Low-lying excitations in neutron-rich nuclei: Deformation and pairing

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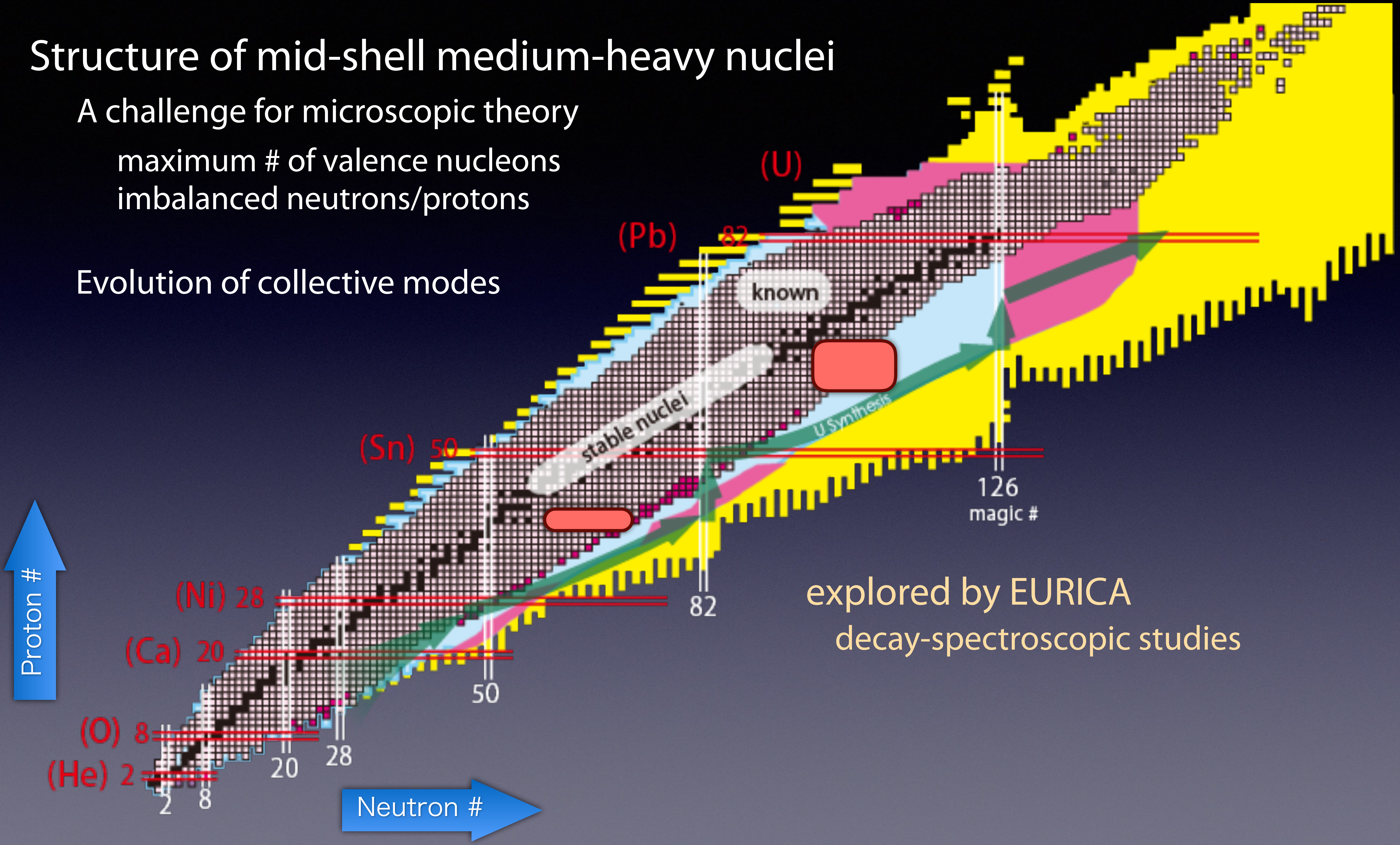
Structure of mid-shell medium-heavy nuclei

A challenge for microscopic theory

maximum # of valence nucleons
imbalanced neutrons/protons

Evolution of collective modes



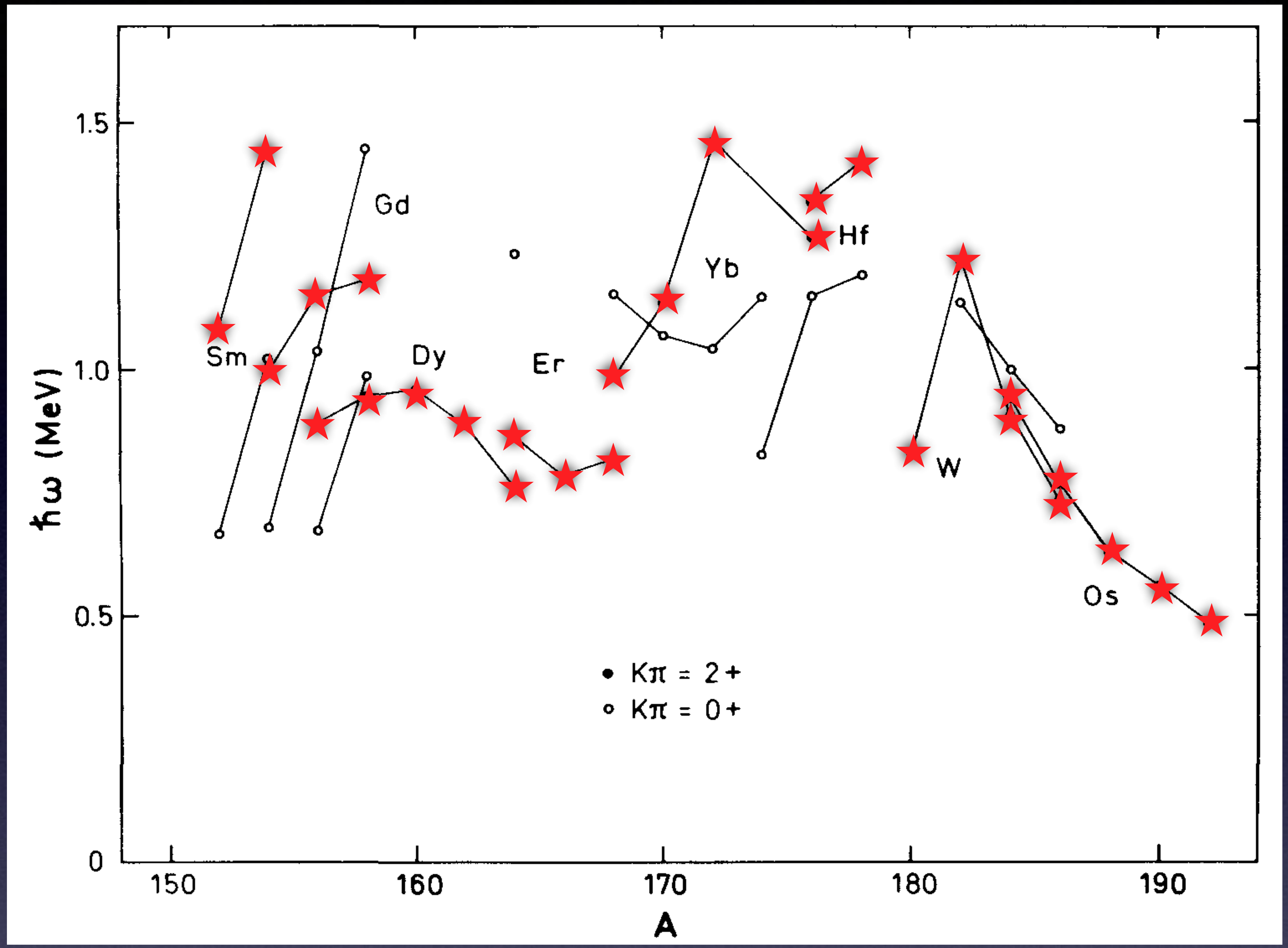
explored by EURICA
decay-spectroscopic studies

Gamma vibration

A well-established collective vibration

- ✓ Systematically appears in the even-even deformed nuclei
- ✓ Low-frequency quadrupole vibration along the γ direction
- ✓ Soft mode of the triaxial deformation

sensitive to the shell structures
classical picture not applicable



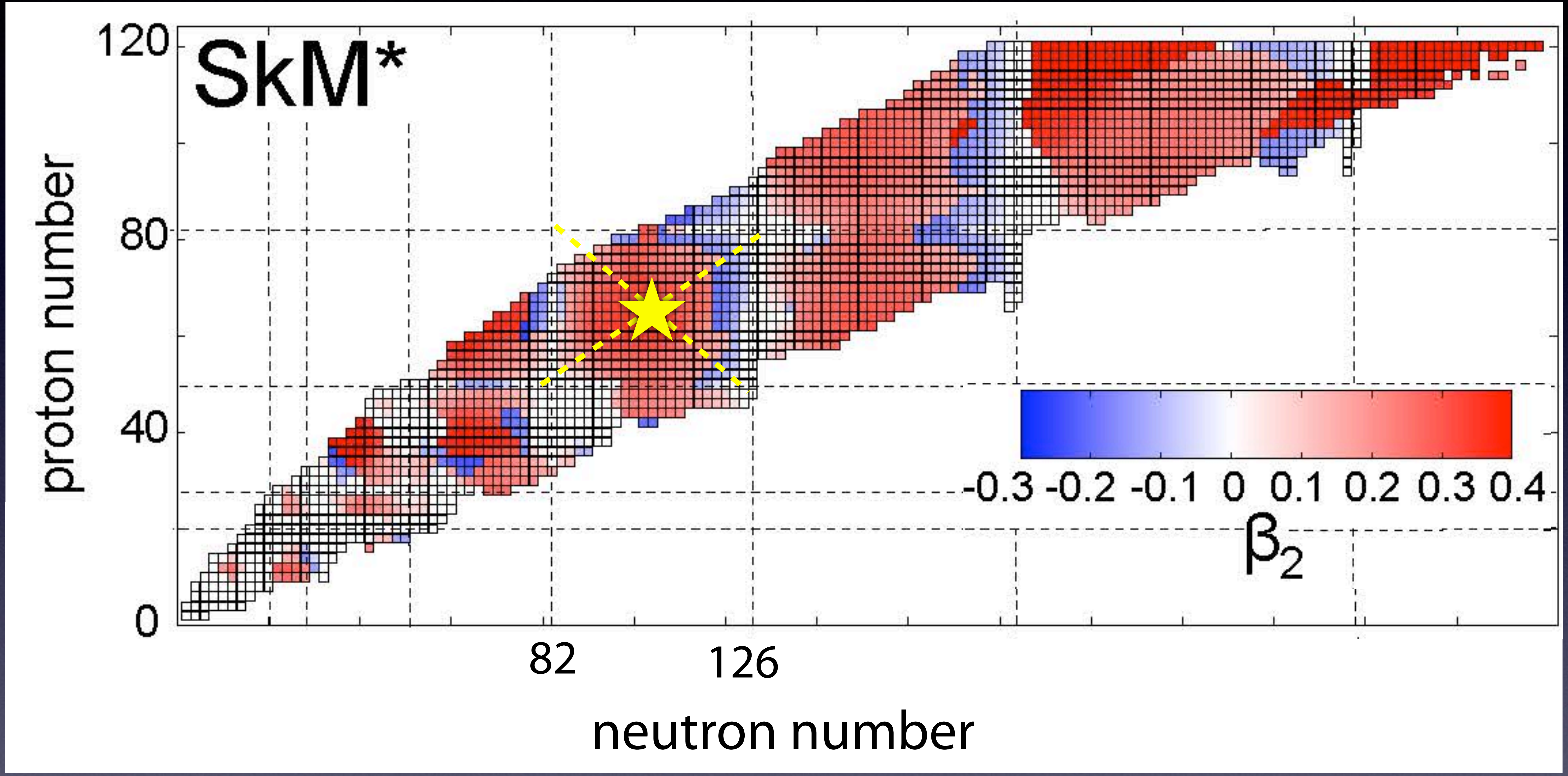
Bohr and Mottelson, Vol. 2

How about in neutron-rich deformed nuclei?

universality of emergence of the collective mode across the nuclear chart

Exploring the quadrupole collectivity around $^{170}_{66}Dy_{104}$

Middle of the major shells between ^{132}Sn and ^{208}Pb



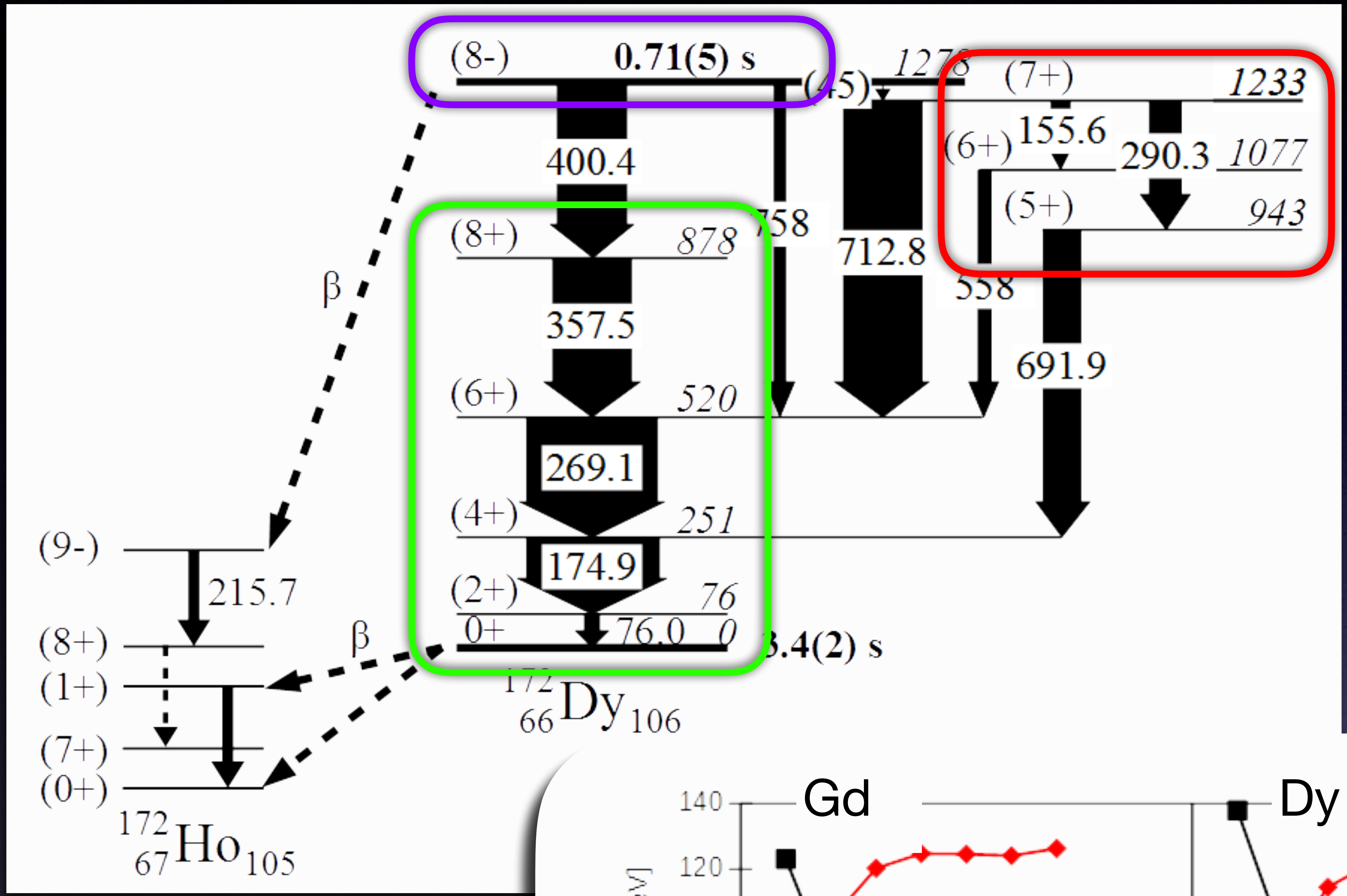
J. Erler et al., Nature 486(2012)509

✓Effect of neutron excess on the occurrence of γ-vibration

✓Shell structure in neutron-rich medium-heavy nuclei

Decay spectroscopy at RIKEN RIBF

H. Watanabe et al., PLB760(2016)641
P.-A. Söderström et al., PLB762(2016)404



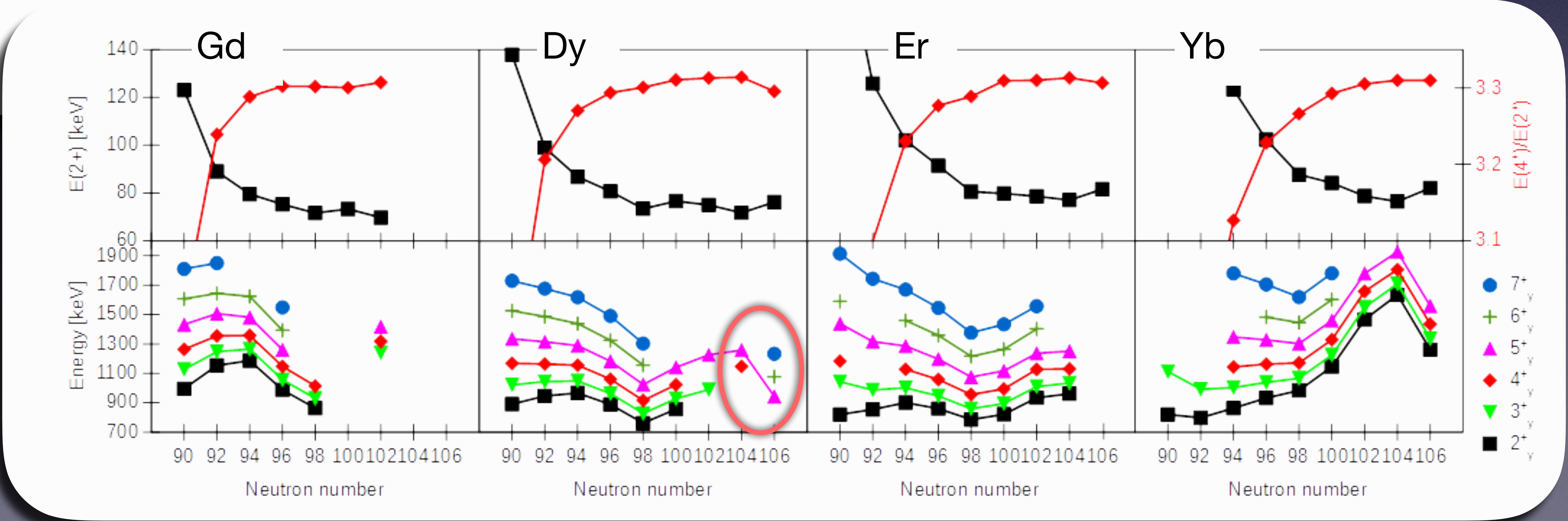
$^{172}Dy_{106}$

Long-lived isomeric state

Ground-state rotational band

Possible gamma band

Sudden decrease in the excitation energy at *N*=106



Nuclear DFT for collective vibration

w/ Skyrme + pairing energy-density functional $\mathcal{E}[\rho, \tilde{\rho}](\boldsymbol{r})$

Hartree-Fock-Bogoliubov (HFB) like equation in coordinate space

$$\begin{pmatrix} h^q(r\sigma) - \lambda^q & \tilde{h}^q(r\sigma) \\ \tilde{h}^q(r\sigma) & -(h(r\sigma) - \lambda^q) \end{pmatrix} \begin{pmatrix} \varphi^q_{1,\alpha}(r\sigma) \\ \varphi^q_{2,\alpha}(r\sigma) \end{pmatrix} = E_\alpha \begin{pmatrix} \varphi^q_{1,\alpha}(r\sigma) \\ \varphi^q_{2,\alpha}(r\sigma) \end{pmatrix} \qquad q = \nu,\ \pi$$

"s.p." hamiltonian and pair potential:

$$h^q = \frac{\delta \mathcal{E}}{\delta \rho^q}, \qquad \tilde{h}^q = \frac{\delta \mathcal{E}}{\delta \tilde{\rho}^q}$$

Response to the weak external field $\hat{F}$: $v^{\mathrm{ext}}(r)e^{-i\omega t}$

$$\delta\rho_i(r) = \int dr' \chi_0^{ij}(r, r') \left[\frac{\delta^2 \mathcal{E}}{\delta\rho_j \delta\rho_k} \delta\rho_k(r') + v_j^{\mathrm{ext}}(r') \right] \Longleftrightarrow$$

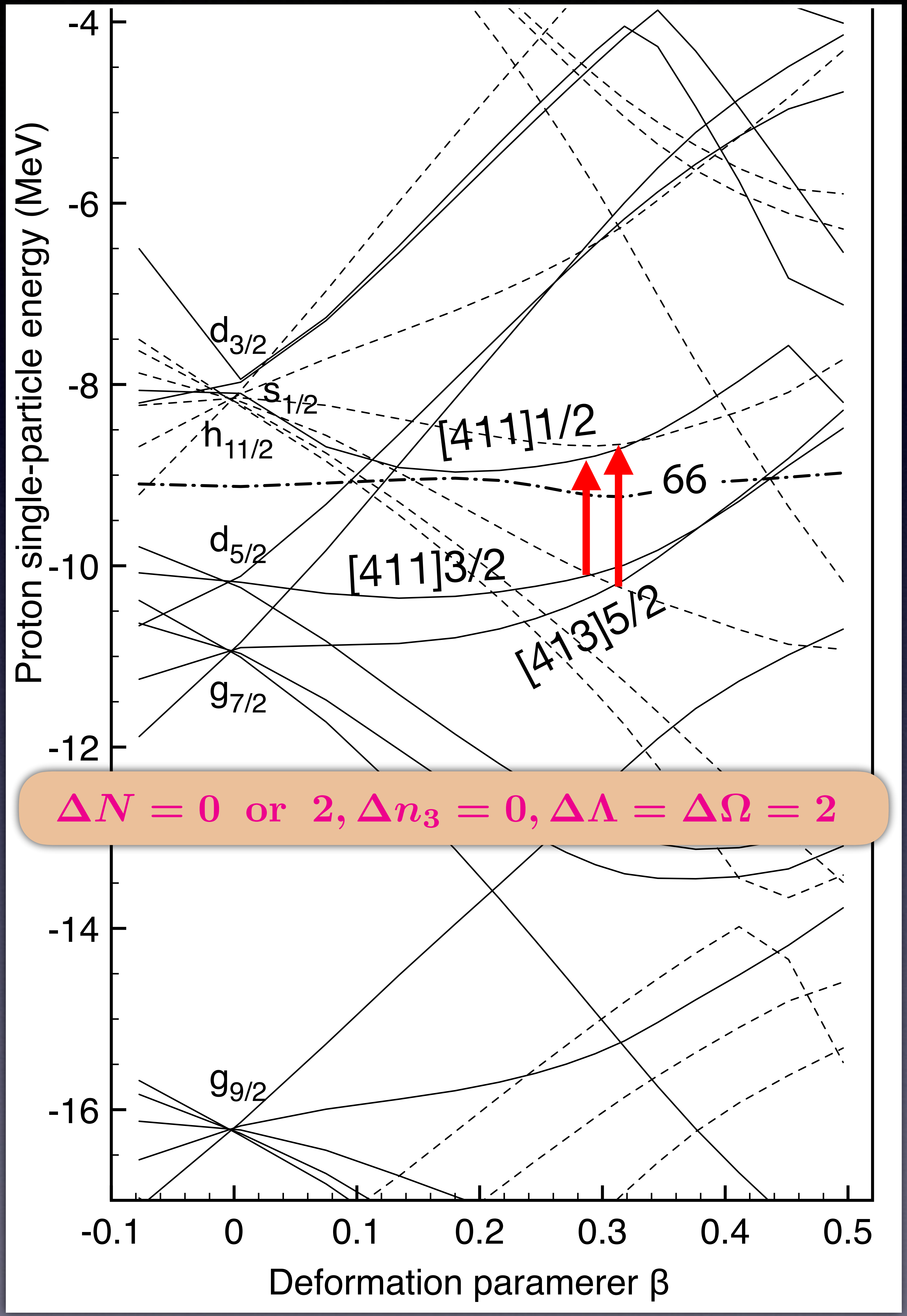
QRPA: $[H, \Gamma^\dagger_\lambda]|\Psi_0\rangle = \omega_\lambda \Gamma^\dagger_\lambda |\Psi_0\rangle$

$$|\Psi_\lambda\rangle = \Gamma^\dagger_\lambda|\Psi_0\rangle = \sum_{\alpha\beta}[X^\lambda_{\alpha\beta} a^\dagger_\alpha a^\dagger_\beta - Y^\lambda_{\alpha\beta} a_\beta a_\alpha]|\Psi_0\rangle$$

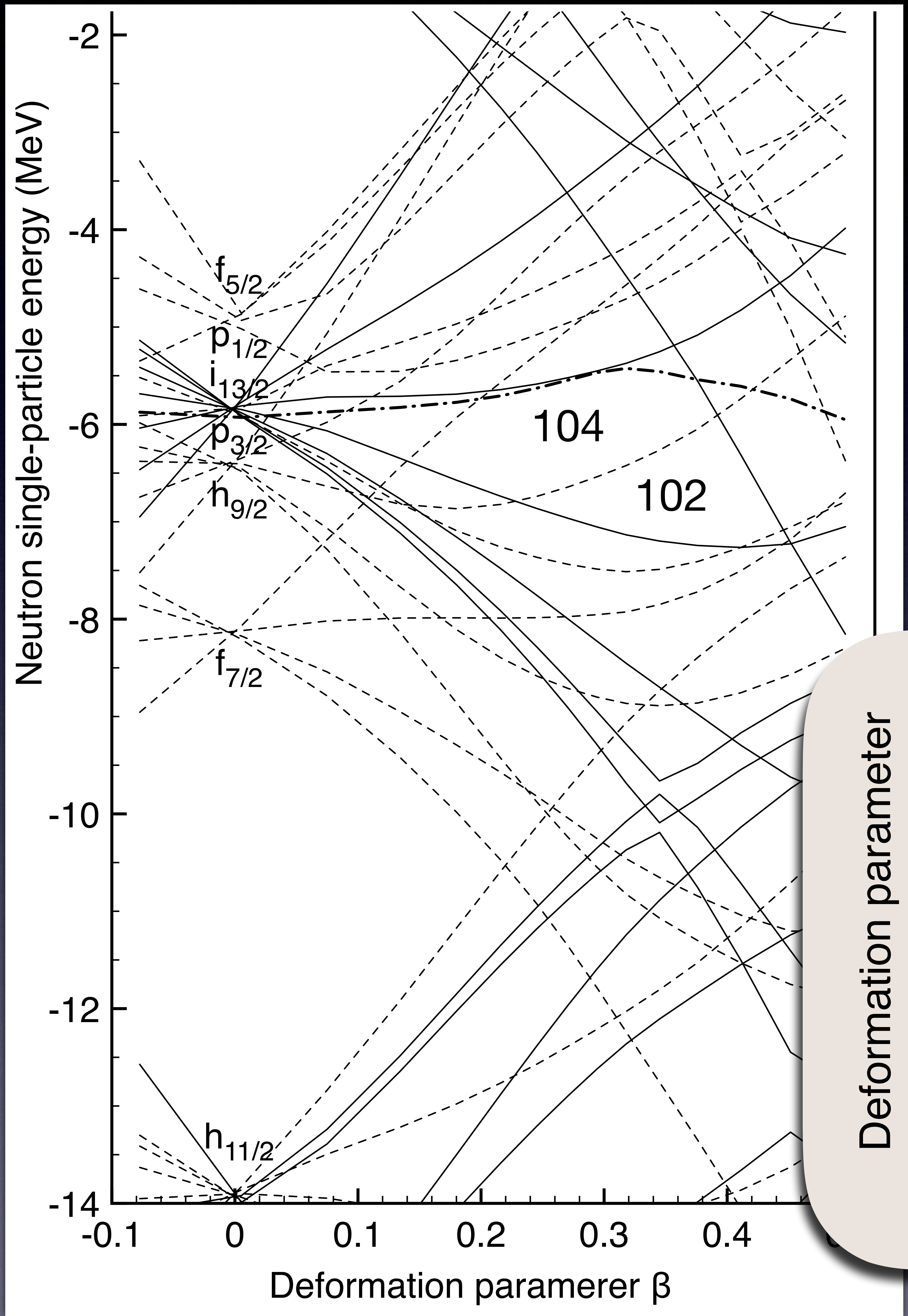
collective mode = coherent superposition of 2qp excitations

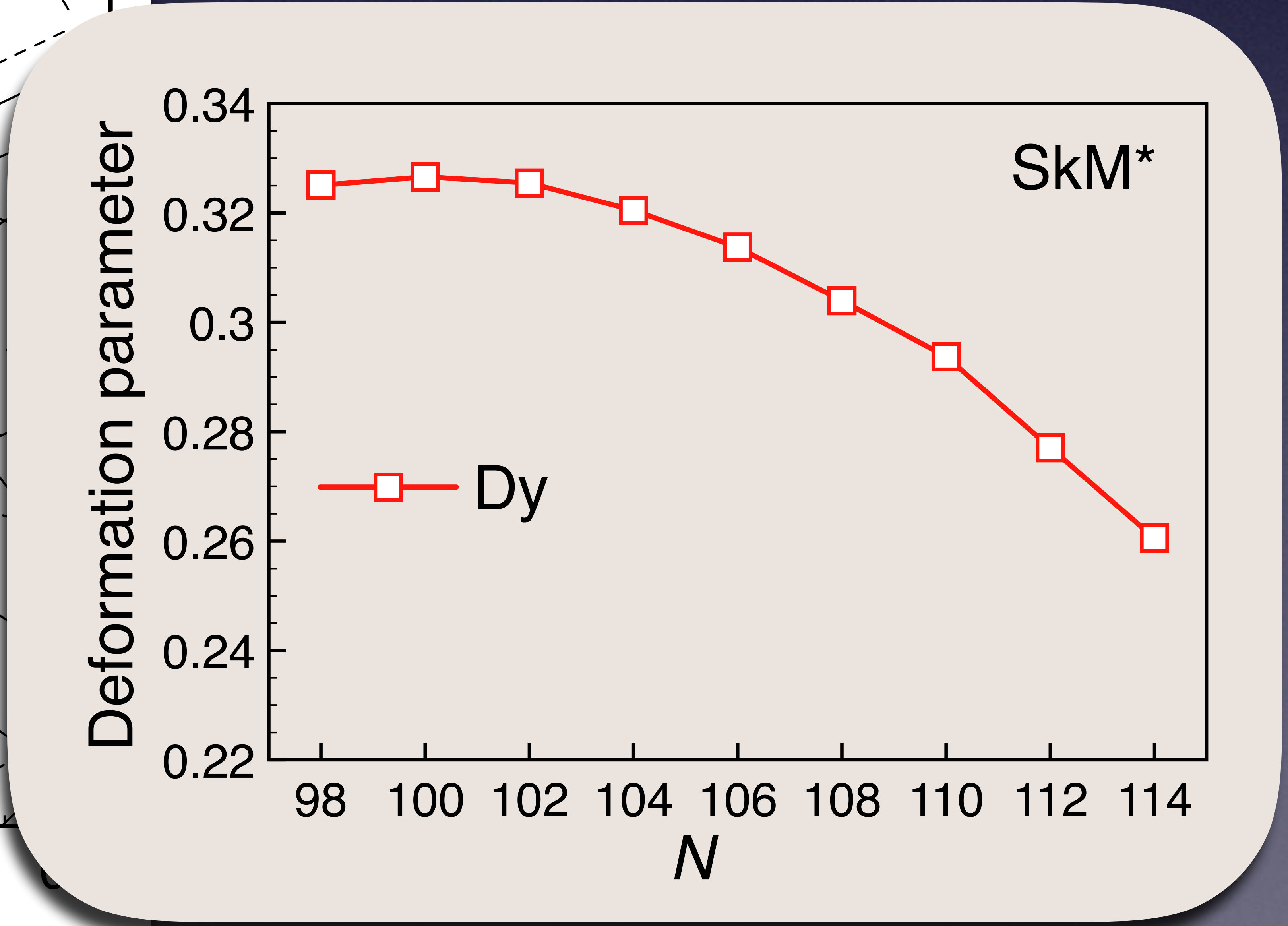
transition matrix elements: $\langle \Psi_\lambda | \hat{F} | \Psi_0 \rangle = \int dr \delta\rho(r; \omega_\lambda) v^{\mathrm{ext}}(r)$

Single-particle energies in ^{172}Dy



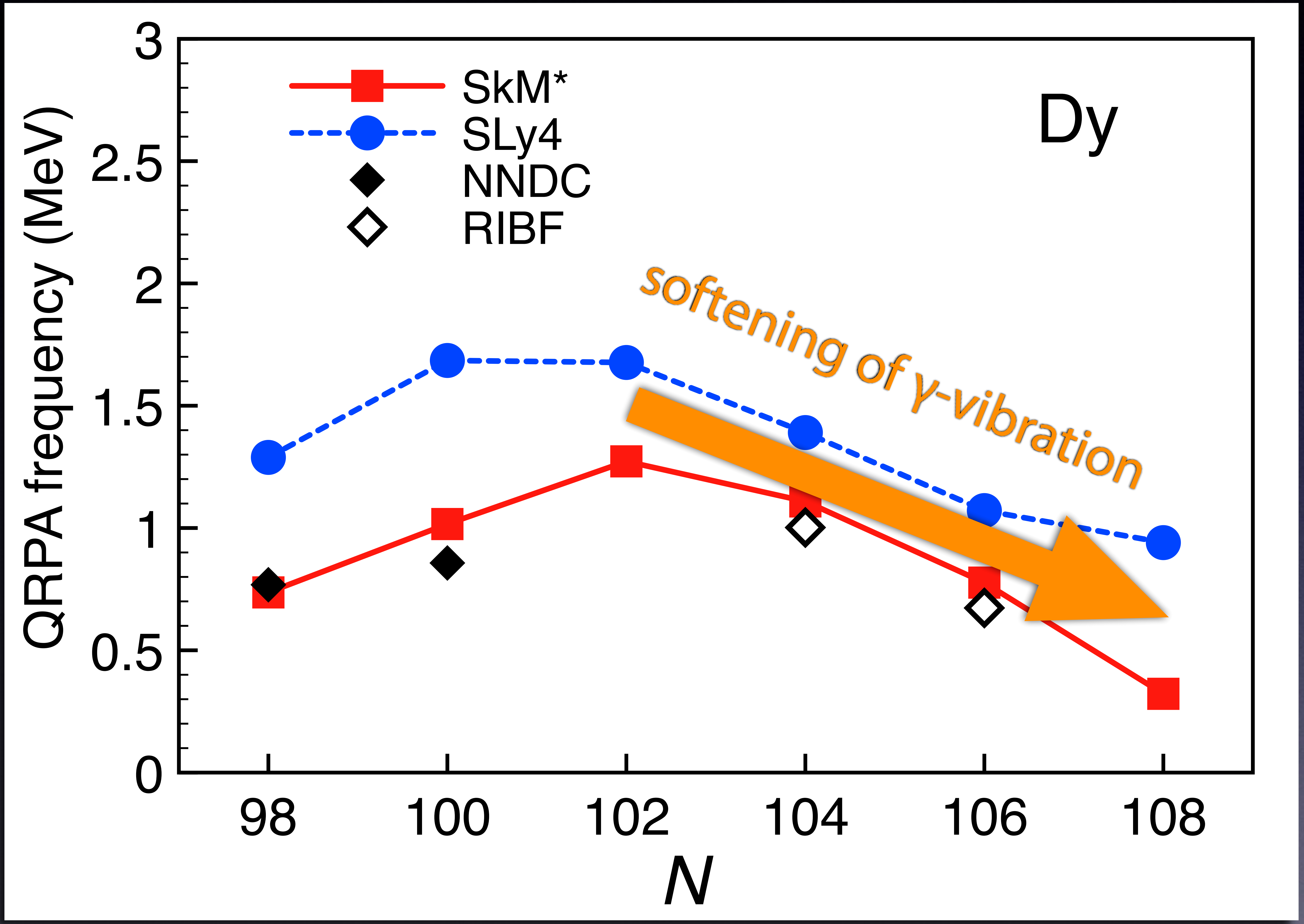
$$\Delta N = 0 \text{ or } 2, \Delta n_3 = 0, \Delta\Lambda = \Delta\Omega = 2$$





Gamma-vibration in the neutron-rich Dy isotopes

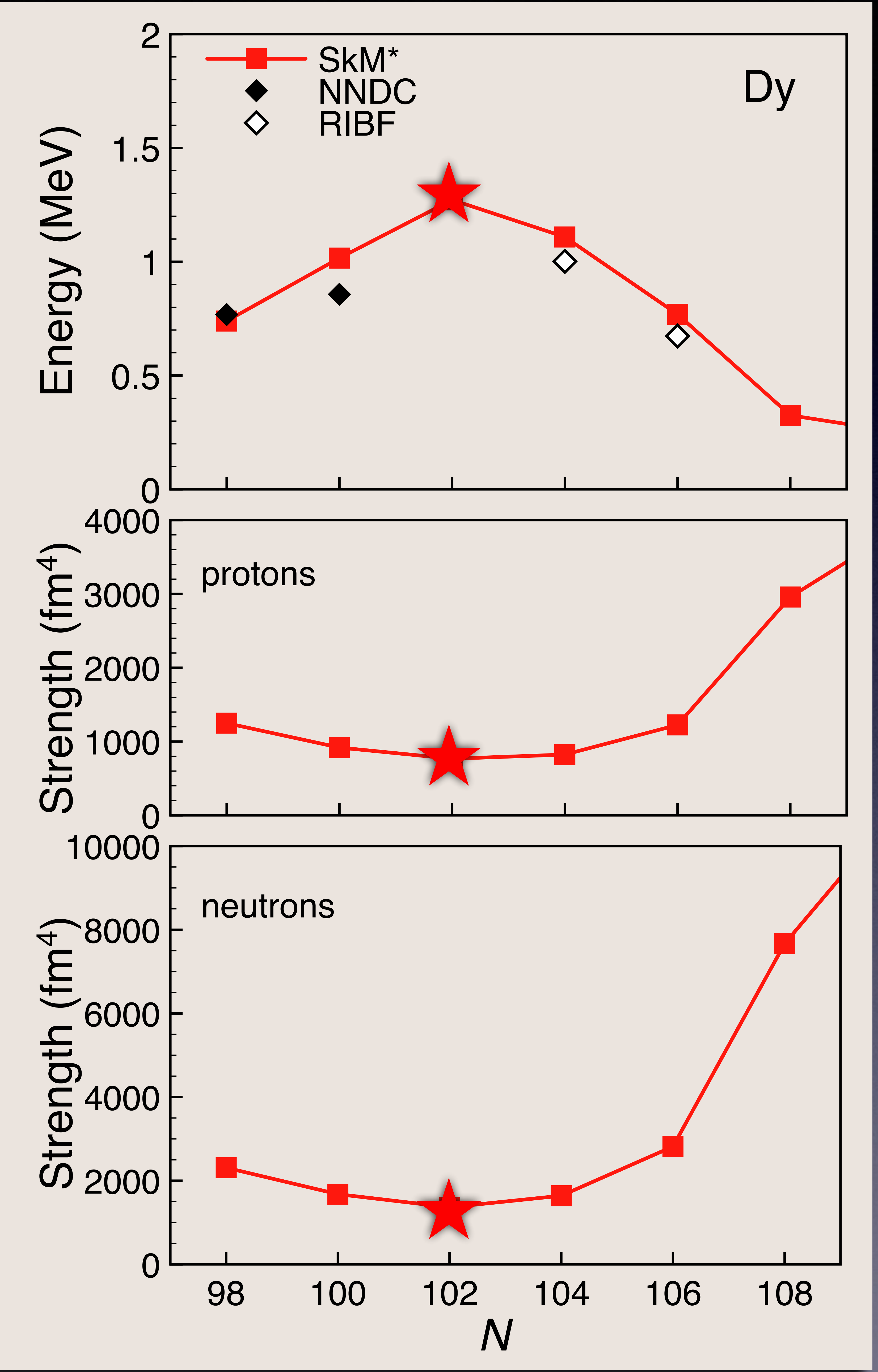
KY, H. Watanabe, PTEP (in press.)

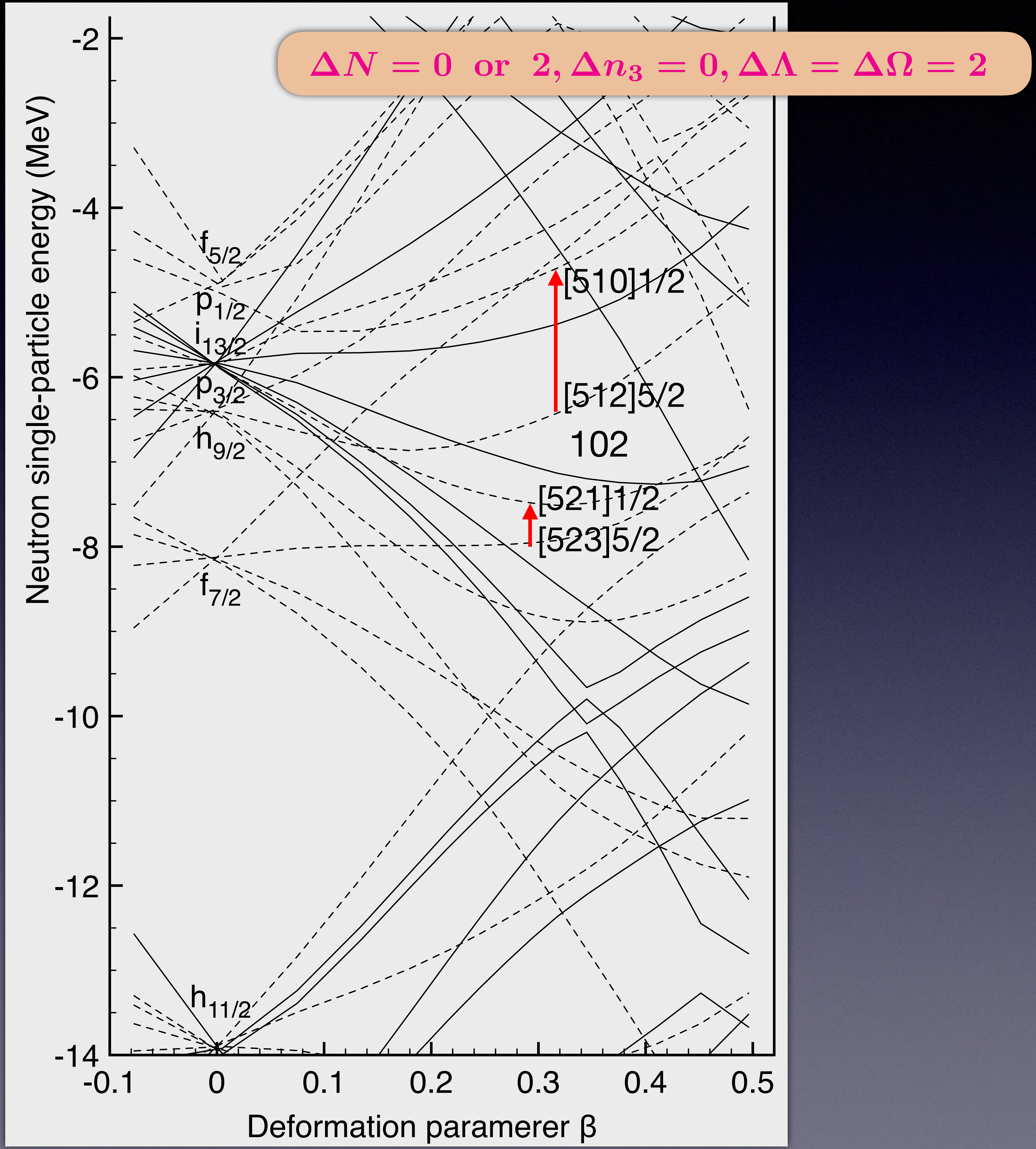


H. Watanabe et al., PLB760(2016)641
P.-A. Söderström et al., PLB762(2016)404

Microscopic structure of the γ-vibration: isotopic dependence

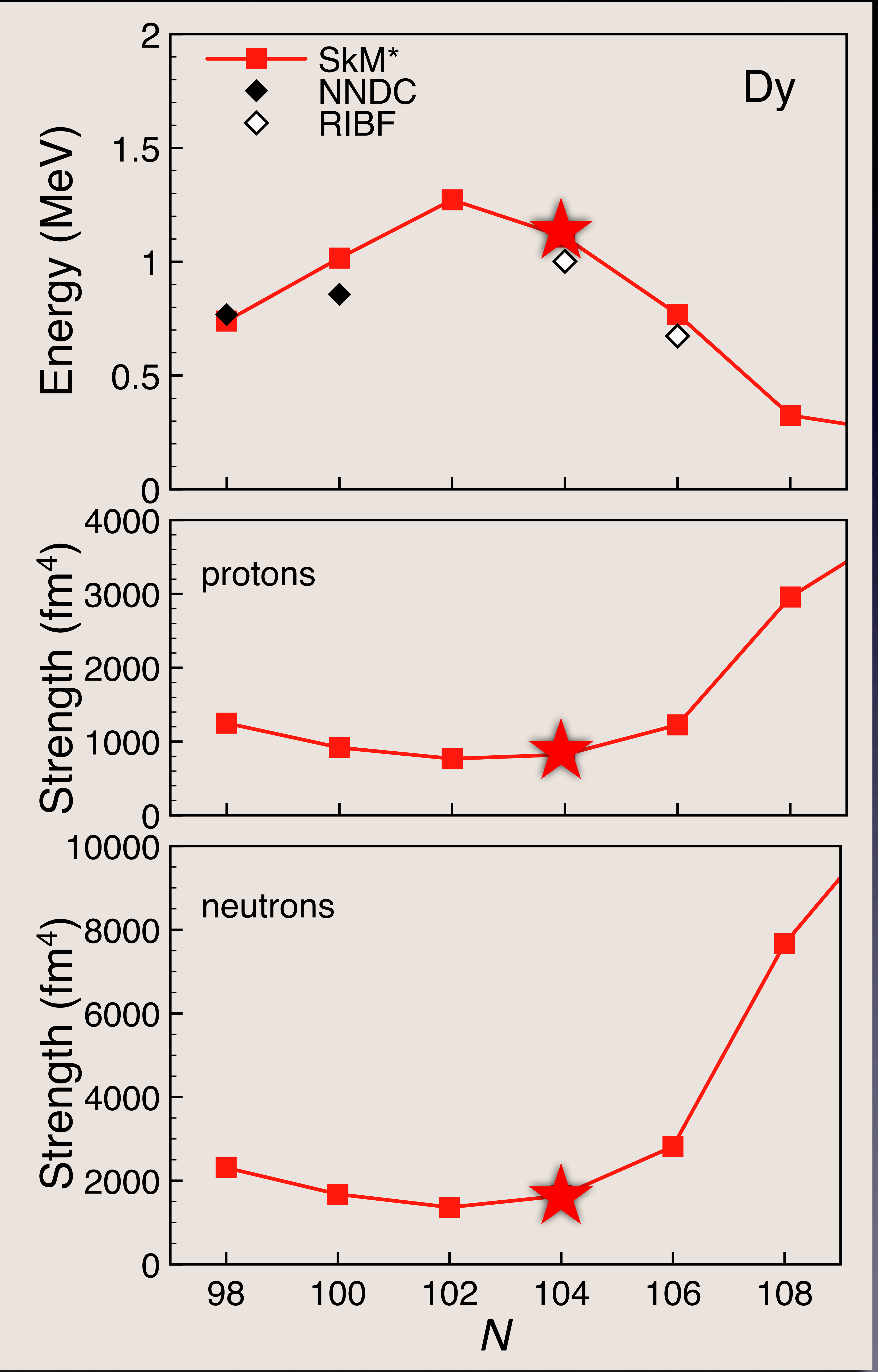
@N=102



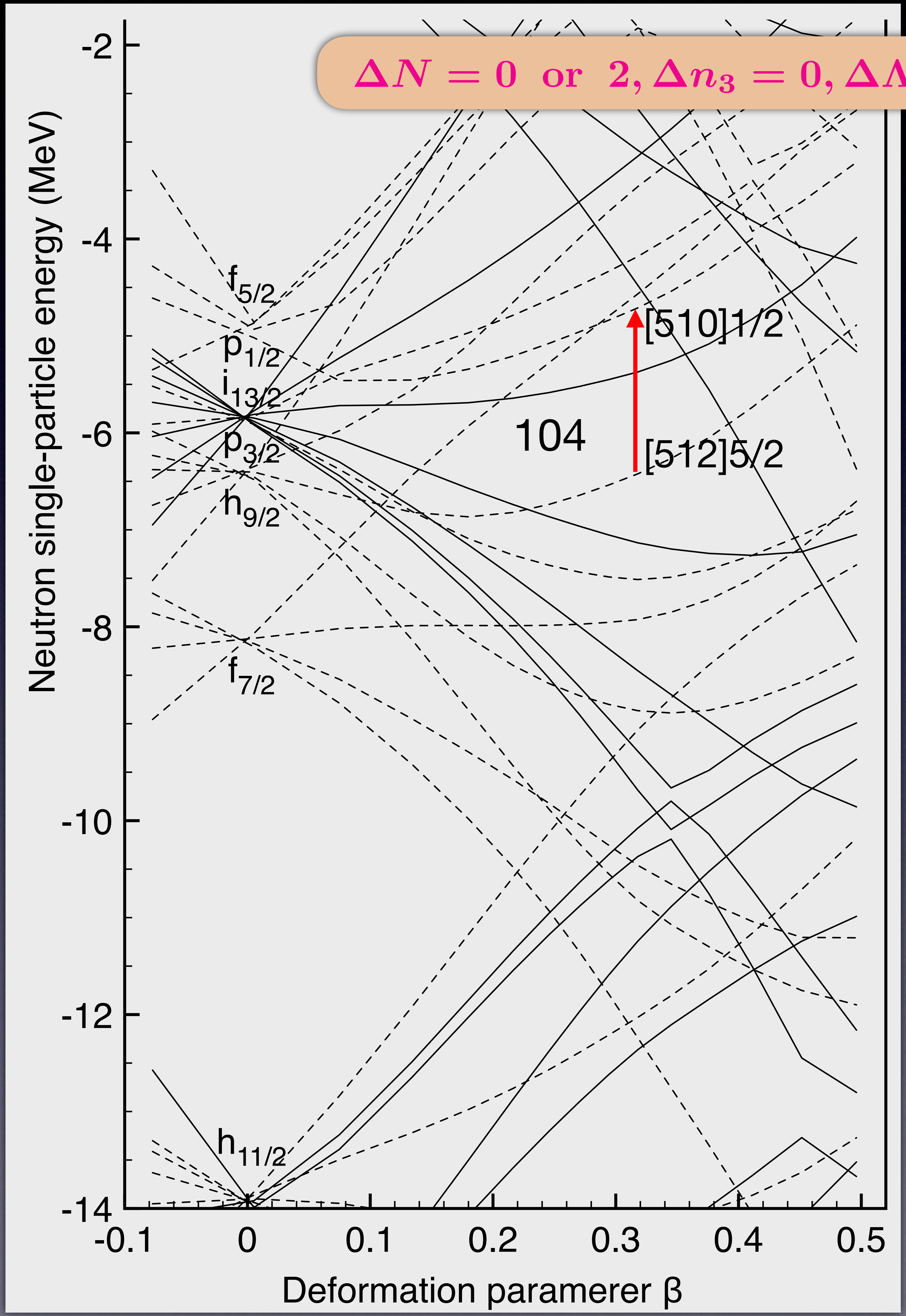


Microscopic structure of the γ-vibration: isotopic dependence

@N=104

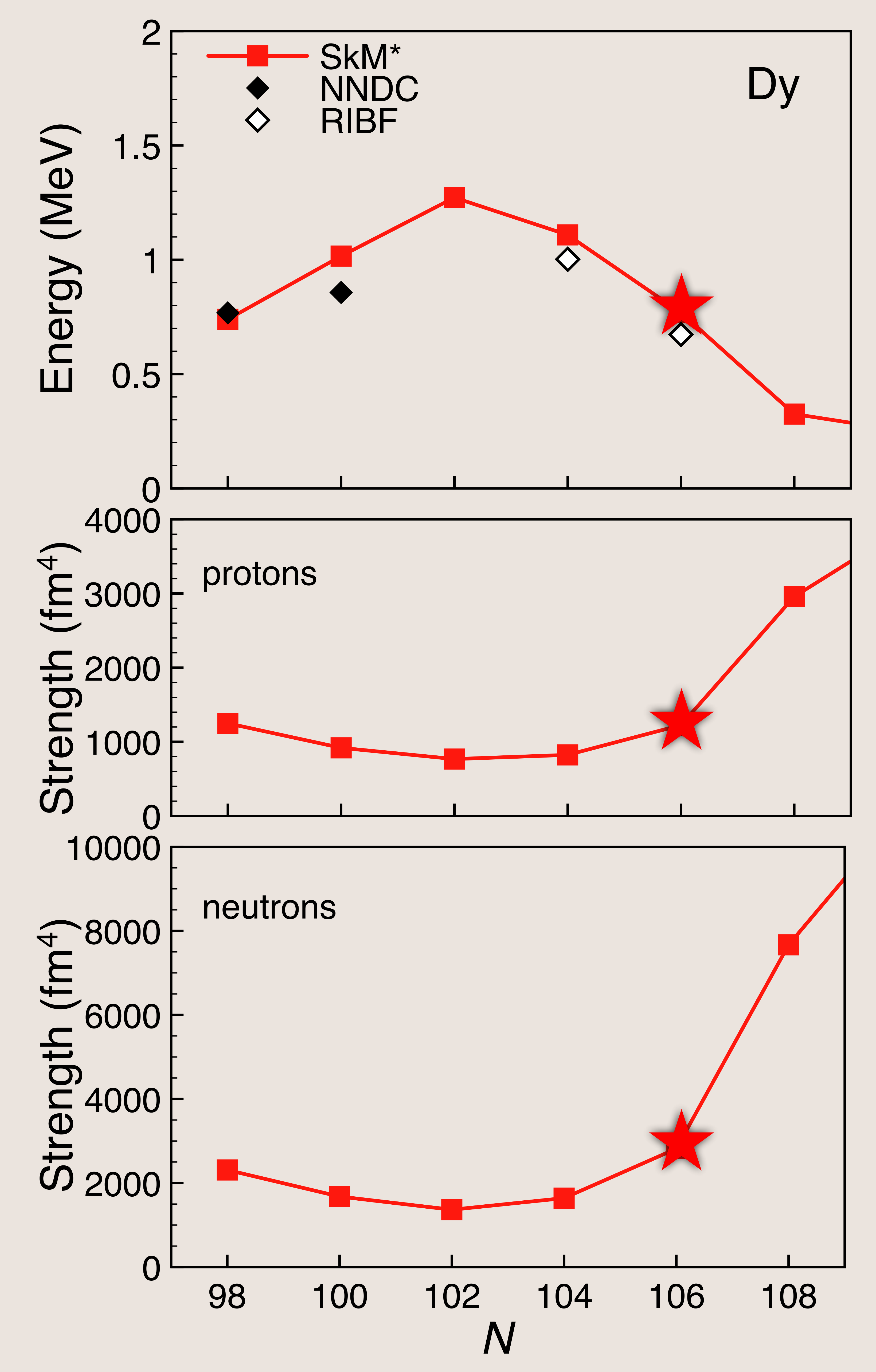


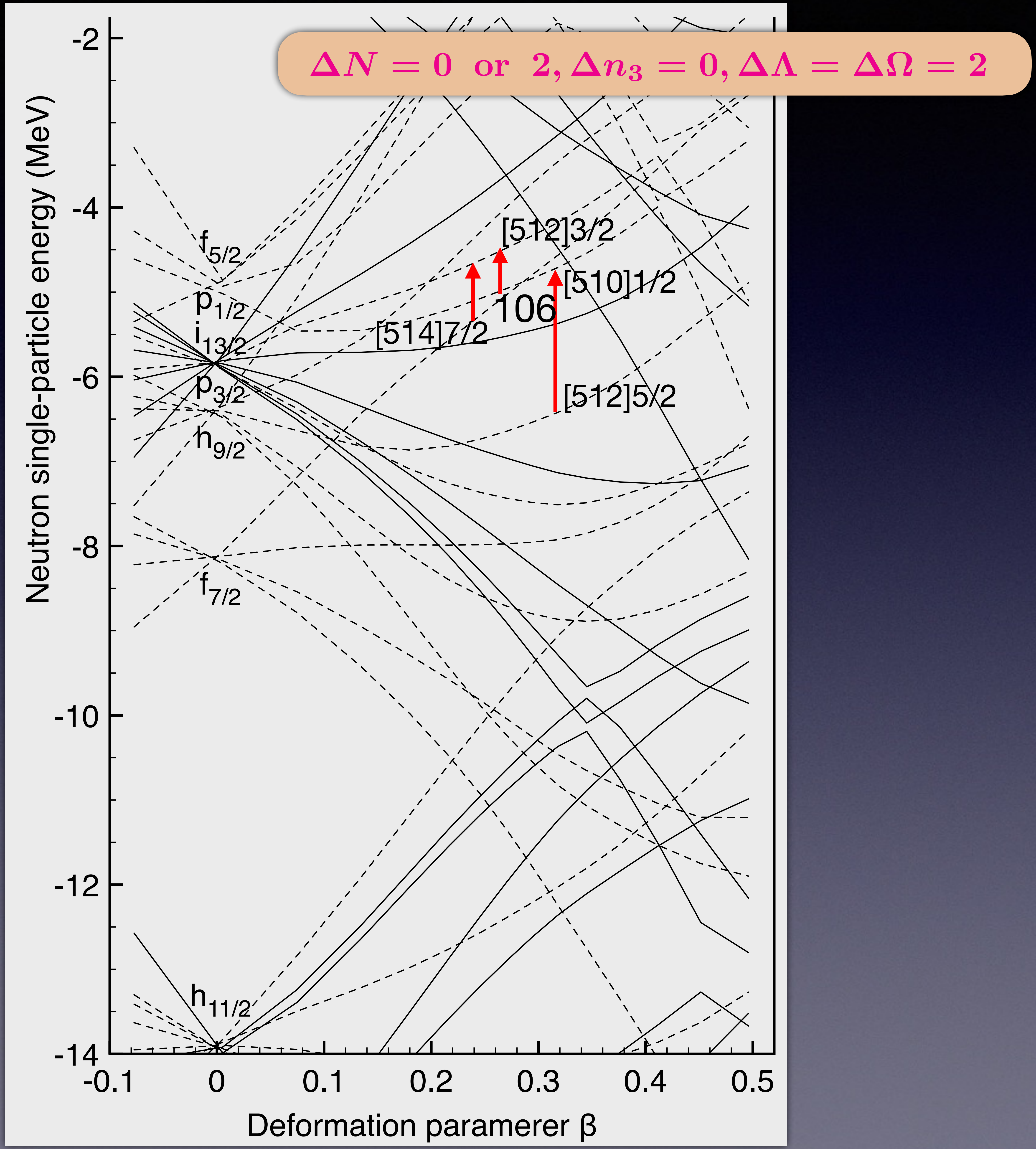
$\Delta N = 0$ or $2, \Delta n_3 = 0, \Delta\Lambda = \Delta\Omega = 2$



Microscopic structure of the γ-vibration: isotopic dependence

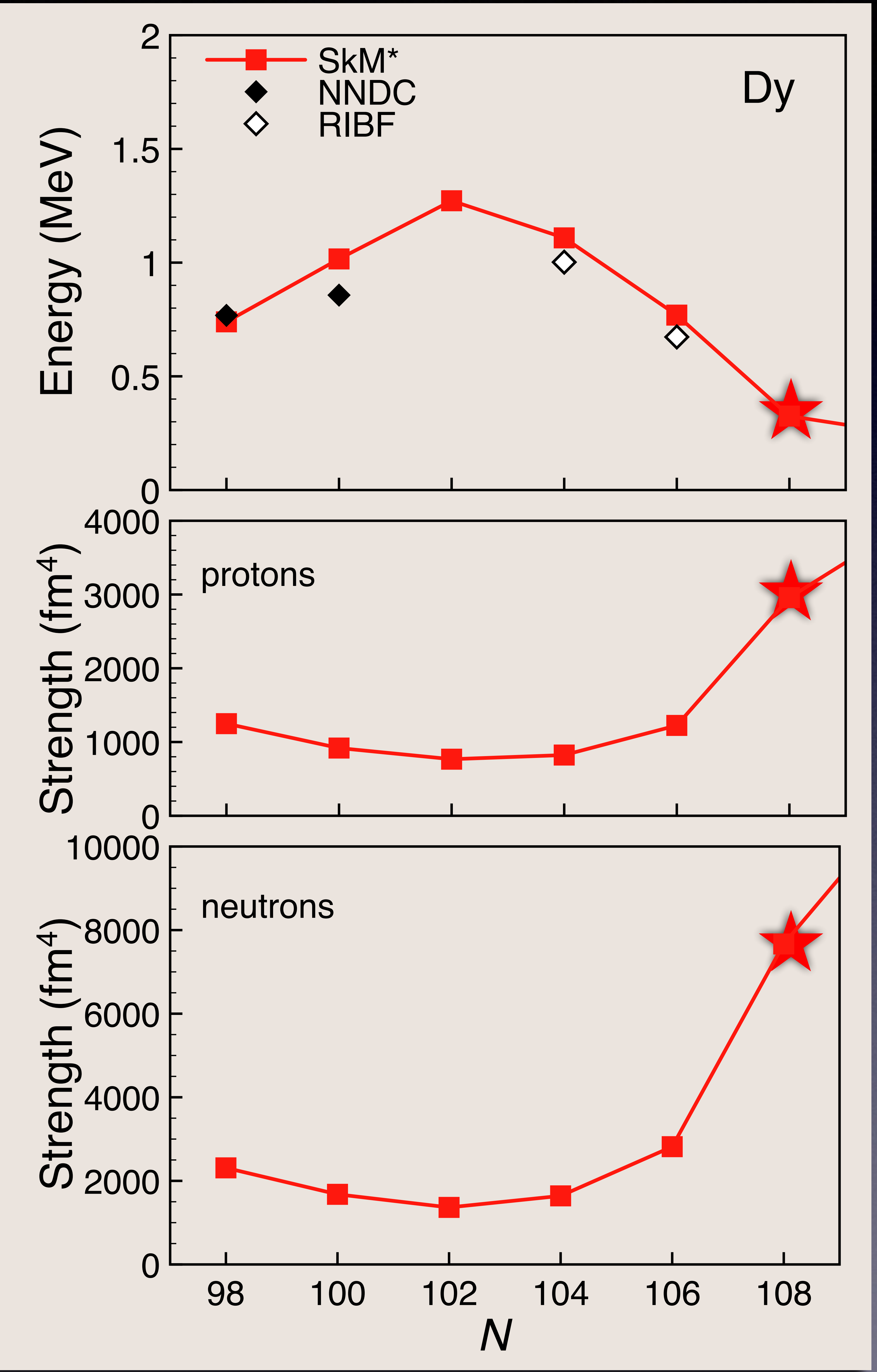
@N=106



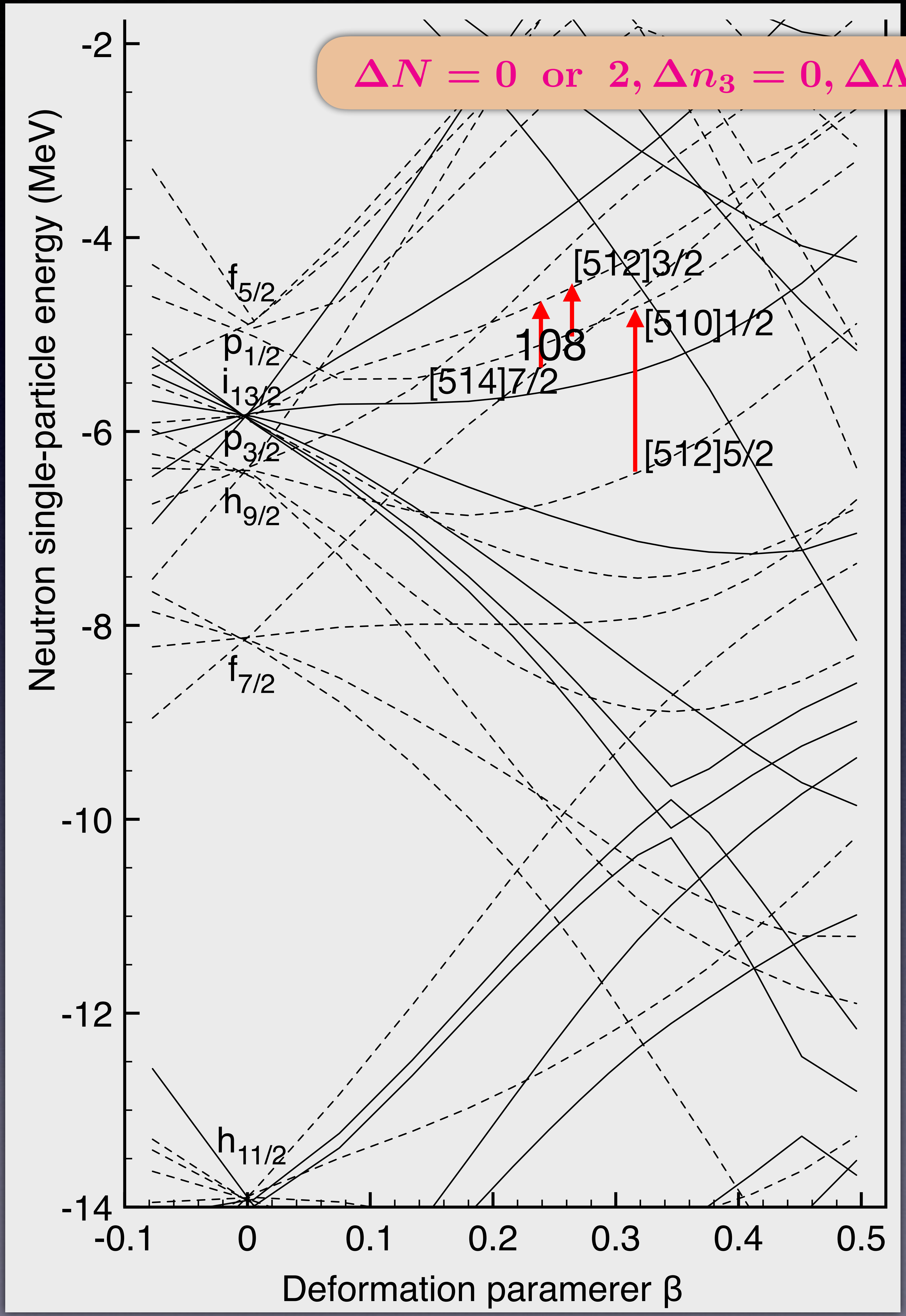


Microscopic structure of the γ-vibration: isotopic dependence

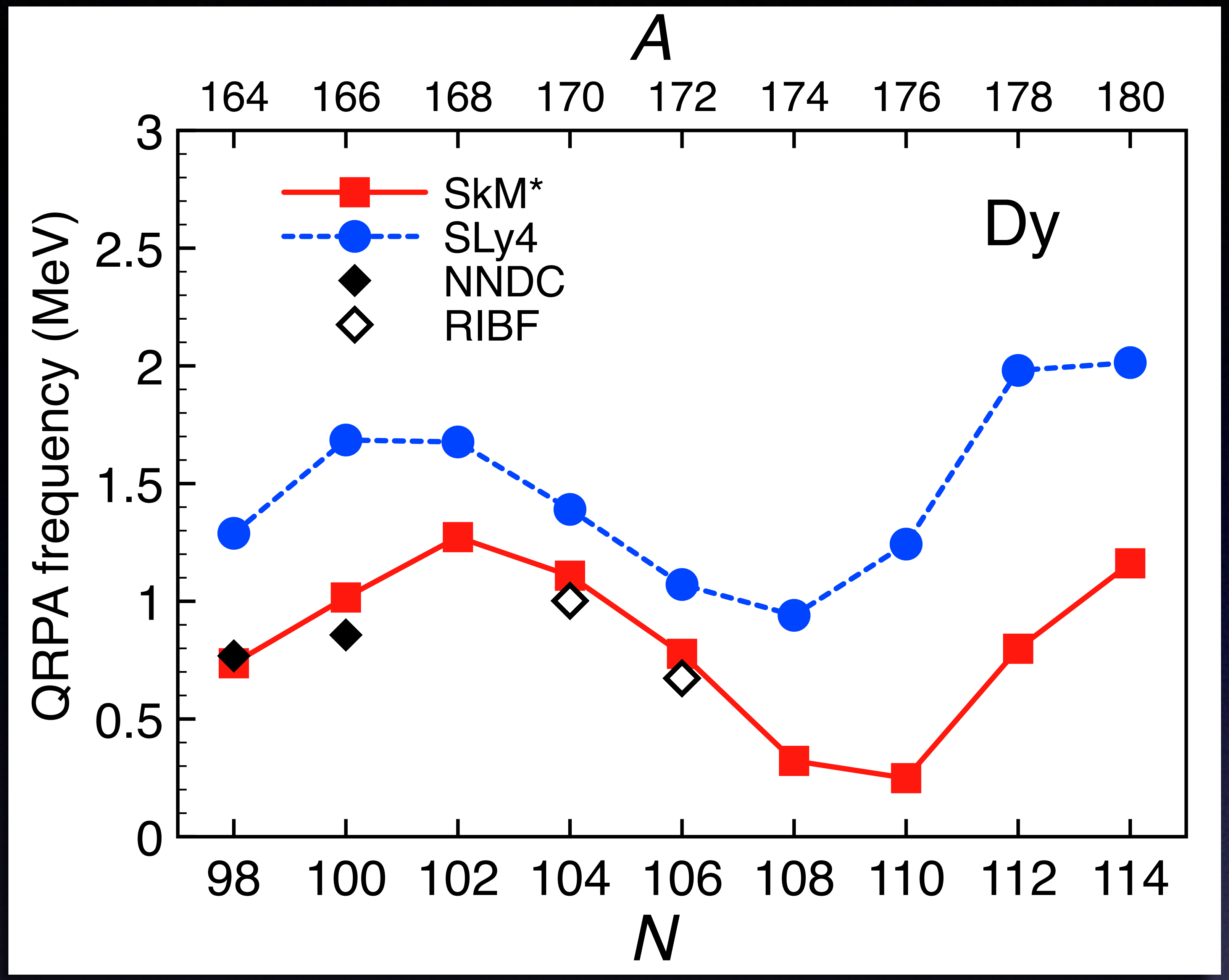
@N=108



$$\Delta N = 0 \text{ or } 2, \Delta n_3 = 0, \Delta\Lambda = \Delta\Omega = 2$$



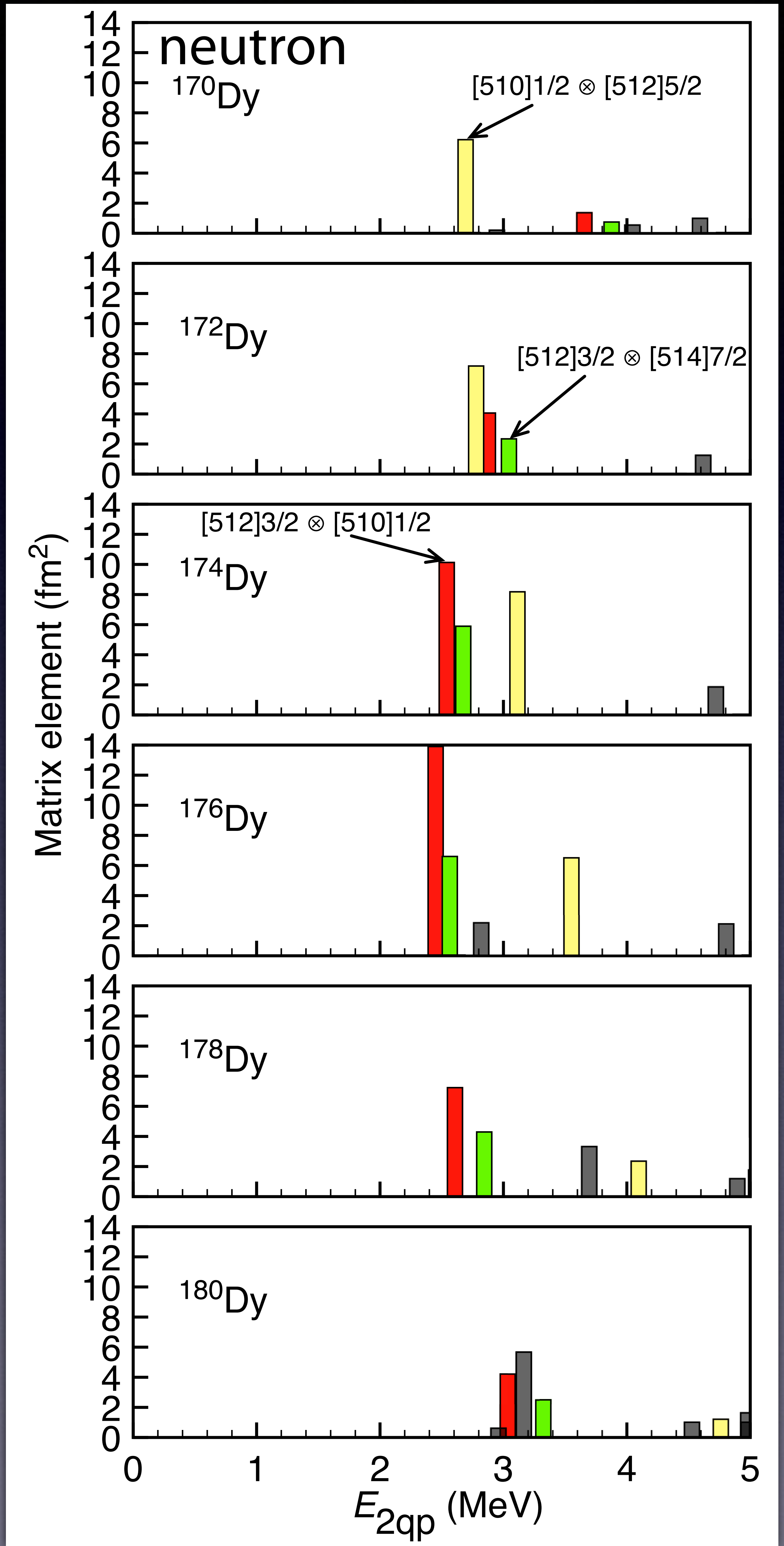
Strong collectivity of the γ-vibration around N=108-110



2qp matrix elements constructing the γ-vib.

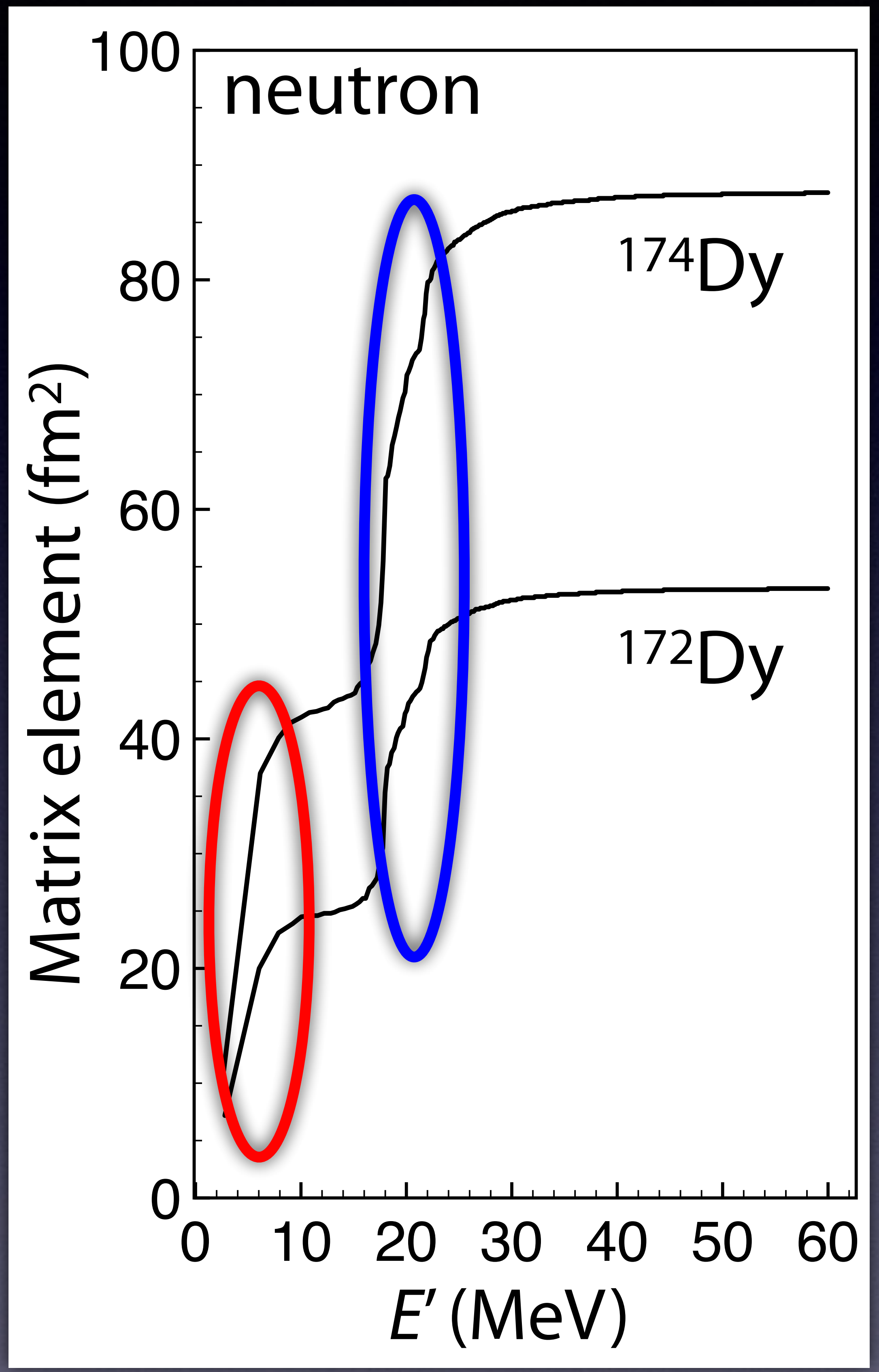
$$\langle i|\hat{F}^q_{\lambda K}|0\rangle = \sum_{\alpha\beta} M^{q,i}_{\alpha\beta}$$

Isotopic dependence is governed by the 2qp excitations near the Fermi level



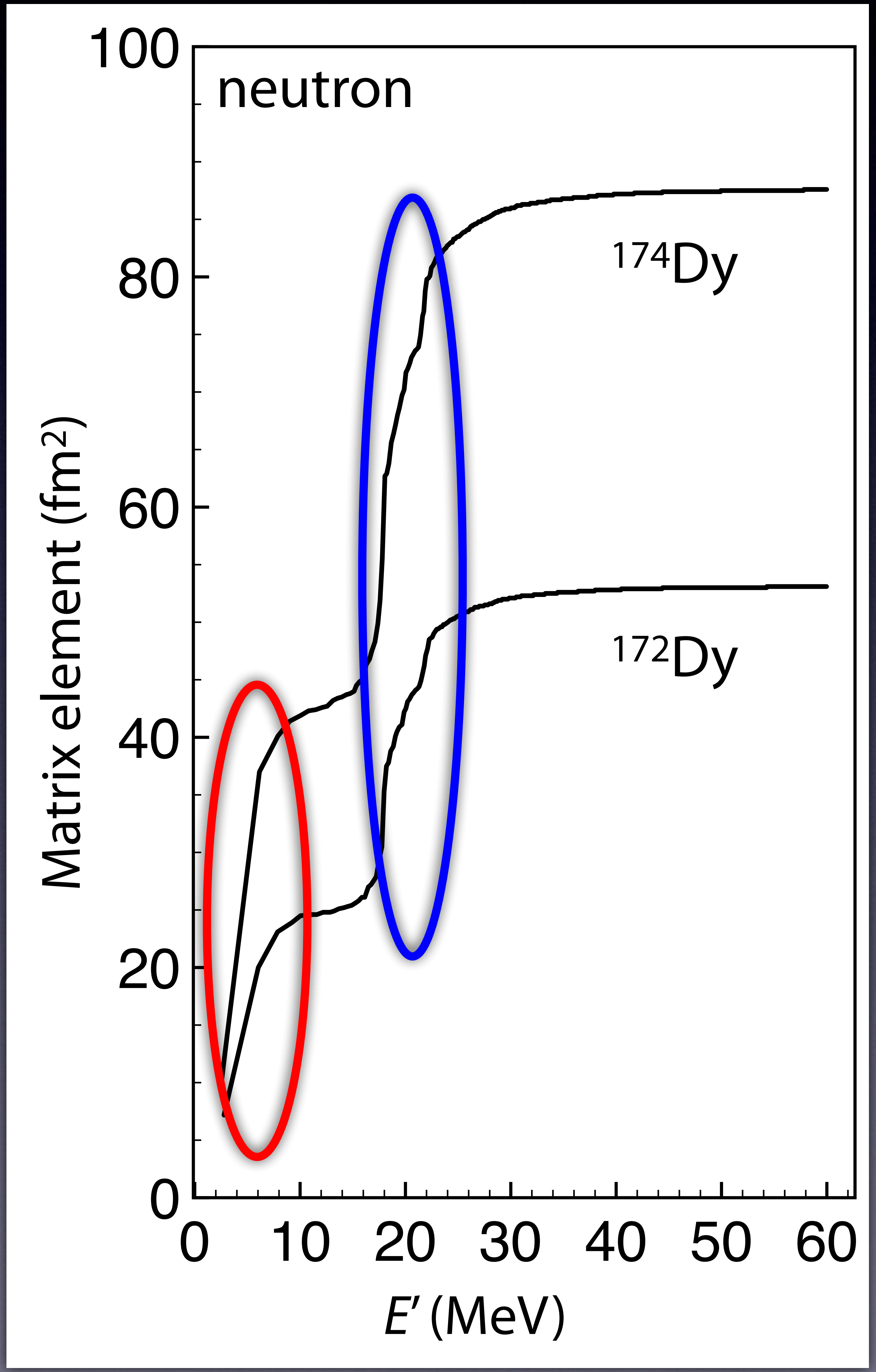
SkM*

cumulative ME $\sum_{E_{2qp}<E'} M^{q,i}_{\alpha\beta}$

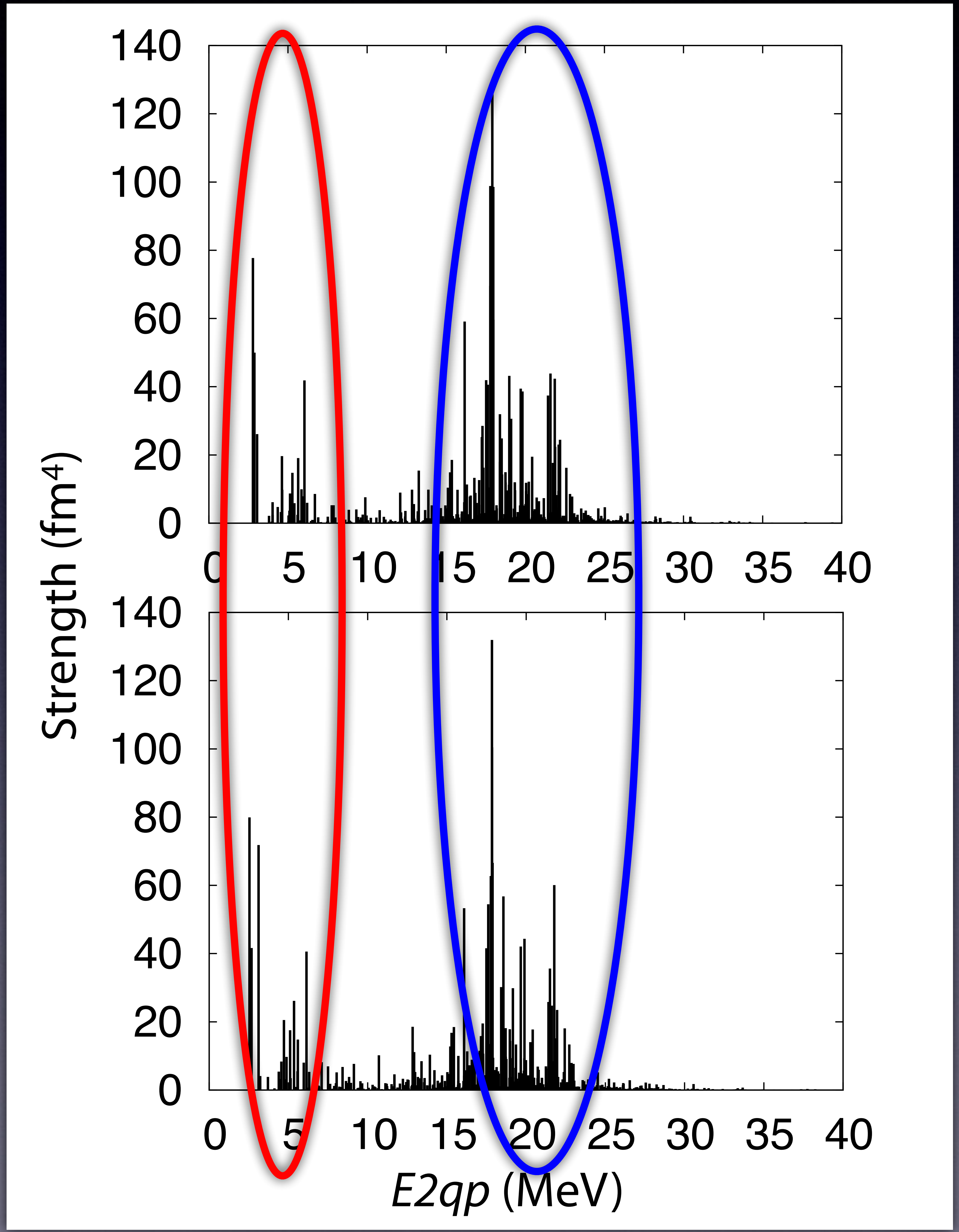


Enhancement in the transition strength

cumulative ME $\sum_{E_{2\mathrm{qp}}<E'} M^{q,i}_{\alpha\beta}$



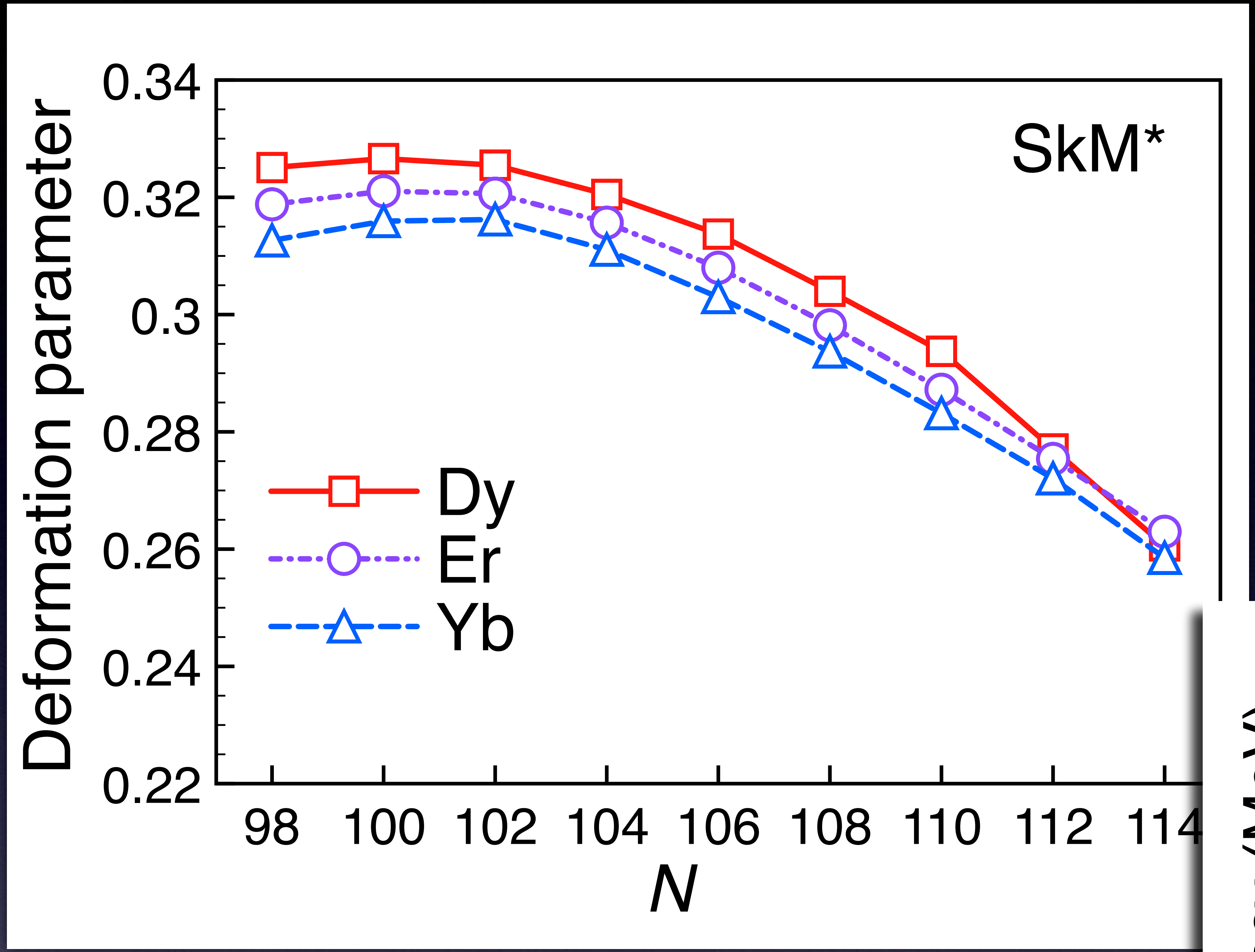
unperturbed strength of neutrons

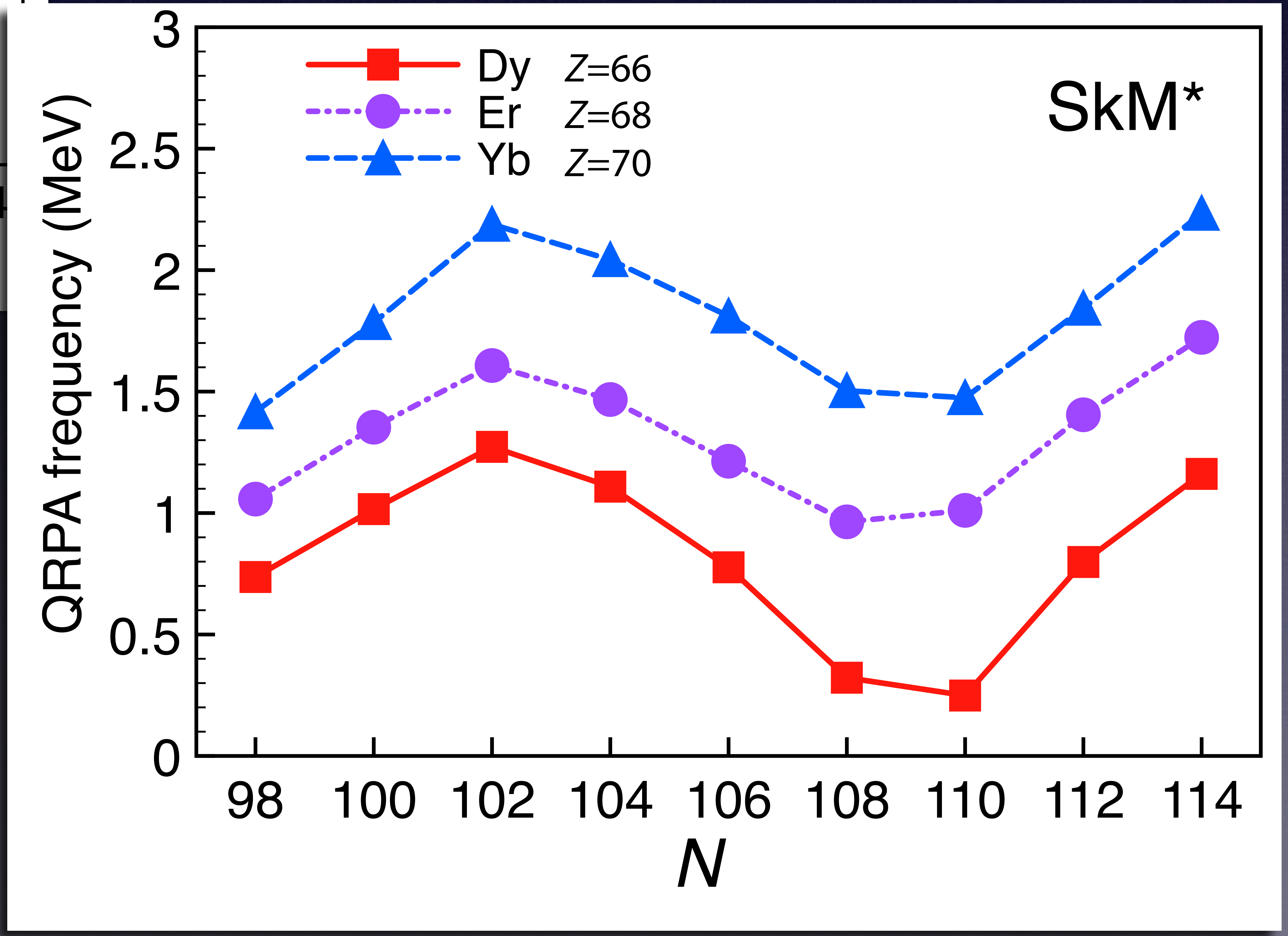


coherent contribution of 2qp excitations in the giant-resonance region

The γ-vib. in these nuclei are strongly collective.

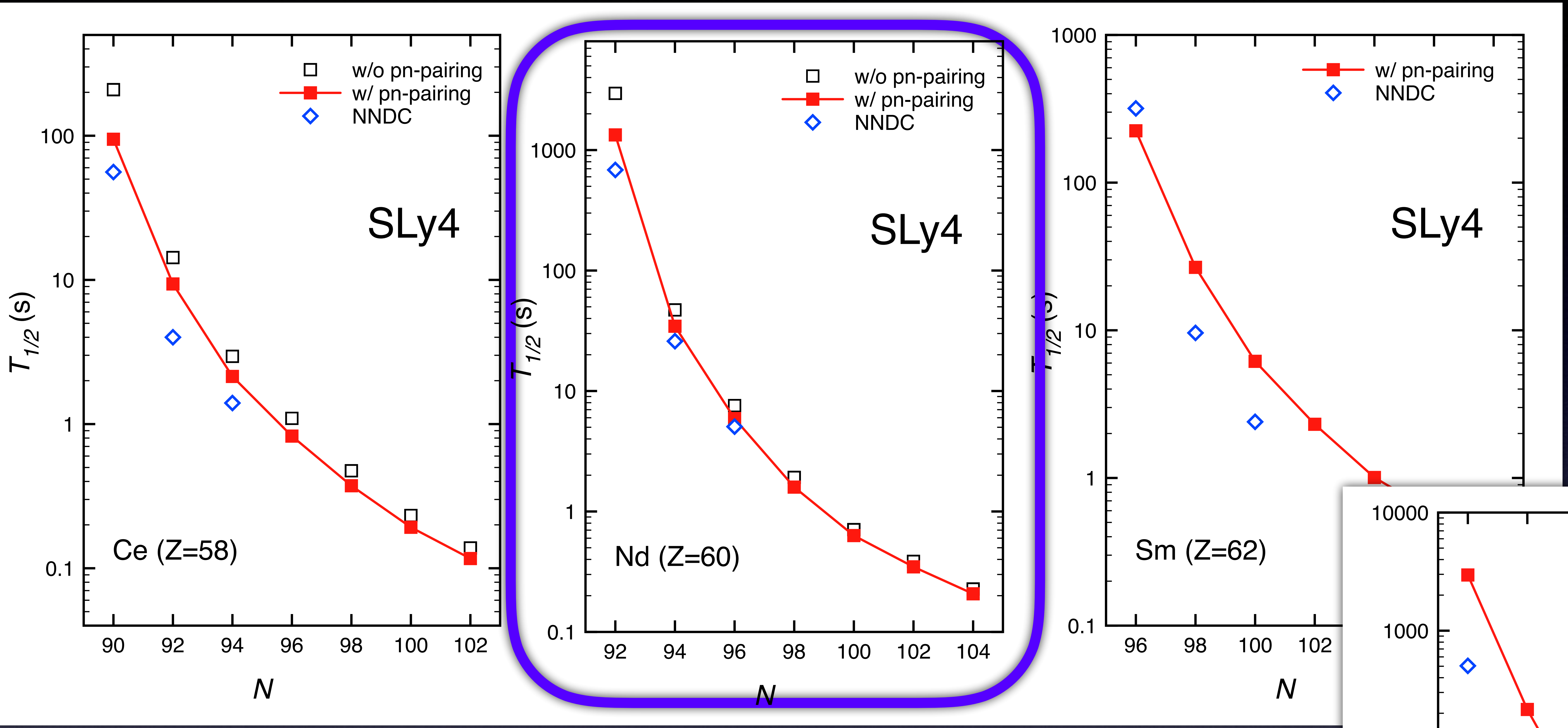
Similar isotopic dependence in the neighbouring nuclei



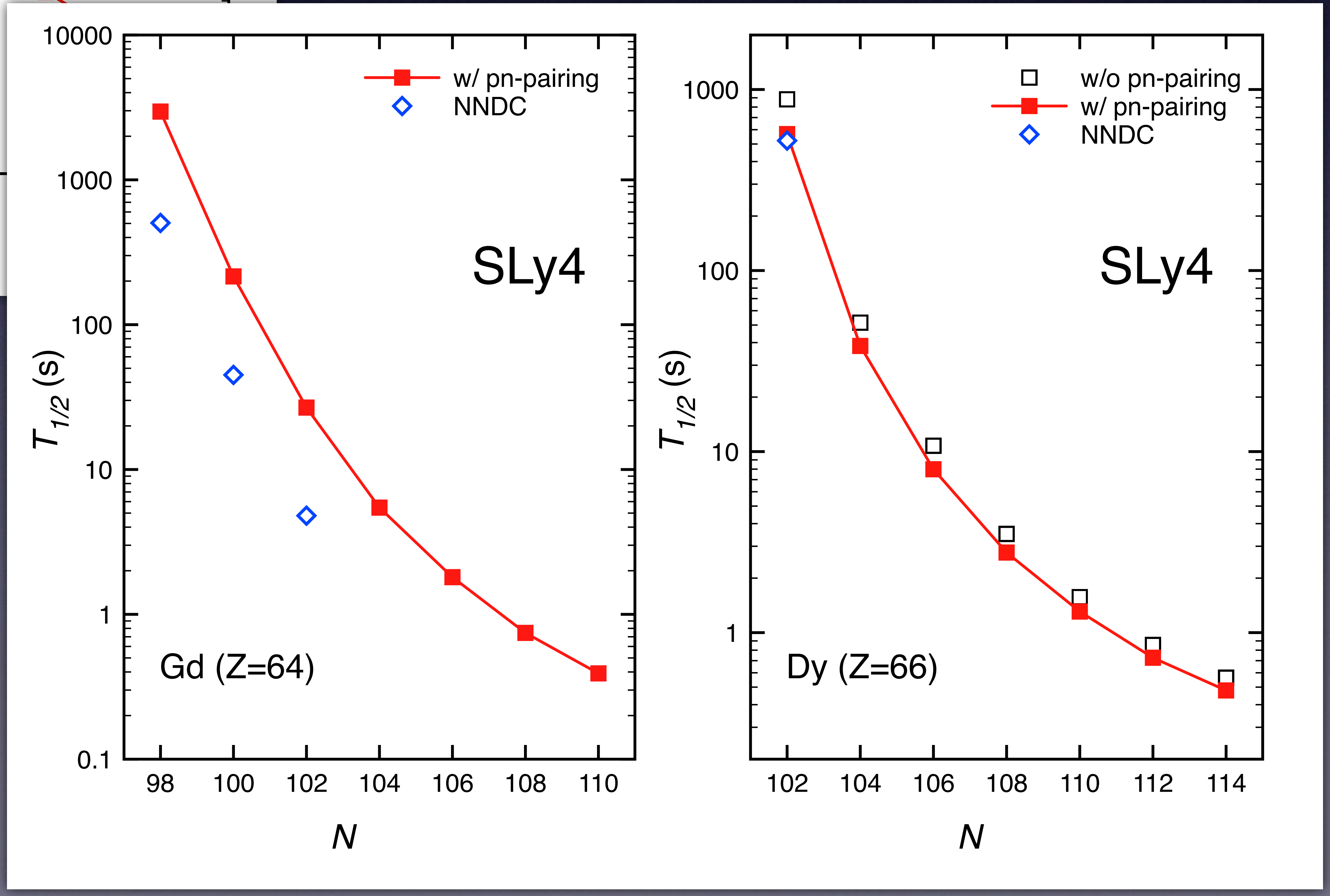


less contributions of protons

β-decay properties of the neutron-rich rare-earth nuclei



EURICA@RIBF:
Wu and Nishimura et al.



systematic and microscopic description of β-decay half-life now available

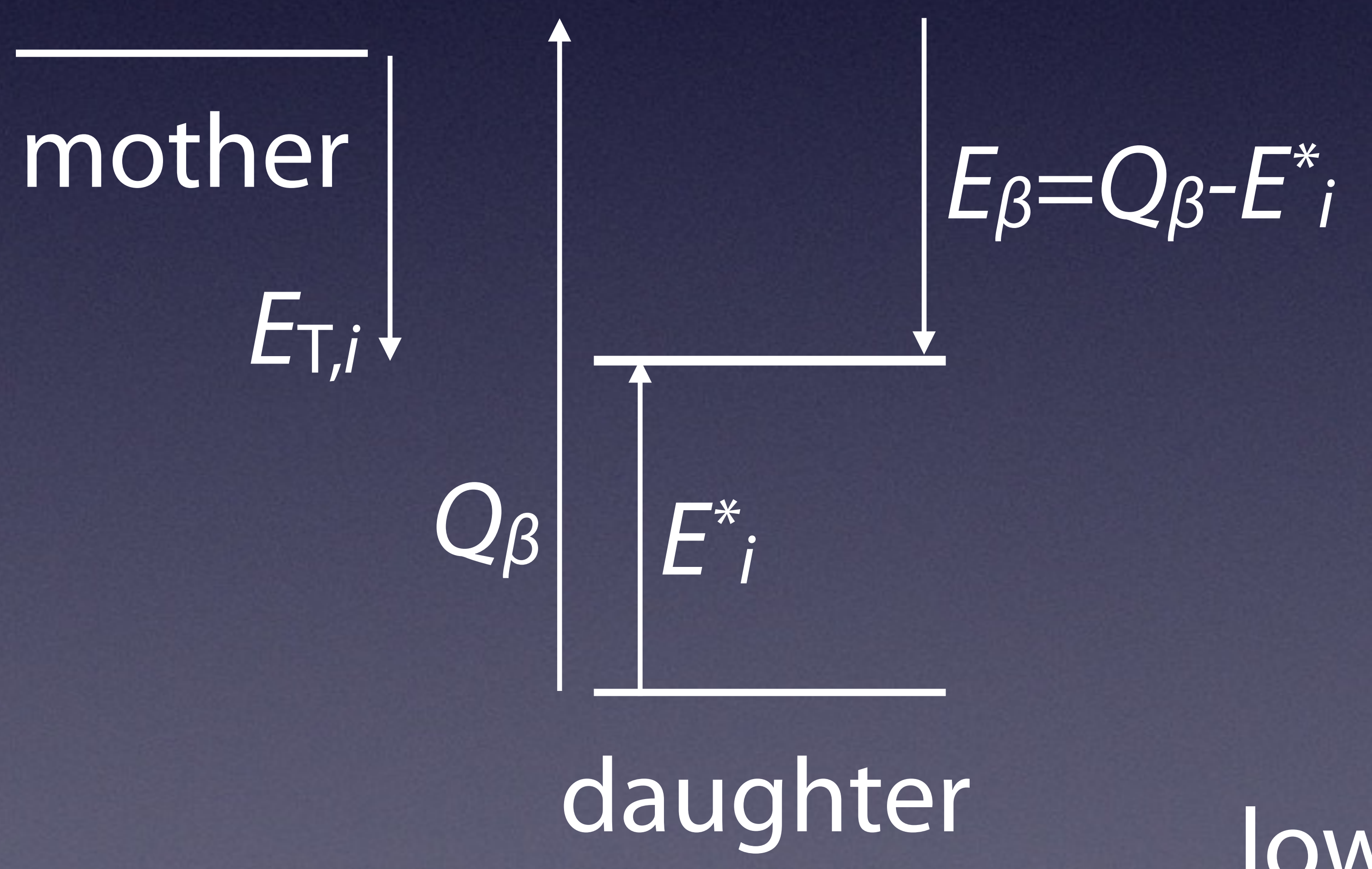
spin-isospin response calculations (GT and F)

Microscopic description of the nuclear β-decay

charge-exchange mode of excitation
= superposition of 2qp excitations of a proton and a neutron

$$\hat{O}_i^\dagger = \sum_{\alpha\beta} X^i_{\alpha\beta} \hat{a}^\dagger_{\alpha,\nu} \hat{a}^\dagger_{\beta,\pi} - Y^i_{\alpha\beta} \hat{a}_{\bar{\beta},\pi} \hat{a}_{\bar{\alpha},\nu}$$

$$\frac{1}{T_{1/2}} = \frac{(g_A/g_V)^2_{\rm eff}}{D} \sum_K \sum_{E_i^* < Q_\beta} f(Z, Q_\beta - E_i^*) \underline{|\langle i|\hat{F}_K^-|0\rangle|^2}$$

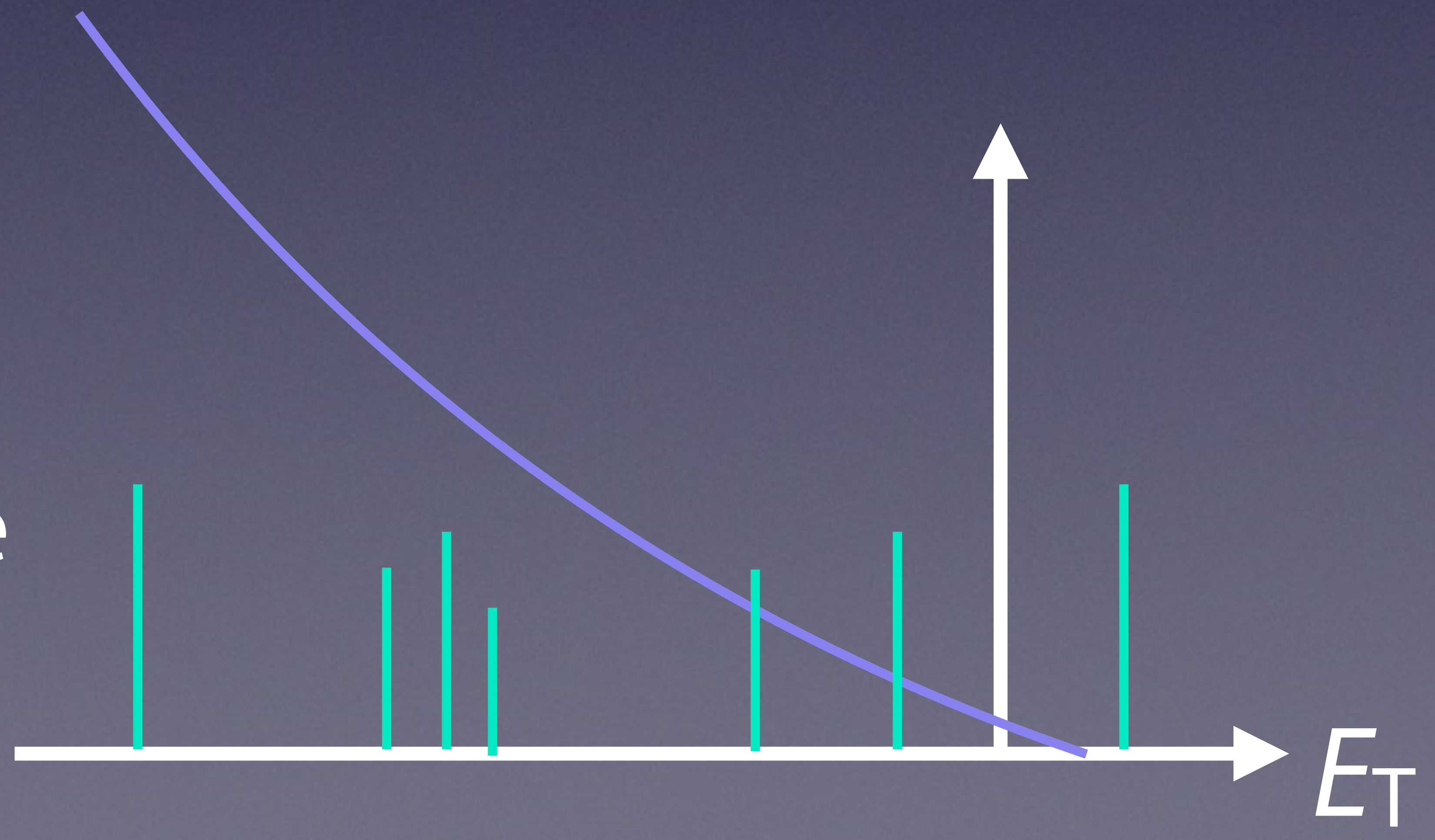


$$Q_\beta - E_i^* \simeq \Delta M_{n-H} - \omega_i + \lambda_\nu - \lambda_\pi$$
$$= \Delta M_{n-H} - E_{\mathrm{T},i}$$

$$\hat{F}_K^- = \sum_{\sigma\sigma'} \int dr \hat{\psi}_\pi^\dagger(r\sigma') \langle\sigma'|\sigma_K|\sigma\rangle \hat{\psi}_\nu(r\sigma)$$

J. Engel et al., PRC60(1999)014302

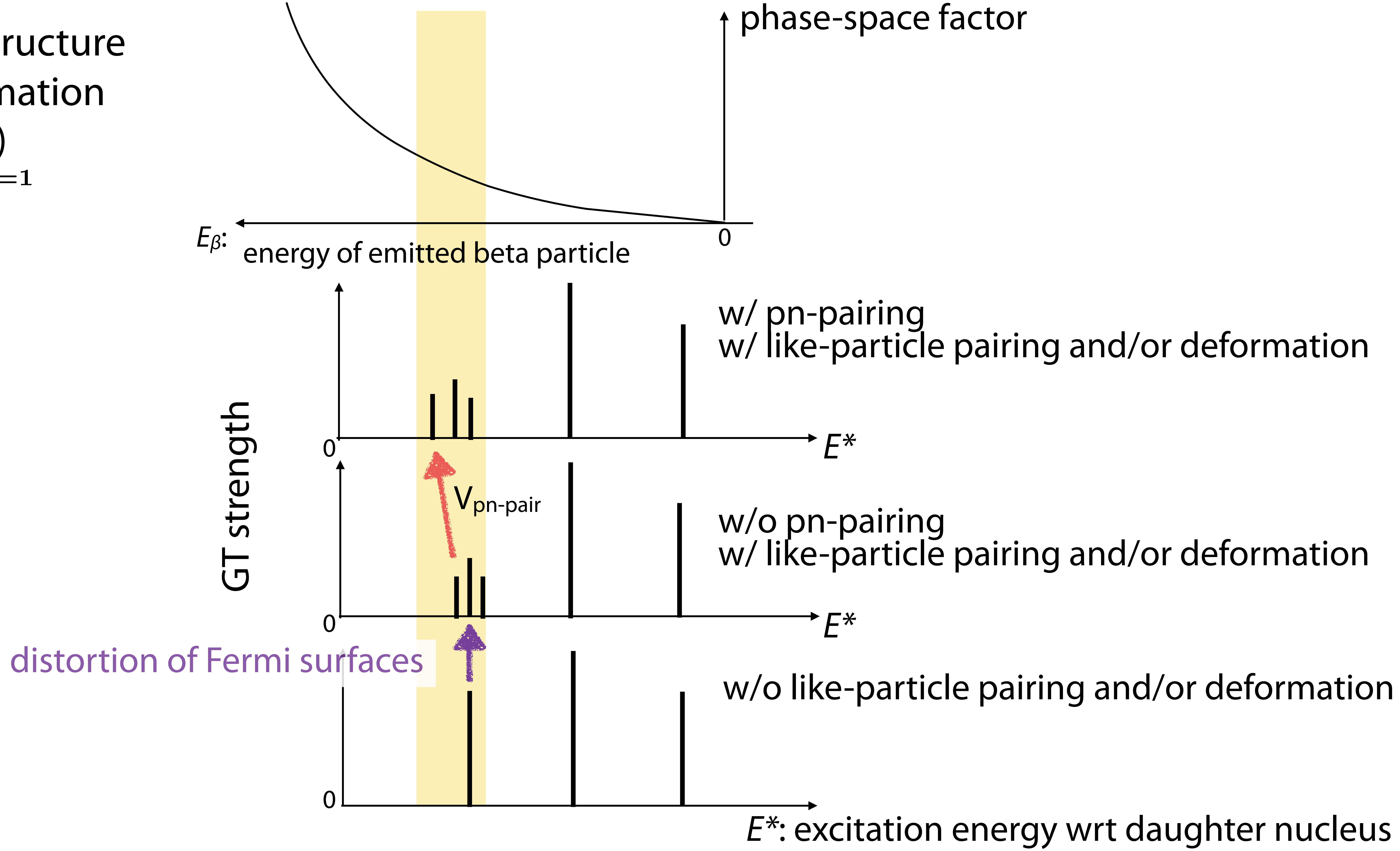
low-lying GT states are decisive for the half-life



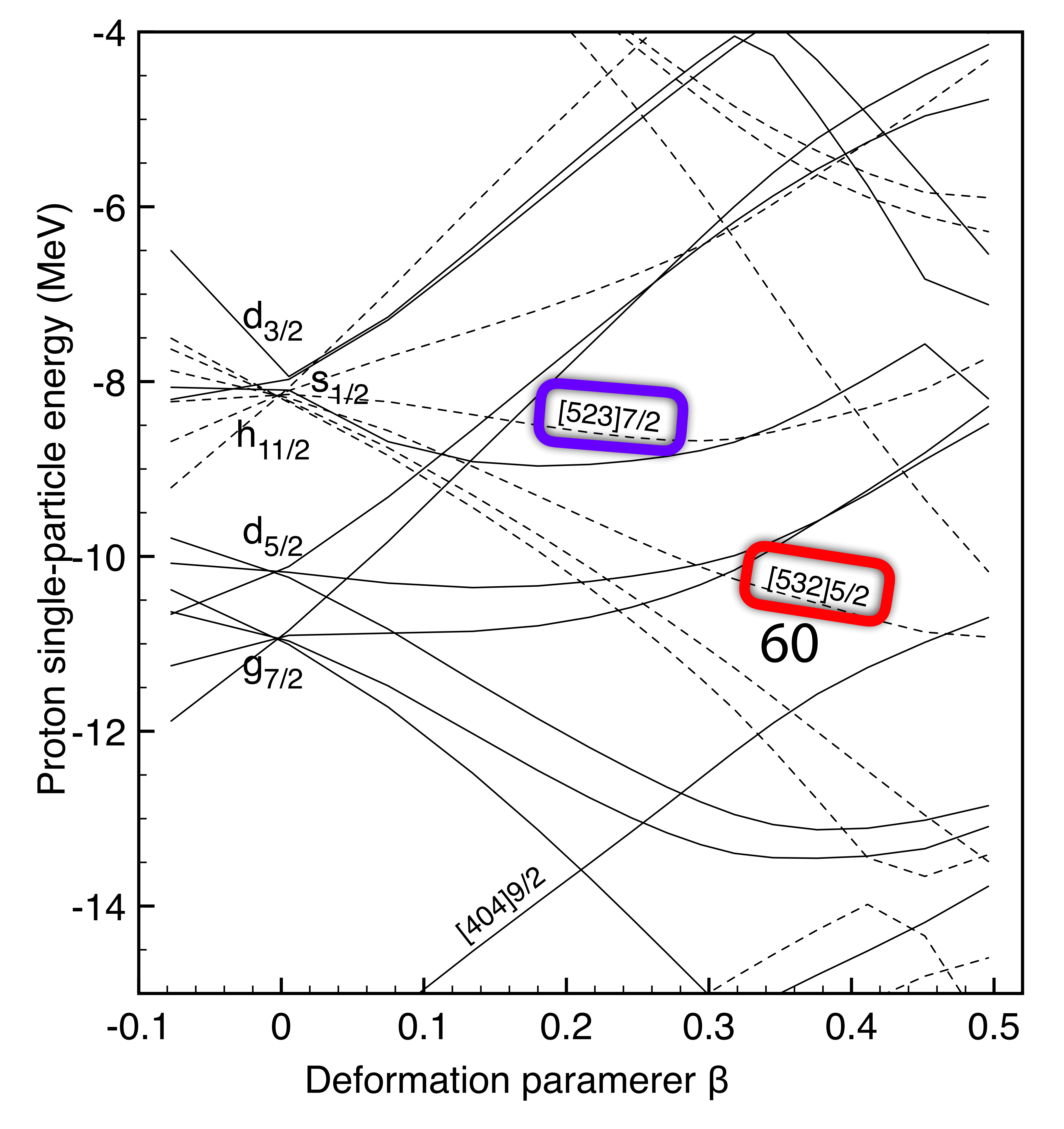
Roles of pairing on beta-decay

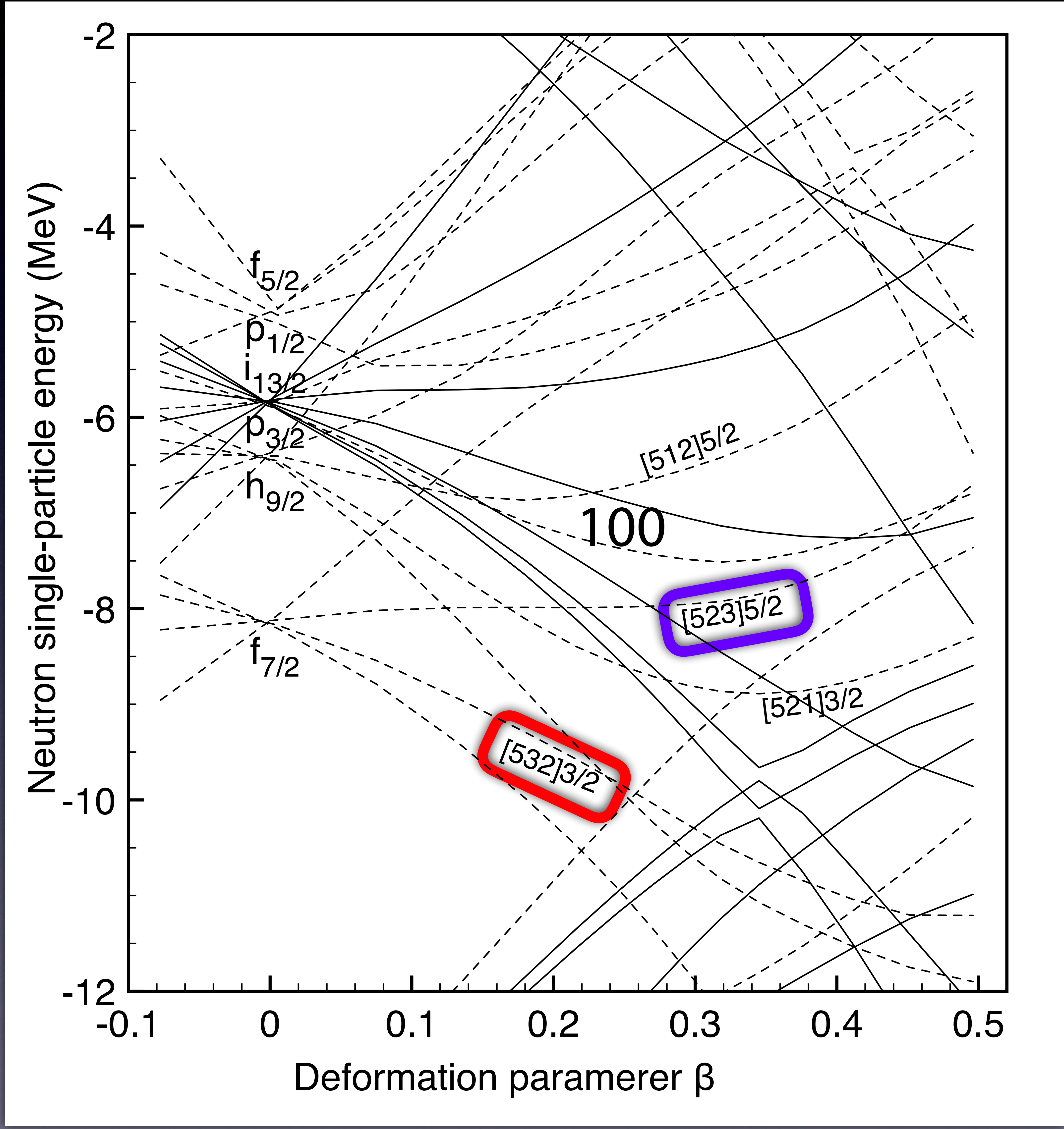
sensitive to shell structure
and pairing/deformation
(both T=0 and T=1)

$$V^{T=0} = f \cdot V^{T=1}$$

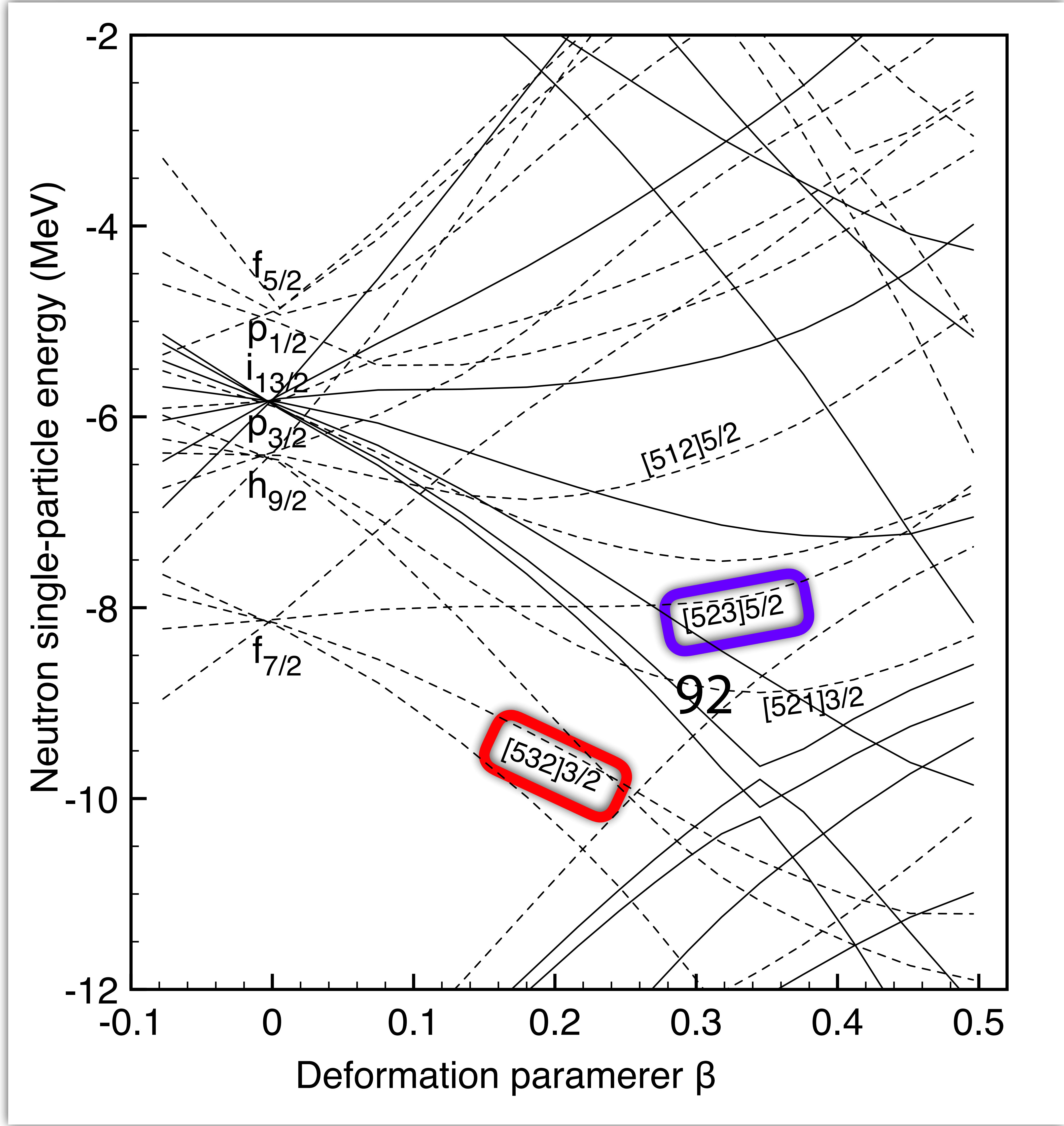


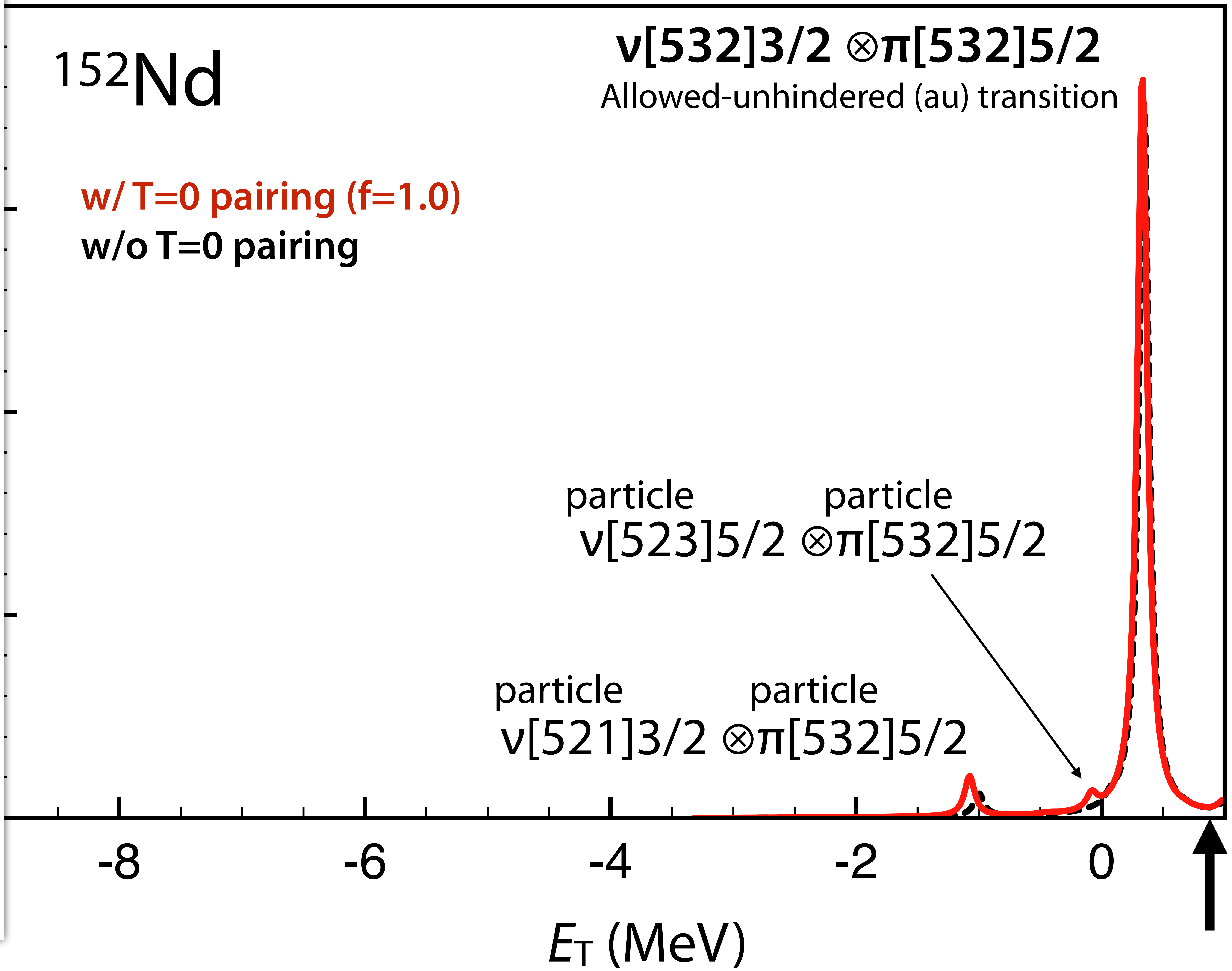
Single-particle energies



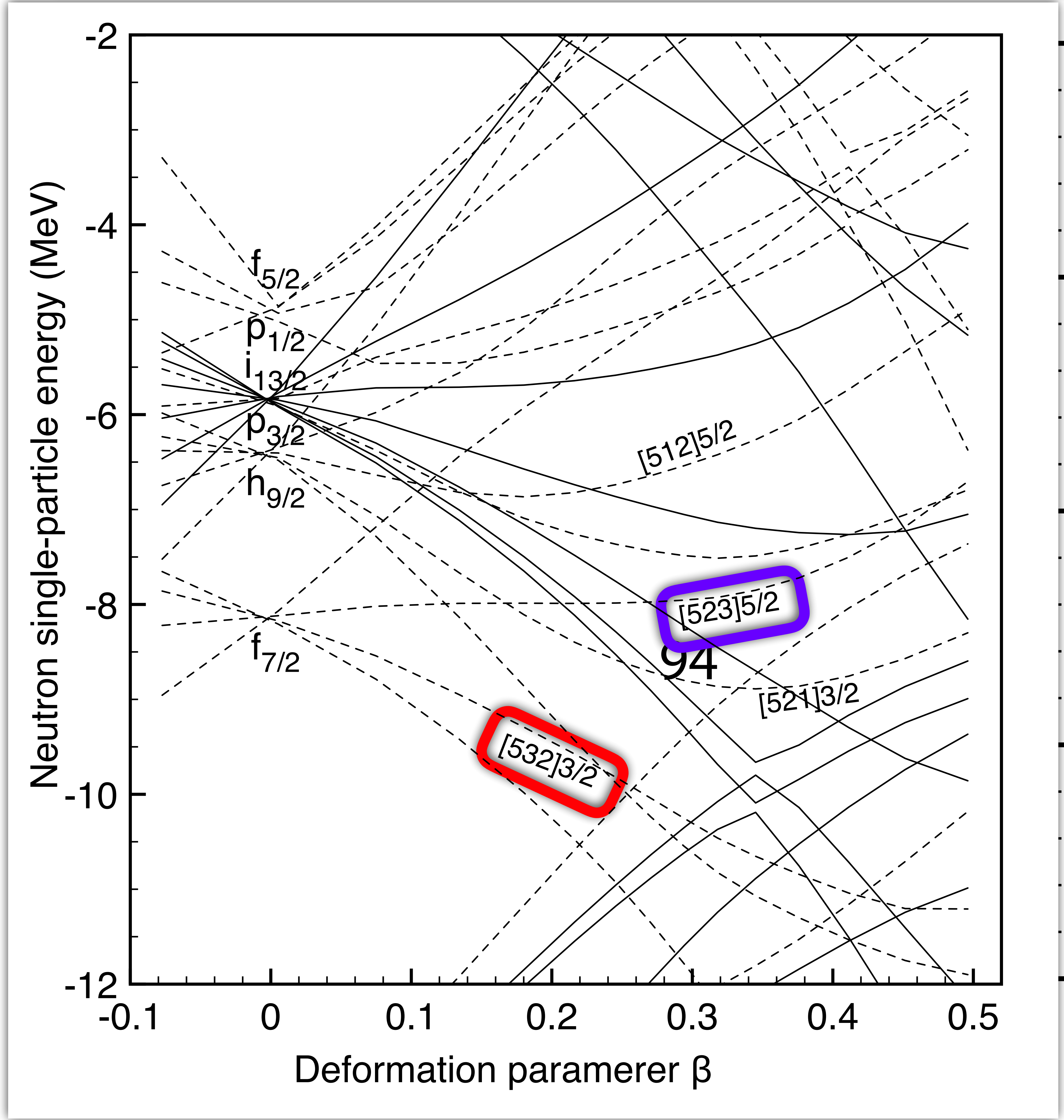


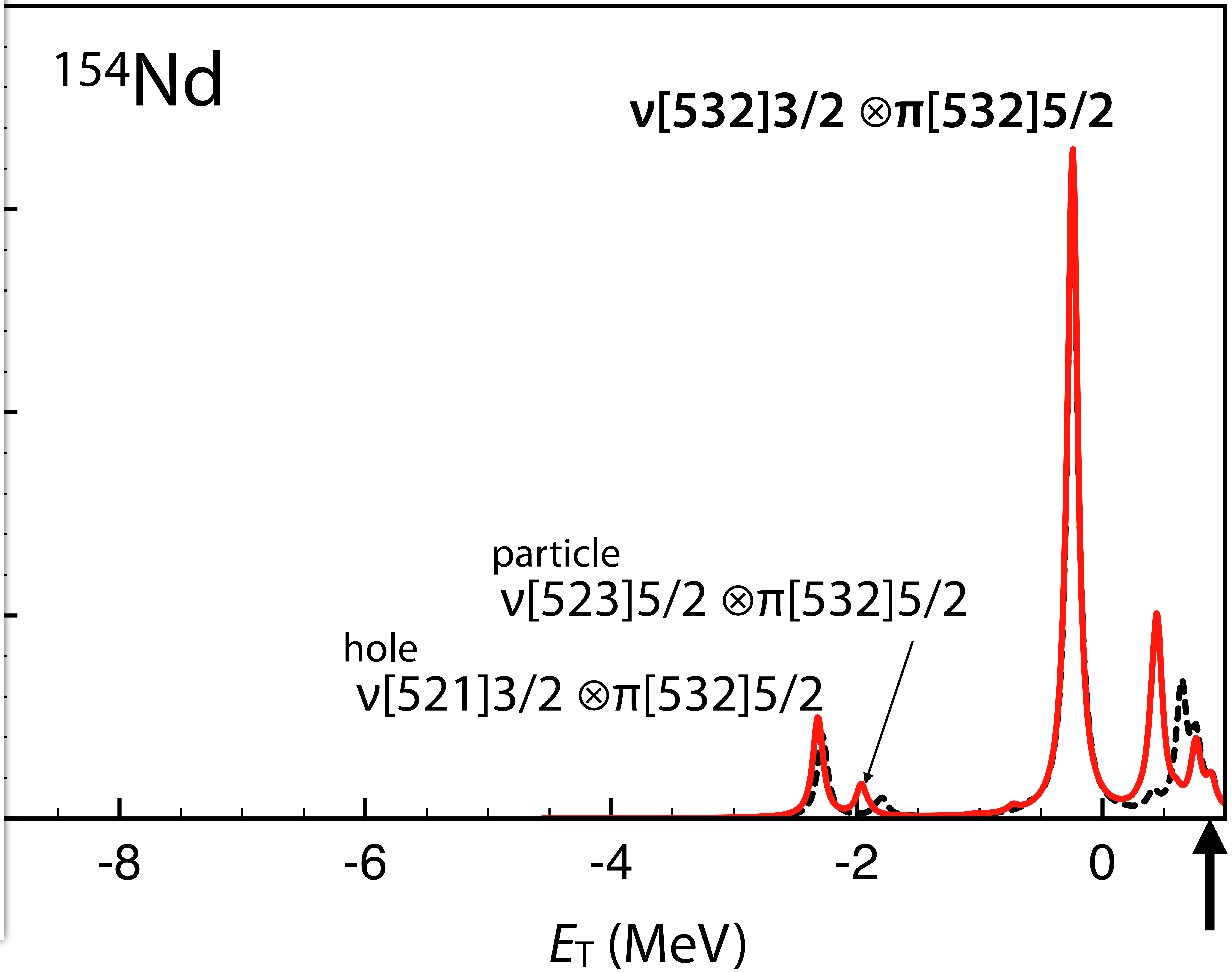
Low-lying GT states in ^{152}Nd



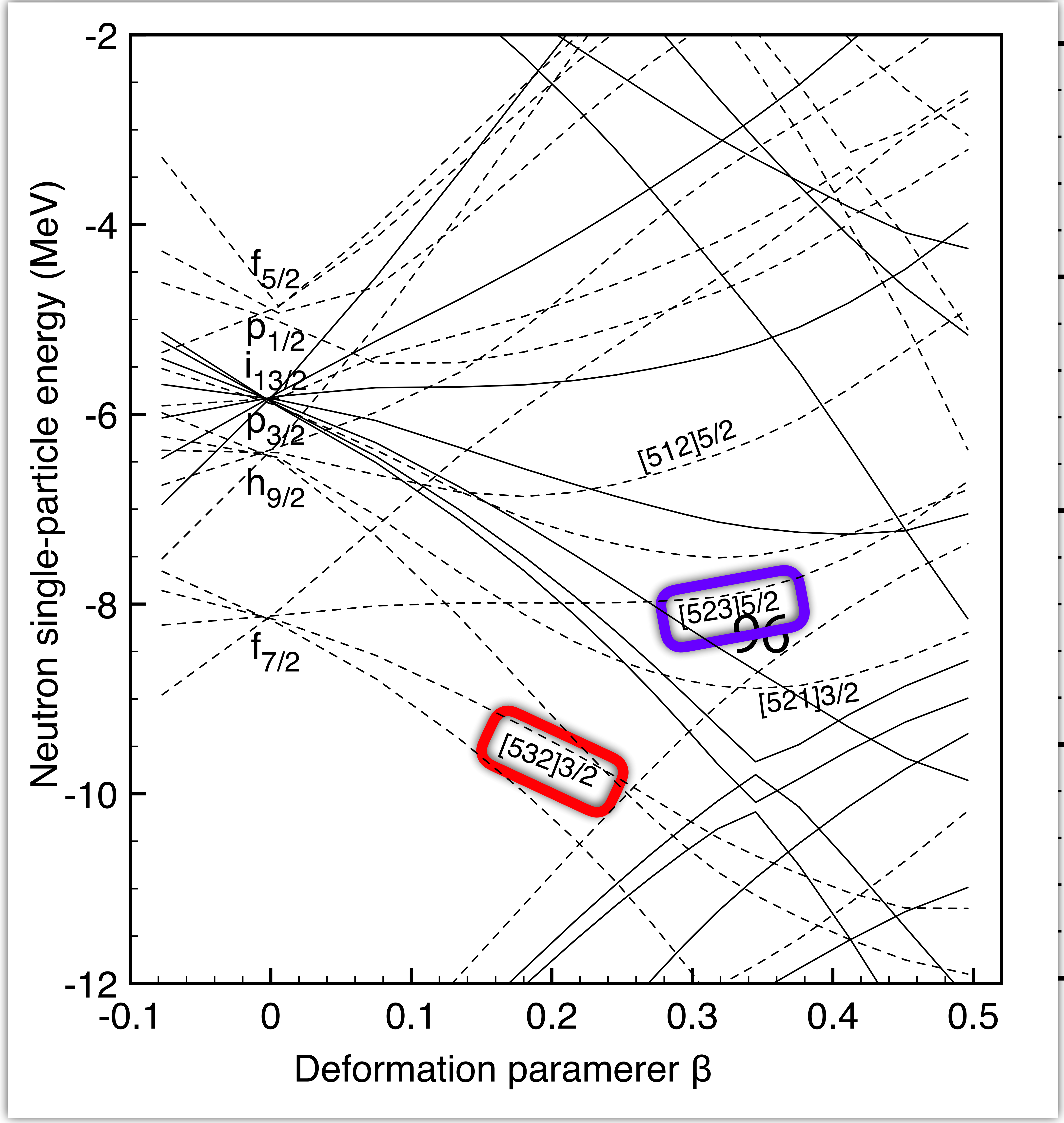


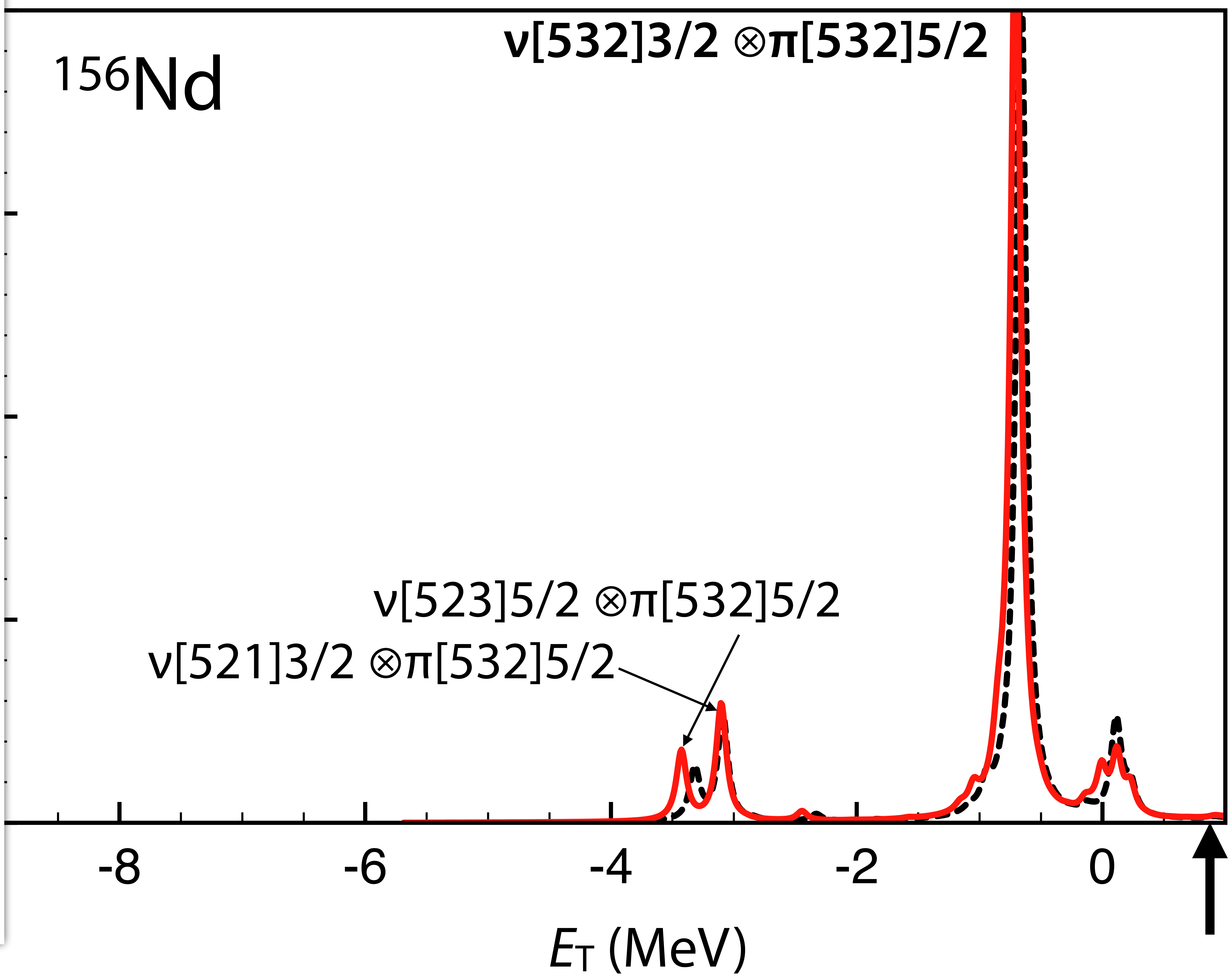
Low-lying GT states in ^{154}Nd





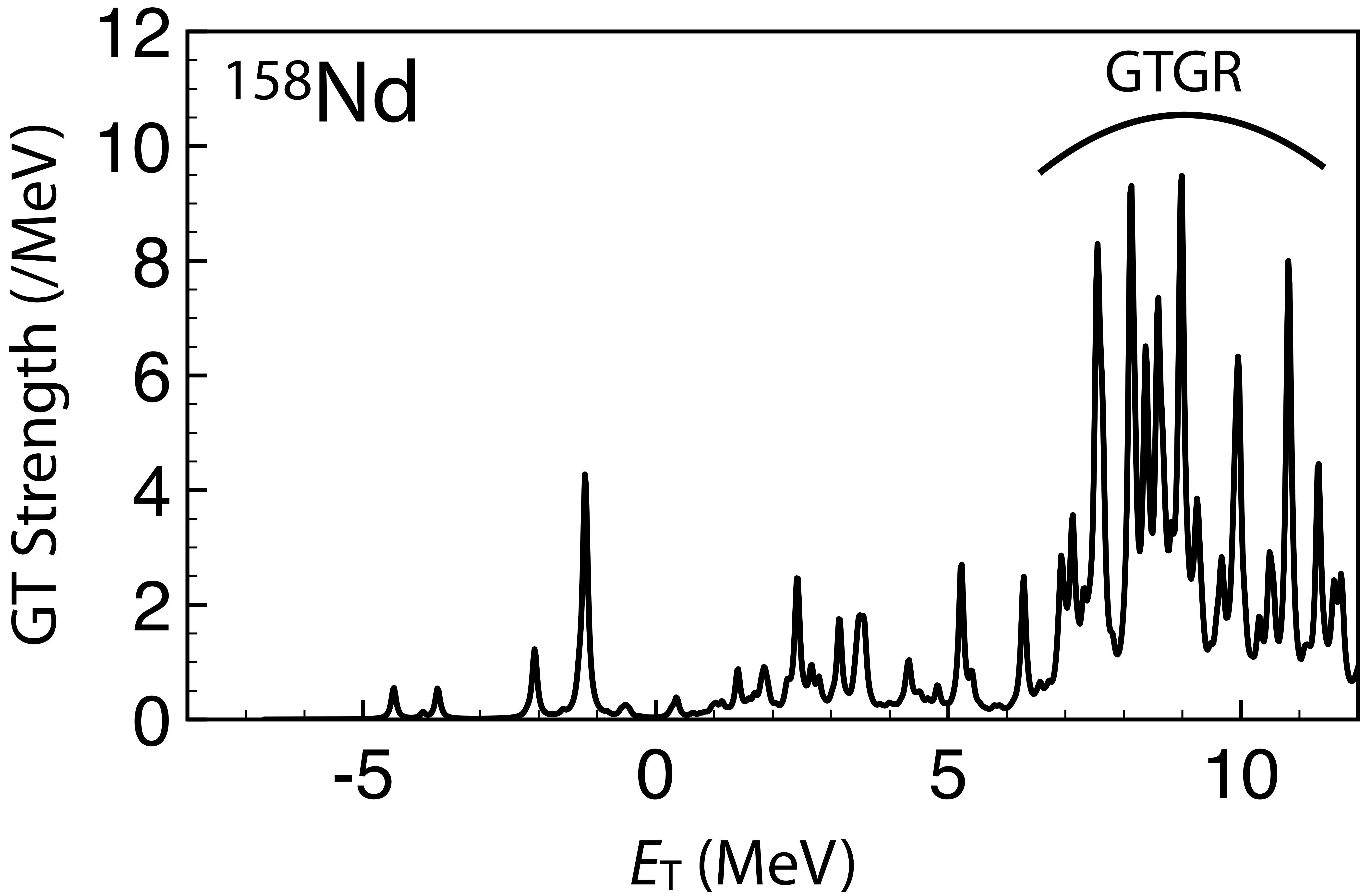
Low-lying GT states in ^{156}Nd





Low-lying GT states in ^{158}Nd

GT-strength distribution in ^{158}Nd



Most of the strengths are concentrated in the GR region.
strongly collective

Collectivity of the low-lying states relevant to the β-decay is quite weak.

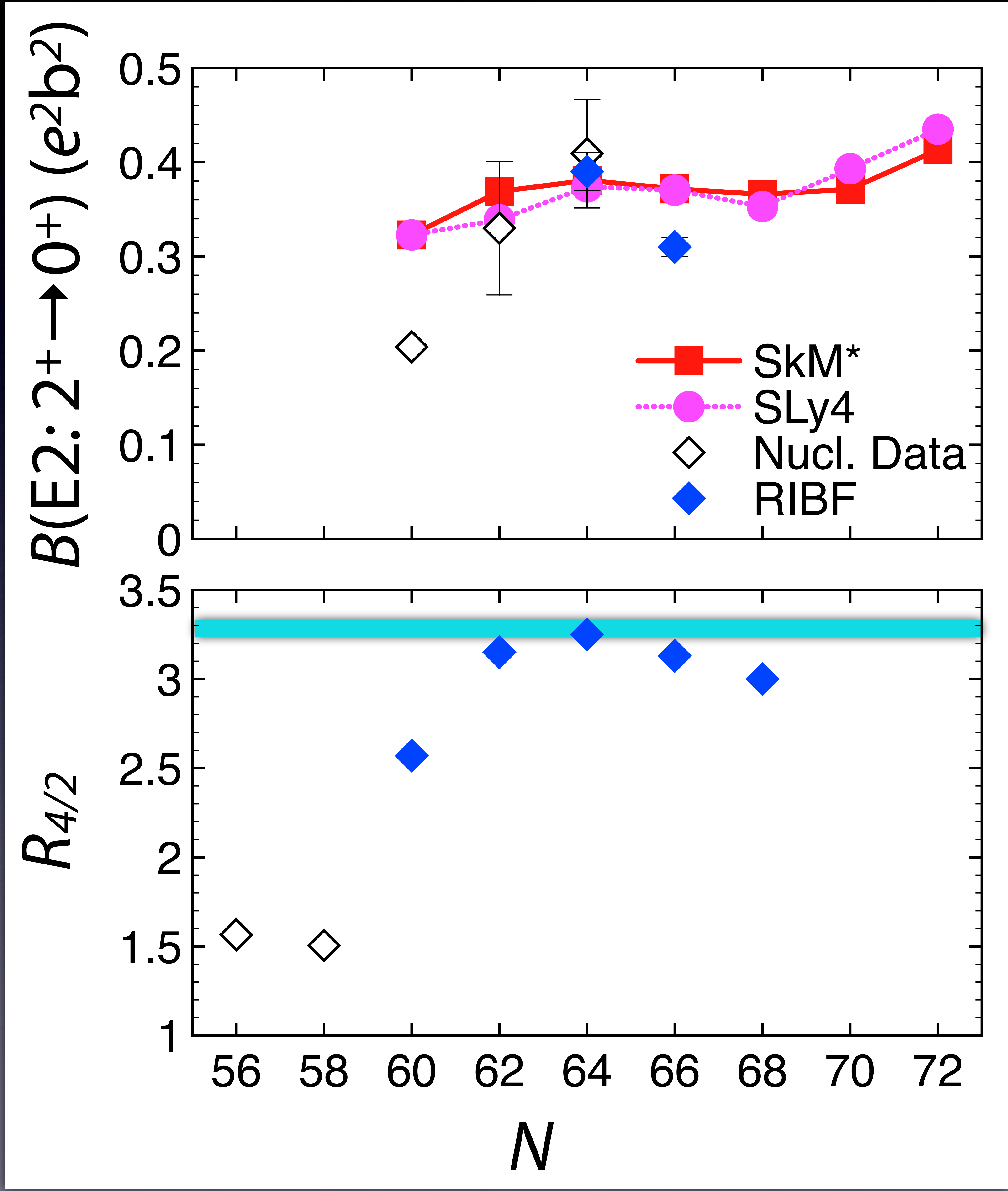
Summary

Low-lying modes of excitation in medium-heavy neutron-rich nuclei are described microscopically in a framework of the Skyrme-EDF based QRPA.

- neutron-rich rare-earth nuclei: heaviest neutron-rich nuclei with spectroscopic studies been made
- isotopic trend in the γ-vibartion and β-decay properties are well reproduced
- shell structure of the medium-heavy neutron-rich nuclei are reasonably described
  - stronger collectivity of the γ-vib. around $^{174\text{-}176}$Dy is predicted
- deformation and *T*=1 pairing correlations lead to fragmentation of the GT states
  - *T*=0 pairing interaction should be investigated in more detail

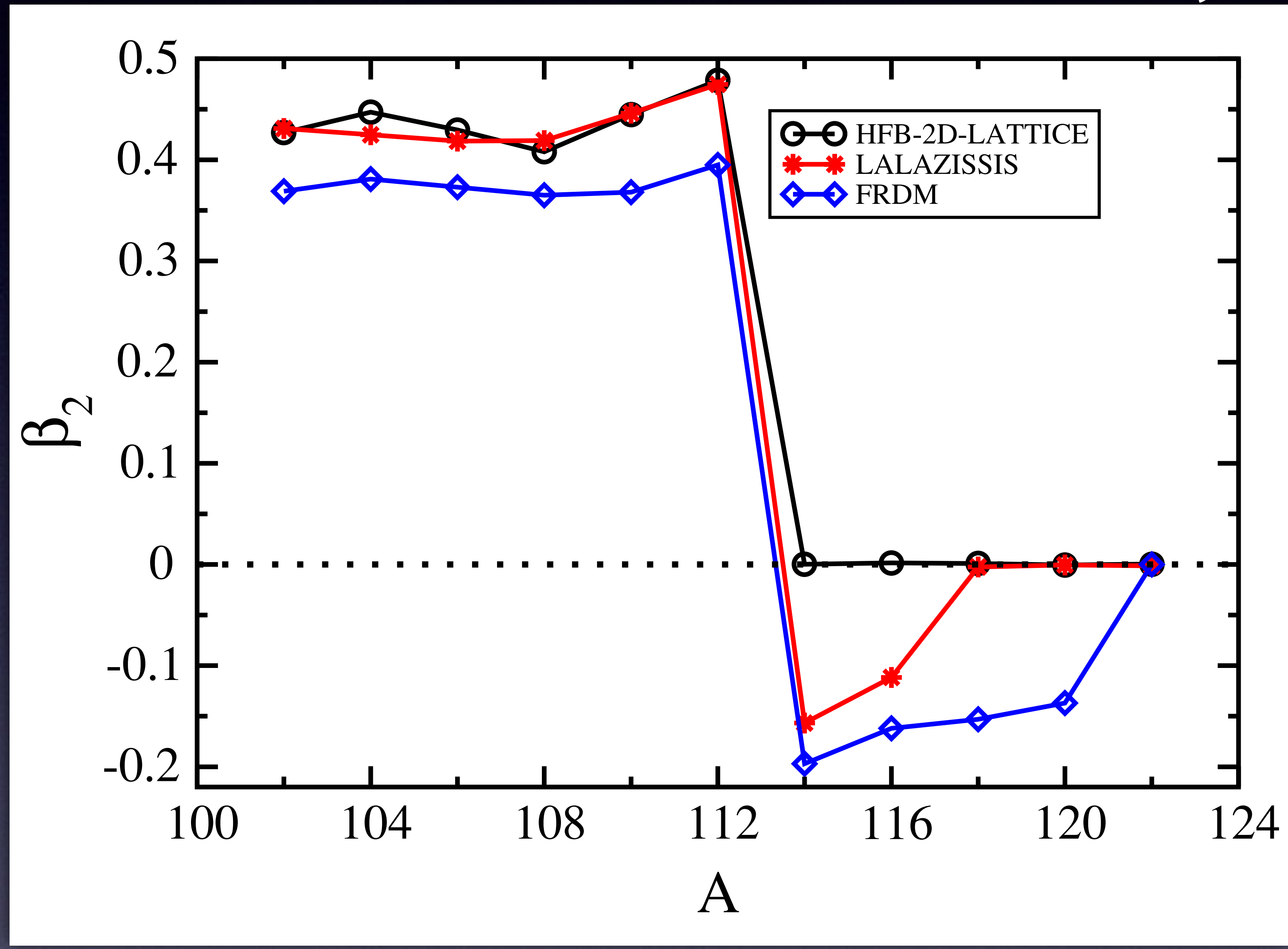
The EDF-based deformed QRPA is a promising tool to investigate/predict the excitation modes of excitation in exotic nuclei.

Highly deformed toward N=72 in the neutron-rich Zr isotopes



$$B(\mathbf{E2}:\mathbf{2}_1^+ \to \mathbf{0}_{\mathbf{gs}}^+) = \frac{Q_0^2}{\mathbf{16}\pi}$$

SLy4



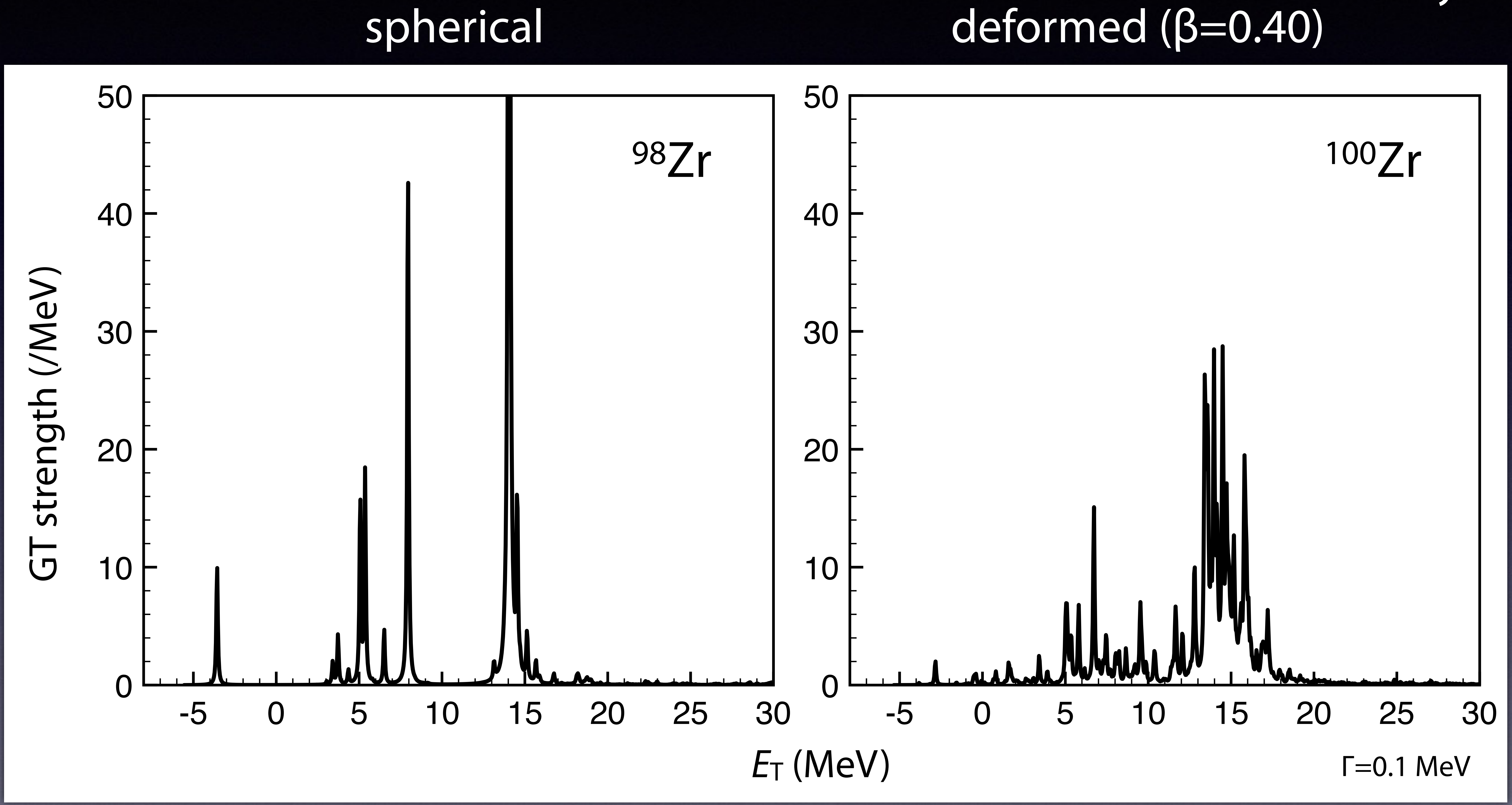
A. Blazkiewski et al., PRC71 (2005) 054321

F. Browne et al., PLB750 (2015) 448

T. Sumikama et al., PRL106 (2011) 202501

Deformation effect on GT strength distributions

SLy4

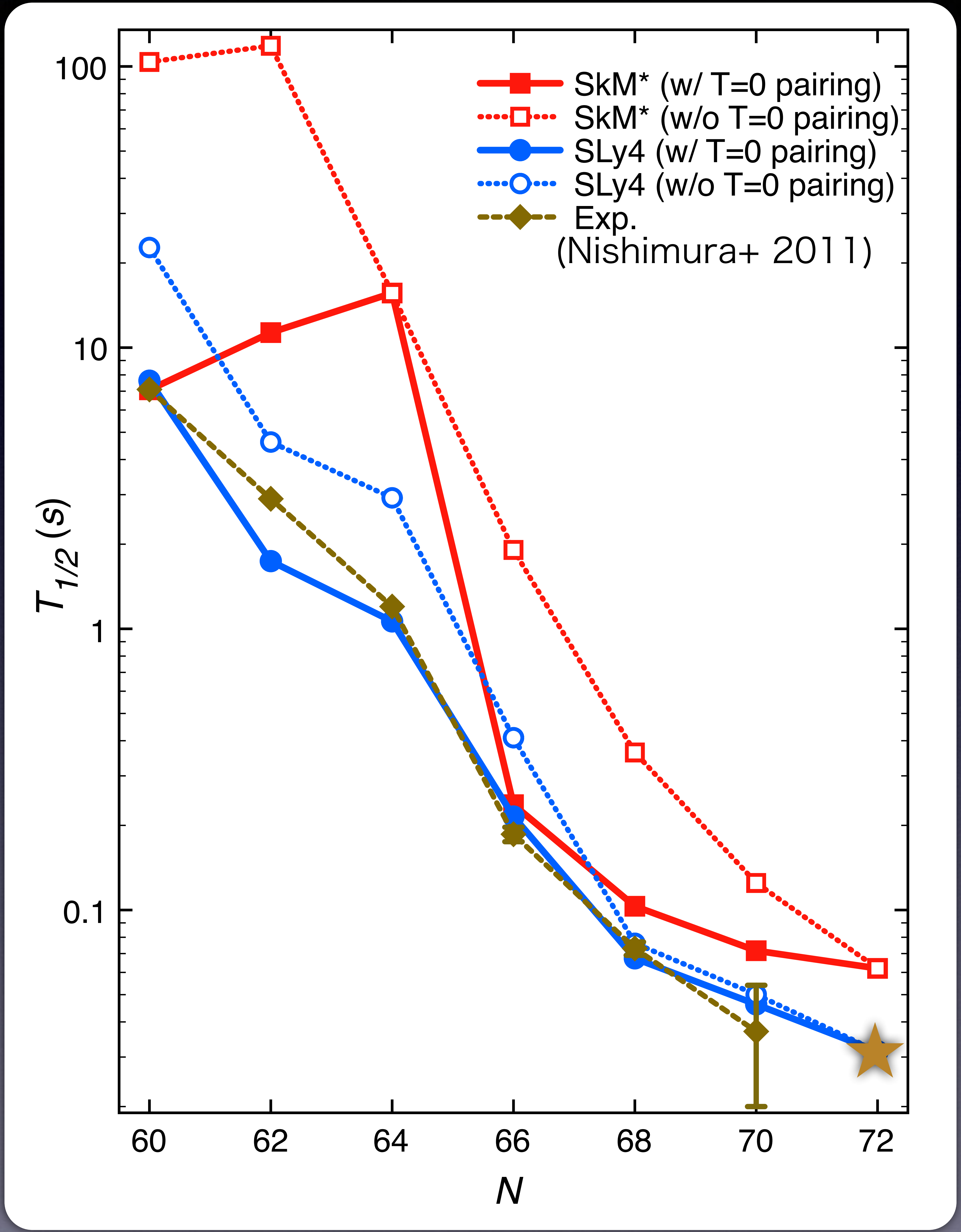


Fragmentation of strengths

GT strength (/MeV)

Beta-decay half-lives of Zr isotopes w/ *T*=0 pairing int.

KY, PTEP (2013) 113D02



✓Strength of *T*=0 pairing determined at *N*=60

SLy4

✓reproduces well the observed isotopic dependence with *T*=0 pairing

✓Effect of the *T*=0 pairing is small beyond *N*=68

SkM*

✓gives a strong deformed gap at *N*=64

Deformed gap at *N*=72

✓pairing correlations inactive

(Lorusso, Nishimura+ 2015)