INT Program INT-11-2d
Interfaces between structure and reactions for rare isotopes and nuclear astrophysics
August 8 - September 2, 2011

Deformed halo and r-process calculation with covariant density-functional theory

Jie Meng 孟 杰

北京大学物理学院
School of Physics
Peking University (PKU)

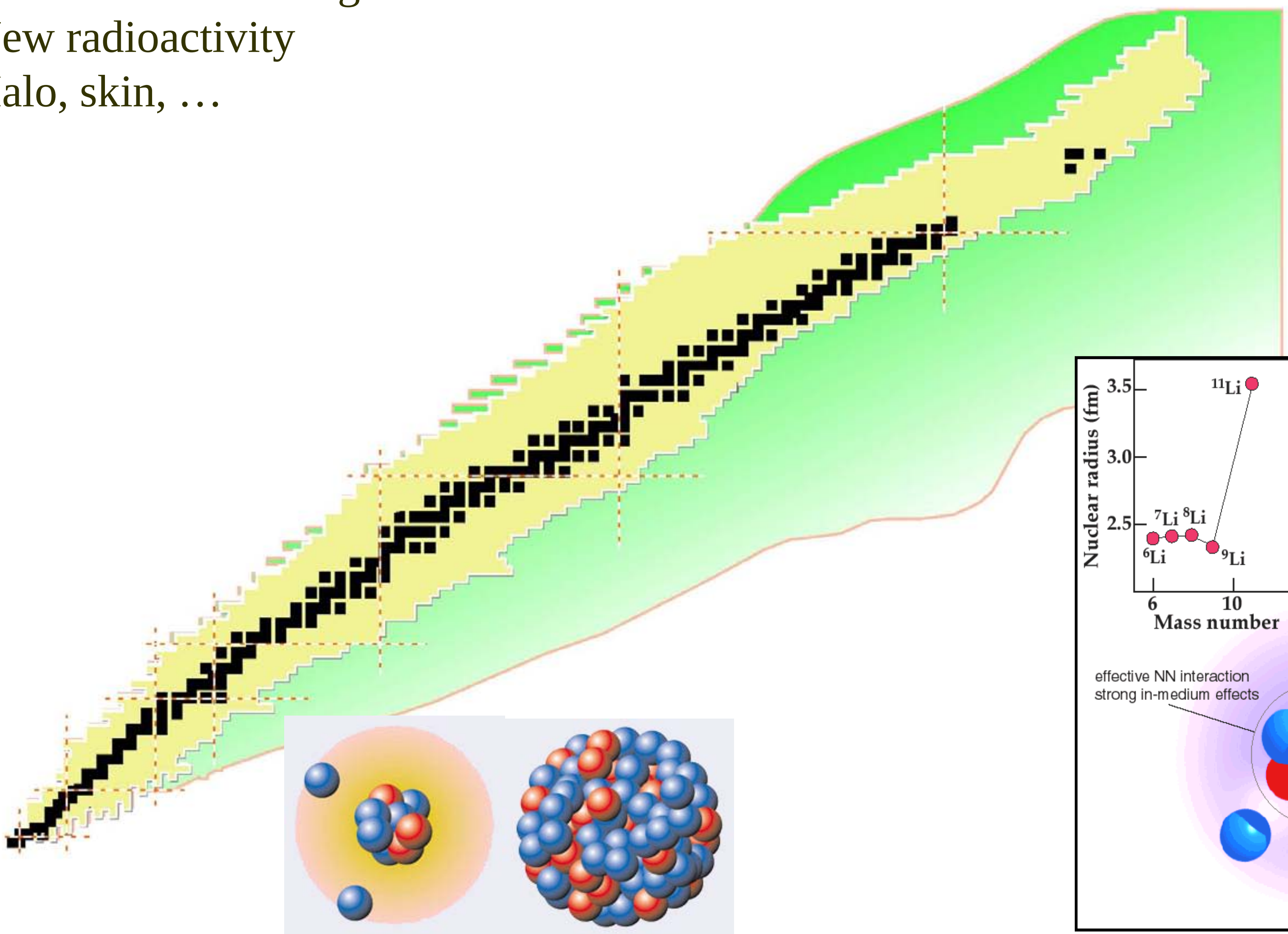
北京航空航天大学物理与核能工程学院
School of Physics and Nuclear Energy Engineering
Beihang University (BUAA)

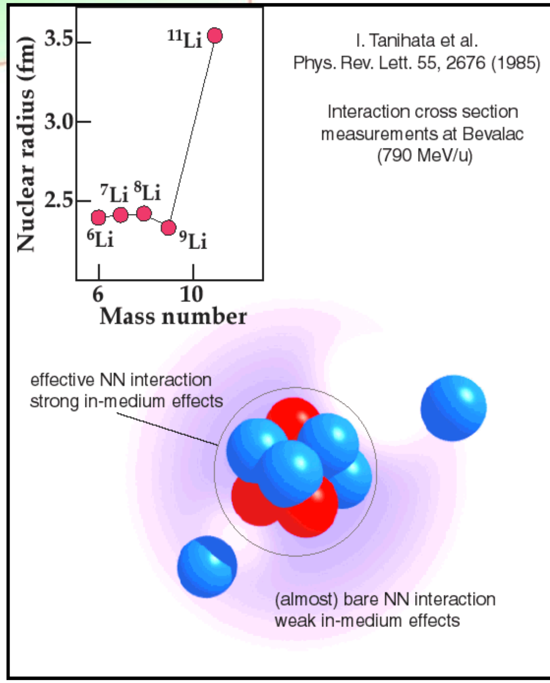
Outline

- Introduction
- Halos in Density Functional Theory: Skyrme HFB / DD RHFB / GF Skyrme HFB
- Deformed halos
- R-process calculation with CDFT Mass table
- Summary & Perspectives

Exotic phenomena in nuclei with extreme N/Z

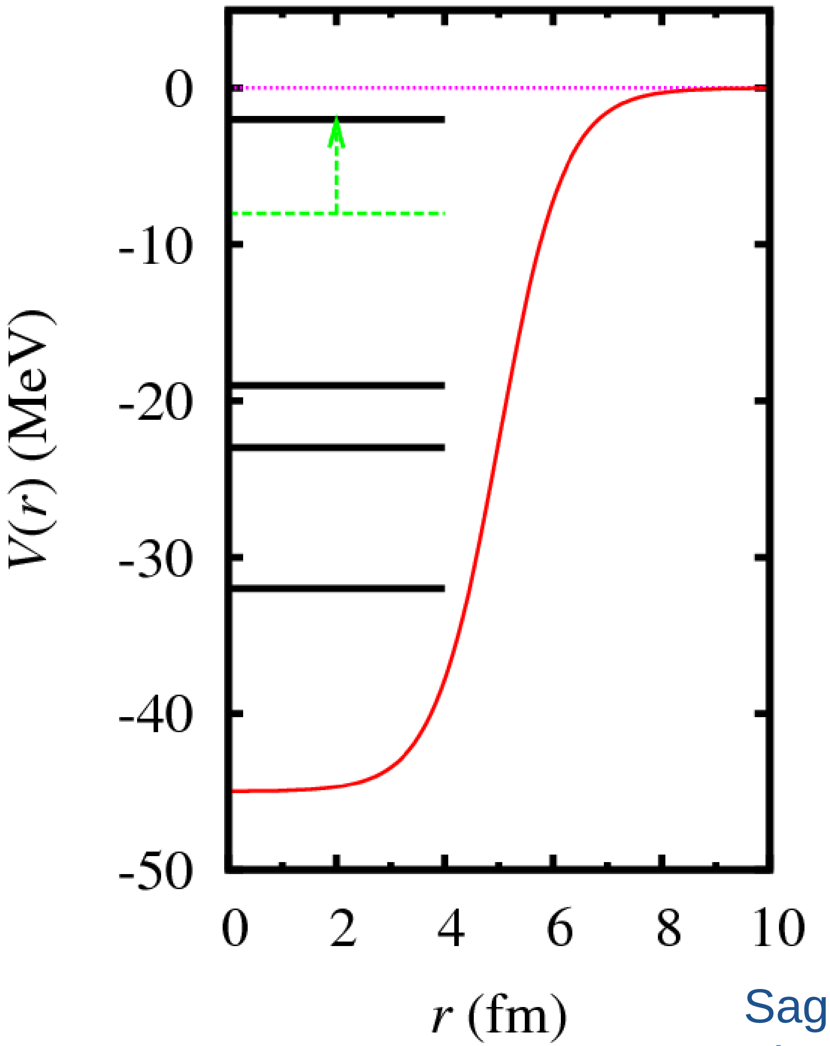
- Modifications of magic numbers
- New radioactivity
- Halo, skin, …
- …

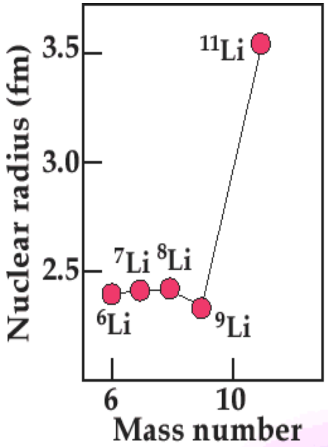




Halo in spherical nuclei

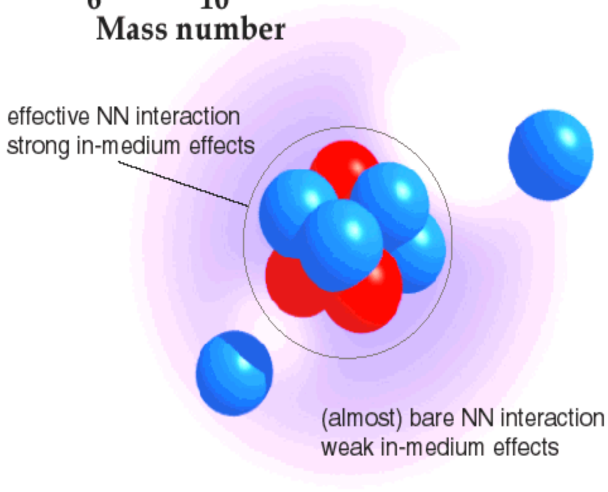
SPL in mean field model





I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

Interaction cross section measurements at Bevalac (790 MeV/u)

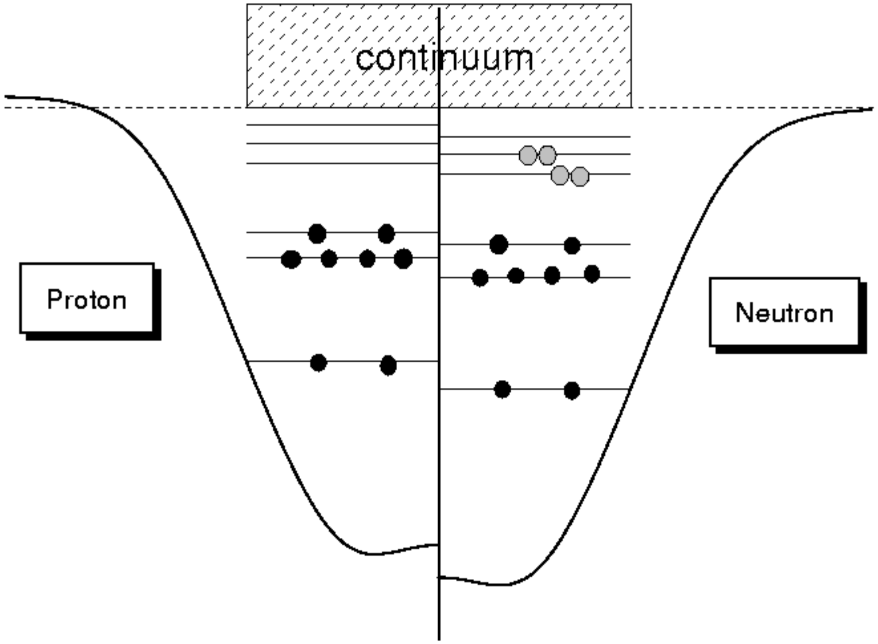


Sagawa, Phys. Lett. B **286, 7 (1992).**
Zhu *et al., Phys. Lett. B* ***328, 1 (1994).***

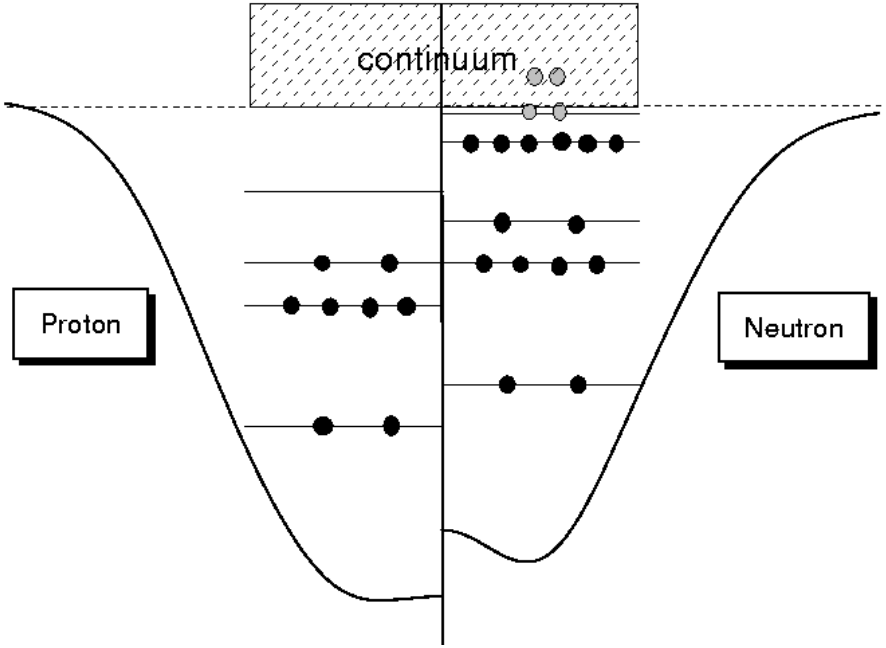
Contributions from the continuum

- **Weakly bound; large spatial extension**
- **Continuum can not be ignored**

连续谱



Stable nucleus



Unstable nucleus

Contribution of continuum in r-HFB

$$\sum_{\sigma}\int d^3\mathbf{r}'\begin{pmatrix} h(\mathbf{r}\sigma;\mathbf{r}'\sigma')-\lambda & \Delta(\mathbf{r}\sigma;\mathbf{r}'\sigma') \\ -\Delta^*(\mathbf{r}\sigma;\mathbf{r}'\sigma') & -h(\mathbf{r}\sigma;\mathbf{r}'\sigma')+\lambda \end{pmatrix}\begin{pmatrix} U_E(\mathbf{r}'\sigma') \\ V_E(\mathbf{r}'\sigma') \end{pmatrix} = E\begin{pmatrix} U_E(\mathbf{r}\sigma) \\ V_E(\mathbf{r}\sigma) \end{pmatrix}$$

When *r* goes to infinity, the potentials are zero

$$-\frac{\hbar^2}{2M}\frac{d^2}{dr^2}U_E(\mathbf{r}\sigma) = (\lambda+E)U_E(\mathbf{r}\sigma)$$

$$-\frac{\hbar^2}{2M}\frac{d^2}{dr^2}V_E(\mathbf{r}\sigma) = (\lambda-E)V_E(\mathbf{r}\sigma)$$

U and *V* behave when *r* goes to infinity

$$U_E(\mathbf{r}\sigma) \sim \begin{cases} \cos(k_U r+\delta) & \text{for } \lambda+E>0 \\ \exp(-k'_U r) & \text{for } \lambda+E<0 \end{cases}$$

$$V_E(\mathbf{r}\sigma) \sim \begin{cases} \cos(k_V r+\delta) & \text{for } \lambda-E>0 \\ \exp(-k'_V r) & \text{for } \lambda-E<0 \end{cases}$$

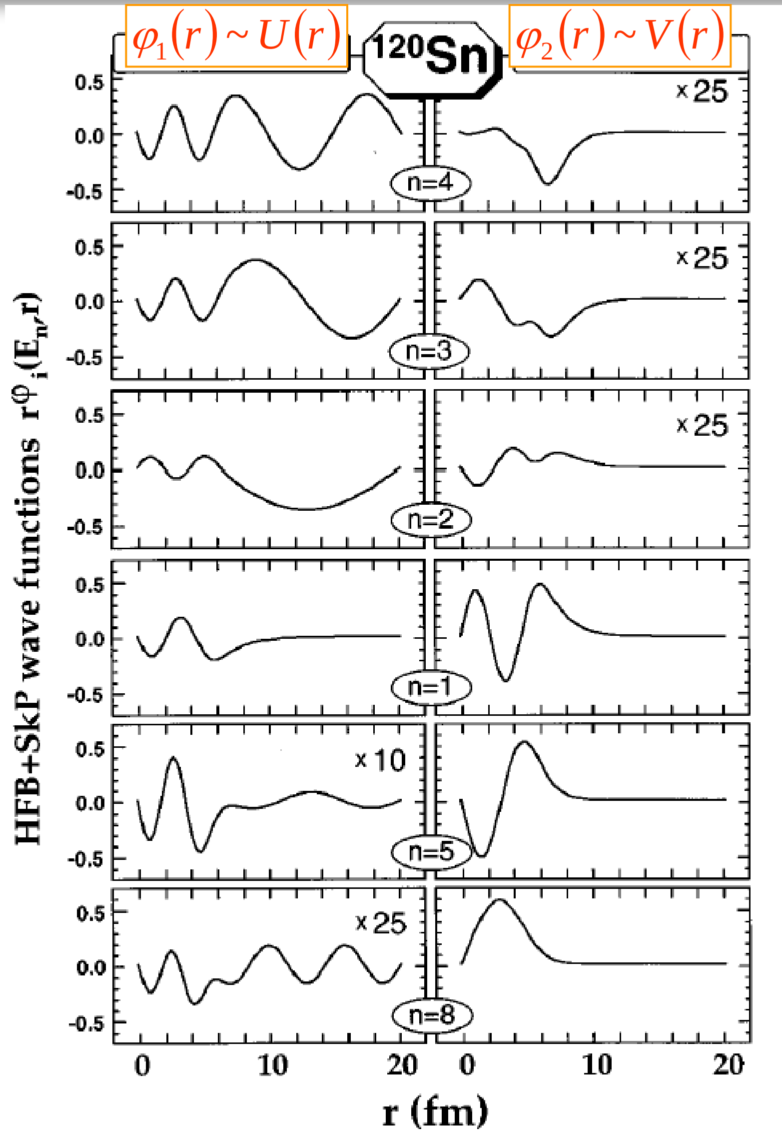
Continuum contributes automatically and the density is still localized

Bulgac, 1980 & nucl-th/9907088

Dobaczewski, Flocard&Treiner, NPA422(84)103

Bertsch and Esbensen, Ann. Phys. (N.Y.) **209,** 327 (1991).

Contribution of continuum in r-HFB



Positive energy States

- *V*(*r*) determines the density
- the density is localized even if *U*(*r*) oscillates at large *r*

Bound States

Dobaczewski, et al., PRC53(96)2809

Relativistic Hartree-Bogoliubov theory

- Quantizing the system;
- Eliminating the mesonic degrees of freedom;
- Factorizing the higher order Greens functions;
- Neglecting retardation effects

H. Kucharek and P. Ring, Z. Phys. A**339** (1991) 193.

RHB Equation

$$\int d\mathbf{r}' \begin{pmatrix} h(\mathbf{r},\mathbf{r}') - \lambda & \Delta(\mathbf{r},\mathbf{r}') \\ \Delta(\mathbf{r},\mathbf{r}') & -h(\mathbf{r},\mathbf{r}') + \lambda \end{pmatrix} \begin{pmatrix} \psi_U(\mathbf{r}') \\ \psi_V(\mathbf{r}') \end{pmatrix} = E \begin{pmatrix} \psi_U(\mathbf{r}) \\ \psi_V(\mathbf{r}) \end{pmatrix}$$

Relativistic continuum Hartree Bogoliubov (RCHB) theory

RHB equations:

$$\begin{pmatrix} h-\lambda & \Delta \\ -\Delta^* & -h^*+\lambda \end{pmatrix} \begin{pmatrix} \psi_U \\ \psi_V \end{pmatrix} = E \begin{pmatrix} \psi_U \\ \psi_V \end{pmatrix}$$

$$h(\mathbf{r}) = [\boldsymbol{\alpha}\cdot\mathbf{p} + V(\mathbf{r}) + \beta(M+S(\mathbf{r}))]$$

$$\Delta_{kk'}(\mathbf{r},\mathbf{r}') = -\int d^3\mathrm{r}_1 \int d^3\mathrm{r}'_1 \sum_{\tilde{k}\tilde{k}'} V_{kk',\tilde{k}\tilde{k}'}(\mathbf{r}\mathbf{r}';\mathbf{r}_1\mathbf{r}'_1)\kappa_{\tilde{k}\tilde{k}'}(\mathbf{r}_1,\mathbf{r}'_1)$$

Pairing tensor

$$\kappa_{kk'}(\mathbf{r},\mathbf{r}') = \langle|a_{k,i}a_{k',i'}|\rangle = \sum_{E_i>0} \psi_U^{k,i}(\mathbf{r})^*\psi_V^{k',i}(\mathbf{r}')$$

Baryon density

$$\rho(\mathbf{r},\mathbf{r}') = \sum_{k,E_i>0} \psi_V^{k,i}(\mathbf{r})^*\psi_V^{k,i}(\mathbf{r}')$$

Pairing force

$$V(\boldsymbol{r}_1,\boldsymbol{r}_2) = V_0\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\frac{1}{4}[1-\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2]\left(1-\frac{\rho(r)}{\rho_0}\right)$$

RCHB 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.)

Relativistic Continuum Hartree-Bogoliubov(RCHB) theory

for spherical nuclei

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

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

Some comments

- Nucleus has finite volume: the asymptotic RCHB equations for $r \to \infty$:

$$\begin{cases} \dfrac{d^2 G_U(r)}{dr^2} = -(E+\lambda)(2M+E+\lambda)G_U(r) \\ \dfrac{d^2 G_V(r)}{dr^2} = -(\lambda-E)(2M+\lambda-E)G_V(r) \end{cases}$$

similar for FU (r)

similar for FV(r

- Asymptotic solutions:

$$\begin{cases} F_U(r), G_U(r) \sim \begin{cases} \cos(k_U r), \lambda+E>0 \\ \exp(-k_U' r), \lambda+E<0 \end{cases} \\ F_V(r), G_V(r) \sim \begin{cases} \cos(k_V r), \lambda-E>0 \\ \exp(-k_V' r), \lambda-E<0 \end{cases} \end{cases}$$

if $E < -\lambda$, U components is localized, discrete

if $E > -\lambda$, U components is non-localized, continuum

RCHB theory

Densities

$$
\begin{cases}
4\pi r^2\rho_s(r) & = & \sum_i(|G_V^i(r)|^2 - |F_V^i(r)|^2), \\
4\pi r^2\rho_v(r) & = & \sum_i(|G_V^i(r)|^2 + |F_V^i(r)|^2), \\
4\pi r^2\rho_3(r) & = & \sum_i \tau_3(|G_V^i(r)|^2 + |F_V^i(r)|^2), \\
4\pi r^2\rho_c(r) & = & \sum_i \frac{1}{2}(1-\tau_3)(|G_V^i(r)|^2 + |F_V^i(r)|^2),
\end{cases}
$$

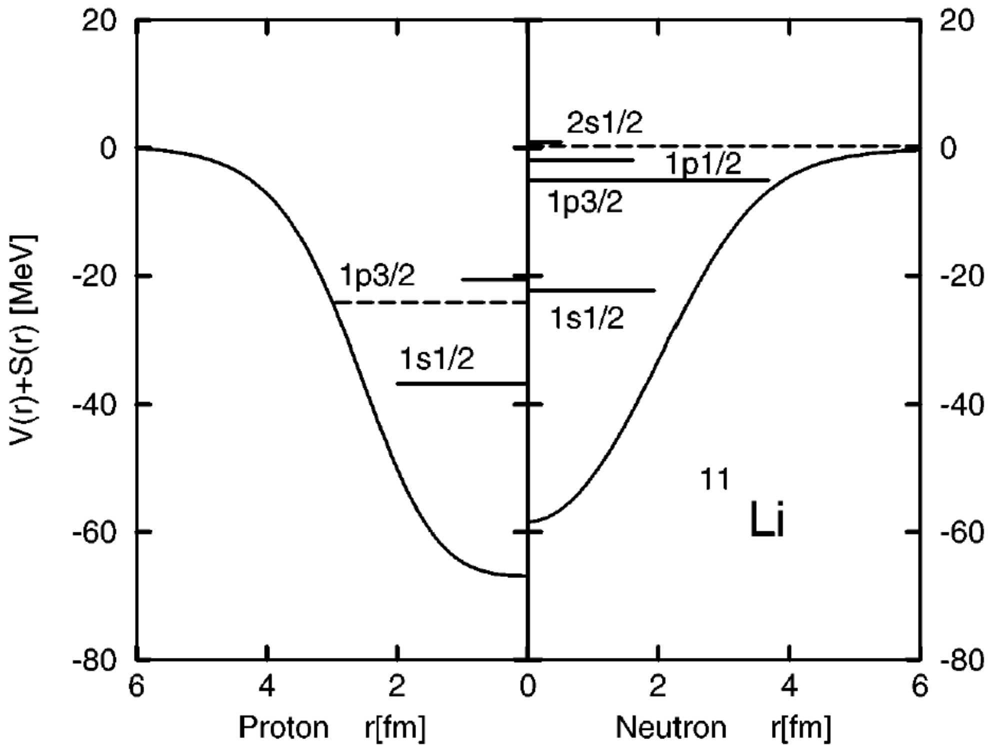
Total binding energy

$$
E \;=\; E_{\text{nucleon}} + E_\sigma + E_\omega + E_\rho + E_c + E_{\text{CM}},
$$

$$
E_{\text{nucleon}} = \sum_i \int dr(\lambda - E^i)\left[|G_V^i(r)|^2 + |F_V^i(r)|^2\right] - 2E_{\text{pair}},
$$

$$
E_{\text{pair}} = -\frac{1}{2}\text{Tr}\Delta\kappa
$$

^{11}Li: self-consistent RCHB description

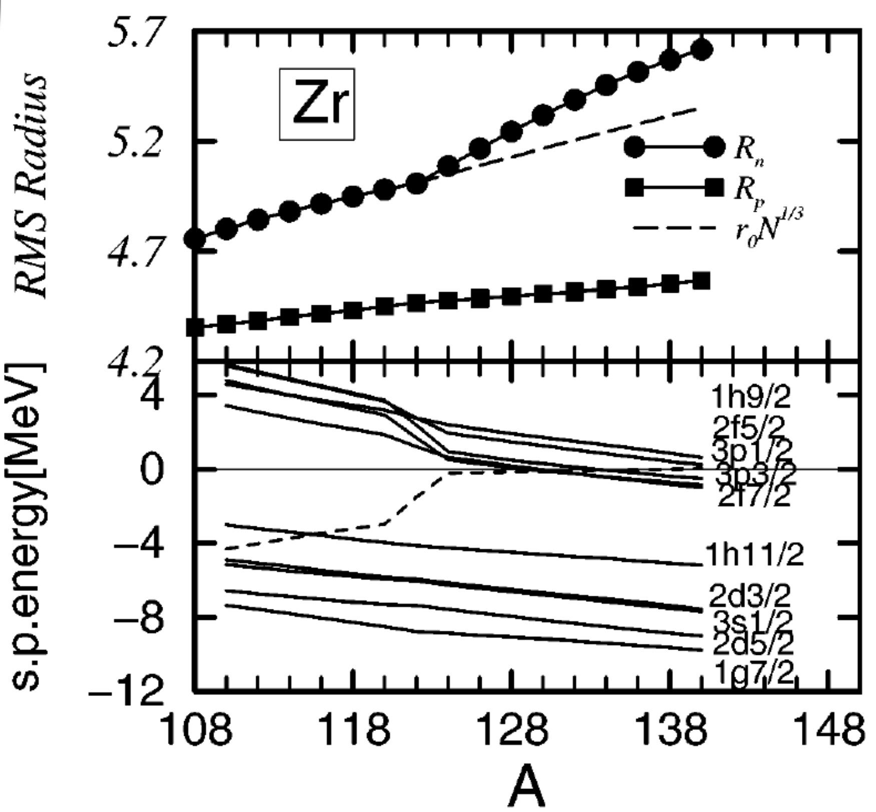


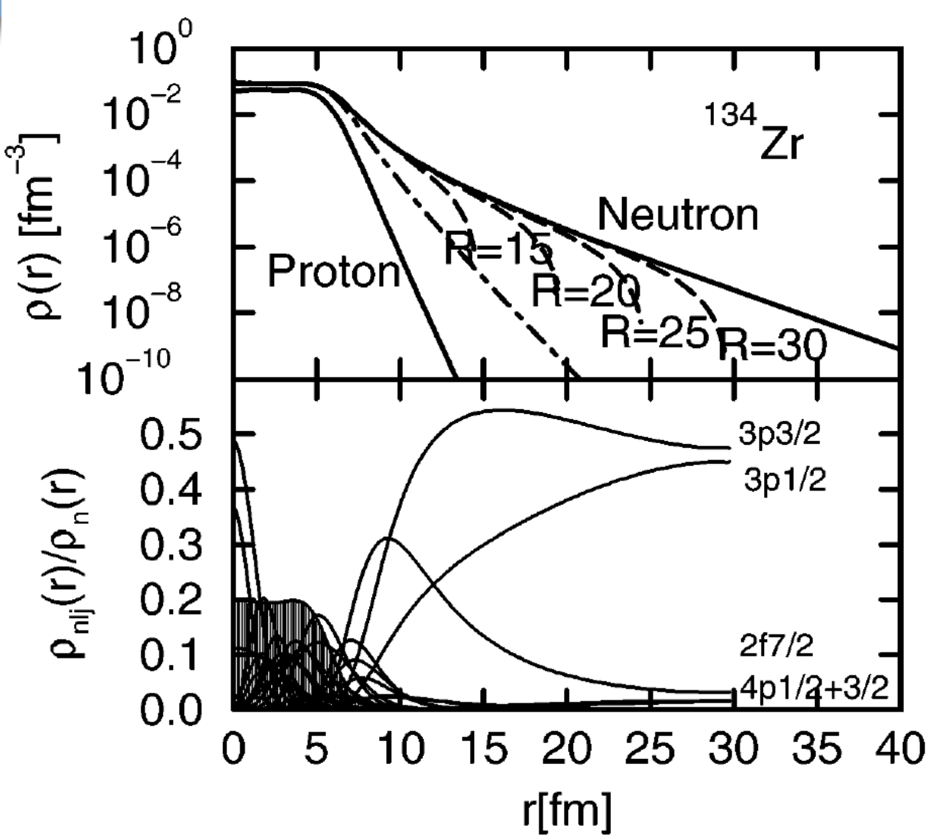
Meng & Ring, PRL77,3963 (96)

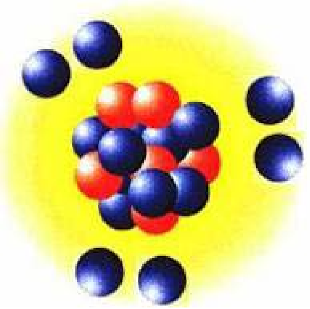
Contribution of continuum

Important roles of low-*l* orbitals close to the threshold

Giant halo: predictions of RCHB







Halos consisting of up to 6 neutrons

Important roles of low-*l* orbitals close to the threshold

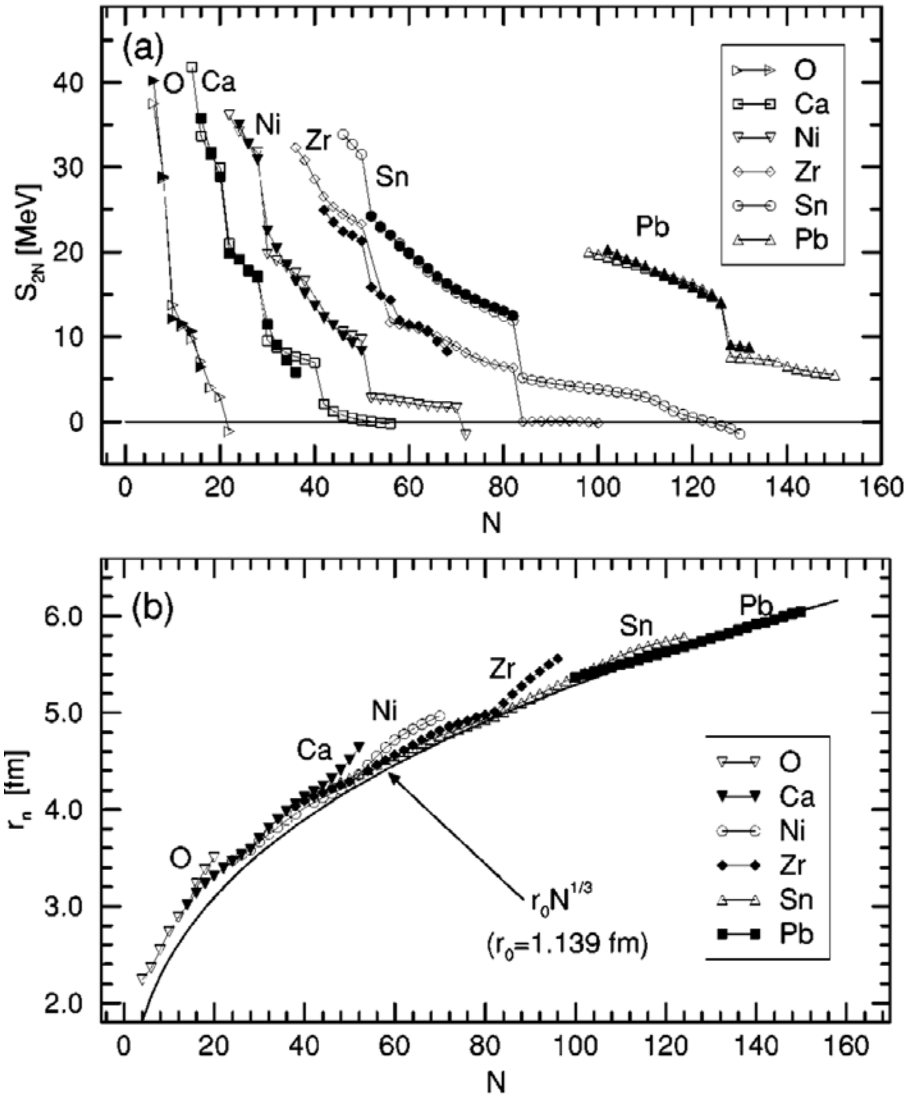
Meng & Ring, PRL80,460 (1998)

Prediction of giant halo

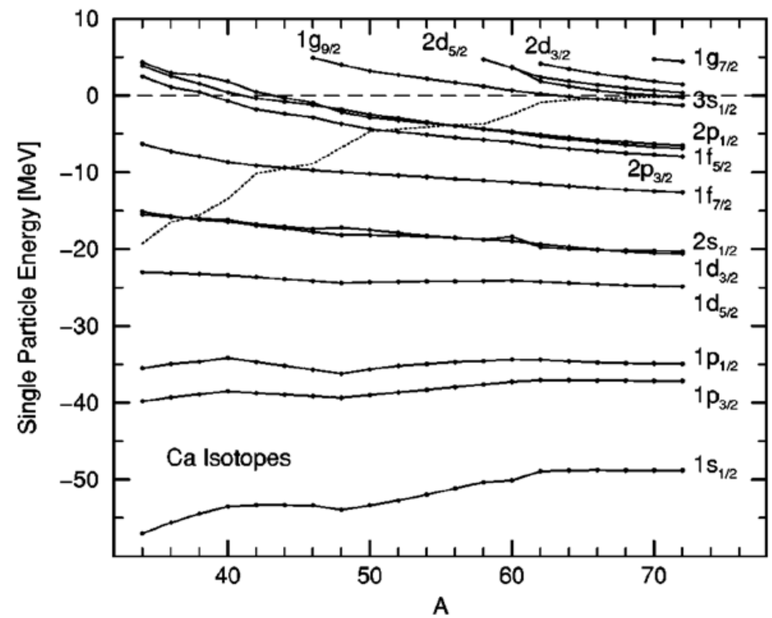
Meng, Toki, Zeng, Zhang & Zhou, PRC65,041302R (2002)

Zhang, Meng, Zhou & Zeng, CPL19,312 (2002)

Zhang, Meng & Zhou, SCG33,289 (2003)



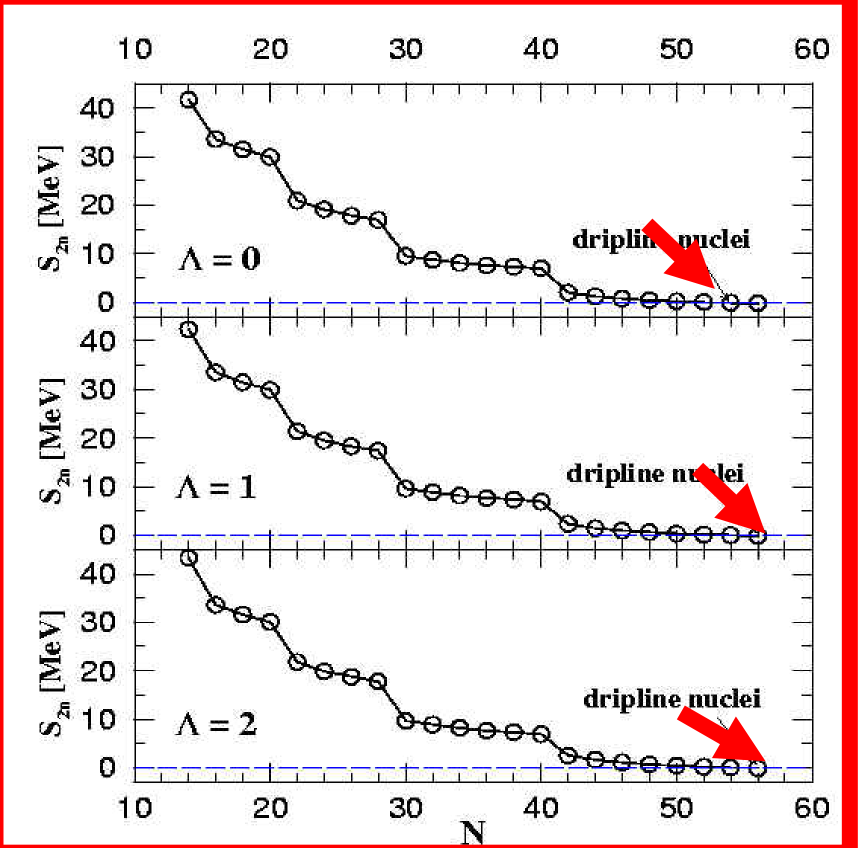
Giant halos in lighter isotopes



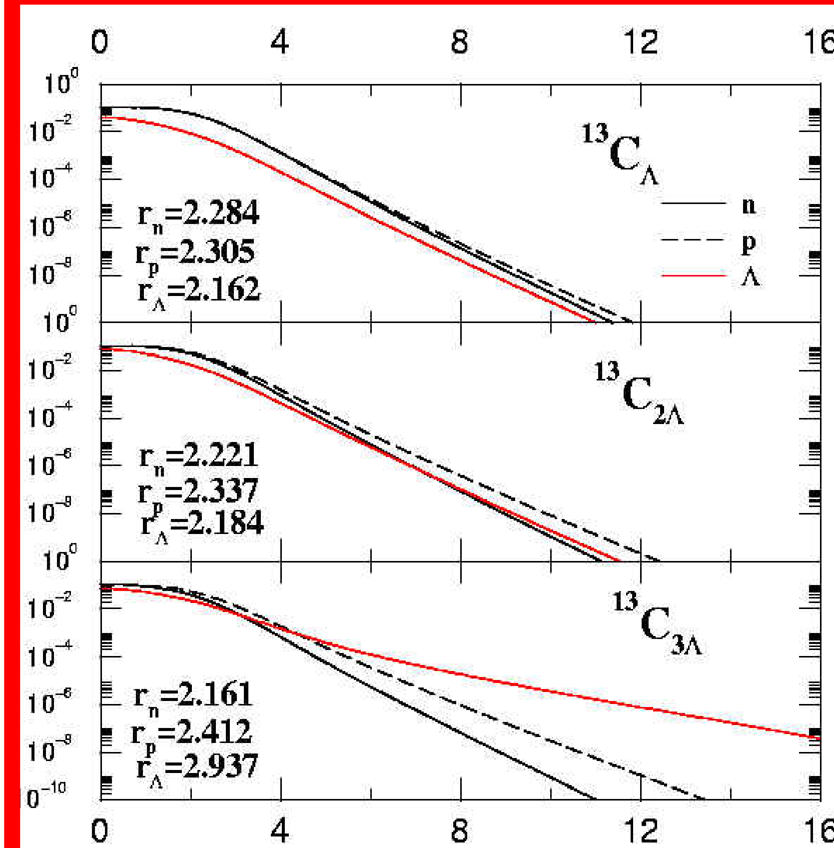
Exotic Phenomena

Lu & Meng, CPL 19, 1775(2002)
Lu, Meng, Zhang & Zhou, EPJ A17,19 (2003)

Neutron halos in hyper Ca nuclei



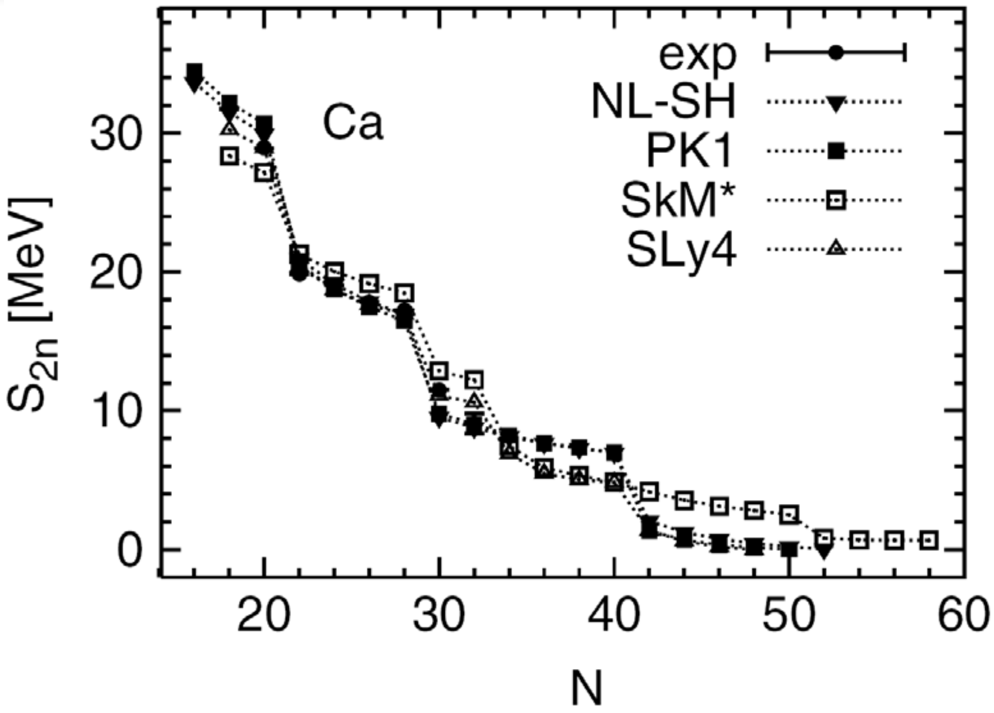
Hyperon halos in $^{13}C_{\Lambda}$

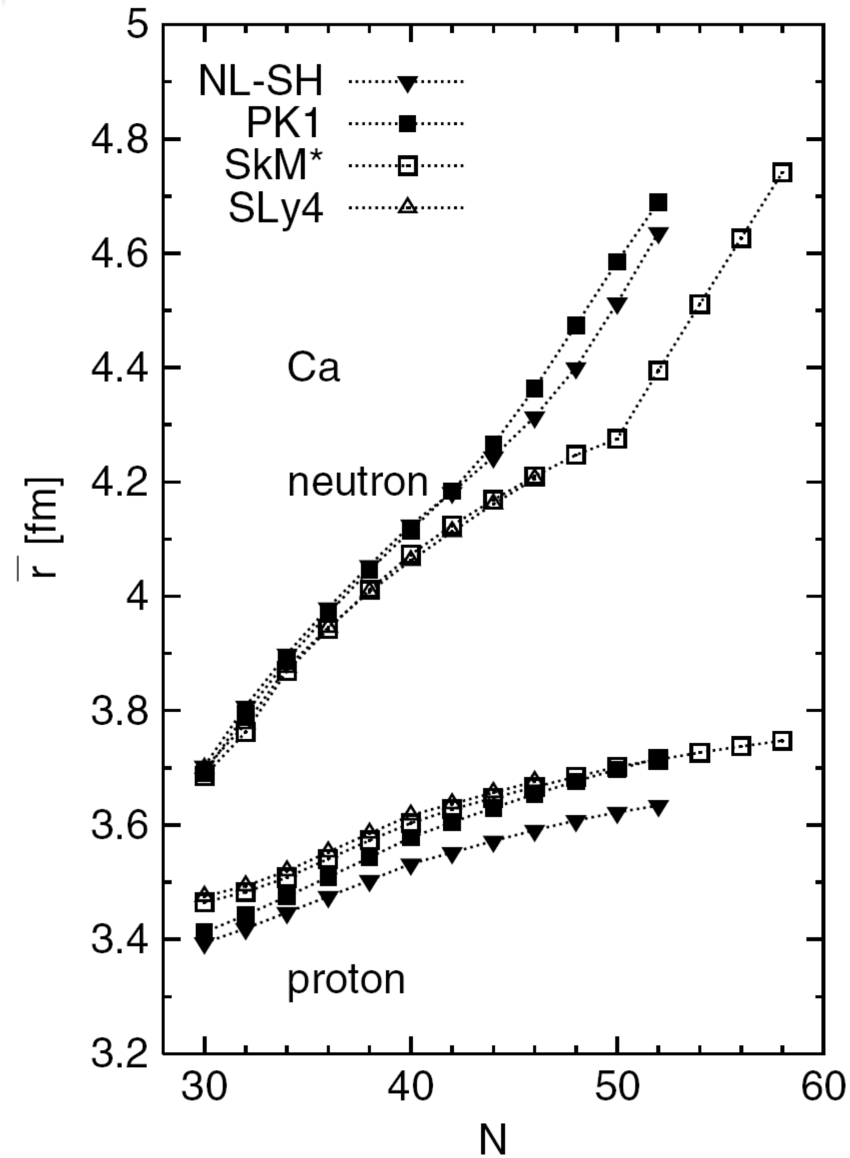


Outline

- Introduction
- Halos in Density Functional Theory: Skyrme HFB / DD RHFB / GF Skyrme HFB
- Deformed halos
- R-process calculation with CDFT Mass table
- Summary & Perspectives

Giant halo from Skyrme HFB and RCHB





Giant halos from non-rela. HFB

Different predictions for drip line

Terasaki, Zhang, Zhou, & Meng, PRC74 (2006) 054318

Role of pion and Exchange term: DDRHFB

- **RHFB equation**

$$\int d\mathbf{r}' \begin{pmatrix} h(\mathbf{r},\mathbf{r}') - \lambda & \Delta(\mathbf{r},\mathbf{r}') \\ \Delta(\mathbf{r},\mathbf{r}') & -h(\mathbf{r},\mathbf{r}') + \lambda \end{pmatrix} \begin{pmatrix} \psi_U(\mathbf{r}') \\ \psi_V(\mathbf{r}') \end{pmatrix} = E \begin{pmatrix} \psi_U(\mathbf{r}) \\ \psi_V(\mathbf{r}) \end{pmatrix}$$

- **Single particle Hamiltonian:** $h = h^{\mathrm{kin}} + h^{\mathrm{D}} + h^{\mathrm{E}}$

Kinetic energy: $h^{\mathrm{kin}}(\mathbf{r},\mathbf{r}') = [\alpha \cdot \mathbf{p} + \beta M]\, \delta(\mathbf{r},\mathbf{r}'),$

Local potentials: $h^{\mathrm{D}}(\mathbf{r},\mathbf{r}') = [\Sigma_T(\mathbf{r})\gamma_5 + \Sigma_0(\mathbf{r}) + \beta\Sigma_S(\mathbf{r})]\, \delta(\mathbf{r},\mathbf{r}'),$

Non-local Potentials: $h^{\mathrm{E}}(\mathbf{r},\mathbf{r}') = \begin{pmatrix} Y_G(\mathbf{r},\mathbf{r}') & Y_F(\mathbf{r},\mathbf{r}') \\ X_G(\mathbf{r},\mathbf{r}') & X_F(\mathbf{r},\mathbf{r}') \end{pmatrix}$

- **Pairing Force: Gogny D1S**

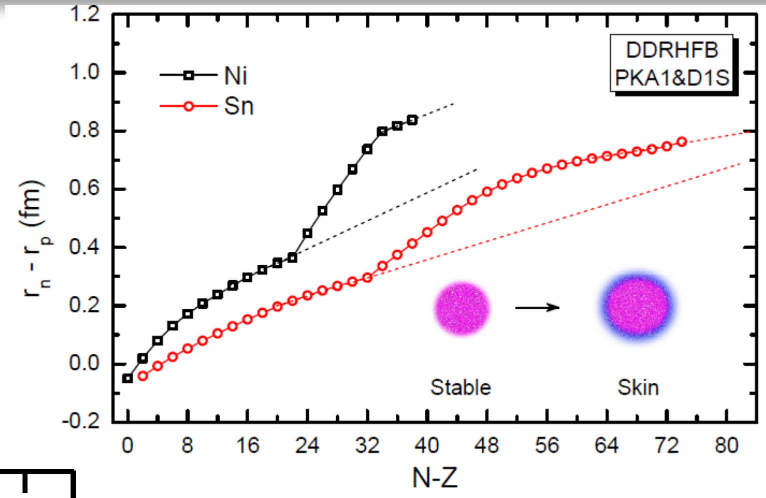
$$V(\mathbf{r},\mathbf{r}') = \sum_{i=1,2} e^{((r-r')/\mu_i)^2} (W_i + B_i P^\sigma - H_i P^\tau - M_i P^\sigma P^\tau)$$

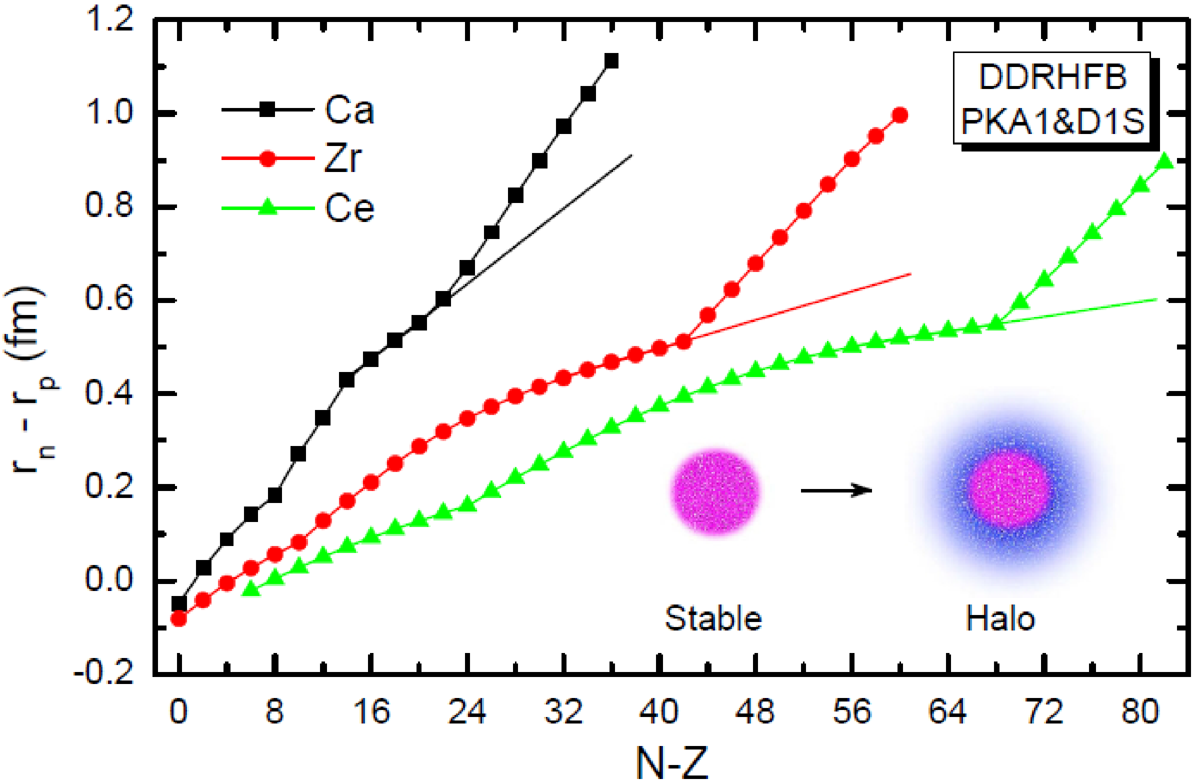
- **Dirac Woods-Saxon Basis** **S.-G. Zhou (2003)**

➔ **To Solve the integro-differential RHFB equation**

Halo and giant halo in DDRHFB

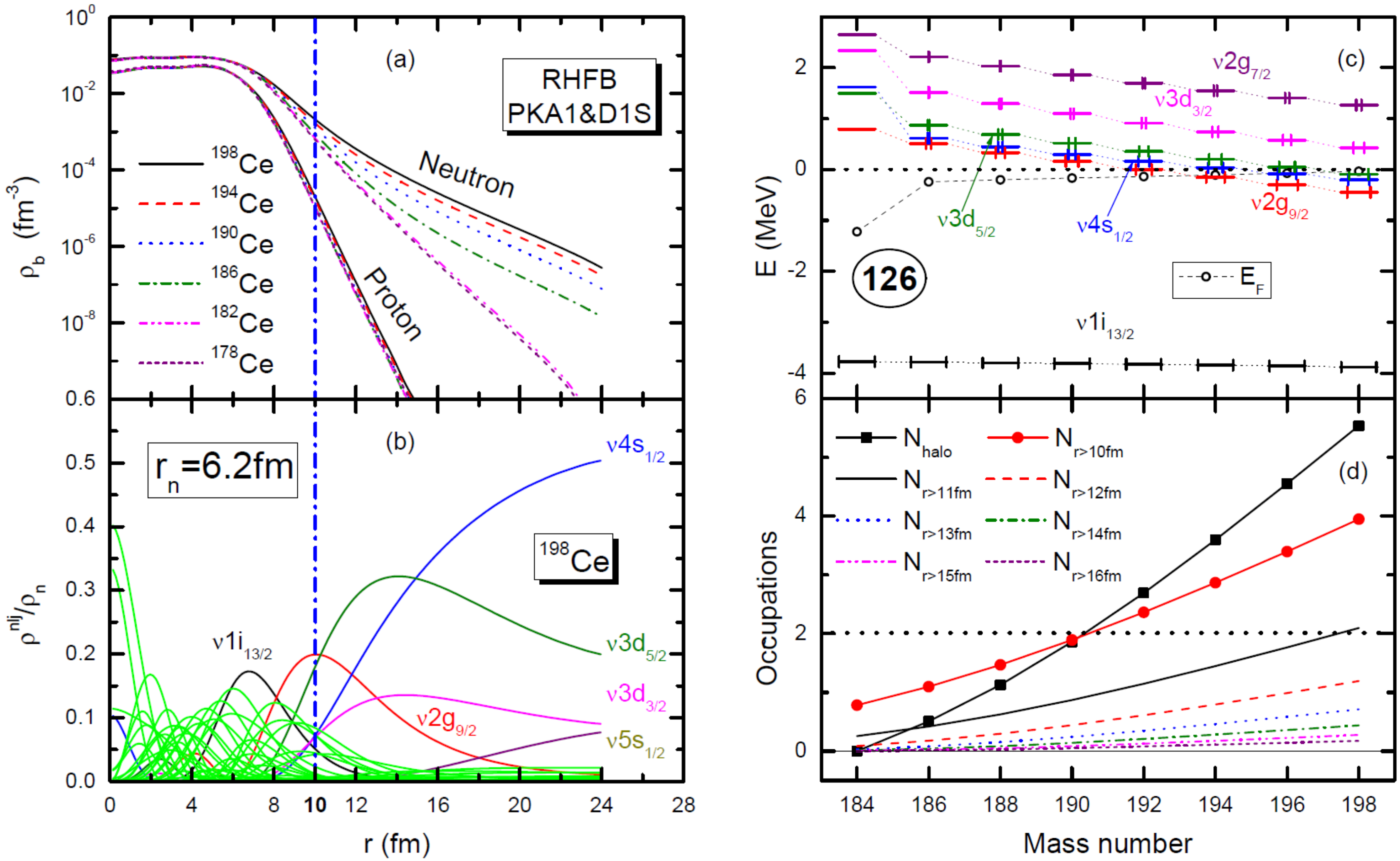
1. Long, Ring, Giai, and Meng, Physical Review C 81, 024308 (2010)
2. Long, Ring, Meng, Giai, and Bertulani, Physical Review C 81, 031302(R) (2010)





Halo structures in Cerium isotopes

Halos: $^{186,\,188,\,190}$Ce; Giant halos: $^{192,\,194,\,196,\,198}$Ce



❖ Density in discretized and continuum HFB approach

$$\rho(\mathbf{r}\sigma,\mathbf{r}'\sigma') \equiv \left\langle \Phi_0 \middle| \psi^\dagger(\mathbf{r}'\sigma')\psi(\mathbf{r}\sigma) \middle| \Phi_0 \right\rangle$$

$$\tilde{\rho}(\mathbf{r}\sigma,\mathbf{r}'\sigma') \equiv \left\langle \Phi_0 \middle| \psi(\mathbf{r}'\tilde{\sigma}')\psi(\mathbf{r}\sigma) \middle| \Phi_0 \right\rangle$$

$$\rho(\mathbf{r}\sigma,\mathbf{r}'\sigma') = \sum_{0<E_i<|\lambda|} \varphi_2(E_i,\mathbf{r}\sigma)\varphi_2^*(E_i,\mathbf{r}'\sigma') + \int_{|\lambda|}^{\infty} dE\ \varphi_2(E,\mathbf{r}\sigma)\varphi_2^*(E,\mathbf{r}'\sigma')$$

$$\tilde{\rho}(\mathbf{r}\sigma,\mathbf{r}'\sigma') = -\sum_{0<E_i<|\lambda|} \varphi_2(E_i,\mathbf{r}\sigma)\varphi_1^*(E_i,\mathbf{r}'\sigma') - \int_{|\lambda|}^{\infty} dE\ \varphi_2(E,\mathbf{r}\sigma)\varphi_1^*(E,\mathbf{r}'\sigma')$$

discretized HFB

$$\rho(\mathbf{r}\sigma,\mathbf{r}'\sigma') = \sum_{0<E_i<E_{\mathrm{cut}}} \varphi_2(E_i,\mathbf{r}\sigma)\varphi_2^*(E_i,\mathbf{r}'\sigma')$$

$$\tilde{\rho}(\mathbf{r}\sigma,\mathbf{r}'\sigma') = -\sum_{0<E_i<E_{\mathrm{cut}}} \varphi_2(E_i,\mathbf{r}\sigma)\varphi_1^*(E_i,\mathbf{r}'\sigma')$$

continuum HFB

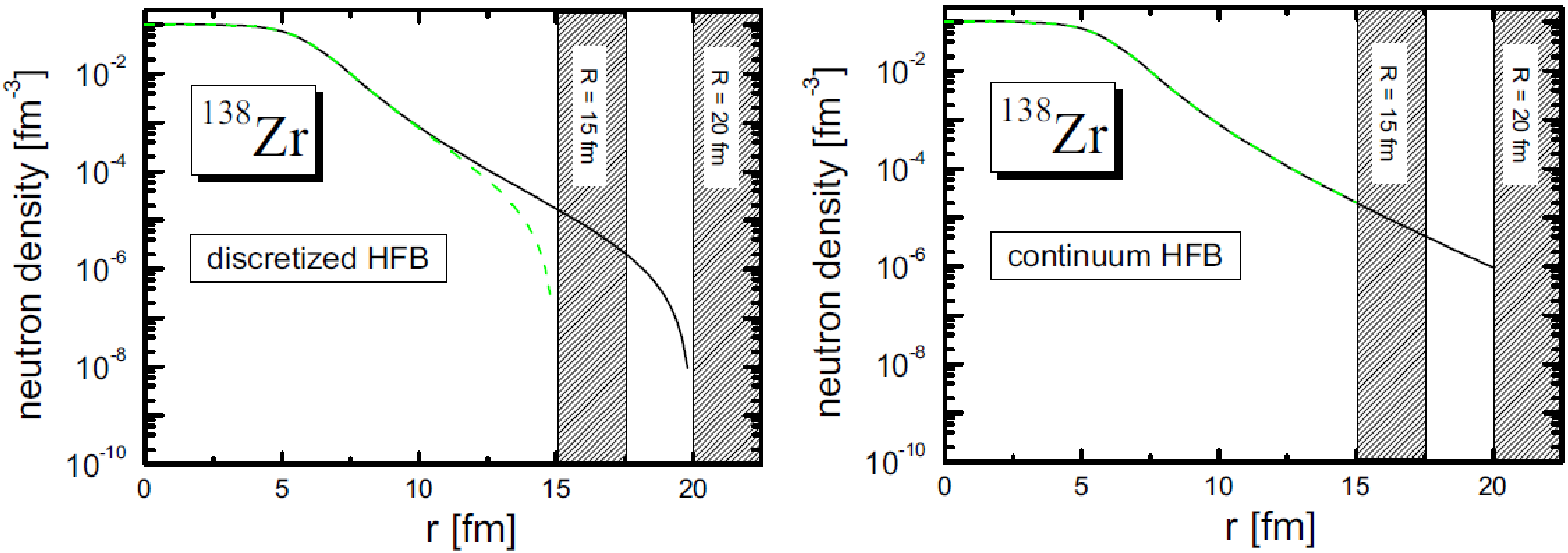
$$\rho(\mathbf{r}\sigma,\mathbf{r}'\sigma') = \frac{1}{2\pi i}\oint_{C_{E<0}} dE\ \varphi_2(E,\mathbf{r}\sigma)\varphi_2^*(E,\mathbf{r}'\sigma')$$

$$\tilde{\rho}(\mathbf{r}\sigma,\mathbf{r}'\sigma') = -\frac{1}{2\pi i}\oint_{C_{E<0}} dE\ \varphi_2(E,\mathbf{r}\sigma)\varphi_1^*(E,\mathbf{r}'\sigma')$$

PRC83, 054301(2011)

Continuum Skyrme HFB with Green's function method

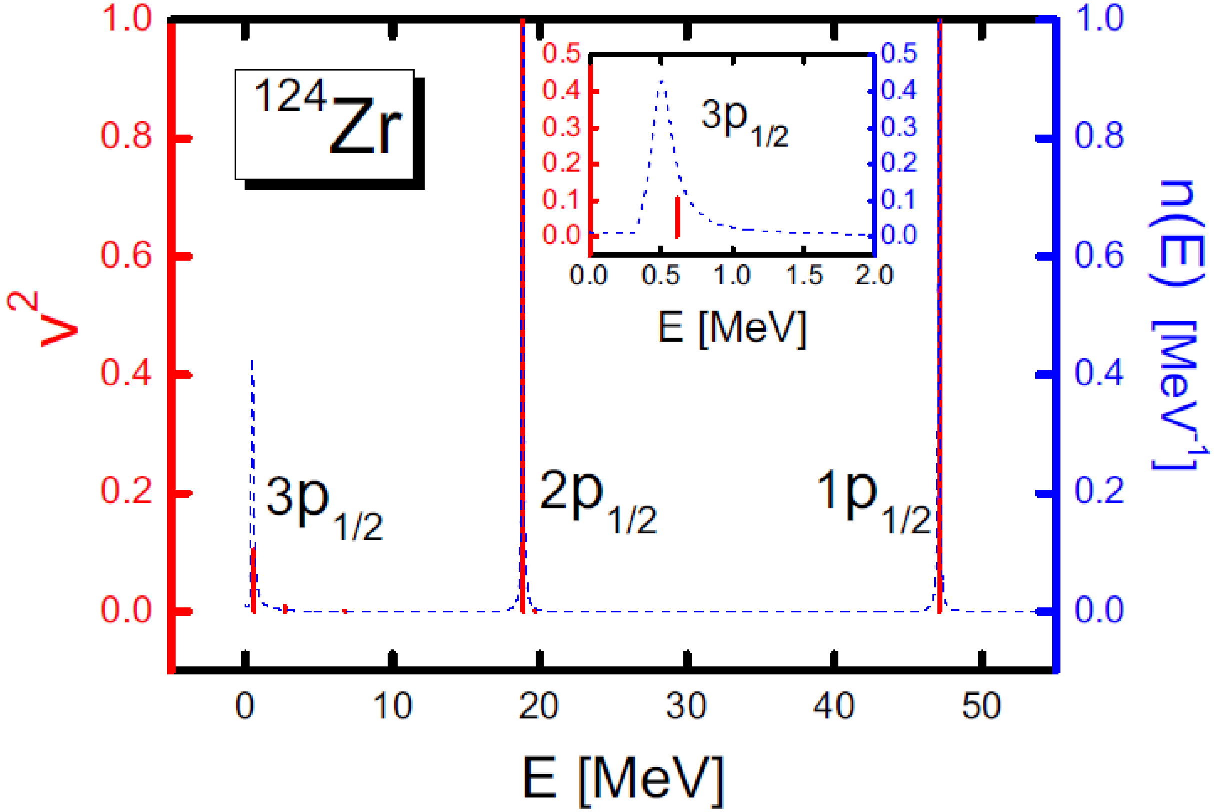
❖ **Density obtained from discretized and continuum HFB approach**



independent on the box size for continuum HFB

Continuum Skyrme HFB with Green's function method

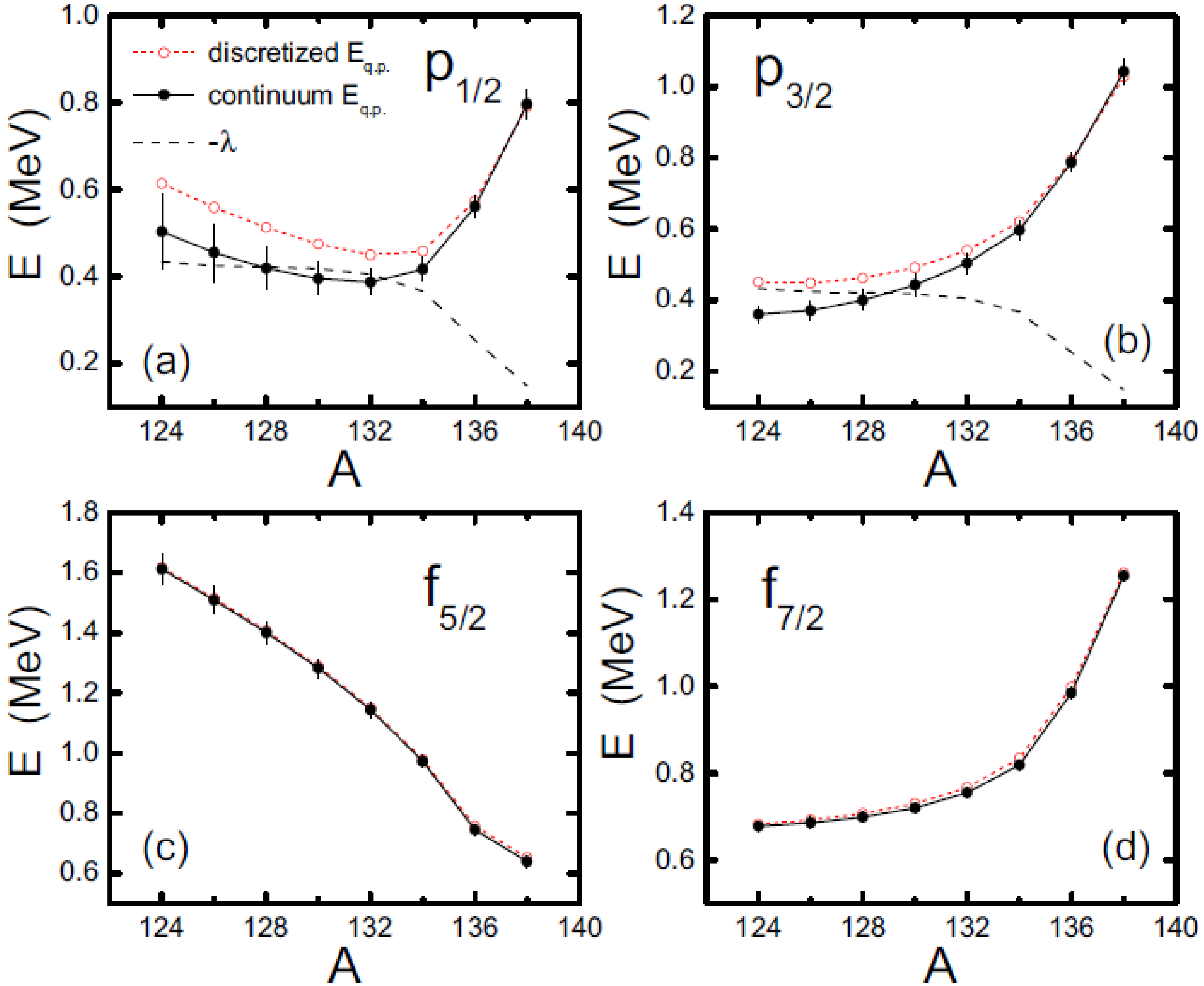
- ❖ **n(E): occupation number density by continuum HFB cal.**
- ❖ **v^2: occupation probability by discretized HFB cal.**



New information: width of q.p. resonance for continuum HFB

Continuum Skyrme HFB with Green's function method

❖ Quasiparticle resonance



Outline

- Introduction
- Halos in Density Functional Theory: Skyrme HFB / DD RHFB / GF Skyrme HFB
- Deformed halos
- R-process calculation with CDFT Mass table
- Summary & Perspectives

Deformed RHB in a Woods-Saxon basis

Axially deformed nuclei

$$\beta_{km}^{+} = \sum_{(i\kappa)} u_{k,(i\kappa)}^{(m)} a_{i\kappa m}^{+} + v_{k,(i\tilde{\kappa})}^{(m)} \tilde{a}_{i\kappa m}$$

$$\begin{pmatrix} U_k^{(m)}(\mathbf{r}\sigma p) \\ V_k^{(m)}(\mathbf{r}\sigma p) \end{pmatrix} = \sum_{i\kappa} \begin{pmatrix} u_{k,(i\kappa)}^{(m)} \varphi_{i\kappa m}(\mathbf{r}\sigma p) \\ v_{k,(i\tilde{\kappa})}^{(m)} \tilde{\varphi}_{i\kappa m}(\mathbf{r}\sigma p) \end{pmatrix}$$

$$\varphi_{i\kappa m}(\mathbf{r}\sigma p) = \frac{1}{r} \begin{pmatrix} iG_{i\kappa}(r) Y_{\kappa m}(\Omega\sigma) \\ -F_{i\kappa}(r) Y_{\kappa m}(\Omega\sigma) \end{pmatrix}$$

$$\sum_{\sigma p} \int d^3\mathbf{r}' \begin{pmatrix} h(\mathbf{r}\sigma p;\mathbf{r}'\sigma' p') - \lambda & \Delta(\mathbf{r}\sigma p;\mathbf{r}'\sigma' p') \\ -\Delta^*(\mathbf{r}\sigma p;\mathbf{r}'\sigma' p') & -h(\mathbf{r}\sigma p;\mathbf{r}'\sigma' p') + \lambda \end{pmatrix} \begin{pmatrix} U_E(\mathbf{r}'\sigma' p') \\ V_E(\mathbf{r}'\sigma' p') \end{pmatrix} = E \begin{pmatrix} U_E(\mathbf{r}\sigma p) \\ V_E(\mathbf{r}\sigma p) \end{pmatrix}$$

$$\begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix} \begin{pmatrix} \mathbf{U} \\ \mathbf{V} \end{pmatrix} = E \begin{pmatrix} \mathbf{U} \\ \mathbf{V} \end{pmatrix}$$

$$\mathbf{U} = \left(u_{k,(i\kappa)}^{(m)} \right) \qquad \mathbf{V} = \left(v_{k,(i\tilde{\kappa})}^{(m)} \right)$$

DRHB matrix elements

$$\mathrm{A}_{(i\kappa),(i'\kappa')} = \left(h^{(m)}_{(i\kappa),(i'\kappa')}\right) - \lambda\mathbf{I} \qquad \mathrm{B}_{(i\kappa),(i'\tilde{\kappa}')} = \left(\Delta^{(m)}_{(i\kappa),(i'\tilde{\kappa}')}\right)$$

$$\mathrm{C}_{(i\tilde{\kappa}),(i'\kappa')} = \left(-\Delta^{(m)}_{(i\tilde{\kappa}),(i'\kappa')} = \Delta^{(m)}_{(i\kappa),(i'\tilde{\kappa}')}\right) \qquad \mathrm{D}_{(i\tilde{\kappa}),(i'\tilde{\kappa}')} = \left(-h^{(m)}_{(i\tilde{\kappa}),(i'\tilde{\kappa}')}\right) + \lambda\mathbf{I}$$

$$V(\mathbf{r}) = \sum_{\lambda\mu} V_{\lambda\mu}(r) Y_{\lambda\mu}(\Omega) \qquad S(\mathbf{r}) = \sum_{\lambda\mu} S_{\lambda\mu}(r) Y_{\lambda\mu}(\Omega)$$

$$h^{(m)}_{(i\kappa),(i'\kappa')} = \sum_{\lambda} \int dr \{G_{i\kappa}(r) G_{i'\kappa'}(r)[V_{\lambda}(r) + S_{\lambda}(r)] + F_{i\kappa}(r) F_{i'\kappa'}(r)[V_{\lambda}(r) - S_{\lambda}(r)]\} A(\lambda, \kappa, \kappa', m)$$

$$\Delta(\mathbf{r}, \sigma_1\sigma_2) = \sum_{\lambda\mu} \sum_{SM_S} Y_{\lambda\mu}(\Omega) \chi_{SM_S}(\sigma_1\sigma_2) \Delta^{SM_S}_{\lambda\mu;p_1p_2}(r)$$

λ, even or odd
$\mu = 0, \pm 1$

$$\Delta^{(m)}_{(i_1\kappa_1),(i_2\tilde{\kappa}_2)} = \frac{1}{2} \sum_{\lambda\mu} \sum_{SM_S} \delta_{M_S,-\mu} \sum_{p_1p_2} \eta^{SM_S}_{\lambda\mu;\alpha_1 p_1 \bar{\alpha}_2 p_2} \int dr R^{p_1}_{i_1\kappa_1}(r) R^{p_2}_{i_2\kappa_2}(r) \Delta^{SM_S}_{\lambda\mu;p_1p_2}(r)$$

Pairing interaction

- **Phenomenological pairing interaction with parameters: V_0, ρ_0, γ, and the smooth cut off parameters E_{cut} and Γ**

$$V^{\text{pair}} = \frac{1}{4} V_0 \delta(\mathbf{r}_1 - \mathbf{r}_2) \left(1 - \frac{\rho(\mathbf{r}_1)}{\rho_0}\right)^{\gamma}$$

$$s(E_k) = \frac{1}{2}\left(1 - \frac{E_k - E_{\text{cut}}^{\text{q.p.}}}{\sqrt{(E_k - E_{\text{cut}}^{\text{q.p.}})^2 + (\Gamma_{\text{cut}}^{\text{q.p.}})^2}}\right)$$

Finite range?
Volume or surface?
Microscopic?

PHYSICAL REVIEW C57 (1988) 1229

How to fix the pairing strength and the pairing window

^{20}Mg: spherical from DRHBWS calculation

$$\text{NL3}, \quad R_{\max} = 20 \text{ fm}, \quad \Delta r = 0.1 \text{ fm}$$

Zero pairing energy for the neutron

Model	Pairing force	Parameters	$E^{\rm p}_{\rm pair}$ (MeV)
SRHBHO	Gogny	D1S	-9.2382
RCHB	Surface δ	$V_0 = 374$ MeV fm^3	-9.2387
		$\rho_0 = 0.152$ fm^3	
	Sharp cutoff	$E^{\rm q.p.}_{\rm cut} = 60$ MeV	
DRHBWS	Surface δ	$V_0 = 380$ MeV fm^3	-9.2383
		$\rho_0 = 0.152$ fm^3	
	Smooth cutoff	$E^{\rm q.p.}_{\rm cut} = 60$ MeV	
		$\Gamma = 5.65$ MeV	

Zhou, Meng, Ring, Zhao
PRC82(10)011301R

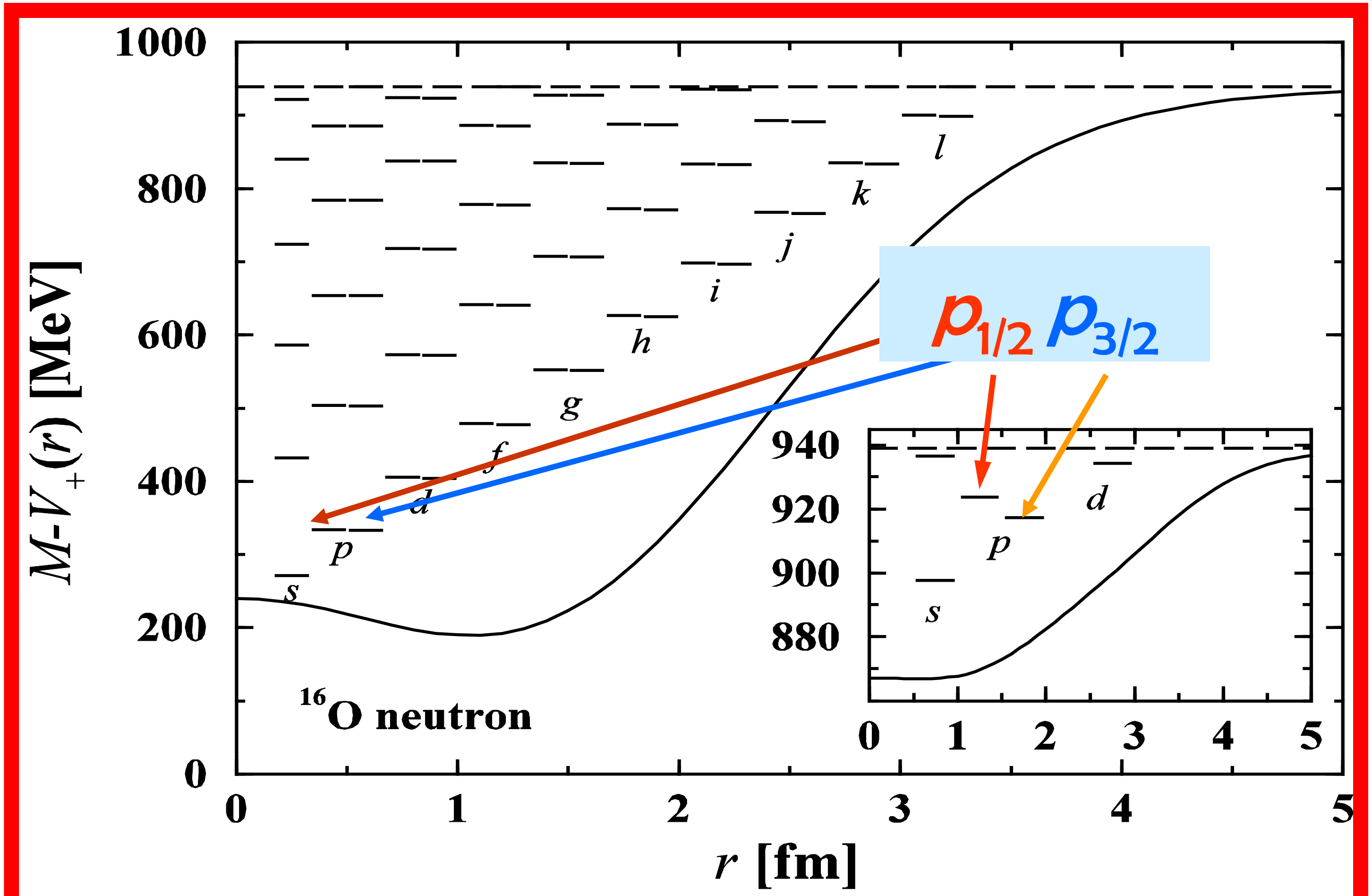
RMF in a Woods-Saxon basis: progress

Shapes	Model	Schrödinger W-S basis	Dirac W-S basis	
Spherical	Rela. Hartree Zhou, Meng & Ring, PRC68,034323(03); PRL91, 262501 (03)	SRH SWS	SRH DWS	✓
Axially deformed	Rela. Hartree + BCS Zhou, Meng & Ring, AIP Conf. Proc. 865, 90 (06)		DRH DWS	✓
Axially deformed	Rela. Hartree-Bogoliubov Zhou,Meng, Ring, ISPUN 2007		DRHB DWS	✓
Triaxially deformed	Rela. Hartree-Bogoliubov		TRHB DWS	

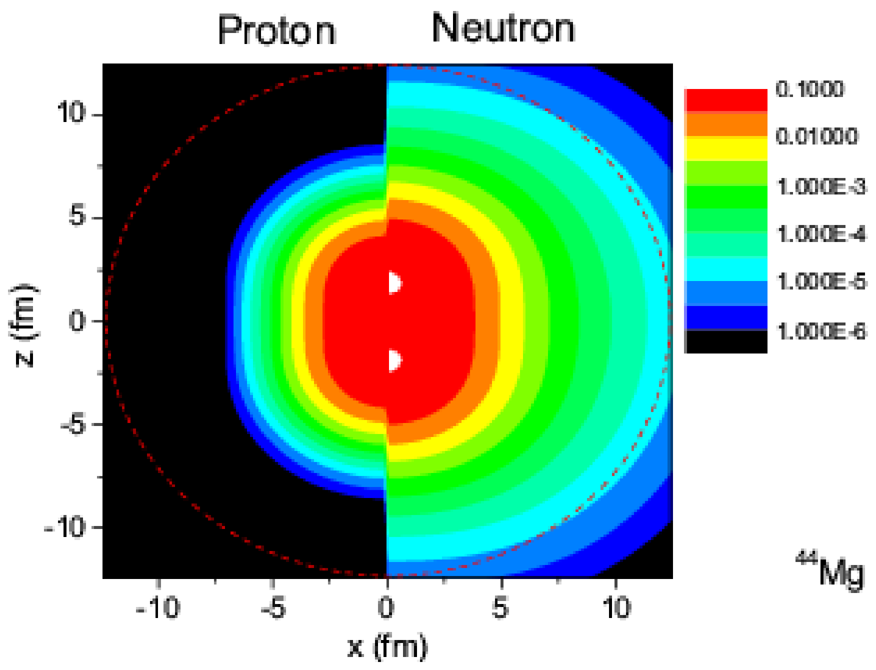
Woods-Saxon basis might be a reconciler between the HO basis and r space

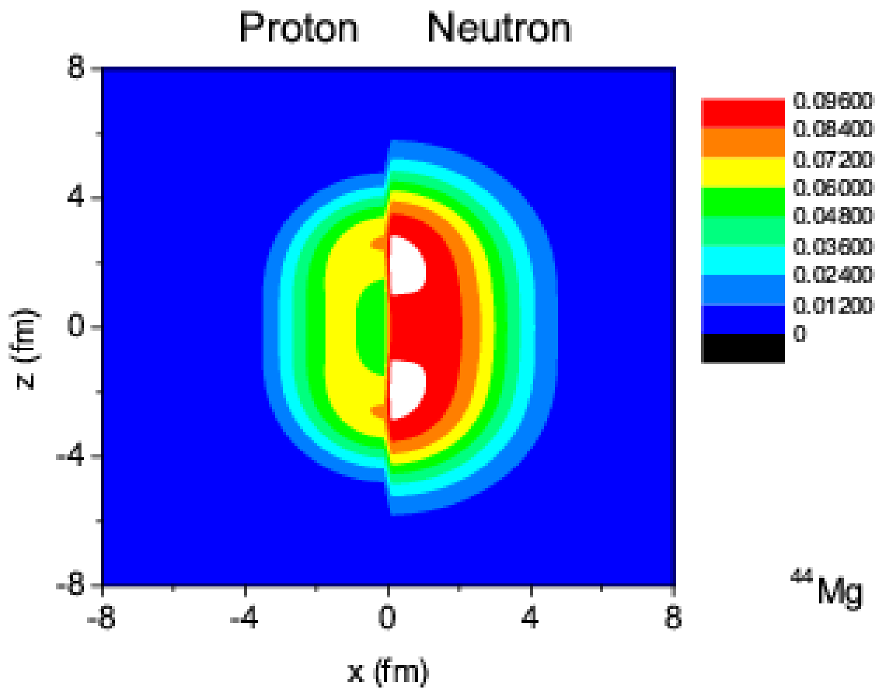
Origin of the symmetry - Anti-nucleons

Zhou,Meng&Ring, PRL92(03)262501



^{44}Mg from DRHBWS



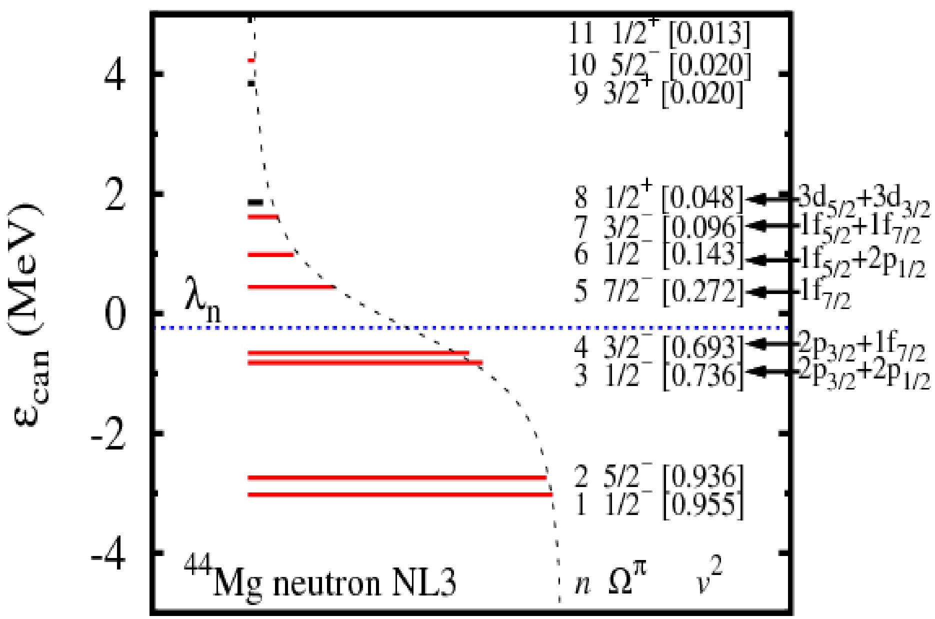


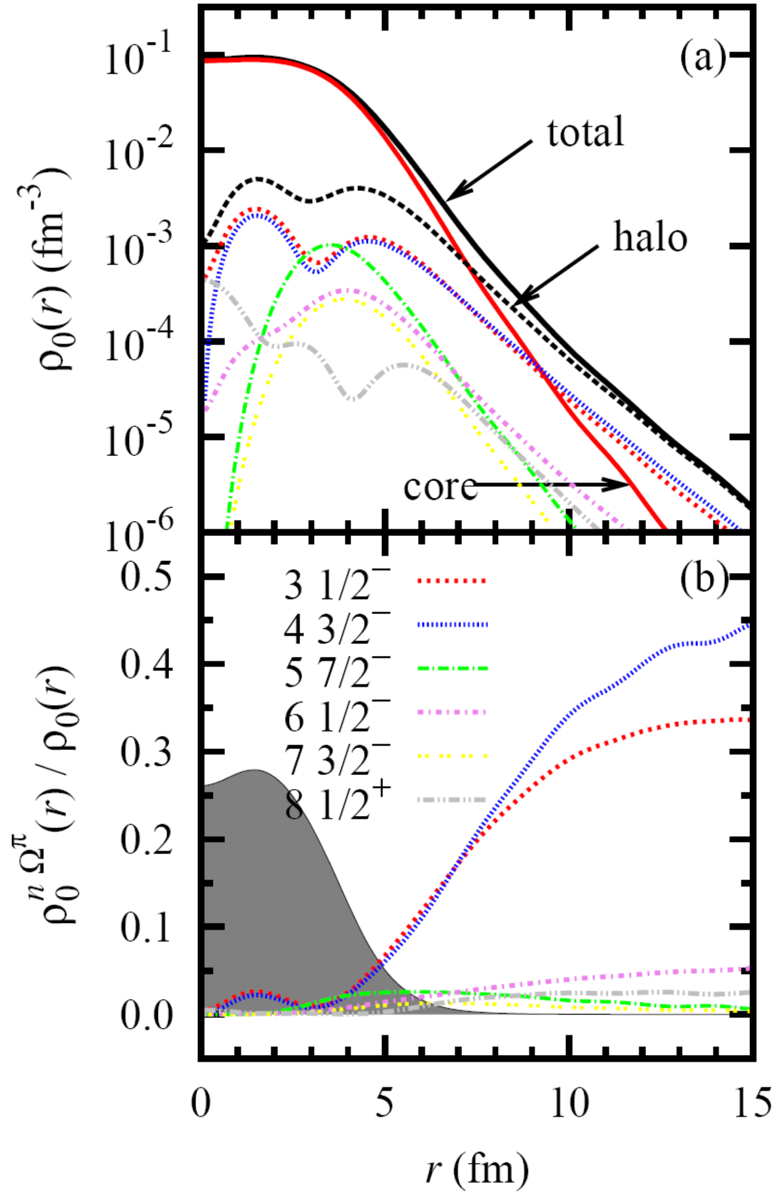
Zhou, Meng, Ring, Zhao
PRC82(10)011301R

- ❖ Prolate deformation
- ❖ Large spatial extension in neutron density distribution

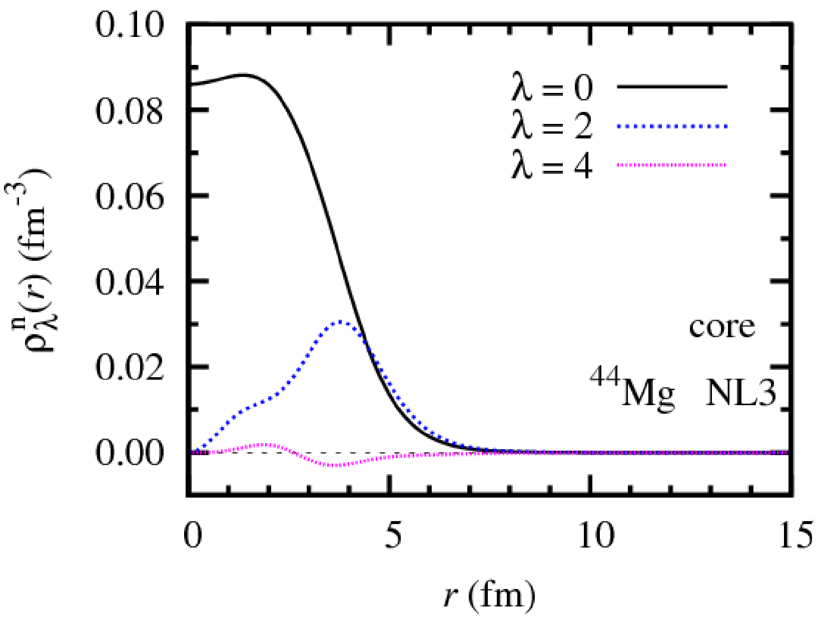
Decomposition of neut. density distri.

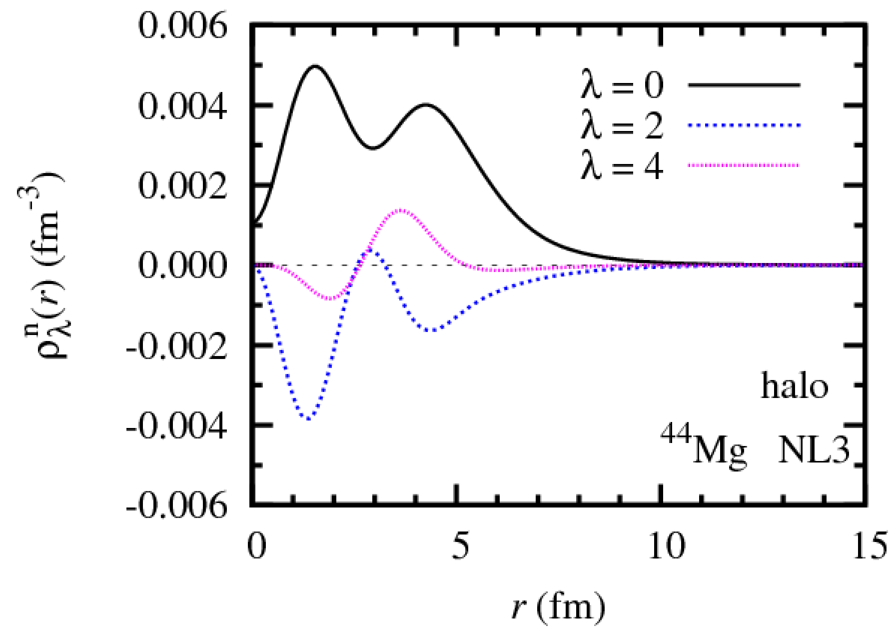
- **The 3rd & 4th states contribute to tail part of neutron density distribution**
- **Main component: $2p_{3/2}$**
- $R_{\rm core} = 3.72$ fm, $R_{\rm halo} = 5.86$ fm





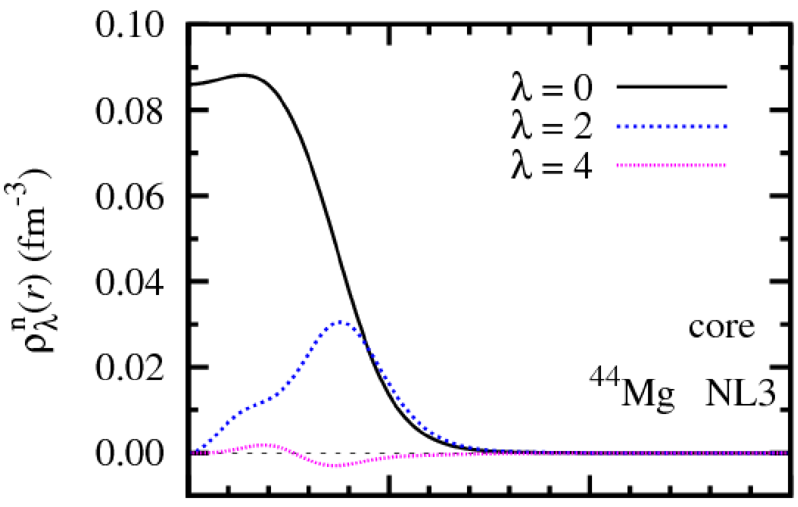
Density of core & halo

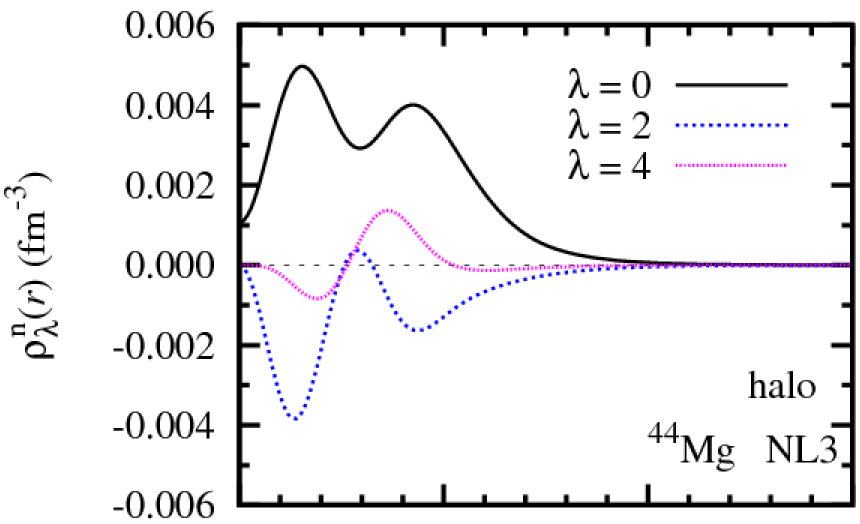


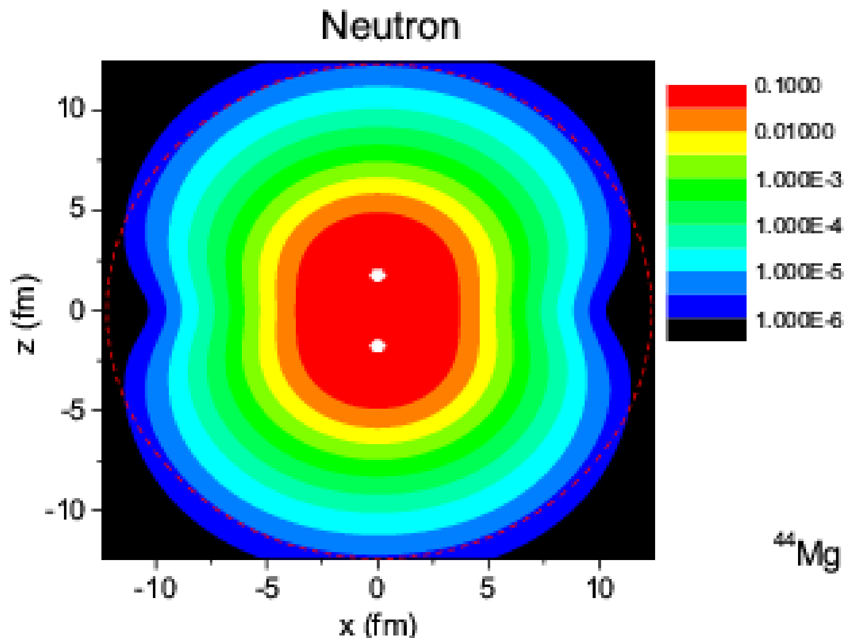


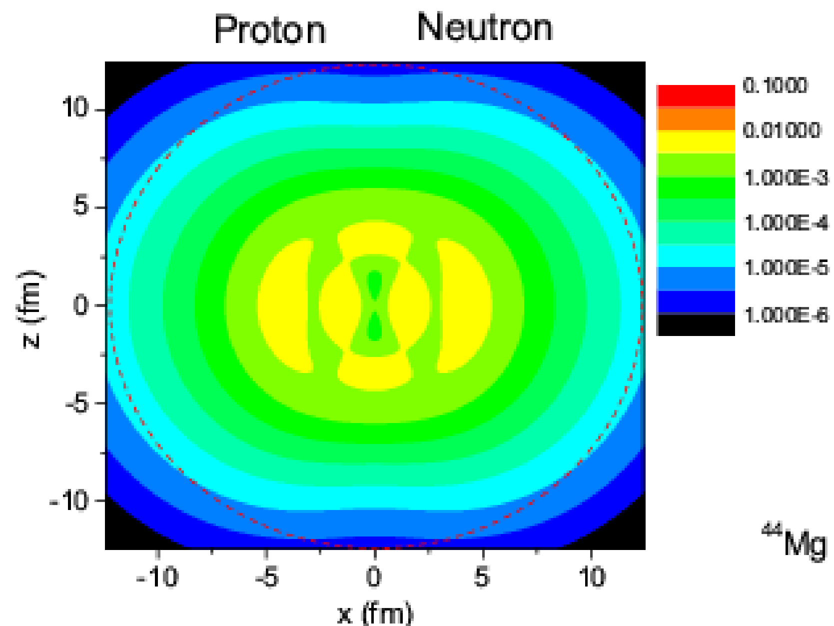
- **Prolate core, but slightly oblate halo with sizable hexadecapole component !**
- **Decoupling of deformation betw. core & halo**

Density of core & halo









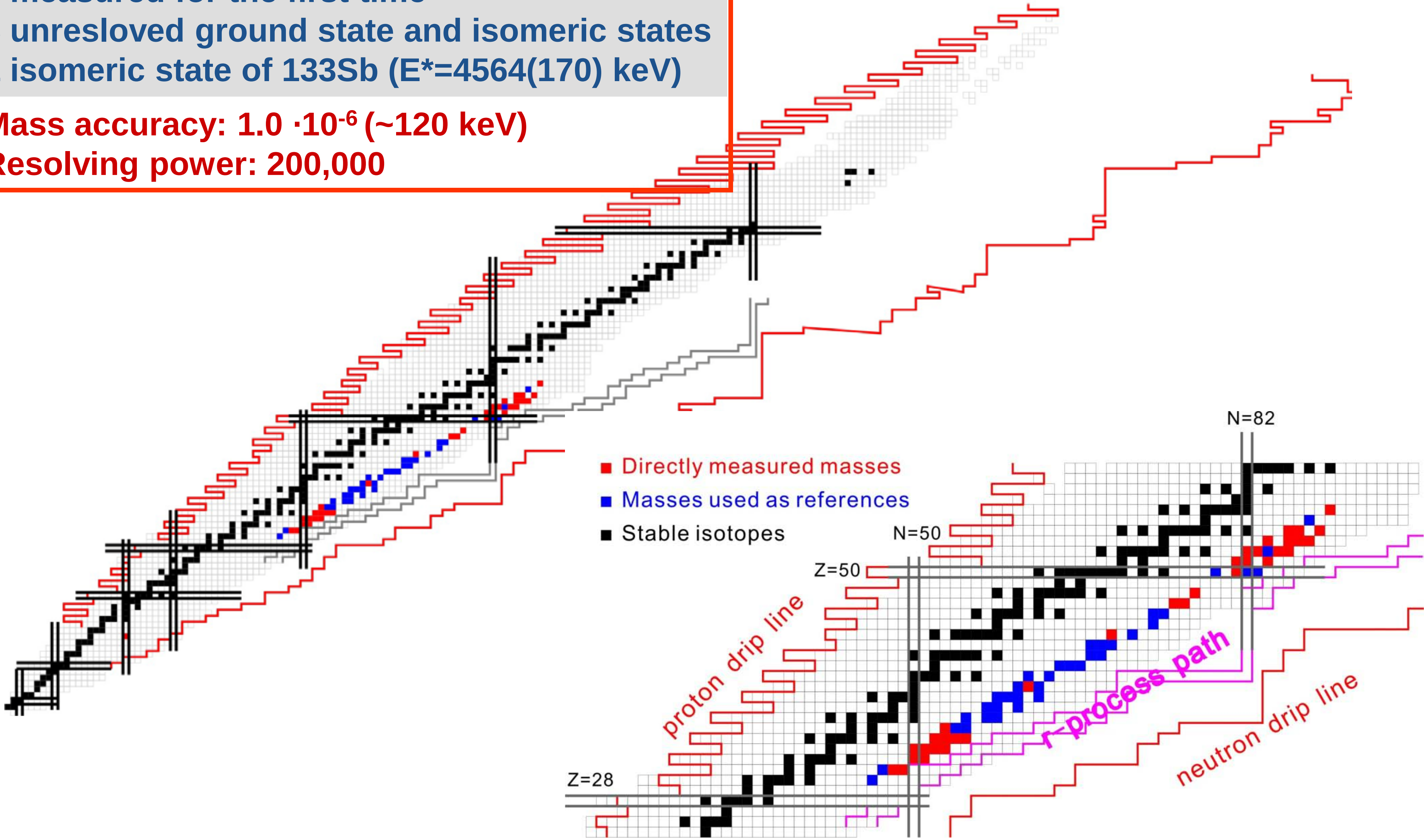
Outline

- Introduction
- Halos in Density Functional Theory: Skyrme HFB / DD
  RHFB / GF Skyrme HFB
- Deformed halos
- R-process calculation with CDFT Mass table
- Summary & Perspectives

Short-Lived Neutron-Rich Nuclei with the Novel Large-Scale Isochronous Mass Spectrometry at the FRS-ESR Facility Sun et al. NPA 812: 1-12 , 2008

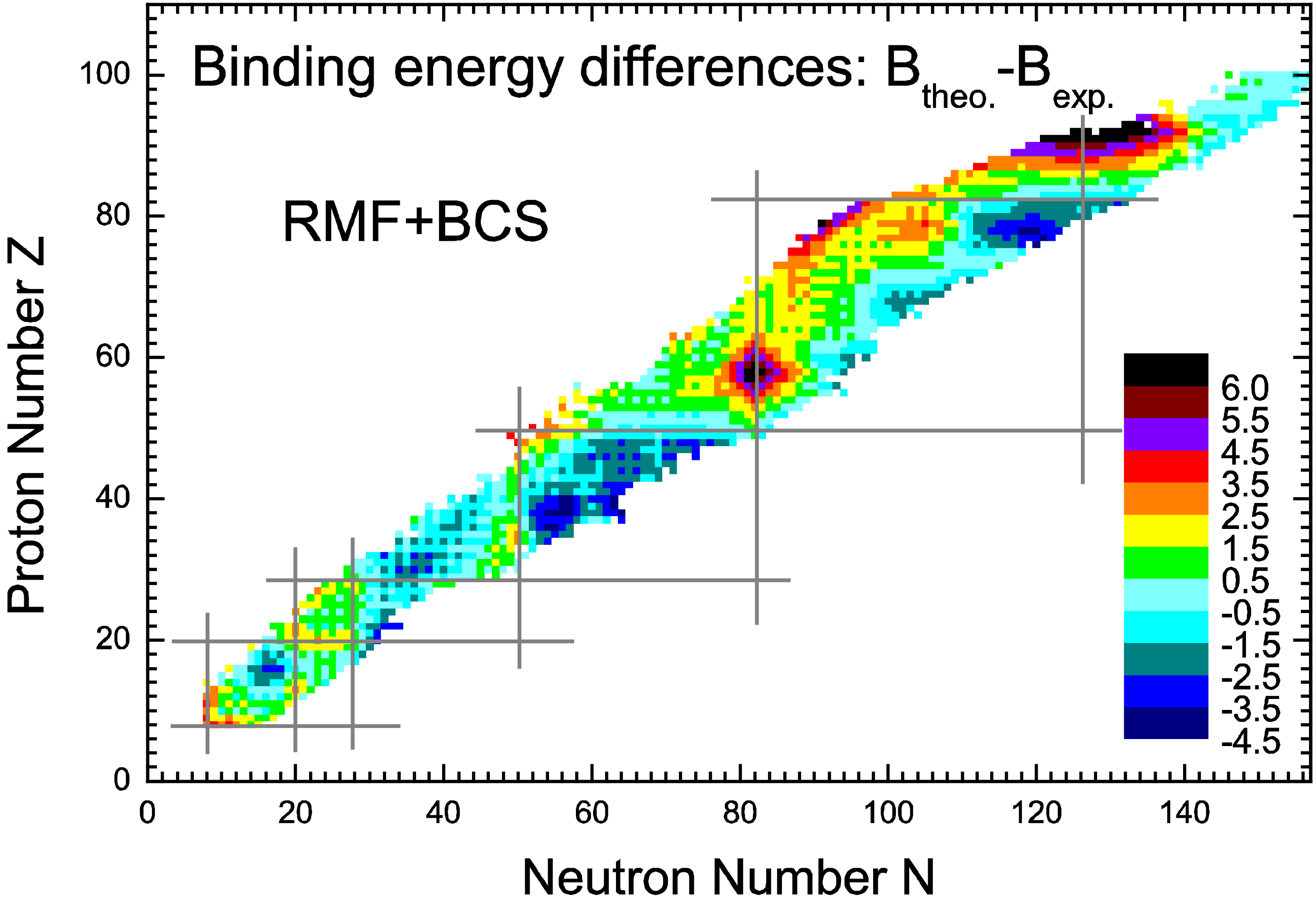
71 nuclides covered
27 nuclides were measured
8 measured for the first time
8 unresloved ground state and isomeric states
1 isomeric state of 133Sb (E*=4564(170) keV)

Mass accuracy: 1.0 $\cdot 10^{-6}$ (~120 keV)
Resolving power: 200,000



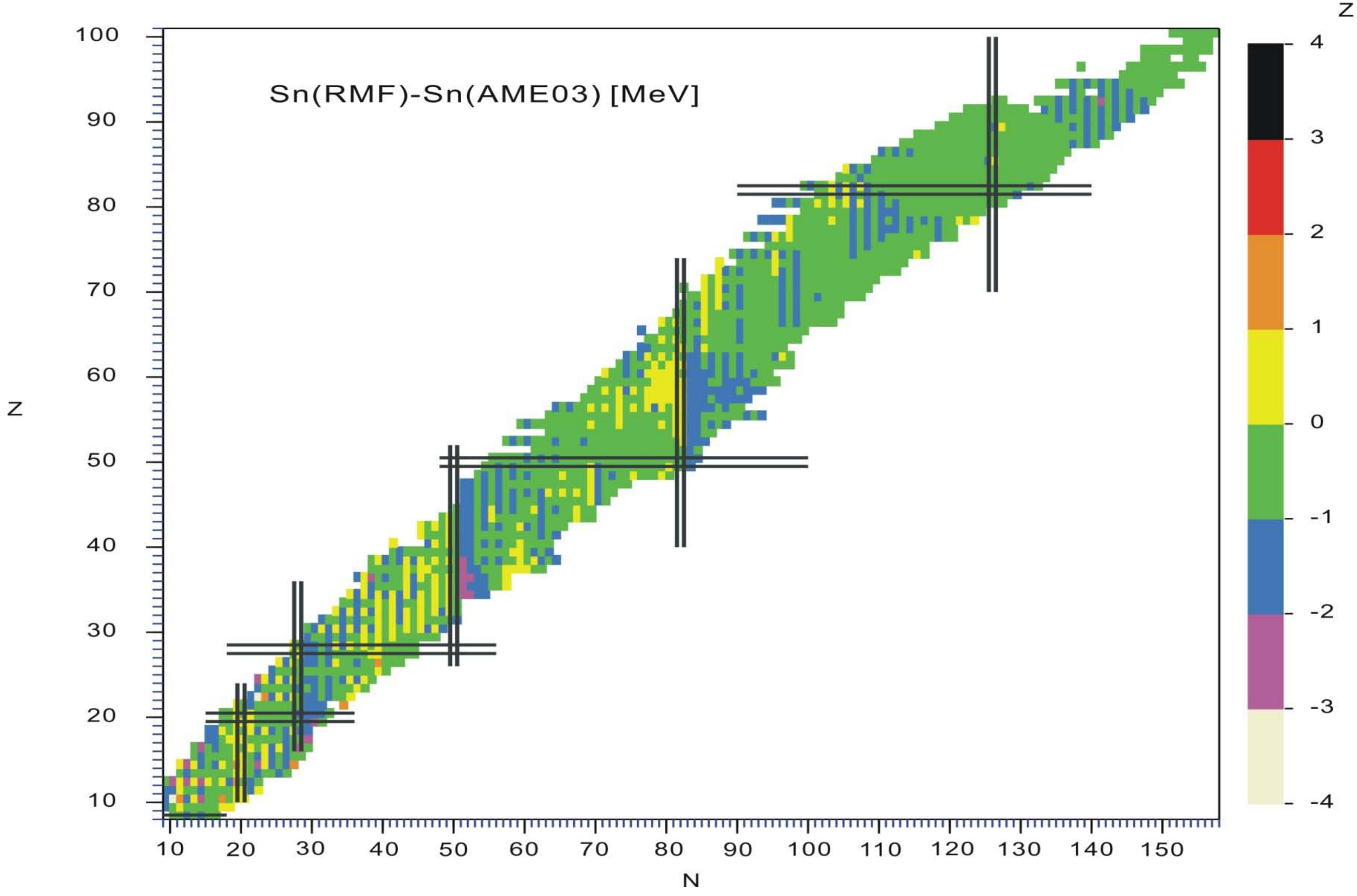
First RMF mass table in 2005: Theo. vs. Exp.

rms deviation of nuclear masses： 2.1 MeV



Nuclear single neutron separation energy：Theo. vs. Exp.

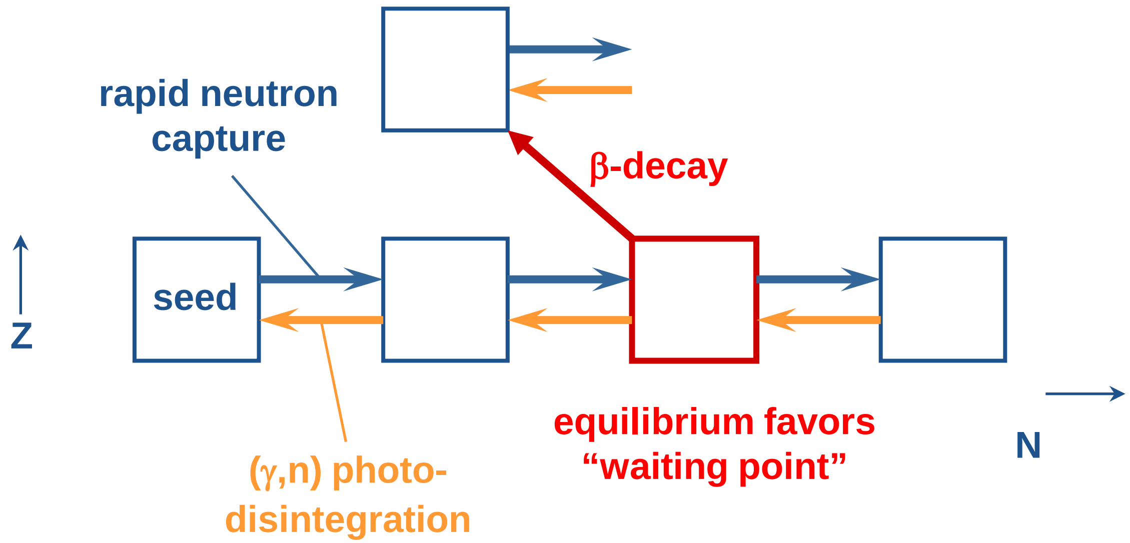
rms deviation of S_n: 0.654 MeV



Classical r-process calculation

Assume:

- (n,γ) ↔ (γ,n) equilibrium within isotopic chain, and
- elemental distribution of neighboring z-chain is determined by the β-decays
- neglect the effect of fission
- constant T_9, multi r-process components with $n_n=10^{20-27}$.



The nucleus with maximum abundance in each isotopic chain has smaller neutron capture rate and must wait for the longer time to continue via β-decay

Classical r-process calculation

Astrophysical conditions:

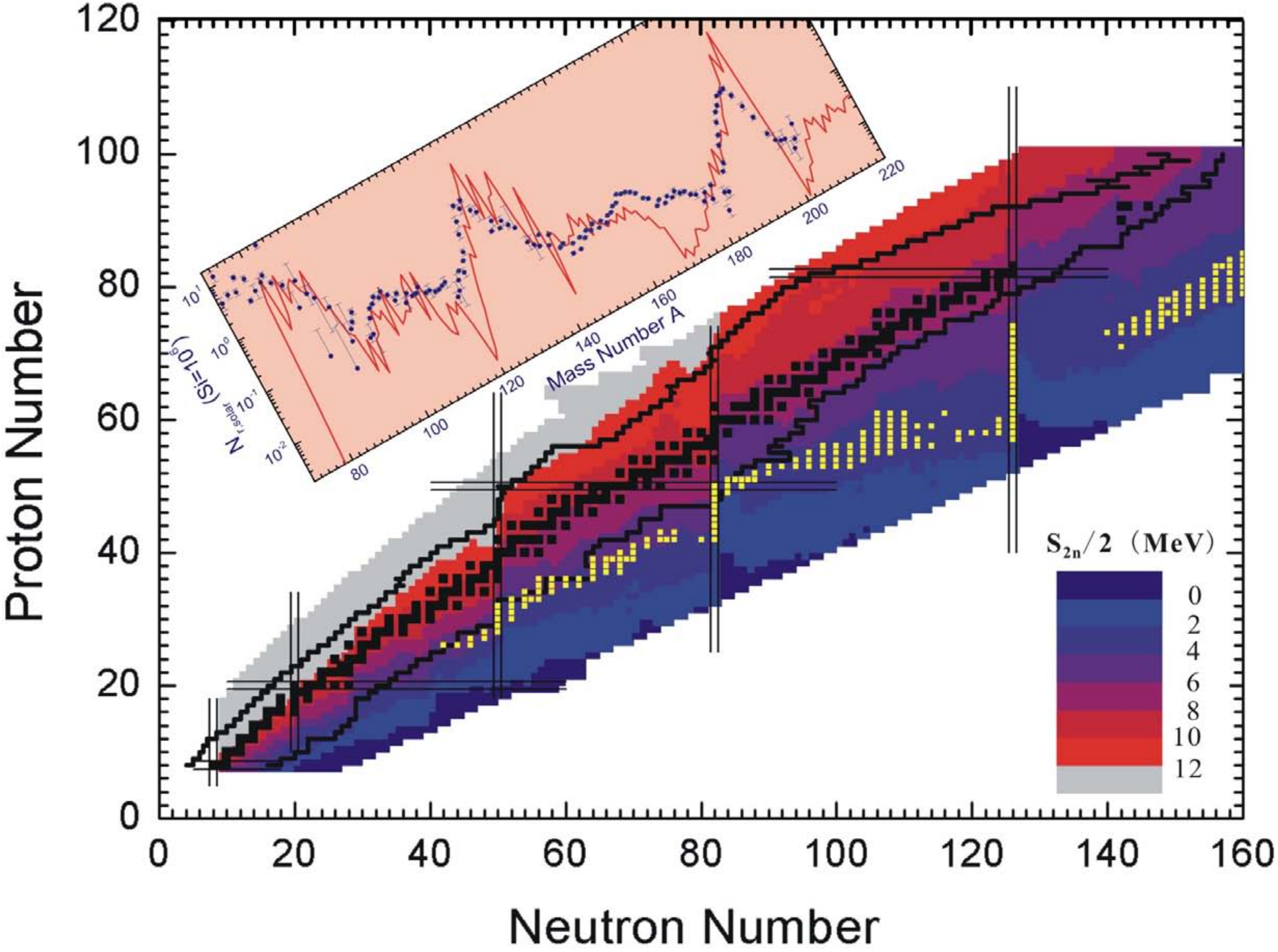
T_9=1.5,
16-component fit with $n_n=10^{20}$-$3*10^{27}$ cm^{-3},
which fulfill the following equations:

$$\omega(n_n) = n_n^a, \tau(n_n) = bn_n^c$$

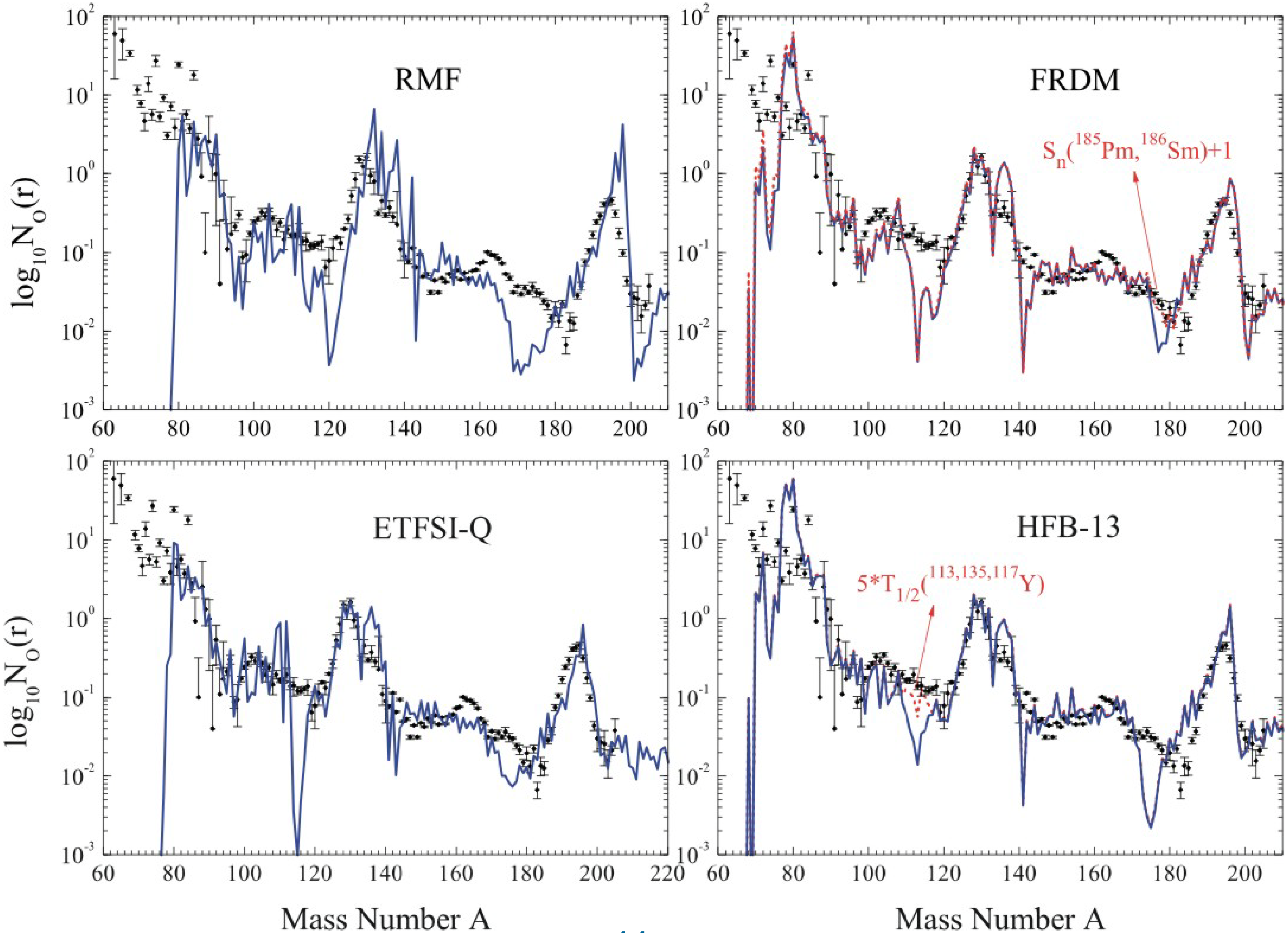
where ω and τ are respectively the weight and neutron irradiation time, and a, b, c are the alterable parameters, which will be determined by least-square fit to the solar r-process abundance.

Good approximation for astrophysical environment studies！

nuclear inputs: S_n(RMF), $T_{1/2}$(β-decay), P_{1n}, P_{2n}, P_{3n} (FRDM),
astrophysical parameters: T_9=1.5, n_n=$10^{20\text{-}28}$, ω, τ (least-square fit),



Nuclear Mass Model dependence



Th/U chronometer

- The age of the universe is one of the most important physical quantities in cosmology.
- The metal-poor star is formed at the early stage of the universe, so its age provides constraint to the age of the universe.
- The age of metal-poor star:

$$\left.\frac{Th}{U}\right|_{\text{present}} = \left.\frac{Th}{U}\right|_{\text{initial}} e^{-(\lambda_{Th}-\lambda_U)t}$$

- ➢ Present abundances: astronomical observations.

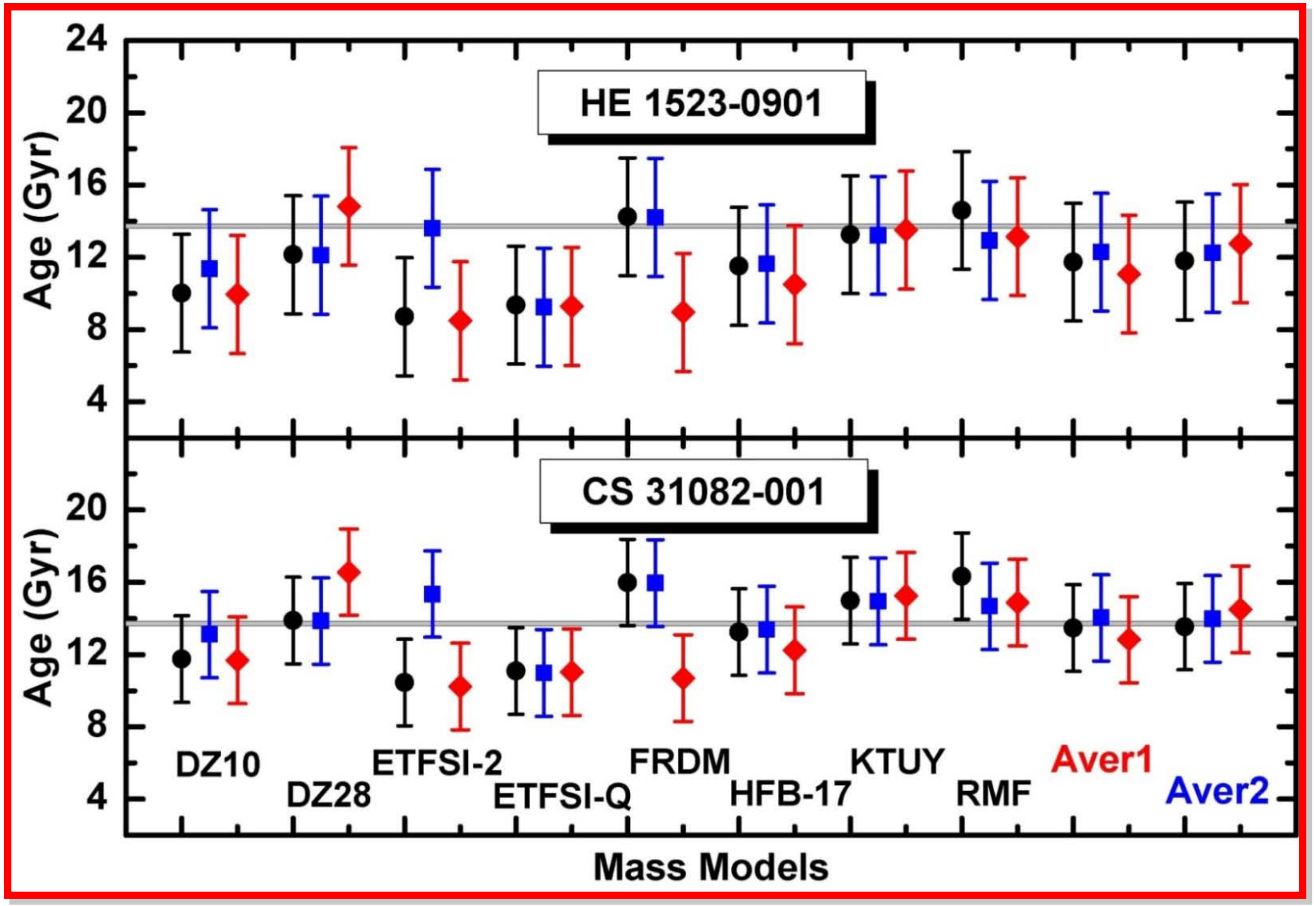
  R. Cayrel, et al., Nature 409, 691 (2001).
  J.J. Cowan, et al., ApJ 572, 861 (2002).
  A. Frebel, et al., ApJ 660, 117 (2007).

- ➢ Initial abundances: r-process calculations (Th, U are r-only nuclei).

- ➢ The classical r-process model is usually employed in r-process calculations.

  P.A. Seeger, et al., ApJS 11, 121 (1965).
  K.-L. Kratz, et al., ApJ 403, 216 (1993).

Ages of metal-poor stars



Age (HE 1523-0901)=11.8 ± 3.7 Gyr **Age (CS 31082-001)=13.5 ± 2.9 Gyr**

Z. Niu et al., PRC 80 065806 (2009)

Calibrating the cosmic clock

Influence of nuclear physics inputs and astrophysical conditions on the Th/U chronometer

Zhongming Niu (牛中明), Baohua Sun (孙保华), and Jie Meng (孟杰)

Phys. Rev. C 80, 065806 (Published December 22, 2009)

• Cosmology • Nuclear Physics

Knowing when nucleosynthesis—the formation of new nuclei from existing nuclei—occurred in astrophysical sites can be crucial to our understanding of cosmology. One method to pin the process down in time is to compare the current abundance ratio of thorium to uranium (both of which have lifetimes of the order of the age of the universe) with calculations of this ratio at the time at which the nucleosynthesis that formed these elements took place. The assumption is that the nucleosynthesis itself happens over a time scale that is short compared to the time since it occurred.

In a paper published in *Physical Review C*, Zhongming Niu of Peking University and Baohua Sun and Jie Meng of Beihang University, both in China, present a study of the uncertainties in the calculation of the initial ratio of thorium to uranium. In particular, they focus on the importance of the models used to determine the nuclear masses and the nucleosynthesis processes themselves. Utilizing the abundances of uranium and thorium in the sun to restrict the models, Niu *et al.* are able to minimize the impact of the uncertainties. They find that the error due to the nuclear input alone is about 1.6–2.2 billion years (for reference, the age of the universe is about 14.6 billion years). This estimate is lower, but not significantly so, than the observational uncertainties. In addition, they determine when nucleosynthesis occurred for three stars. New observations for other elements in stars and improved mass models could make a major impact on the thorium-uranium chronometer, and in general, studies of this kind help us learn what parts of the universe were undergoing the extreme conditions needed for nucleosynthesis to occur, and when. – *William Gibbs*

Coming Soon in *Physics*

- Symmetry breaking in bilayer graphene
- Discovery of a neutron halo in ^{22}C

Now in Focus

Chemistry Drives Convection

January 29, 2010

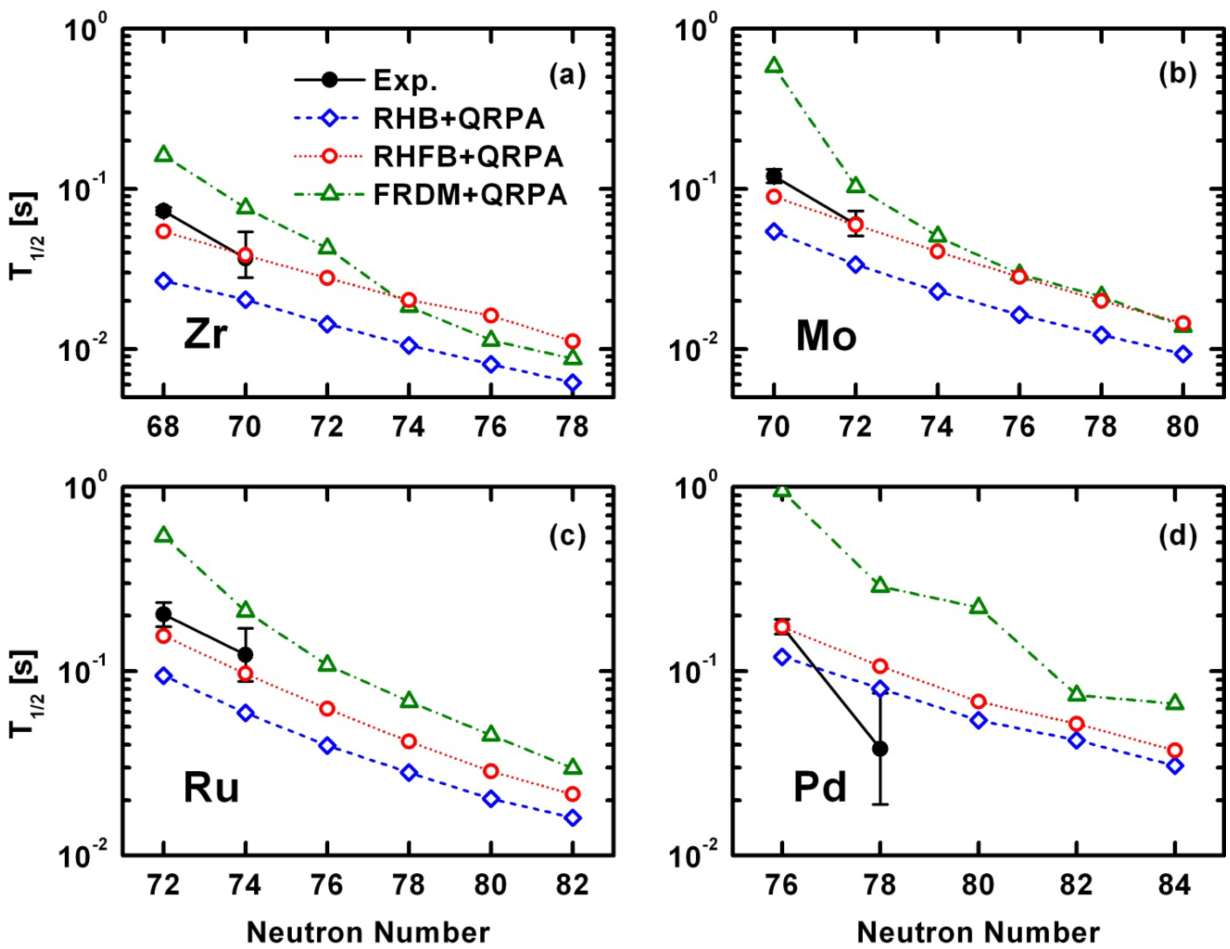
A combination of simulations and experiments explicitly demonstrates that common chemical reactions can drive convection flows in fluids.

Feedback

Let us know what you think of *Physics*. Please email physics@aps.org with your comments, ideas, or suggestions for topics.

" Phys. Rev. C (2009) **80**, 065806 " was reported as an important progress of nuclear physics and cosmology on "physics.aps.org" webpage

Future: β-decay half-lives from CDFT

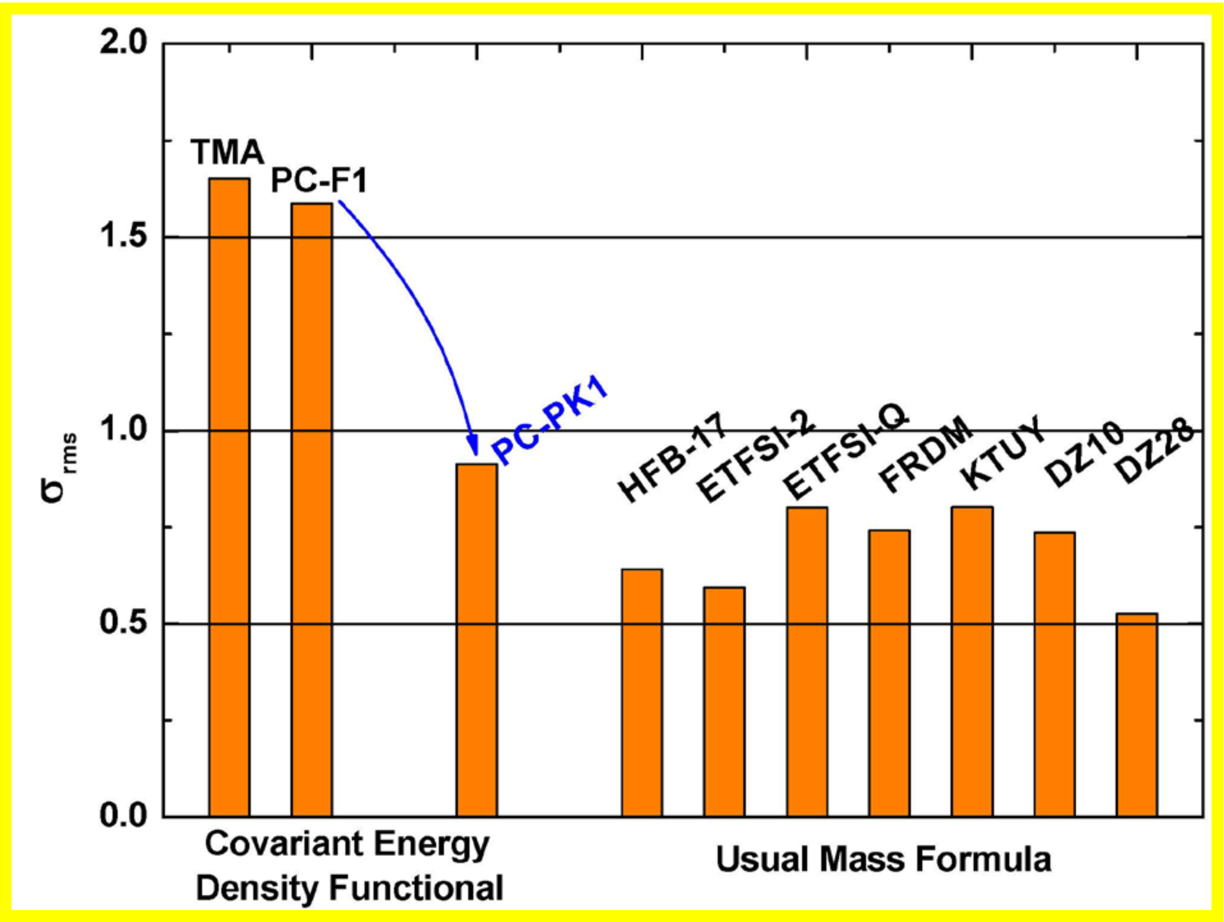


- RHFB+QRPA: well reproduces the experimental data
- RHB+QRPA: underestimates the half-lives of ^{108,110}Zr, ^{112,114}Mo, and ^{116,118}Ru.
- FRDM+QRPA: systematically overestimates the nuclear half-lives.

Observed neutron-richest e-e nuclei with 26≤Z≤100

rms mass deviations:

$$\sigma_{\rm rms} = \sqrt{\sum_{i=1}^{N} \frac{\left(M_i^{\rm cal} - M_i^{\rm exp}\right)^2}{N}}$$

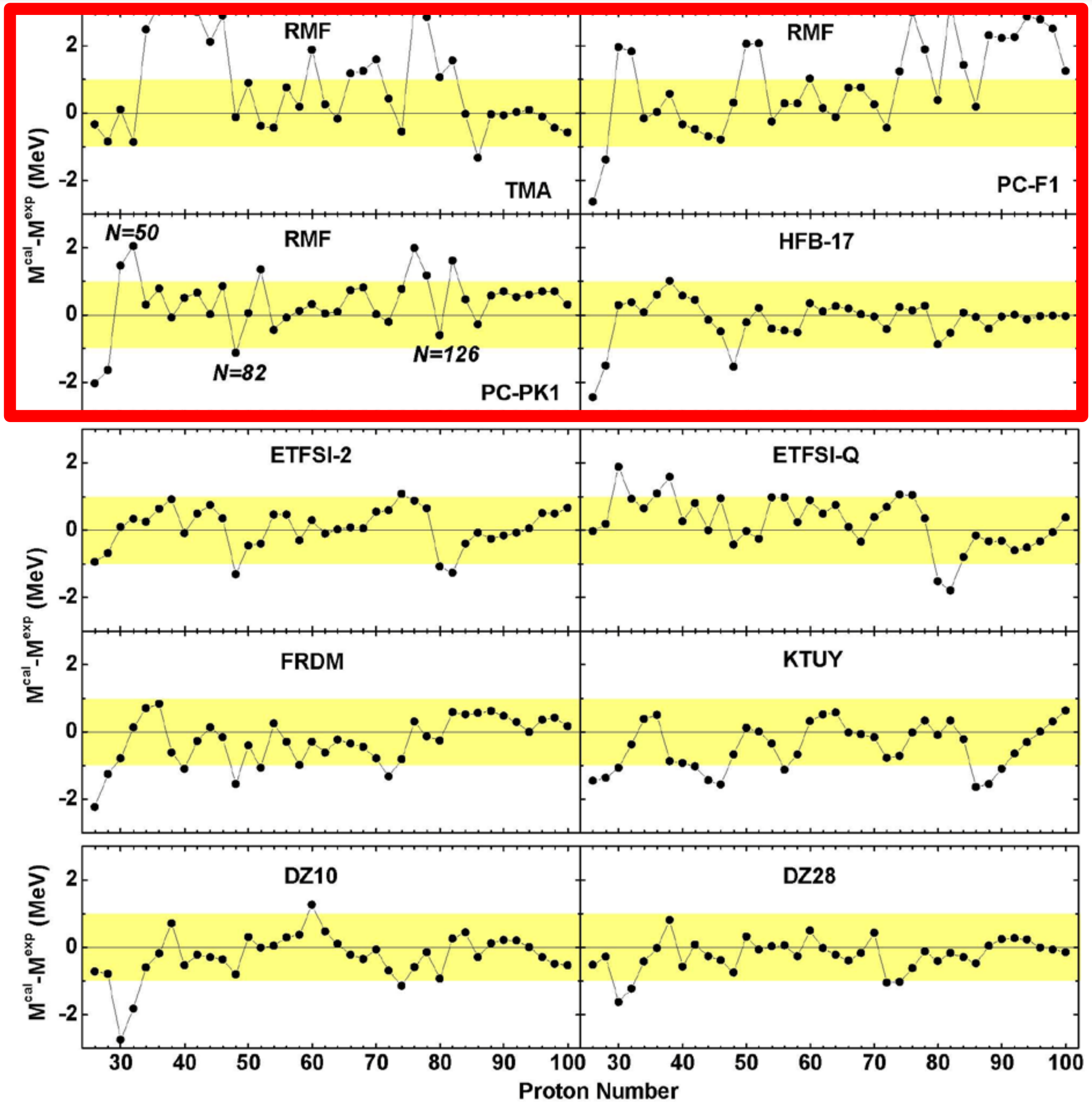


- PC-PK1 improves the description remarkably .
- Similar accuracy for the others

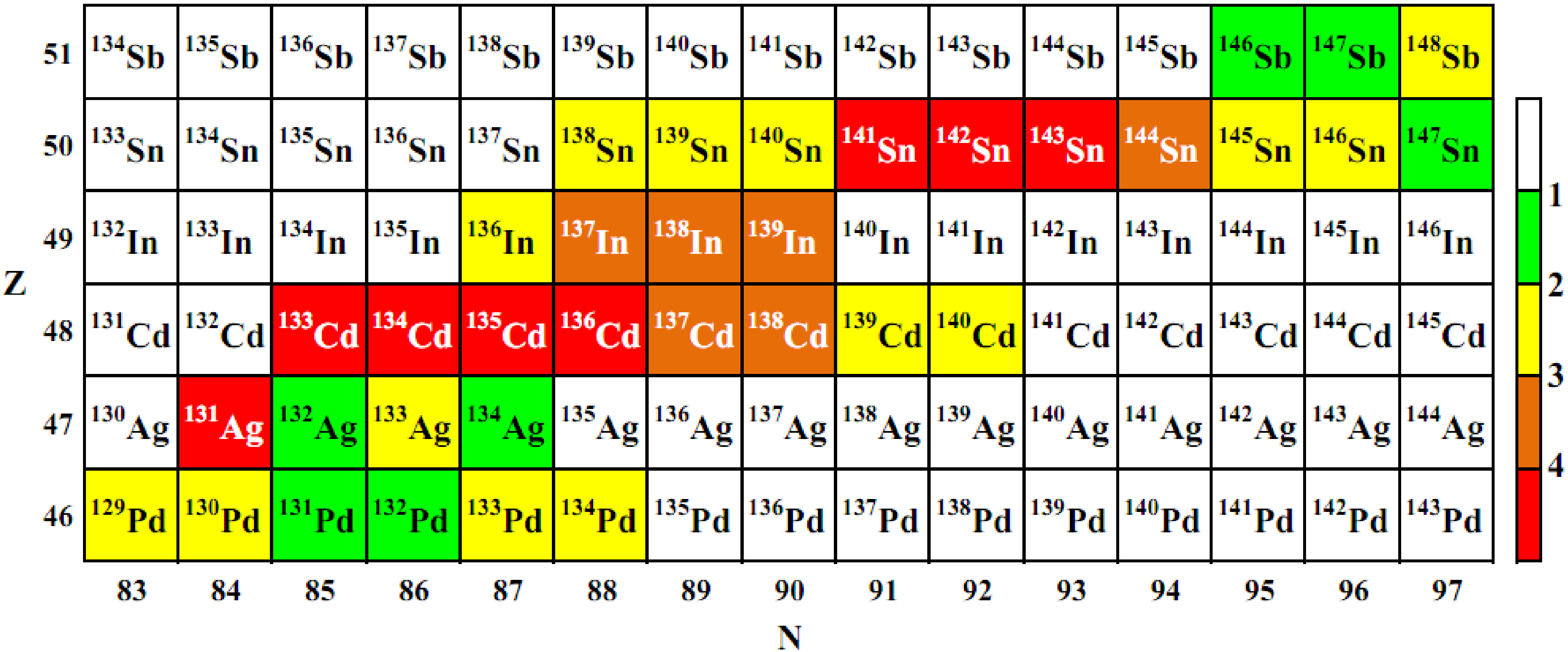
PC-PK1: RRC 82, 054319

TMA: PTP 113, 785.
PC-F1: PRC 65, 044308
HFB-17: PRL 102, 152503.
ETFSI-2: AIP 529, 287.
ETFSI-Q: PLB 387, 455.
KTUY: PTP 113, 305.
DZ28: PRC 52, R23.

Observed neutron-richest e-e nuclei with 26≤Z≤100



Key nucleus in r-process: S_n(A~140) change by 1 MeV



Mass model: HFB-17

β-decay properties: FRDM+QRPA

S. Goriely, N. Chamel, and J. M. Pearson, PRL 102, 152503.

P. Moller, B. Pfeiffer, and K.-L. Kratz, PRC 67, 055802.

$$F = \sum_{A=90}^{209} \left| \lg(Y_{A,\mathrm{baseline}}) - \lg(Y_A) \right|$$

- S_n of Ag, Cd, Sn have great influence on the r-process abundances
- ^{131}Ag, ^{133,134}Cd, ^{141,142}Sn: F>4 using both HFB-17 and FRDM

Summary and Perspectives

- Recent development
  - RH or RHB in WS basis
  - Resonance in RMF+ACCC
  - DDRHFB+QRPA
  - Tilted Cranking RMF
  - Time-odd (constrained) Triaxial RMF
  - DDRHF + RPA
  - 3D AMP+GCM
  - **Bohr H based on CDFT** ...
- Recent application
  - (Deformed) Exotic phenomena: halos
  - CDFT mass formula and r-process calculation
  - Symmetry: Spin and pseudo-spin symmetry
  - Low-lying nuclear spectra
  - Magnetic rotation & chirality
  - Quantum shape transitions
  - Spin-Dipole Resonances
  - CKM matrix $|V_{ud}|$ . . .
- Open issues
  - (Q)RPA for excited states
  - 3D Cranking RMF for chirality
  - Projected RMF:H-K isomers | shape transition | NP pairing
  - Deformed RHF & RHFB & (Q)RPA

Thank You!