The PGCM and its connection to collective states and resonances

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Introduction

NUCLEAR THEORY ⟶ solve the many-body problem (structure, reactions).

Difficulties:

a. Challenging nature of nuclear interaction
b. Quantum A-body coupled system

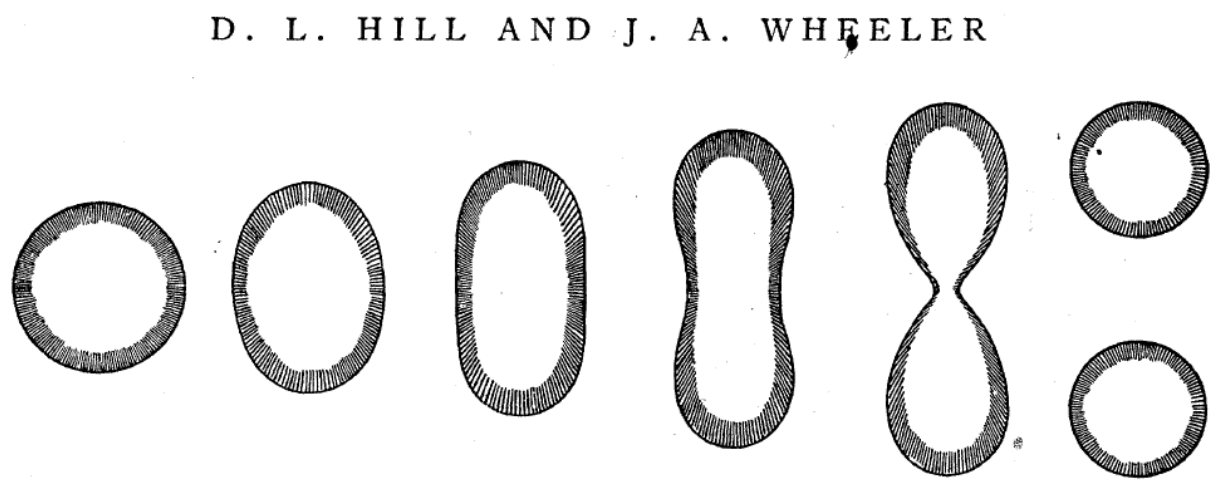
Even if we knew the nuclear interaction: exact energies and wave functions out of reach due to the immense dimensionality of Many-Body Hilbert Space

➢ **Approximate Methods**: variational principle

- Quasiparticle Random Phase Approximation (QRPA)
- …
- Projected Generator Coordinate Method (PGCM)

Introduction

PGCM: symmetry-restored Generator Coordinate Method (GCM)



D. L. Hill, J. A. Wheeler, *Phys. Rev.* **89**, 1102 (1953)

Quantum linear superposition of product states

Introduction

PGCM: symmetry-restored Generator Coordinate Method (GCM)

- First PGCM implementations (SCCM, MR-EDF):

  Gogny: R. Rodríguez-Guzmán, J. L. Egido, L. M. Robledo, *Phys Lett. B* **474**, 15 (2000)

  Skyrme: P.-H. Heenen, A. Valor, M. Bender, P. Bonche, H. Flocard, *Eur Phys J A* **11**, 393–402 (2001)

  Relativistic MF: T. Nikšić, D. Vretenar, P. Ring , *Phys. Rev. C* **73**, 034308 (2006)

- Even though historically PGCM has been associated with EDF, nowadays it has been extended to other kind of interactions

- Related methods:
  - Discrete non-orthogonal shell model (DNO-SM)
  - Monte Carlo shell model (MCSM)

Introduction

- Kind of nuclei

- even-even nuclei (blocking required if multi-quasiparticle excitations are included)
- even-odd/odd-even nuclei (blocking mandatory) 🔥
- odd-odd nuclei (blocking mandatory) 🔥

- Observables and physical quantities

- Ground state and excitation energies
- electromagnetic transition probabilities (low-lying states)
- Beta-decay rates 🔥
- Electromagnetic responses / resonances (higher-lying states) 🔥

Contents

PGCM: ansatz

Variational method based on the mixing of configurations. The many-body wave functions of the system is expressed as:

$$|\Psi_{\sigma}^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} P_{MK}^{J} P^{N} P^{Z} P^{\pi} |\Phi(q)\rangle$$

coefficients — intrinsic (projected) states

PGCM: ansatz

Variational method based on the mixing of configurations. The many-body wave functions of the system is expressed as:

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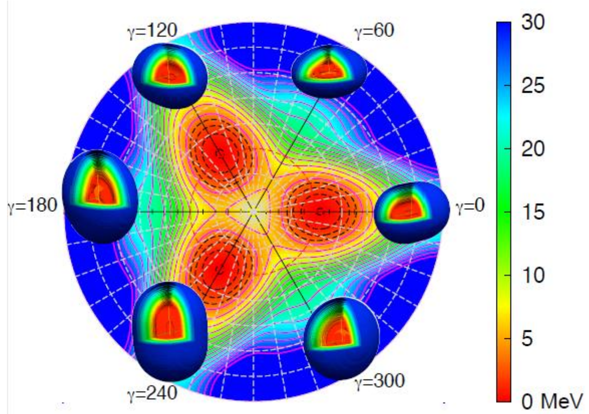
Where:

- $\{|\Phi(q_i)\rangle\}$ is a set of intrinsic many-body wave functions defined parametrically along the variables, q
  - Multipole deformations
  - Pairing correlations
  - Cranking
  - …
  - Several at the same time



T. R. Rodríguez and J. L. Egido
Phys. Rev. C **81**, 064323 (2010)

“You are the architect of your own destiny.” - Ralph Waldo Emerson

(and your PGCM calculations)

PGCM: ansatz

Variational method based on the mixing of configurations. The many-body wave functions of the system is expressed as:

$$|\Psi_{\sigma}^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} P_{MK}^{J} P^{N} P^{Z} P^{\pi} |\Phi(q)\rangle$$

Intrinsic self-consistent mean-field (HFB-like, Bogoliubov quasiparticle vacuum) states:

$$\beta_b^{\dagger}(q) = \sum_a U_{ab}(q) c_a^{\dagger} + V_{ab}(q) c_a \qquad |\Phi(q)\rangle = \prod_{j=1}^{A} \beta_j(q) \, | - \rangle \quad \longrightarrow \quad \beta_k(q)|\Phi\rangle = 0 \;\; \forall \, k$$

But these states are not limited to be quasiparticle vacua! $|\Phi_{k_1 k_2}(q)\rangle = \beta_{k_1}^{\dagger}(q)\beta_{k_2}^{\dagger}(q)|\Phi(q)\rangle$

Blocking

- For odd-mass and odd-odd nuclei, blocking must be applied by definition.

PGCM: ansatz

Variational method based on the mixing of configurations. The many-body wave functions of the system is expressed as:

$$|\Psi_{\sigma}^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} P_{MK}^{J} P^{N} P^{Z} P^{\pi} |\Phi(q)\rangle$$

We minimize the (constrained) energy functional:

$$\beta_b^{\dagger}(q) = \sum_a U_{ab}(q) c_a^{\dagger} + V_{ab}(q) c_a$$

variational

$$E[|\Phi(q)\rangle] = \frac{\langle\,\Phi(q)\,|\,\hat{H}\,|\,\Phi(q)\,\rangle}{\langle\,\Phi(q)\,|\,\Phi(q)\,\rangle} - \langle\,\Phi(q)\,|\,\lambda_q\,\hat{Q}\,|\,\Phi(q)\,\rangle$$

$$E'_{\text{PNVAP}}\left[|\Phi(q)\rangle\right] = \frac{\langle\Phi(q)|\hat{H}P^{N}P^{Z}|\Phi(q)\rangle}{\langle\Phi(q)|P^{N}P^{Z}|\Phi(q)\rangle} - \langle\Phi(q)|\lambda_q\hat{Q}|\Phi(q)\rangle$$

PGCM: ansatz

Variational method based on the mixing of configurations. The many-body wave functions of the system is expressed as:

$$|\Psi_\sigma^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} P_{MK}^J P^N P^Z P^\pi |\Phi(q)\rangle$$

projection operators

Symmetry restoration (lost at mean-field level):

$P_{MK}^J \longrightarrow$ angular momentum projection operator

$P^N \longrightarrow$ neutron number projection operator

$P^Z \longrightarrow$ proton number projection operator

$P^\pi \longrightarrow$ spatial parity projection operator

PGCM: ansatz

Variational method based on the mixing of configurations. The many-body wave functions of the system is expressed as:

$$|\Psi_\sigma^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} P_{MK}^J P^N P^Z P^\pi |\Phi(q)\rangle$$

where

- $f_{\sigma;qK}^{JMNZ\pi}$ are the PGCM variational parameters that minimize the energy.

$$\delta E[|\Psi^\sigma\rangle] = 0 \Rightarrow \sum_{q'K'} \left(\mathcal{H}_{qK,q'K'}^\Gamma - E_\sigma^\Gamma \mathcal{N}_{qK,q'K'}^\Gamma\right) f_{\sigma;q'K'}^\Gamma = 0$$

$\Gamma \equiv (JMNZ\pi)$

Hill-Wheeler-Griffin (HWG) equation

$$\mathcal{H}_{qK,q'K'}^\Gamma = \langle\Phi(q)|\hat{H} P_{KK'}^J P^N P^Z P^\pi|\Phi(q')\rangle$$
$$\mathcal{N}_{qK;q'K'}^\Gamma = \langle\Phi(q)|P_{KK'}^J P^N P^Z P^\pi|\Phi(q')\rangle$$

Generalized eigenvalue problem!

PGCM: solution of the HWG equation

How do we get to the usual eigenvalue problem? Creating an orthonormal basis

1. Finding the eigenvalues and eigenvectors of the norm overlap matrix:

$$\sum_{j=1}^{N_{\text{int}}} \mathcal{N}_{q_i,q_j} u_{\lambda_k,q_j} = \lambda_k u_{\lambda_k,q_i}$$

2. From them, building a set of orthonormal states ("natural basis"):

$$|\Lambda_k\rangle = \sum_{i=1}^{N_{\text{int}}} \frac{u_{\lambda_k,q_i}}{\sqrt{\lambda_k}} |\Phi_{q_i}\rangle \qquad \langle\Lambda_k|\Lambda_{k'}\rangle = \delta_{k,k'}$$

3. Rewriting the HWG equation and the PGCM ansatz wave function:

$$\sum_{k'=1}^{N_{\text{nat}}} \langle\Lambda_k|\hat{H}|\Lambda_{k'}\rangle g_{k'}^{\sigma} = E^{\sigma} g_k^{\sigma}$$

Regular eigenvalue problem!

$$|\Psi^{\sigma}\rangle = \sum_{k=1}^{N_{\text{nat}}} g_k^{\sigma} |\Lambda_k^{\sigma}\rangle = \sum_{i=1}^{N_{\text{int}}} \sum_{k=1}^{N_{\text{nat}}} g_k^{\sigma} \frac{u_{\lambda_k,q_i}}{\sqrt{\lambda_k}} |\Phi_{q_i}\rangle$$

where $f_{q_i}^{\sigma} = \sum_{k=1}^{N_{\text{nat}}} g_k^{\sigma} \frac{u_{\lambda_k,q_i}}{\sqrt{\lambda_k}}$

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PGCM: solution of the HWG equation

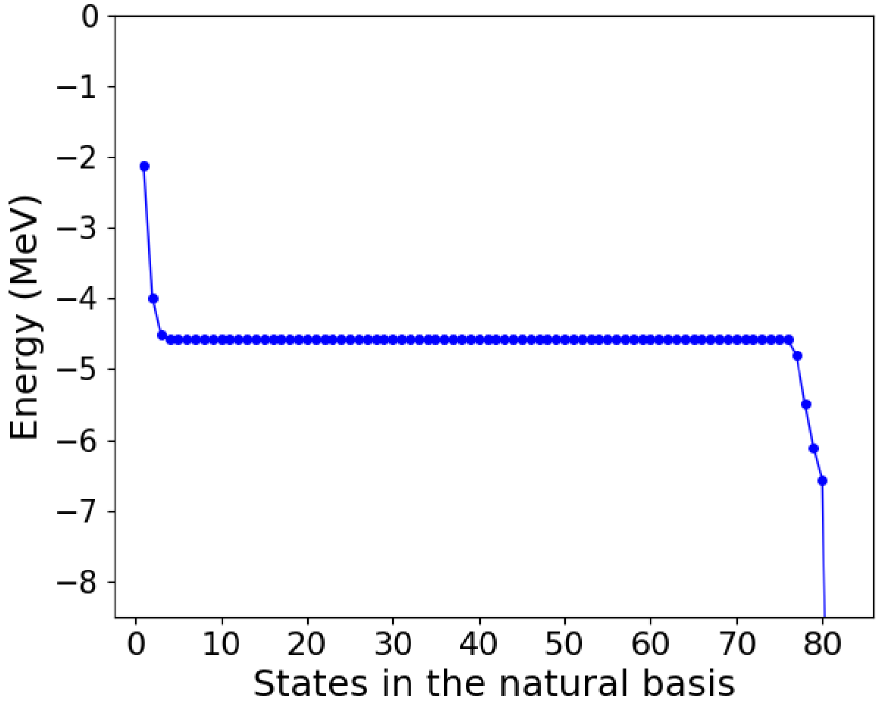
$$\sum_{k'=1}^{N_{\text{nat}}} \langle \Lambda_k | \hat{H} | \Lambda_{k'} \rangle g_{k'}^{\sigma} = E^{\sigma} g_k^{\sigma}$$

The usual analysis: *plateau* condition

I. Given the states of the natural basis, we sort them by the eigenvalues of the norm overlap matrix from largest (higher contributions) to smallest.

II. We solve the HWG equation with only one natural basis state and obtain the energy, then with two and so on.

III. As the eigenvalues decrease, we expect smaller contributions, so that the energy remains fairly constant ➡ *plateau* condition



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PGCM: solution of the HWG equation

The usual analysis: *plateau* condition

$$\sum_{k'=1}^{N_{\text{nat}}} \langle \Lambda_k | \hat{H} | \Lambda_{k'} \rangle g_{k'}^{\sigma} = E^{\sigma} g_k^{\sigma}$$

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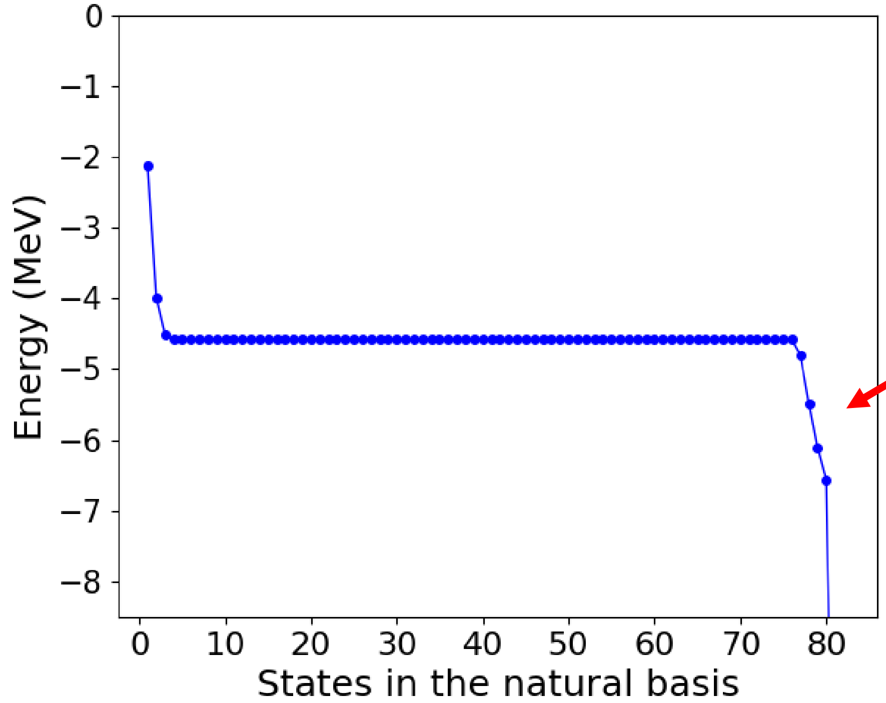

Linear dependencies!!

$$|\Lambda_k\rangle = \sum_{i=1}^{N_{\text{int}}} \frac{u_{\lambda_k, q_i}}{\sqrt{\lambda_k}} |\Phi_{q_i}\rangle$$

$$N_{\text{nat}} \leq N_{\text{int}}$$

PGCM: solution of the HWG equation

Actually, we have:

- Initial set of intrinsic states $\{|\Phi_{q_i}\rangle\}_{i=1,\dots,N_{\text{int}}}$ $\Rightarrow$ N_{int}

Through the norm overlap matrix: N_{int} eigenvalues λ_k and eigenvectors u_{λ_k} :

- Exact linear dependencies such as $\lambda = 0$ $\Rightarrow$ L_{exa}
- Approximate linear dependencies such as $\lambda \neq 0$ but $\lambda \approx 0$ $\Rightarrow$ L_{app}
- Final set of well-defined natural basis states $\{|\Lambda_k\rangle\}_{k=1,\dots,N_{\text{nat}}}$

with $$N_{\text{nat}} = N_{\text{int}} - L_{\text{exa}} - L_{\text{app}}$$

Zero is an accumulation point for the norm overlap eigenvalues!

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PGCM: solution of the HWG equation

Non-orthogonality and approximate linear dependence

- Let us have two vectors in $\mathbb{R}^2$ such that:

$$\vec{v}_1 \cdot \vec{v}_1 = 1\,, \qquad \vec{v}_2 \cdot \vec{v}_2 = 1\,, \qquad \vec{v}_1 \cdot \vec{v}_2 = \mu$$

- The norm overlap matrix is

$$\mathcal{N}_{ij} = \vec{v}_i \cdot \vec{v}_j = \begin{pmatrix} 1 & \mu \\ \mu & 1 \end{pmatrix} \Rightarrow \text{ Eigenvalues: } \lambda_\pm = 1 \pm \mu$$

- Then:

$$\mu = 0 \Rightarrow \;\vec{v}_1 \perp \vec{v}_2\,, \quad \lambda_\pm = 1,\, 1 \;\; \text{(orthonormal)}$$
$$\mu = 1 \Rightarrow \;\vec{v}_1 = \vec{v}_2\,, \quad \lambda_\pm = 2,\, 0 \;\; \text{(exact linear dependency!)}$$

- For $0 < \mu < 1$, the natural basis does not contain exact LD. However, if $\mu \approx 1$, the natural state with $\lambda = 1 - \mu$ could be ill-defined!

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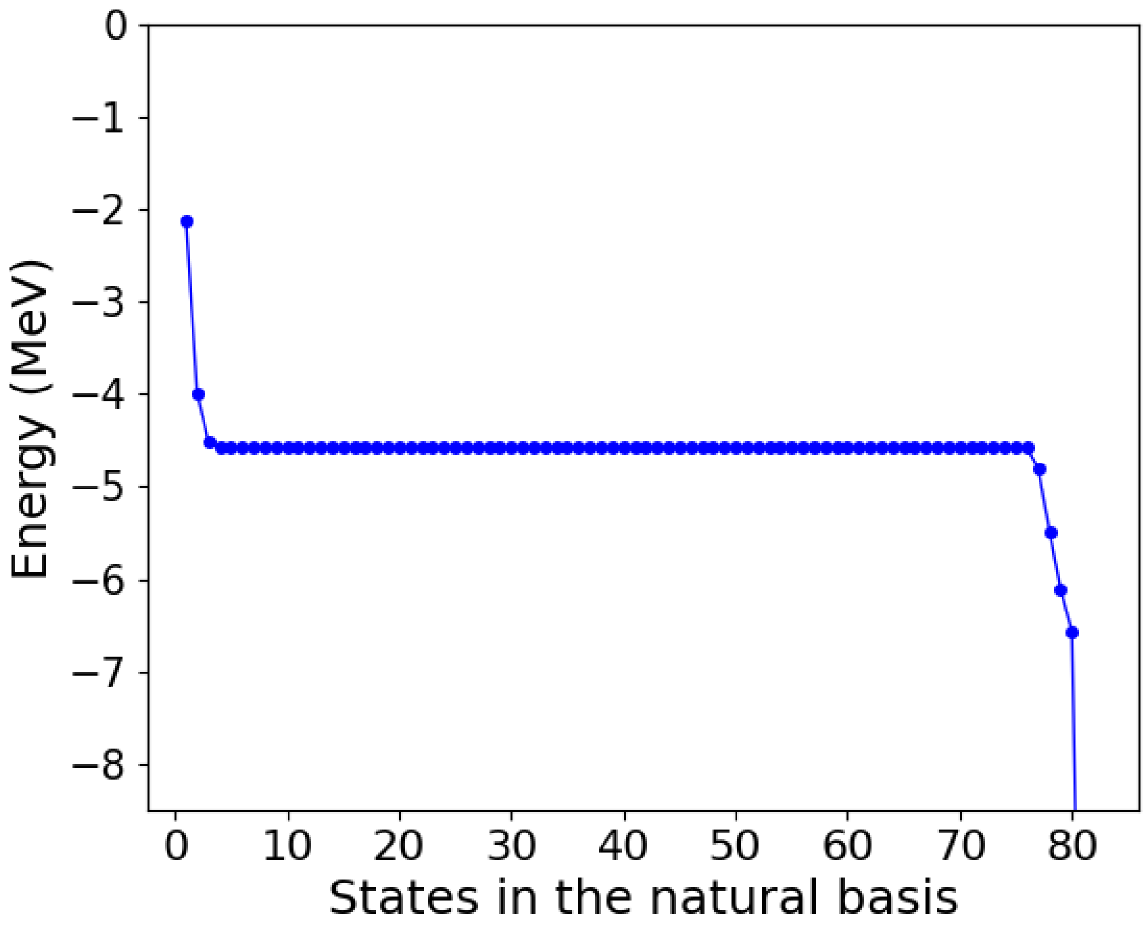
PGCM: solution of the HWG equation

Usually: cutoff to the eigenvalues, ε_λ



Problems:

1. Cutoff chosen heuristically.

2. Ideal value depends on the calculation.

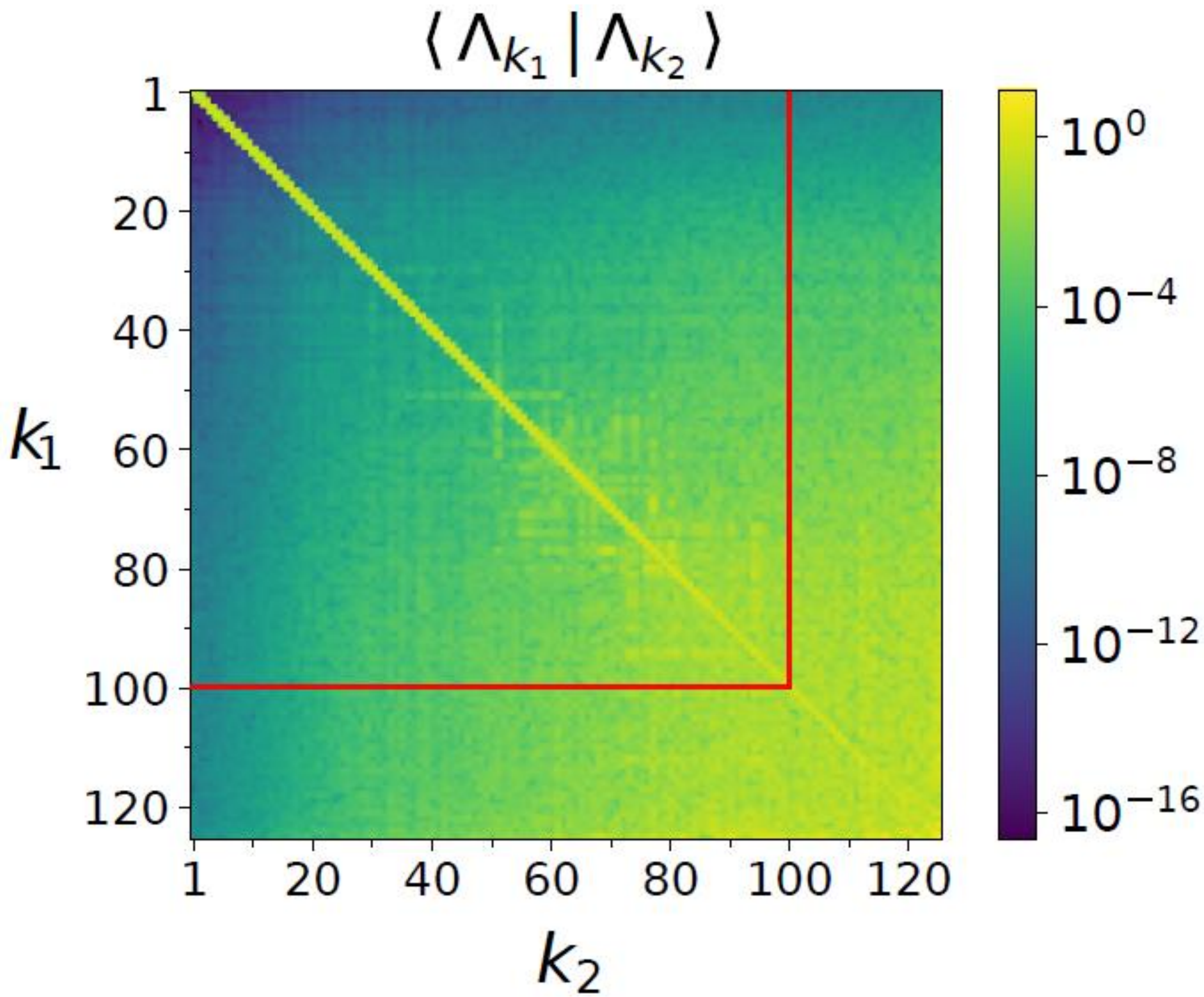
3. Big jump is a sign of these approximate linear dependencies, **but there could be more…**

PGCM: new considerations

J. Martínez-Larraz and T. R. Rodríguez *Phys. Rev. C* **106**, 054301 (2022)

Evidence!

Orthonormality is not met, ill-defined natural states (LD)



Usual cutoff does not avoid the LD spoiling of the natural basis

PGCM: new considerations

J. Martínez-Larraz and T. R. Rodríguez *Phys. Rev. C* **106**, 054301 (2022)

New method: orthonormality condition of the natural states.

- The orthonormality of the natural basis, $\langle \Lambda_k | \Lambda_{k'} \rangle = \delta_{k,k'}$, is eventually lost.
- However, we could restore its viability by imposing the condition:

$$\langle \Lambda_k | \Lambda_{k'} \rangle - \delta_{kk'} < \varepsilon_{\text{nat}} \;\; ; \;\; \forall k, k'$$

and removing the natural states that do not fulfill it.

PGCM: new considerations

Big jump is a sign of these approximate linear dependencies, **but there could be more...**

- Picket-fence model:

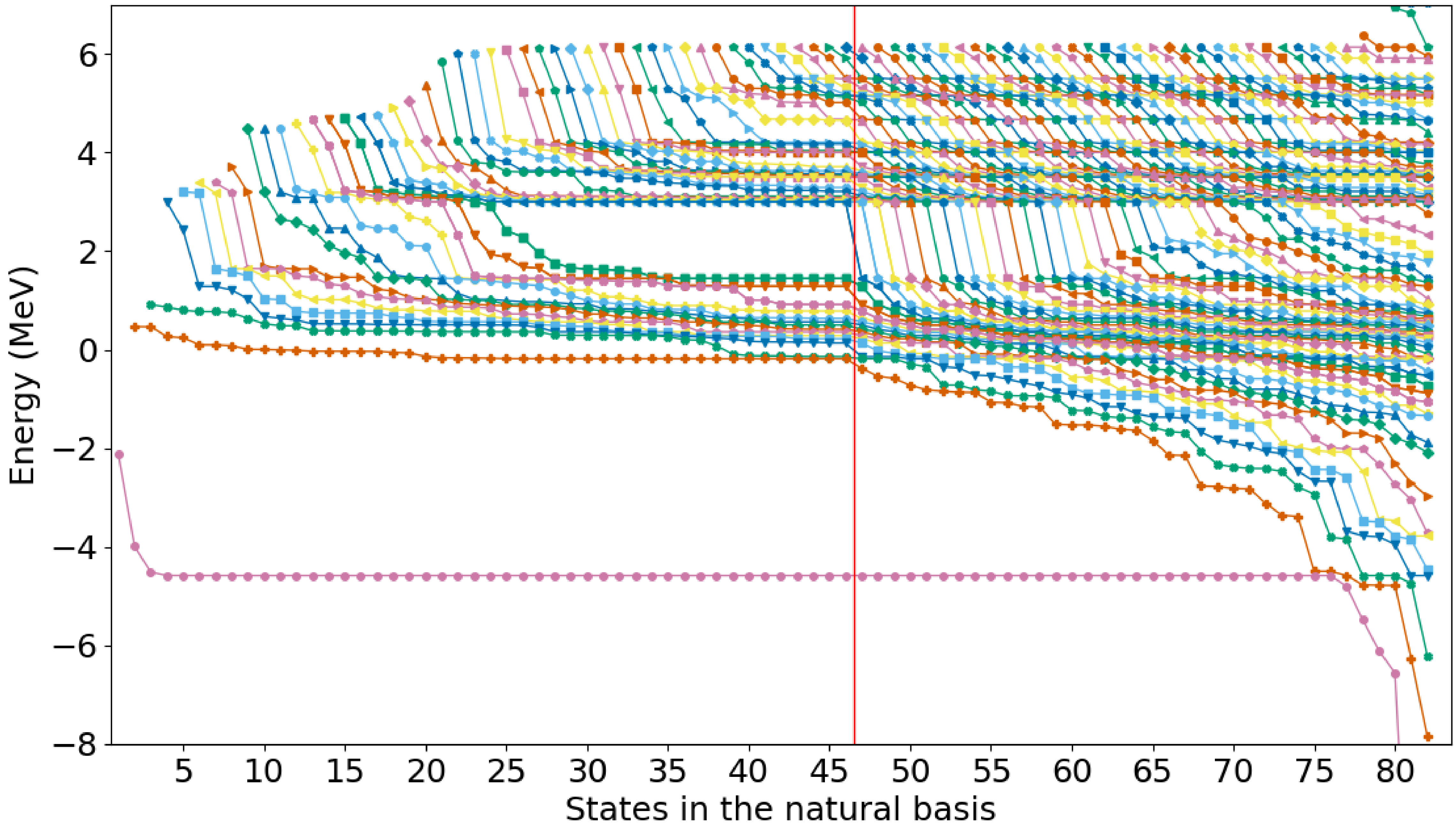
$$\hat{H} = \sum_{k=1}^{N_{lev}} \varepsilon_k \left(c_k^\dagger c_k + c_{\bar{k}}^\dagger c_{\bar{k}} \right) - G \sum_{k,k'=1}^{N_{lev}} c_k^\dagger c_{\bar{k}}^\dagger c_{\bar{k}'} c_{k'}$$

$$N = 4$$

k	Orbital	ε_k (MeV)
5	$4s_{1/2}$	2.0
4	$3s_{1/2}$	1.5
3	$2s_{1/2}$	1.0
2	$1s_{1/2}$	0.5
1	$0s_{1/2}$	0.0

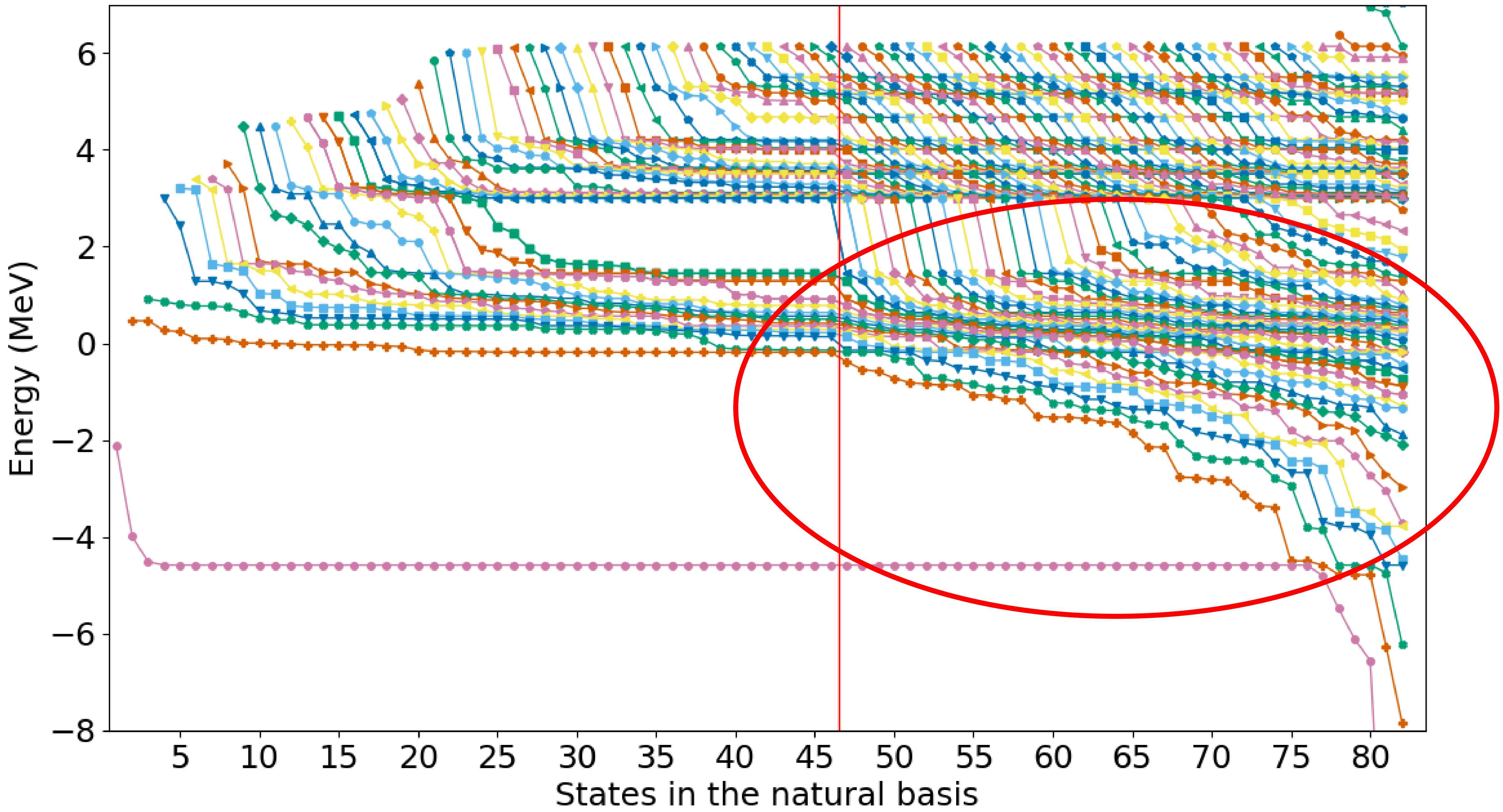
- Total exact space: 50 0^+ states
- PGCM: 46 exact 0^+ states

PGCM: new considerations



J. Martínez-Larraz *PhD thesis.*

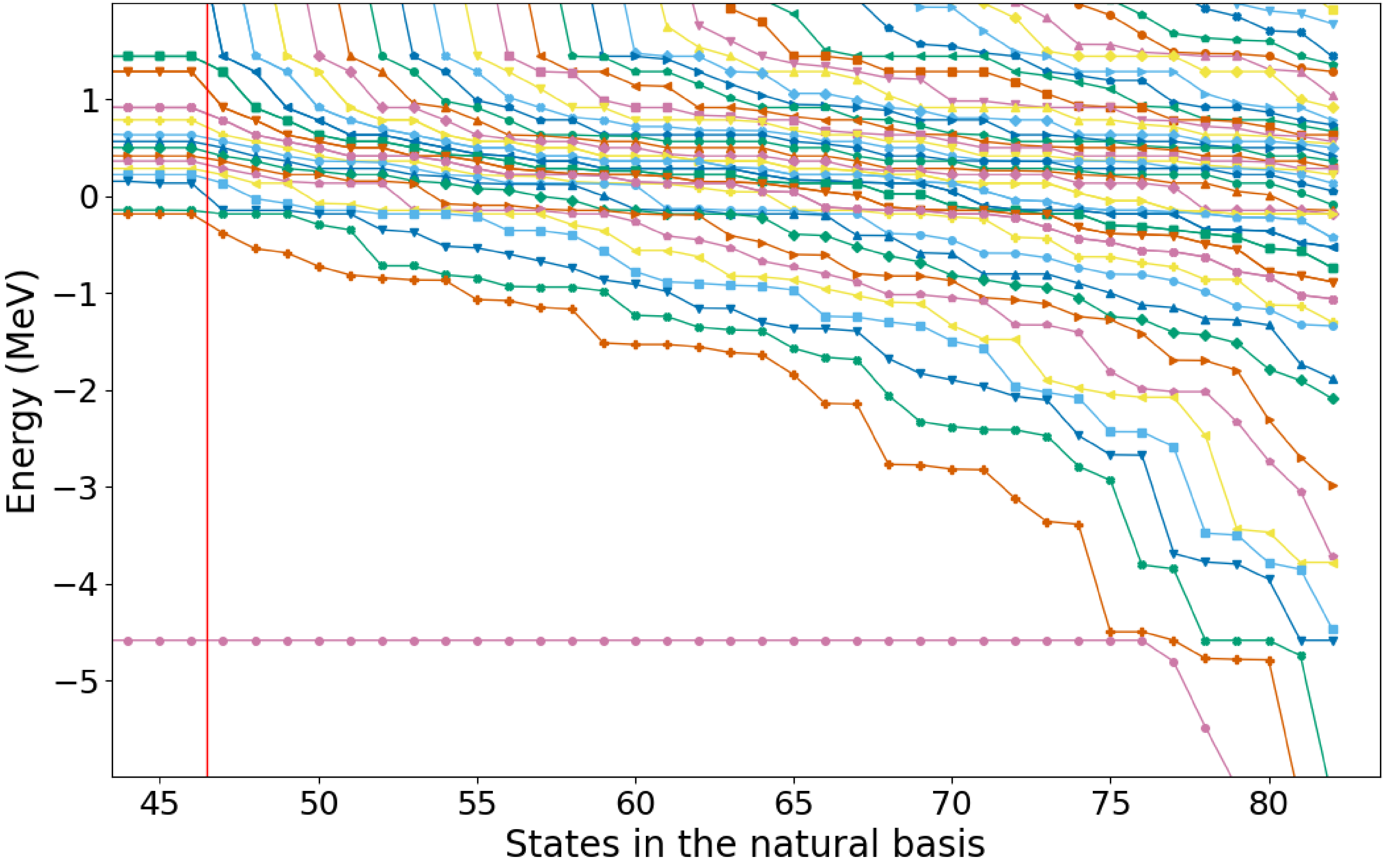
PGCM: new considerations



J. Martínez-Larraz *PhD thesis.*

PGCM: new considerations

Why does this happen?



J. Martínez-Larraz *PhD thesis.*

PGCM: new considerations

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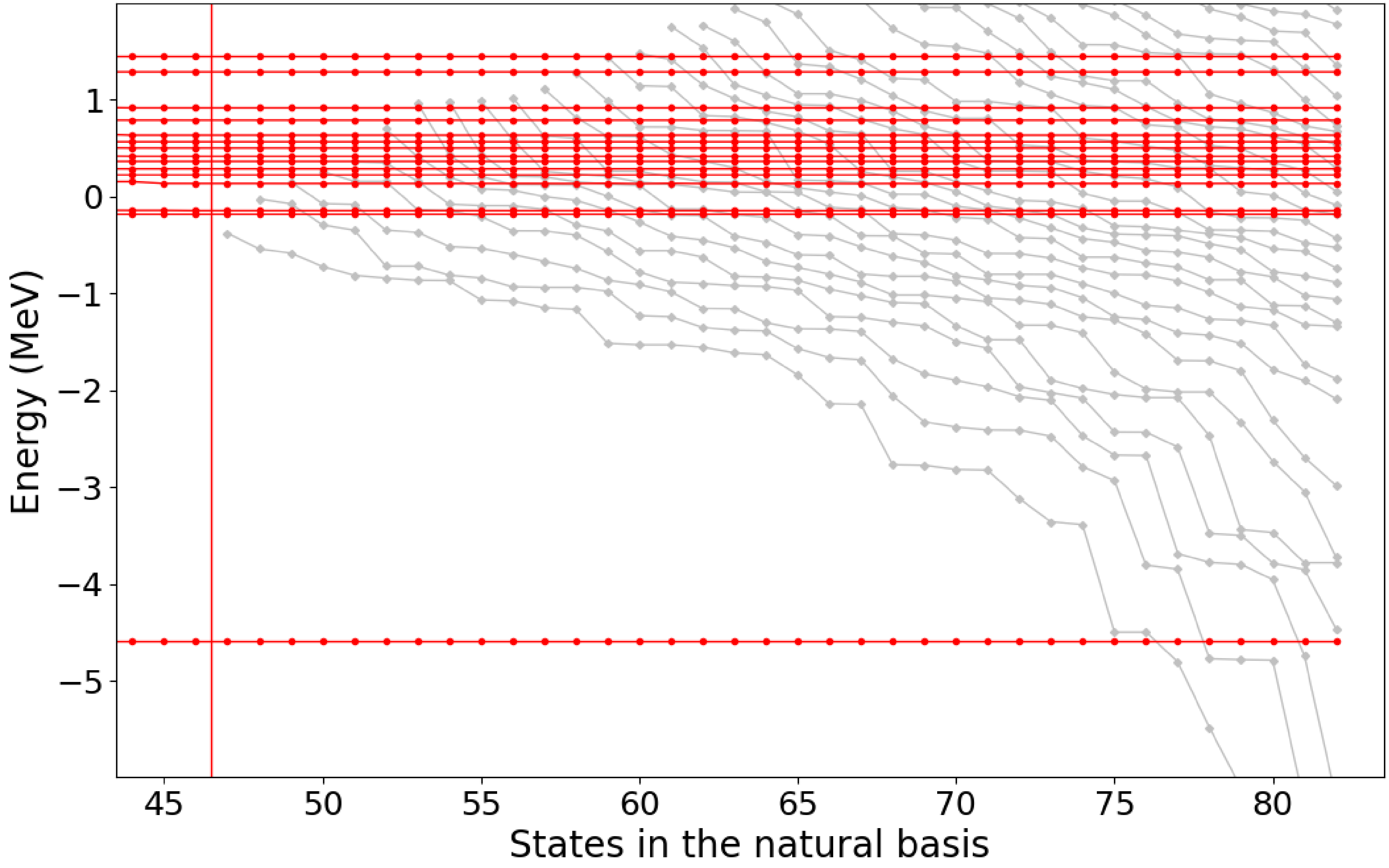

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PGCM: new considerations

$$|\,\Psi^{N,Z;\,J;\,\sigma}_{PGCM}\,\rangle = \sum_k g_\sigma^{N,Z,J}(k)\;|\,\Lambda_k\,\rangle \longrightarrow |g_\sigma(k)|^2$$

characteristic weight distribution

J. Martínez-Larraz *PhD thesis.*

PGCM: new considerations

$$|\,\Psi^{N,Z;J;\sigma}_{PGCM}\,\rangle = \sum_k g^{N,Z,J}_{\sigma}(k)\,|\,\Lambda_k\,\rangle \longrightarrow |g_\sigma(k)|^2$$

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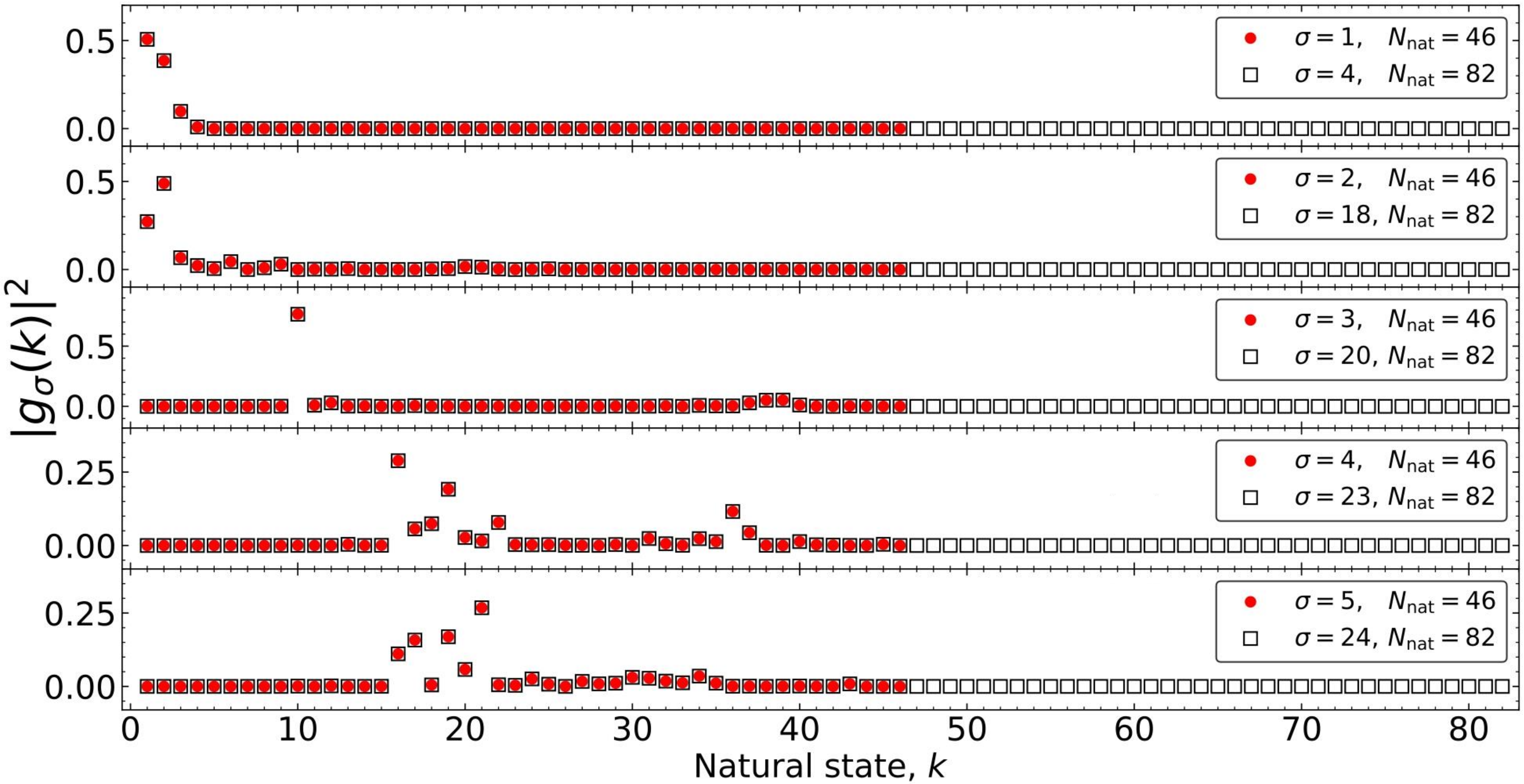

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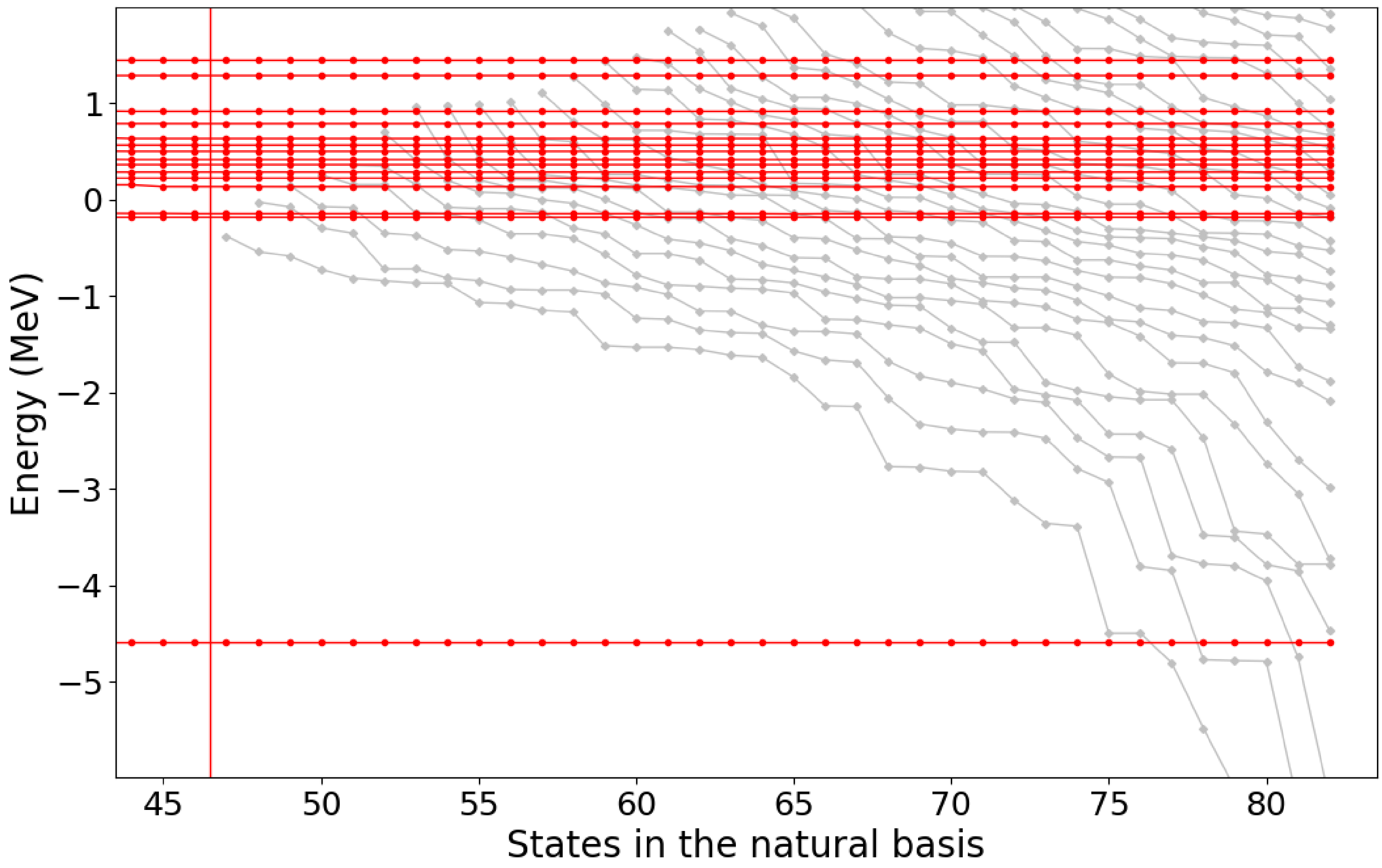
PGCM: new considerations



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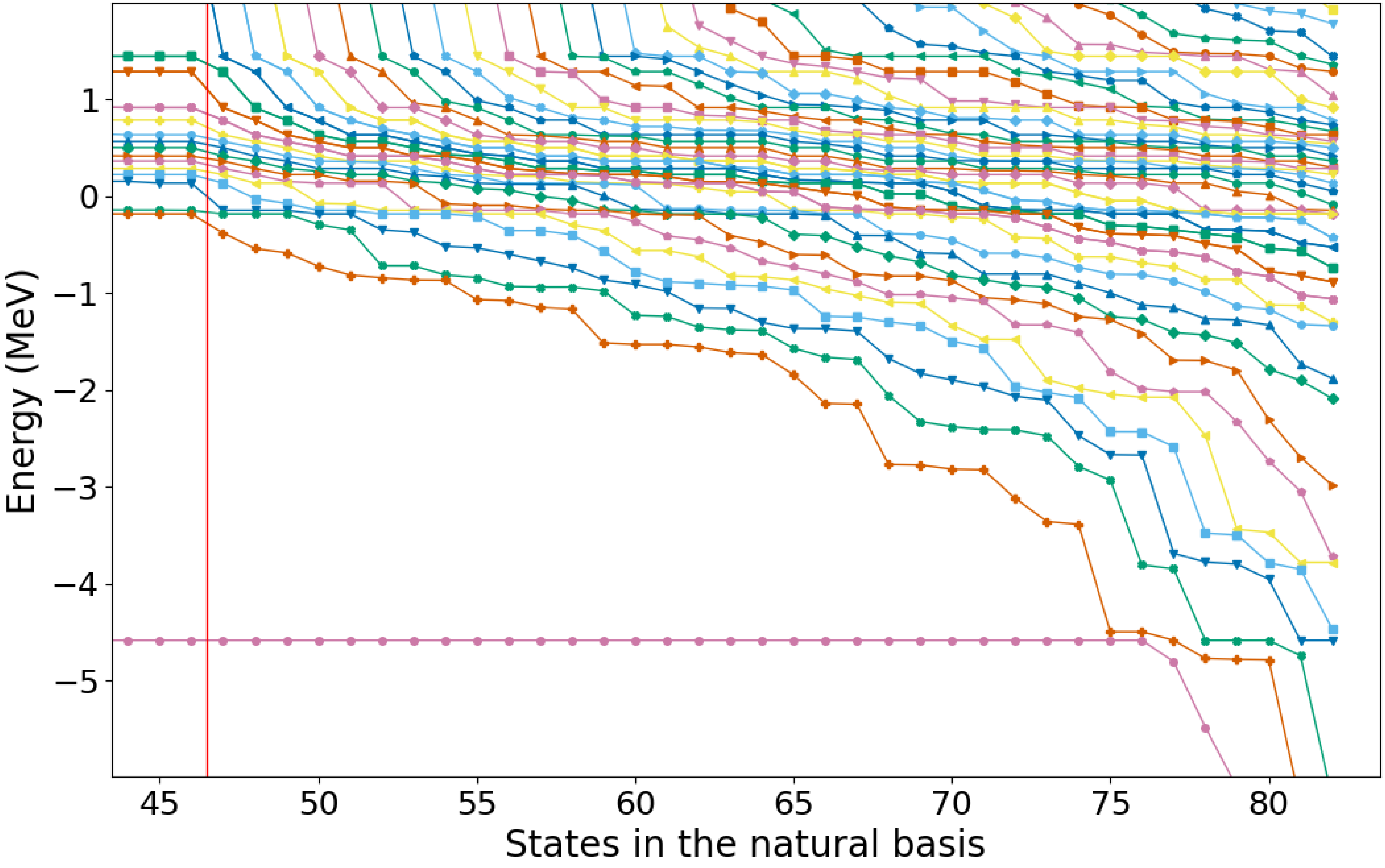
PGCM: new considerations



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PGCM: new considerations

1. To ensure the orthonormality of the NB is important
2. The LD breakdown can be related to spurious states
3. *Plateau* conditions are not a good way of studying convergence
4. They only account for the specific distributions of PGCM states
5. We could look at the continuity of the weight distributions

J. Martínez-Larraz *PhD thesis.*

Contents

Applications

Once we have found the proper dimension of the natural basis, N_{nat} , we solve the HWG equation for each angular momentum :

$$\sum_{k'}^{N_{\text{nat}}} \langle \Lambda_k \,|\, \hat{H} \,|\, \Lambda_{k'} \rangle \, g_\sigma^{N,Z,J}(k') \;=\; E_\sigma^{N,Z,J} \, g_\sigma^{N,Z,J}(k)$$

retrieving the PGCM nuclear energies of the **yrast state and excited states** on the same footage, besides the wave functions,

$$|\, \Psi_{PGCM}^{N,Z;\,J;\,\sigma} \rangle = \sum_k g_\sigma^{N,Z,J}(k) \;|\, \Lambda_k \rangle$$

We can also compute the collective wave functions to obtain an interpretation in terms of the intrinsic states:

$$|\, F_\sigma^{N,\,Z,\,J}(\vec{q}_i) \,|^2 = \left| \sum_k g_\sigma^{N,Z,J}(k) \;\cdot\; u_k^{N,Z,J}(\vec{q}_i) \right|^2$$

Applications

With the PGCM states defined, we can compute quantities such as the electromagnetic strength functions:

$$B(E\lambda; J_i^\pi \rightarrow J_f^\pi) = \frac{1}{2J_i + 1} |\langle J_f^\pi || \hat{M}_\lambda^{\text{elec}} || J_i^\pi \rangle|^2$$

$$B(M\lambda; J_i^\pi \rightarrow J_f^\pi) = \frac{1}{2J_i + 1} |\langle J_f^\pi || \hat{M}_\lambda^{\text{mag}} || J_i^\pi \rangle|^2$$

Strategy:

- Compute the initial and final states by solving the nuclear many-body problem separately.
- Compute the transition matrix elements between individual states.
- Energies, electromagnetic and decay properties are obtained within the same framework.

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Applications: EM responses

The main goal in the PGCM calculations is to represent the nuclear states as good as possible. However, in some cases it is difficult:

$$J^{\pi} = 1^{+}$$ challenge!

Obtaining 1^+ states from HFB-like wave-functions

Aim: to reliably reproduce a high density of 1^+ states in PGCM calculations (resonances)

Collaboration:
- Kamila Sieja
- Thomas Duguet
- Mikael Frosini
- Stavros Bofos
- Benjamin Bally
- Tomás Rodríguez
- Jaime Martínez-Larraz

Conclusions

PROS

- Applicable to all regions of nuclear chart.
- Adaptable and flexible.
- Continuous and discrete coordinates.
- Beyond-mean-field technique.
- Complete restoration of symmetries.
- Description of nuclear states in terms of collective variables.
- Energies, transitions and decay properties: same framework

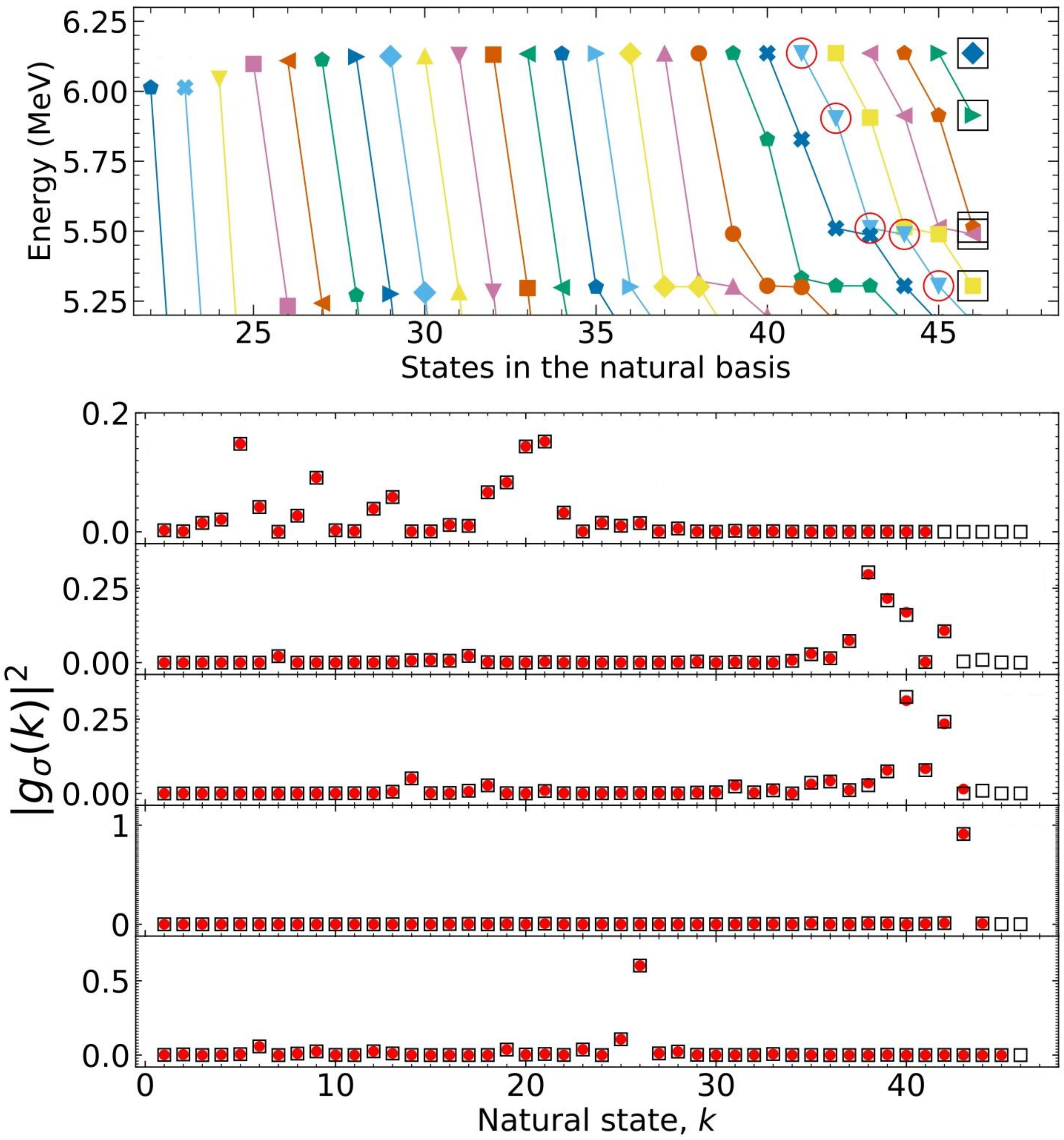
CONS

- Approximate solutions.
- Depends on the choice of d.o.f.
- Depends on the quality of mean-field wave functions.
- Calculations can be computationally expensive.
- To delimit a proper natural basis can be complex in some cases.

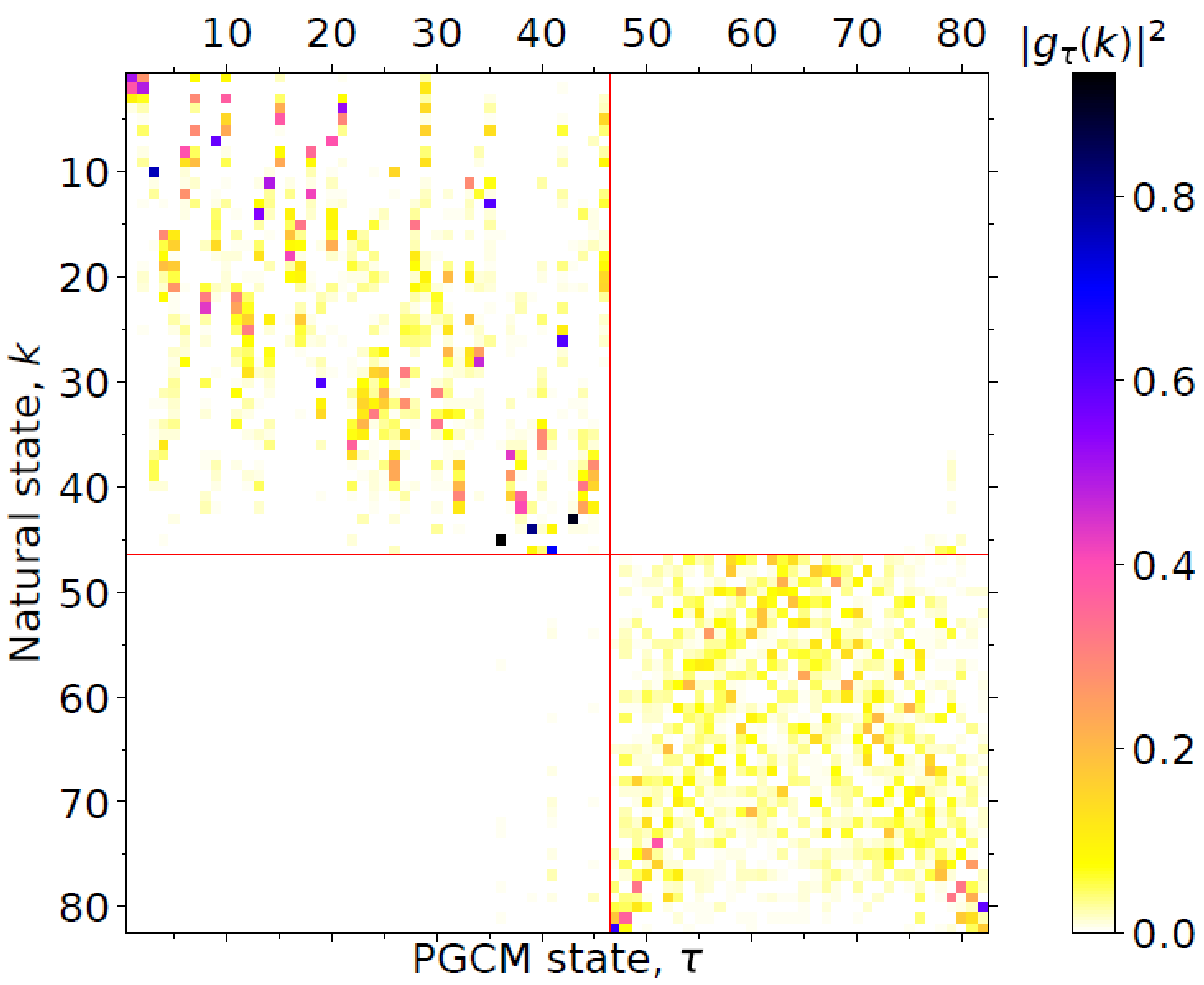
The end

Thank you for your attention!

PGCM: new considerations



PGCM: new considerations



Applications: EM responses

The intrinsic HFB-like state can be decomposed in angular momentum eigenstates:

$$|\Phi(q)\rangle = \sum_{\alpha}\sum_{J}\sum_{K=-J}^{J} c_{\alpha,JK}(q)|\alpha, JK\rangle$$

α other quantum numbers

If the intrinsic HFB-like preserves simultaneously:

(typically preserved in self-consistent symmetries imposed in most of the mean-field solvers)

$$\hat{T}|\Phi\rangle = |\Phi\rangle$$

$$\hat{P}|\Phi\rangle = |\Phi\rangle$$

$$\hat{R}_x|\Phi\rangle = e^{-i\pi\hat{J}_x}|\Phi\rangle = |\Phi\rangle$$

$$\Rightarrow c_{\alpha,J_{odd}K}(q) = 0$$

we cannot produce J=1 projected states

- constraints: cranking, isoscalar pairing, etc
- n-quasiparticle states

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Applications: EM responses

- Magnetic transitions:

$$B(M1; 1^+_\sigma \to 0^+_1)$$

$$|J_i\rangle = |1^+_\sigma\rangle \qquad |J_f\rangle = |0^+_1\rangle$$

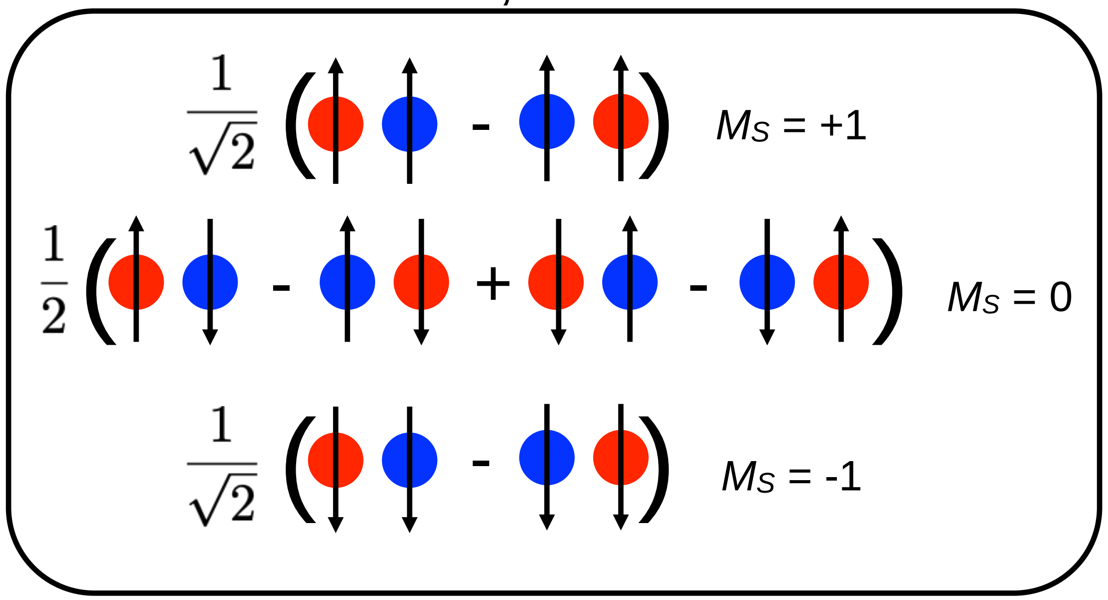
set of excited states (level density) — ground state

- Nuclei: ^{20}Ne and ^{24}Mg (N=Z)
- USDB shell model interaction (^{16}O core)
- Benchmark results from the first one hundred 1^+ states

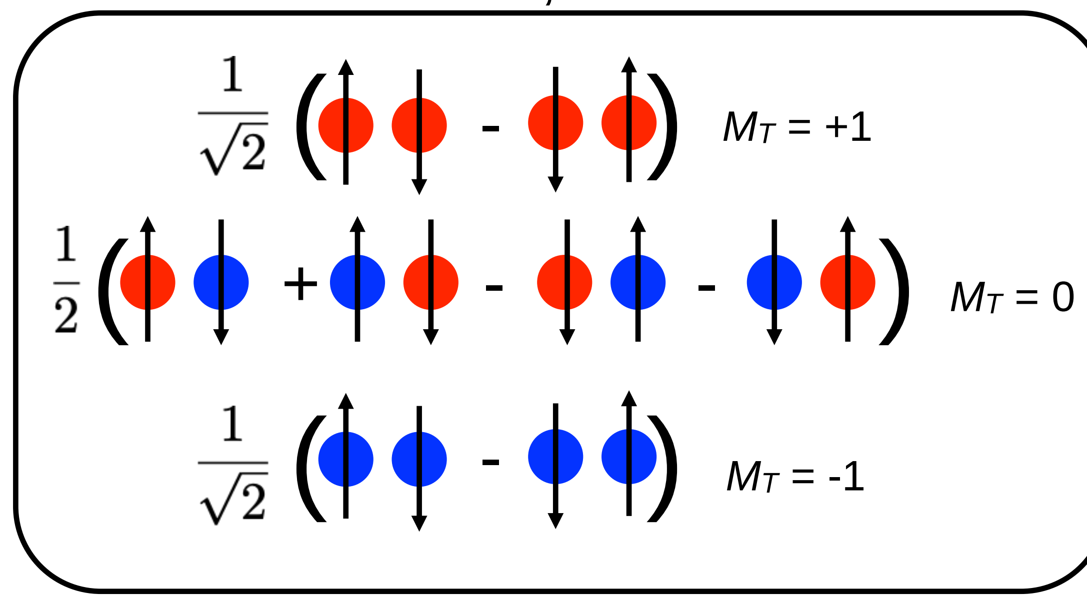
Applications: EM responses

- Generating coordinates (constraints): **proton-neutron pairing content**

$S = 1;\ T = 0$



$S = 0;\ T = 1$



$$\delta^{J_p T_p}_{M_{J_p} M_{T_p}} = \frac{1}{2}\langle\Phi(q)|\left[\hat{P}\right]^{J_p T_p}_{M_{J_p} M_{T_p}} + \left[\hat{P}^{\dagger}\right]^{J_p T_p}_{M_{J_p} M_{T_p}} |\Phi(q)\rangle$$

“creates” pairs coupled to angular momentum and isospin

$$\delta^{J_p T_p}_{M_{J_p} M_{T_p}} = \begin{cases} \delta^{01}_{01} \equiv \delta_{nn} \\ \delta^{01}_{0-1} \equiv \delta_{pp} \\ \delta^{01}_{00} \equiv \delta^{1}_{pn} \\ \delta^{10}_{00} \equiv \delta^{0}_{pn} \end{cases}$$

$$E'_{\mathrm{PNVAP}}\left[|\Phi(q)\rangle\right] = \frac{\langle\Phi(q)|\hat{H}P^N P^Z|\Phi(q)\rangle}{\langle\Phi(q)|P^N P^Z|\Phi(q)\rangle} - \langle\Phi(q)|\lambda_q \hat{\delta}^{J_p T_p}_{M_{J_p} M_{T_p}}|\Phi(q)\rangle$$

Applications: EM responses

- Generating coordinates (constraints): **proton-neutron pairing content**

- In TAURUS, general HFB (real) transformation allows the inclusion of proton-neutron pairing

$$|\Phi(q)\rangle \rightarrow \beta_b(q)|\Phi(q)\rangle = 0 \ \ \forall \ \ b \qquad\qquad \beta_b^\dagger(q) = \sum_a U_{ab}(q) c_a^\dagger + V_{ab}(q) c_a$$

$$U = \begin{pmatrix} U_{pp} & U_{pn} \\ U_{np} & U_{nn} \end{pmatrix}; V = \begin{pmatrix} V_{pp} & V_{pn} \\ V_{np} & V_{nn} \end{pmatrix}$$

European Commission
Marie Skłodowska-Curie Actions
TAURUS (ID:839847)

* B. Bally, A. Sánchez, T. R. R., EPJA 57, 69 (2021)

Applications: EM responses

- Generating coordinates (constraints): **proton-neutron pairing content**

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European Commission

Marie Skłodowska-Curie Actions

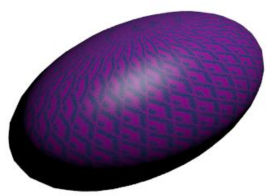
TAURUS (ID:839847)

* B. Bally, A. Sánchez, T. R. R., EPJA 57, 69 (2021)

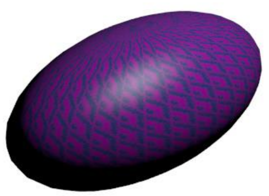
Applications: EM responses

- Generating coordinates (constraints): **intrinsic rotations (cranking)**

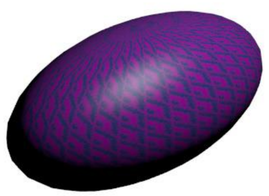
J_x=0



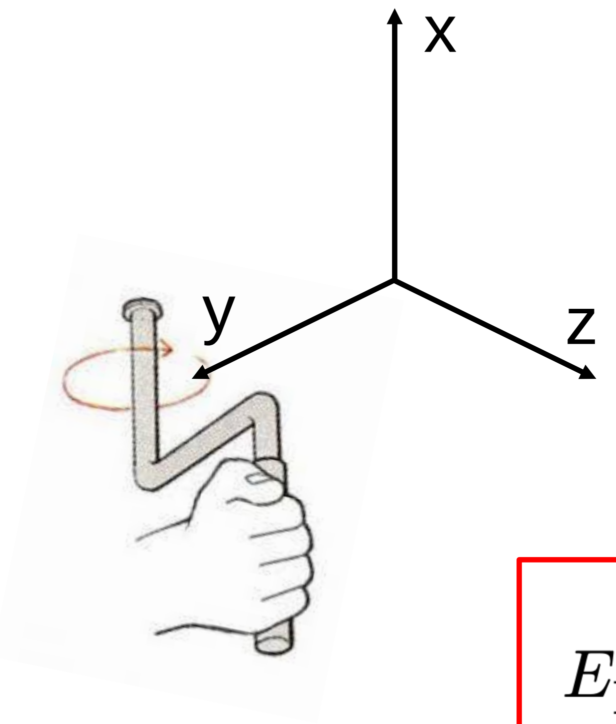
J_x=2



J_x=4

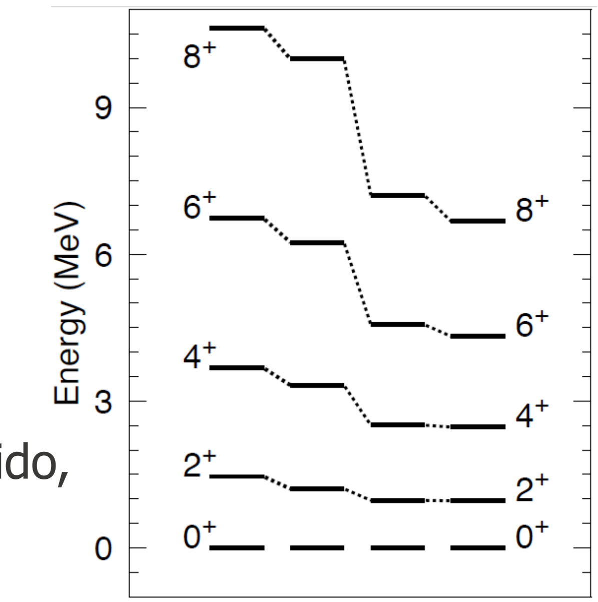


Time-reversal symmetry breaking!



Angular momentum correlations

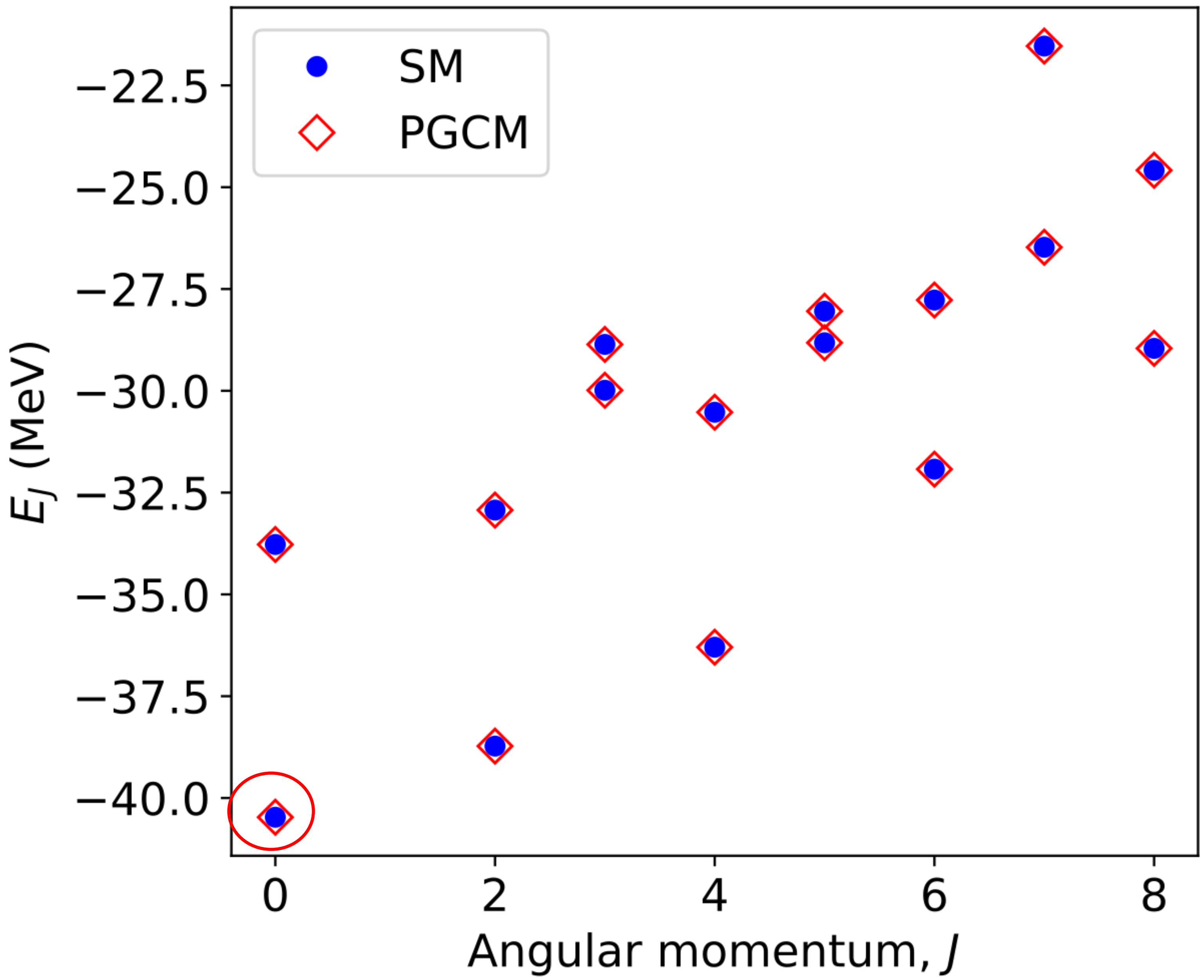
M. Borrajo, T. R. Rodríguez, J. L. Egido, *Phys. Lett. B* **746**, 341 (2015)



$$E'_{\mathrm{PNVAP}}\left[|\Phi(q)\rangle\right] = \frac{\langle\Phi(q)|\hat{H}P^{N}P^{Z}|\Phi(q)\rangle}{\langle\Phi(q)|P^{N}P^{Z}|\Phi(q)\rangle} - \langle\Phi(q)|\lambda_q \hat{J}_x|\Phi(q)\rangle$$

Applications: EM responses

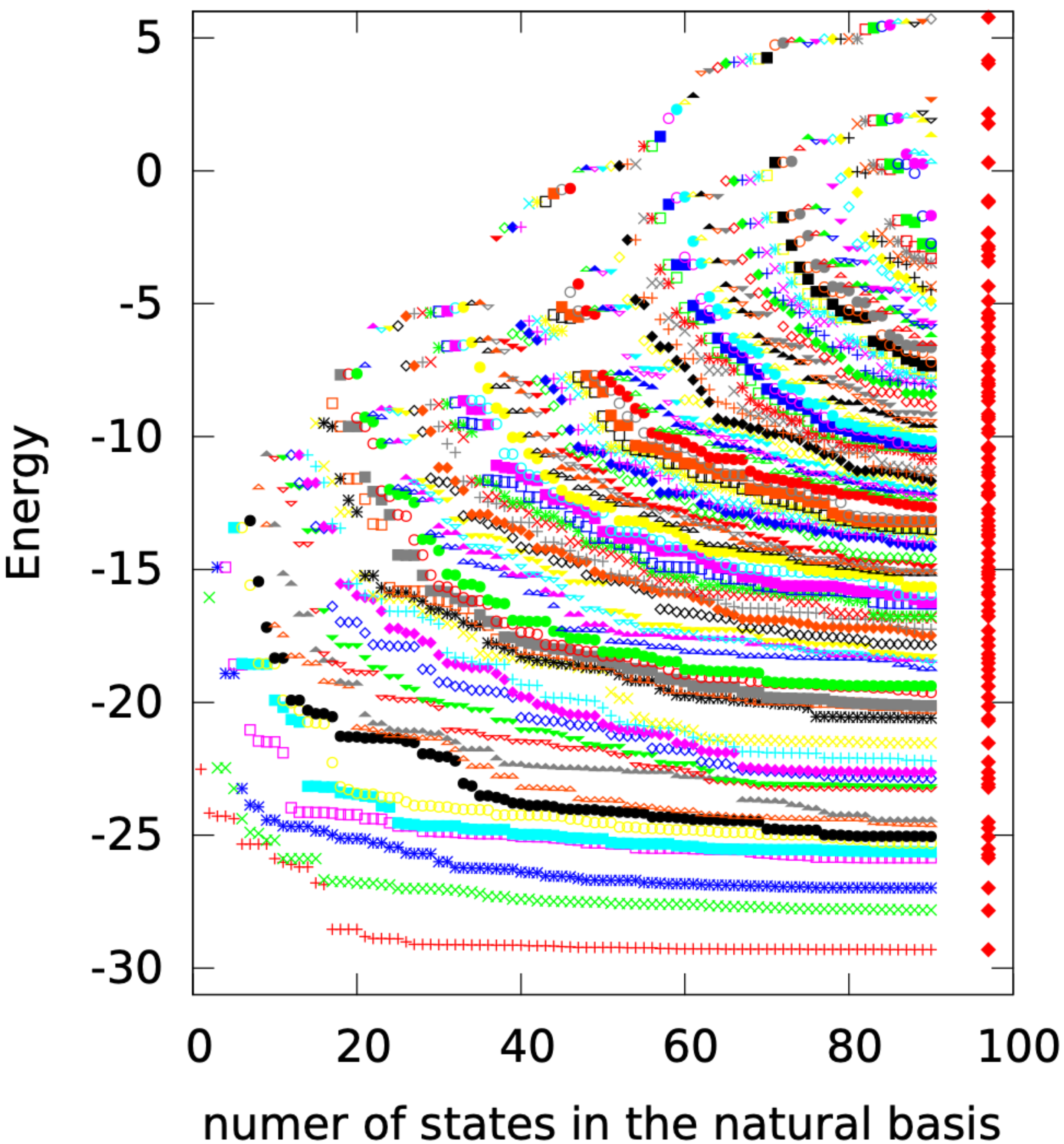
Exploring cranking, pn-pairing (isoscalar and isovector) $\{|\Phi(j_x, \delta_{pn}^{T=0}, \delta_{pn}^{T=1})\rangle\}$



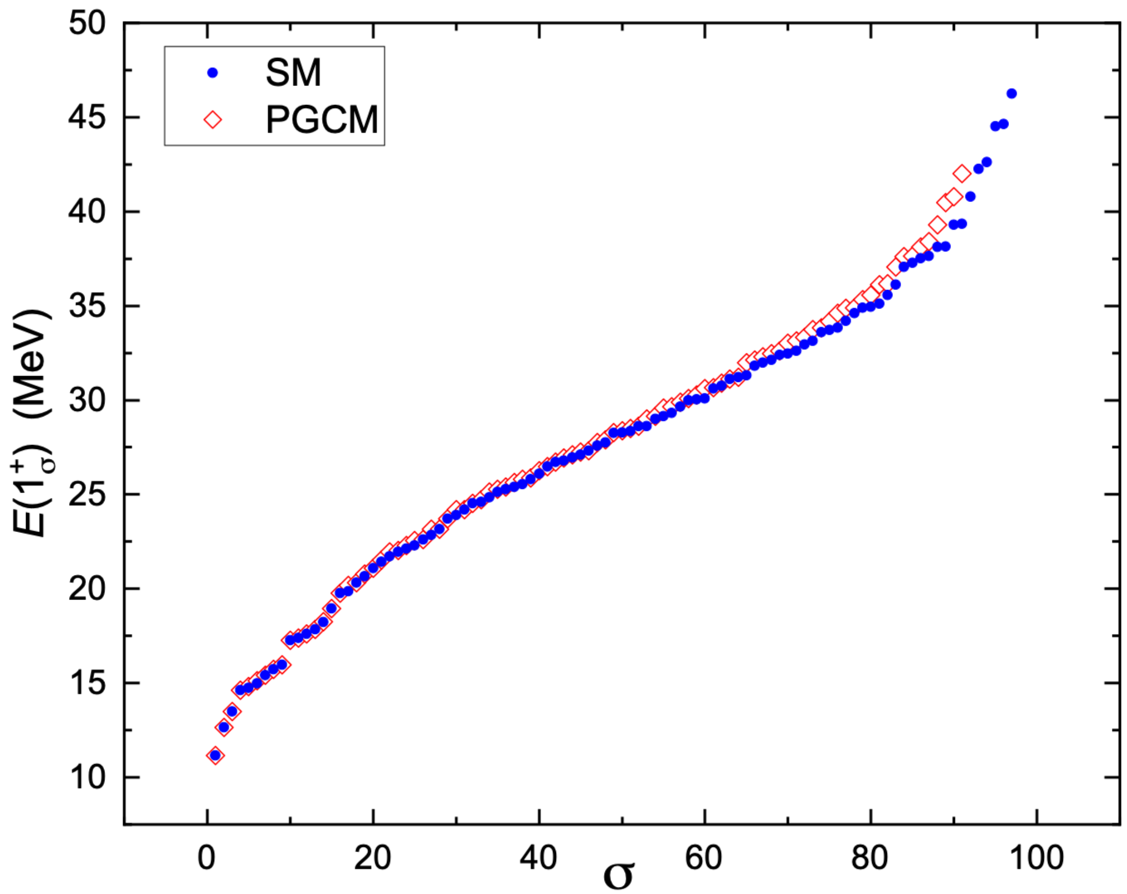
- exact ground state energy
- exact description of low-lying excited energies

Applications: EM responses

Exploring cranking, pn-pairing (isoscalar and isovector) $\{|\Phi(j_x, \delta_{pn}^{T=0}, \delta_{pn}^{T=1})\rangle\}$



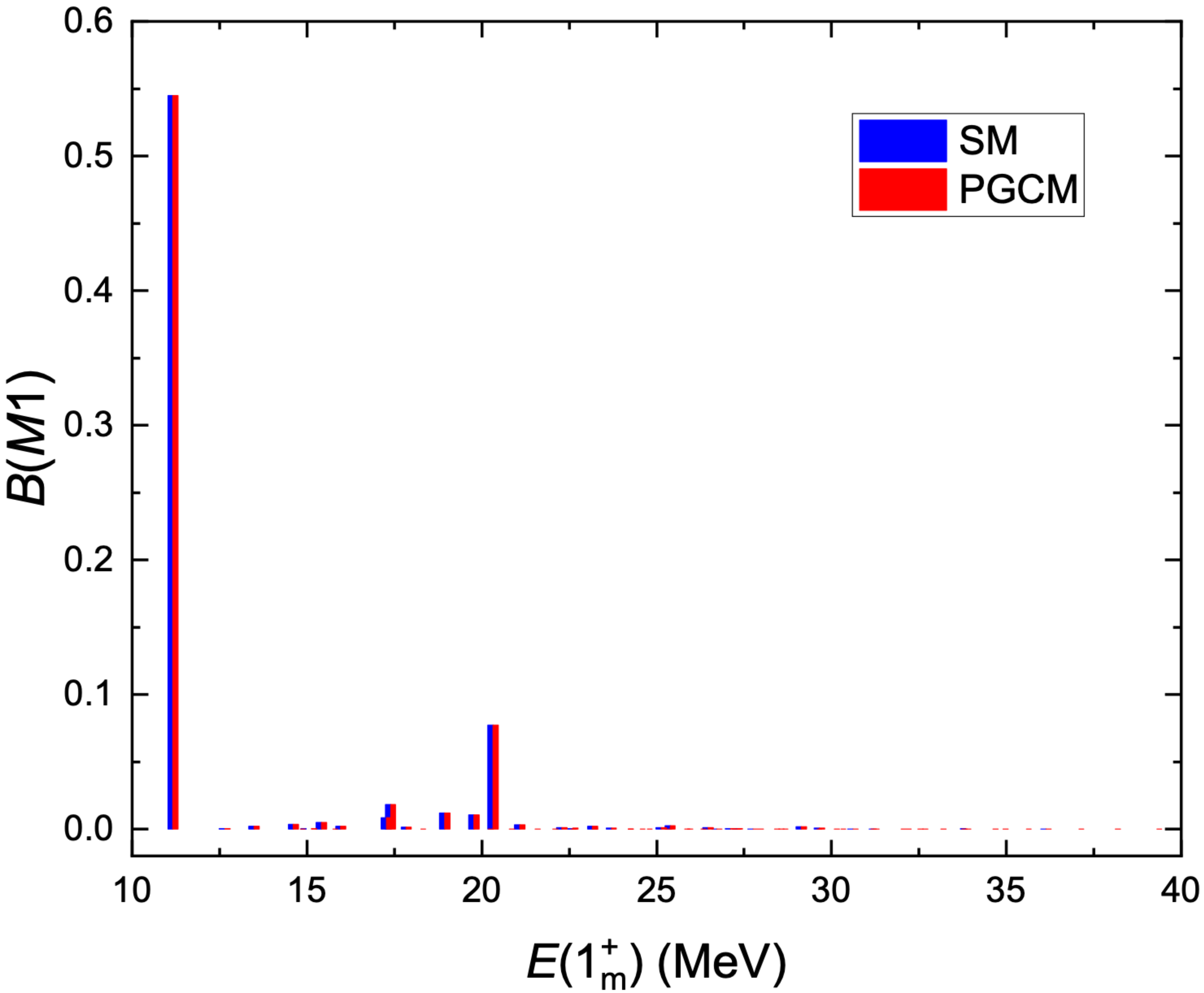
- Excellent description of the lowest excited 1^+ states



- convergence of highly excited states can be tricky
- we have to abandon the idea of "plateau condition"

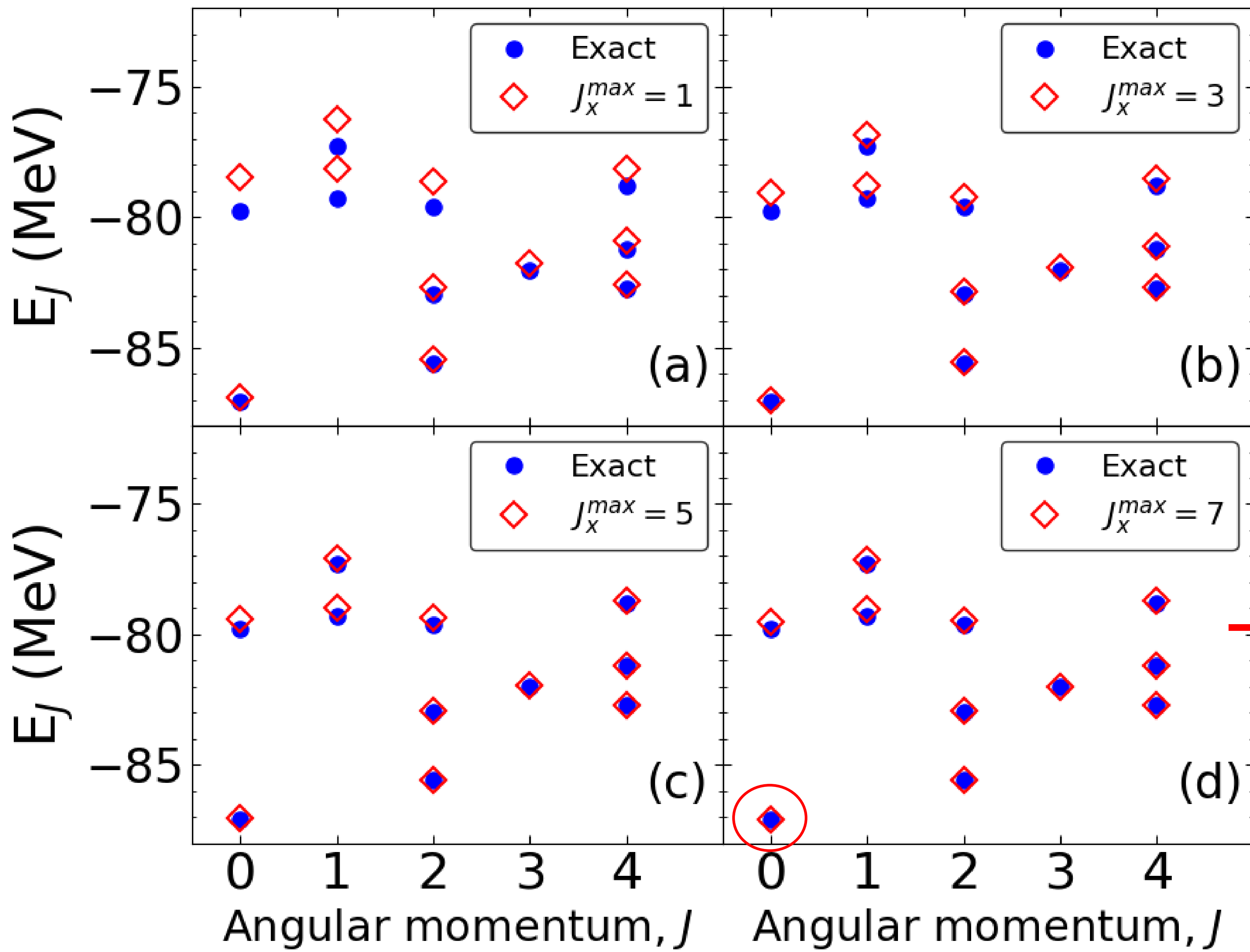
Applications: EM responses

Exploring cranking, pn-pairing (isoscalar and isovector) $\{|\Phi(j_x, \delta_{pn}^{T=0}, \delta_{pn}^{T=1})\rangle\}$



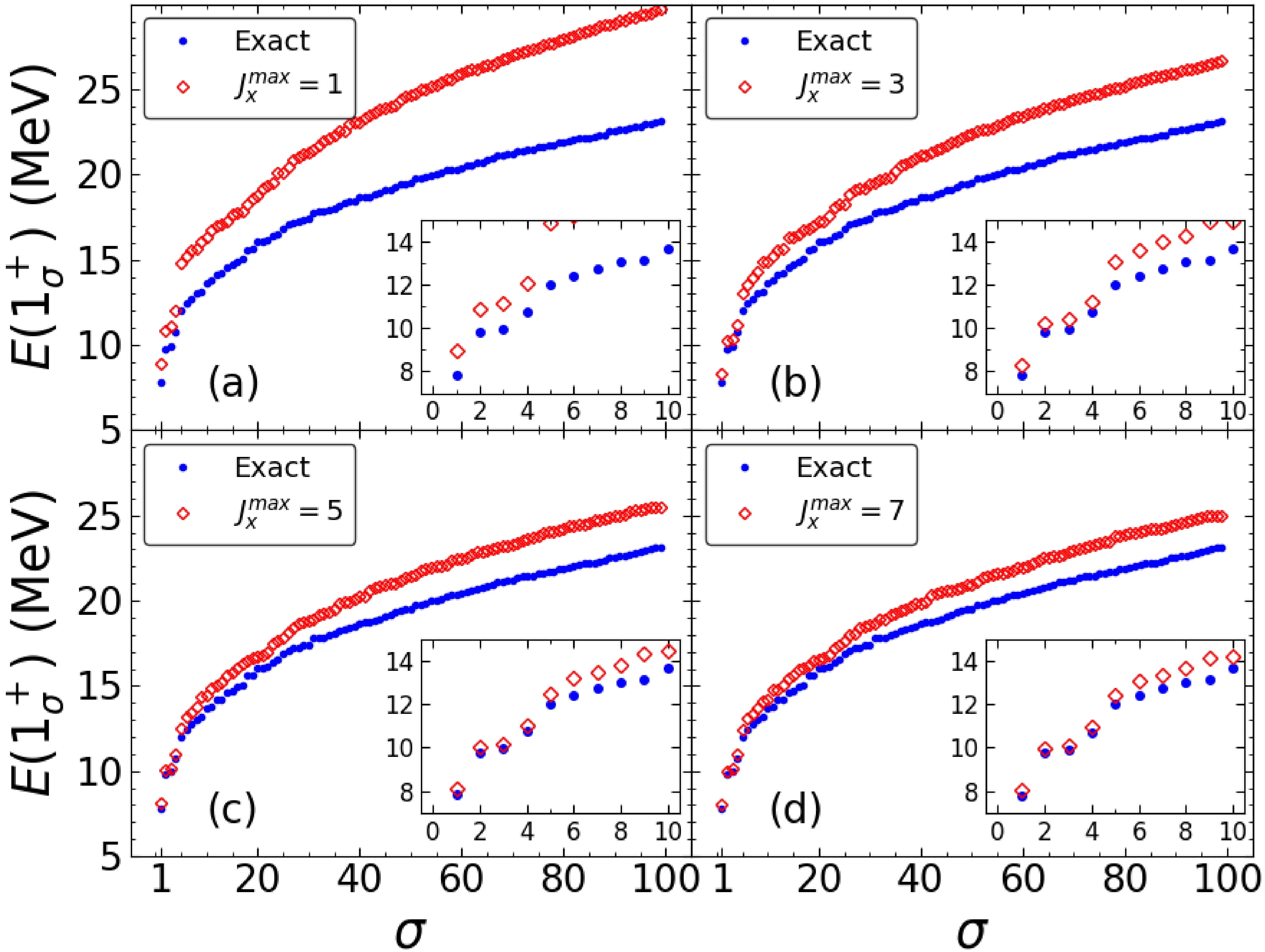
Applications: EM responses

Exploring cranking, pn-pairing (isoscalar and isovector) $\{|\Phi(j_x, \delta_{pn}^{T=0}, \delta_{pn}^{T=1})\rangle\}$



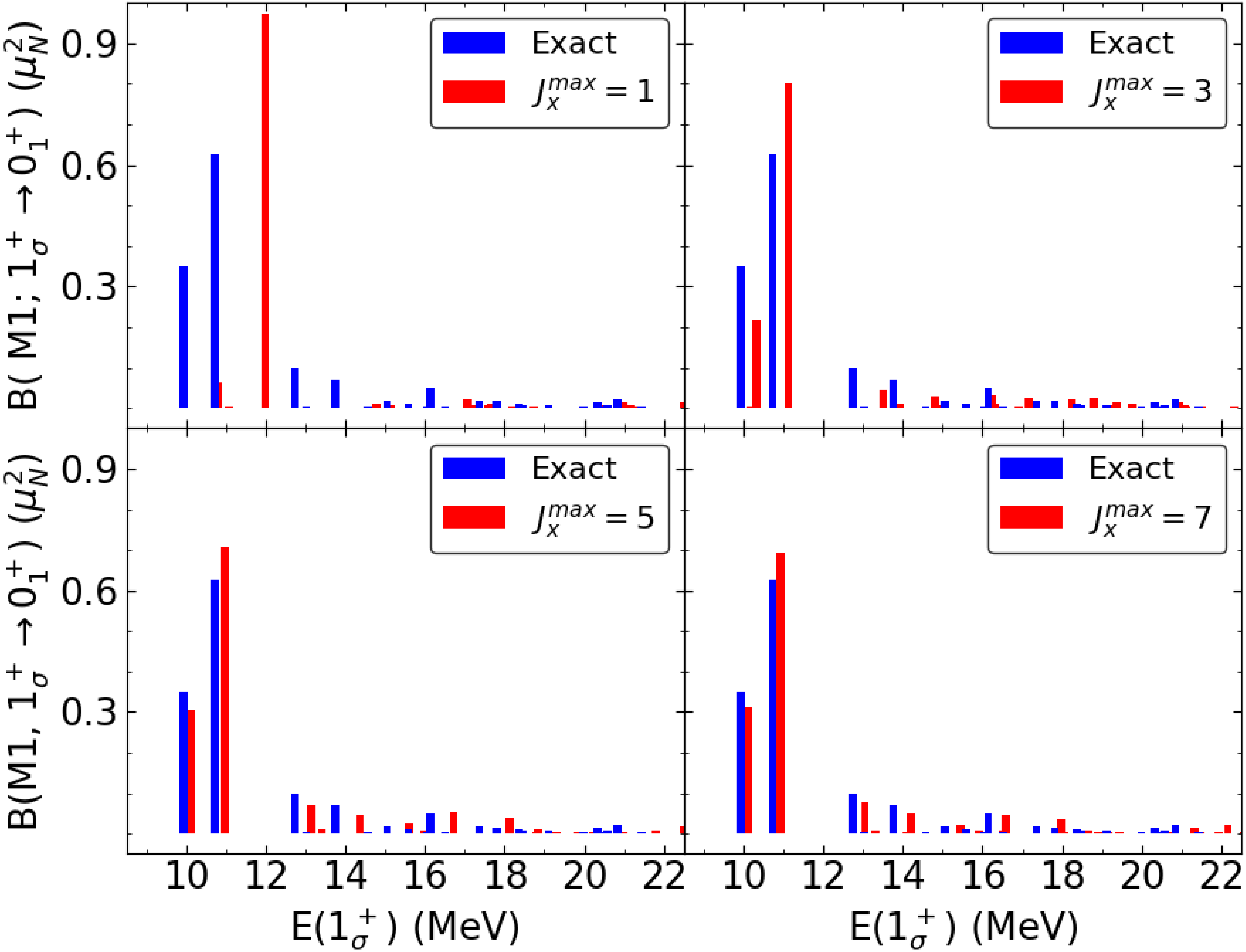
J^π	ΔE (MeV)
0_1^+	0.02
2_1^+	0.02
4_1^+	0.01
3_1^+	0.04
2_2^+	0.05
4_2^+	0.03

Applications: EM responses

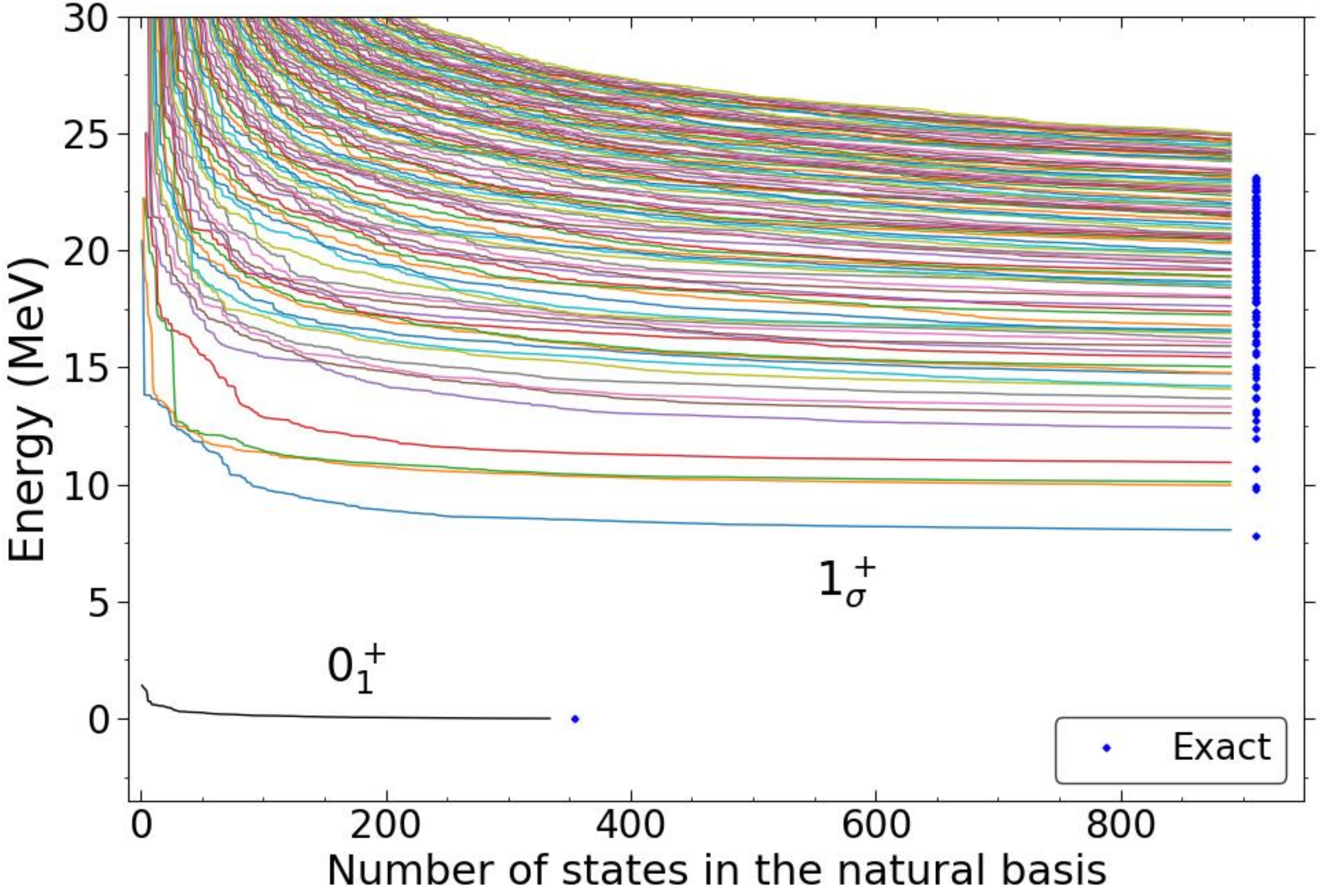


J^π	ΔE (MeV)
1_1^+	0.25
1_2^+	0.19
1_3^+	0.23
1_4^+	0.23

Applications: EM responses

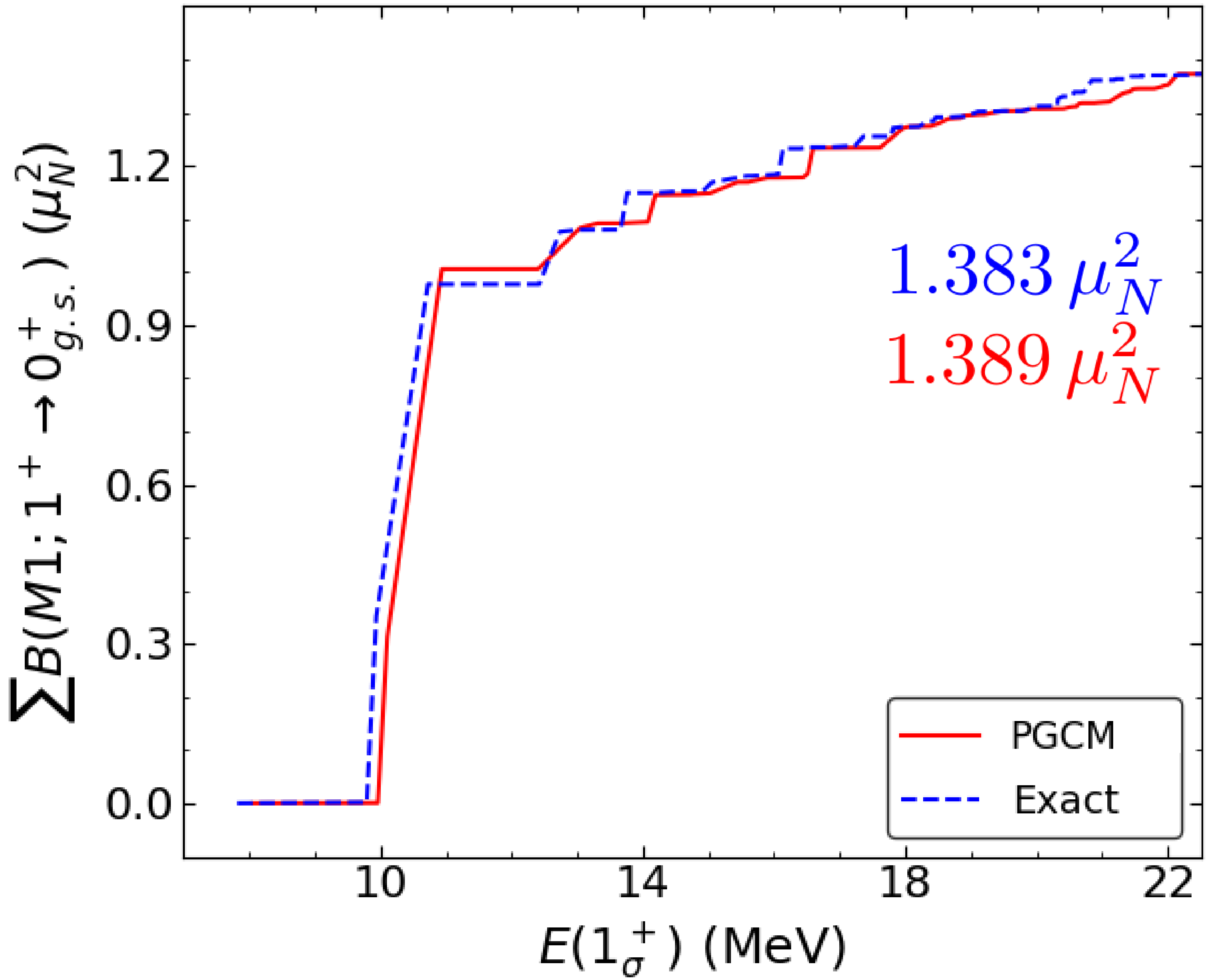


Projected Generator Coordinate Method



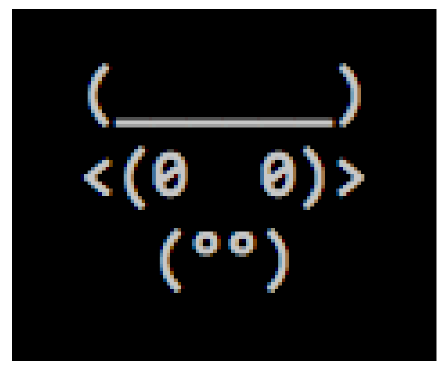
Projected Generator Coordinate Method

Exploring cranking, pn-pairing (isoscalar and isovector) $\{|\Phi(j_x, \delta_{pn}^{T=0}, \delta_{pn}^{T=1})\rangle\}$



Introduction

- **Even though historically PGCM has been associated with EDF, nowadays it has been extended to other kind of interactions:**



TAURUS
(Theory for A Unified descRiption of nUclear Structure)

B. Bally, T. R. Rodríguez, and A. Sánchez-Fernández, *Zenodo* **99,** 062501 (2020)
B. Bally and T. R. Rodríguez *Eur. Phys. J. A* **60**, 62 (2024)