Helium halo isotopes and other neutron-rich stories

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In collaboration with:
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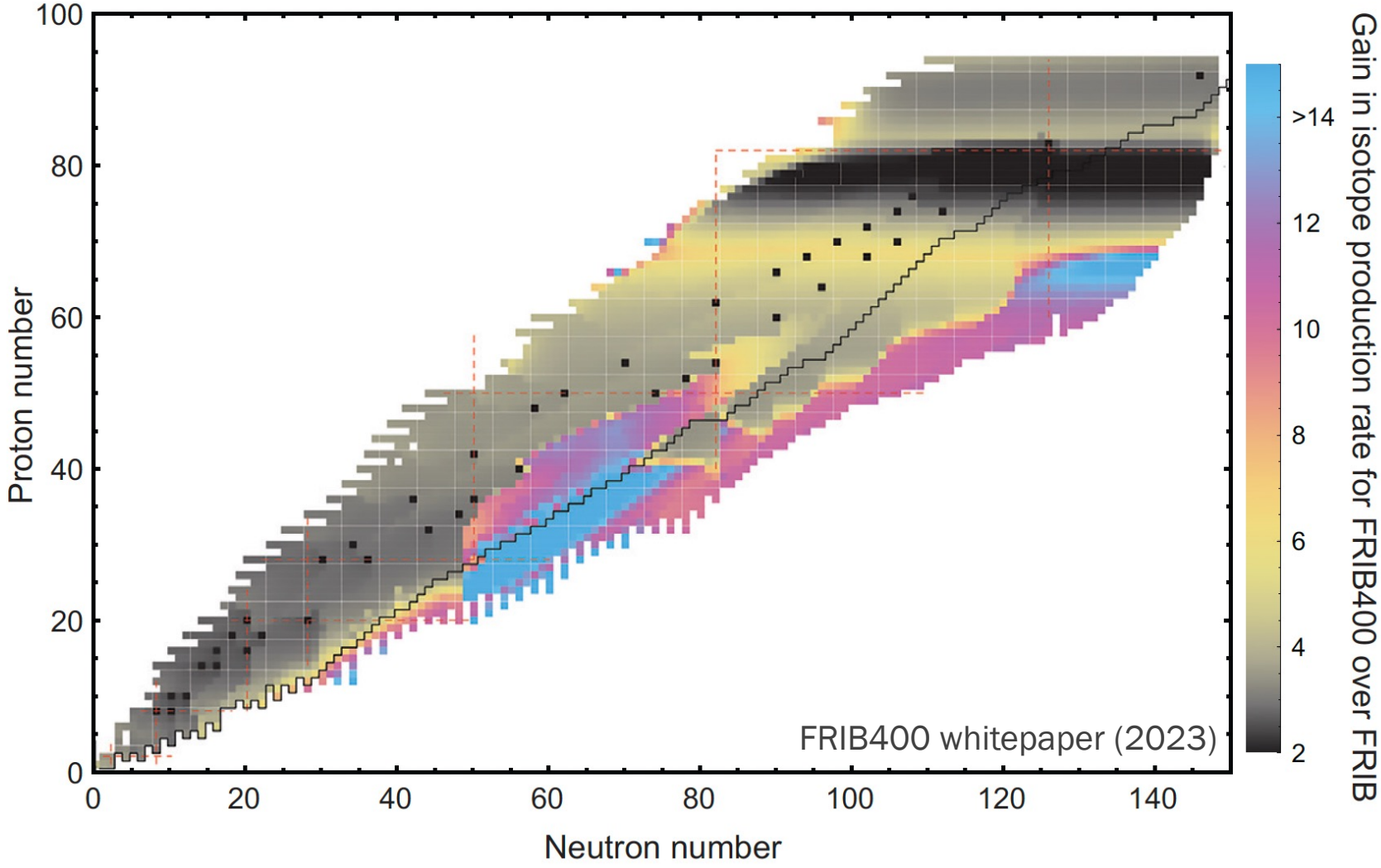
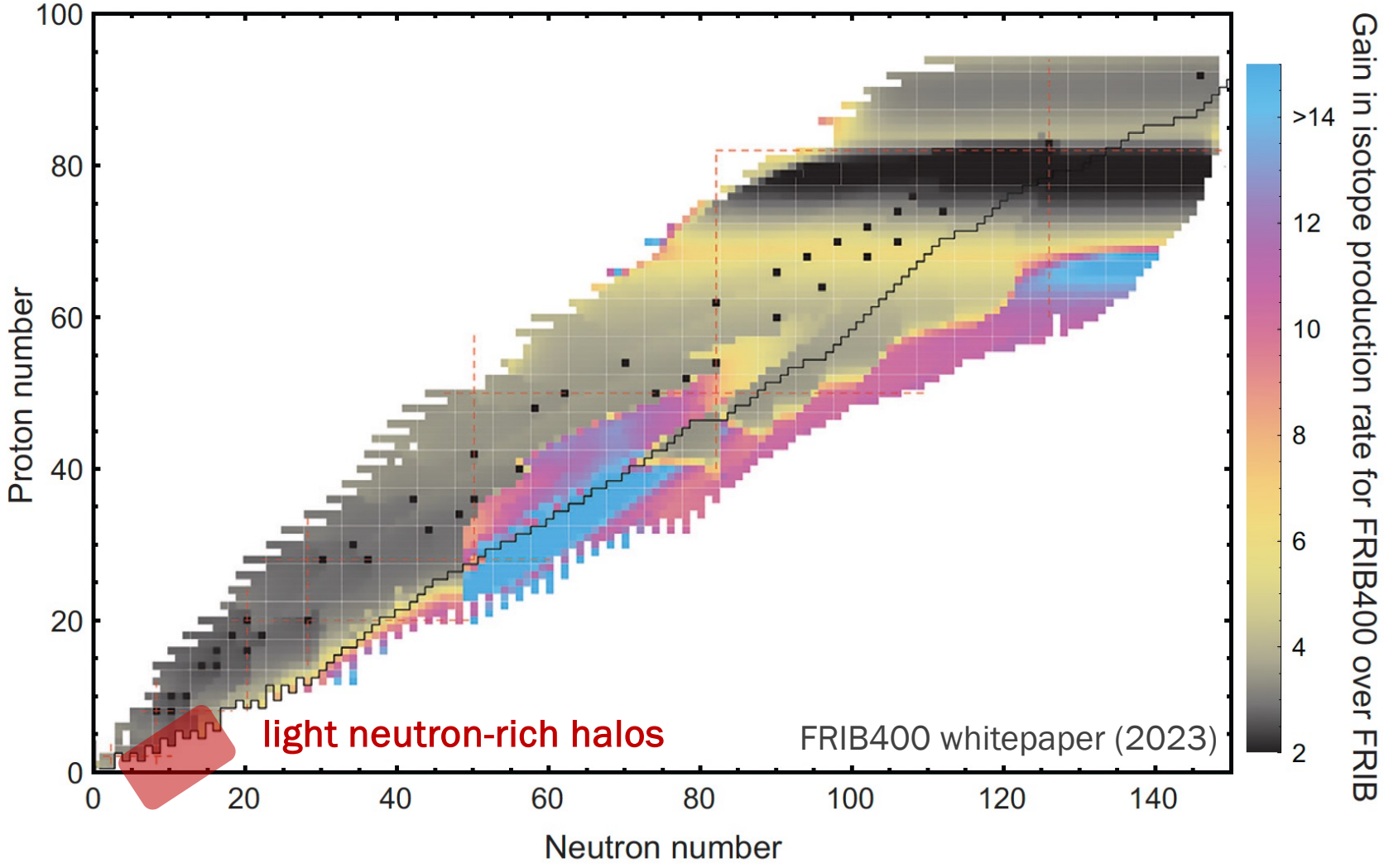
Thomas Papenbrock (ORNL/UTK)

The neutron-rich frontier



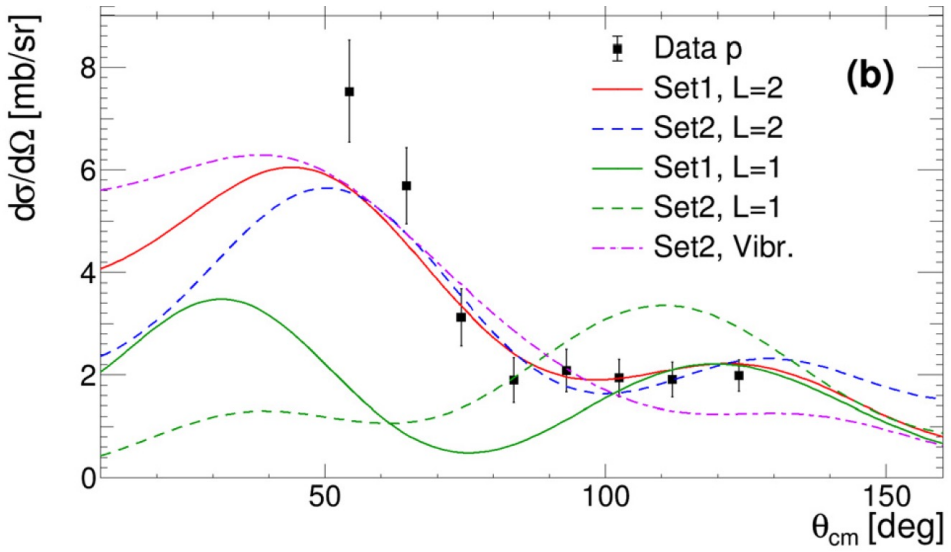
The neutron-rich frontier



Is there a soft dipole mode in ^{8}He?

Proton inelastic scattering on ^{8}He @ TRIUMF

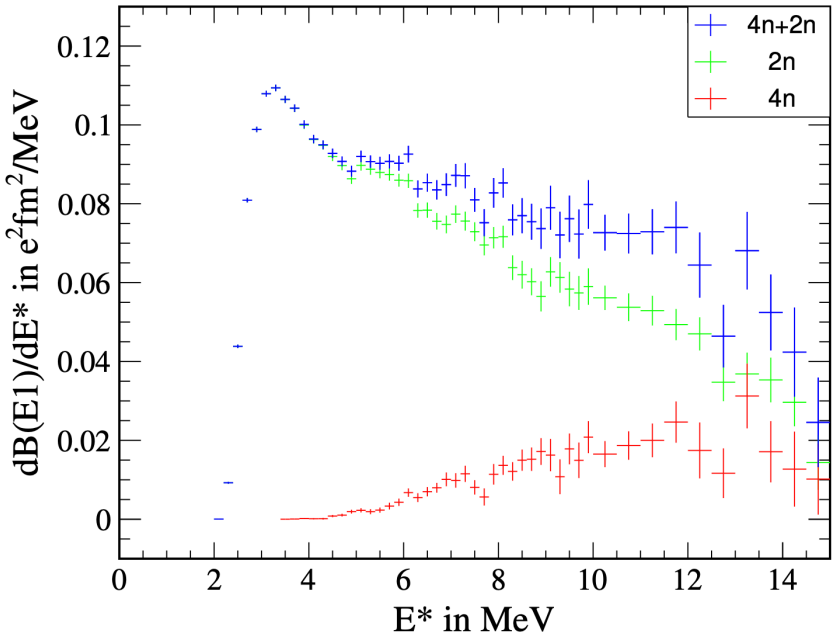
No sign of dipole resonances below 6 MeV.



M. Holl et al, PLB 822 136710 (2021).

Coulomb excitation experiment on ^{8}He @RIKEN

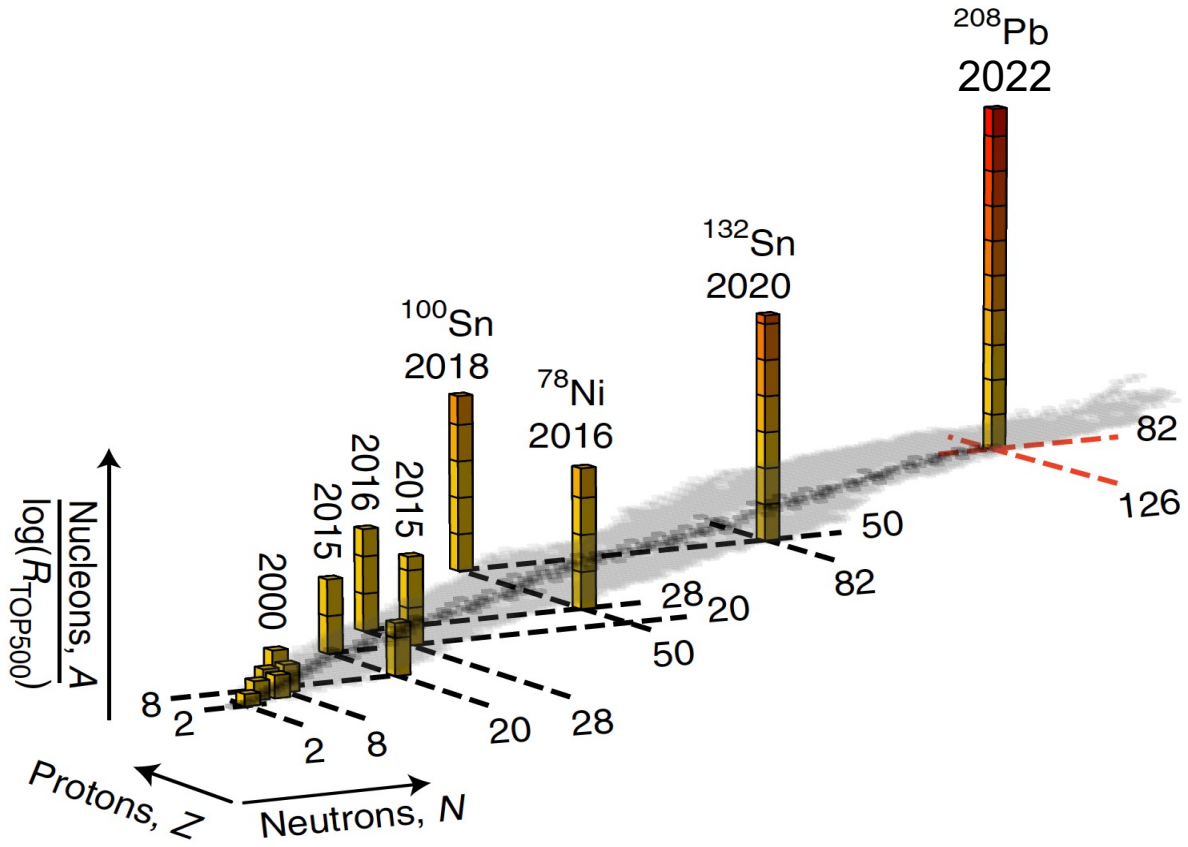
High-precision study of 2n and 4n breakup channels.
Low-energy strength appearing at 3-4 MeV.



C. Lehr (TU Darmstadt PhD thesis, 2021)
& SAMURAI collab.

What does theory say about this?

Ab initio nuclear theory



- Building blocks: **protons and neutrons.**
- Solve **quantum many-body problem**

$$H\,|\psi\rangle = E\,|\psi\rangle$$
$$H = T + V_{NN} + V_{3N}$$

with **controlled approximations**.

- 2 ingredients: **chiral EFT interactions** and **coupled-cluster theory** as many-body solver.

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

Coupled-cluster theory

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

$$|\Psi_0\rangle = e^T |\Phi_0\rangle$$

with

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

→ coefficients from coupled-cluster equations

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

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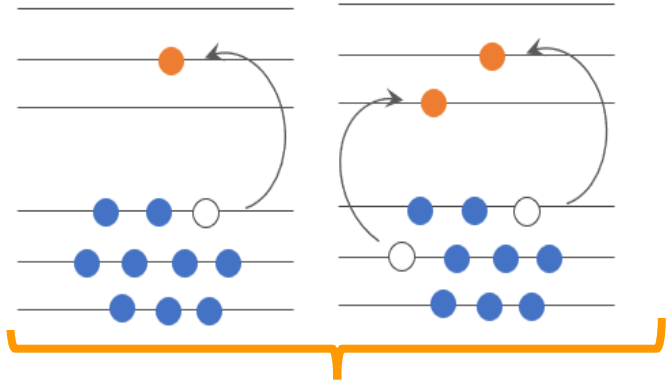
singles and doubles (CCSD)



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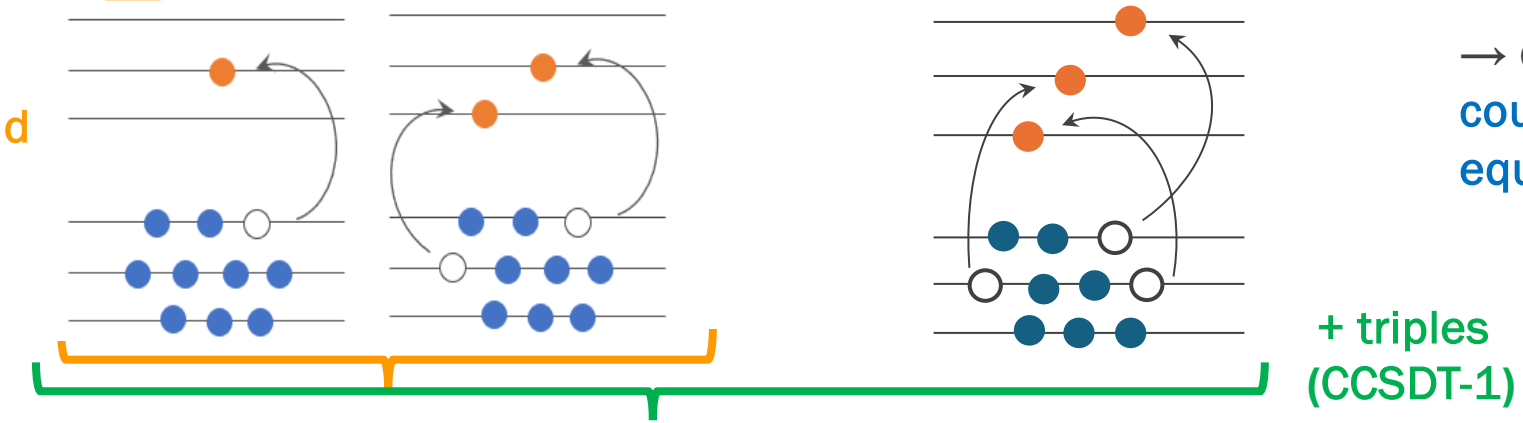

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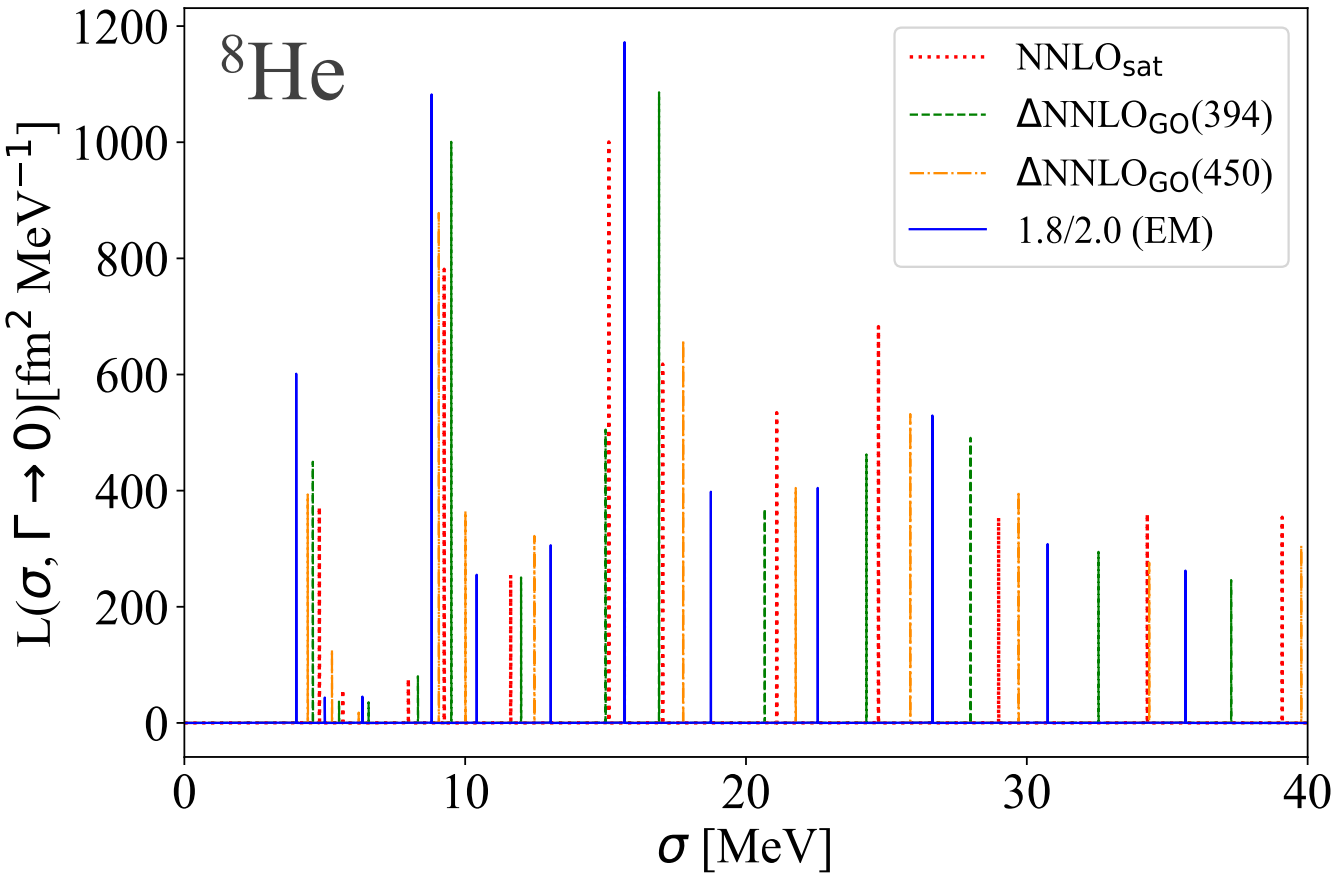
From ground to dipole-excited states

Dipole excitations described by the **nuclear response function**.

$$R(\omega) = \sum_f |\langle f|\hat{\Theta}|0\rangle|^2 \delta(\omega - E_f + E_0)$$

→ **continuum problem** addressed via **Lorentz Integral Transform** method.



FB et al., PRC 105, 034313 (2022).
FB et al., FBS 65, 54 (2024).

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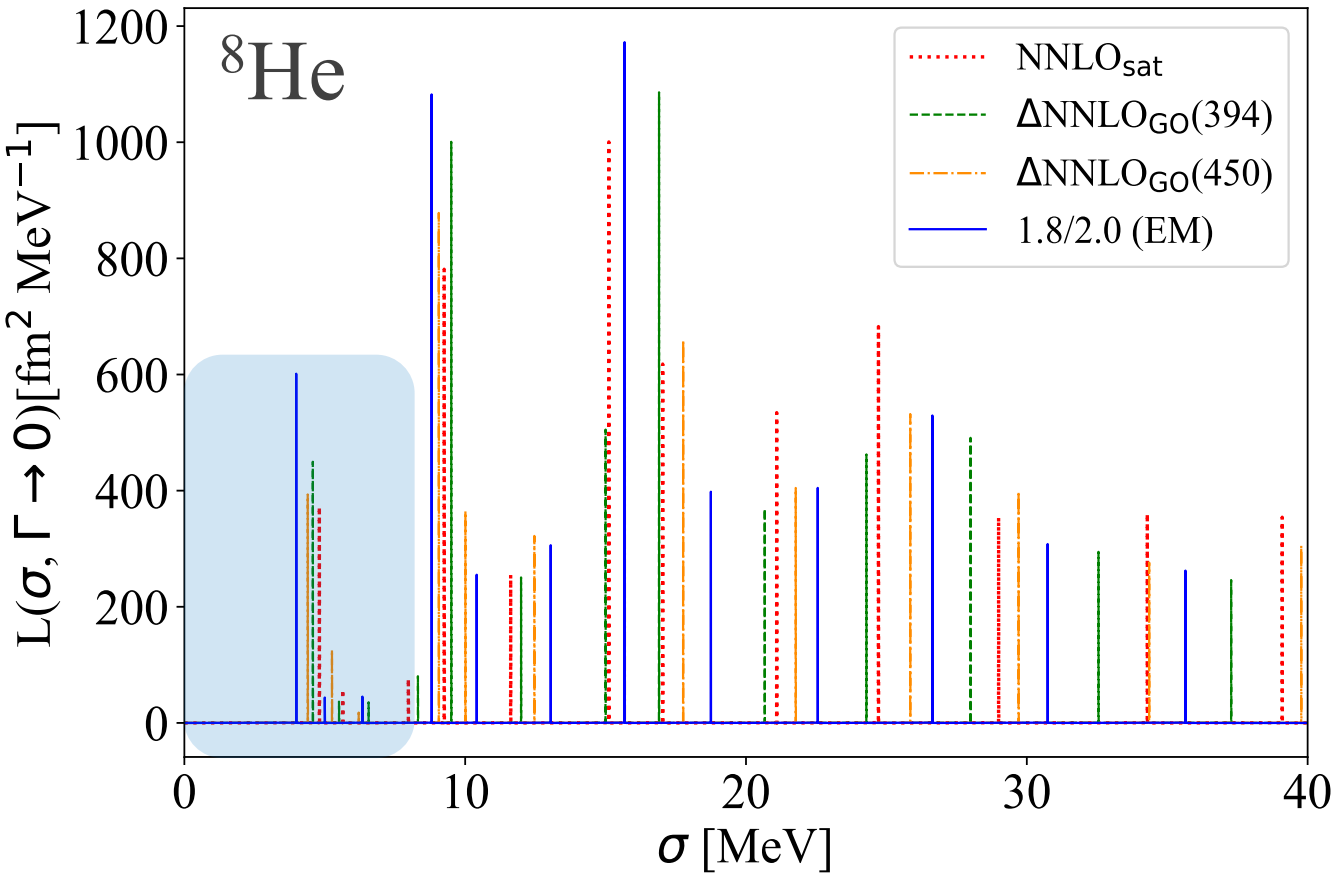
We study the **low-energy spectrum** via the **dipole polarizability**:

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



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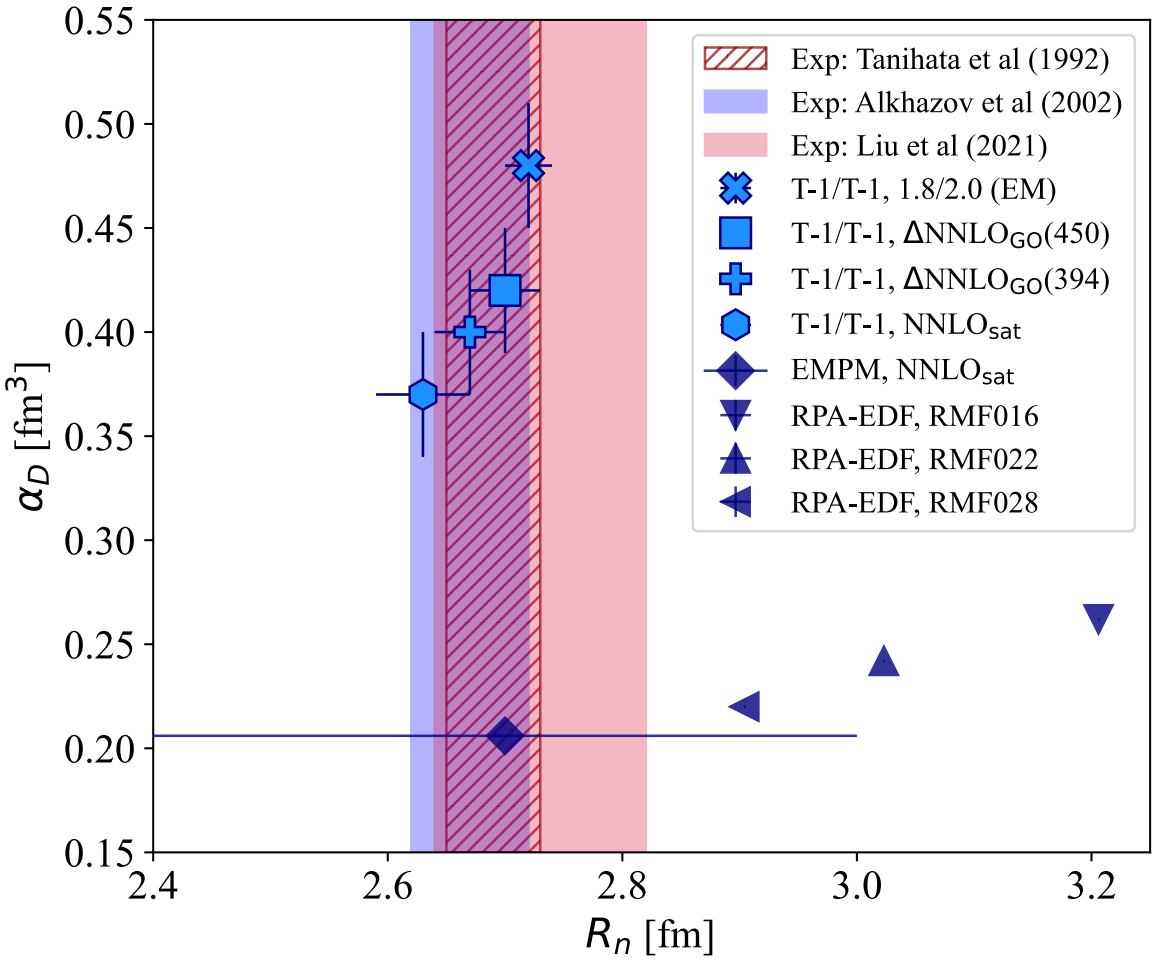
Correlation between α_D and neutron radius



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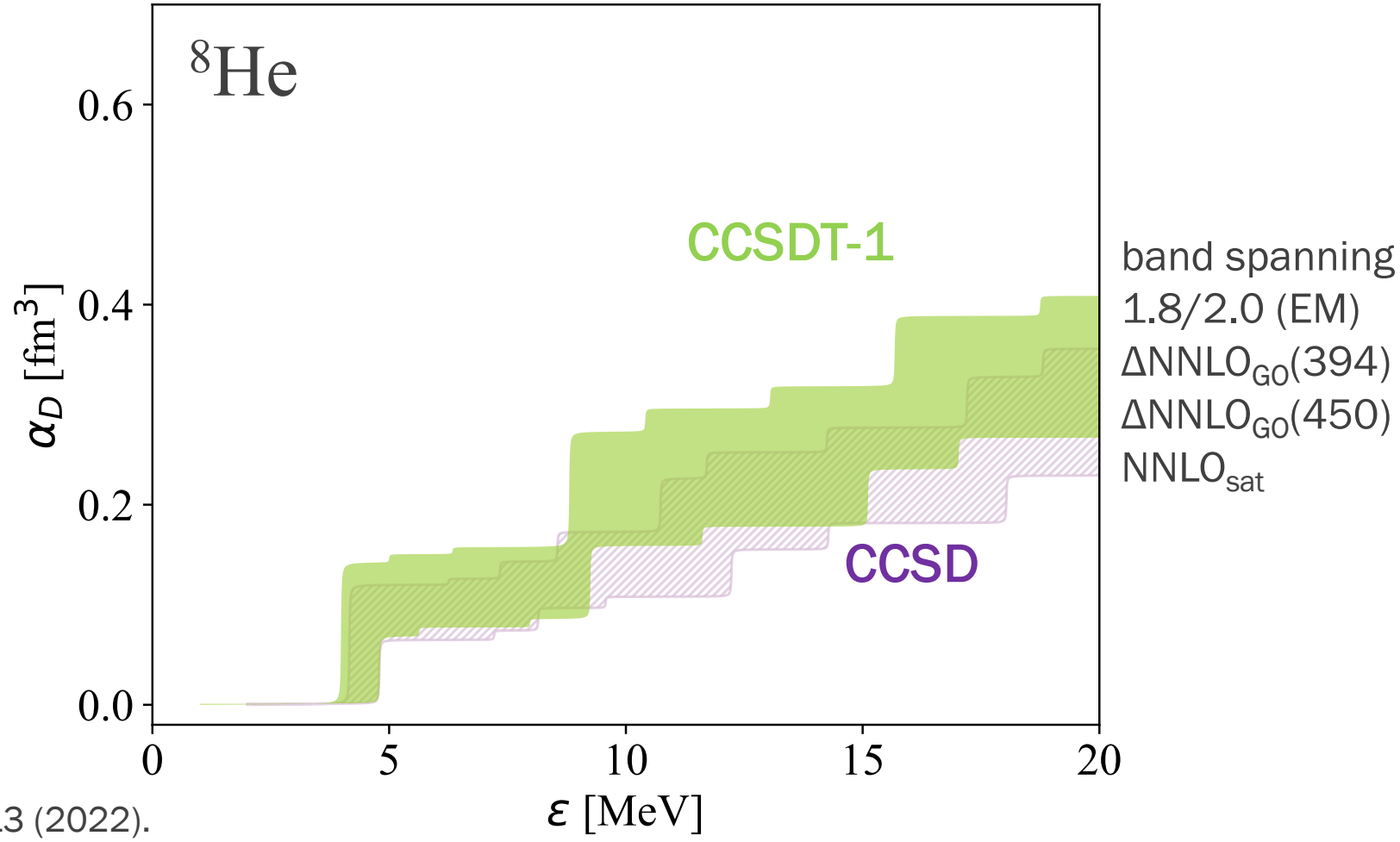
Theory…



band spanning
1.8/2.0 (EM)
ΔNNLO$_{GO}$(394)
ΔNNLO$_{GO}$(450)
NNLO$_{sat}$

FB et al., PRC 105, 034313 (2022).
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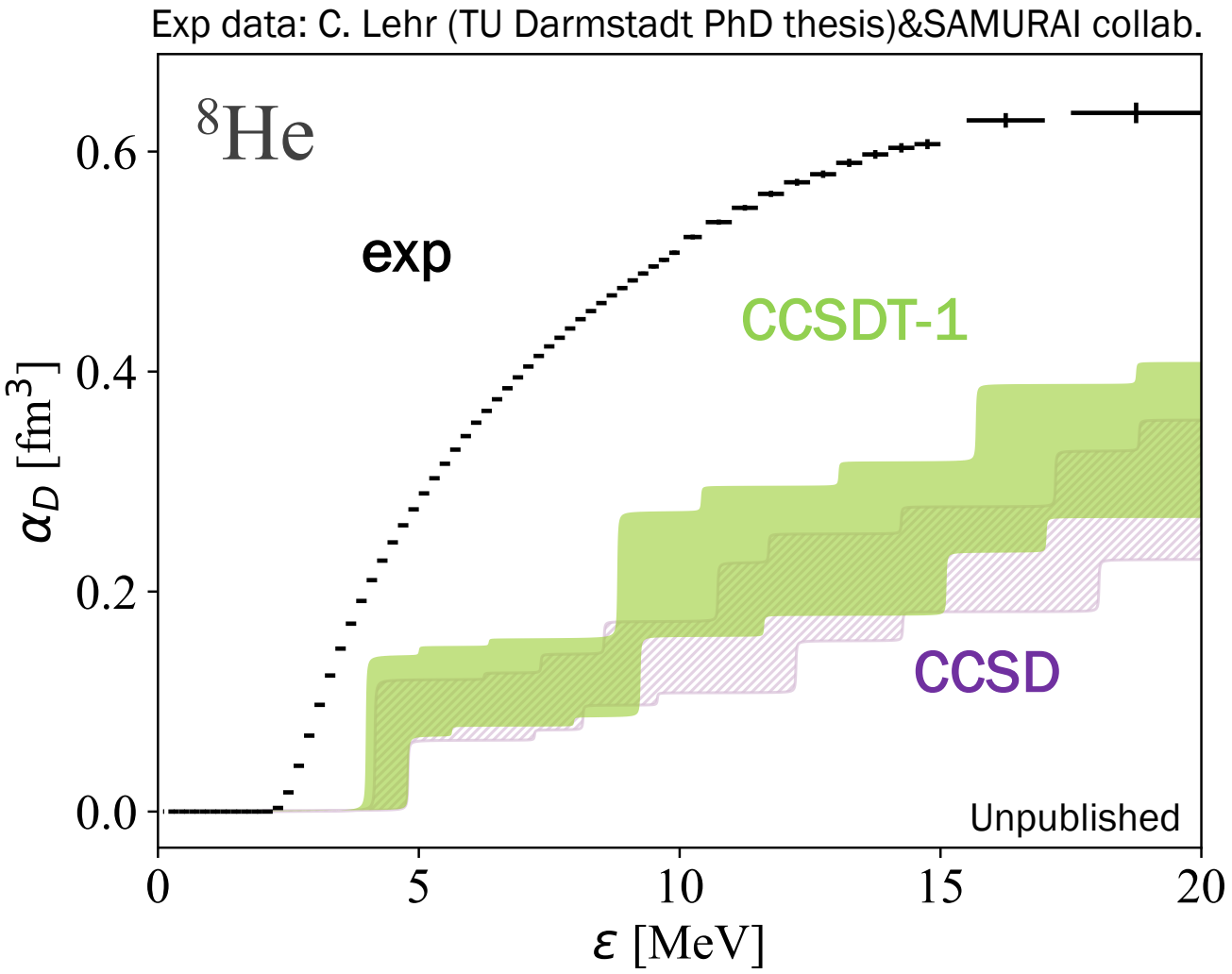
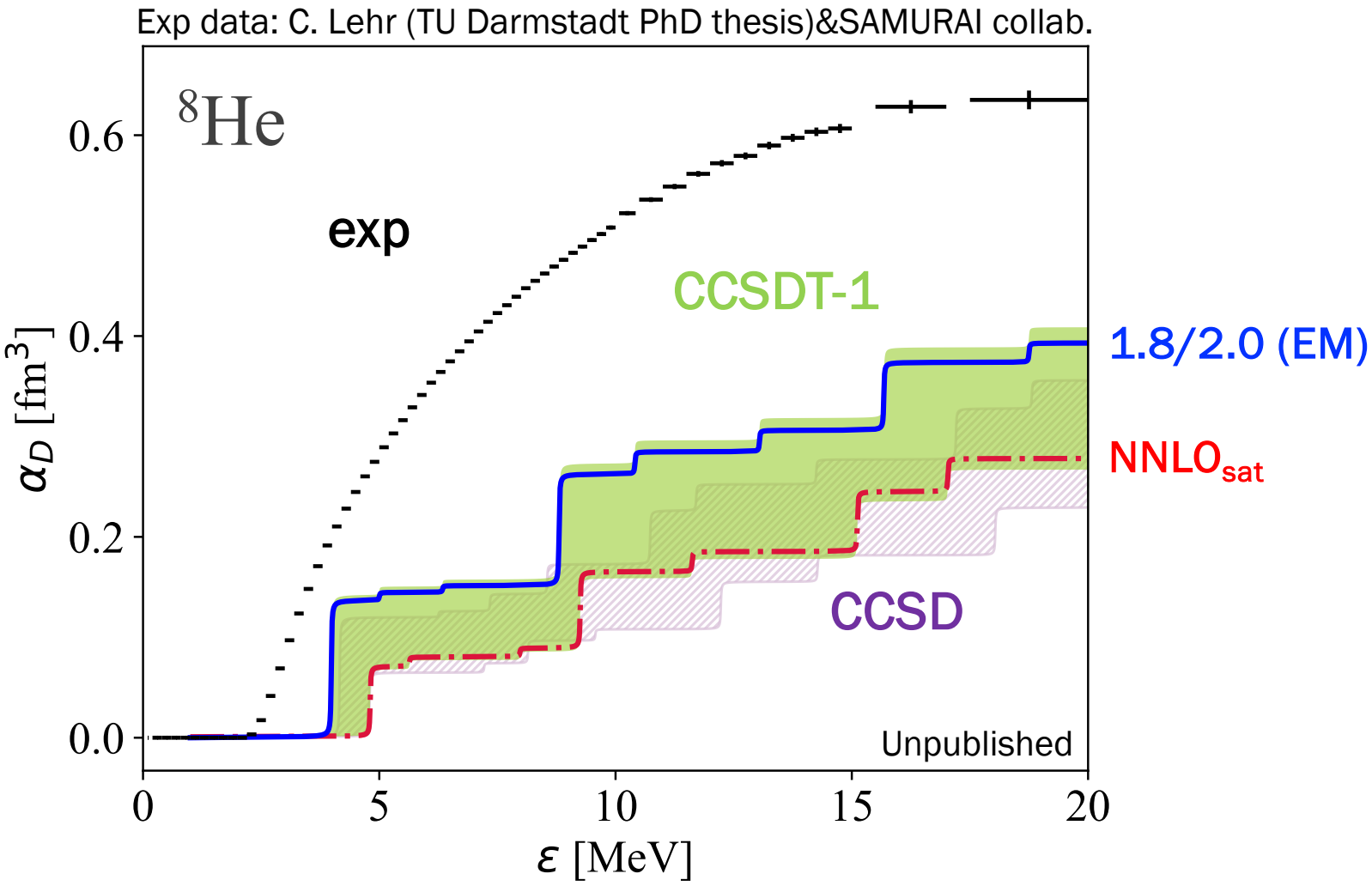
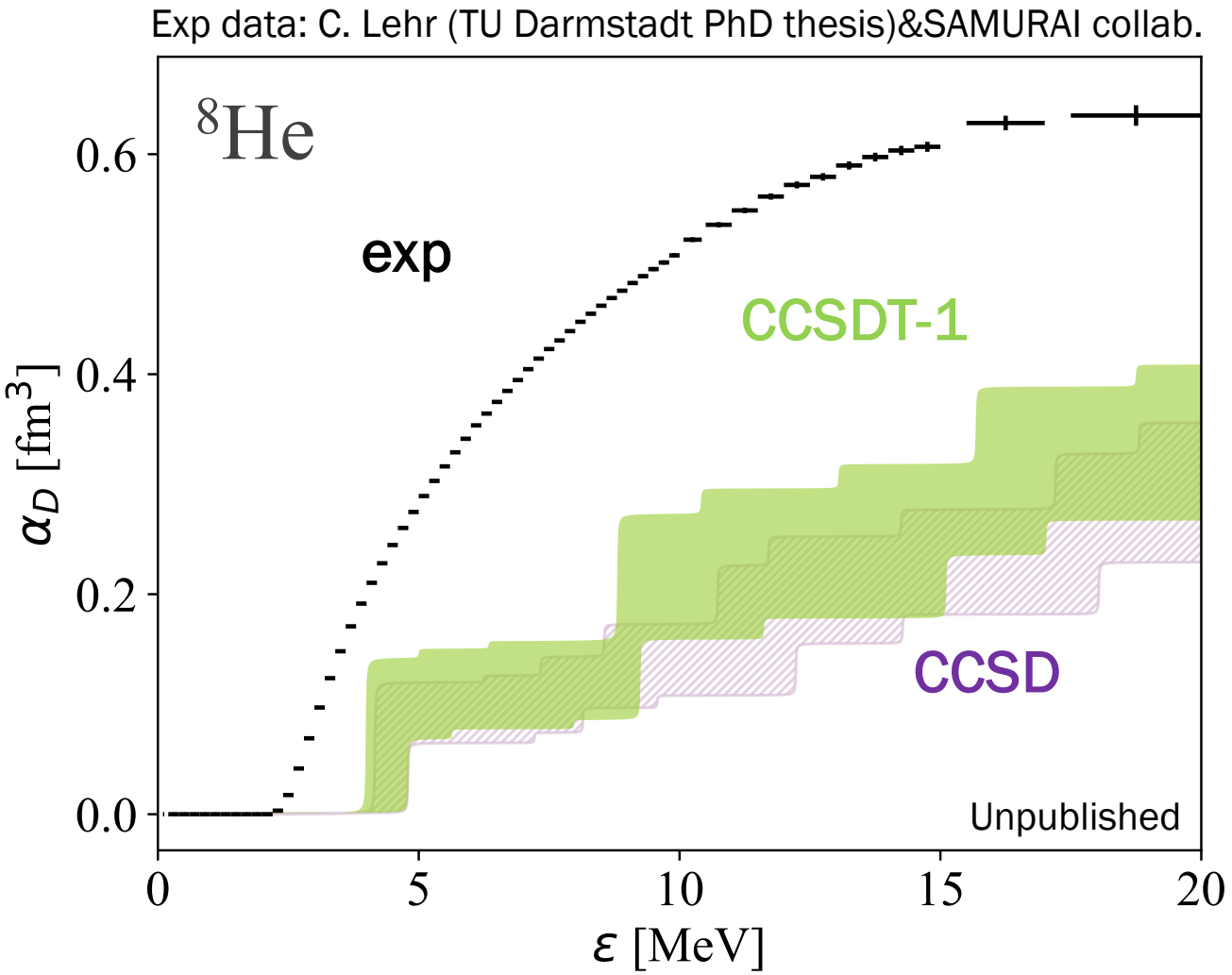
… and experiment



Strong dependence on the Hamiltonian



Missing higher order correlations?



For $NNLO_{sat}$, NCSM value available
[C. Stumpf, PhD thesis, TU Darmstadt, 2017]

$\alpha_D = 0.4454(19)$ fm^3

compared to CC

$\alpha_D = 0.37(3)$ fm^3.

Indication of the impact of 4p-4h correlations?

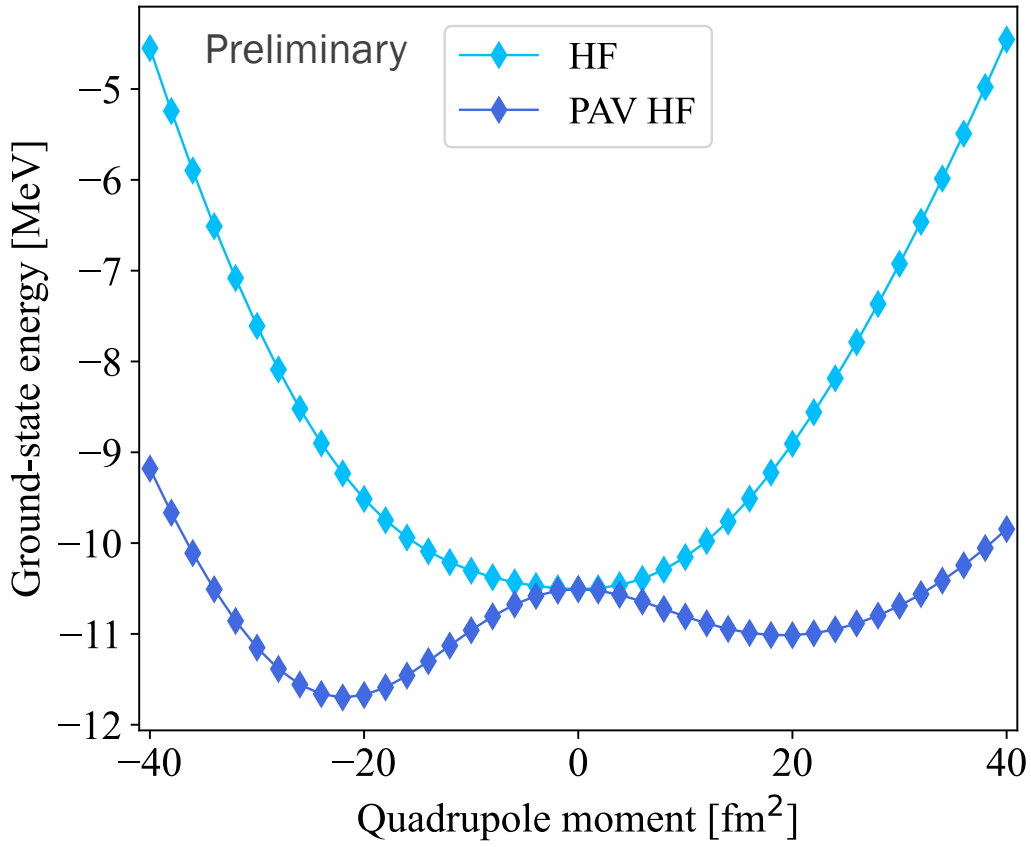
Deformation in ^{8}He?

CC calculations with **references breaking rotational symmetry** now possible
→ see Thomas Papenbrock's talk.

We start from **Hartree-Fock calculations** where:

- ❑ only axial symmetry is assumed,
- ❑ we minimize the energy under the constraint of a **fixed expectation value for the quadrupole moment**.

We then perform an **angular momentum projection** after variation (PAV) of the E_{gs} vs Q curve.



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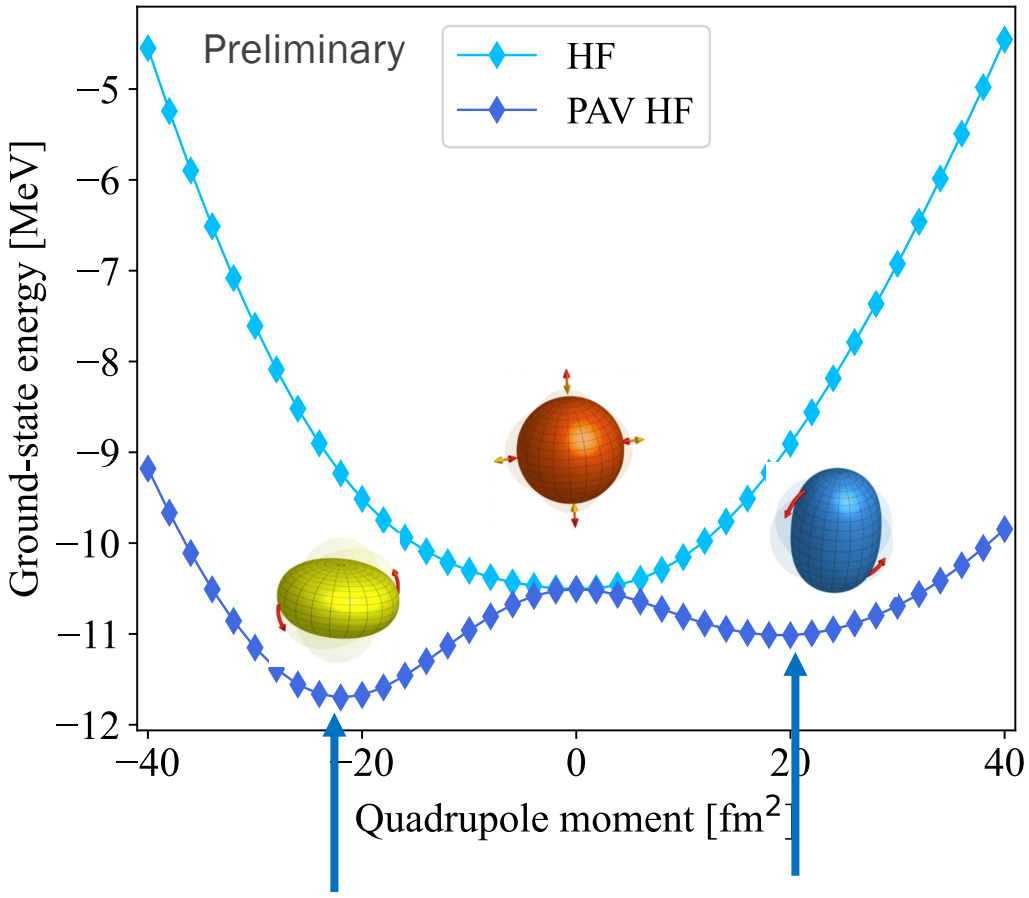
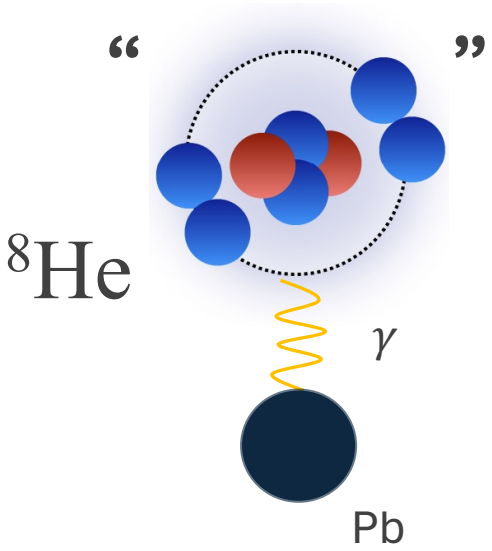
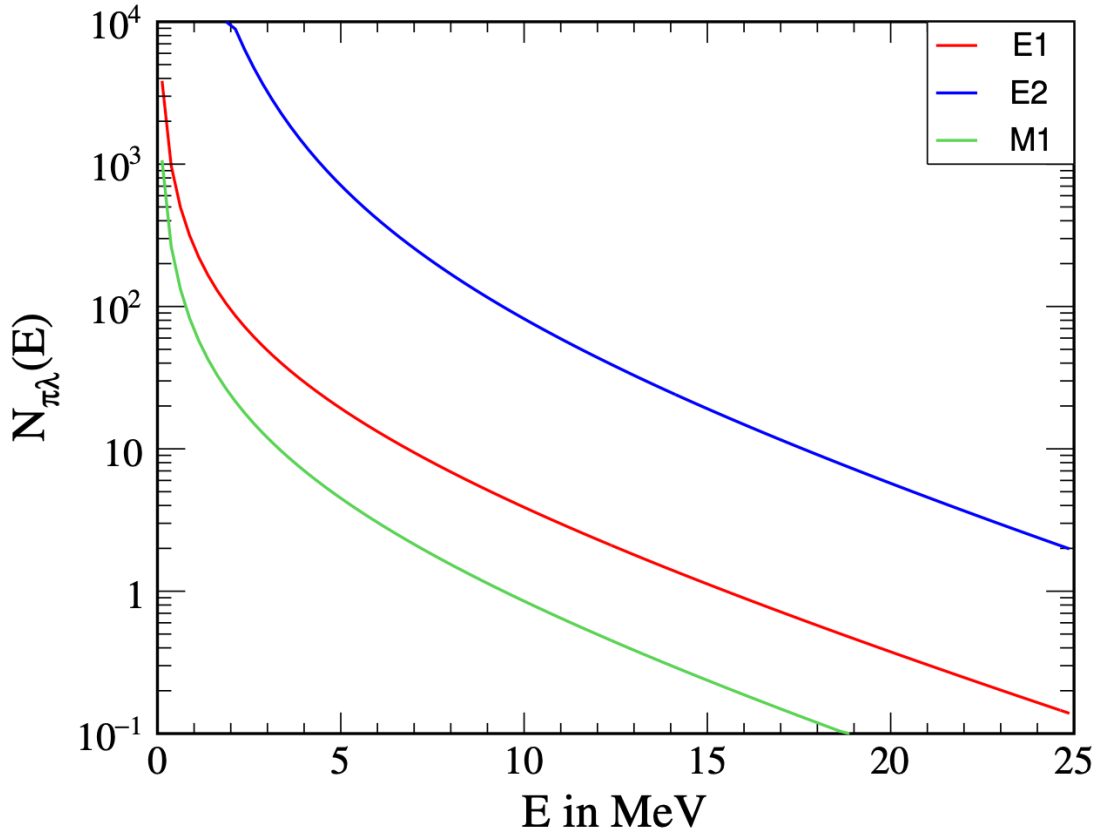


two minima away from the spherical point!

Can higher order multipolarities contribute?



C. Lehr (PhD thesis, TU Darmstadt, 2021)



E2 photons >> E1 photons at exp beam energy + confirmed low-lying 2+ state in ^{8}He

→ can this lead to significant E2 component in Coulex?

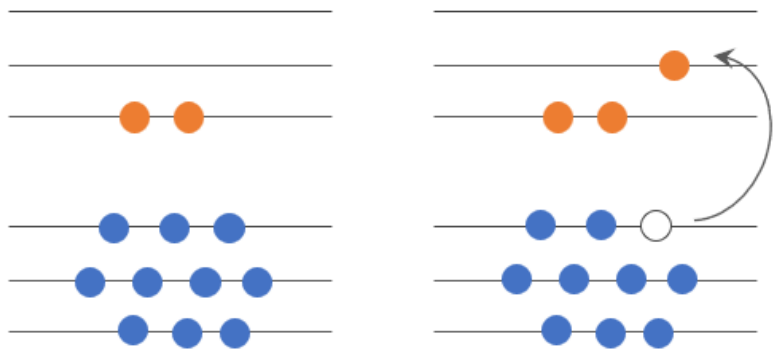
What about ^{6}He?

see also e.g.
Matthias Göbel's talk

Open-shell nuclei: two particles outside closed shells (2PA)

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

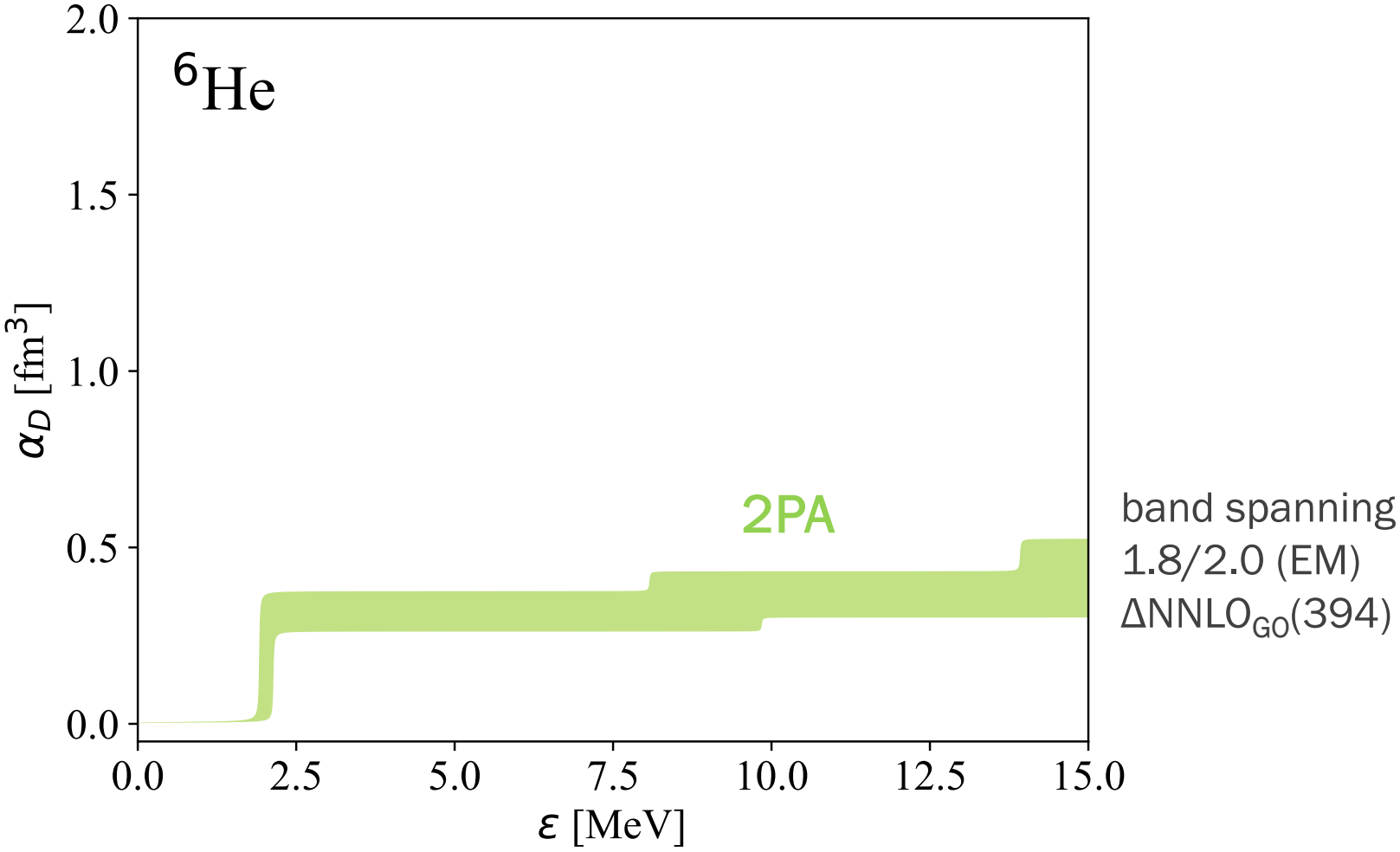
$$|\Psi_{\mathrm{2PA}}\rangle = \mathcal{R}\,|\Psi_{\mathrm{closed-shell}}\rangle$$



2p-0h 3p-1h

FB et al., arXiv:2405.05608 [nucl-th]

Dipole polarizability in ^{6}He



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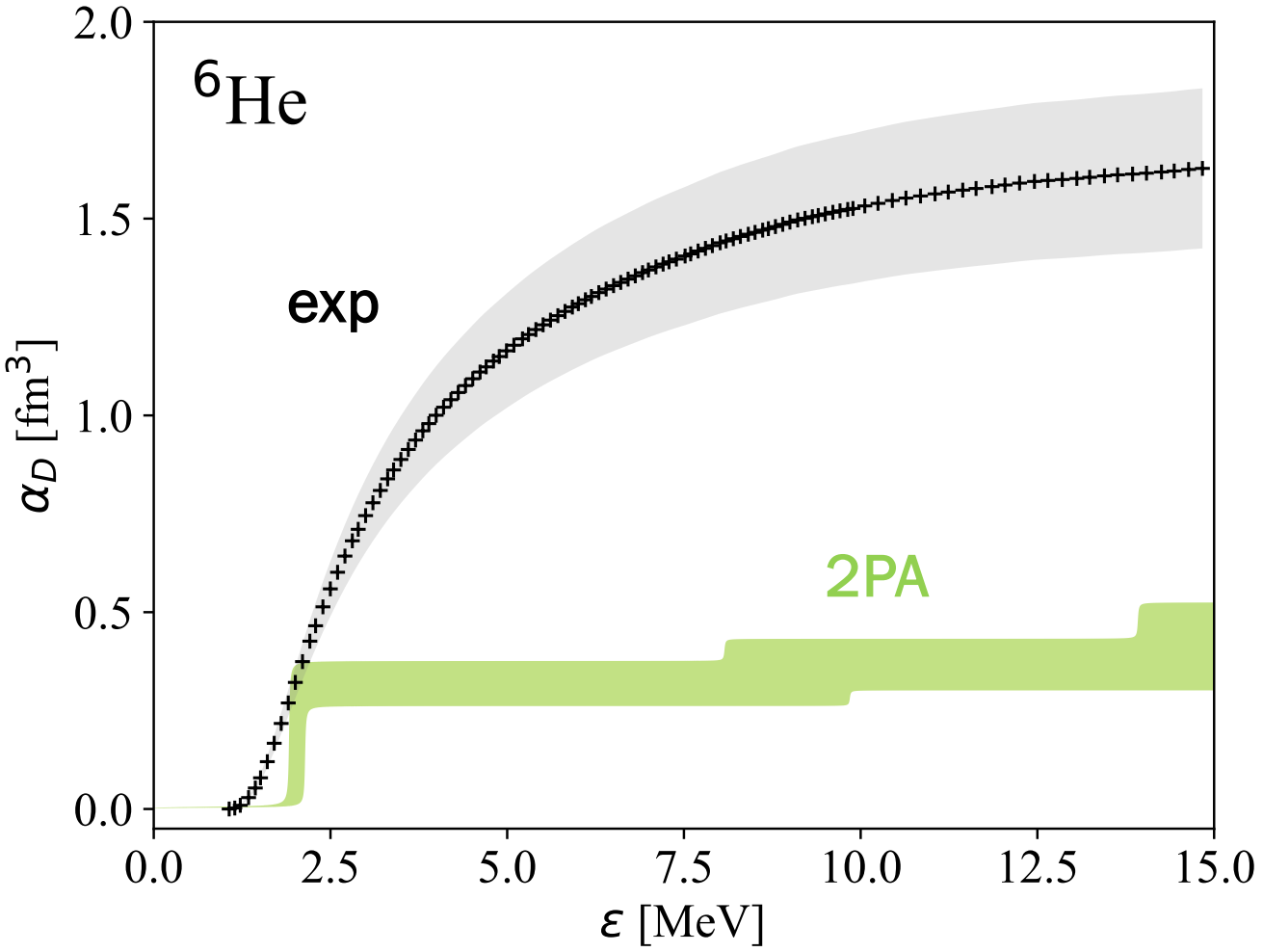
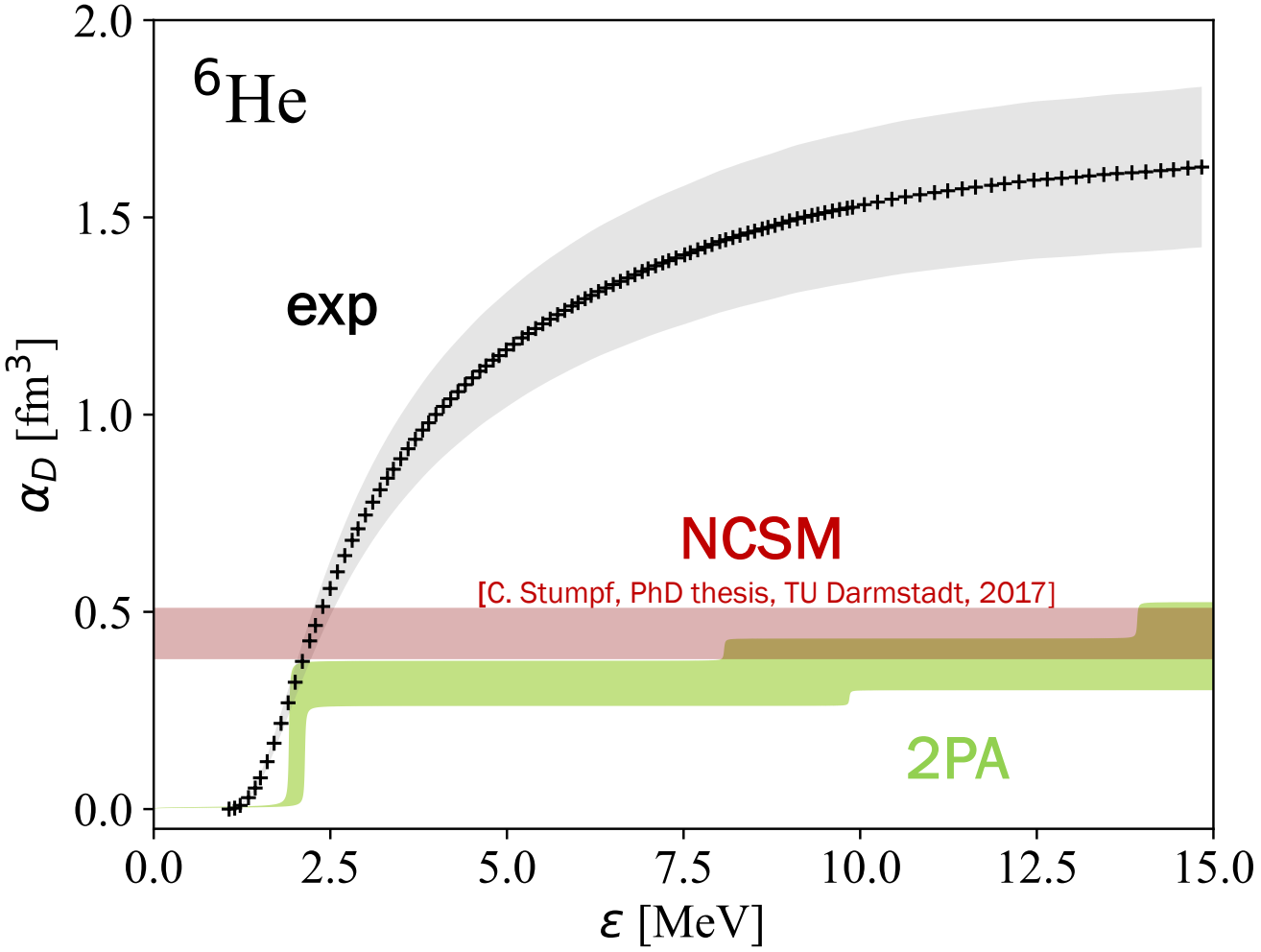


FB et al., preliminary

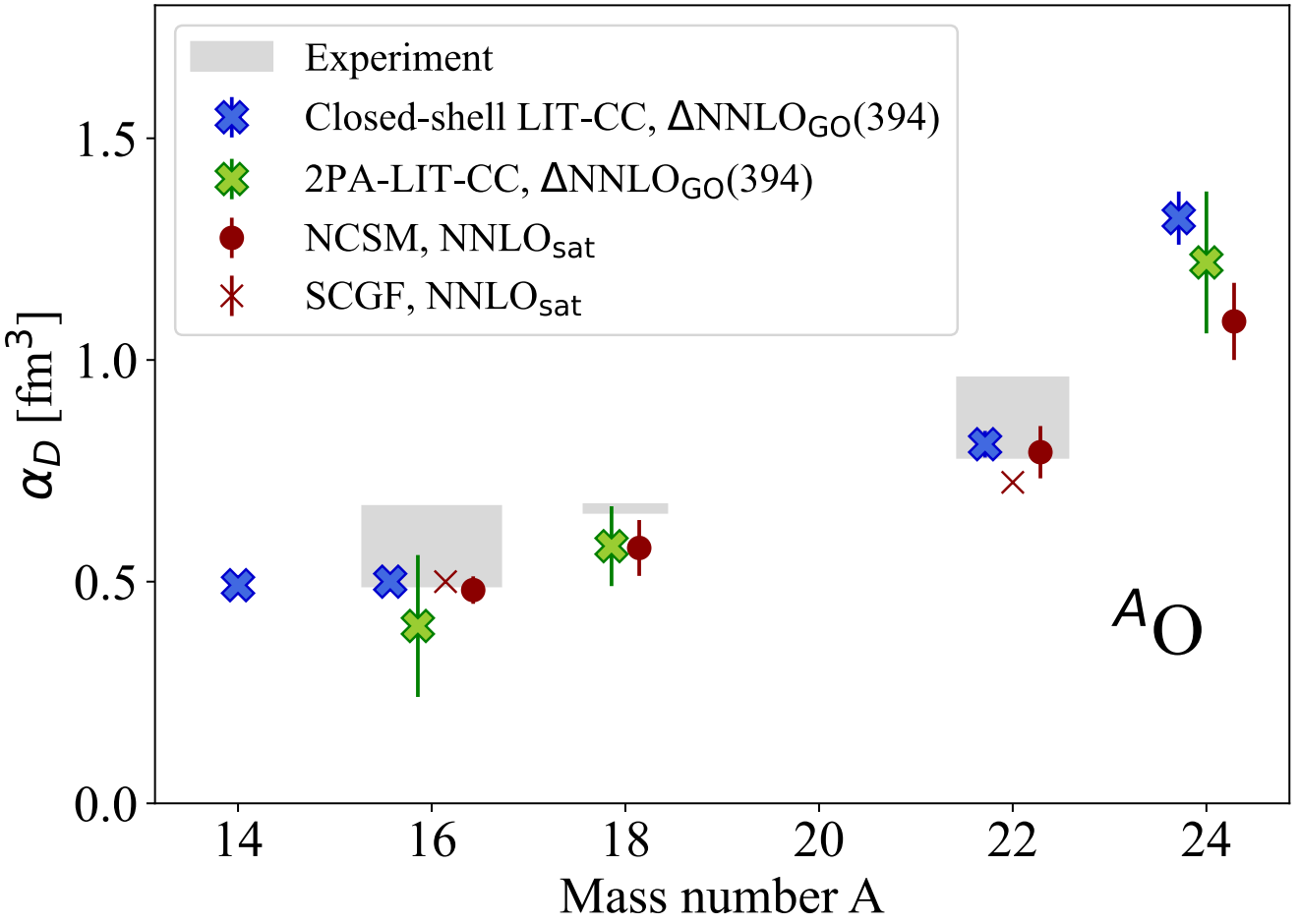
Missing higher order correlations also here?



FB et al., preliminary

Going to the medium-mass region

α_D along the oxygen chain



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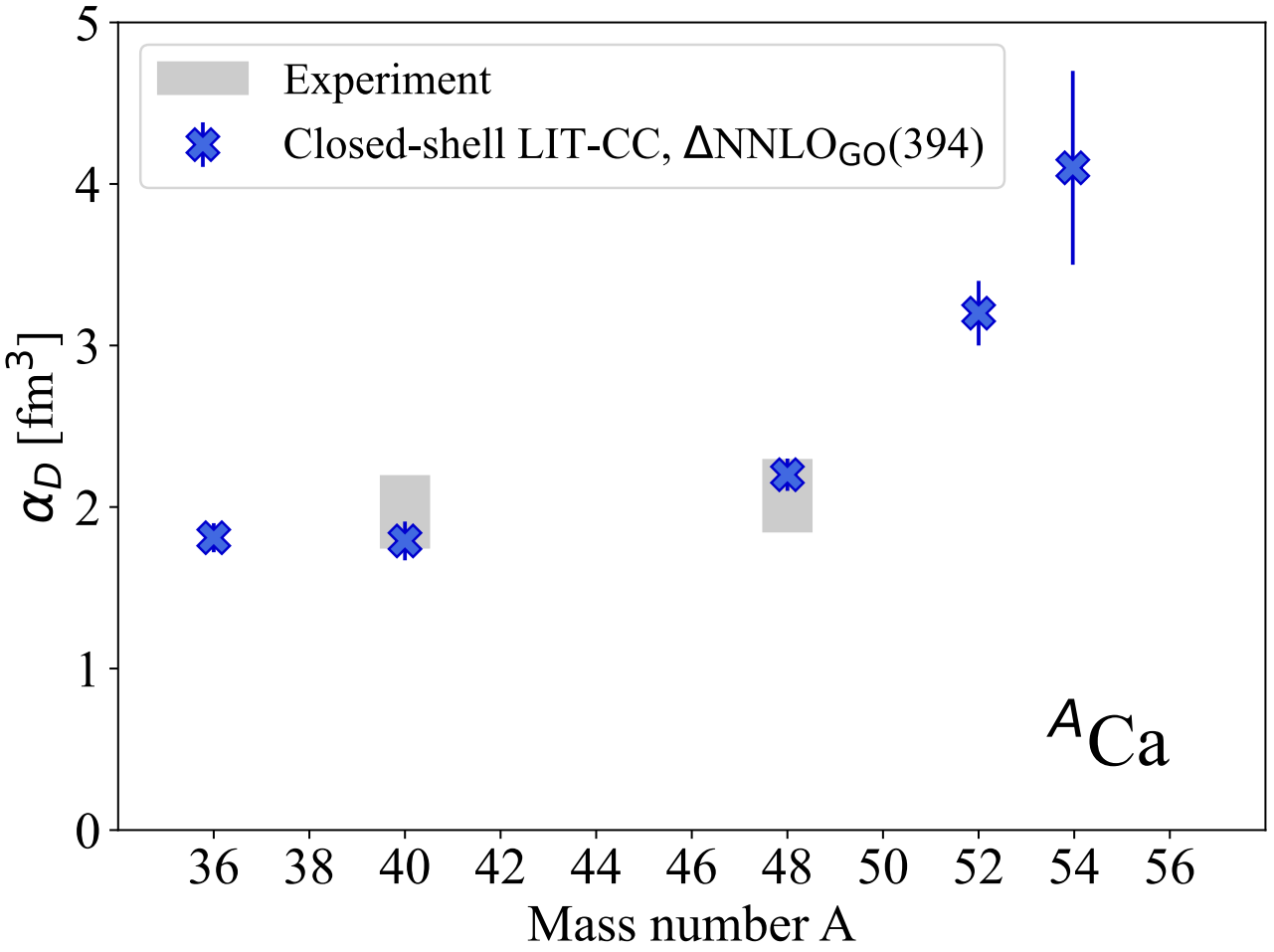
α_D along the calcium chain



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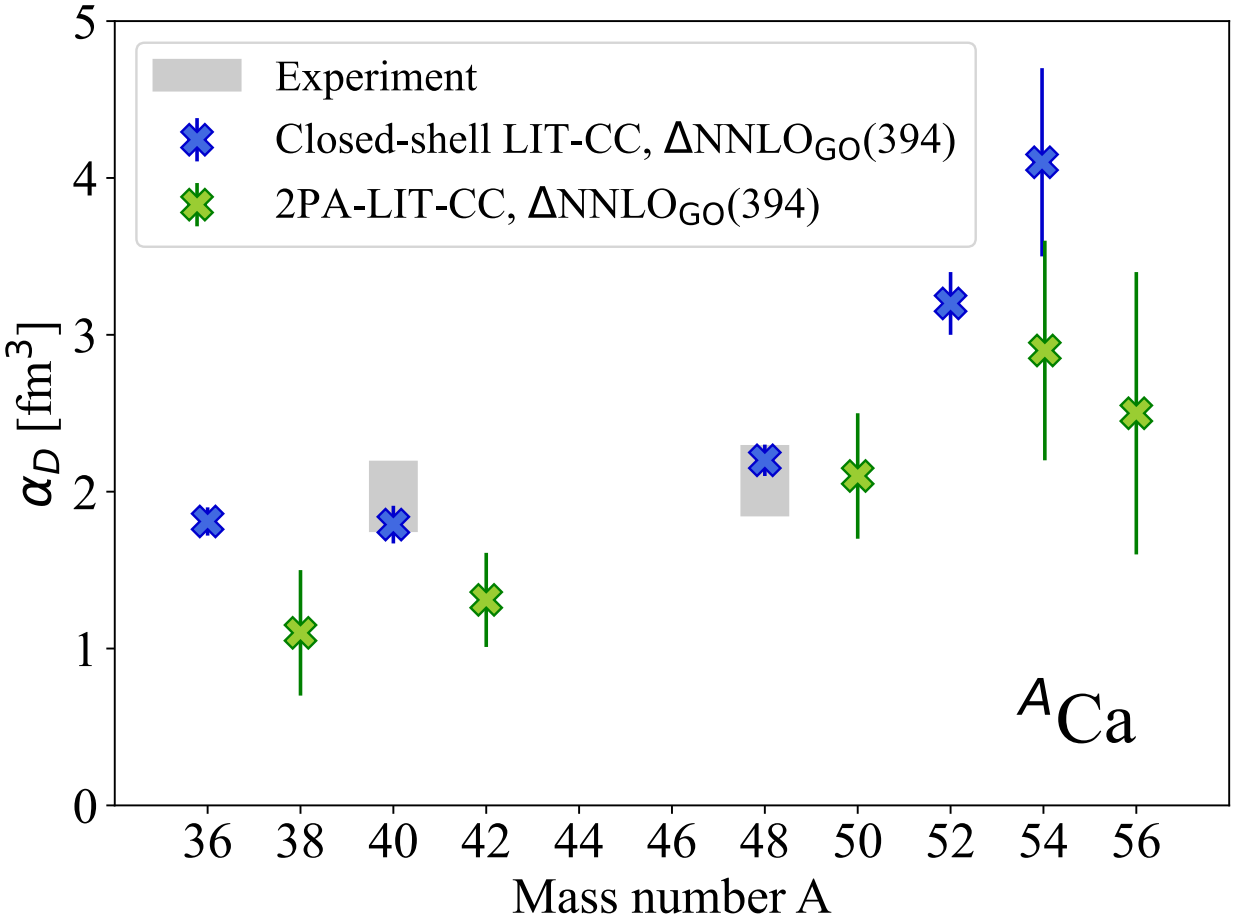

FB et al., arXiv:2405.05608 [nucl-th]

Let's discuss!

- How do we reconcile **different exp indications** on **soft dipole mode in ^{8}He**?

- What drives the **discrepancy between theory and exp** in the polarizability of helium halo isotopes? Deficiencies in Hamiltonian, many-body method, deformation effects, contributions from higher-order multipolarities (e.g. E2) in exp data?

- Could **experiments on α_D in neutron-rich calcium isotopes** inform current discrepancies observed in charge radii?

Thank you for your attention!