Photons and pions off nuclei as probes for the nuclear matter equation of state

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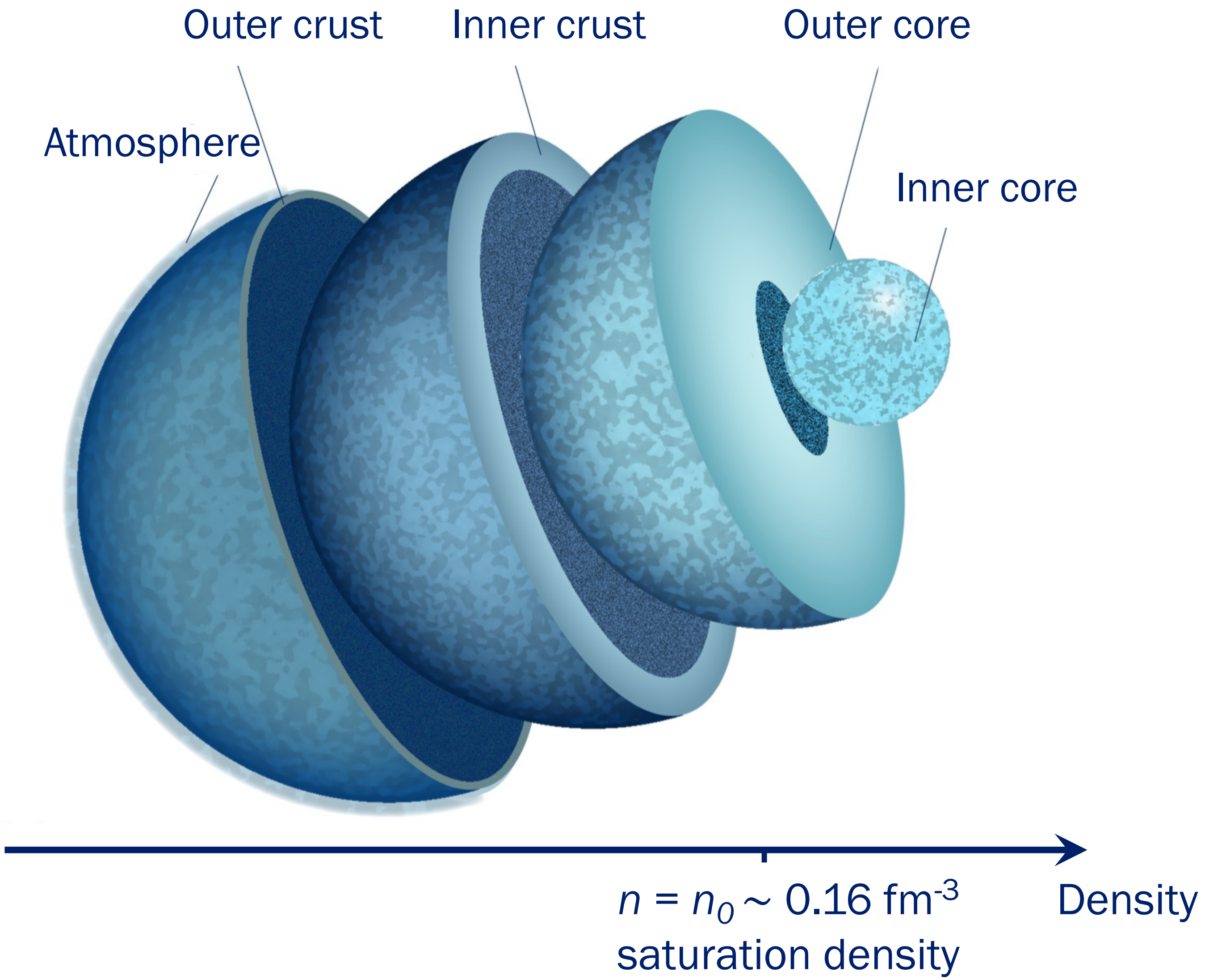
WORKSHOP ON "LEPTON INTERACTIONS WITH NUCLEONS AND NUCLEI", MARCIANA MARINA, ITALY

JUNE 23, 2025

Extreme matter in neutron stars



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MUSES Collaboration

Nuclear matter equation of state (EOS)

$$\frac{E}{A}(n,\alpha) = \frac{E}{A}(n,0) + S(n)\alpha^2 + \mathcal{O}[\alpha^4]$$

symmetry energy

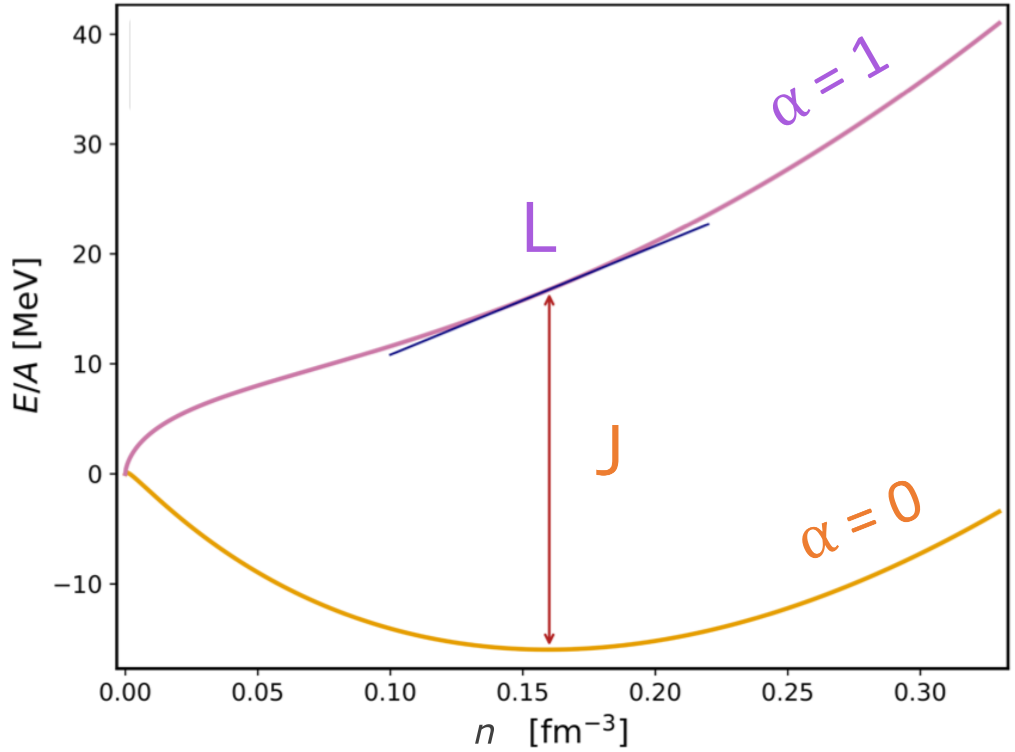
$$n = n_p + n_n$$

$$\alpha = \frac{n_n - n_p}{n}$$

$$S(n) = J + L\frac{n - n_0}{3n_0} + \ldots$$

symmetry energy at saturation density

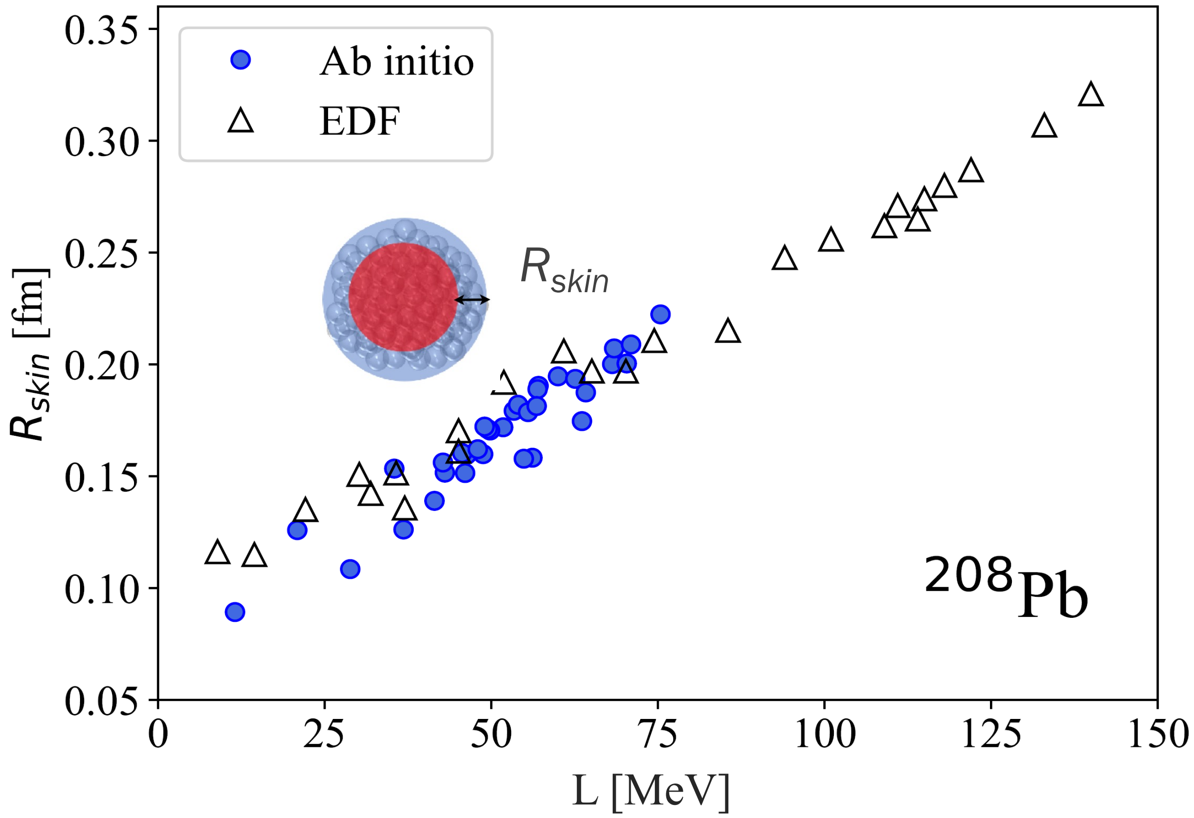
slope parameter, related to **pressure of pure neutron matter** at saturation density



How to constrain the symmetry energy?

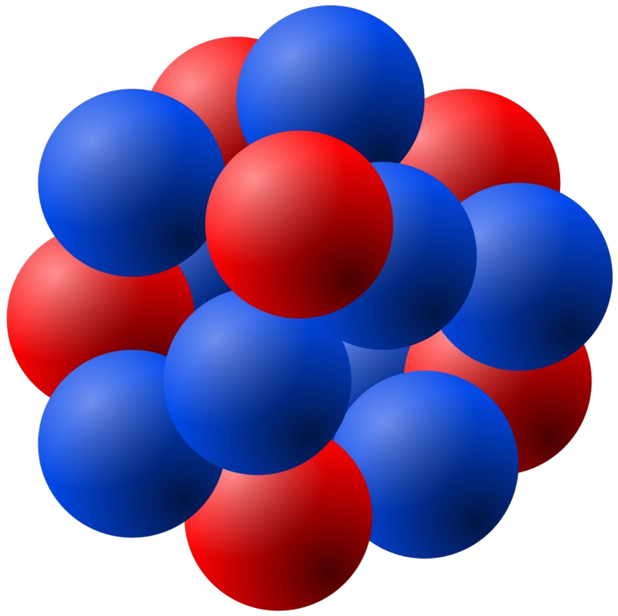
Neutron-skin thickness

$$R_{skin} = R_n - R_p$$



Data from M. Centelles et al, PRC 82, 054314 (2010), Hu et al, Nat Phys. 18, 1196–1200 (2022).

Ab initio nuclear theory



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

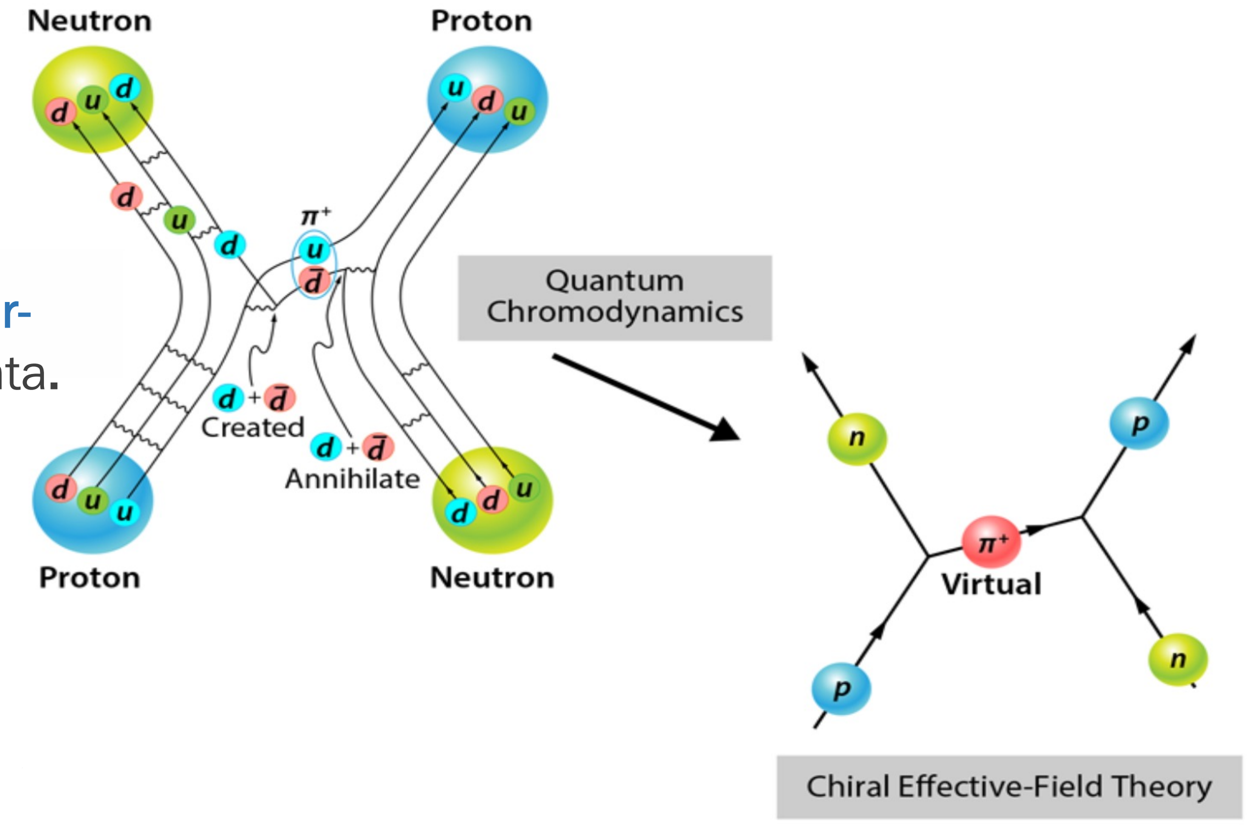
$$H|\psi\rangle = E|\psi\rangle$$
$$H = T + V_{NN} + V_{3N}$$

with controlled approximations.

- 2 ingredients: nuclear interactions and many-body solver.

Chiral Effective Field Theory (EFT)

- Low-energy approximation of QCD, with π, n, (Δ) as degrees of freedom.
- Separation of scales → systematic order-by-order expansion in powers of momenta.
- Short-range physics enclosed in low-energy constants.



APS/Alan Stonebraker

Weinberg, van Kolck, Epelbaum, Meißner, Entem, Machleidt, …

Coupled-cluster theory

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

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

with

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

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

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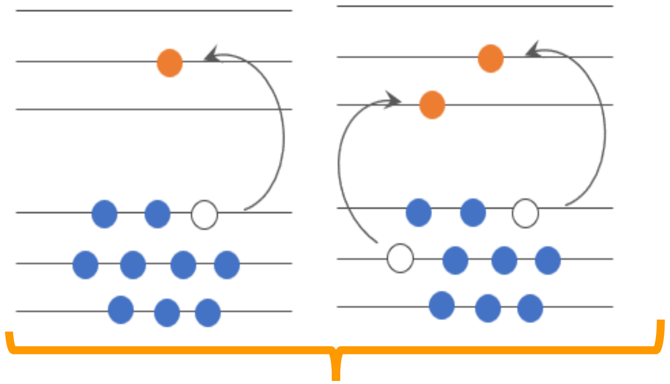
singles and doubles (CCSD)



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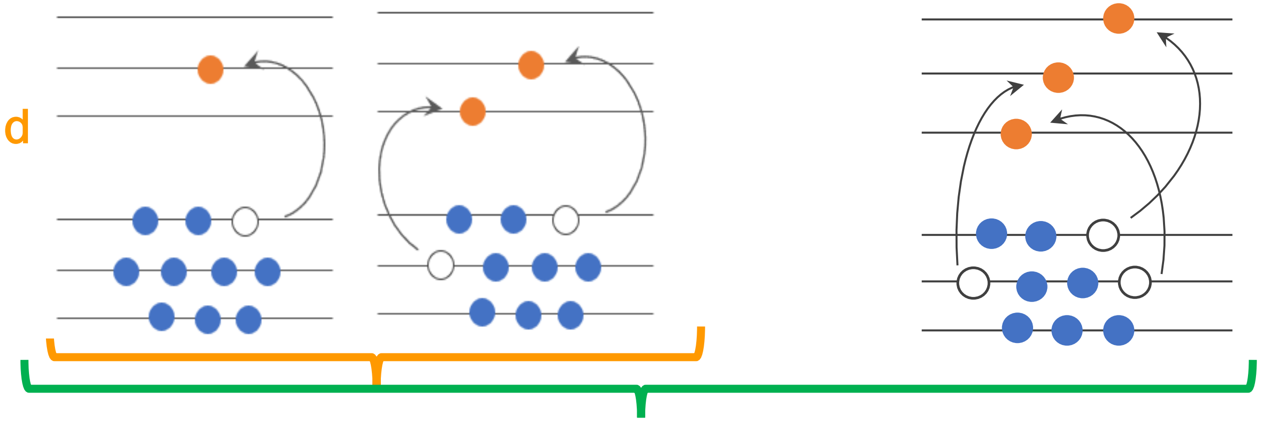

+ triples (CCSDT-1)

→ coefficients from **coupled-cluster equations**

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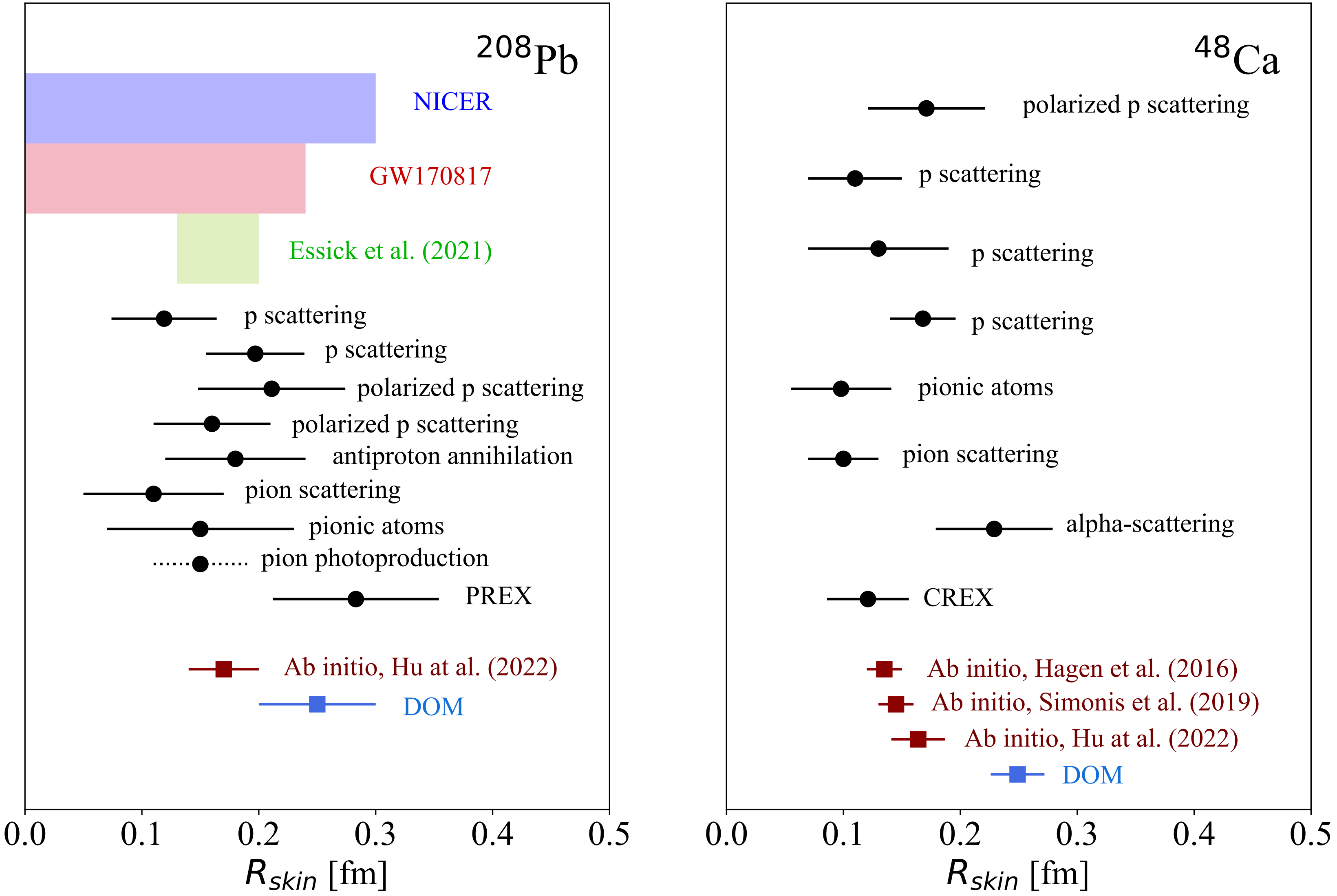
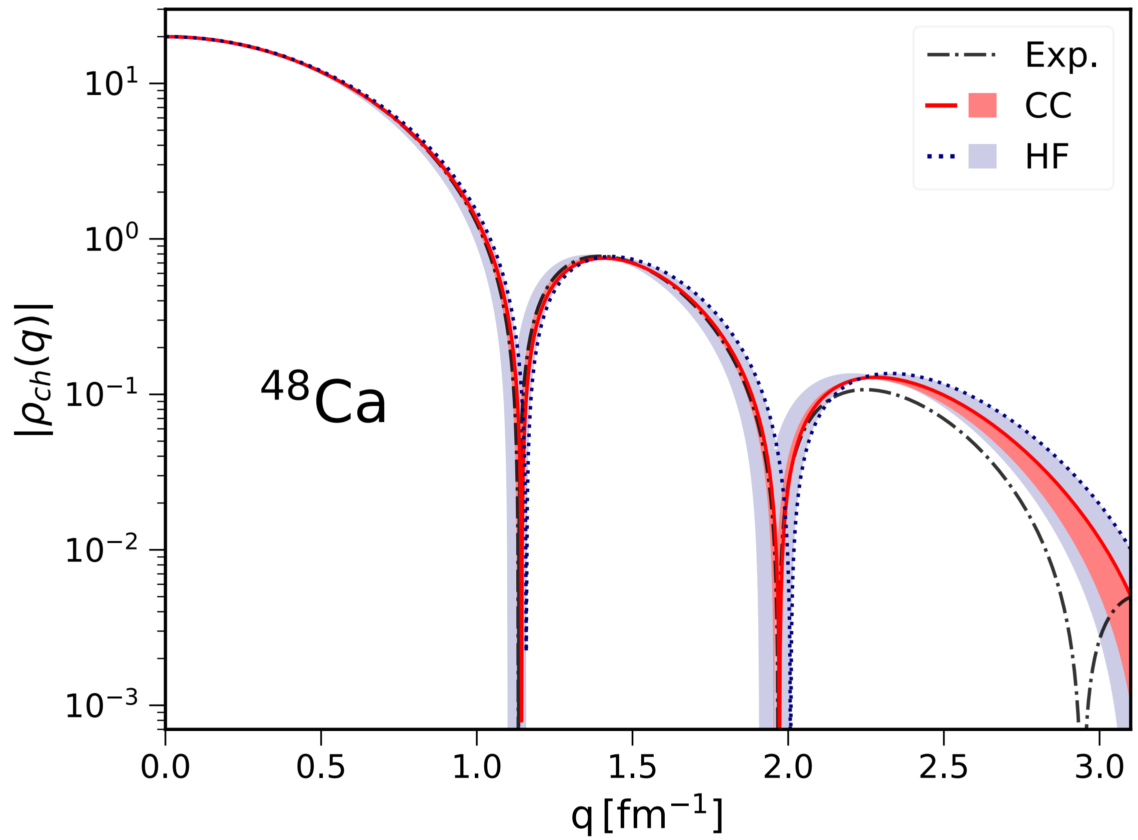
Neutron skin measurements



FB, PhD Thesis, JGU Mainz (2024).

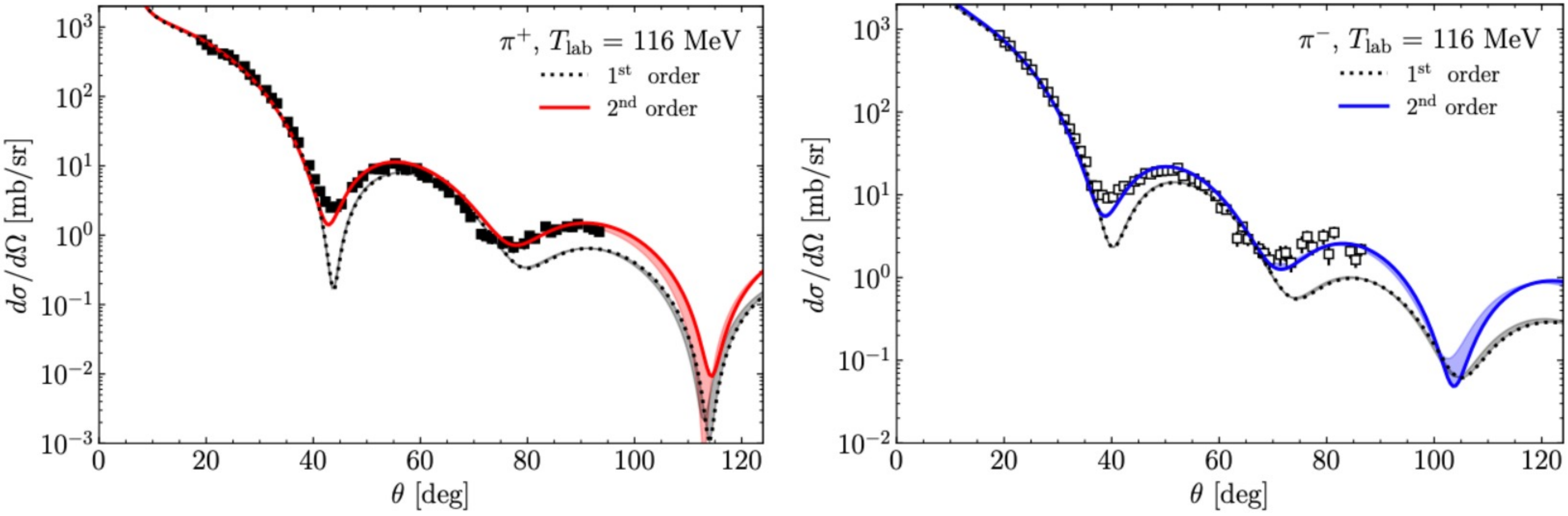
Nuclear structure input for pion scattering

- **Goal:** predict differential cross sections for pion scattering off non-zero isospin nuclei, as ^{48}Ca.
- Structure input for reaction calculation: **one-body densities** at first order, and **two-nucleon correlation functions** at second order .
- Densities from **coupled-cluster** and correlation functions from **Hartree-Fock** using the $\Delta NNLO_{GO}(394)$ and $NNLO_{sat}$ chiral forces.



V. Tsaran, F. Marino, S. Bacca, **FB** et al, arXiv:2505.18459 [nucl-th].

Pion scattering off ^{48}Ca



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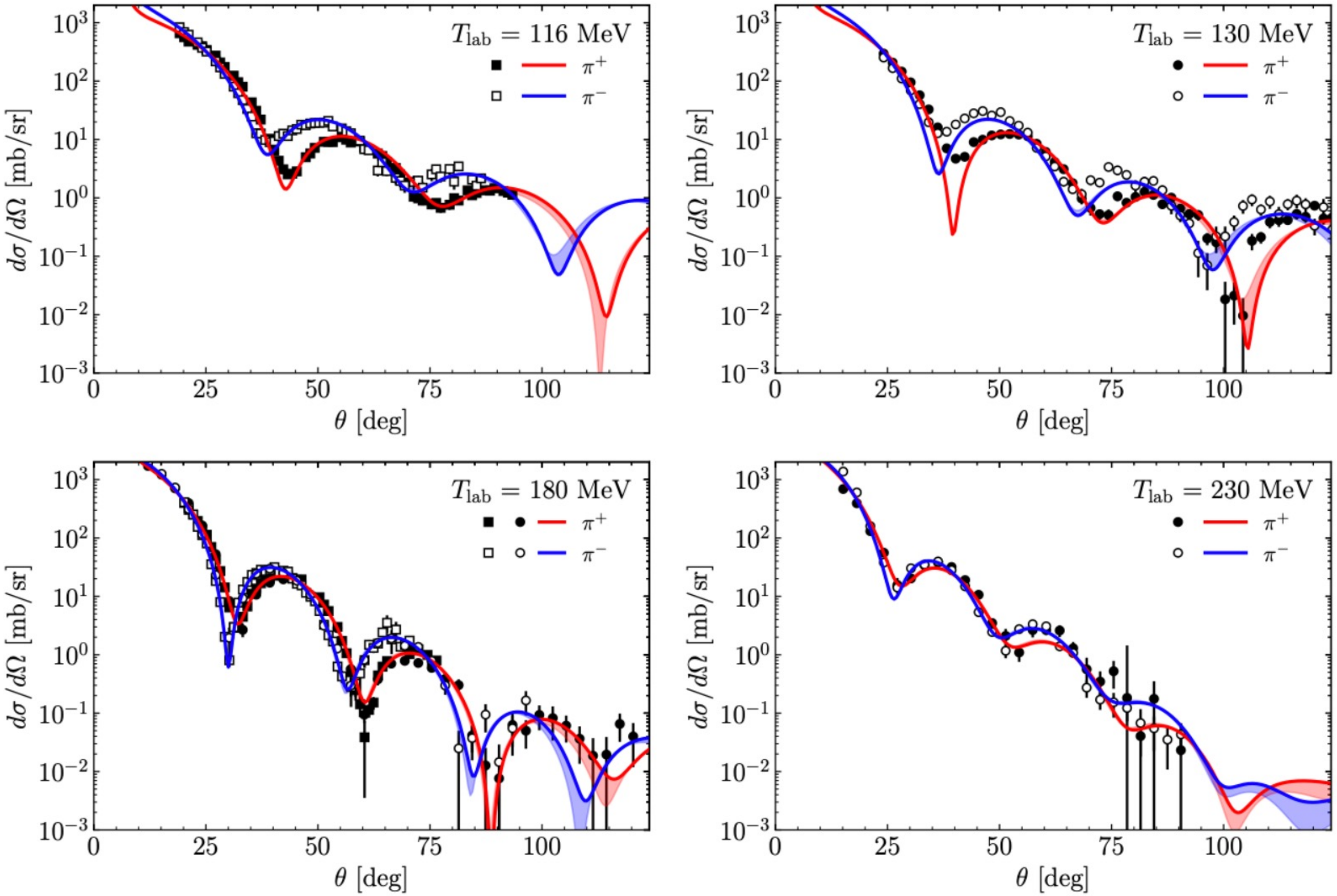

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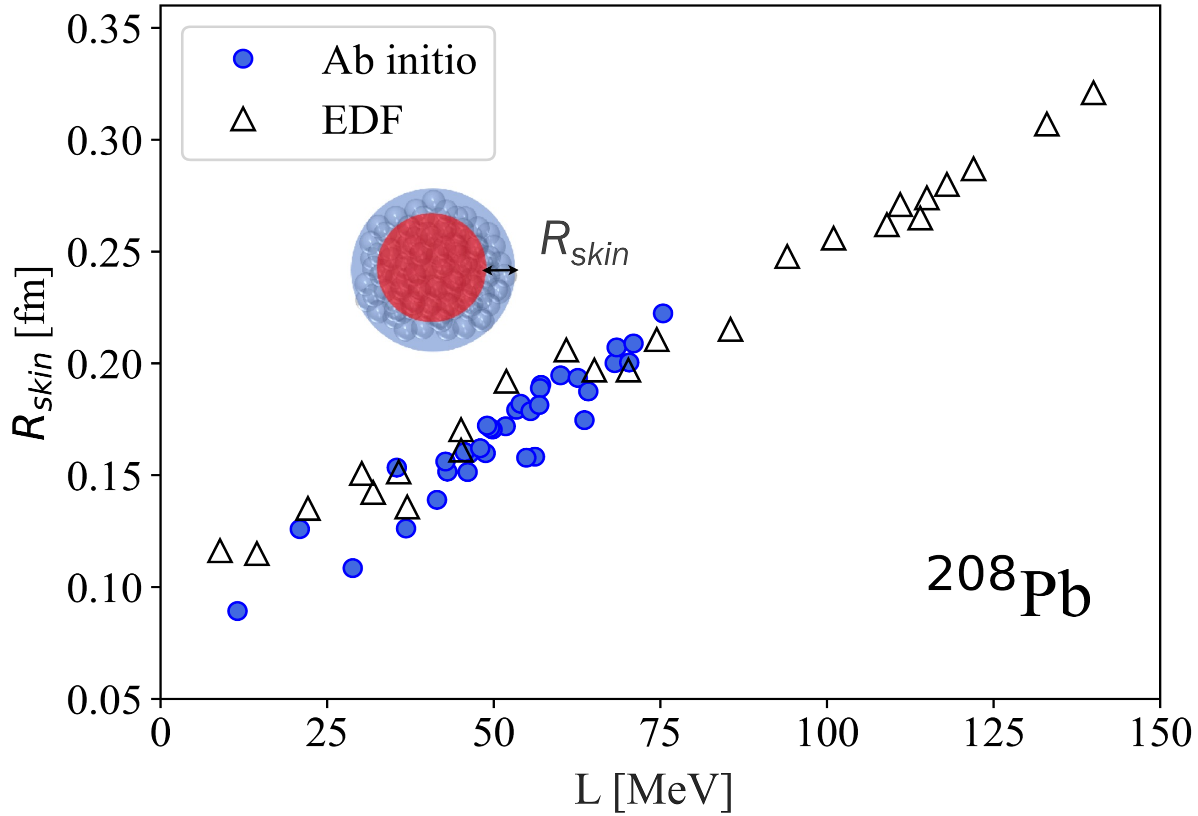
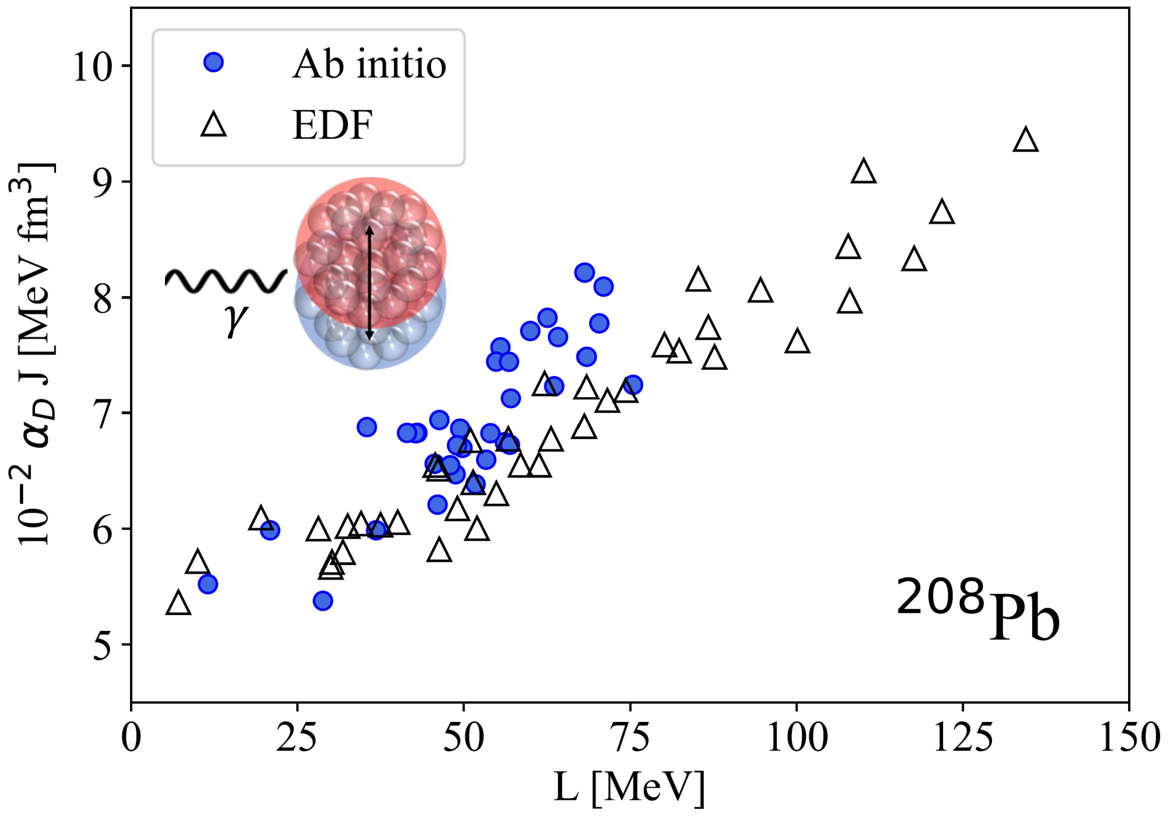
Electric dipole polarizability

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

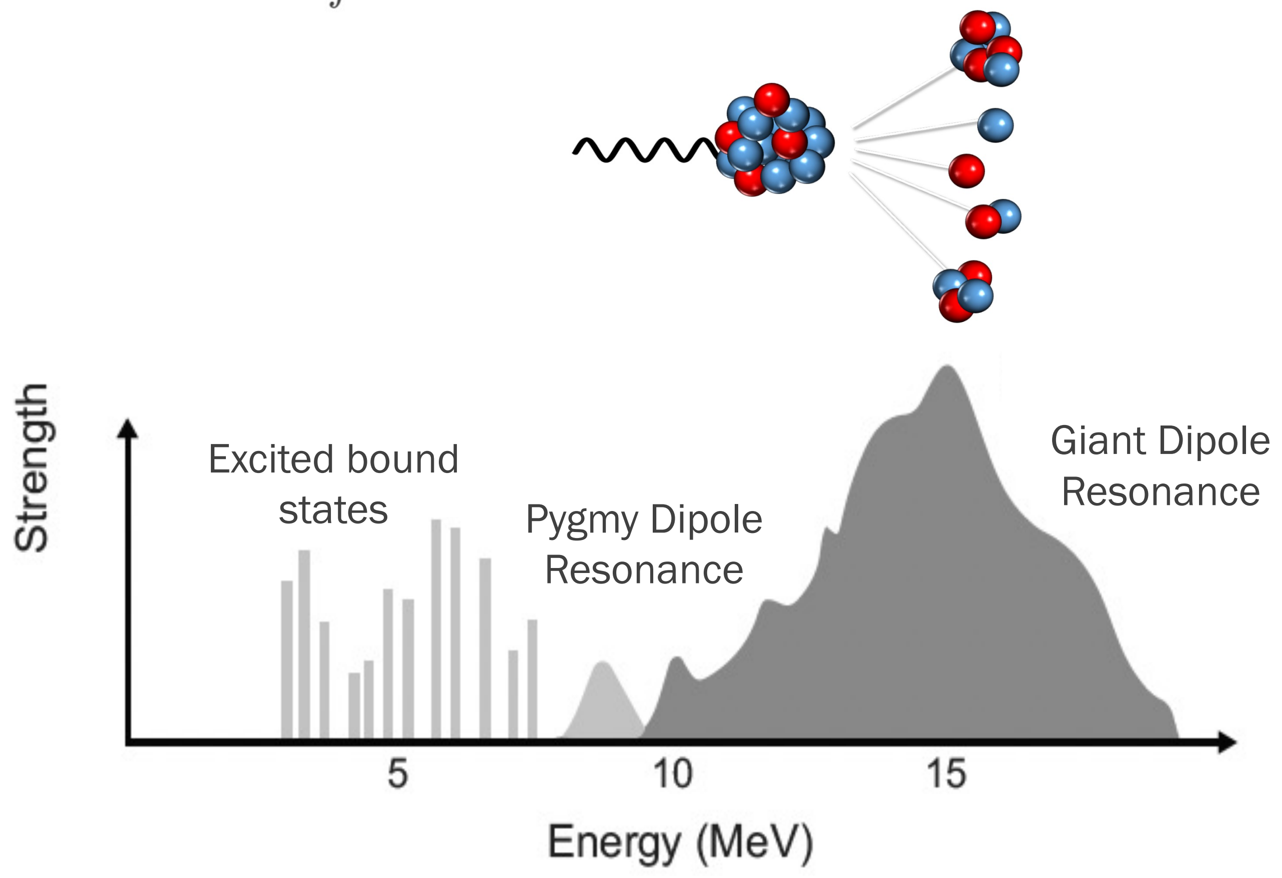




Data from M. Centelles et al, PRC 82, 054314 (2010), X. Roca-Maza et al, PRC 88, 024316 (2013), Hu et al, Nat Phys. 18, 1196–1200 (2022).

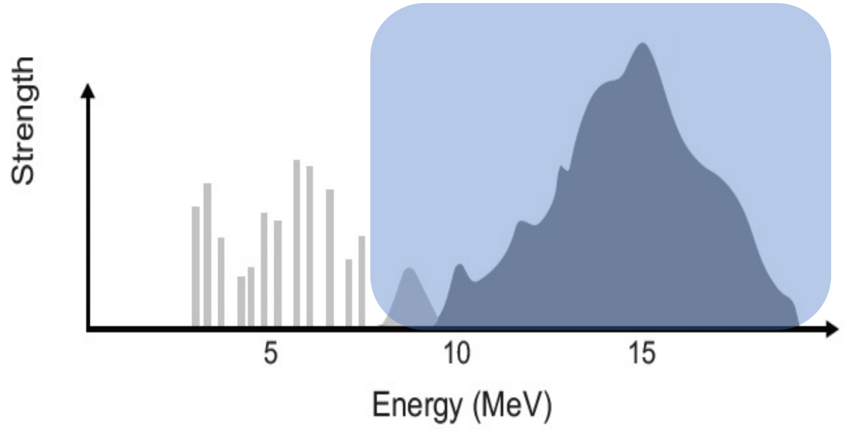
Nuclear response functions

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



From bound to dipole-excited states

$R(\omega)$



Continuum problem

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

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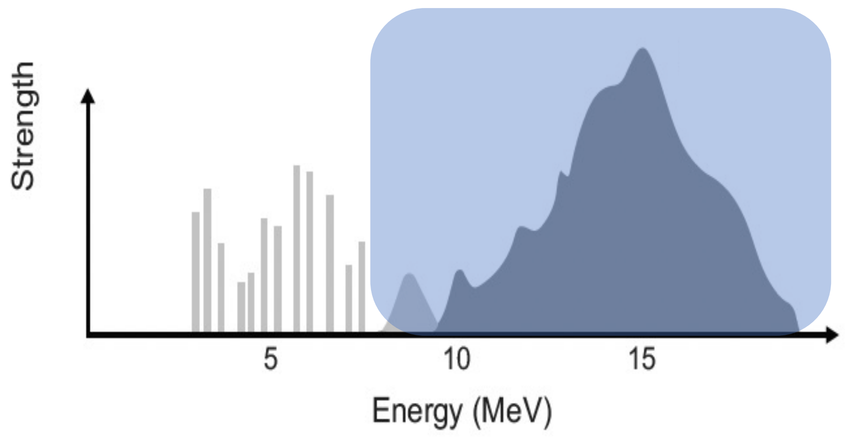

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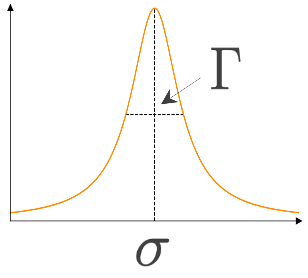
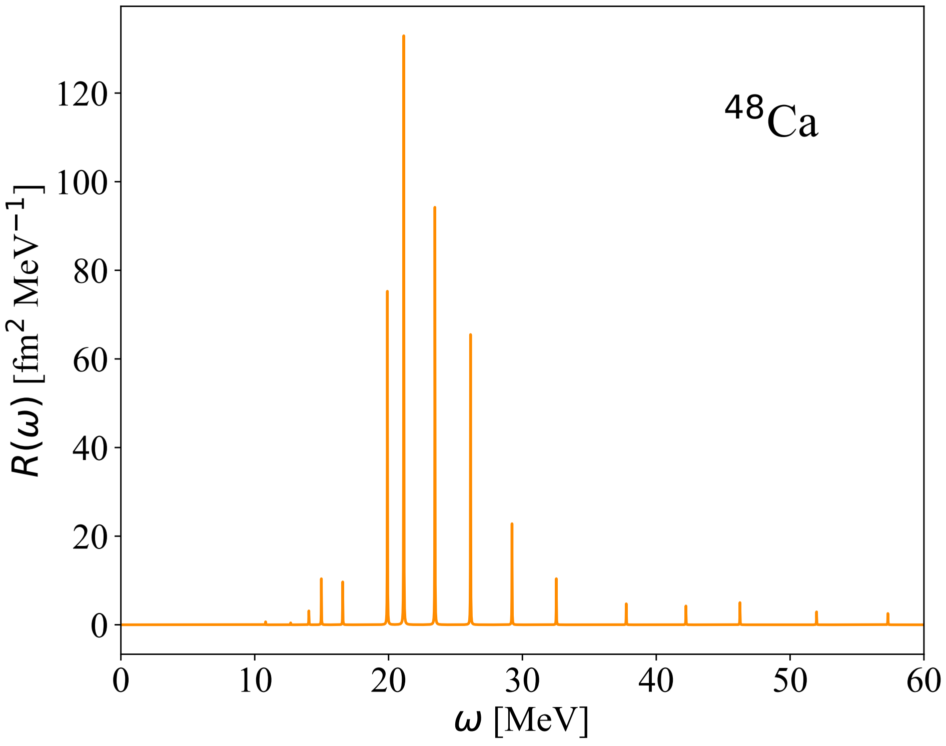


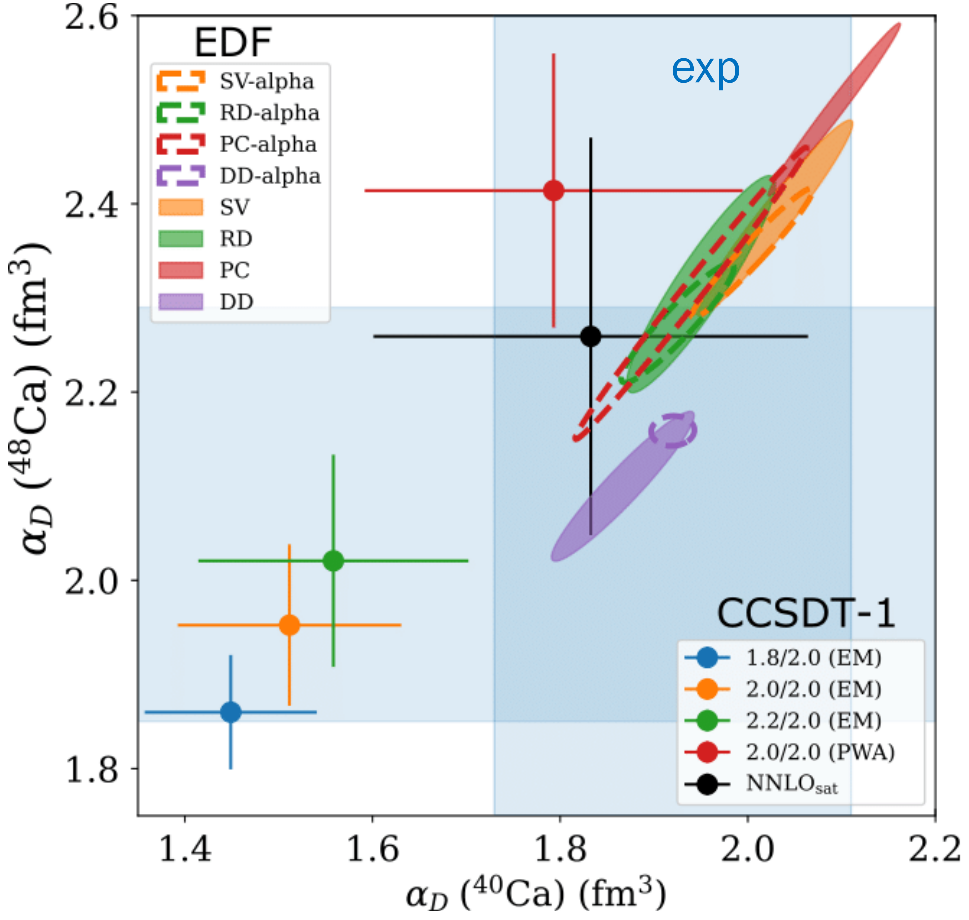
Lorentz Integral Transform (LIT)



Bound-state like problem

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

The case of ^{40,48}Ca



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

Constraints on symmetry energy

$$S(n) = J + L\frac{n - n_0}{3n_0} + \dots$$

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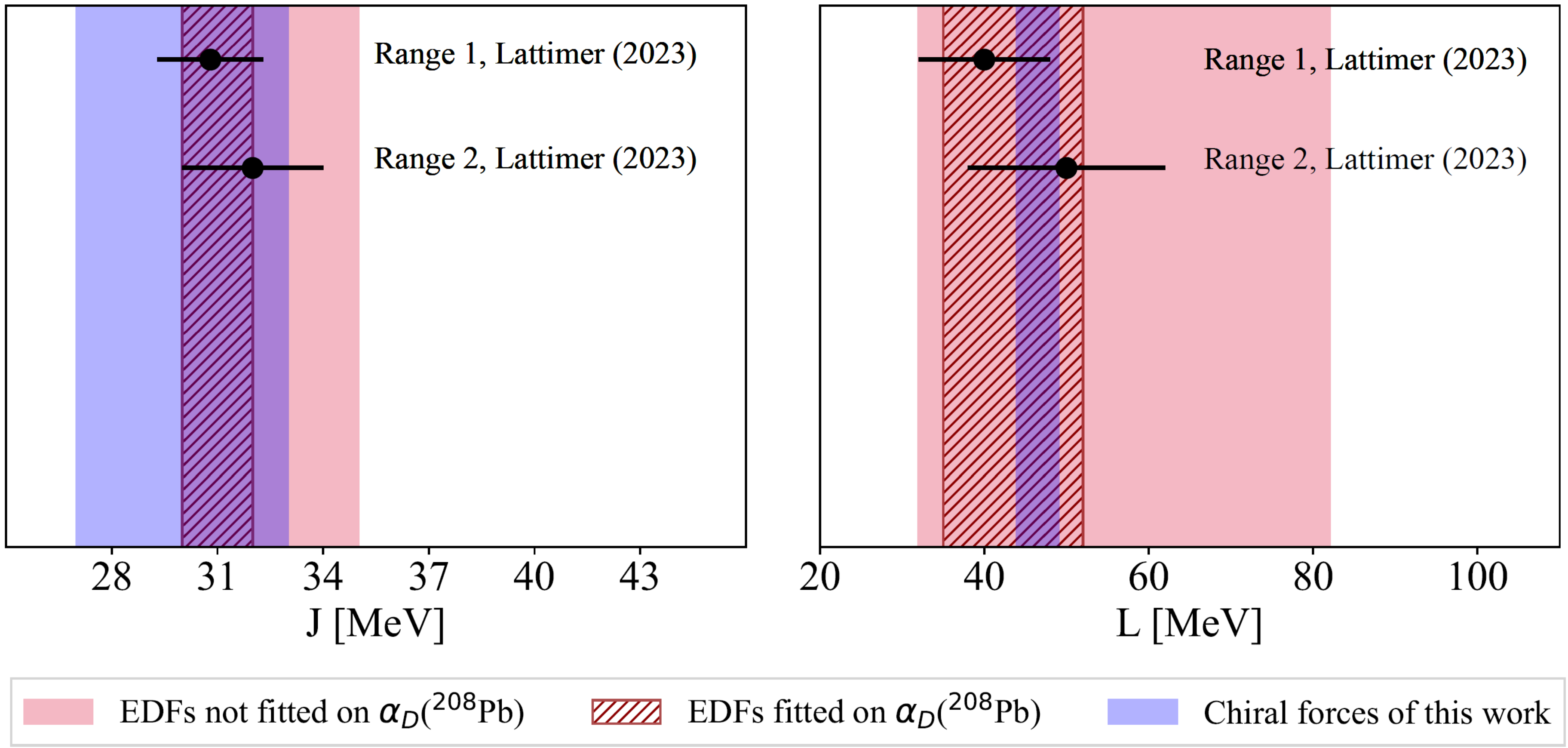

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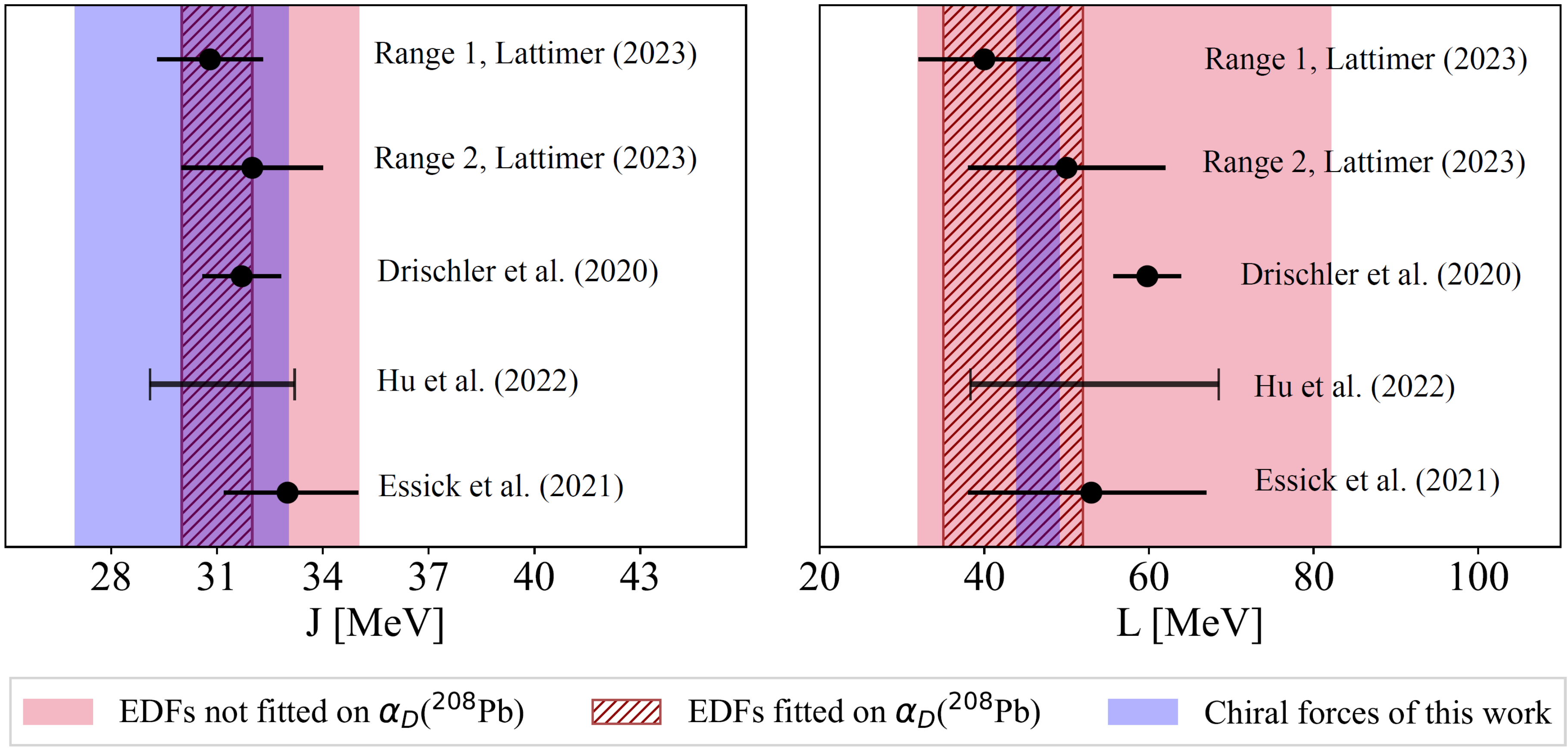

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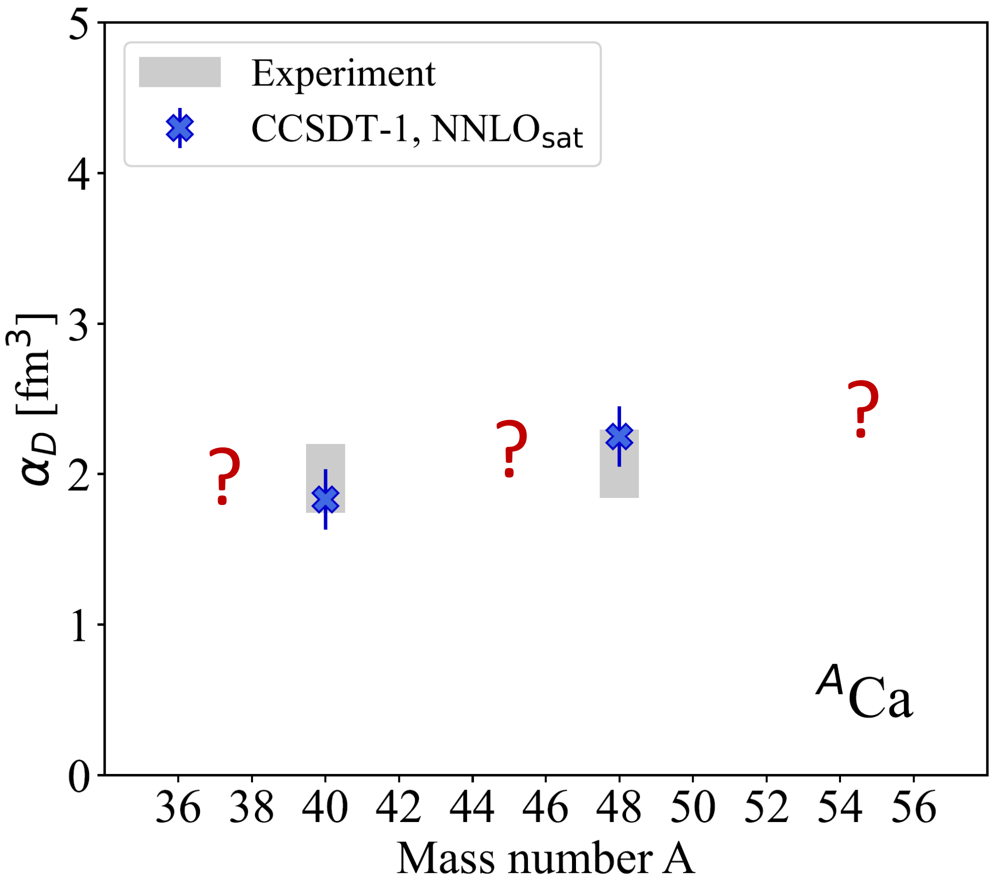
Happy ending for ^{40,48}Ca... but what's next?



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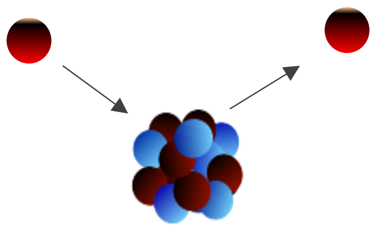
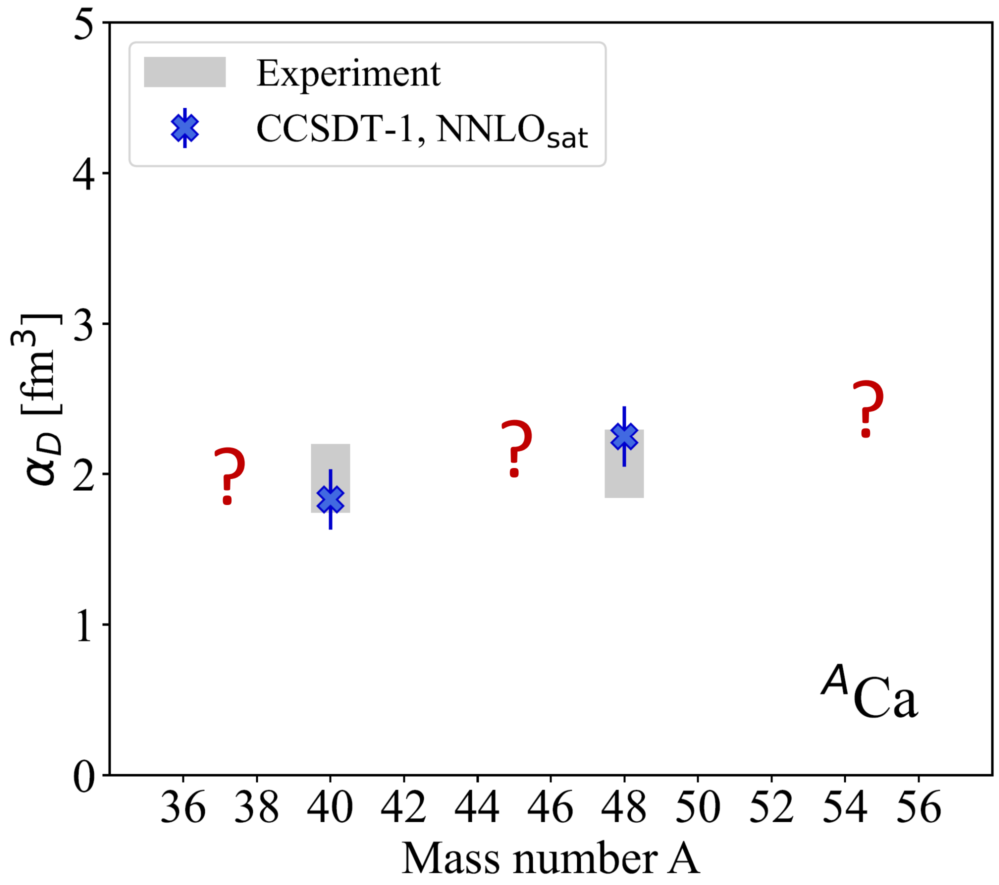


New **(p,p') experiments** in open-shell Ca, Ni isotopes, as e.g. ^{42}Ca, ^{58}Ni…



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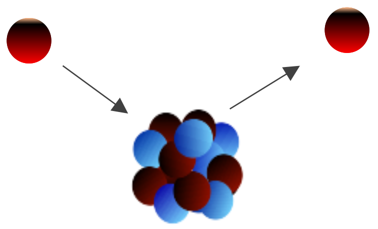

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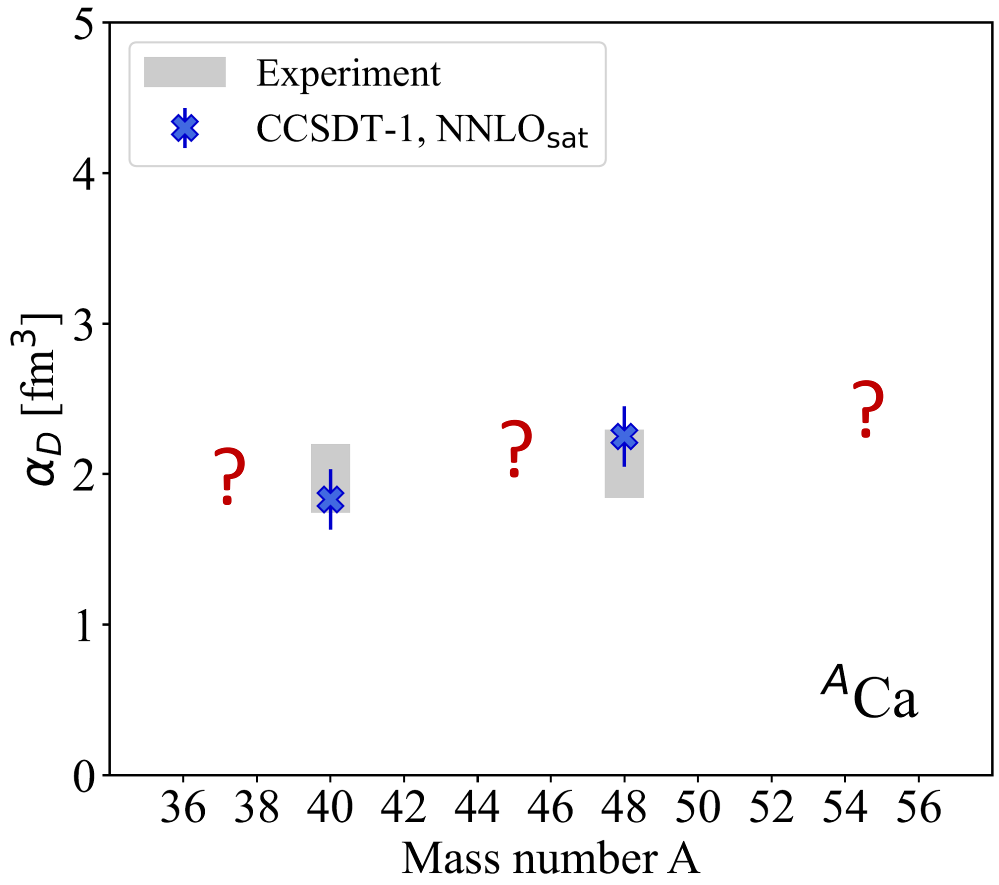

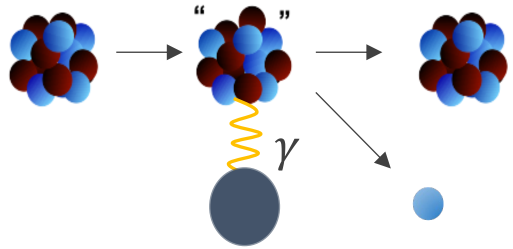

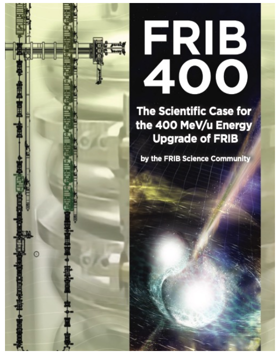

… and with future upgrades, **Coulomb excitation possible** for **very neutron-rich nuclei**.

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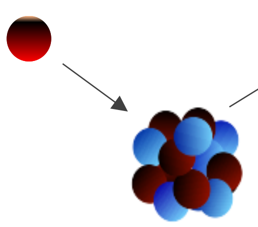

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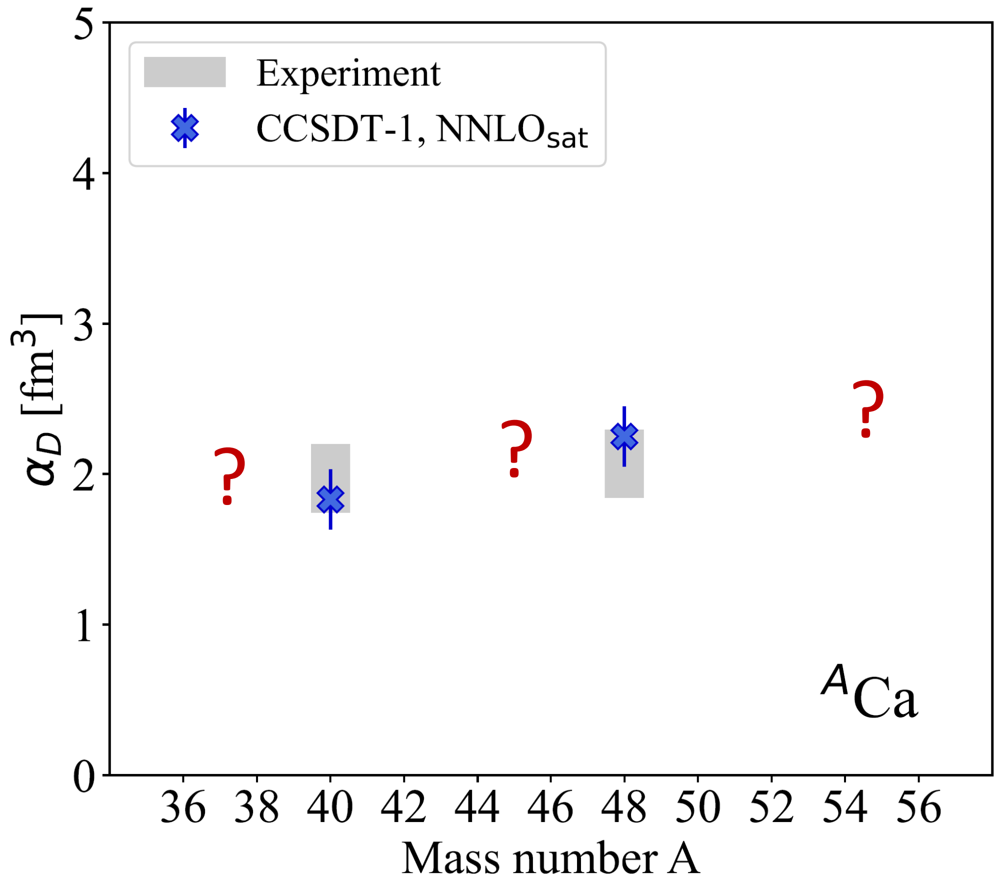
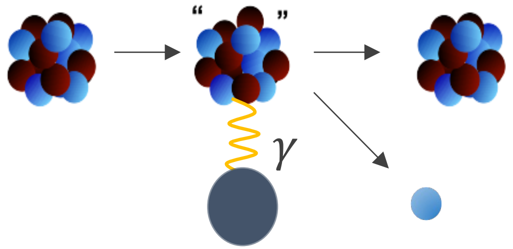
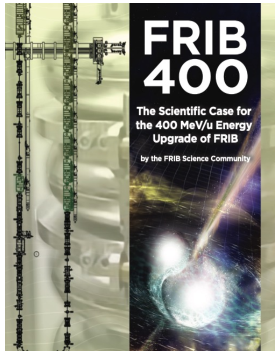






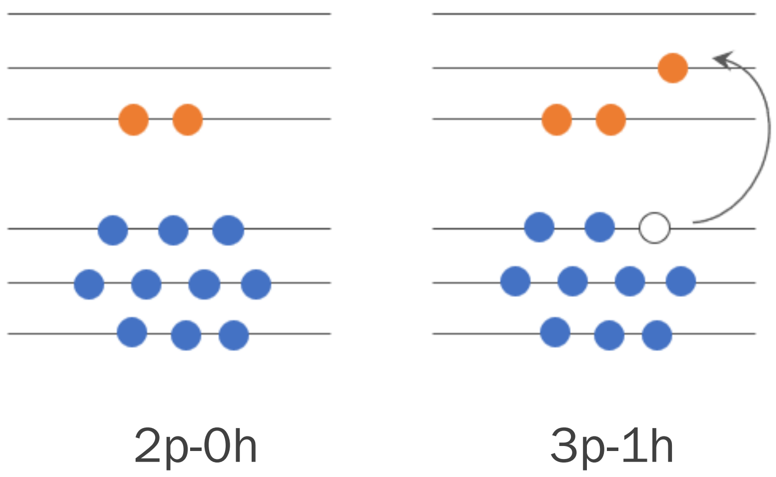
… and with future upgrades, **Coulomb excitation possible** for **very neutron-rich nuclei**.

We need to extend our method beyond closed-shell nuclei!

Open-shell nuclei: two-particle-attached systems (2PA)

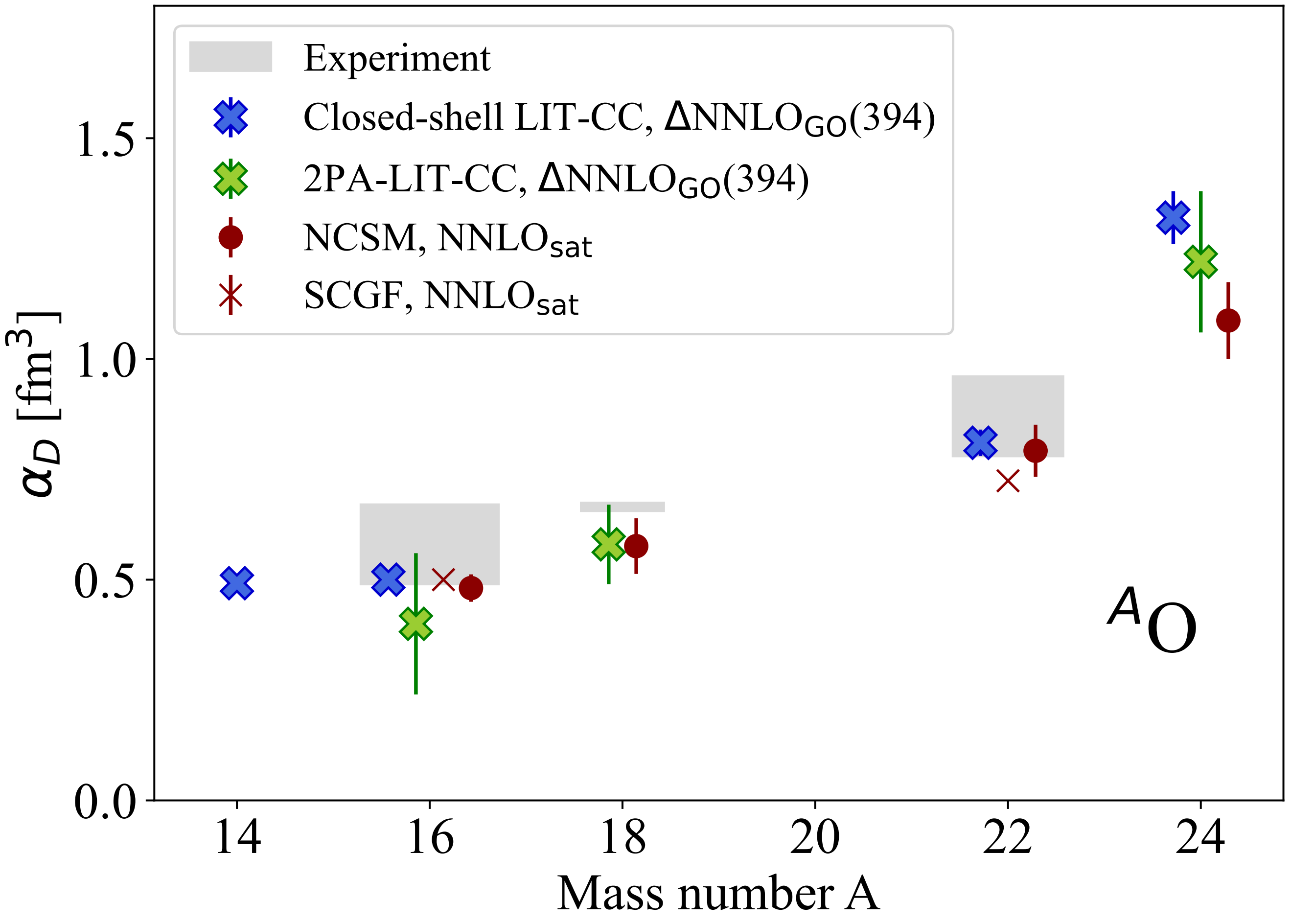
$$\mathcal{R} = \frac{1}{2}\sum r^{ab} a_a^\dagger a_b^\dagger + \frac{1}{6}\sum r_i^{abc} a_a^\dagger a_b^\dagger a_c^\dagger a_i + \dots$$

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



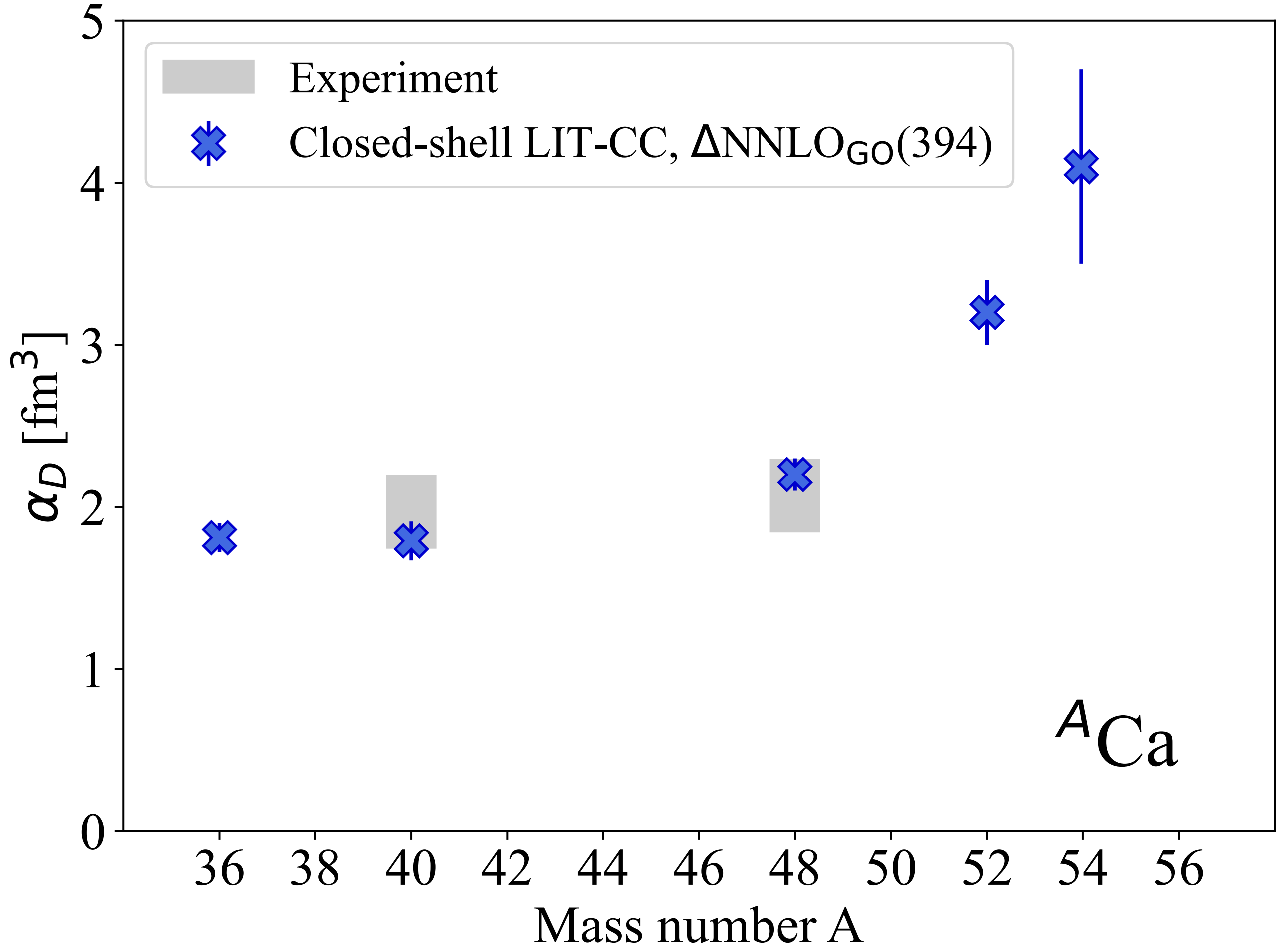
FB et al., PRC 110, 044306 (2024).

α_D along the oxygen chain



FB et al., PRC 110, 044306 (2024).

α_D along the calcium chain



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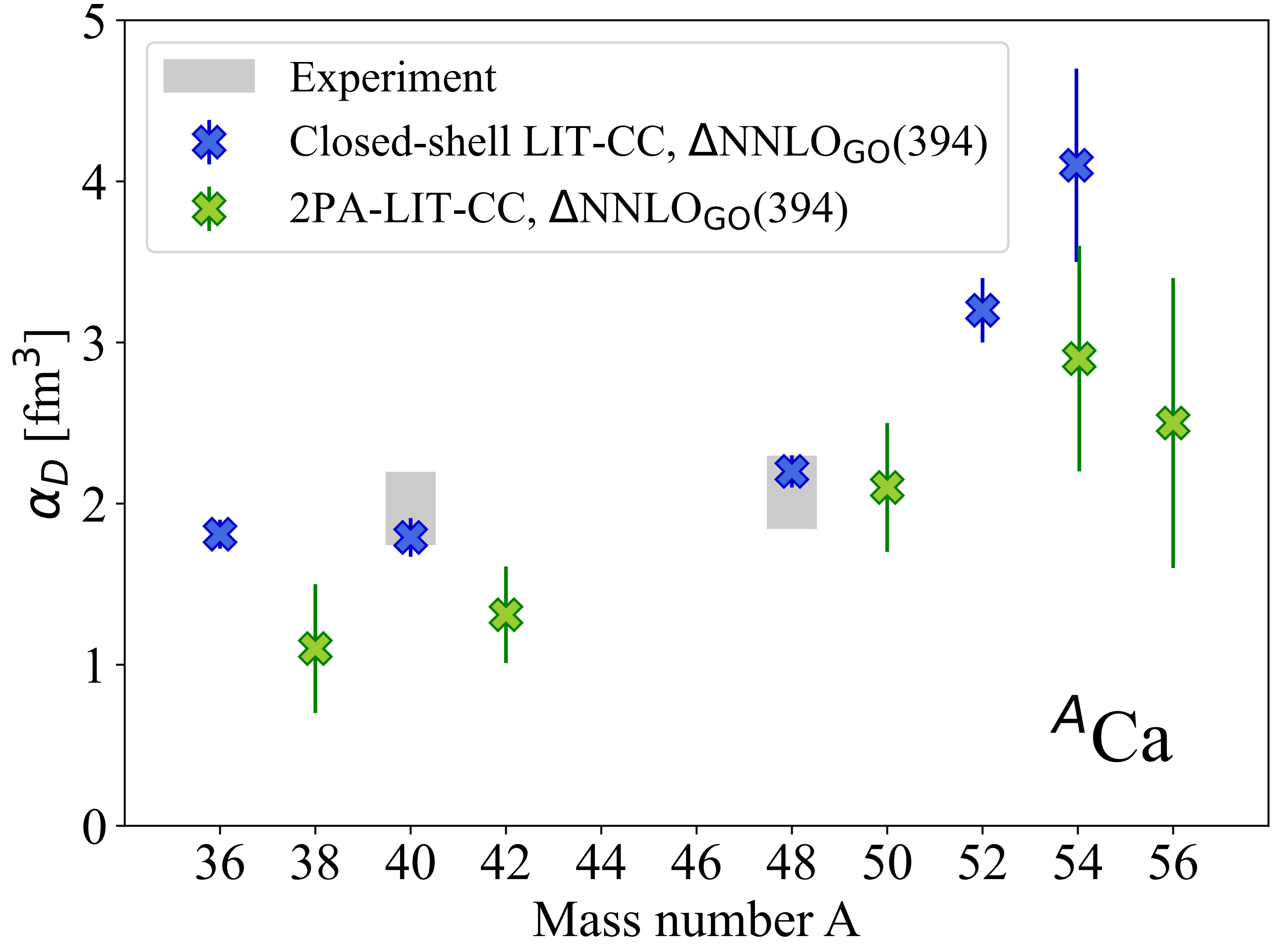


FB et al., PRC 110, 044306 (2024).

Back to the EOS

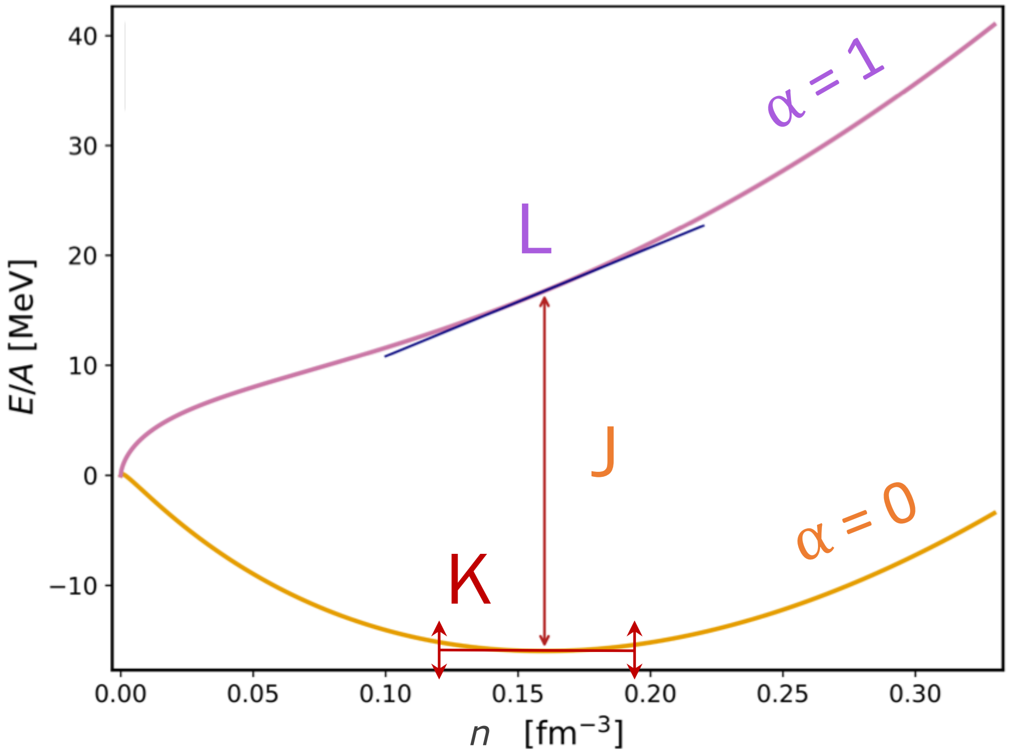
$$\frac{E}{A}(n,\alpha) = \frac{E}{A}(n,0) + S(n)\alpha^2 + \mathcal{O}[\alpha^4]$$

$$n = n_p + n_n$$

$$\alpha = \frac{n_n - n_p}{n}$$

$$\frac{E}{A}(n,0) = -B + \frac{1}{2}K\frac{(n-n_0)^2}{9n_0^2} + \dots$$

incompressibility of **symmetric nuclear matter**



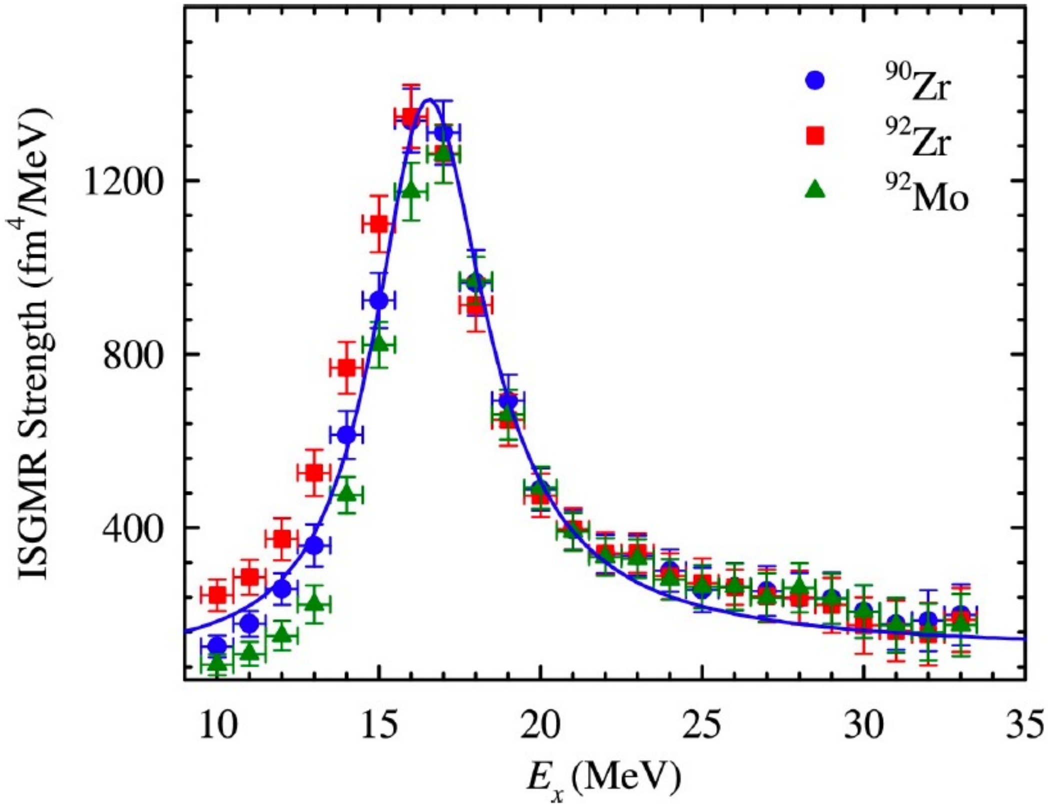
Incompressibility of a finite nucleus

Incompressibility of a finite nucleus

$$K_A = \frac{M}{\hbar^2} R_m^2 E_{\text{monopole}}^2$$

from moments of the isoscalar monopole response

$$E_{\text{monopole}}^2 = \frac{m_1}{m_{-1}}$$



Y. Gupta et al, PLB 760, 482–485 (2016).

Incompressibility of nuclear matter

$$K_A = K_{\text{vol}} + K_{\text{surf}} A^{-1/3} + \ \ldots$$

incompressibility of nuclear matter

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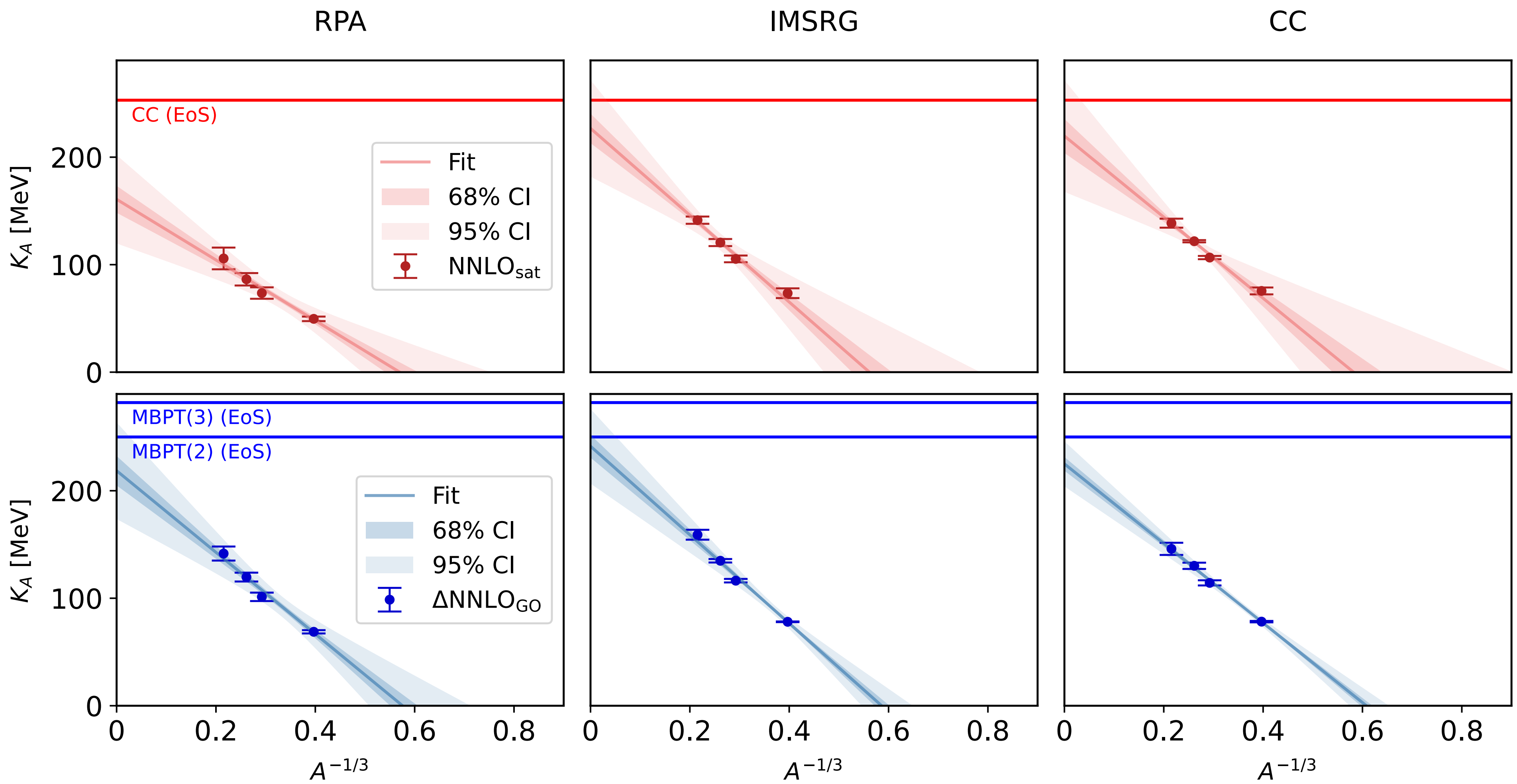

A. Porro, **FB** et al, in preparation.

Conclusions

- Modern nuclear structure input can help in refining uncertainties in pion scattering differential cross sections.
- Electromagnetic observables cast light on the collective excitations of the nucleus as well as constraining the symmetry energy.
- We extended ab initio reach of this observable to nuclei in the vicinity of closed shells.
- Estimates of the incompressibility of symmetric nuclear matter based on ab initio predictions of monopole moments in finite nuclei are consistent with nuclear matter calculations.

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@JGU Mainz: Sonia Bacca, Tim Egert, Weiguang Jiang, Francesco Marino, Viacheslav Tsaran, Marc Vanderhaegen
@LLNL: Cody Balos, Carol Woodward
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NUCLEI Nuclear Computational Low-Energy Initiative