# Ab initio computations of the nuclear spectral function



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Neutrino detection and interactions: challenges and opportunities for ab initio nuclear theory

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## Outline

### ⦿ **Introduction**

⦿ **Self-consistent Green's function approach**

### ⦿ **Applications**

- Ground-state properties
- Spectral function
- Response function

### ⦿ **Conclusions**

### Evolution of ab initio nuclear chart

- Since 2000's ○ SCGF, CC, IMSRG ⦿ Approximate approaches for closed-shell nuclei
	- Polynomial scaling
- Since 2010's ⦿ Approximate approaches for open-shells
	- GGF, BCC, MR-IMSRG
	- Polynomial scaling



### Evolution of ab initio nuclear chart



### Chiral effective field theory & nuclear interactions



circles, filled boxes, filled boxes, filled boxes, respectively. The boxes surrounding various classes of diagrams are surrounding various classes of diagrams are surrounding various classes of diagrams are surrounding var √ **√ Ideally: apply to the many-nucleon system (and propagate the theoretical error)** he many-nucleon system (and propagate the theoretical error)  $\,|\,$ band the theoretical cribit For the breakdown scale, we use the same values as in n system (and propagate the theoretical error) |  $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ 

⇤*b*

⇤*b*

for *R* = 0*.*8 *...* 1*.*0 fm, *R* = 1*.*1 fm and *R* = 1*.*2 fm, respectrum in the theoretical uncertainty at lower orders at lower orders at lower orders at lower orders at low

⇤*b*

mixing angles  $\sim$ 1,  $\sim$ 2 up to N4LO based on the cuto $\sim$ *R* = 0*.*9 fm in comparison with the NPWA [21] (solid dots)

mixing angles  $\overline{a}$ *R* = 0*.*9 fm in comparison with the NPWA [21] (solid dots)

tainty at  $\mathcal{L}$ N<sup>2</sup>LO (color online: green) and NLO (color online: yellow).

tainty at N<sup>4</sup>LO (color online: red), N<sup>3</sup>LO (color online: blue), N<sup>2</sup>LO (color online: green) and NLO (color online: yellow).

⇤*b*

for *R* = 0*.*8 *...* 1*.*0 fm, *R* = 1*.*1 fm and *R* = 1*.*2 fm, respectrum in the theoretical uncertainty at lower orders at lower orders at lower orders at lower orders at low

order, NLO next-to-leading order and so on. The various vertices according to equation (29) with % *<sup>i</sup>* 0, 1, 2, 3, 4 are denoted by small

results when doing calculations in momentum space. So

#### Self-consistent Green's function approach 21 lsten **Y***<sup>k</sup>† a* ∂#*ab*(ω) ∂ω  $\cdot$  $\epsilon$ **Y***k b,* (64b) Moreover, normalization condition (64b) reduces in this case to the well-known  $\frac{1}{2}$  $a^2$ *ab a* ∂ω " " −ω*<sup>k</sup>* where the property of the property  $\bigcap$  the well-known  $\bigcap$  $\alpha$ <sup>1</sup>Department of Physics, University of Surrey, Guildford GU2 7XH, UK <sup>2</sup>CEA-Saclay, IRFU/Service de Physique Nucl´eaire, F-91191 Gif-sur-Yvette, France <sup>3</sup>KU Leuven, Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium <sup>4</sup>National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, MICHIGAN STATE UNIVERSity State University, Annual State University, USA University, USA 1 UUCLL  $\mathcal{L}(\omega)$

Let us now stress that, despite the energy independence of first-

"**Y***k* " <sup>=</sup> !

"*Uk* " +!

"*Vk* "

= 1*.* (68)

 $\odot$  Solution of the *A*-body Schrödinger equation  $\langle H|\Psi_k^A\rangle=E_k^A|\Psi_k^A\rangle$  achieved by Schrödinger equation ander displayed. Diagrammatic rules in the displayed of the displayed of the displayed  $\alpha$  $\tau$ or $A$  some fraction  $\tau A$  $\mu_1 \vee \mu_2 \wedge \mu_3 = \mu_1 \vee \mu_3 \wedge \mu_4$  acniev  $\overline{a}$  are  $\overline{b}$  in particular,  $\overline{b}$  in particular,  $\overline{b}$  in particular,  $\overline{b}$  in particular,  $\overline{b}$ anomalous self-energies are displayed. Diagrammatic rules f the A<sub>r</sub>hody Schrödinge for the self-edge of self-edge in the self- $\mathbf{u} \cdot \mathbf{u} \cdot \mathbf{u}$ equation  $H(\Psi_h) \equiv E_h$  $\frac{1}{\sqrt{5}}$  are already smaller than  $\frac{1}{\sqrt{5}}$  are already smaller than one.  $H|\Psi_k^A\rangle=E_k^A|\Psi_k^A\rangle\,$  $T_{\text{tot}}$  17 topologically distinct distribution dis

energy independence of the auxiliary potential.

**B. First-order self-energies**

- 1) Rewriting it in terms of  $1$ -,  $2$ -, .... A-body objects  $G_1 = G$ ,  $G_2$ , ...  $G_A$  (Green's functions)  $\text{IS} \text{ OI} \text{ I}$ -,  $\text{Z}$ -, ....  $A$ -DOQV OD] truncation scheme is addressed in Sec. VI. for  $C_1$   $\subset$   $C_2$   $\subset$   $C_1$  (Croop)  $\mathbf{u}$  is  $\mathbf{u}_1\mathbf{-u}$ ,  $\mathbf{u}_2$ , ...  $\mathbf{u}_A$  (ditting truncation scheme is addressed in Sec. VI. Ig it in terms of 1-. 2-. ....  $\mathcal O$ , and  $\mathcal O$ l hody objects  $C-C$ r-pouy opjects ing to Gordon ADC(3), all containing three interactions  $\mathcal{L}_{\mathcal{A}}$  $\mathsf{lc}$   $\mathsf{C}_{1}$   $\mathsf{C}_{2}$   $\mathsf{C}_{3}$   $\mathsf{C}_{4}$   $\mathsf{C}_{4}$   $\mathsf{C}_{5}$   $\mathsf{C}_{9}$   $\mathsf{C}_{10}$  $\mathsf{c}_1$ s G $_1$ =G, G $_2$ , ... GA (Green's 9
- 2) Expanding these objects in perturbation (in practise **G** ➟ **one-body observables**, etc..)  $\dot{\rm i}$ octe in norturhatio #11 (1) *ab* = +! *V*¯ *ab,* (65a)  $\mathbf{p}$ rtise  $\mathbf G$  "" one-body obse are to be included in the calculation, first-order self-energies, first-order self-energies,  $\sigma$  $\frac{1}{2}$ *cd*  $\alpha$ กลtบon (บุก practบรe (÷ ┉ on  $\sum_{i=1}^n$  further  $\sum_{i=1}^n$  the quasiparticle strength) such that  $\sum_{i=1}^n$  $d = 0$  depending on the interaction interaction interaction interaction interaction in the i  $\det$   $\mathbf{G} \to \mathbf{on}$ e-bod
- **Self-consistent** schemes resum (infinite) subsets of perturbation-theory contributions *cd*  $\boldsymbol{\mathrm{e}}$ s resum (infinite*)* sub  $\mathcal{G}_\mathcal{A}$  are self-consistently modified (in particular, through  $\mathcal{G}_\mathcal{A}$ the of norturhation theory to of perturbation theory  $\overline{\text{mathrm}}$  schemes resum  $\lim_{\epsilon \to 0}$  outpoote of the spite of hinite) subsets of perturbation-thed B33 = B313 =  $\mathbf{O}$ IIIIID $\mathbf{O}$ UUUID



#### ⦿ **Access a variety of quantities**

- $\Delta$  thomas.  $\epsilon$  vell  $\lambda$  $\circ$  One-body GF  $\rightarrow$  Ground-state properties of even-even *A* + spectra of odd-even neighbours
- $\circ$  Two-body GF  $\rightarrow$  Excited spectrum of even-even *A*
- Self-energy → Optical potential for nucleon-nucleus scattering

#### Gorkov-Green's functions for open-shell systems  $\overline{\phantom{0}}$  $p$ en-shell systen ⇡ Im *Gaa*(!) (16) are irreducible by definition. An example at second or- $\overline{C}$  der is given by the first term of  $\overline{C}$ ns for open-shell systen ab (t, t) -Green s functions for ope GOTKOV-Green's functions f  $\epsilon$  for anon chall everyone lo Tot open ditch dydethio

<u>Σ</u><br>Σ22 (1)<br>Σ22 (1)

one can write the four propagators (26) in the four propagators (26) in the matrix  $\alpha$ 

<u>ab (w) = −i</u>ii = −iii = −ii = −ii

cdef gh,k1k2k<sup>3</sup>

22 (1)<br>Σ22 (1)<br>Σ22 (1)

contribution (C14b) can be generated by two successive products of two successive products of two successive p

⦿ Standard expansion schemes fail to account for superfluidity <sup>h</sup> *<sup>A</sup>* <sup>0</sup> *<sup>|</sup>aa<sup>|</sup> <sup>A</sup>*+1 *<sup>k</sup>* ih *<sup>A</sup>*+1 *<sup>k</sup> |a†* and expansion schemes fail to account for superfluidity ab (ω) = −i l expansion schemes fail to account for superfluidit none 2π ion schem C Standard expansion schemes fair to account for supermularly

 $G_{\mathbf{F}}$ <sup>(1)</sup>  $GF$  theory to superfluid systems der incory to dupermum dydic  $\bullet$ ses CF theory to synerfluid s  $\circ$  Gorkov scheme generalises GF theory to superfluid s v to superfluid systems cheme generalises GF theory to superfluid systems  $\sim$  (C18) C↑ **π**  $\sim$  $\boldsymbol{\mathsf{C}}$ eneralisد **GOTKOV SCHEME GENETALISES**  $\overline{a}$  $\odot$  Gorko Theory to supern<br>|e number) to effe v scheme generalises GF theory to superfluid syste "  $\alpha$ 2π or 2π .<br>1i 2π  $\odot$  Gorkov scheme generalises GF theory to superfluid systems

o Use symmetry breaking (particle number) to effectively include pairing correlations rticle fiumber) to enectively include pairing correlati  $\sim$  expressed  $\sim$ ab(ω) ≡ ↑ ω  $\circ$  Use symmetry breaking (particle number) to effect ively include pairing co  $\gamma$ mmetry breaking (particle number) to effectively include  $\gamma$ dω′  $\mathbf{u}$ correla  $\alpha$  $\frac{1}{2}$ ○ Use symmetry breaking (particle number) to effectively nclud  $\frac{1}{\sqrt{2}}$ airit اg correla  $\overline{\phantom{a}}$ 2  $\overline{\mathbf{c}}$ o Use symmetry breaking (part ح<br>۱ metry breaking  $\circ$  Us <mark>ymmetr</mark> f<mark>ectively i</mark>n ---<br>ev  $\alpha$  poiring correction <sup>7</sup>ely include t**ry breaking** (particle number) to effectively include pairing corre .<br>2010 2π  $\mathbf{h}$ g (particle number) to effectively include pai:

 $|\Psi_0\rangle \equiv$  $\sum$  $c_A \, |\psi_0^A\>$ ○ Start expansion from symmetry-breaking reference | <sup>|</sup>  $\overline{C}$  $\sigma$  $ce$  $|\Psi_0\rangle \equiv$  $|\Psi_{\Omega}\rangle$  $\ket{a} \equiv \sqrt{a}$  $\sum_{\text{C}\,A}$ expansion from symmetry-breaking reference  $\frac{1}{\sqrt{2}}$  $\int C A$  $|\psi$ A<br>)  $\mathcal{S}$  are the same of the same of the same of the reducible case, with  $\mathcal{S}$ the only difference that dressed propagators (C9) have to o Start expansion from syn  $\ket{\Psi_{\text{0}}}$  $=$  $\sum$  $\sum c_A$  $_4\,|\psi^\n_0$  $\overline{\!\!\mathcal{V}}$ Jahon<br>Jan symme  $rt$  expansion Start expansion from symmetry-breaking reference  $|\Psi_0\rangle \equiv \sum_A c_A |\psi_A\rangle$  $\mathbf{e}$  $\langle 0 \rangle$  =  $\frac{1}{\sqrt{2}}$  $\frac{1}{2}$  $\overline{6}$ 

 $\sqrt{2}$  tone body Gornov propagators i film and the state of the <sup>o</sup> 4 one-body Gorkov propagators ∂ 4 one-body Gorkov propa 2 ω′ + ω<sup>k</sup> − iη uy G oropaga one-body Gorkov propagators

), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28), (28),

 $\overline{\phantom{a}}$ 

and and an<br>box of the contract of the con<br>and the contract of the contract of

cd<br>code<br>code )

2π

<sup>N</sup> <sup>c</sup><sup>N</sup> <sup>G</sup>11 (N,N)

<u>Σ</u>

 $\frac{1}{\sqrt{2}}$ 

2

Start expansion from symmetry-breaking reference 
$$
|\Psi_0\rangle \equiv \sum_{A}^{\text{even}} c_A |\psi_0^A\rangle
$$
  
4 one-body Gorkov propagators 
$$
G_{ab} = \begin{pmatrix} G_{ab}^{11} & G_{ab}^{12} \\ G_{ab}^{21} & G_{ab}^{22} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}
$$

ab defined in Gorkov's space

!

V¯

"

dω′

 $\frac{1}{2}$ ωk3 + iη i

and and an<br>construction

"

 $\overline{\phantom{a}}$ 

 $\overline{\phantom{0}}$ 

"

)

a<del>ndari</del><br>Ca<sup>22</sup>

 $\overline{\phantom{a}}$ ′ )

 $[Gorkov 1958]$ 

 $\frac{1}{2}$  +  $\frac{1}{2}$ 

 $\circ$  Symmetry must be eventually restored try  $\overline{ }$  ${\bf S}$ ymmetry must be eventually restored in the contour can be contour can be contour formula to  ${\bf S}$ ○ Symmetry must be eventually restored



### Systematics of medium-mass nuclei

⦿ Calculation of complete mid-mass isotopic chains possible

○ Chiral N3LO 2N (500) + N2LO 3N (400 local/non-local) interaction, further SRG-ed to 2.0 fm-1



#### ⦿ **Total energies**

- Missing correlation energy from higher-order diagrams
- Overall trends reasonable

### Systematics of medium-mass nuclei

⦿ Calculation of complete mid-mass isotopic chains possible

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### ⦿ **Total energies**

- Missing correlation energy from higher-order diagrams
- Overall trends reasonable
- ⦿ **Energy differences (2N separation energies)**
	- *N*=20 gap overestimated
	- *N*=28 gap OK, pf shell well reproduced

### ○ Drip lines?

### Systematics of medium-mass nuclei

⦿ Charge radii along calcium and nickel chains



○ Large sensitivity on the employed nuclear Hamiltonian

○ Discrepancies between different Hamiltonians depend on the observable  $\circ$  Good reproduction of nuclear radii with NNLOsat  $\leftrightarrow$  saturation properties

#### Charge density distribution of <sup>34</sup>Si frequencies on  $\mathcal{L}$

**☉ Unconventional depletion** ("bubble") in the centre of  $ρ<sub>ch</sub>$  conjectured for <sup>34</sup>Si distribution, and for  $\frac{1}{2}$  one of  $\frac{1}{2}$  or  $\frac{1}{2}$  or itre of  $\rho_{ch}$  conjectured for  $\sigma$ 31

- $\circ$  Purely quantum mechanical effect (vacancy of  $\ell = 0$  states embedded in larger- $\ell$  orbitals)  $\sigma$  . The nuclear charge density can be obtained the set of  $\sigma$
- $\circ$  Conjectured associated effect on spin-orbit splitting (reduction for low- $\ell$  spin-orbit partners)
- ⦿ **Charge density** computed through folding with the finite charge of the proton  $\begin{bmatrix} 1 & c & 1 \end{bmatrix}$  contribution for our contribution  $\begin{bmatrix} 0 & 1 \end{bmatrix}$ and  $\alpha$  relativistic spin-orbit corrections  $\alpha$  is the transmitted term to the typical value of  $\alpha$  and  $\alpha$ [Duguet *et al.* 2017]



$$
\rho_{\rm ch}(r) = \sum_{i=1}^{3} \frac{\theta_i}{r_i \sqrt{\pi}} \int_0^{+\infty} dr' \frac{r'}{r} \rho_{\rm p}(r') \left[ e^{-\left(\frac{r-r'}{r_i}\right)^2} - e^{-\left(\frac{r+r'}{r_i}\right)^2} \right]
$$

distribution of protons but also for the protons but also for the protons but also for the protons of the inter

- ➟ Folding smears out central depletion superposition of three Gaussians and have been adjusted  $\rightarrow$  rolding sinears out central depietion
- **Good agreement with experiment for 36S**  $\left[1\right]$  Creminates density contribution  $\left[1\right]$ [Rychel *et al.* 1983]
	- $\sigma$  *c* 1 1 1 is present into a 210: **■ Central depletion predicted for 34Si**

 $\circ$  Ch factor, which relates to the nuclear charge density distribution  $\mathcal{L}_\text{c}$ **⊙** Charge form factor measured in (e,e) experiments sensitive to bubble structure?

would lead to measure the electromagnetic charge formulation the electromagnetic charge formulation  $\mathcal{L}_\text{max}$ 

0 )2*/a*<sup>2</sup> #

*,*



# On convergence

⦿ Calculations performed within different many-body truncations **E** ADC(1) ADC(3) ADC(3) ADC(3) EXPERIMENT ADC(3) EXPERIMENT ADC(3)

 $\circ$  ADC(1) = HF, ADC(2) & ADC(3)

### ⦿ **Model space convergence**



 $\odot$  Many-body convergence

Binding energies
and-state energies

at various charge radii  $\sigma$  truncation scheme are compared to ex-

$E$ [MeV]	$\mathrm{ADC}(1)$	ADC(2)	ADC(3)	$  $ Experiment
$34$ $Si$	-84.481	$-274.626$	$-282.938$	-283.427
36 <sub>S</sub>	$-90.007$	$-296.060$	$-305.767$	$-308.714$

 $\overline{\phantom{a}}$ ADC(3) brings only ~5% additional binding  $\qquad \qquad$  Radii converged already at ADC(2) level binding, which represents about 5% of the correlation enpattern of reduction in the correlation energy added at

Table is the state in the state  $\mathbf{S}$  and the original binding energies in the state in the state in the state in

ing to ADC(3) indeed brings about 8-10 MeV additional





 $P_1$  and  $P_2$  and  $P_3$  and  $P_4$  and  $P_5$  and  $P_6$  and  $P_7$  and  $P_8$  and  $P_7$  and  $P_8$  and  $P_9$  and Kadil converged aire

TABLE IV. Experimental charge radii (in the original charge radii (in th

Table in  $\mathcal{M}$  is a computed with  $\mathcal{M}$  in function  $\mathcal{M}$  in function  $\mathcal{M}$ 

## Spectral representation



 $\delta$  ominator result in the spectral function  $\delta$  $\overline{a}$  to the  $\overline{a}$ Combining numerator and denominator result in the spectral function Combining numerator and denominator result in the spectral function

where the first (second) sum is restricted to eigenstates of *H* in the Hilbert space *HA*+1 (*H<sup>A</sup>*<sup>1</sup>) associated with the

$$
\mathbf{S}(z) \equiv \sum_{\mu \in \mathcal{H}_{A+1}} \mathbf{S}_{\mu}^{+} \delta(z - E_{\mu}^{+}) + \sum_{\nu \in \mathcal{H}_{A-1}} \mathbf{S}_{\nu}^{-} \delta(z - E_{\nu}^{-})
$$
\n
$$
\longrightarrow \begin{pmatrix}\n\text{Spectral strength distribution} \\
\mathcal{S}(z) \equiv \text{Tr}_{\mathcal{H}_{1}}[\mathbf{S}(z)] \\
\qquad = \sum_{\mu \in \mathcal{H}_{A+1}} SF_{\mu}^{+} \delta(z - E_{\mu}^{+}) + \sum_{\nu \in \mathcal{H}_{A-1}} SF_{\nu}^{-} \delta(z - E_{\nu}^{-}) \\
\qquad \qquad + \sum_{\mu \in \mathcal{H}_{A+1}} SF_{\mu}^{-} \delta(z - E_{\mu}^{-})\n\end{pmatrix}
$$

*<sup>G</sup>ab*(*z*) = <sup>X</sup>

 $\frac{X}{X}$ 

<sup>0</sup> *<sup>|</sup>a<sup>a</sup> <sup>|</sup> <sup>N</sup>*+1 *<sup>µ</sup>* ih *<sup>N</sup>*+1 *<sup>µ</sup> | a† b<sup>|</sup> <sup>N</sup>* <sup>0</sup> i  $\pmb{\mathbb{S}}$ er Spectral representation  $\mu = \mu$  $\mu$   $E_0$  $\mathbf 0$  $|\Psi_{\kappa}^{N\pm1}\rangle$  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\frac{1}{2}$ ⌫ *z E* ⌫ on *H*<sup>1</sup> through  $\mu = \frac{1}{\mu}$  . The spectral function  $S(\mu)$ . The spectral function denotes an energy- $\frac{1}{2}$ Sentation

 $\overline{\phantom{a}}$ 

*<sup>r</sup>*<sup>0</sup> *<sup>|</sup> <sup>N</sup>*<sup>1</sup>



## Spectral strength in experiments

⦿ Clean connection to (*e,e'p*) experiments



○ Measuring **q** and **p** gives information on **pm** ○ Similarly for missing energy Em  $\circ$  Spectral strength distribution  $\leftrightarrow$  P(p<sub>m</sub>, E<sub>m</sub>)

⦿ Spectroscopy via knockout/transfer exp.



⦿ 34Si neutron addition & removal strength



### **ADC(1)**

○ Independent-particle picture

**☉** <sup>34</sup>Si neutron addition & removal strength



#### **ADC(2)**

○ Second-order dynamical correlations fragment IP peaks

**☉** <sup>34</sup>Si neutron addition & removal strength



#### **ADC(3)**

○ Third-order compresses the spectrum (main peaks) ○ Further fragmentation is generated



○ Third-order correlations compress the spectrum ○ Further fragmentation is generated

Reduction of  $E_{1/2}$  -  $E_{3/2}$  spin-orbit splitting (unique in the nuclear chart) well reproduced

### Spectral function of 40Ar



Neutrons Protons Protons



### Spectral function of 40Ar

⦿ ADC(2) truncation, NNLOsat interaction

-40 -30 -20 -10 0 10 20 0.01 0.1 1 7/2-  $E_k^{\pm}$  [MeV] 0.01 0.1 1 3/2- 0.01 0.1 1  $5/2^+$ 0.01 0.1 1  $3/2^{+}$ L<br>S  $\overline{\mathbf{K}}$  $^{\mathrm{+}}$ 0.01 0.1 1 1/2- 0.01 0.1  $\overline{^{39}Ar}$   $|$   $|^{41}Ar$ -40 -30 -20 -10 0 10 20 0.01 0.1 1 7/2-  $E_k^{\pm}$  [MeV] 0.01 0.1 1 3/2- 0.01 0.1 1  $5/2^+$ 0.01 0.1 1  $3/2^{+}$ SF  $\overline{\mathbf{K}}$  $\pm$ 0.01 0.1 1  $1/2^{-}$ 0.01 0.1  $1^{39}$ Cl  $1^{1}$   $1^{41}$ K

Neutrons Protons

## Spectral function of 40Ar

⦿ ADC(2) truncation, NNLOsat interaction



#### Fragmentation of single-particle strength in infinite matter riagnichianon of single-particle in all the quantities shown  $\mathcal{L}$ trength in infinite matter  $\blacksquare$

#### numerical solution of Eq. (8), shown with a cross. **◉ Spectral function depicts correlations**

location of the fully dressed pole is consistent with the

- renormalization properties are visible and properties are visible and  $\alpha$  $\circ$  broad peak signals depart from mean-field / independent partic <sup>o</sup> Broad peak signals depart from mean-field/independent particle picture  $\frac{1}{2}$  $\mathcal{L}_{\mathcal{D}}$  fm  $\mathcal{L}_{\mathcal{D}}$  fm  $3$  TeV  $\mathcal{L}_{\mathcal{D}}$  and  $\mathcal{L}_{\mathcal{D}}$
- o Well-defined (long-lived) quasiparticles at the Fe  $\circ$  Well-defined (long-lived) quasiparticles at the Fermi surface ○ Well-defined (long-lived) quasiparticles at the Fermi surface
- $\circ$  Long mean free path for  $\rm E < E_{F}$



### Electromagnetic response

(*E*)=4⇡<sup>2</sup>↵ *ER*(*E*) (91)

(*E*)=4⇡<sup>2</sup>↵ *ER*(*E*) (91)

⦿ Nuclear response produced by an isovector dipole operator



⦿ Total photoabsorption cross section

$$
\sigma_{\gamma}(E) = 4\pi^2 \alpha ER(E)
$$

⦿ Dipole polarisability

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

# Electromagnetic response

⦿ Computed σ from RPA response vs. σ from photoabsorption and Coulomb excitation

160  $R = \frac{1}{2}$ **SCGF** 140  $100<sup>1</sup>$ Ahrens 120 160  $120$ DysADC3\_RPA, NI DysADC3 RPA, NNLOsat bare • Leistneschneider ( Ahrens 1 (1975)  $\sigma(\mathrm{E}_X)[\mathrm{mb}]$  $100$ 140  $16<sub>C</sub>$ 100 • **Ahrens 2 (1975)** 120 80  $16$ O  $N_{max}=13, \hbar\omega=20$ 100  $\sigma(\mathbf{E}_X)$  [mb]  $_{\chi}$ )  $[\mathrm{mb}]$  $\alpha_D = 0.7242$  $N_{max}=13$ ,  $\hbar\omega=20$  MeV 60 80  $\alpha_D = 0.499596 fm^3$ σ(E 60  $40\,$ 40 20 20  $0<sub>0</sub>$  $\mathbf{0}$  $\overline{3}$  $\overline{\overset{30}{\mathbf{E}_X}$  [MeV] 60 0 10 20 30 40 50 60 70 80 20 30 10 40 50  $\mathbf{E}_X$  [MeV]  $\mathbf{E}_X$  [MeV]  $\mathbf{L}$ <sub>X</sub> [*NICV*]

○ GDR position of 16O well reproduced  $\mathbf{e}^{(1)}$  and the neutron-rich isotopedia soft dipole mode on the neutron-rich isotopedia soft dipole mode on the neutron-rich isotopedia soft dipole model is  $\mathbf{e}^{(1)}$ 

- Hint of a soft dipole mode in 22O
- $\circ$  Comparison with CC LIT results for  $\alpha_D$



[Raimondi *et al.* in preparation]

# Electromagnetic response

⦿ Computed σ from RPA response vs. σ from photoabsorption and Coulomb excitation **Example topes which and Caulamb** excitation



○ GDR positions reproduced ○ Total sum rule OK but poor strength distribution  $\circ$  Comparison with CC LIT results for  $\alpha_D$ 



### **EXECUTING RECOPPONDE** Electromagnetic response

@ Comparison with coupled-cluster Lorentz integral transform (CC-LIT)

[Raimondi *et al.* in preparation] In and M. Miorelli and S. Bacca (TRAINS) and S. Bacca (TRAINS) and S. Bacca (TRAINS) and S. Bacca (T



o Different ways of including correlations

- $\sim$  Little problem to a bound-state-like problem to a bound-state-like problem to a bound-state-like problem to a bound-state problem to a bound-state problem to a bound-state problem to a bound-state-like problem to a b  $GF \rightarrow RPA$  (first-order 2-body correlator) on top of fully correlated reference state
	- $CC \rightarrow SD$  (analogous to second RPA) on top of HF reference state

## Conclusions

### ⦿ **Ab initio calculations routinely access mid-mass nuclei**

- Many-body formalism well grounded
- Interactions currently represent largest source of uncertainty
- Pragmatic choices lead to successful applications
- Thorough assessment of theoretical error?



#### ⦿ **Self-consistent Green's function approach gives access to a variety of observables**

- Ground-state properties along isotopic chains, spectral functions, response functions
- $\circ$  Case of <sup>40</sup>Ar to be investigated in ADC(3) scheme (work in progress...)