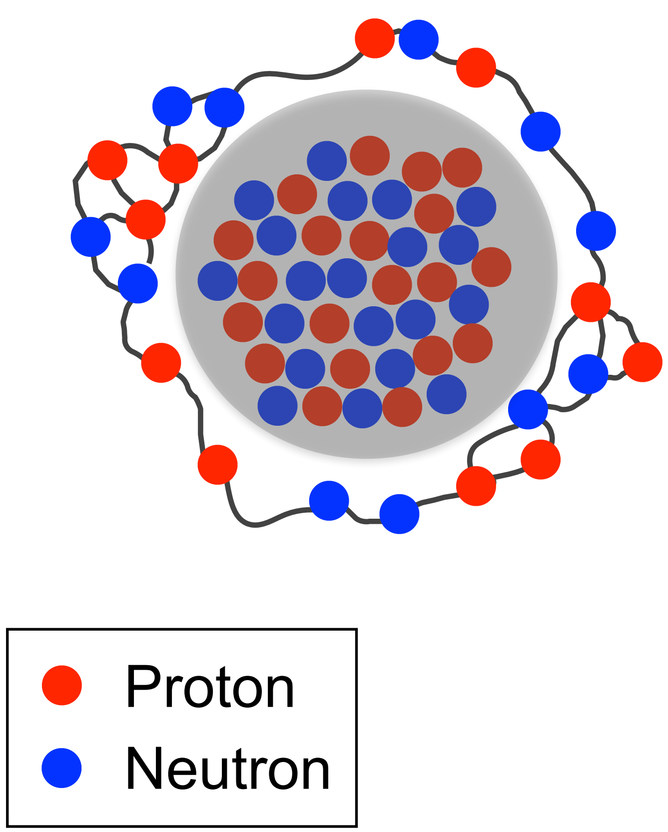
Microscopic and algebraic theory for complex nuclear shapes and dynamics

Kosuke Nomura - GANIL/Zagreb

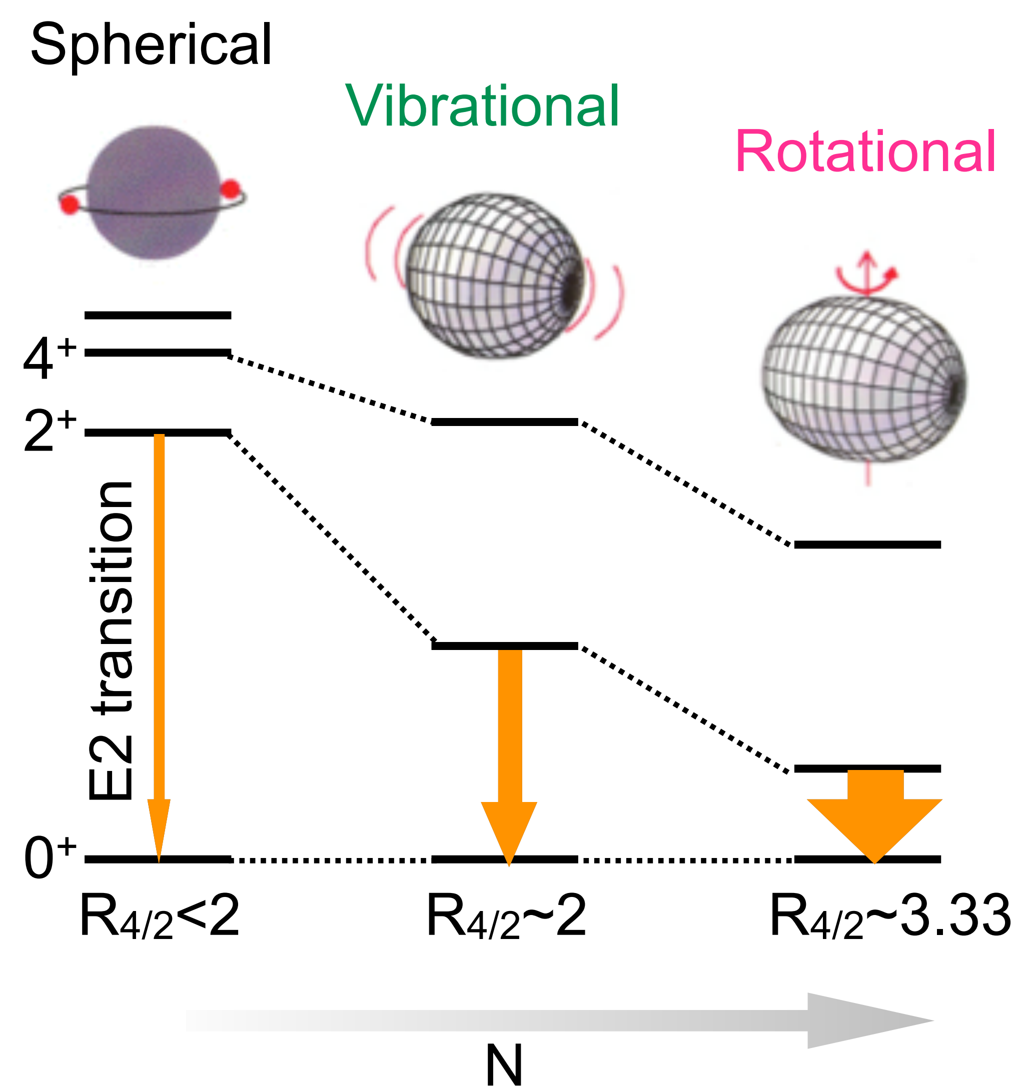
SDANCA-15 @ Sofia, Oct. 2015

Can one understand nuclear shapes and collective excitations (as well as their beautiful regularity) only from nucleonic d.o.f.?

Nuclear many-body system



Collective excitations



Plan of this talk

A novel method: combined algebraic and microscopic theory for universal description of nuclear shapes and spectroscopy

Two examples:

(i) Shape coexistence

(ii) Octupole shapes

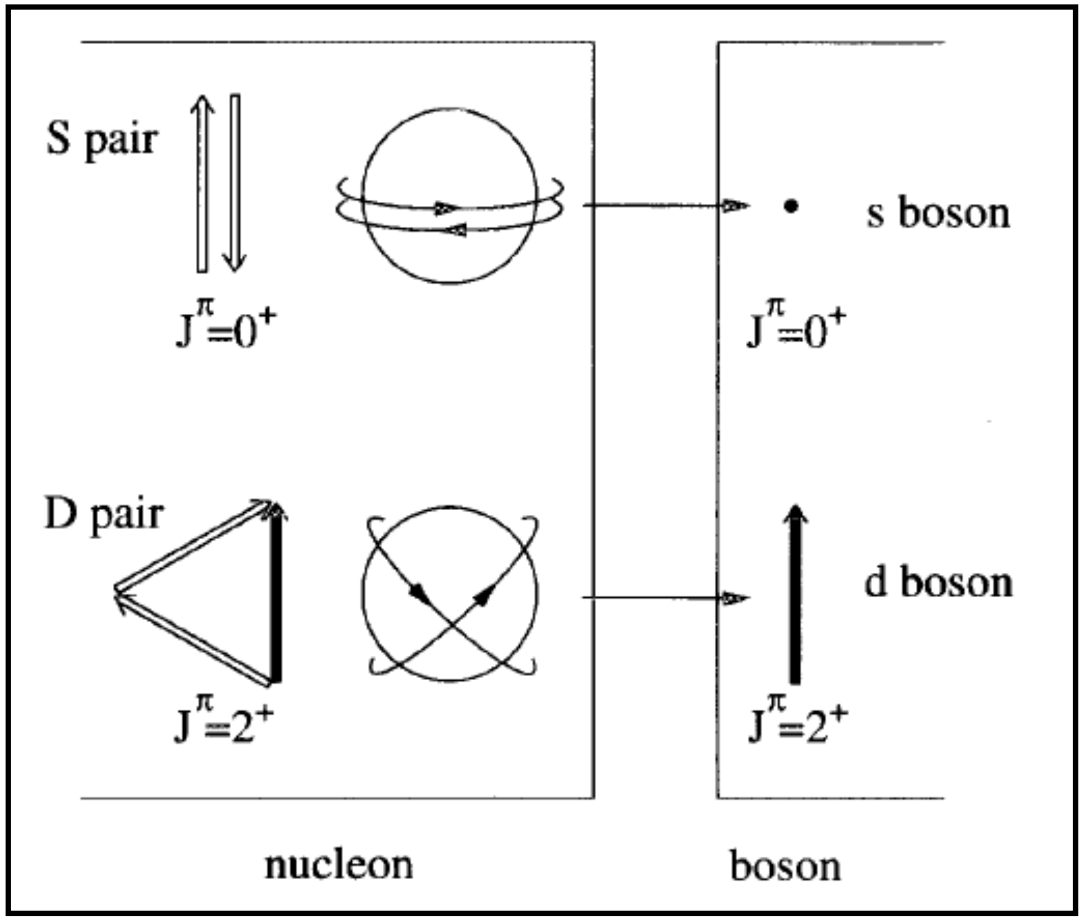
Algebraic theory of interacting bosons

Interacting boson model (IBM) Arima-Iachello (1974)

Approximation of pair of valence nucleons by boson

—> drastic reduction of Hilbert space

—> Use of group theory (U(5), SU(3), SO(6))



Dimension:

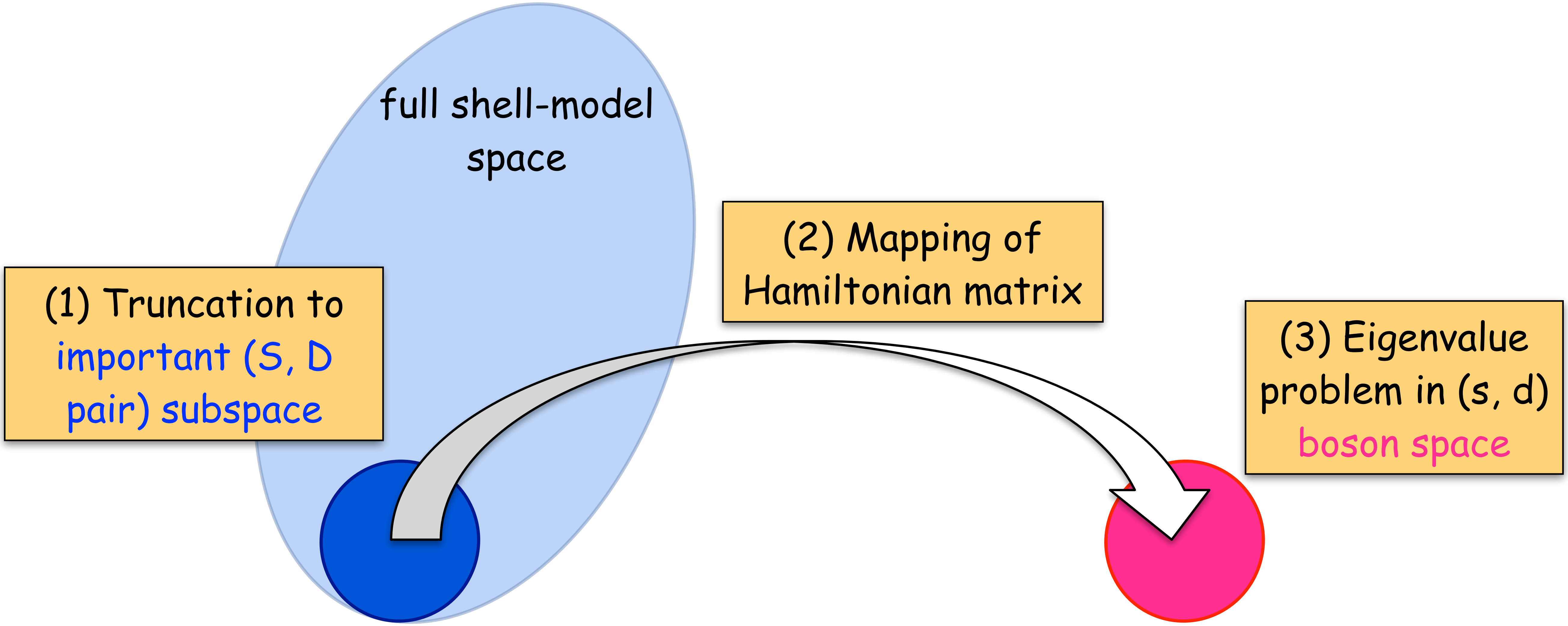
e.g., ^{154}Sm: 22 valence nucleons (12 protons + 10 neutrons)

- Shell model: ~ $O(10^{14})$ 2+ states
- IBM: 26 2+ states

Beautiful regularity in complex nuclei !

IBM from shell model

Otsuka-Arima-Iachello (1978)

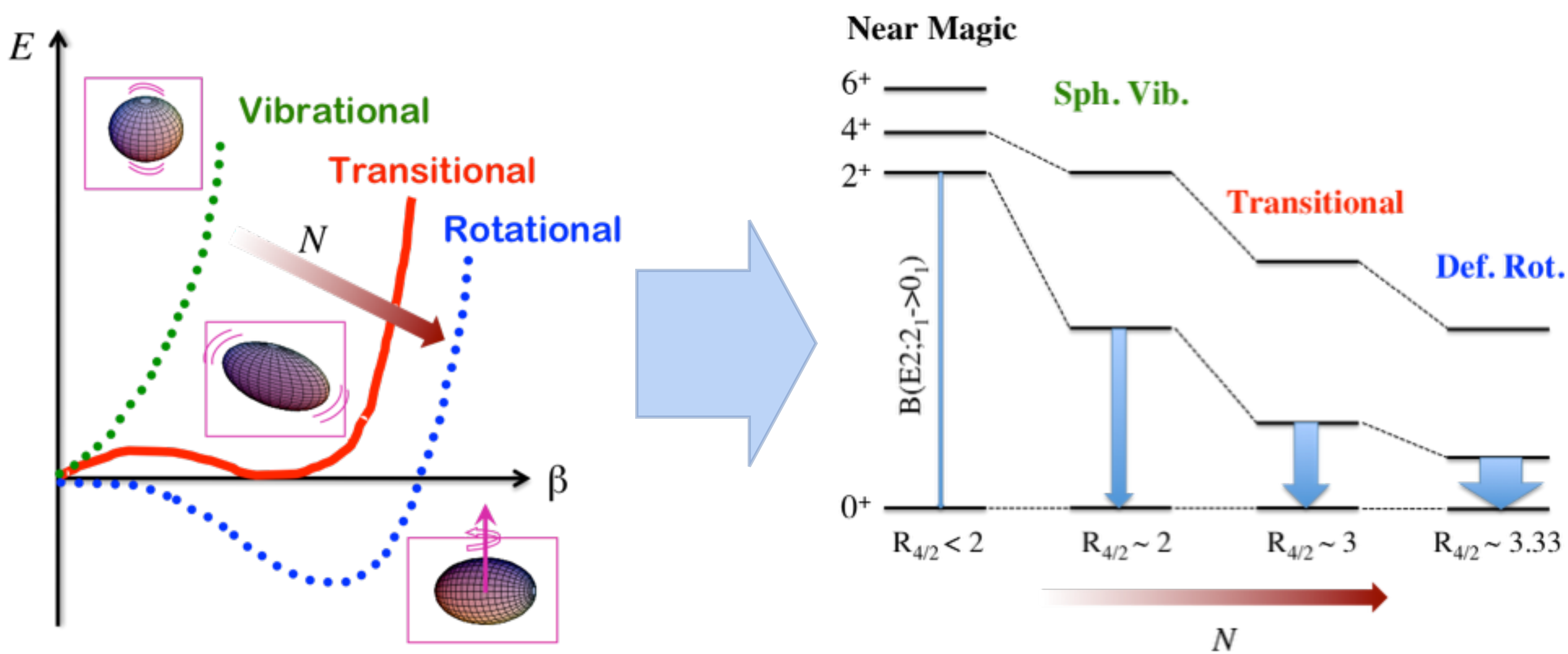


This approach was limited to spherical shapes...

For general (deformed) shapes?

This work — Principal idea

- One can choose a starting point of direct relevance to deformation (or shape).
- Good starting point would be mean-field calculation on potential energy surface with a given effective interaction of EDF (Skyrme, Gogny, RMF, etc).



IBM from DFT

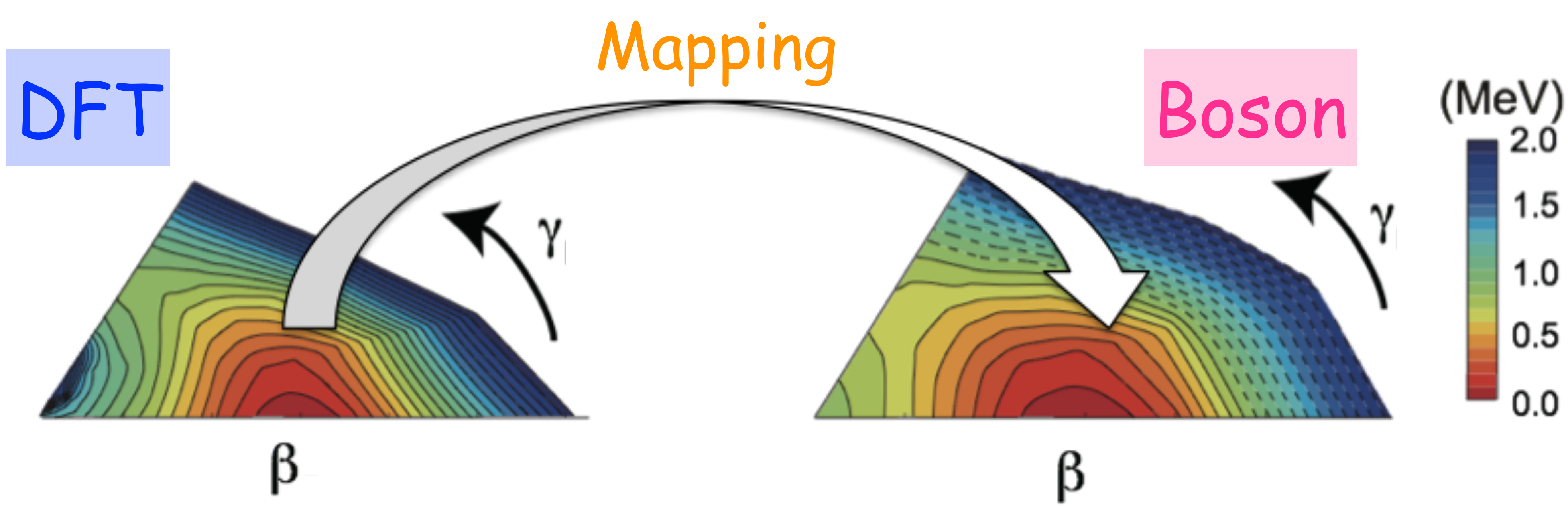
PRL **101**, 142501 (2008) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2008

Mean-Field Derivation of the Interacting Boson Model Hamiltonian and Exotic Nuclei

Kosuke Nomura,[1] Noritaka Shimizu,[1] and Takaharu Otsuka[1,2,3,4]

Novel way

1. Determine the IBM Hamiltonian by mapping fermionic (DFT) to bosonic (IBM) potential energy surfaces (PES).



2. Diagonalization of the boson Hamiltonian —> energies & transitions

How does it go?

Essential IBM(-2) Hamiltonian

$$\hat{H}^B = \epsilon(\hat{n}_{d\pi} + \hat{n}_{d\nu}) + \kappa\hat{Q}_\pi \cdot \hat{Q}_\nu$$

Spherical driving   Deformation driving

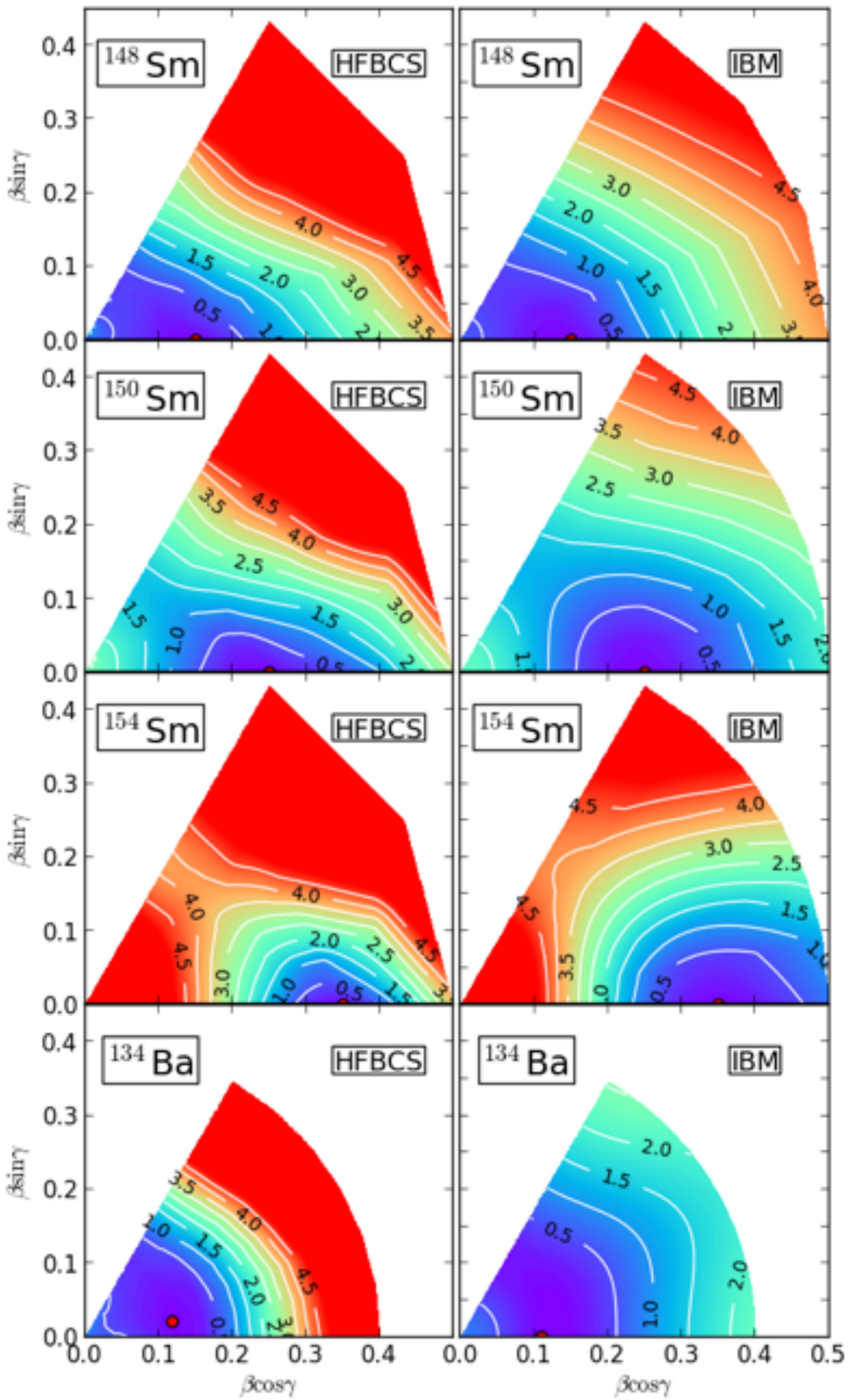
$$\hat{n}_{d\rho} = d_\rho^\dagger \cdot \tilde{d}_\rho \qquad \hat{Q}_\rho = s_\rho^\dagger\tilde{d}_\rho + d_\rho^\dagger\tilde{s}_\rho + \chi_\rho[d_\rho^\dagger \times \tilde{d}_\rho]$$

Four boson parameters (ε, κ, χ_π, χ_ν) are determined so that the IBM PES reproduces (i.e., is fitted to) the topology of the DFT PES around energy minimum.

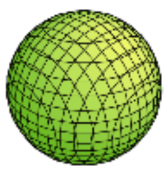
Boson Hamiltonian is derived only from DFT-based calculation (not adjusted to data).

Benchmark for basic quadrupole modes (1/3)

βγ-PES

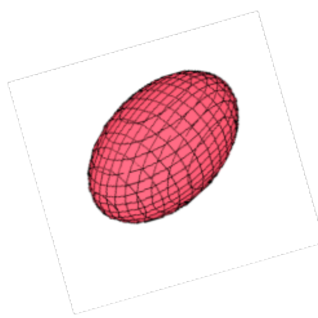


148Sm: Spherical vibrational (minimum close to βγ=0). ~U(5)

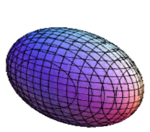


Transitional (softer both in βγ directions)

154Sm: Strongly deformed (minimum at larger β). ~SU(3)

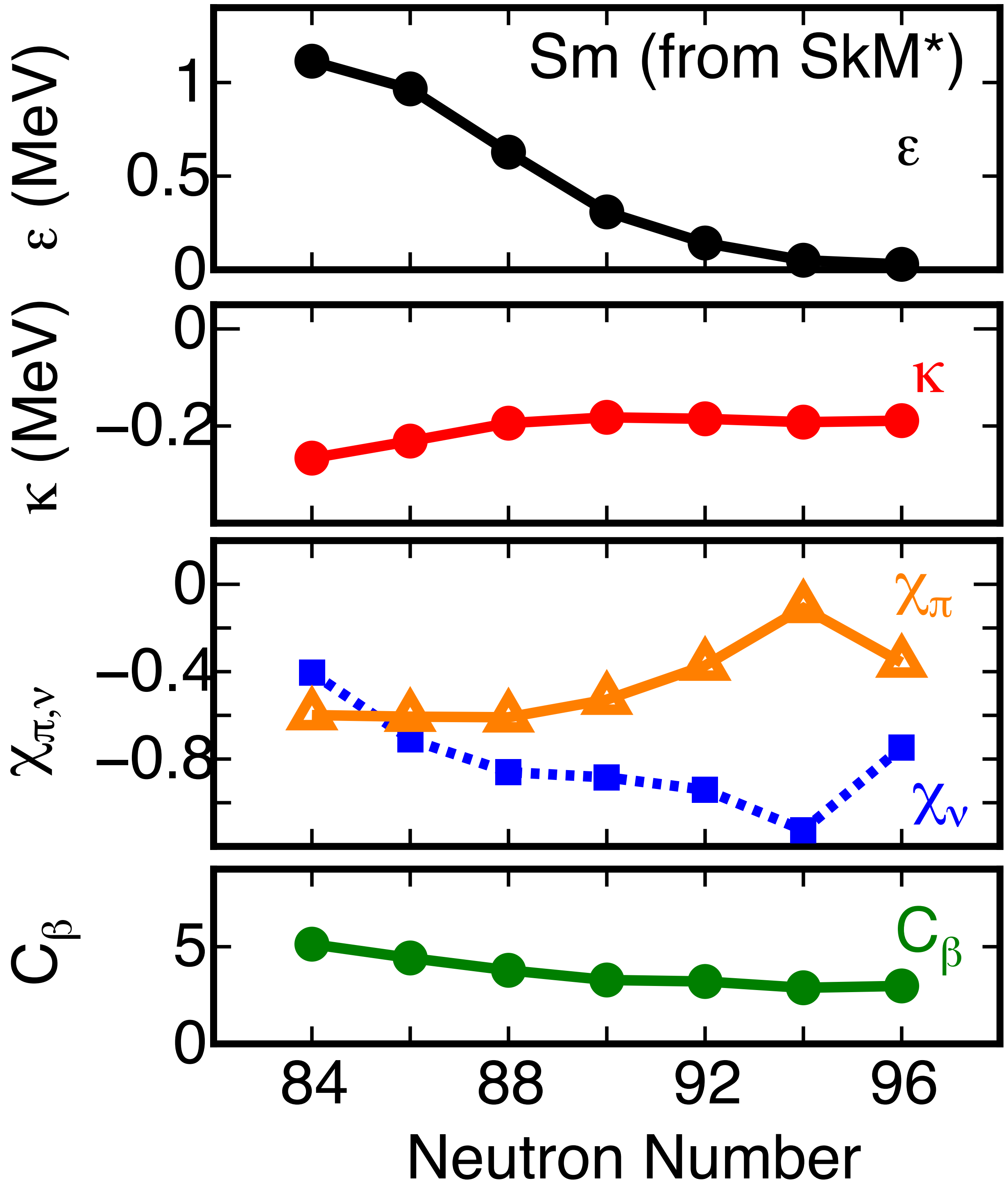


134Ba: γ-Soft, ~O(6)/E(5)



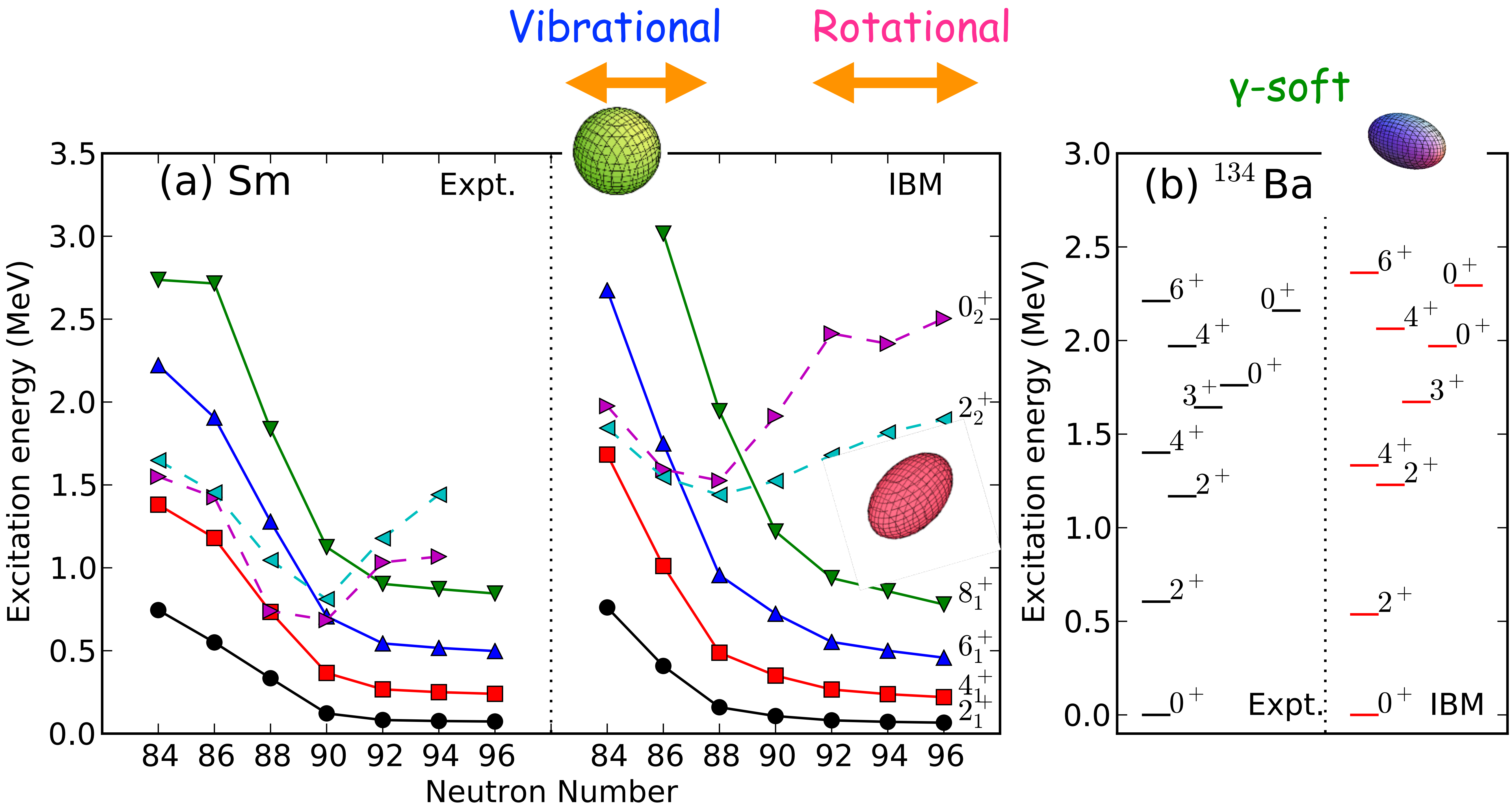
Benchmark for basic quadrupole modes (2/3)

IBM parameters determined microscopically



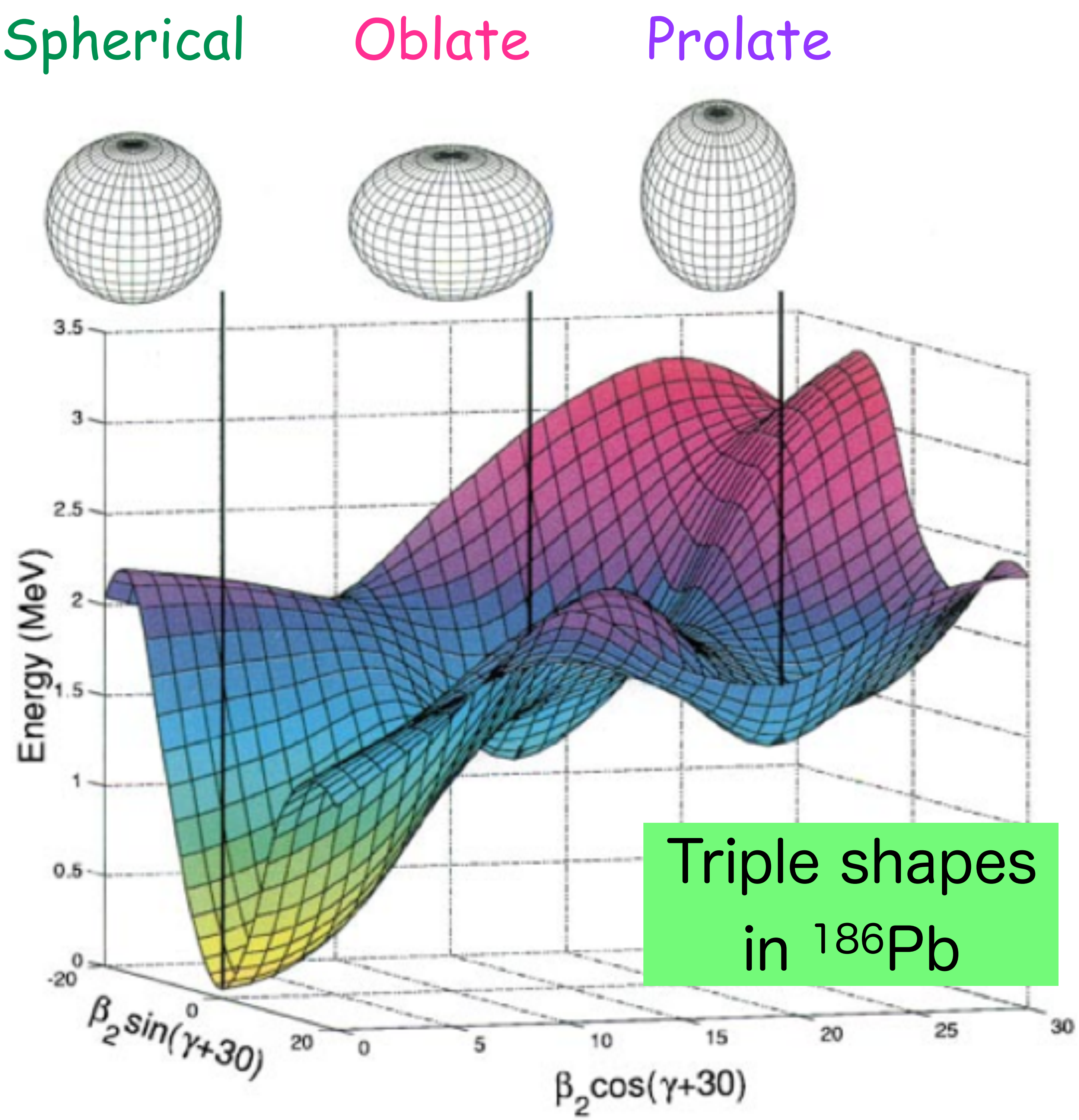
- Smooth variation with mass
- Consistent with the phenomenologically determined parameters

Benchmark for basic quadrupole modes (3/3)



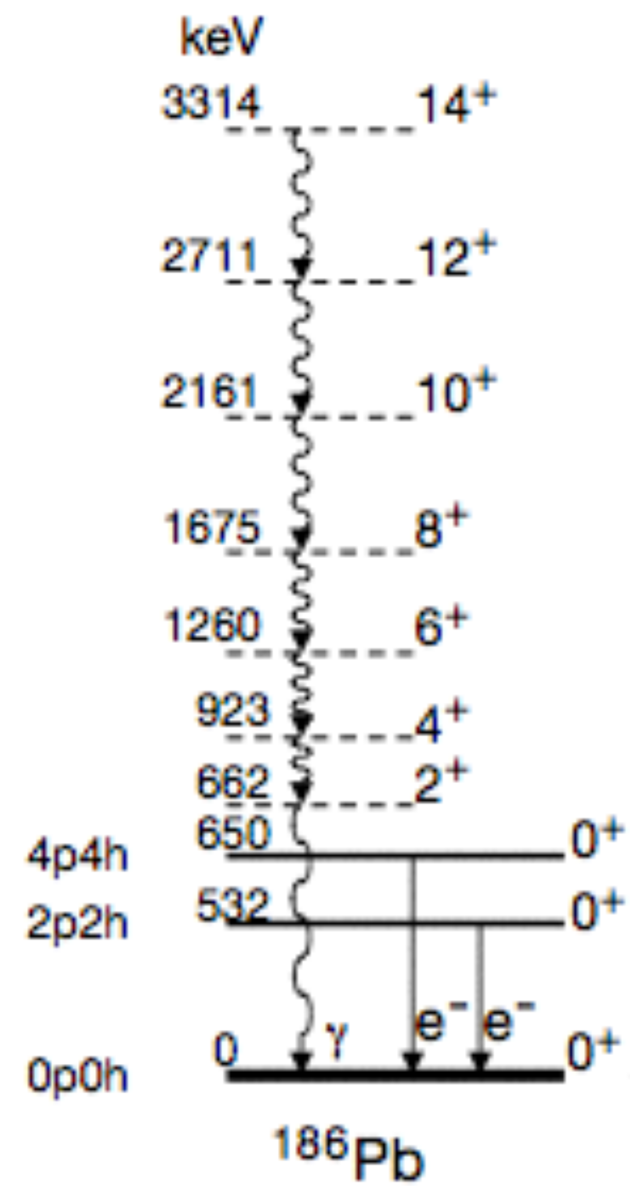
"Parameter-free" description of vibrational, rotational and γ-soft states

Nuclear structure around ^{208}Pb: good test of models



Triple shapes in ^{186}Pb

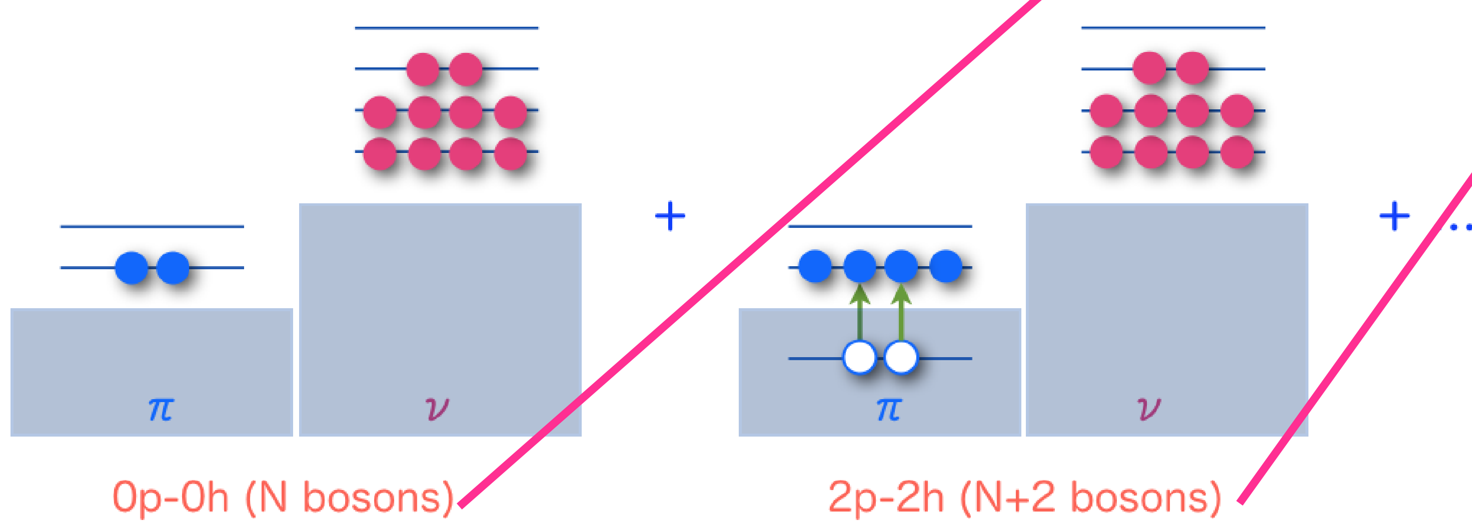
Low-lying 0+ states

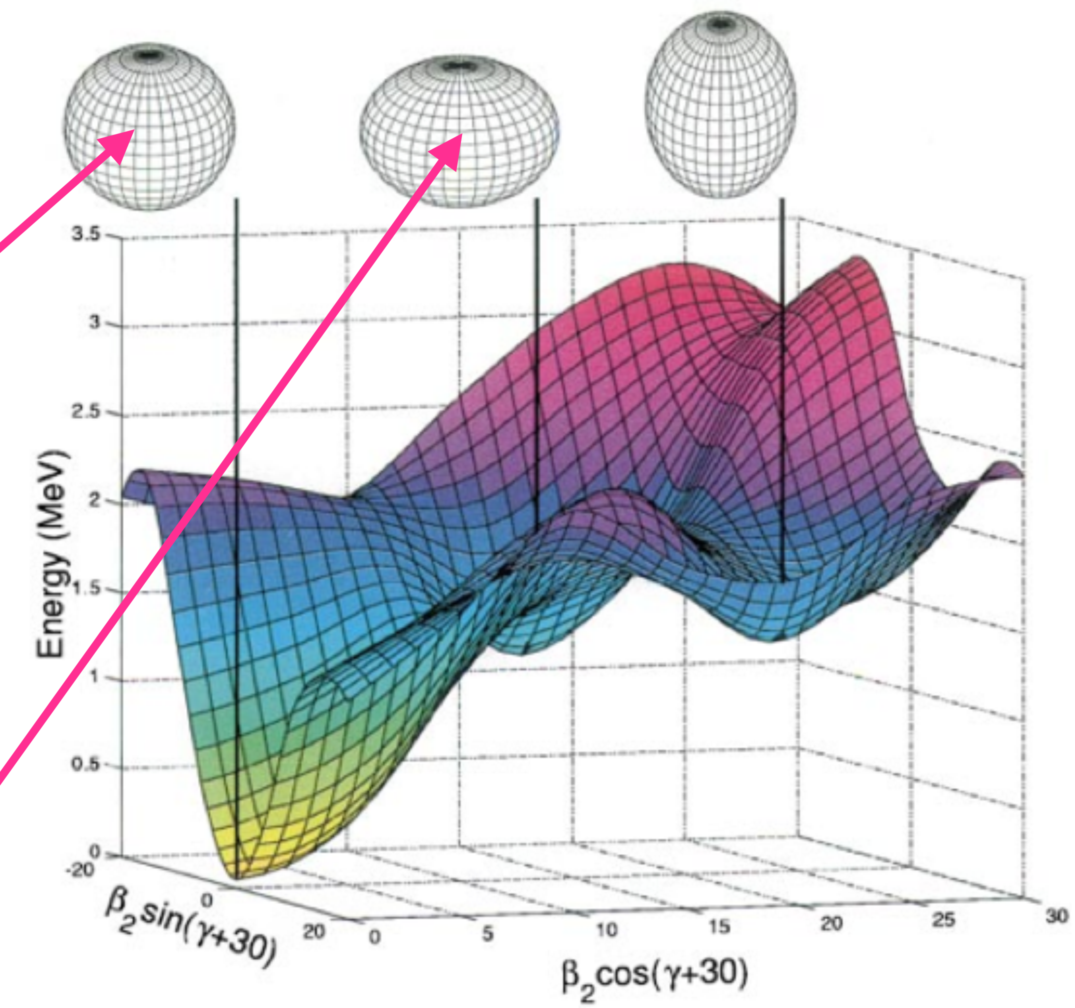


A. N. Andreyev et al., Nature (2000)

Interpretation in a simple picture

Many low-lying 0+ states can be attributed to intruder states in a shell model, that are associated with the corresponding shapes in a mean-field picture.

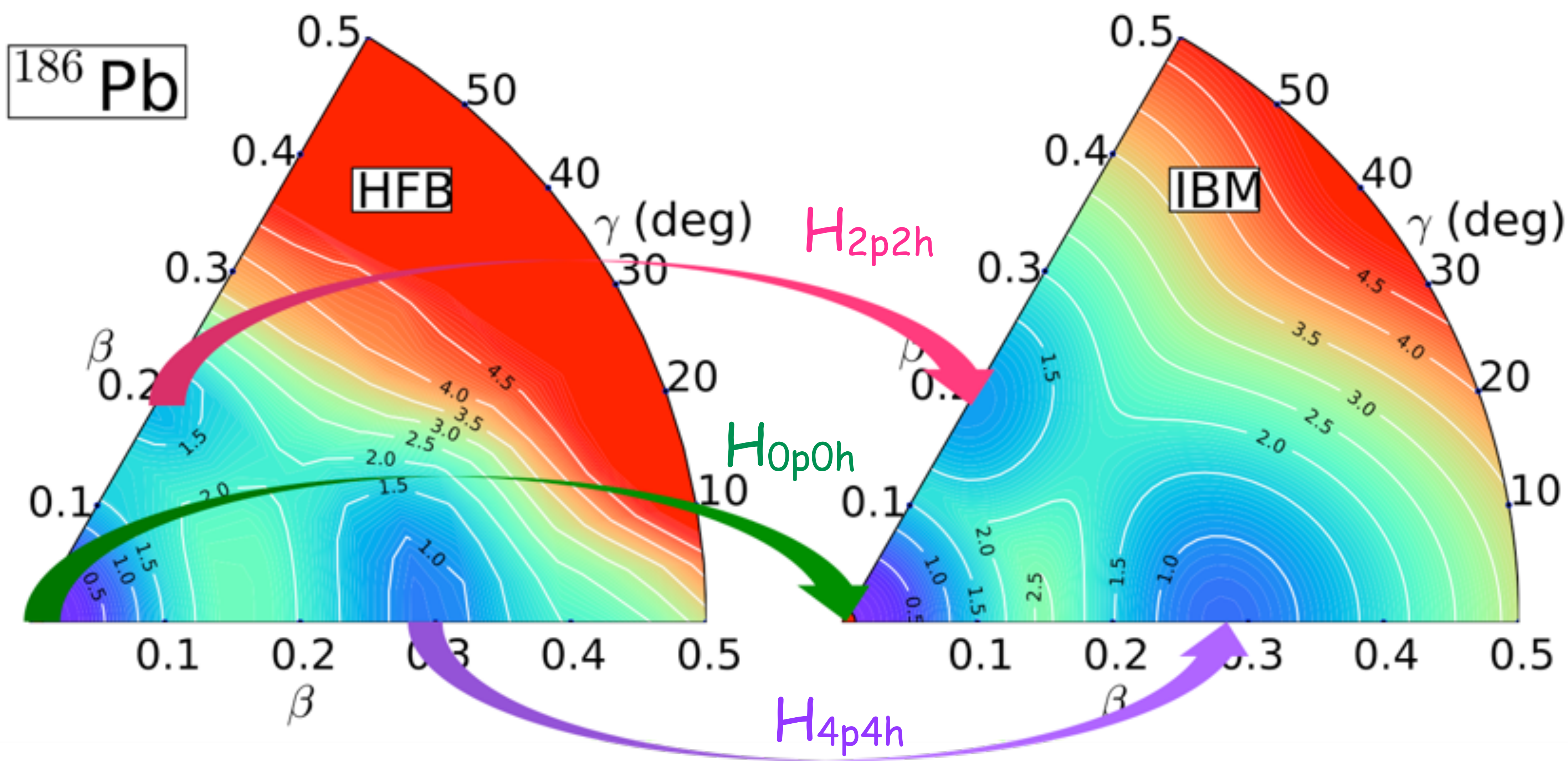




New IBM description of shape coexistence

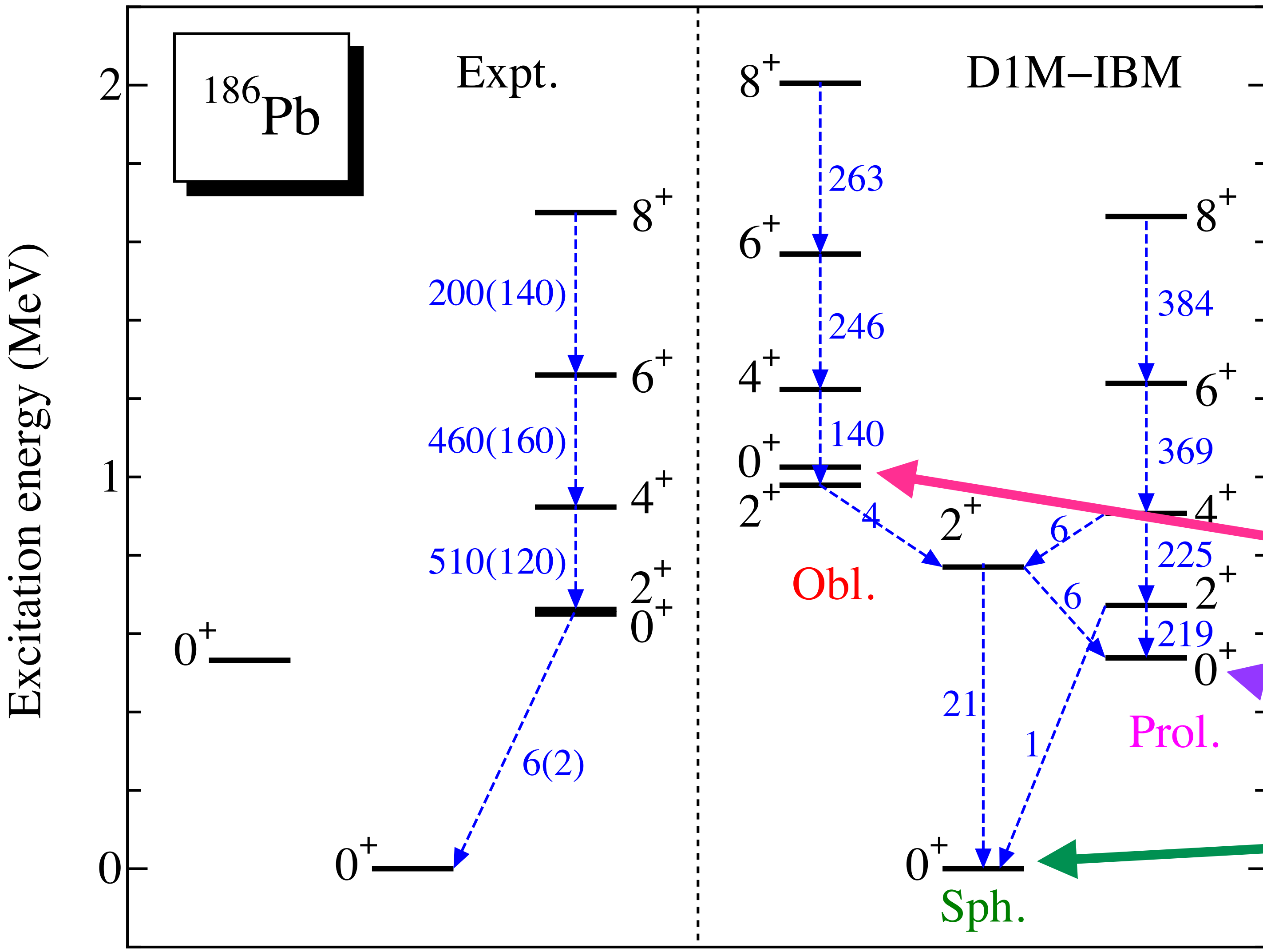
Mixing of Hamiltonians for 2n-particle-2n-hole excitations (n=0, 1, …). Each Hamiltonian is associated with the corresponding mean-field minimum.

$$H = H_{0p0h} + H_{2p2h} + H_{4p4h} + H_{mix}$$

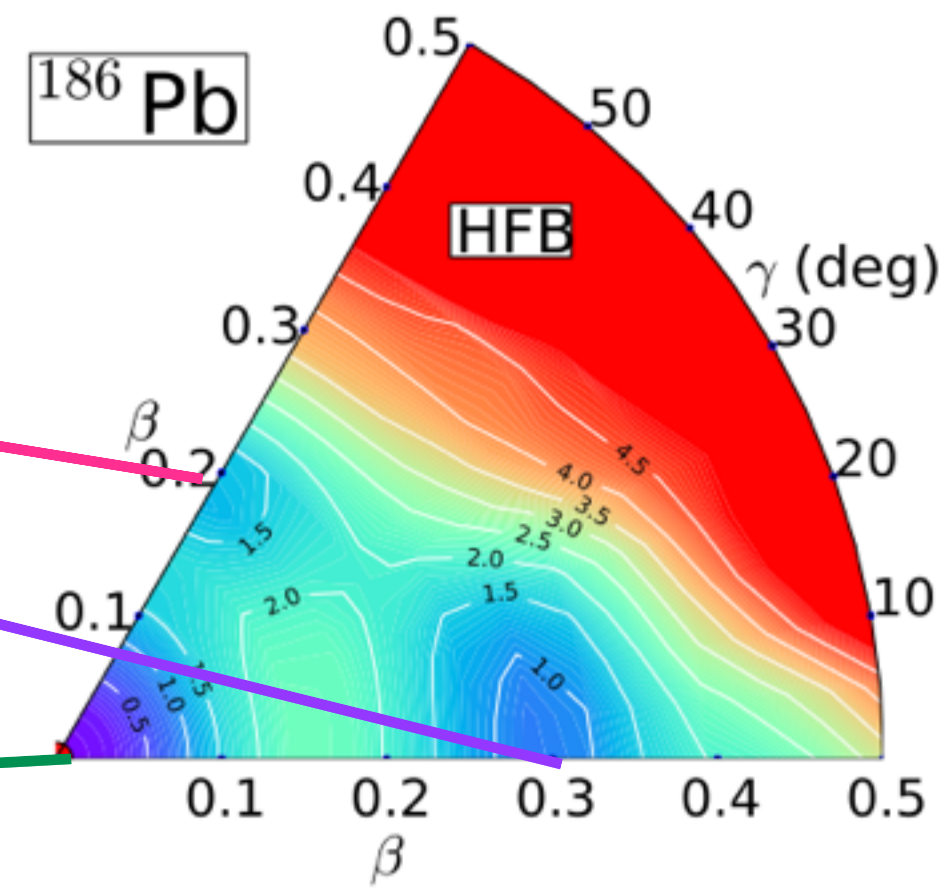


Level scheme of ^{186}Pb

Three low-energy collective bands

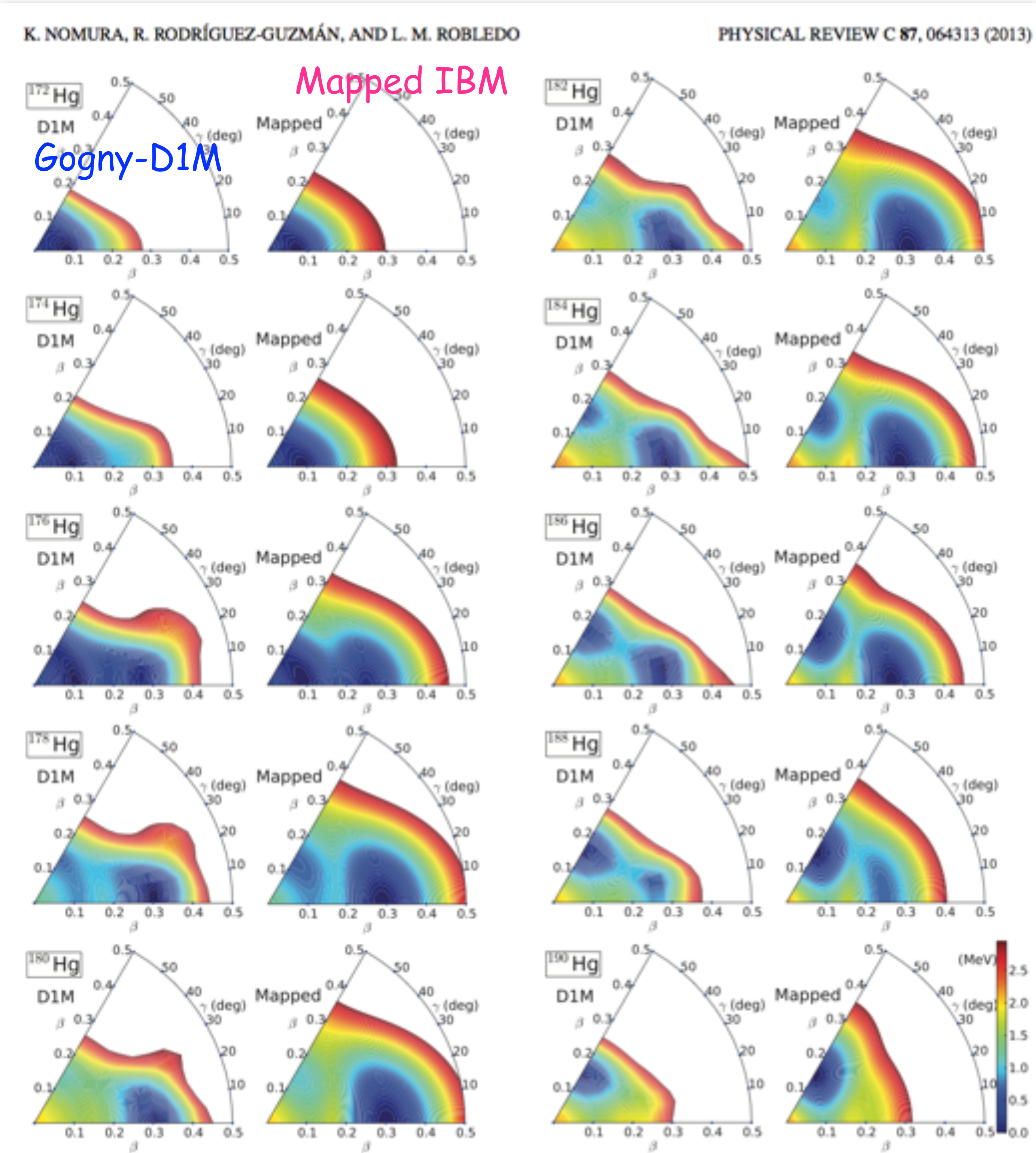


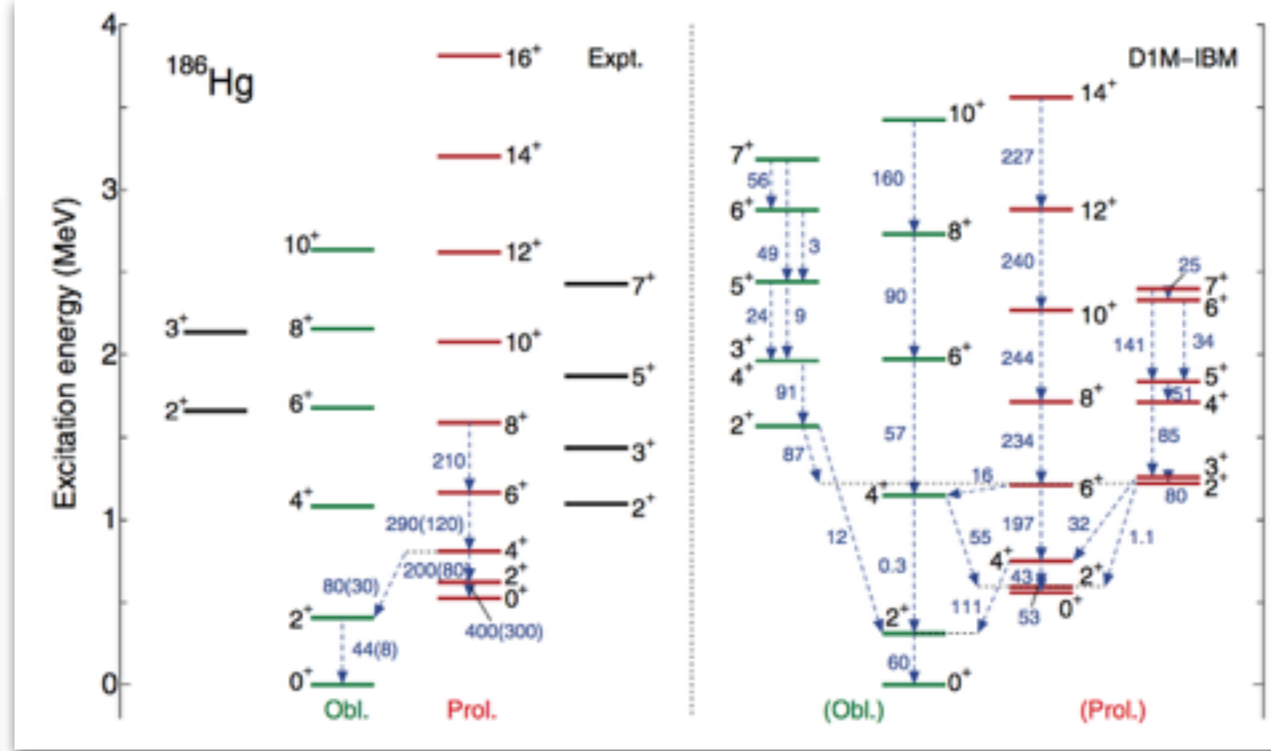
Gogny-HFB PES:
three minima

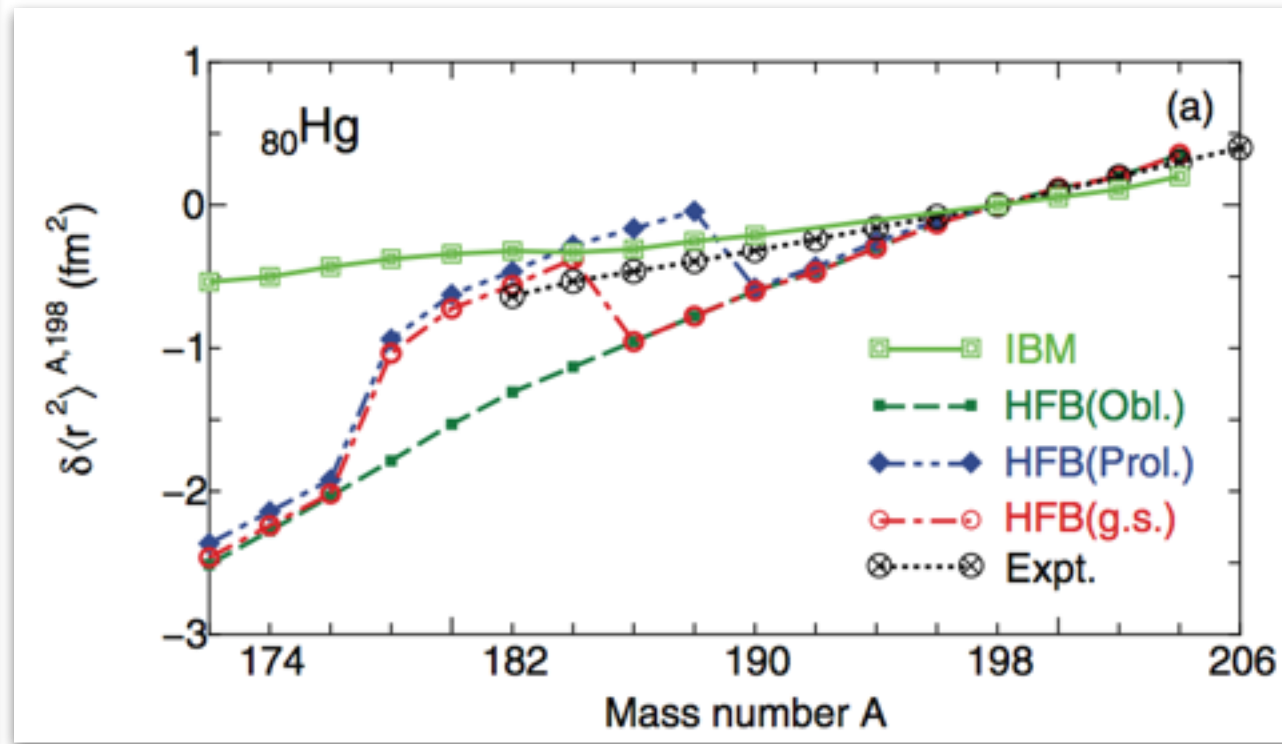


K. Nomura, R. Rodríguez-Guzmán, L. M. Robledo, N. Shimizu, PRC86, 034322 (2012)

Systematics: Hg chain







K. Nomura, R. Rodríguez-Guzmán, L. M. Robledo, PRC87, 064313 (2013)

- Spherical-Prolate-Oblate transition
- Reasonable description of spectroscopic and intrinsic properties

Growing general interest in "pear-shaped" nuclei

Enhanced electric dipole transition characteristic of reflection asymmetry —> test of CP violation

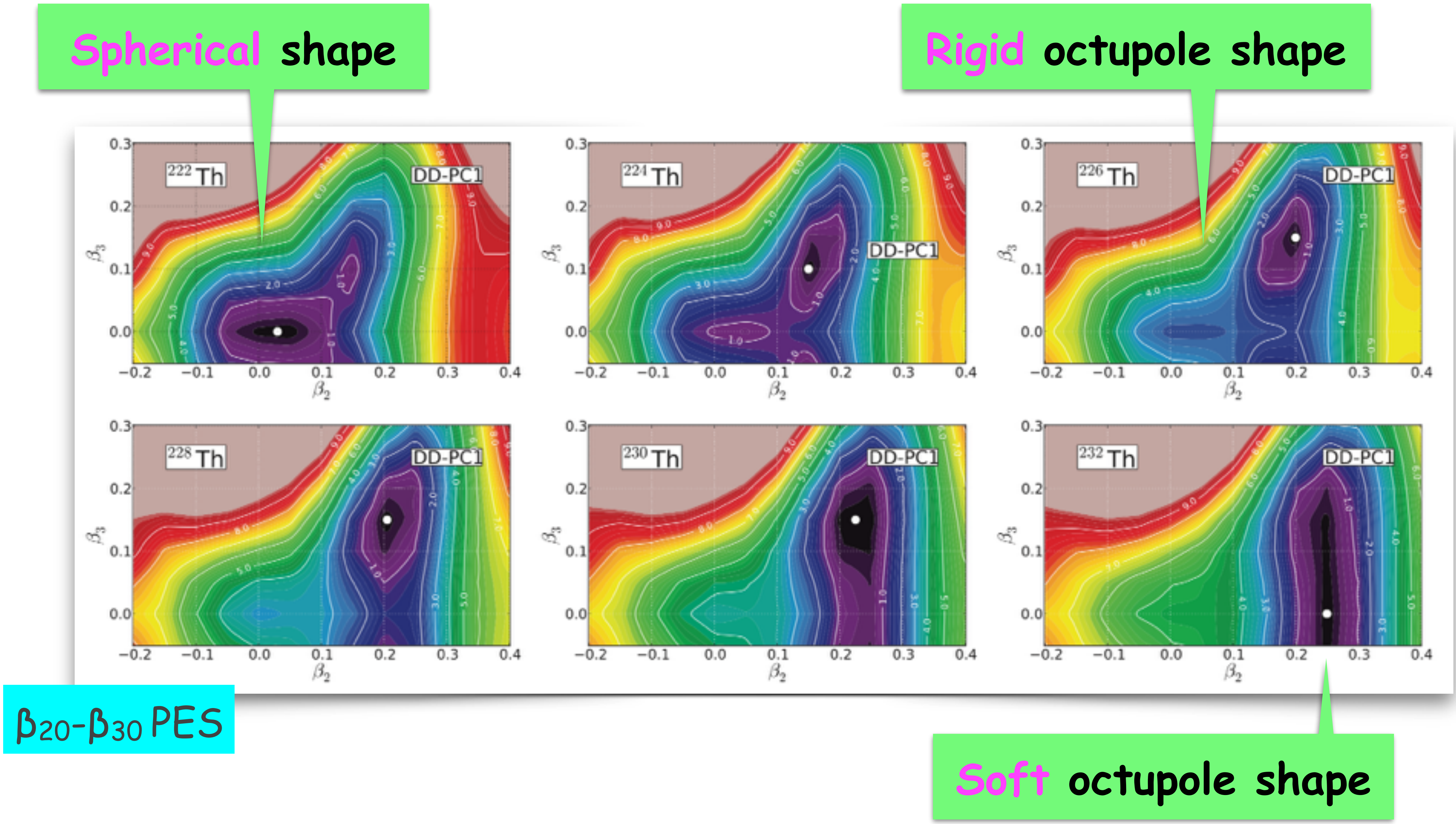
Permanent octupole deformation in light actinide (Coulex @ REX-ISOLDE, CERN)

PRC Editors' Suggestion

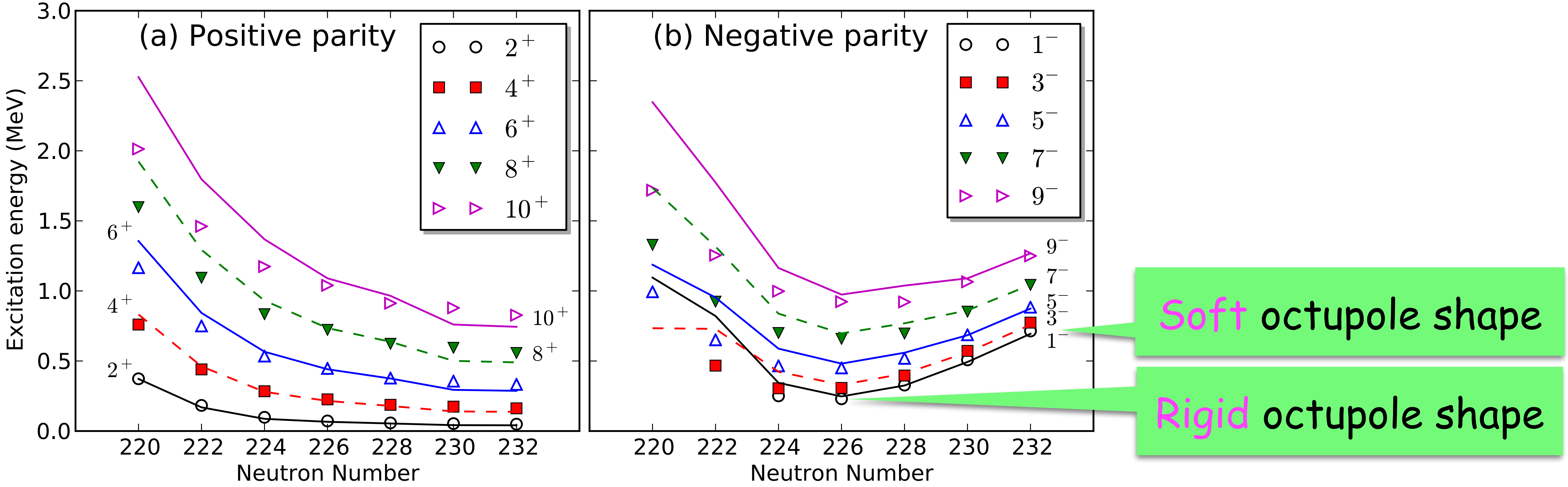
Microscopic description of octupole shape-phase transitions in light actinide and rare-earth nuclei

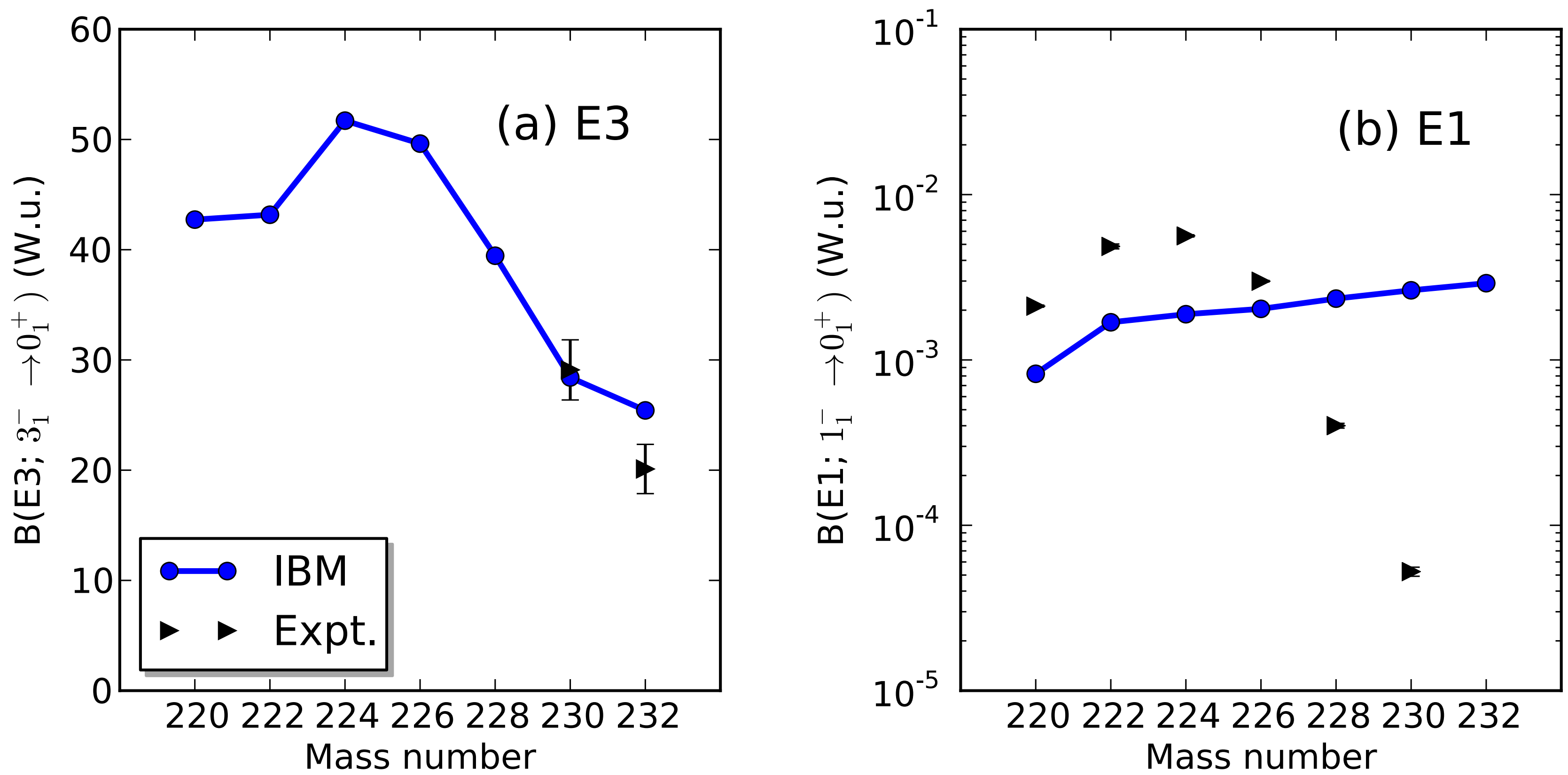
K. Nomura, D. Vretenar, T. Nikšić, and Bing-Nan Lu

Phys. Rev. C **89**, 024312 (2014) – Published 24 February 2014



Energies & transitions from mapped sdf-IBM

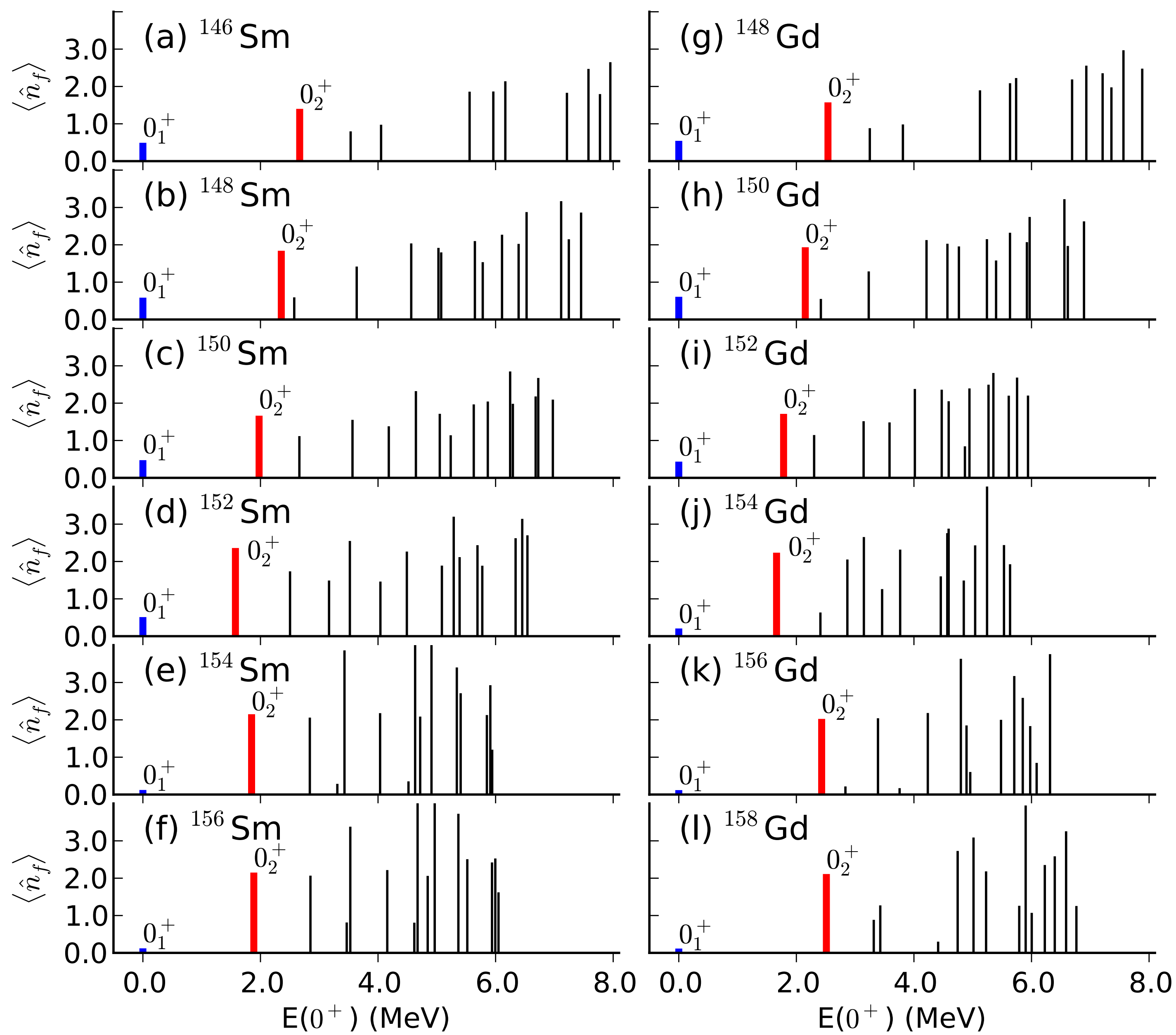




0+ states in rare-earth nuclei

Energy distribution of 0+ states

# of octupole phonons



In many of the rare-earth nuclei, the first excited 0+ state is formed by the coupling of double octupole phonons (<n_f>~2).

K.N., R. Rodriguez-Guzman, L. M. Robledo, PRC92, 014312 (2015)

Concluding remarks

Novel method linking DFT and IBM

- Mapping of the intrinsic states between DFT and IBM
- Valid for any shapes
- With input from DFT, the IBM now allows a "parameter-free" description of nuclear shapes and spectroscopy.
- Microscopic basis of IBM in general cases

Perspectives

- Precise description of E1 systematics
- Validity of current EDFs. A more realistic interaction?

Main collaborators

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L. M. Robledo (Madrid)

R. Rodríguez-Guzmán (Kuwait)

P. Van Isacker (GANIL)

... and thank you for your attention!