# Chiral Four-Nucleon Interactions

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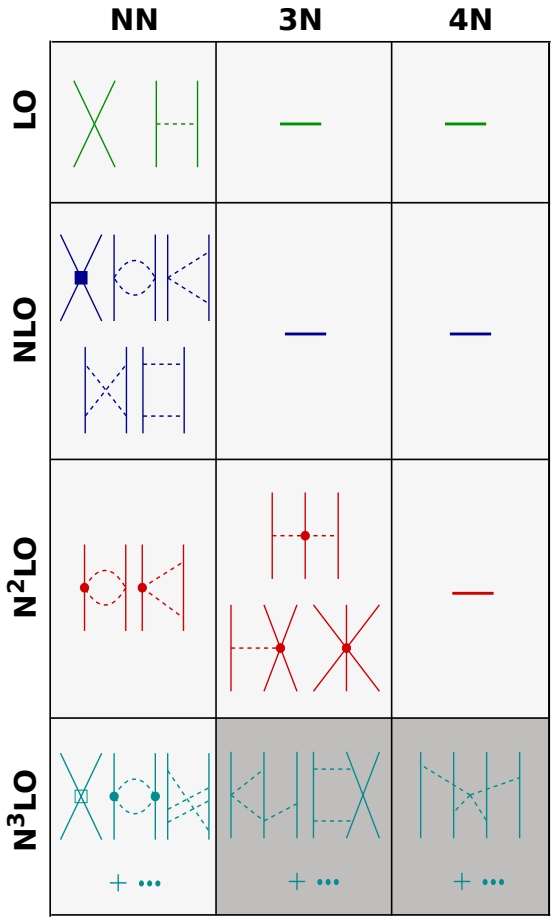
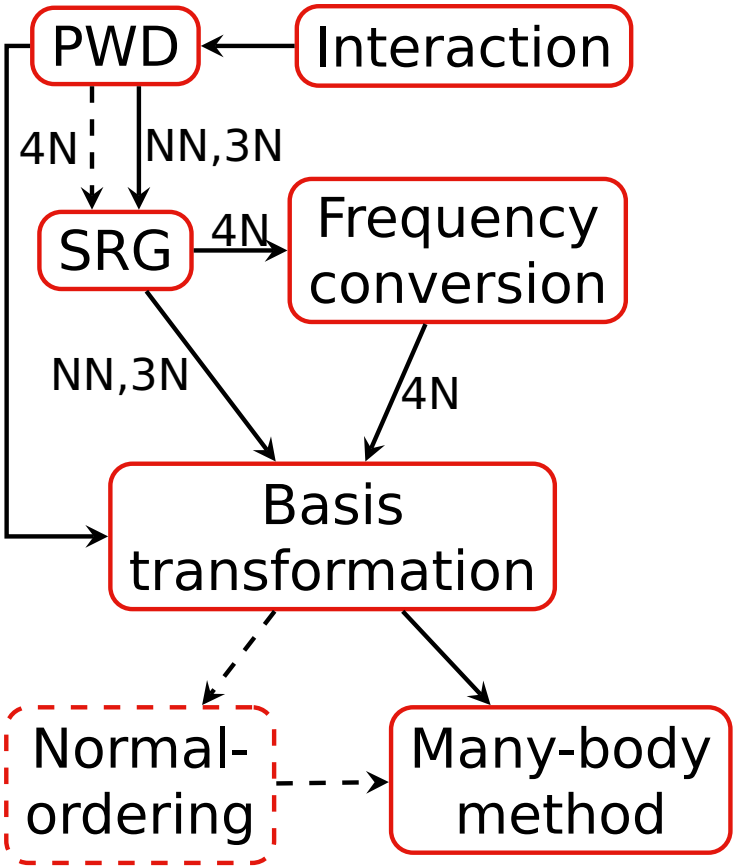
# Why Four-Body Forces?

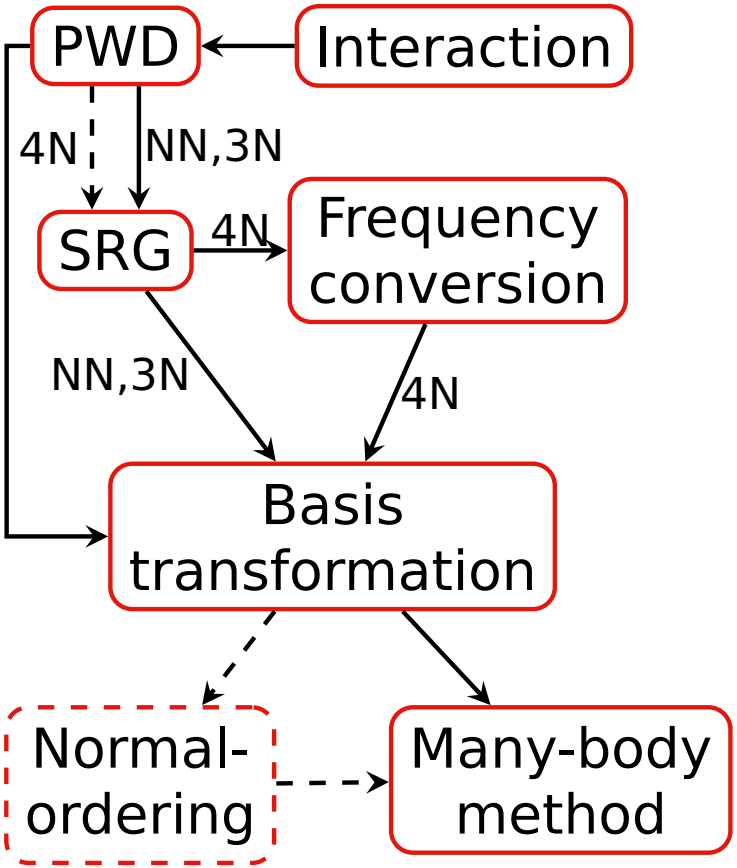
**Goals of A02**

- Precision nuclear structure calculations
  ⇒ Are 4N forces relevant?
- Consistent ab-initio descriptions
  ⇒ 4N forces required starting at $N^3LO$
- Theoretical uncertainties
  ⇒ Effect of neglected 4N forces?



# Framework

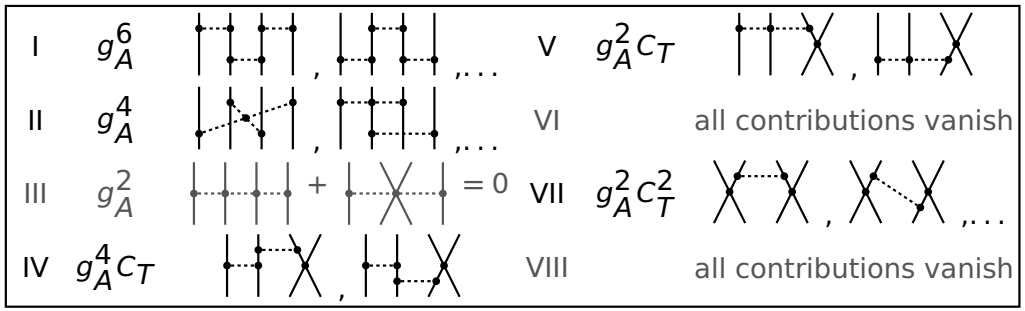

PWD
Interaction
4N
NN,3N
SRG
4N
Frequency conversion
NN,3N
4N
Basis transformation
Normal-ordering
Many-body method




## Chiral 4N at N$^3$LO

- PWD for 5 classes
  - 11 different operator structures
  - Crosschecks: Monte-Carlo integration
- Limit on $E_4^{\max} \approx 4$ ($E_3^{\max} \approx 14$)
- Local regulator ⇒ speedup

$$\exp\left[-\left(\frac{(\vec{\Pi}_1'-\vec{\Pi}_1)^2+(\vec{\Pi}_2'-\vec{\Pi}_2)^2+(\vec{\Pi}_3'-\vec{\Pi}_3)^2}{3\Lambda^2}\right)^n\right]$$



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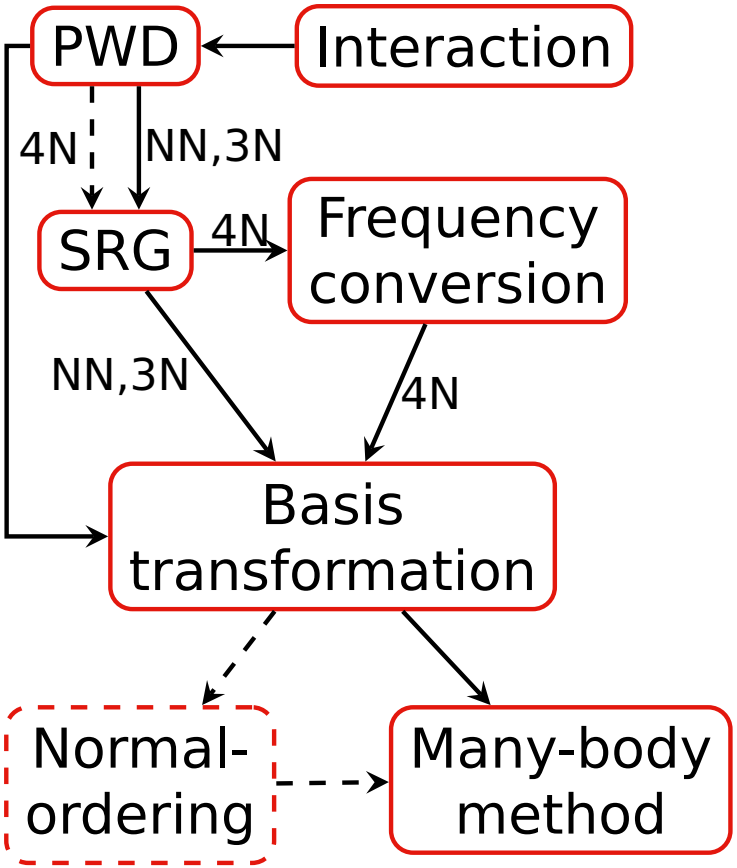
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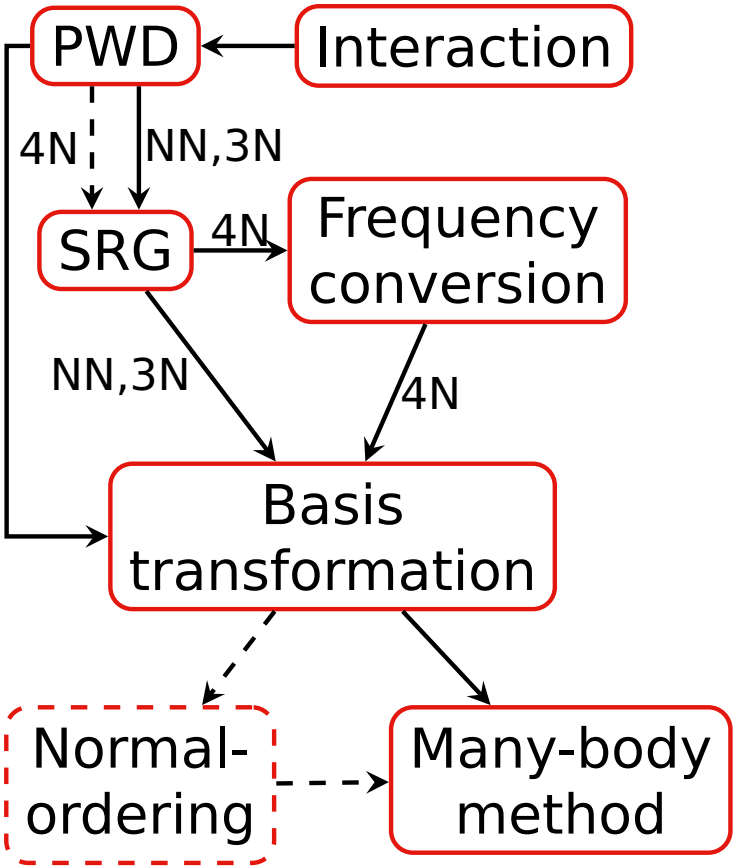
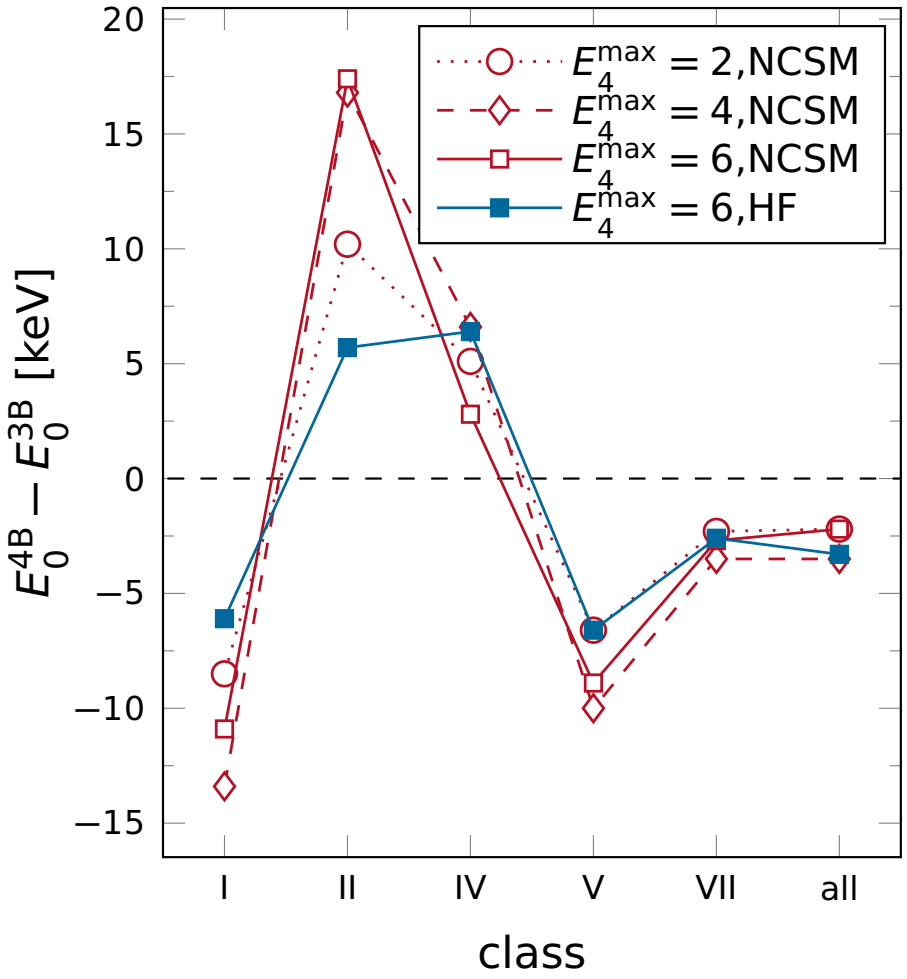



- Single-particle basis
- NCSM & HF handle 4N forces explicitely
- Normal-ordering for other many-body methods

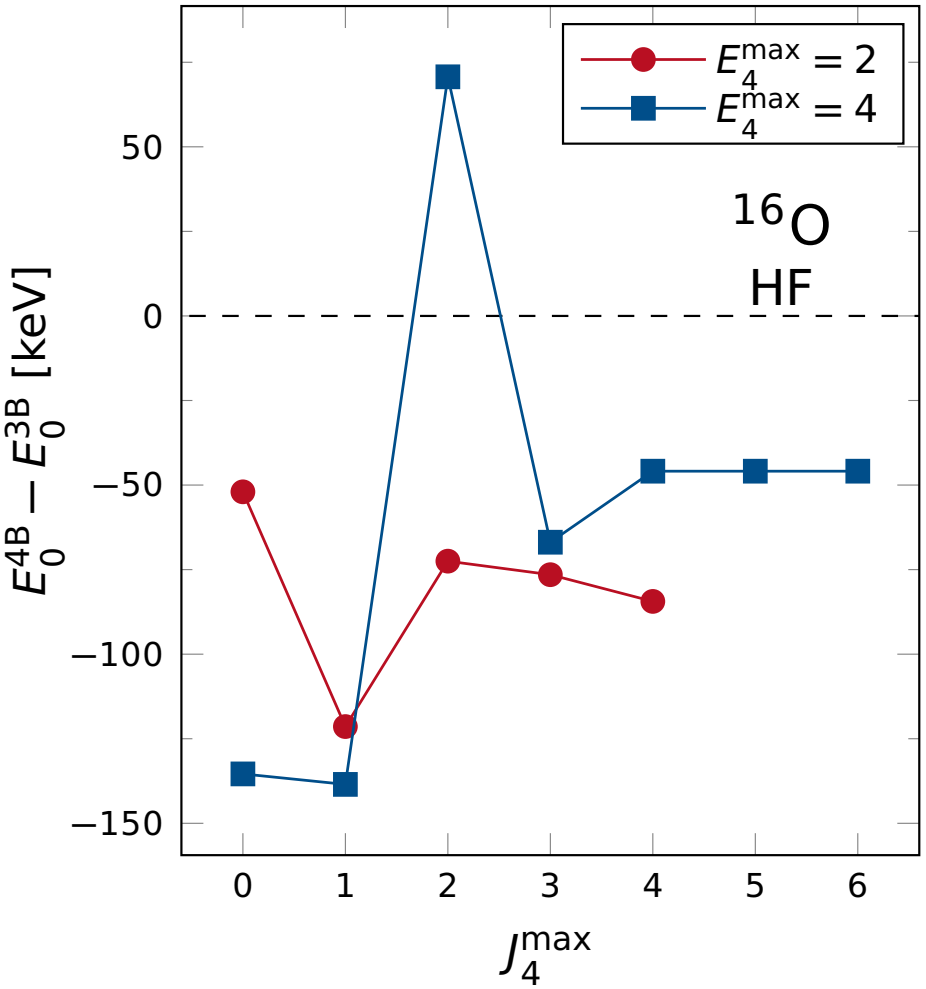
# Ground State of $^4$He

- Cancellation between different classes
- Not completely converged
- Differs from previous estimate
  A. Nogga et al., EPJ Web of Conferences 3, 05006 (2010).
  - Sensitive to NN+3N interaction
  - Different regulator, model space, . . .
- Weak overall effect




$N_{max} = 20$, $\hbar\omega = 24$ MeV, $\alpha_{2B} = \alpha_{3B} = 0.08\,\mathrm{fm}^4$
NN interaction at N$^3$LO with $\Lambda = 500$ MeV/c D. R. Entem et al., PRC 68, 041001 (2003)
3N interaction at N$^2$LO with $\Lambda = 400$ MeV/c R. Roth et al., PRL 109, 052501 (2012)
4N interaction with $\Lambda_{4B} = 400$ MeV/c, $n = 2$, and $C_T = 0.21\,\mathrm{fm}^2$ E. Epelbaum, The EPJ A 34, 2, 197 (2007).

# Channel Contributions




- Weak overall effect
- $J_4 = 2$ channels are important
- No convergence in $E_4^{\max}$

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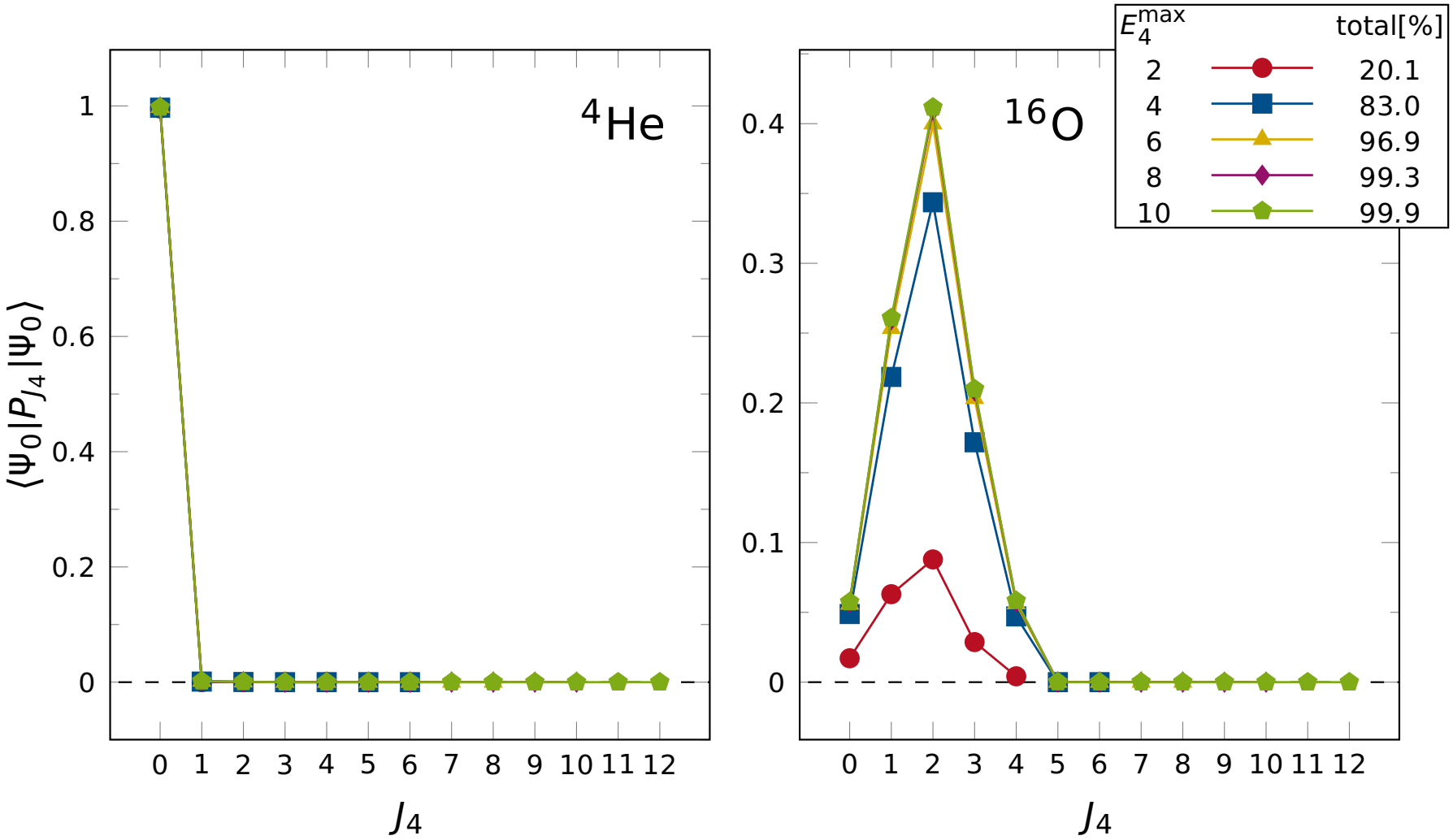
# Channel Structure

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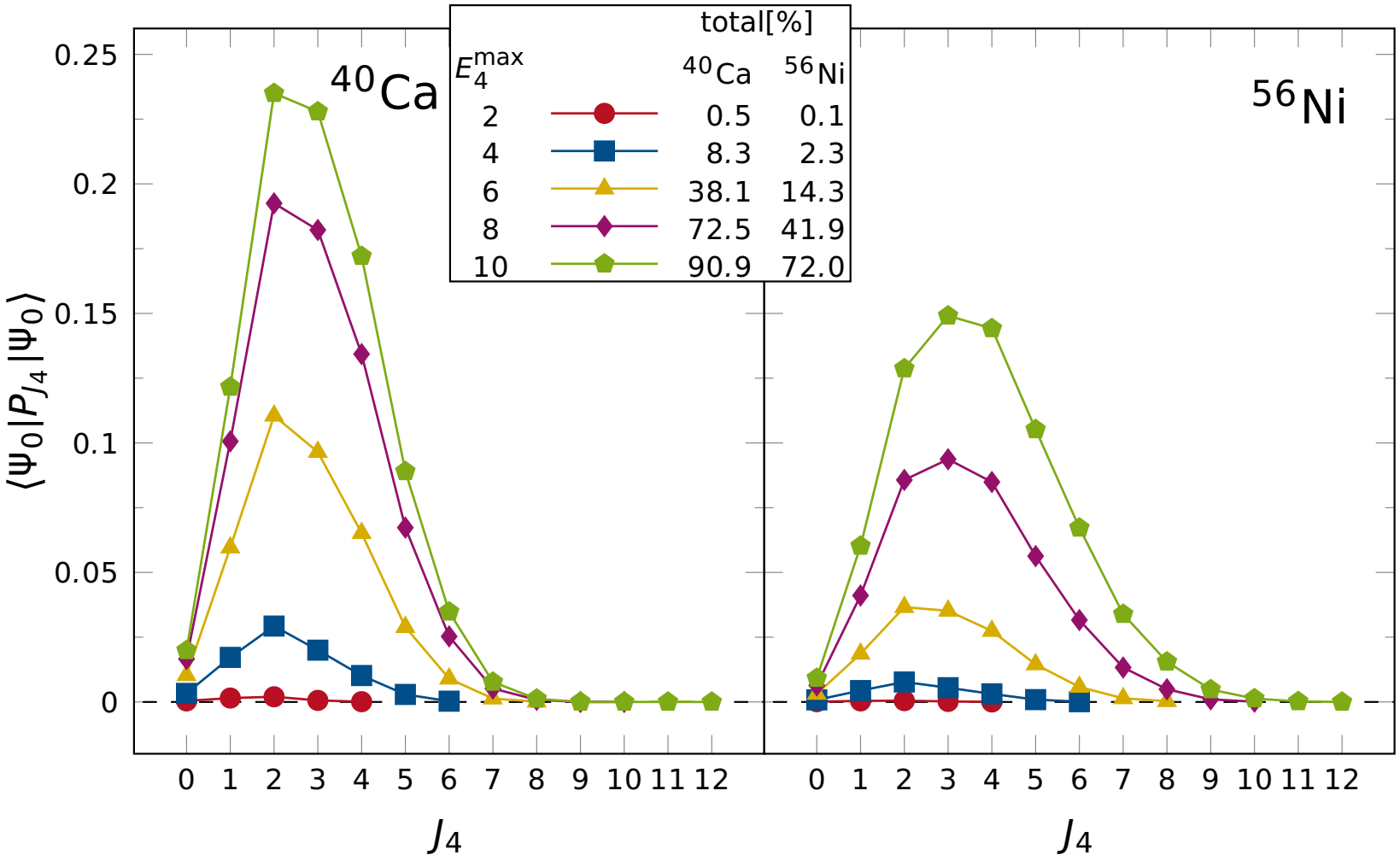


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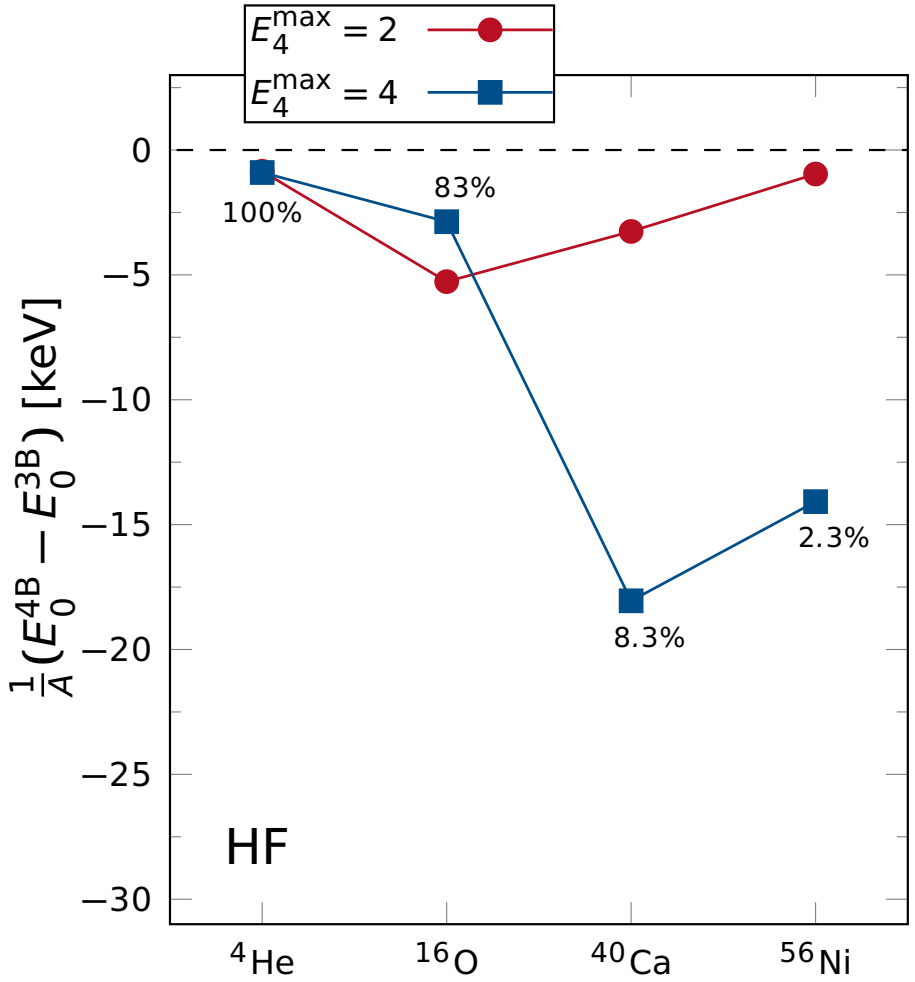
# Heavier Nuclei




- Contribution increases with number of nucleons
- Not converged w.r.t. $E_4^{\max}$
- Weak overall effect
- More reliable for lighter nuclei

$e_{\max} = 10$, $\hbar\omega = 24$ MeV, $\alpha_{2B} = \alpha_{3B} = 0.08\,\mathrm{fm}^4$
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# Take-Home Message

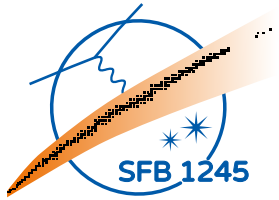
- 4N interaction computationally expensive ⇒ low $E_4^{\max}$
- Chiral 4N interactions negligible for light nuclei
- Potentially more important for heavier nuclei
  No indication found so far!

# Epilogue

- **Thanks to my group**
  - S. Alexa, E. Gebrerufael, T. Hüther, **R. Roth**, C. Stumpf, A. Tichai, K. Vobig, R. Wirth

    Institut für Kernphysik, TU Darmstadt

- **Thank you for your attention!**

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