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Octupole deformation in the nuclear chart based on the three dimensional mean field calculation

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革新的研究開発推進プログラム ImPACT
Impulsing Paradigm Change through Disruptive Technologies Program

Introduction

Main topic: Nuclear Deformation

How to investigate nuclear deformation? There are many aspects for the **Deformation**

Spontaneous symmetry breaking

The spherical symmetry is broken by the correlation between individual particle motions and quantum fluctuations ("single-particle" vs. "collectivity").

S.P. states in deformed mean field

The degeneracy of single-particle states is solved in deformed mean field.

← **Neutron**, **Proton** states in the vicinity of Fermi surface have a key role to define the nuclear shape

Role of Pairing

Amplitude of pairing correlation which is sensitive to the **level density** plays important roles for the shape.

Many kinds of deformation

Quadrupole(prolate, oblate, triaxial), Octupole(l=3,m), Hexadecapole(β_4)

How do we regard the nuclear deformation?

- ■ Rotational bands
- ■ Large quadrupole moment
- ■ Changes of S.P. states
- ■ Isomer in nuclear fission
- □ Changes of reaction cross section(?)

Method S.E. et al., PRC**82**(2010) 034306, N.Tajima, et al., NPA**603** (1996) 23.

Procedure to calculate self-consistent HF+BCS state

Interaction (*ph*) : Skyrme (SkM*),
(*pp*, *hh*) : Constant (monopole)

$$\Delta_k(t) = \sum_{l>0} G_{kl}\kappa_l(t) \qquad G_{kl} = gf(\epsilon_k^0)f(\epsilon_l^0)$$

$f(\epsilon)$: cutoff function

ϵ_k^0 : s.p. energy at g.s.

1, HF calculation : Imaginary-time method

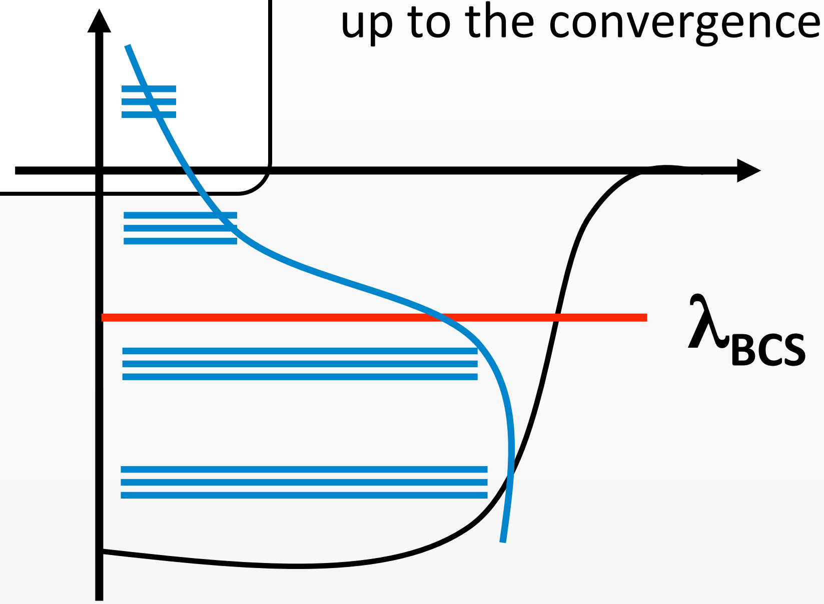
2, Unoccupied states are calculated up to the cutoff energy.

3, Occupation probabilities v_k are evaluated by BCS gap equation.

3', Calculate density including $|v_k|^2$

4, HF+BCS calculation : Imaginary-time method

Iterative calculation up to the convergence



Cutoff Ene.

$$f(\varepsilon) = \left(1 + \exp\left[\frac{\varepsilon - \epsilon_c}{0.5\mathrm{MeV}}\right]\right)^{-1/2} \theta(e_c - \varepsilon)$$

$$\epsilon_c = \tilde{\lambda} + 5.0\mathrm{MeV} \qquad e_c = \epsilon_c + 2.3\mathrm{MeV}$$

Ave. of LUMO & HOMO

Method S.E. et al., PRC**82**(2010) 034306

* This is **NOT** EV8 calculation.

Calculation space for the self-consistent HF+BCS states

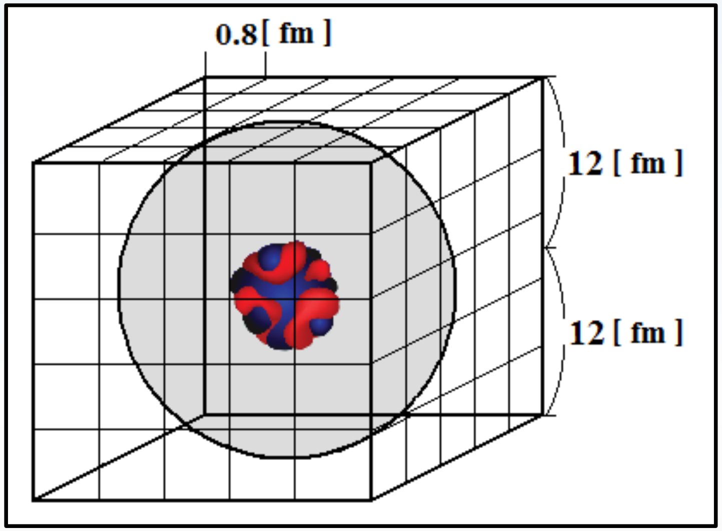
Fully 3D-Spherical meshed box:

Our subject is Nuclear chart. We calculate the even-even nuclei with Z= 6 - 92.

For light nuclei ($6 < Z < 20$),
we use the box has radius **12** [fm] and meshed by **0.8** [fm].

For middle heavy nuclei ($20 < Z < 82$),
we use the box has radius **15** [fm] and meshed by **1.0** [fm].

For heavy nuclei ($82 < Z < 92$),
we use the box has radius **20** [fm] and meshed by **1.0** [fm].



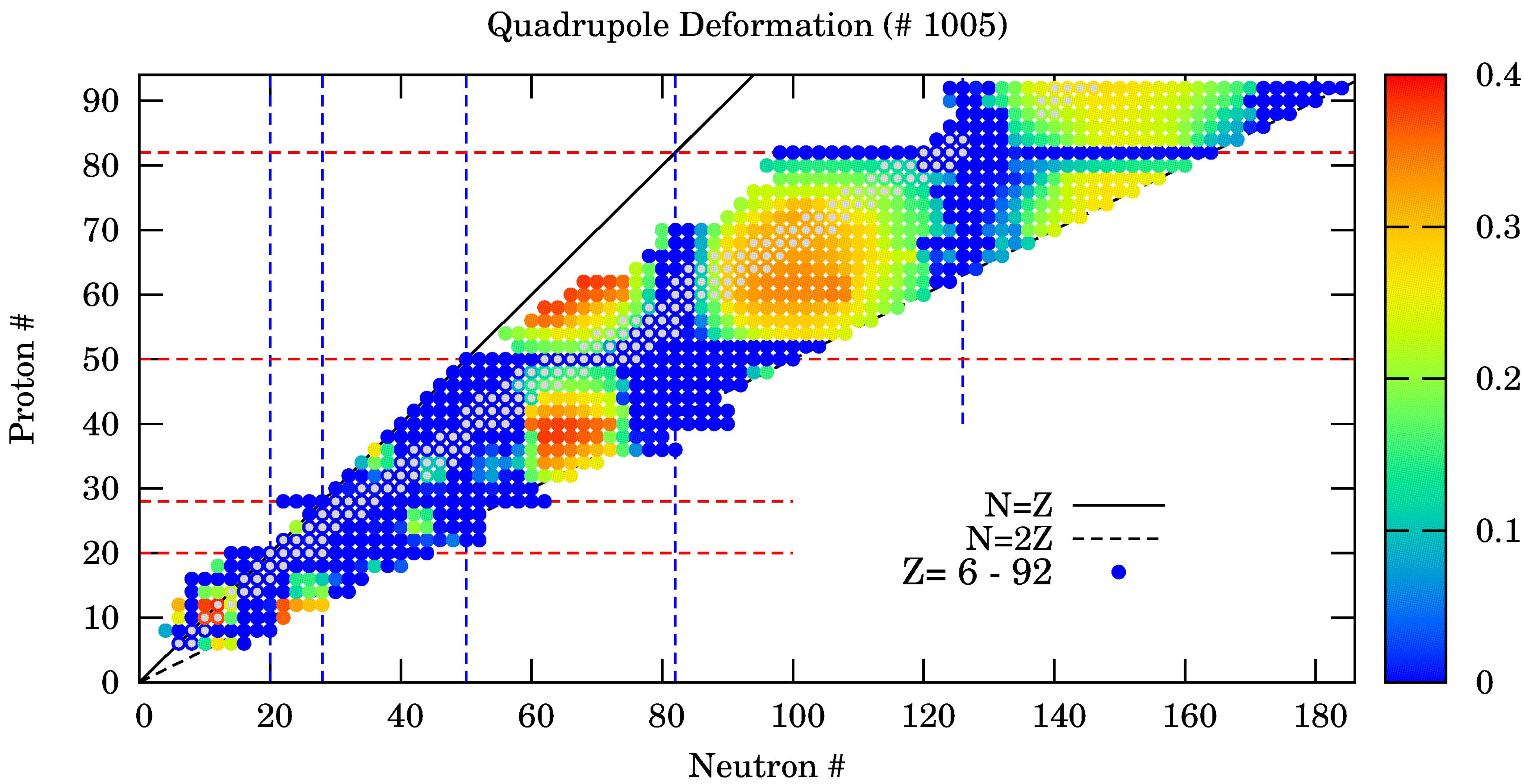
$$\phi_l(\vec{r},\sigma;t) \rightarrow \phi_l(x,y,z,\sigma;t)$$

$$x + y + z \sim 15{,}000 - 32{,}000$$

Each single-particle state has many lattice points to describe.

Results

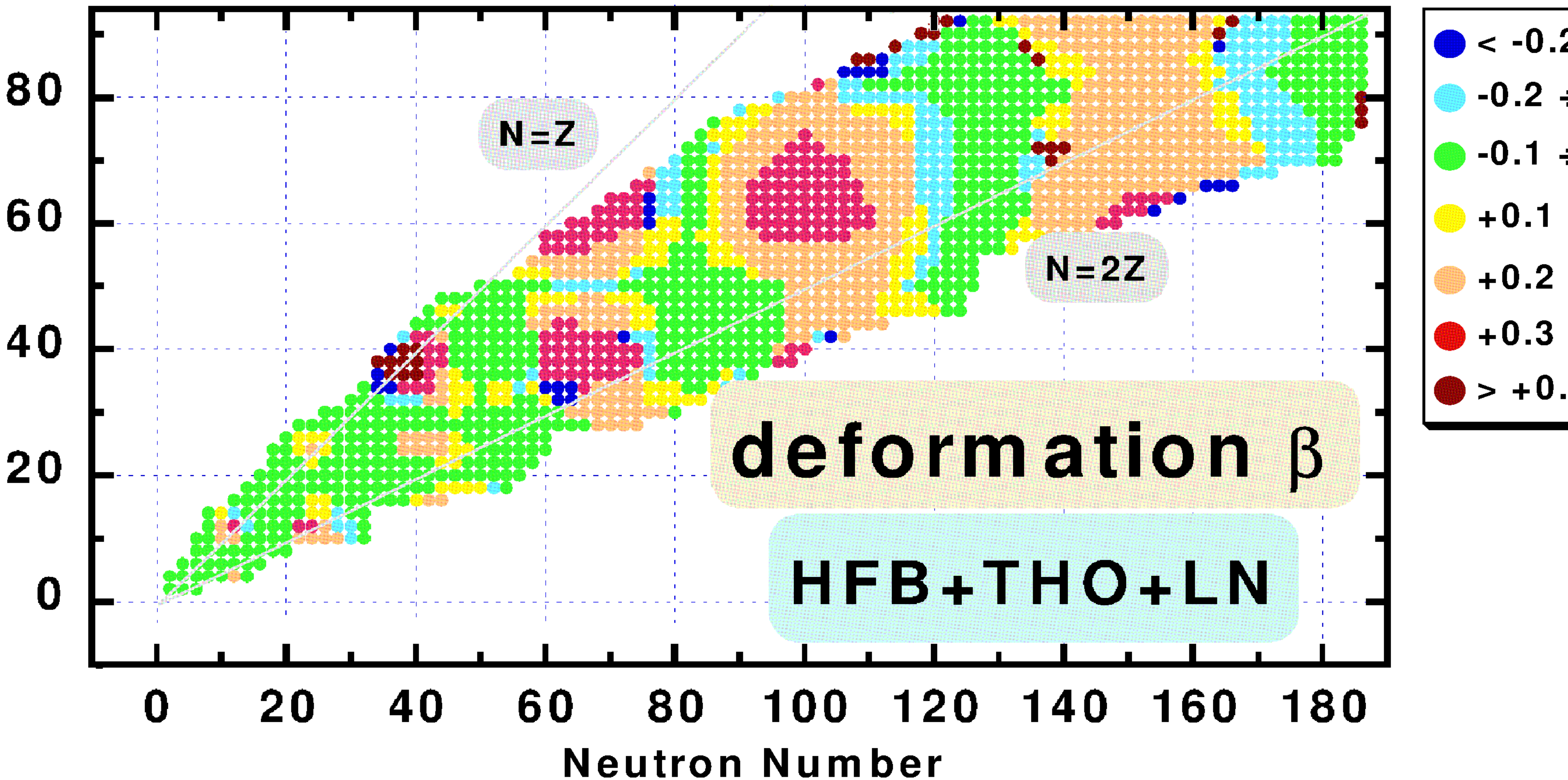
3D HF+BCS Cal. w/ SkM*　　From N=Z to N=2Z, Z=6-92 even-even (Total # 1005)



Comparison

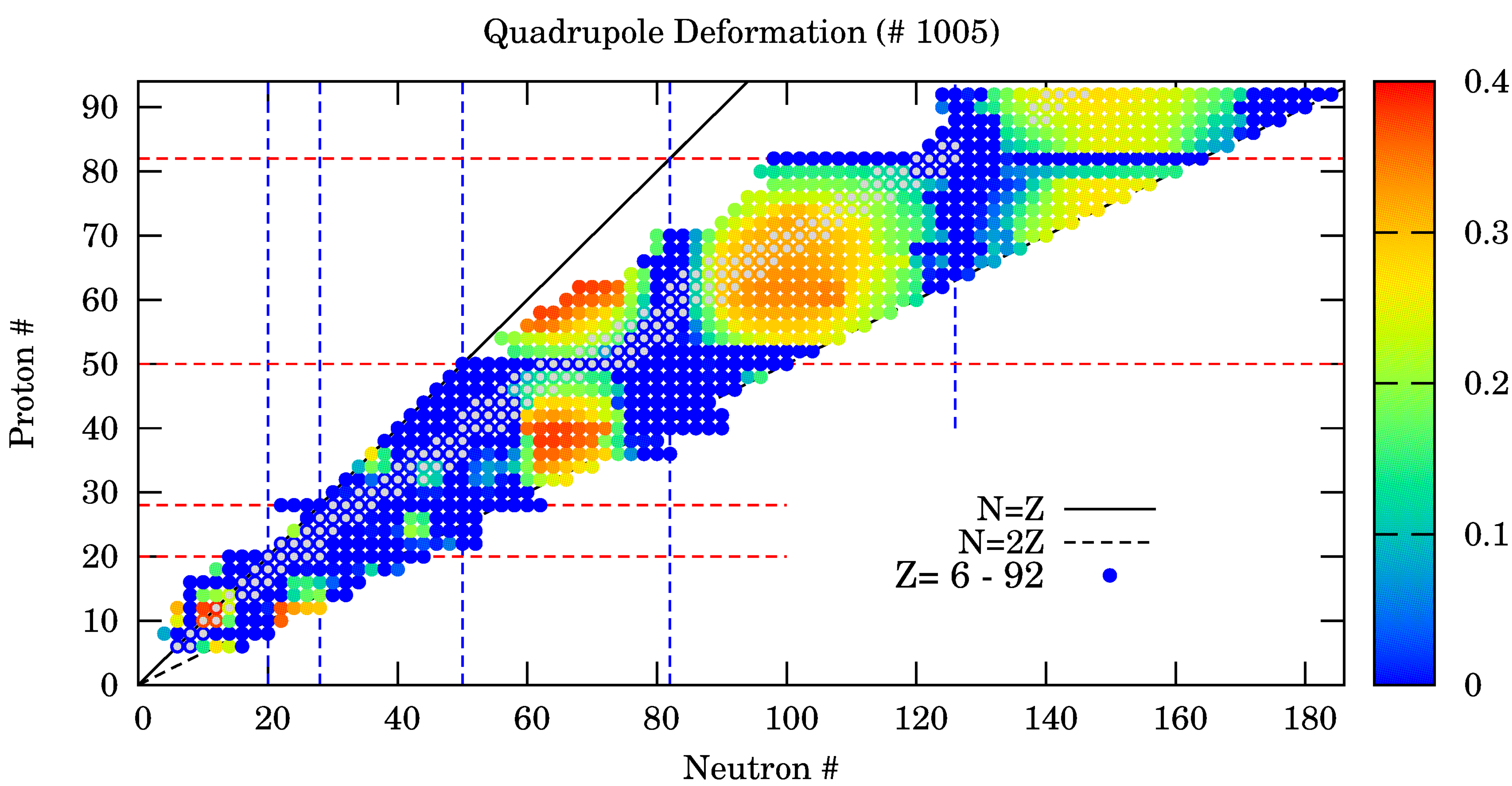
with M. V. Stoitsov, et. al. PRC**68** (2003) 054312

Axial deformed HFB+THO+LN Cal. w/ SkM* + δ -Vol. pairing



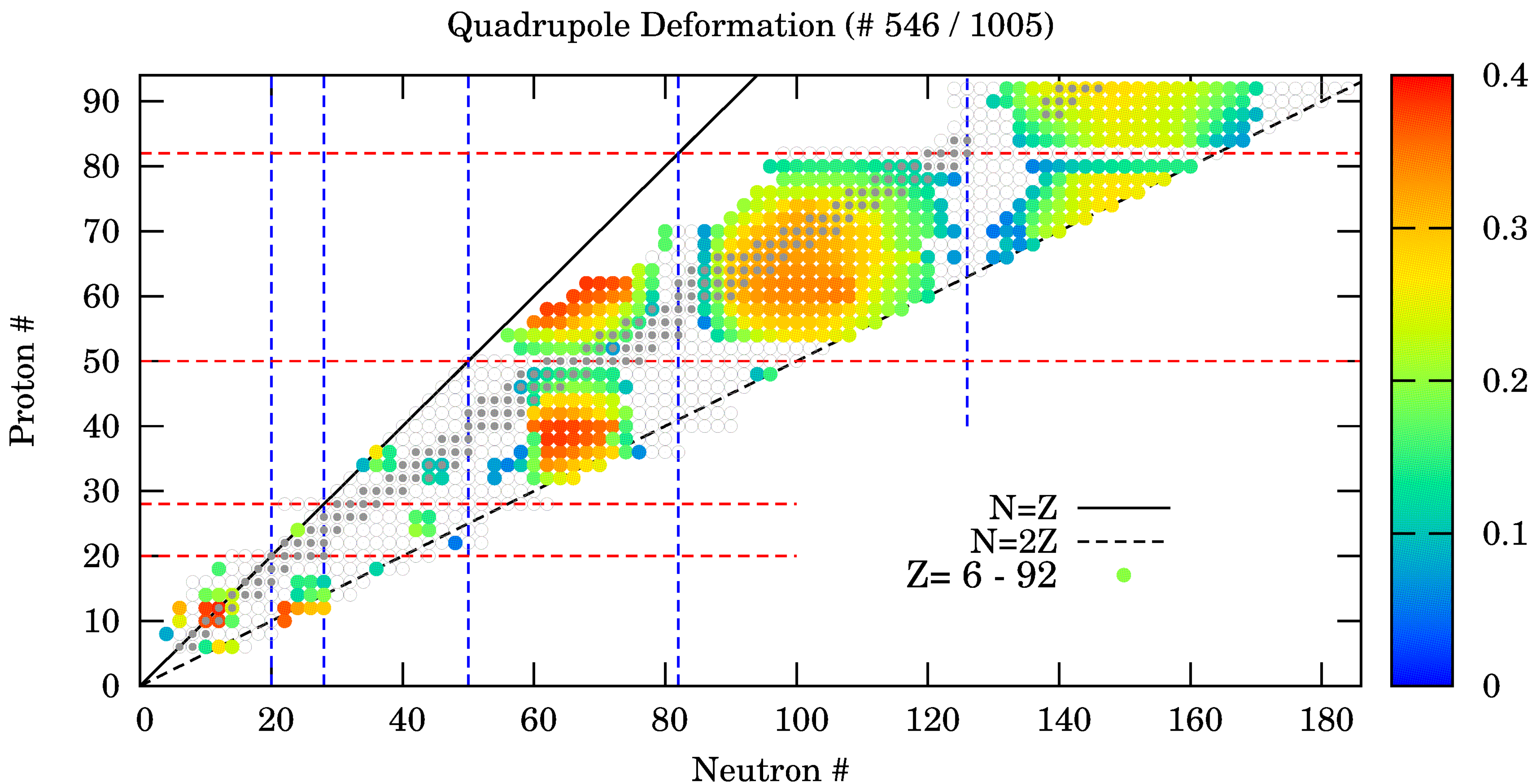
Results

3D HF+BCS Cal. w/ SkM*   From N=Z to N=2Z, Z=6-92 even-even (Total # 1005)



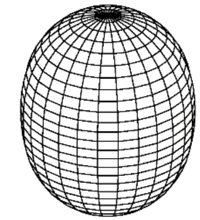
Results (Deformed)

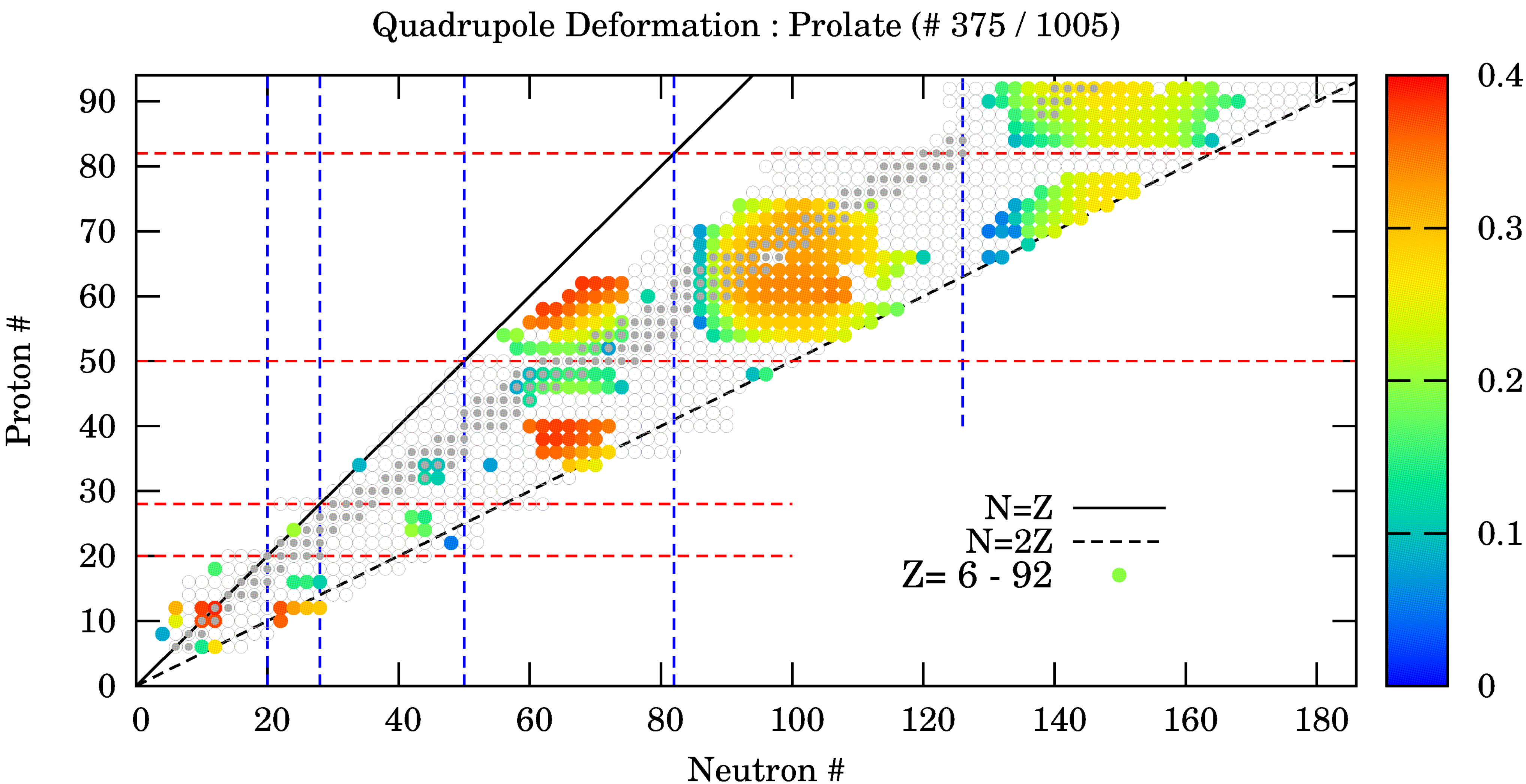
3D HF+BCS Cal. w/ SkM* Deformed nuclei: $|\beta_2| > 0.05$



Results (Deformed: prolate)

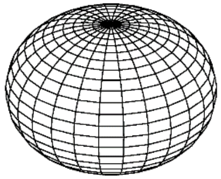
3D HF+BCS Cal. w/ SkM*   Deformed nuclei: $|\beta_2| > 0.05$, $\gamma < 1.5^\circ$

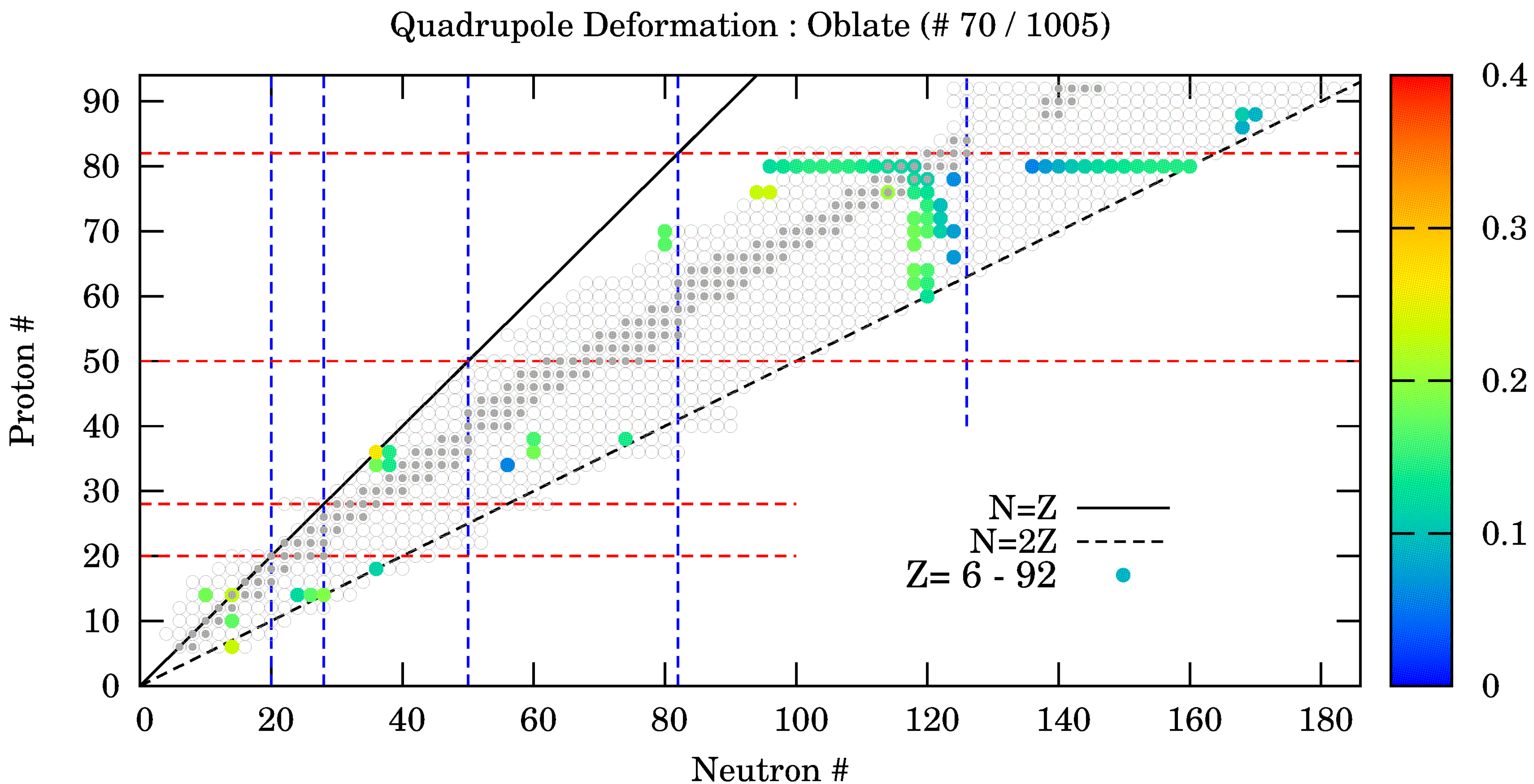




Results (Deformed: oblate)

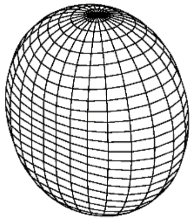
3D HF+BCS Cal. w/ SkM*　　Deformed nuclei: $|\beta_2| > 0.05$, $58.5^o < \gamma < 60°$

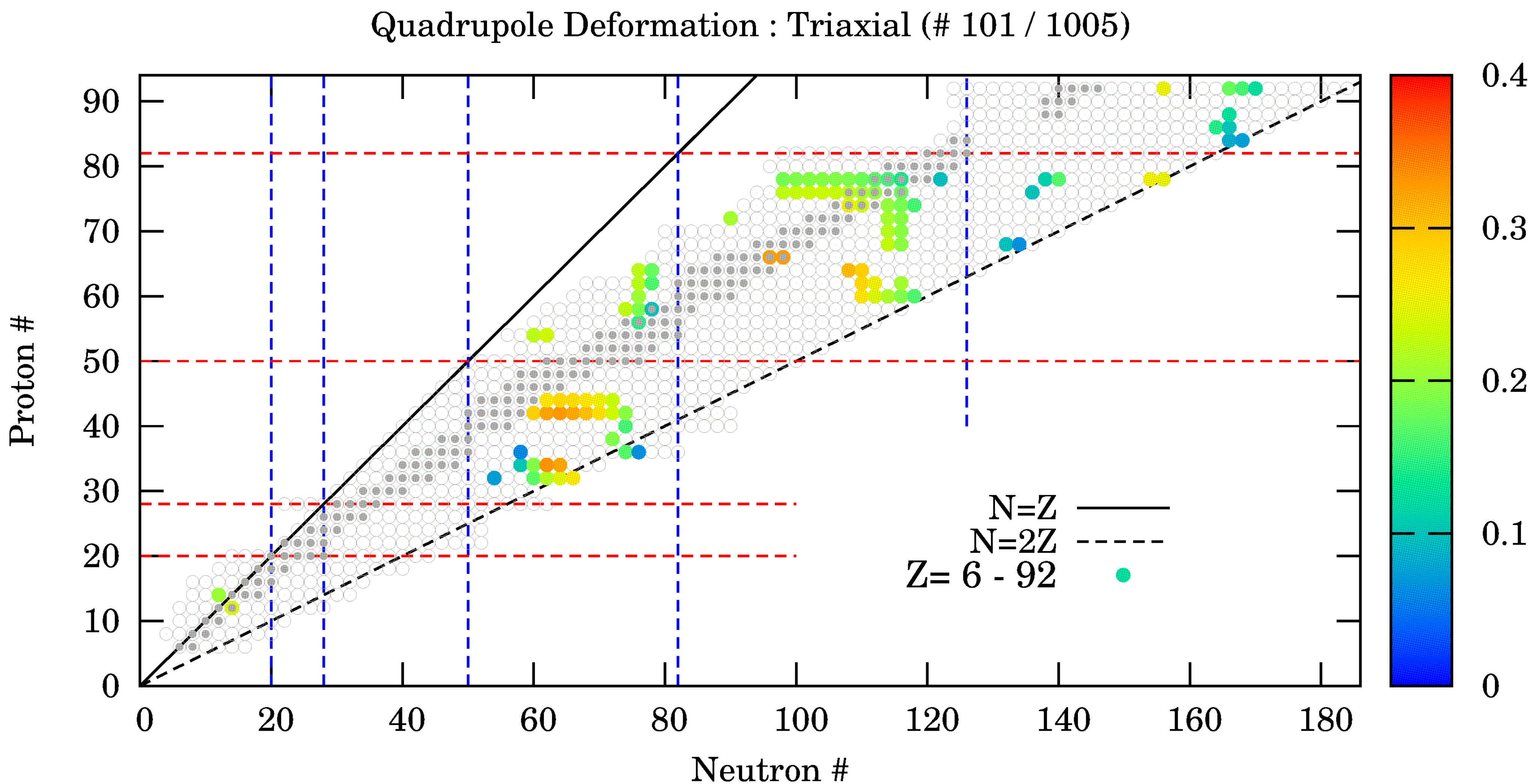




Results (Deformed: triaxial)

3D HF+BCS Cal. w/ SkM*   Deformed nuclei: $|\beta_2| > 0.05$, $1.5^\circ < \gamma < 58.5^\circ$





Results (octupole)

3D HF+BCS Cal. w/ SkM* can describe octupole moments in the ground state.

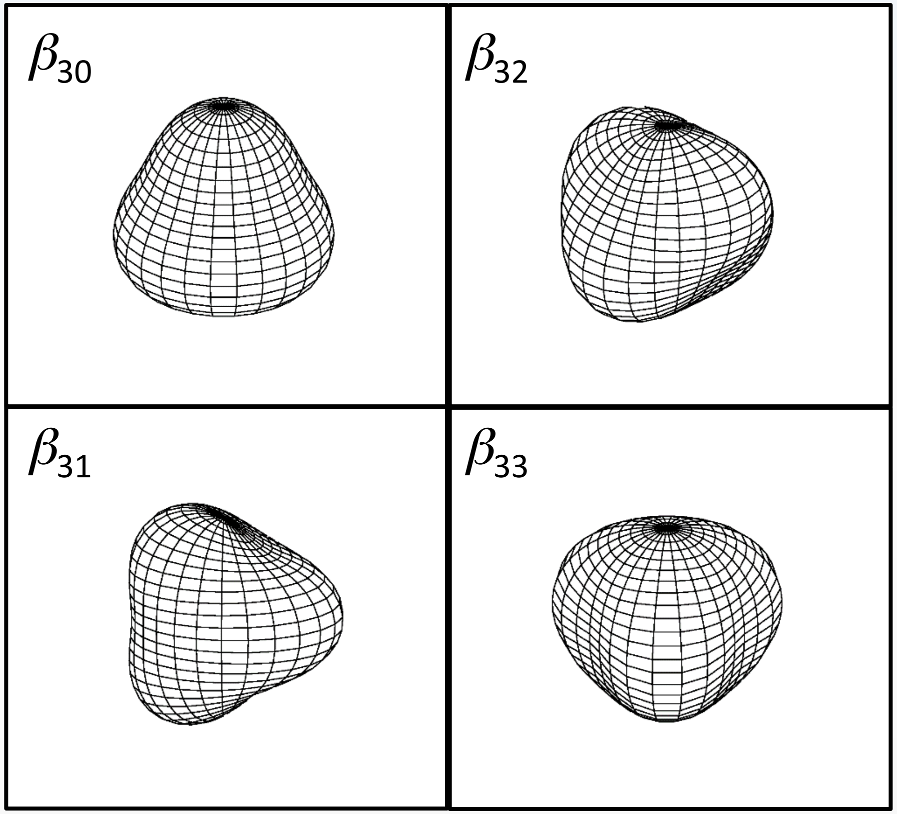
The octupole deformation parameter is defined using the axis of rotational symmetry.

(<Q22> = <xy-yx> = 0 → z is regarded as the axial symmetric axis.)

Octupole deformation parameter β_3, β_{3m}

$$\beta_3 = \left(\sum_{m=-3}^{3} \alpha_{3m}^2 \right)^{1/2}$$

$$\beta_{3m} = (\alpha_{3m}^2 + \alpha_{3-m}^2)^{1/2}$$



The mass-multipole moment

$$\alpha_{lm} \equiv \frac{4\pi}{3A\bar{R}^l} \int r^l X_{lm}(\Omega)\rho(r)d\boldsymbol{r}$$

$$\bar{R} = \sqrt{5\langle \sum_{i=1}^{A} r_i^2 \rangle / 3A}$$

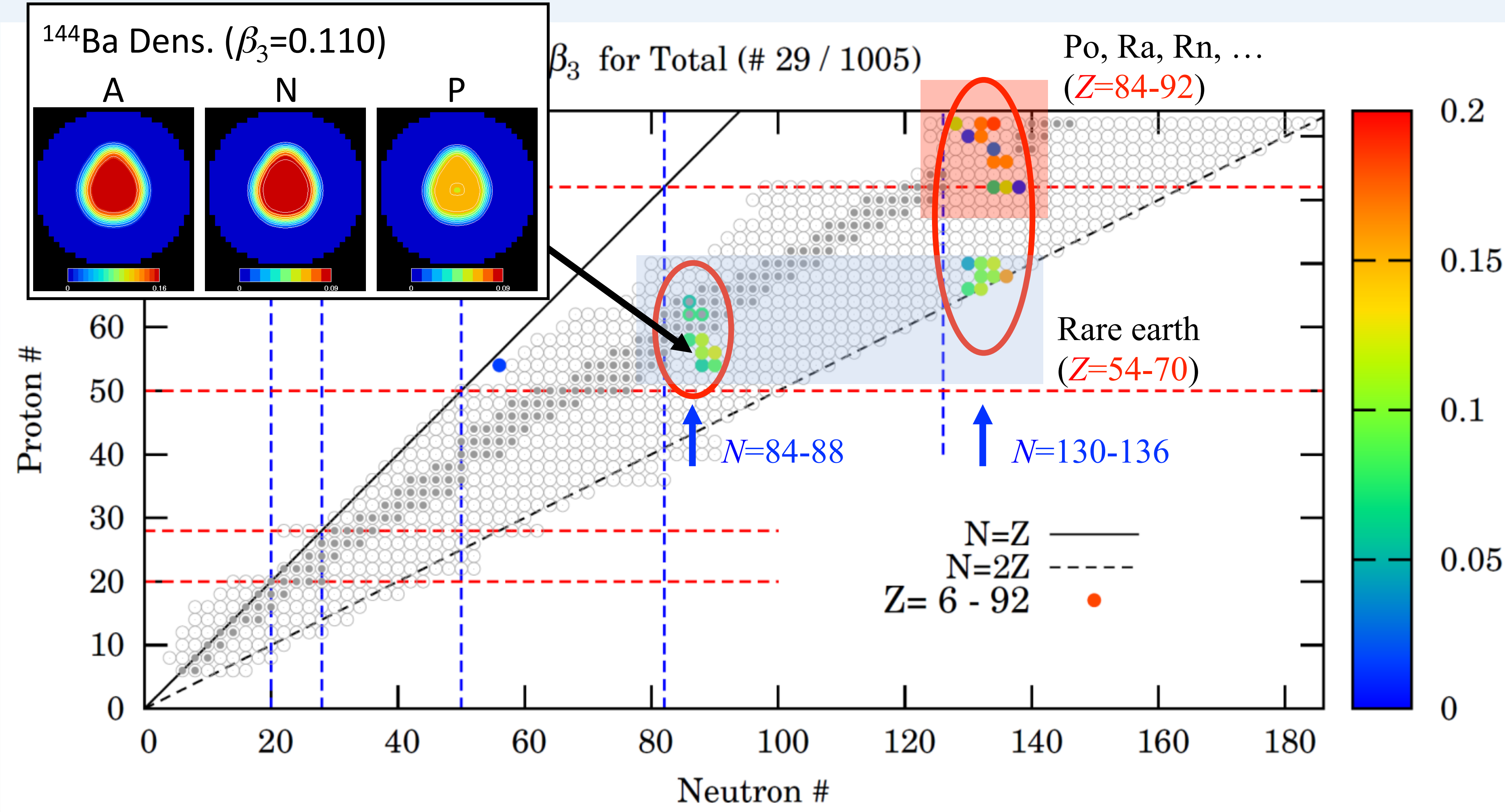
$$X_{l0} = Y_{l0}$$

$$X_{lm} = \frac{1}{\sqrt{2}}(Y_{l-|m|} + Y_{l-|m|}^*)$$

$$X_{l-|m|} = \frac{-i}{\sqrt{2}}(Y_{l|m|} - Y_{l|m|}^*)$$

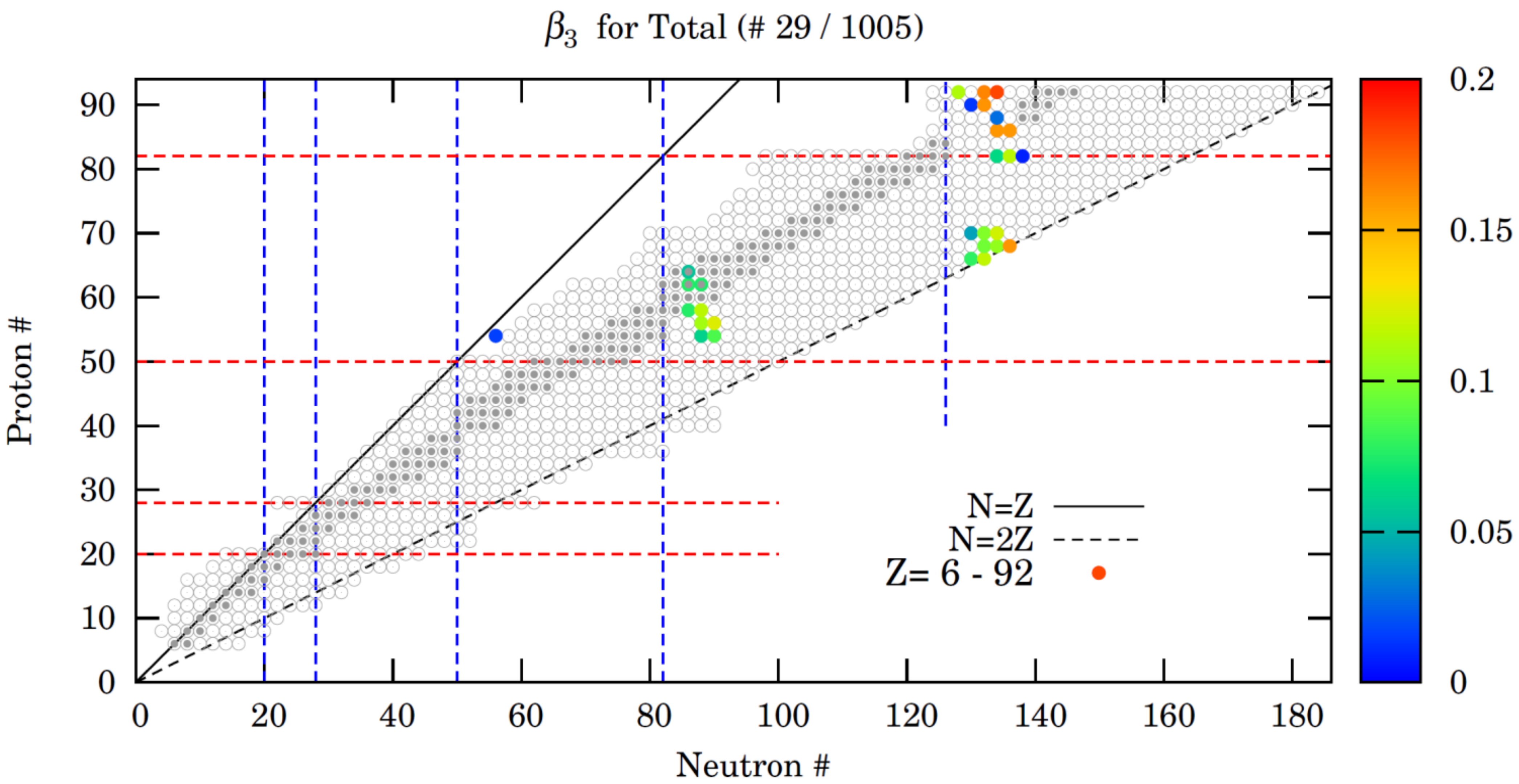
Results (Deformed: octupole)

3D HF+BCS Cal. w/ SkM* Octupole deformed nuclei: $|\beta_3| > 0.01$



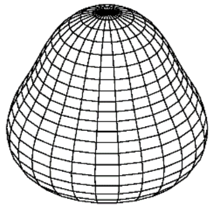
Results (Deformed: octupole)

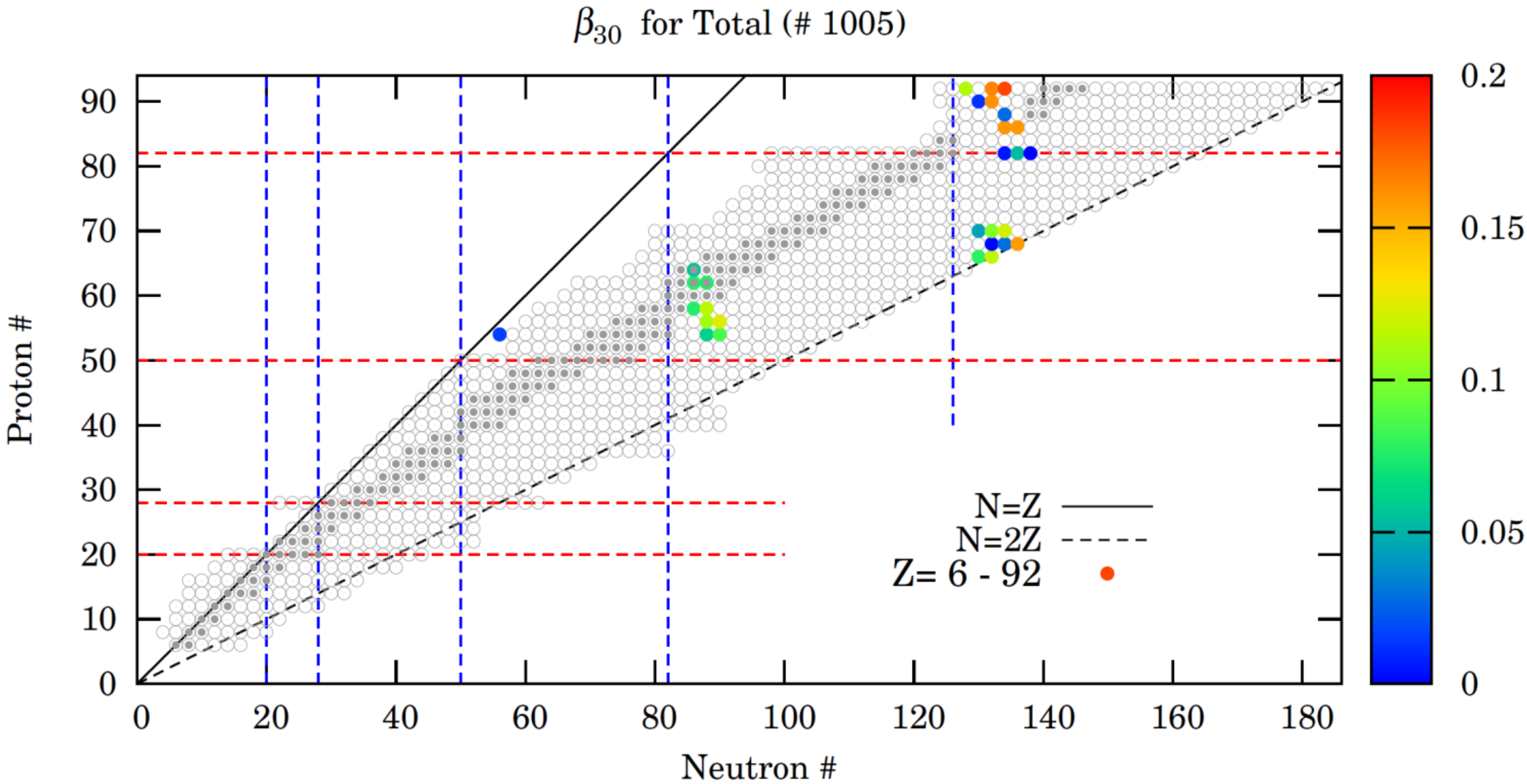
3D HF+BCS Cal. w/ SkM* Octupole deformed nuclei: $|\beta_3| > 0.01$



Results (Deformed: octupole β_{30})

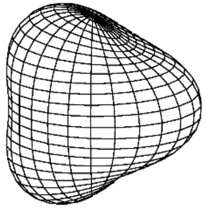
3D HF+BCS Cal. w/ SkM* Octupole deformed nuclei: $|\beta_3| > 0.01$

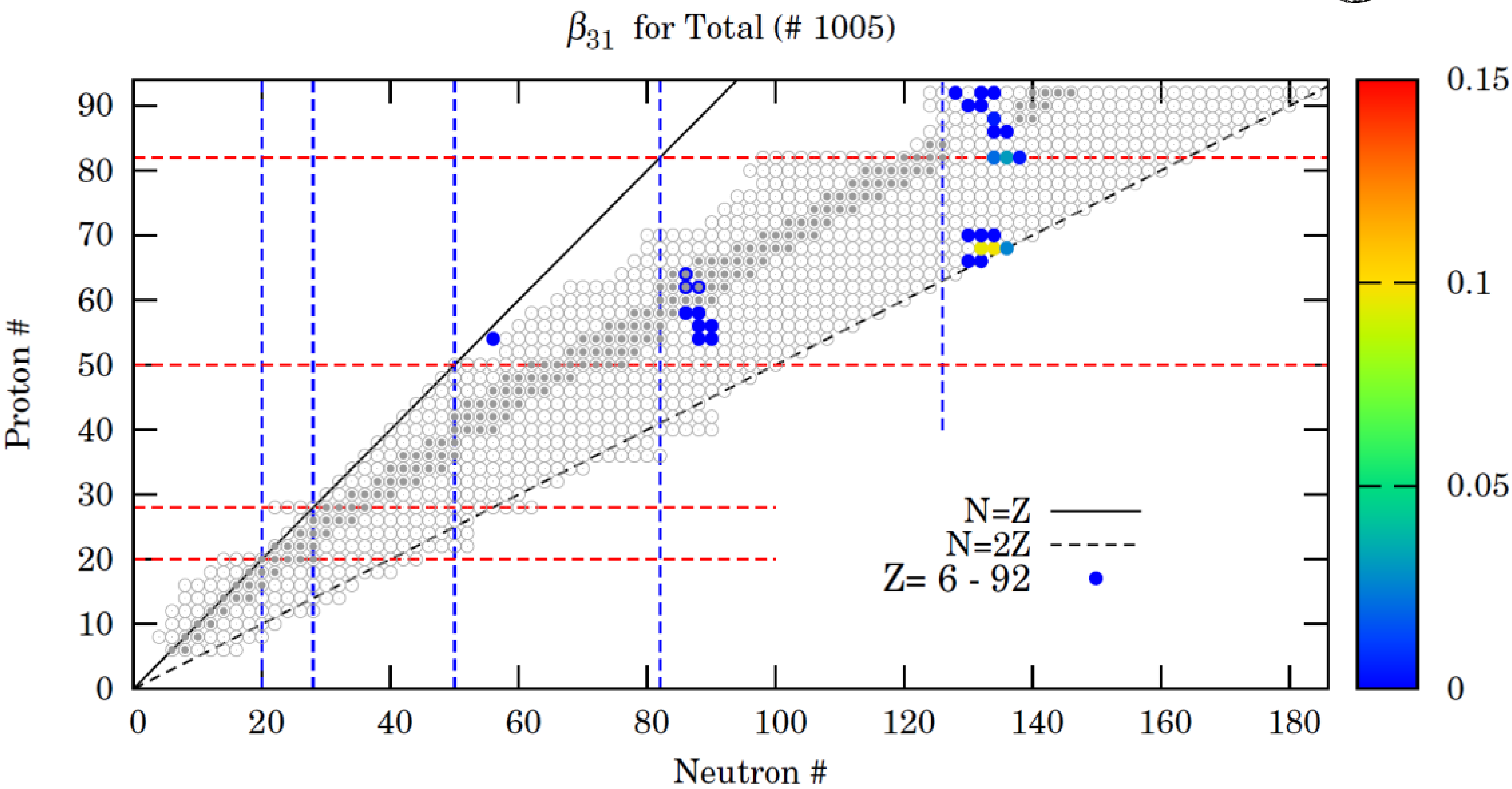




Results (Deformed: octupole β_{31})

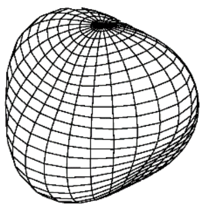
3D HF+BCS Cal. w/ SkM* Octupole deformed nuclei: $|\beta_3| > 0.01$

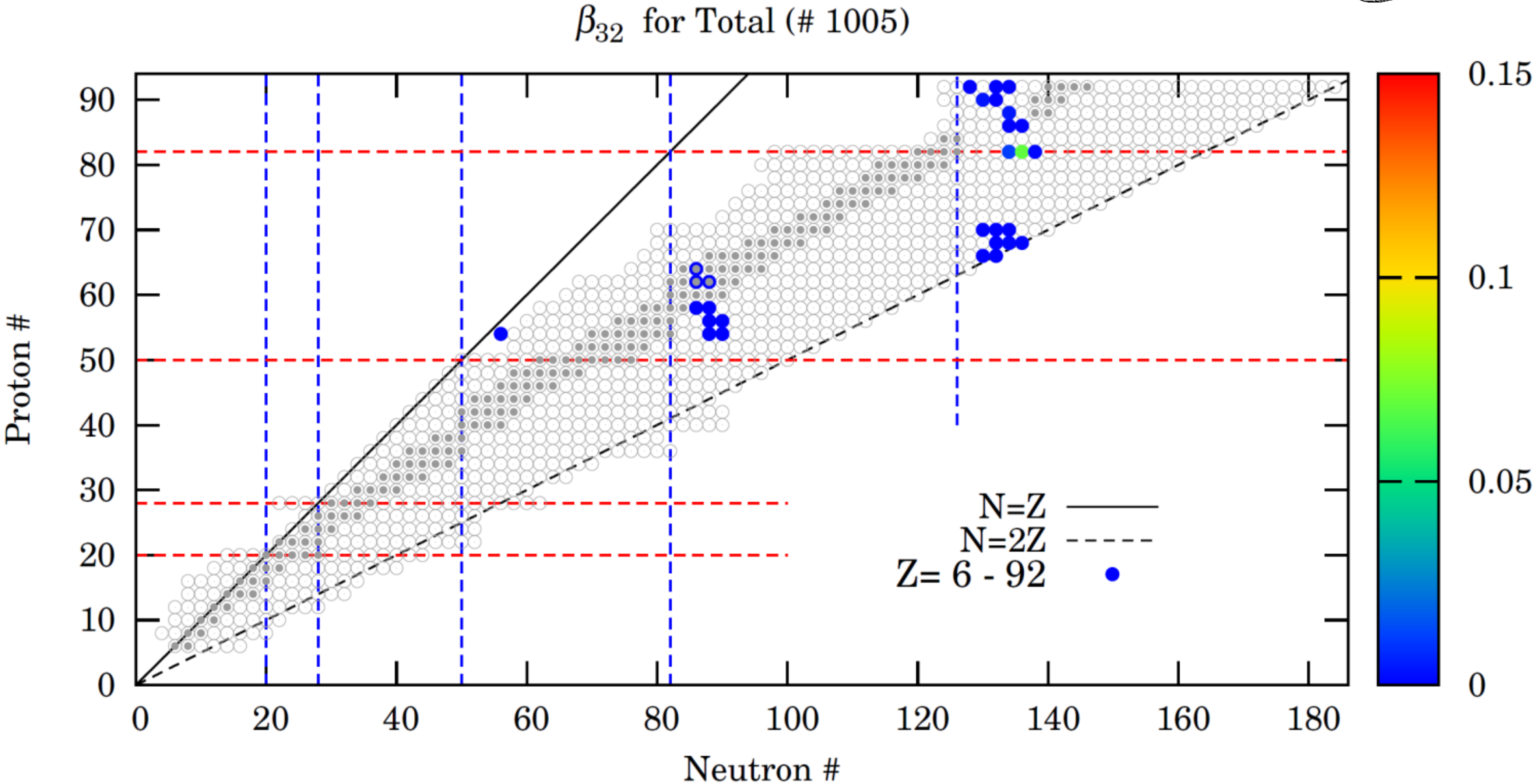




Results (Deformed: octupole β_{32})

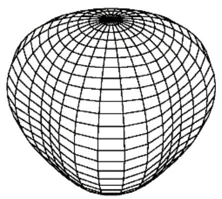
3D HF+BCS Cal. w/ SkM*   Octupole deformed nuclei: $|\beta_3| > 0.01$

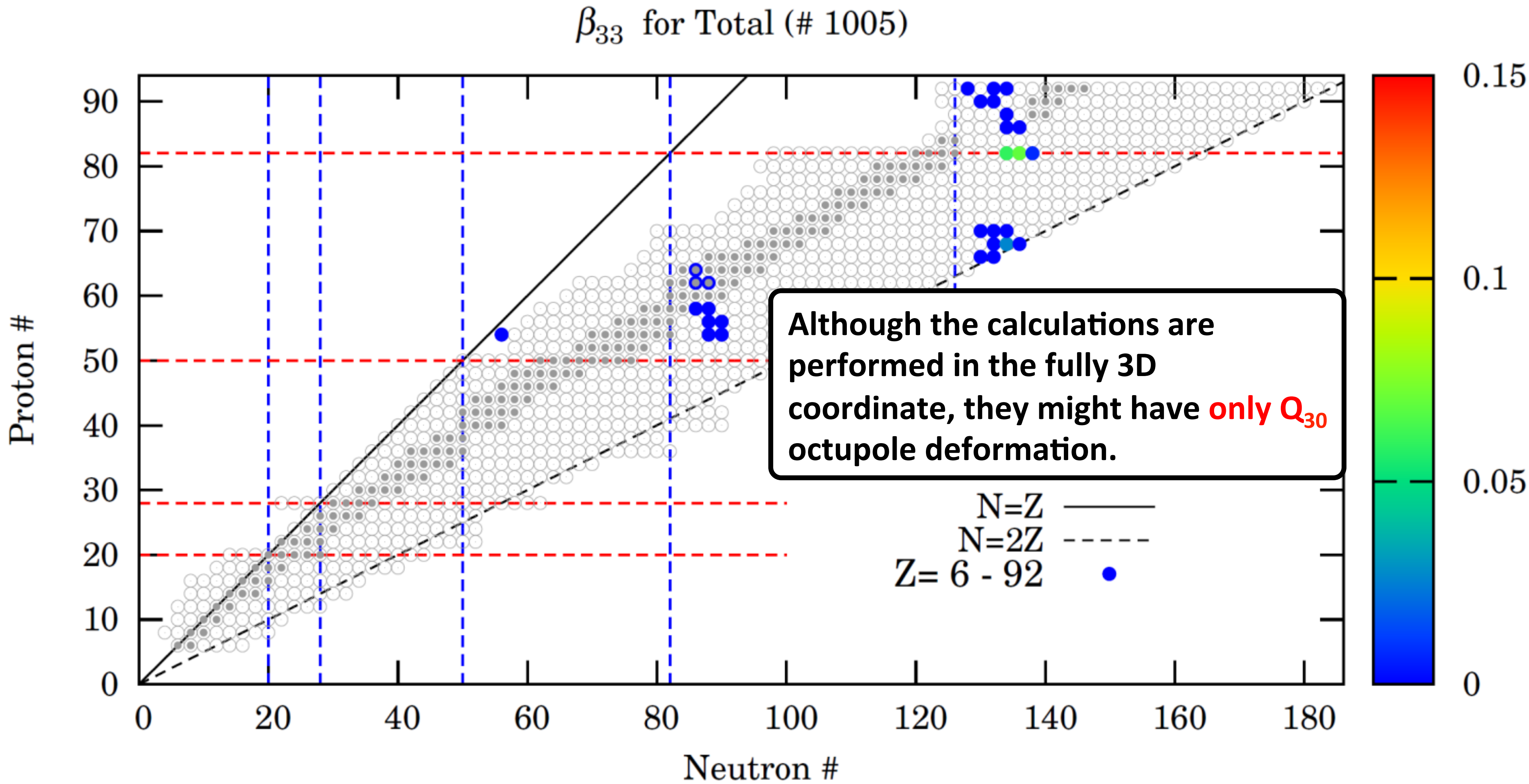




Results (Deformed: octupole β_{33})

3D HF+BCS Cal. w/ SkM*   Octupole deformed nuclei: $|\beta_3| > 0.01$

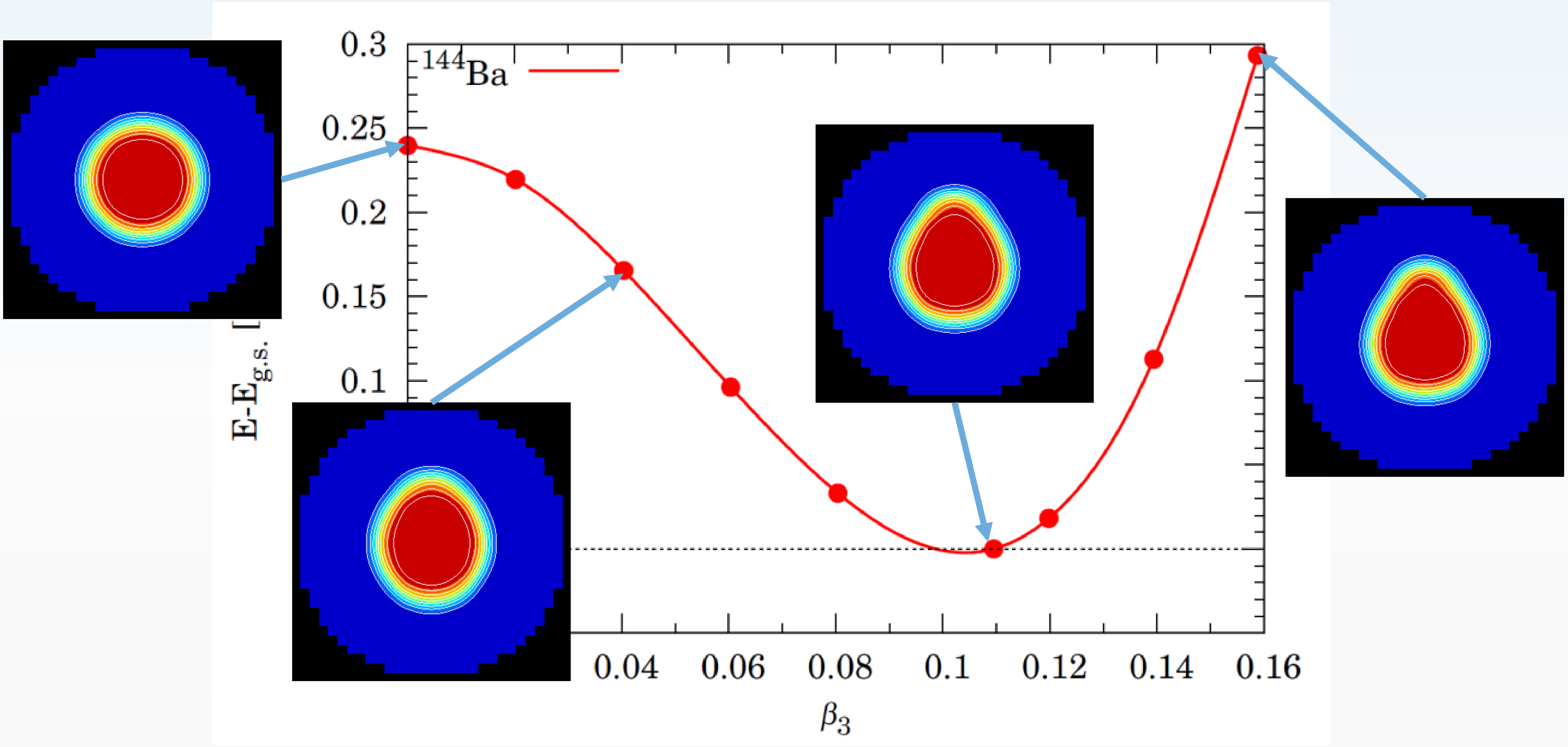




Although the calculations are performed in the fully 3D coordinate, they might have only Q_{30} octupole deformation.

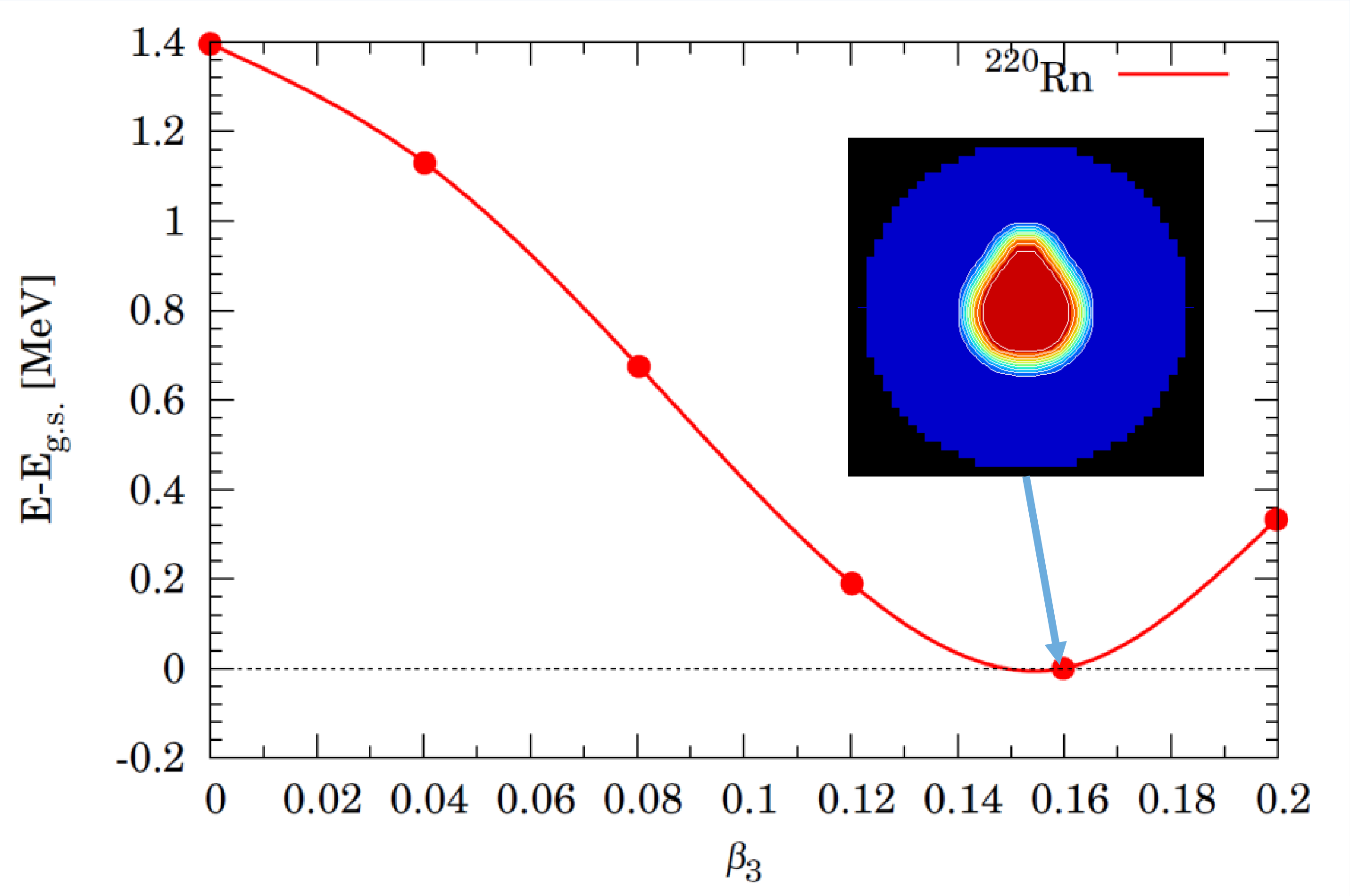
Results (Octupole correlations: ^{144}Ba) Skyrme HF + BCS + Constraints

W/ Q_{30} constraints



Results (Octupole correlations: ^{220}Rn) Skyrme HF + BCS + Constraints

W/ Q_{30} constraints



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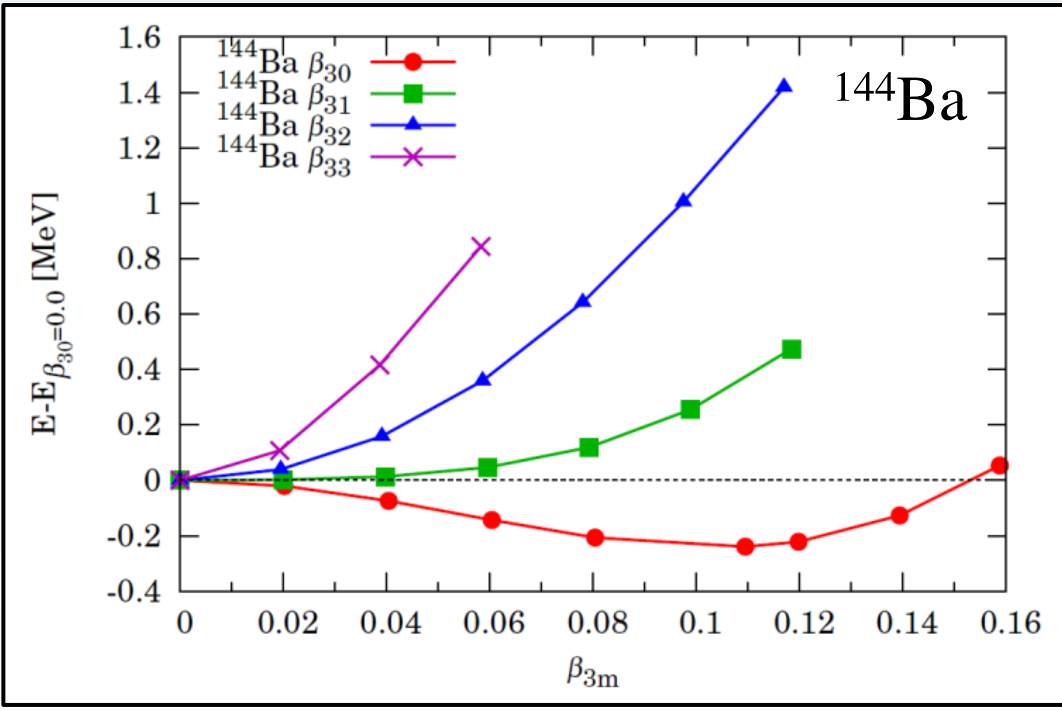
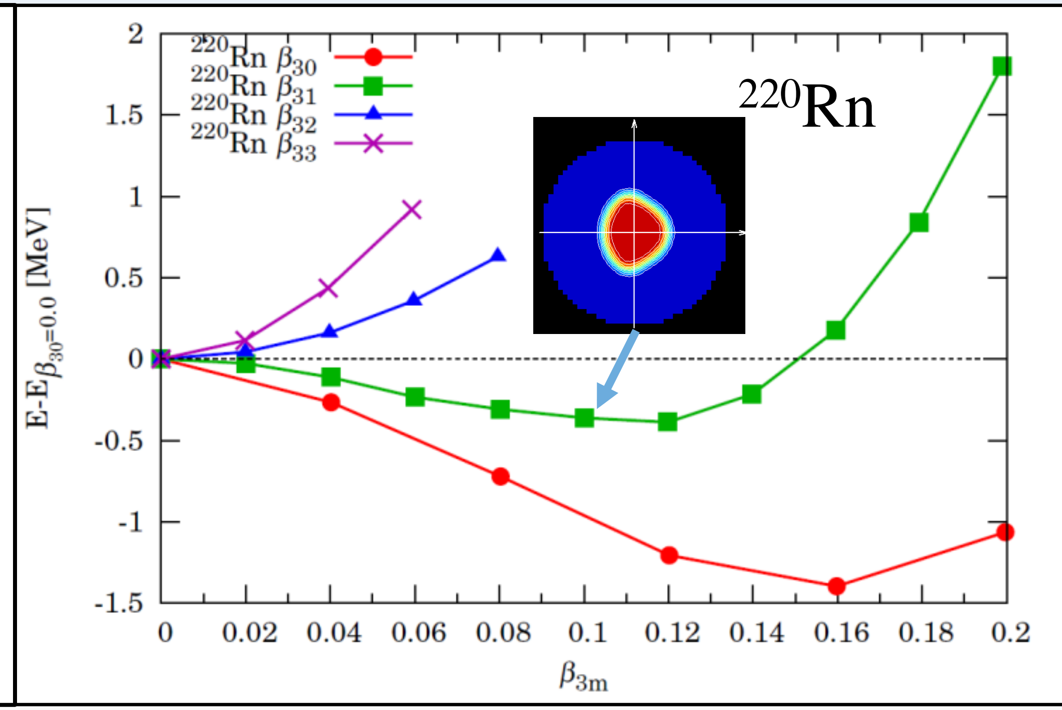
Results (β_{30} vs. β_{31} vs. β_{32} vs. β_{33} : ^{144}Ba, ^{220}Rn) Skyrme HF + BCS + Constraints

w/ Q_{3m} constraints



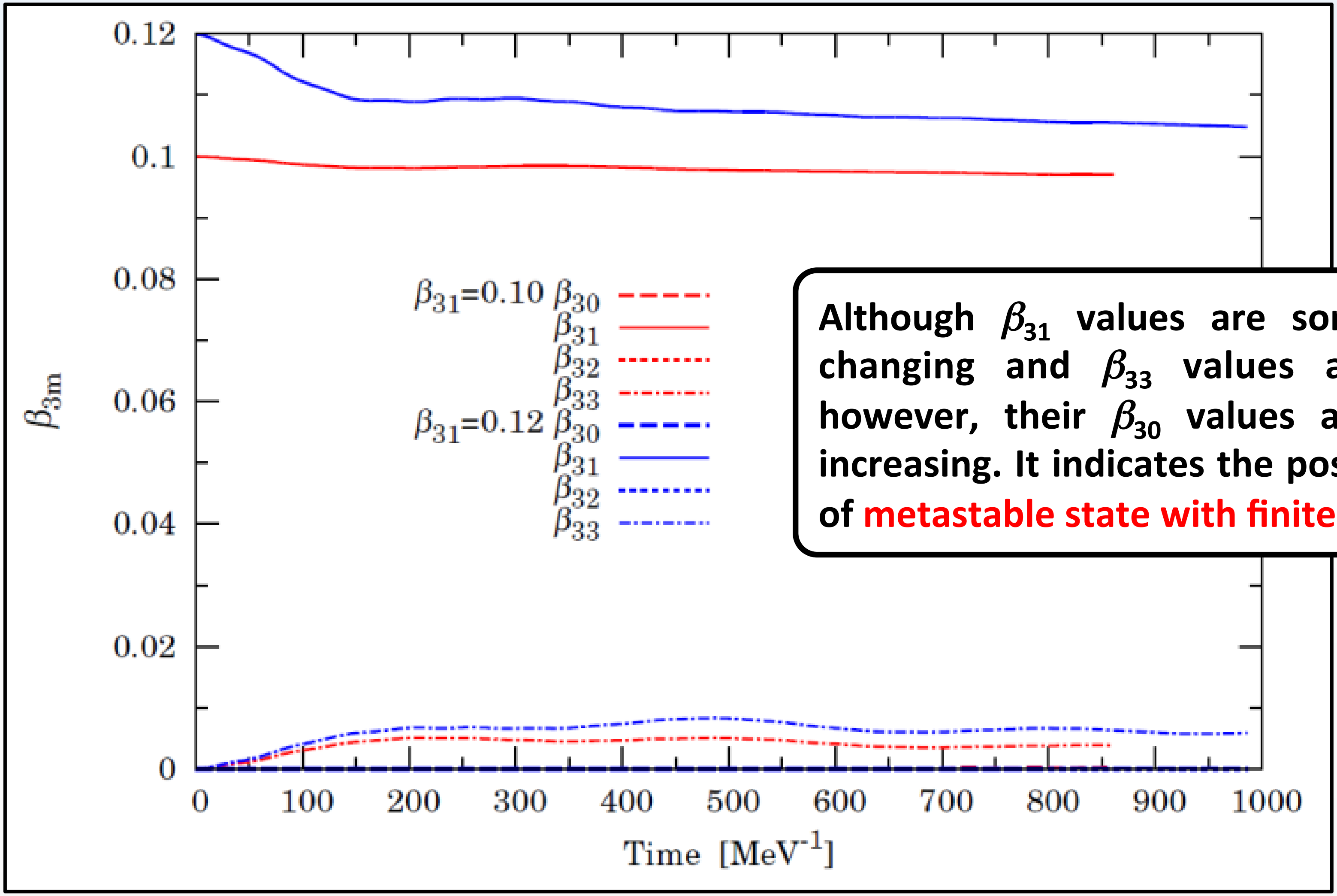


In both, β_{30} is lowest in the energy surface under the octupole constraints.

In this work, ^{144}Ba does not have local minimum on the β_{31}, β_{32} and β_{33} surfaces. Although we need more investigation, ^{220}Rn has some possibility of a local minimum on the β_{31} energy surface.

Results (check the pocket of β_{31} : ^{220}Rn)

Using real-time evolution (w/ Cb-TDHFB), check the stability of β_{31} potential pocket.



Although β_{31} values are somehow changing and β_{33} values appear, however, their β_{30} values are not increasing. It indicates the possibility of metastable state with finite β_{31}.

Summary

- ✓ We investigate the ground states for even-even nuclei in the nuclear chart by 3D HF+BCS. We found about 54% deformed nuclide in the chart.
- ✓ In the quadrupole deformed nuclei, the Prolate nuclei is 70%, Oblate is 12%, and Triaxial is 18%. We found the Prolate dominance.
- ✓ The nuclei with **octupole deformation** in their ground states are found (about 30 nuclei). They appear in the mass region with ***Z*=54-70, 86-92** **and** ***N*=86-90, 130-138,** which is consistent to the region of **Δl=3 correlation.** They might appear only with the correlations in both ***proton*** and ***neutron***.
- ✓ The octupole deformed nuclei might have **only pear shape** (Q_{30} type), although this work are performed in the 3D coordinate.
- ✓ We investigate octupole correlations in ^{144}Ba and ^{220}Rn using **multi-constraints** for Q_{30}, Q_{31}, Q_{32}, and Q_{33}. **^{220}Rn metastable state might be indicated in Q_{31}**.

Remains to do …

- Stable calculation for octupole deformed nuclei
- Parity projection
- Octupole correlation strength
  - Relation between deformed nuclei region and pairing strength
  - Space between single-particle orbits

Thank you !