Collective excitations of even-even (closed-shell) nuclei via the LIT-CC method

Sonia Bacca

JGU

May 21st, 2024

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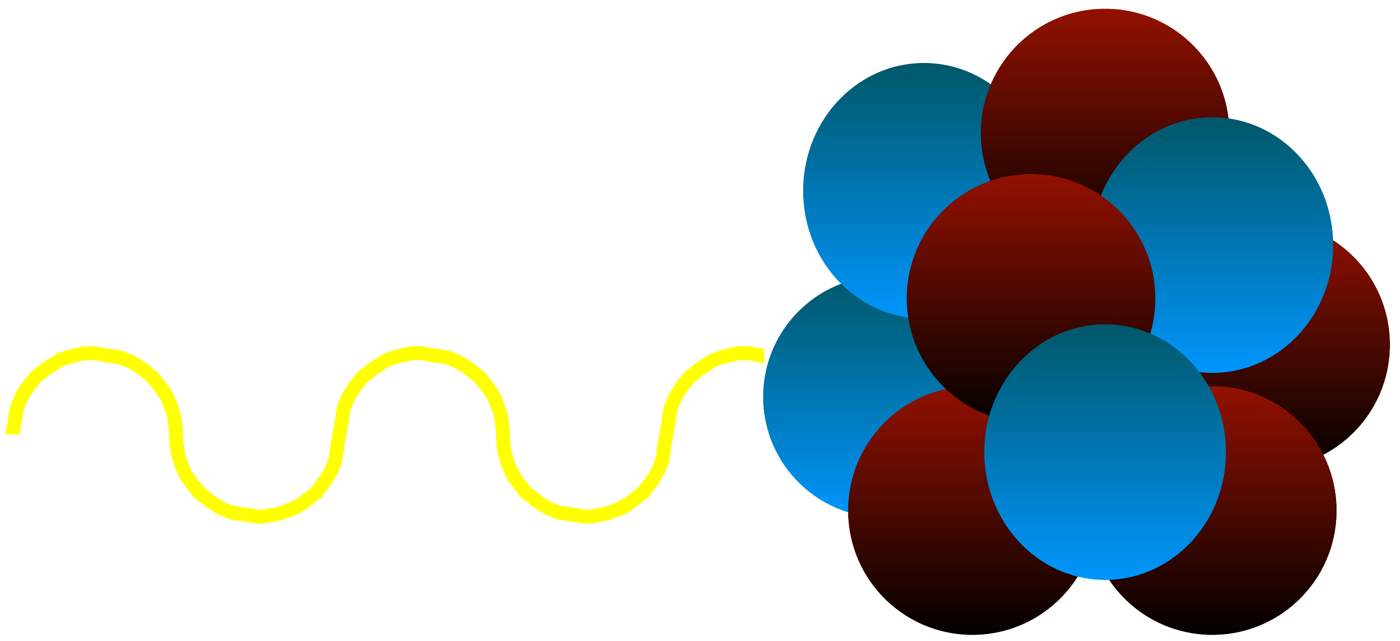
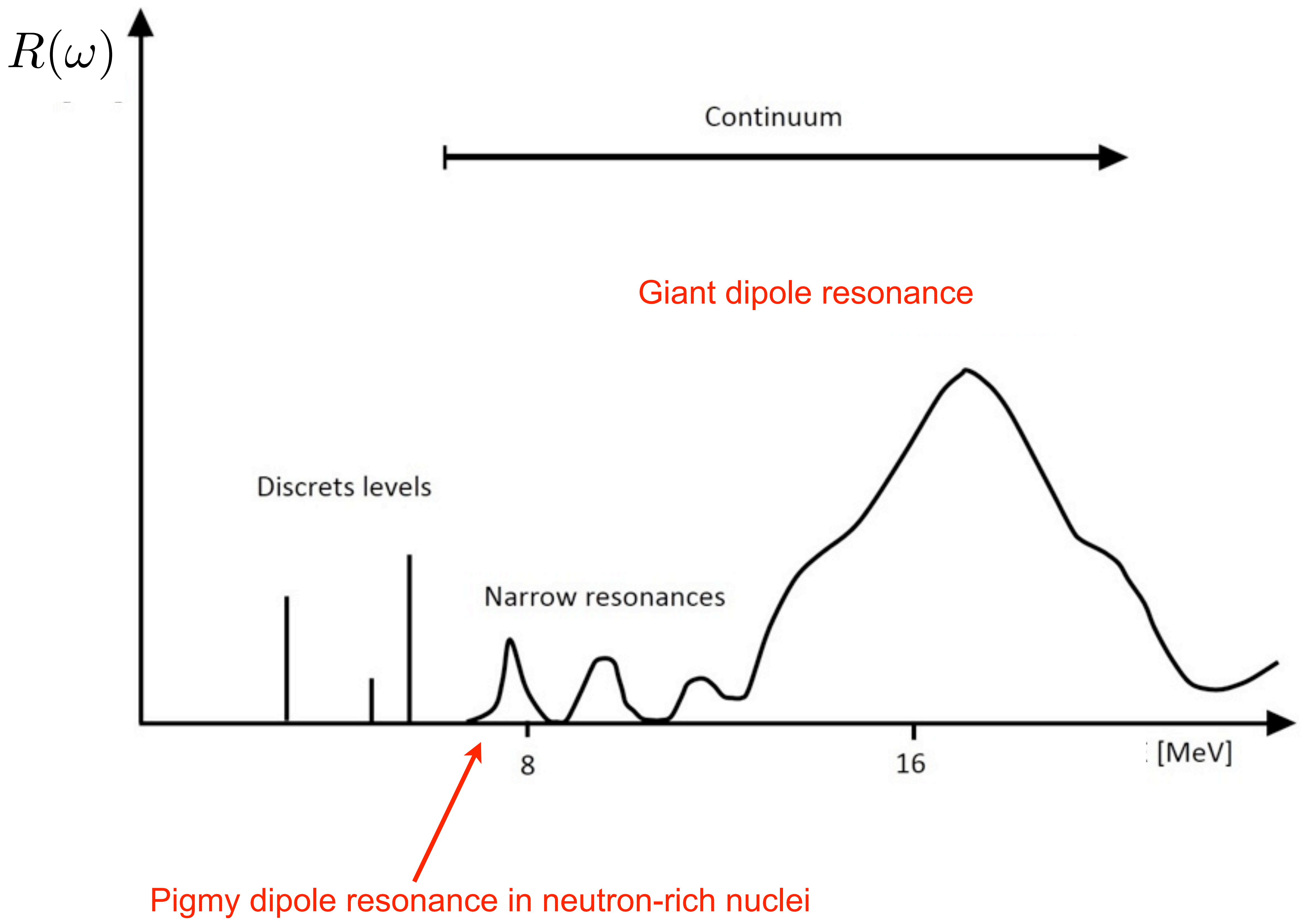
Observables of interest



Cross Section $\sigma_{ew} \sim R(\omega) = \sum_f \left| \left\langle \psi_f \left| J^\mu \right| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$

Electroweak operator

Typical response function, e.g. dipole

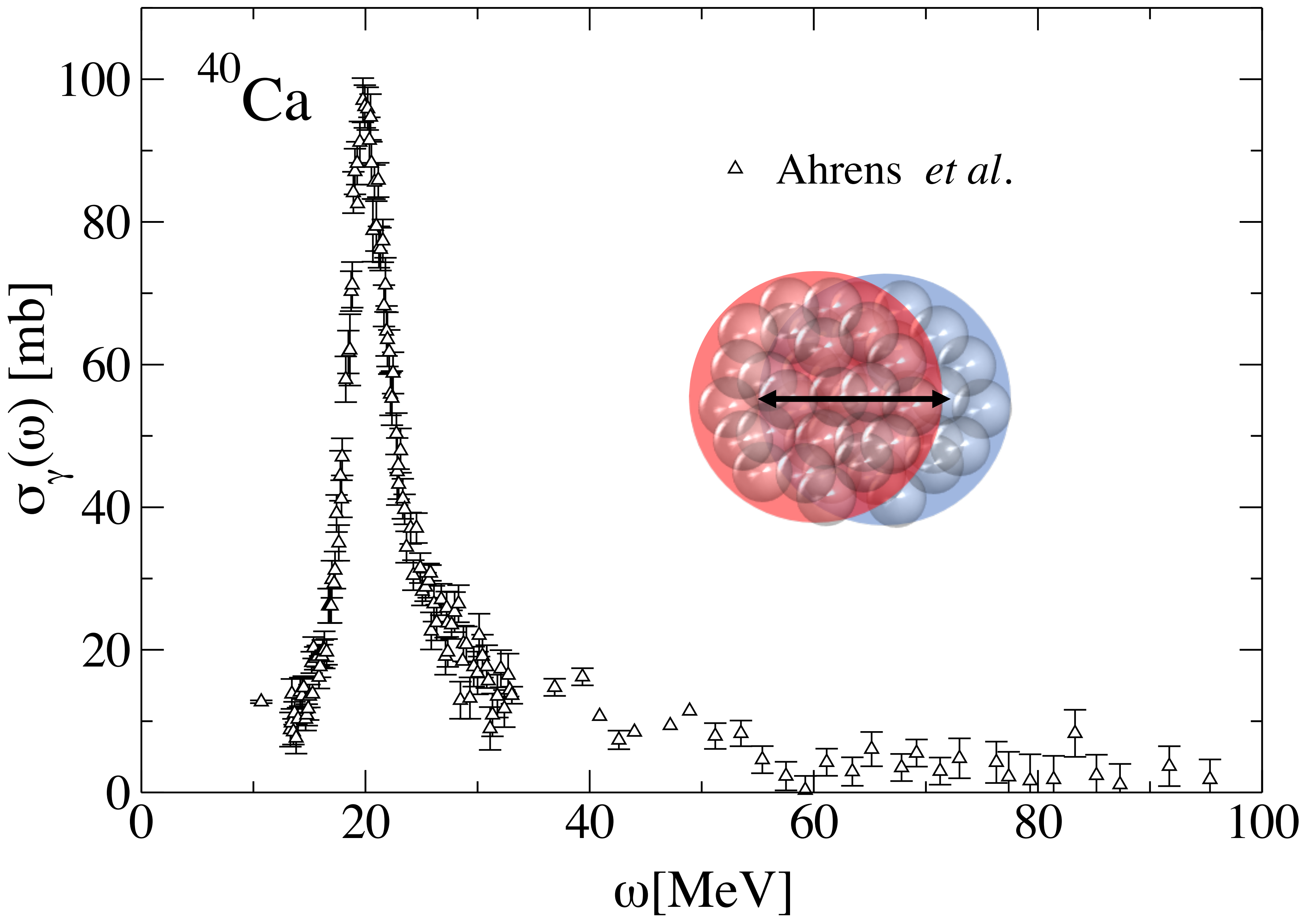


Electric dipole polarizability $\alpha_D = 2\alpha \int_{\omega_{th}}^{\infty} d\omega \frac{R(\omega)}{\omega}$ → Low-energy part of strength dominates

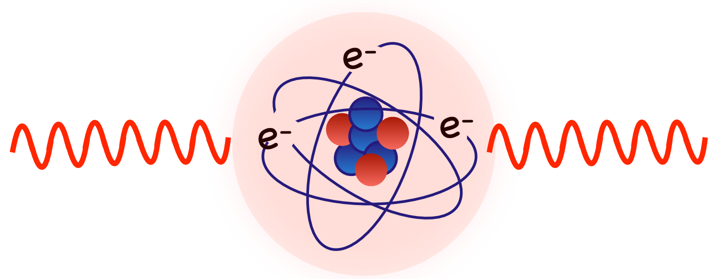
Experimental motivation

Stable Nuclei

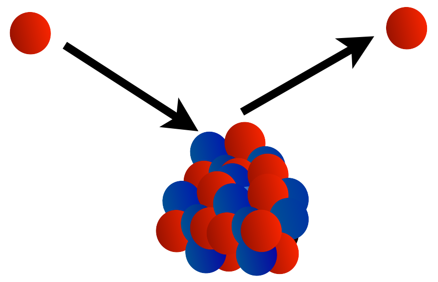
Giant dipole resonances



Photoabsorption experiments

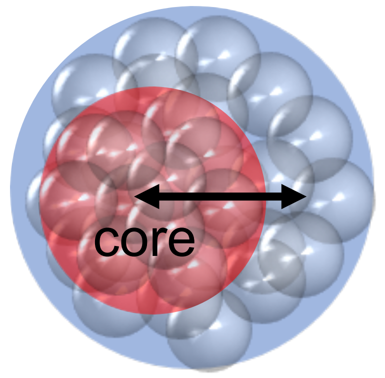


(p,p') experiments

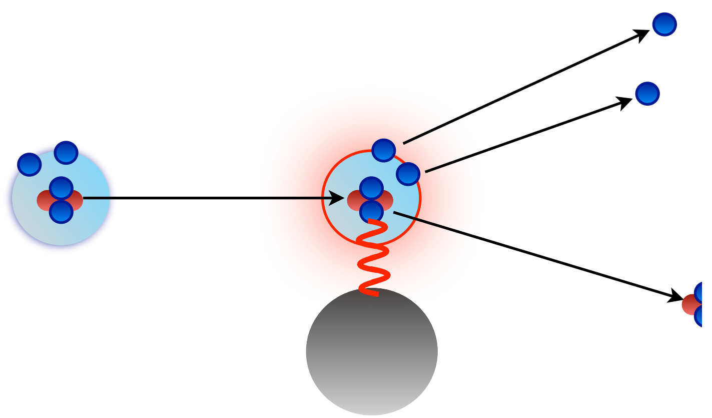


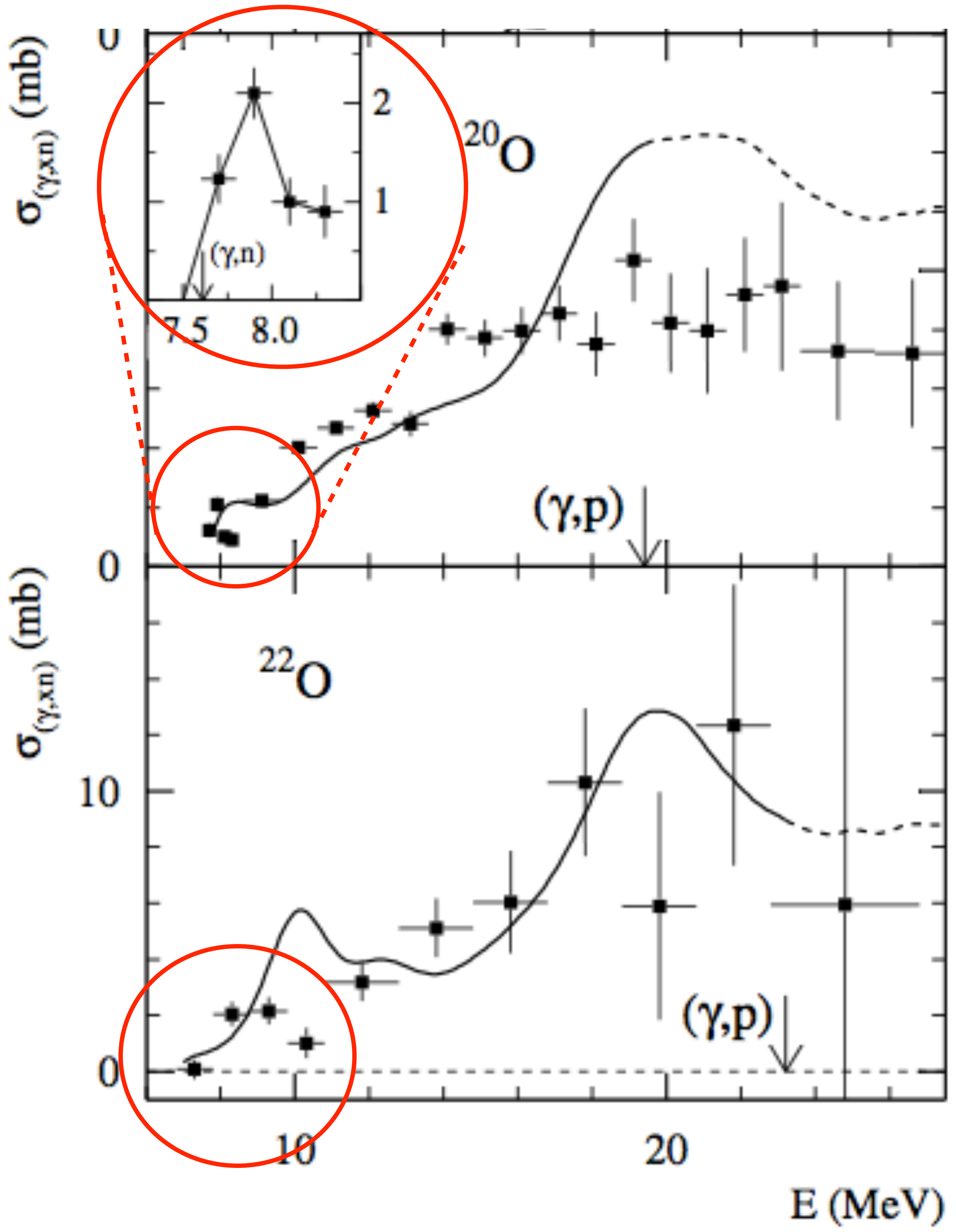
Unstable Nuclei

Pigmy dipole resonances



Coulex experiment



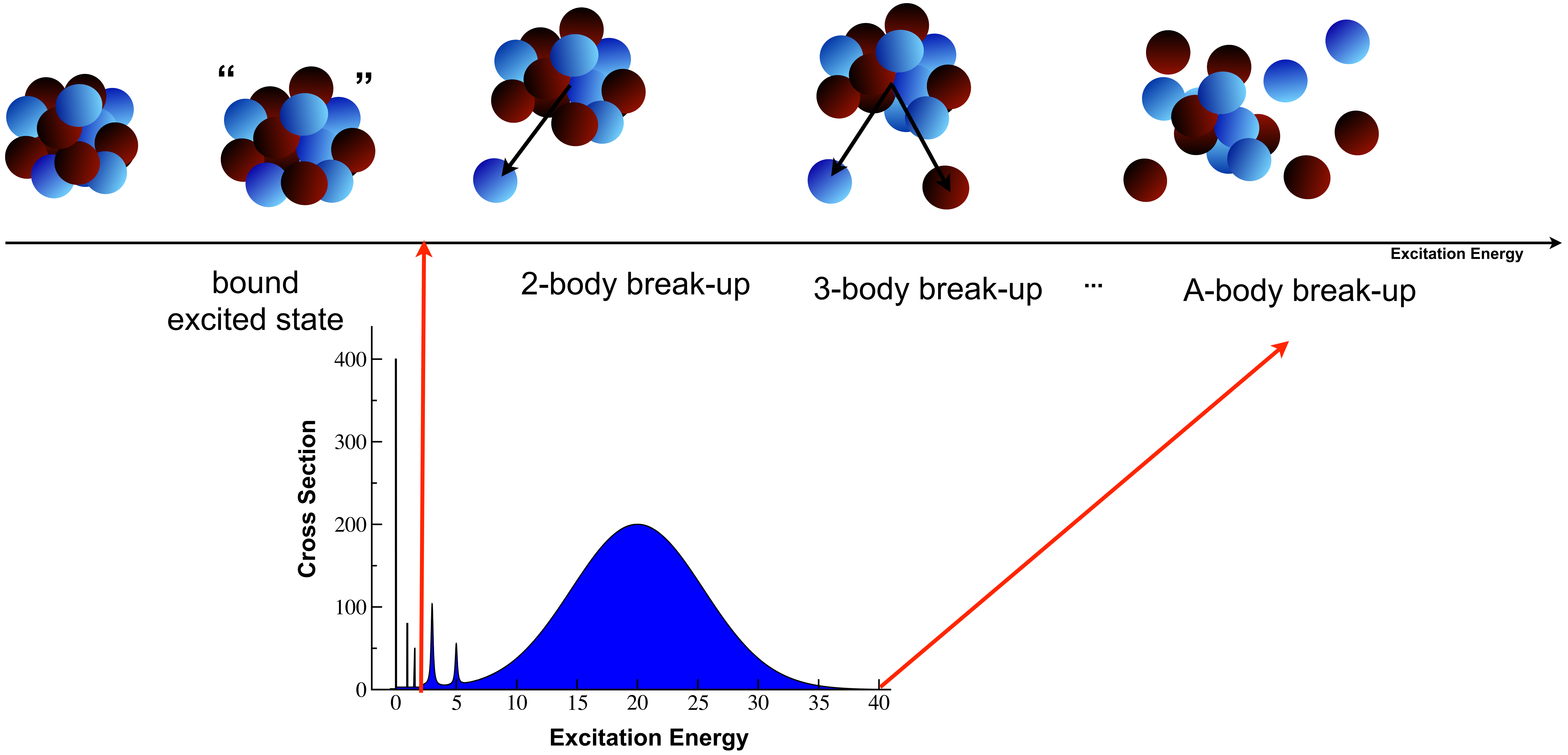


Do we see the emergence of collective motions from first principle calculations?

The continuum problem

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

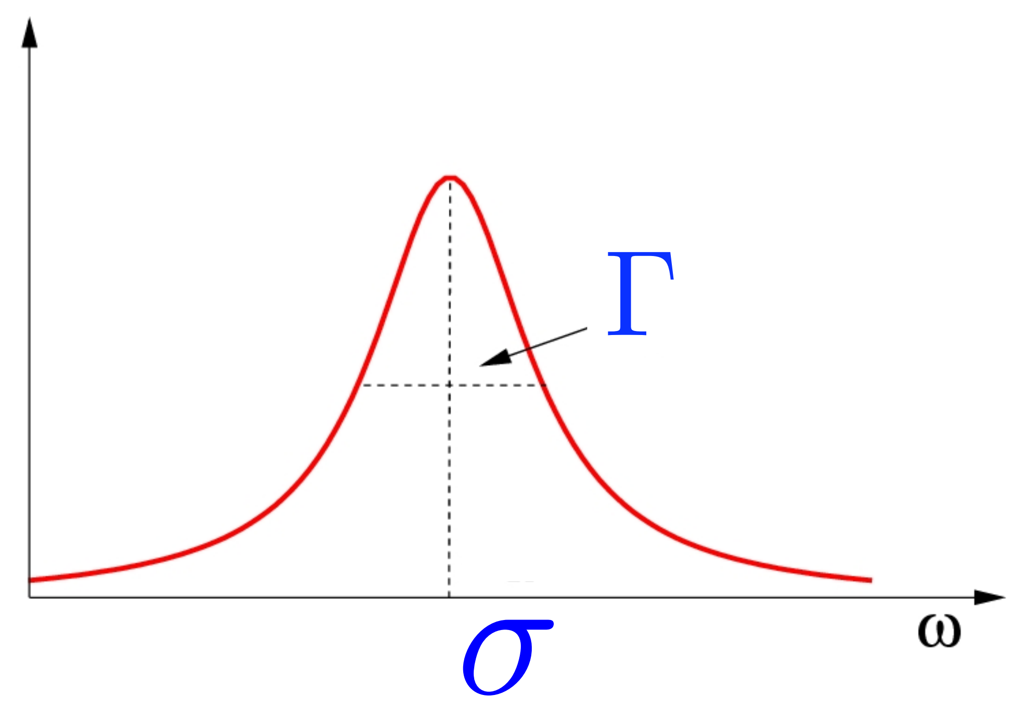
Depending on E_f, many channels may be involved



The Lorentz integral transform (LIT)

inversion

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



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

$$(H - E_0 - \sigma + i\Gamma)\,|\,\tilde{\psi}\rangle = J^{\mu}|\,\psi_0\rangle$$

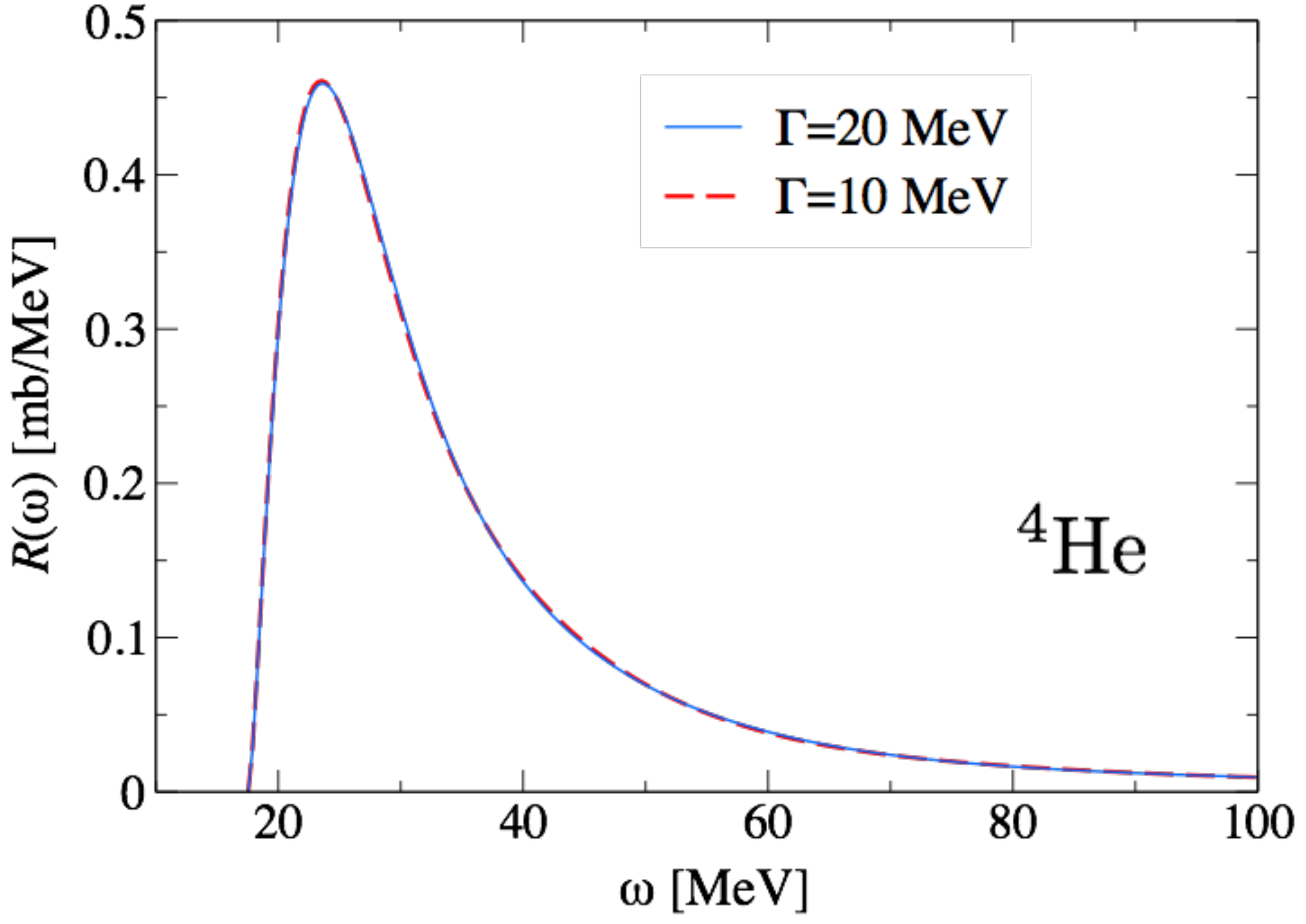
Reduce the continuum problem to a bound-state-like equation

The Lorentz integral transform (LIT)

The inversion is performed numerically with a regularization procedure (ill-posed problem)

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

fit



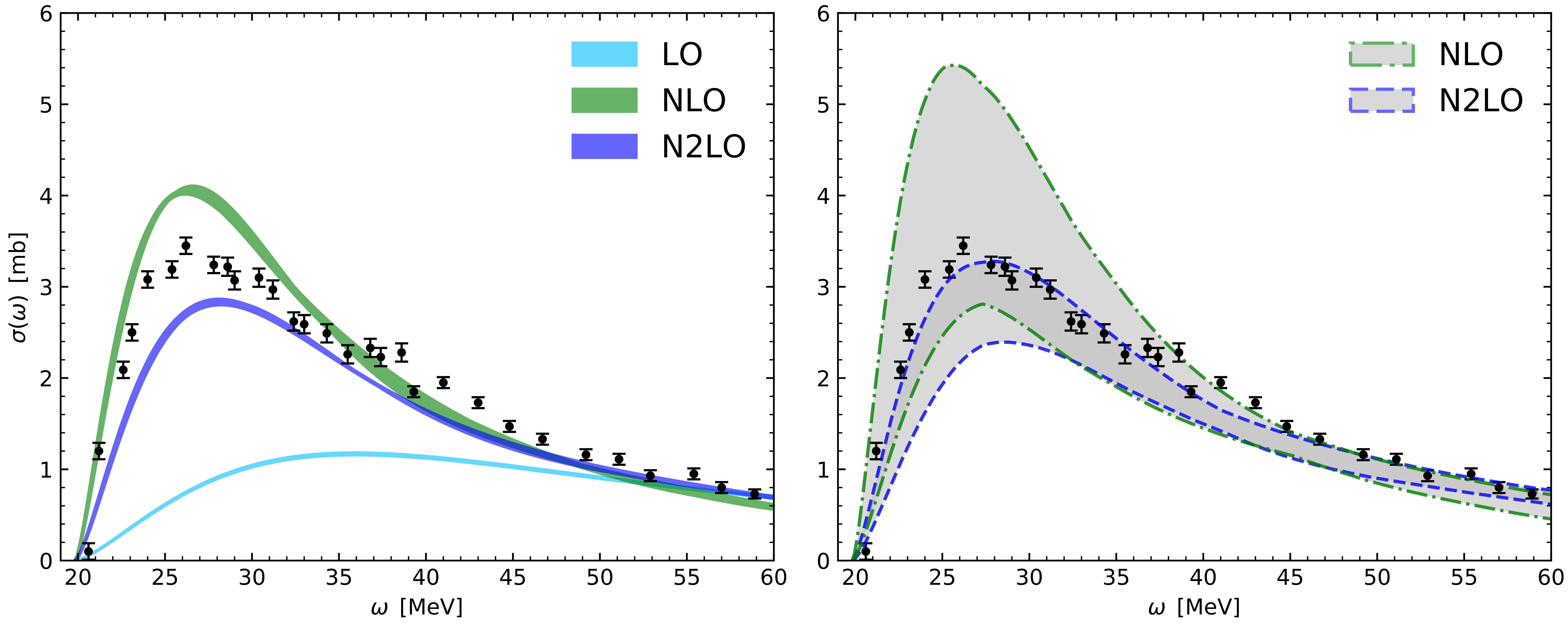
Message: Inversions are stable if the LIT is calculated precisely enough

^{4}He photoabsorption cross-section

Simone Li Muli

Acharya, SB, Bonaiti, Li Muli, Sobczyk, Front. Phys.10:1066035 (2023)

With local chiral potentials from Phys. Rev. C **90**, 054323 and hyper-spherical harmonics

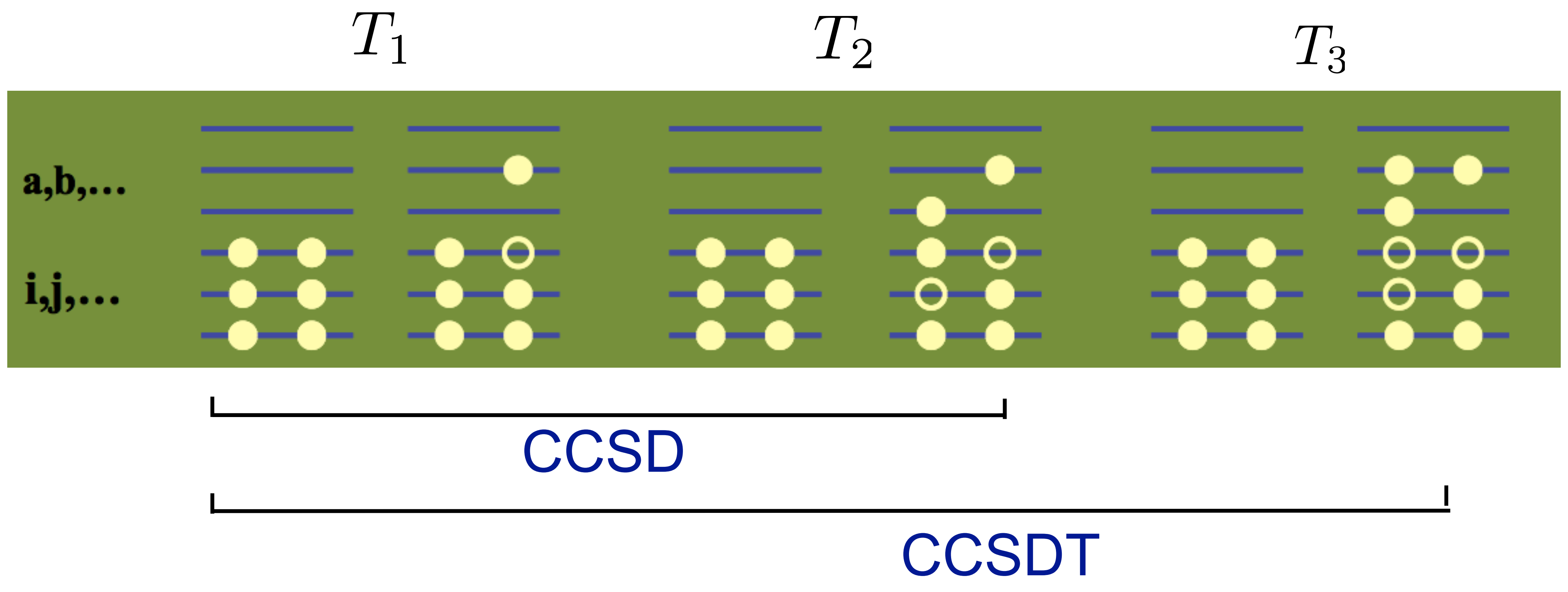


How about heavier nuclei?

Coupled-cluster theory

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

cluster expansion



CCSD algorithm scales as $n_o^2 n_u^4$

Hagen et al., Rep. Prog. Phys. Rep. Prog. Phys. 77, 096302 (2014)

Coupled-cluster formulation of the LIT

$$(H - E_0 - \sigma + i\Gamma)\,|\,\tilde{\psi}\rangle = J^\mu|\,\psi_0\rangle$$

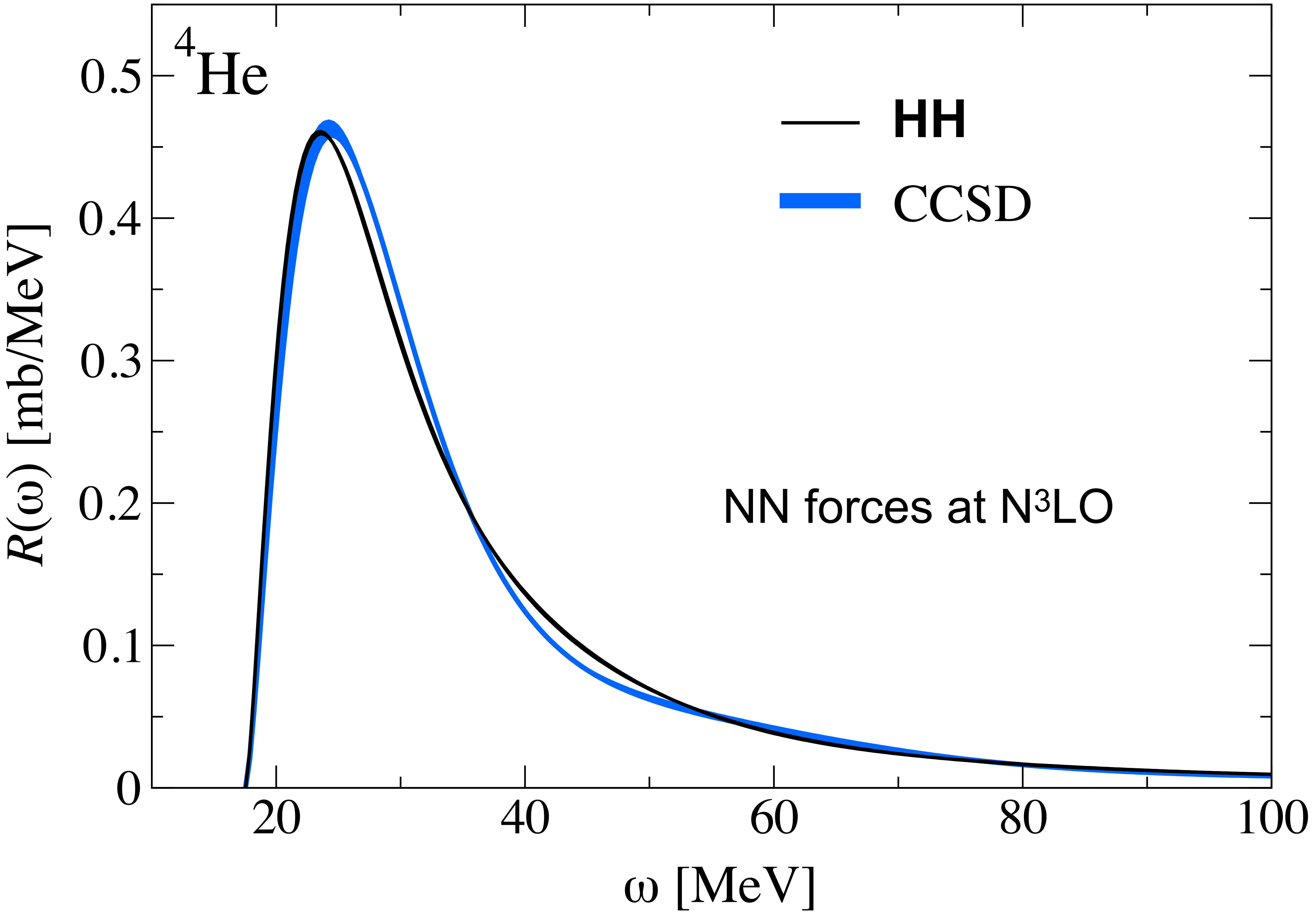
SB et al., Phys. Rev. Lett. 111, 122502 (2013)

$$(\bar{H} - E_0 - \sigma + i\Gamma)|\tilde{\Psi}_R\rangle = \bar{\Theta}|\Phi_0\rangle \longrightarrow \begin{cases} \bar{H} = e^{-T} H e^{T} \\ \bar{\Theta} = e^{-T} \Theta e^{T} \\ |\tilde{\Psi}_R\rangle = \hat{R}|\Phi_0\rangle \end{cases}$$

$$\mathcal{R}(z) = r_0(z) + \sum_{ai} r_i^a(z) a_a^\dagger a_i + \frac{1}{4}\sum_{abij} r_{ij}^{ab}(z) a_a^\dagger a_b^\dagger a_j a_i + \ldots$$

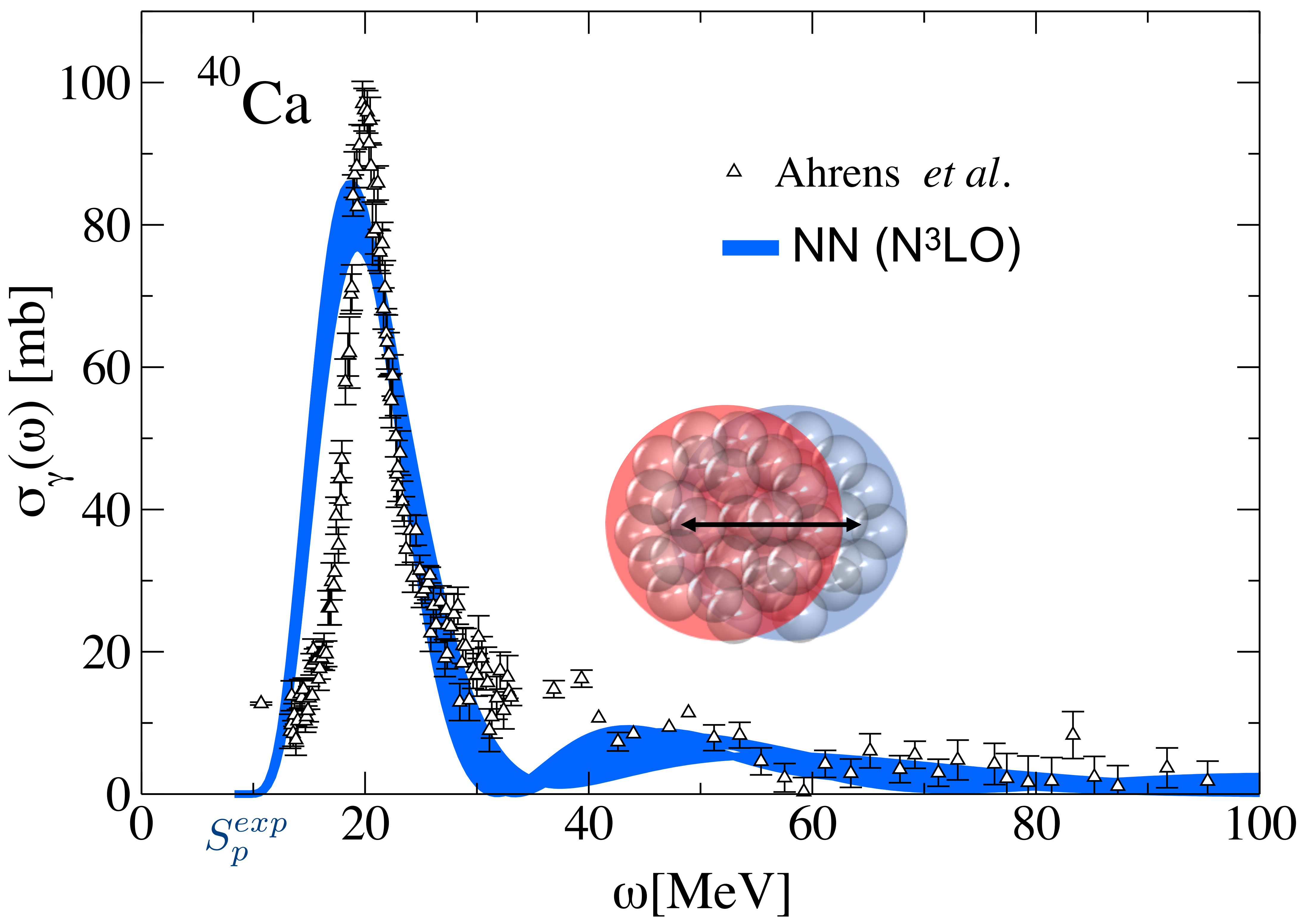
Benchmark on ^{4}He

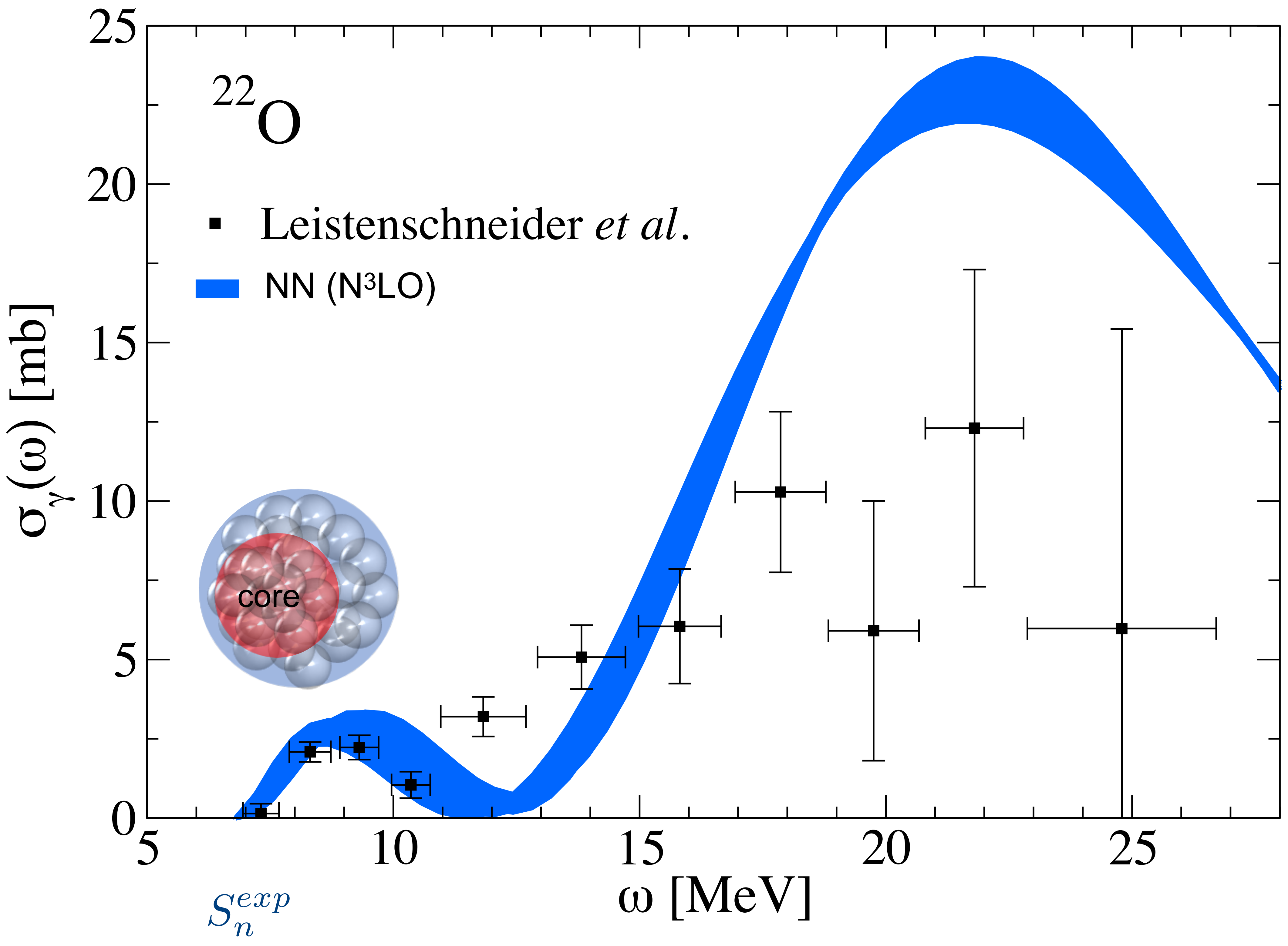
SB et al., Phys. Rev. Lett. 111, 122502 (2013)



Medium-mass nuclei

SB et al., PRC 90, 064619 (2014)





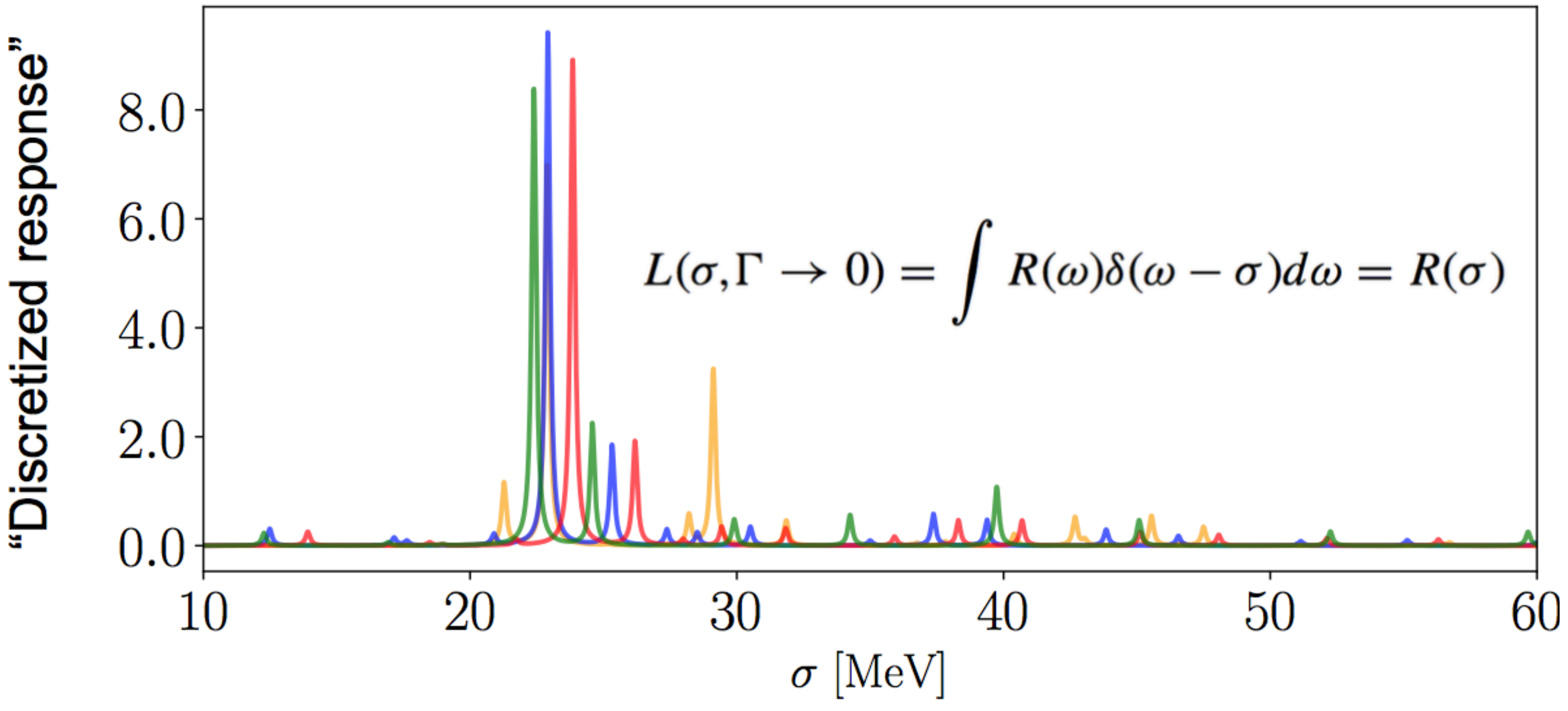
Sum rules and polarizability

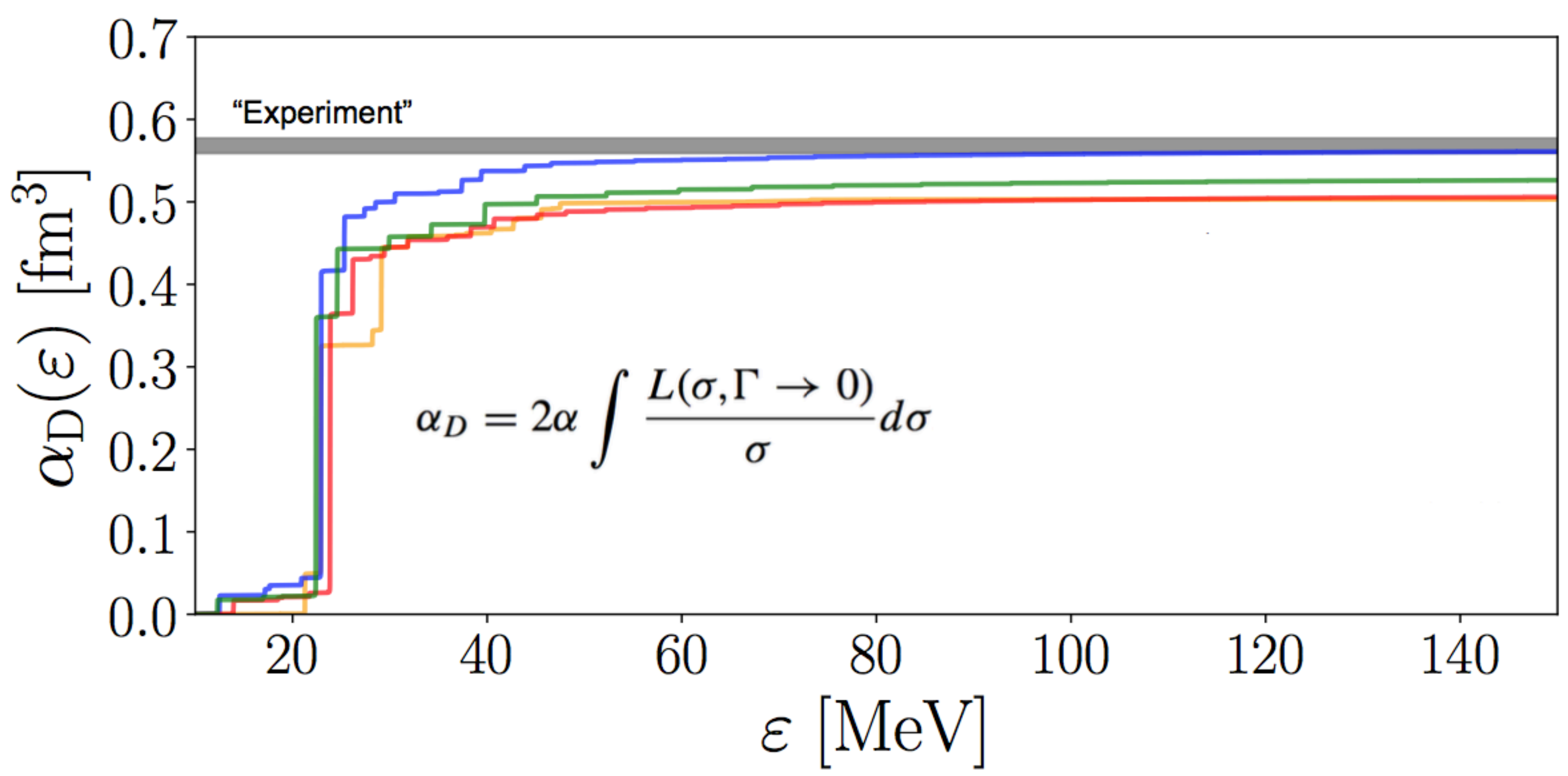
$$m_n = \int_0^\infty d\omega\ \omega^n R(\omega) = \langle \Psi_0 | \hat{\Theta}^\dagger (\hat{H} - E_0)^n \hat{\Theta} | \Psi_0 \rangle$$

The electric-dipole polarizability is an inverse-energy weighted sum rule of the dipole response function

$$\alpha_D = 2\ \alpha\ m_{-1} = 2\ \alpha\ \langle \Psi_0 | \Theta^\dagger \frac{1}{(H - E_0)} \Theta | \Psi_0 \rangle$$

Can be obtained from the Lorentz Integral Transform in the limit of $\Gamma \to 0$

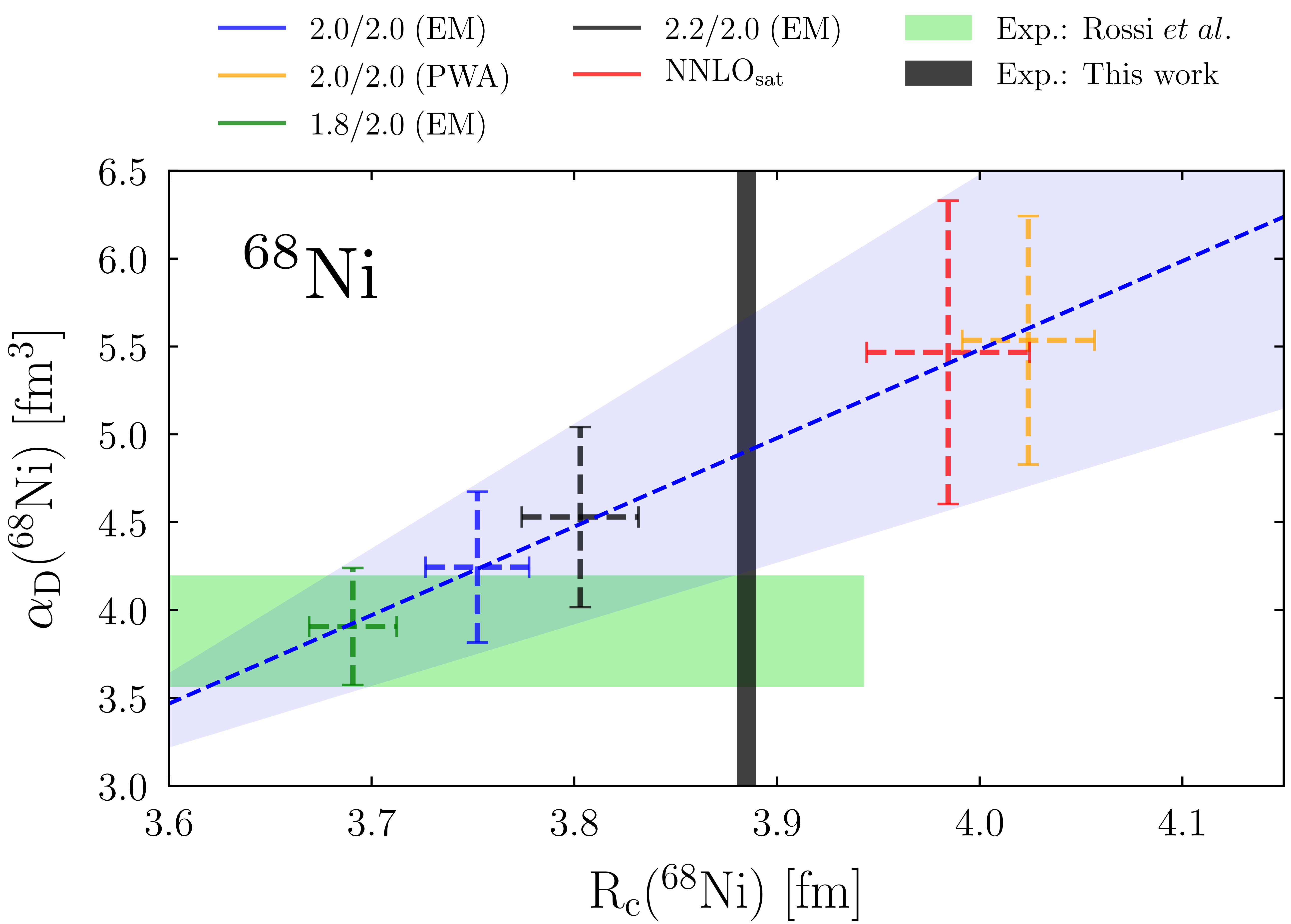




Exotic Nuclei

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

S.Kaufmann, J. Simonis, SB et al., PRL 104 (2020) 132505



CCSD

Exotic Nuclei

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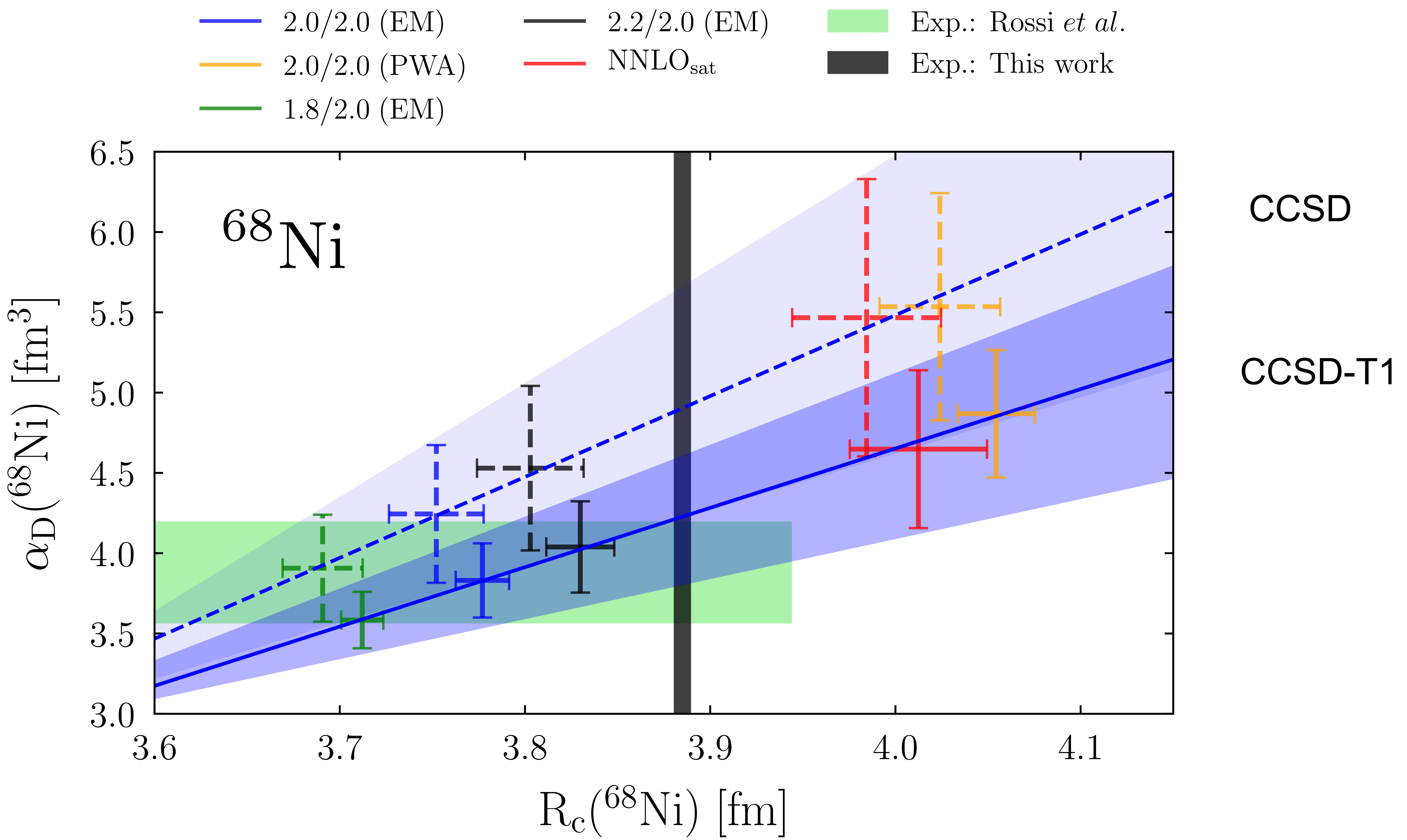
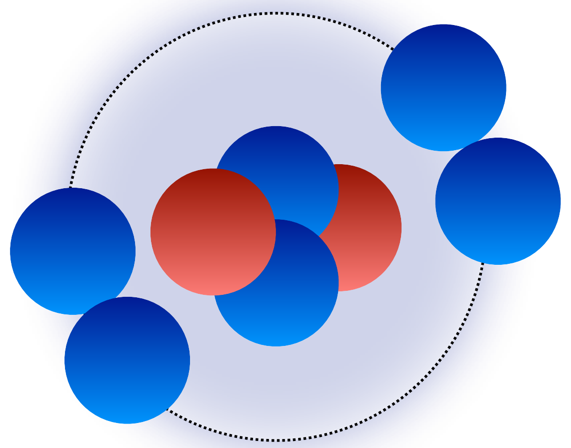
S.Kaufmann, J. Simonis, SB et al., PRL 104 (2020) 132505



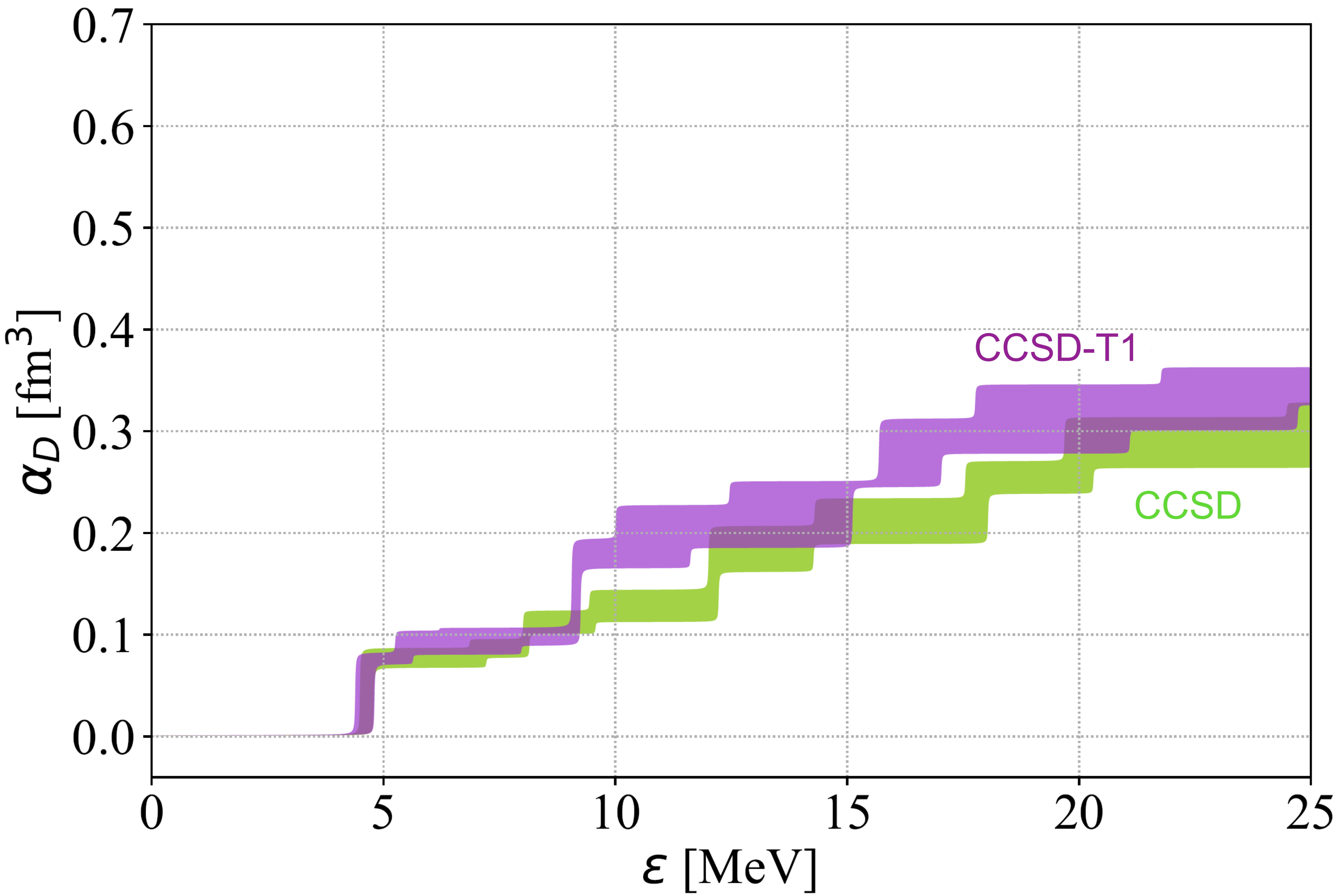
Most Exotic Nucleus N/Z=3


Francesca Bonaiti

$^8\mathrm{He}$

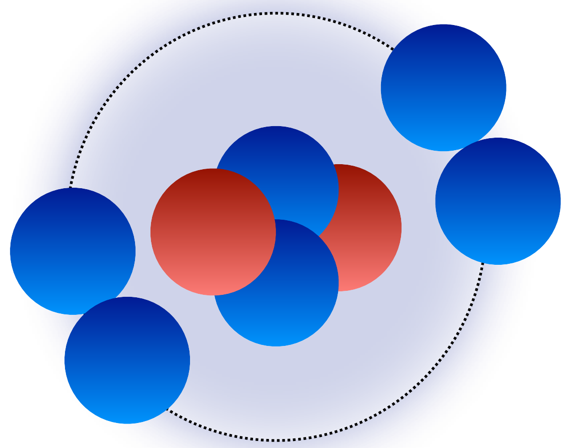

Halo nucleus

F. Bonaiti, SB, G.Hagen, PRC 105, 034313 (2022)



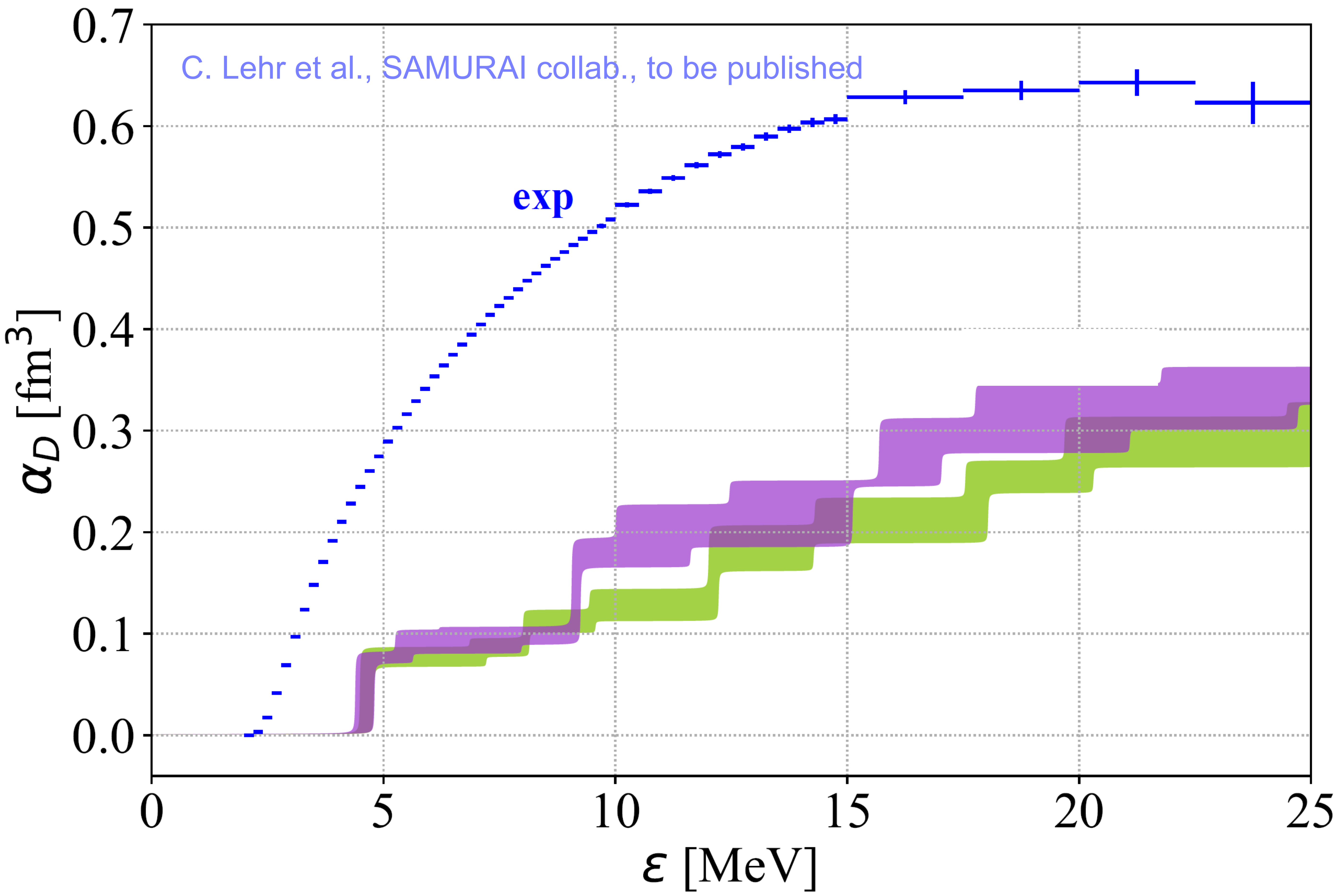
Most Exotic Nucleus N/Z=3

^{8}He



Halo nucleus

F. Bonaiti, SB, G.Hagen, PRC 105, 034313 (2022)

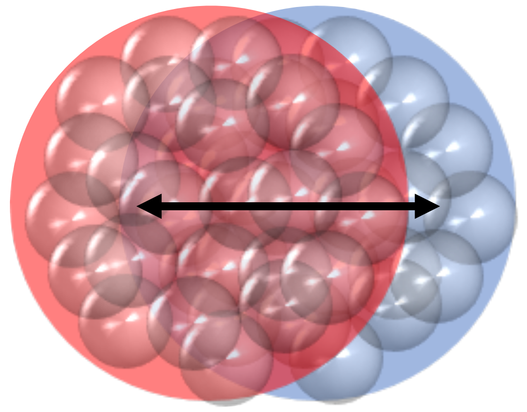


Francesca Bonaiti

Bridge to Astrophysics

Neutron stars

The nuclear EOS



Constraining the symmetry energy *S(ρ) through properties of finite nuclei*

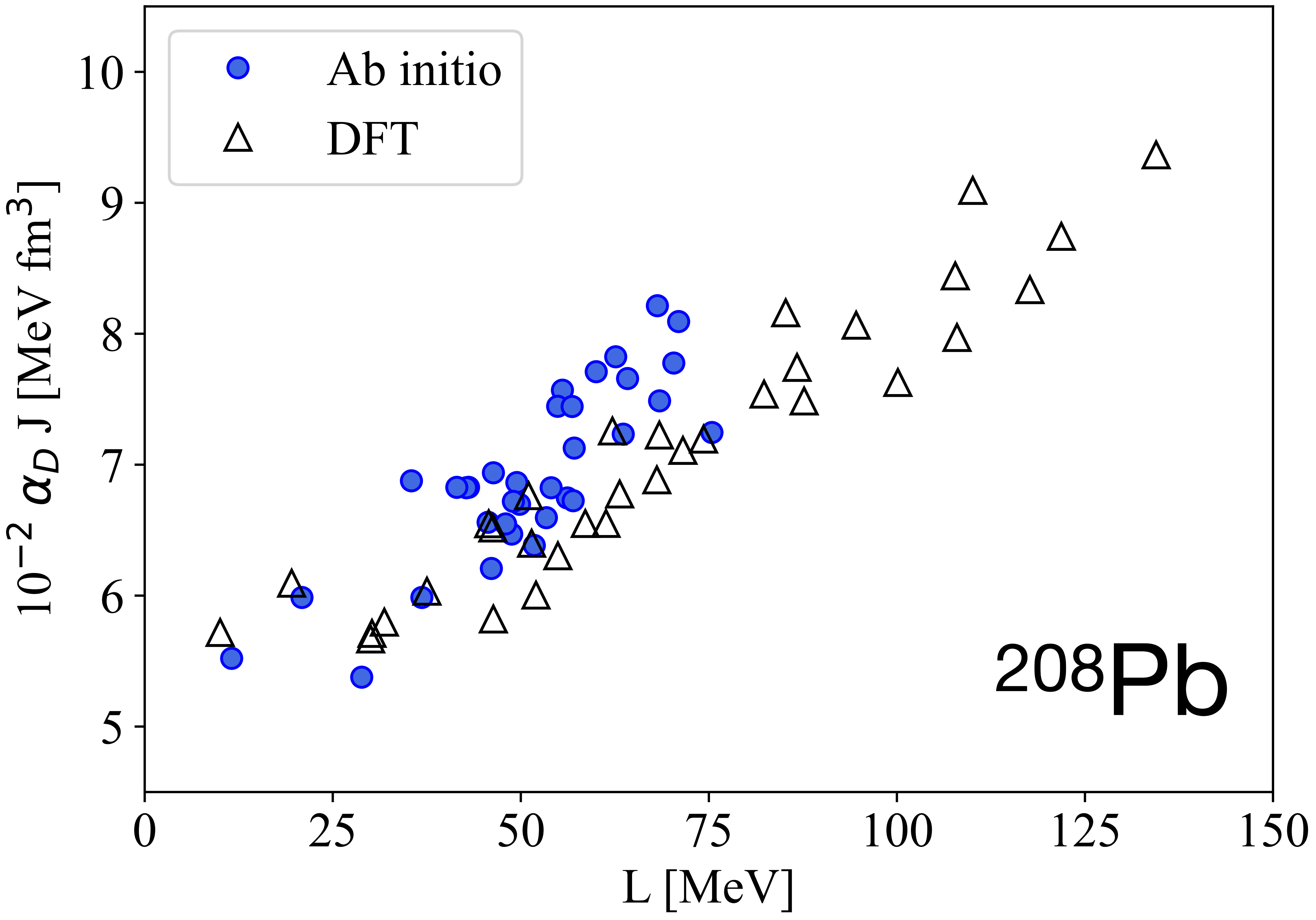
$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2 \mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

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

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

symmetry energy

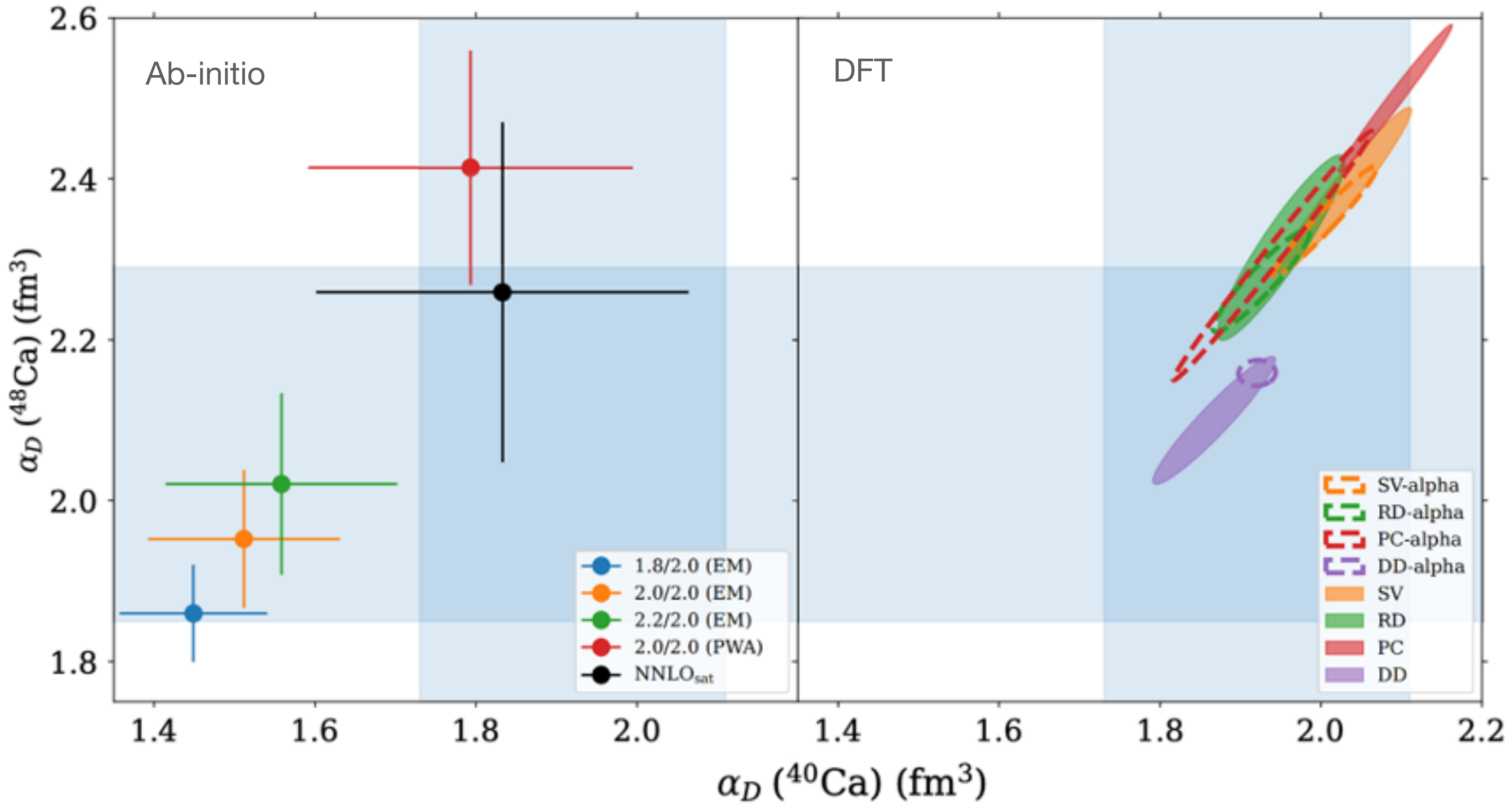
slope parameter



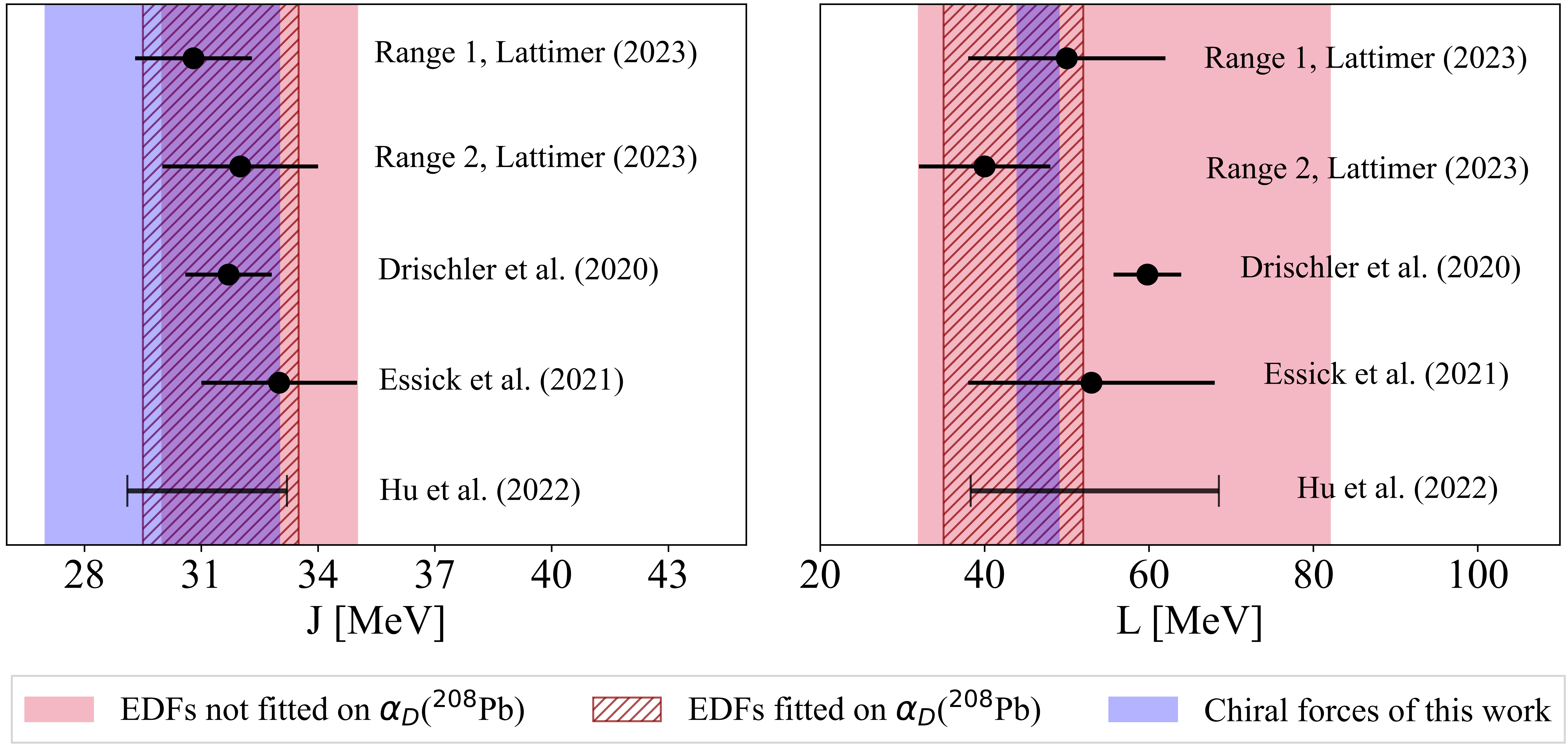
Curtesy of Francesca Bonaiti

Electric dipole polarizability

Fearick et al, PRRL (2023)



Comparison to other analyses



Curtesy of Francesca Bonaiti

How to go beyond closed shell nuclei?

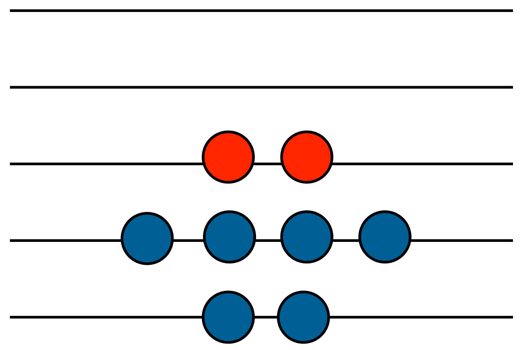
Open shell nuclei

Two particles outside the closed-(sub)shell

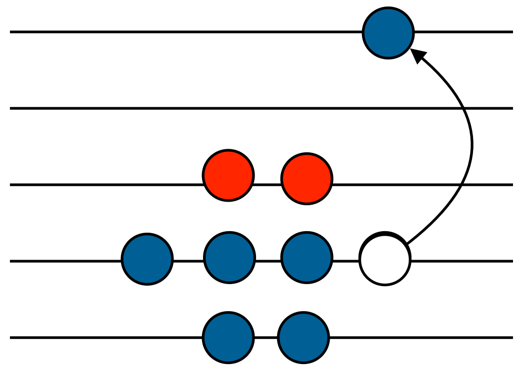
Francesca Bonaiti

$$|\tilde{\Psi}_R\rangle = \hat{R}|\Phi_0\rangle$$

$$\mathcal{R}(z)|\Phi_0\rangle = \left(\frac{1}{2} \sum_{ab} r^{ab}(z) a_a^\dagger a_b^\dagger + \frac{1}{6} \sum_{abci} r_i^{abc}(z) a_a^\dagger a_b^\dagger a_c^\dagger a_i + \dots \right) |\Phi_0\rangle$$



2p-0h



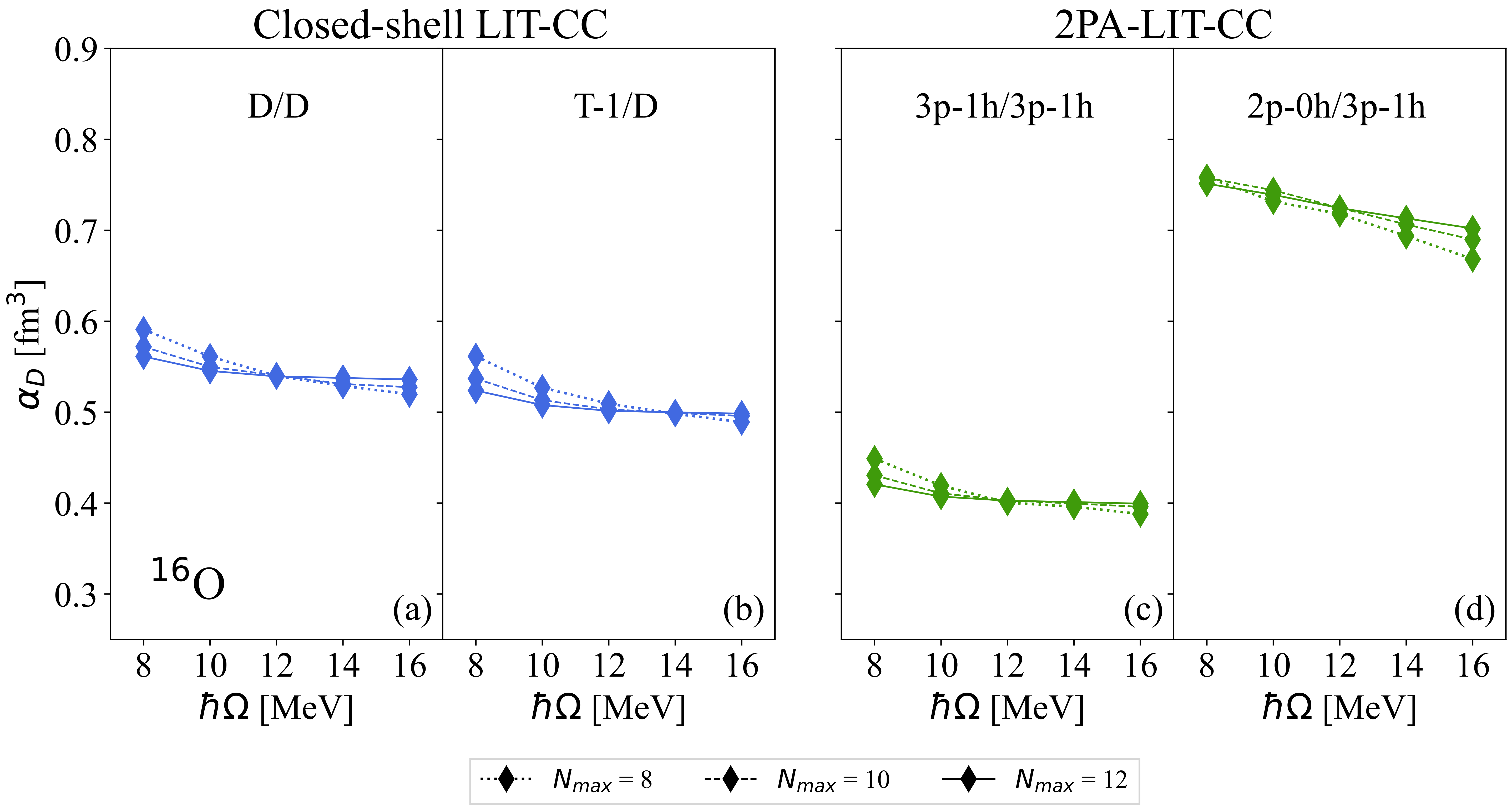
3p-1h

Open shell nuclei

Two particles outside the closed-(sub)shell

Francesca Bonaiti

F. Bonaiti, SB, G.Hagen, G. R. Jansen, arXiv: 2405.05608



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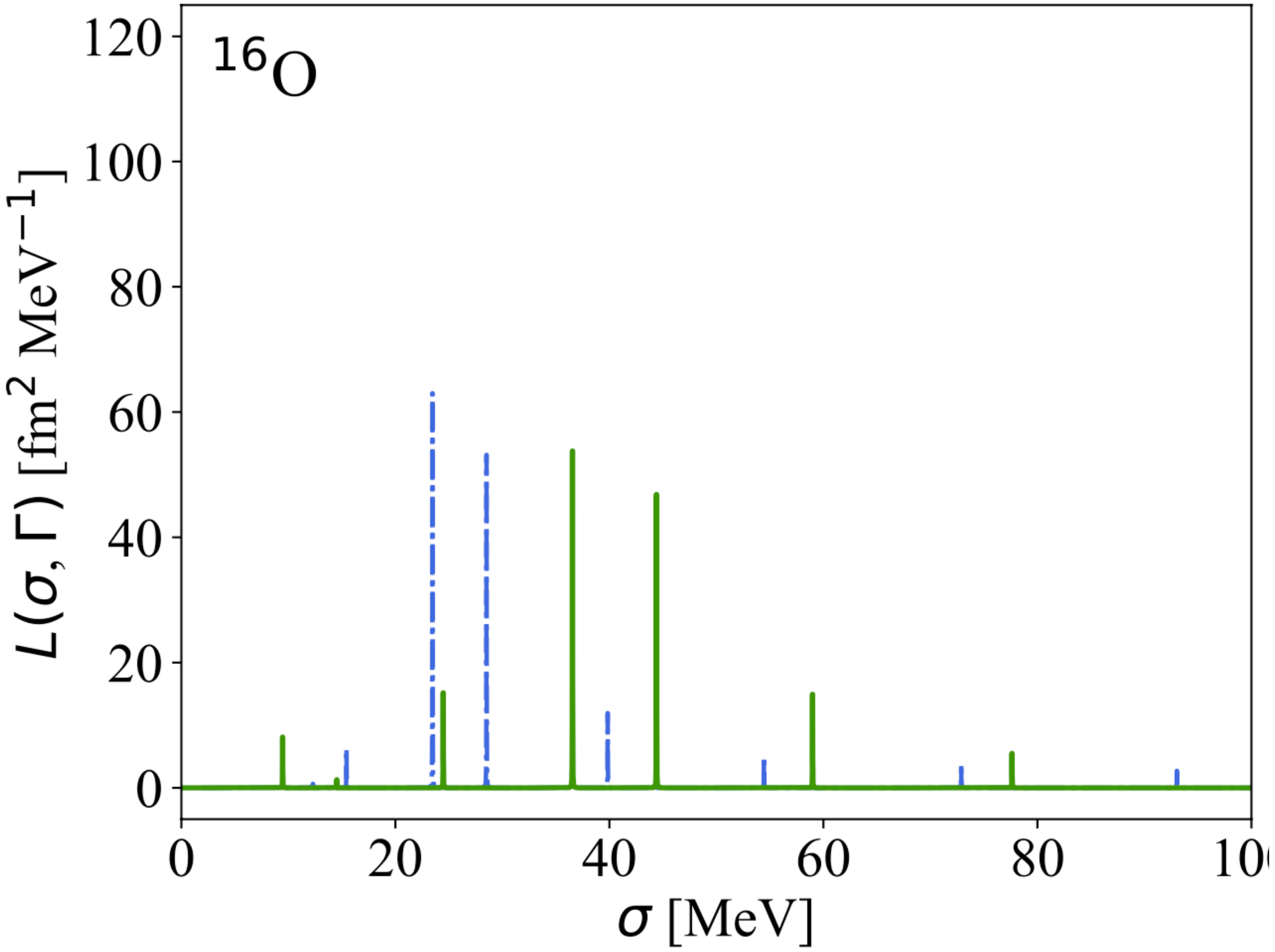

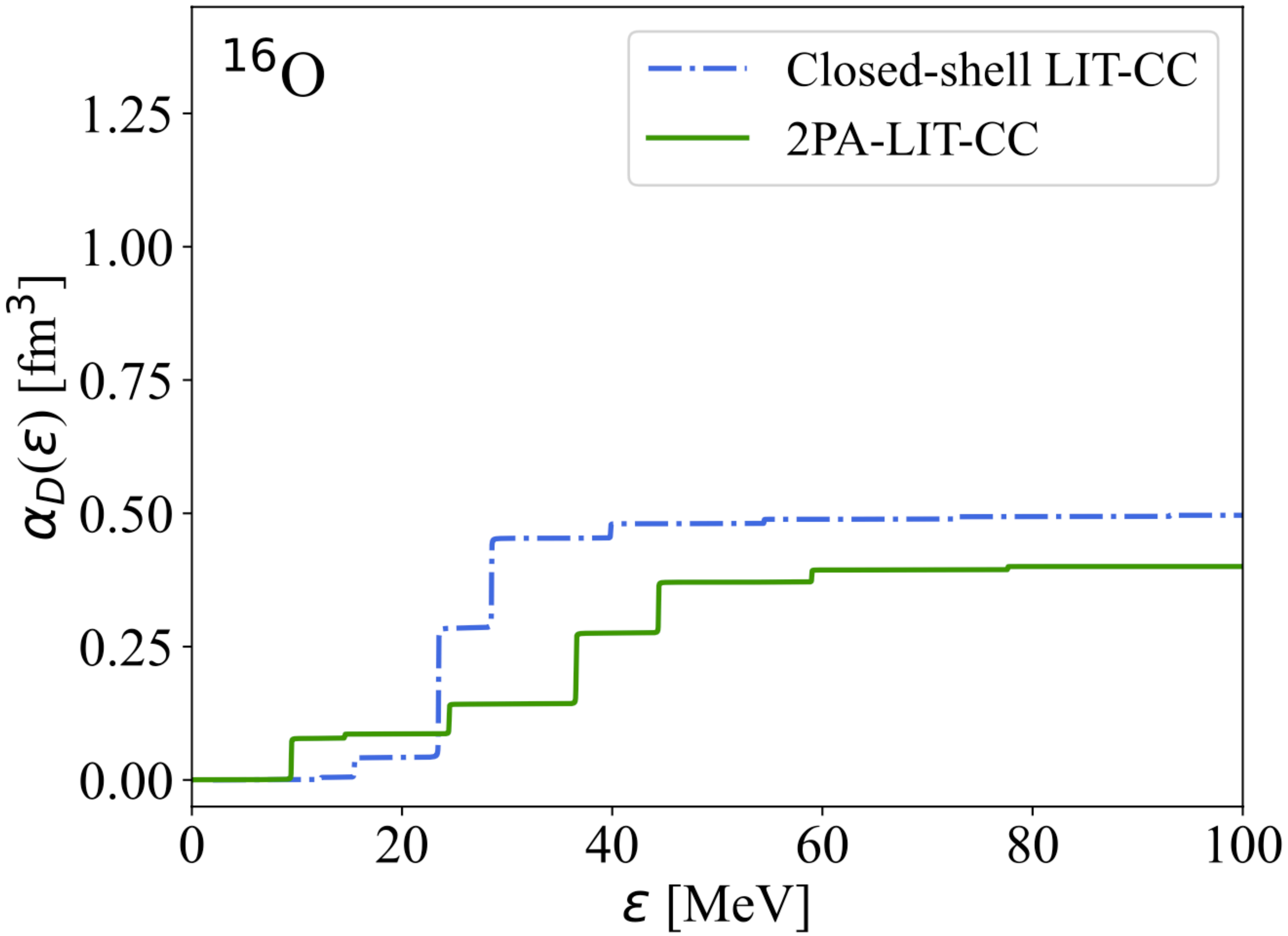

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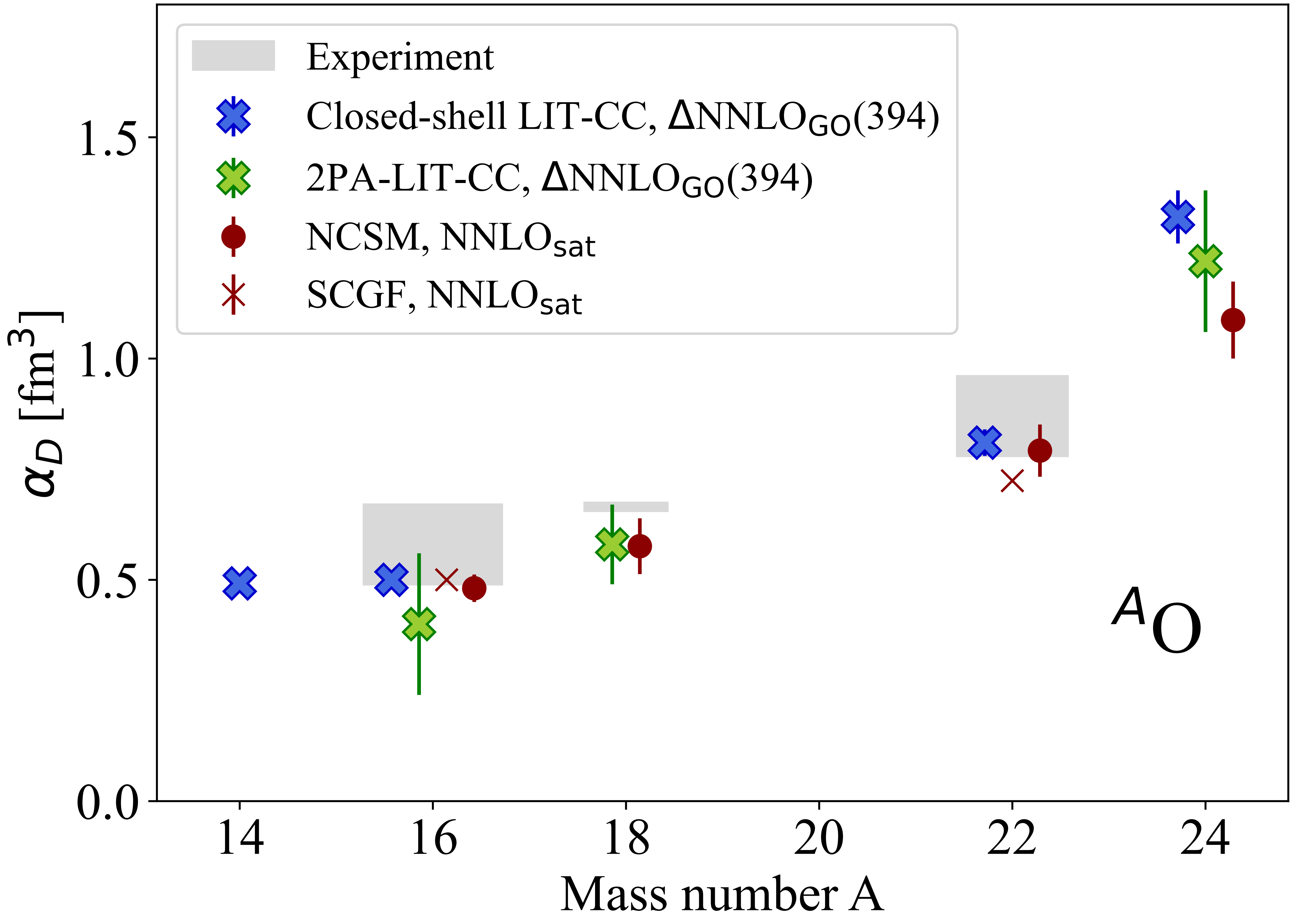

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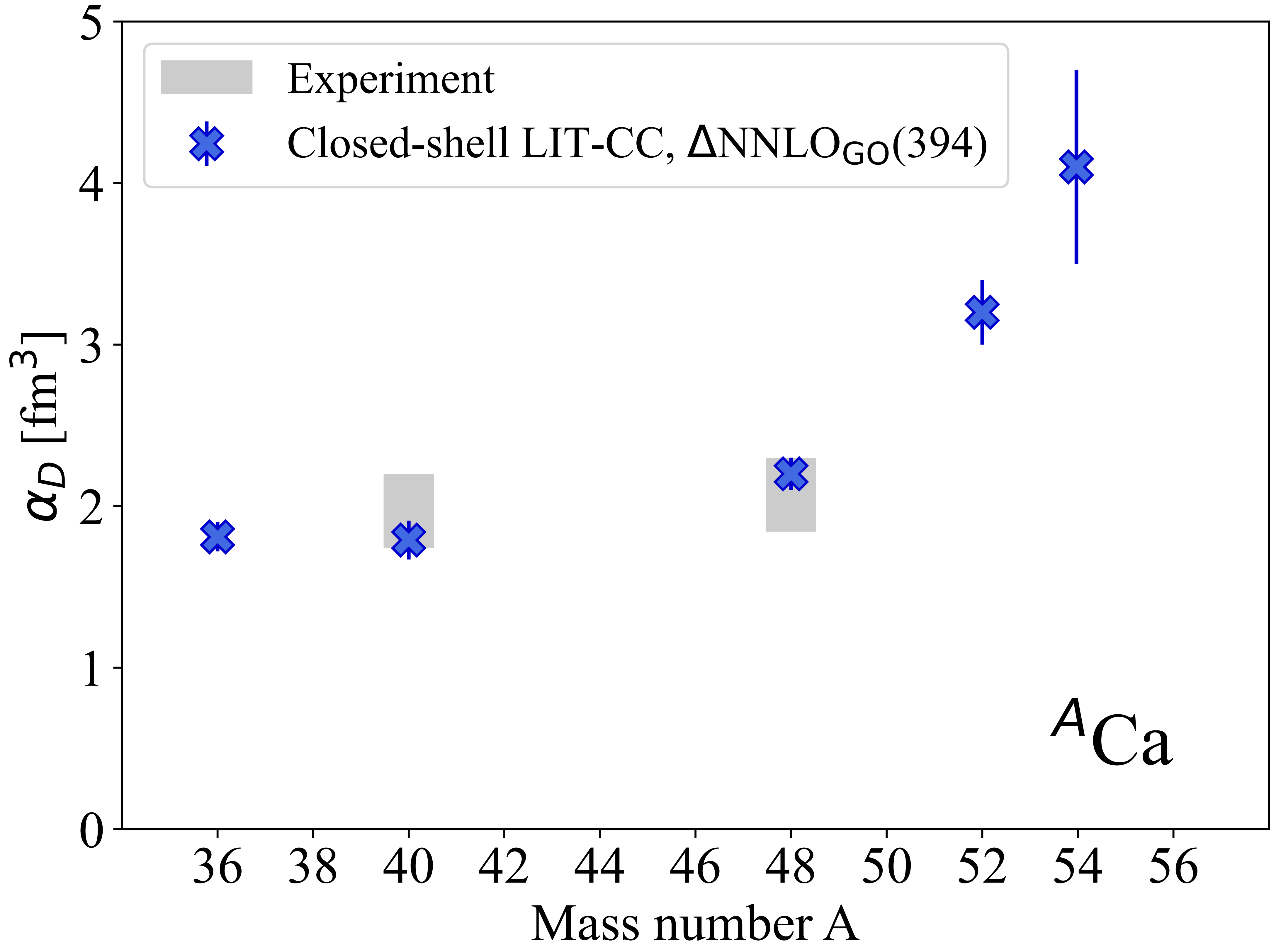

Open shell nuclei

Two particles outside the closed-(sub)shell

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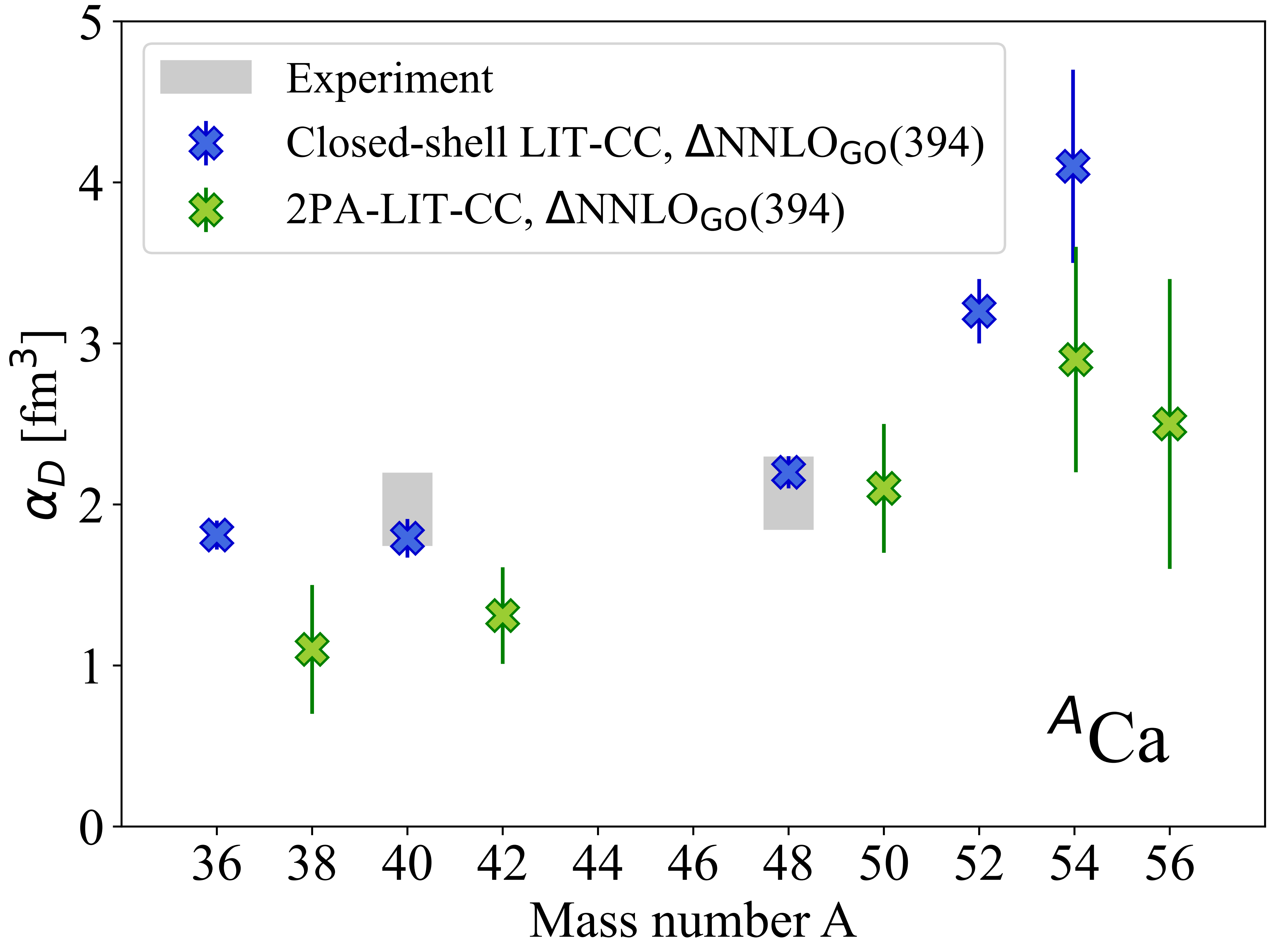
F. Bonaiti, SB, G.Hagen, G. R. Jansen, arXiv: 2405.05608



Applications to neutrino physics

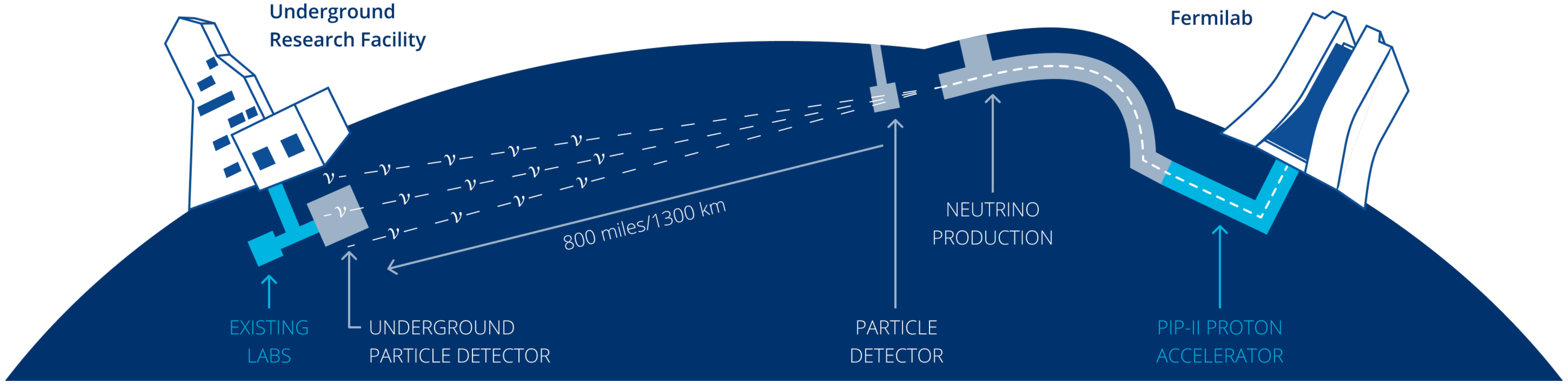
Neutrino oscillations

Next generation experiments

Hyper-K

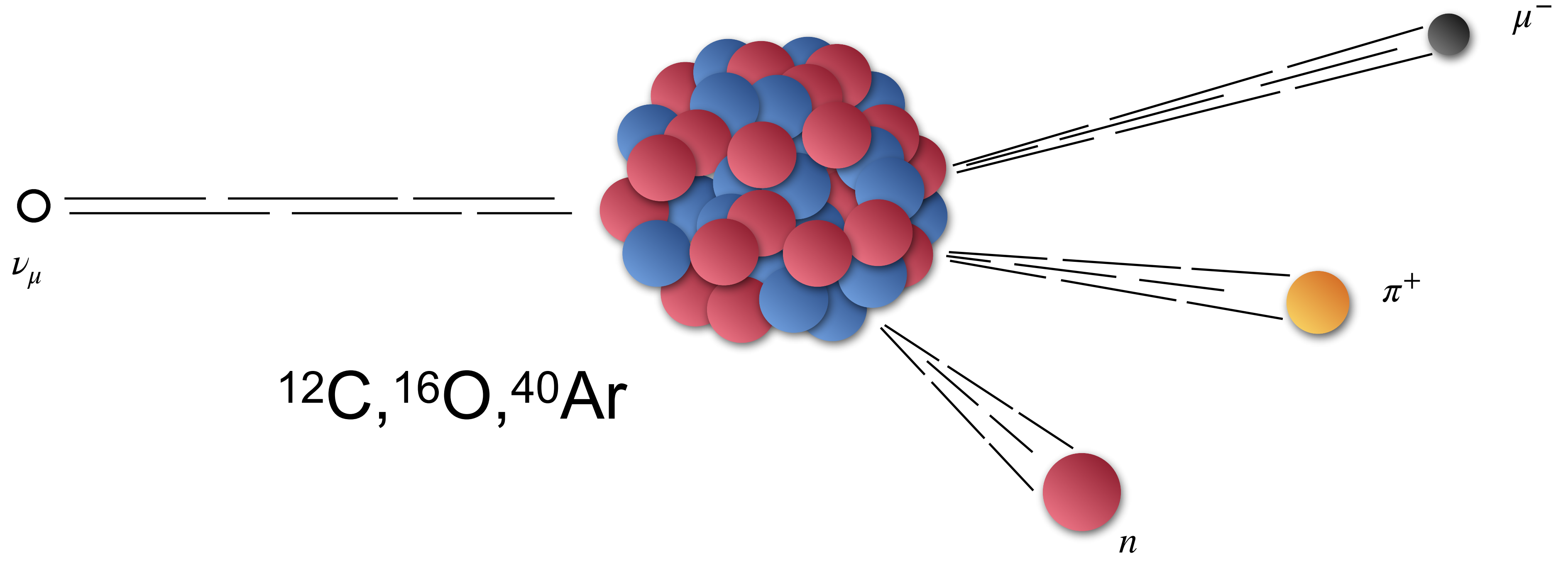
https://cerncourier.com/

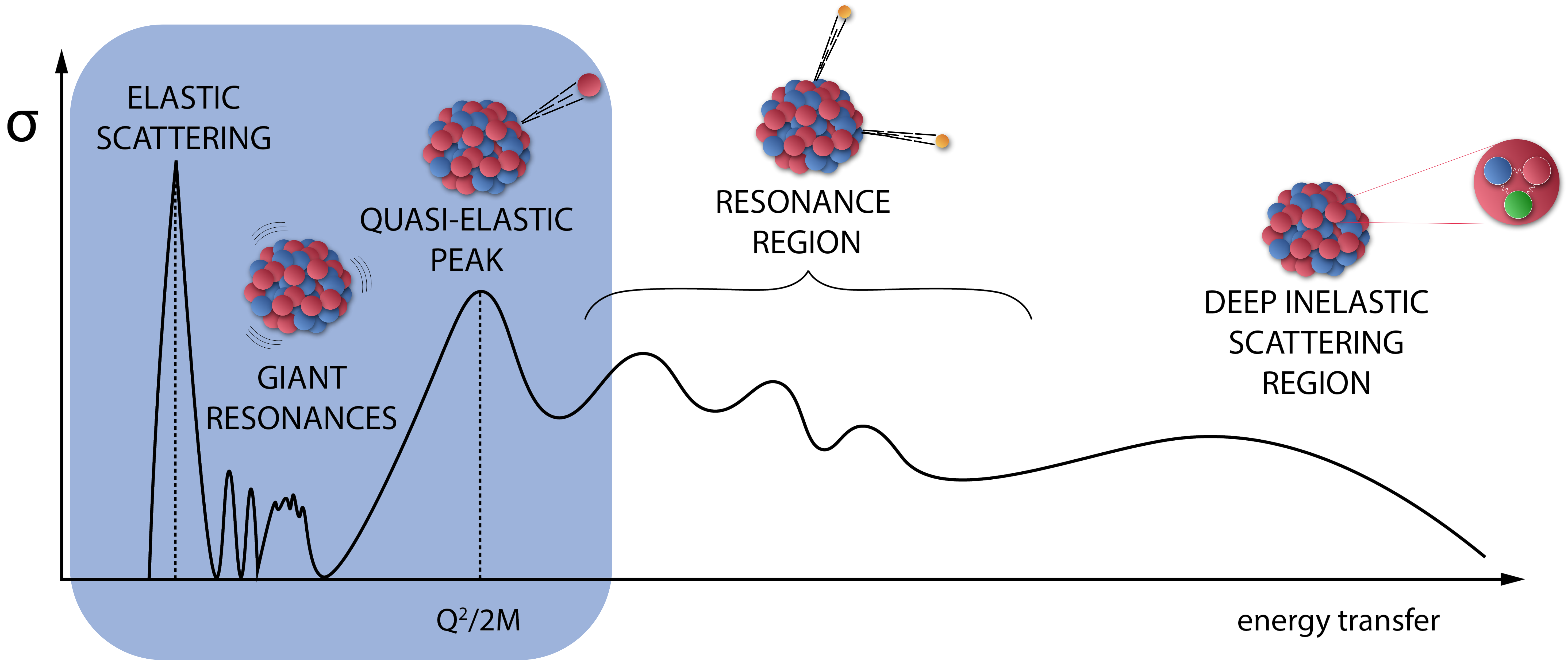
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



https://lbnf-dune.fnal.gov/

Challenges and opportunities





Electrons for neutrinos

ν-A scattering

$$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}\omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left[\ell_{CC}R_{CC} + \ell_{CL}R_{CL} + \ell_{LL}R_{LL} + \ell_T R_T \pm \ell_{T'}R_{T'}\right]$$

e-A scattering

$$\left.\frac{d^2\sigma}{d\Omega d\omega}\right|_e = \sigma_M\left[\frac{Q^4}{q^4}R_L + \left(\frac{Q^2}{2q^2} + \tan^2\frac{\theta_e}{2}\right)R_T\right]$$

Electron scattering

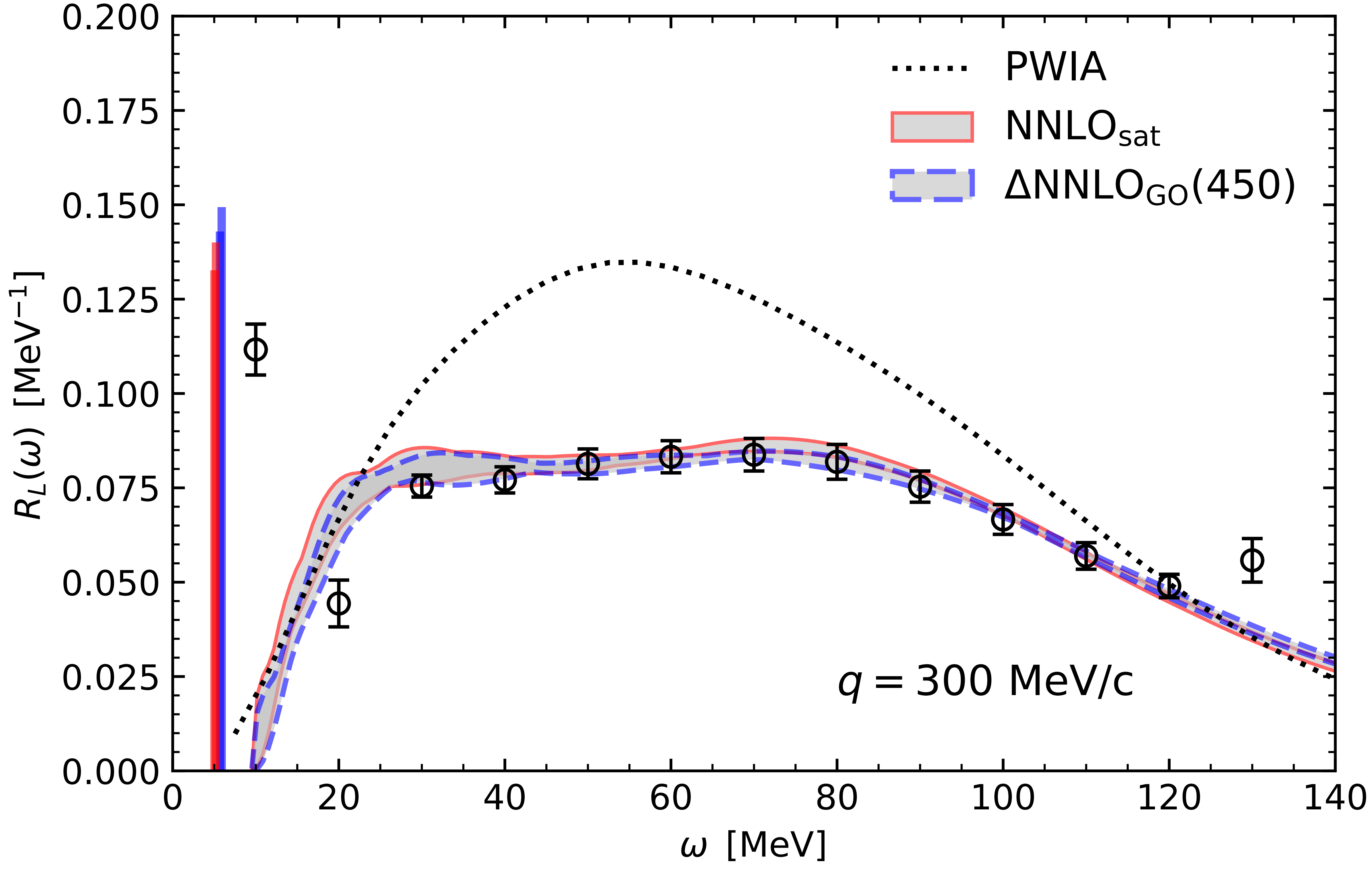
^{40}Ca(e,e')X

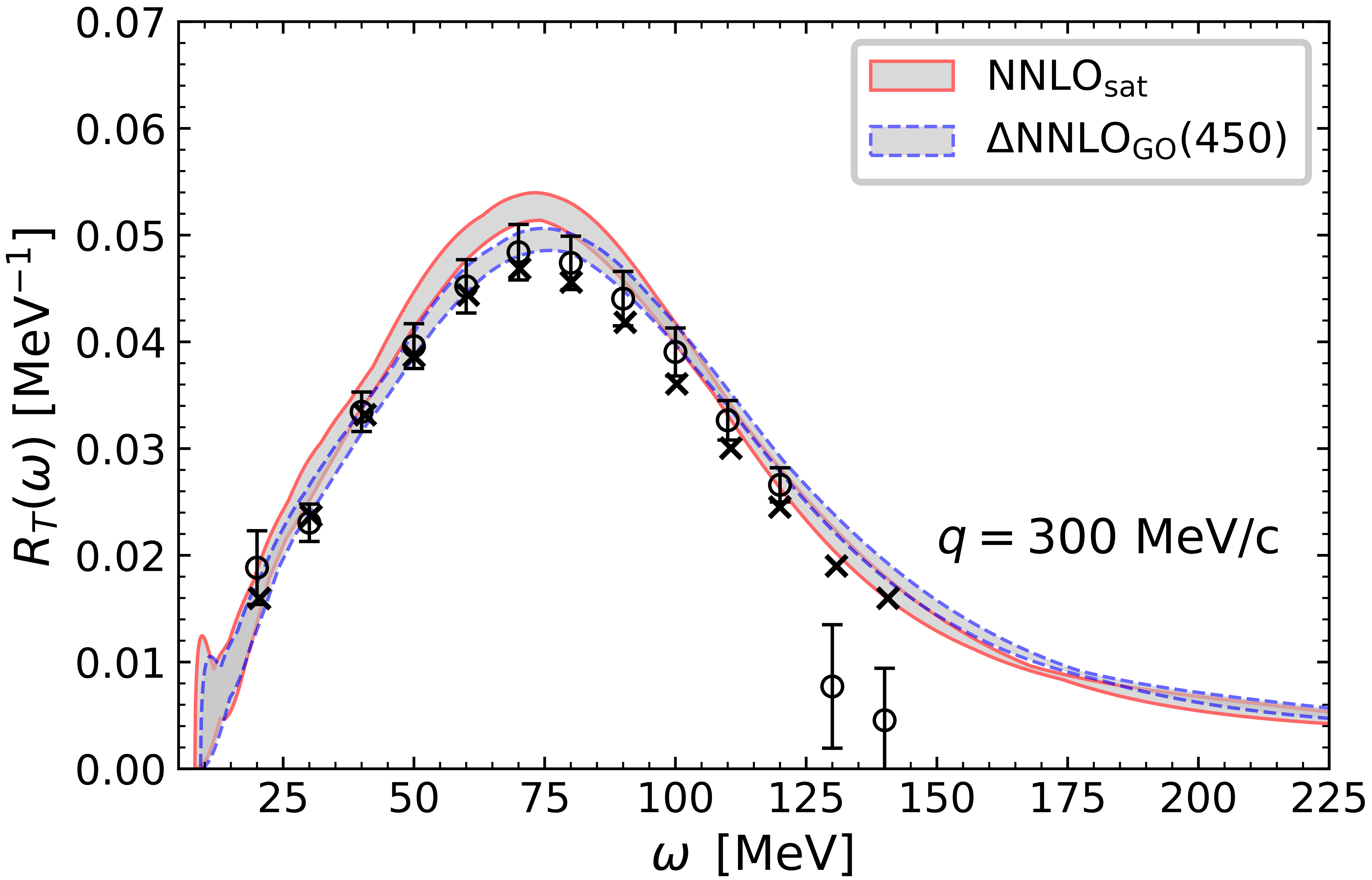

J.E. Sobczyk


B. Acharya

Sobcyzk, Acharya, SB, Hagen, PRL 127 (2021) 7, 072501

Sobcyzk, Acharya, SB, G. Hagen, PRC 109 (2024) 2, 025502





Conclusions and outlook

- Remarkable progress in ab initio calculations
- Electroweak reactions are fascinating because they allow to connect nuclear physics to astrophysics and to particle physics

Thanks to all my collaborators:

B. Acharya, F. Bonaiti, G. Hagen, **W. Jiang,** W. Leidemann, **S.S. Li Muli**, G. Orlandini, T. Papenbrock, **I. Reis**, A. Schwenk, J. Simonis, **J.E. Sobczyk,** et al.

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