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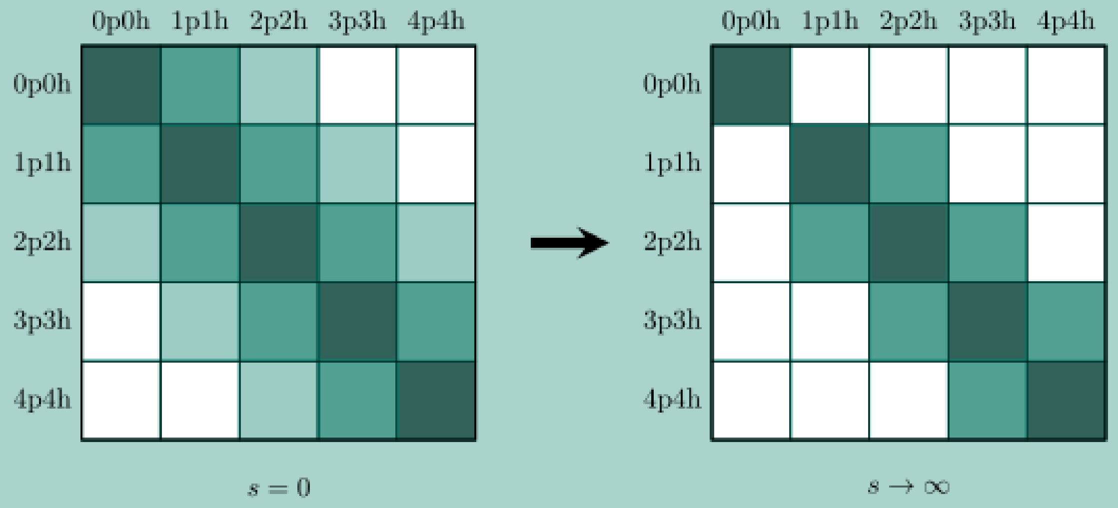
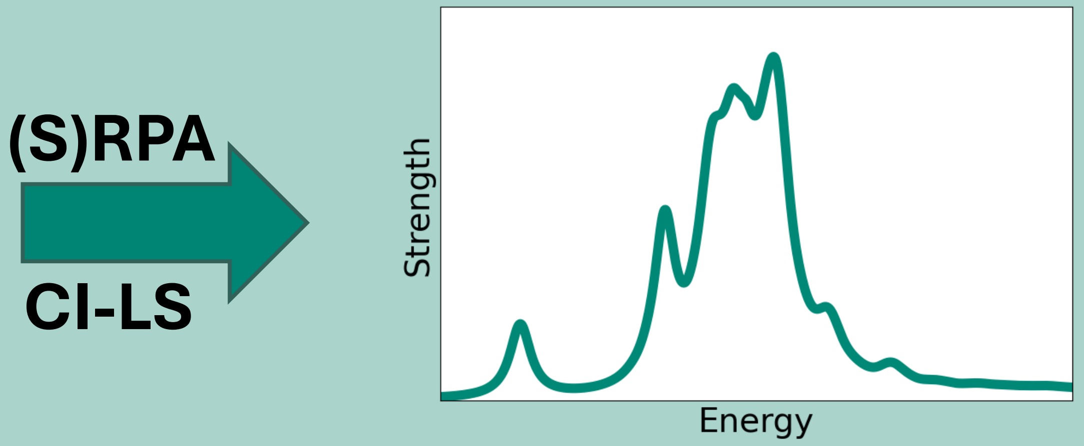
Towards Collective Excitations in Open-Shell Nuclei: From IM-(S)RPA to IM-CI

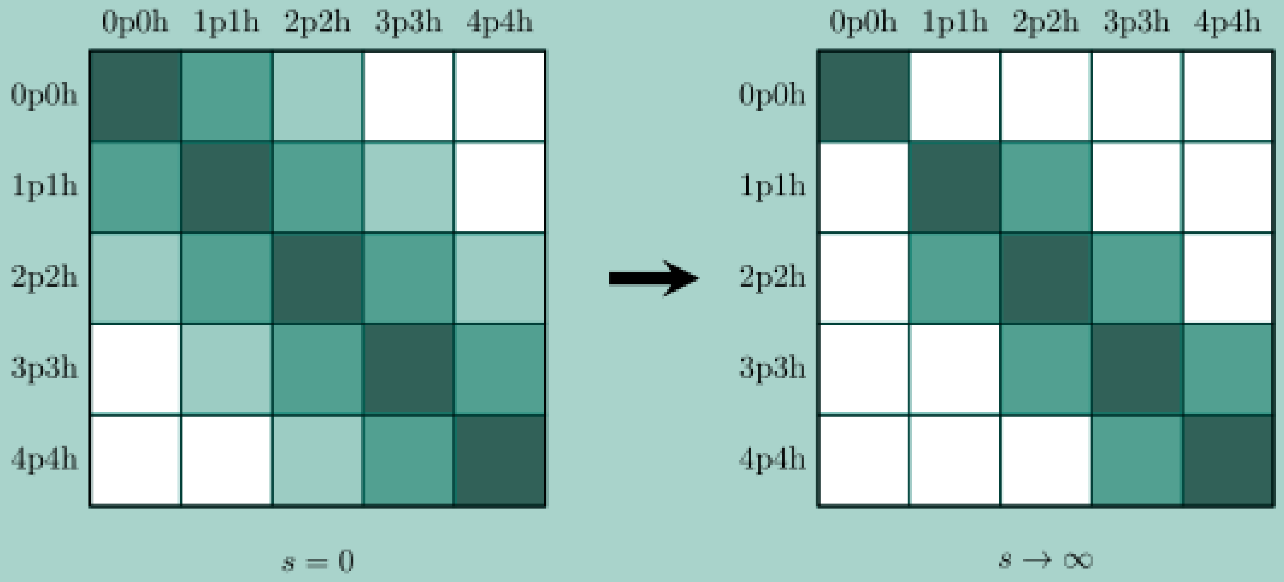
Michelle Müller





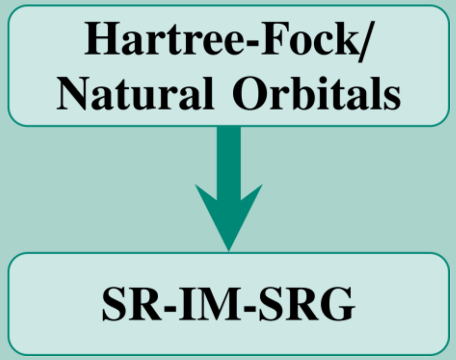
In-Medium Similarity Renormalization Group

- reference state is decoupled from its ph excitations



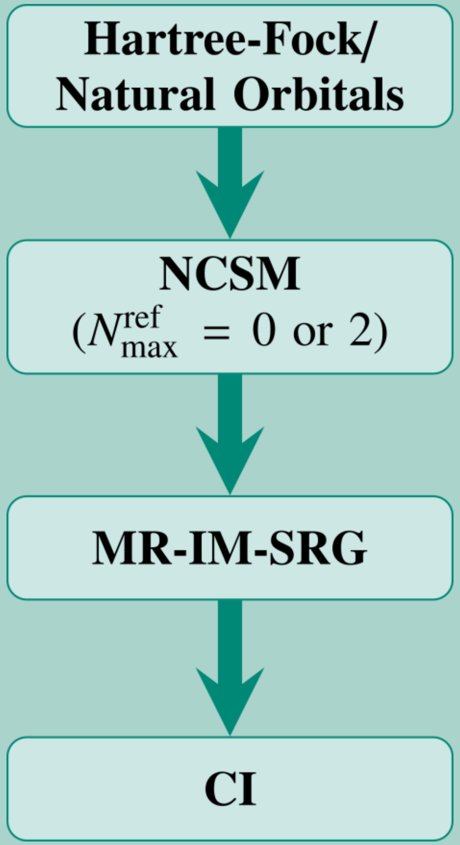
In-Medium Similarity Renormalization Group

Single-Reference IM-SRG



closed-shell nuclei

Multi-Reference IM-SRG



open-shell nuclei

Random-Phase and Tamm-Dancoff Approximation

- standard methods to describe giant resonances in closed-shell nuclei

- **(S)TDA:** excited states built on Hartree-Fock ground state via 1p1h (+2p2h) excitations

- **(S)RPA:** excited states built on correlated ground state via 1p1h (+2p2h) excitations and de-excitations

  but: typically, ground state is replaced by Hartree-Fock state via quasi-boson approximation

In-Medium (S)RPA and (S)TDA

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- idea: implementing SR-IM-SRG evolved matrix elements in (S)RPA

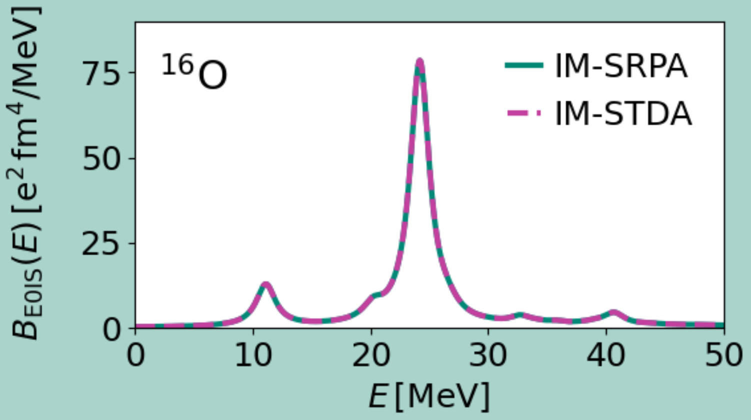
  → improved treatment of correlations *beforehand* (i.e. in IM-SRG), while maintaining simple structure of the formalism

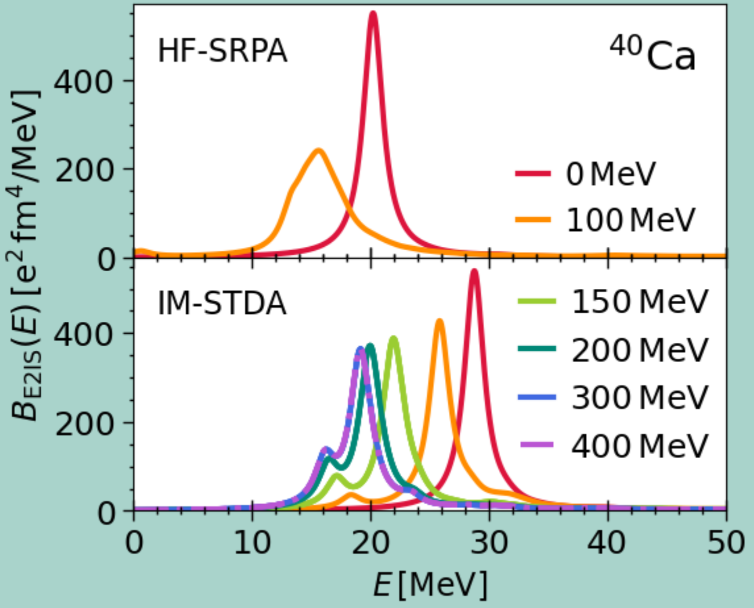
- for IM-(S)RPA, all contributions from de-excitations vanish

  → IM-(S)RPA is reduced to IM-(S)TDA

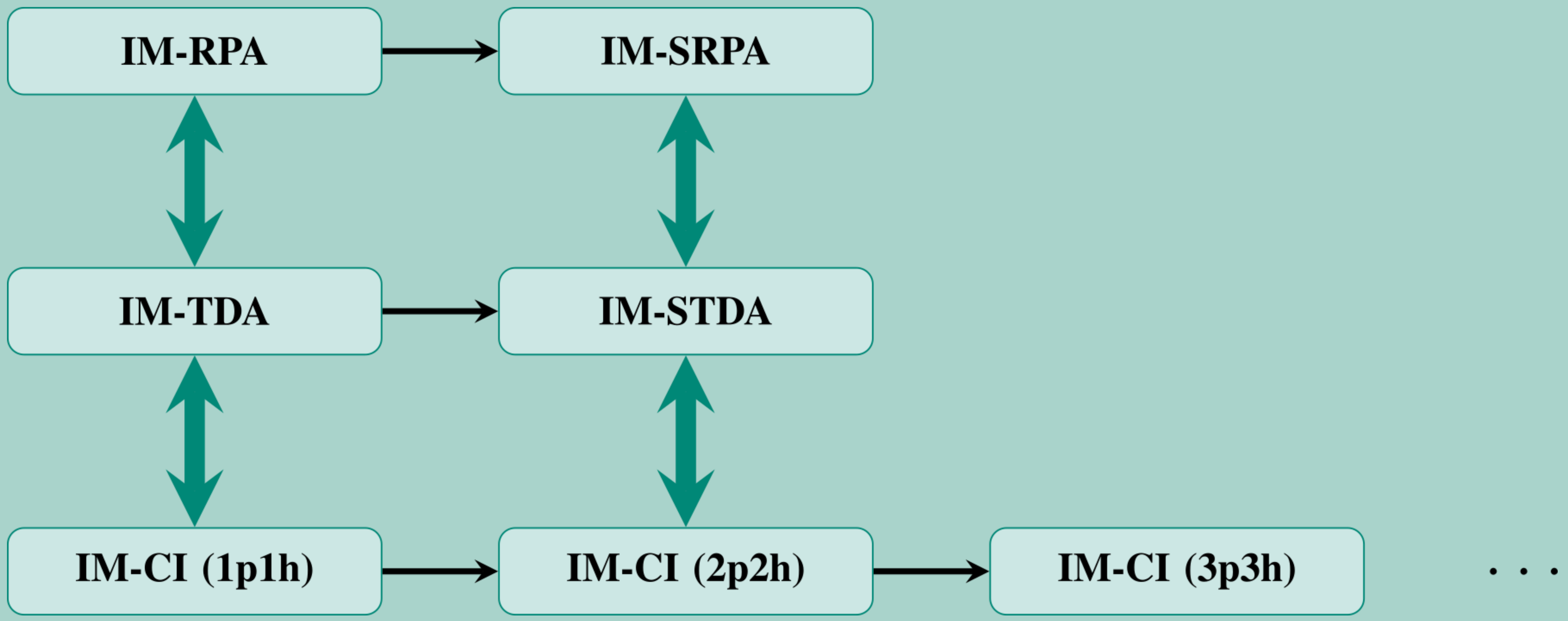
  → improvement in computational effort

  → access to converged results for heavier nuclei, e.g. $^{40}\mathrm{Ca}$ or $^{48}\mathrm{Ca}$





From IM-(S)TDA to IM-CI



CI with Lanczos Strength-Function Method

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- relatively novel approach to calculate transition strengths
- idea: constructing orthonormal basis $V_p = (\vec{v}_1, \vec{v}_2, ..., \vec{v}_p)$ in which Hamiltonian becomes tridiagonal
- clever choice of **pivot vector**

electric multipole operator

$$|v_1\rangle = \frac{1}{\sqrt{S}} \hat{T}_{\mathrm{E}\lambda}|\Psi_0\rangle, \quad S = \langle\Psi_0|\hat{T}^\dagger_{\mathrm{E}\lambda}\hat{T}_{\mathrm{E}\lambda}|\Psi_0\rangle$$

- diagonalization of tridiagonal matrix yields approximate Hamiltonian eigenpairs

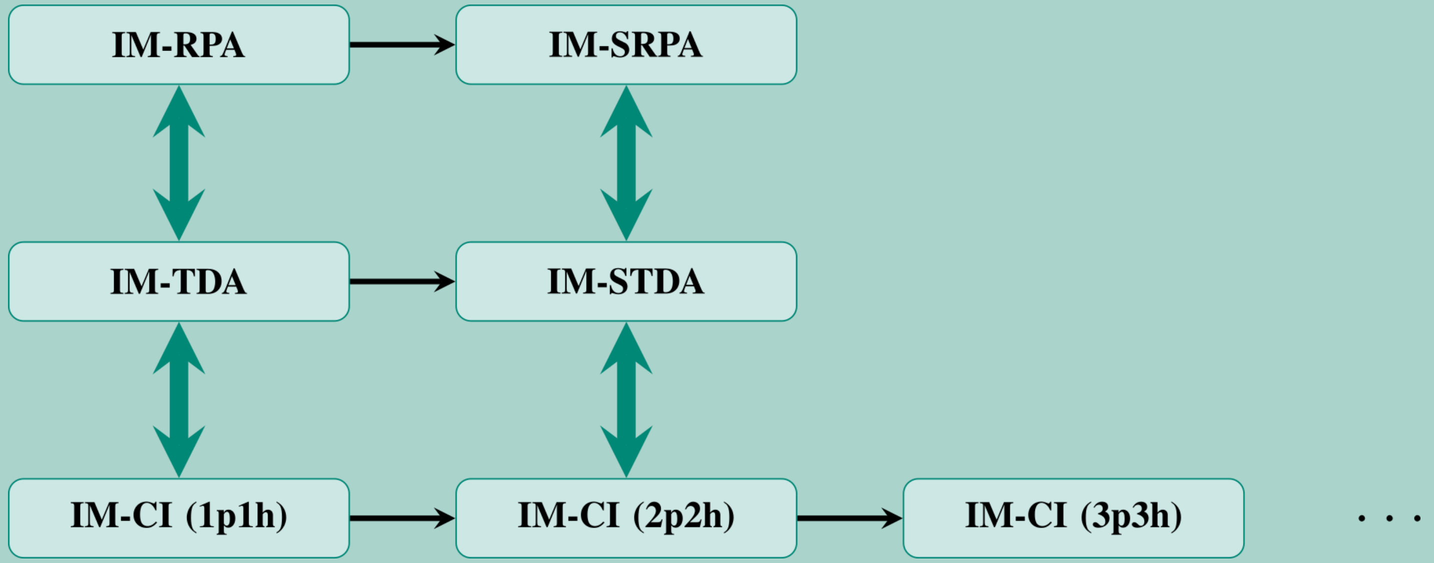
$$|\Phi_n\rangle = \sum_{j=1}^{p} C_j^{(n)}|v_j\rangle$$

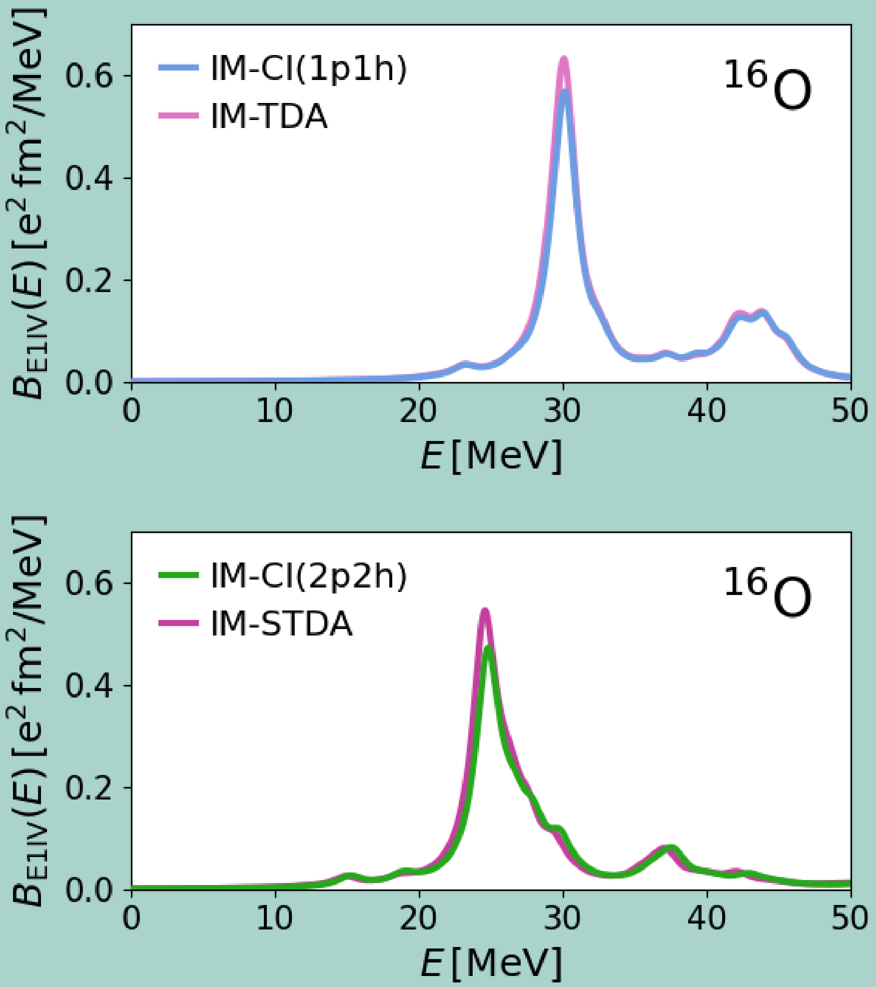
- due to choice of pivot vector: first coefficient provides **transition matrix element**

$$C_1^{(n)} = \langle\Phi_n|v_1\rangle = \frac{1}{\sqrt{S}}\langle\Phi_n|\hat{T}_{\mathrm{E}\lambda}|\Psi_0\rangle$$

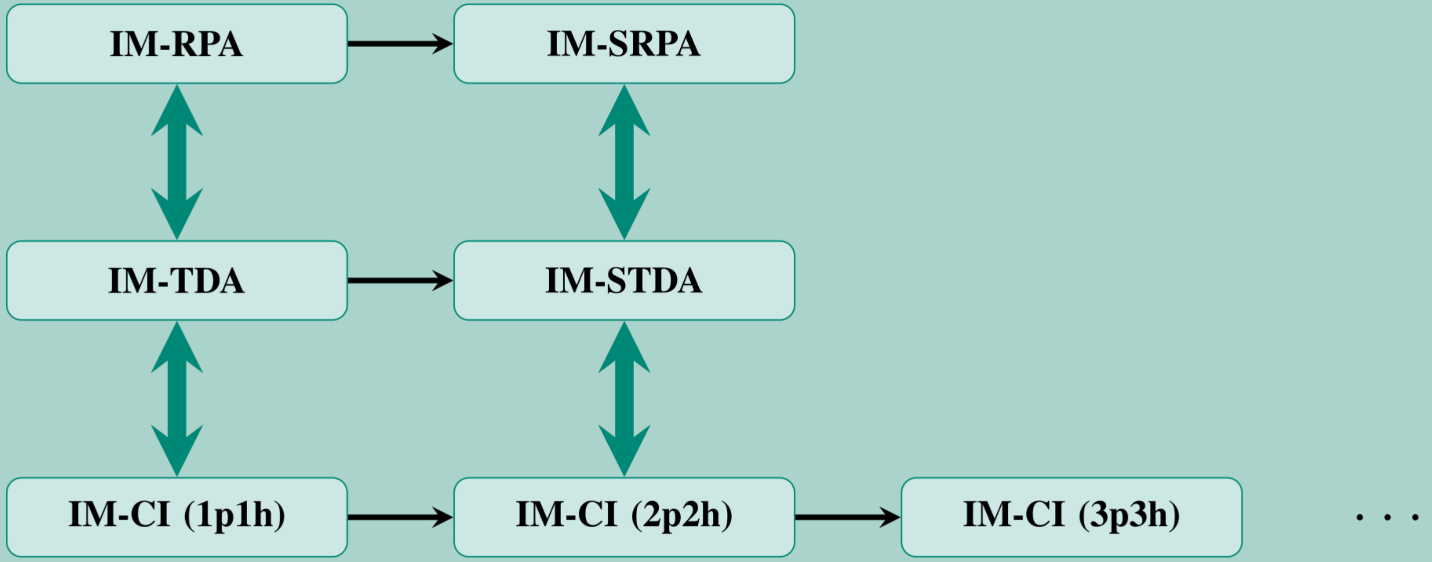
← **ground state determined by preceding CI**

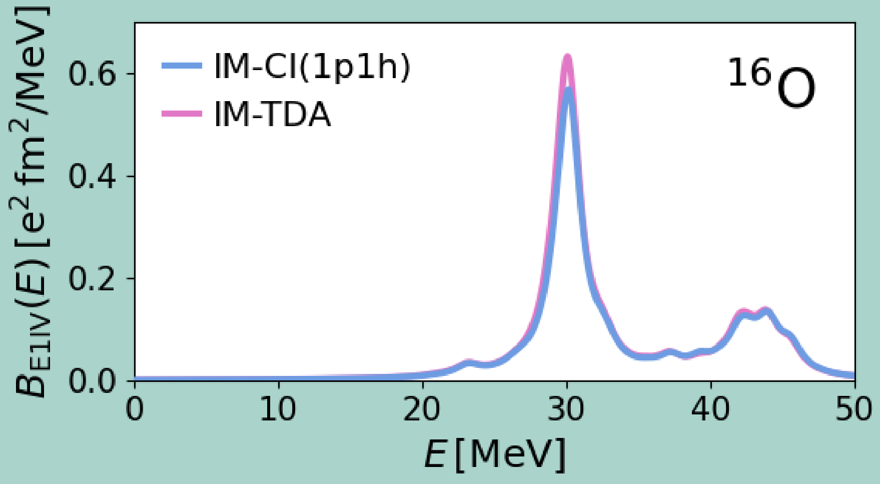
In-Medium CI with Lanczos Strength-Function Method

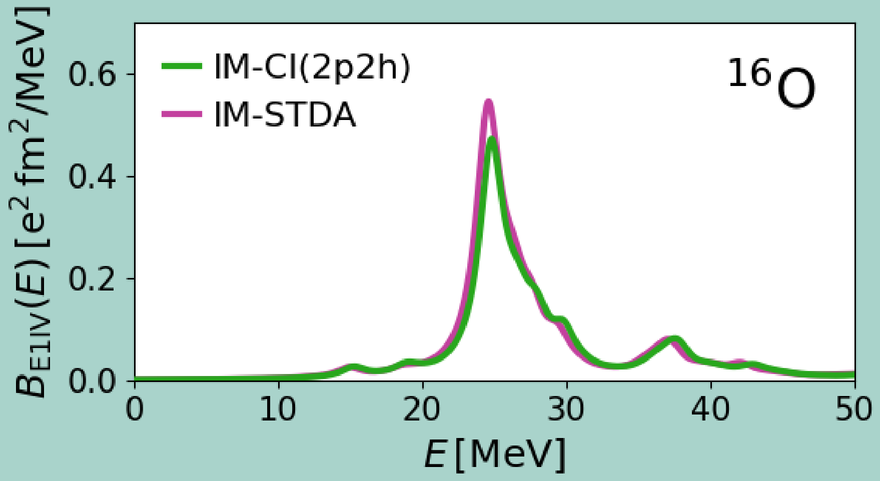




In-Medium CI with Lanczos Strength-Function Method







- two major advantages of CI compared to (S)RPA and (S)TDA:
  1. possibility to study **higher ph ranks** (convergence!)
  2. access to **open-shell** nuclei

In-Medium CI with Lanczos Strength-Function Method

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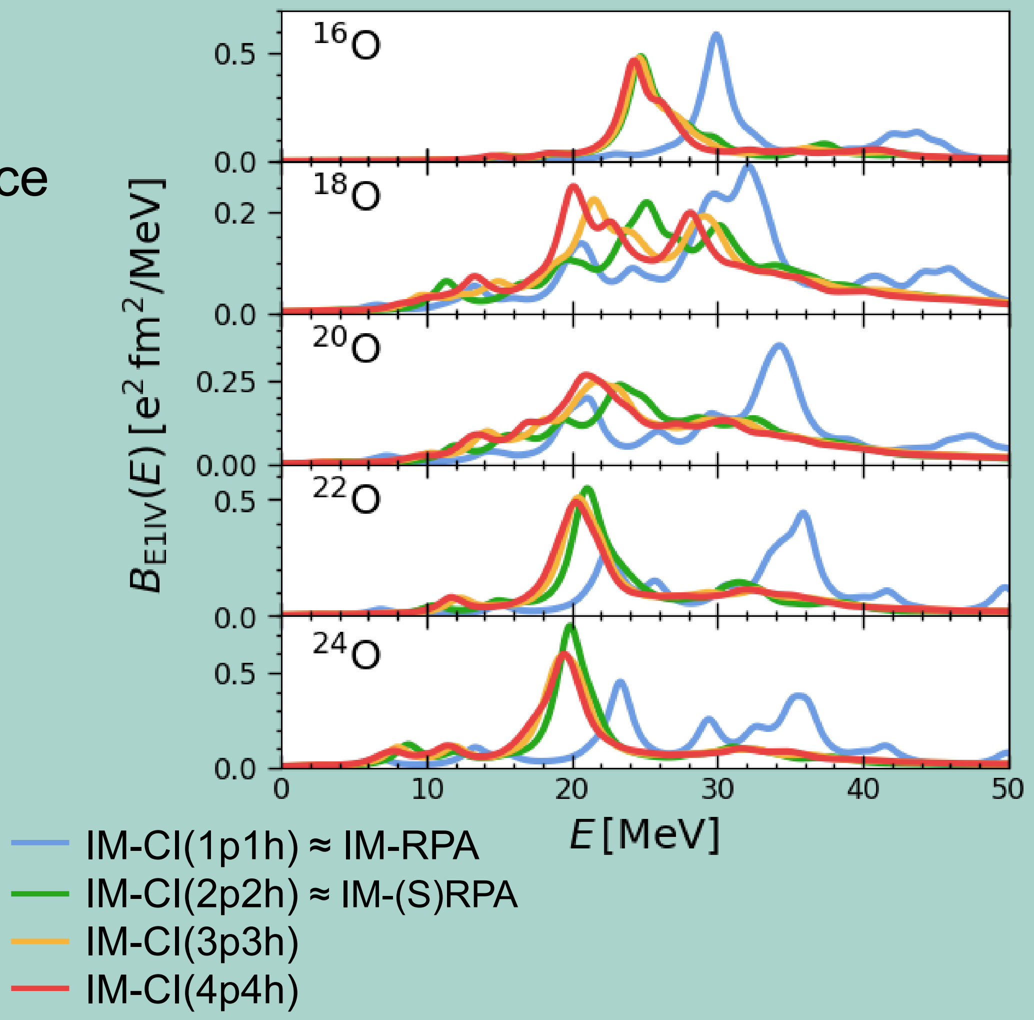
Oxygen Isotopes – E1IV

- truncation at 1p1h rank yields results far from convergence
- truncation at 2p2h rank already provides results close to convergence for most oxygen isotopes
- strength distributions are converged at 3p3h level for all oxygen isotopes except $^{18}\mathrm{O}$



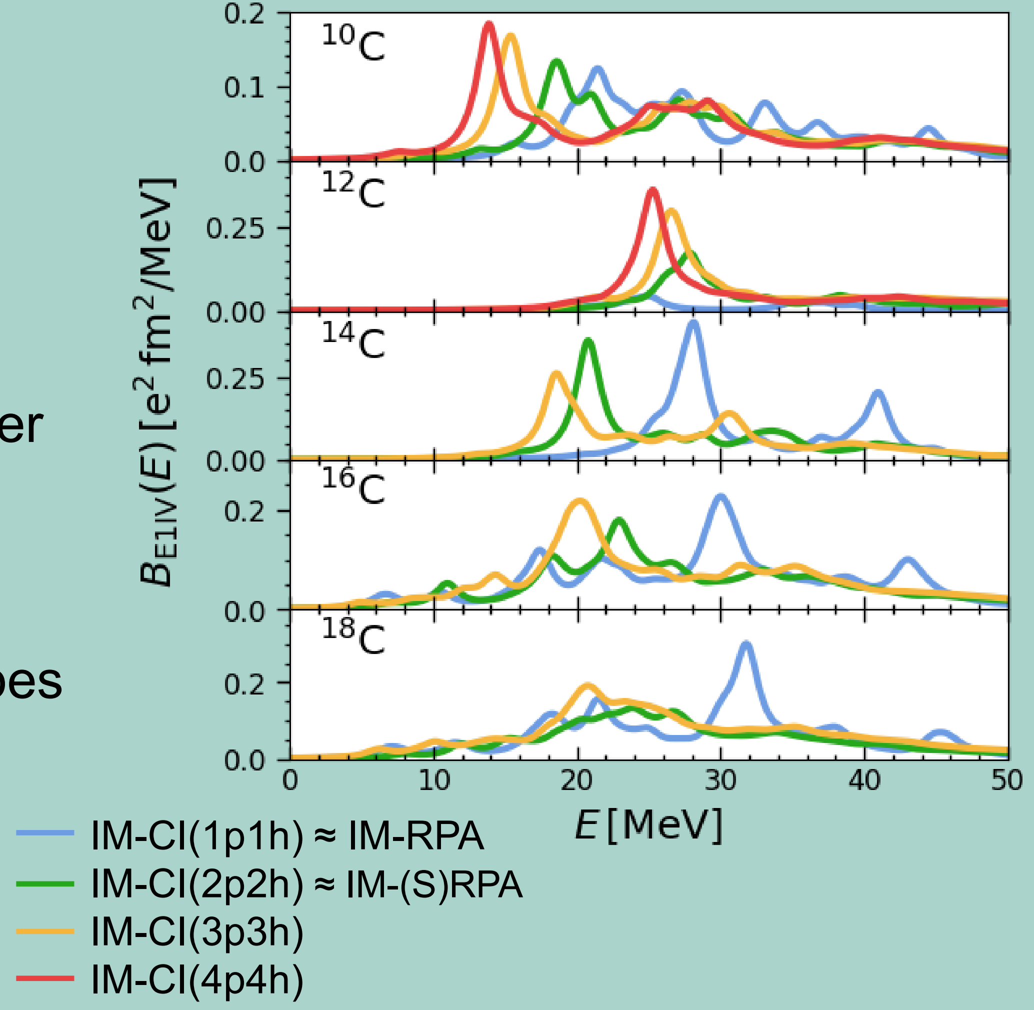
In-Medium CI with Lanczos Strength-Function Method

Carbon Isotopes – E1IV

- both 1p1h and 2p2h truncations yield results far from convergence for most carbon isotopes

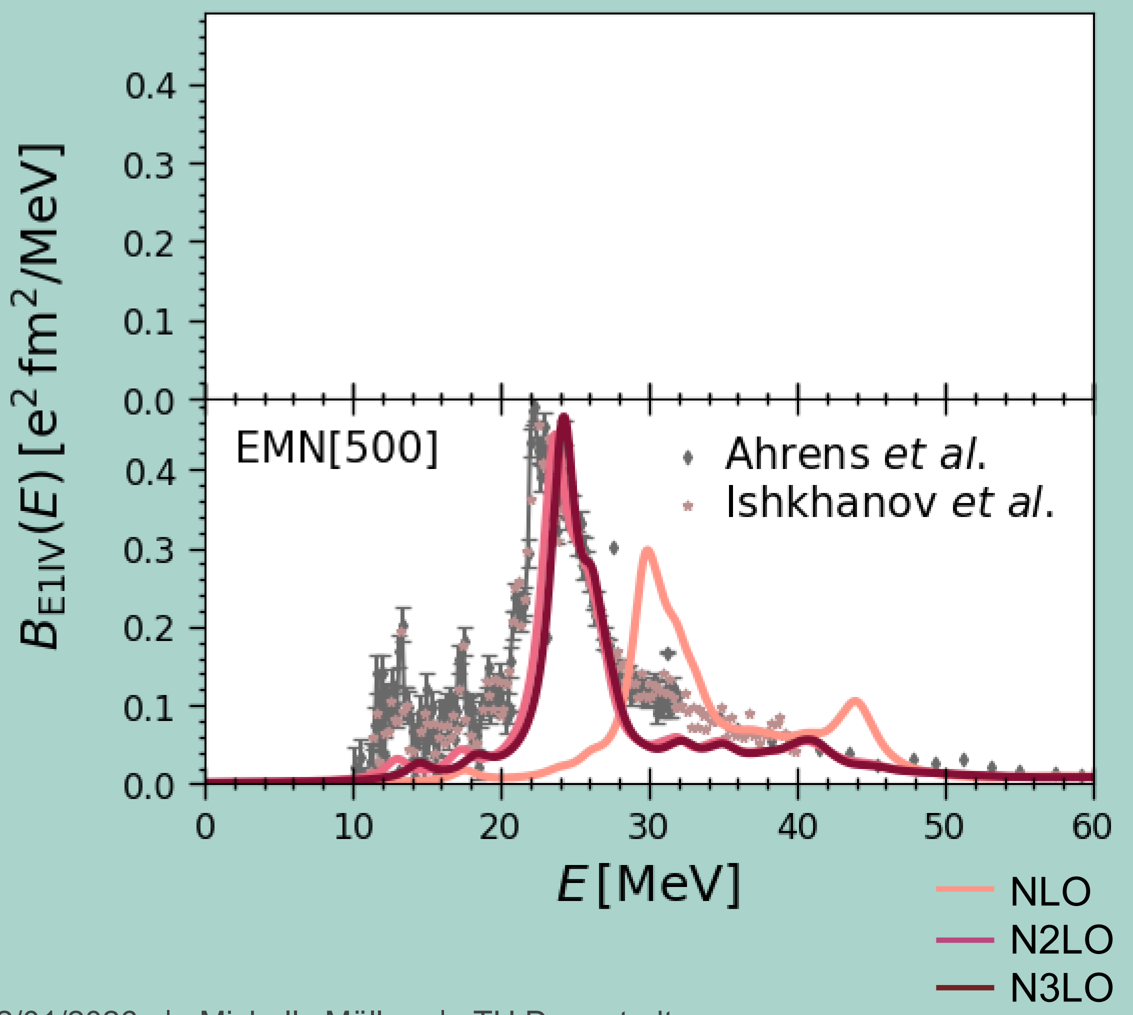
- significant downward shifts of the main peaks when higher ph ranks are included

- higher contributions than 3p3h necessary for most isotopes



Impact of Interaction Cutoffs

^{16}O



- interaction applied in plots throughout the talk: chiral NN+3N interactions with cutoff of 500 MeV

  NN: Entem, Machleidt, Nosyk, Phys. Rev. C 96, 024002 (2017)
  3N: Hüther, Vobig, Hebeler, Machleidt, Roth, Phys. Lett. B 808, 135651 (2020)

  → reasonable results for ground-state observables

- comparing different chiral orders at 4p4h truncation
- N2LO and N3LO yield similar strength distributions
- strengths at higher energies compared to experiment

  → also found for other transition modes and nuclei

Impact of Interaction Cutoffs

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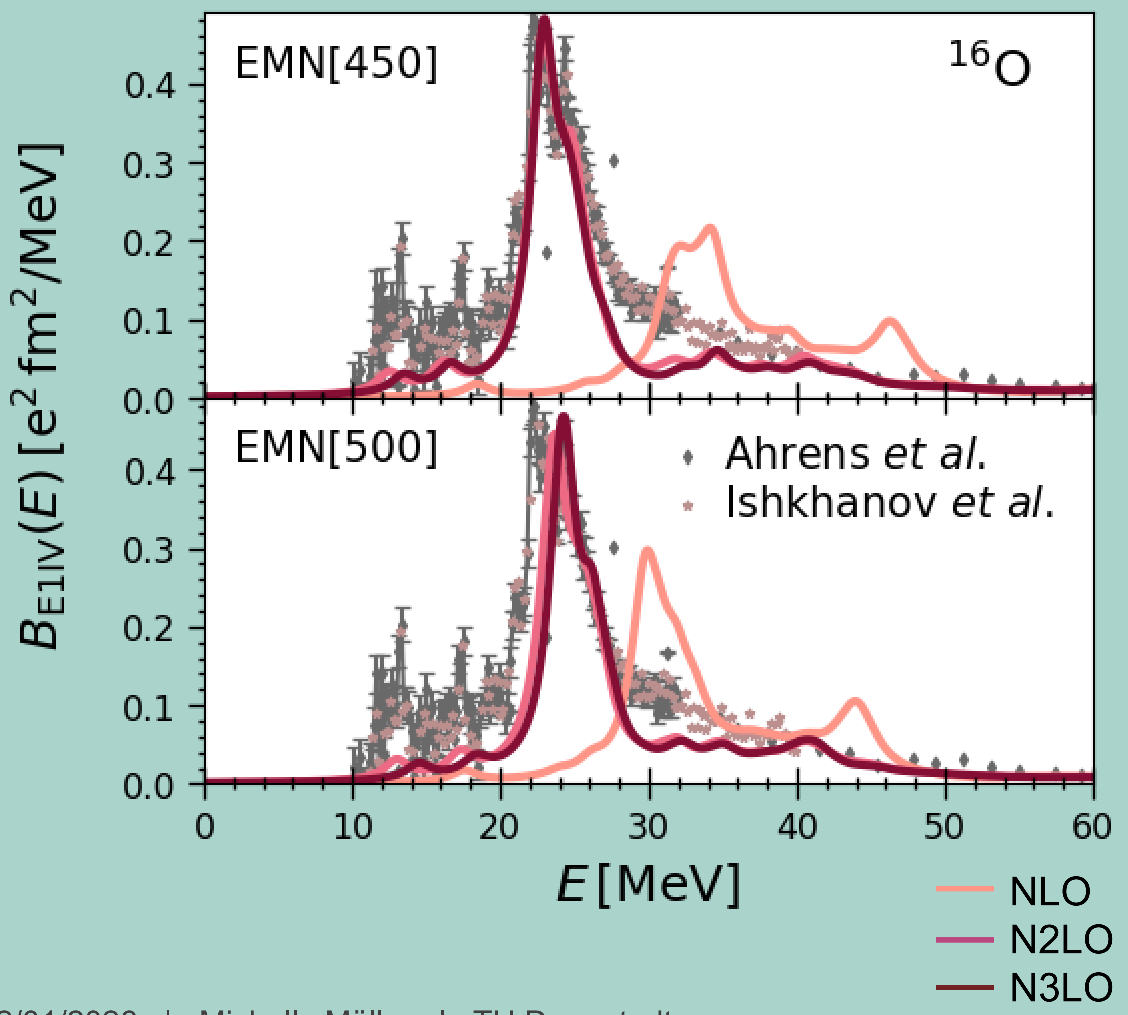
^{16}O



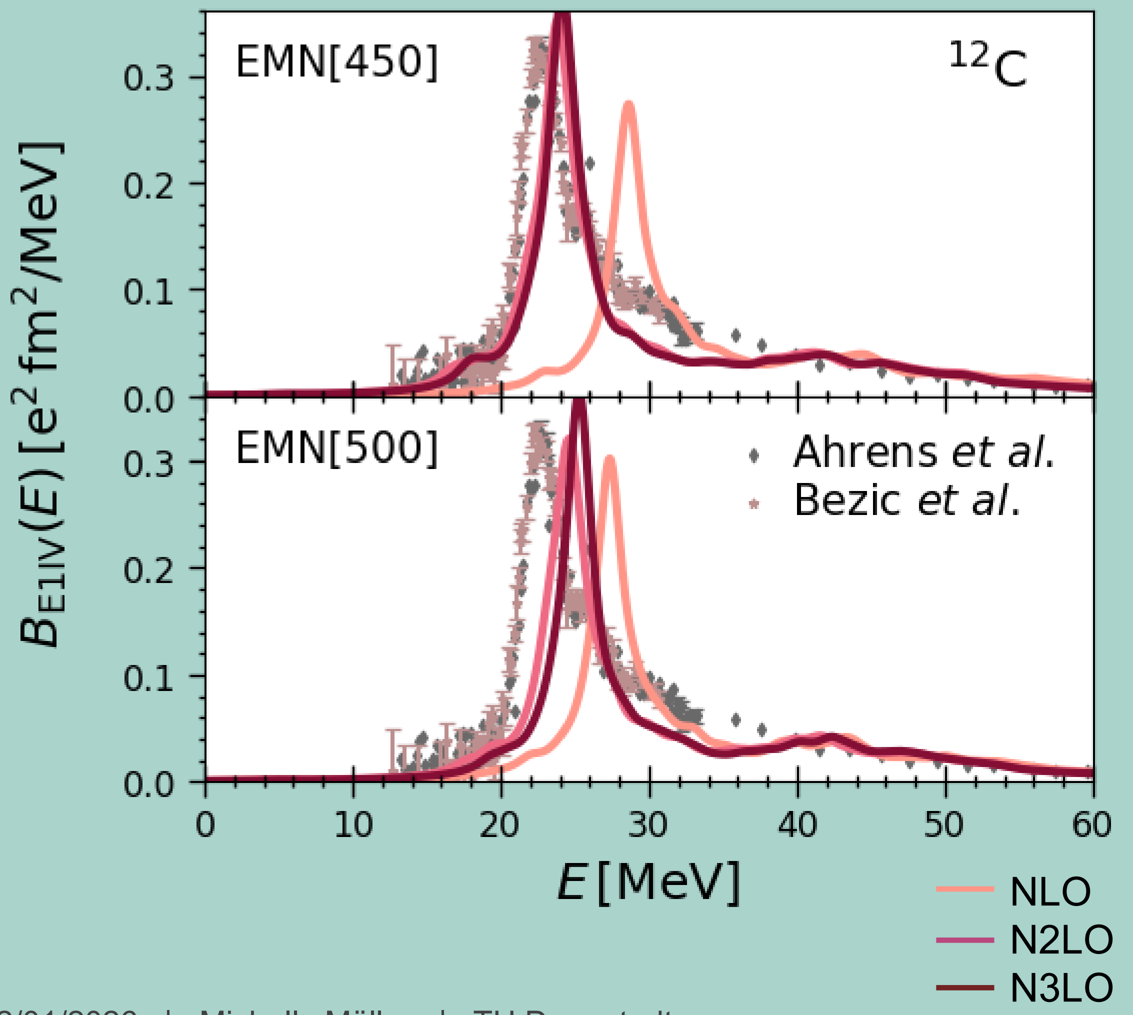
- chiral NN+3N interactions at two different cutoffs

  NN: Entem, Machleidt, Nosyk, Phys. Rev. C 96, 024002 (2017)
  3N: Hüther, Vobig, Hebeler, Machleidt, Roth, Phys. Lett. B 808, 135651 (2020)

- comparing different chiral orders at 4p4h truncation
- N2LO and N3LO yield similar strength distributions
- 450MBO at N3LO consistent with experimental data

Impact of Interaction Cutoffs

^{12}C



- chiral NN+3N interactions at two different cutoffs

  NN: Entem, Machleidt, Nosyk, Phys. Rev. C 96, 024002 (2017)
  3N: Hüther, Vobig, Hebeler, Machleidt, Roth, Phys. Lett. B 808, 135651 (2020)

- comparing different chiral orders at 4p4h truncation (reminder: ^{12}C is not converged at this truncation)
- N2LO and N3LO yield similar strength distributions
- 450MBO at N3LO close to experimental data

Conclusion and Outlook

Take-Home Messages

- inclusion of IM-SRG improves treatment of correlations
- IM-(S)RPA, IM-(S)TDA and IM-CI are formally equivalent methods
- IM-CI allows exploration of higher ph ranks and open-shell nuclei
- 450MBO yields strength distributions consistent with experimental data

Future Plans

- further studies of interaction dependence: different interaction families and cutoffs
- giant resonances in heavier nuclei, e.g. Neon isotopic chain: investigation of deformation effects

Thank you for your attention!

Backup Slides

CI with Lanczos Strength-Function Method

- relatively novel approach to calculate transition strengths
- idea: constructing orthonormal basis $V_p = (\vec{v}_1, \vec{v}_2, ..., \vec{v}_p)$ in which Hamiltonian becomes tridiagonal
- recursive formulation of Lanczos vectors

$$\vec{v}_{i+1} = \frac{1}{\beta_i}(H\vec{v}_i - \beta_{i+1}\vec{v}_{i-1} - \alpha_i\vec{v}_i)$$

$$\alpha_i = \vec{v}_i^T H\vec{v}_i, \quad \beta_i = ||H\vec{v}_i - \beta_{i-1}\vec{v}_{i-1} - \alpha_i\vec{v}_i||$$

- clever choice of **pivot vector**

$$|v_1\rangle = \frac{1}{\sqrt{S}}\hat{T}_{\mathrm{E}\lambda}|\Psi_0\rangle, \quad S = \langle\Psi_0|\hat{T}^\dagger_{\mathrm{E}\lambda}\hat{T}_{\mathrm{E}\lambda}|\Psi_0\rangle$$

↑ **electric multipole operator**

CI with Lanczos Strength-Function Method

- after *p* iteration steps, Hamiltonian can be rewritten in tridiagonal form:

$$H_p = \begin{pmatrix} \alpha_1 & \beta_1 & 0 & \dots & 0 \\ \beta_1 & \alpha_2 & \beta_2 & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & \beta_{p-2} & \ddots & \beta_{p-1} \\ 0 & \dots & 0 & \beta_{p-1} & \alpha_p \end{pmatrix}$$

- diagonalization yields approximation of Hamiltonian eigenstates

$$|\Phi_n\rangle = \sum_{j=1}^{p} C_j^{(n)} |v_j\rangle$$

- choice of pivot vector: first coefficient provides **transition matrix element**

$$C_1^{(n)} = \langle \Phi_n | v_1 \rangle = \frac{1}{\sqrt{S}} \langle \Phi_n | \hat{T}_{\mathrm{E}\lambda} | \Psi_0 \rangle \longleftarrow$$

ground state determined by preceding CI

In-Medium CI with Lanczos Strength-Function Method

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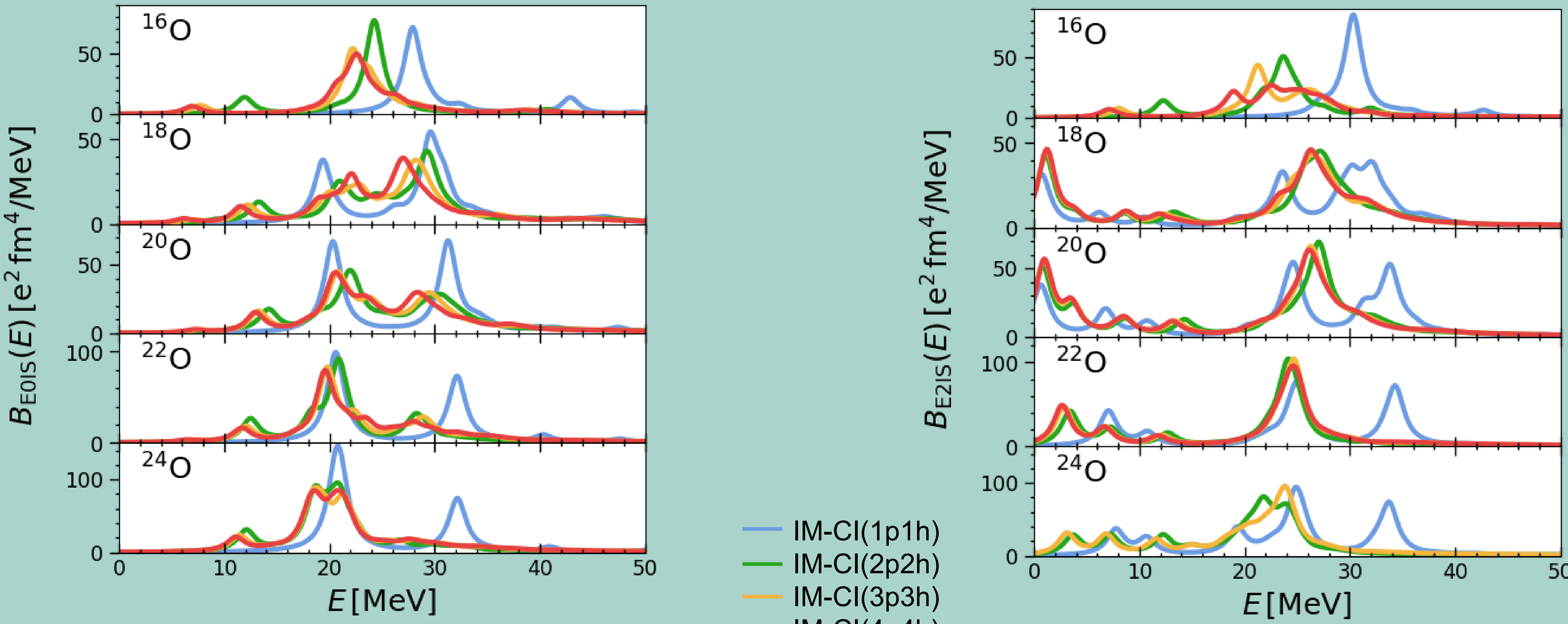
Oxygen Isotopes – E0IS and E2IS



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In-Medium CI with Lanczos Strength-Function Method

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Carbon Isotopes – E0IS and E2IS