

Deformation and clusterization in multi- Λ hypernuclei within RMF approach

arXiv:1812.07713 [nucl-th], submitted to PRC

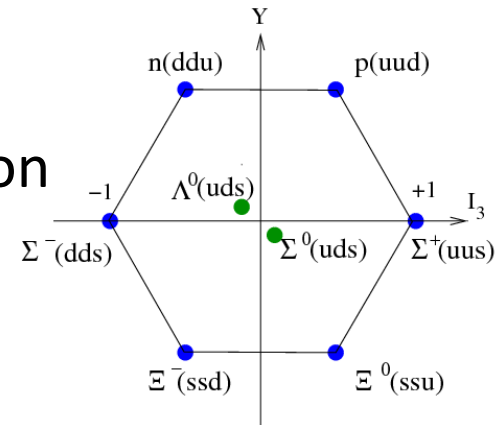
Yusuke Tanimura (Tohoku University)



Tsukuba-CCS workshop on “microscopic theories of nuclear structure and dynamics”,
10-12 Dec. 2018, Tsukuba University

Hypernuclear physics

- Nuclei with hyperon(s) Λ , Σ , Ξ ...
 - ✓ Unified understanding of B-B interaction
 - ✓ Dense matter in neutron star
 - ✓ Hyperons as unique probe of nuclear structure



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 - ✓ A unique probe of nuclear structure

- **Impurity effects of (a few) Λ hyperon**

- ✓ Shrinkage of inter-cluster distance

Hiyama et al., PRC**59**, 2351 (1999).

- ✓ Reduction/disappearance of deformation

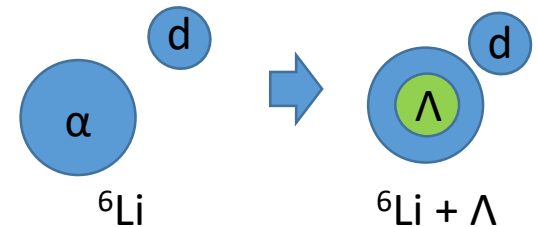
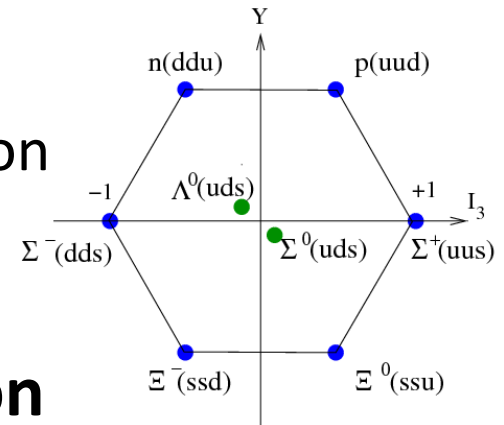
- ✓ Extension of drip lines

- ✓ Fission barrier

Minato and Chiba, NPA**856**, 55 ('11)

- ✓ New collective modes

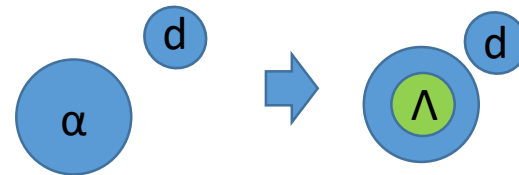
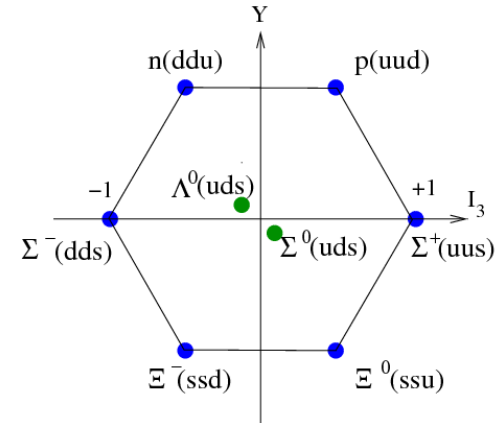
Minato and Hagino, PRC**85**, 024316 ('11)



~ 20 % reduction of $\alpha - d$ distance
 K. Tanida, et al., PRL**86**, 1982('01)
 Hiyama et al., PRC**59**, 2351 ('99).

Hypernuclear physics

- Nuclei with hyperon(s) $\Lambda, \Sigma, \Xi \dots$
 - ✓ Unified understanding of B-B interaction
 - ✓ Dense matter in neutron star
 - ✓ A unique probe of nuclear structure
- **Impurity effects of (a few) Λ hyperon**
 - ✓ Shrinkage of inter-cluster distance
 - ✓ Reduction/disappearance of deformation
 - ✓ Extension of drip lines
 - ✓ Fission barrier
 - ✓ New collective modes
- **Multi- Λ nuclei: Λ as a 3rd constituent of nuclear many-body system**
 - ✓ Structure?
 - ✓ Collective motions?



Multi- Λ hypernuclei: experiments

- (ground-state) binding energies have been measured for a few systems: ${}_{2\Lambda}^6\text{He}$ ($={}^4\text{He}+2\Lambda$), ${}_{2\Lambda}^{10}\text{Be}$ ($={}^8\text{Be}+2\Lambda$), etc.

Nakazawa et al., NPA835, 207 (2010)

- More data are expected from the ongoing analysis of experiment E07 at J-PARC

https://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p07-Nakazawa.pdf

✓ Hyperon-hyperon interaction

✓ Step towards **multi- Λ system**

- Multi- Λ nuclei ($N_\Lambda > 2$) expected at future experiments at GSI and HIAF (China)

Saito et al., NPA835, 110 ('10)

Multi- Λ hypernuclei: theory

($N_\Lambda > 2$)

- Hyperon halo

Rufa et al., PRC**42**, 2469 ('90); Lü and Meng, Chin. Phys. Lett. **19**, 1775 ('02)

- Binding-energy systematics

Khan, Margueron, Gulminelli, and Raduta, PRC**92**, 044313 ('15)

- $\Lambda\Lambda$ pairing correlation

Güven, Bozkurt, Khan, and Margueron, PRC**98**, 014318 ('18)

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- Limited to spherical systems

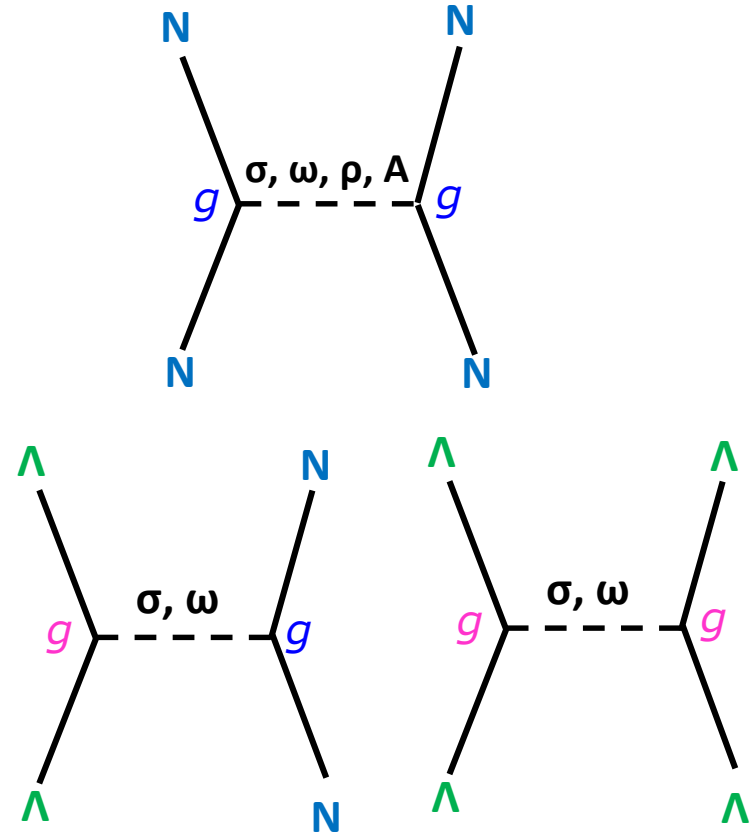
→ deformation/clusterization in multi- Λ nuclei

Model Lagrangian

$$\begin{aligned}
 \mathcal{L} = & \bar{\psi}_N (i\partial - m_N) \psi_N + \bar{\psi}_\Lambda (i\partial - m_\Lambda) \psi_\Lambda \\
 & + \frac{1}{2} (\partial_\mu \sigma) (\partial^\mu \sigma) - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{c_3}{3} \sigma^3 - \frac{c_4}{4} \sigma^4 \\
 & - \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{d_4}{4} (\omega^\mu \omega_\mu)^2 \\
 & - \frac{1}{4} \vec{R}^{\mu\nu} \cdot \vec{R}_{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}^\mu \cdot \vec{\rho}_\mu \\
 & - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \\
 & - \bar{\psi}_N \left(g_{\sigma N} \sigma + g_{\omega N} \not{\omega} + g_{\rho N} \vec{\rho} \cdot \vec{\tau} + e A \frac{1 - \tau_3}{2} \right) \psi_N \\
 & - \bar{\psi}_\Lambda \left(g_{\sigma \Lambda} \sigma + g_{\omega \Lambda} \not{\omega} + \frac{f_{\omega \Lambda}}{4 m_\Lambda} G_{\mu\nu} \sigma^{\mu\nu} \right) \psi_\Lambda
 \end{aligned}$$

Nucleon sector: PK1 Long et al., PRC **69** 034319 ('04)

Hyperon sector: Liu et al., PRC **98**, 024316 ('18)



$$m_\Lambda = 1115.6 \text{ MeV}$$

$$g_{\sigma \Lambda} = 0.618 g_{\sigma N} \rightarrow \text{Fitted to } {}_\Lambda^{40}\text{Ca}$$

$$\left. \begin{aligned} g_{\omega \Lambda} &= (2/3) g_{\omega N} \\ f_{\omega \Lambda} &= -g_{\omega \Lambda} \end{aligned} \right\} \text{Quark model}$$

Cohen and Weber, PRC **44**, 1181 ('91)

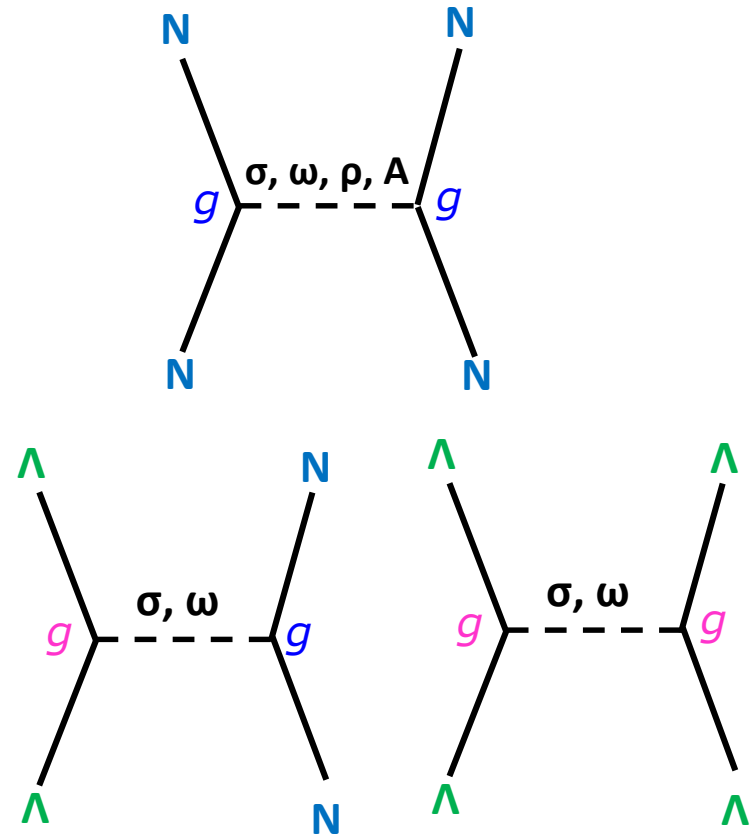
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 \end{aligned}$$

Nucleon sector: PK1 Long et al., PRC **69** 034319 ('04)

Hyperon sector: Liu et al., PRC **98**, 024316 ('18)

Solved on 3D lattice: 24³ points, a = 0.8 fm



$$m_\Lambda = 1115.6 \text{ MeV}$$

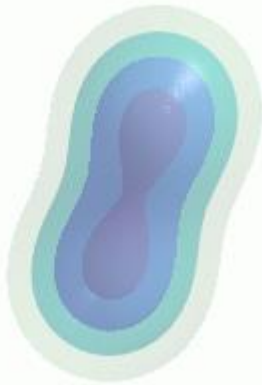
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} Quark model

“Hyper isotopes” to be studied



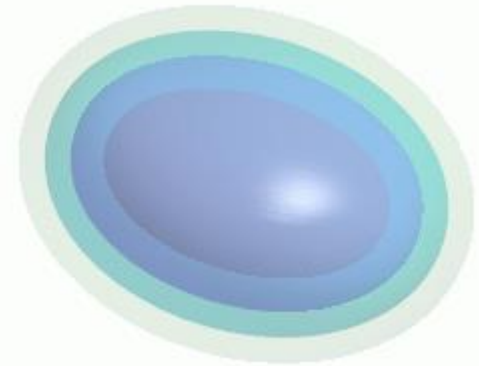
^8Be

$+2\Lambda, +4\Lambda$



^{20}Ne

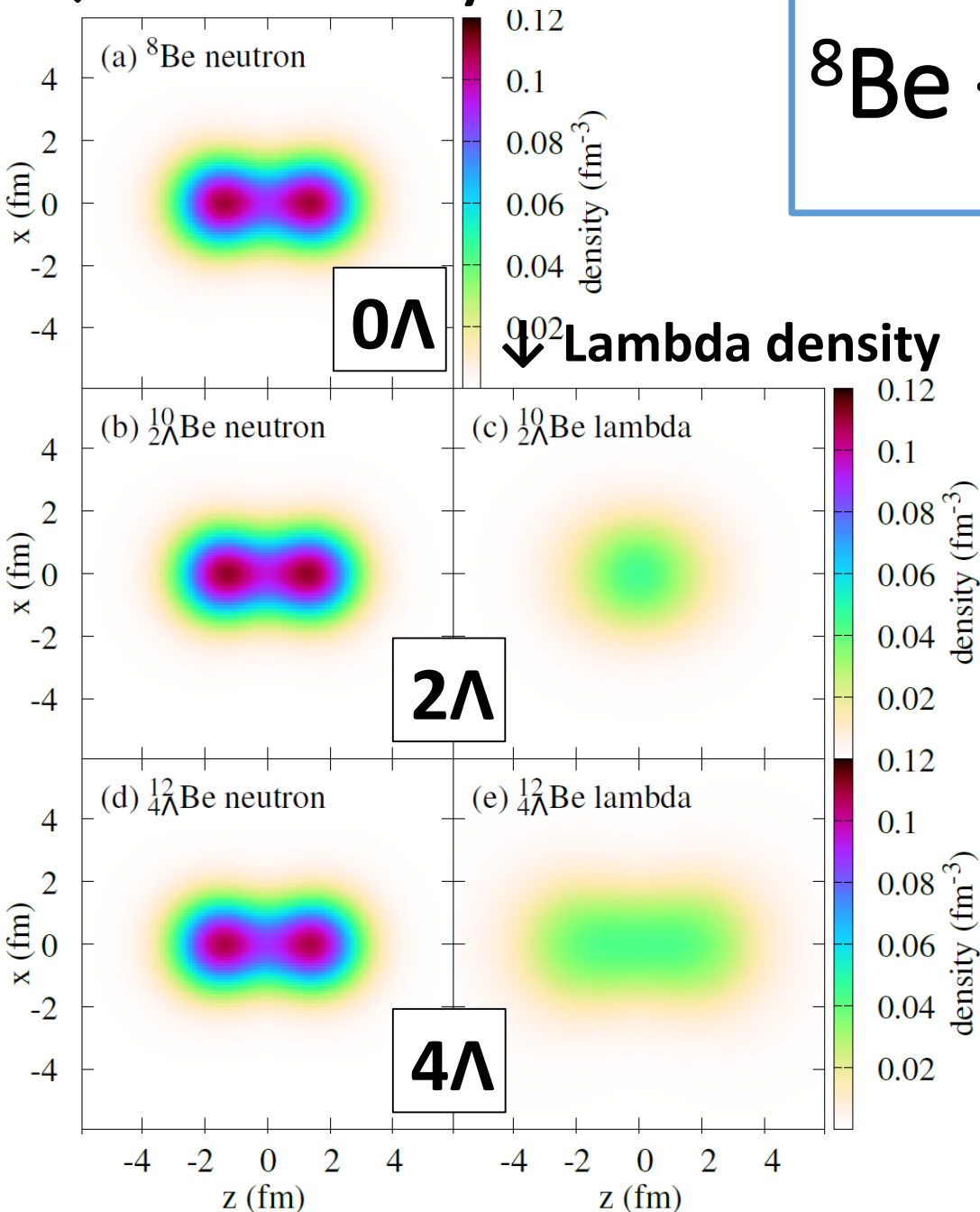
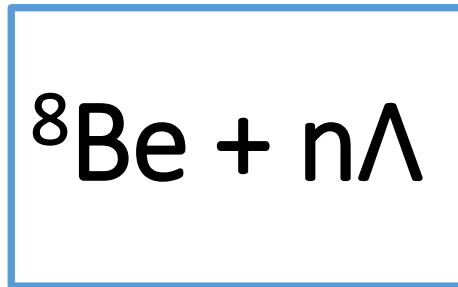
$+2\Lambda, +8\Lambda$



^{28}Si

$+2\Lambda, +8\Lambda$

↓neutron density

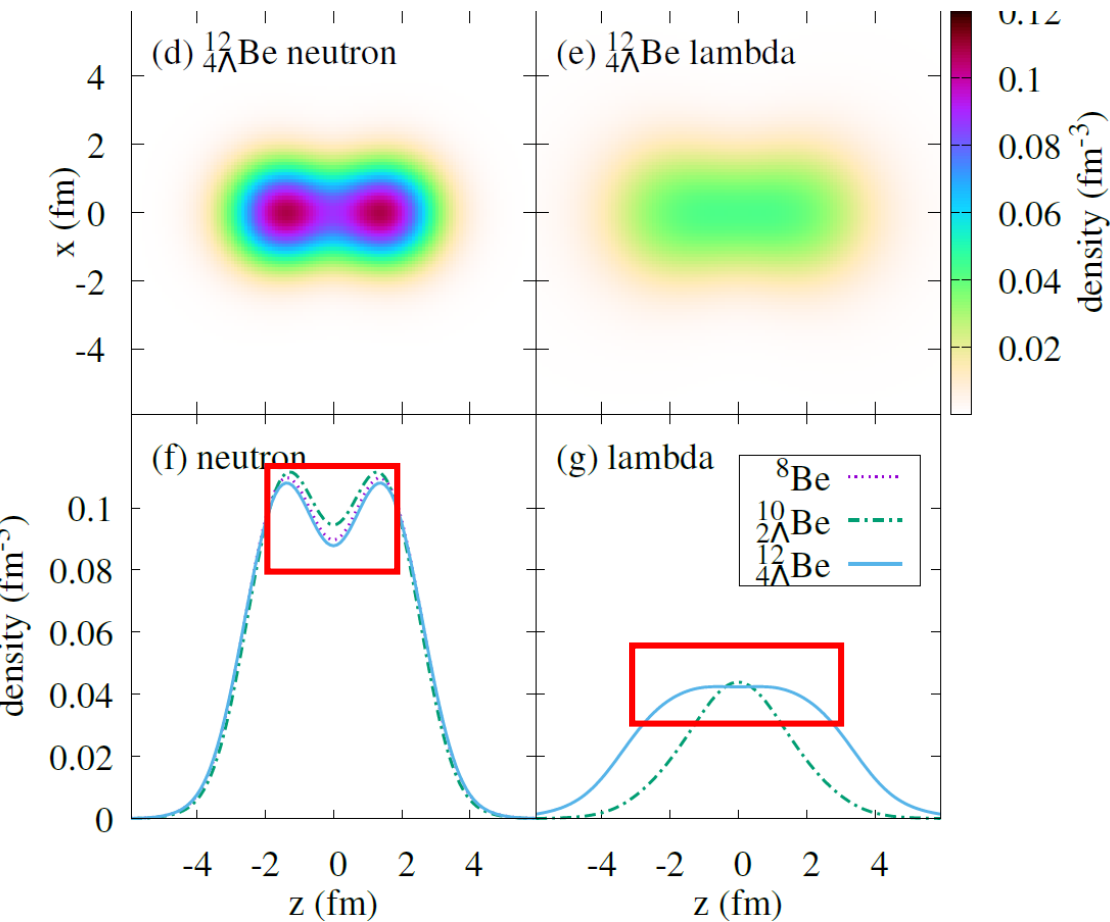


- 2 α clusters
- 2 Λ : α - α distance shrinks
- 4 Λ : α - α distance recovered

$$\beta_2 \equiv \frac{4\pi}{3} \frac{\int d^3r r^2 Y_{20} \rho}{\int d^3r r^2 \rho} \quad R \equiv \frac{\int d^3r r^2 \rho}{\int d^3r \rho}$$

N_Λ	β_{2N}	$\beta_{2\Lambda}$	R_N (fm)	R_Λ (fm)
Be hyper isotopes				
0	1.12	—	2.43	—
2	1.06	0.30	2.36	2.59
4	1.13	0.95	2.42	3.49

Cluster structure in ${}^8\text{Be} + 4\Lambda$?



Two ${}_{2\Lambda}{}^6\text{He}$ clusters?

→ not clear in the one-body densities

- ρ_n : neck at the middle
($\leftarrow 2\alpha$ clusters)
- ρ_Λ : flat at the middle

Λ 's are not so tightly bound to α as nucleons are

Cluster structure in ${}^8\text{Be} + 4\Lambda$?

Localization function for a fermion kind q with spin σ

Becke and Edgecombe, J. Chem. Phys. 92, 5397('90); Reinhard et al., PRC **83**, 034312 ('11);

Schuetrumpf and Nazarewicz,, PRC **96**, 064608 ('17); Ebran, Khan, and Nikšić, J. Phys. G **44** 103001 ('17).

$$C_{q\sigma}(\mathbf{r}) = \left[1 + \left(\frac{\rho_{q\sigma}\tau_{q\sigma} - j_{\sigma}^2 - \frac{1}{4}(\nabla\rho_{q\sigma})^2}{\rho_{q\sigma}\tau_{q\sigma}^{\text{TF}}} \right)^2 \right]^{-1}$$

Two-body correlation

$C_{q\sigma} \approx 1$: Particle $q\sigma$ is isolated (Unlikely that another particle is nearby)

$C_{q\sigma} \approx 1/2$: Uniform Fermi gas

α cluster $\rightarrow C_{q\sigma} \approx 1$ for $(q\sigma) = n\uparrow, n\downarrow, p\uparrow, p\downarrow$

${}_{2\Lambda}^6\text{He}$ cluster $\rightarrow C_{q\sigma} \approx 1$ for $(q\sigma) = n\uparrow, n\downarrow, p\uparrow, p\downarrow, \Lambda\uparrow, \Lambda\downarrow$

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$$C_{n\uparrow} = C_{n\downarrow} \approx C_{p\uparrow} = C_{p\downarrow} \text{ and } C_{\Lambda\uparrow} = C_{\Lambda\downarrow}$$

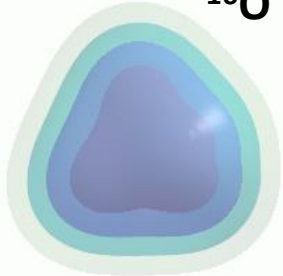
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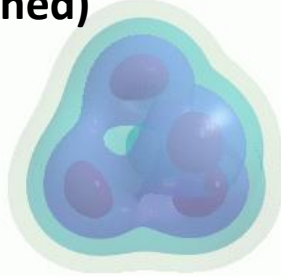
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^{16}O (constrained)



$\rho_{n\uparrow}$

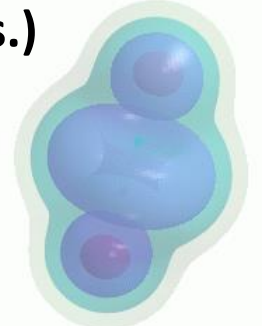


$$\bar{C}_{n\uparrow}(\mathbf{r}) = C_{n\uparrow}(\mathbf{r}) \frac{\rho_{n\uparrow}(\mathbf{r})}{\max \rho_{n\uparrow}(\mathbf{r})}$$

^{20}Ne (g.s.)



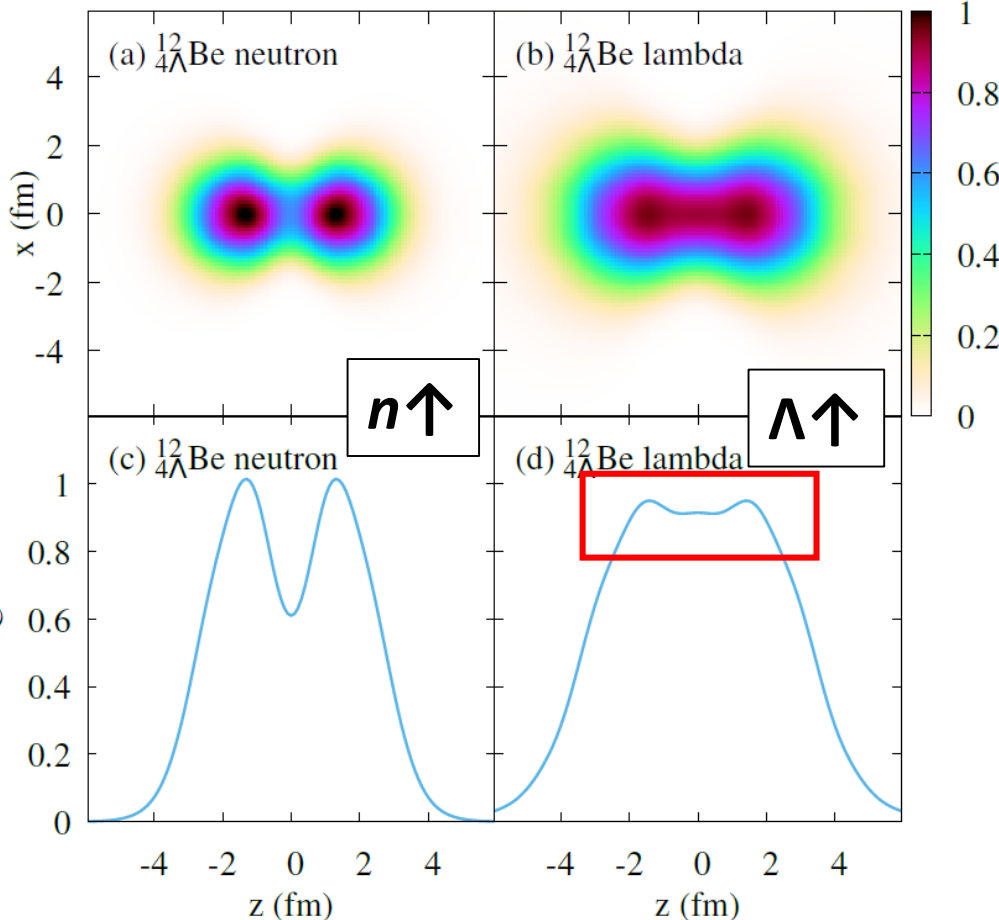
$\rho_{n\uparrow}$



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Cluster structure in ${}^8\text{Be} + 4\Lambda$?

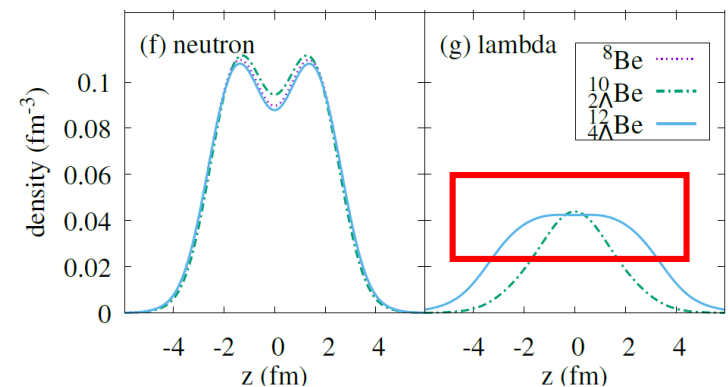
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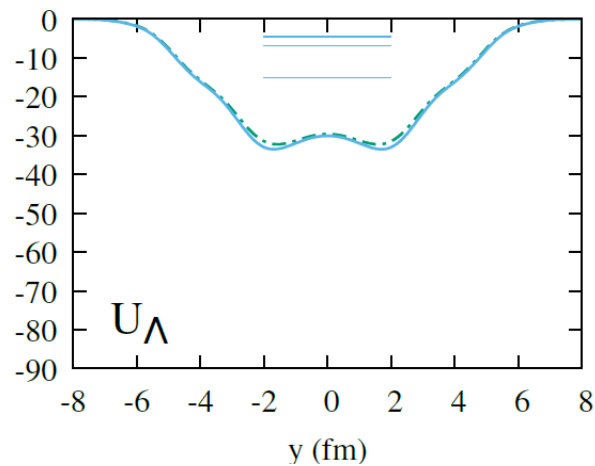
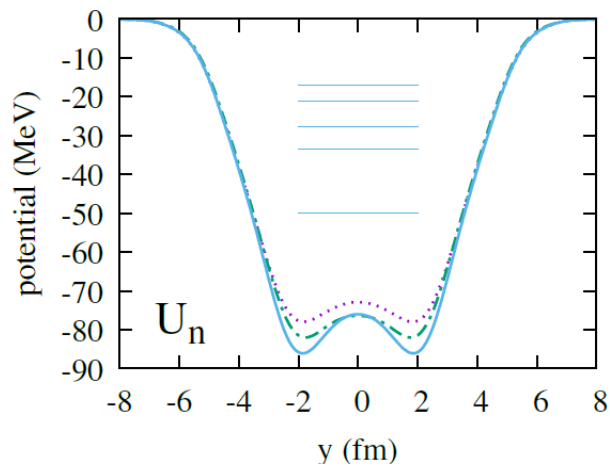
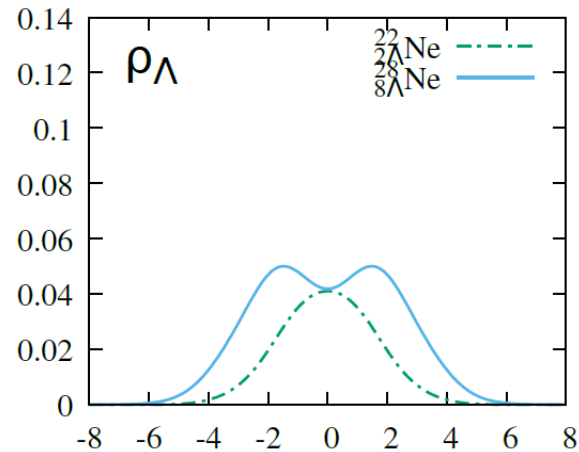
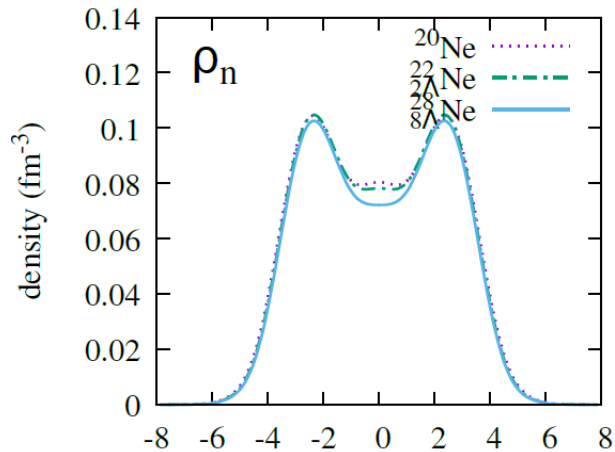
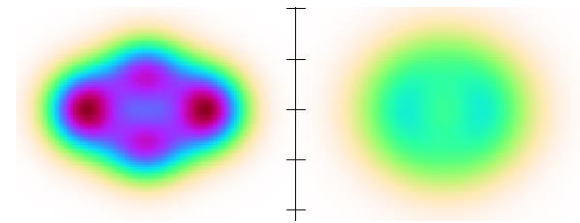
Bumps in Λ localization function (much more obscure than neutron)

→ sign of ${}^6_{2\Lambda}\text{He}$ clusterization is seen in the two-body correlation

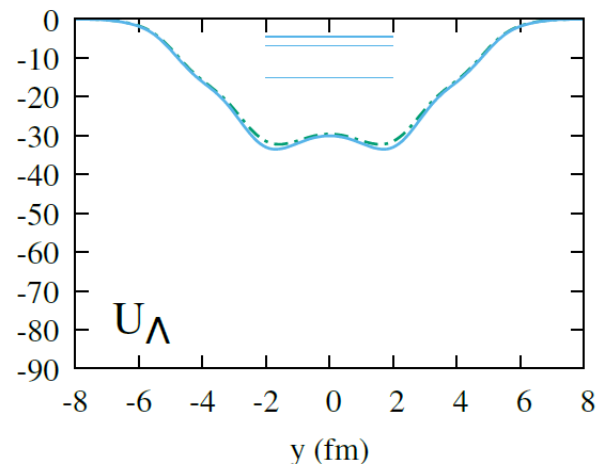
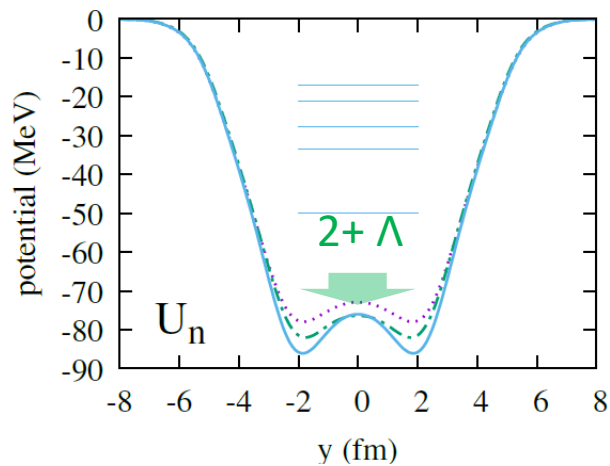
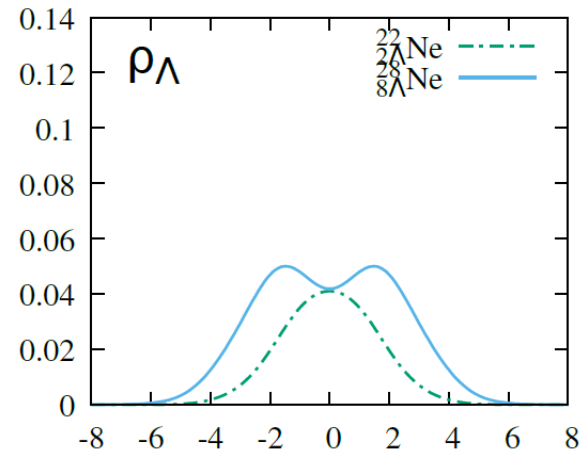
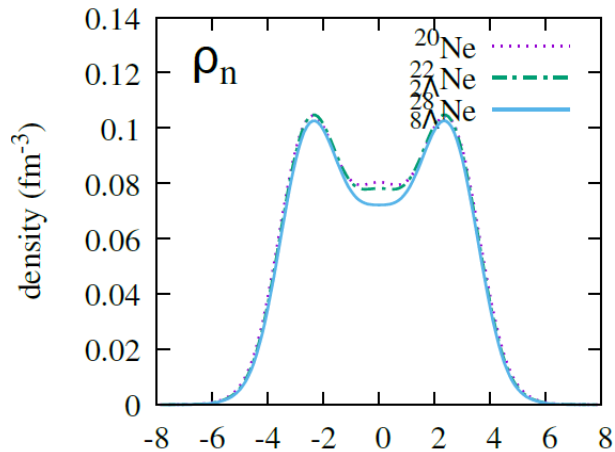
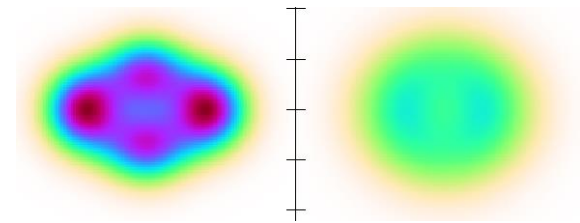
cf. one-body densities



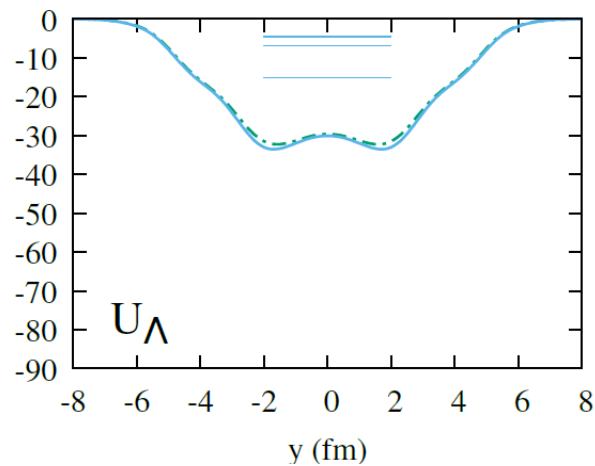
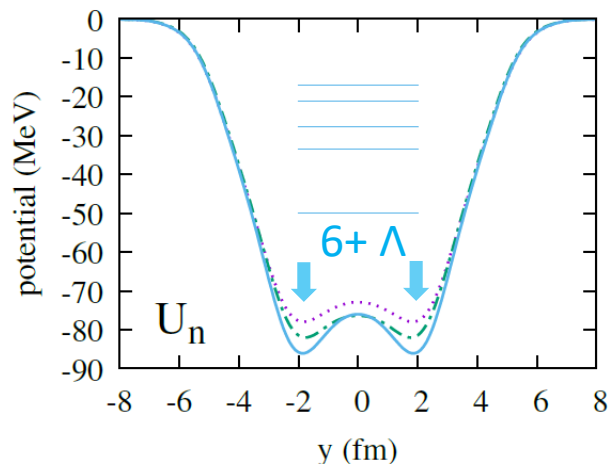
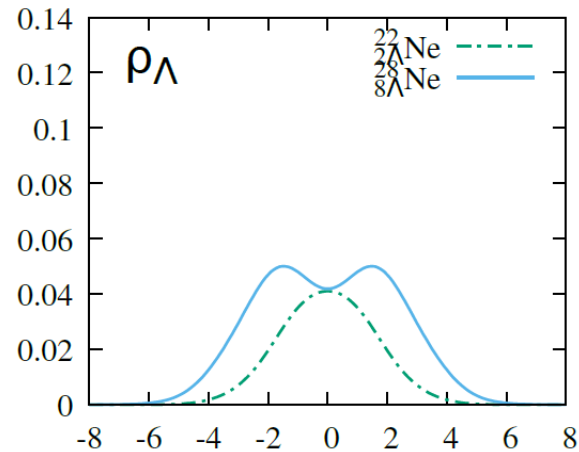
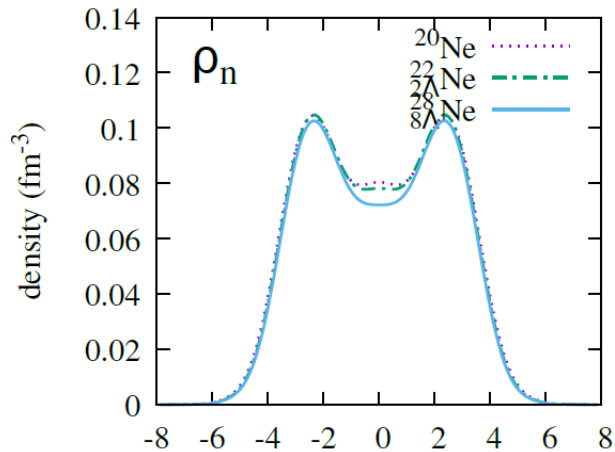
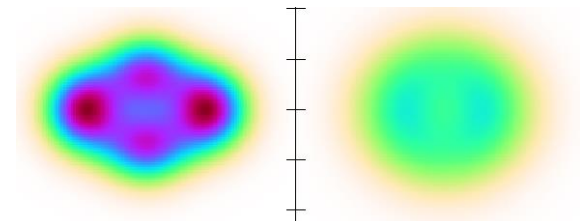
Hole in density of $^{20}\text{Ne} + 8\Lambda$



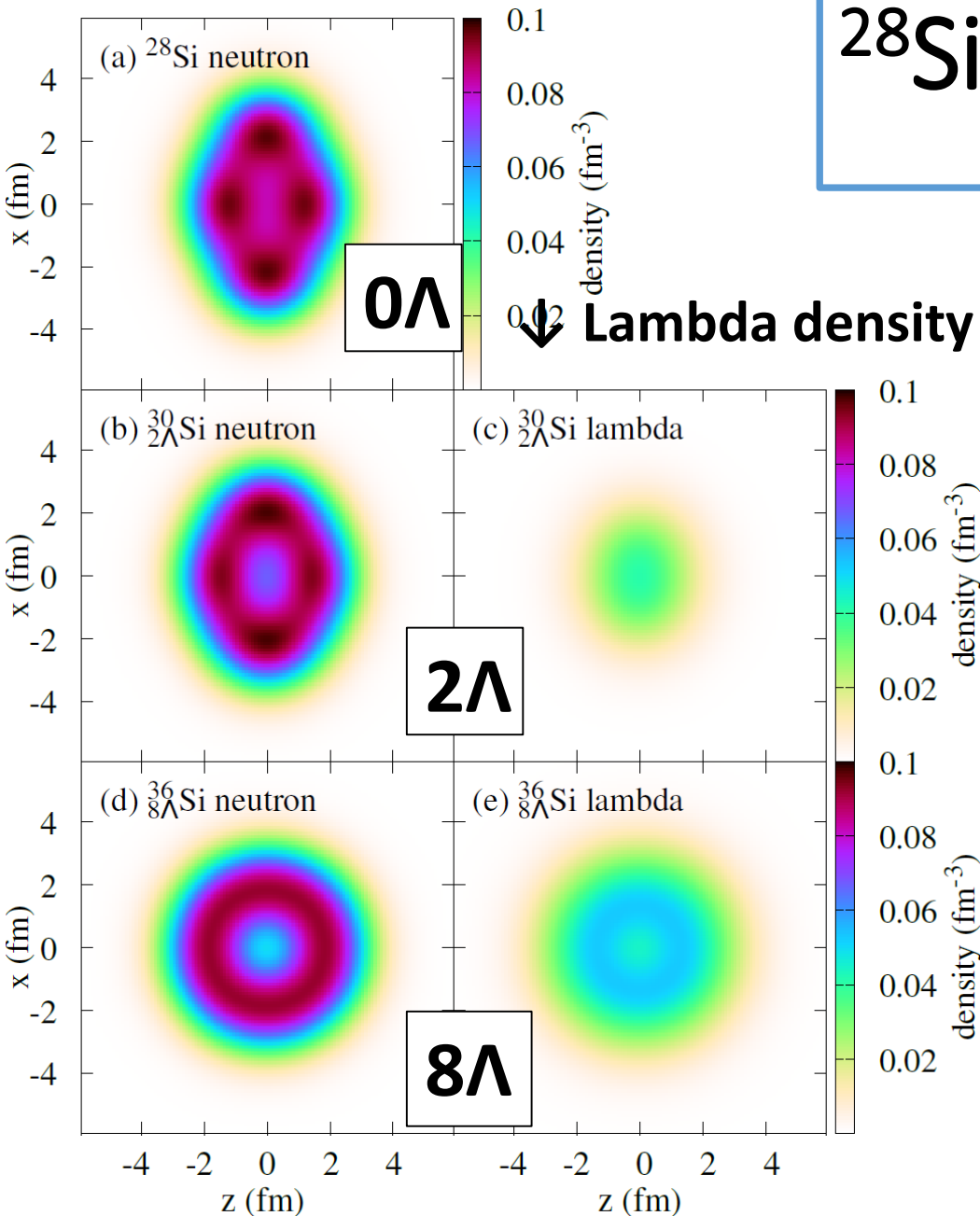
Hole in density of $^{20}\text{Ne} + 8\Lambda$



Hole in density of $^{20}\text{Ne} + 8\Lambda$



↓neutron density



- Oblate deformation
- 2Λ : $|\beta_{2N}|$ decreases significantly
- 8Λ : $|\beta_{2N}|$ vanishes
- Nucleons become spherical:
 $(s_{1/2})^2(p_{3/2})^4(p_{1/2})^2(d_{5/2})^6$
 due to the spherical magicity of 8Λ

N_Λ	β_{2N}	$\beta_{2\Lambda}$	R_N (fm)	R_Λ (fm)
Si hyper isotopes				
0	-0.52	—	3.14	—
2	-0.37	-0.20	2.95	2.49
8	0.00	0.00	2.92	3.14

Summary and perspectives

- Deformed multi- Λ systems within RMF theory
- Be hyper isotopes
 - ✓ ${}_{4\Lambda}^{12}\text{Be}$: sign of two- ${}_{2\Lambda}^6\text{He}$ clusterization is seen in the two-body correlation
- Ne and Si hyper isotopes
 - ✓ deformation decreases/vanishes by addition of Λ 's
- Systematic study with NN (and $\Lambda\Lambda$) pairing
- More general multi-strangeness systems (multi- Σ/Ξ)
- Collective excitations with GCM, TDRMF, or (Q)RPA

