Coupled-cluster theory + Lorentz integral transform

Present and Future

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Disclaimer:

This talk is not really going to answer any of the questions posed by Doron, and probably mostly out of topic

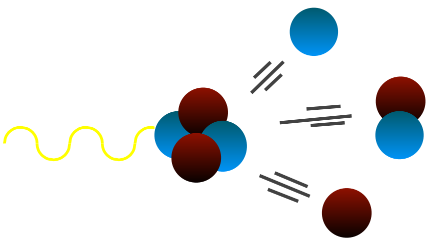
The idea is to see if the machinery we recently developed can be any useful to the subjects discussed in this workshop

Present

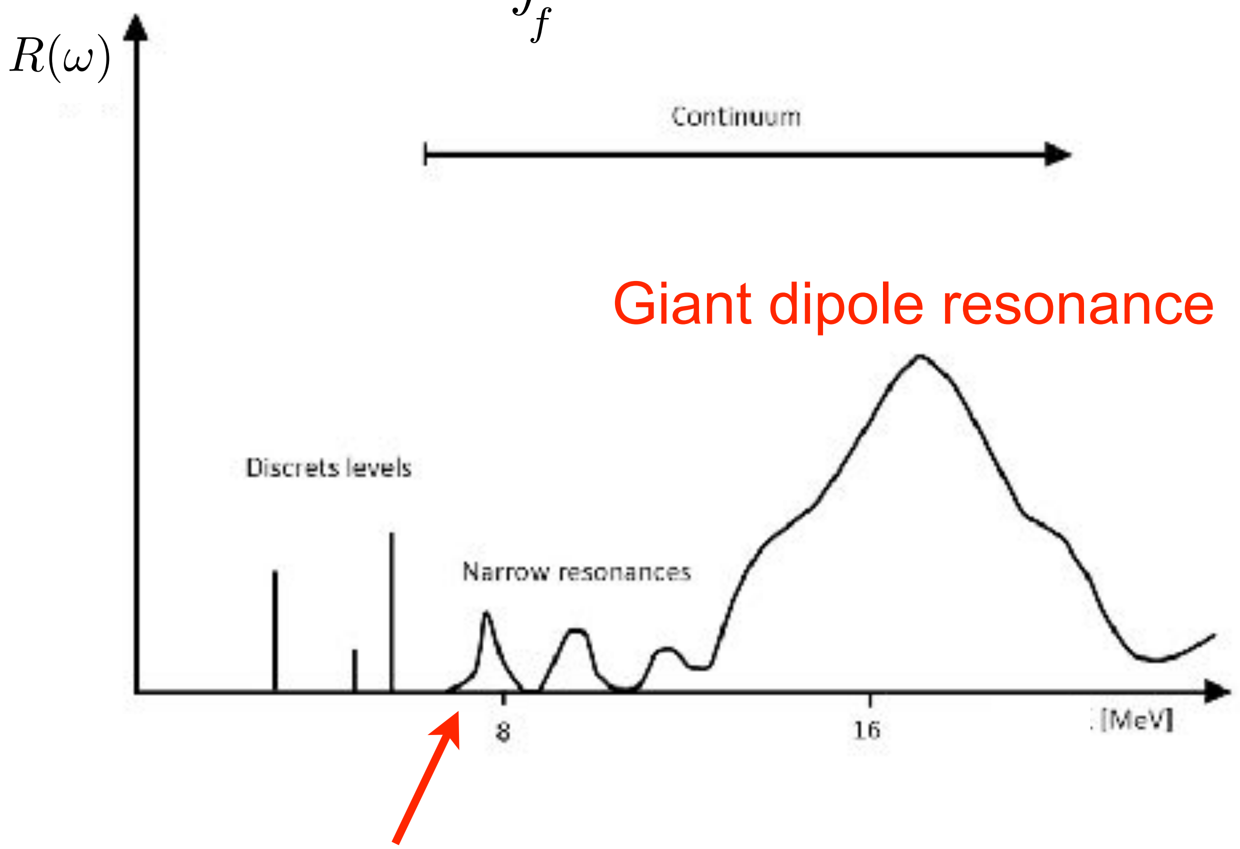
Mostly investigations of dipole response functions and related sum rules

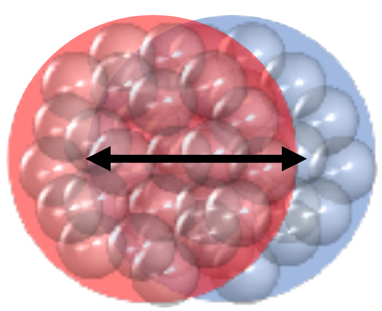
Dipole strength functions

How does the nucleus respond to external electromagnetic excitations?

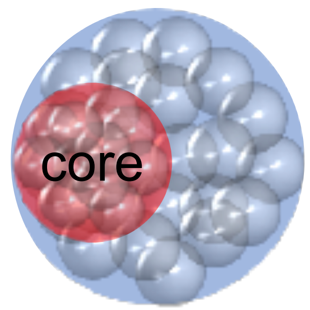


$$R(\omega) = \sum\!\!\!\!\!\!\!\int_f |\langle \Psi_f | \Theta | \Psi_0 \rangle|^2 \delta(\omega - E_f + E_0)$$





Pigmy dipole resonance in neutron-rich nuclei



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

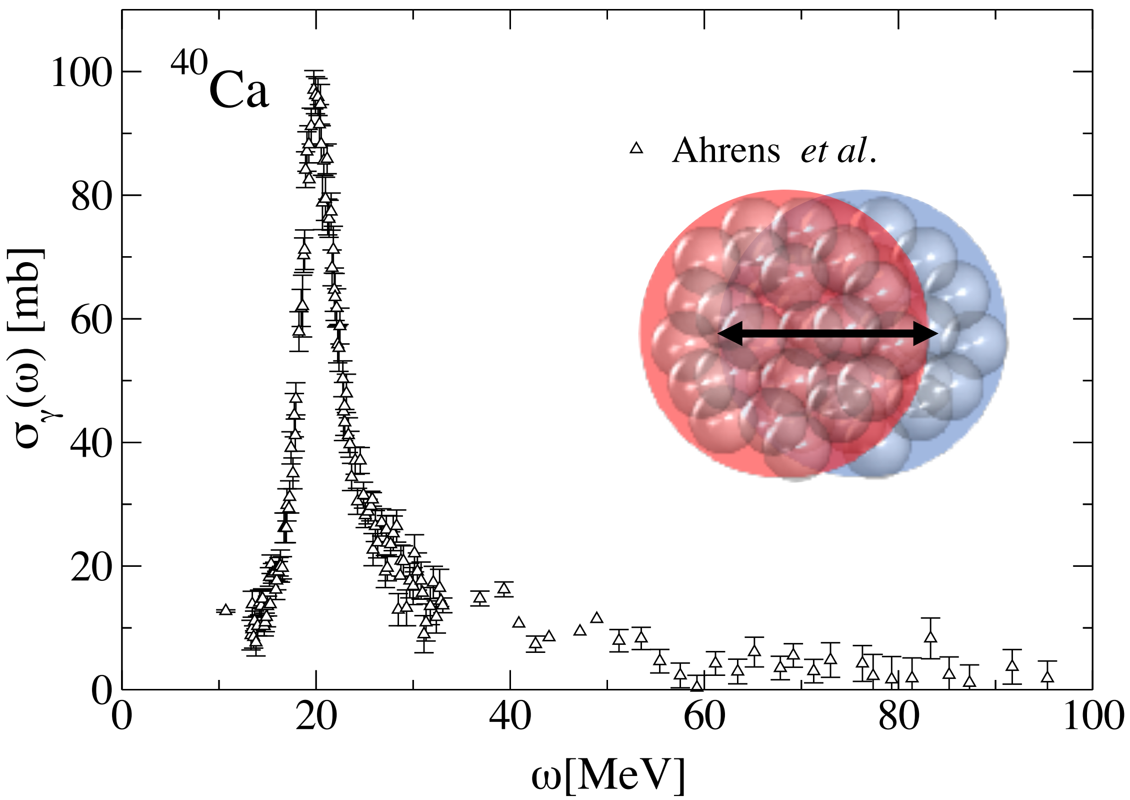
→ Low-energy part of strength dominates

Experimental Status

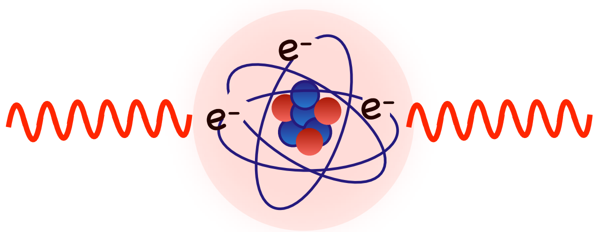
Stable Nuclei

We have data on ~180 stable nuclei

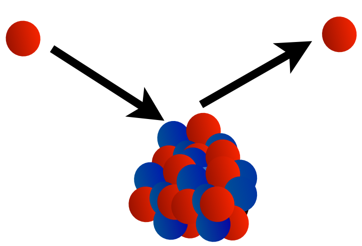
Giant dipole resonances



From photoabsorption experiments

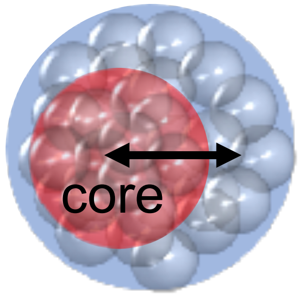


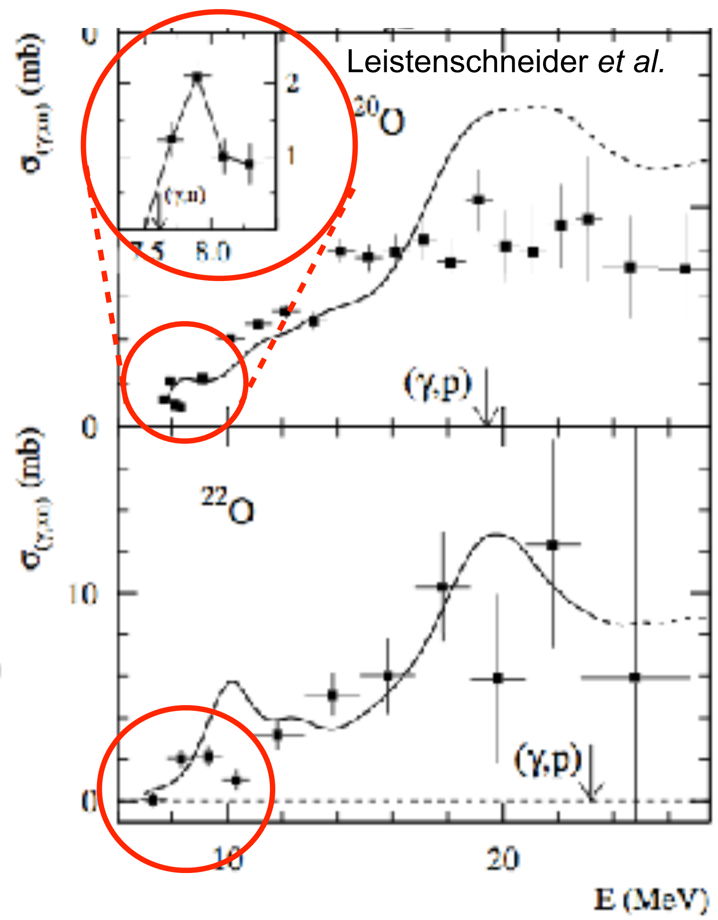
(p,p') experiments



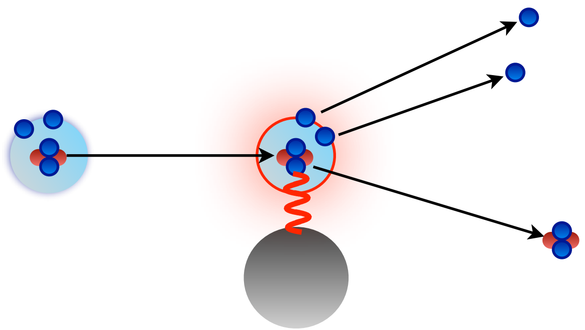
Unstable Nuclei

Fewer data, pigmy dipole resonances



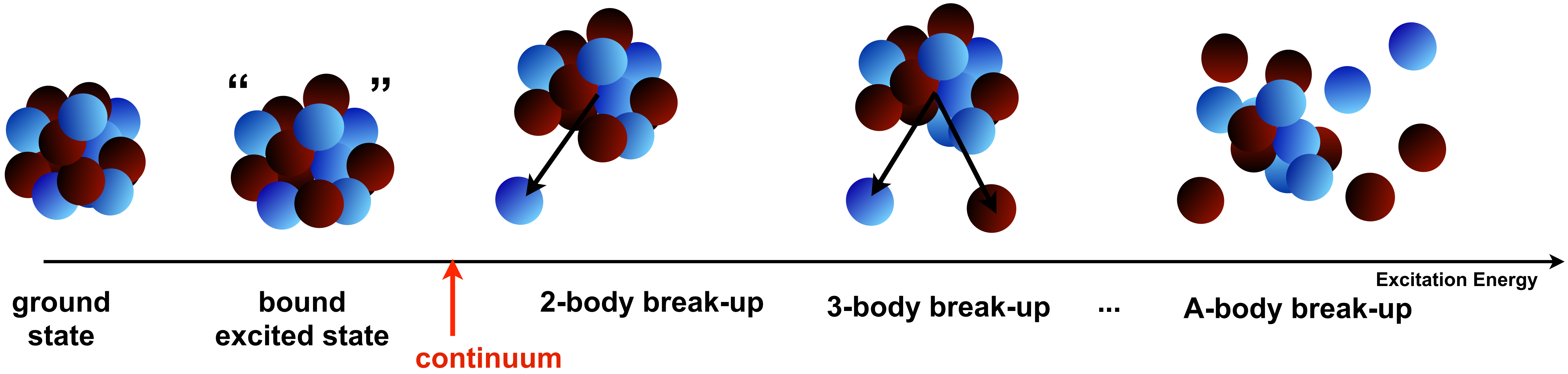


From Coulomb excitation experiments



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

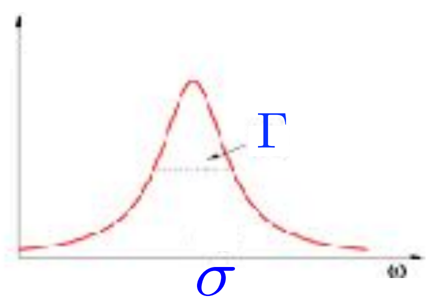
Continuum problem



$$R(\omega) \propto \left| \langle \Psi_f | \Theta | \Psi_0 \rangle \right|^2 \quad \Longleftrightarrow \quad L(\sigma, \Gamma) = \frac{\Gamma}{\pi} \int d\omega \frac{R(\omega)}{(\omega - \sigma)^2 + \Gamma^2} = \langle \tilde{\psi} | \tilde{\psi} \rangle$$

Exact knowledge limited in energy and mass number

Lorentz Integral Transform



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

$$\Rightarrow \quad (H - E_0 - \sigma + i\Gamma) \, | \tilde{\psi} \rangle = \Theta \, | \psi_0 \rangle$$

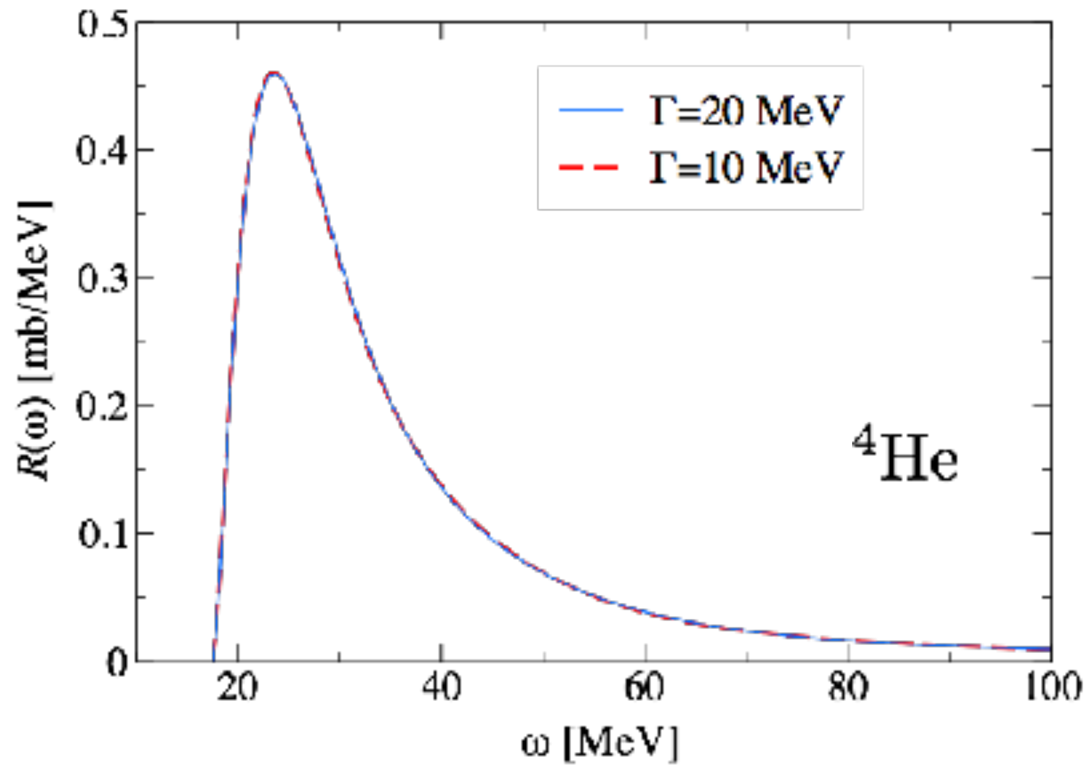
Reduce the continuum problem to a bound-state-like equation

Inversion of the LIT

The inversion is performed numerically with a regularization procedure needed for the solution of an ill-posed problem

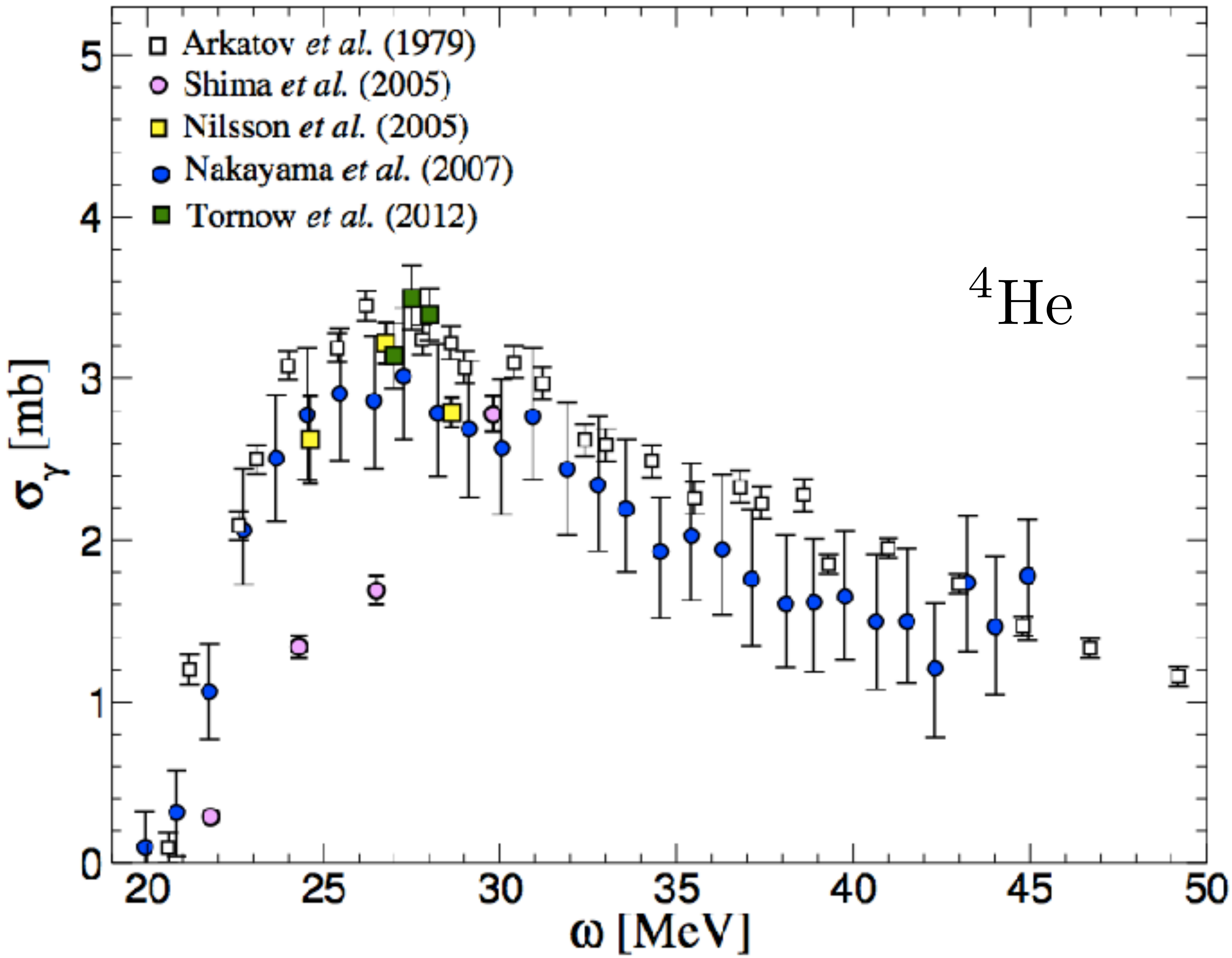
Ansatz $$R(\omega) = \sum_i^{I_{max}} c_i \chi_i(\omega, \alpha) \quad \Rightarrow \quad L(\sigma, \Gamma) = \sum_i^{I_{max}} c_i \mathcal{L}[\chi_i(\omega, \alpha)]$$

Least square fit of the coefficients c_i to reconstruct the response function



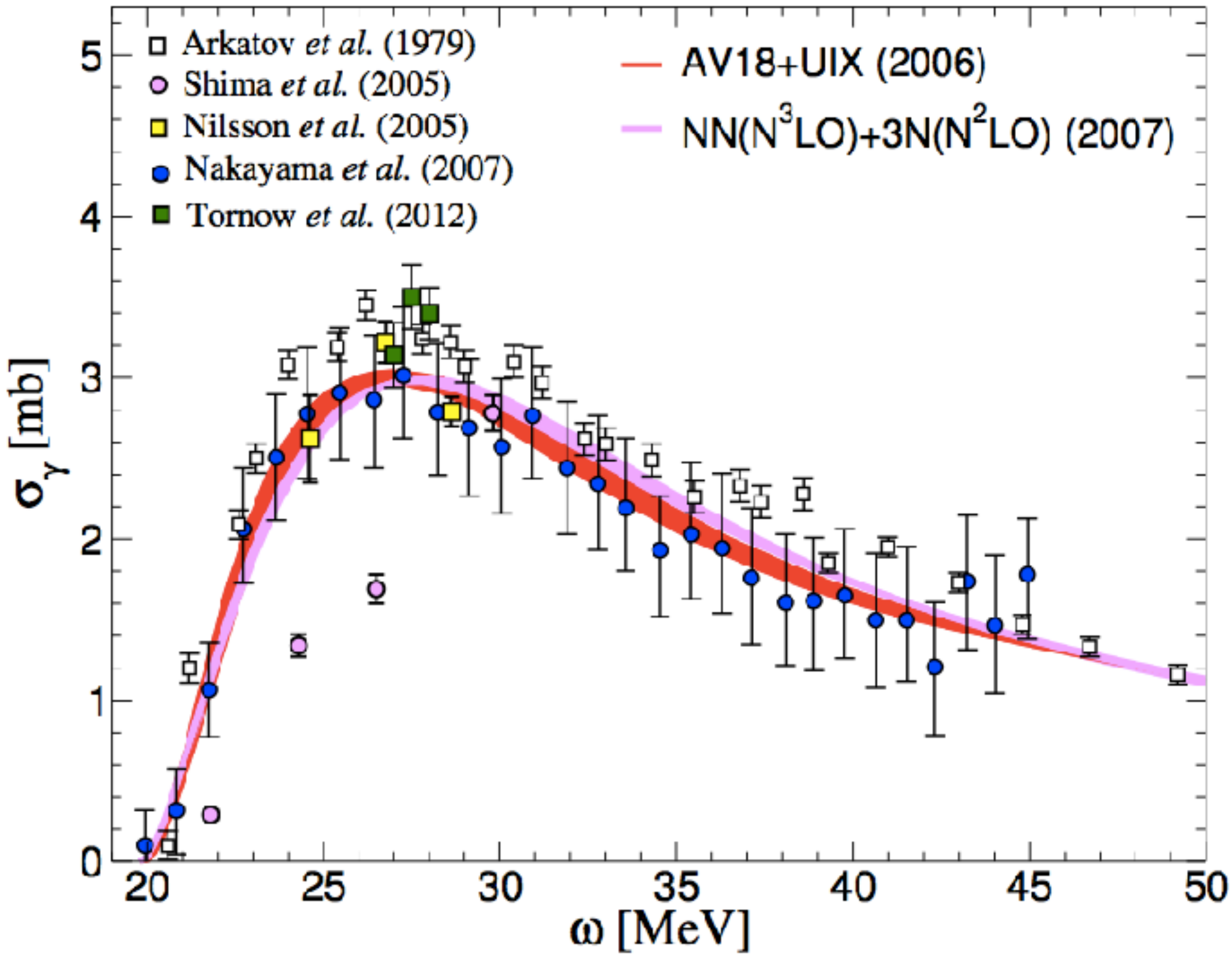
Message: using bound-states techniques to calculate the LIT is correct and inversions are stable If the LIT is calculated precisely enough

A few-body example



S.B. and Saori Pastore, Journal of Physics G.: Nucl. Part. Phys. **41**, 123002 (2014)

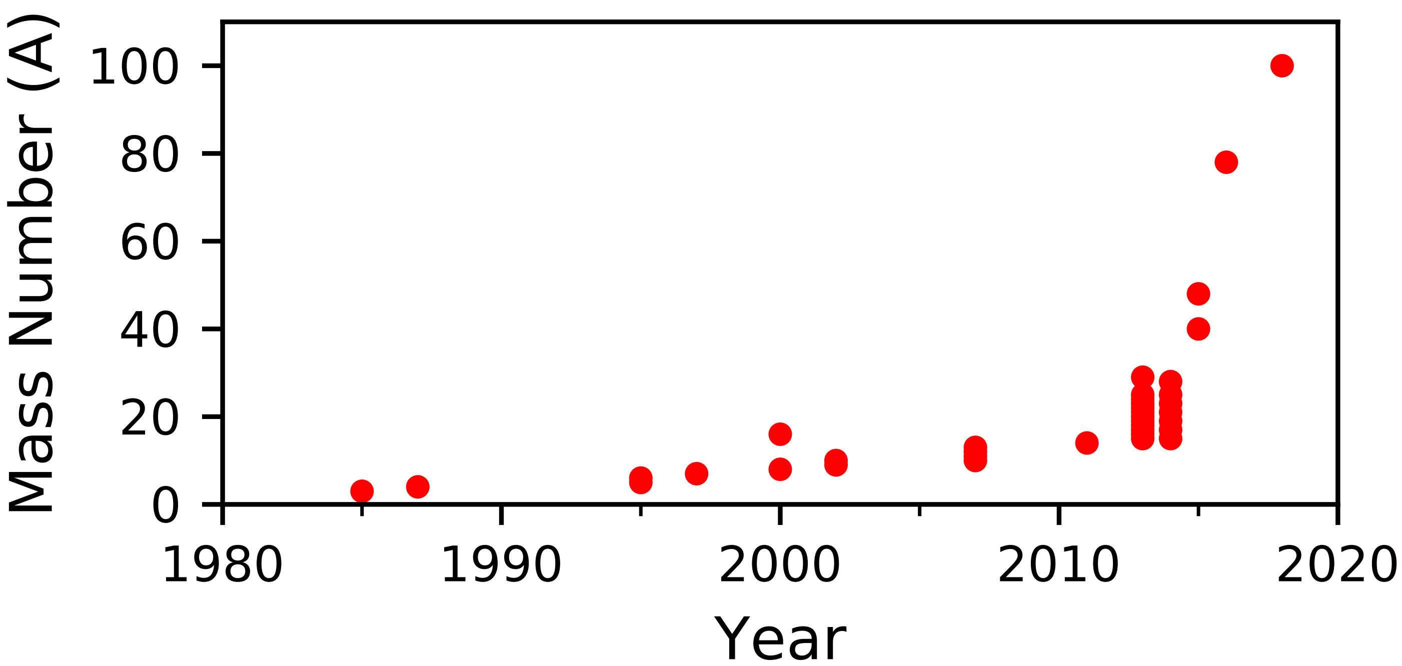
A few-body example



S.B. and Saori Pastore, Journal of Physics G.: Nucl. Part. Phys. **41**, 123002 (2014)

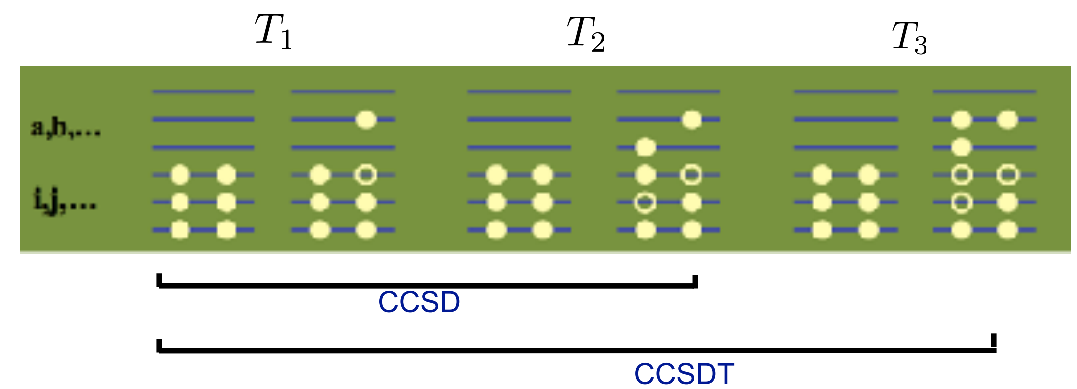
Coupled-cluster theory formulation

See Gaute's talk



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

$$T = \sum T_{(A)}$$ cluster expansion



S.B. *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)

$$(\bar{H} - E_0 - \sigma + i\Gamma)|\tilde{\Psi}_R\rangle = \bar{\Theta}|\Phi_0\rangle$$

$$\bar{H} = e^{-T} H e^{T}$$

$$\bar{\Theta} = e^{-T} \Theta e^{T}$$

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

Results with implementation at CCSD level

$$T = T_1 + T_2$$

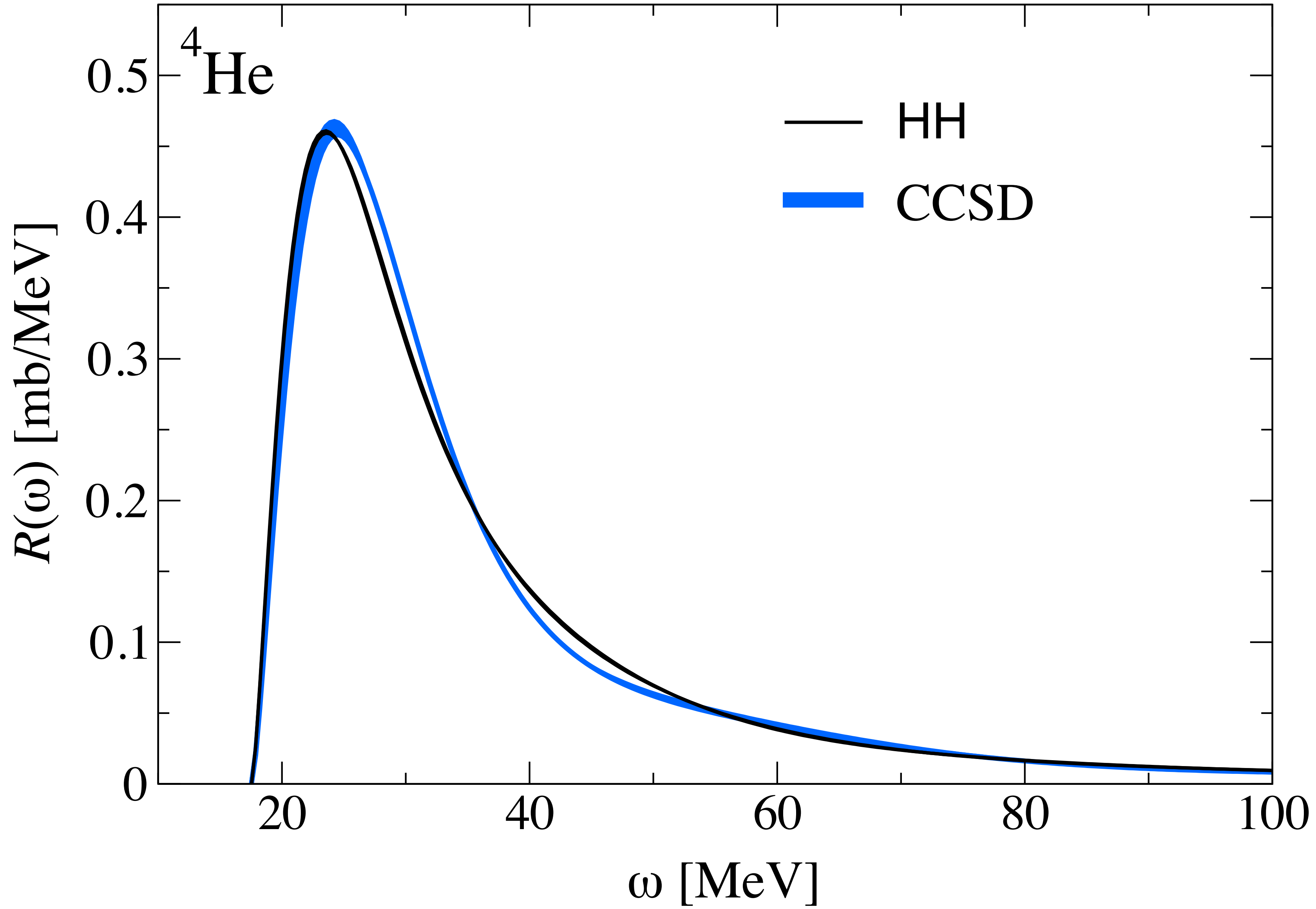
$$R = R_0 + R_1 + R_2$$

Validation in ^{4}He

Dipole response function

Comparison of CCSD with exact hyperspherical harmonics with NN forces at N^3LO

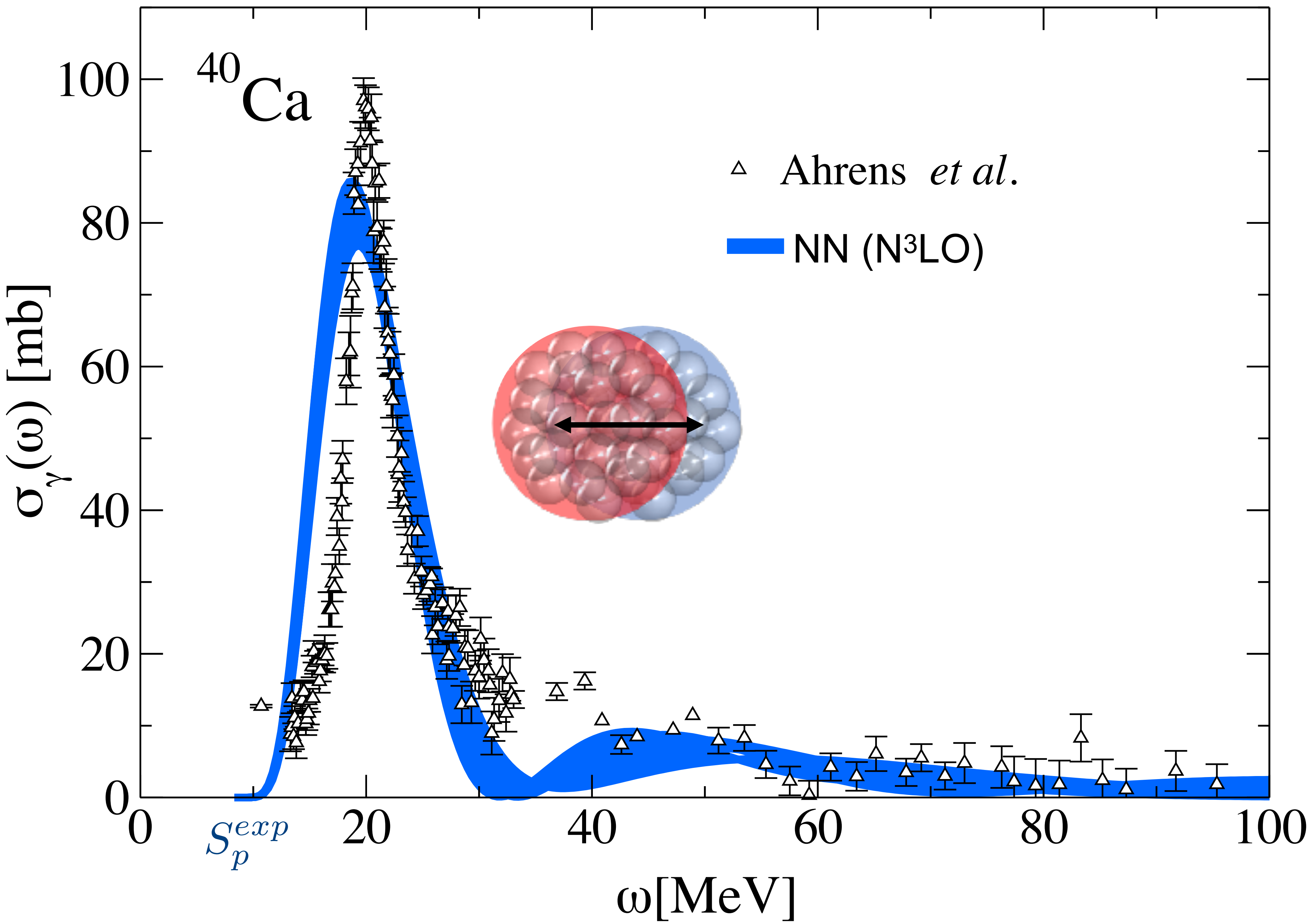
S.B. *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)



Addressing medium-mass nuclei

Theory helps interpret existing experimental data

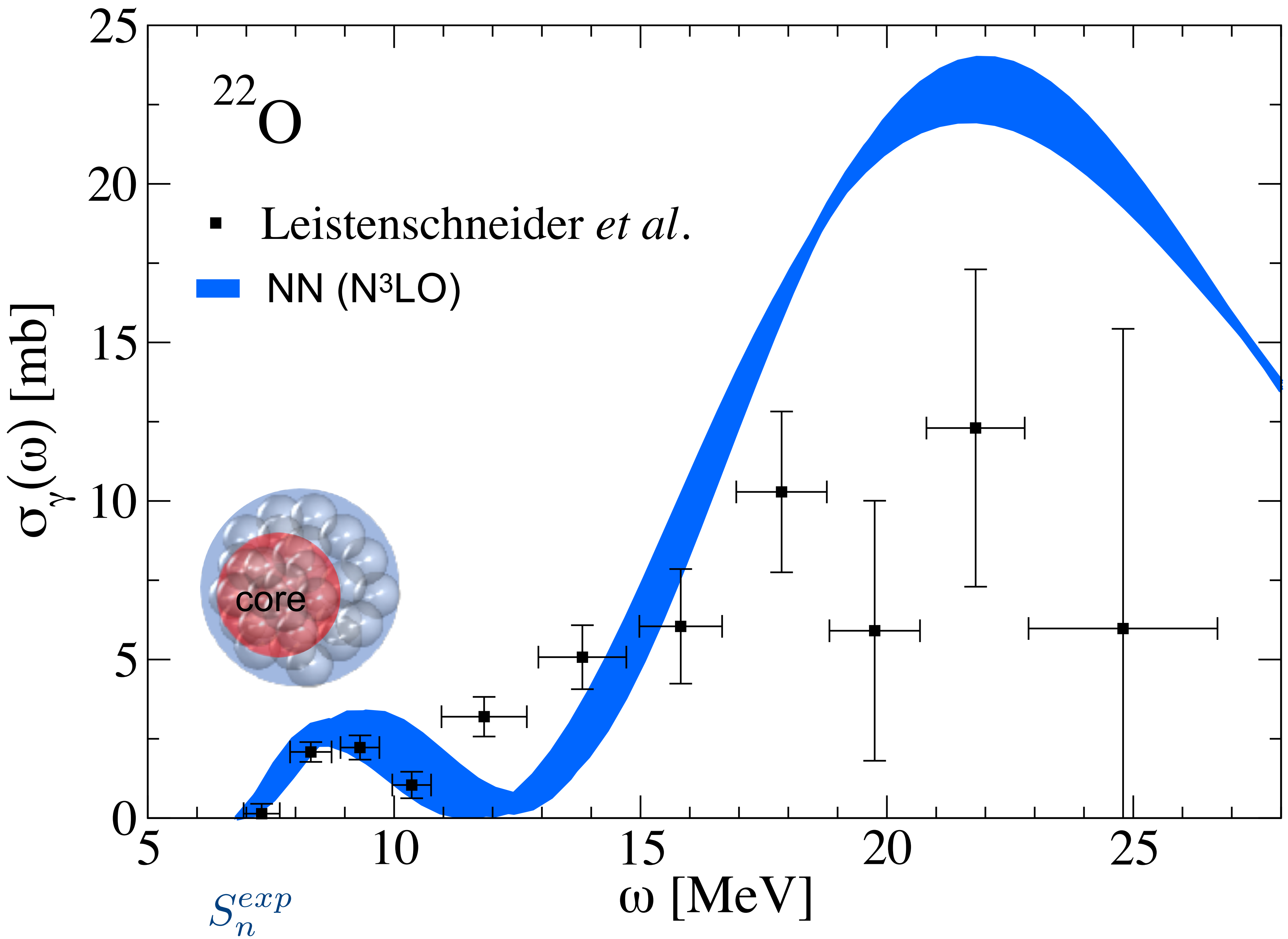
SB et al., PRC **90**, 064619 (2014)



Addressing neutron-rich nuclei

Theory helps interpret existing experimental data

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



^{48}Ca electric dipole polarizability

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

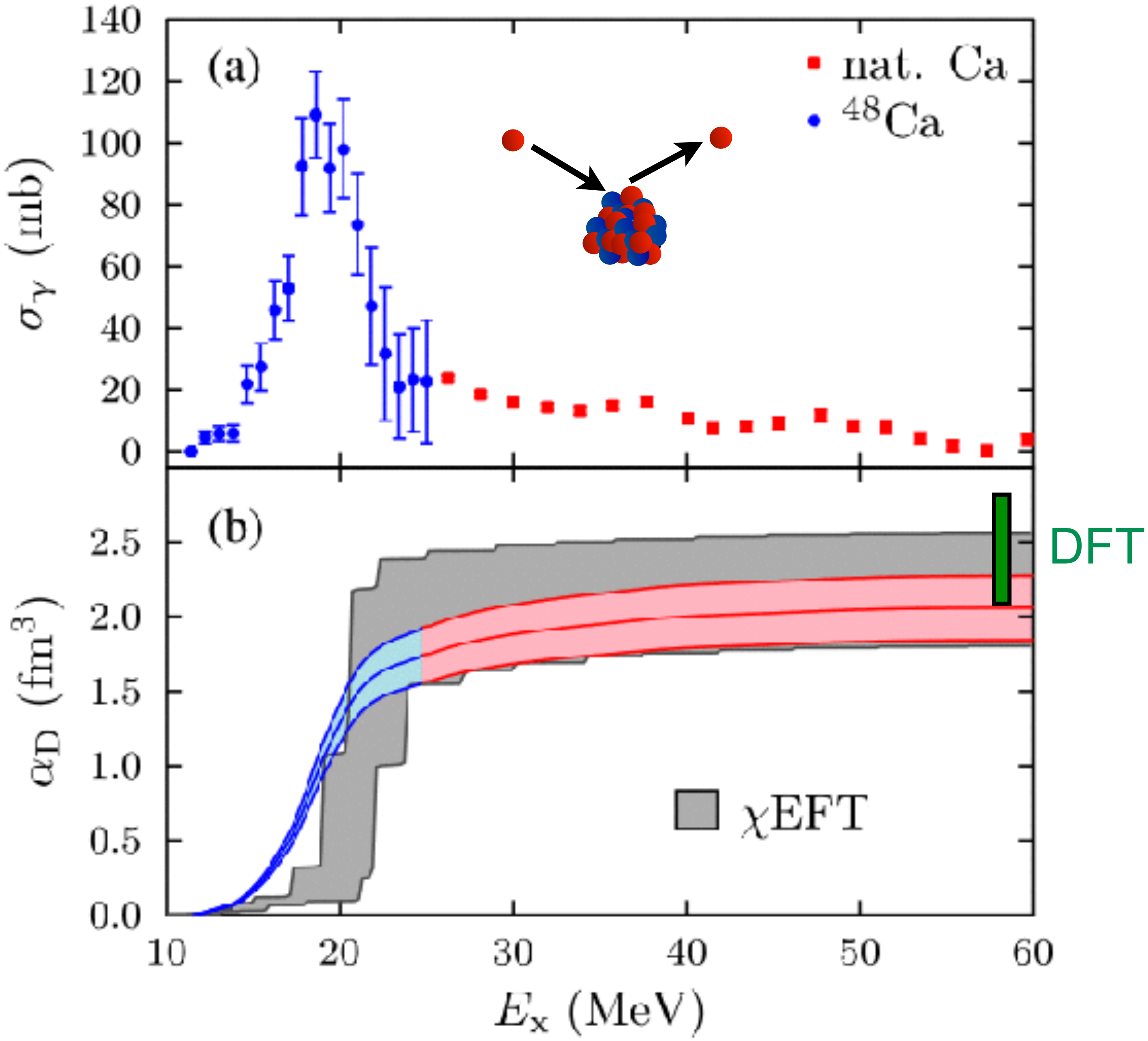
Can be calculated:

(1) by integrating the strength obtained from LIT inversion

(2) Directly from the Lanczos coefficients (not going via the inversion)
Phys. Rev. C **94,** 034317 (2017)

$$\alpha_D \rightarrow \left\{ \frac{1}{(a_0+\sigma) - \frac{b_0^2}{(a_1+\sigma) - \frac{b_1^2}{(a_2+\sigma)-\cdots}}} \right\}$$

J.Birkhan, *et al.*, Phys. Rev. Lett. **118,** 252501 (2017)

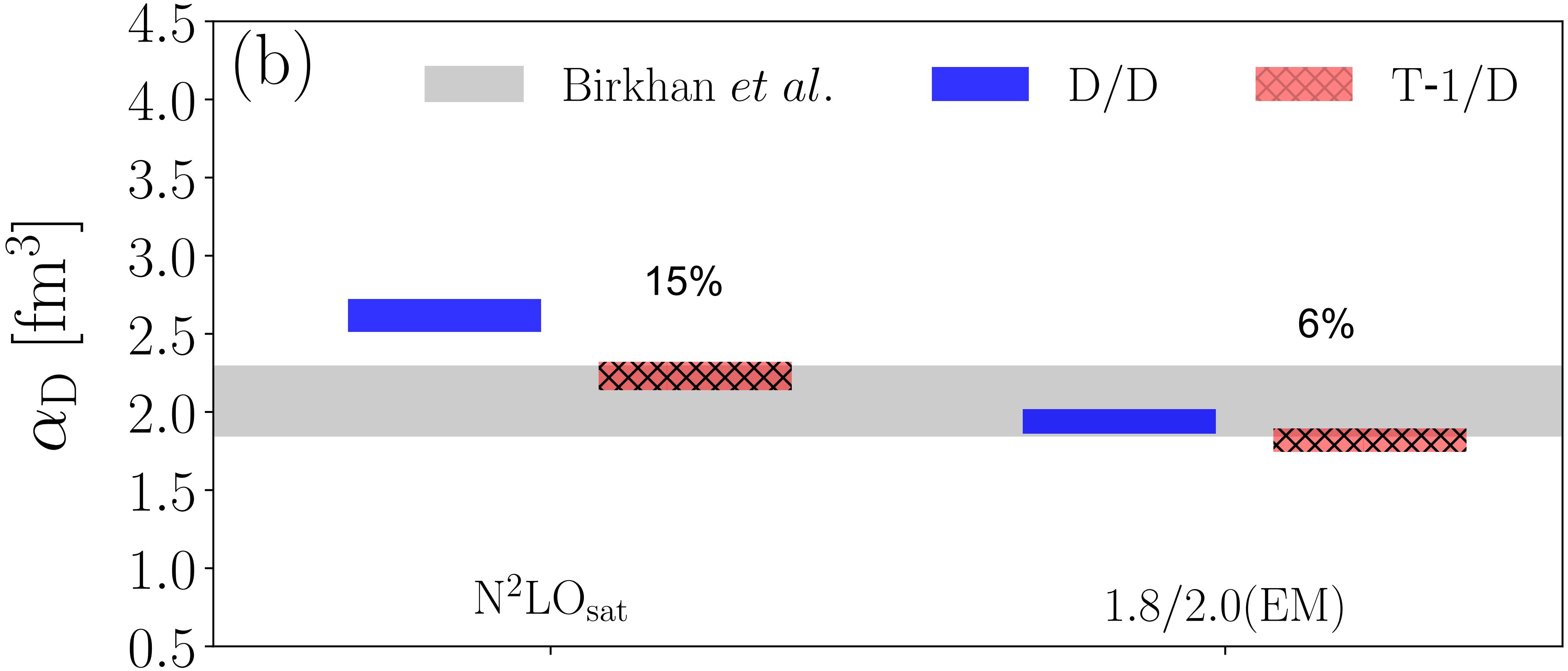


Theory tends to overestimate experiment

Can we improve the theoretical prediction?

Adding triples in ^{48}Ca

M. Miorelli *et al.*, PRC 98, 014324 (2018)



Higher order correlations are important

They improve the comparison with experiment

Future

Extend these studies to weak operators, e.g., Gamow-Teller strengths

$$\Theta \rightarrow GT = \sum_i \sigma_i \tau_i^+$$

In principle any one-body operator …

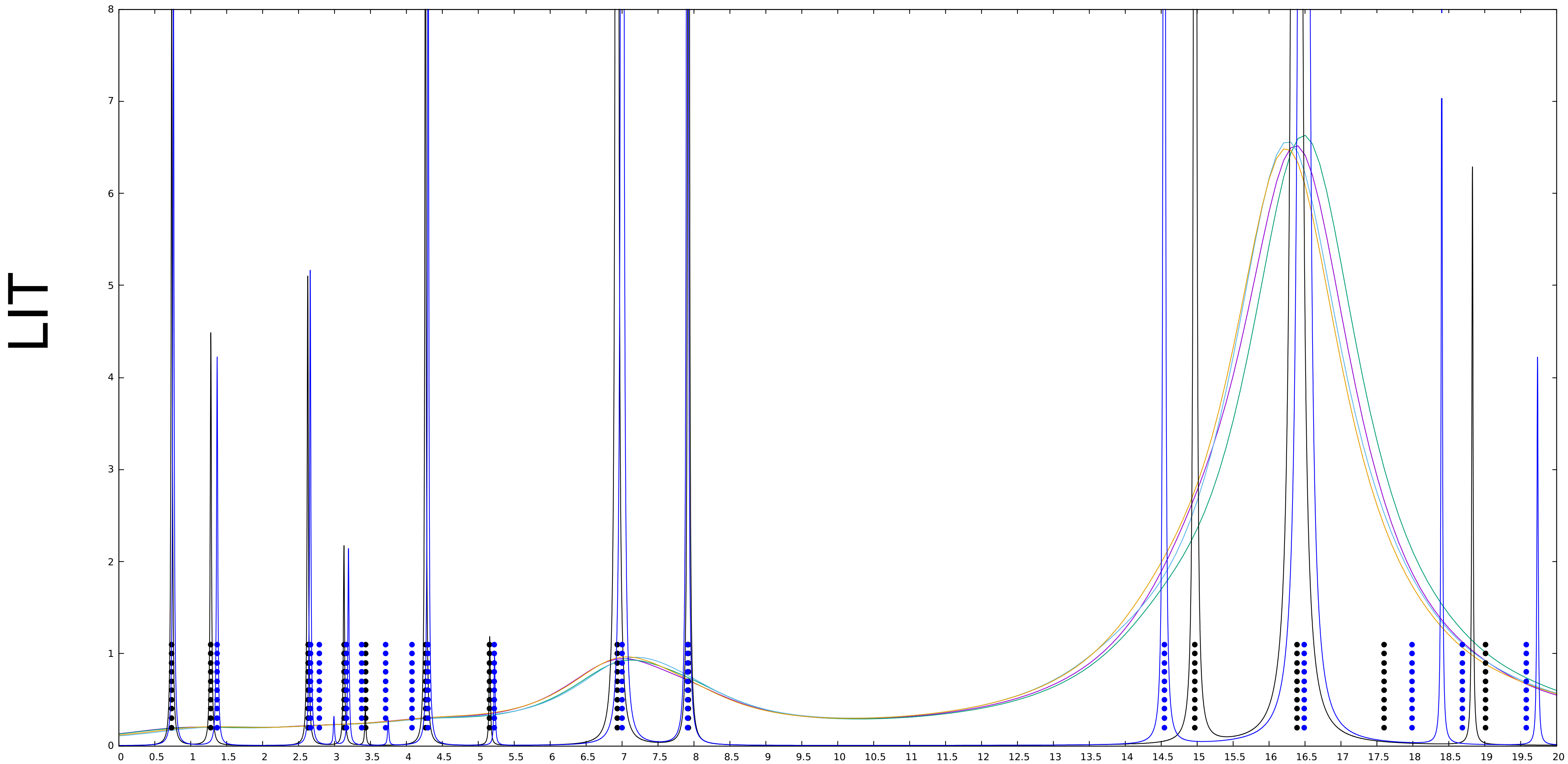
Gamow-Teller strength

Calculations by M.Miorelli, 2017

Broad curves: LIT with Γ=1 MeV for $\hbar\omega = 10, 12, \quad N_{max} = 10, 12$

Peaked curves: LIT with Γ= 0.01 for $\hbar\omega = 12 \quad N_{max} = 10, 12$ $\quad L(\sigma, \Gamma \to 0) = \int R(\omega)\delta(\omega - \sigma)d\omega = R(\sigma)$

Dots: from diagonalization of Lanczos $\hbar\omega = 12 \quad N_{max} = 10, 12$



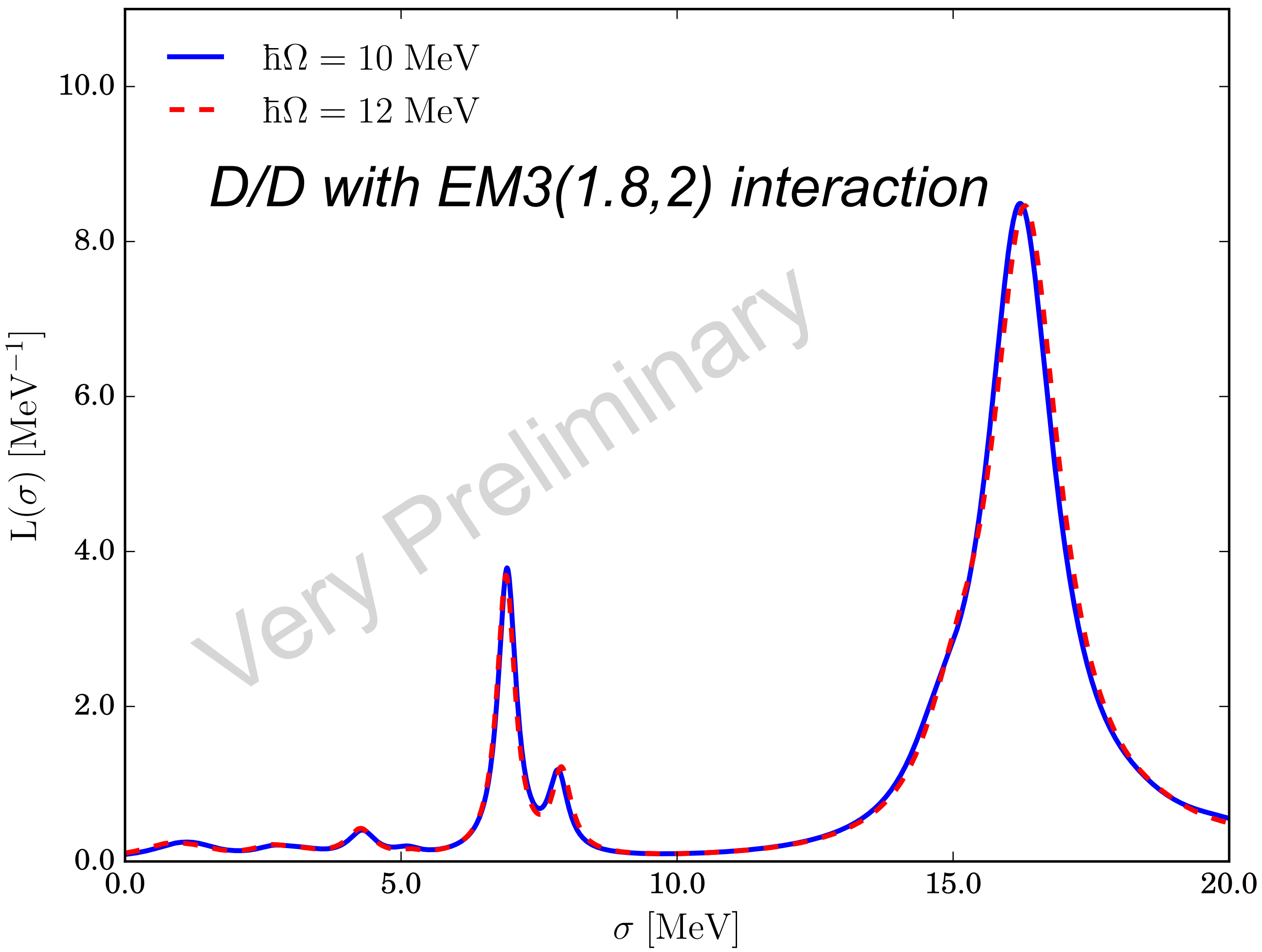
Kind of convergent at low-energy, much more than for electric dipole case…

Gamow-Teller strength in ^{132}Sn

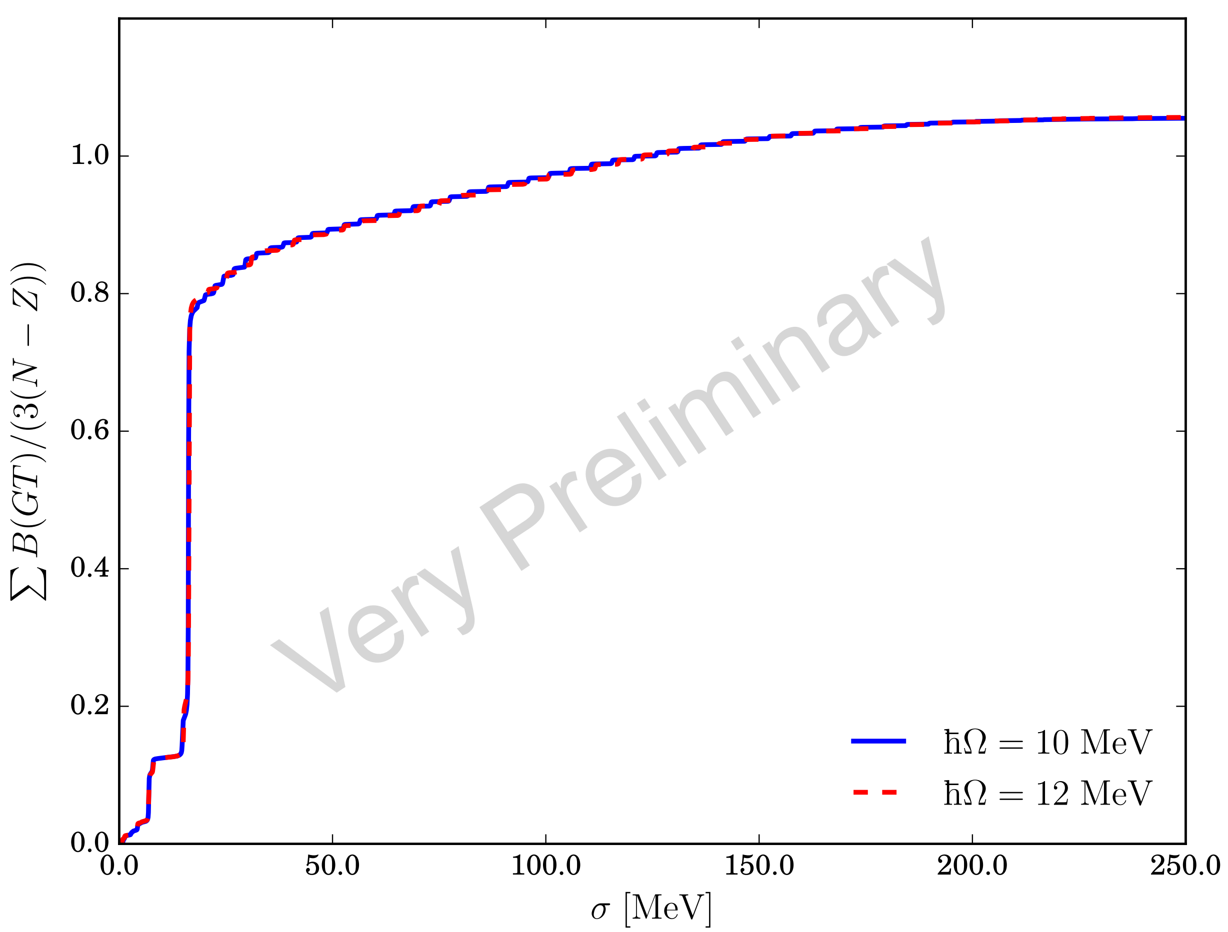
Calculations by M.Miorelli, 2017

If stable at small Γ, then do not need to invert → *LIT with variable width*

0.5 at low energy and 1 MeV at higher energy

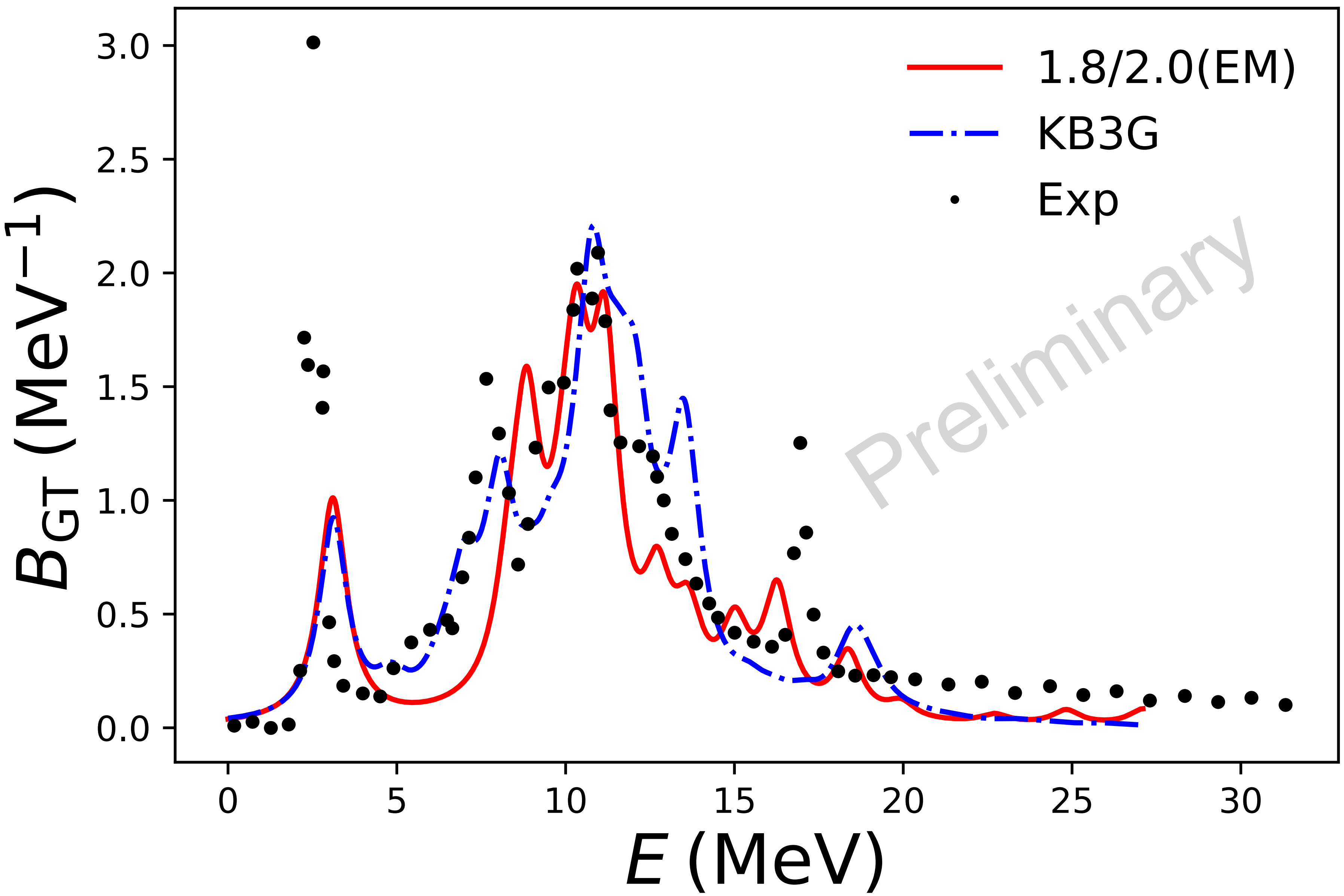


Running sum rules



Gamow-Teller strength in ^{48}Ca

Calculations by S.Novario, 2019



D/T-1, no 2BC
Discretized strength, folded with a Lorentzian of 0.5 MeV

Outlook

- Remarkable progress in first principle calculations of electromagnetic reactions; the theoretical progress is key to guide and support major experimental efforts

- Much of what we have developed in the electromagnetic sector can be used also for the weak sector.
  See Bijaya Acharya's talk about our plans for electron and neutrino scattering.

Thanks to all my collaborators

B. Acharya, N. Barnea, G. Hagen, **M. Miorelli**, **S.Novario**, G. Orlandini, T. Papenbrock, **J. Simonis**, A. Schwenk, and many more

Thanks for your attention!