Exploring new physics and nuclear structure with ytterbium isotope shifts

Door, Yeh, **MH**, et al., PRL **134** (2025)

Matthias Heinz, ORNL

CIPANP 2025
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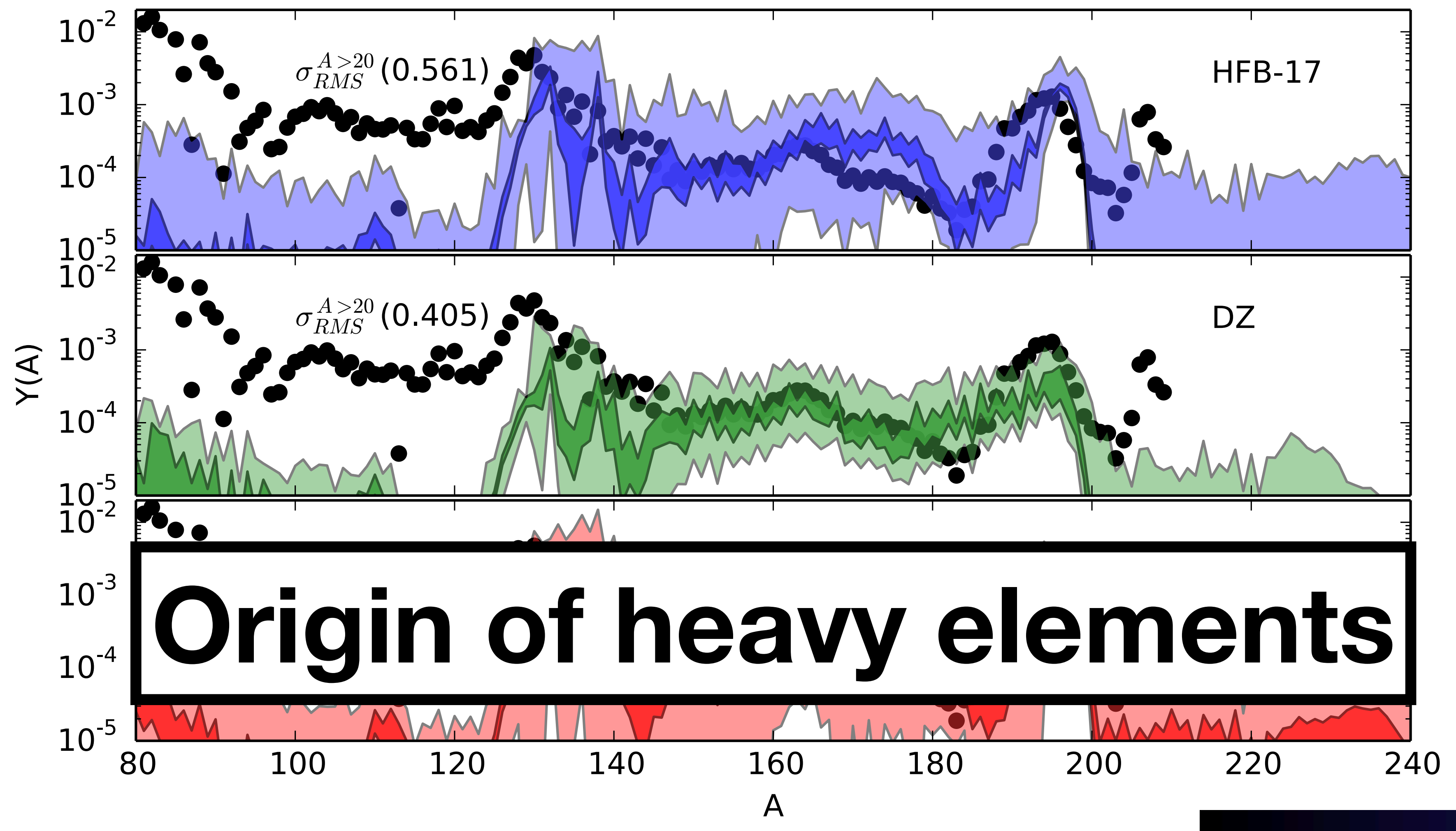
Nuclear structure motivations



See talks by, e.g., Nicole Vassh, Francesca Bonaiti

Mumpower et al., EPJ WoC **93** (2015)

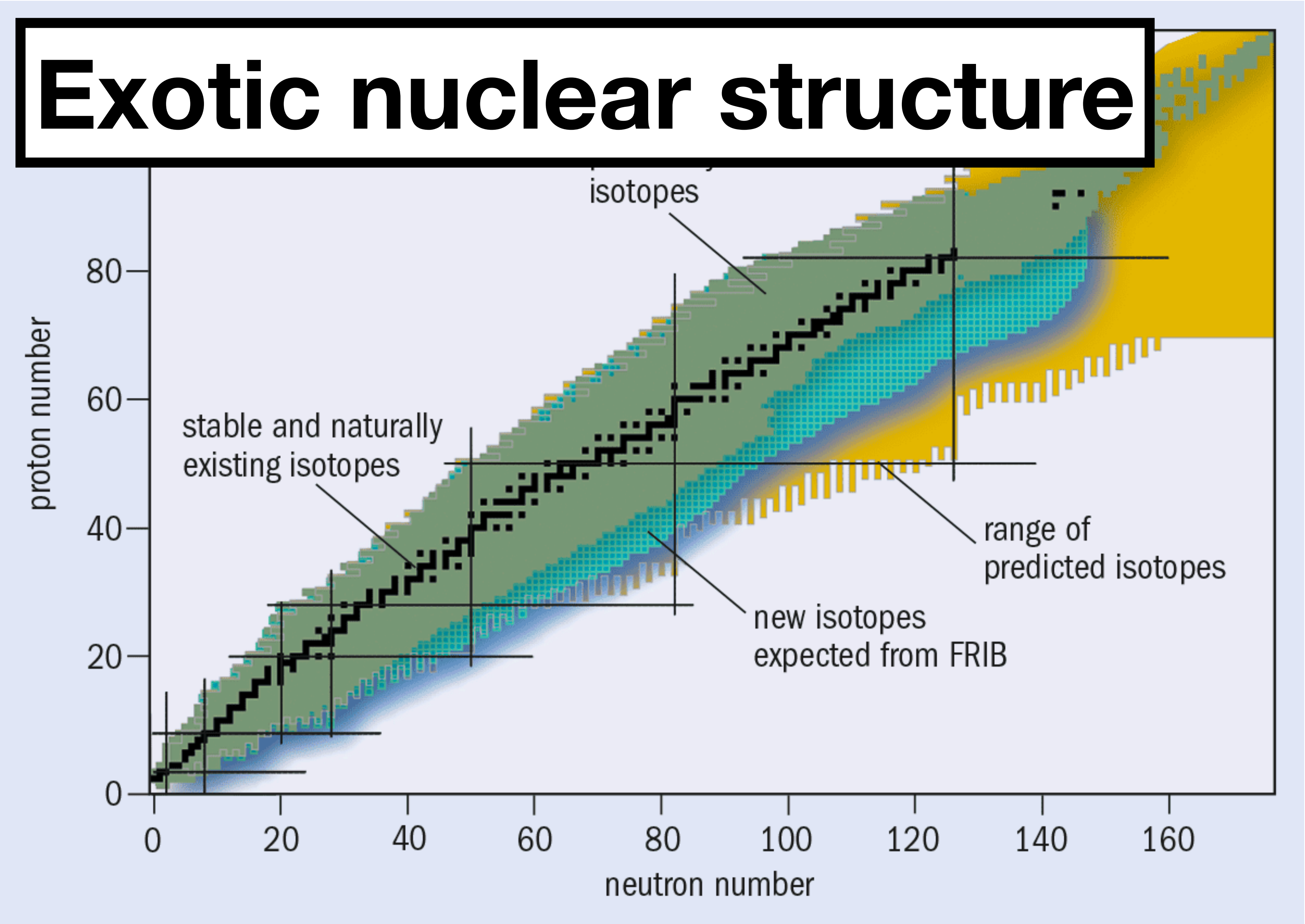


Figure: FRIB

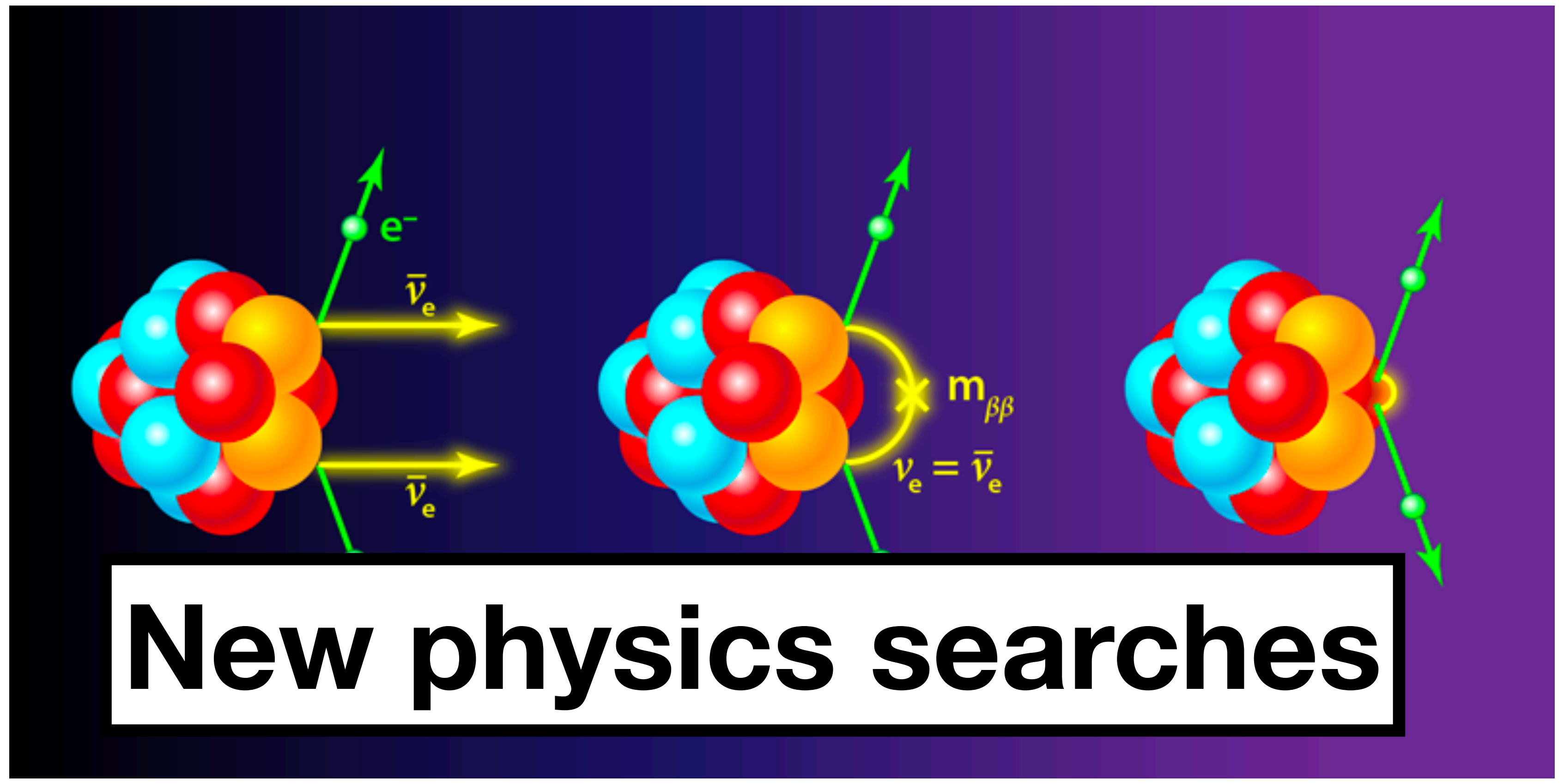


Figure: LEGEND Collaboration

Theory predictions with quantified uncertainties essential!

Nonlinear King plot in ytterbium isotope shifts

Delaunay et al., PRD **96** (2017)
Counts et al., PRL **125** (2020)
Allehabi et al., PRA **103** (2021)
Hur et al., PRL **128** (2022)
Figueroa et al., PRL **128** (2022)
Ono et al., PRX **12** (2022)
and more

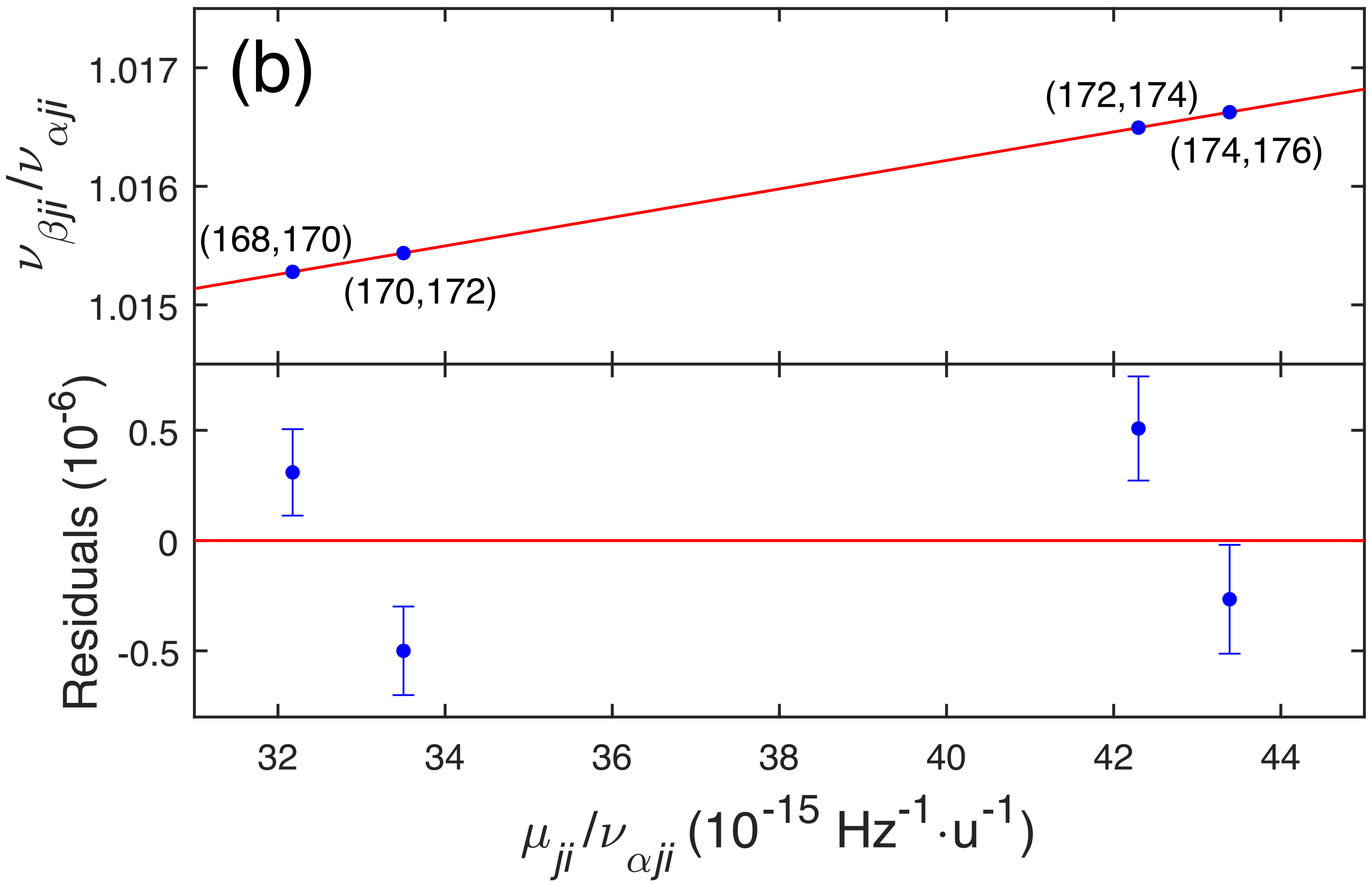
Nonlinear King plot in ytterbium

- **Isotope shift** in atomic transition frequencies
- Leading order:

$$\nu_\tau^{A,A'} = \nu_\tau^{A} - \nu_\tau^{A'} \approx K_\tau w^{A,A'} + F_\tau \delta\langle r^2\rangle^{A,A'}$$

mass shift **field shift**

- Leads to **linear King plot**



Counts et al., PRL **125** (2020)

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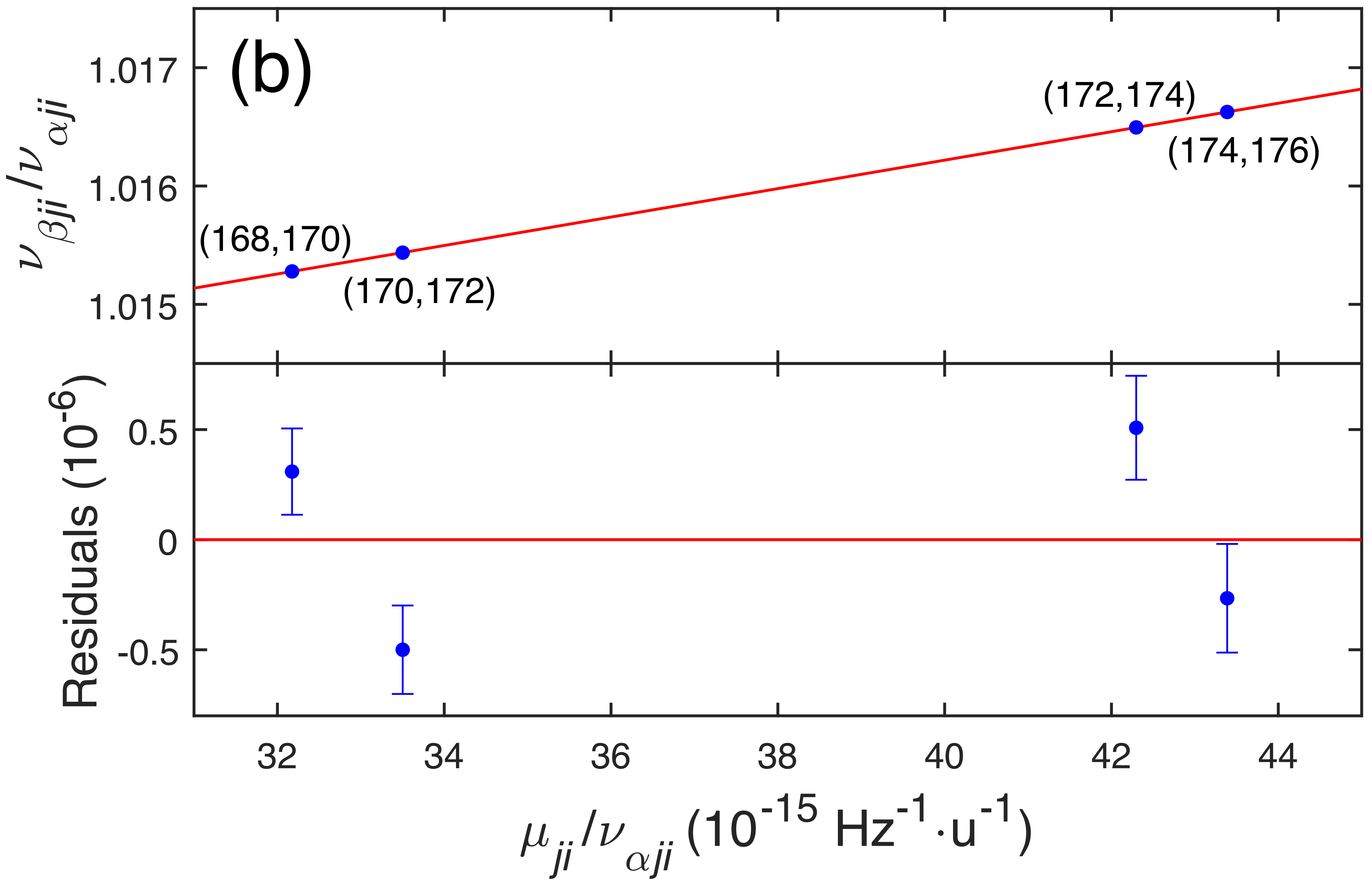

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mass shift **field shift**

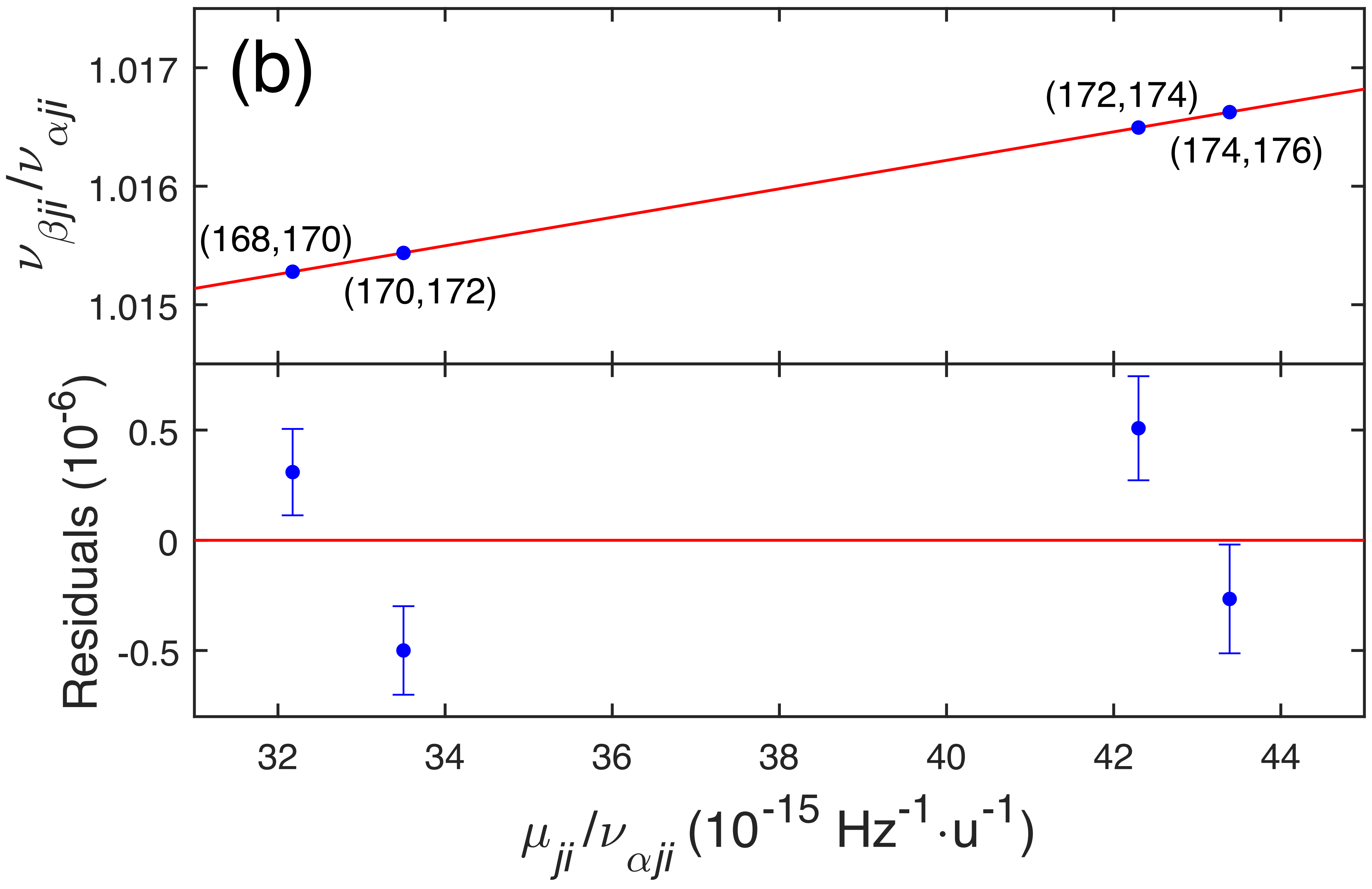
- Leads to **linear King plot**
- Nonlinear behavior due to other effects:

$$\nu_{\tau,\text{nonlin.}}^{A,A'} = G_\tau^{(2)}(\delta\langle r^2\rangle^2)^{A,A'} + G_\tau^{(4)}\delta\langle r^4\rangle^{A,A'}$$

higher-order nuclear structure

$$+\frac{\alpha_{\text{NP}}}{\alpha_{\text{EM}}} D_\tau h^{A,A'} + \dots$$

possible new boson



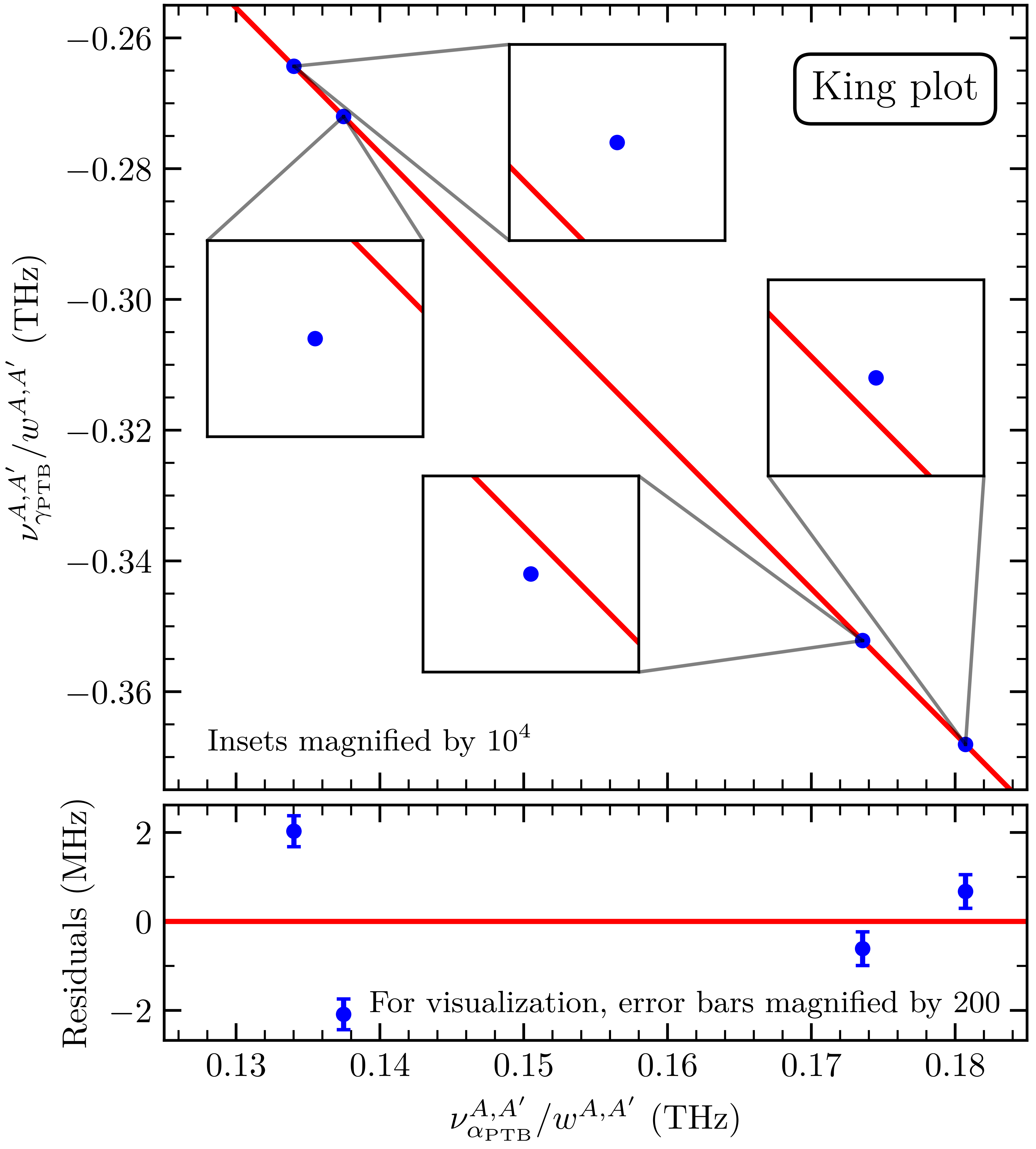
Counts et al., PRL **125** (2020)

Nonlinear King plot in ytterbium

New data:

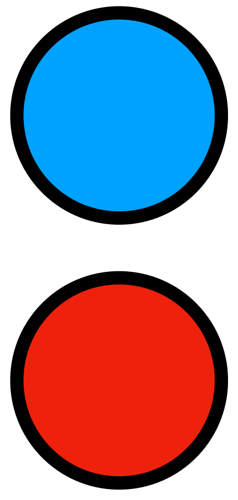
- $^{168,170,172,174,176}\mathrm{Yb}$ (4 isotope pairs)
- Frequencies with 10^{-15} relative precision (Yeh, Mehlstäubler @**PTB Braunschweig**)
- Mass-ratios with 10^{-12} relative precision (Door, Blaum @**MPIK Heidelberg**)

Nonlinearity observed with high significance!
Is this new physics?



Ab initio nuclear structure theory

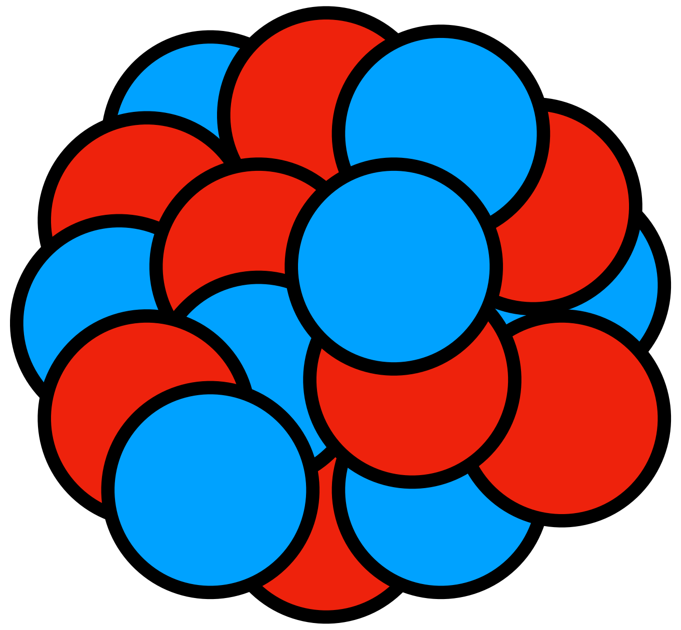
Ab initio nuclear structure



N **neutrons**

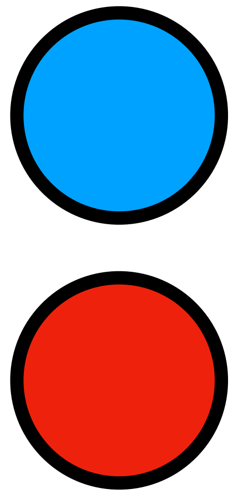
Z **protons**

A **nucleons**



$$H|\Psi\rangle = E|\Psi\rangle$$

Ab initio nuclear structure



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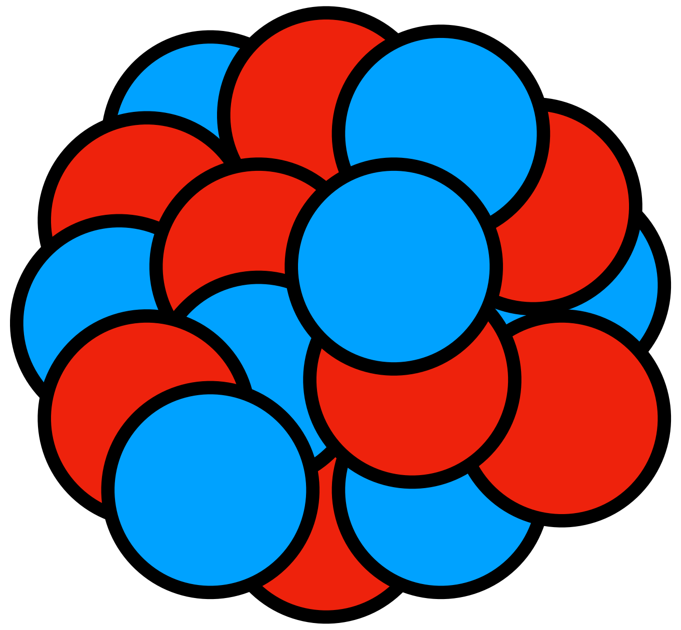

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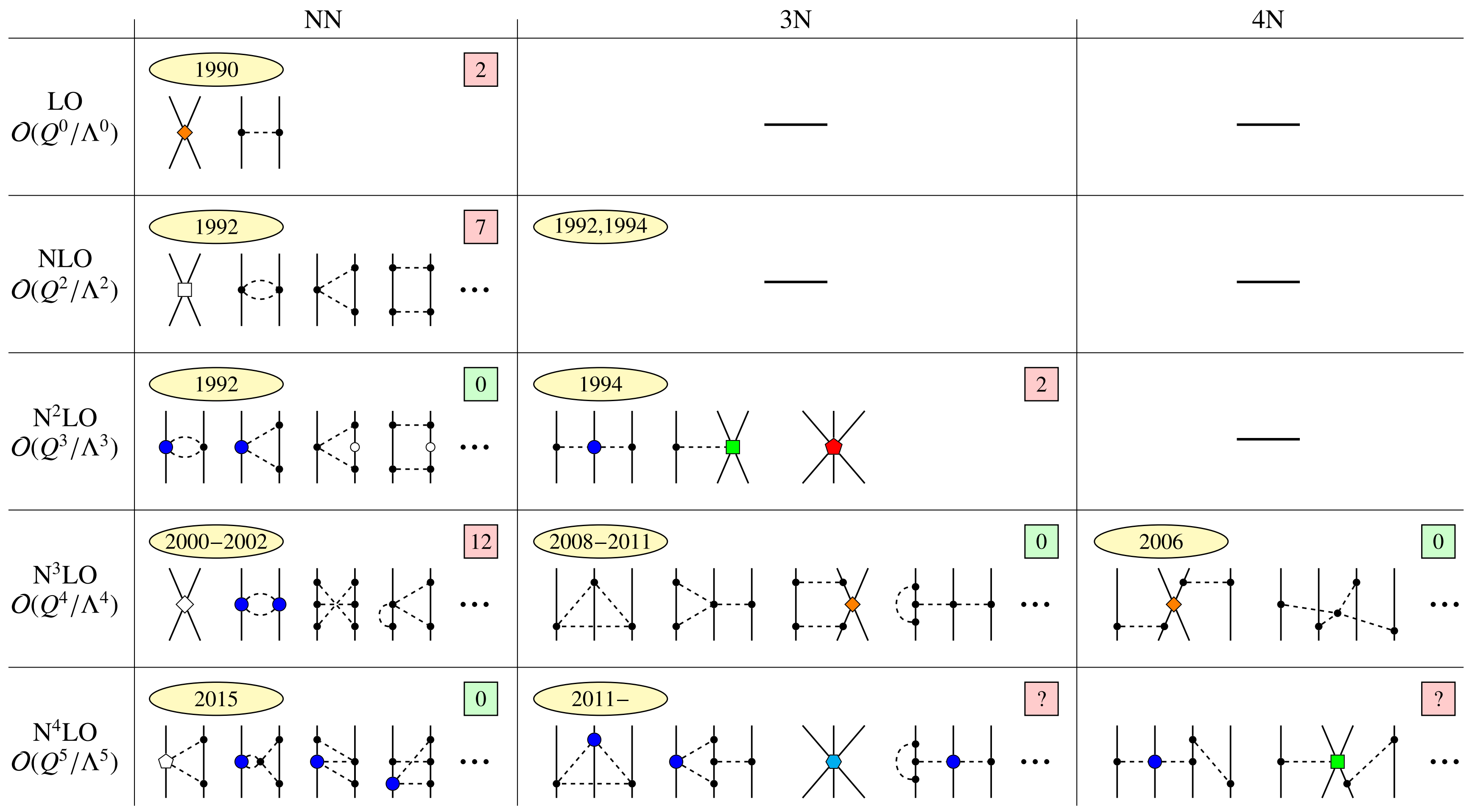
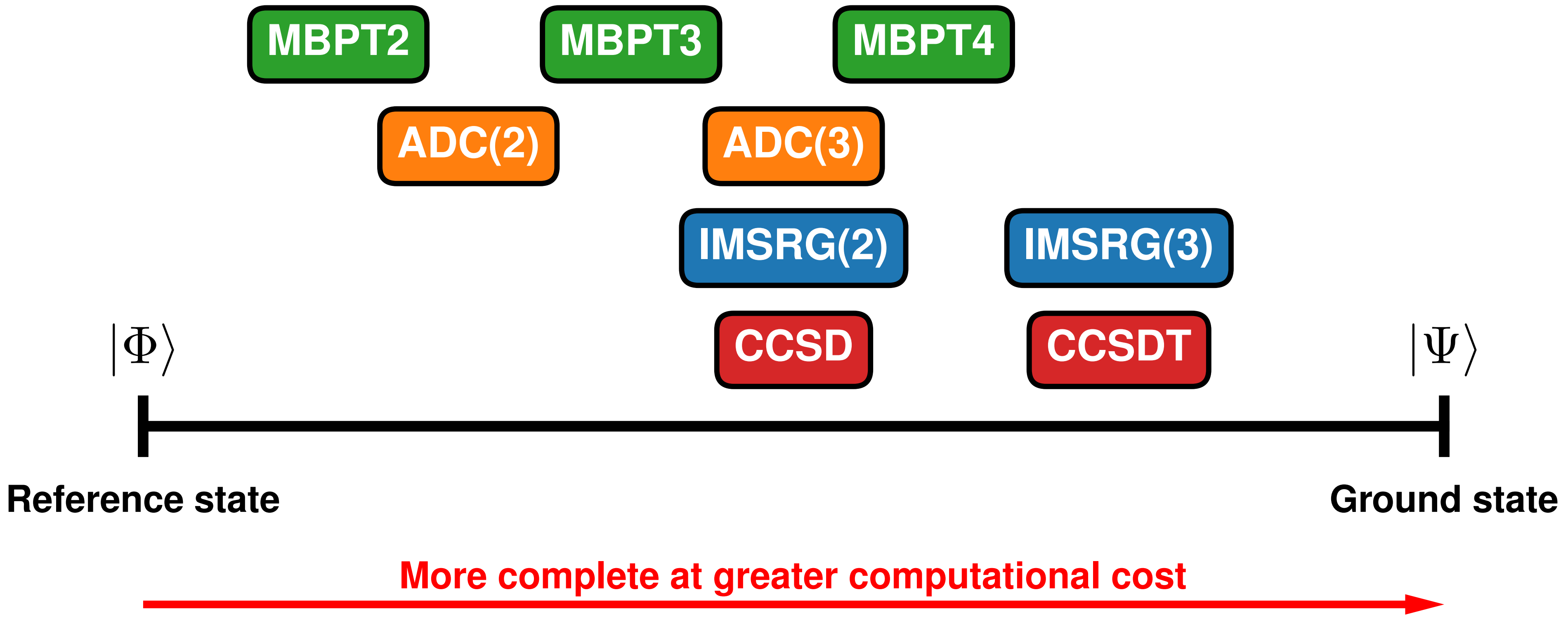
Nuclear forces



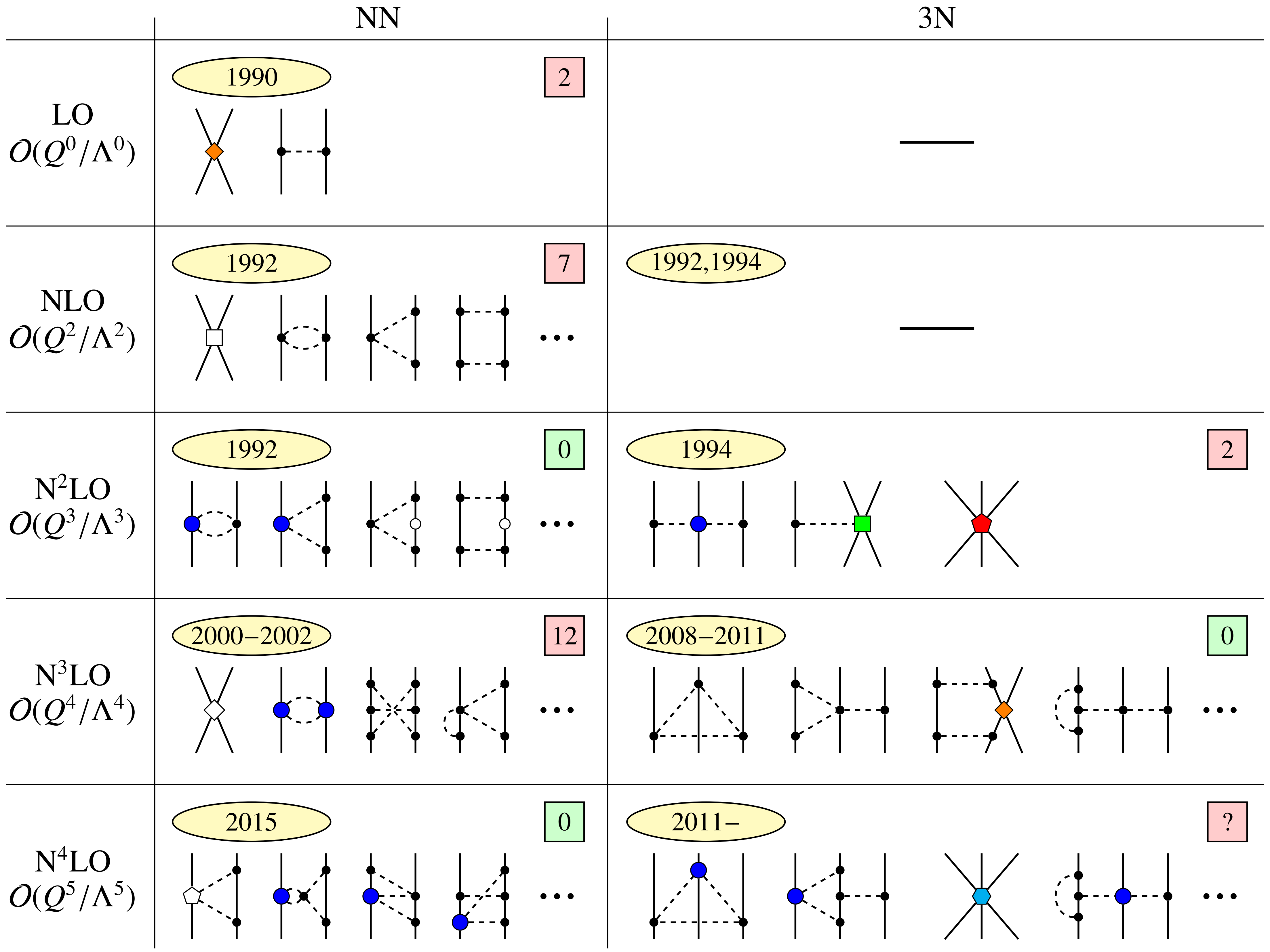
Hebeler, Phys. Rep. **890** (2021)

Many-body methods



Chiral EFT for nuclear forces

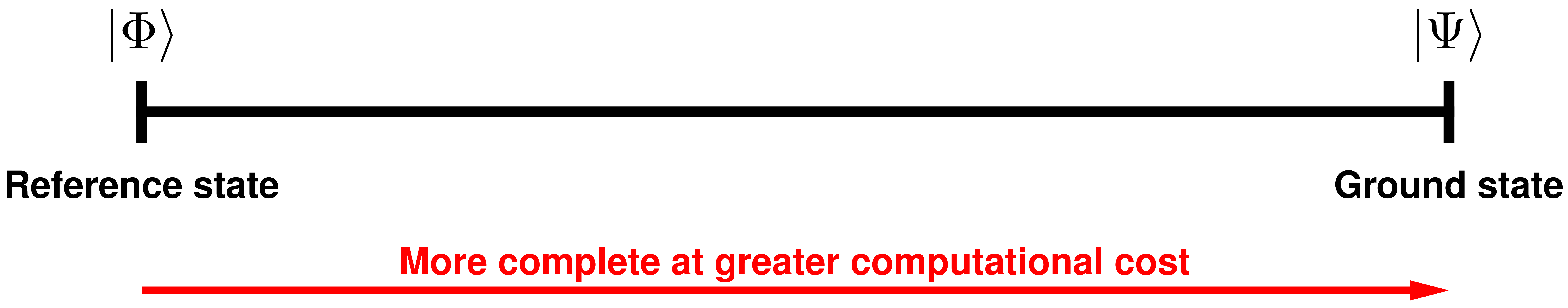
effective field theory



Hebeler, Phys. Rep. **890** (2021)

- **Nuclear forces are uncertain**
- Chiral EFT:
  Low-energy expansion of QCD
- Free couplings to fit to data
- **Systematically improvable**
- **Uncertainty quantifiable**

Many-body expansion methods



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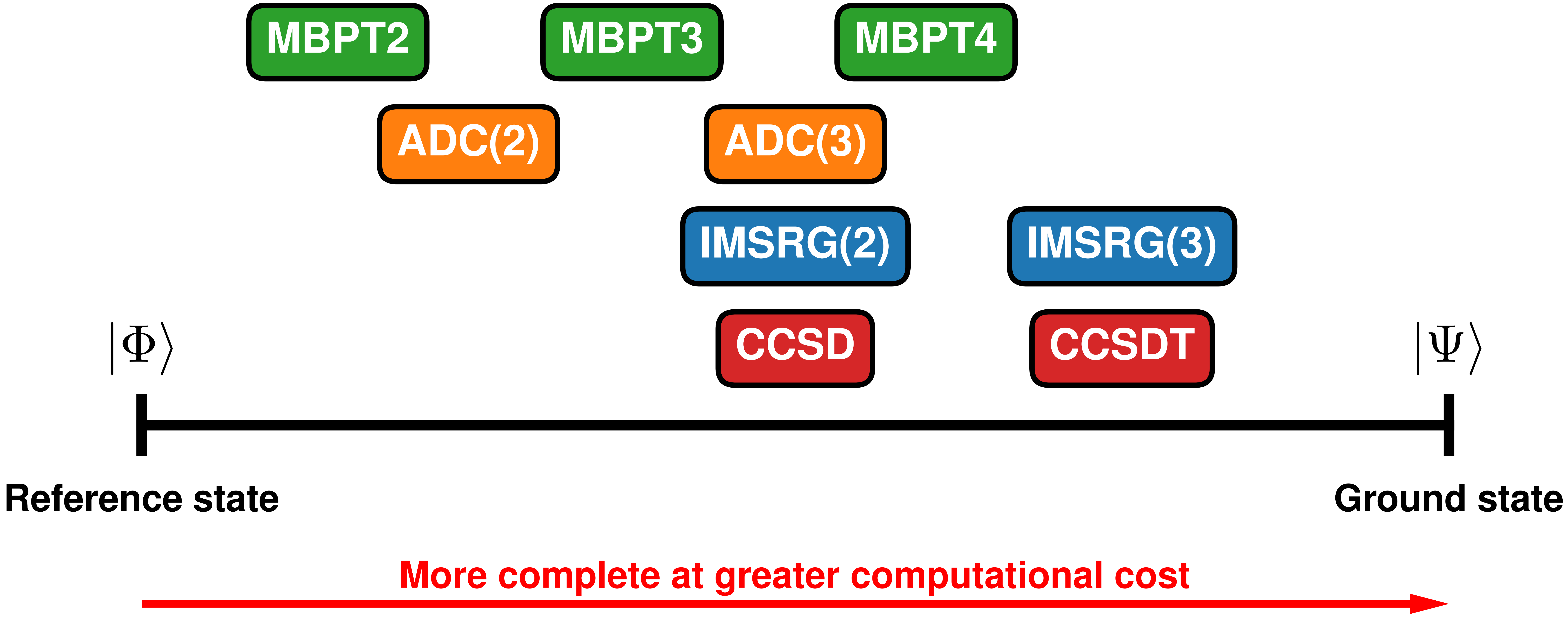
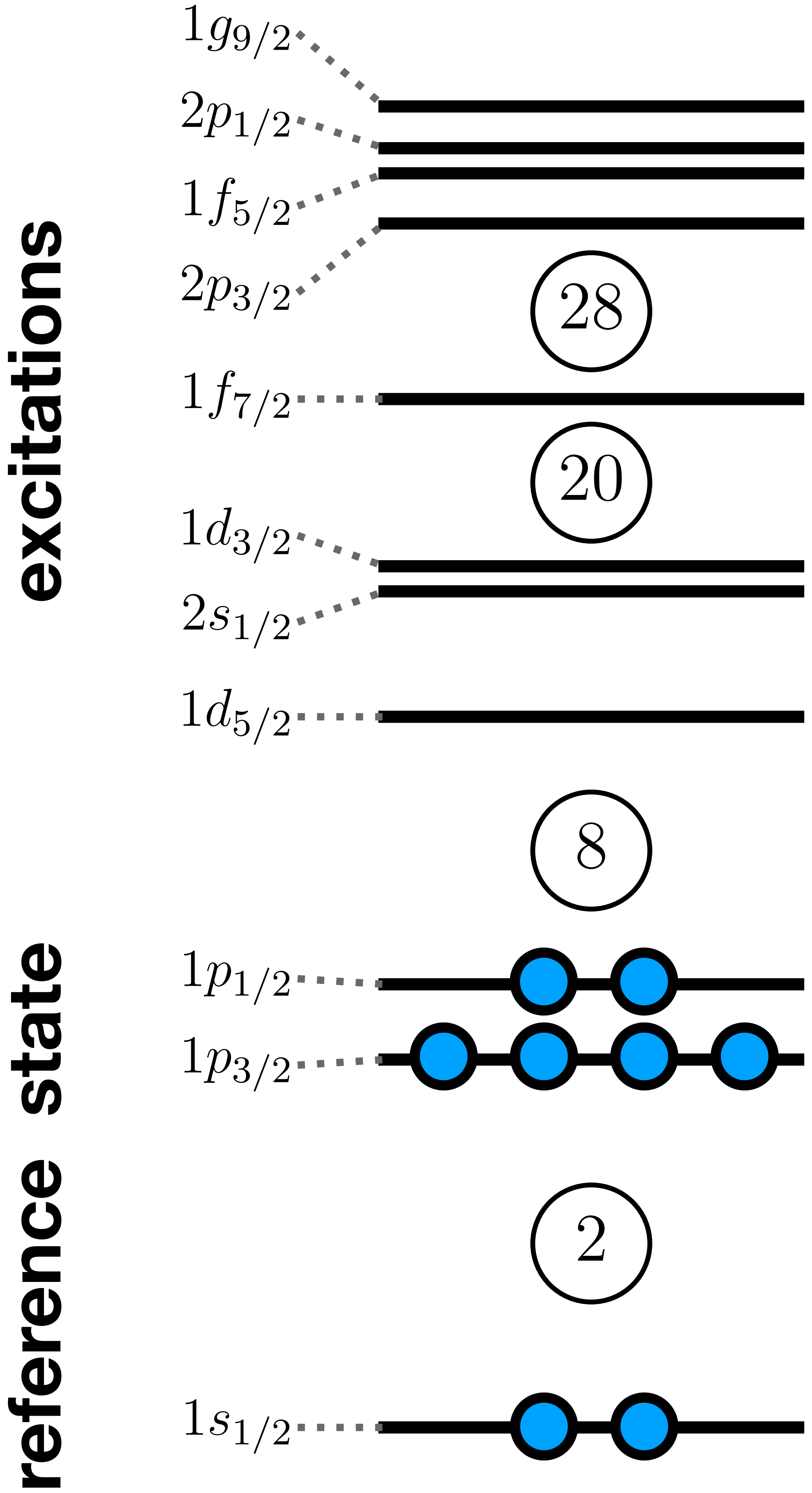


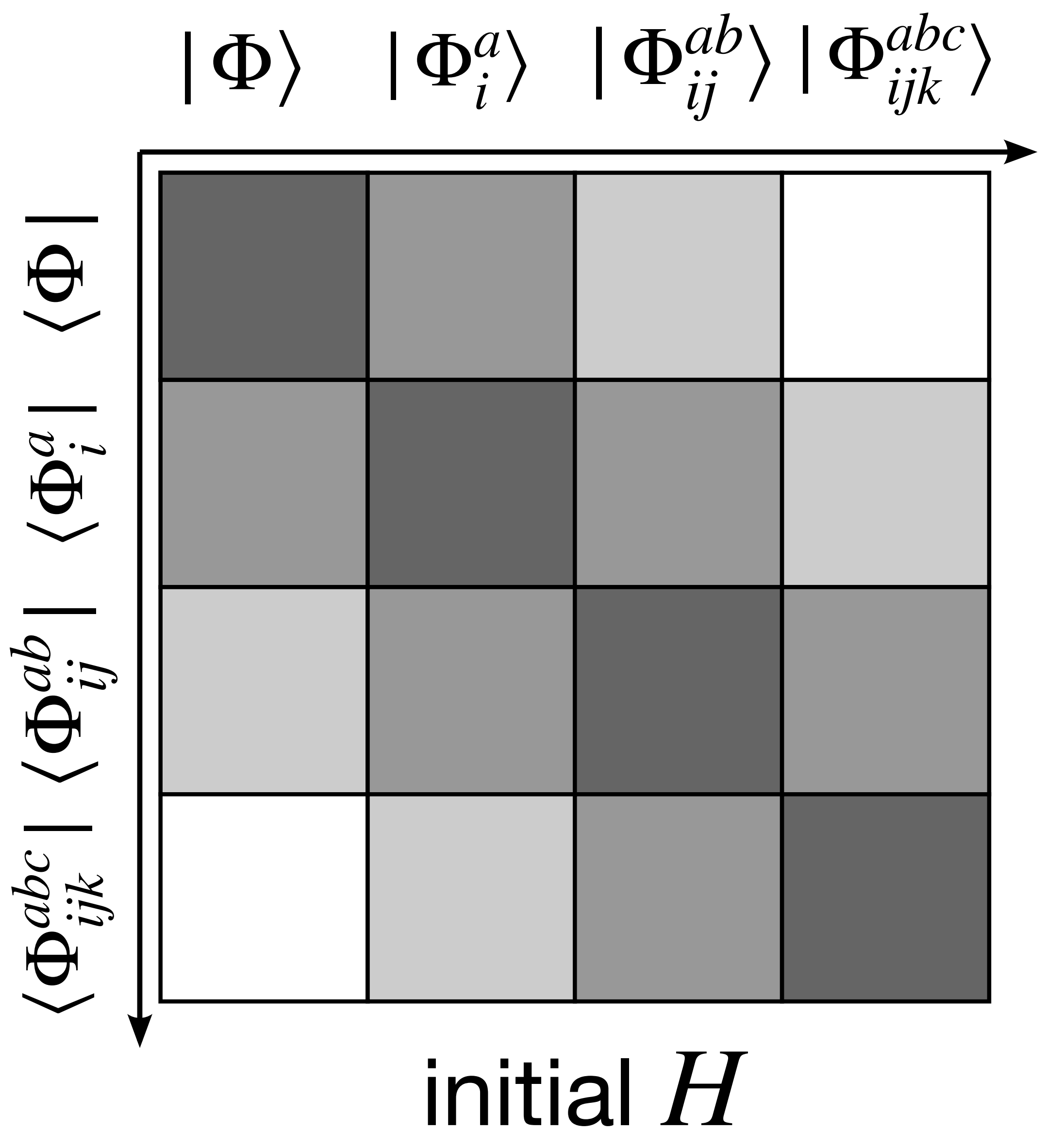
- **Systematically improvable expansion** around reference state $|\Phi\rangle$
- **Tractable computational cost** in larger nuclei
- Approximate many-body solution with **quantifiable uncertainty**

Tsukiyama et al., PRL **106** (2011)
Hergert et al., Phys. Rep. **621** (2016)

The IMSRG

in-medium similarity renormalization group





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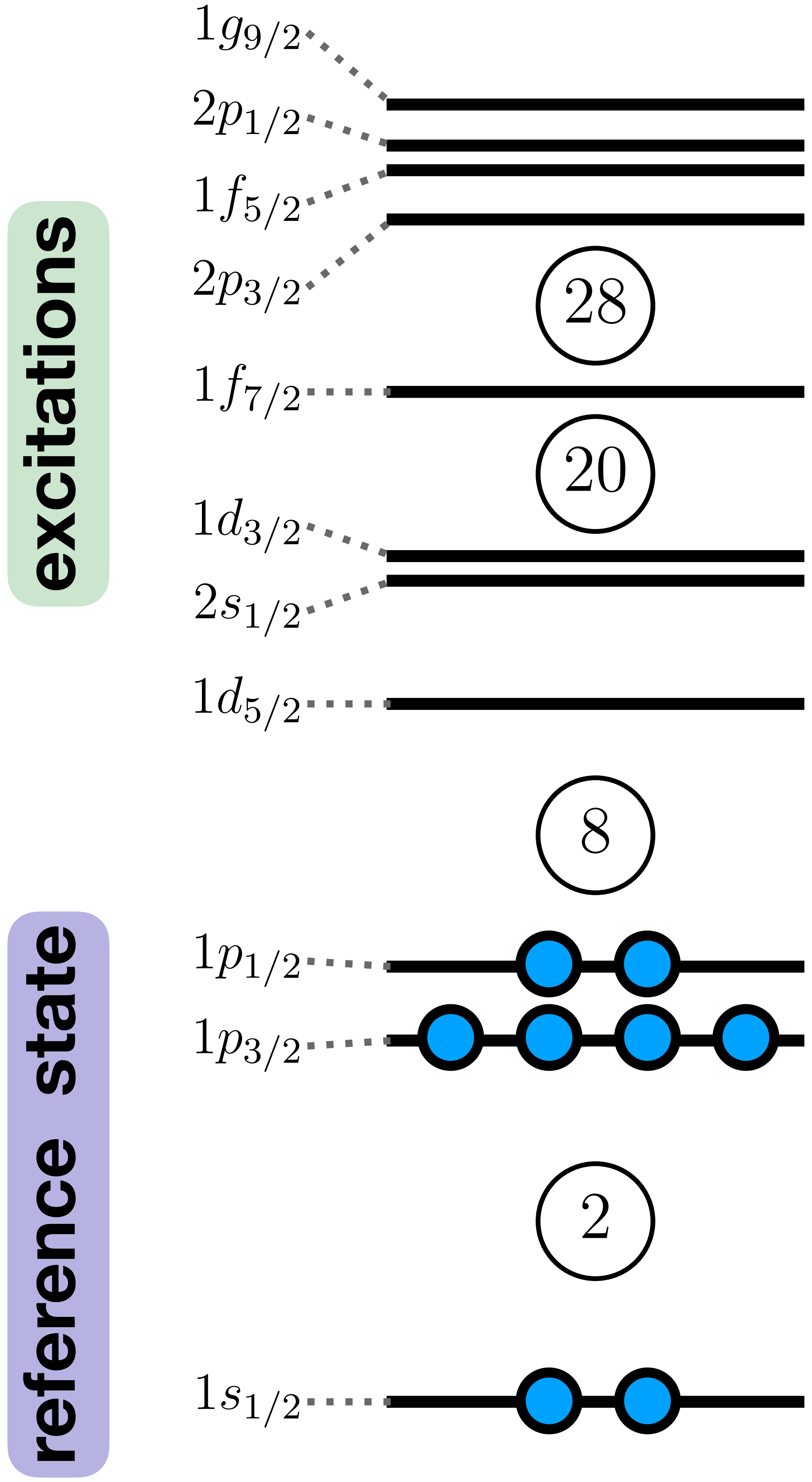

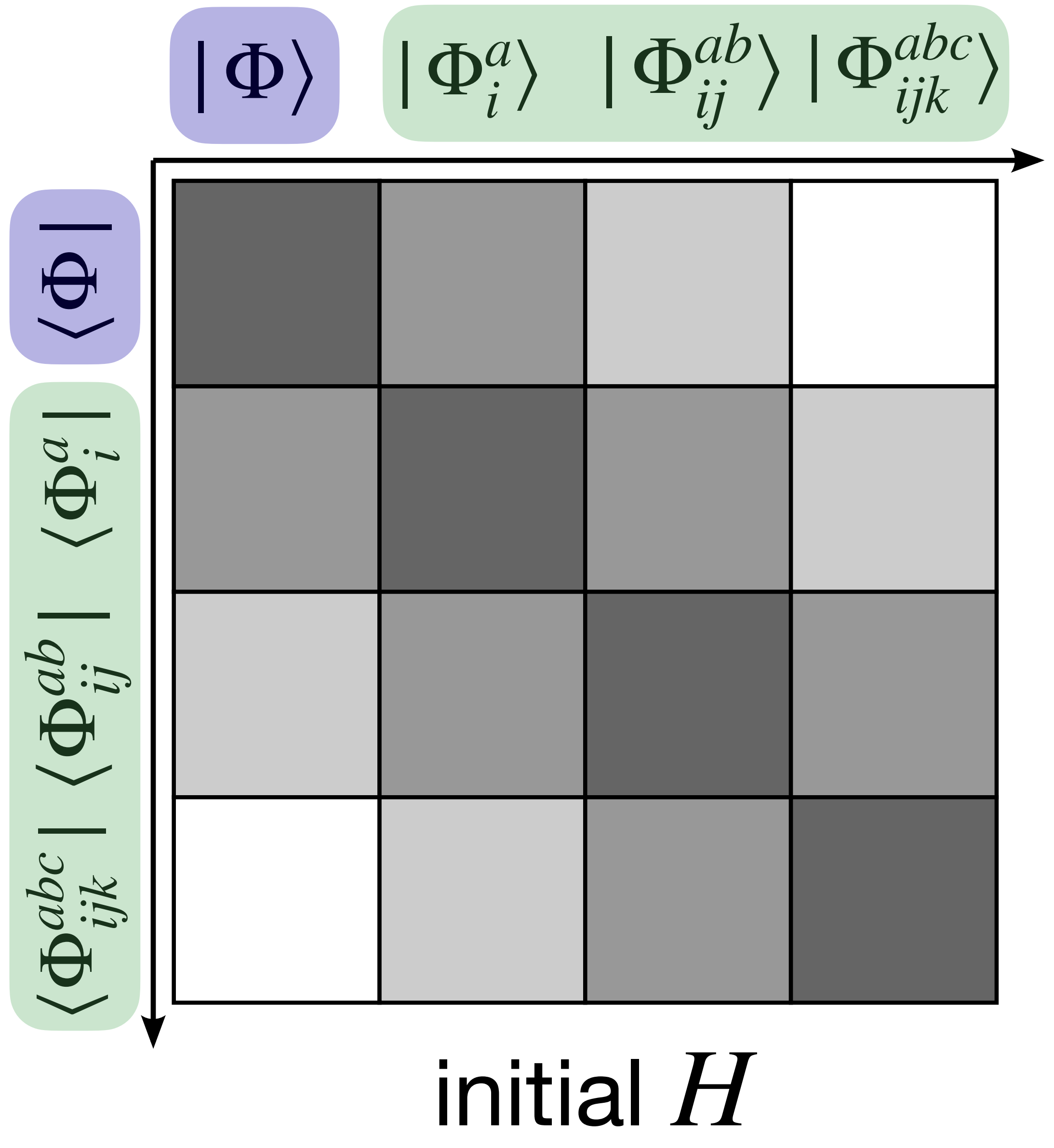

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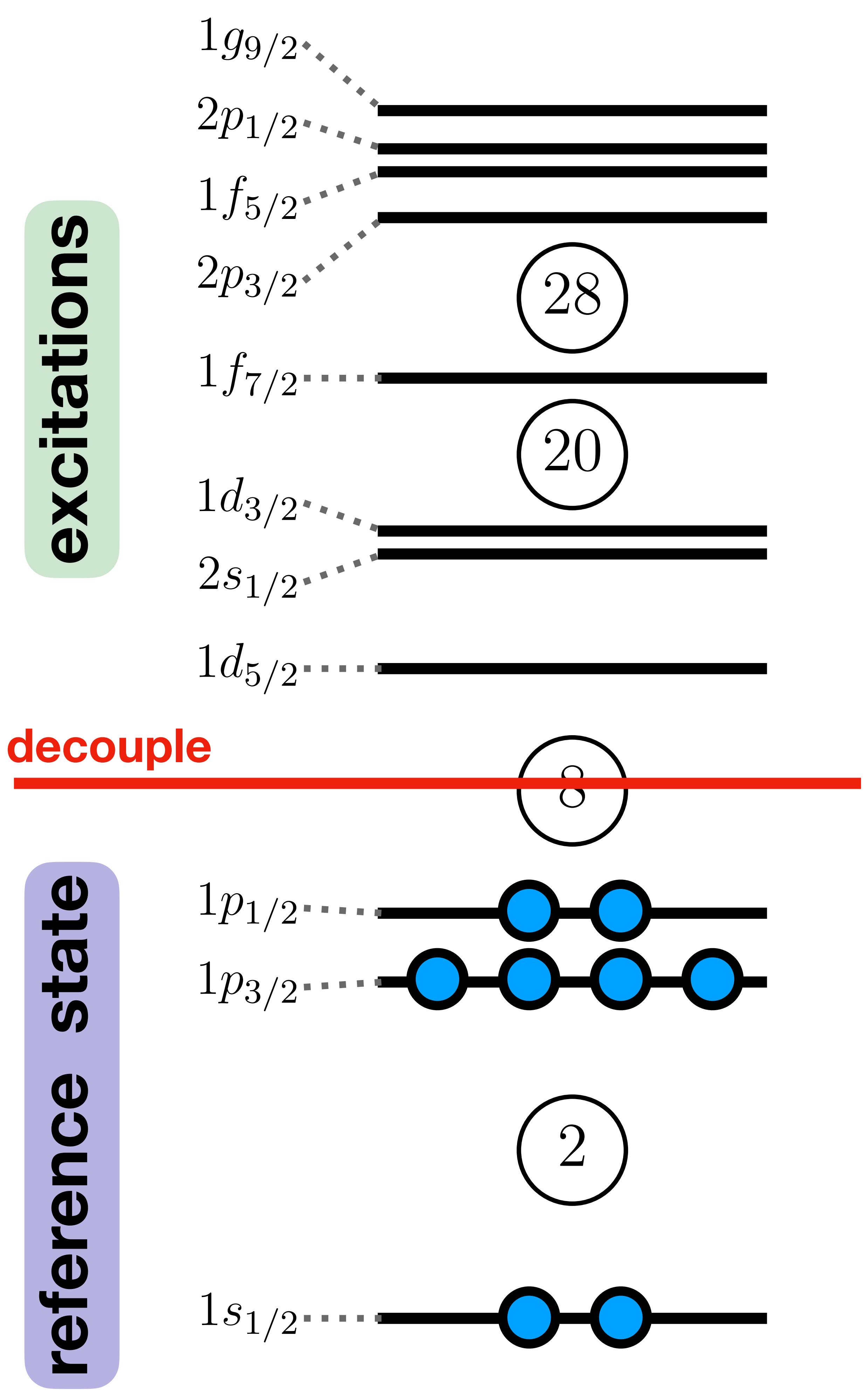

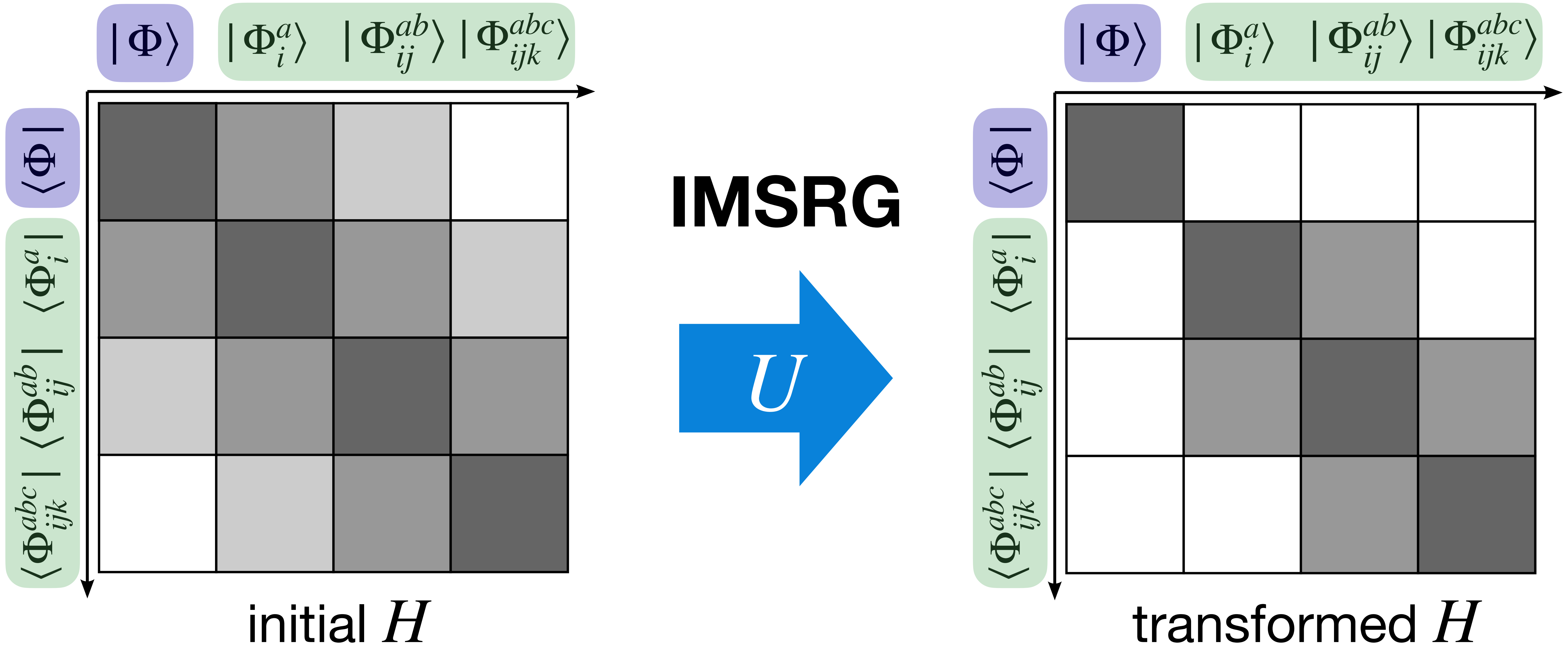

Hergert et al., Phys. Rep. **621** (2016)

- **IMSRG**: Unitary transformation $U = e^{\Omega}$ to decouple reference state from excitations

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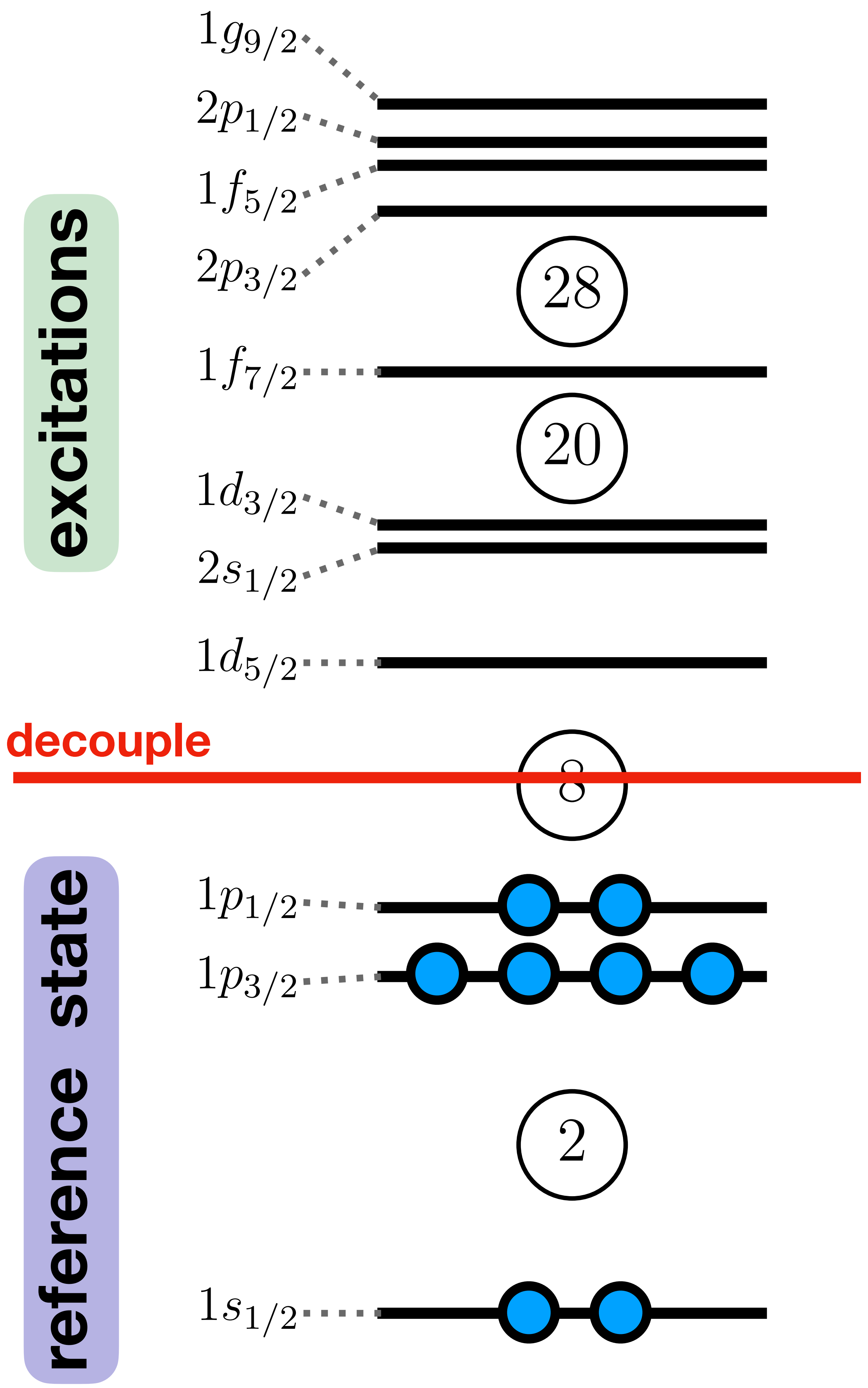

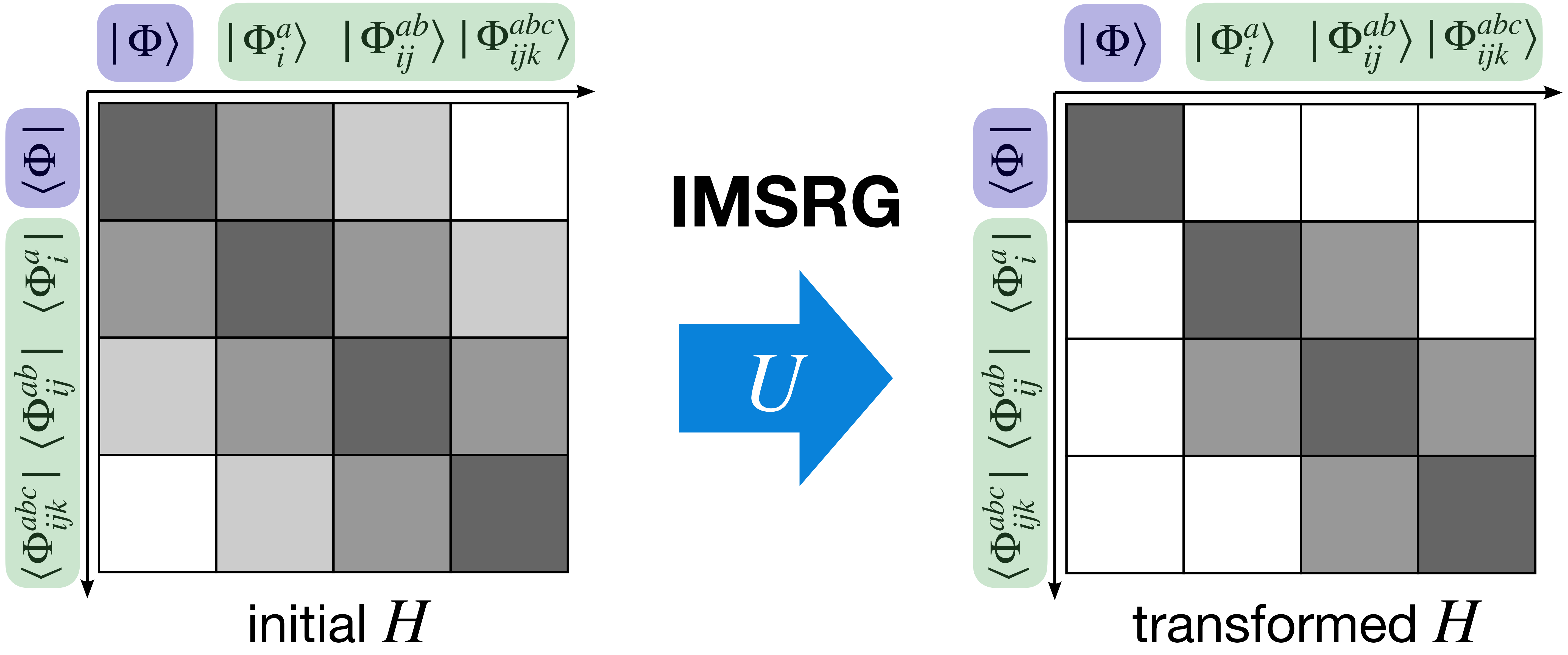

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- **IMSRG**: Unitary transformation $U = e^{\Omega}$ to decouple reference state from excitations
- Expansion and truncation in **many-body operators**

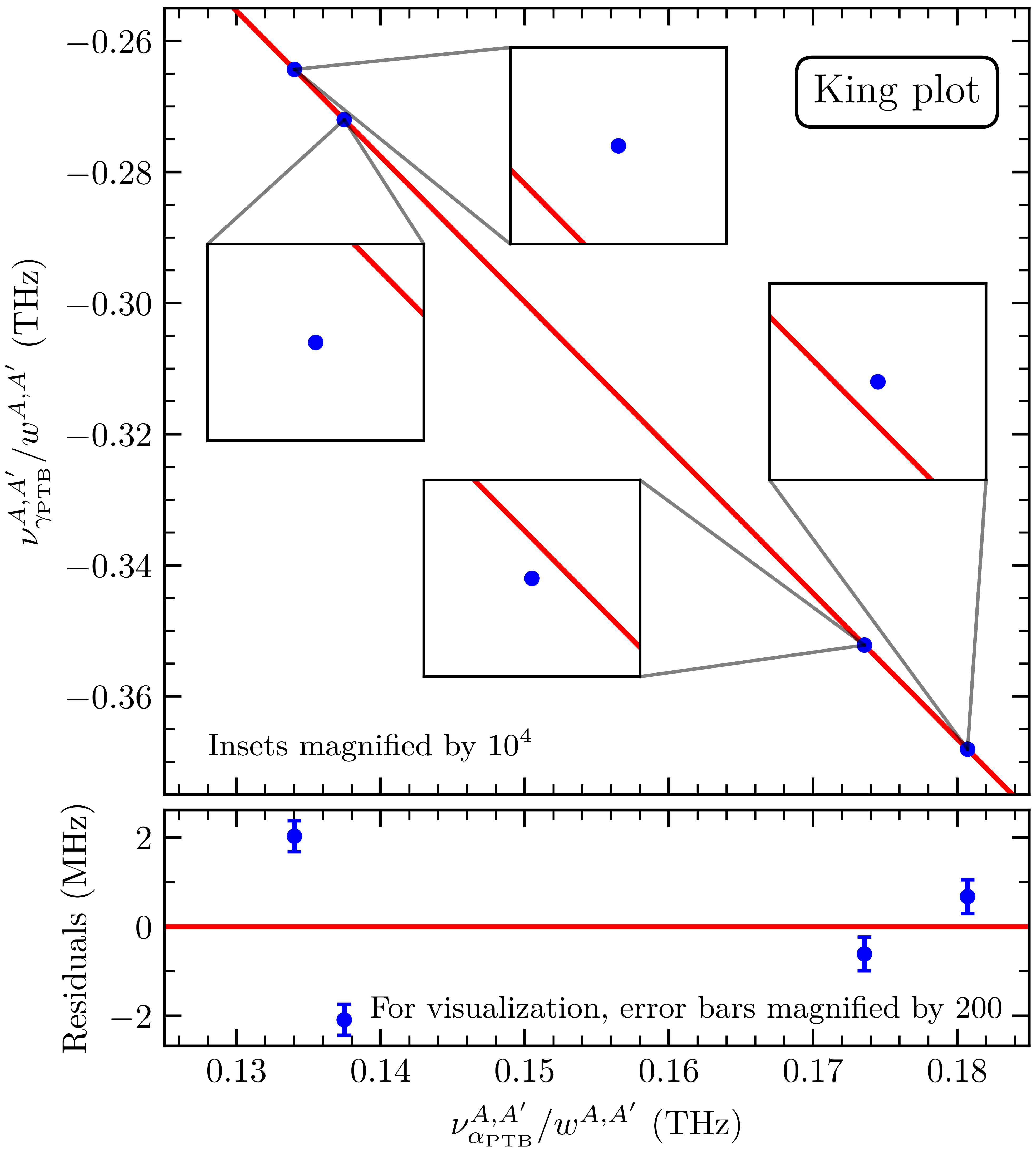
$$U = e^{\Omega} = e^{\Omega_1+\Omega_2+\Omega_3+\dots}$$

MH et al., PRC **103** (2021)

- **IMSRG(3)** for **precision** and **uncertainty quantification**

Understanding the nonlinearity with ab initio nuclear structure

Analyzing the nonlinearity



Door, Yeh, **MH**, et al., PRL 134 (2025)

- Describe 4 data points as vector: $\tilde{\boldsymbol{x}}$
- Decompose in basis of 4 vectors: $\mathbf{1}$, $\tilde{\boldsymbol{\nu}}_\tau$, $\boldsymbol{\Lambda}_+$, $\boldsymbol{\Lambda}_-$

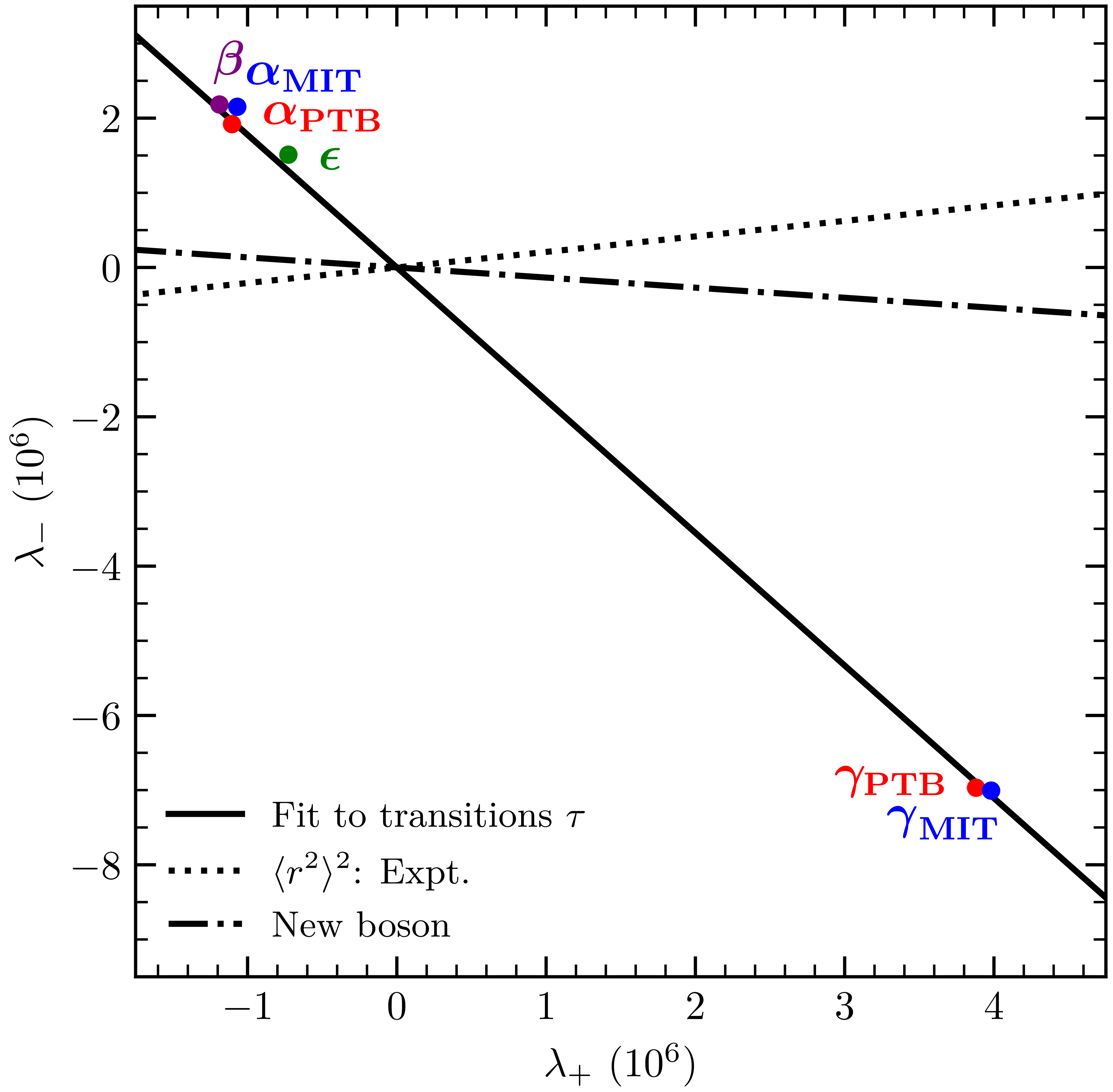
linear part **nonlinear part**

$$\tilde{\boldsymbol{x}} = K\mathbf{1} + F\tilde{\boldsymbol{\nu}}_\tau + \lambda_+\boldsymbol{\Lambda}_+ + \lambda_-\boldsymbol{\Lambda}_-$$

- Nonlinear contribution described by coefficients λ_+, λ_-
- Assuming **1 dominant nonlinearity**, slope λ_-/λ_+ is same for all transitions
  $\rightarrow$ **same underlying nuclear-structure effect responsible for nonlinearity**

Door, Yeh, **MH**, et al., PRL 134 (2025)

Impact of nuclear structure effects



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- Nonlinearity analysis suggests **single dominant higher-order term**
- $\langle r^2\rangle^2$ and new boson **incompatible** with observed nonlinearity
- **Theory predictions for $\langle r^4\rangle$ required!**

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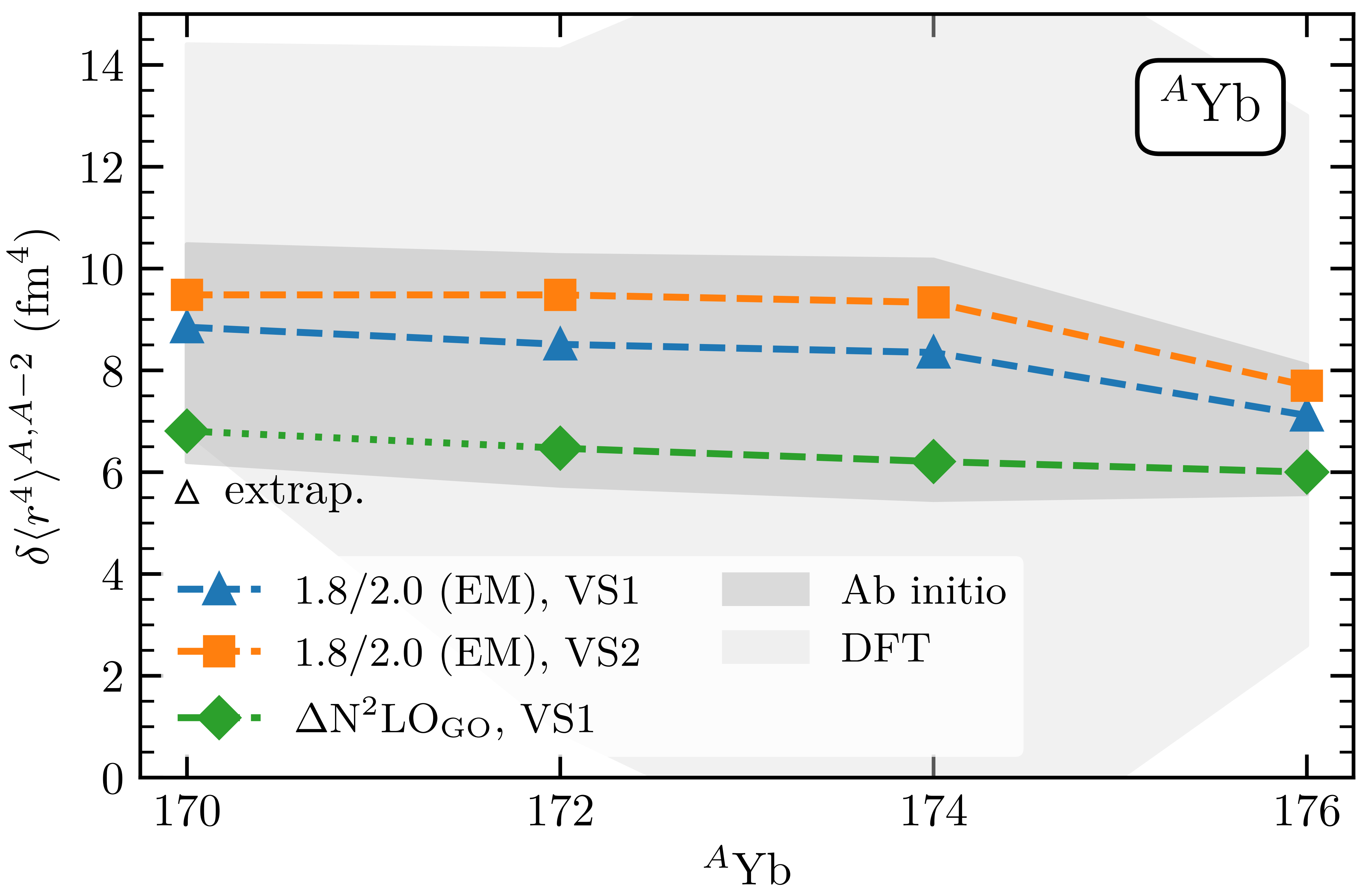

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- Two Hamiltonians, two valence spaces
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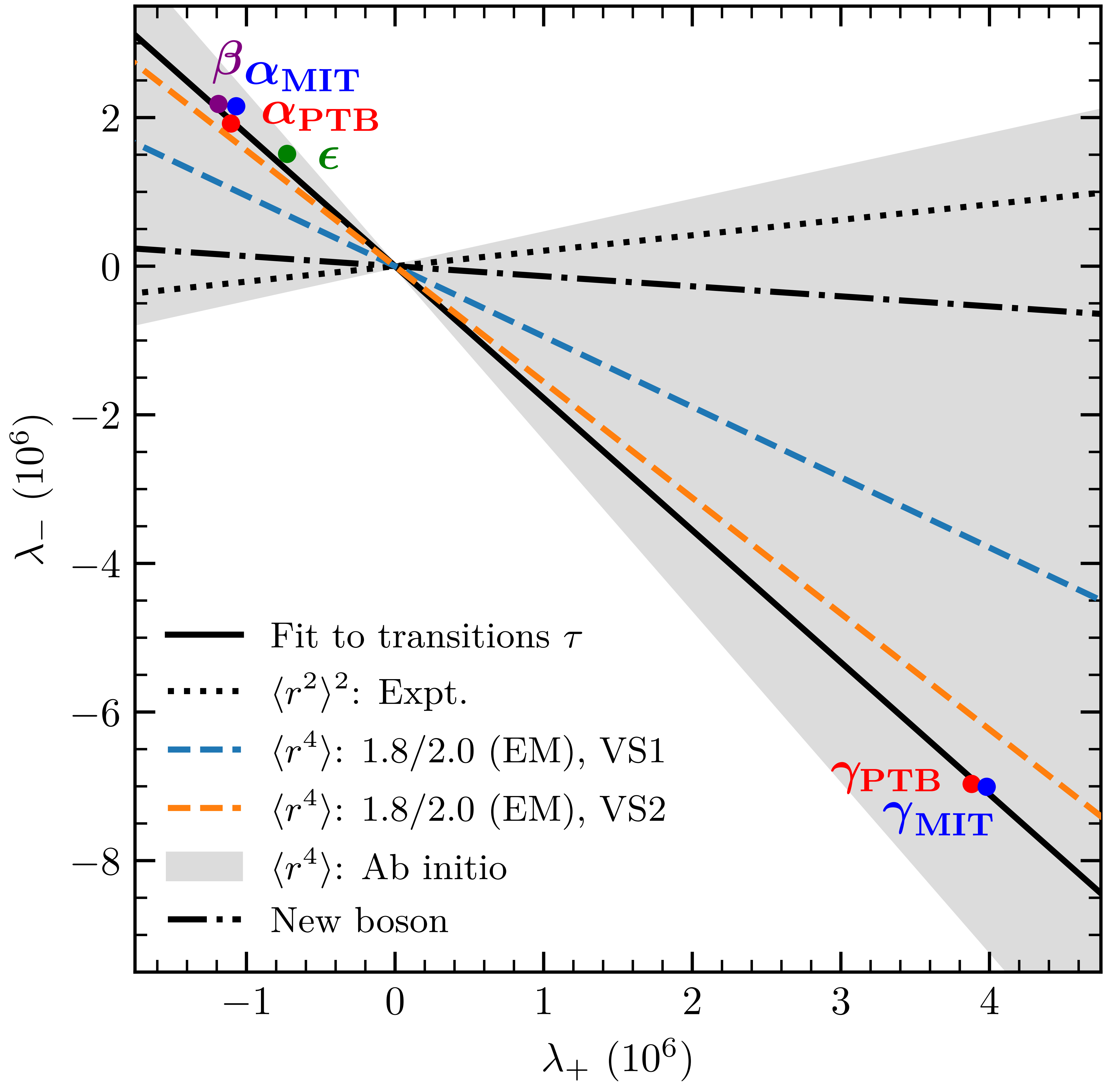

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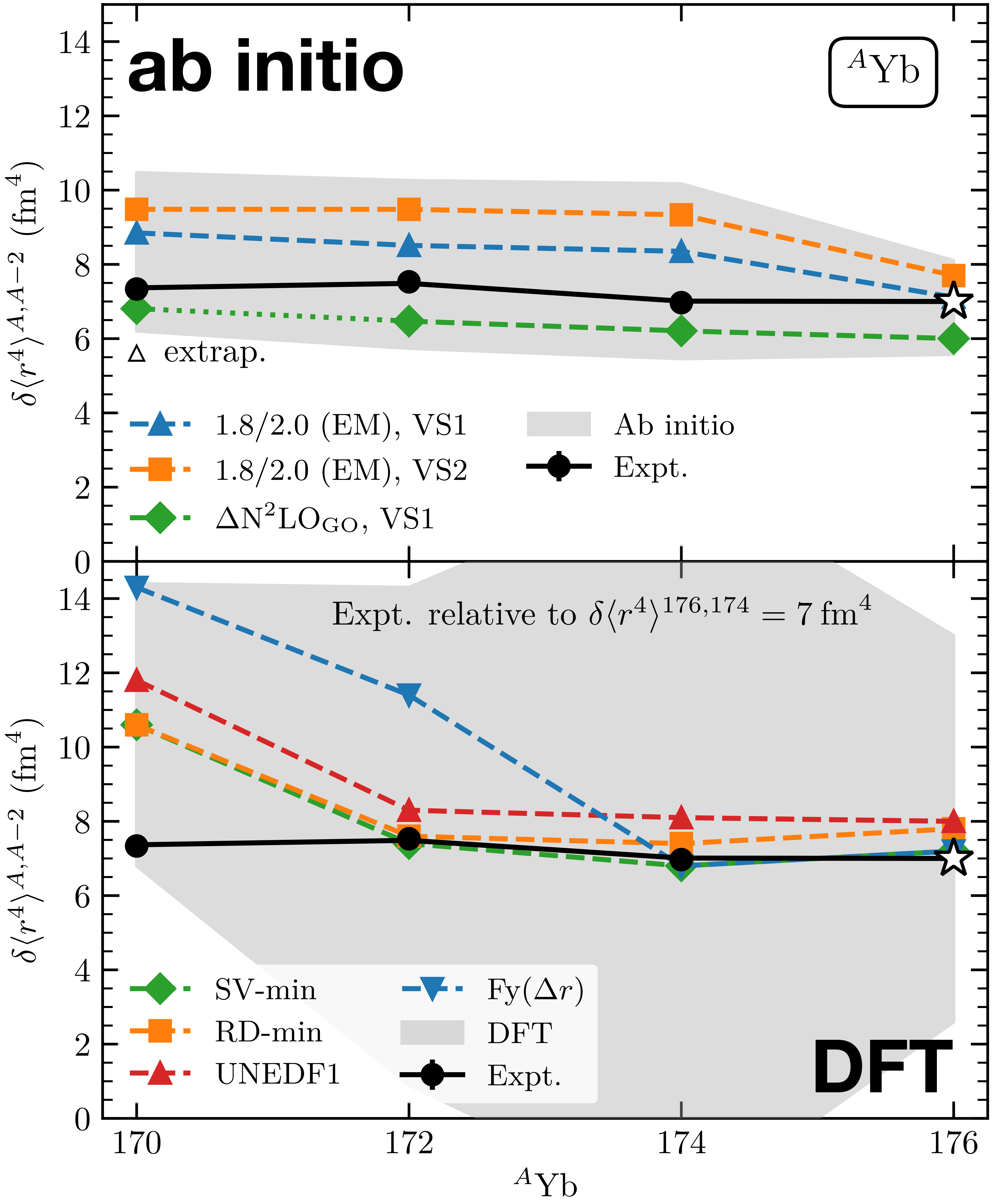
Nuclear theory: $\langle r^4 \rangle$, not new boson, is leading source of nonlinearity!

Door, Yeh, **MH**, et al., PRL 134 (2025)

New insights into nuclear structure

- Assume nonlinearity due to $\langle r^4 \rangle$
- Extract information on $\langle r^4 \rangle$ from experimental data
- Subtlety: Only sensitive to nonlinearity
  $\rightarrow$ Extraction only sensitive to relative changes in $\delta\langle r^4 \rangle^{A,A'}$
- **New observable related to deformation**

Trends more consistent with ab initio than DFT



Door, Yeh, **MH**, et al., PRL 134 (2025)

Reed, **MH**, et al., arXiv:2505.00828

Improving global mean-field models

- Ab initio calculations have **global reach**
  Stroberg et al., PRL **126** (2021)
  Hu et al., PLB **855** (2024)
  Sun et al., PRX **15** (2025)
- Including description of heavy nuclei and nuclear matter
  Miyagi et al., PRC **105** (2022), Hu et al., Nat. Phys. **18** (2022)
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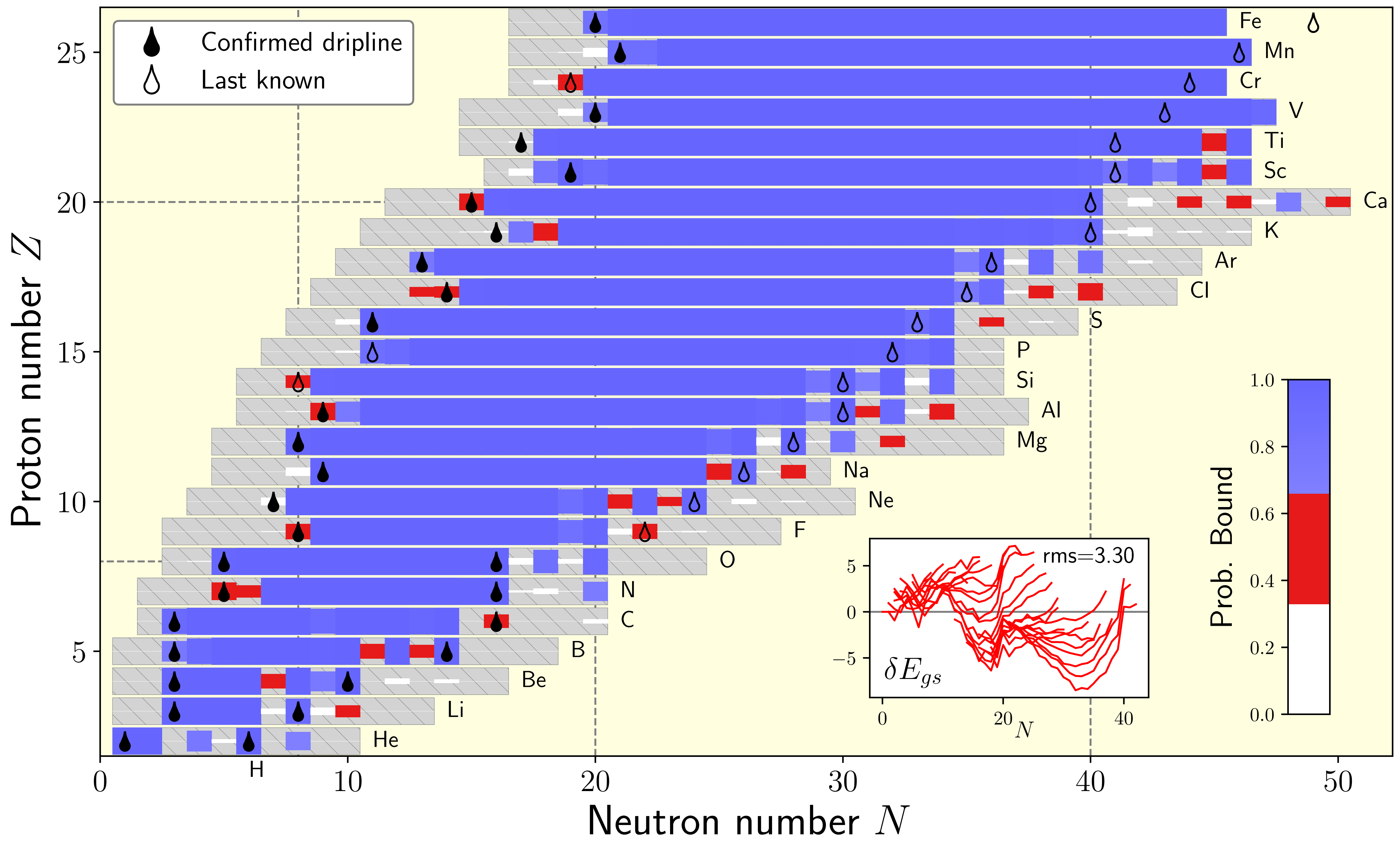
- **Idea:** Fit mean-field models to microscopic pseudodata
- **Discrepancies** between ab initio input and mean-field predictions can guide **improvement of functionals**



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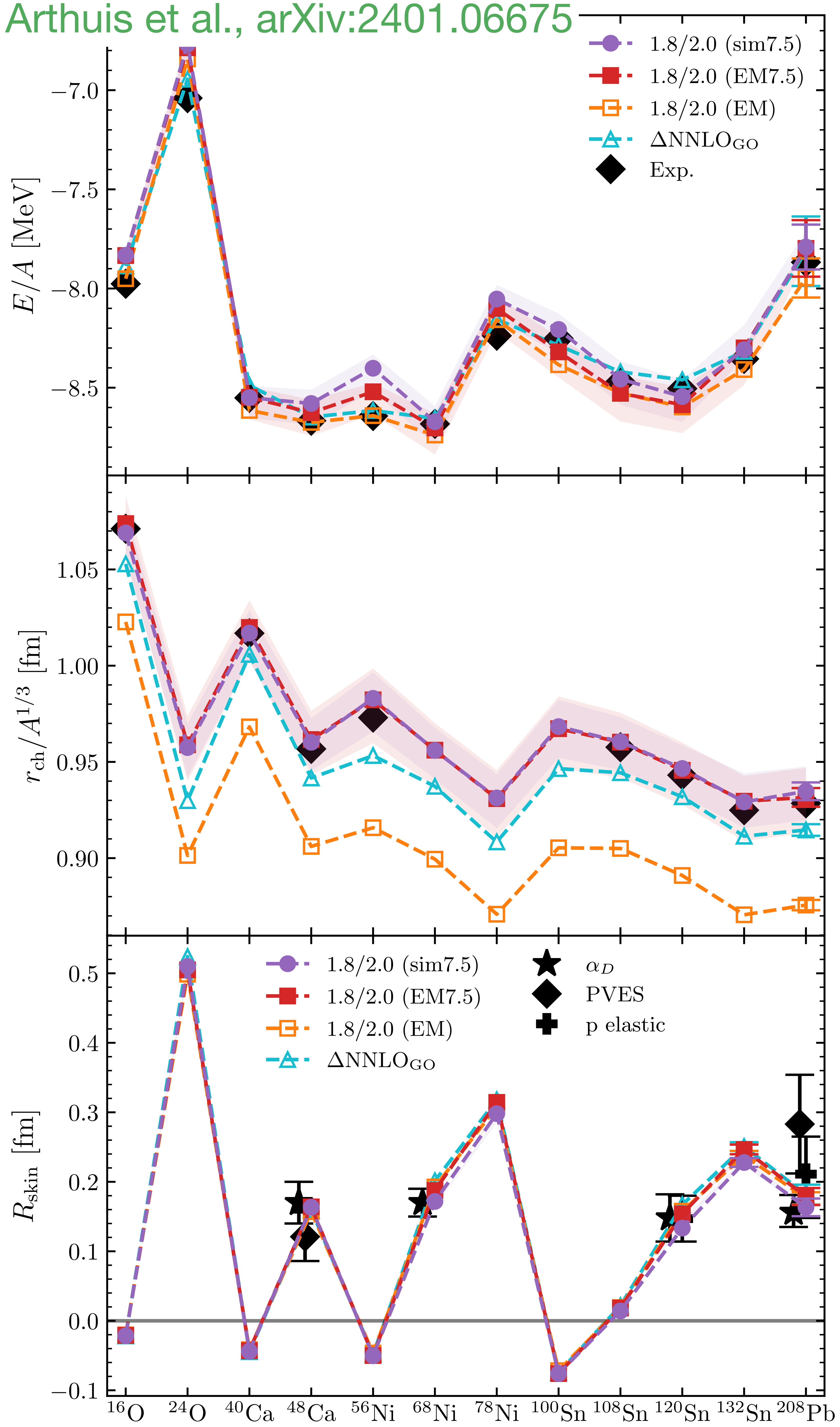

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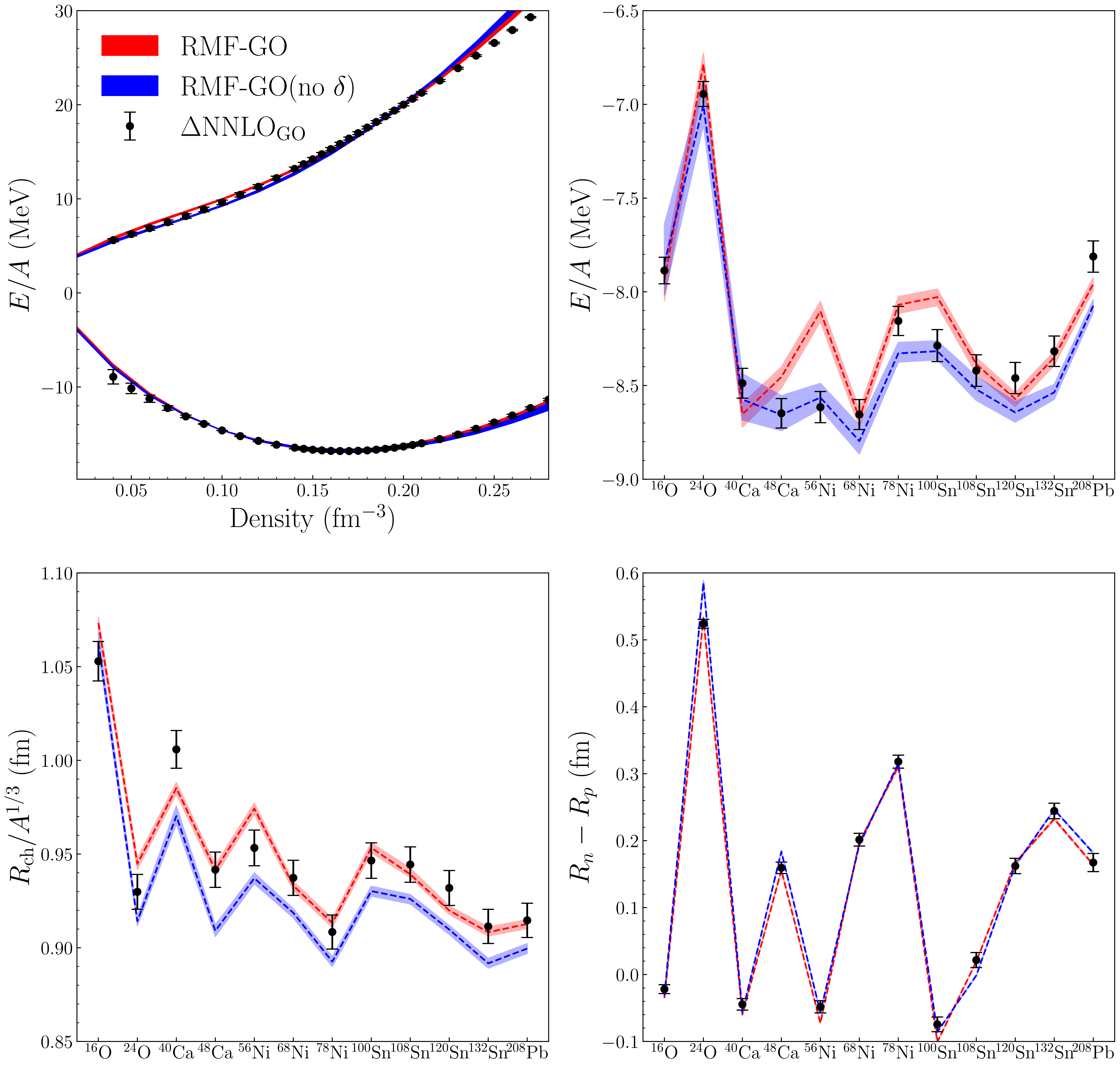

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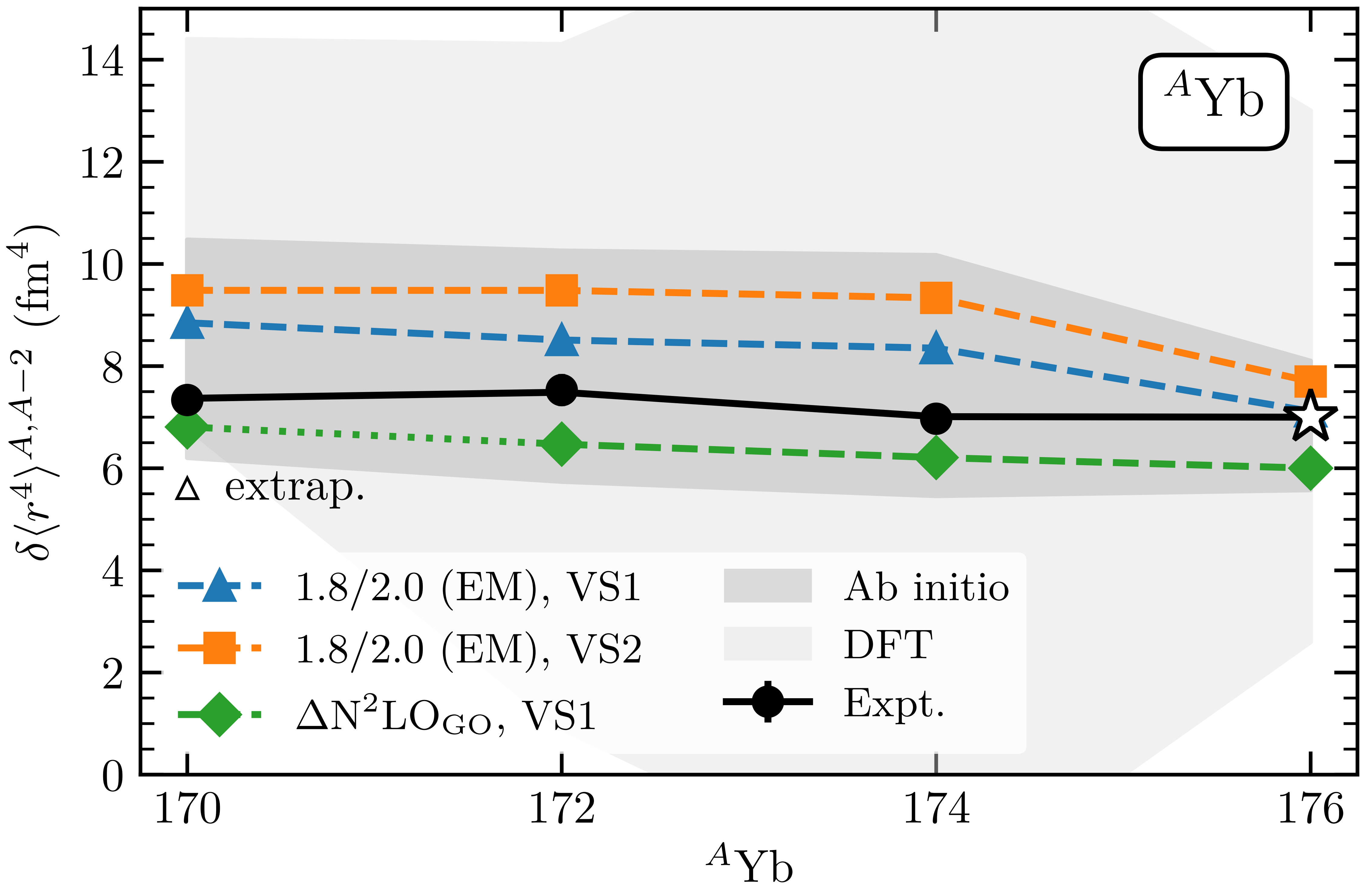
Conclusion and outlook

- **Significant progress** on **reach, precision**, and **applications** of ab initio nuclear structure calculations
- Nuclear structure input with **quantified uncertainties essential** to understand Yb King plot
- Leading signal due to **nuclear structure, not new physics**
- Remarkable reach to provide input for **new physics searches** in heavy nuclei



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Acknowledgments

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- **Leibniz University Hannover**: **Fiona Kirk**,
  Elina Fuchs
- **UNSW**: Julian Berengut
- **University of Tsukuba**: Noritaka Shimizu
- **LANL**: **Brendan Reed**, Ingo Tews
- **CNRS Orsay**: Pierre Arthuis

Thank you for your attention!