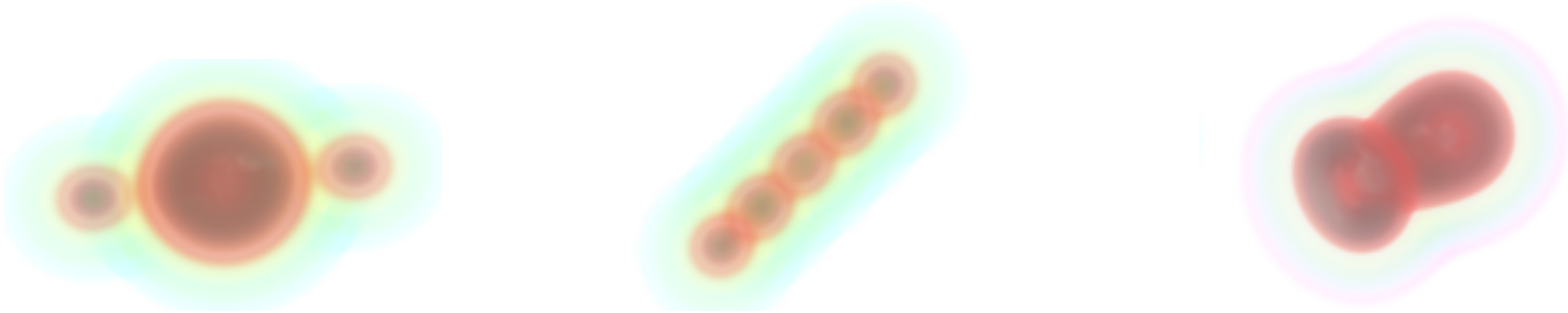

Nuclear clustering in the energy density functional approach

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[1]CEA, DAM, DIF

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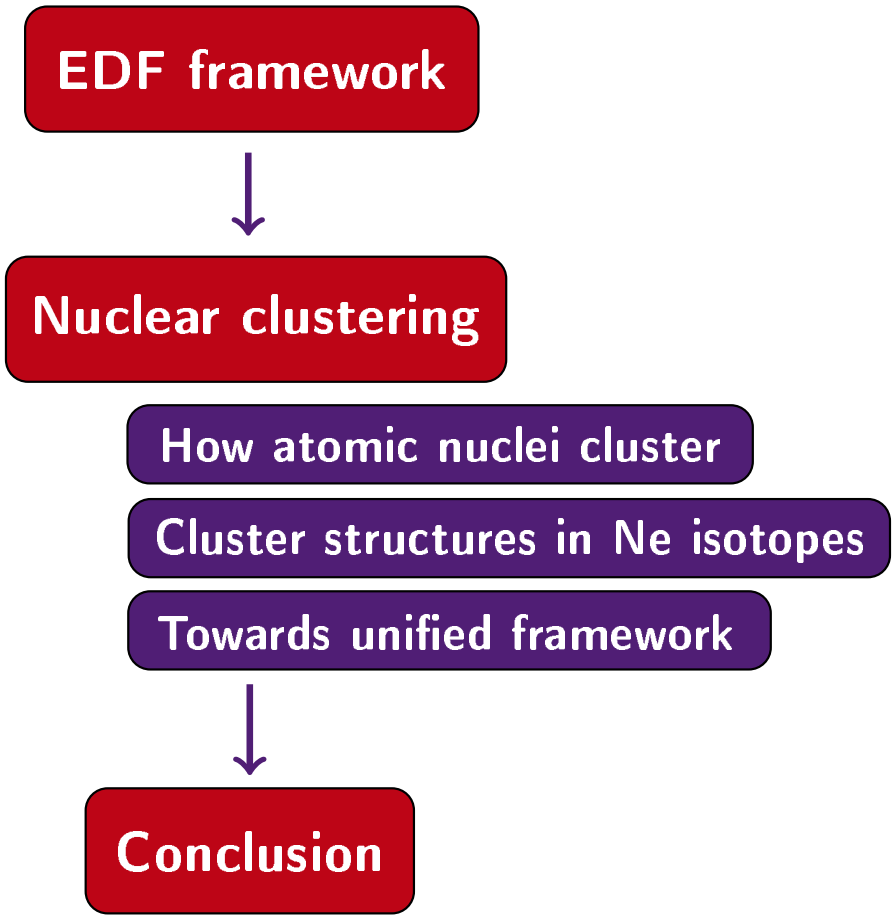
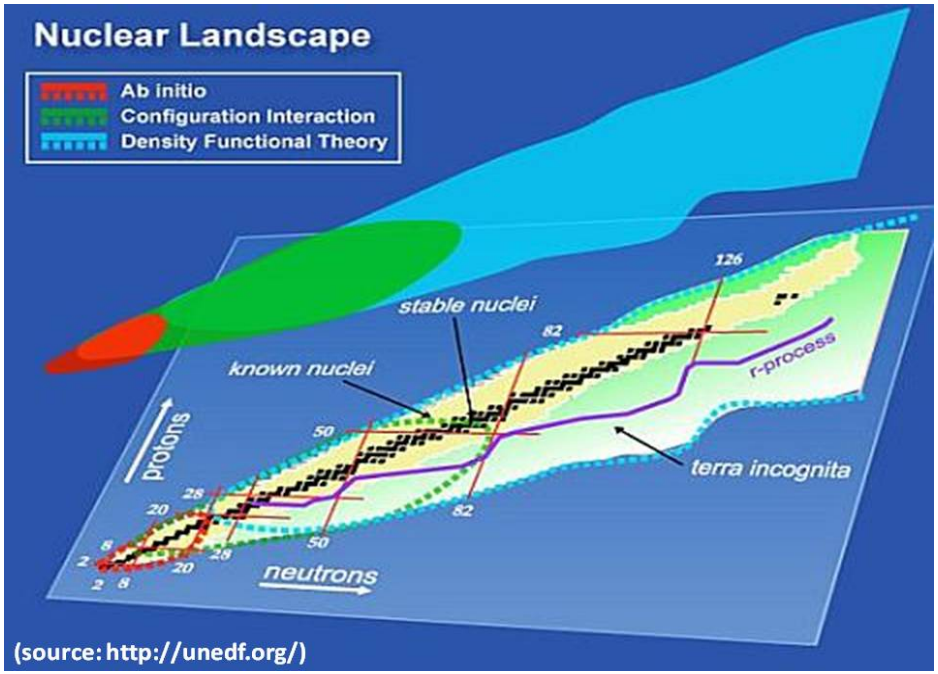
Outline

Brief outline of the talk



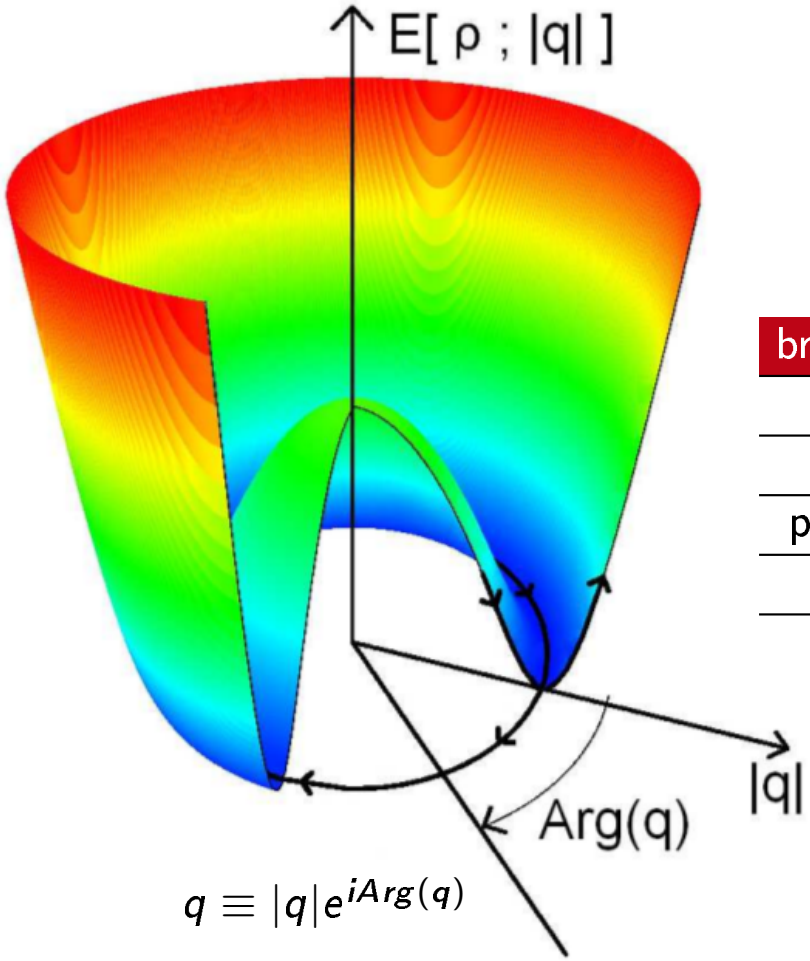
EDF framework

EDF framework
Basic properties of the theory



- the nuclear many-body problem is mapped onto a one-body problem
- covariant functionals: meson-exchange or contact interaction
- the coupling parameters are fine-tuned to experimental data
- self-consistent calculation of bulk properties

EDF framework
Spontaneous symmetry breaking



broken symmetry	nuclei	cause
translational	all	localization
rotational	non-spherical	deformation
particle number	superfluid	pairing
parity	pear-shaped	octupole def.

T. Duguet, Lectures in Theoretical Nuclear Structure (Leuven, 2015).

EDF framework
Symmetry restoration and configuration mixing

- linear combination of symmetry-projected RHB states

$$\underbrace{|JM\pi;\alpha\rangle}_{\text{collective state}} = \sum_j \sum_K \underbrace{f_\alpha^{JK\pi}(q_j)}_{\text{weight function}} \underbrace{\hat{P}^J_{MK}\hat{P}^\pi}_{\text{projectors}} \underbrace{|\phi(q_j)\rangle}_{\text{RHB state}}$$

- variational principle leads to HWG equation

$$\sum_j [\underbrace{\mathcal{H}^{J\pi}(q_i,q_j)}_{\text{Hamiltonian kernel}} - E_\alpha^{J\pi} \underbrace{\mathcal{N}^{J\pi}(q_i,q_j)}_{\text{norm kernel}}] f_\alpha^{J\pi}(q_j) = 0$$

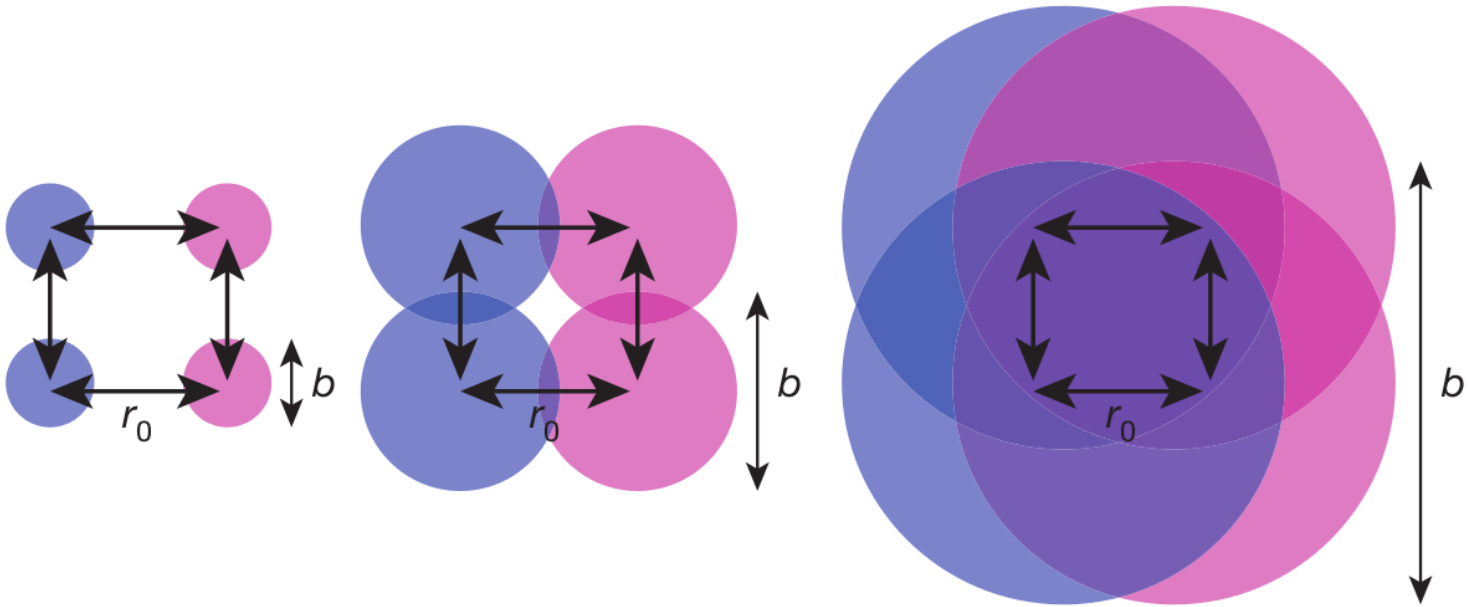
- after *a bit* of maths, we obtain modified HWG equation:

$$\sum_l \mathcal{H}^{J\pi c}_{kl} g_l^{J\pi\alpha} = E_\alpha^{J\pi} g_k^{J\pi\alpha}$$

- calculation of excitation spectra and various observables

Nuclear clustering

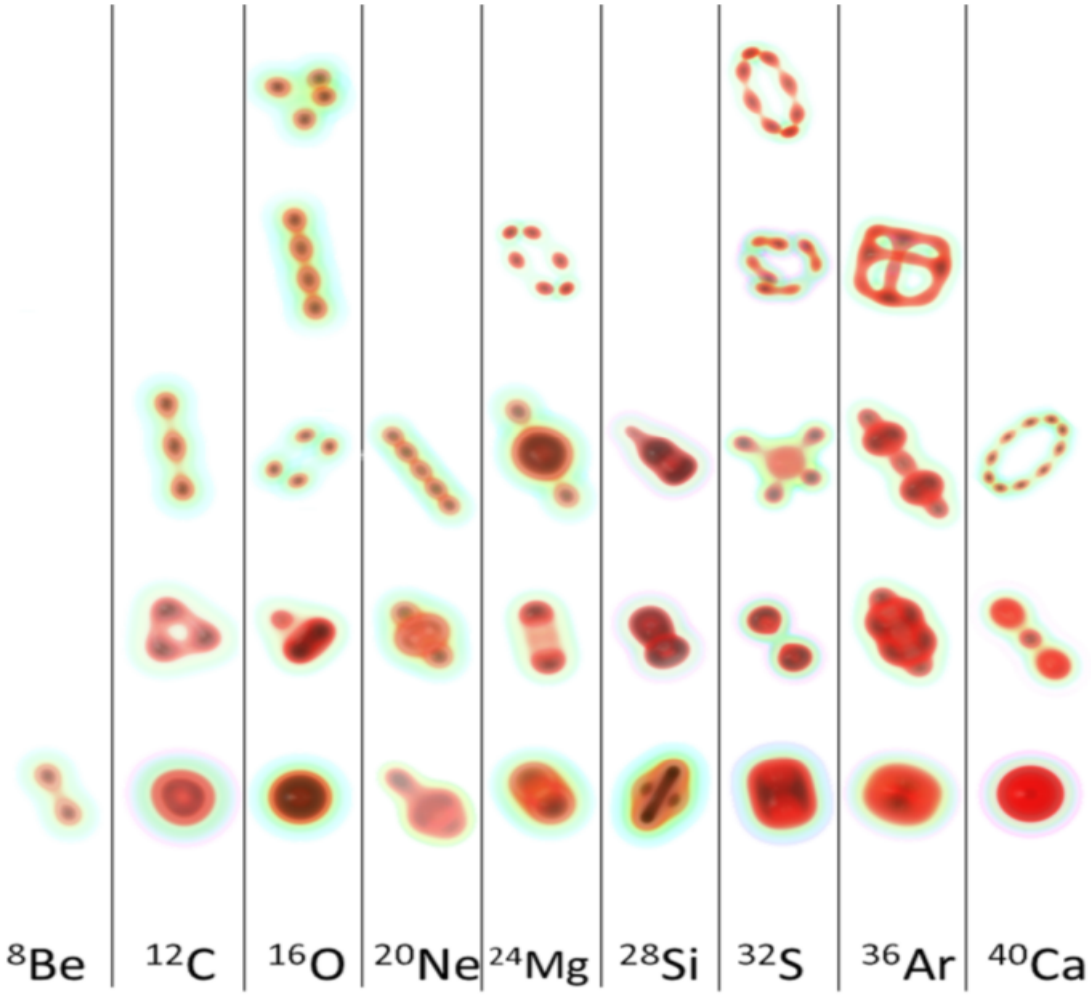
Nuclear clustering
Clustering as transitional phenomenon



Crystal **Cluster** **Quantum liquid**

J.-P. Ebran *et al.*, Nature 487, 341 (2012).

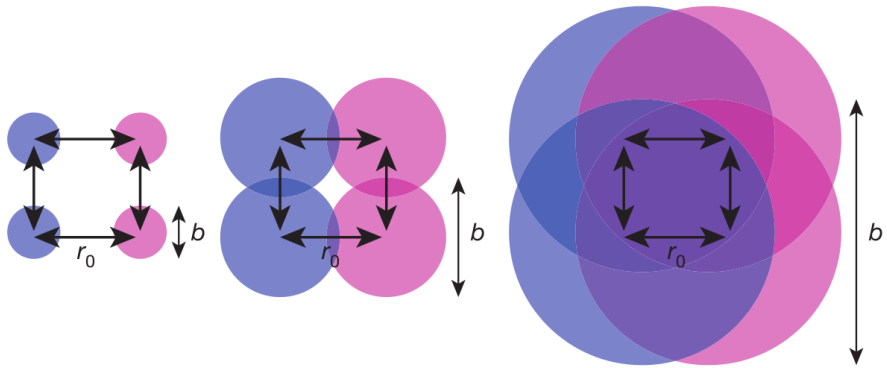
Nuclear clustering
Variety of shapes



J.-P. Ebran *et al.*, PRC 90, 054329 (2014).

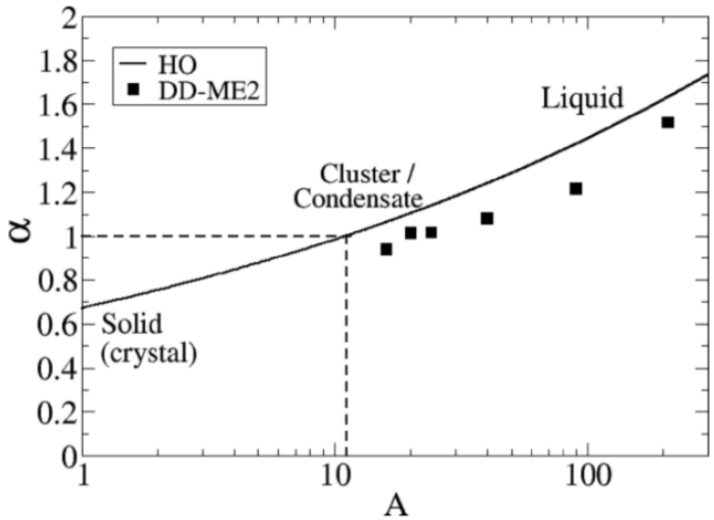
Nuclear clustering
Localisation parameter

$$\alpha = \frac{b}{r_0} = \frac{\sqrt{\hbar} A^{1/6}}{(2 m V_0 r_0^2)^{1/4}}$$



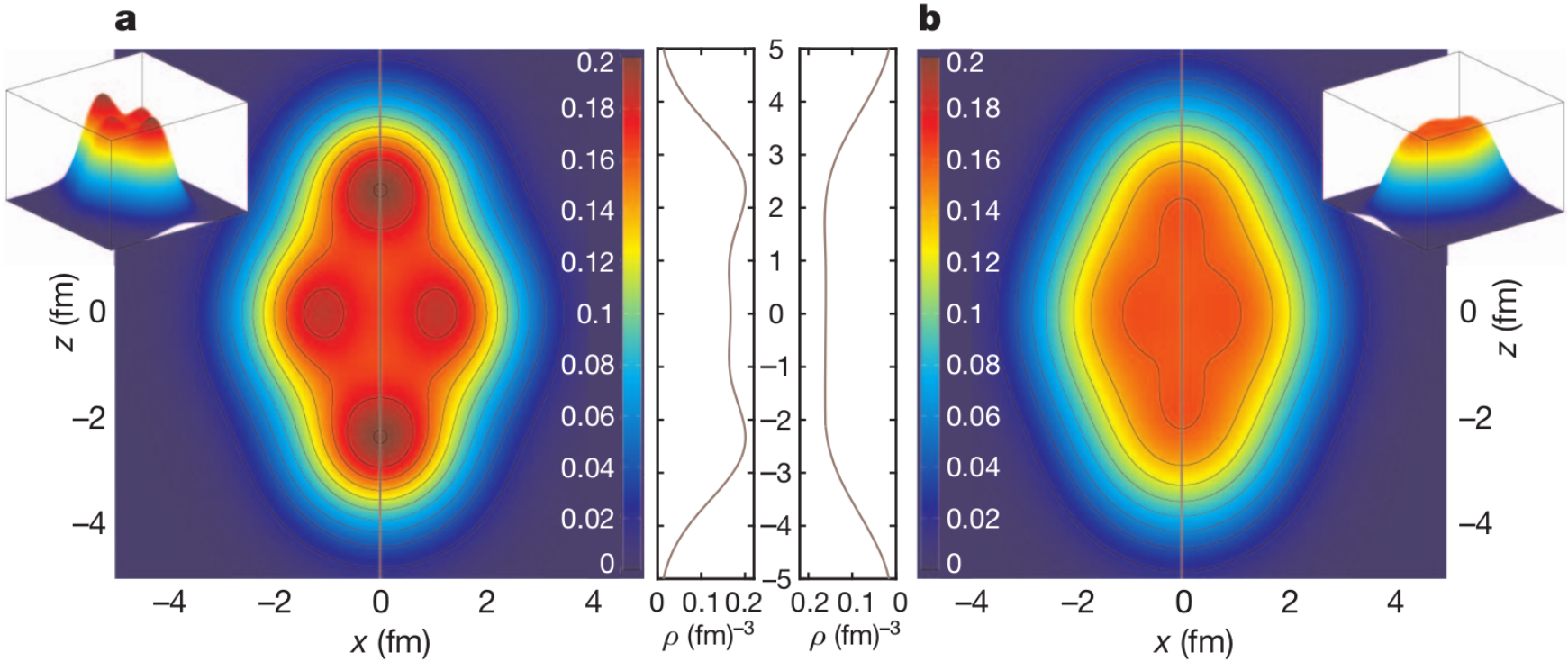
$\alpha < 1$ $\alpha \approx 1$ $\alpha > 1$

	Self-consistent	
	SLy4	DDME2
^{20}Ne	0.99	0.97
^{24}Mg	1.00	0.95
^{28}Si	0.99	0.96
^{32}S	0.99	0.96
^{208}Pb	1.28	1.31



J.-P. Ebran *et al.*, PRC 87, 044307 (2013).

Nuclear clustering
Relativistic vs. non-relativistic functionals



DD-ME2

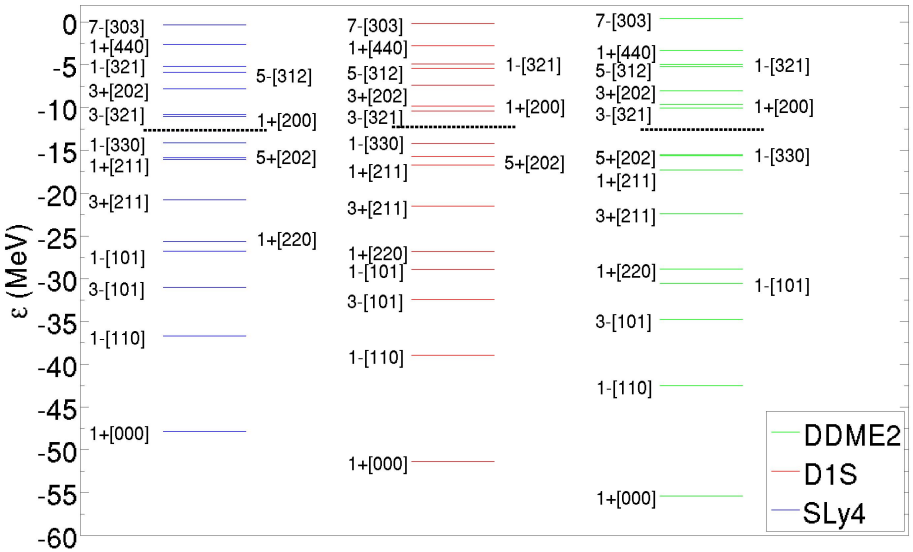
$V_0 = -82.4$ **MeV**

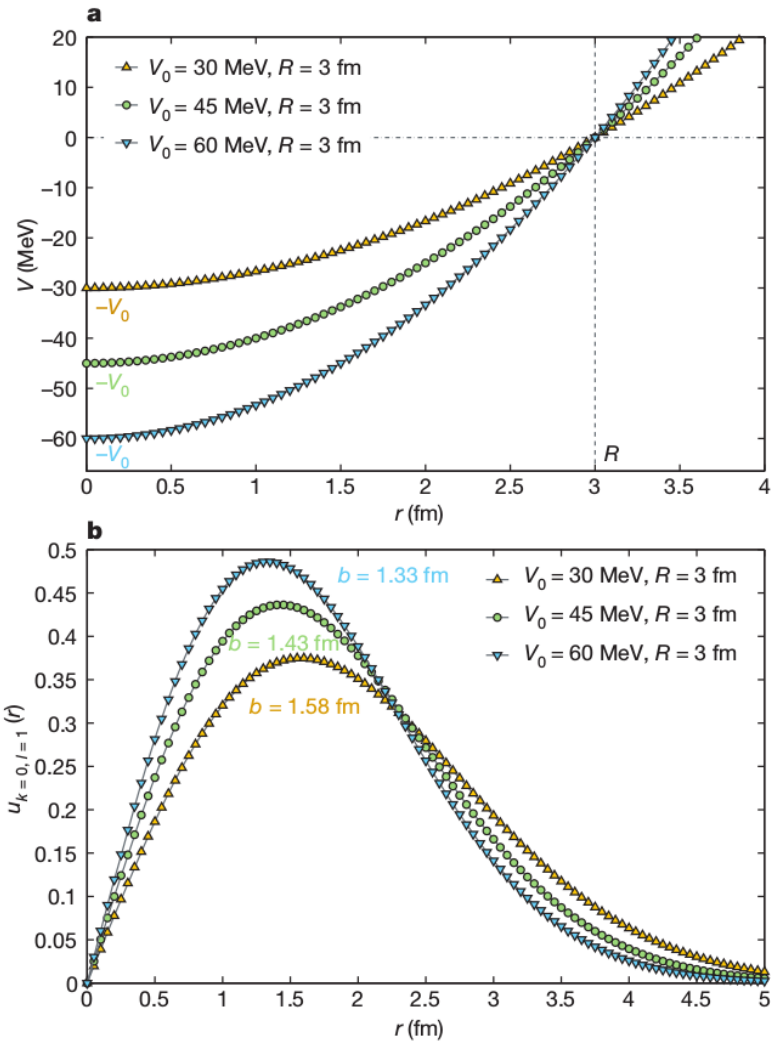
Sly4

$V_0 = -72.4$ **MeV**

J.-P. Ebran *et al.*, Nature 487, 341 (2012).

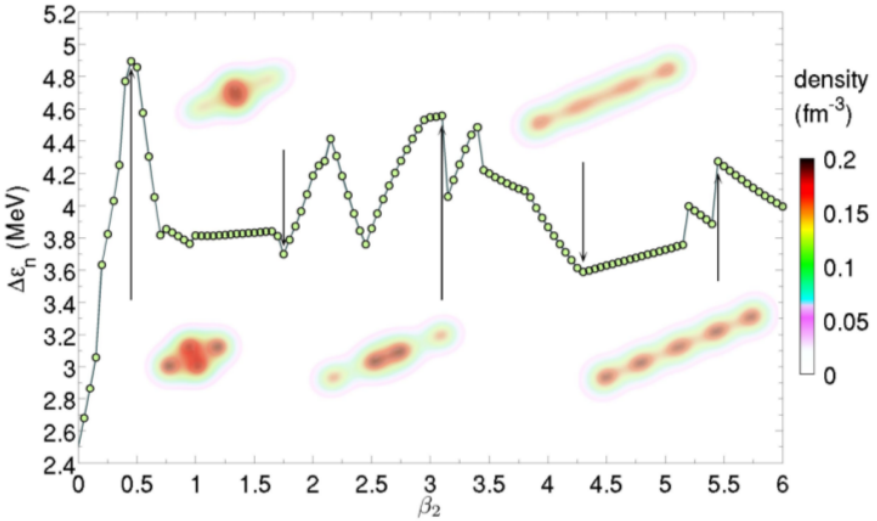
Nuclear clustering
Depth of the confining potential





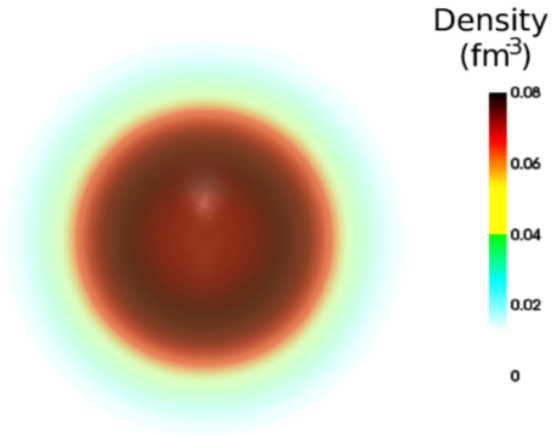
J.-P. Ebran *et al.*, Nature 487, 341 (2012)., PRC 90, 054329 (2014).

Nuclear clustering
Role of deformation and density



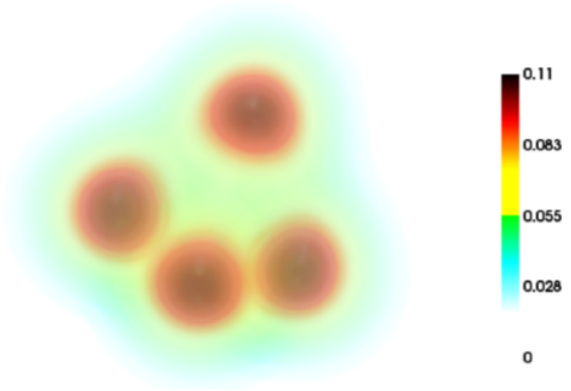
(a)

r = 3.32 fm



(b)

r = 3.34 fm



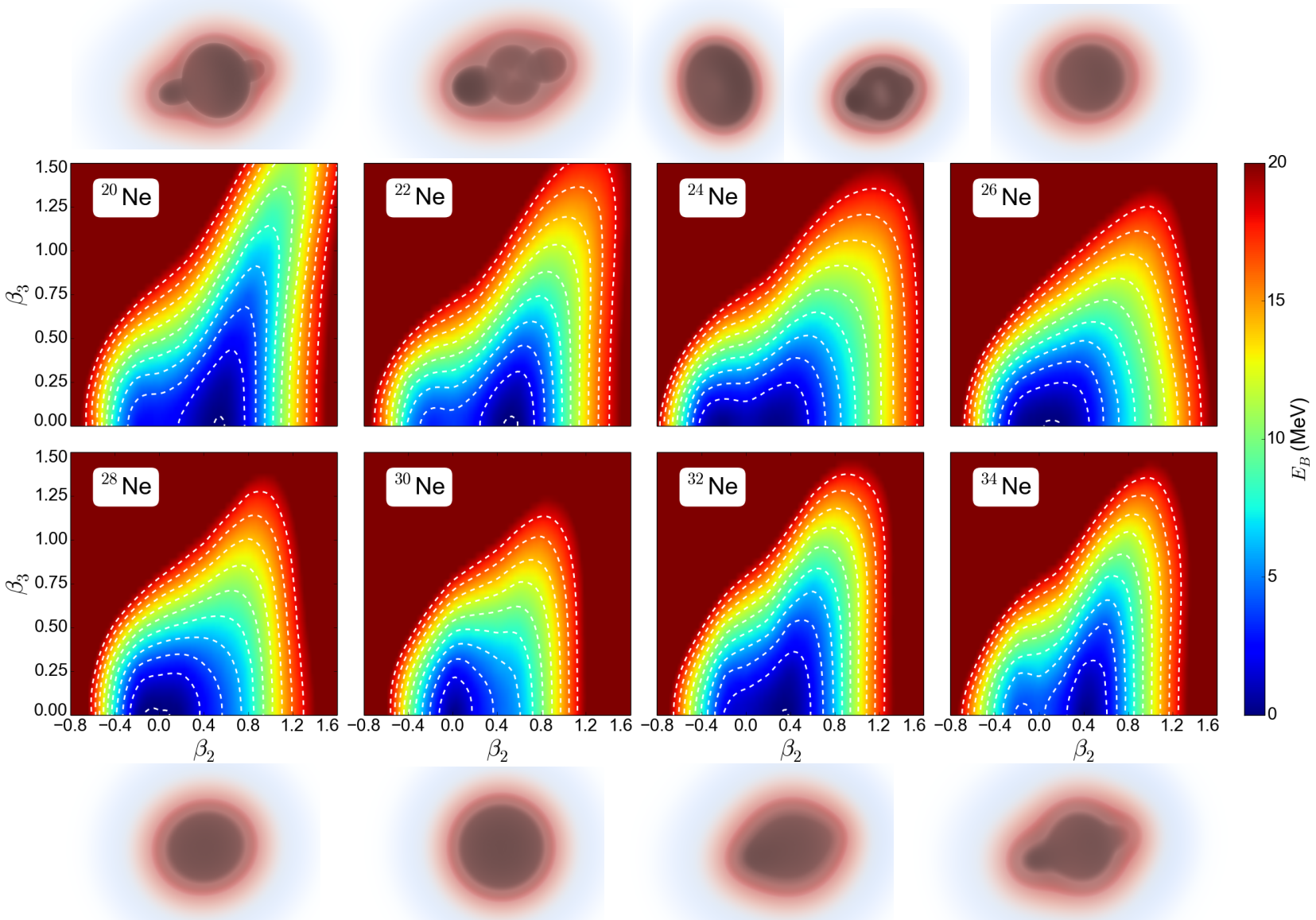
J.-P. Ebran *et al.*, PRC 90, 031303(R) (2014)., PRC 90, 054329 (2014).

Structure of Neon isotopes

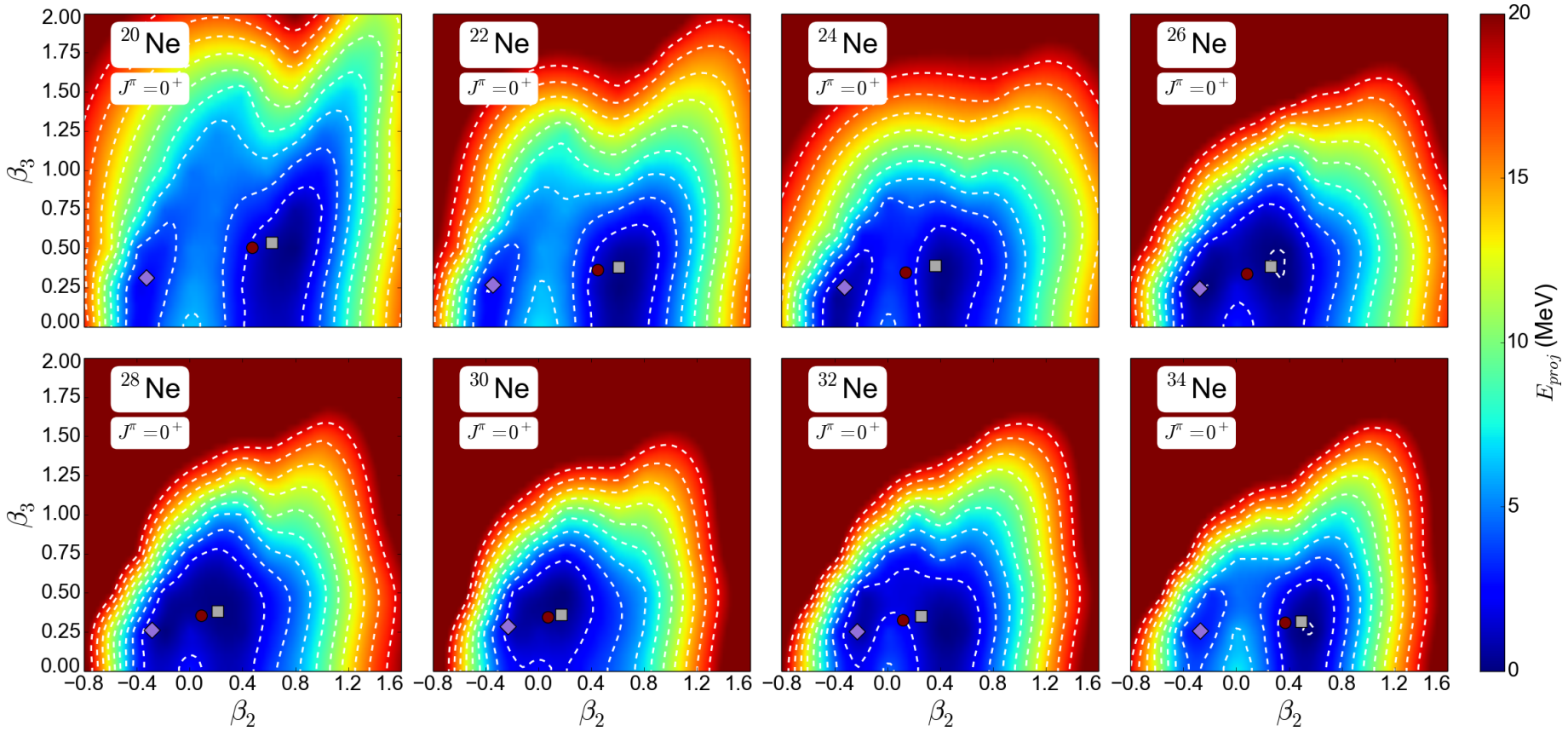
Structure of Neon isotopes
Parameters of the calculation

- RHB wave functions expanded in HO basis with $N_{\mathrm{sh}}^{\mathrm{max}} = 10(11)$
- DD-PC1 functional and TMR pairing
- angular momentum and parity projection
- mixing of $130 - 150$ configurations with $\beta_2 \in [-0.8, 1.6]$ and $\beta_3 \in [-2.0, 2.0]$

Structure of Neon isotopes
Mean-field potential energy surfaces

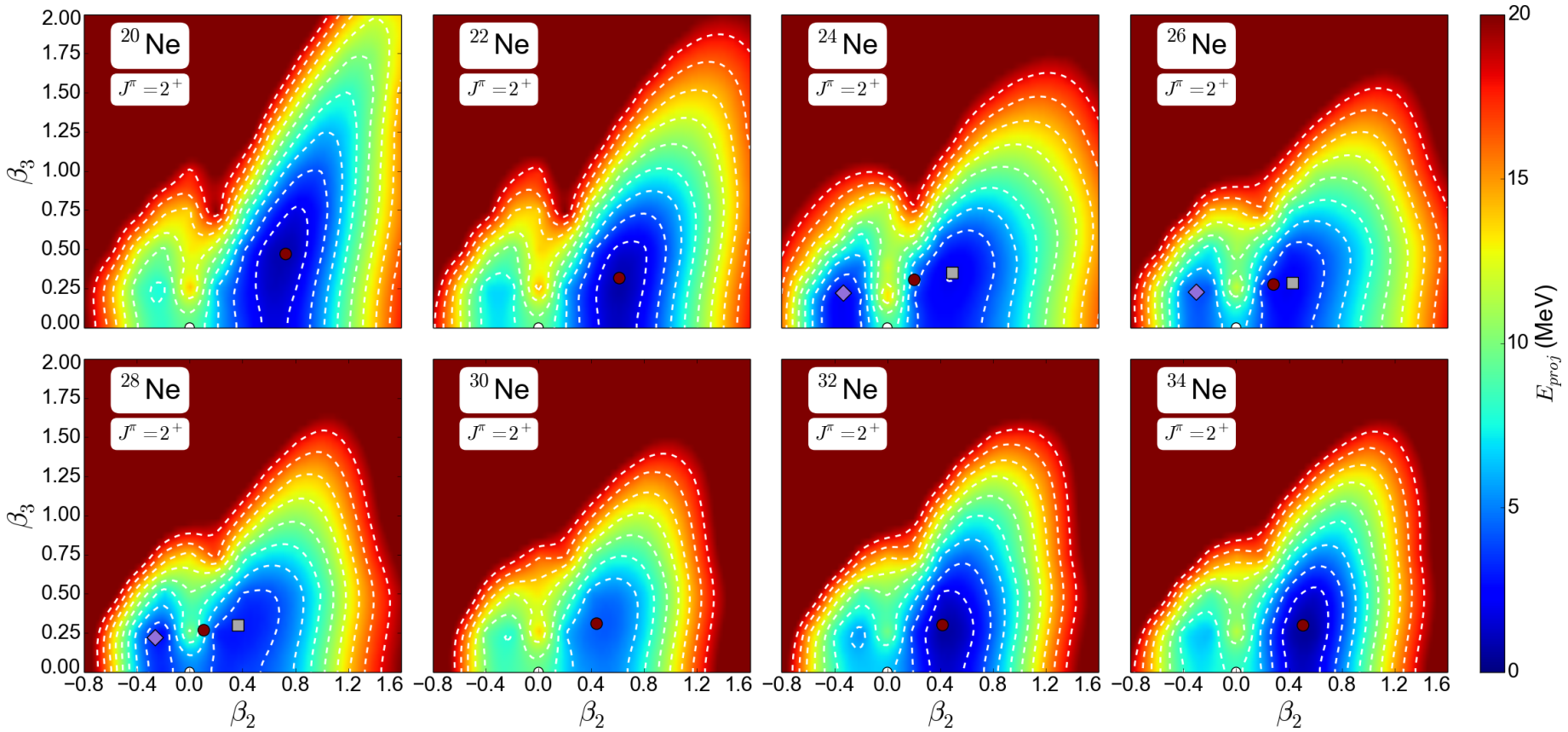


Structure of Neon isotopes
Symmetry-projected potential energy surfaces



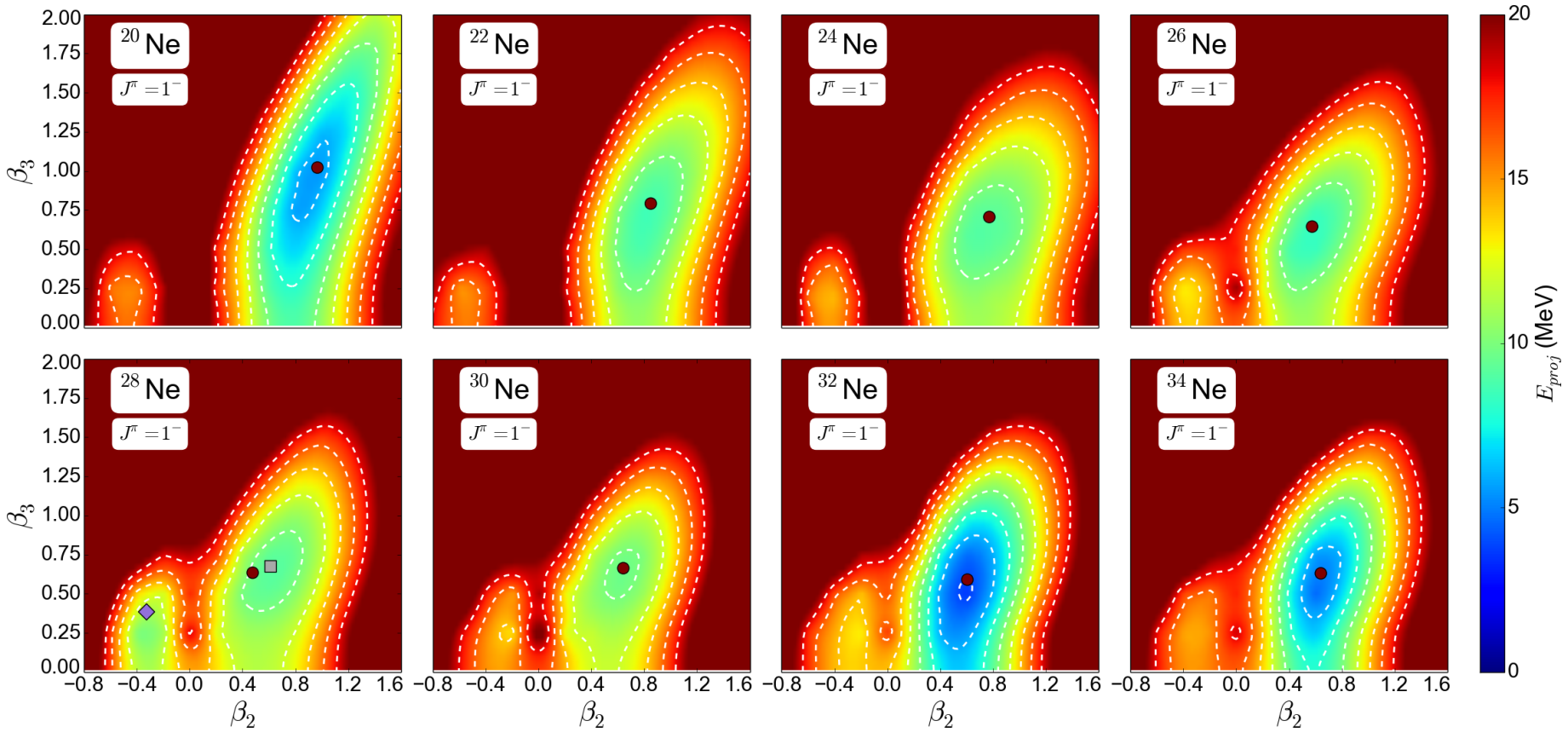
P.M. *et al.*, submitted to PRC

Structure of Neon isotopes
Symmetry-projected potential energy surfaces



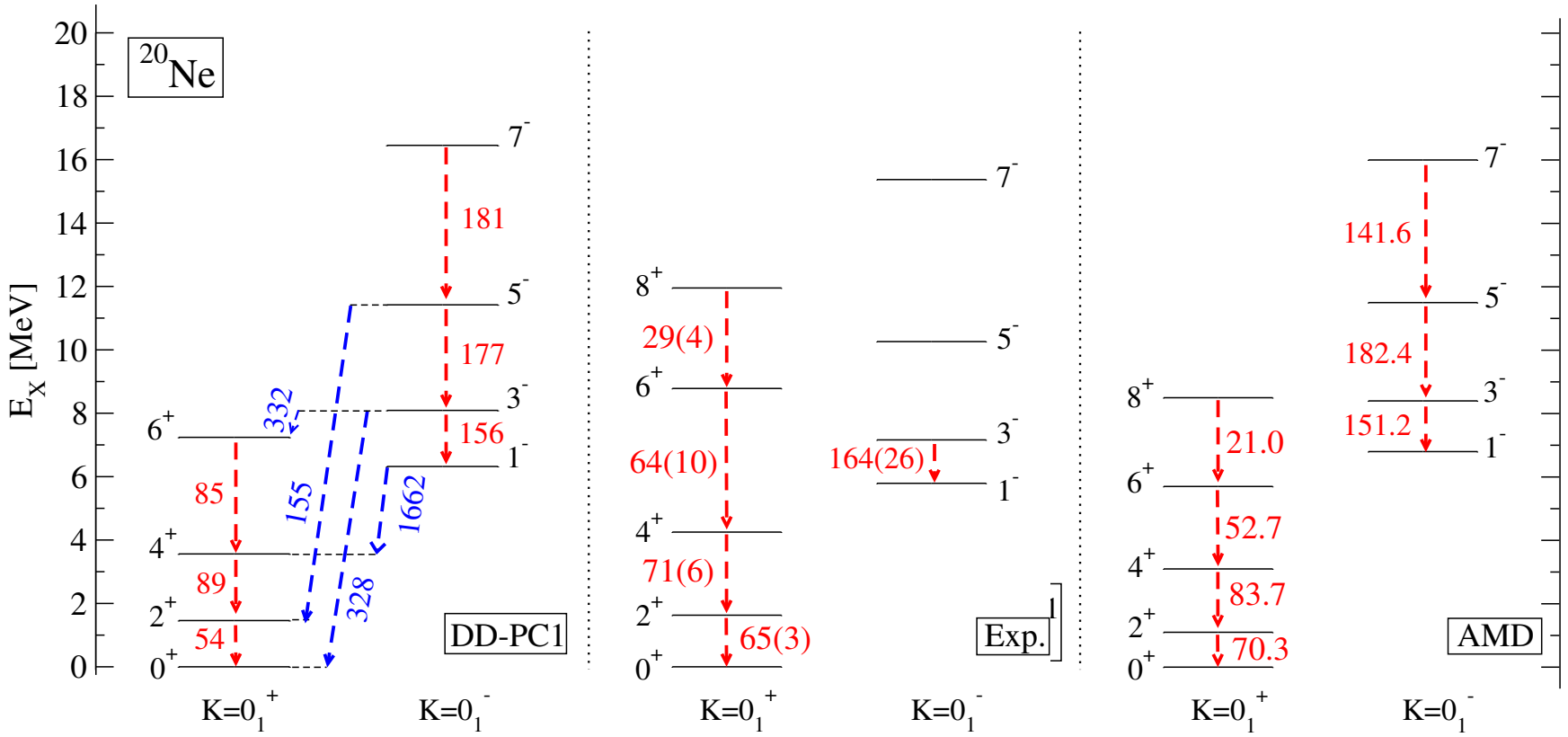
P.M. *et al.*, submitted to PRC

Structure of Neon isotopes
Symmetry-projected potential energy surfaces



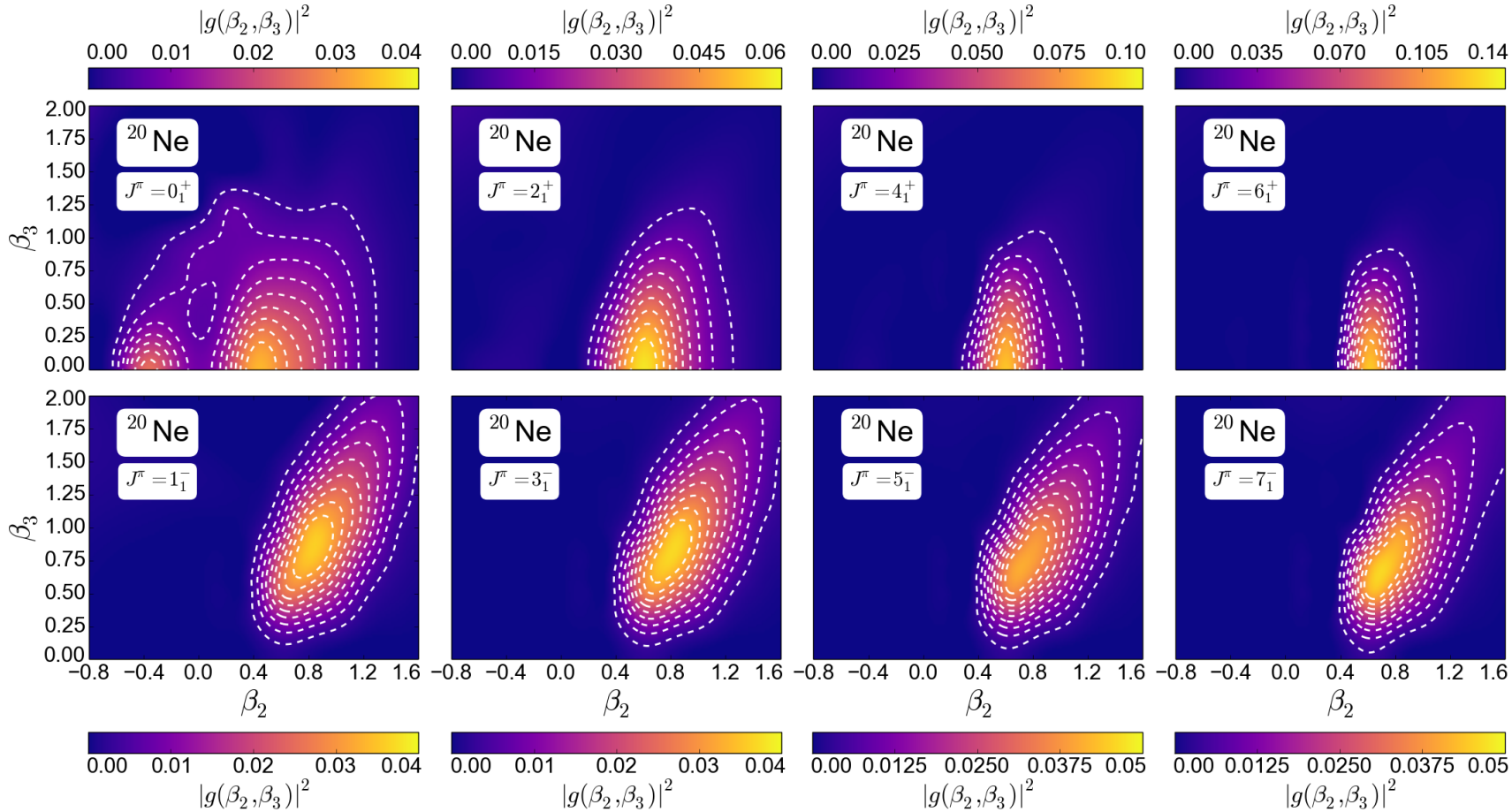
P.M. *et al.*, submitted to PRC

Structure of Neon isotopes
Collective energy spectra of ^{20}Ne



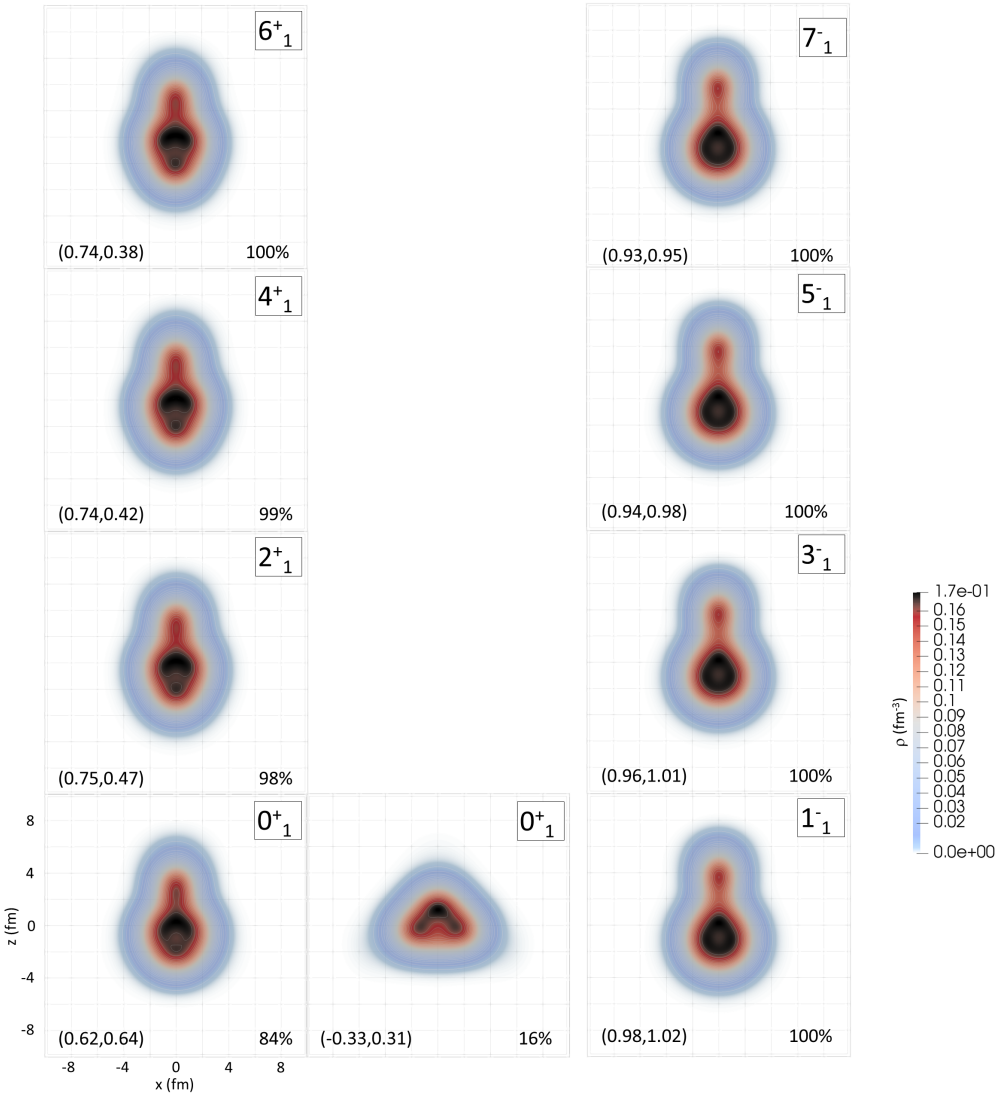
P.M. *et al.*, submitted to PRC

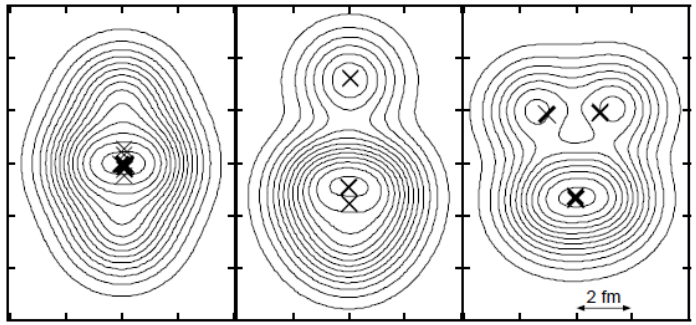
Structure of Neon isotopes
Collective wave functions of ^{20}Ne



P.M. *et al.*, submitted to PRC

Structure of Neon isotopes
Characteristic intrinsic nucleon densities



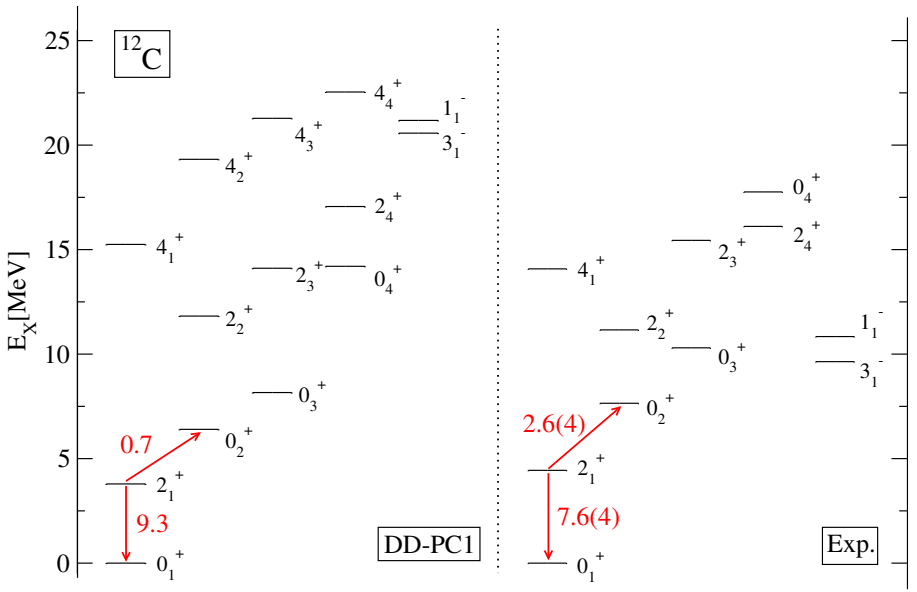


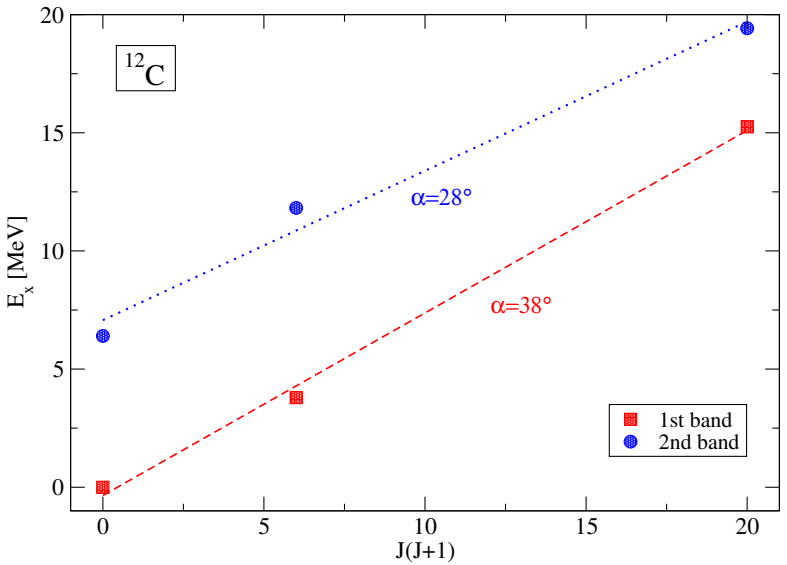
Y. Taniguchi *et al.* PTP (2004) 112 (3)

P.M. *et al.*, submitted to PRC

Towards unified framework

Towards unified framework
Collective energy spectra of ^{12}C and the Hoyle state





- restoration of particle number symmetry
- calculation of (in)elastic form factors
- unified description of quantum-liquid and cluster states

P.M. *et al.*, preliminary

Conclusion

The wrap-up

- EDF as powerful tool for nuclear structure calculations
- description of clustering in atomic nuclei
  - depth of the confining potential
  - role of deformation and density
- going beyond mean-field: spectroscopic predictions
- application of the model: cluster structures in Neon isotopes
- towards unified description of quantum liquid and cluster states