Three-nucleon force correlations and electromagnetic response in finite nuclei with Self-Consistent Green's Functions

Cortona

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Collaborators:

Carlo Barbieri (University of Surrey)

Andrea Idini (University of Surrey)

Francesco Raimondi

(University of Surrey)

Outline

- Extension of the Algebraic Diagrammatic Construction (ADC) method with three-nucleon interactions
- Dipole Response Function and Polarisability in Oxygen and Calcium isotopes
- Effective charges in Oxygen and Nickel isotopes from realistic nuclear interactions

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Motivations: Role of 3N forces in nuclear phenomena

See C. Barbieri’s and T. Fukui's talks

Method: Self-consistent Green's function formalism

Green's functions for nuclear physics

W. Dickhoff, C. Barbieri, Prog. Part. Nucl. Phys. **52**, 377 (2004)
C. Barbieri, A. Carbone, Lectures notes in Phys., Vol. **936**, 571 (2017)

Microscopic nuclear Hamiltonian

$$\hat{H} = \sum_{\alpha} \varepsilon^0_\alpha \, a^\dagger_\alpha a_\alpha - \sum_{\alpha\beta} U_{\alpha\beta} \, a^\dagger_\alpha a_\beta + \frac{1}{4} \sum_{\substack{\alpha\gamma \\ \beta\delta}} V_{\alpha\gamma,\beta\delta} \, a^\dagger_\alpha a^\dagger_\gamma a_\delta a_\beta + \frac{1}{36} \sum_{\substack{\alpha\gamma\epsilon \\ \beta\delta\eta}} W_{\alpha\gamma\epsilon,\beta\delta\eta} \, a^\dagger_\alpha a^\dagger_\gamma a^\dagger_\epsilon a_\eta a_\delta a_\beta$$

Green's function (Lehmann representation)

$$g_{\alpha\beta}(\omega) = \sum_n \frac{\langle \Psi^A_0 | a_\alpha | \Psi^{A+1}_n \rangle \langle \Psi^{A+1}_n | a^\dagger_\beta | \Psi^A_0 \rangle}{\omega - \varepsilon^+_n + i\eta} + \sum_k \frac{\langle \Psi^A_0 | a^\dagger_\beta | \Psi^{A-1}_k \rangle \langle \Psi^{A-1}_k | a_\alpha | \Psi^A_0 \rangle}{\omega - \varepsilon^-_k - i\eta}$$

Dyson equation

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

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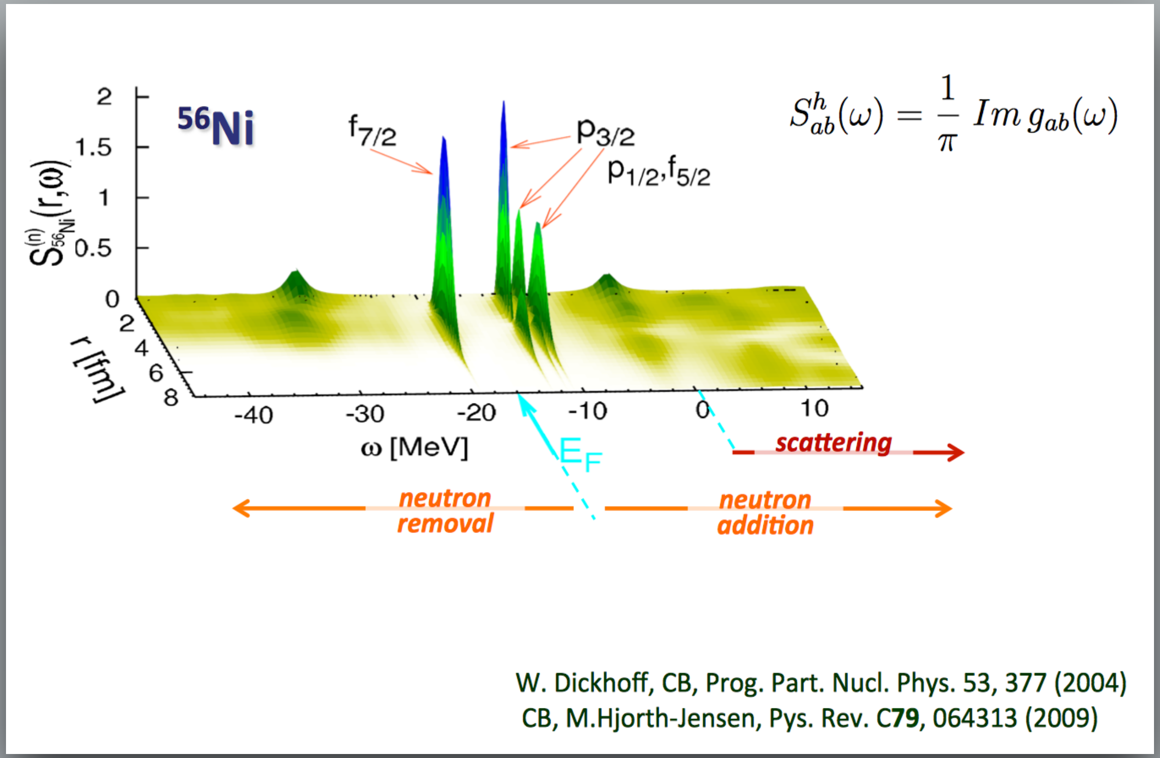
Gorkov formalism: C. Barbieri, T. Duguet, V. Somà

Green's functions for nuclear physics

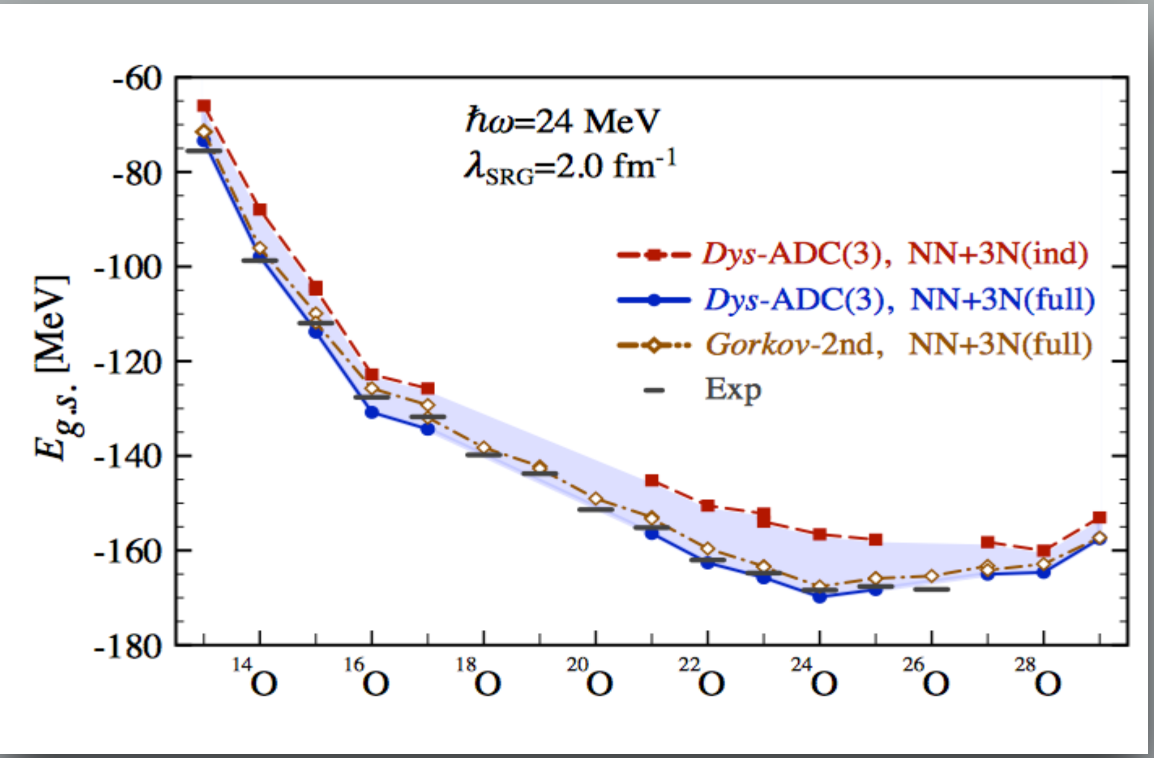
"What a nucleon does in the nucleus"

(i.e. in a strongly interacting many-fermions systems)?

Spectroscopic information (^{56}Ni)



Binding energies and driplines (O)



- Ground state properties
- Spectroscopic informations
- One- (two-, …) body operators matrix elements
- Optical potentials (A. Idini, C. Barbieri, Acta Phys. Pol. B **88**, 273 (2017))

Green's functions for nuclear physics

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

Inclusion of 3N forces via effective interactions

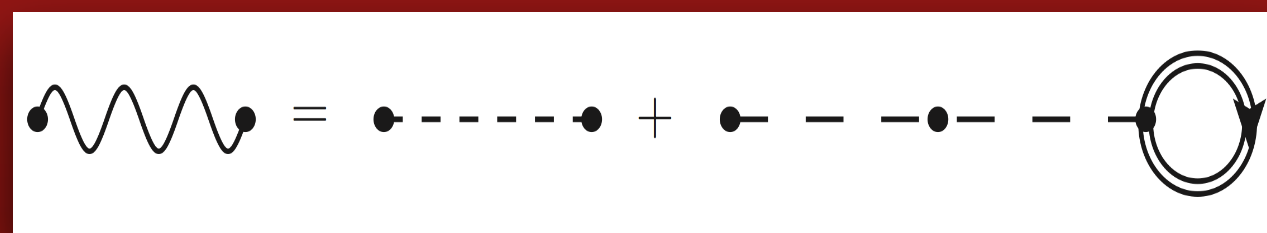
(A. Carbone et al, Phys. Rev. C **88** (2013) 054326)

With 3N forces, # of self-energy diagrams is too cumbersome…

BASIC IDEA:

Effective interaction concept generalises the HF approximation of the two-body forces to the N-body forces and with respect to the correlated propagator

Example of two-body effective interaction



$$\widetilde{V} = \frac{1}{4}\sum_{\substack{\alpha\gamma \\ \beta\delta}} \left[V_{\alpha\gamma,\beta\delta} - i\hbar \sum_{\epsilon\eta} W_{\alpha\gamma\epsilon,\beta\delta\eta}\, G_{\eta\epsilon}(t - t^{+}) \right] a^{\dagger}_{\alpha} a^{\dagger}_{\gamma} a_{\delta} a_{\beta}$$

Density matrices defined wrt correlated wave functions

$$\rho^{1B}_{\eta\epsilon}$$

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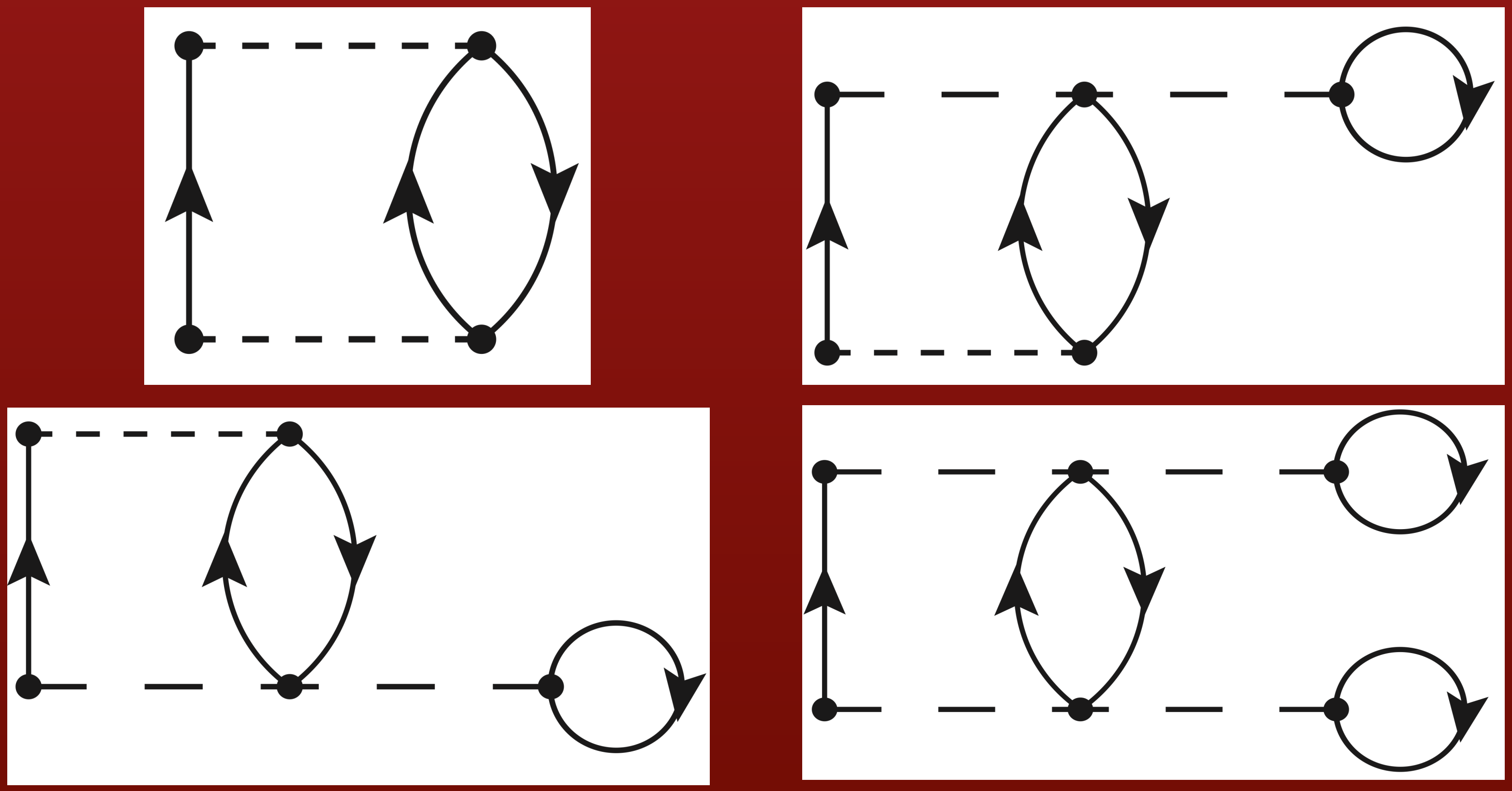
Example of diagram with effective interaction

Four interaction-reducible diagrams with 2N and 3N



Fermions (solid lines)

Interactions (dashed lines)

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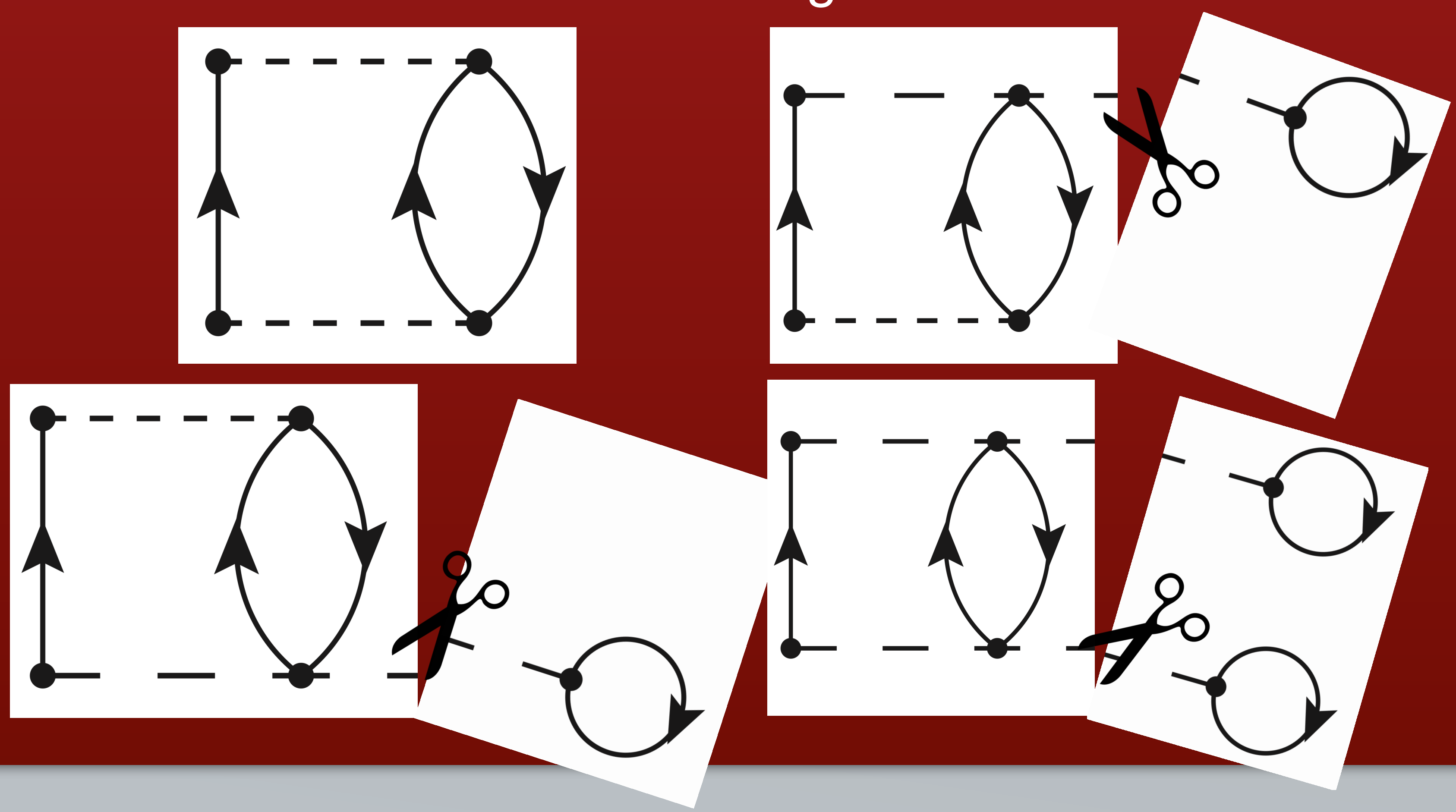

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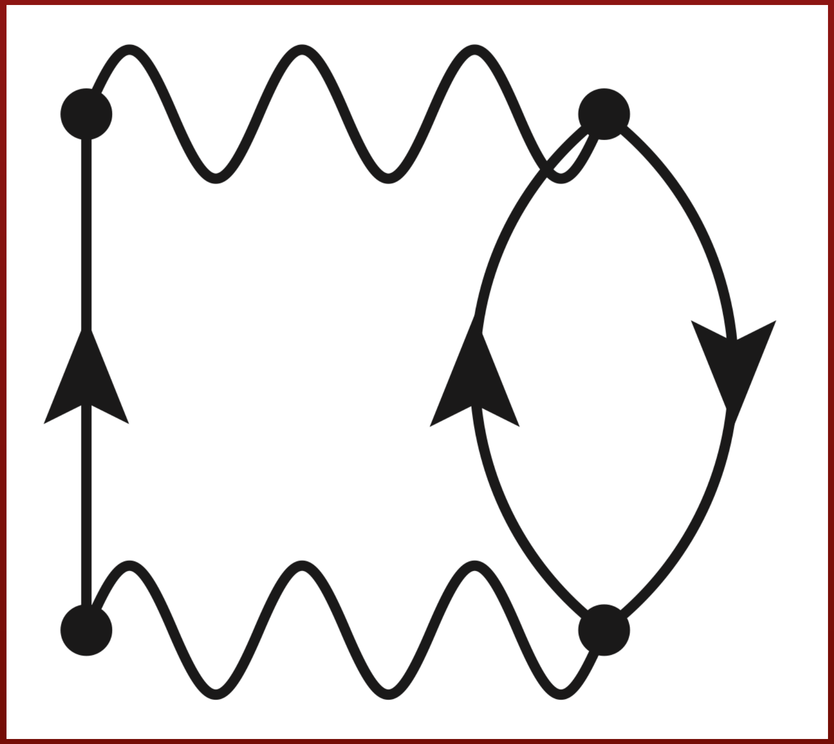
1p Interaction-**irreducible** second-order self-energy diagram

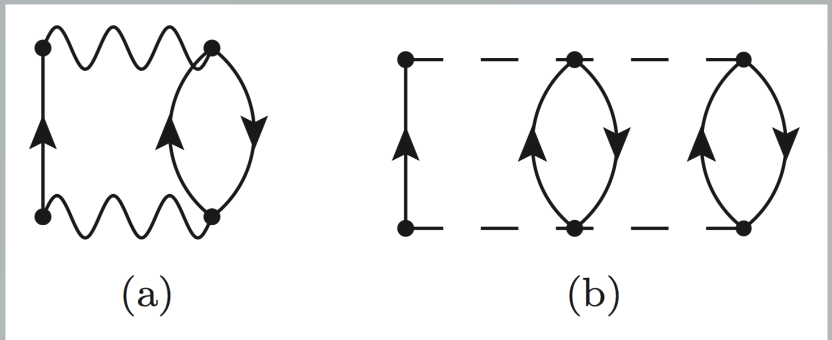


Interaction-irreducible Self-Energy with 3N forces

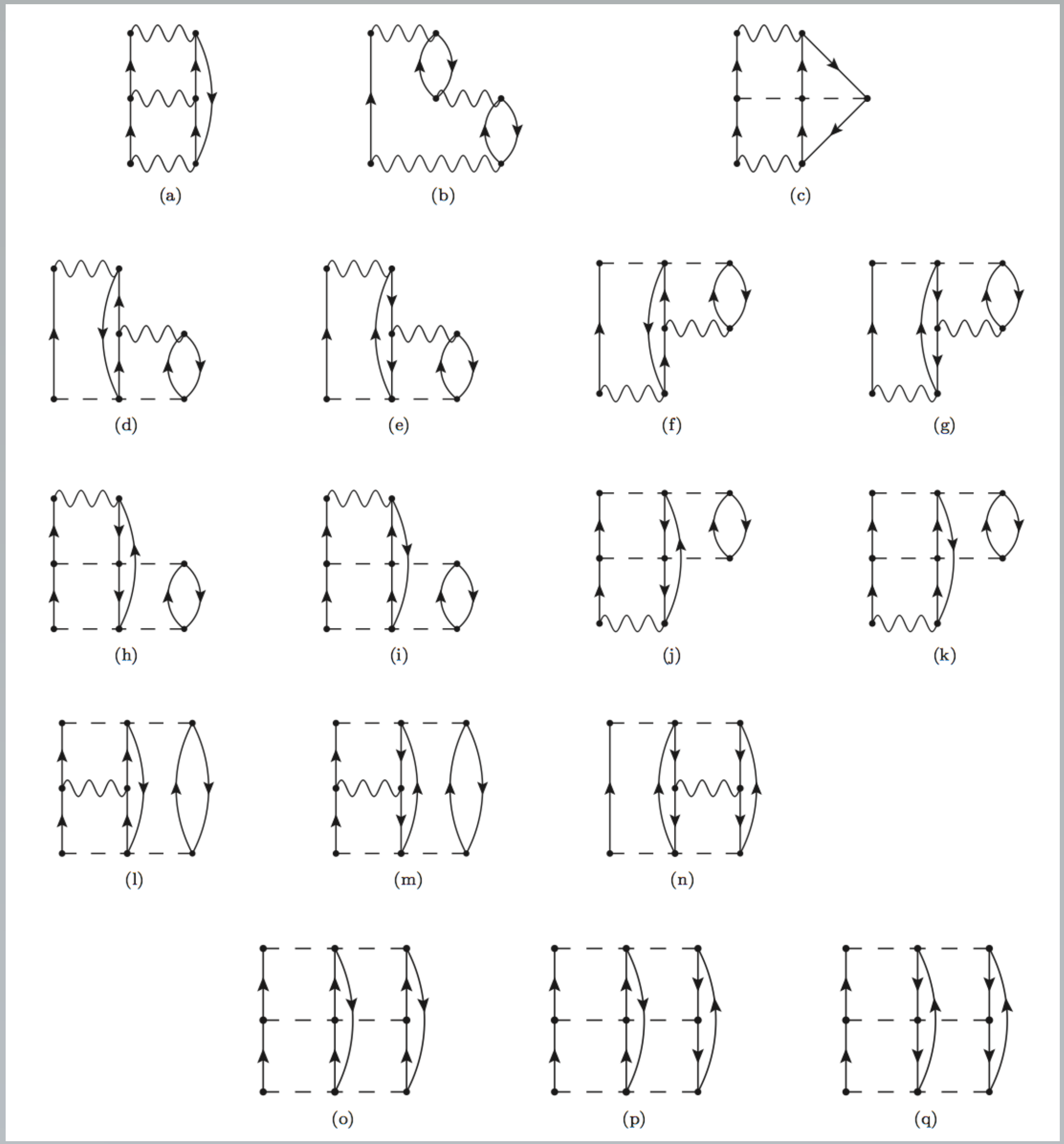
(A. Carbone et al, Phys. Rev. C **88** (2013) 054326)

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

Second-order diagrams with 3N forces



Third-order diagrams with 3N forces



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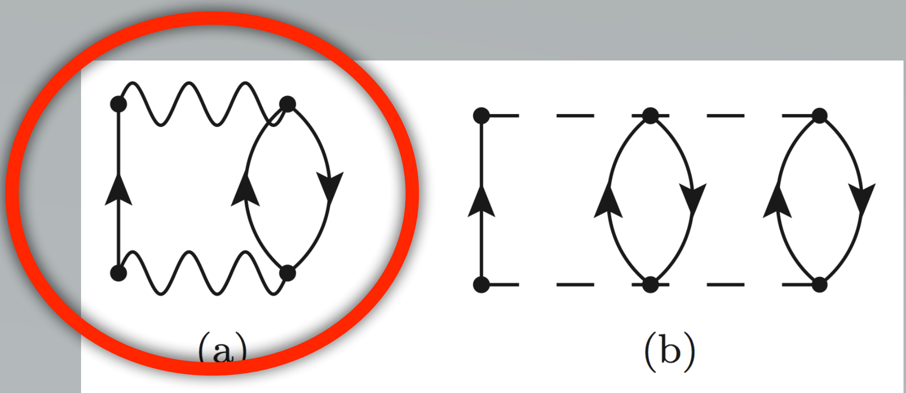

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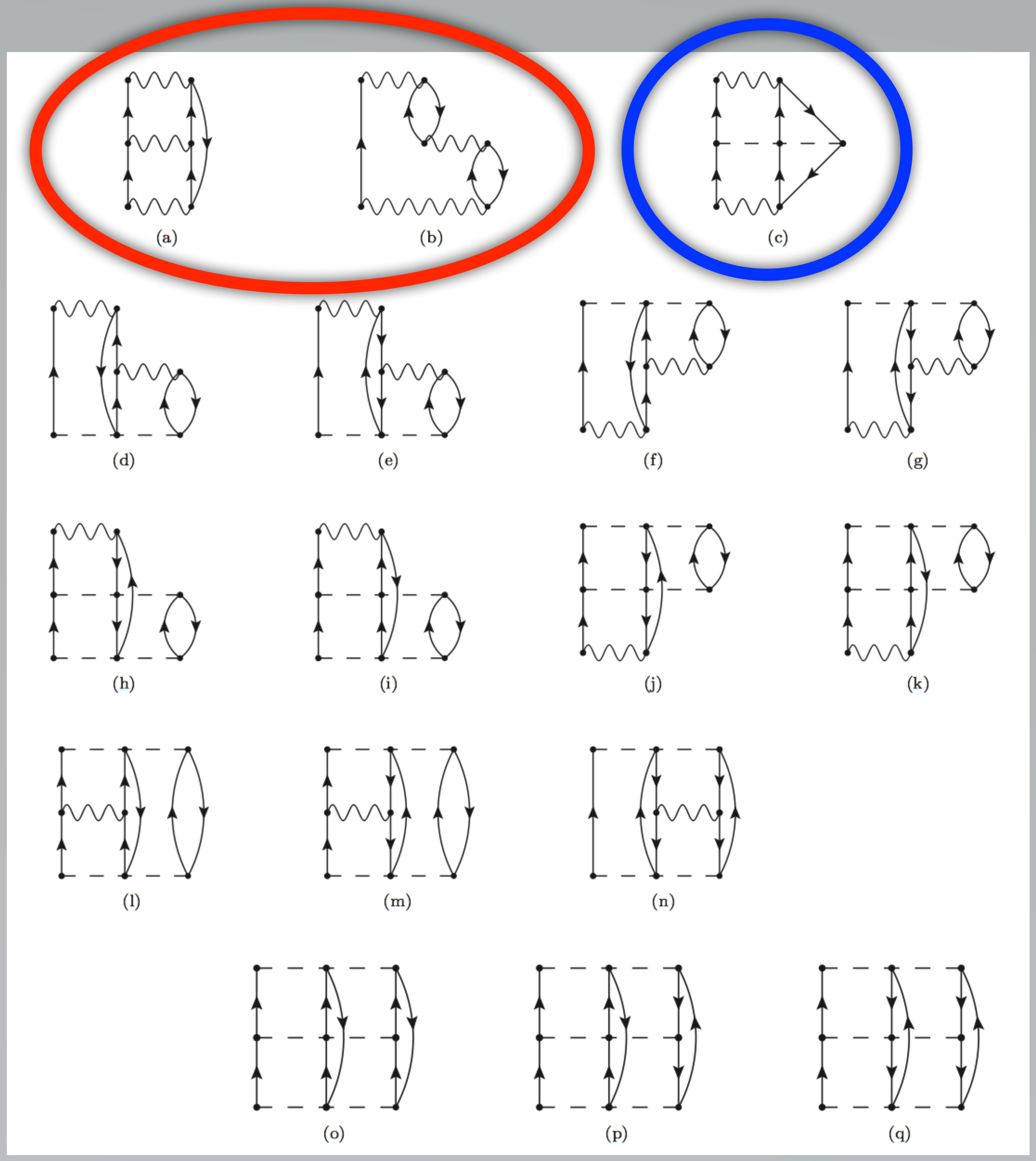


Diagrams with effective 2N forces

(A. Cipollone et al, Phys. Rev. C 92 (2015) 014306)

Diagram with irreducible 3N forces

(F.R., C. Barbieri, Proceeding of NTSE (2016))
(F.R., C. Barbieri, arXiv:1709.04330 (2017))

Algebraic Diagrammatic Construction method at order 3

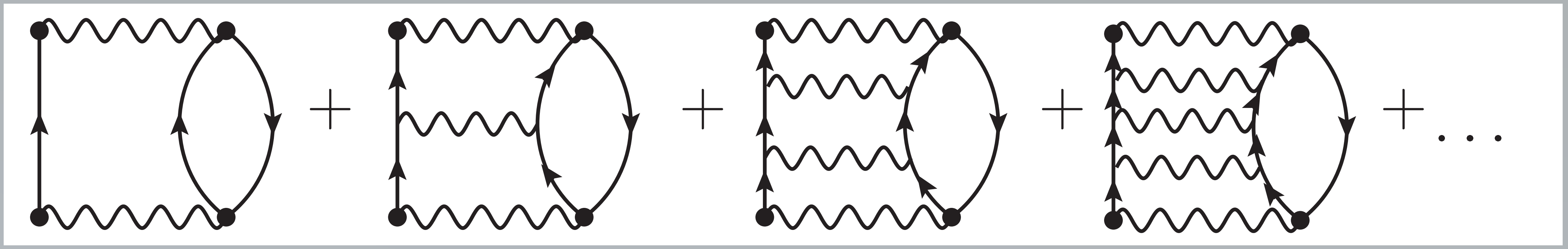
J. Schirmer and collaborators:

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



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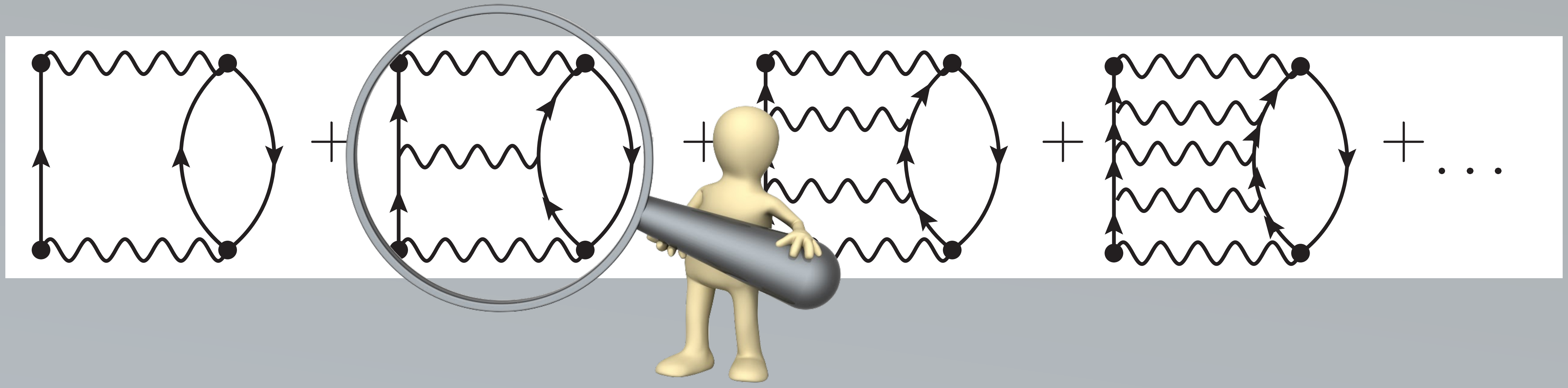

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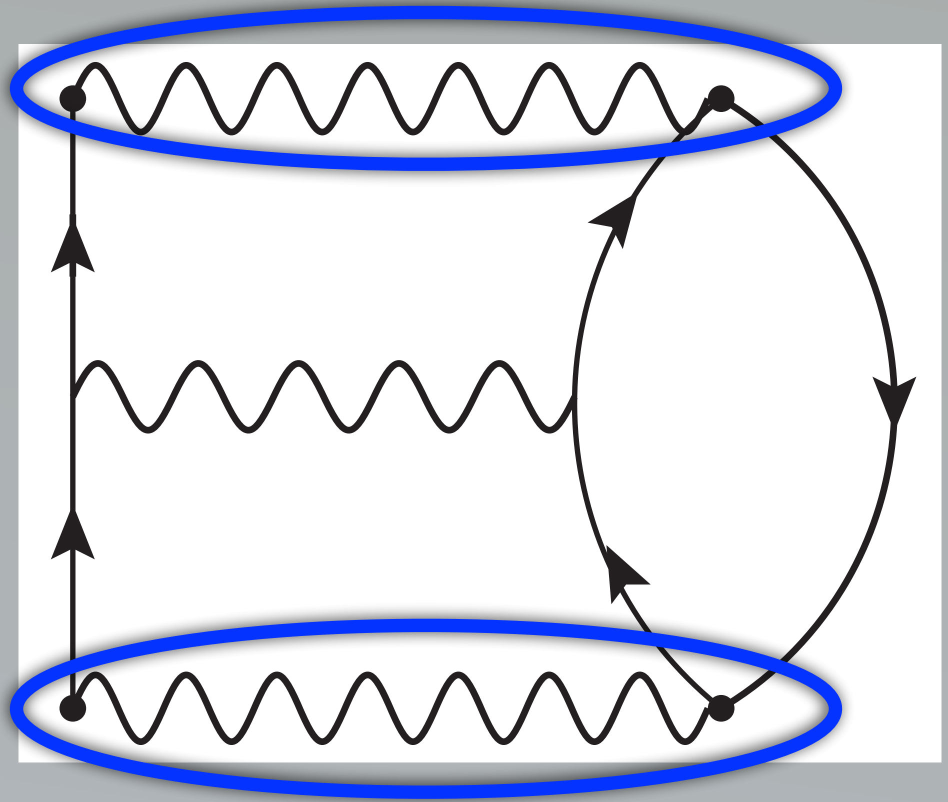

$\mathcal{M}$: matrices coupling the single-particle propagator to more complex intermediate configurations

Dyson-ADC(n)

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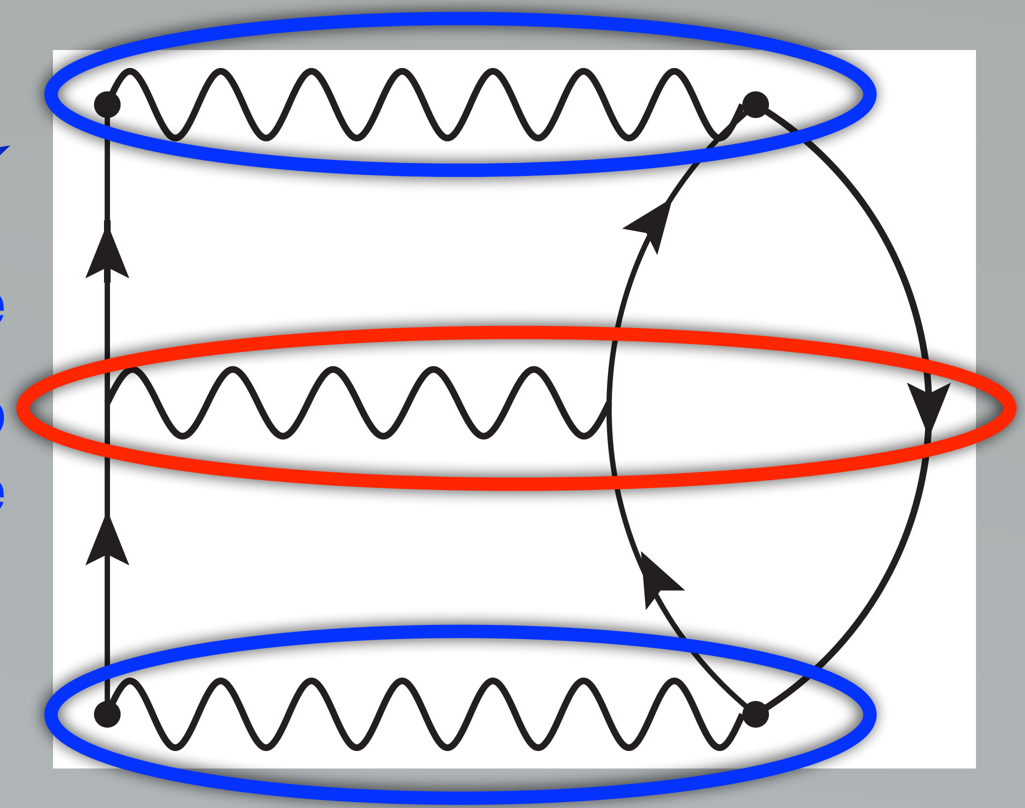

C: interaction matrix linked only to internal fermion lines

Dyson-ADC(n)

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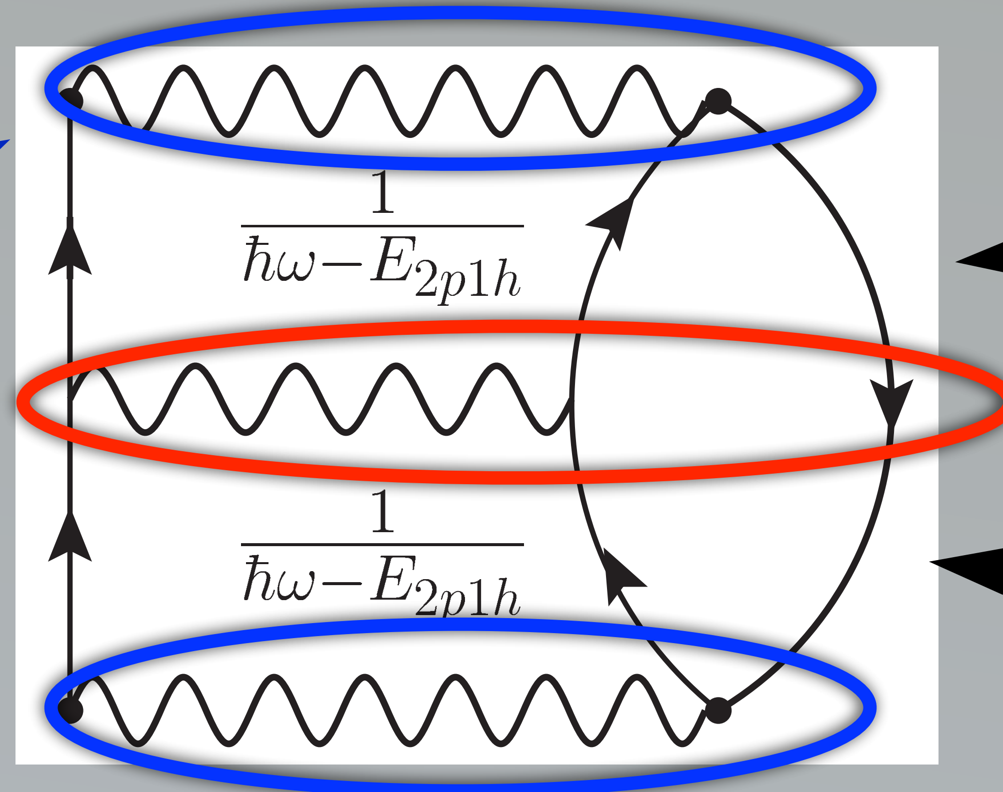
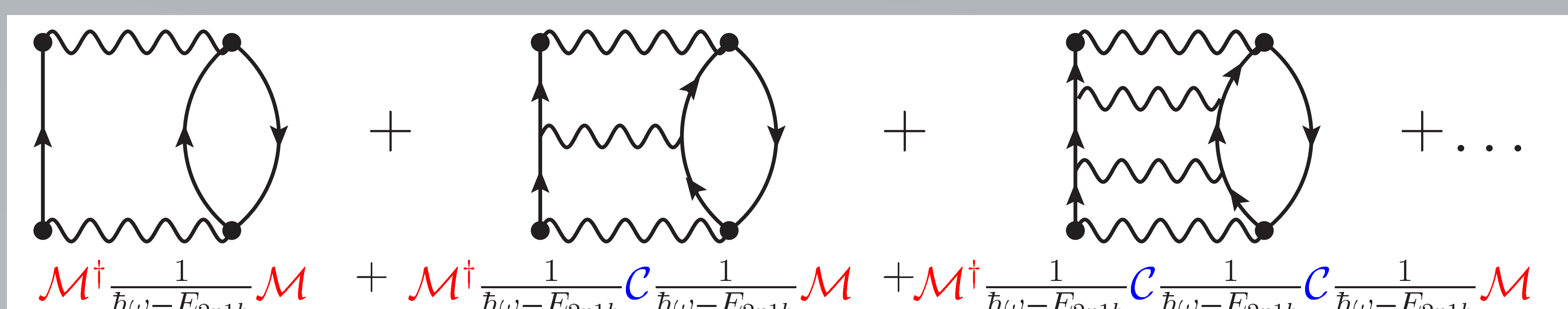


Propagator
(intermediate state configurations)

$\mathcal{C}$: interaction matrix linked only to internal fermion lines

Propagator
(intermediate state configurations)

The set of ladder diagrams is a geometric series



Sum

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

How does ADC(n) work practically

General form of the irreducible self-energy

$$\Sigma_{\alpha\beta}(\omega) = \mathcal{M}^\dagger \frac{1}{\hbar\omega - E_{ph} - \mathcal{C}} \mathcal{M}$$

ε_{2p1h}, ε_{3p2h}, ...

First order in the interaction

Formal expansion of $\mathcal{M}$ in powers of interactions

$$\mathcal{M} = \mathcal{M}^{(I)} + \mathcal{M}^{(II)} + \mathcal{M}^{(III)} + \dots$$

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Explicit expressions for $\mathcal{M}$ and C are found by comparing with derived expressions of self-energy Goldstone diagrams up to the same order

$$\begin{aligned}\mathcal{M}^\dagger \frac{1}{\hbar\omega - E_{ph} - \mathcal{C}} \mathcal{M} = {} & \mathcal{M}^{(I)\dagger} \frac{1}{\hbar\omega - E_{ph}} \mathcal{M}^{(I)} \\ & + \mathcal{M}^{(II)\dagger} \frac{1}{\hbar\omega - E_{ph}} \mathcal{M}^{(I)} + \mathcal{M}^{(I)\dagger} \frac{1}{\hbar\omega - E_{ph}} \mathcal{M}^{(II)} + \mathcal{M}^{(I)\dagger} \frac{1}{\hbar\omega - E_{ph}} \mathcal{C} \frac{1}{\hbar\omega - E_{ph}} \mathcal{M}^{(I)} \\ & + \text{fourth order} + \dots\end{aligned}$$

How does ADC(n) work practically

General form of the irreducible self-energy

$$\Sigma_{\alpha\beta}(\omega) = \mathcal{M}^\dagger \frac{1}{\hbar\omega - E_{ph} - \mathcal{C}} \mathcal{M}$$

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$$+ \mathcal{M}^{(II)\dagger} \frac{1}{\hbar\omega - E_{ph}} \mathcal{M}^{(I)} + \mathcal{M}^{(I)\dagger} \frac{1}{\hbar\omega - E_{ph}} \mathcal{M}^{(II)} + \mathcal{M}^{(I)\dagger} \frac{1}{\hbar\omega - E_{ph}} \mathcal{C} \frac{1}{\hbar\omega - E_{ph}} \mathcal{M}^{(I)}$$

$$+ \text{fourth order} + \ldots$$

Features of Self-Energy in ADC(n)

$\Sigma_{\alpha\beta}(\omega)$

- Compatible with the Lehmann representation
- Principle of Causality
- Hermitian
- Non perturbative resummation

Dyson equation is solved as eigenvalue problem

poles and residues of the propagator are found as eigenvalues and eigenvectors of the Self-Energy Hermitian matrix

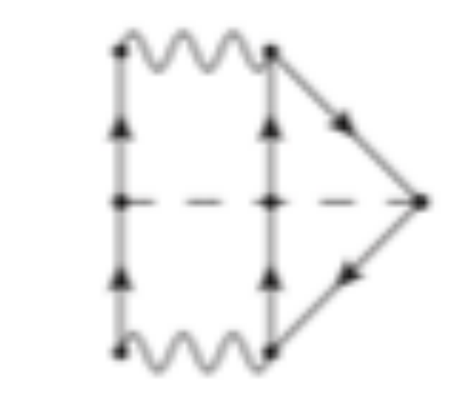
Complete set of ADC(3) working equations can be found in:

(F.R., C. Barbieri, Proceeding of NTSE (2016))

(F.R., C. Barbieri, ArXiv:1709.04330 (2017))

Work in progress:

Implementation in BcDor Code



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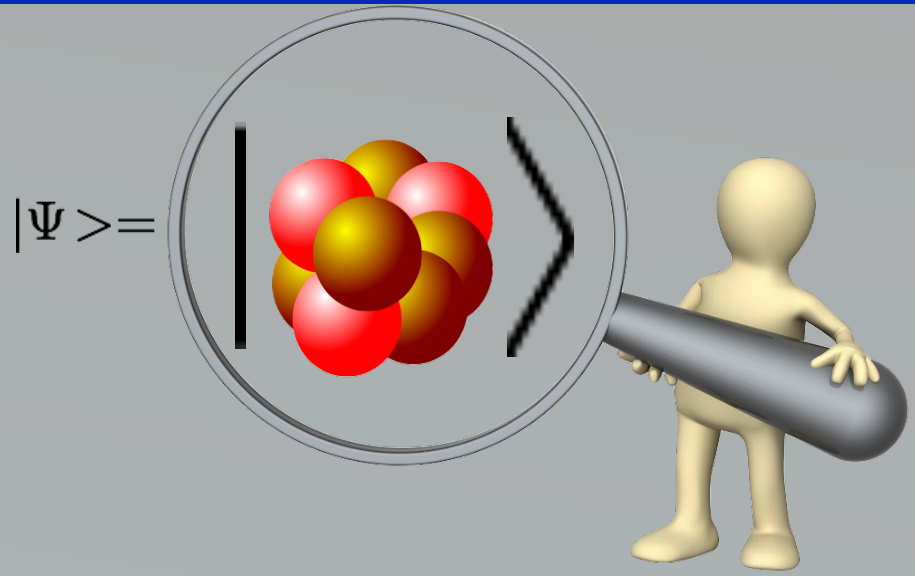
Electric Dipole Polarizability α_D

In general:

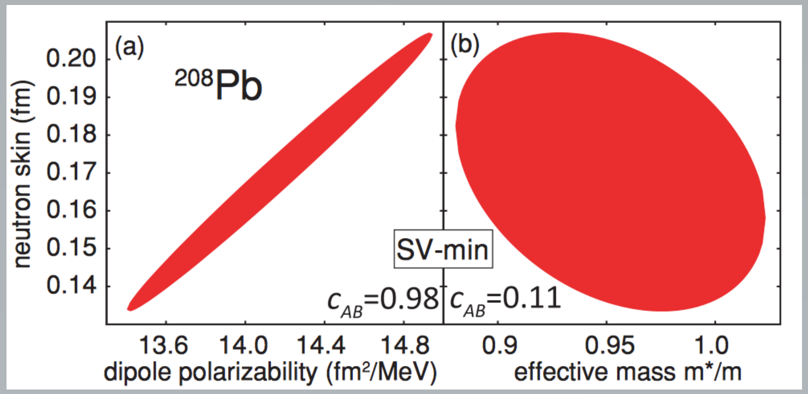
$\alpha_D \propto$ E1 electromagnetic response

(quality of the nuclear wave function correlations)



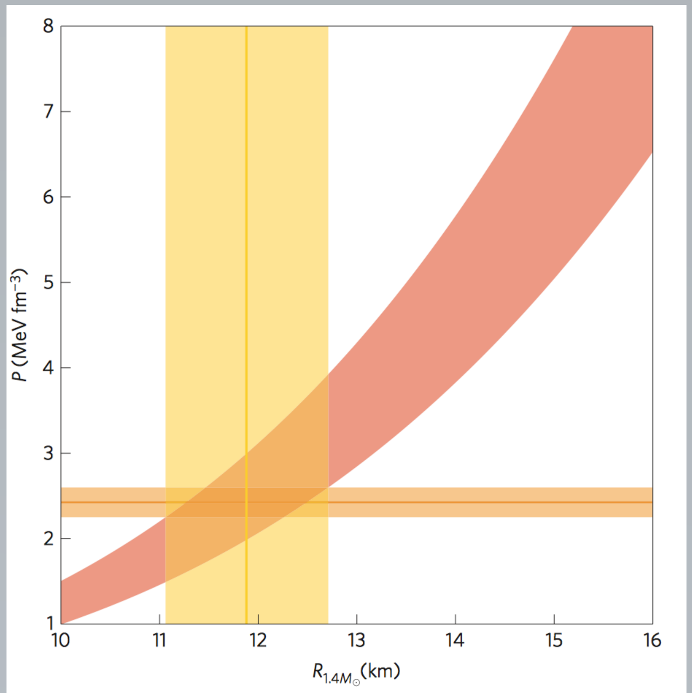
Recent studies:

- Reinhard *et al,* PRC 81 051303(R) 2010
- Piekarewicz *et al*, PRC 85 041302(R) 2012



α_D as input quantity for constraining the isovector part of the nuclear interaction

- Hagen *et alii*, Nature Physics 12, 186 (2015)



Theory input for determining the Radius of Neutron stars

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

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

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

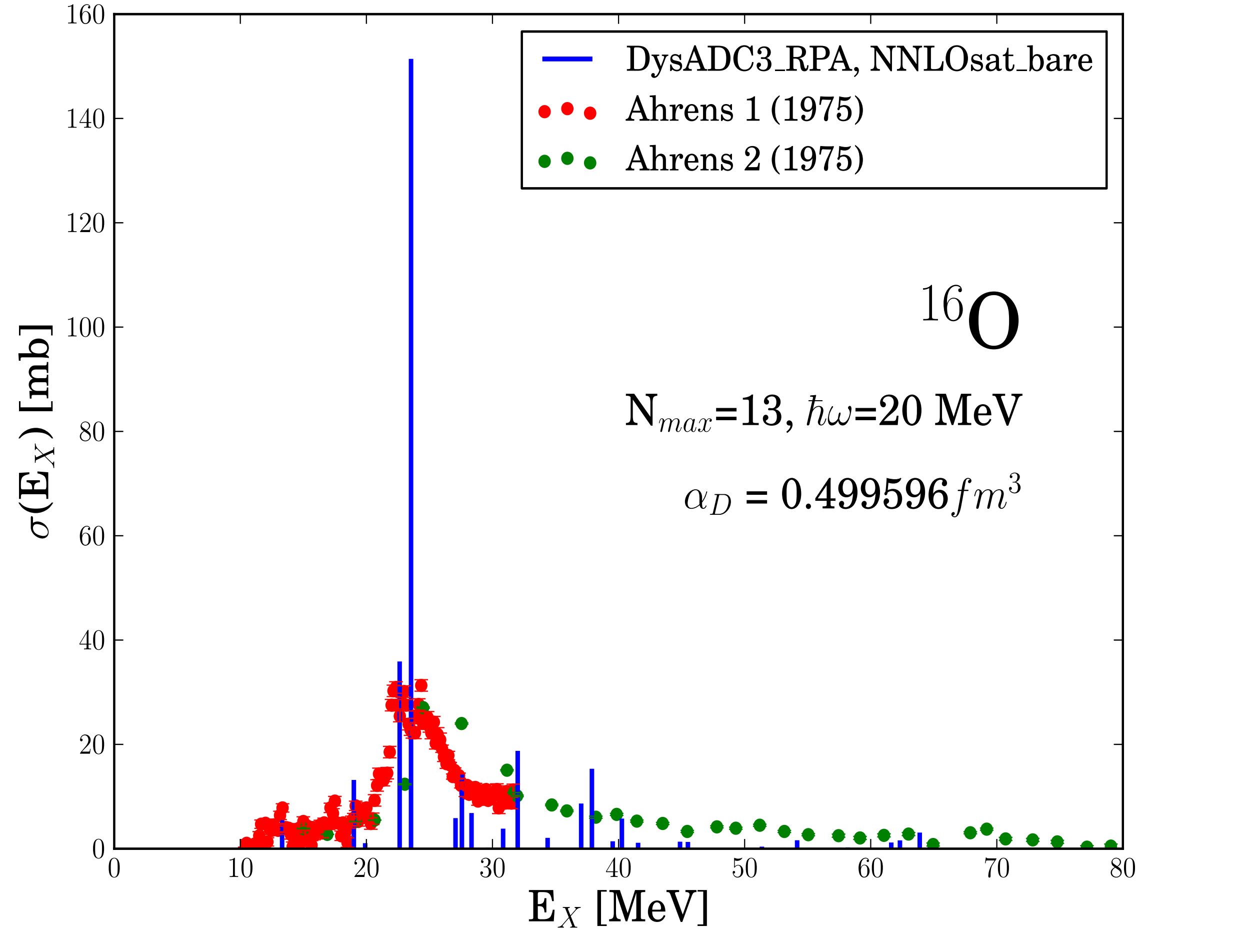
Nuclear structure correlations:
g^{II} RPA level (first order)
g^{I} "dressed" ADC(3)

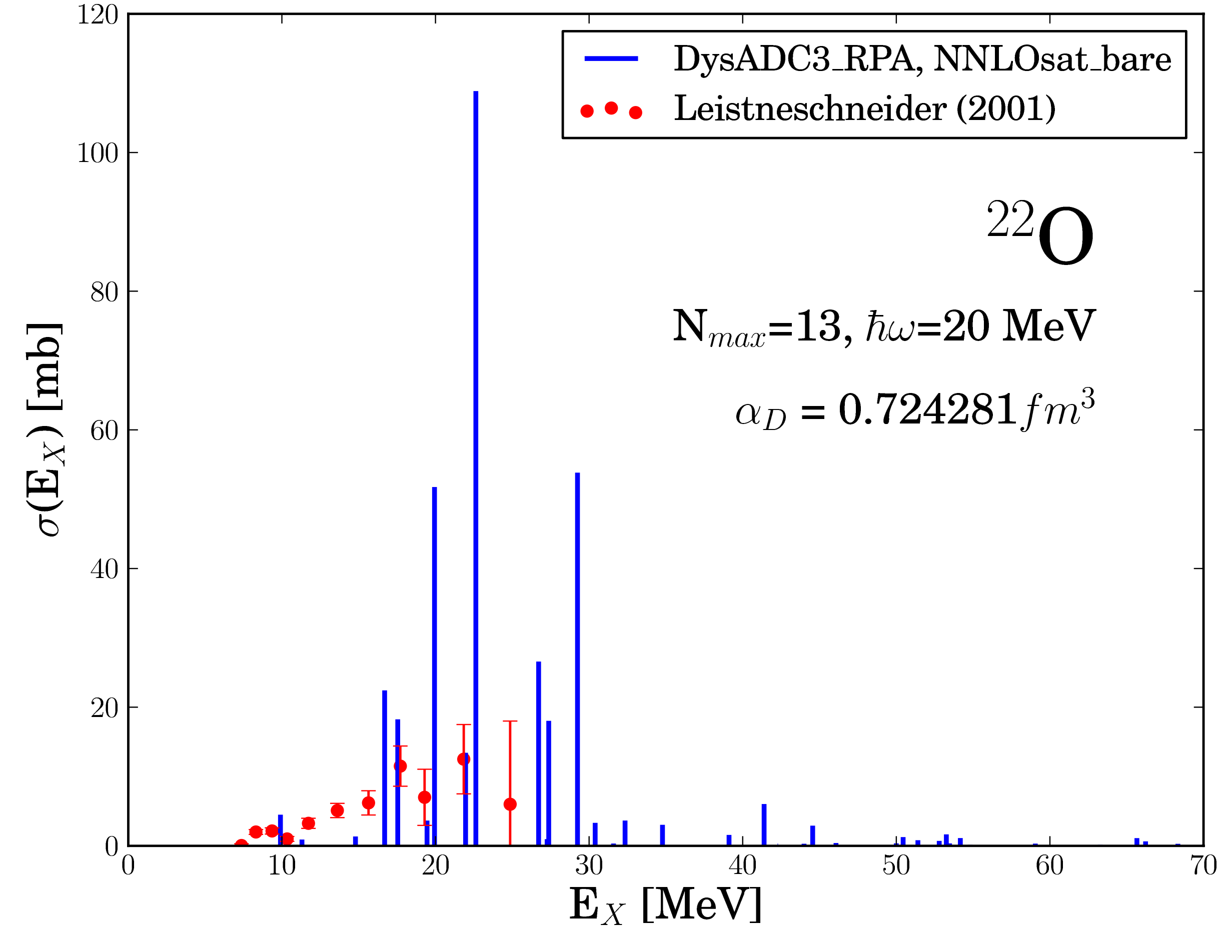
Results: cross section and dipole polarisability

^{16}O ^{22}O ^{40}Ca ^{48}Ca

Results for Oxygen isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation





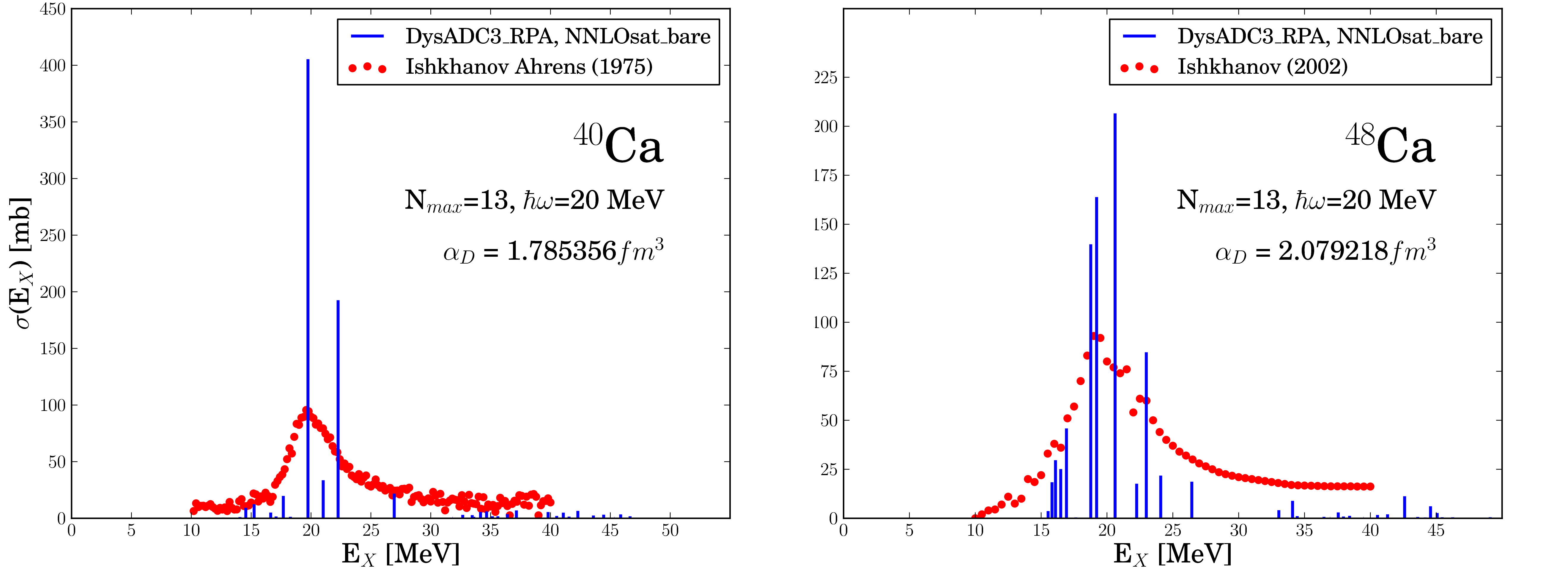
NNLO$_{sat}$

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

Dipole polarizability α_D (fm^3)			
Nucleus	SCGF	CC/LIT	Exp
^{16}O	0.50	0.57(1)	0.585(9)
^{22}O	0.72	0.86(4)	0.43(4)

Results for Calcium isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation



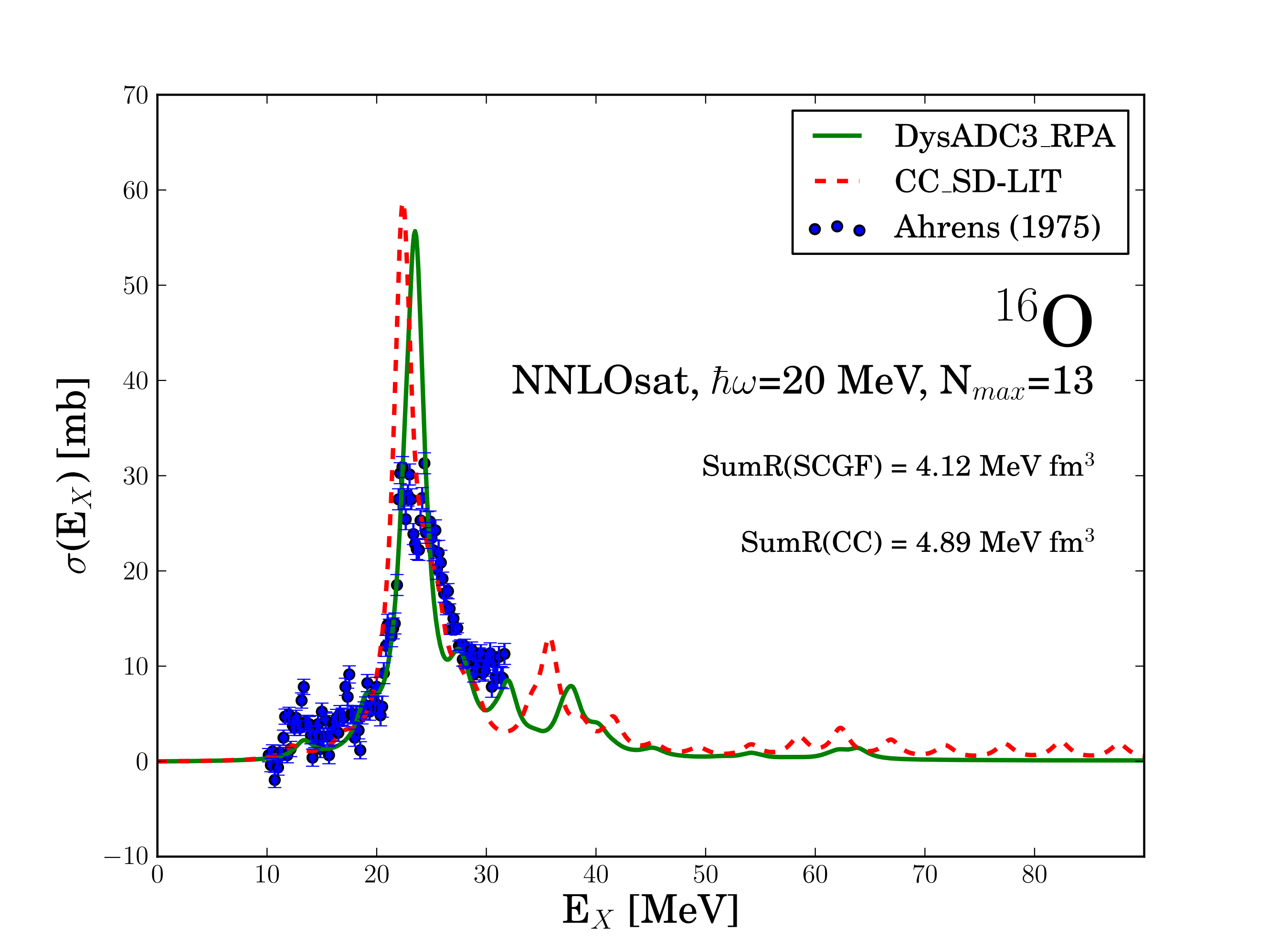
NNLO$_{sat}$

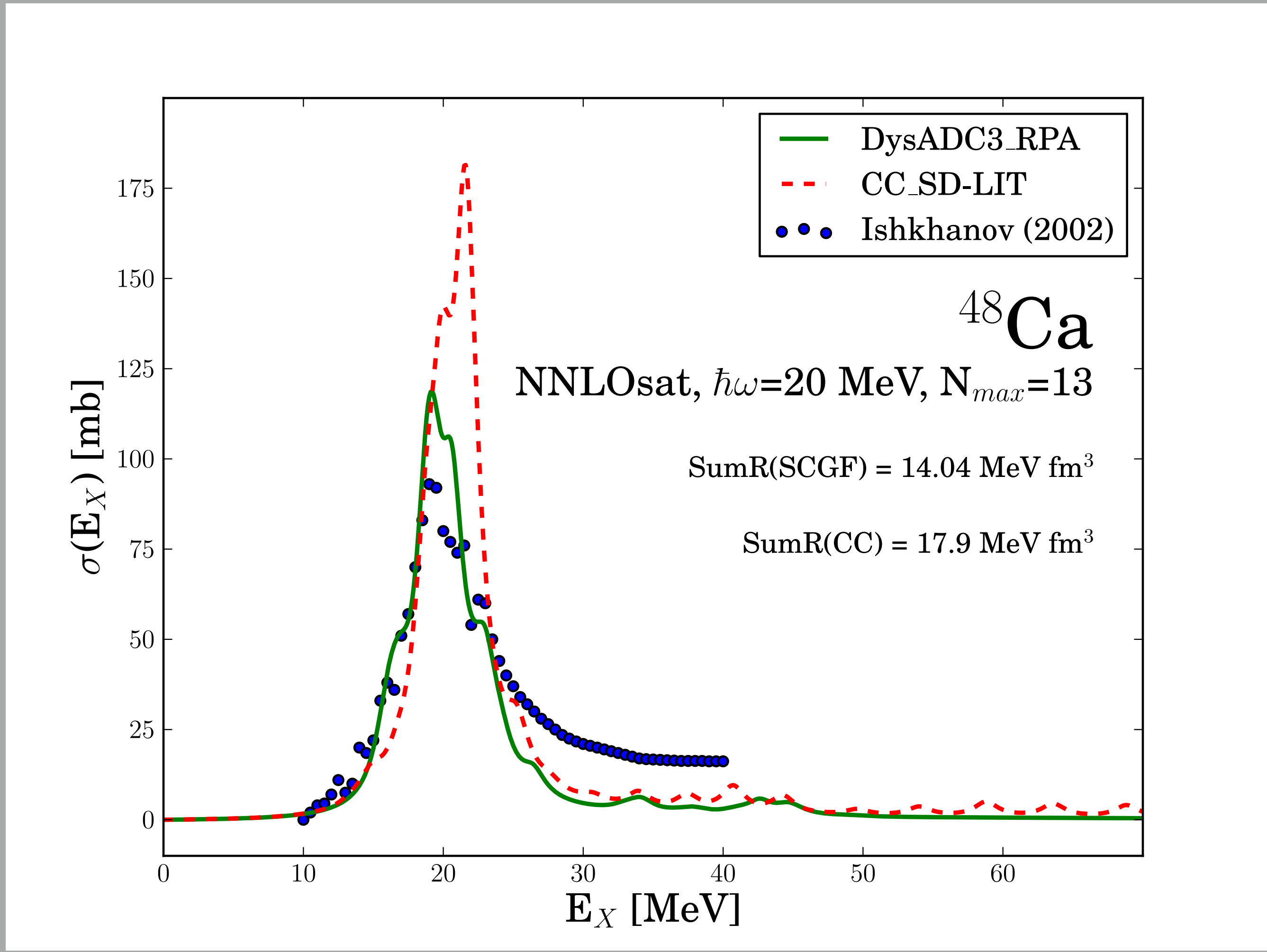
- GDR positions reproduced
- Total sum rule reproduced but poor strength distribution (Lack of correlations)

Dipole polarizability α_D (fm^3)			
Nucleus	SCGF	CC/LIT	Exp
^{40}Ca	1.79	1.47 $(1.87)_{thresh}$	1.87(3)
^{48}Ca	2.08	2.45	2.07(22)

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

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



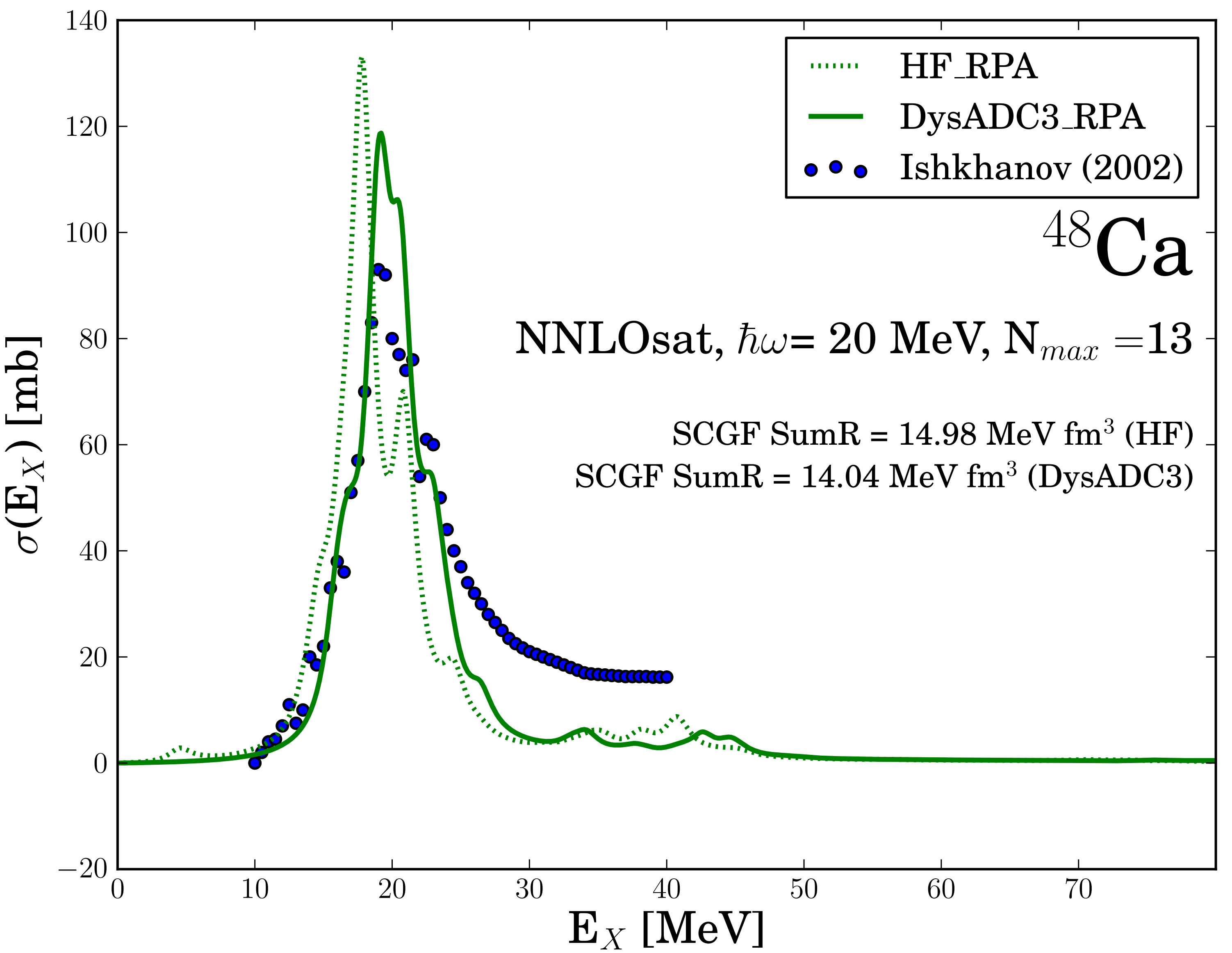


- CC-Singles-Doubles (analogous to 2nd RPA)
- LIT reduces a continuum state problem to a bound-state-like problem

Different treatment of the correlations:

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

Role of the correlations included in the reference state



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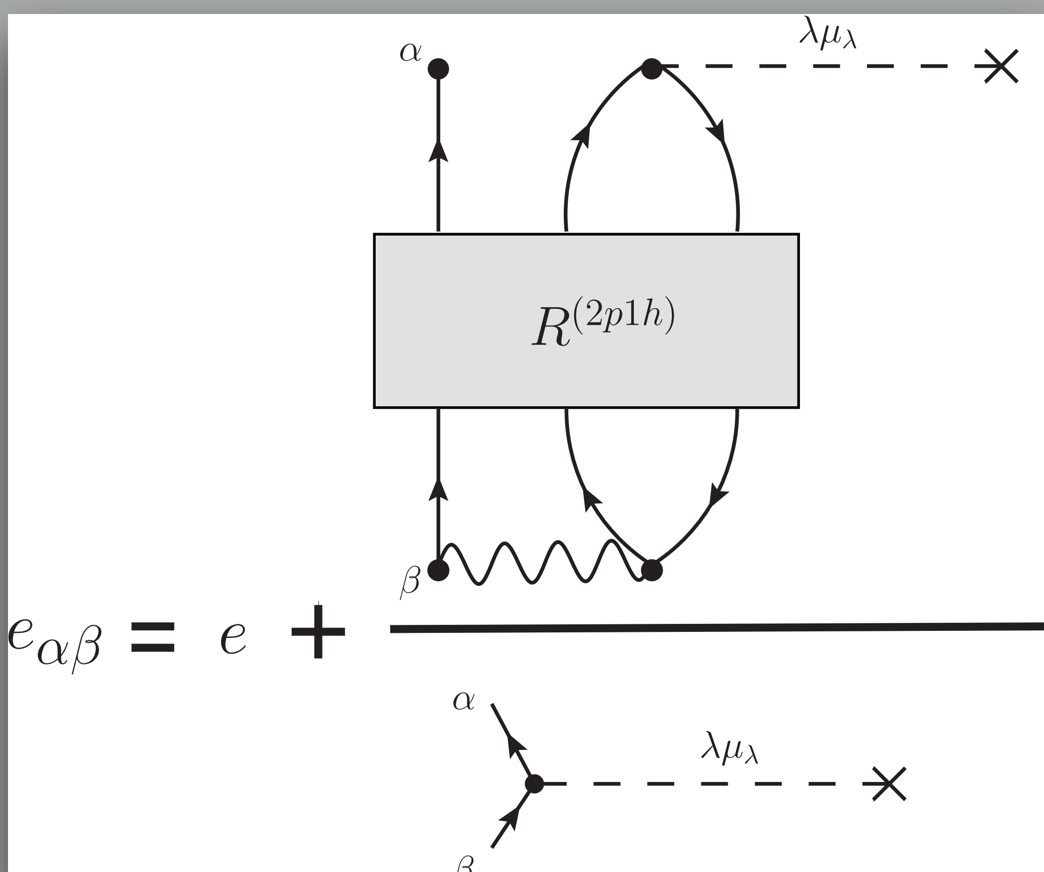
Methods: Particle-Vibration coupling in the Self-consistent Green function formalism

Theoretical effective charges
(as opposed to the ones extracted from experiment)

Our purpose is to calculate effective charges without resorting to any measurement of electromagnetic observables

Basic idea: calculate the core-polarization effect felt by the single-particle orbital of interest because of the energy-dependent effective potential, calculated at ADC(3) level



Effective charge as the ratio between the transition strengths (with and without the core-polarization) of a given multipole field:

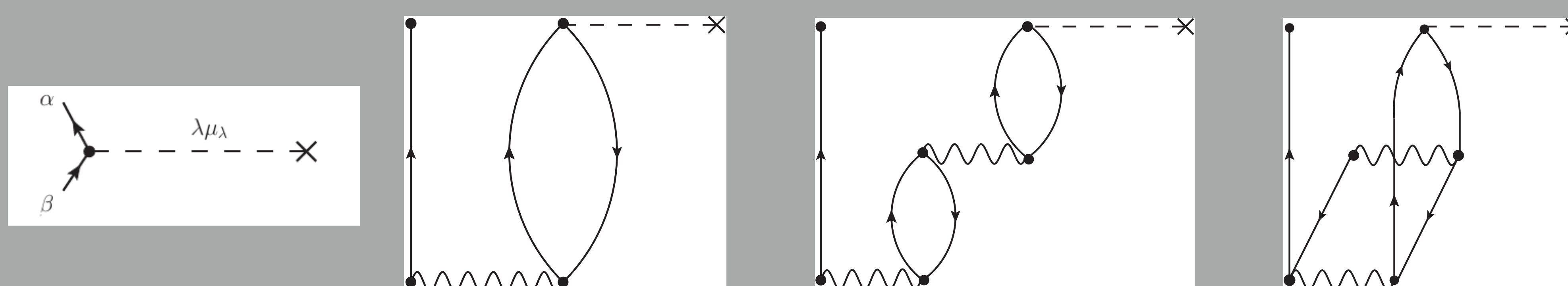
$$\frac{\langle\tilde{\alpha}|\hat{\phi}^{(\lambda\mu_\lambda)}|\tilde{\beta}\rangle}{\langle\alpha|\hat{\phi}^{(\lambda\mu_\lambda)}|\beta\rangle} = 1 + \frac{\tilde{\Sigma}^{(\lambda\mu)}_{\alpha\beta}}{\langle\alpha|\hat{\phi}^{(\lambda\mu_\lambda)}|\beta\rangle}$$

$|\tilde{\alpha}\rangle \equiv$ s.p. state with correlations induced by the nuclear interaction and electromagnetic operator

Results: Theoretical effective charges of Oxygen and Nickel isotopes for E2 operator

Features of the calculation

- Medium-mass isotopes:
  - Oxygen isotopes in *sd* and *psd* valence space: ^{14}O, ^{16}O, ^{22}O and ^{24}O
  - Nickel isotopes in $0f1p0g_{9/2}$: ^{48}Ni, ^{56}Ni, ^{68}Ni and ^{78}Ni
- NN and 3N nuclear interaction $\mathrm{NNLO_{sat}}$ (Phys. Rev. C 91, 051301(R))
- Electric quadrupole operator E2 $\hat{\phi}^{(2\mu)} = \sum_i r_i^2 Y_{2\mu}(\hat{r}_i)$
- Dyson equation solved with self-energy truncated at ADC(3) level:



- Nuclear many-body wave function expanded in HO wave functions with N_{max}=13 and hΩ=20 MeV

Results for Oxygen isotopes

	^{14}O	^{16}O	^{22}O	^{24}O
$\nu s_{\frac{1}{2}}\ \nu d_{\frac{3}{2}}$	0.27	0.19	0.12	0.12
$\nu s_{\frac{1}{2}}\ \nu d_{\frac{5}{2}}$	0.41	0.30 (0.40 ± 0.01)	0.21	0.24
$\nu p_{\frac{1}{2}}\ \nu p_{\frac{3}{2}}$	0.41	0.49 ★	0.41	0.47 ★
$\nu p_{\frac{3}{2}}$	0.48	0.36	0.95 ★	0.32
$\nu d_{\frac{3}{2}}$	0.27	0.19	0.15	0.16
$\nu d_{\frac{3}{2}}\ \nu d_{\frac{5}{2}}$	0.46	0.36	0.24	0.23
$\nu d_{\frac{5}{2}}$	0.44	0.33 (0.37 ± 0.14)	0.31	0.30
	0.3 - 0.5 (0.65)	0.2 - 0.4 (0.53)	0.1 - 0.4 (0.31)	0.1 - 0.3 (0.27)
$\pi s_{\frac{1}{2}}\ \pi d_{\frac{3}{2}}$	0.69	1.07	1.04	1.03
$\pi s_{\frac{1}{2}}\ \pi d_{\frac{5}{2}}$	1.17	1.14 (1.10 ± 0.01)	1.16	1.15
$\pi p_{\frac{1}{2}}\ \pi p_{\frac{3}{2}}$	1.17	1.17	1.21	1.18
$\pi p_{\frac{3}{2}}$	1.03	1.01	1.07	1.05
$\pi d_{\frac{3}{2}}$	0.46	1.03	1.04	1.02
$\pi d_{\frac{3}{2}}\ \pi d_{\frac{5}{2}}$	0.79	1.16	1.22	1.19
$\pi d_{\frac{5}{2}}$	1.13	1.09	1.11	1.09
	0.5 - 1.2 (1.35)	1.0 - 1.2 (1.29)	1.0 - 1.2 (1.15)	1.0 - 1.2 (1.11)

Standard values of experimental effective charges in *psd* nuclei are e_p=1.3 and e_n=0.5

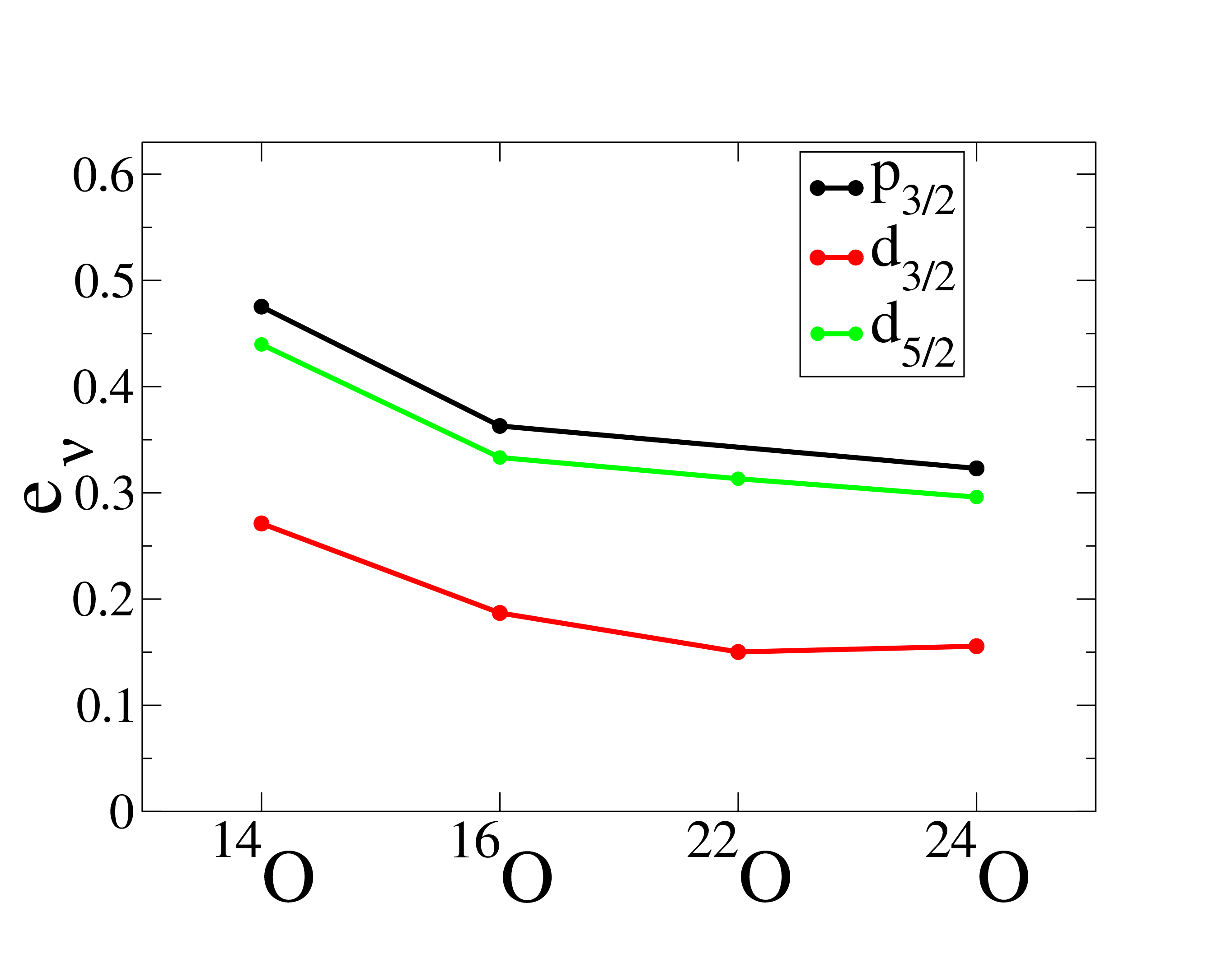
- Neutron-rich nuclei have weaker core polarisation (quench of neutron effective charge)
- Significant isotopic dependence especially for neutrons (compared with Bohr-Mottelson Eq. 6-386b with Sagawa parametrisation of PRC 70, 054316, 200

$$e_{\pi}^{eff} = e + a\frac{Z}{A} + b\frac{N-Z}{A} - \left(c + d\frac{Z}{A}\frac{N-Z}{A}\right)$$)

$$e_{\nu}^{eff} = a\frac{Z}{A} + b\frac{N-Z}{A} + \left(c + d\frac{Z}{A}\frac{N-Z}{A}\right)$$

- Single-particle state dependence also significant (yet to be studied and understood…)

Results for Oxygen isotopes



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Conclusions and Perspectives

- ADC(n) as a non-perturbative method for many-body physics

- Set of effective charges for Oxygen and Nickel isotopes calculated from realistic potential (ready to be used as input in Shell Model calculations)
- Expected isospin-dependence of neutron effective charges is found

- Dipole response and polarisability calculated from first principles
- Continuum to be included, but dipole polarisability seems quite insensitive to it
- Correlations: comparison with CC-LIT and extension of ADC to polarization propagator