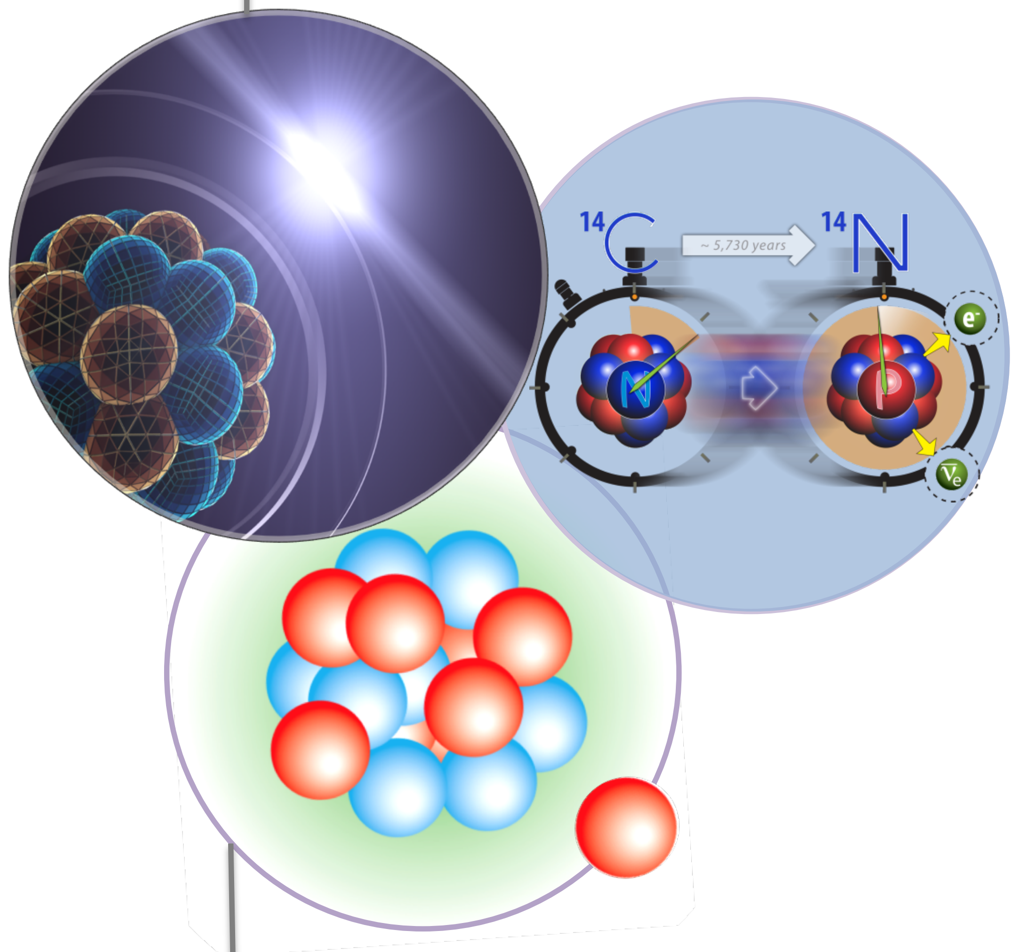
Neutron skins and dipole polarizabilities from first principles computations



Gaute Hagen
Oak Ridge National Laboratory

Neutron Skins of Nuclei

MITP, May 19th, 2016

U.S. DEPARTMENT OF ENERGY
NUCLEI Nuclear Computational Low-Energy Initiative
BSF United States – Israel Binational Science Foundation
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Collaborators

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@ MSU/ U Oslo: M. Hjorth-Jensen

@ U. Idaho: R. Machleidt

@ Trento: G. Orlandini

@ TRIUMF: S. Bacca, **M. Miorelli**, P. Navratil

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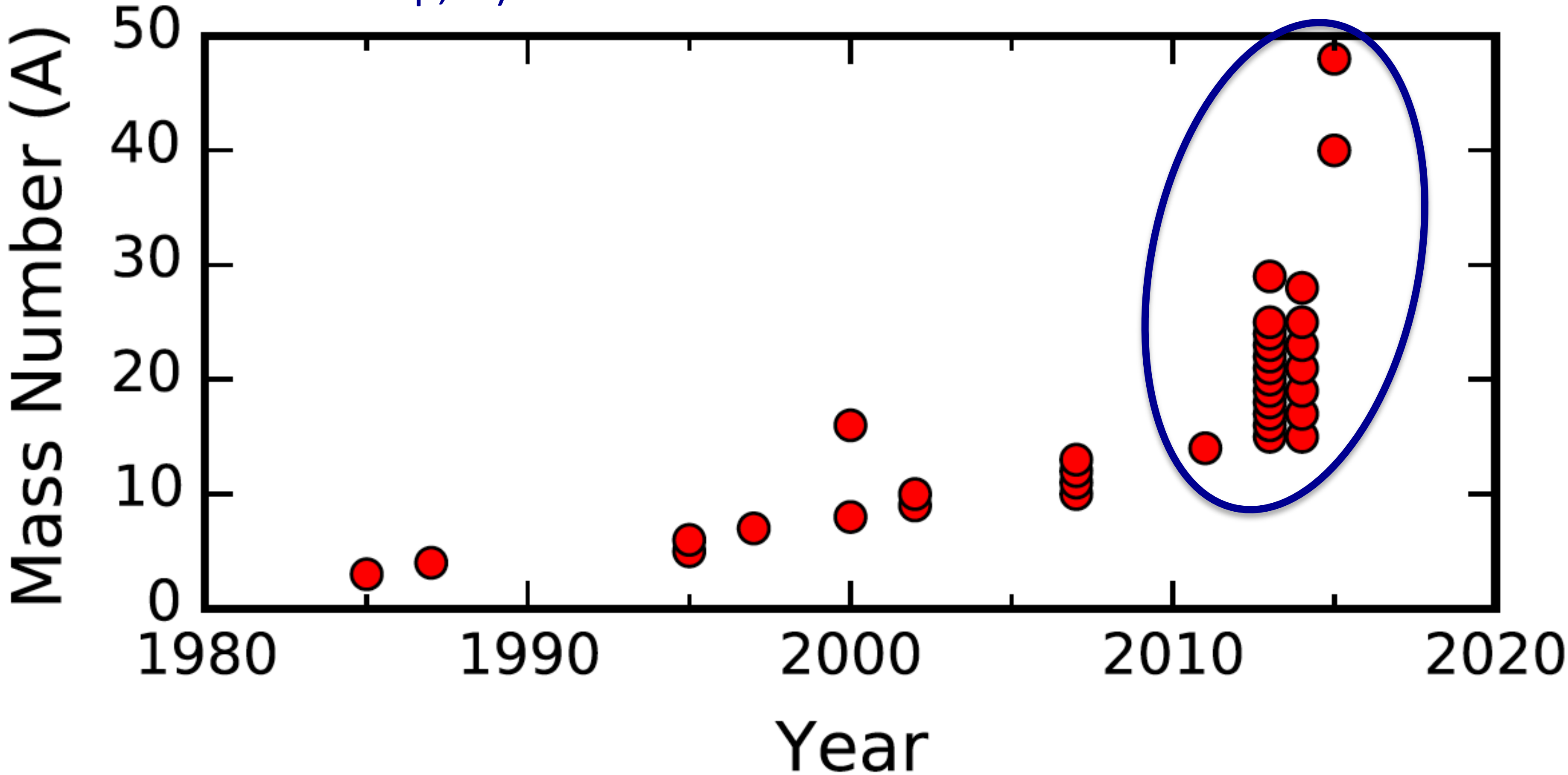
Outline

- Status of ab initio computations of nuclei
- Accurate binding energies and radii from a chiral interaction
- The neutron skin and dipole polarizability of ^{48}Ca
  - Symmetry energy and size of a neutron star
- Charge radii of neutron-rich ^{52}Ca
- Neutron skin and dipole polarizability of ^{8}He
- Towards heavier nuclei
  - Dipole polarizability of ^{68}Ni and ^{90}Zr
  - What is the structure of ^{78}Ni?

Trend in realistic ab-initio calculations

Explosion of many-body methods (Coupled clusters, Green's function Monte Carlo, In-Medium SRG, Lattice EFT, MCSM, No-Core Shell Model, Self-Consistent Green's Function, UMOA, …)

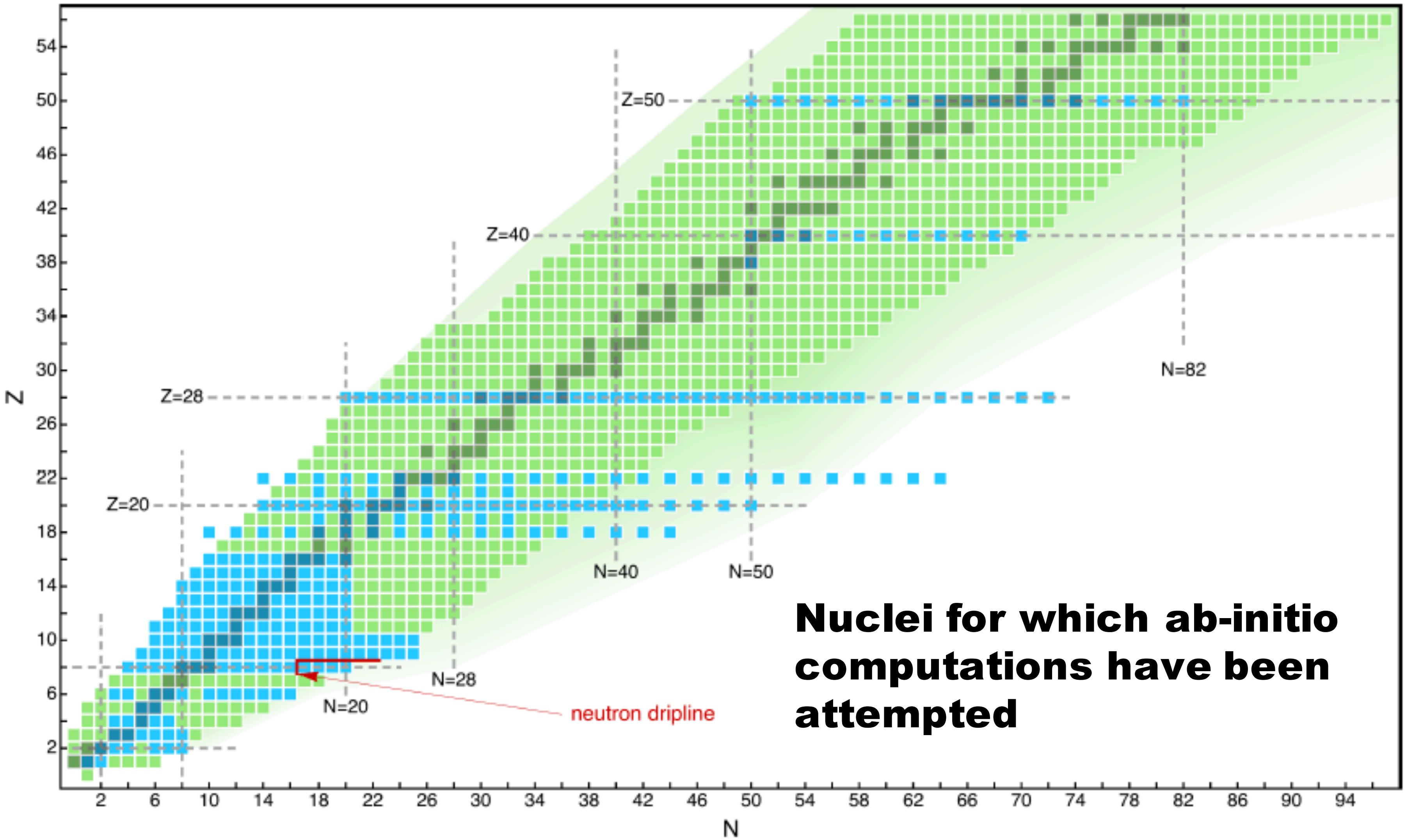
Application of ideas from EFT and renormalization group (V_{low-k}, Similarity Renormalization Group, …)



Computational capabilities exceed accuracy of available interactions

[Binder *et al*, Phys. Lett. B 736 (2014) 119]

Reach of ab-initio computations of nuclei

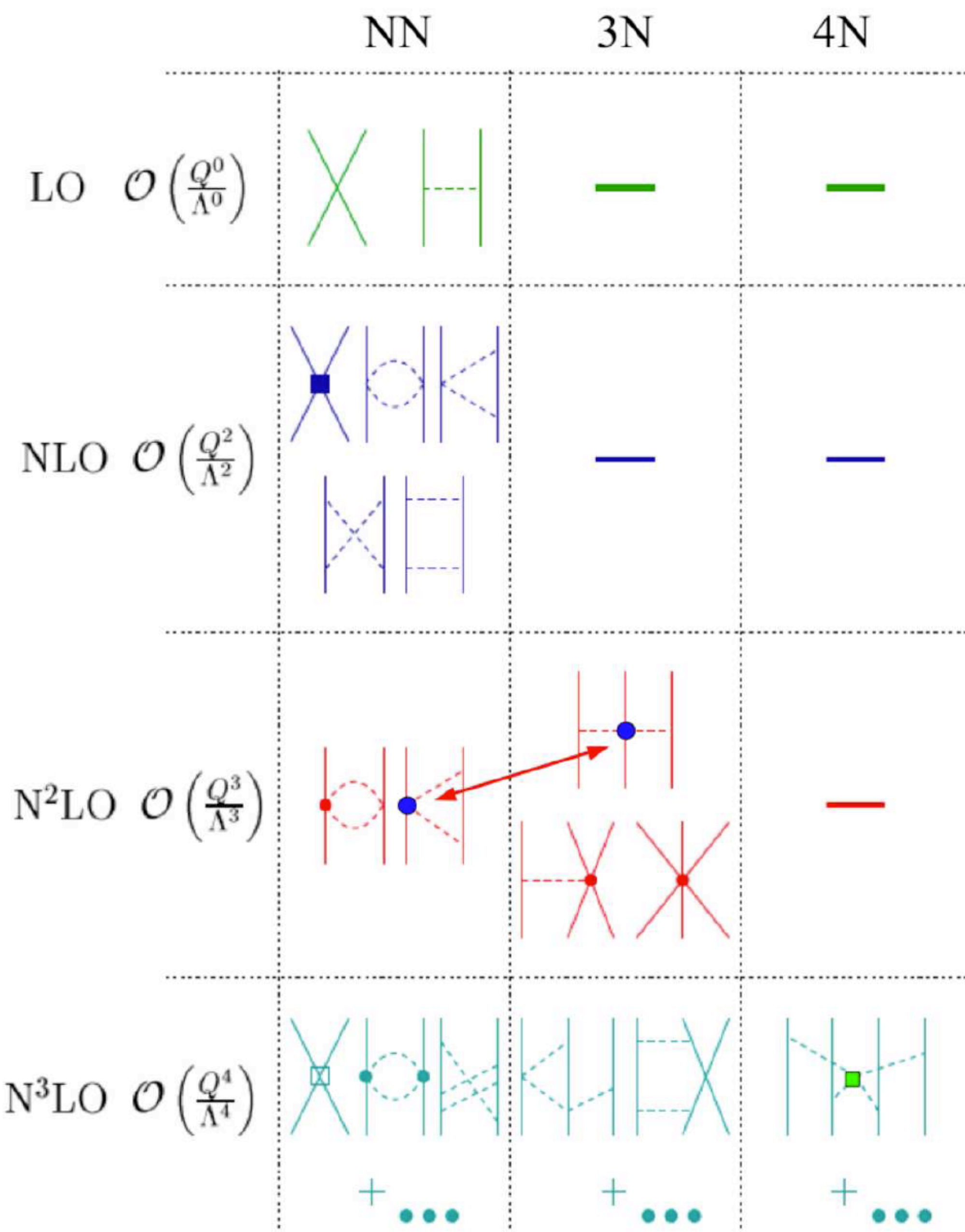


Nuclei for which ab-initio computations have been attempted

H. Hergert *et al*, Physics Reports 621, 165-222 (2016)

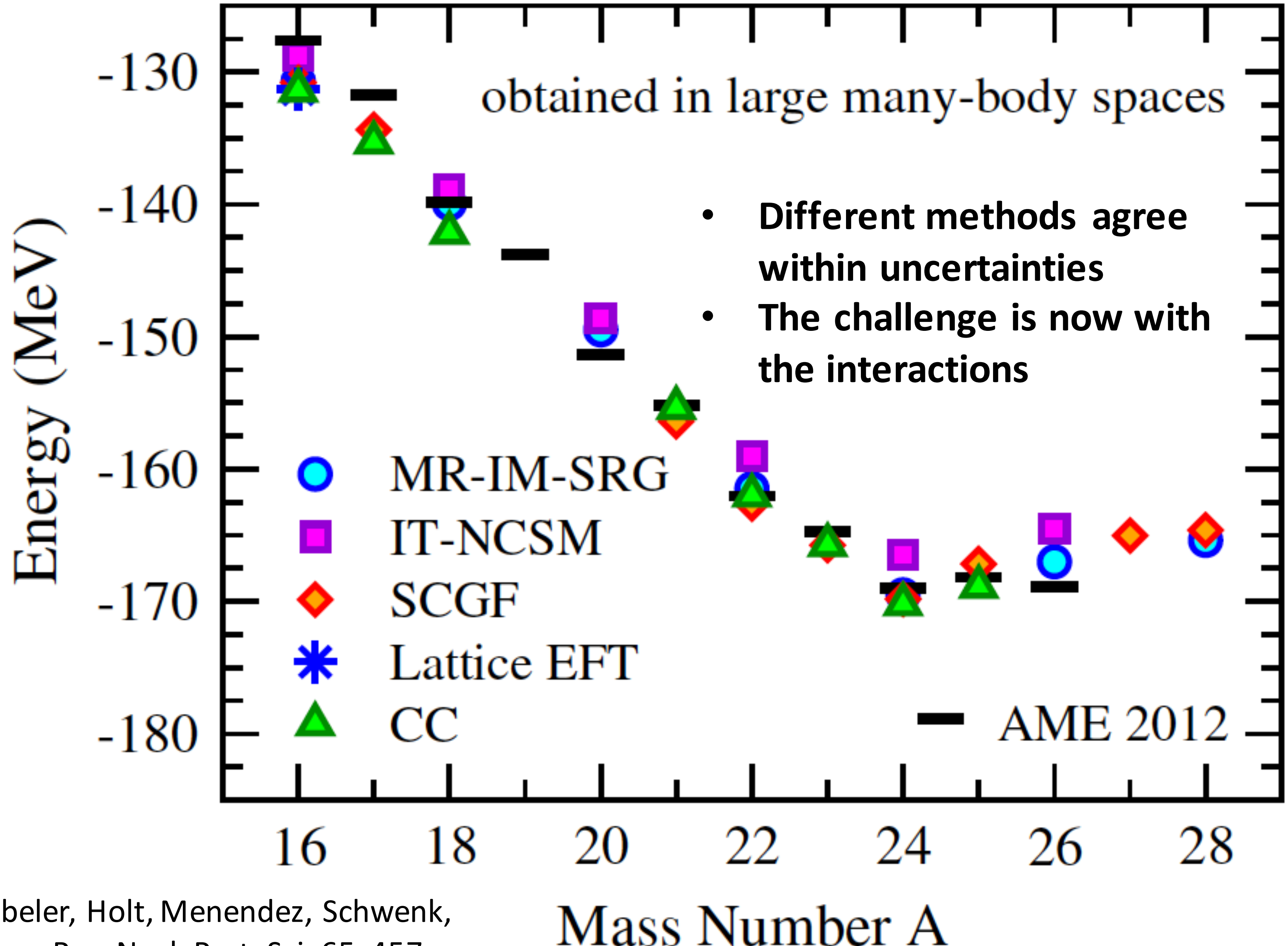
Nuclear forces from chiral effective field theory

[Weinberg; van Kolck; Epelbaum *et al.*; Entem & Machleidt; …]



- developing higher orders and higher rank (3NF, 4NF) [Epelbaum 2006; Bernard et al 2007; Krebs et al 2012; Hebeler et al 2015; …]
- local / non-local formulations [Gezerlis et al 2013/2014]
- propagation of uncertainties on horizon [Navarro Perez 2014, Carlsson et al 2015]
- different optimization protocols [Ekström et al 2013]
- Improved understanding and handling via renormalization group transformations [Bogner et al 2003; Bogner et al 2007]
- Problem: Not RG invariant.

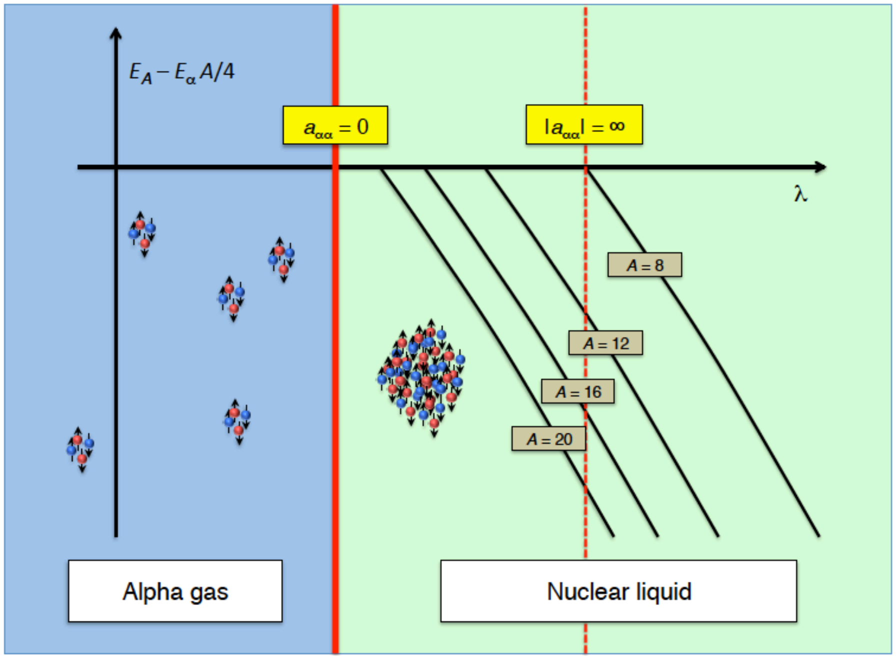
Oxgyen chain with interactions from chiral EFT



- **Different methods agree within uncertainties**
- **The challenge is now with the interactions**

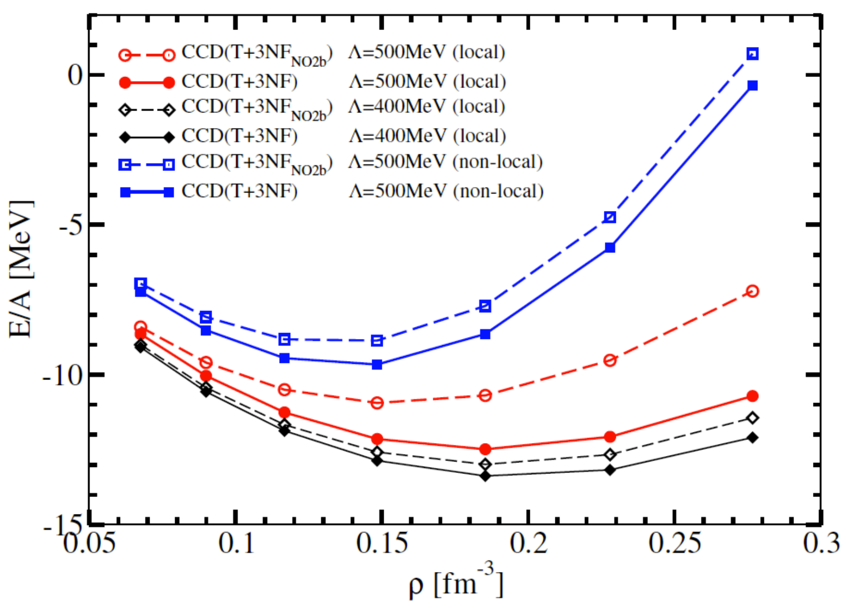
Hebeler, Holt, Menendez, Schwenk, Annu. Rev. Nucl. Part. Sci. 65, 457 (2015)

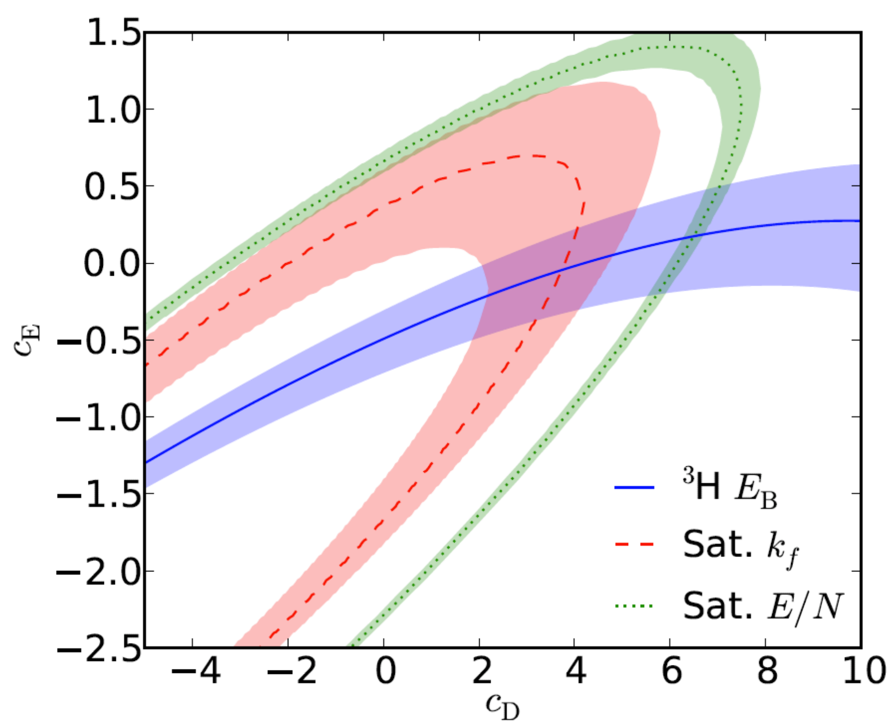
Nuclear saturation is finely tuned



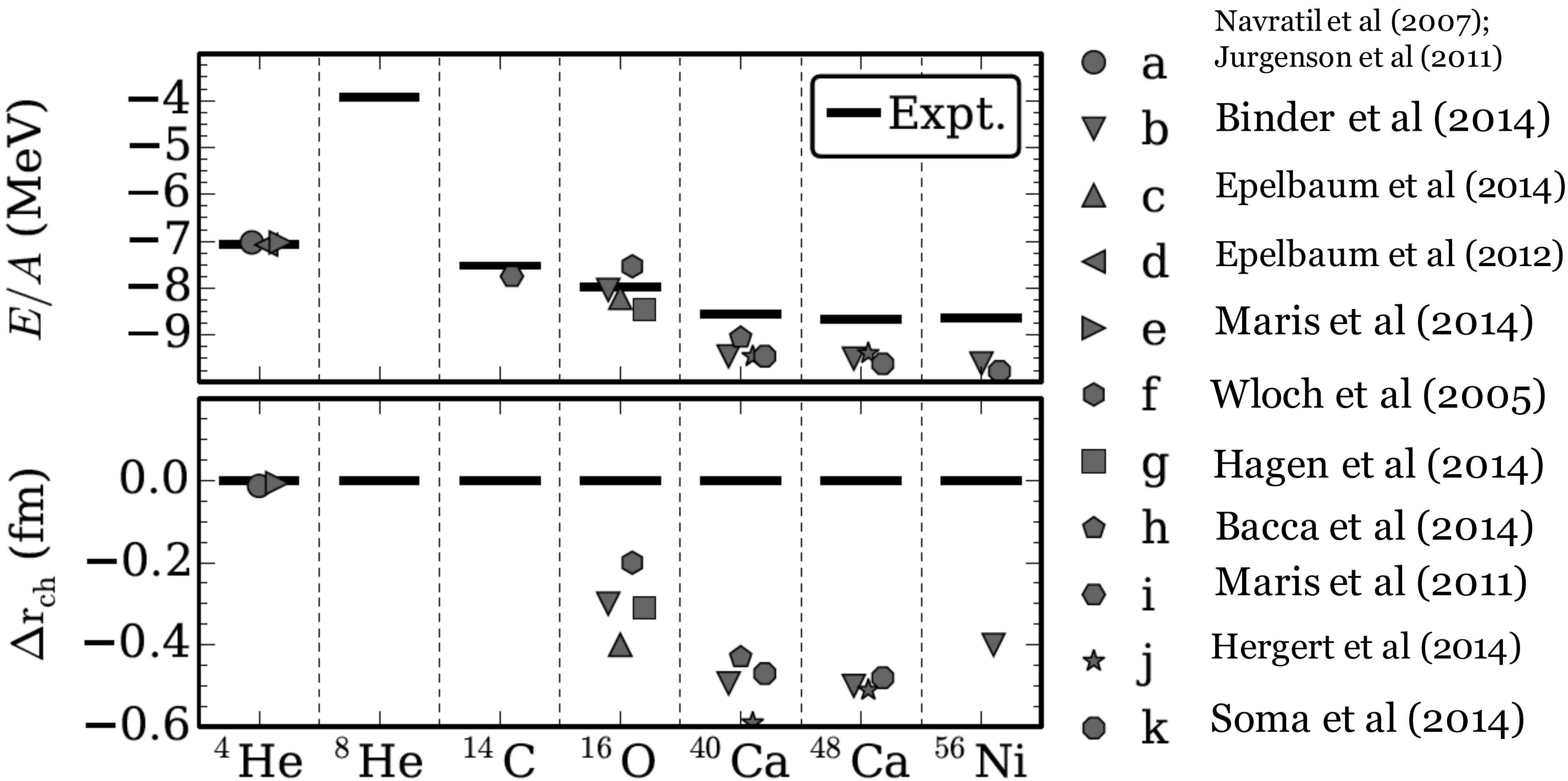
- Lattice EFT suggests that nuclei are close to a quantum phase transition [Elhatisari et al., (2016)]
- Regulator dependence in saturation properties of nuclear matter
- Difficult to describe nuclear matter and light nuclei by only adjusting c_E and c_D

G. Hagen *et al.*, PRC 89 014319 (2013)]



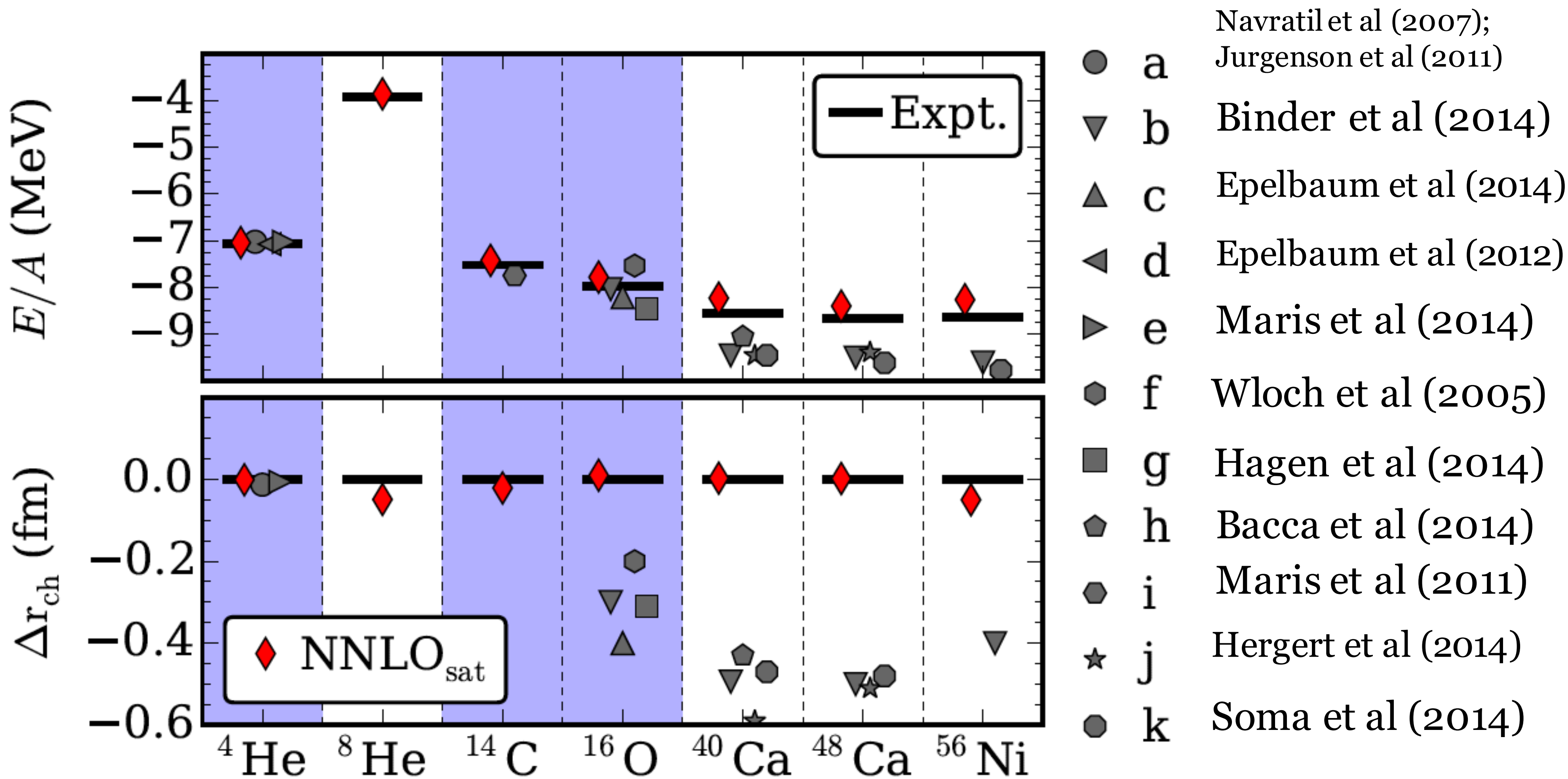


Accurate nuclear binding energies and radii from a chiral interaction



- Chiral interactions have failed at describing both binding energies and radii of nuclei
- Predictive power does not go together with large extrapolations
- Nuclear saturation may be viewed as an emergent property

Accurate nuclear binding energies and radii from a chiral interaction



Solution: Simultaneous optimization of NN and 3NFs

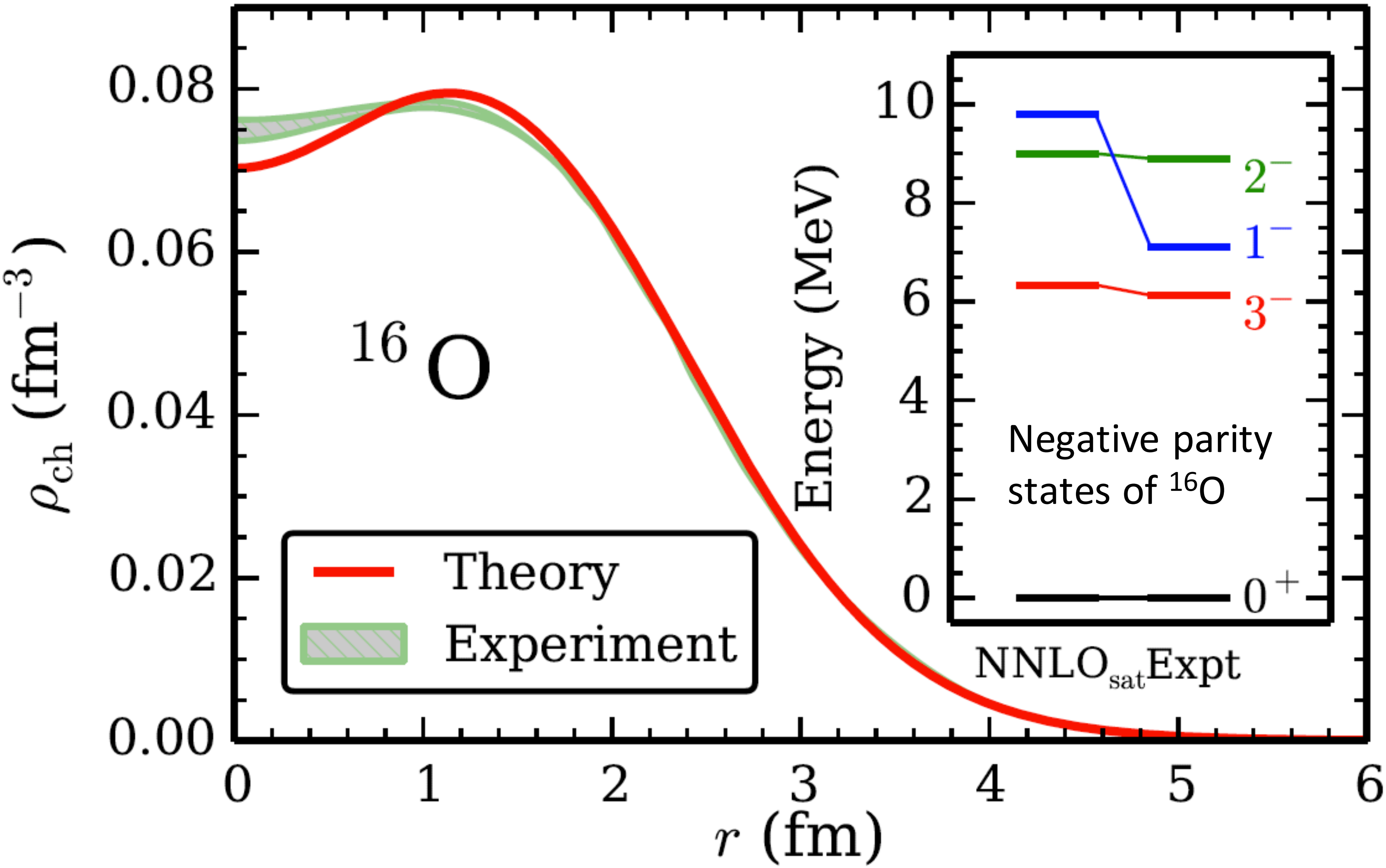
Include charge radii and binding energies of ^{3}H, $^{3,4}He$, ^{14}C, ^{16}O in the optimization ($NNLO_{sat}$)

Not new: GFMC with AV18 and Illinois-7 are fit to 23 levels in nuclei with A <10

A. Ekström *et al*, Phys. Rev. C **91**, 051301(R) (2015).

G. Hagen et al, arXiv:1601.08203 (2016).

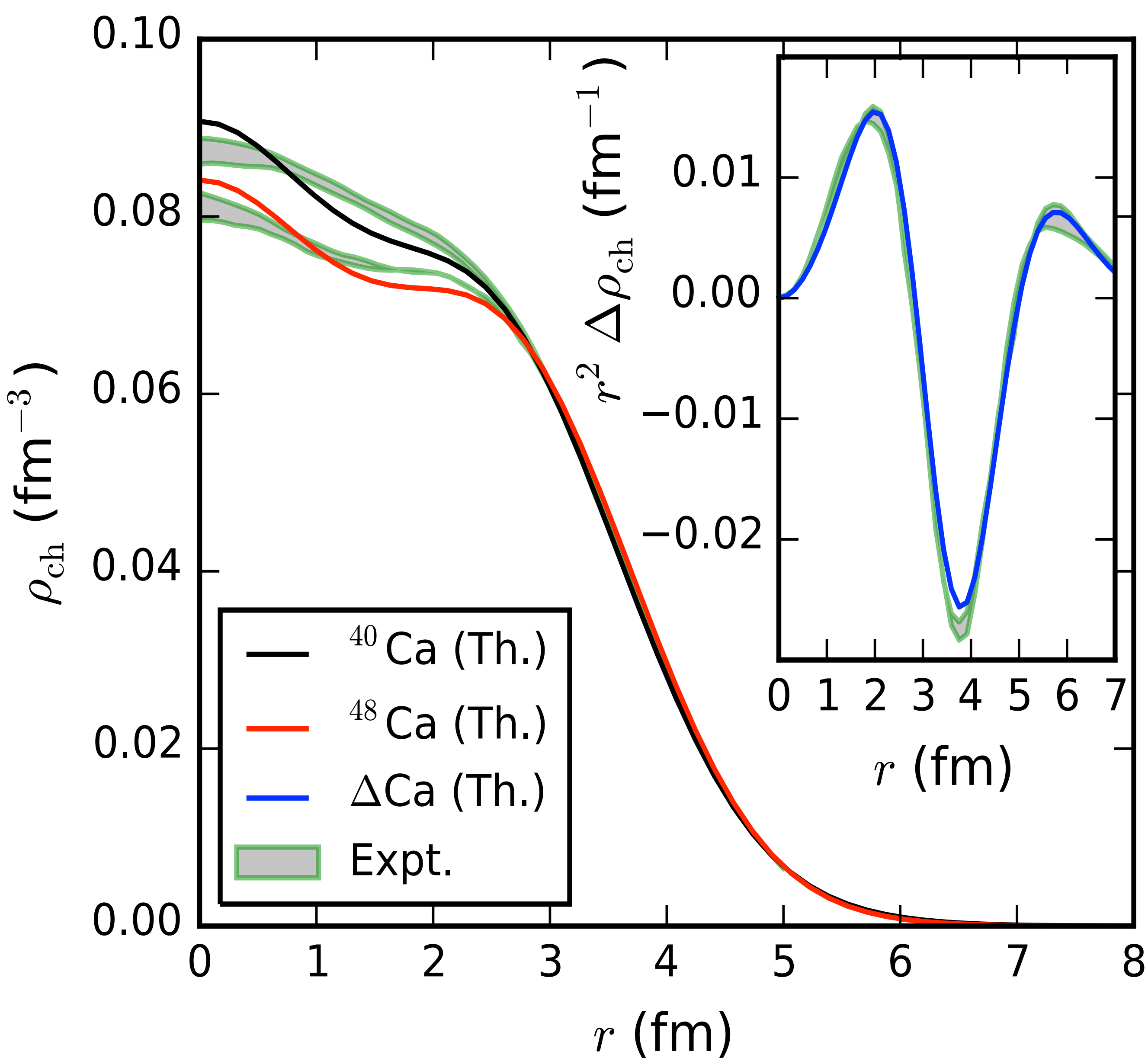
Charge density of ^{16}O from $NNLO_{sat}$



A. Ekström, G. Jansen, K. Wendt et al, PRC 91, 051301 2015

Charge densities of ^{40,48}Ca from NNLO$_{sat}$

G. Hagen *et al*, Nature Physics **12**, 186–190 (2016)



Electric charge distributions have been a long-standing problem for *ab initio* theory

^{40}Ca

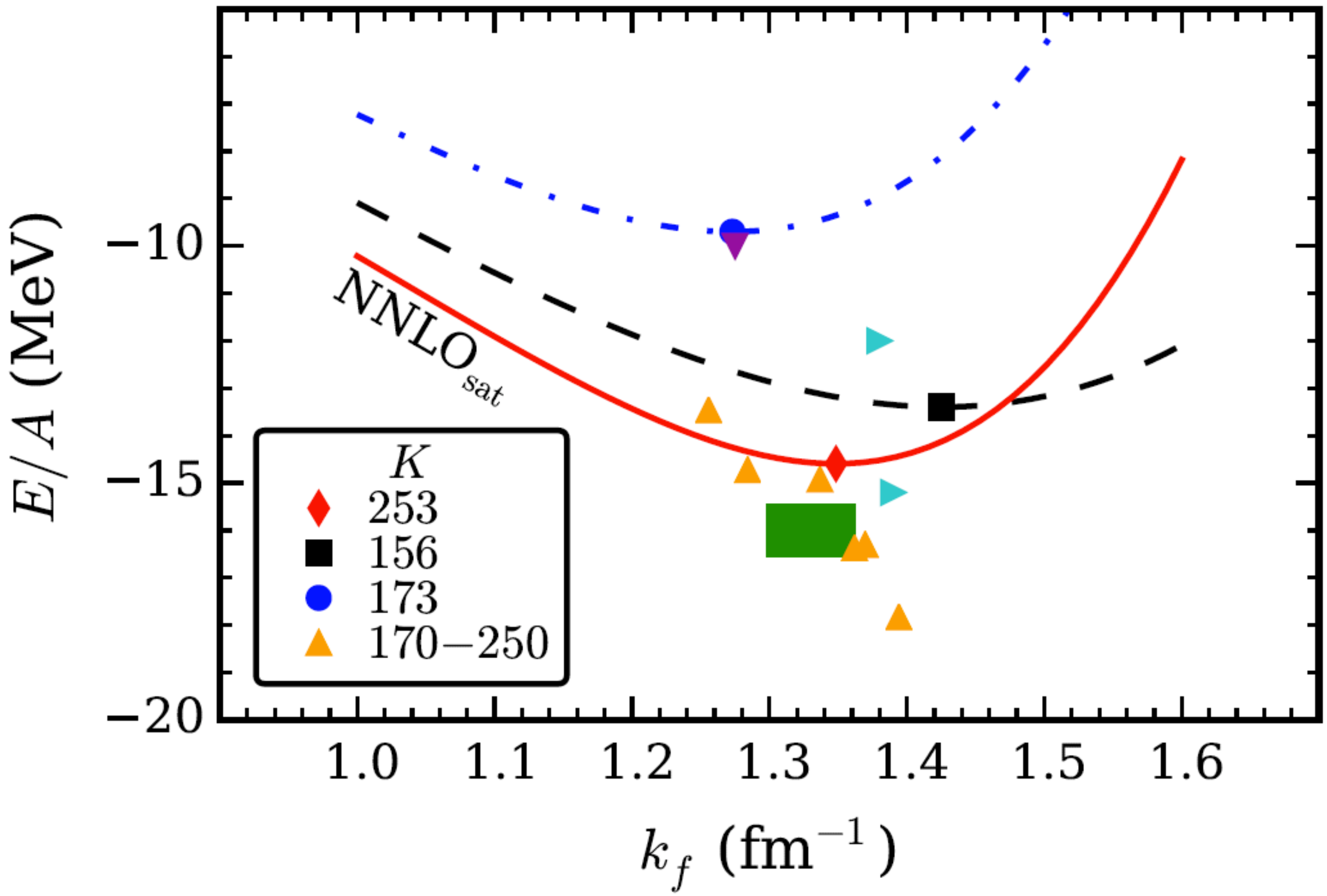
BE(Th)	*BE*(Exp)
326(3) MeV	342 MeV
R_{Ch} (Th)	$R_{Ch.}$(Exp)
3.49(2) fm	3.4776 fm

^{48}Ca

BE(Th)	*BE*(Exp)
404(3) MeV	416 MeV
R_{Ch} (Th)	$R_{Ch.}$(Exp)
3.48(3) fm	3.4771 fm

Nuclear matter from NNLO$_{sat}$

A. Ekström, G. Jansen, K. Wendt et al, PRC 91, 051301 (2015)



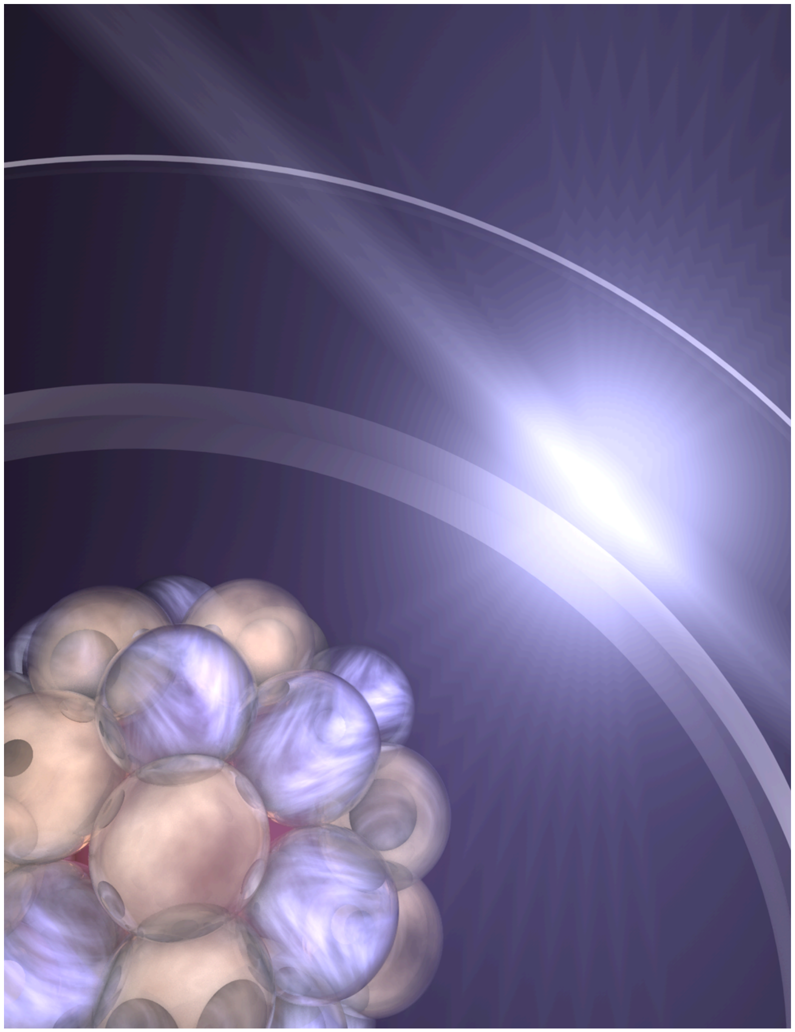
Nuclear matter saturation curves for NNLO$_{sat}$ and other interactions.

Hagen et al (2014); Carbone et al (2013); Coraggio et al 2014;

▲ **K. Hebeler *et al* PRC 83, 031301 2011**

- Interactions from Hebeler *et al* not constrained by heavier nuclei.
- They reproduce binding energy and radii of few-body systems
- Non-local regulators in the 3NF important for saturation

What is the neutron skin of ^{48}Ca



Neutron skin = Difference between radii of neutron and proton distributions

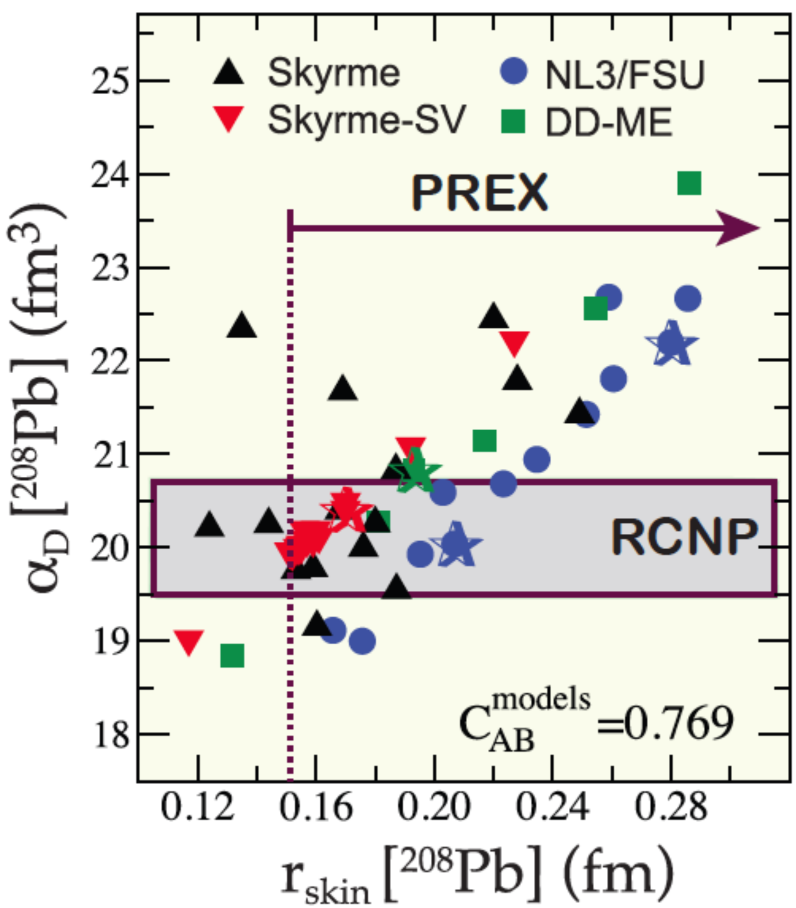
Relates atomic nuclei to neutron stars via neutron EOS

Correlated quantity: dipole polarizability

Model-independent measurement possible via parity-violating electron scattering (P-REX/C-REX at JLab)

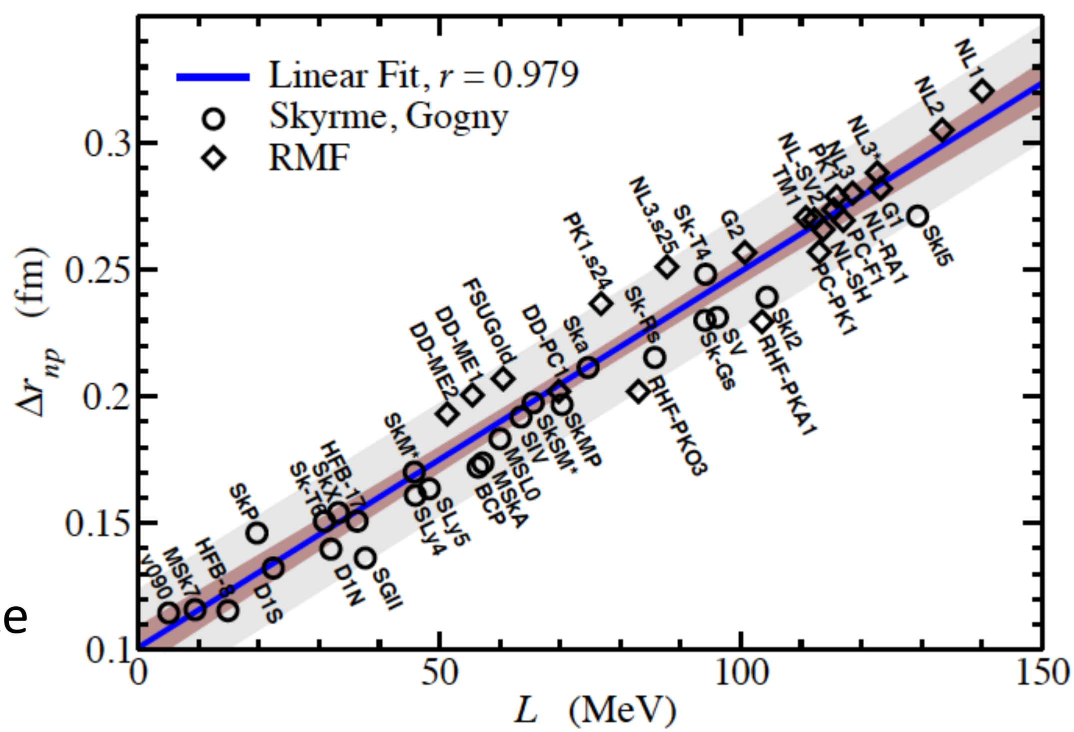
Neutron skin and dipole polarizability of ^{48}Ca

J. Piekarewicz e al, PRC 85, 041302(R) (2012)



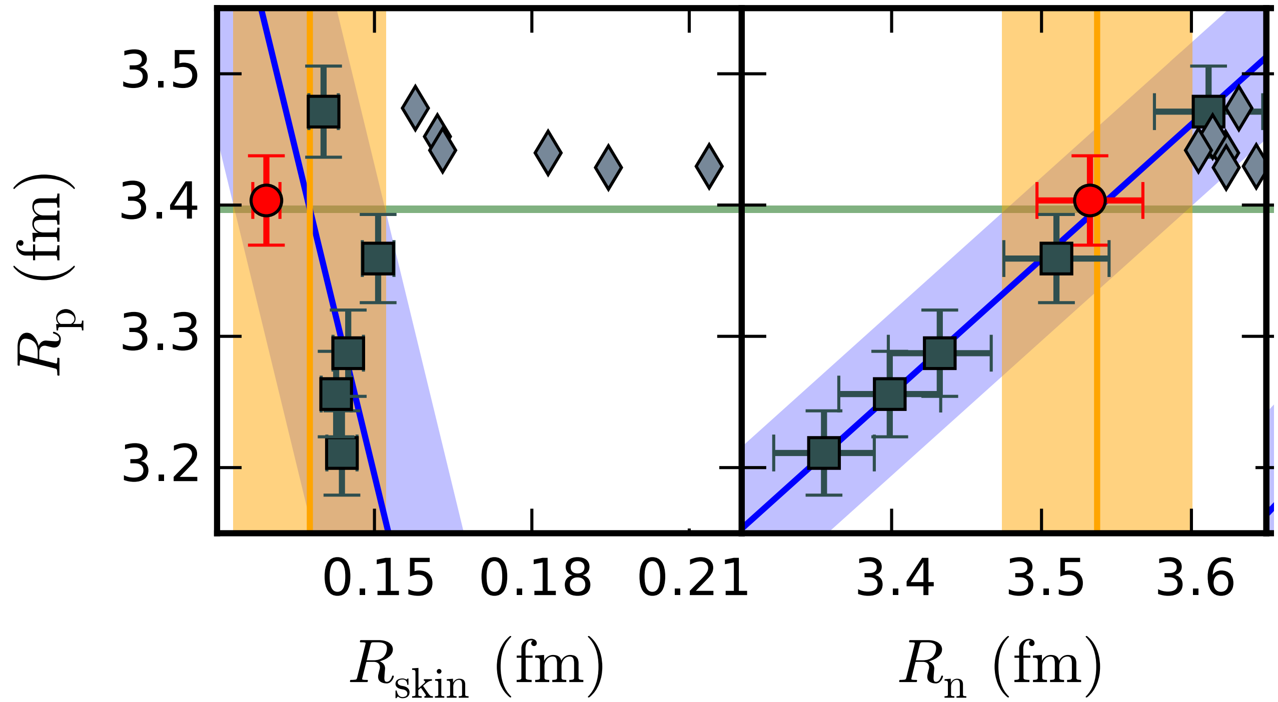
- Impacts limits of stability and physics of neutron stars
- C-REX will measure the weak charge form
- Darmstadt-Osaka collaboration has measured α_D (Talk on Friday by Peter von Neumann-Cosel)

X. Viñas et al, Eur. Phys. J. A 50, 27 (2014)



- Our knowledge about neutron skins is so far mainly based on DFT models.
- What does ab-initio theory add to our knowledge of the neutron skin and size of nuclei?

Neutron radius and skin of ^{48}Ca

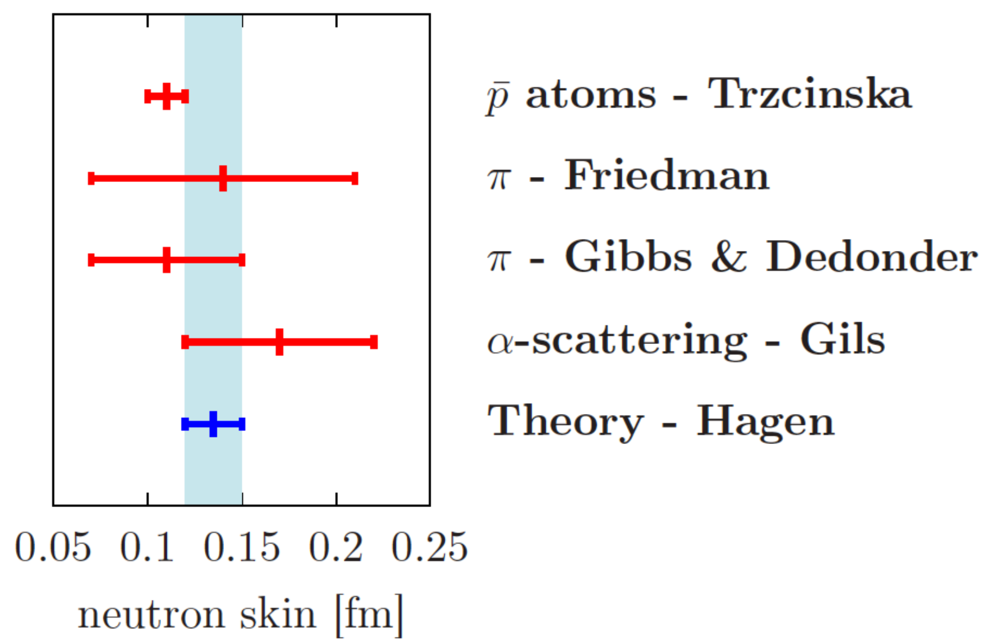


G. Hagen *et al*, Nature Physics **12**, 186–190 (2016)

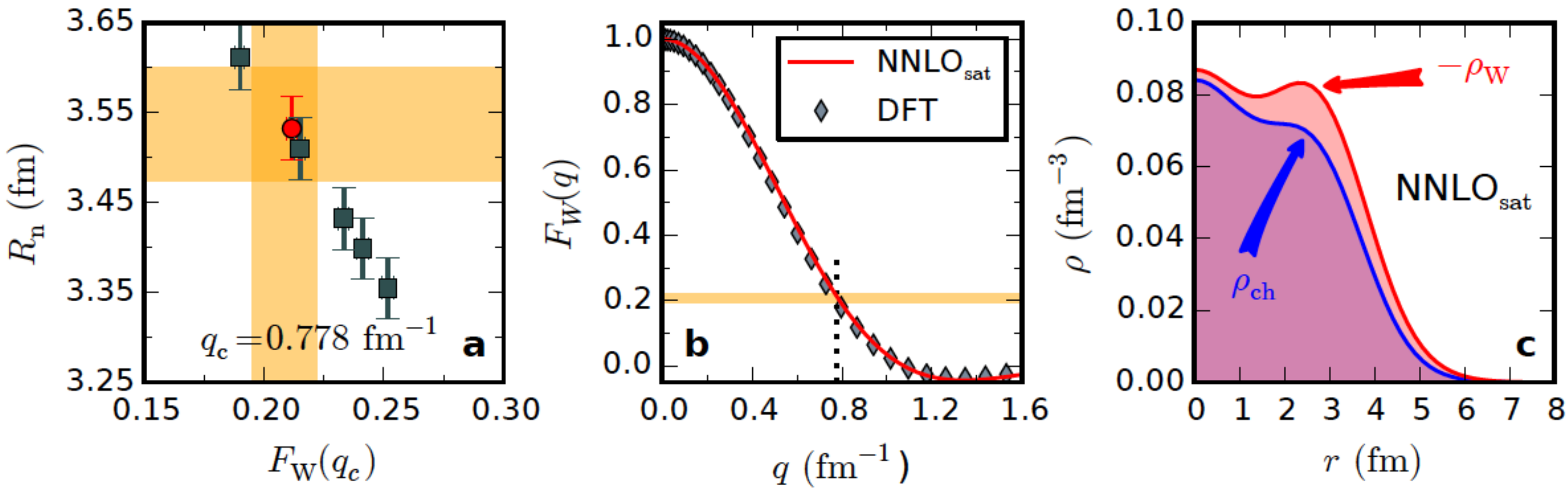
Uncertainty estimates from family of chiral interactions.

DFT:
SkM*, SkP, Sly4, SV-min, UNEDF0, and UNEDF1

- Neutron skin significantly smaller than in DFT
- Neutron skin almost independent of the employed Hamiltonian
- Our predictions for ^{40,48}Ca are consistent with existing data



Weak charge form-factor of ^{48}Ca



***Ab-initio* predictions:**

$0.195 \lesssim F_W(q_c) \lesssim 0.222$, $3.59 \lesssim R_W \lesssim 3.71$ fm, $0.12 \lesssim R_{skin} \lesssim 0.15$ fm

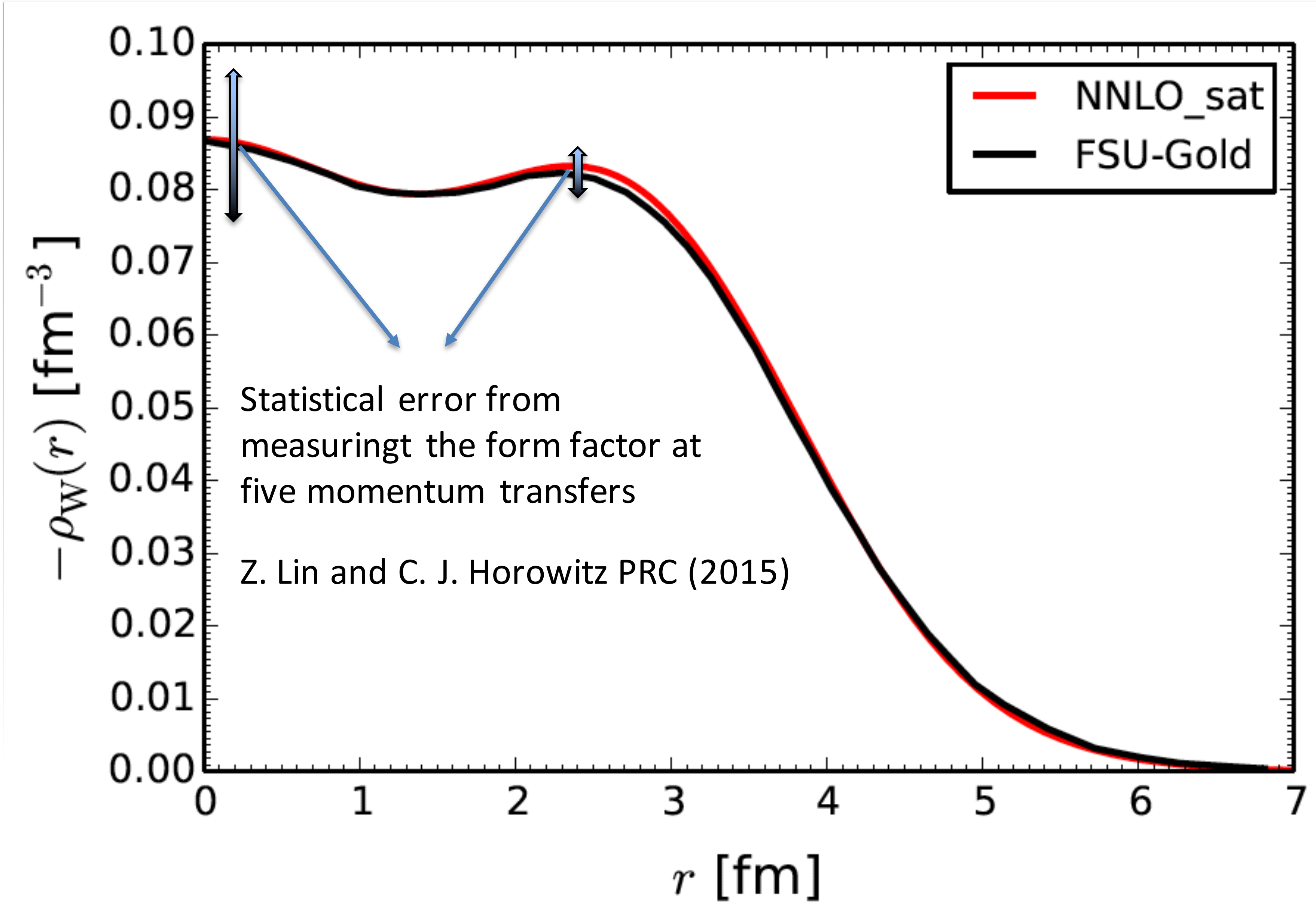
DFT predictions:

SV-min: $F_W(q_C) = 0.1986$ R_{skin} = 0.1830 fm

FSUBJ: $F_W(q_C) = 0.205$ R_{skin} = 0.1925 fm

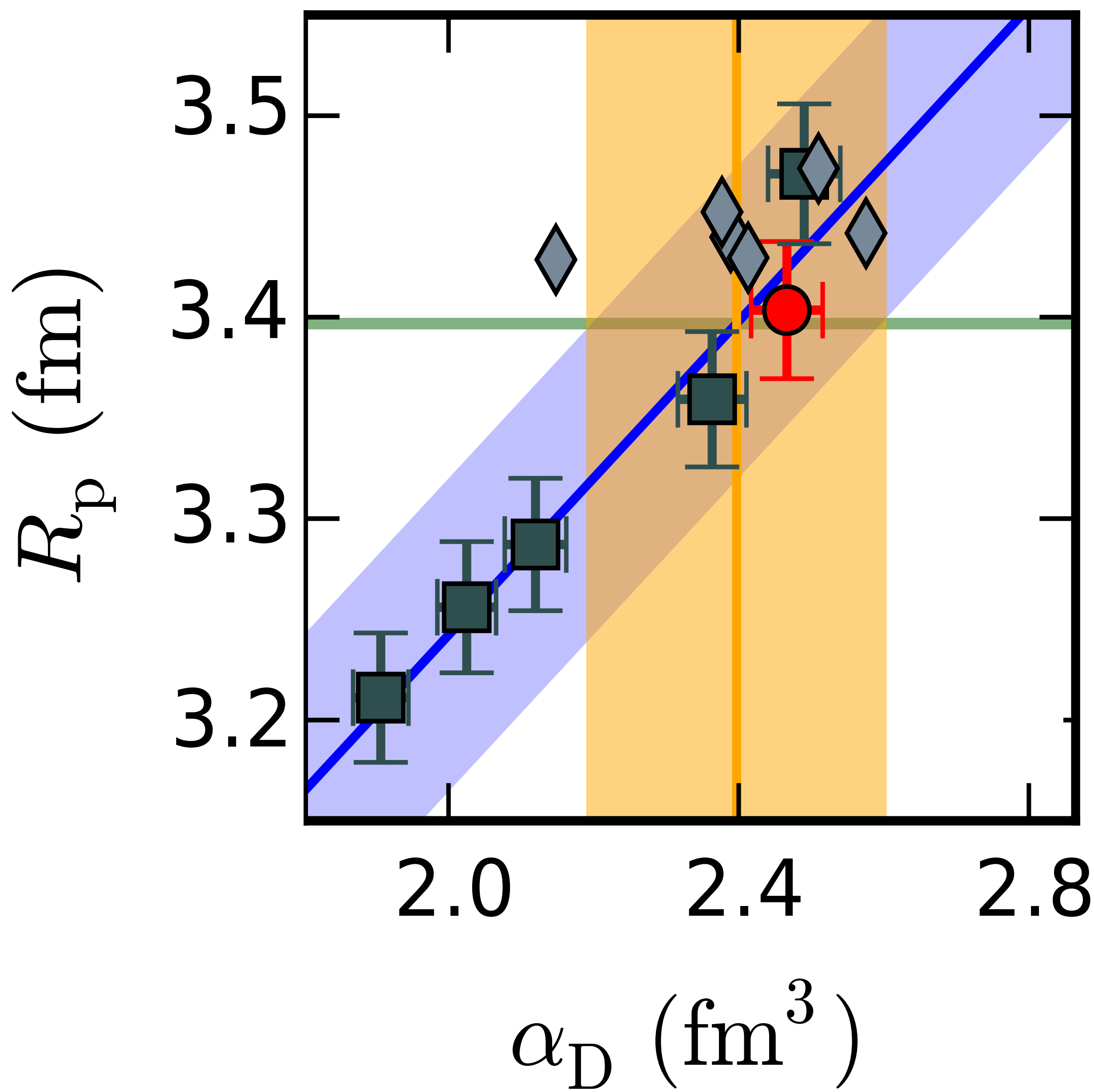
Can we reliably extract the neutron skin from a single measurement?

Weak charge form-factor of ^{48}Ca



Dipole polarizability of ^{48}Ca

G. Hagen *et al*, Nature Physics **12**, 186–190 (2016)



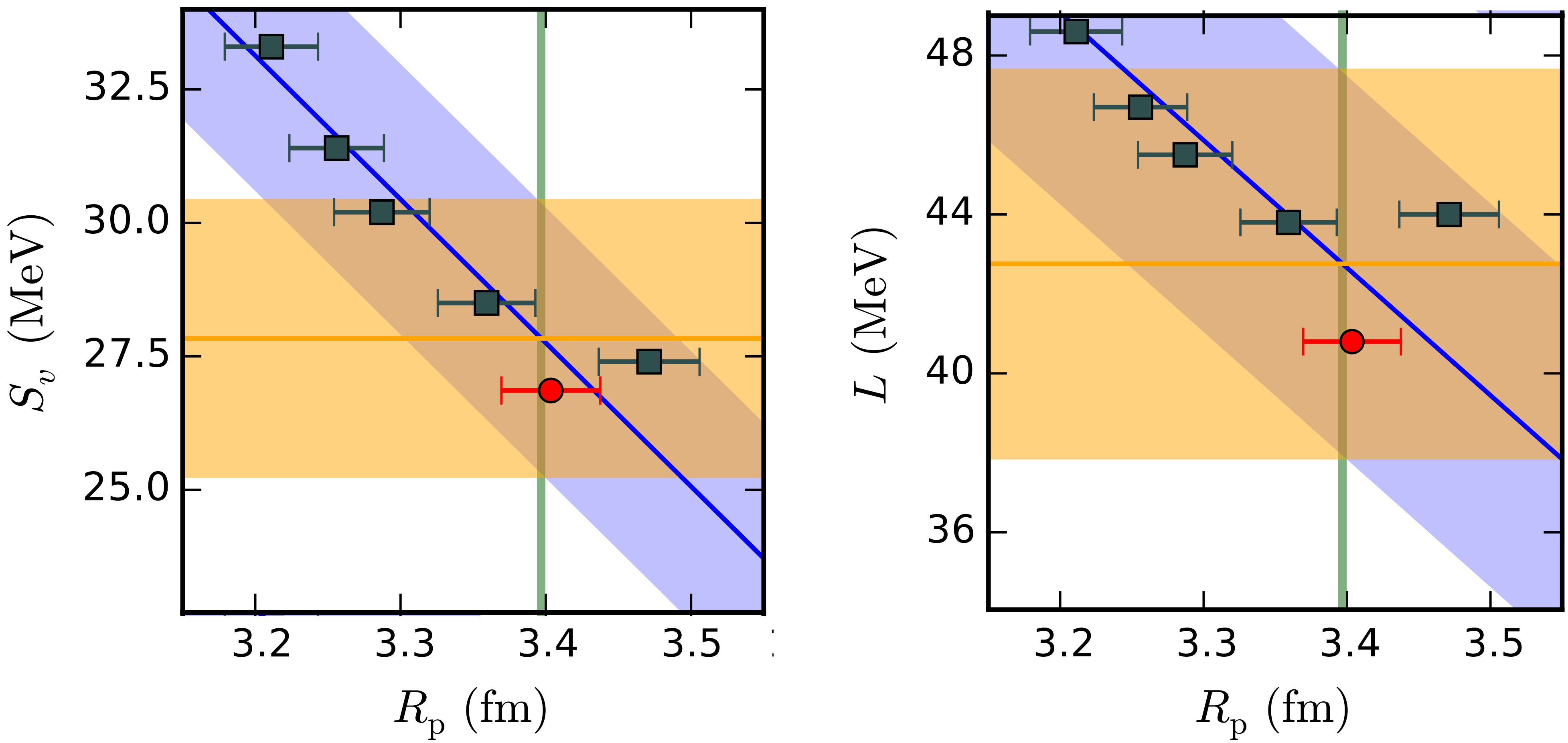
DFT results are consistent and within band of ab-initio results

Data has been analyzed by Osaka-Darmstadt collaboration
(Talk on Friday by Peter von Neumann-Cosel)

Ab-initio prediction:
$2.19 \lesssim \alpha_D \lesssim 2.60$ fm^3

See talk by S. Bacca next week

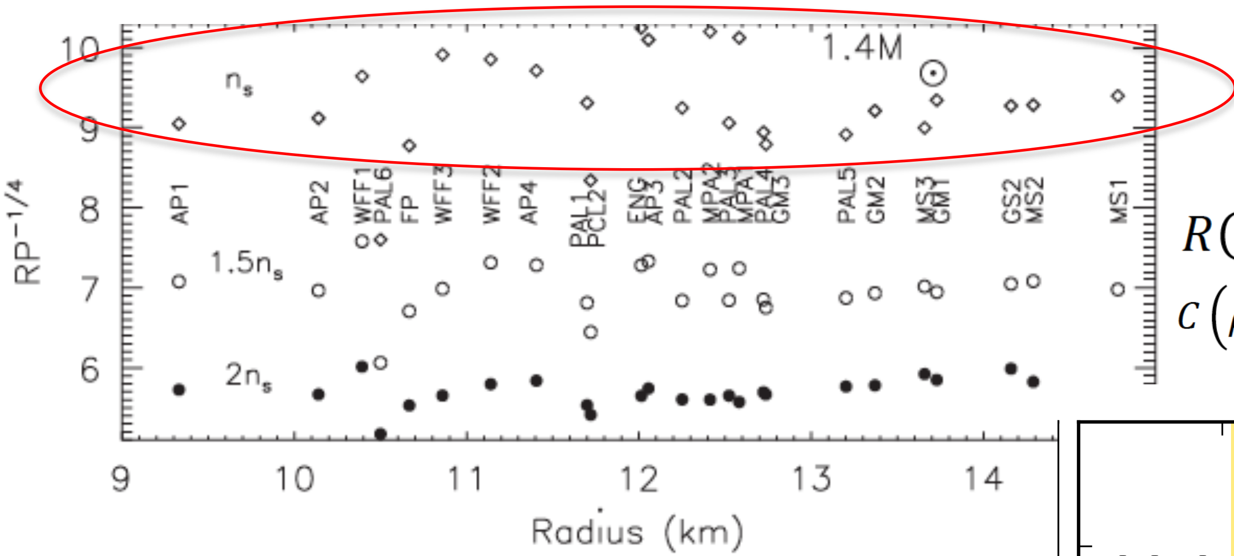
Symmetry energy and L from chiral EFT



- S_v and L correlates with dipole polarizability and proton radius
- Ab-initio prediction for S_v and L from chiral EFT:

  $25.2 \lesssim S_v \lesssim 30.4$ MeV, $37.8 \lesssim L \lesssim 47.7$ MeV
- Consistent with Lattimer and Lim:
- $29 \lesssim S_v \lesssim 32.7$ MeV and $40.5 \lesssim L \lesssim 61.9$ MeV

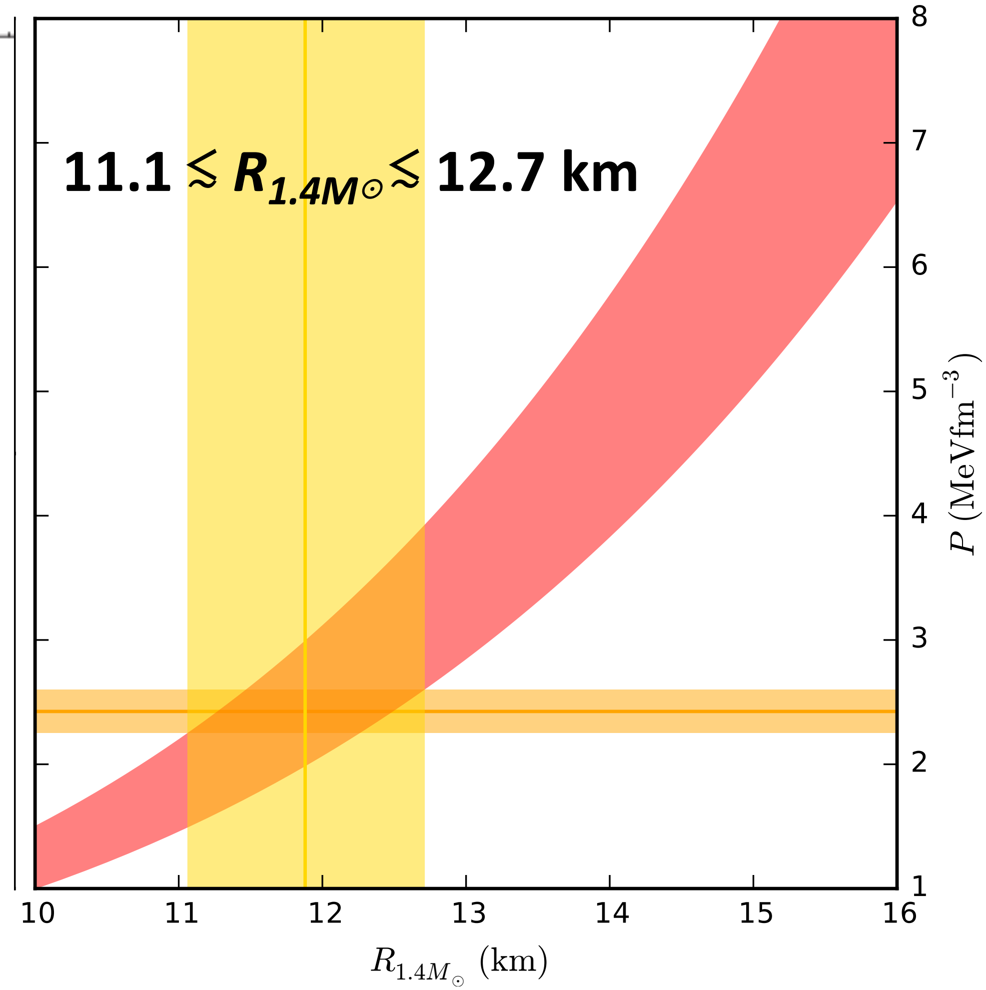
The radius of a 1.4M$_\odot$ neutron star



Lattimer and Prakash, Phys. Rep. 442, 109 (2007)

$$R(M) = C(\rho, M)(P(\rho)/\text{MeV fm}^{-3})^{1/4}$$

$$C\left(\rho = 0.16\ \text{fm}^{-3}, M = 1.4\ M_\odot\right) = 9.52\ \pm 0.49\ \text{km}$$



- Empirical power law relates neutron-star radii to the pressure P at nuclear saturation density.
- P is strongly connected to S_v and L
- We correlate P with the charge radius of ^{48}Ca and get at an estimate: $2.3 \lesssim P \lesssim 2.6$ MeV fm^{-3}
- Ab-initio prediction consistent with Lattimer and Lim $10.7 \lesssim R_{1.4M_\odot} \lesssim 13.1$

Lattimer and Lim Ap J. 771, 51 (2013)

Large charge radii questions magicity of ^{52}Ca

R. F. Garcia Ruiz *et al*, Nature Physics (2016)
doi:10.1038/nphys3645

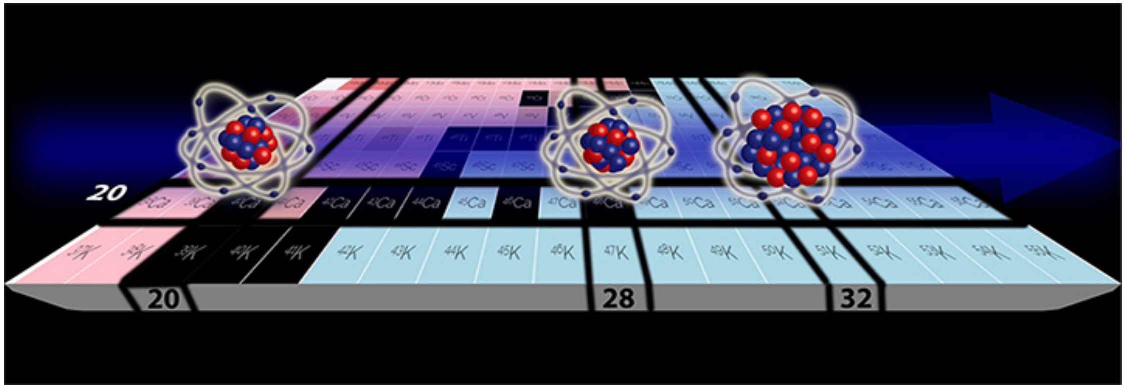
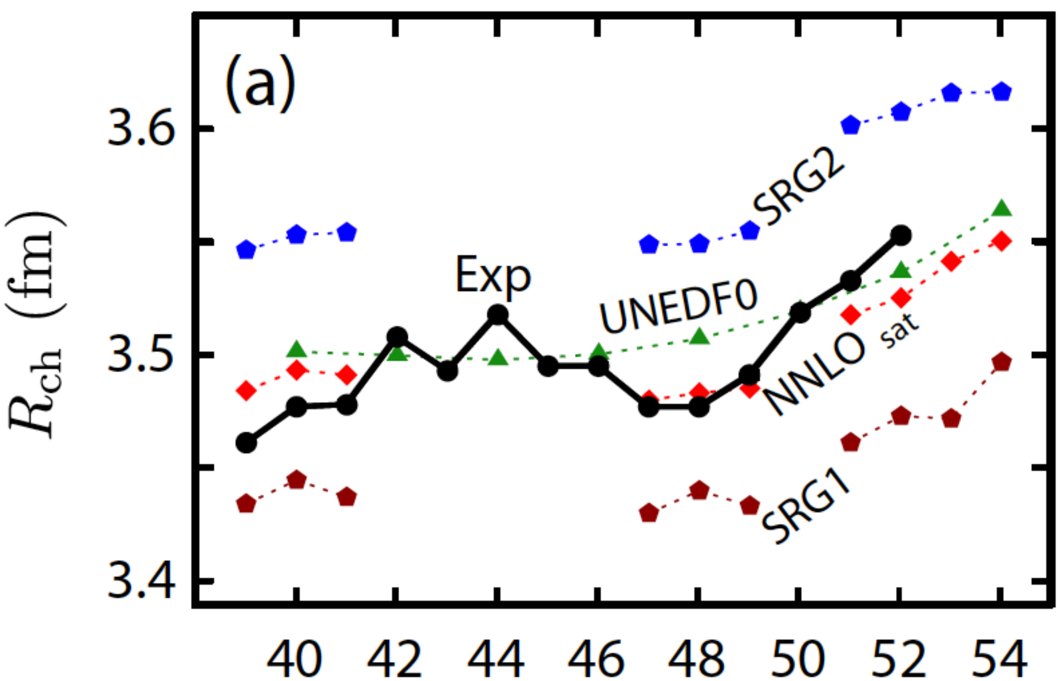
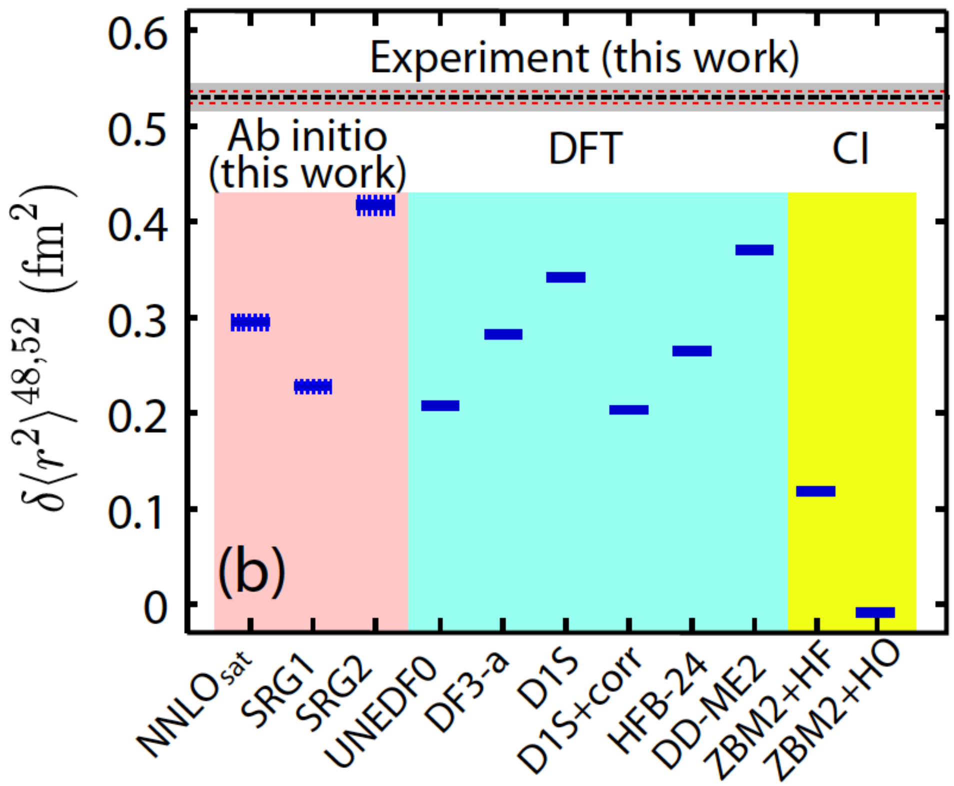


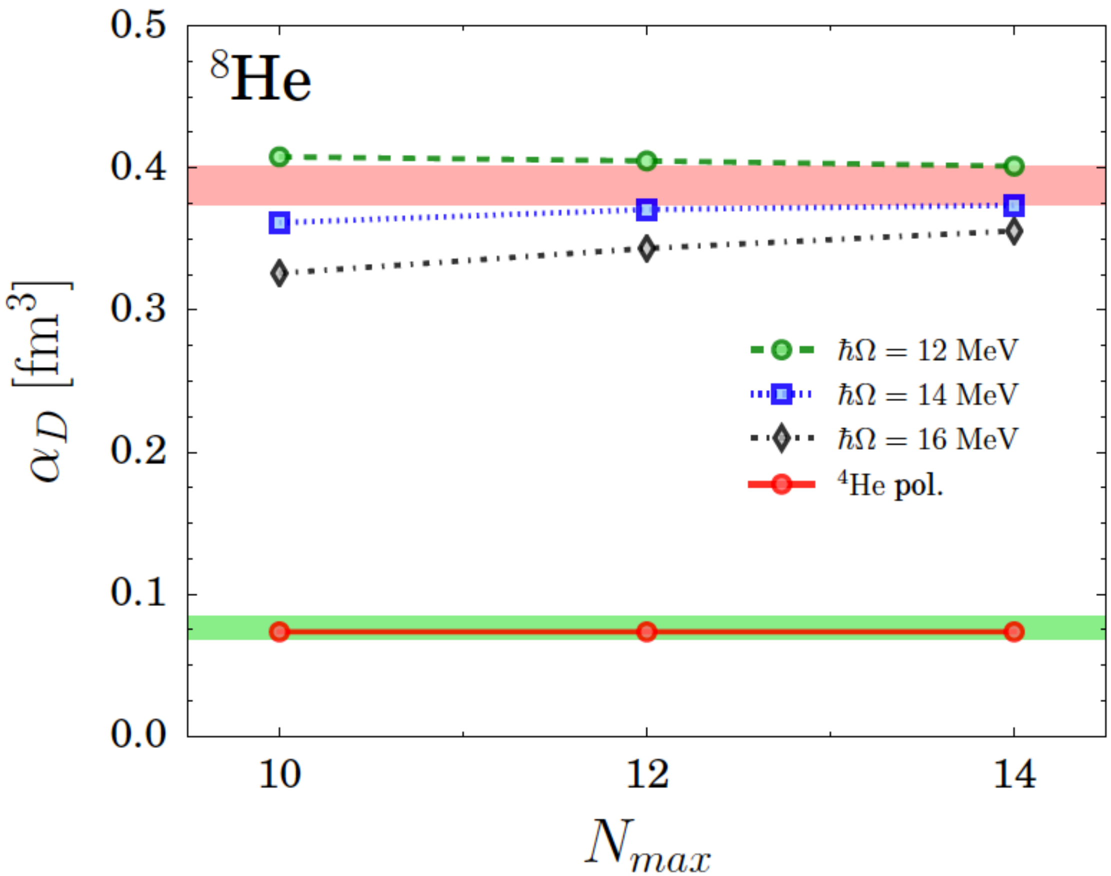
Image: COLLAPS Collaboration/Ronald Fernando Garcia Ruiz.

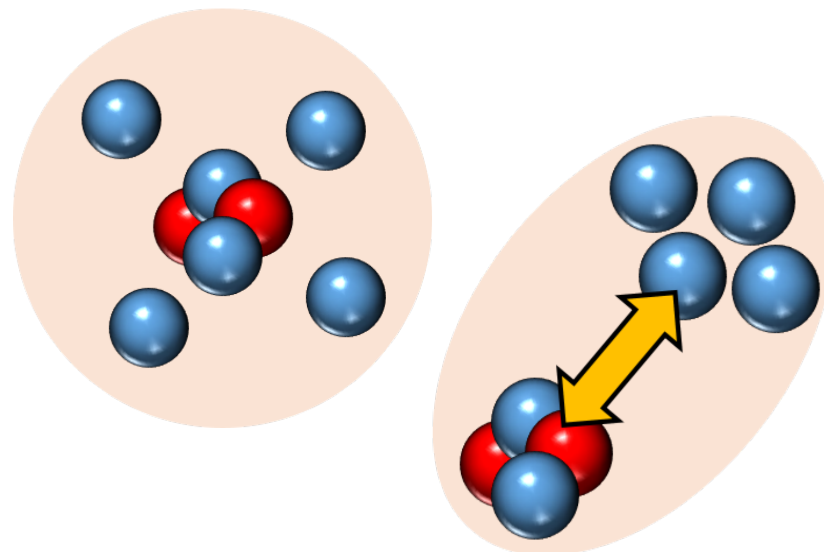
- Charge radii of ^{49,51,52}Ca, obtained from laser spectroscopy experiments at ISOLDE, CERN
- Unexpected large charge radius questions the magicity of ^{52}Ca
- Theoretical models all underestimate the charge radius
- Ab-initio calculations reproduce the trend of charge radii

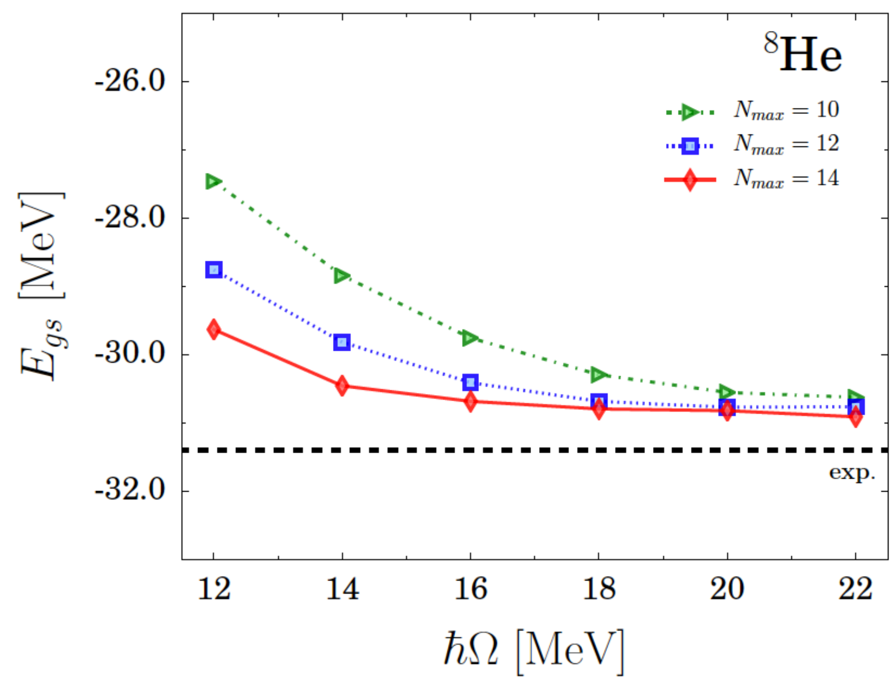




A "giant" pygmy resonance in ^{8}He



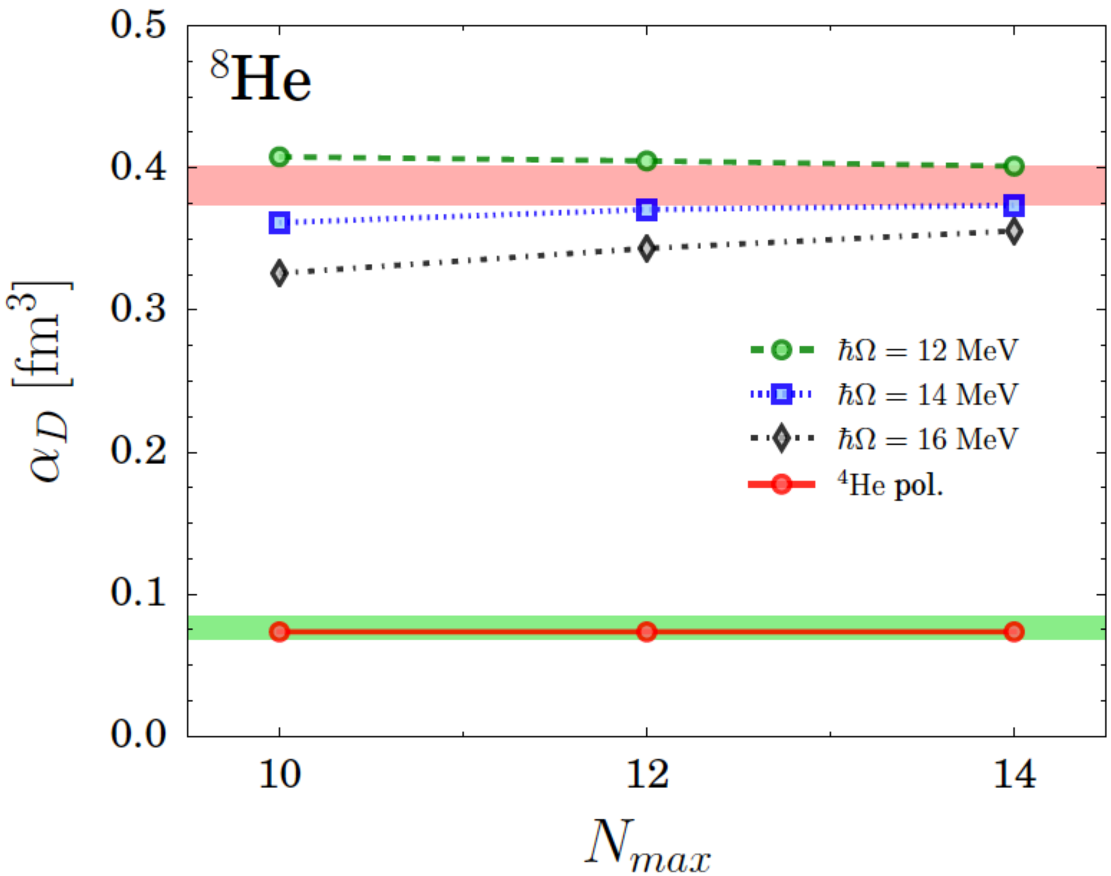


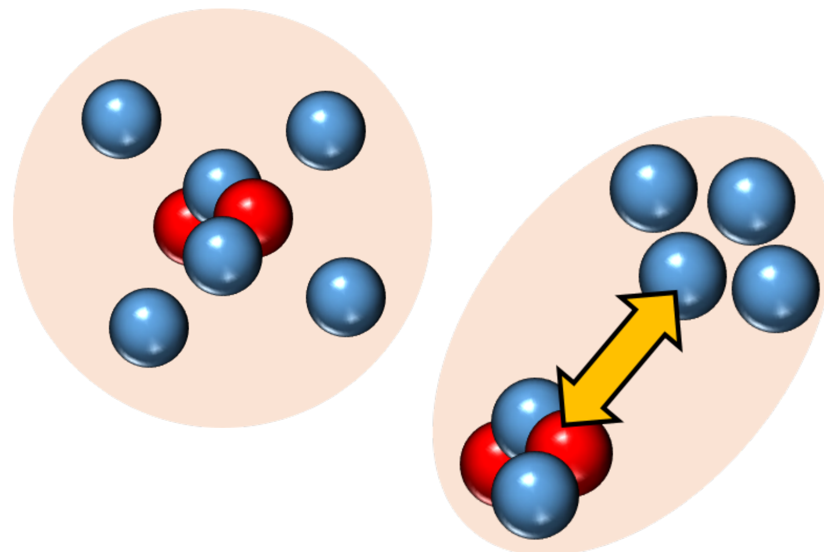


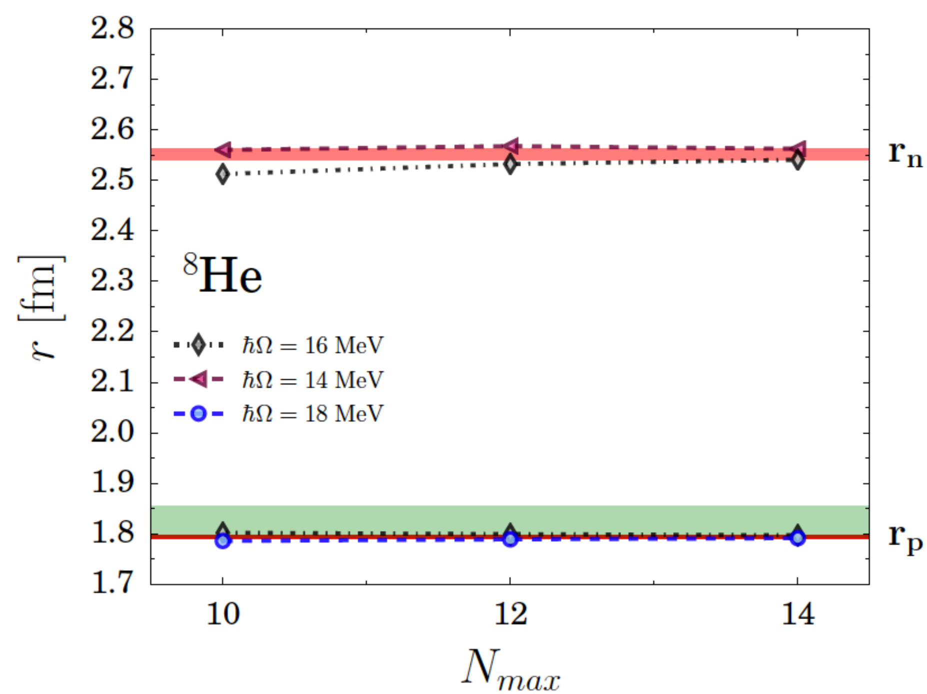
- BE and charge radius of ^{8}He reproduced with $NNLO_{sat}$
- A large neutron radius R_n = 2.57(2) fm gives a neutron skin R_{skin} = 0.8 fm
- R_{skin} of ^{8}He is 2-4 times larger than the R_{skin} of ^{208}Pb

M. Miorelli et al, in preparation (2016)

A “giant” pygmy resonance in ^{8}He







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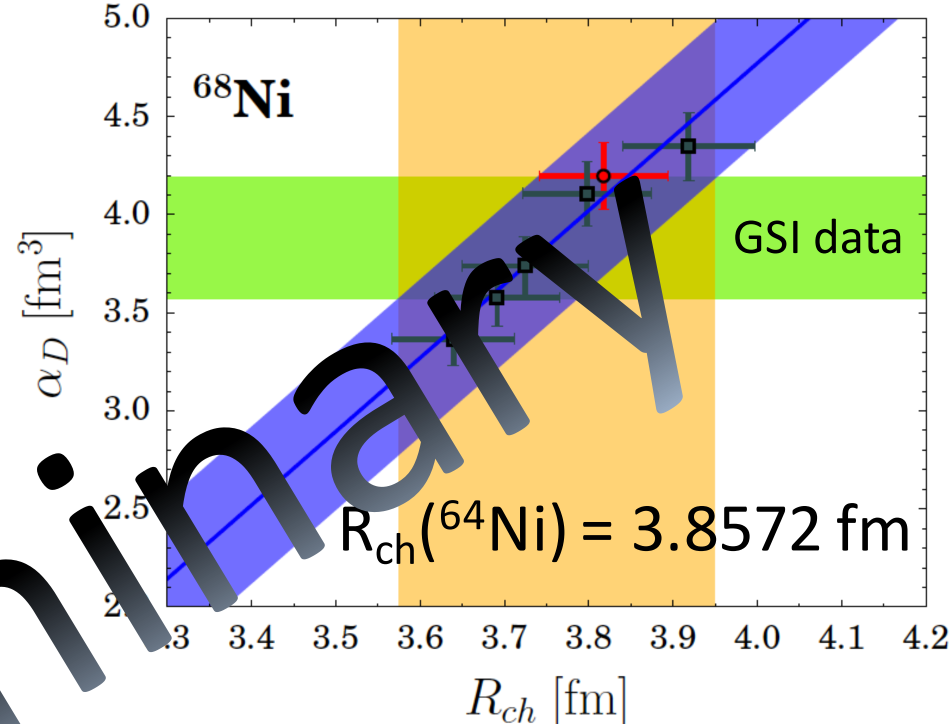
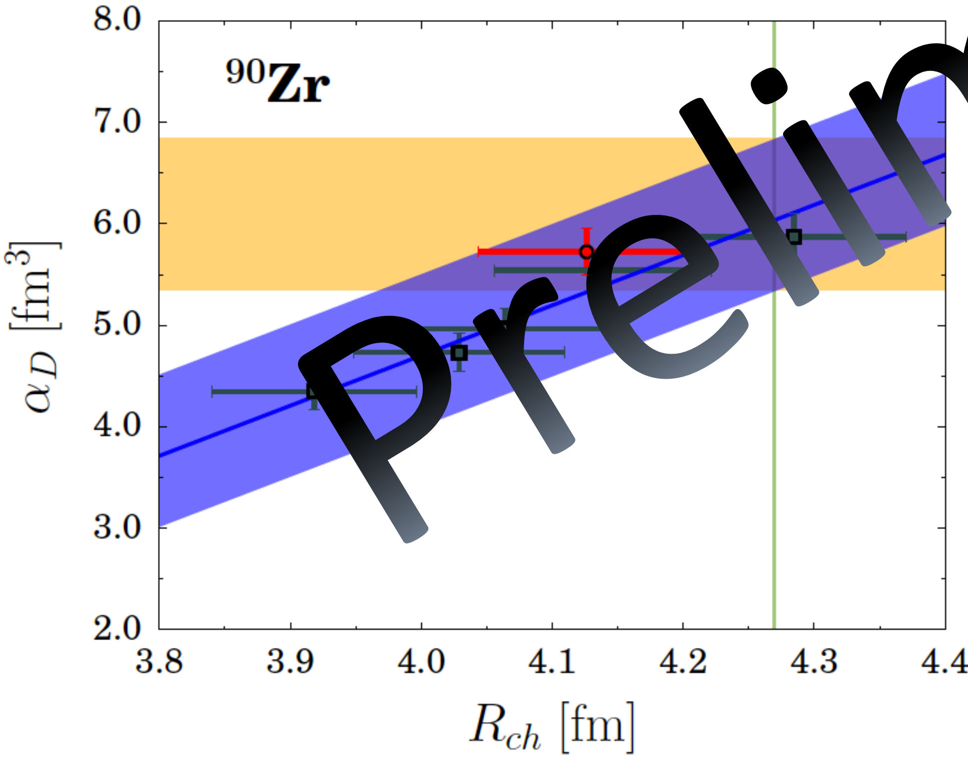
M. Miorelli et al, in preparation (2016)

Results for ^{68}Ni and ^{90}Zr

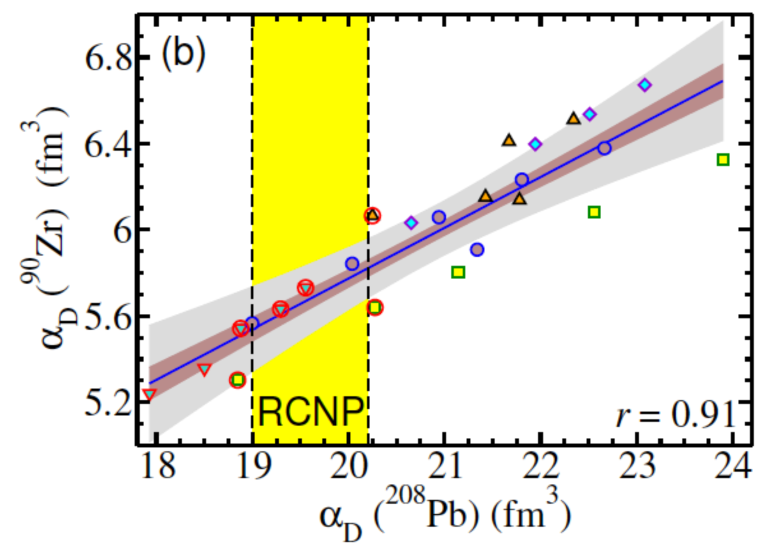
- Results for ^{68}Ni and ^{90}Zr are consistent with data and DFT
- Results are not yet converged with respect to model-space size
- What about 3p3h excitations?



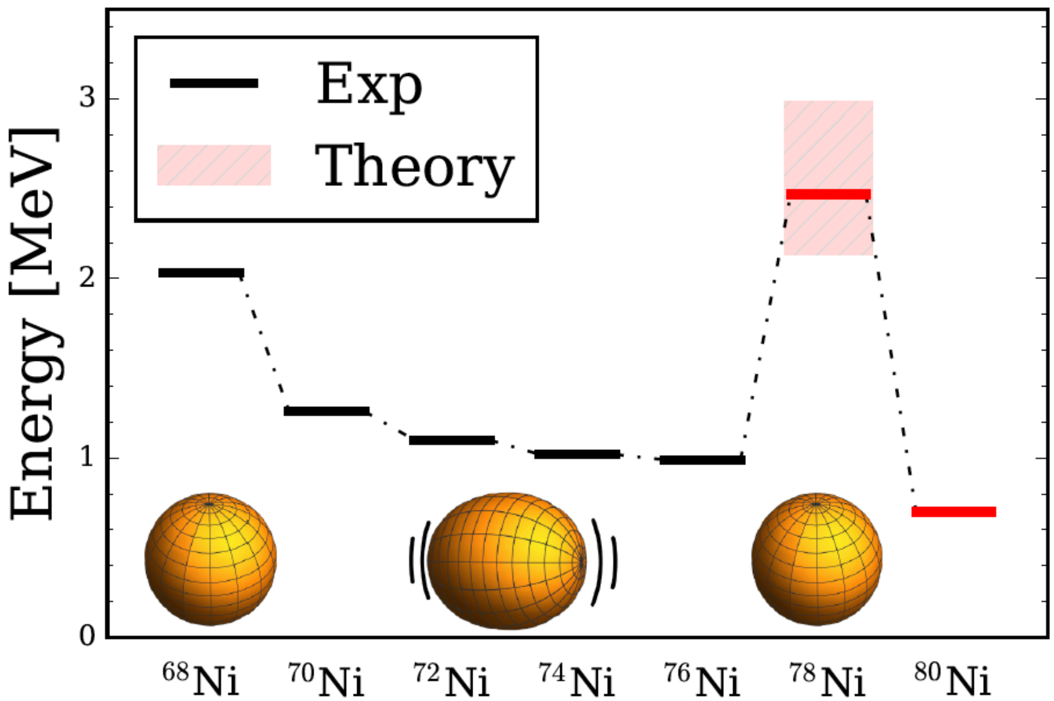
M. Miorelli et al, in preparation (2016)



X. Roca-Maza, et al PRC **92** (2015)



Structure of ^{78}Ni from first principles

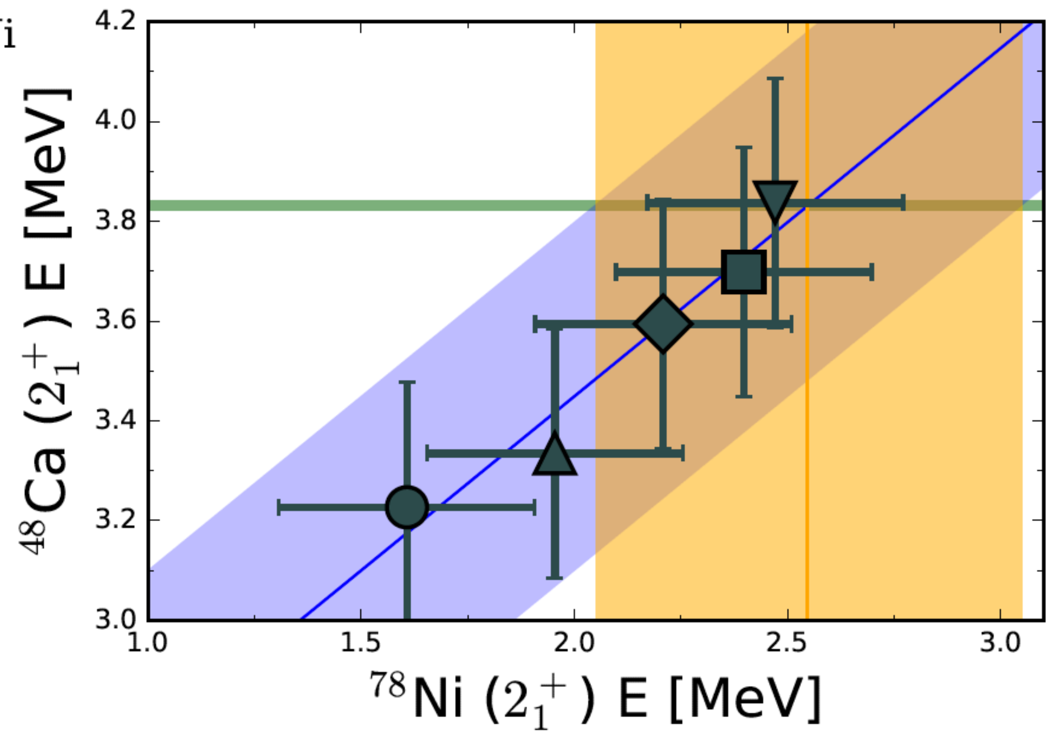


A high 2^+ energy in ^{78}Ni indicates that this nucleus is doubly magic

A measurement of this state has been made at RIBF, RIKEN
R. Taniuchi *et al.*, in preparation

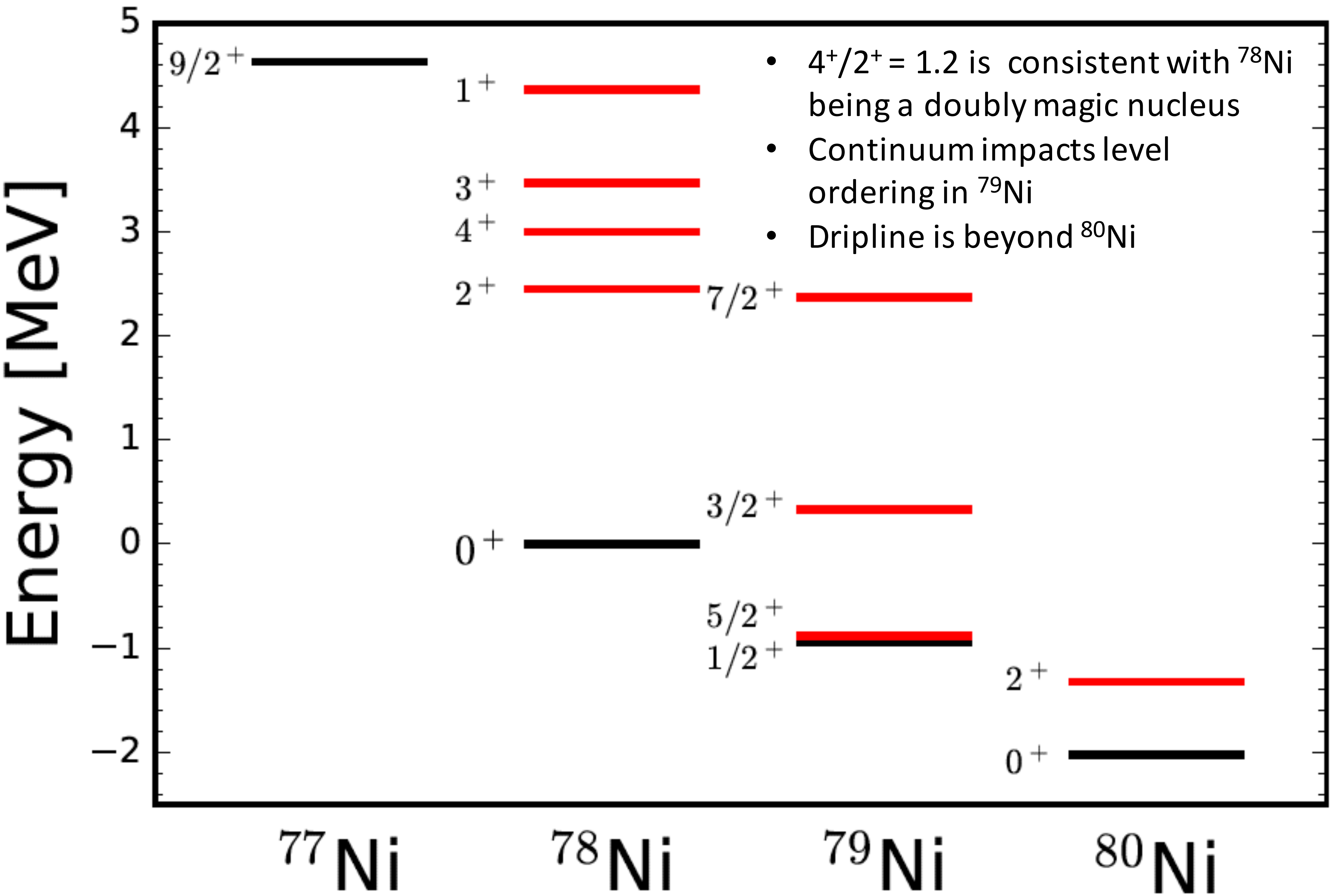
Consistent with recent shell-model studies
F. Nowacki *et al.*, arXiv:1605.05103 (2016)

- From an observed correlation we predict the 2^+ excited state in ^{78}Ni using the experimental data for the 2^+ state in ^{48}Ca
- Similar correlations have been observed in other nuclei, e.g. Tjon line in light nuclei



G. Hagen, G. R. Jansen, and T. Papenbrock
arXiv (2016)

Excited states in ^{78}Ni and its neighbors



- $4^+/2^+ = 1.2$ is consistent with ^{78}Ni being a doubly magic nucleus
- Continuum impacts level ordering in ^{79}Ni
- Dripline is beyond ^{80}Ni

Summary

- Exciting times in nuclear theory:
  - explosion of many-body solvers
  - many new developments regarding interactions and currents
- Neutron skin, dipole polarizability in ^{48}Ca, and charge radii of neutron-rich calciums
- Neutron skin and dipole polarizability of neutron-rich ^{8}He
- Towards heavy nuclei with ab-initio methods:
  - Dipole polarizability of ^{68}Ni and ^{90}Zr
  - Structure of neutron-rich ^{78}Ni suggest it is doubly magic

- How to address the problem of finetuned interactions, regulator dependencies and saturation in nuclei?
- Propagation of uncertainties from the interaction to the nuclear many-body problem on the horizon
- Quantifying systematic uncertainties associated with truncations in ab-initio methods is still a challenge