Ground and dipole-excited states of the halo nucleus ^{8}He

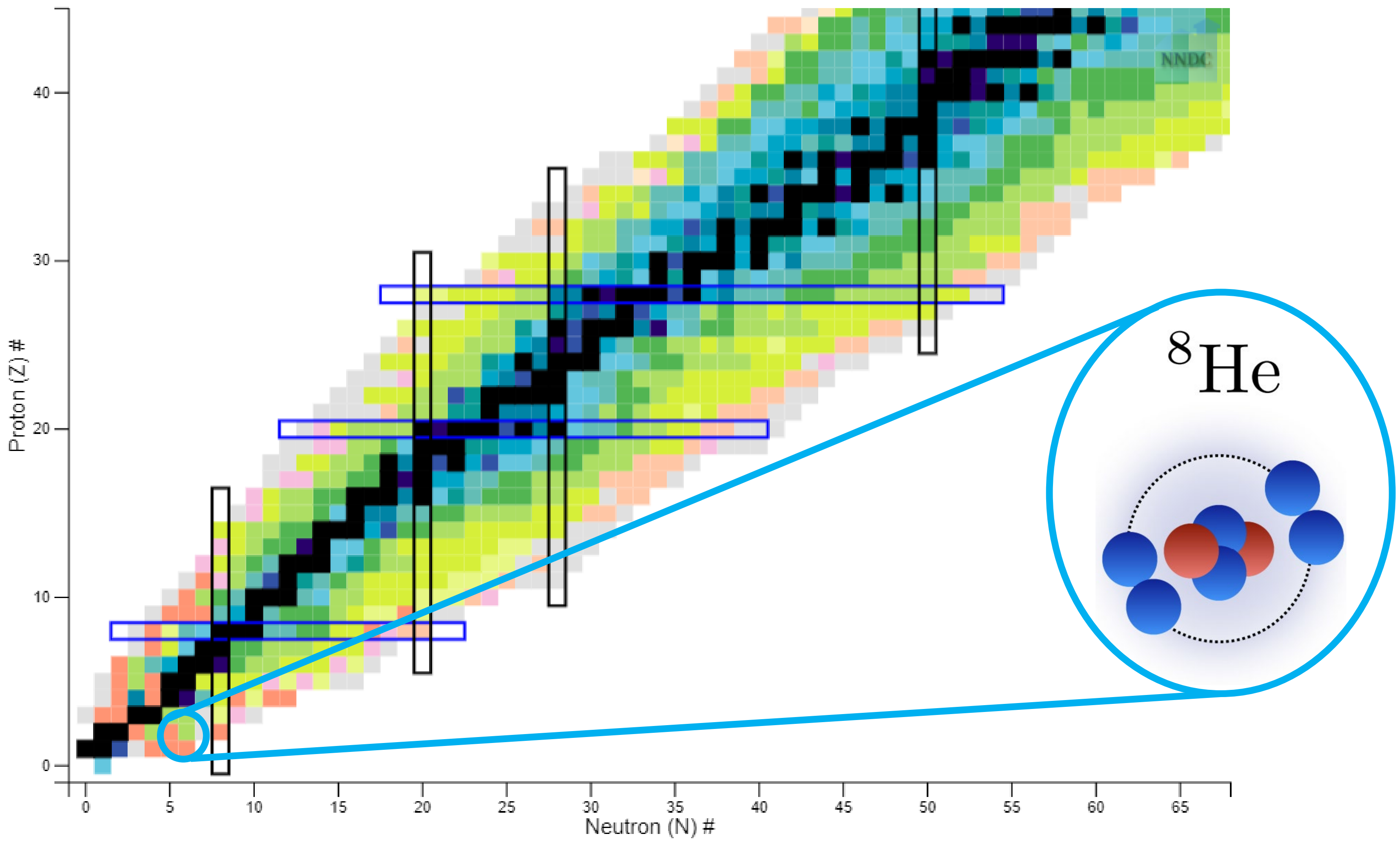
FRANCESCA BONAITI, JGU MAINZ (PROJECT B04)

SFB 1245 ANNUAL WORKSHOP @ DARMSTADT

OCTOBER 5, 2022

In collaboration with:
Sonia Bacca
Gaute Hagen (ORNL)

Motivation



Proton (Z) #
Neutron (N) #
0
10
20
30
40
0
5
10
15
20
25
30
35
40
45
50
55
60
65
NNDC
^{8}He

Motivation

Article | Open Access | Published: 27 January 2021

Measuring the α-particle charge radius with muonic helium-4 ions

Julian J. Krauth, Karsten Schuhn

Nature **589**, 527–531 (2021) | Cite

ELSEVIER

Physics Letters B

Volume 822, 10 November 2021, 136710

Proton inelastic scattering reveals deformation in ^{8}He

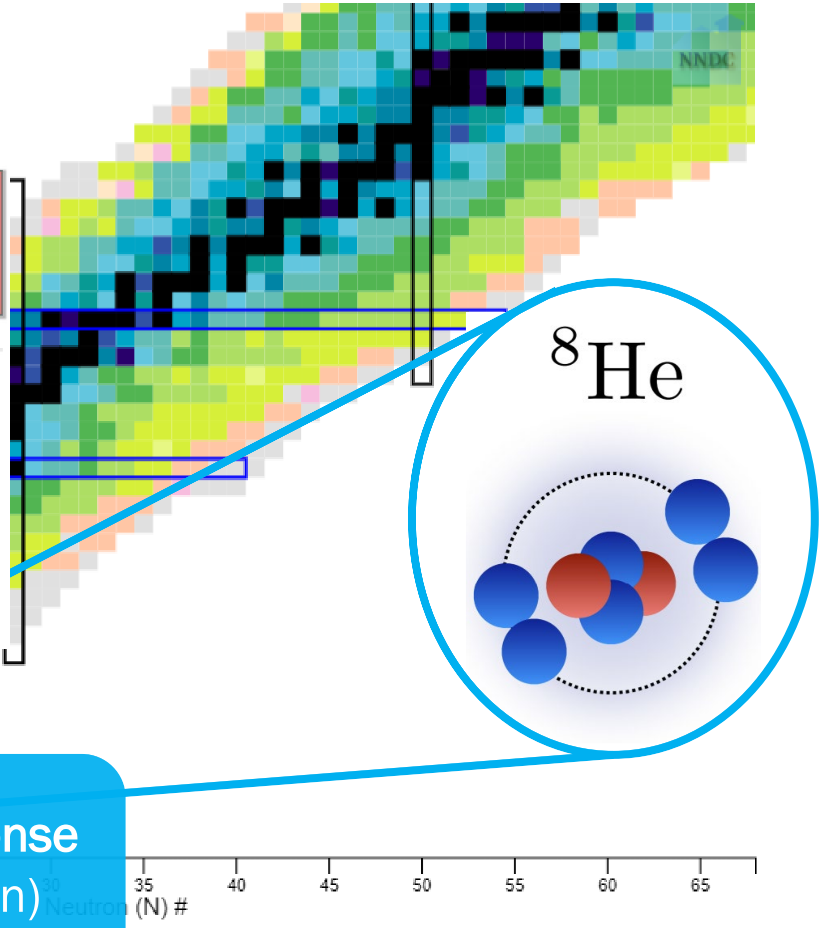
M. Holl [a, b], R. Kanungo [a, b], Z.H. Sun [c, d], G. Hagen [c, d], J.A. Lay [e, f], A.M. Moro [e, f], P. Navrátil [b],

Article | Open Access | Published: 22 June 2022

Observation of a correlated free four-neutron system

M. Duer, T. Aumann, … M. V. Zhukov + Show authors

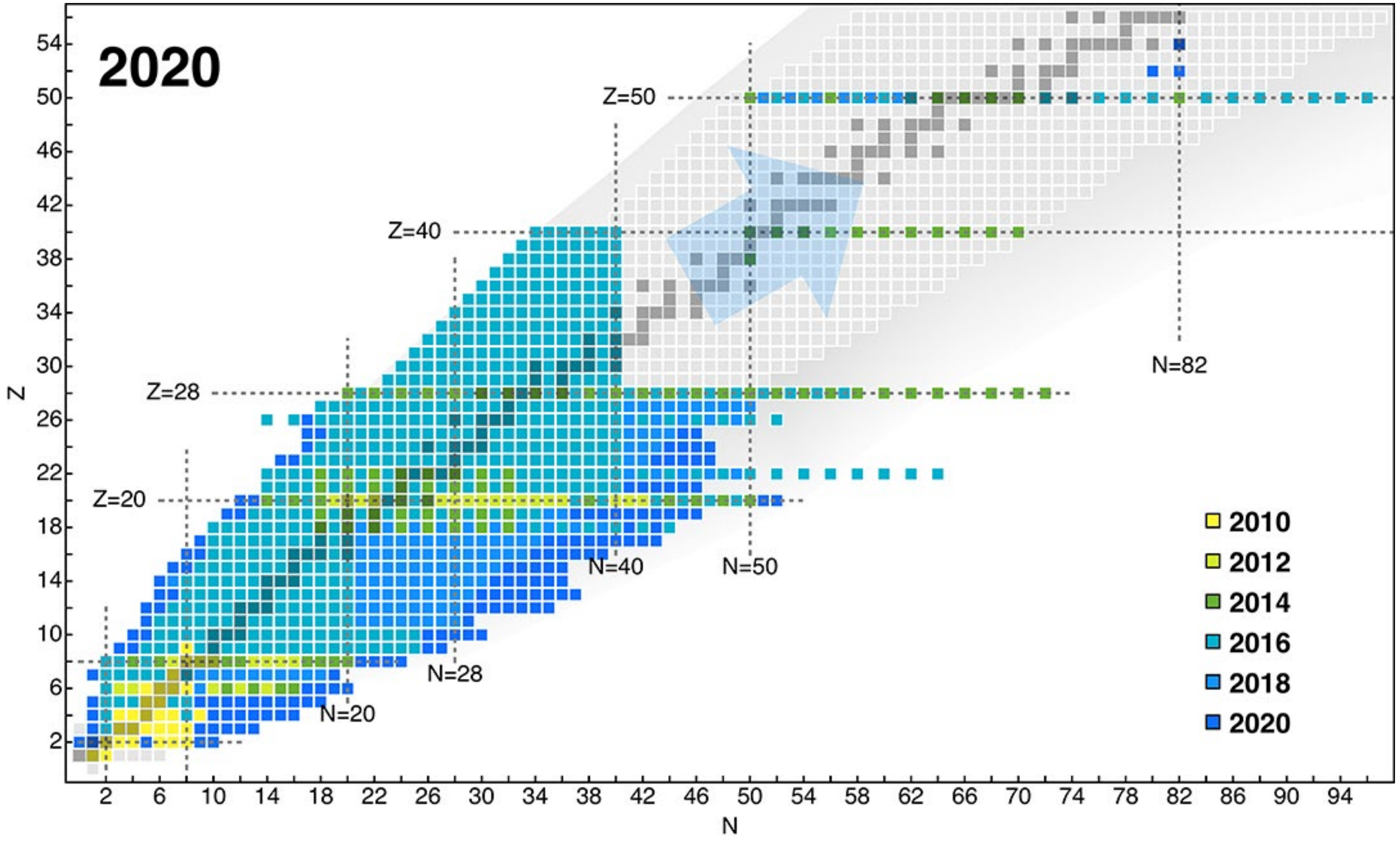
Nature **606**, 678–682 (2022) | Cite this article



Low-energy dipole response
(SAMURAI collaboration)
→ SFB project A06 (T. Aumann's group)

Ab initio methods

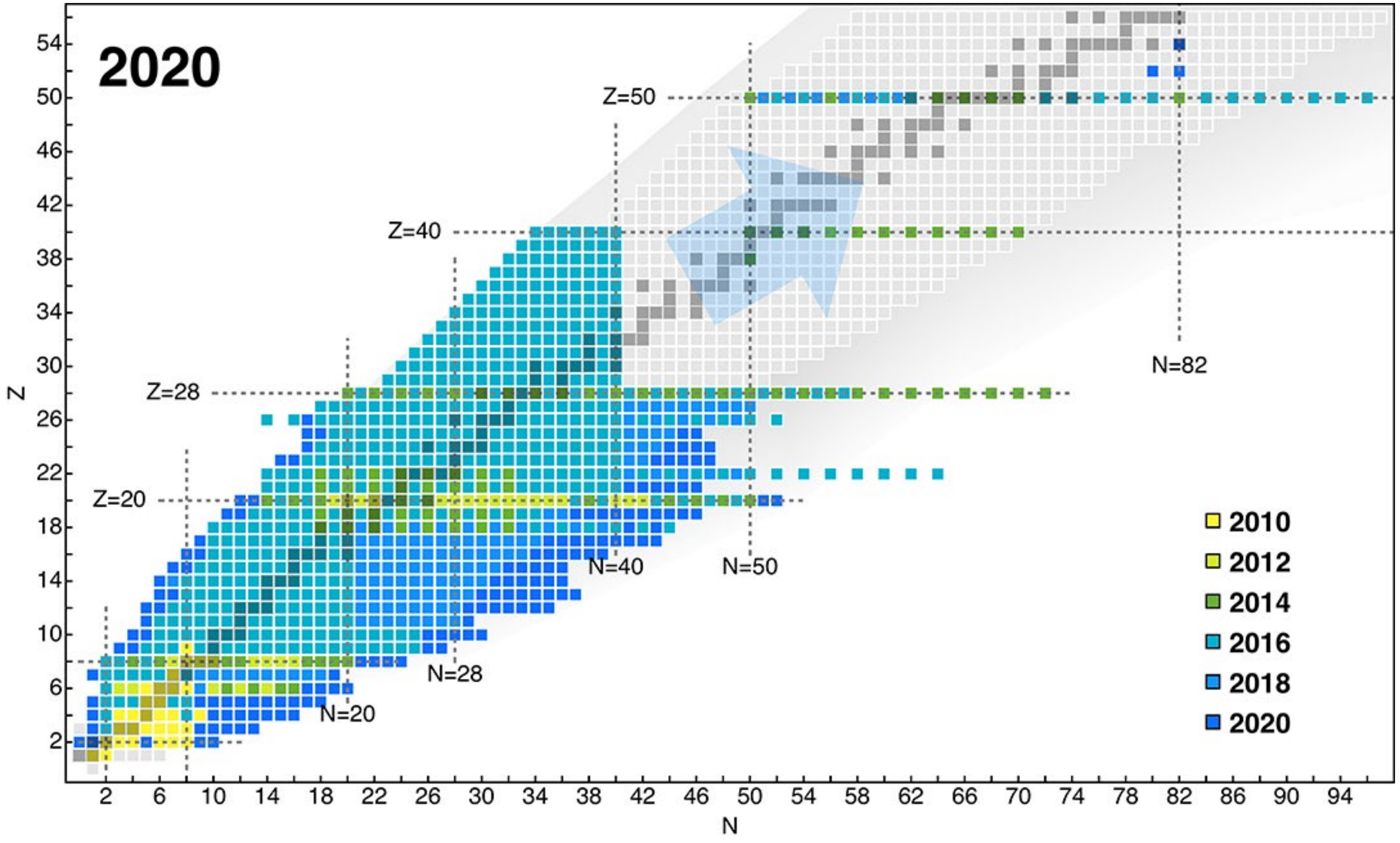
H. Hegert, Front.in Phys. 8 379 (2020)



Ab initio methods

2021: ^{208}Pb
B. Hu et al,
arXiv:2112.01125

H. Hegert, Front.in Phys. 8 379 (2020)



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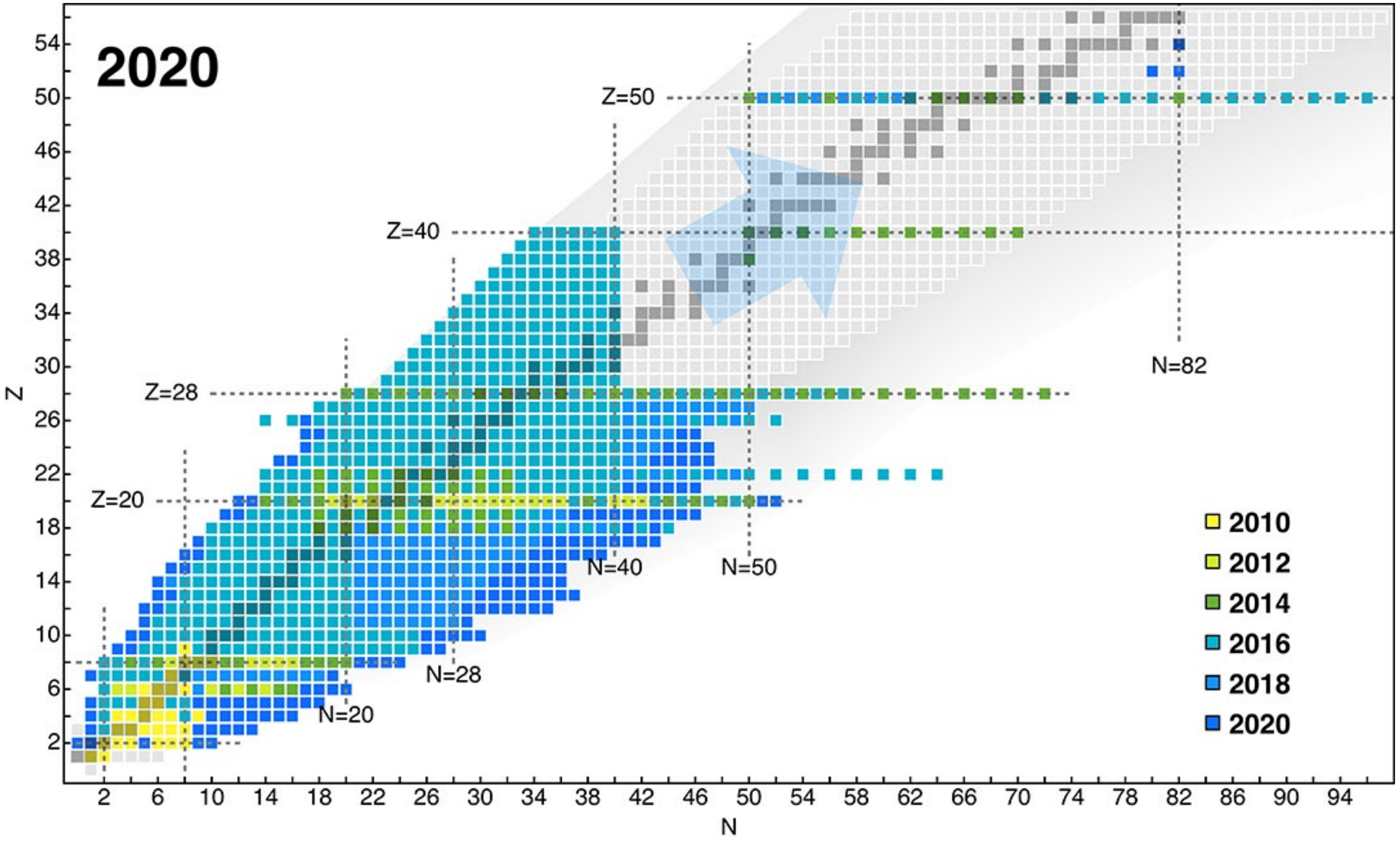

- Main degrees of freedom of the problem: **protons and neutrons.**
- Solve

$$H\,|\psi\rangle = E\,|\psi\rangle$$

$$H = T + V_{NN} + V_{3N}$$

with **controlled approximations.**

- Two ingredients: a **nuclear interaction model** and a **many-body solver.**

Nuclear interaction models

We work with Chiral Effective Field Theory interactions:

- Low-energy approximation of QCD, with π, n, (Δ) as degrees of freedom.
- Separation of scales allows for low-momentum expansion, many-body forces arise naturally in the theory.
- Short-range physics enclosed in low-energy constants, fitted to experiment.

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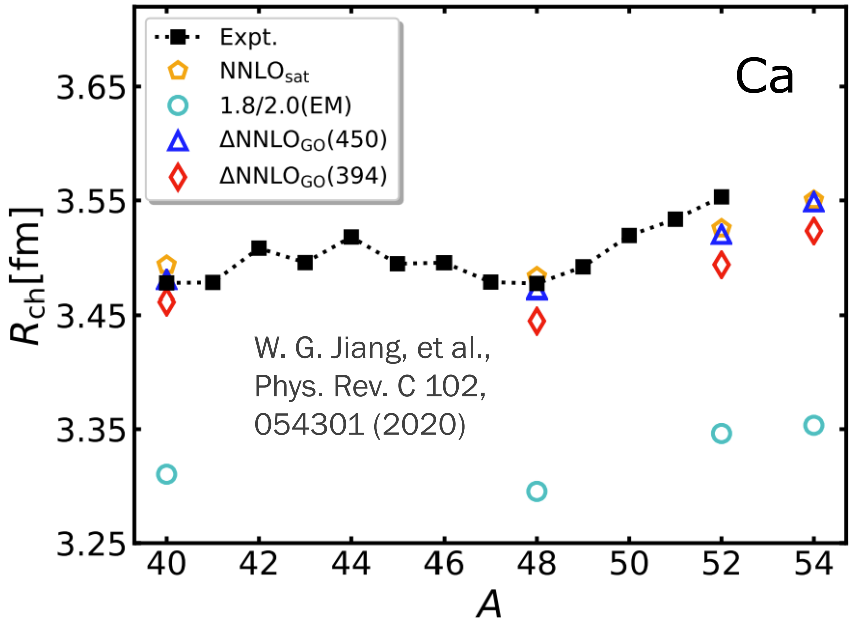

$NNLO_{sat}$ [A. Ekstrom et al, 2015]

- ❑ Fitted on radii and BEs of light and medium-mass nuclei, including carbon and oxygen isotopes.

$\Delta NNLO_{GO}$ [W. G. Jiang et al, 2020]

- ❑ Includes Δ explicitly.
- ❑ Fitted on radii and BEs of light nuclei and nuclear matter saturation.
- ❑ Two cutoffs: 394 and 450 MeV.

Coupled-cluster theory

- Starting point: Hartree-Fock reference state on the HO basis $|\phi\rangle$
- Correlations are included via exponential ansatz:

$$|\psi\rangle = e^T |\phi\rangle$$

with

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

$\longrightarrow$ coefficients obtained via coupled-cluster equations

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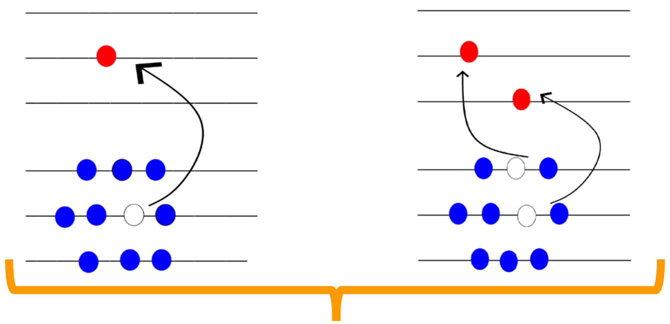
singles and doubles (CCSD)



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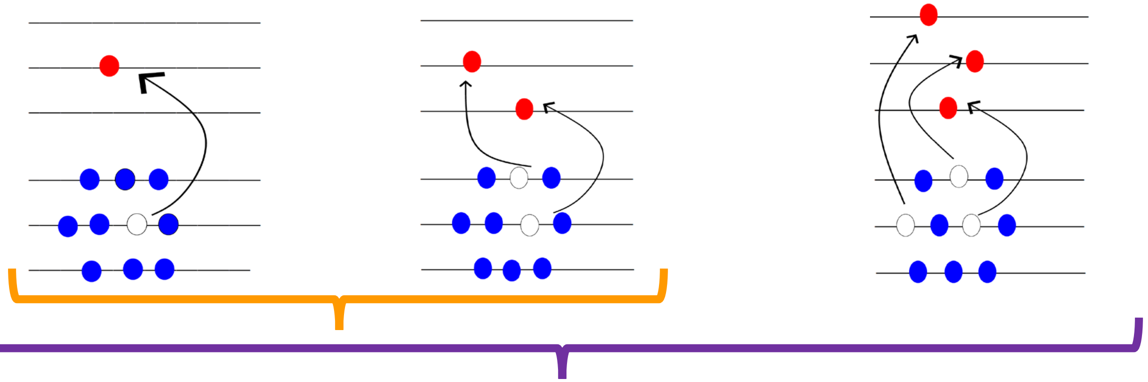
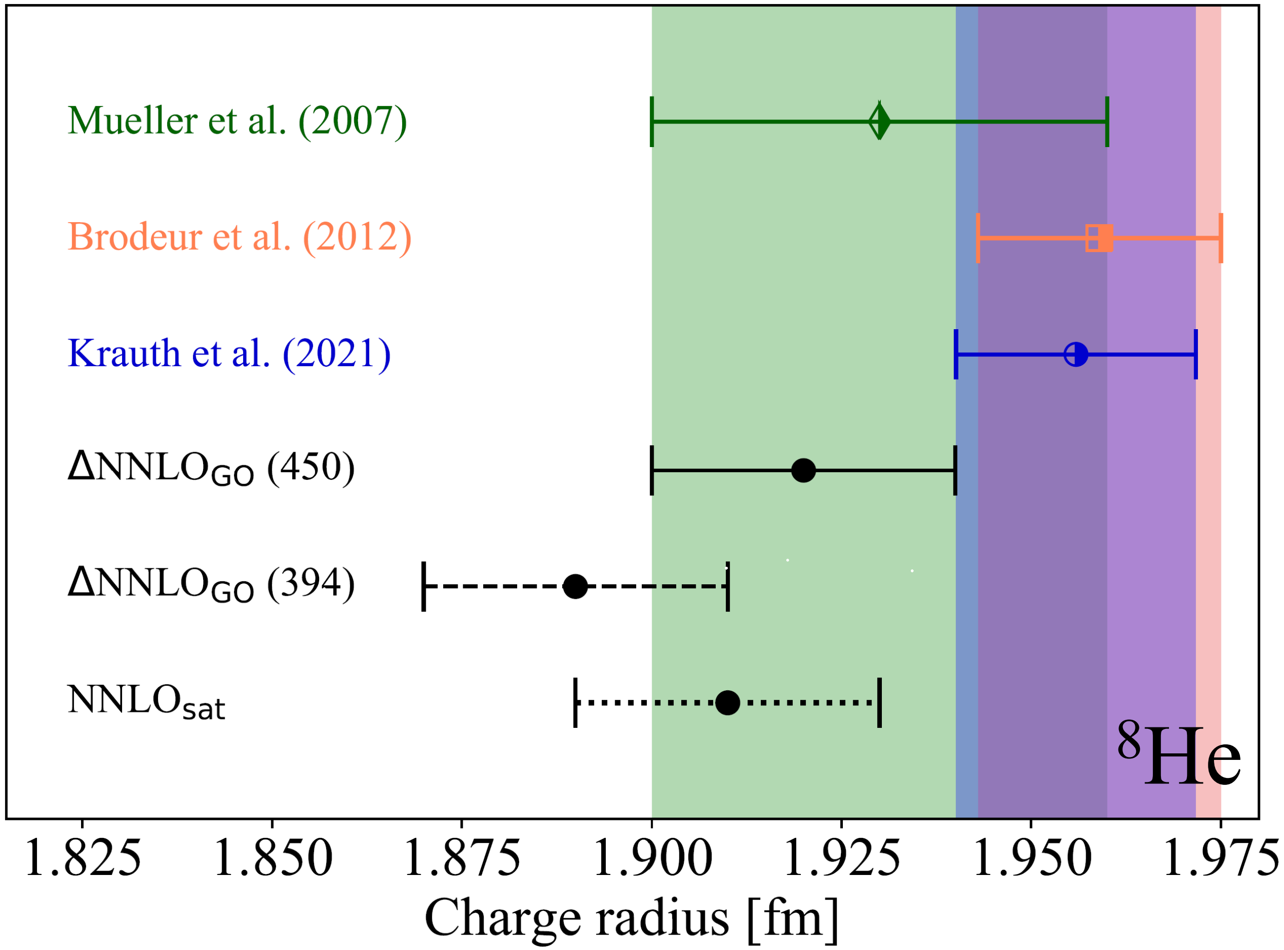


singles and doubles (CCSD)

+ triples (CCSDT-1)

→ coefficients obtained via coupled-cluster equations

Charge radius



FB et al., PRC 105, 034313 (2022)

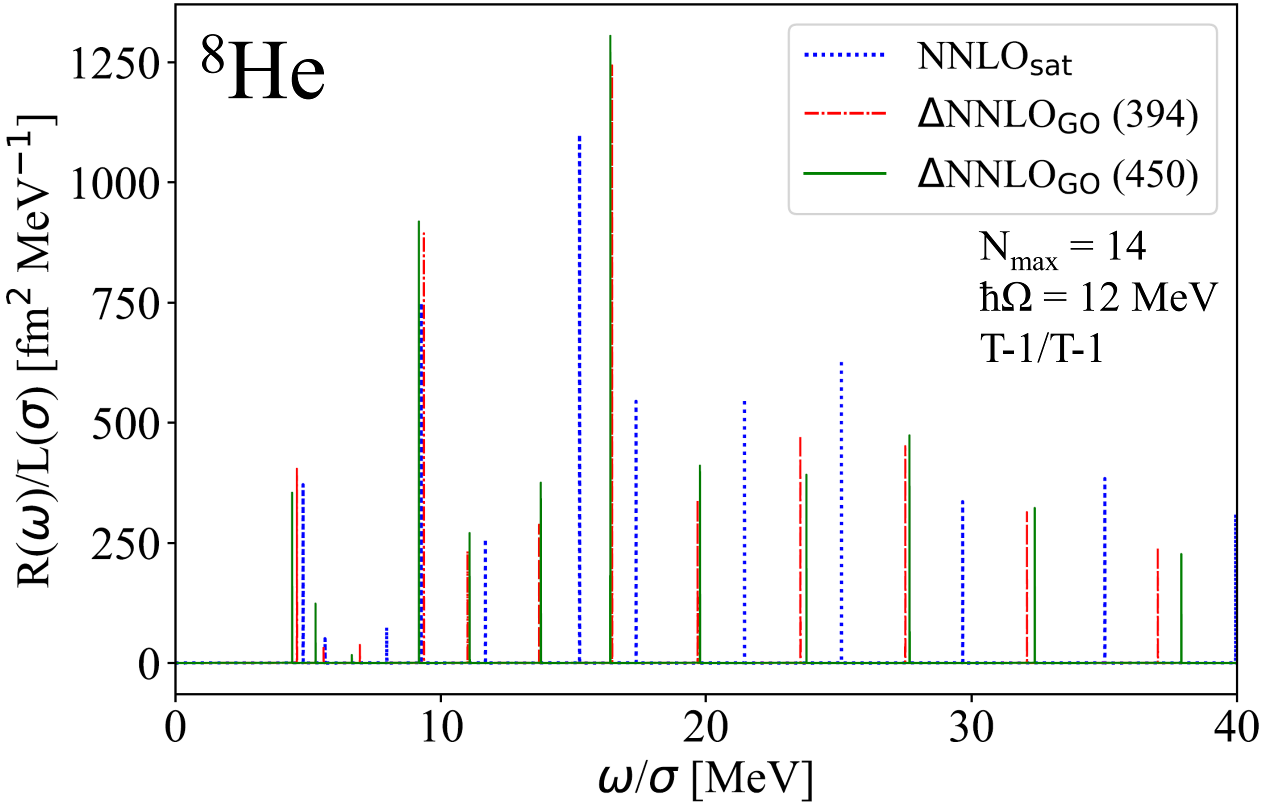
From ground to dipole-excited states

- Dipole excitations are 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)



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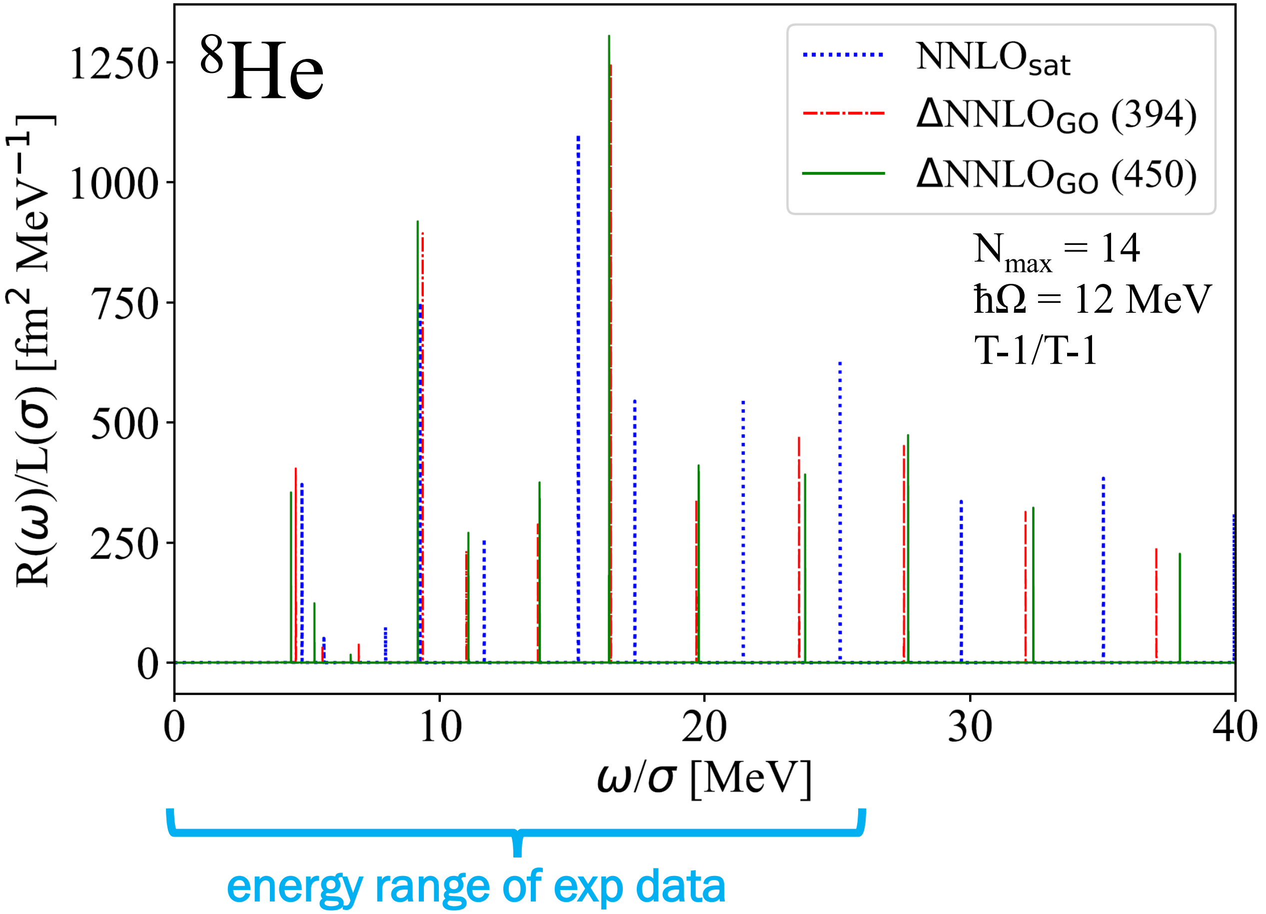
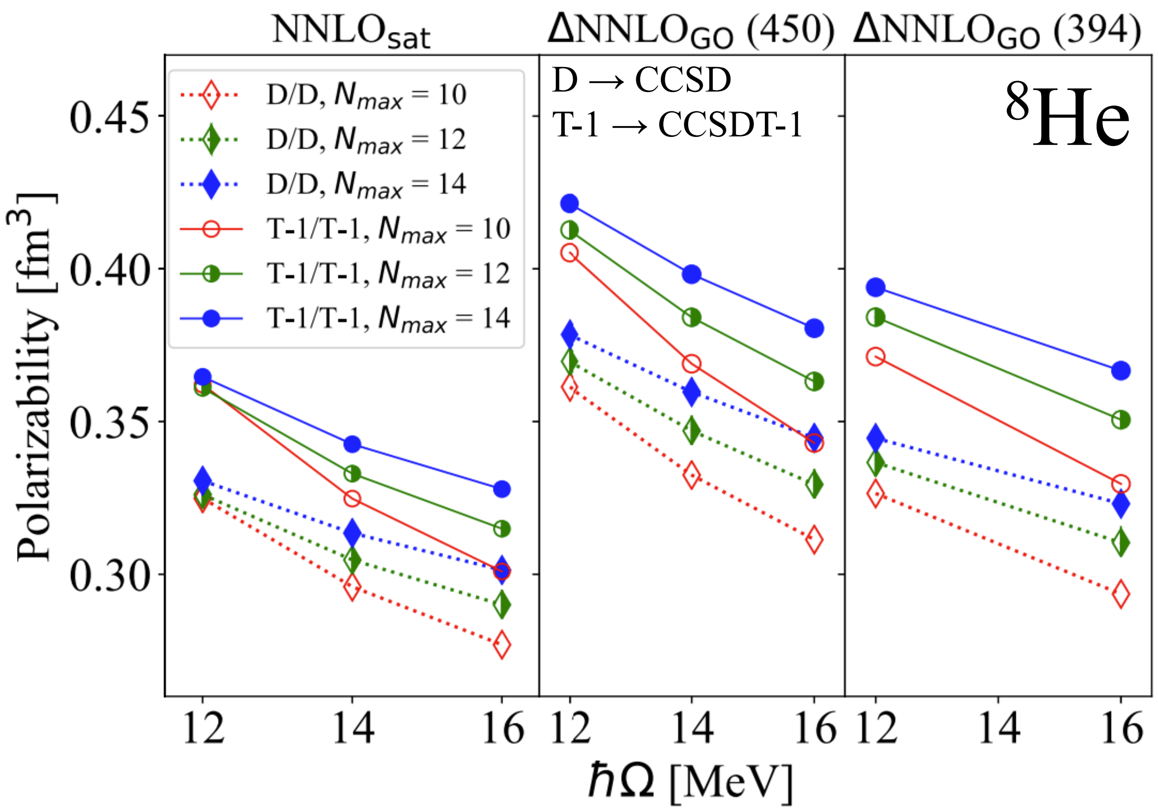


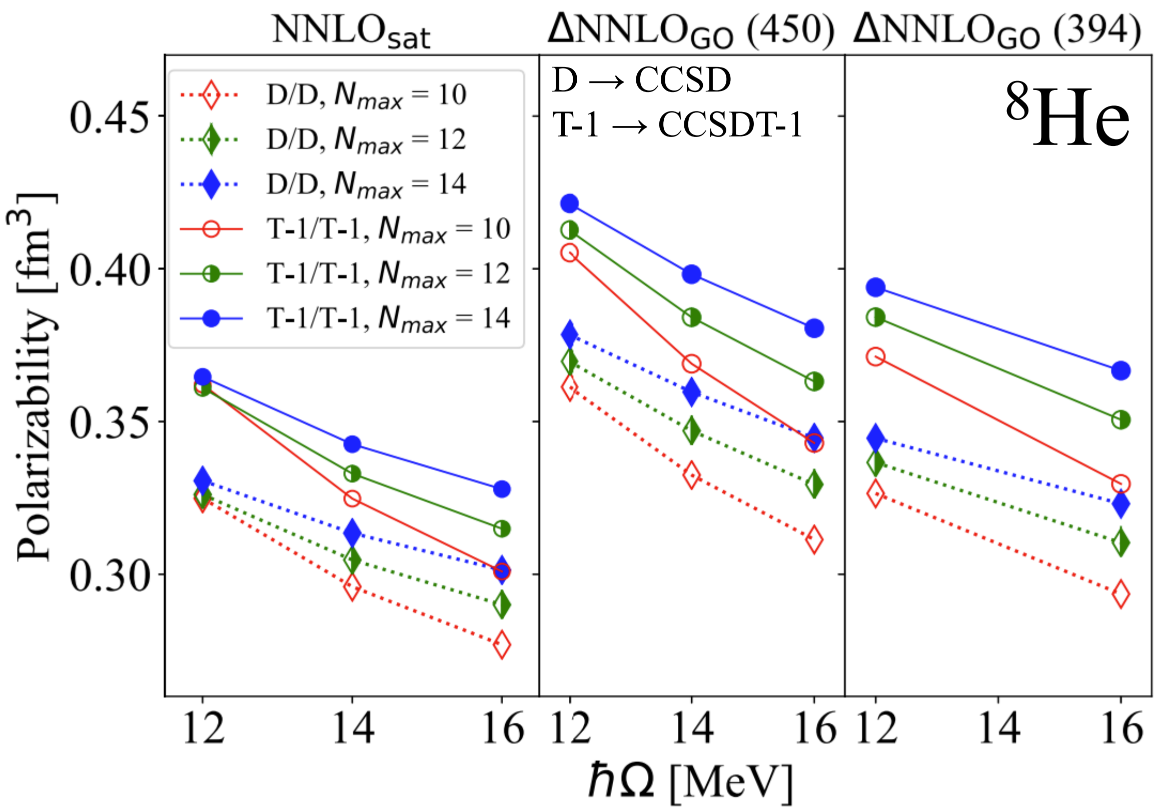
Dipole polarizability



$$\alpha_D = 2\alpha\hbar c \int_0^\infty d\omega\, \omega^{-1}\, R(\omega)$$

FB et al., PRC 105, 034313 (2022)

Dipole polarizability



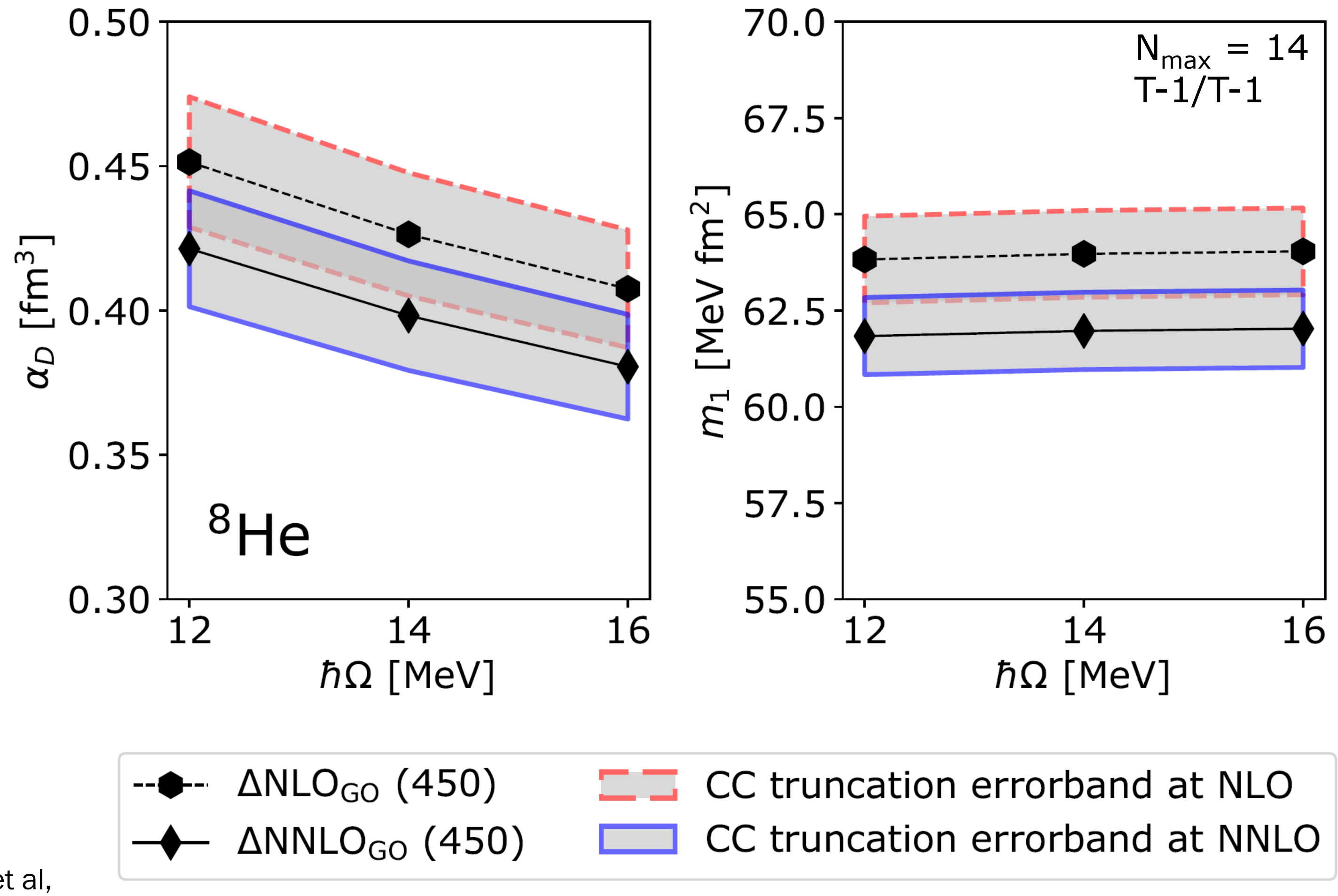
$$\alpha_D = 2\alpha\hbar c \int_0^\infty d\omega\, \omega^{-1}\, R(\omega)$$

Interaction	α_D (fm^3)
$\mathrm{NNLO_{sat}}$	0.37(3)
$\Delta\mathrm{NNLO_{GO}}(450)$	0.42(3)
$\Delta\mathrm{NNLO_{GO}}(394)$	0.39(2)

- 5 times larger than $\alpha_D(^4\mathrm{He}) = 0.074(9)$ fm^3 [Arkatov et al, 1975, 1980, Pachucki et al, 2006].

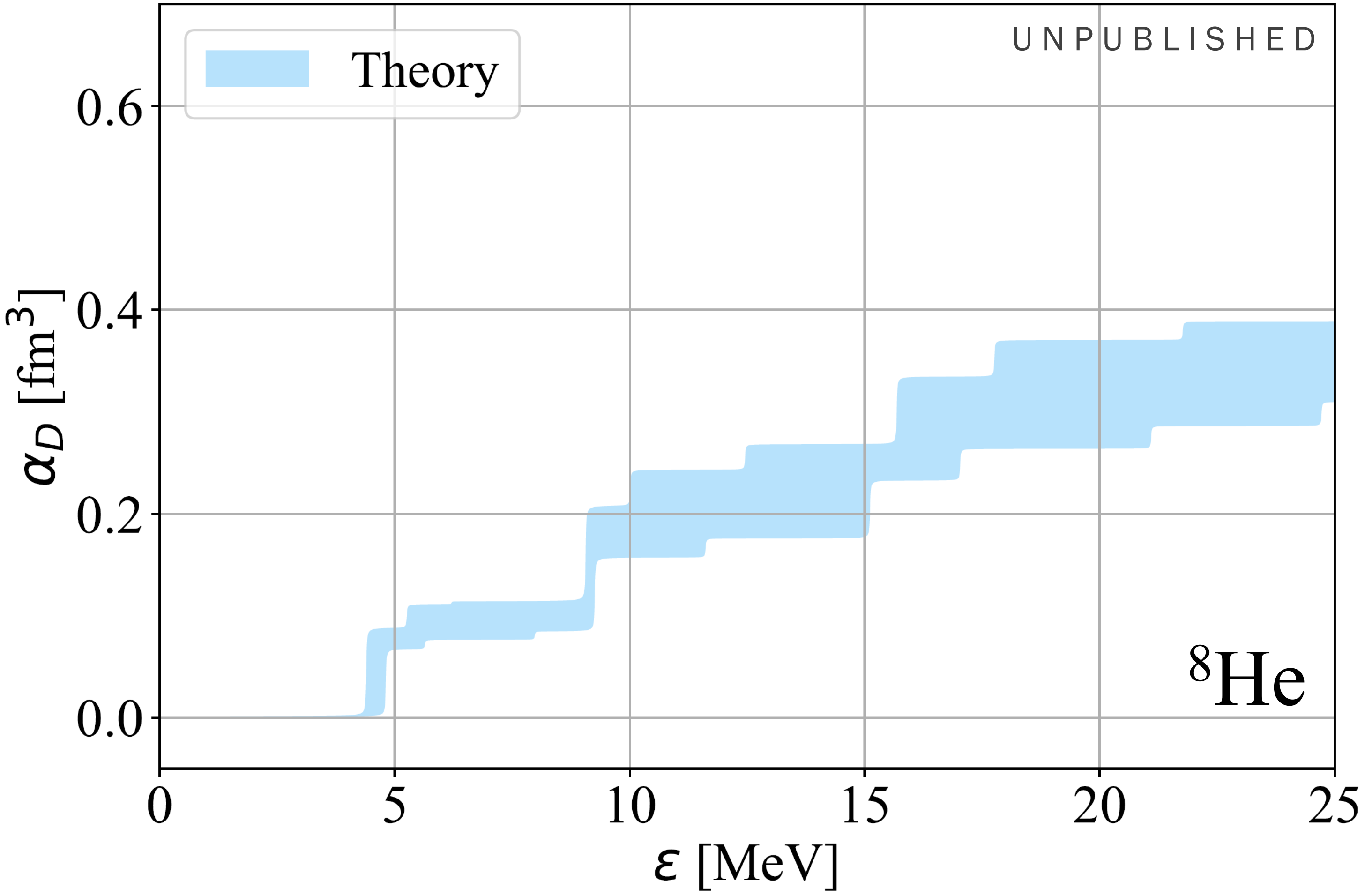
FB et al., PRC 105, 034313 (2022)

Comparison between chiral orders



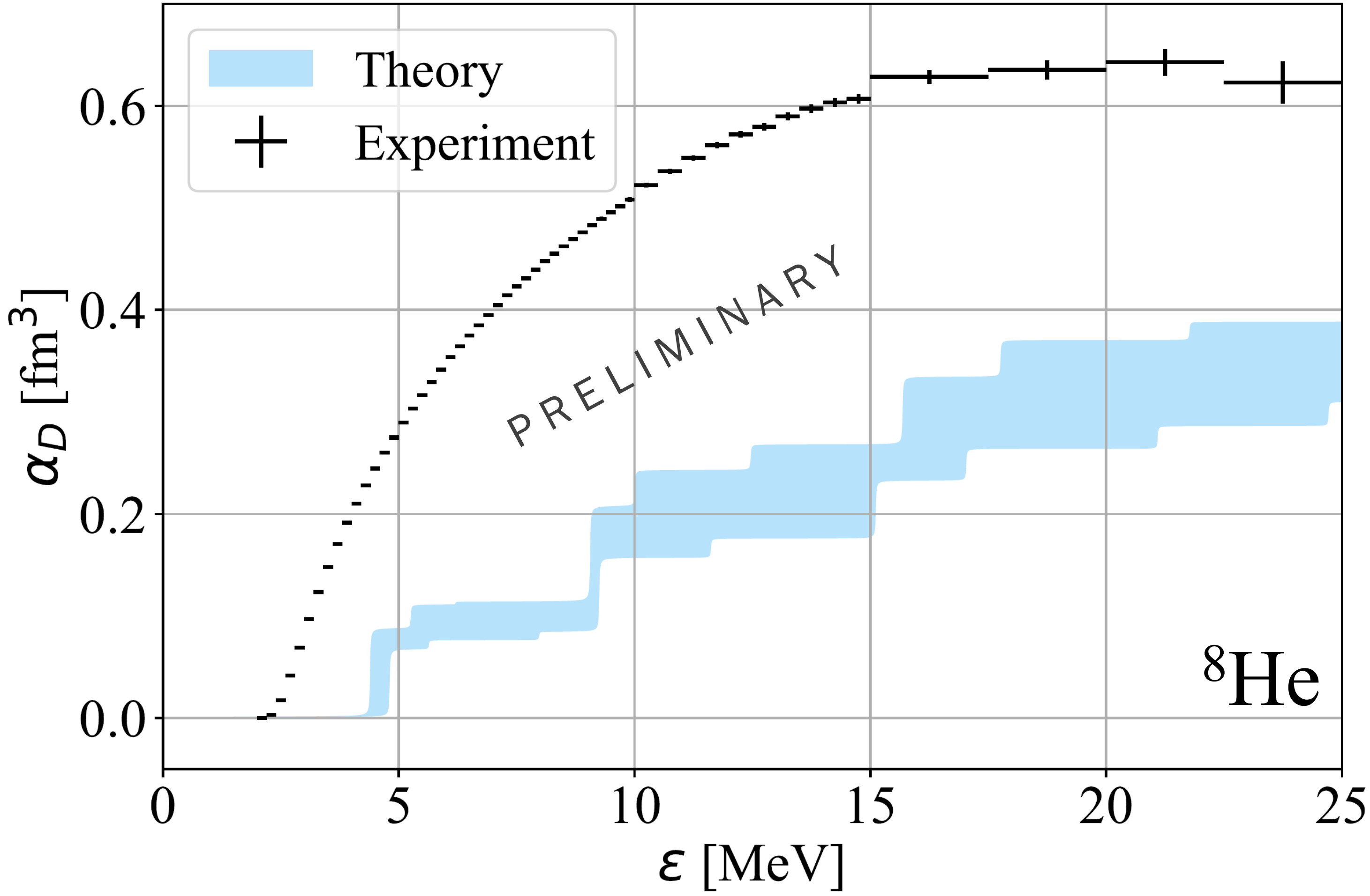
B. Acharya, S. Bacca, **FB** et al,
arXiv:2210.04632

Running sums



Running sums

Exp data: C. Lehr (TU Darmstadt PhD thesis) and the SAMURAI collaboration



more weight to **low-energy states**

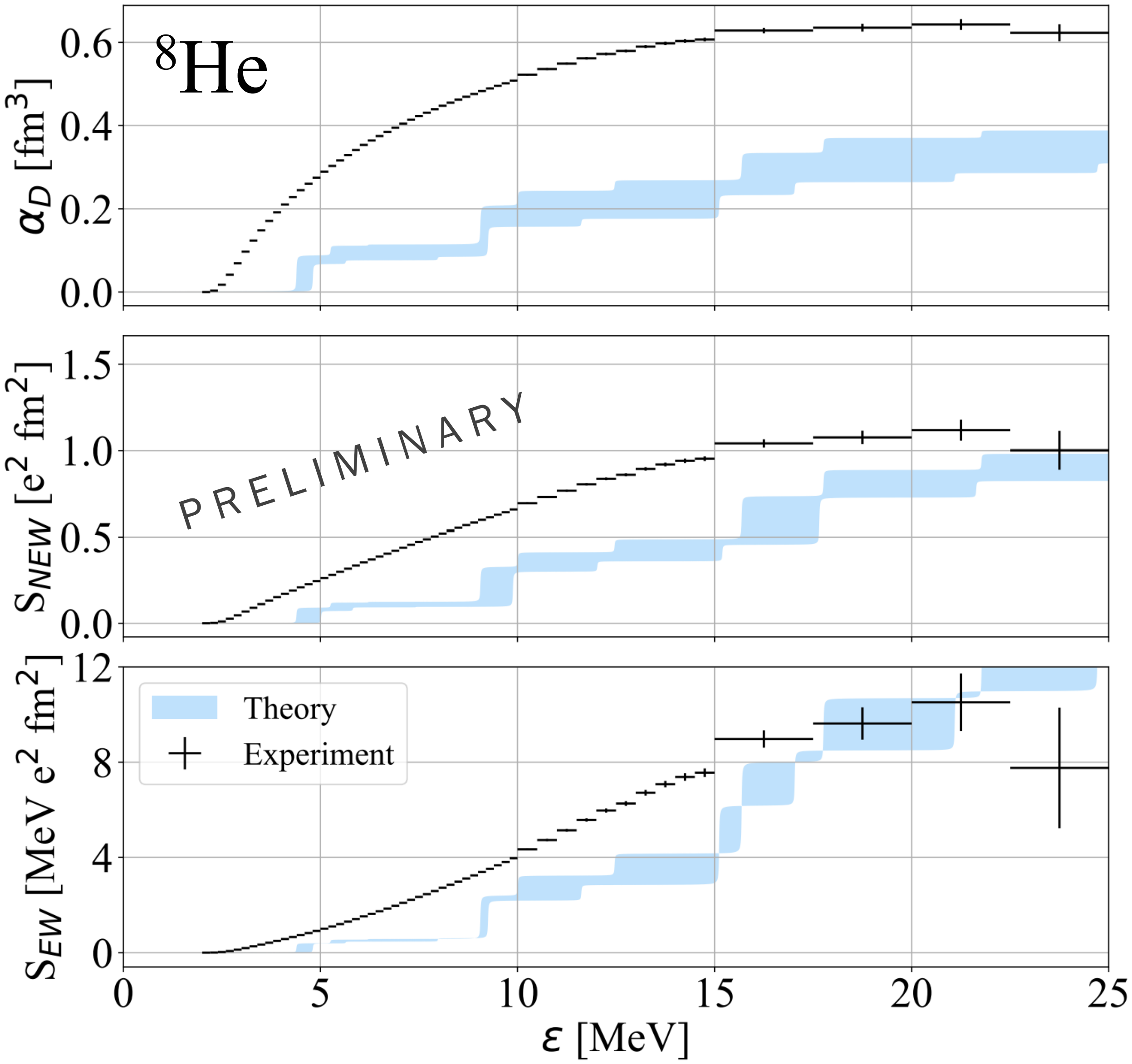
$$\alpha_D \propto \int_0^{\epsilon} d\omega\, \omega^{-1} R(\omega)$$

$$S_{NEW} \propto \int_0^{\epsilon} d\omega\, \omega^{0} R(\omega)$$

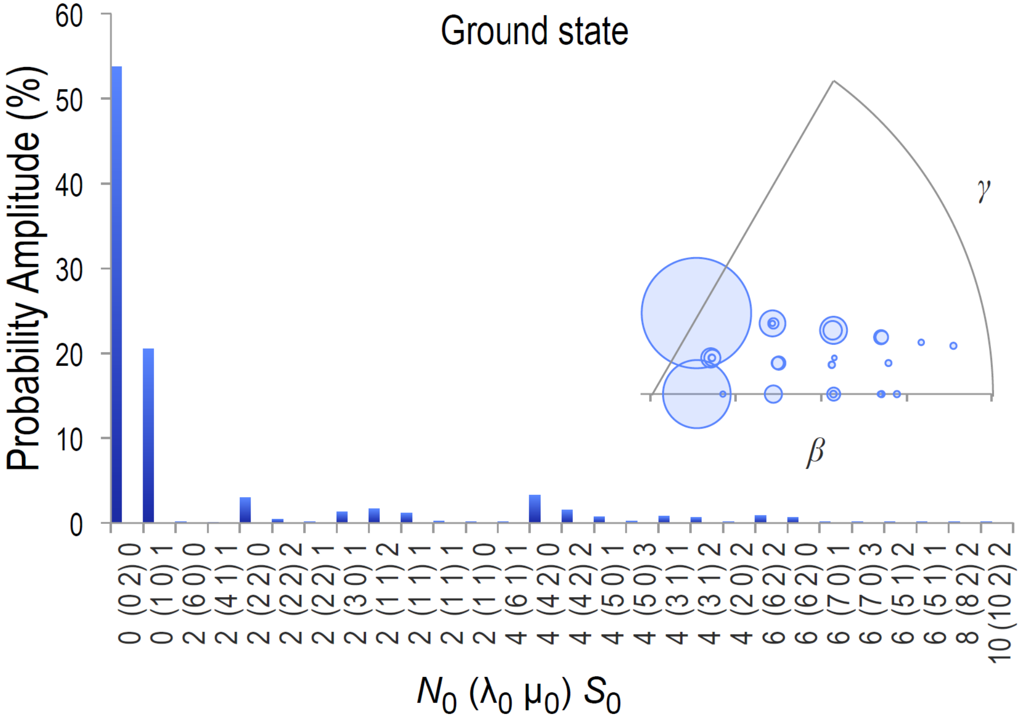
$$S_{EW} \propto \int_0^{\epsilon} d\omega\, \omega\, R(\omega)$$

more weight to **high-energy states**

Exp data: C. Lehr (TU Darmstadt PhD thesis) and the SAMURAI collaboration



Deformation in ^{8}He?

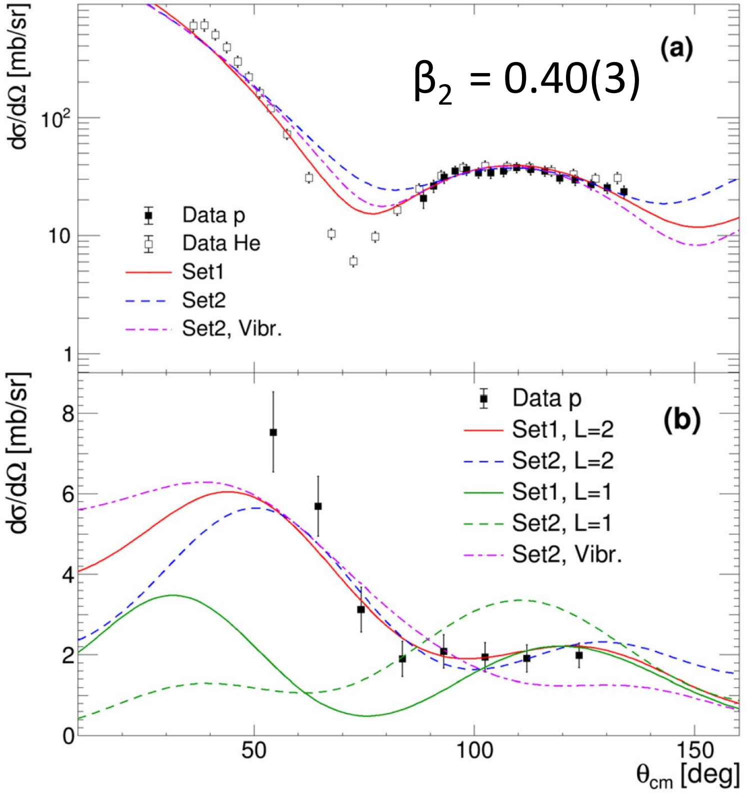


SA-NCSM ground state calculations

Launey et al., EPJ Special Topics 229, 2429-2441 (2020)

First 2+ excited state

M. Holl et al, Phys. Lett. B 822 136710 (2021)



Coupled cluster theory for deformed nuclei

- ❑ Coupled-cluster computations starting from **axially-symmetric reference states** now possible [S. J. Novario et al, 2020].

- ❑ Need of **symmetry restoration** [G. Hagen et al, 2022].

- ❑ To do that, we calculate the expectation value:

$$E_J = \frac{\langle\widetilde{\Psi}|P_J H|\Psi\rangle}{\langle\widetilde{\Psi}|P_J|\Psi\rangle}$$

- ❑ In this way we project a state with J_z = 0 on total angular momentum J.

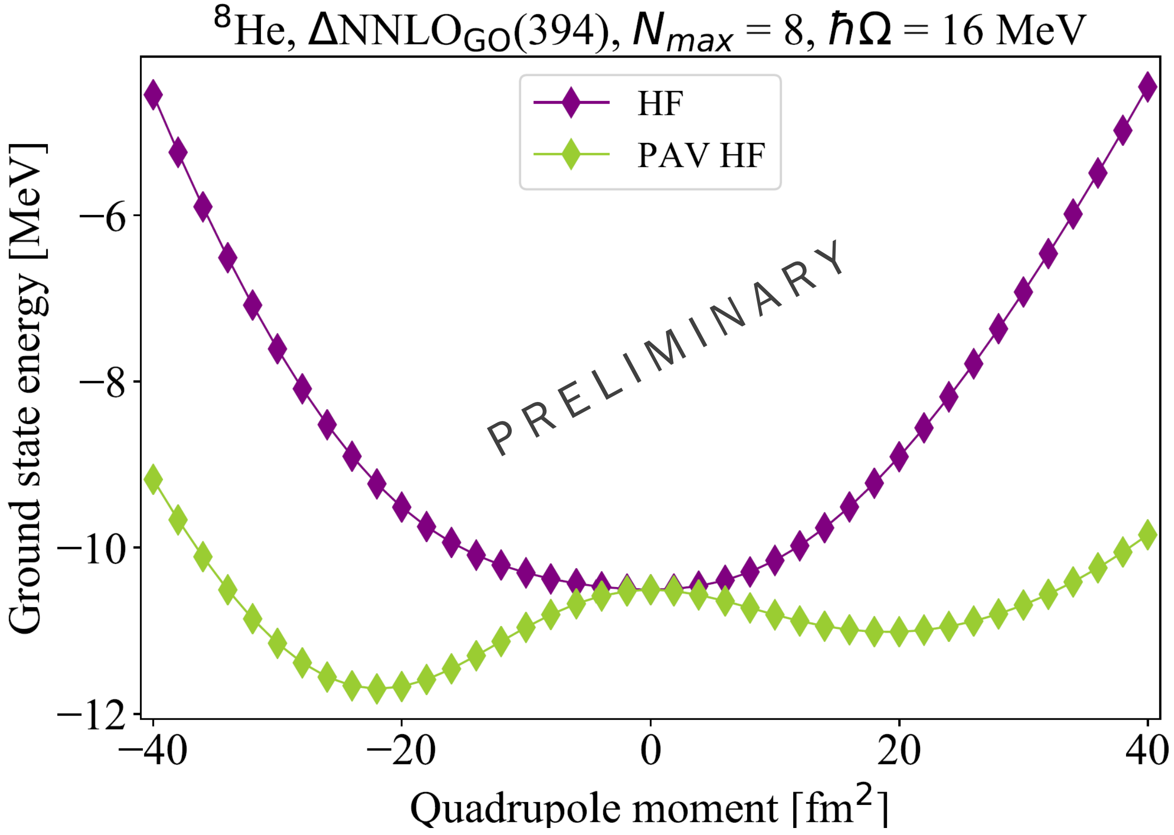
Guggenheim Museum in New York City, photo by me

Deformed reference states for ^{8}He

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

- ❑ we assume J_z conservation,
- ❑ 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.

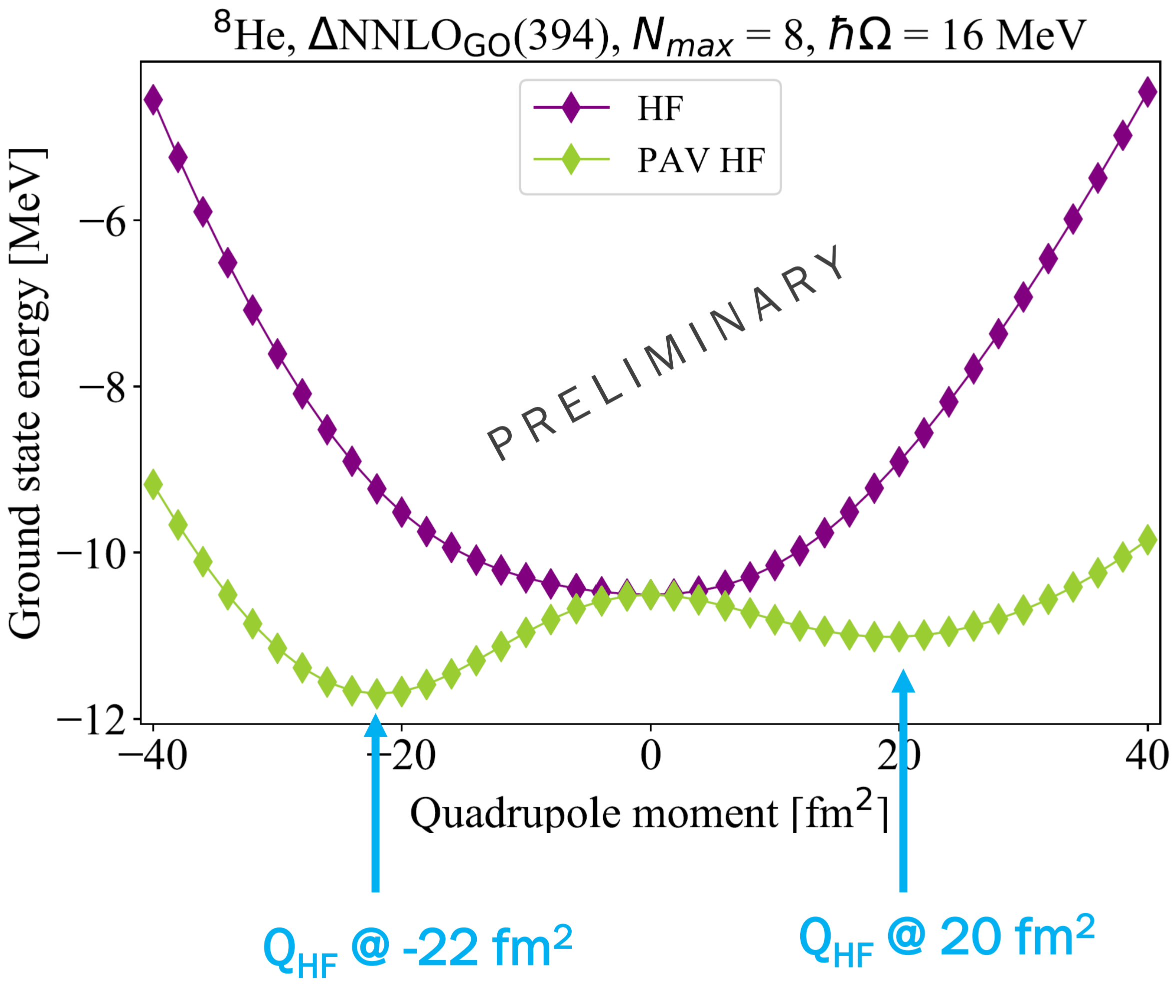


Deformed reference states for ^{8}He

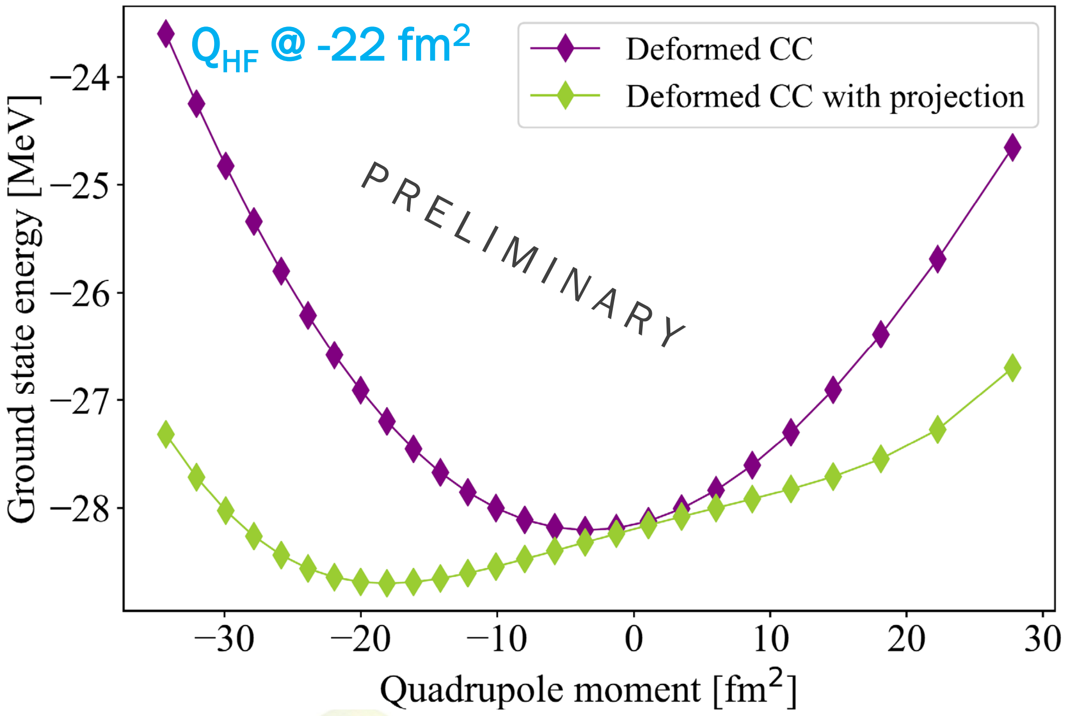
We start from **Hartree-Fock calculations** where:

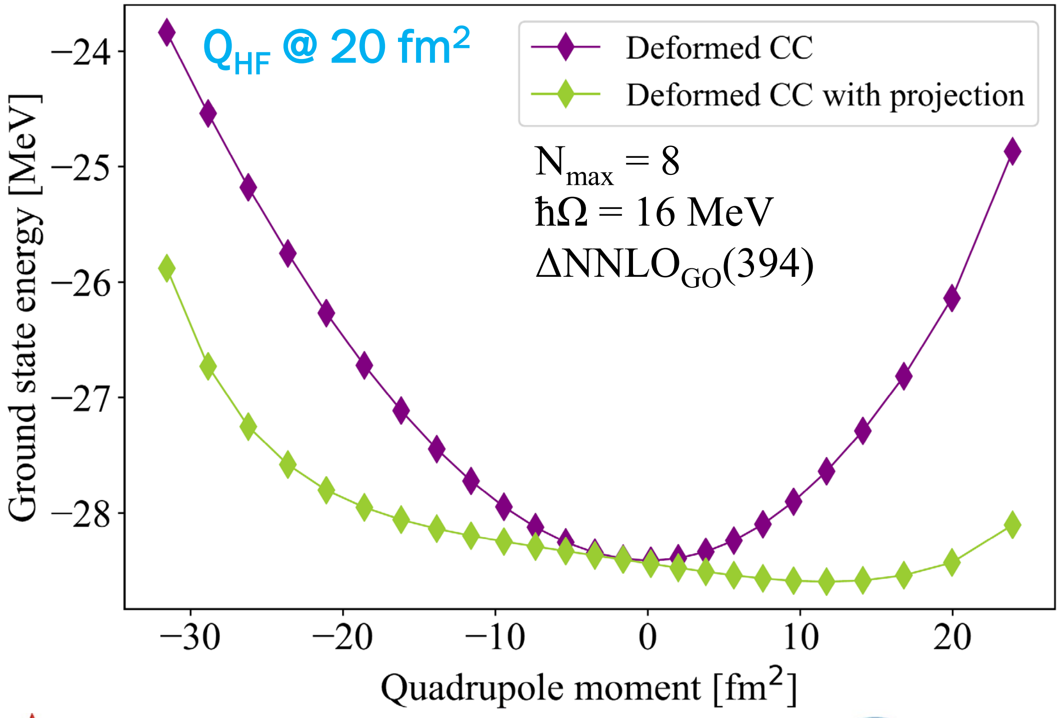
- only axial symmetry is assumed,
- we minimize the energy under the constraint of a **fixed expectation value for the quadrupole moment**.

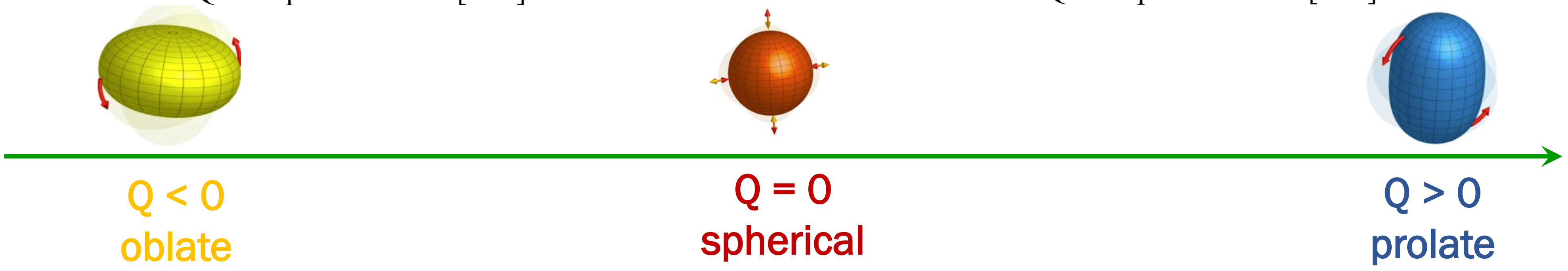
We then perform an **angular momentum projection** after variation (PAV) of the E_{gs} vs Q curve.



Deformed CC results for ^8He





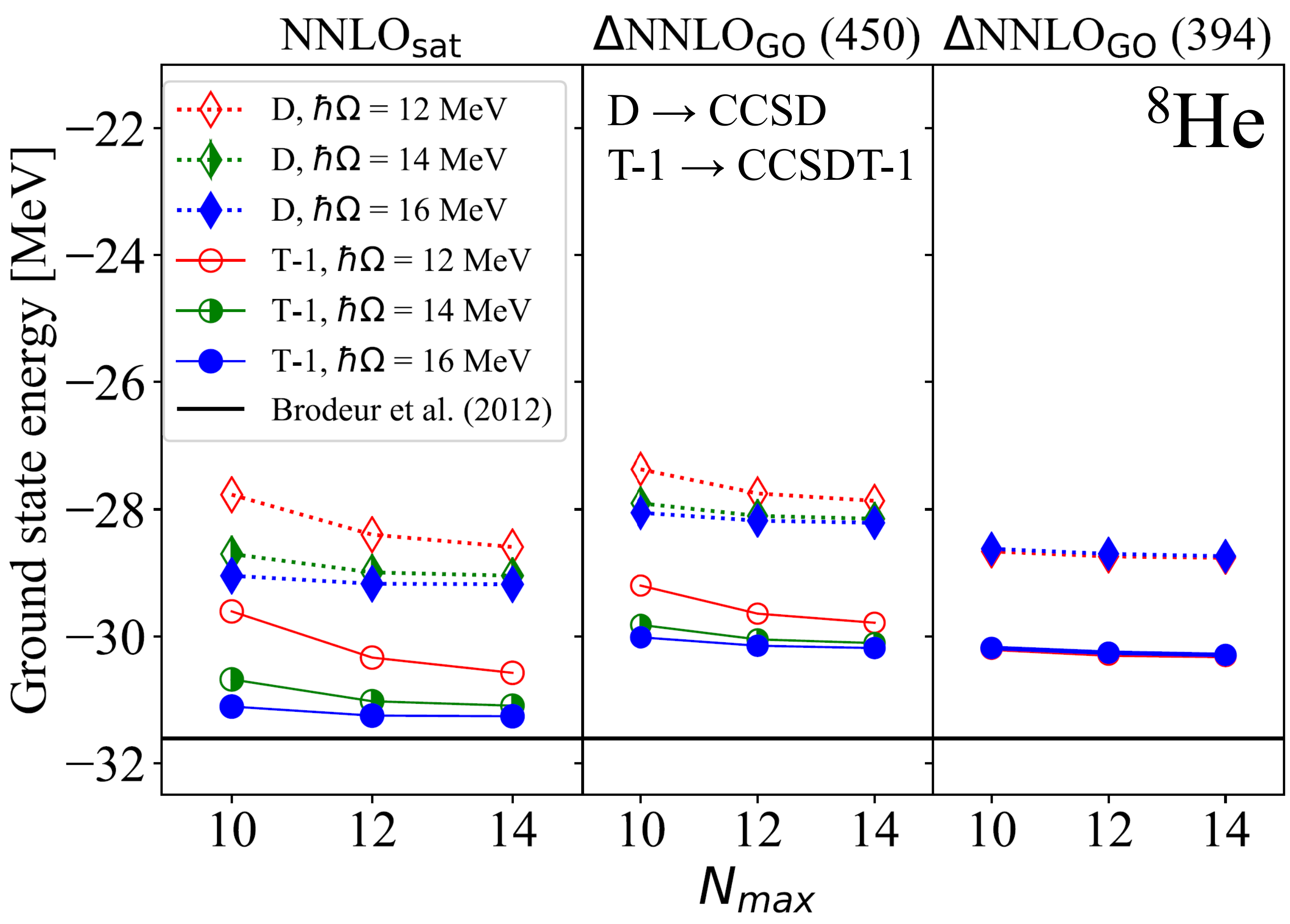


Conclusions and outlook

- ❑ Good agreement between theory and experiment for ground-state properties of ^{8}He.
- ❑ Our theory may miss some correlations in the description of the low-lying dipole states.
- ❑ Neglecting the nuclear deformation effects could be a possible reason.
- ❑ Symmetry-restored CC calculations point to an interplay of prolate and oblate shapes in the ground state of ^{8}He.
- ❑ Our plan is to extend our α_D calculations to the deformed coupled cluster framework.

BACKUP

Ground state energy

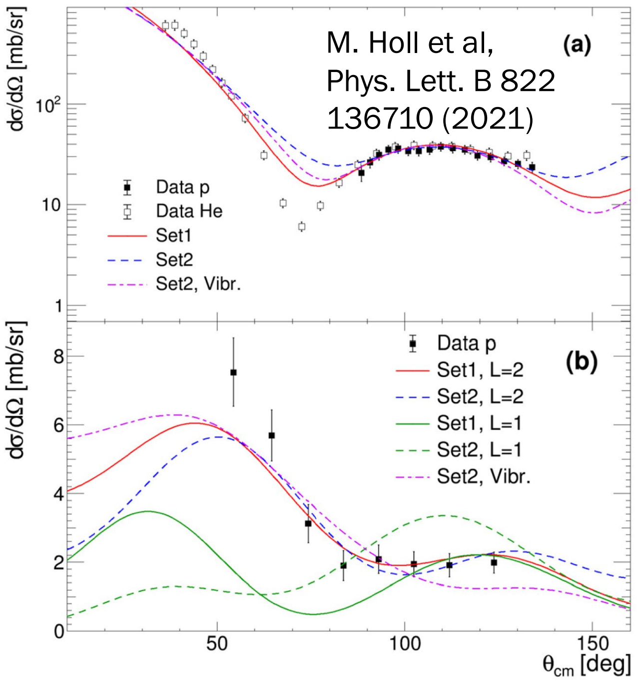


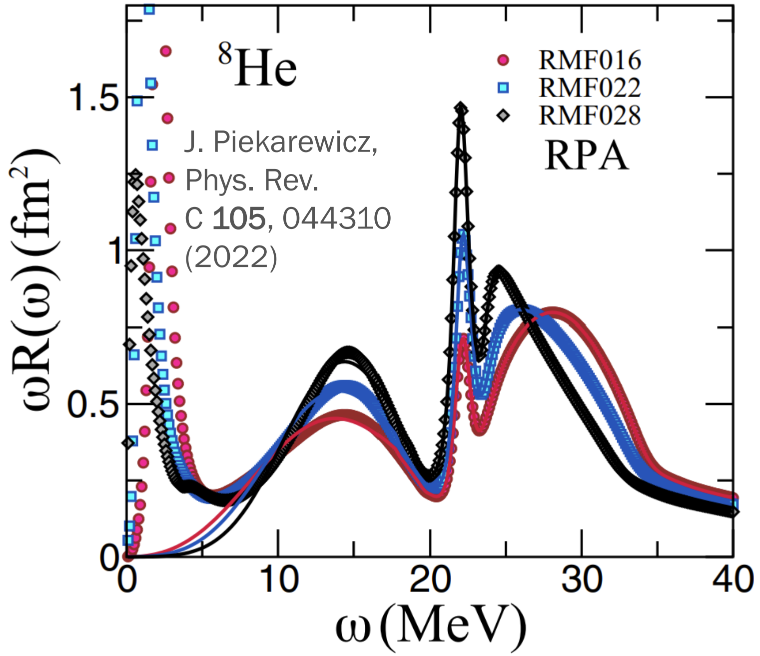
FB et al., PRC 105, 034313 (2022)

Low-lying dipole states in ^{8}He

Proton inelastic scattering on ^{8}He

No sign of dipole resonances below 6 MeV, compatible with NCSMC calculations with NN-N4LO.



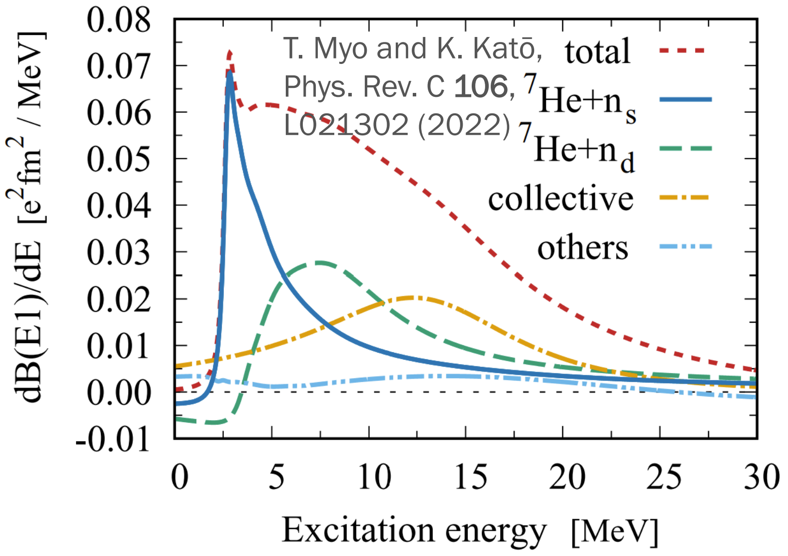


Dipole response in DFT-RPA framework

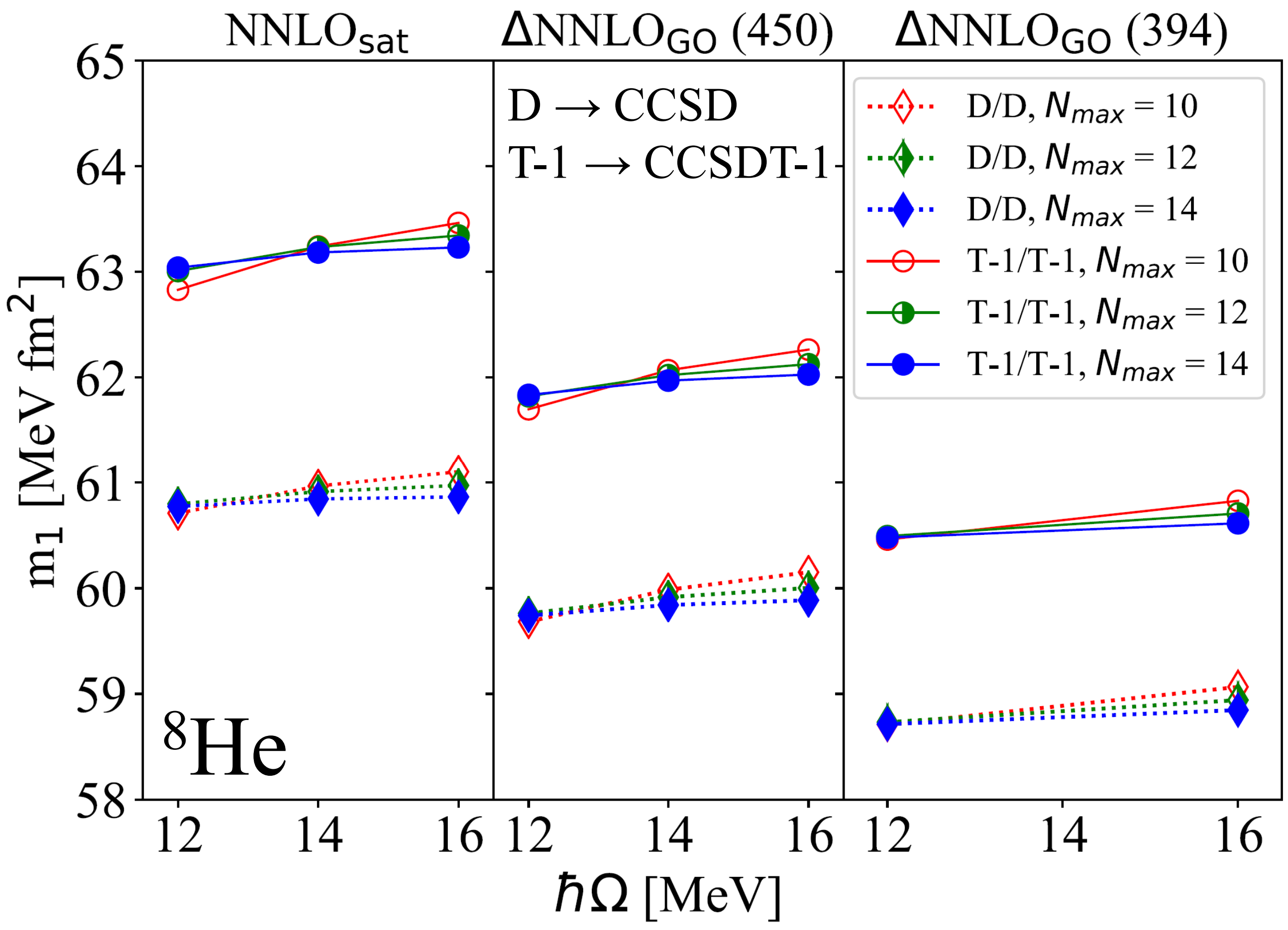
Presence of a soft dipole mode disfavoured (attributed to spurious CM contamination).

Cluster orbital shell model calculation

Predicted strength at low-energy, associated with ^{7}He + n channel.



Energy-weighted dipole sum rule



$$m_1 = \int d\omega \, \omega \, R(\omega)$$

The **photoabsorption cross section** is:

$$\sigma_\gamma(\omega) = 4\pi^2 \alpha \omega R(\omega)$$

so we get:

$$m_1 \propto \int d\omega \, \sigma_\gamma(\omega)$$

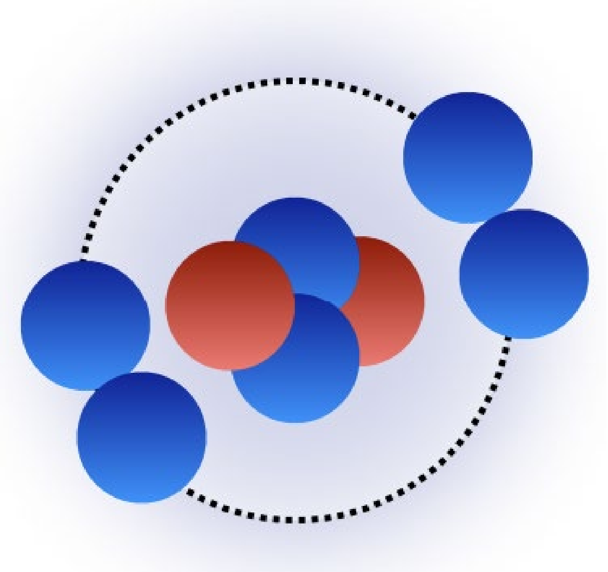
Interaction	m_1 (MeV fm^2)
NNLO$_{sat}$	63(1)
ΔNNLO$_{GO}$(450)	62(1)
ΔNNLO$_{GO}$(394)	60.5(9)

FB et al., PRC 105, 034313 (2022)

Cluster sum rule

- How much of the **dipole strength of ^{8}He** is related to the **relative motion between core and halo?**
- Let us describe ^{8}He in terms of an ^{4}He **core** and a **four-neutron halo.**
- Comparing the m_1 sum rule for ^{8}He to

$$\int_{\omega_{th}}^{\infty} d\omega \left[\sigma_\gamma(\omega) - \sigma_\gamma^{cl_1}(\omega) - \sigma_\gamma^{cl_2}(\omega)\right] =$$
$$5.974 \frac{(Z_1 A_2 - Z_2 A_1)^2}{A A_1 A_2} \text{MeV fm}^2 \, (1+\kappa).$$



we probe a **new dipole degree of freedom**, connected to the relative motion of two "clusters" inside the nucleus (**cluster sum rule**).

- Using $NNLO_{sat}$, and the m_1 sum rule value for ^{4}He ($\approx$ 41 MeV fm^2), we get:

$$\frac{S_{cluster}}{S_{^8\mathrm{He}}} \approx 30\%$$

From ground to dipole-excited states

- Dipole excitations in nuclei can be studied calculating the **nuclear response function.**

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- To avoid the **continuum problem** we calculate a **Lorentz Integral Transform** of the response.

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

- In this way we obtain a **bound-state-like problem**, that we can handle in CC theory.

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- Then via **inversion** we get to the response.

S. Bacca et al, Phys. Rev. C **90**, 064619 (2014)