Progress in *Ab Initio* Nuclear Theory for Neutrinoless Double Beta Decay

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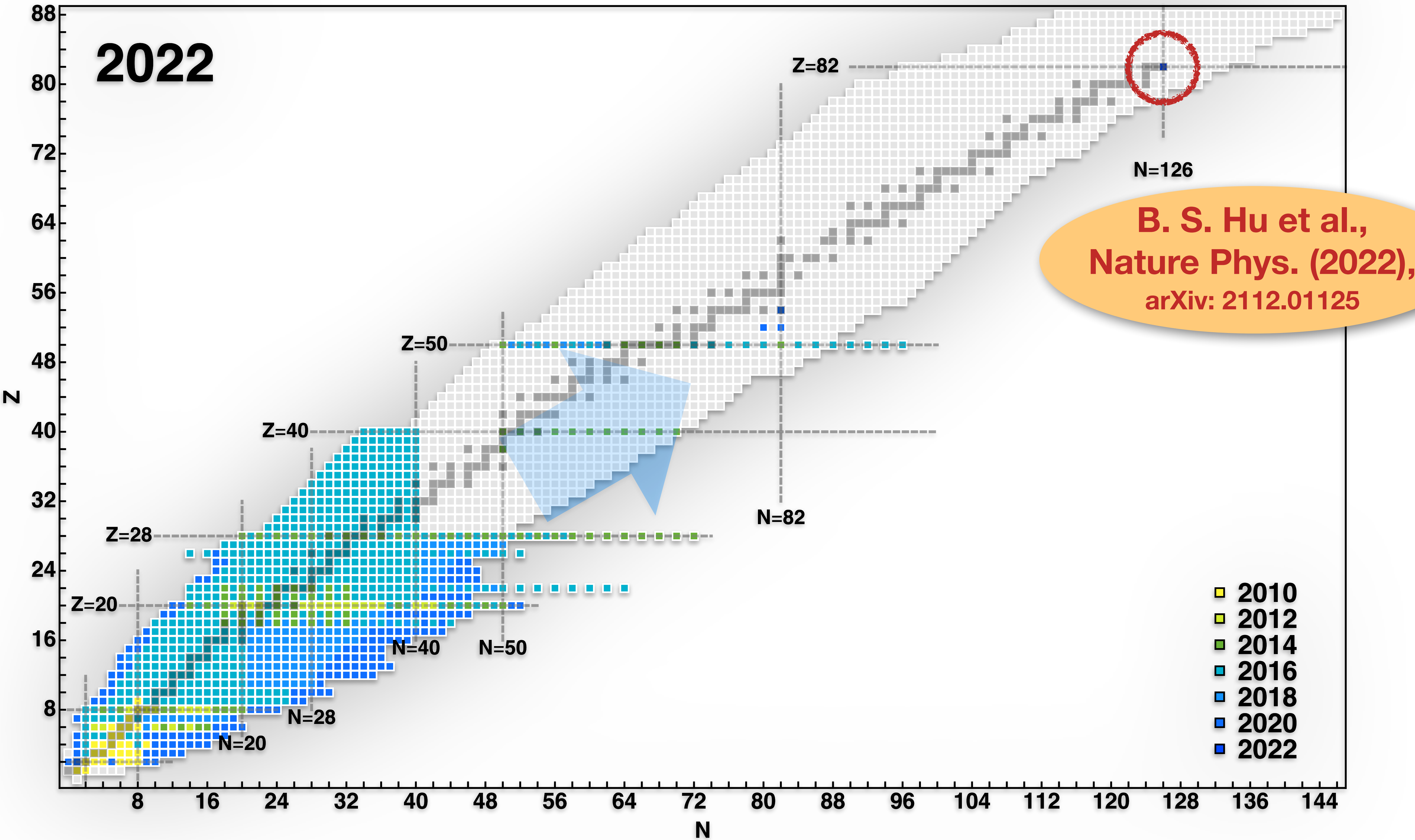
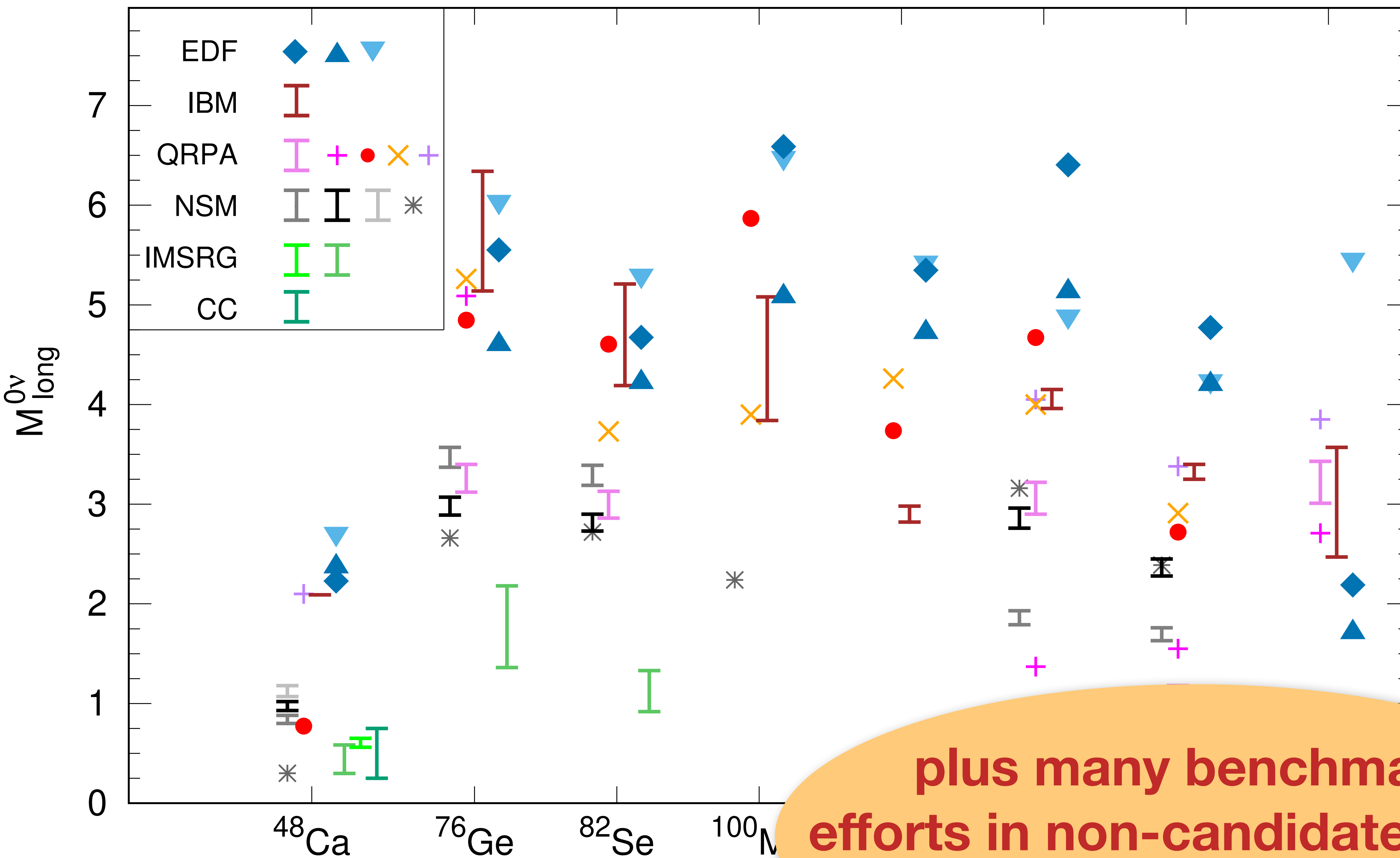
Progress in *Ab Initio* Calculations

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



Nuclear Matrix Elements: Status

M. Agostini et al., to appear in RMP, arXiv: 2202.01787



plus many benchmark efforts in non-candidate nuclei with NCSM, QMC, …

(Multi-Reference) In-Medium Similarity Renormalization Group

HH, Phys. Scripta **92**, 023002 (2017)

HH, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tuskiyama, Phys. Rept. **621**, 165 (2016)

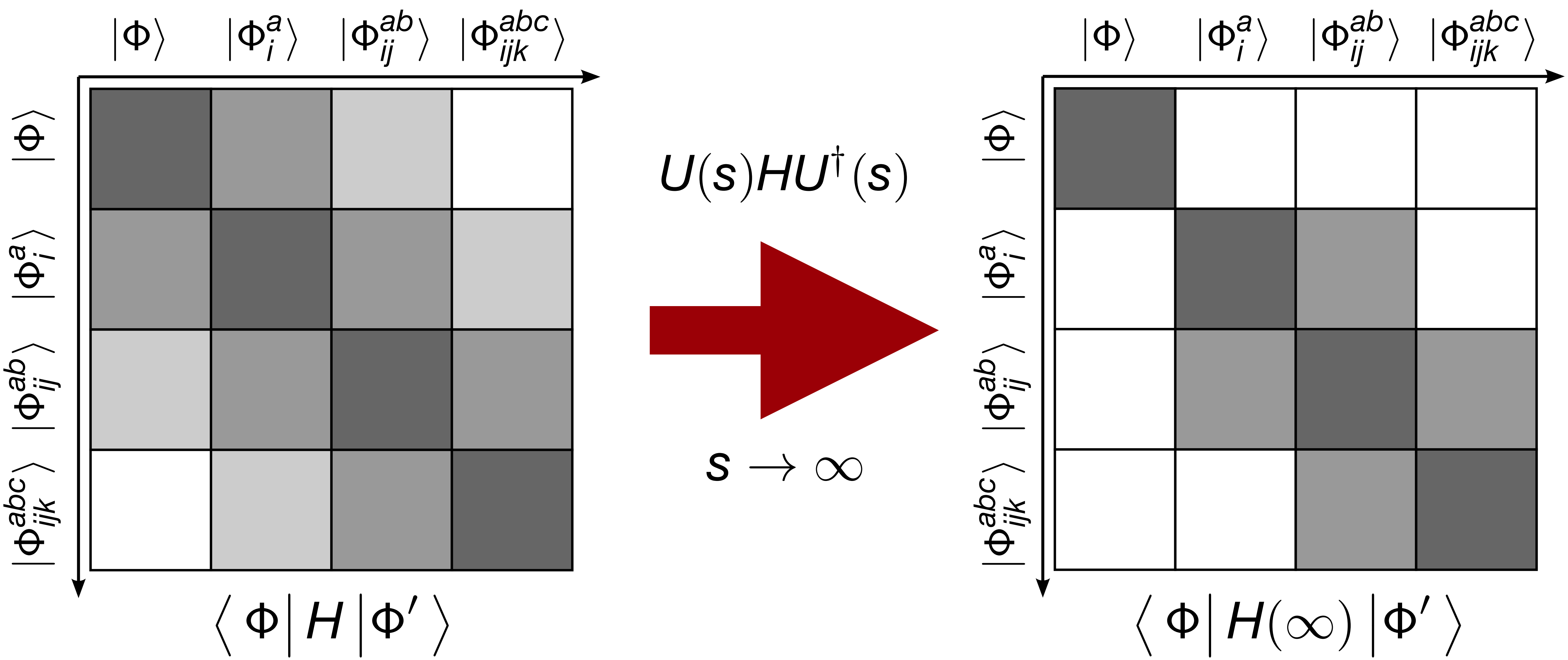
HH, S. K. Bogner, T. Morris, S. Binder, A. Calci, J. Langhammer, R. Roth, Phys. Rev. C **90**, 041302 (2014)

HH, S. Binder, A. Calci, J. Langhammer, and R. Roth, Phys. Rev. Lett **110**, 242501 (2013)

K. Tsukiyama, S. K. Bogner, A. Schwenk, PRL **106**, 222502 (2011)

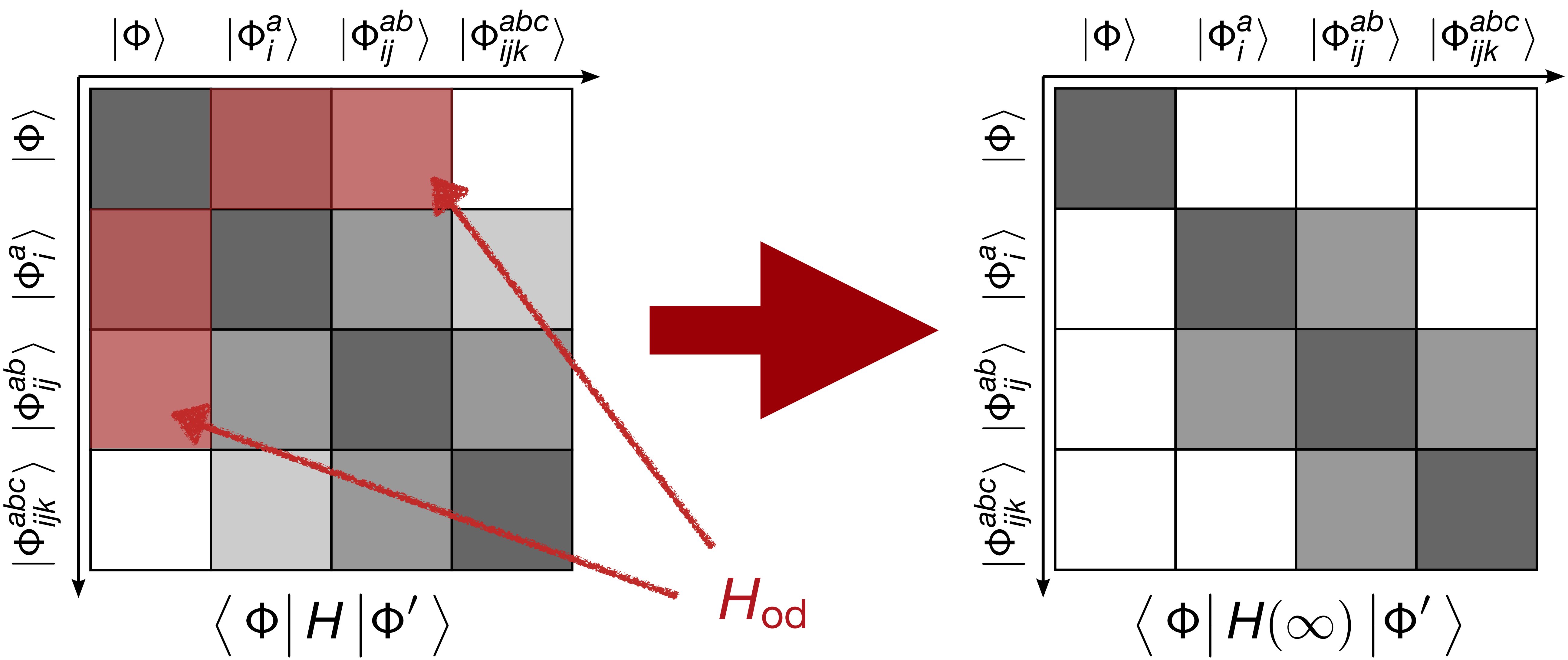
S. K. Bogner, R. J. Furnstahl, and A. Schwenk, Prog. Part. Nucl. Phys. **65**, 94

Decoupling in A-Body Space



goal: decouple reference state $|\Phi\rangle$ from excitations

Flow Equation

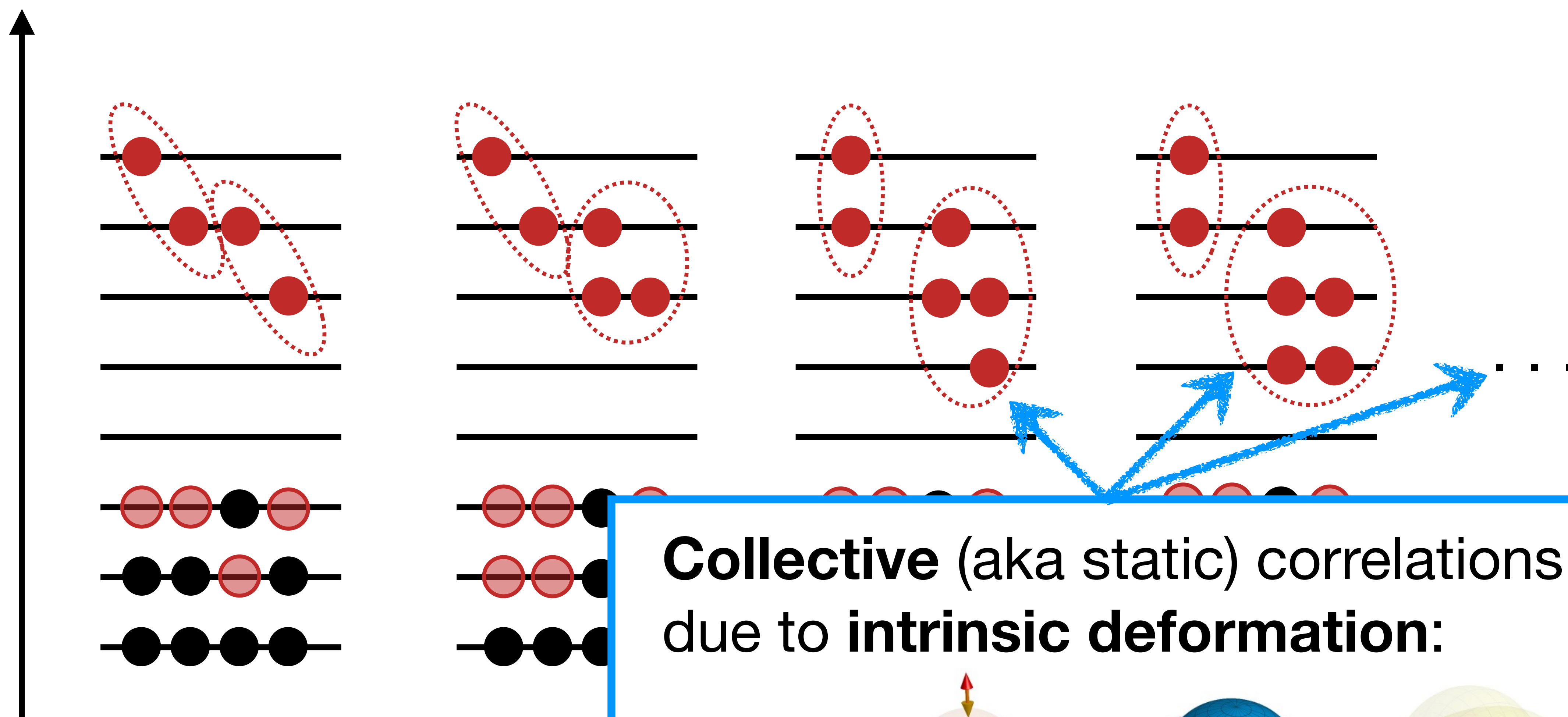


$$\frac{d}{ds}H(s) = [\eta(s), H(s)],$$

Operators
truncated at **two-body level** -
matrix is never constructed explicitly!

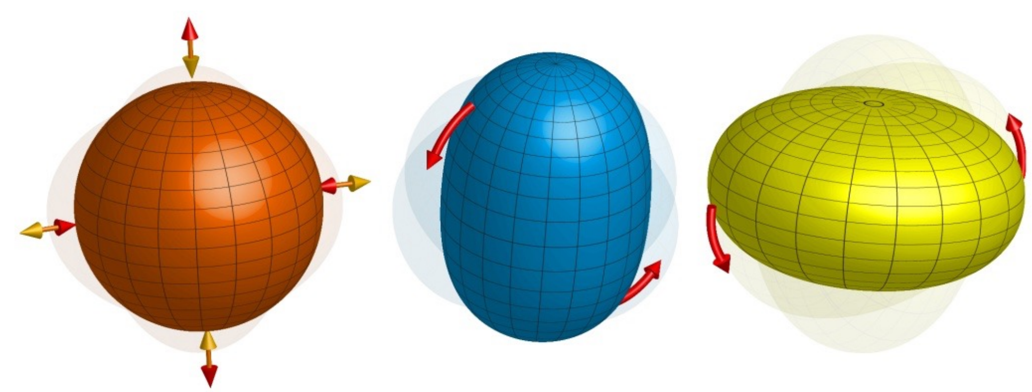
Correlated Reference States

IMSRG(2) IMSRG(3) IMSRG(4) IMSRG(5)

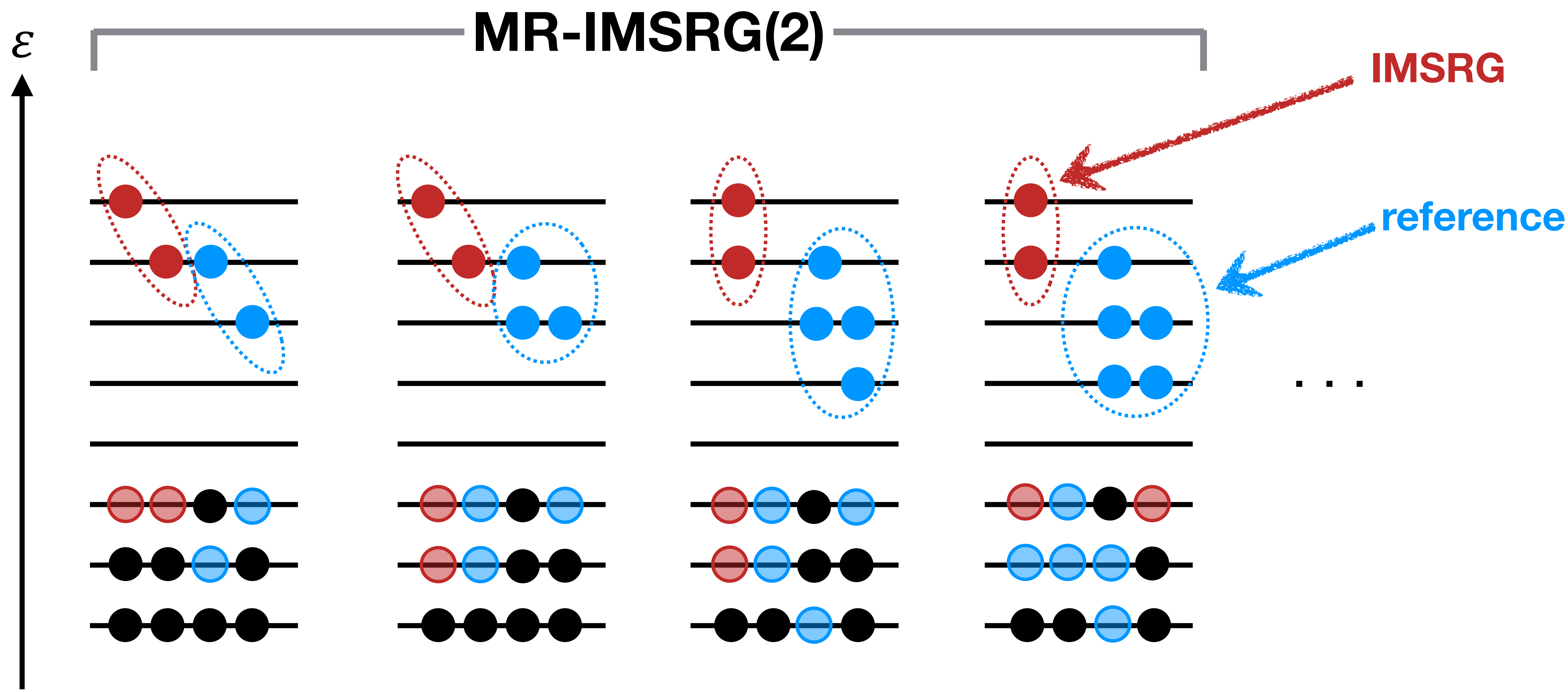


“standard” IMS
Slater determinan

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

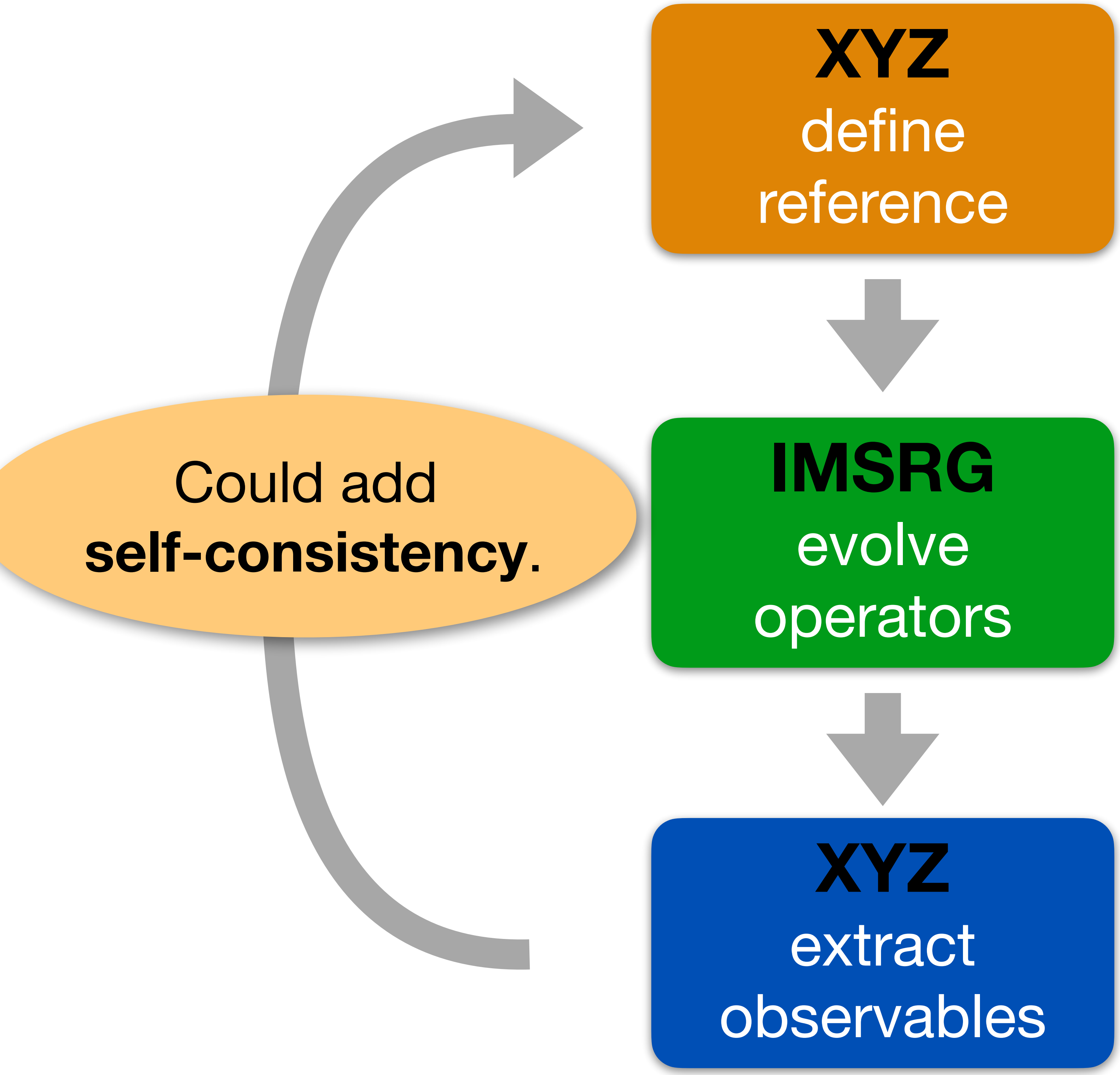


Correlated Reference States



MR-IMSRG: build correlations on top of **already correlated** state (e.g., from a method that describes static correlation well)

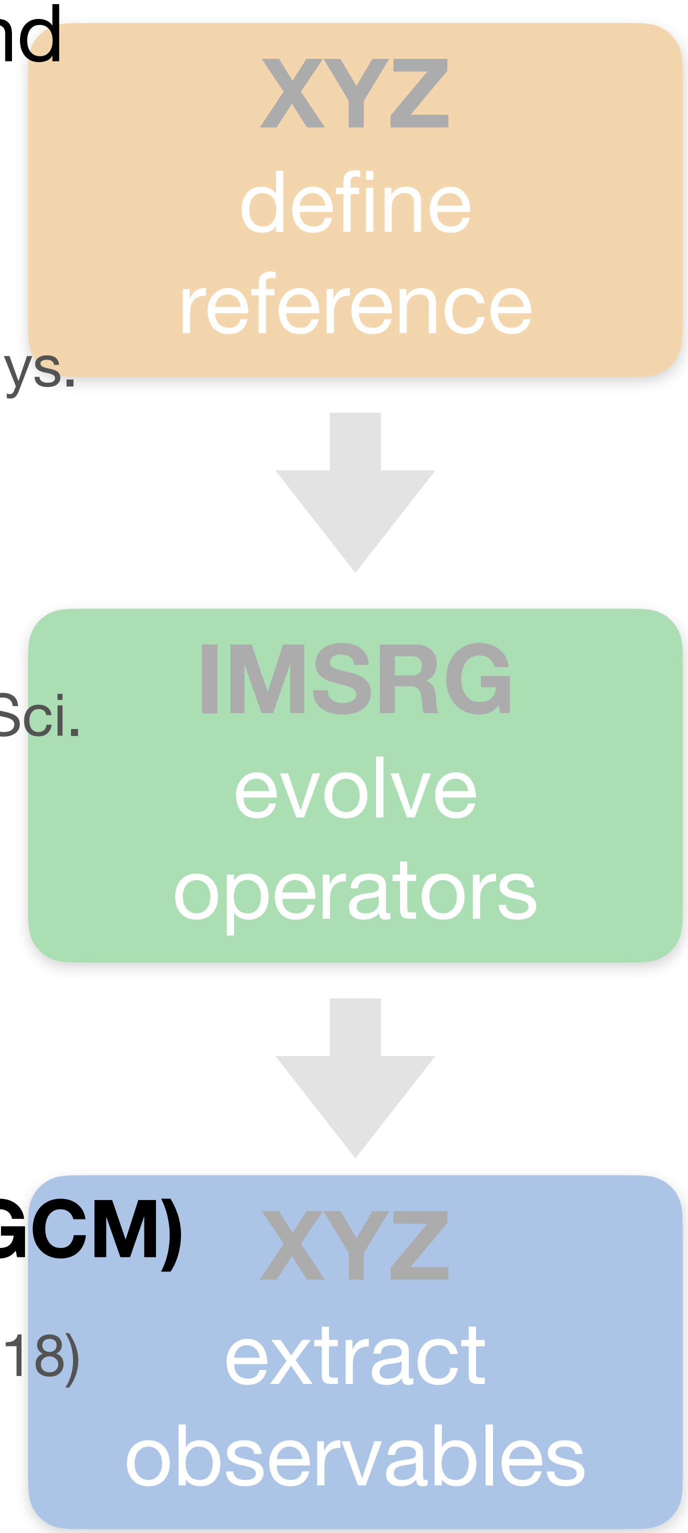
IMSRG-Improved Methods



* mean field or
explicitly correlated

IMSRG-Improved Methods

- IMSRG for closed and open-shell nuclei: IM-HF and IM-PHFB
  - HH, Phys. Scripta, Phys. Scripta 92, 023002 (2017)
  - HH, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tuskiyama, Phys. Rept. 621, 165 (2016)
- **Valence-Space IMSRG (VS-IMSRG)**
  - S. R. Stroberg, HH, S. K. Bogner, J. D. Holt, Ann. Rev. Nucl. Part. Sci. **69**, 165
- In-Medium No Core Shell Model (IM-NCSM)
  - E. Gebrerufael, K. Vobig, HH, R. Roth, PRL **118**, 152503
- **In-Medium Generator Coordinate Method (IM-GCM)**
  - J. M. Yao, J. Engel, L. J. Wang, C. F. Jiao, HH PRC 98, 054311 (2018)
  - J. M. Yao et al., PRL 124, 232501 (2020)



Merging IMSRG and CI: Valence-Space IMSRG

Review:

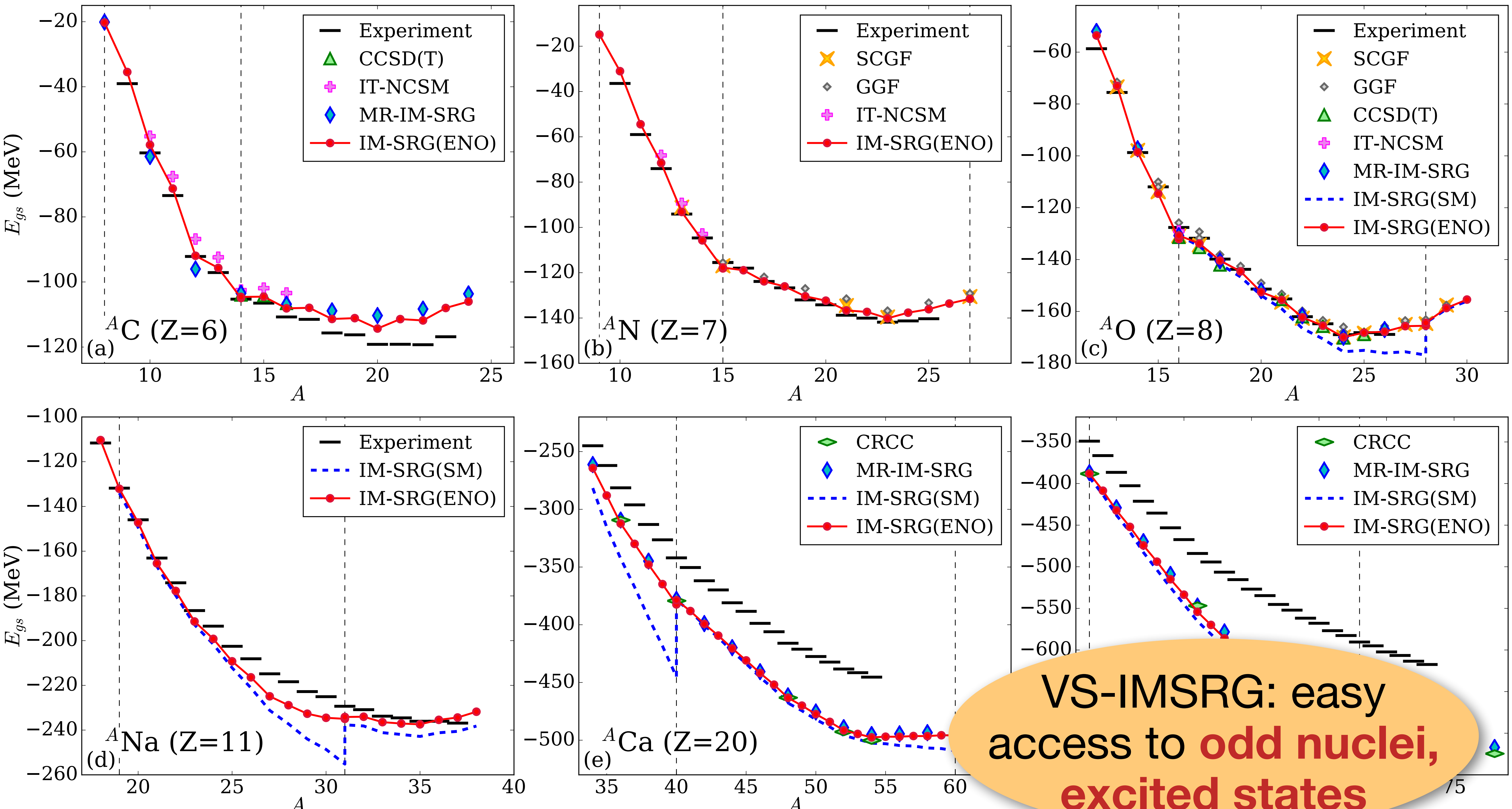
S. R. Stroberg, HH, S. K. Bogner, and J. D. Holt, Ann. Rev. Part. Nucl. Sci. **69**, 165 (2019)

Full CI:

E. Gebrerufael, K. Vobig, HH, and R. Roth, Phys. Rev. Lett. **118**, 152503 (2017)

Ground-State Energies

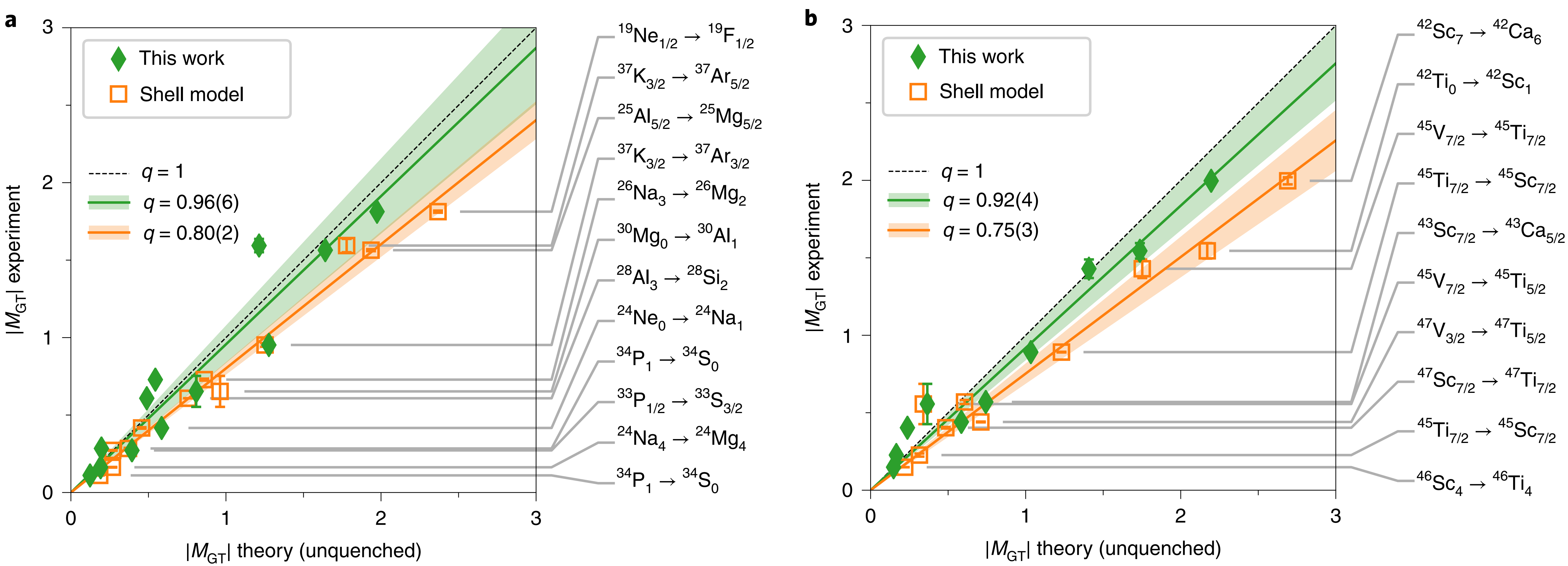
S. R. Stroberg, A. Calci, HH, J. D. Holt, S. K.Bogner, R. Roth, A. Schwenk, PRL **118**, 032502 (2017)
S. R. Stroberg, HH, S. K. Bogner, J. D. Holt, Ann. Rev. Part. Nucl. Sci. **69**, 307 (2019)



VS-IMSRG: easy access to **odd nuclei, excited states**

Quenching of Gamow-Teller Decays

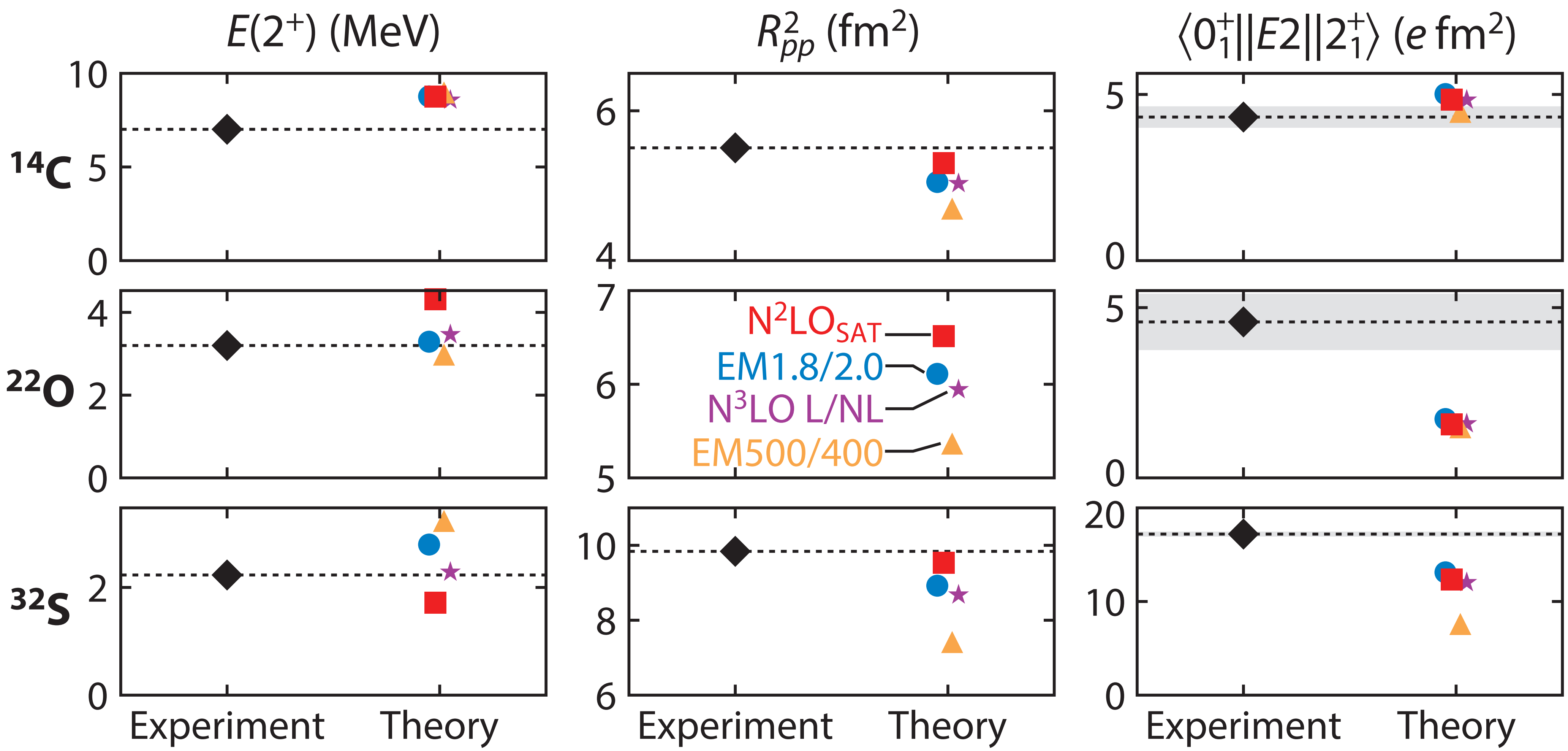
P. Gysbers et al., Nature Physics ***15****, 428 (2019)*



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

Transitions

S. R. Stroberg, HH, S. K. Bogner, J. D. Holt, Ann. Rev. Part. Nucl. Sci. **69**, 307 (2019)
N. M. Parzuchowski, S. R. Stroberg et al., PRC **96**, 034324 (2017)
S. R. Stroberg et al. PRC **105**, 034333 (2022)



- **B(E2) much too small:** missing collectivity due to intermediate 3p3h, … states that are truncated in IMSRG evolution (**static correlation**)

Capturing Collective Correlations: In-Medium Generator Coordinate Method

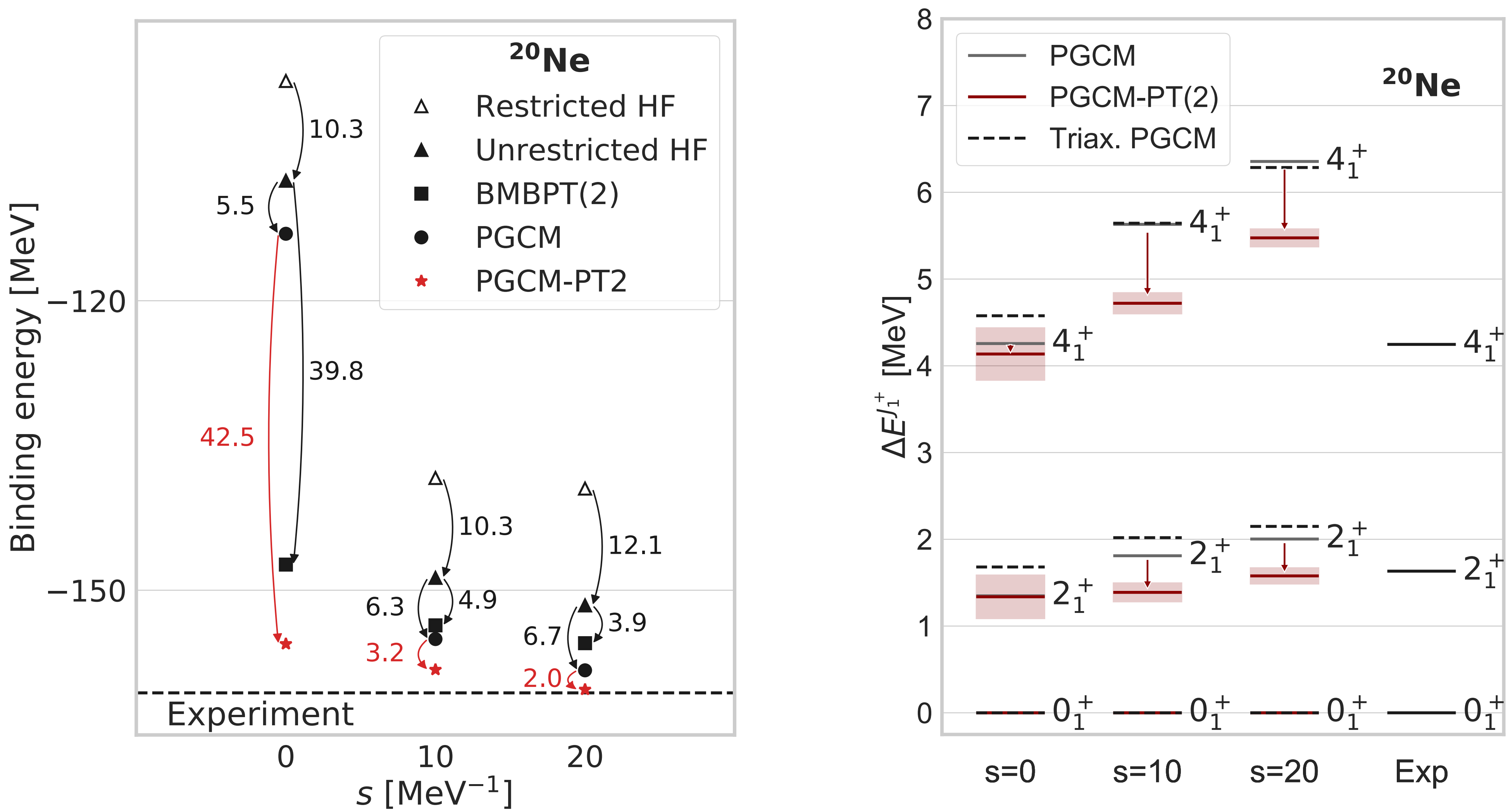
J. M. Yao, A. Belley, R. Wirth, T. Miyagi, C. G. Payne, S. R. Stroberg, HH, J. D. Holt, PRC **103**, 014315 (2021)

J. M. Yao, B. Bally, J. Engel, R. Wirth, T. R. Rodriguez, HH, PRL **124**, 232501 (2020)

J. M. Yao, J. Engel, L. J. Wang, C. F. Jiao, HH, PRC **98**, 054311 (2018)

Perturbative Enhancement of IM-GCM

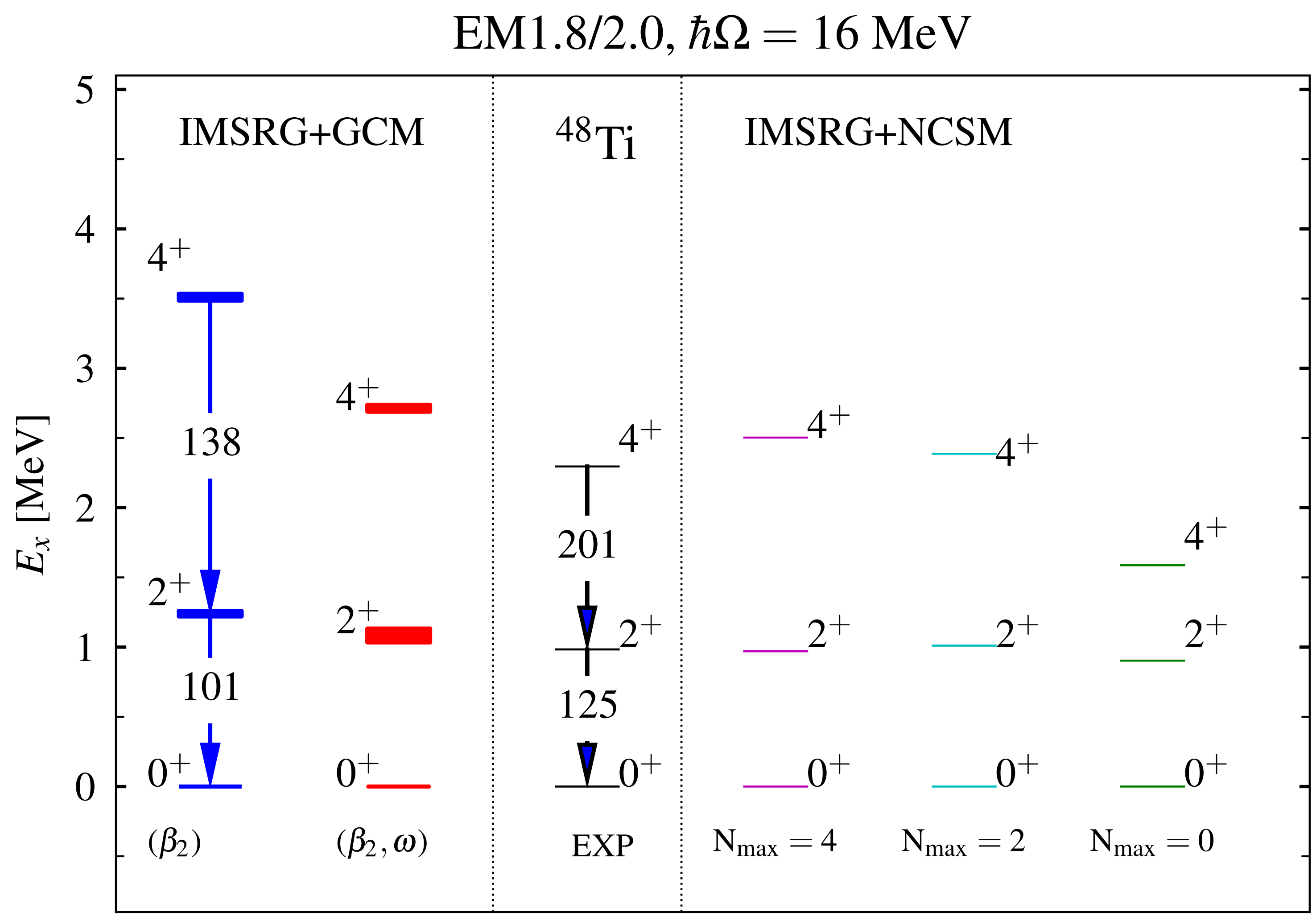
M. Frosini et al., EPJA ***58****, 64 (2022)*



- 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

IM-GCM: $0\nu\beta\beta$ Decay of ^{48}Ca

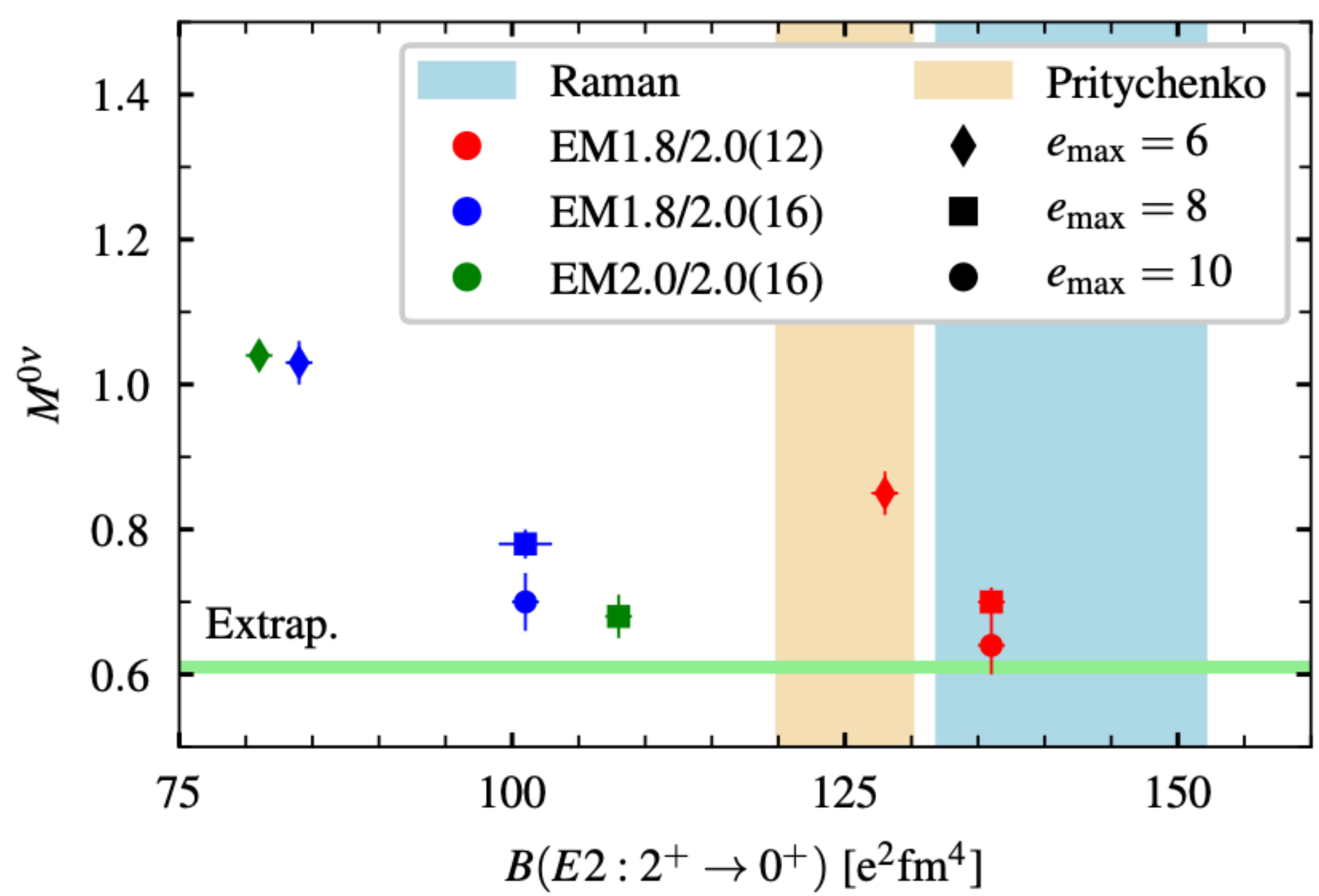
*J. M. Yao et al., PRL **124**, 232501 (2020); HH, Front. Phys. **8**, 379 (2020)*



- richer GCM state through **cranking**
- **consistency** between IM-GCM and IM-NCSM

$0\nu\beta\beta$ Decay of ^{48}Ca

J. M. Yao et al., PRL **124**, 232501 (2020); PRC **103**, 014315 (2021)

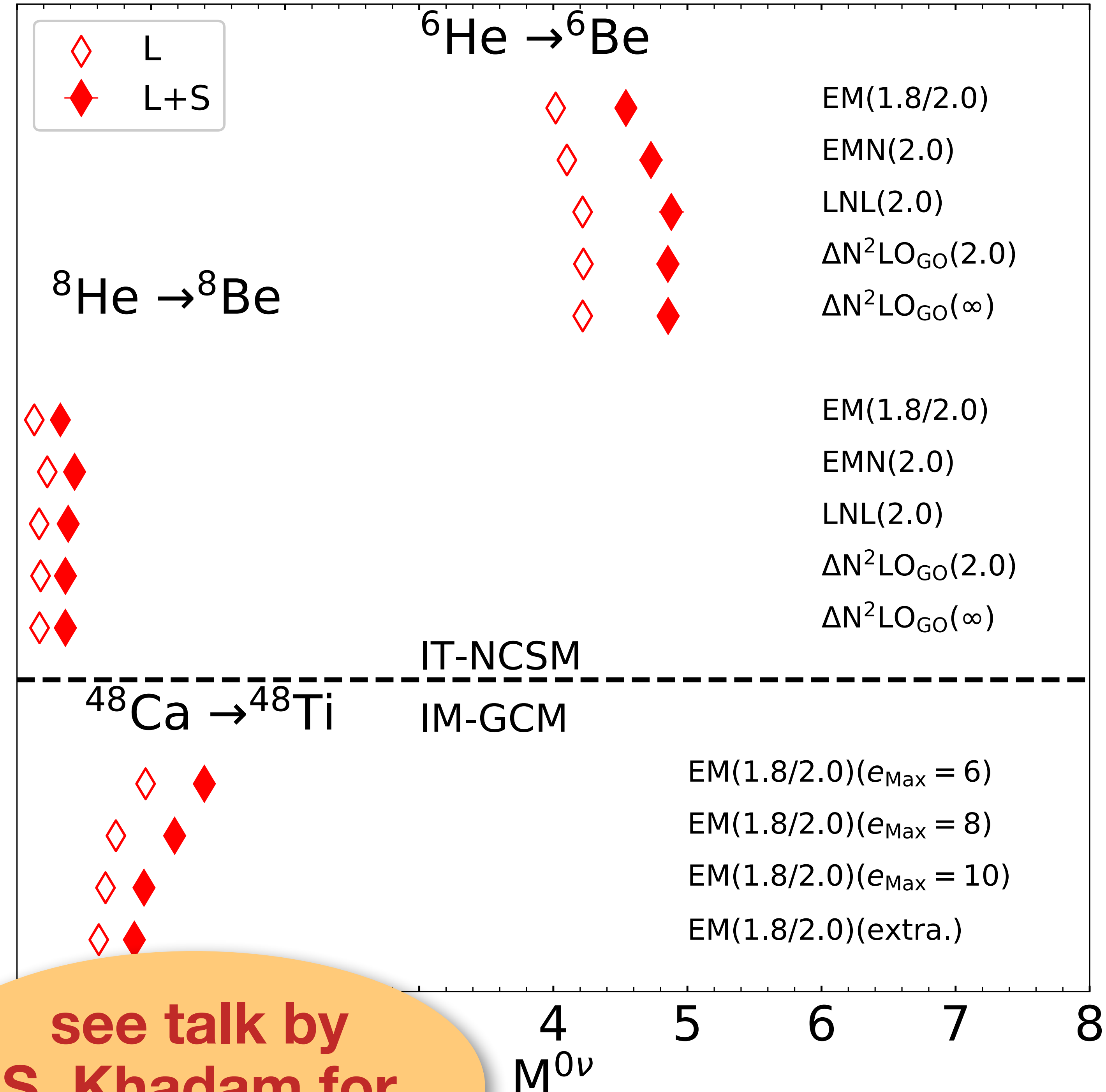


- NME from different methods **consistent** for consistent interactions & transition operators
  (A. Belley et al., PRL 126, 042502, S. Novario e
- interpretation and features differ from e
  only **weak correlation** between NME and

not the full story yet: improve IMSRG truncations, additional GCM correlations, include currents, …

Counterterm in $0\nu\beta\beta$ Operator

R. Wirth, J. M. Yao, H. Hergert, PRL **127**, 242502
also see: L. Jokiniemi, P. Soriano, J. Menendez, PLB **823**, 136720

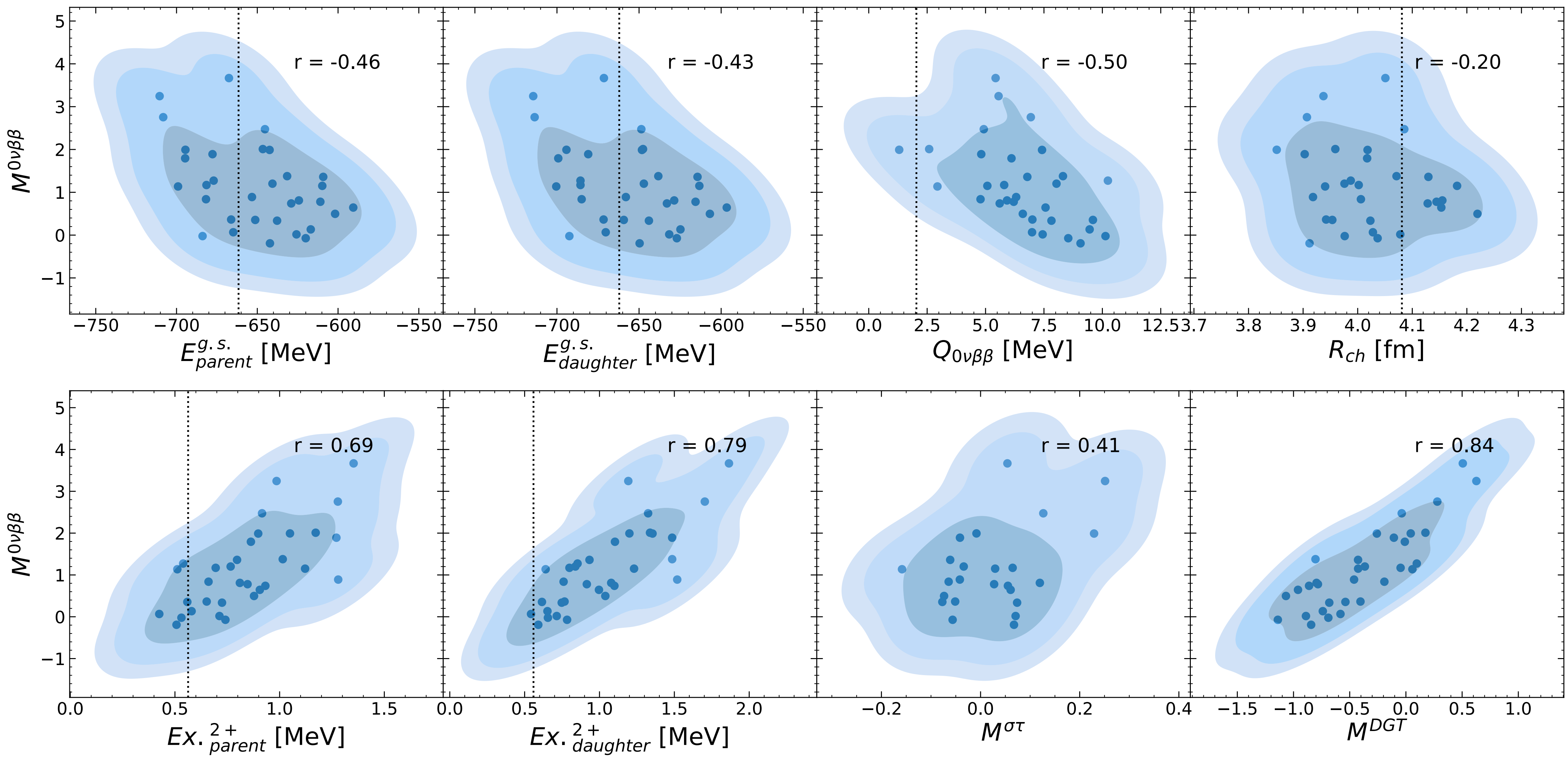


- Cirigliano et al.: RG invariance of the DBD transition operator requires **contact term**
- determine LEC from $nn \rightarrow ppe^{-}e^{-}$
- counter term yields **robust enhancement**
  - varied EFT orders, RG scales, interactions

see talk by S. Khadam for QCD approach

Correlations Revisited

A. Belley et al., arXiv:2210.05809 [nucl-th]; also see J. M. Yao et al., PRC 106, 014315



^{76}Ge, VS-IMSRG, 34 non-implausible Δ-full N2LO interactions
(cf. B.S. Hu et al., Nature Phys.)

- possible correlation with **Double Gamow Teller** transition, **2^+ energies** (but the latter only in ^{76}Ge)

Looking Ahead

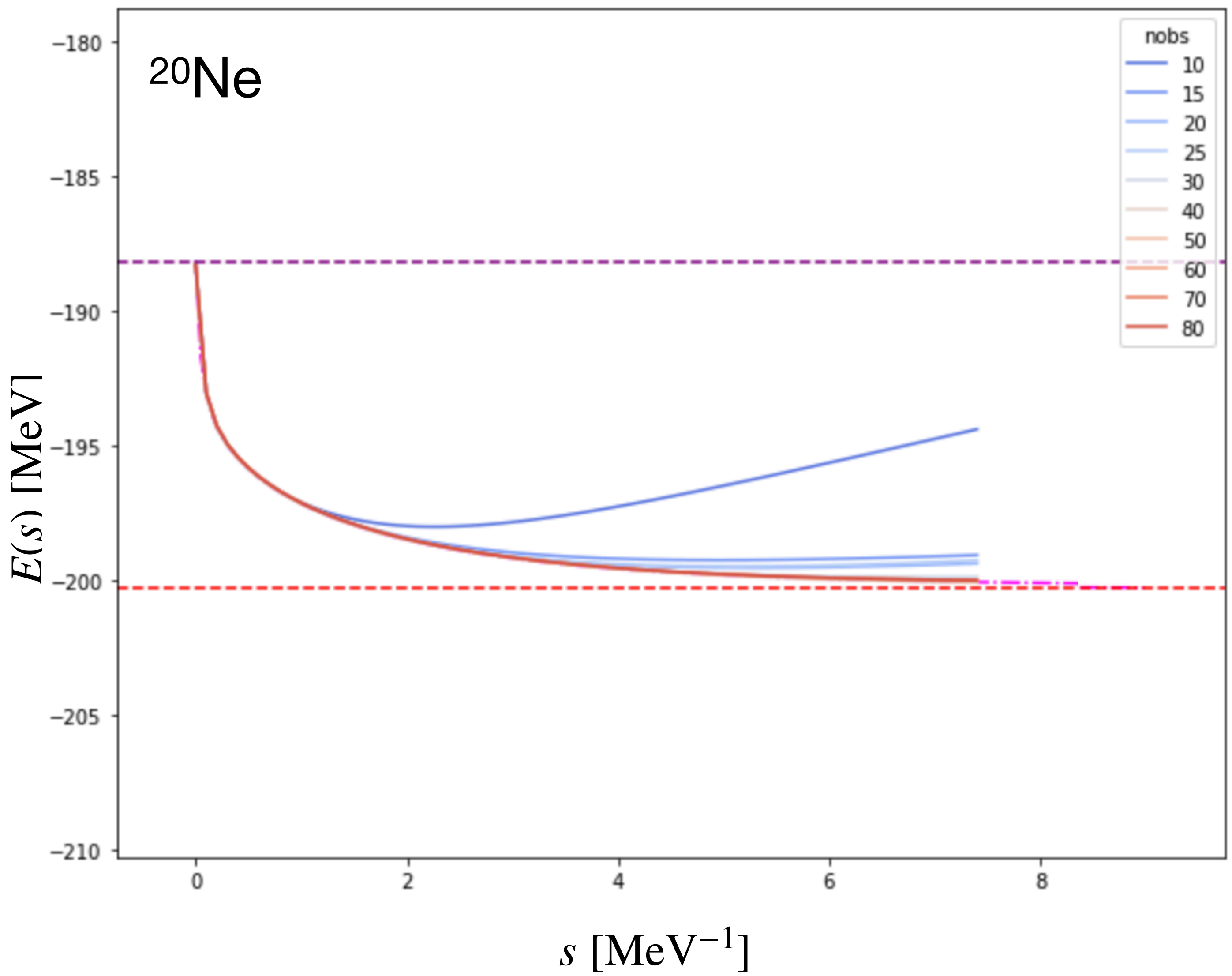
What is Next?

- **Neutrinoless Double Beta Decay** matrix elements for ^{76}Ge and other candidates
    - studies with **multiple complementary methods**: IM-GCM, VS-IMSRG, Coupled Cluster (w/angular momentum projection), …
    - use VS-IMSRG for heavy lifting in parameter sensitivity analysis & UQ because IM-GCM is too costly
    - **accelerate IMSRG & IM-GCM** (GPUs, factorization, Machine Learning, …)
      [A. M. Romero et al., PRC 104, 054317; X. Zhang et al., PRC 107, 024304]
- **Uncertainty Quantification / Sensitivity Analysis**
    - need cheap **surrogate models (emulators)**

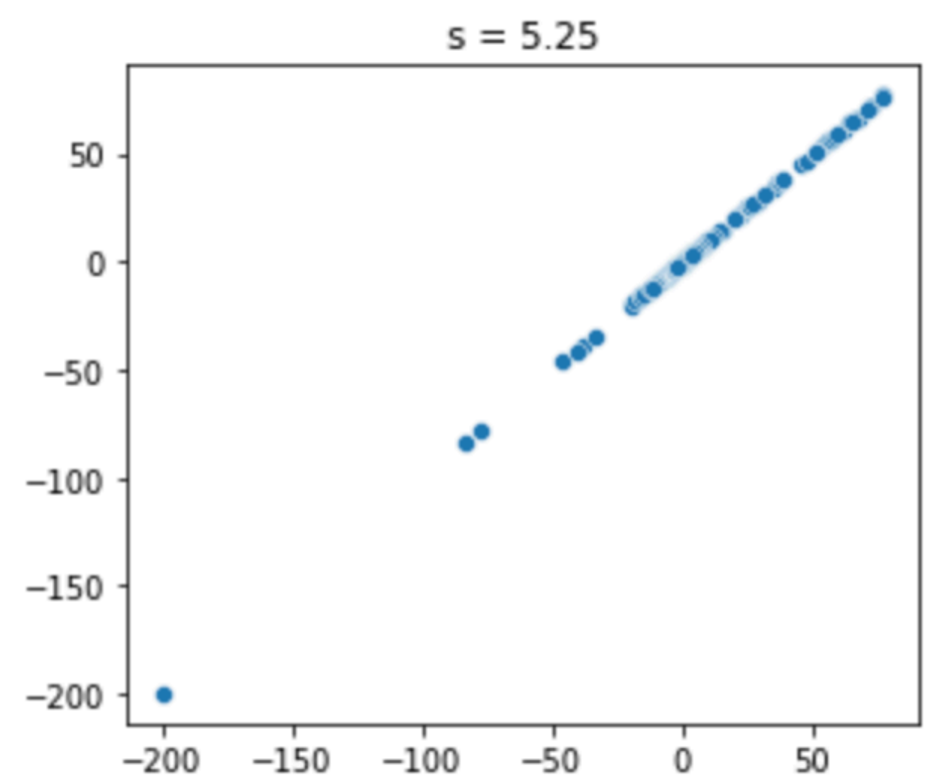
Emulating IMSRG Flows

***J. Davison, J. Crawford**, S. Bogner, HH, in preparation*

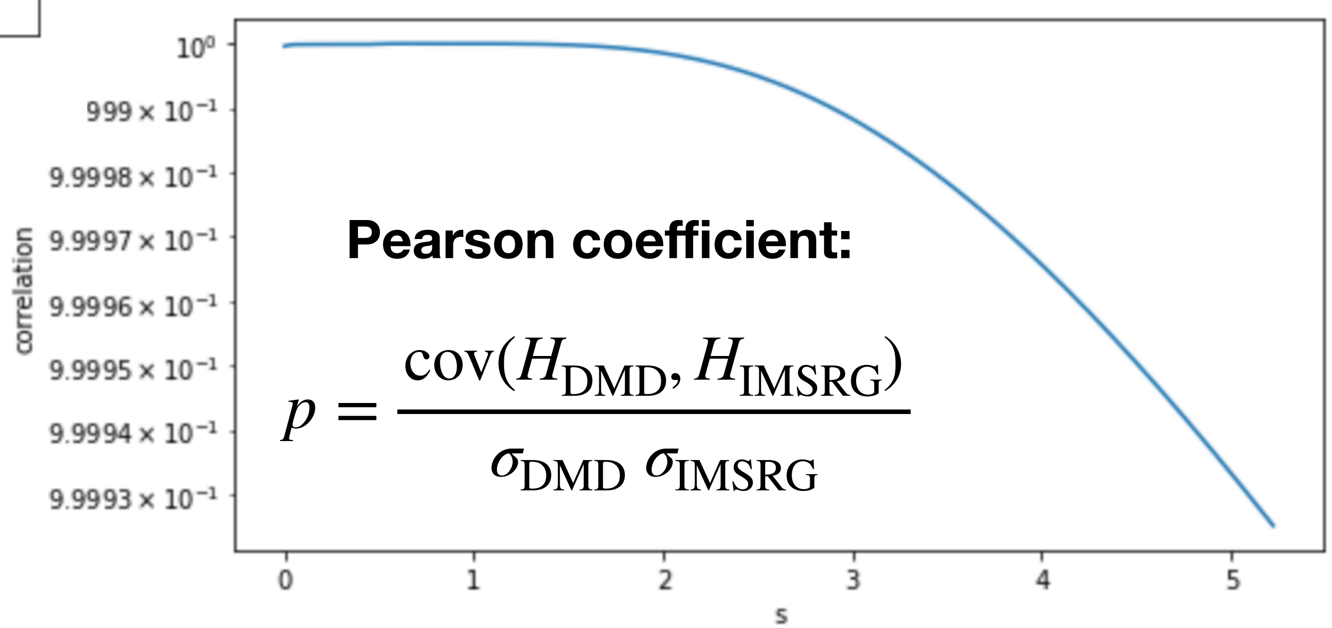
EM(500) N³LO, $\lambda = 2.0\,\mathrm{fm}^{-1}$



$H_{\mathrm{DMD}}(s)$ vs. $H_{\mathrm{IMSRG}}(s)$



Dynamic Mode Decomposition **emulator** "learns" **all flowing operator coefficients** from snapshots!

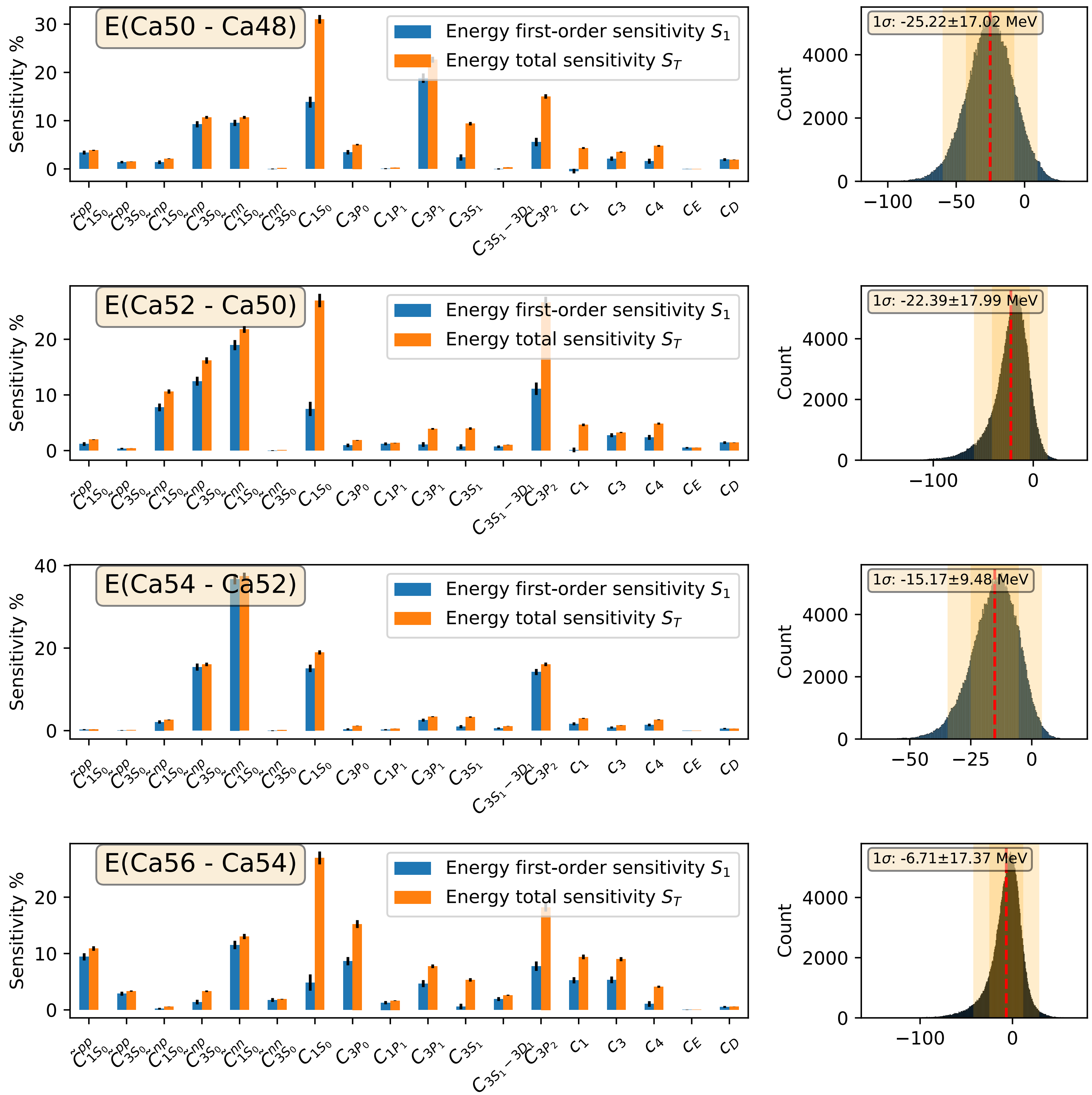


Pearson coefficient:

$$p = \frac{\mathrm{cov}(H_{\mathrm{DMD}}, H_{\mathrm{IMSRG}})}{\sigma_{\mathrm{DMD}}\,\sigma_{\mathrm{IMSRG}}}$$

Parametric DMD

J. Davison, J. Crawford, *S. Bogner, HH, in preparation*



- Δ-full, NNLO NN+3N
- $e_{max} = 12$, $E_{3max} = 14$
- 200000+ samples
- **4-5 order of magnitude reduction in computational effort**

Additional Opportunities

- use wave functions to explore **other NLDBD mechanisms** or other transitions
    - (provided the **same scale and scheme** is used as for the Hamiltonian)

see talks by L. Graf, K. Fuyuto

- towards **precise beta decays** & **Schiff moments**
    - develop IM-GCM for **odd nuclei**
    - tackle nuclei for which **large multi-shell valence-spaces** make VS-IMSRG difficult or prohibitive
- **(sensitive) feedback on EFTs**

Some References

arXiv:2202.01787v2 [hep-ex] 10 Nov 2022

Toward the discovery of matter creation with neutrinoless double-beta decay

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(Dated: November 11, 2022)

The discovery of neutrinoless double-beta decay could soon be within reach. This hypothetical ultra-rare nuclear decay offers a privileged portal to physics beyond the Standard Model of particle physics. Its observation would constitute the discovery of a matter-creating process, corroborating leading theories of why the universe contains more matter than antimatter, and how forces unify at high energy scales. It would also prove that neutrinos and anti-neutrinos are not two distinct particles, but can transform into each other, with their mass described by a unique mechanism conceived by Majorana. The recognition that neutrinos are not massless necessitates an explanation and has boosted interest in neutrinoless double-beta decay. The field stands now at a turning point. A new round of experiments is currently being prepared for the next decade to cover an important region of parameter space. In parallel, advances in nuclear theory are laying the groundwork to connect the nuclear decay with the underlying new physics. Meanwhile, the particle theory landscape continues to find new motivations for neutrinos to be their own antiparticle. This review brings together the experimental, nuclear theory, and particle theory aspects connected to neutrinoless double-beta decay, to explore the path toward — and beyond — its discovery.

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arXiv:2202.01787

arXiv:2203.12169v1 [hep-ph] 23 Mar 2022

Submitted to the Proceedings of the U.S. Community Study
on the Future of Particle Physics (Snowmass 2021)

**Neutrinoless Double-Beta Decay:
A Roadmap for Matching Theory to Experiment**

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arXiv:2203.12169

arXiv:2207.01085v1 [nucl-th] 3 Jul 2022

**Towards Precise and Accurate Calculations of Neutrinoless Double-Beta Decay:
Project Scoping Workshop Report**

V. Cirigliano,[1] Z. Davoudi,[2] J. Engel,[3,*] R.J. Furnstahl,[4] G. Hagen,[5,6] U. Heinz,[4] H. Hergert,[7] M. Horoi,[8] C.W. Johnson,[9] A. Lovato,[10,11,12] E. Mereghetti,[13] W. Nazarewicz,[7,†] A. Nicholson,[3,14] T. Papenbrock,[6,5] S. Pastore,[15] M. Plumlee,[16,17] D.R. Phillips,[18,‡] P.E. Shanahan,[19] S.R. Stroberg,[10] F. Viens,[20] A. Walker-Loud,[14] K.A. Wendt,[21] and S.M. Wild[22,17]

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arXiv:2207.01085

[plus J. de Vries, HH, E. Mereghetti, S. Pastore, in prep.]

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and many more…

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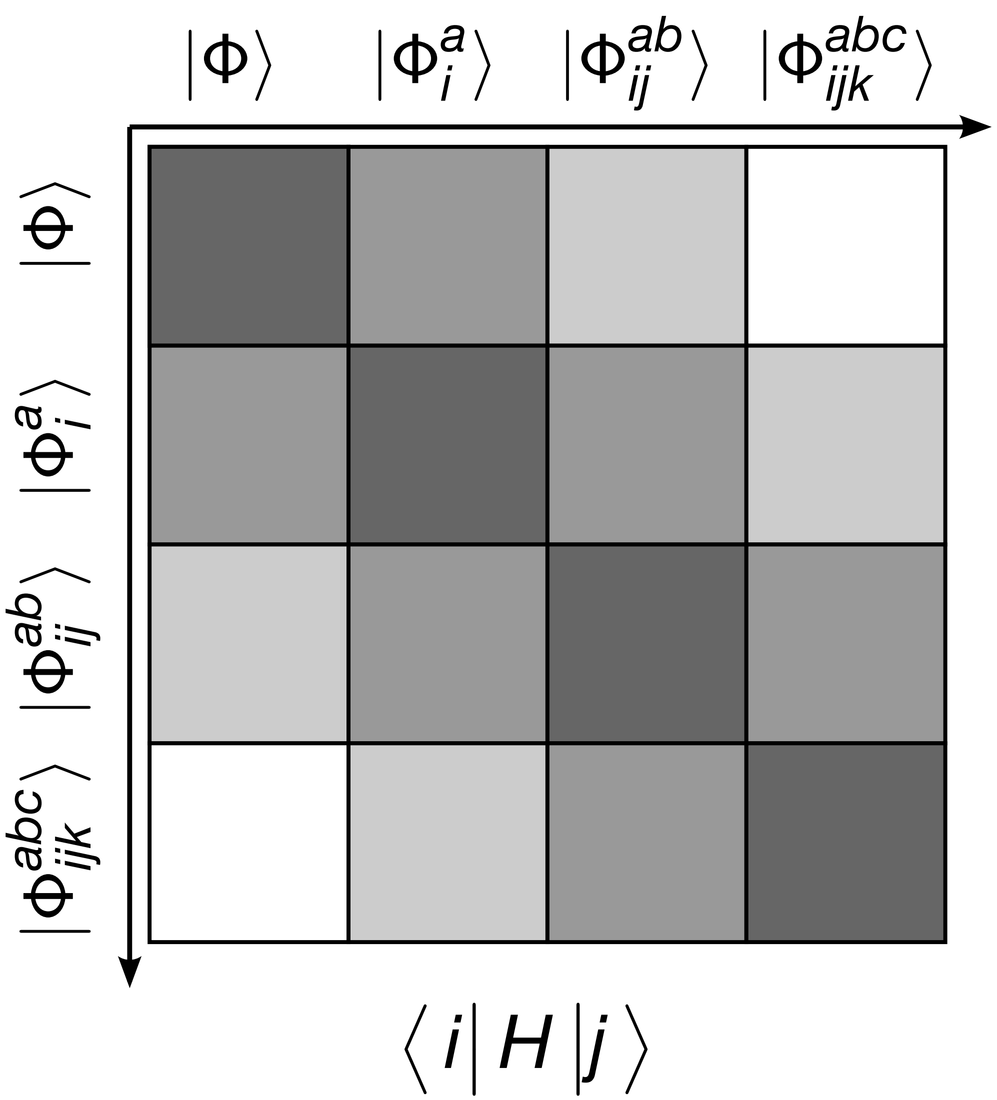
NUCLEI Nuclear Computational Low-Energy Initiative

Supplements

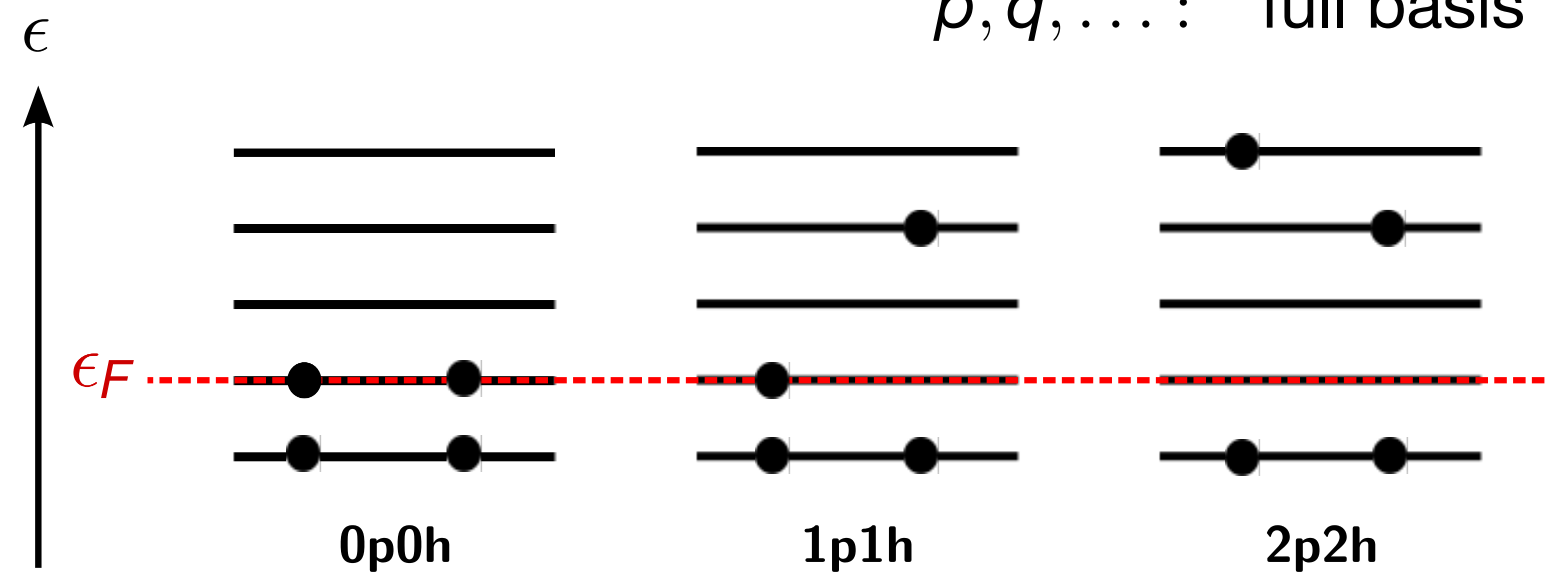
Transforming the Hamiltonian



$a, b, \ldots : \quad \epsilon > \epsilon_F$

$i, j, \ldots : \quad \epsilon \leq \epsilon_F$

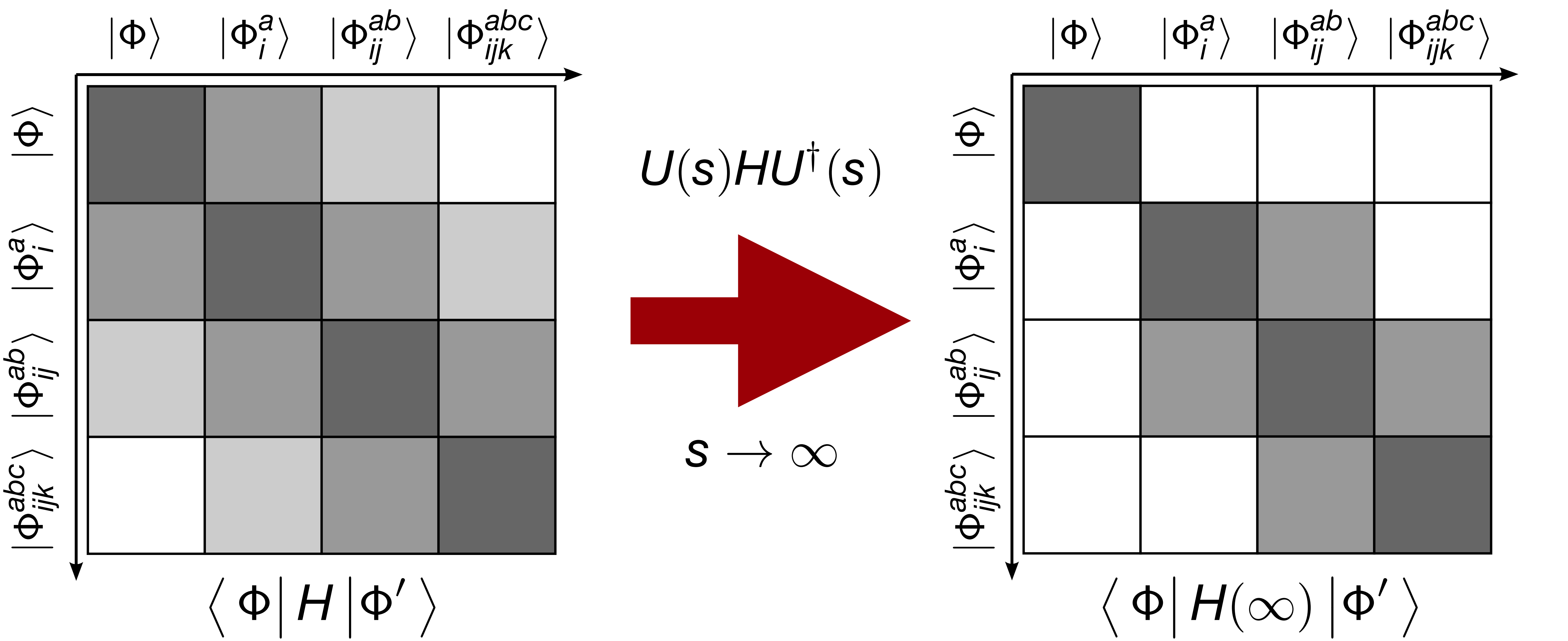
$p, q, \ldots :$ full basis



- reference state: **single Slater determinant**

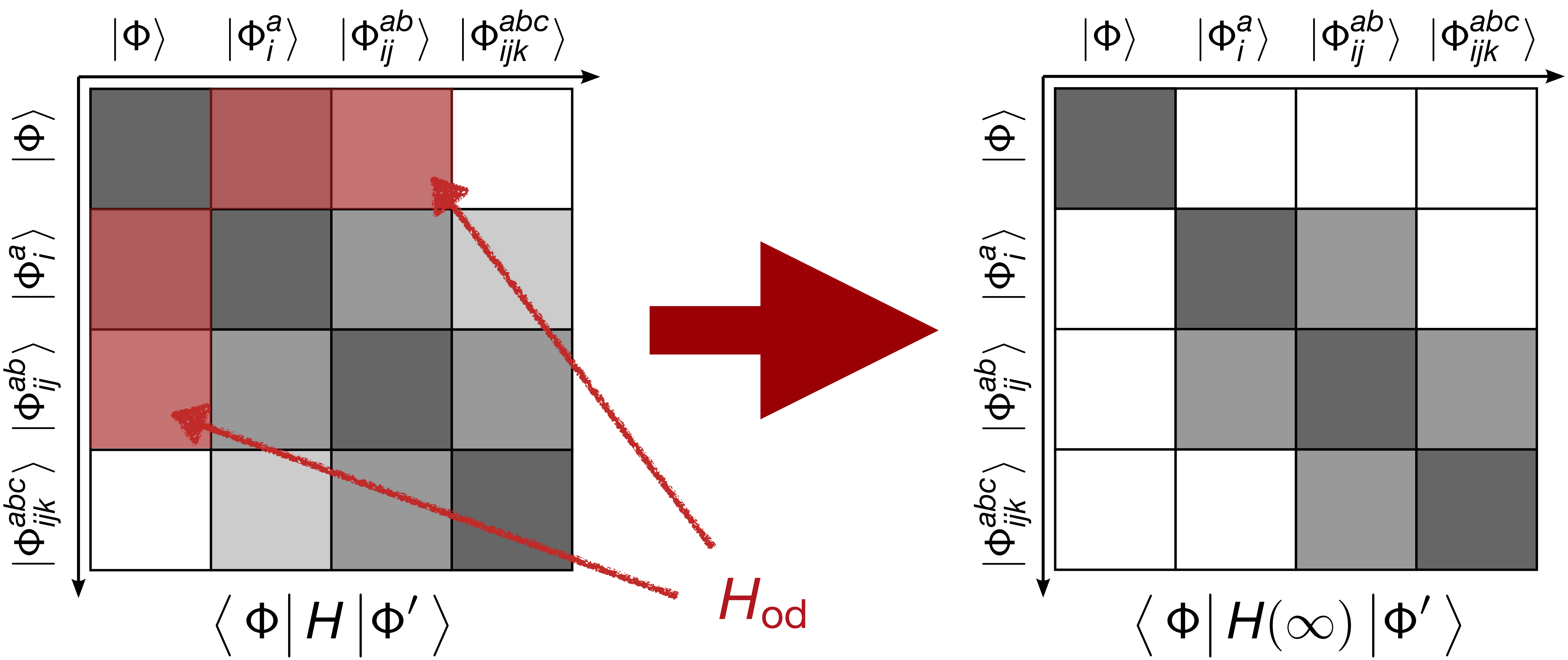
excitations relative to reference state: **normal-ordering**

Decoupling in A-Body Space



goal: decouple reference state $|\Phi\rangle$ from excitations

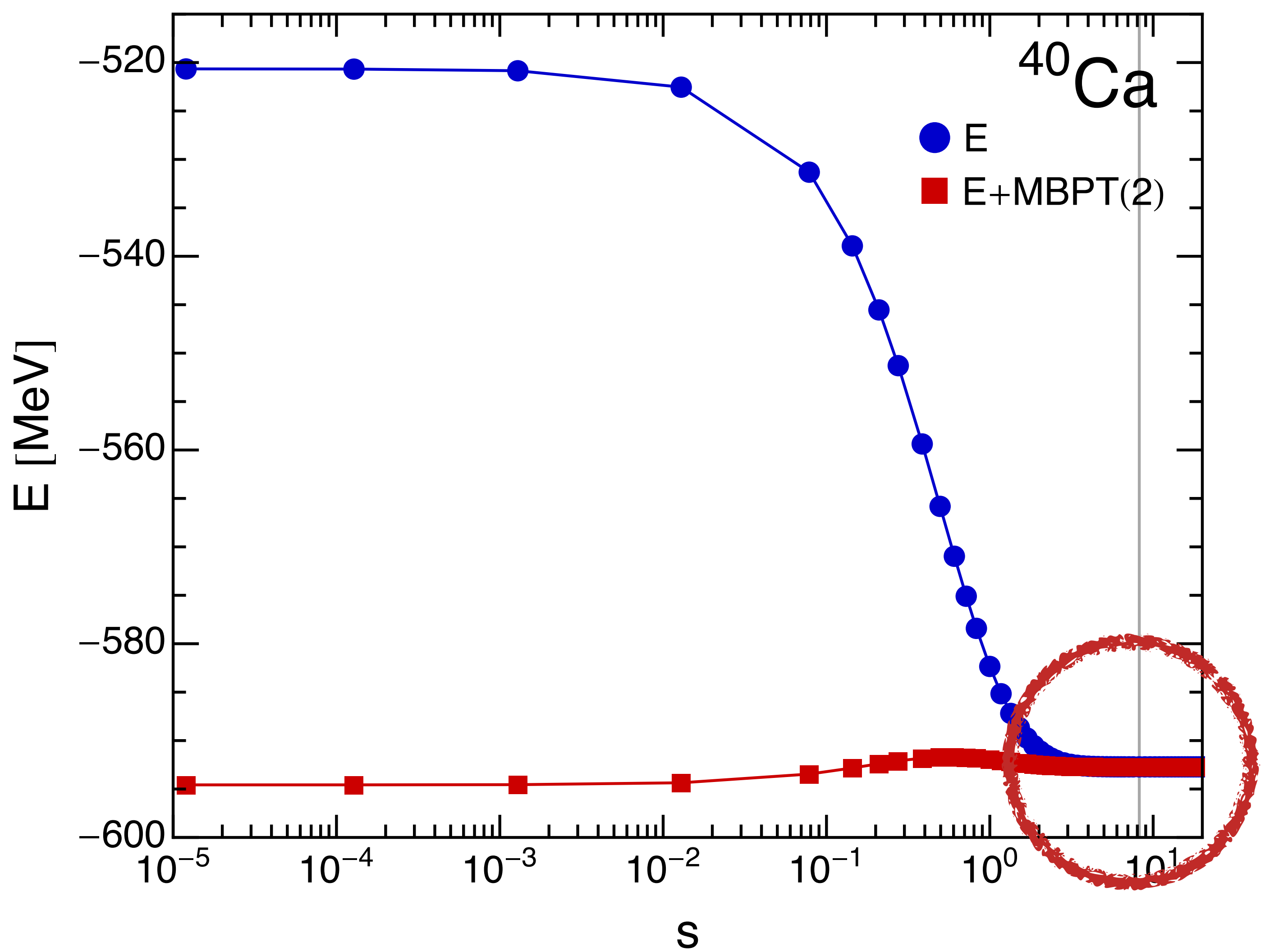
Flow Equation

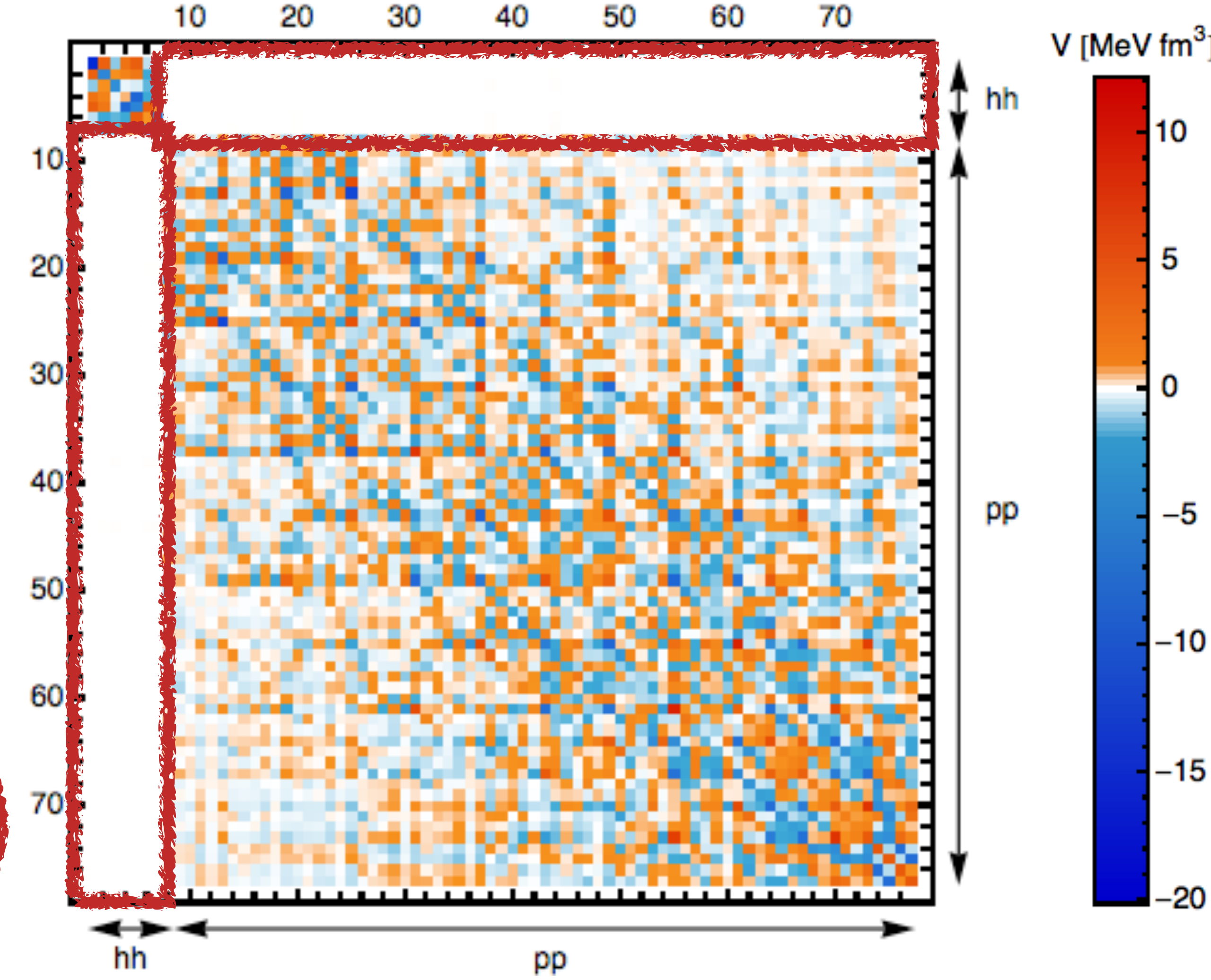


$$\frac{d}{ds}H(s) = \left[\eta(s), H(s)\right],$$

Operators truncated at **two-body level** - **matrix is never constructed explicitly!**

Decoupling



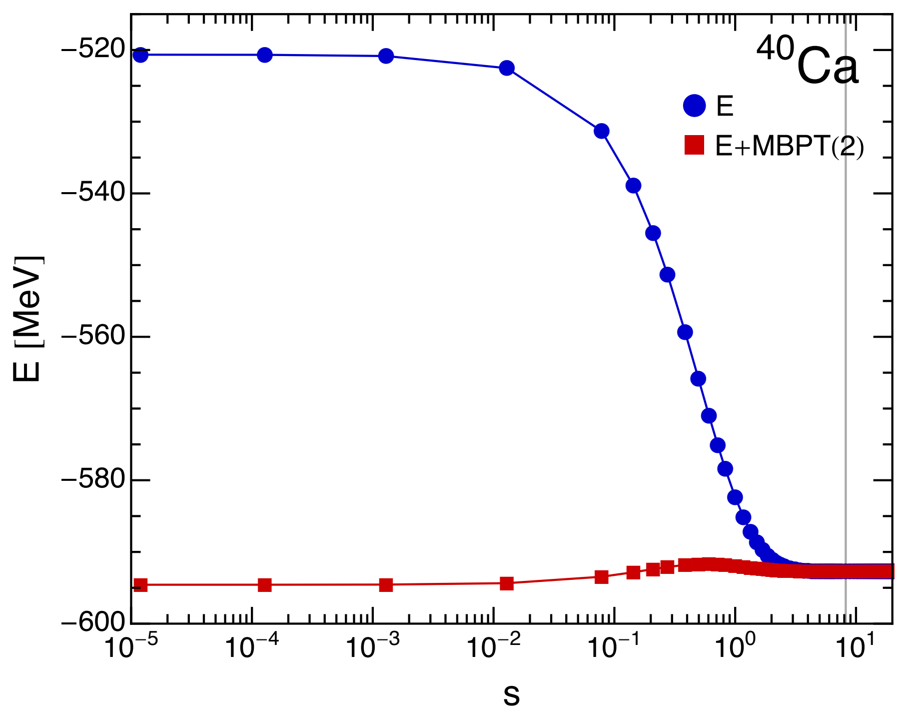


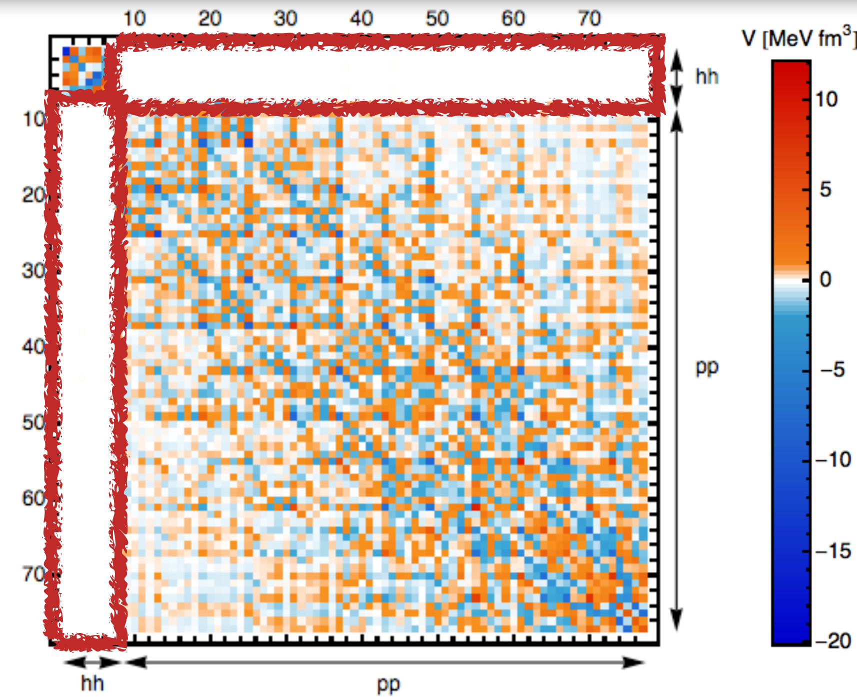
N3LO, $\lambda = 2.0\ \mathrm{fm}^{-1}, e_{\mathrm{Max}} = 8$

non-perturbative resummation of MBPT series **(correlations)**

off-diagonal couplings are rapidly driven to zero

Decoupling





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

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

$$U(s)HU^{\dagger}(s)U(s)\left|\Psi_n\right\rangle = E_n U(s)\left|\Psi_n\right\rangle$$

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

$$U(s)\left|\Psi_n\right\rangle \stackrel{!}{=} \left|\Phi\right\rangle$$