June 2014, Tokyo

Advances in the microscopic study of the Interacting Boson Model

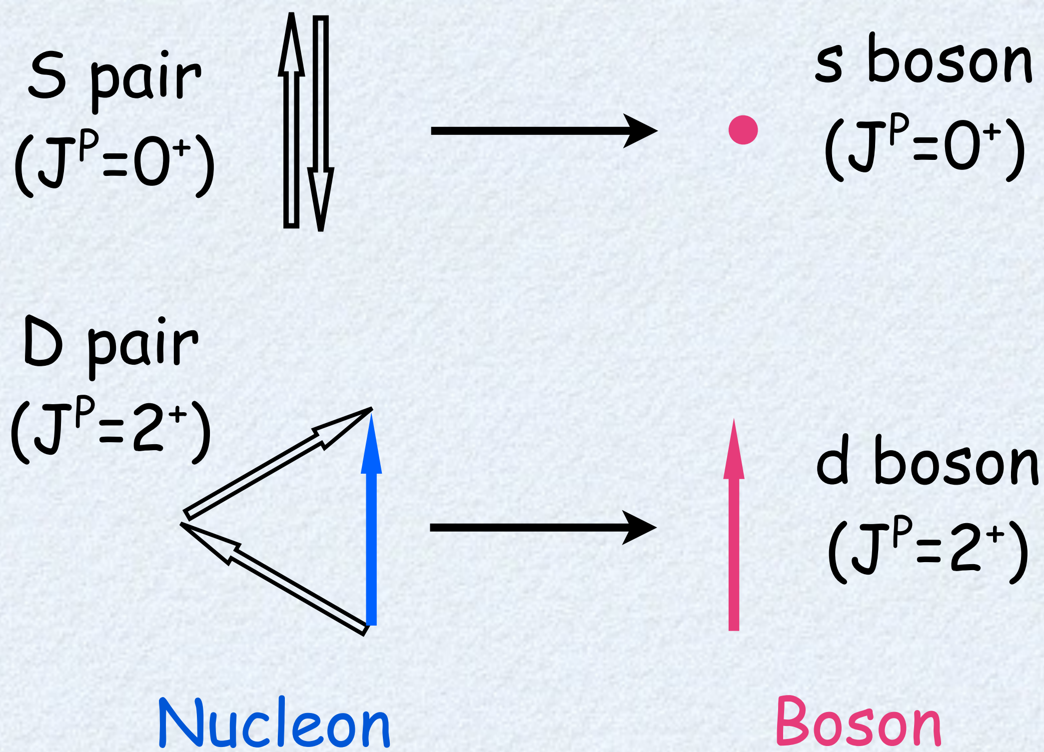
Kosuke Nomura (GANIL)

Interacting boson model (IBM)

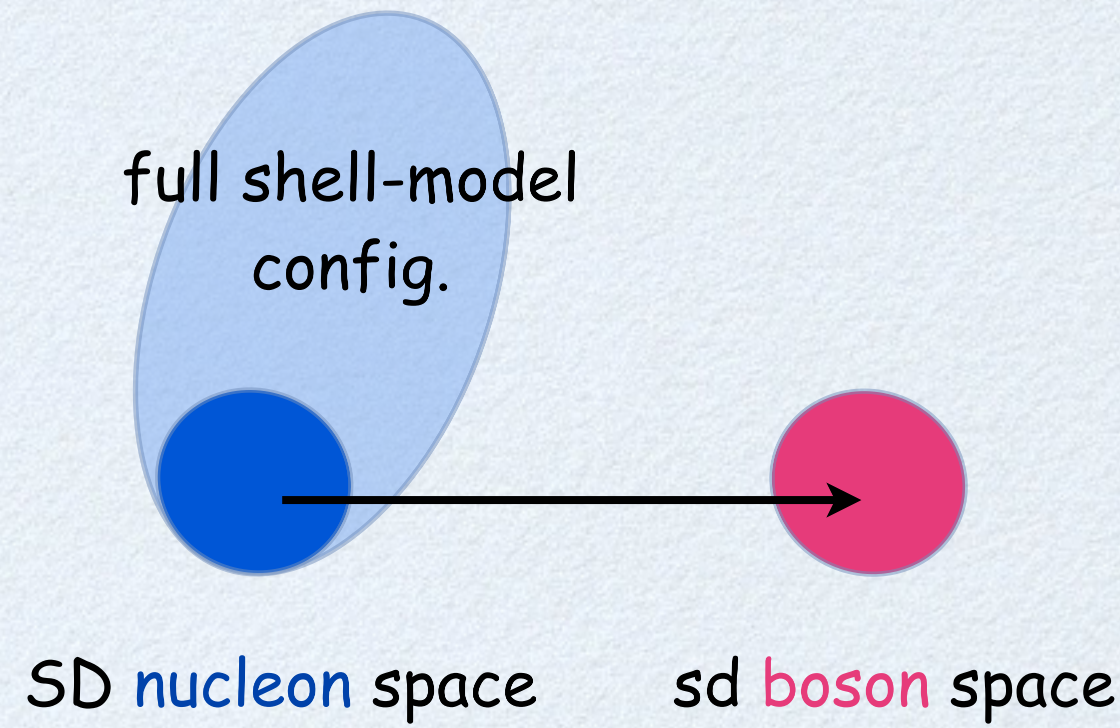
- Ingredients: collective pairs of valence nucleons
- shell-model derivation. Valid for near vibrational nuclei

Refs:
- A. Arima, F. Iachello (1974)
- T. Otsuka, A. Arima, F. Iachello (1978)
- T. Mizusaki, T. Otsuka (1996)
- …

Microscopic basis



Otsuka-Arima-Iachello (OAI) mapping



Q. Can we derive IBM Hamiltonian in some unified way ?

Long-standing problem

Physica Scripta, Vol. 22, 468–474, 1980

Features of Nuclear Deformations Produced by the Alignment of Individual Particles or Pairs

Aage Bohr and Ben R. Mottelson

The Niels Bohr Institute and Nordita, Blegdamsvej 15, DK-2100 Copenhagen, Denmark

"IBM may not be sufficient to describe some properties of strongly deformed nuclei because of the SD truncation."

Many debates over the validity of the IBM. Concrete answer still missing.

- Nilsson-BCS model (T. Otsuka et al., 1982; D. Bes et al., 1982)
- Renormalization of G pair or inclusion of g boson (e.g., T. Otsuka, Ginocchio, 1985; T. Otsuka, M. Sugita, 1988)
- Conventional boson mapping (e.g., M. R. Zirnbauer, 1984)
- J projection on the intrinsic wave function (N. Yoshinaga et al., 1984)
- … Many others

This talk

A unified way of deriving IBM Hamiltonian for all known cases of basic low-lying collective states:

- Vibrational (weakly deformed) nuclei [1,2]
- rotational (strongly deformed) nuclei [3]
- Triaxial (or γ-soft) nuclei [4]
- … (Other relevant cases)

Relevant publications:

[1] K.N., N. Shimizu, T. Otsuka, PRL101, 142501 (2008)

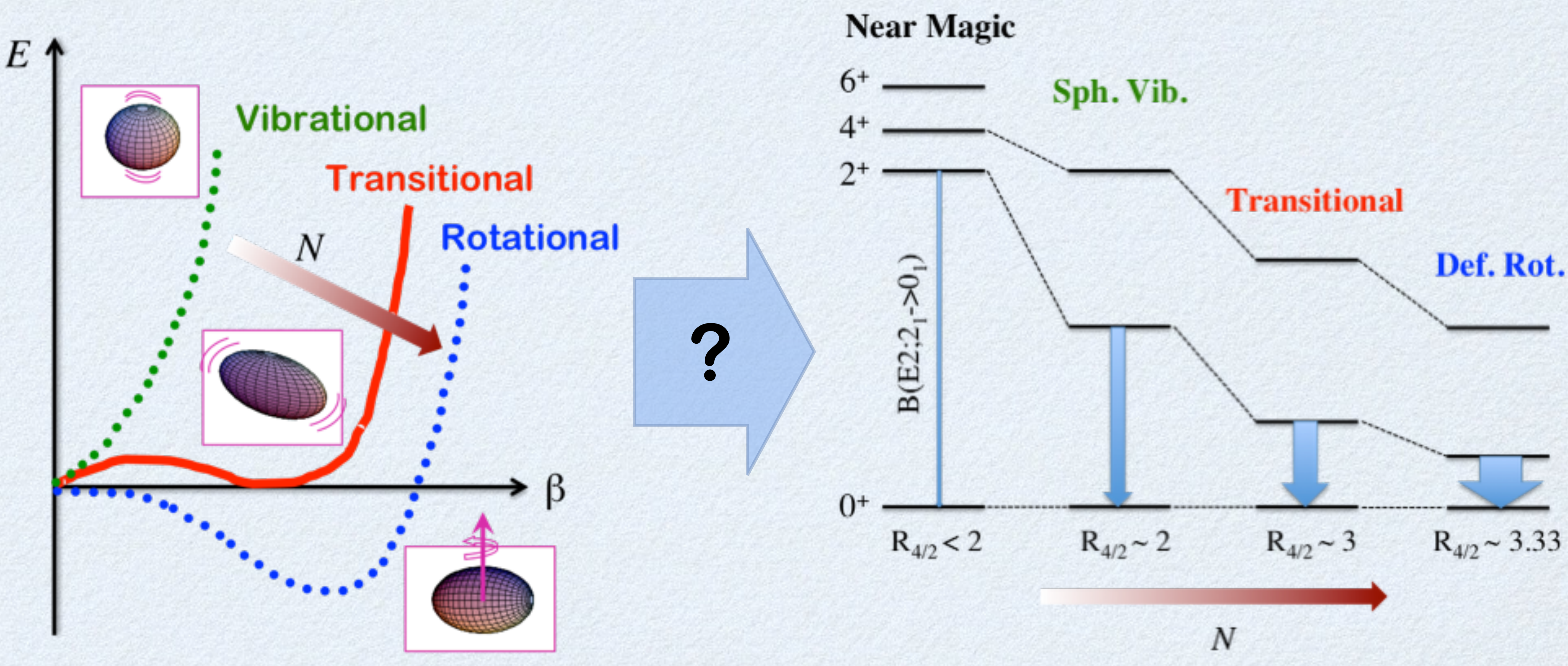
[2] K.N., N. Shimizu, T. Otsuka, PRC81, 044307 (2010)

[3] K.N., T. Otsuka, N. Shimizu, L. Guo, PRC83 041302(R) (2011)

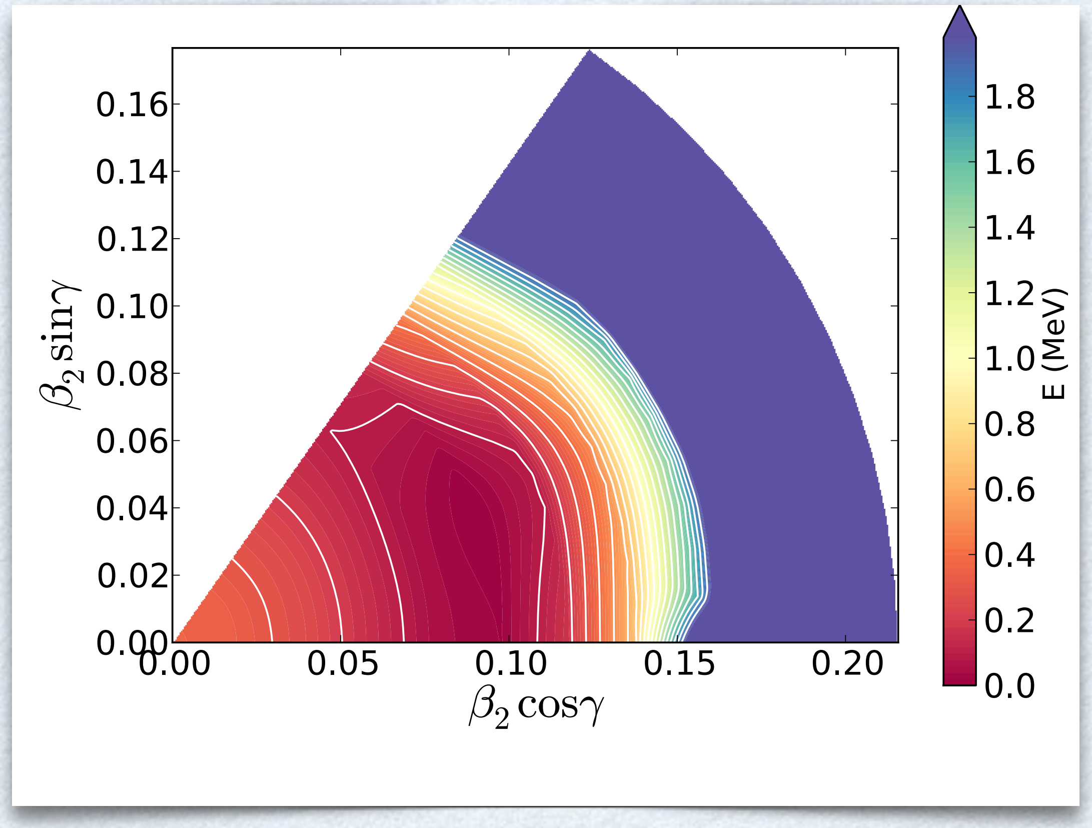
[4] K.N., N. Shimizu, D. Vretenar, T. Nikšić, T. Otsuka, PRL108, 132501 (2012)

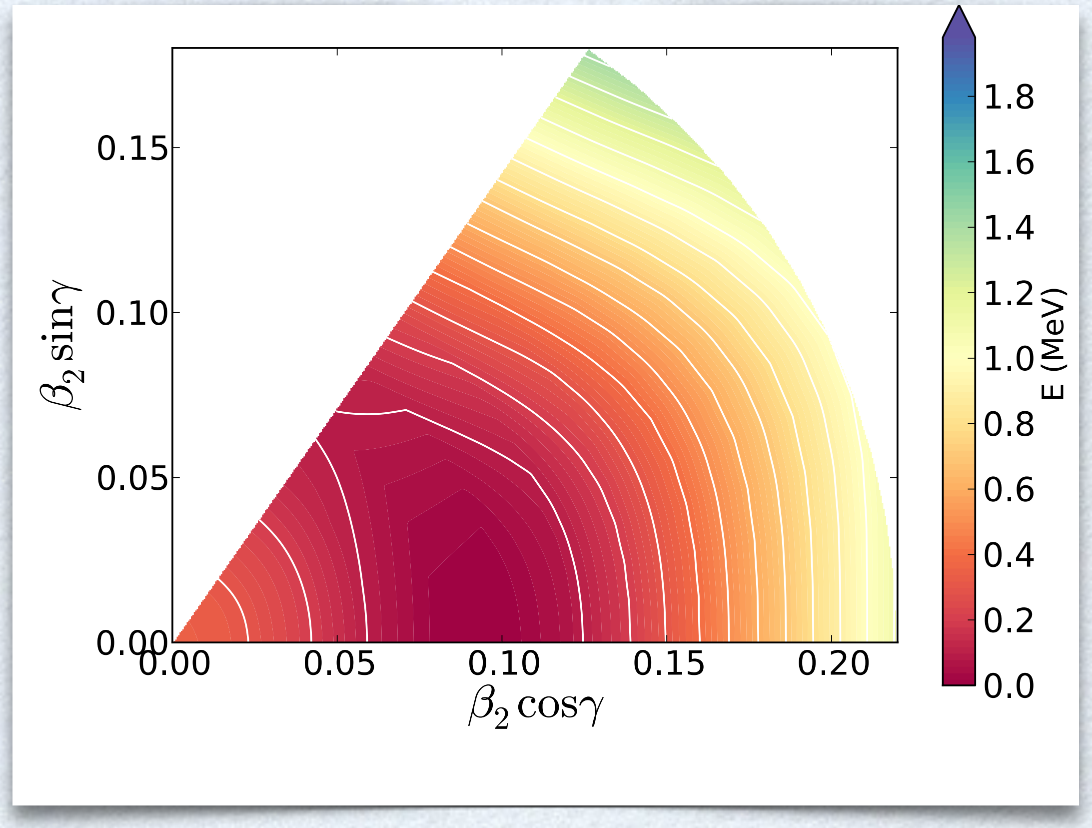
Principal idea

- A given mean-field model (Skyrme, Gogny, RMF, etc) can be a good starting point for computing spectra of the intrinsic state of interest.
- We construct an IBM(-2) Hamiltonian by mapping the mean-field solution onto the interacting-boson state.



Basic case: mapping energy surface





Total energy of constrained HFB within a given mean-field model

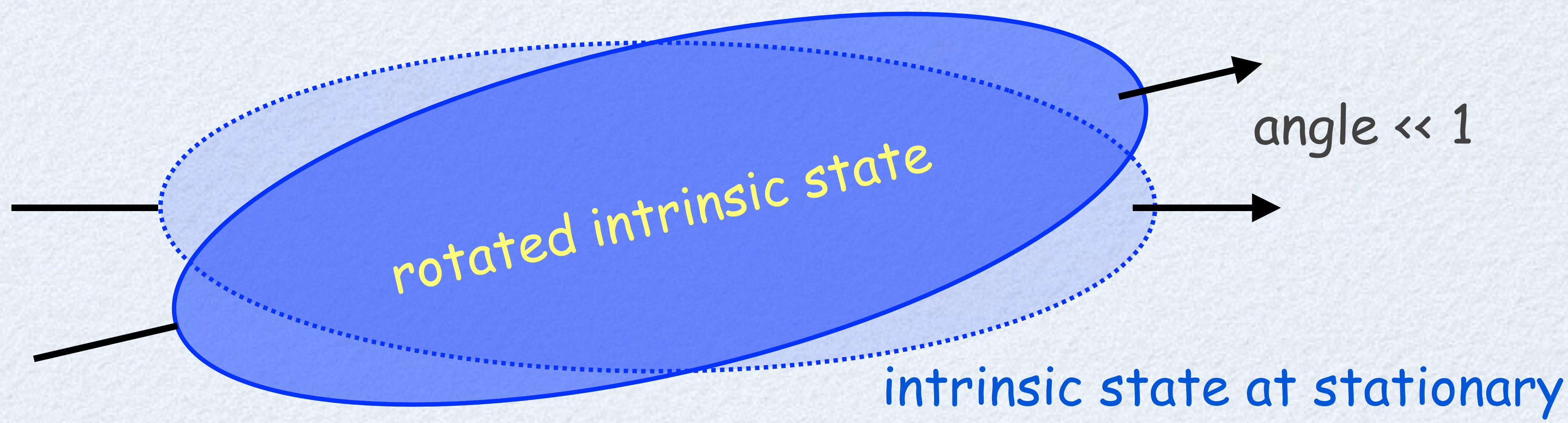
Total energy for a boson condensation (energy expectation value of boson system)

An IBM-2 Hamiltonian is determined by the equality $E_{HFB} \approx E_{IBM}$; energy levels and wave functions with good spin, particle number, parity, etc.

Fermion-boson mapping for deformed nuclei

- A basic rotational property should be also reproduced by bosons. We consider rotational response (= energy shift due to infinitesimal rotation of nucleon intrinsic state).
- The missing piece is the rotational LL term in the IBM, giving correct moment of inertia.

- Intuitive picture -



"Essential" boson Hamiltonian

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

Step 1) "Basic part": mapping of the PES. Valid for near-spherical and γ-unstable cases

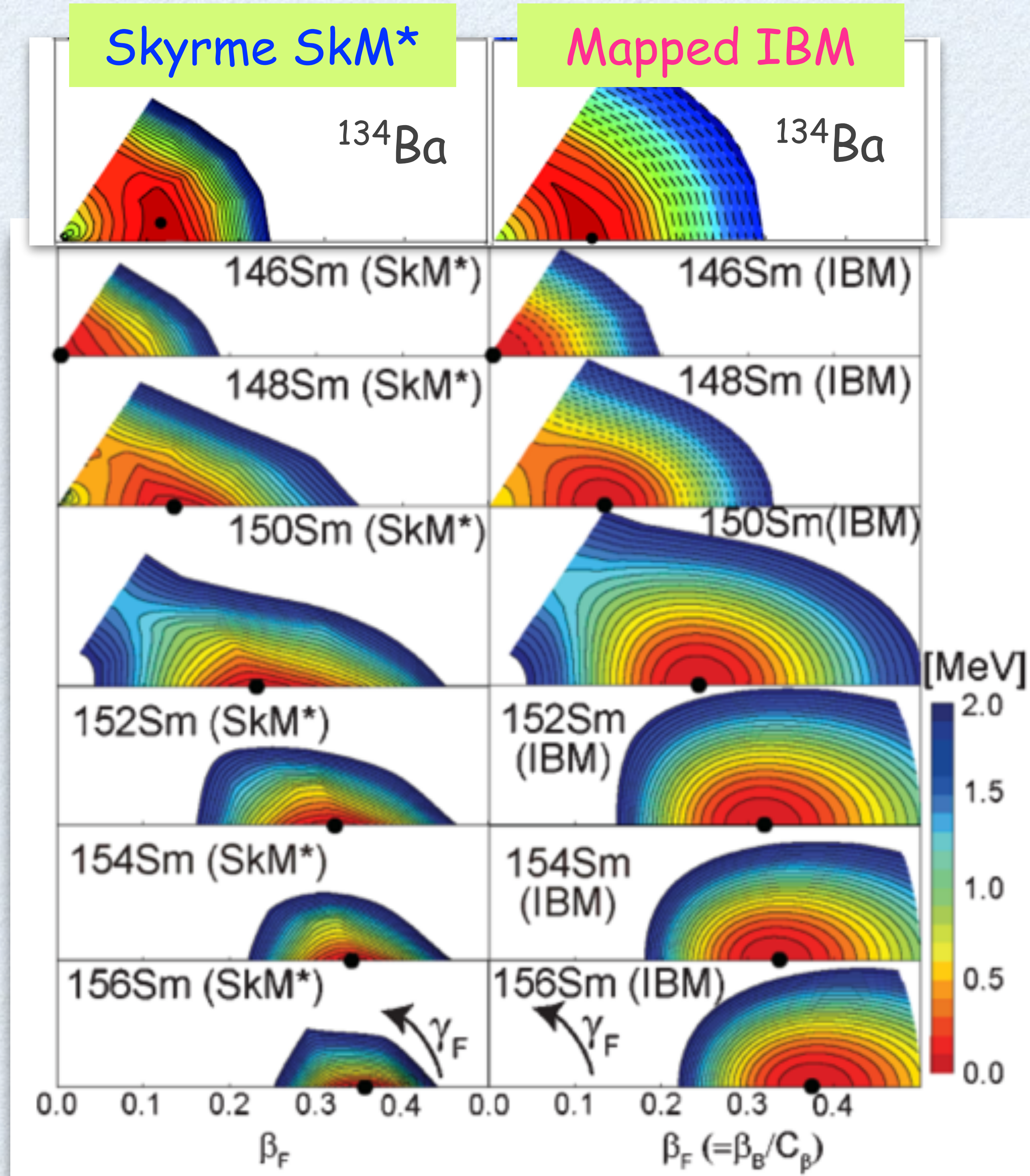
$$\langle\phi^F|\hat{H}^F|\phi^F\rangle \sim \langle\phi^B|\hat{H}^B|\phi^B\rangle$$

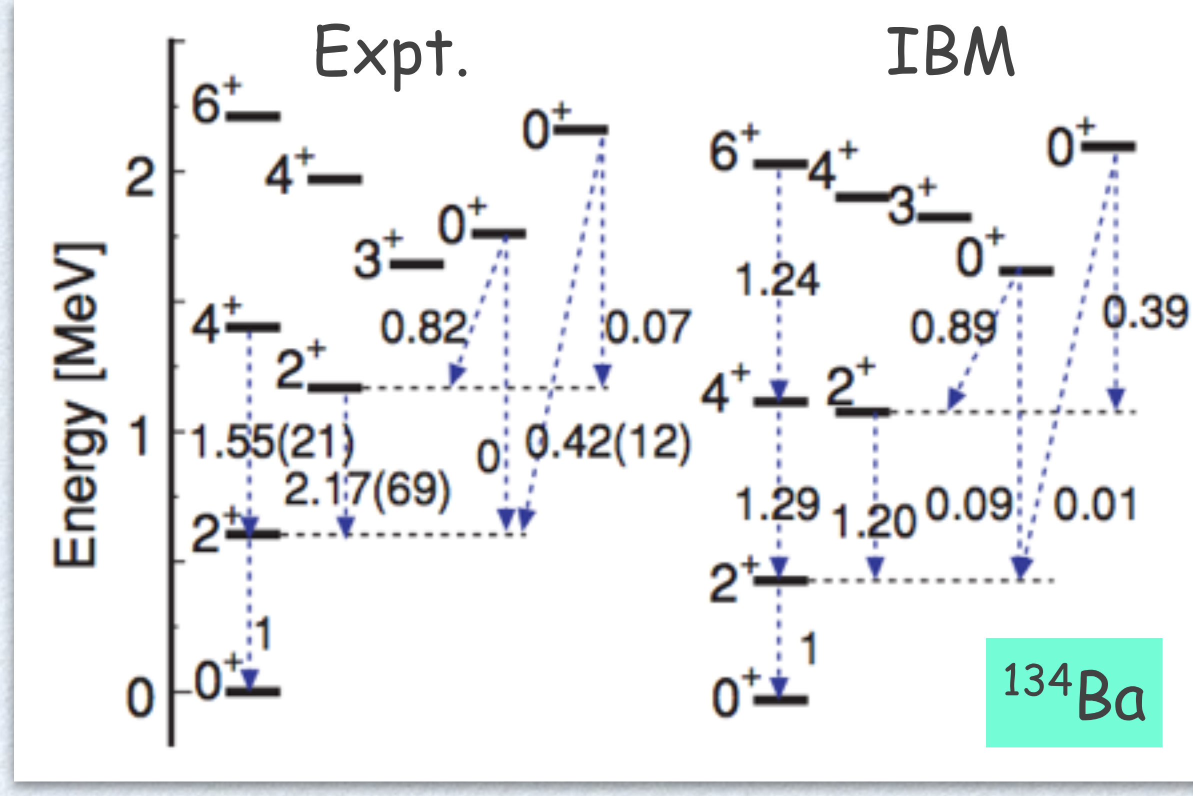
Step 2) LL term: rotational response (cranking) at a mean-field minimum. "Basic part" is kept unchanged. Necessary for strongly deformed nuclei.

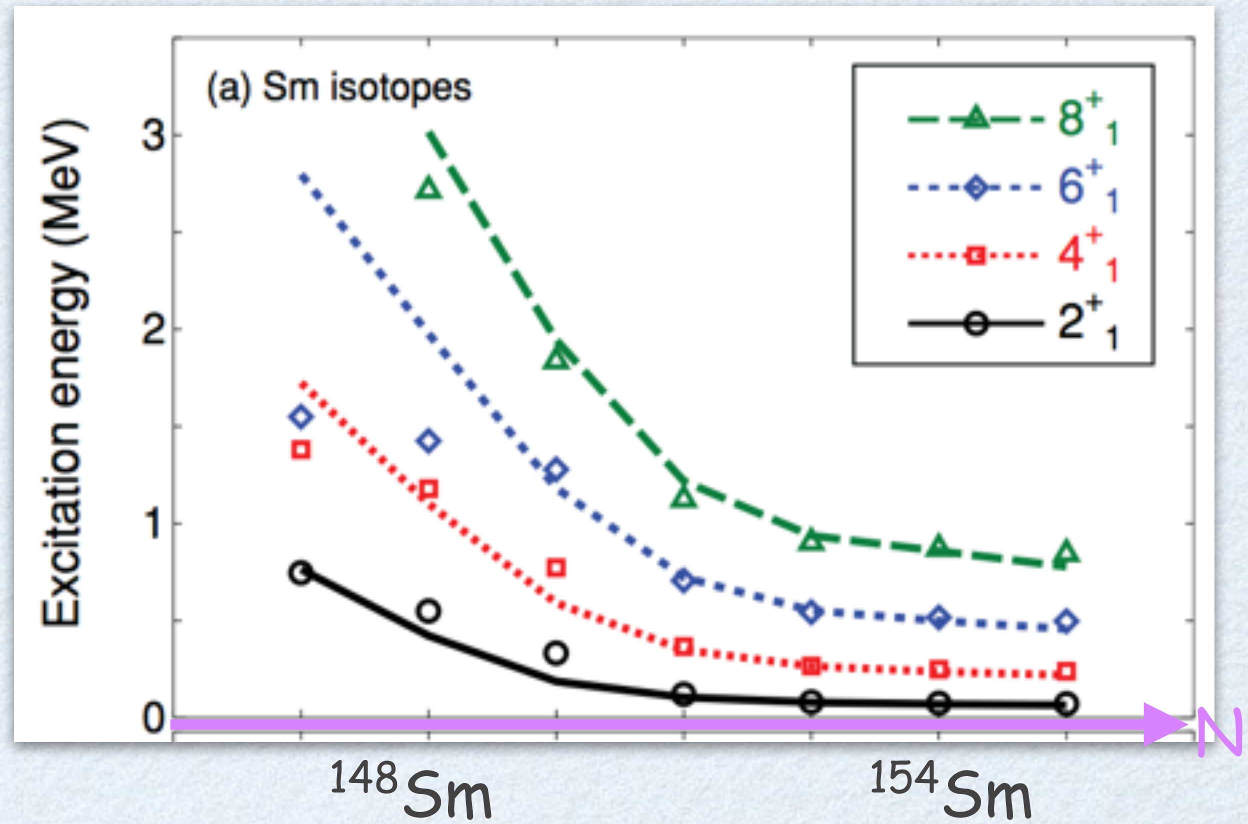
$$\delta\langle\phi^F|\hat{H}^F e^{-i\hat{J}_y\delta\theta}|\phi^F\rangle \sim \delta\langle\phi^B|\hat{H}^B e^{-i\hat{J}_y\delta\theta}|\phi^B\rangle$$

angle $\delta\theta \ll 1$

Proof of principle

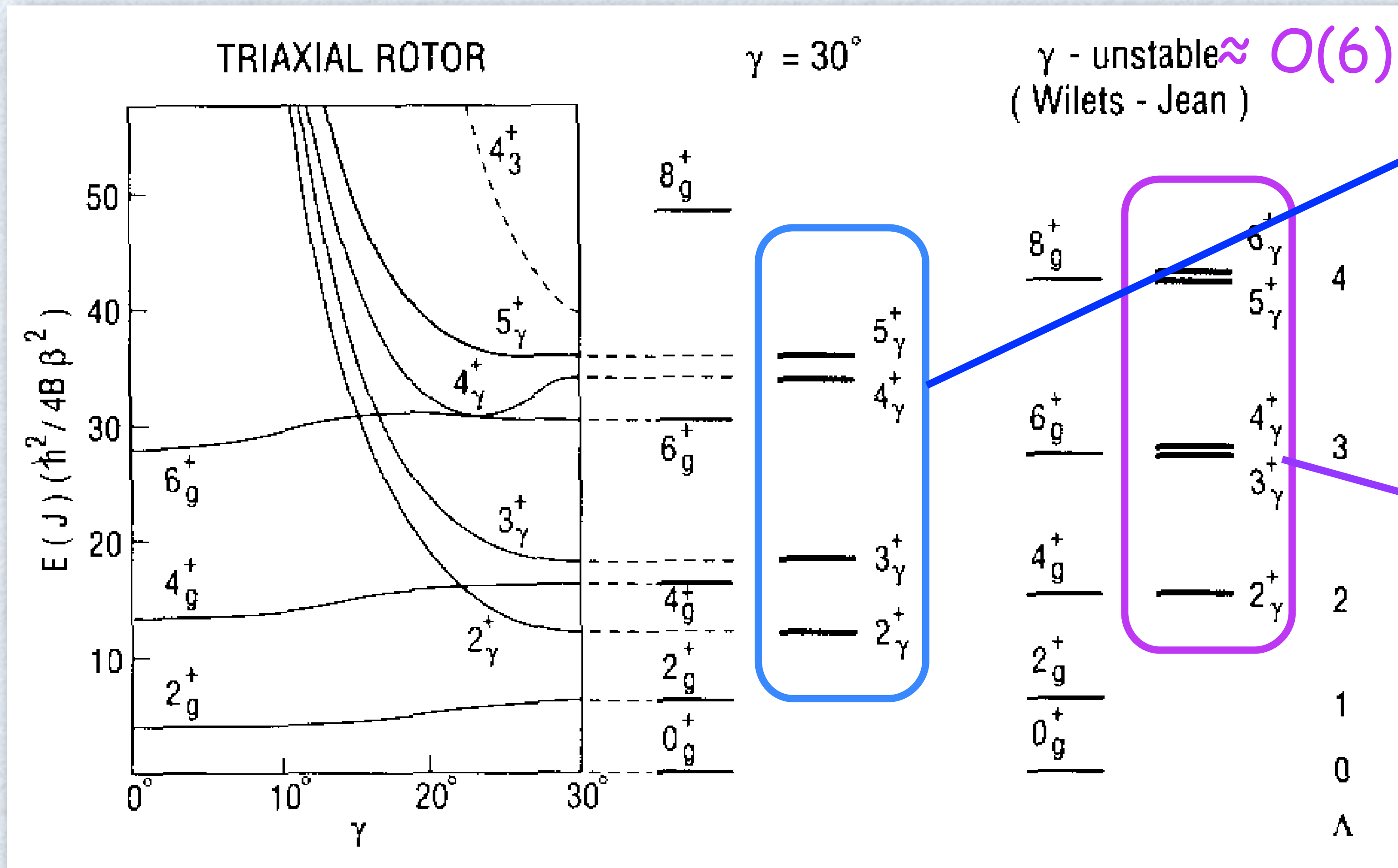


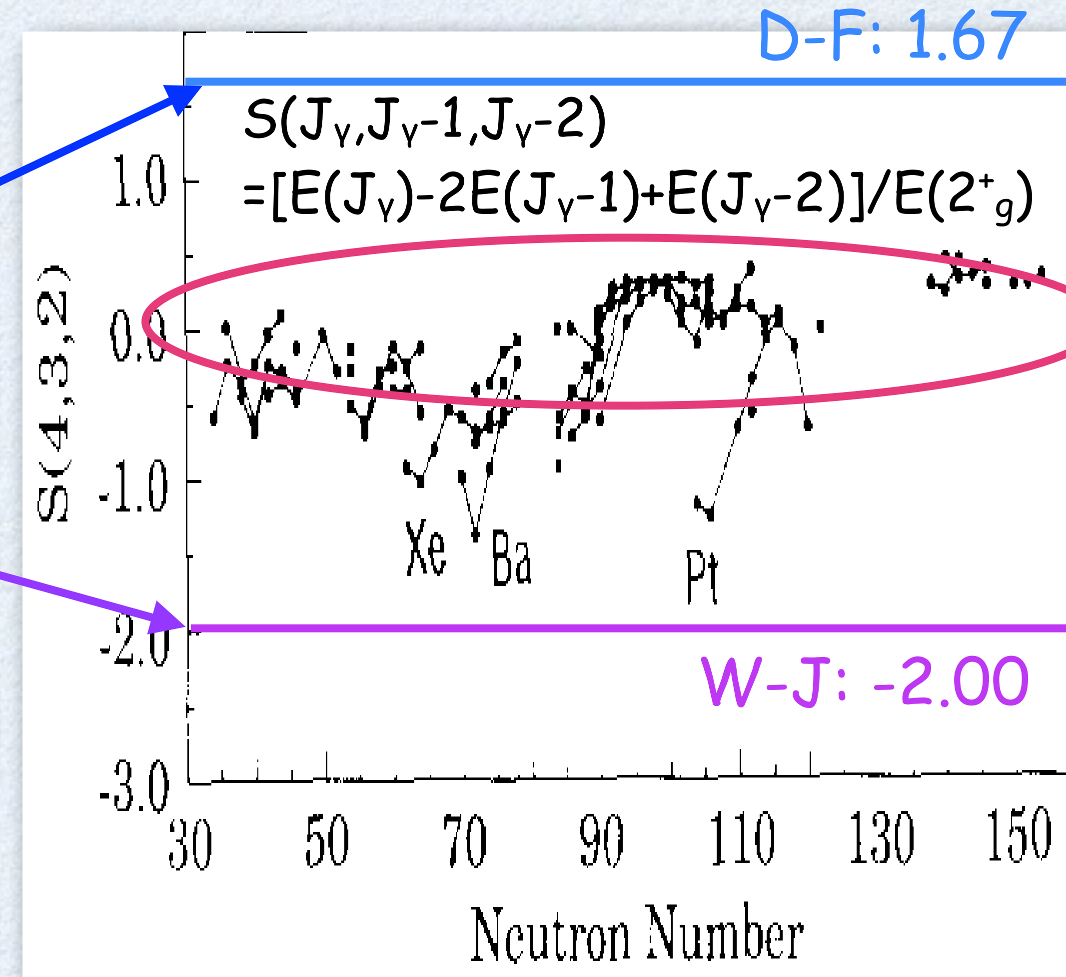




- Spherical-Deformed transition in Sm; **Rotational band** is reproduced nicely.
- Good description of **γ-soft nucleus** ^{134}Ba

Is a triaxial nucleus γ rigid or unstable ?

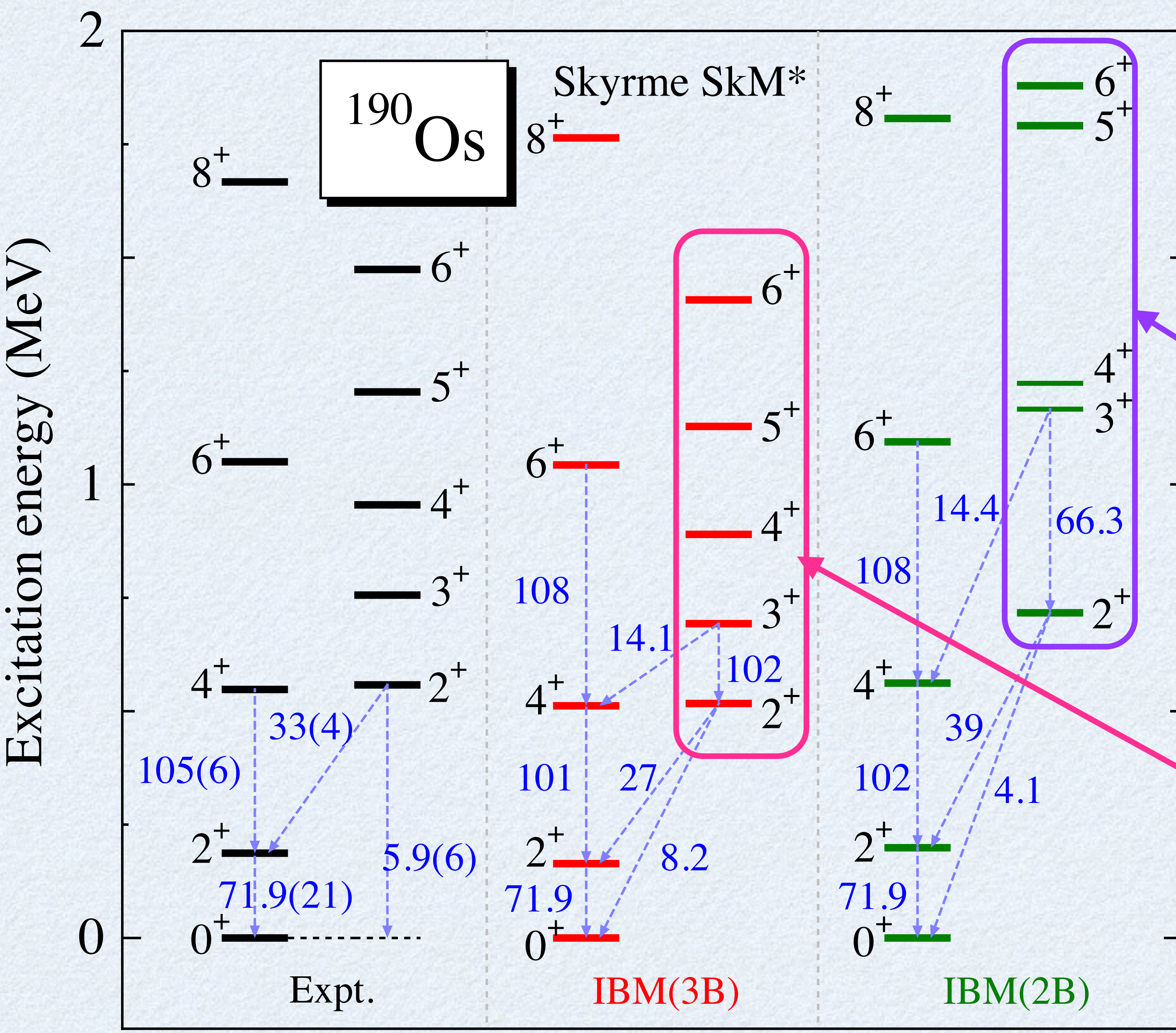


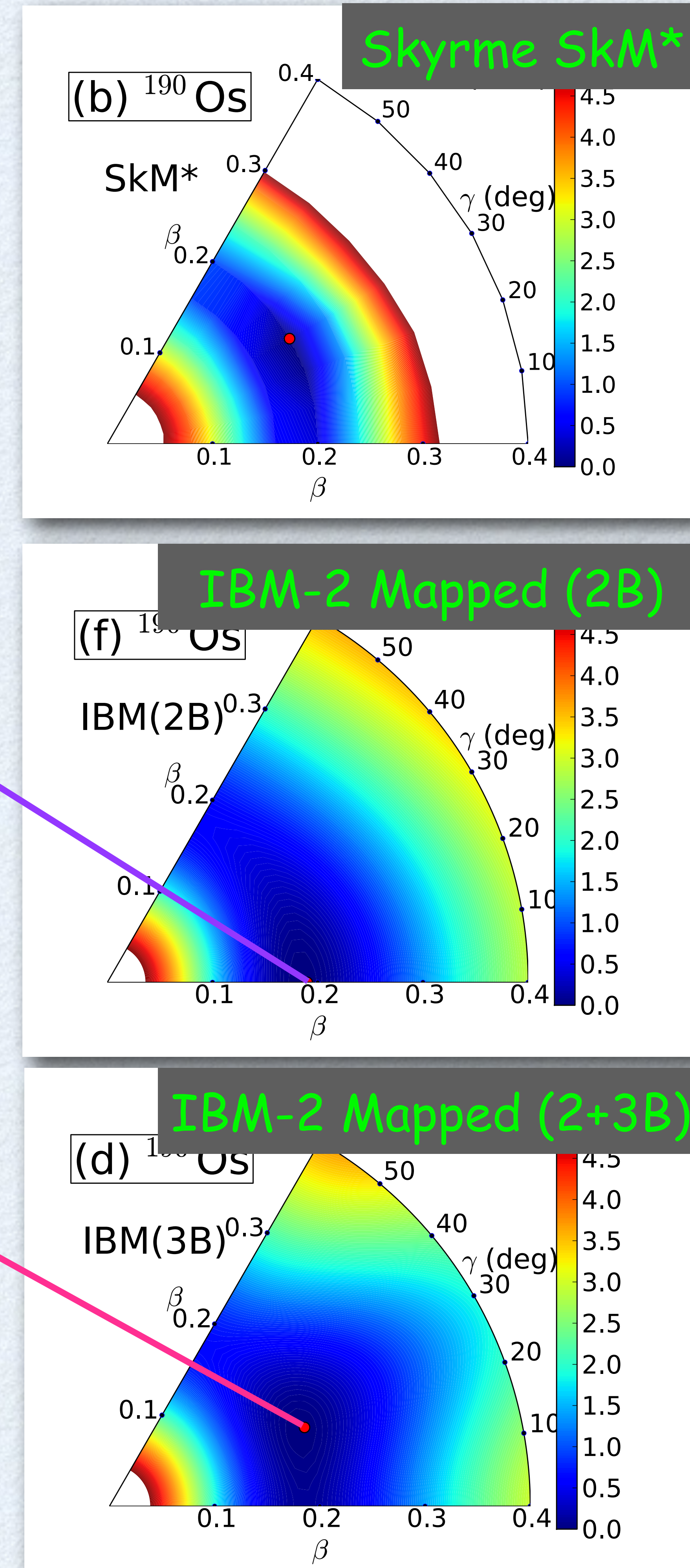


Majority of observed soft nuclei are halfway. Empirical models cannot explain it. Microscopic realization?

- Rigid triaxial rotor model (Davydov & Filippov, 1958)
- γ-unstable rotor model (Wilets & Jean, 1956)
- Equivalence between W-J and O(6) in IBM (Ginocchio & Kirson, 1980)

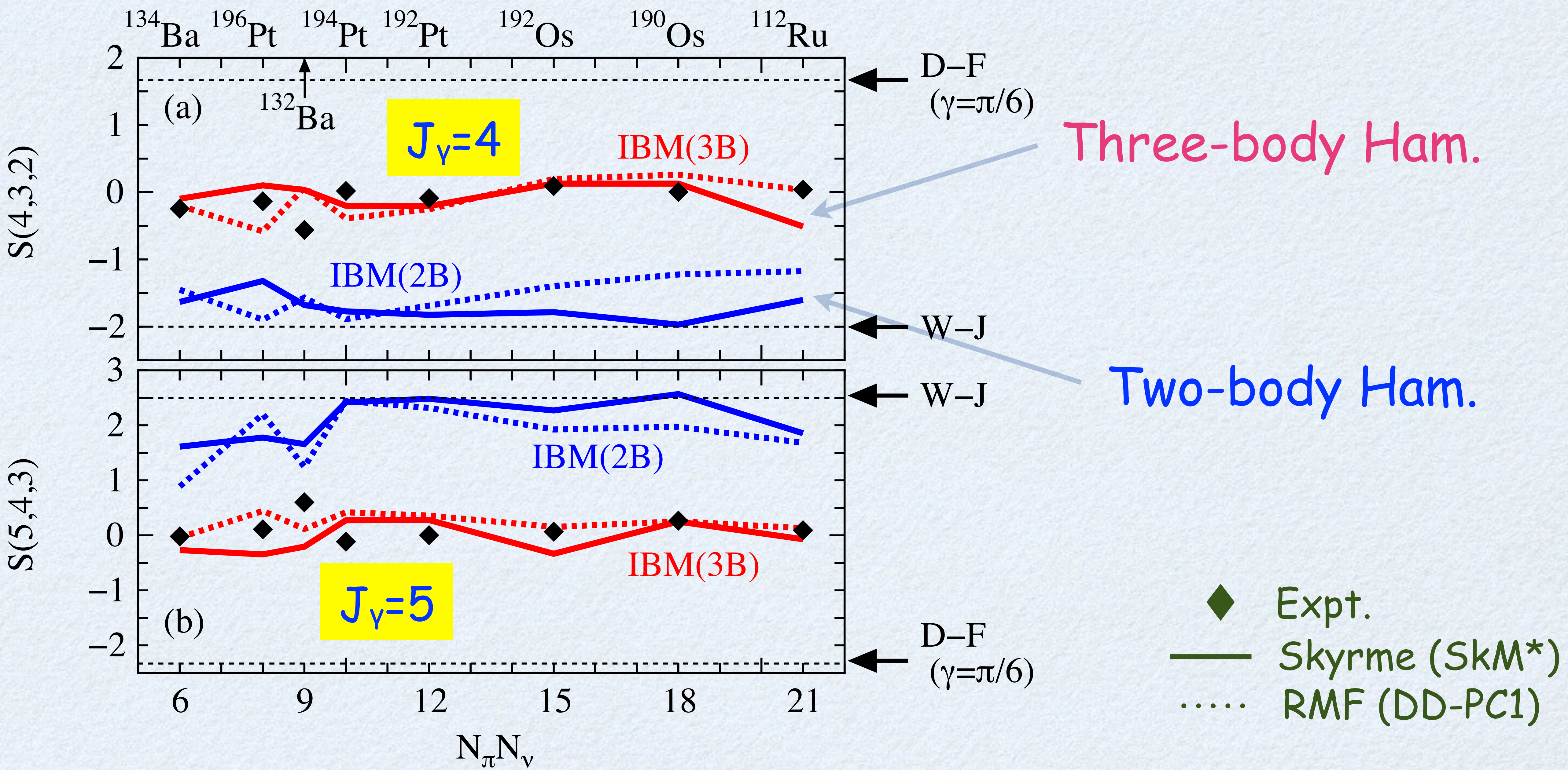
The "harmonic" structure of quasi-γ band is reproduced **only if** the IBM-2 Hamiltonian is comprise of up to **three-body** boson terms.



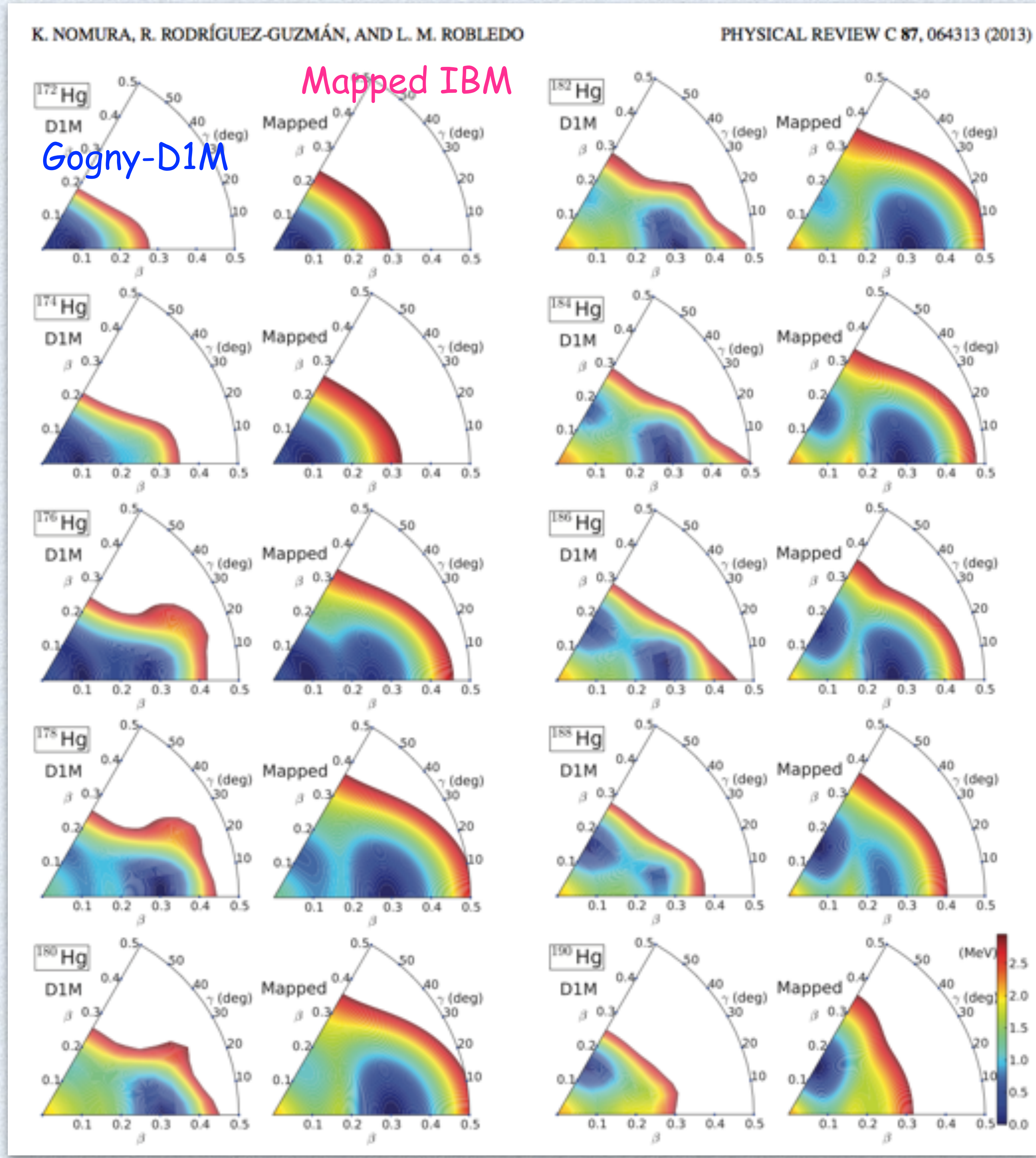


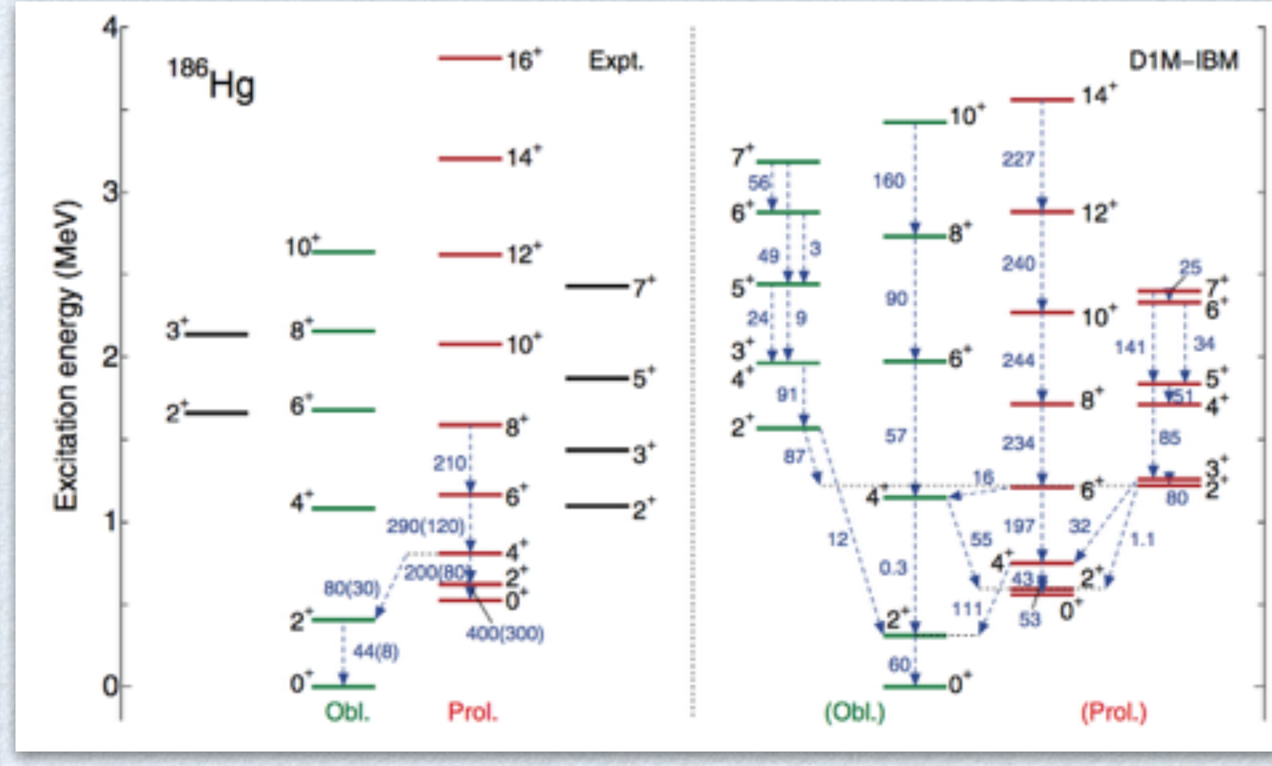
Robustness

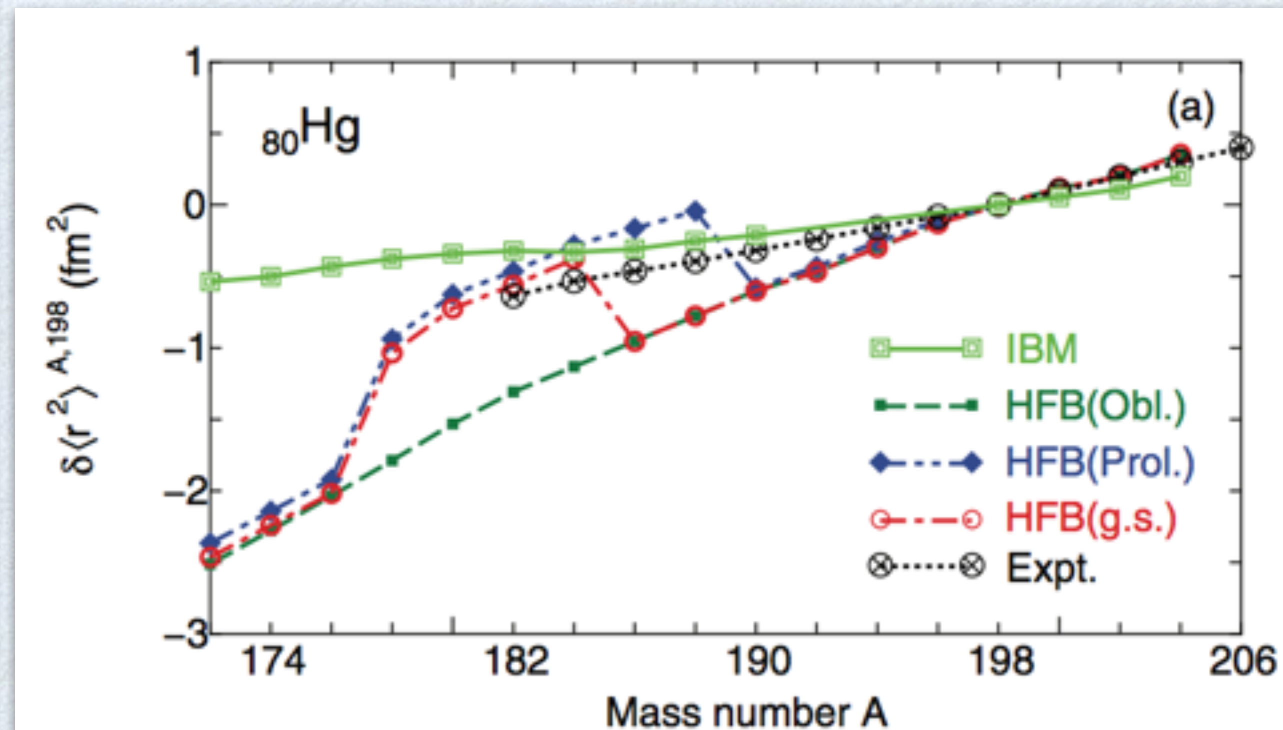
- Independently of EDFs, neither W-J nor D-F picture is realized in presumably all triaxial nuclei. New symmetry/phase?
- In the IBM, 3B term **must be** included.



Shape coexistence in Hg







- IBM-2 with config. mixing (0p-0h + 2p-2h) using Duval-Barrett's technique
- Spherical-Prolate-Oblate transition
- Reasonable spectroscopic and intrinsic properties

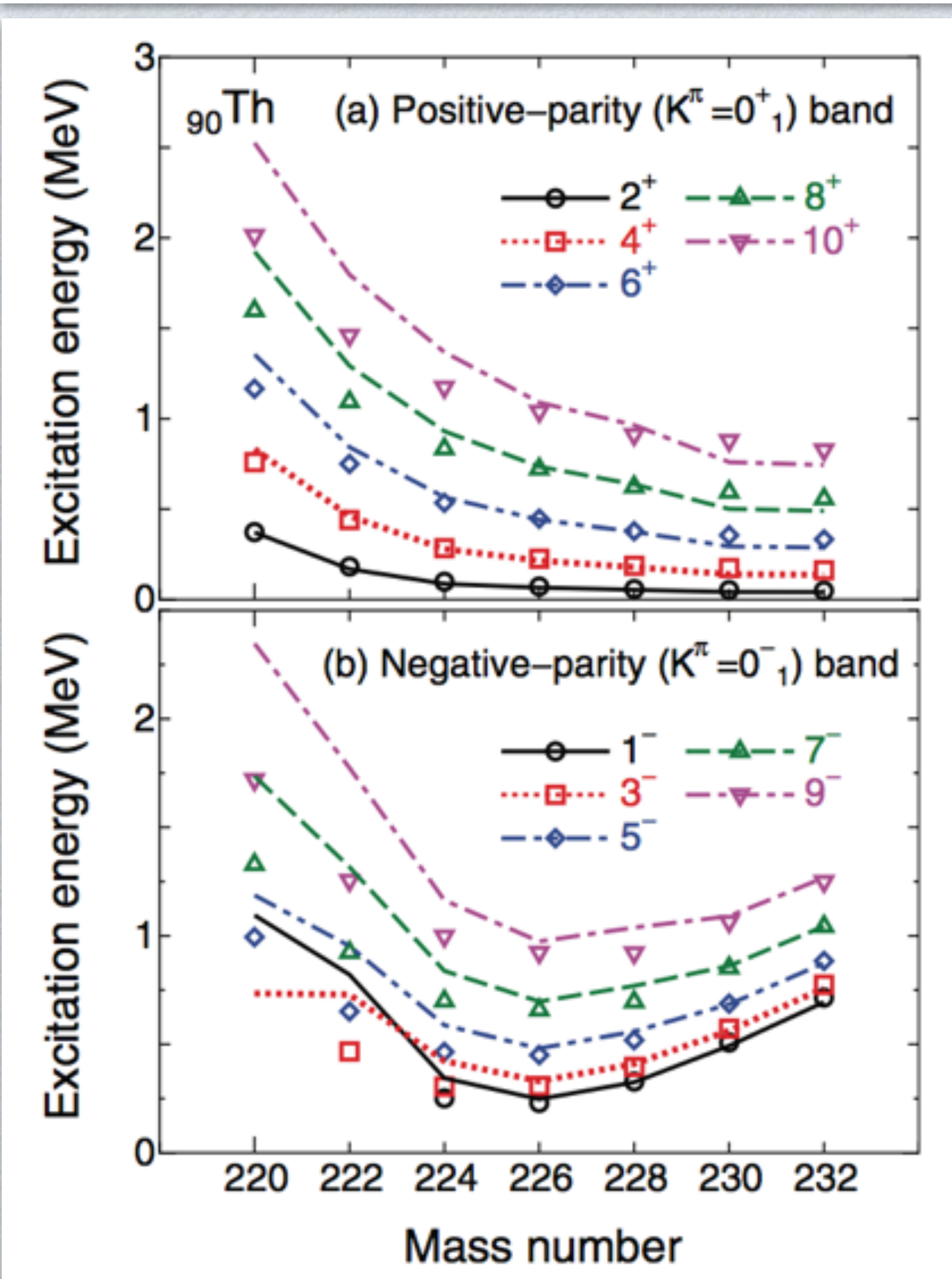
Application to "pear-shaped" nuclei

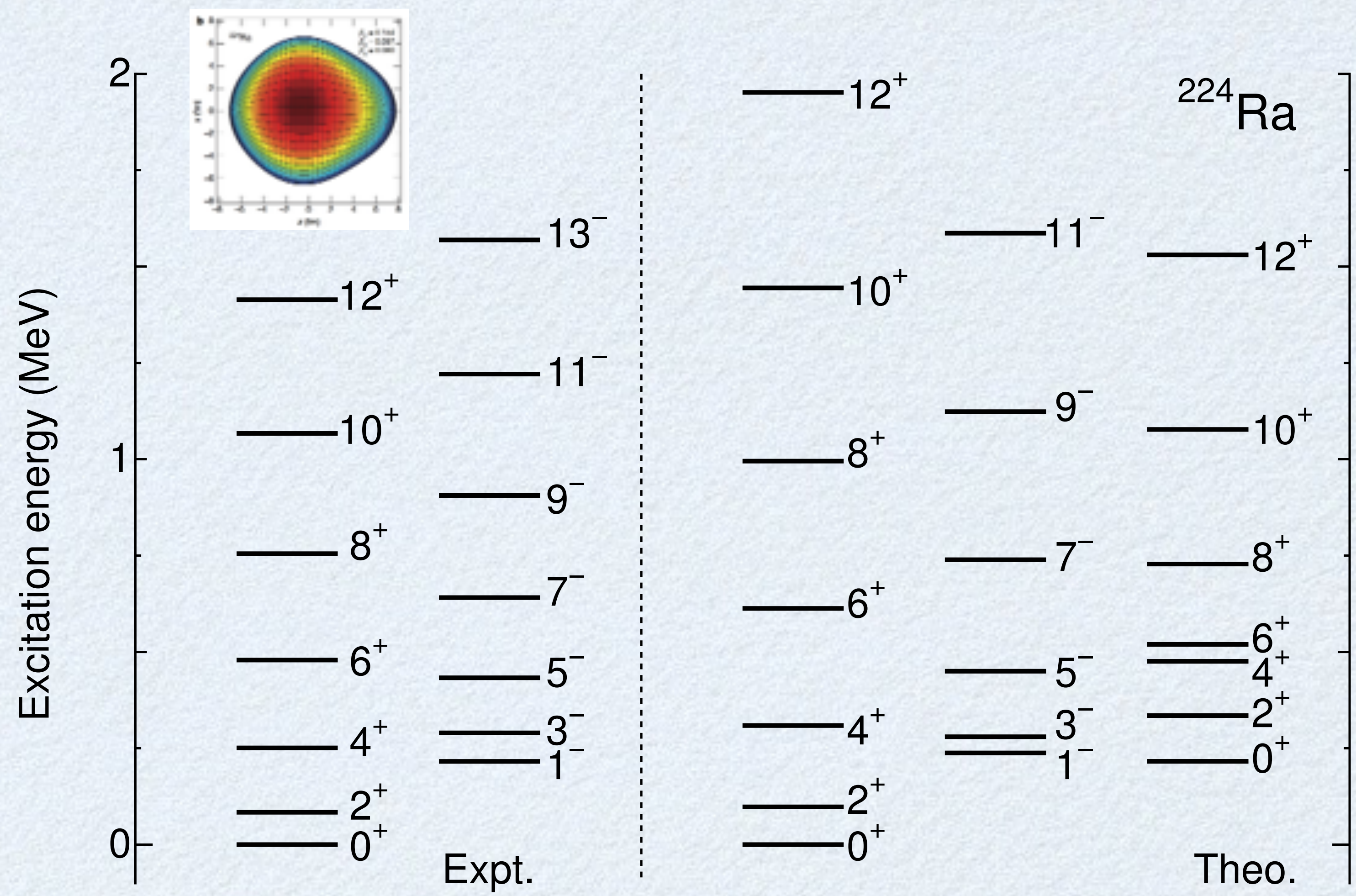
PRC Editors' Suggestion

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





- Calc. by sdf-IBM mapped from RMF DD-PC1
- Most pronounced octupole deformation at ^{226}Th, being a transition point.
- Good description of "octupole nucleus" ^{224}Ra (cf. L. P. Gaffney et al. Nature (2013))

Summary

New formulation of the IBM has been developed. Bridge the gap between IBM and nuclear mean-field model.

- Physical observables in lab frame
- Valid for (in principle) any situation:

  - "Basic" part: mapping of energy surface. Static problem.
  - LL term: mapping of rotational response. Dynamical problem.
  - 3-B term: necessary for a triaxial minimum

- Real prediction for heavy unknown nuclei
- Remaining issues: mixed symmetry (in progress), super deformation, ... etc.

Thanks to

Main collaborators:

T. Otsuka (Tokyo)

N. Shimizu (Tokyo)

L. Guo (Tokyo, now in Beijing)

D. Vretenar (Zagreb)

L. M. Robledo (Madrid)

R. Rodríguez-Guzmán (Rice U)

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Thank you for your attention!

ありがとうございます！