

# Status and challenges of chiral EFT calculations of nuclei and dense matter

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TECHNISCHE  
UNIVERSITÄT  
DARMSTADT



New Ideas in Constraining Nuclear Forces, ECT\*, June 5, 2018



Bundesministerium  
für Bildung  
und Forschung

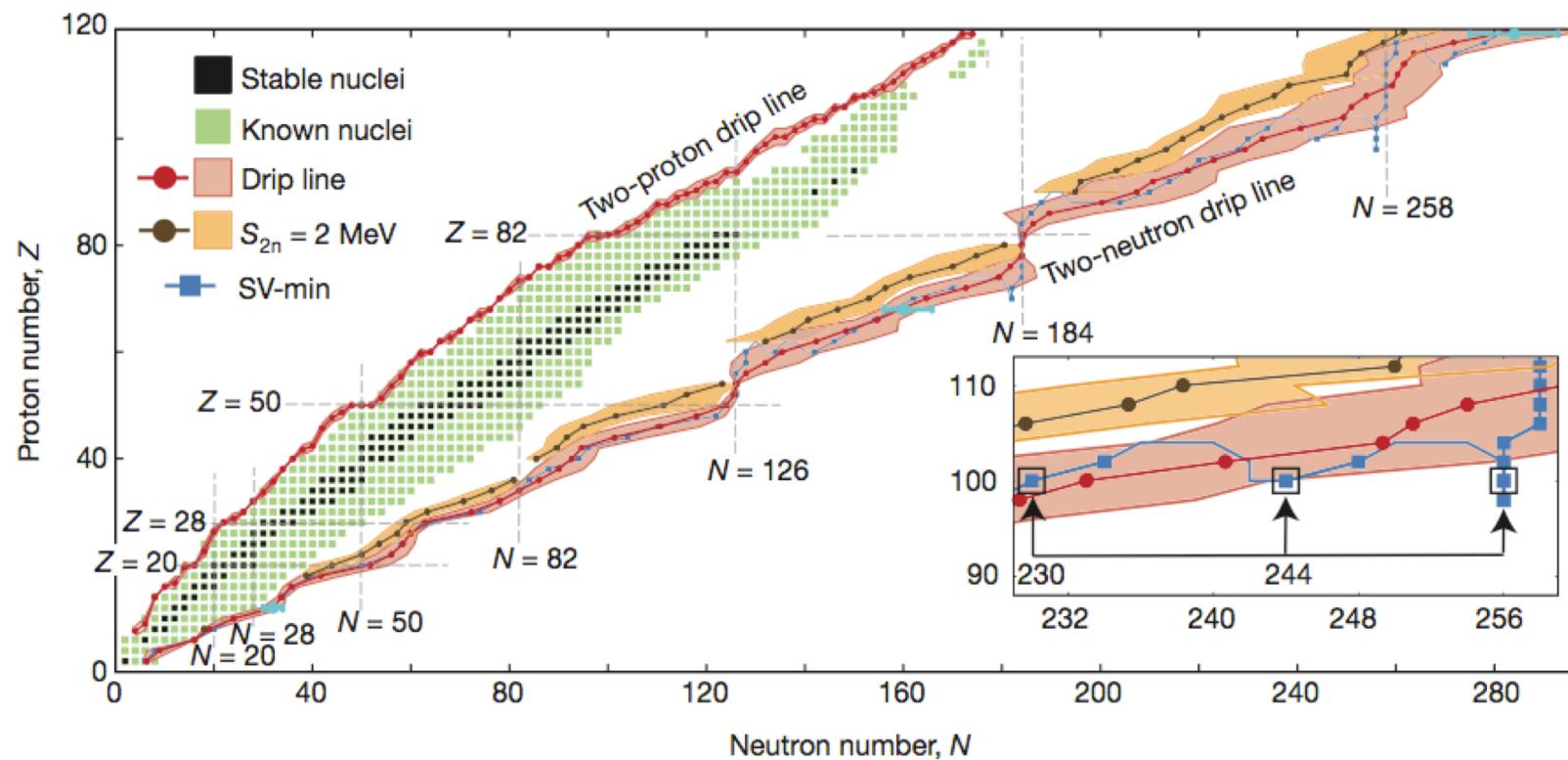


# Nuclei bound by strong interactions

doi:10.1038/nature11188

## The limits of the nuclear landscape

Jochen Erler<sup>1,2</sup>, Noah Birge<sup>1</sup>, Markus Kortelainen<sup>1,2,3</sup>, Witold Nazarewicz<sup>1,2,4</sup>, Erik Olsen<sup>1,2</sup>, Alexander M. Perhac<sup>1</sup> & Mario Stoitsov<sup>1,2†</sup>

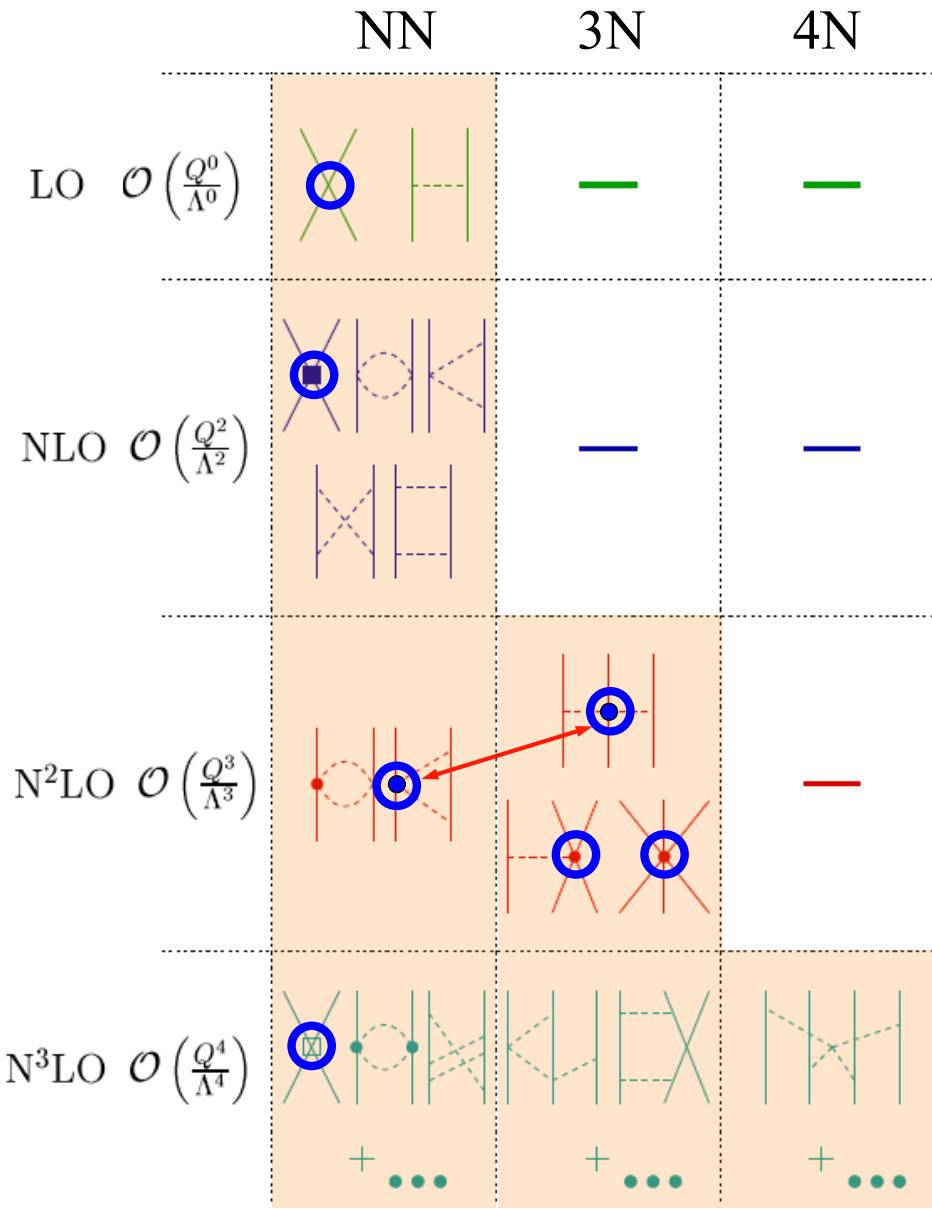


How does the nuclear chart emerge from quantum chromodynamics?

Lattice QCD and effective field theories of the strong interaction  
for few nucleons      for all nuclei

# Chiral effective field theory for nuclear forces

Separation of scales: low momenta  $\frac{1}{\lambda} = Q \ll \Lambda_b$  breakdown scale  $\sim 500$  MeV  
 $\sim m_\Delta - m_N \dots m_\rho$



include long-range  
pion physics

short-range couplings,  
fit to experiment once



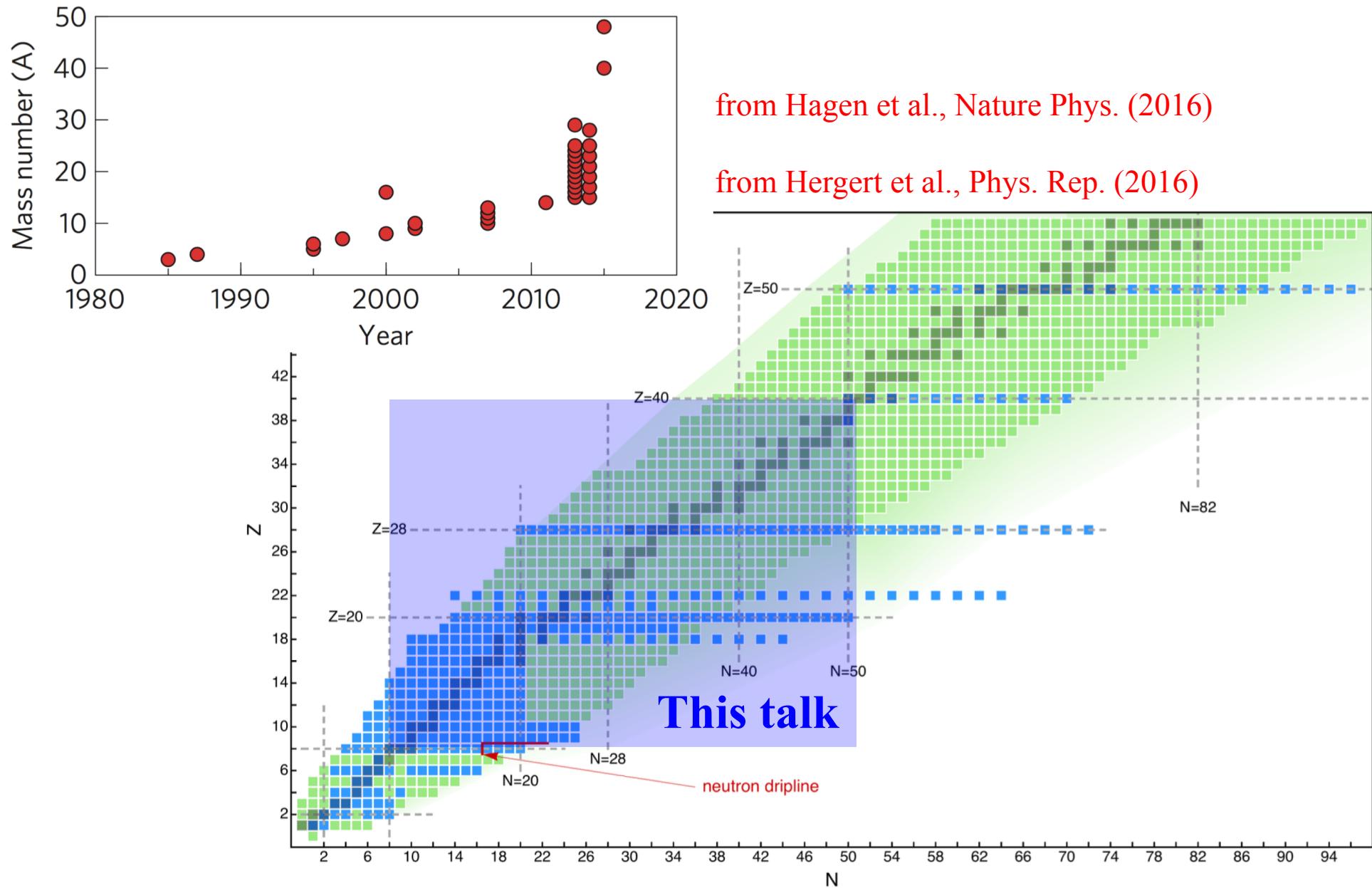
consistent NN-3N-4N interactions

new developments in power counting,  
uncertainty quantification,  
optimization Ekström, Forssen, Furnstahl,...

consistent electroweak interactions  
and matching to lattice QCD

# Progress in ab initio calculations of nuclei

dramatic progress in last 5 years to access nuclei up to  $A \sim 50$



# Ab initio calculations of neutron-rich oxygen isotopes

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

CC theory/CCEI

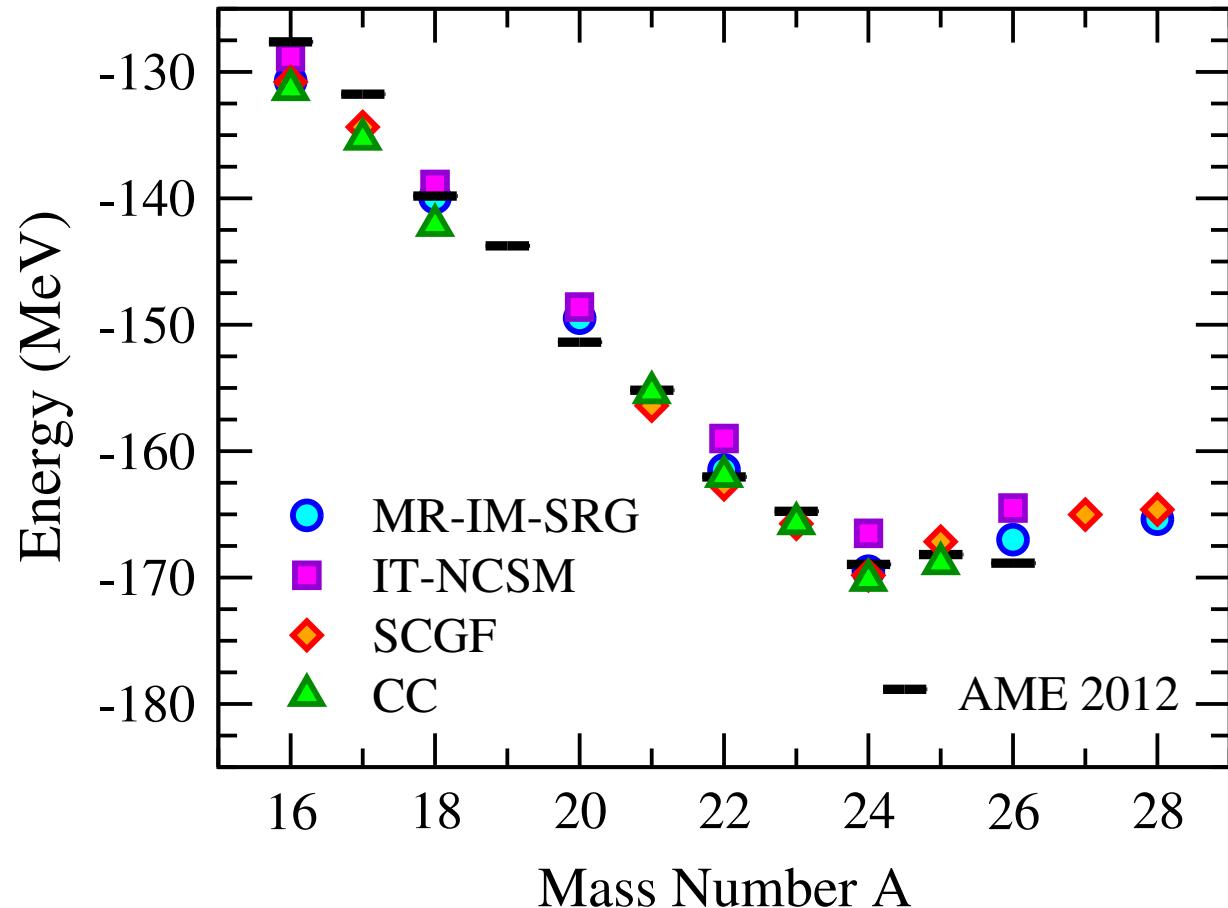
Hagen et al., PRL (2012),  
Jansen et al., PRL (2014)

Multi-Reference  
In-Medium SRG  
and IT-NCSM

Hergert et al., PRL (2013)

Self-Consistent  
Green's Functions

Cipollone et al., PRL (2013)

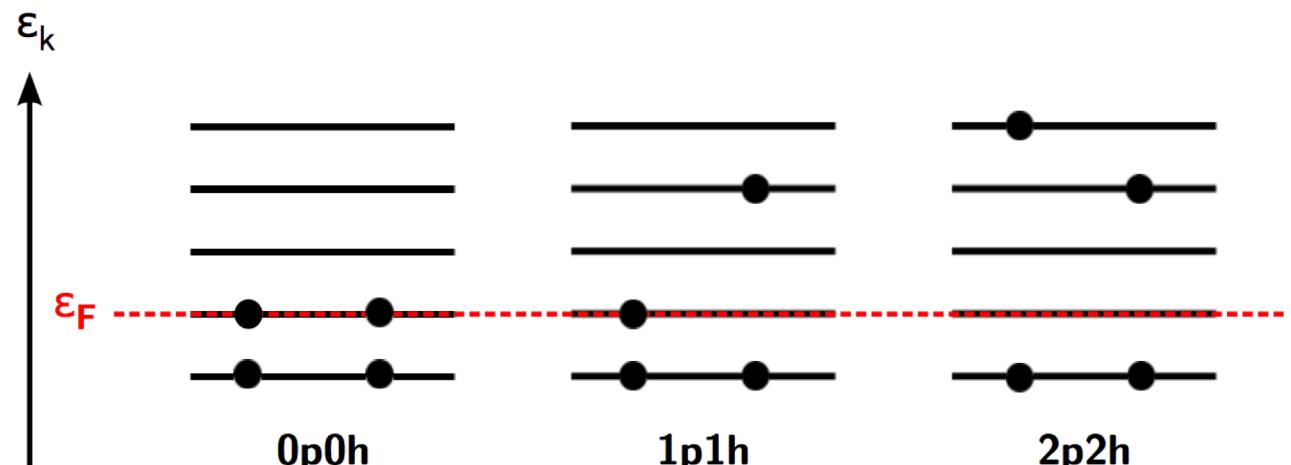
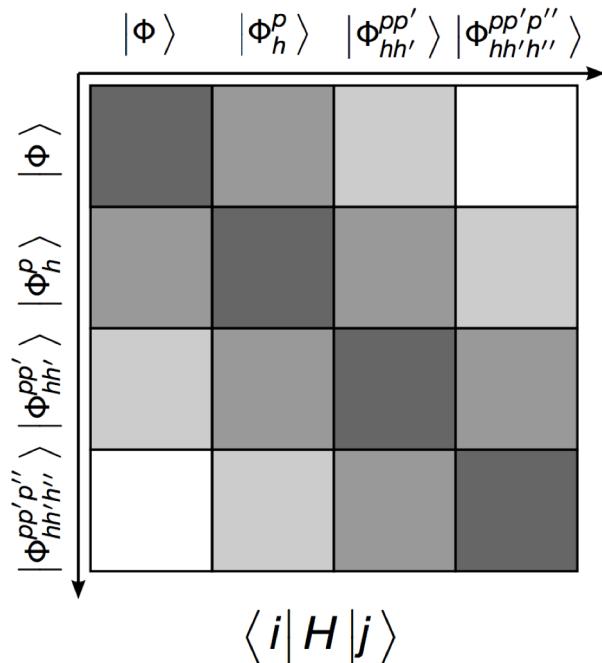


Many-body calculations of medium-mass nuclei have smaller uncertainty compared to uncertainties in nuclear forces

# In-medium similarity renormalization group

flow equations to decouple higher-lying particle-hole states

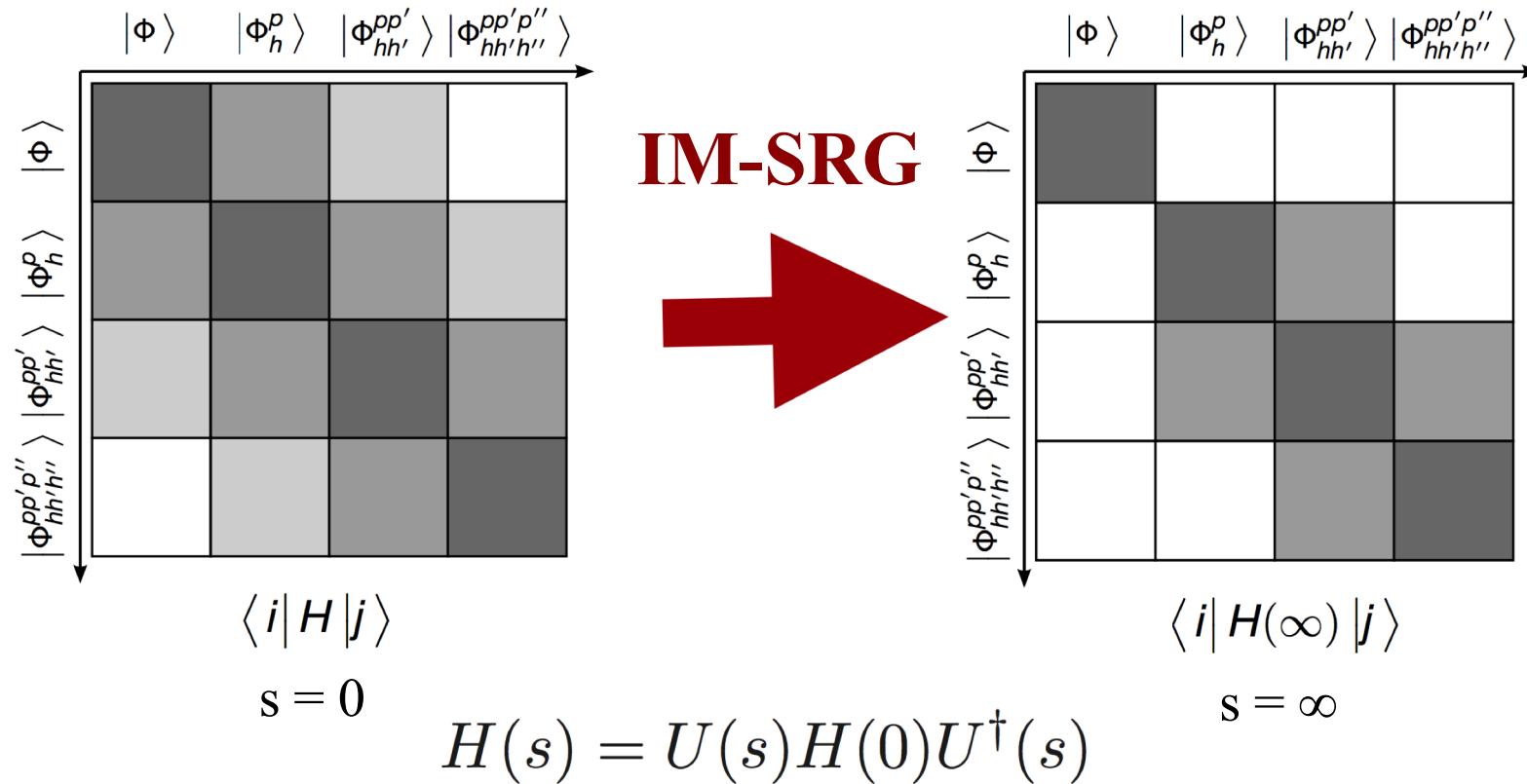
Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)



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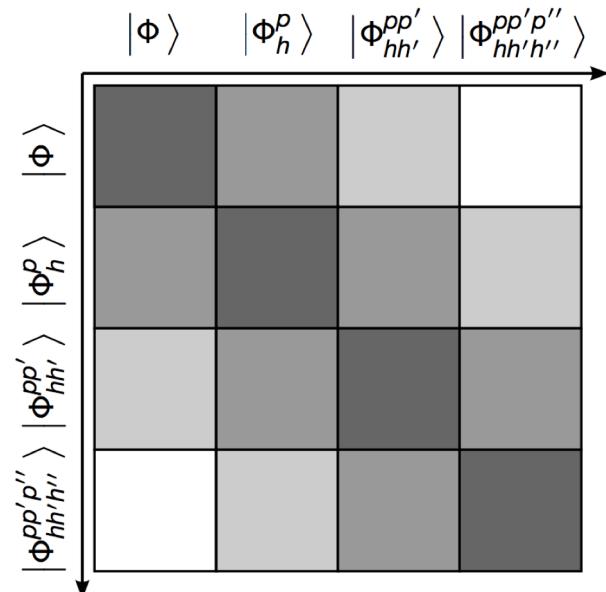
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# In-medium similarity renormalization group

flow equations to decouple higher-lying particle-hole states

Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)



$$\langle i | H | j \rangle$$

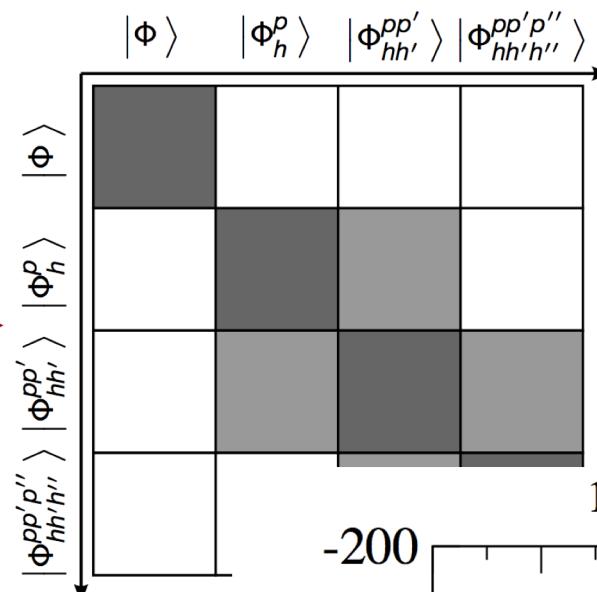
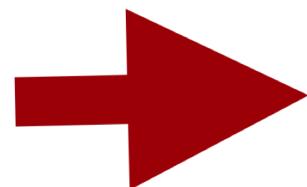
$$s = 0$$

$$H(s) = U(s)H(0)U^\dagger(s)$$

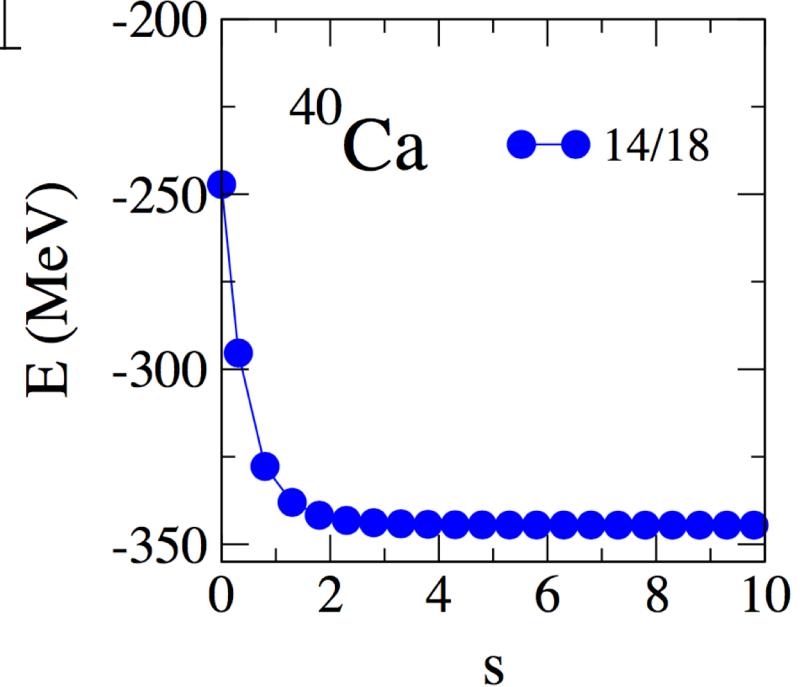
$$\frac{d}{ds}H(s) = [\eta(s), H(s)]$$

with generator  $\eta = [H^d(s), H^{od}(s)]$

**IM-SRG**



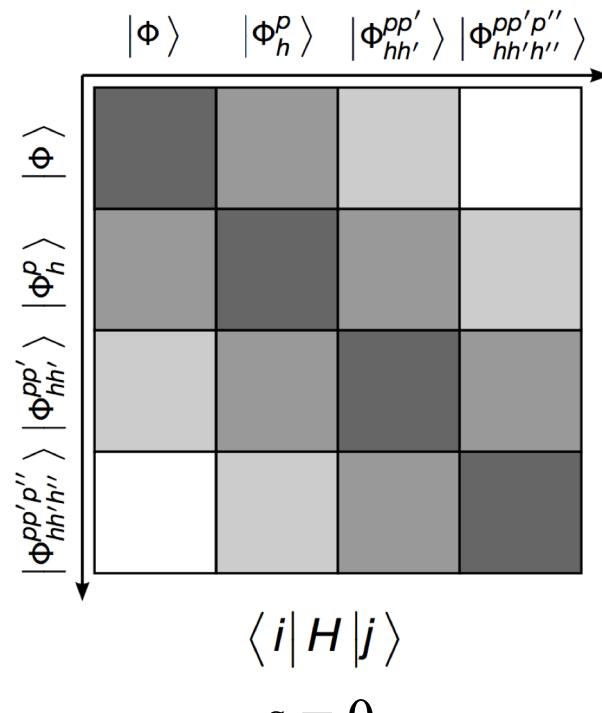
1.8/2.0 (EM)



# In-medium similarity renormalization group

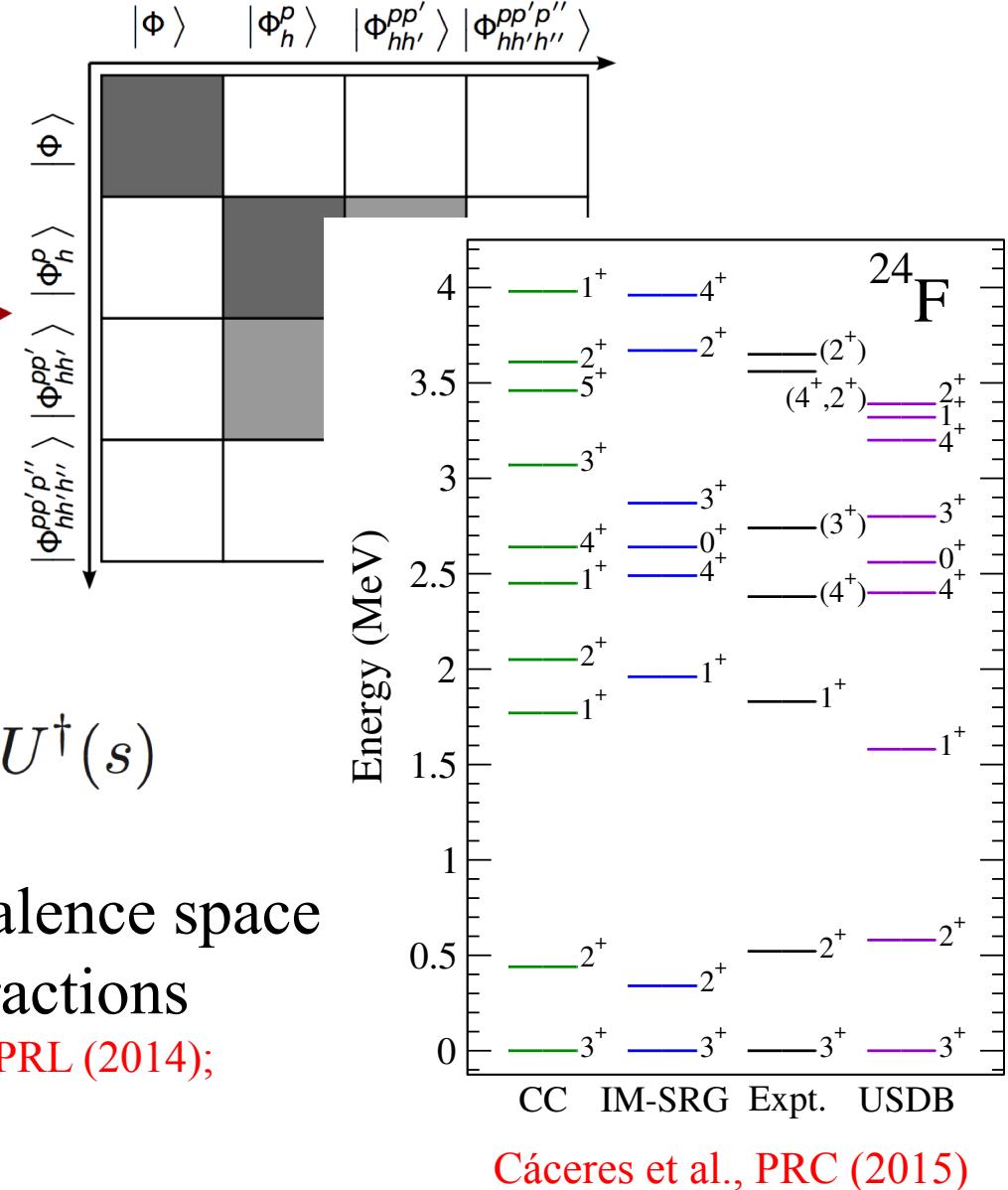
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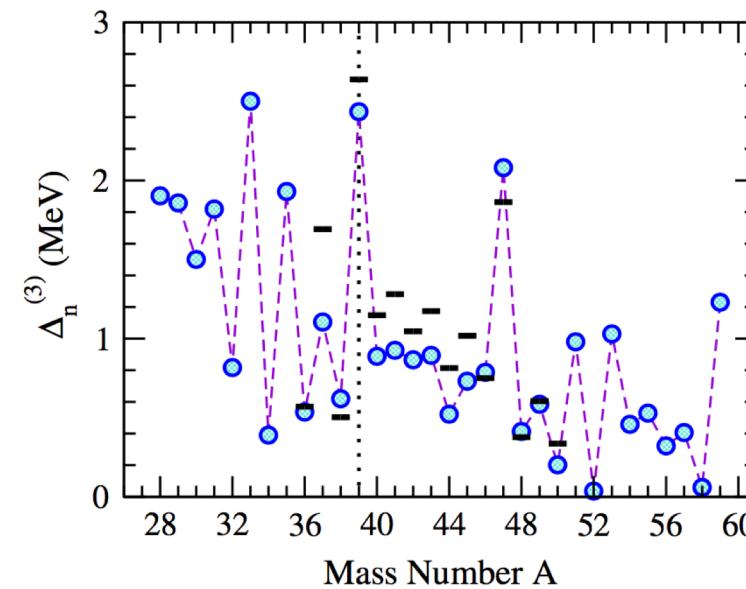
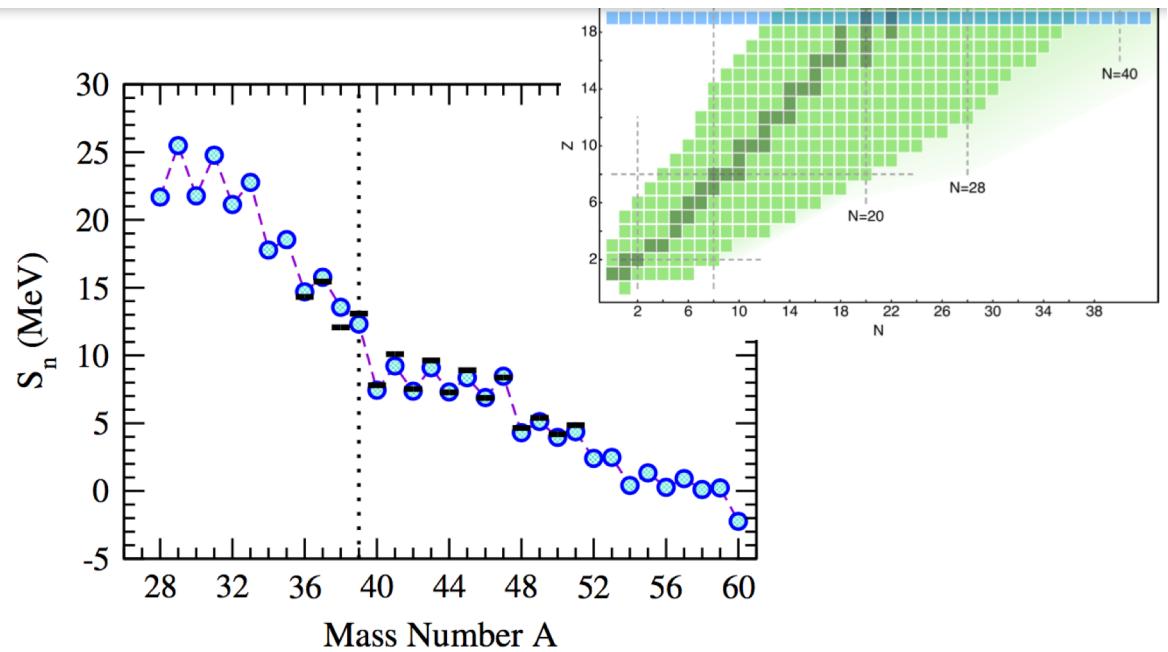
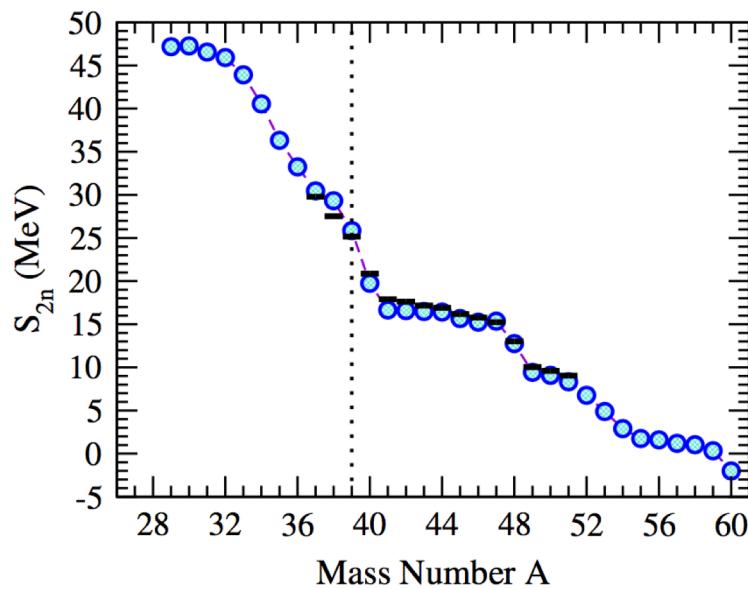
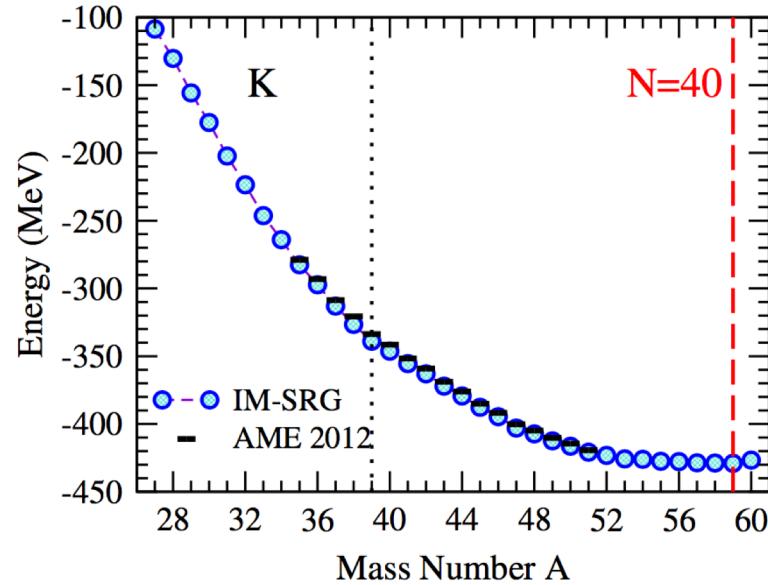
valence-space IMSRG: decouple valence space  
to derive nonpert. shell-model interactions

Tsukiyama, Bogner, AS, PRC (2012); Bogner et al., PRL (2014);  
Stroberg et al., PRL (2016) see Ragnar's talk



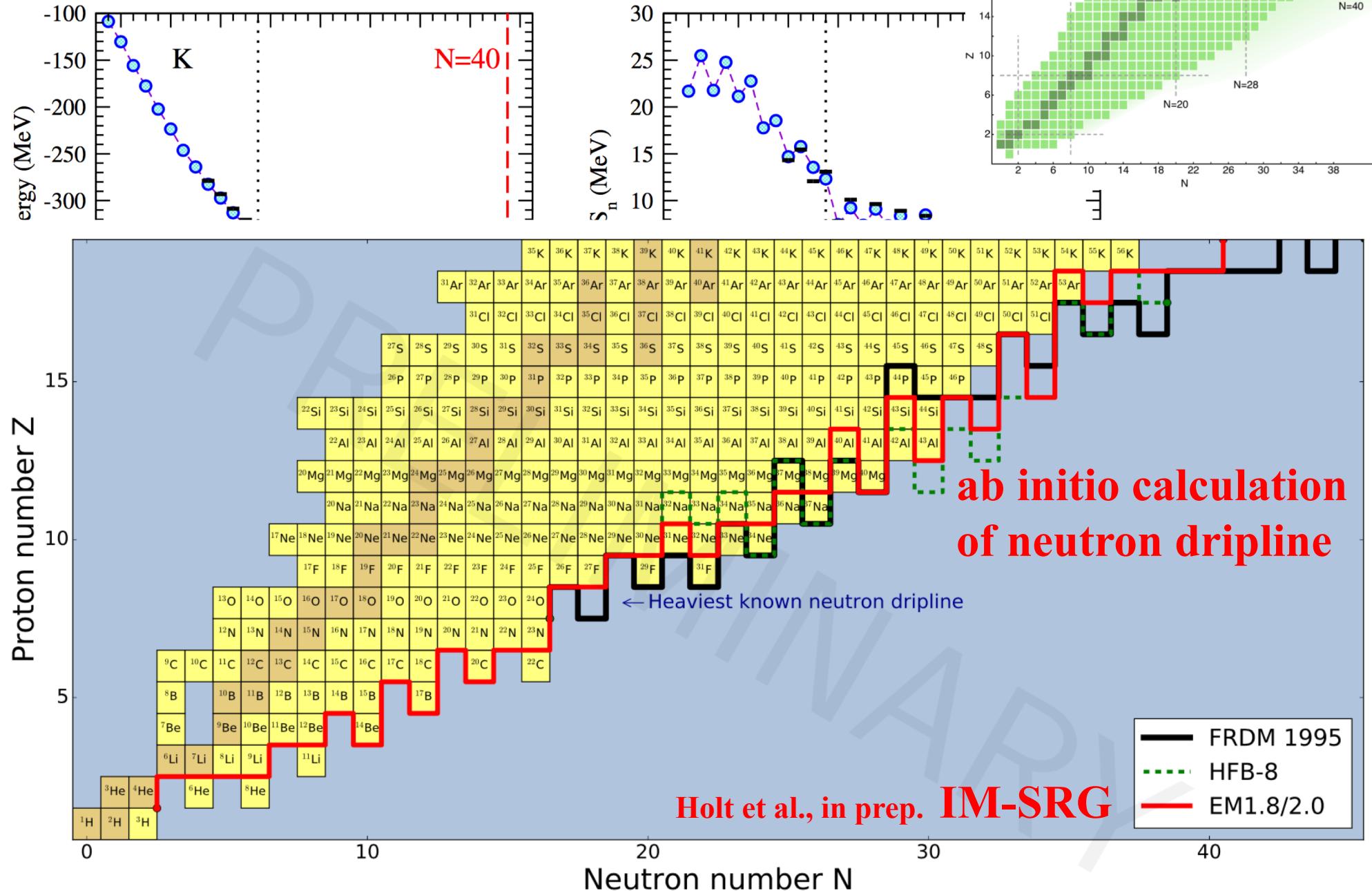
# Great progress from medium to heavy nuclei

J. Simonis, S. R. Stroberg et al., arXiv:1704.02915

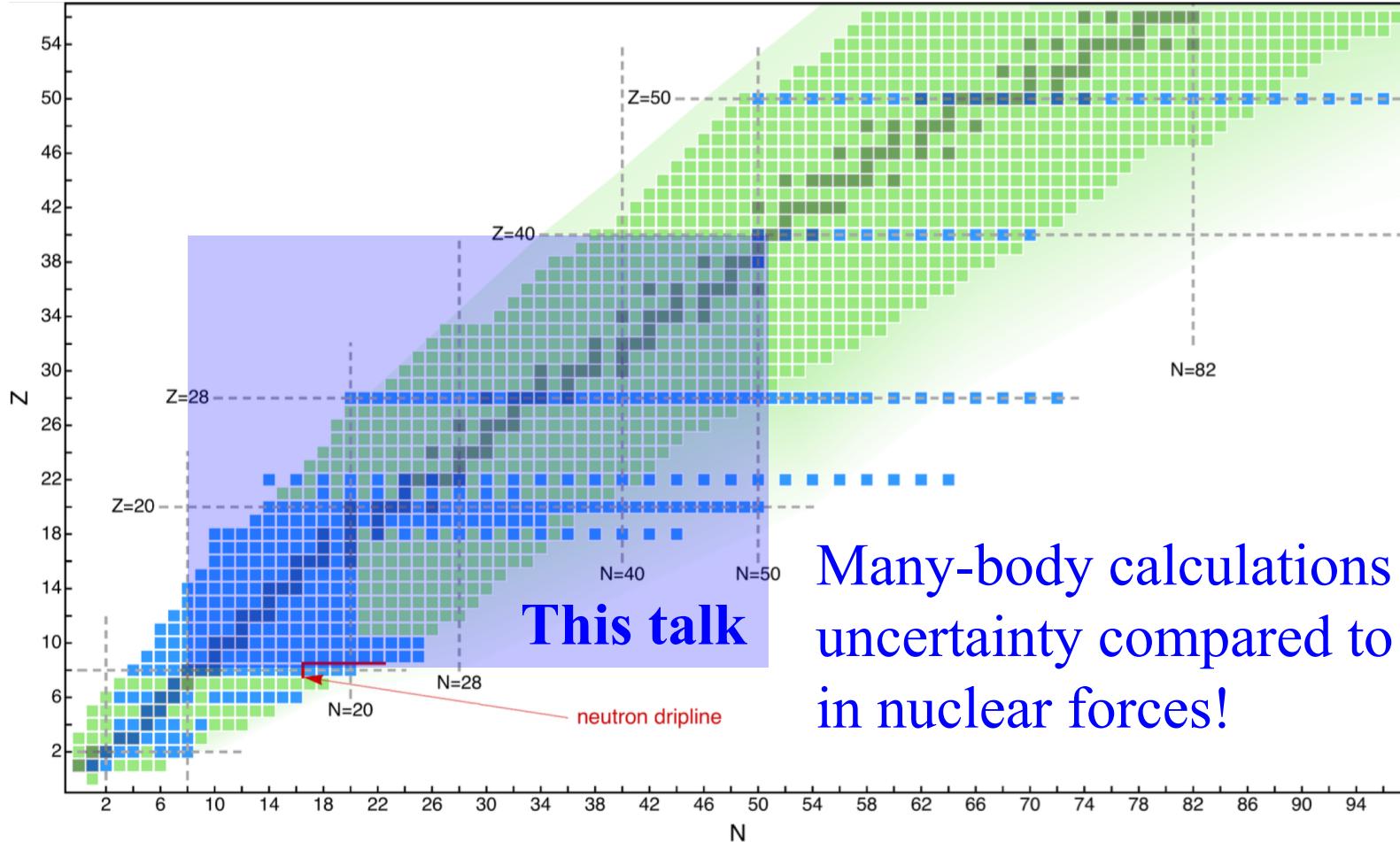


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# Many-body calculation versus input nuclear forces



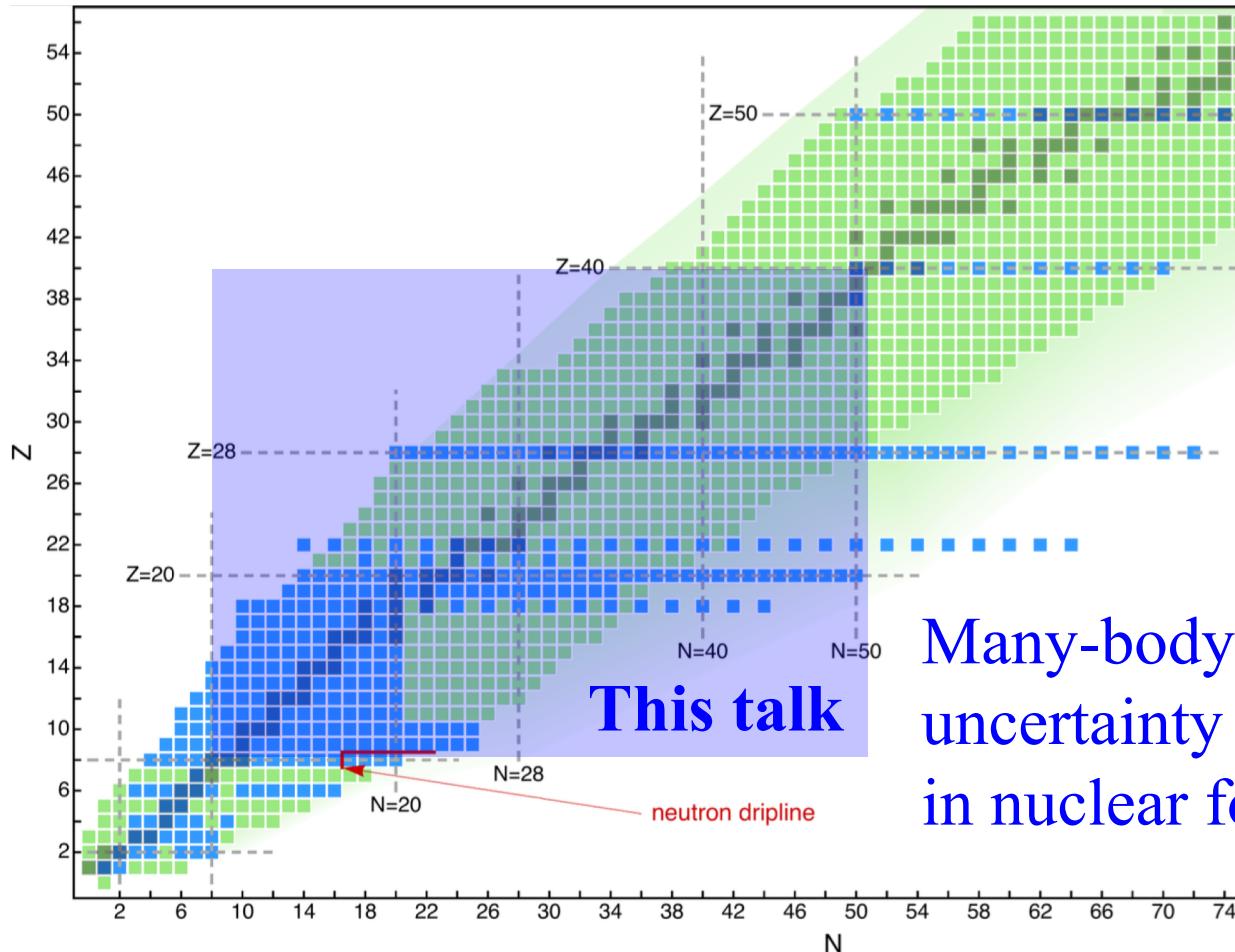
Important for medium-mass nuclei:

Consider nuclear forces with good (nuclear matter) saturation properties

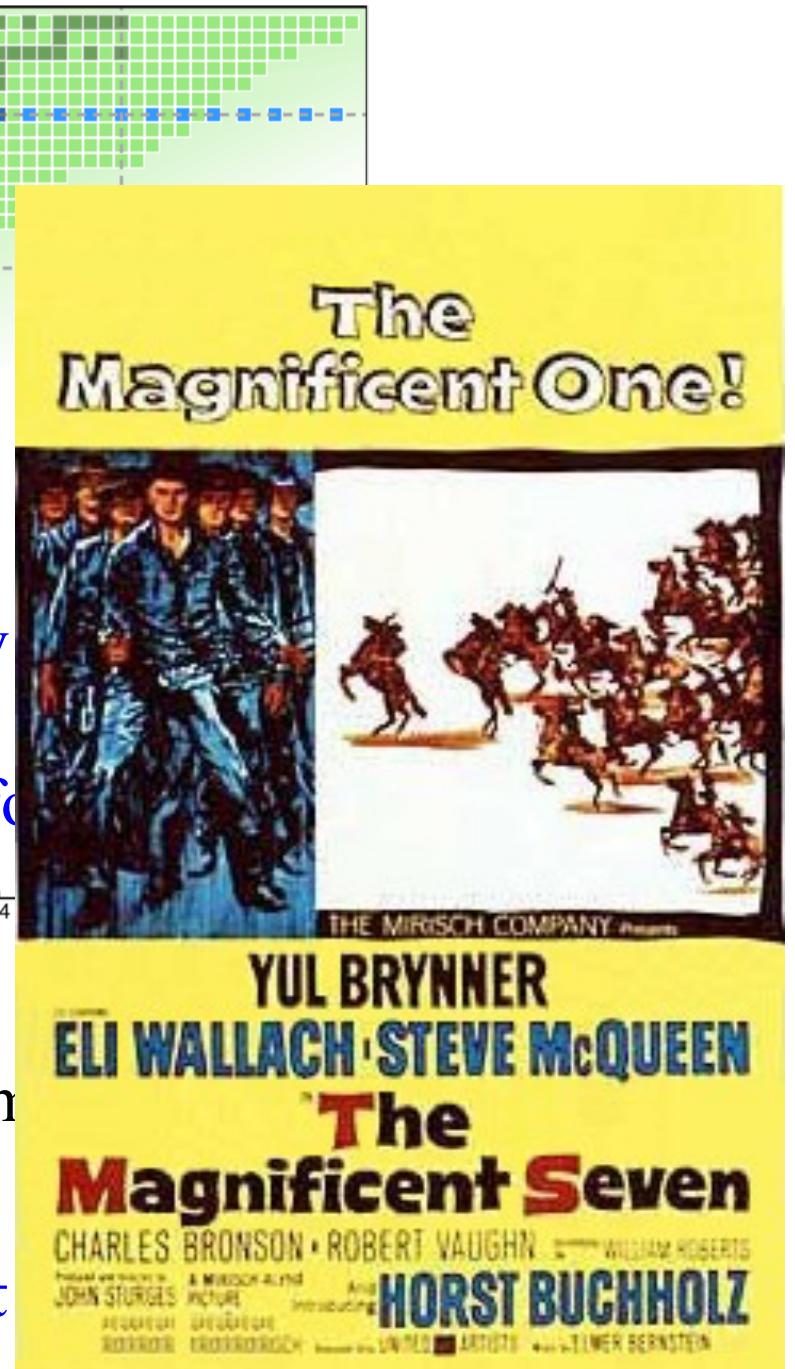
$N^2LO_{sat}$  fit to selected nuclei up to  $A=24$

“Magnificent Seven”: NN evolved + 3N fit to  ${}^3H$ ,  ${}^4He$

# Many-body calculation versus input nuclear forces



Many-body  
uncertainty  
in nuclear fo



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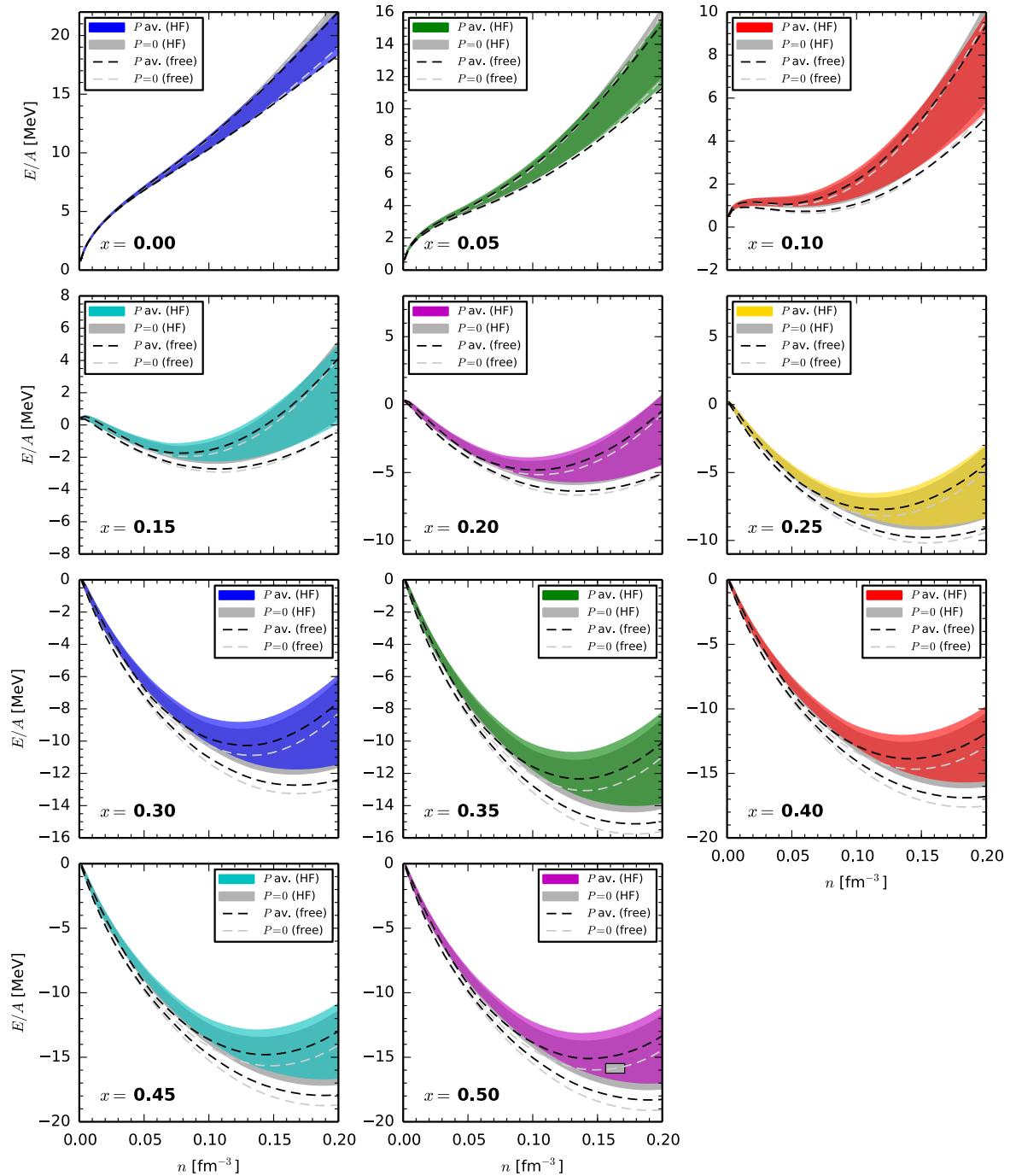
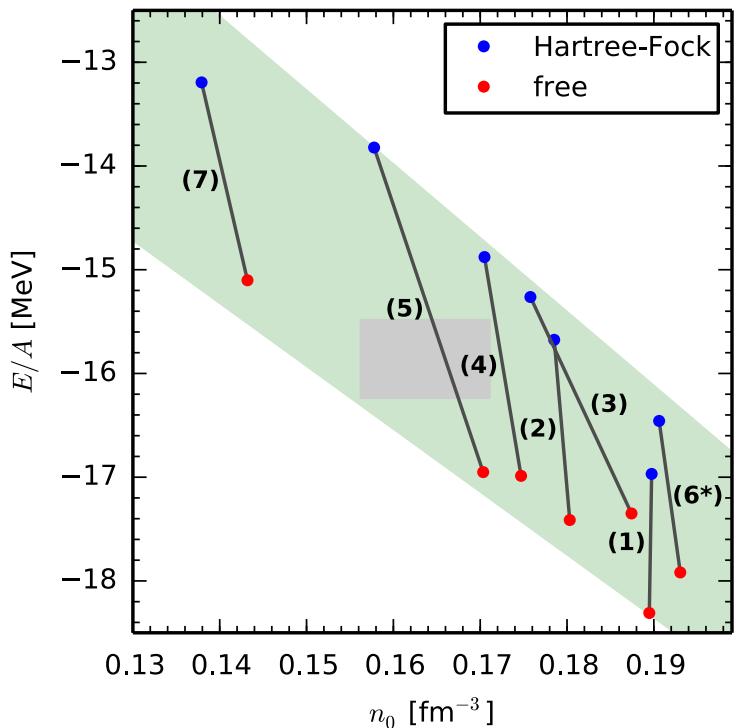
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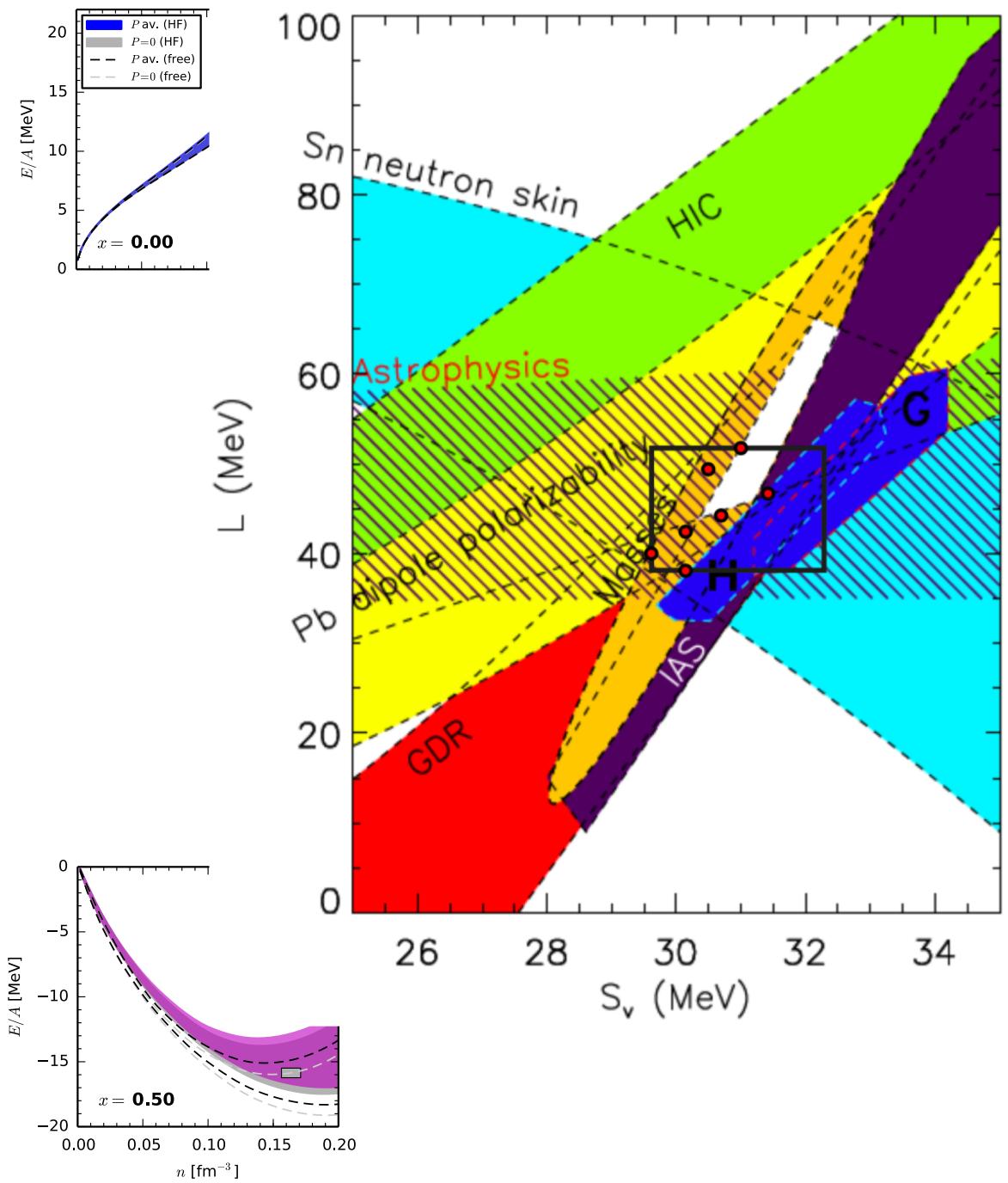
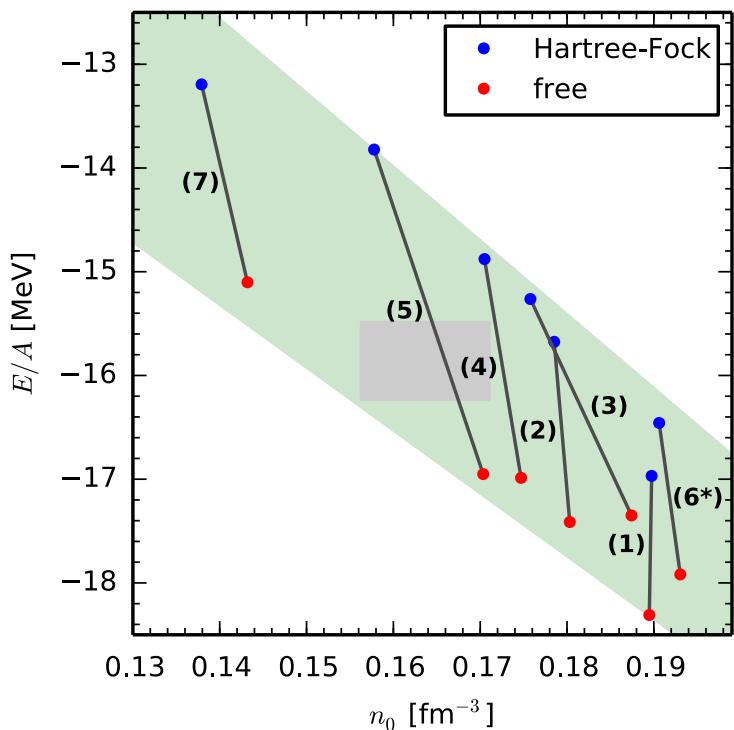
# asymmetric matter with improved treatment of 3N forces

Drischler, Hebeler, AS, PRC (2016)  
see also Holt, Kaiser, Weise, Wellenhofer



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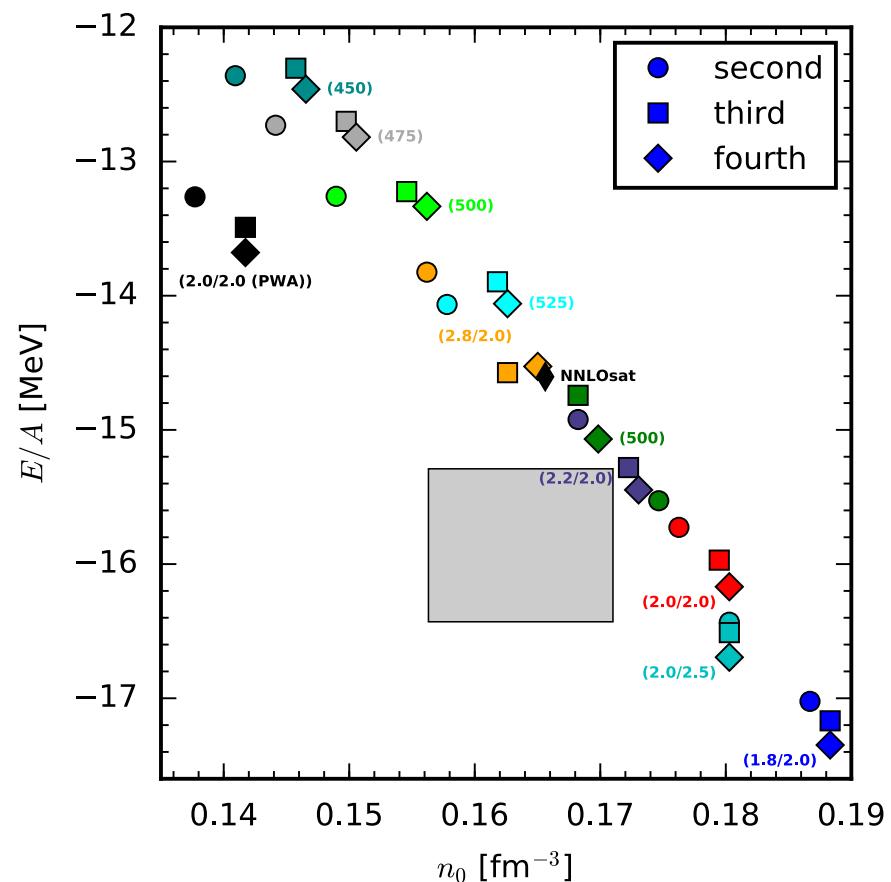
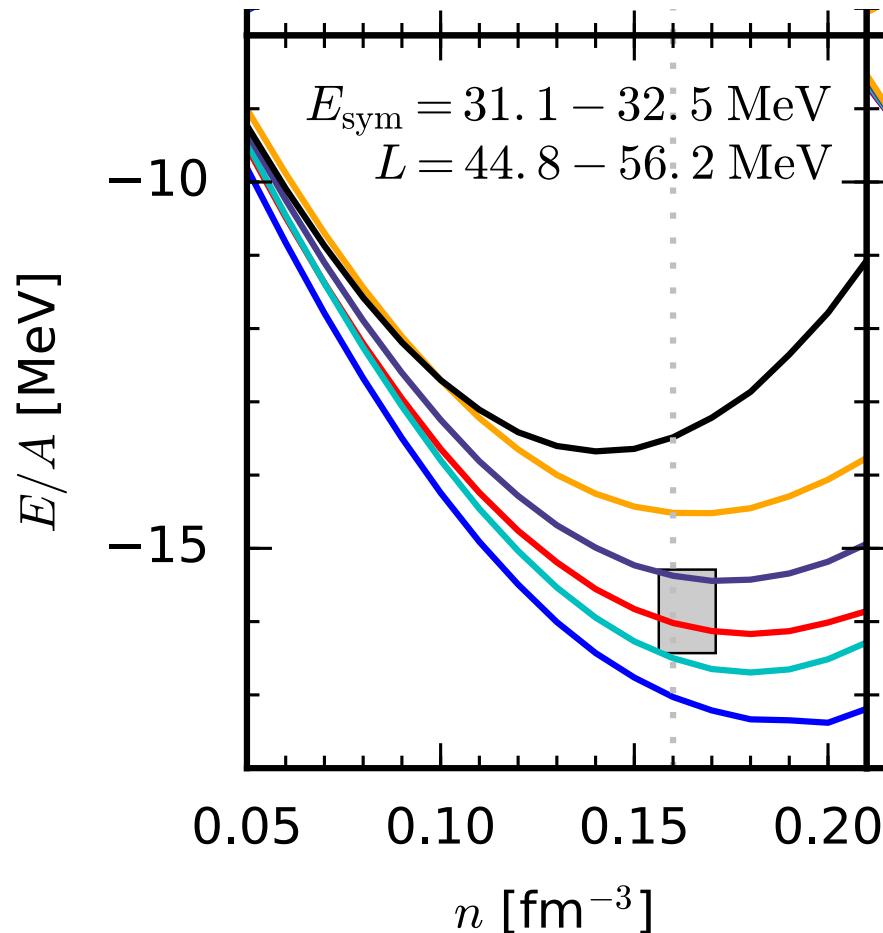


# Nuclear forces and nuclear matter

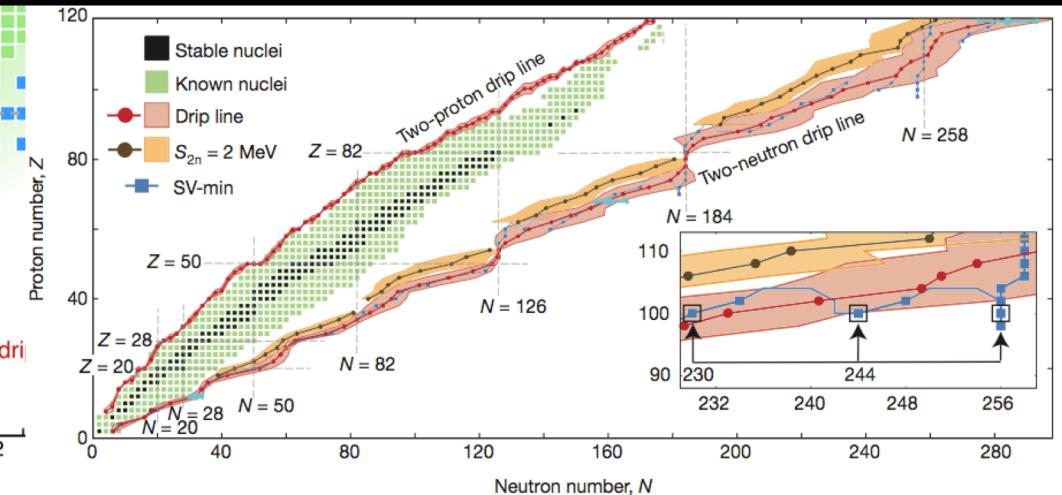
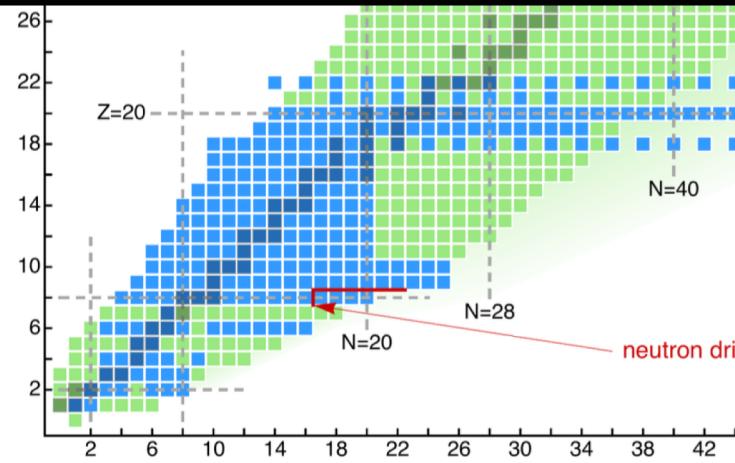
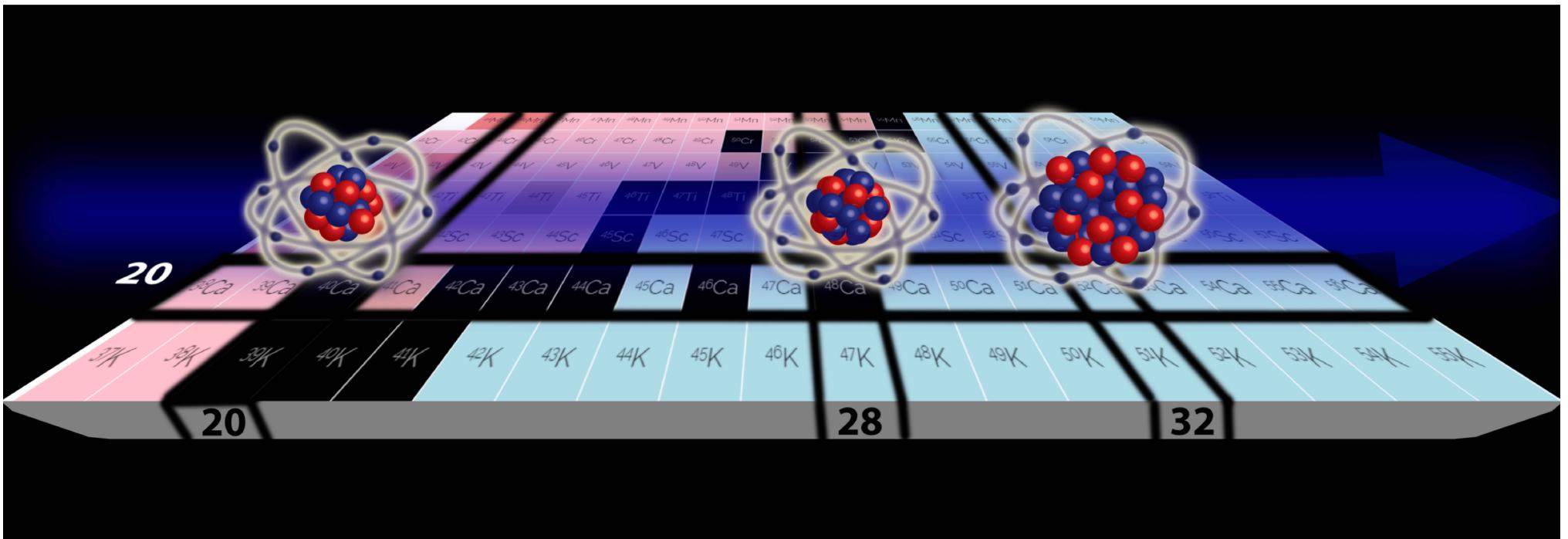
Monte-Carlo calculation of all energy diagrams  
up to 4th order in MBPT

Drischler, Hebeler, AS, arXiv:1710.08220

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

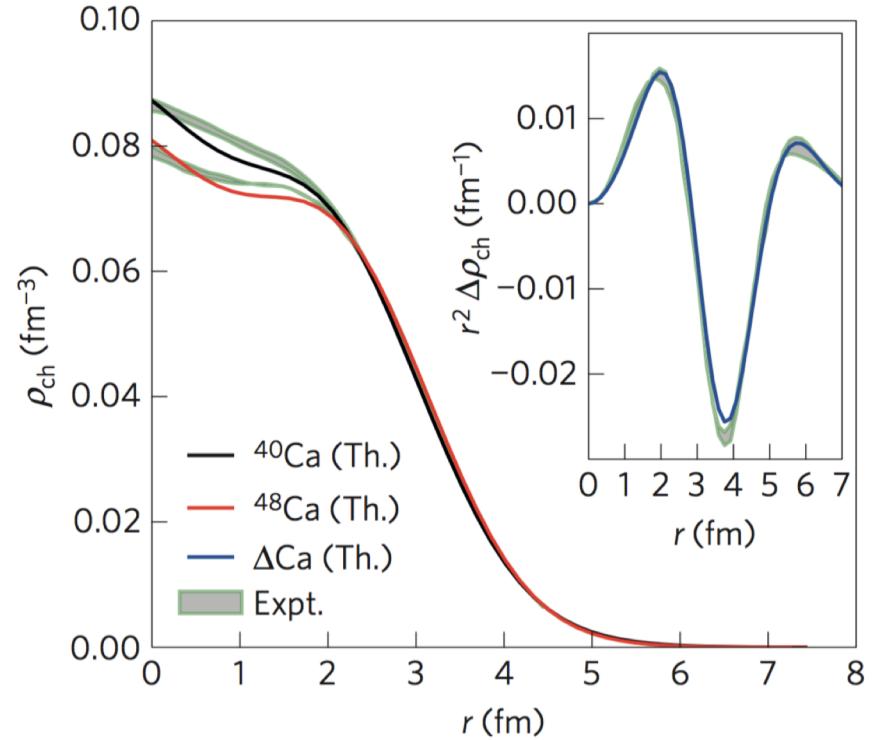


# Neutron-rich calcium isotopes



# Neutron and weak-charge distributions of $^{48}\text{Ca}$

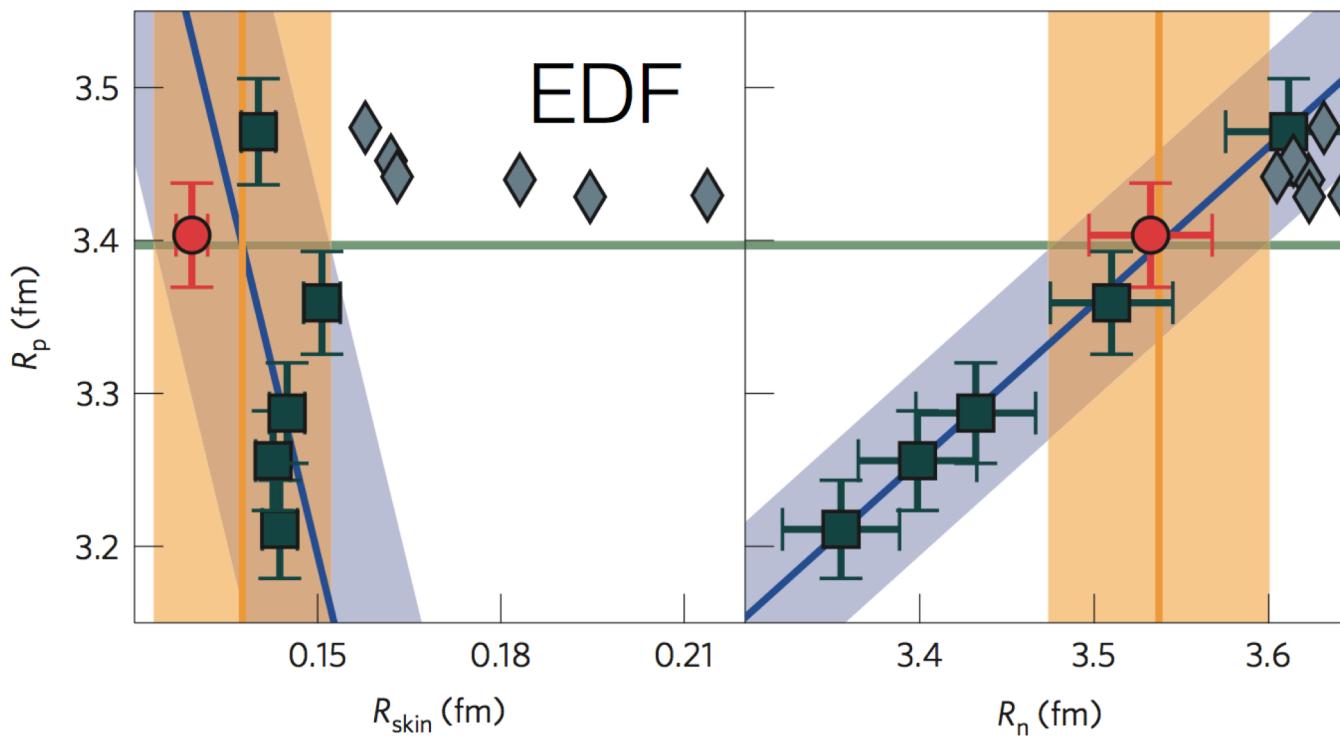
ab initio calculations lead to charge distributions consistent with experiment



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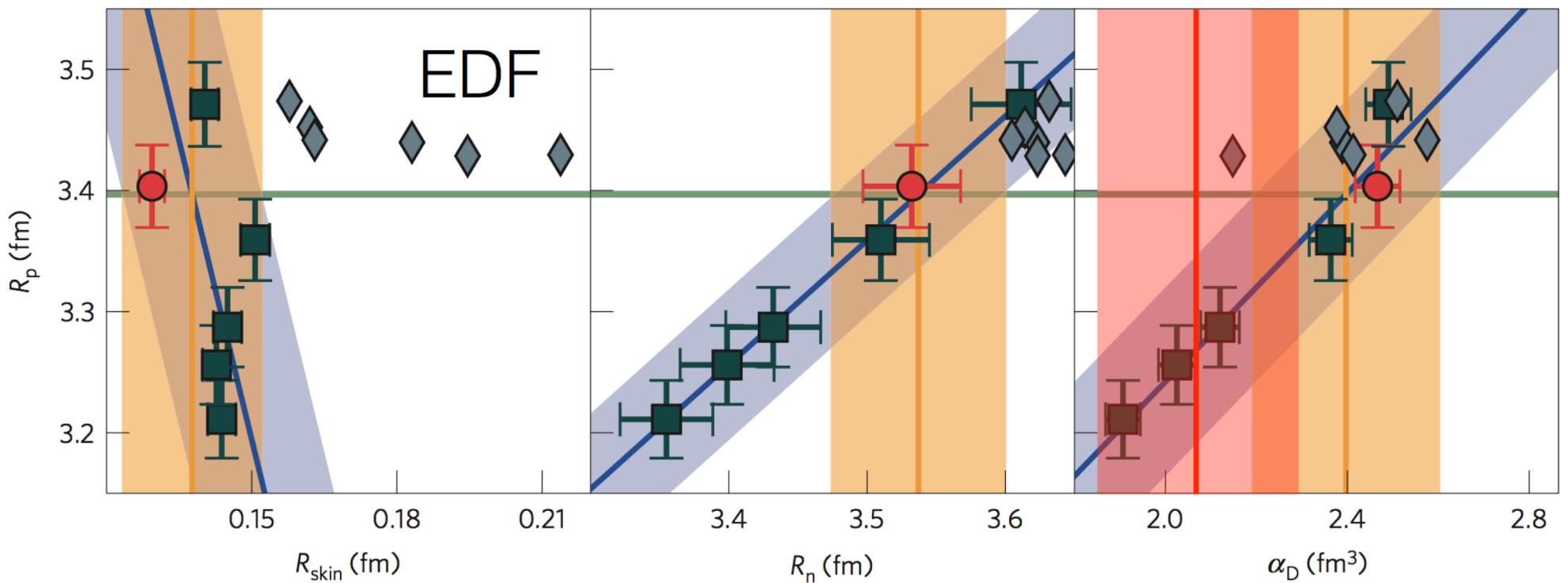
predict **small neutron skin**



# Neutron and weak-charge distributions of $^{48}\text{Ca}$

ab initio calculations lead to charge  
distributions consistent with experiment

predict **small neutron skin**, dipole polarizability, and weak formfactor



dipole polarizability  
in good agreement with  
recent DA-Osaka expt.  
Birkhan, Miorelli, et al., PRL (2017)

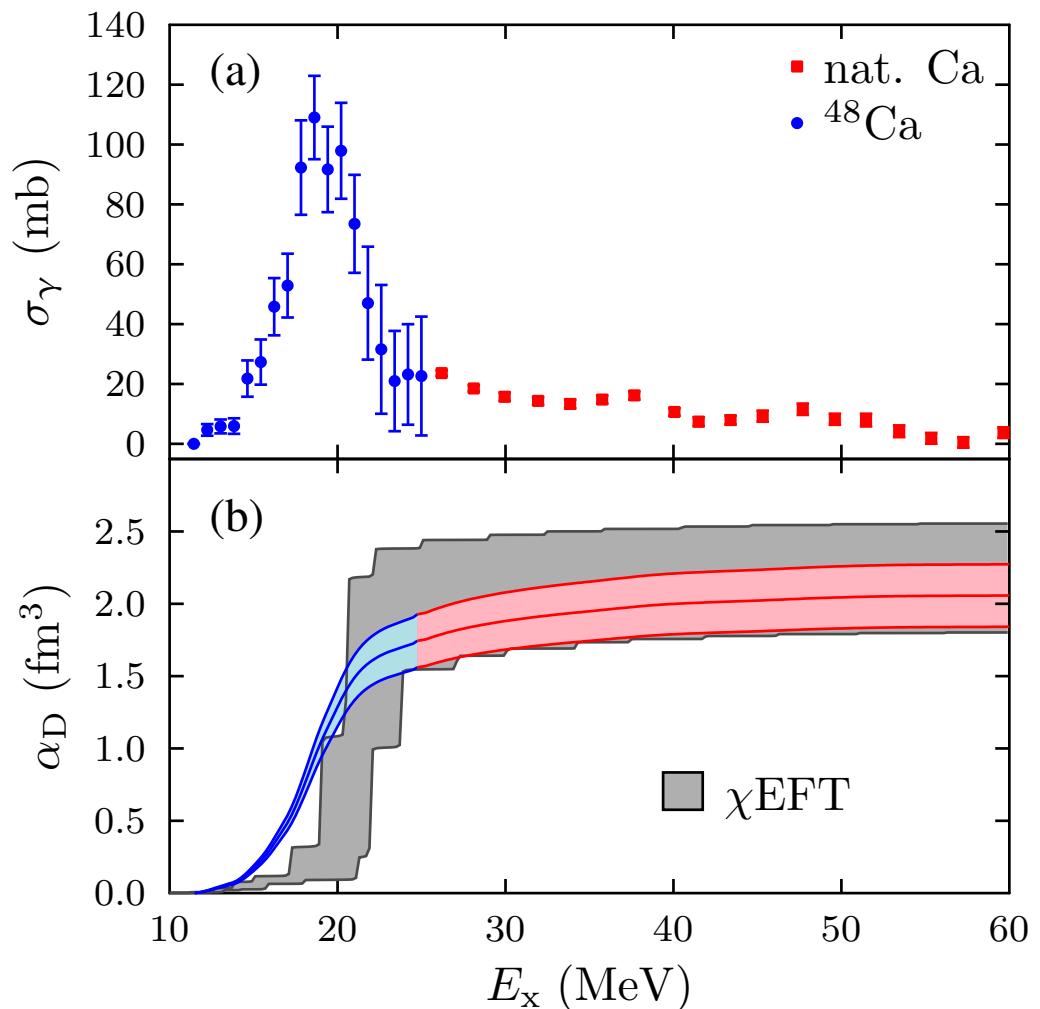
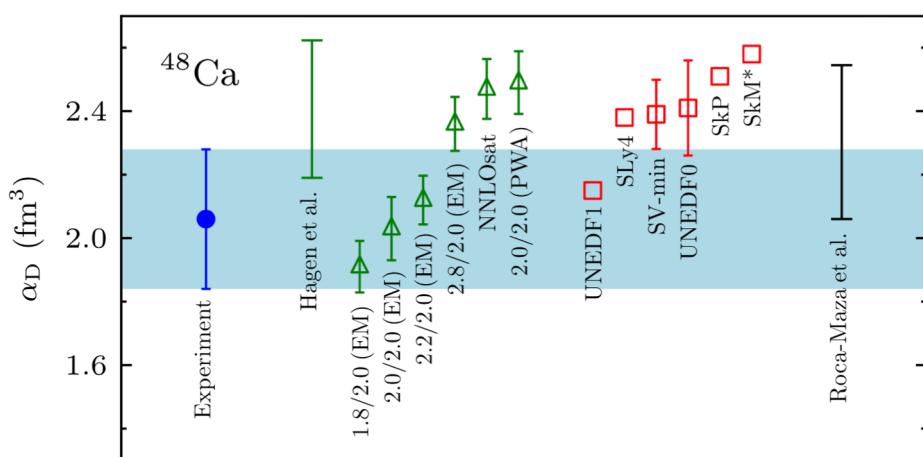
## Electric Dipole Polarizability of $^{48}\text{Ca}$ and Implications for the Neutron Skin

J. Birkhan,<sup>1</sup> M. Miorelli,<sup>2,3</sup> S. Bacca,<sup>2,4</sup> S. Bassauer,<sup>1</sup> C. A. Bertulani,<sup>5</sup> G. Hagen,<sup>6,7</sup> H. Matsubara,<sup>8,9</sup>  
 P. von Neumann-Cosel,<sup>1,\*</sup> T. Papenbrock,<sup>6,7</sup> N. Pietralla,<sup>1</sup> V. Yu. Ponomarev,<sup>1</sup> A. Richter,<sup>1</sup>  
 A. Schwenk,<sup>1,10,11</sup> and A. Tamii<sup>8</sup>

from photo-absorption cross section, measured at Osaka up to 25 MeV

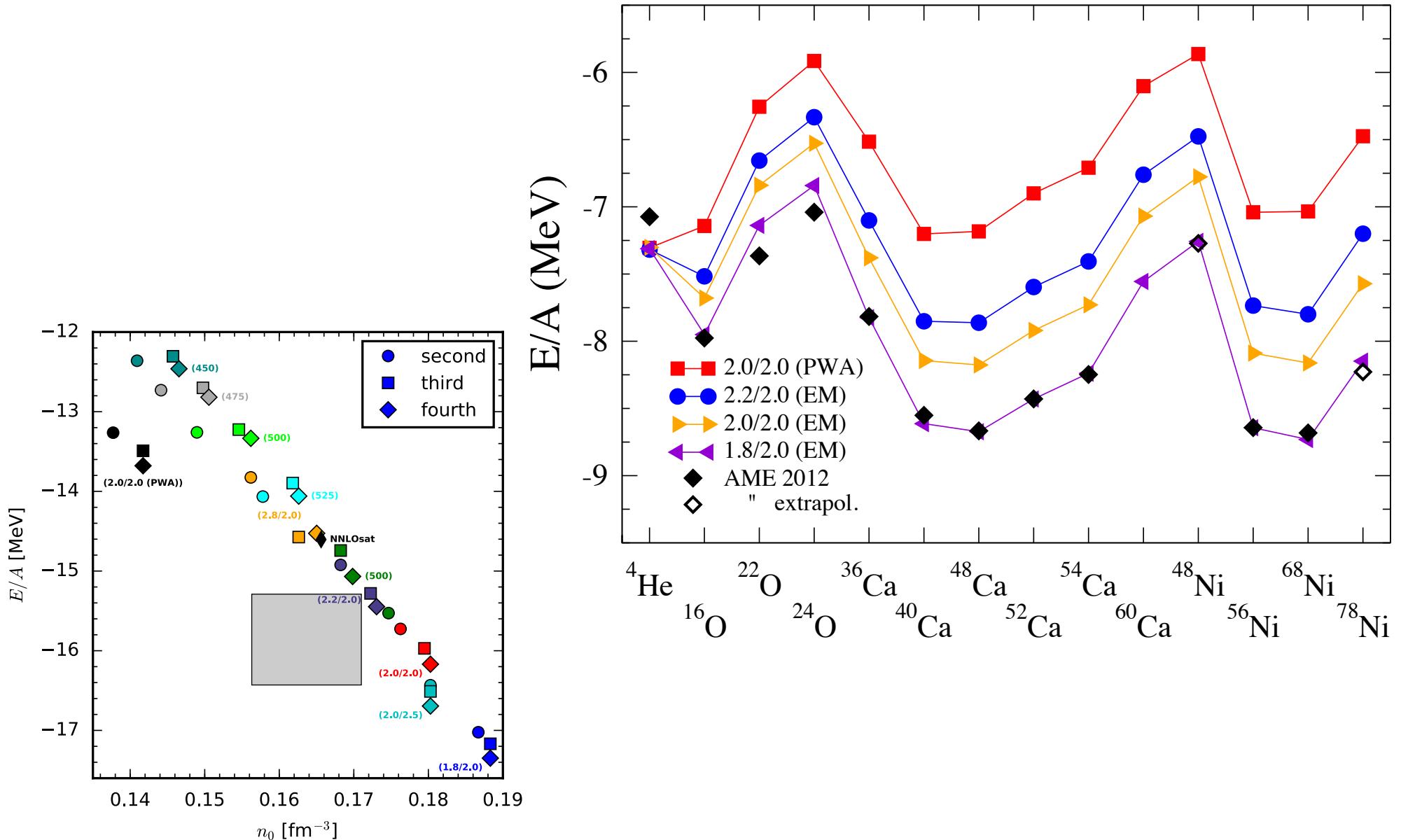
good agreement with  
chiral EFT predictions

theory comparison gives  
 $R_{\text{skin}} = 0.14\text{-}0.20 \text{ fm}$



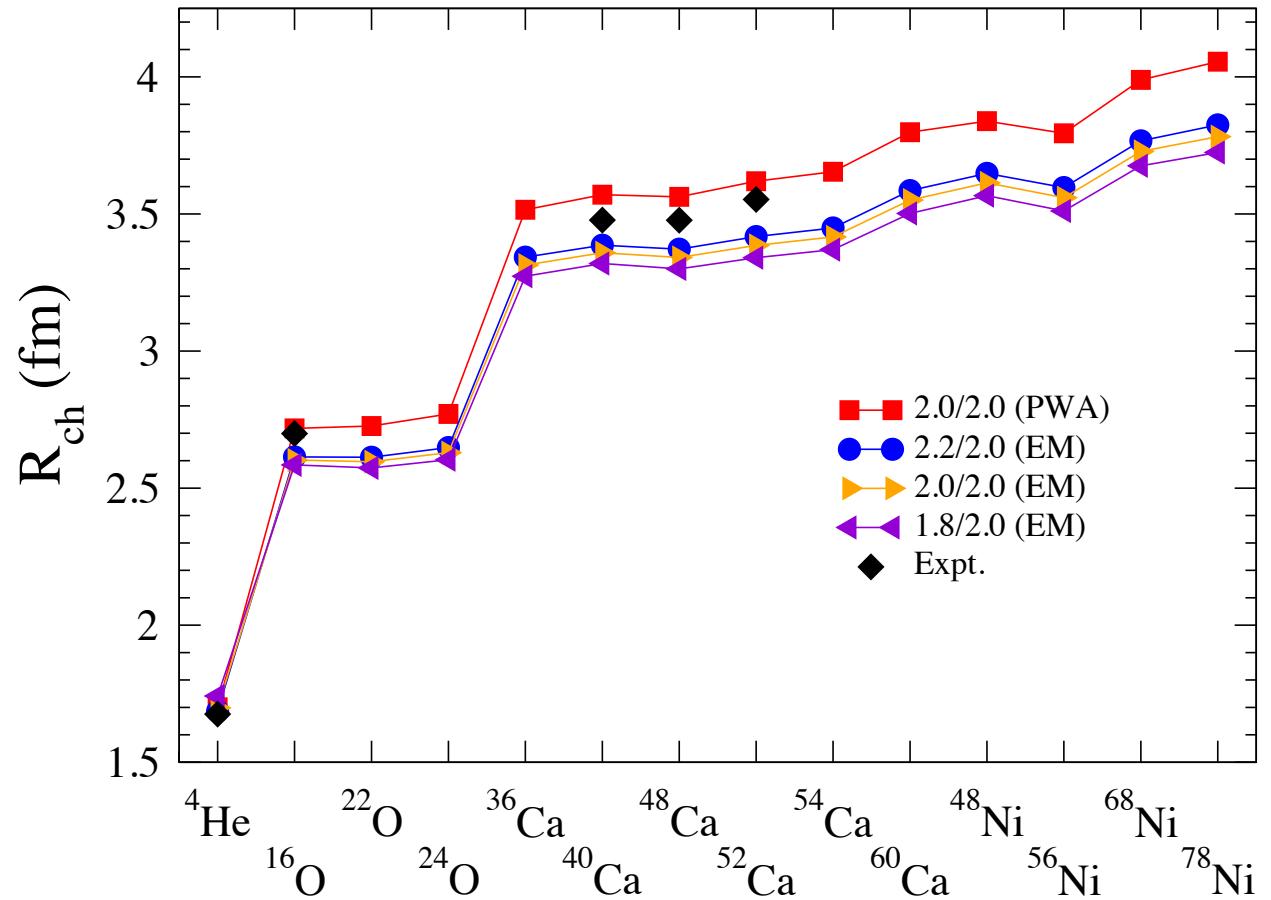
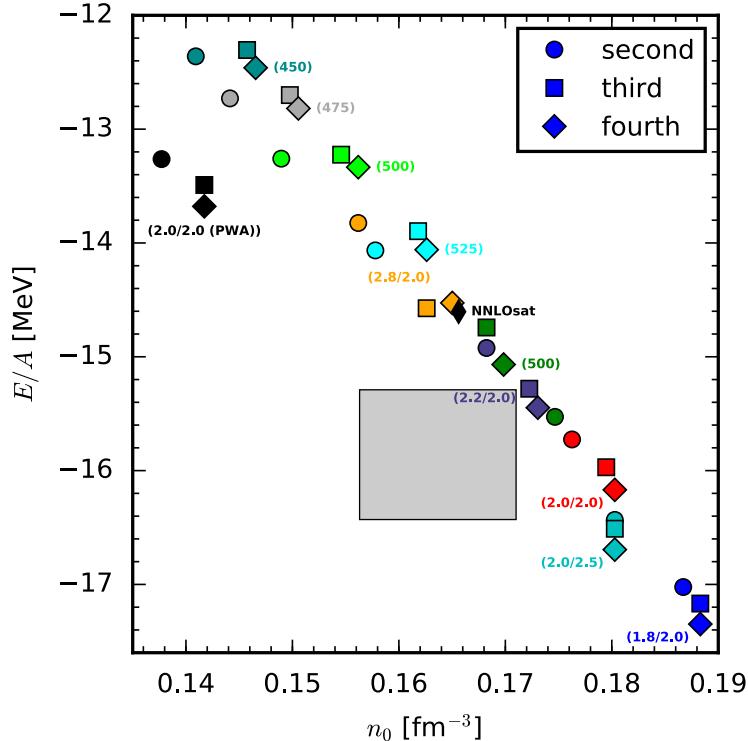
# Importance of saturation for nuclear forces Simonis, Stroberg et al. (2017)

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



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



# Nuclear forces and nuclear matter

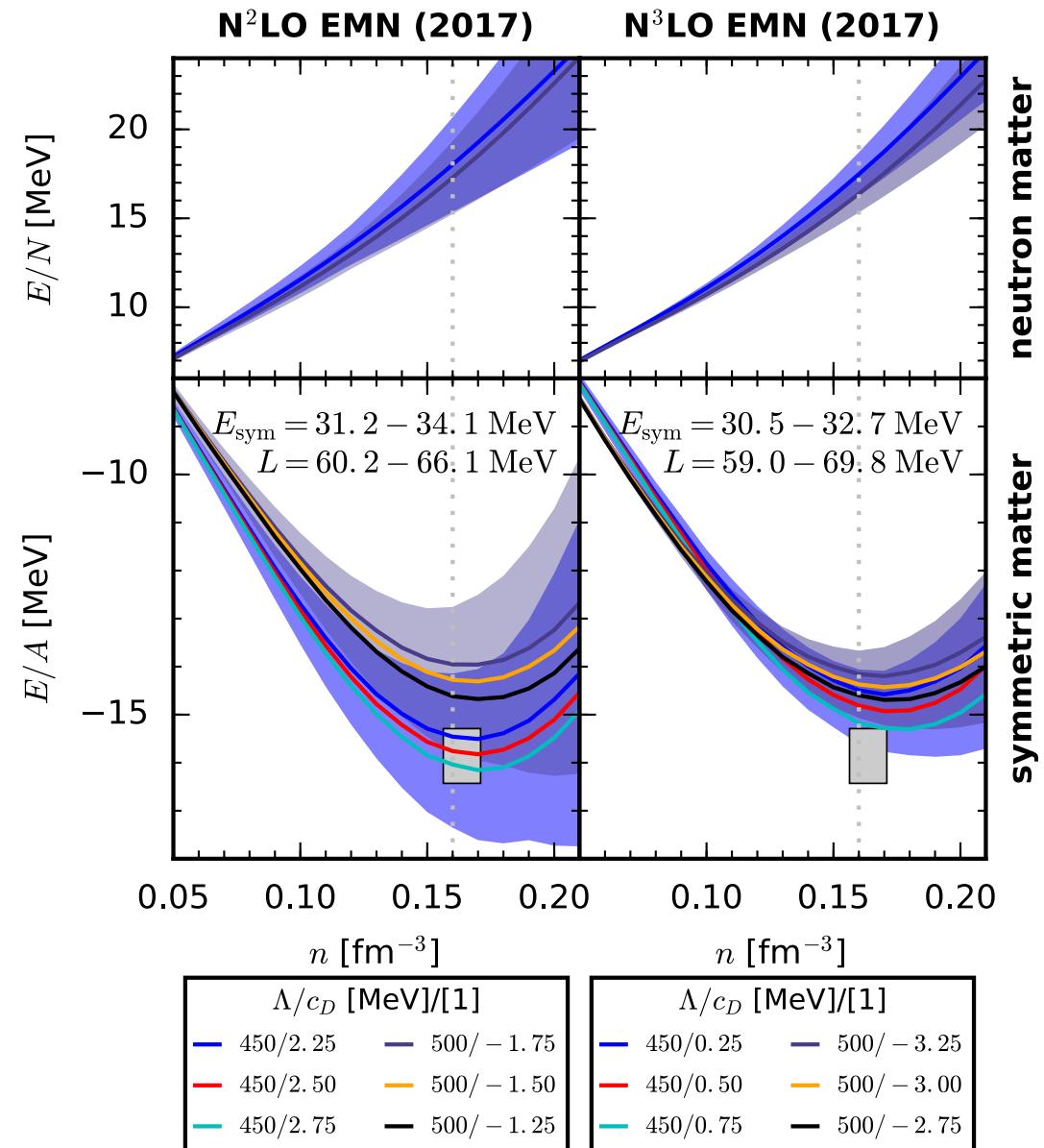
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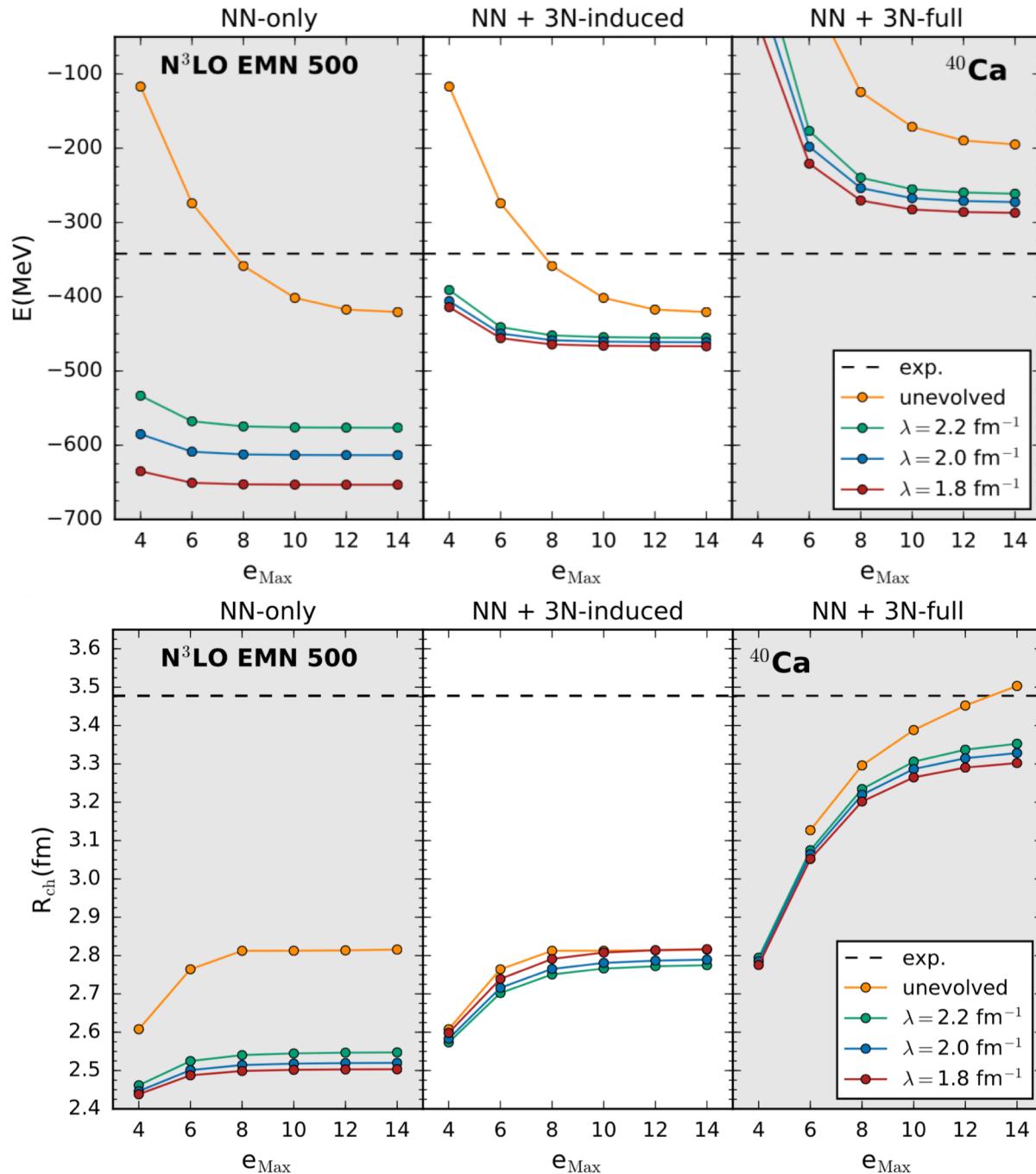
including NN, 3N, 4N  
3N fit to saturation region

systematic improvement  
from N<sup>2</sup>LO to N<sup>3</sup>LO

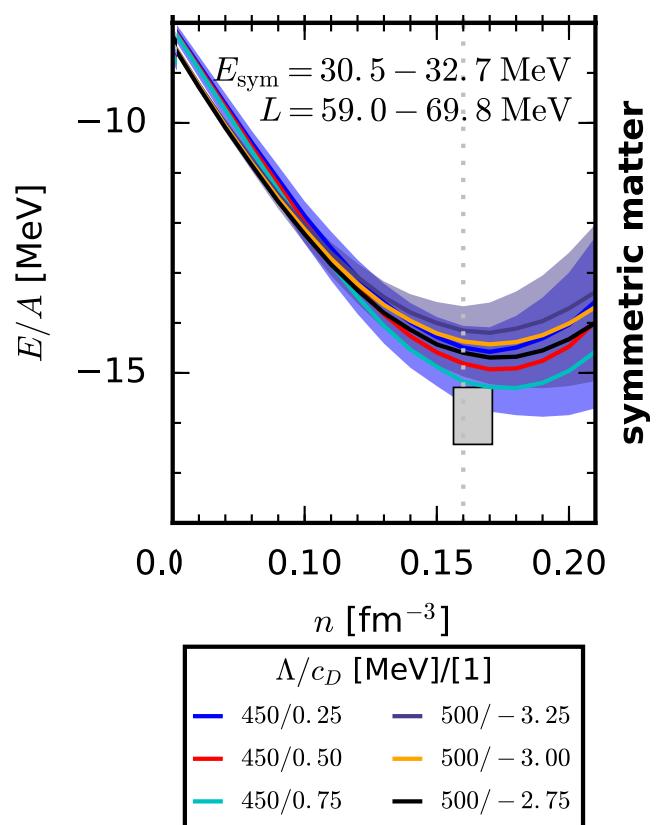
first full N<sup>3</sup>LO Hamiltonians  
for use in nuclear structure!



# First (preliminary) N<sup>3</sup>LO results for nuclei Hoppe, Simonis et al.



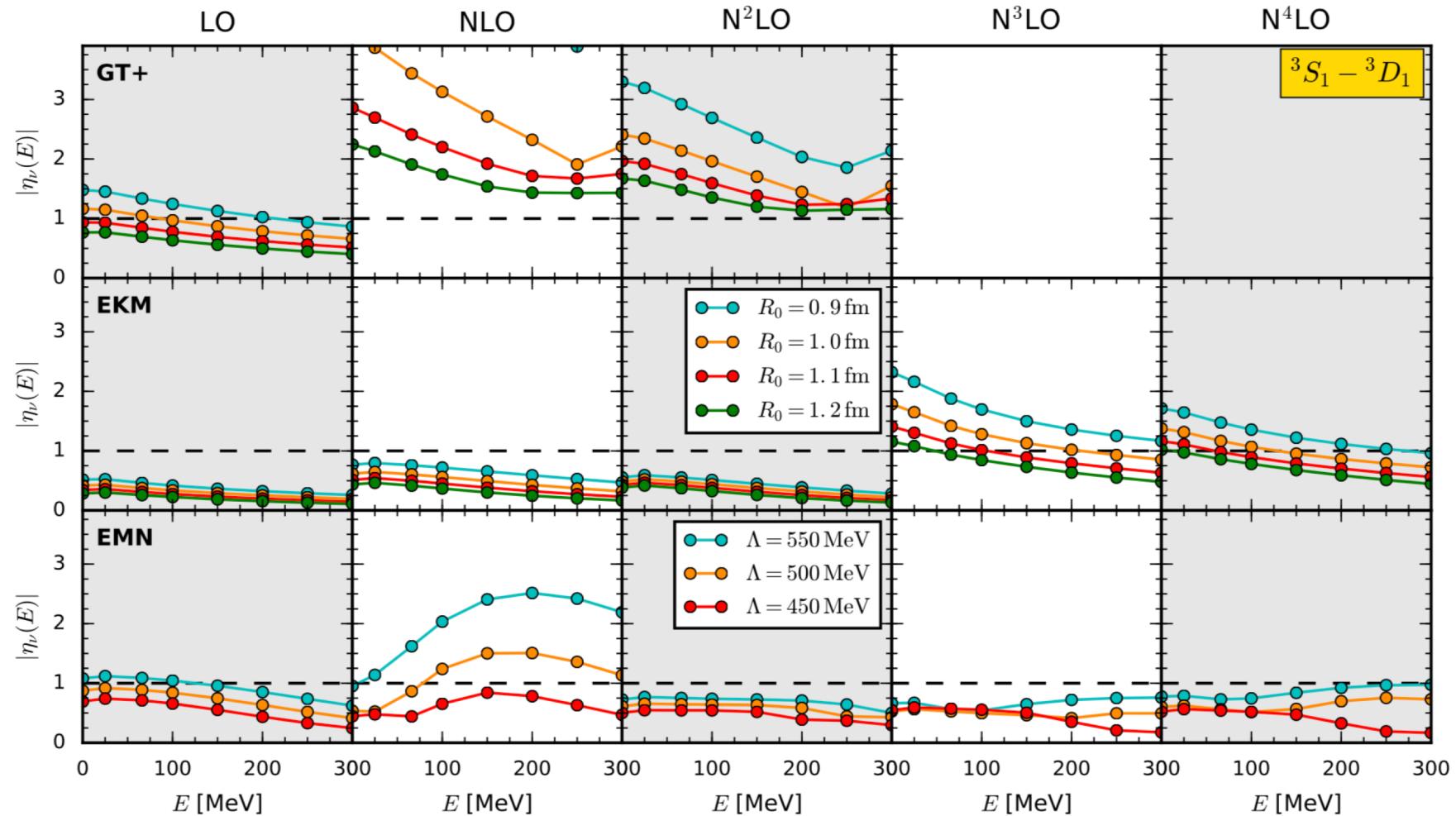
energy and radius trends  
as expected from nuclear  
matter saturation, but  
more studies needed!



# Need to explore broader range of chiral EFT interactions

Weinberg eigenvalues of local GT+, nonlocal EMN, semi-local EKM

Hoppe, Drischler et al., PRC (2017)



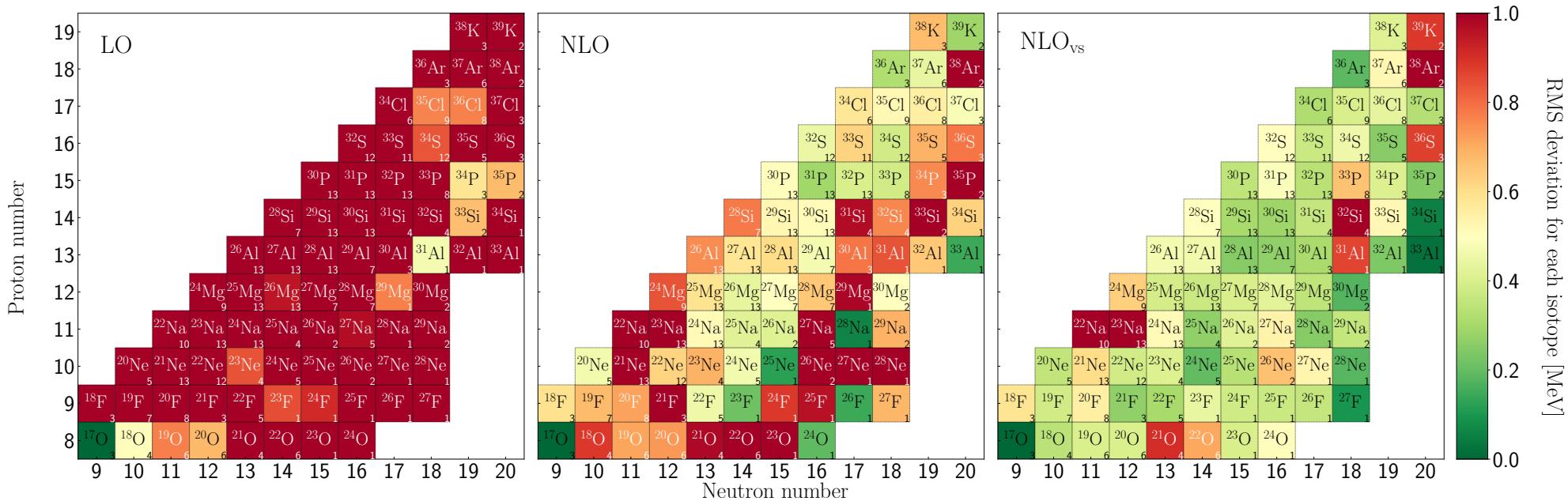
- + soft local [Durant, Huth et al., arXiv:1708.02527](#) and soft semi-local [Reinert et al.](#)
- + Delta-full potentials [Piarulli et al., Ekström et al.](#)

# Chiral shell model interactions

use chiral EFT interactions as basis and fit in sd shell directly

Huth, Durant et al., arXiv:1804.04990

includes new valence-space (vs) operators  
all LECs turn out natural



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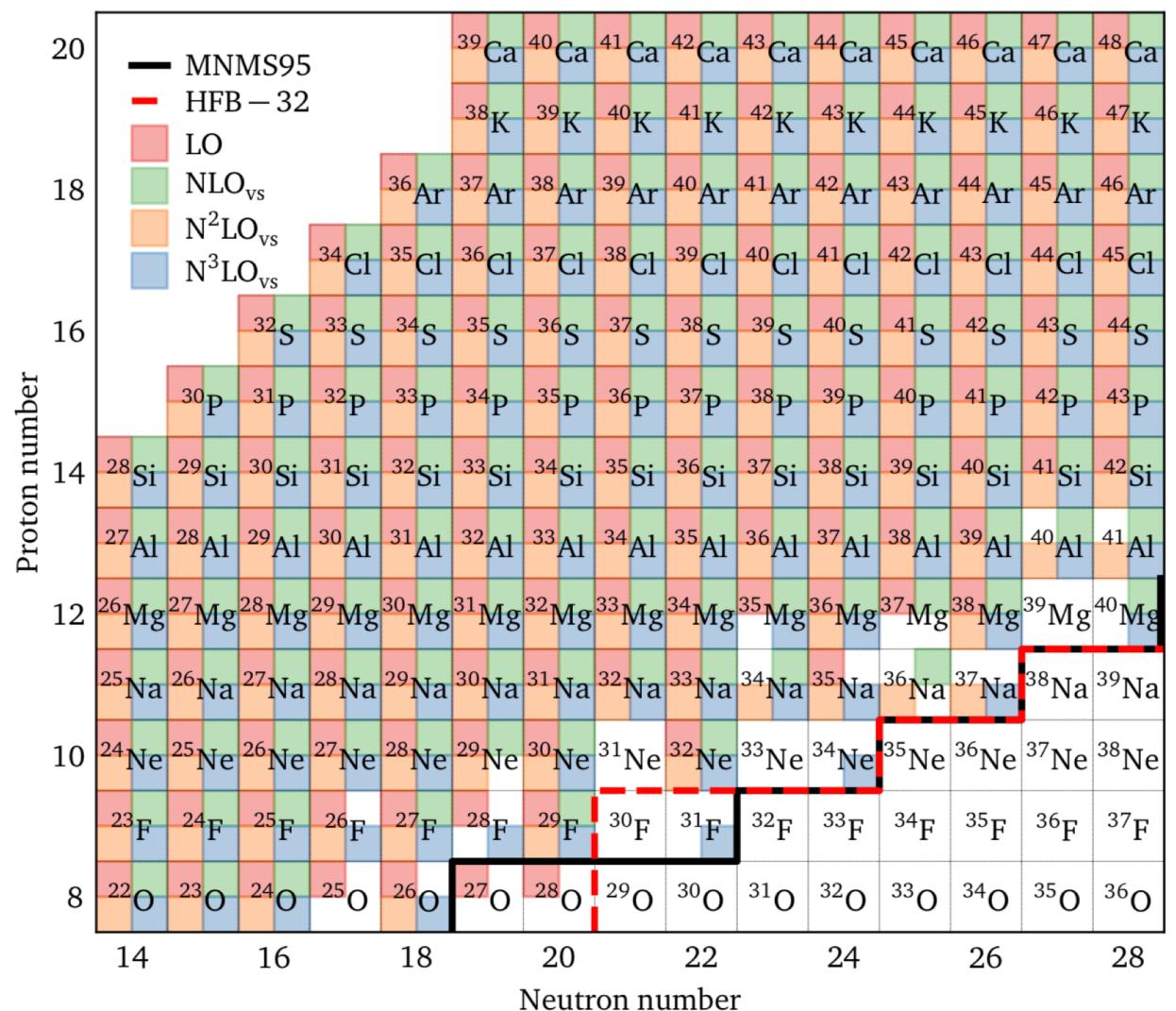
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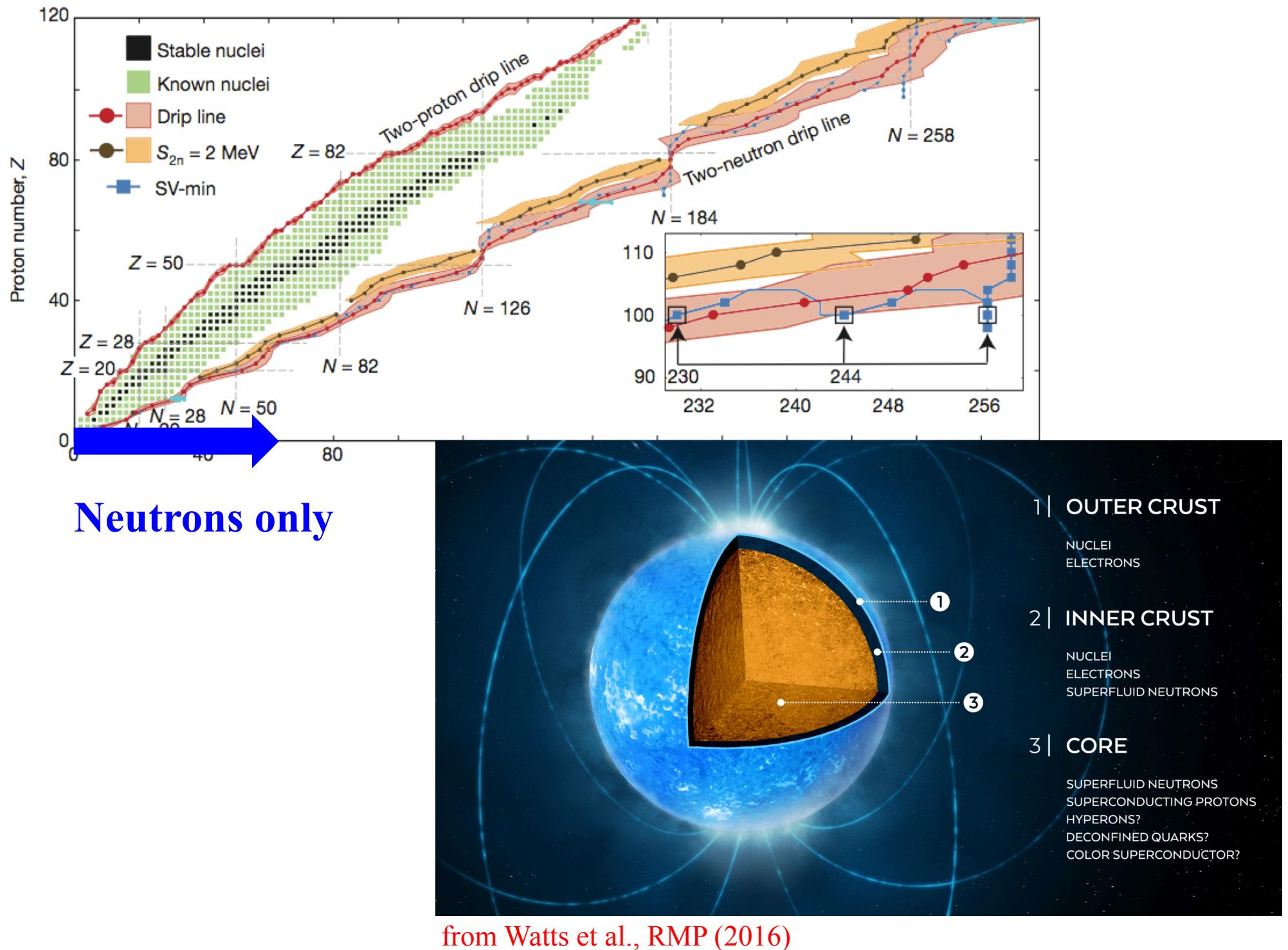
includes new valence-space (vs) operators

all LECs turn out natural

explore dripline  
in  $sdf_{7/2}$  space

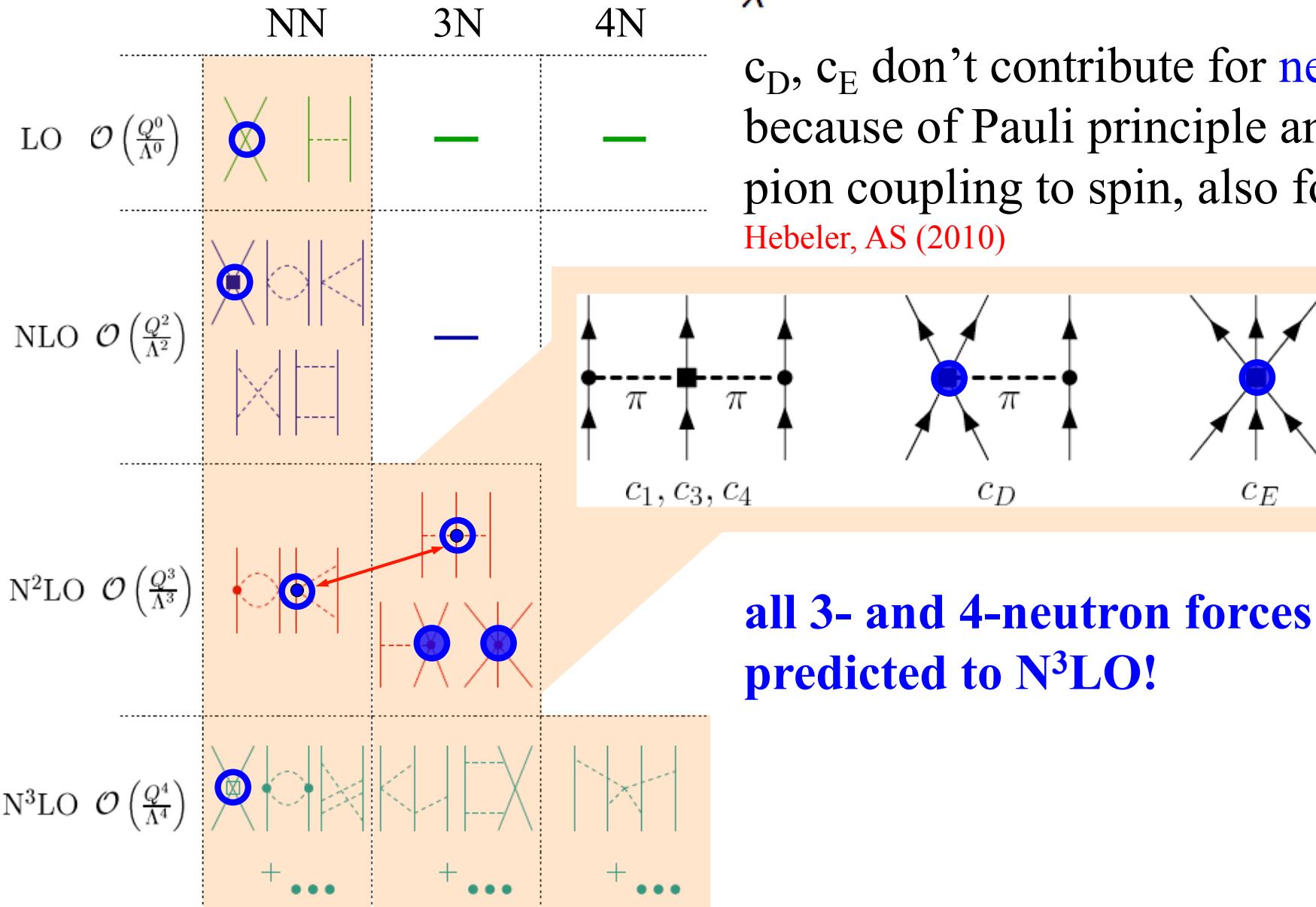
Huth et al., in prep.





# Chiral effective field theory for nuclear forces

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

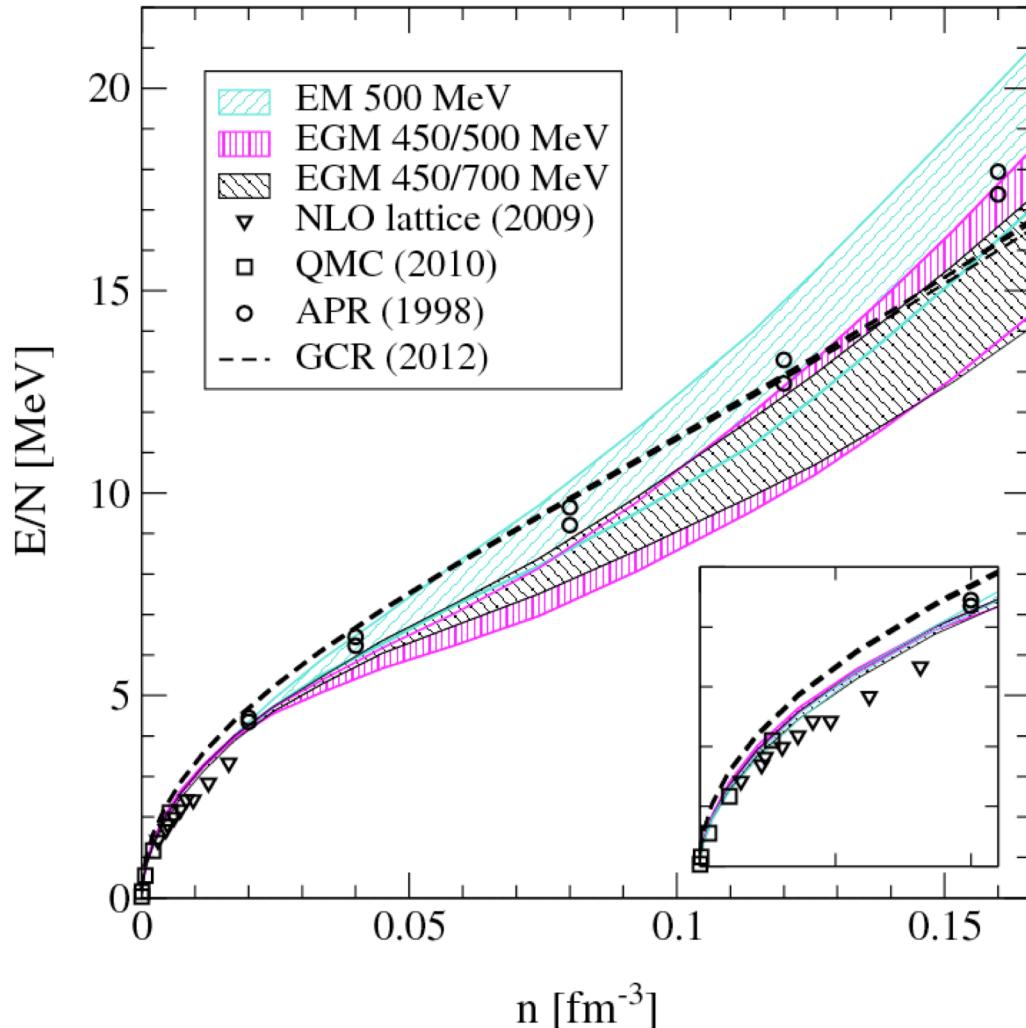


**all 3- and 4-neutron forces are predicted to  $\mathcal{N}^3\text{LO}$ !**

# Complete N<sup>3</sup>LO calculation of neutron matter

first complete N<sup>3</sup>LO result [Tews, Krüger, Hebeler, AS, PRL \(2013\)](#)

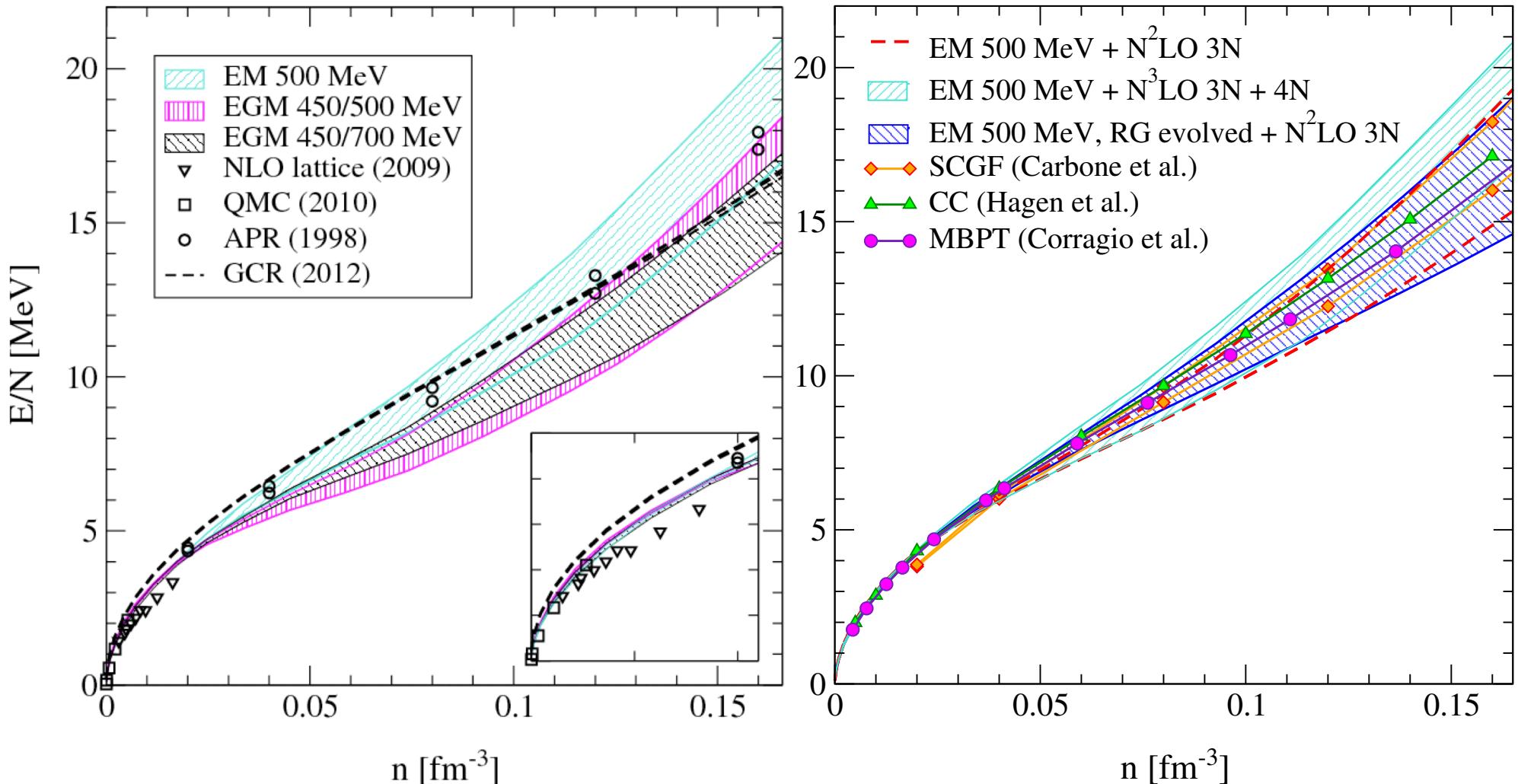
includes uncertainties from NN, 3N (dominates), 4N



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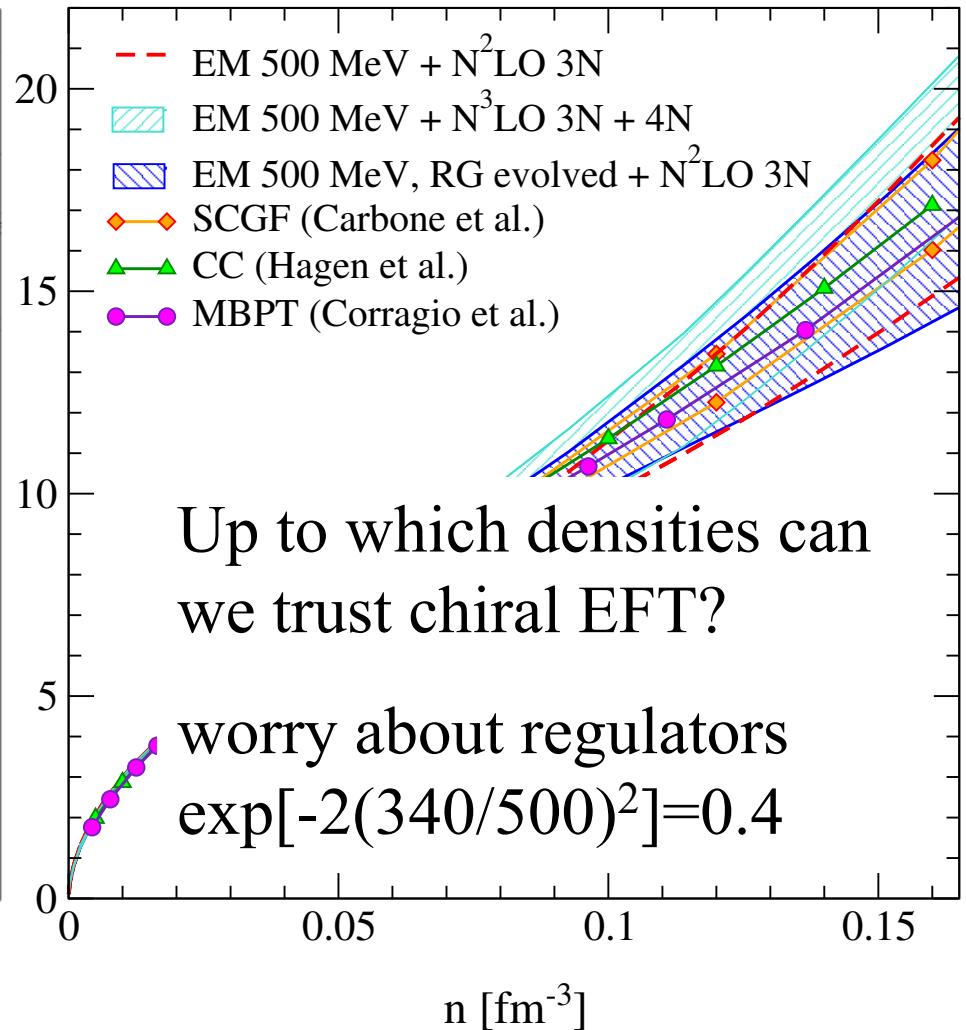
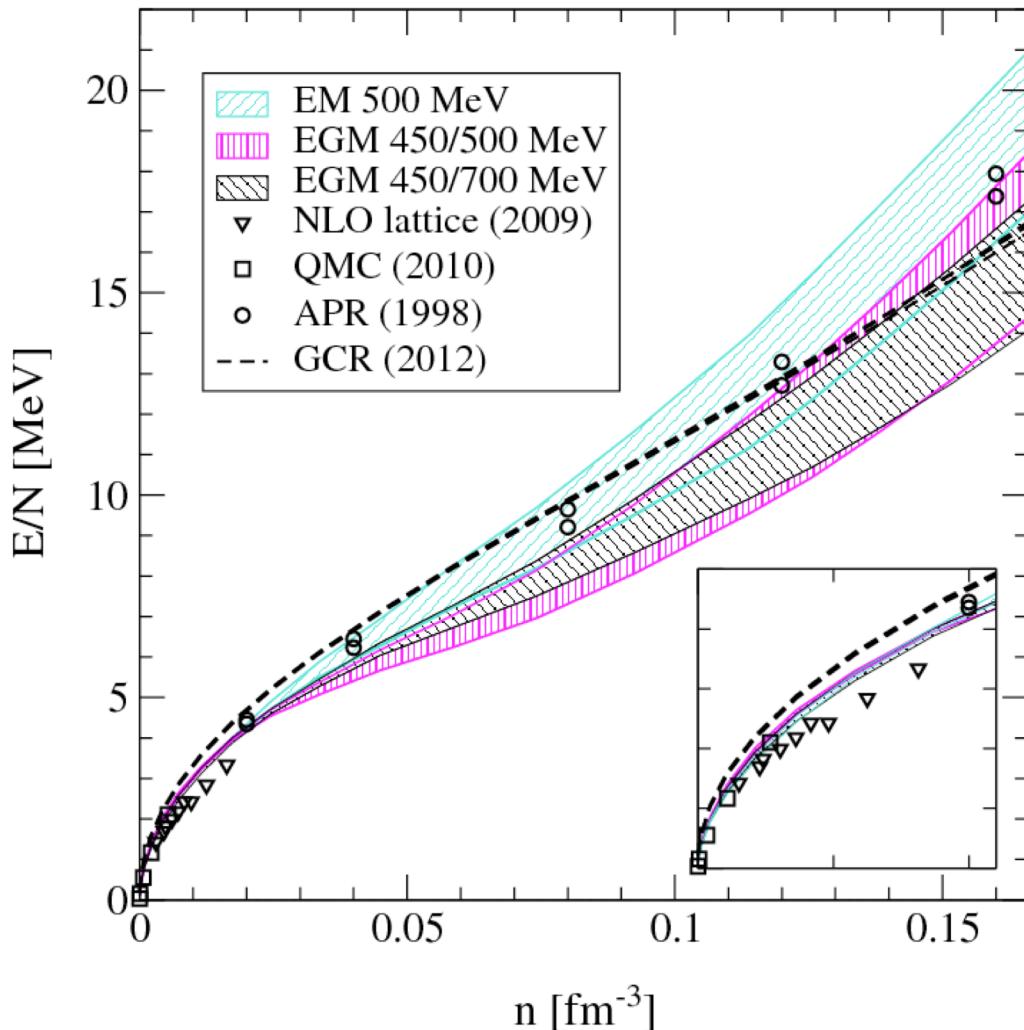


excellent agreement with other methods

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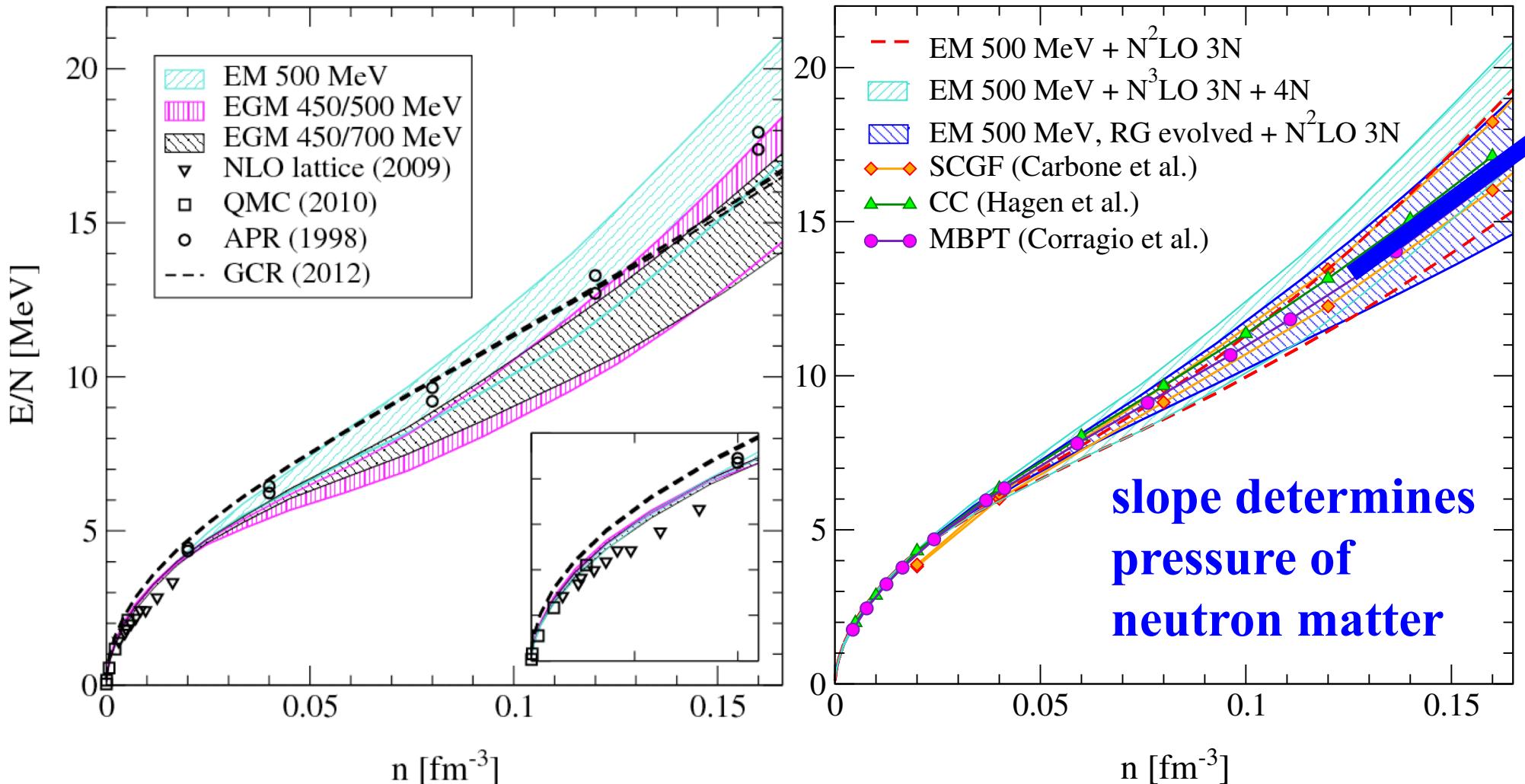


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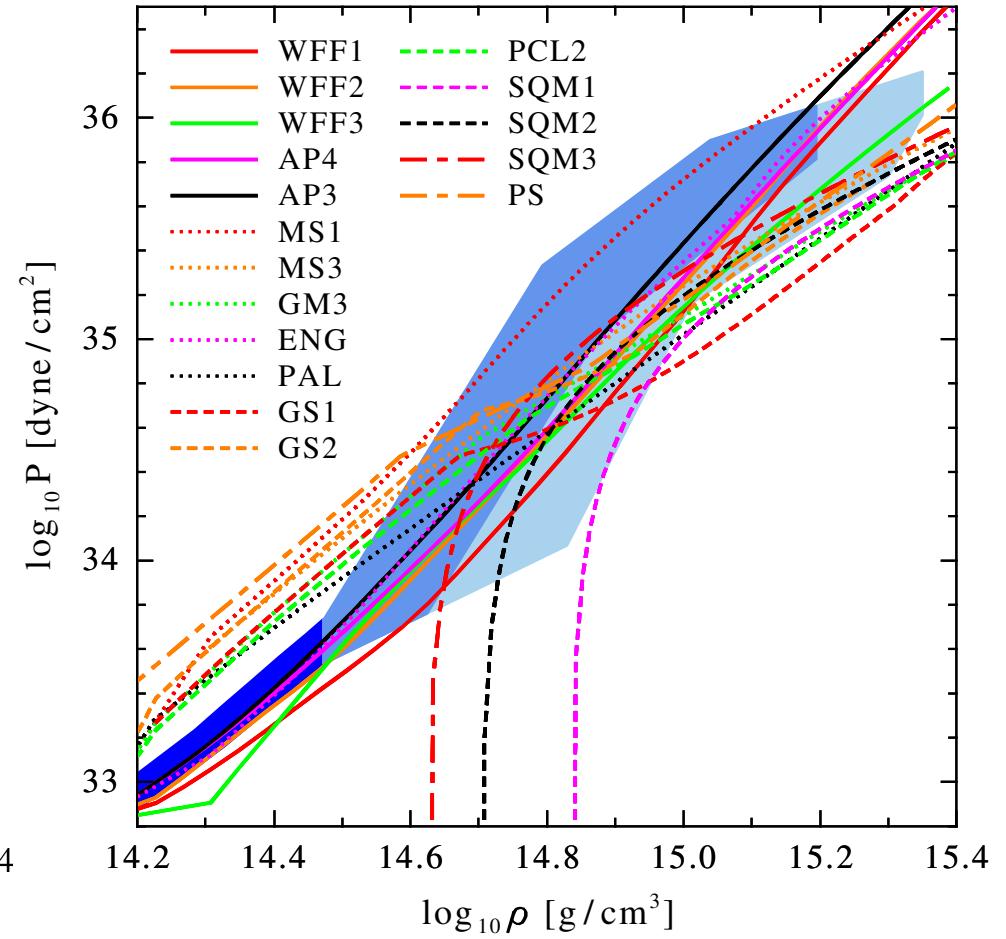
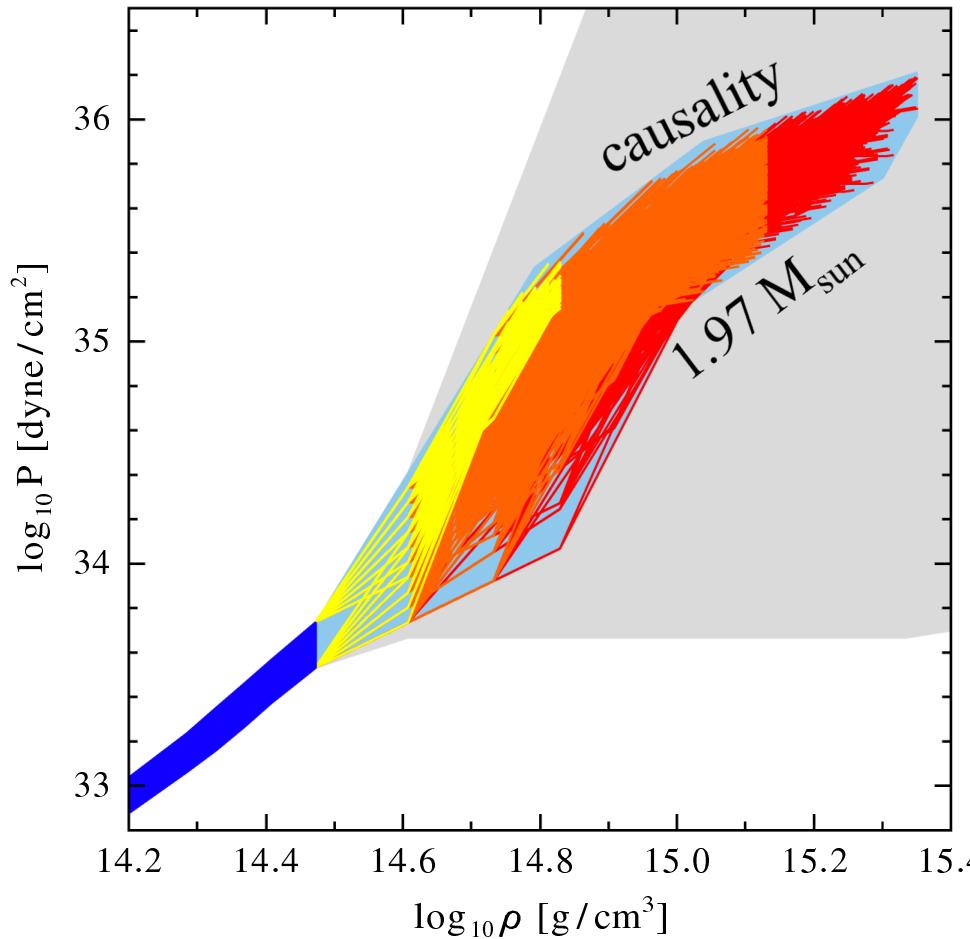
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excellent agreement with other methods

# Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

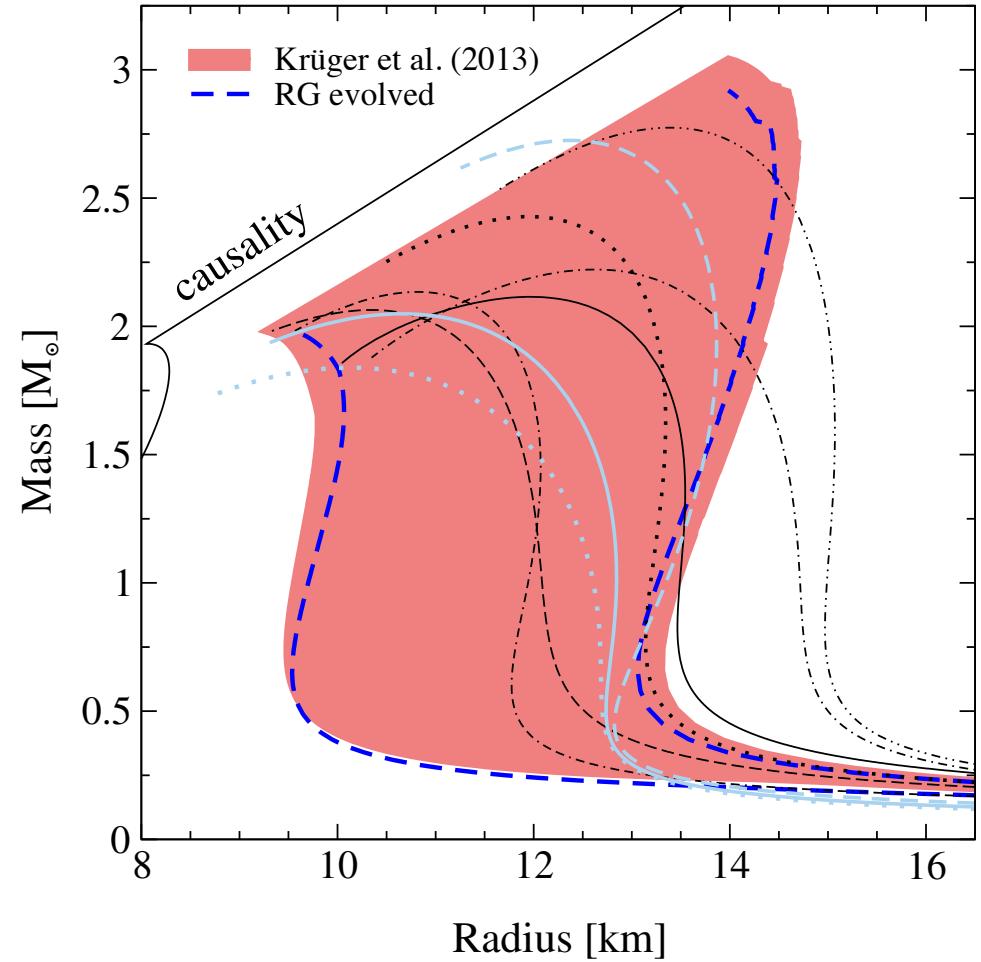
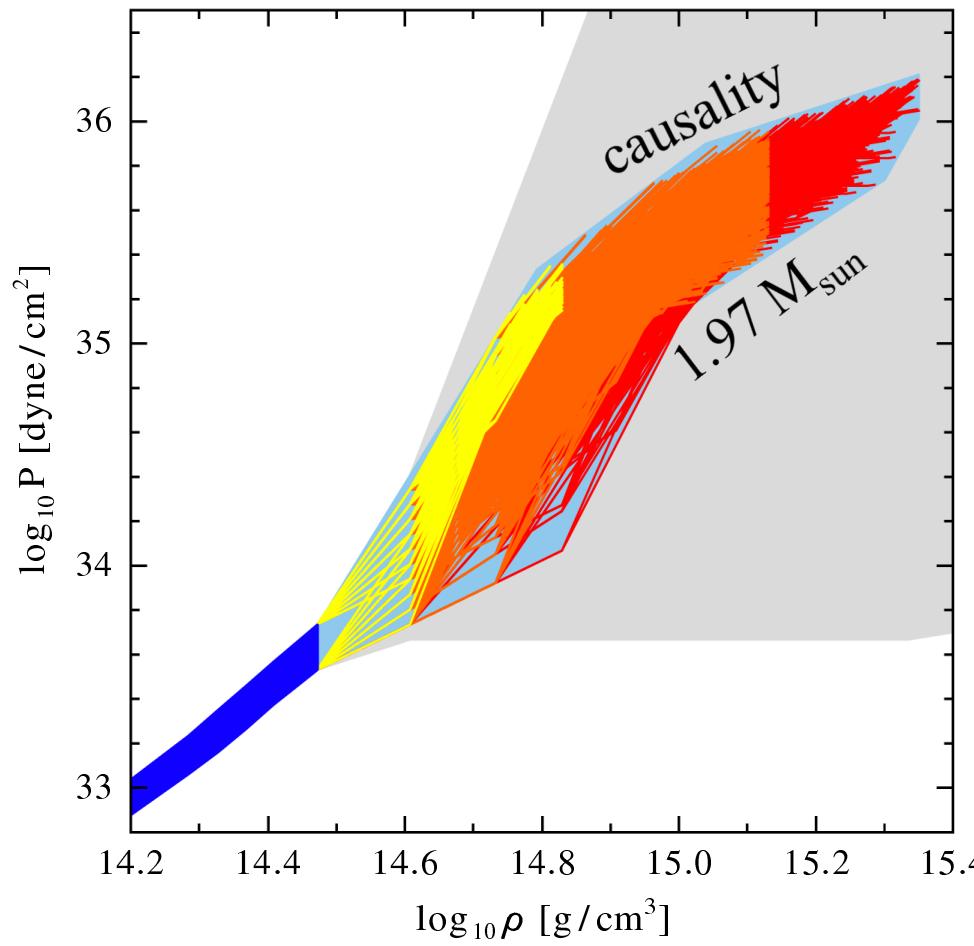
constrain high-density EOS by causality, require to support  $2 M_{\text{sun}}$  star



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

# Impact on neutron stars [Hebeler, Lattimer, Pethick, AS, PRL \(2010\), ApJ \(2013\)](#)

constrain high-density EOS by causality, require to support  $2 M_{\text{sun}}$  star



predicts neutron star radius:  $9.7\text{-}13.9 \text{ km}$  for  $M=1.4 M_{\text{sun}}$

$1.8\text{-}4.4 \rho_0$  modest central densities

speed of sound needs to exceed  $\sim 0.65c$  to get  $2 M_{\text{sun}}$  stars [Greif et al., in prep.](#)

# Neutron-star mergers and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger predictions for gravitational-wave signal, including NP uncertainties

Bauswein, Janka, PRL (2012)

Bauswein, Janka, Hebeler, AS, PRD (2012)

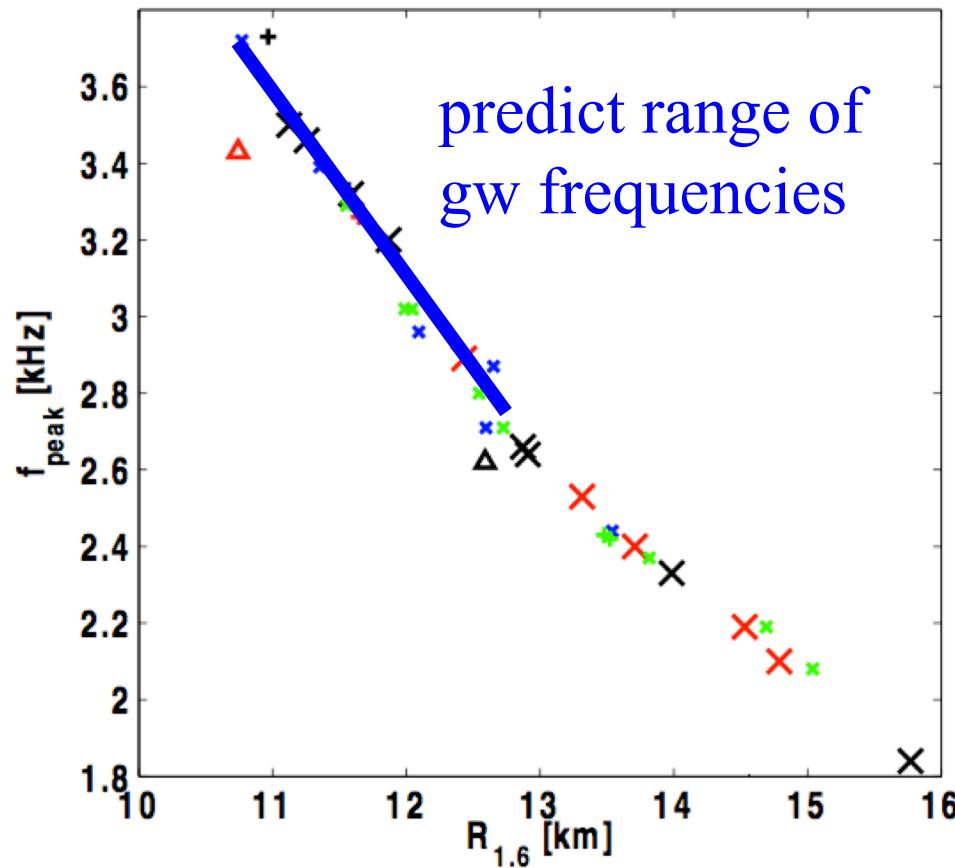
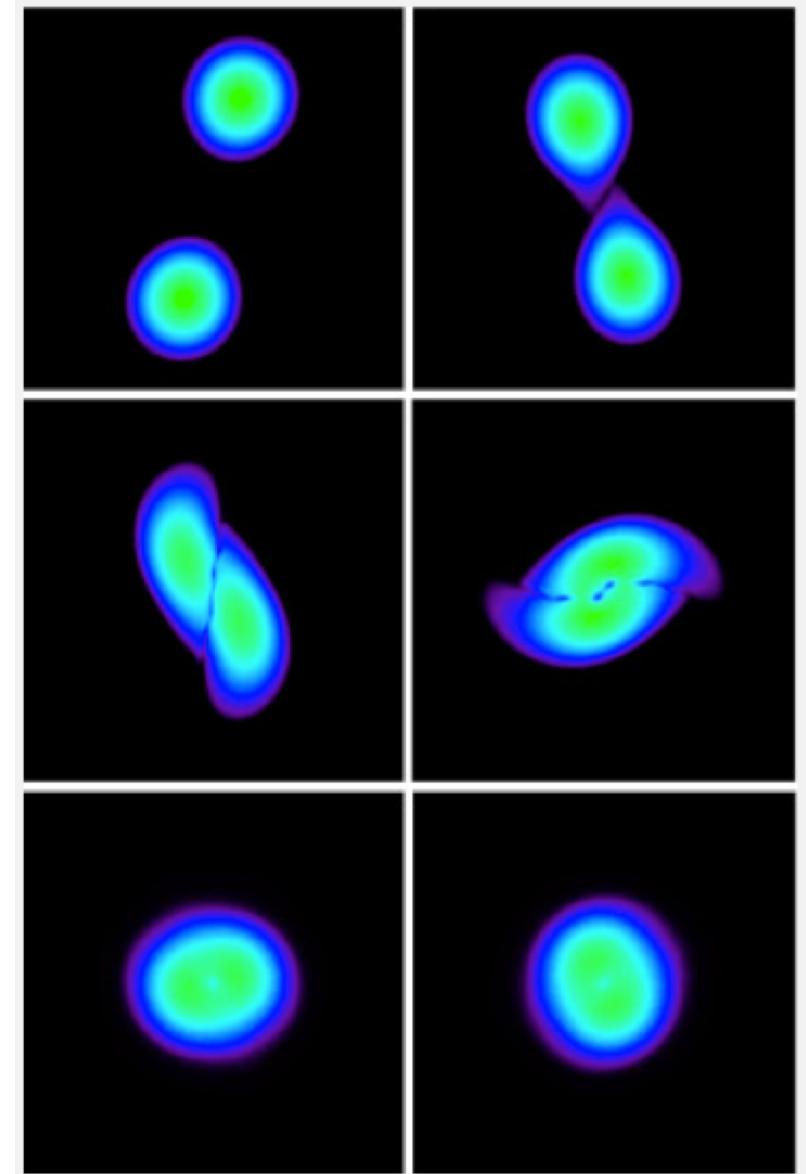


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with  $1.6 M_{\odot}$  for different EoSs. Symbols have the same meaning as in Fig. 8.



## Summary

Exciting era with EFT of the strong interaction and ab initio approaches

IM-SRG is powerful ab initio method, especially for open-shell nuclei

Exotic nuclei provide new tests of nuclear forces

Many-body calculations have smaller uncertainty compared to uncertainties in nuclear forces

Role of nuclear matter properties (saturation,...)  
for next generation of nuclear forces with new MC approach

**Thanks to:** S. Bacca, S. Bogner, C. Drischler, V. Durant, G. Hagen,  
**K. Hebeler**, H. Hergert, J.D. Holt, L. Huth, J. Lattimer, J. Lynn,  
**J. Menéndez**, M. Miorelli, W. Nazarewicz, T. Papenbrock, C. Pethick,  
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