Electric dipole polarizability in medium-mass nuclei

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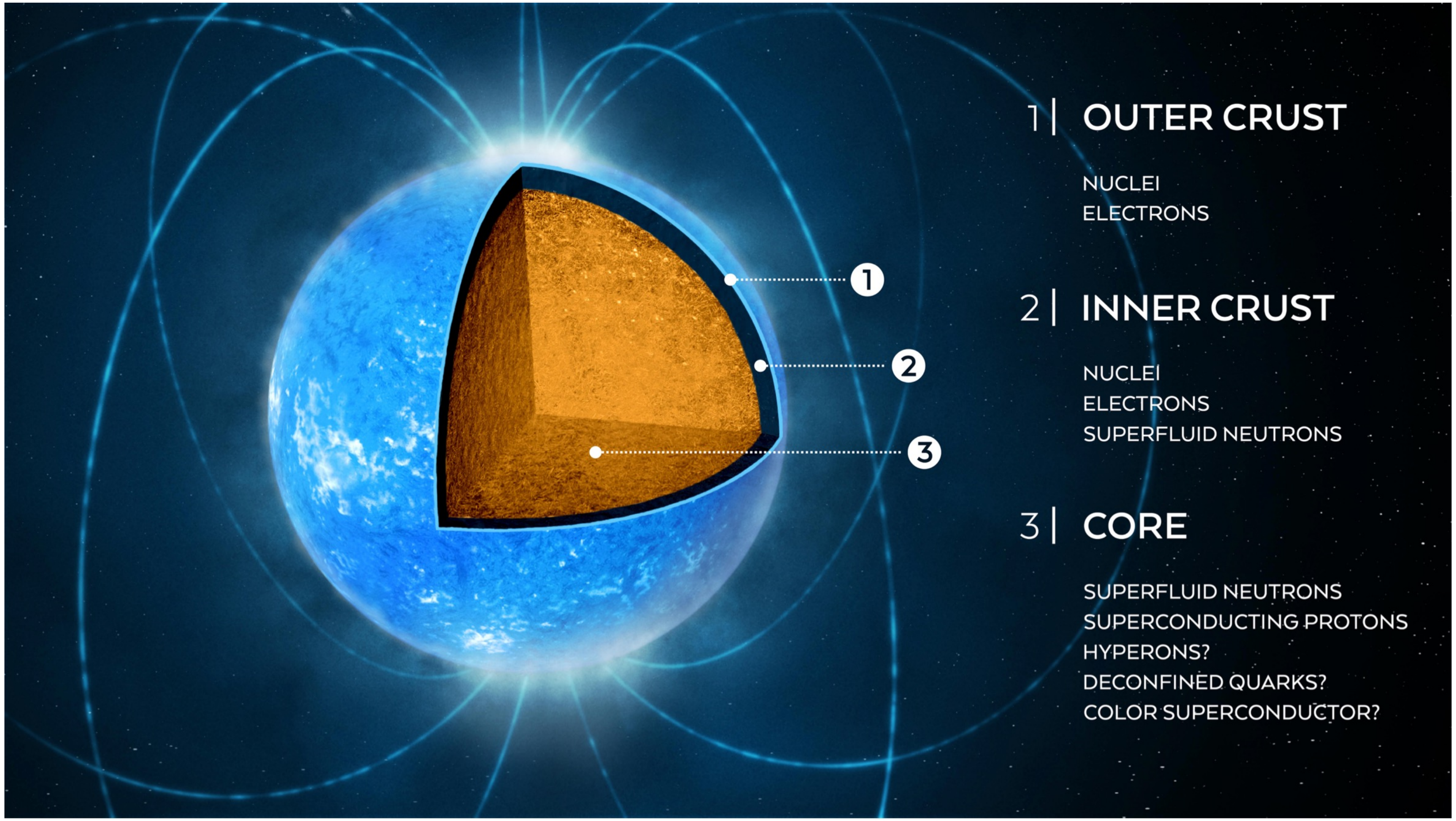
Gustav R. Jansen (ORNL)
Thomas Papenbrock (ORNL/UTK)

Extreme matter in neutron stars



A. Watts et al, RMP 88, 021001 (2016).

Neutron matter equation of state (EOS)

Infinite **nuclear matter EOS**:

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2 \mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

$$\rho = (\rho_n + \rho_p) \qquad \alpha = (\rho_n - \rho_p)/\rho$$

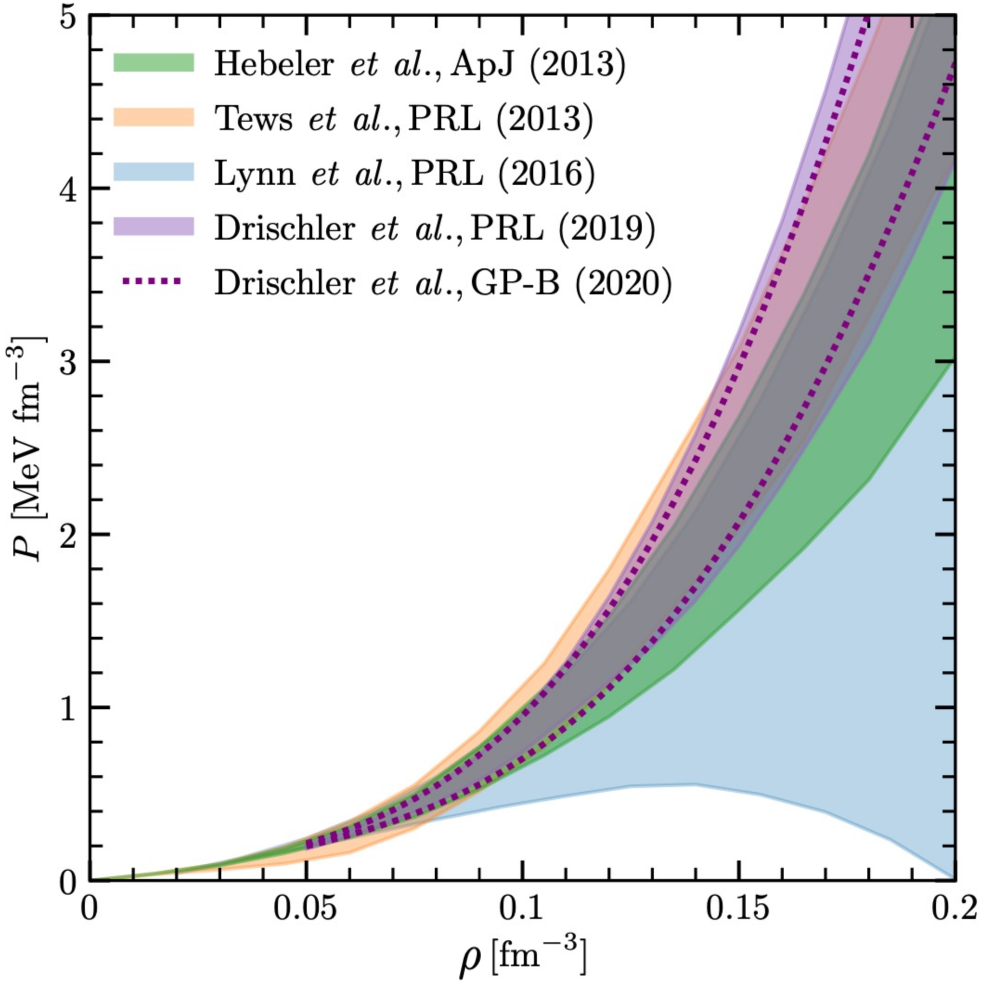
where the **symmetry energy** is:

$$\mathcal{S}(\rho) = J + L\frac{(\rho-\rho_0)}{3\rho_0} + \ldots$$

symmetry energy at saturation density

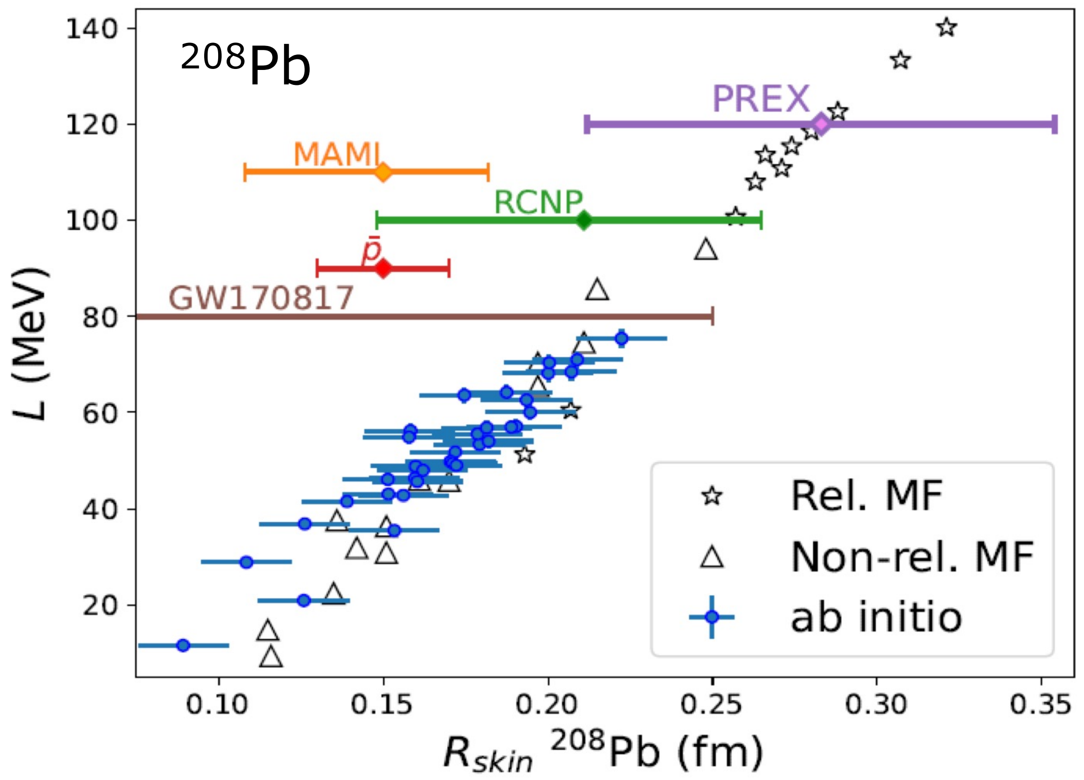
slope parameter, related to **pressure of pure neutron matter** at saturation density

S. Huth et al, PRC 103, 025803 (2021).



How to constrain L?

Neutron-skin thickness



B. Hu et al, Nat. Phys. **18**, 1196–1200 (2022).

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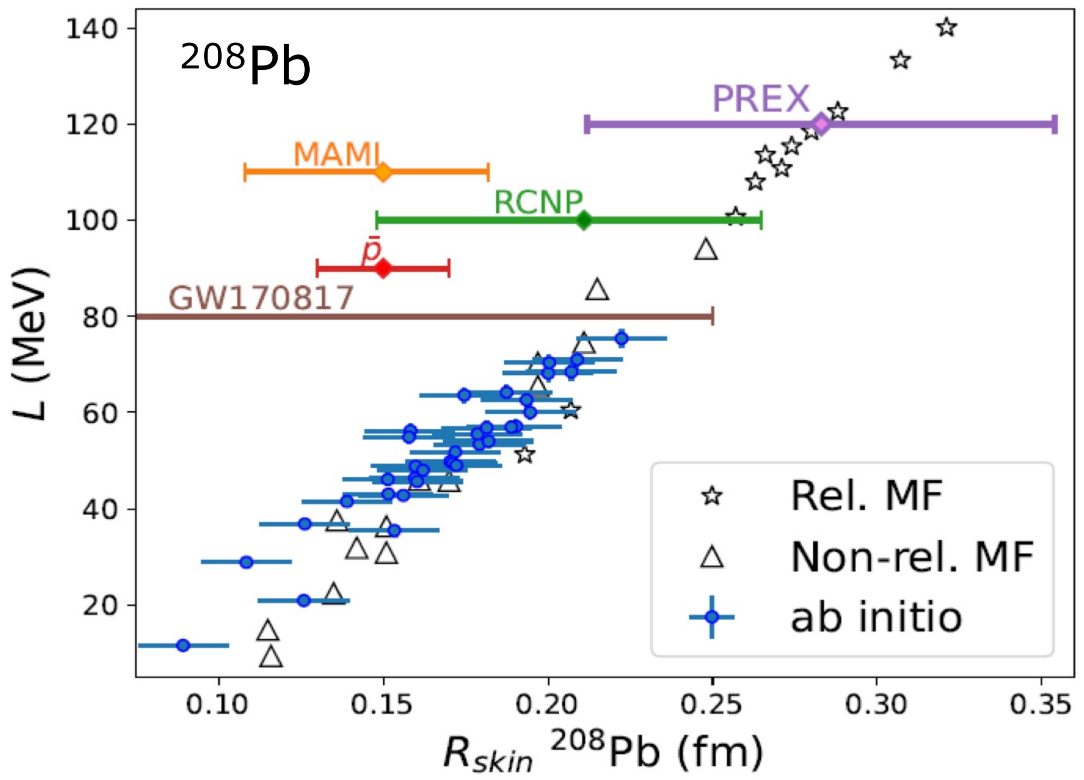

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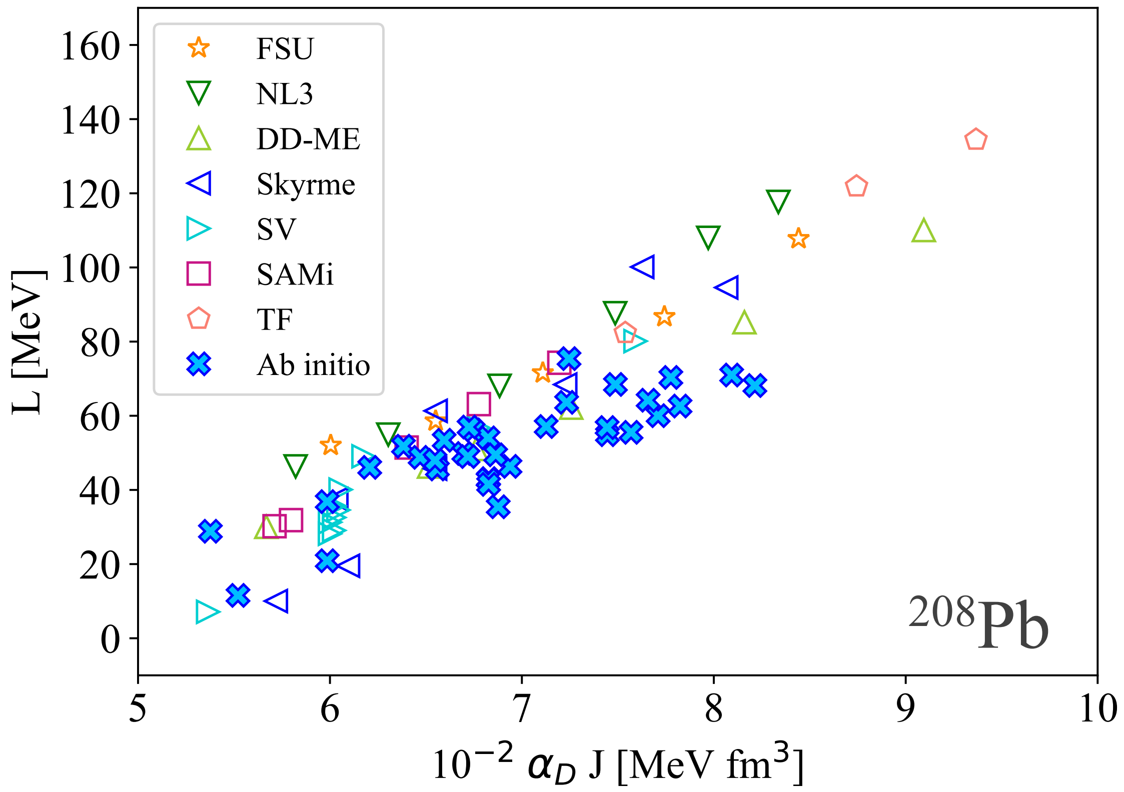
Electric dipole polarizability

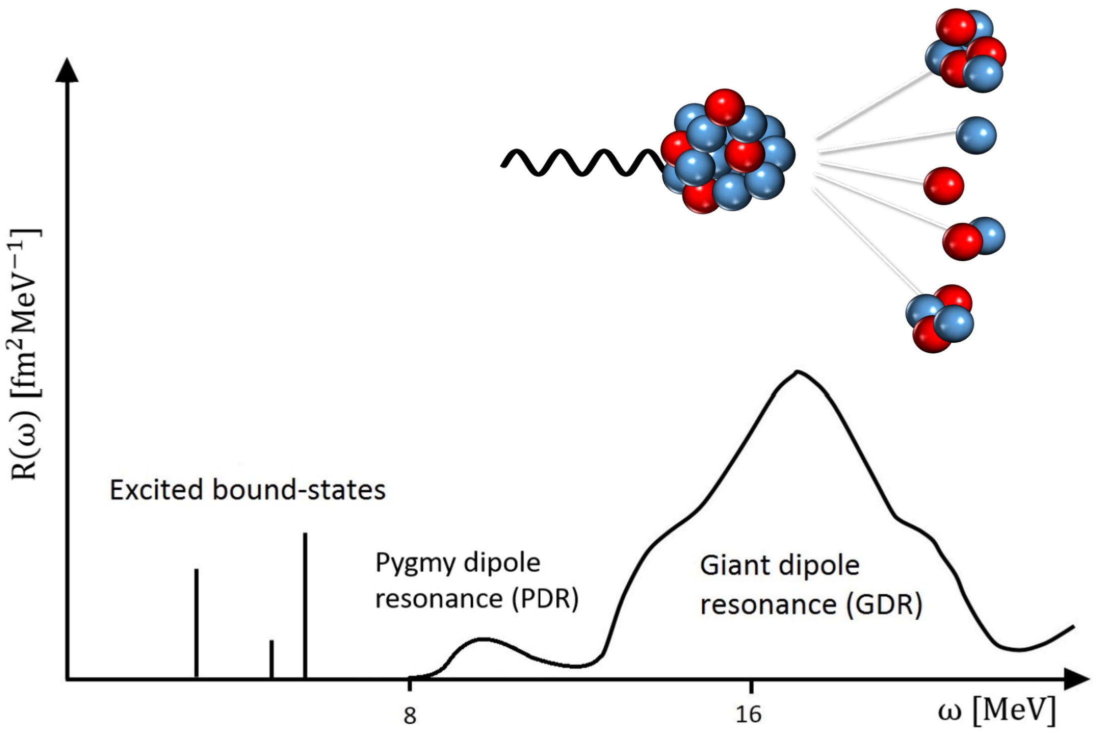
$$\alpha_D = 2\alpha \int d\omega \frac{R(\omega)}{\omega}$$



Data from X. Roca-Maza et al, PRC 88, 024316 (2013), B. Hu et al, Nat. Phys. 18, 1196-1200 (2022).

Nuclear response functions

$$R(\omega) = \sum\!\!\!\!\!\!\int_f \left| \langle \Psi_f | \Theta | \Psi_0 \rangle \right|^2 \delta(E_f - E_0 - \omega)$$



Coupled-cluster theory

- Starting point: Hartree-Fock reference state on the HO basis $|\Phi_0\rangle$
- Add correlations via:

$$e^{-T}He^{T}|\Phi_0\rangle = \overline{H}|\Phi_0\rangle = E_0|\Phi_0\rangle$$

Similarity-transformed Hamiltonian (non-Hermitian)

with

$$T = \sum t_i^a a_a^\dagger a_i + \sum t_{ij}^{ab} a_a^\dagger a_b^\dagger a_j a_i + \sum t_{ijk}^{abc} a_a^\dagger a_b^\dagger a_c^\dagger a_k a_j a_i + \ldots$$

→ coefficients from coupled-cluster equations

G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, RPP 77, 096302 (2014).

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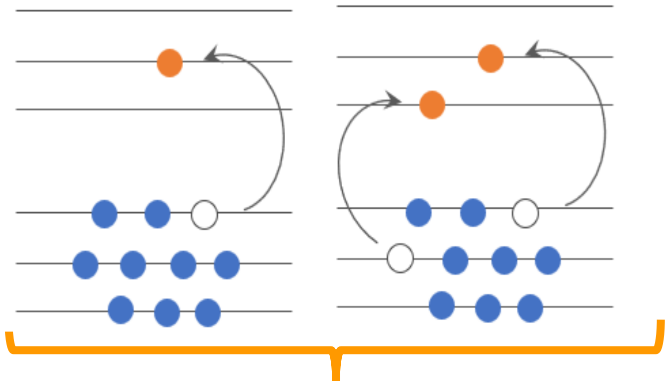
singles and doubles (CCSD)



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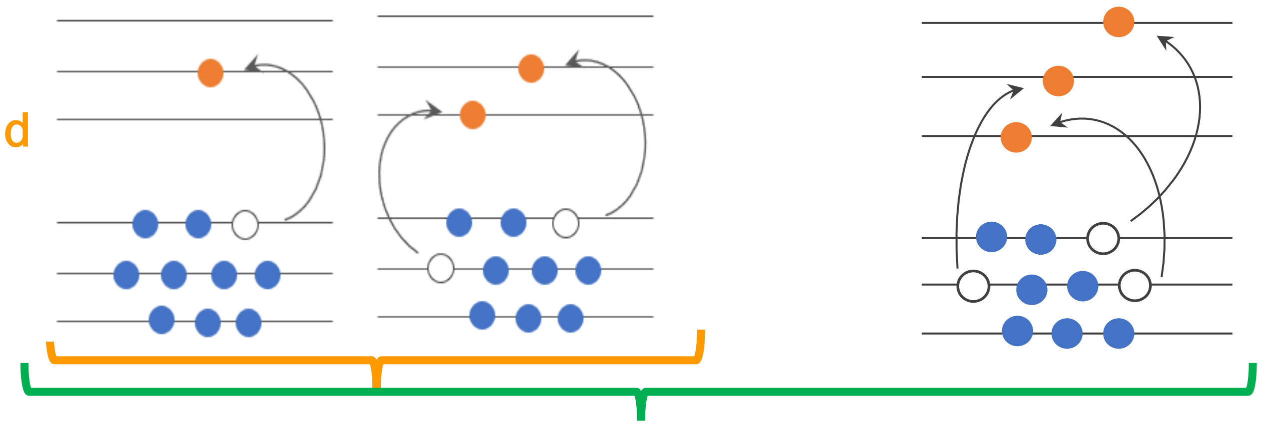

+ triples (CCSDT-1)

$\rightarrow$ coefficients from **coupled-cluster equations**

G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, RPP 77, 096302 (2014).

From bound to dipole-excited states

$$R(\omega) = \sum\!\!\!\!\!\!\!\int_f \left| \langle \Psi_f | \Theta | \Psi_0 \rangle \right|^2 \delta(E_f - E_0 - \omega)$$

S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock, PRL **111**, 122502 (2013).

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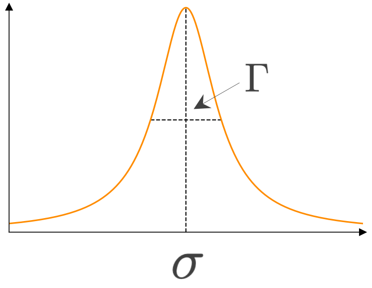
$$R(\omega) = \sum_f \left| \langle \Psi_f | \Theta | \Psi_0 \rangle \right|^2 \delta(E_f - E_0 - \omega)$$

$$L(\sigma, \Gamma) = \frac{\Gamma}{\pi} \int d\omega \, \frac{R(\omega)}{(\omega - \sigma)^2 + \Gamma^2} = \frac{\Gamma}{\pi} \langle \Psi_L | \Psi_R \rangle$$



Lorentz Integral Transform (LIT)

S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock, PRL **111**, 122502 (2013).

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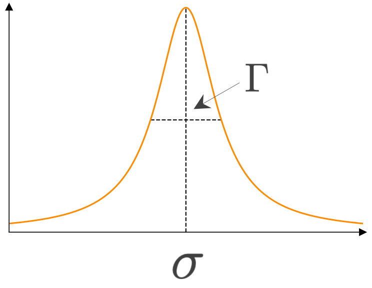

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where

$$(\overline{H} - E_0 - \sigma - i\Gamma) |\Psi_R\rangle = \overline{\Theta} \, |\Phi_0\rangle$$

CC equation of motion with a source

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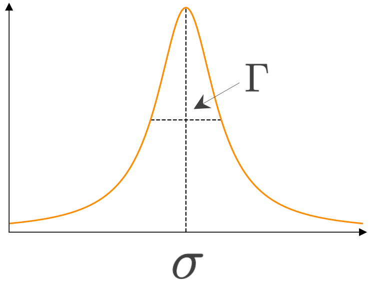

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CC equation of motion with a source

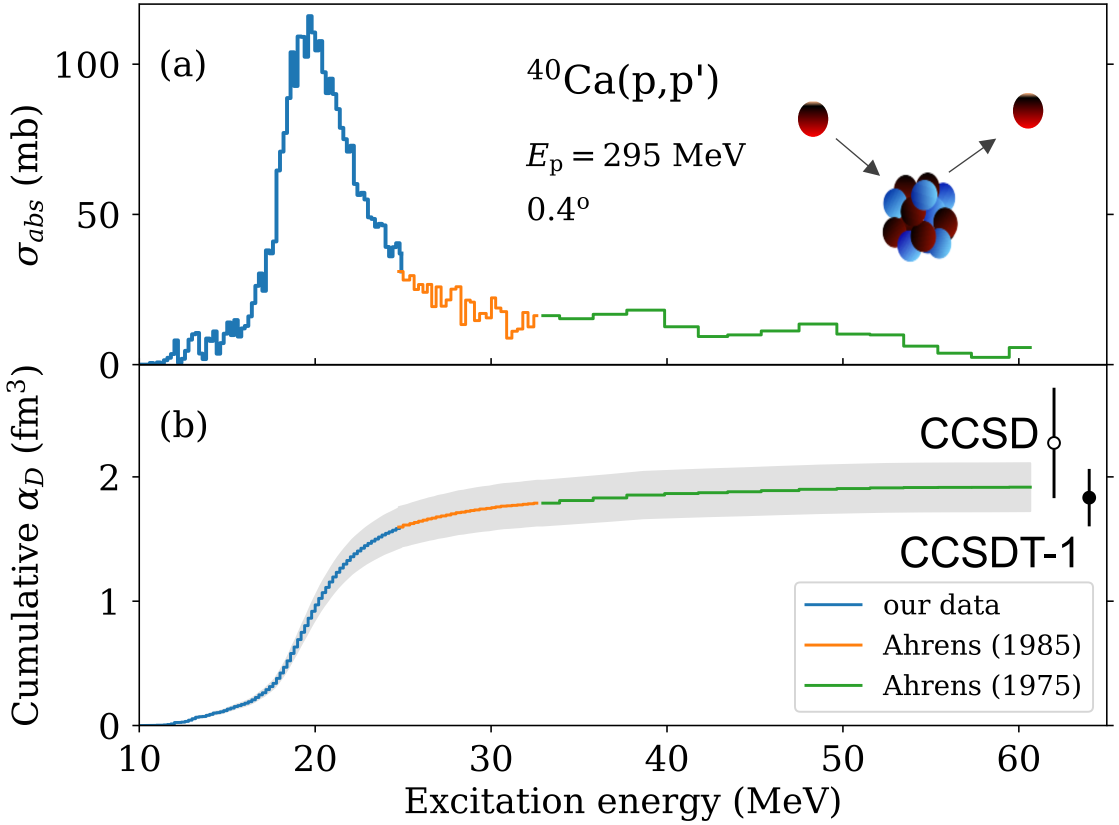
LIT-CC ansatz for closed-shell nuclei:

$$|\Psi_R\rangle = \mathcal{R} |\Phi_0\rangle \qquad \mathcal{R} = r_0 + \sum r_i^a a_a^\dagger a_i + \sum r_{ij}^{ab} a_a^\dagger a_b^\dagger a_j a_i + \dots$$

S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock, PRL **111**, 122502 (2013).

The case of ^{40}Ca

R. Fearick, P. von Neumann-Cosel, S. Bacca, **FB** et al, Phys. Rev. Research **5**, L022044 (2023).



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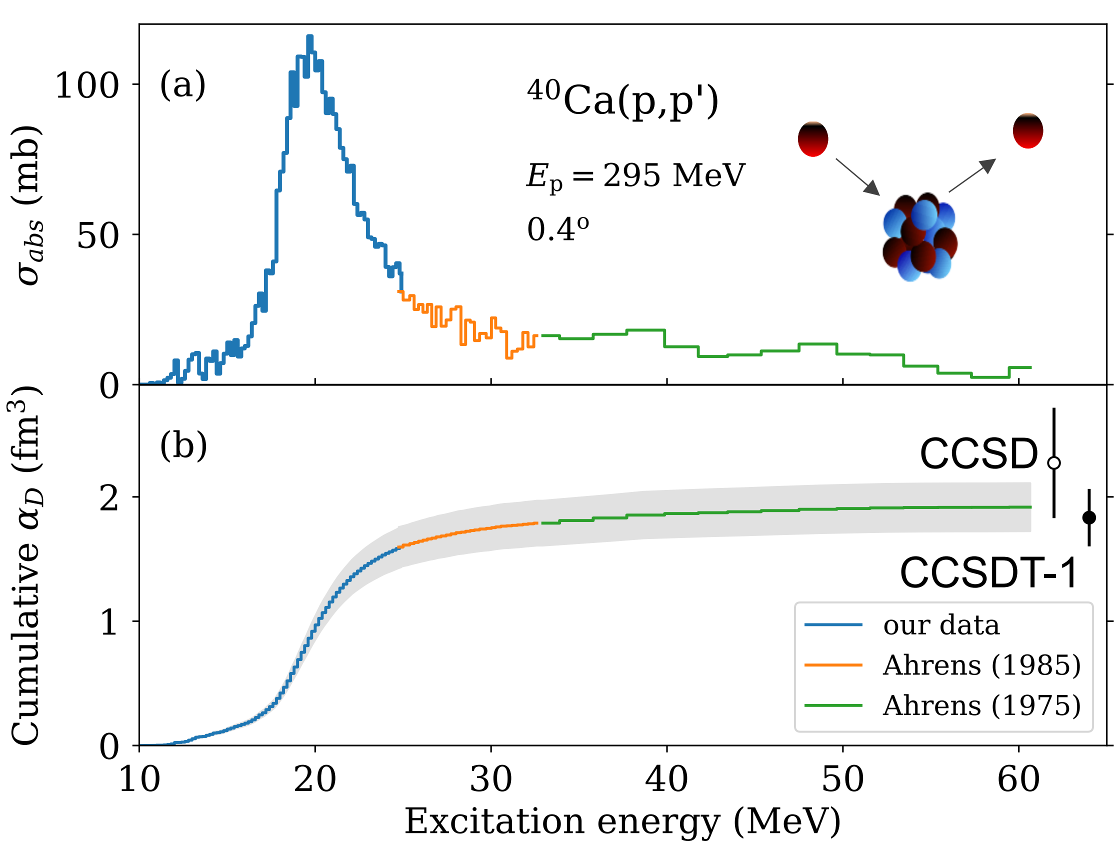
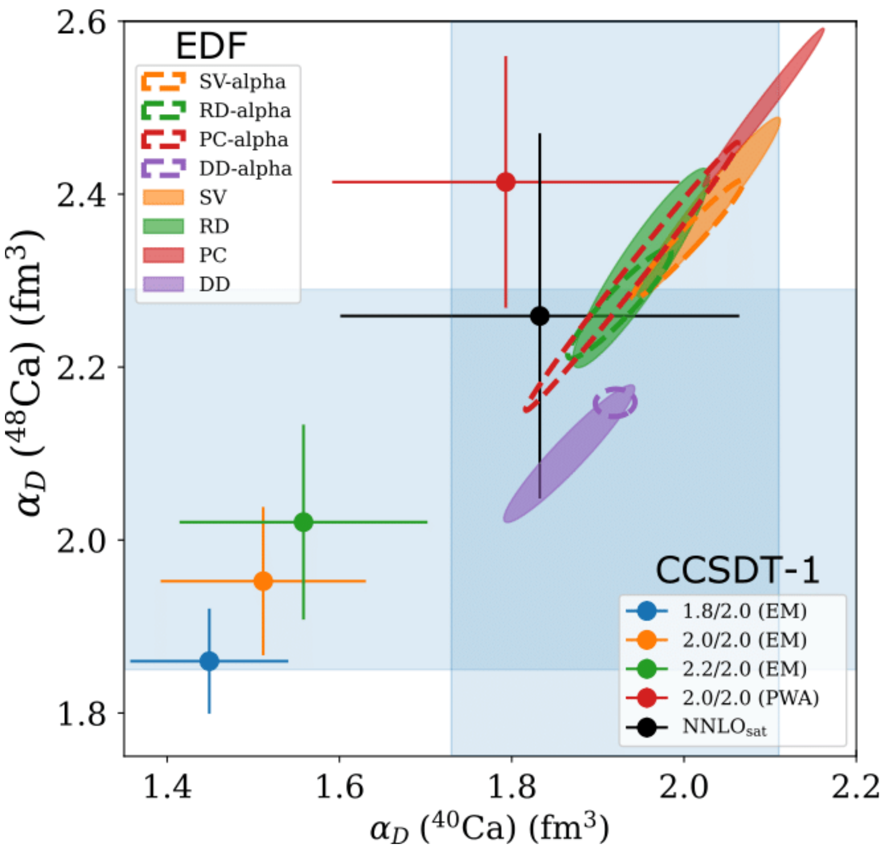
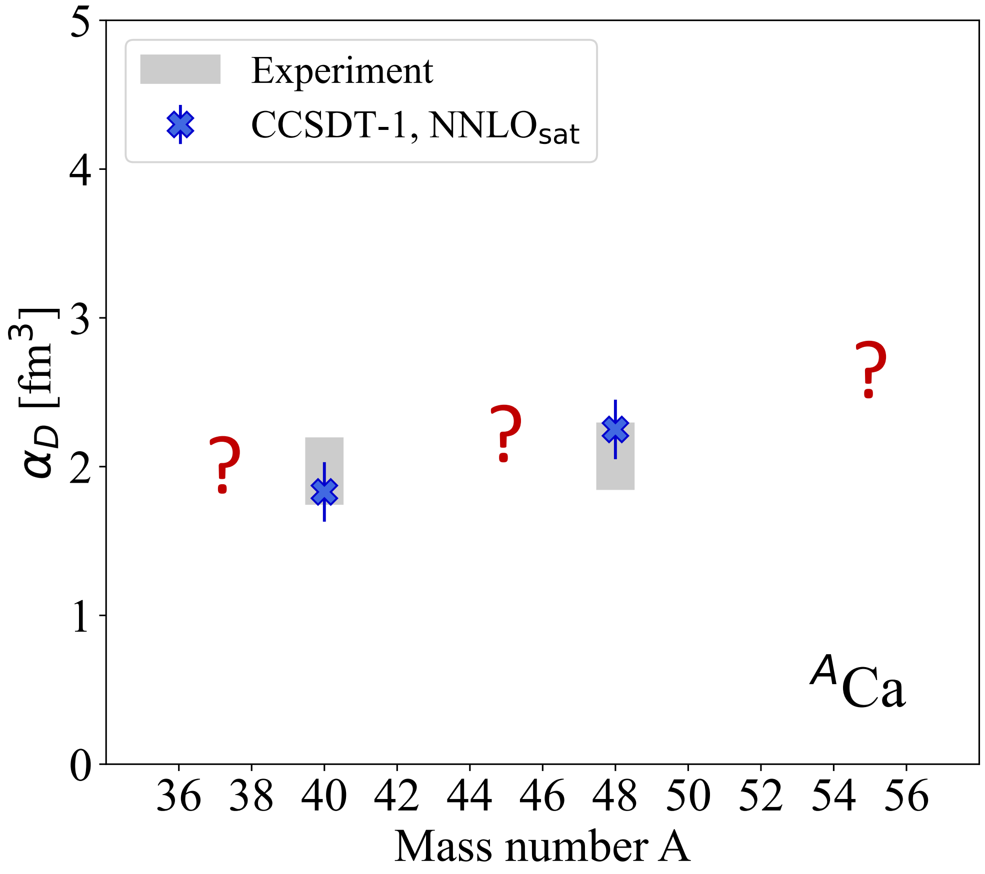




Constraints on slope parameter from chEFT interactions of this work: L = 41 - 49 MeV

Global analysis of all Ca+Pb skin data [J. Lattimer, Particles (2023)]: L = 40 ± 8 MeV

Happy ending for ^{40,48}Ca... but what's next?



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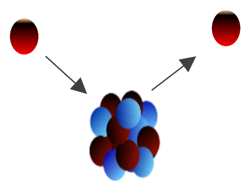
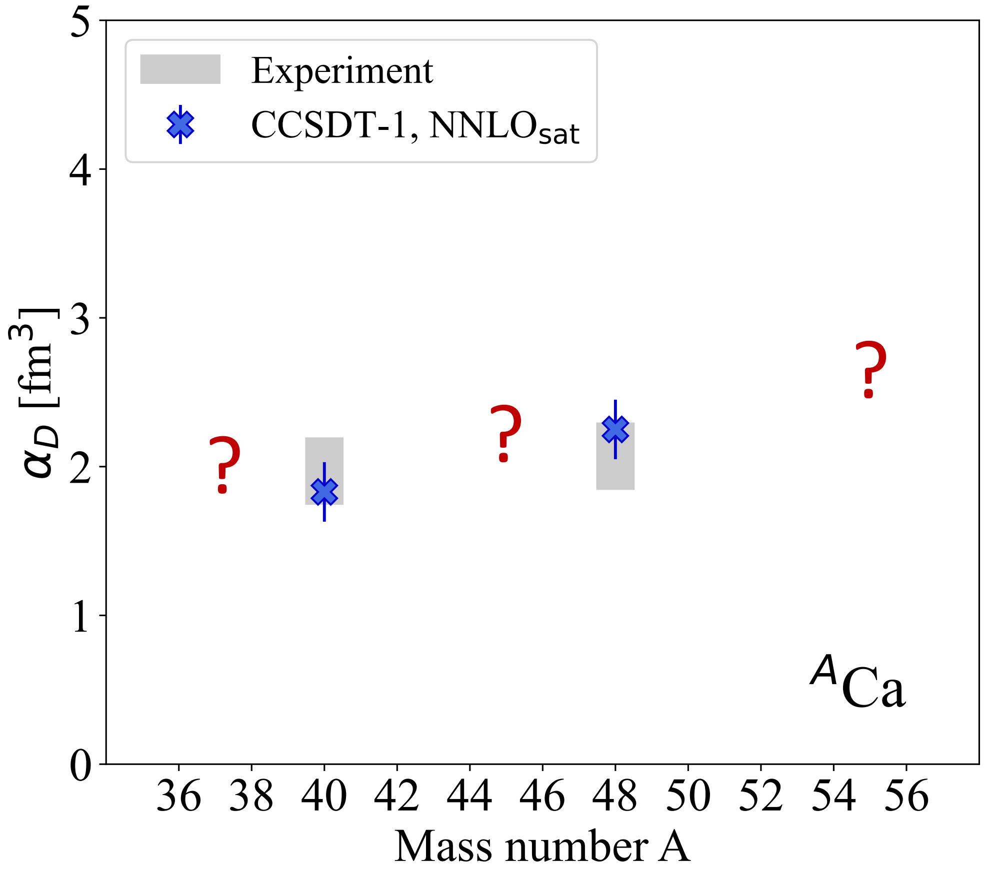
Ongoing **inelastic proton scattering experiments** to measure α_D



at iThemba Labs, South Africa and RNCP, Japan of **nuclei near closed shells**, e.g. ^{42}Ca, ^{58}Ni…



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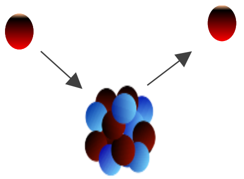

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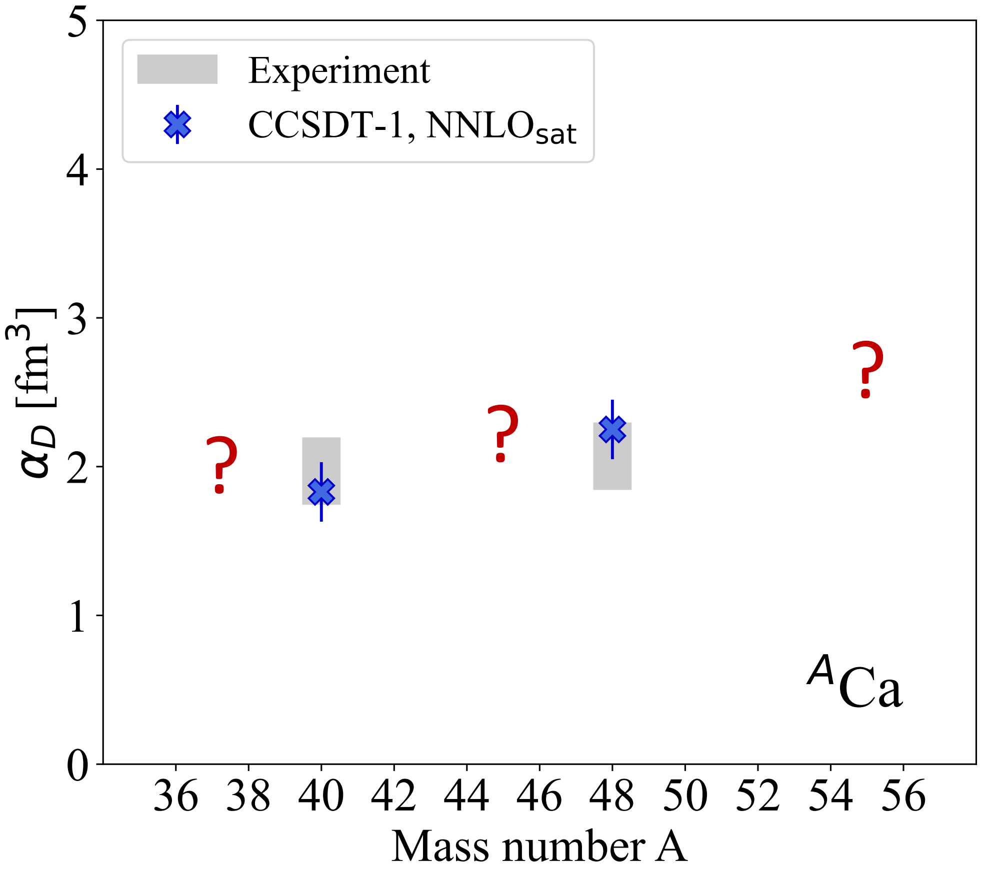

… and in the future, a FRIB400 upgrade will allow studies of **α_D for very neutron-rich nuclei** with **Coulex experiments.**

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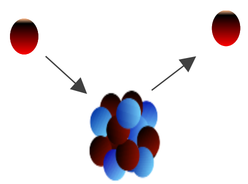

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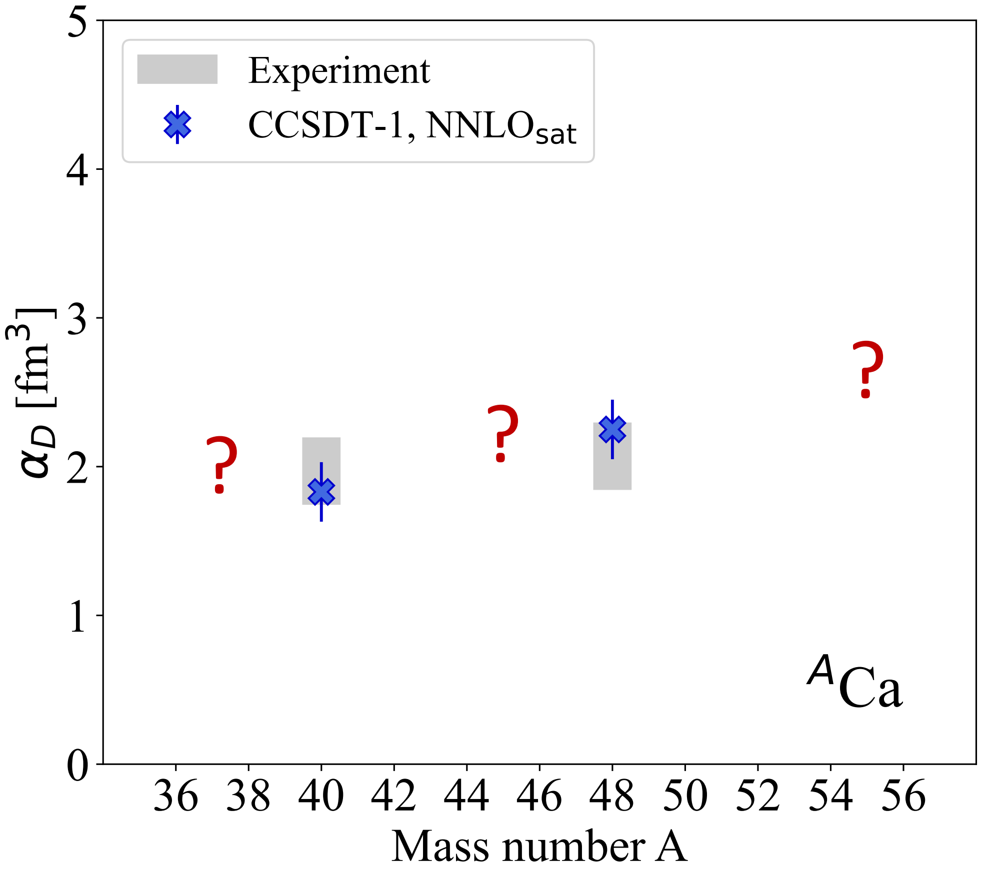

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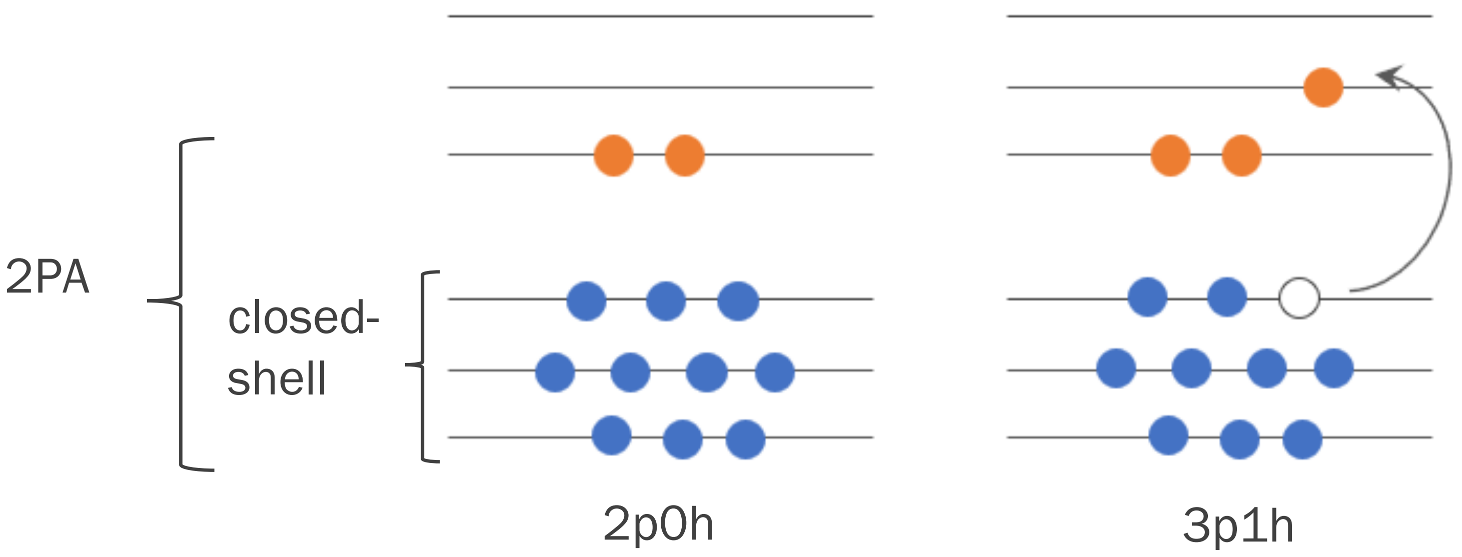
We need to extend the LIT-CC method beyond closed-shell nuclei!

LIT-CC for open-shell nuclei: the 2-Particle-Attached (2PA) case

$$\mathcal{R} = \frac{1}{2}\sum r^{ab} a_a^\dagger a_b^\dagger + \frac{1}{6}\sum r_i^{abc} a_a^\dagger a_b^\dagger a_c^\dagger a_i + \ldots$$

$$|\Psi_R\rangle = \mathcal{R}|\Phi_0\rangle$$



FB et al., in preparation.

Many-body truncations in LIT-CC

To solve

$$(\overline{H} - E_0 - \sigma - i\Gamma)\left|\Psi_R\right\rangle = \overline{\Theta}\left|\Phi_0\right\rangle$$

we have two CC expansions, for ground and excited states.

In the closed-shell case we consider excited states @CCSD and vary ground-state scheme.

We then estimate the many-body uncertainty as:

$$\delta_{\alpha_D}^{CC} \approx \frac{\alpha_D^{CCSD} - \alpha_D^{CCSDT-1}}{2}$$

What about the 2PA case?

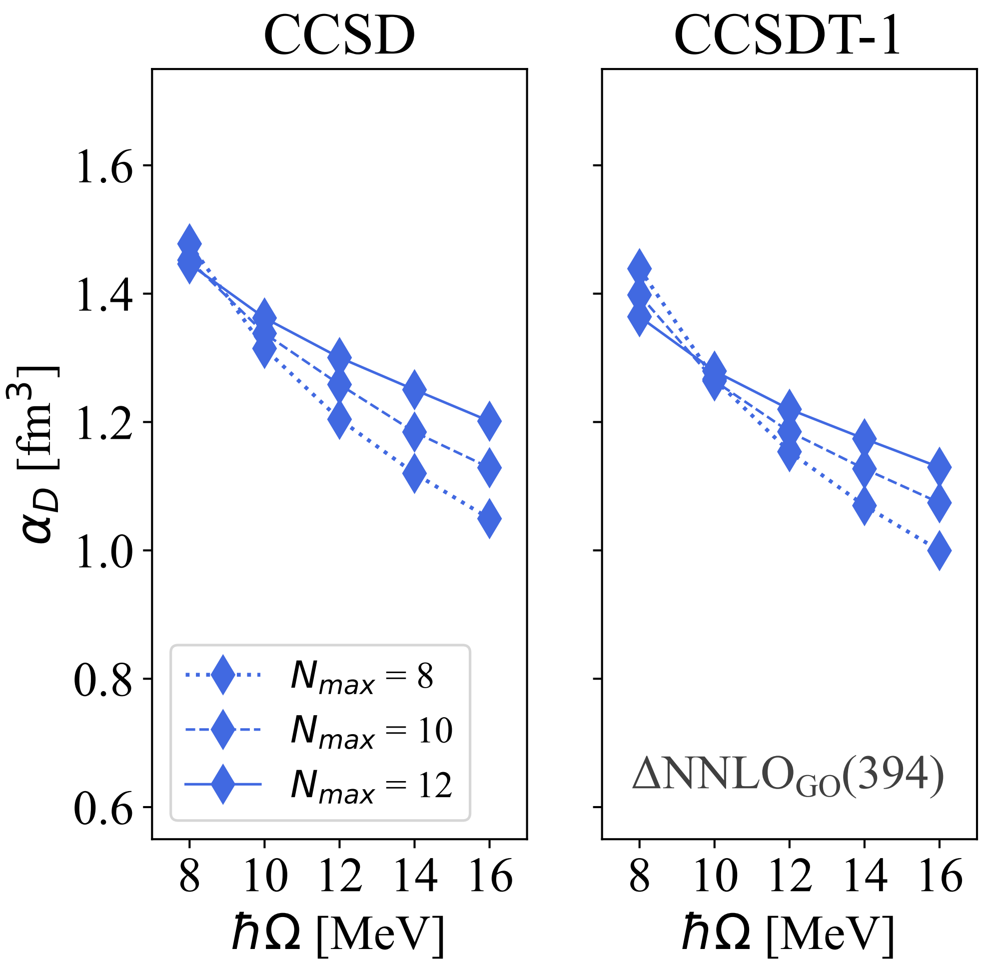
In this case, for the moment we do not have access to orders higher than 3p1h...

If we can't go higher, let's go lower!

We use the 3p1h scheme for excited states, to keep as much correlations as possible in the LIT calculation, and we look at:

$$\delta_{\alpha_D}^{\mathrm{CC}} \approx \frac{\alpha_D^{\mathrm{3p1h/3p1h}} - \alpha_D^{\mathrm{2p0h/3p1h}}}{2}$$

Electric dipole polarizability of ^{24}O



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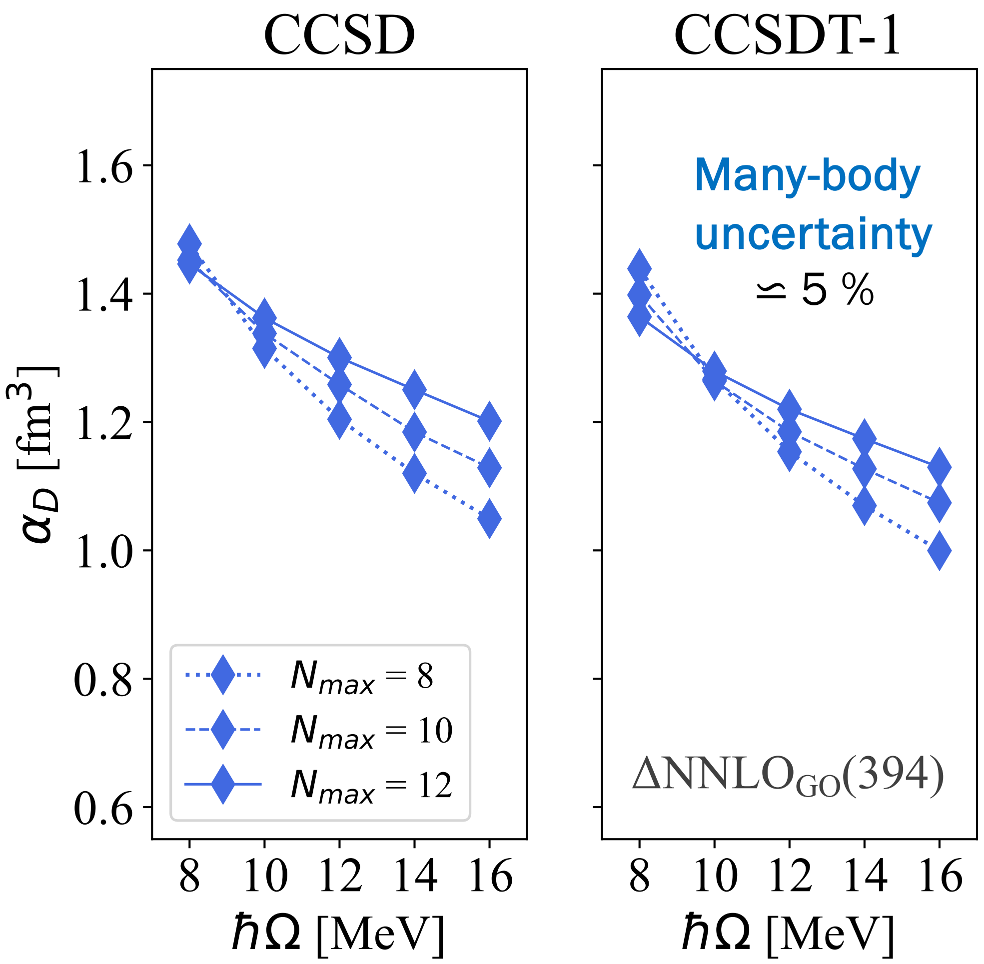

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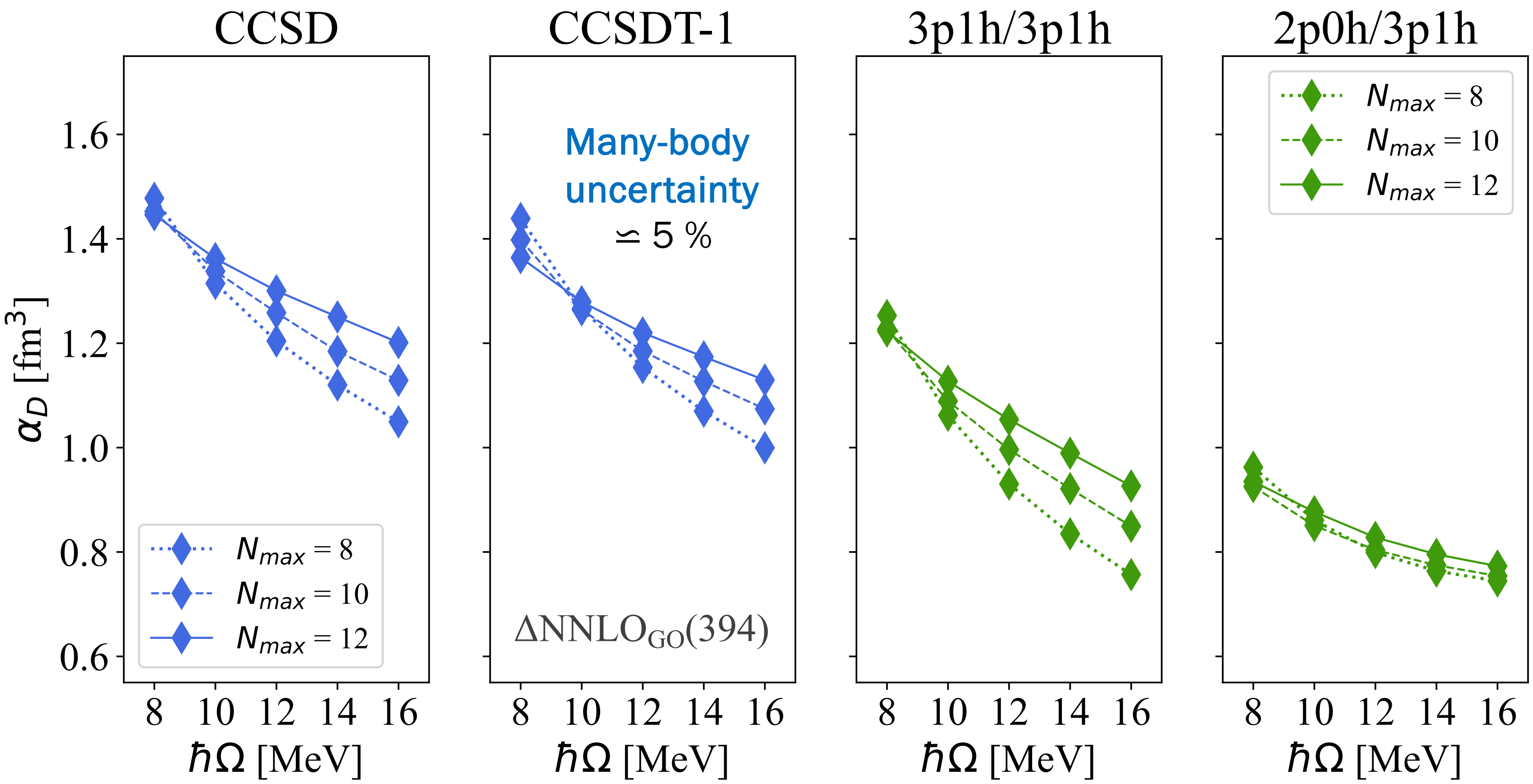

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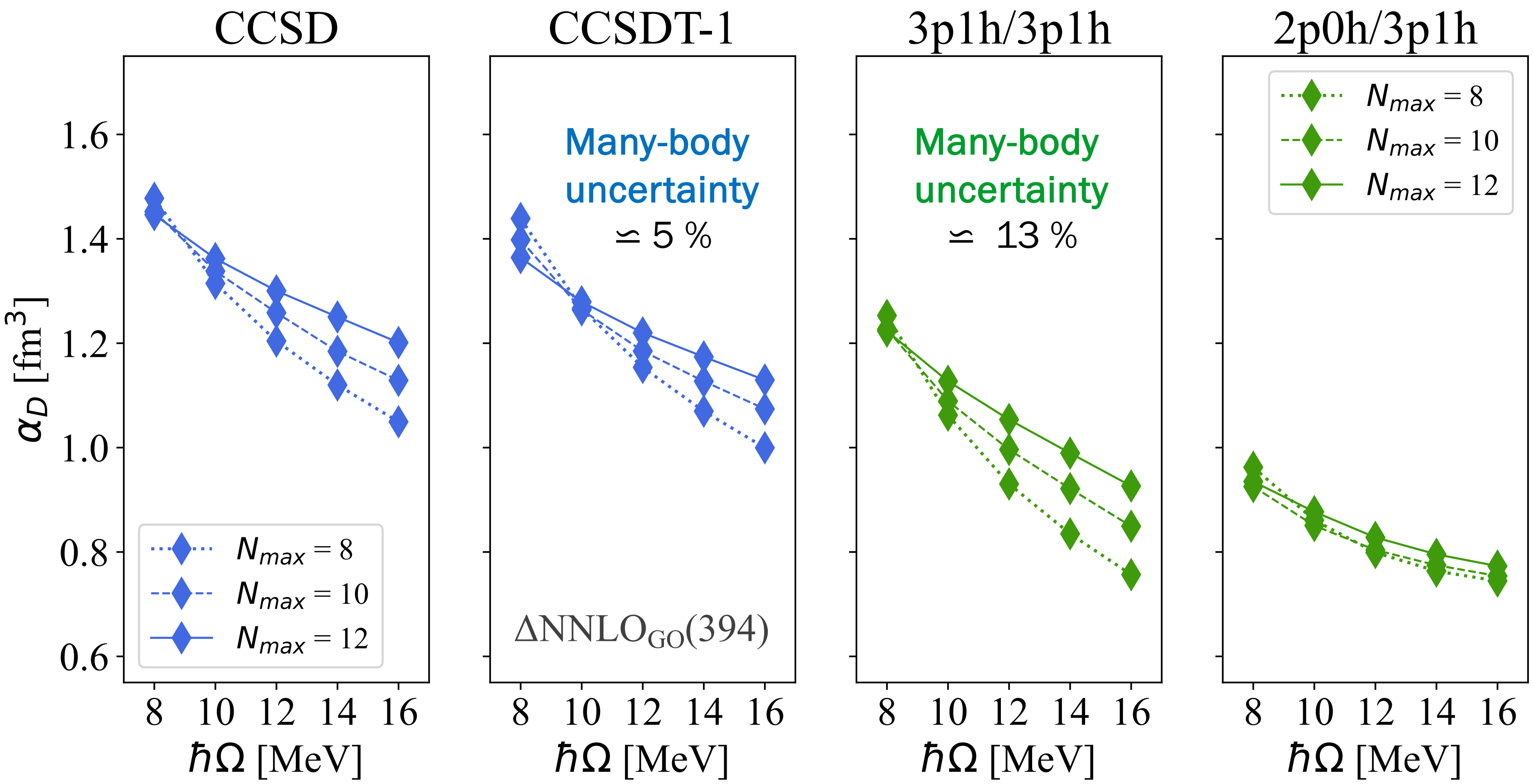

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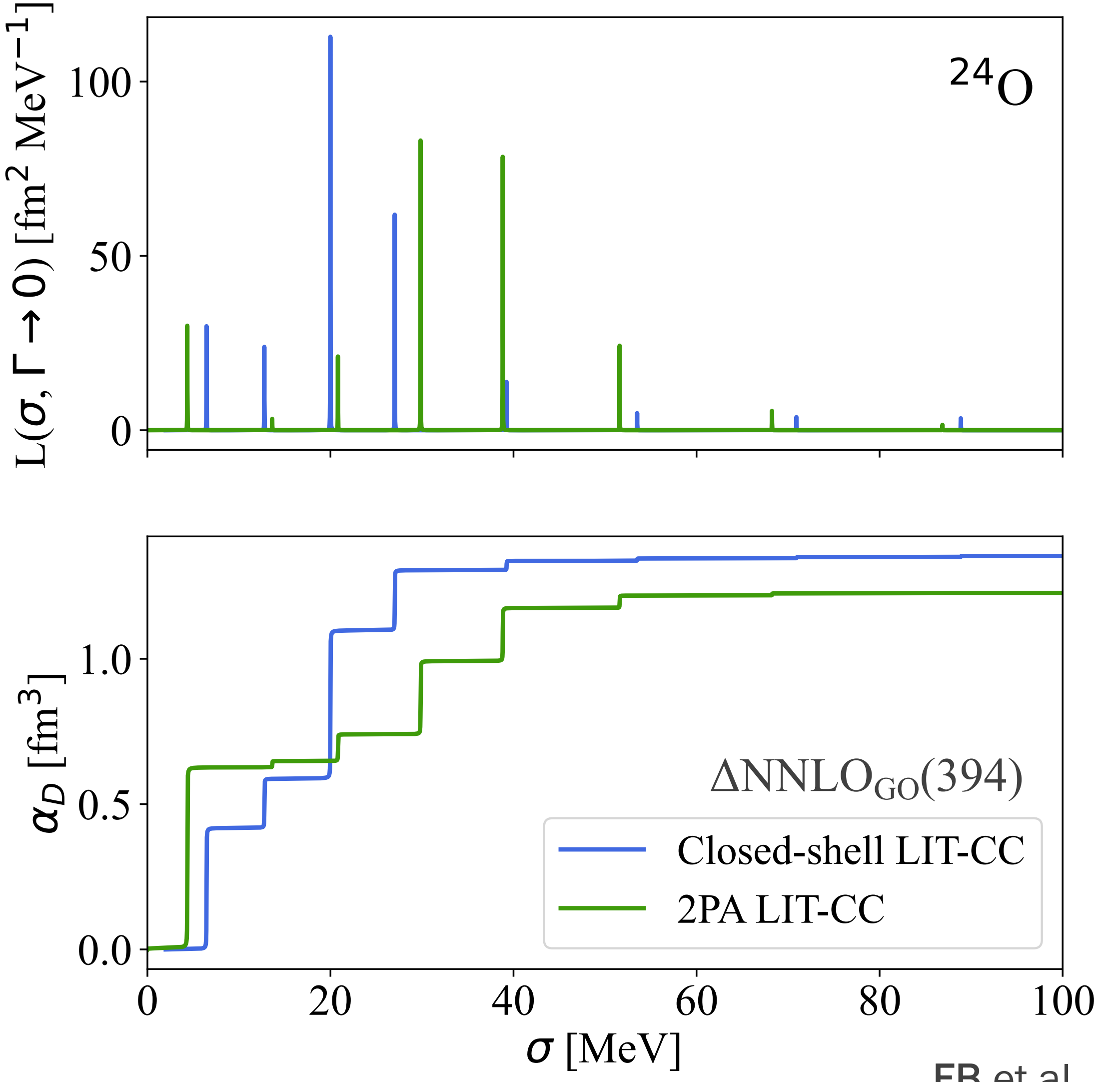
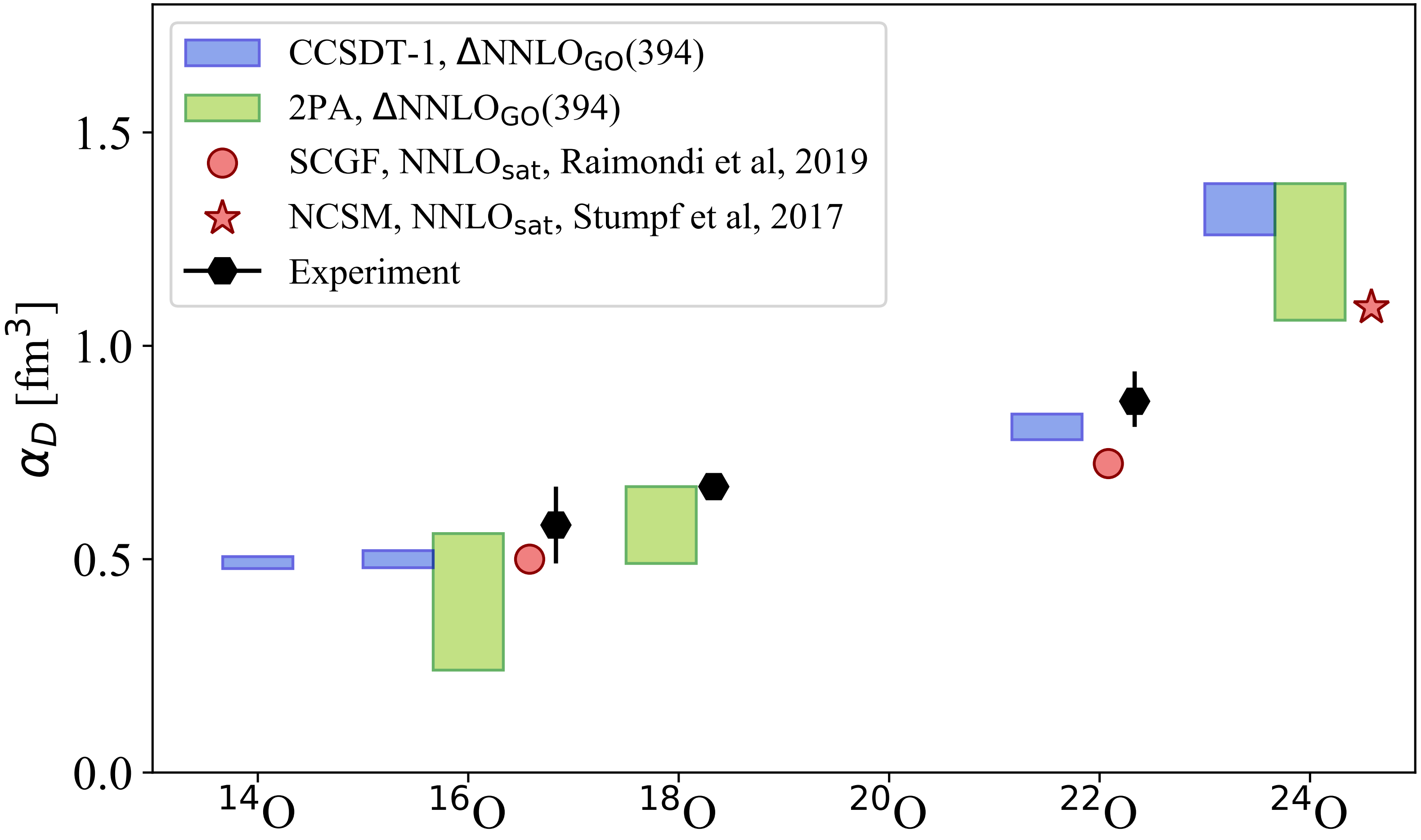


$$L(\sigma, \Gamma \to 0) = \int d\omega\, R(\omega)\delta(\omega - \sigma) = R(\sigma)$$

$$\alpha_D = 2\alpha \int d\sigma\, \frac{L(\sigma, \Gamma \to 0)}{\sigma}$$

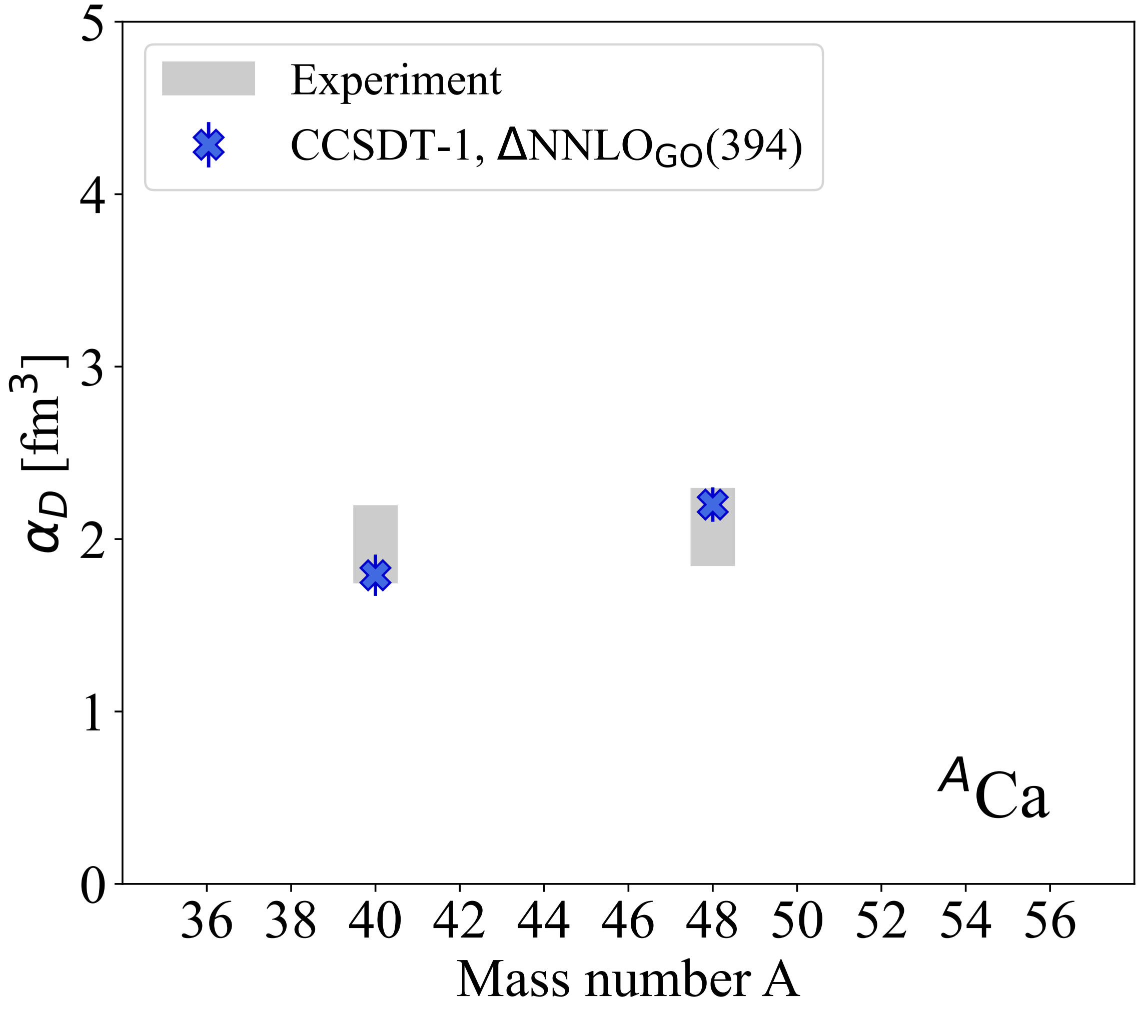
FB et al., in preparation.

α_D along oxygen isotopes



FB et al., in preparation.

… and heavier: α_D in calcium isotopes



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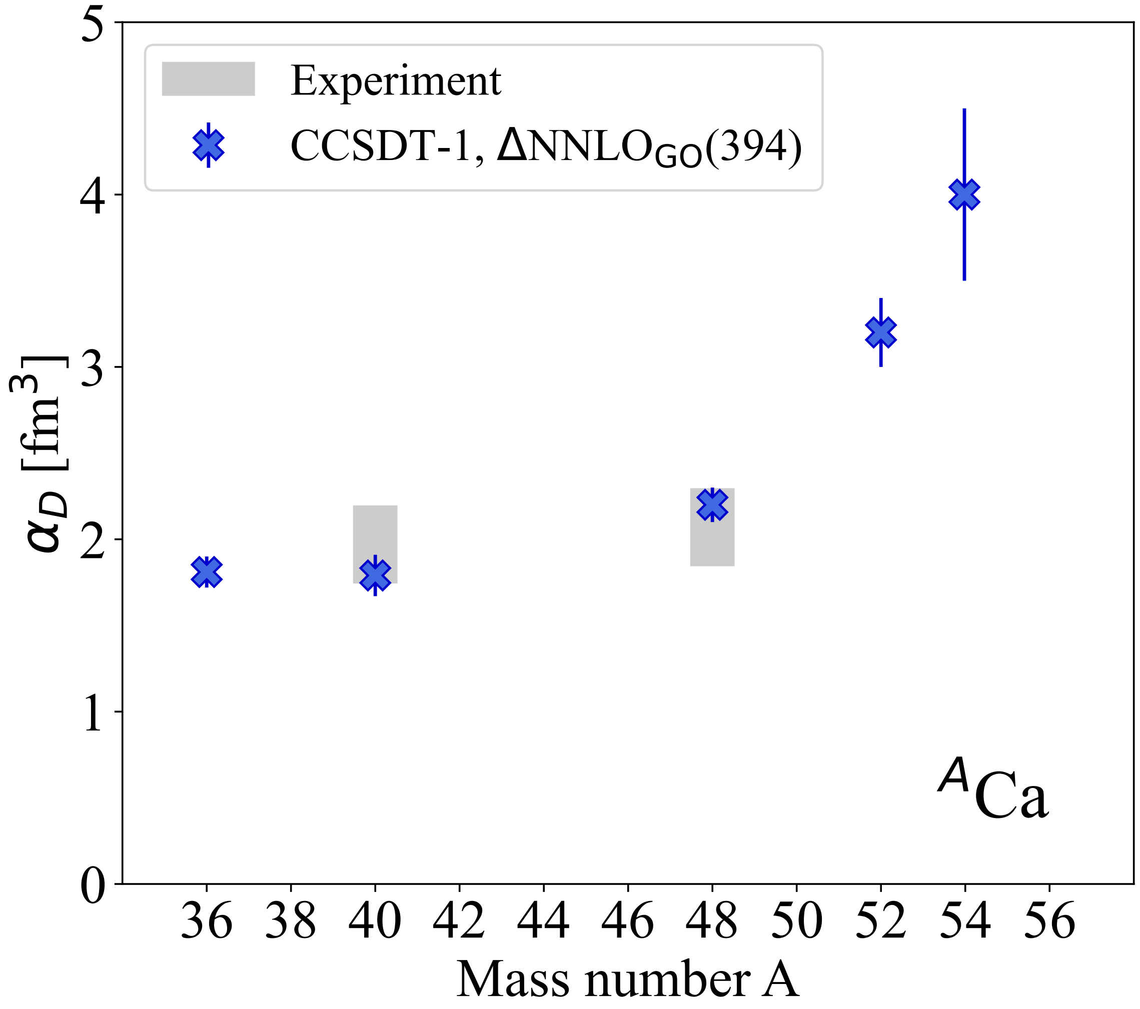

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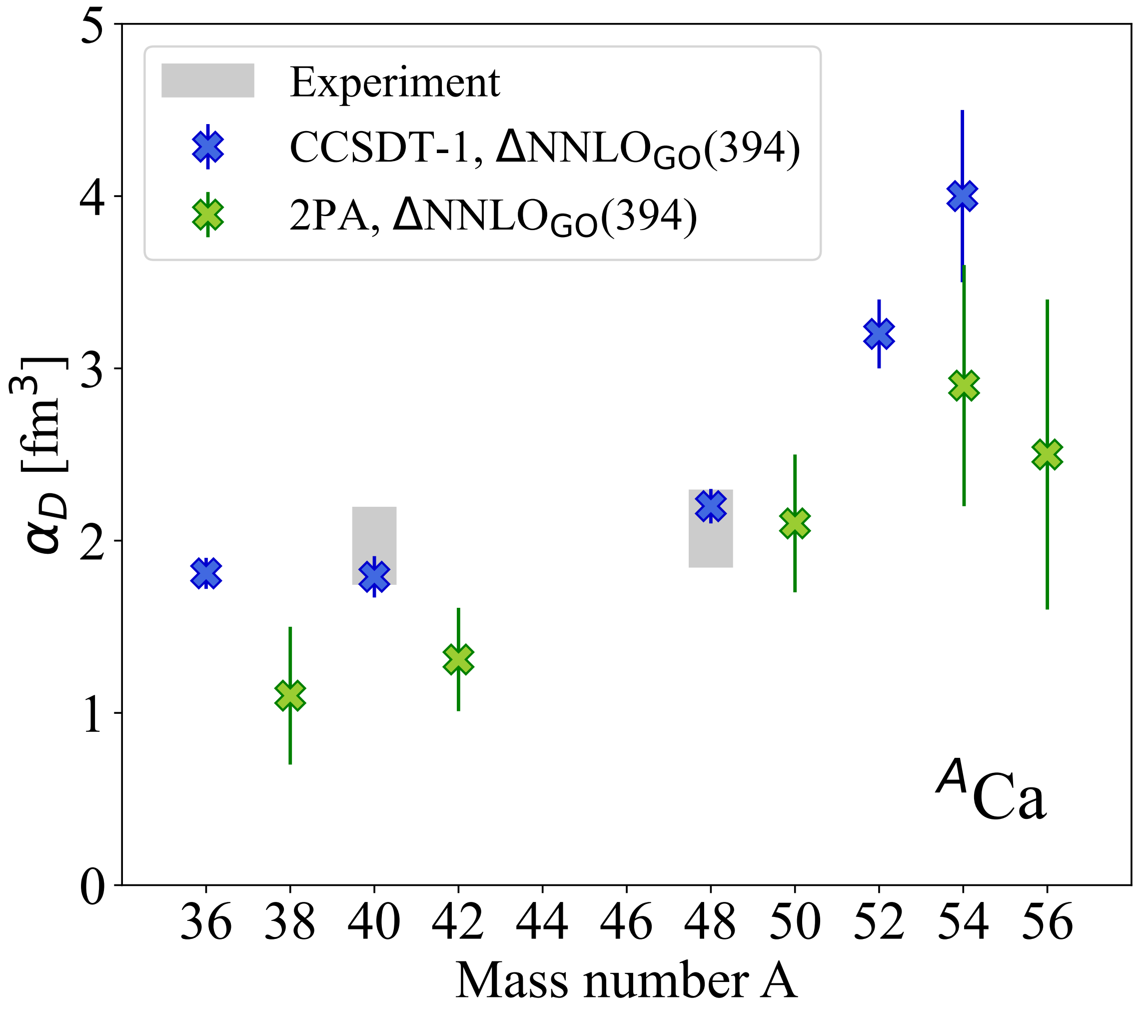

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Conclusions

- ❑ Dipole polarizabilities provide a way to cast light on the collective excitations of the nucleus as well as to put constraints on the nuclear symmetry energy.
- ❑ We extended the reach of ab initio calculations of these electromagnetic observables to nuclei in the vicinity of closed shells, and investigated the effect of many-body truncations.
- ❑ Soon new experimental benchmarks for 2PA nuclei!

Thank you for your attention!