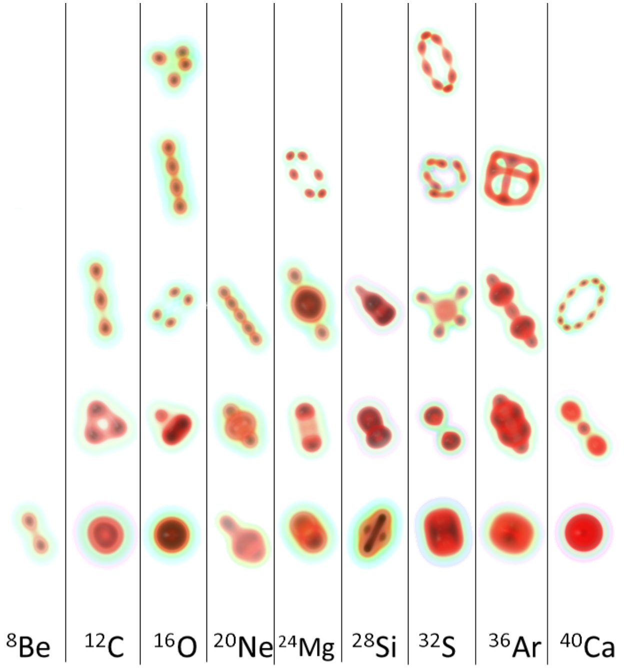
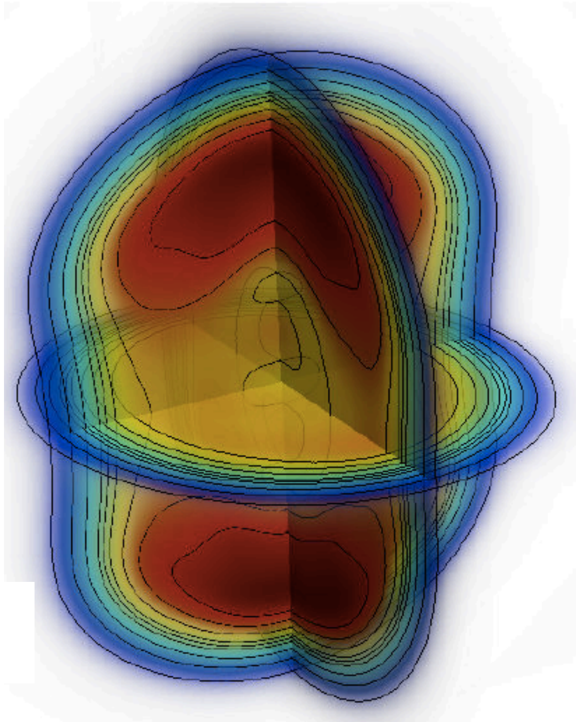
Investigation of nuclear cluster phenomenology with the relativistic EDF approach





Elias Khan

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

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2018 European Nuclear Physics Conference
2-7 September 2018, Bologna

EDF method & clusters

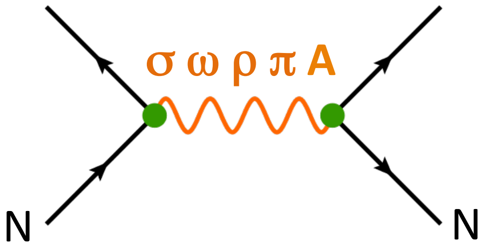
- EDF: many-body system mapped into the **one-body density** and its powers, gradient

$$
\begin{aligned}
\rho_0(\mathbf{r}) &= \rho_0(\mathbf{r},\mathbf{r}) = \sum_{\sigma\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma\tau) \\
\rho_1(\mathbf{r}) &= \rho_1(\mathbf{r},\mathbf{r}) = \sum_{\sigma\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma\tau)\,\tau \\
\mathbf{s}_0(\mathbf{r}) &= \mathbf{s}_0(\mathbf{r},\mathbf{r}) = \sum_{\sigma\sigma'\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma'\tau)\,\boldsymbol{\sigma}_{\sigma'\sigma} \\
\mathbf{s}_1(\mathbf{r}) &= \mathbf{s}_1(\mathbf{r},\mathbf{r}) = \sum_{\sigma\sigma'\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma'\tau)\,\boldsymbol{\sigma}_{\sigma'\sigma}\,\tau
\end{aligned}
$$

$$
\begin{aligned}
\mathbf{j}_T(\mathbf{r}) &= \tfrac{i}{2}(\nabla' - \nabla)\,\rho_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'} \\
\mathcal{J}_T(\mathbf{r}) &= \tfrac{i}{2}(\nabla' - \nabla)\otimes \mathbf{s}_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'} \\
\tau_T(\mathbf{r}) &= \nabla\cdot\nabla'\,\rho_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'} \\
\mathbf{T}_T(\mathbf{r}) &= \nabla\cdot\nabla'\,\mathbf{s}_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'}
\end{aligned}
$$

- **Most general** antisymmetrised product of nucleonic wavefunctions
- **Not any a priori assumption** on the nucleons' wave function
- **Correlations** beyond the mean-field effectively included by the EDF
- Investigate nuclear structure on the **whole nuclear chart**
- **Relativistic**: the depth of the central potential is **consistently predicted**

Relativistic EDF in nuclei



$$\mathcal{L}_{int} = -g_\sigma(\rho_v)\bar{\psi}\sigma\psi - g_\omega(\rho_v)\bar{\psi}\gamma_\mu\omega^\mu\psi - g_\rho(\rho_v)\bar{\psi}\gamma_\mu\vec{\rho}^\mu.\vec{\tau}\psi - \frac{f_\pi(\rho_v)}{m_\pi}\bar{\psi}\gamma_5\gamma_\mu\partial^\mu\vec{\pi}.\vec{\tau}\psi - e\bar{\psi}\gamma_\mu A^\mu\psi$$

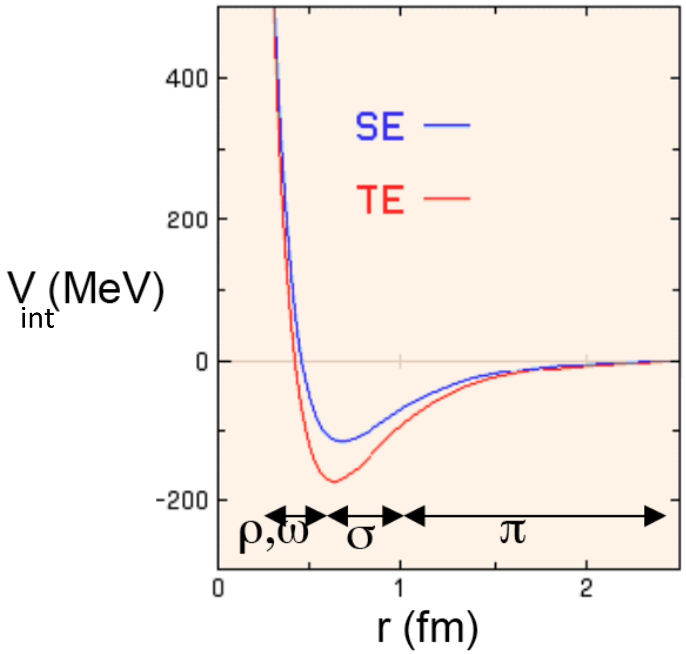
EDF [ρ ; σ,ω,ρ,π,A]

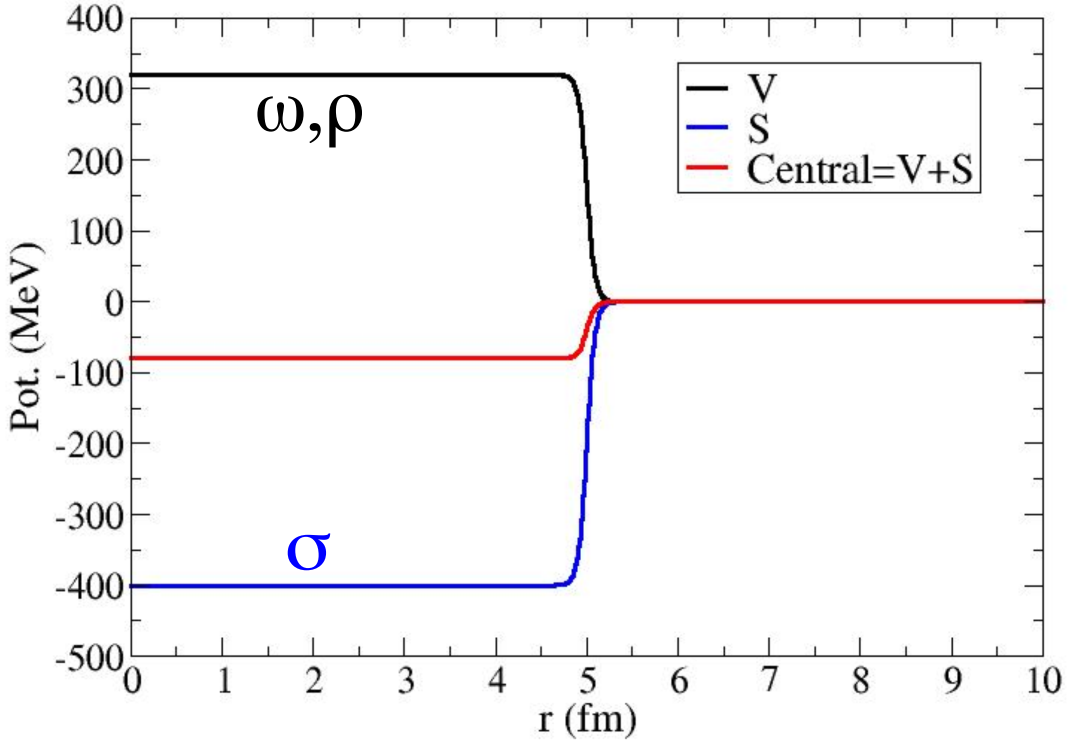
$$\left\{ \boldsymbol{p}\frac{1}{2\tilde{M}(r)}\boldsymbol{p} + W(r) + V_{ls}(r)\boldsymbol{l}.\boldsymbol{s} \right\} \varphi_i = \varepsilon_i^{NR}\varphi_i$$

$$W(r) = [V+S](r)$$

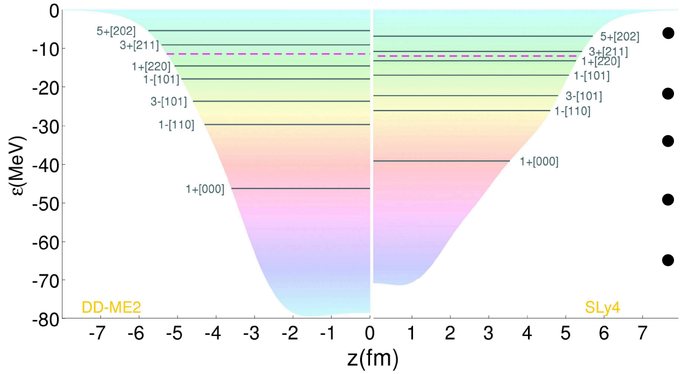
$$V_{ls}(r) = \frac{1}{2\tilde{M}^2(r)}\frac{1}{r}\frac{d}{dr}(V-S)$$

V and S potentials

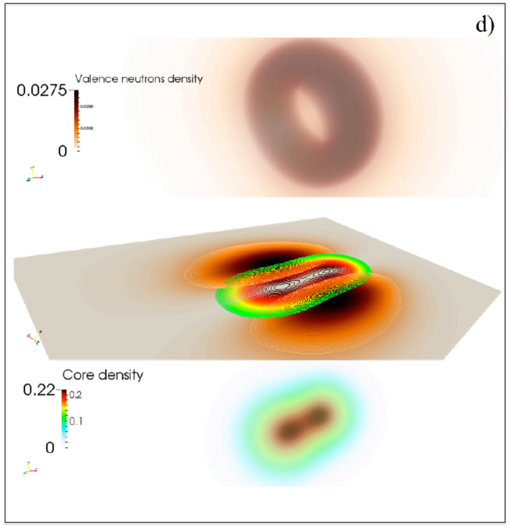




Origins of nuclear clustering



- Depth of the confining potential
- Heavy vs. Light nuclei
- Deformation / excitation energy
- Density
- Neutron excess

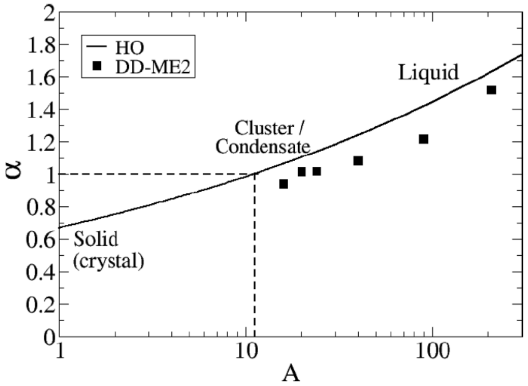


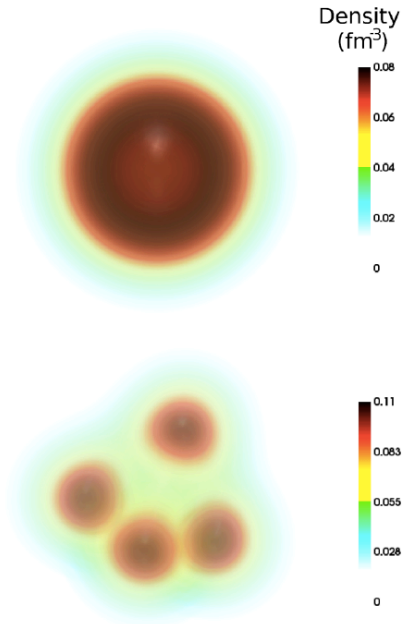
J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, Nature 487(2012)341

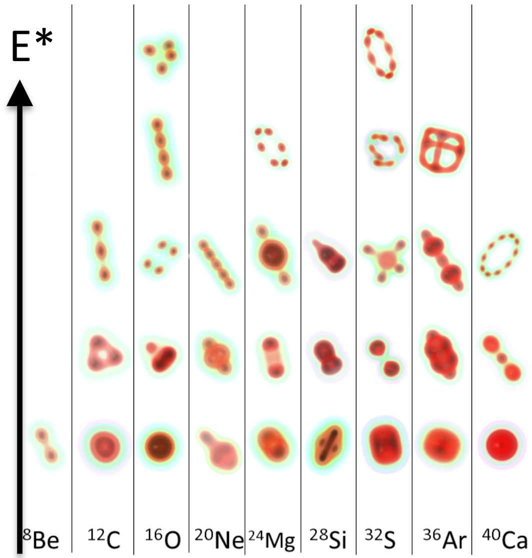
PRC87(2013)044307

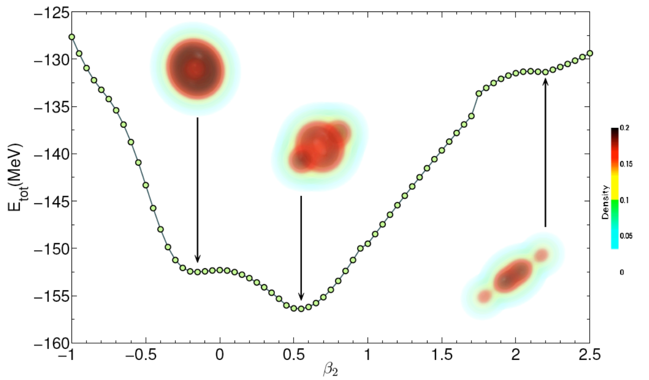
PRC90(2014)054329

PRC89(2014)031303(R)









What's new ?

1) **Quantitative results**: comparison with exp. rotational bands in ^{20}Ne and ^{12}C

__P. Marevic__ , J.-P. Ebran, E. Khan, T. Niksic , and D. Vretenar, PRC 97, 024334 (2018)

2) **More qualitative results** : localisation over the nuclear chart

J.-P. Ebran, E. Khan, __R.-D. Lasseri__, and D. Vretenar. PRC 97, 061301(R) (2018)

3) **Improvement of the method** : effect of pairing and quarteting on clustering

__R.-D. Lasseri__, J.-P. Ebran, E. Khan, and N. Sandulescu, PRC 98, 014310 (2018)

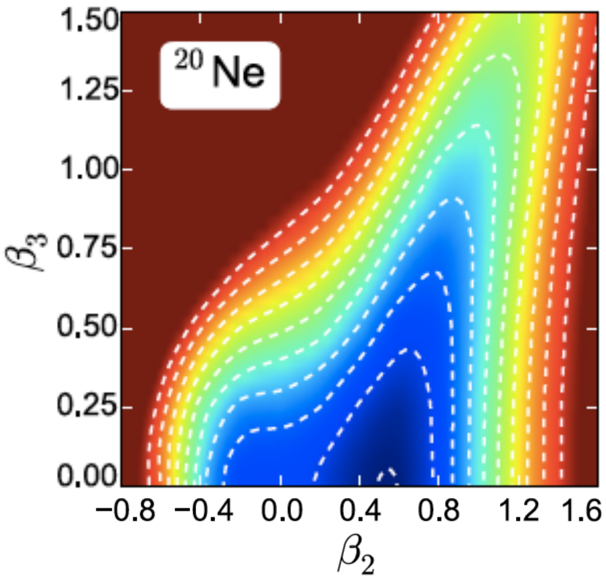
Comparison with exp. on ^{20}Ne

- GCM on top of axially symmetric /reflection asymmetric RHB (DD-PC1) :

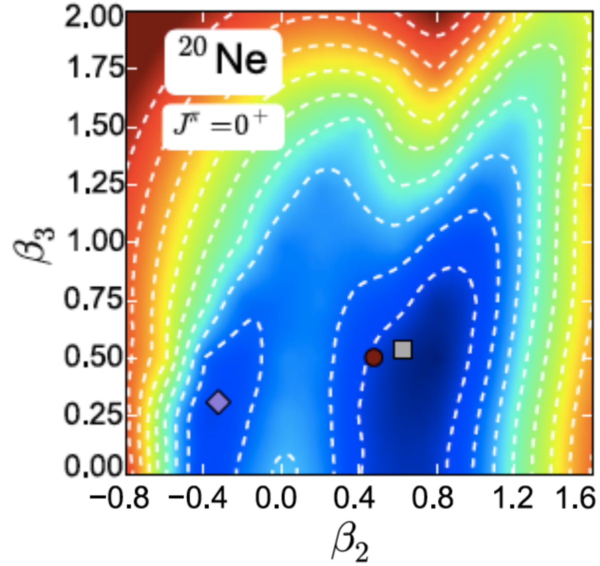
$$|JM\pi;\alpha\rangle = \sum_j \sum_K f_\alpha^{JK\pi}(q_j)\hat{P}^J_{MK}\hat{P}^\pi\,|\phi(q_j)\rangle$$

- Angular momentum, parity and particle number projections

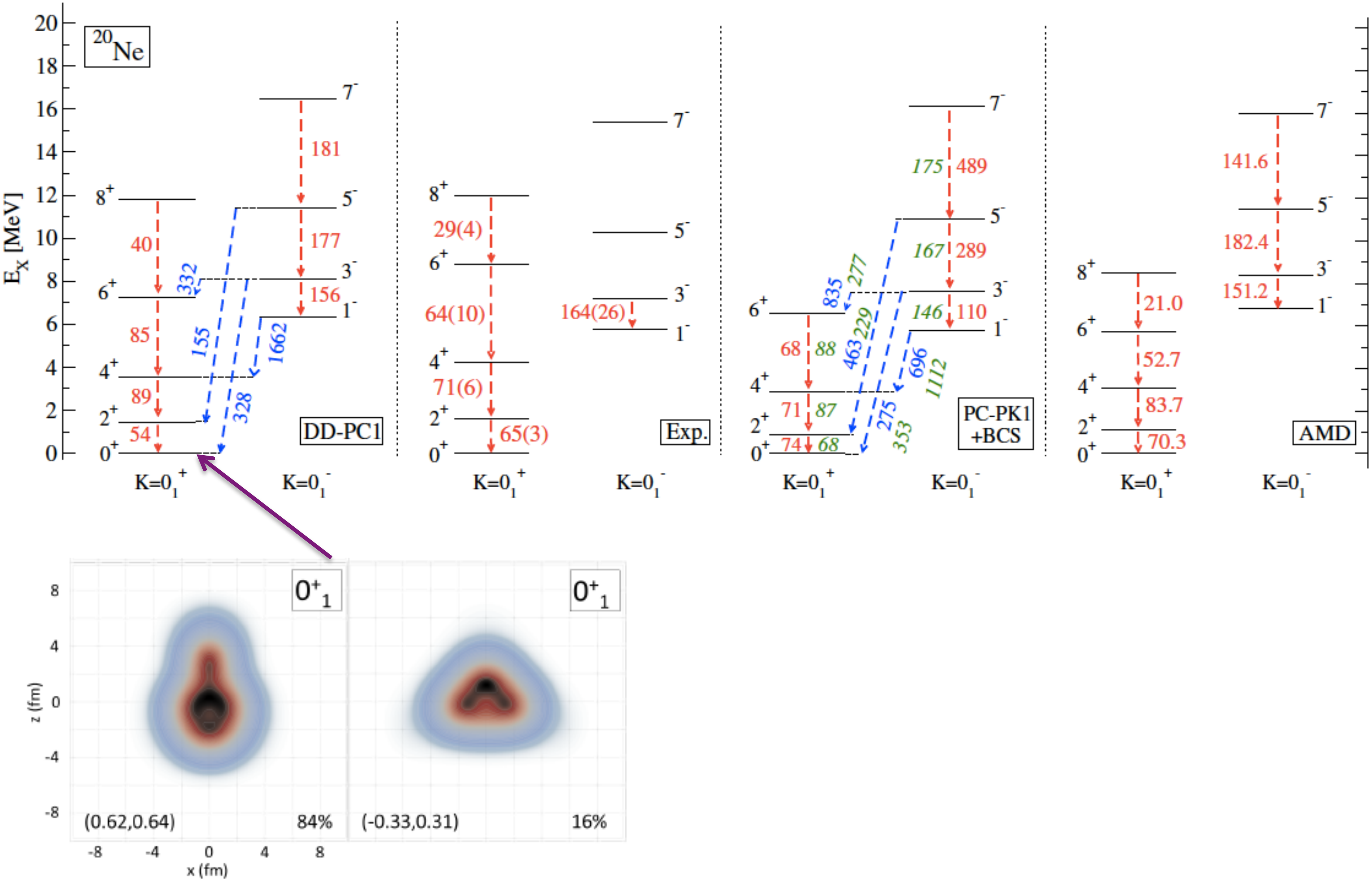
RHB PES



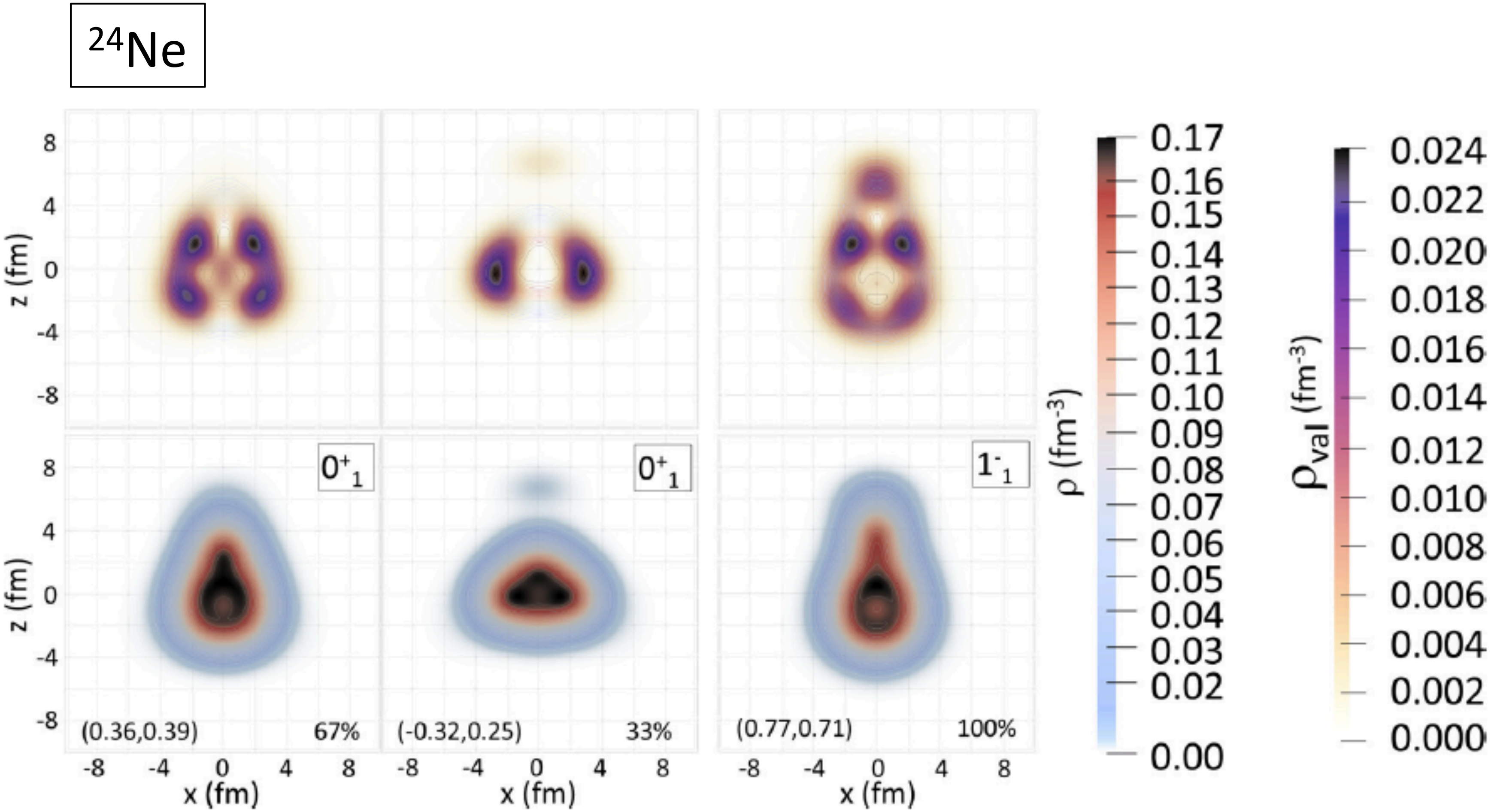
Projected PES



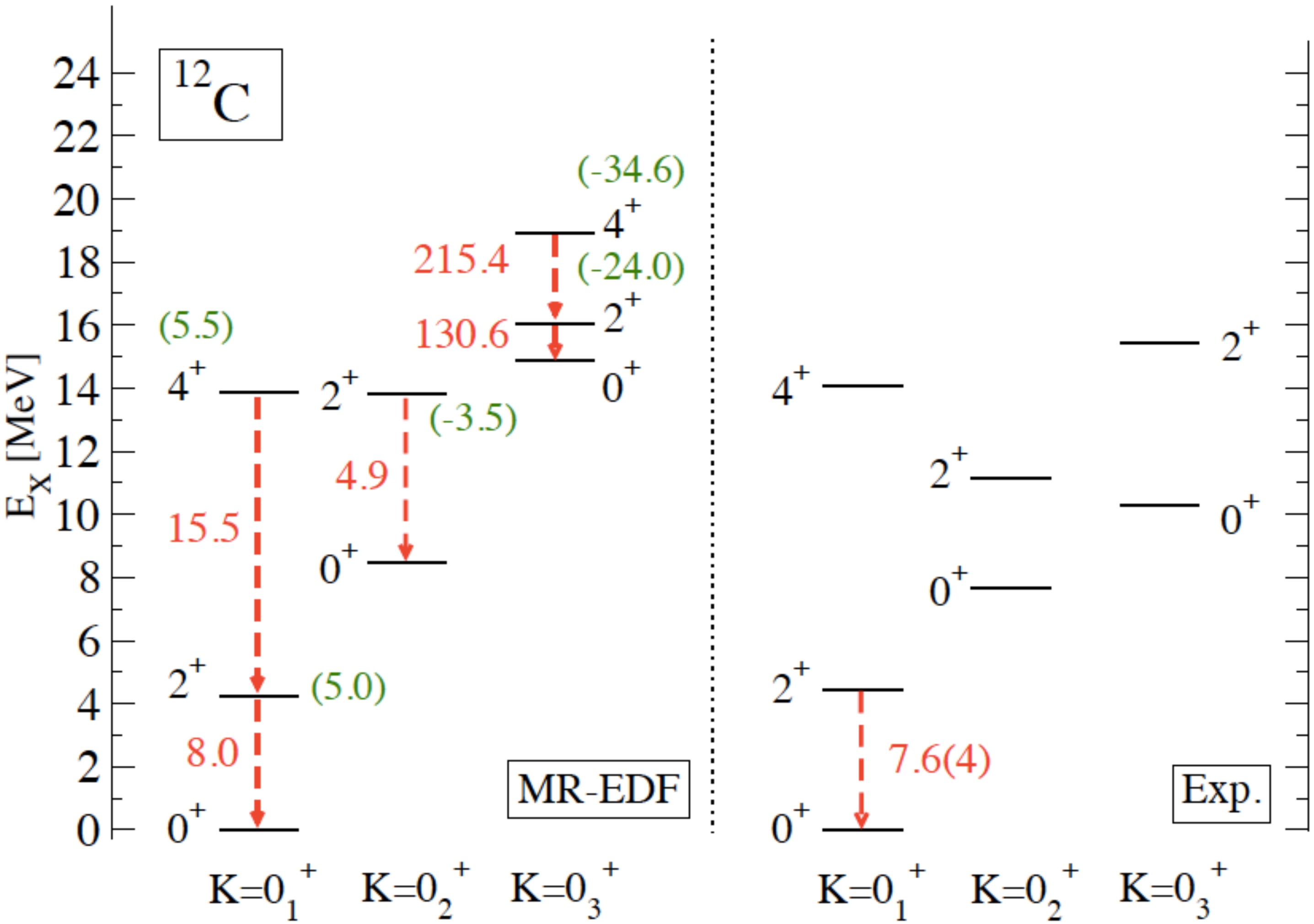
Comparison with the data



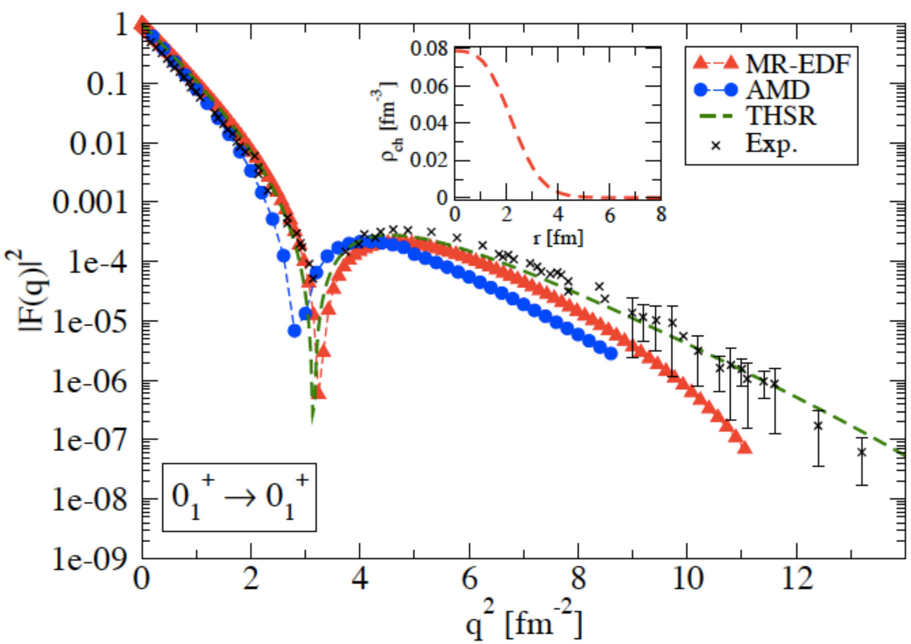
Analysis of the densities

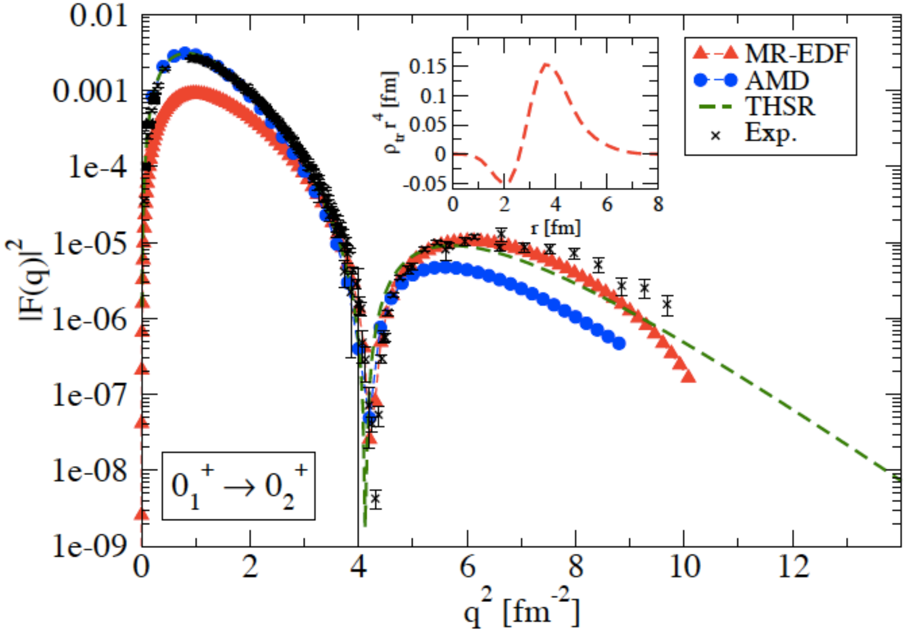


Comparison with exp. on ^{12}C

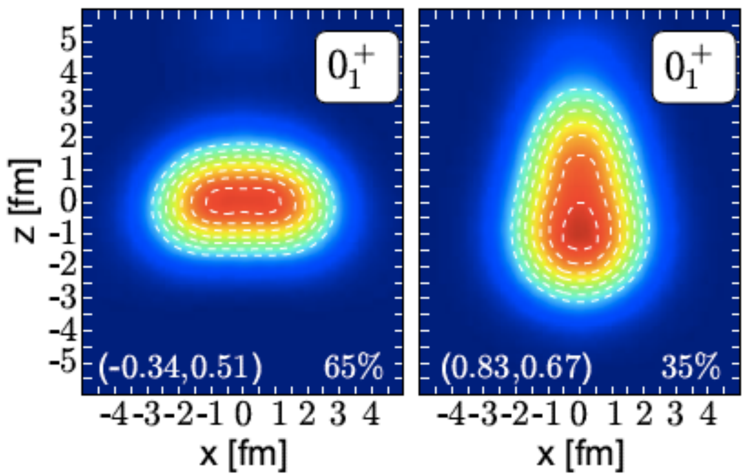


Comparison with exp. on ^{12}C

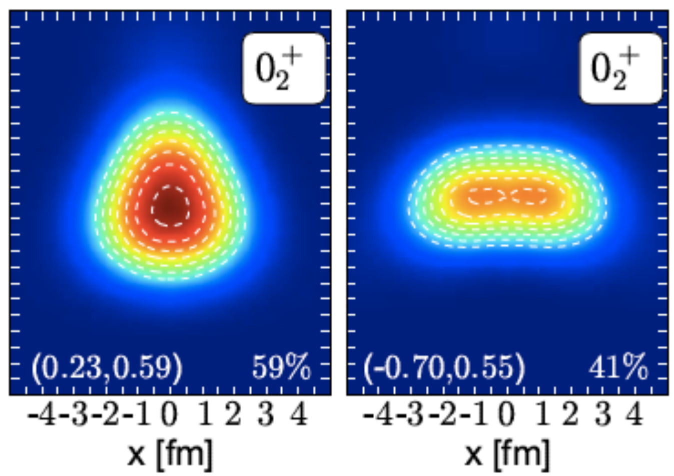




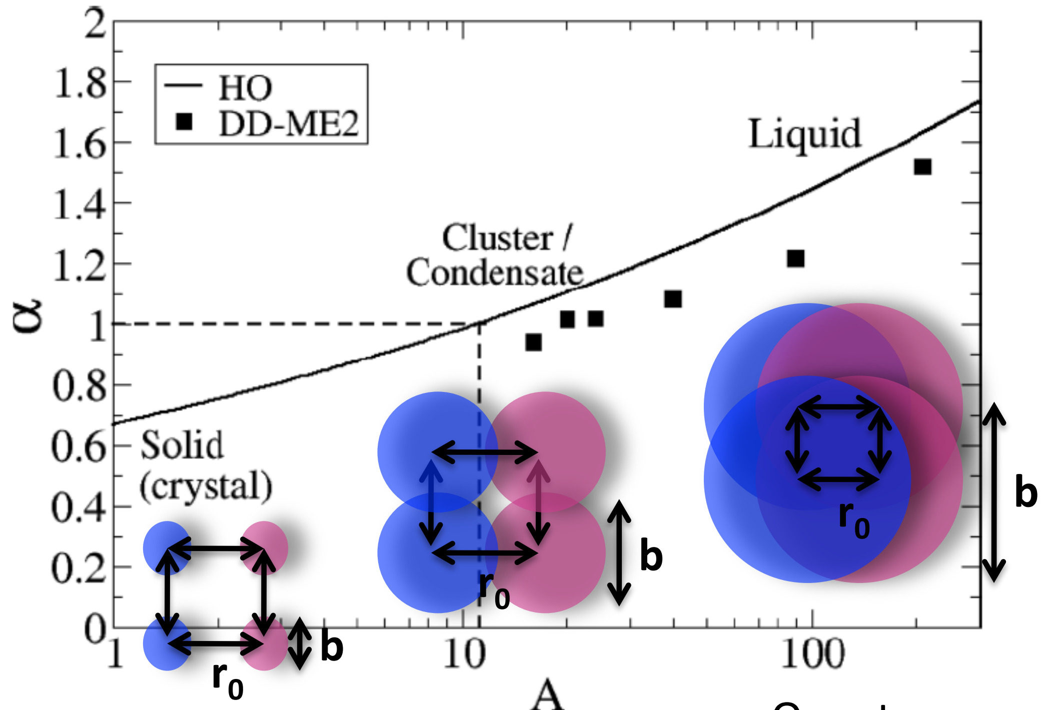
g.s.



Hoyle



Localisation



Crystal
α_{loc} <1

Cluster
$\alpha_{loc} \sim 1$

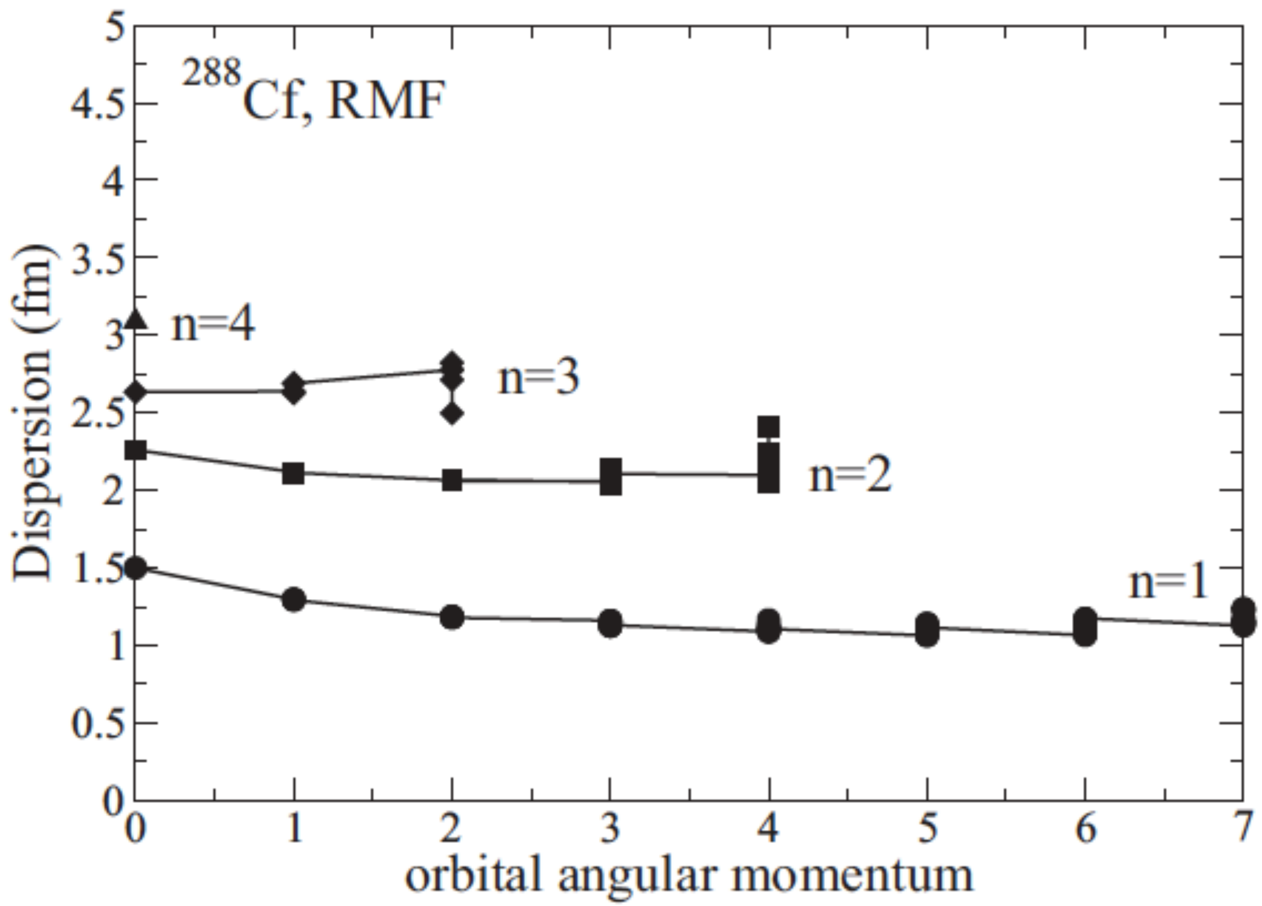
Quantum liquid
$\alpha_{loc} > 1$

J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 87(2013)044307

$$\alpha_{\rm loc} = \frac{2\Delta r}{r_0} \simeq \frac{b}{r_0} = \frac{\sqrt{\hbar}A^{1/6}}{\left(2mV_0 r_0^2\right)^{1/4}}$$

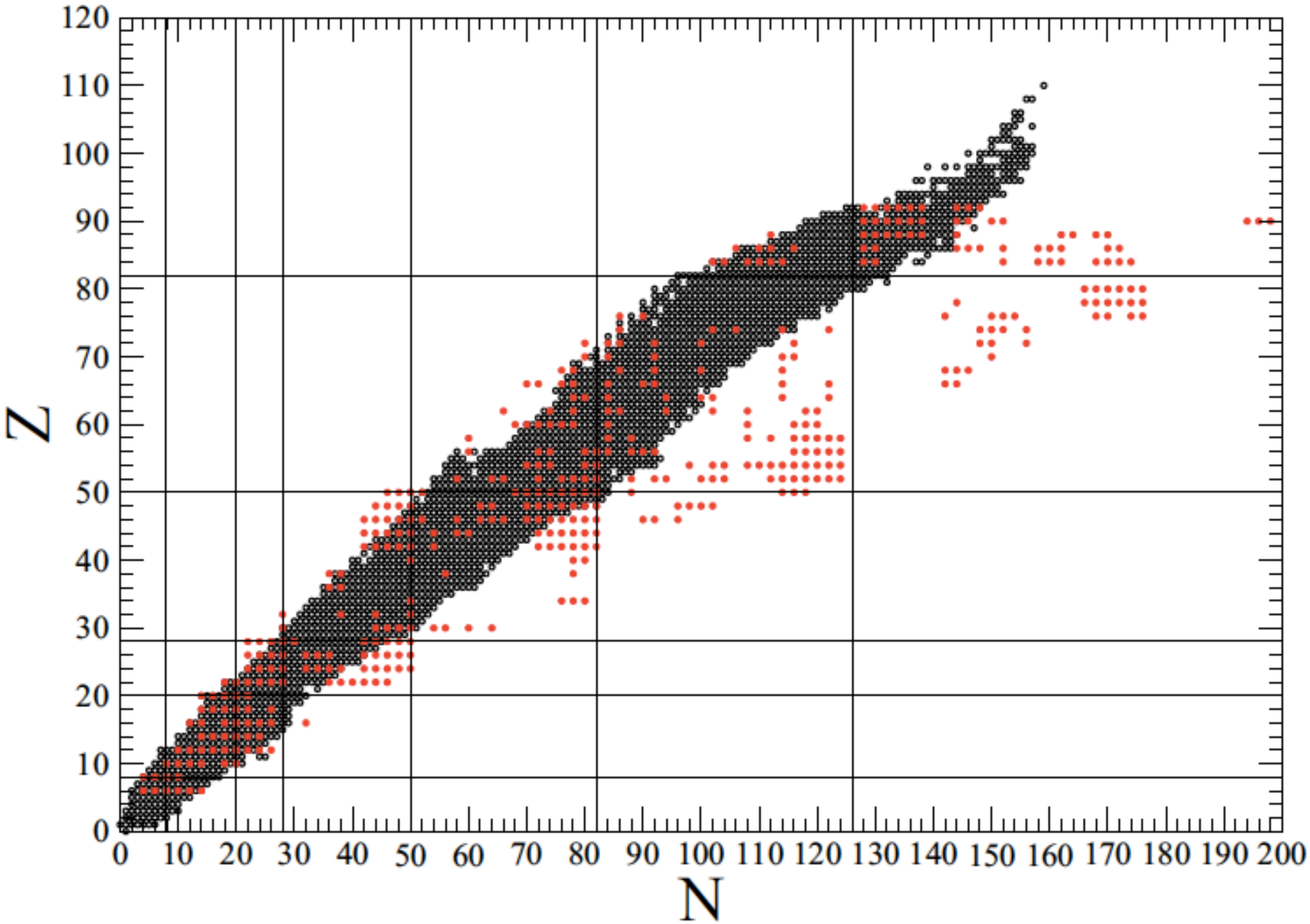
Single particle state dependence of the localisation ?

Dispersion in nuclei: a striking pattern



$$\alpha_{\rm loc} = \frac{2\Delta r}{r_0} \simeq \frac{b}{r_0}\sqrt{2n-1} = \frac{\sqrt{\hbar(2n-1)}}{\left(2mV_0r_0^2\right)^{1/4}} A^{1/6}$$

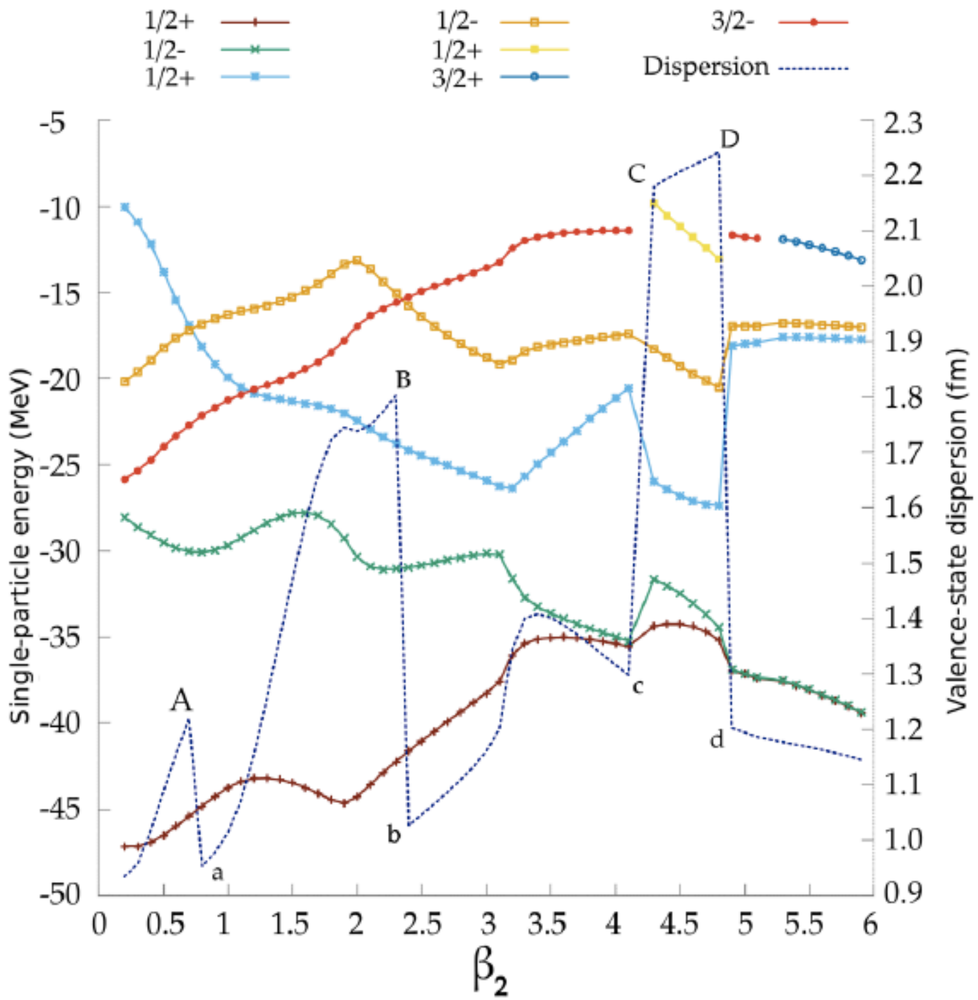
α-valence localisation over the nuclear chart

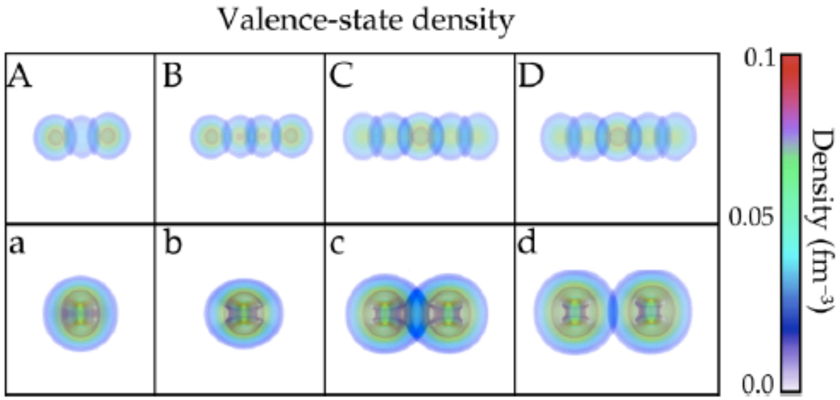


Axially symmetric RHB DD-ME2 calc.

Dispersion and s.p. states

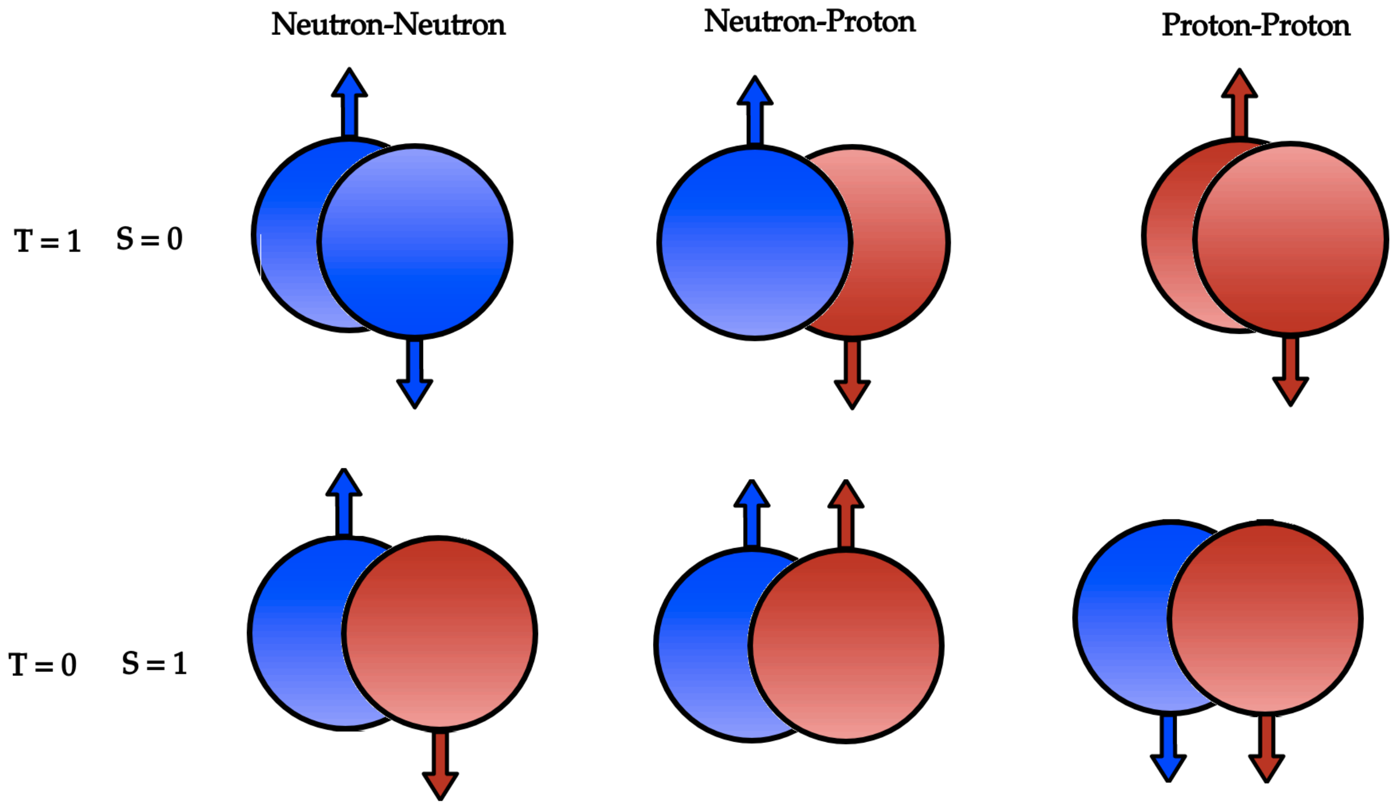
^{20}Ne



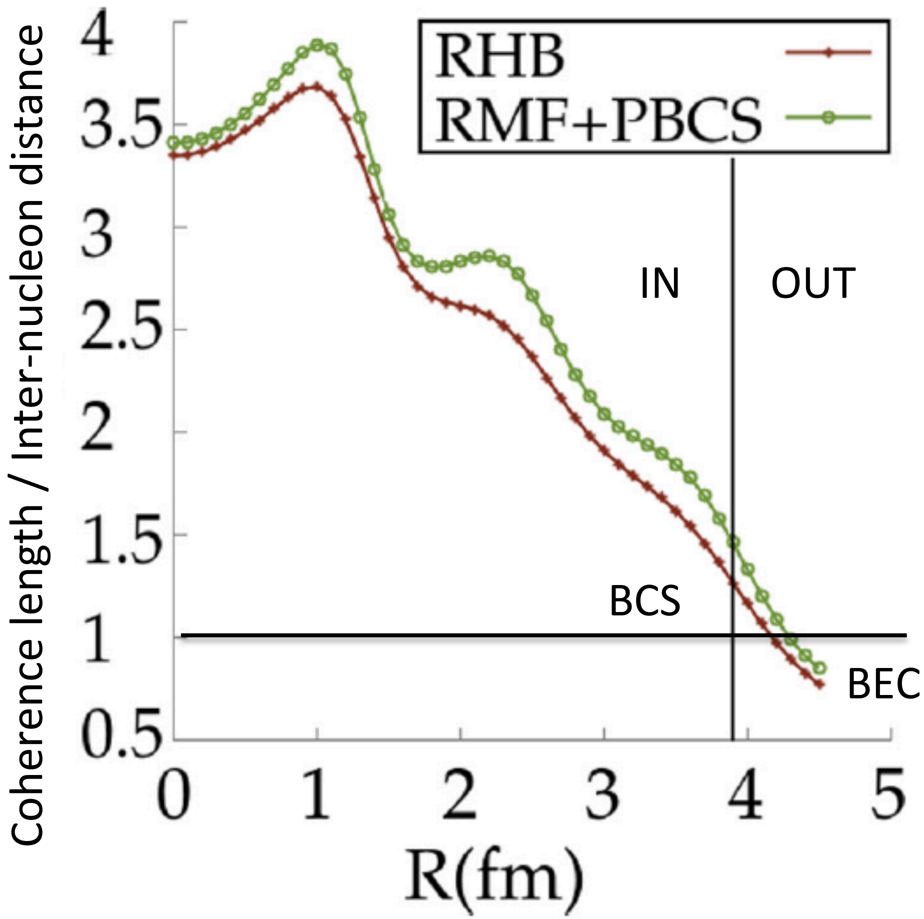


Impact of pairing and quarteting on clustering

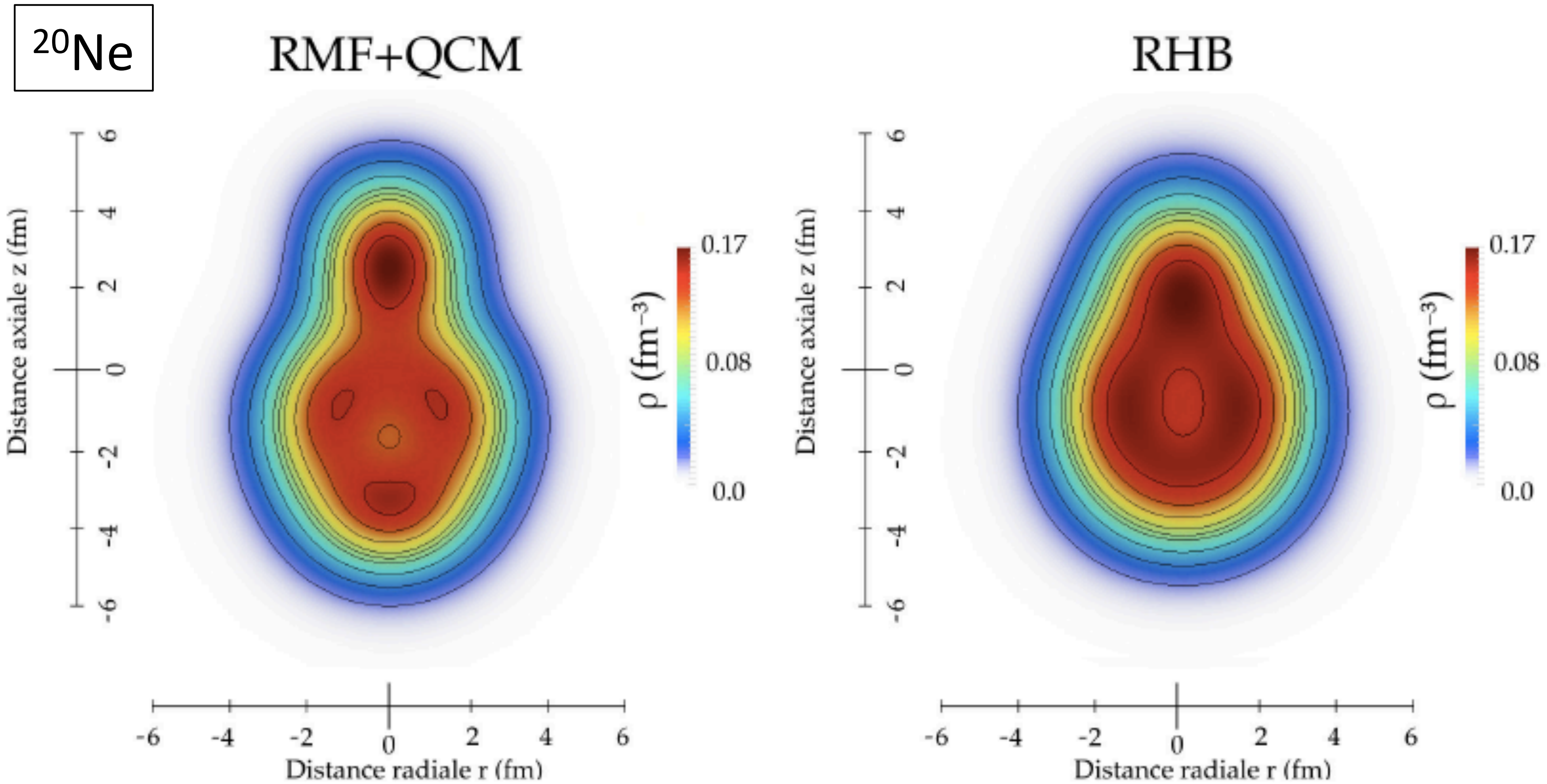
Quarteting = projected BCS in the nn, pp and np channels



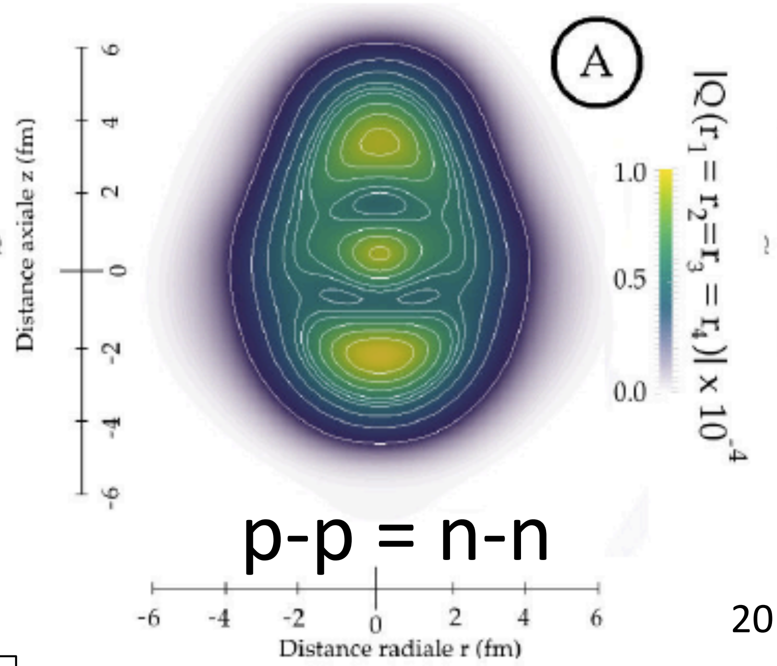
Pairing coherence length vs. inter-nucleon distance



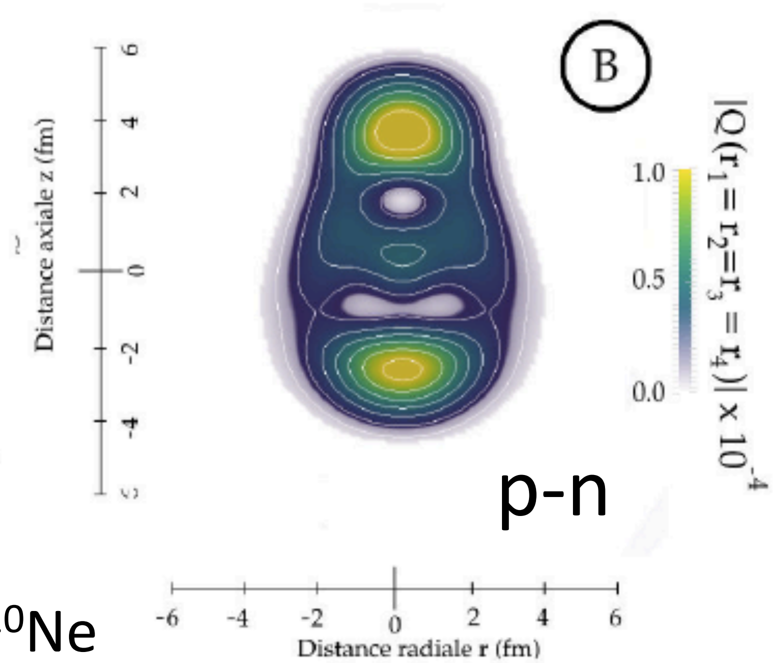
Effect of pairing and quarteting on clustering



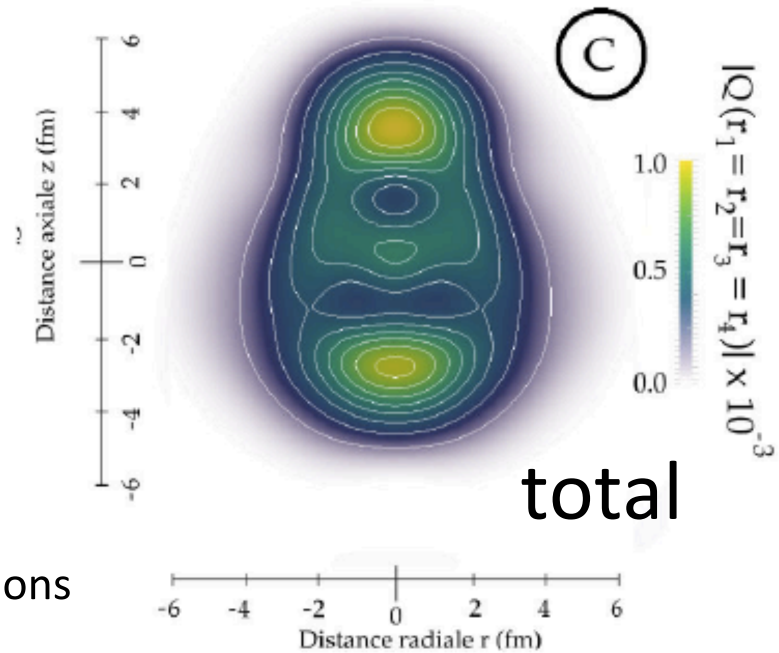
- Pairing acts against clustering (smearing of the density)
- Quarteting is compatible with clustering



^{20}Ne



^{20}Ne



Decisive role of p-n correlations

Conclusions and outlooks

- Nuclear clustering described by relativistic EDF both on qualitative and quantitative grounds
- Clustering persist with quarteting
- General and microscopic view and predictive power on nuclear clustering

- More comparison with data
- Clustering in heavy nuclei
- Relating clustering structure and alpha (cluster) radioactivity
- Density dependence and the Mott transition