Crystal, cluster and quantum liquid nuclear states

1) Localisation in finite systems

2) Microscopic description of nuclear quantum liquids and clusters

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Introduction

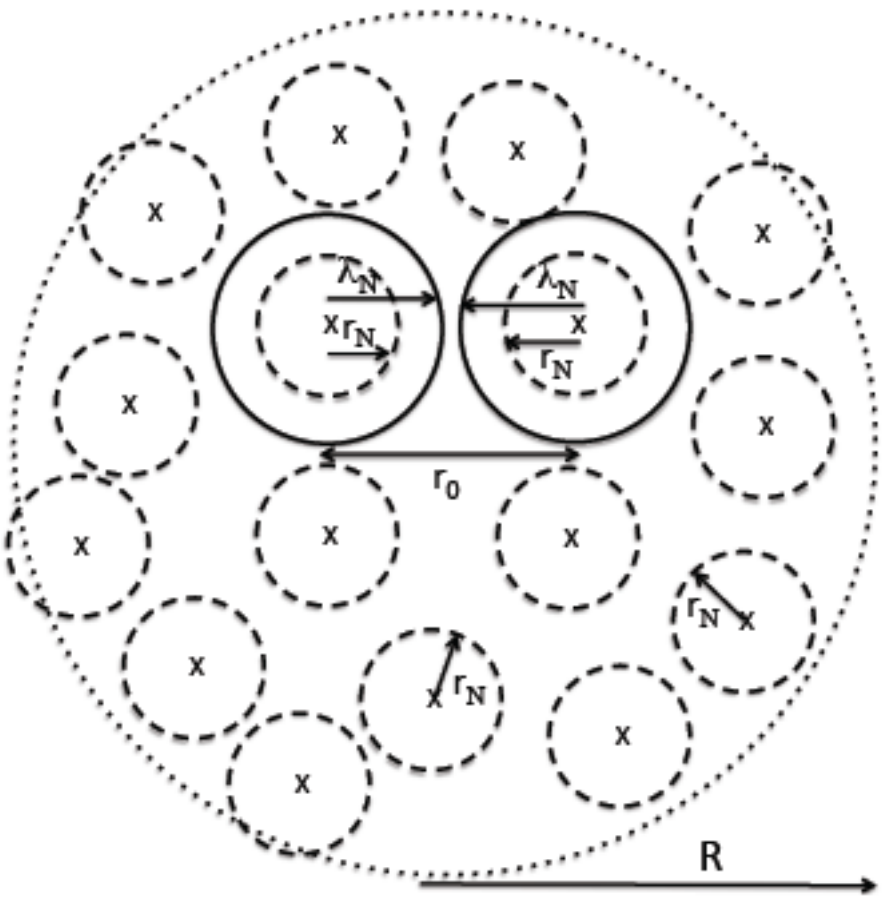
« *The nature of the transition from independent-particle motion to the crystalline state and the associated value of the characteristic parameter present significant unsolved problems* »

Bohr & Mottelson Vol I

 Clusters in nuclei

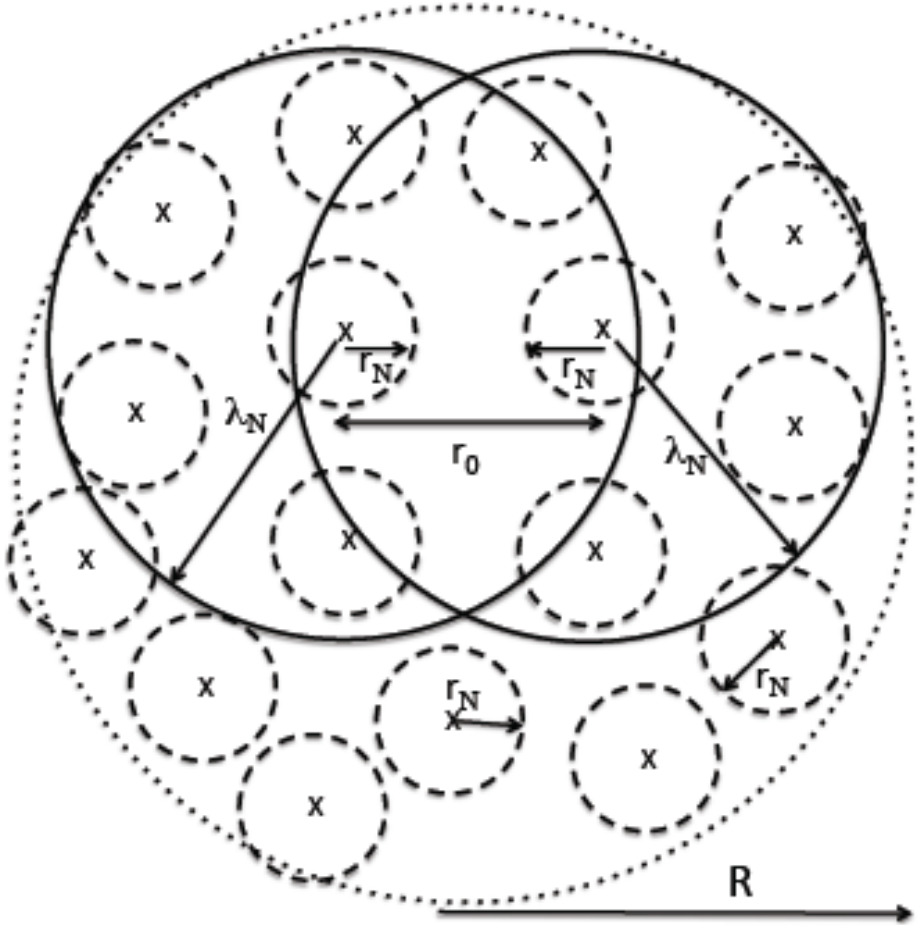
1) Localisation in finite systems

Localisation



Localised (crystal)

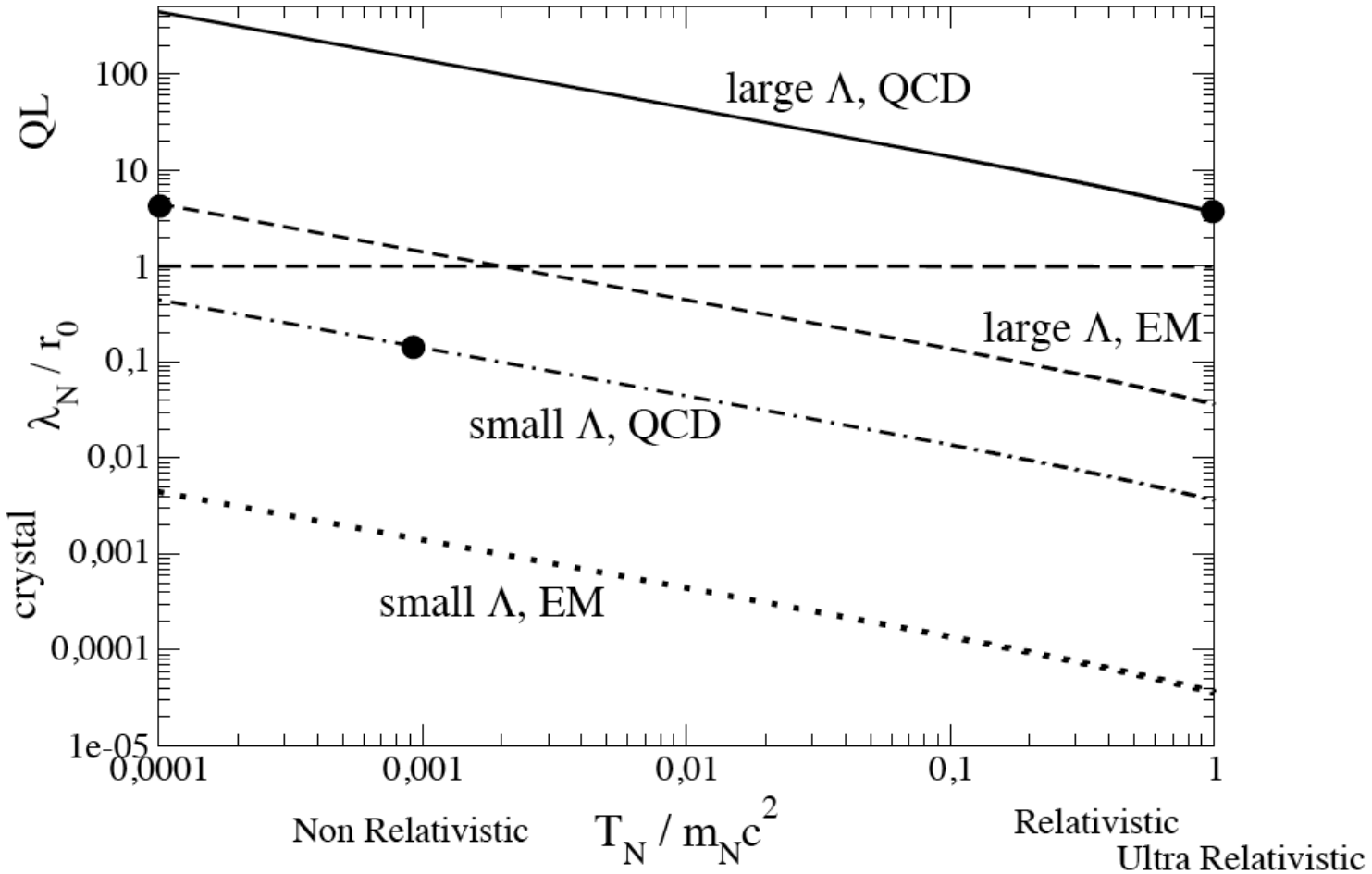
$\lambda_N < r_0$



Delocalised (quantum liquid)

$\lambda_N > r_0$

Localisation parameter



J.-P. Ebran, E. Khan, D. Vretenar, in prep.

Localisation

In its most general form, localisation depends on:

- The interaction coupling constant
- The kinematics of the constituent
- The quantality: $\Lambda \hat{=} \frac{\hbar^2}{m r_0^2 V_0'}$ (B. Mottelson, Proc. Les Houches school (1996))

(interaction effect)

J.-P. Ebran, E. Khan, D. Vretenar, in prep.

Localisation in finite saturating systems

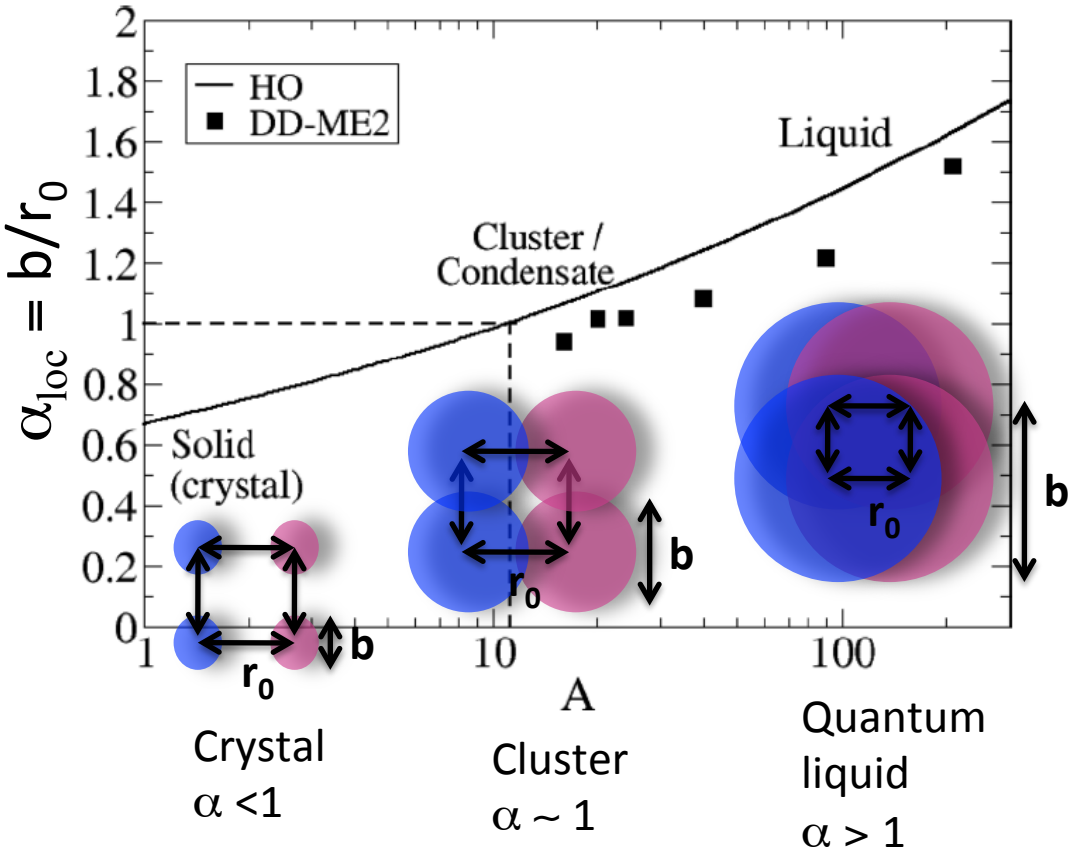
Localisation parameter = w.f. dispersion/internucleon distance

$$\alpha_{loc} \equiv \frac{b}{r_0} = \frac{\sqrt{\hbar} A^{1/6}}{(2 m_N V_0 r_0^2)^{1/4}}$$

$$b \sim \sqrt{r_0 R}$$

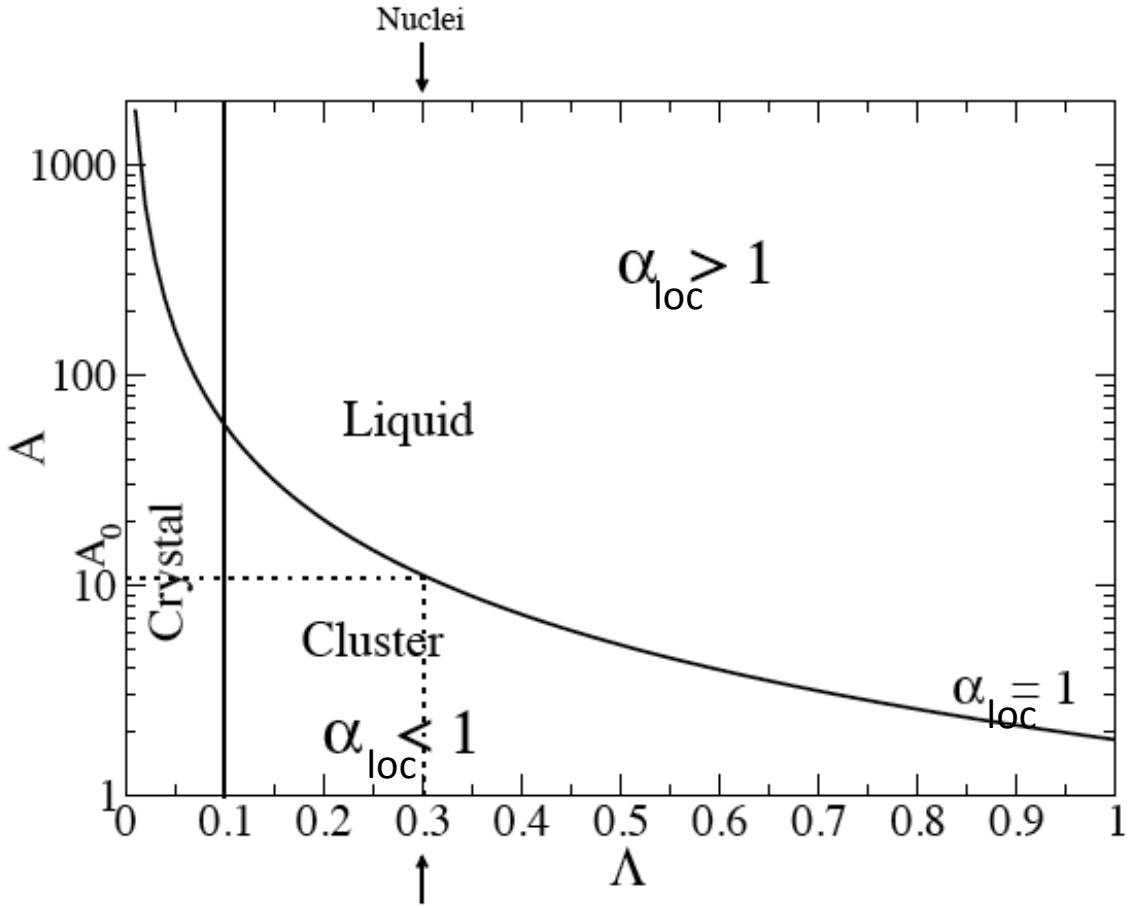
J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 87(2013)044307

Clusters: hybrid nuclear crystal and liquid



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

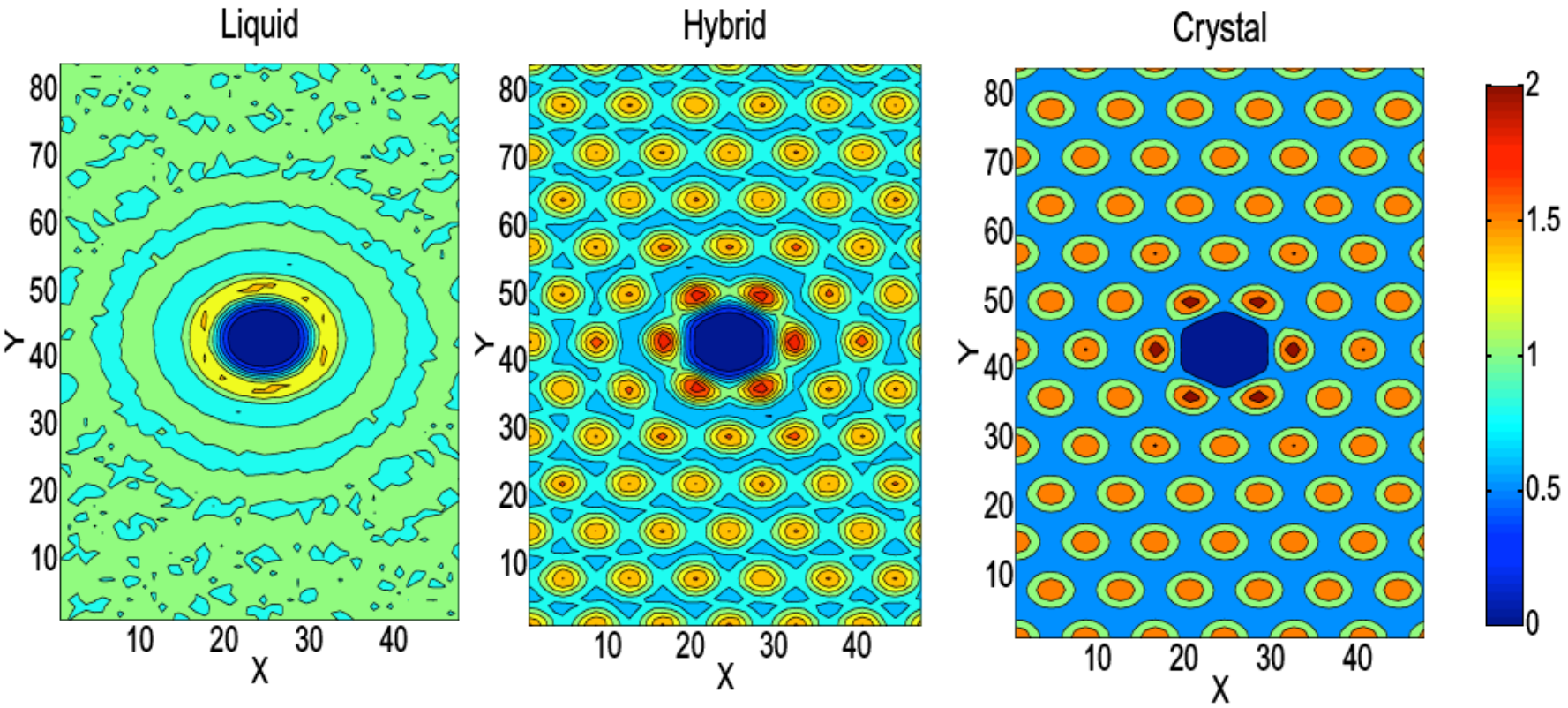
Saturation



Saturation ⟶ Light nuclei: confining potential vs. Quantum liquid delocalisation from the interaction

J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 89(2014)031303(R)

Analogies



2D electronic system

H. Flakshahi and X. Waintal Phys. Rev. Lett 94 (2005) 046801

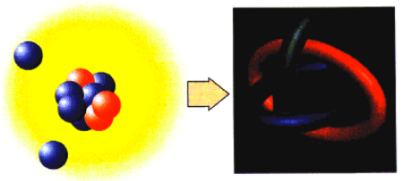
Nuclear states

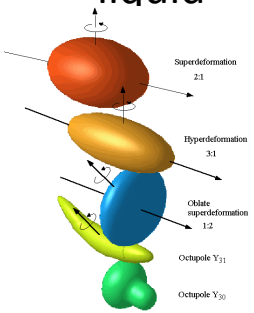
Halo

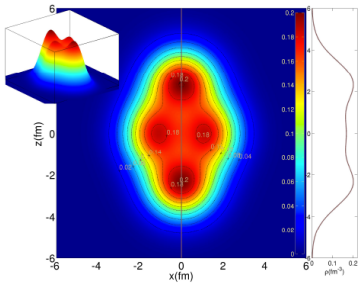
Quantum liquid

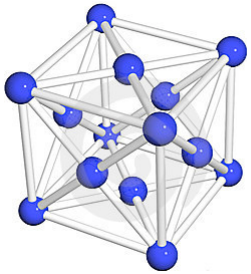
Cluster

Crystal

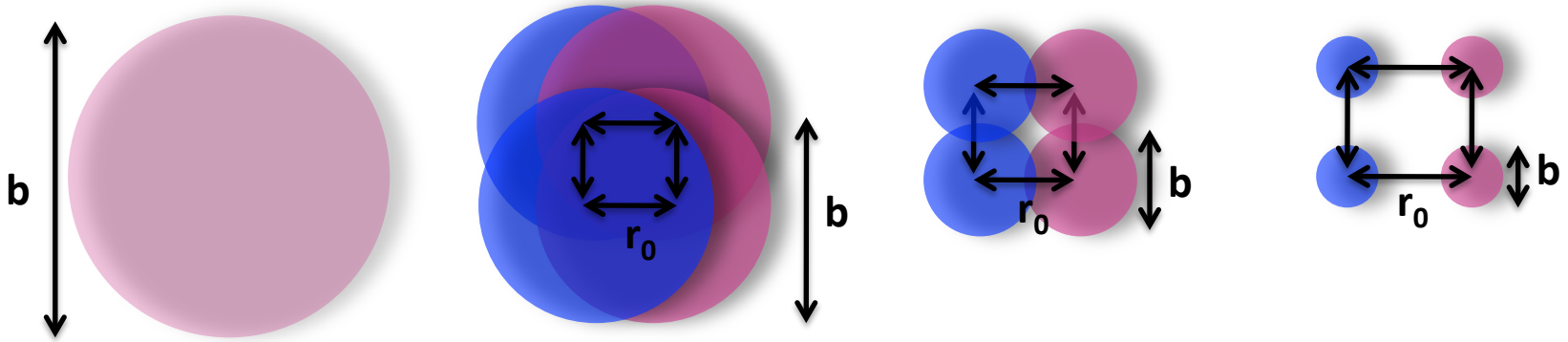


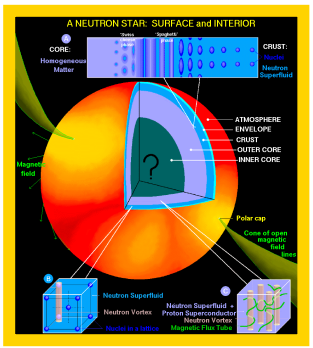


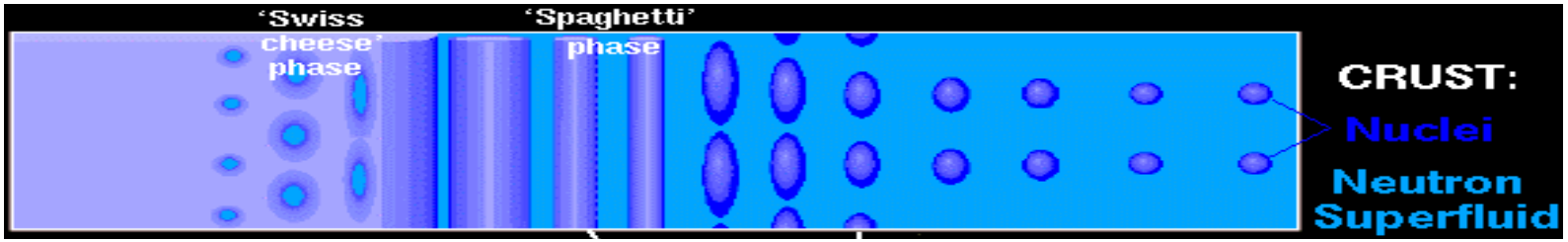




$\alpha_{loc} = b/r_0$







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

2) Microscopic description of nuclear quantum liquids and clusters

Protons

100

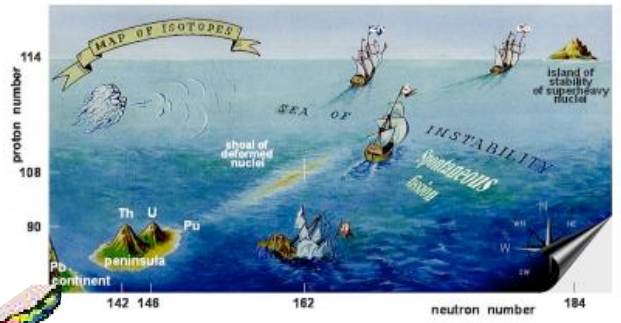
10

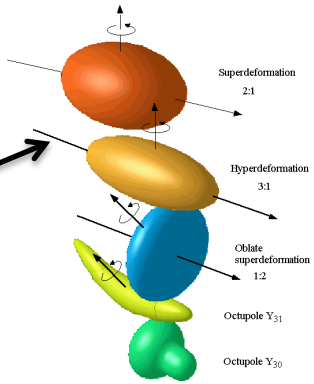
1

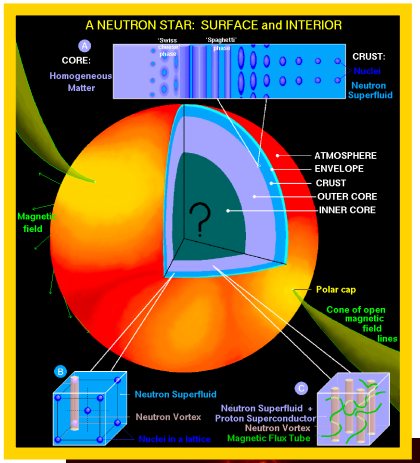
Unified description

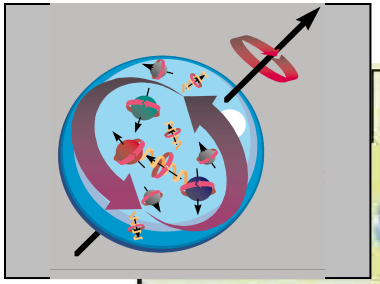
Terra incognita

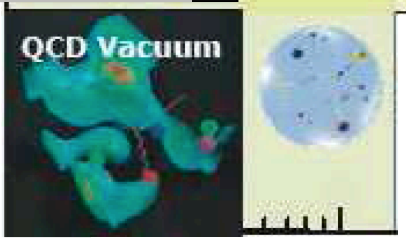
Reactions of synthesis

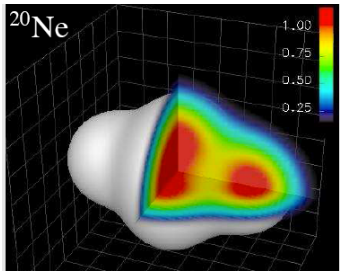


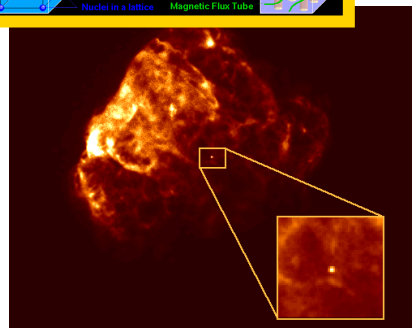












Neutrons

1 10 100 >1000

EDF method & clusters

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

$$\rho_0(\mathbf{r}) = \rho_0(\mathbf{r},\mathbf{r}) = \sum_{\sigma\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma\tau)$$

$$\rho_1(\mathbf{r}) = \rho_1(\mathbf{r},\mathbf{r}) = \sum_{\sigma\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma\tau)\,\tau$$

$$\mathbf{s}_0(\mathbf{r}) = \mathbf{s}_0(\mathbf{r},\mathbf{r}) = \sum_{\sigma\sigma'\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma'\tau)\,\boldsymbol{\sigma}_{\sigma'\sigma}$$

$$\mathbf{s}_1(\mathbf{r}) = \mathbf{s}_1(\mathbf{r},\mathbf{r}) = \sum_{\sigma\sigma'\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma'\tau)\,\boldsymbol{\sigma}_{\sigma'\sigma}\,\tau$$

$$\mathbf{j}_T(\mathbf{r}) = \tfrac{i}{2}(\nabla' - \nabla)\,\rho_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'}$$

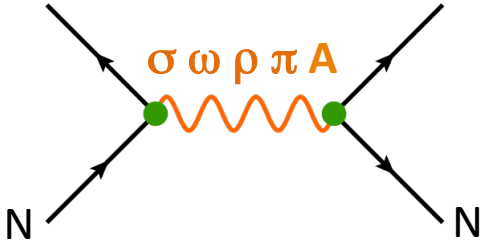
$$\mathcal{J}_T(\mathbf{r}) = \tfrac{i}{2}(\nabla' - \nabla) \otimes \mathbf{s}_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'}$$

$$\tau_T(\mathbf{r}) = \nabla \cdot \nabla'\,\rho_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'}$$

$$\mathbf{T}_T(\mathbf{r}) = \nabla \cdot \nabla'\,\mathbf{s}_T(\mathbf{r},\mathbf{r}')\big|_{\mathbf{r}=\mathbf{r}'}$$

- **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
- Results are obtained in the **intrinsic** frame of the nucleus
- Investigate nuclear structure on the **whole nuclear chart**
- **Relativistic**: the depth of the central potential is **consistently predicted**

Relativistic EDF in nuclei



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

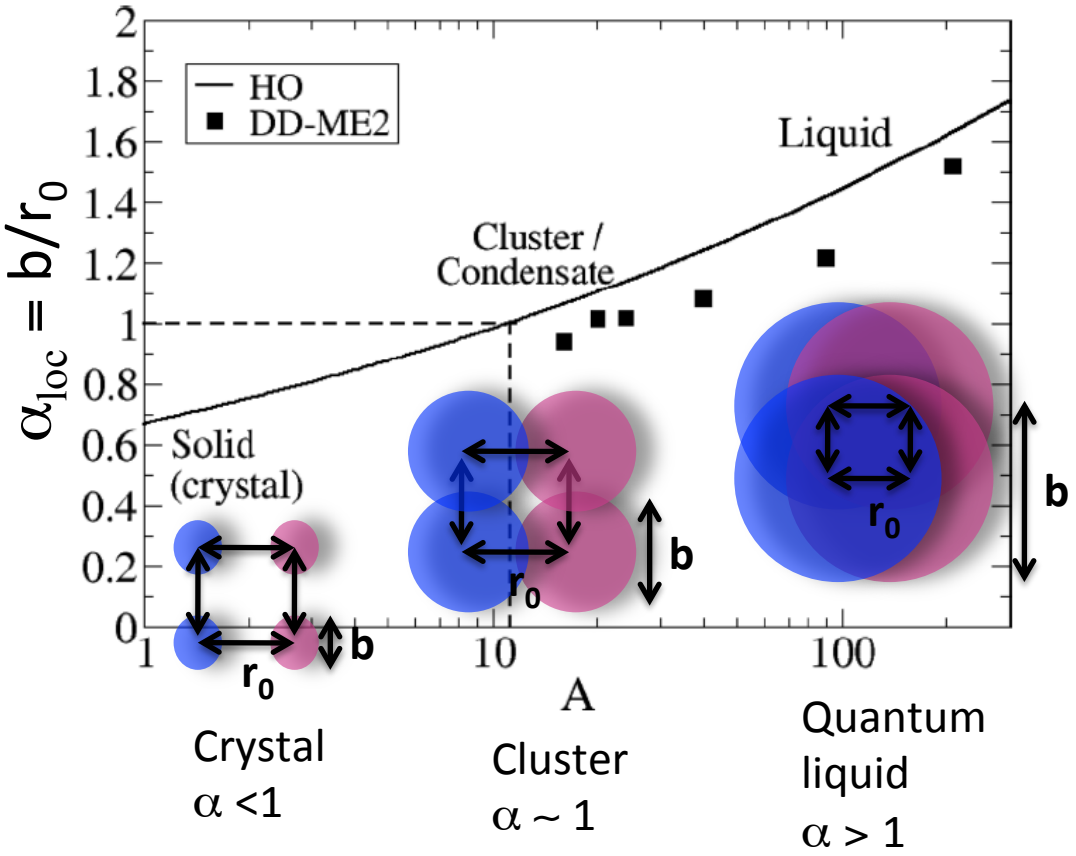
EDF [ρ ; σ,ω,ρ,π,A]

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

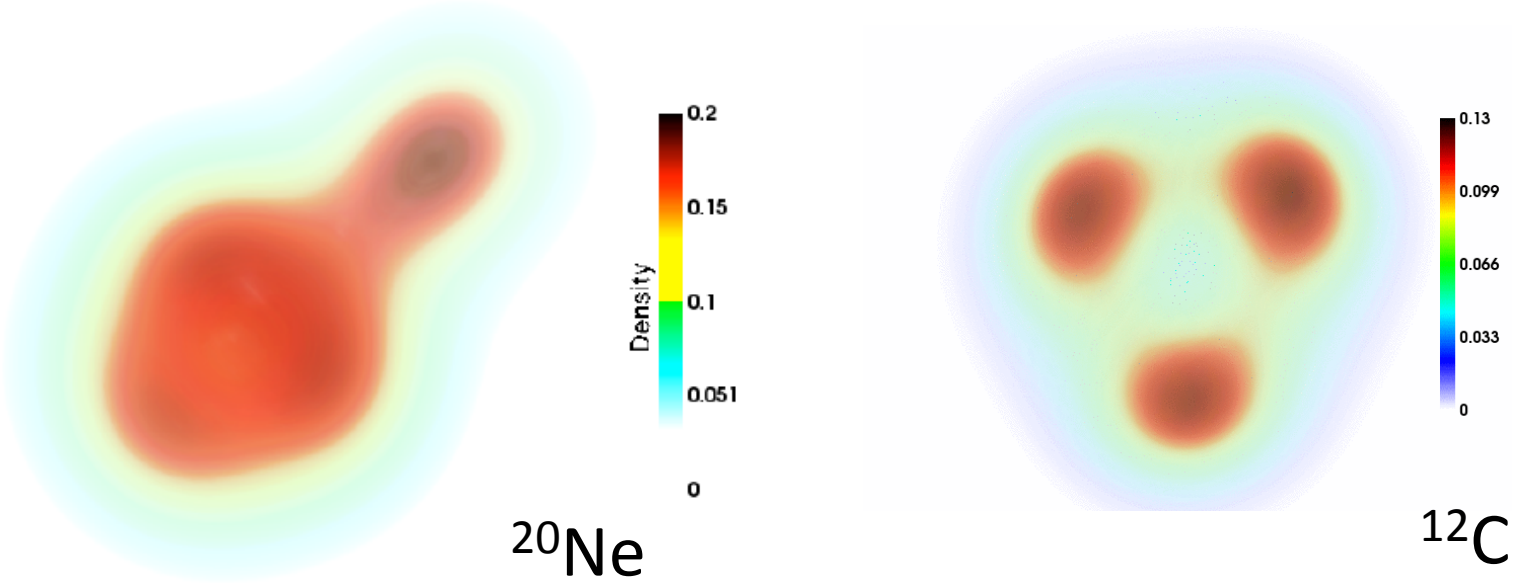
$$W(r) = [V + S](r)$$

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

Clusters: hybrid nuclear crystal and liquid



Quadrupole + octupole deformations

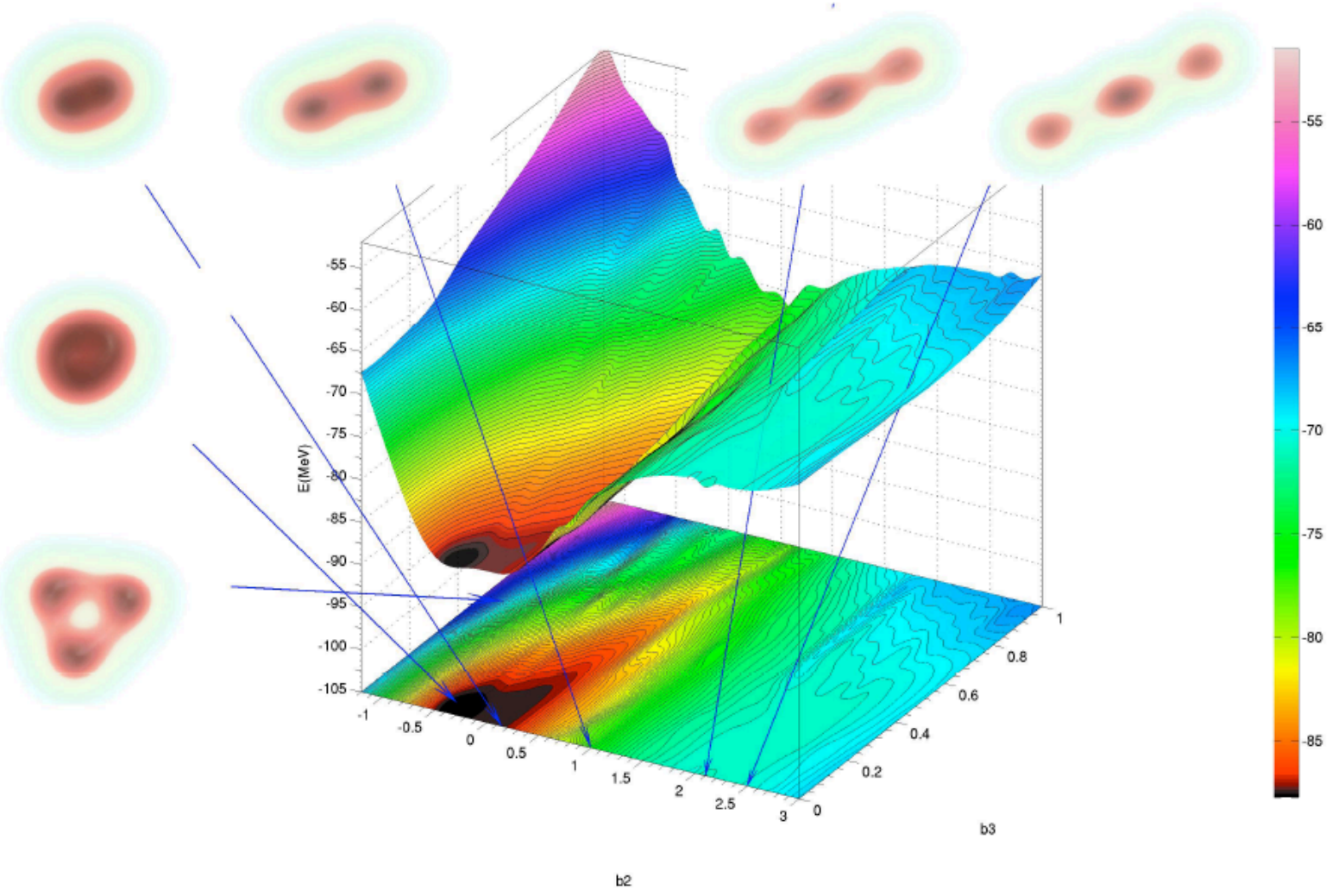


^{20}Ne ^{12}C

Constrained RHB (DDME2)
β_2, β_3, parity proj.

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

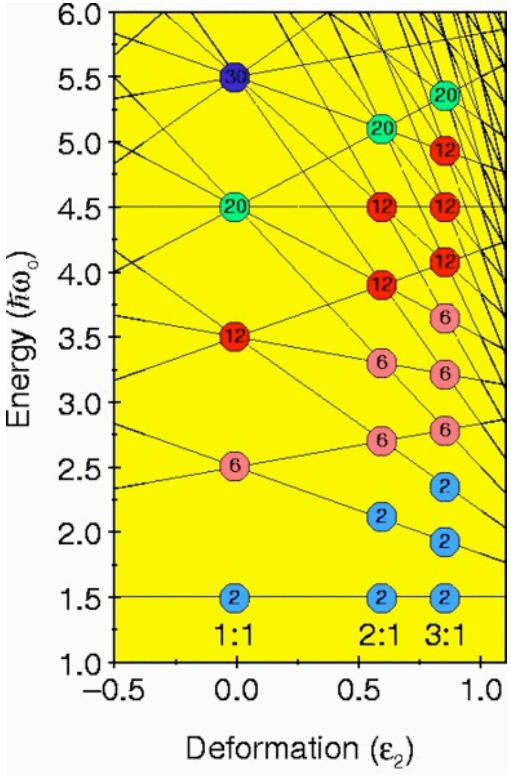
Parity-projected quadrupole/octupole results



$^{12}\mathrm{C}\ (K^{\pi} = 0^{+})\ \mathrm{PAV}$

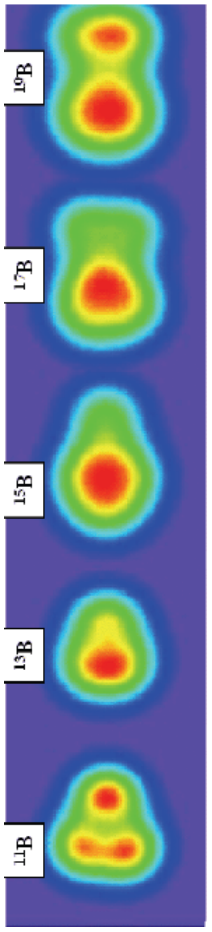
Towards a global picture

deformation and degeneracy



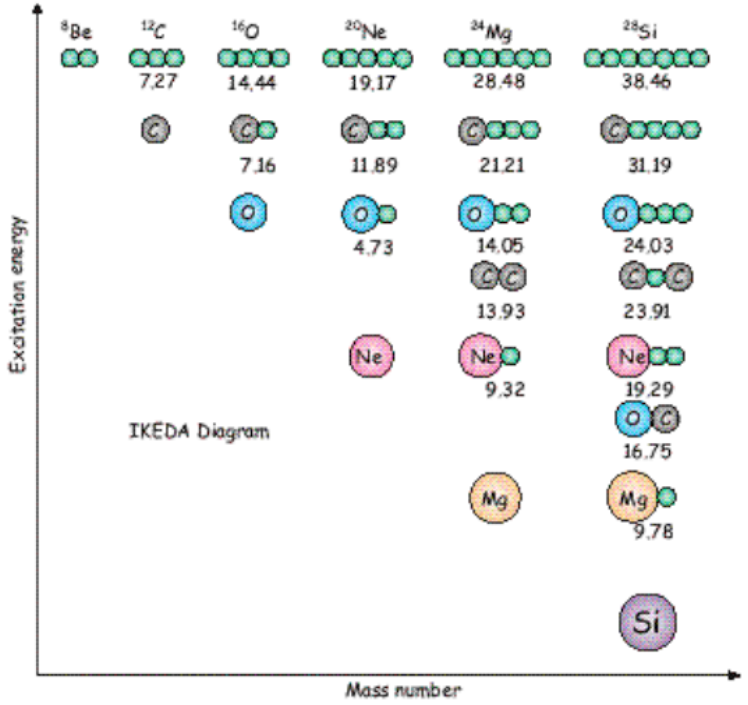
Von Oertzen, Freer, Kanada-En'yo,
Phys. Rep. 432(2006)43

neutron excess



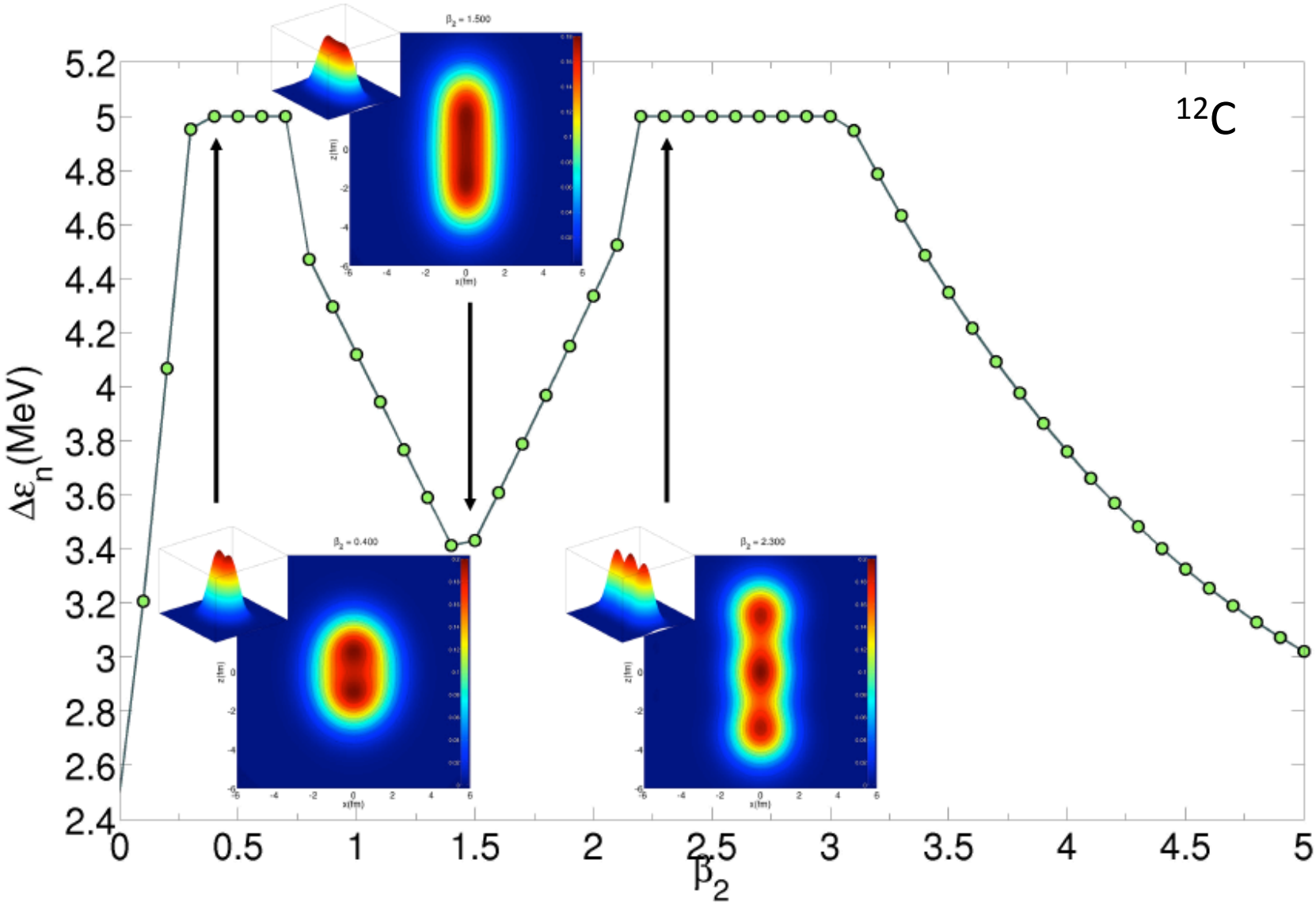
Kanada-En'yo, Horiuchi,
PRC 52(1995)647

excitations



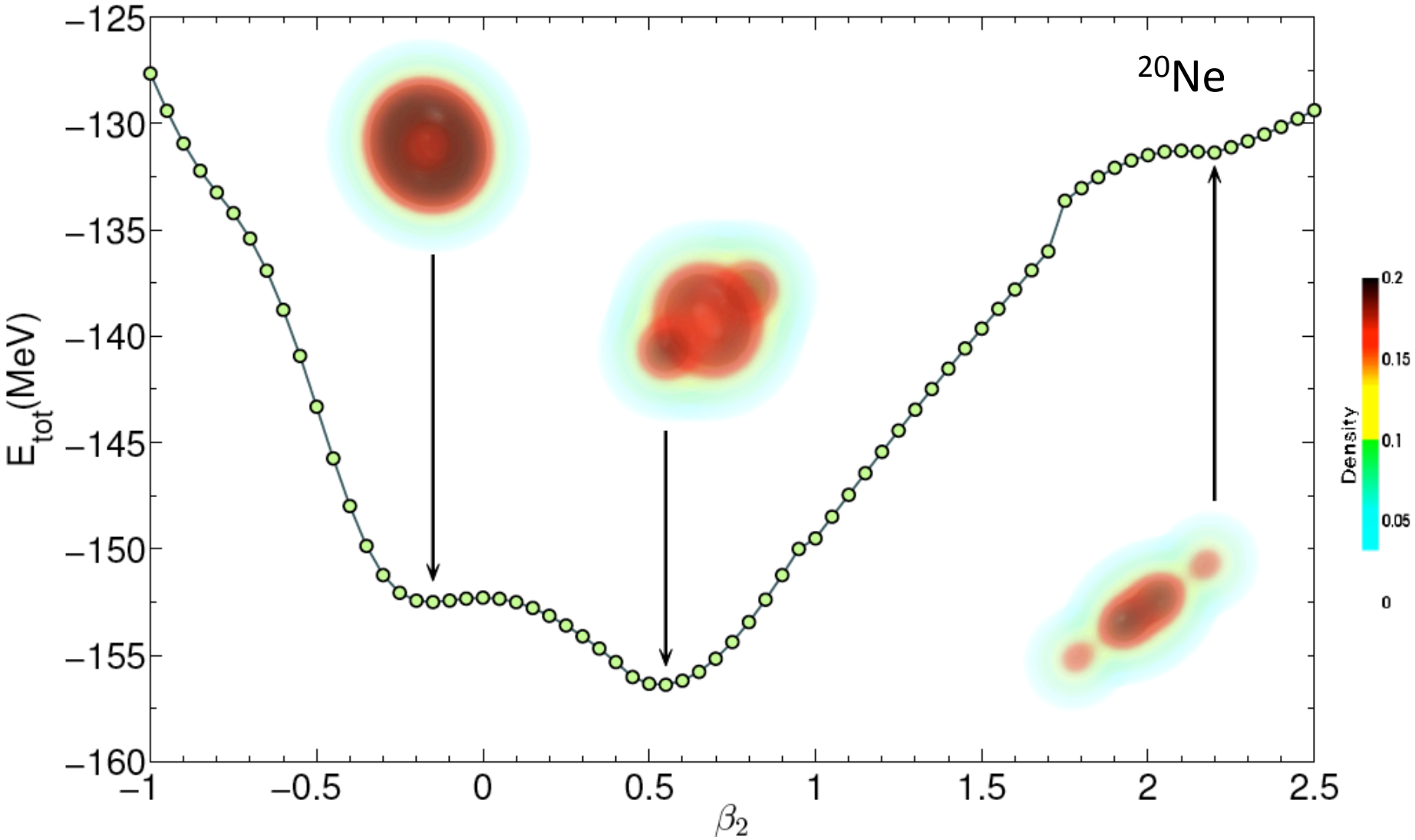
Ikeda, Tagikawa, Horiuchi,
Prog. Theor. Phys. 464(1968)464

Effect of the deg. raising

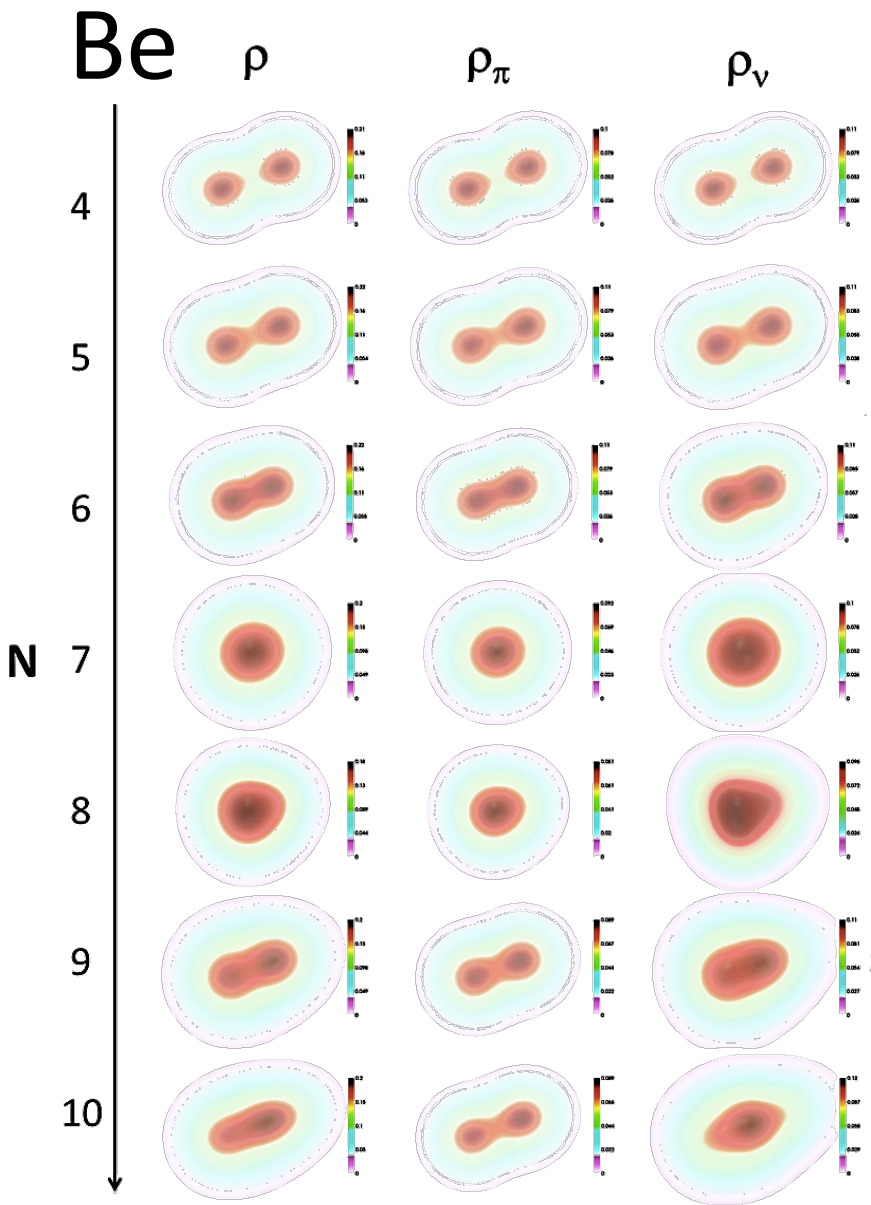


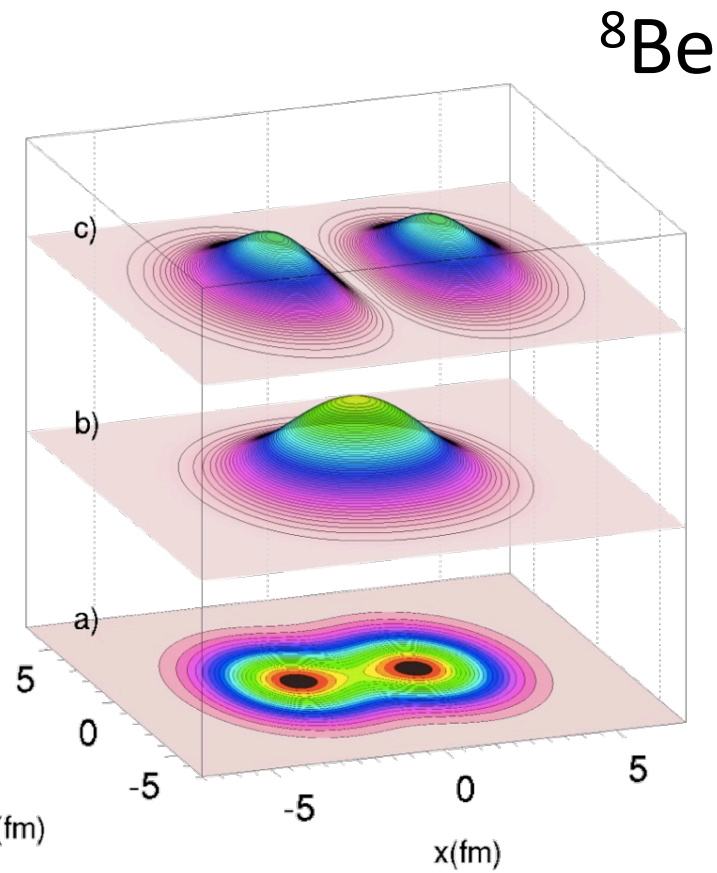
J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 90(2014)054329

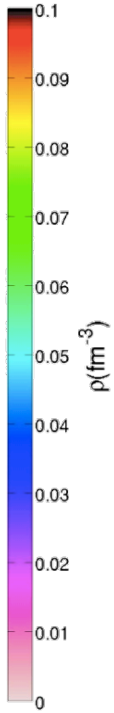
Effect of deformation & excitation



Isotopic dependence

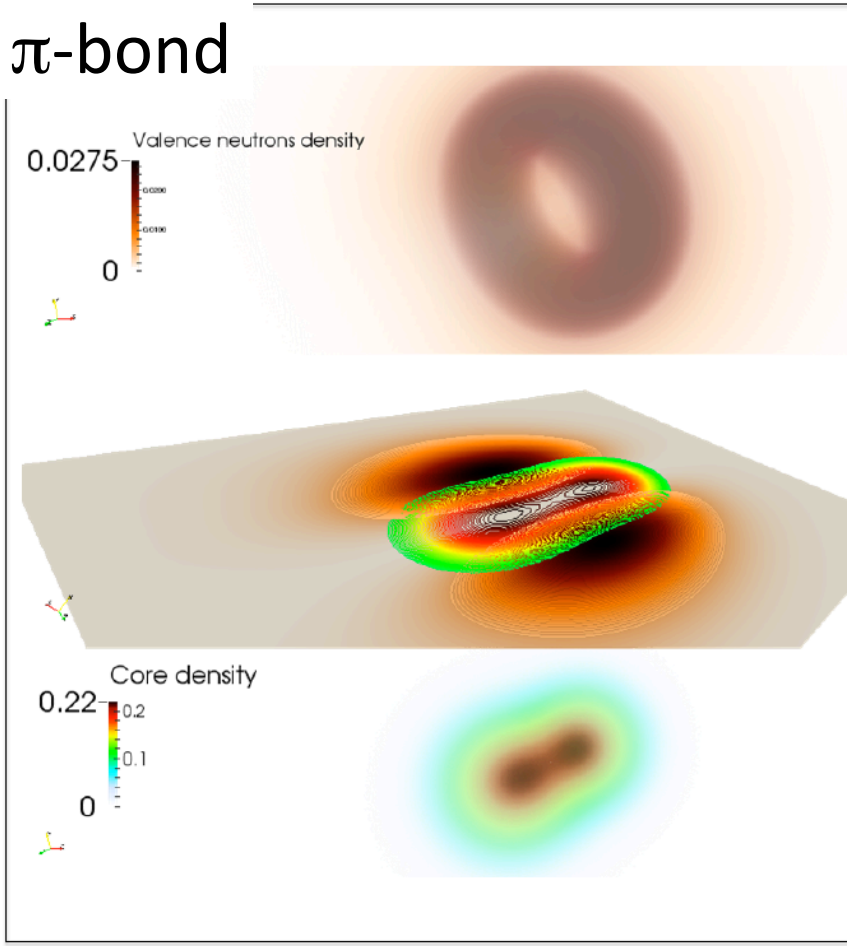




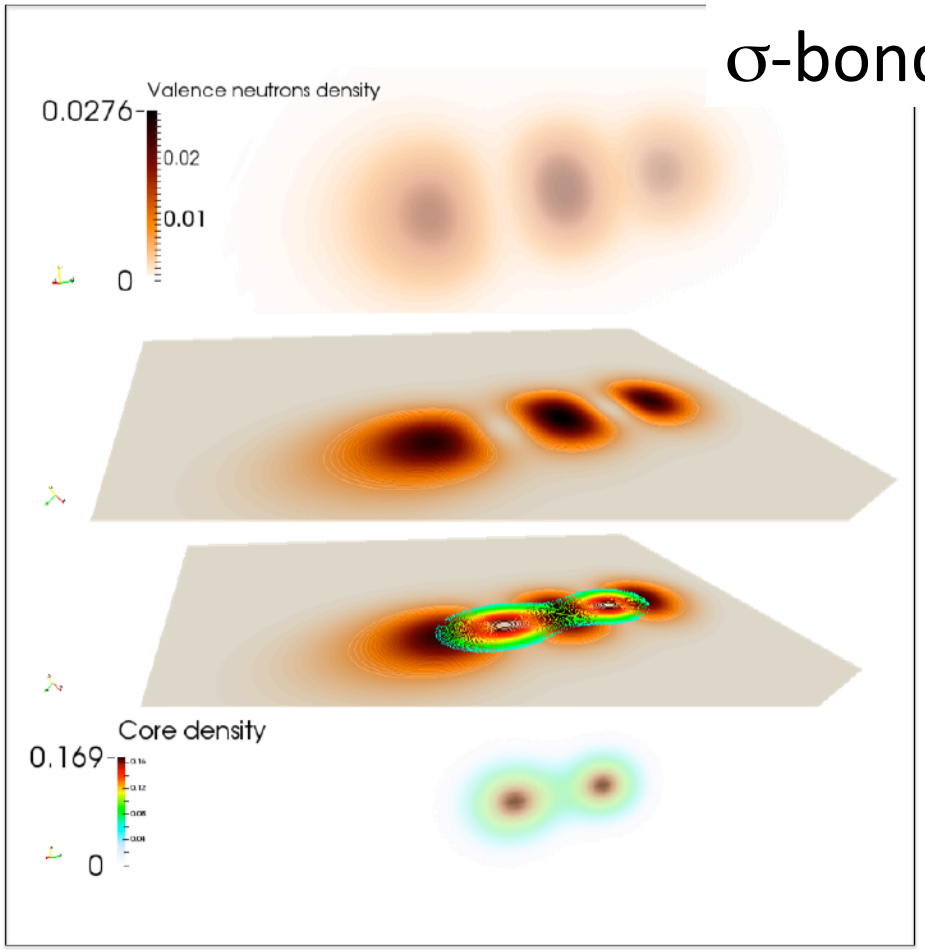


n valence molecular bond

π-bond



σ-bond



^{10}Be g.s.

^{10}Be exc.

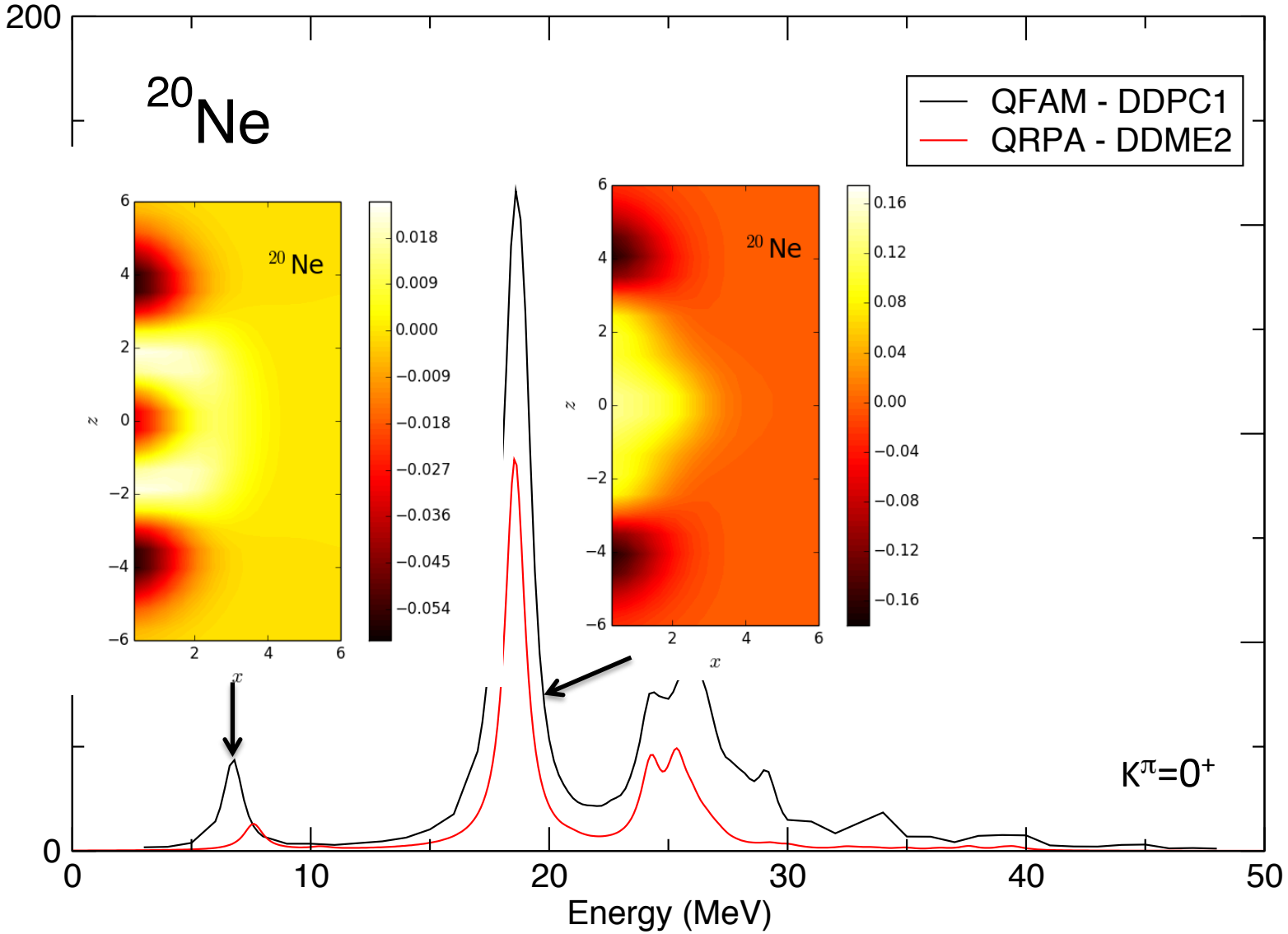
Excitations modes as clustering signature

- Relativistic + deformation: RQRPAz
- Vibration + rotations: collective Bohr Hamiltonian
- Correlations: IBM mapping
- Nucleus-to-clusters transition

QRPA-FAM

FAM: Iterative method to reach the QRPA solution

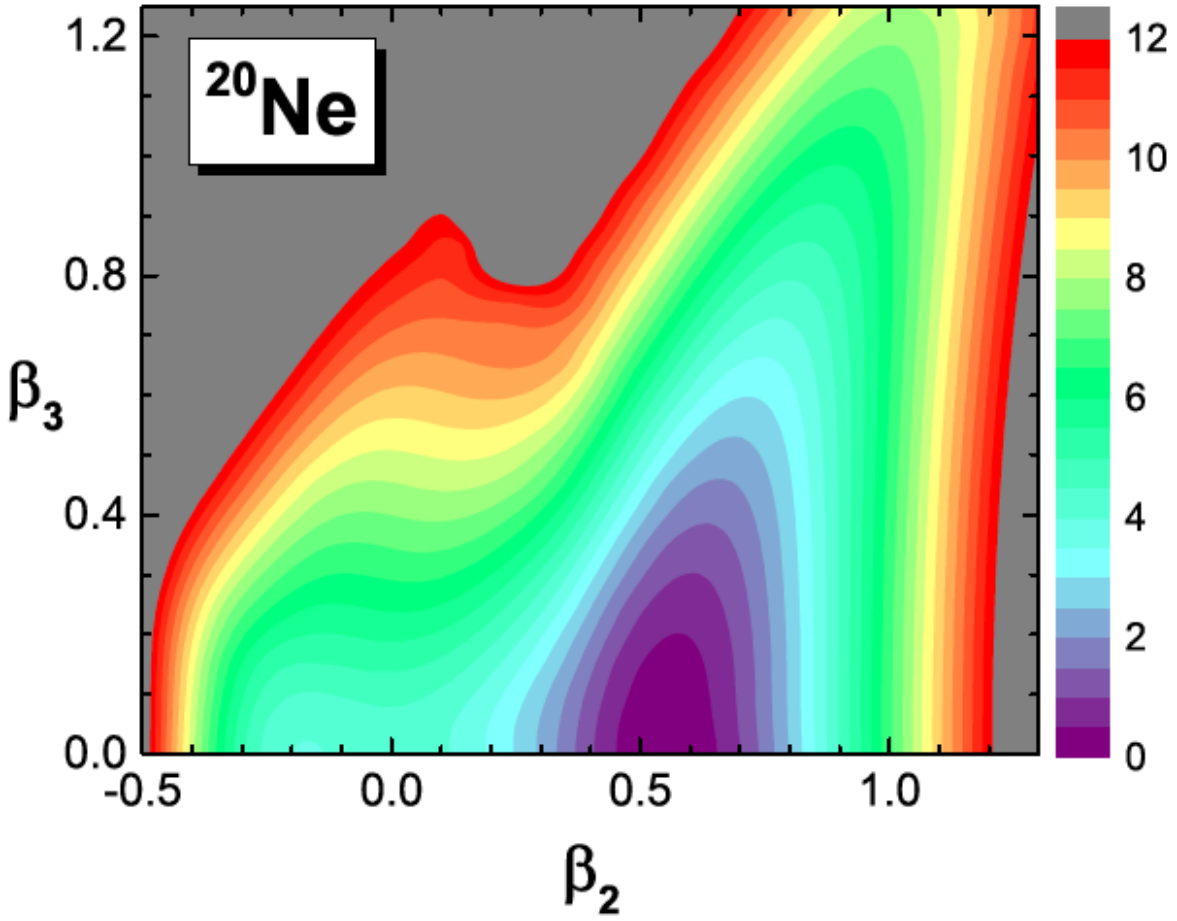
T. Niksic, D. Peña Arteaga, D. Vretenar



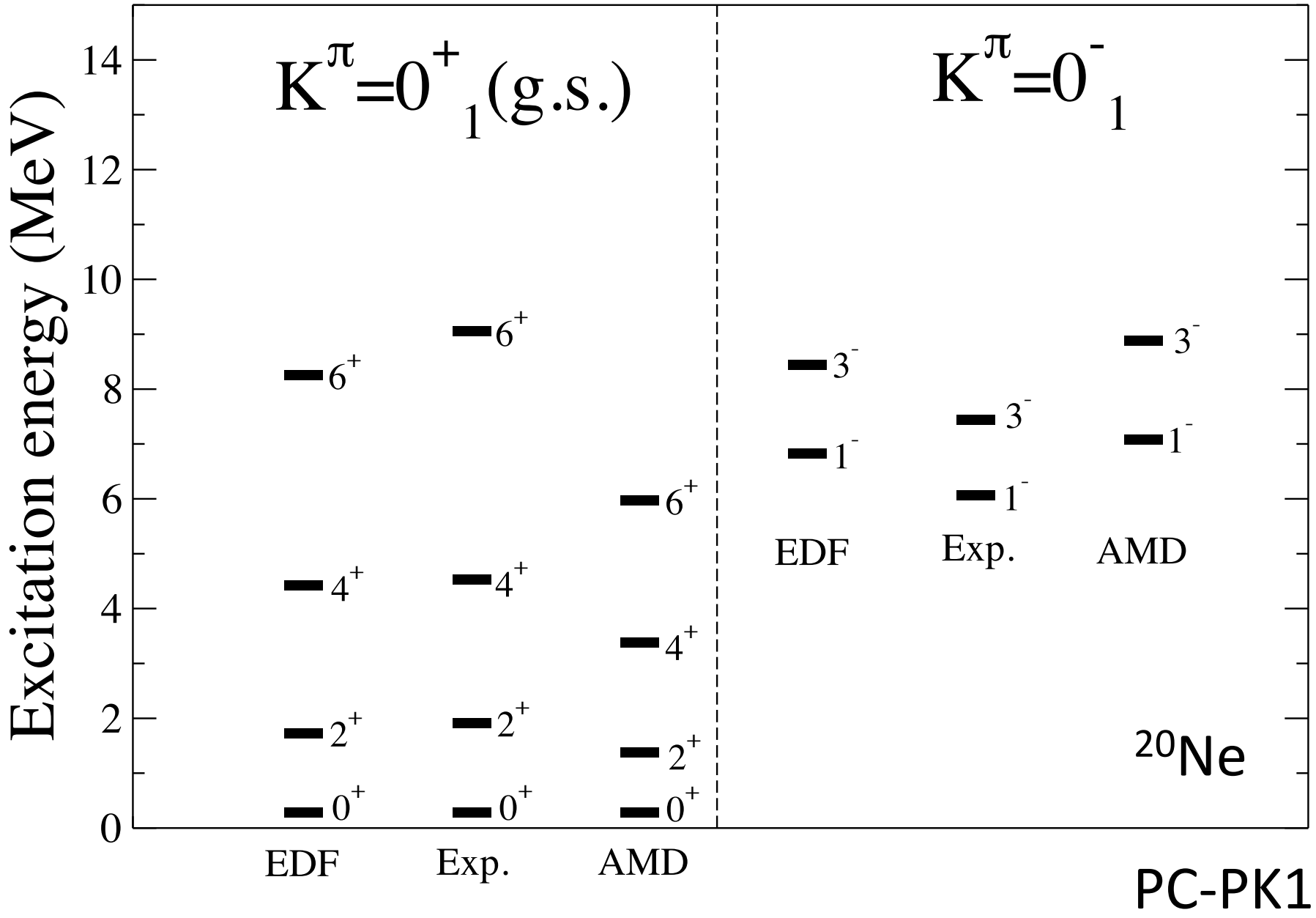
5DCH

Z.P. Li, T. Niksic, D. Vretenar

$$\mathcal{H}_{\rm coll} = \mathcal{T}_{\rm vib}(\beta_2, \beta_3) + \mathcal{T}_{\rm rot}(\beta_2, \beta_3, \Omega) + \mathcal{V}_{\rm coll}(\beta_2, \beta_3)$$



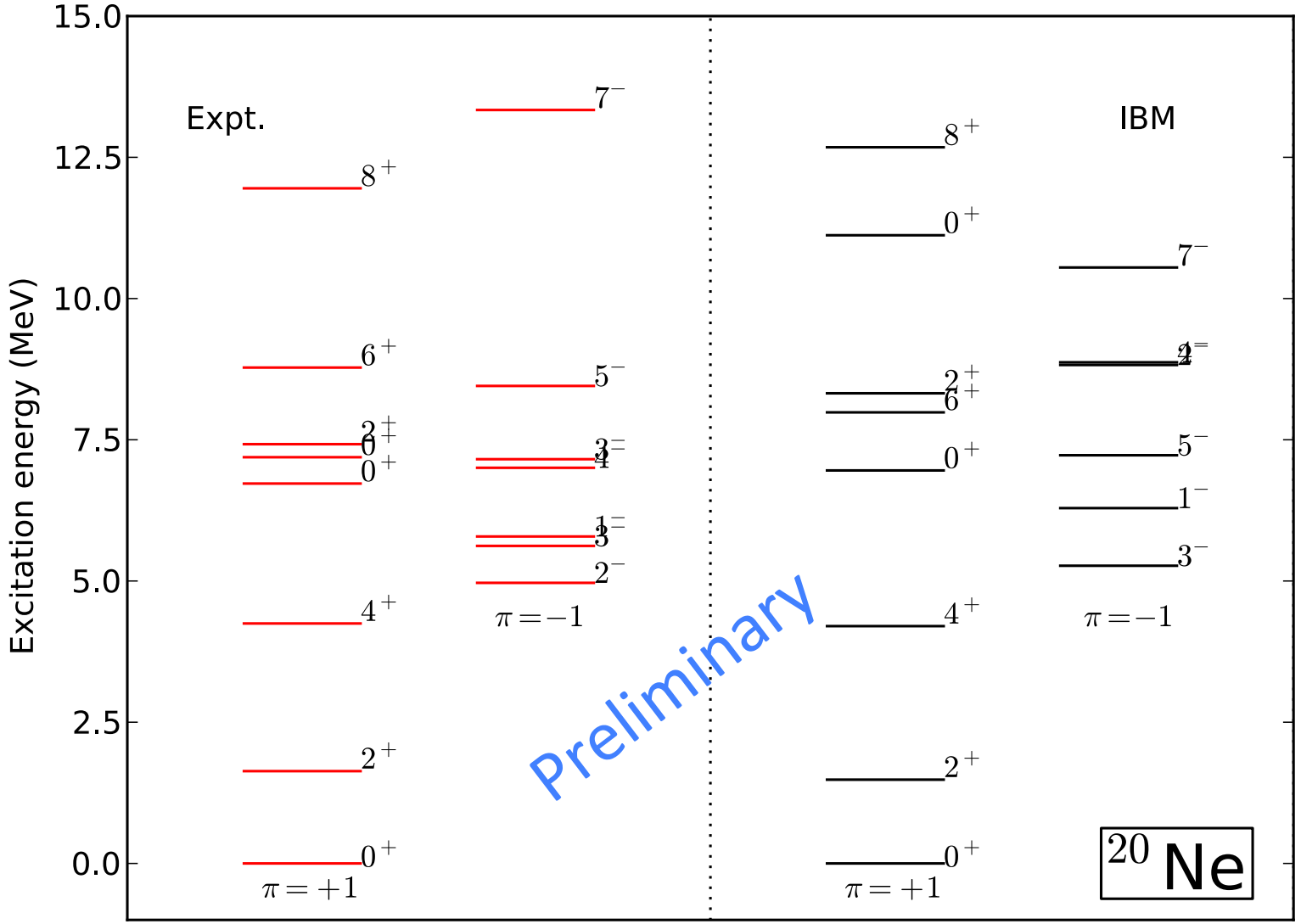
5DCH


Excitation energy (MeV)
0
2
4
6
8
10
12
14
$K^\pi=0^+_1$(g.s.)
$K^\pi=0^-_1$
0^+
2^+
4^+
6^+
6^+
4^+
2^+
0^+
6^+
4^+
2^+
0^+
3^-
1^-
3^-
1^-
3^-
1^-
EDF
Exp.
AMD
EDF
Exp.
AMD
^{20}Ne
PC-PK1

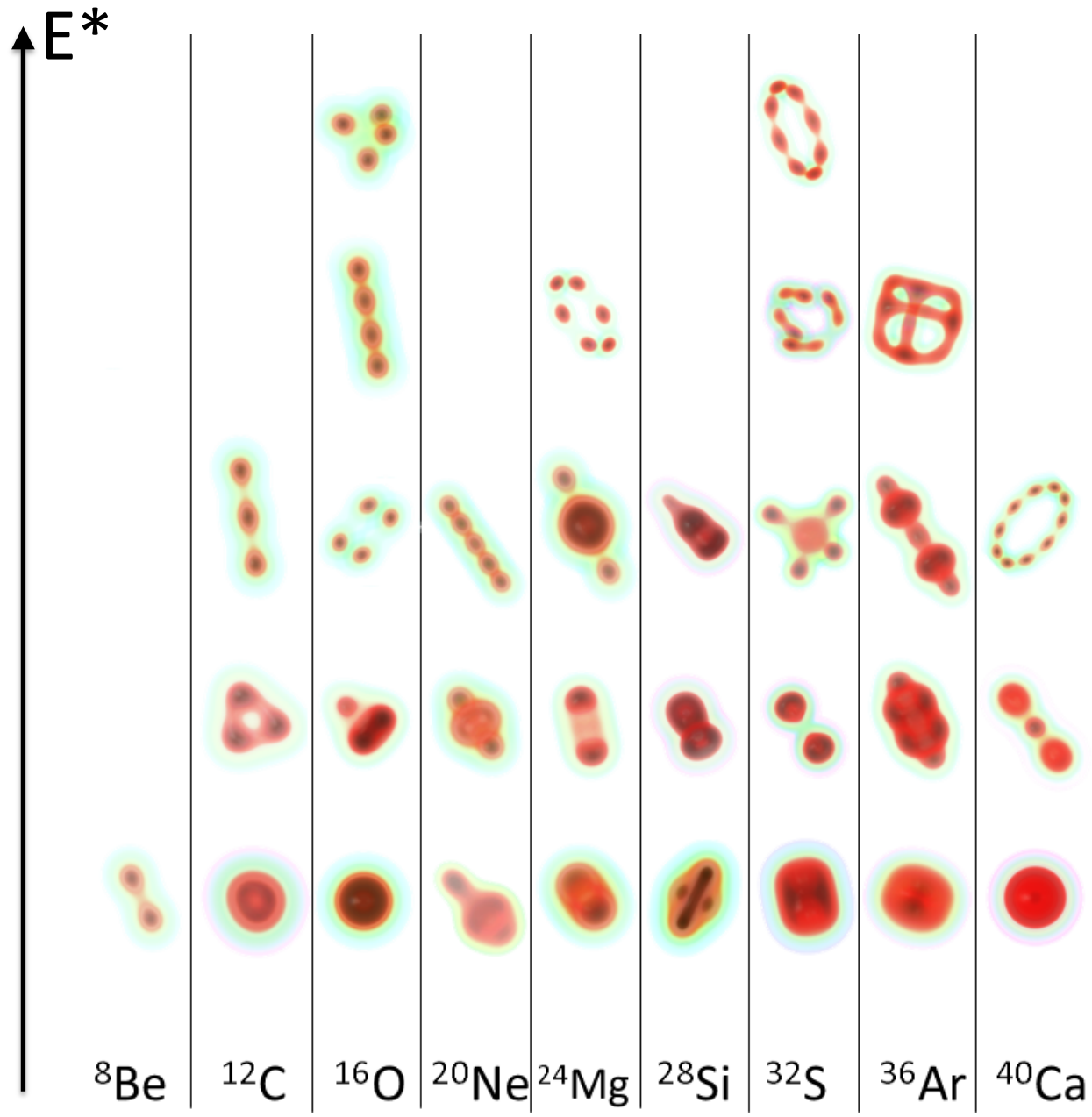
RMF+IBM

$$\hat{H} = \hat{H}_{sd} + \hat{H}_f + \hat{H}_{sdf}$$

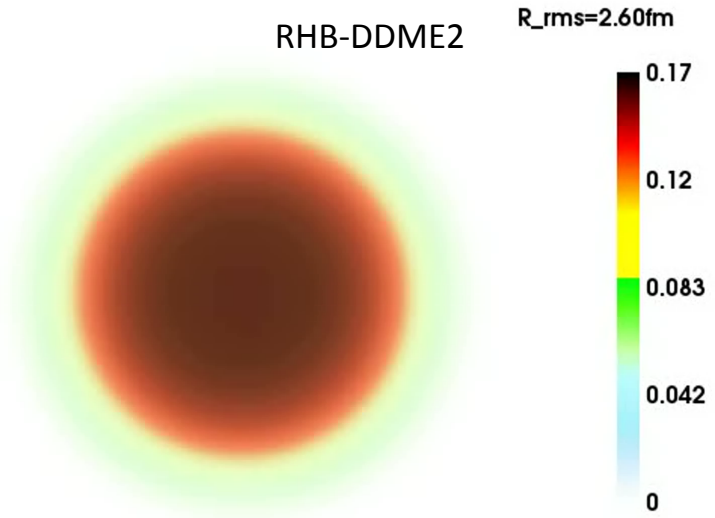
K. Nomura, T. Niksic, D. Vretenar



Microscopic grounds to Ikeda's conjecture



Clusters in low density nuclear matter



Dilution of ^{16}O

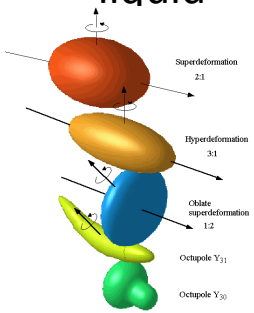
See also: P. Schuck and M. Girod PRL 111 (2013) 132503

$b/r_0 \sim 1 \longrightarrow T \sim 3$ MeV

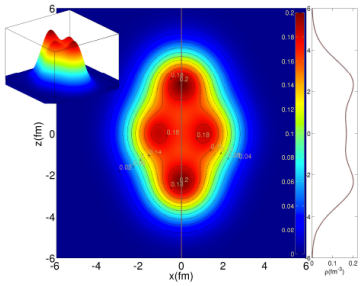
Exp: see B. Borderie et al. PLB 755 (2016) 475

States of matter

Quantum liquid



Cluster



Solid

Liquid

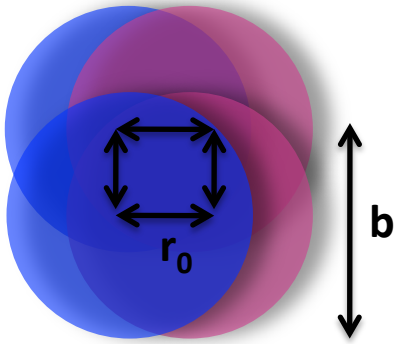
Gas

MACRO

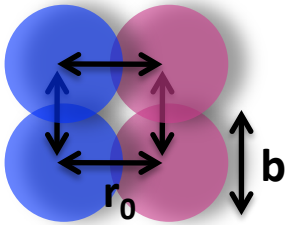
$\alpha_{loc} = b/r_0$; Λ ; λ

ρ; A

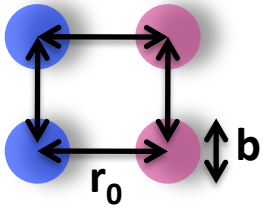
T



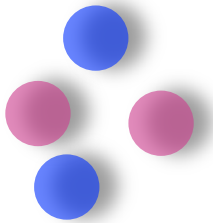
Delocalised dense system



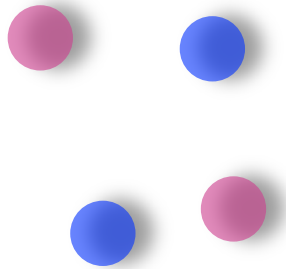
Molecule



Crystal



Epot<Ekin



Epot<<Ekin

MICRO

Quantum

Classical

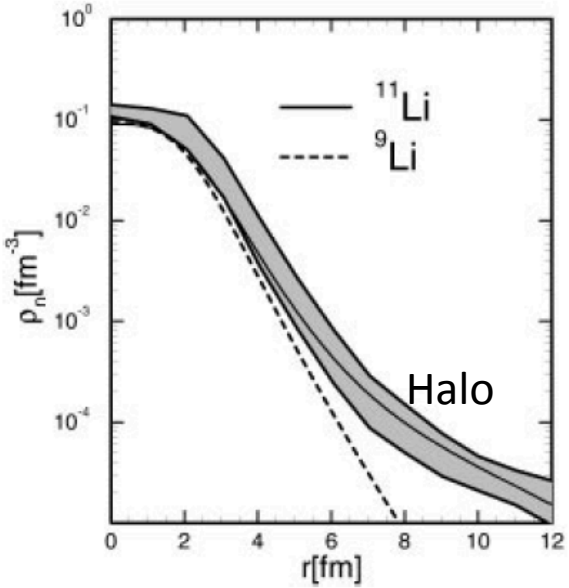
Haloes and clusters

- Halo: **binding energy** impacts spatial behavior **outside** the potential

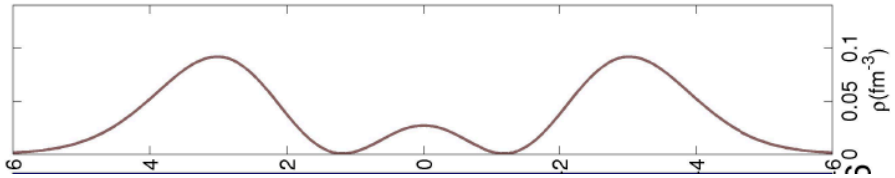
Hansen and Jonson, Eur. Phys. Lett. 4(1987)409

- Cluster: **depth of the potential** impacts spatial behavior **inside** the potential

Ebran, Khan, Niksic, Vretenar, Nature 487 (2012) 341



Meng, Ring, PRL77(1996)3963



Cluster

Summary

« *The nature of the transition from independent-particle motion to the*

crystalline state and the associated value of the characteristic parameter

present significant unsolved problems »

Bohr & Mottelson Vol I

- Localisation study in nuclei supports:
  clusters = hybrid states between quantum liquid and crystal
- Role of the localisation parameter
- Rel. EDF provides unified description of nuclear states: liquid drop, cluster (Ikeda), and halo
- Role of deformation and neutron excess in clusters: microscopically understood
- Comparison with Exp. excited energy spectrum