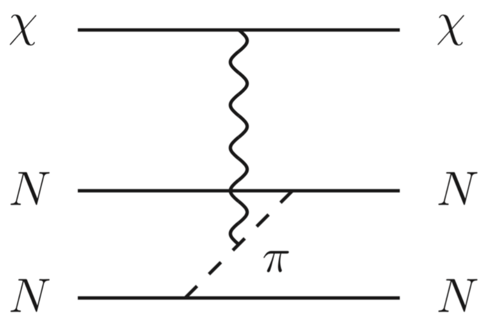
larger m* results in smaller pressure (cold and thermal)

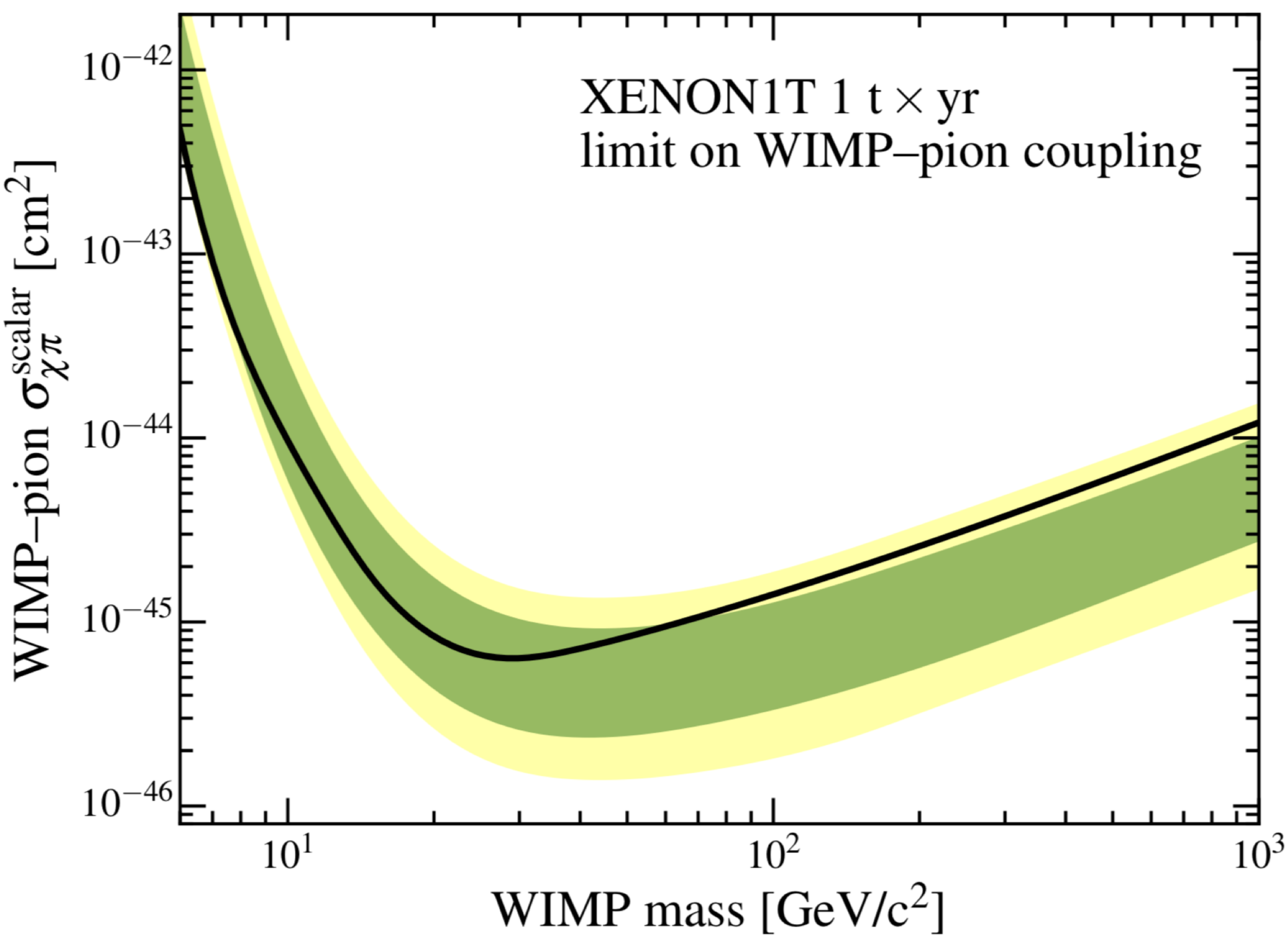


First limits for WIMP-pion interactions

in collaboration with XENON1T Aprile et al., PRL last week

based on chiral EFT for WIMP-nucleon/pion interactions





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