

Ab Initio Theory for Neutrinoless Double-Beta Decay: Recent Developments

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



Overview



- Inputs - V. Cirigliano
- Application / Correlation Analysis - A. Lovato
- Many-Body Methods - HH

DISCLAIMER: This list is not exhaustive.

- **Lattice QCD**
 - Controlling excited state contamination
He et al. arXiv:2104:05226, Walker-Loud et al. POS(CD2018), 020
 - Matching LQCD to EFT
Davoudi & Kadam PRL 126, 152003 and arXiv:2111:11599
- **EFT**
 - Short-range contribution to the transition operator
Cirigliano et al., PRL 126, 172002; JHEP 05(2021), 289
 - Short presentation by V. Cirigliano

Many-Body Methods



DISCLAIMER: This list is not exhaustive.

- **Coupled Cluster**

- deformed CC + angular momentum projection
Hagen et al., arXiv:2201.07298

- **IMSRG Methods**

- addition of 3p3h correlations / triples
Heinz (PRC 103, 044318), HH et al. (J. Phys. Conf. Ser. 1041, 012007 & in progress), Stroberg et al. in progress

- IM-GCM

- configuration selection algorithm

Romero et al., PRC 104, 054317

- perturbative enhancement

Frosini et al., arXiv:2111.01461

DISCLAIMER: This list is not exhaustive.

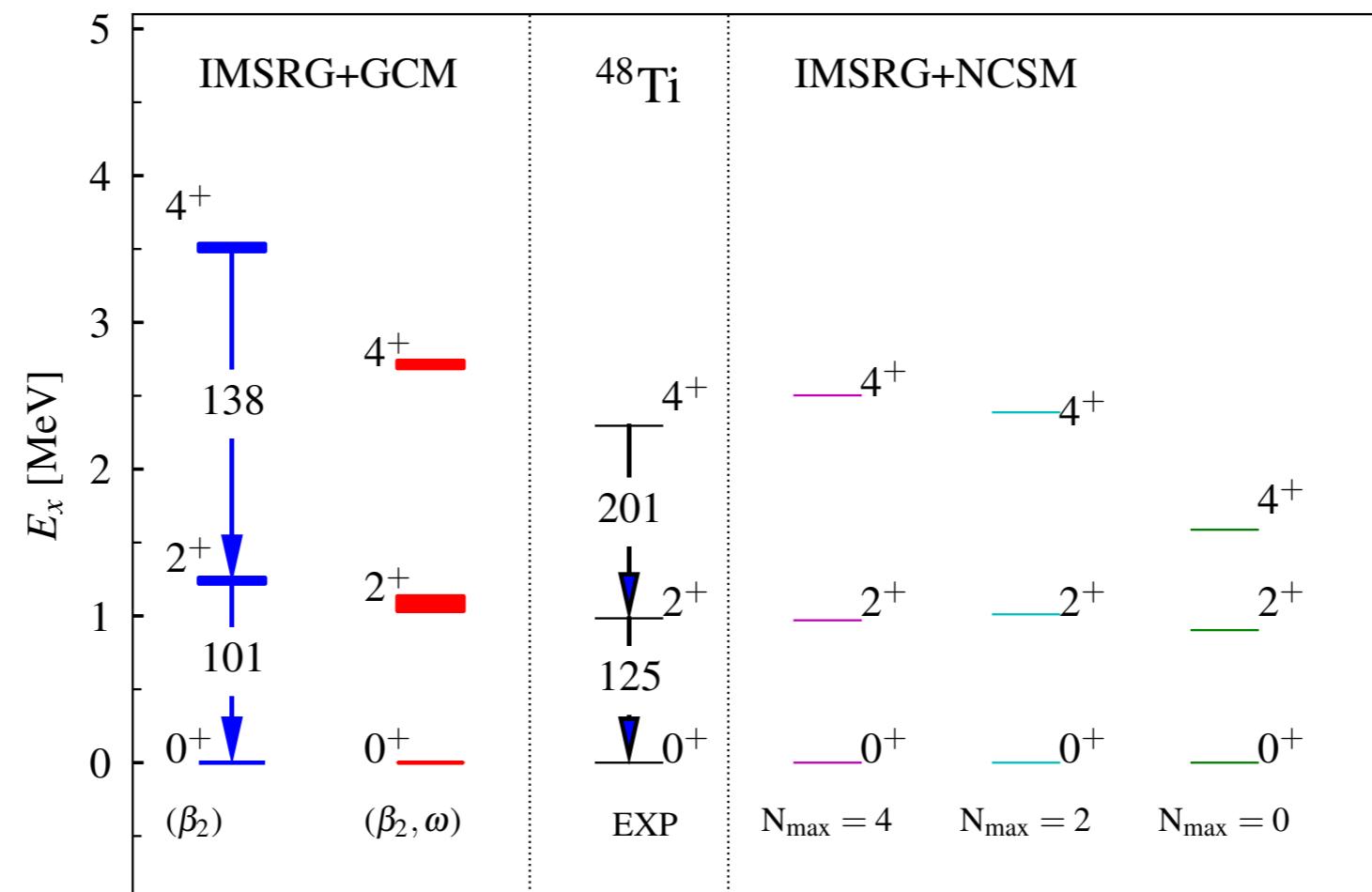
- Short presentation by A. Lovato: Contact formalism for DBD
Weiss et al., arXiv:2112.08146
- Short-Range contribution in empirical calculations
Jonkiniemi et al., PLB **823**, 136720
- Constraints from correlations between NLDBD and other processes:
 - $0\nu\beta\beta$ vs. $2\nu\beta\beta$, DGT, $\gamma\gamma$, ... (Menendez)
Romeo, et al., arXiv:2102.11101, Shimizu et al., PRL **120**, 142502
 - double charge exchange reactions ?
Cavallaro et al., arXiv:2002.02761; Cappuzzello et al., EPJA **51**, 145 (2015)
- EFT for Heavy Nuclei
Brase et al., arXiv:2108.11805

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)

EM1.8/2.0, $\hbar\Omega = 16$ MeV

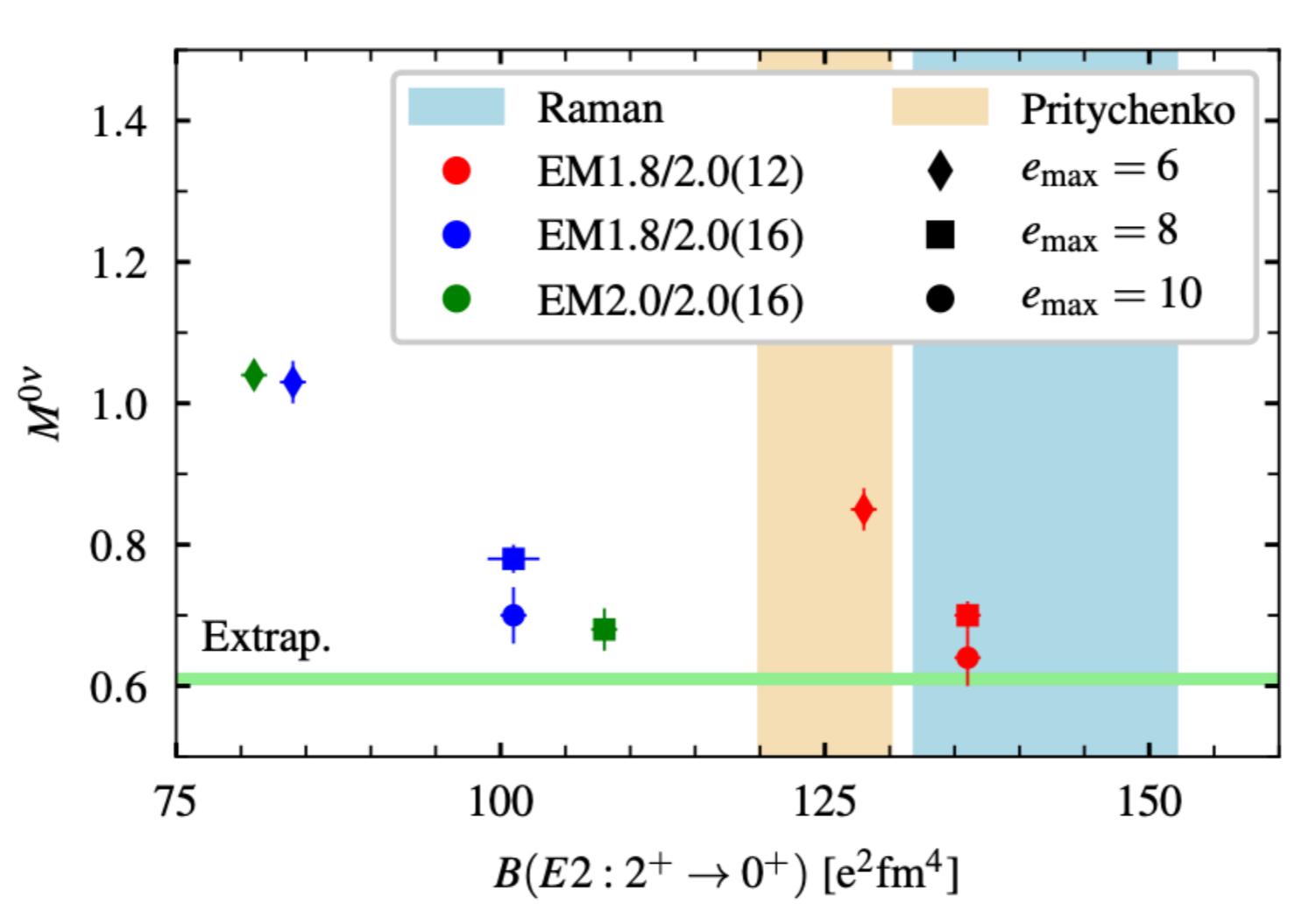


- **consistency** between IM-GCM and IM-NCSM
- nuclear matrix element **insensitive to spread of spectrum**
 - Compatibility with “lore” based on phenomenological interactions? (**scale/scheme dependence**)

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



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

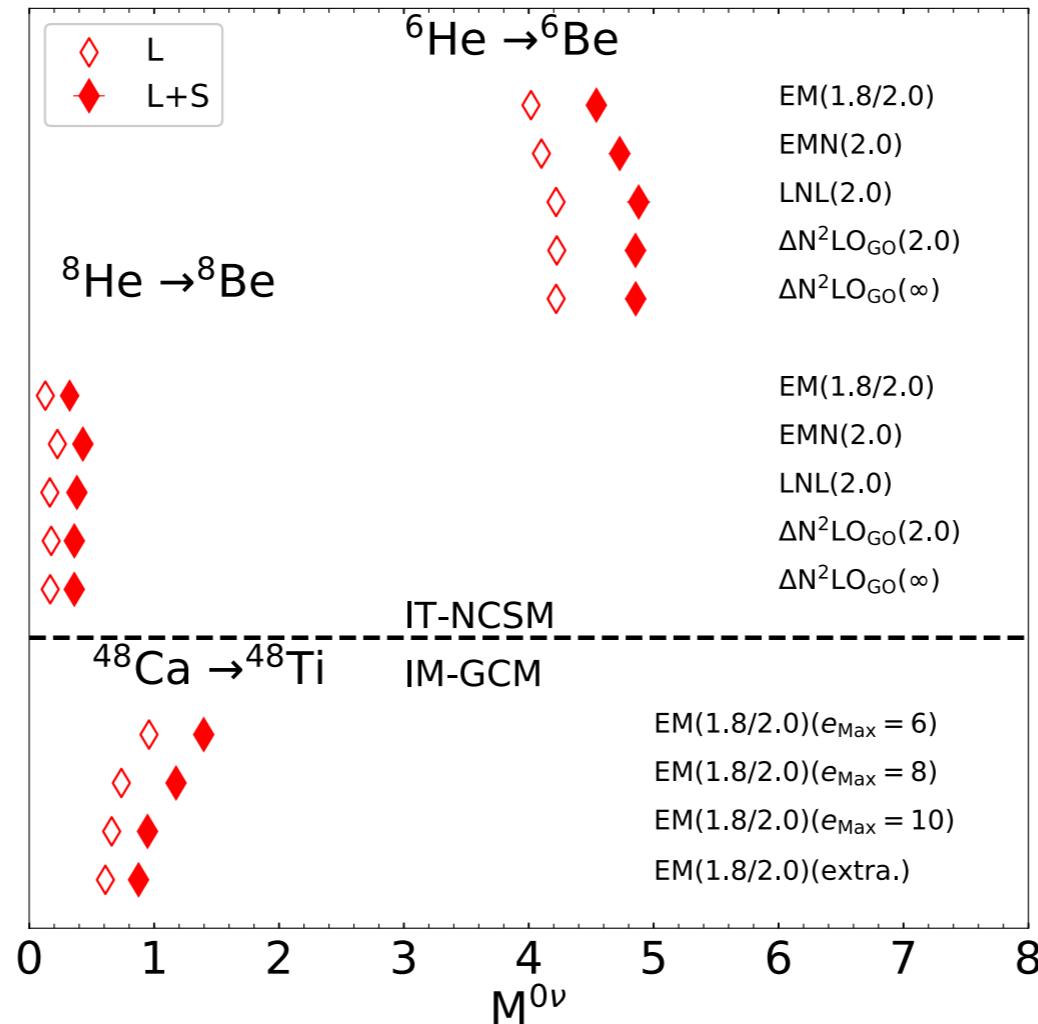


- NME from different methods **consistent** for consistent interactions & transition operators
(A. Belley et al., PRL 126, 042502, S. Novario et al., PRL 126, 182502)
- interpretation and features differ from empirical approaches (e.g., only **weak correlation** between NME and $B(E2)$ value)

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



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



- Short-range contribution yields **robust enhancement**
 - varied EFT orders, RG scales, interactions
 - additional validation that synthetic amplitude is weakly scheme dependent (cf. Jonkiniemi et al., PLB 823, 136720; Weiss et al., arXiv: 2112.08146)

Starting the “Shopping List”



- **Inputs from Lattice QCD, EFT**
 - pipeline for currents, transition operators for other mechanisms, ...
 - matching of LECs (regulators, ...)
- **Interactions & Operators for Nuclear Structure**
 - free-space SRG incl. induced 3B, in place (Navratil, Quaglioni) - only need to setup workflow (?)
 - new organization of routines to facilitate LEC variation (for use with emulators in UQ)

Starting the “Shopping List”



- **Many-Body Calculations**
 - efficient triples-level for UQ & sensitivity analysis
 - emulators ((IM)SRG: full operators / emulation in theory space, more complicated than EC)
- **Correlation Analysis**
 - e.g., $0\nu\beta\beta$ vs. $2\nu\beta\beta$, DGT, $\gamma\gamma$, ...
 - empirical models vs ab initio:
 - Spurious correlations due to simple Hamiltonians / EDFs, or...
 - ... do ab initio calculations require currents etc.?

Acknowledgments

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

J. M. Yao
Sun Yat-sen University

S. R. Stroberg
Argonne National Laboratory

B. Bally, T. R. Rodríguez
Universidad Autonoma de Madrid

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

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

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

K. Fossez
Florida State University

J. Rotureau
Lund University

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

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

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

R. J. Furnstahl
The Ohio State University

Grants: US Dept. of Energy, Office of Science, Office of Nuclear Physics **de-sc0017887** and **de-sc0018083**
(SciDAC-4 NUCLEI Collaboration)



NUCLEI
Nuclear Computational Low-Energy Initiative

NERSC

ICER

Supplements

Capturing Collective Correlations: IM-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)

In-Medium GCM



J. M. Yao, et al., *PRC* **98**, 054311 (2018), *PRL* **124**, 232501 (2020), *arXiv*: 2010.08609

GCM
define
reference

- no-core (or valence space) GCM calculation to prepare reference state



IMSRG
evolve
operators

- evolve Hamiltonian and observables with MR-IMSRG
- decoupling in A-body space



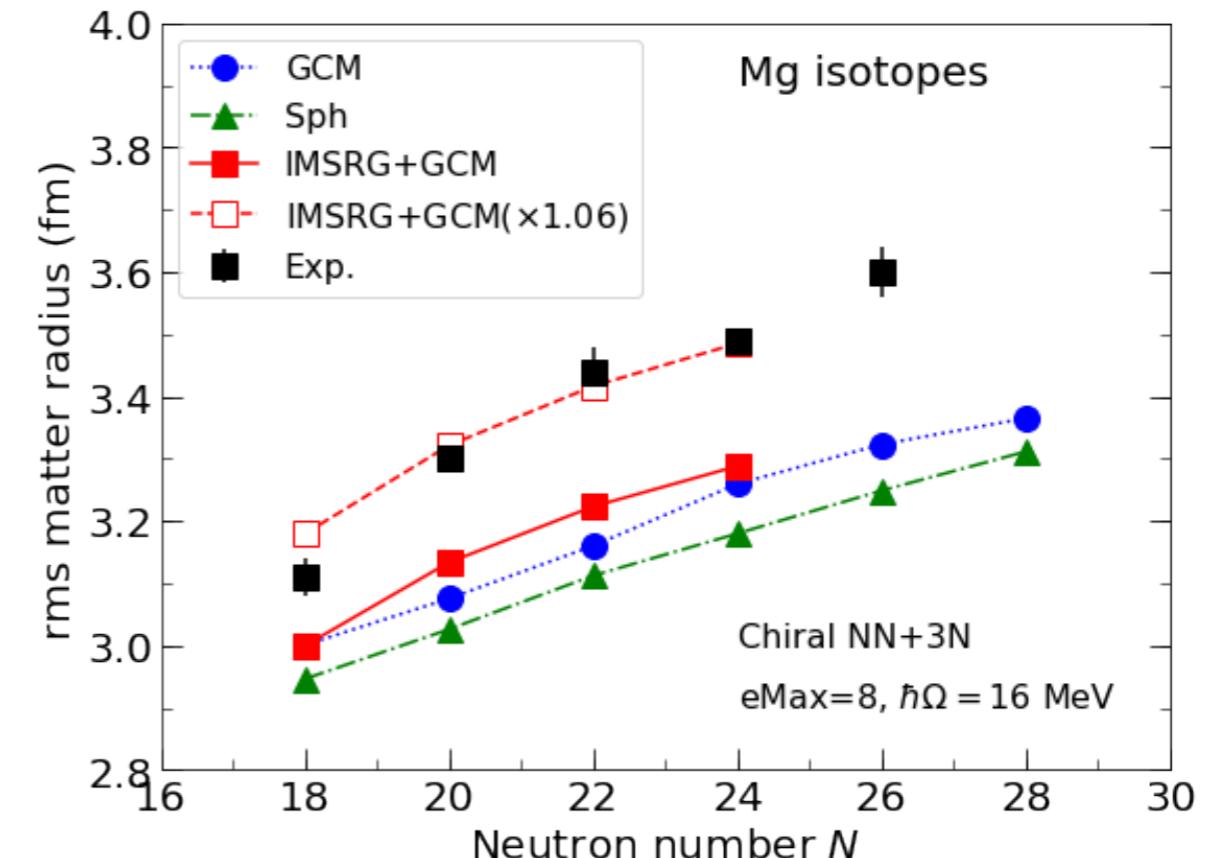
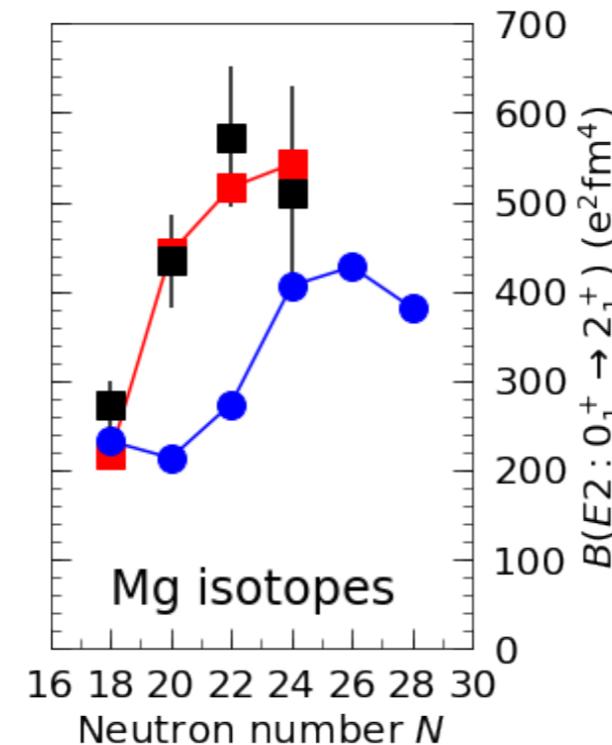
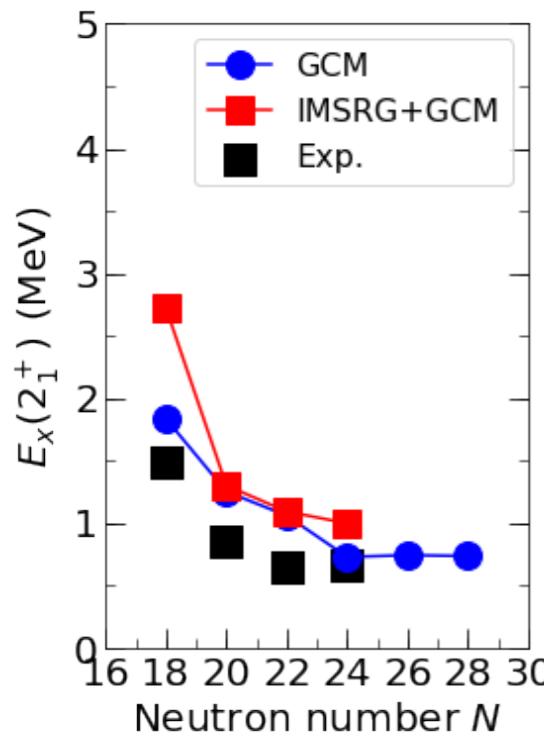
GCM
extract
observables

- no-core GCM calculation using evolved Hamiltonian
- calculate GCM wave functions, observables

Collectivity in Magnesium Isotopes



J. M. Yao, HH, *in preparation*

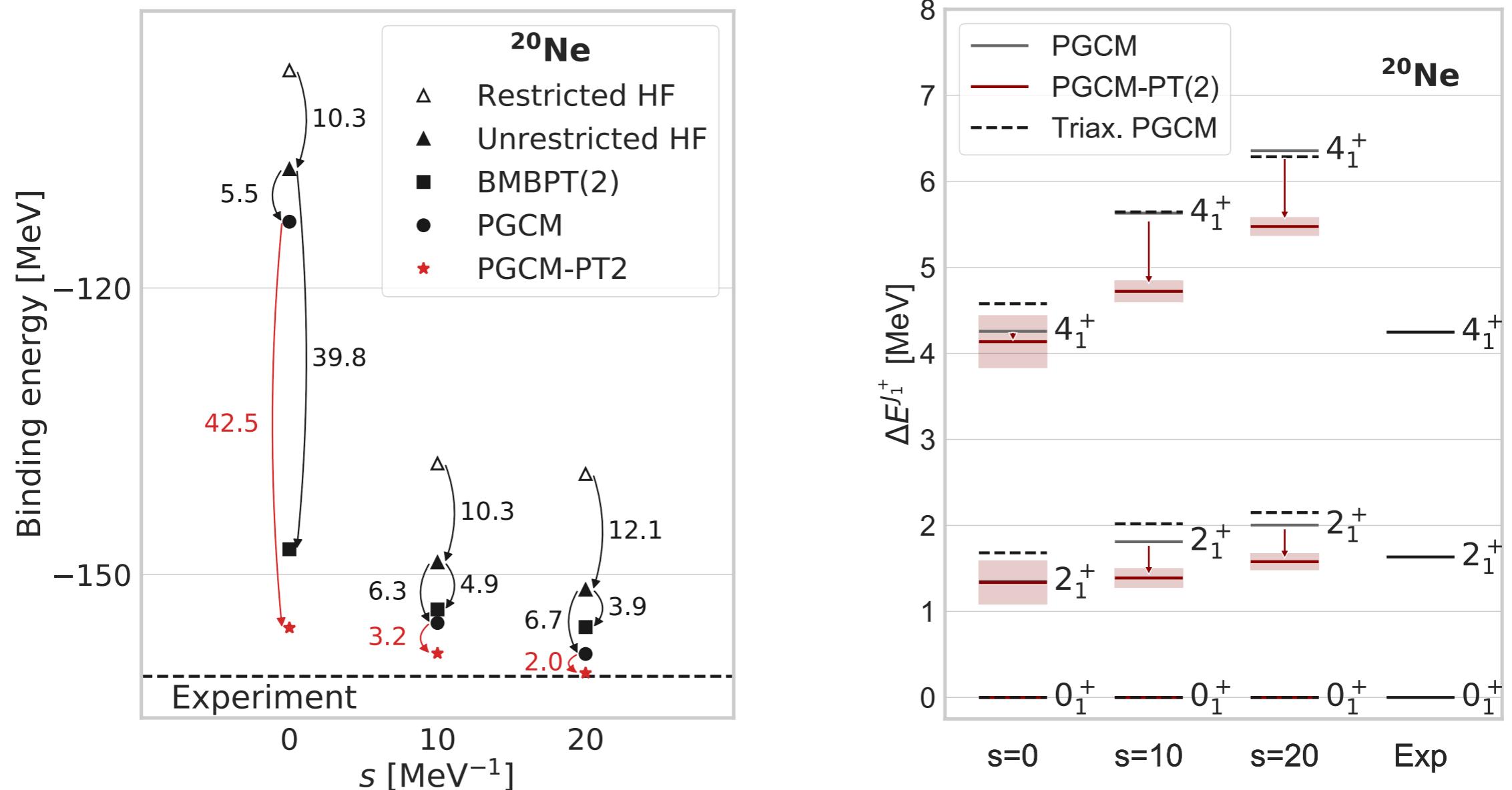


- significantly increased $B(E2)$ values for $^{32,34}\text{Mg}$ compared to GCM calculation or VS-IMSRG calculations: **dynamical and static correlations!**
- **induced 2B quadrupole operator is small**, contrary to typical VS-IMSRG findings: GCM reference equips operator basis with better capability to capture collectivity

Perturbative Enhancement of IM-GCM



M. Frosini et al., arXiv:2110.15737, arXiv:2111.00757, arXiv:2111.01461



- **PGCM-PT:** perturbation theory for projected GCM states
- IMSRG shuffles dynamical correlation into operators
 - **need IMSRG(3) for certain observables**