Hirschegg 2015 Nuclear Structure and Reactions: Weak, Strange and Exotic

International Workshop XLIII on Gross Properties of Nuclei and Nuclear Excitations

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Extending the nuclear landscape by continuum: from spherical to deformed

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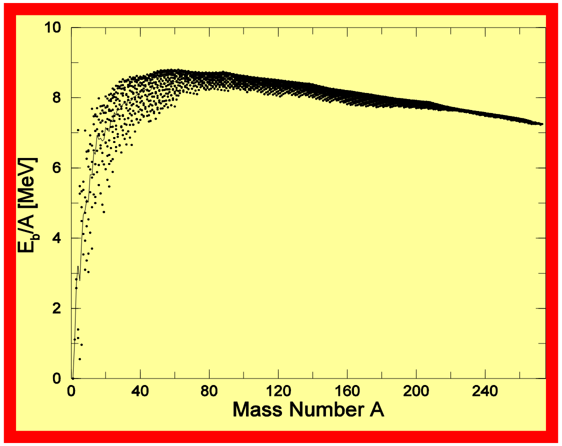
Outline

- Macroscopic-microscopic mass formula
- Nuclear mass in CDFT
- Energy and width for resonant states in Dirac equation
- Energy and width in GF-RCHB
- Nuclear landscape extended by continuum
- Perspectives

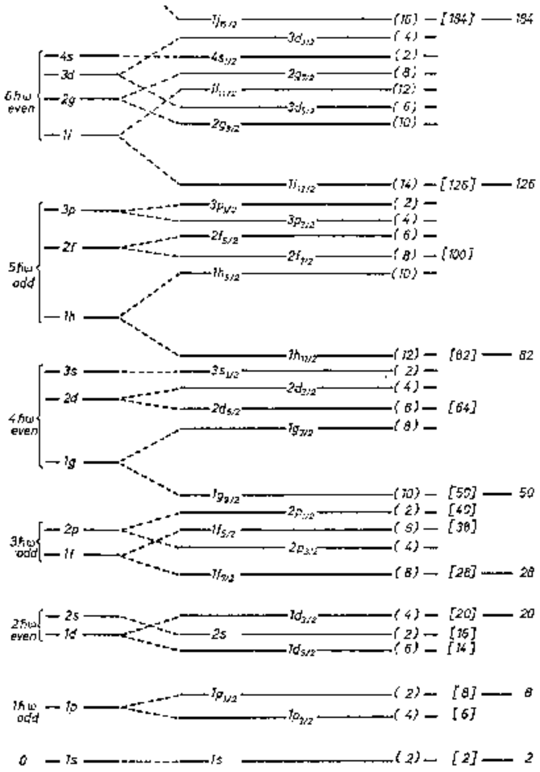
- Semi Empirical Mass Formula (Bethe and von Weizsäcker, 1935):

$$B(A,Z) = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_{sym}(N-Z)^2/A + B_p$$

Pairing term Bp : > 0 for even-even; < 0 for odd-odd; and = 0 for odd-A



General trend but no quantum fluctuation !



Shell model fails even qualitatively !

H = T+U

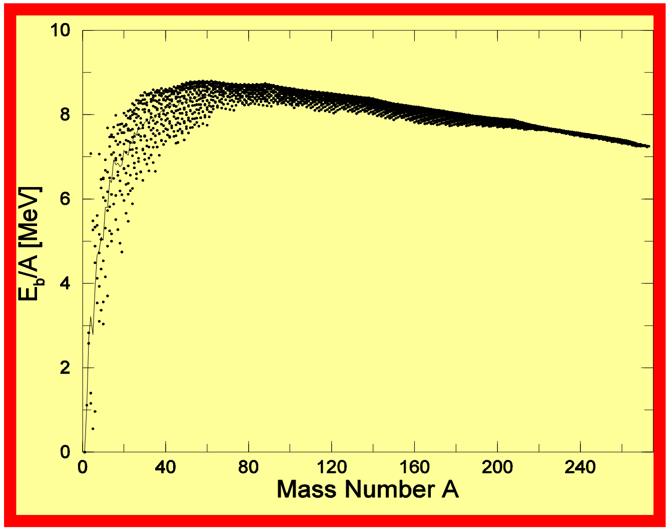
Strutinsky Shell correction calculation

V.M. Strutinsky, Shell effects in nuclear masses and deformation energies, Nuclear Physics A 95 (1967) 420

Times Cited: 1,664

“Shells” in deformed nuclei, Nuclear Physics A 122 (1968) 1

Times Cited: 1,040



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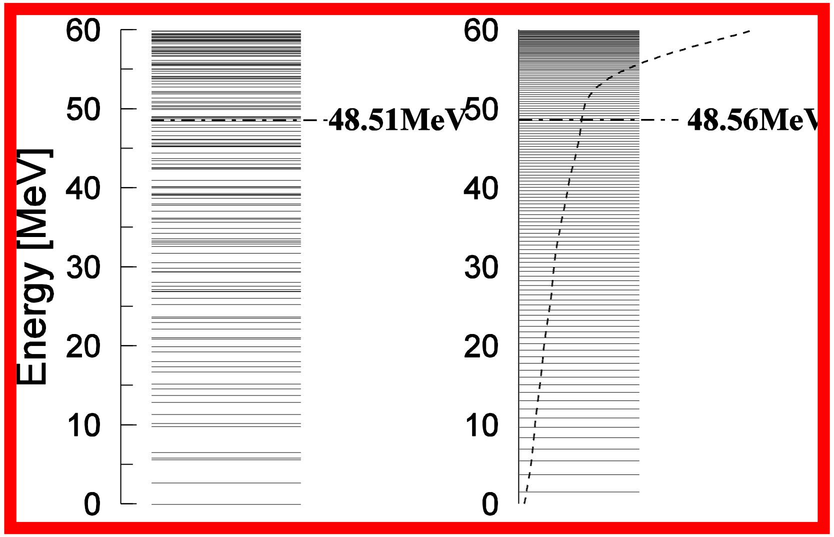


Compromise between Shell model and collective model

Great success for
FRDM
WS4 …

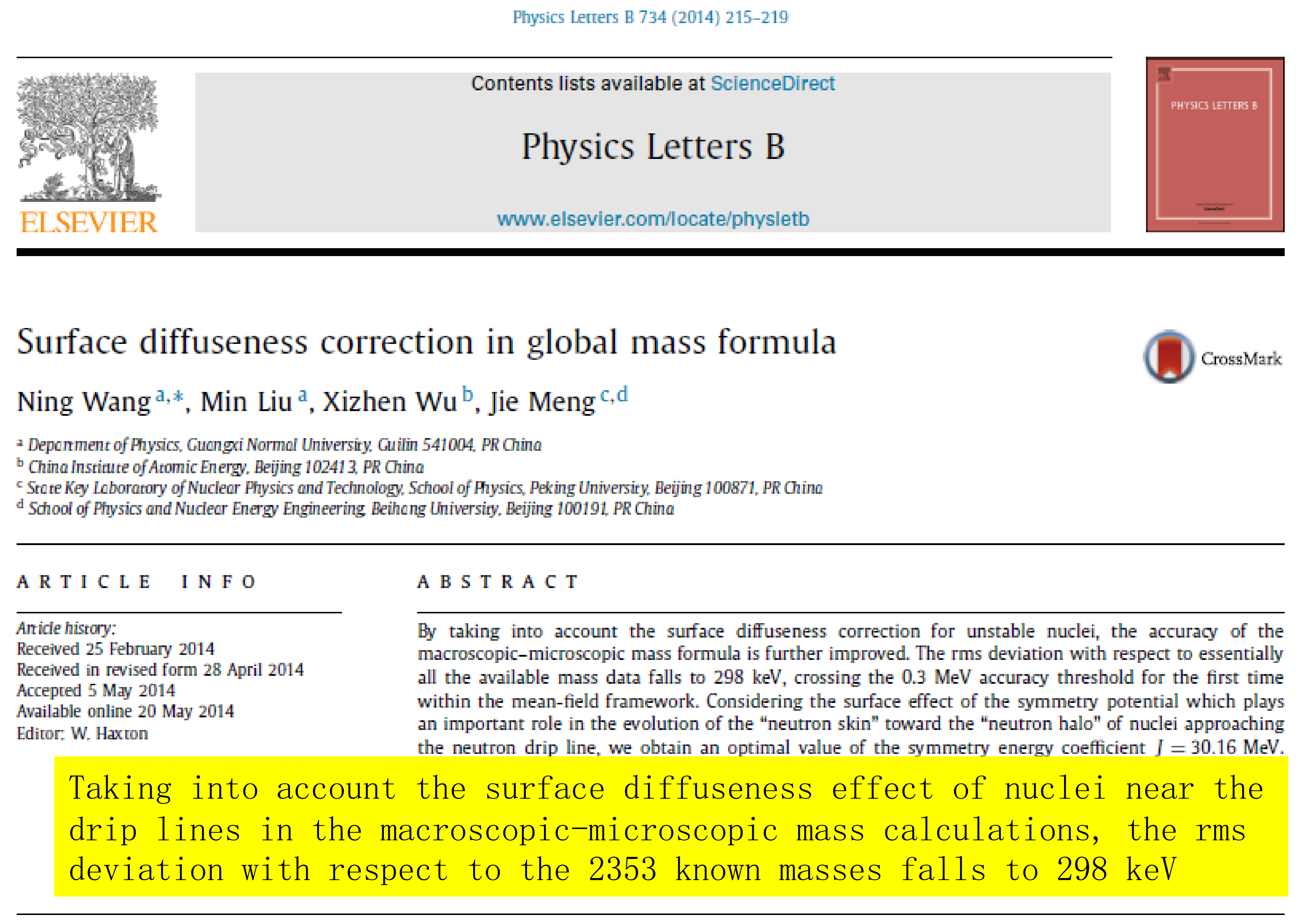
Finite-Range Droplet Model (FRDM)

P. Möller, J.R. Nix, W.D. Myers, W.J. Swiatecki, At. Data Nucl. Data Tables 59, 185 (1995).

Weizsäcker-Skyrme (WS) formula inspired by the Skyrme energy-density functional and a macroscopic-microscopic mass formula, with an rms deviation of 336 keV with respect to the 2149 measured masses in 2003 Atomic Mass Evaluation.

N. Wang, M. Liu and X. Z. Wu, Phys. Rev. C 81, 044322 (2010).
N. Wang, Z. Y. Liang, M. Liu and X. Z. Wu, Phys. Rev. C 82, 044304 (2010).
[M. Liu, N. Wang, Y. G. Deng, and X. Z. Wu, Phys. Rev. C 84, 014333 (2011).

Isospin for S-O & E_sym + mirror nuclei



Physics Letters B 734 (2014) 215–219

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Surface diffuseness correction in global mass formula

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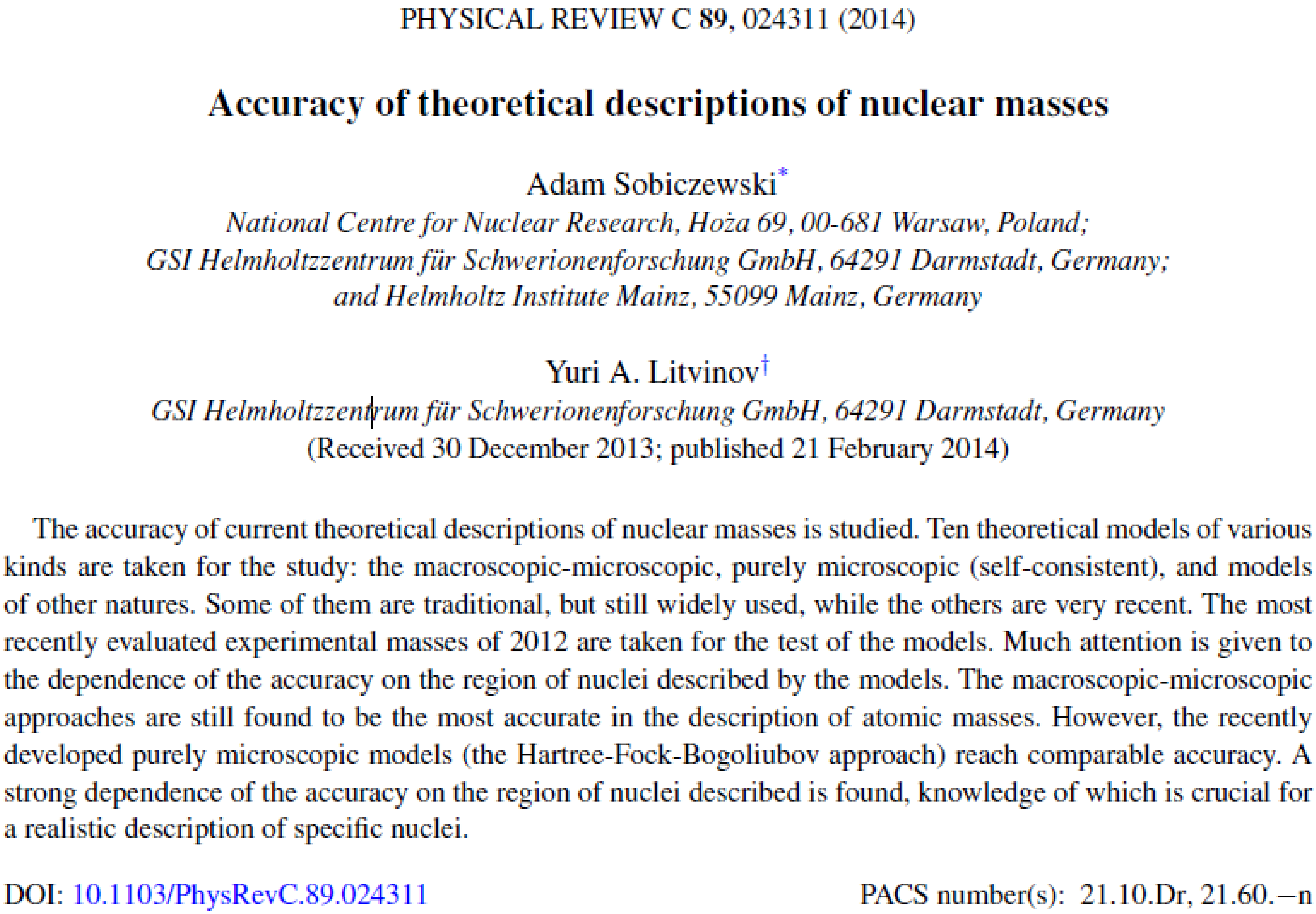
ABSTRACT

By taking into account the surface diffuseness correction for unstable nuclei, the accuracy of the macroscopic–microscopic mass formula is further improved. The rms deviation with respect to essentially all the available mass data falls to 298 keV, crossing the 0.3 MeV accuracy threshold for the first time within the mean-field framework. Considering the surface effect of the symmetry potential which plays an important role in the evolution of the “neutron skin” toward the “neutron halo” of nuclei approaching the neutron drip line, we obtain an optimal value of the symmetry energy coefficient $J = 30.16$ MeV.

Taking into account the surface diffuseness effect of nuclei near the drip lines in the macroscopic-microscopic mass calculations, the rms deviation with respect to the 2353 known masses falls to 298 keV



PHYSICAL REVIEW C **89**, 024311 (2014)

Accuracy of theoretical descriptions of nuclear masses

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(Received 30 December 2013; published 21 February 2014)

The accuracy of current theoretical descriptions of nuclear masses is studied. Ten theoretical models of various kinds are taken for the study: the macroscopic-microscopic, purely microscopic (self-consistent), and models of other natures. Some of them are traditional, but still widely used, while the others are very recent. The most recently evaluated experimental masses of 2012 are taken for the test of the models. Much attention is given to the dependence of the accuracy on the region of nuclei described by the models. The macroscopic-microscopic approaches are still found to be the most accurate in the description of atomic masses. However, the recently developed purely microscopic models (the Hartree-Fock-Bogoliubov approach) reach comparable accuracy. A strong dependence of the accuracy on the region of nuclei described is found, knowledge of which is crucial for a realistic description of specific nuclei.

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ILLUSTRATION OF ACCURACY OF PRESENTLY USED NUCLEAR-MASS MODELS

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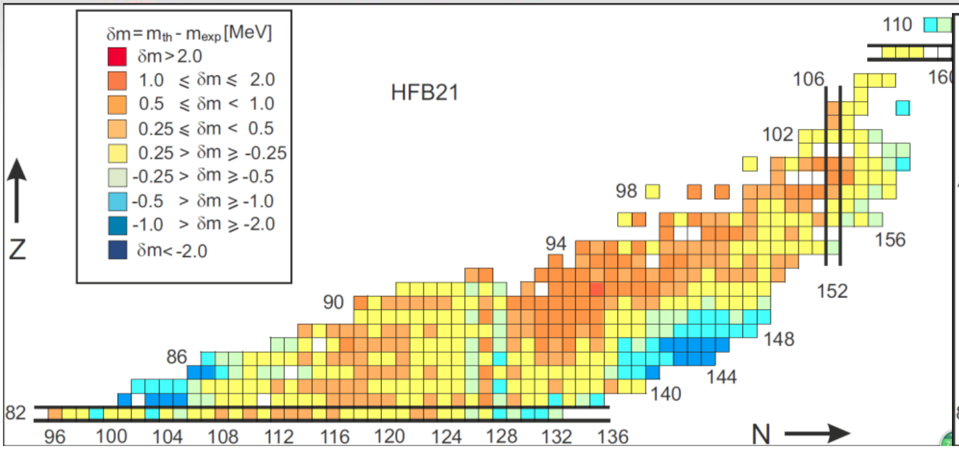
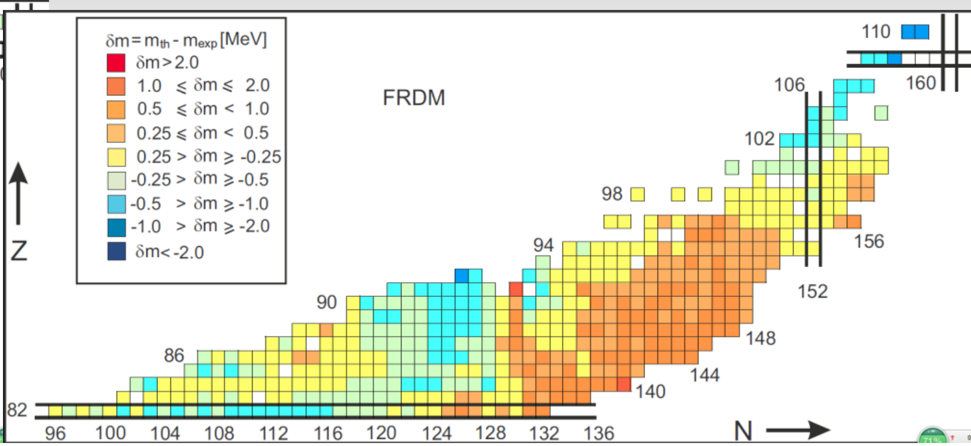
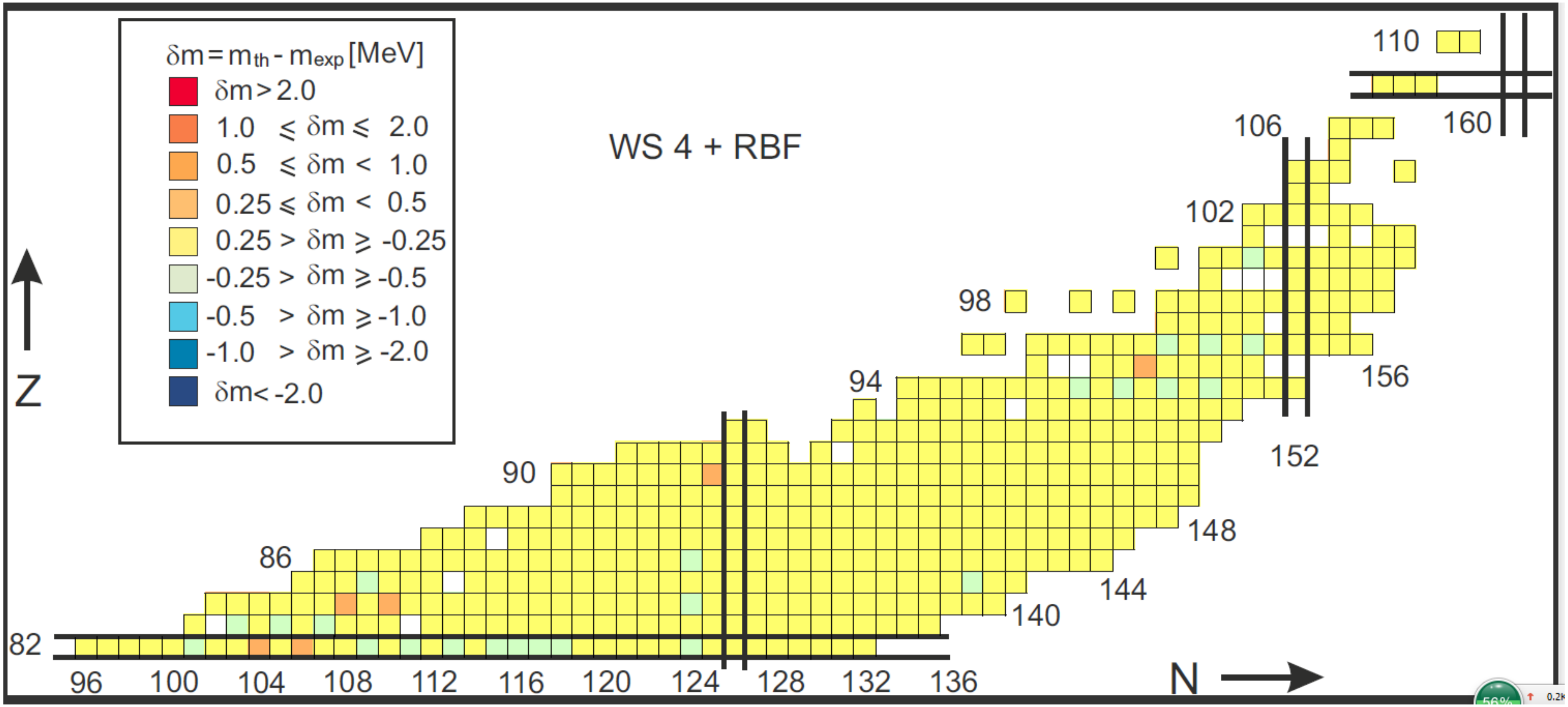
(Received June 30, 2014; revised version received August 25, 2014)







courtesy of Adam Sobiczewski

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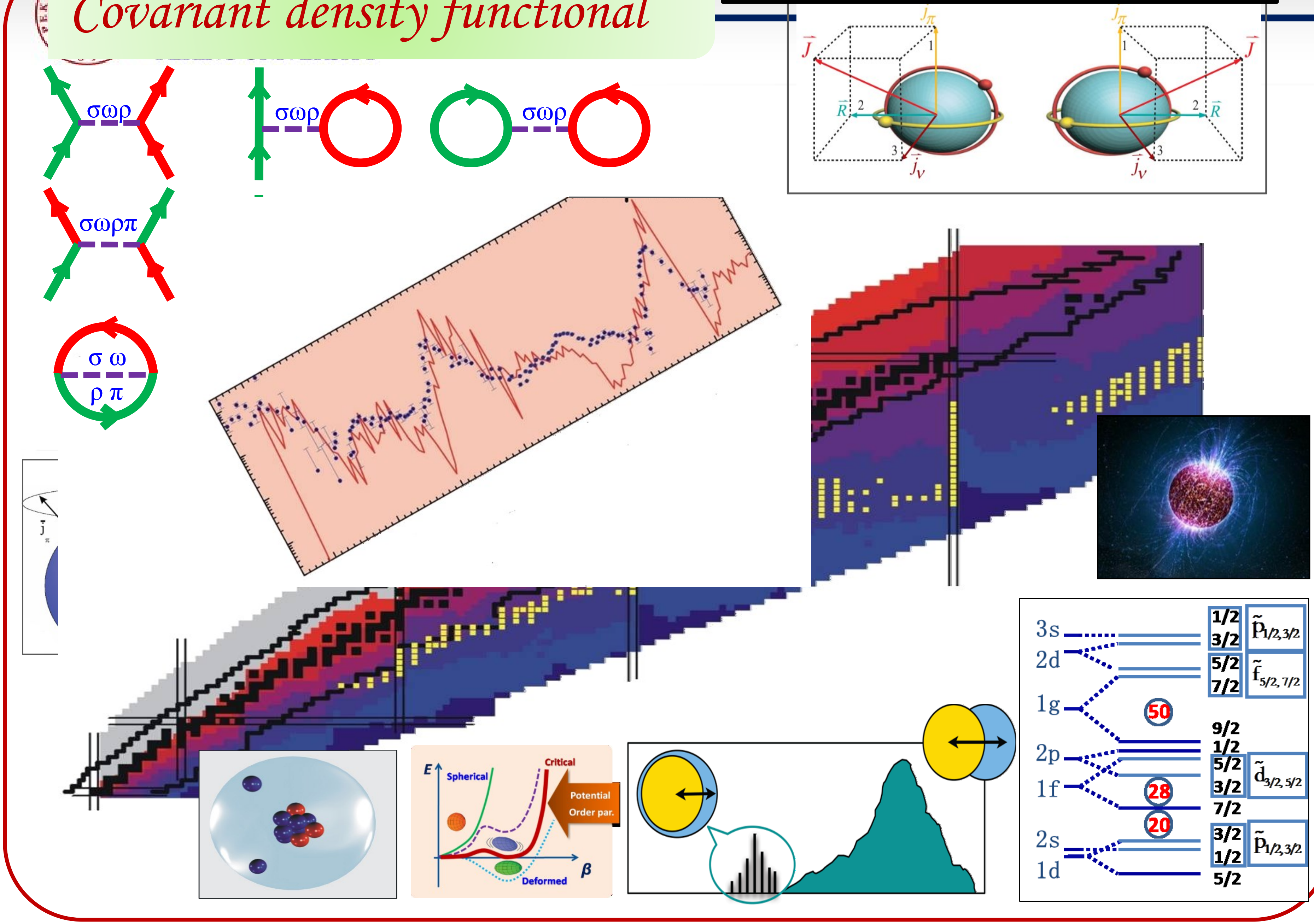
- ☐ Perspectives

Covariant density functional

Progress in Physics. 31(2011)199-336.



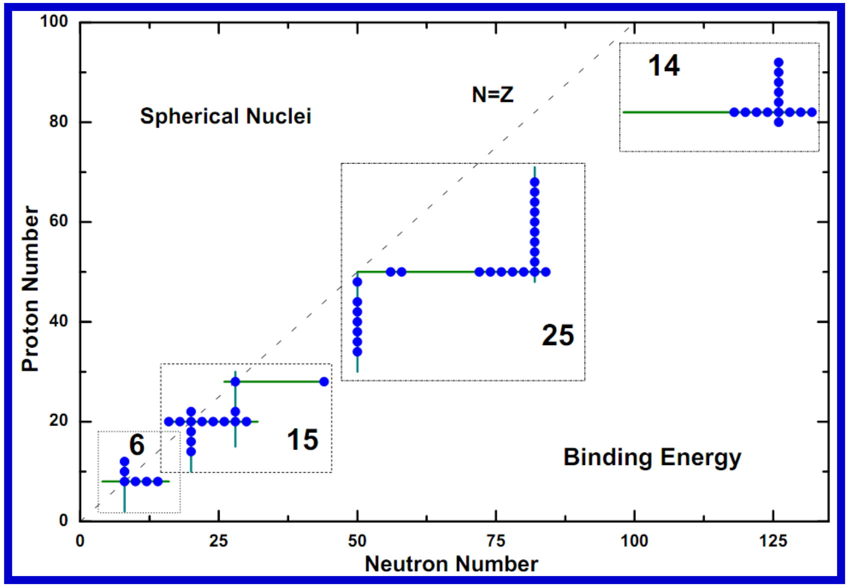
PEKING UNIVERSITY

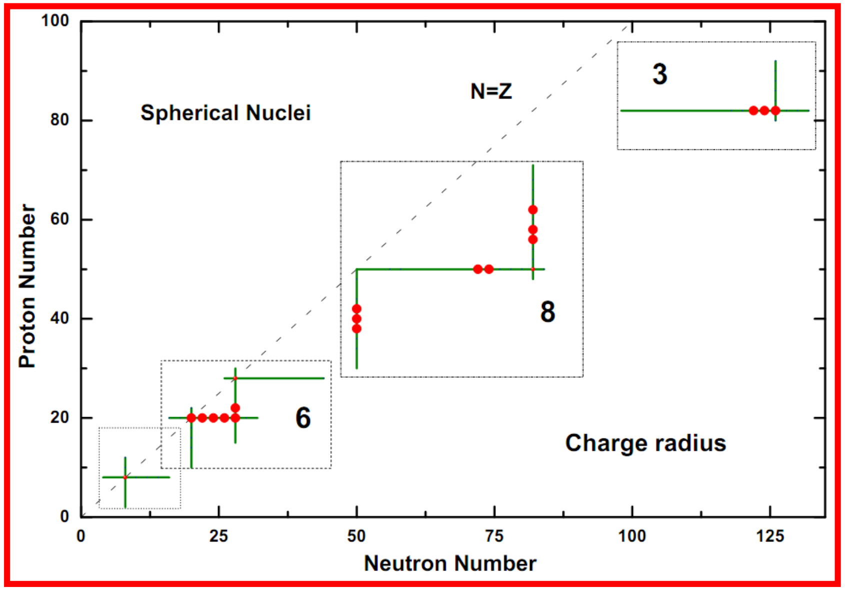
CDFT with non-linear point coupling interaction

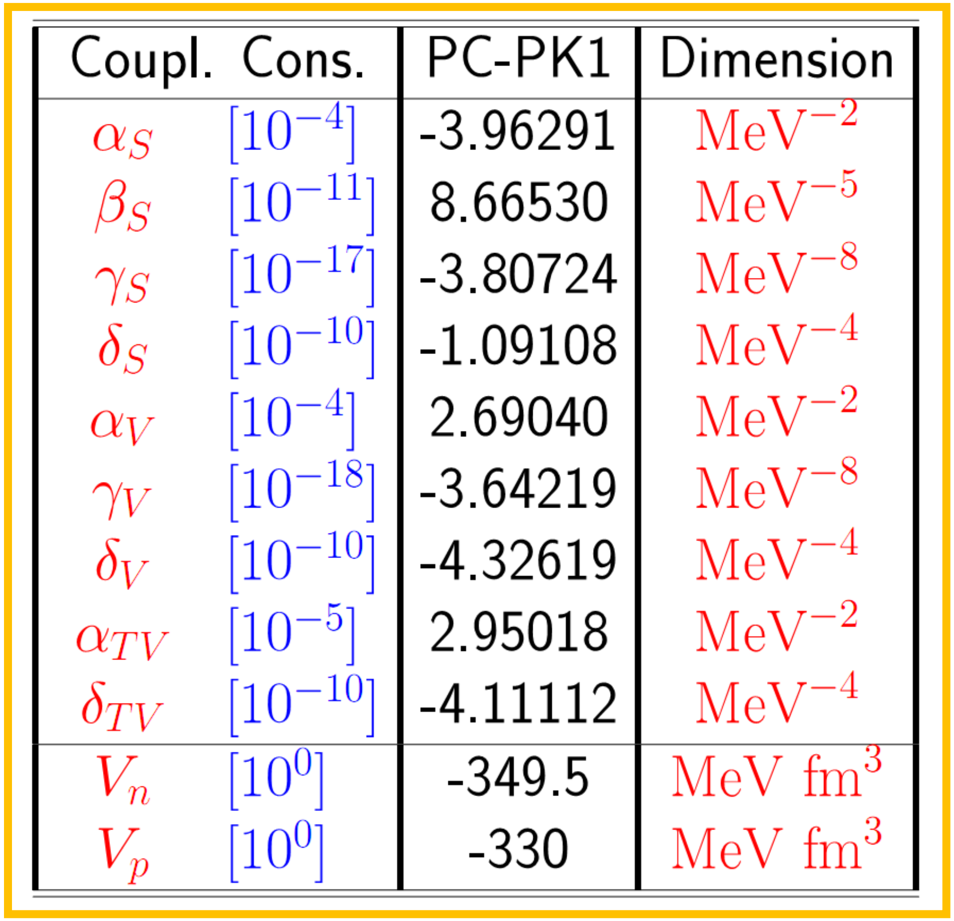
Lagrangian density

$$
\begin{aligned}
L = & \bar{\psi}(i\gamma_{\mu}\partial^{\mu} - m)\psi \\
& -\frac{1}{2}\alpha_{S}(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_{V}(\bar{\psi}\gamma_{\mu}\psi)(\bar{\psi}\gamma^{\mu}\psi) - \frac{1}{2}\alpha_{TV}(\bar{\psi}\vec{\tau}\gamma_{\mu}\psi)(\psi\vec{\tau}\gamma' \psi) \\
& -\frac{1}{3}\beta_{S}(\bar{\psi}\psi)^{3} - \frac{1}{4}\gamma_{S}(\bar{\psi}\psi)^{4} - \frac{1}{4}\gamma_{V}[(\bar{\psi}\gamma_{\mu}\psi)(\bar{\psi}\gamma^{\mu}\psi)]^{2} \\
& -\frac{1}{2}\delta_{S}\partial_{\nu}(\bar{\psi}\psi)\partial^{\nu}(\bar{\psi}\psi) - \frac{1}{2}\delta_{V}\partial_{\nu}(\bar{\psi}\gamma_{\mu}\psi)\partial^{\nu}(\bar{\psi}\gamma^{\mu}\psi) - \frac{1}{2}\delta_{TV}\partial_{\nu}(\bar{\psi}\vec{\tau}\gamma_{\mu}\psi)\sigma\ (\psi\vec{\tau}\gamma_{\mu}\psi) \\
& -e\frac{1-\tau_{3}}{2}\bar{\psi}\gamma^{\mu}\psi A_{\mu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}
\end{aligned}
$$

Covariant Density Functional: PC-PK1



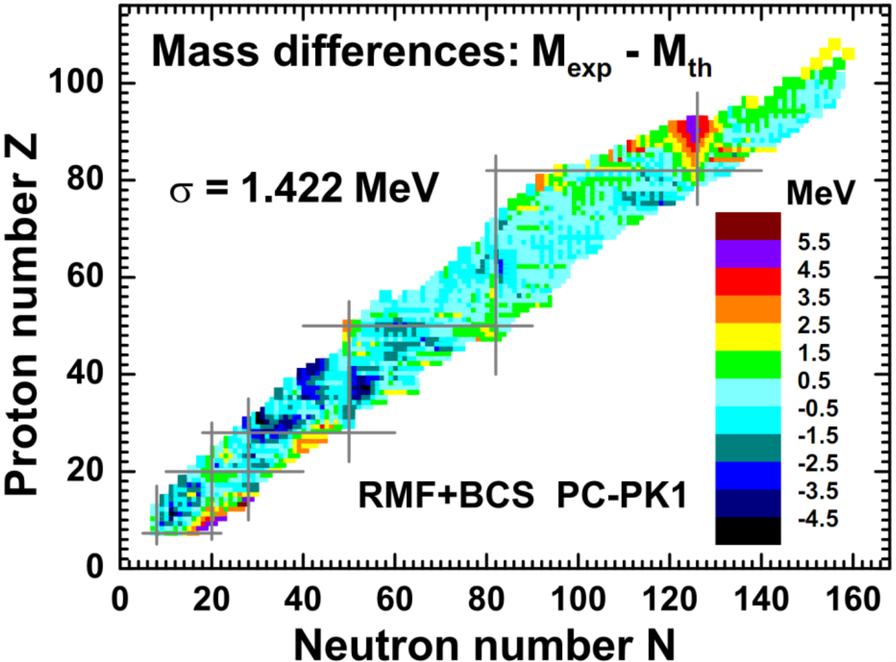




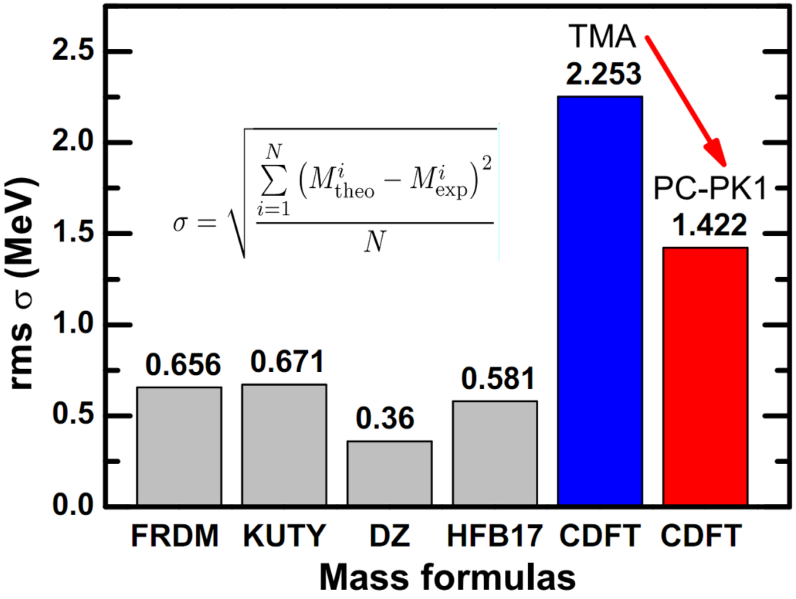
Coupl. Cons.		PC-PK1	Dimension
α_S	$[10^{-4}]$	-3.96291	MeV^{-2}
β_S	$[10^{-11}]$	8.66530	MeV^{-5}
γ_S	$[10^{-17}]$	-3.80724	MeV^{-8}
δ_S	$[10^{-10}]$	-1.09108	MeV^{-4}
α_V	$[10^{-4}]$	2.69040	MeV^{-2}
γ_V	$[10^{-18}]$	-3.64219	MeV^{-8}
δ_V	$[10^{-10}]$	-4.32619	MeV^{-4}
α_{TV}	$[10^{-5}]$	2.95018	MeV^{-2}
δ_{TV}	$[10^{-10}]$	-4.11112	MeV^{-4}
V_n	$[10^{0}]$	-349.5	$\mathrm{MeV\ fm}^{3}$
V_p	$[10^{0}]$	-330	$\mathrm{MeV\ fm}^{3}$

Zhao, Li, Yao, Meng, PRC 82, 054319 (2010)

Nuclear Mass

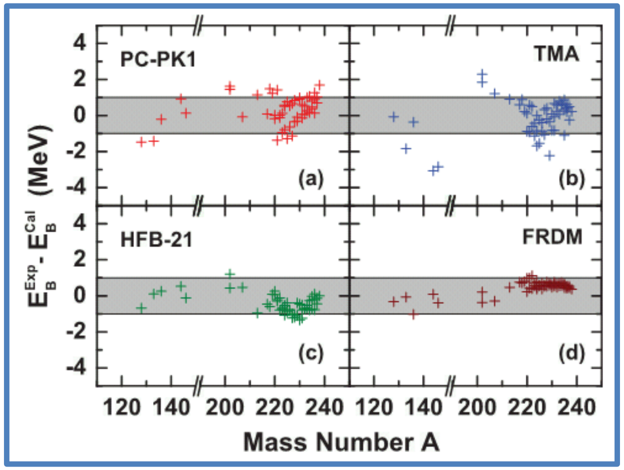


Data for 2149 nuclei from Audi et al. NPA2003



$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(M^i_{\text{theo}} - M^i_{\text{exp}}\right)^2}{N}}$$

Meng, Peng, Zhang, Zhao, Front. Phys. 8, 55 (2013)



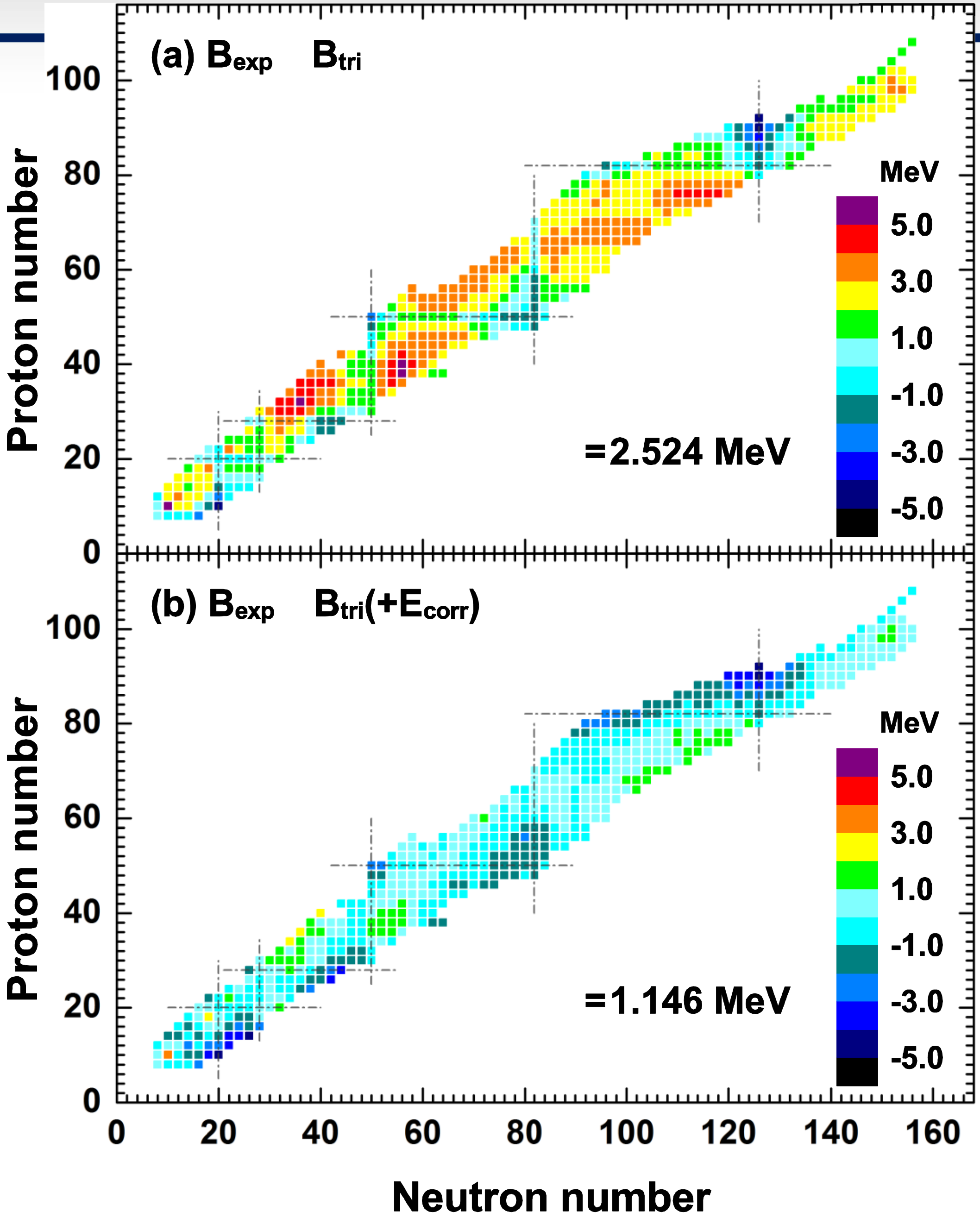
Long-term plan

Improve the mass description based on CDFT to $\sigma \sim 0.5$ MeV.

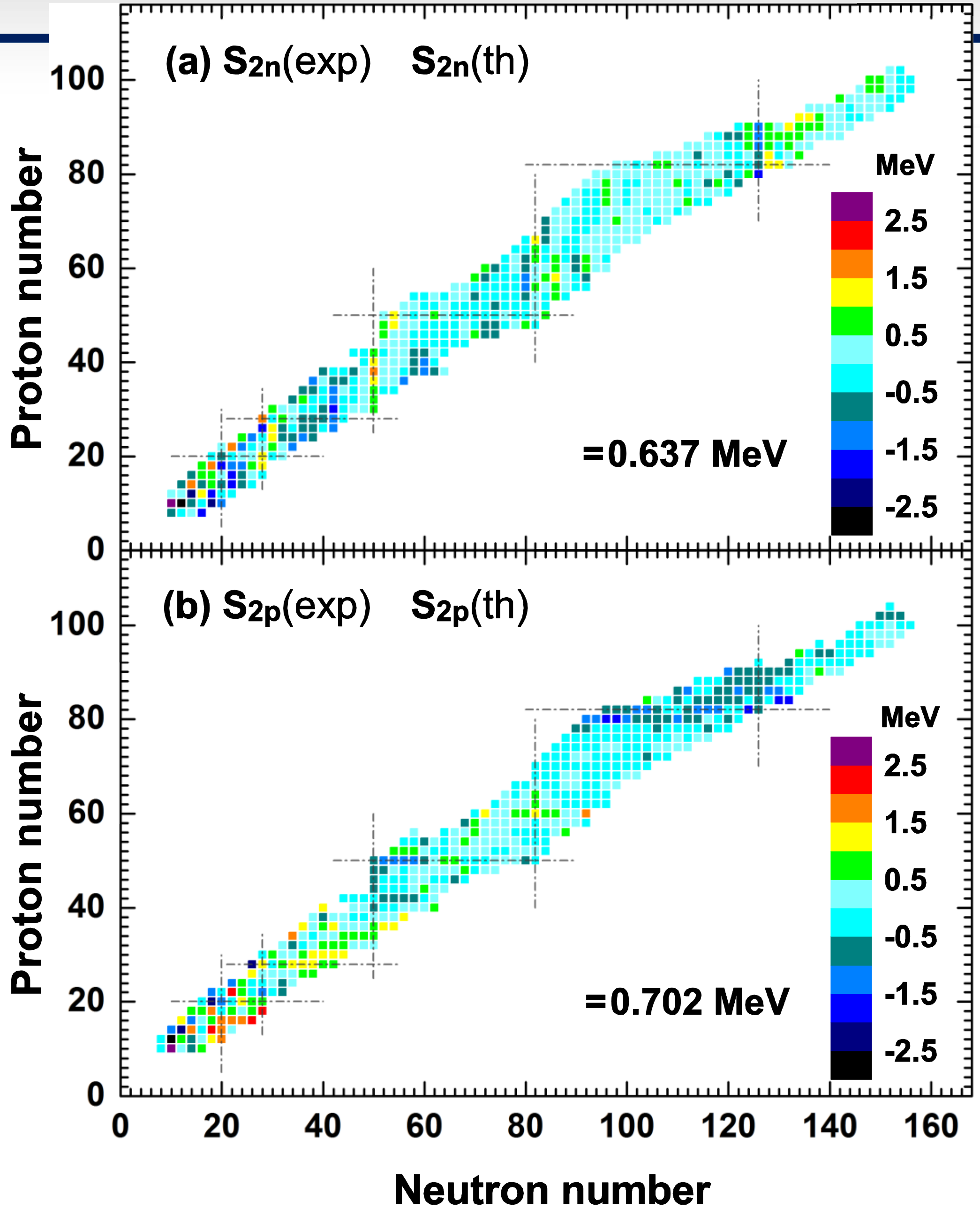
Zhao, Song, Sun. Geissel, Meng, Phys. Rev. C 86, 064324 (2012)

Crucial test for covariant density functional theory with new and accurate mass measurements from Sn to Pa

Discrepancy of the CDFT calculated binding energies by PC-PK1 with the data for 575 even-even nuclei: (a) the CDFT calculated binding energies; (b) the dynamical correlation energies taken into account.



Dynamical correlation energies by 5DCH



Discrepancy of the PC-PK1 two-neutron (panel a) and two-proton (panel b) separation energies extracted from the calculated binding energies including the DCEs with respect to the data

Dynamical correlation energies by 5DCH

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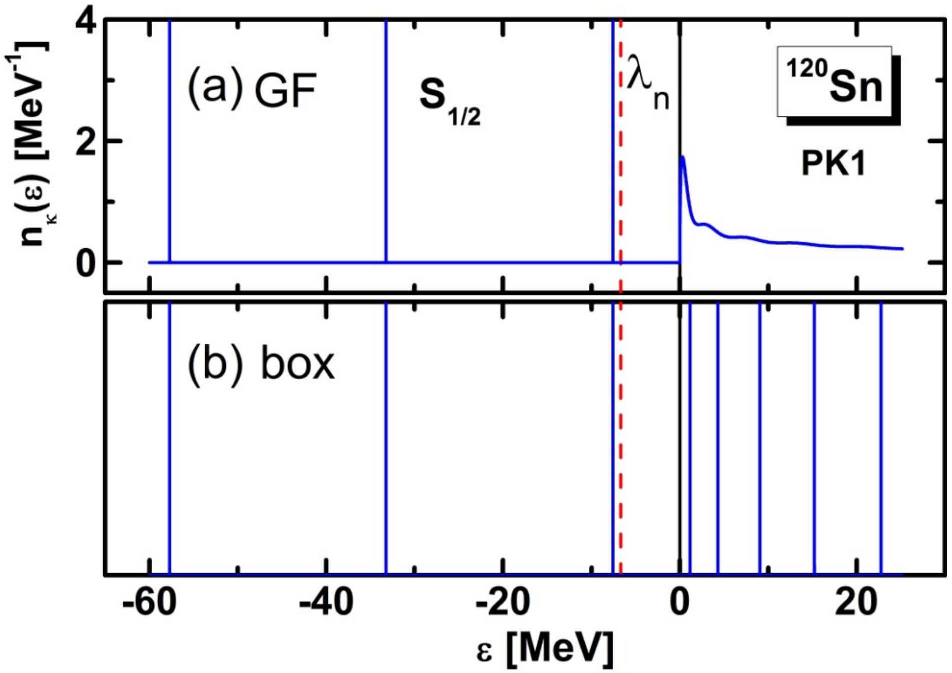
neutron density of states

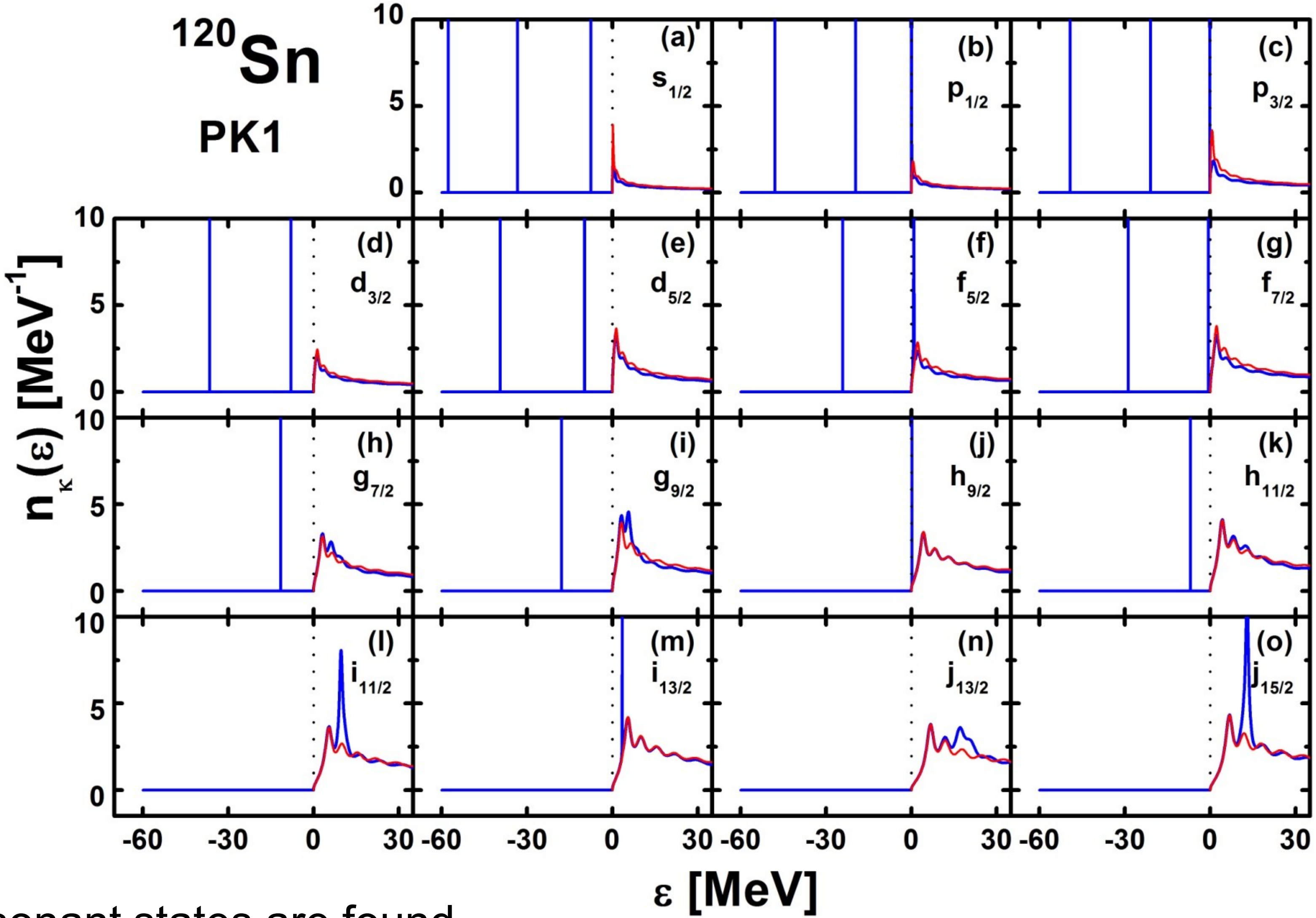


- GF: discrete bound states & continuum
- box: discretized the continuum

Table: Single-neutron energies for $s_{1/2}$ bound states in ^{120}Sn. Unit is MeV.

	GF	box
$S_{1/2}$	-57.7043	-57.7043
	-33.2498	-33.2498
	-7.5663	-7.5663

Density of states



- Resonant states are found
- Energy and with for resonant states extracted from the density of states

Sun, Zhang, Zhang, Hu and Meng, Phys. Rev. C 90, 054321 (2014)

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Relativistic Continuum Hartree-Bogoliubov theory

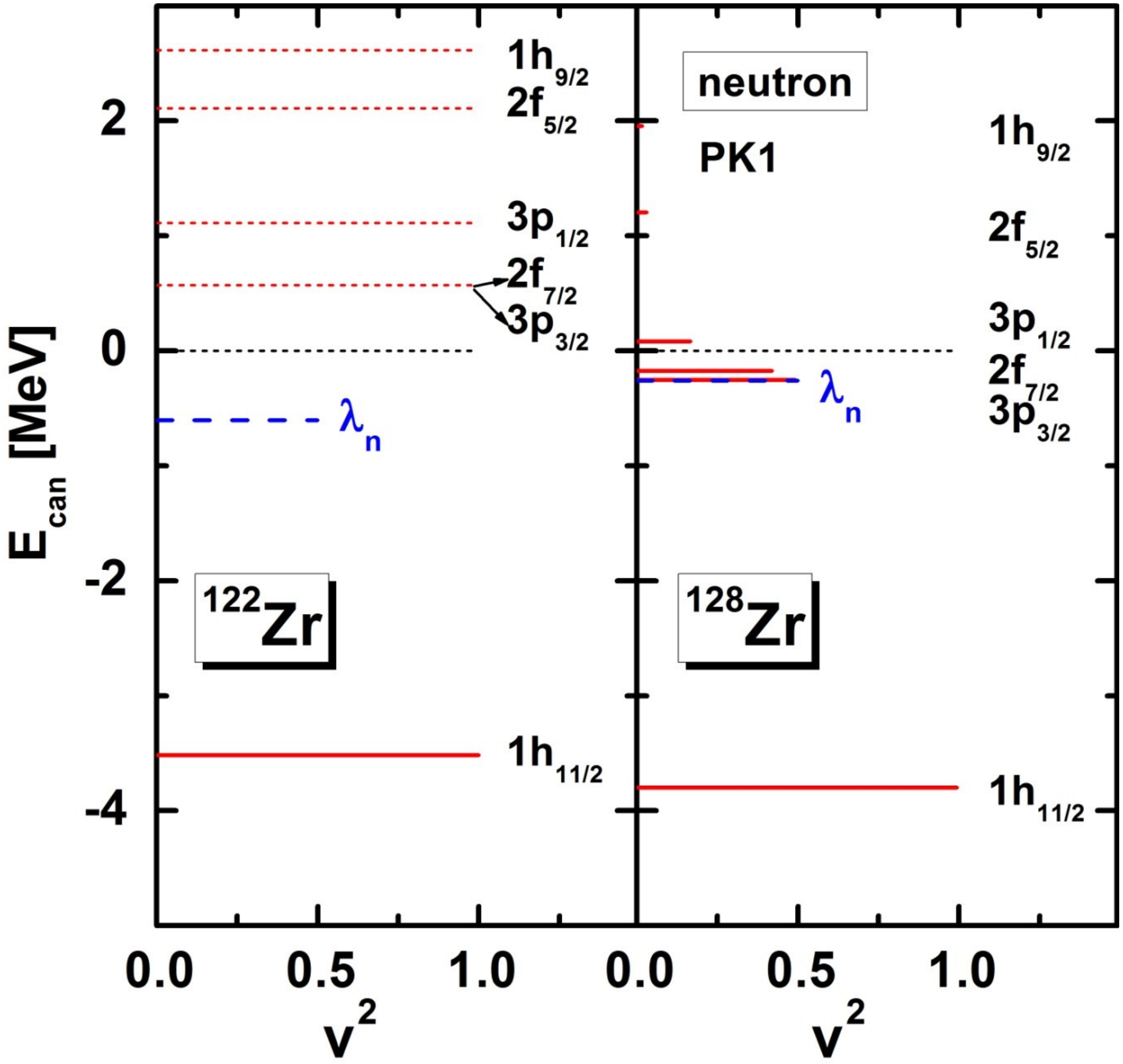
- To describe bound states, continuum and the coupling between them, RHB equation must be solved in suitable methods
- Radial RHB equation in spherical case

(J. Meng, Nucl. Phys. A**635** (1998) 3, and references therein.)

$$\psi_U^i = \frac{1}{r}\begin{pmatrix} iG_U^{i\kappa}(r)Y_{jm}^{l}(\theta,\phi) \\ -F_U^{i\kappa}(r)Y_{jm}^{\tilde{l}}(\theta,\phi)\end{pmatrix}\chi_t(t) \qquad \psi_V^i = \frac{1}{r}\begin{pmatrix} iG_V^{i\kappa}(r)Y_{jm}^{l}(\theta,\phi) \\ -F_V^{i\kappa}(r)Y_{jm}^{\tilde{l}}(\theta,\phi)\end{pmatrix}\chi_t(t)$$

$$\left\{\begin{array}{rcl}
\dfrac{dG_U(r)}{dr} + \dfrac{\kappa}{r}G_U(r) - (E+\lambda-V(r)+S(r))F_U(r) + r^2\Delta(r)F_V(r) & = & 0, \\
\dfrac{dF_U(r)}{dr} - \dfrac{\kappa}{r}F_U(r) + (E+\lambda-V(r)-S(r))G_U(r) + r^2\Delta(r)G_V(r) & = & 0, \\
\dfrac{dG_V(r)}{dr} + \dfrac{\kappa}{r}G_V(r) + (E-\lambda+V(r)-S(r))F_V(r) + r^2\Delta(r)F_U(r) & = & 0, \\
\dfrac{dF_V(r)}{dr} - \dfrac{\kappa}{r}F_V(r) - (E-\lambda+V(r)+S(r))G_V(r) + r^2\Delta(r)G_U(r) & = & 0,
\end{array}\right.$$

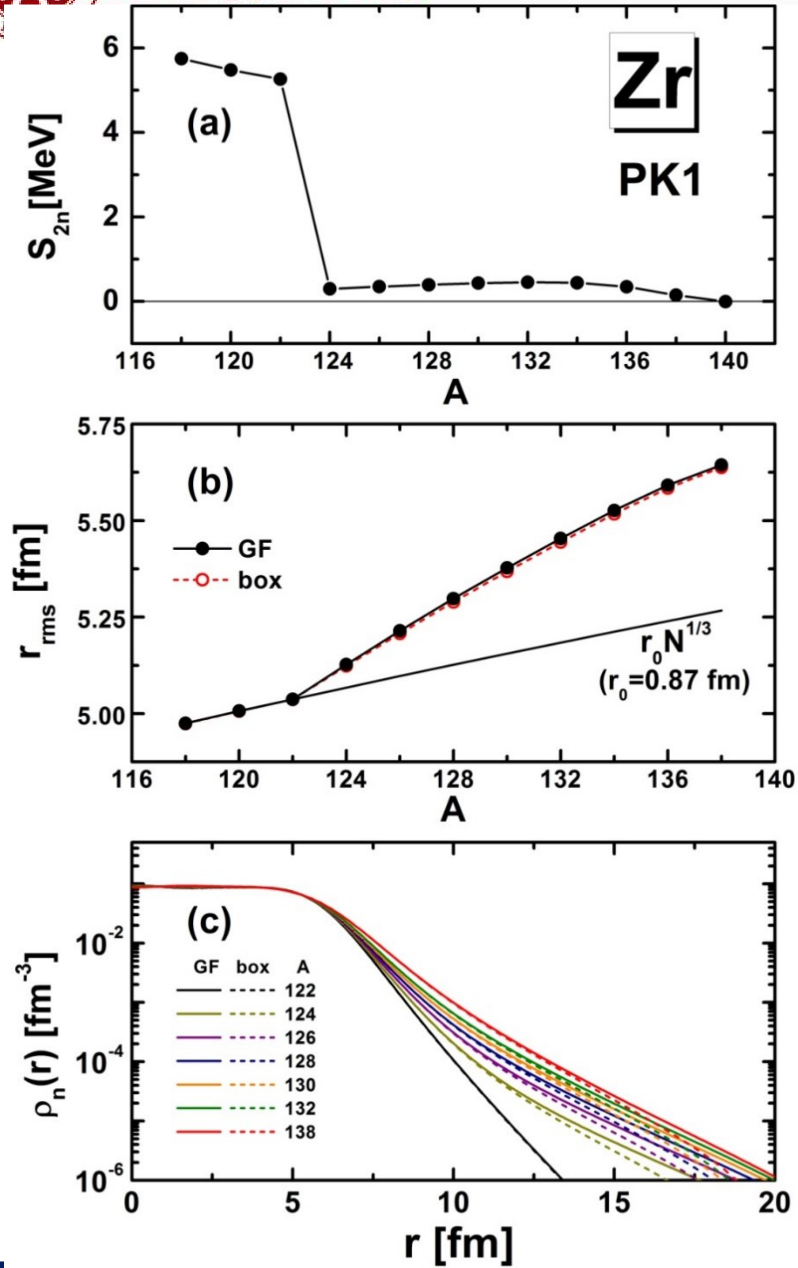
Single Particle Energy in canonical basis



Giant halo

Meng and Ring, PRL 80 (1998)460

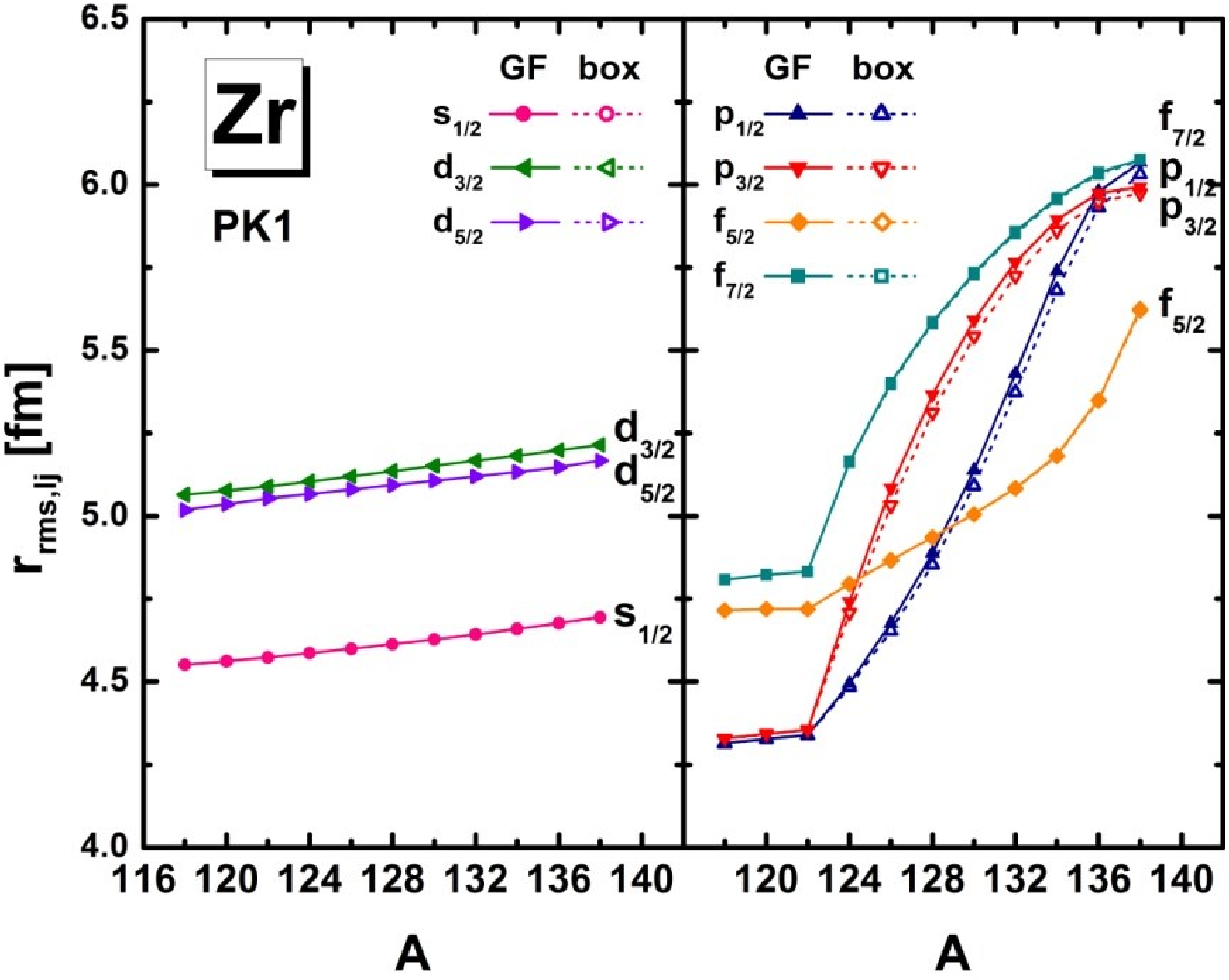
Giant halos in Zr isotopes



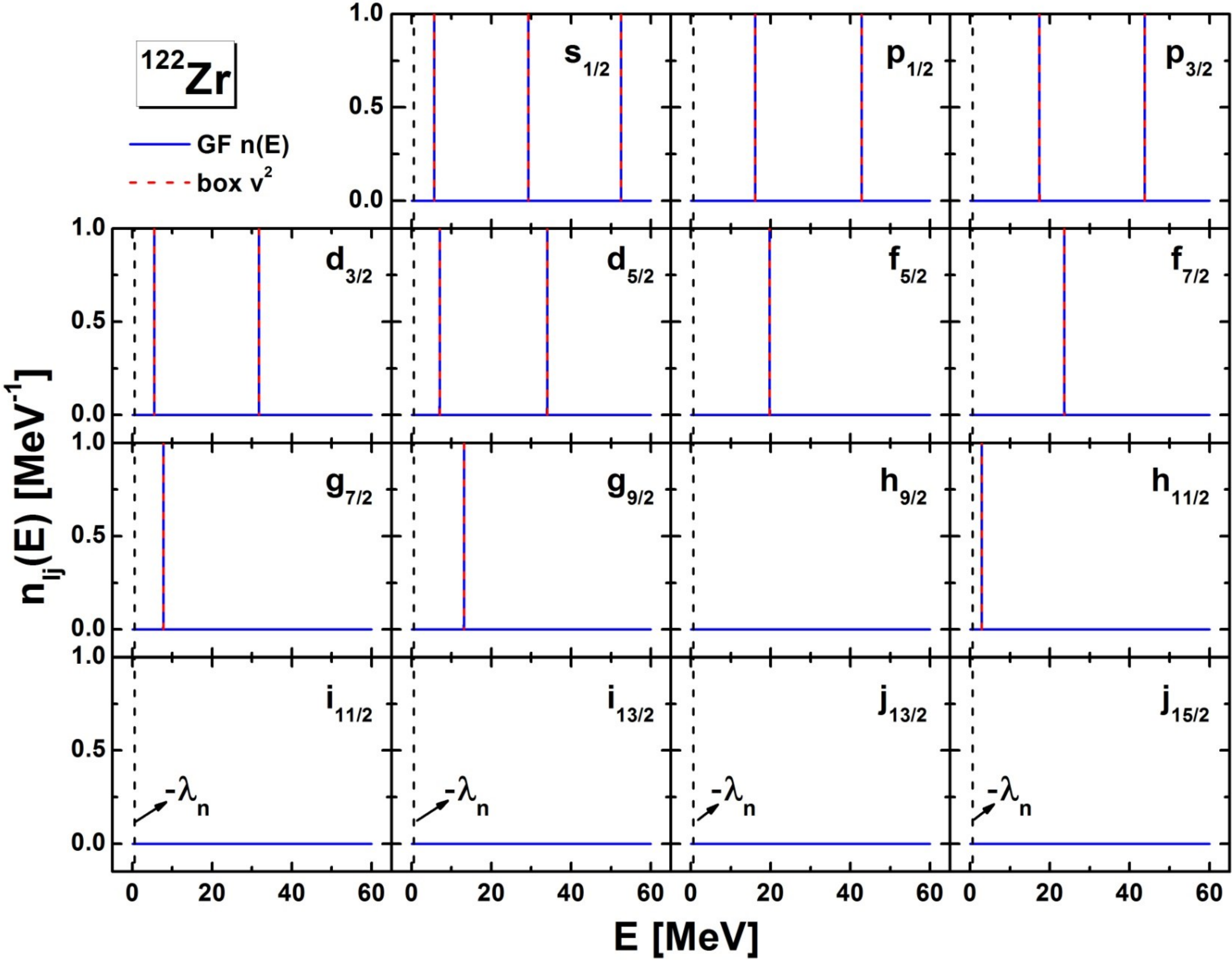
MengPRL1998
SandulescuPRC2003
GrassoPRC2006
ZhangPRC2012

- ☐ Neutron density
  - Density extends with long tails;
  - GF method describe the asymptotic densities for the weakly bound nuclei very well.

Neutron radii



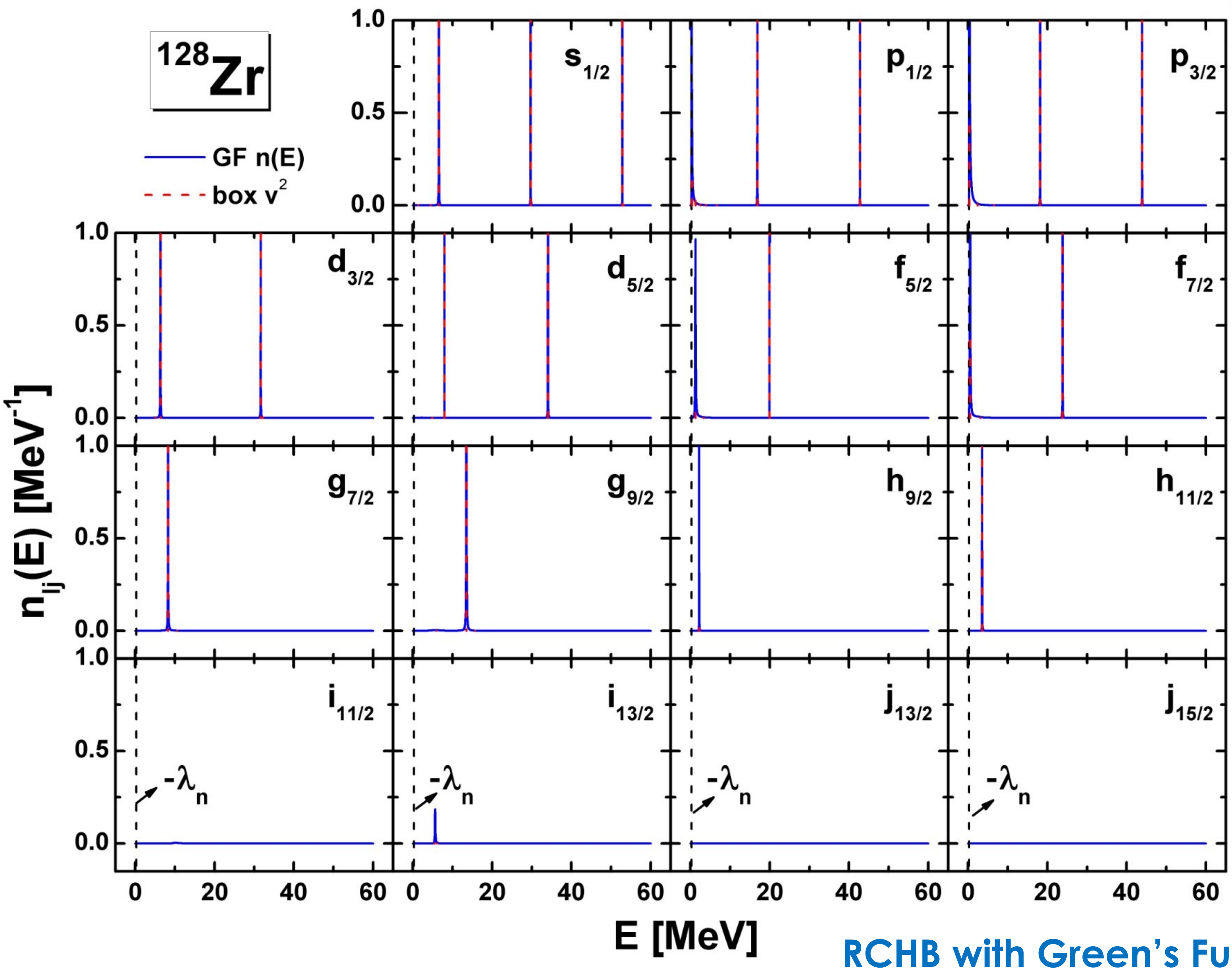
Occupation Number Density



Sun, Zhang, Zhang, Hu and Meng, Phys. Rev. C 90, 054321 (2014)

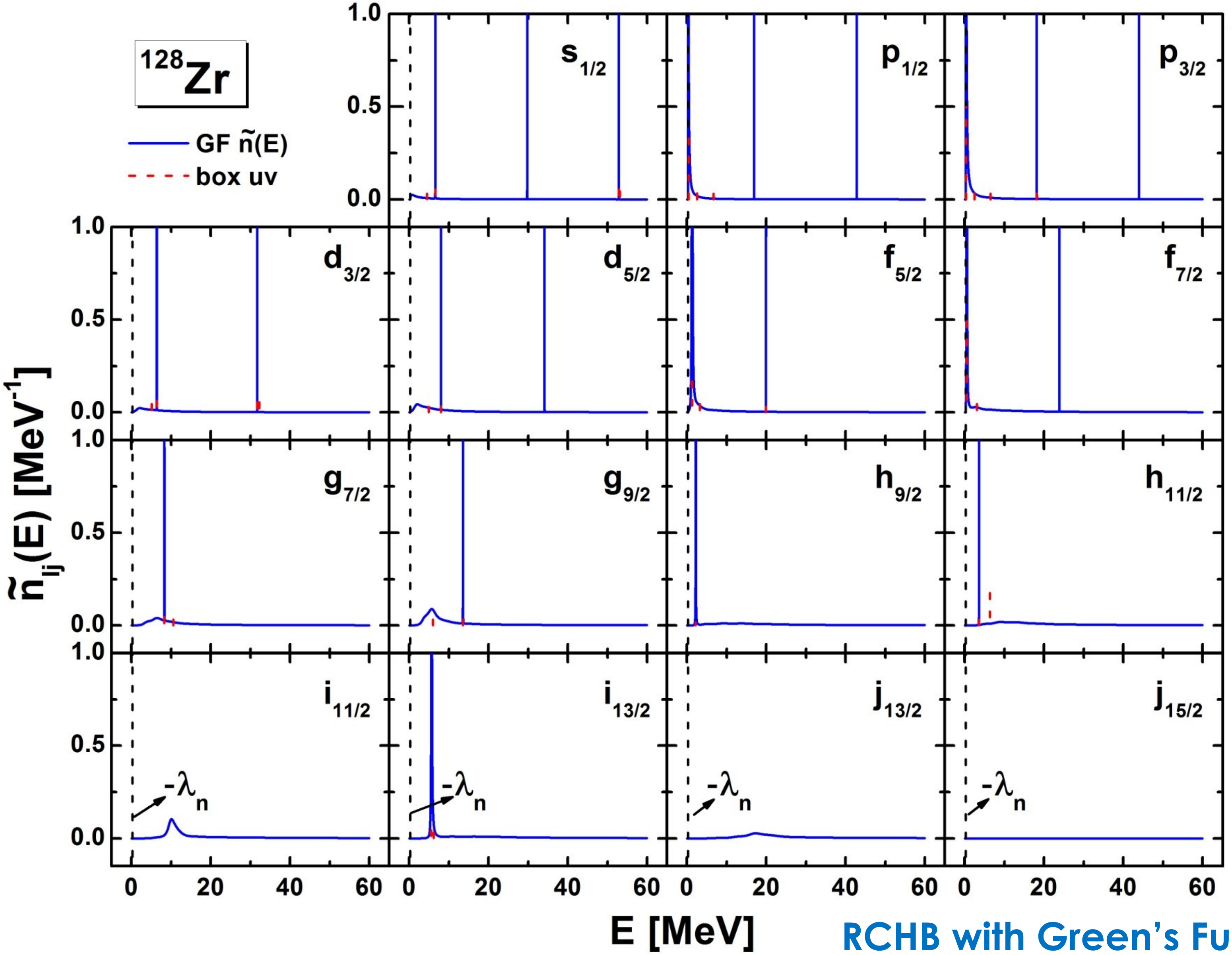
RCHB with Green's Function

Occupation Number Density



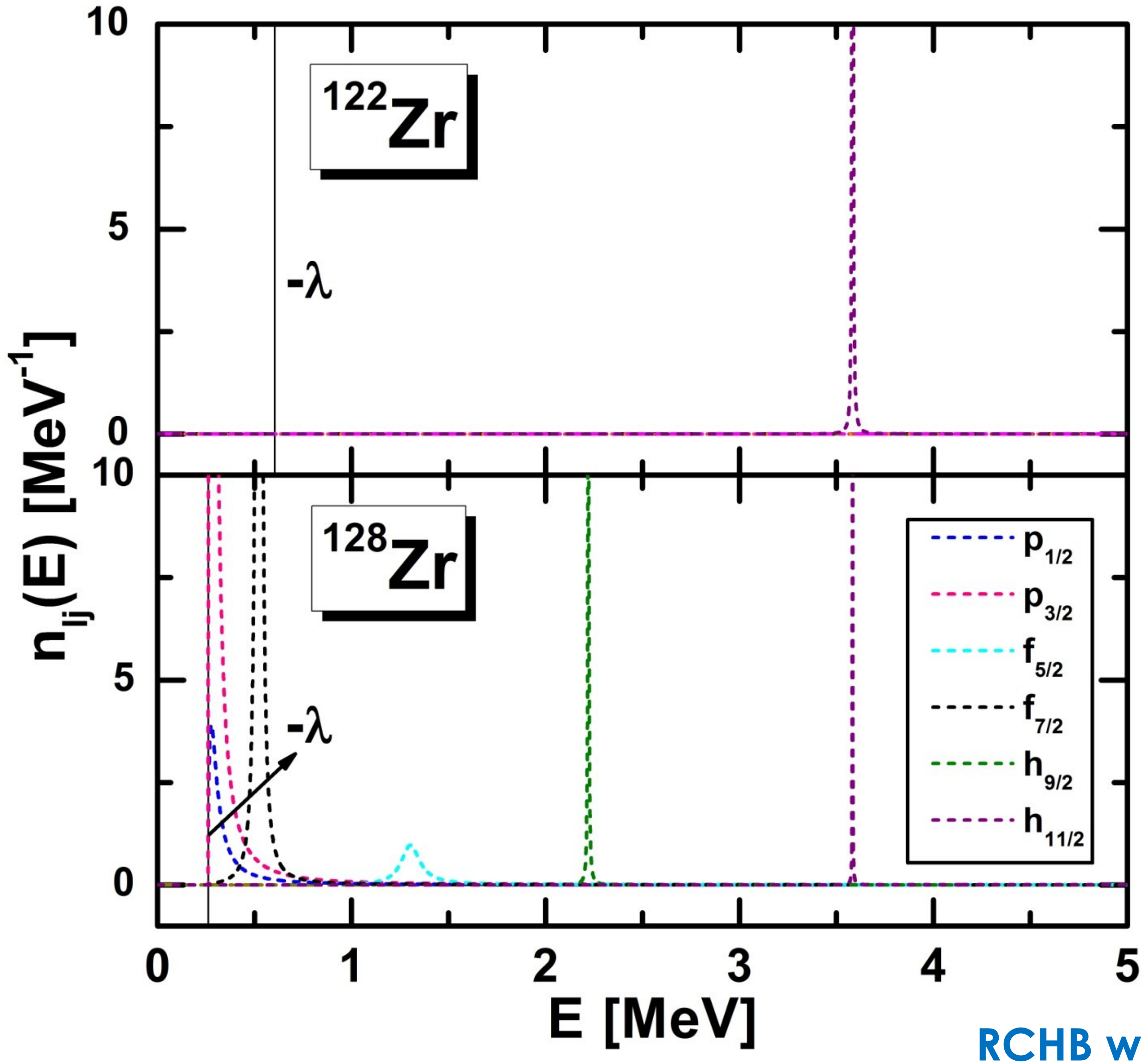
RCHB with Green's Function

Pairing Density



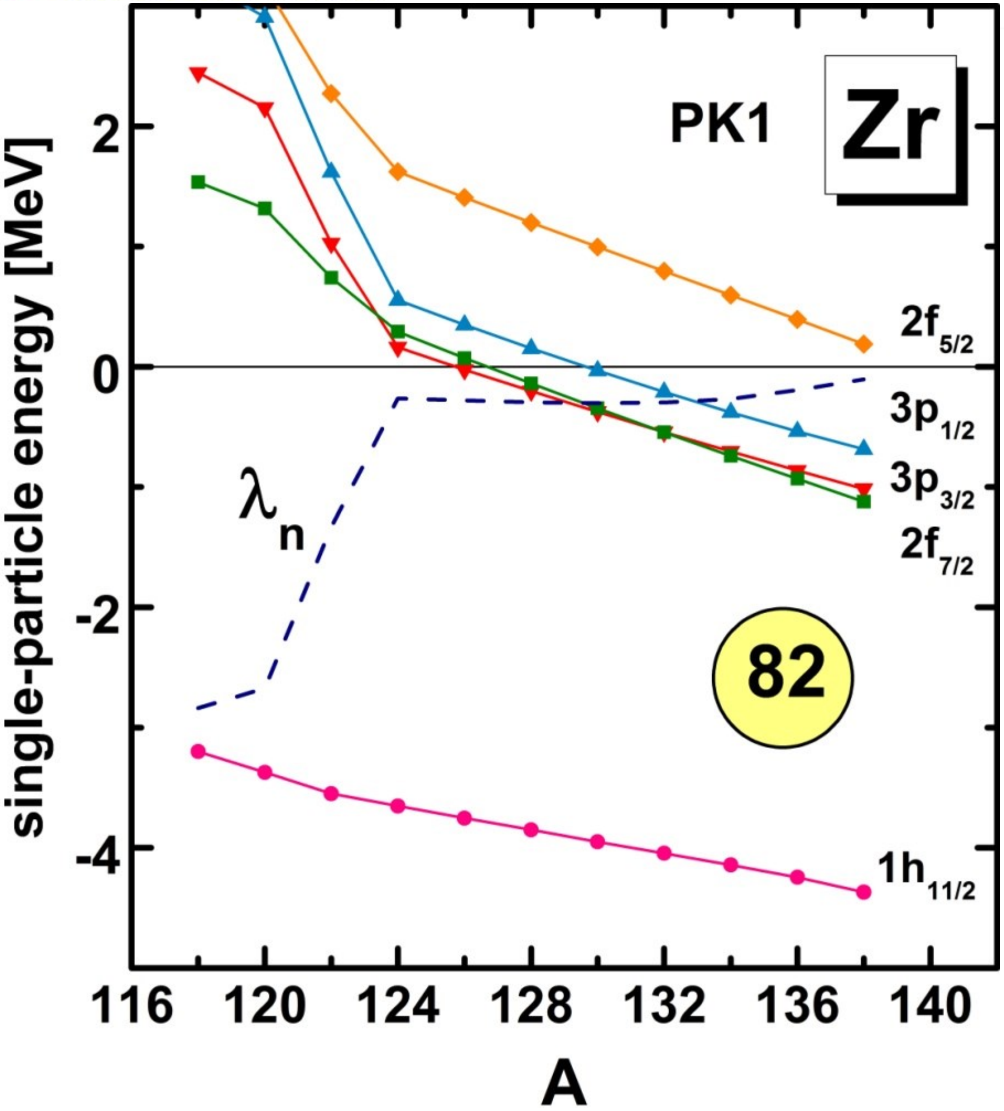
RCHB with Green's Function

Occupation Number Density near Fermi Surface



RCHB with Green's Function

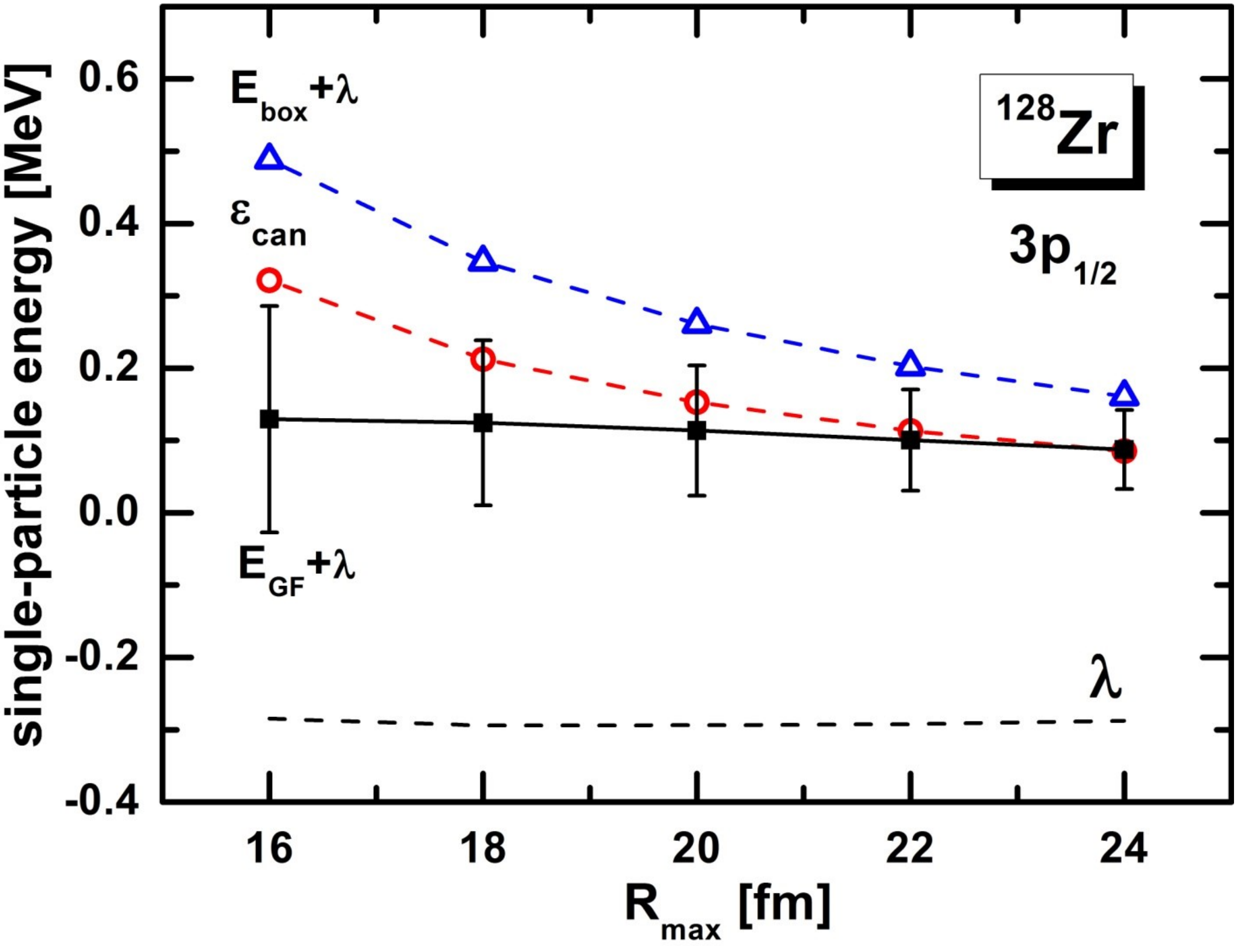
Single-particle levels



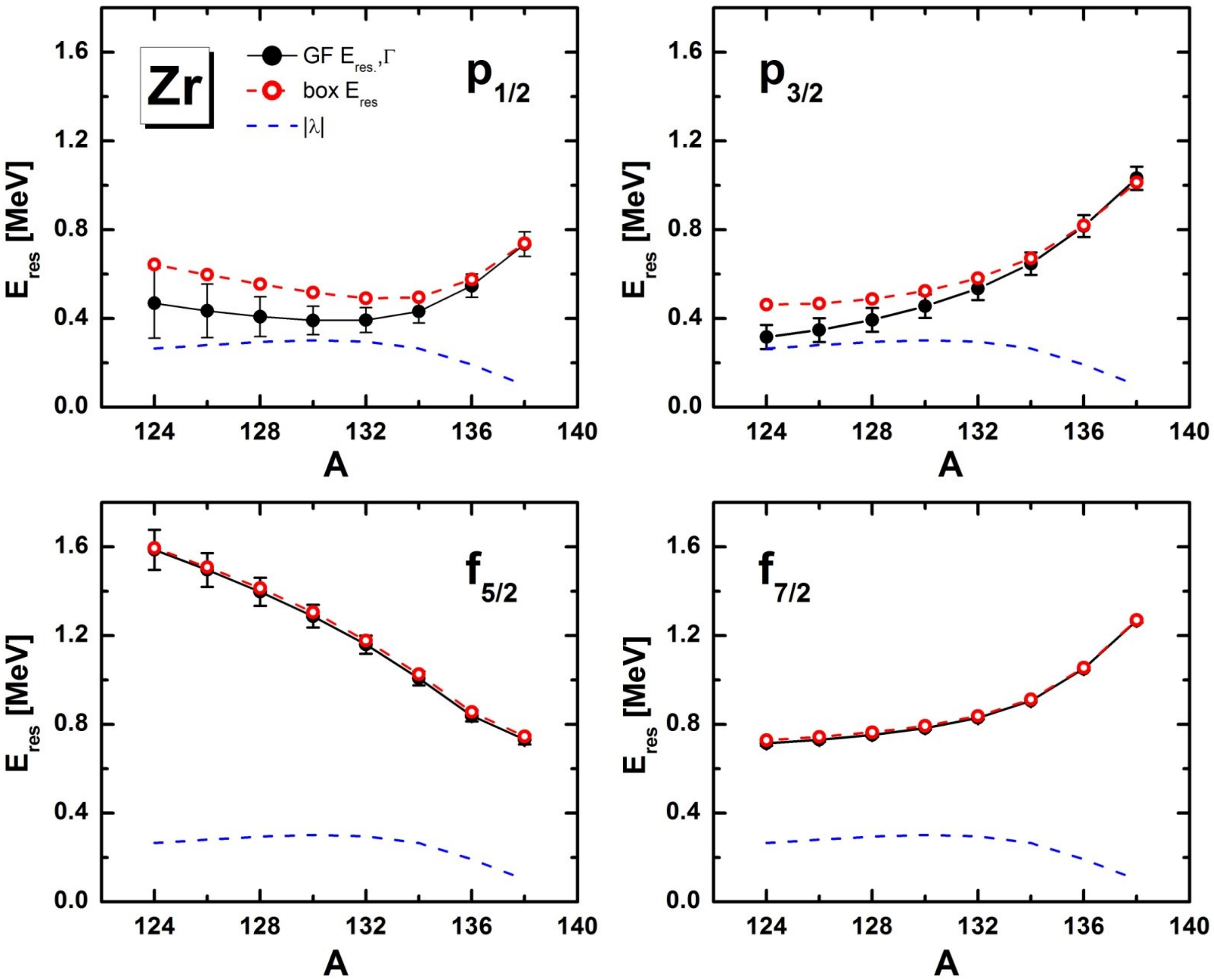
Meng and Ring, PRL 80 (1998)460

- Single-particle levels in canonical basis around neutron Fermi surface

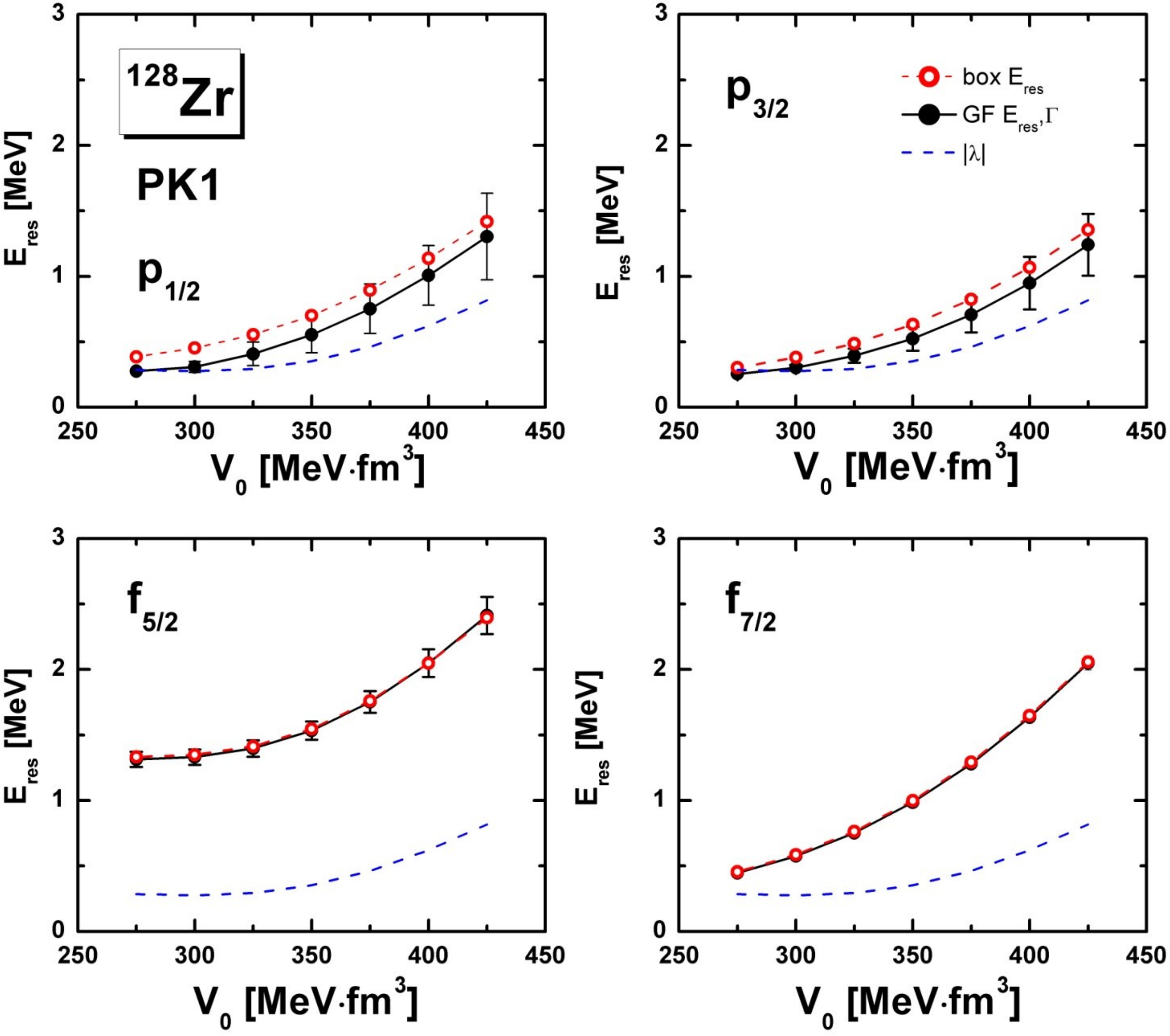
Single-particle energy



Quasi-particle resonances



Pairing and qp resonances



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Explore the nuclear chart boundary / nucleus existence limit

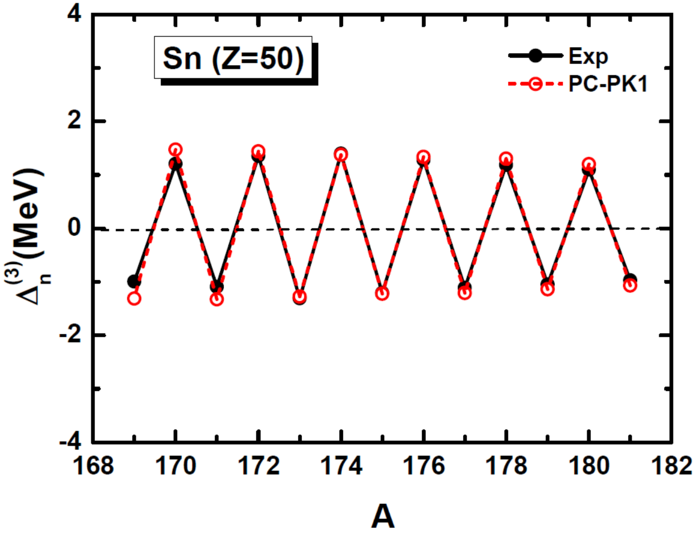
- The neutron drip-line nuclei extended by the continuum couplings should be emphasized.
- Ranging from O to Z=130
- Relativistic Continuum Hartree-Bogoliubov theory with PC-PK1, which provide a proper treatment of pairing correlations in the continuum.

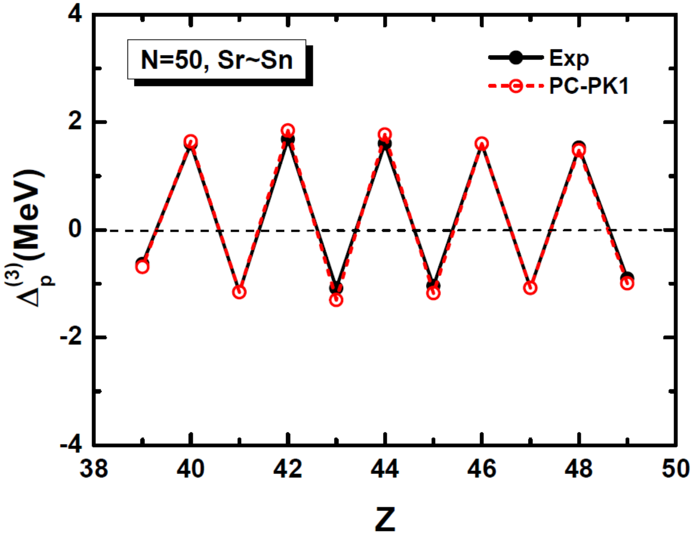
Numerical details

- PC-PK1: for nucleus with Z=8 to Z=130
- Box size: 20 fm; mesh size: 0.1 fm
- J_{max}=19/2, E_{cut}=100 MeV
- Density-dependent delta pairing force

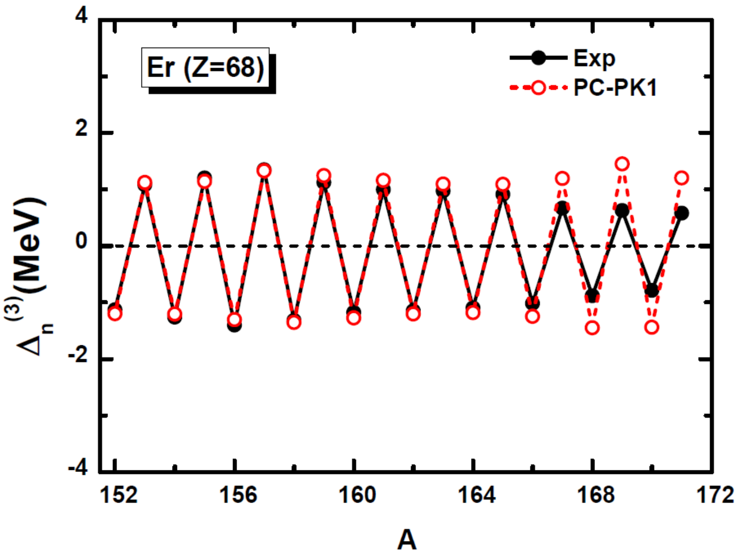
$$V^{pp}(\boldsymbol{r},\boldsymbol{r}') = \frac{V_0}{4}(1-P^{\sigma})\delta(\boldsymbol{r}-\boldsymbol{r}')(1-\frac{\rho(\boldsymbol{r})}{\rho_{sat}})$$

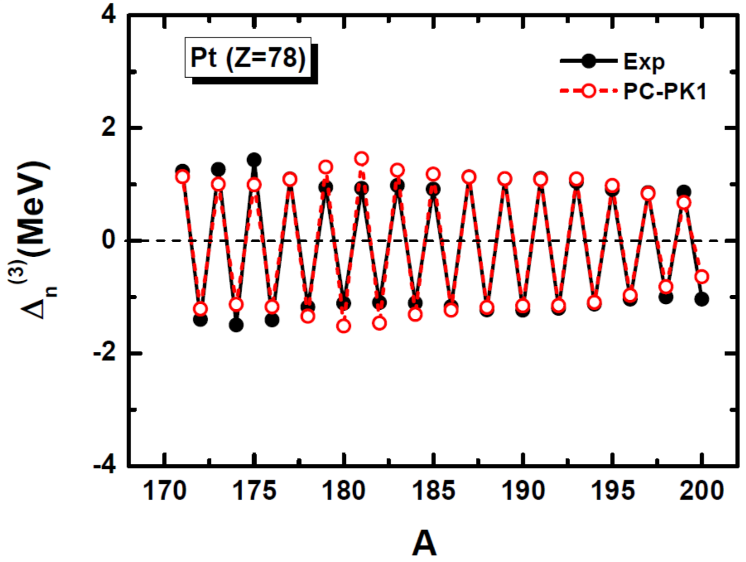
with the saturation density $\rho_{sat} = 0.152\ \mathrm{fm}^{-3}$, and the pairing force strength $V_0 = 685.0\ \mathrm{MeV}\cdot\mathrm{fm}^{-3}$

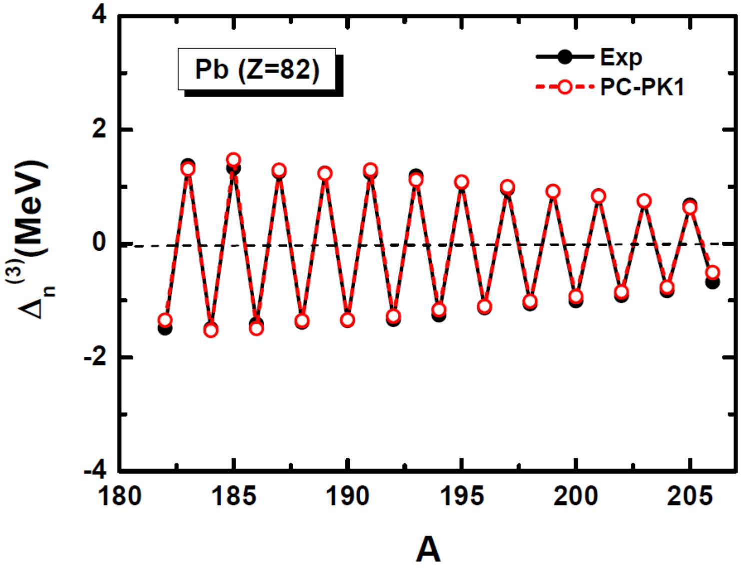


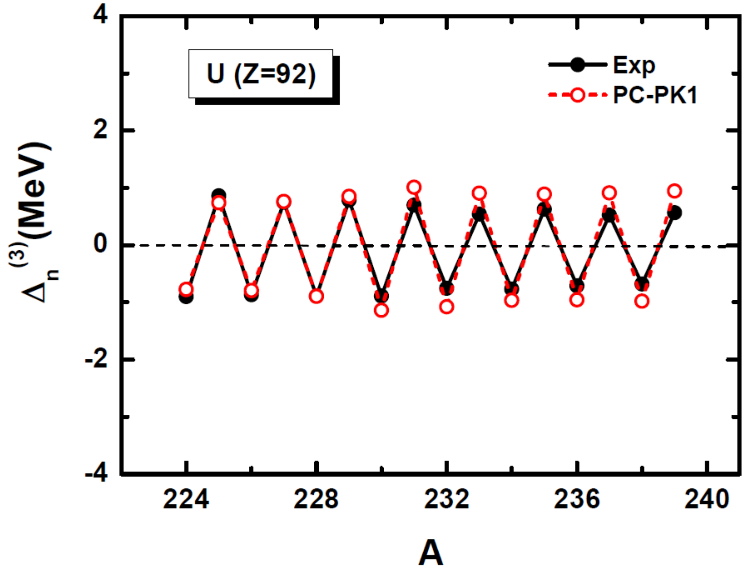


Pairing force and odd-even staggering









Drip-lines in variant models

The number of bound nuclides with between 2 and 120 protons is around 7,000 28 JUNE 2012 | VOL 486 | NATURE | 509

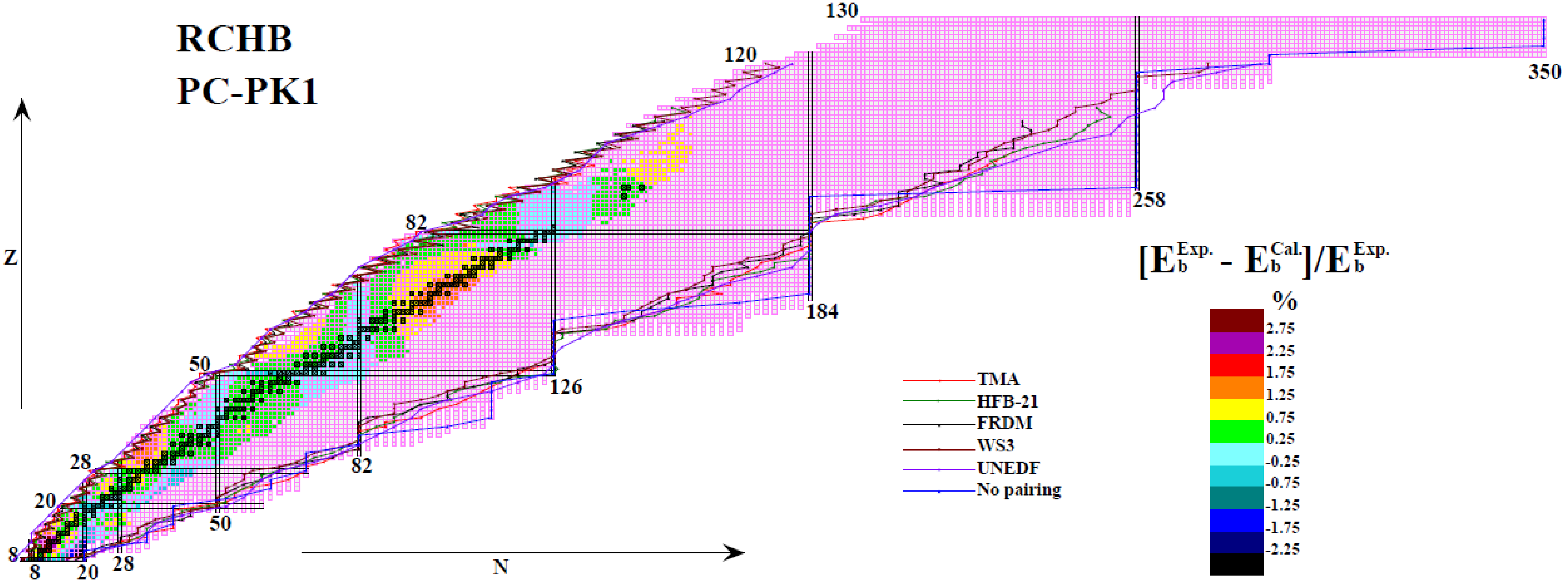


Figure: 10532 bound nuclei from Z=8 to Z=130 predicted by RCHB theory with PC-PK1. For 2227 nuclei with data, binding energy differences between data and calculated results are shown in different color. The nucleon drip-lines predicted TMA, HFB-21, WS3, FRDM , UNEDF and without pairing correlation are plotted for comparison.

Continuum contributions

Afanasjev et al PhysicsLettersB726(2013)680–684

Particle-bound e-e *Z*<120 nuclei is respectively 2040, 2050, 2057 and 2216 for DD-PC1, DD-ME2, DD-Meδ and NL3*

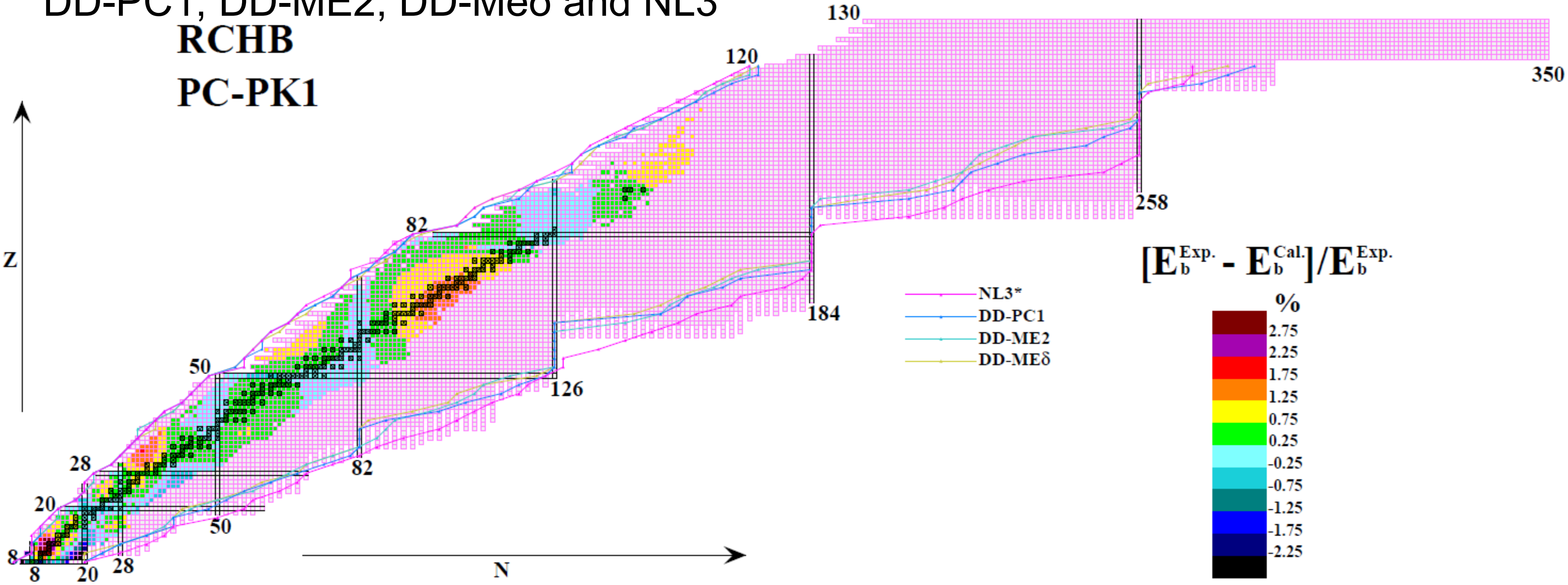


Figure: 10532 bound nuclei from Z=8 to Z=130 predicted by RCHB theory with PC-PK1. For 2227 nuclei with data, binding energy differences between data and calculated results are shown in different color. The nucleon drip-lines predicted without pairing correlation are plotted for comparison.

Continuum contributions

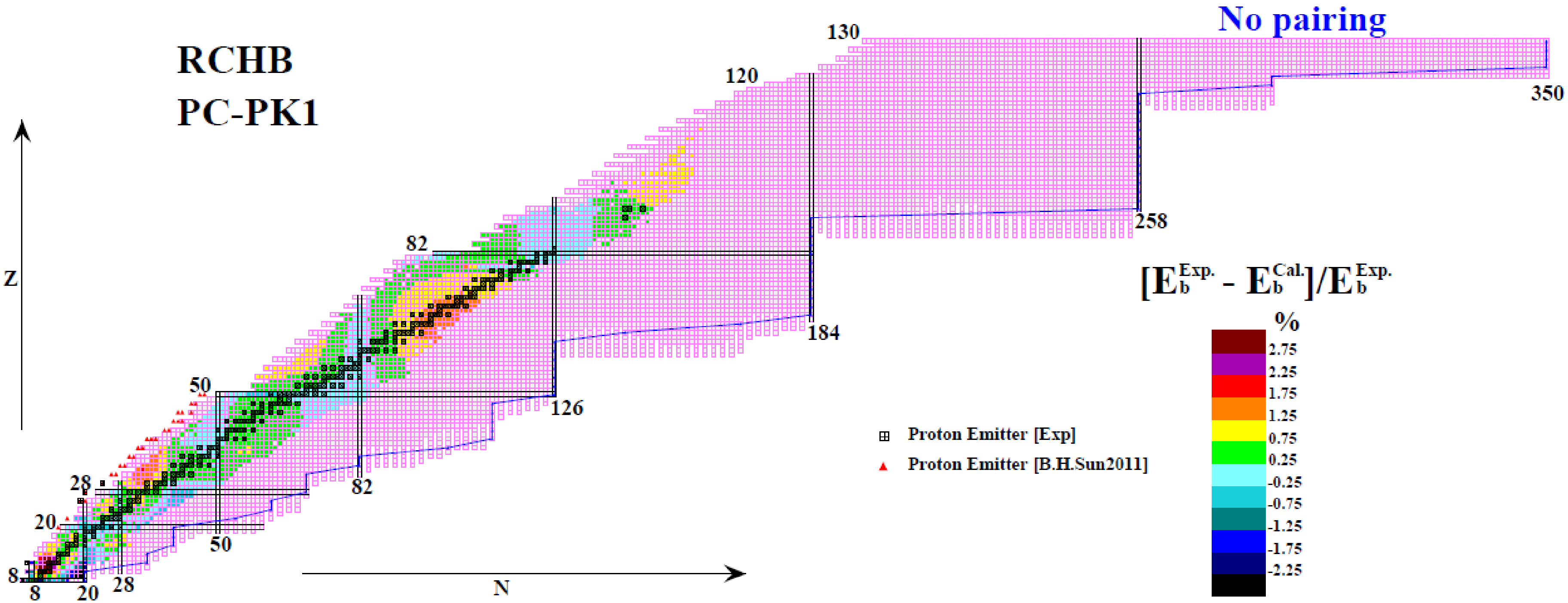
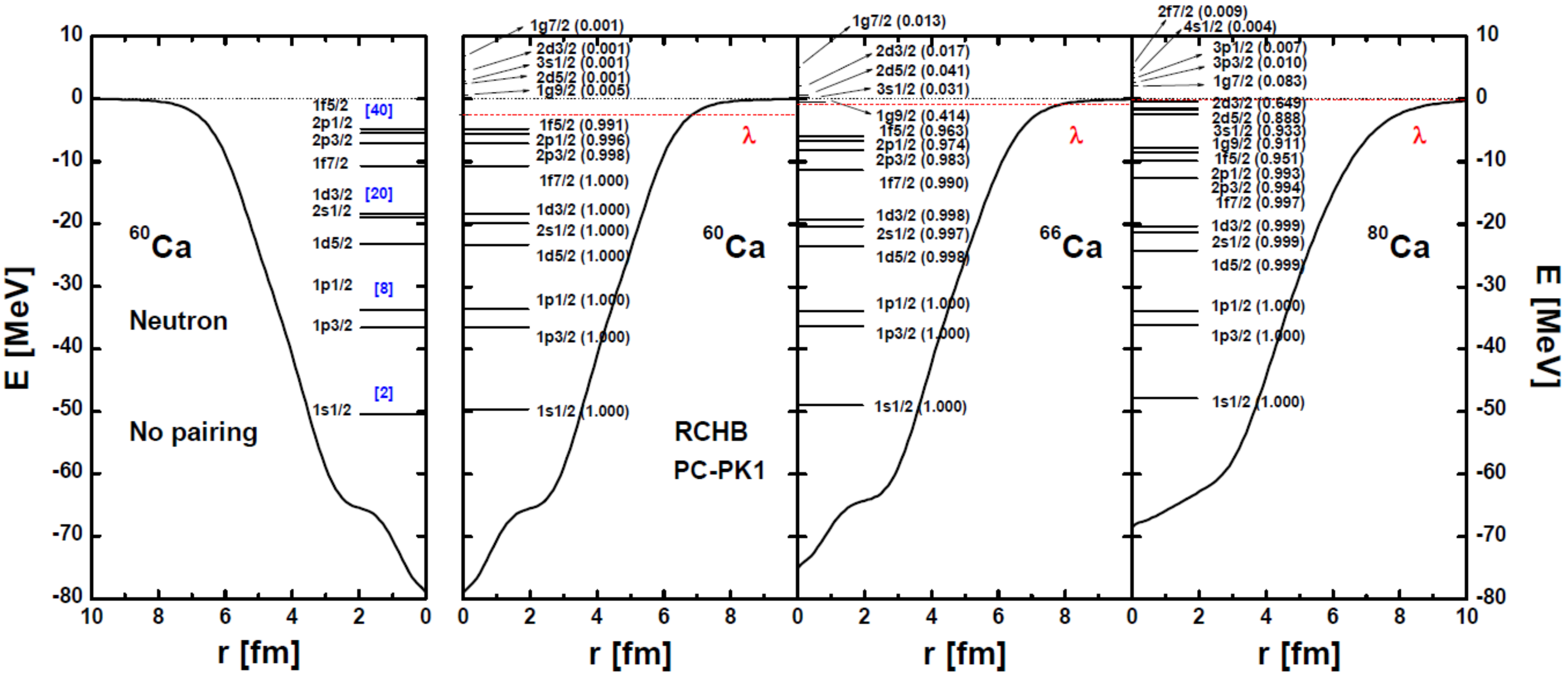


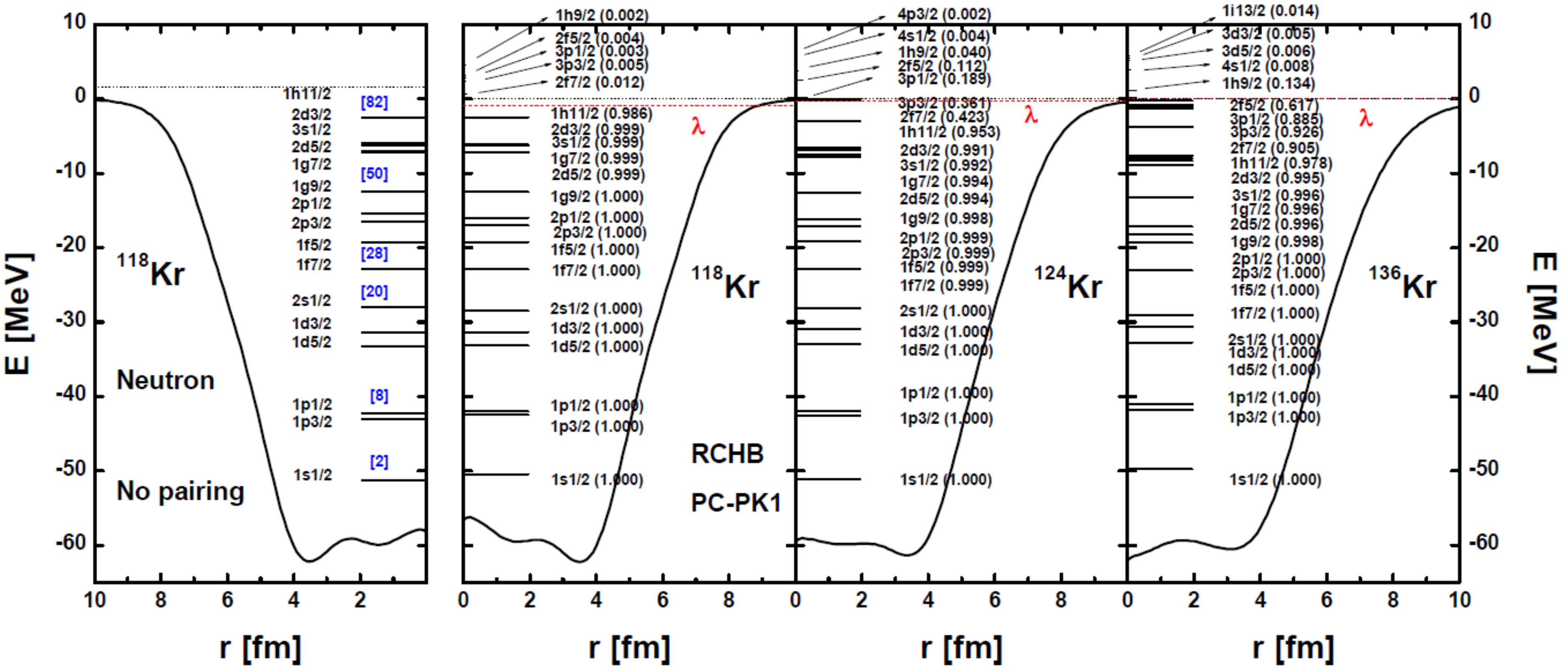
Figure: 10532 bound nuclei from Z=8 to Z=130 predicted by RCHB theory with PC-PK1. For 2227 nuclei with data, binding energy differences between data and calculated results are shown in different color. The nucleon drip-lines predicted without pairing correlation are plotted for comparison.

Boundary extended by pairing and continuum for Z=20



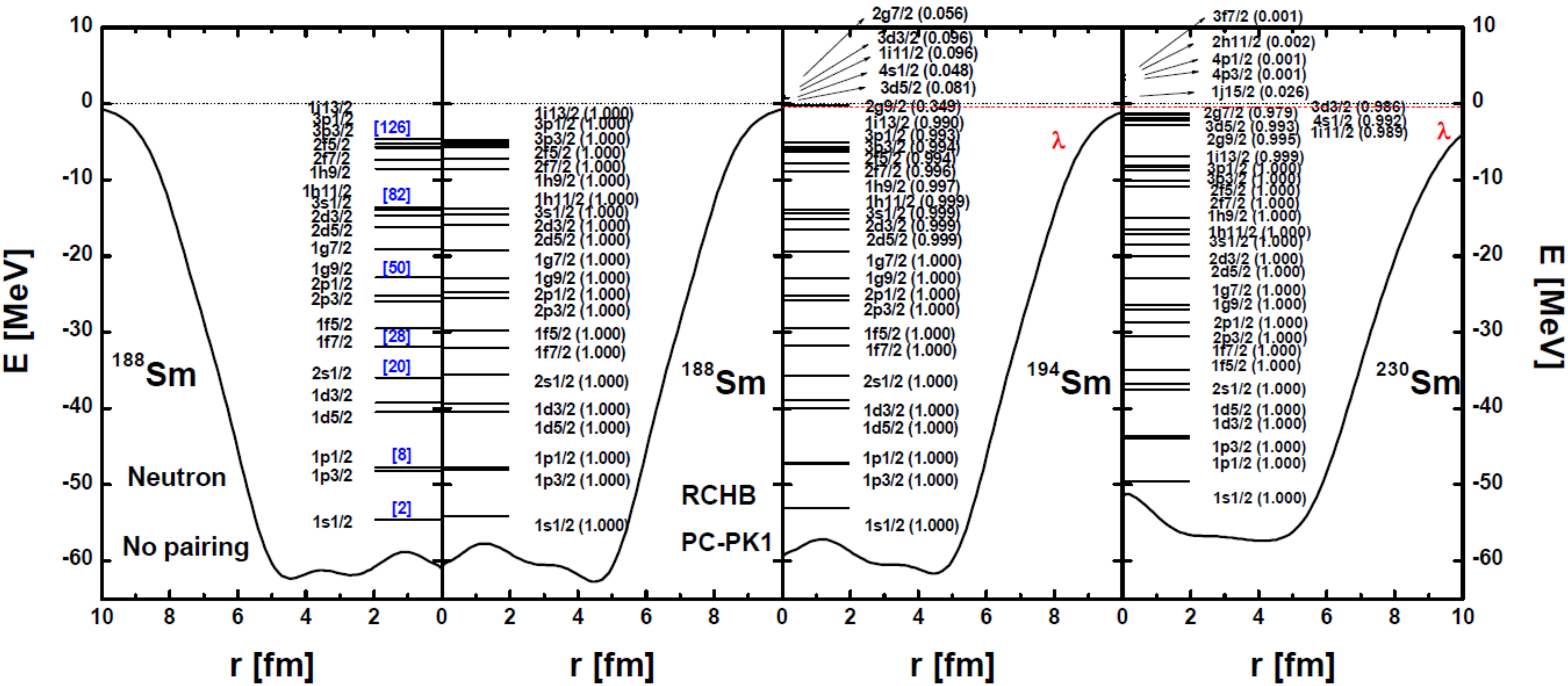
For Calcium isotopes, the neutron drip-line is extended from N=40 to N=60.

Boundary extended by pairing and continuum for Z=36



For Krypton isotopes, the neutron drip-line is extended from N=82 to N=100.

Boundary extended by pairing and continuum for Z=62



For Samarium isotopes, the neutron drip-line is extended from N=126 to N=168.

Two-neutron separation energy

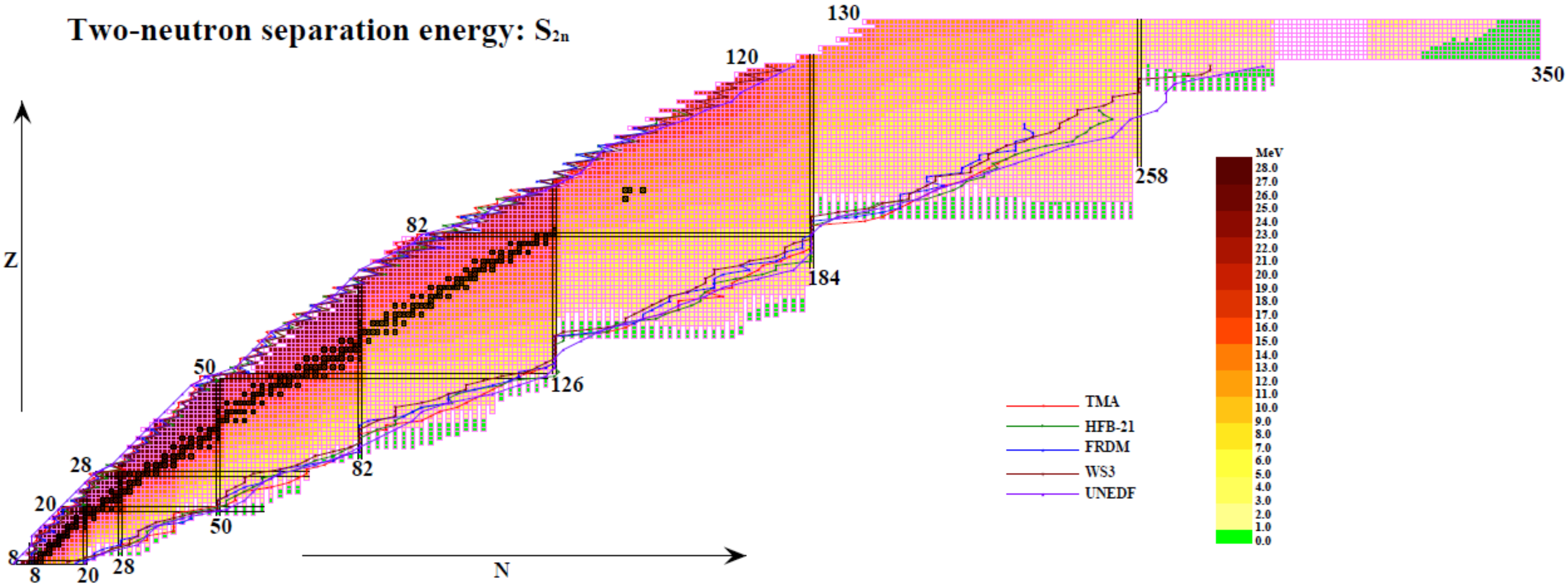


Figure: Two-neutron separation energy S_{2N} of 10532 bound nuclei from O(Z=8) to Uuy(Z=130) by the RCHB theory with PC-PK1

The nucleus S_{2N} < 1 MeV are marked in green.

One-neutron separation energy

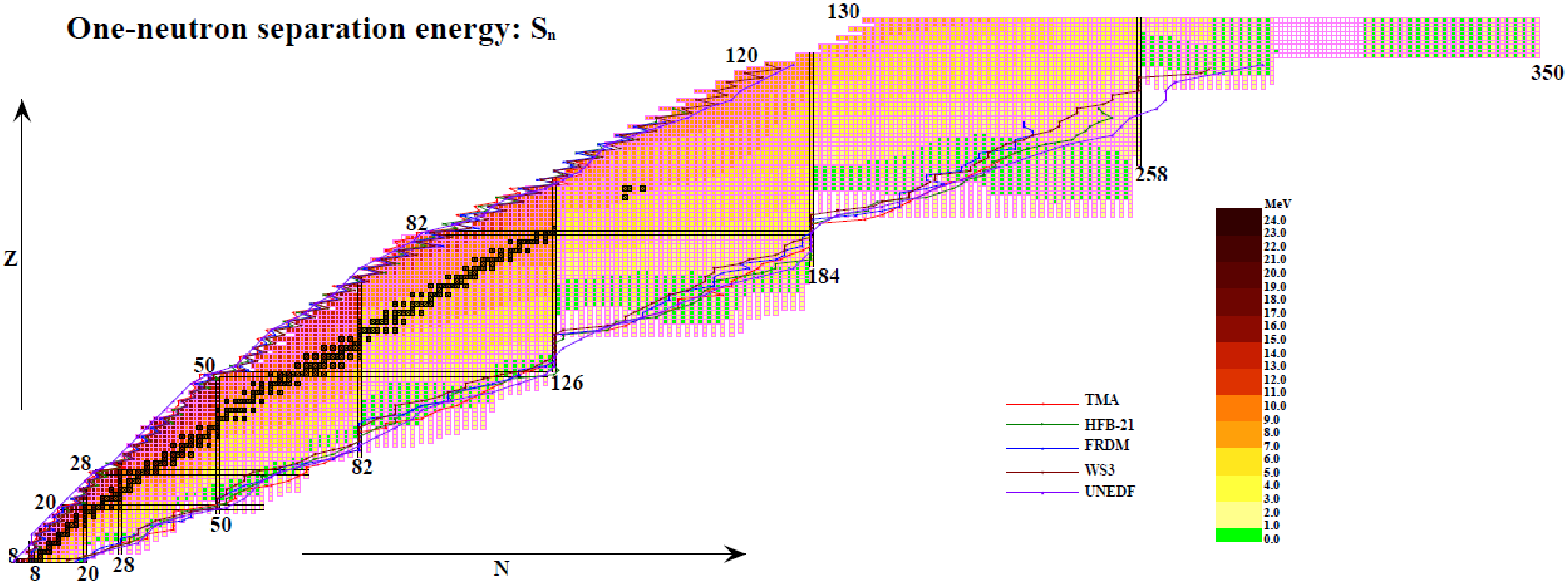


Figure: One-neutron separation energy of 10532 bound nuclei from O(Z=8) to Uuy(Z=130) by RCHB theory with PC-PK1.

The odd-N nucleus S_N < 1 MeV are marked in green.

One-proton separation energy

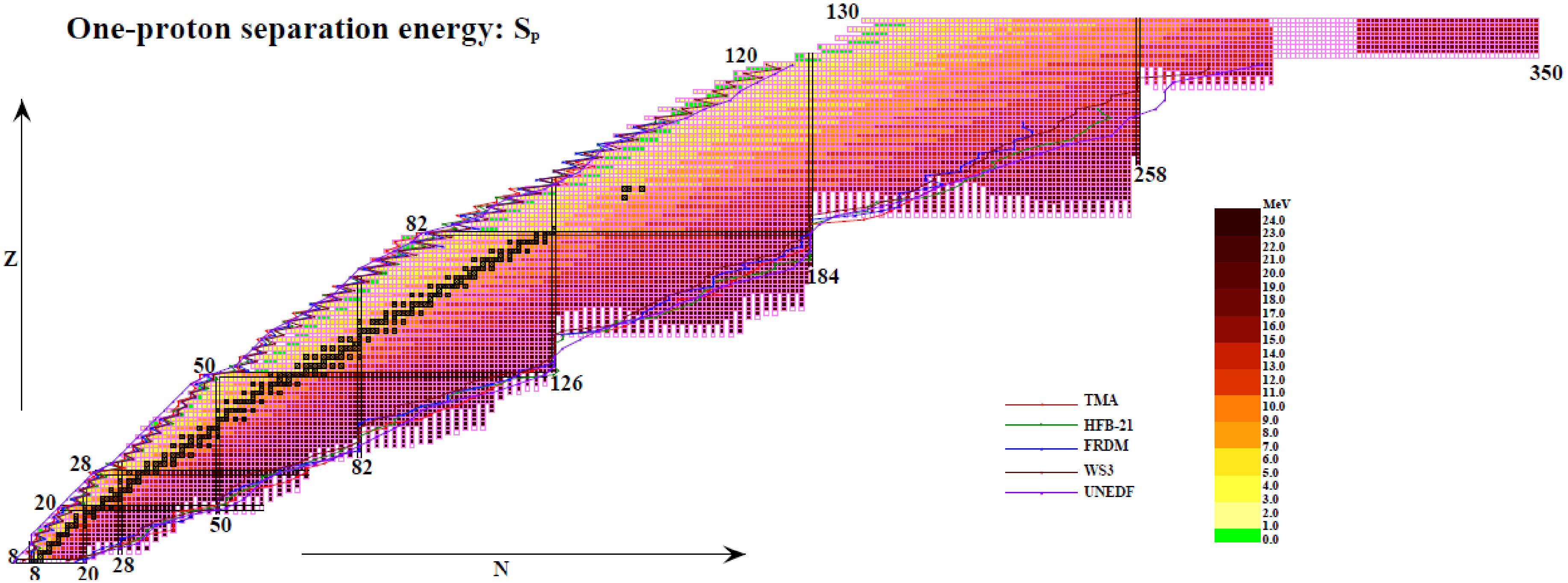


Figure: one-proton separation energy of 10532 bound nuclei from O(Z=8) to Uuy(Z=130) by the RCHB theory with PC-PK1

The nucleus S_P < 1 MeV are marked in green.

Two-proton separation energy

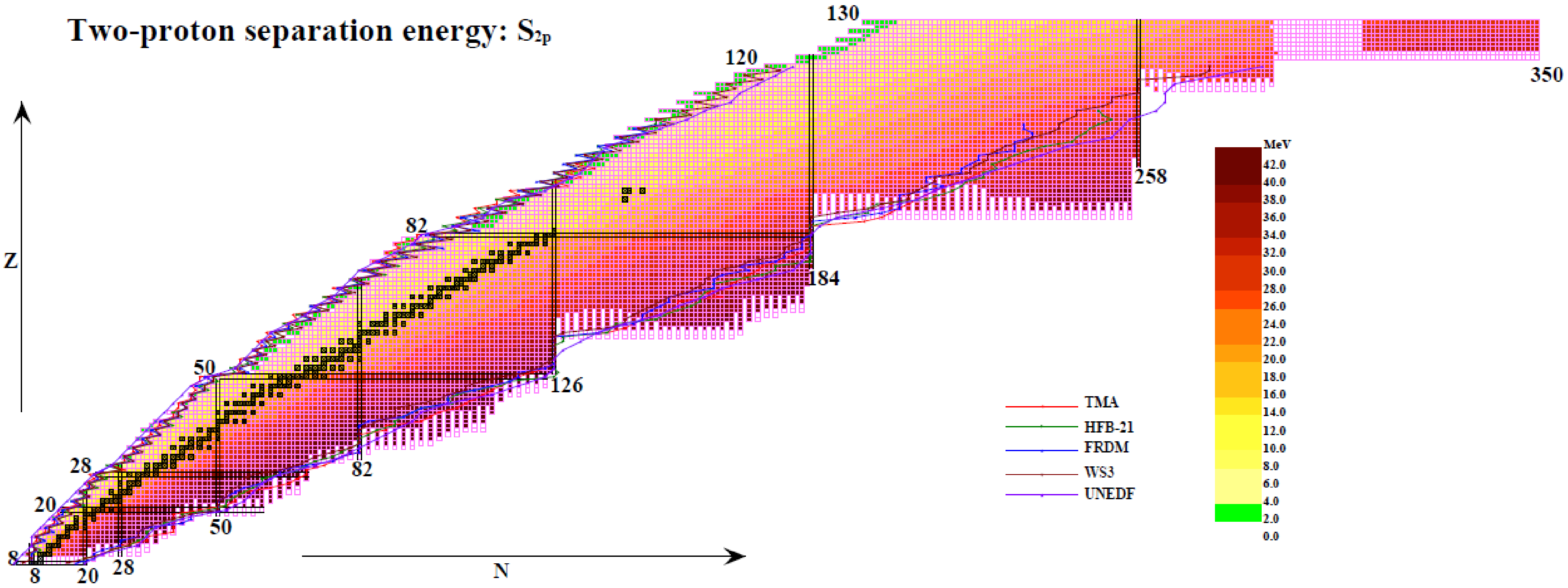


Figure: Two-proton separation energy of 10532 bound nuclei from O(Z=8) to Uuy(Z=130) by the RCHB theory with PC-PK1

The nucleus S_{2P} < 1 MeV are marked in green.

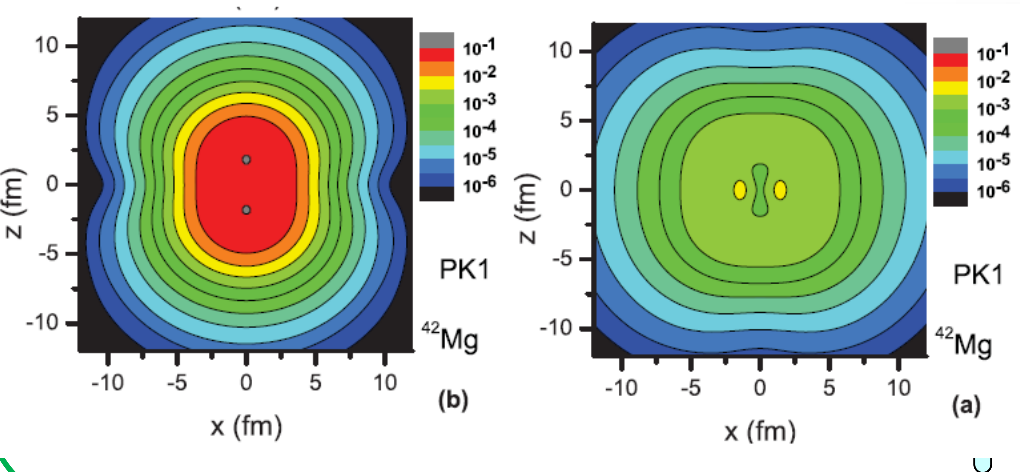
To be finished work …

- Potential diffuse systematics
- Halo nucleus in heavy and superheavy nucleus
- Proton emission nuclei
- Alpha emission nuclei
- Heavy-ion emission nuclei
- Shell structure evolution
- New magic number
- Stability line in superheavy mass region
- Proton number up-limit
- …

Outline

- ☐ Macroscopic-microscopic mass formula
- ☐ Nuclear mass in CDFT
- ☐ Energy and width for resonant states in Dirac equation
- ☐ Energy and width in GF-RCHB
- ☐ Nuclear landscape extended by continuum
- ☐ Perspectives

Deformed RHB theory in continuum

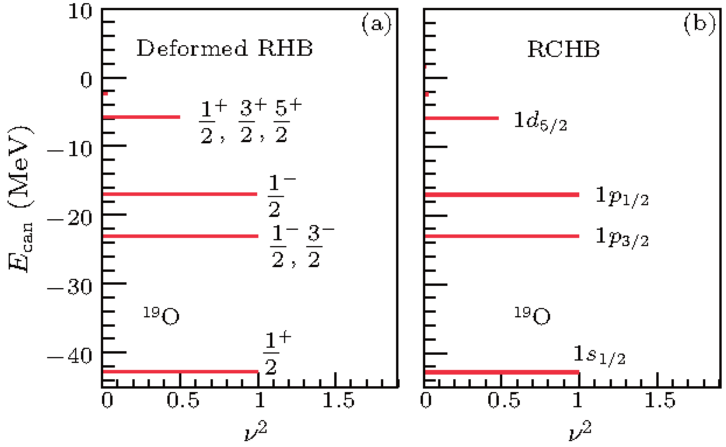


- **Describe bound states, continuum, and the coupling between them, as well as asymptotical density and deformation effect self-consistently.**
- **Predicte shape decoupling between the core and halo in ^{42}Mg .**

Zhou, Meng, Ring & Zhao, PRC 82, 011301R (2010)

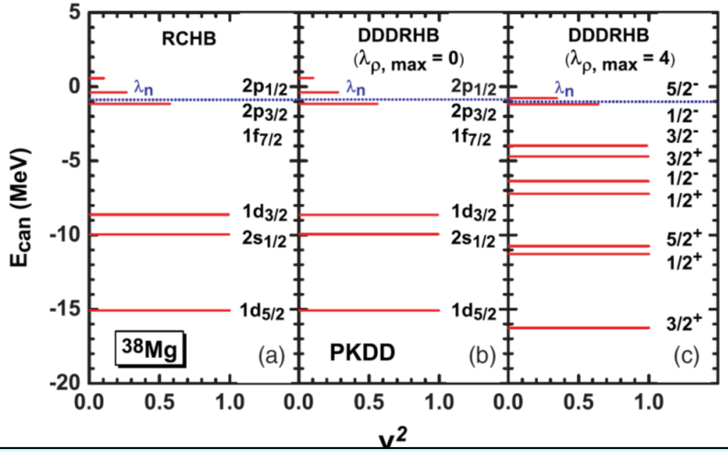
Li, Meng, Ring, Zhao, Zhou, PRC 85, 024312 (2012)

- **Blocking effect incorporated to treat odd-A or odd-odd exotic nuclei**



Li, Meng, Ring, Zhao, Zhou, Chin. Phys. Lett. 29, 042101 (2012)

- **DDDRHB: Generalized to density dependent meson-nucleon couplings**

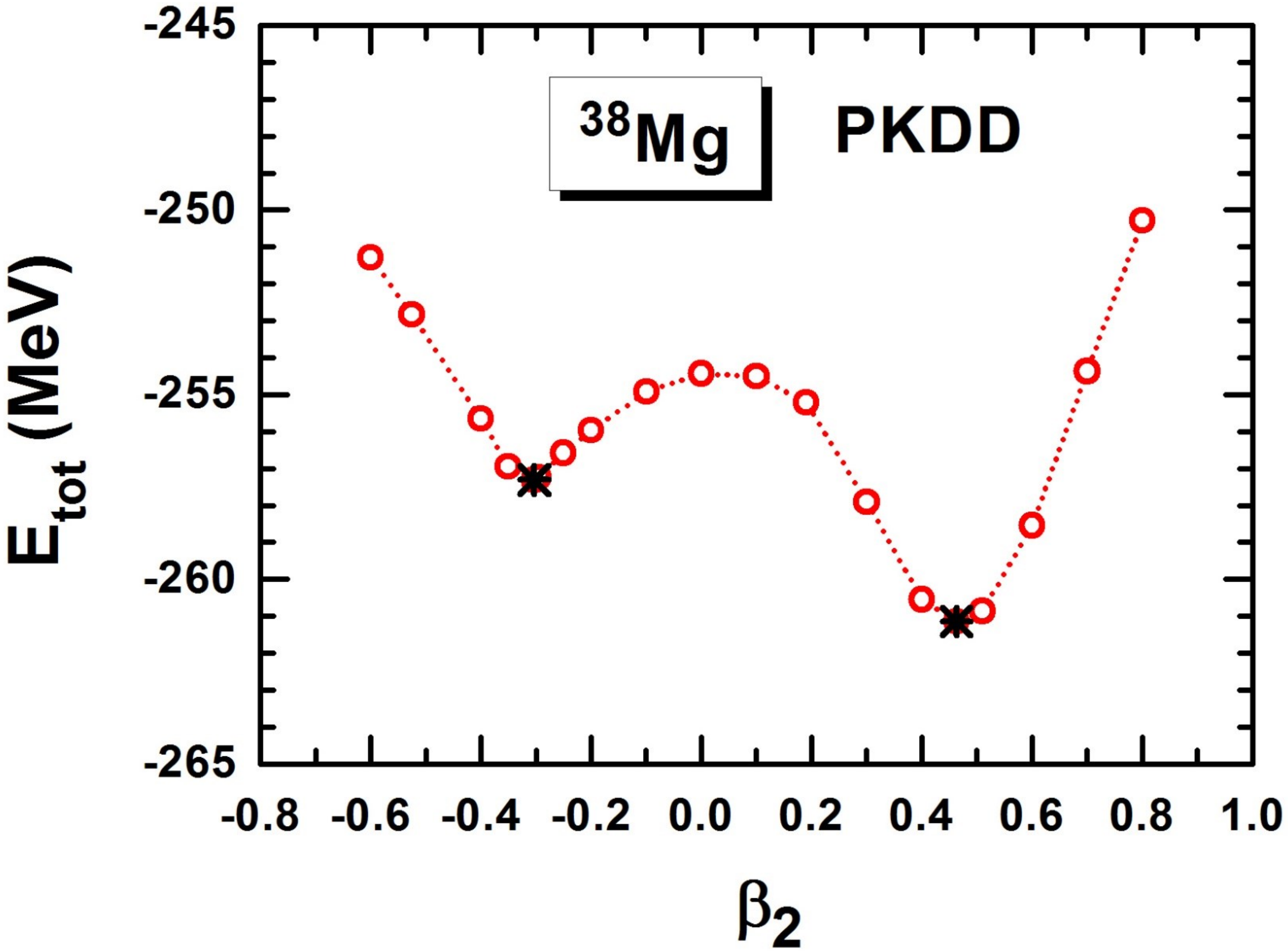


Chen, Li, Liang, Meng, PRC 85, 067301 (2012)

☐ Deformation: halo in ^{37}Mg and ^{38}Mg

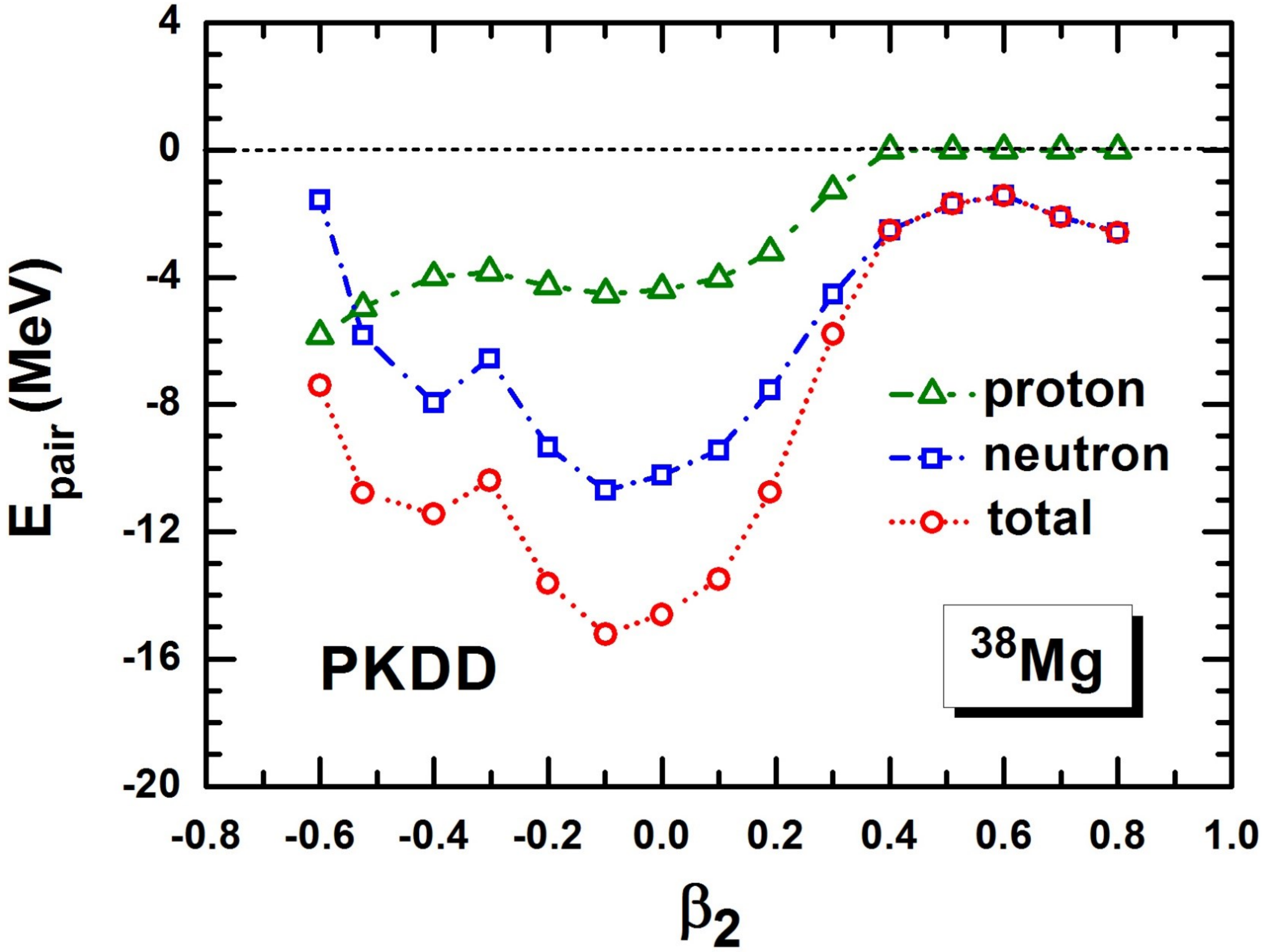
Time-odd effect, continuum, blocking effect and quadruple deformation constrained

Potential energy surface



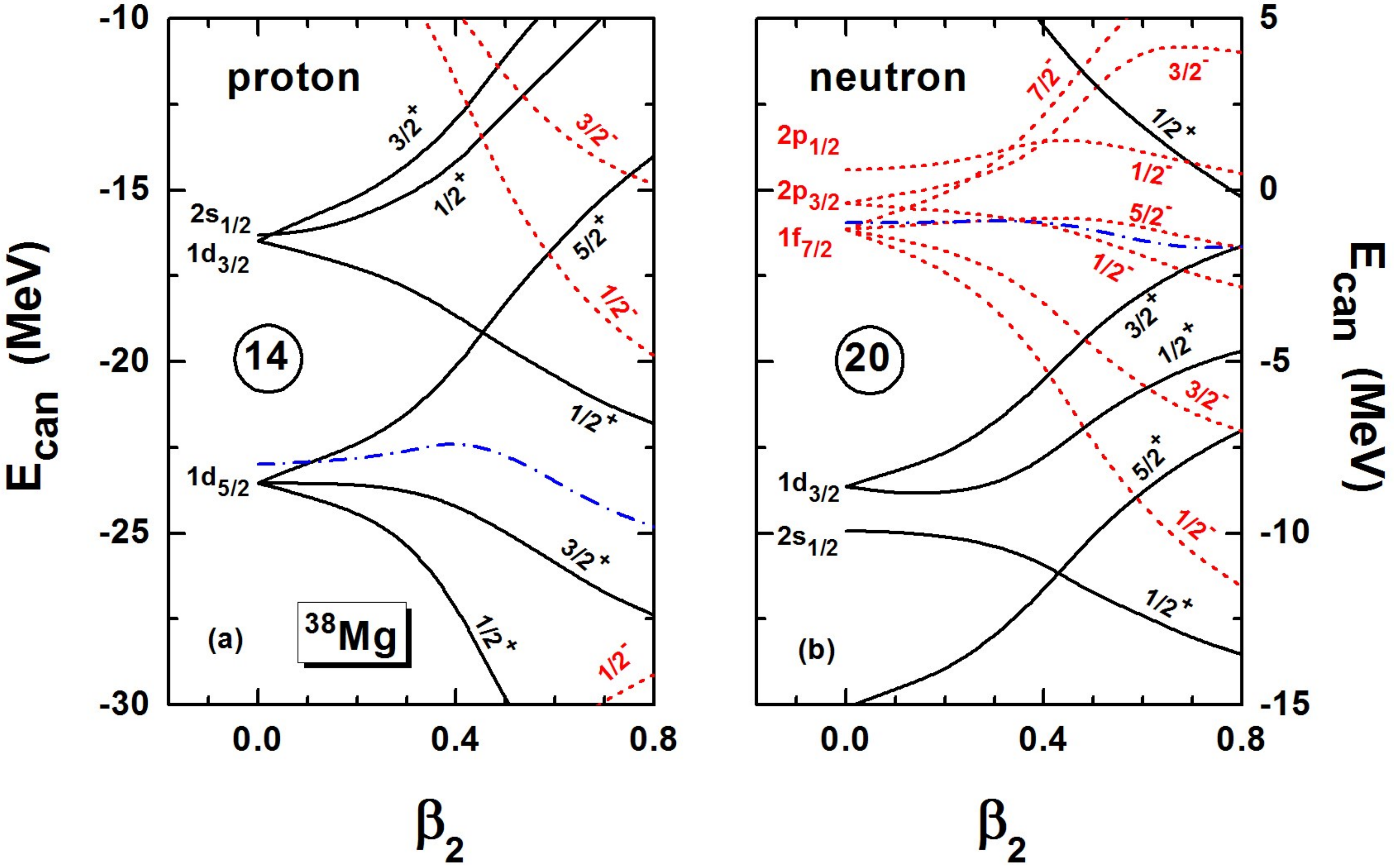
Constrained deformed RHB theory in continuum developed

Pairing energy varies with deformation

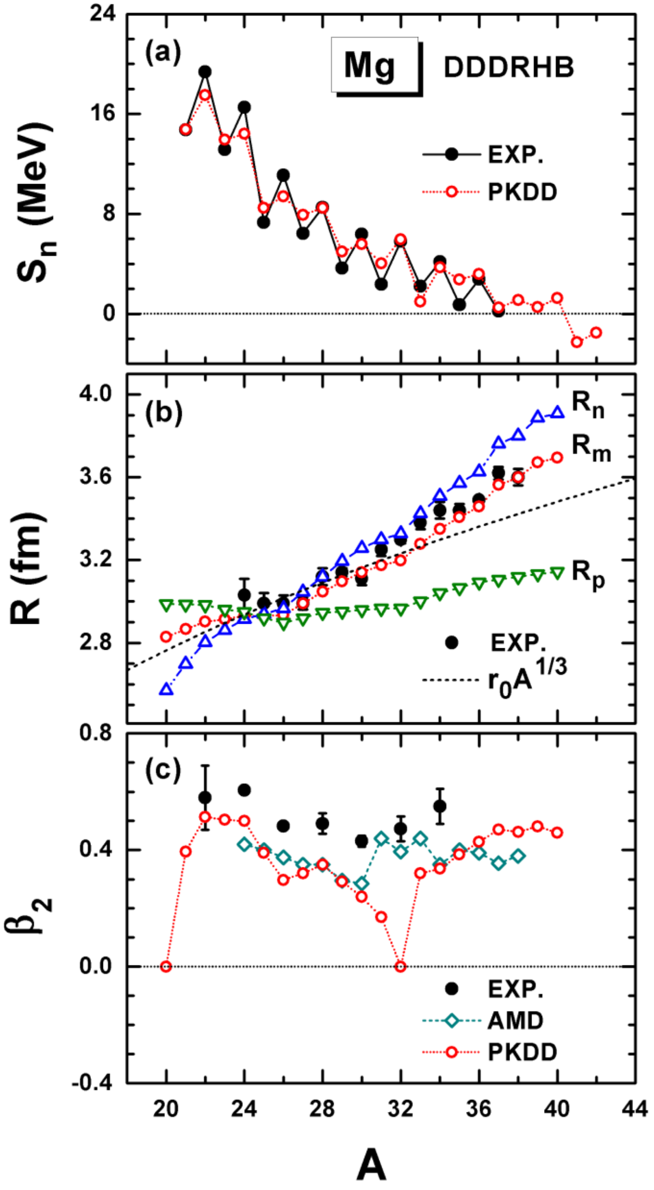


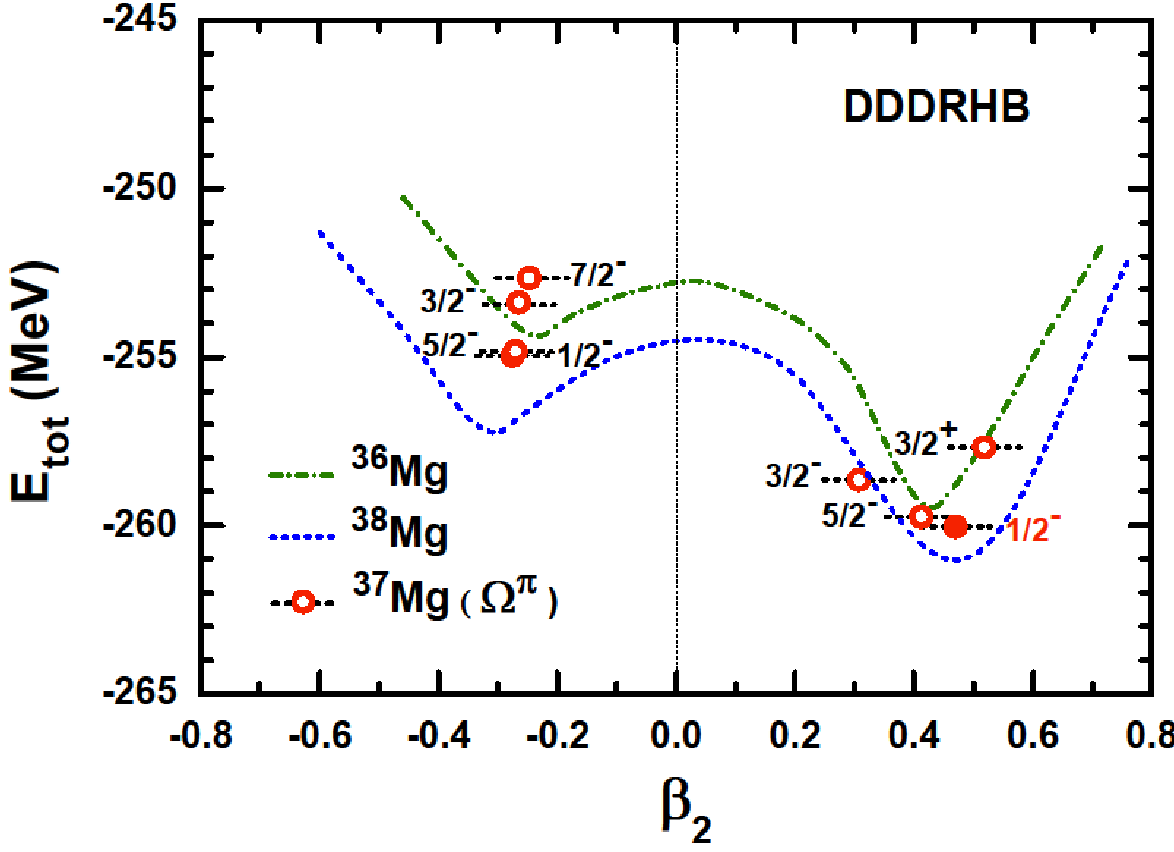
Constrained deformed RHB theory in continuum developed

Single particle levels



Deformed halo in ^{37}Mg and ^{38}Mg

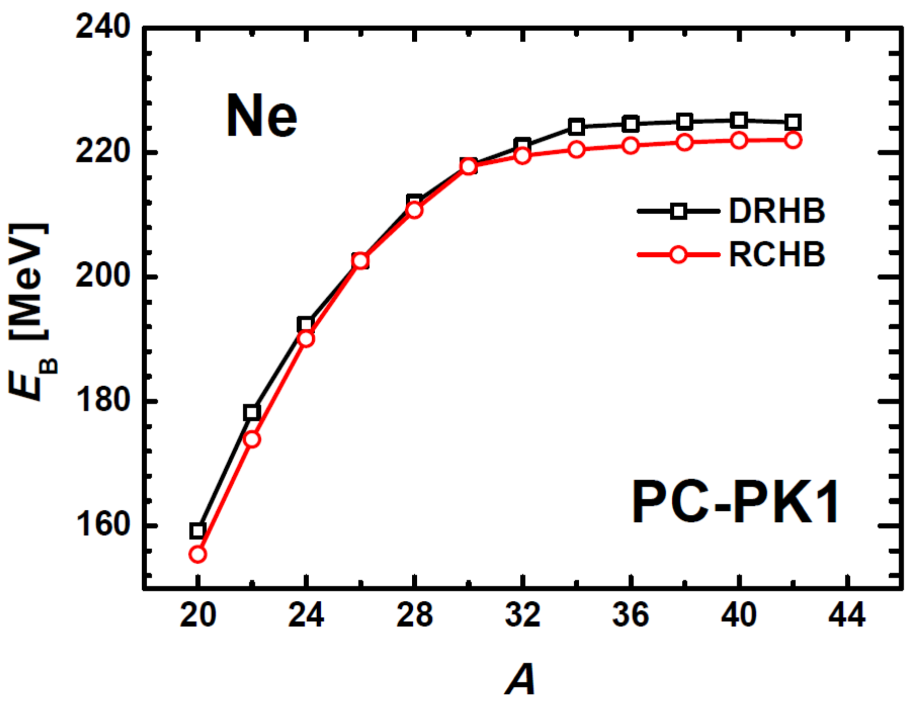


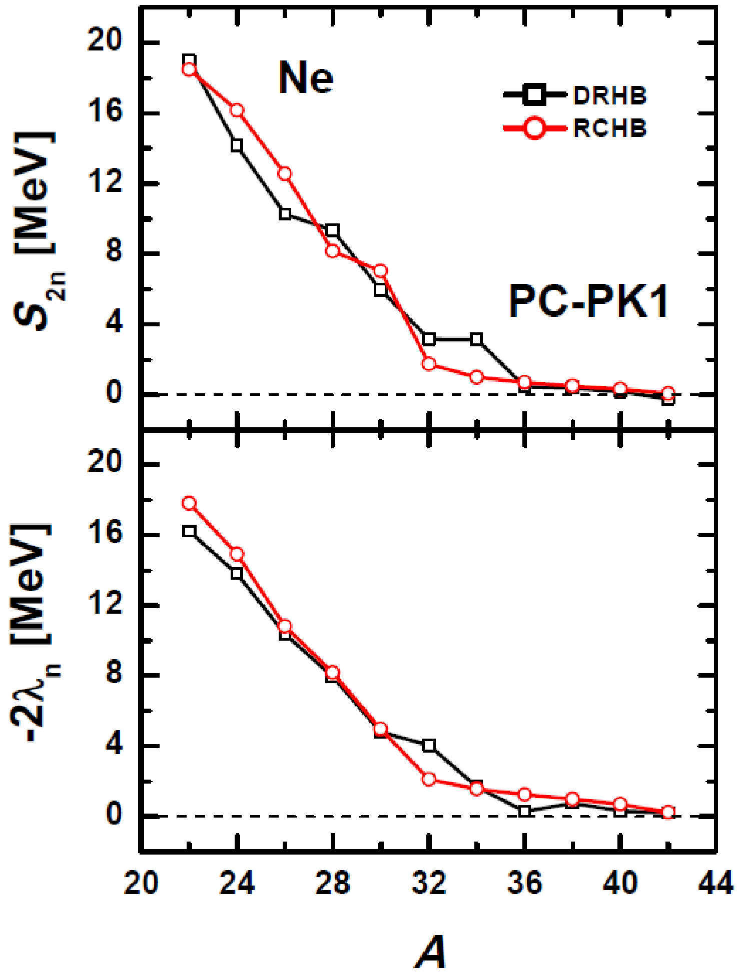


Time-odd deformed relativistic Hartree-Bogoliubov theory in continuum with blocking and quadruple deformation constrained

Chen, et al, to be published

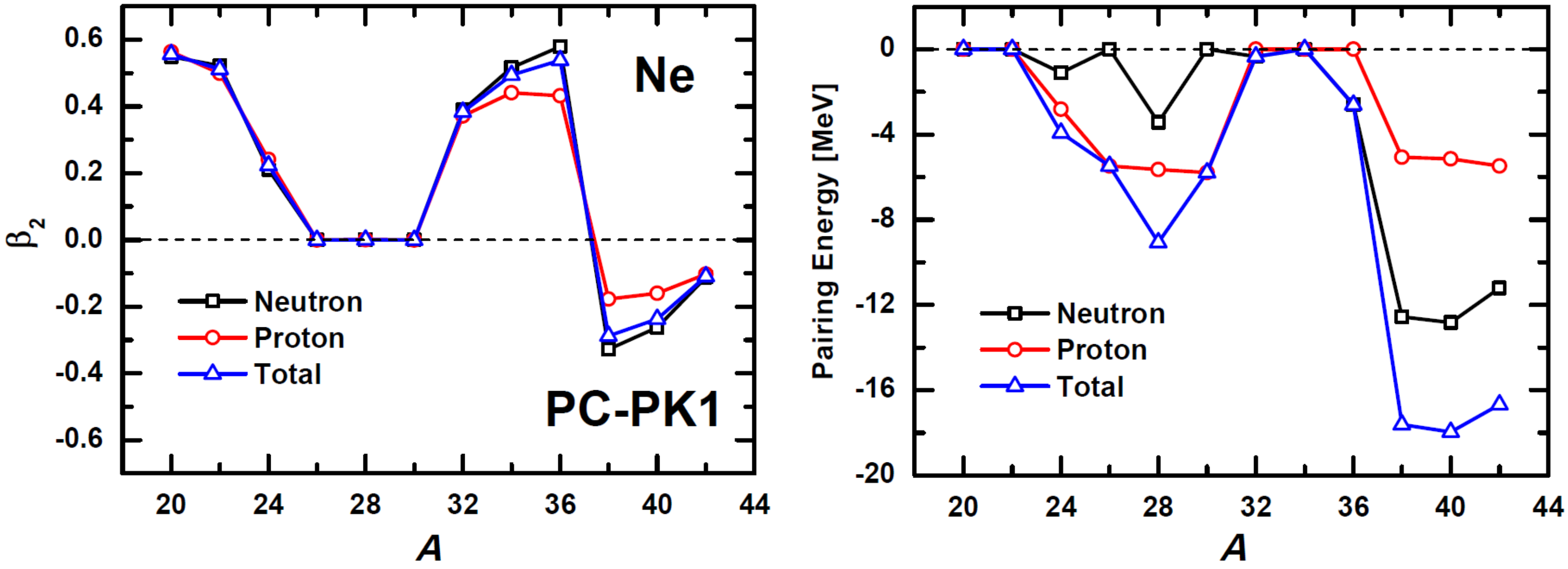
Deformation: Binding energy





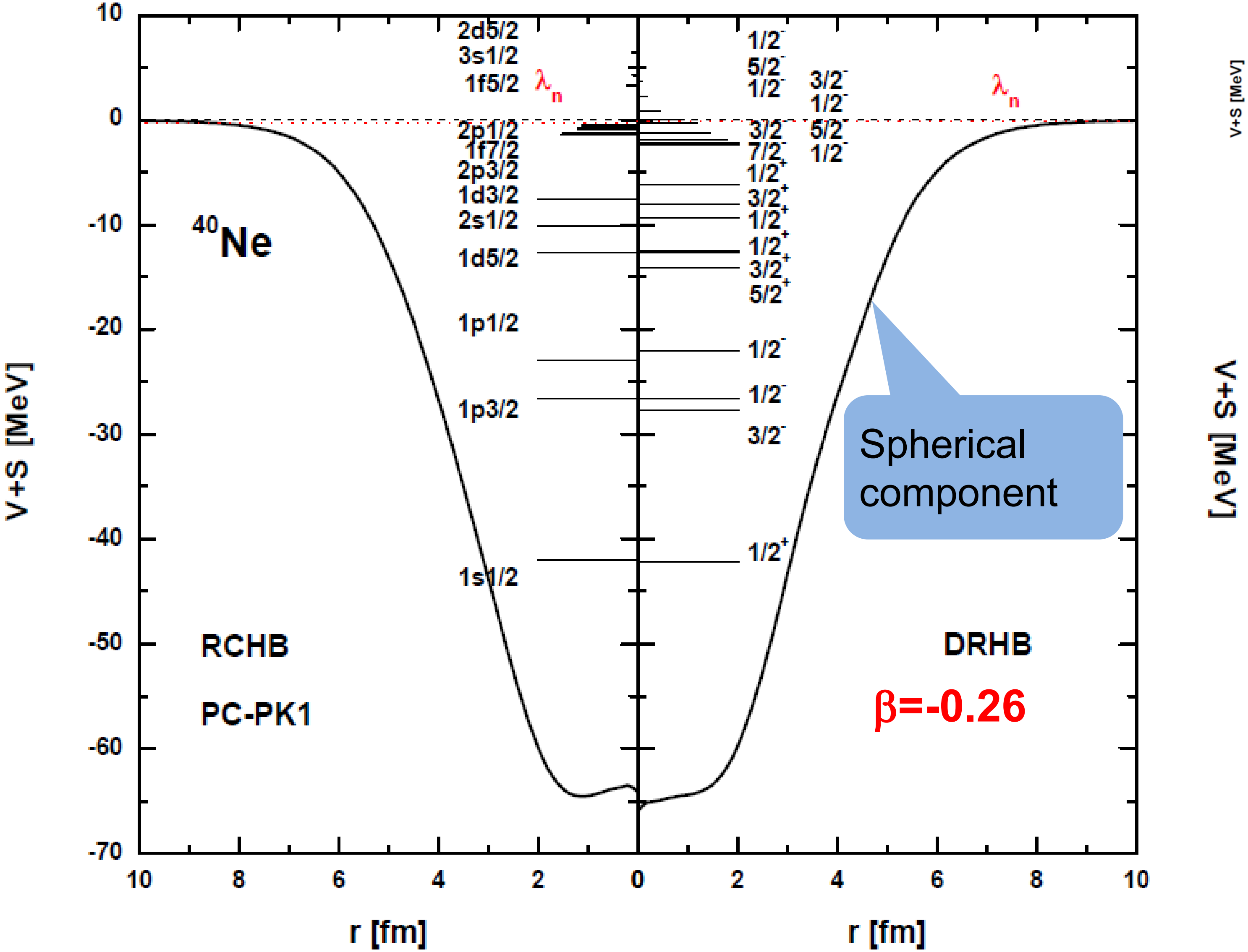
Binding energy and two-neutron separation energy of Ne isotopes calculated with PC-PK1.

Deformation and pairing energy

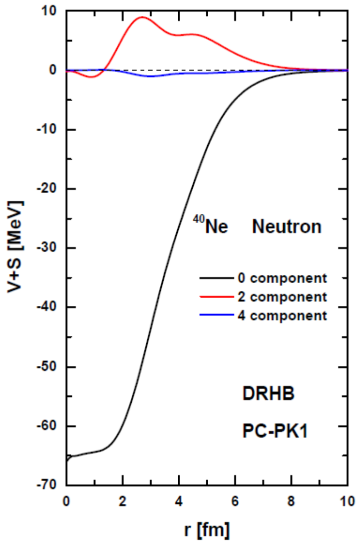


Deformation and pairing energy of Ne isotopes calculated with PC-PK1.

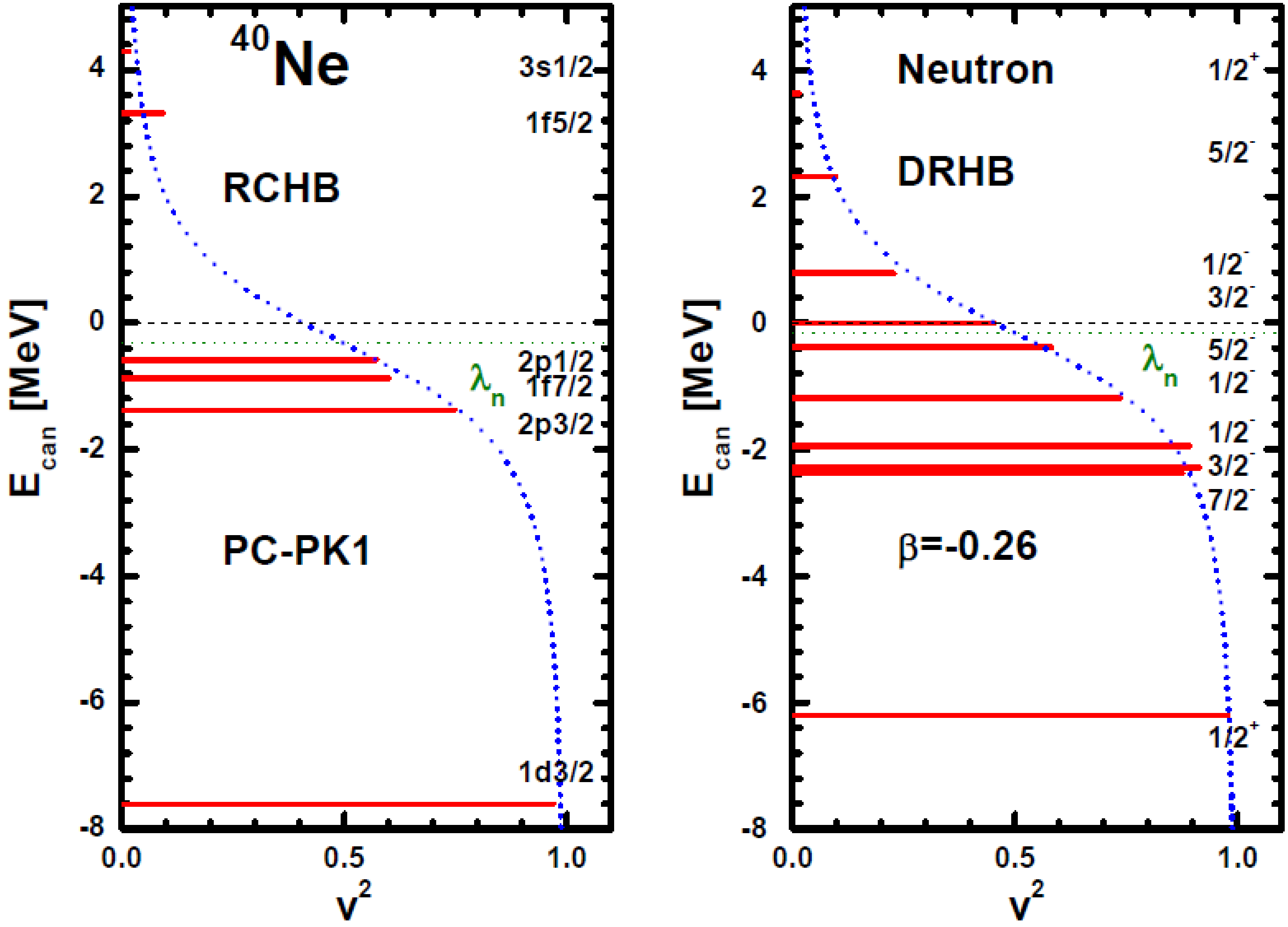
Single Neutron Levels in ^{40}Ne in comparison



Spherical component



Single Neutron Levels in ^{40}Ne in comparison



Summary and Perspectives

☐ Summary

- Deformed relativistic Hartree-Bogoliubov theory in continuum：**time-odd component, blocking effect and quadruple deformation constrained**
- Covariant density functional theory formulated with Green’s function method
  - GF-RMF single-particle resonances
  - GF-RCHB giant halo

☐ Perspectives

- Systematic deformed halo investigation possible
- Predicting deformed halo in even/odd A nucleus
- Relation between pairing and deformation
- Resonance in stable/unstable nucleus
- Pairing enhancement/suppress beyond dripline
- Continuum and width effect on halo
- CDFT mass with deformation and continuum …

Thank you!