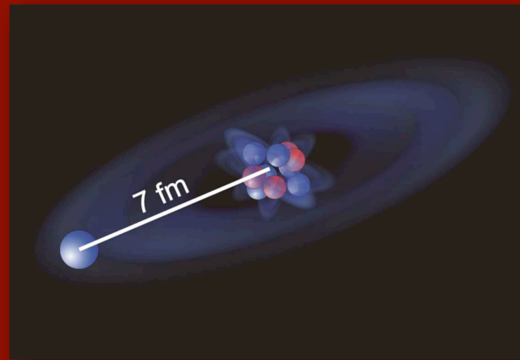
Electromagnetic strengths in ab-initio approaches

Sonia Bacca | TRIUMF

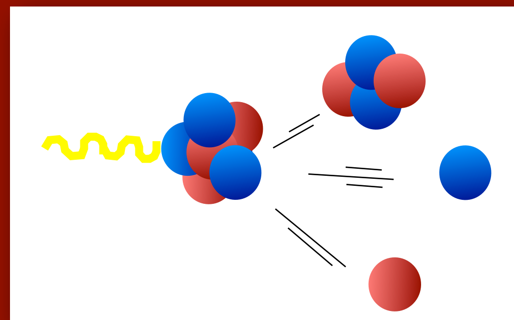
The 5th international conference on
"COLLECTIVE MOTION IN NUCLEI UNDER EXTREME CONDITIONS"
COMEX5

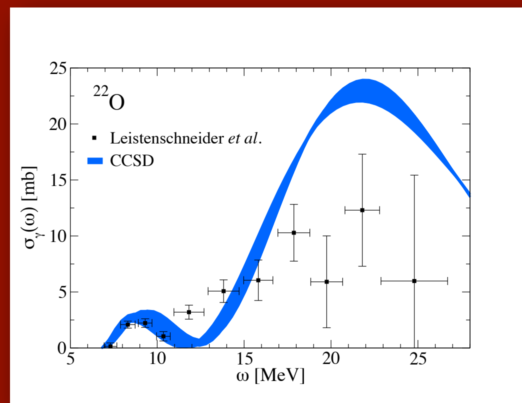
National Research Council Canada

NSERC CRSNG



Nuclear Halo


Electromagnetic Reactions

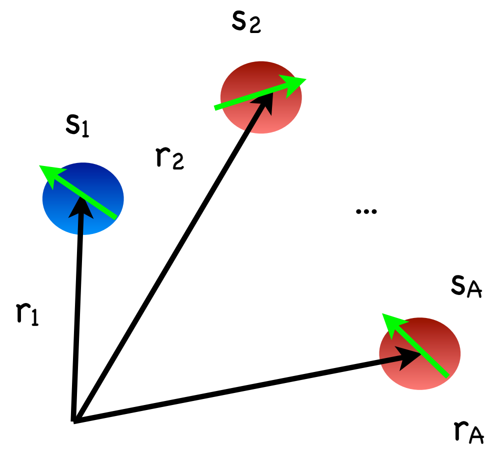


Pigmy Resonance

"Ab-initio" methods

- Start from neutrons and protons as building blocks (centre of mass coordinates, spins, isospins)

- Solve the non-relativistic quantum mechanical problem of A-interacting nucleons



$$H|\psi_i\rangle = E_i|\psi_i\rangle$$

$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \dots$$

- Find numerical solutions with no approximations or controllable approximations (error bars)

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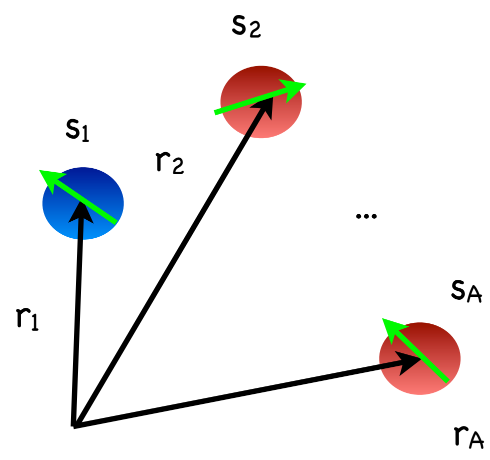

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- Calculate low-energy observables and compare with experiment to test nuclear forces and provide predictions for future experiments or quantity that cannot be measured

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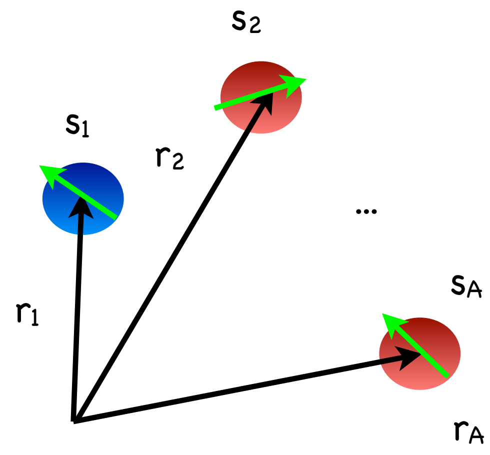

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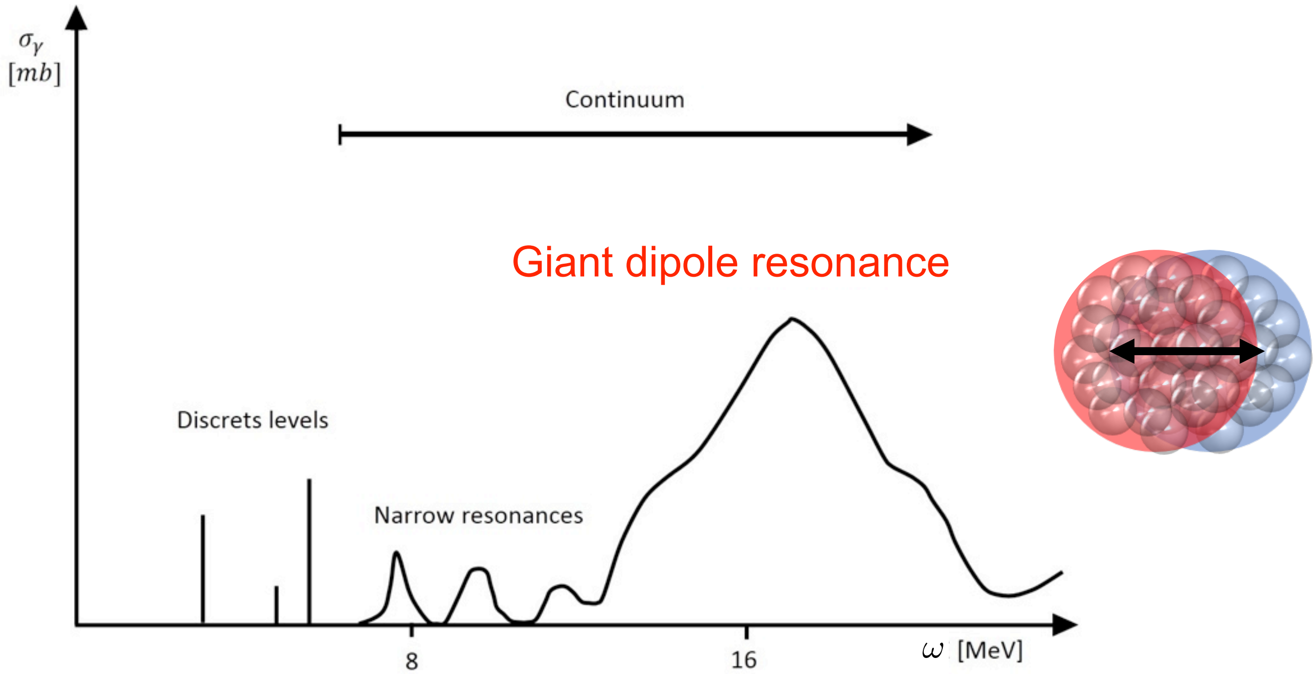
Observables

Dipole strength functions



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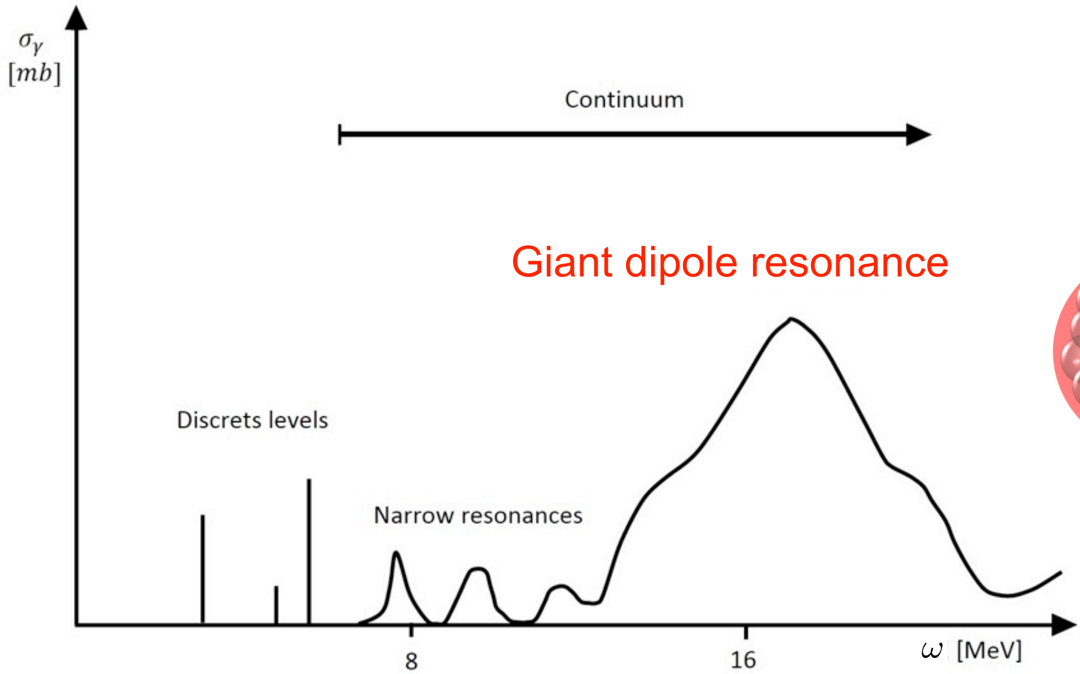

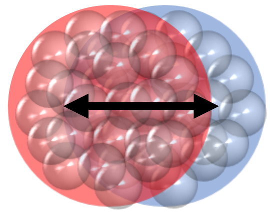

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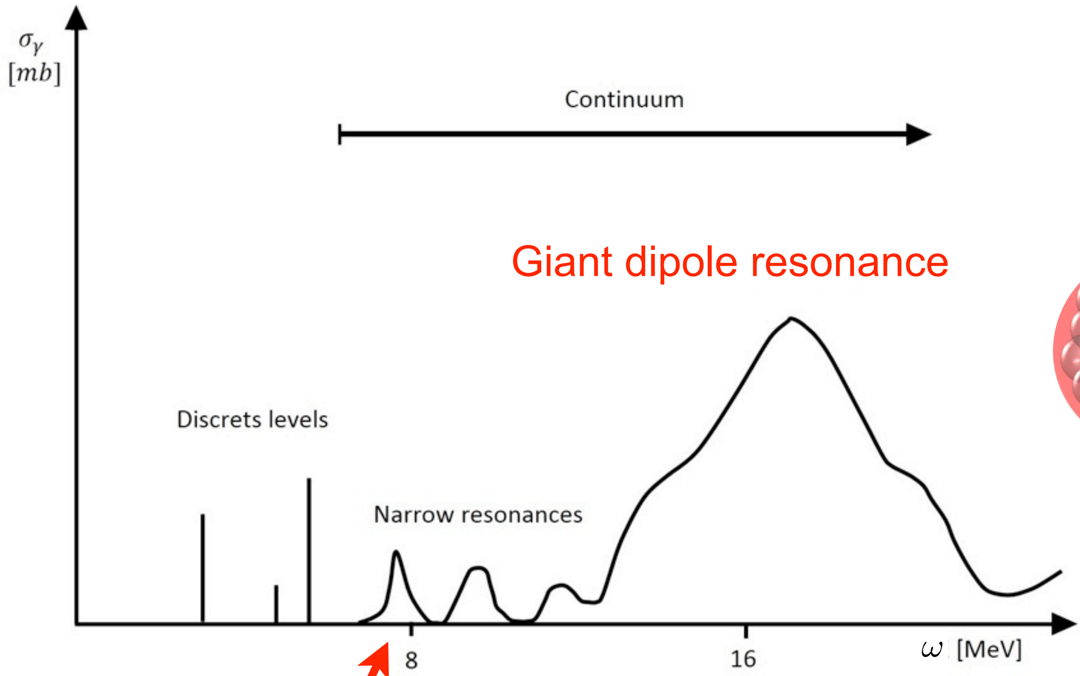
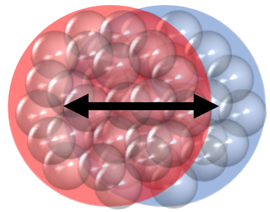
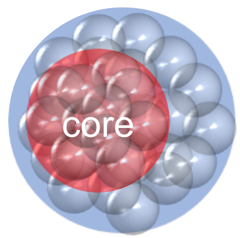


Giant dipole resonance

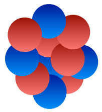


Pigmy dipole resonance in neutron-rich nuclei



Observables

Electric dipole polarizability



A

Observables

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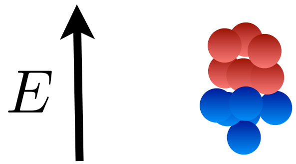


A*

$$D = \alpha_D E$$

$$\alpha_D = 2\alpha \int_{\omega_{th}}^{\infty} d\omega \frac{\overset{D}{R}(\omega)}{\omega}$$

Low-energy part of response dominates

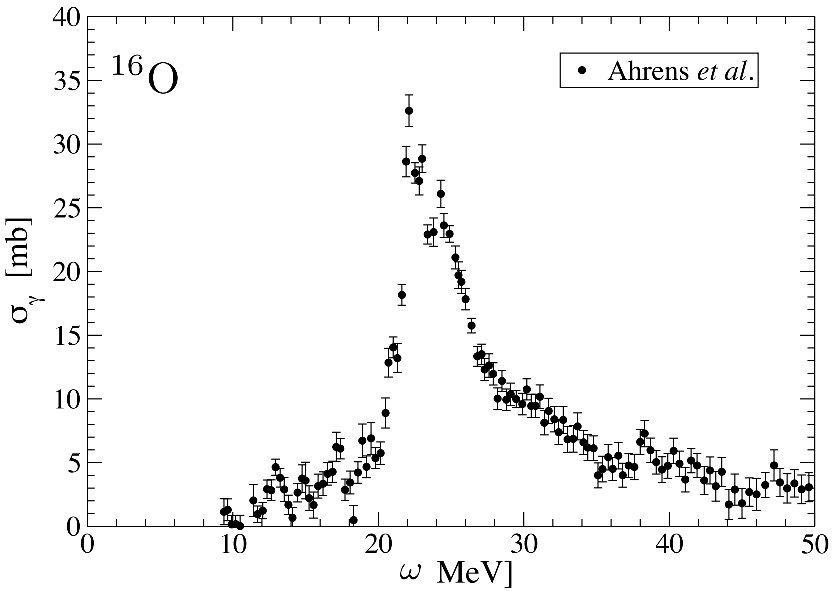
Very interesting for neutron-rich nuclei:

soft modes at low energy enhance the polarizability

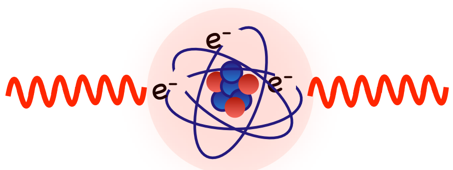
Experimental status

Stable Nuclei

We have data on ~180 stable nuclei
Giant dipole resonances

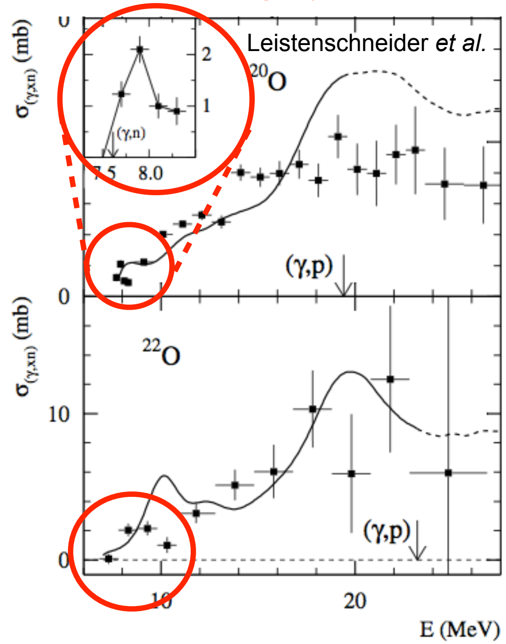


From photoabsorption experiments



Unstable Nuclei

Fewer data, pigmy dipole resonances



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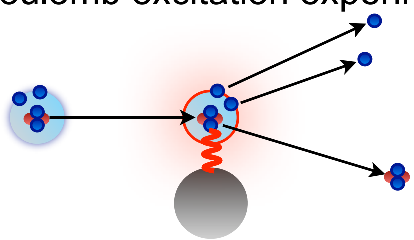

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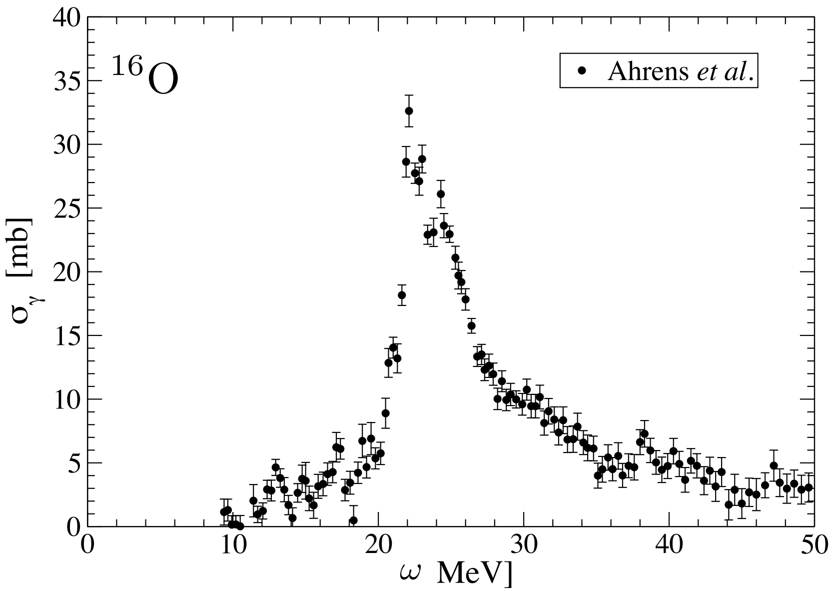

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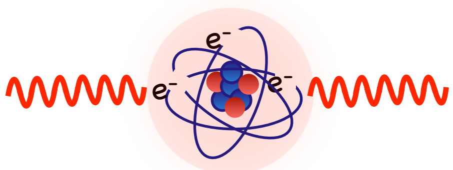

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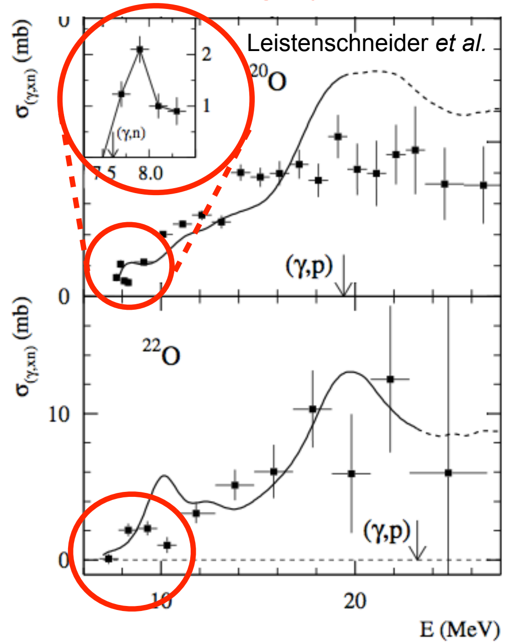

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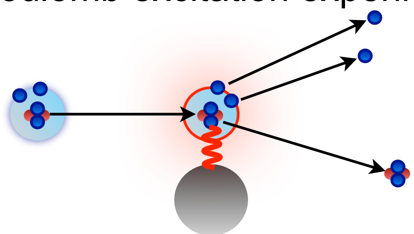

Do we see the emergence of collective motions from first principle calculations?

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^{48}Ca - an interesting case

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

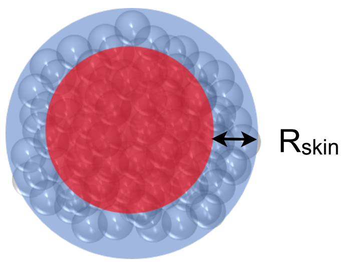
- Parity violation electron scattering Calcium Radius Experiment (CREX) at JLab to measure R_{skin}

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

The weak force probes the neutron distribution

$$Q_W^n \approx -1$$

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



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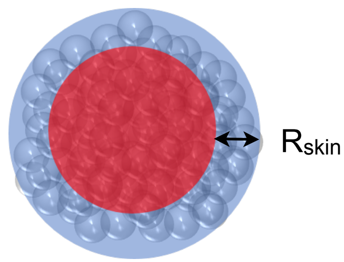

Can we give a first principle predictions for these future experiments?

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Theoretical Status

- These observables on medium and heavy nuclei have been the subject of intense theoretical studies within density functional theory, shell model, etc...

- Not much has been done with ab-initio methods and we want to fill this gap!

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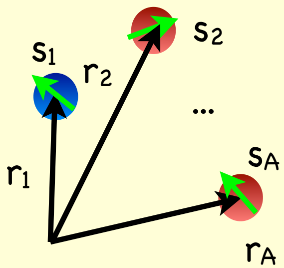
Electromagnetic Reactions on Light Nuclei
S. Bacca and S. Pastore
J. Phys. G: Nucl. Part. Phys. **41** 123002 (2014).

Ab-initio Approach



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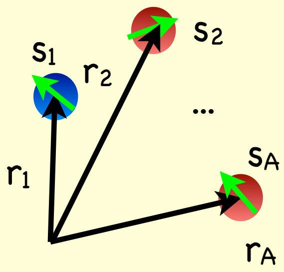

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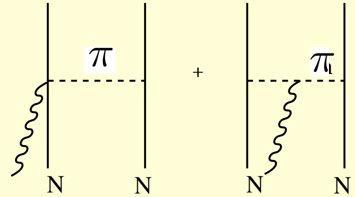

two-body currents (or MEC)

subnuclear d.o.f.

J^μ consistent with V

$$\nabla \cdot J = -i[V, \rho]$$

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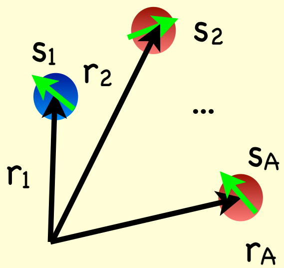

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Chiral Effective Field Theory

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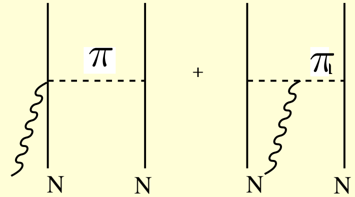

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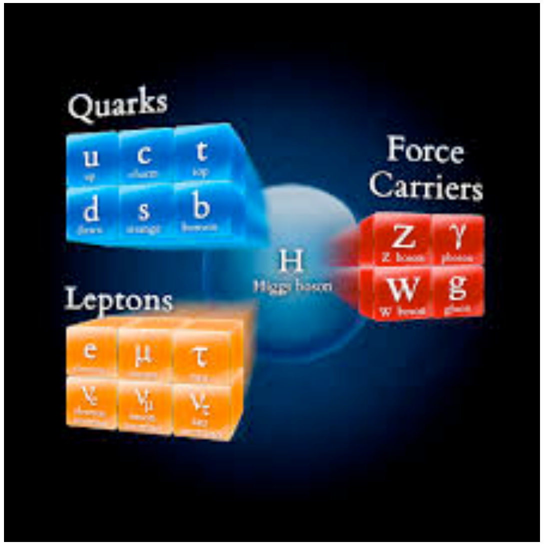
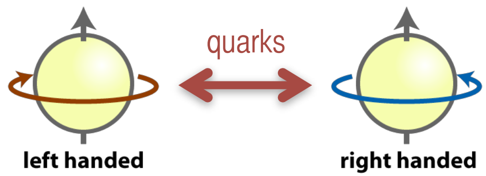


Quark/gluon (high energy) dynamics

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \bar{q}_L i \gamma_\mu D^\mu q_L + \bar{q}_R i \gamma_\mu D^\mu q_R - \bar{q} \mathcal{M} q$$

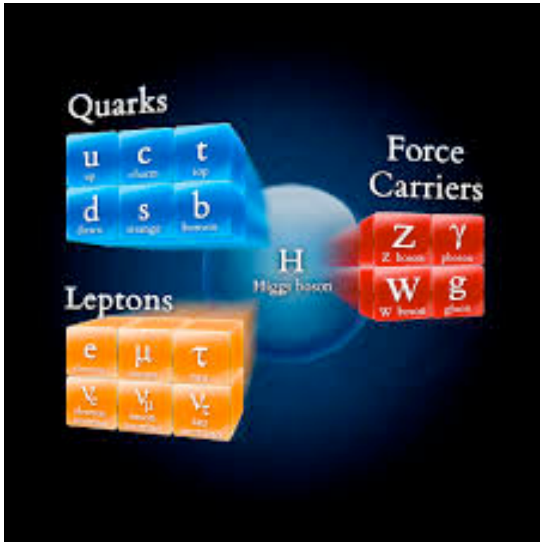
In the limit of vanishing quark masses the QCD Lagrangian is invariant under chiral symmetry

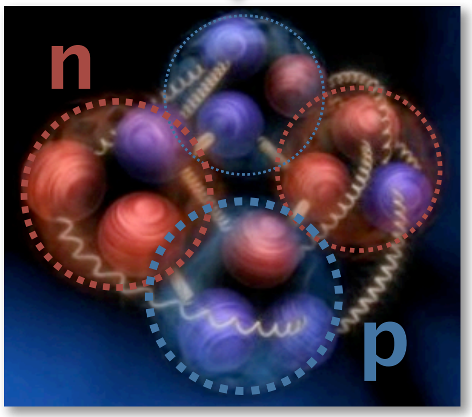
QCD chiral symmetry



Chiral symmetry is explicit and spontaneous broken

Chiral Effective Field Theory





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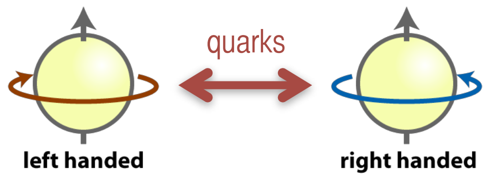


Chiral symmetry is explicit and spontaneous broken

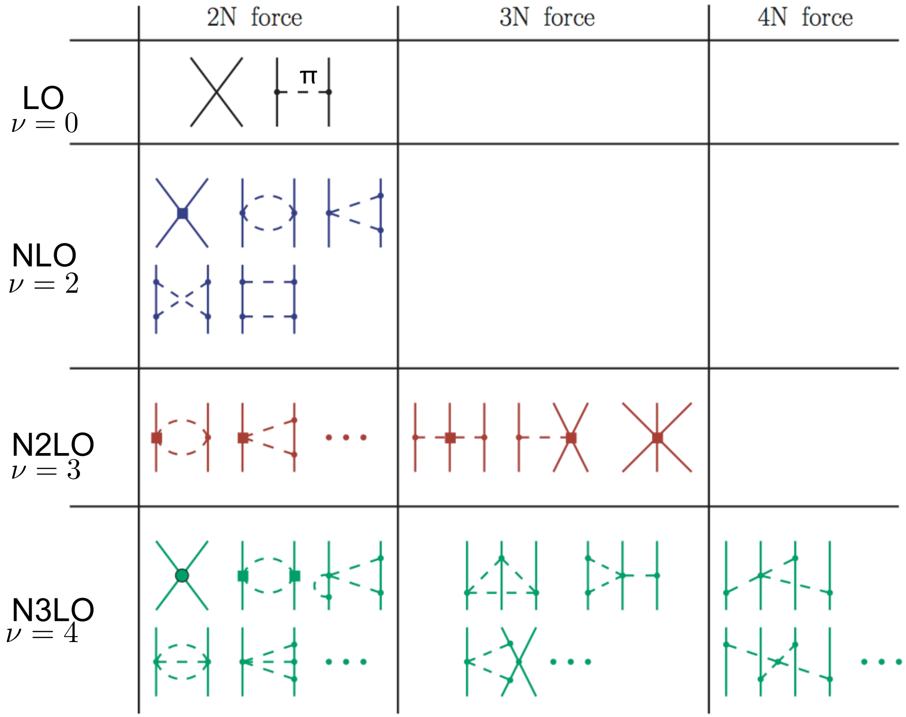
Nucleon/pion (low energy) dynamics

$$\mathcal{L}_{eff} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \dots$$

Compatible with explicit and spontaneous **chiral symmetry breaking**

Chiral Effective Field Theory

Systematic expansion $\mathcal{L} = \sum_{\nu} c_{\nu} \left(\frac{Q}{\Lambda_b} \right)^{\nu}$



Details of short distance physics not resolved, but captured in low energy constants (LEC)

TRIUMF

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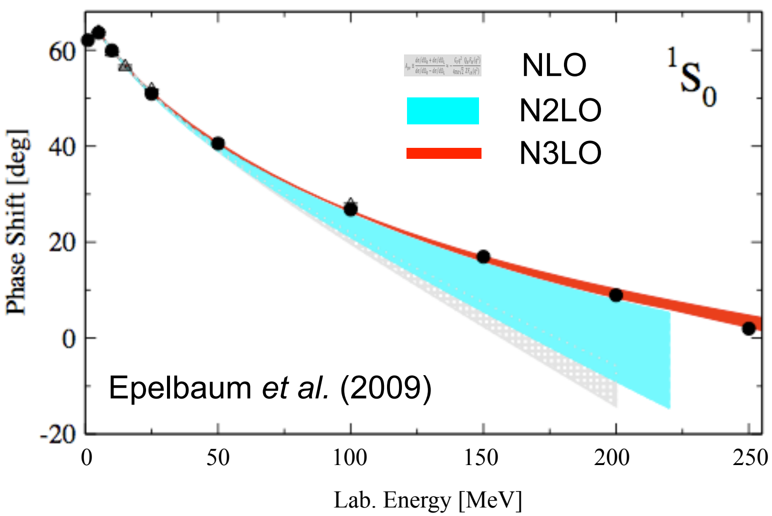
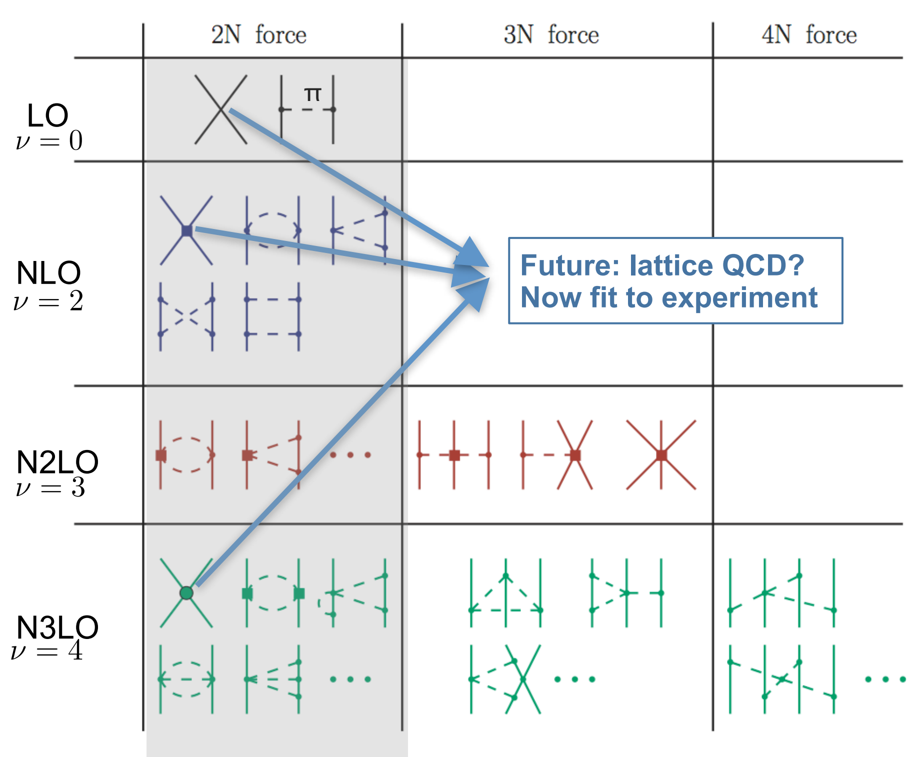
LEC fit to experiment - NN sector -





Traditional Paradigm:
(i) Fit NN on scattering data first

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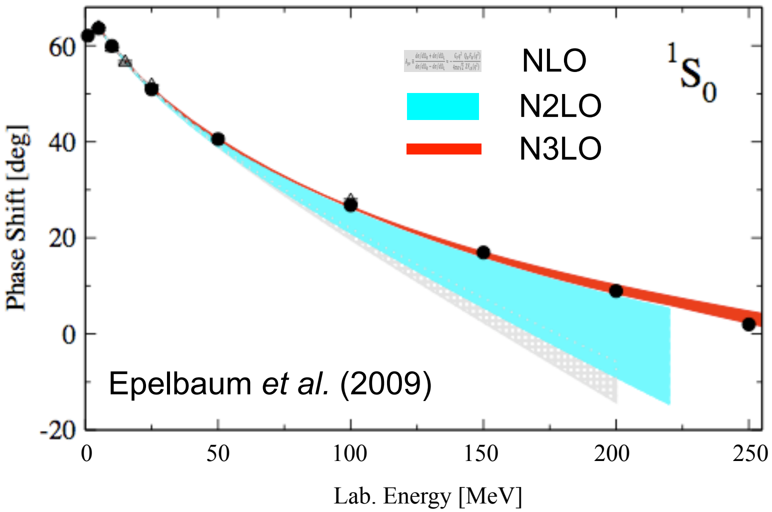
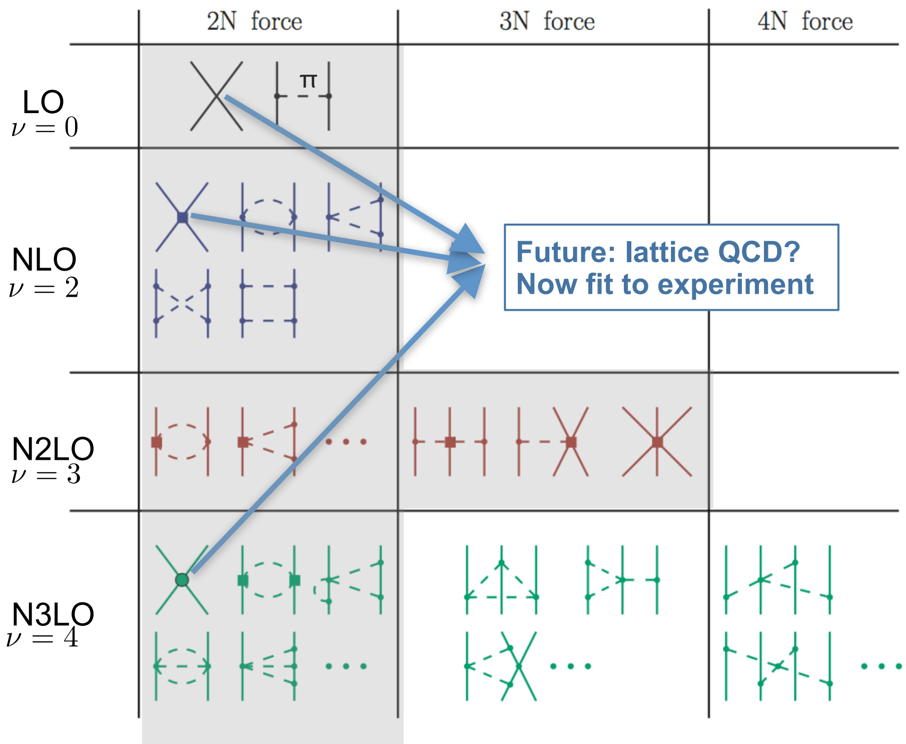
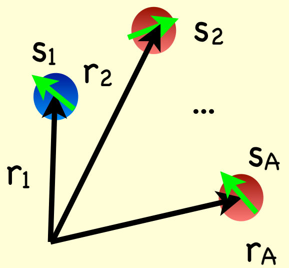




Traditional Paradigm:
(i) Fit NN on scattering data first
(ii) add 3N forces fitting on $^3H/^3He$

Ab-initio Approach



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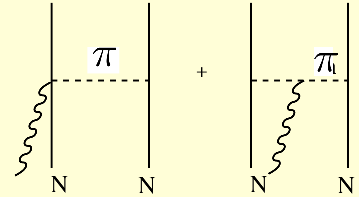

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$$\sigma \propto \left|\langle \Psi_f | J^\mu | \Psi_0 \rangle\right|^2$$

Need many-body continuum effects

TRIUMF

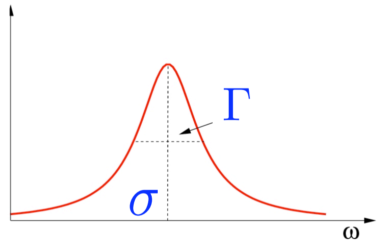
Lorentz Integral Transform Method

Efros, *et al.*, JPG.: Nucl.Part.Phys. **34** (2007) R459

Reduce the continuum problem to a bound-state problem

$$R(\omega) = \sum_f \left| \left\langle \psi_f \middle| J^\mu \middle| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2 + \Gamma^2} = \left\langle \tilde{\psi} | \tilde{\psi} \right\rangle < \infty$$



where $\left|\tilde{\psi}\right\rangle$ is obtained solving

$$\boxed{(H - E_0 - \sigma + i\Gamma)|\tilde{\Psi}\rangle = J^\mu |\Psi_0\rangle}$$

- Due to imaginary part Γ the solution $\left|\tilde{\psi}\right\rangle$ is unique
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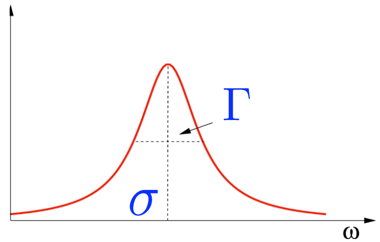

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$$L(\sigma, \Gamma) \xrightarrow{\text{inversion}} R(\omega)$$

The exact final state interaction (FSI) is included in the continuum rigorously!

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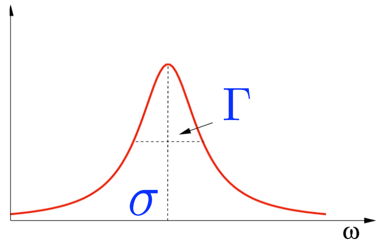

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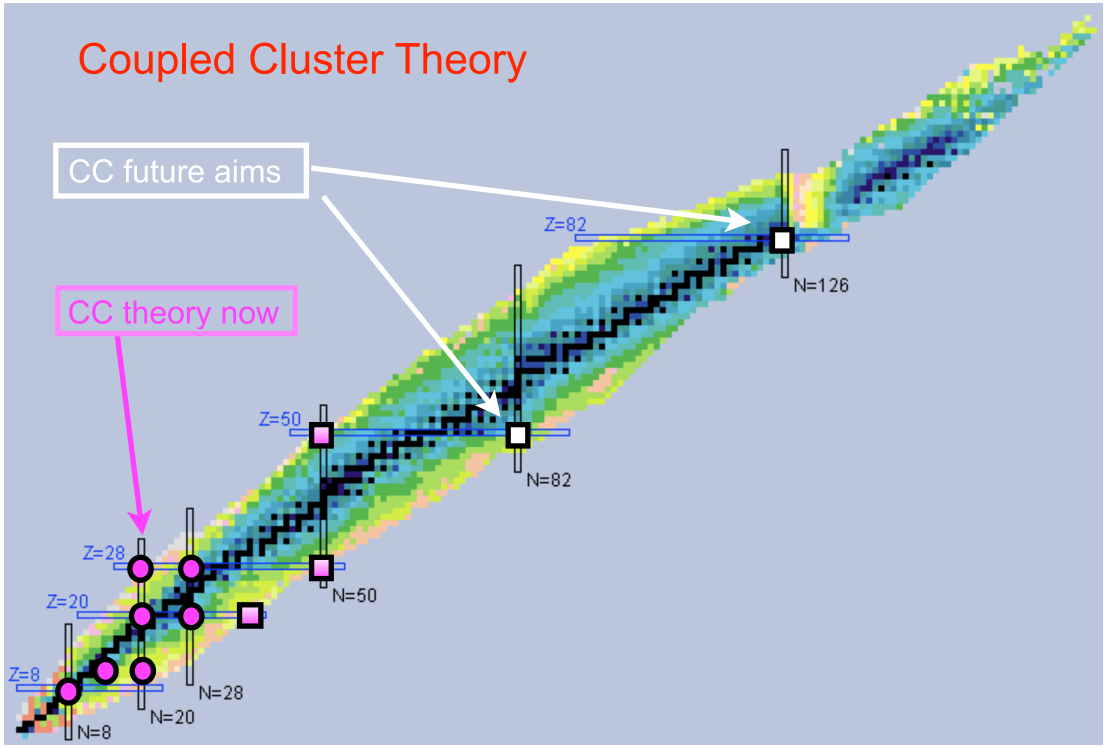
The exact final state interaction (FSI) is included in the continuum rigorously!

Solved for A=3,4,6,7 with hyper-spherical harmonics expansions and for A=4 with NCSM

Extension to medium-mass nuclei

Challenge: develop new ab-initio methods that can extend the frontiers to heavier nuclei



- Optimal for closed shell nuclei (±1, ±2)

$$|\psi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle = e^T |\phi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle$$

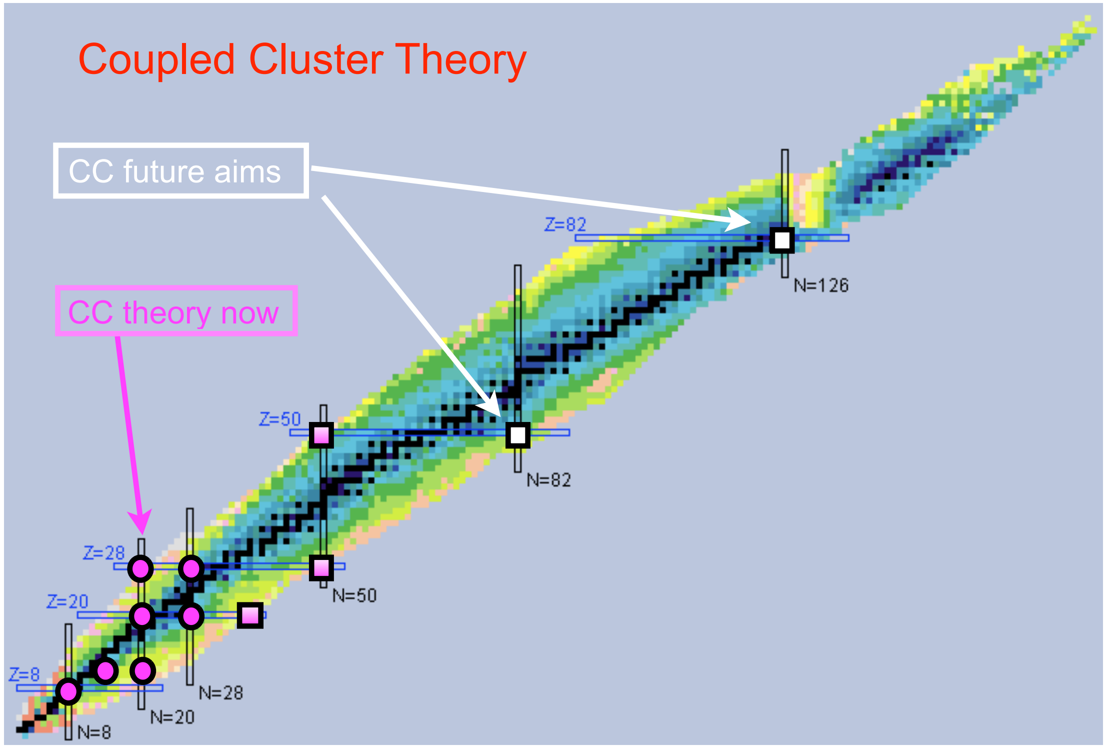
$T = \sum T_{(A)}$ cluster expansion

Very successful in nuclear theory

ORNL group and collaborators: PRL **108**, 242501 (2012), PRL **109,** 032502 (2012); PRL **110**, 192502 (2013), PRL **113**, 262504 (2014), PRL **113**, 142502 (2014) ...

Extension to medium-mass nuclei

Challenge: develop new ab-initio methods that can extend the frontiers to heavier nuclei



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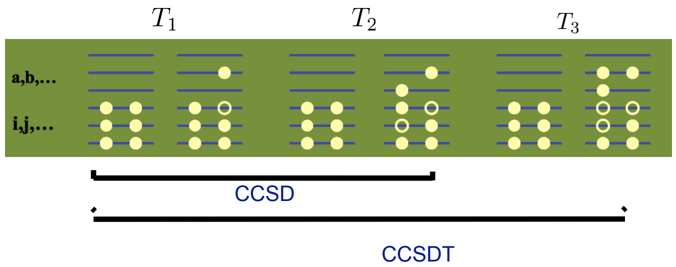
Approximation schemes



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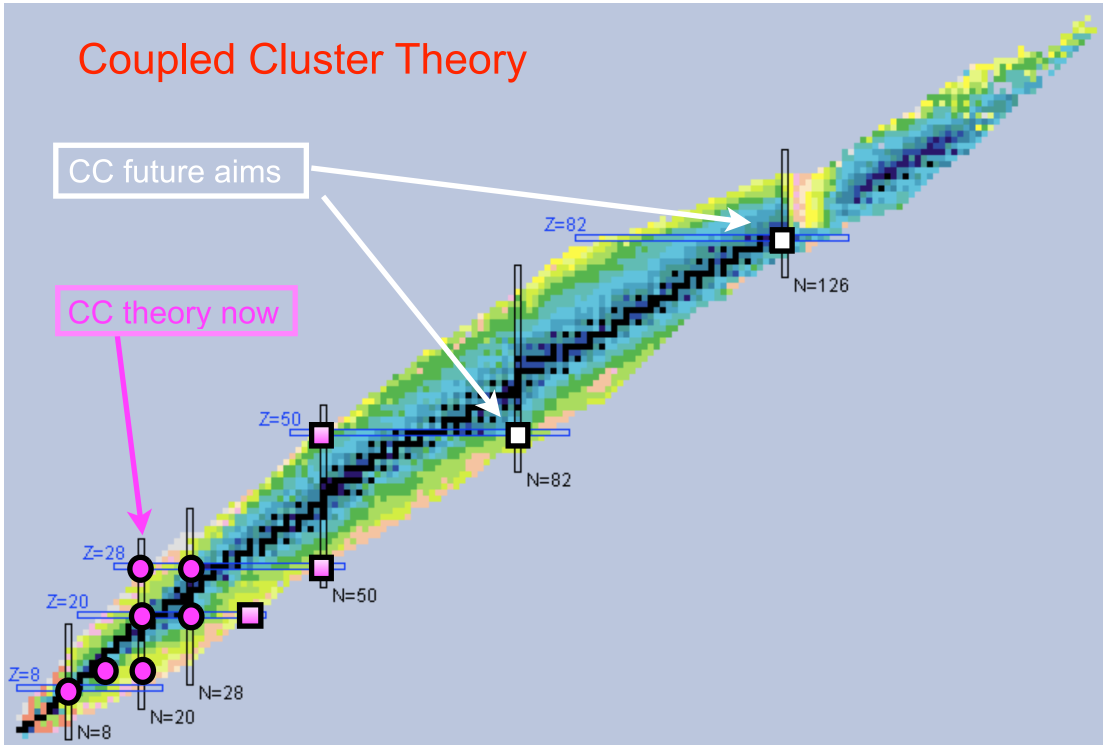

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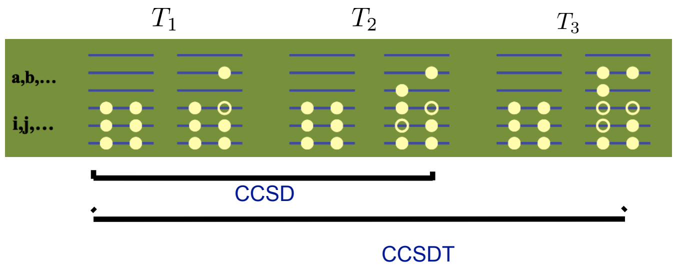

Good computational scaling

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Giant Dipole Resonances

Merging the Lorentz integral transform method with coupled-cluster theory :
New many-body method to extend *ab-initio* calculations of em reactions to medium-mass-nuclei

S.B. *et al.*, PRL **111**, 122502 (2013) → **LIT-CCSD**

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NN forces derived from
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The comparison is very good
Small difference due to missing
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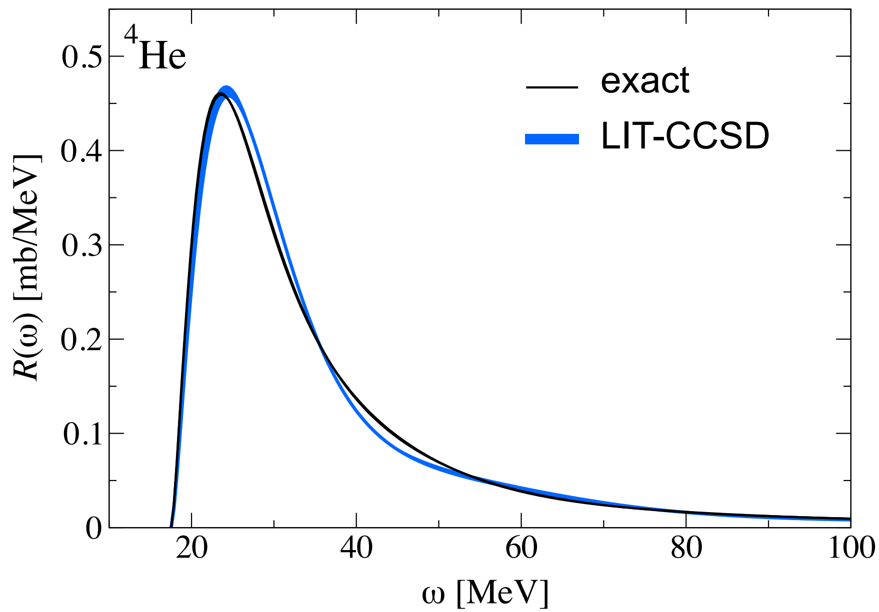

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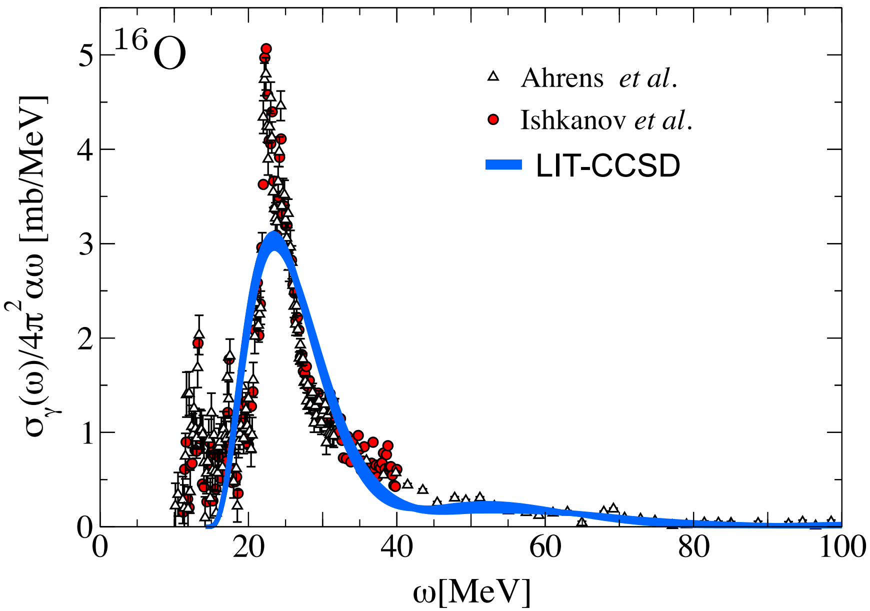

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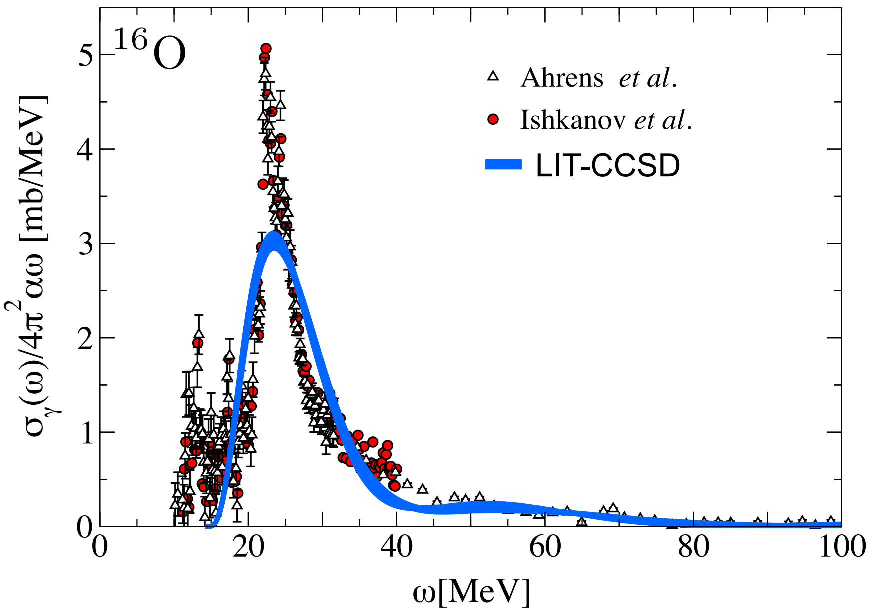

The position of the GDR is described from first principles for the first time

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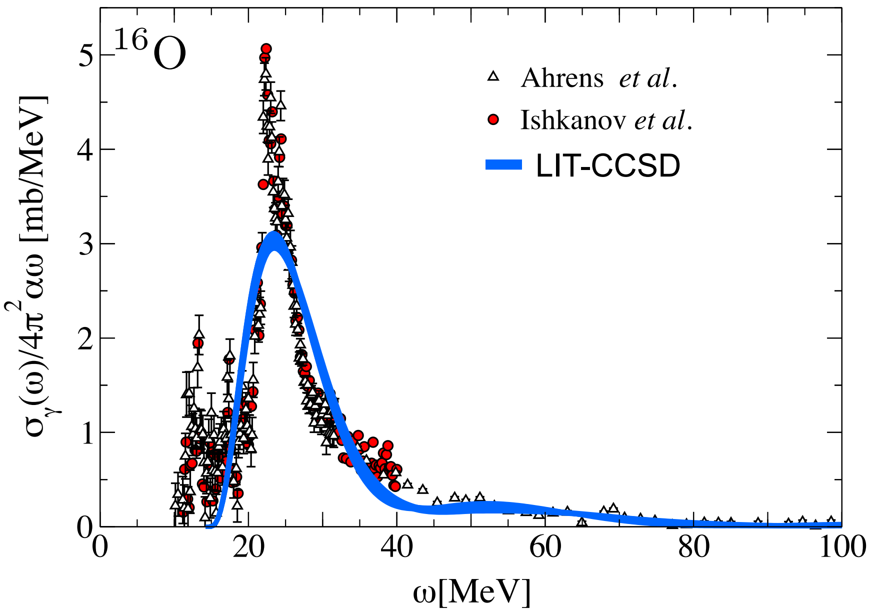
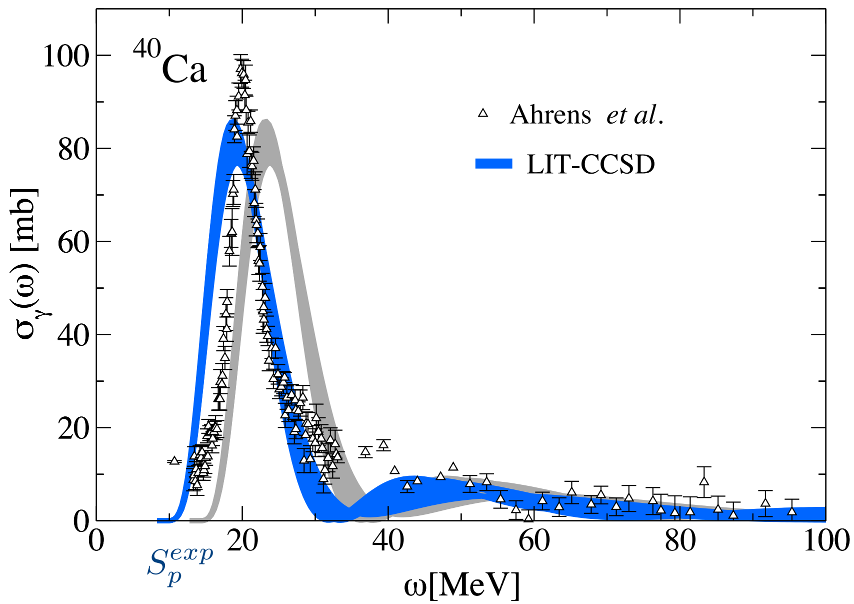


S.B. *et al.*, PRC **90**, 064619 (2014)



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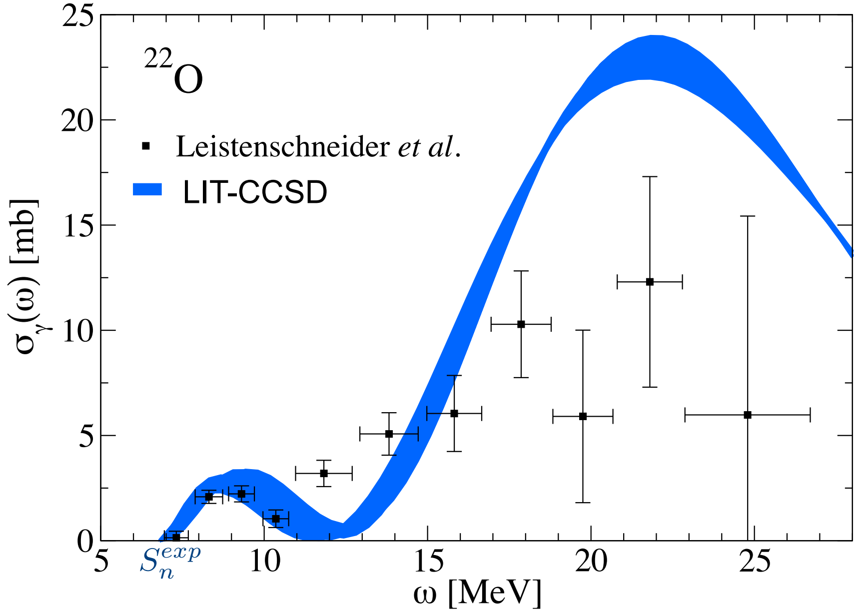
Pigmy Dipole Resonances

Extension to neutron-rich nuclei

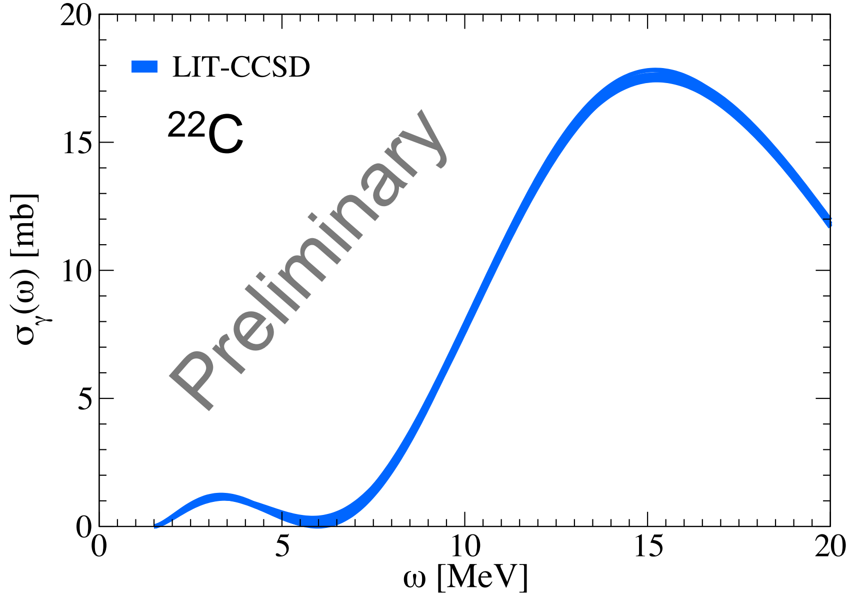
NN forces derived from chiral EFT (N^3LO)

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



^{22}O data from GSI

With Mirko Miorelli, PhD student



^{22}C being measured at RIKEN

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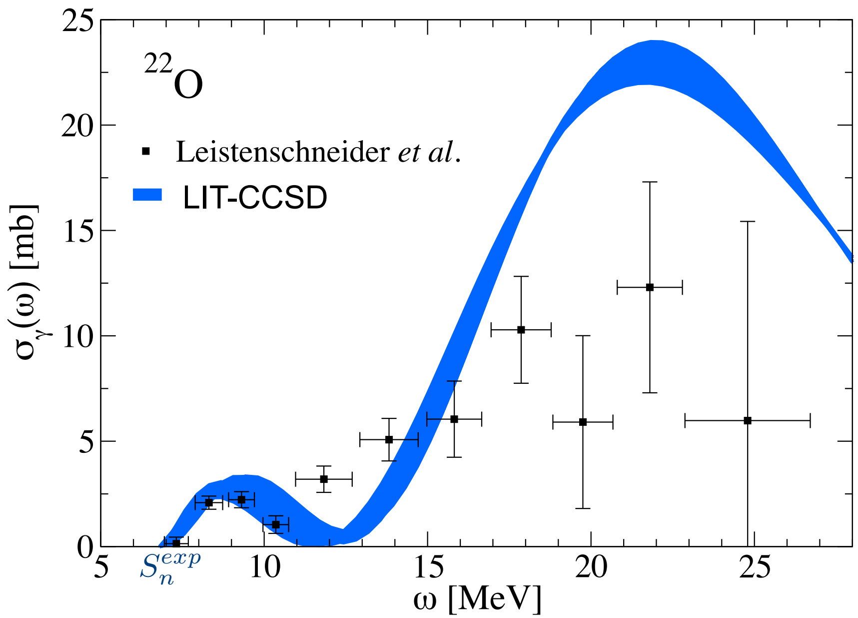
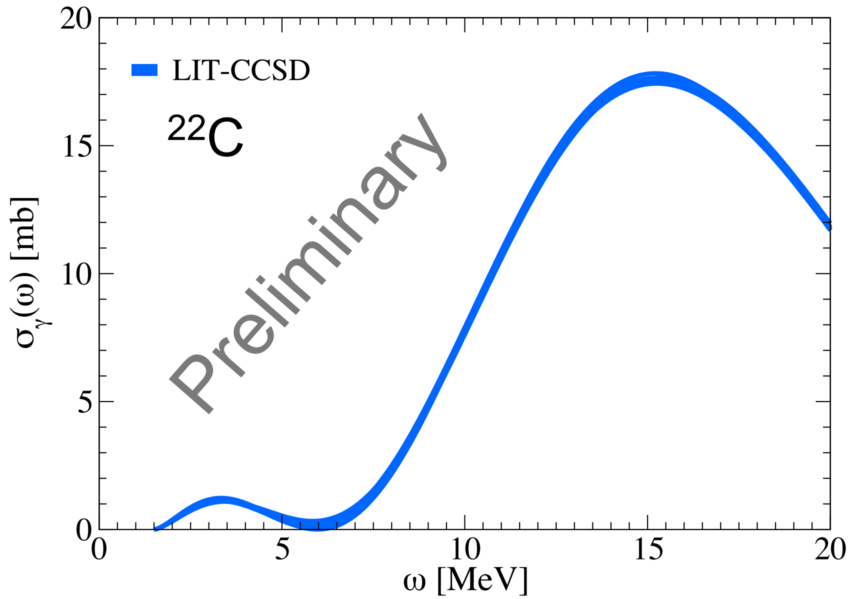




^{22}O data from GSI

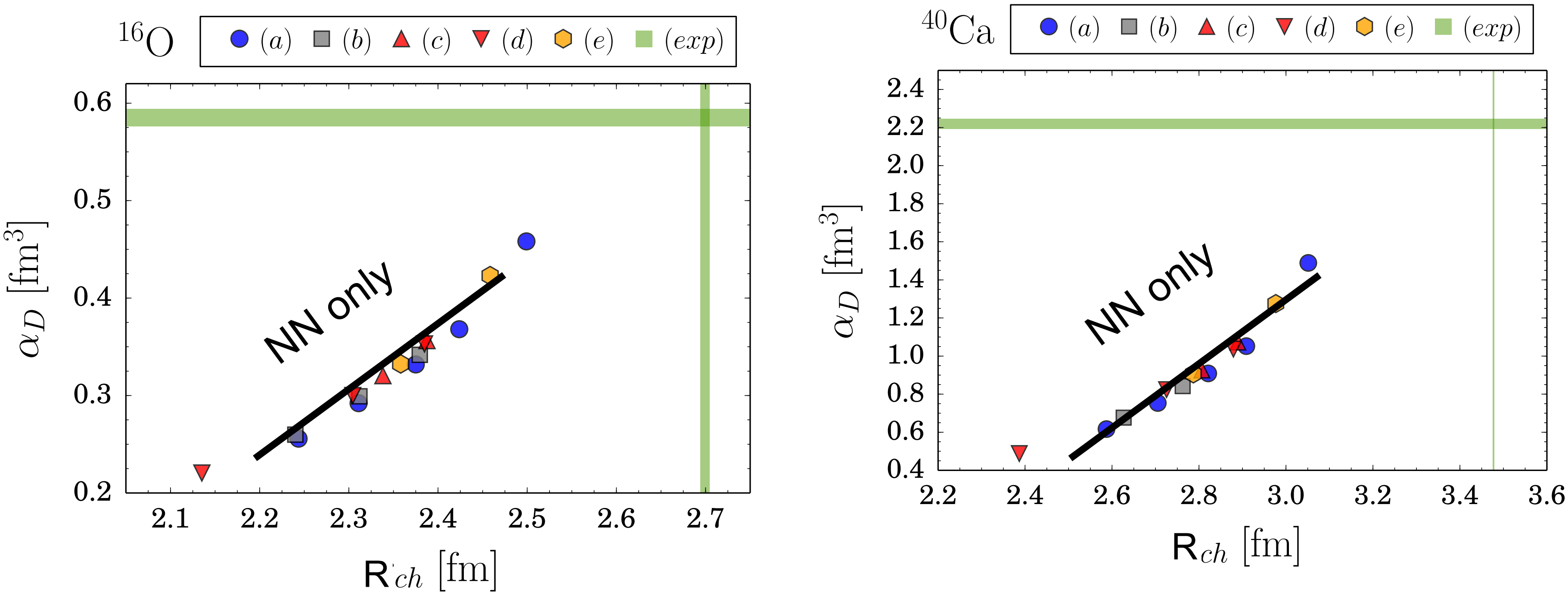
^{22}C being measured at RIKEN

Soft dipole mode emerges from first principle calculations

Electric Dipole Polarizability

NN interactions

M. Miorelli *et al.*, in preparation (2015)



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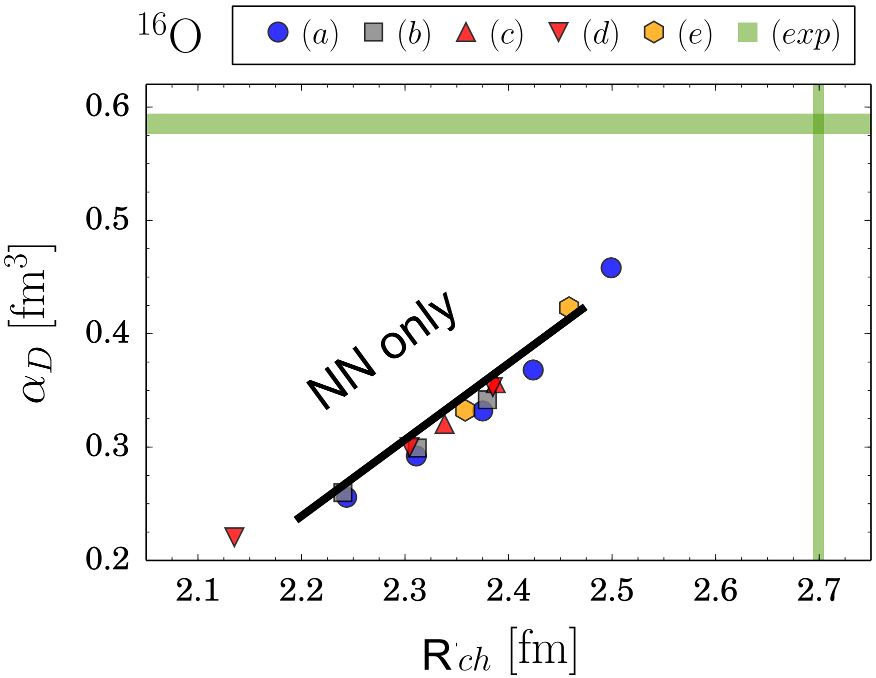

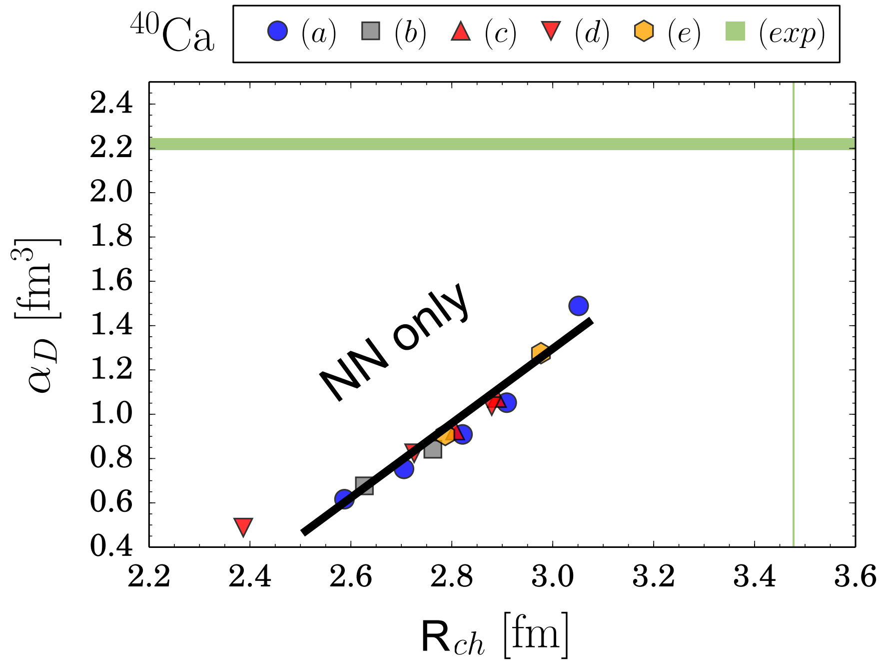

We observe correlations between polarizability and radii (R_{ch}, R_p, R_n)

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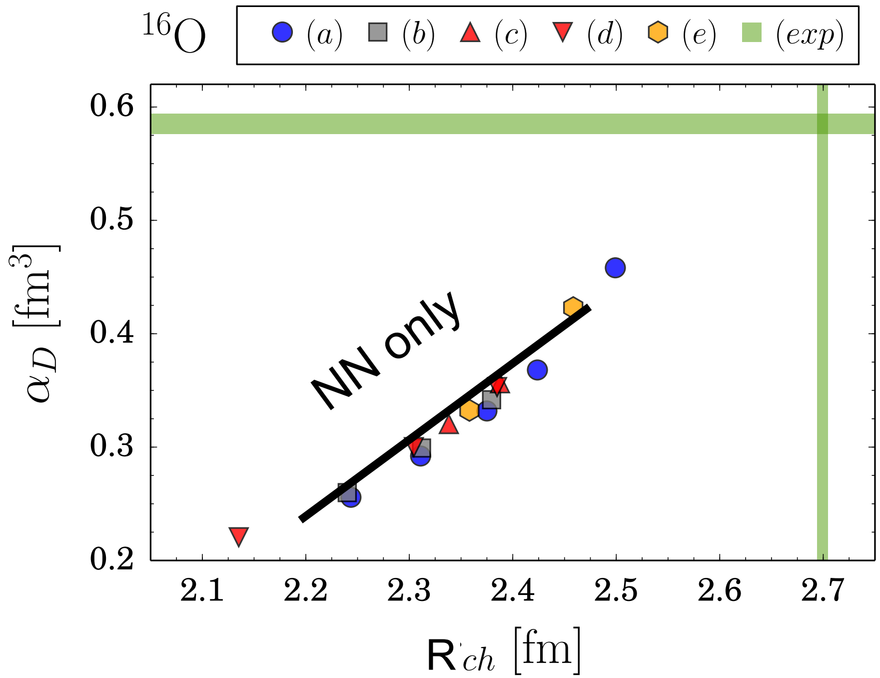
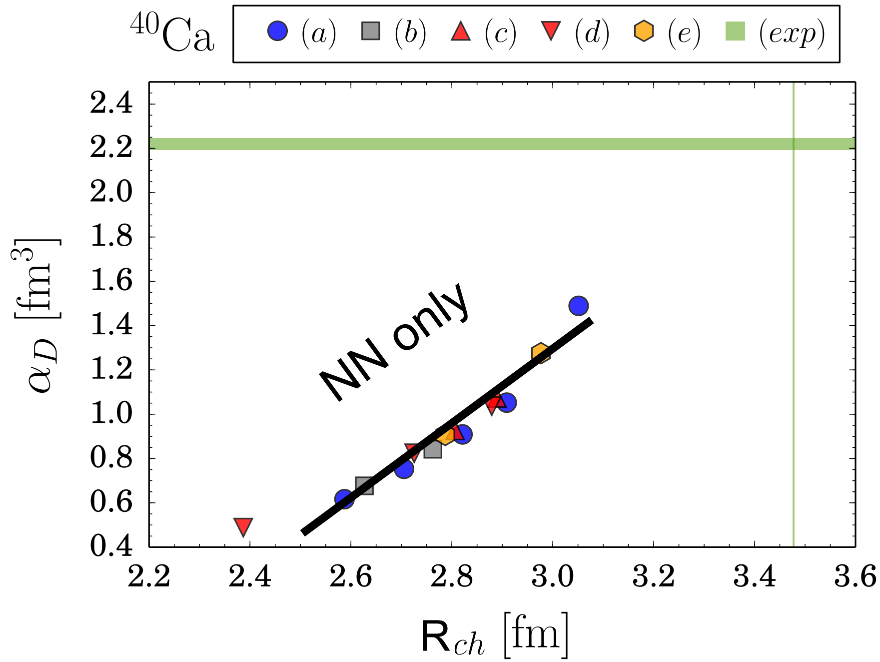




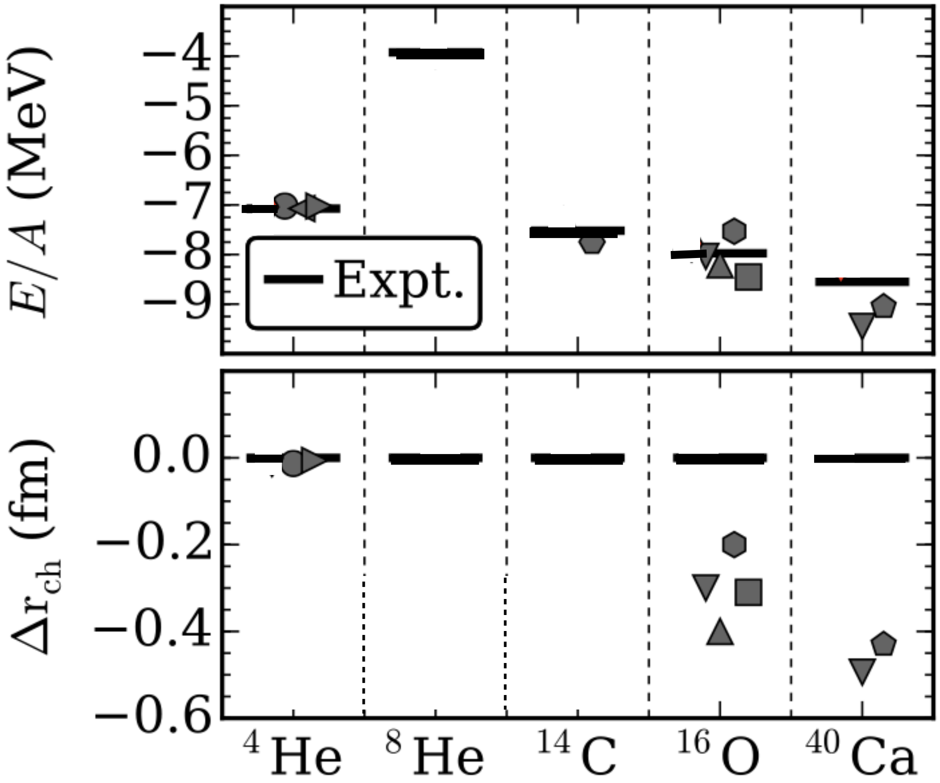
We observe correlations between polarizability and radii (R_{ch}, R_p, R_n)

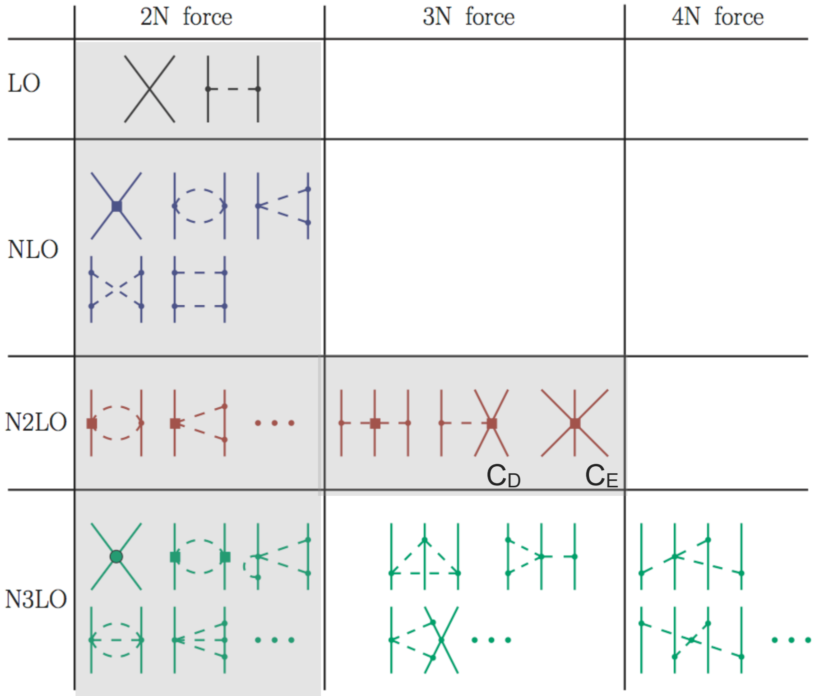
Two-body Hamiltonian underestimates both radii and electric dipole polarizabilities

TRIUMF

Including three-nucleon forces

We need accurate interactions able to reproduce both energies and radii





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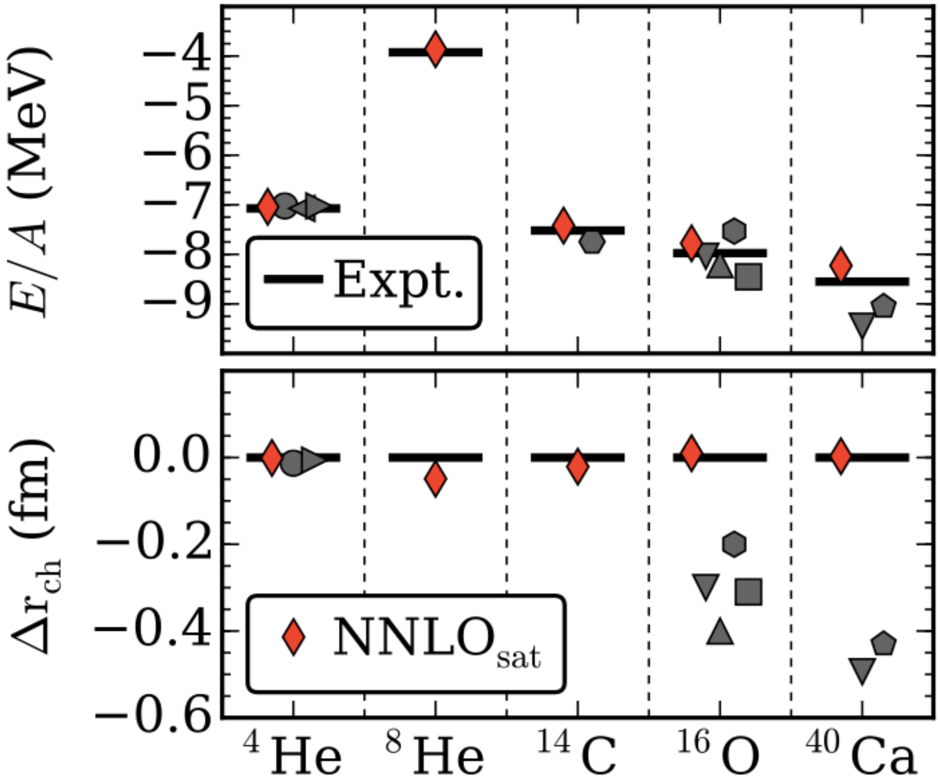
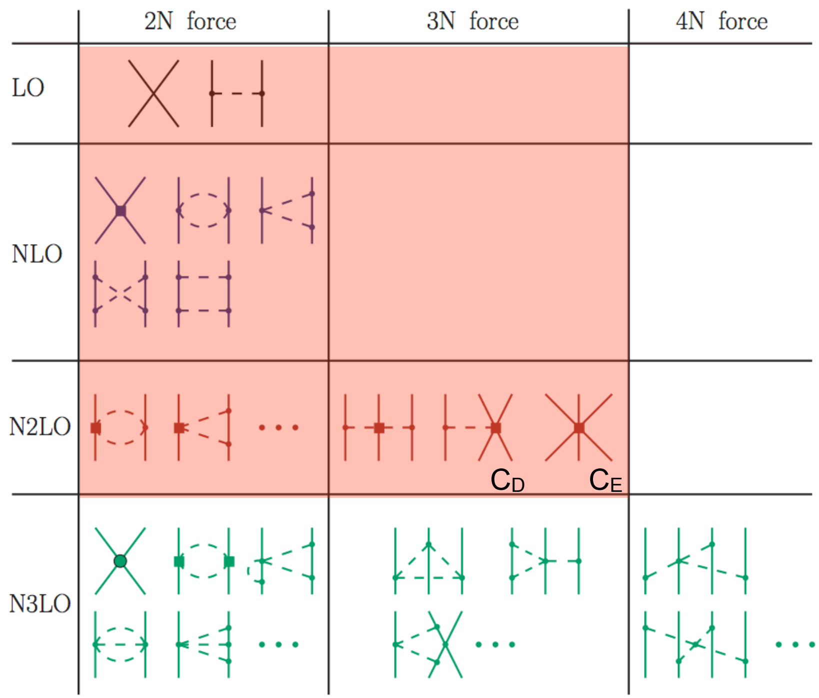




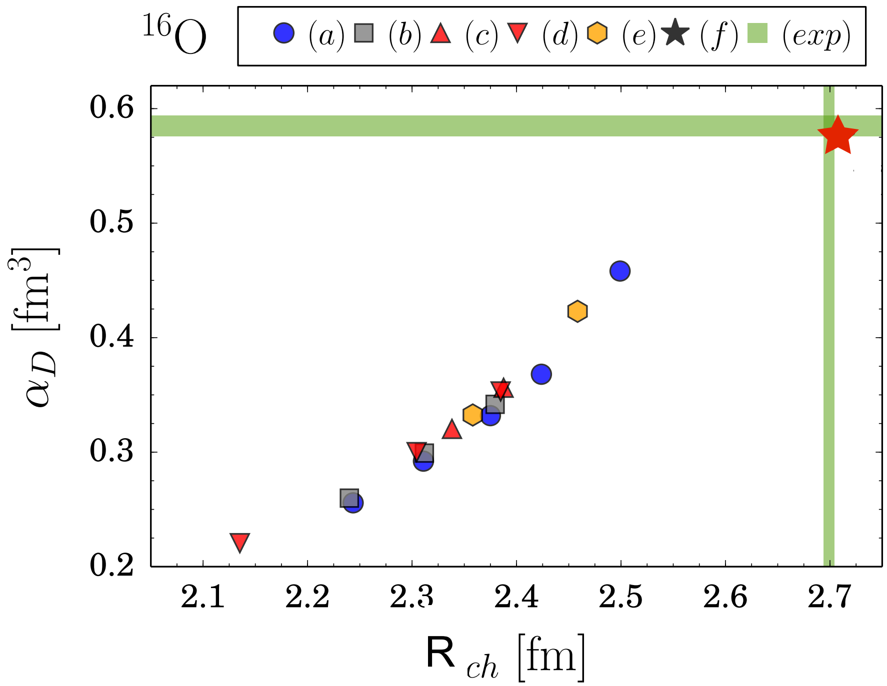
Include radii in the fit of LEC for the three-body force

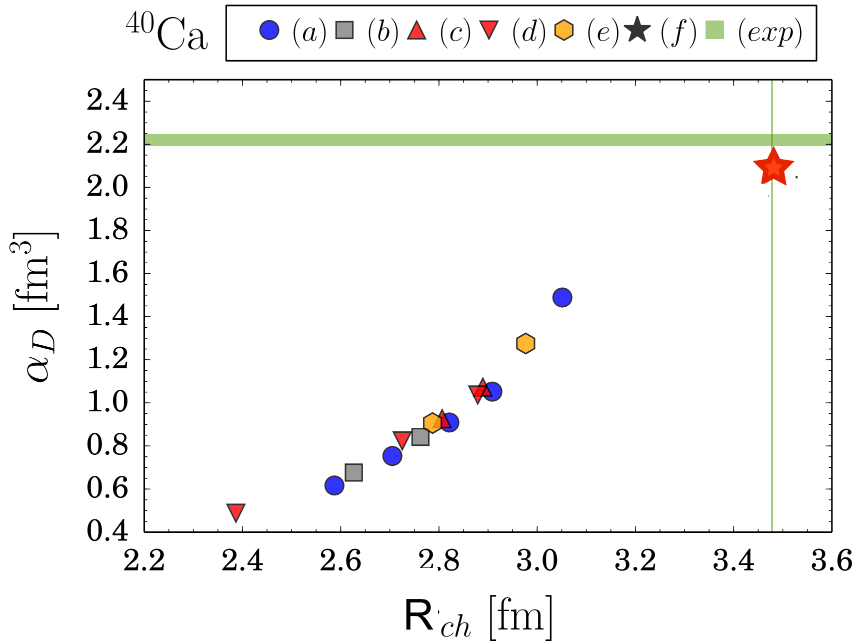
New Paradigm: **NNLO$_{sat}$**: Fit of all LEC at N^{2}LO on NN data and nuclear radii Phys. Rev. C **91**, 051301(R) (2015)

TRIUMF

Electric Dipole Polarizability

with 3N forces ★ NNLO$_{sat}$





Tuesday, 15 September, 15

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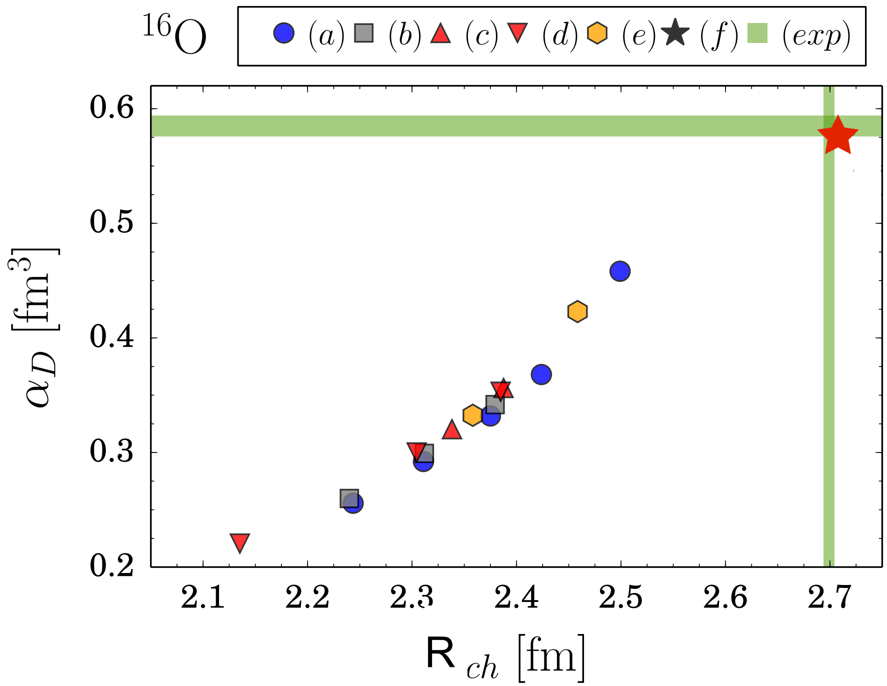
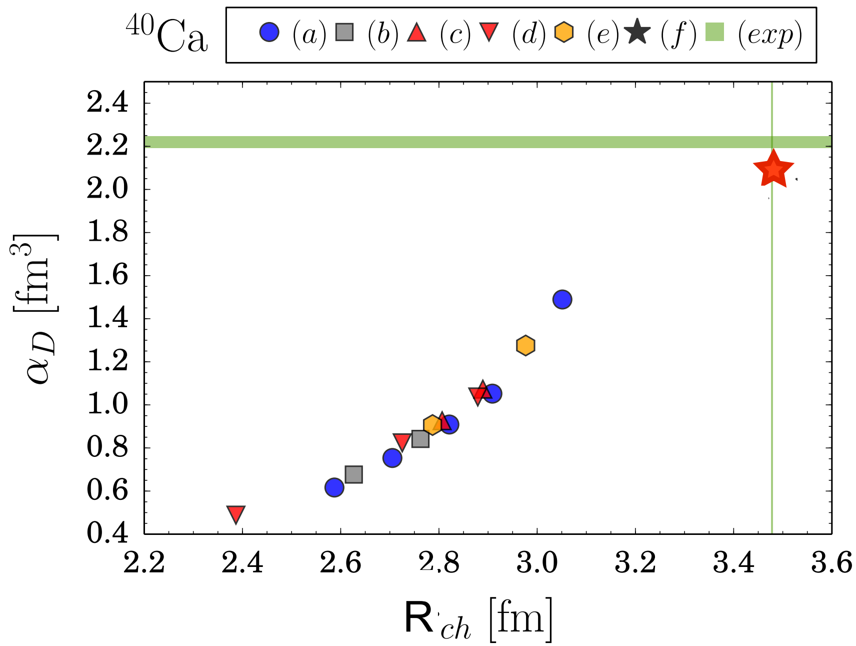
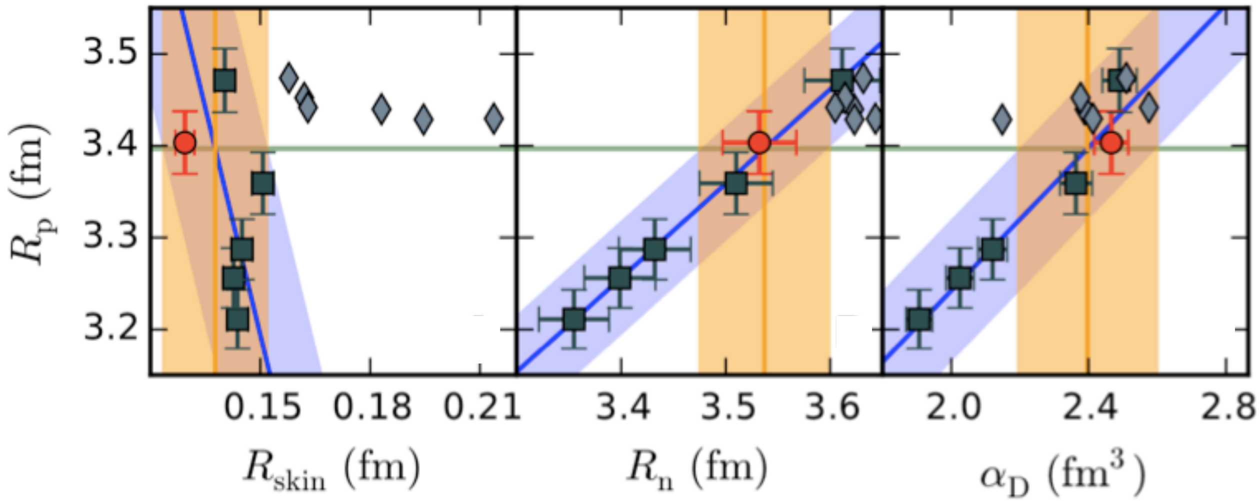




Much better agreement with experimental data

Results for ^{48}Ca

Hagen *et al.*, (2015)



NNLO$_{sat}$

Soft NN(N^{3}LO)+3N(N^{2}LO) Hebeler *et al.*

Density Functional Theory

TRIUMF

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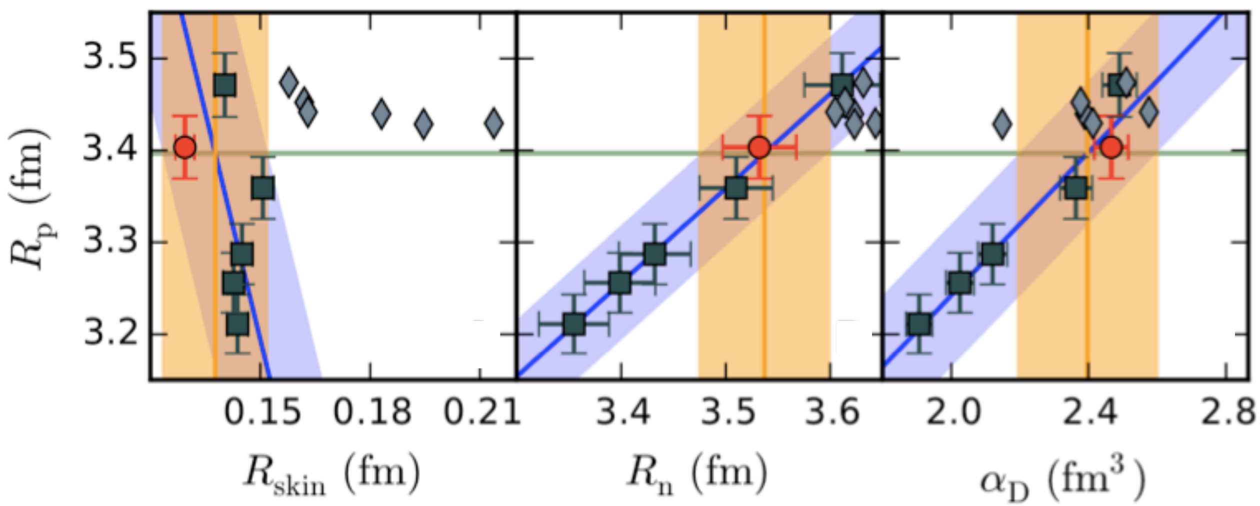

NNLO$_{sat}$

Soft NN(N^{3}LO)+3N(N^{2}LO) Hebeler *et al.*

Density Functional Theory

Exploiting correlations among observables and the very precise measurement of Rp, we predict:

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

- Will be measured at JLab by CREX with parity-violation electron scattering

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

- Being measured at RCNP (Osaka) wit (p,p')

Conclusions and Outlook

- Electromagnetic observables are key to test our understanding of nuclear forces
- Extending first principles calculations to medium mass nuclei is possible and very exciting: more applications/impact on experiments in the future
- Monopole strengths, M1 and GT teller transitions

Thanks to my collaborators:

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M. Hjorth-Jensen, G. R. Jansen, W. Leidemann, M.Miorelli, W. Nazarewicz, G. Orlandini,

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Thank you!

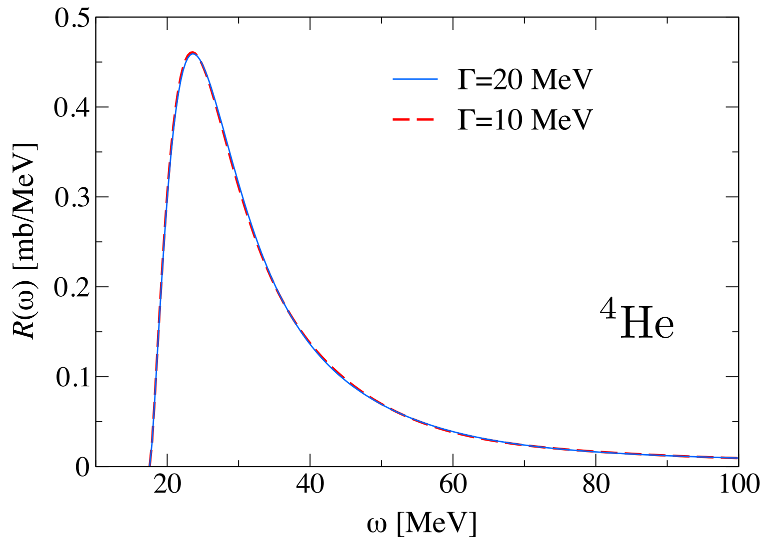
Backup

Inversion Procedure

The inversion is performed numerically with a regularization procedure

Ansatz $$R(\omega) = \sum_i^{I_{\max}} c_i \chi_i(\omega, \alpha) \Longrightarrow L(\sigma, \Gamma) = \sum_i^{I_{\max}} c_i \mathcal{L}[\chi_i(\omega, \alpha)]$$

Least square fit of the coefficients c_i to reconstruct the response function



Message: using bound-states techniques to calculate the LIT is correct and inversions are stable

TRIUMF

LIT with Coupled Cluster Theory

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

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

$$\boxed{(H - z^*)|\tilde{\Psi}\rangle = J^\mu|\psi_0\rangle} \longrightarrow \boxed{(\bar{H} - z^*)|\tilde{\Psi}_R(z^*)\rangle = \bar{\Theta}|\Phi_0\rangle}$$

with $z = E_0 + \sigma + i\Gamma$

$$\bar{H} = e^{-T} H e^{T}$$

$$\bar{\Theta} = e^{-T} \Theta e^{T}$$

$$L(\sigma,\Gamma) = \left\langle \tilde{\Psi} | \tilde{\Psi} \right\rangle \longrightarrow L(\sigma,\Gamma) = \left\langle \tilde{\Psi}_L | \tilde{\Psi}_R \right\rangle =$$

$$-\frac{1}{2\pi}\Im\left\{\langle \bar{0}_L|\bar{\Theta}^\dagger \left[|\tilde{\Psi}_R(z^*)\rangle - |\tilde{\Psi}_R(z)\rangle\right]\right\}$$

with $|\tilde{\Psi}_R(z^*)\rangle = \hat{R}(z^*)|\Phi_0\rangle$

Formulation based on the solution of an Equation of Motion with source   No approximations done so far!

Present implementation in the CCSD scheme

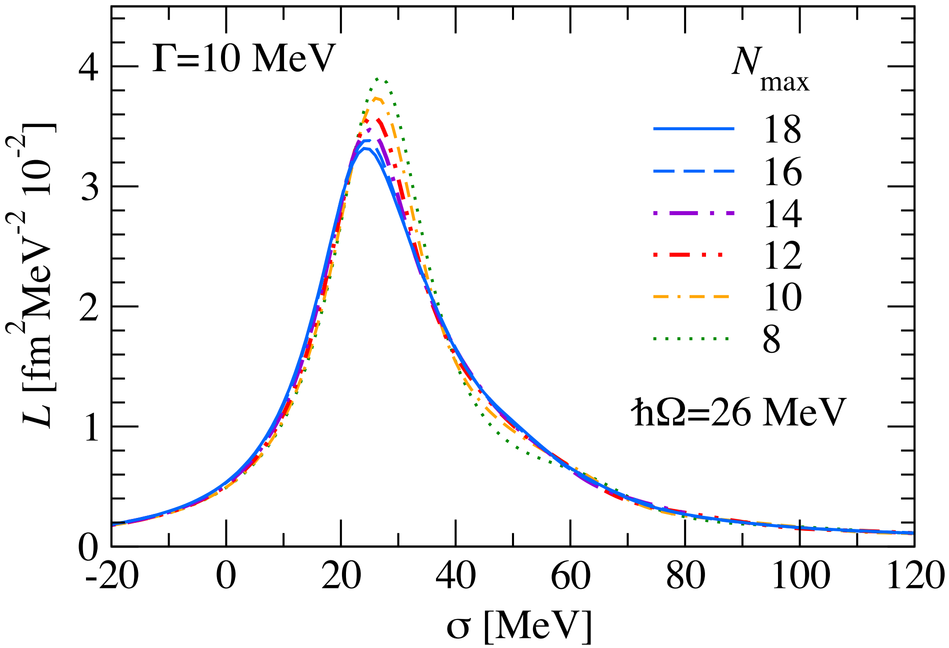
$$T = T_1 + T_2$$

$$\hat{R} = \hat{R}_0 + \hat{R}_1 + \hat{R}_2$$

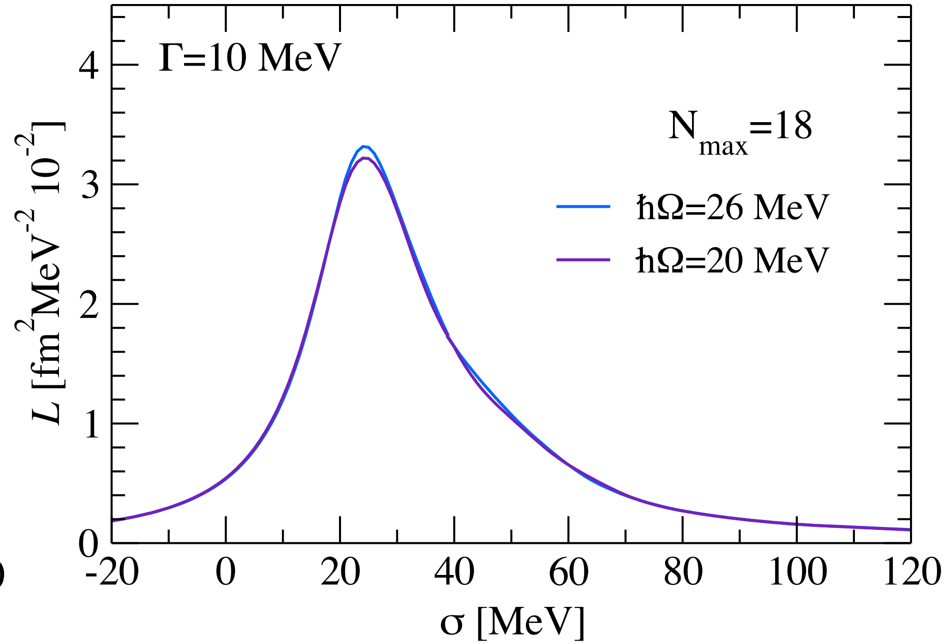
LIT with Coupled Cluster Theory

Extension to ^{16}O with NN forces derived from chiral EFT (N^3LO)

➡ Convergence in the model space expansion



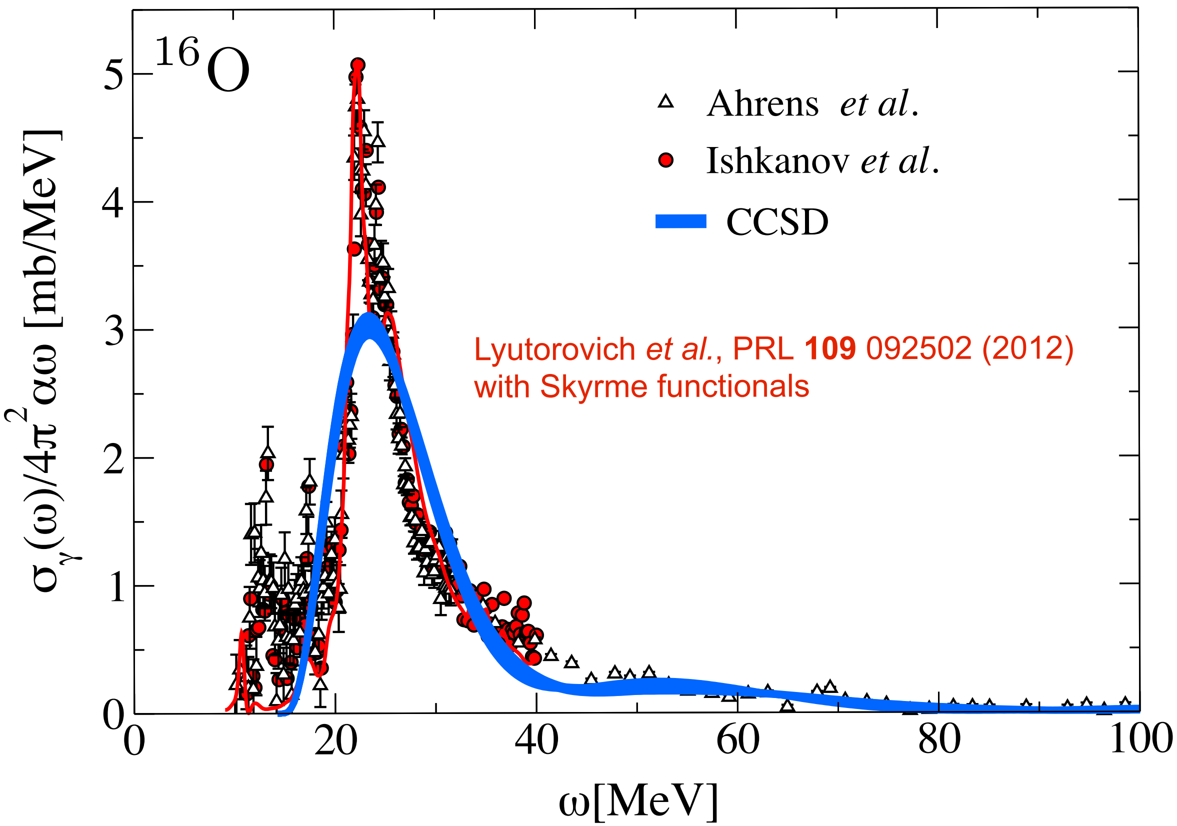
Good convergence



Small HO dependence: use it as error bar

Giant Dipole Resonances

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

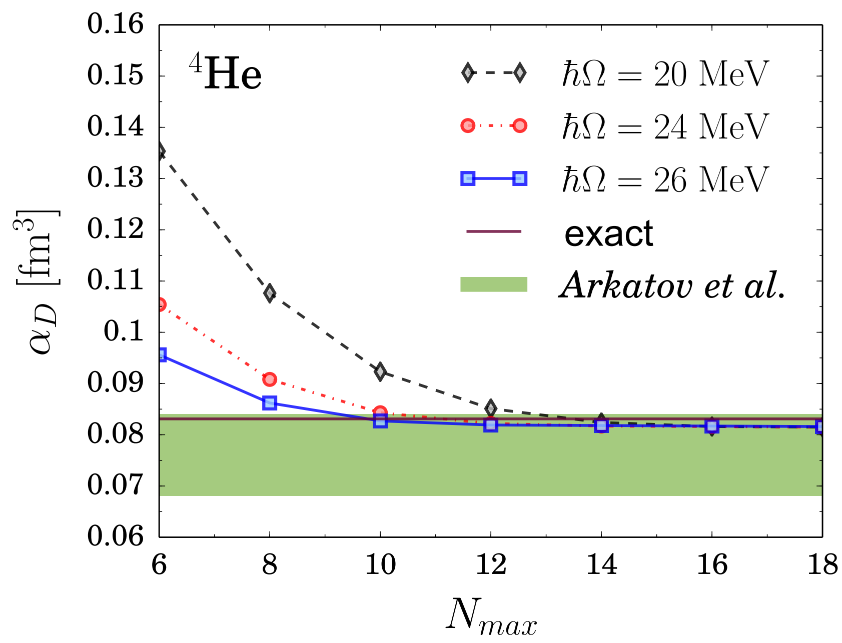


Giant Dipole Resonances

Validation for ^{4}He: comparison with exact hyperspherical harmonics

NN forces derived from chiral EFT (N^{3}LO)

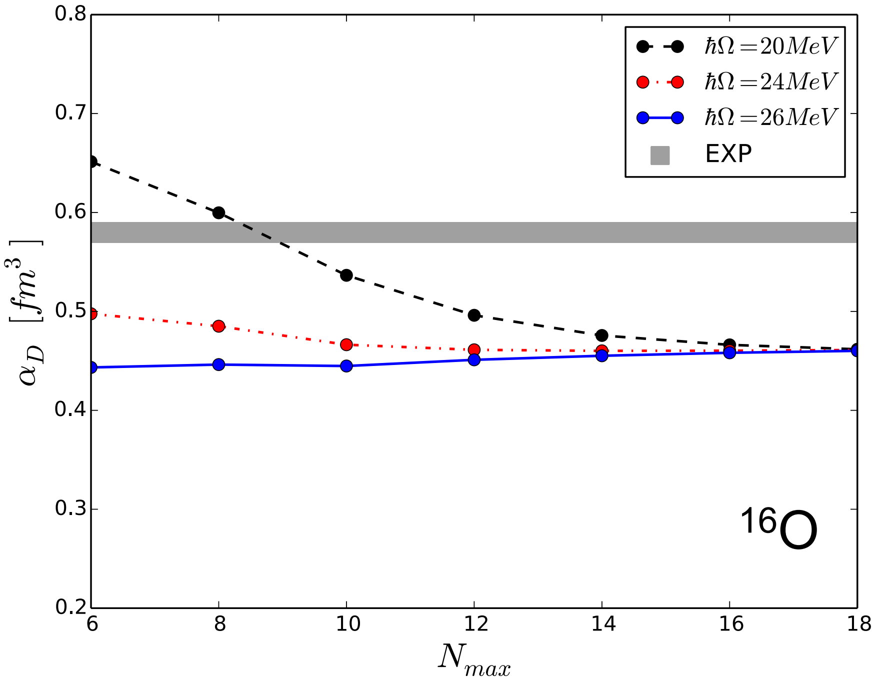
Miorelli *et al.*, in preparation

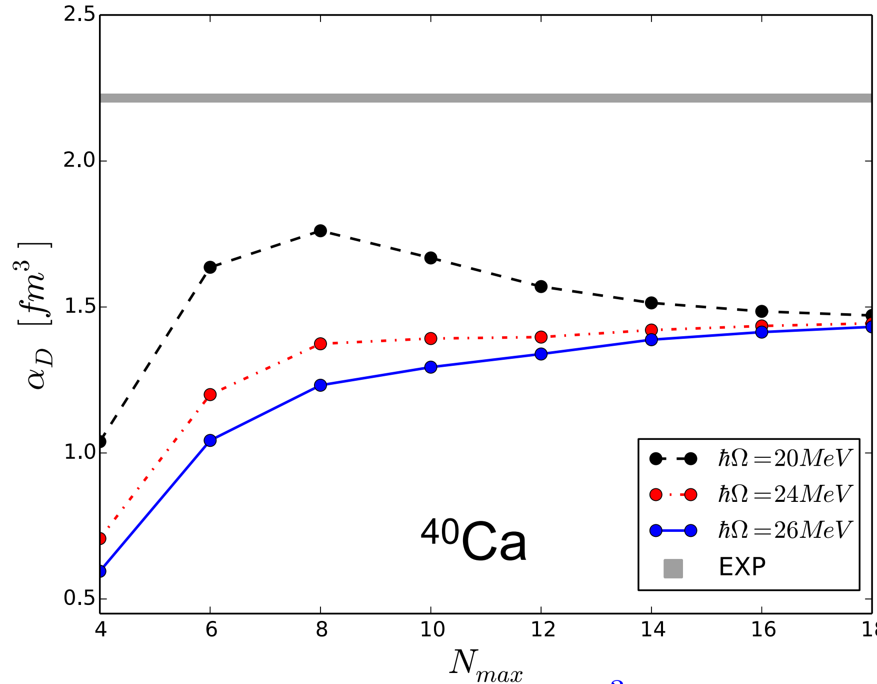


The comparison with exact theory is very good
Small difference due to missing triples and quadruples

Electric Dipole Polarizability

Medium-mass nuclei with NN(N^{3}LO) M. Miorelli *et al.*, in preparation (2015)





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

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

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

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

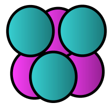
The present Hamiltonian underestimates both radii and electric dipole polarizabilities

Giant Dipole Resonance in A=6

with Hyperspherical Harmonics

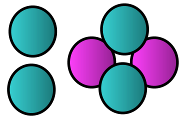
$$\sigma_\gamma = \frac{4\pi^2\alpha}{3}\omega R^{E1}(\omega)$$

$$E1 = \sum_i^Z (z_i - Z_{cm})$$



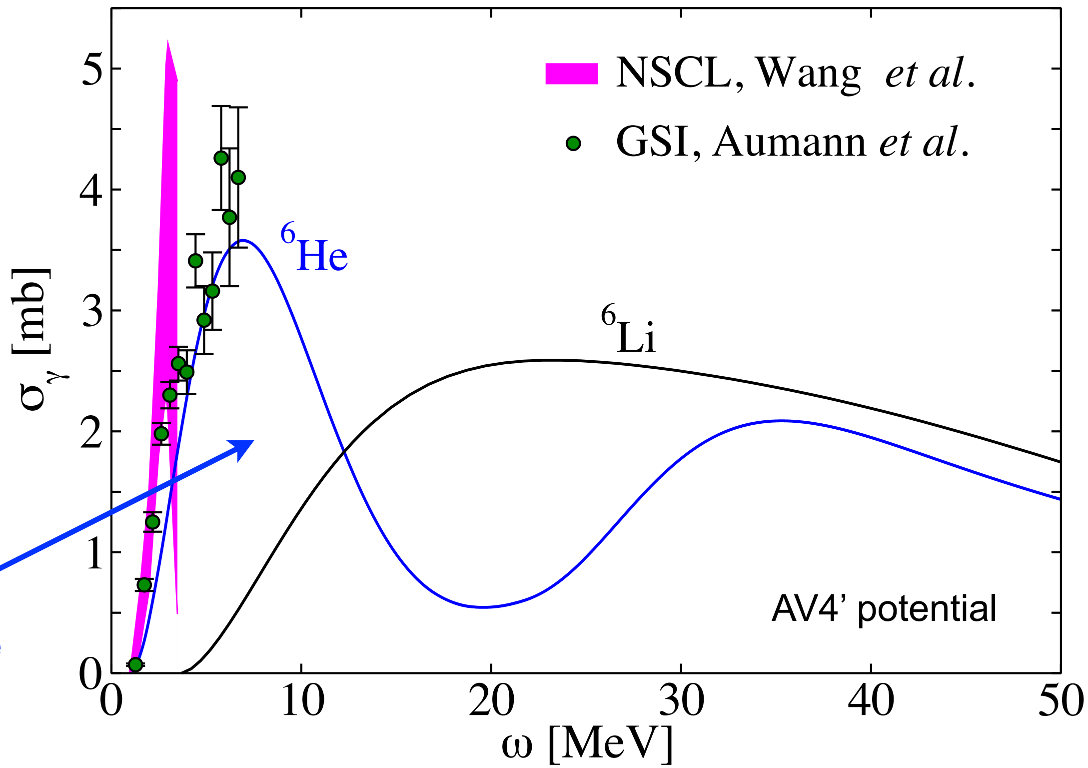
^{6}Li

stable



^{6}He

unstable $T_{1/2} = 806$ ms



Soft Dipole Mode

S.B. *et al.* PRL **89** 052502/PRC **69** 052502 (2004)