Super- and hyperheavy nuclei in covariant density functional theory: recent results

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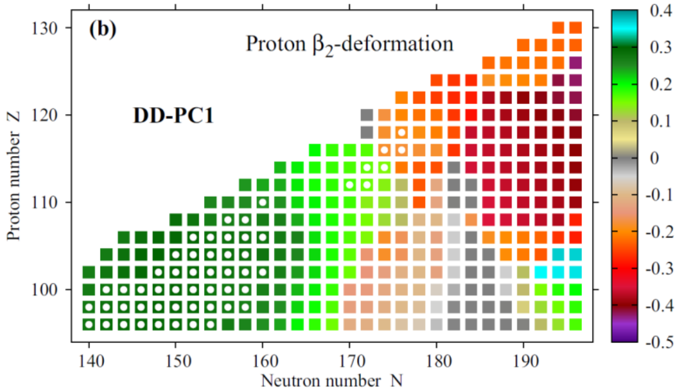
1. Motivation
2. Superheavy nuclei: impact of beyond mean field correlations on ground states and fission properties.
3. Hyperheavy (Z>126) nuclei: exploring the limits of nuclear landscape at extreme Z values
4. Conclusions

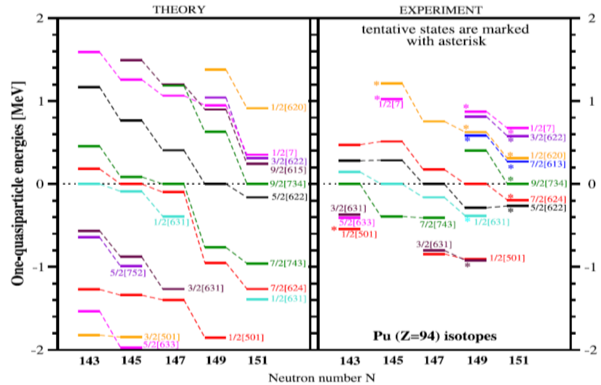
In collaboration with S. Abgemava (MSU), A. Gyawali (MSU), A.Taninah (MSU), P. Ring (TU Munich, Germany) T. Nakatsukasa (Univ. of Tsukuba, Japan), Z. Shi (Beihang U, China), Z. Li (Southwest U, China) and Jie Meng (Peking U, China)

Overview of the CDFT studies in actinides/superheavy nuclei

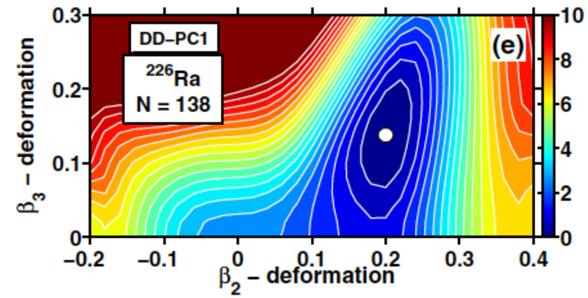
Ground states properties:
PRC 67, 024309 (2003),
PRC 89, 054320 (2014),
PRC 92, 054310 (2015)

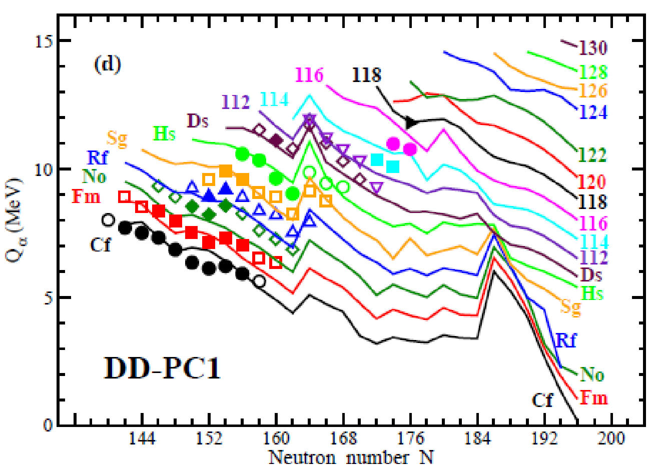


Single-particle properties:
PRC 67, 024309 (2003), PLB 706, 177 (2011), NPA 944, 388 (2015)

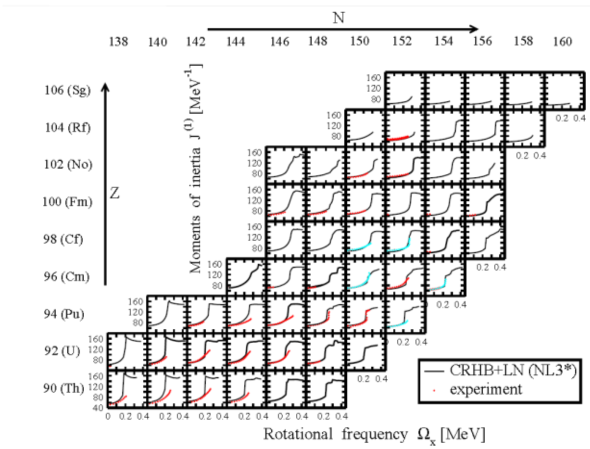


Octupole deformation:
PRC 93, 044304 (2016),
PRC 96, 024301 (2017)

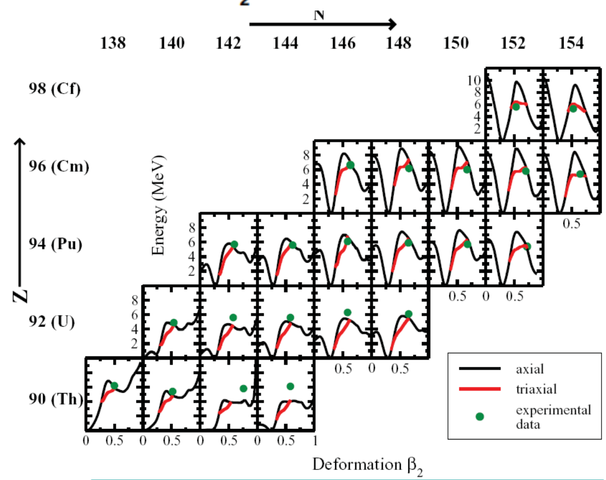




α-decay properties:
PRC 92, 054310 (2015)

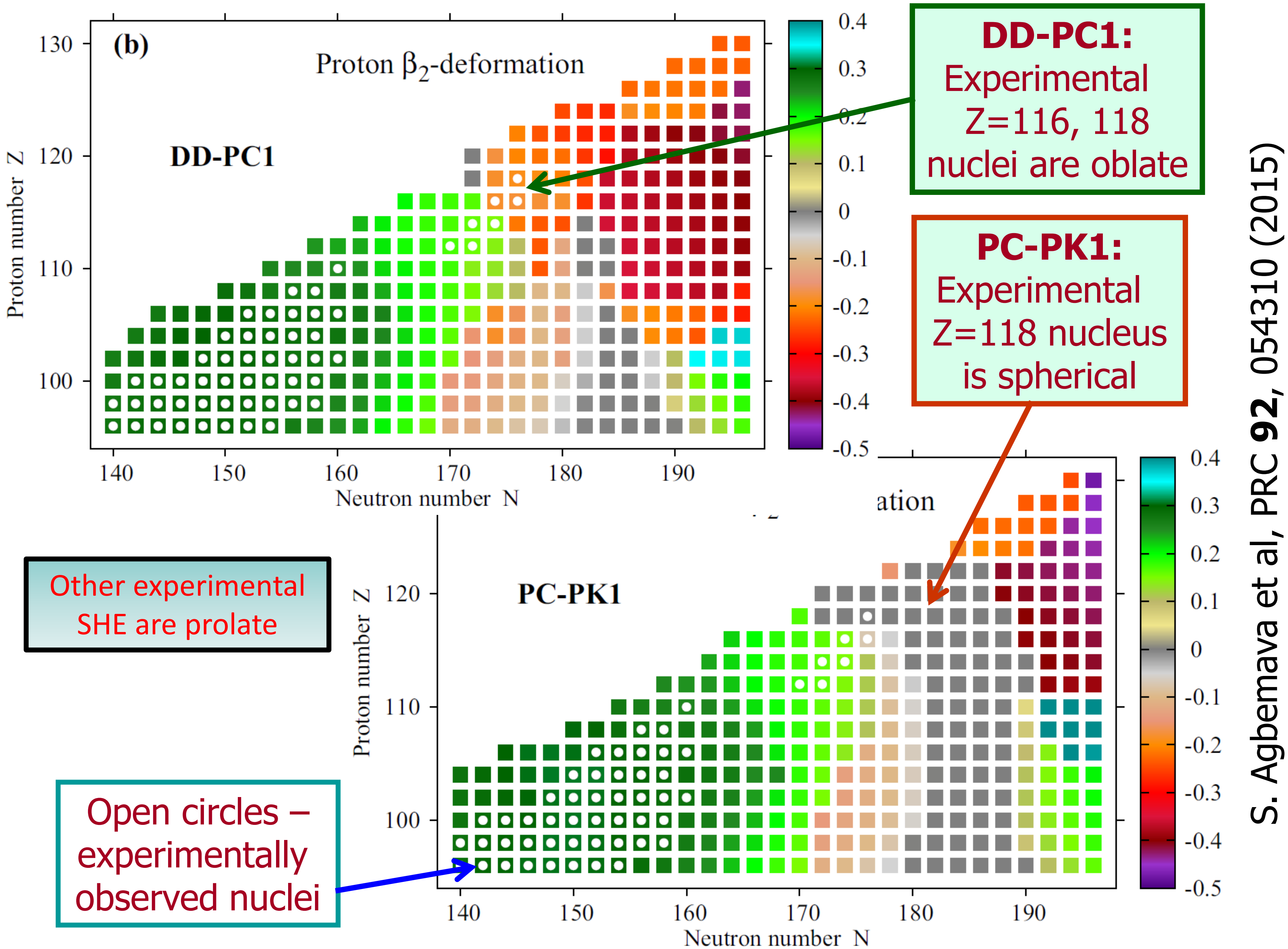


Rotational properties:
PRC 88, 014320 (2013),
Phys. Scripta 89, 054001 (2014)

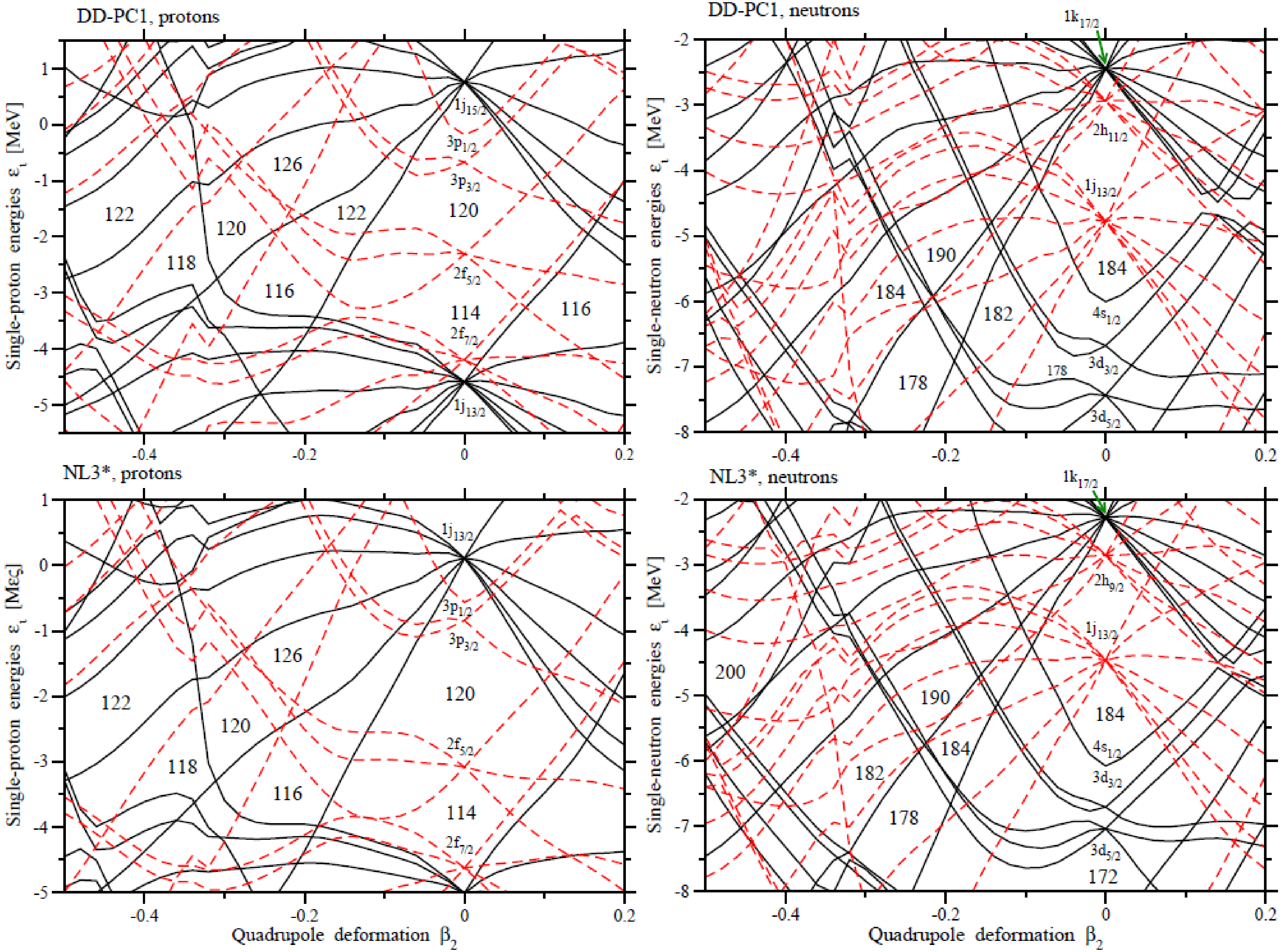


Fission barriers:
PLB 689, 72 (2010),
PRC 82, 044303 (2010),
PRC 85, 024314 (2012),
PRC 95, 054324 (2017)

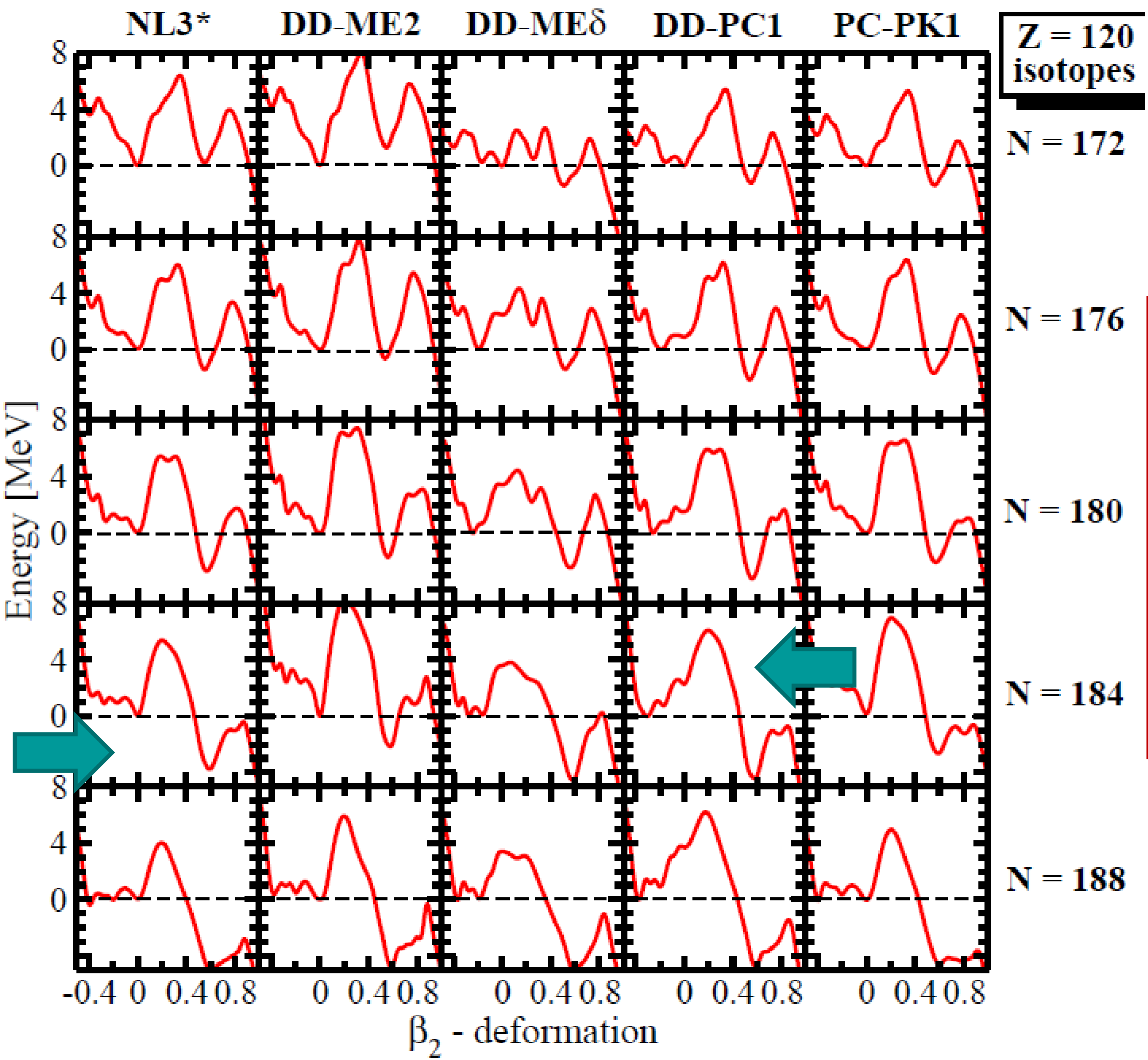
2. Superheavy nuclei: impact of beyond mean field correlations on ground state and fission properties


(b)
Proton β2-deformation
DD-PC1
Proton number Z
Neutron number N
DD-PC1:
Experimental
Z=116, 118
nuclei are oblate
PC-PK1:
Experimental
Z=118 nucleus
is spherical
PC-PK1
Other experimental
SHE are prolate
Open circles –
experimentally
observed nuclei
S. Agbemava et al, PRC 92, 054310 (2015)

The source of oblate shapes – the low density of s-p states

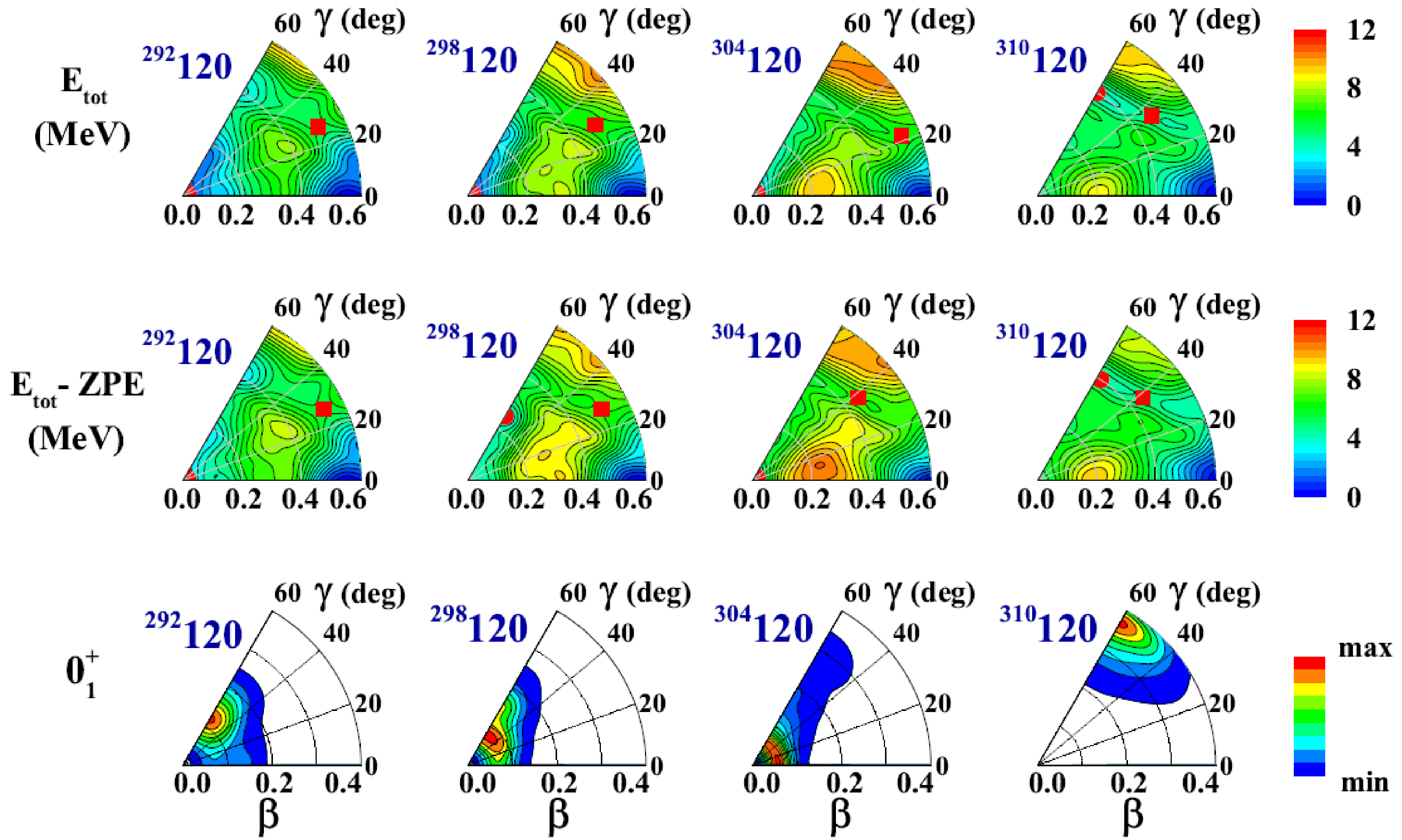


S. Agbemava et al, PRC **92**, 054310 (2015)



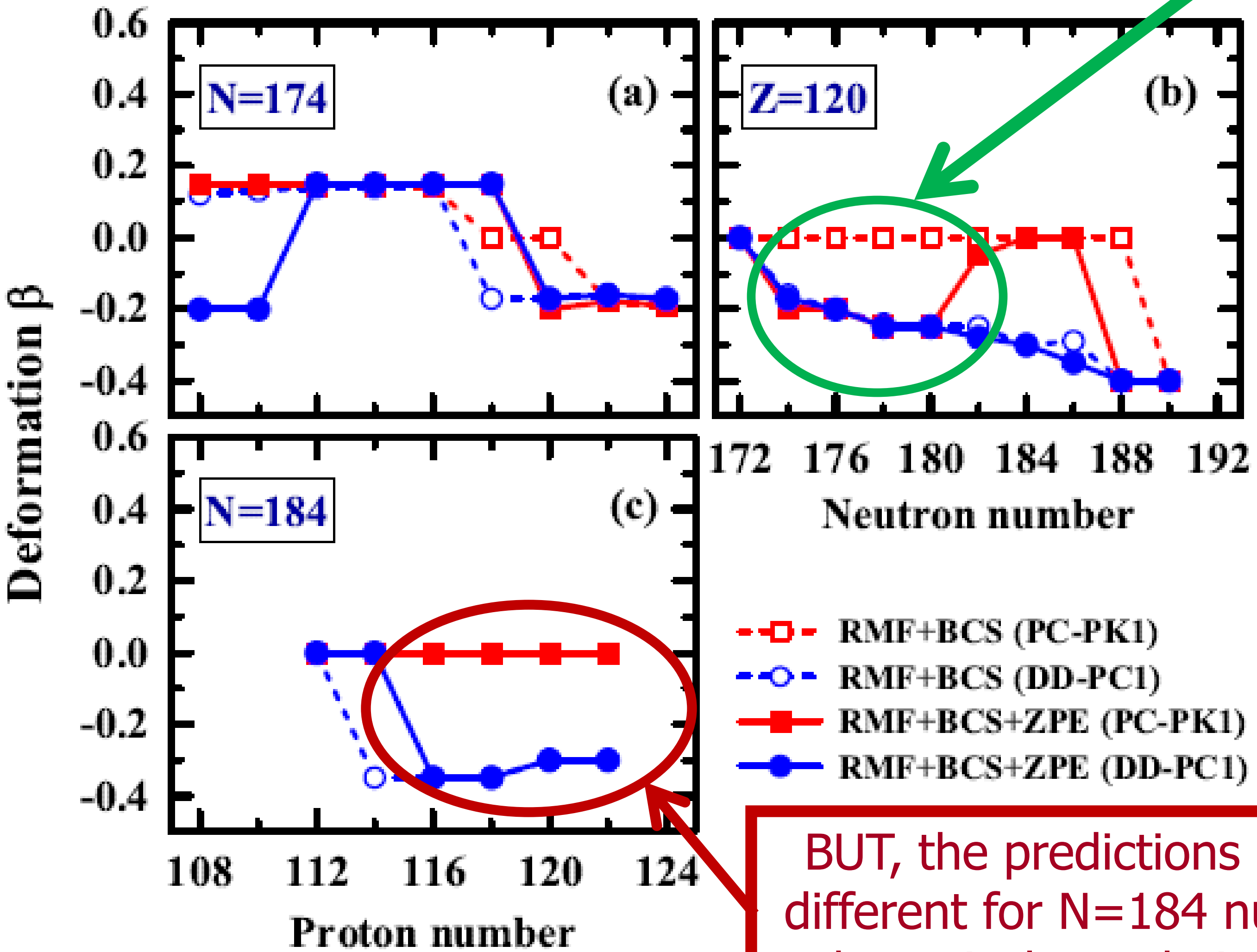
Potential energy surfaces in axially symmetric RHB calculations with separable pairing

Impact of the correlations beyond mean field on the ground states and saddle points of superheavy nuclei



The energy difference between the neighboring contour lines is 0.5 MeV.

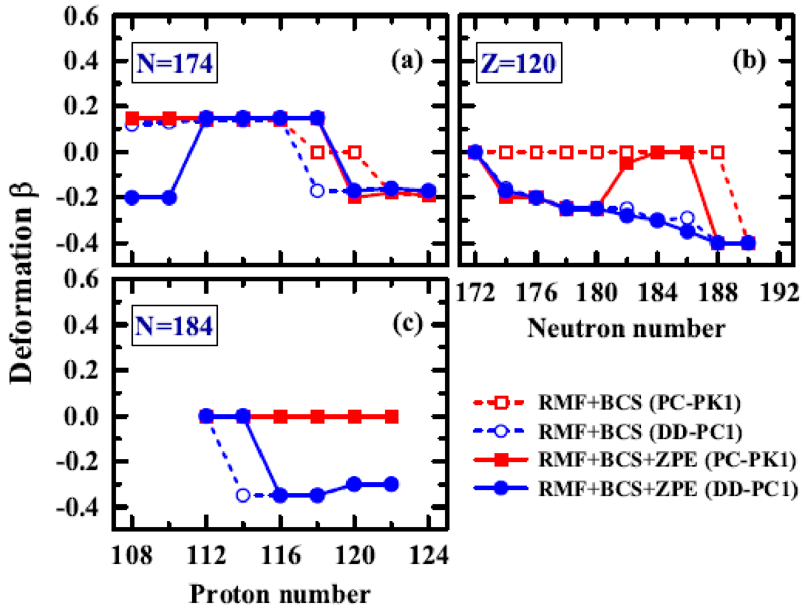
Impact of the correlations beyond mean field on the ground states of superheavy nuclei

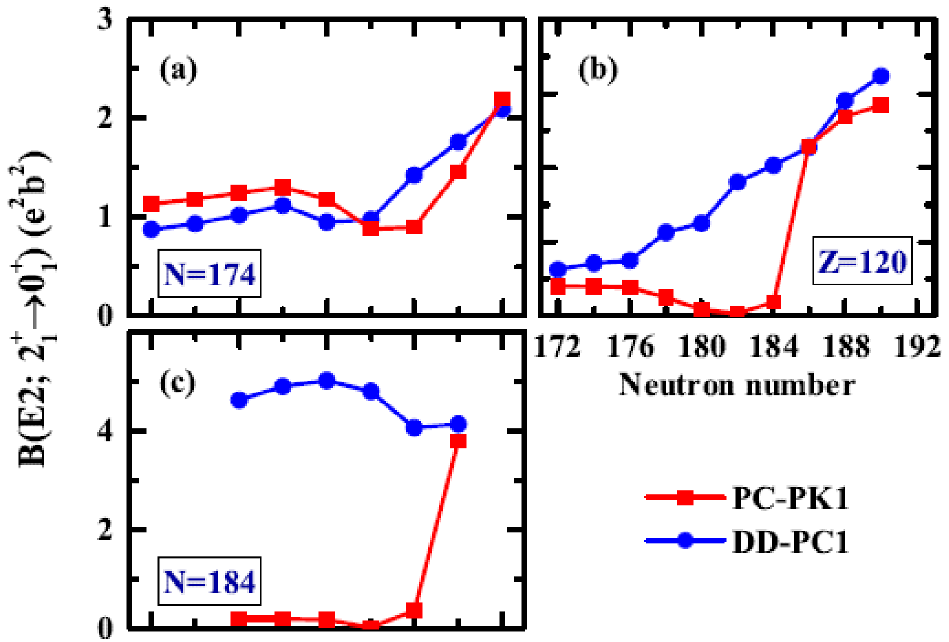


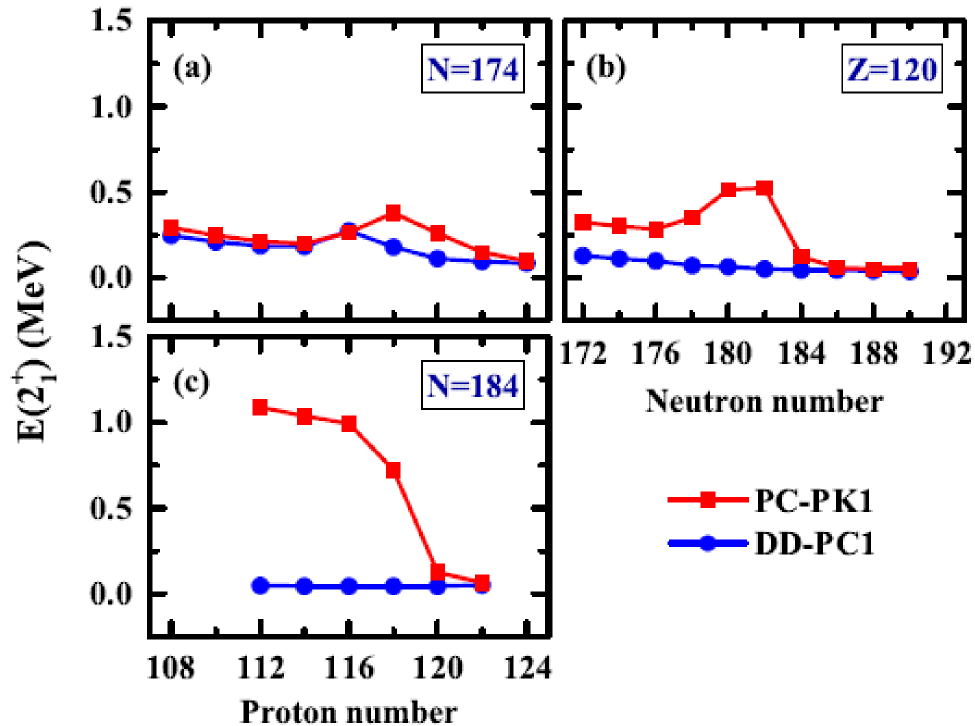
The inclusion of dynamical correlations brings the predictions ff DD-PC1 and PCPK1 functionals closer for nuclei along the Z=120 line

BUT, the predictions remain distinctly different for N=184 nuclei even when dynamical correlations are included

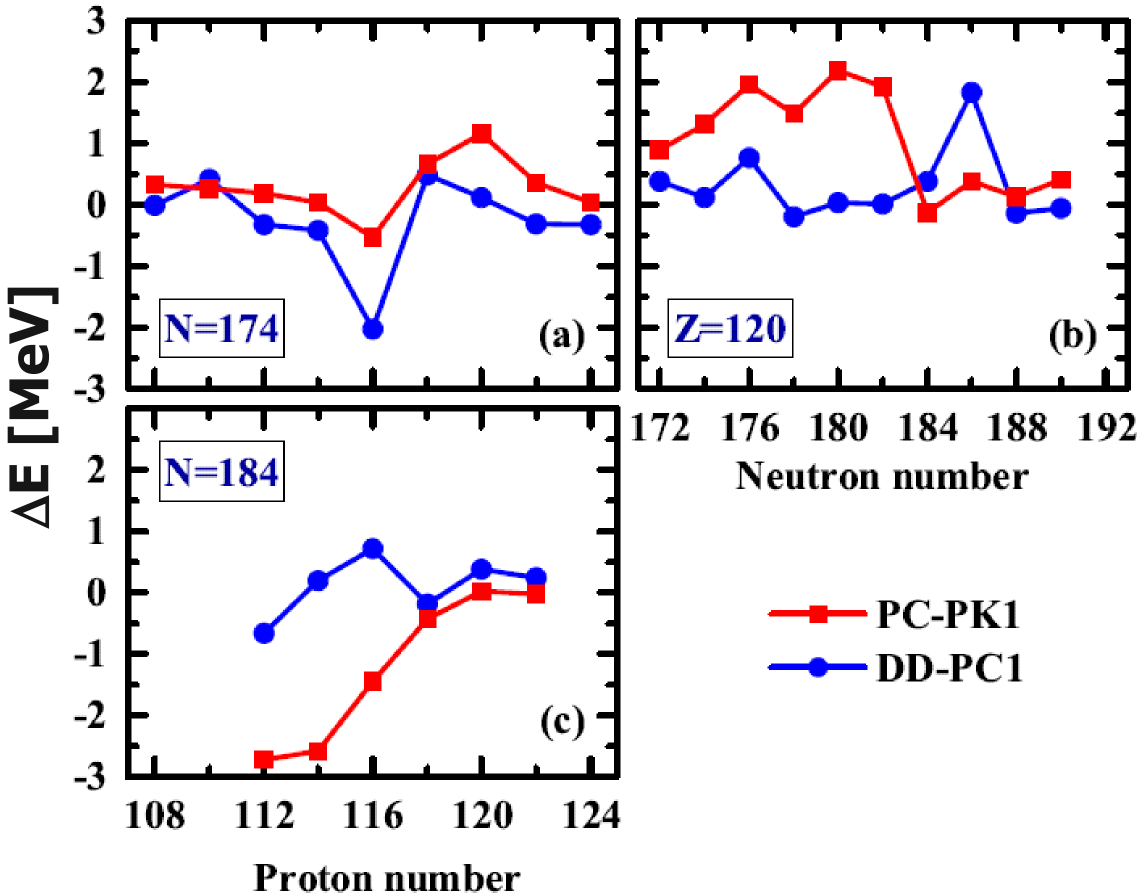
Impact of the correlations beyond mean field on the ground states of superheavy nuclei







Impact of the correlations beyond mean field on the heights of fission barriers in superheavy nuclei



ΔE [MeV] – the change of the fission barrier height due to dynamical correlations

The impact of dynamical correlations on the height of inner fission barrier is typically moderate (significant) when the ground state is deformed (spherical) at the mean field level.

If ΔE < 0 fission barrier is higher when dynamical correlations are included

3. Hyperheavy (Z>126) nuclei:

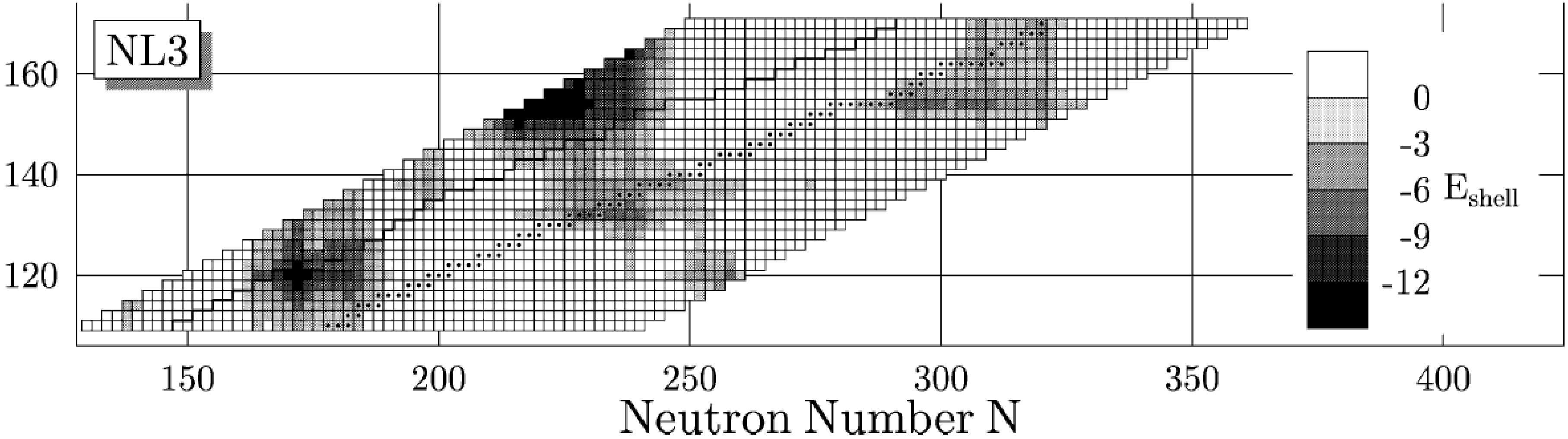
- how the limits of nuclear landscape are defined?
- do relatively stable hyperheavy nuclei exist?

Full results are presented in AA, S. Agbemava and A. Gyawali, PLB 782, 533 (2018) and its supplemental material. In addition, big manuscript with extra details is in preparation.

Historical overview of the studies of hyperheavy nuclei

All systematic studies are restricted to spherical shape !!!

Example: shell correction energies in spherical hyperheavy nuclei
M. Bender et al, PLB 515 (2001) 42 [RMF and Skyrme HFB]



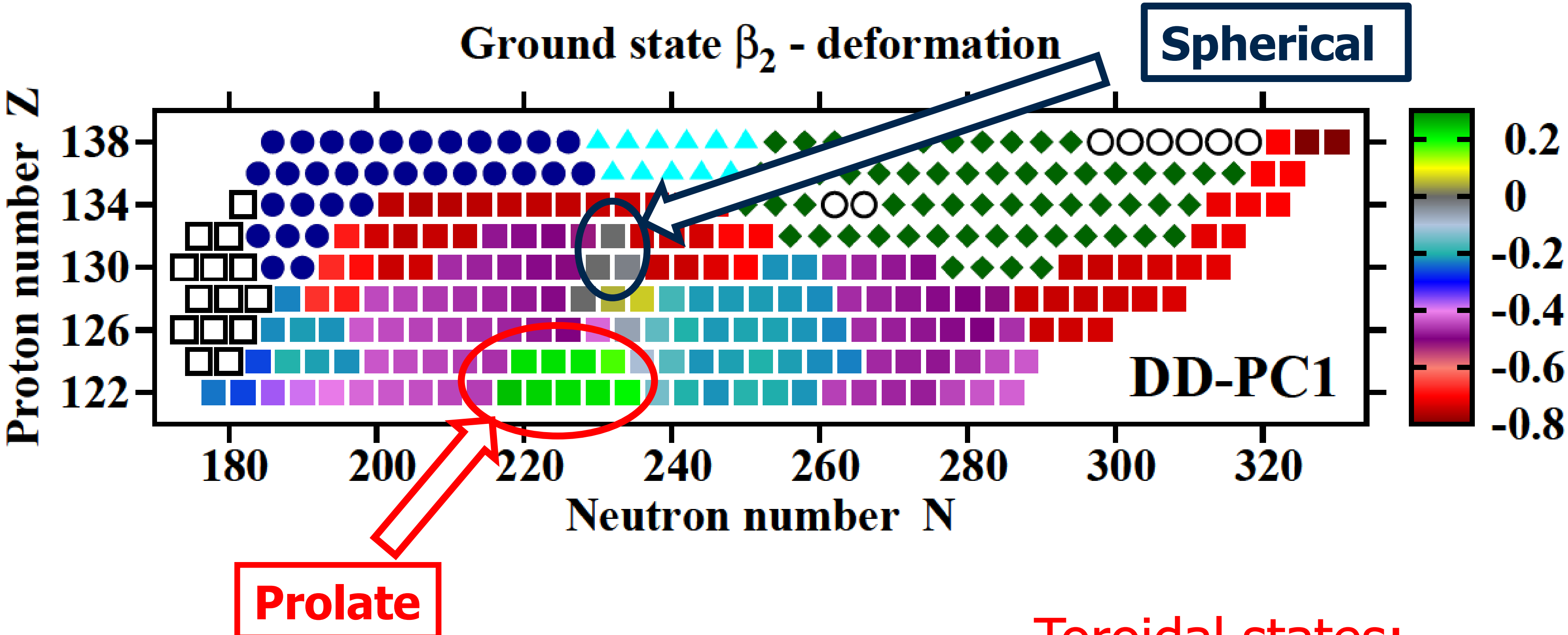
V.Yu.Denisov, Phys.At. Nucl. 68, 1133 (2005)
spherical Woods-Saxon potential, 76<Z<400

M. Ismail et al, J.Phys. G 43, 015101 (2016),
spherical Woods-Saxon potential, 72<Z<282

Y.K.Gambhir et al, J.Phys.G 42 (2015) 125105
Spherical RMF+BCS calculation: nuclear landscape ends at Z=146.

M. Warda, Int. J. Mod. Phys. E 16, 452 (2007): toroidal lowest in energy states in axial Gogny HFB calculations of 2 hyperheavy (Z=164/184) nuclei

Ground state quadrupole deformations in axial RHB calculations



Toroidal states:

□ $-2.0 < \beta_2 < -1.5$

● $-2.5 < \beta_2 < -2.0$

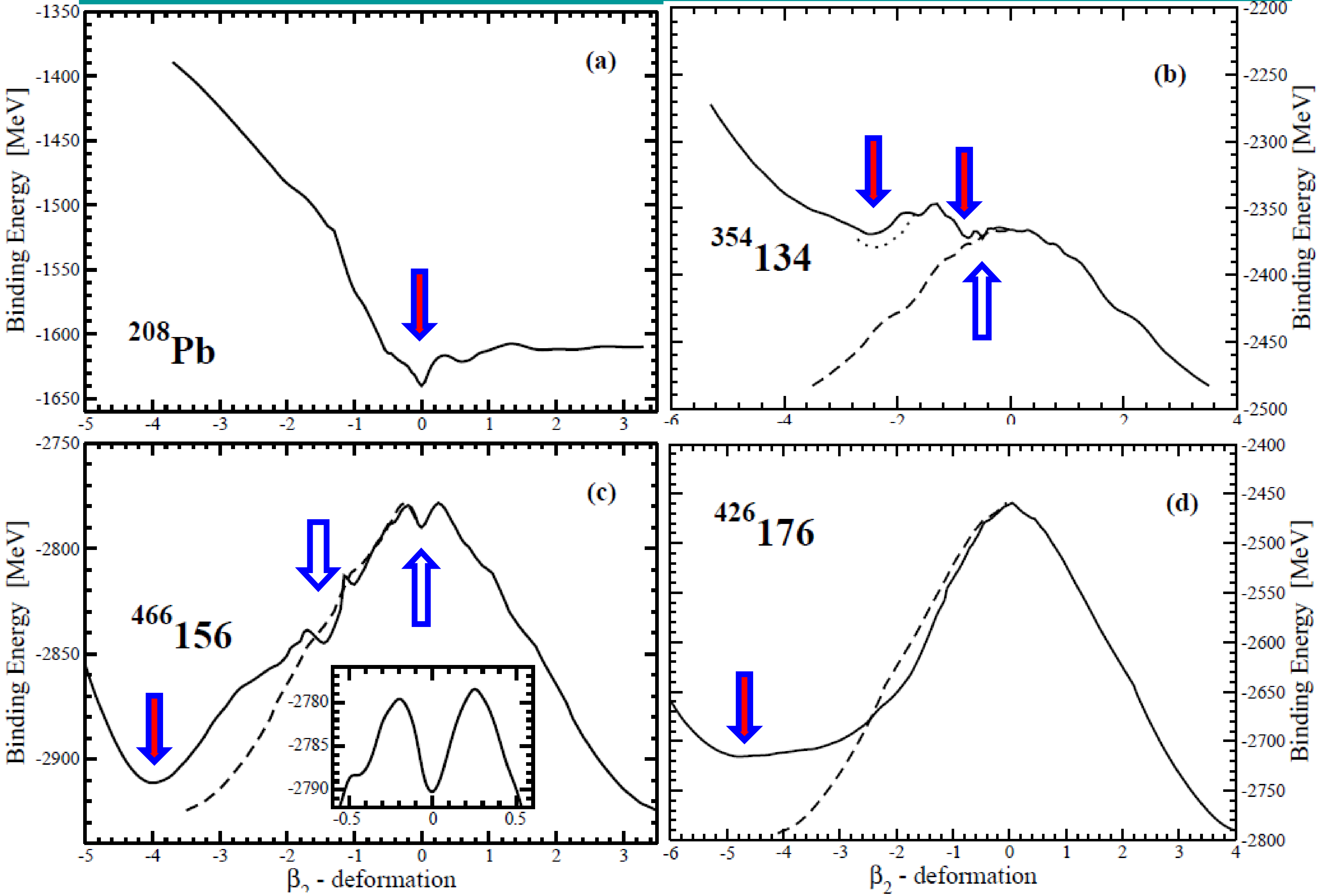
▲ $-3.0 < \beta_2 < -2.5$

◆ $-3.5 < \beta_2 < -3.0$

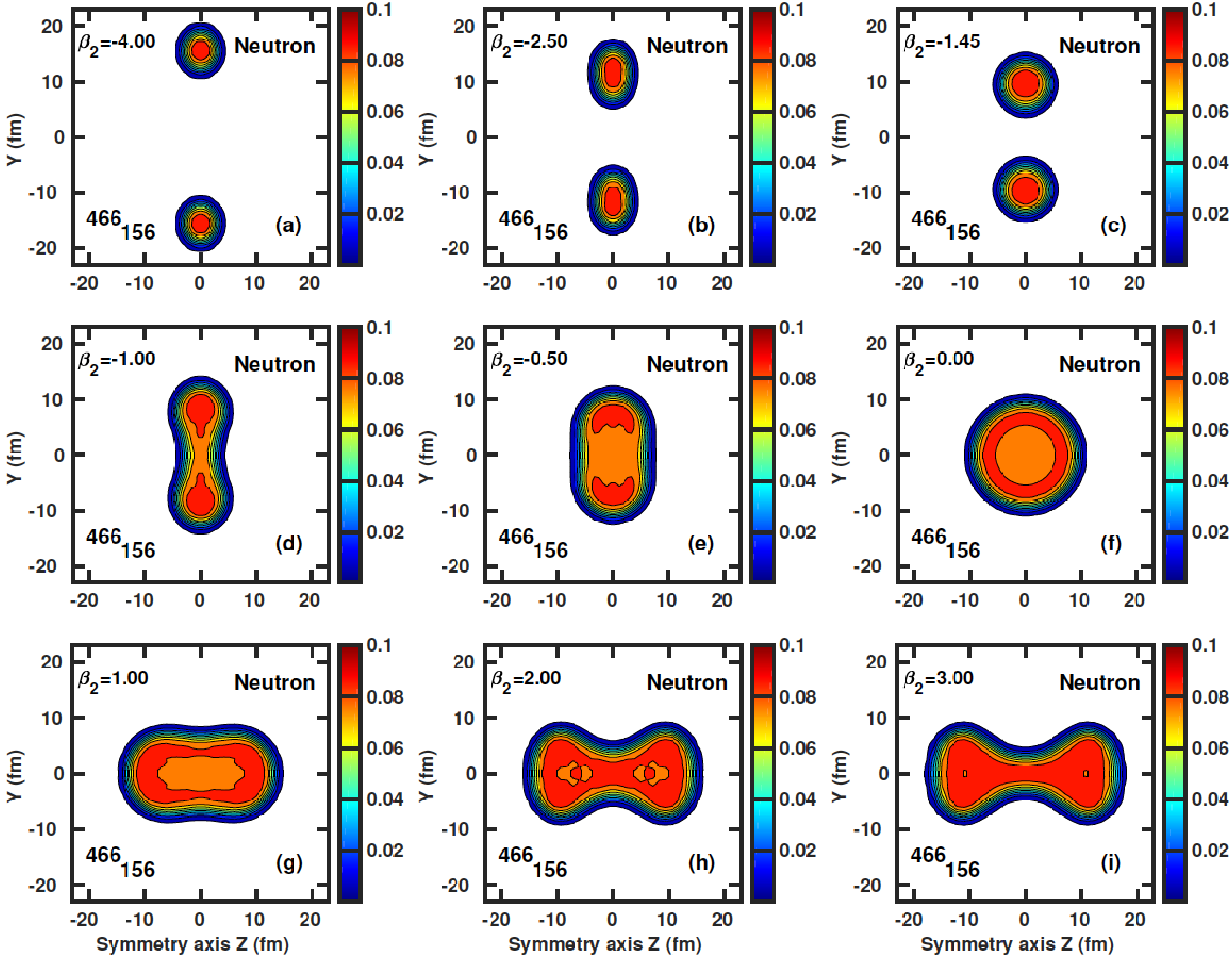
○ $\beta_2 < -3.5$

The nuclear landscape is dominated by oblate highly- and superdeformed ground states and toroidal states

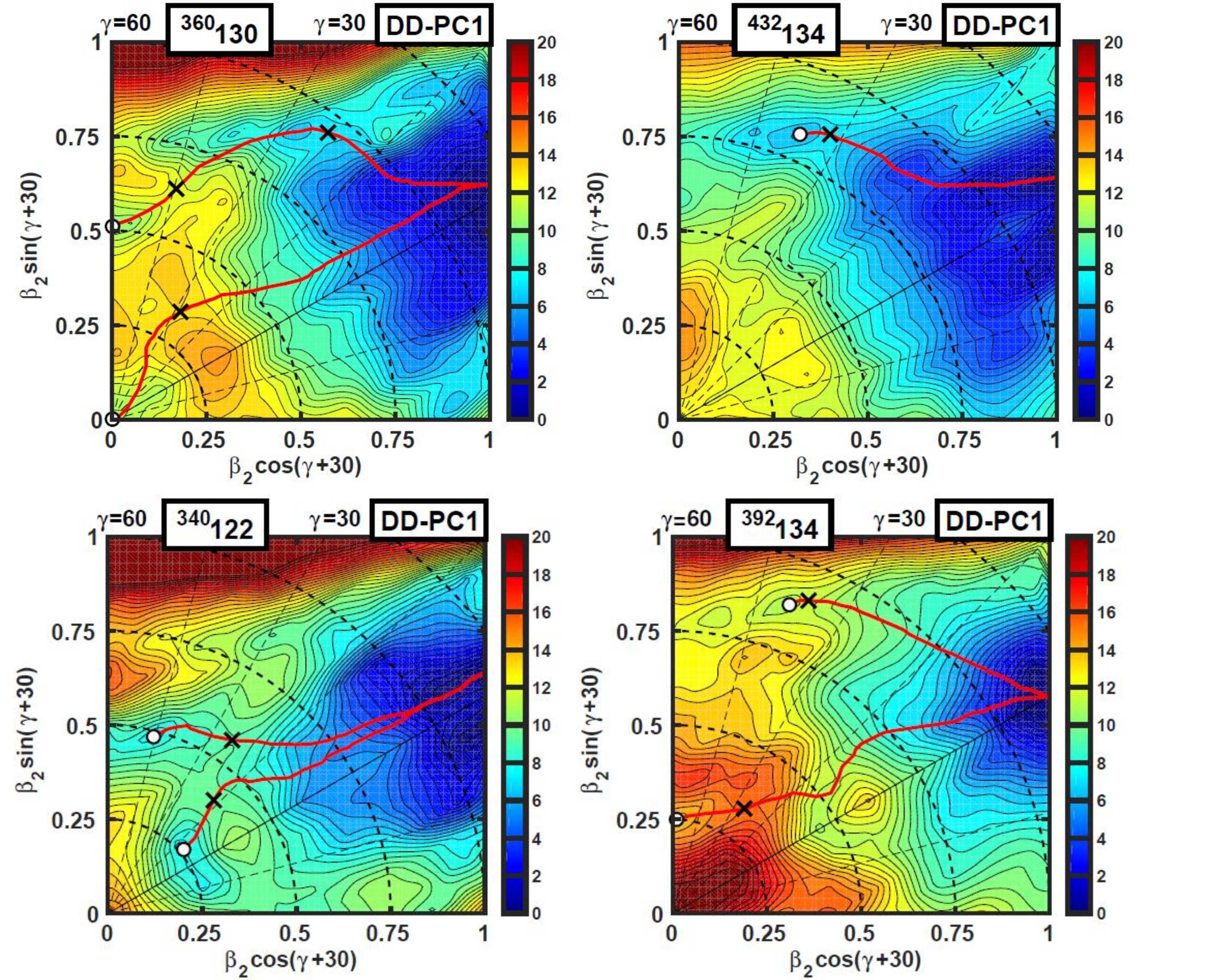
Evolution of potential energy curves with proton number in axial RHB calculations



Neutron density distributions in the $^{466}156$ nucleus



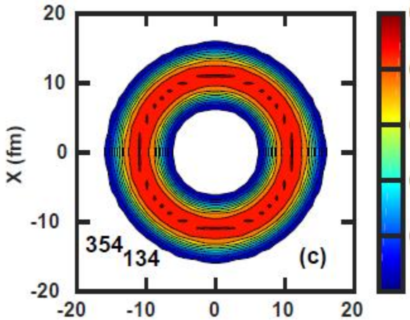
The instability of the oblate minima in high-Z systems

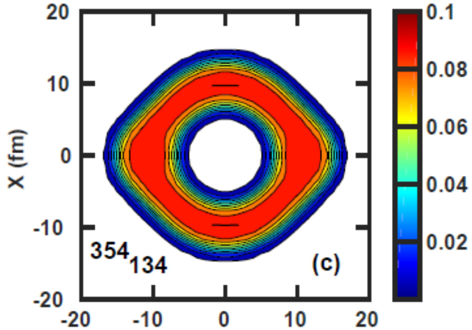


The instability of the oblate minima in high-Z systems

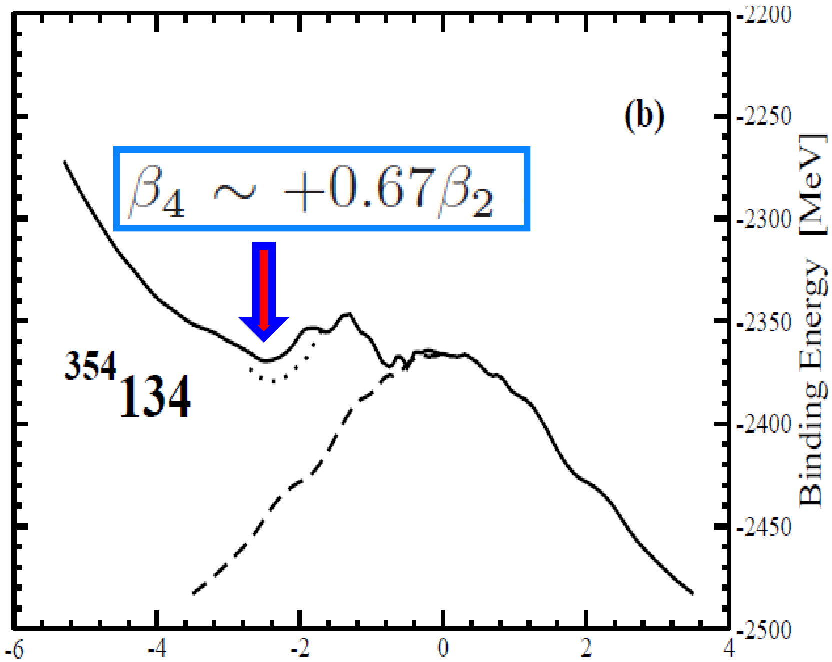
Z	N	β_{min}	Axial RHB	FB	$(\beta, \gamma)_{min}$	Triaxial RHB	FB
130	206	-0.74	0.00	8.99	0.82,37	0.84,31)	0.68
		-0.46* [0.19]	0.00	8.80	no	no	no
	226	-0.50	-0.25	5.22	0.50,58	0.56,33	3.02
		0.12* [1.69]	0.33	3.44	0.15,2	0.35,27	1.21
		-0.74* [2.19]	-0.64	3.38	0.82,37	0.83,34	0.70
	230	-0.01	0.32	4.86	0.00,0	0.34,26	2.77
		-0.53* [0.81]	0.32	4.05	0.52,55	0.63,44	2.04
	246	-0.72	0.25	6.68	0.73,59	0.75,50	0.67
		-0.21* [0.28]	0.25	6.40	0.26,58	0.47,35	3.12
	266	-0.47	0.01	9.05	0.48,59	0.48,54	0.56
		-0.78* [0.74]	0.01	8.31	no	no	no
		-0.23* [1.57]	0.01	7.48	0.28,33	0.34,20	0.58
	286	-0.75	0.00	8.19	0.77,40	0.75,35	1.28
		-0.51* [0.27]	0.00	7.92	0.54,51	0.57,38	1.35
134	258	-0.79	0.00	10.24	0.88,39	0.90,37	0.56
		-0.23* [2.69]	0.00	7.55	0.25,58	0.33,25	2.08
	278	-0.50	0.07	10.68	0.51,56	0.52,49	1.54
		-0.79* [0.17]	0.07	10.51	0.79,38	0.79,33	2.56
	298	-0.74	-0.21	8.16	0.82,37	0.85,32	1.30
	318	-0.71	0.28	11.59	0.71,59	0.78,47	1.37

The potential stability of toroidal shapes with $\beta_2 \sim -2.5$ and $\beta_4>0$ in high-Z systems

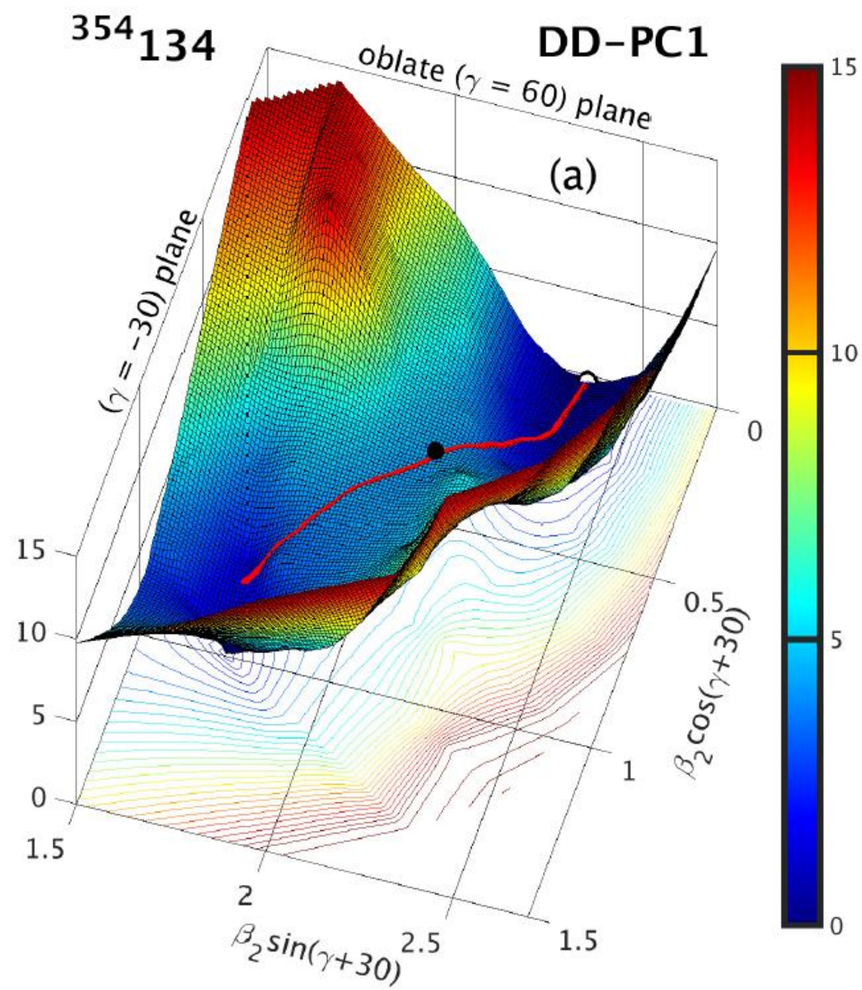




Fission barrier at E=4.2 MeV



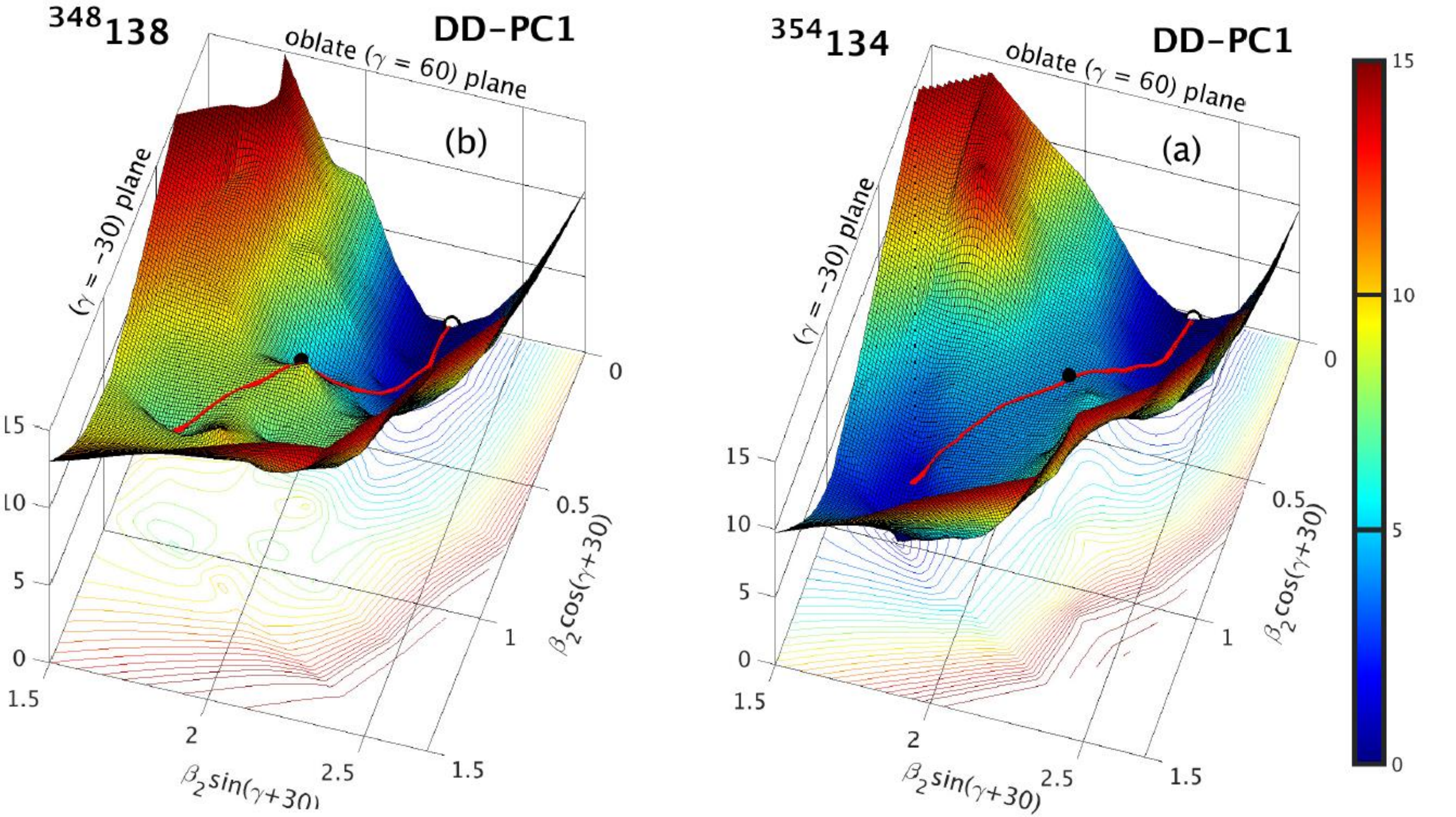
β_2-deformation



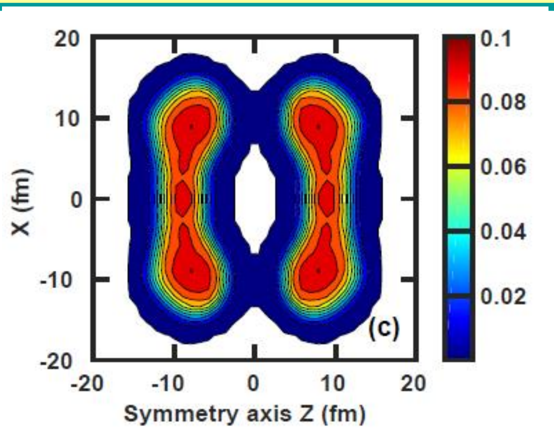
The potential stability of toroidal shapes with $\beta_2 \sim -2.5$ and $\beta_4>0$ in high-Z systems

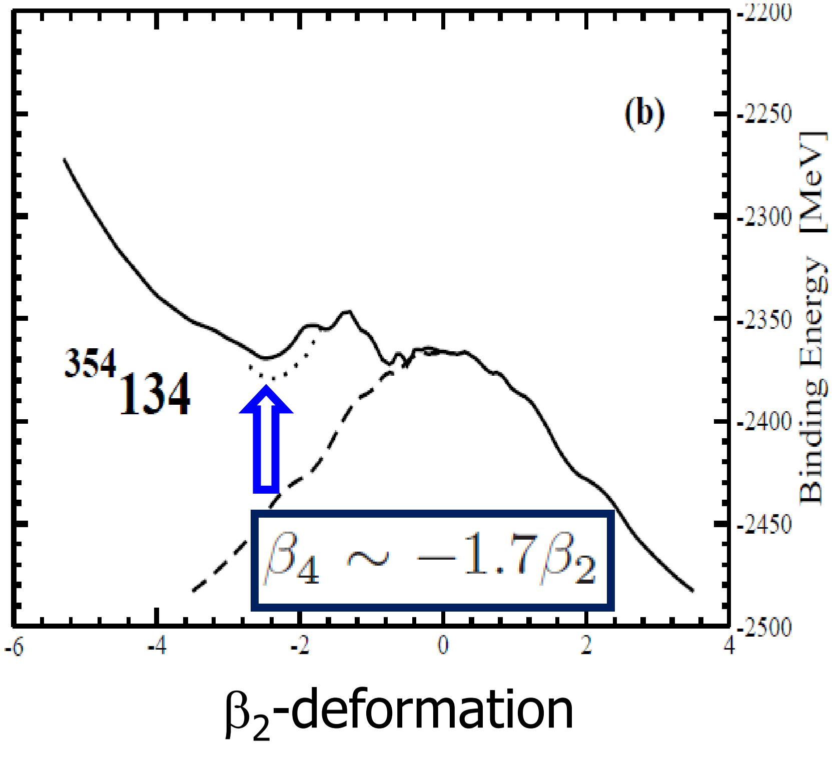
Fission barrier at E=8.5 MeV

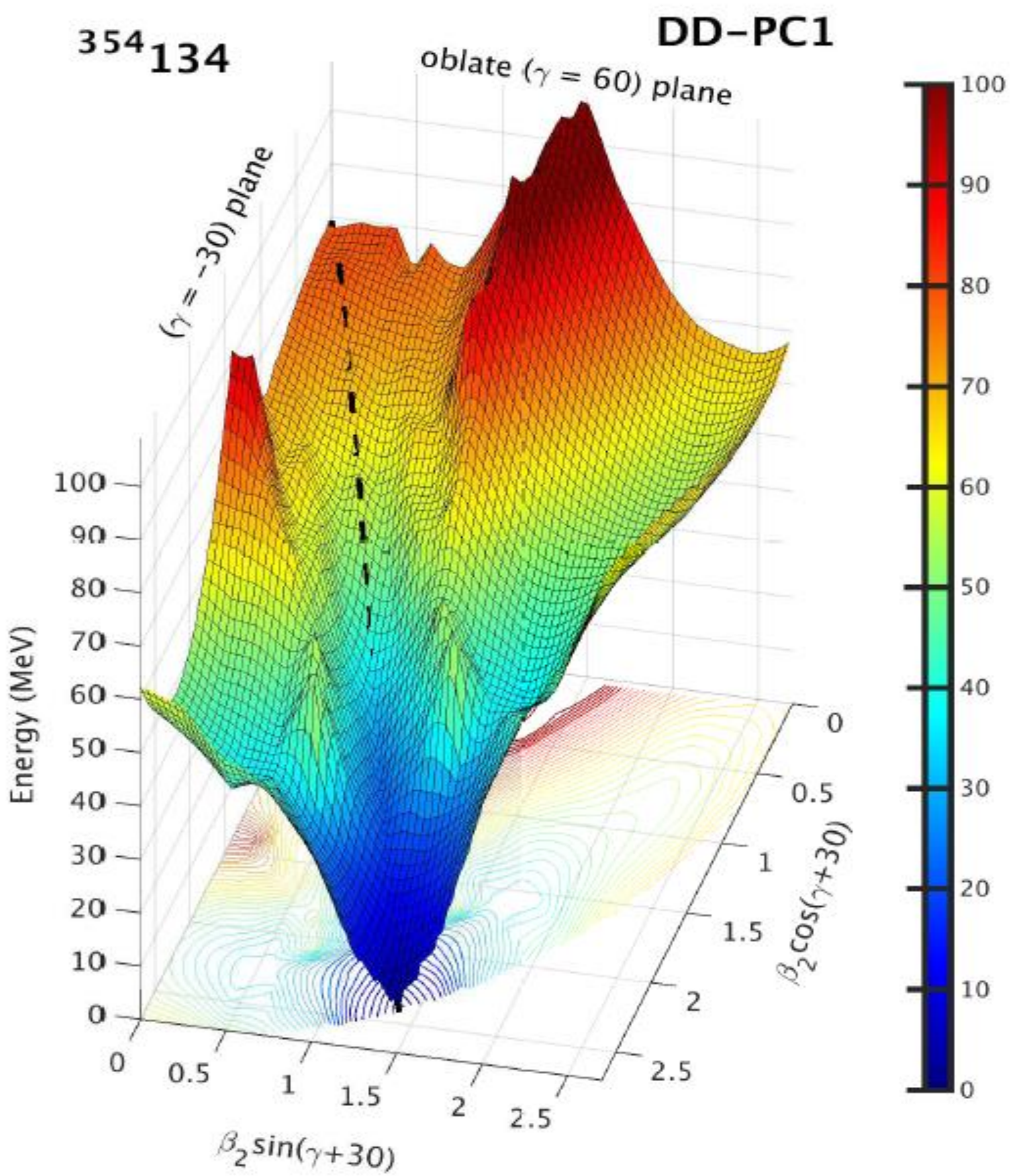
Fission barrier at E=4.2 MeV



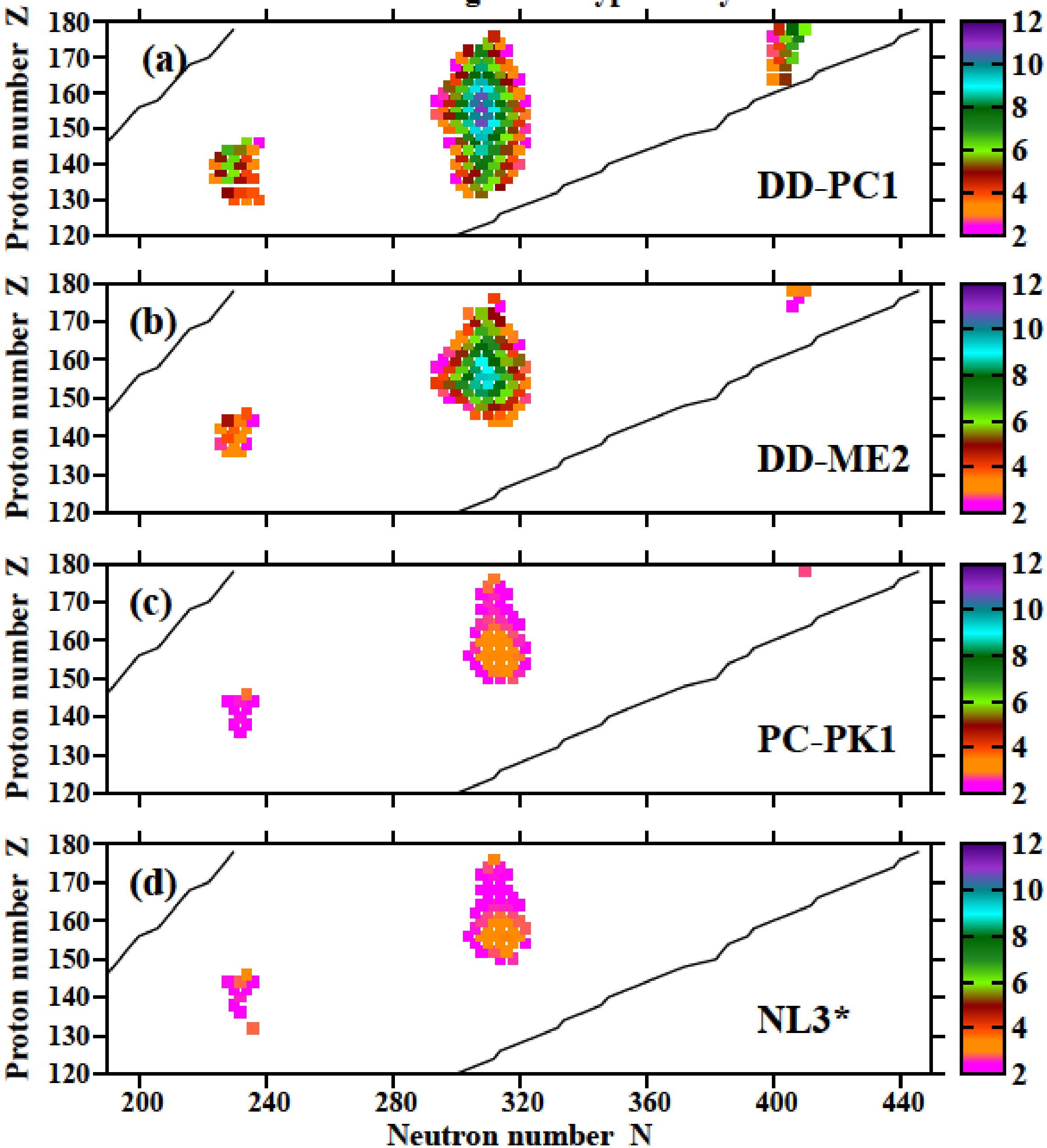
The instability of toroidal shapes with $\beta_2 \sim -2.5$ and $\beta_4<0$ in high-Z systems







Fission barrier heights around "excited" spherical minimum

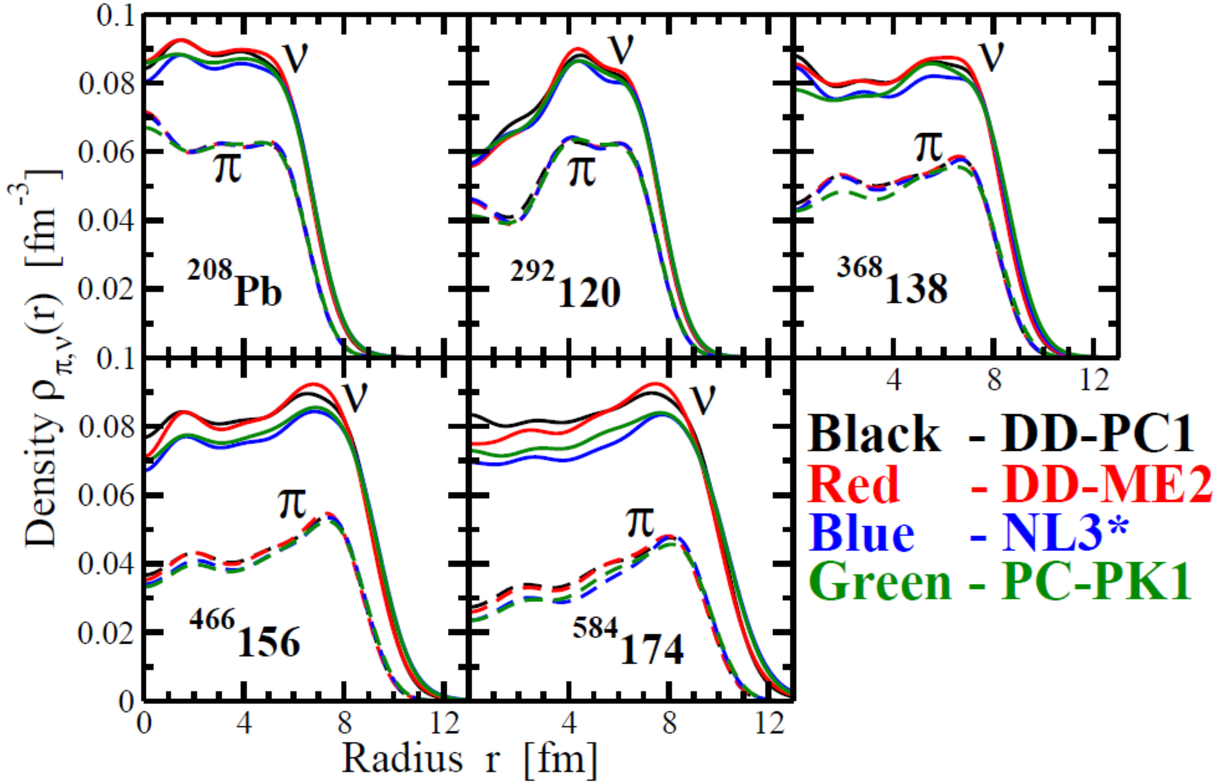


For the first time, we demonstrate the existence of three regions of hyperheavy nuclei centered around **(Z~138, N~230)**, **(Z~156, N~310)** and **(Z~174, N~ 410)** which are expected to be relatively stable against spontaneous fission.

Neither octupole nor triaxial distortions significantly affect their stability

These nuclei are relatively stable with respect of α-decay

The predictions of which functionals to prefer?



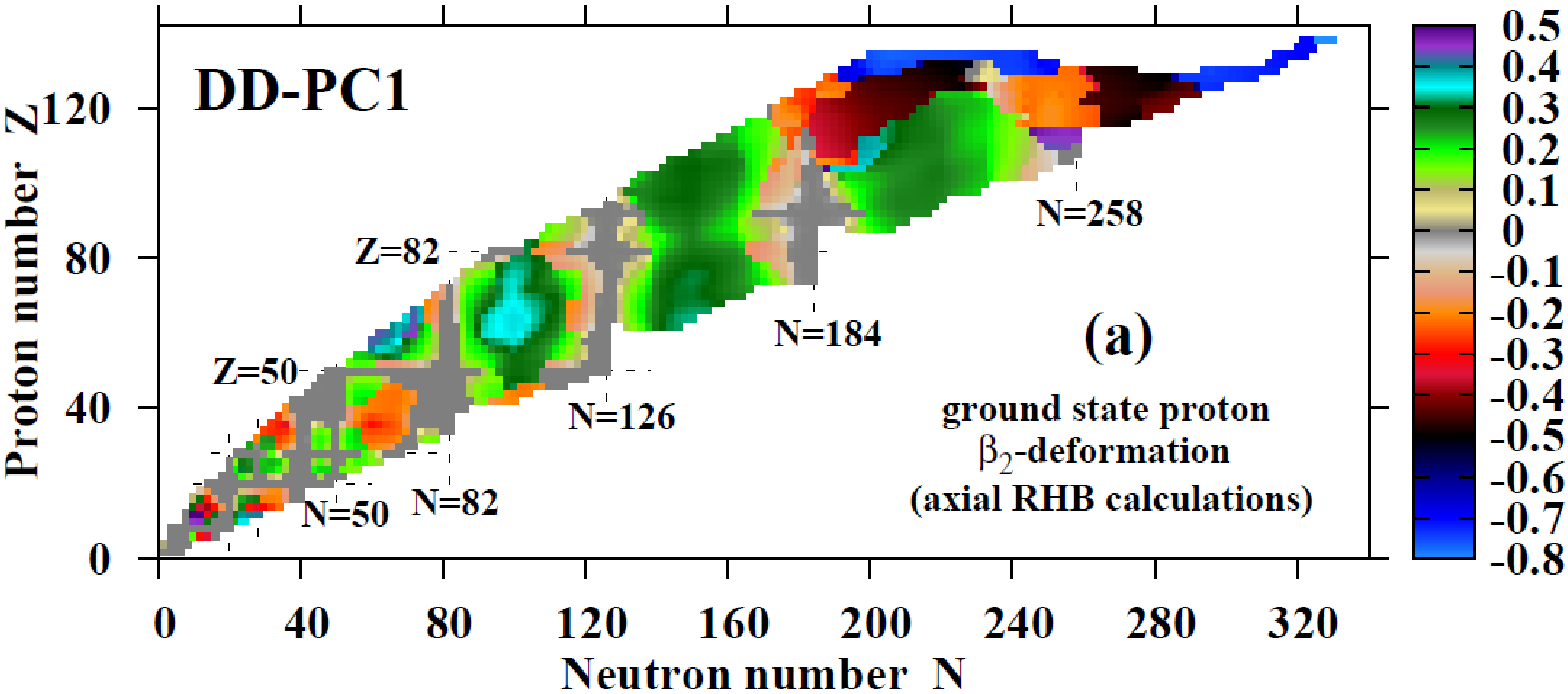
DD functionals predict smaller charge radii and smaller skins as compared with NL functionals

DD – functionals:

1. Better nuclear matter properties → better extrapolaribility to unknown regions
2. Better global description of masses and charge radii

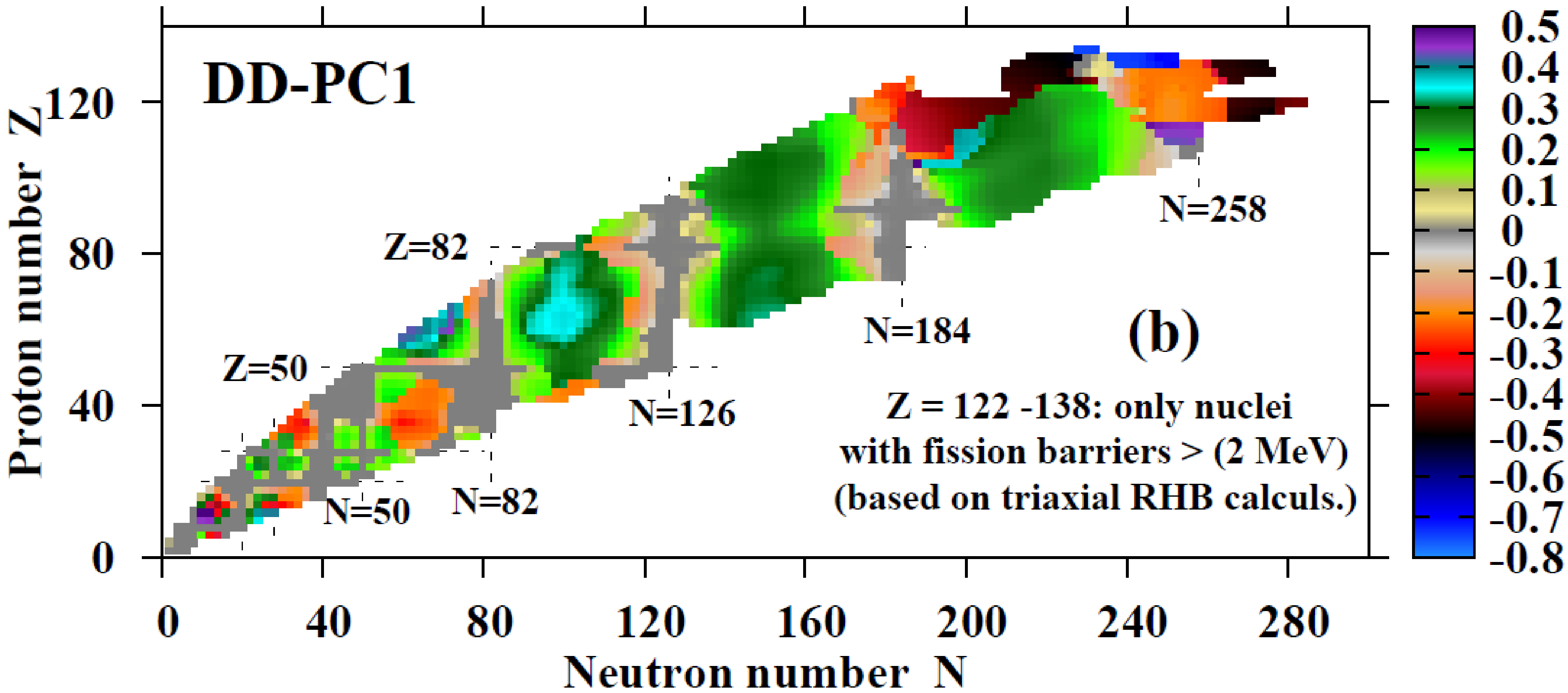
Need the results of future PREX-2 experiment to discriminate the predictions of the DD and NL functionals with respect of neutron skin in ^{208}Pb

Expansion of nuclear landscape to hyperheavy nuclei

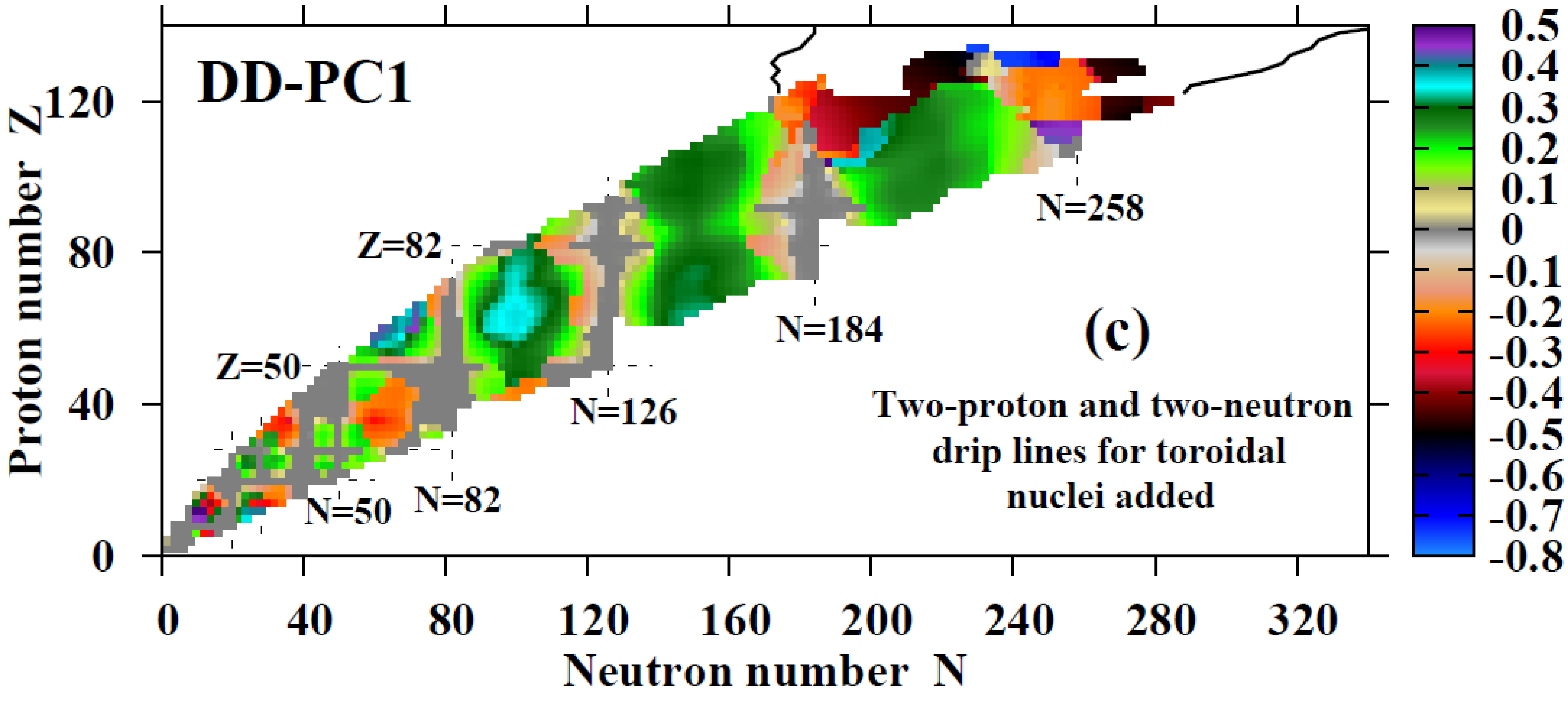


The results for Z<120 nuclei are from
S. Agbemava, AA, D. Ray and P. Ring, PRC 89, 054320 (2014)

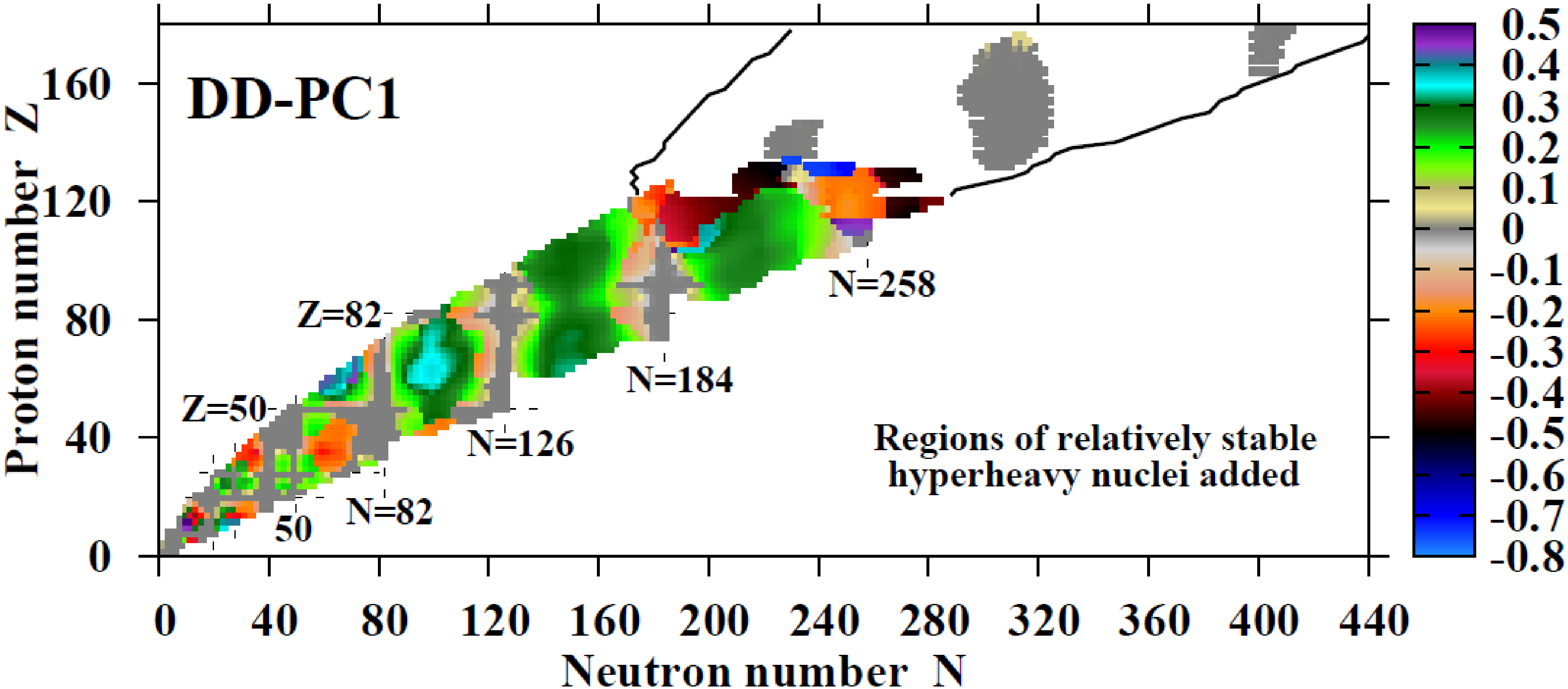
Expansion of nuclear landscape to hyperheavy nuclei



Expansion of nuclear landscape to hyperheavy nuclei



Expansion of nuclear landscape to hyperheavy nuclei



Majority of toroidal nuclei are expected to be unstable with respect of so-called sausage deformations leading to multifragmentation. However, this conclusion is based on liquid drop model analysis (C.Y.Wong, Annals of Physics 77, 279 (1973)) and needs to be verified in fully self-consistent calculations.

Conclusions

Over the recent years we gained in CDFT significantly better understanding of the limits of nuclear landscape for Z<120, the properties of superheavy nuclei and related theoretical uncertainties and their sources (~ 15 publications on these topics)

For high-Z (Z>126) part of nuclear landscape:

- ellipsoidal deformed shapes either do not exist or are unstable with respect of triaxial distortions

- in axial RHB calculations the lowest in energy solutions have toroidal shapes (their stability ???)

- the regions of potentially stable spherical hyperheavy nuclei are predicted for the first time

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