Neutron halo in deformed nuclei: decoupling between core and halo

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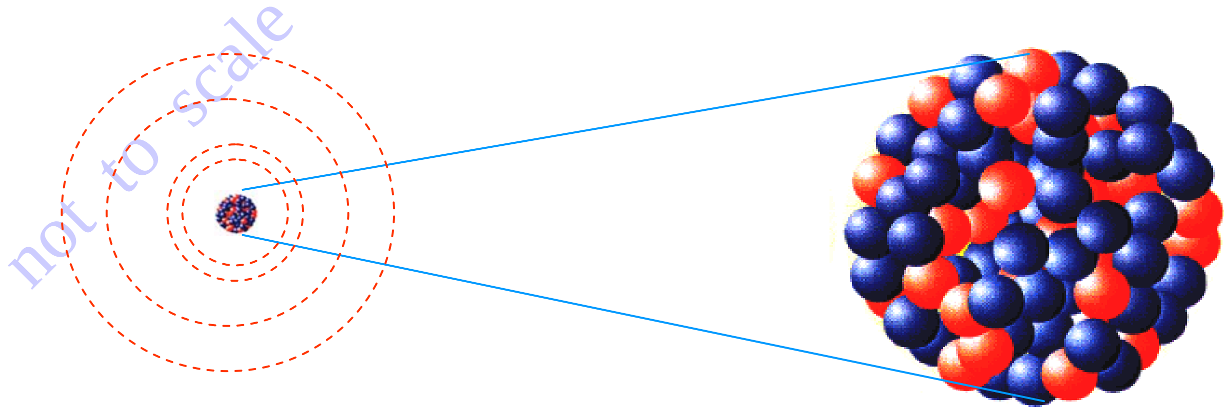
Outline

- **Introduction**
  - Atomic nuclei
  - Current hot topics: exotic nuclei, nuclear astrophysics & SHE
- **Deformation effects in exotic nuclei**
  - Nuclear shapes
  - Halos in deformed nuclei: exists or not? if yes, what's new?
- **Relativistic Hartree (Bogoliubov) model for exotic nuclei**
  - A brief introduction to RMF: what, why & how
  - Deformed Relativistic Hartree-Boboliubov model in a Woods-Saxon basis
- **Neutron halo in deformed nuclei: ^{44}Mg**
  - Density distributions; single particle states in canonical basis; rms radii
  - Decoupling between deformations of core & halo
  - Mechanism of the decoupling
- **Summary**

原子核 Atomic nuclei

困难：核力
有限多体
…

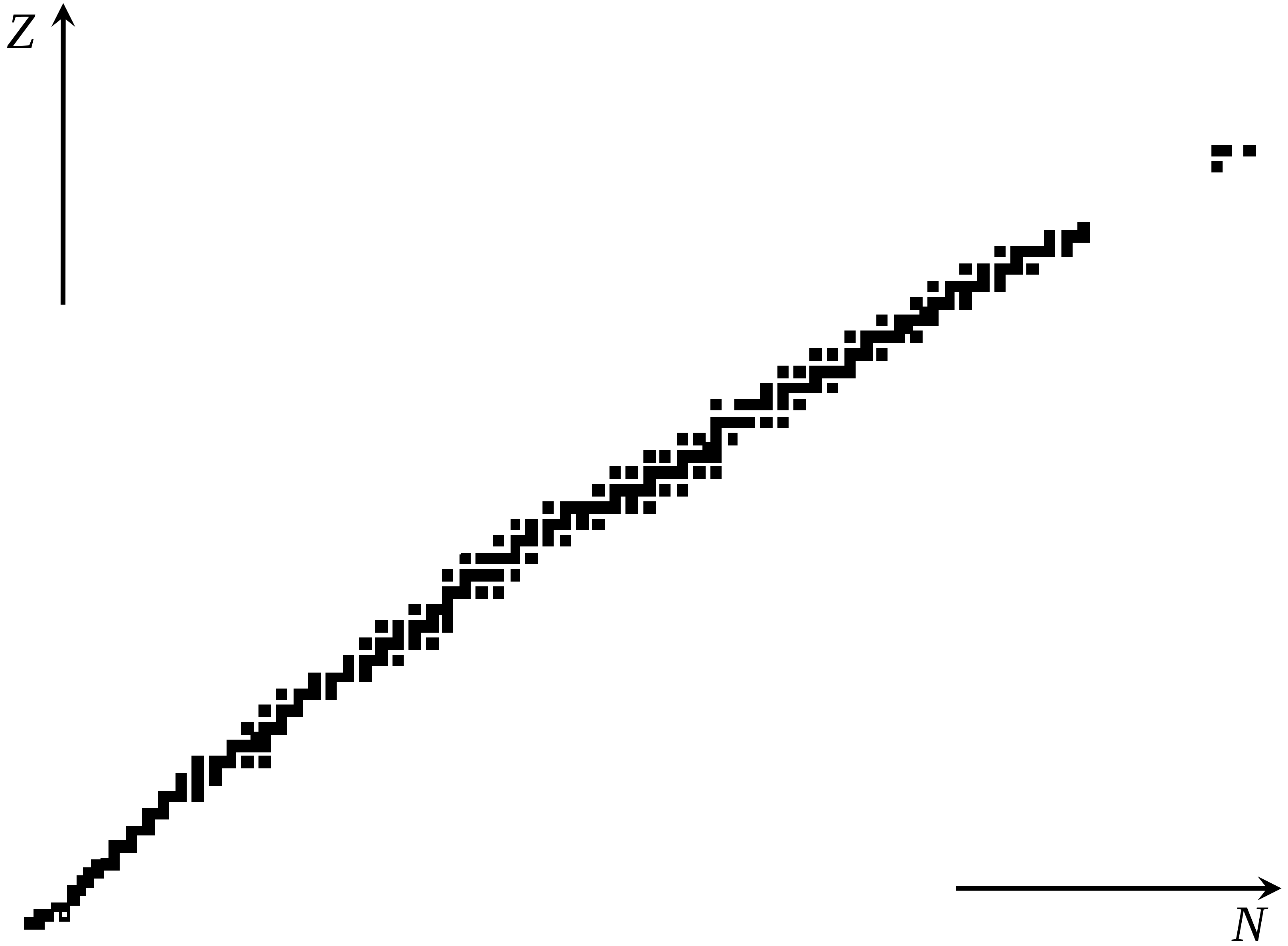
10^{-9} m



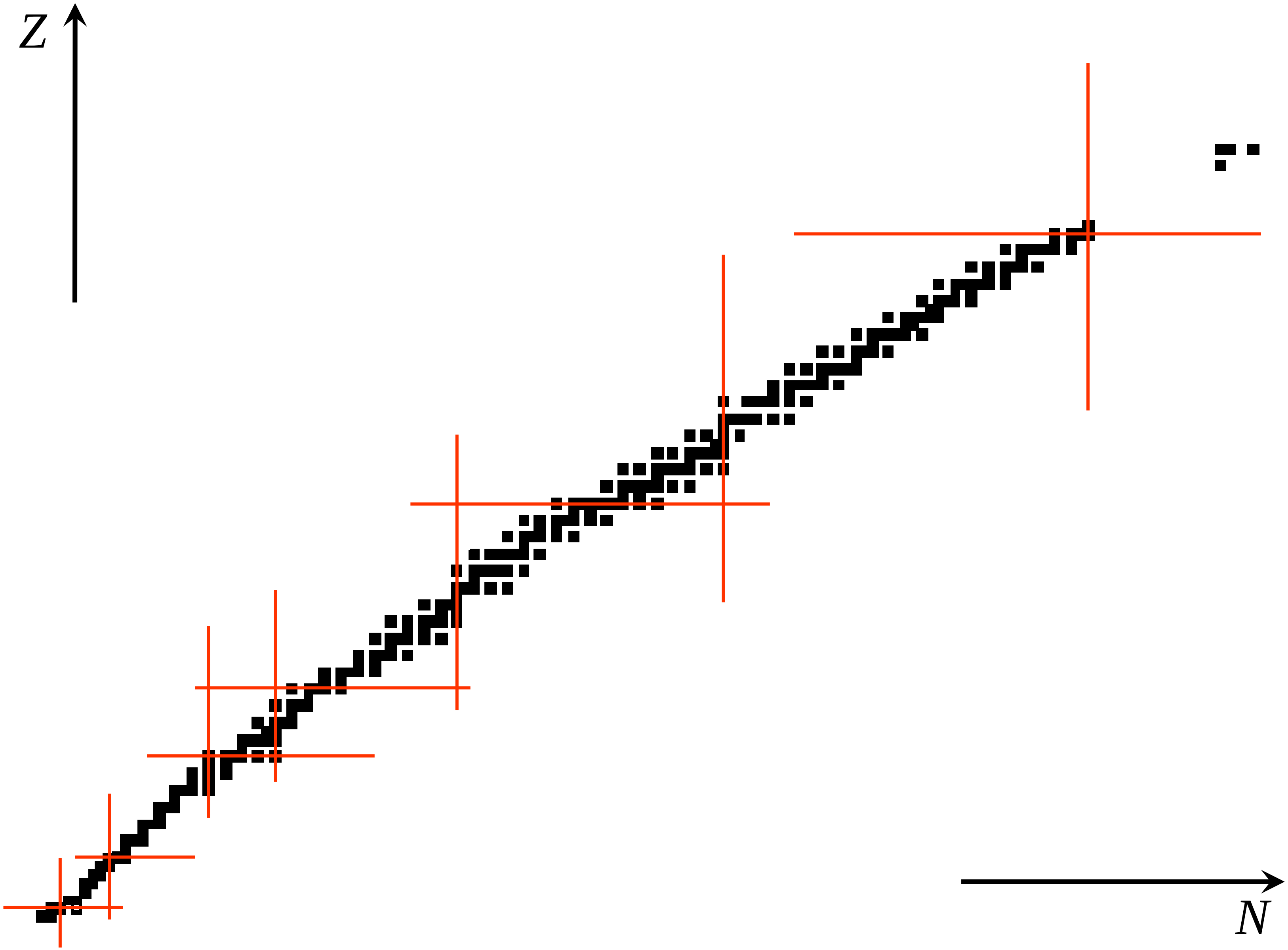
10^{-14} m

- ✓ 原子核（核素）：质子 & 中子（核子）
- ✓ 元　素：质子数Z相同的原子核的统称，例如氧 O ($Z = 8$)
- ✓ 同位素：质子数相同、中子数不同的核素，例如^{16}O ($Z = 8$, $N = 8$) & ^{18}O ($Z = 8$, $N = 10$), …
- ✓ 原子核性质 $\Leftarrow Z$ & N, $A = Z+N$
  - ✓大小：$V \sim A$, $R \sim A^{1/3}$（核力饱和性、核物质不可压缩性）
  - ✓平均结合能：约为 8 MeV （稳定核）
- ✓ 幻数：2, 8, 20, 28, 50, 82, …

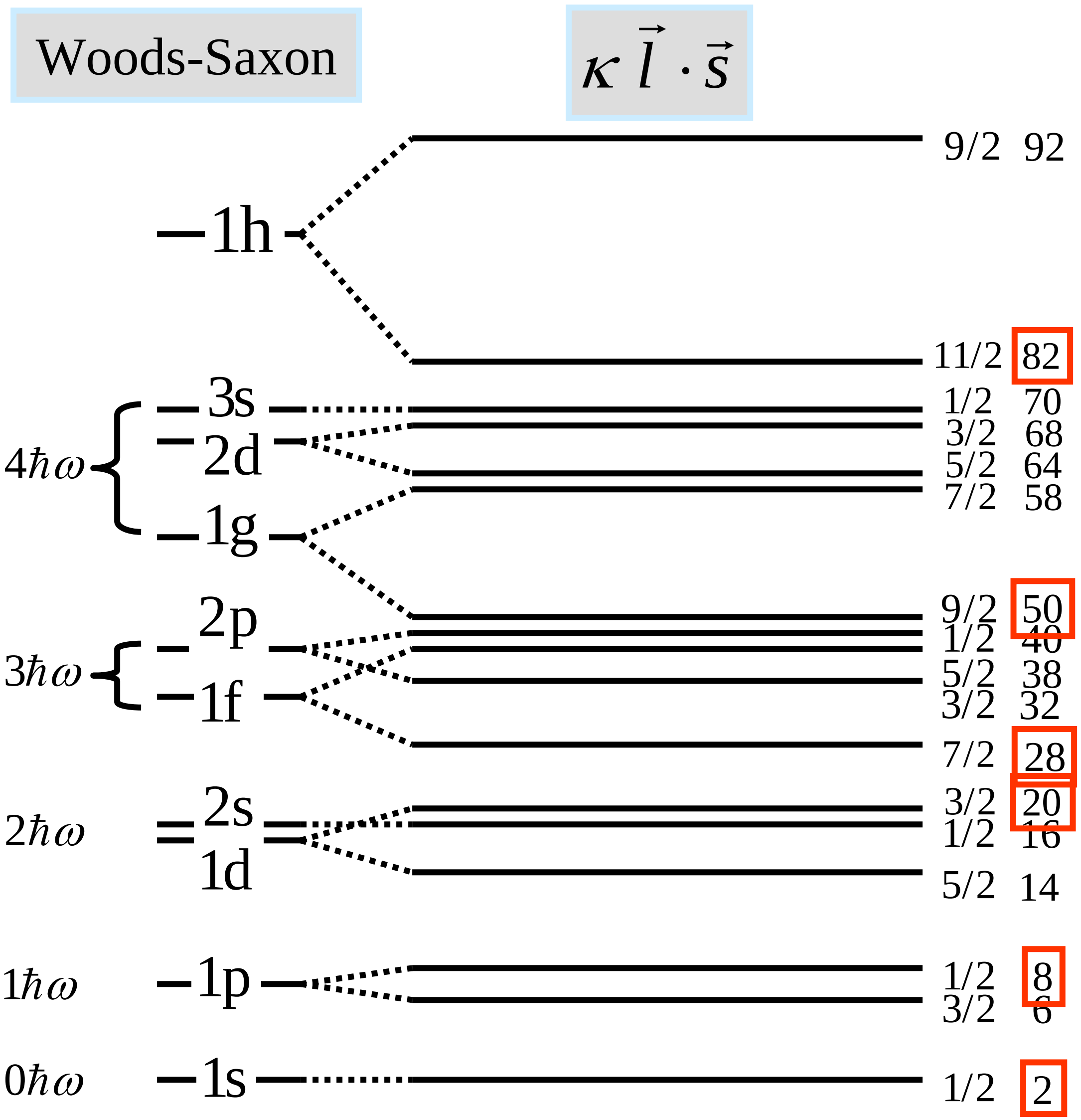
“Stable” nuclei (<300)



Magic numbres 幻数



独立粒子运动与壳层结构 Nuclear shell model



实验观测

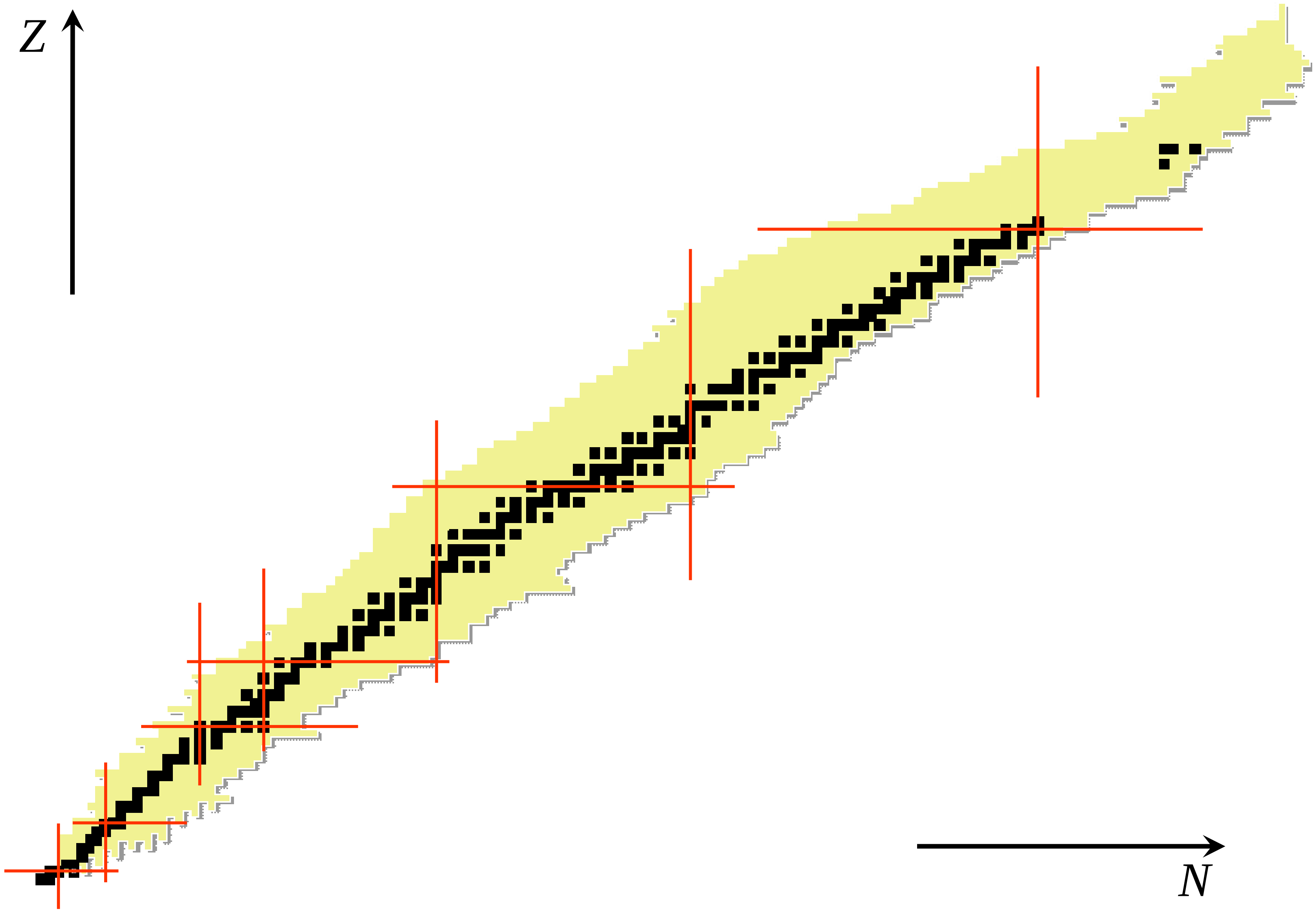
幻数

magic numbers

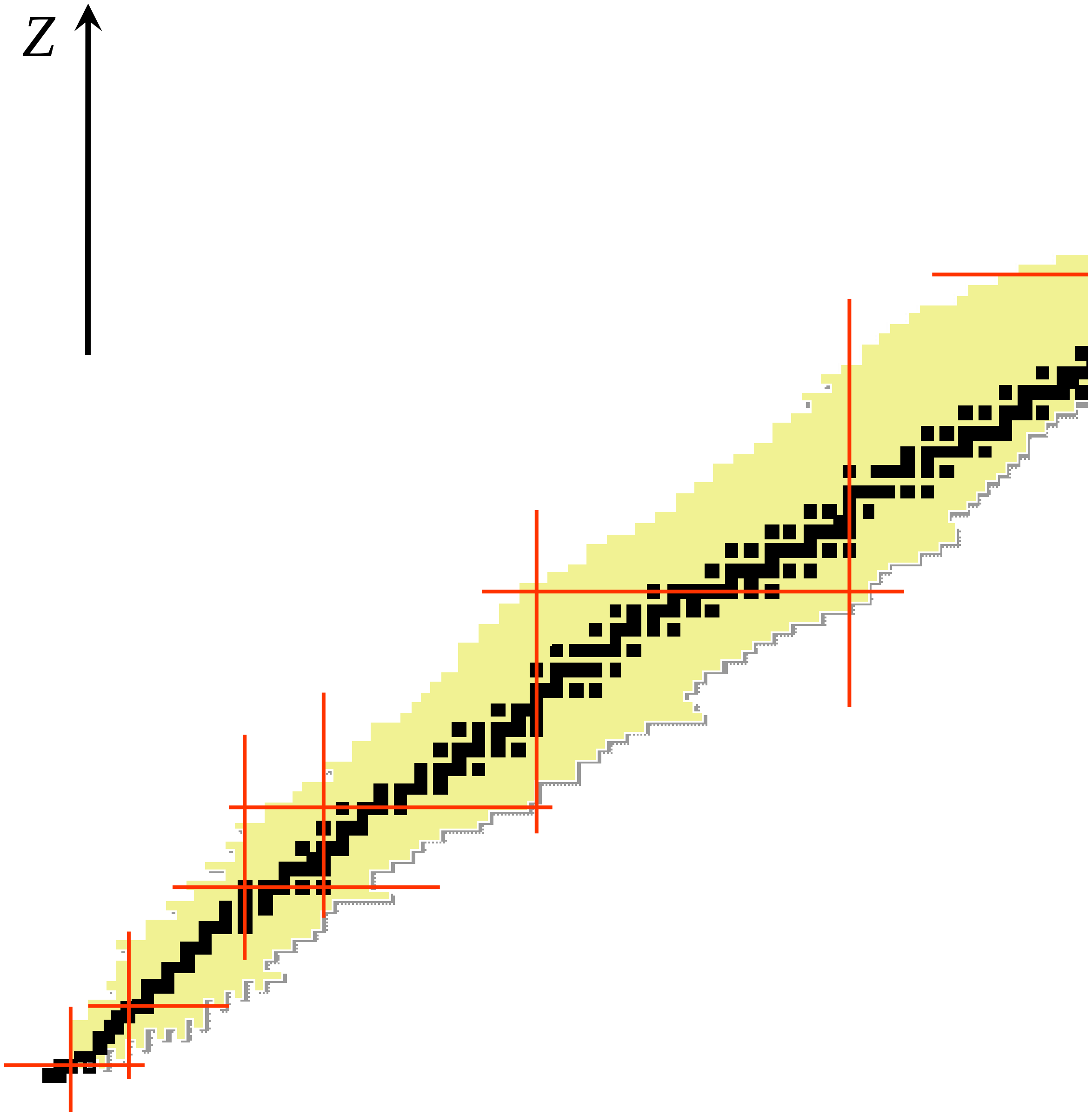
幻数——

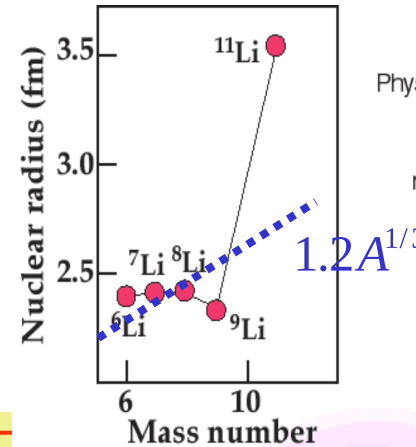
壳模型的基础

Exotic nuclei 奇特核



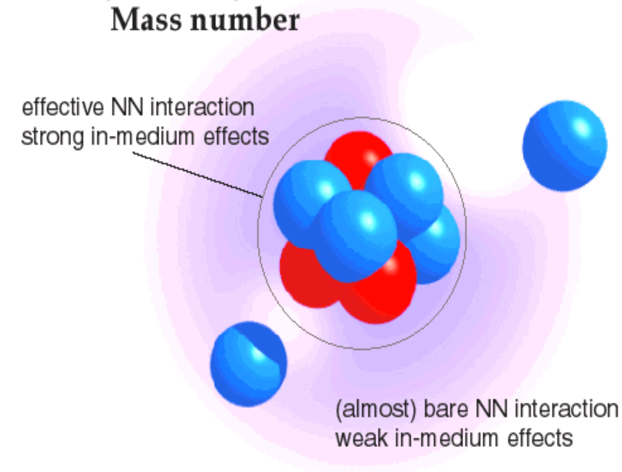
Halo nuclei 晕核





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

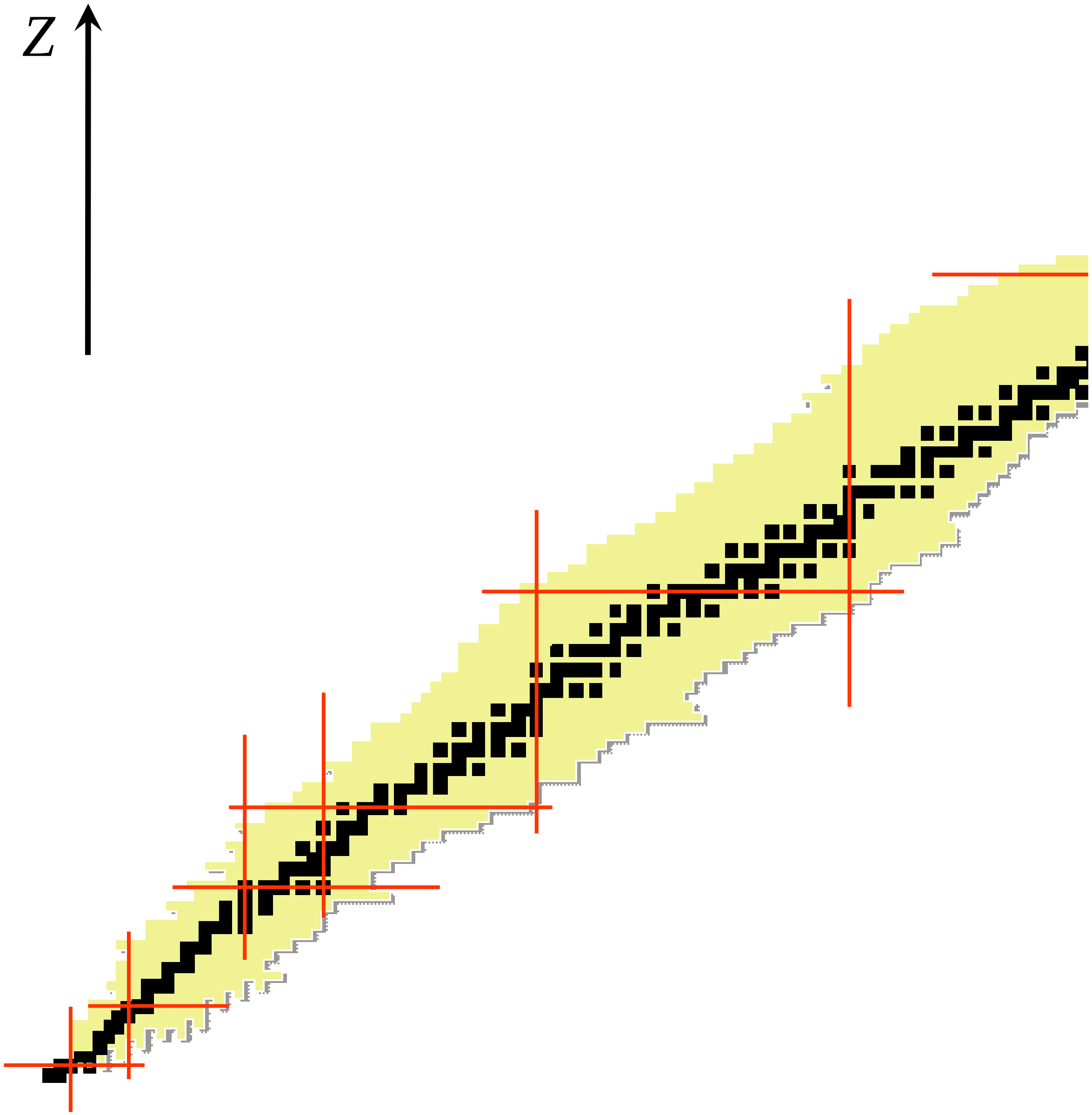
Interaction cross section measurements at Bevalac (790 MeV/u)

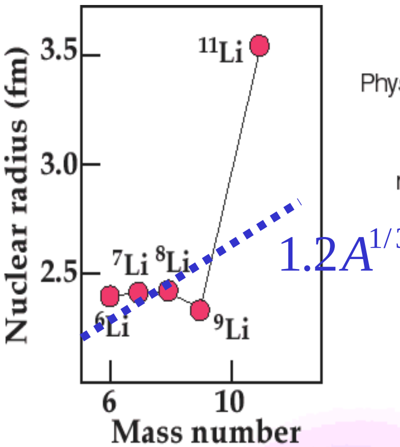


N

^{208}Pb

Halo nuclei 晕核





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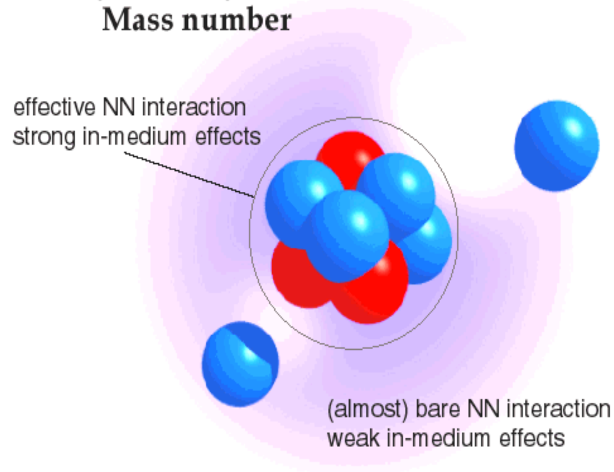
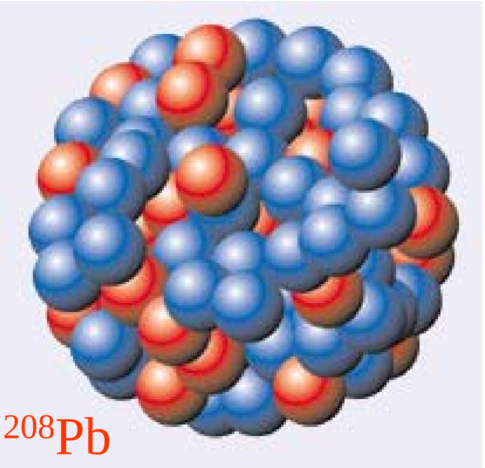
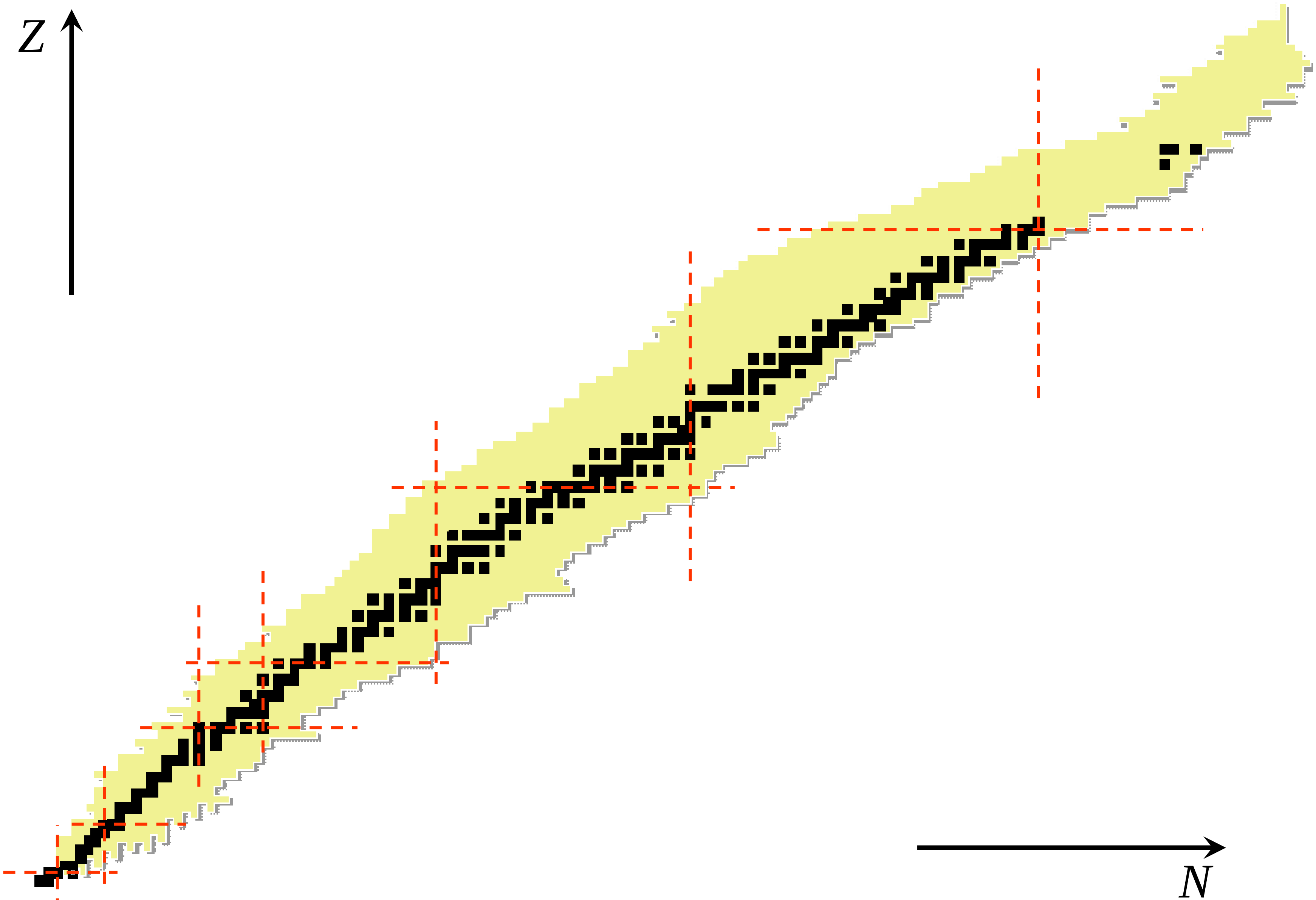
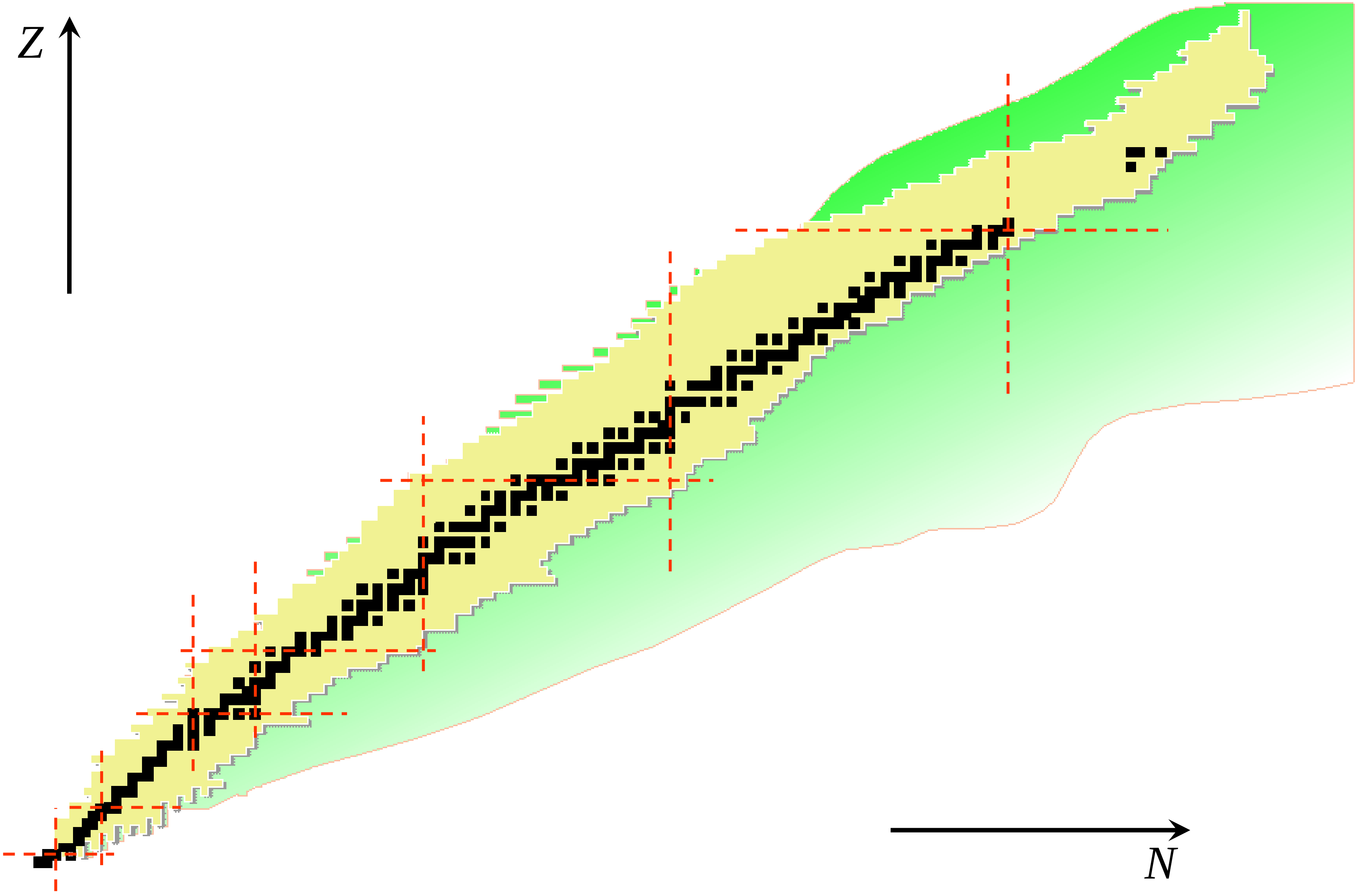




Changes of MAGIC numbers

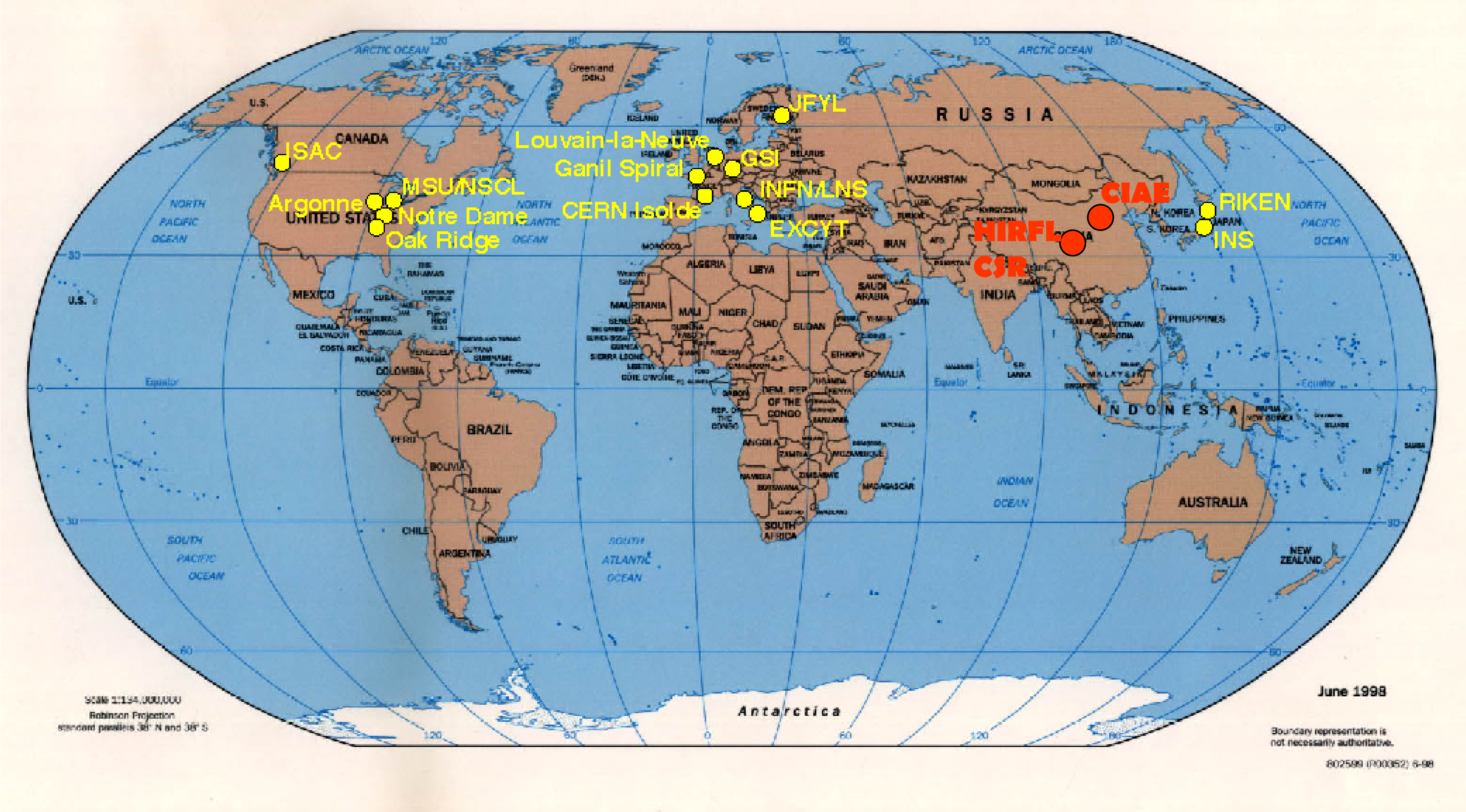


Theory: much more exotic nuclei !



世界范围的放射性核束装置

Radioactive ion beam facilities



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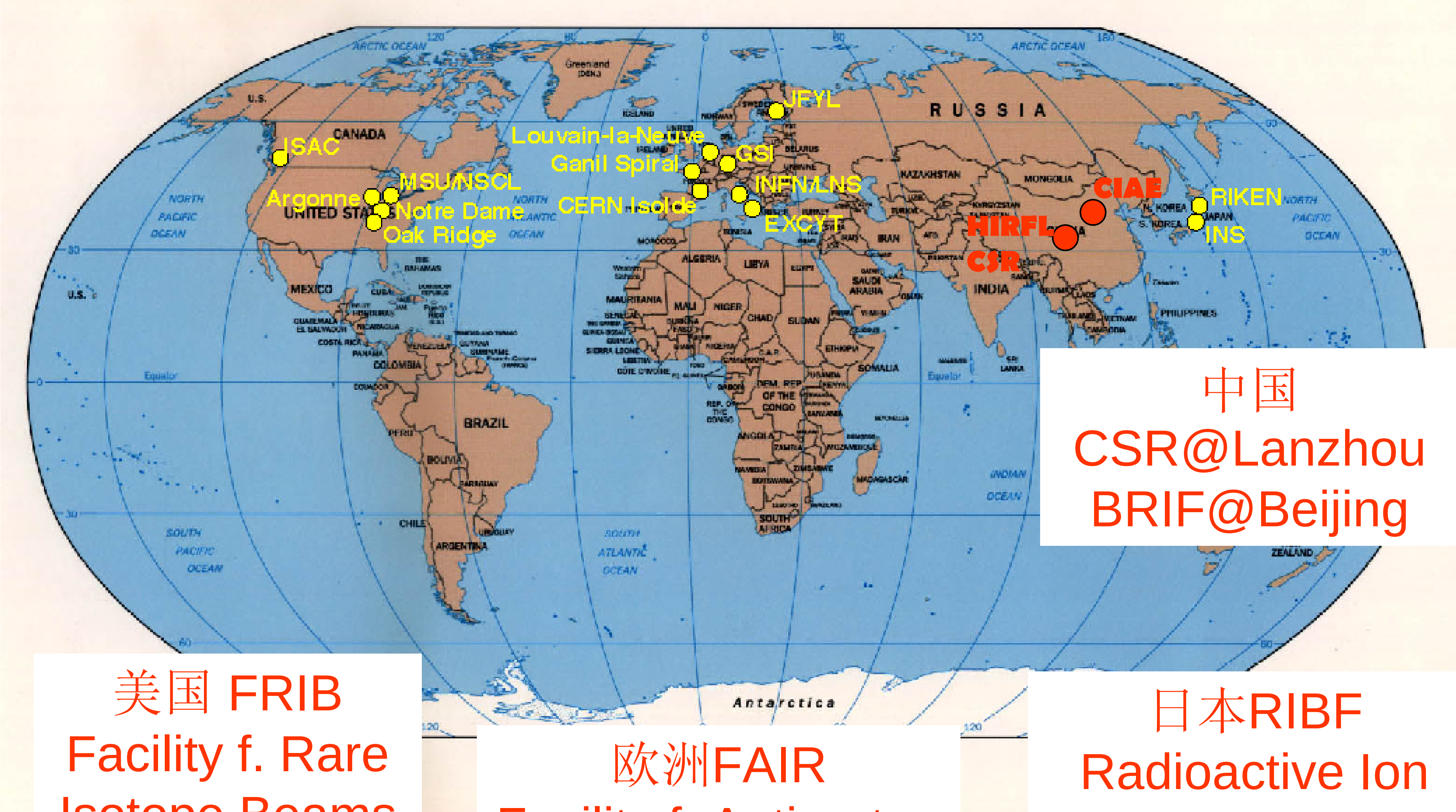

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CSR@Lanzhou
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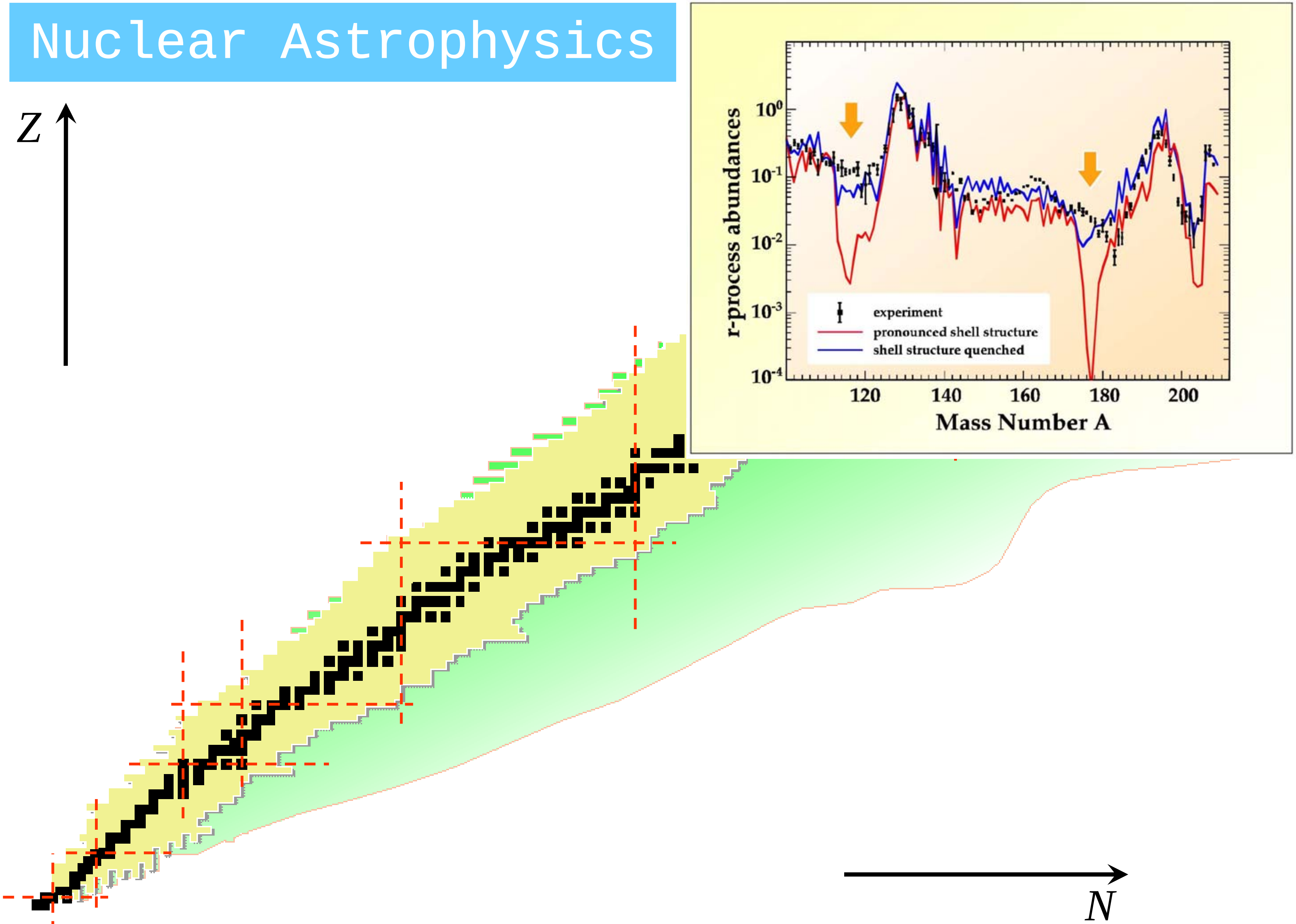
美国 FRIB
Facility f. Rare Isotope Beams

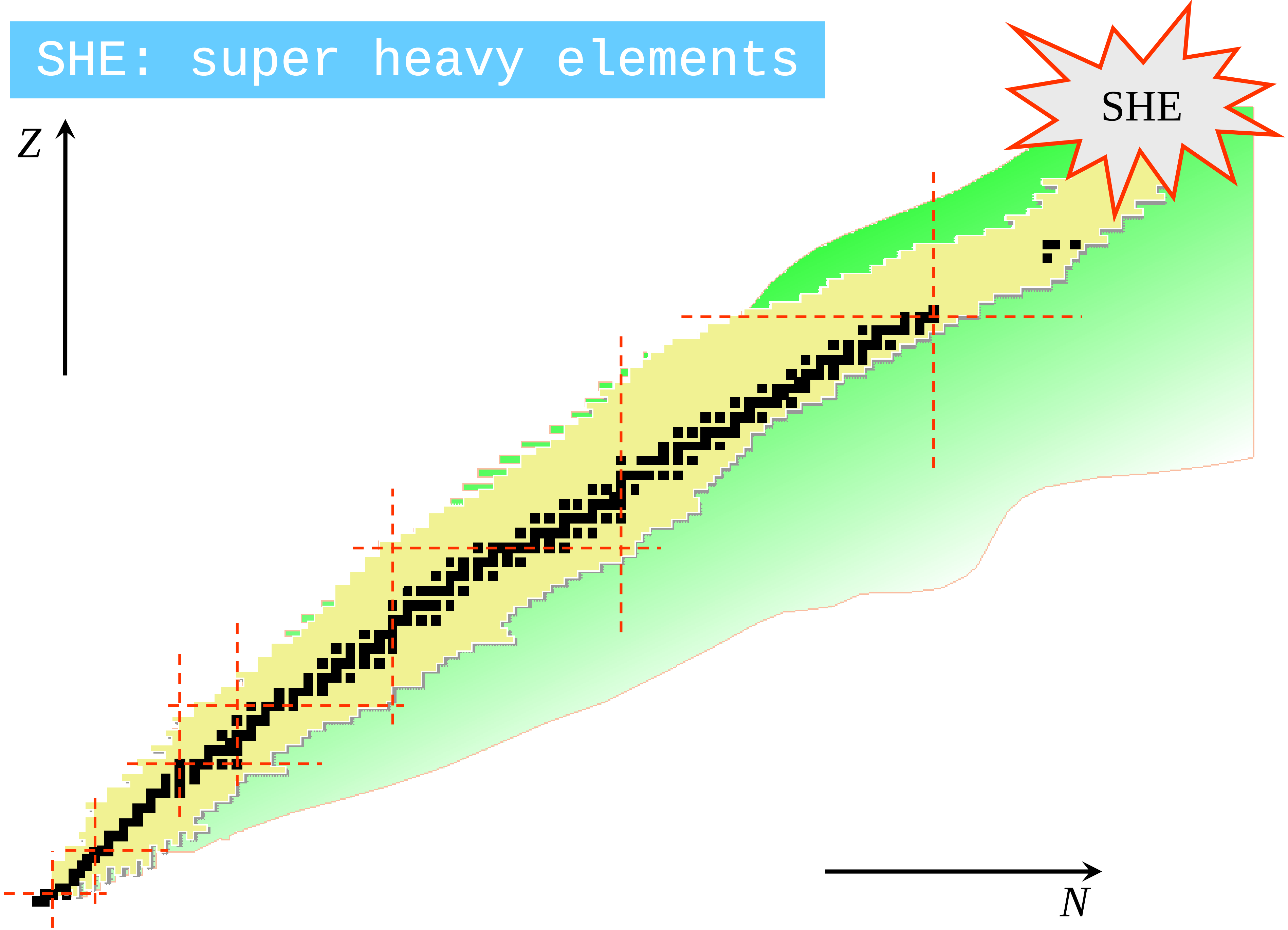
欧洲FAIR
Facility f. Antiproton & Ion Research

日本RIBF
Radioactive Ion Beam Factory

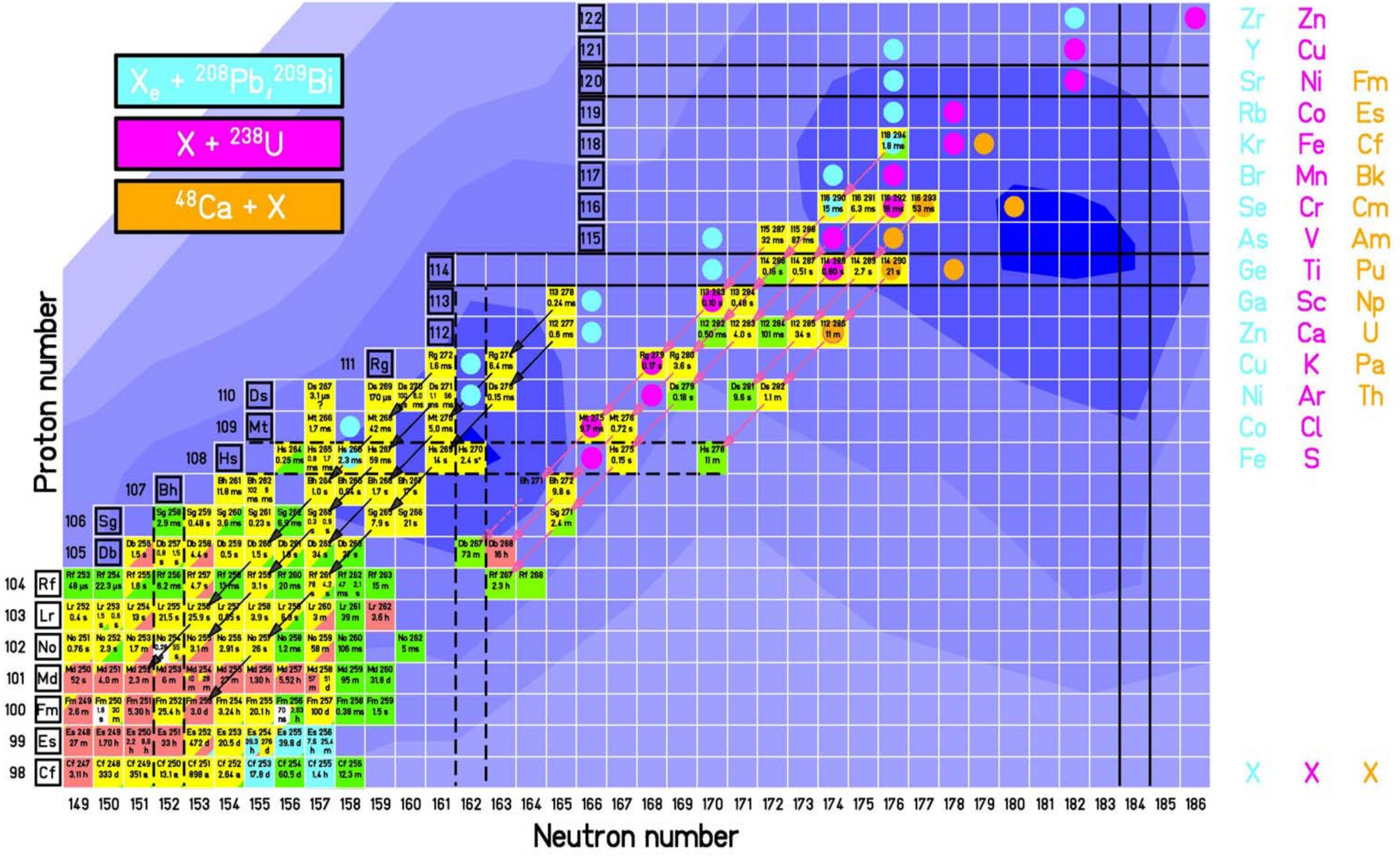
Nuclear Astrophysics



SHE: super heavy elements



SHE: experimental status



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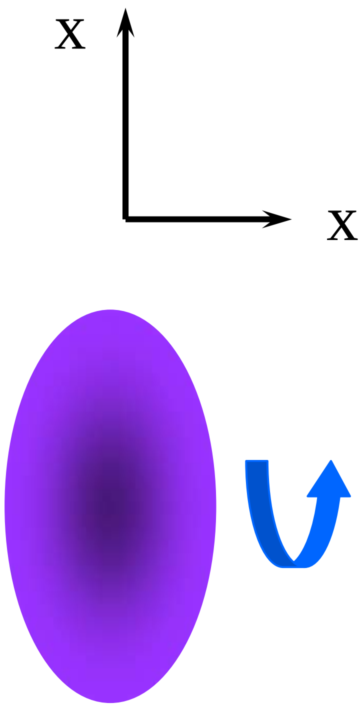
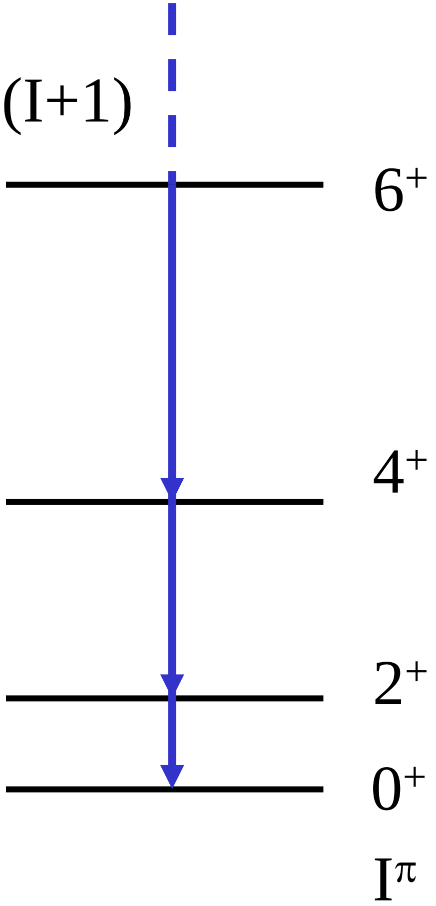
Nuclear Shapes

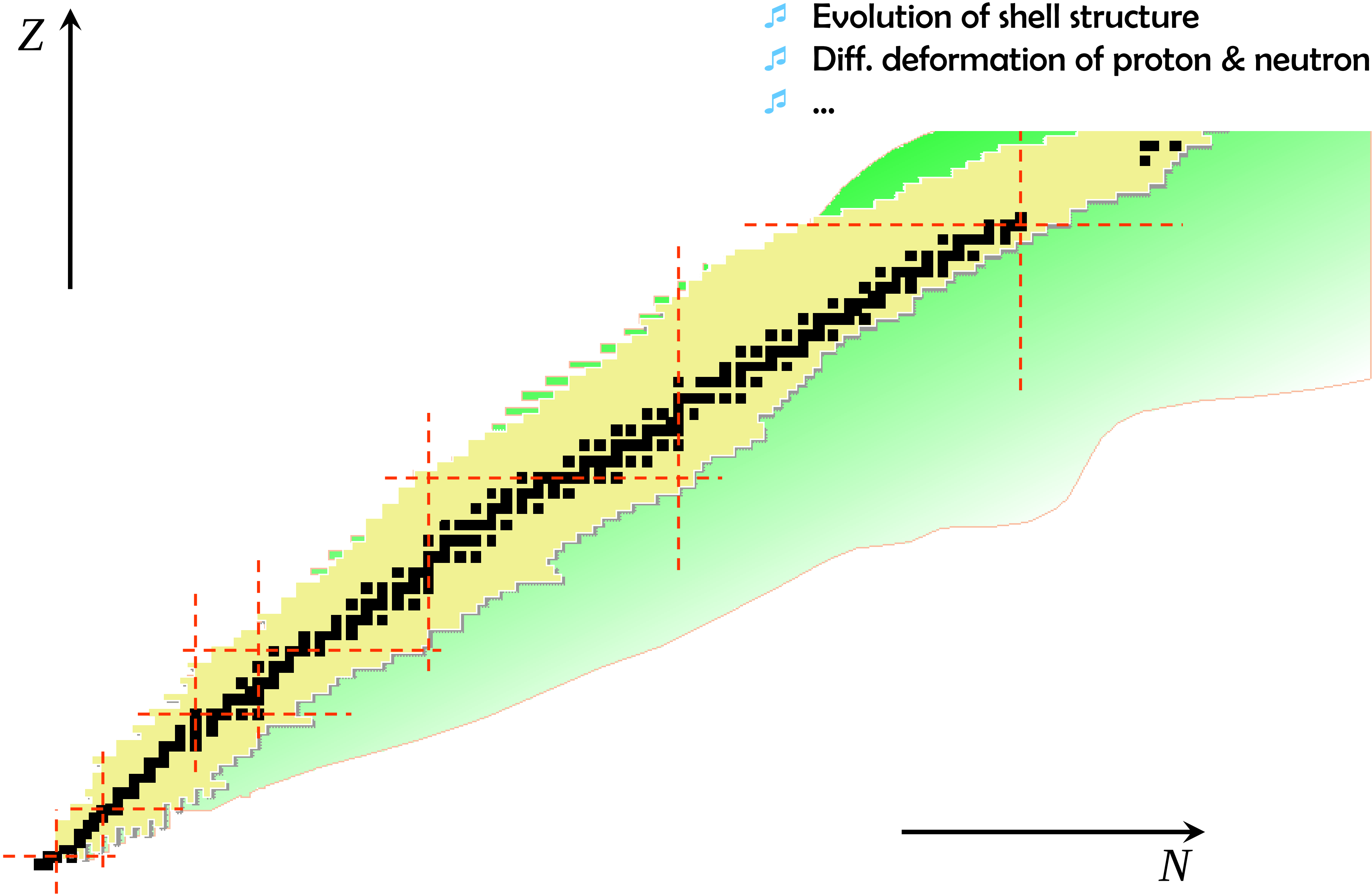


$$E(I) \propto I\,(I+1)$$



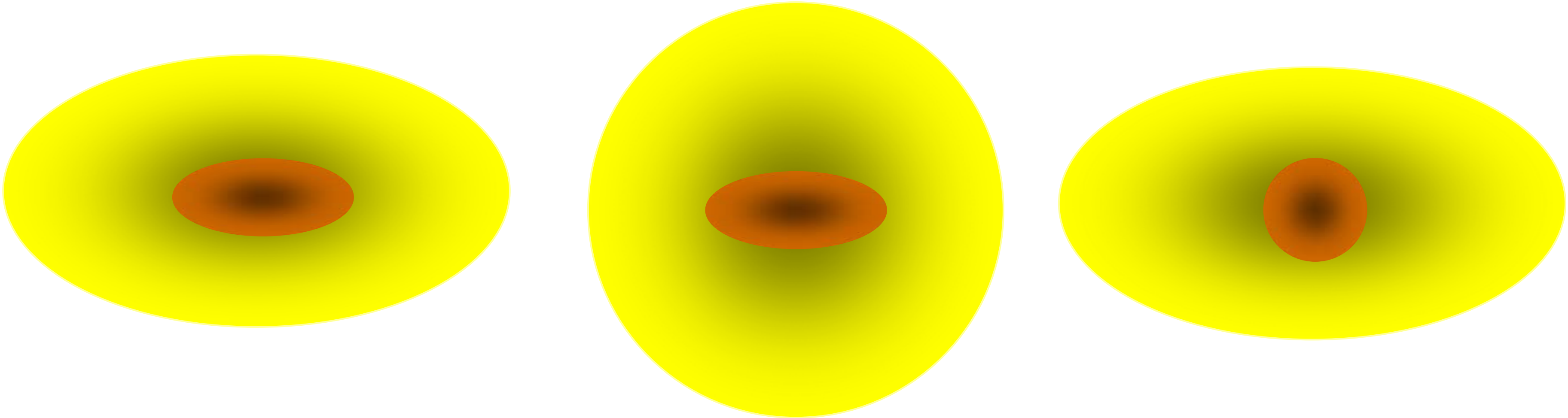
Deformation effects

- Halo in deformed nucl.
- Island of inversion
- Evolution of shell structure
- Diff. deformation of proton & neutron
- ...



Deformed Halo? Deformed core?

Decoupling of the core and halo in deformed nuclei？



^{11,14}Be

Ne isotopes

…

Poschl et al., PRL79(97)3841

Misu, Nazarewicz, Aberg, NPA614(97)44

Bennaceur et al., PLB296(00)154

Hamamoto & Mottelson, PRC68(03)034312

Hamamoto & Mottelson, PRC69(04)064302

Nunes, NPA757(05)349

Pei, Xu & Stevenson, NPA765(06)29

Nakada, NPA808(08)47

Misu et al.: Decoupling betw. Core&Halo !

Misu, Nazarewicz, Aberg, NPA614(97)44

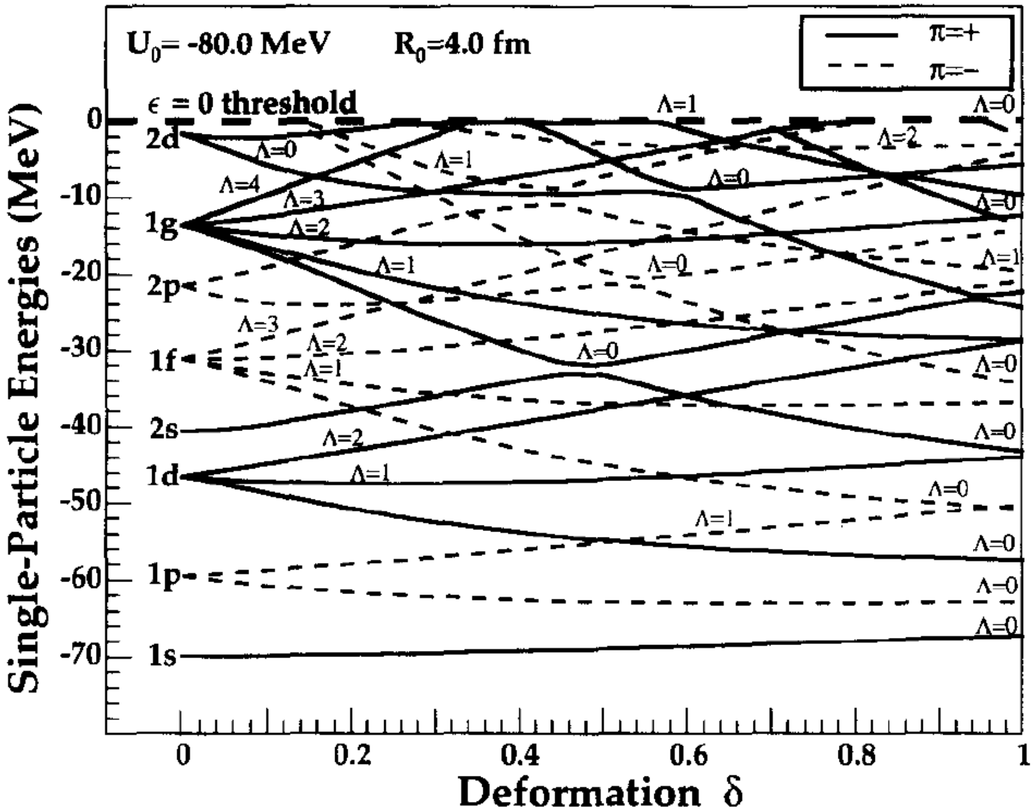
The deformed spheroidal square well potential is given by

$$U(\xi) = \begin{cases} U_0 & \text{for } \xi \le \xi_0, \\ 0 & \text{for } \xi > \xi_0, \end{cases}$$

$$x = a\sqrt{(\xi^2-1)(1-\eta^2)}\cos\phi,$$

$$y = a\sqrt{(\xi^2-1)(1-\eta^2)}\sin\phi,$$

$$z = a\xi\eta,$$



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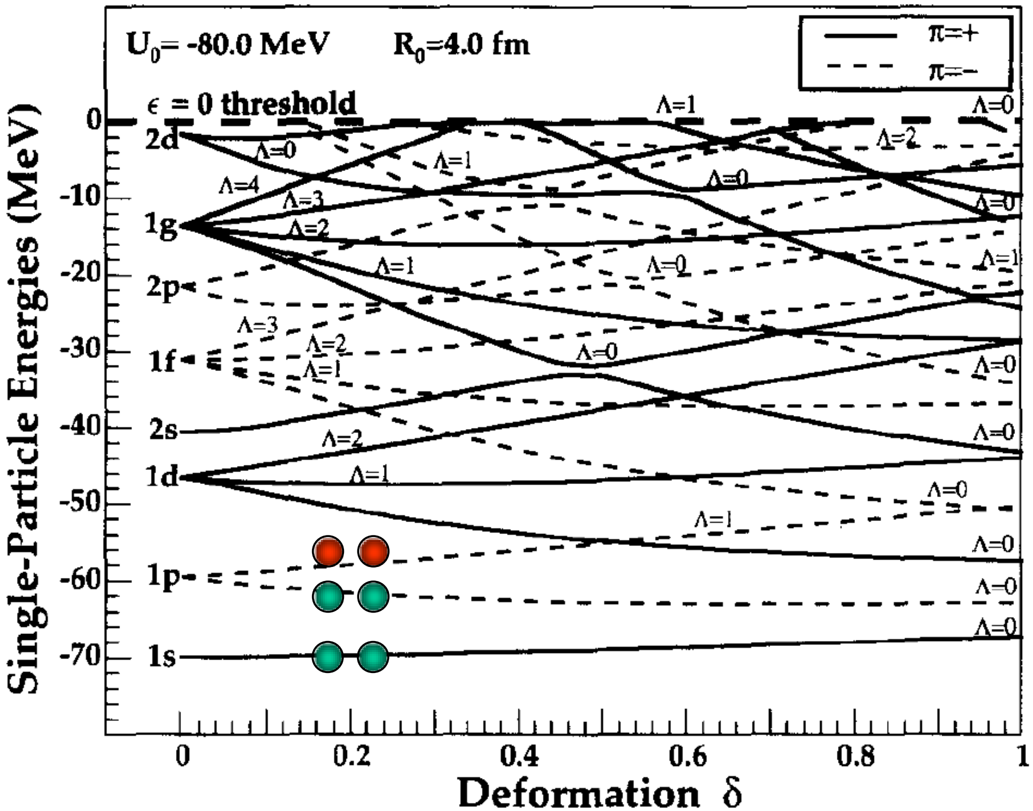

$\delta = 0.2$ and two valuen nucleons occupy the $[11-]$ orbital with $\epsilon = -5$ keV.

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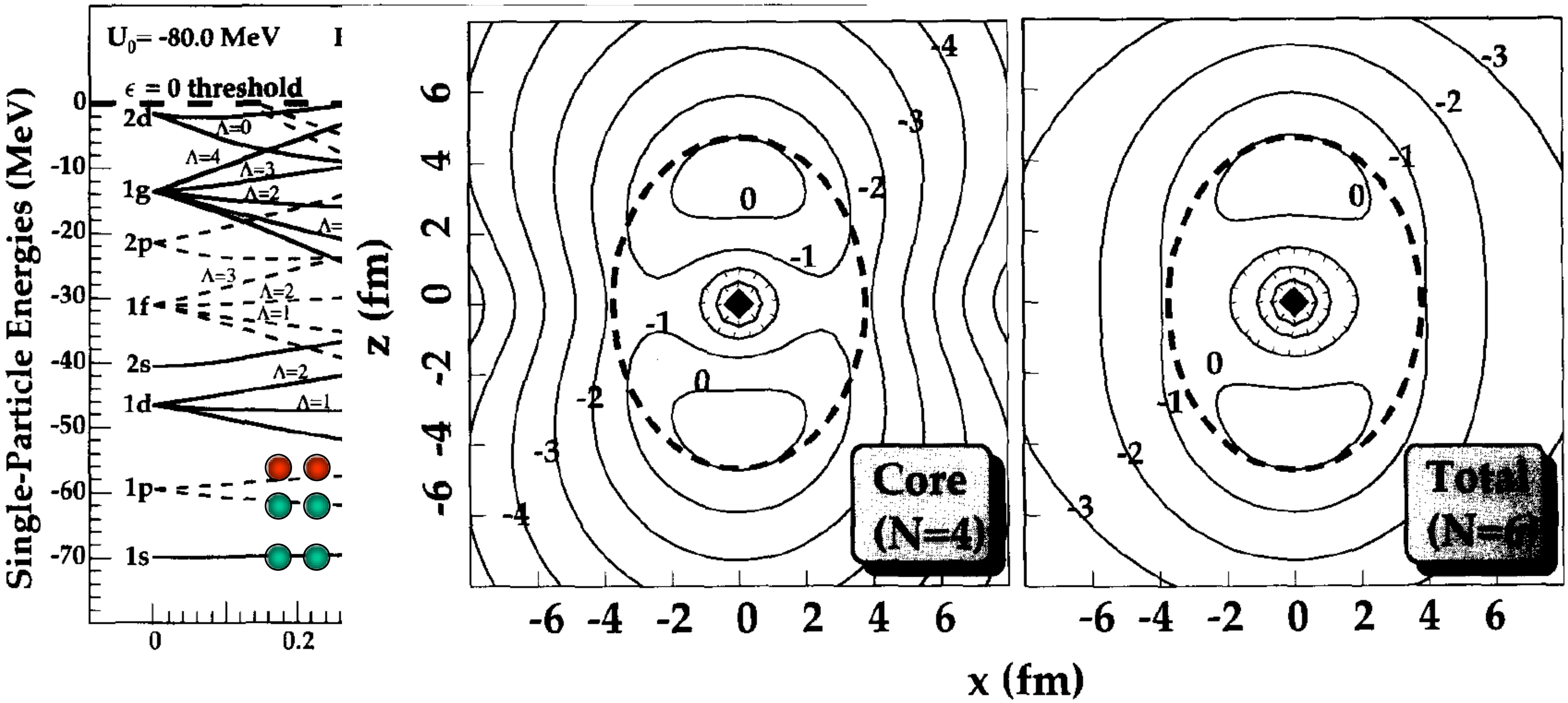
Misu, Nazarewicz, Aberg, NPA614(97)44



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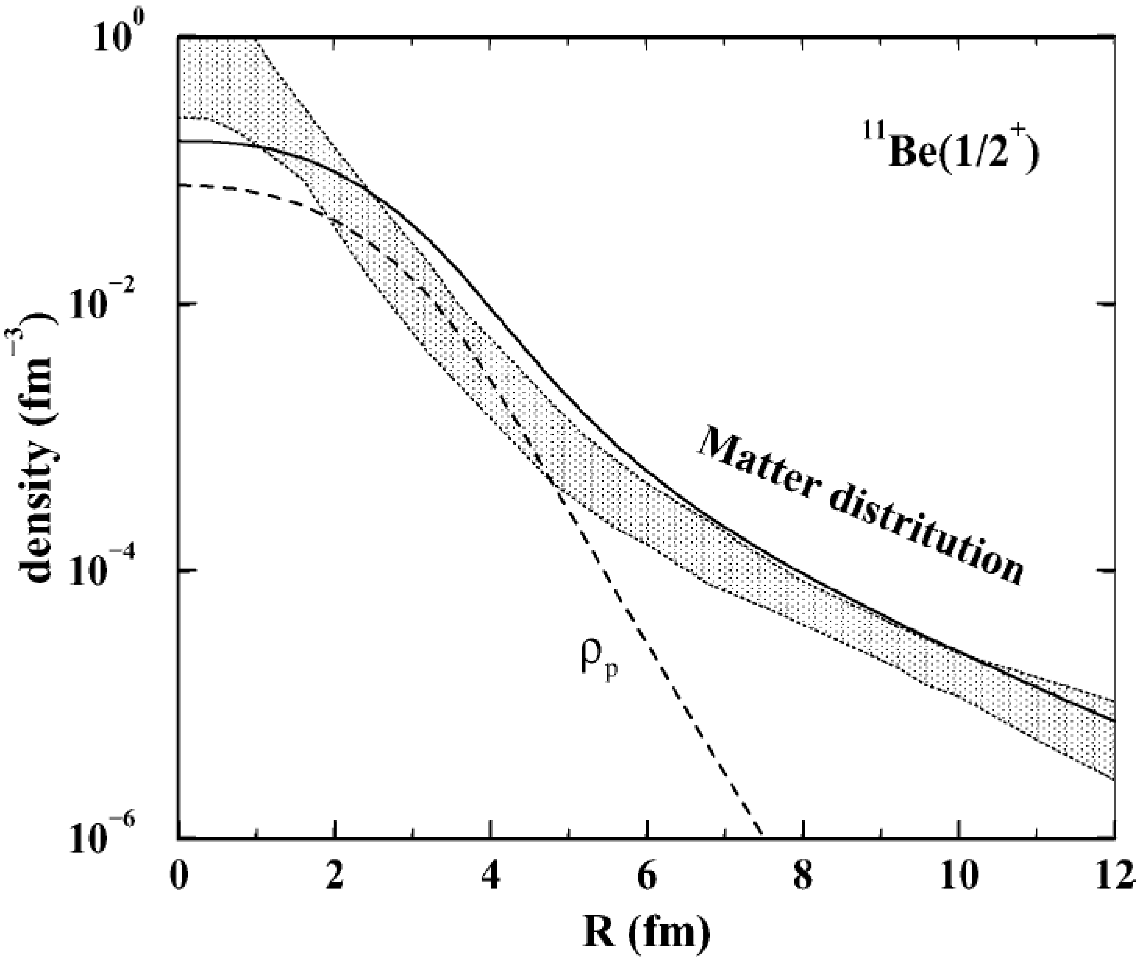
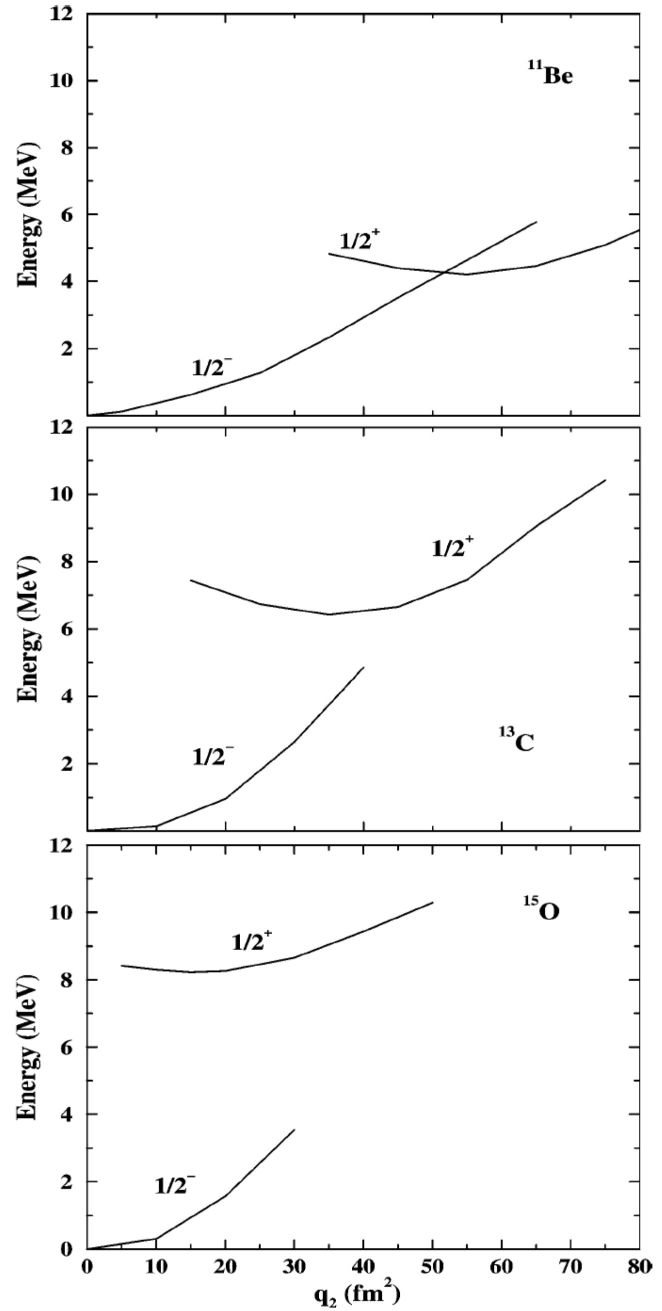
Skyrme Hartree-Fock calc. for ^{11}Be

Pei, Xu & Stevenson, NPA765(06)29





Nunes: no halo in deformed nuclei !

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Nuclear Physics A 757 (2005) 349–359

NUCLEAR PHYSICS A

Valence pairing, core deformation and the development of two-neutron halos

F.M. Nunes [1]

NSCL and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

Received 7 February 2005; received in revised form 1 April 2005; accepted 5 April 2005

Available online 3 May 2005

Abstract

We explore the evolution of the structure of the ground state of a nucleus with two valence nucleons as the system approaches the two particle threshold. We use a three-body model of core + n + n where the core is deformed and allowed to excite. We find that both NN correlations and correlations due to deformation/excitation of the core inhibit the formation of halos. Our results suggest that it is unlikely to find halo nuclei on the dripline of deformed nuclei.

Nunes: no halo in deformed nuclei !

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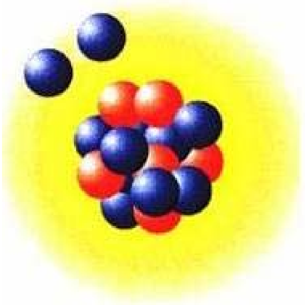
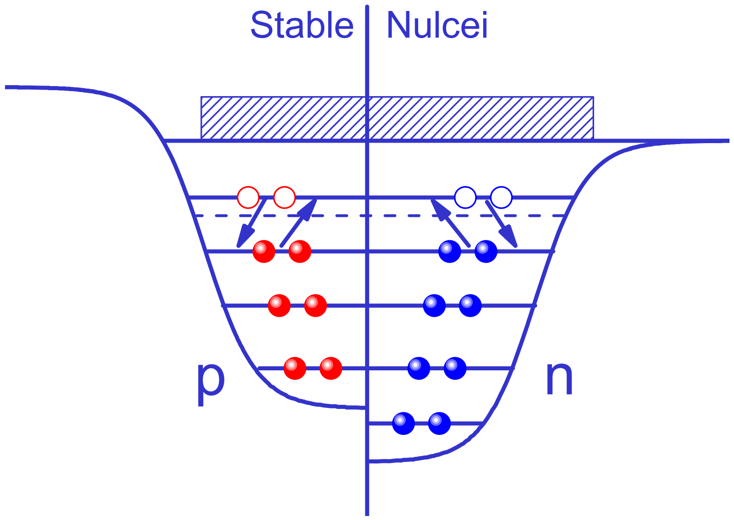
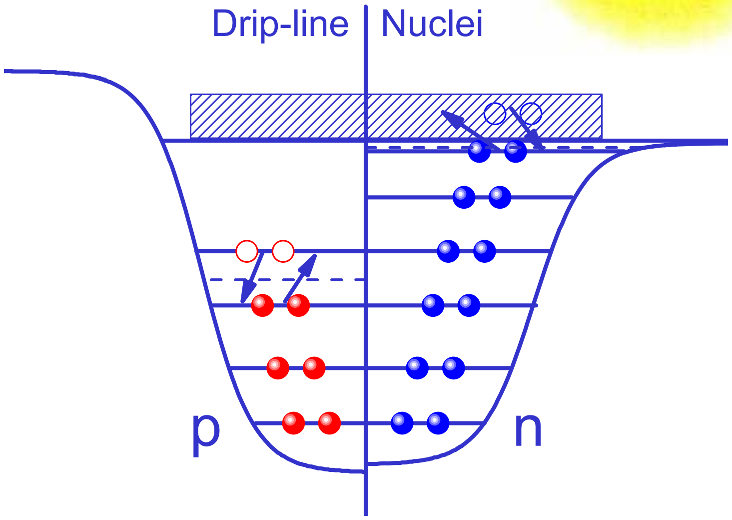
Characteristics of halo nuclei

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







Meng, Toki, SGZ, Zhang, Long & Geng, Prog. Part. Nucl. Phys. 57 (06) 470

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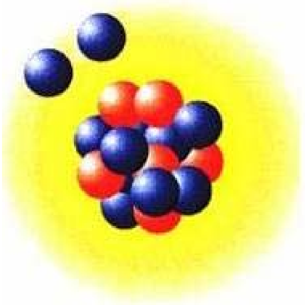
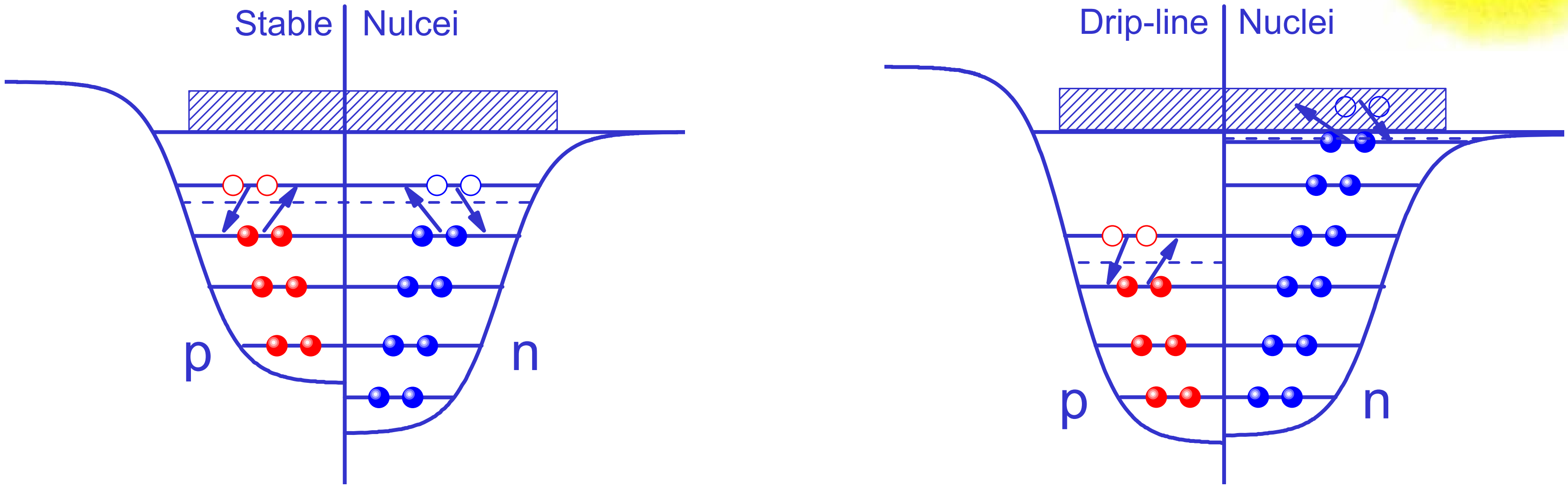


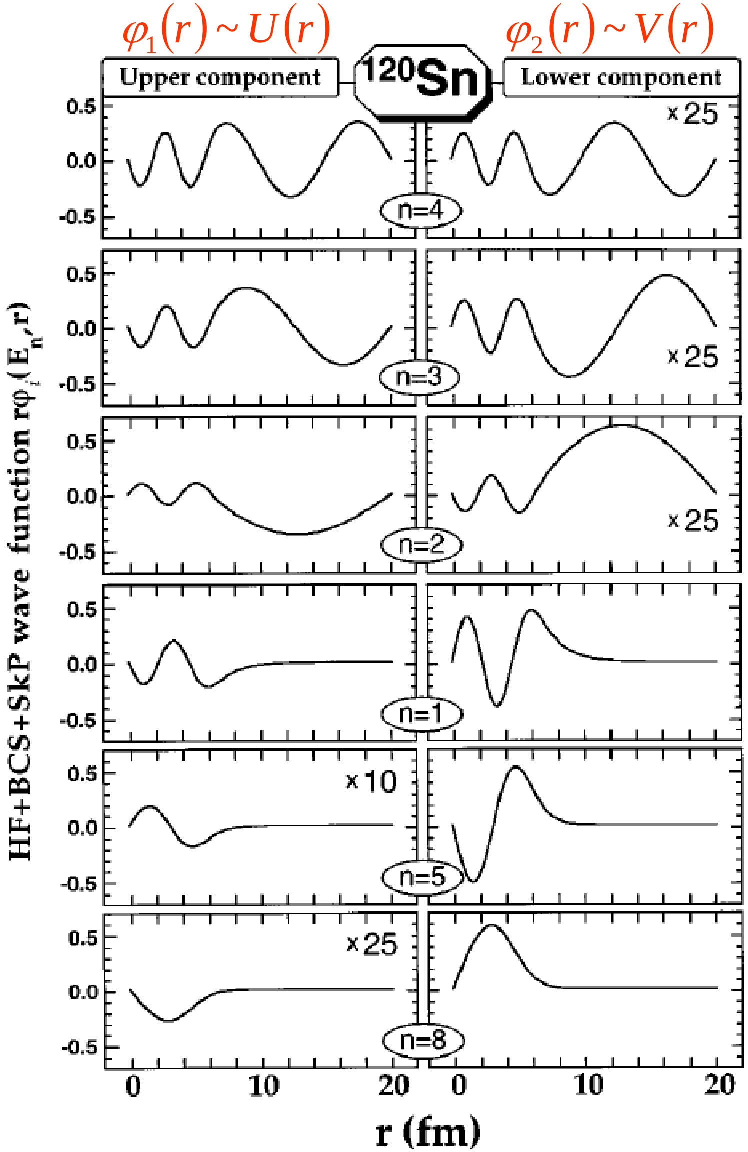


Self-consistent description:

- Deformation
- Weakly bound, continuum
- Large spatial distribution
- Couplings among …

Meng, Toki, SGZ, Zhang, Long & Geng,
Prog. Part. Nucl. Phys. 57 (06) 470

BCS and Continuum

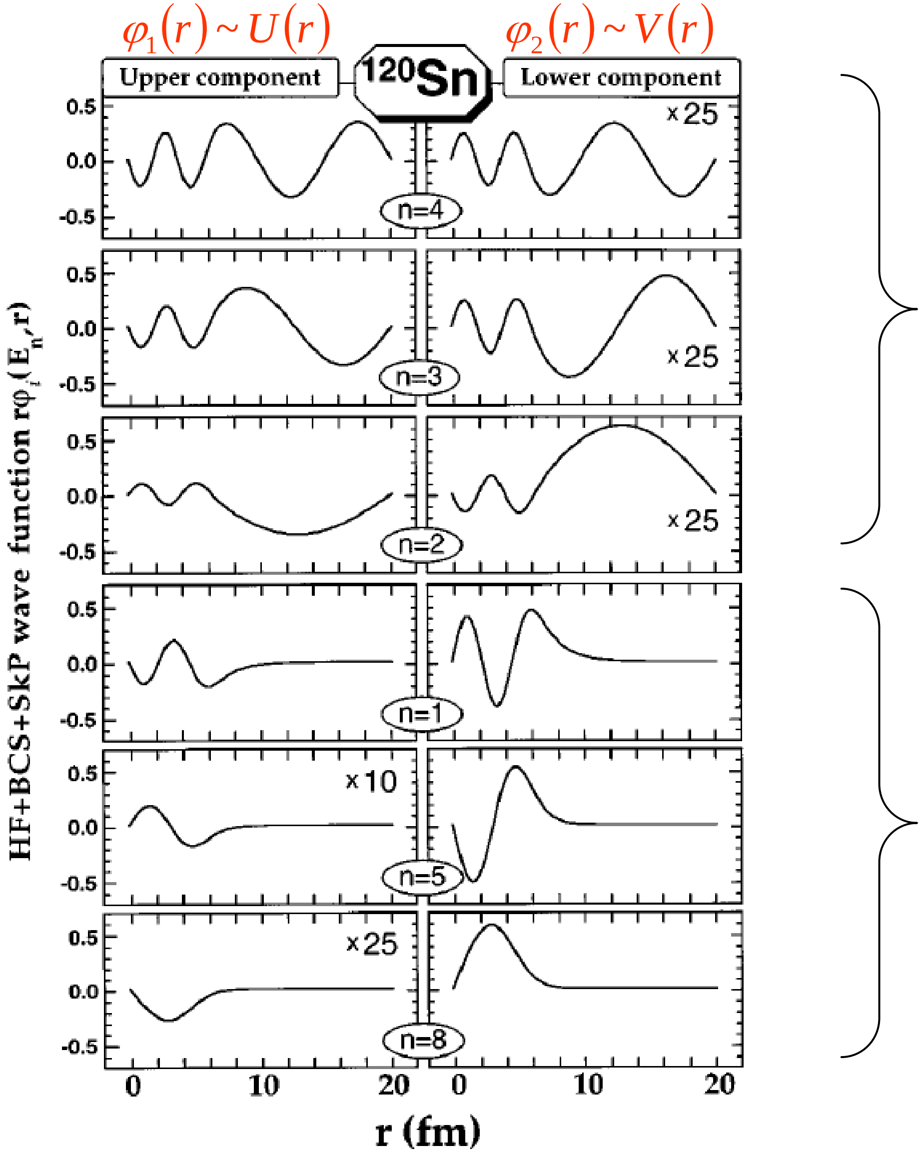


Positive energy States

Bound States

Dobaczewski, et al., PRC53(96)2809

BCS and Continuum



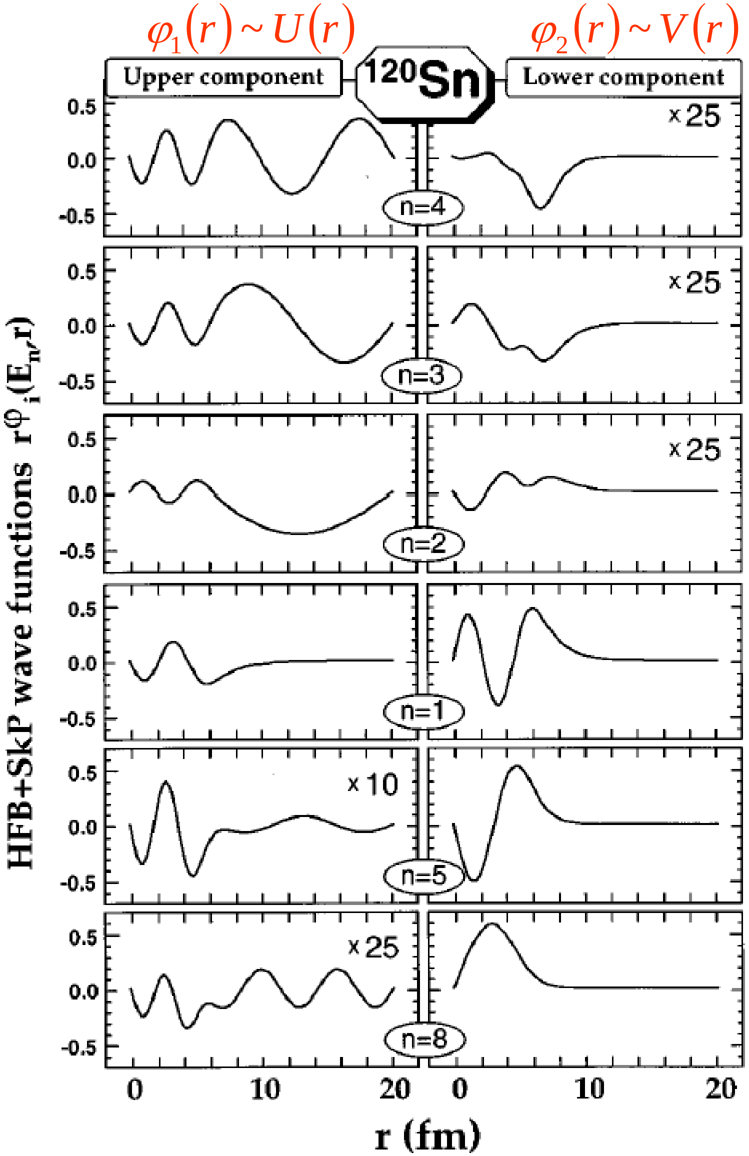
Positive energy States

Even a smaller occupation of positive energy states gives a non-localized density

Bound States

Dobaczewski, et al., PRC53(96)2809

Contribution of continuum in r-HFB



Positive energy States

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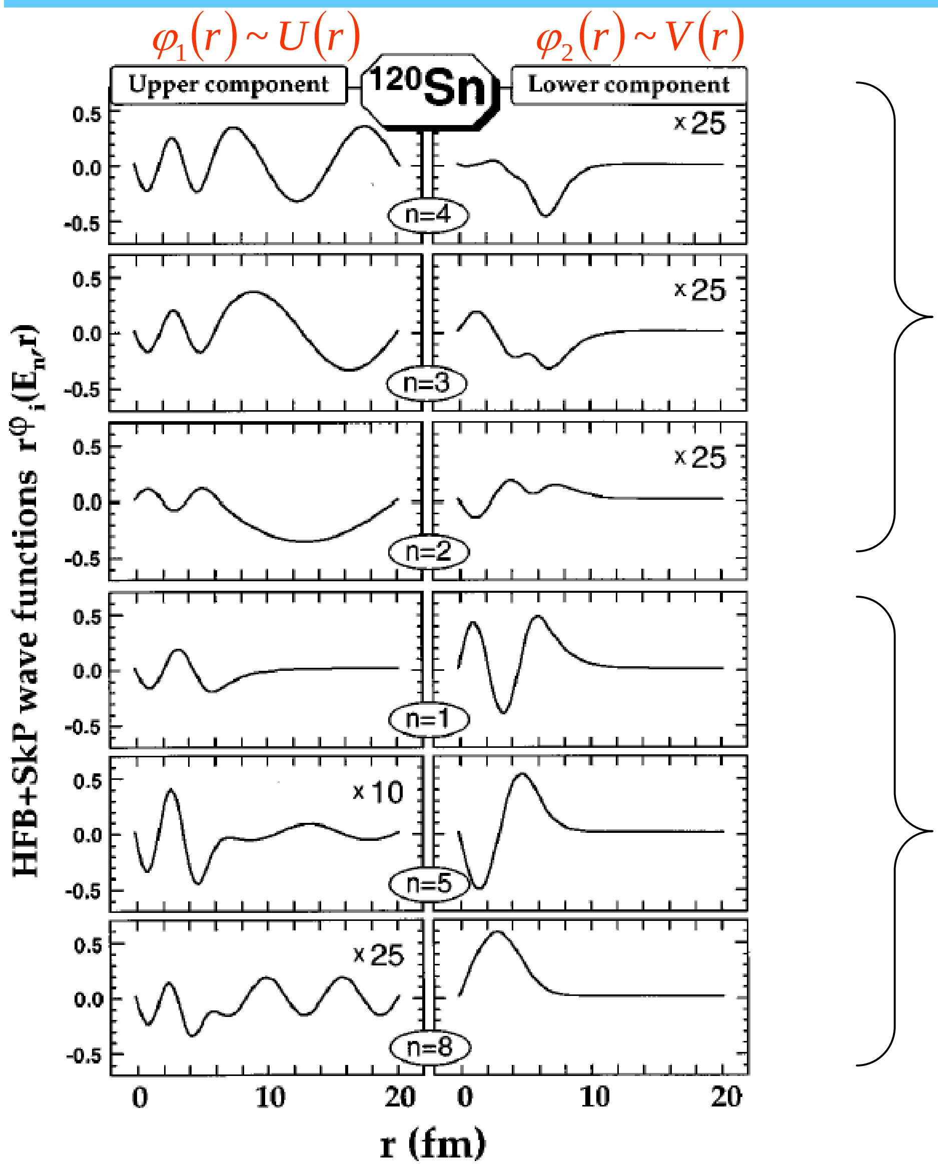

Positive energy States

- *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

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Relativistic mean field model

$$L = \overline{\psi}_i \left(i\gamma_\mu \partial^\mu - M \right) \psi_i + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - U(\sigma) - g_\sigma \overline{\psi}_i \sigma \psi_i$$

$$- \frac{1}{4} \Omega_{\mu\nu} \Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - g_\omega \overline{\psi}_i \gamma_\mu \omega^\mu \psi_i$$

$$- \frac{1}{4} \vec{R}_{\mu\nu} \vec{R}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \vec{\rho}^\mu - g_\rho \overline{\psi}_i \gamma_\mu \vec{\rho}^\mu \vec{\tau} \psi_i$$

$$- \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - e \overline{\psi}_i \frac{1 - \tau_3}{2} \gamma_\mu A^\mu \psi_i$$

Serot & Walecka, Adv. Nucl. Phys. 16 (86) 1

Reinhard, Rep. Prog. Phys. 52 (89) 439

Ring, Prog. Part. Nucl. Phys. 37 (96) 193

Vretenar, Afnasjev, Lalazissis & Ring
Phys. Rep. 409 (05) 101

Meng, Toki, SGZ, Zhang, Long & Geng,
Prog. Part. Nucl. Phys. 57 (06) 470

RMF: advantages

Nucleon-nucleon interaction

- Mesons degrees of freedom included
- Nucleons interact via exchanges mesons

Relativistic effects

- Two potentials: scalar and vector potentials
  - ⇒ the relativistic effects important dynamically
  - ⇒ New mechanism of saturation of nuclear matter
  - ⇒ Psedo spin symmetry explained neatly and successfully
- Spin orbit coupling included automatically
  - ⇒ Anomalies in isotope shifts of Pb

Others

- More easily dealt with
- Less number of paramters
- …

RMF (RHB) description of nuclei

- **Ground state properties of nuclei**
  - Binding energies, radii, neutron skin thickness, etc.
- **Halo nuclei**
  - RMF description of halo nuclei
  - Predictions of giant halo
  - Study of deformed halo
- **Symmetries in nuclei**
  - Pseudo spin symmetry
  - Spin symmetry
- **Hyper nuclei**
  - Neutron halo and hyperon halo in hyper nuclei
- **…**

Meng, Toki, SGZ, et al.,
Prog. Part. Nucl. Phys. 2006

Meng, SGZ, Zhang, et al.,
Condens. Matter Theor. 2007

RMF in a Woods-Saxon basis: progress

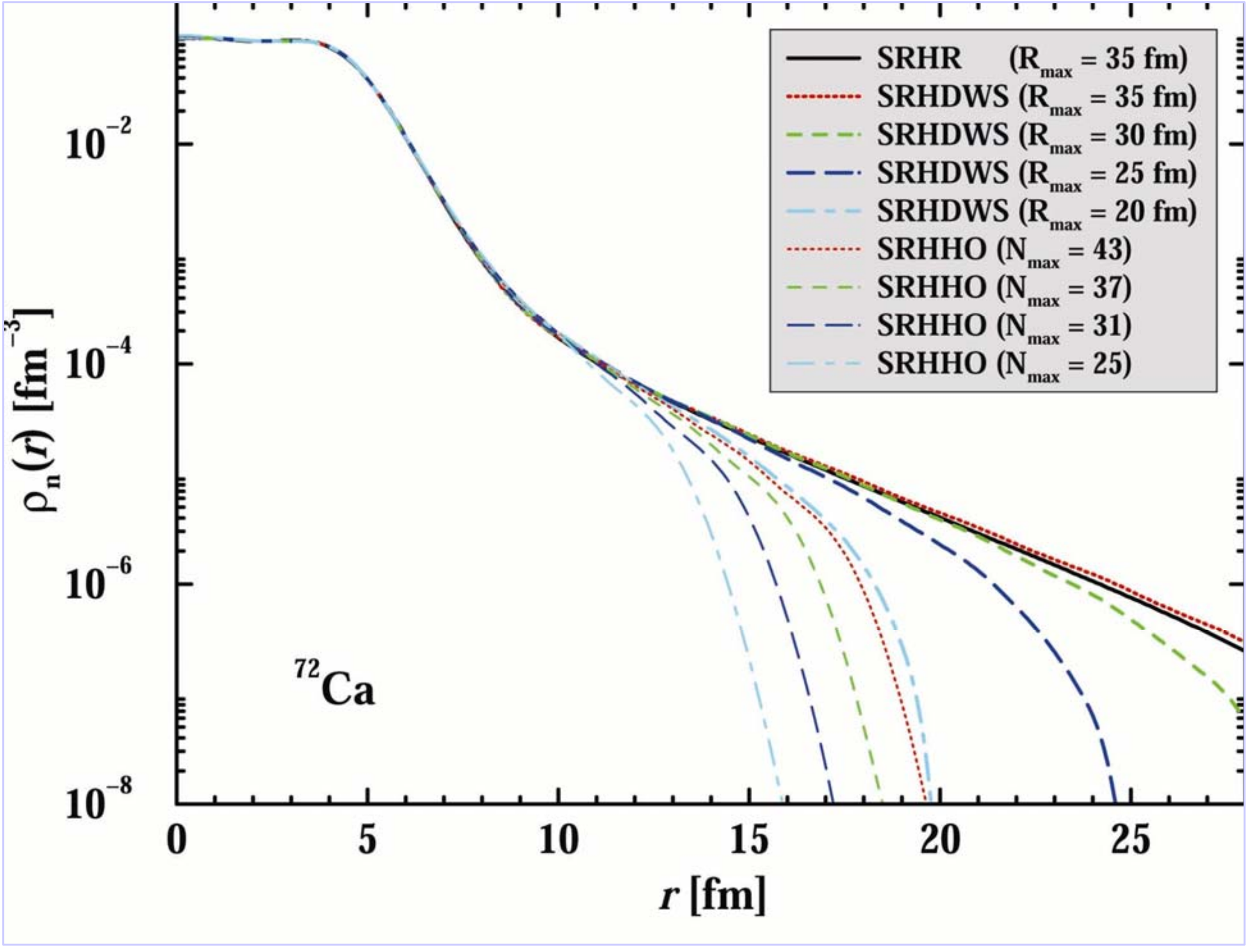
Shapes	Mean field or Beyond	Schrödinger W-S basis	Dirac W-S basis	
Spherical	Rela. Hartree	SRH SWS	SRH DWS	√
	SGZ, Meng & Ring, PRC68, 034323 (03); PRL91, 262501 (03)			
Axially deformed	Rela. Hartree + BCS		DRH DWS	√
	SGZ, Meng & Ring, AIP Conf. Proc. 865, 90 (06)			
Axially deformed	Rela. Hartree-Bogoliubov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

Many difficulties to solve deformed problem in r space

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

Schunck & Egido 2008

Spherical Rela. Hartree Theory: ^{72}Ca

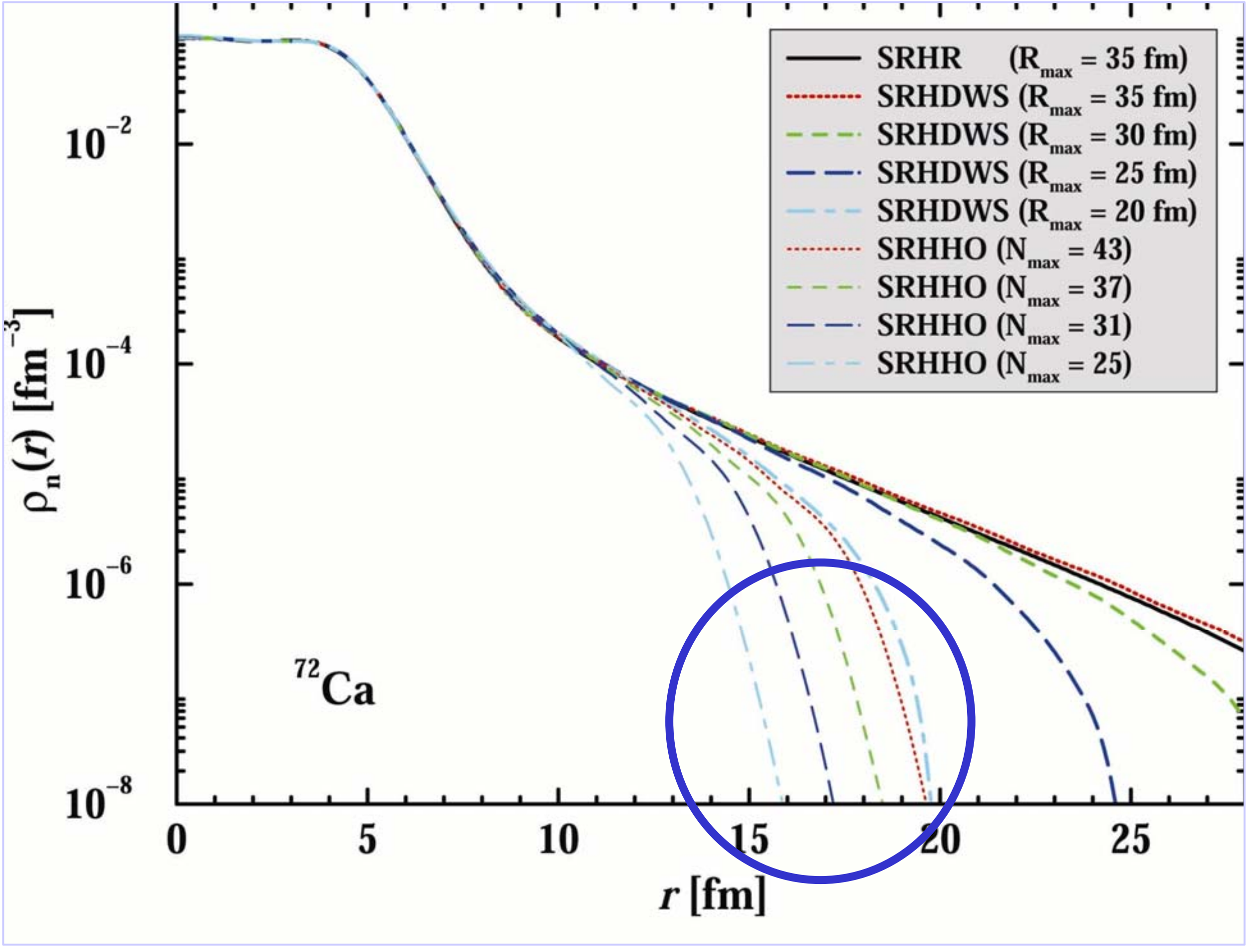


SGZ, Meng & Ring, PRC68,034323(03)

SGZ, Meng & Ring, PRL91,262501(03)

Woods-Saxon basis reproduces r space

Spherical Rela. Hartree Theory: ^{72}Ca



SGZ, Meng & Ring, PRC68,034323(03)

SGZ, Meng & Ring, PRL91,262501(03)

Woods-Saxon basis reproduces r space

Deformed RHB in a Woods-Saxon basis

Axially deformed nuclei

$$\beta^+_{km} = \sum_{(i\kappa)} u^{(m)}_{k,(i\kappa)} a^+_{i\kappa m} + v^{(m)}_{k,(i\tilde{\kappa})} \tilde{a}_{i\kappa m}$$

$$\begin{pmatrix} U^{(m)}_k(\boldsymbol{r}\sigma p) \\ V^{(m)}_k(\boldsymbol{r}\sigma p) \end{pmatrix} = \sum_{i\kappa} \begin{pmatrix} u^{(m)}_{k,(i\kappa)} \varphi_{i\kappa m}(\boldsymbol{r}\sigma p) \\ v^{(m)}_{k,(i\tilde{\kappa})} \tilde{\varphi}_{i\kappa m}(\boldsymbol{r}\sigma p) \end{pmatrix}$$

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

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

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

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

DRHB matrix elements

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

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

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

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

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

λ, even or odd
μ, 0 or ±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**

$$V^{\rm pair} = \frac{1}{4} V_0 \delta(\mathbf{r}_1 - \mathbf{r}_2) \left(1 - \frac{\rho(\mathbf{r}_1)}{\rho_0}\right)^{\gamma} [1 - 4\vec{\sigma}_{11'} \cdot \vec{\sigma}_{22'}] [\mathbf{I}^p_{11'} \cdot \mathbf{I}^p_{22'}]$$

$$s(E_k) = \frac{1}{2}\left(1 - \frac{E_k - E^{\rm q.p.}_{\rm cut}}{\sqrt{(E_k - E^{\rm q.p.}_{\rm cut})^2 + (\Gamma^{\rm q.p.}_{\rm cut})^2}}\right)$$

Finite range?
Volume or surface?
Microscopic?

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  - ✧ Halos in deformed nuclei: exists or not? if yes, what's new?
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  - ✧ Mechanism of the decoupling
- **Summary**

How to fix the pairing strength and the pairing window

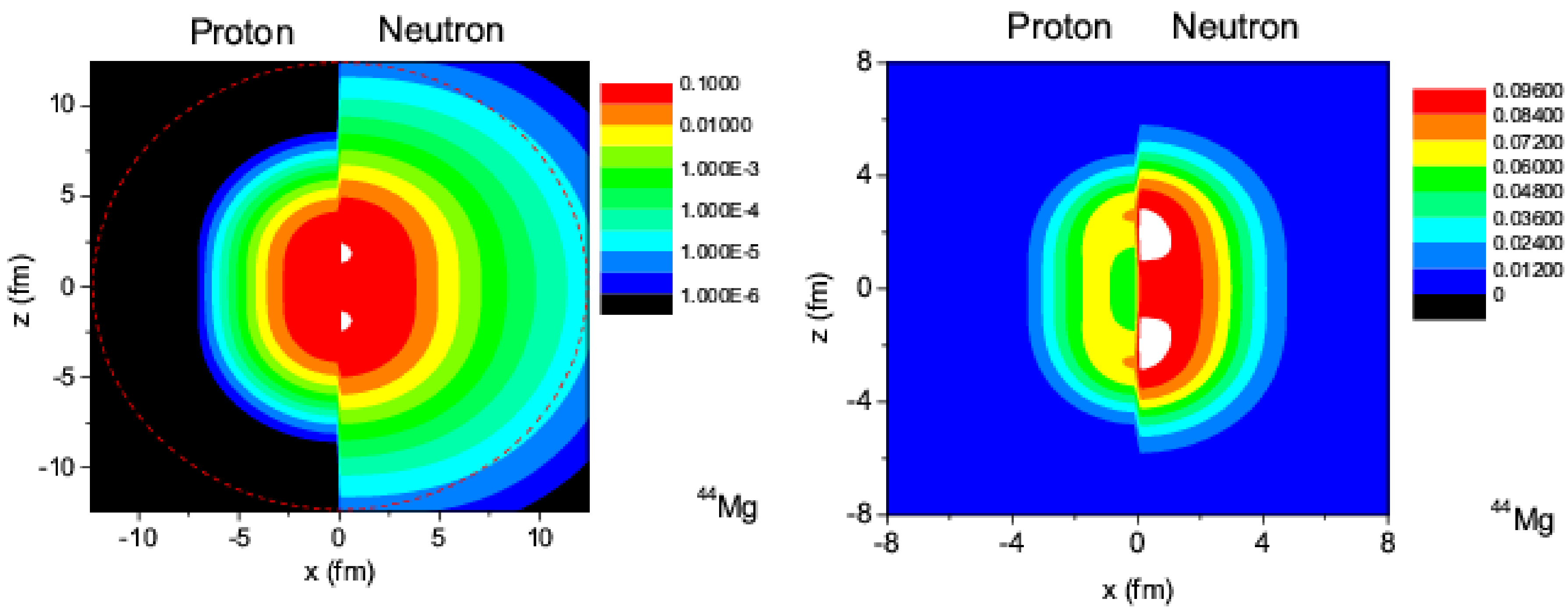
^{20}Mg: spherical from DRHBWS calculation

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

Zero pairing energy for the neutron

Model	Pairing force	Parameters	$E^{\text{p}}_{\text{pair}}$ (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	$E^{\text{q.p.}}_{\text{cut}} = 60$ MeV	
DRHBWS	Surface δ	$V_0 = 380$ MeV fm^3	-9.2383
		$\rho_0 = 0.152$ fm^3	
	Smooth cutoff	$E^{\text{q.p.}}_{\text{cut}} = 60$ MeV	
		$\Gamma = 5.65$ MeV	

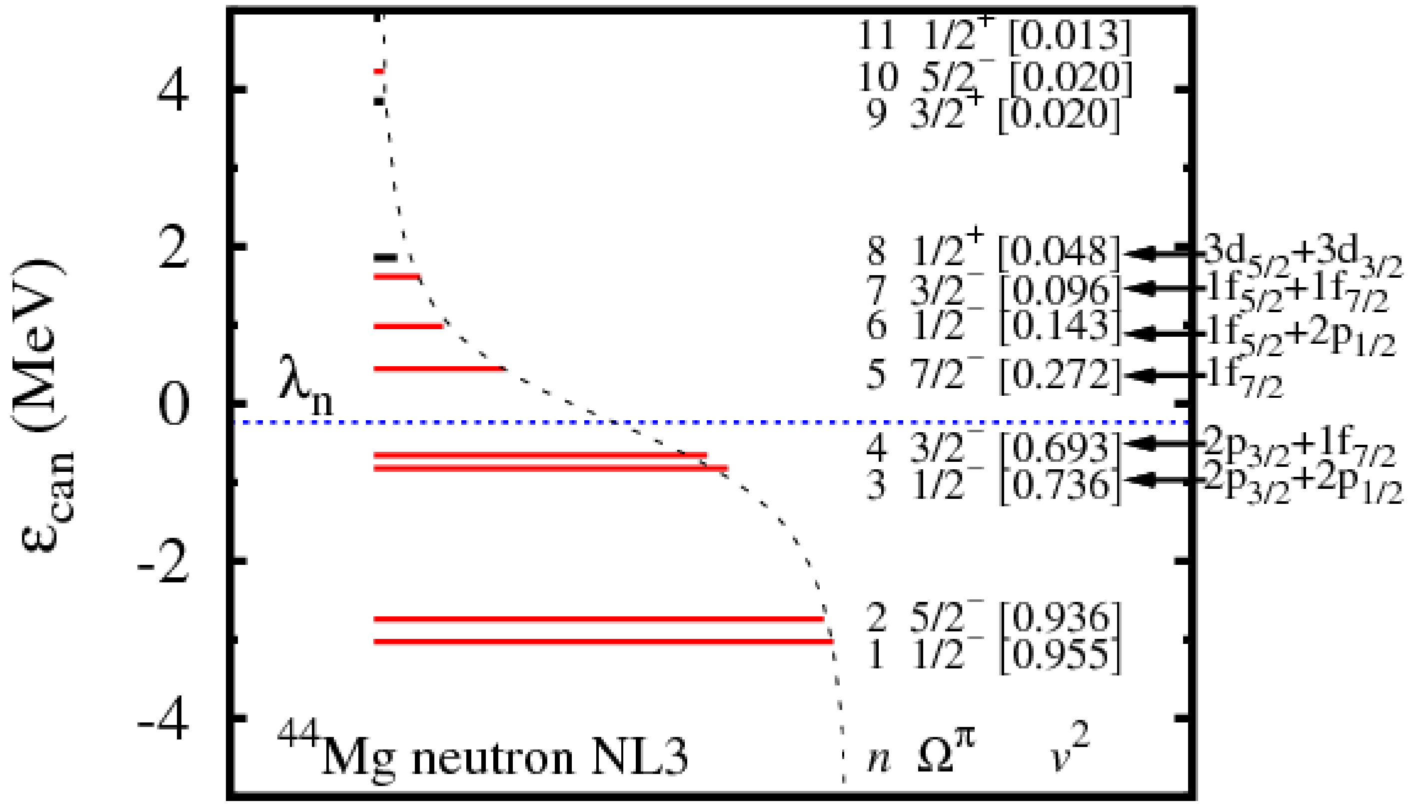
^{44}Mg from DRHBWS



SGZ, Meng, Ring, Zhao
arXiv: 0909.1600 [nucl-th]

- Prolate deformation
- Large spatial extension in neutron density distribution

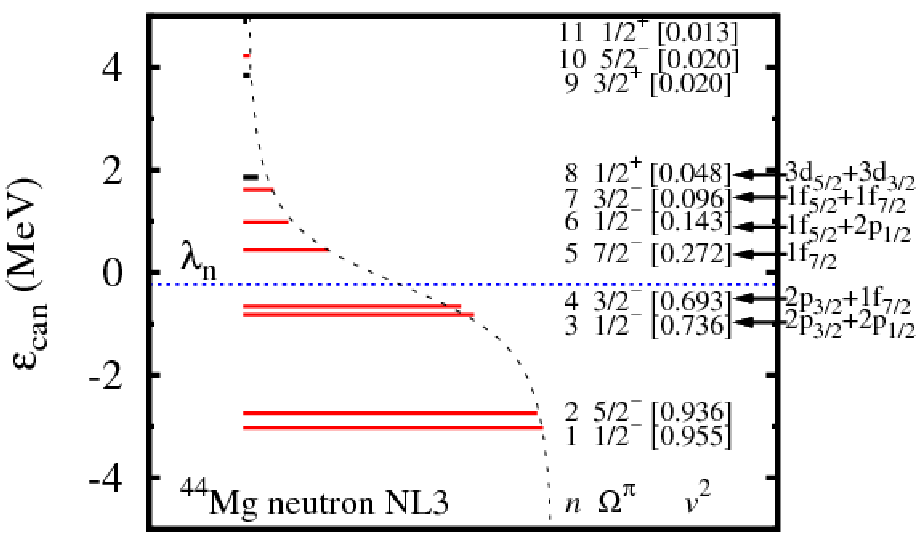
Single neutron states in canonical basis

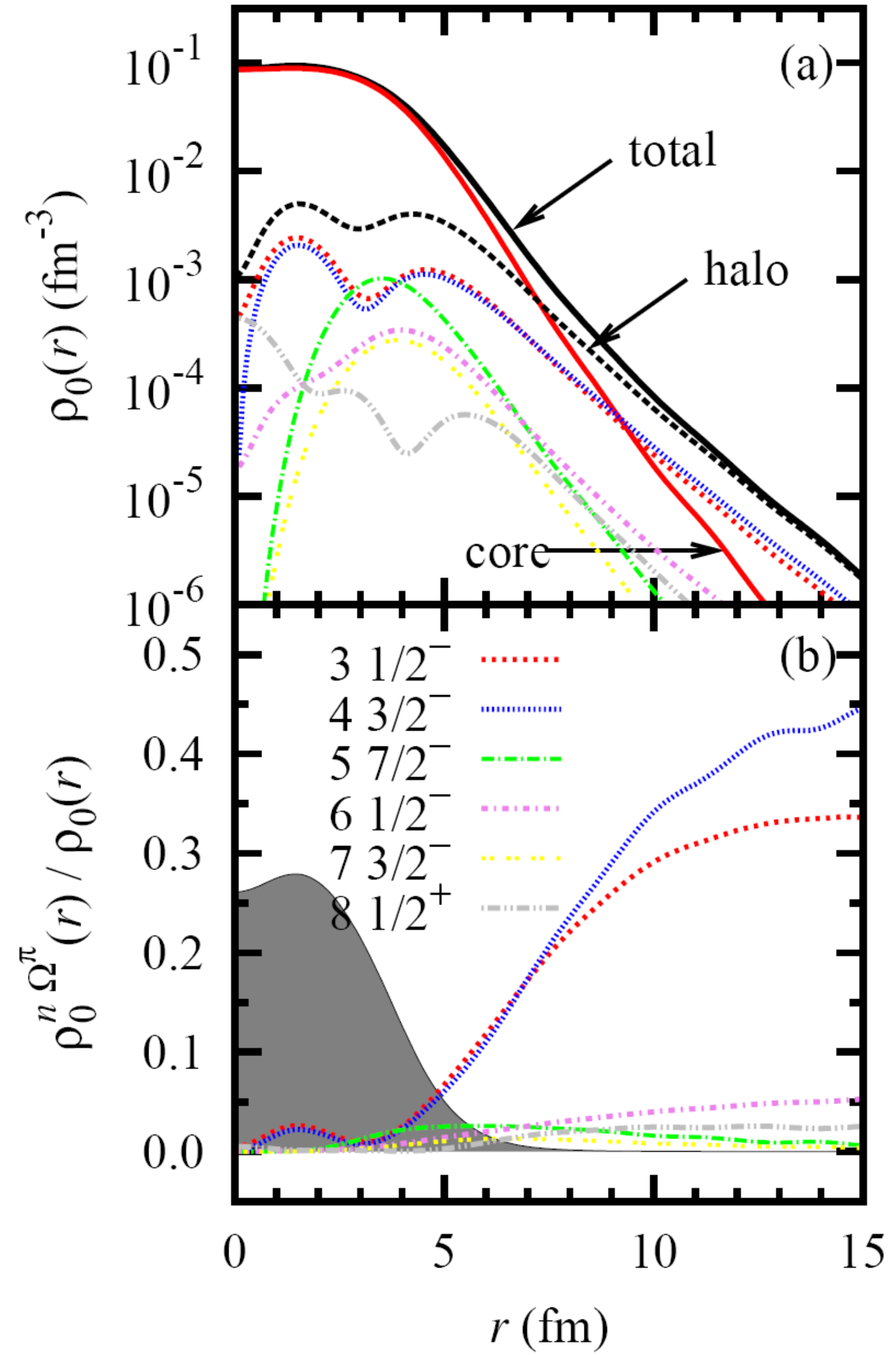


- Continuum contributes
- Negative-parity states around Fermi level

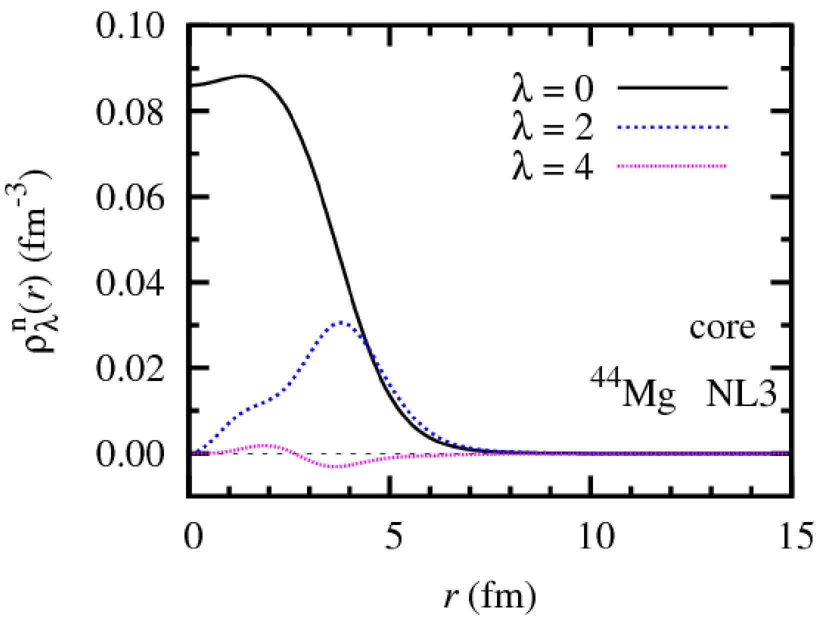
Decomposition of neut. density distri.

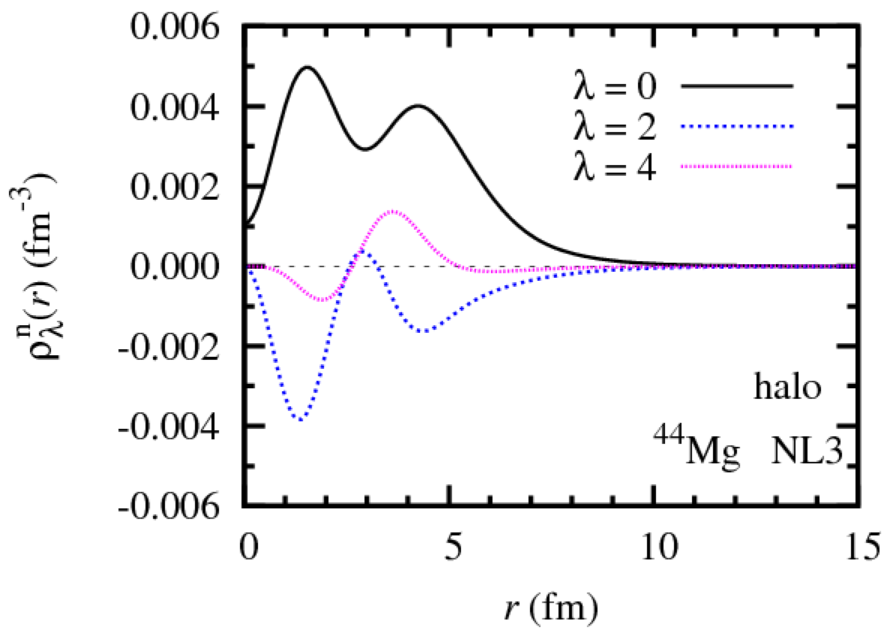
- The 3rd & 4th states contribute to tail part of neutron density distribution
- Main component: $2p_{3/2}$
- $R_{\rm core} = 3.72$ fm, $R_{\rm halo} = 5.86$ fm





Density of core & halo

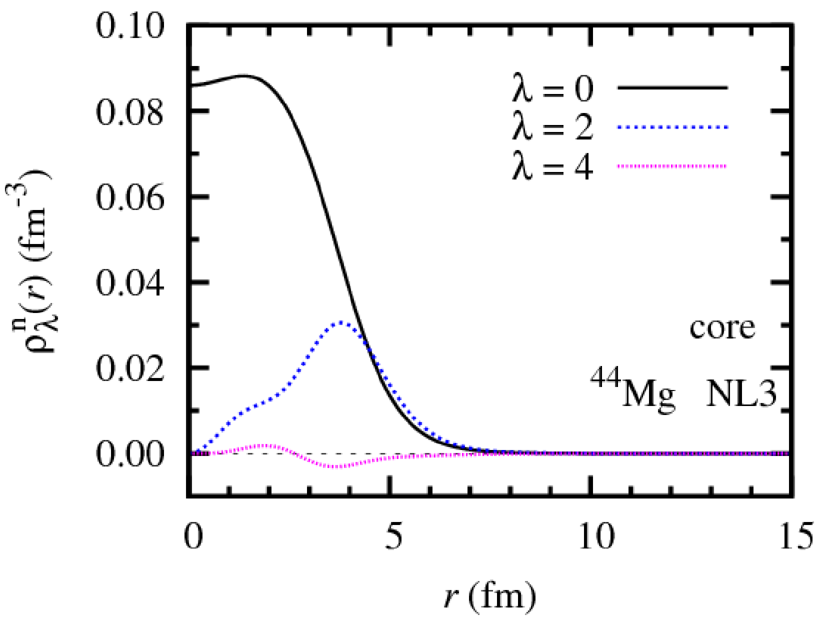


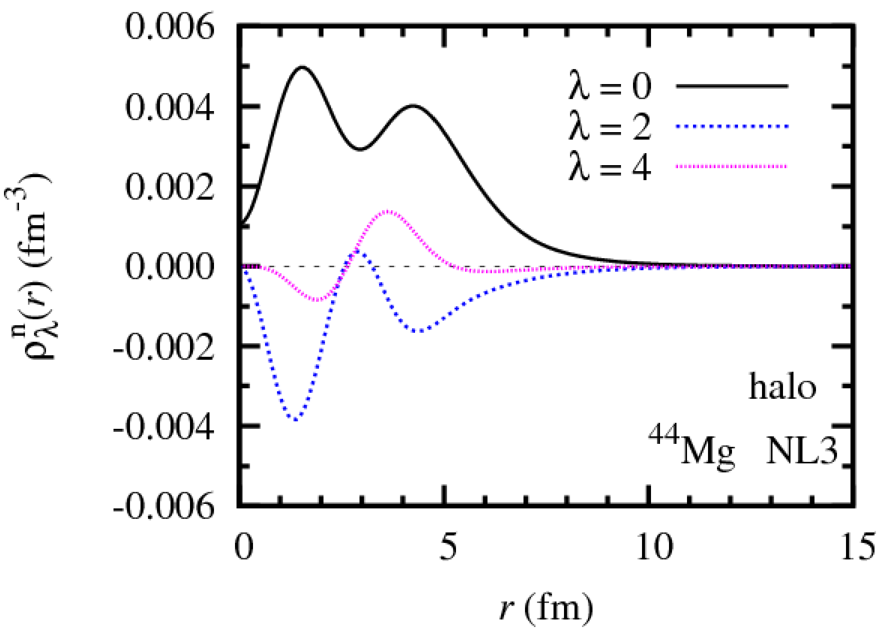


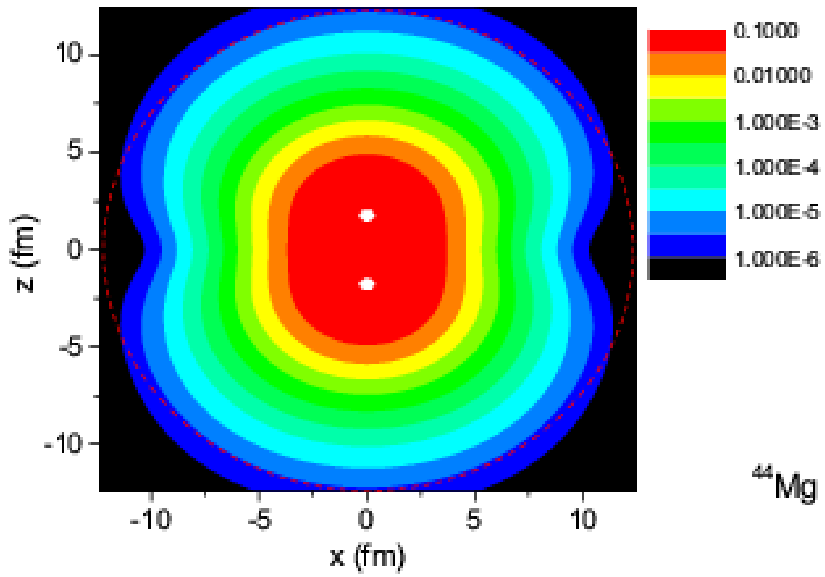
$$\rho(\boldsymbol{r}) = \sum_{\lambda} \rho_{\lambda}(r) P_{\lambda}(\cos\theta), \ \ \lambda = 0, 2, 4, \cdots$$

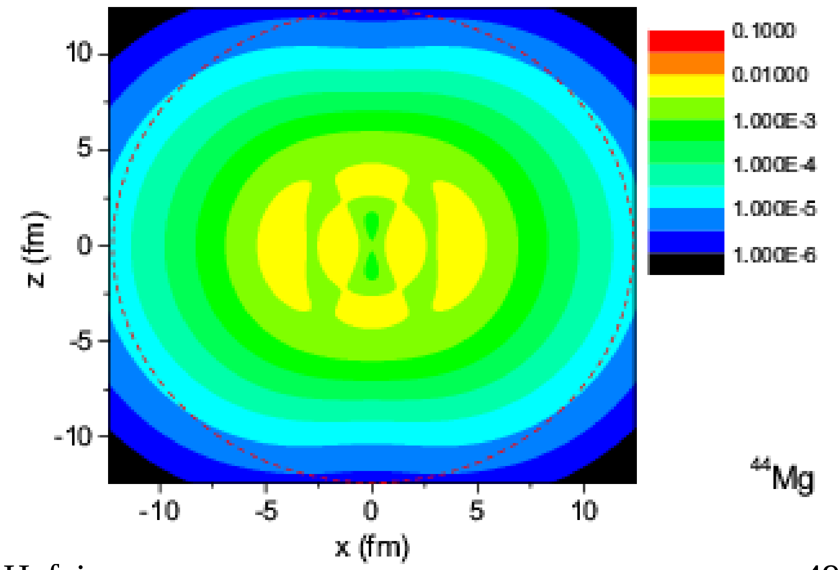
- Prolate core, but slightly oblate halo with sizable hexadecapole component !
- Decoupling of deformation betw. core & halo

Density of core & halo

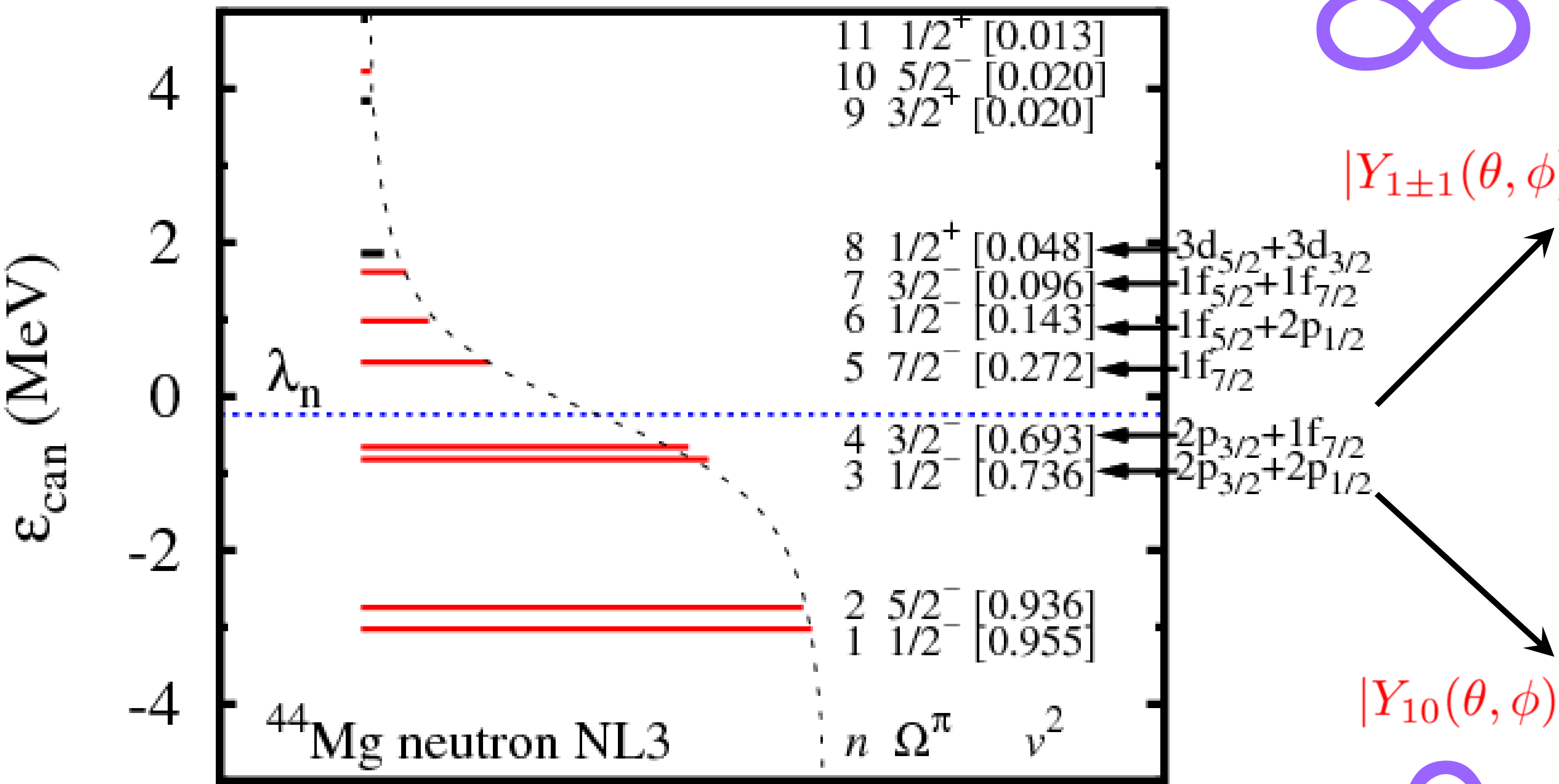






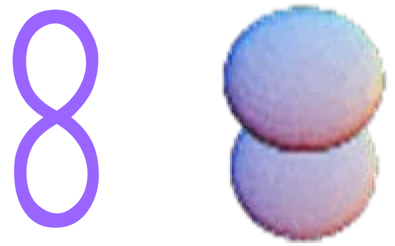


Why the halo slightly oblate?



$|Y_{1\pm1}(\theta,\phi)|^2 \propto \sin^2(\theta)$

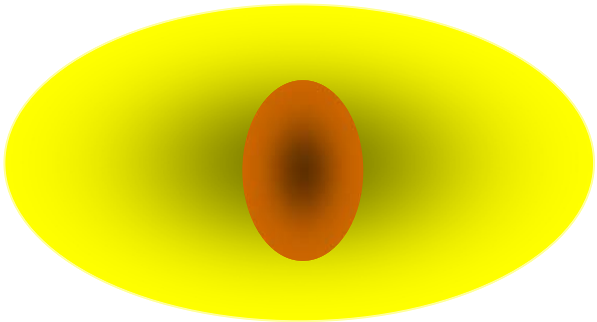
$|Y_{10}(\theta,\phi)|^2 \propto \cos^2(\theta)$



Cartoon plots from *MathWorld*

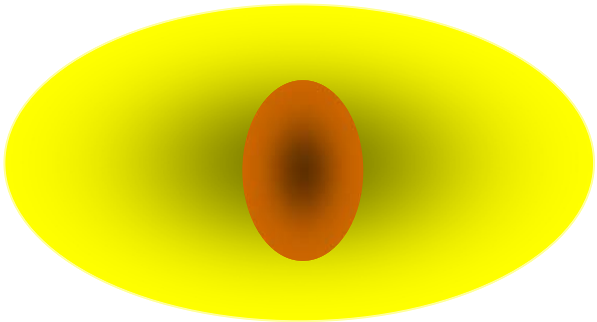
How to measure?

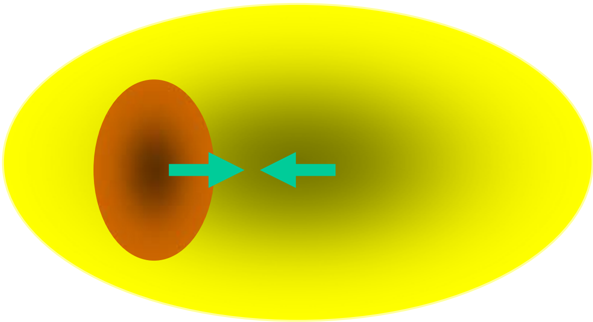
- **Larger cross section**
- **Smaller momentum distribution**
  - Double-hump ! ?

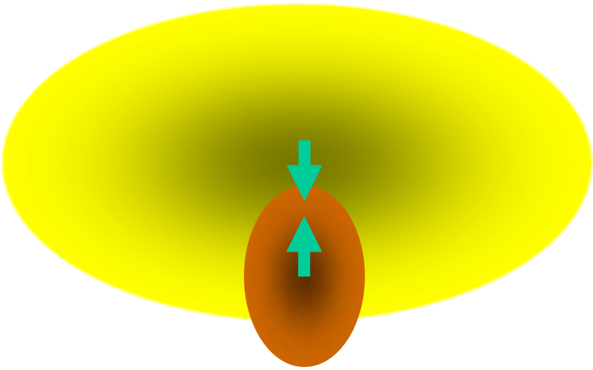


How to measure?

- Larger cross section
- Smaller momentum distribution
  - Double-hump ! ?
- New dipole modes
- …



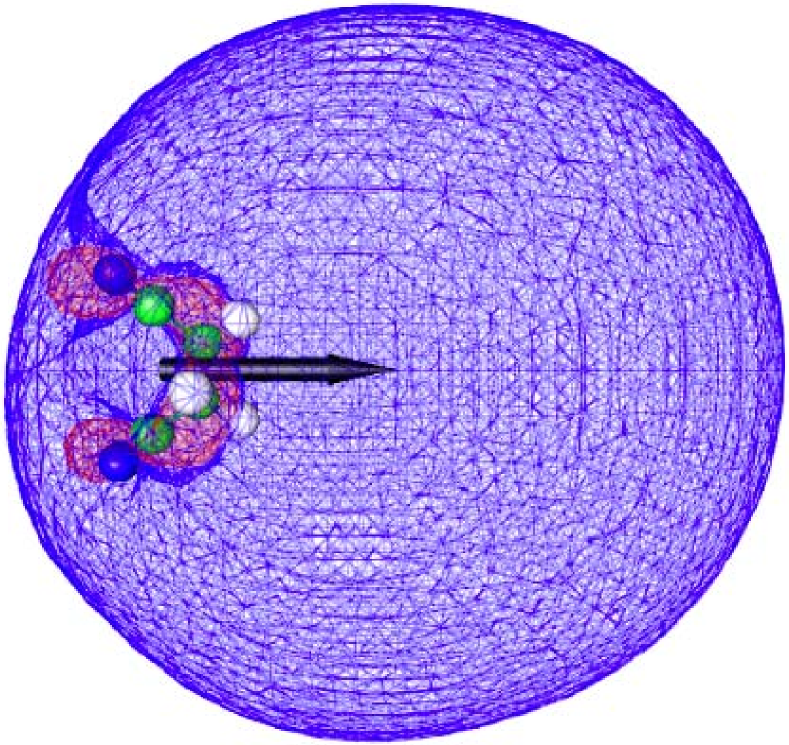




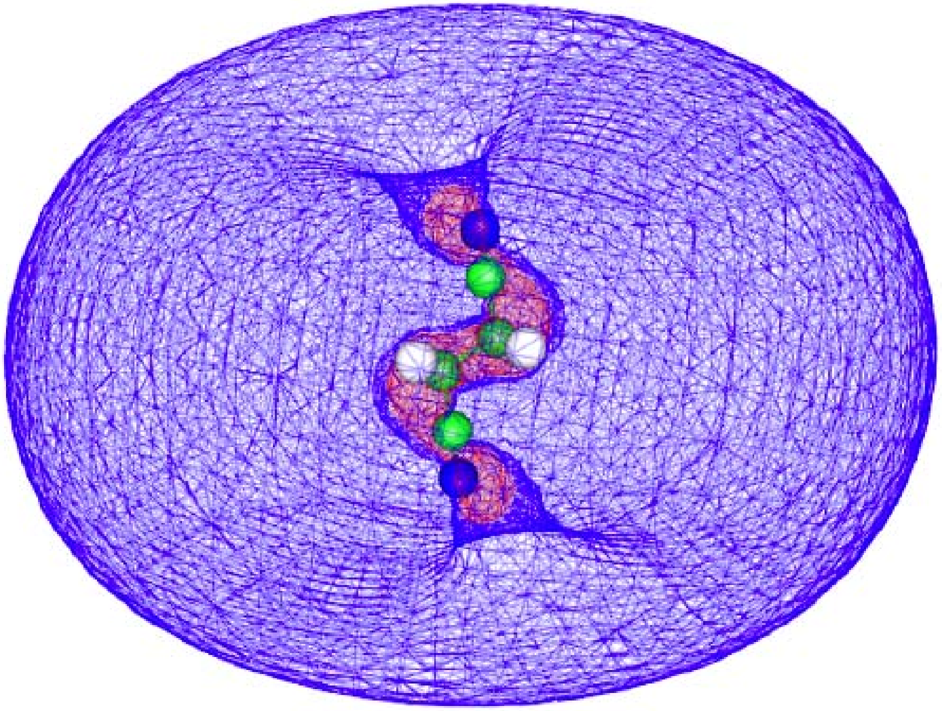
Analogy in moleculear anions

NC-CH_2-CH_2-NC

Desfrancois et al., PRL92(04)083003



Gauche-succinonitrile:
Dipole-bound anion



Trans-succinonitrile:
Quadrupole bound anion

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