Electromagnetic properties of nuclei:
from few- to many-body systems

Lecture 11

Many-body methods - Applications

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November 23rd, 2017

Lecture series for SFB 1245
TU Darmstadt

LIT with coupled cluster theory

S.B. *et al.*, PRL **111**, 122502 (2013)

We have developed a new many-body technique that allows to study break up observables from first principles and is built on the ground of a true many-body method, hence has the potential to surpass previous limits

$$(\bar{H} - z^*)|\tilde{\Psi}_R(z^*)\rangle = \bar{\Theta}|\Phi_0\rangle$$

The first implementation we provided is based on the CCSD approximation scheme

$$T = T_1 + T_2$$

$$R = R_1 + R_2$$

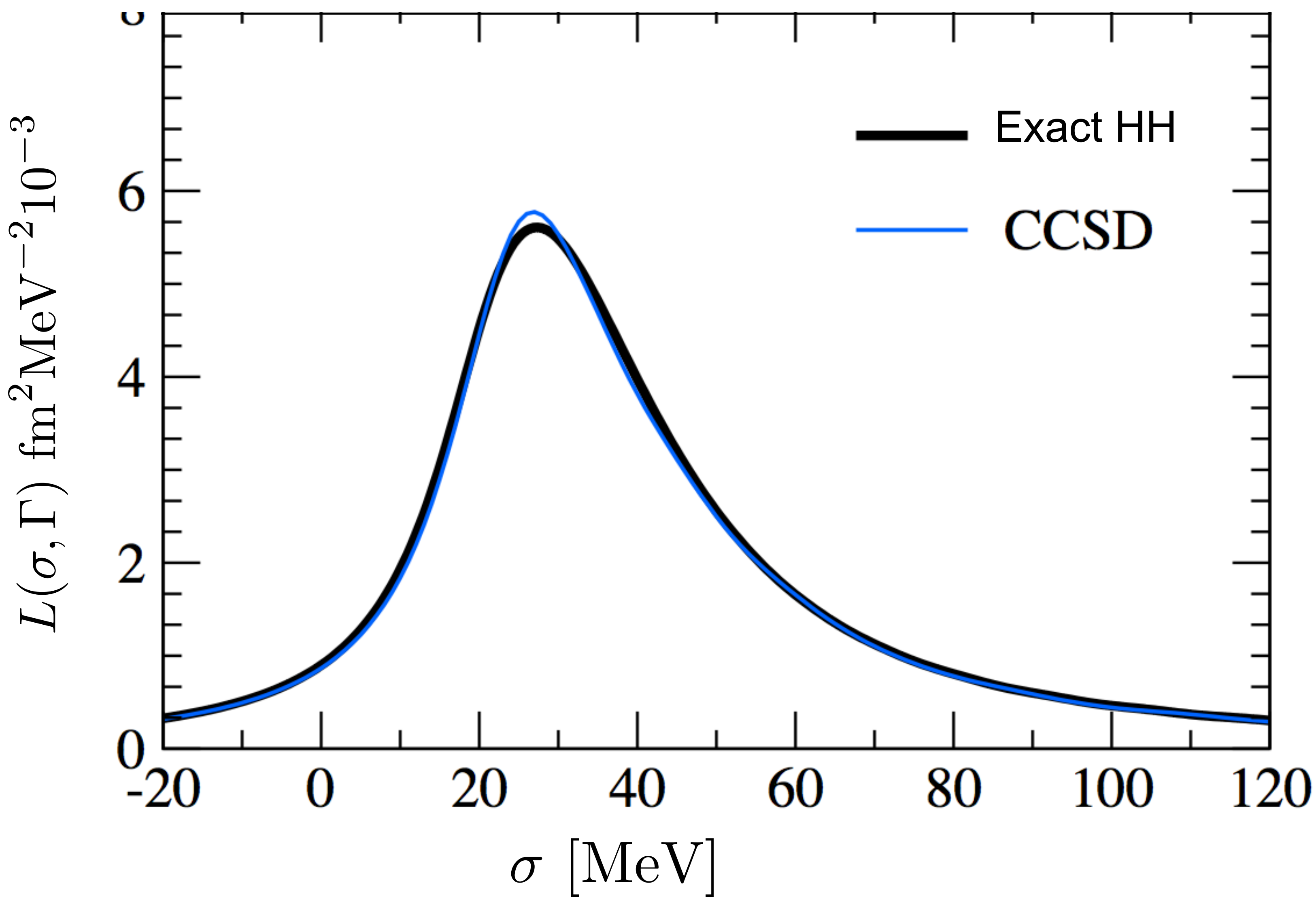
Benchmarking

S.B. *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)

Lorentz Integral Transform with NN forces at N³LO

Validation ^{4}He

$$\Gamma = 10 \text{ [MeV]}$$

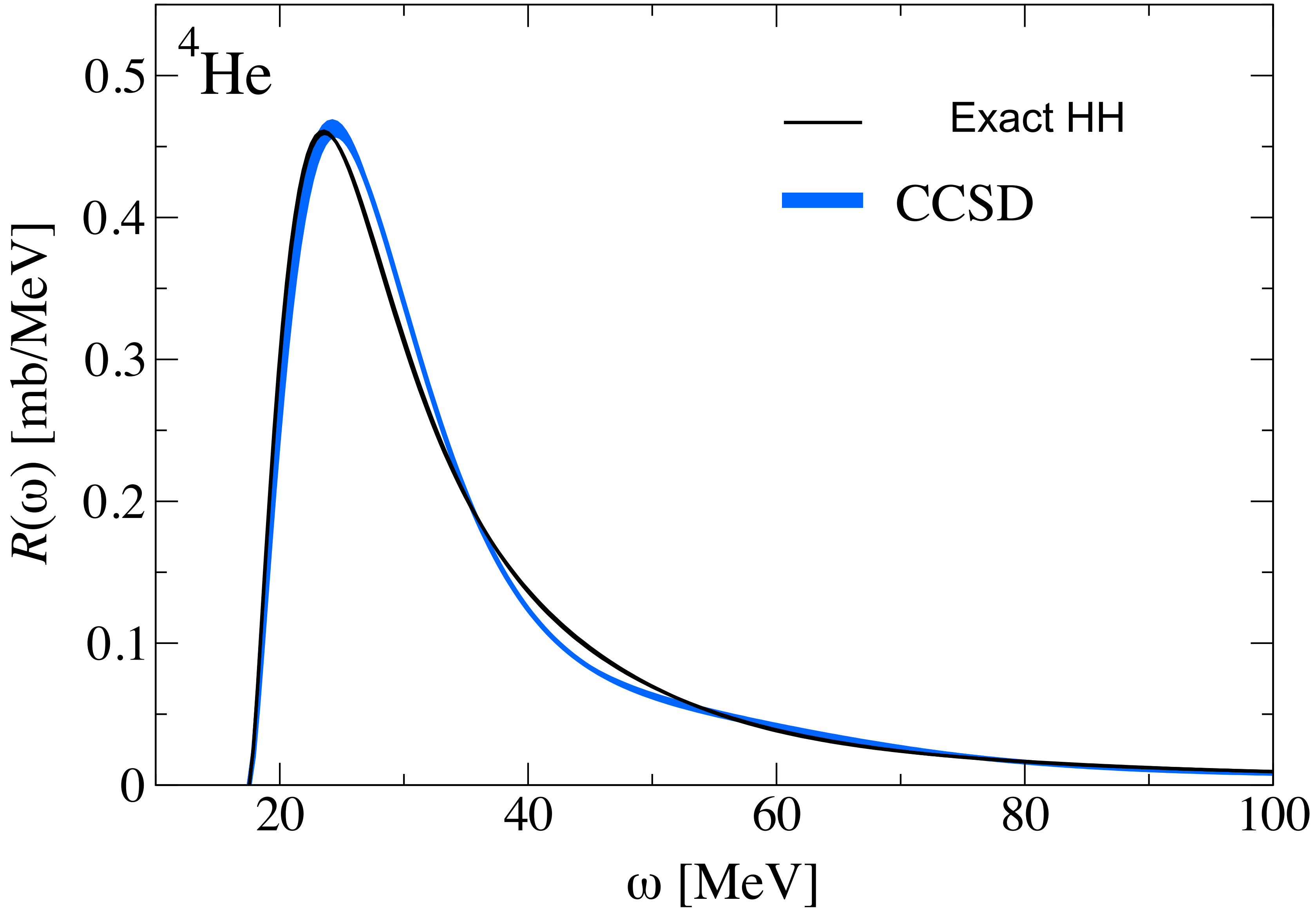


Benchmarking

S.B. *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)

Dipole Response Functions with NN forces at N^{3}LO

Validation ^{4}He

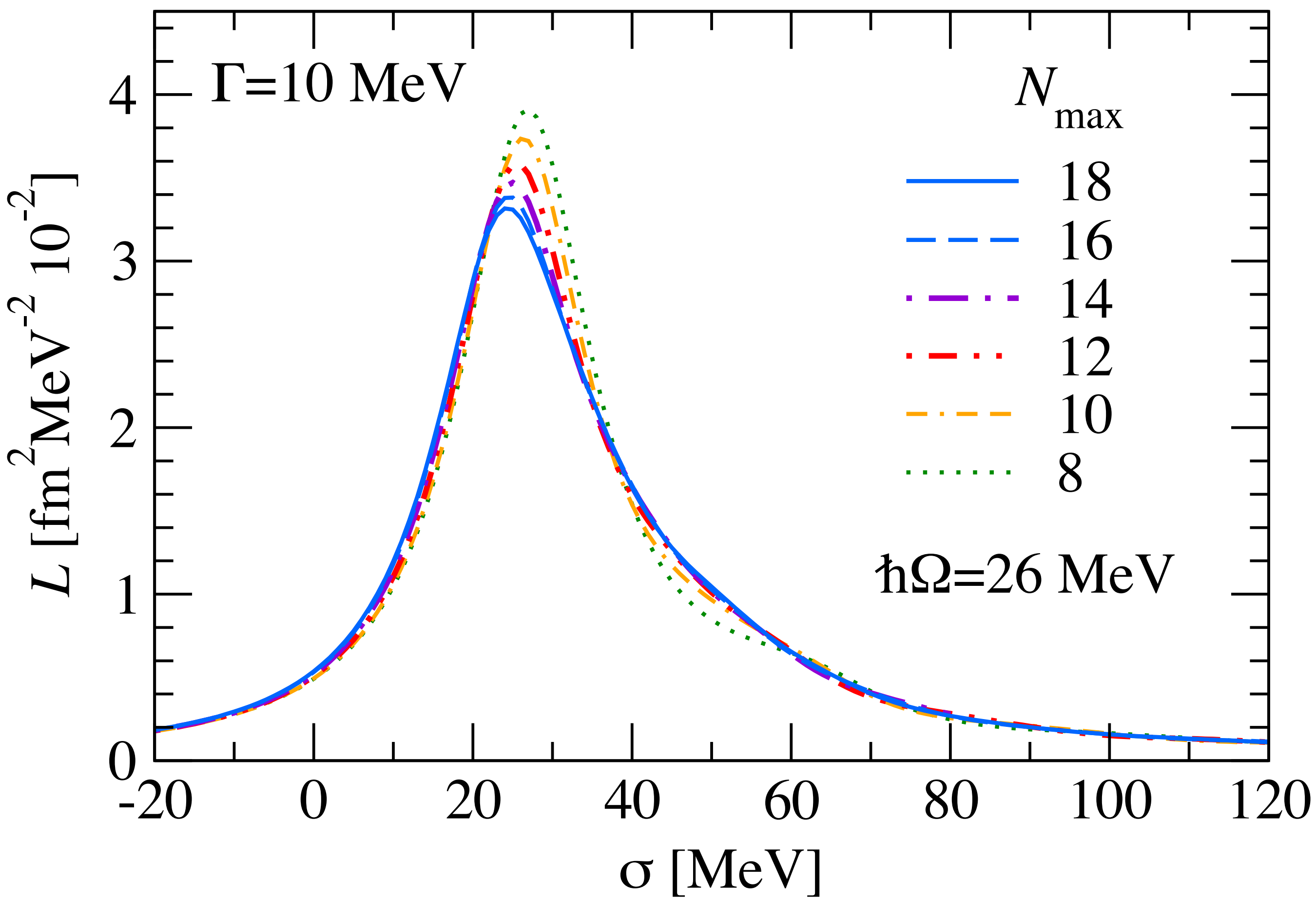


Pushing the mass limits

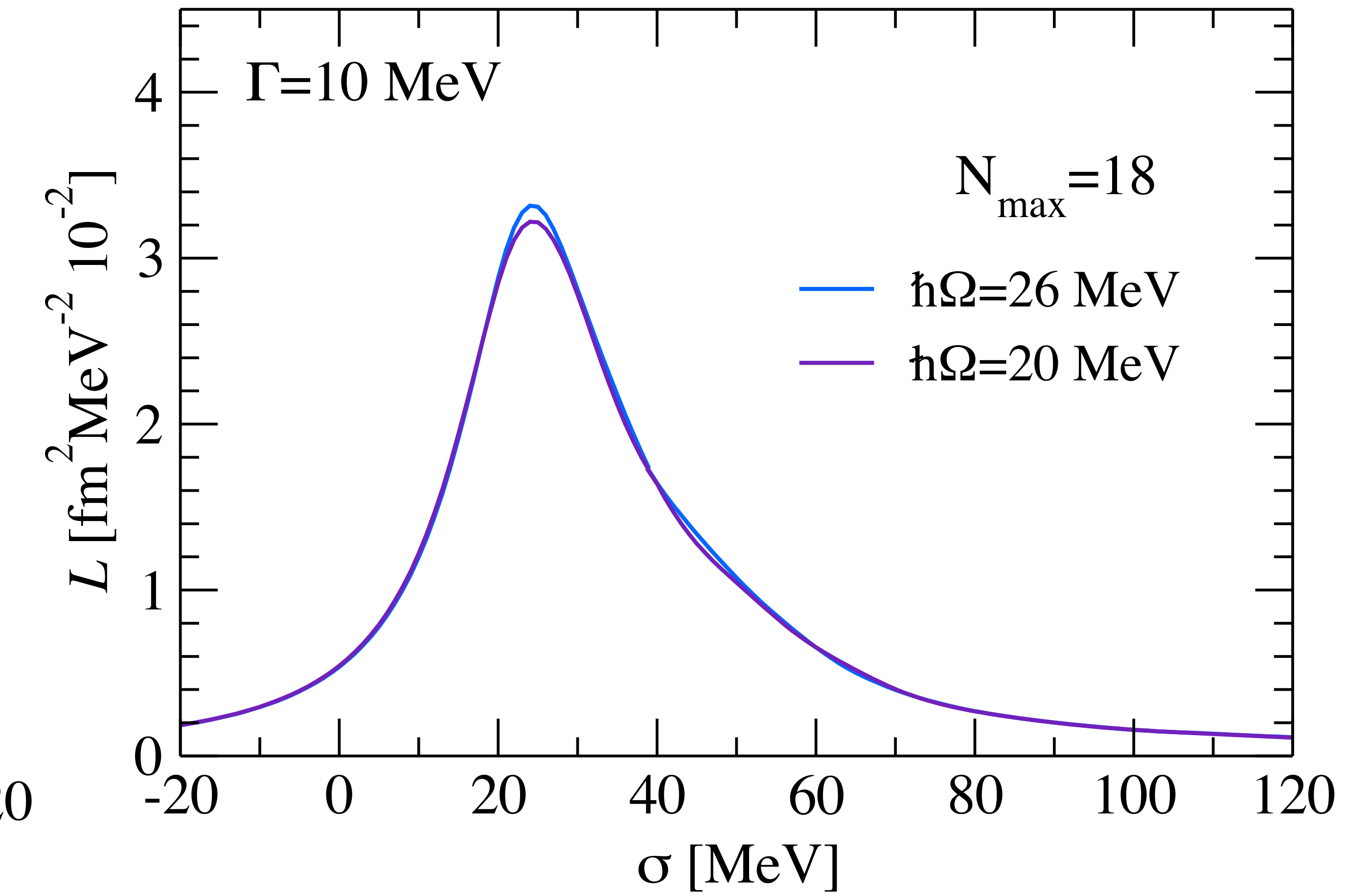
New theoretical method aimed at extending *ab-initio* calculations towards medium mass

Extension to Dipole Response Function in ^{16}O with NN forces derived from χEFT (N^3LO)

Convergence in the model space expansion



Good convergence!



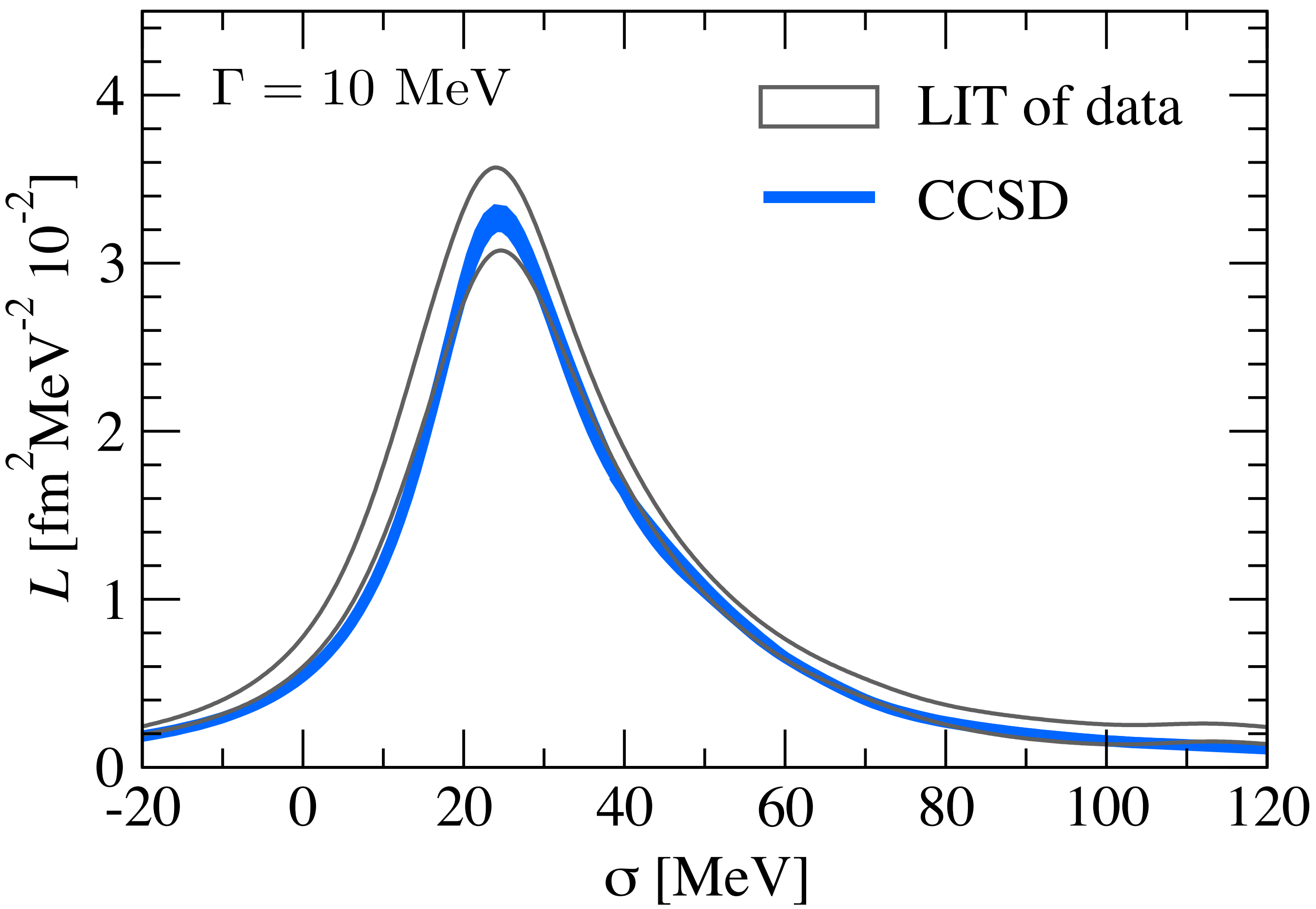
Small HO dependence: use it as error bar

Pushing the mass limits

New theoretical method aimed at extending *ab-initio* calculations towards medium mass

Extension to Dipole Response Function in ^{16}O with NN forces derived from χEFT (N^3LO)

Comparison to the experiment

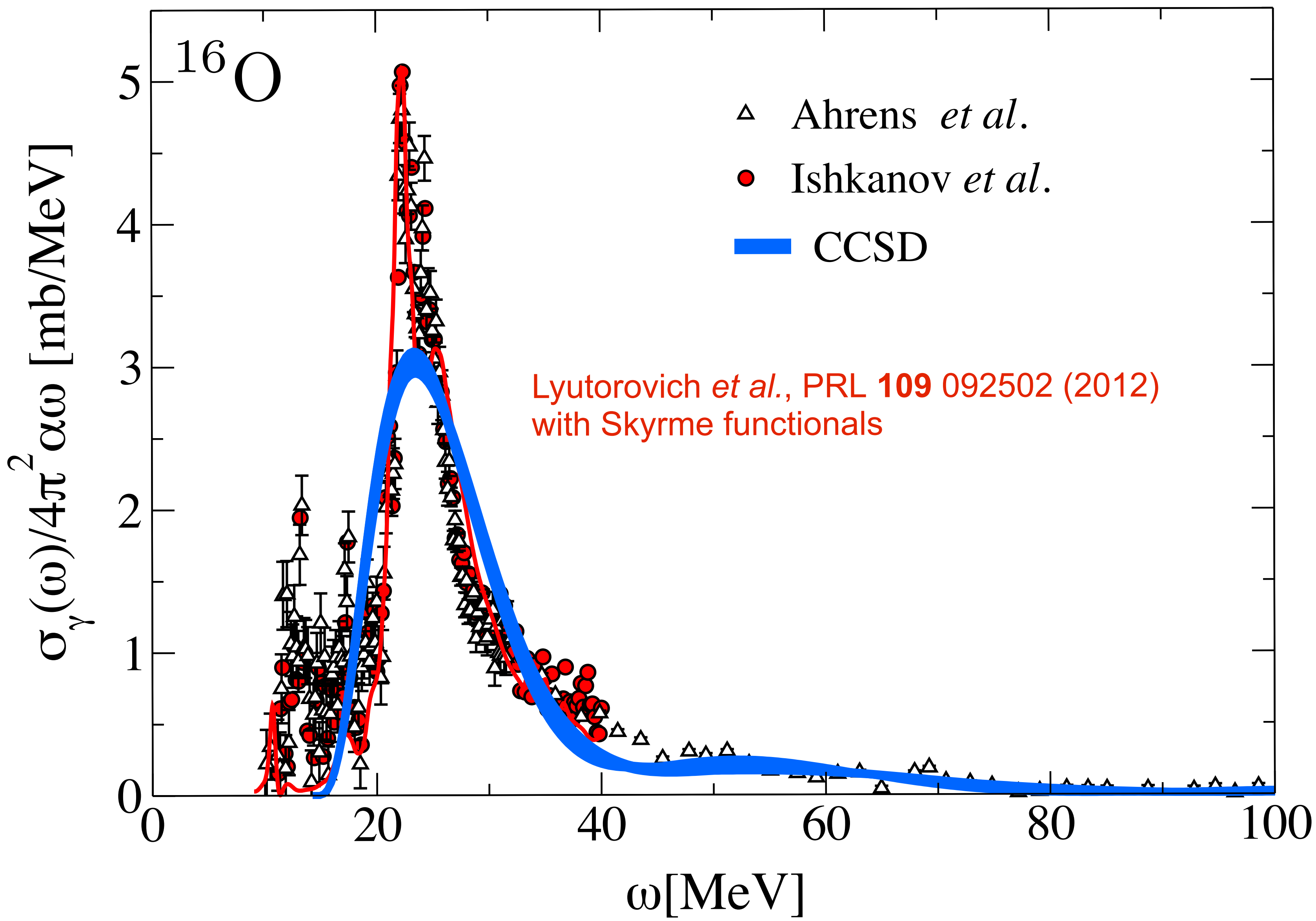


This proves that the total strength is correctly reproduced

Photonuclear reactions

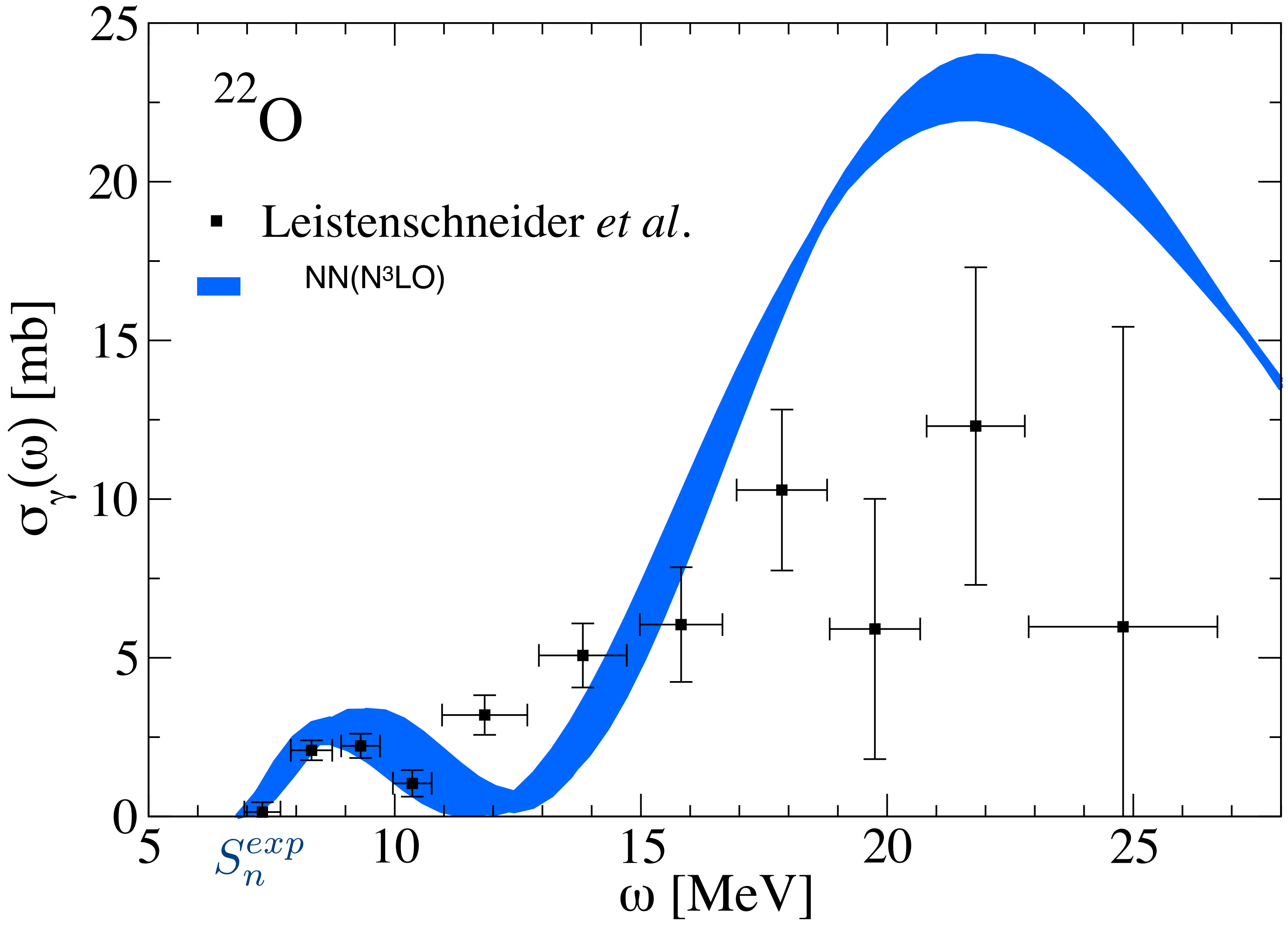
S.B. *et al.*, PRL **111**, 122502 (2013)

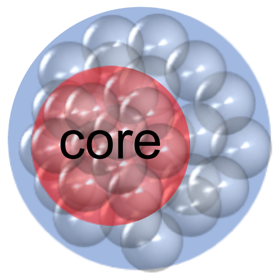
Photoabsorption cross section with NN forces at N³LO



Photoexcitation of neutron-rich nuclei

S.B. *et al.*, PRC **90**, 064619 (2014)





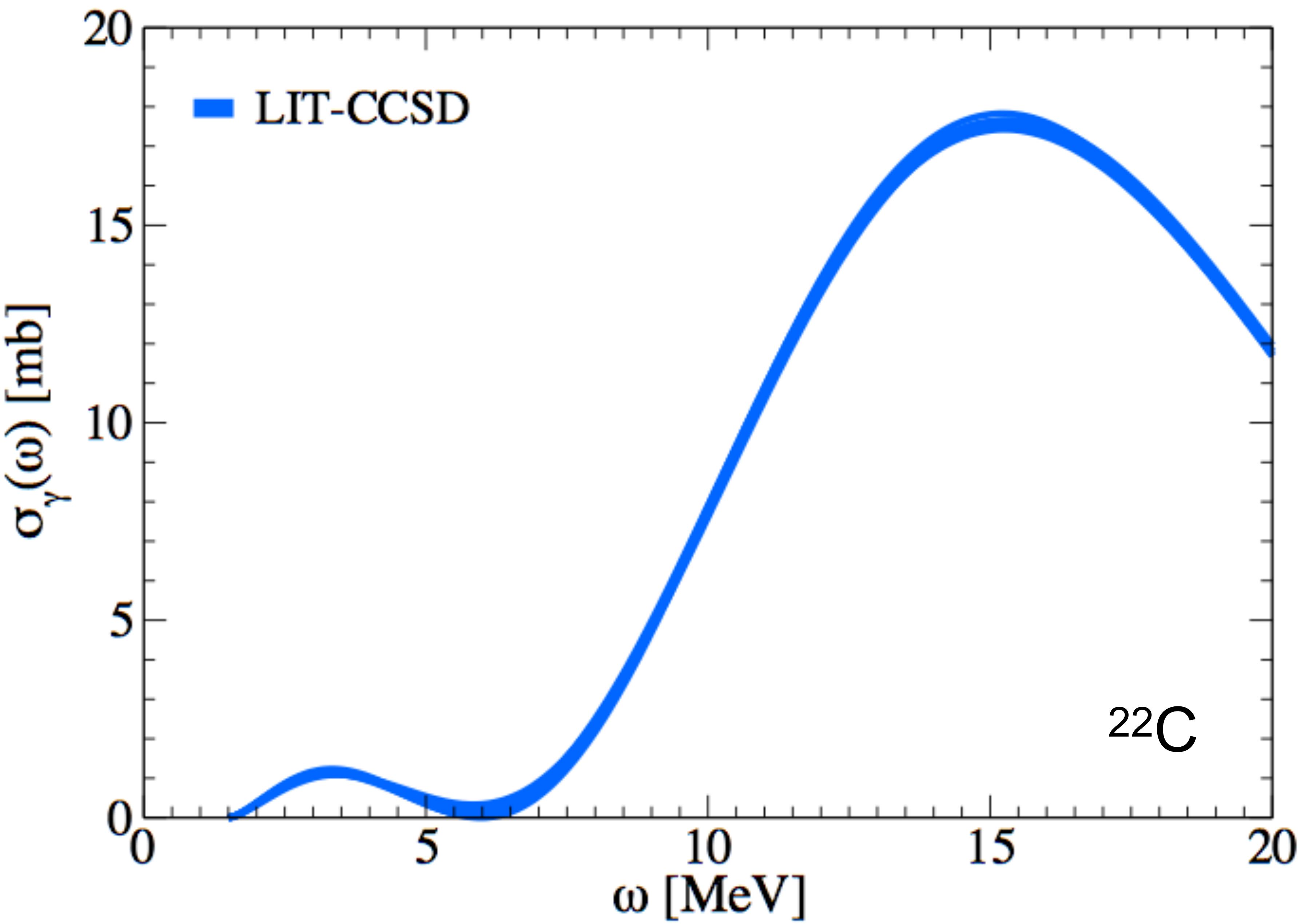
Pigmy Dipole Resonance (PDR)

Nicely described by a first principle calculation

Theory provides a deeper understanding: microscopic interpretation of collective phenomena

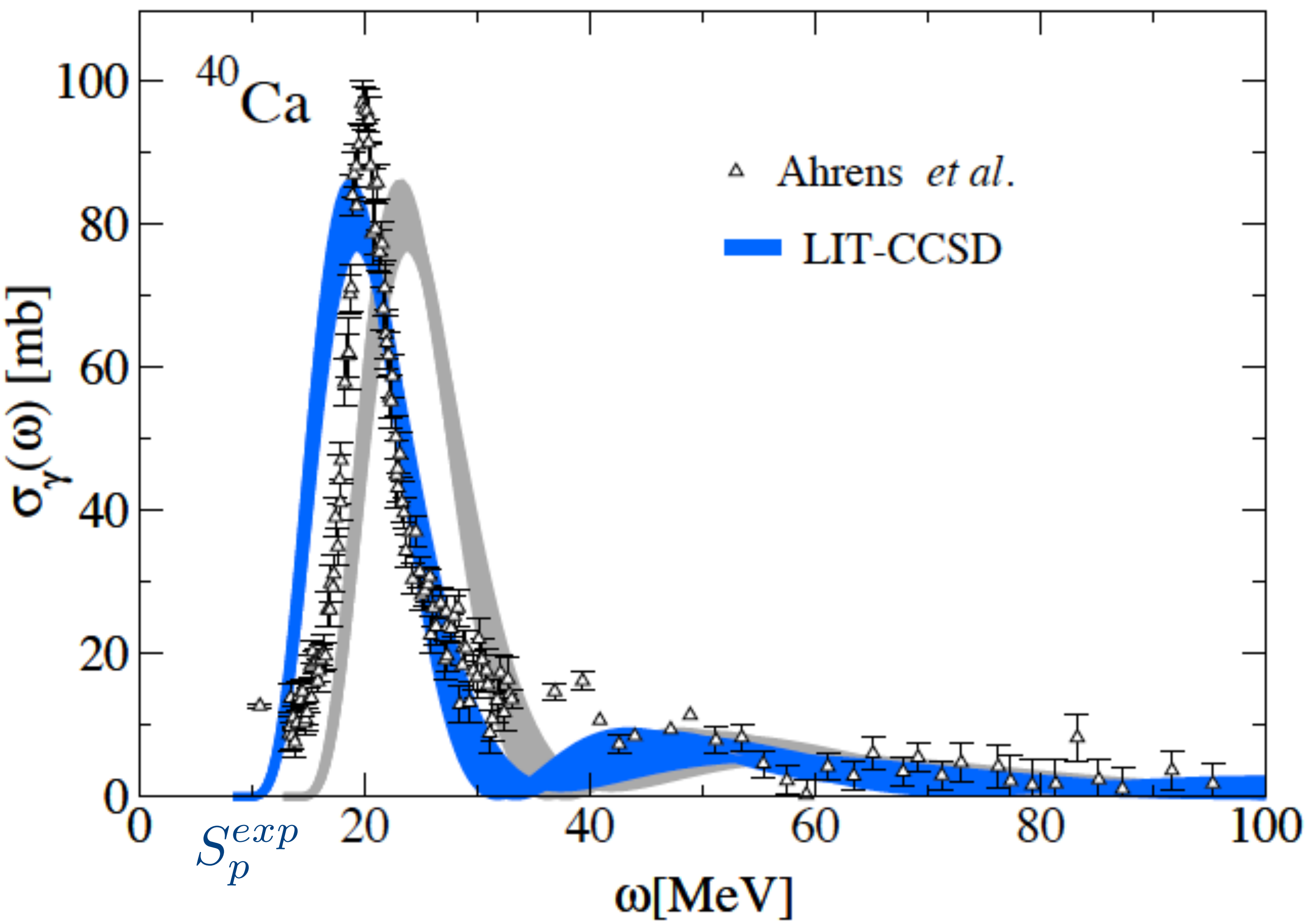
Other preliminary work

M.Miorelli et al.



^{22}C being measured at RIKEN

Photonuclear reactions



Dipole resonance at too high energy related to too small electric Polarizability and too small radii

$$\alpha_D \to \int_0^{E_x} d\omega \; \frac{\sigma_\gamma(\omega)}{\omega^2}$$

$$\alpha_D(\mathrm{Th}) = 1.47 \ \mathrm{fm}^3$$
$$\alpha_D(\mathrm{Exp}) = 2.23(3) \ \mathrm{fm}^3$$

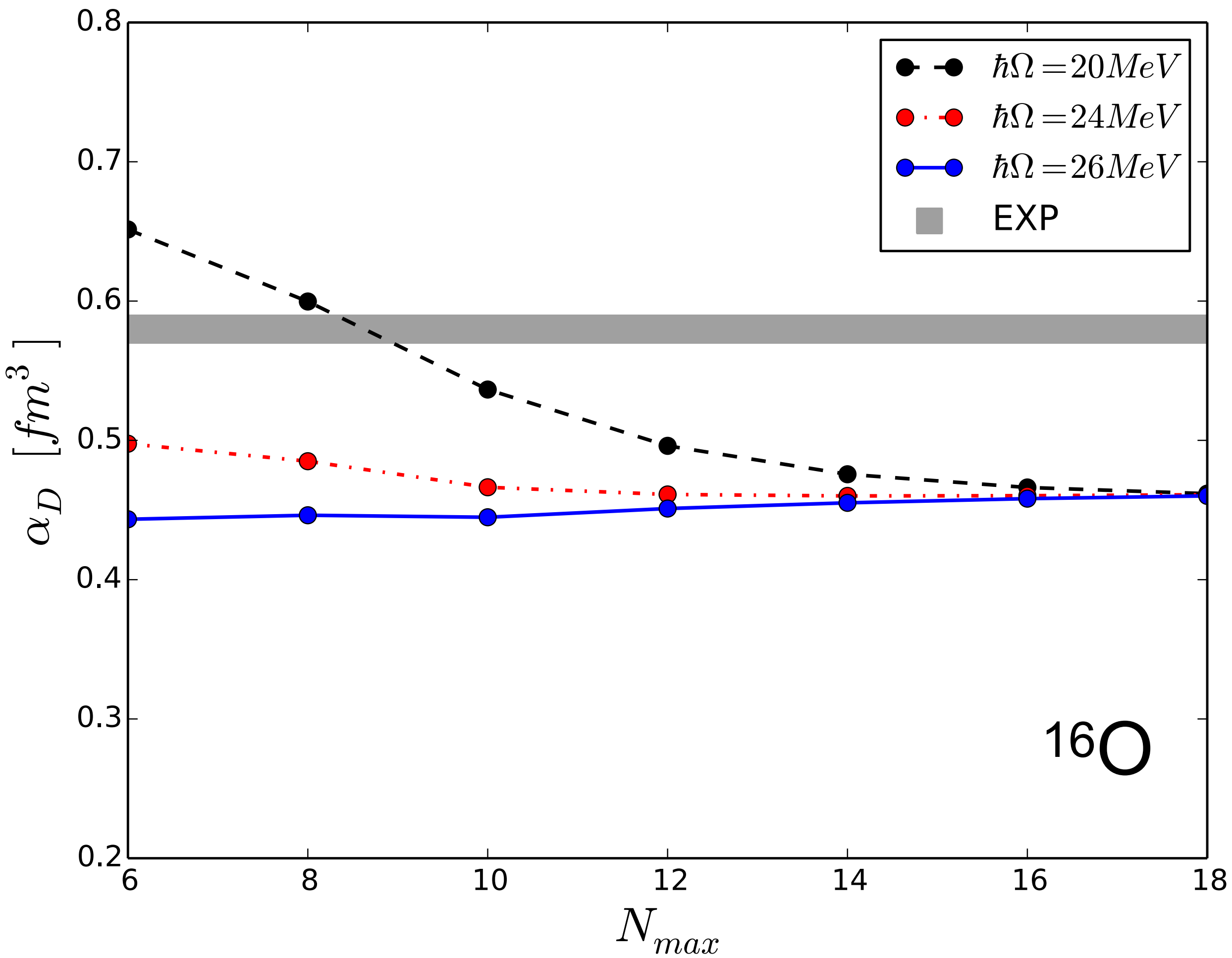
$$R_{\mathrm{ch}}(\mathrm{Th}) = 3.05\mathrm{fm}$$
$$R_{\mathrm{ch}}(\mathrm{Exp}) = 3.48\mathrm{fm}$$

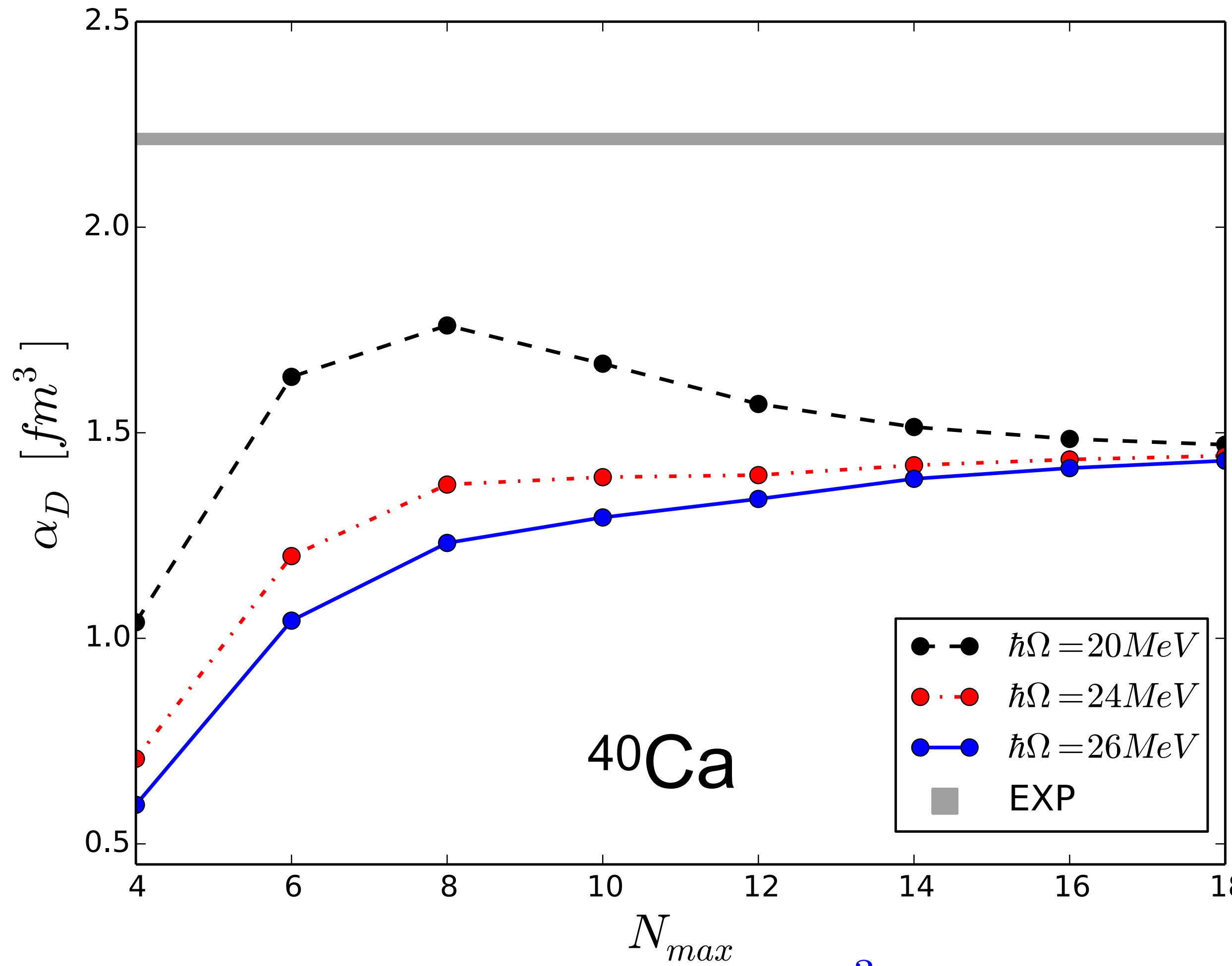
$$E(\mathrm{Th}) = 362\mathrm{MeV}$$
$$E(\mathrm{Exp}) = 342\mathrm{MeV}$$

Radii and binding energies are off the experimental values, as well as dipole polarizability

Electric dipole polarizability

Medium-mass nuclei with NN(N^{3}LO)





$$\alpha_D = 0.46 \text{ fm}^3$$
$$\alpha_D^{exp} = 0.585(9) \text{ fm}^3$$

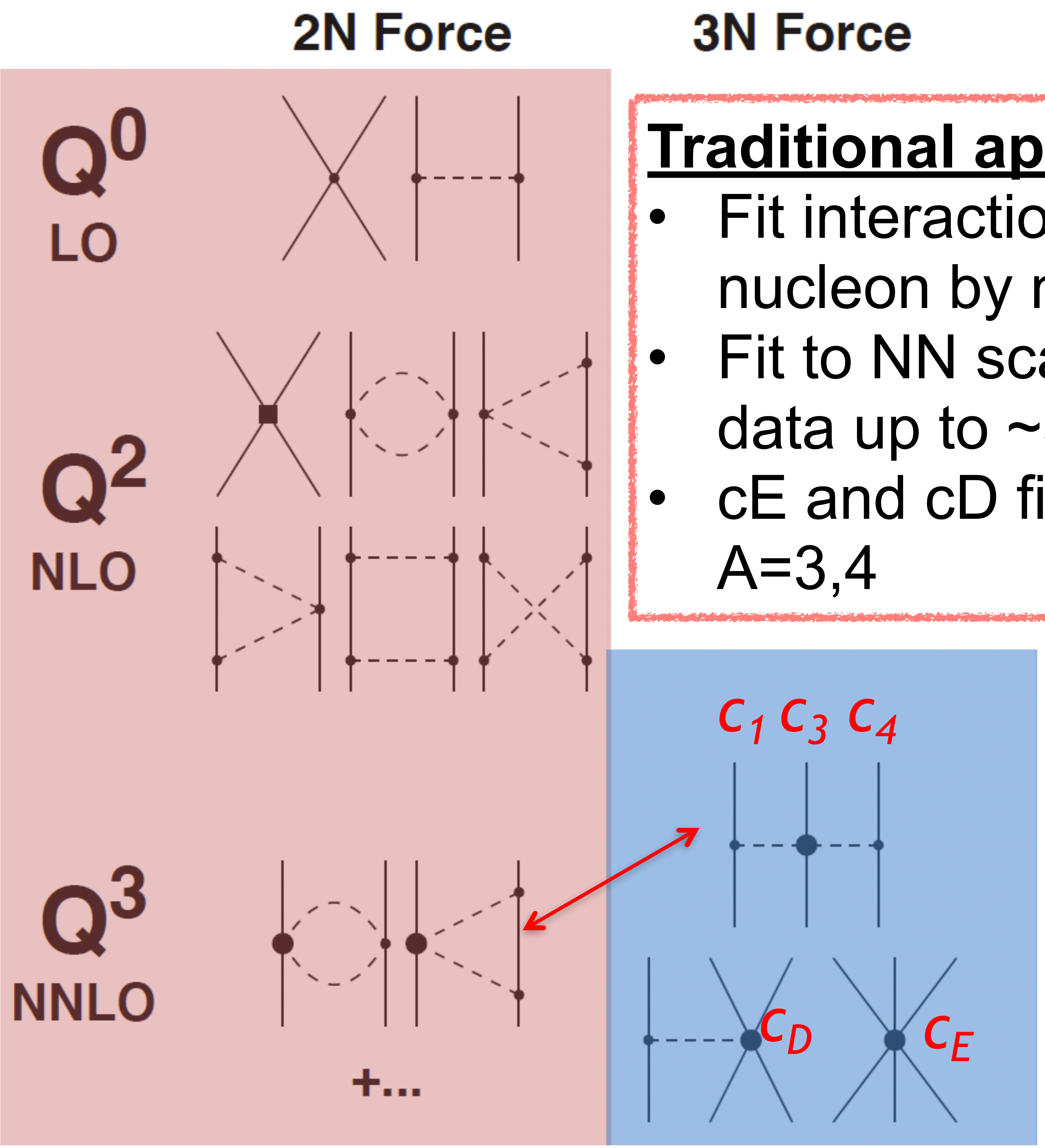
$$R_{ch} = 2.3 \text{ fm}$$
$$R_{ch}^{exp} = 2.6991(52) \text{ fm}$$

$$\alpha_D = 1.47 \text{ fm}^3$$
$$\alpha_D^{exp} = 2.23(3) \text{ fm}^3$$

$$R_{ch} = 3.05 \text{ fm}$$
$$R_{ch}^{exp} = 3.4776(19) \text{ fm}$$

The present Hamiltonian underestimates both radii and electric dipole polarizabilities

What shall we do to solve it?

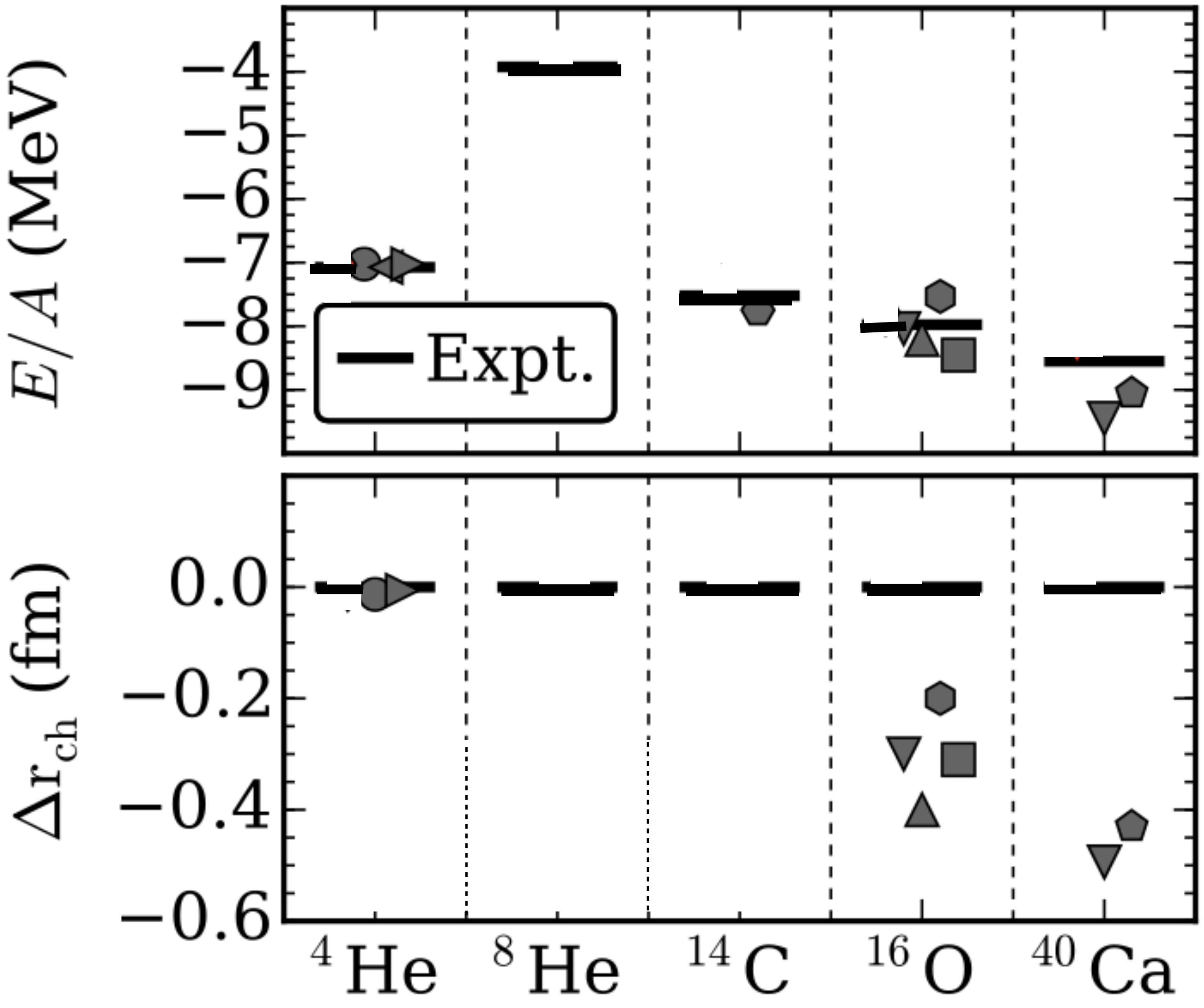


Traditional approach:

- Fit interactions nucleon by nucleon
- Fit to NN scattering data up to ~350MeV
- cE and cD fit to A=3,4

Add three-nucleon forces

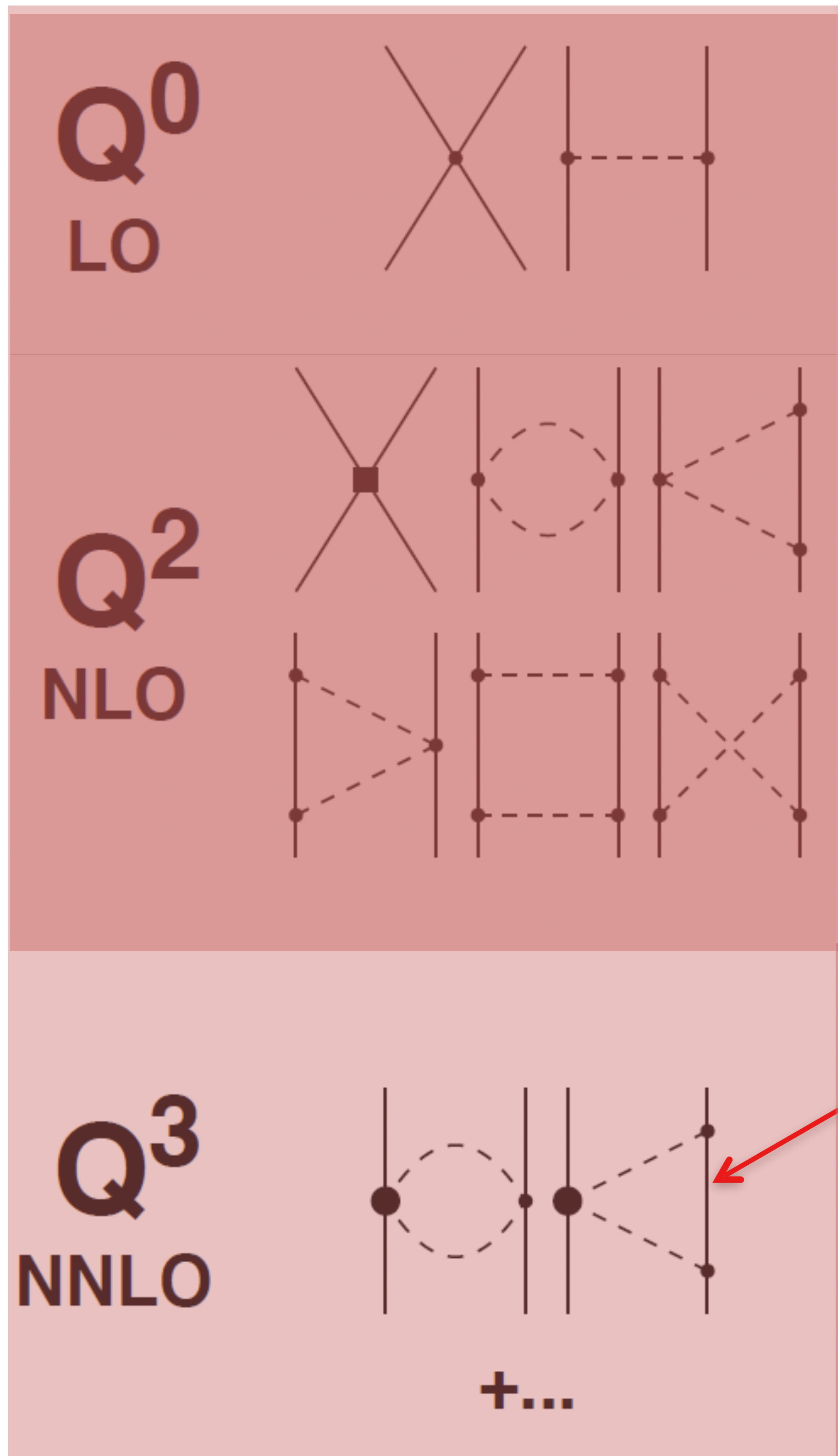
That does not always work



Alternative strategy

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

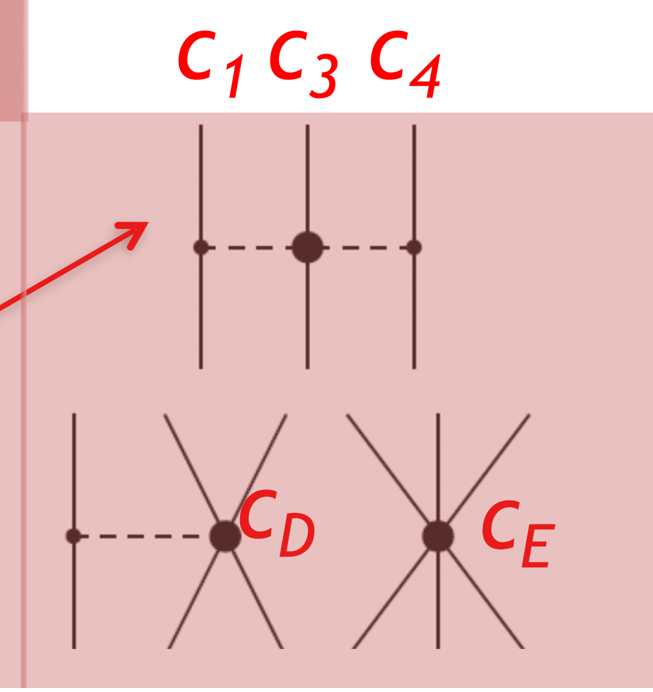
2N Force **3N Force**



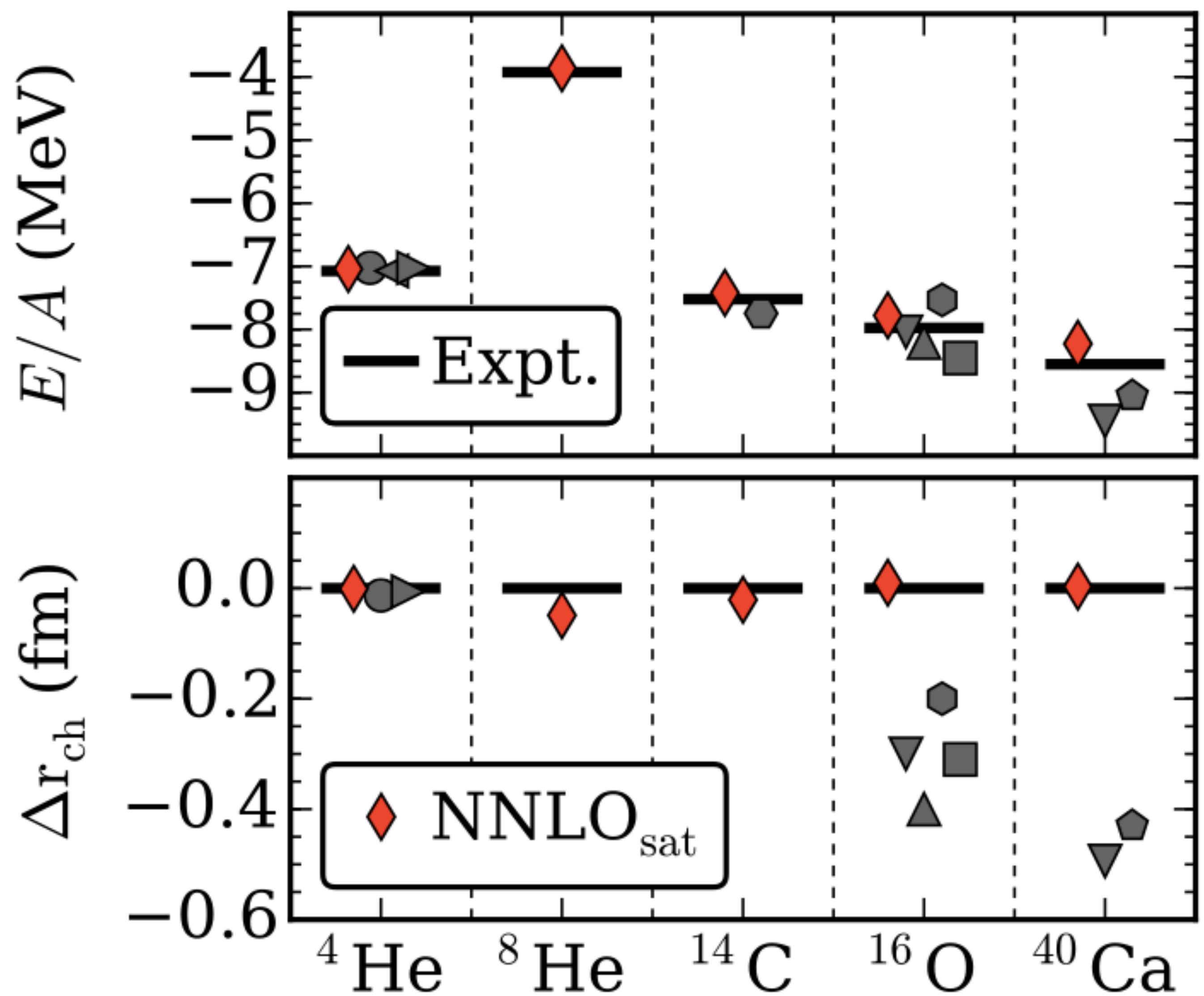
Alternative approach:

- Simultaneous optimization of NN and 3NFs
- Fit to few-body data and BEs/ radii in nuclei with $A \sim 25$

$\mathbf{N2LO_{sat}}$



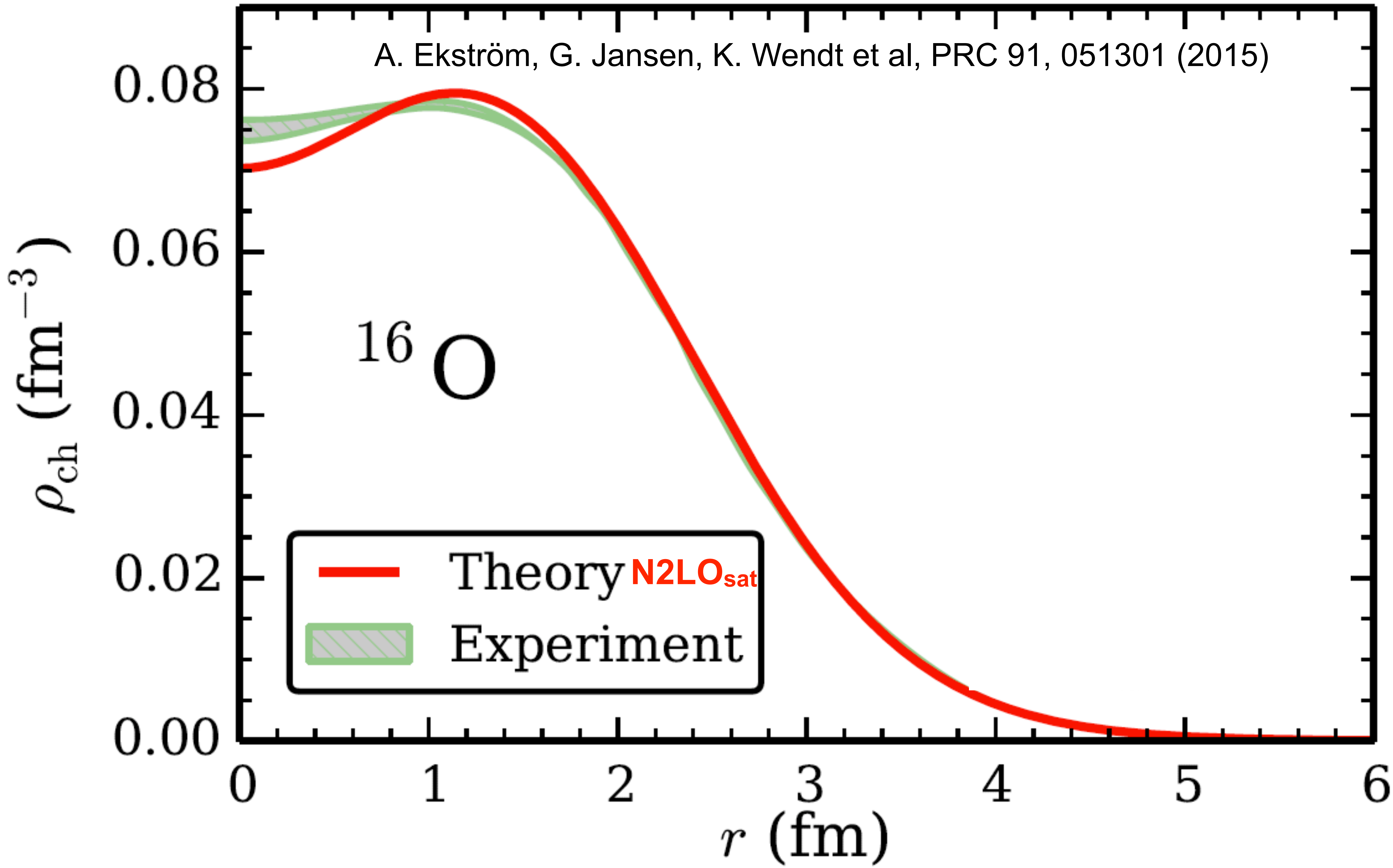
Fixes the radii



Include radii in the fit of LEC for the three-body force

^{40}Ca is a pure prediction

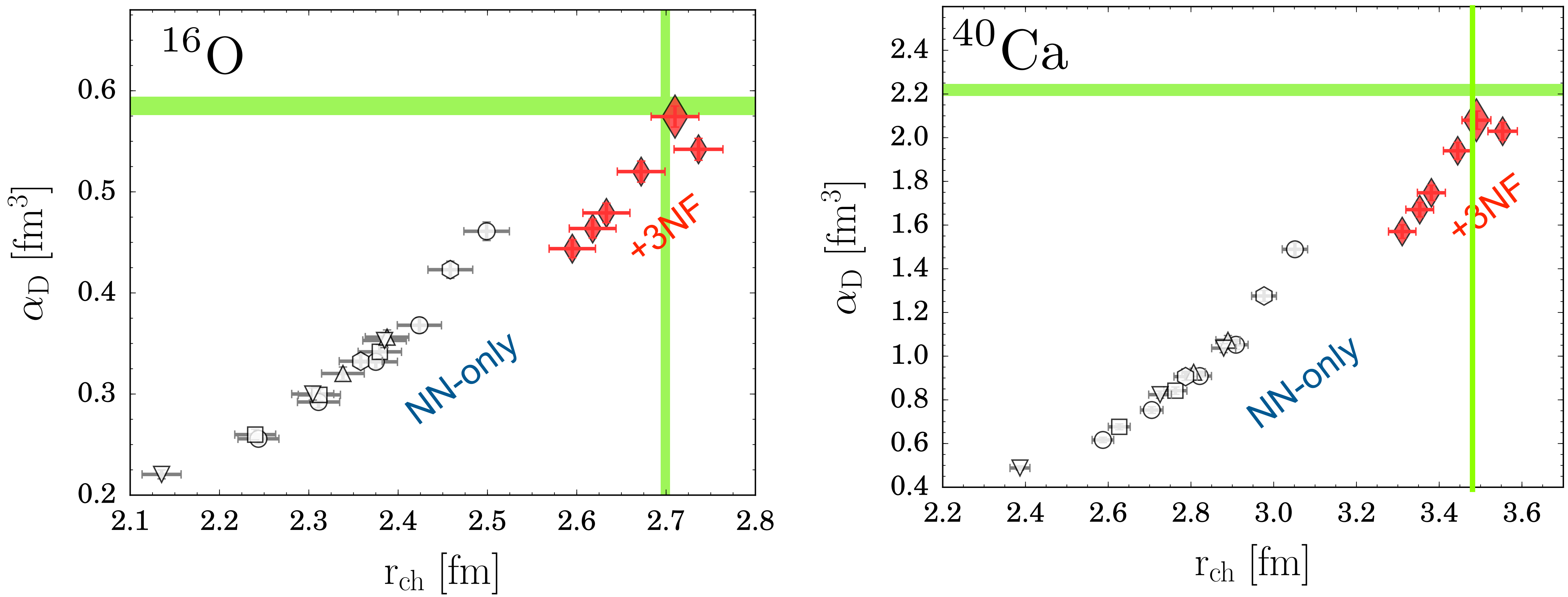
Charge density of ^{16}O



Electric Dipole Polarizabilty

Medium-mass nuclei with NN + 3NF interactions

M. Miorelli *et al.*, PRC **94** 034317 (2016)



3NF A. Ekström *et al.*, Phys. Rev. C91, 051301 (2015)

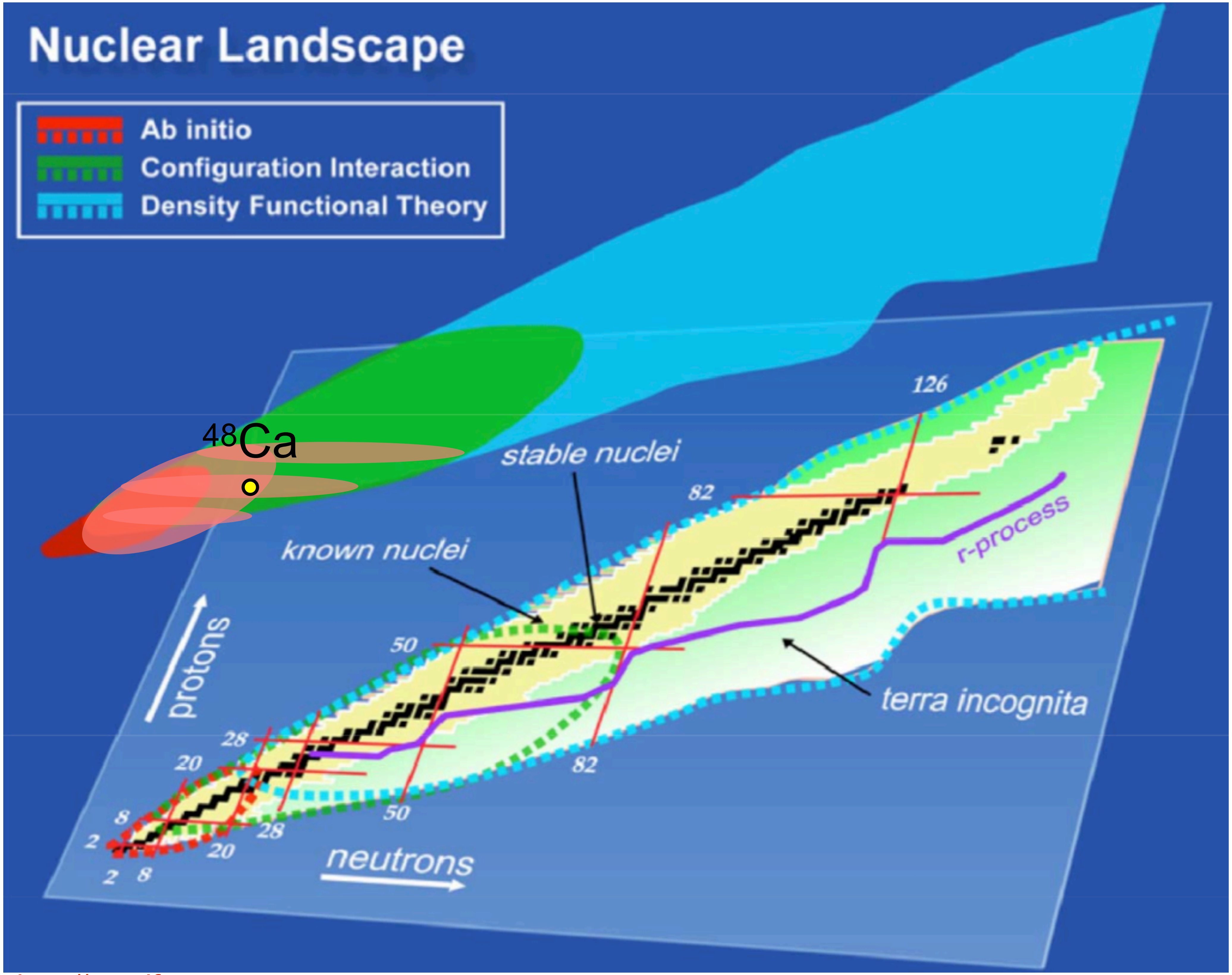
K. Hebeler *et al.*, Phys. Rev. C83, 031301 (2011)

Much better agreement with experimental data

Variation of Hamiltonian can be used to assess the theoretical error bar

What about heavier systems?

^{48}Ca as meeting point *for theory*



http://unedf.org

^{48}Ca as meeting point *for exp*

While neutron-rich, for all practical purposes it can be considered a stable nucleus

- (p,p') scattering to extract the electric dipole polarizability at RCNP, Japan

  α_D is related to the symmetry energy in the EOS of nuclear matter

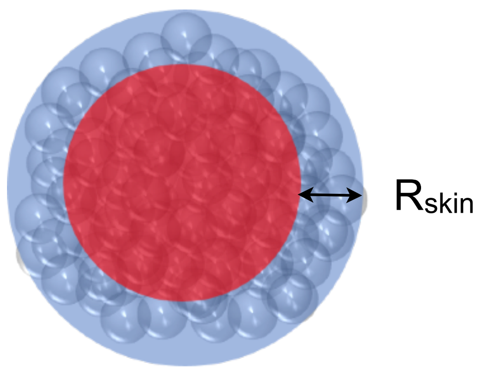
- Parity violation electron scattering Calcium Radius Experiment (CREX) at JLab and the Mainz Radius Experiment (MREX) at MAMI/MESA to measure R_{skin}

$$A_{pv} = \frac{d\sigma/d\Omega_R - d\sigma/d\Omega_L}{d\sigma/d\Omega_R + d\sigma/d\Omega_L} \approx -\frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(q^2)}{Z F_{ch}(q^2)}$$

The weak force probes the neutron distribution

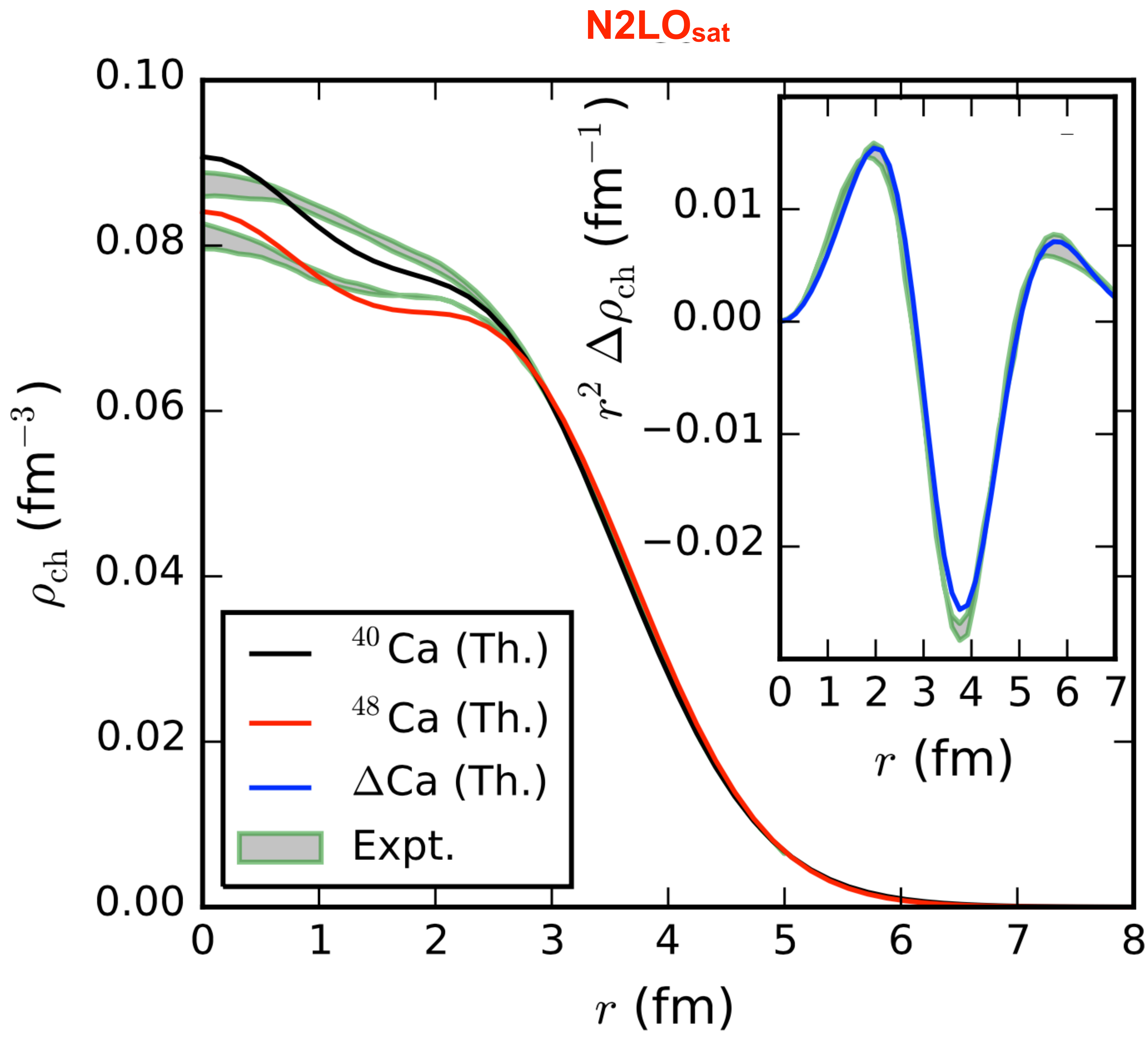
$$Q_W^n \approx -1$$

$$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$$



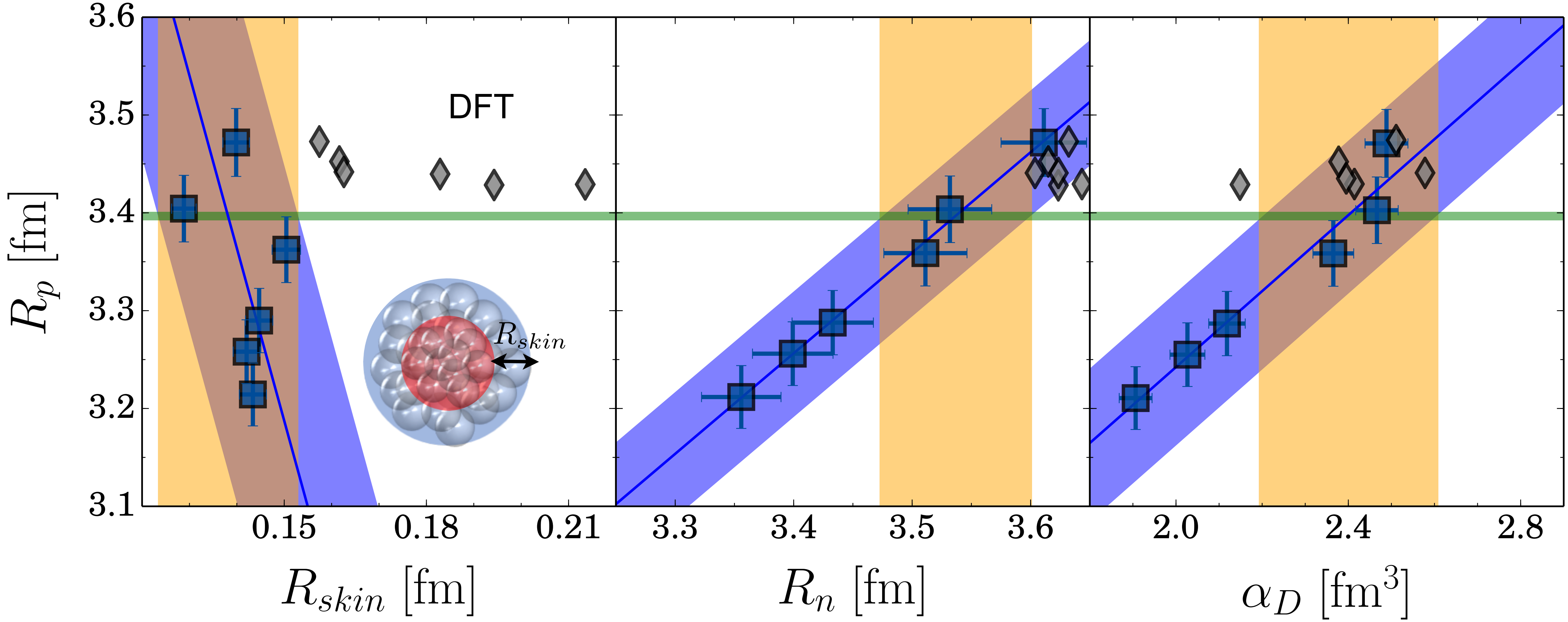
Can we give a first principle predictions for these future experiments?

Charge density of ^{48}Ca



^{48}Ca from first principles

International collaboration (USA/Canada/Europe/Israel) using coupled-cluster theory
Hagen *et al.*, Nature Physics **12**, 186 (2016)



■ Ab initio with three nucleon forces from chiral EFT

Strong correlations with R_p allow to put narrow constraints to R_{skin} and α_D

Ab-initio predictions:

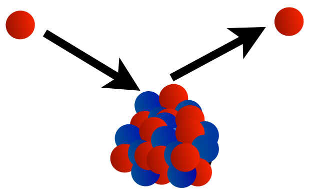
$$0.12 \leq R_{\text{skin}} \leq 0.15 \text{ fm}$$

$$2.19 \leq \alpha_D \leq 2.60 \text{ fm}^3$$

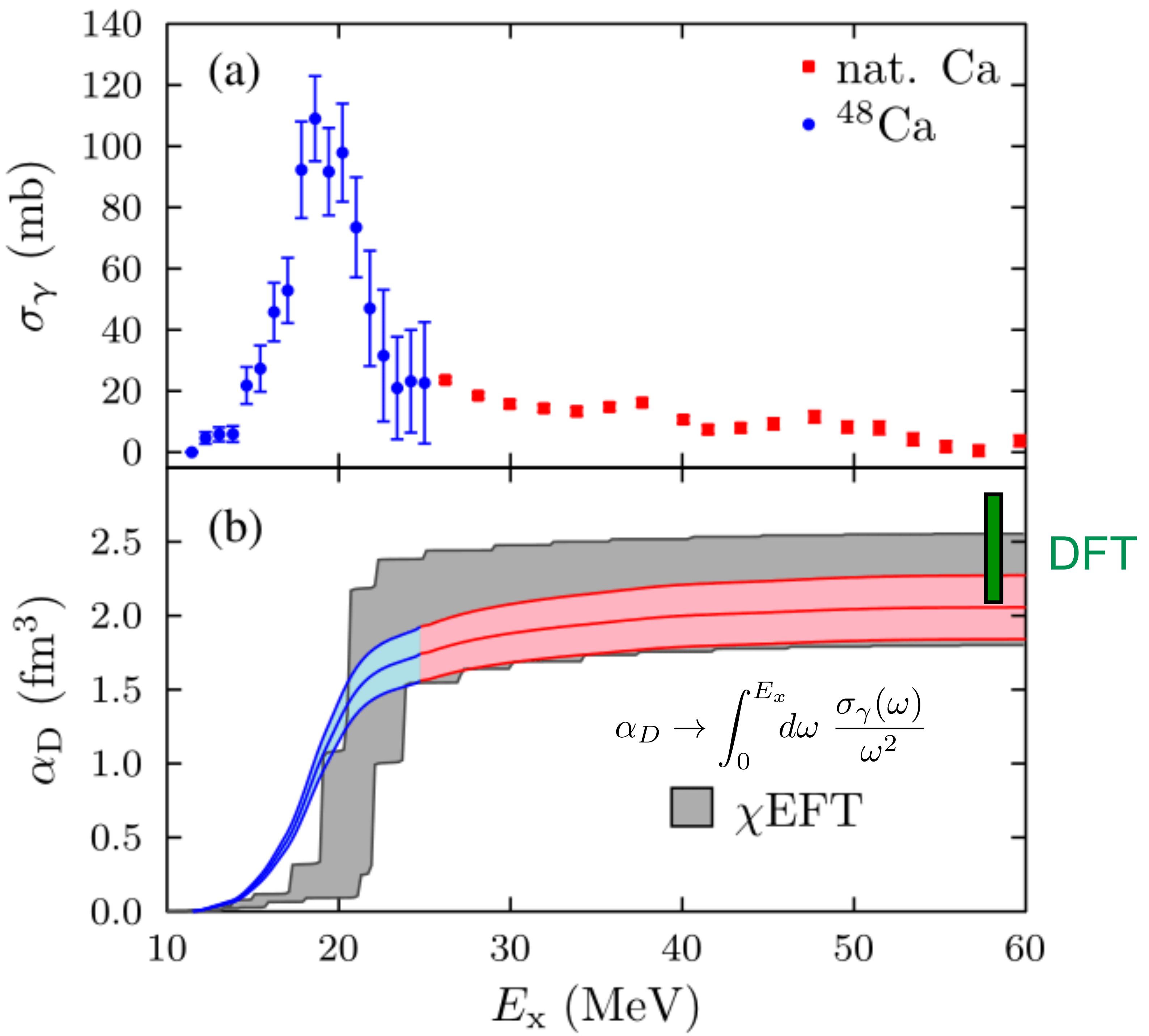
R_{skin} will be measured with Parity violating electron scattering CREX MREX

^{48}Ca electric dipole polarizability

New measurements from the Osaka-Darmstadt collaboration using inelastic proton scattering



J.Birkhan, *et al.*, Phys. Rev. Lett. **118,** 252501 (2017)



How to improve our tools

S.B. *et al.*, PRL **111**, 122502 (2013)

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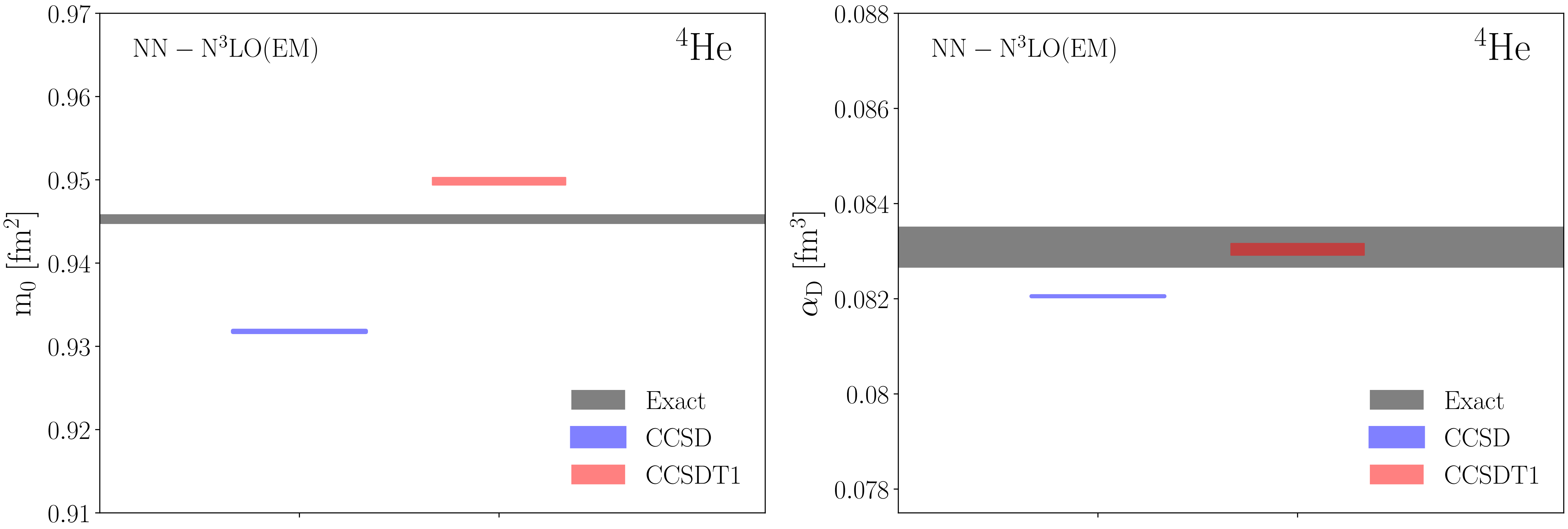
$$(\bar{H} - z^*)|\tilde{\Psi}_R(z^*)\rangle = \bar{\Theta}|\Phi_0\rangle$$

The first implementation we provided is based on the CCSD approximation scheme

Look at triples corrections

How to improve our tools

M. Miorelli *et al.*, in preparation (2017)



CCSD scheme

$$e^T = e^{T_1 + T_2}$$

$$R = R_0 + R_1 + R_2$$

CCSDT1 scheme
(linearized triples)

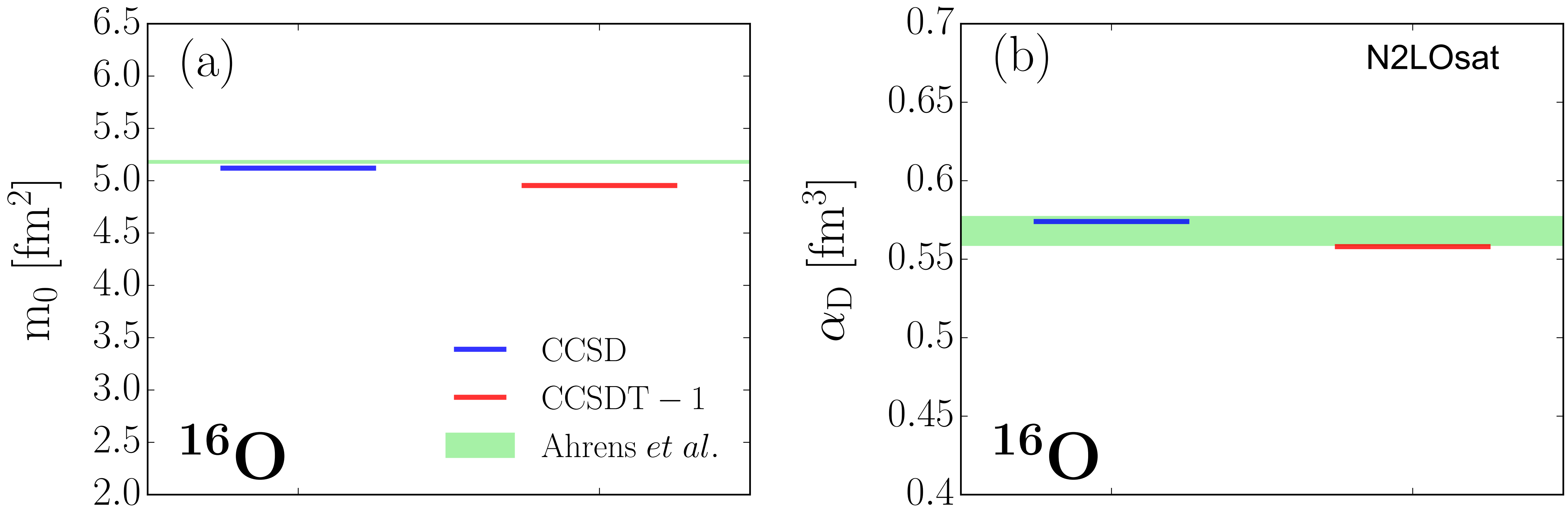
$$e^T = e^{T_1 + T_2} + T_3$$

$$R = R_0 + R_1 + R_2 + R_3$$

Exact ⇒ hyperspherical harmonics, all correlations included (up to quadruples)

How to improve our calculations

M. Miorelli *et al.*, in preparation (2017)



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What's next

More on experimental techniques from *Christopher Lehr and Philipp Ries*

More on theoretical techniques from *Johannes Simonis*