

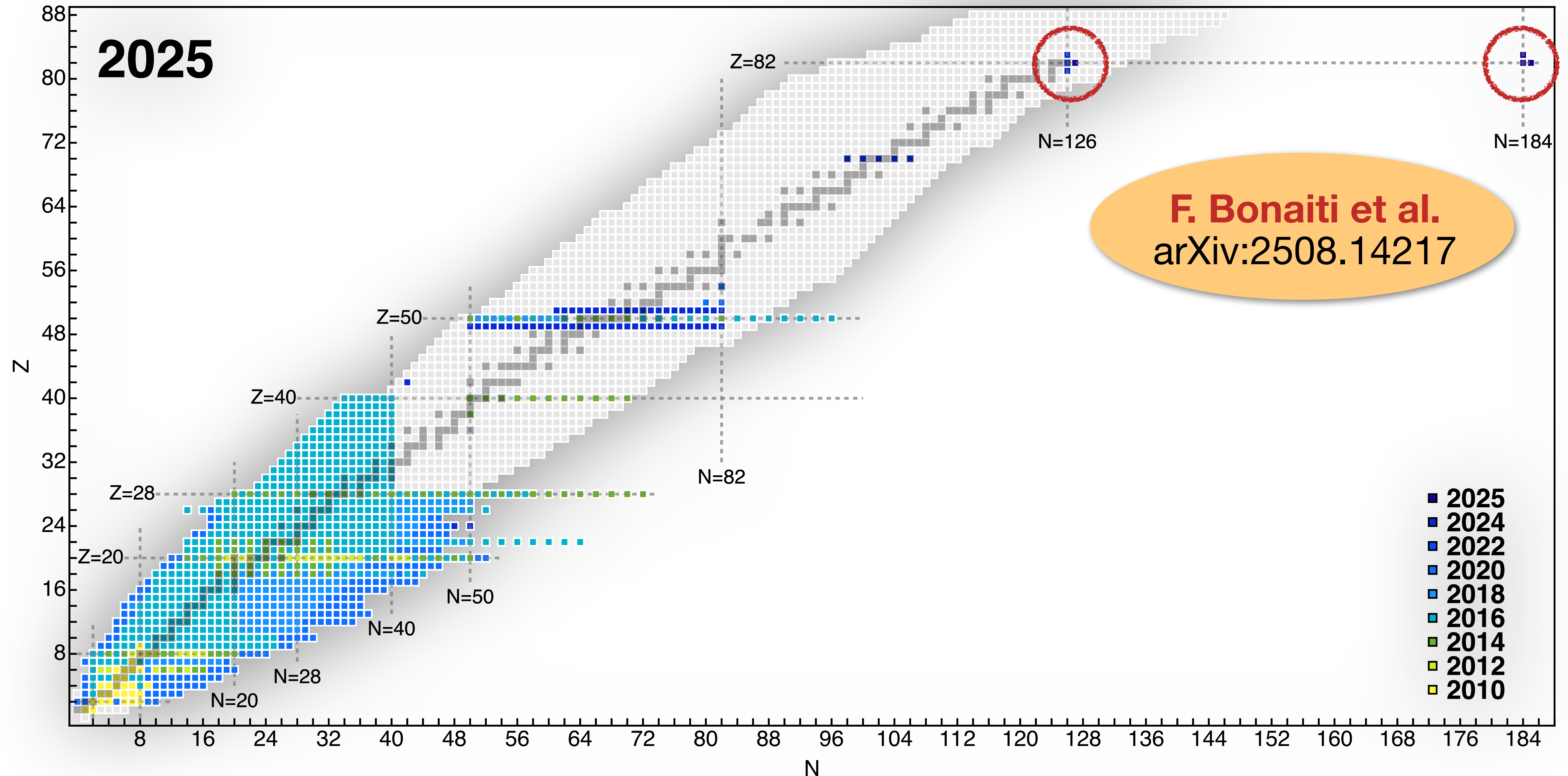
Introduction to *Ab Initio* Nuclear Theory

Heiko Hergert
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& Department of Physics and Astronomy
Michigan State University



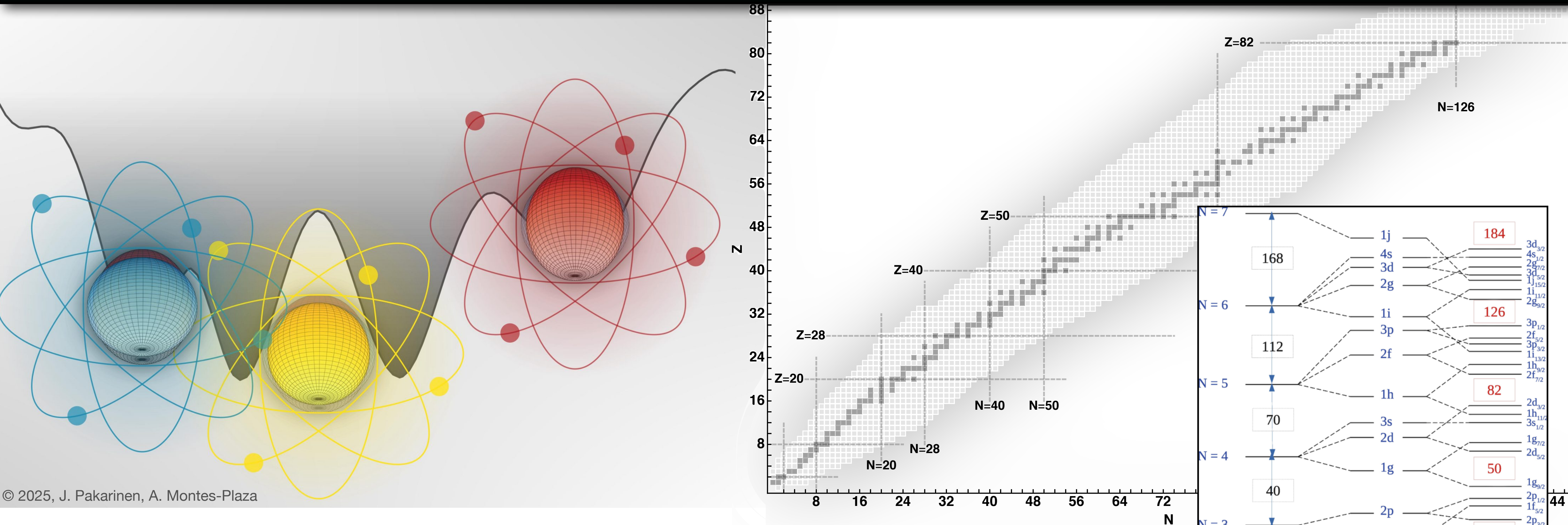
Progress in *Ab Initio* Calculations

[cf. HH, *Front. Phys.* **8**, 379 (2020)]



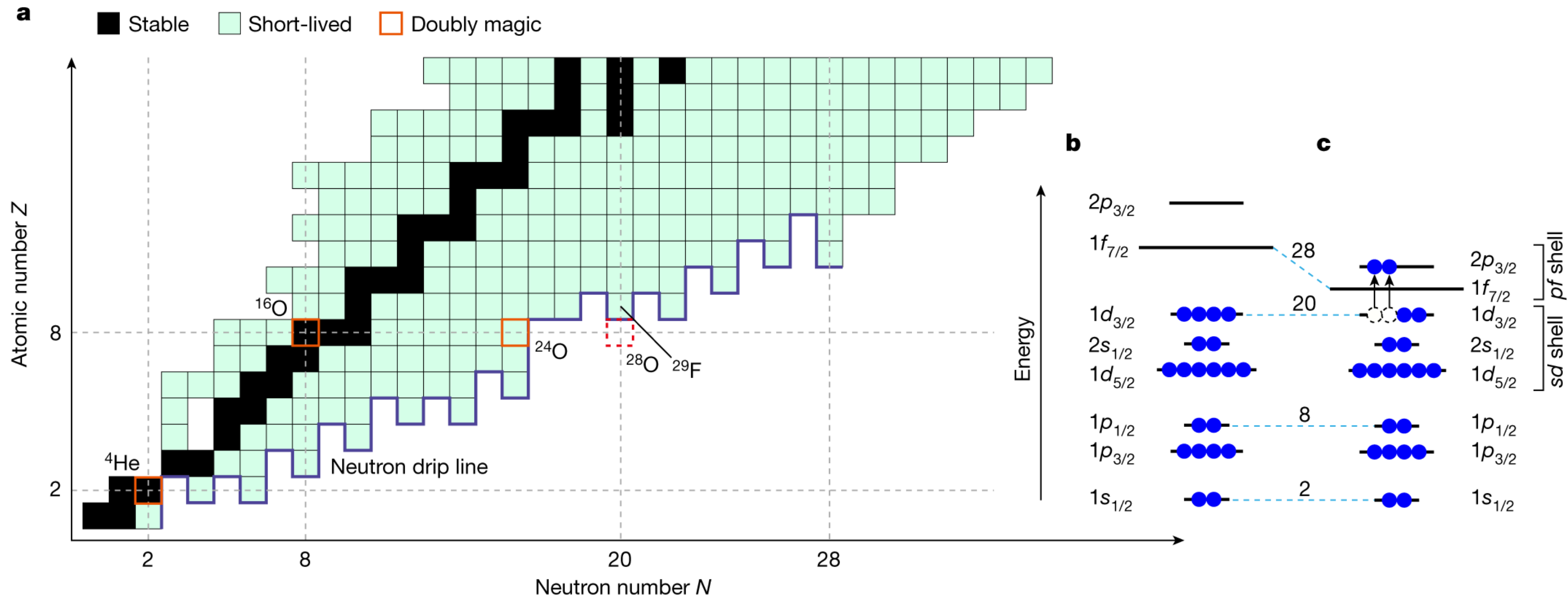
Where Do We Want to Go (Today)?

How Does Nuclear Structure Evolve?

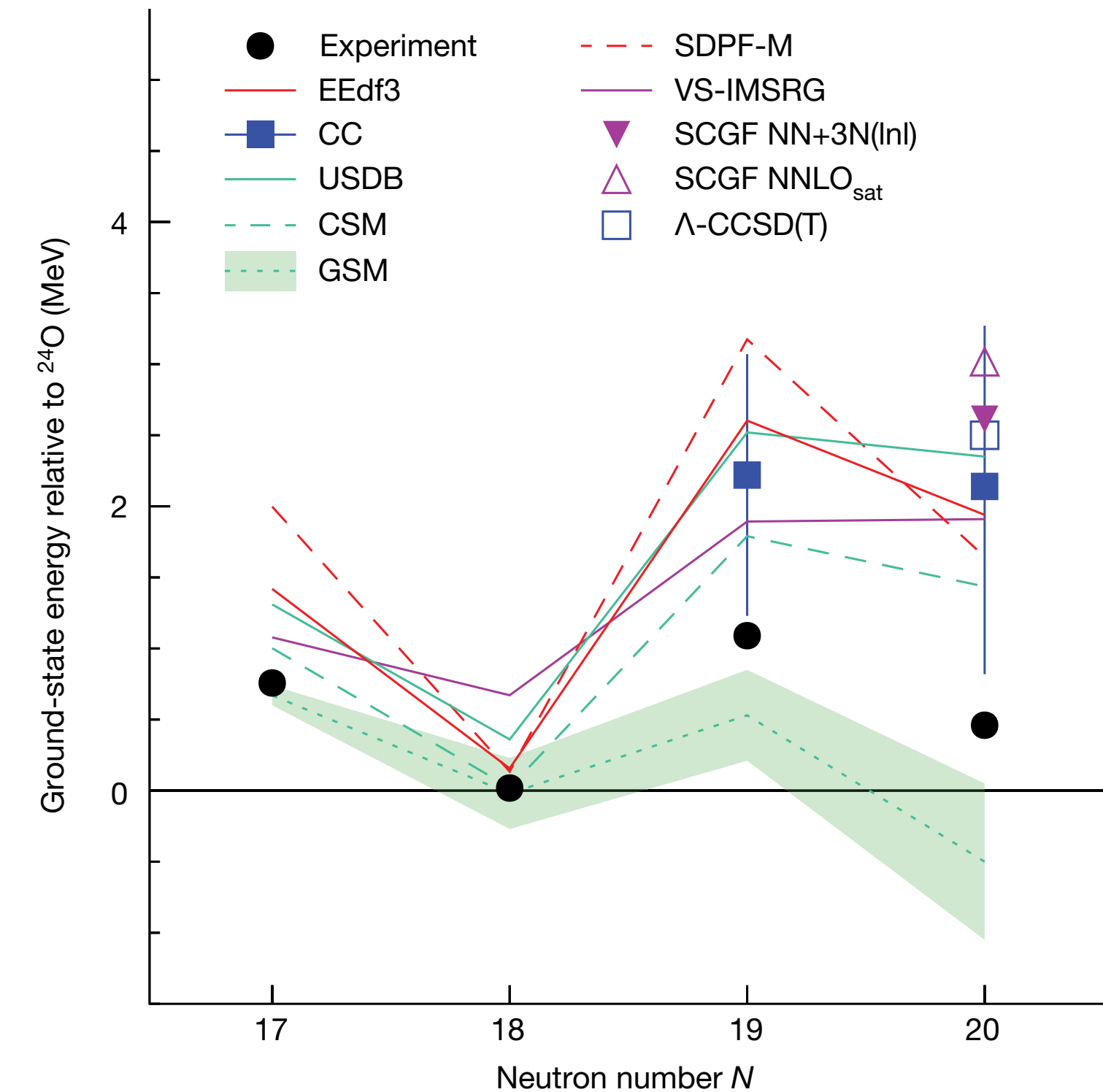


- Evolution of **(intrinsic) shapes** along isotopic chains
- New phenomena: **neutron skins, halos, ...**
- Emergence of **new magic numbers** (and absence of old ones)

What are the Limits of Nuclear Existence?

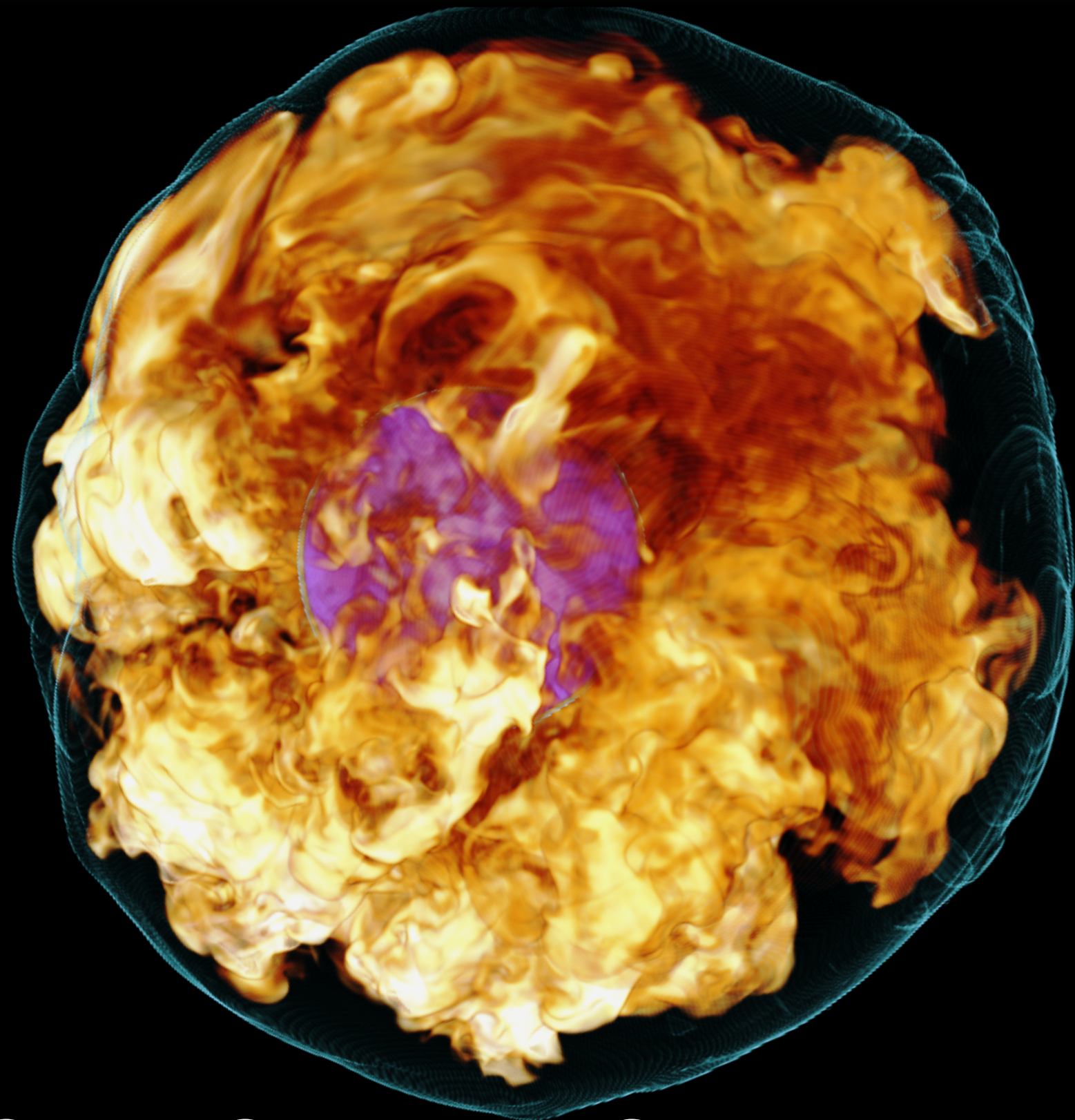


Y. Kondo et al., Nature **620**, 965 (2023)

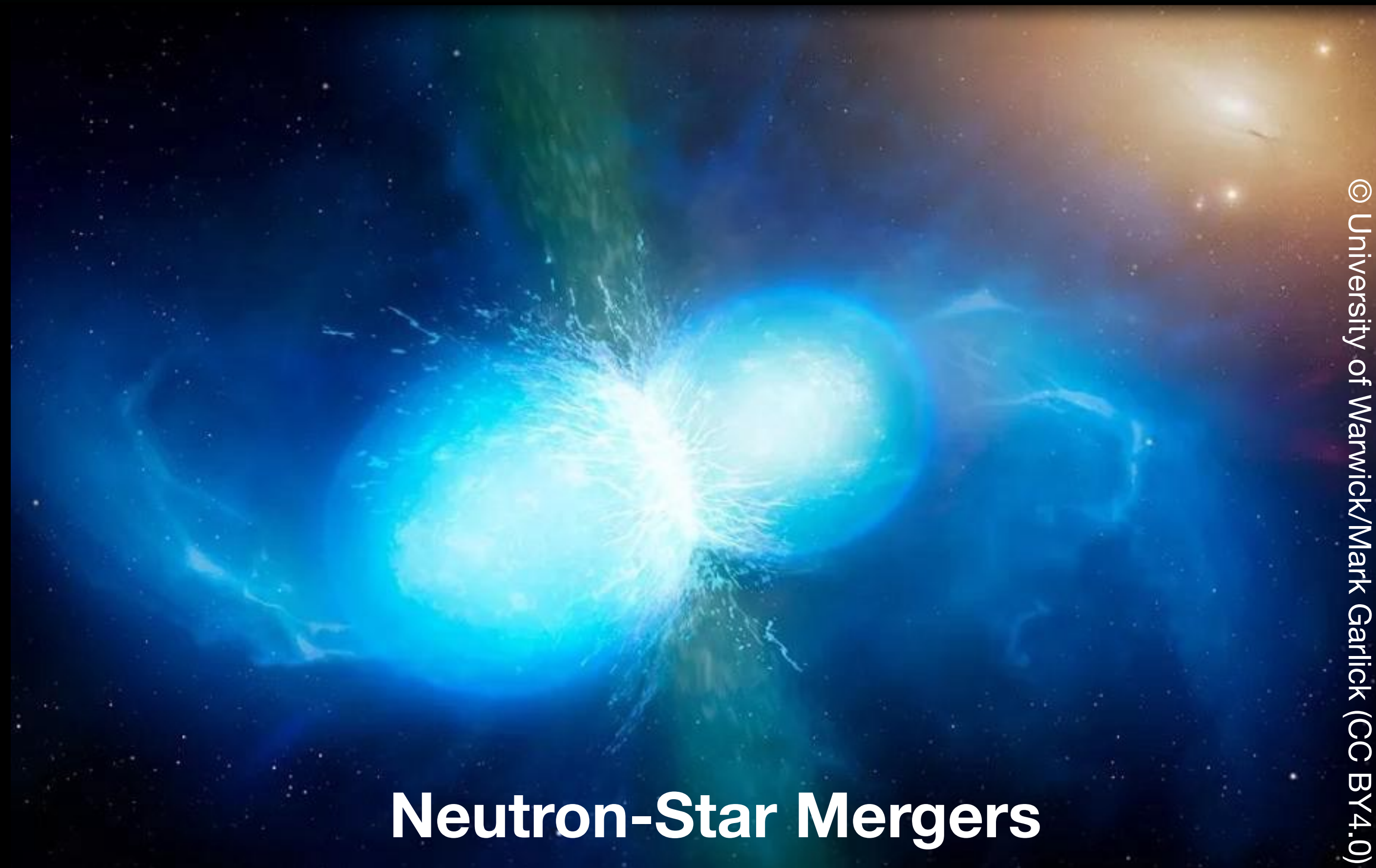


- ^{28}O found to be a **resonance**
- spread of theory predictions: phenomenology, ab initio **with different interactions**, methods with and without **continuum**, potential **deformation** effects, ...

How Were the Elements Made?



Core-Collapse Supernovae



Neutron-Star Mergers

Multi-physics problem that requires microscopic inputs

- **Equation of state (EOS)** of strongly interacting matter
- **Neutrino interactions**
- **Nuclear masses and weak interaction rates**

What Can Nuclei Tell Us about Physics Beyond the Standard Model?

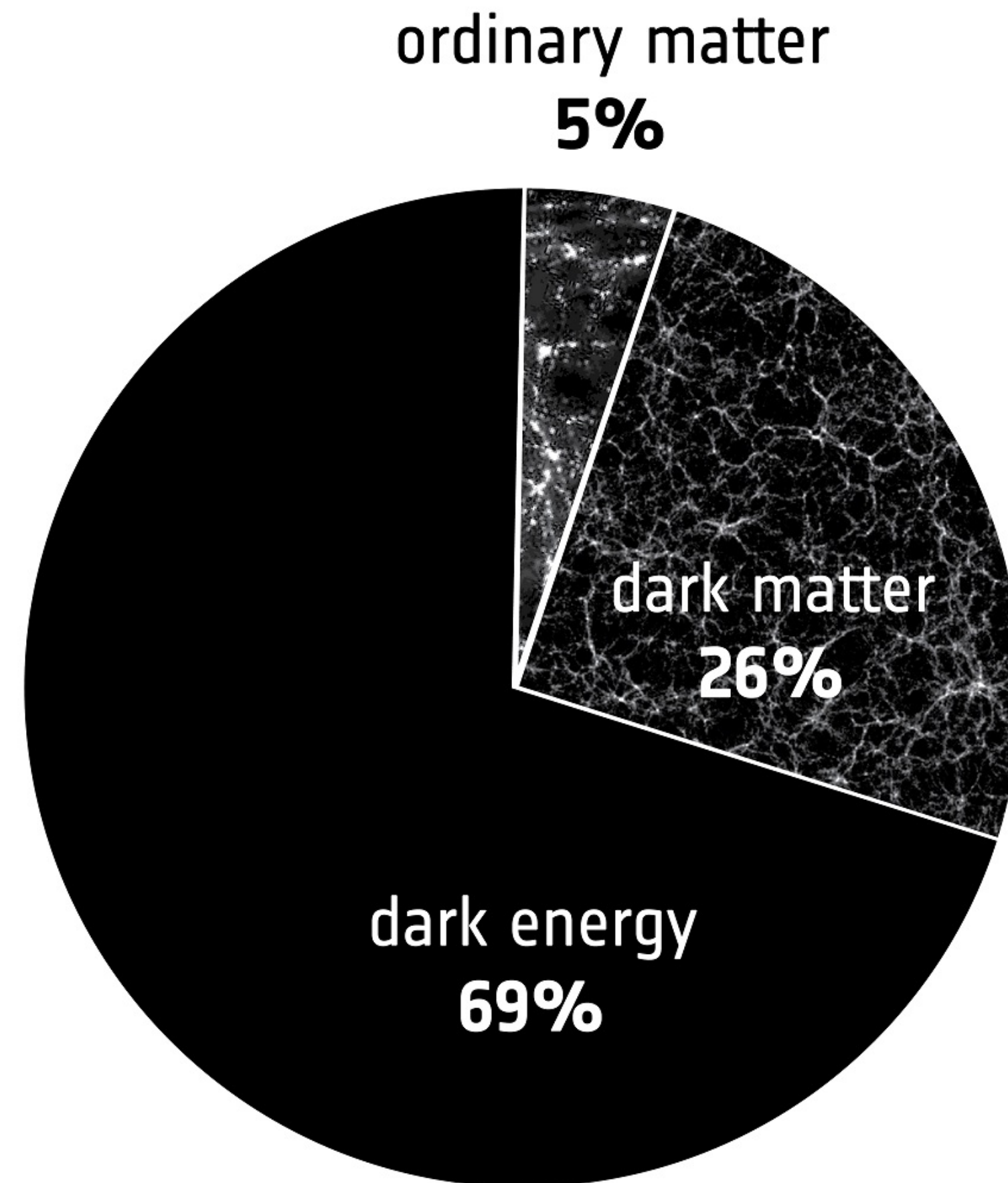
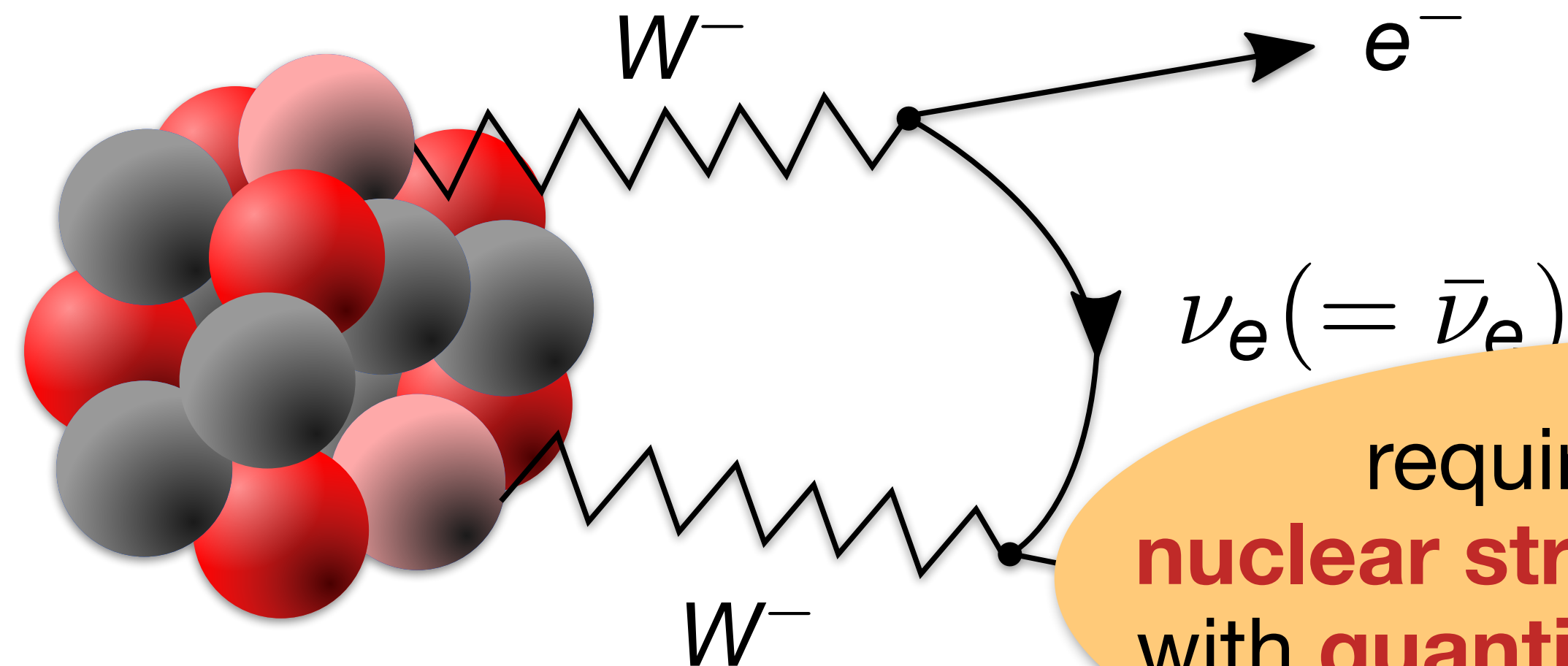


image credit: ESA

<https://sci.esa.int/web/euclid/-/42267-science>

- Standard Model does **not contain** dark matter or dark energy
- SM neutrinos are massless, but **neutrino flavor oscillations** that require mass have been **confirmed experimentally**
- SM does not explain observed **matter-antimatter asymmetry (insufficient CP symmetry violation)**

Neutrinoless Double Beta Decay

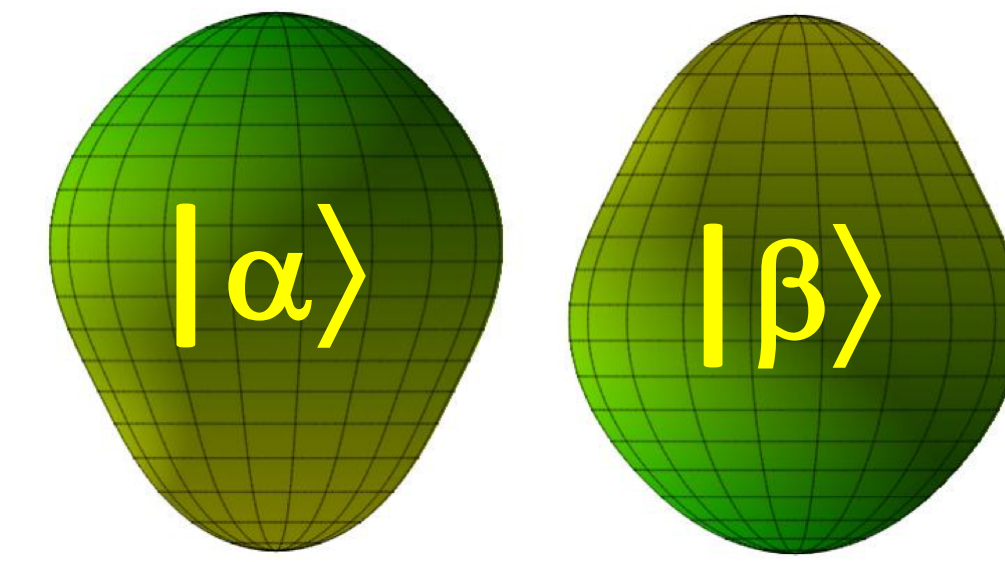


requires **accurate**
nuclear structure description
with **quantified uncertainties**

- observation would imply neutrinos are **Majorana** particles
- gives access to **absolute neutrino mass** (scale)
- mechanism for **leptogenesis**

Electric Dipole Moments

^{225}Ra



55 keV

$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$
$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

image credit: J. Singh

- observation would **confirm and constrain** new **P-, T-violating** interactions
- **baryogenesis**

Where Do We Start?

Scale Separation



by Frits Ahlefeldt

$$F = G \frac{M_E M_A}{R^2}$$

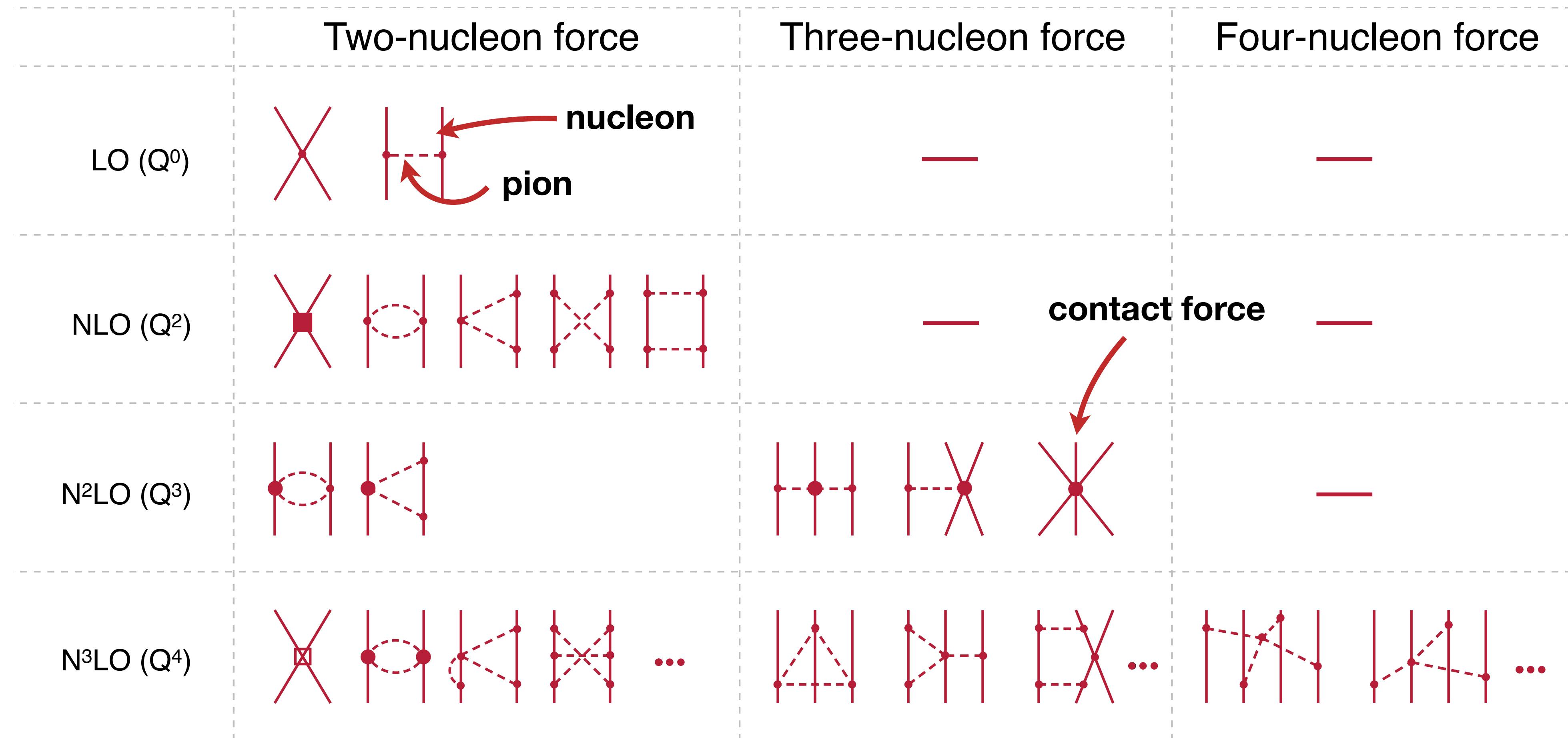
$$R \approx R_E$$

$$g \equiv G \frac{M_E}{R_E^2} \approx 9.81 \frac{m}{s^2}$$

$$F = M_A g$$

Scale separation **simplifies** description of physical processes!

Chiral Effective Field Theory



[figure by H. Krebs]

- organization in powers $(Q/\Lambda_\chi)^n$ allows **systematic improvement**
- low-energy constants **fit to NN, 3N data** (future: from Lattice QCD (??))
- **consistent** NN, 3N, ... interactions & transition operators by coupling to gauge fields

- **premise:** make the Hamiltonian **band- or block diagonal** with respect to a given “uncorrelated” basis
- “**proper**” **RG**: decouple states with low and high momentum/energy
- **but decoupling idea is more general**

- implemented through an **operator flow equation** for $U(s)HU^\dagger(s)$:

$$\frac{d}{ds}H(s) = [\eta(s), H(s)], \quad \eta(s) \equiv \frac{dU(s)}{ds}U^\dagger(s) = -\eta^\dagger(s)$$

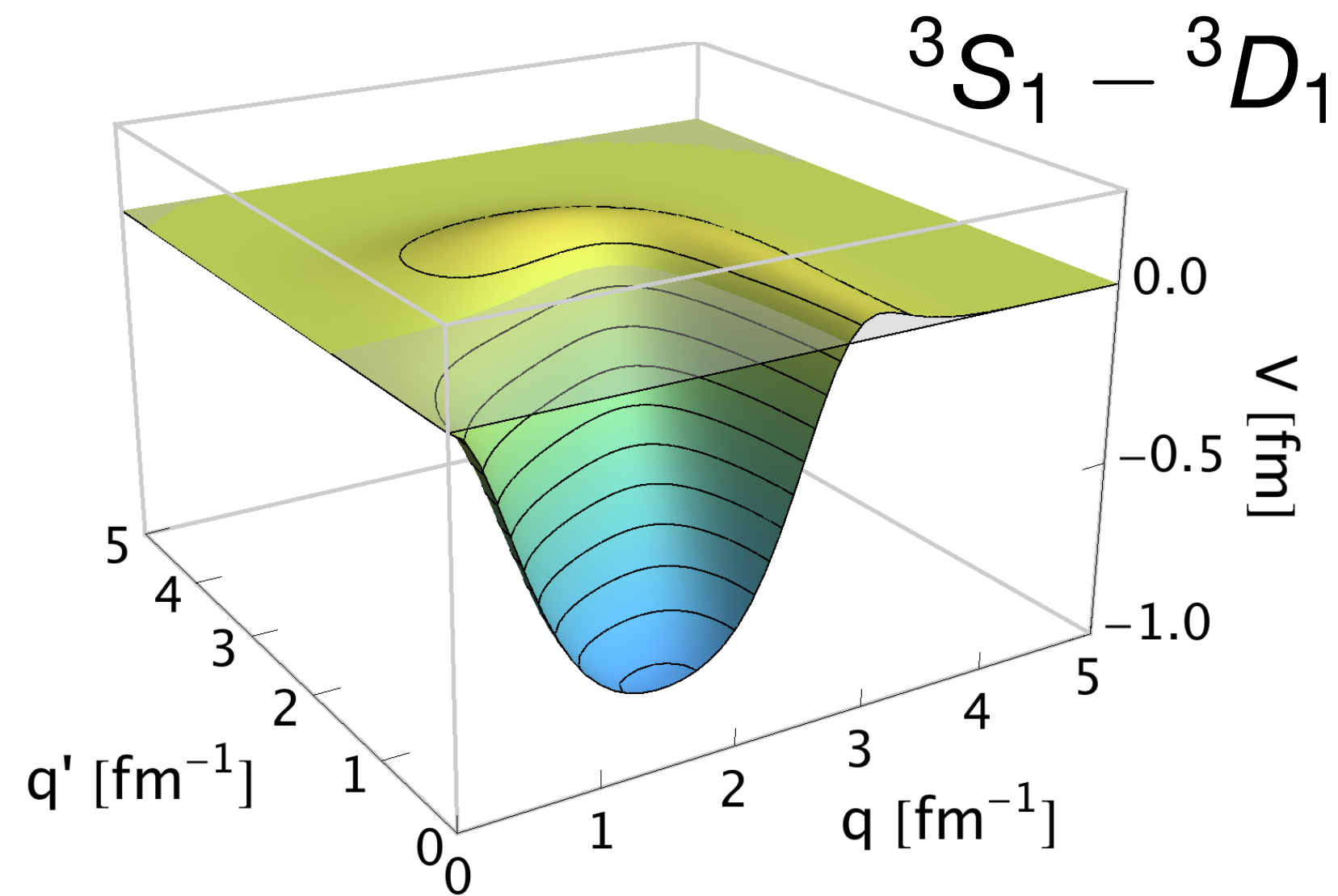
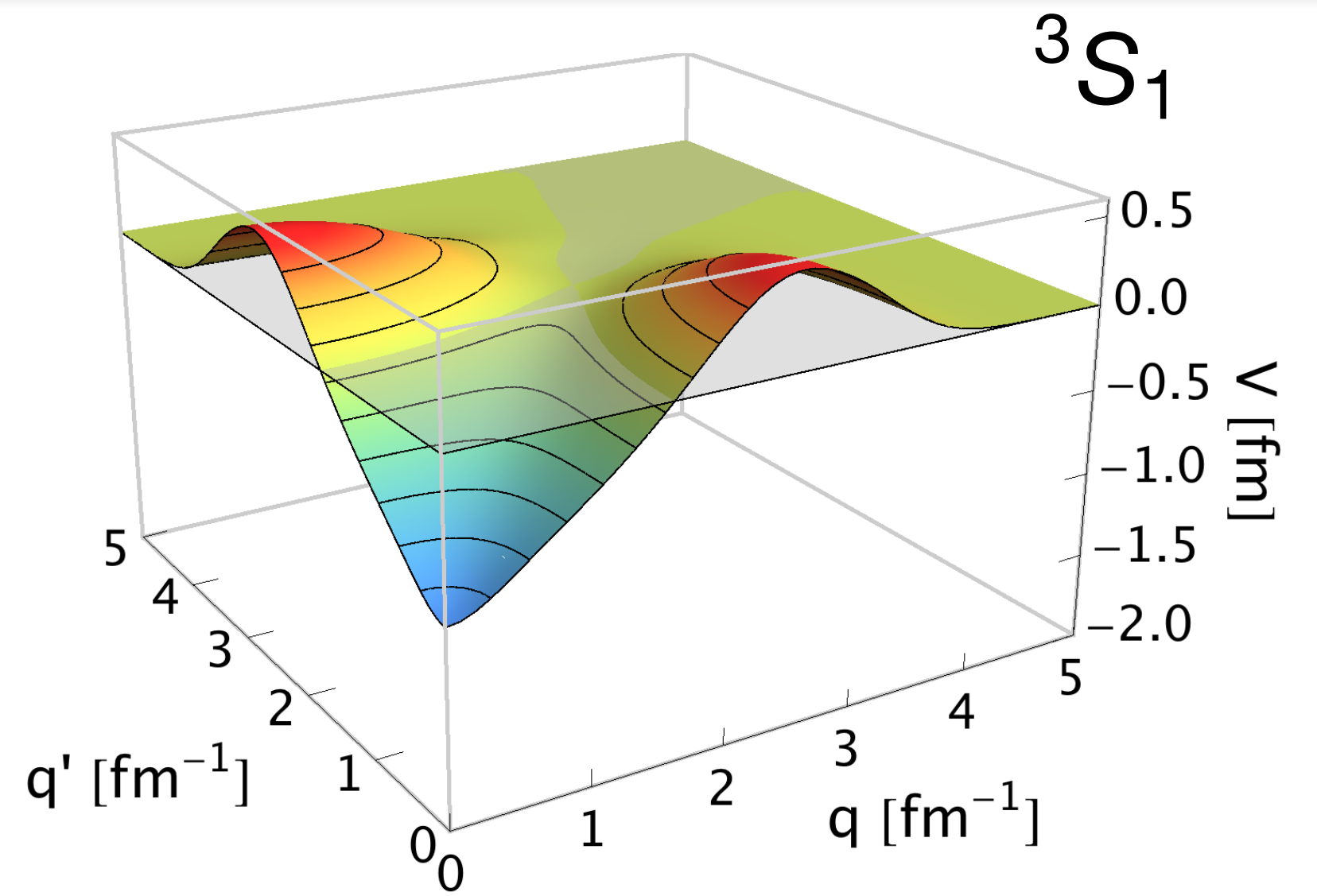
- choose **generator $\eta(s)$** to achieve desired behavior, e.g.,

$$\eta(s) = [H_d(s), H_{od}(s)]$$

to **suppress (suitably defined) off-diagonal Hamiltonian**

- need to **consistently evolve all observables of interest**

momentum space matrix elements



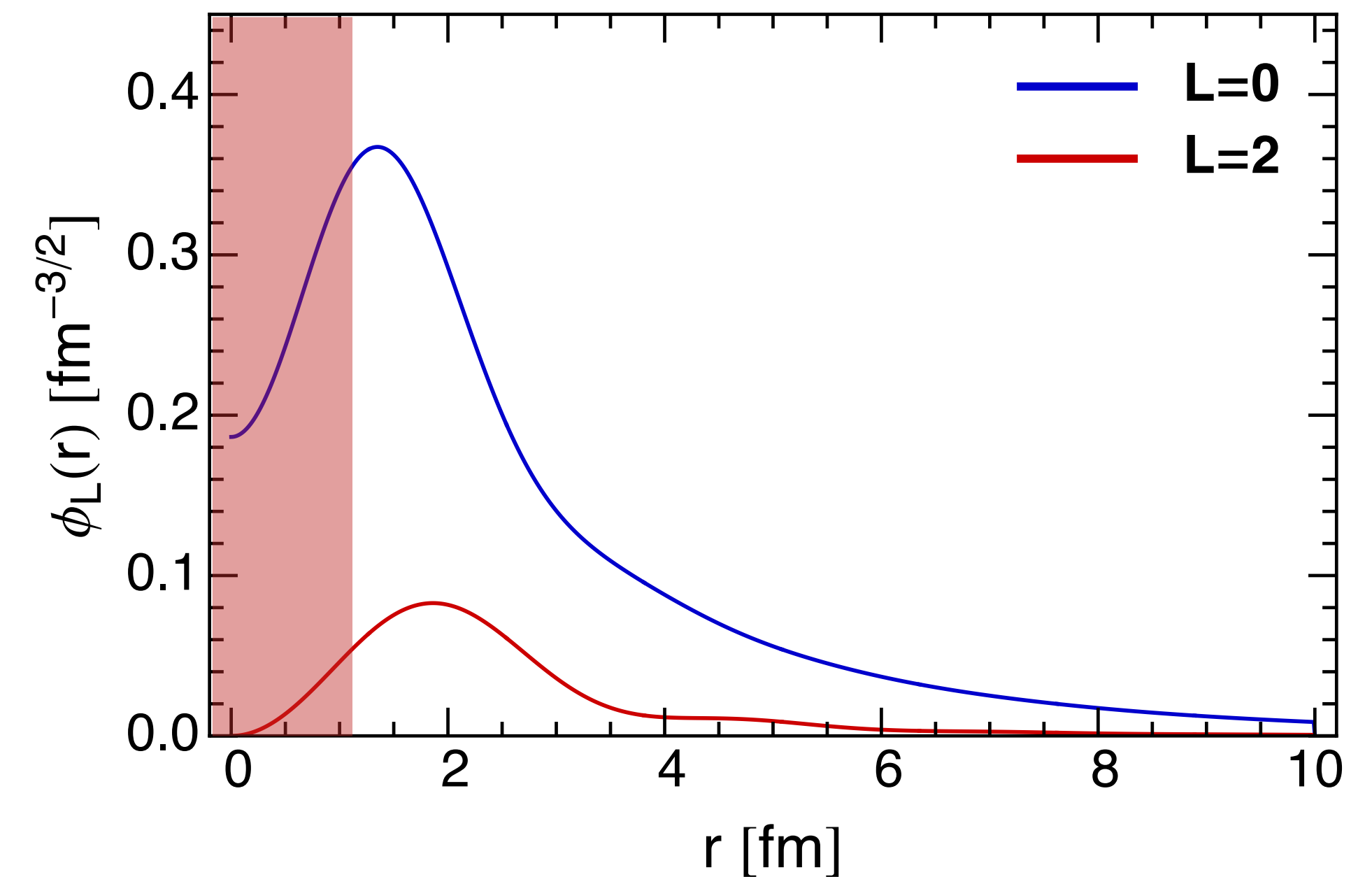
chiral NN

Entem & Machleidt, N3LO

$$\eta(\lambda) = 2\mu [T_{\text{rel}}, H(\lambda)]$$

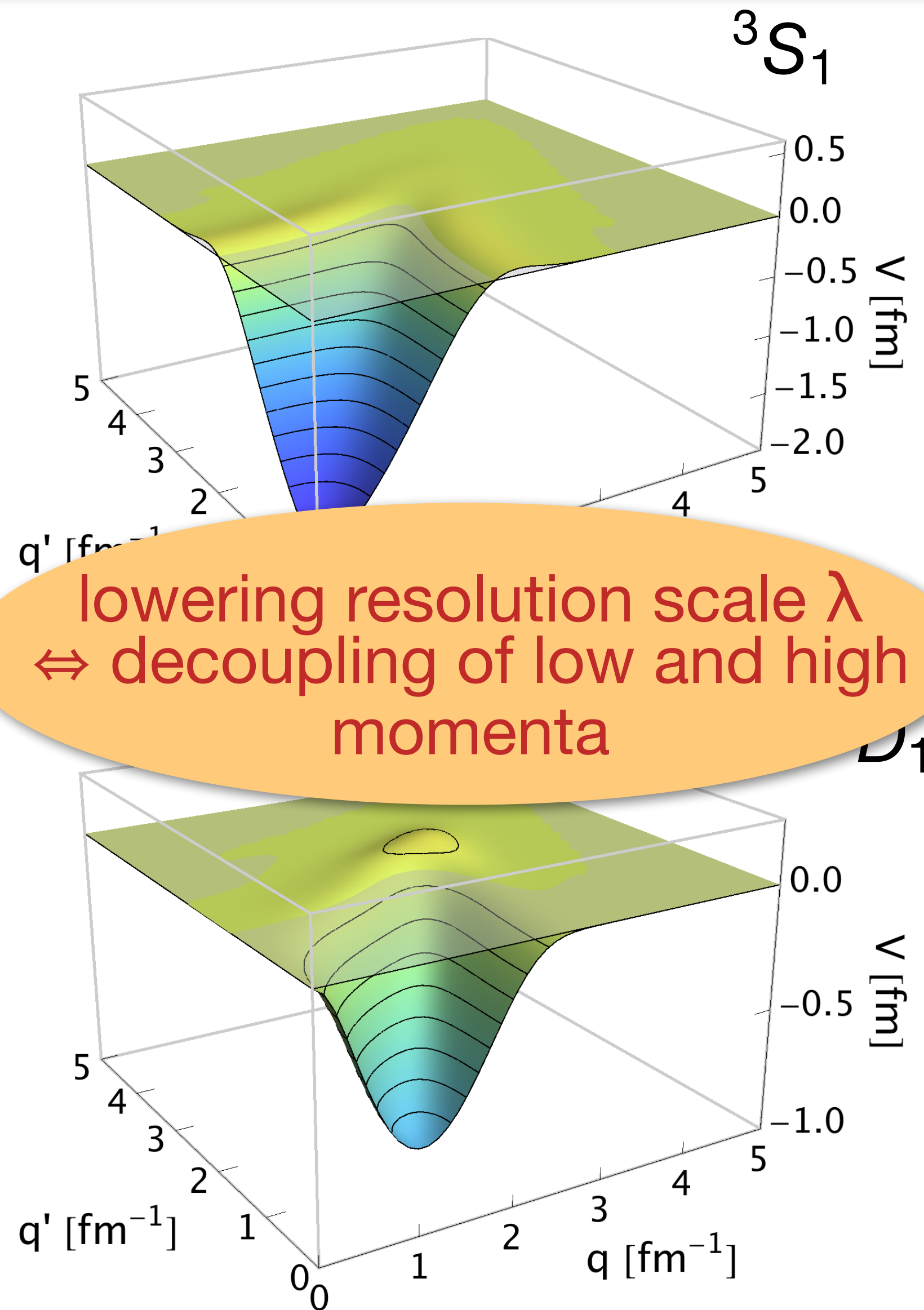
$$\lambda = s^{-1/4}$$

deuteron wave function



Similarity Renormalization Group

momentum space matrix elements

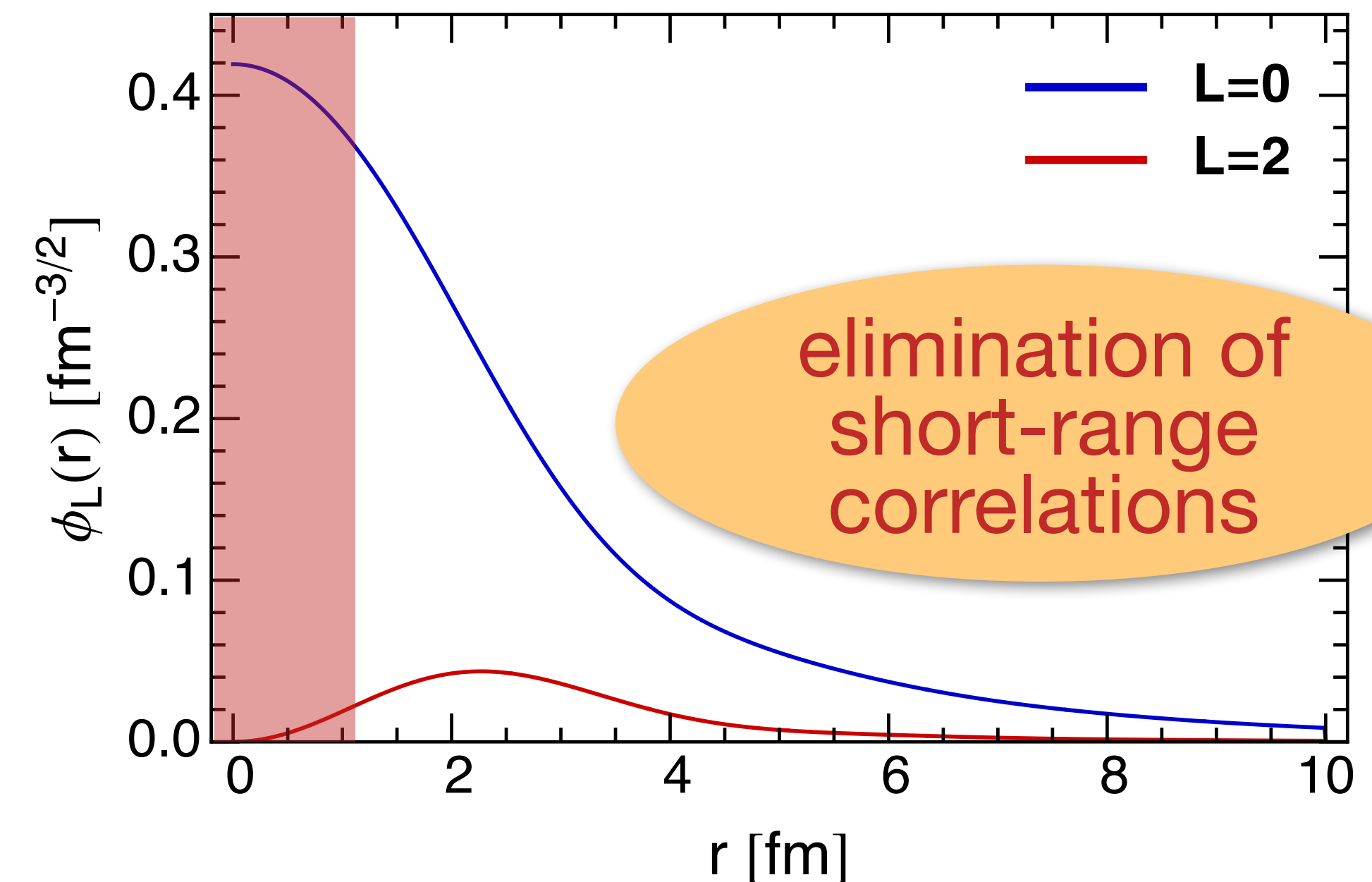


$$\lambda = 1.8 \text{ fm}^{-1}$$

$$\eta(\lambda) = 2\mu [T_{\text{rel}}, H(\lambda)]$$

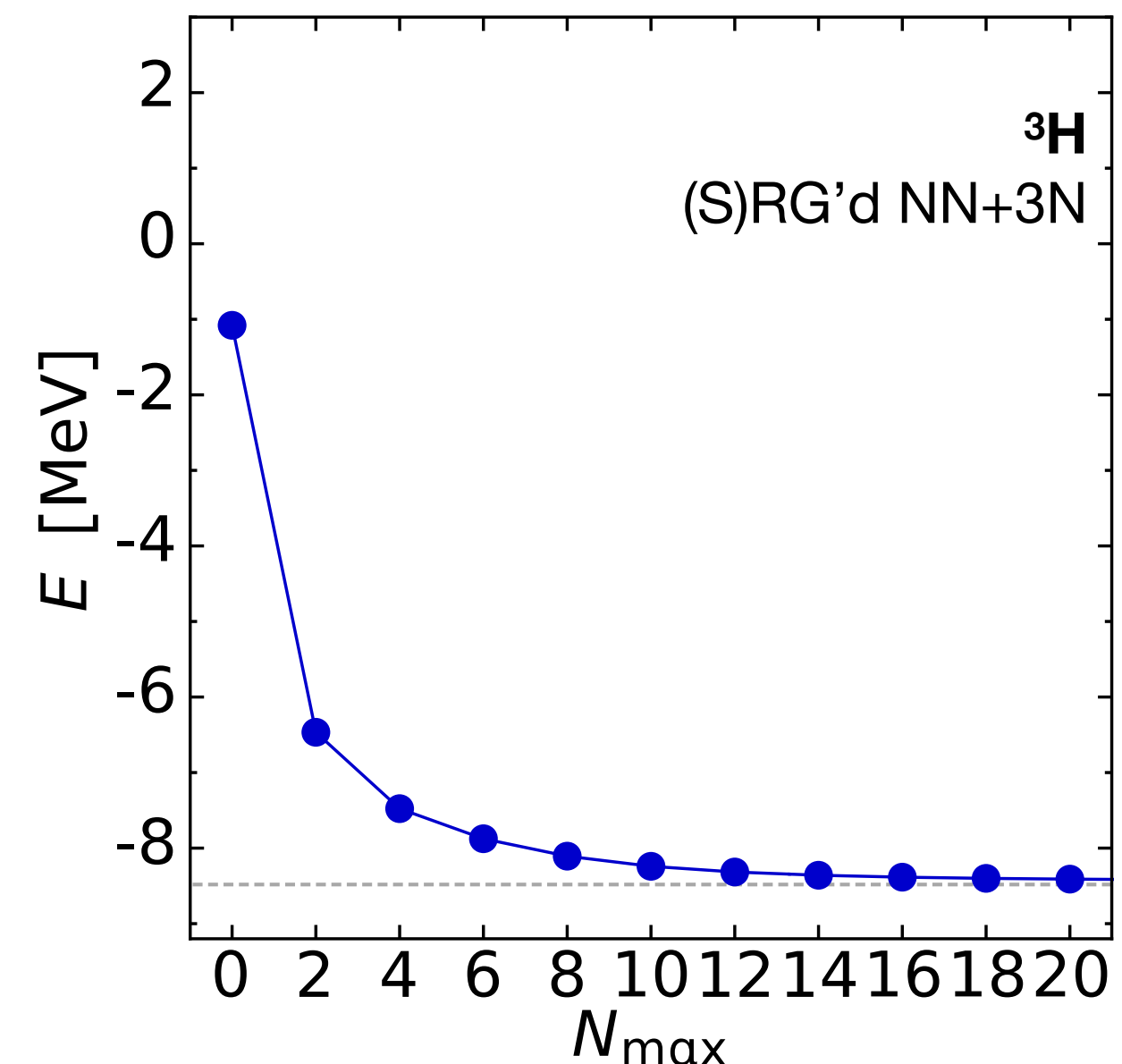
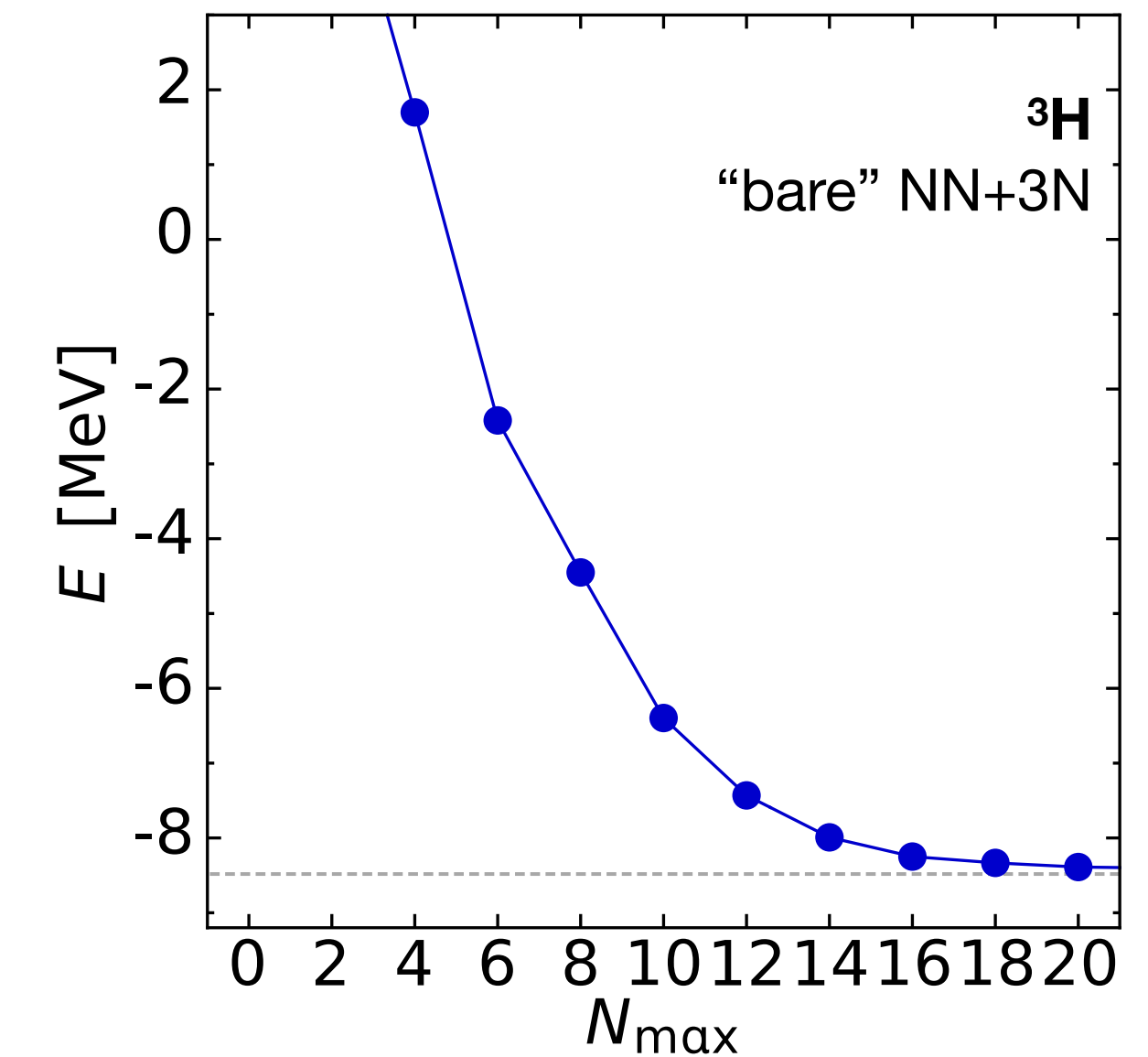
$$\lambda = s^{-1/4}$$

deuteron wave function



Renormalization of Inputs

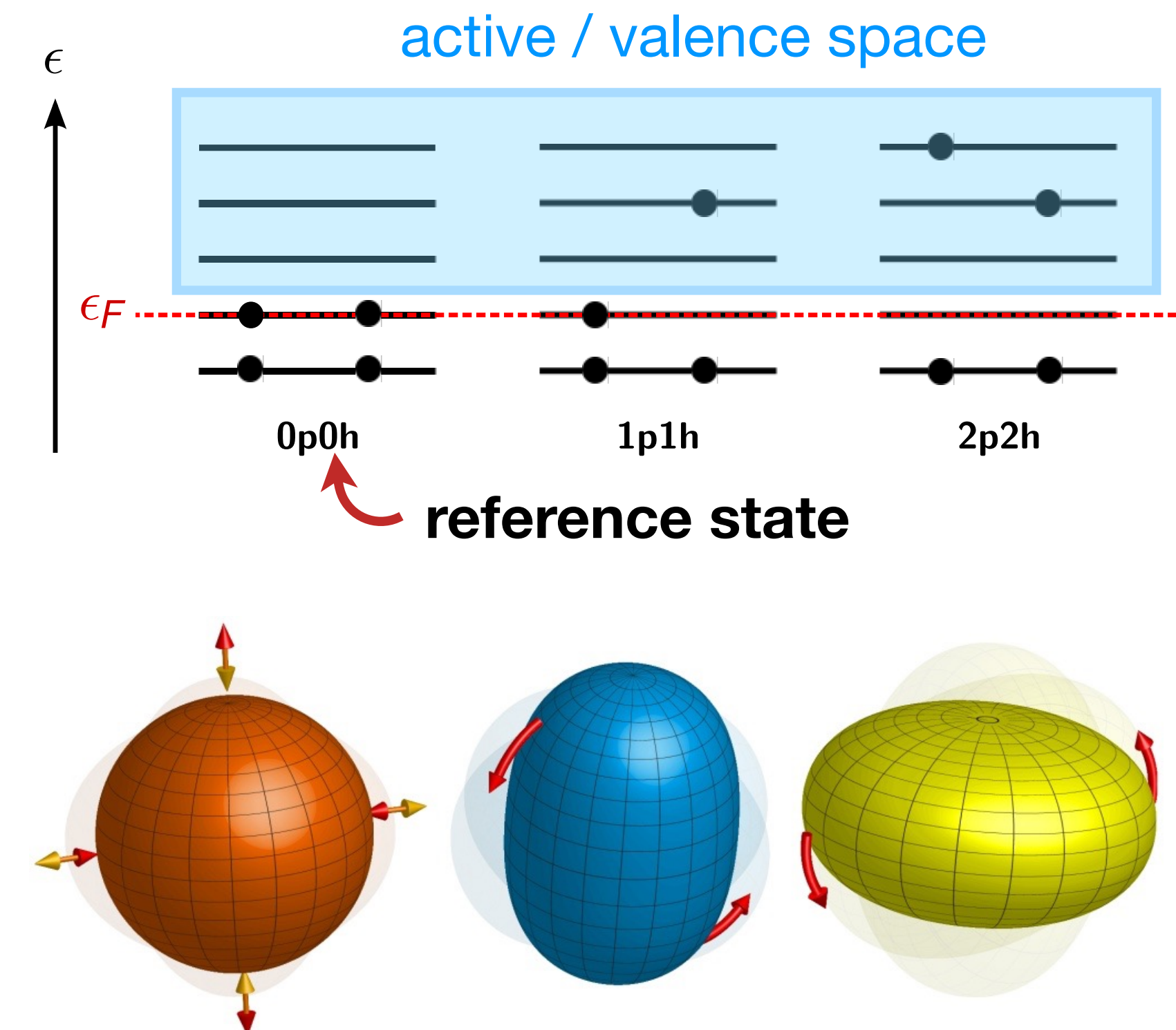
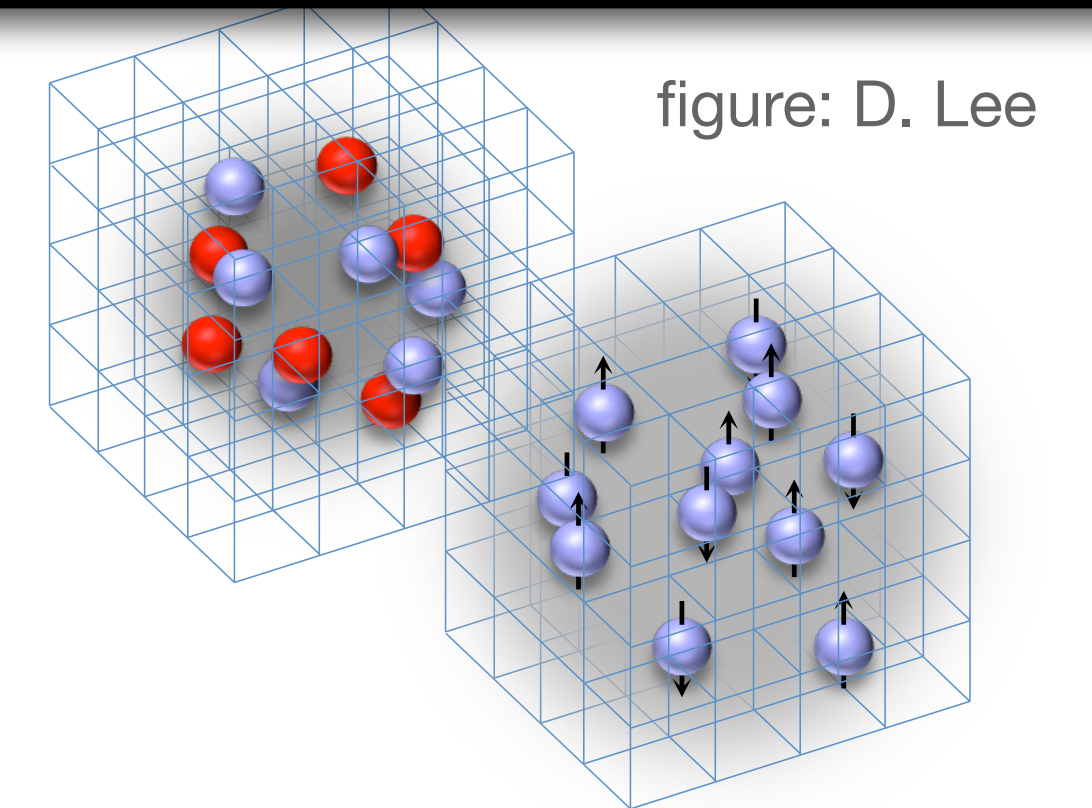
- EFT degrees of freedom (nucleons with a **specific resolution scale**) might not be “optimal” for many-body calculations
- tune **resolution scale** of a theory in **systematic fashion** with **Renormalization Group** methods
- **conserve relevant information** in low-resolution theory
- renormalization reduces effort by **orders of magnitude**, allows many-body methods to **reach heavier nuclei**
- **example:** ^3H ground-state energy from exact diagonalization
- **must be applied consistently to all observables**



How Do We Get There?

Many-Body Methods: Paradigms

- **Coordinate Space**
 - Quantum Monte Carlo
 - Lattice EFT
- **Configuration Space: Particle-Hole Expansions**
 - Many-Body Perturbation Theory (MBPT)
 - (No-Core) Configuration Interaction (aka Shell Model, (NC)SM)
 - Coupled Cluster (CC)
 - In-Medium Similarity Renormalization Group (IMSRG)
 - Self-Consistent Green's Functions (SCGF / ADC)
- **Configuration Space / Coordinate Space: Geometric Expansions**
 - deformed HF(B) + projection
 - projected Generator Coordinate Method (PGCM)
 - symmetry-adapted NCSM



Many-Body Methods: Paradigms



- **Coordinate Space**
 - Quantum Monte Carlo



Recent(-ish) Reviews:

HH, Front. Phys. **8**, 379 (2020)

S. Gandolfi, D. Lonardoni, A. Lovato and M. Piarulli, Front. Phys. **8**, 117 (2020)

D. Lee, Front. Phys. **8**, 174 (2020)

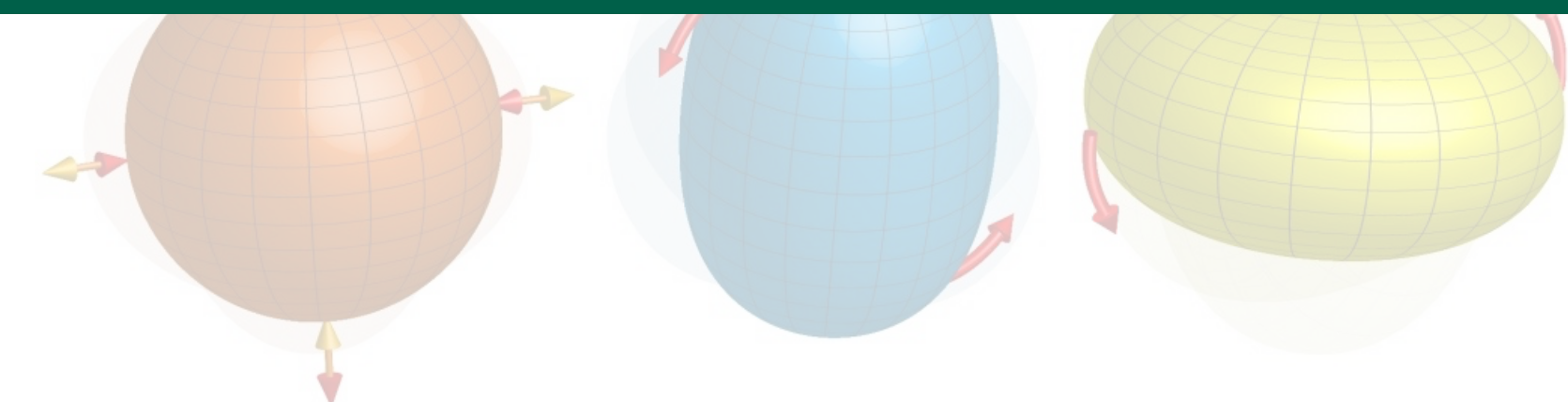
V. Somà, Front. Phys. **8**, 340 (2020)

also see

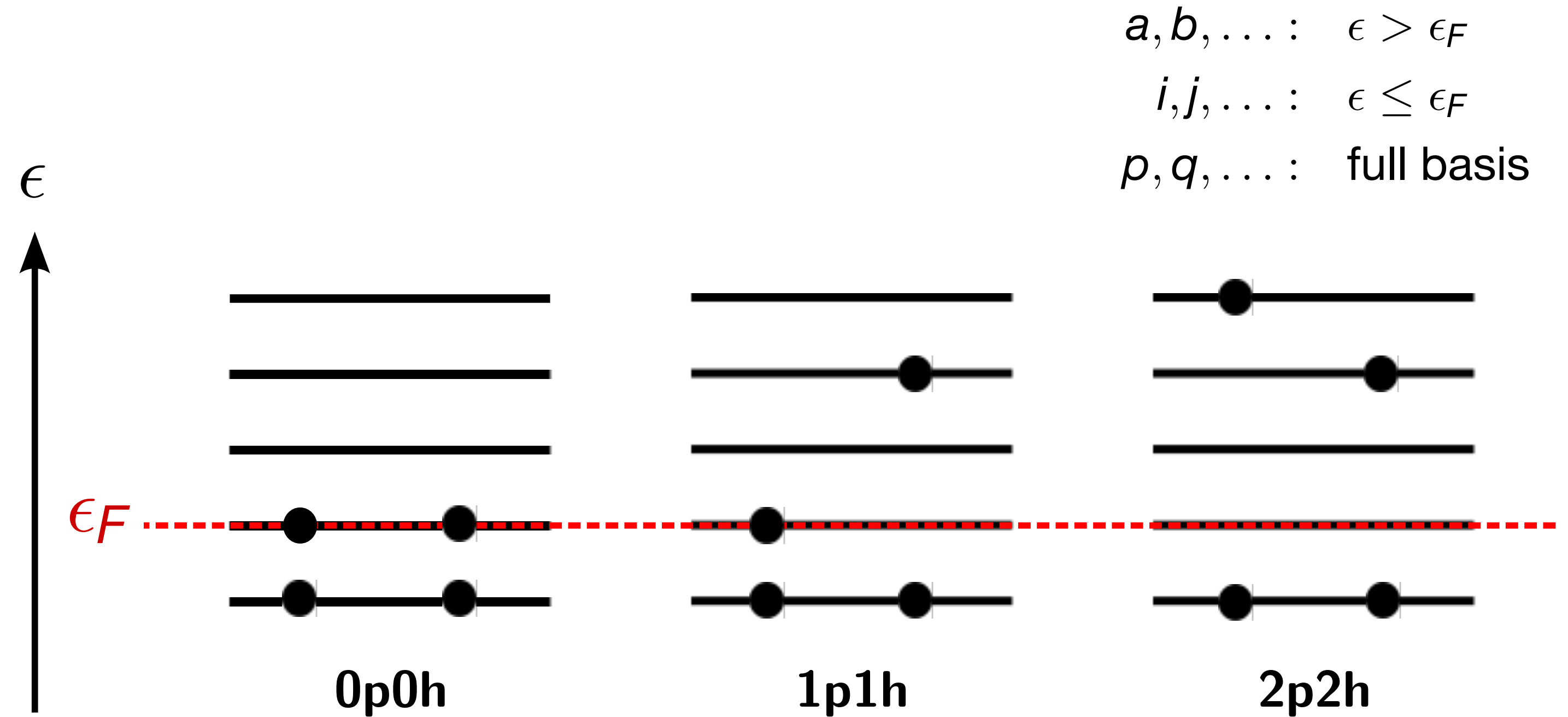
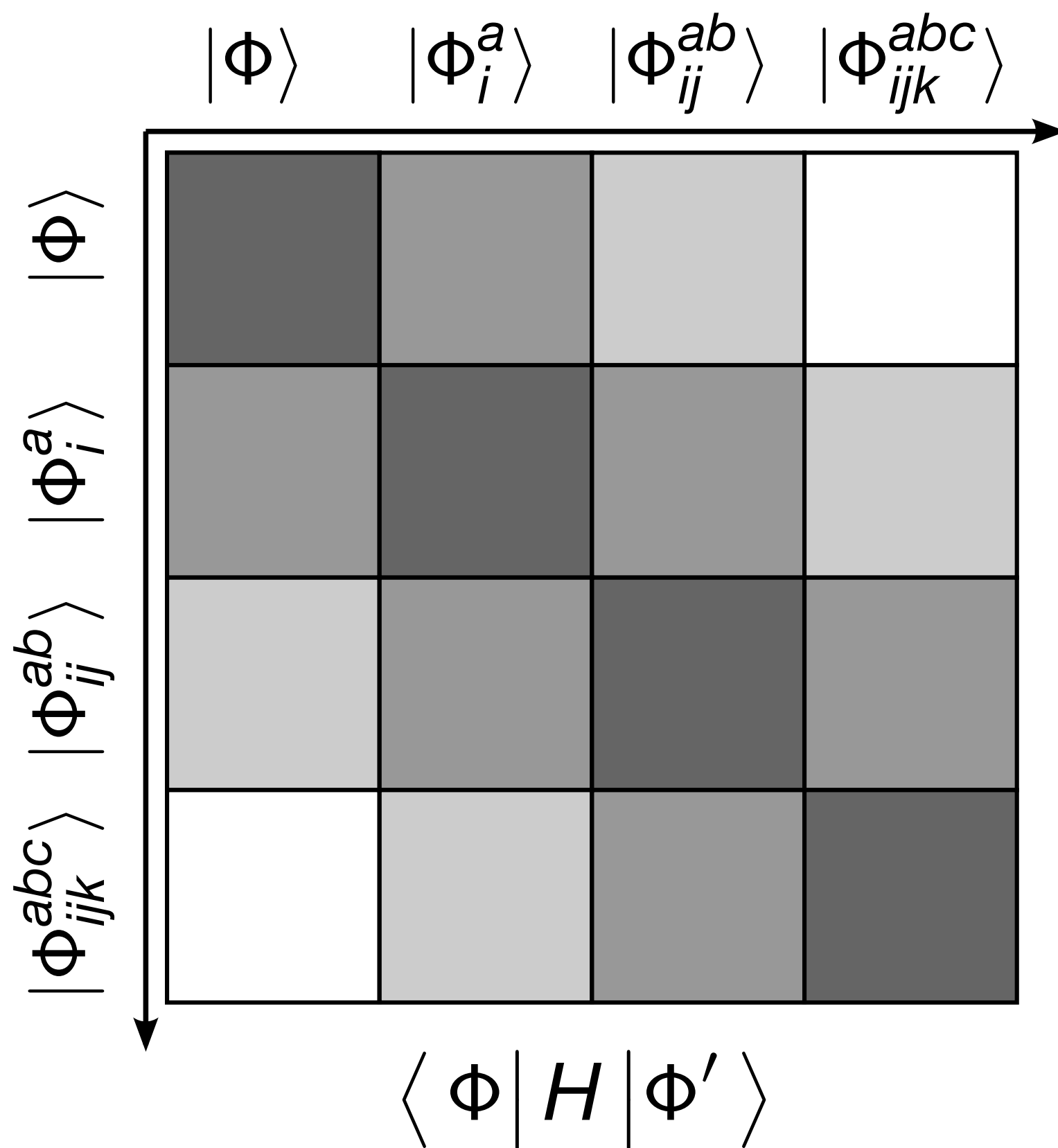
“What is *ab initio* in nuclear theory?”, A. Ekström, C. Forssén, G. Hagen, G. R. Jansen, W. Jiang, T. Papenbrock, Front. Phys. **11**, 1129094 (2023)

“What is *ab initio*?”, R. Machleidt, Few-Body Systems **64**, 77 (2023)

- deformed HF(B) + projection
- projected Generator Coordinate Method (PGCM)
- symmetry-adapted NCSM



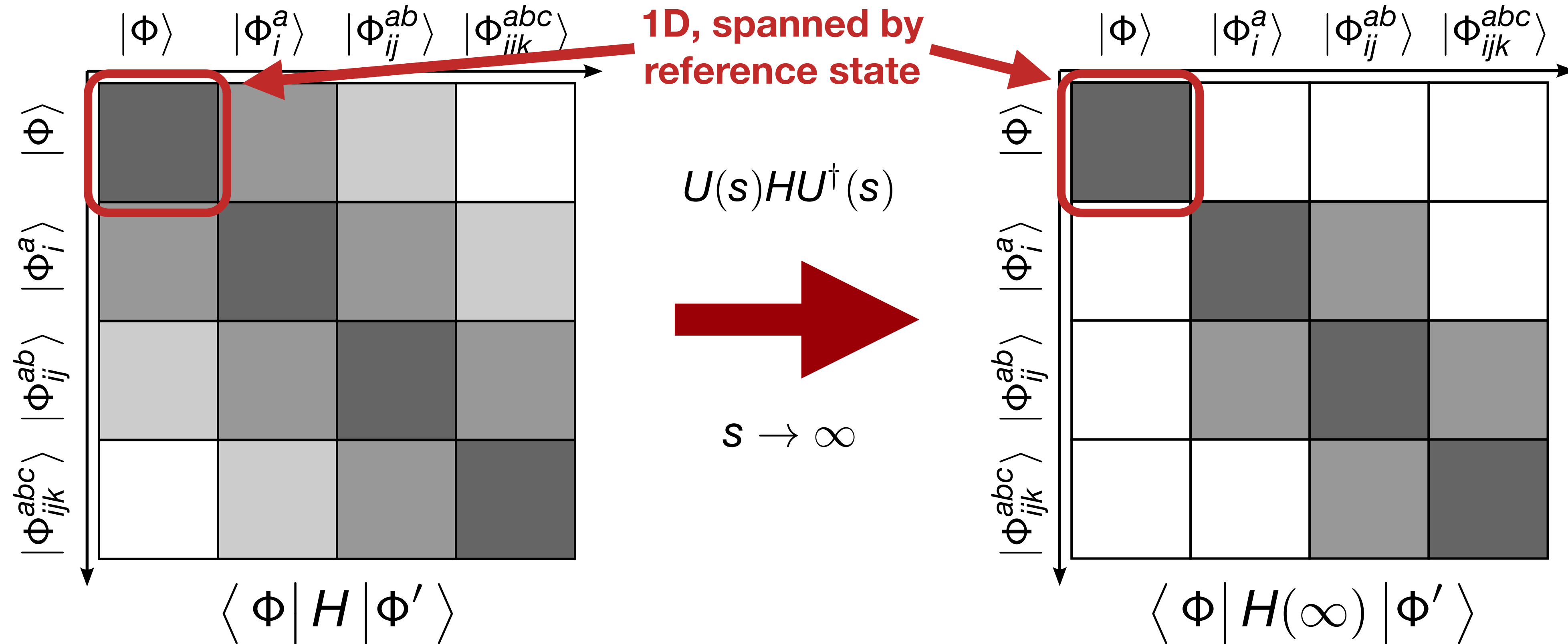
Many-Body Methods: Configuration Space



construct **particle-hole excitations** of a **reference state** - usually an optimized **mean-field Slater determinant**

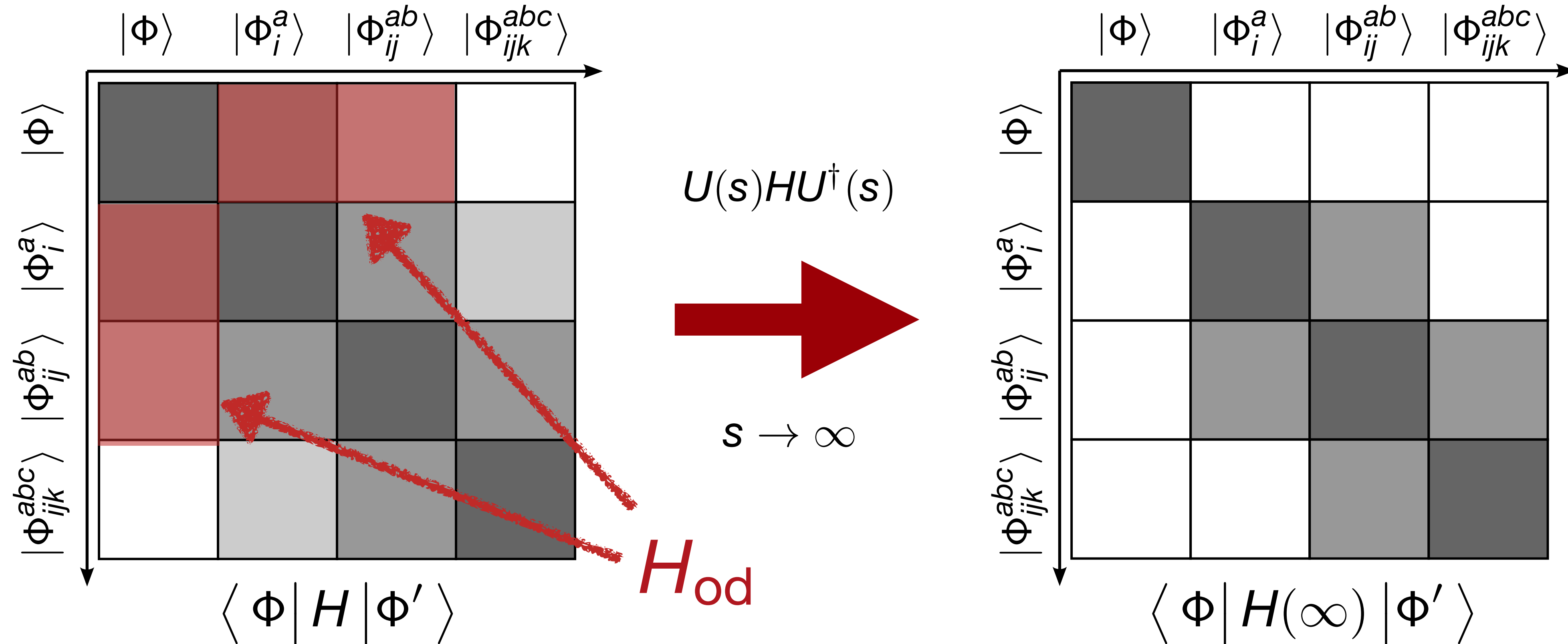
excitations **relative** to reference state:
normal-ordering

In-Medium Similarity Renormalization Group



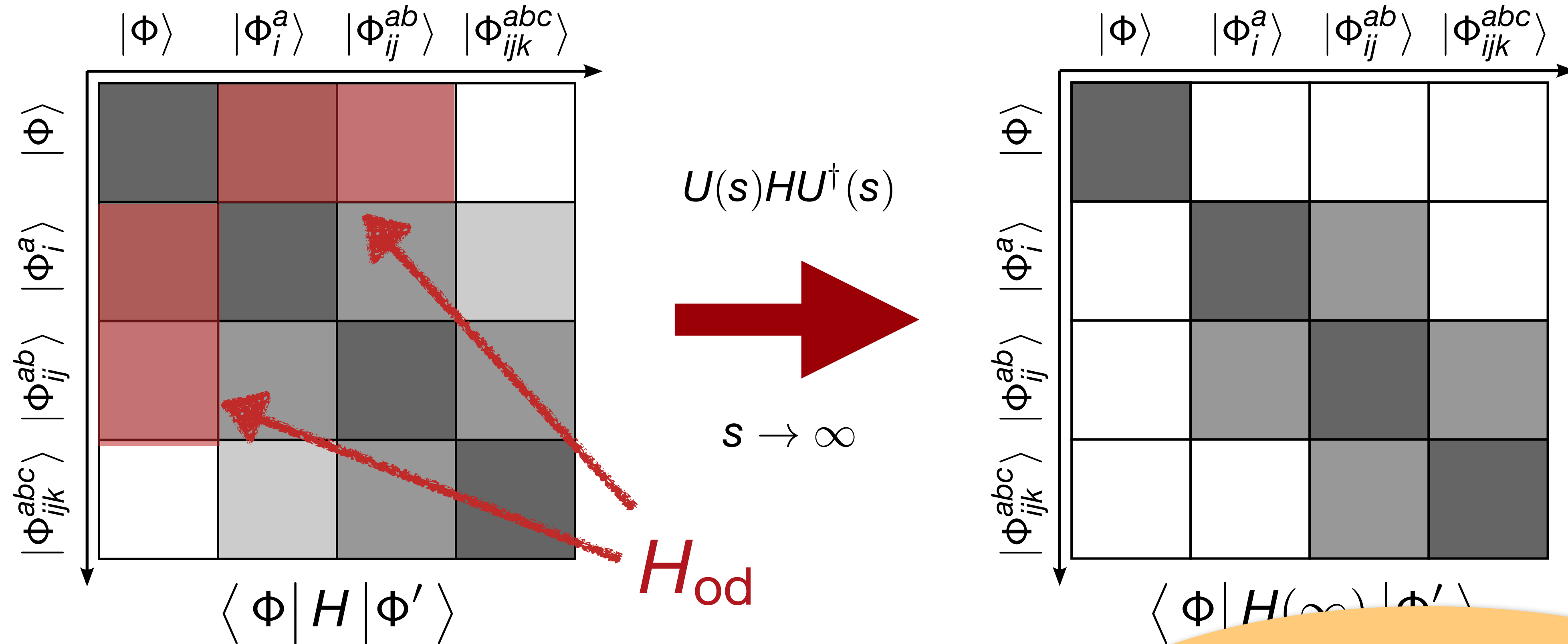
goal: decouple reference state from excitations

In-Medium Similarity Renormalization Group



$$\frac{d}{ds}H(s) = [\eta(s), H(s)], \quad \text{e.g.,} \quad \eta(s) \equiv [H_d(s), H_{od}(s)]$$

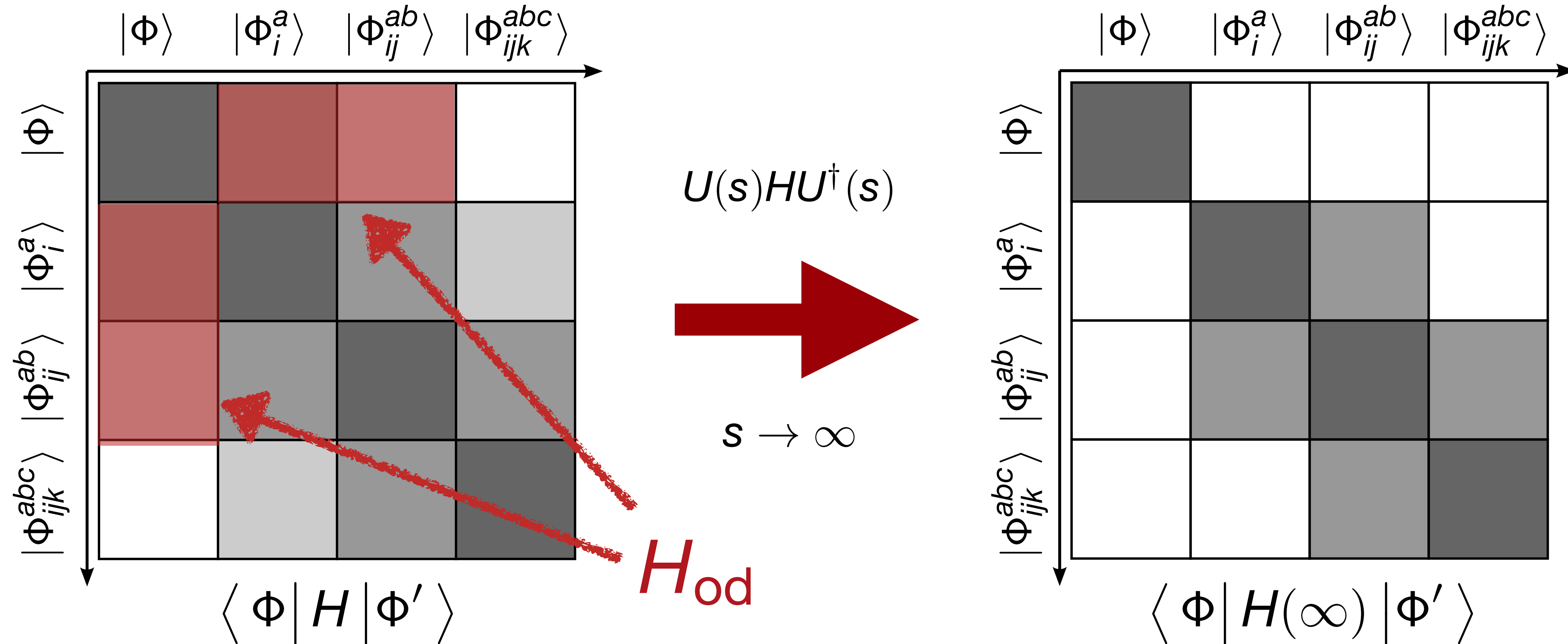
In-Medium Similarity Renormalization Group



$$\frac{d}{ds} H(s) = [\eta(s), H(s)], \quad \text{e.g.,} \quad \eta(s) =$$

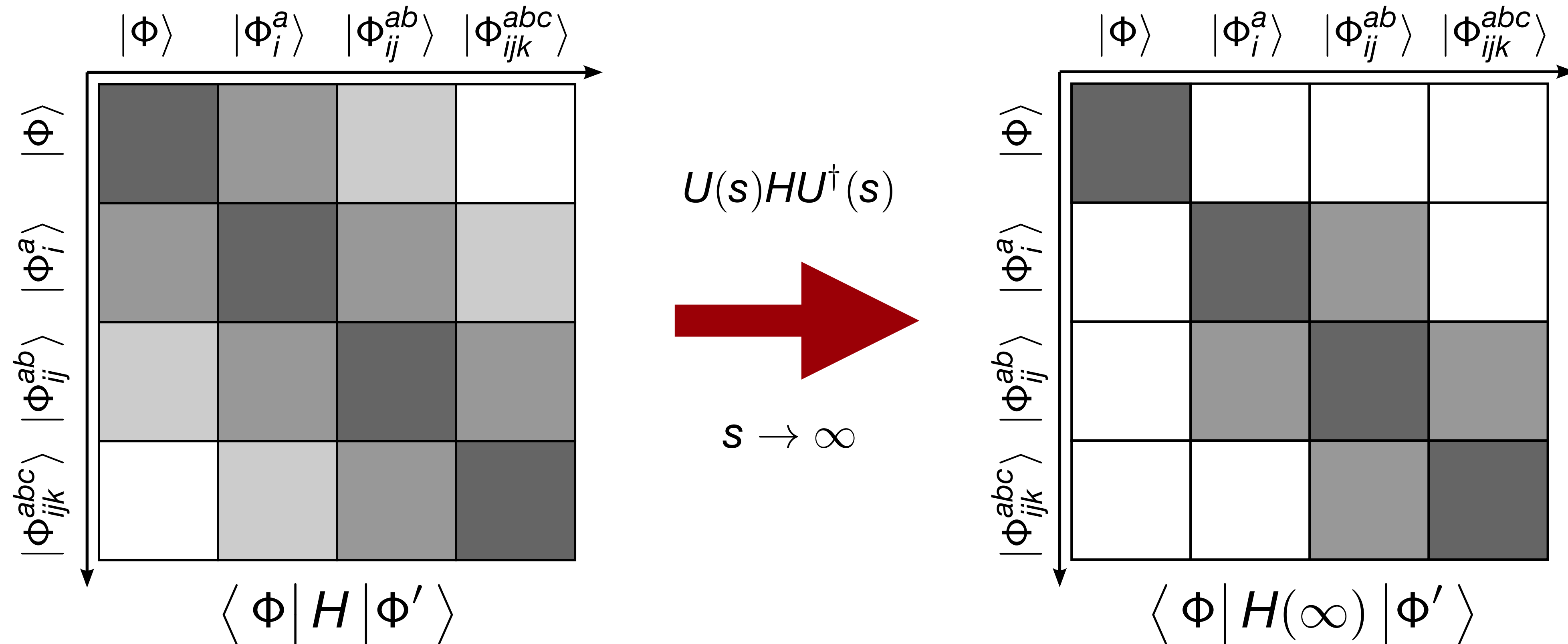
IMSRG(n): Operators truncated at **n-body level** - **matrix is never constructed explicitly!**

Magnus Formulation of IMSRG



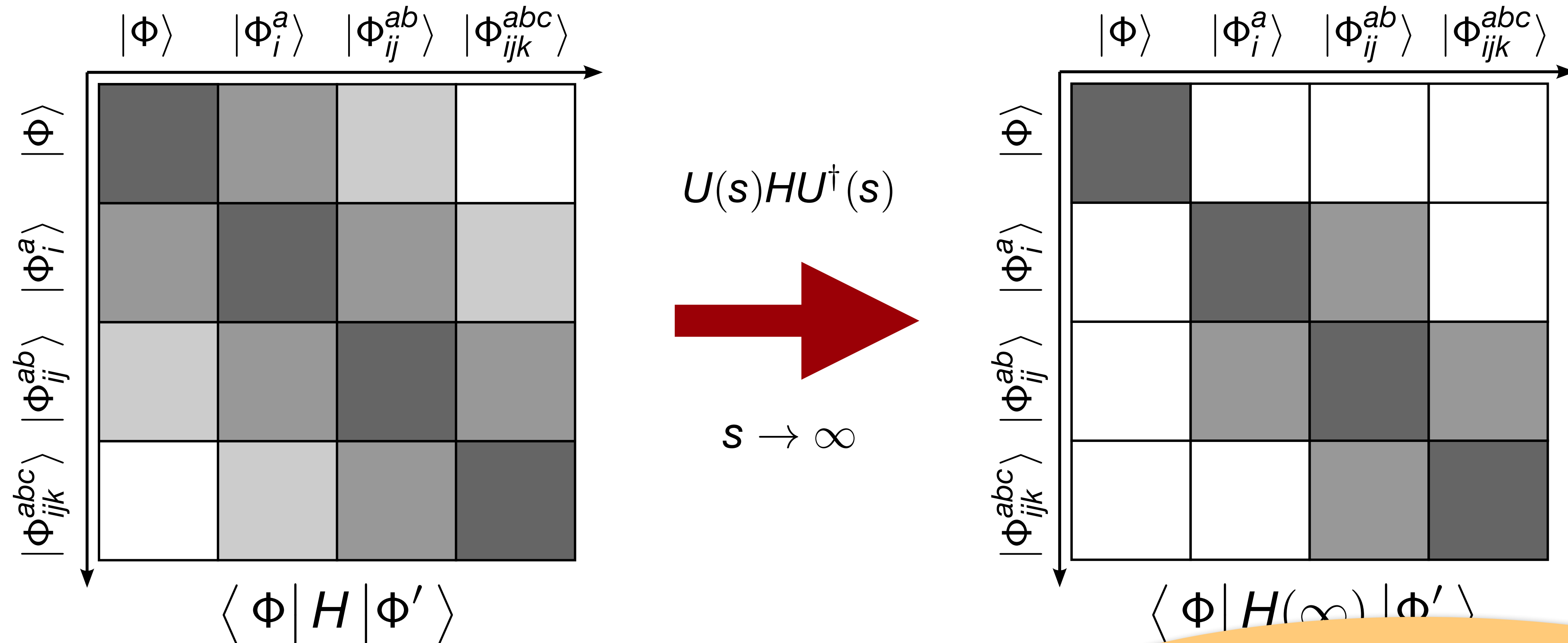
$$U(s) \equiv e^{\Omega(s)}, \quad \frac{d\Omega}{ds} = \sum_n \frac{B_n}{n!} [\Omega, \eta]^{(n)}, \quad [\Omega, \eta]^{(n)} = [\Omega, [\Omega, \eta]^{(n-1)}], \quad [\Omega, \eta]^{(0)} = \eta$$

Decoupling in A-Body Space



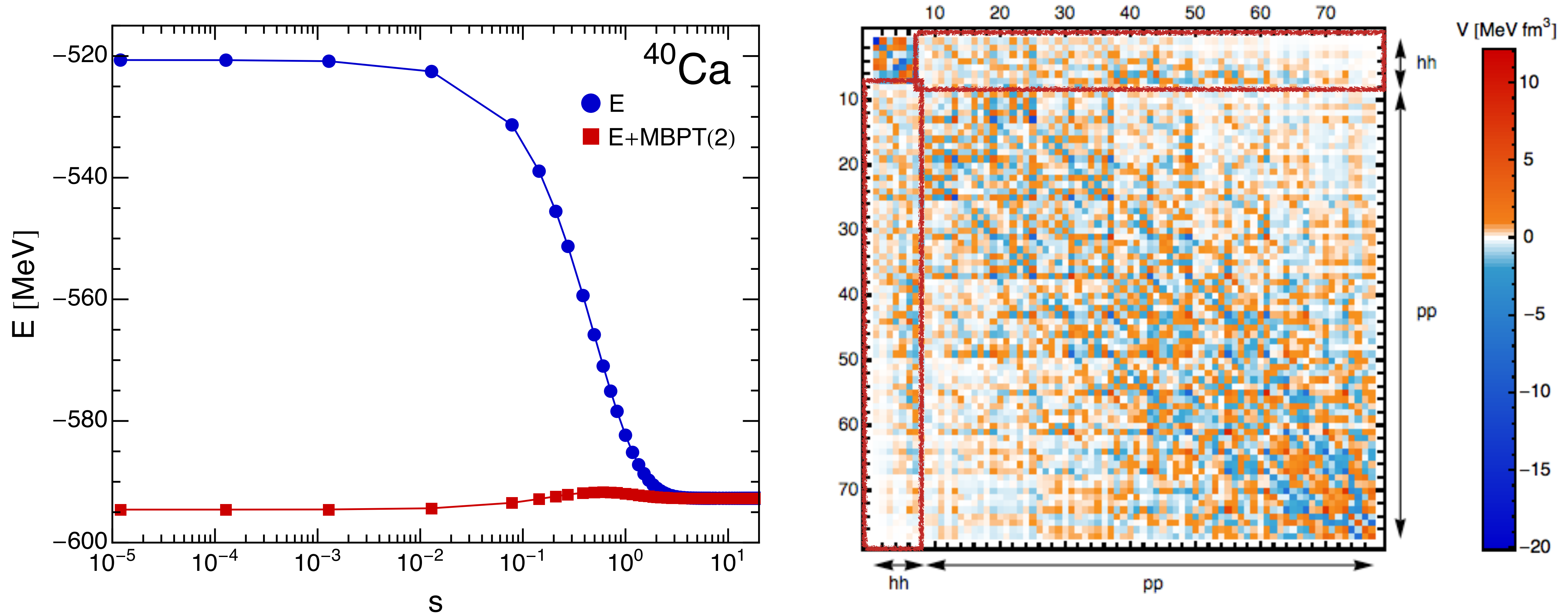
- **identify** the parts of the **operator H** which **couple reference state to excitations**
- **eliminate** them with unitary (**IMSRG**) transformation (cf. **CC**: similarity transformation)
- **efficient: polynomial scaling**, no need to construct matrix !

Decoupling in A-Body Space



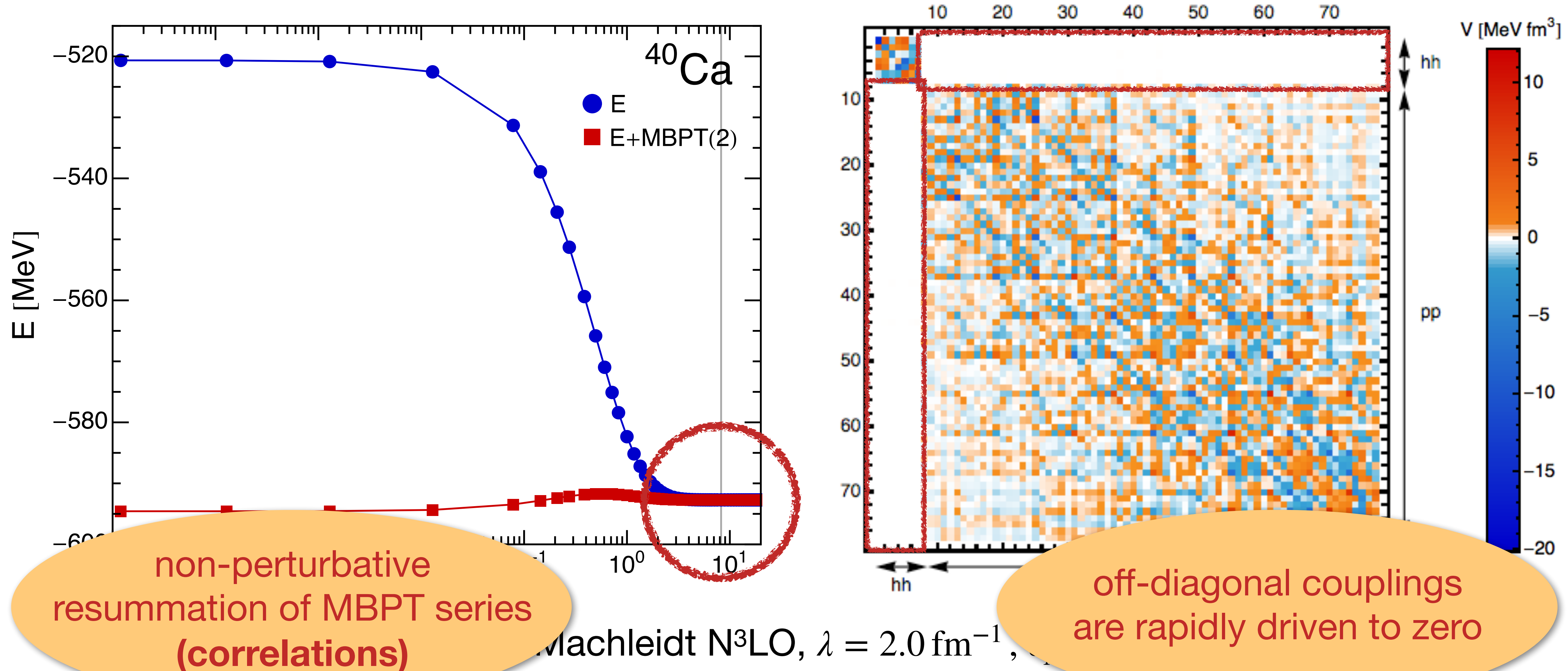
- **identify** the parts of the **operator H** which **couple** **valence space** - only requires slightly **extended definition of H_{od}** !
- **eliminate** them with unitary (**IMSRG**) transformation
- **efficient: polynomial scaling**, no need to construct matrix :

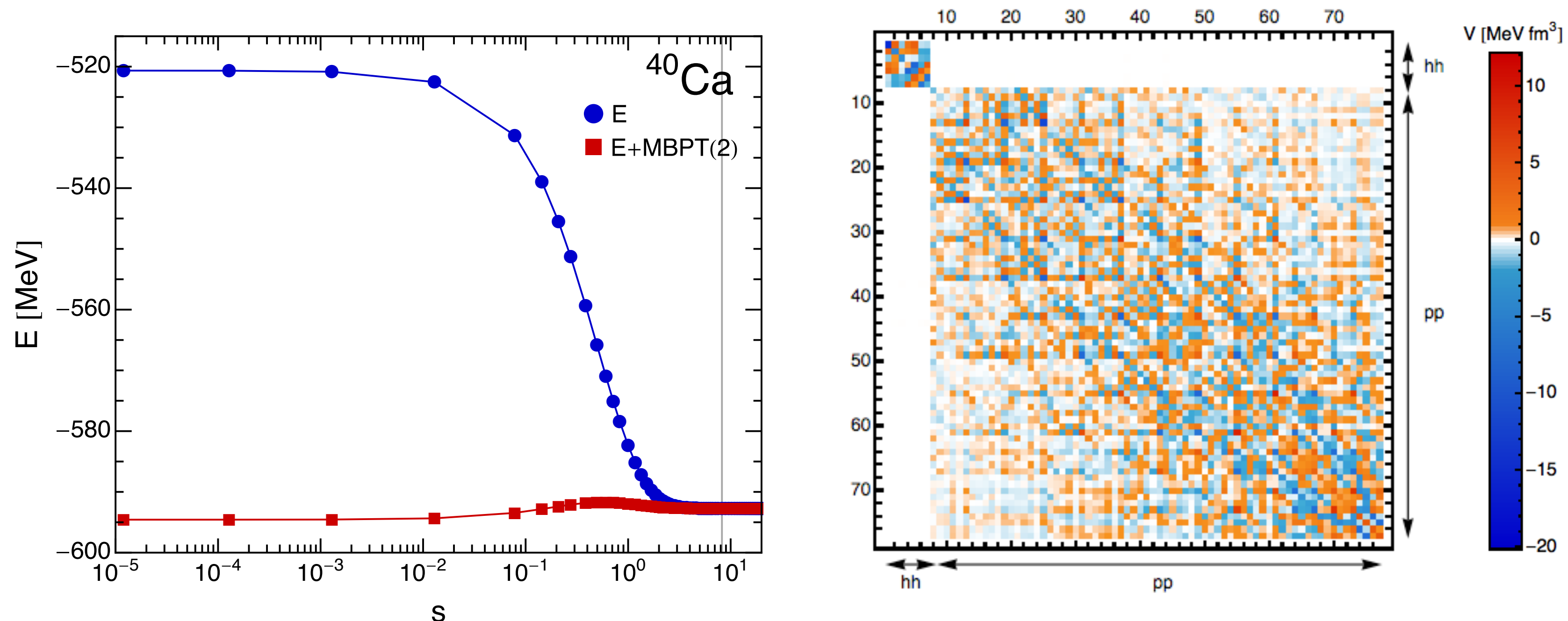
Decoupling



Entem-Machleidt N^3LO , $\lambda = 2.0 \text{ fm}^{-1}$, $e_{\text{Max}} = 8$

Decoupling





Entem-Machleidt N³LO, $\lambda = 2.0 \text{ fm}^{-1}$, $e_{\text{Max}} = 8$

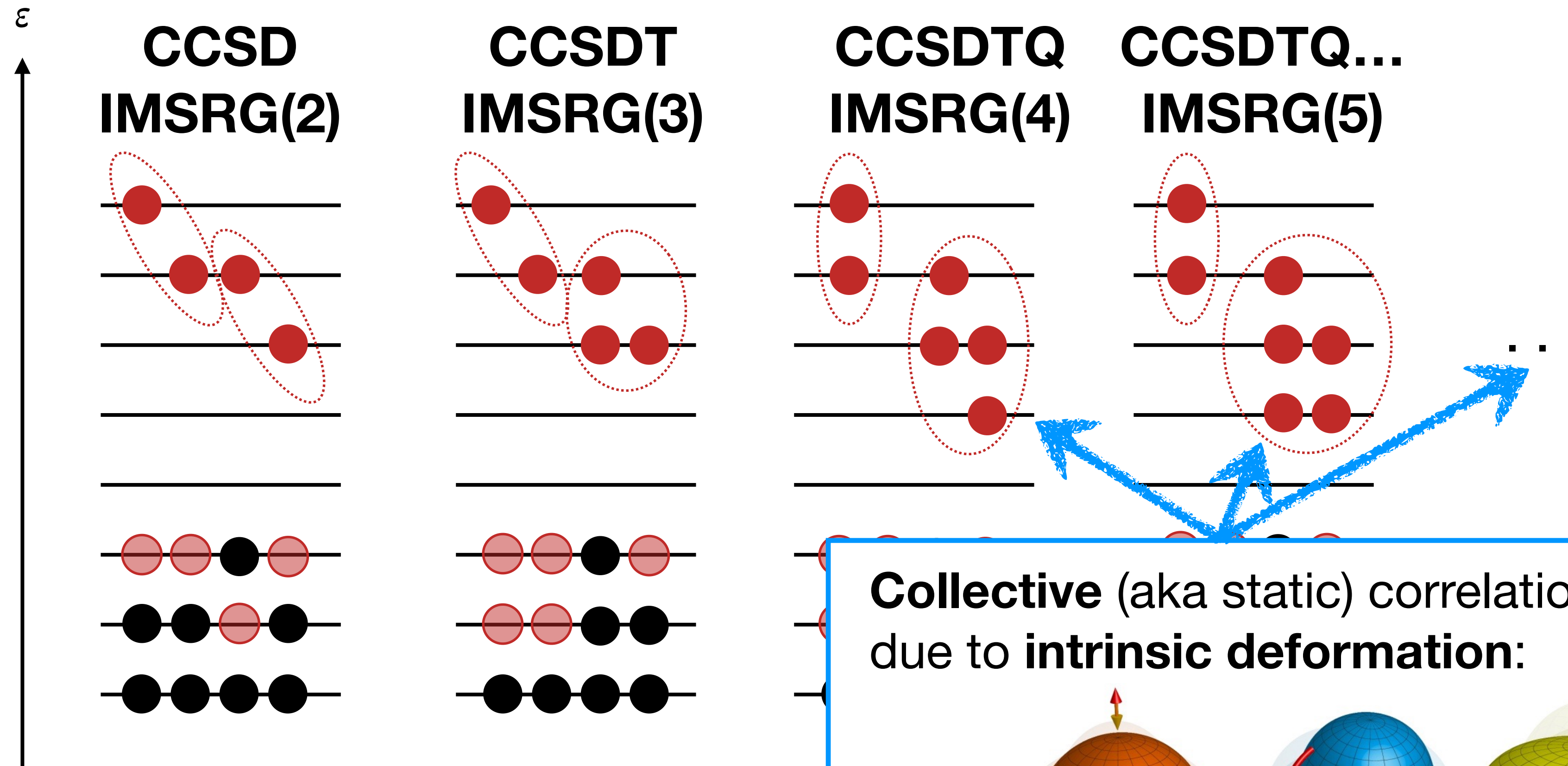
- absorb correlations into **RG-improved Hamiltonian**:

$$U(s) H U^\dagger(s) U(s) |\Psi_n\rangle = E_n U(s) |\Psi_n\rangle$$

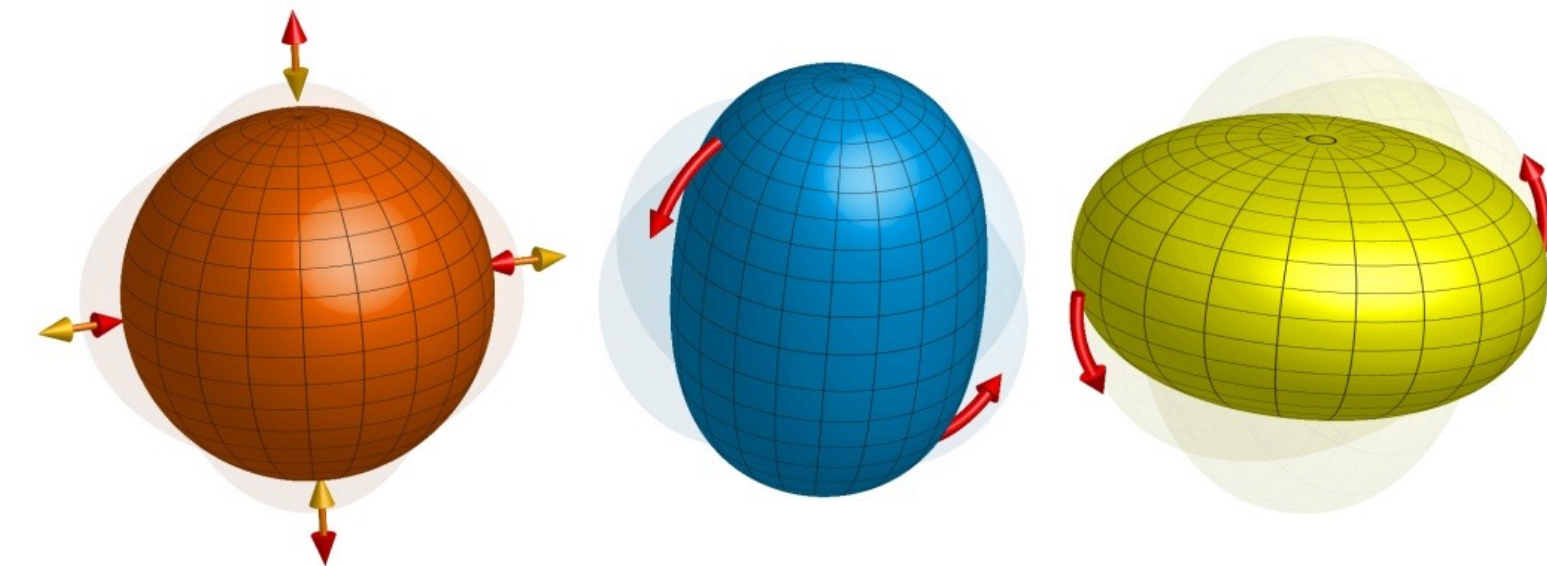
- reference state is ansatz for transformed, **less correlated** reference state:

$$U(s) |\Psi_n\rangle \doteq |\Phi\rangle$$

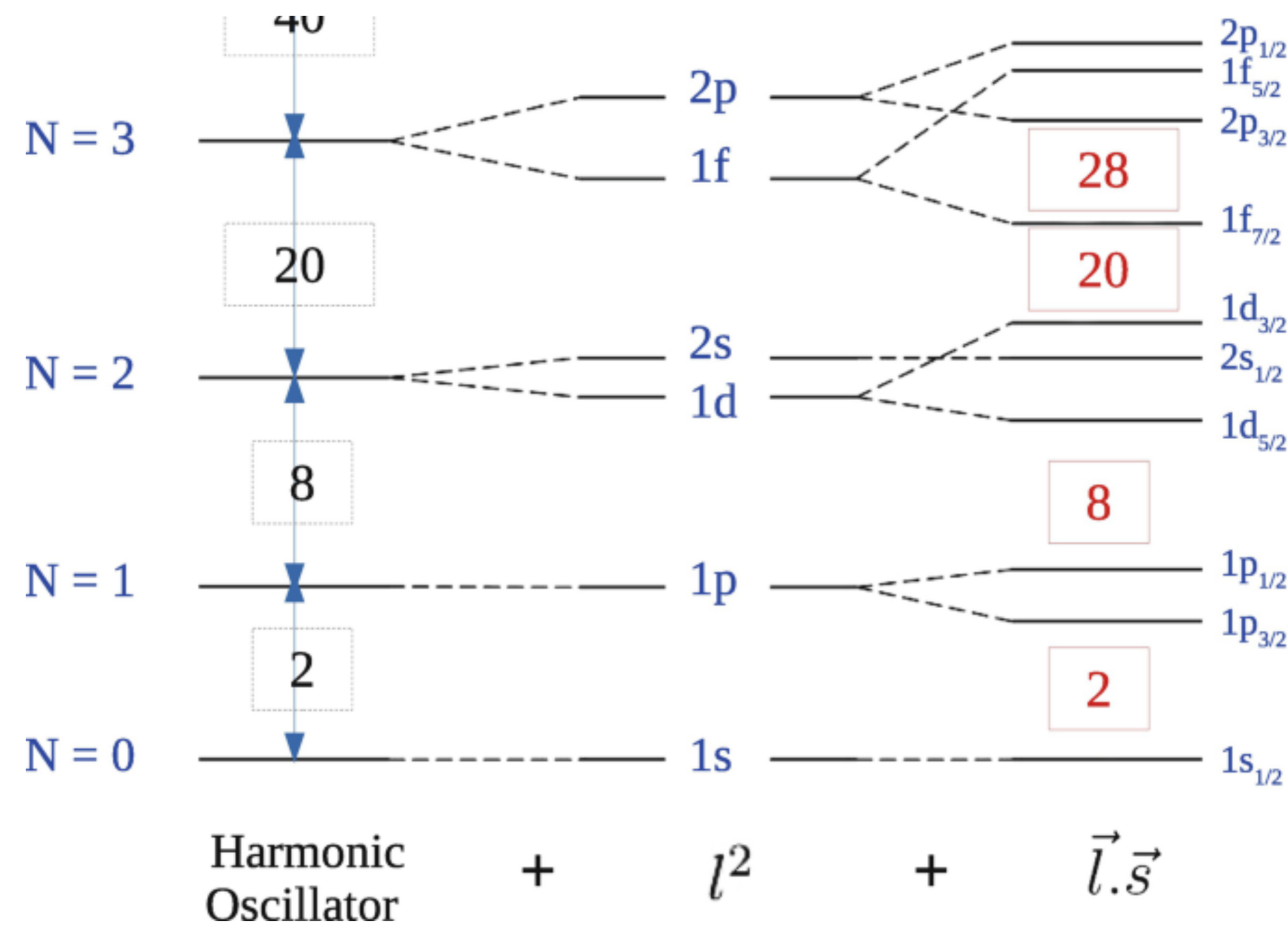
Correlations in Nuclei



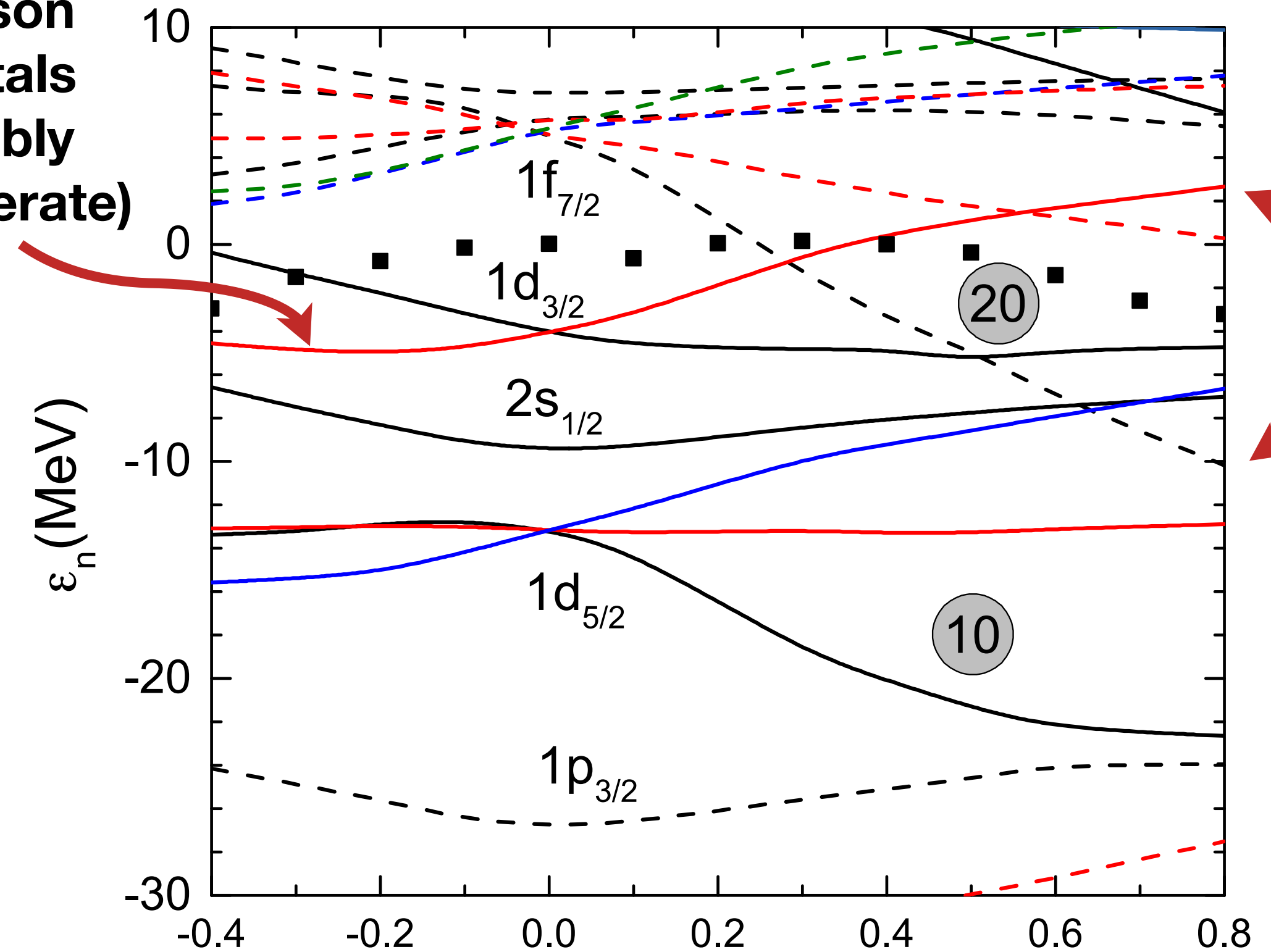
Collective (aka static) correlations, e.g.
due to **intrinsic deformation**:



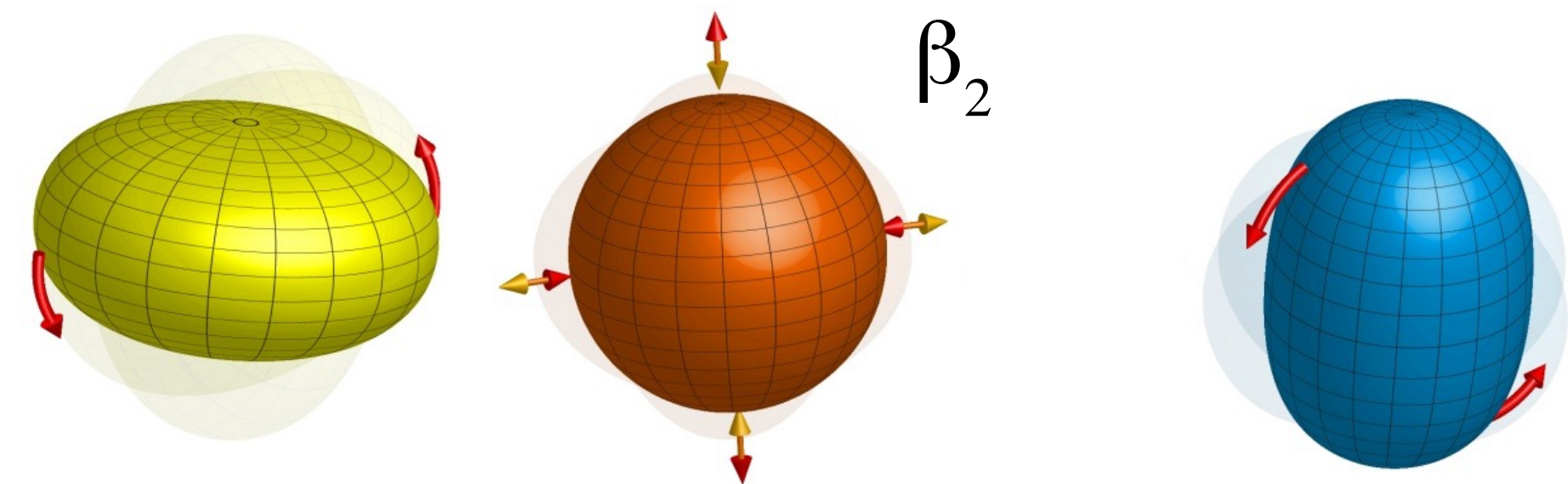
Symmetry Breaking and Restoration



Nilsson orbitals (doubly degenerate)

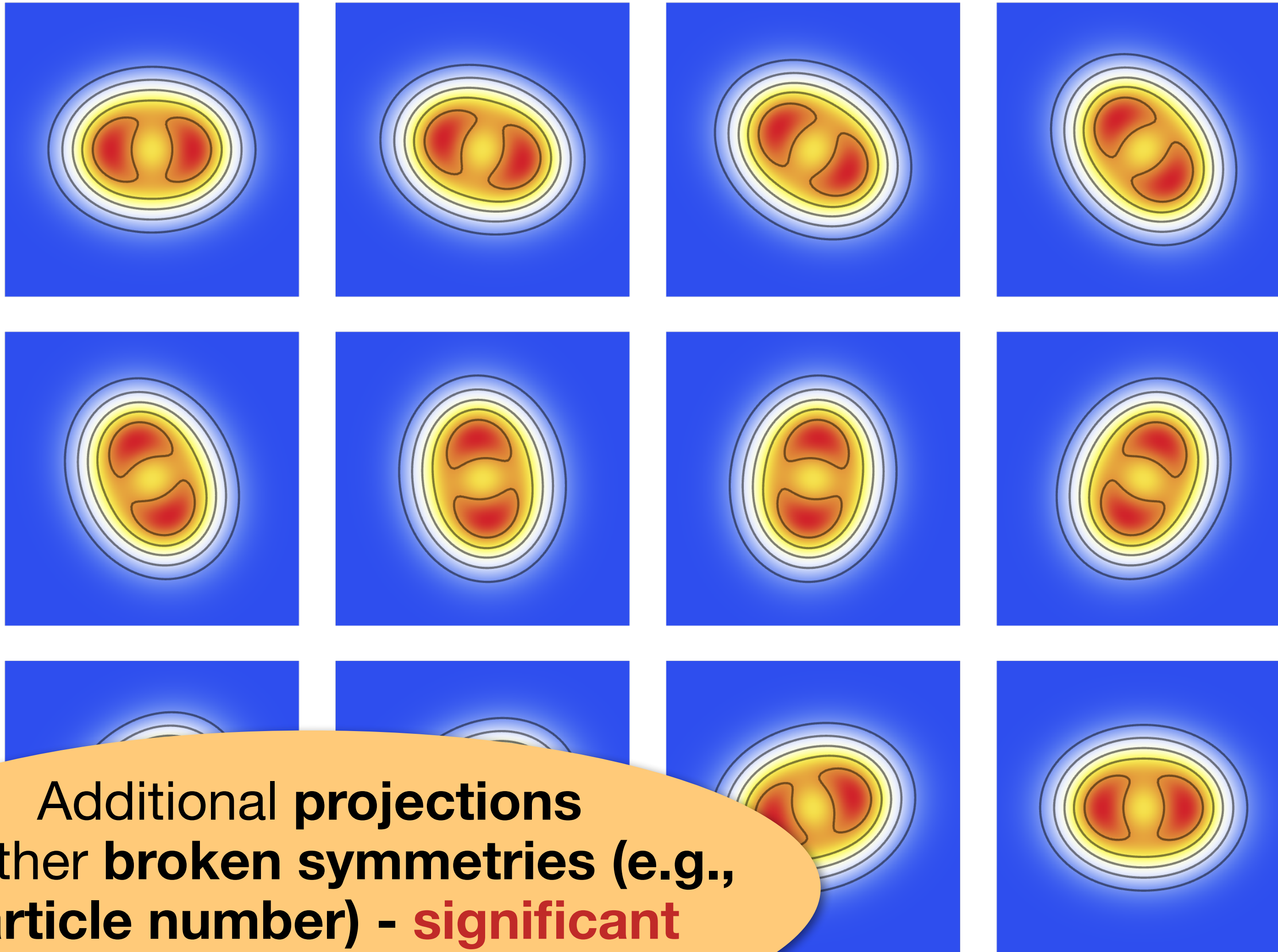


- **break spherical symmetry** to **capture static correlation** from deformation
- **restore symmetry** by constructing (**specific**) **superpositions of all rotations** of intrinsic state (aka **projection**)



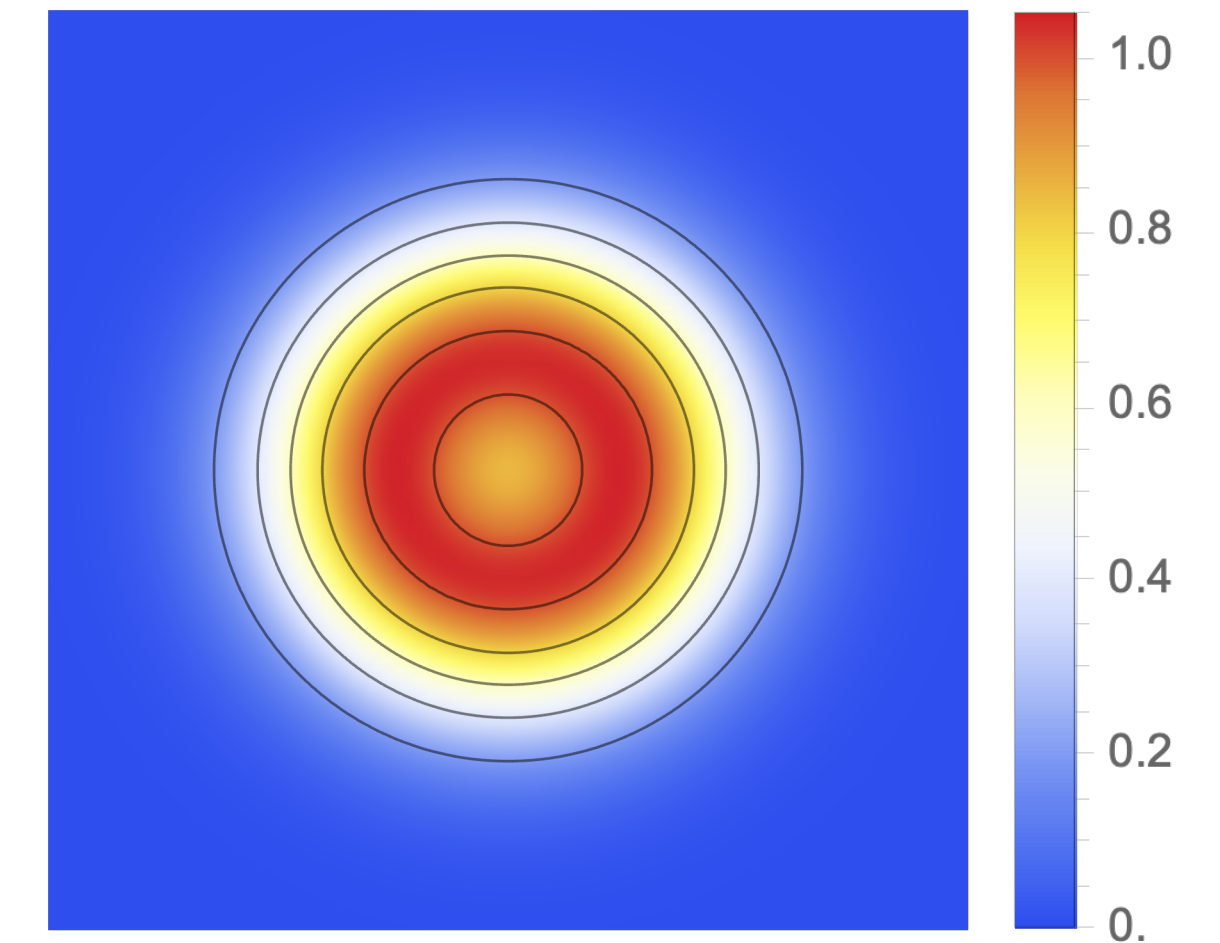
Symmetry Breaking and Restoration

deformed configurations (not a real nucleus)

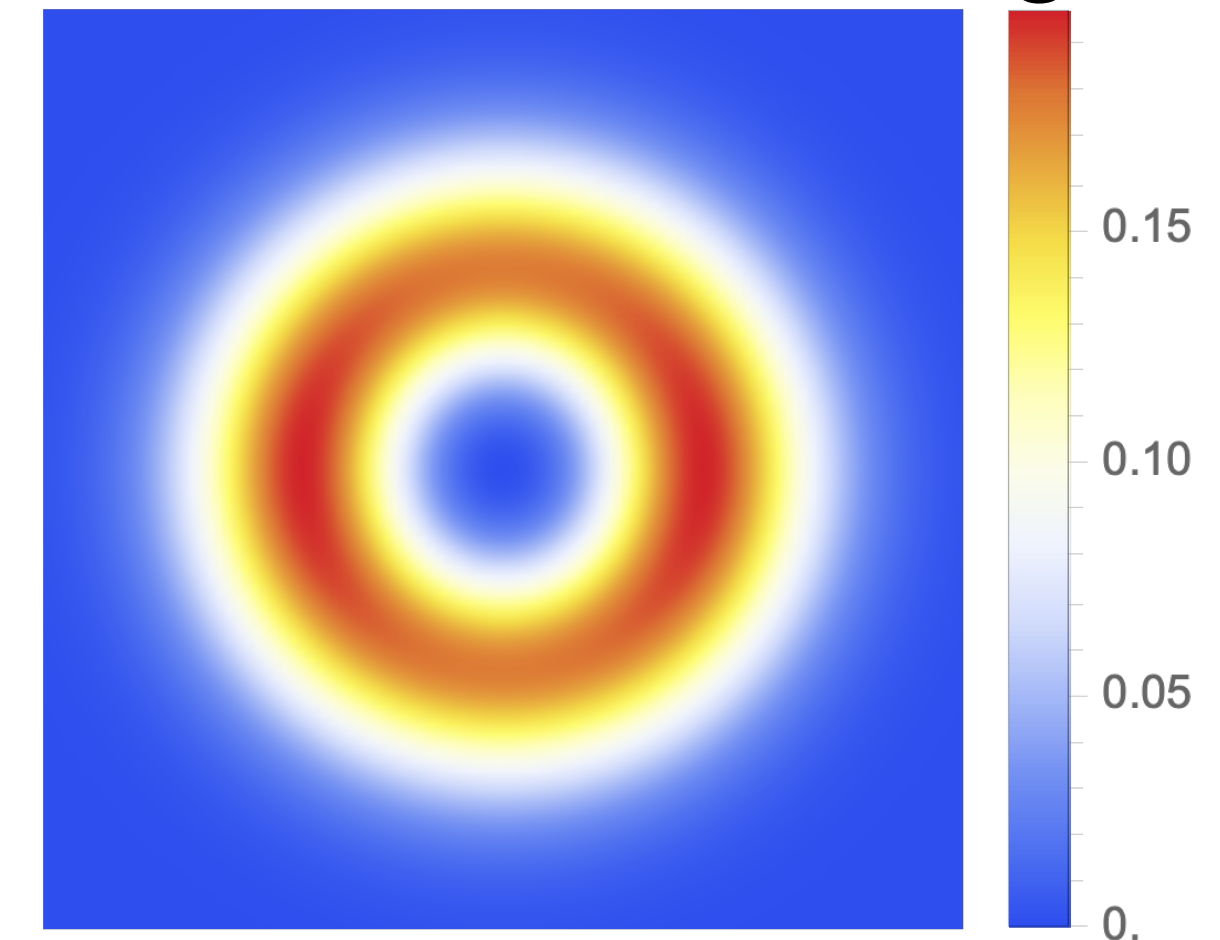


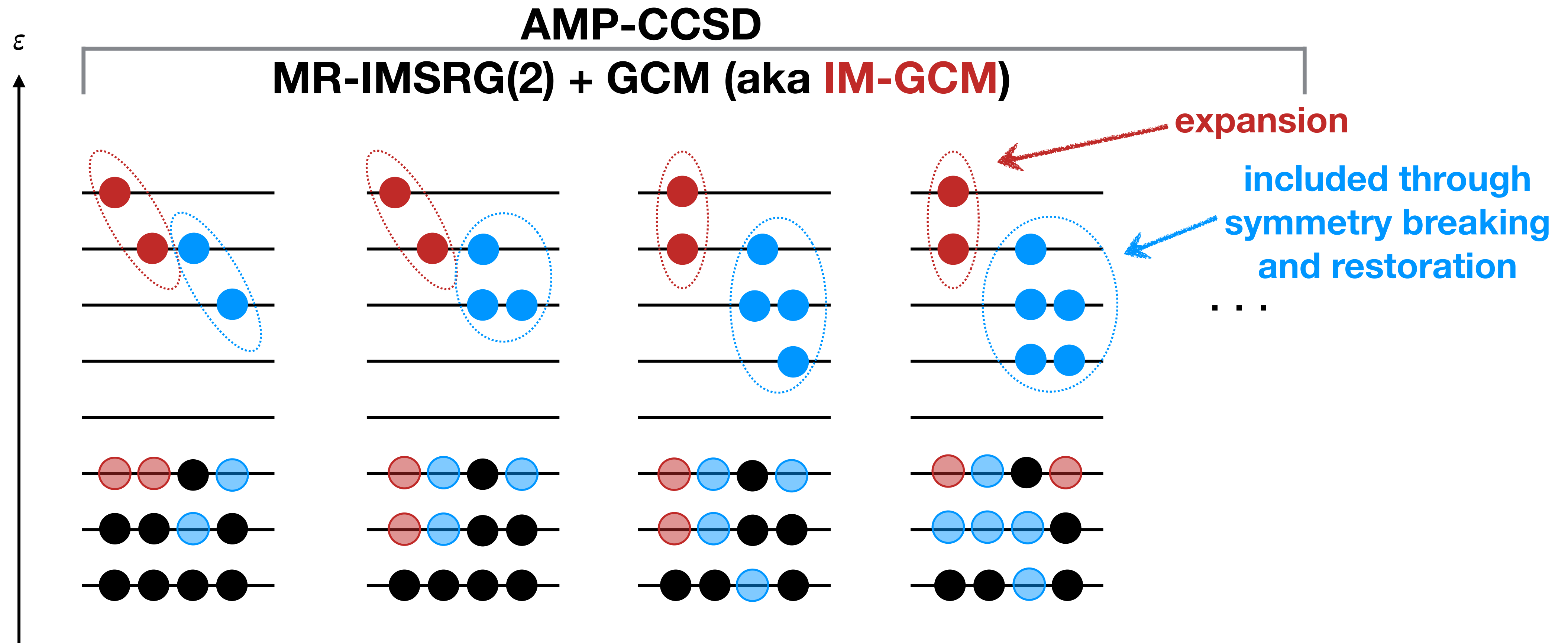
Additional **projections**
for other **broken symmetries** (e.g.,
particle number) - **significant**
overhead!

projected w.f.



difference from spherical w.f.
with same basis size /length scale



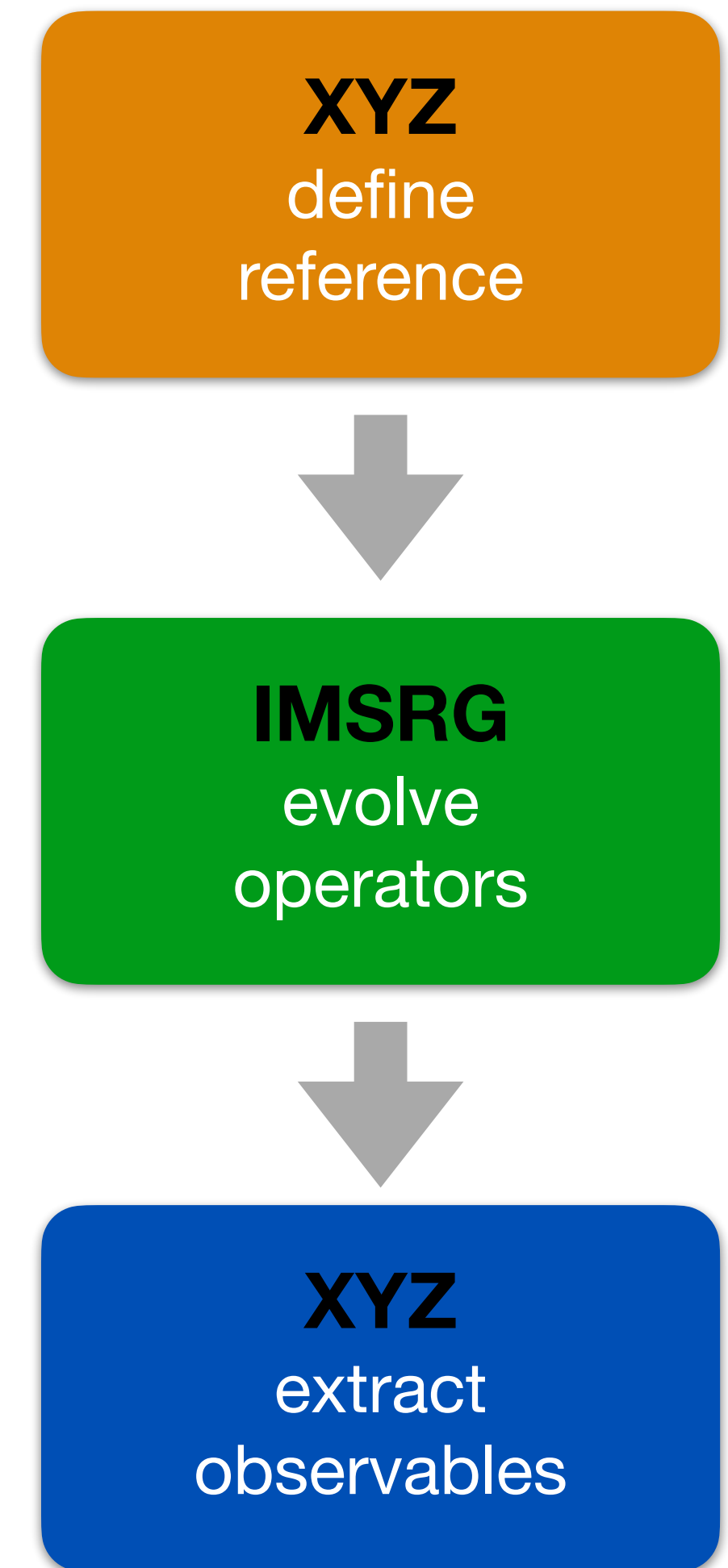


IMSRG-Improved Many-Body Methods



HH et al., Phys. Rept 621, 165; Phys. Scr. 92, 023002
S. R. Stroberg et al., Ann. Rev. Nucl. Part. Sci, 69, 307
J. M. Yao et al., PRC 98, 054311; PRL 124, 232501

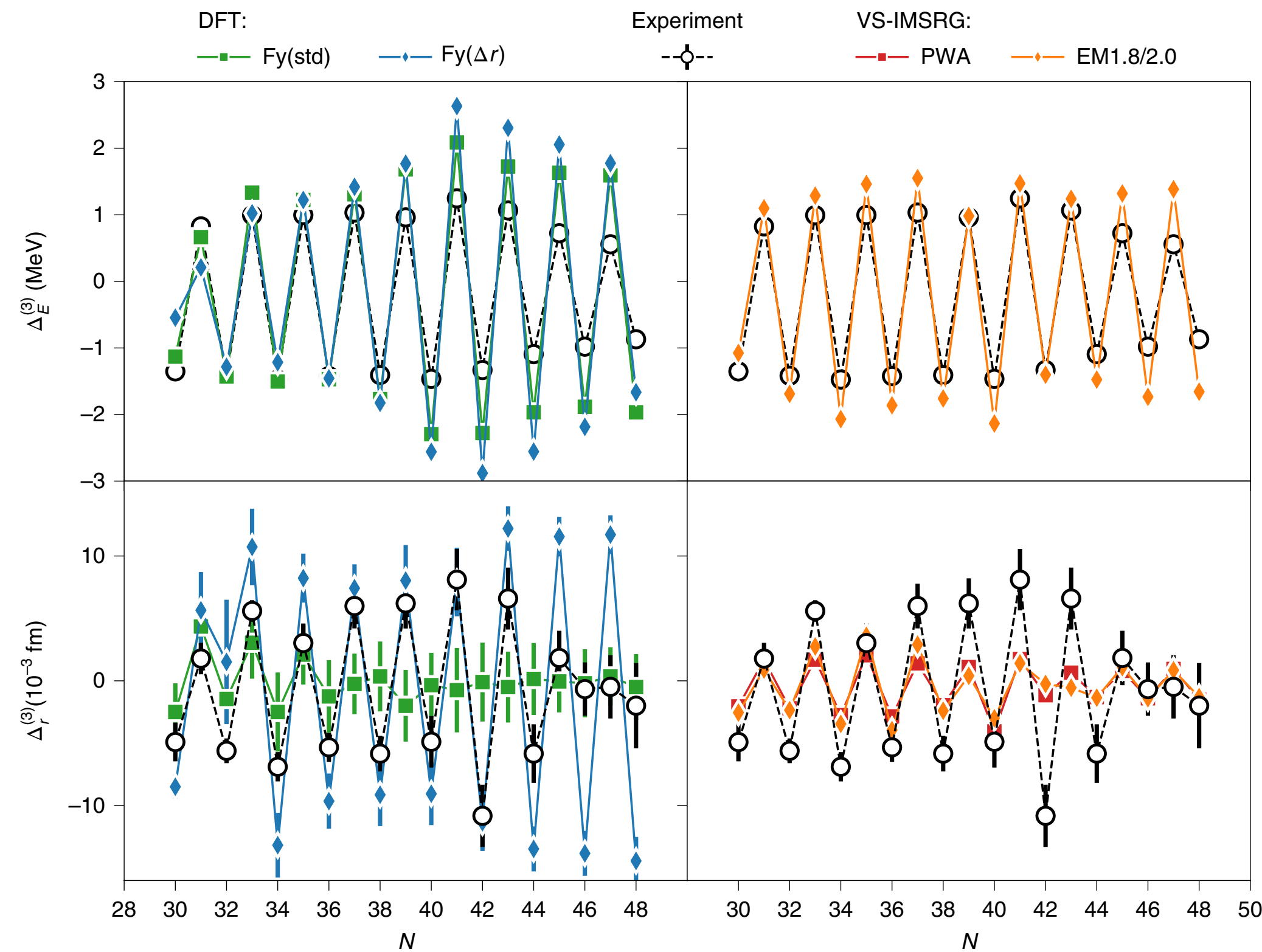
- IMSRG can be used to build specific types of correlations into **RG-improved interactions** and **operators**
 - ideally, IMSRG captures correlations that are **complementary** to target method
 - mean-field or **correlated reference state(s)** for a specific nucleus
define(s) **operator basis** for IMSRG evolution
 - **diagnostic:** flow is unitary if all **relevant operators** are included
- **examples:**
 - (MR-)IMSRG(2) aka In-Medium HF / PHFB
 - **Valence-Space IMSRG for Shell model / VS-CI**
 - In-Medium No-Core Shell Model / NC-CI
 - **In-Medium Generator Coordinate Method (IM-GCM)**



Are We There Yet?

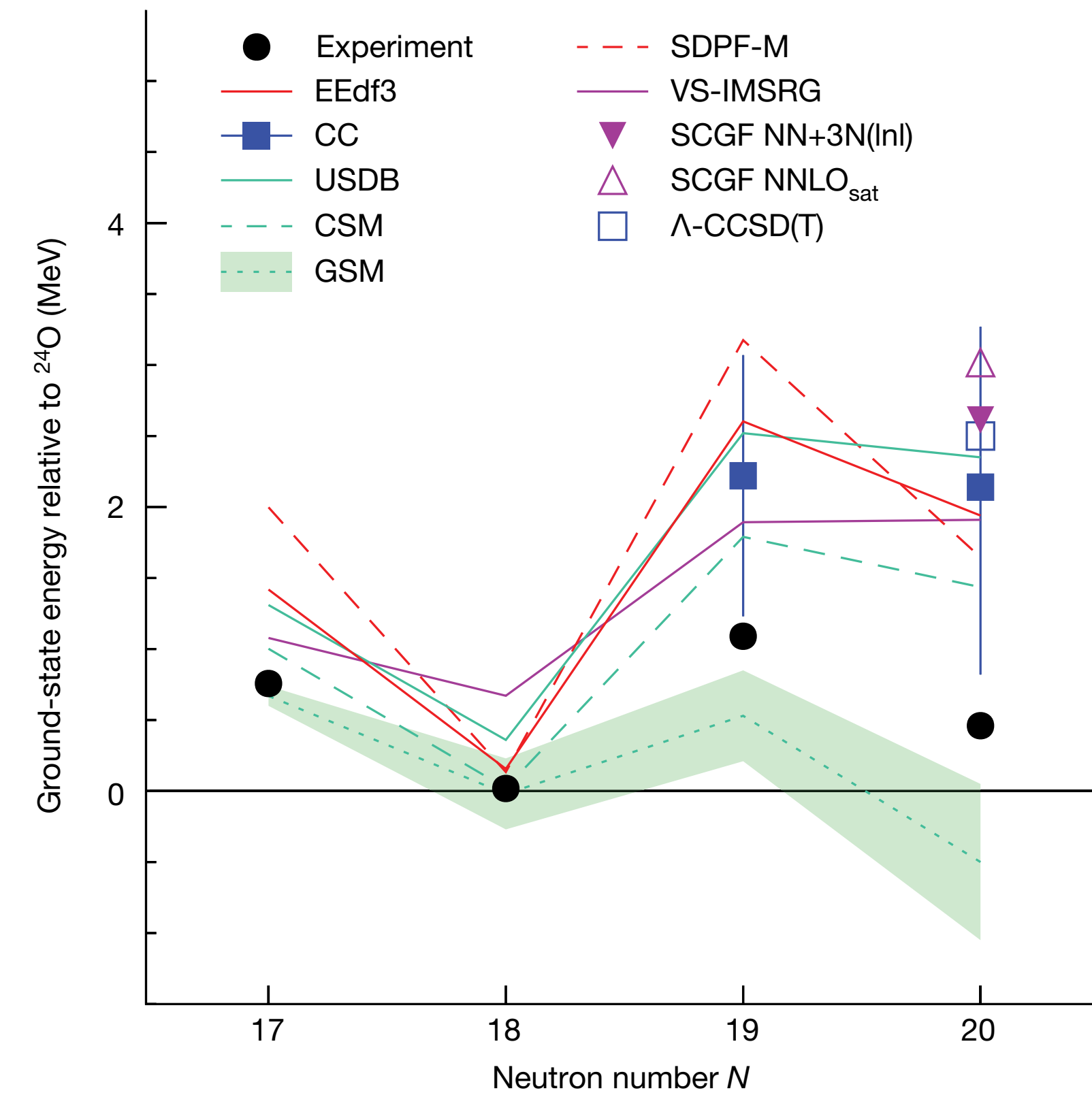
copper isotopes

R. de Groote et al., Nat. Phys. 16, 620 (2020)



oxygen isotopes

Y. Kondo et al., Nature 620, 965 (2023)



Are these results good, bad, or just ok? Is there **genuine tension** between theory and experiment? **How can we know?**

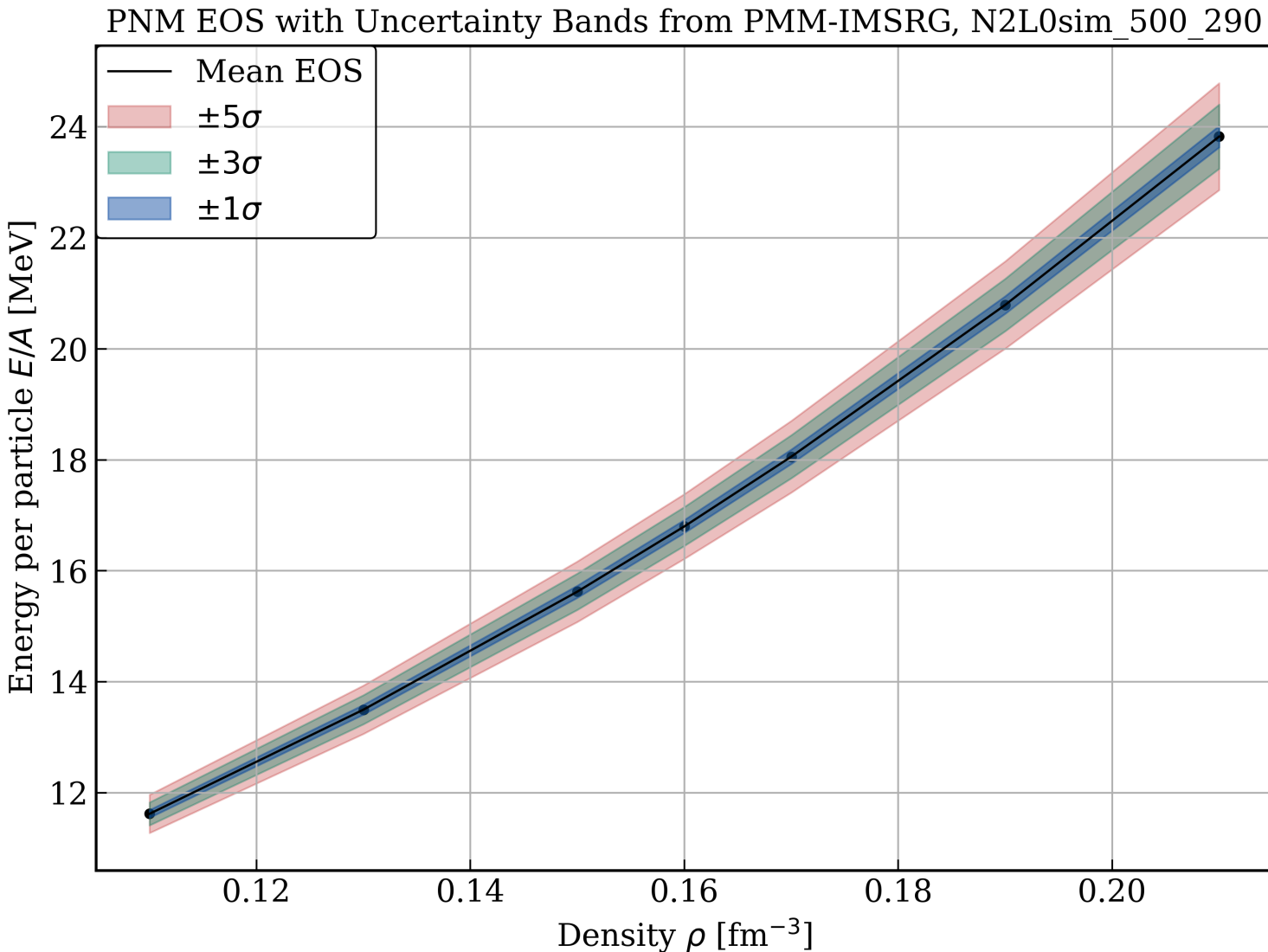
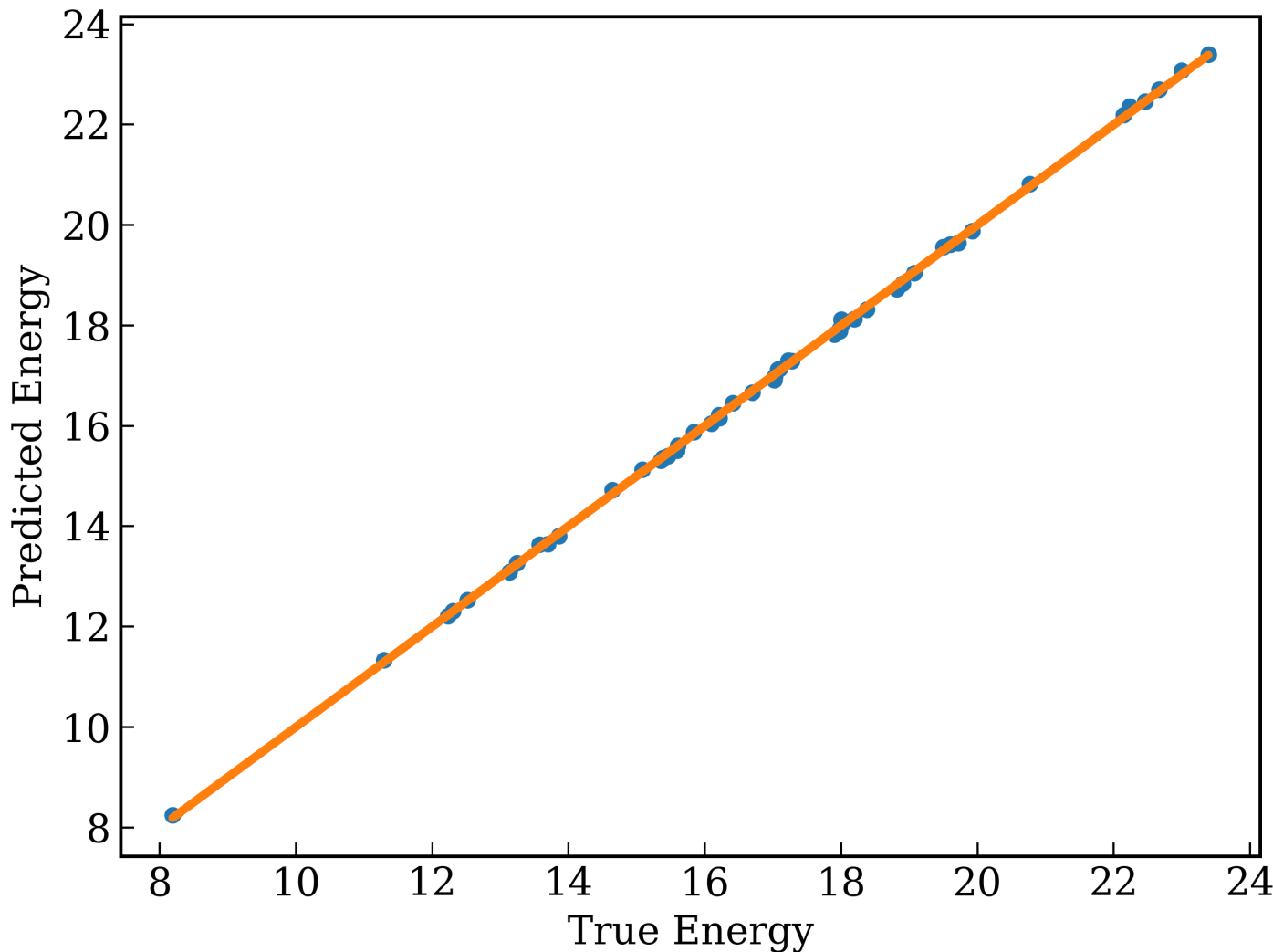
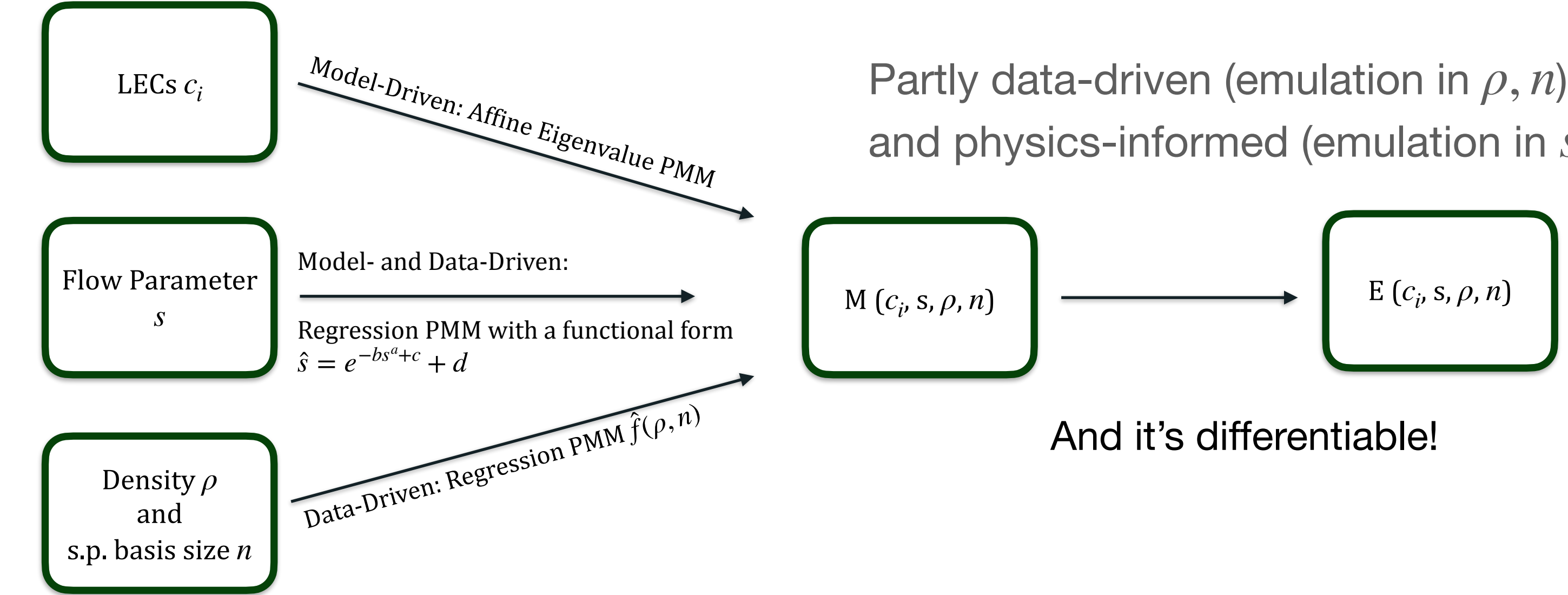
*J. Melendez et al., JPG 49, 102001 (2022), C. Drischler et al., Front. Phys. 10, 1092931 (2023)
E. Bonilla et al., PRC 106, 054322 (2022), P. Giuliani et al., Front. Phys. 10, 1054524 (2023)*

- treat **model parameters** as **probability distributions** rather than just numbers
 - condition, calibrate, and validate with data
- **predictions** for **observables** become **probability distributions** as well
 - allows characterization of likelihood, standard deviations (=error bars), correlations, parameter sensitivity, ...
- **challenge:** need **lots** of **expensive** many-body calculations
- **solution:** construct **emulators** for costly simulations - can reduce computational effort by **many orders of magnitude** (but still need **training data**)
 - DFT, CC, CI: reduced-basis methods (e.g., eigenvector continuation/Galerkin projection)...
 - ... but those work with **wave functions**, we need **operators** in IMSRG methods

Emulating IMSRG with Parametric Matrix Models



P. Cook, K. Yu, C. Drischler, S. Bogner, arXiv:2607.19773



Patrick Cook



Kang Yu



IMSRG



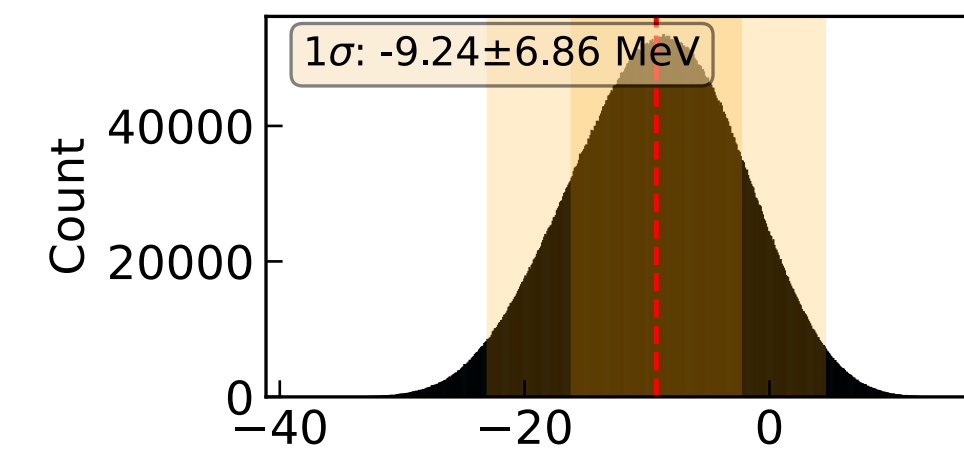
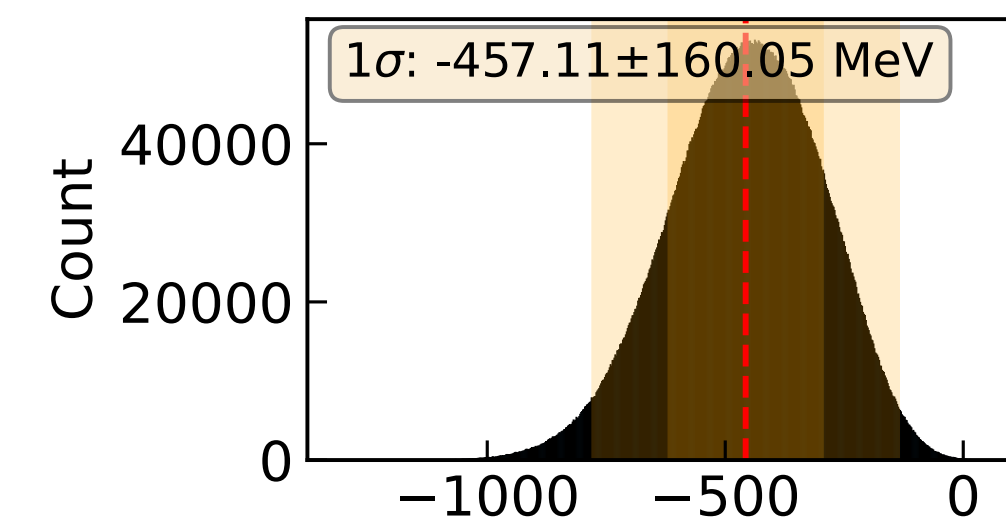
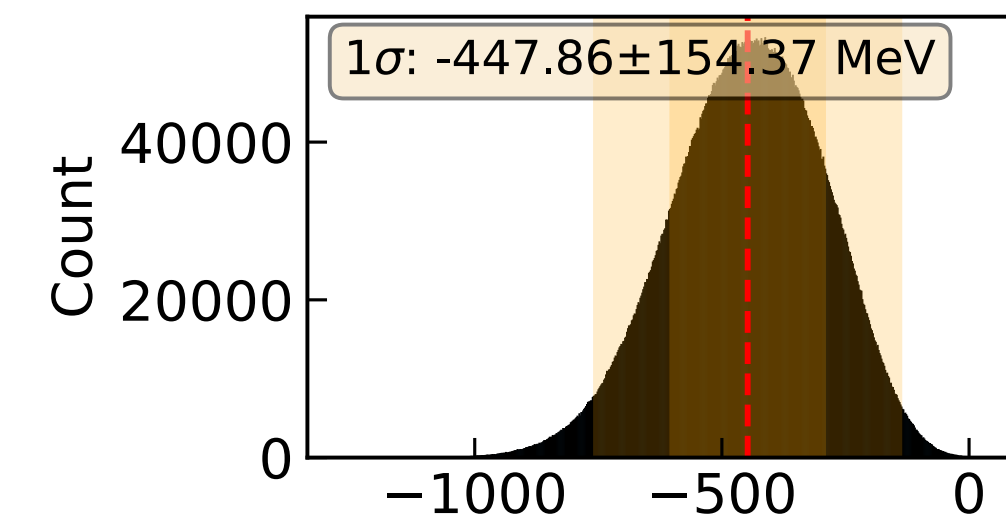
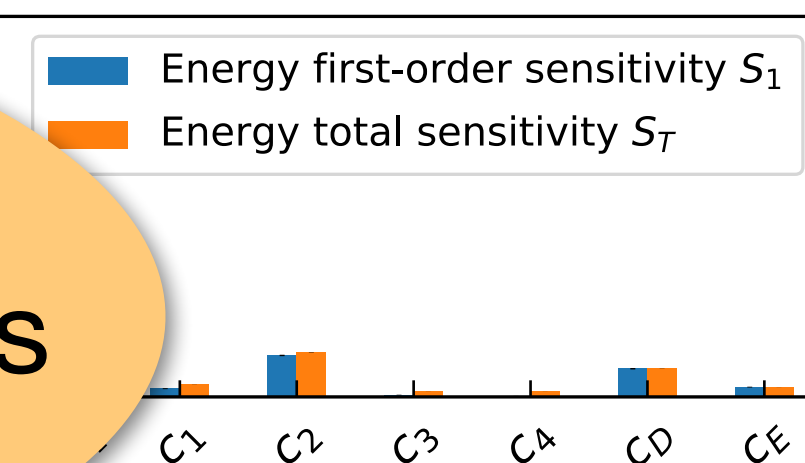
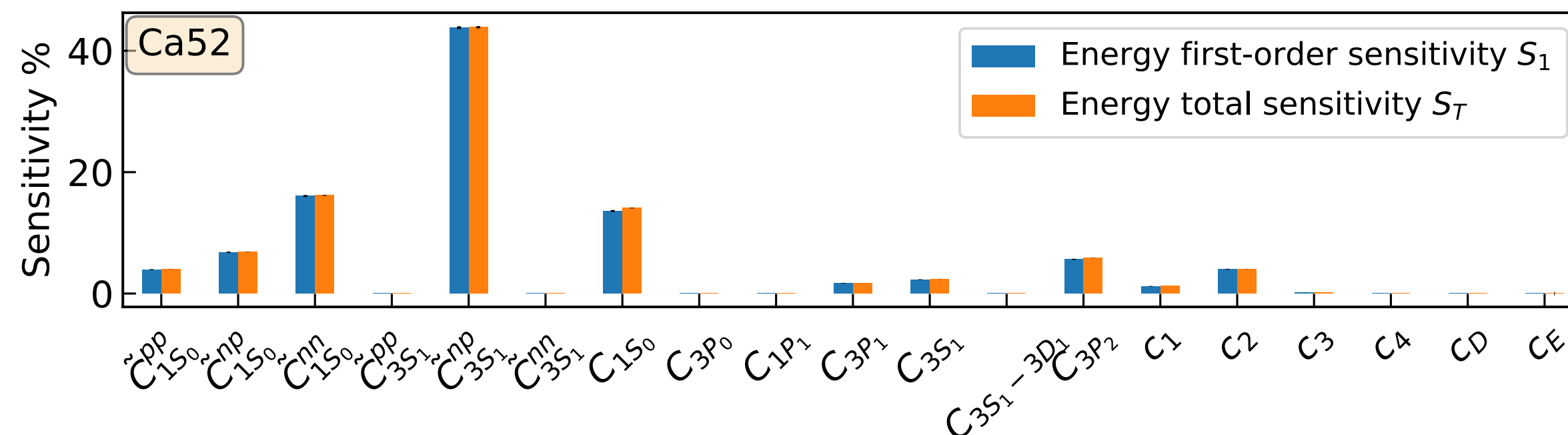
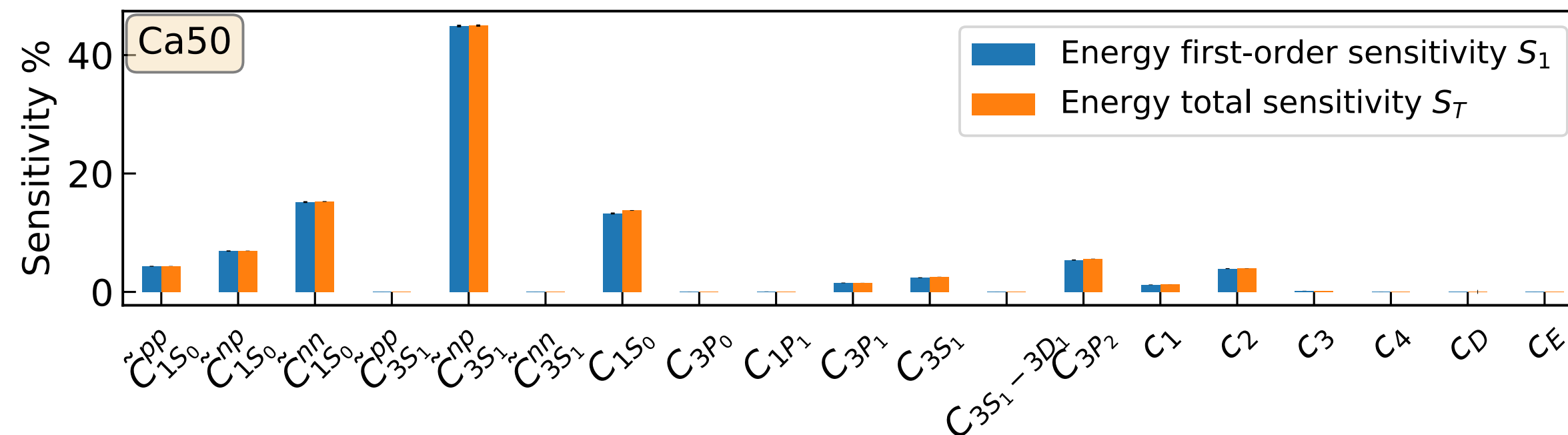
PMM

Hardware	AMD EPYC 7763 Server > \$10,000 per, plus infrastructure		PC with Nvidia RTX A2000 12GB < \$1,000	
Energy	All Runs	~ 965 kWh ~ \$174	Train	< 6 kWh < \$1.08
	Single Run	10 ⁻⁴ to 7.5 kWh \$10 ⁻⁵ to \$1.34	Inference	< 10 ⁻⁶ kWh < \$4 × 10 ⁻⁷
xPU-Time	CPU		GPU	
	All Runs	> 17.5 years	Train	1 day
	Single Run	100 sec to 50 days	Inference	< 1 s
Real-Time	All Runs	> 1 week	Train	1 day
	Single Run	18 sec to 2 days	Inference	< 1 s
Memory	Peak 600 GB		Peak < 12 GB	

Emulators for IMSRG Calculations of Finite Nuclei



J. A. Davison et al., in prep.

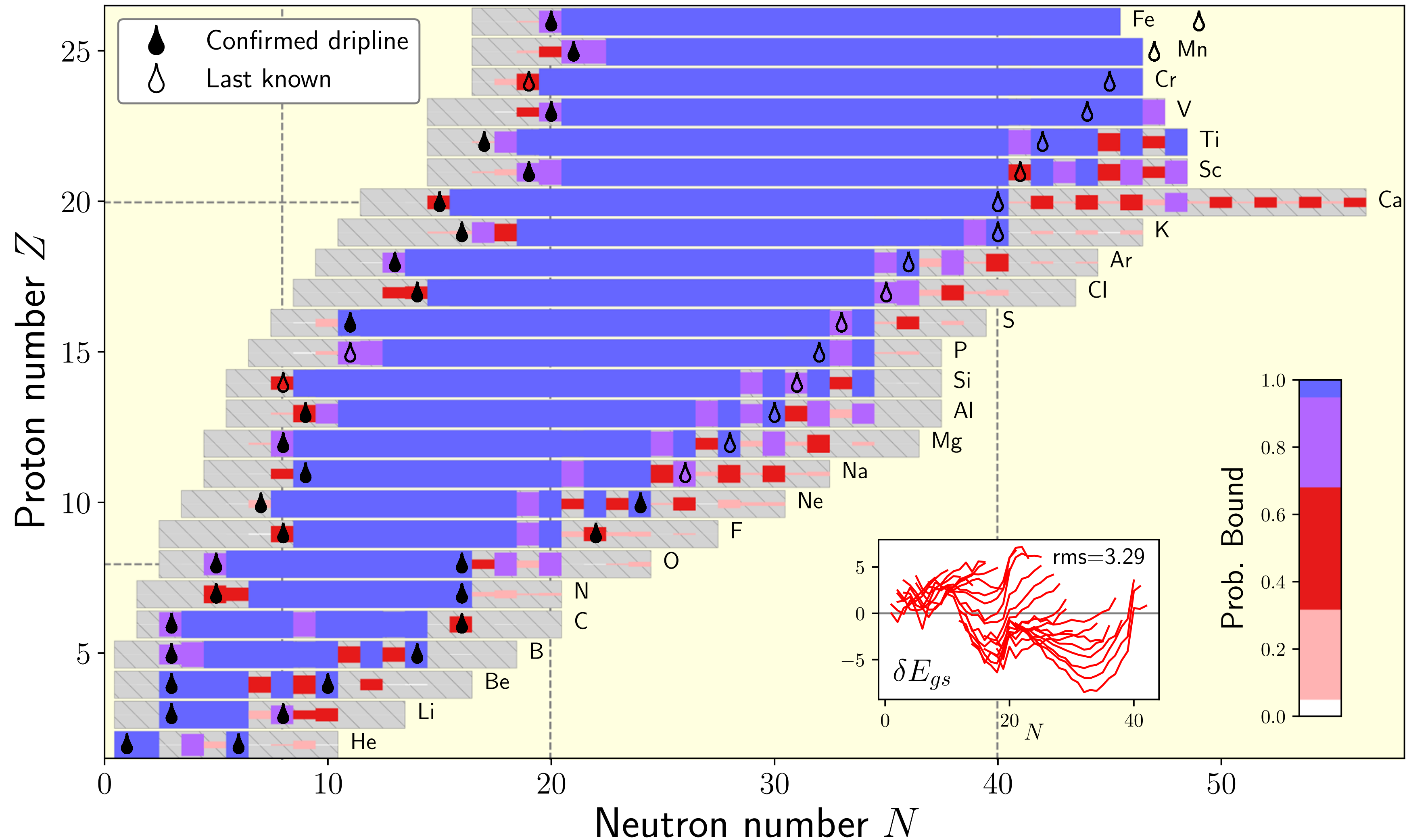


- non-invasive **ROM emulator** based on **Dynamic Mode Decomposition**
- $\Delta\text{NNLO}_{\text{GO}}$, $\text{NN}+3\text{N}$, $e_{\text{max}} = 12, E_{3\text{max}} = 14$
- $\mathcal{O}(10\text{M})$ samples
- **effort reduced by $\sim\mathcal{O}(10^5)$**
- **DMD doesn't work well for Magnus formulation - switch to PMMs**
- **access to $\mathbf{H}(\mathbf{s})$ may allow workaround**

(ambitious) goal: emulate full $H(s)$ or $\Omega(s)$ from snapshots ($\mathcal{O}(10\text{-}100\text{M})$ coefficients)

Selected Applications

Towards *Ab Initio* Mass Tables

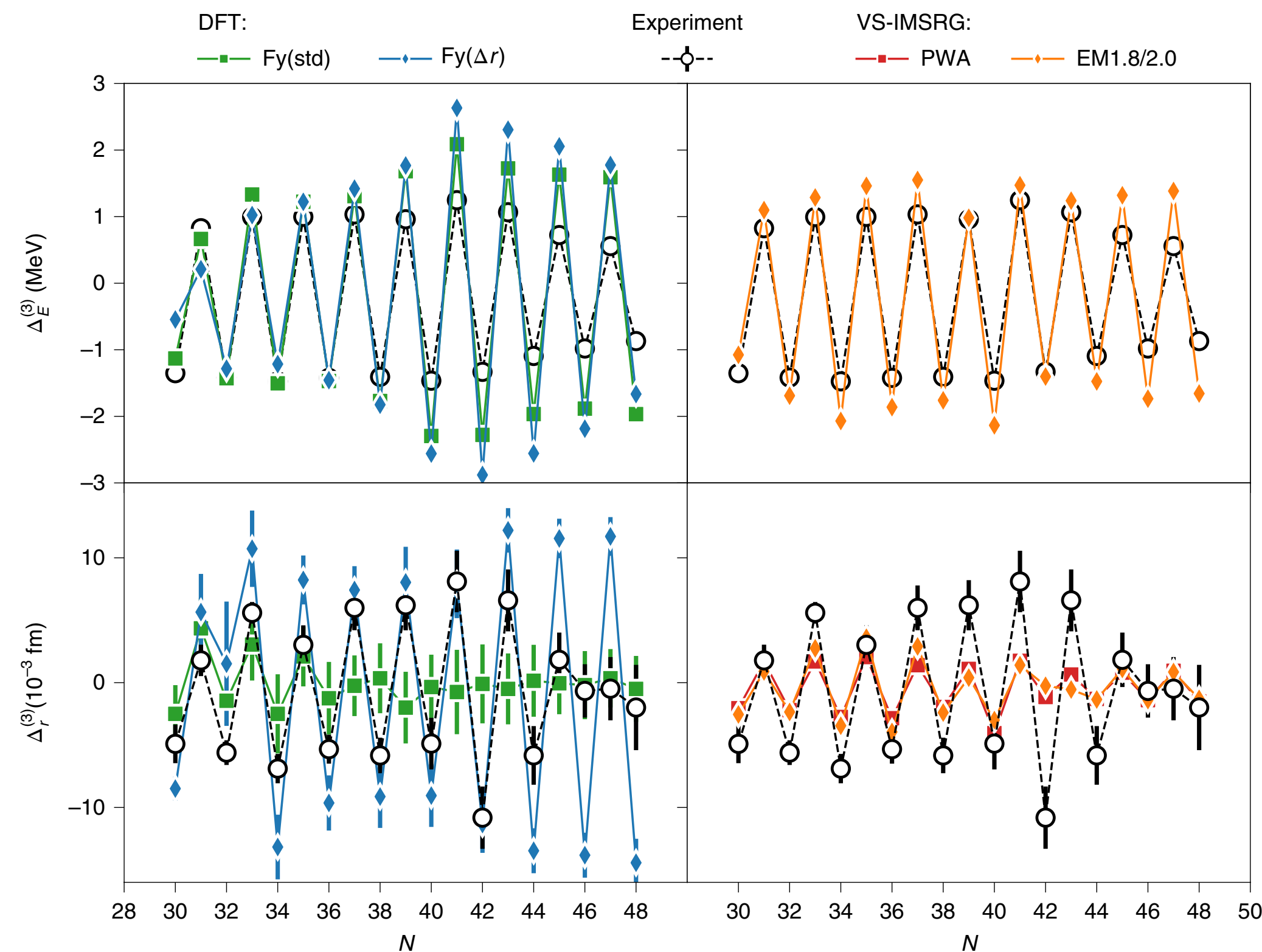


Valence-Space IMSRG “mass table” based on a chiral NN+3N interaction (EM1.8/2.0)

Differential Radii and Trends

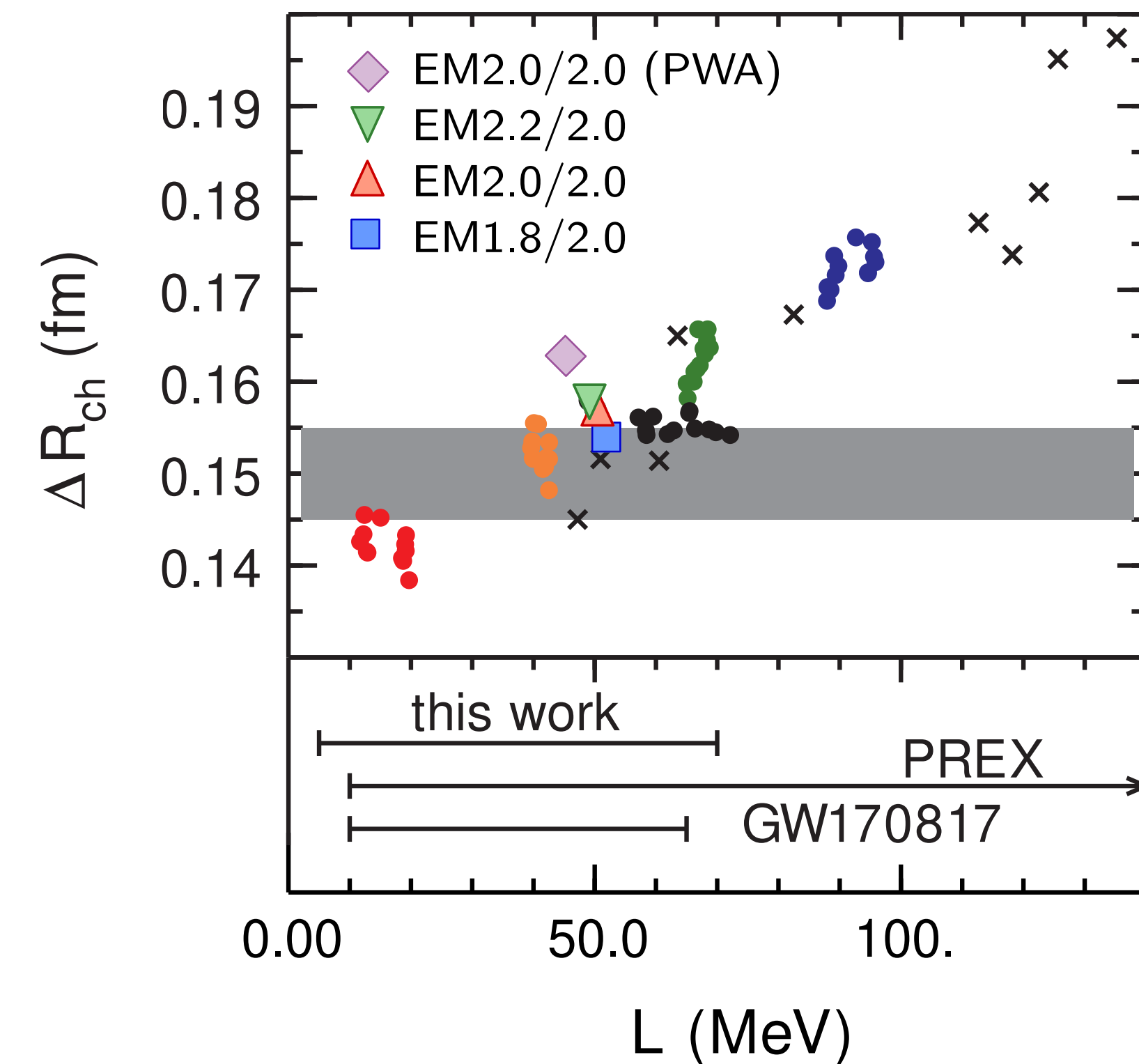
copper isotopes

R. de Groote et al., Nat. Phys. 16, 620 (2020)



$^{36}\text{Ca} - ^{36}\text{S}$

B. A. Brown et al., PRR 2, 022305(R) (2020)



differential observables like the staggering of energies ($\Delta_E^{(3)}$) and radii ($\Delta_r^{(3)}$) or the charge radius difference of mirror nuclei, ΔR_{ch} , are **insensitive** to variations of interaction cutoffs / resolution scale

Neutron Skin of ^{208}Pb

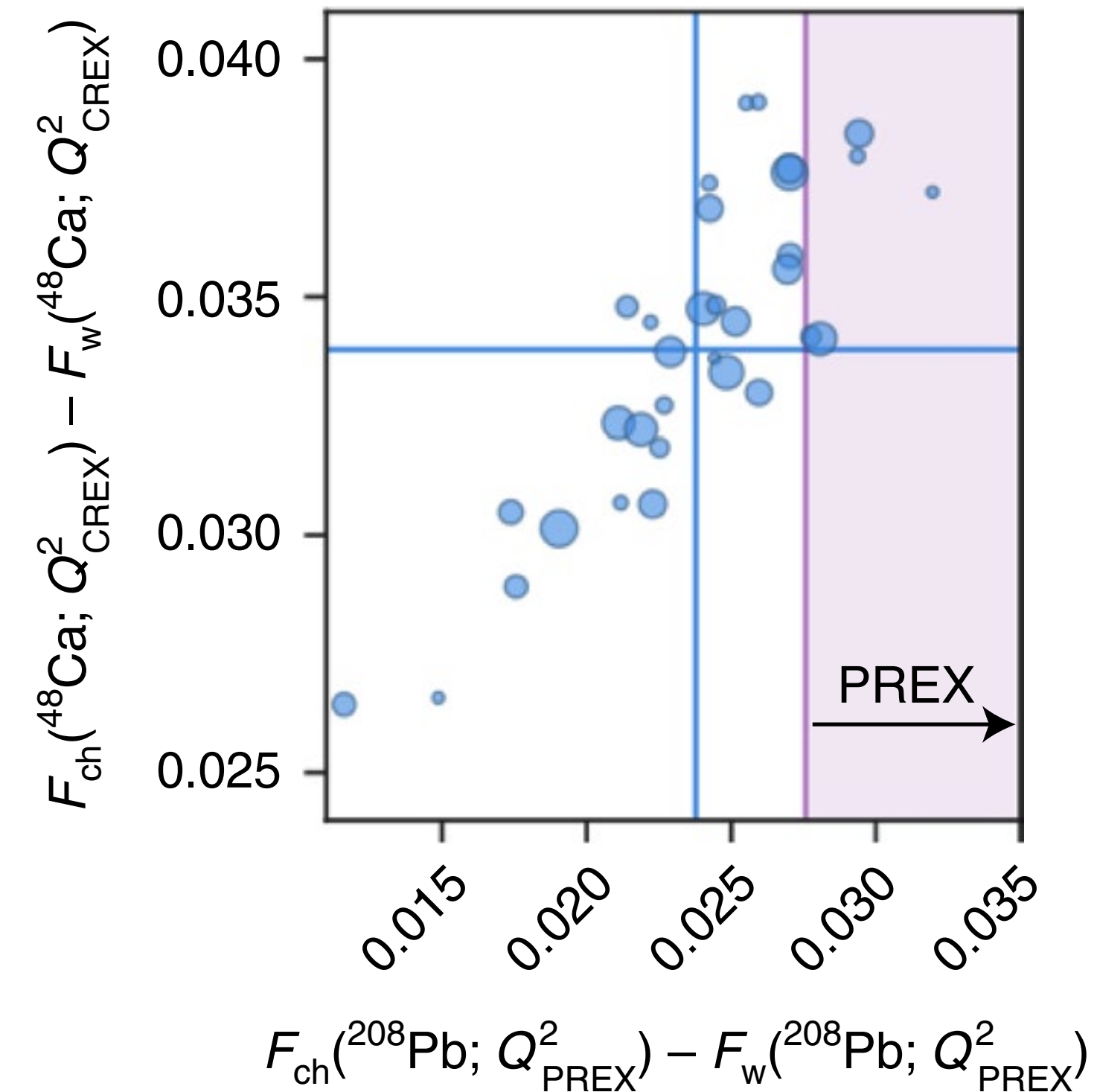
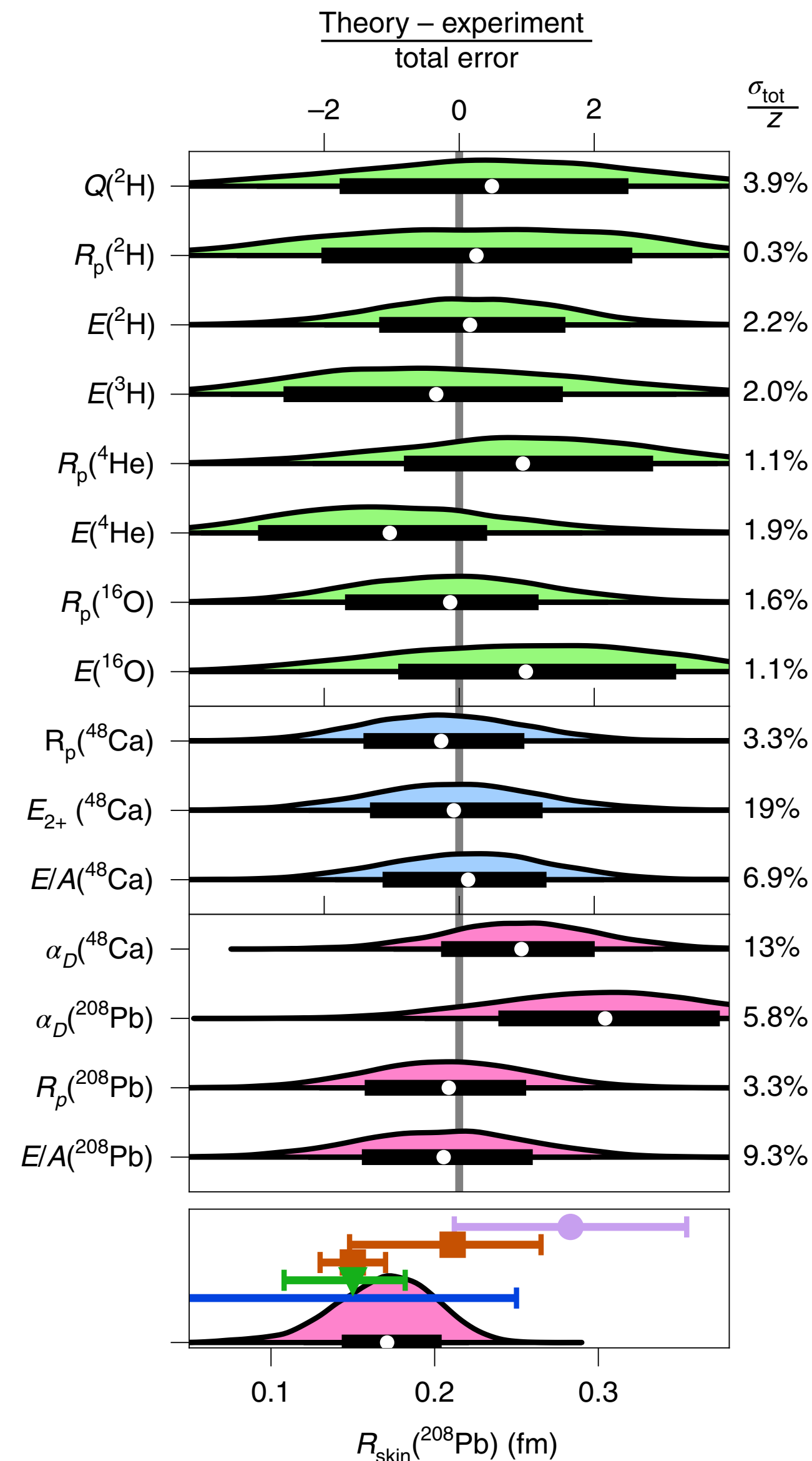
B. S. Hu et al., Nat. Phys. **18**, 1196 (2022)

history matching

calibration

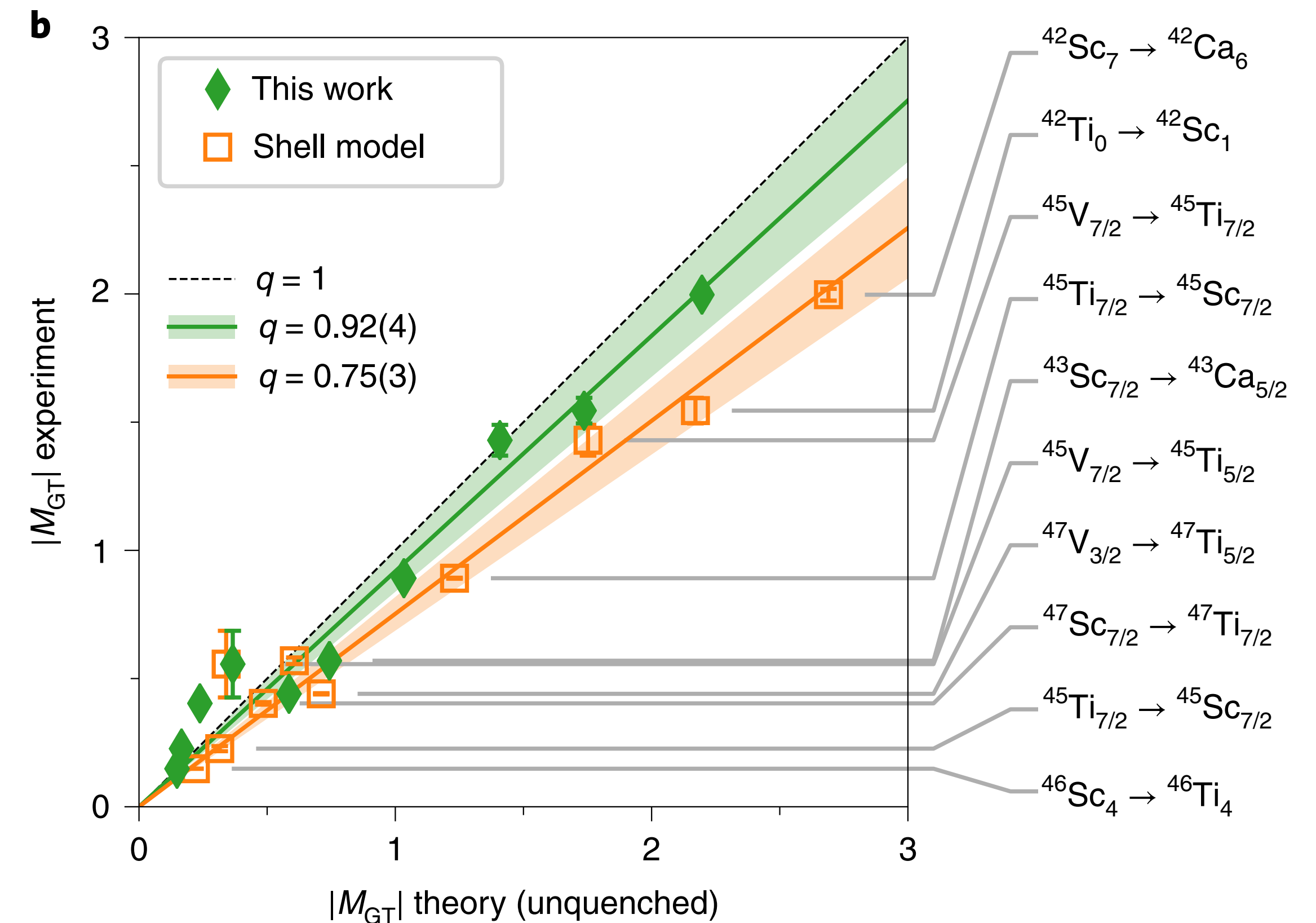
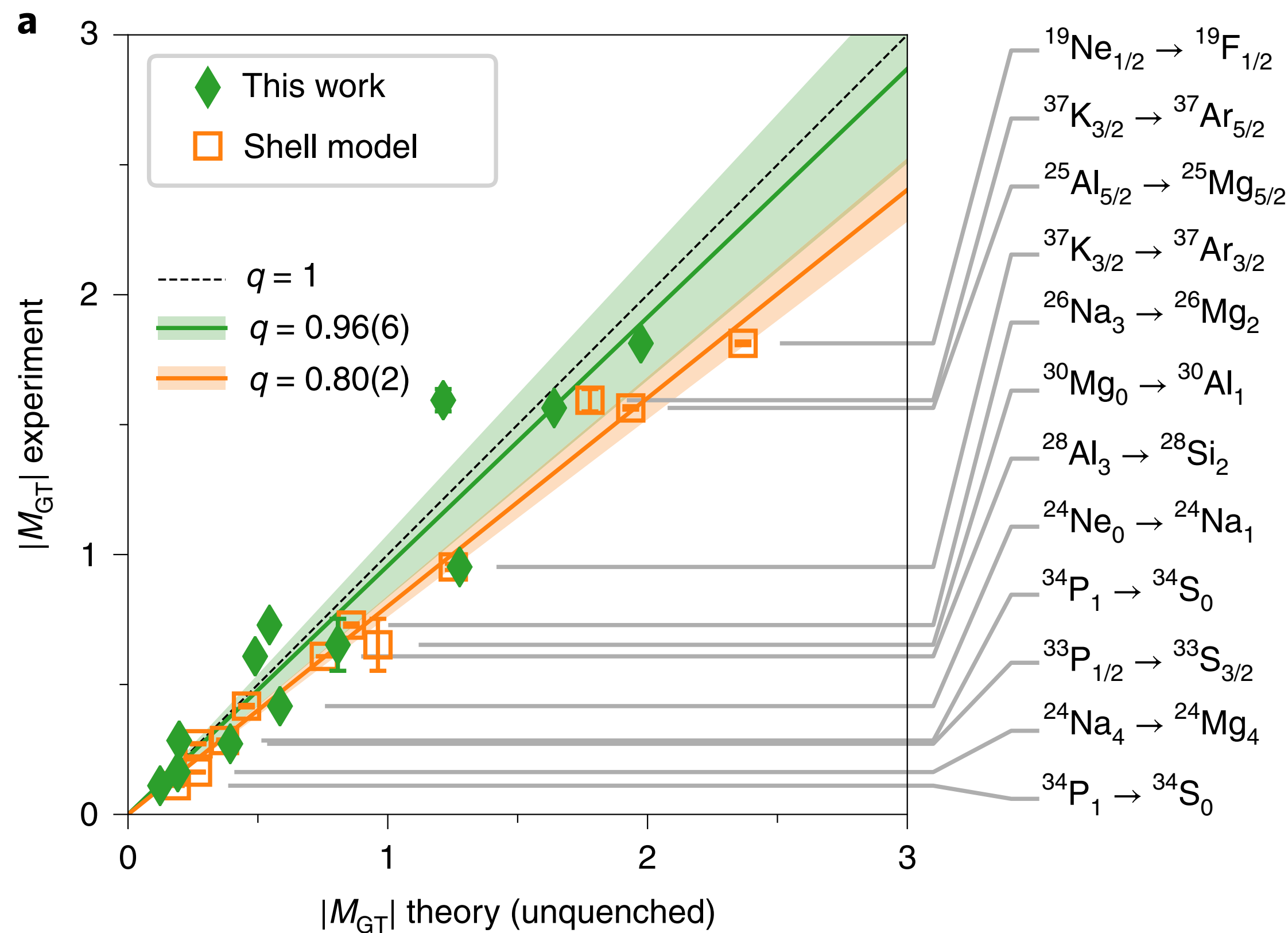
validation

prediction



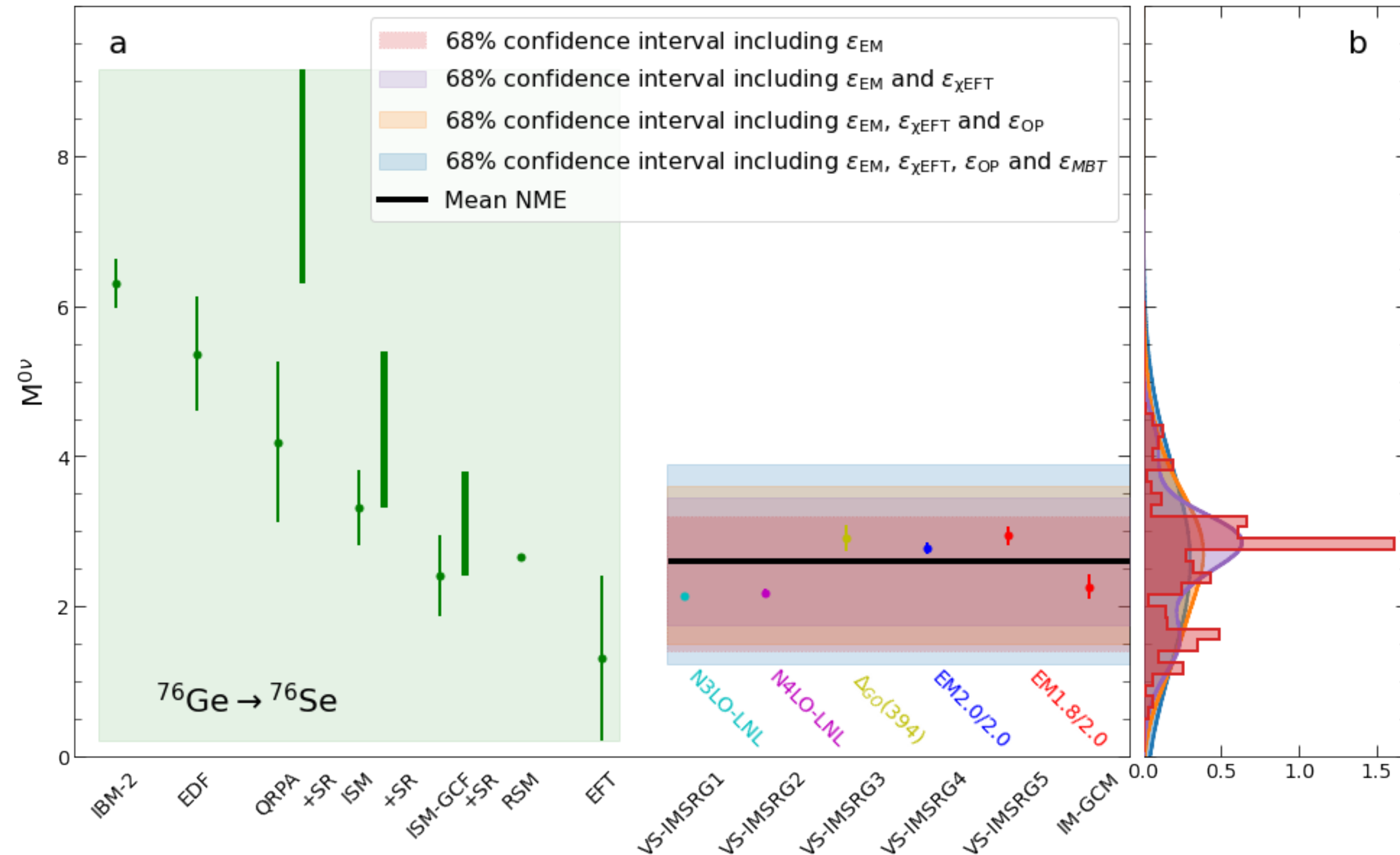
- ^{208}Pb is **heaviest nucleus** for which converged *ab initio* calculations have been achieved (VS-IMSRG, CC)
- chiral forces favor **thin neutron skin**, in **mild tension** with recent experimental result from PREX

Quenching of Gamow-Teller Decays



- **empirical Shell model** calculations require **quenching factors** of the weak axial-vector coupling g_A
- **VS-IMSRG** explains this through consistent **renormalization** of transition operator, incl. **two-body currents**

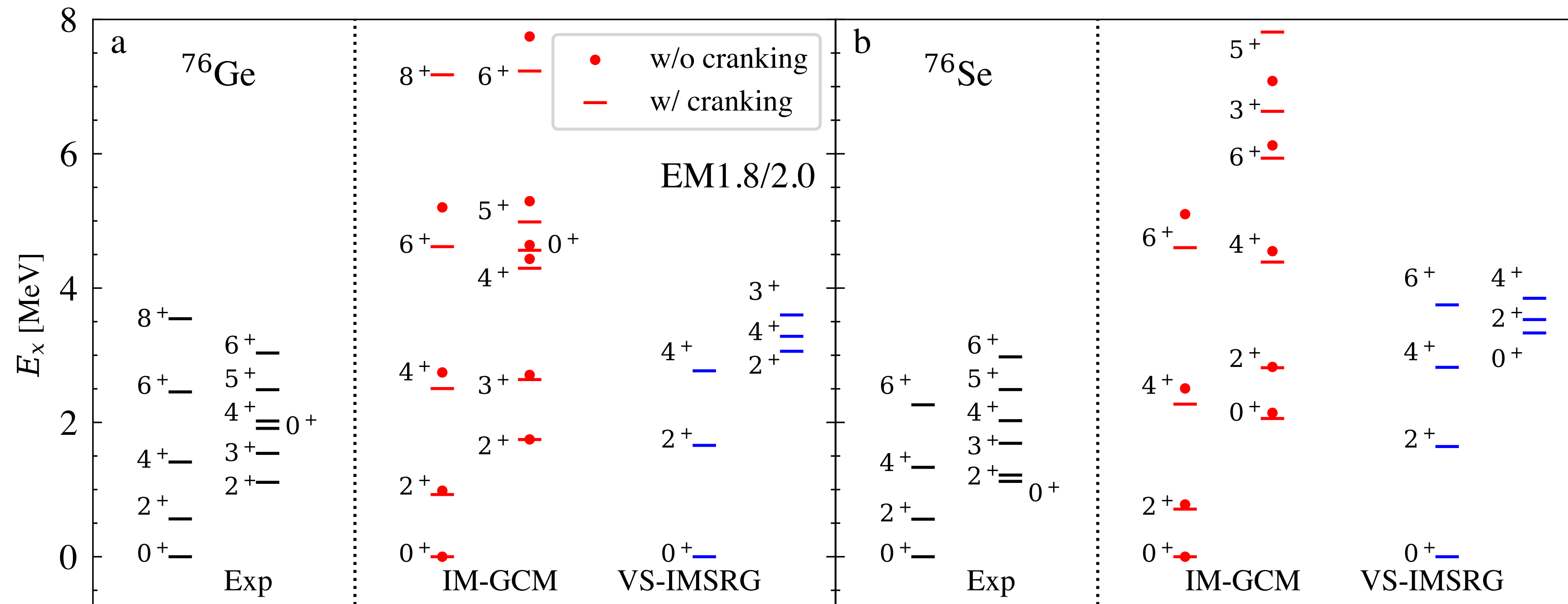
^{76}Ge : Neutrinoless Double Beta Decay



- **complementary methods: IM-GCM & VS-IMSRG**
- explores interactions, many-body and EFT truncations, contact term, ...
- leverages **emulators**
- identifies **main drivers** of uncertainty and what to improve next

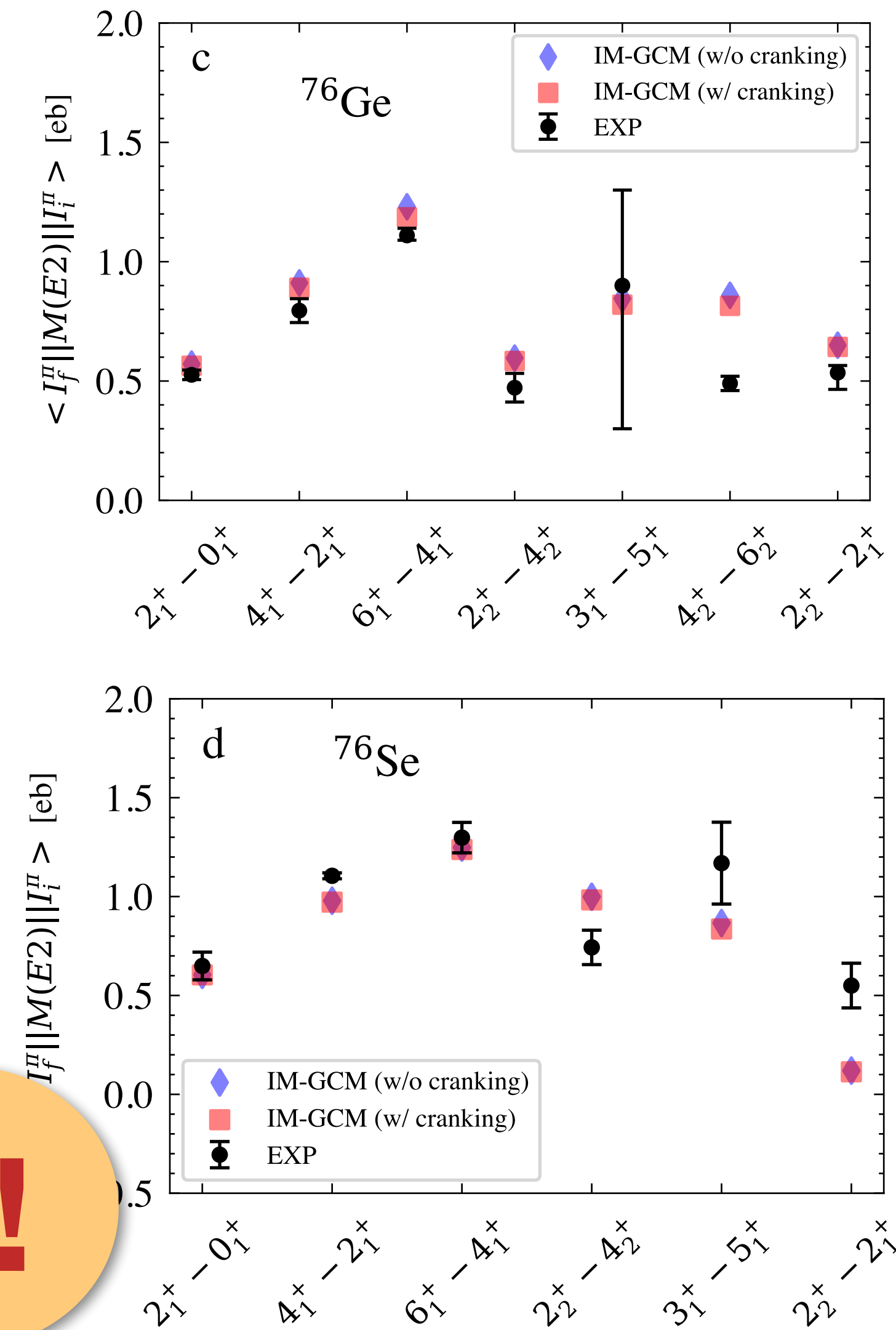
^{76}Ge / ^{76}Se Structure

A. Belley et al., PRL **132**, 182502 (2024)



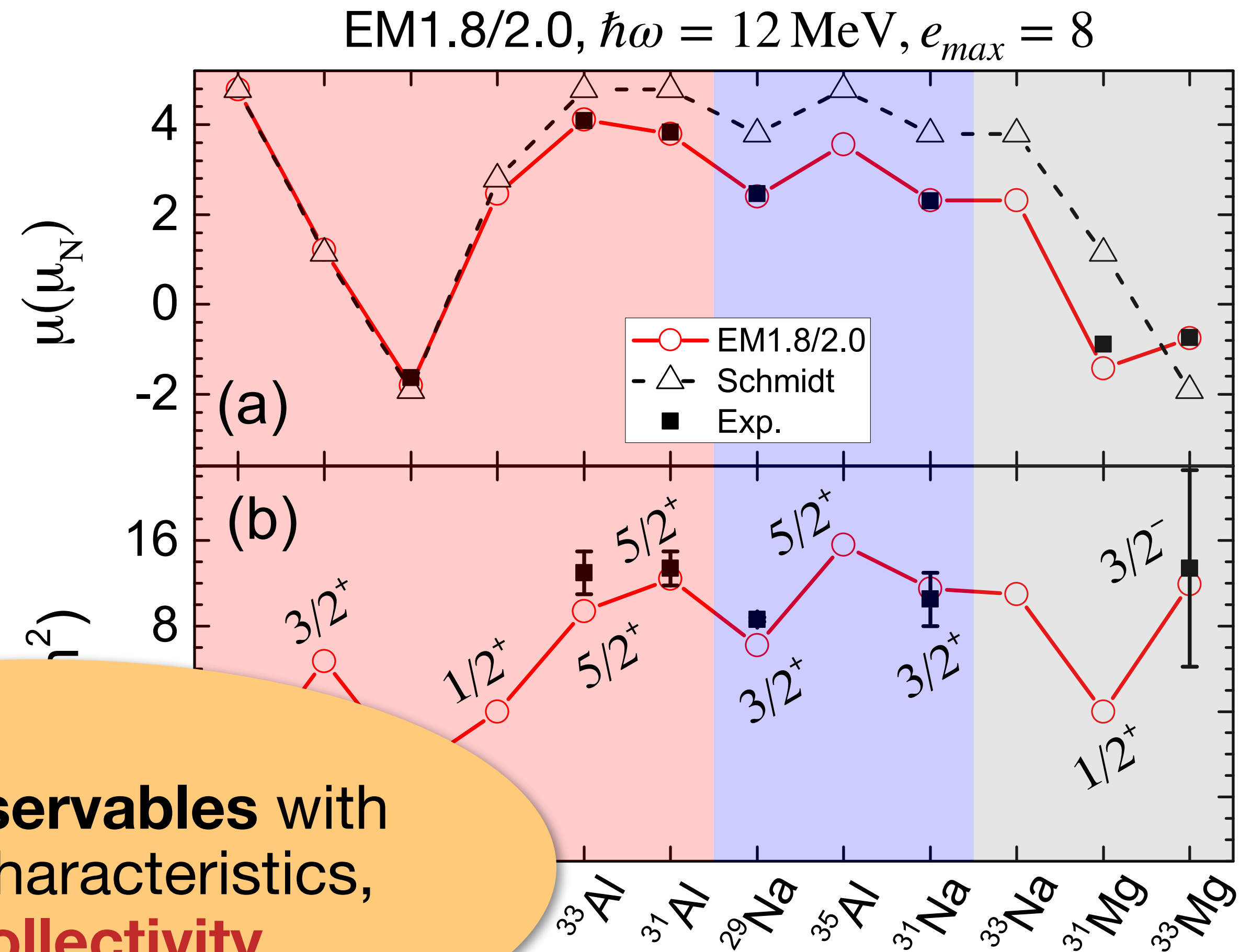
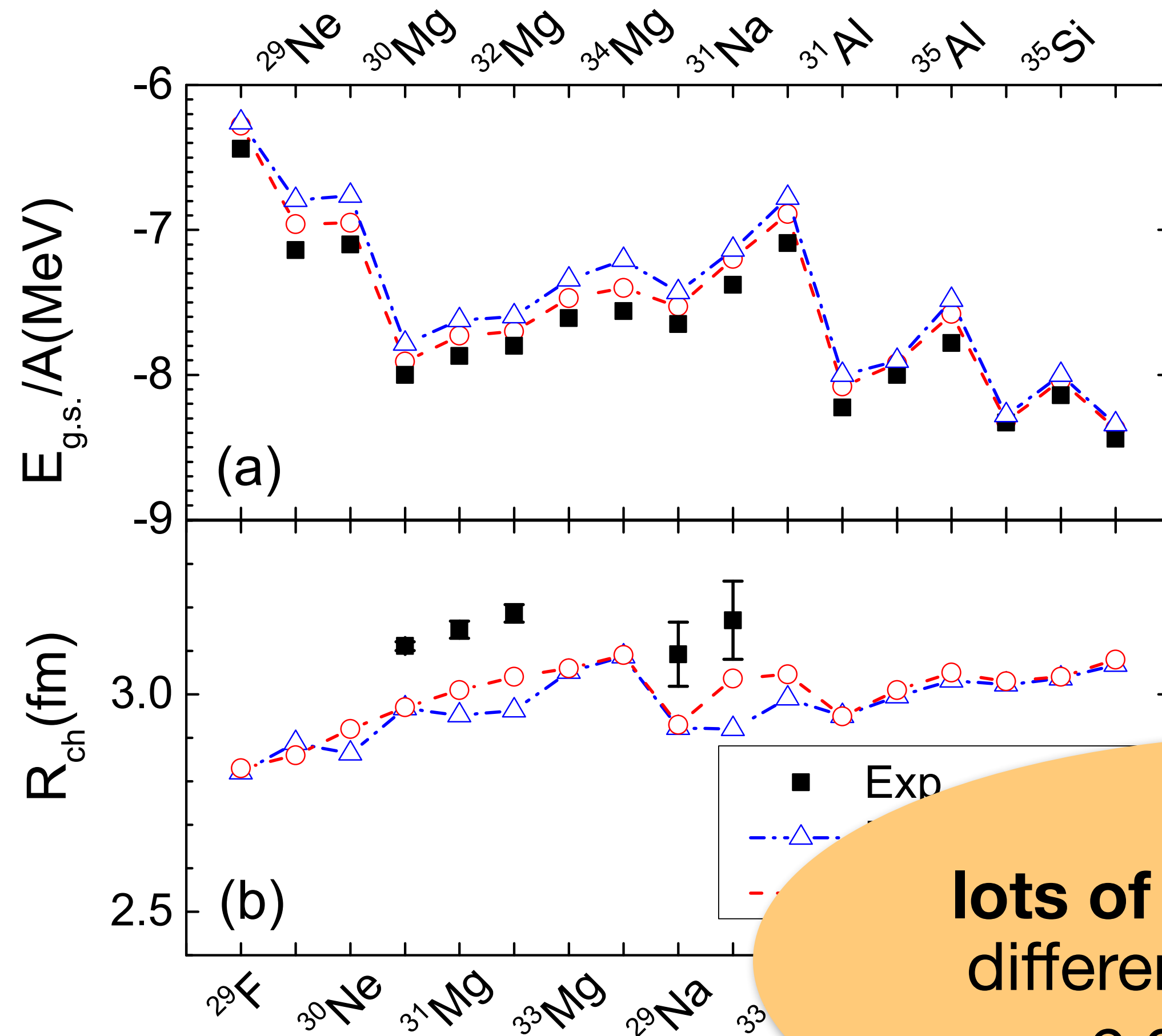
EM1.8/2.0 NN+3N interaction, $\hbar\omega = 12 \text{ MeV}$, $e_{max} = 10$

- IM-GCM spectra too extended (common)
- E2 transitions (and static moments) in **excellent agreement with experiment...**
- ...although EM1.8/2.0 **underpredicts** radii by a few percent



Shape Coexistence: N=20 Island of Inversion Region

E. F. Zhou et al., arXiv:2603.07363 (to appear in PRC)

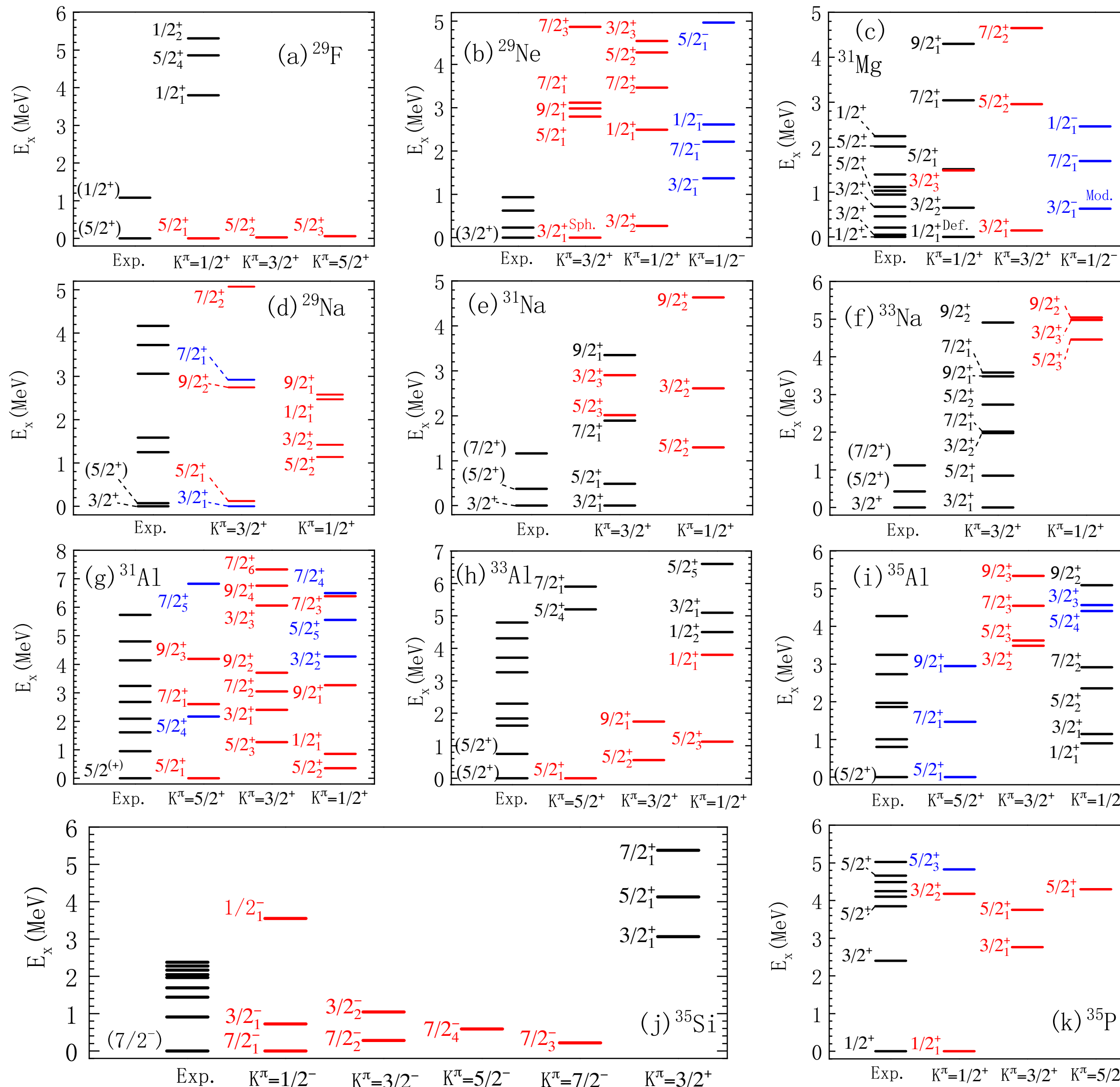


lots of observables with different characteristics, e.g. **collectivity**

Shape Coexistence: N=20 Island of Inversion Region



E. F. Zhou et al., arXiv:2603.07363 (to appear in PRC)



IM-GCM survey of the **island-of-inversion** region

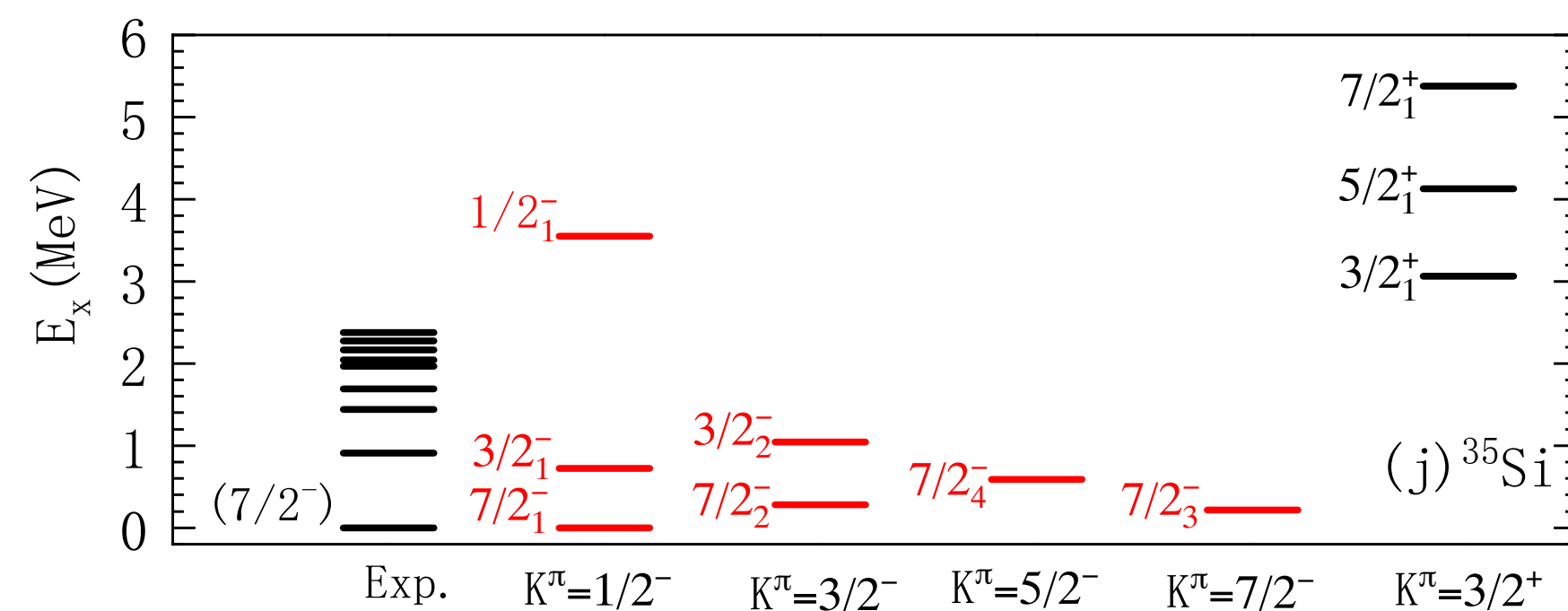
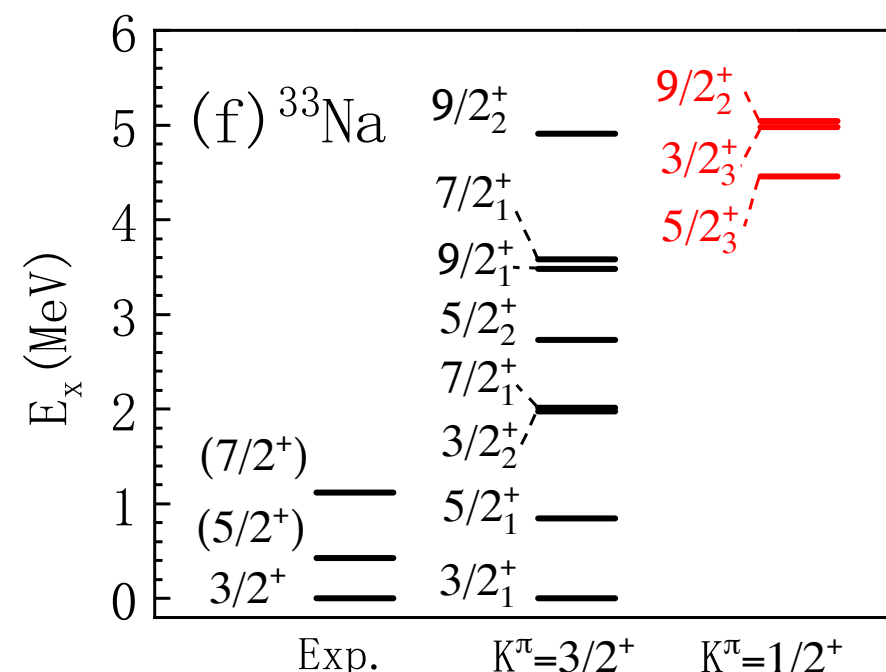
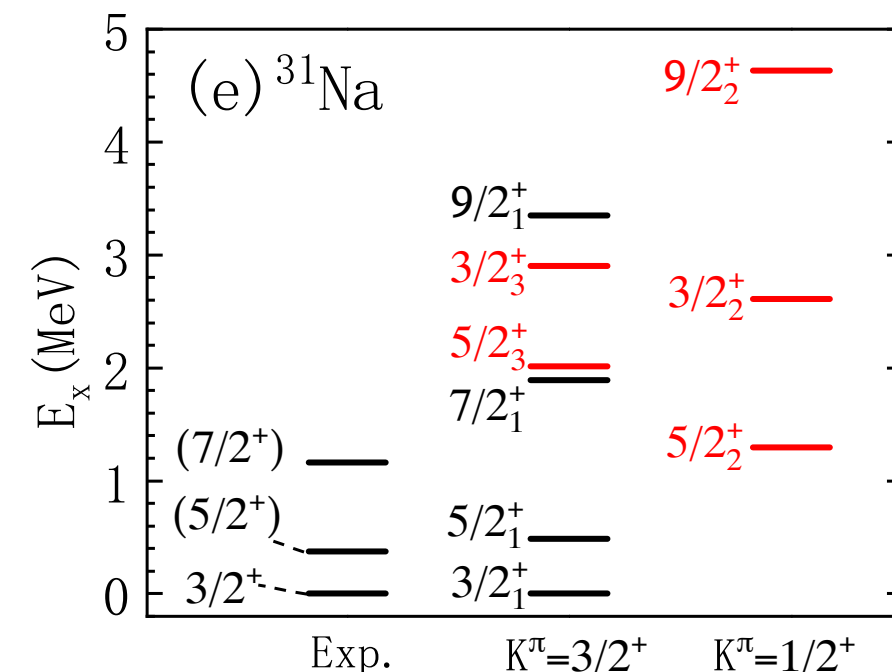
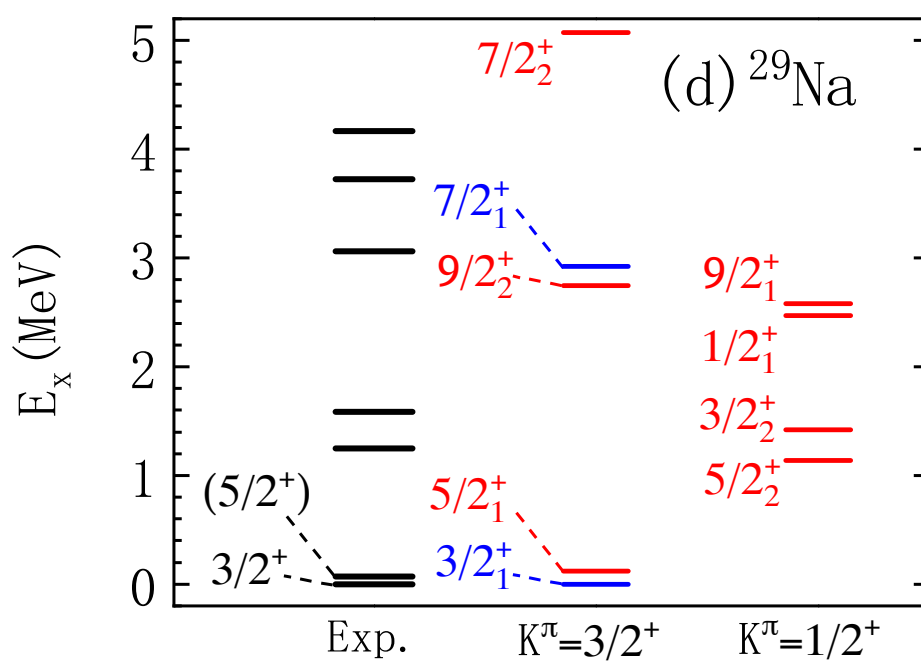
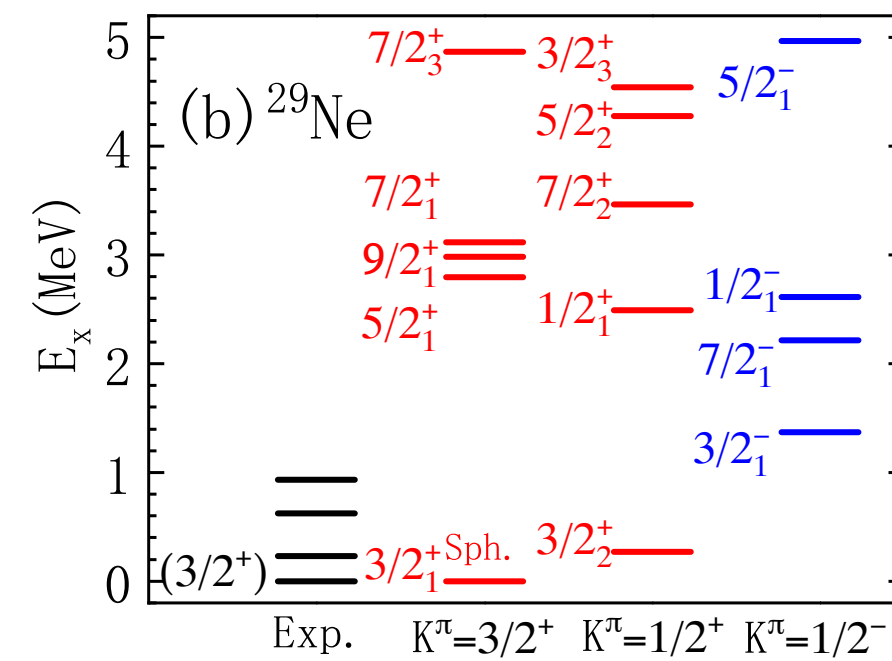
- **even-even and odd-A - odd-odd** nuclei now also possible
- IM-GCM spectra are **spread too wide**, but this will (at least in part) be addressed through
 - improved IMSRG (working on MR-IMSRG(3) variants)
 - more degrees of freedom in GCM: cranking, full triaxiality, explicit quasiparticle excitations, ...

Shape Coexistence: N=20 Island of Inversion Region

E. F. Zhou et al., arXiv:2603.07363 (to appear in PRC)

IM-GCM survey of the **island-of-inversion** region

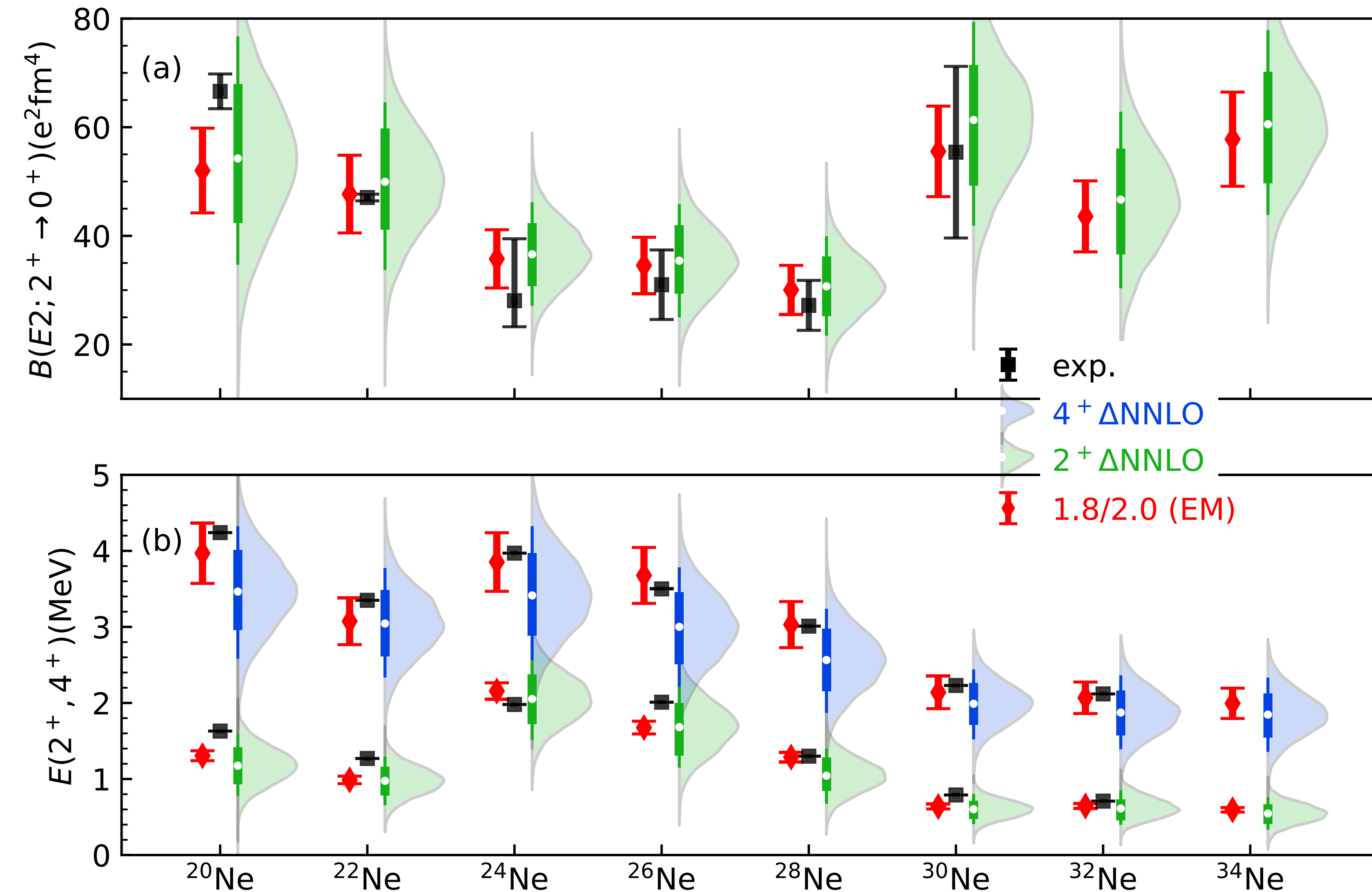
support **state identification**
and offer *ab initio* insights into
intrinsic shapes



AMP-CCSD: Ne, Na, Mg Isotopes

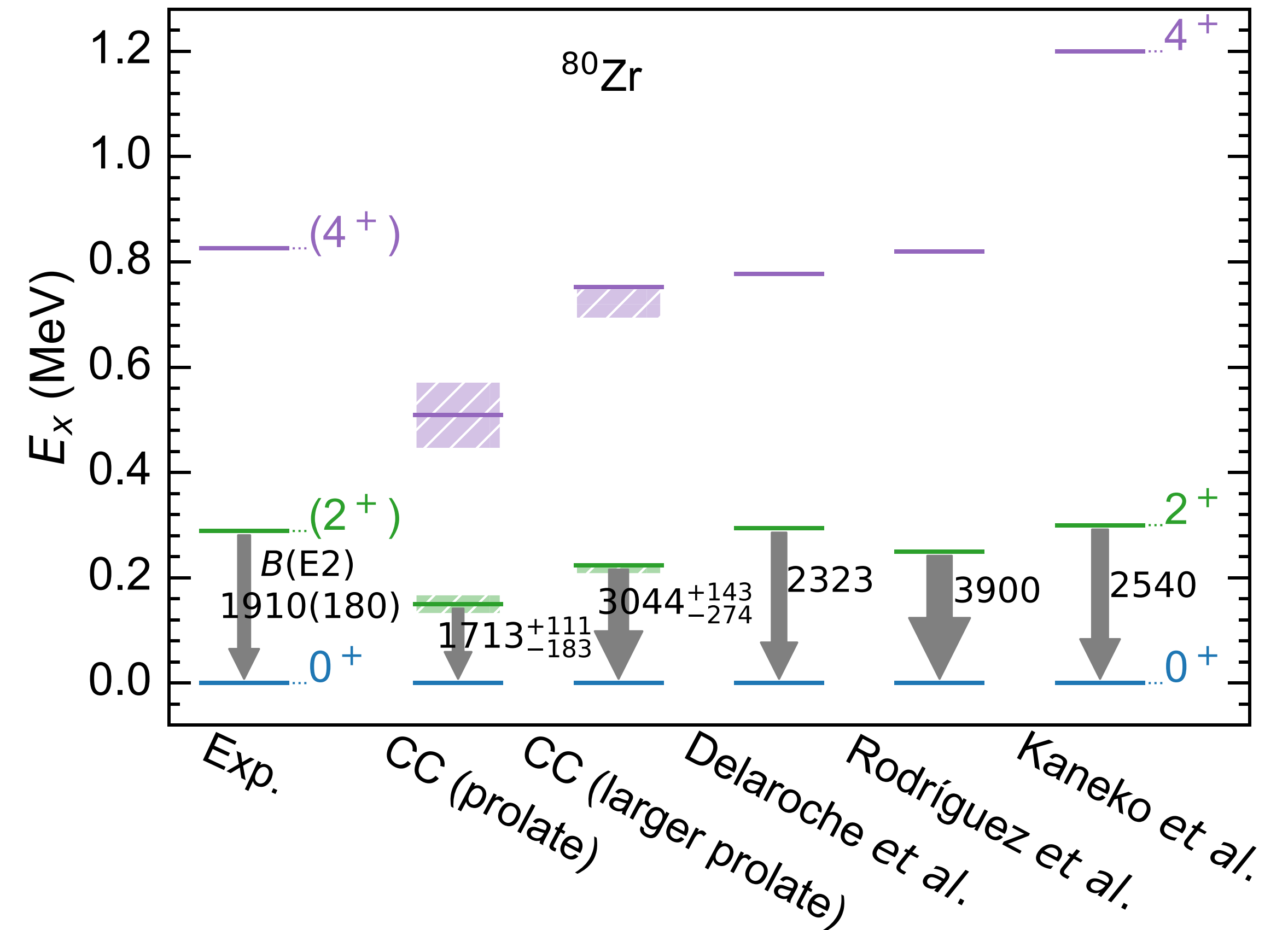
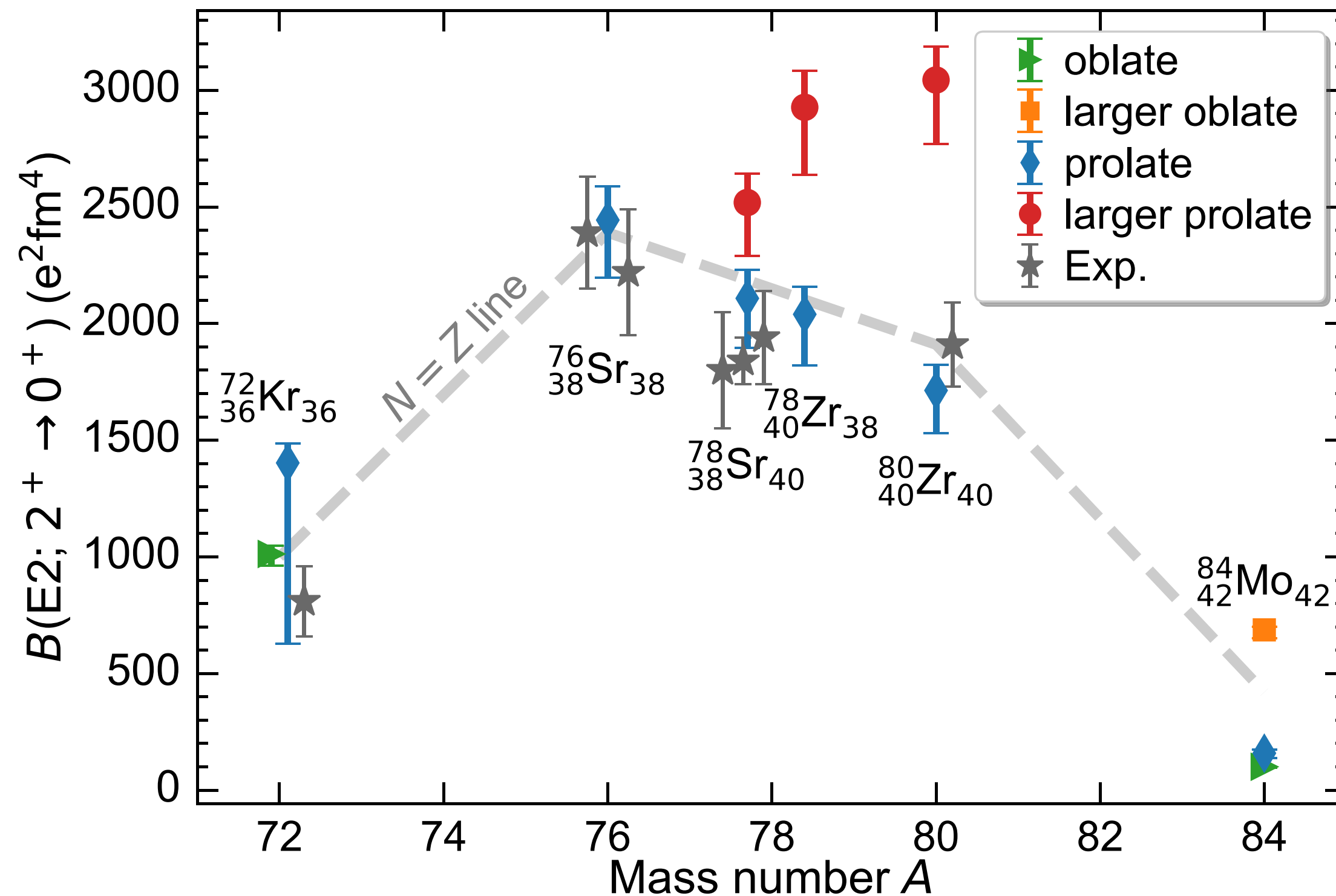


Z. H. Sun et al., *PRX* **15**, 011028 (2025)
Z. H. Sun et al., *arXiv*:2409.02279



- AMP-CCSD for **even and odd Ne, Na, Mg** isotopes
- **emulators for UQ**
- rotational bands and $B(E2, 2^+ \rightarrow 0^+)$ values in **very good agreement** with data
- **consistent results** for EM1.8/2.0 and a family of 8000+ $\Delta\text{N}2\text{LO}$ interactions

AMP-CCSD: Z~80 Region



- *ab initio* calculations poised to offer insight into **rich shape coexistence phenomena** in $N=Z$ nuclei near ^{80}Zr
- **challenges:** computational cost restricts model size, effects of **shape mixing**, ...

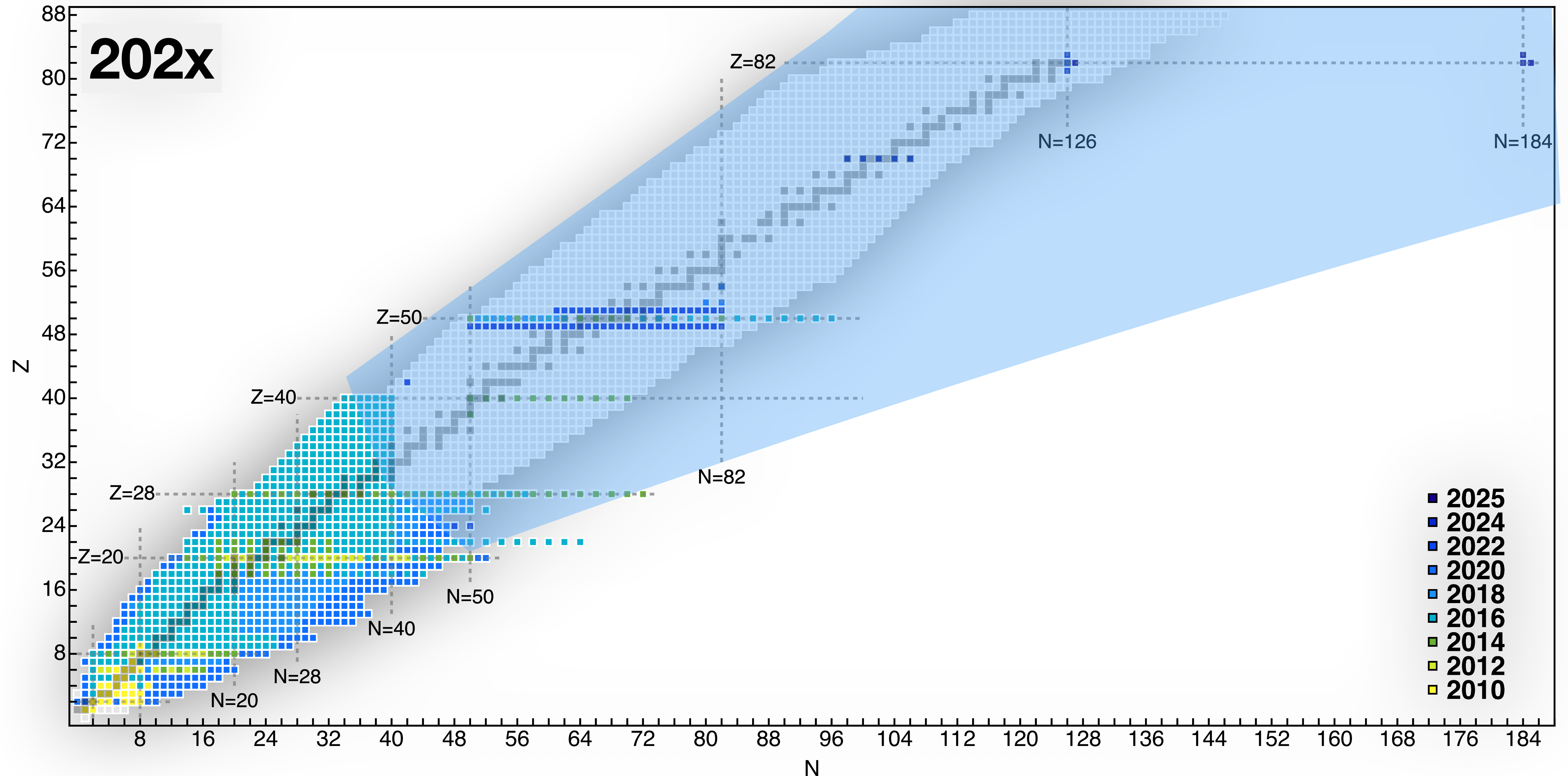
Epilogue

- *ab initio* approach is key for a **predictive theory** of nuclear structure and reactions
 - rooted in QCD (**proper symmetries**)
 - **systematically improvable** interactions and operators through (chiral) EFT, as well as many-body methods
 - **quantified uncertainties** through modern statistics & emulators
- **renormalization group** methods are a **powerful tool** for nuclear theory
- **open challenges remain: EFT** power counting/convergence, efficient handling of (large-amplitude) **collectivity**, bridge to **reactions**, **sufficient precision**
- always growing capabilities - more **exciting applications** than I could show here, and **many more to come**

You will also see **much more during this program**,
from **CC, IMSRG, Lattice EFT, QMC, SCGF, ...**

Where Do We Want To Go?

[cf. HH, *Front. Phys.* **8**, 379 (2020)]



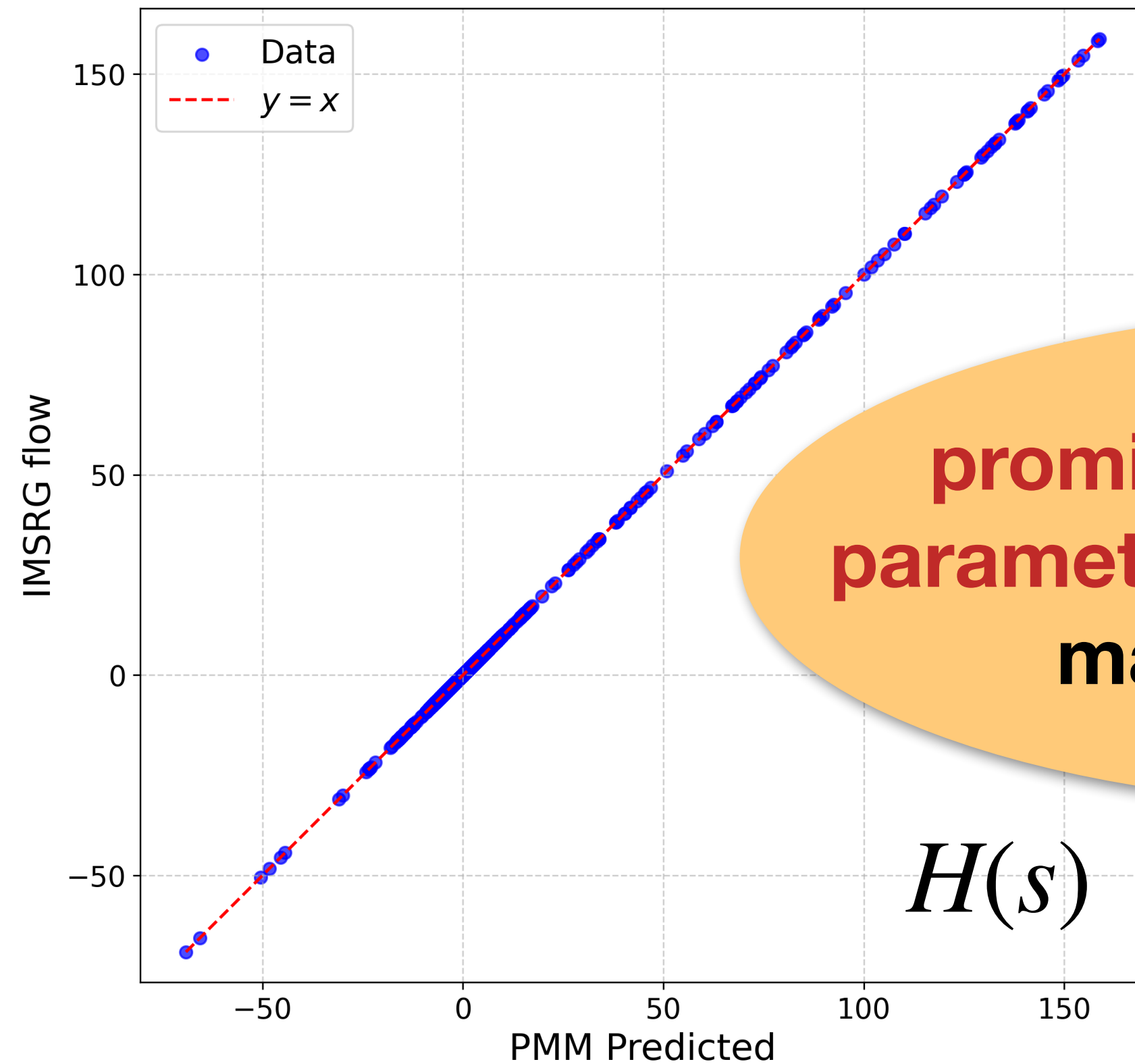
H. Hergert - MITP Program “Many-Body Physics: Nuclear Physics Meets Quantum Chemistry”, Aug 24, 2026

Supplements

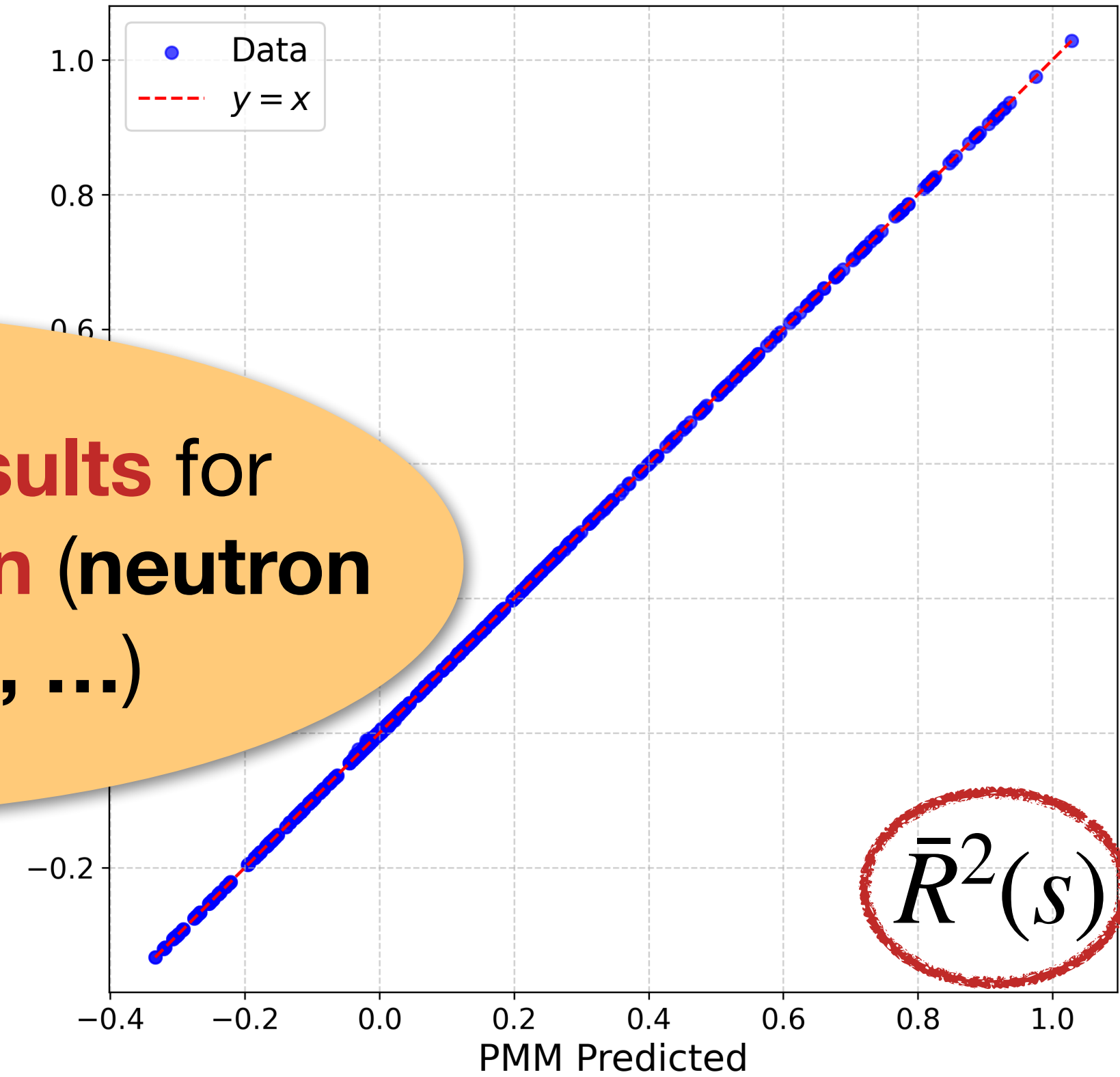
Parametric Matrix Models

B. Clark et al., in progress

^{48}Ca , EM1.8/2.0, $e_{\text{max}} = 10$, $E_{3\text{max}} = 14$



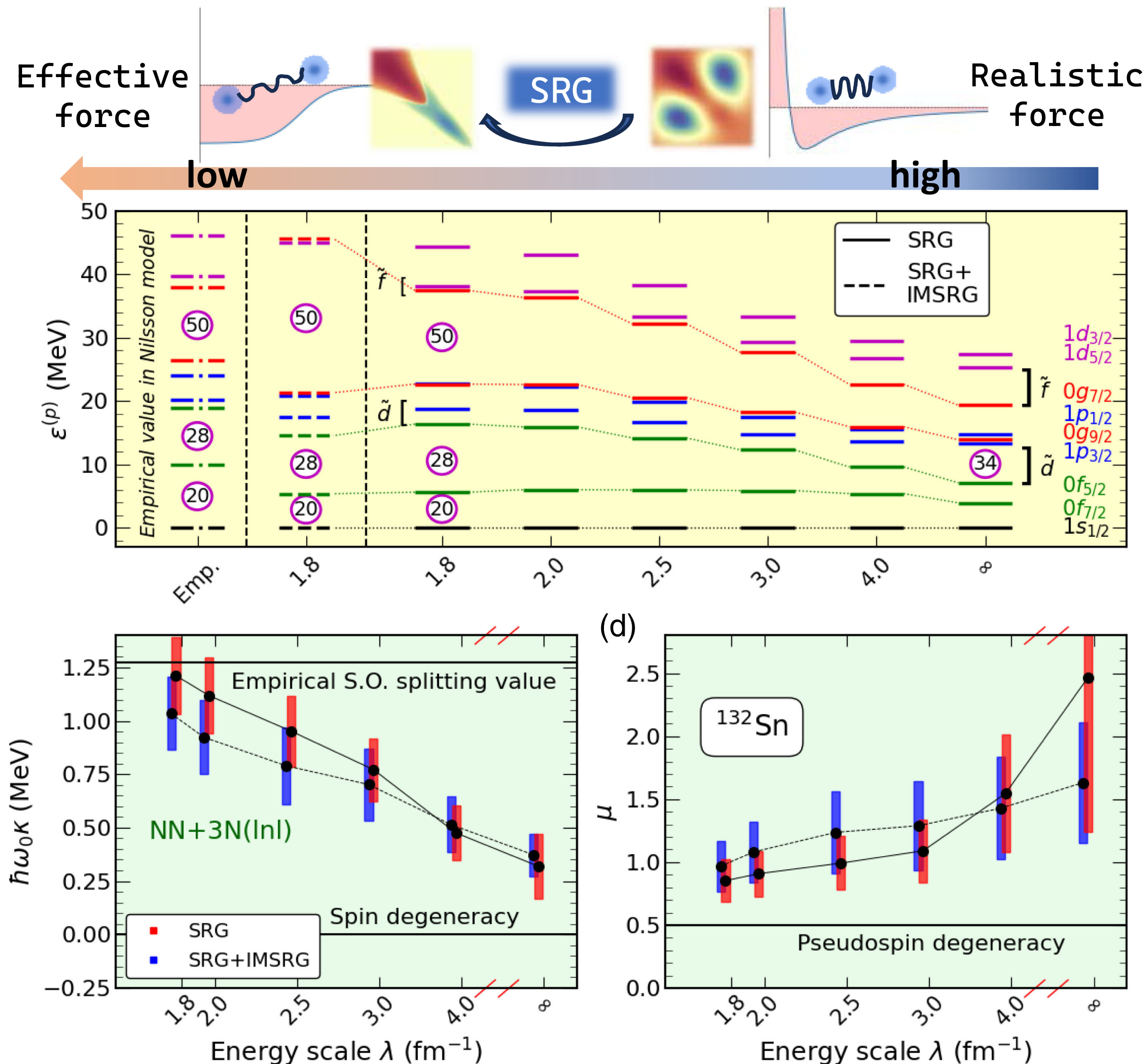
^{44}Ca , EM1.8/2.0, $e_{\text{max}} = 12$, $E_{3\text{max}} = 14$



promising first results for
parametric emulation (neutron
matter @N3LO, ...)

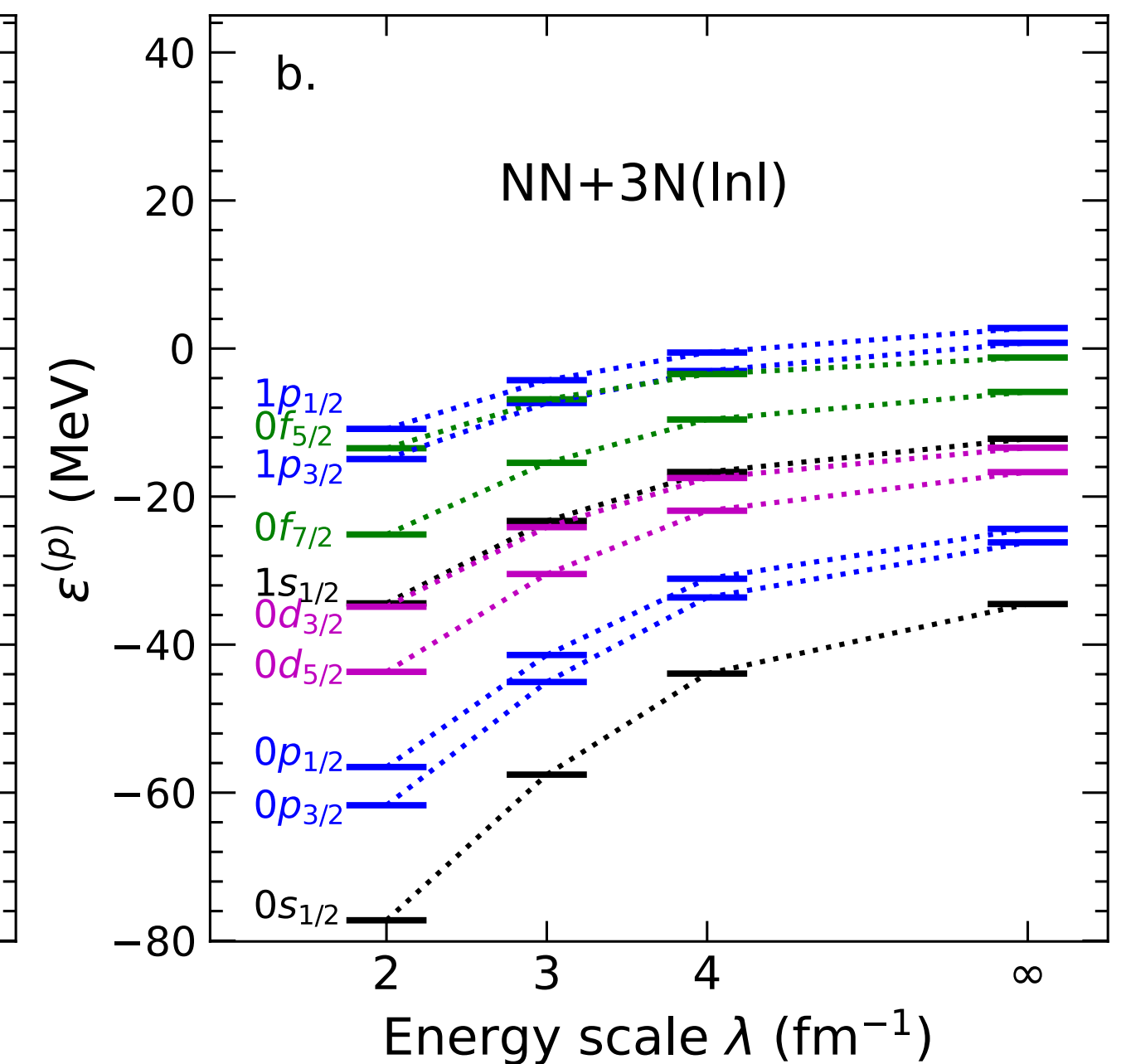
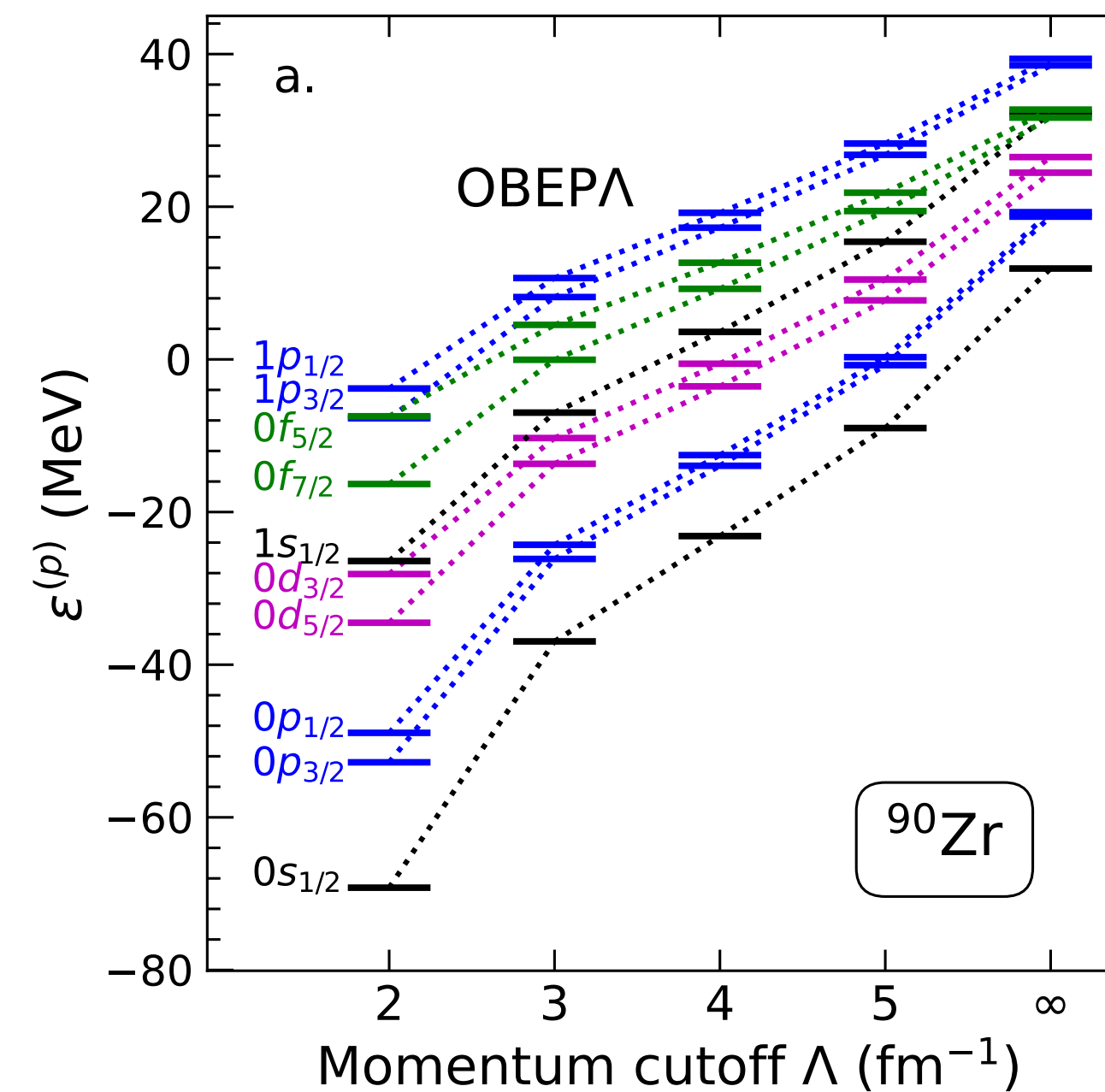
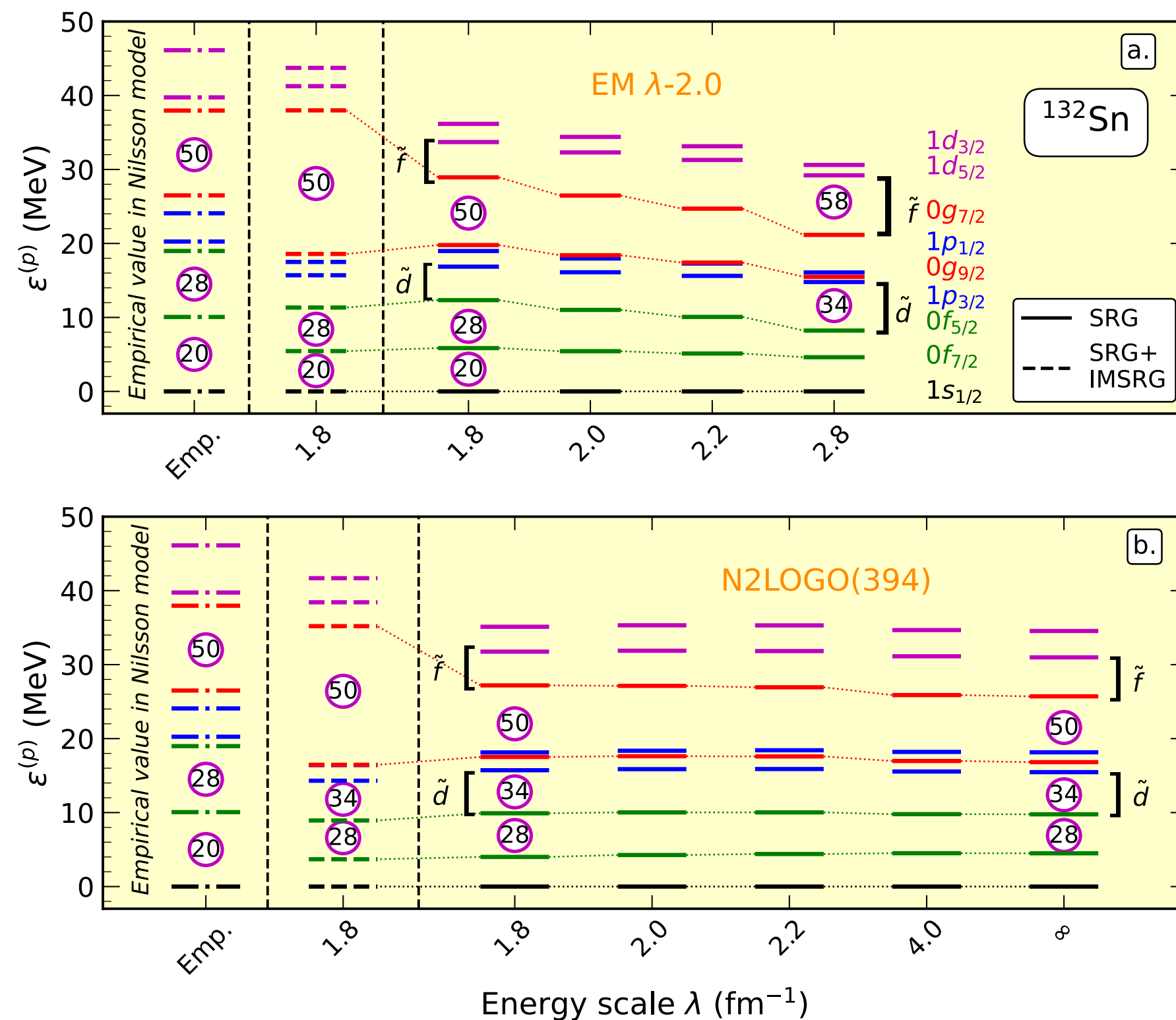
- DMD fails to emulate $\Omega(s)$ unless training is done at large s ...
- ... **but PMMs work** - trained on first $\sim 10\%$ of integration steps

Evolution of Effective Single-Particle Energies



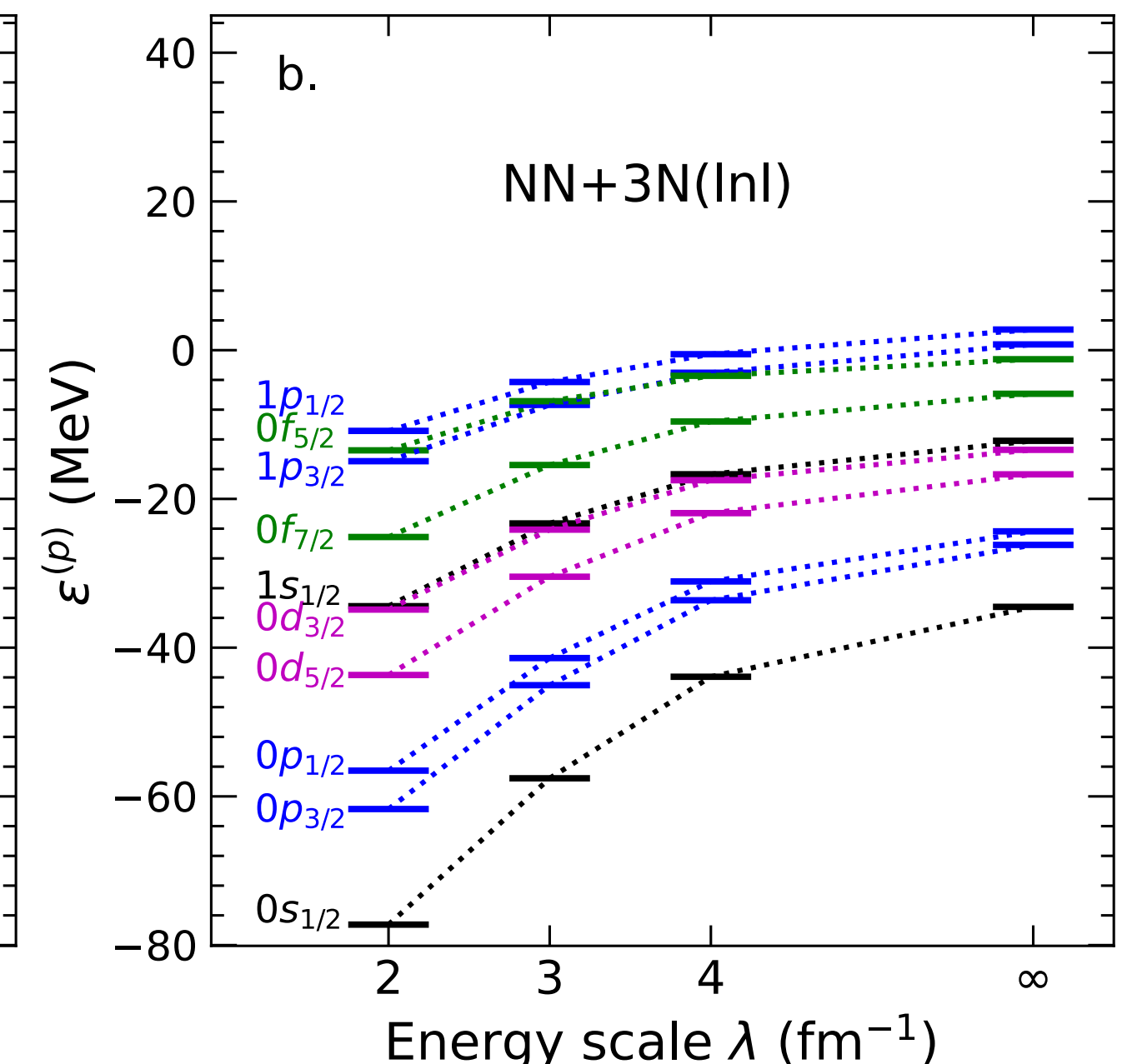
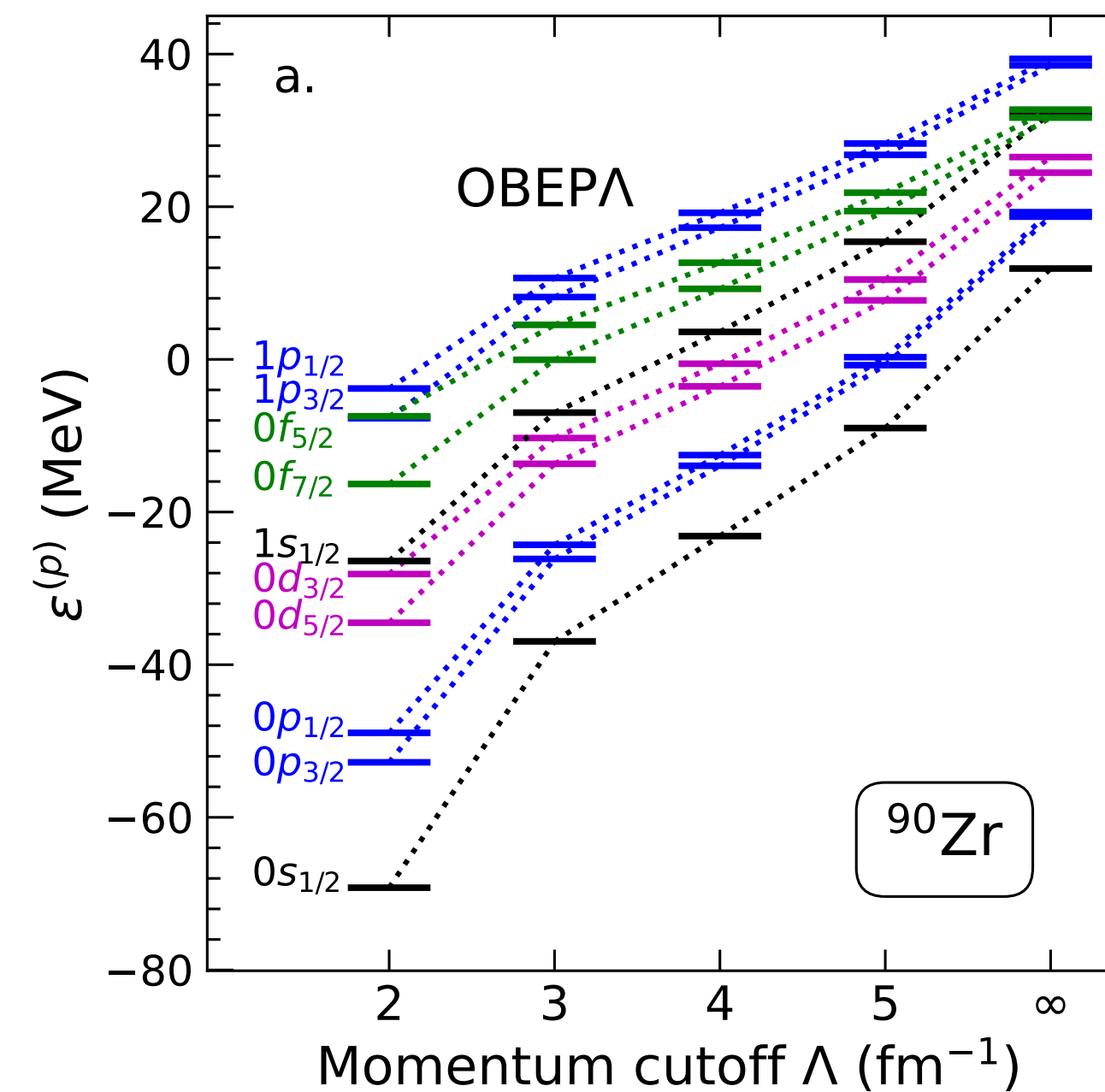
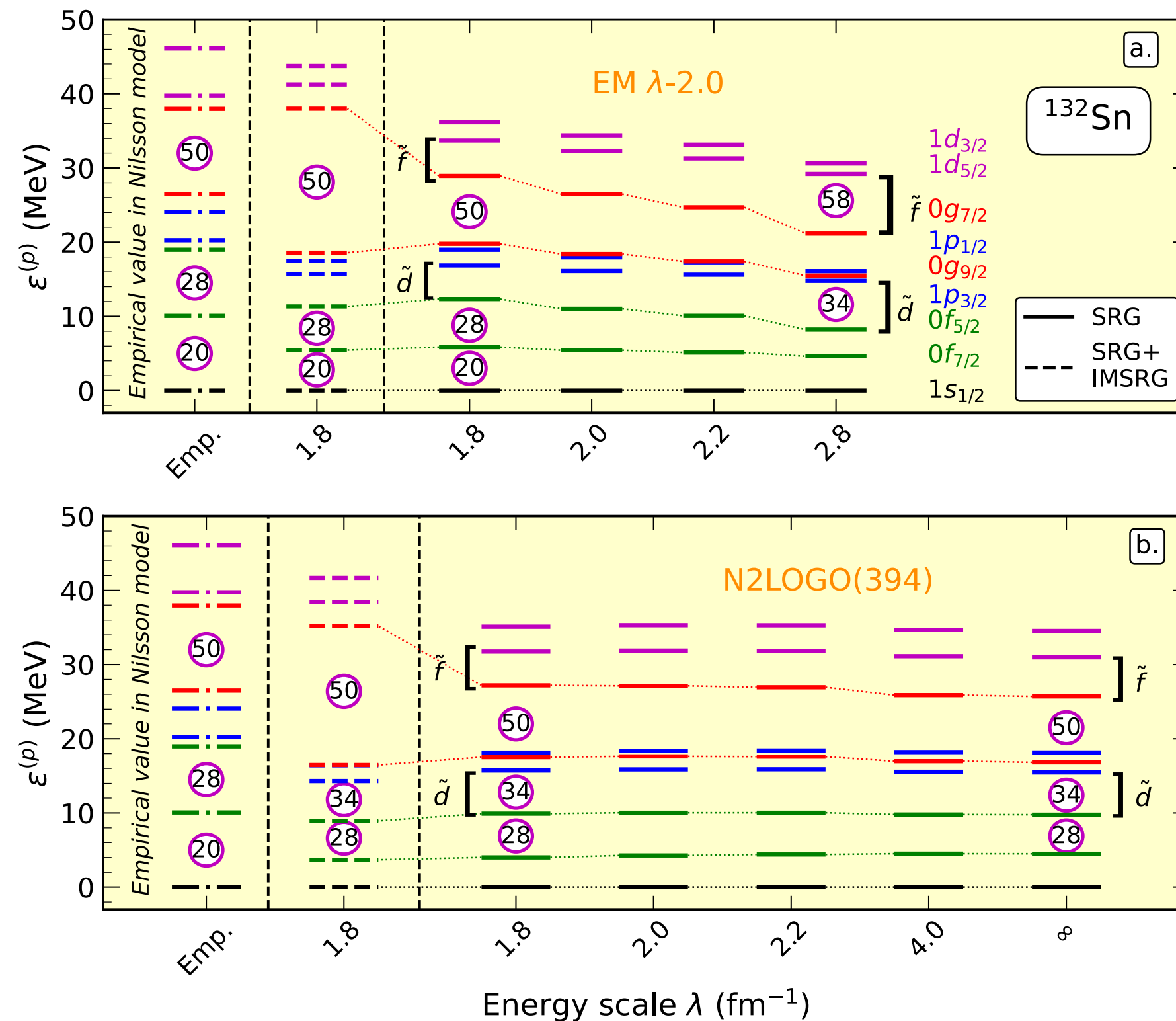
- **Mean-field / Shell model** is inherently a **low-momentum picture**
- empirical density functionals/ Shell model interactions are **“effective” parameterizations of low-resolution nuclear forces (+ correlations)**
- SRG + IMSRG can be used to **quantitatively bridge** high- and low-resolution descriptions of nuclear forces **and correlations**

Evolution of Effective Single-Particle Energies



- **low-resolution interactions** already exhibit much of the **expected features & symmetries** at the mean-field level
- behavior is **consistent** in **non-relativistic and relativistic** approaches

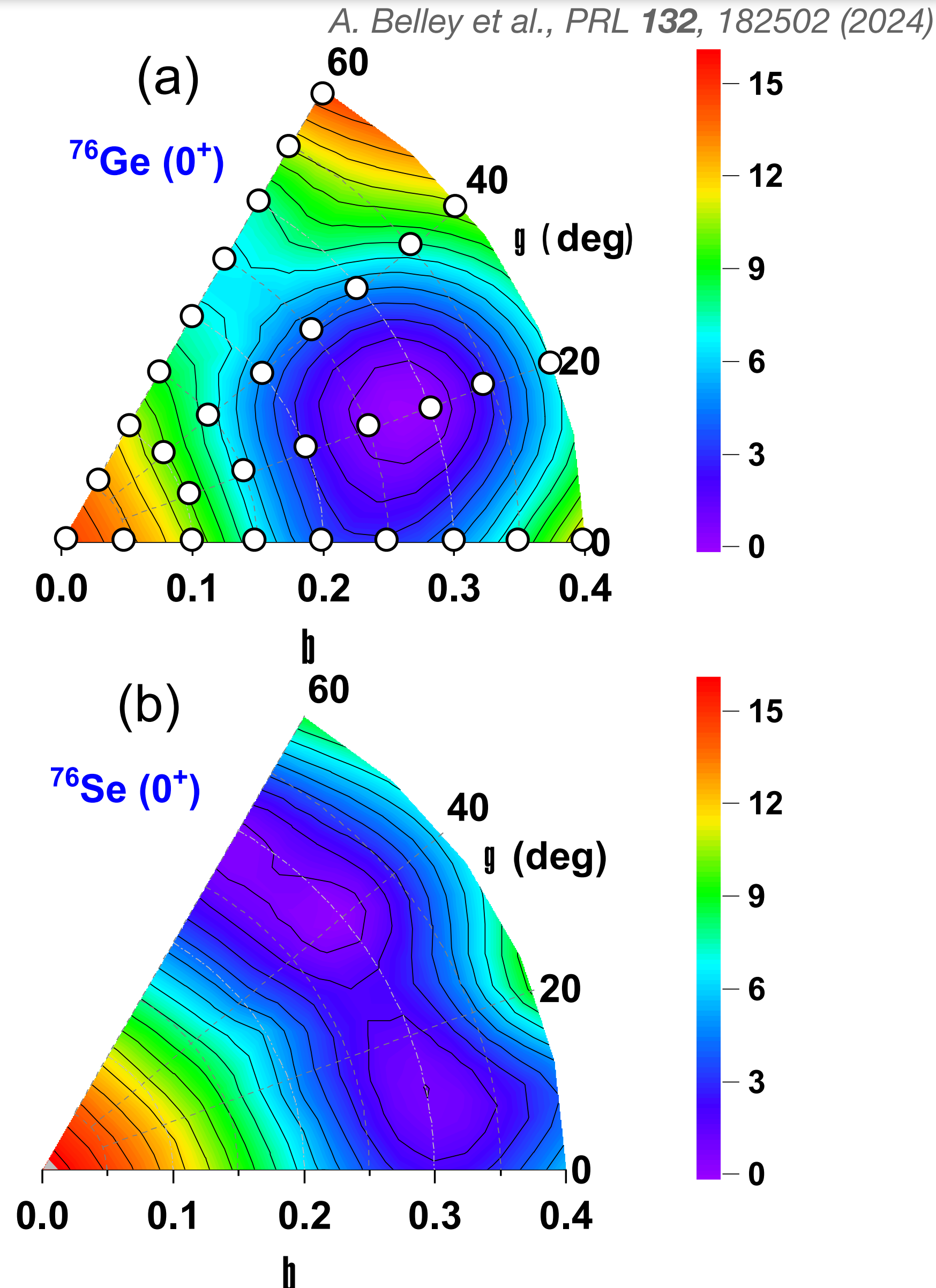
Evolution of Effective Single-Particle Energies



- **low-resolution interactions** already exhibit much of the **symmetries** at the mean-field level
- behavior is **consistent** in **non-relativistic** and **relativistic** frameworks

cf. g_A **quenching**,
[P. Gysbers et al., Nat. Phys. 15, 428]
emergence of rotational bands,
[M. Caprio et al., PLB 719, 179;
Z. H. Sun et al., PRX 15, 011028]
etc.

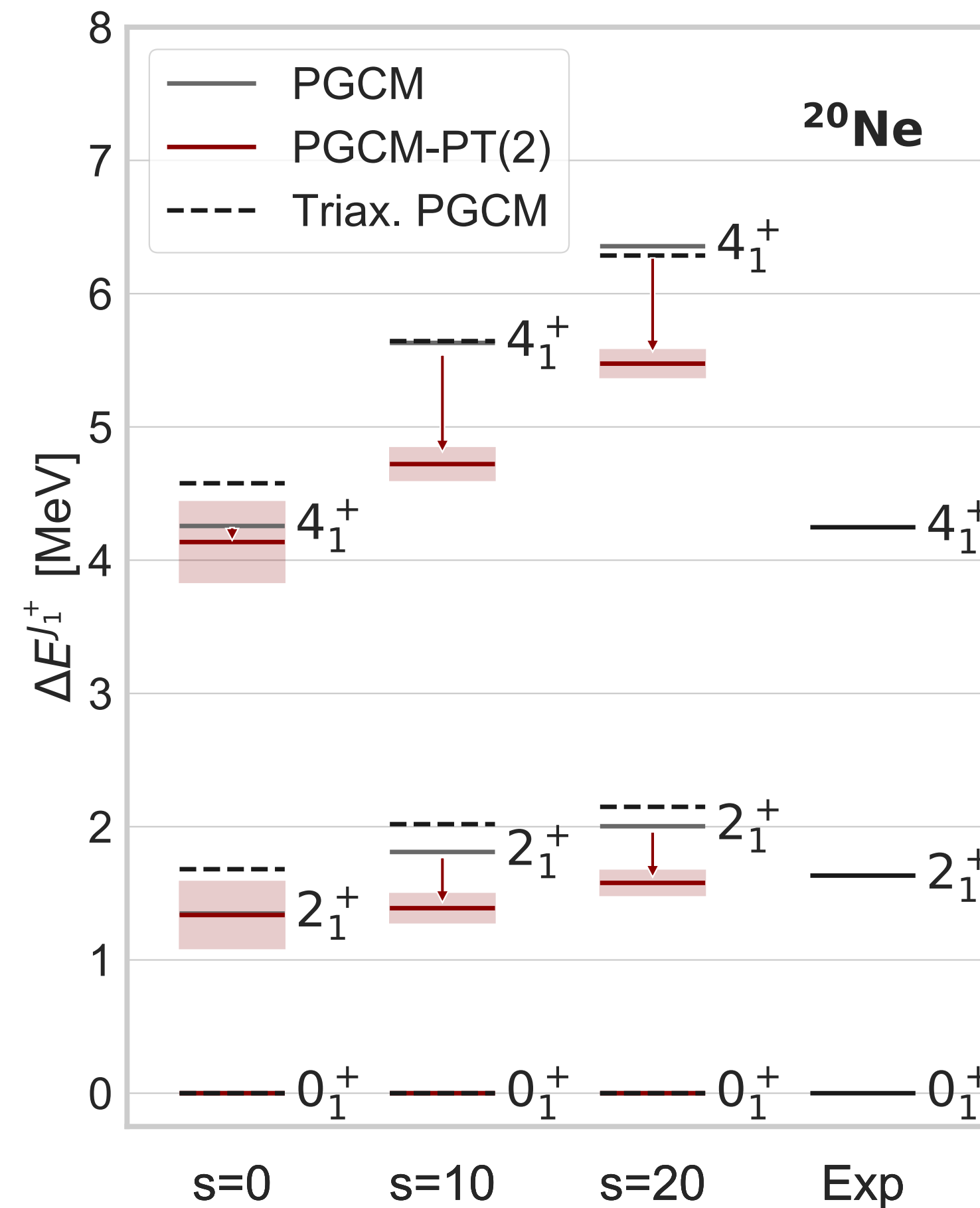
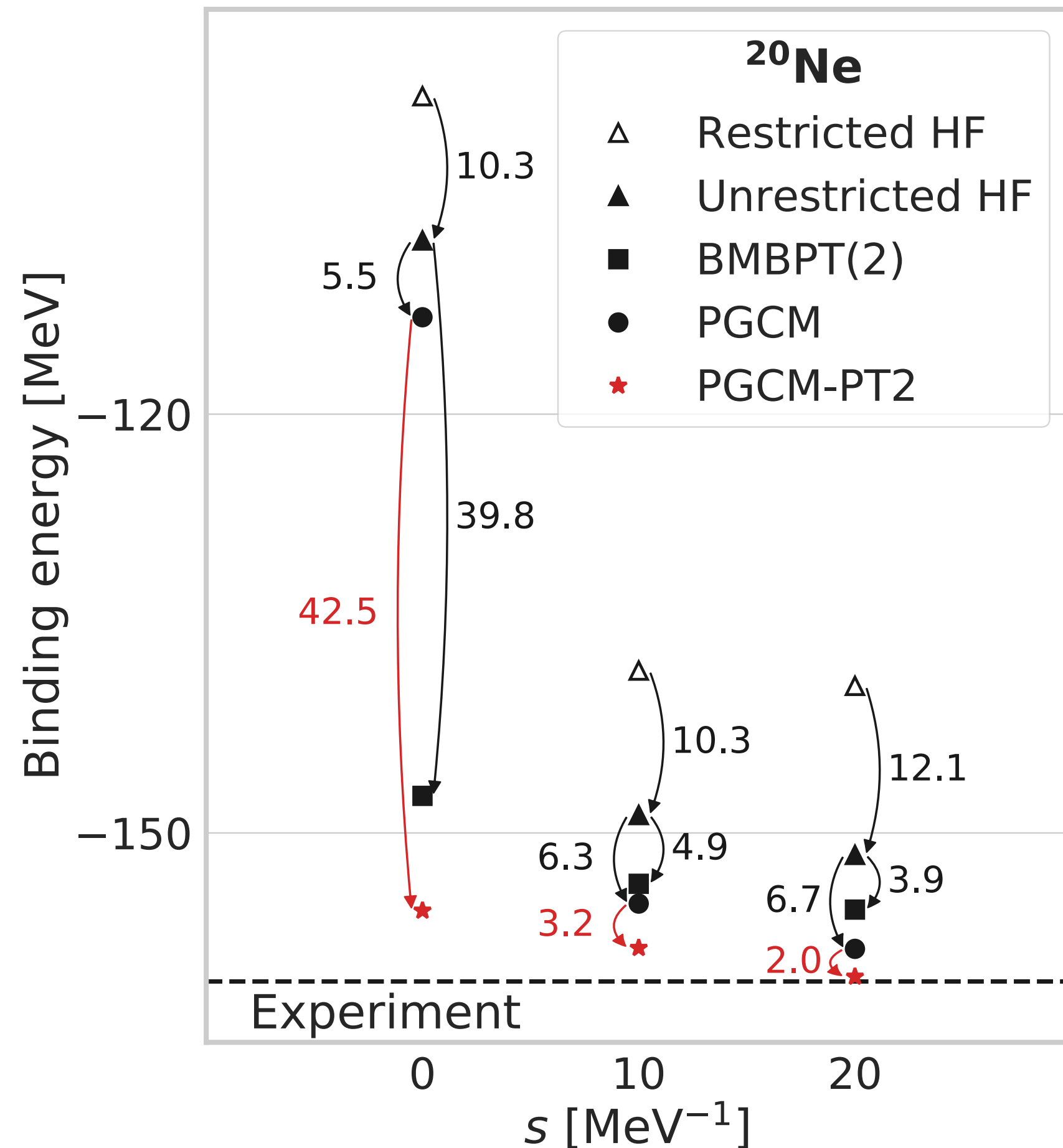
- **IMSRG evolution** ($O(\bar{N}^6)$, $\bar{N} \sim O(100)$, J-scheme)
- potential energy surface from **constrained (VAP)HFB** with IMSRG-evolved Hamiltonian
- **particle-number** and **angular momentum projection** for basis configurations
- solve **Hill-Wheeler-Griffin** equation (generalized EVP)
- GCM stage: $O(n_{\text{conf}}^2 \cdot n_{\text{AMP}} \cdot n_{\text{PNP}} \cdot N^4)$
 - $n_{\text{conf}} \sim 10 - 100$ configurations
 - $n_{\text{AMP}} \sim O(10^4)$ Euler angle sets / orientations
 - $n_{\text{PNP}} \sim O(10^2)$ gauge rotations
 - $N \sim O(1000)$ single-particle states (M-scheme)



- recall **GCM cost**: $O(n_{\text{conf}}^2 \cdot n_{\text{AMP}} \cdot n_{\text{PNP}} \cdot N^4)$
- GCM calculations (currently?) **limited to** $e_{\text{max}} \approx 8 - 10$, with $N = 660, 1144$ (**code scaling & compute time**)
- **idea**: can perform IMSRG evolution in larger basis, e.g., $e_{\text{max}} = 14$ ($N = 2720$) and apply evolved Hamiltonian in smaller basis
- usual MR-IMSRG decoupling simplifies structure of the Hamiltonian, but we could also try explicit adaptations to generator if necessary
- **would put s.p. basis size formally on par with VS-IMSRG**
- **~2 order of magnitude** savings if we can do bulk of IM-GCM calculations in $e_{\text{max}} \approx 6 - 8$ basis

Stay tuned!

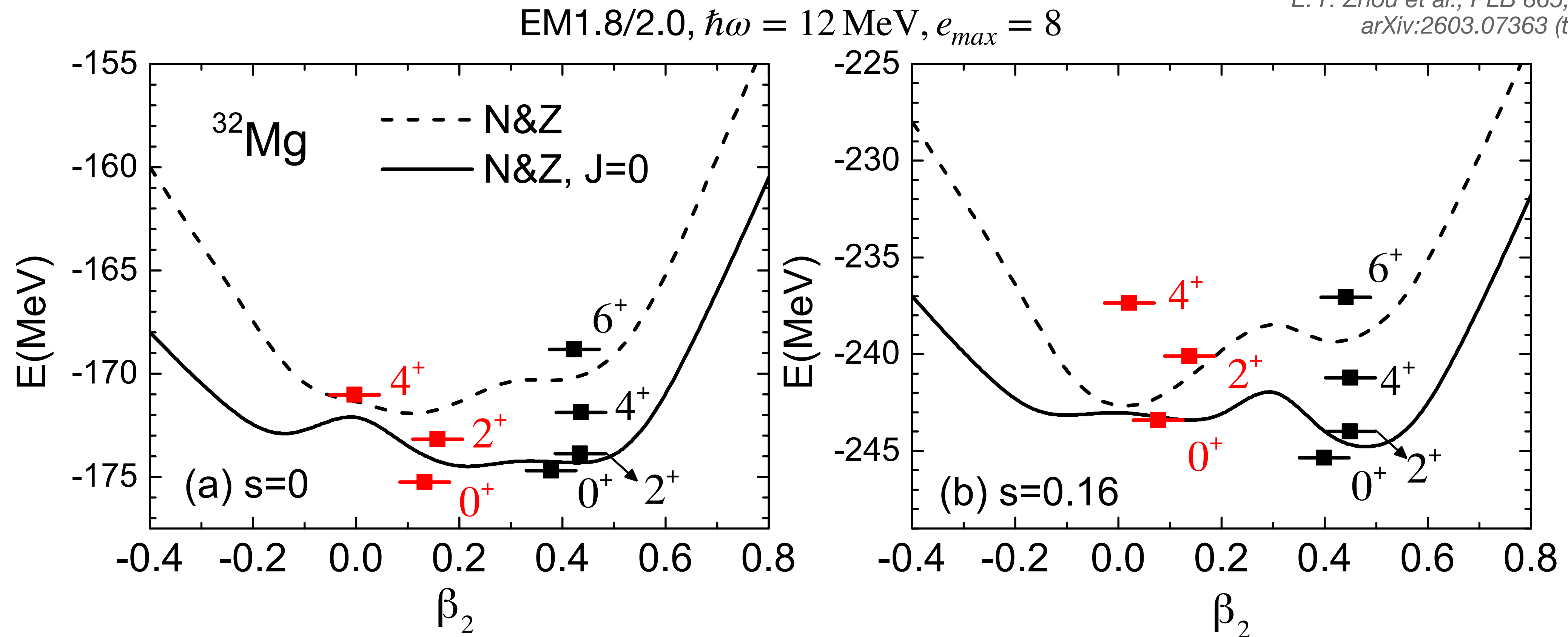
IM-GCM: Reshuffling of Correlations



- s-dependence is a **built-in diagnostic tool** for IM-GCM (**not available in phenomenological GCM**)
- if operator and wave function offer sufficient degrees of freedom, **evolution of observables is unitary**
- need **richer references and/or IMSRG(3)** for certain observables

Shape Coexistence: ^{32}Mg

*E. F. Zhou et al., PLB 865, 139464 (2025) &
arXiv:2603.07363 (to appear in PRC)*

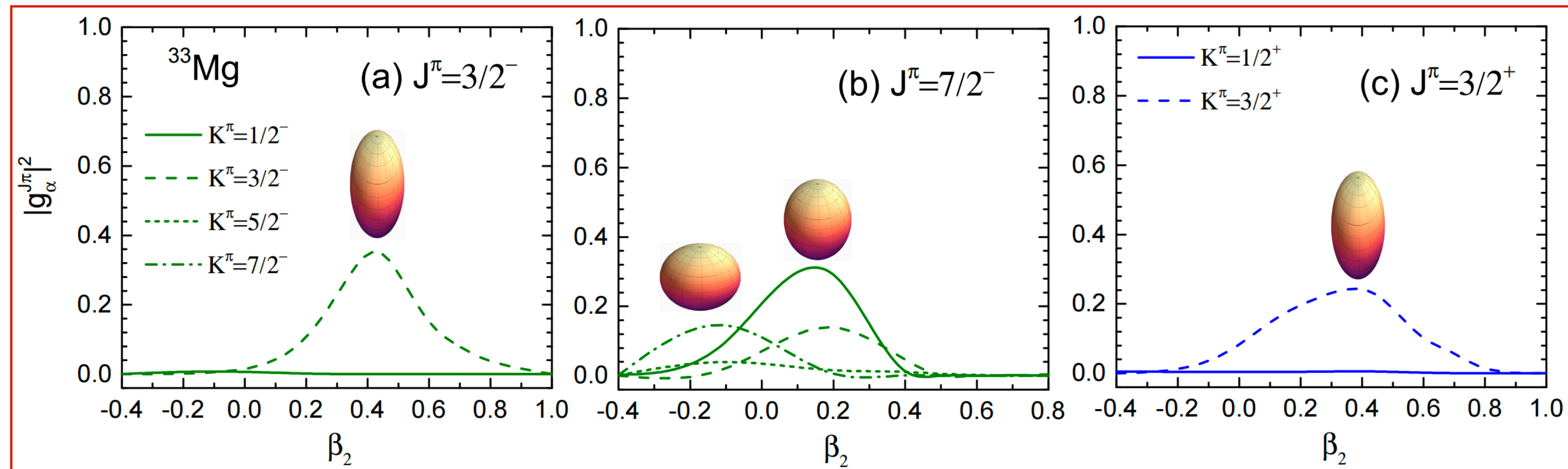
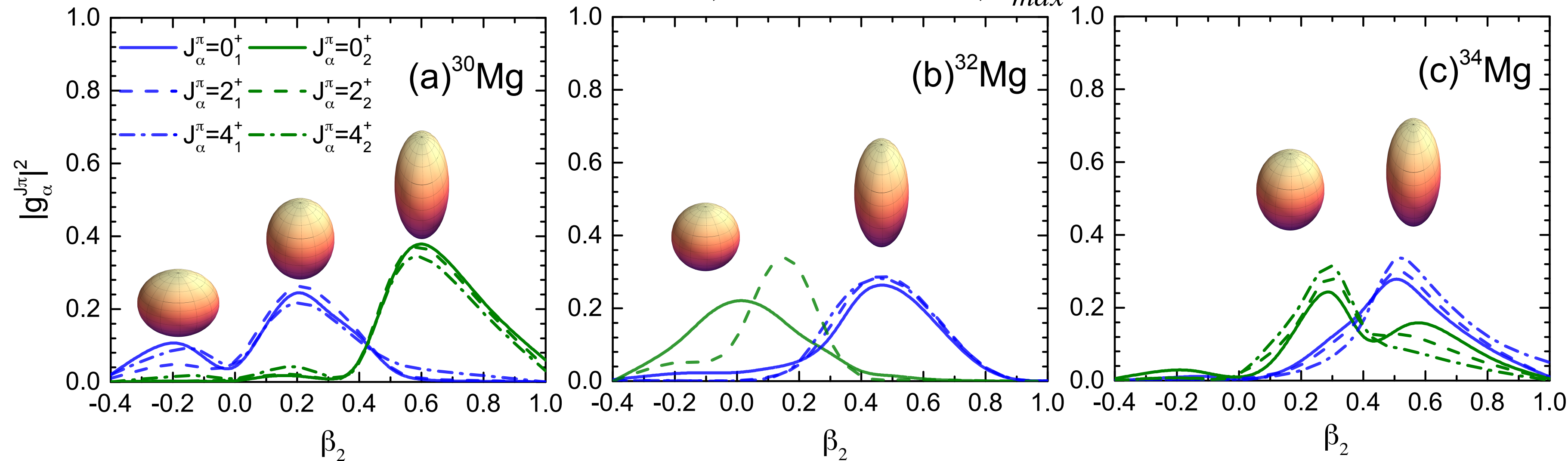


- **Dynamic correlations** captured by IMSRG...
- bring **absolute energies** close to experiment ($E = -249.7 \text{ MeV}$ (AME) vs. -249.5 MeV (extrapolated theory))
- reveal prominent **prolate deformation** of the **ground state**

N=20 Island of Inversion: $^{32-34}\text{Mg}$

EM1.8/2.0, $\hbar\omega = 12 \text{ MeV}$, $e_{\max} = 8$

E. F. Zhou et al., PLB 865, 139464 (2025) & arXiv:2603.07363 (to appear in PRC)

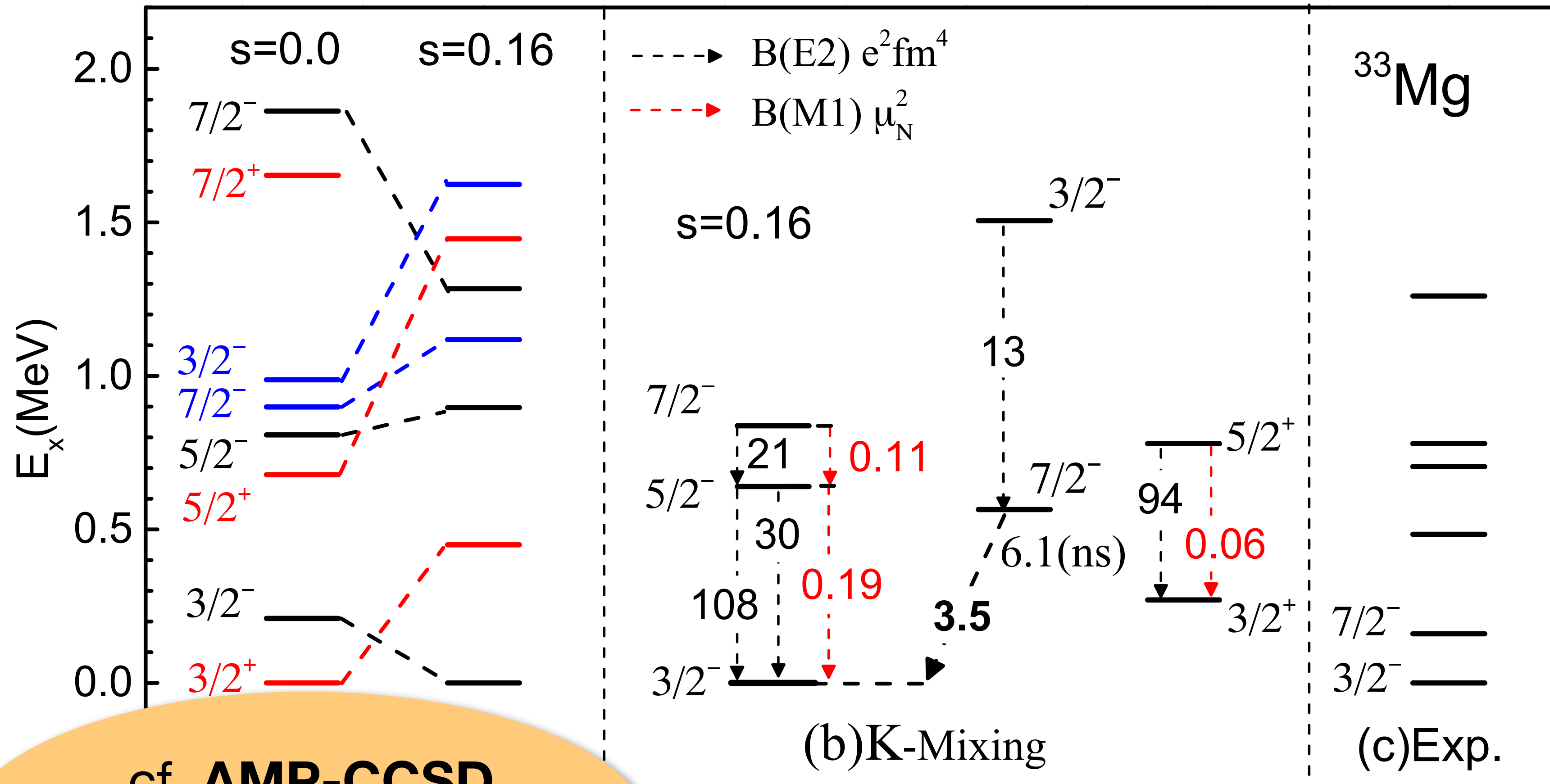


- **shape coexistence** comes with **shape mixing**
- **caveat:** (collective) wave functions are not observable - **compare with care!**

N=20 Island of Inversion: ^{33}Mg

E. F. Zhou et al., PLB 865, 139464 (2025) & arXiv:2603.07363 (to appear in PRC)

EM1.8/2.0, $\hbar\omega = 12 \text{ MeV}$, $e_{\text{max}} = 8$



- **shape and K mixing** have notable impact on ^{33}Mg spectrum
- **boosts** lifetime of $\frac{7}{2}^-$ state - **predicted to be a shape isomer**
- related to ^{32}Na shape isomer measured at FDSi in 2023 ?
[Gray et al., PRL 130, 132501]

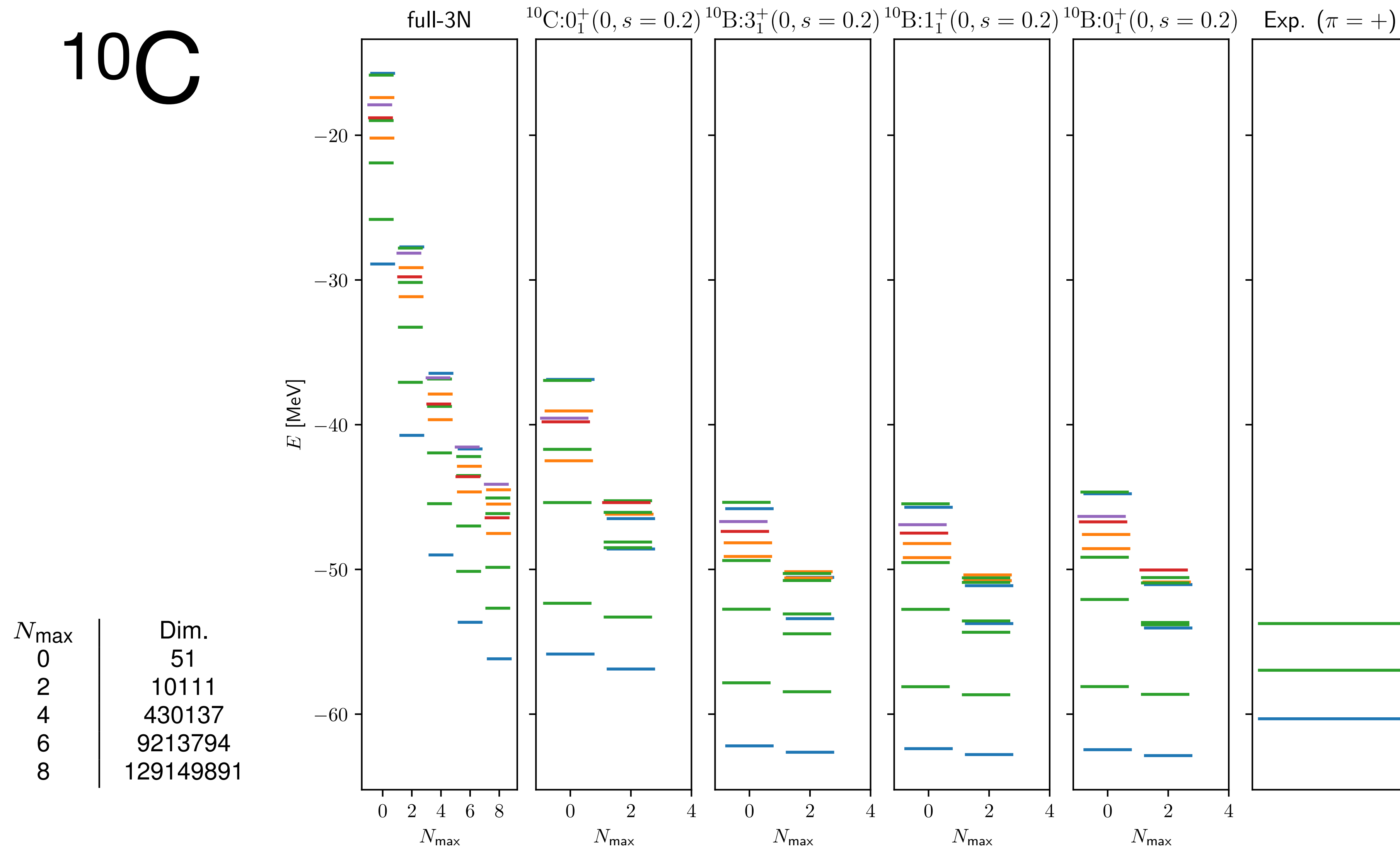
cf. **AMP-CCSD**

Z. H. Sun et al., arXiv:2409.02279 & PRX 15, 011028; G. Hagen et al., PRC 105, 064311

(IM-)NCSM for Super-Allowed Decays



^{10}C

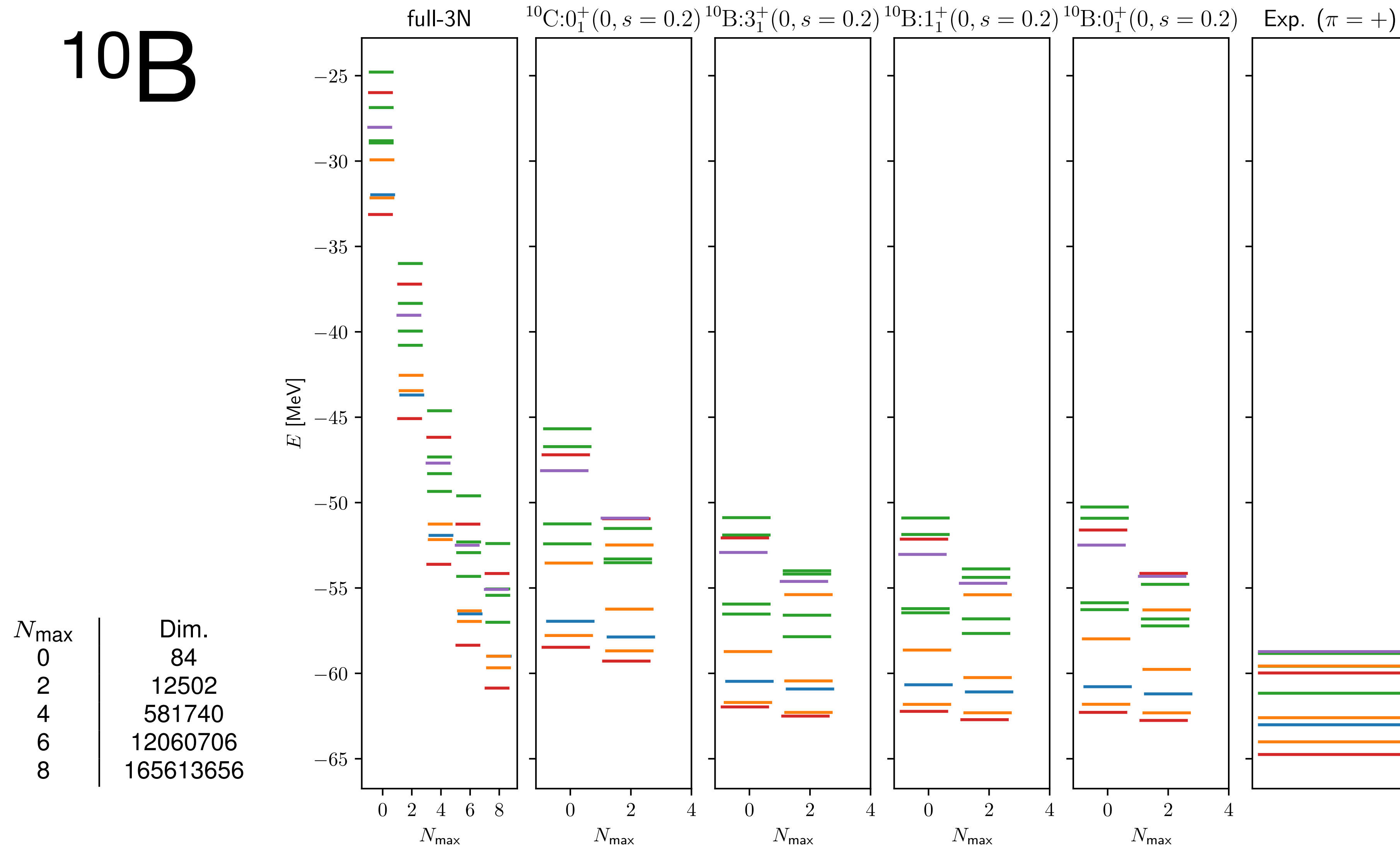


Eta: ImTime
Int: n4lo500-3NlnIE7
 $e_{\text{max}} = 8$
 $\hbar\Omega = 18\text{MeV}$

(IM-)NCSM for Super-Allowed Decays



^{10}B



Eta: ImTime
Int: n4lo500-3NlnIE7
 $e_{\text{max}} = 8$
 $\hbar\Omega = 18\text{MeV}$

Super-Allowed Beta Decays



- **Super-allowed beta decays constrain $|V_{ud}|$ in the CKM matrix**
- **Precision treatment requires radiative corrections** that are sensitive to **nuclear structure**: δ_C and δ_{NS}
- *ab initio* calculations of $A = 10, 14$ decays in **light nuclei** using NCSM and QMC [Gennari et al., PRL 134, 012501; Cirigliano et al., PRC 110, 055502; King et al., arXiv:2509.07310]
- use **IM-NCSM** to extend mass range ^{22}Mg , ^{26m}Al , ...
- benchmarks for CC, IM-GCM, VS-IMSRG, ...
- test exact sum over intermediate states vs. new EFT approach

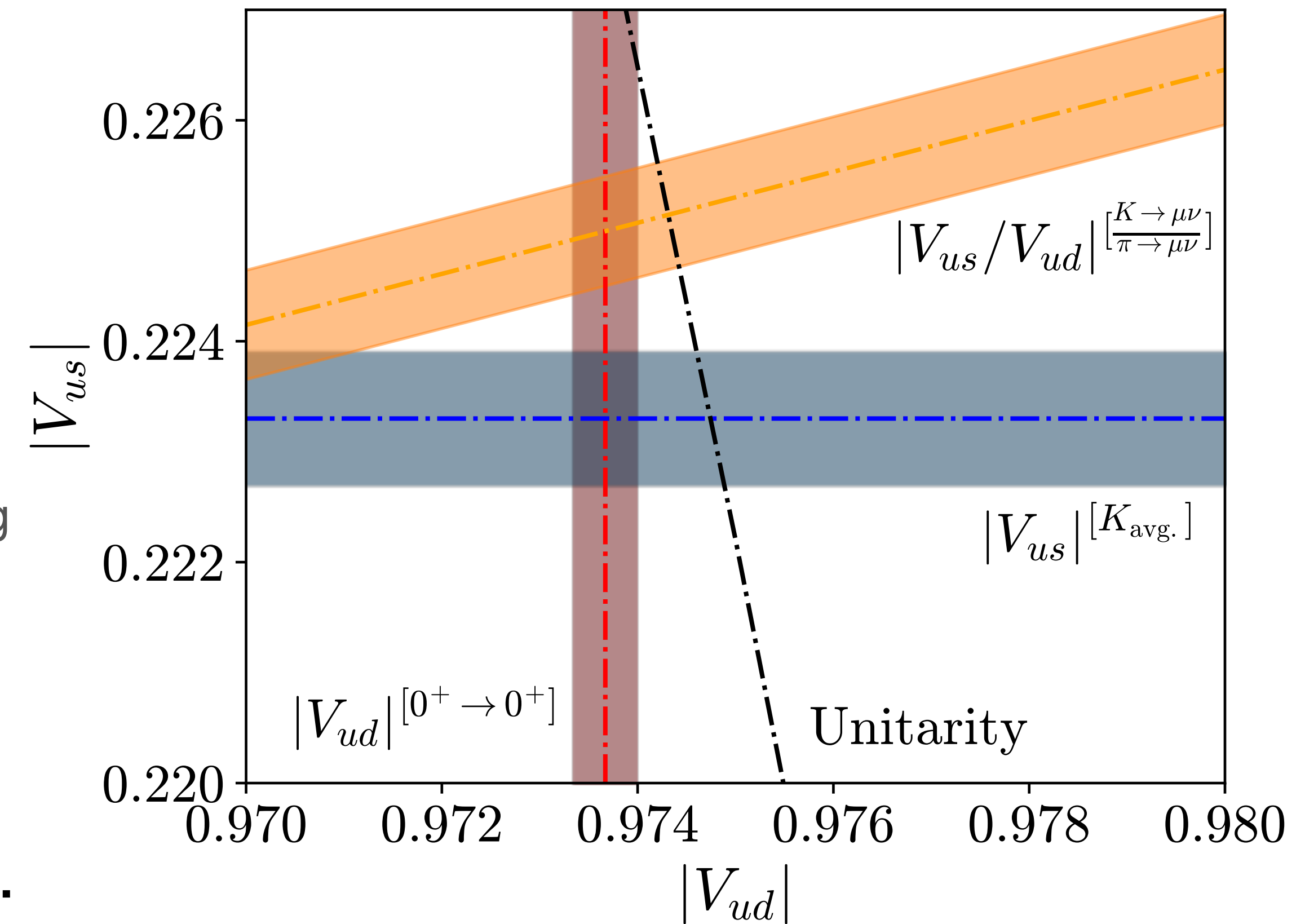


image credit: M. Gennari

- describe “excited” states based on reference state $|\Phi_k\rangle = Q_k^\dagger |\Phi_0\rangle$
- **(MR-)IMSRG effective Hamiltonian** in EOM approach:

$$[H(s), Q_k^\dagger(s)] |\Phi_0\rangle = \omega_k(s) Q_k^\dagger(s) |\Phi_0\rangle, \quad \omega_k(s) \equiv E_k(s) - E_0(s)$$

- **approximations** make $\omega_k(s)$ **s-dependent**
- ansätze for excitation operators (**g.s. correlations built into Hamiltonian**):

$$Q_k^\dagger(s) = \sum_{pq} (Q^{(k)})_{pq}(s) : a_p^\dagger a_q : + \frac{1}{4} \sum_{pqrs} (Q^{(k)})_{pqrs}(s) : a_p^\dagger a_q^\dagger a_s a_r : + \dots$$

$$Q_k^\dagger(s) = \sum_p (Q_k^{(k)})_p(s) : a_p^\dagger : + \frac{1}{4} \sum_{pqr} (Q^{(k)})_{pqr}(s) : a_p^\dagger a_q^\dagger a_r : + \dots$$

- **polynomial** effort, commutator formulation **identical to flow equations**