Introduction of CAS & ITP

Chinese Academy of Sciences (CAS)

- Independent of Ministry of Education, but award degrees
- >100 institutes in China; ~50 in Beijing

Institute of Theoretical Physics (ITP)

- Smallest institute in CAS; founded in 1978
- ~35 permanent staffs; ~20 postdocs; ~100 students
- Atomic, nuclear, particle, cosmology, condensed matter, biophysics, statistics, quantum physics & quantum information

- Kavli Institute for Theoretical Physics China: running programs

Theoretical Nuclear Physics Group

- En-Guang Zhao, SGZ, 1 postdoc fellow, 4 students
- Heavy-ion reactions & synthesis mechanism of superheavy nuclei
- Structure of exotic nuclei & superheavy nuclei

Neutron halo in deformed nuclei

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Oct. 14-15, 2010, Beihang Univ.

International Symposium on Nuclear Physics in Asia

Outline

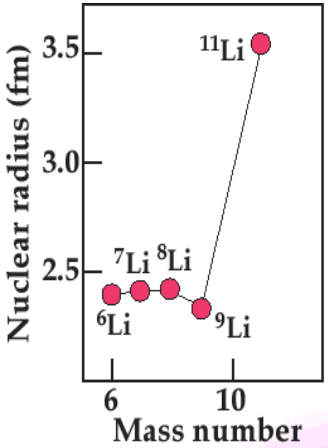
- Introduction

- Relativistic Hartree (Bogoliubov) model for exotic nuclei
  - RMF - a brief introduction
  - 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
  - Decoupling between deformations of core & halo
  - Mechanism of the decoupling

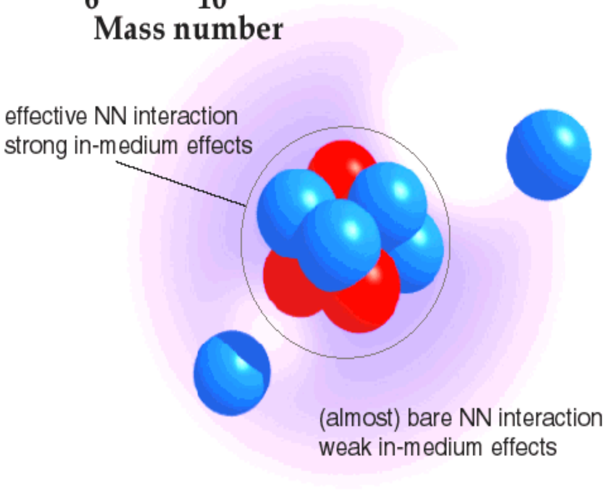
- Summary & perspectives

Halo in spherical nuclei



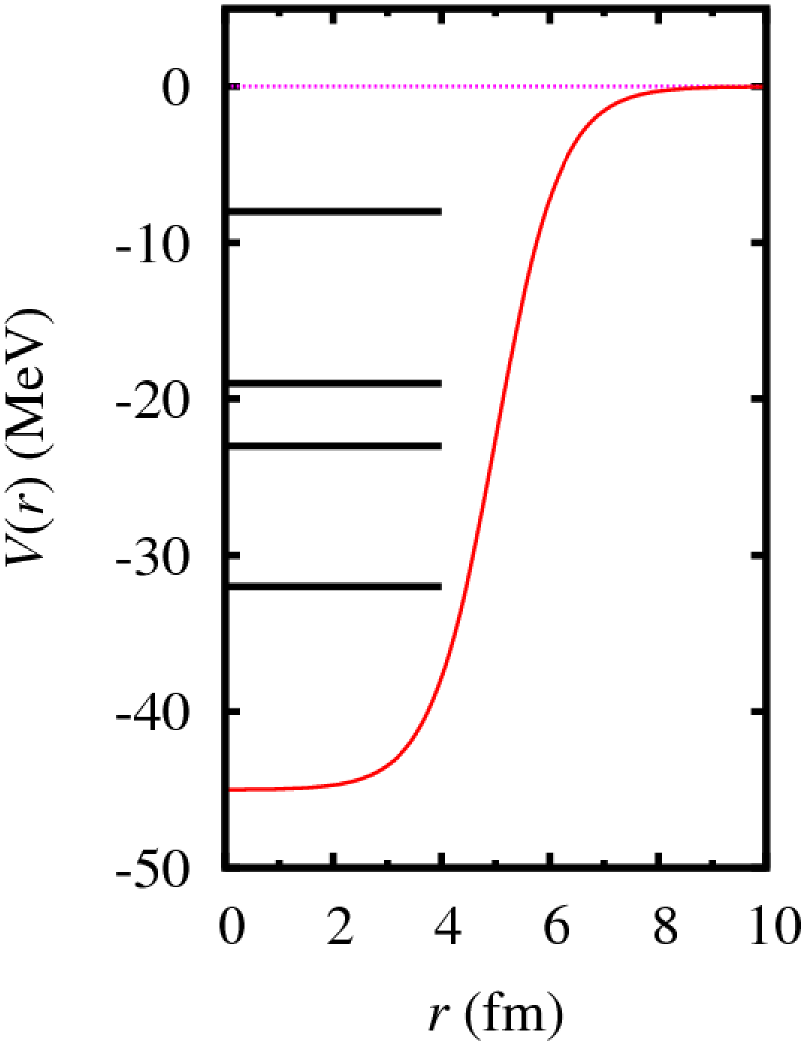
I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

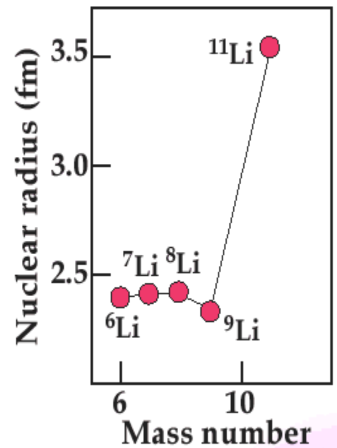
Interaction cross section measurements at Bevalac (790 MeV/u)



Halo in spherical nuclei

SPL in mean field model





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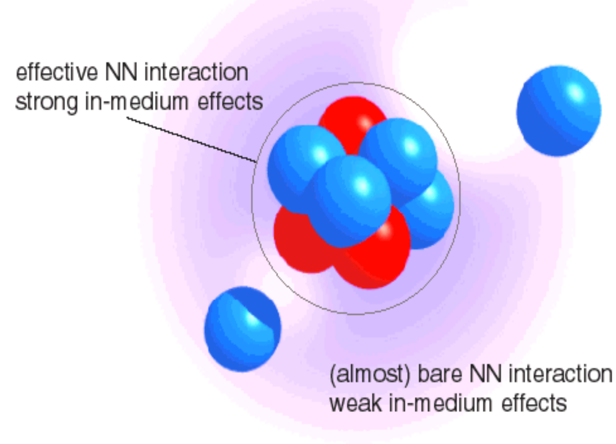

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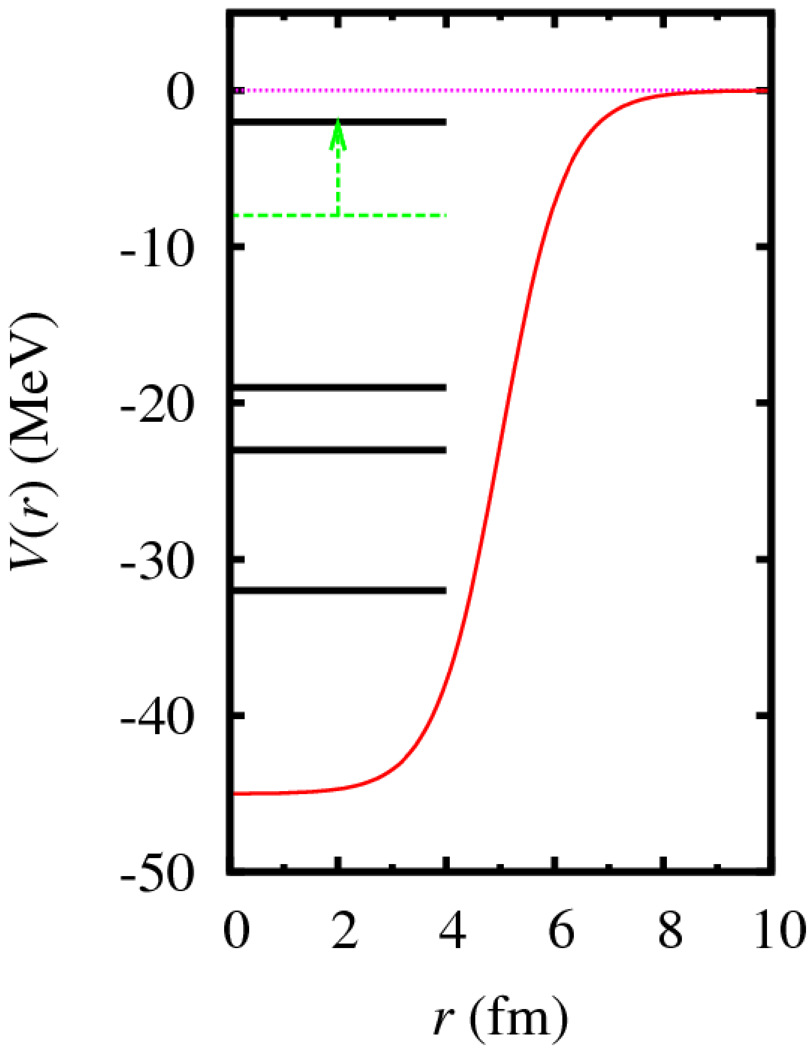

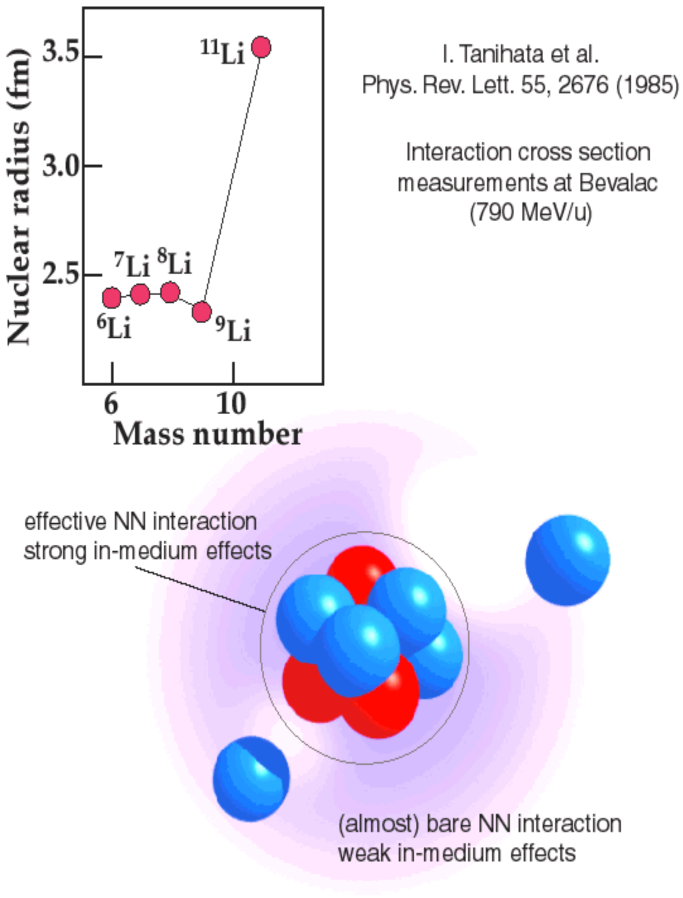

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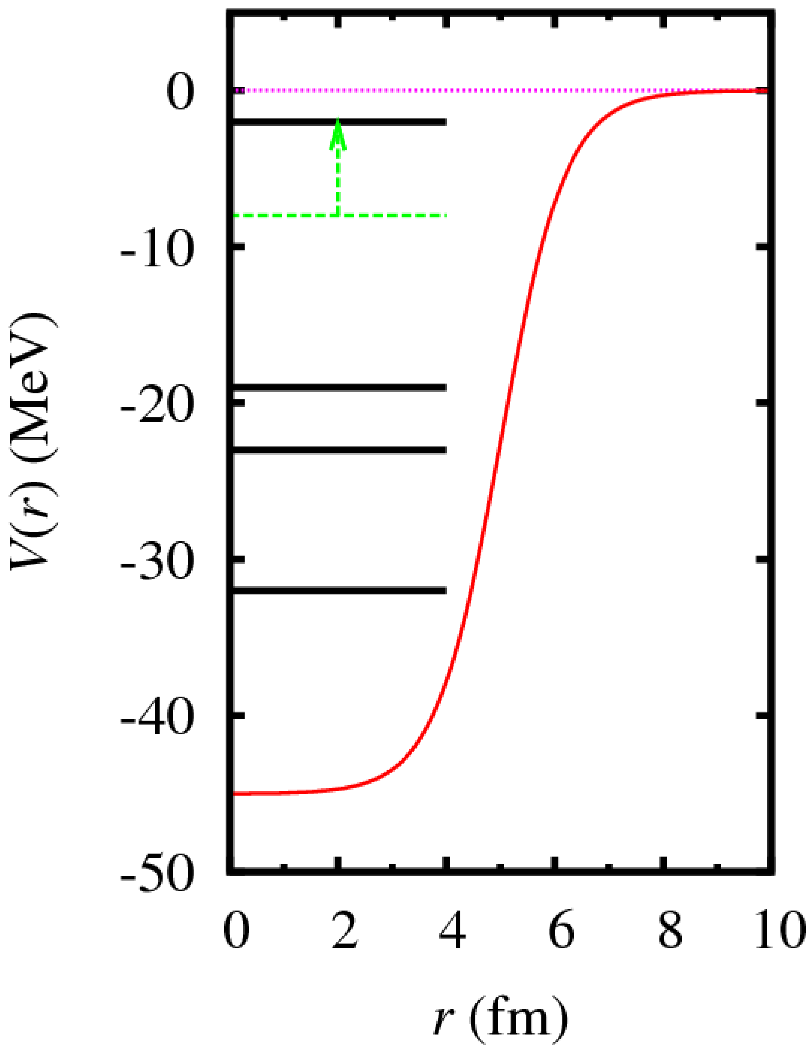
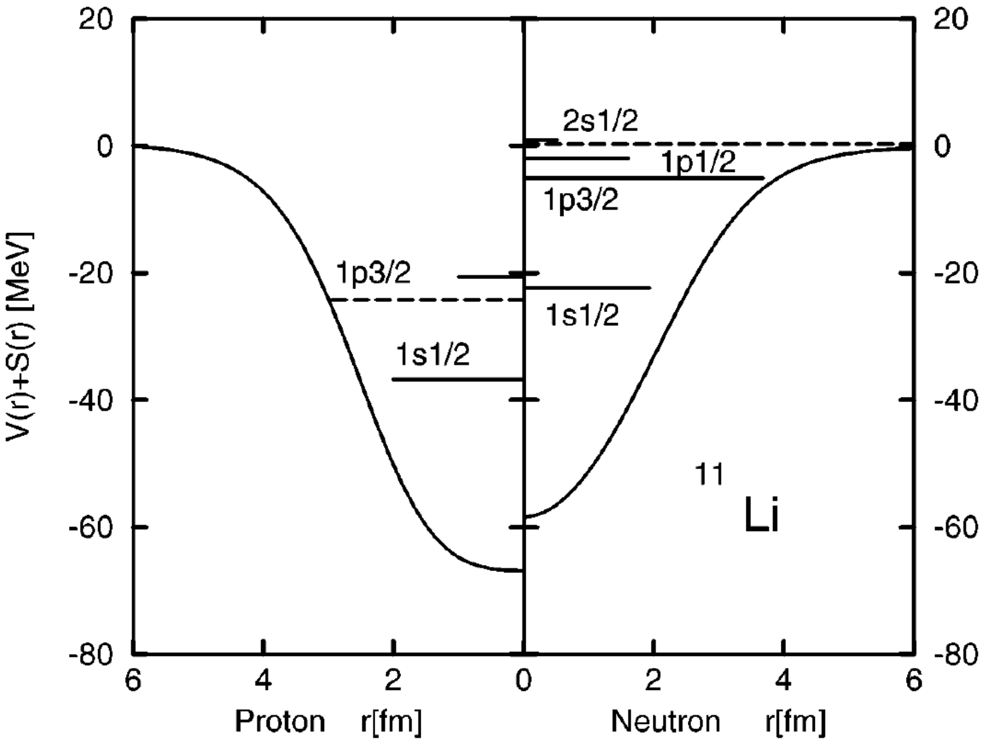
SPL in mean field model





Canonical SPL in self-consistent *r*-space relativistic Hartree-Bogoliubov model

Meng & Ring, PRL77(1996)3963

Halo in deformed nuclei? deformed halo?

Halo in deformed nuclei? deformed halo?

- Deformed single particle model: square well, spin-orbit interaction neglected

  "in the limit of very small binding energy the valence particles in specific orbitals, characterized by a very small Λ, can give rise to the halo structure which is completely decoupled from the rest of the system" Misu, Nazarewicz, Aberg, NPA614(97)44

- Deformed Skyrme Hartree-Fock model: by blocking the first 1/2+ neutron level, a large deformation is found

  "Such a large deformation can result in a good agreement between the calculated and experimental density distributions for the nucleus" Pei, Xu & Stevenson, NPA765(06)29

- …

What we aim at

A self-consistent description of :

- ✓ Deformation
- ✓ Continuum contribution
- ✓ Large spatial distribution
- ✓ Interplay between them

Relativistic mean field model

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

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

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

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

References:

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

Deformed RHB in a Woods-Saxon basis

Kucharek&Ring, ZPA339(91)23

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

SGZ, Meng & Ring, PRC68(03)034323

Axially deformed nuclei

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

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

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

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

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

Parameter set for ph & pp channels

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

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

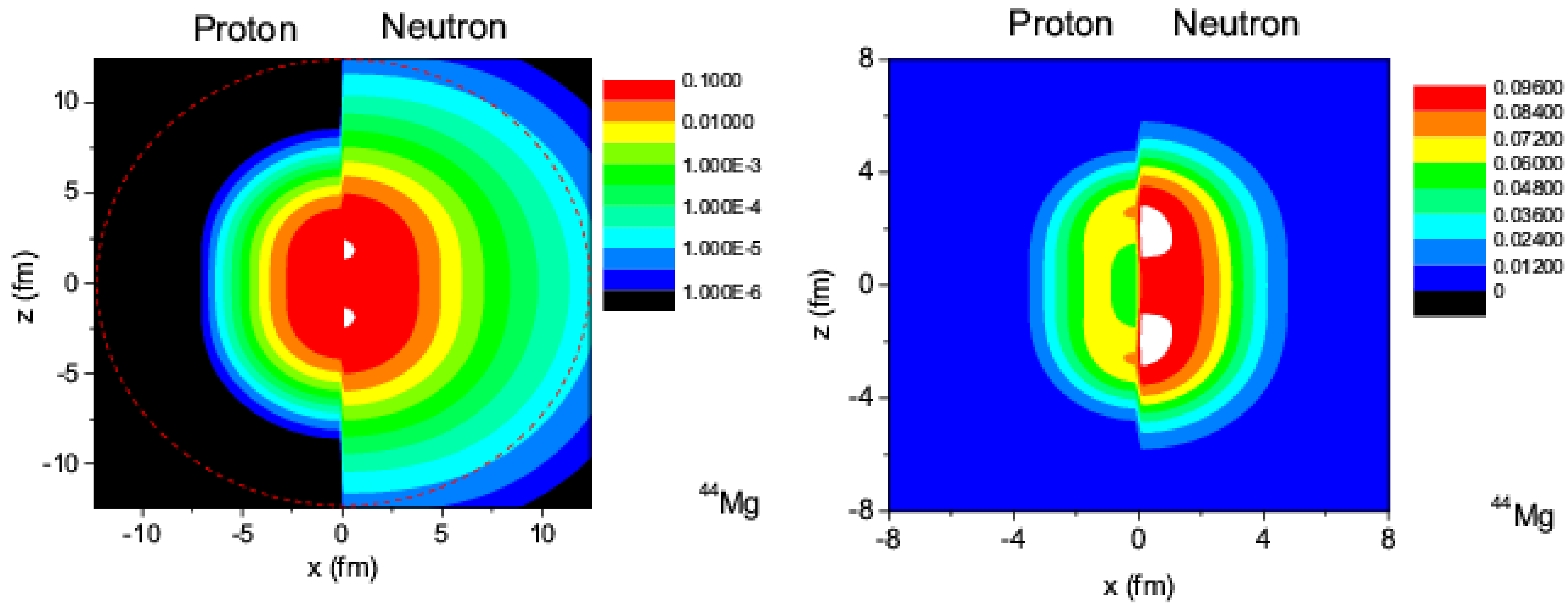
^{20}Mg: spherical from DRHBWS calculation

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

SGZ,Meng,Ring&Zhao, PRC82(10)011301R

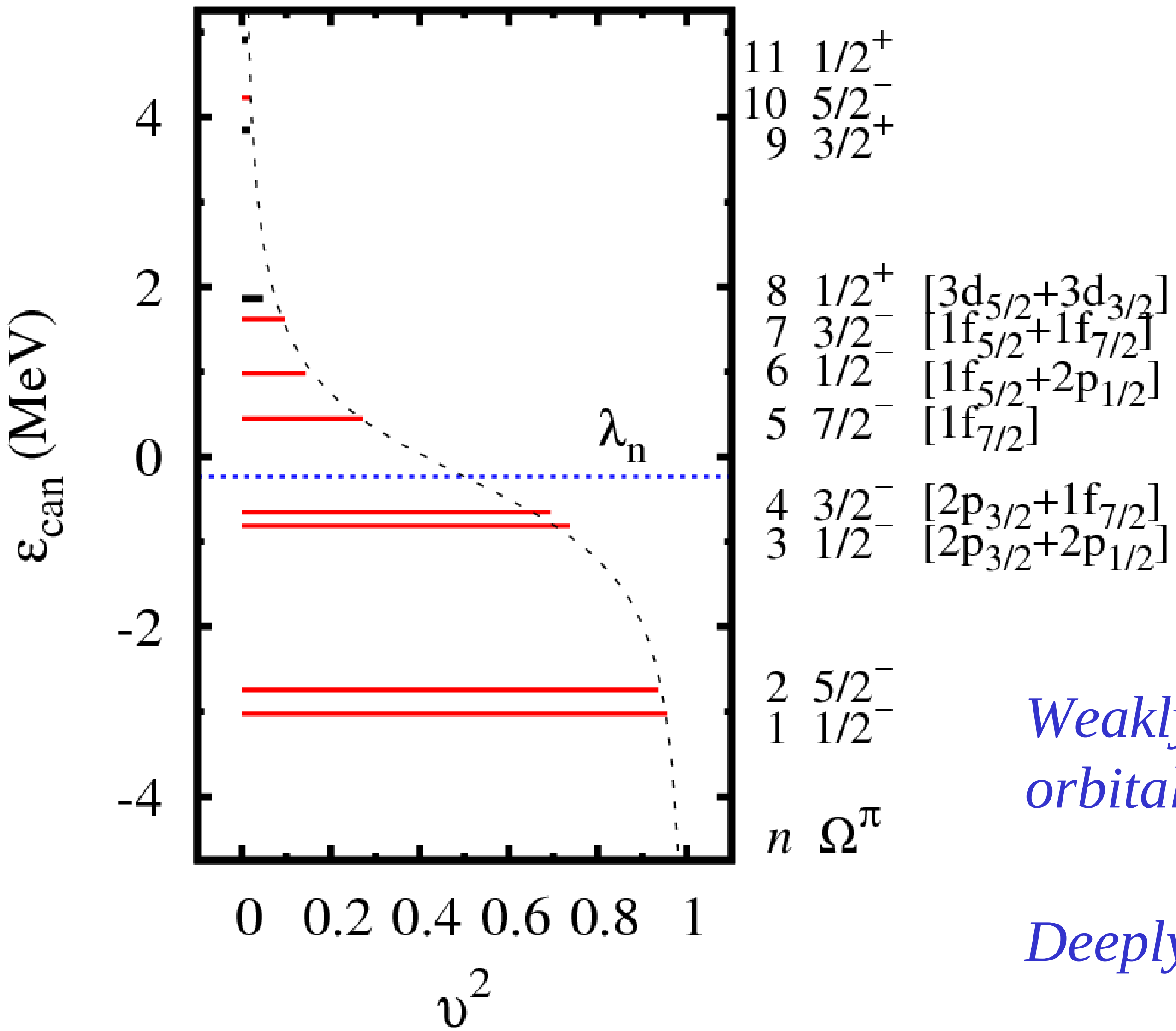
^{44}Mg from DRHBWS

SGZ,Meng,Ring&Zhao, PRC82(10)011301R



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

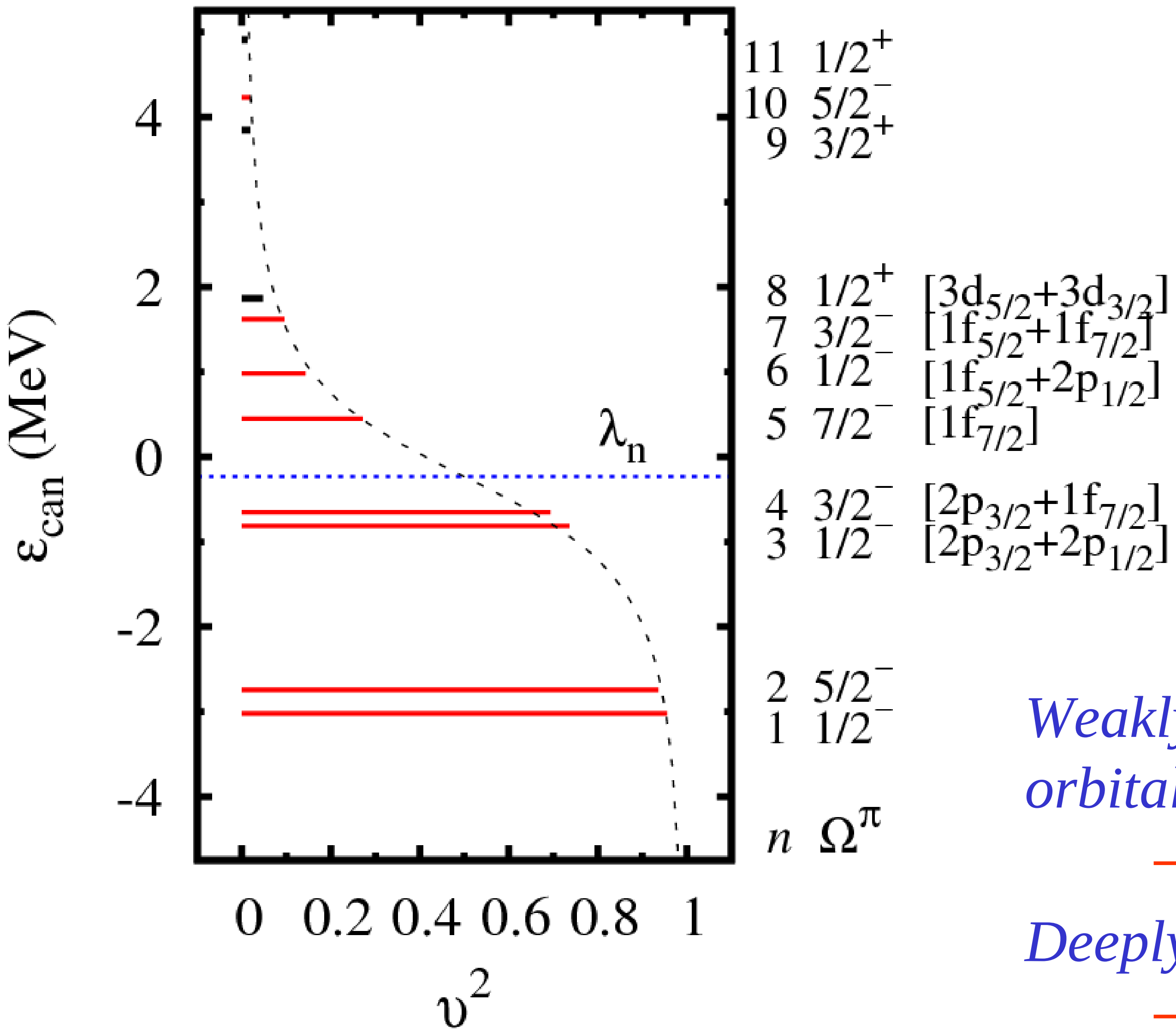
Single neutron states in canonical basis



Weakly bound & continuum orbitals

Deeply bound orbitals

Single neutron states in canonical basis



Weakly bound & continuum orbitals

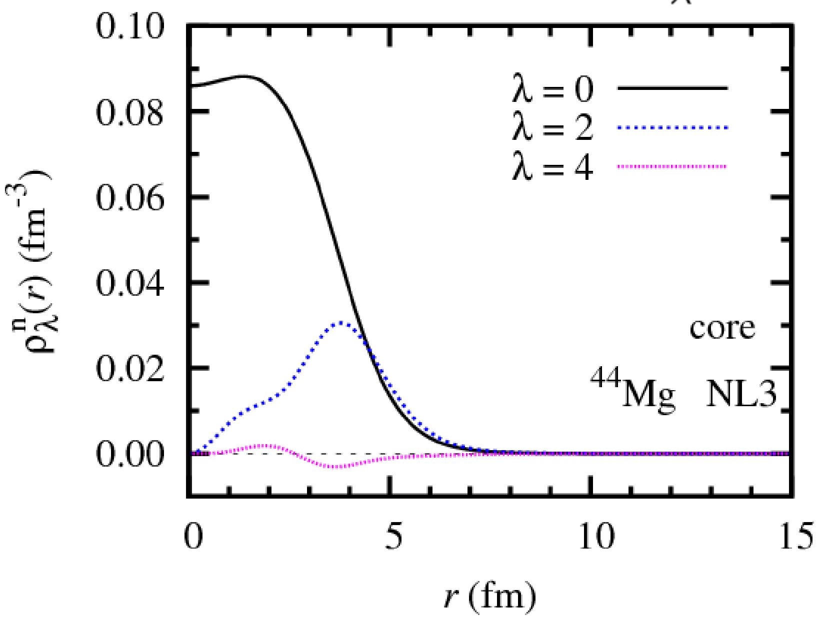
→ halo

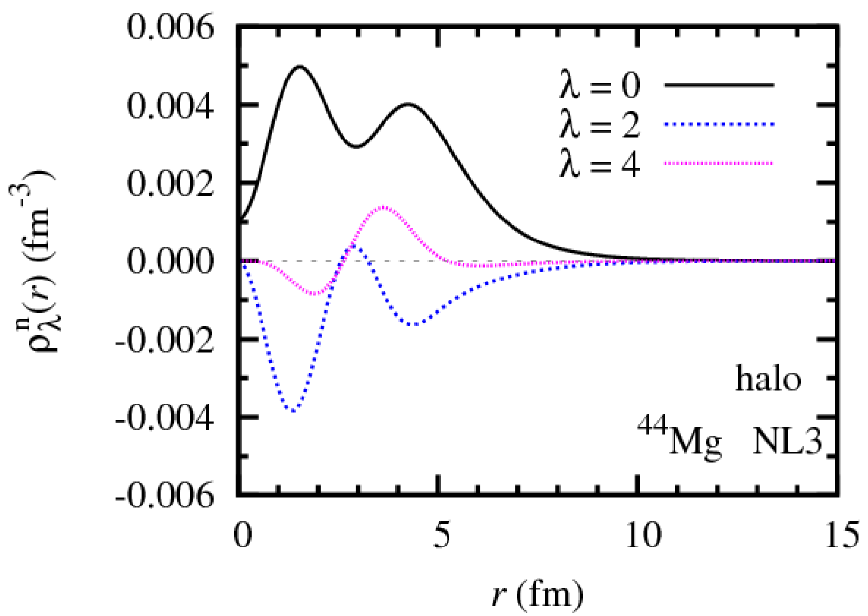
Deeply bound orbitals

→ core

Density of core & halo: shape decoupling

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





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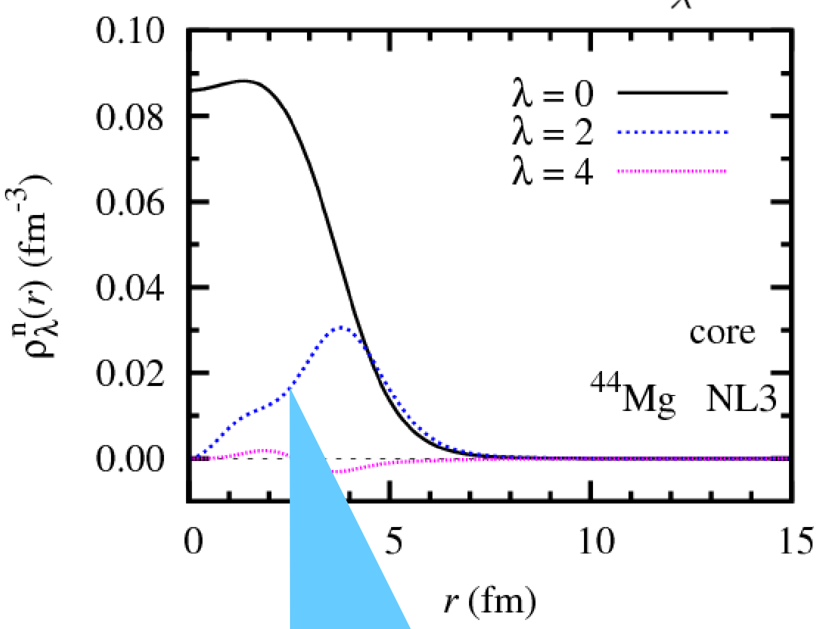

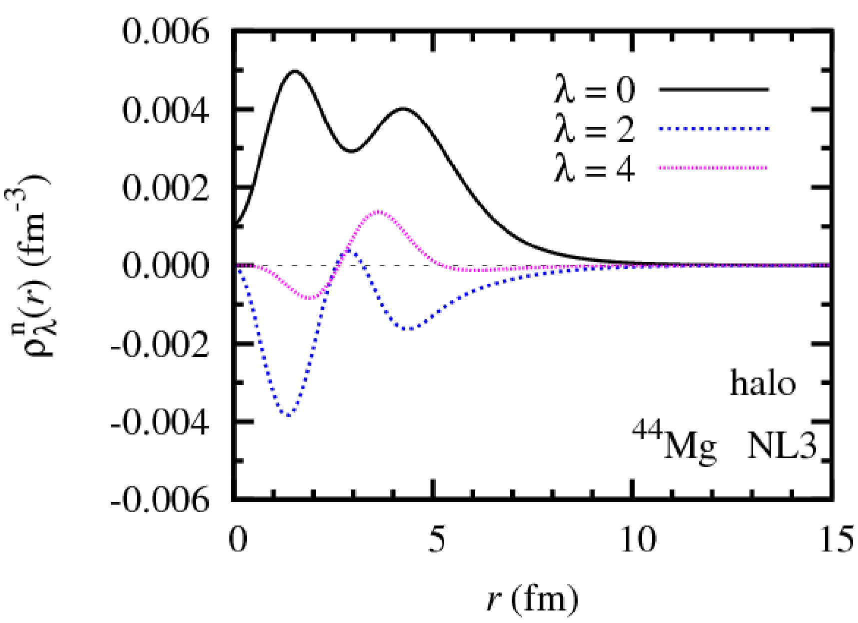

Core: prolate

Density of core & halo: shape decoupling

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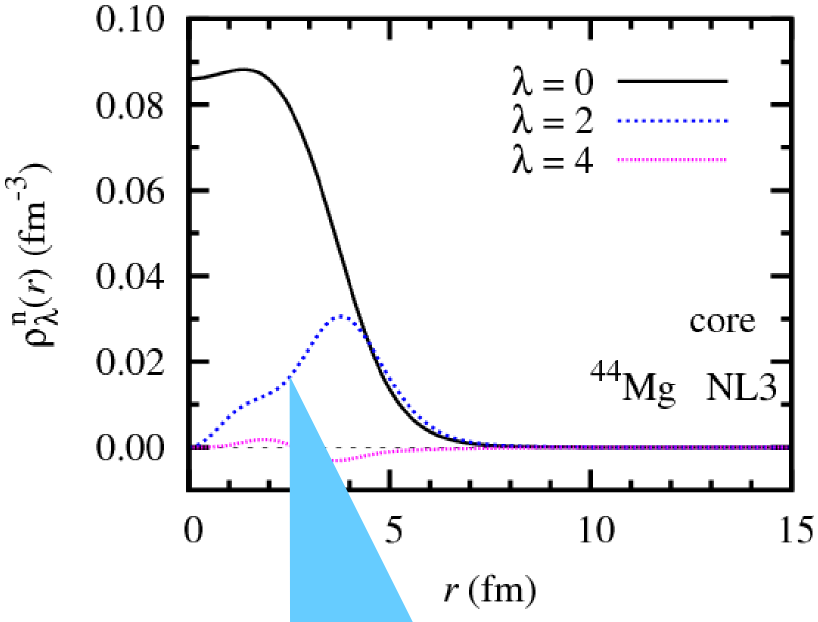

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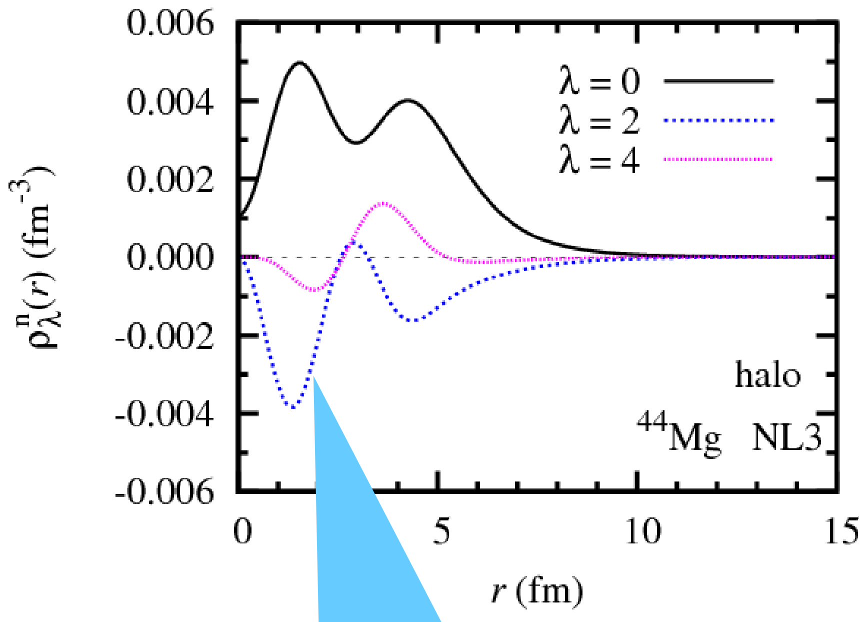
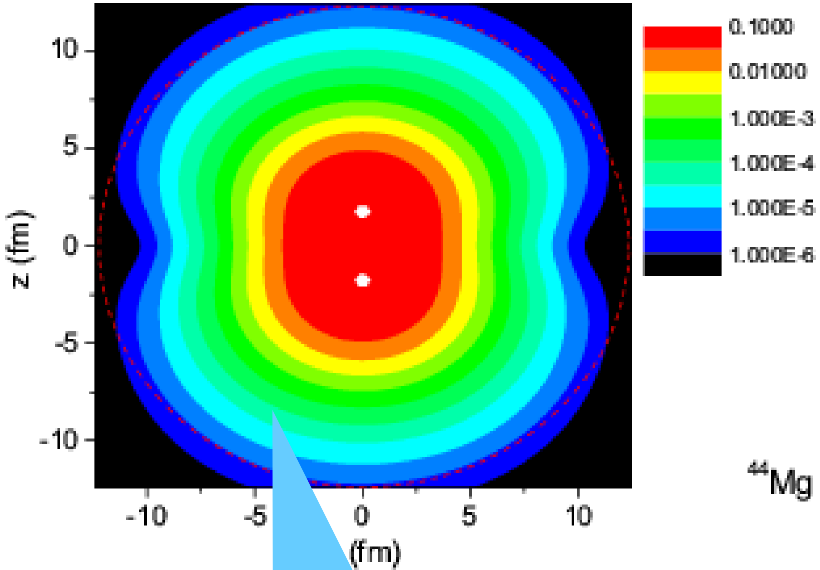


halo: oblate

Density of core & halo: shape decoupling



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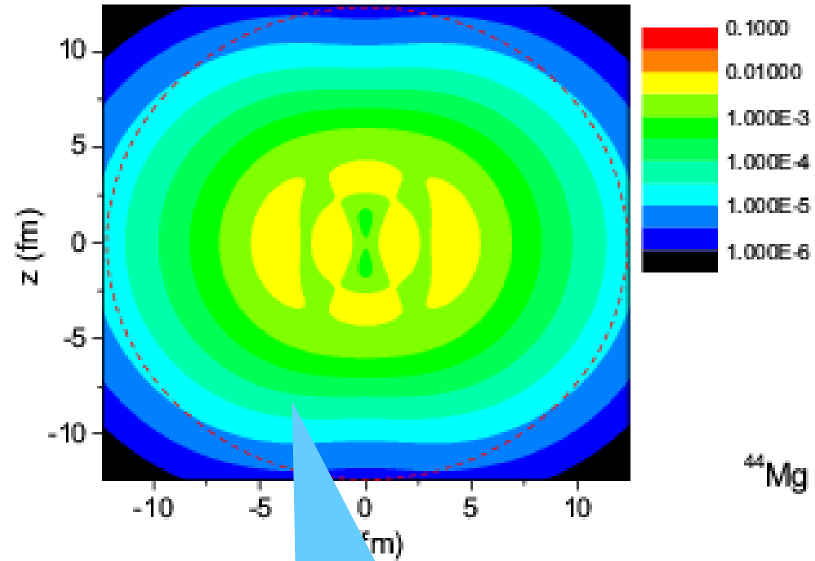
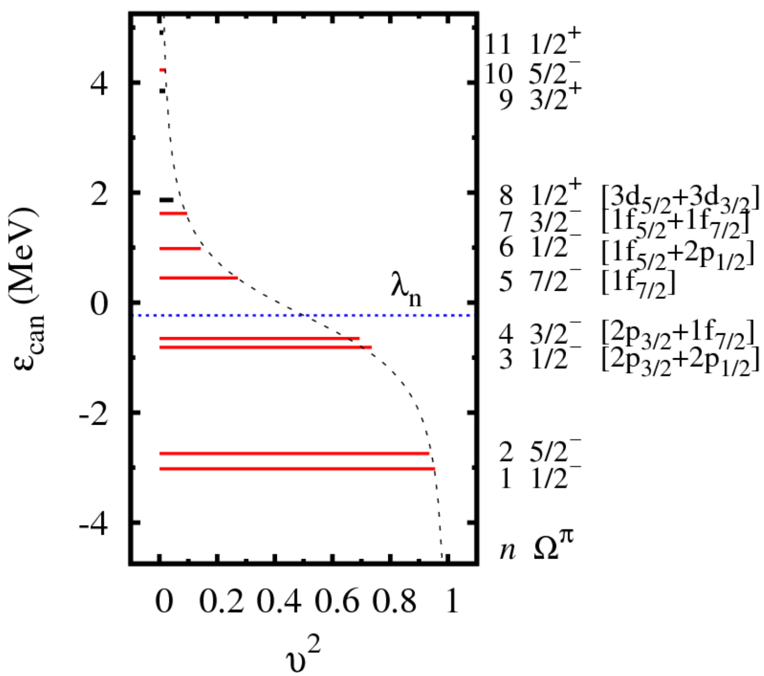
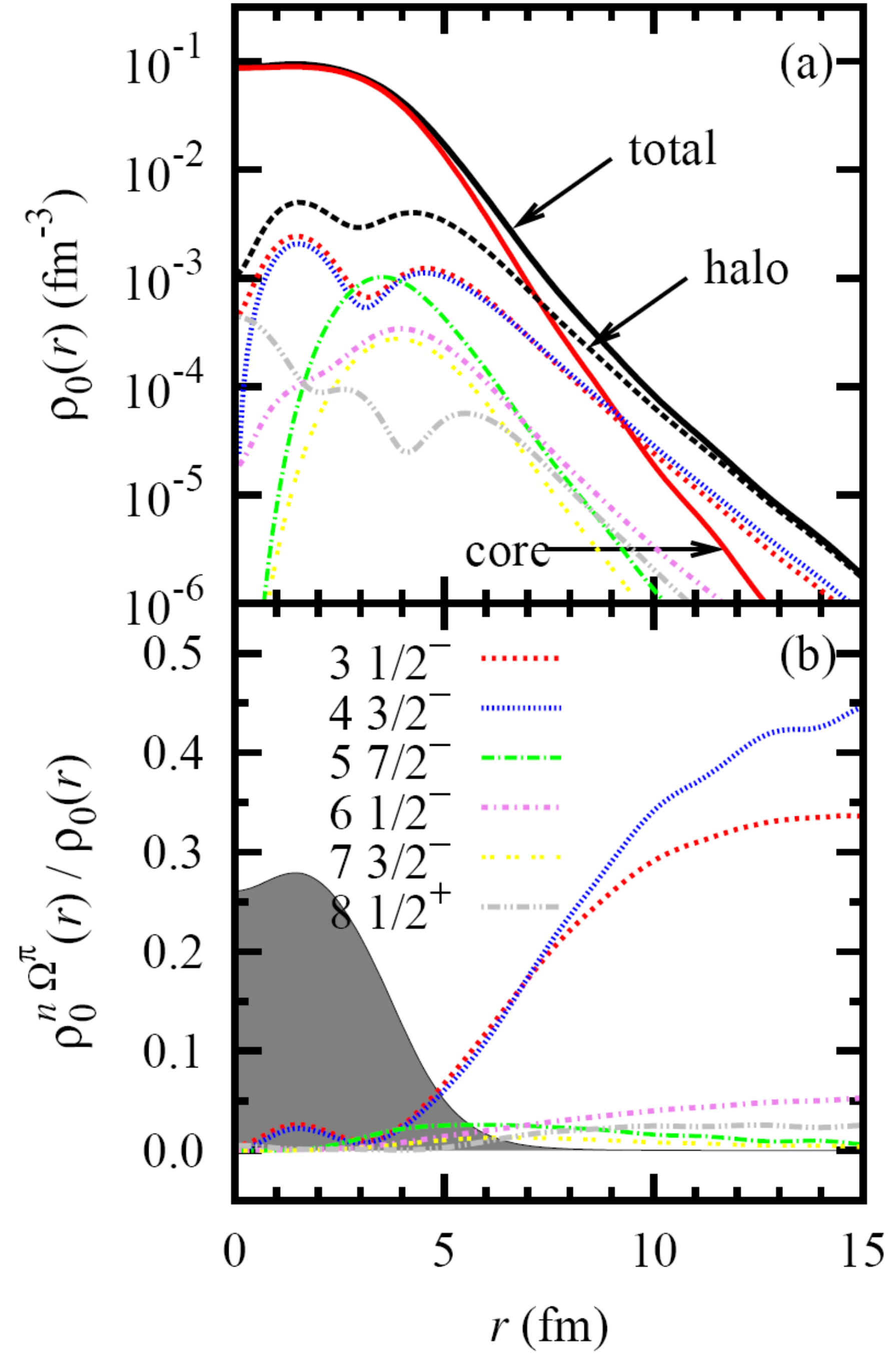


halo: oblate

Decomposition of neut. density distri.

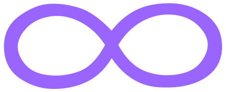
- The 3rd & 4th states contribute to tail part of neutron density distribution
- Main component: $2p_{3/2}$
- $R_{\mathrm{core}} = 3.72$ fm, $R_{\mathrm{halo}} = 5.86$ fm

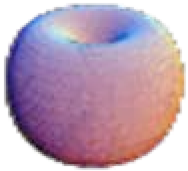




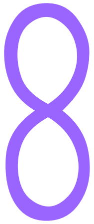
Shape of low-l single particle orbital

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



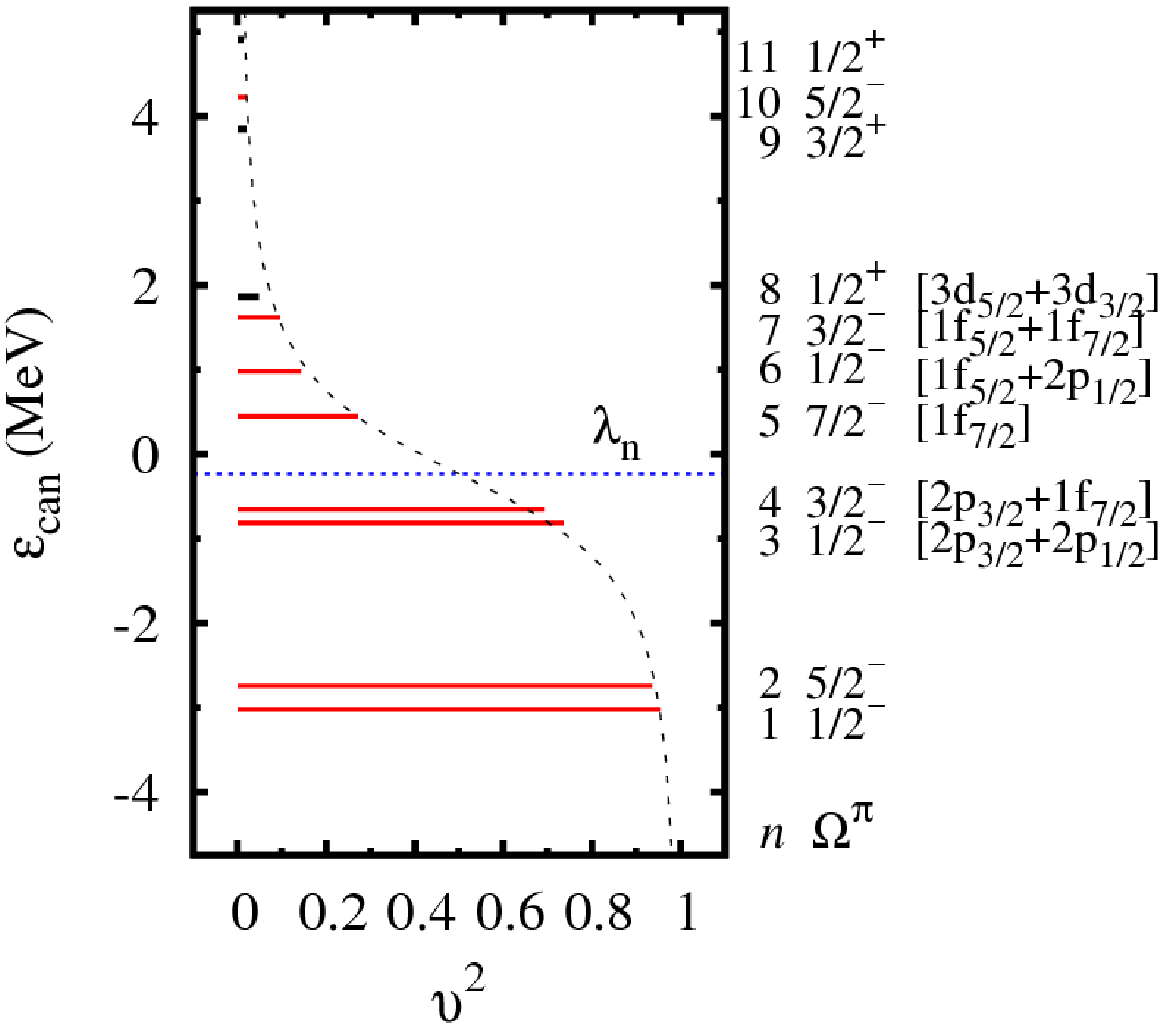


$l = 1, \Lambda = 0$ $|Y_{10}(\theta,\phi)|^2 \propto \cos^2(\theta)$



Misu, Nazarewicz, Aberg, NPA614(97)44

Mechanism of shape decoupling



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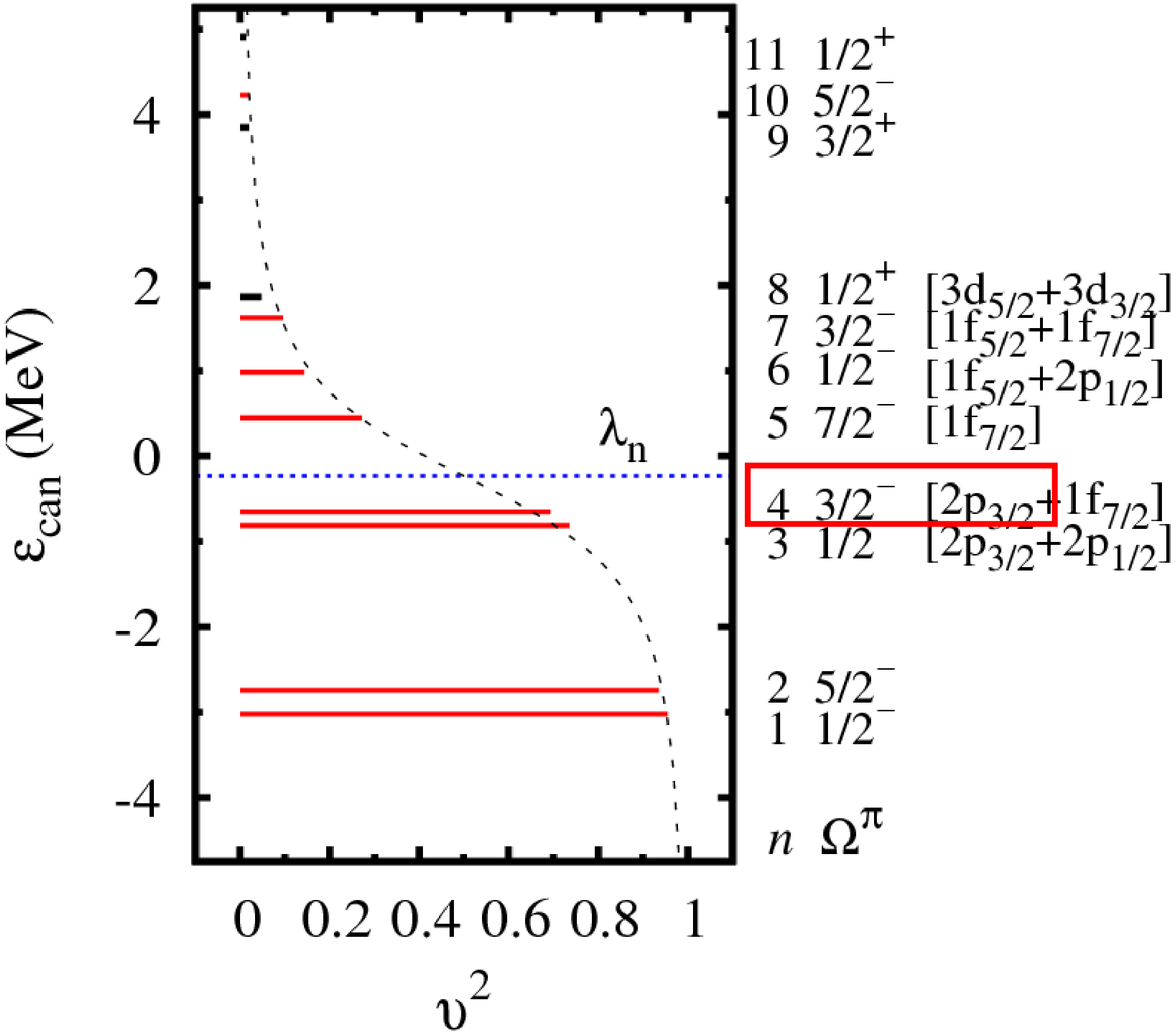
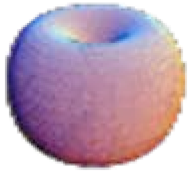


$\Lambda = \pm 1$



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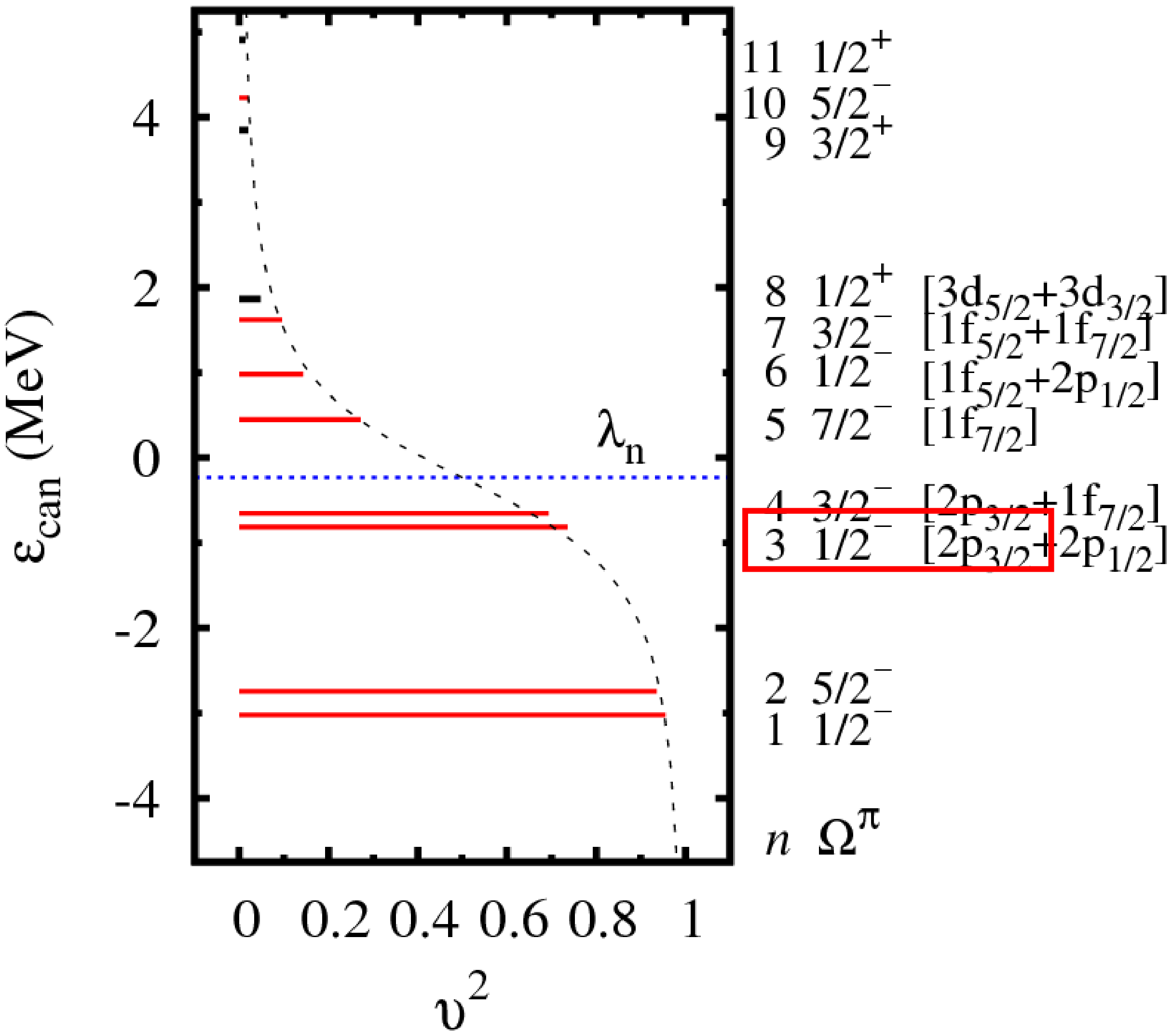
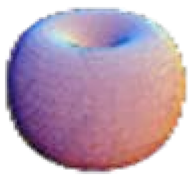


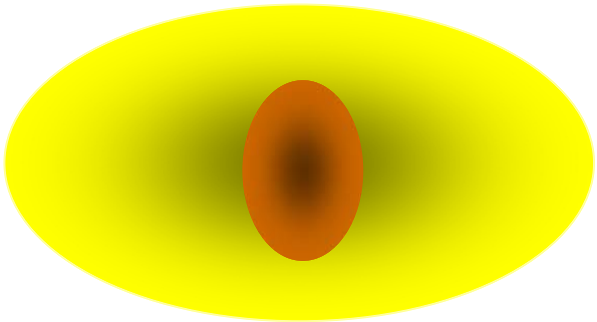
$\Lambda = \pm 1$

$\Lambda = 0$



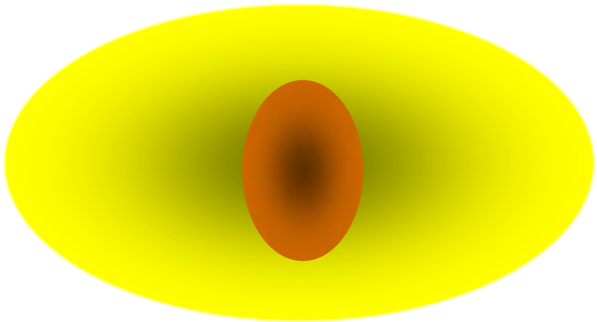
How to probe the decoupling?

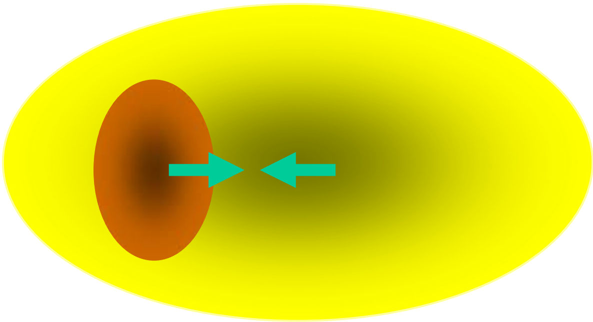
- Larger cross section
- Narrower momentum distribution
  - Double-hump ! ?

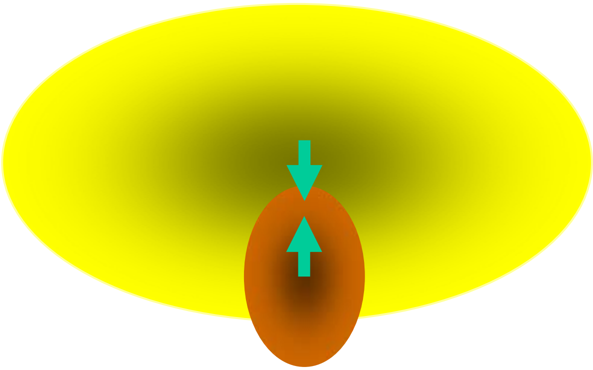


How to measure?

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







Summary & perspectives

- Is there a halo in deformed nuclei or a deformed halo?

- A deformed relativistic Hartree-Bogoliubov model in a Woods-Saxon basis which describes self-consistently
  - Deformation; Large spatial distribution
  - Weakly bound & continuum

- In deformed nuclei close to neutron drip line
  - Halo may occur, depending on intrinsic properties of orbitals around the Fermi level
  - There might be shape decoupling between core and halo

- How to observe?
  - Momentum distribution
  - Soft dipole modes

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