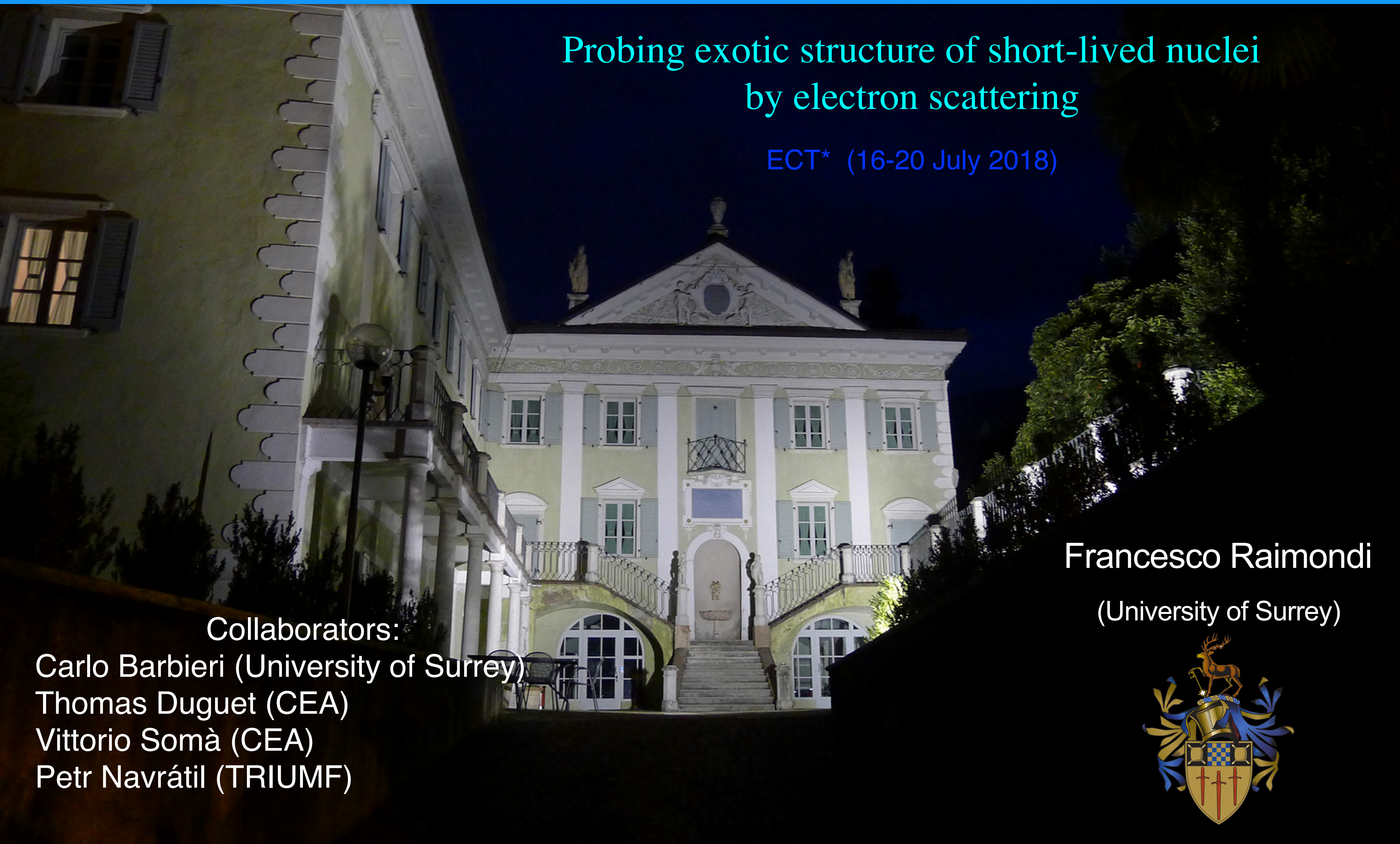
Nuclear dipole photoabsorption cross section and polarizability in the Self-Consistent Green's Function approach



Probing exotic structure of short-lived nuclei by electron scattering

ECT* (16-20 July 2018)

Francesco Raimondi

(University of Surrey)

Collaborators:
Carlo Barbieri (University of Surrey)
Thomas Duguet (CEA)
Vittorio Somà (CEA)
Petr Navrátil (TRIUMF)

Outline

- Self-consistent Green's function (SCGF) method
  - Non-perturbative treatment
  - Three-nucleon interactions
- Dipole Response Function and Polarisability in medium mass nuclei
  - ^{14}O, ^{16}O, ^{22}O and ^{24}O
  - ^{36}Ca, ^{40}Ca, ^{48}Ca and ^{54}Ca
  - ^{68}Ni

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  - ^{68}Ni

Electromagnetic response in SCGF

OBSERVABLES

$$\sigma_\gamma(E) = 4\pi^2 \alpha E\, R(E)$$ PHOTOABSORPTION CROSS SECTION

$$\alpha_D = 2\alpha \int dE\, \frac{R(E)}{E}$$ ELECTRIC DIPOLE POLARIZABILITY

Response $R(E)$ depends on excited states of the nuclear system, when "probed" with dipole operator $\hat{D}$

$$R(E) = \sum_\nu |<\psi_\nu^A|\hat{D}|\psi_0^A>|^2\, \delta_{E_\nu, E}$$

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$$\sum_{ab} <a|\hat{D}|b> <\psi_\nu^A|c_a^\dagger c_b|\psi_0^A>$$

s.p. matrix element of the dipole one-body operator

Nuclear structure component: Transition density matrix

Polarization propagator and Bethe-Salpeter equation

$$\Pi_{\gamma\delta,\alpha\beta}(\omega) = \sum_n \frac{< \Psi_0^A | a_\delta^\dagger a_\gamma | \Psi_n^A > < \Psi_n^A | a_\alpha^\dagger a_\beta | \Psi_0^A >}{\hbar\omega - (E_n^A - E_0^A) + \mathrm{i}\eta}$$

Two-body Propagator

$$\epsilon_n^\pi \equiv E_n^A - E_0^A$$

Energies of the excited states of the A-nucleon system

Equation for the polarization propagator

$$\Pi_{\gamma\delta,\alpha\beta}(\omega) = \Pi^f_{\gamma\delta,\alpha\beta}(\omega) + \Pi^f_{\gamma\delta,\mu\rho}(\omega) K^{(p-h)}_{\mu\sigma,\rho\nu}(\omega) \Pi_{\nu\sigma,\alpha\beta}(\omega)$$

Free polarization Propagator

p-h kernel

Approximated solution of the Bethe-Salpeter equation

$$\Pi_{\gamma\delta,\alpha\beta}(\omega) = \Pi^f_{\gamma\delta,\alpha\beta}(\omega) + \Pi^f_{\gamma\delta,\mu\rho}(\omega) K^{(p-h)}_{\mu\sigma,\rho\nu}(\omega) \Pi_{\nu\sigma,\alpha\beta}(\omega)$$

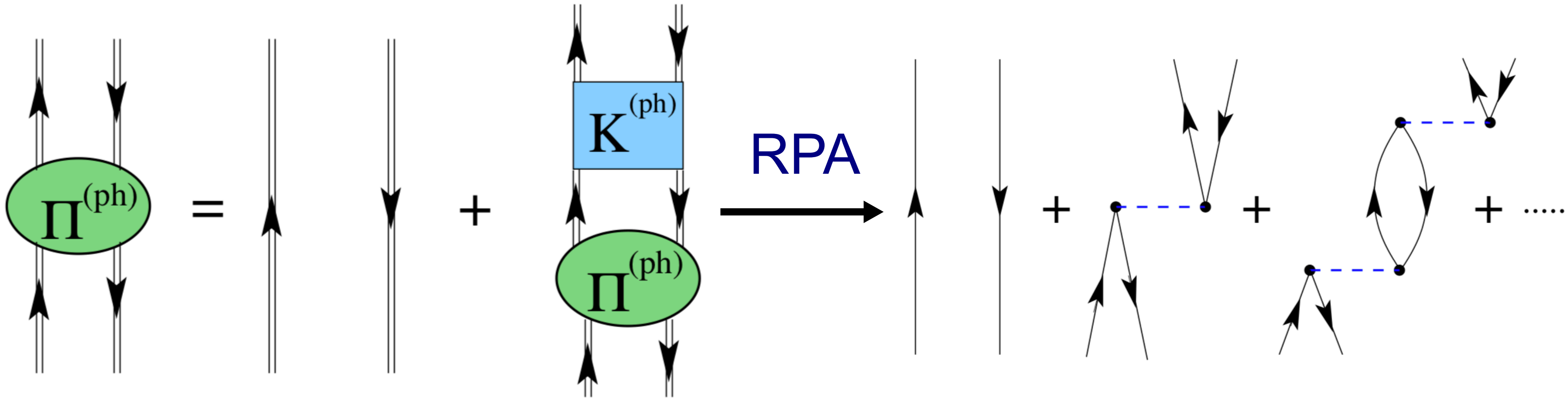


Fig. from PRC 68, 014311 (2003)

Extension of the RPA: 1) Fully-dressed (correlated) single-particle propagator in the RPA diagrams

C. Barbieri, W. Dickhoff PRC 68, 014311 (2003)

2) Reduction of the number of poles of the dressed propagator

C. Barbieri, M. Hjorth-Jensen PRC 79, 064313 (2009)

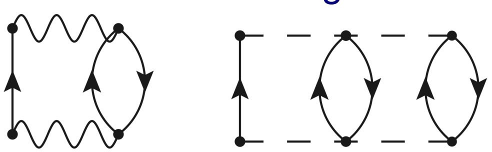
Self-energy and Dyson equation

$$G_{\alpha\beta}(\omega) = G^{(0)}_{\alpha\beta}(\omega) + \sum_{\gamma\delta} G^{(0)}_{\alpha\gamma}(\omega)\Sigma^{\star}_{\gamma\delta}(\omega) G_{\delta\beta}(\omega)$$

Self-energy: effective potential affecting the s.p. propagation in the nuclear medium

- Post-Hartree-Fock method based on self-consistency
- Based on realistic 2N and 3N forces
- Expansion of self-energy in Feynman diagrams
- Non-perturbative resummation of the correlations.

Second Order diagrams



(a) (b)

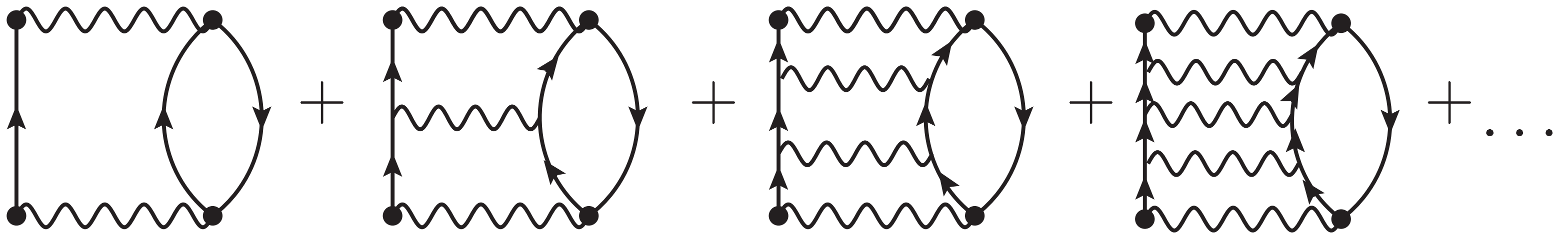
Algebraic Diagrammatic Construction (ADC(n))

J. Schirmer and collaborators:
Phys. Rev. A26, 2395 (1982)
Phys. Rev. A28, 1237 (1983)

Dyson ADC(n)

Self-energy expansion is treated NON-perturbatively:

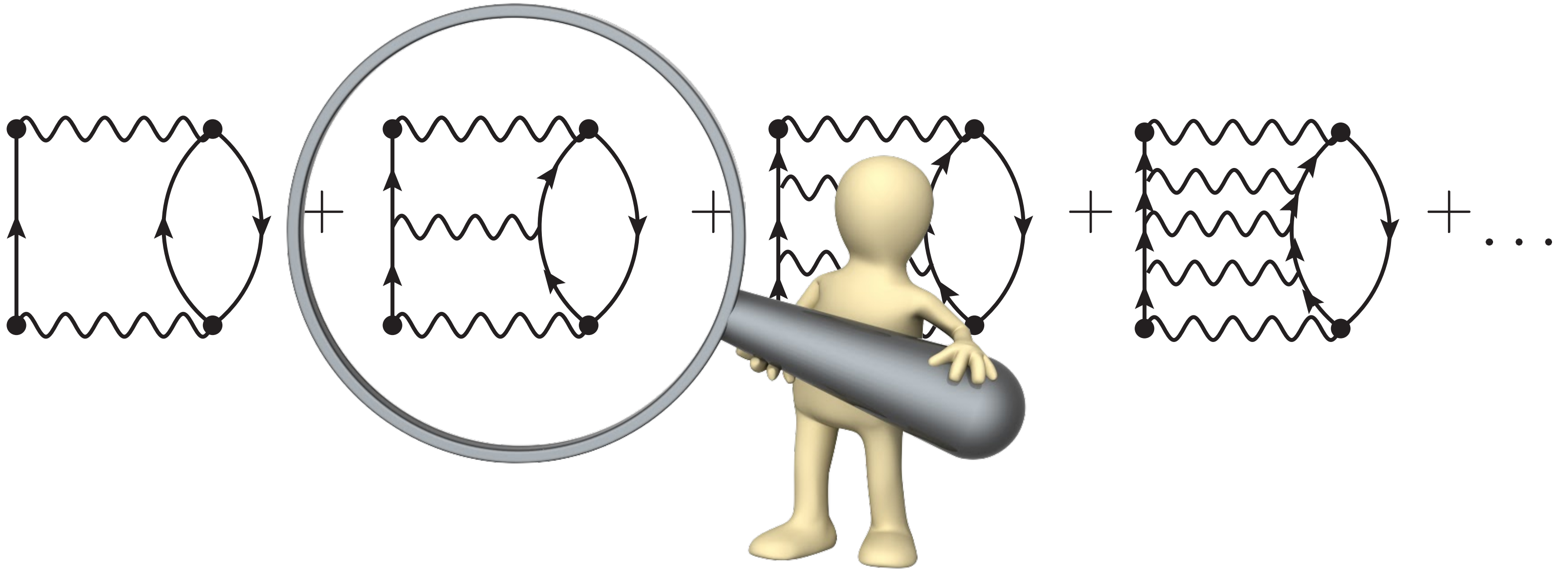
Entire classes of self-energy diagrams (ladder and ring) are summed at infinite order by means of a geometric series



Dyson ADC(3)

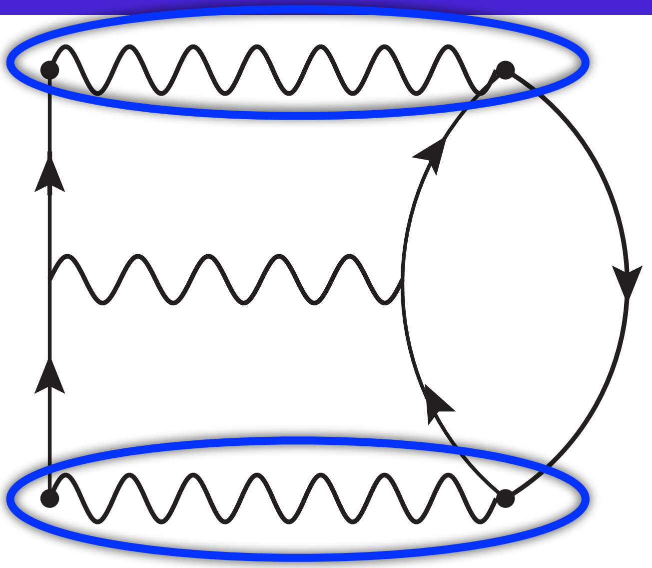
Self-energy expansion is treated NON-perturbatively:

Entire classes of self-energy diagrams (ladder and ring) are summed at infinite order by means of a geometric series



Dyson ADC(3)

M: matrices coupling the single-particle propagator to more complex intermediate configurations



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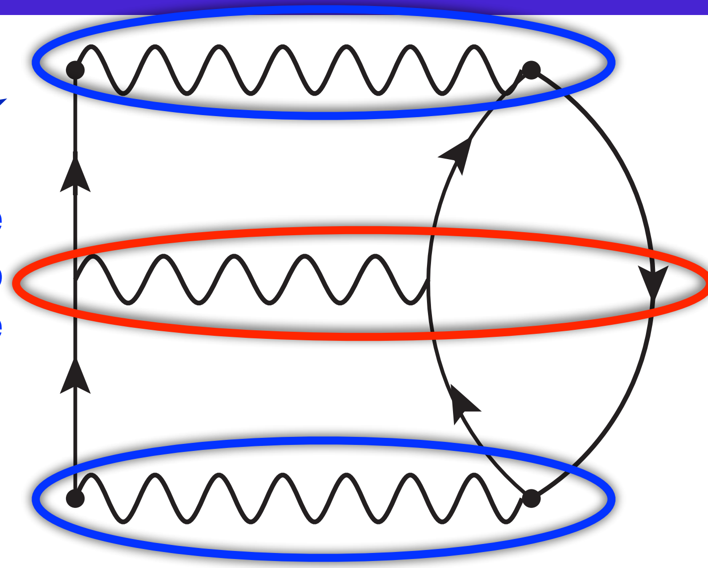
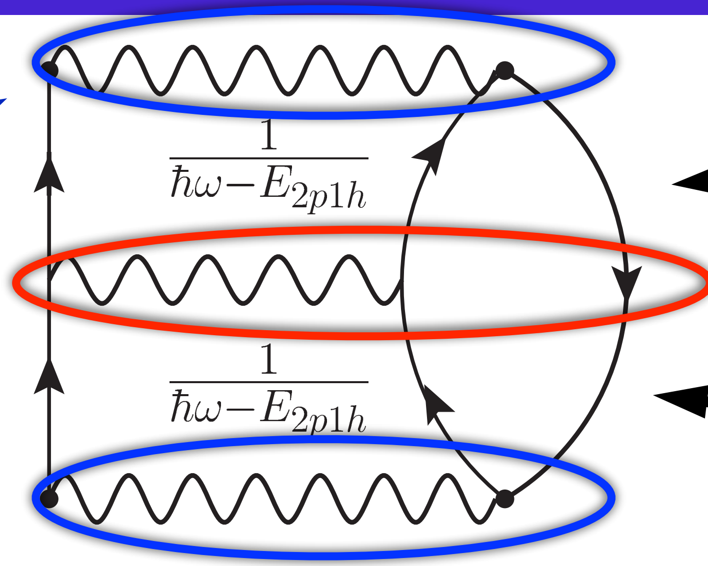


C: interaction matrix linked only to internal fermion lines

Dyson ADC(3)



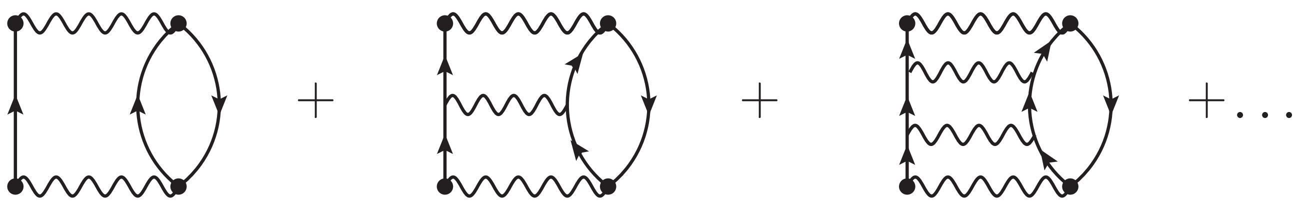
M: matrices coupling the single-particle propagator to more complex intermediate configurations

Propagator (intermediate state configurations)

C: interaction matrix linked only to internal fermion lines

Propagator (intermediate state configurations)

The set of ladder diagrams is a geometric series



$$\mathcal{M}^\dagger \frac{1}{\hbar\omega - E_{2p1h}} \mathcal{M} + \mathcal{M}^\dagger \frac{1}{\hbar\omega - E_{2p1h}} \mathcal{C} \frac{1}{\hbar\omega - E_{2p1h}} \mathcal{M} + \mathcal{M}^\dagger \frac{1}{\hbar\omega - E_{2p1h}} \mathcal{C} \frac{1}{\hbar\omega - E_{2p1h}} \mathcal{C} \frac{1}{\hbar\omega - E_{2p1h}} \mathcal{M}$$

Sum

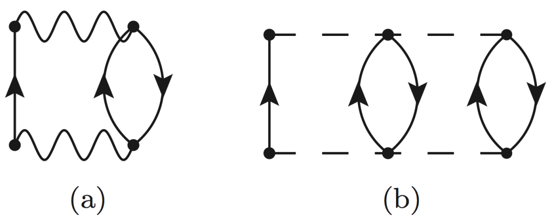
$$\mathcal{M}^\dagger \frac{1}{\hbar\omega - E_{2p1h} - \mathcal{C}} \mathcal{M}$$

Interaction-irreducible Self-Energy with NN and 3NFs

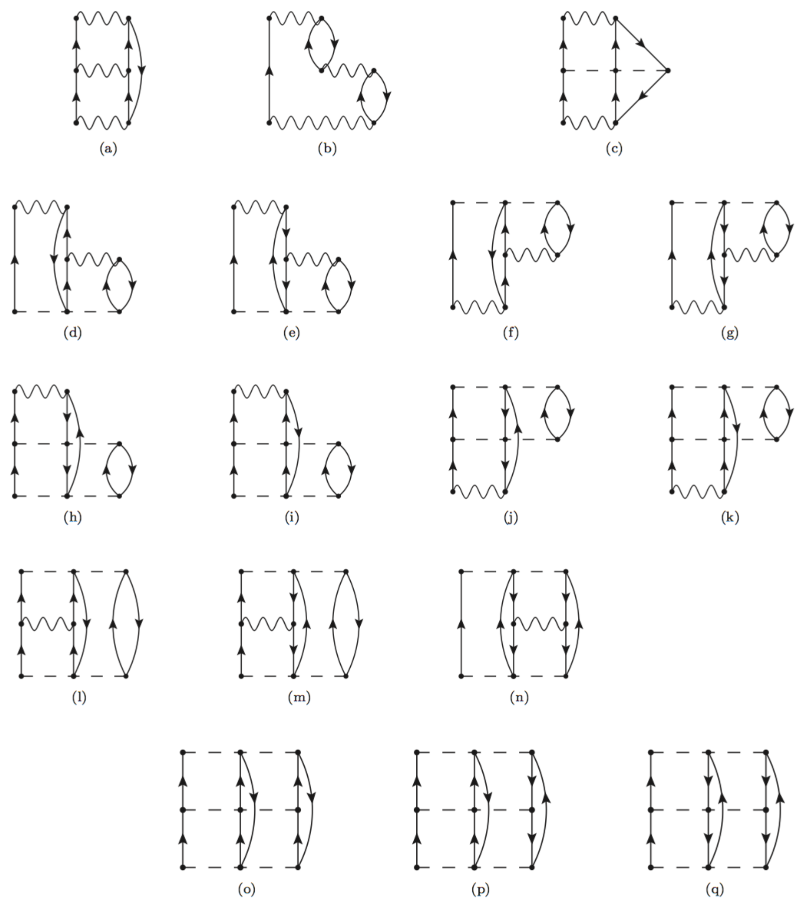
ADC(2) (≠ 2nd order)

ADC(3) (≠ 3rd order)

Second-order diagrams with NN and 3N forces



Third-order diagrams with NN and 3N forces



Complete set of ADC(3) working equations in
FR, C. Barbieri
Phys Rev C **97**, 054308 (2018)

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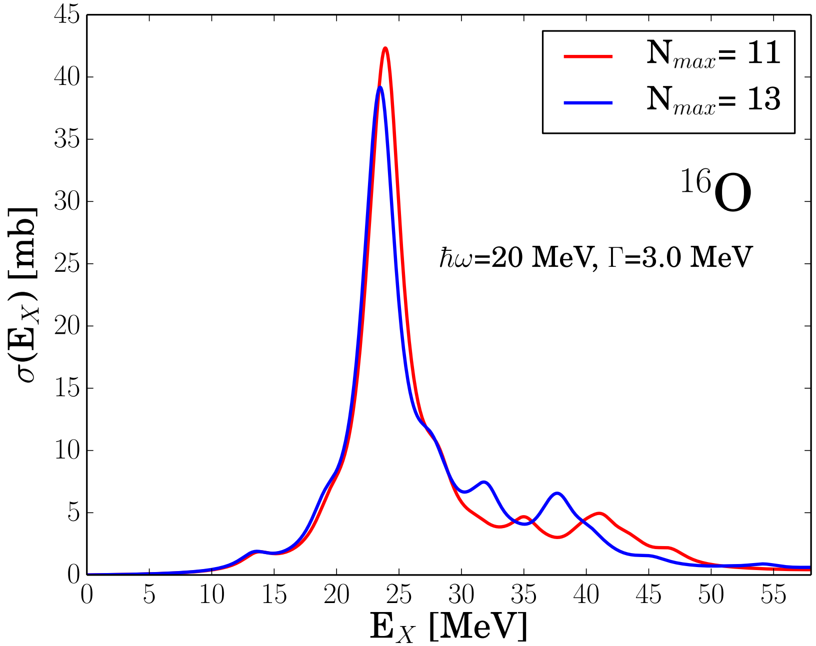
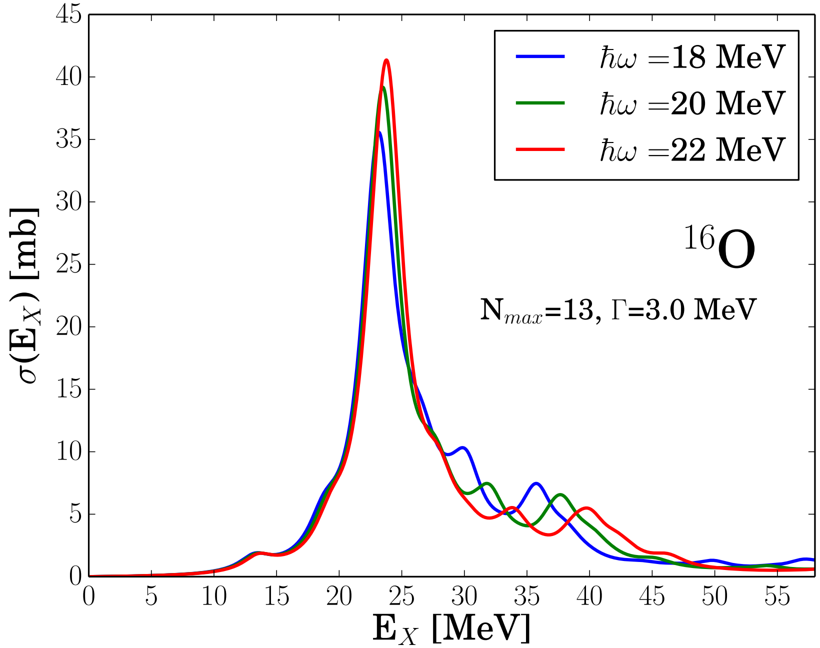
Features of the calculation

- NN and 3N nuclear interaction NNLO$_{sat}$ (Phys. Rev. C 91, 051301(R))
- Electric dipole operator E1 $\hat{\mathcal{Q}}^{T=1}_{1m} = \frac{N}{N+Z}\sum_{p=1}^{Z} r_p Y_{1m} - \frac{Z}{N+Z}\sum_{n=1}^{N} r_n Y_{1m}$
- Single-particle harmonic oscillator basis (N$_{max}$, $\hbar\omega$)

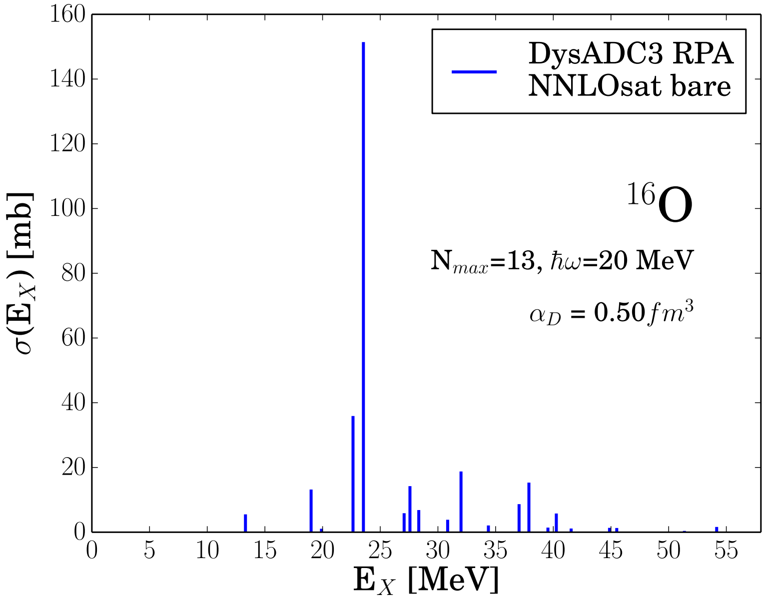


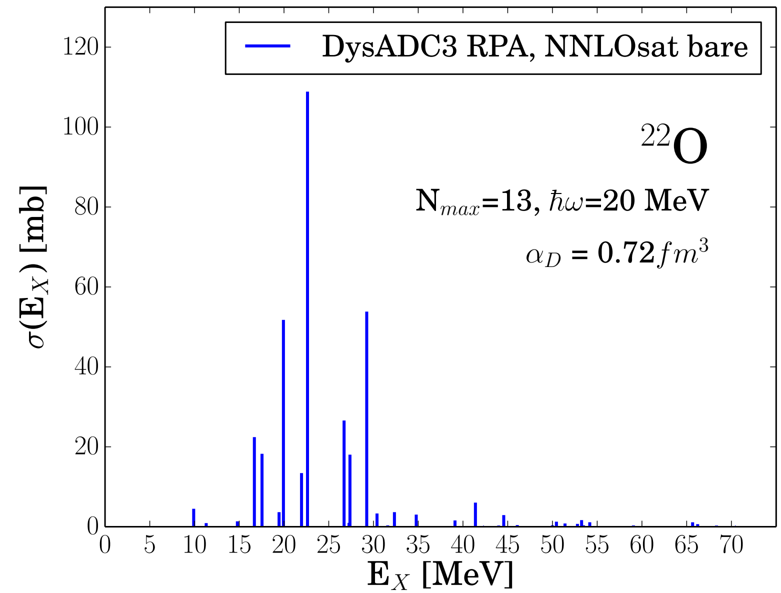
δ(α$_D$, N$_{max}$)=2%

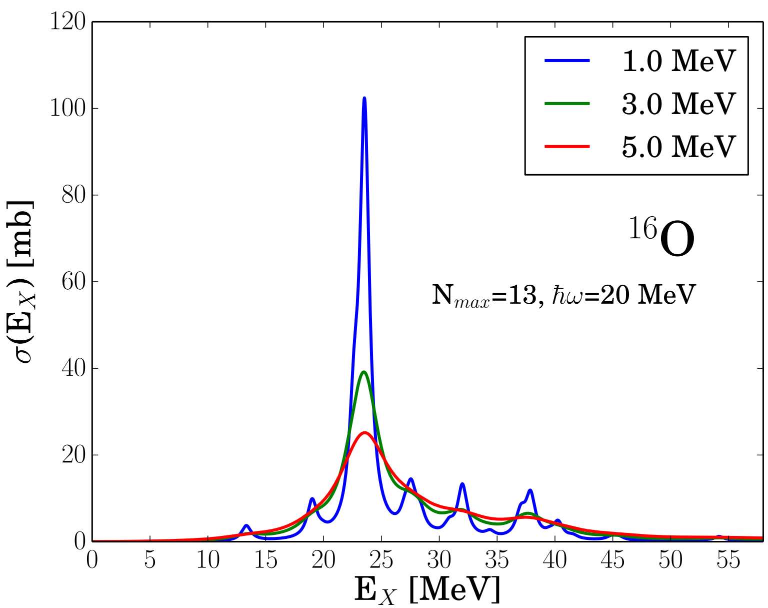


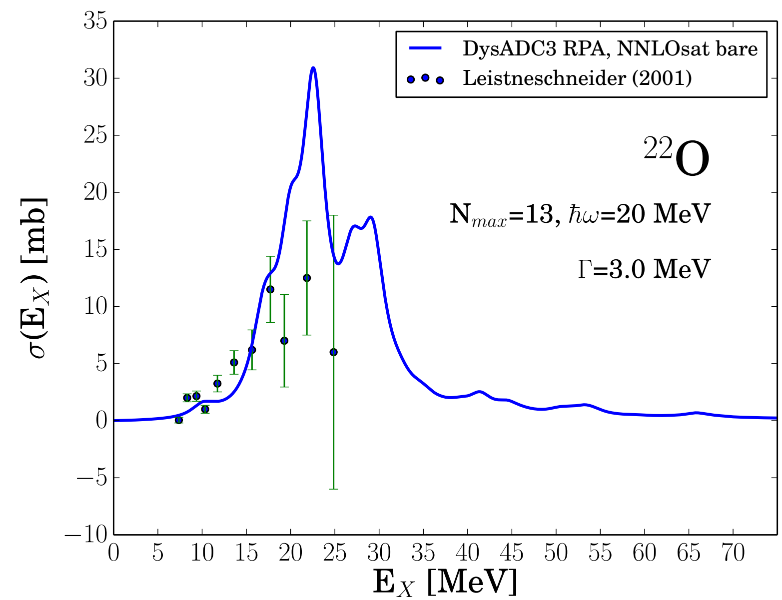
δ(α$_D$, $\hbar\omega$)=1.5%

Discrete vs convoluted photoabsorption σ

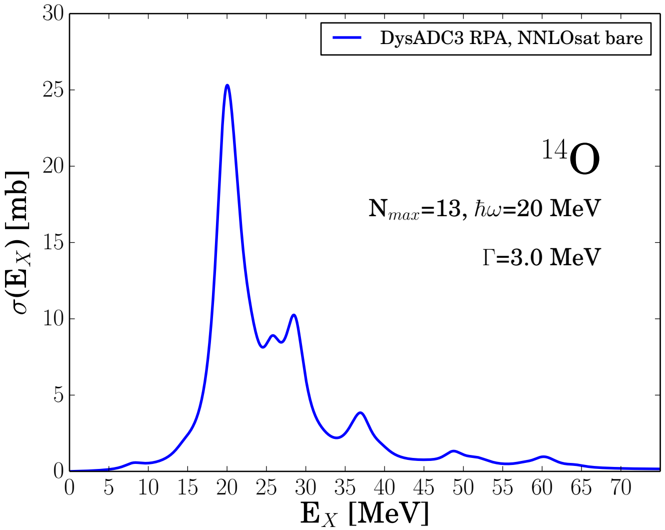


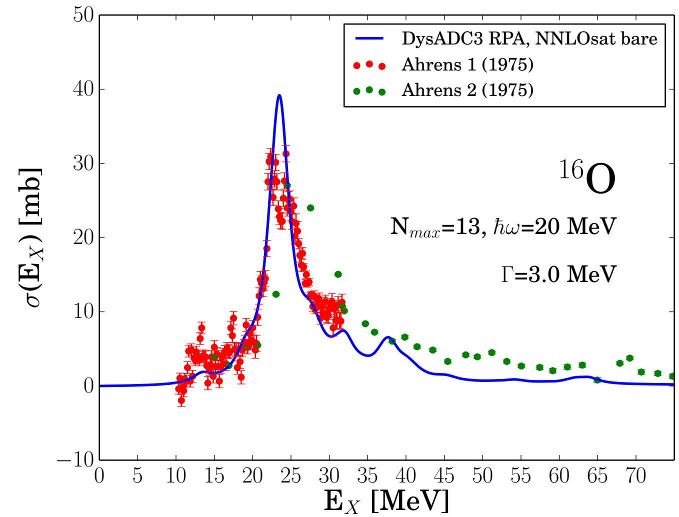


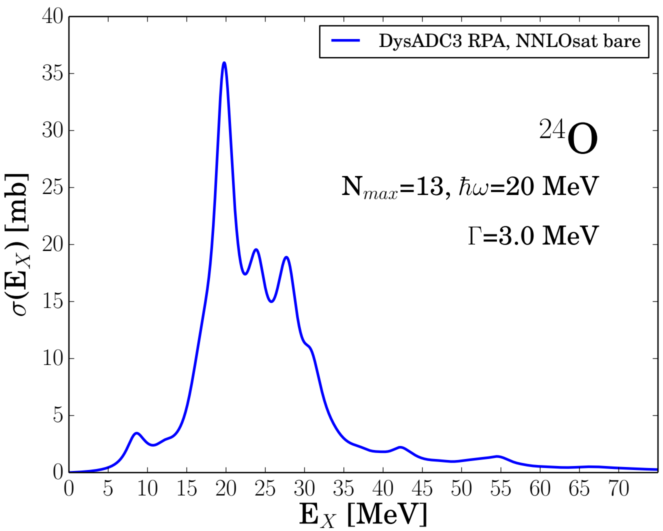


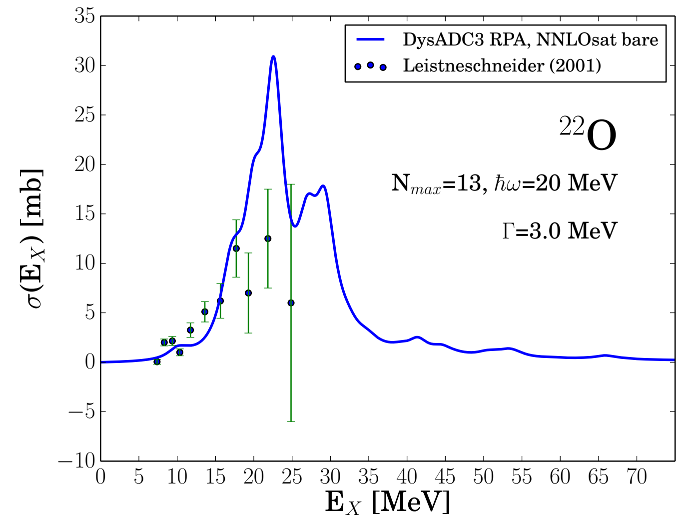


Results for Oxygen isotopes









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

- GDR position of ^{16}O reproduced
- Hint of a soft dipole mode on the neutron-rich isotope

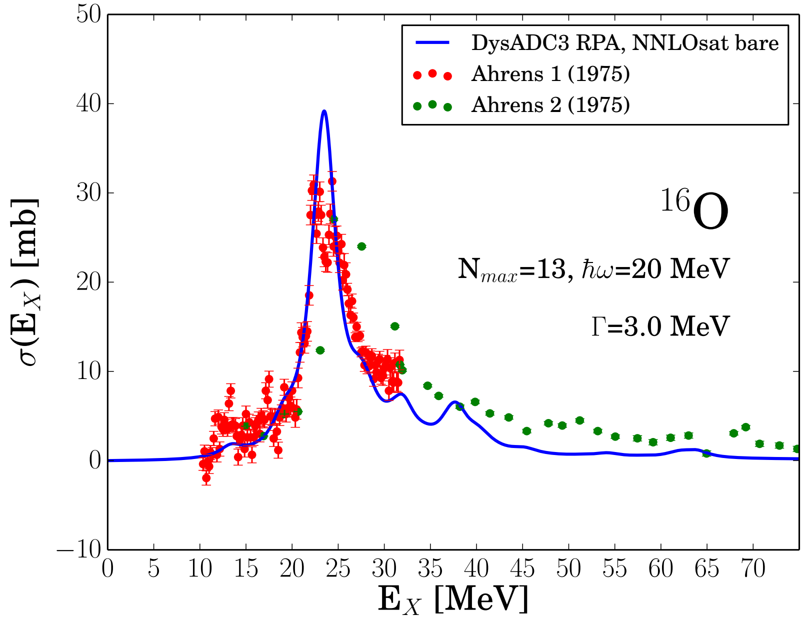
Polarizability in ^{16}O and ^{22}O

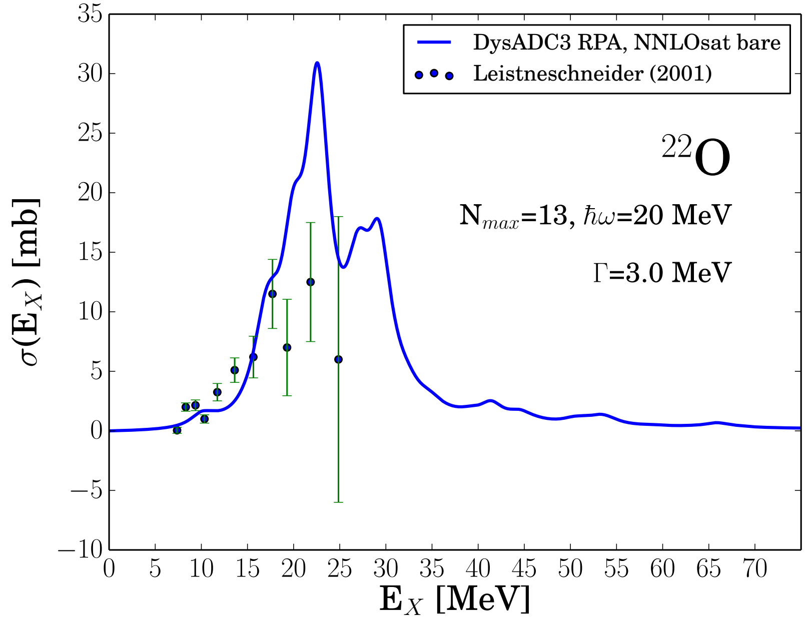
$$\alpha_D = 2\alpha \int dE \, \frac{R(E)}{E}$$

α_D (fm³)	*Exp*	*SCGF*	*CC-LIT*
^{16}O	***0.585(9)***	***0.50***	***0.57(1)*** * ***0.528*** **
^{22}O	***0.43(4)***	***0.72***	***0.86(4)*** * ***na*** **

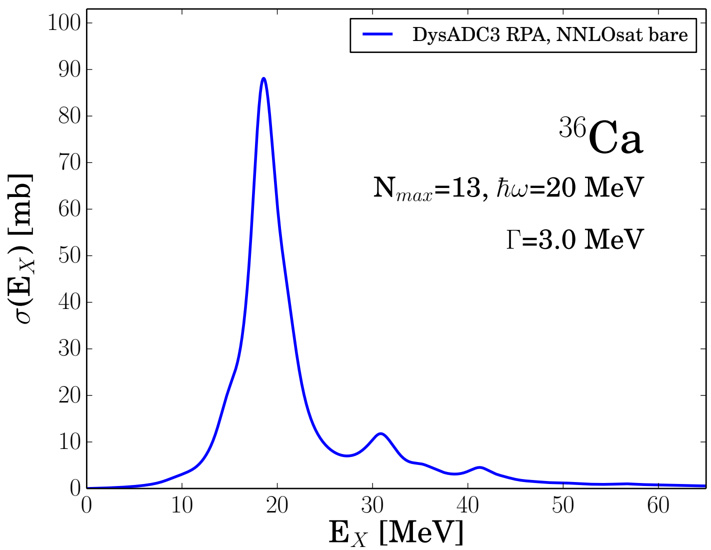
$\delta(\alpha_D$, th-exp$) \simeq 15\%$

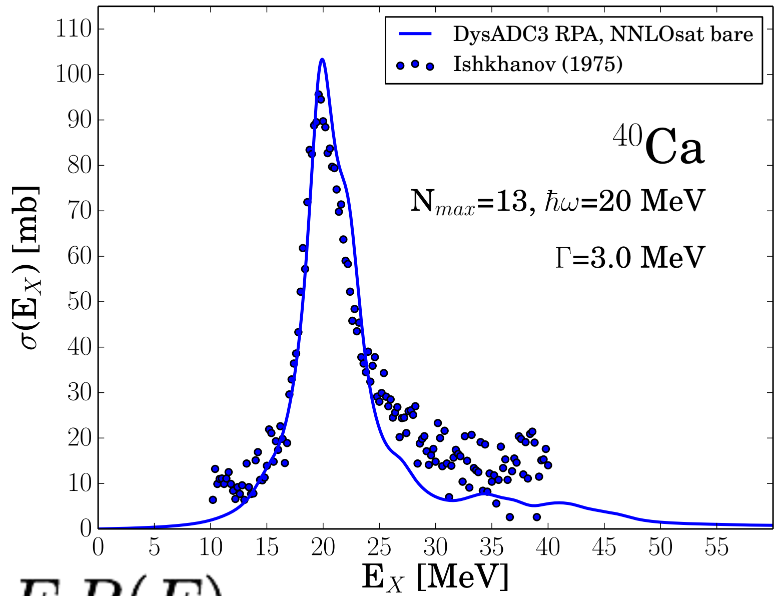
Coupled-Cluster + LIT
M. Miorelli et al arXiv:1804.01718:
* Doubles/Doubles. ** Triples/Triples



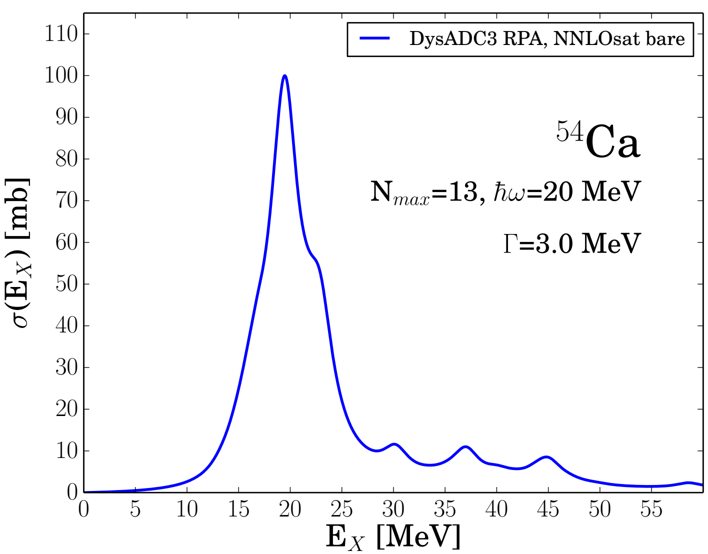


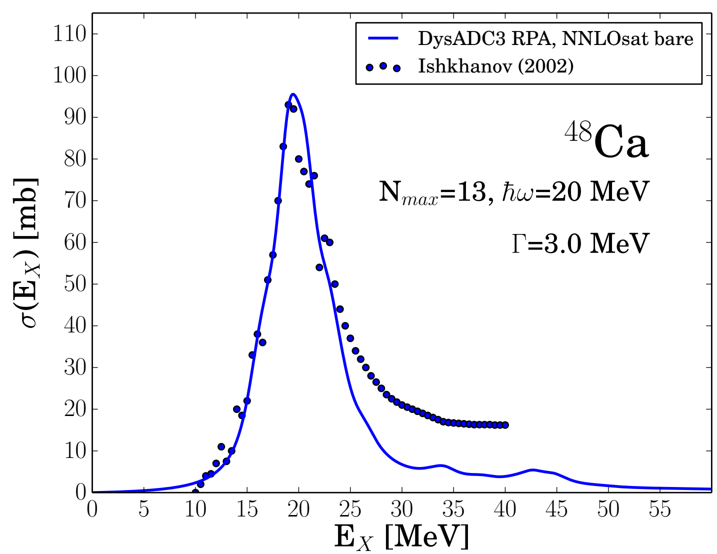
Results for Calcium isotopes





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



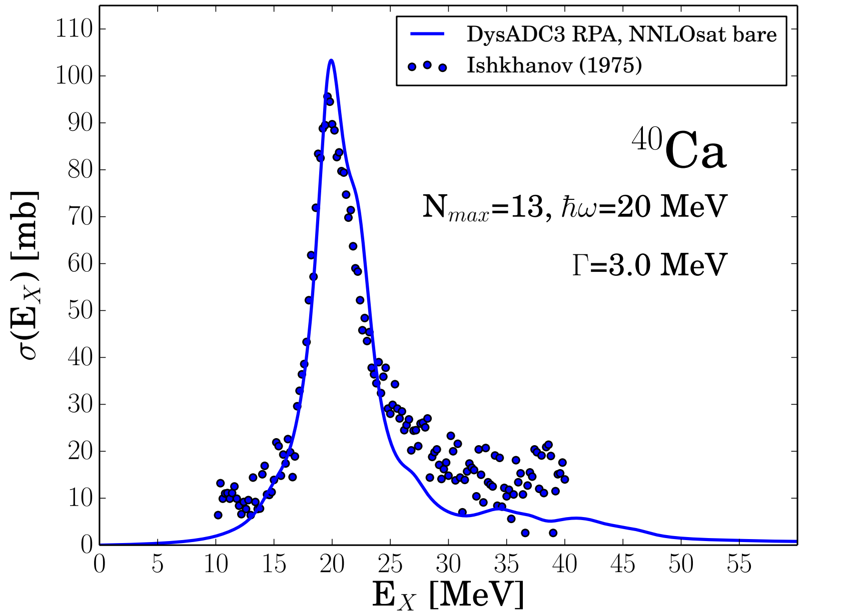


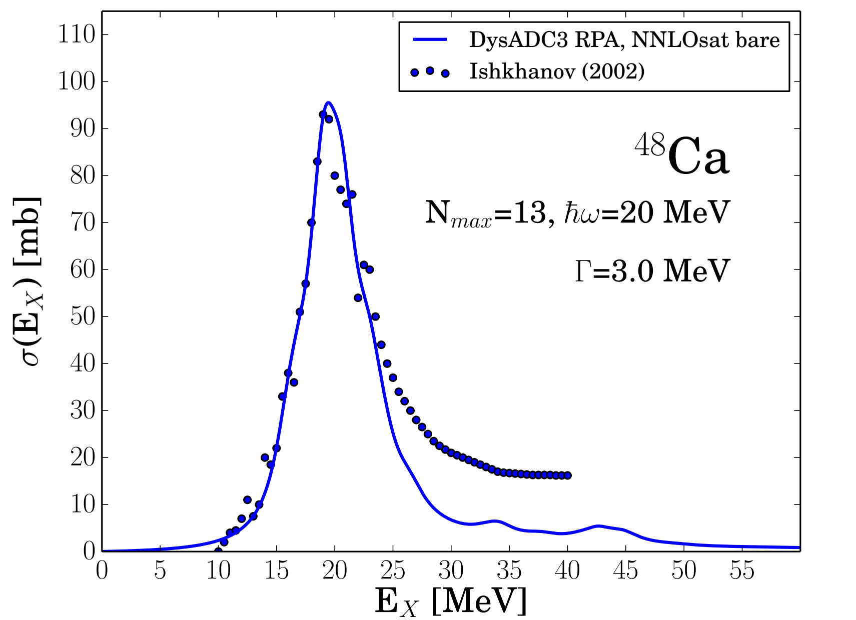
Polarizability in ^{40}Ca and ^{48}Ca

$$\alpha_D = 2\alpha \int dE \, \frac{R(E)}{E}$$

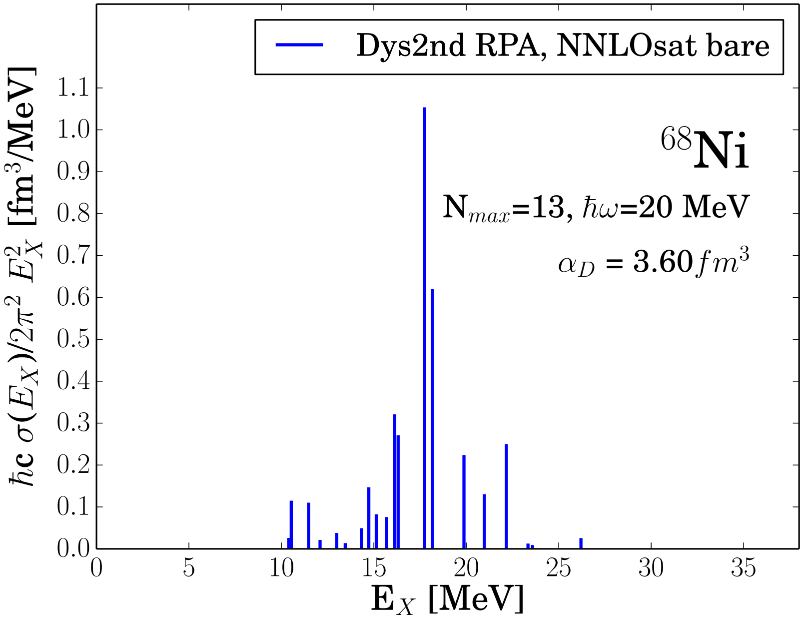
α_D (fm^3)	Exp	SCGF	CC-LIT
^{40}Ca	2.23(3)	1.79	1.87(3) * na **
^{48}Ca	2.07(22) (Birkhan et al)	2.06	2.45 * 2.25(8)**

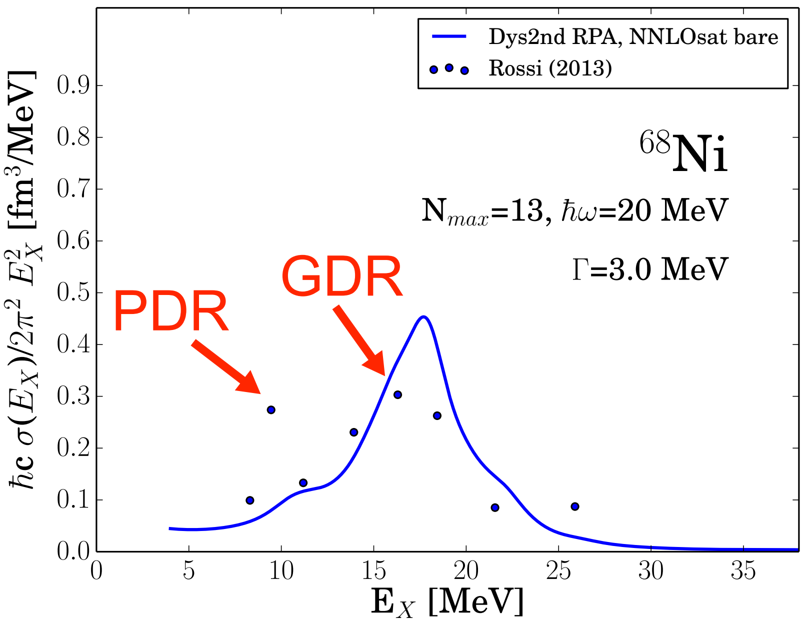
Coupled-Cluster + LIT
M. Miorelli et al arXiv:1804.01718:
* Doubles/Doubles. ** Triples/Triples





Results for ^{68}Ni





Comparison with experimental Coulomb excitation

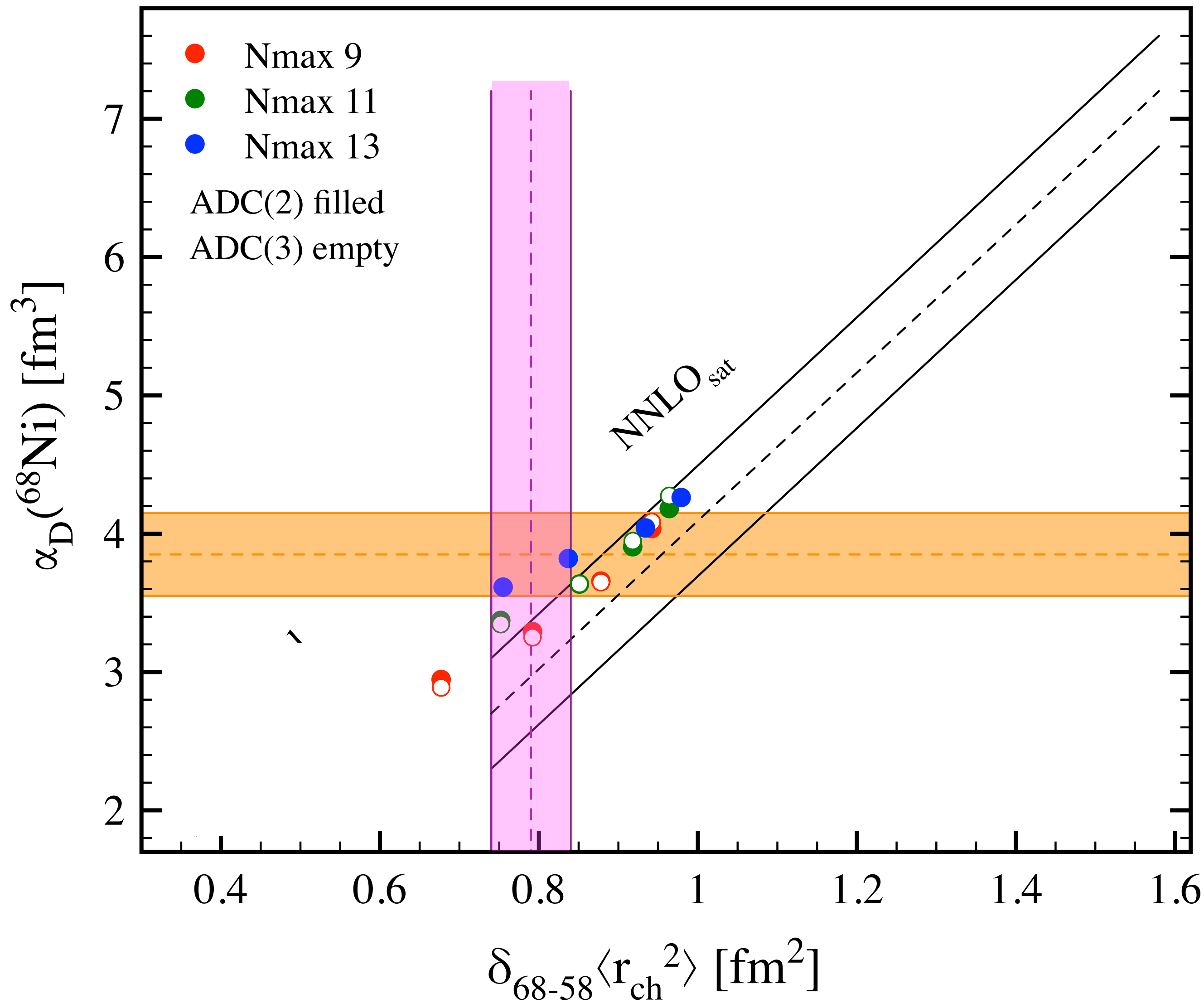
(Rossi *et al* PRL, 111, 242503 (2013))

	Exp	*SCGF*
Pigmy (MeV)	9.55(17)	10.53 11.47
Giant (MeV)	17.1(2)	17.75
α_D (fm^3)	3.88(31)	3.60

$\delta(\alpha_D$, th-exp$) \simeq 7\%$

α_D-isotopic shift correlation line for ^{68}Ni

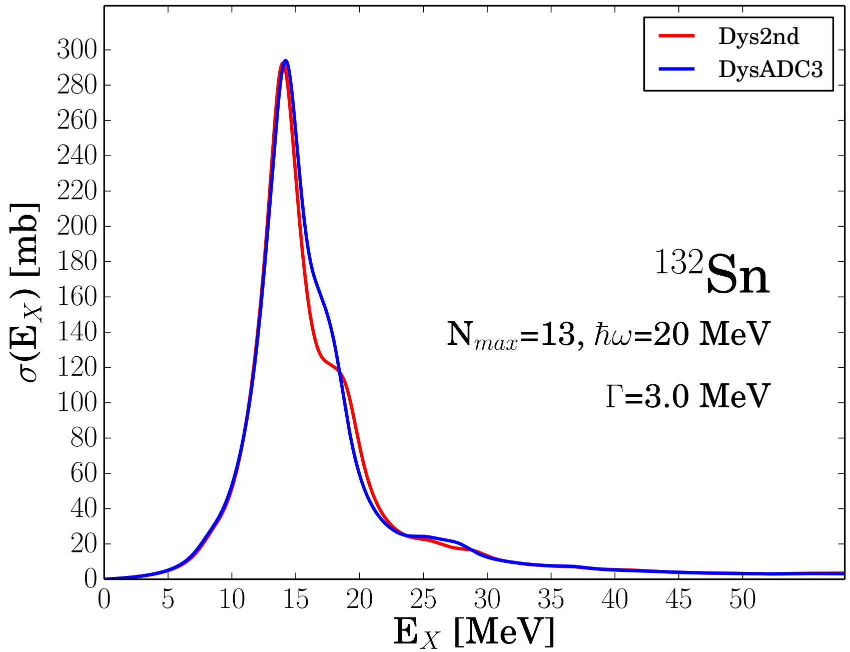
COLLAPS Collaboration (R. Garcia Ruiz talk's on Monday)



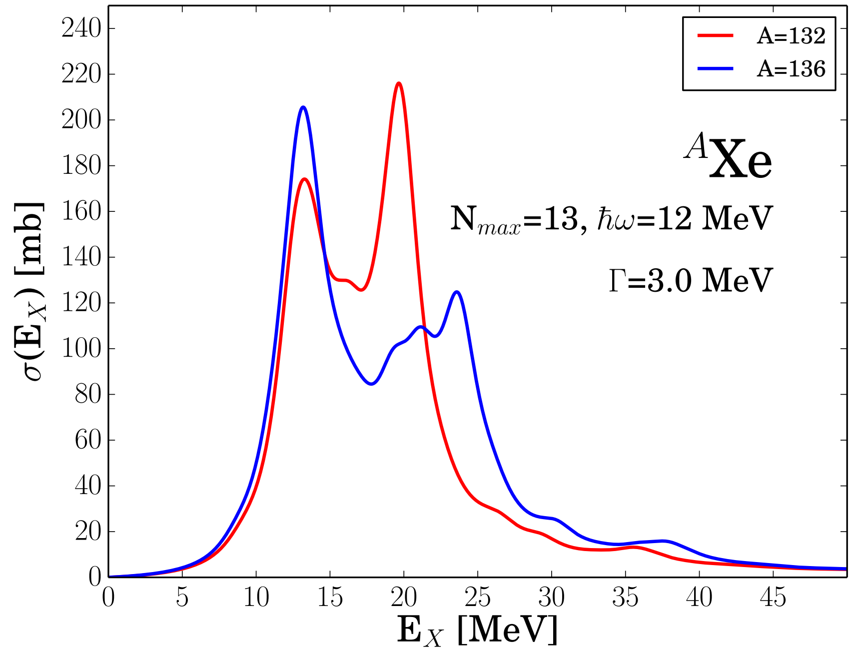
Rossi *et al*
PRL, 111, 242503 (2013)

Going to heavier nuclei: Sn and Xe

ADC(2) vs ADC(3) many-body truncation



Test case for SCRIT
(K. Tsukada's talk on Tuesday)

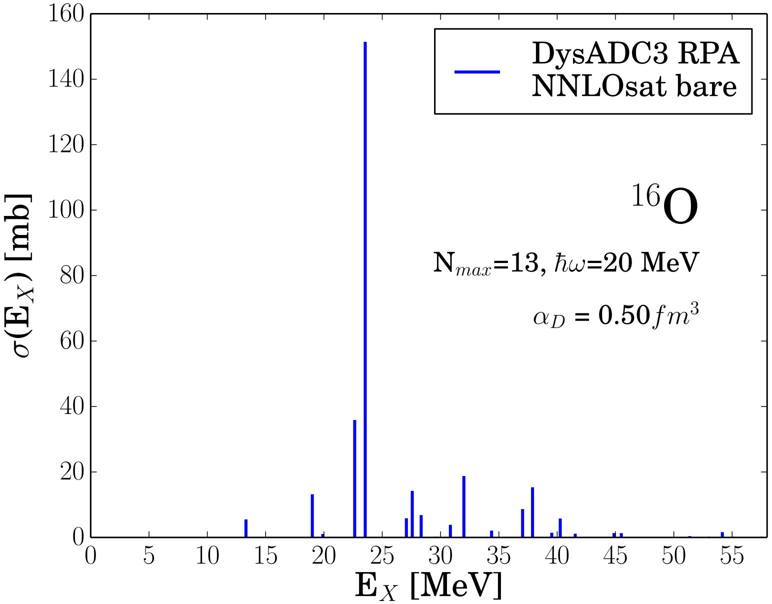


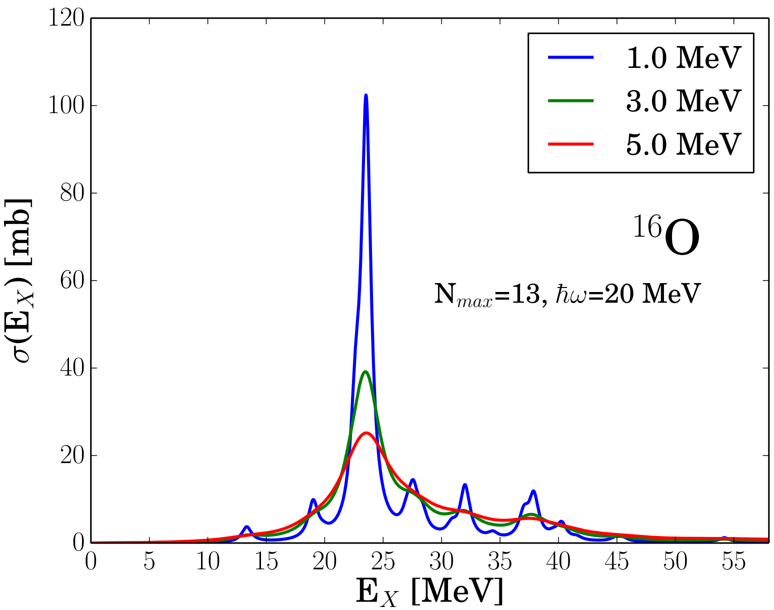
Conclusion and perspectives

- Dipole response and polarisability calculated from first principles
- Continuum to be included
- Correlations: going beyond 1st order RPA approximations

Backup slide

Discrete spectrum convolution



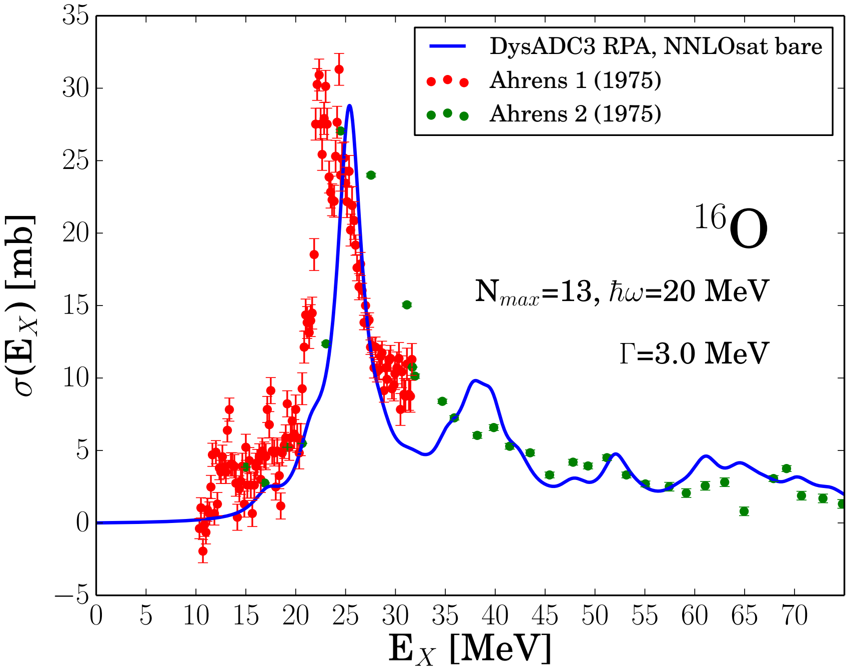


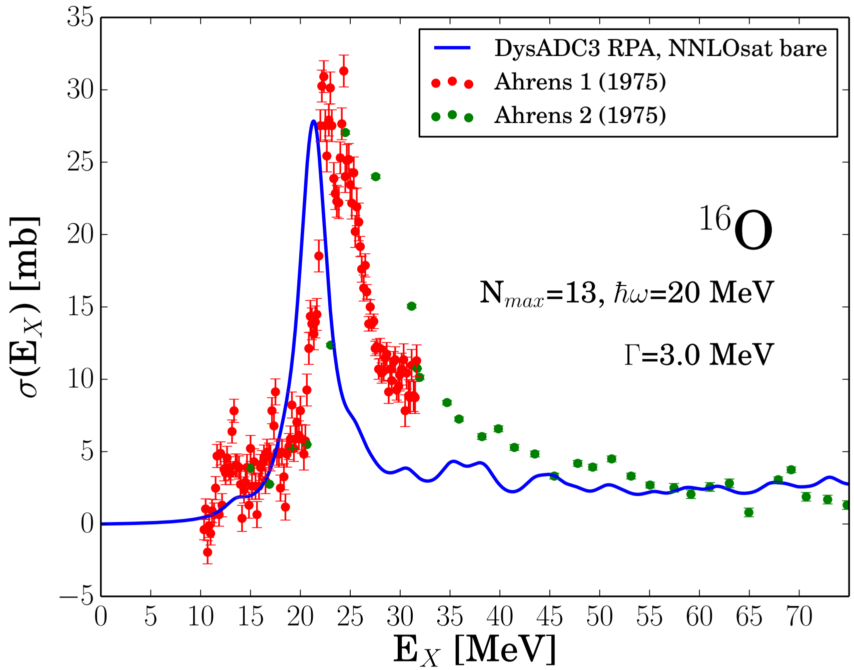
No treatment of the continuum

$$R_\Gamma(E) = \sum_n (\langle \Psi_n^A | \hat{\mathcal{Q}}_{1m}^{T=1} | \Psi_0^A \rangle)^2 \frac{\Gamma/2\pi}{(E_n^A - E)^2 + \Gamma^2/4}$$

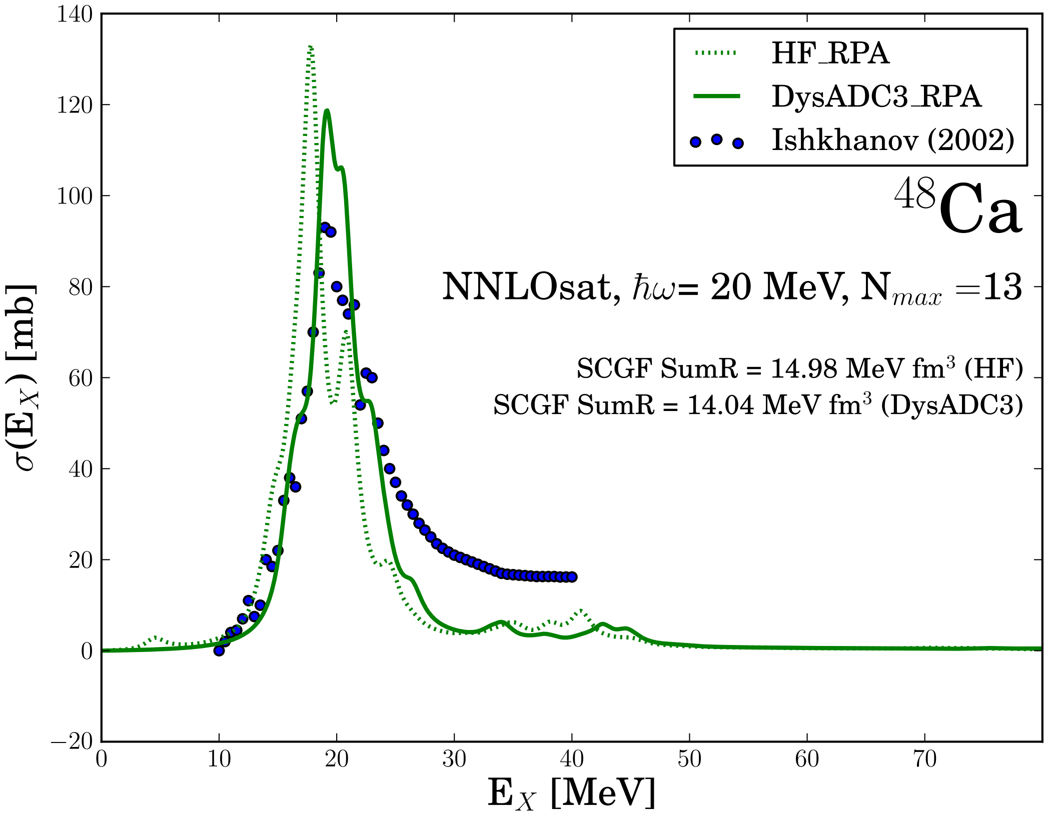
Γ width of the Lorentzian

Different reductions of the dressed propagator





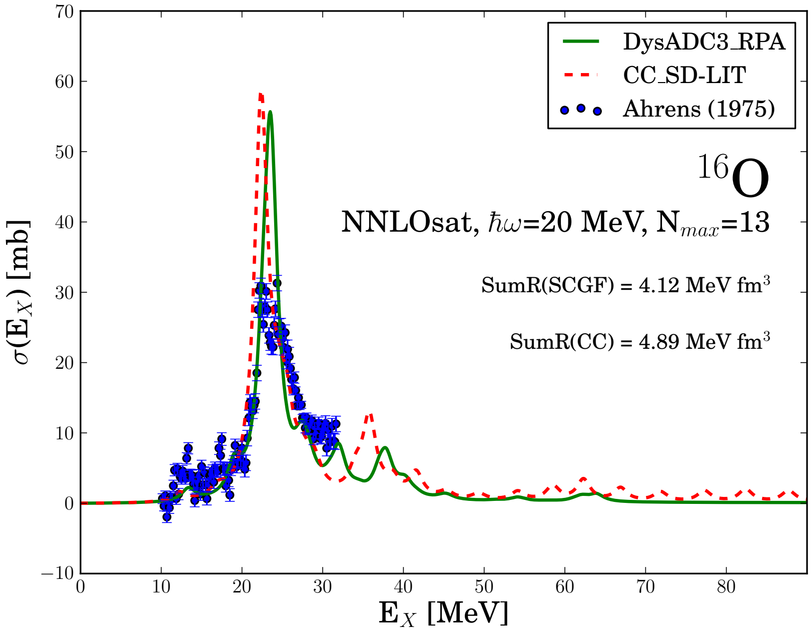
Role of the correlations included in the reference state

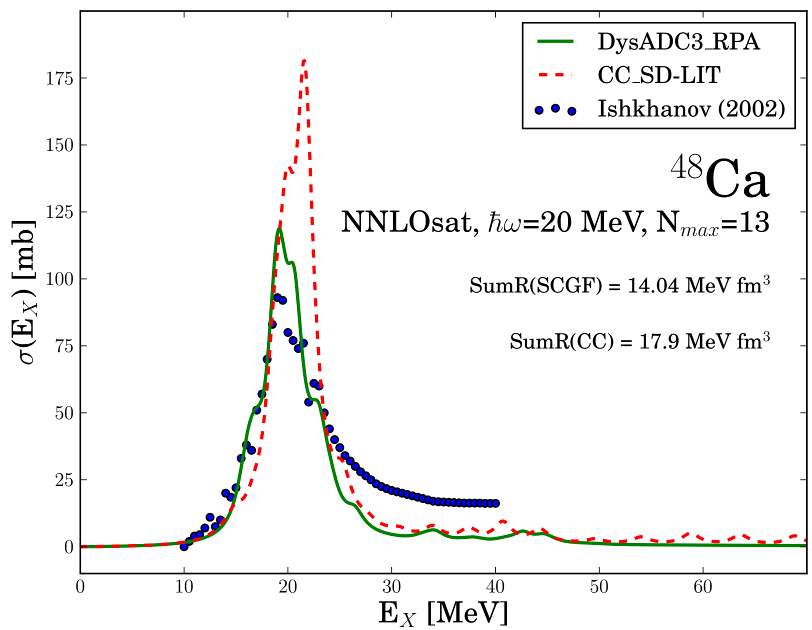


Role of correlations beyond Hartree-Fock expected to be important for other observables

Comparison with CC-LIT
(Couple Cluster- Lorentz Integral Transform method)

In collaboration with M. Miorelli and S. Bacca (TRIUMF, University of Mainz)





- CC-Singles-Doubles (analogous to 2nd RPA)
- LIT reduces a continuum state problem to a bound-state-like problem

Different treatment of the correlations:

SCGF	**CC-SD-LIT**
Reference state correlated	HF Reference state
RPA (first-order two-body correlator)	Singles-Doubles