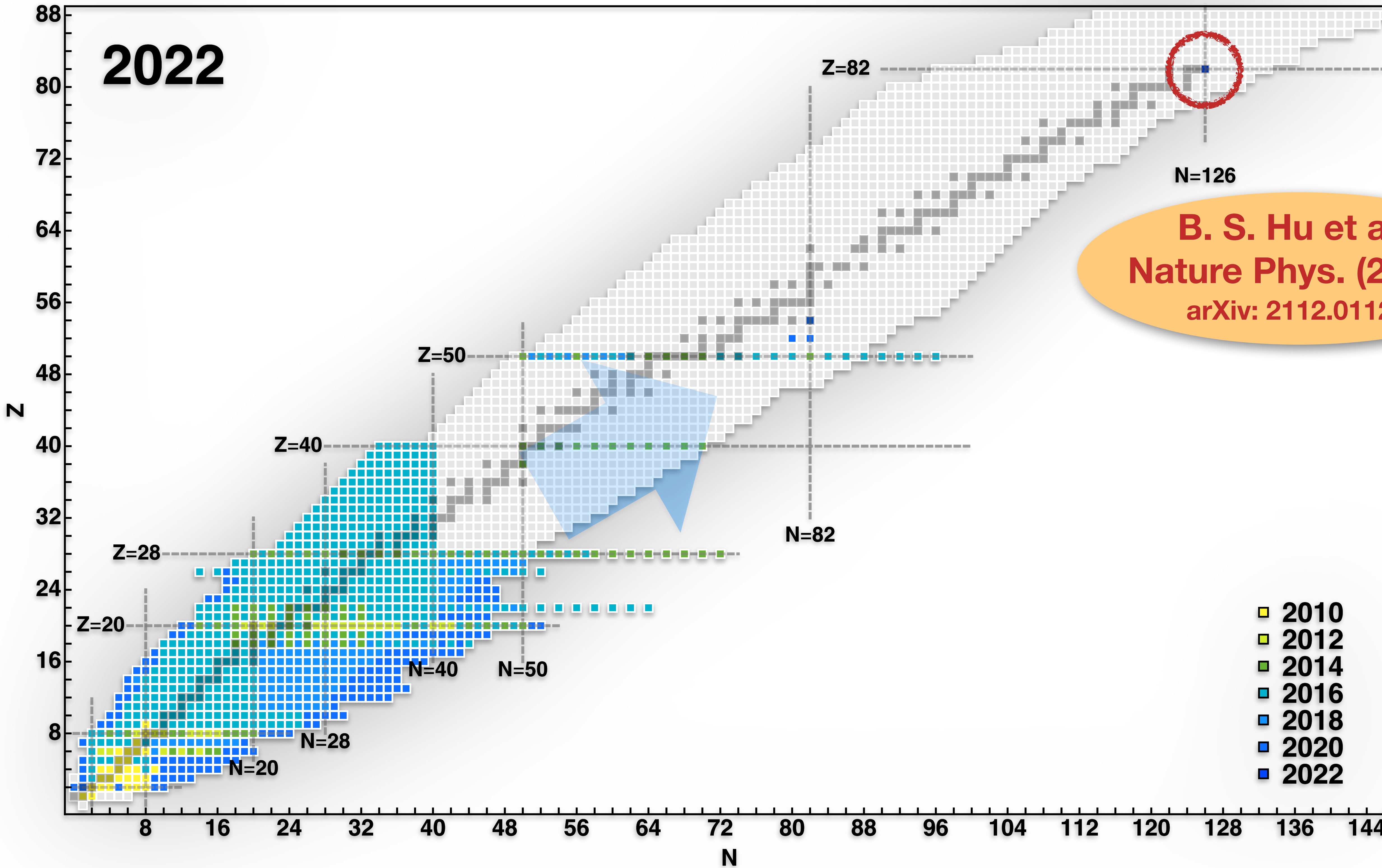
Progress in *Ab Initio* Nuclear Theory for Neutrinoless Double Beta Decay

Heiko Hergert
Facility for Rare Isotope Beams
& Department of Physics and Astronomy
Michigan State University

FRIB

Progress in *Ab Initio* Calculations

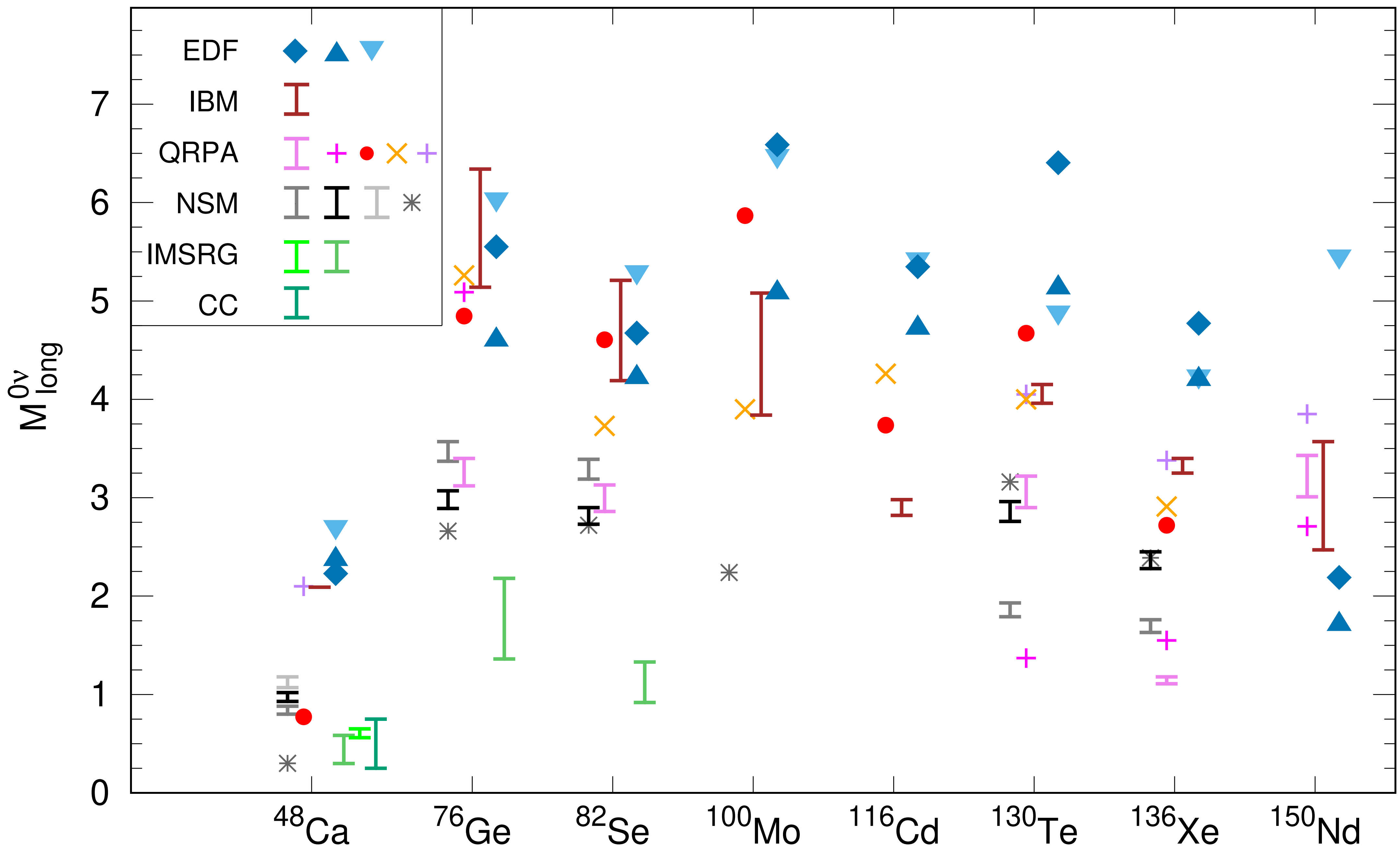
[cf. HH, Front. Phys. **8**, 379 (2020)]



B. S. Hu et al., Nature Phys. (2022), arXiv: 2112.01125

Nuclear Matrix Elements: Status

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



(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)

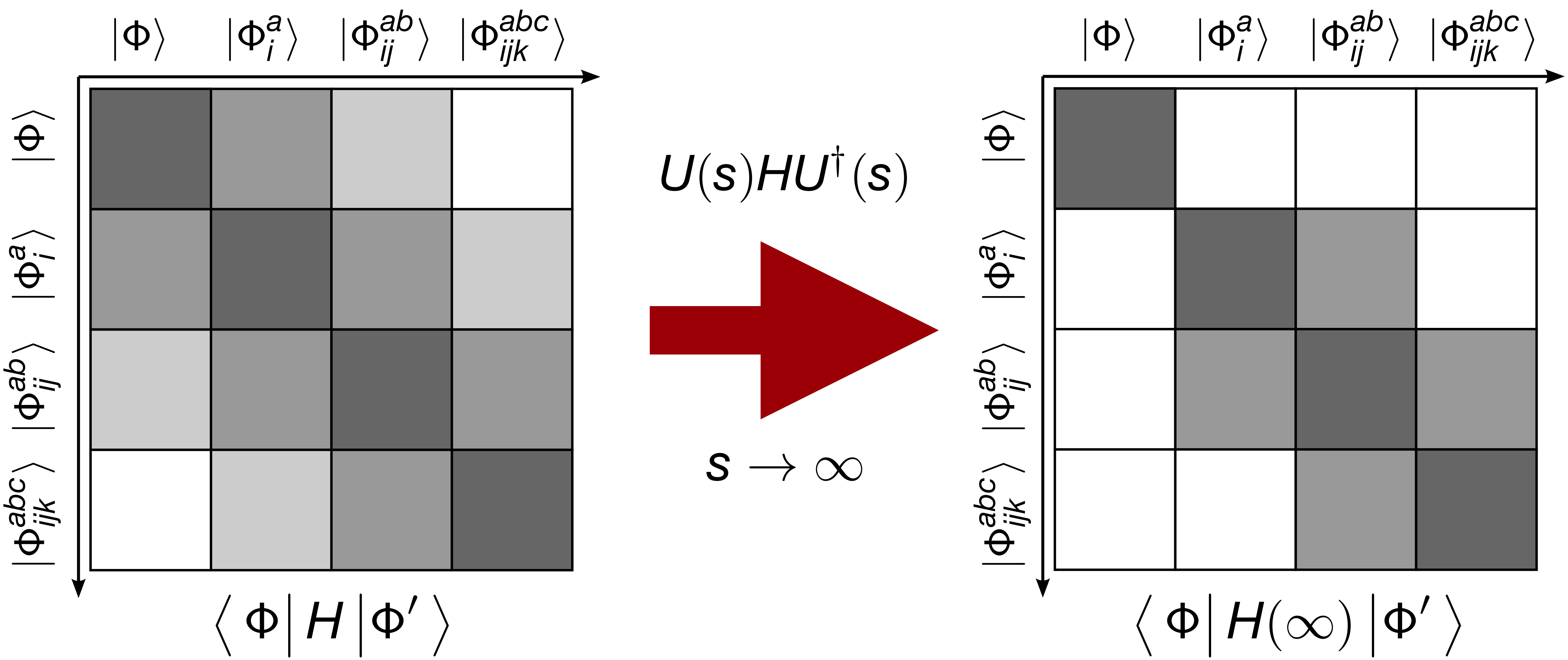
HH, S. K. Bogner, T. Morris, S. Binder, A. Calci, J. Langhammer, R. Roth, Phys. Rev. C **90**, 041302 (2014)

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)

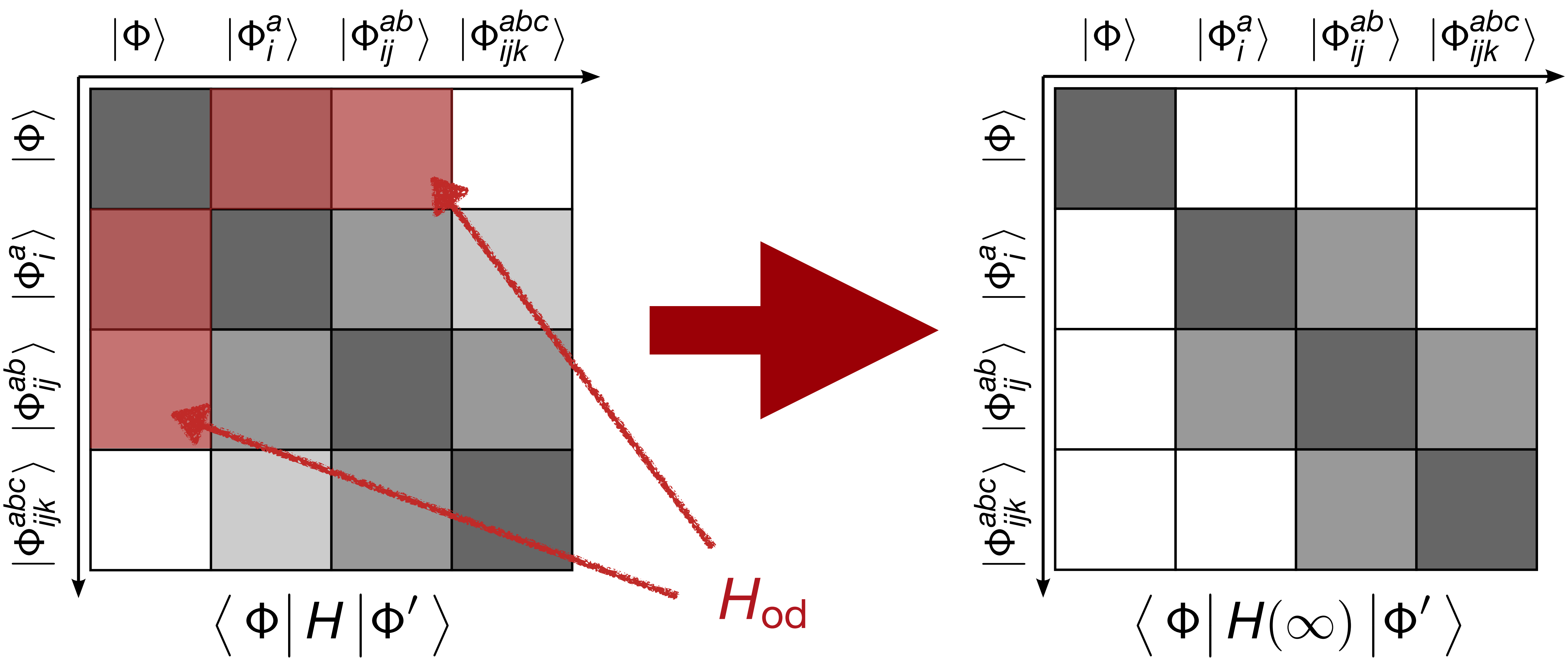
S. K. Bogner, R. J. Furnstahl, and A. Schwenk, Prog. Part. Nucl. Phys. **65**, 94

Decoupling in A-Body Space



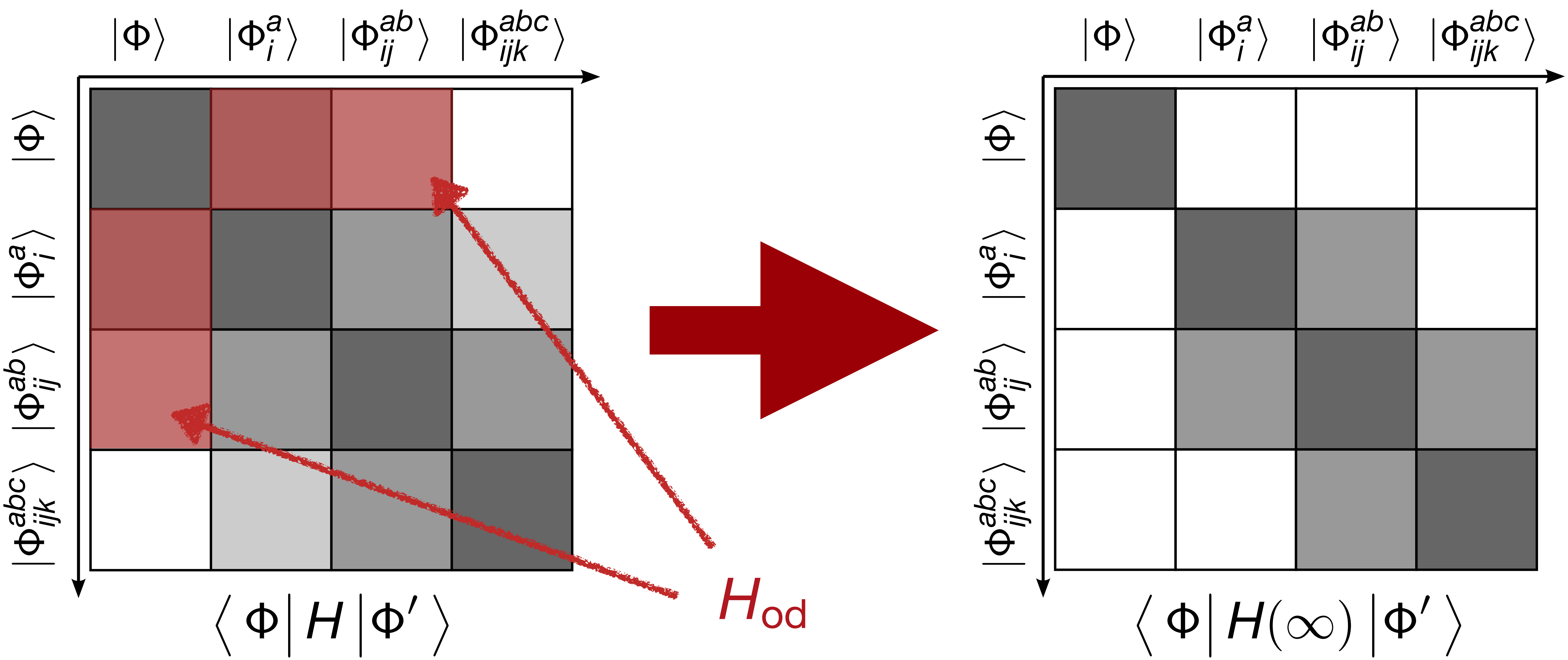
goal: decouple reference state $|\Phi\rangle$ from excitations

Flow Equation



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

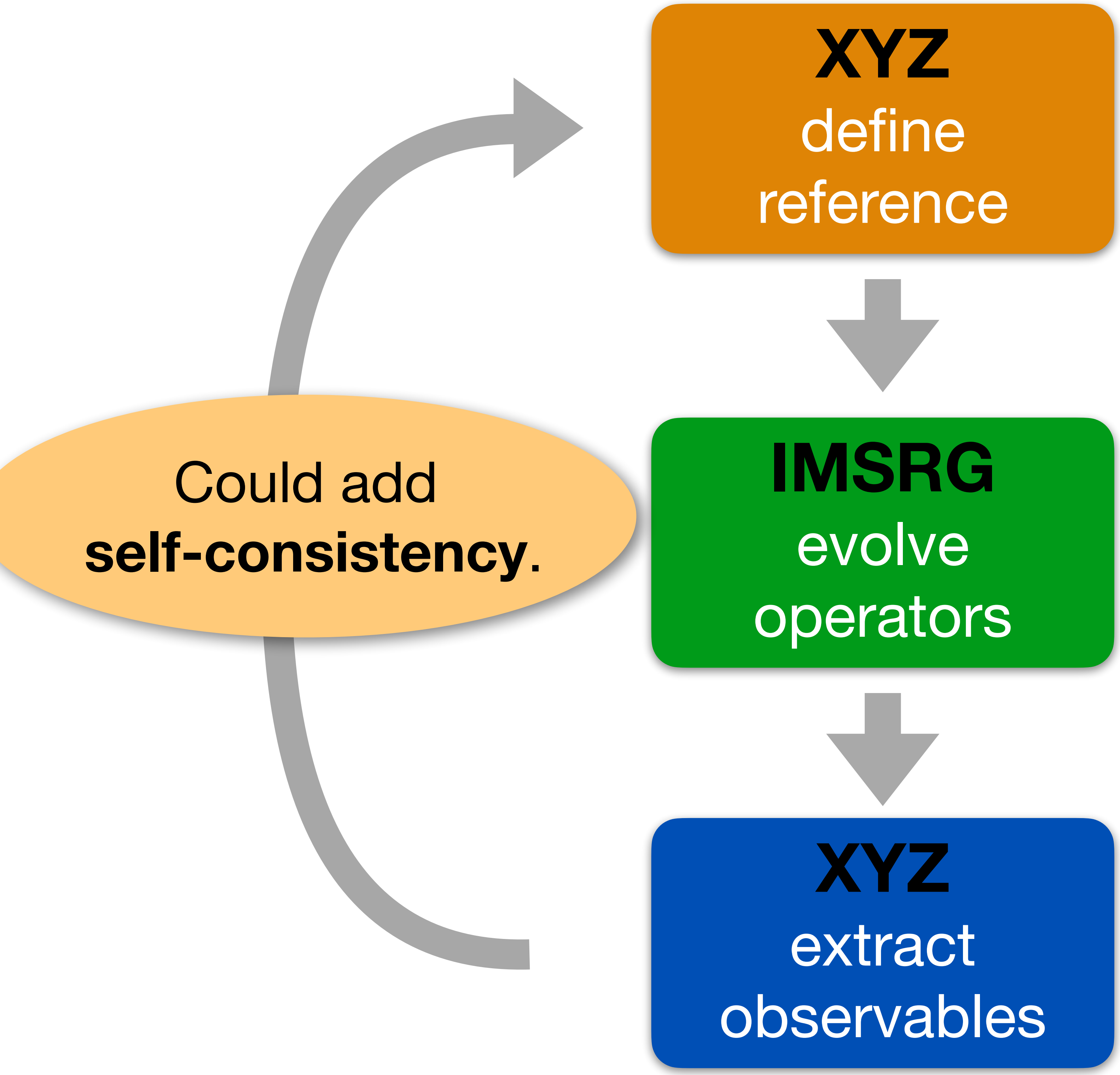
Flow Equation



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

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

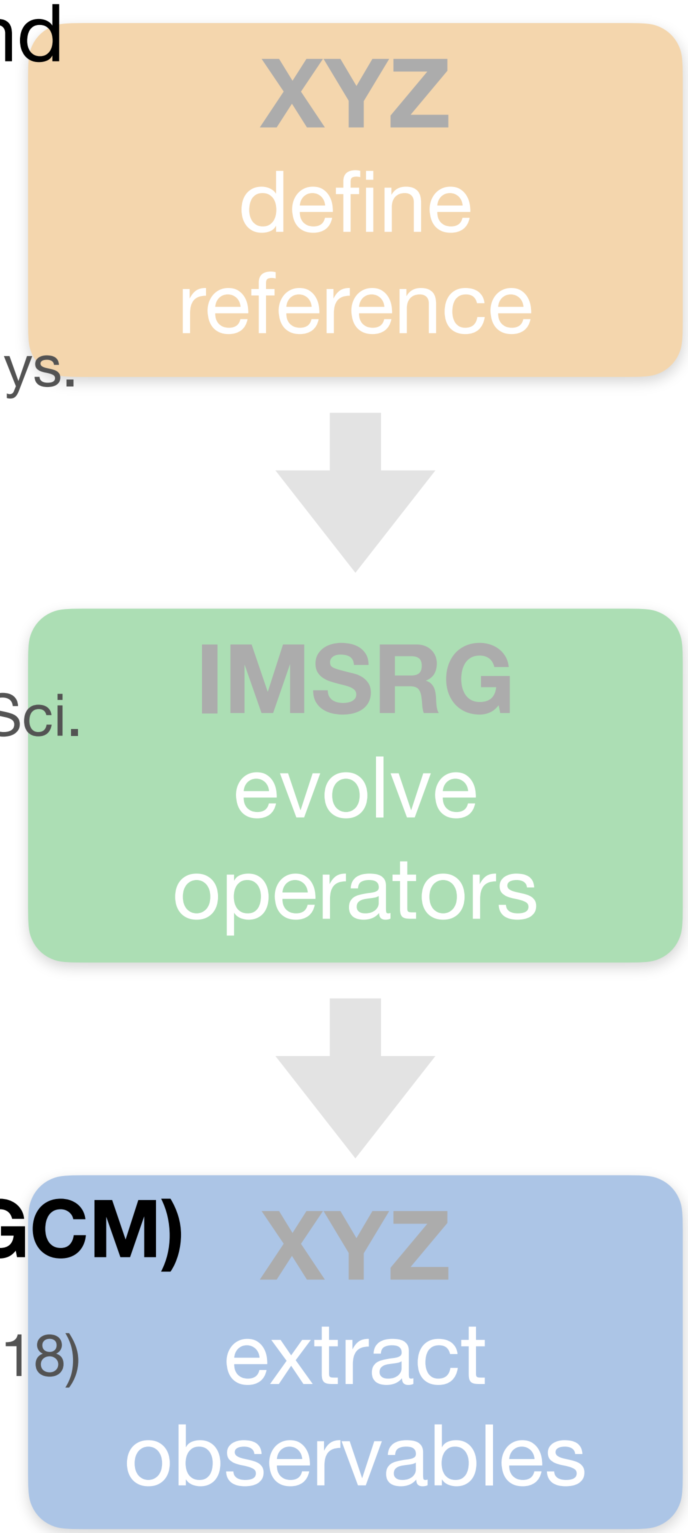
IMSRG-Improved Methods



* 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:

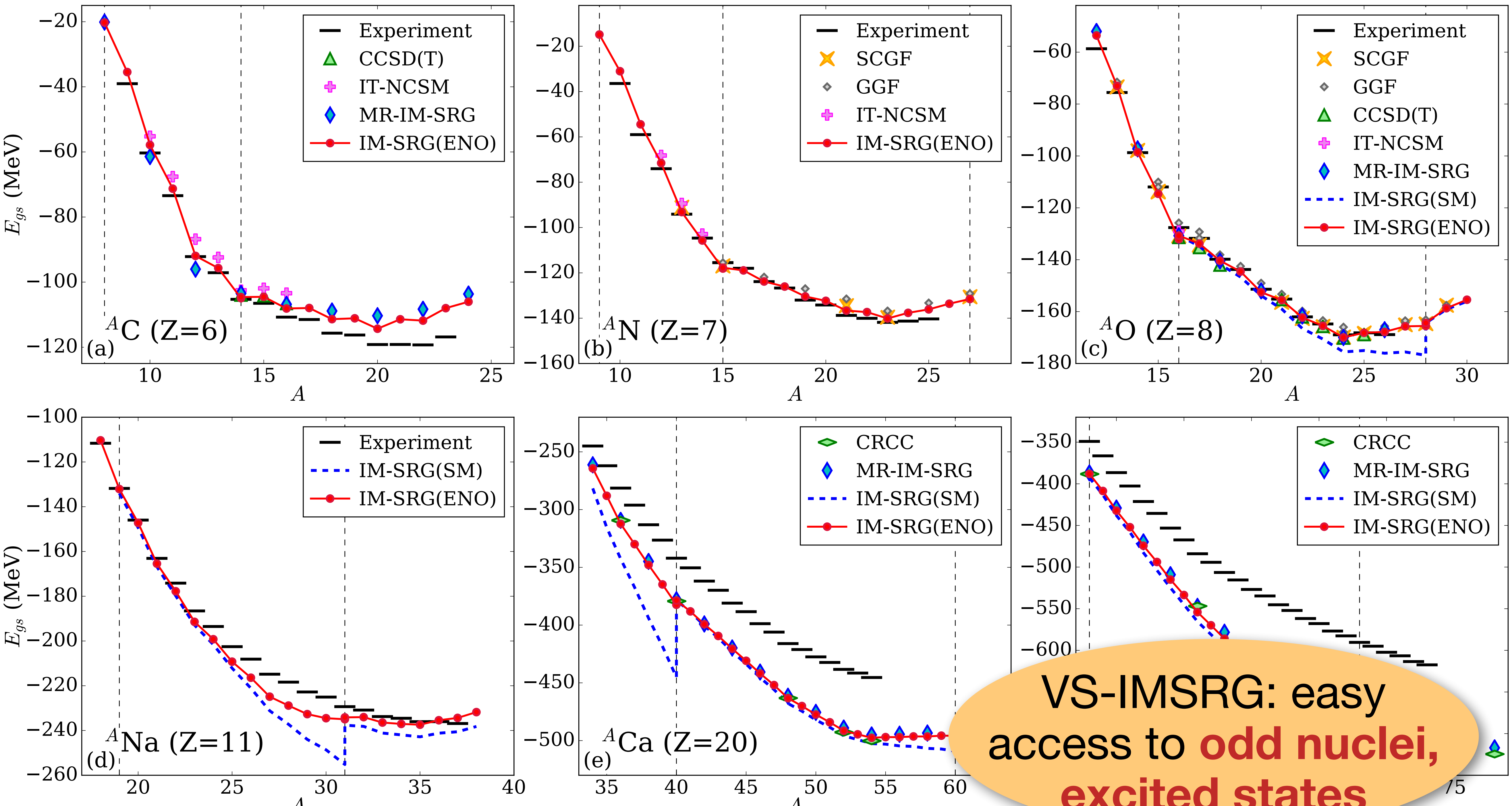
S. R. Stroberg, HH, S. K. Bogner, and J. D. Holt, Ann. Rev. Part. Nucl. Sci. **69**, 165 (2019)

Full CI:

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

Ground-State Energies

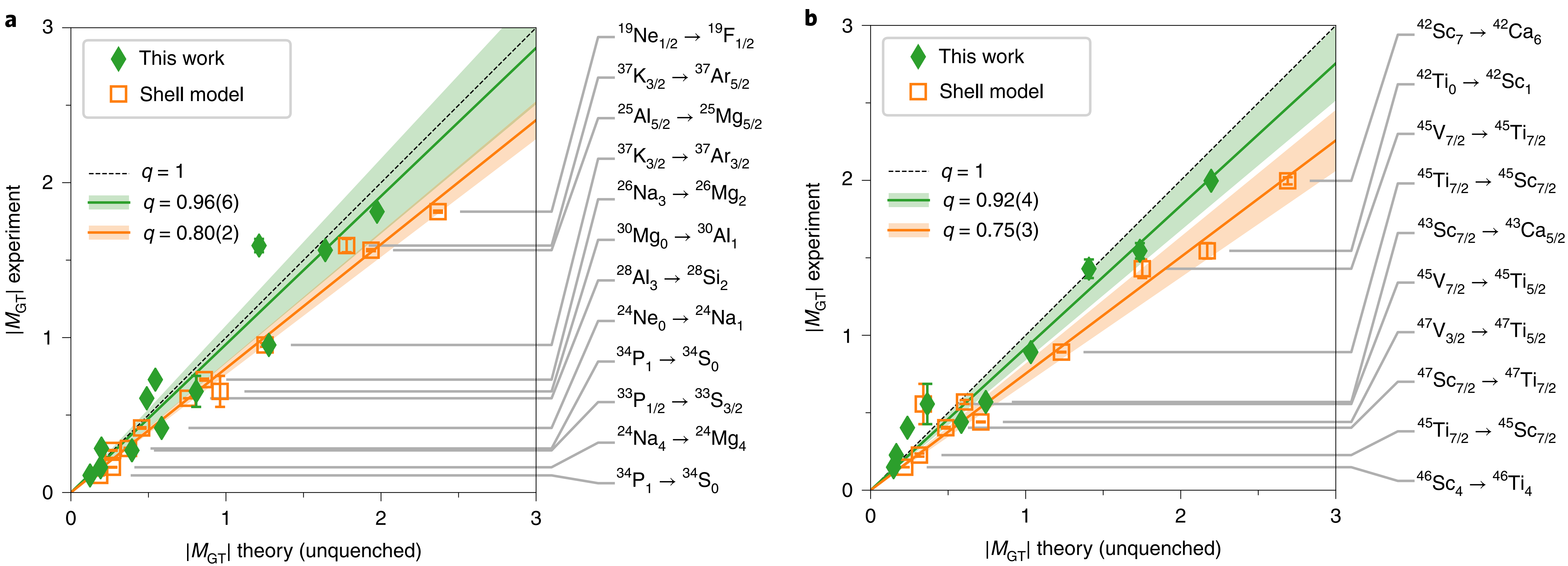
S. R. Stroberg, A. Calci, HH, J. D. Holt, S. K.Bogner, R. Roth, A. Schwenk, PRL **118**, 032502 (2017)
S. R. Stroberg, HH, S. K. Bogner, J. D. Holt, Ann. Rev. Part. Nucl. Sci. **69**, 307 (2019)



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

Quenching of Gamow-Teller Decays

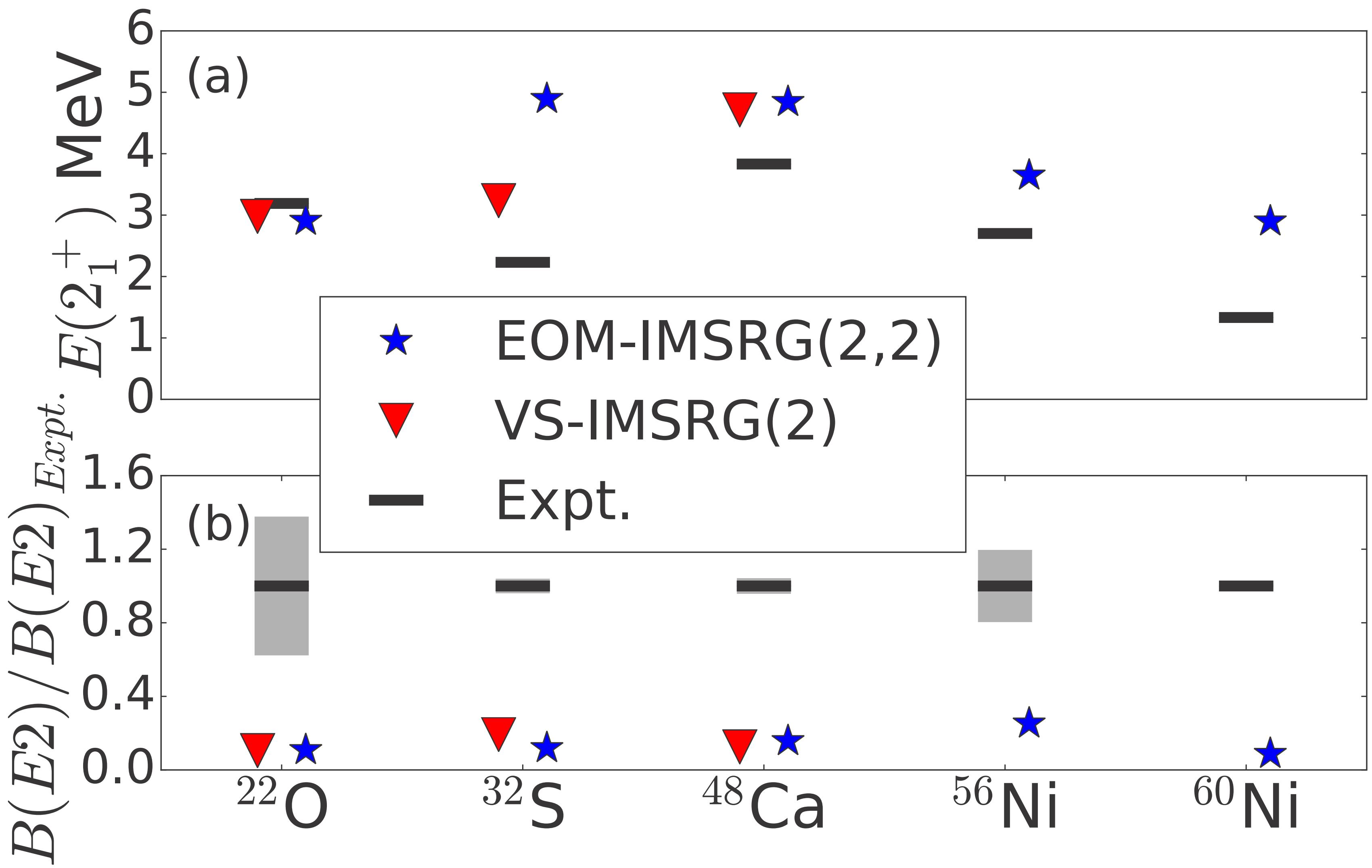
P. Gysbers et al., Nature Physics **15**, 428 (2019)



- **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

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

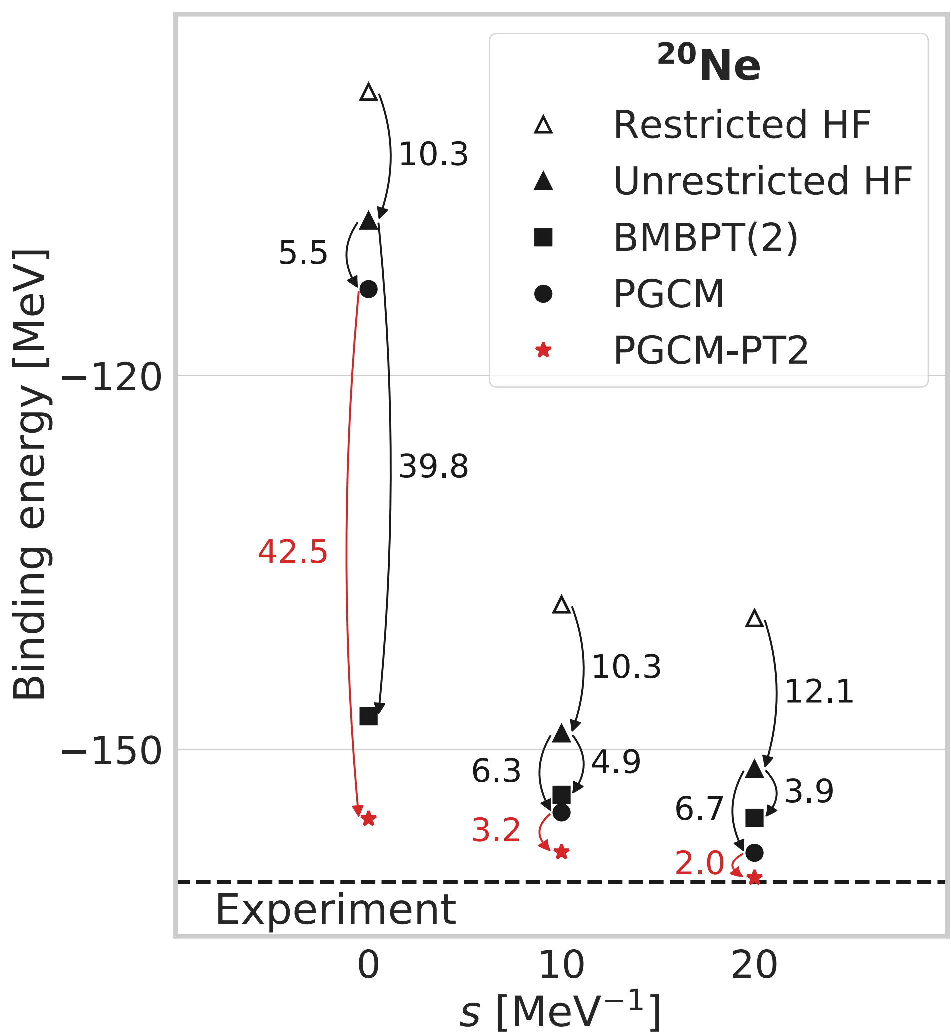
J. M. Yao, B. Bally, J. Engel, R. Wirth, T. R. Rodriguez, HH, PRL **124**, 232501 (2020)

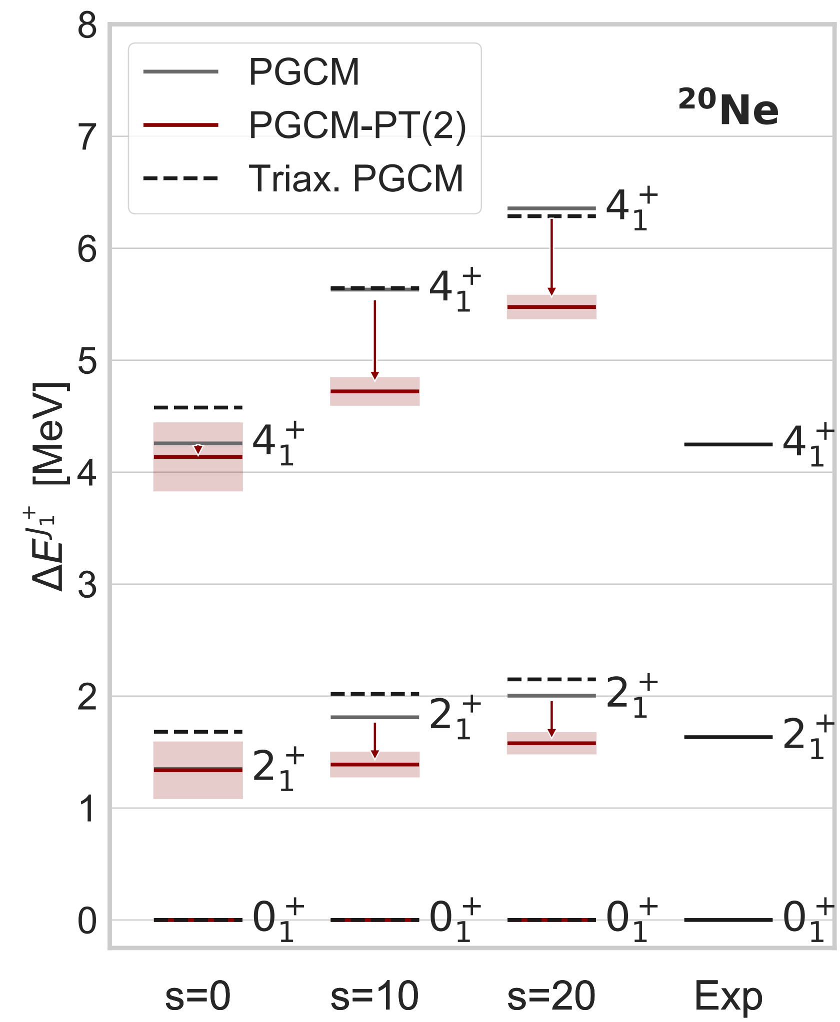
J. M. Yao, J. Engel, L. J. Wang, C. F. Jiao, H. H., PRC **98**, 054311 (2018)

HH, J. M. Yao, T. D. Morris, N. M. Parzuchowski, S. K. Bogner and J. Engel, J. Phys. Conf. Ser. 1041, 012007 (2018)

Perturbative Enhancement of IM-GCM

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

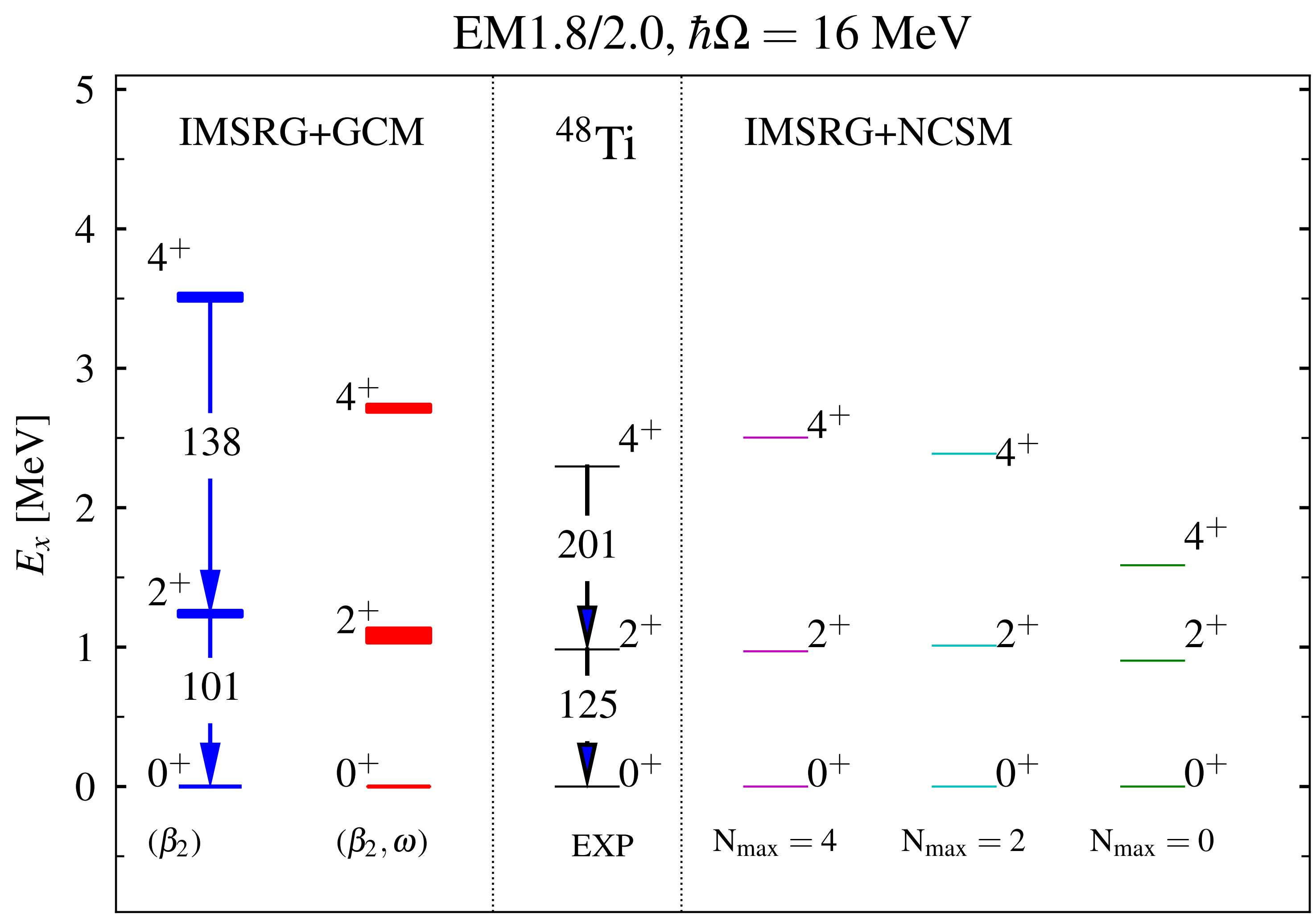




- s-dependence is a **built-in diagnostic tool** for IM-GCM **(not available in phenomenological GCM)**
  - if operator and wave function offer sufficient degrees of freedom, evolution of observables is unitary
- need **richer references and/or IMSRG(3)** for certain observables

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

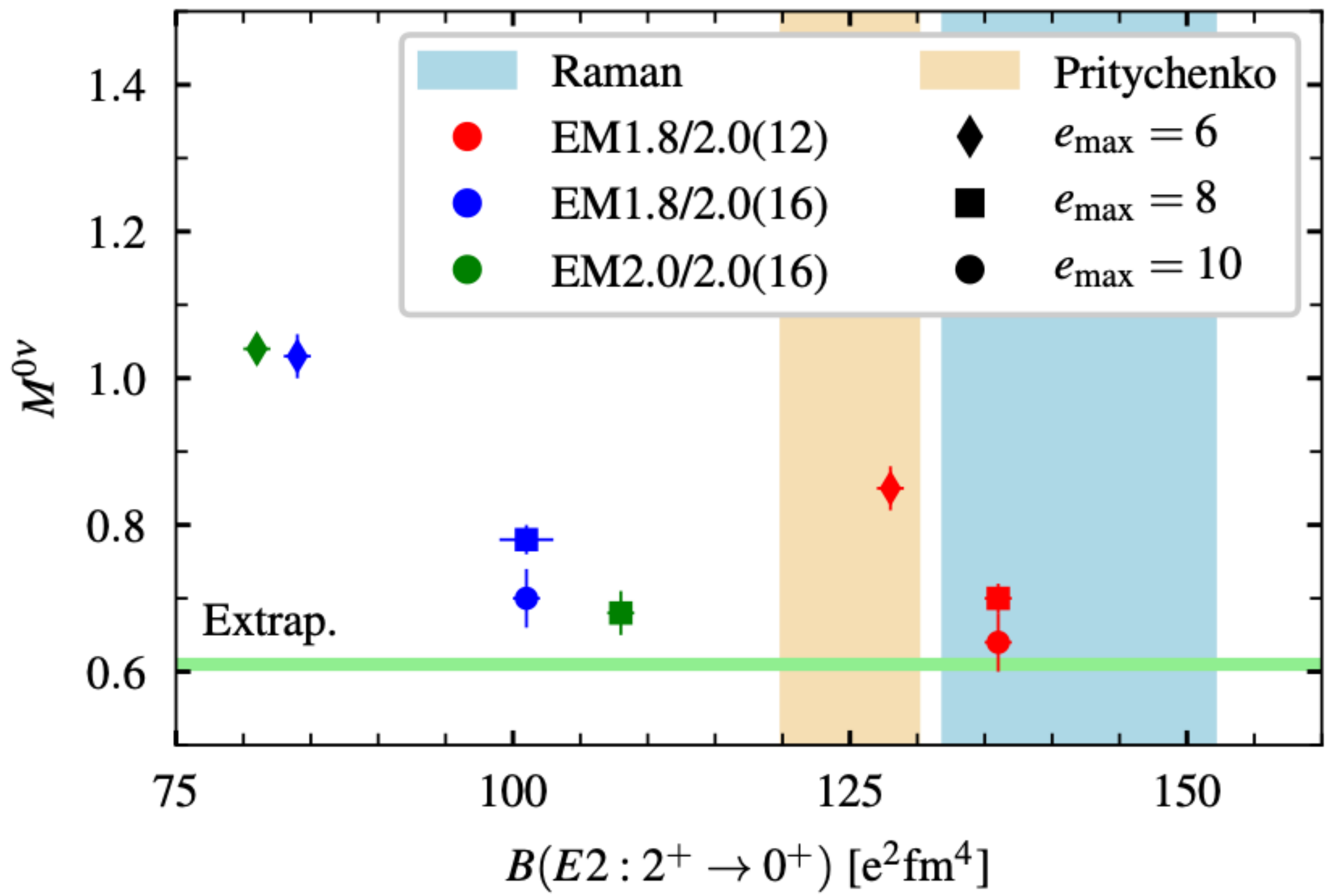
*J. M. Yao et al., PRL **124**, 232501 (2020); HH, Front. Phys. **8**, 379 (2020)*



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

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

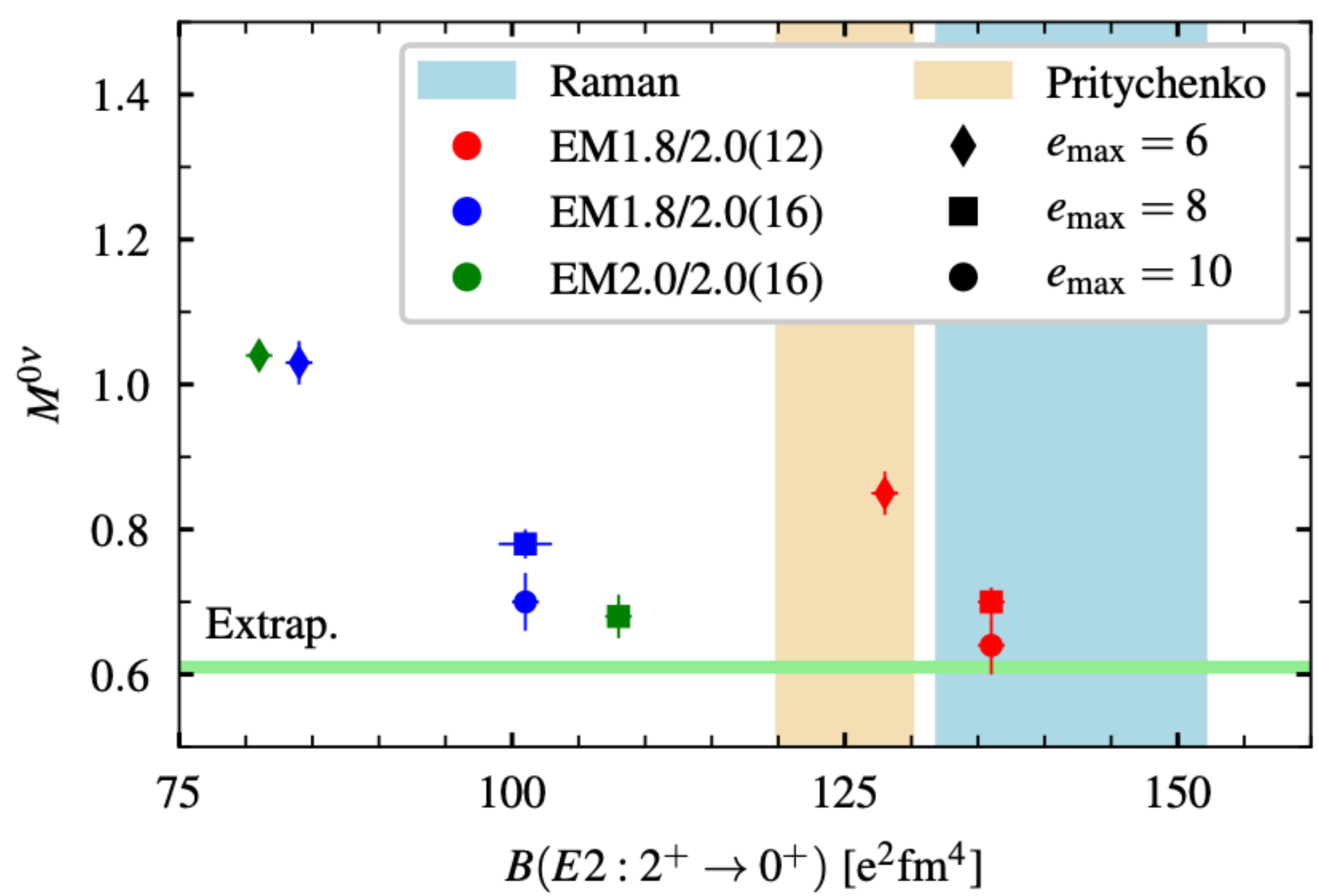
J. M. Yao et al., PRL **124**, 232501 (2020); PRC **103**, 014315 (2021)



- NME from different methods **consistent** for consistent interactions & transition operators
  (A. Belley et al., PRL 126, 042502, S. Novario et al., PRL 126, 182502)
- interpretation and features differ from empirical approaches (e.g., only **weak correlation** between NME and B(E2) value)

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

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

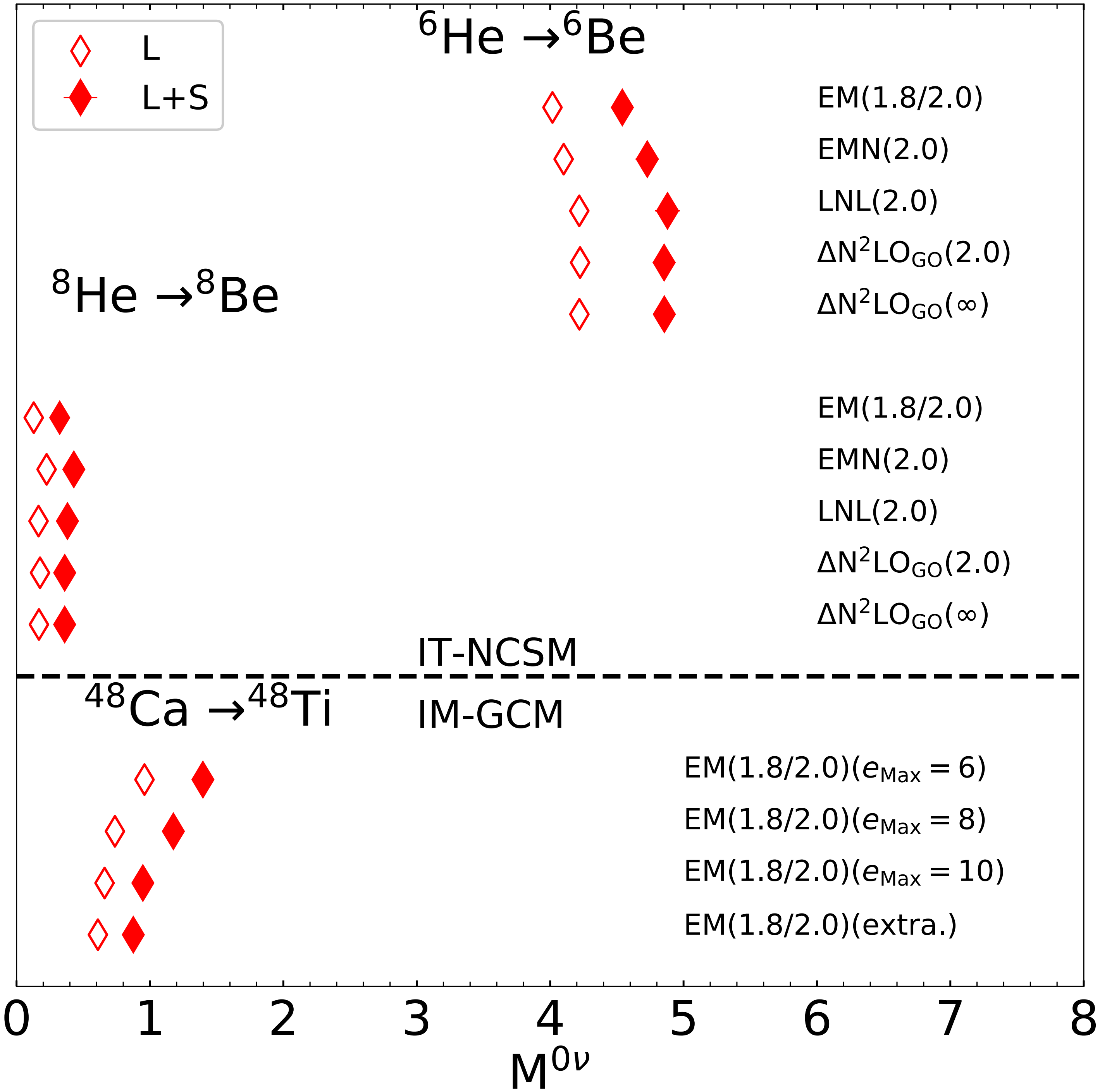


- NME from different methods **consistent** for consistent interactions & transition operators
  (A. Belley et al., PRL 126, 042502, S. Novario e
- interpretation and features differ from e
  only **weak correlation** between NME and

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

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

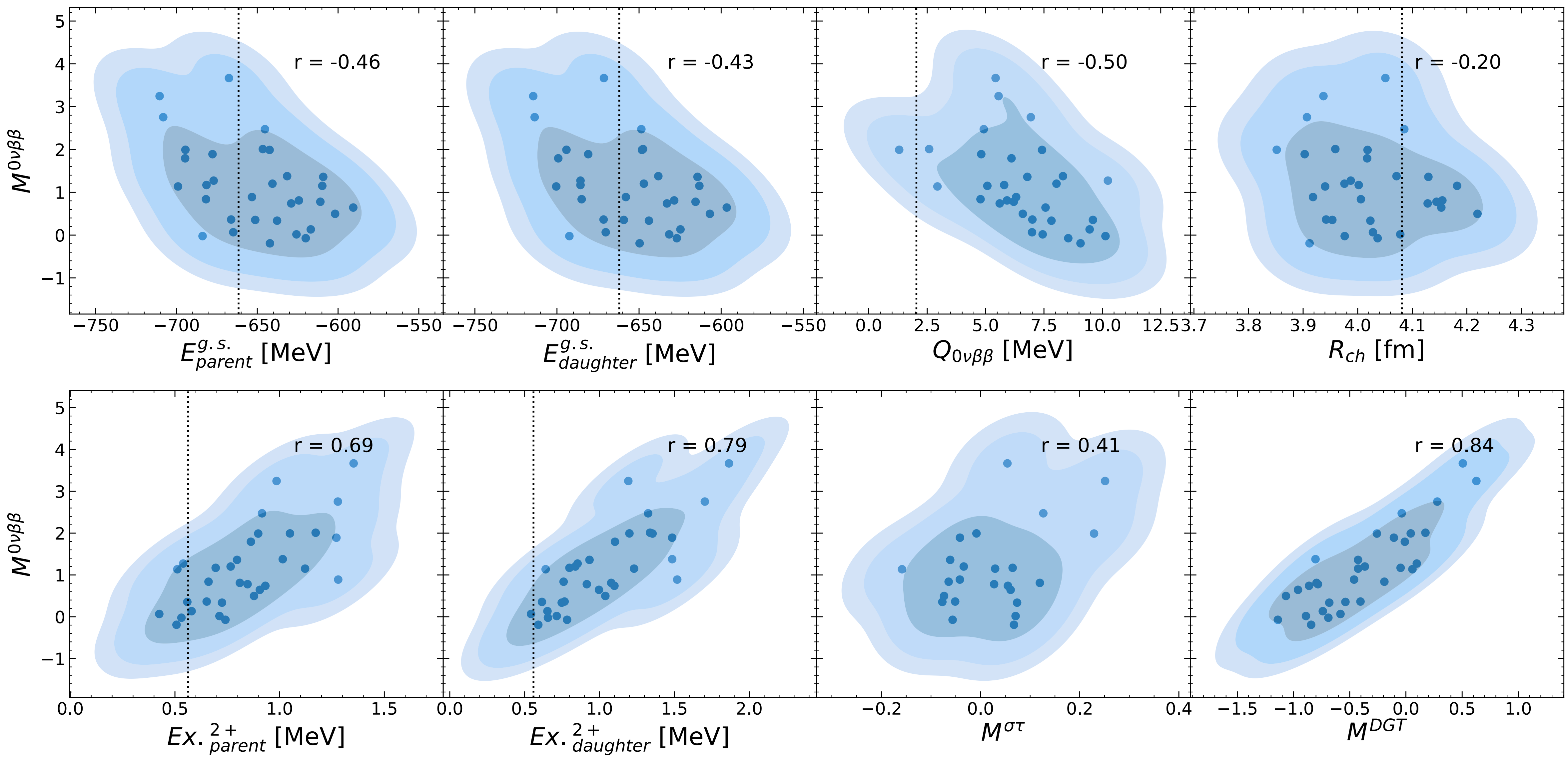
*R. Wirth, J. M. Yao, H. Hergert, PRL **127**, 242502 (2021)*



- Cirigliano et al.: RG invariance of the DBD transition operator requires **contact term**
- Counter term yields **robust enhancement**
  - varied EFT orders, RG scales, interactions
- **Next:**
  - more interactions
  - inclusion of currents
  - LEC sensitivity / UQ

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

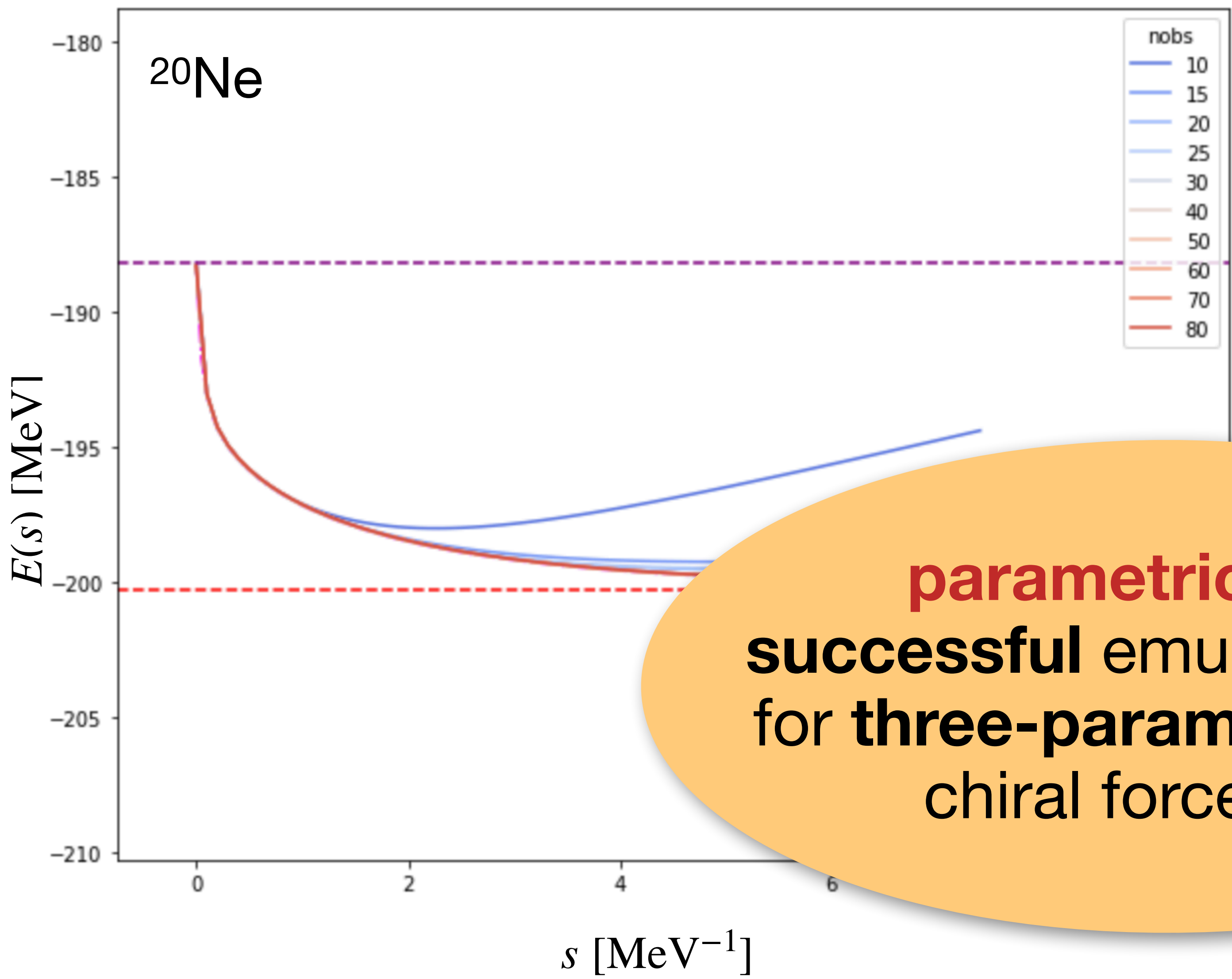
What is Next?

- **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; J. M. Yao et al., arXiv:2211.02797]
- **Uncertainty Quantification / Sensitivity Analysis**
  - need cheap **surrogate models (emulators)**

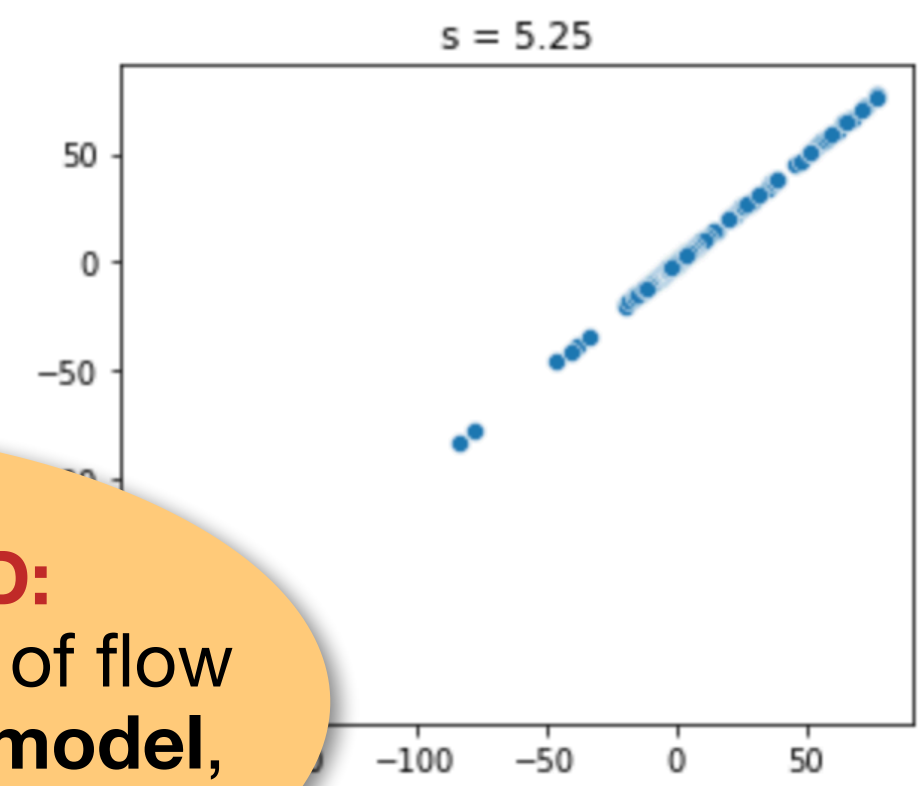
Emulating IMSRG Flows

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

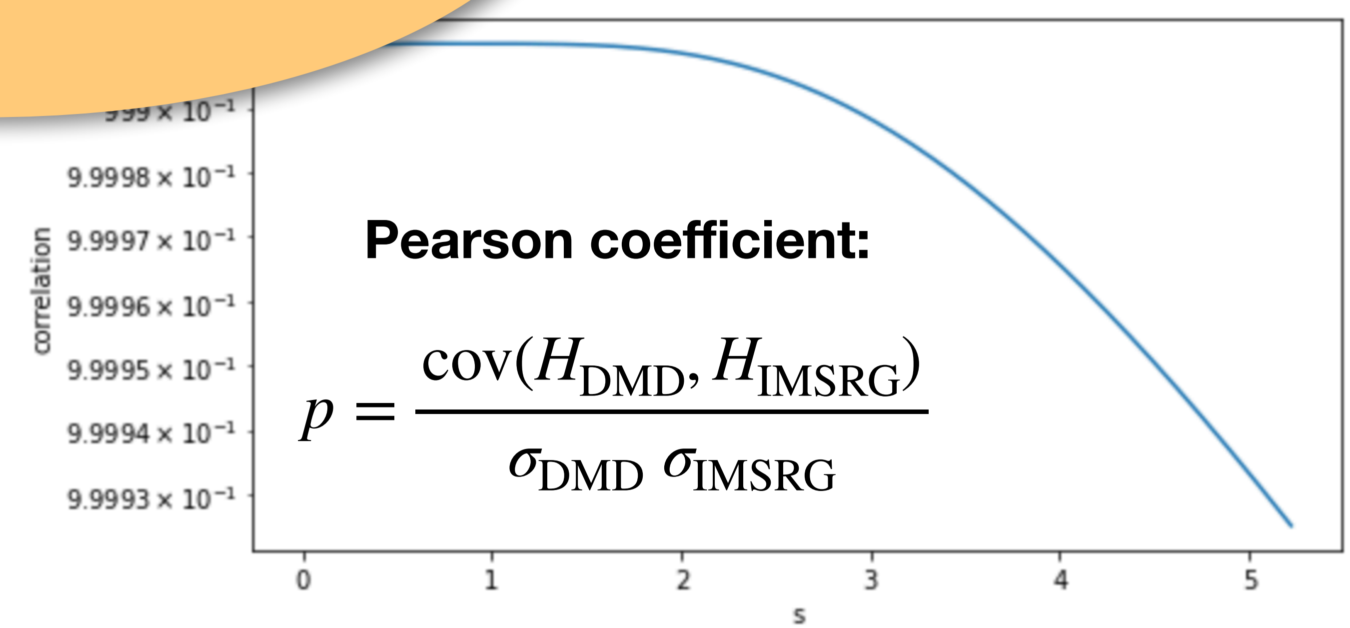
EM(500) N³LO, $\lambda = 2.0\,\mathrm{fm}^{-1}$



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



parametric DMD:
successful emulation of flow for **three-parameter model**, chiral forces next



Pearson coefficient:

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

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

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)
- 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

Matteo Agostini[*]

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

Giovanni Benato[†]

INFN, Laboratori Nazionali del Gran Sasso, 67100 Assergi, L'Aquila, Italy[‡]

Jason A. Detwiler[§]

Center for Experimental Nuclear Physics and Astrophysics and Department of Physics, University of Washington, Seattle, WA 98115, USA

Javier Menéndez[¶]

Department of Quantum Physics and Astrophysics and Institute of Cosmos Sciences, University of Barcelona, 08028 Barcelona, Spain

Francesco Vissani[**]

INFN, Laboratori Nazionali del Gran Sasso, 67100 Assergi, L'Aquila, Italy

(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.

* matteo.agostini@ucl.ac.uk
† giovanni.benato@lngs.infn.it
‡ Now at Gran Sasso Science Institute, 67100 L'Aquila, Italy
§ jasondet@uw.edu
¶ menendez@fqa.ub.edu
** vissani@lngs.infn.it

arXiv:2202.01787

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

Submitted to the Proceedings of the U.S. Community Study
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Neutrinoless Double-Beta Decay:
A Roadmap for Matching Theory to Experiment

Vincenzo Cirigliano,[1] Zohreh Davoudi,[2,*] Wouter Dekens,[1] Jordy de Vries,[3,4] Jonathan Engel,[5,†] Xu Feng,[6,7,8] Julia Gehrlein,[9,‡] Michael L. Graesser,[10,§] Lukáš Gráf,[11,12] Heiko Hergert,[13,¶] Luchang Jin,[14,15] Emanuele Mereghetti,[10,**] Amy Nicholson,[16,††] Saori Pastore,[17,18] Michael J. Ramsey-Musolf,[19,20,‡‡] Richard Ruiz,[21] Martin Spinrath,[22,23] Ubirajara van Kolck,[24,25] and André Walker-Loud[26]

[1] *Institute for Nuclear Theory, University of Washington, Seattle WA 91195-1550, USA*
[2] *Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, MD 20742, USA*
[3] *Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*
[4] *Nikhef, Theory Group, Science Park 105, 1098 XG, Amsterdam, The Netherlands*
[5] *Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27516-3255, USA*
[6] *School of Physics, Peking University, Beijing 100871, China*
[7] *Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[8] *Center for High Energy Physics, Peking University, Beijing 100871, China*
[9] *High Energy Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
[10] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[11] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[12] *Department of Physics, University of California, San Diego, CA 92093, USA*
[13] *Facility for Rare Isotope Beams and Department of Physics & Astronomy, Michigan State University, East Lansing, MI 48824-1321, USA*
[14] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[15] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Building 510, Upton, NY 11973, USA*
[16] *Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27516-3255, USA*
[17] *Department of Physics, Washington University in Saint Louis, Saint Louis, MO 63130, USA*
[18] *McDonnell Center for the Space Sciences at Washington University in St. Louis, MO 63130, USA*
[19] *Tsung Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200120 China*
[20] *University of Massachusetts, Amherst, MA 01003 USA*
[21] *Institute of Nuclear Physics – Polish Academy of Sciences* (IFJ PAN), *Kraków 31-342, Poland*
[22] *Department of Physics, National Tsing Hua University, Hsinchu, 30013, Taiwan*
[23] *Center for Theory and Computation, National Tsing Hua University, Hsinchu, 30013, Taiwan*
[24] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[25] *Department of Physics, University of Arizona, Tucson, AZ 85721, USA*
[26] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

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]

[1] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA*
[2] *Department of Physics and Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA.*
[3] *Department of Physics, University of North Carolina, Chapel Hill, NC 27514, USA*
[4] *Department of Physics, Ohio State University, Colubmus, OH 43210, USA*
[5] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[6] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[7] *FRIB Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[8] *Department of Physics, Central Michigan University, Mount Pleasant, MI 48859, USA*
[9] *Department of Physics, San Diego State University, San Diego, CA 92182, USA*
[10] *Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[11] *Computational Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[12] *INFN-TIFPA Trento Institute of Fundamental Physics and Applications, 38123 Trento, Italy*
[13] *Theory Division, Los Alamos National Laboratory, Los Alamos, NM 87544, USA*
[14] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[15] *Department of Physics and McDonnell Center for the Space Sciences, Washington University in Saint Louis, Saint Louis, MO 63130*
[16] *Industrial Engineering and Management Sciences, Northwestern University, Evanston, Illinois 60208, USA*
[17] *NAISE, Northwestern University, Evanston, Illinois 60208, USA*
[18] *Department of Physics and Astronomy and Institute of Nuclear and Particle Physics, Ohio University, Athens, OH 45701, USA*
[19] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge MA 02139, USA*
[20] *Department of Statistics and Probability, Michigan State University, East Lansing, MI 48824, USA*
[21] *Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94550*
[22] *Mathematics and Computer Science Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*

(Dated: July 5, 2022)

* engelj@physics.unc.edu
† witek@frib.msu.edu
‡ phillid1@ohio.edu

arXiv:2207.01085

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

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S. K. Bogner, B. A. Brown, J. Davison, M. Hjorth-Jensen, D. Lee, G. Perez, R. Wirth, B. Zhu
FRIB, Michigan State University

J. M. Yao
Sun Yat-sen University

S. R. Stroberg
University of Notre Dame

T. R. Rodríguez
Universidad Autonoma de Madrid

J. Engel, A. M. Romero
University of North Carolina - Chapel Hill

P. Arthuis, K. Hebeler, M. Heinz, R. Roth, T. Mongelli, T. Miyagi, A. Schwenk, A. Tichai
TU Darmstadt

C. Haselby, M. Iwen, A. Zare
CMSE, Michigan State University

K. Fossez
Florida State University

A. Belley, J. D. Holt, P. Navrátil
TRIUMF, Canada

G. Hagen, G. Jansen, J. G. Lietz, T. D. Morris, T. Papenbrock
UT Knoxville & Oak Ridge National Laboratory

B. Bally, T. Duguet, M. Frosini, V. Somà
CEA Saclay, France

R. J. Furnstahl
The Ohio State University

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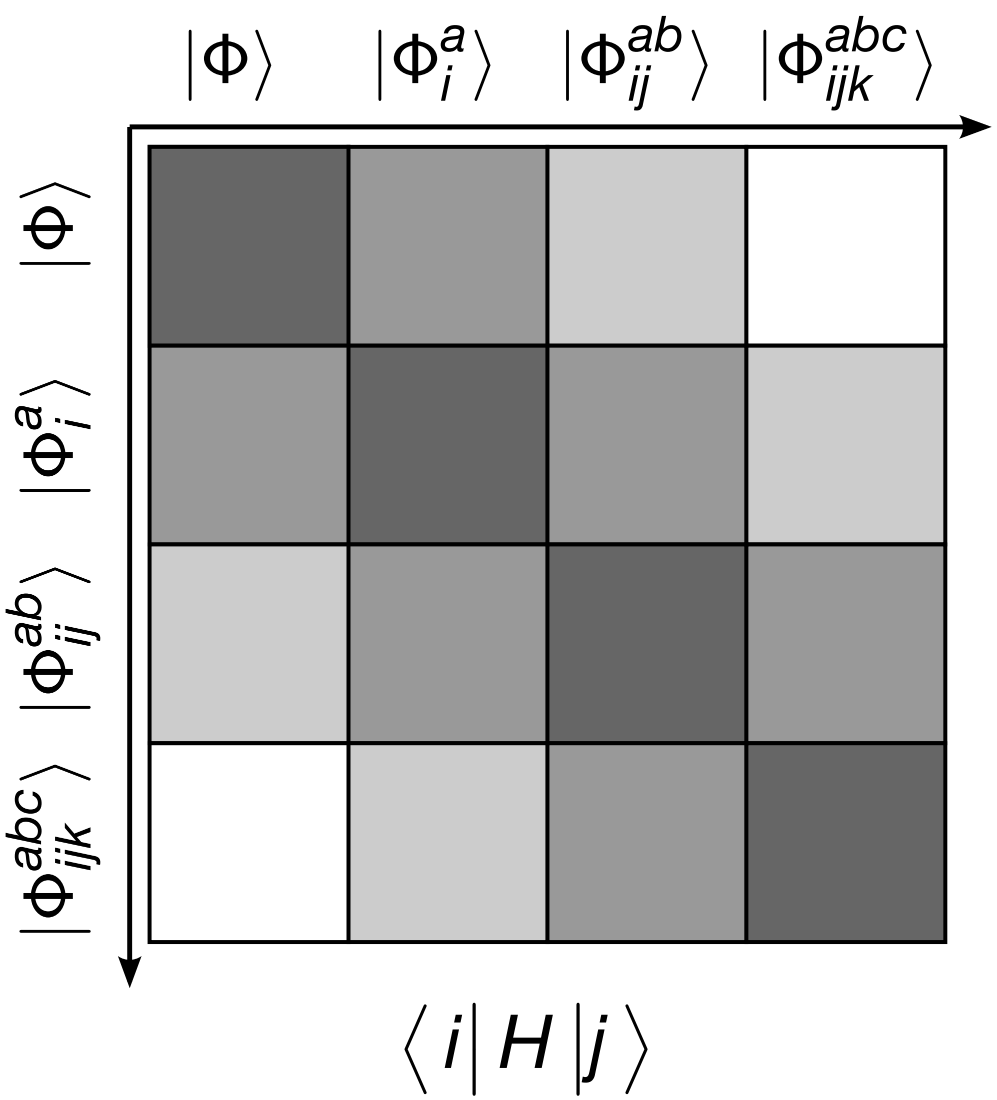
Supplements

Transforming the Hamiltonian

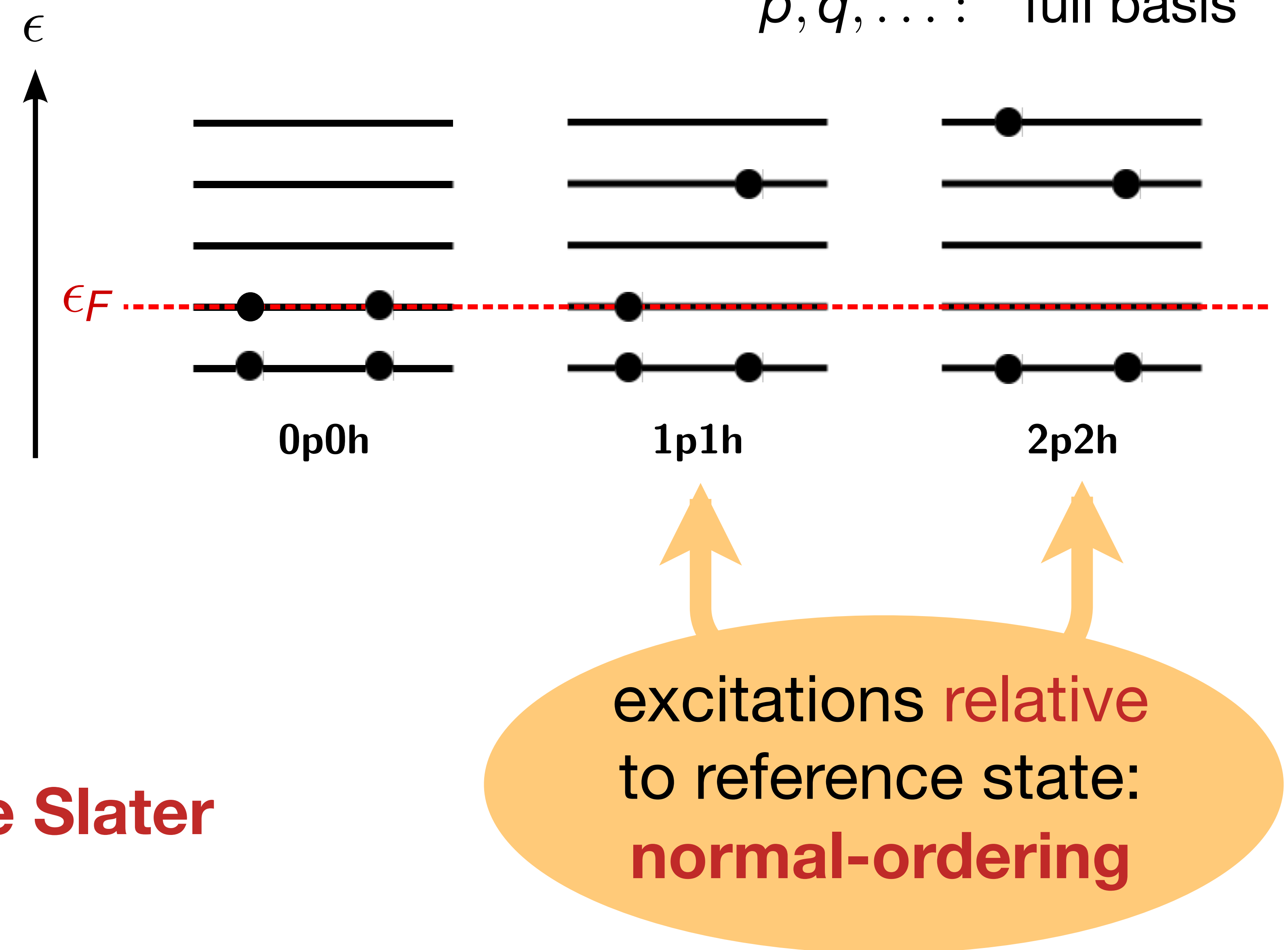


- reference state: **single Slater determinant**

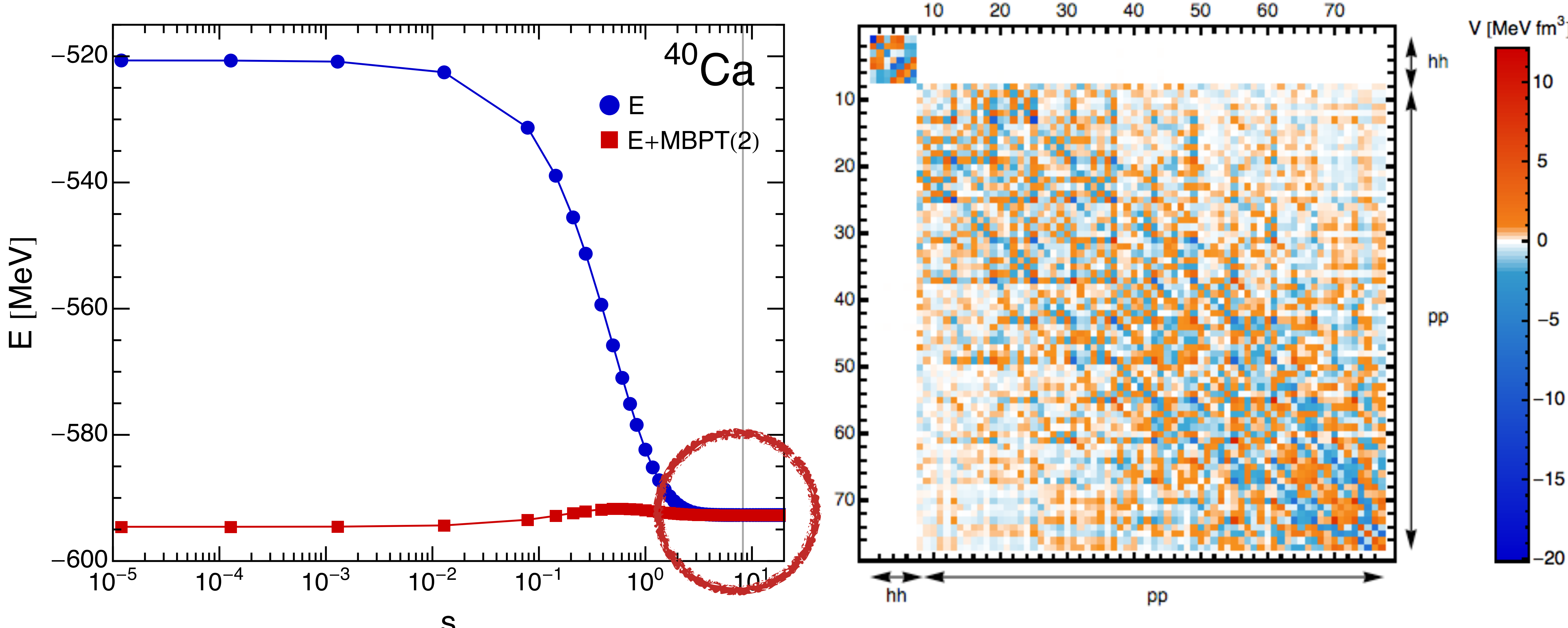
$a, b, \ldots : \quad \epsilon > \epsilon_F$

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

$p, q, \ldots :$ full basis



Decoupling

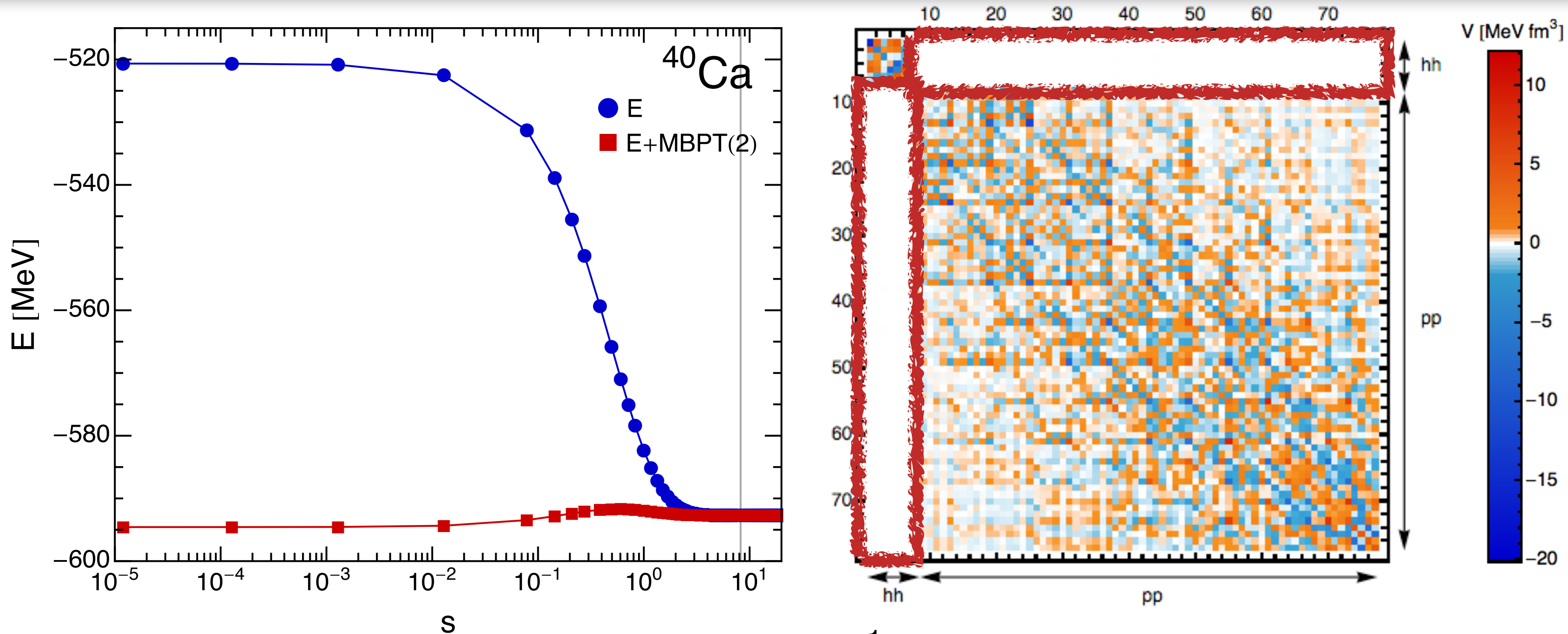


N3LO, $\lambda = 2.0\ \mathrm{fm}^{-1}, e_{\mathrm{Max}} = 8$

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

off-diagonal couplings are rapidly driven to zero

Decoupling



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

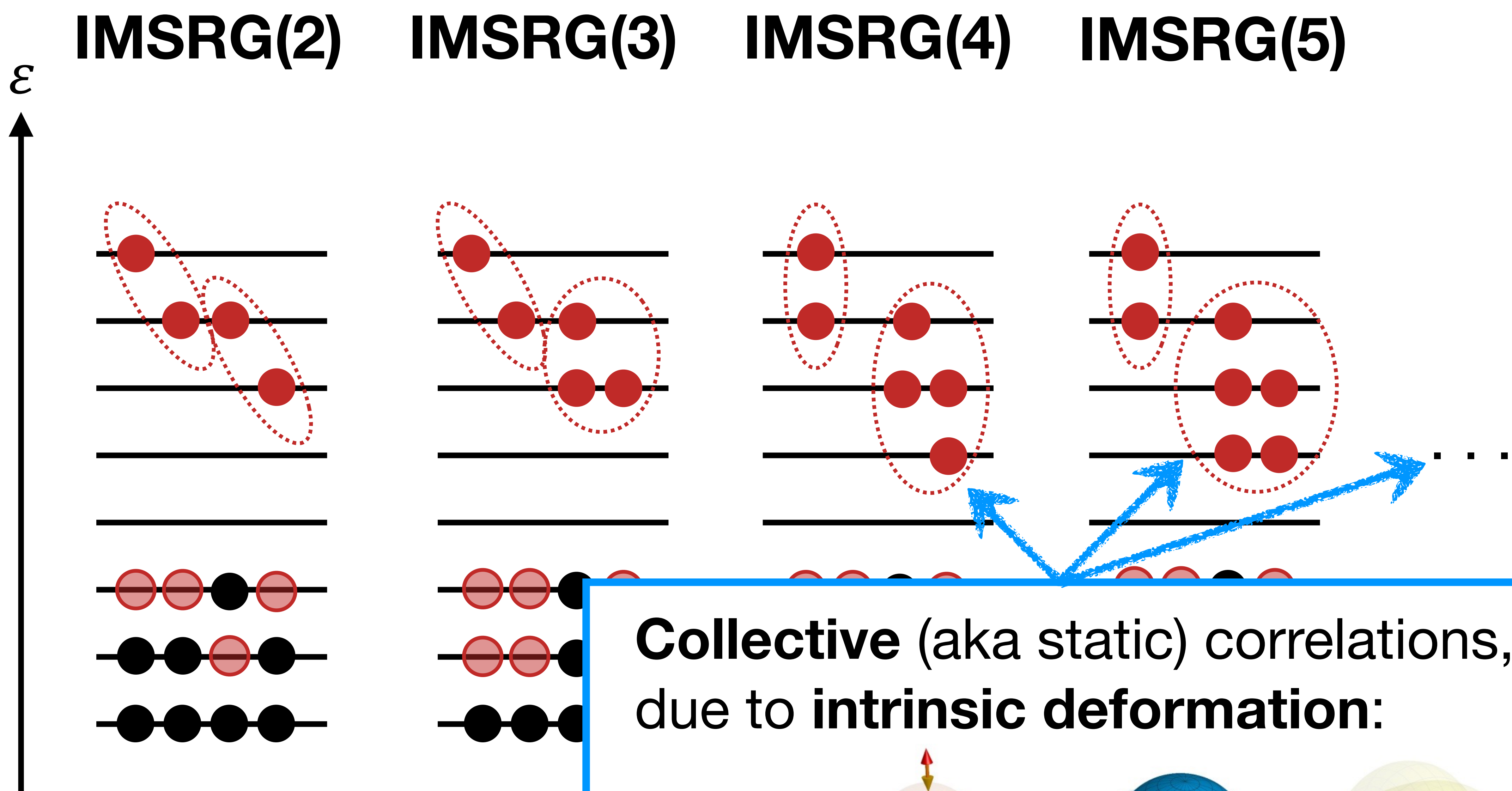
- absorb correlations into **RG-improved Hamiltonian**

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

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

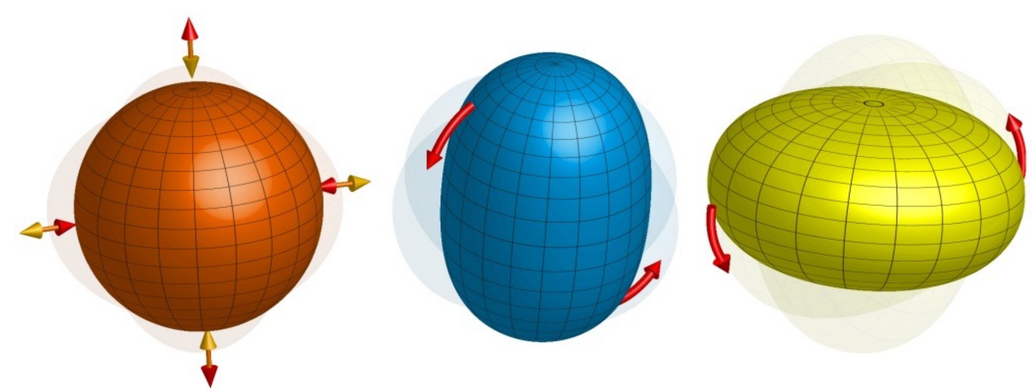
$$U(s)\left|\Psi_n\right\rangle \stackrel{!}{=} \left|\Phi\right\rangle$$

Correlated Reference States

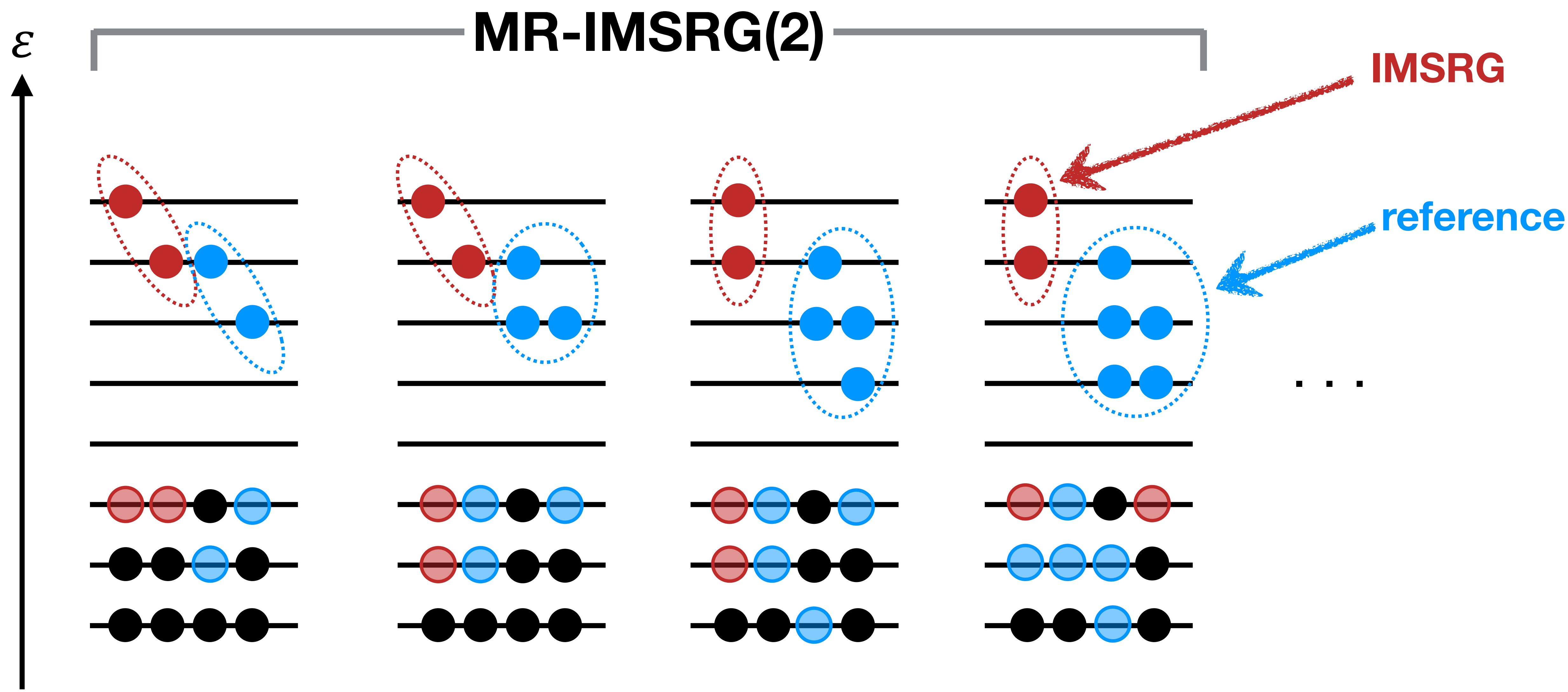


"standard" IMS
Slater determinar

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

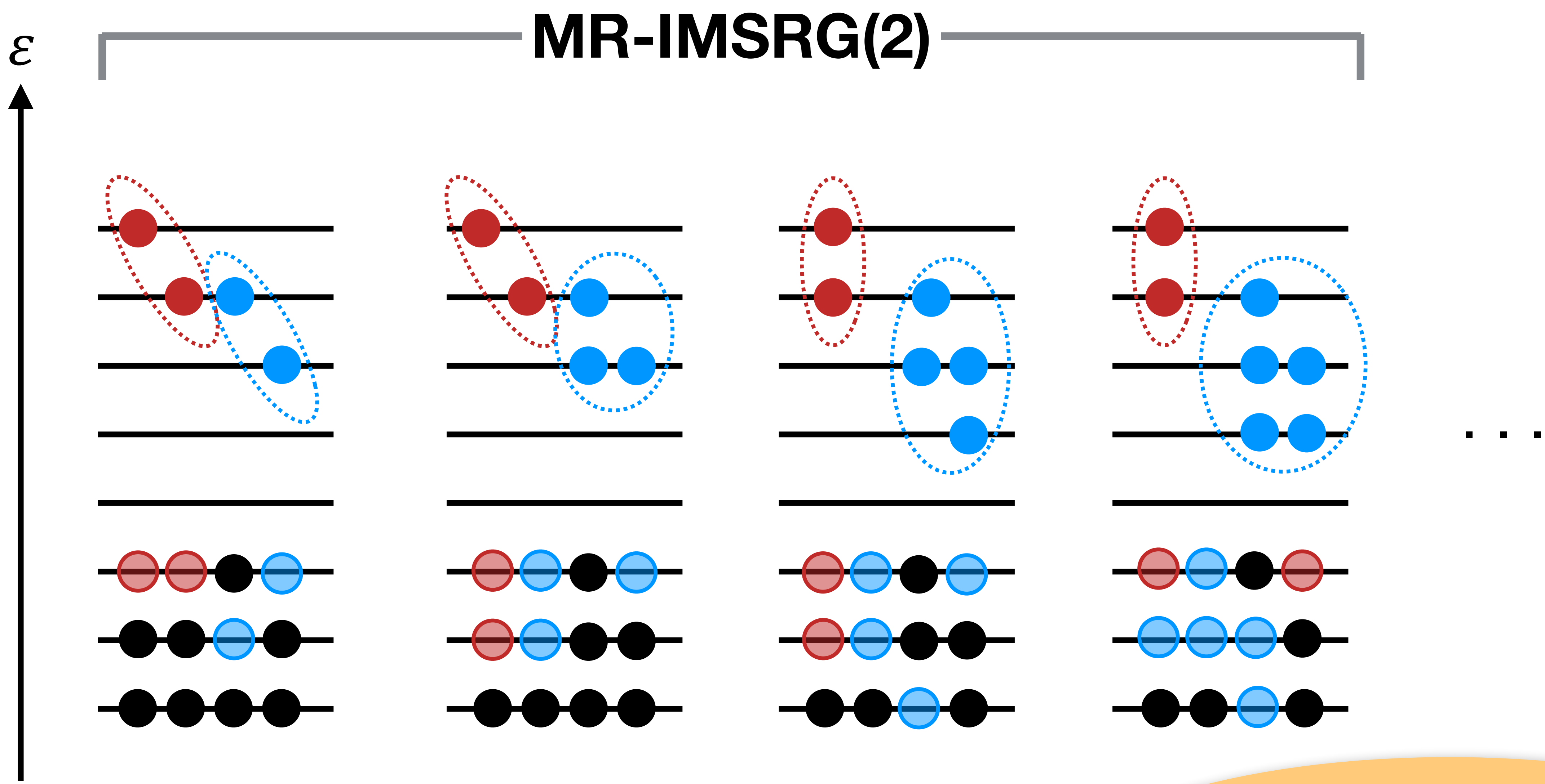


Correlated Reference States



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

Correlated Reference States



MR-IMSRG: build correlations
already correlated state (e.g., fro
describes static correlation

use generalized normal ordering with 2B,… densities