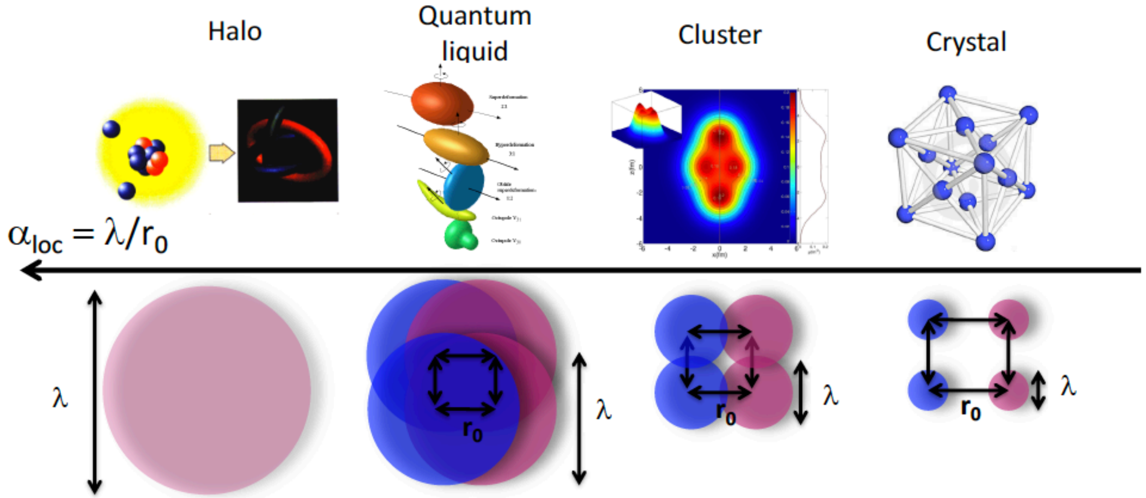
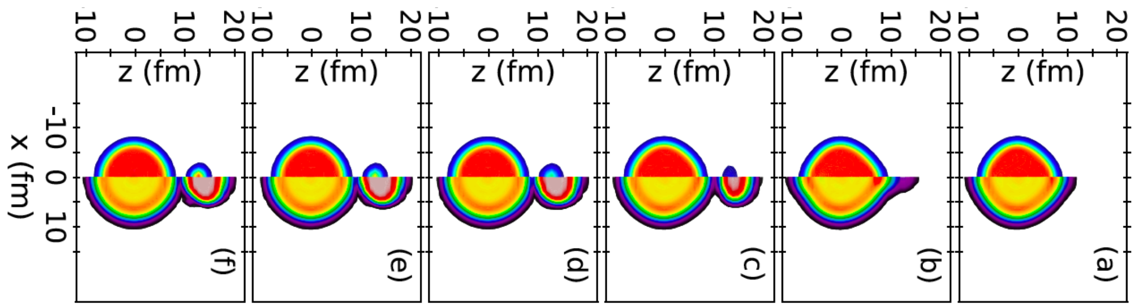
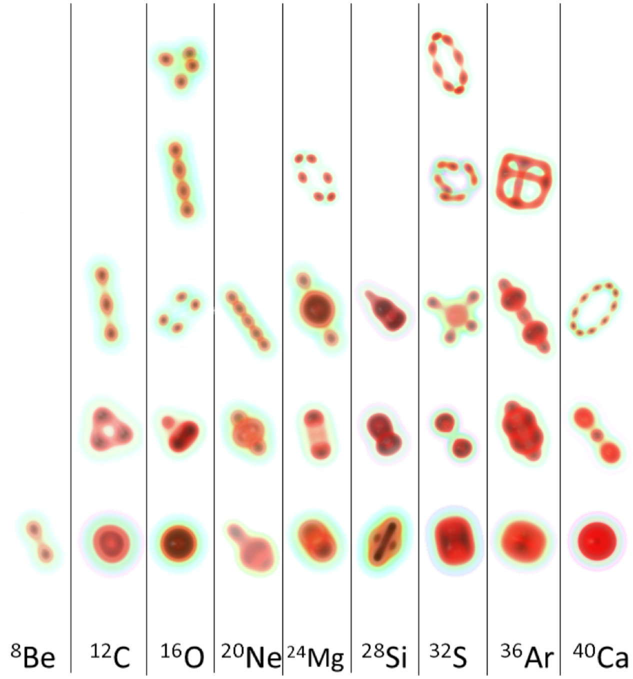
Exotic nuclear phases, structure, and decays







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cnrs dépasser les frontières IN2P3 Les deux infinis

IUF institut universitaire de France

INTERNATIONAL SYMPOSIUM COMMEMORATING THE 40TH ANNIVERSARY OF THE HALO NUCLEI, October 12-18, 2025, BEIJING

Outline

- Quantality: nuclear interaction and quantum liquid phase
- Localisation parameter: cluster phase and its origins
- Comparison to experiment: spectrum and (exotic) decays
- Spin-orbit and pseudospin effects: shell structure in exotic nuclei

Quantality:

nuclear interaction and quantum liquid phase

Quantality

- Introduced by de Boer (1948)
- Used by Mottelson (1999): reason for the large m.f.p of nucleons and validity of mean-field

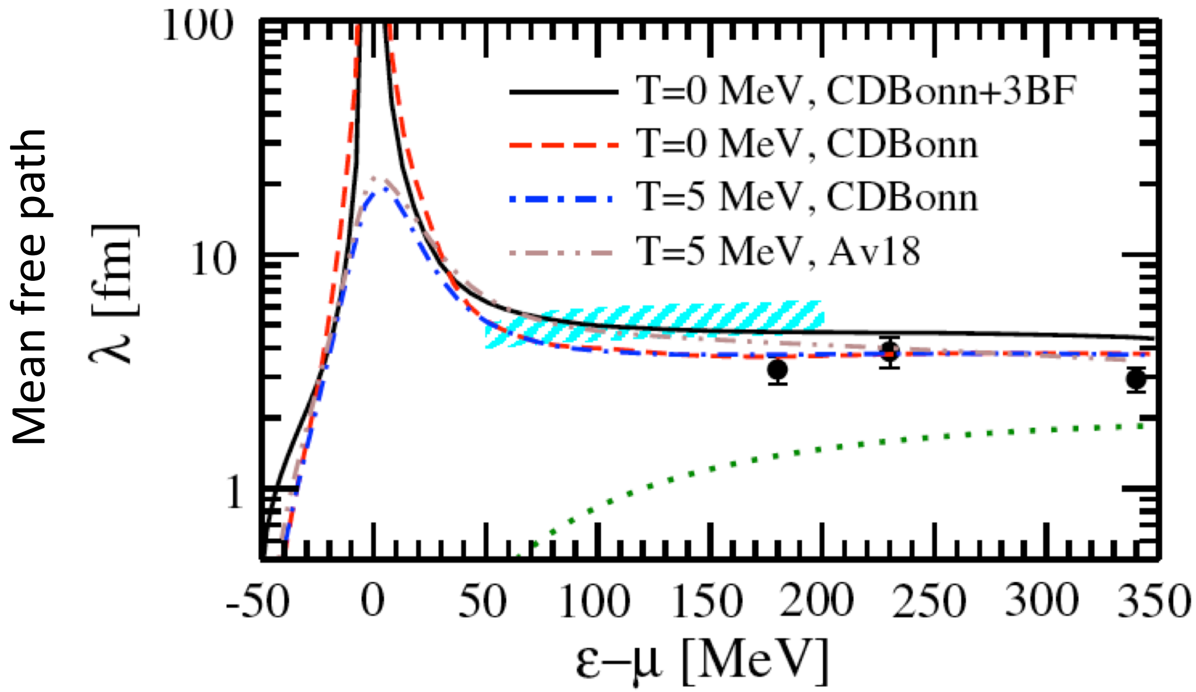
Zero Point Energy

$$\boxed{\Lambda \equiv \frac{2T_0}{V_0} = \frac{\hbar^2}{m r_0^2 V_0}}$$

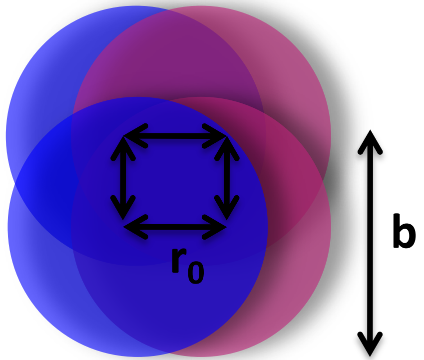
Magnitude of the interaction

Constituent	m	r_0 (nm)	V_0 (eV)	T_0 (eV)	Λ	State
^{20}Ne atom	20	0.31	31×10^{-4}	1.1×10^{-5}	0.007	Crystal
H_2 molecule	2	0.33	32×10^{-4}	9.5×10^{-5}	0.06	Crystal
^{4}He atom	4	0.29	8.6×10^{-4}	6.0×10^{-5}	0.14	QL
^{3}He atom	3	0.29	8.6×10^{-4}	0.8×10^{-5}	0.19	QL
Nucleon	1	10^{-6}	100×10^6	25×10^6	0.41	QL
e^- in atoms	5×10^{-4}	0.05	10	16	3.1	QL

Nuclei: a quantum liquid feature



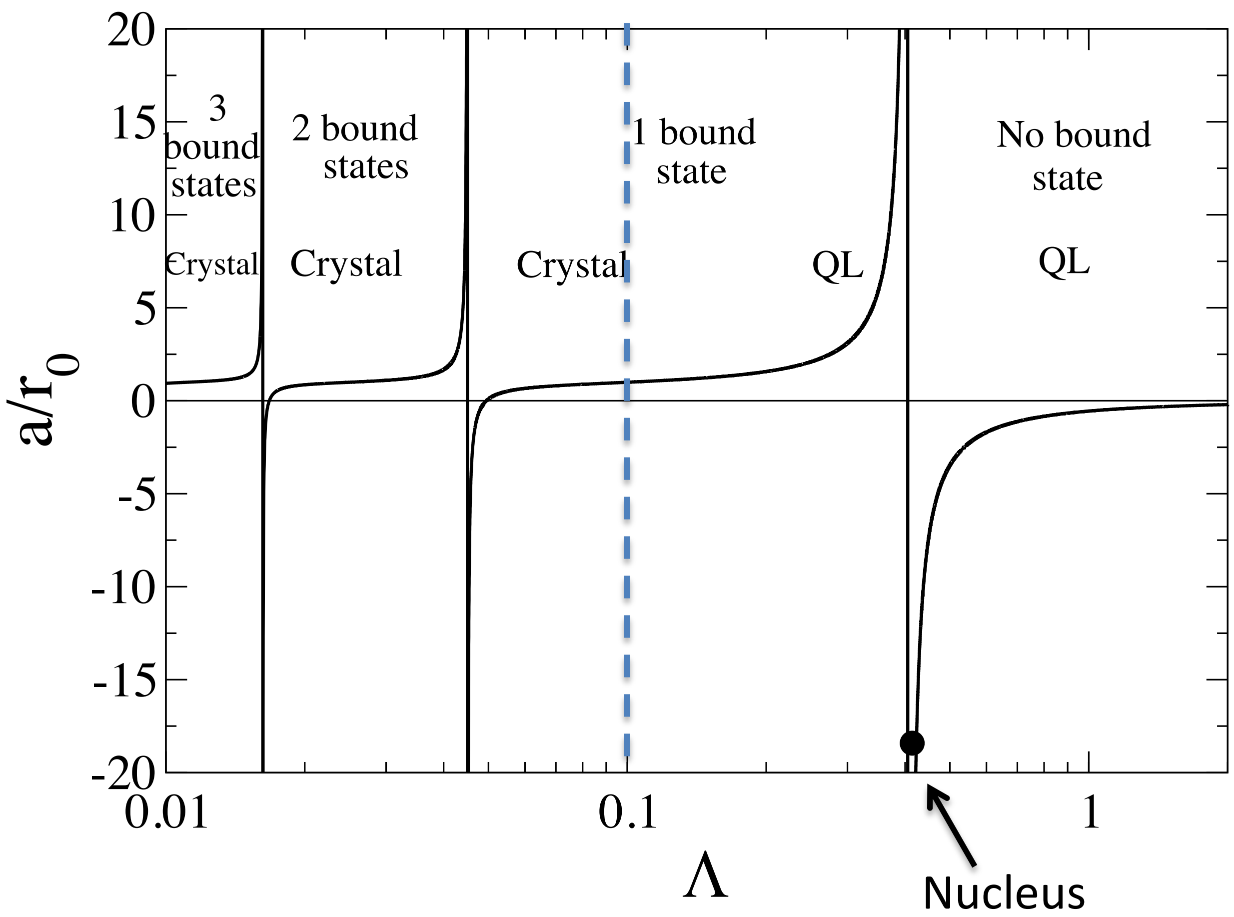
A. Rios & V. Soma PRL108(2012)012501



B. Mottelson ⇒ the concept of independent particle motion is based on the fact that the orbits of individual nucleons are delocalized and reflect the shape and radial dependence of the effective potential over the entire nucleus!

Quantality and scattering length

Scattering length: $$a = r_0\left[1 - \sqrt{\Lambda}\tan\left(\frac{1}{\sqrt{\Lambda}}\right)\right]$$



J.-P. Ebran, L. Heitz, E. Khan, Phys. Rev. C 110, 044311 (2024)

Nuclei: saturation vs. packing densities

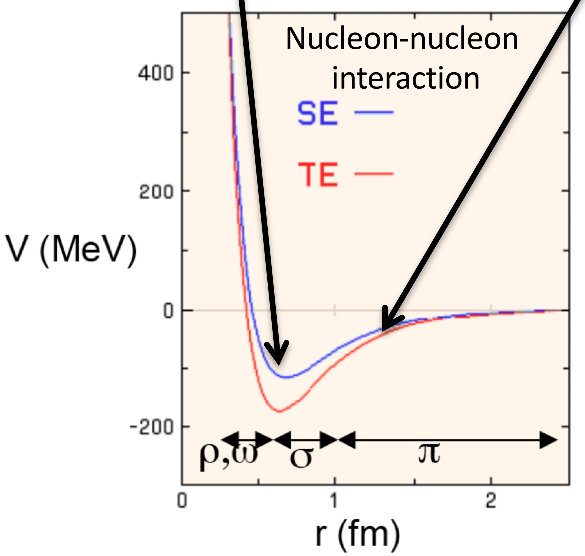
- Due to « crystalisation/delocalisation » effects monitored by the quantality, the actual density of a system can be smaller than the packed/limit one

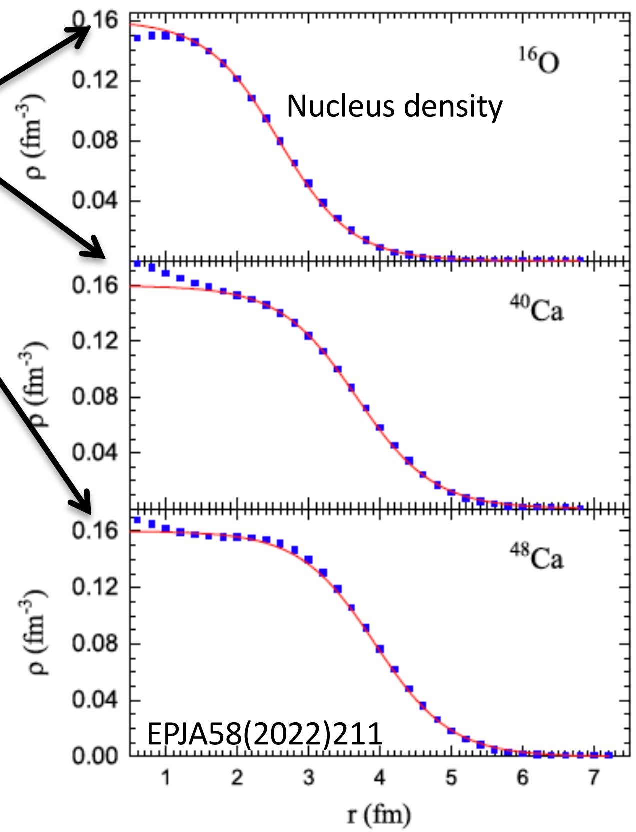
- In nuclei ($\Lambda \sim 0.5$):

$$\rho_l = \left(\frac{2}{\Lambda}\right)^{3/2} \rho_0 \simeq 10\rho_0 \simeq 1.5\ \text{fm}^{-3} \longrightarrow \boxed{\rho_0 \sim \Lambda^{3/2}\,\rho_\ell}$$

Packing density

Saturation density





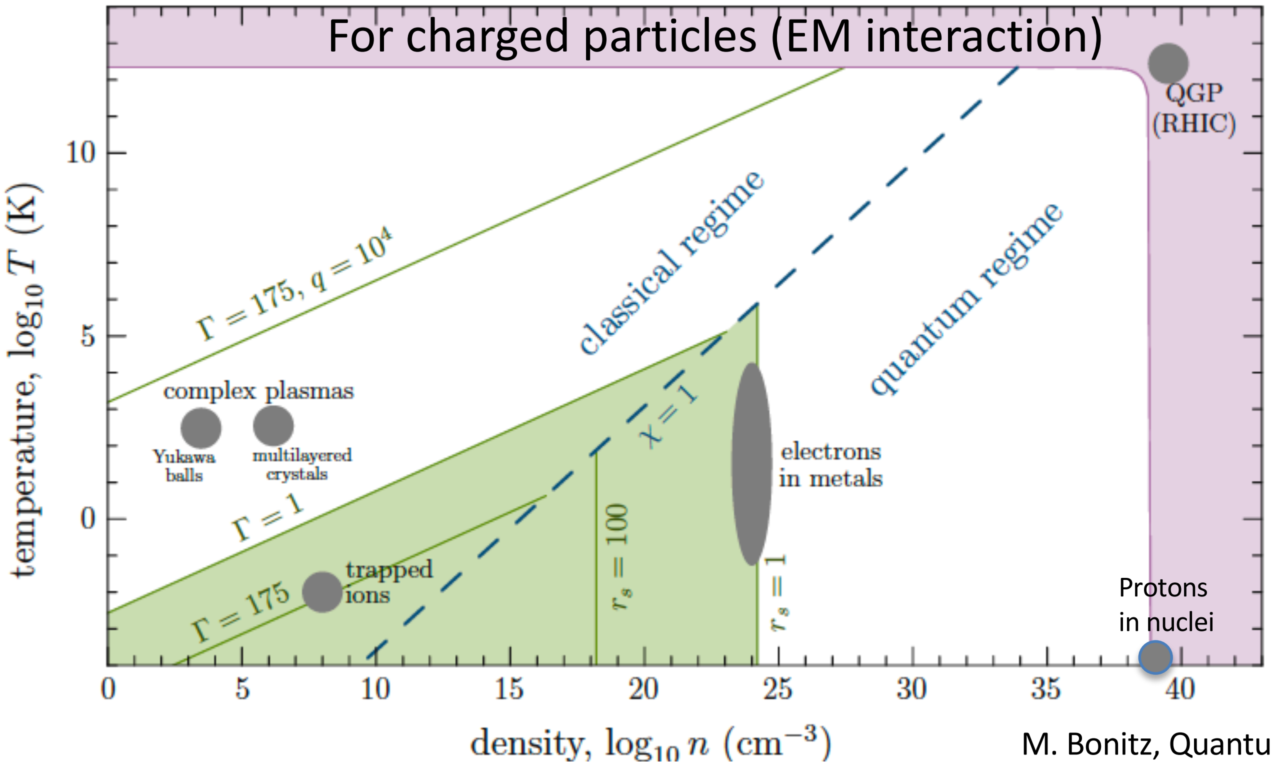
- For atomic electrons, $\Lambda \sim 2$ and $\rho_\ell \simeq \rho_0 \simeq a_B^{-3}$

Localisation parameter:

cluster phase and its origins

The Brückner (Wigner) parameter for nuclei

- Nuclei: needs for a parameter impacted by the spatial localisation of the system
- Condensed matter (EM interaction): $r_s = \frac{\langle V \rangle}{\langle K \rangle} \sim \frac{\bar{r}}{a_B}$



M. Bonitz, Quantum Kinetic Theory (Springer Int. Cham, 1998)

- Nuclei: derive a Brückner parameter for the strong interaction $\longrightarrow$ localisation parameter

The localisation parameter

Strong interaction in nuclei

Spatial extension of a nucleon w.f.

$$r_s = \frac{\langle V \rangle}{\langle K \rangle} \longrightarrow \boxed{\alpha_{loc} \simeq \frac{1}{\sqrt{r_s}} \simeq \frac{\lambda}{\bar{r}}}$$

Interconstituent distance

(= $r_0 \simeq$ 1.2 fm in nuclei at equilibrium)

HO approx in nuclei

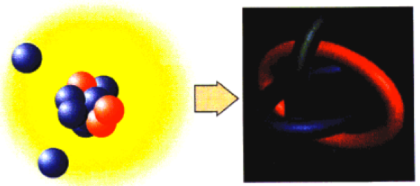
$$\boxed{\alpha_{loc} = \left(\frac{\Lambda}{2}\right)^{1/4} A^{1/6}}$$

= quantality x size effects

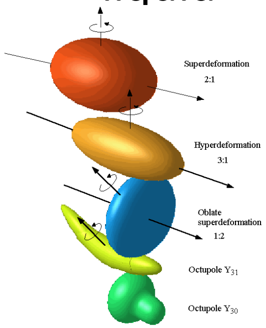
J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, Nature 487(2012)341

A global indicator for clusterization

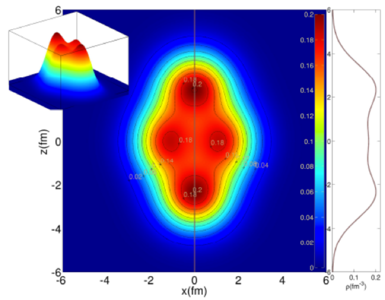
Halo



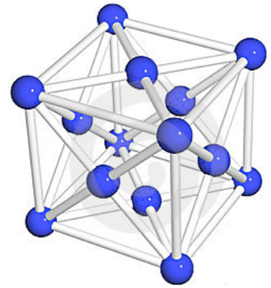
Quantum liquid



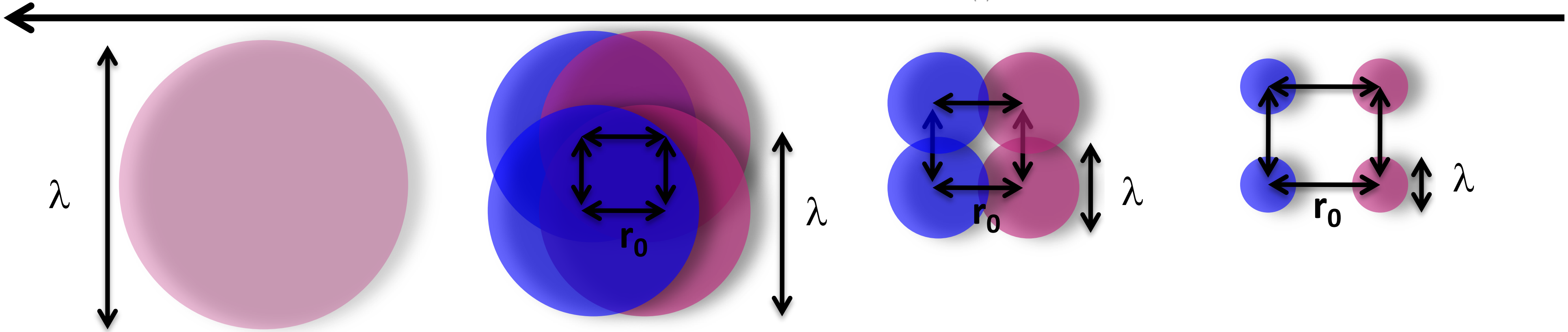
Cluster

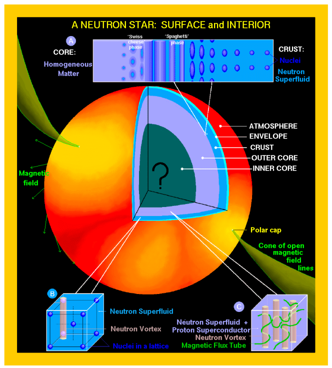


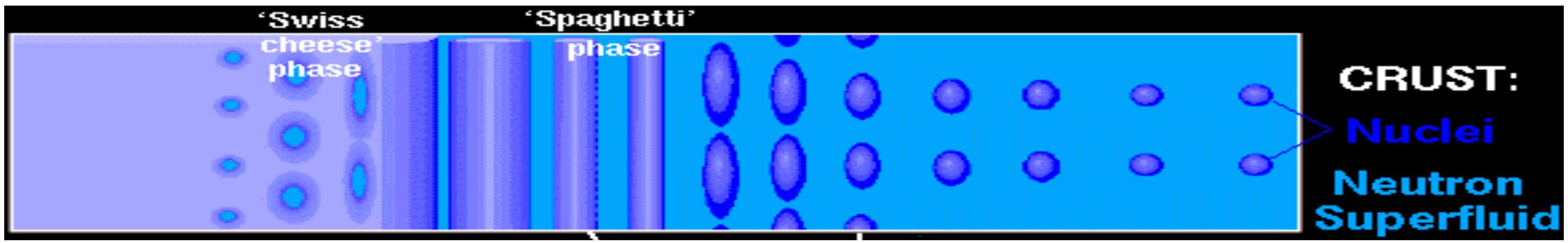
Crystal



$\alpha_{loc} = \lambda / r_0$





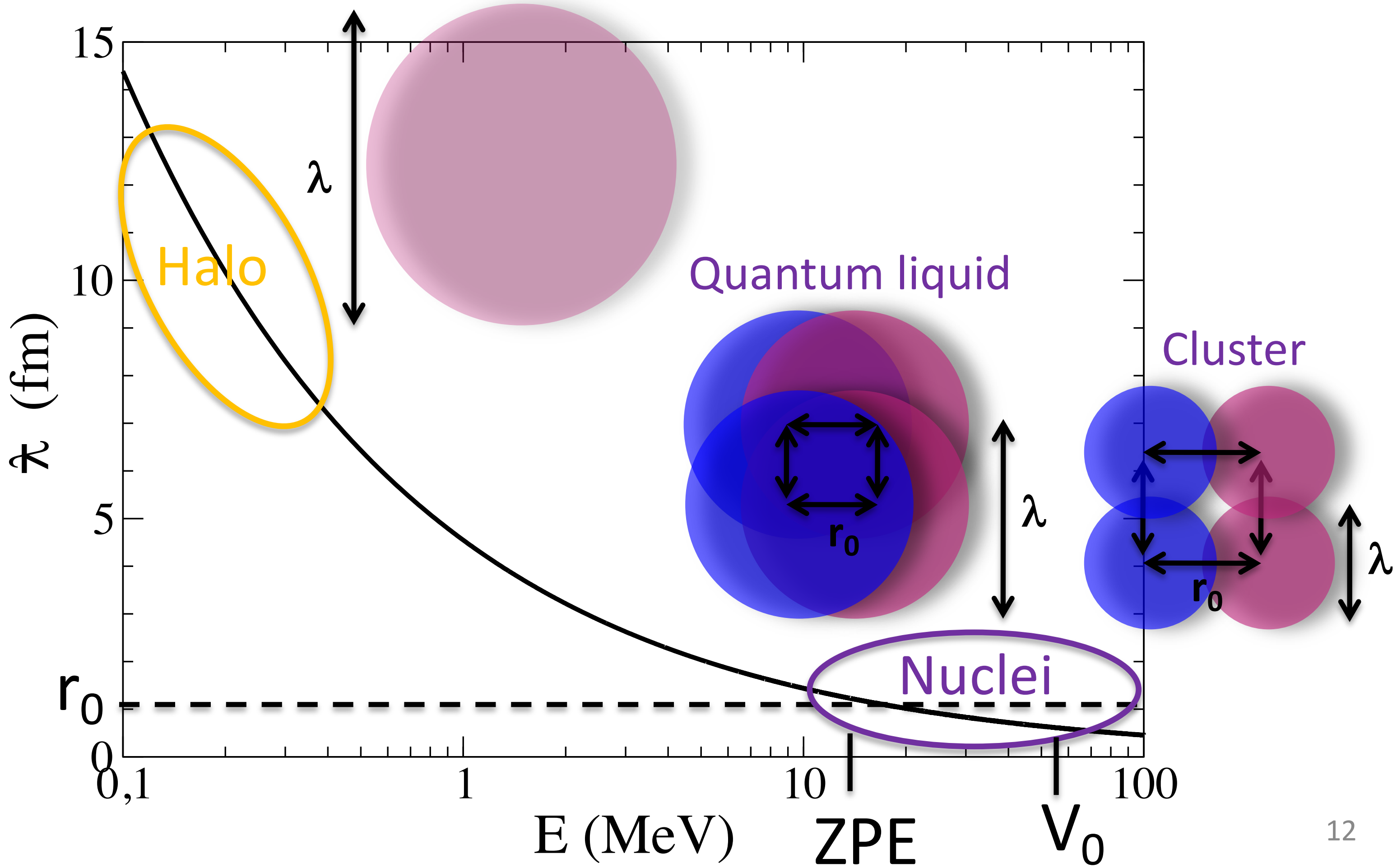


Haloes and clusters

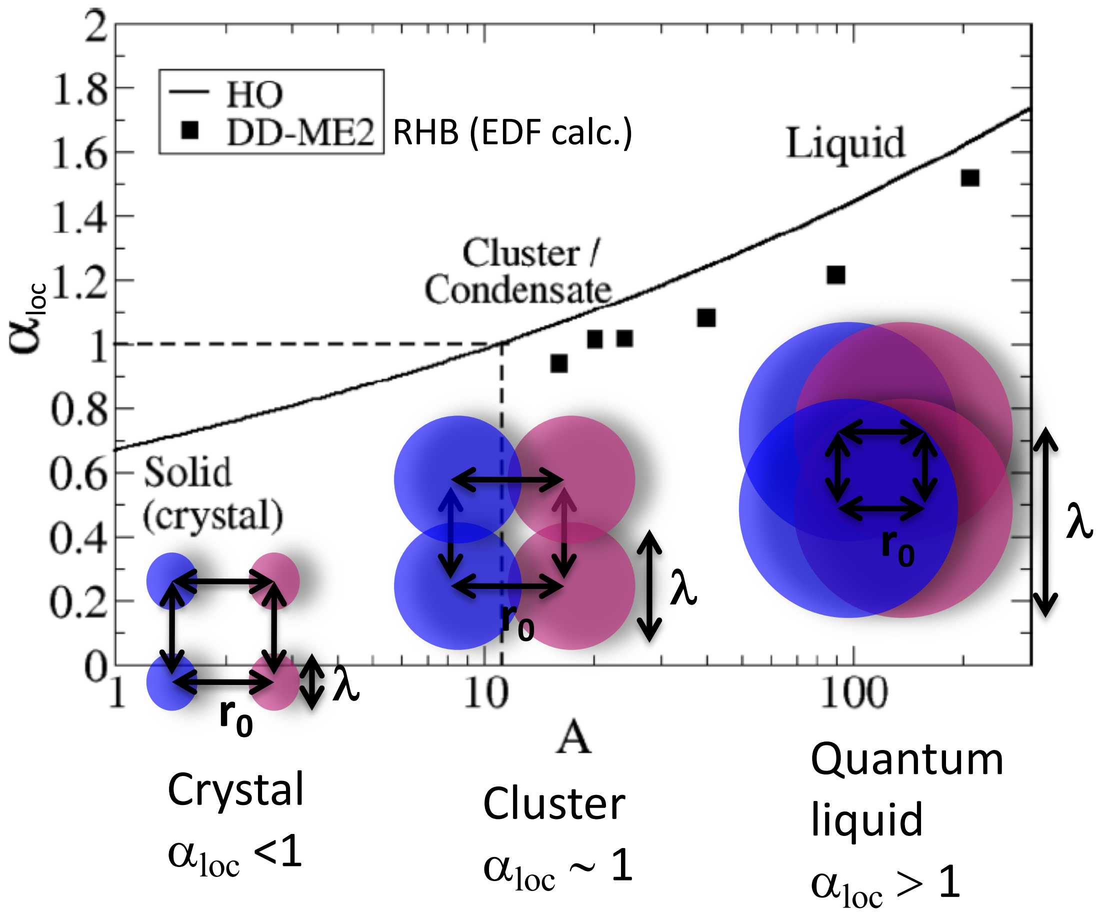
- Reduced nucleon wavelength: $\lambdabar(E) = \dfrac{\hbar}{\sqrt{2mE}}$ I. Tanihata and B. Jonson, Handbook of Nuclear Physics, p985 (2023)

- Generalisation to E = energy distance from the bottom of the potential

$\longrightarrow$ common monitor to delocalization (halo) and nucleonic localization (cluster)



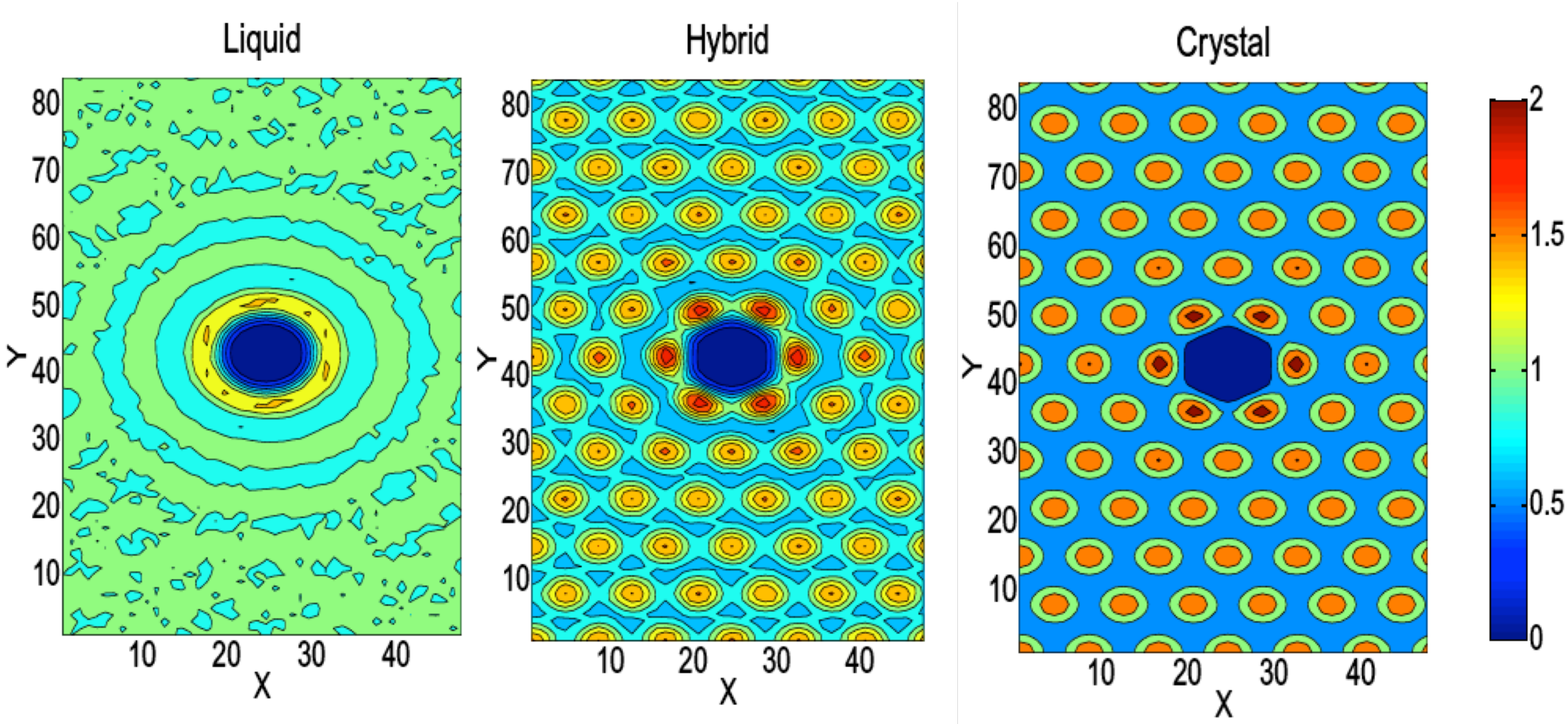
A global indicator for localization



$$\alpha_{loc} = \left(\frac{\Lambda}{2}\right)^{1/4} A^{1/6}$$

J.-P. Ebran, E. Khan, T. Nikšić, and D. Vretenar, Phys. Rev. C **87**, 044307 (2013)
J.-P. Ebran, E. Khan, R. Lasseri, and D. Vretenar, Phys. Rev. C **97**, 061301(R) (2018)

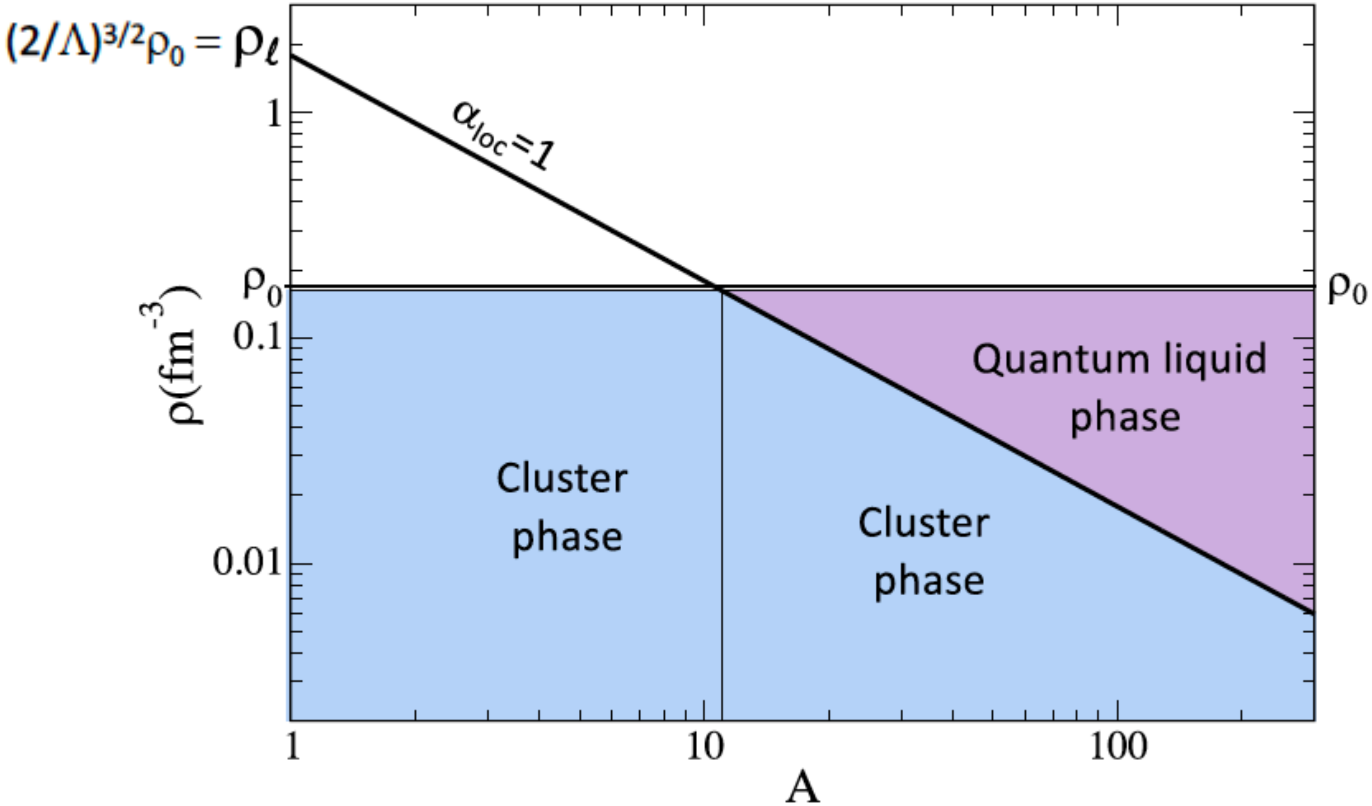
Analogies



2D system of spinless electrons

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

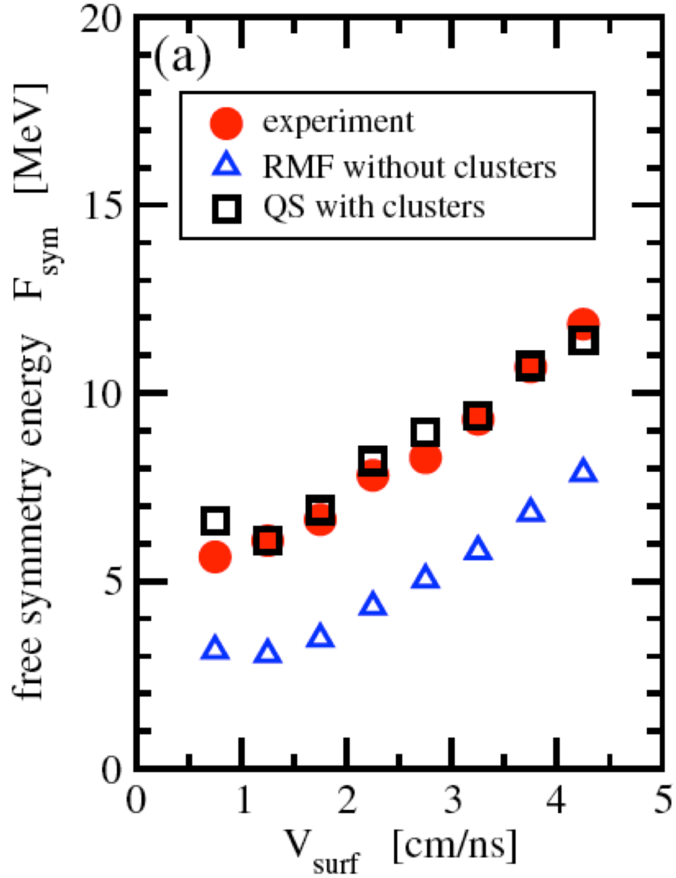
Density vs. number of nucleons as control parameters of the cluster phase in nuclei



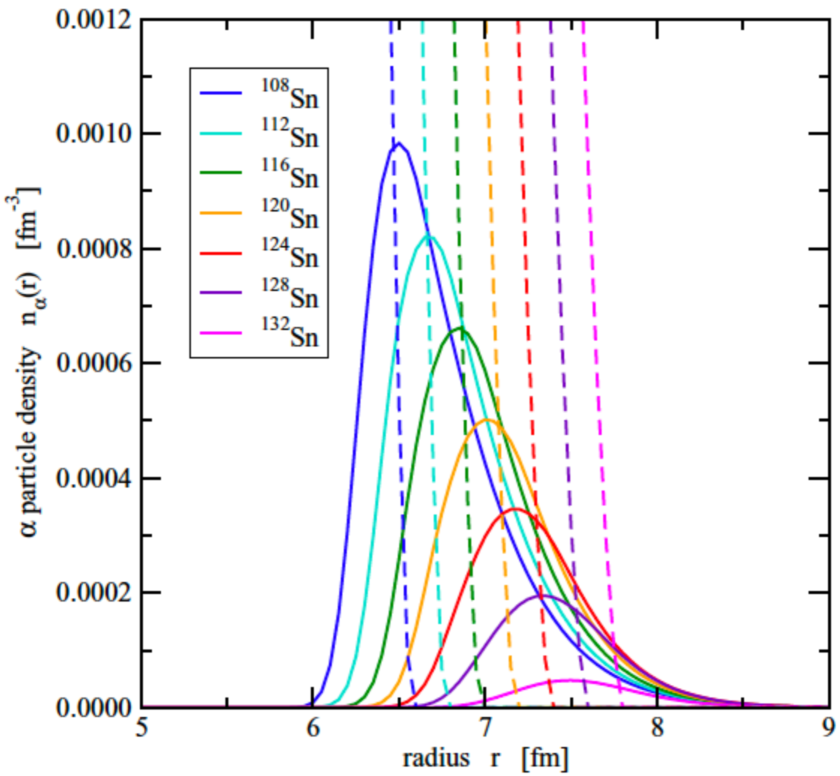
Driven by the quantality and related to the packing density

J.-P. Ebran, L. Heitz, E. Khan, Phys. Rev. C 110, 044311 (2024)

Clusters in low density nuclear matter



J.B. Natowicz et al. PRL104(2010)202501



α density appears in the surface of nuclei
(low density-Mott effect)

S. Typel, PRC 89(2014) 064321

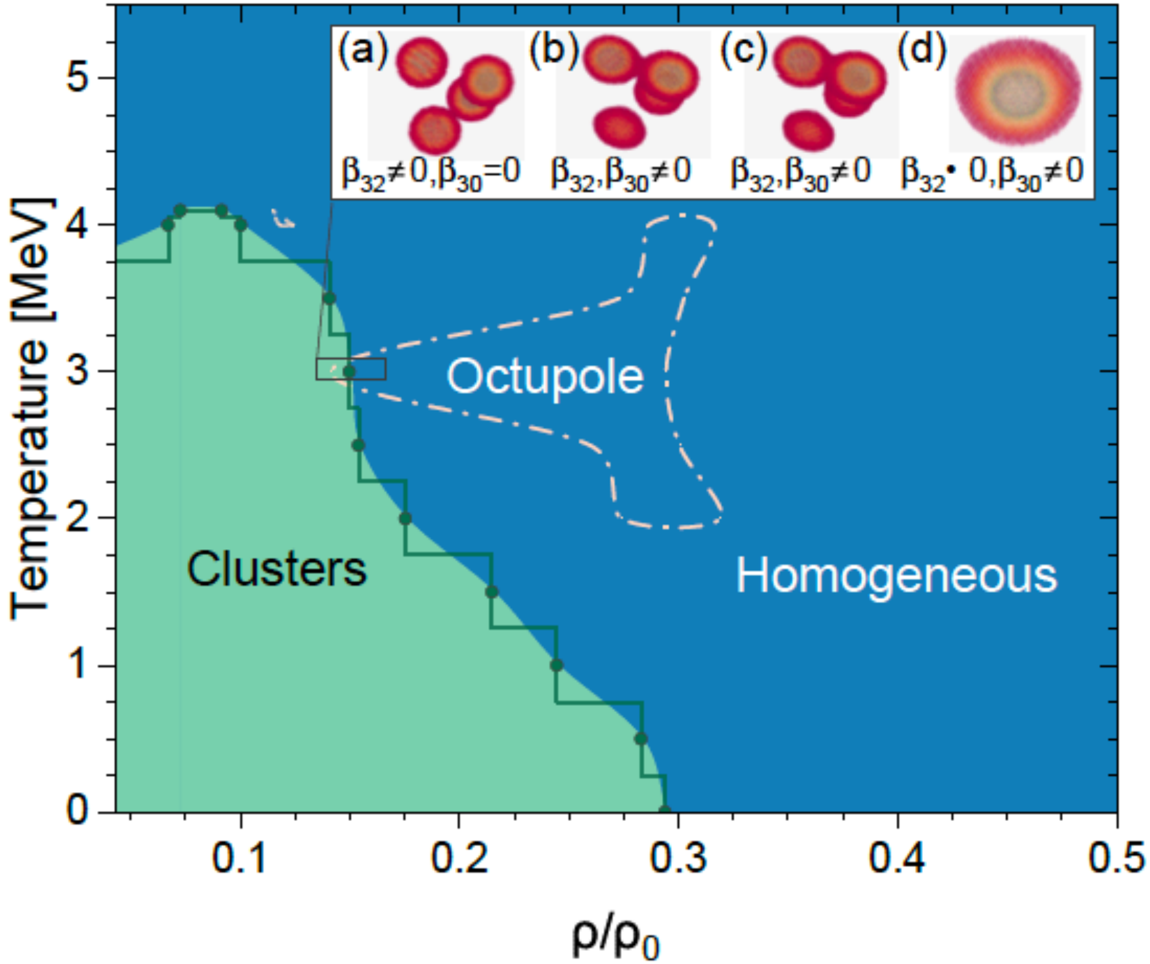
Clusters in EoS better describe experiment
Data from heavy ion collision

Exp: ^{A}Sn(p,pα)$^{A-4}$Cd

J. Tanaka et al., Science 371(2021)260

Temperature vs. density as control parameters of the cluster phase in nuclei

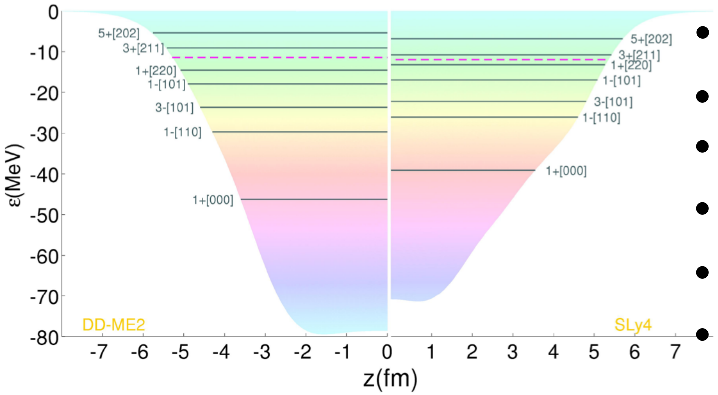
^{16}O



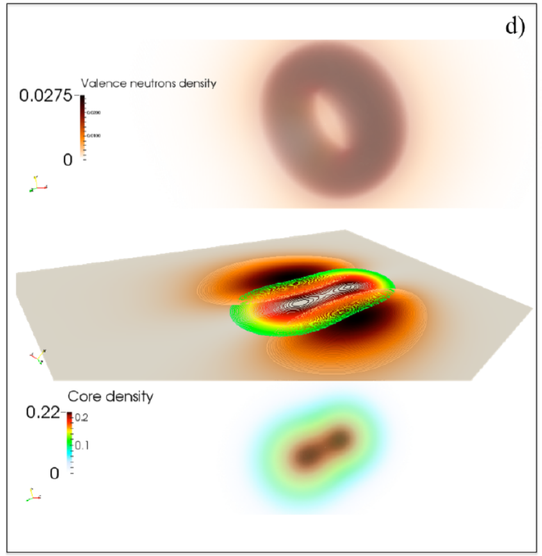
Microscopic finite temperature Relativistic Hartree-Bogoliubov calculations with DD-ME2

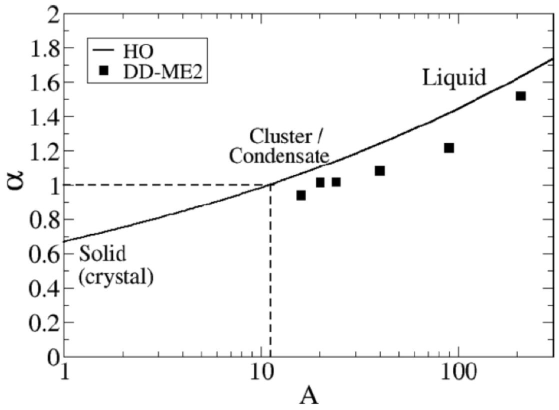
M. Davies, E. Yüksel, J.-P. Ebran, E. Khan, P. Stevenson, Phys. Rev. C 112, 014311 (2025)

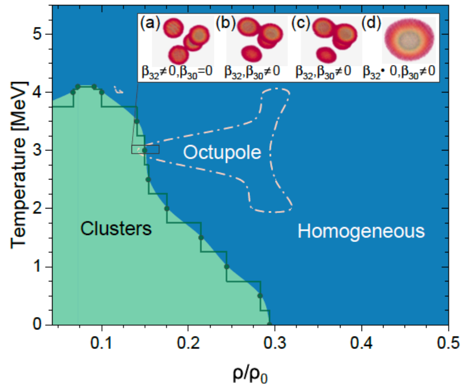
Origins of nuclear clustering

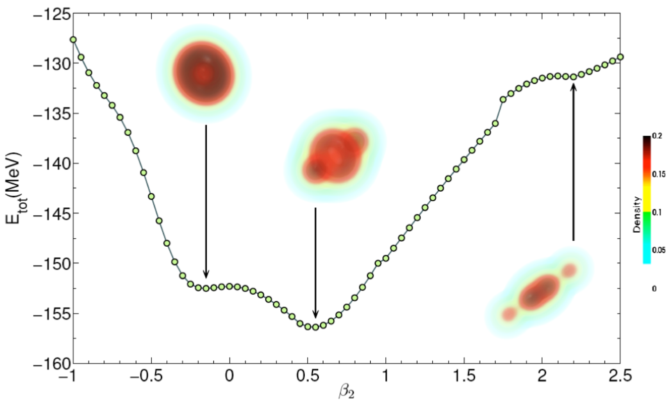


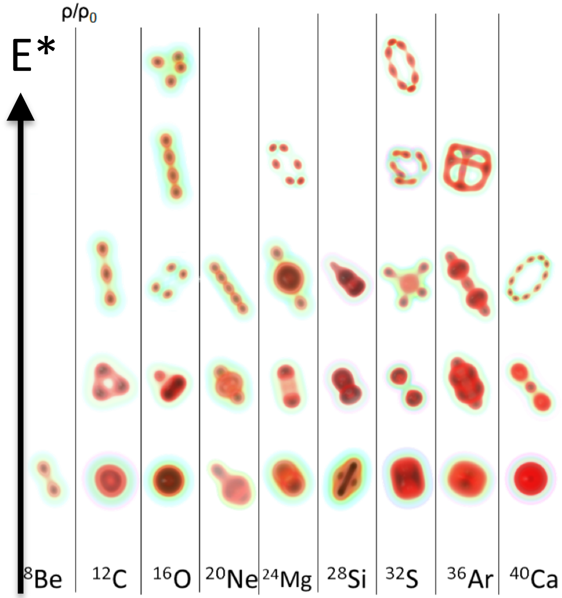
- Depth of the confining potential
- Heavy vs. Light nuclei
- Deformation / excitation energy
- Density
- Neutron excess
- Temperature

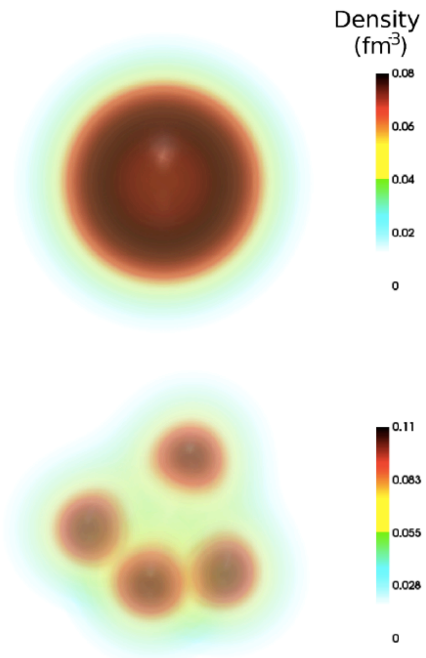






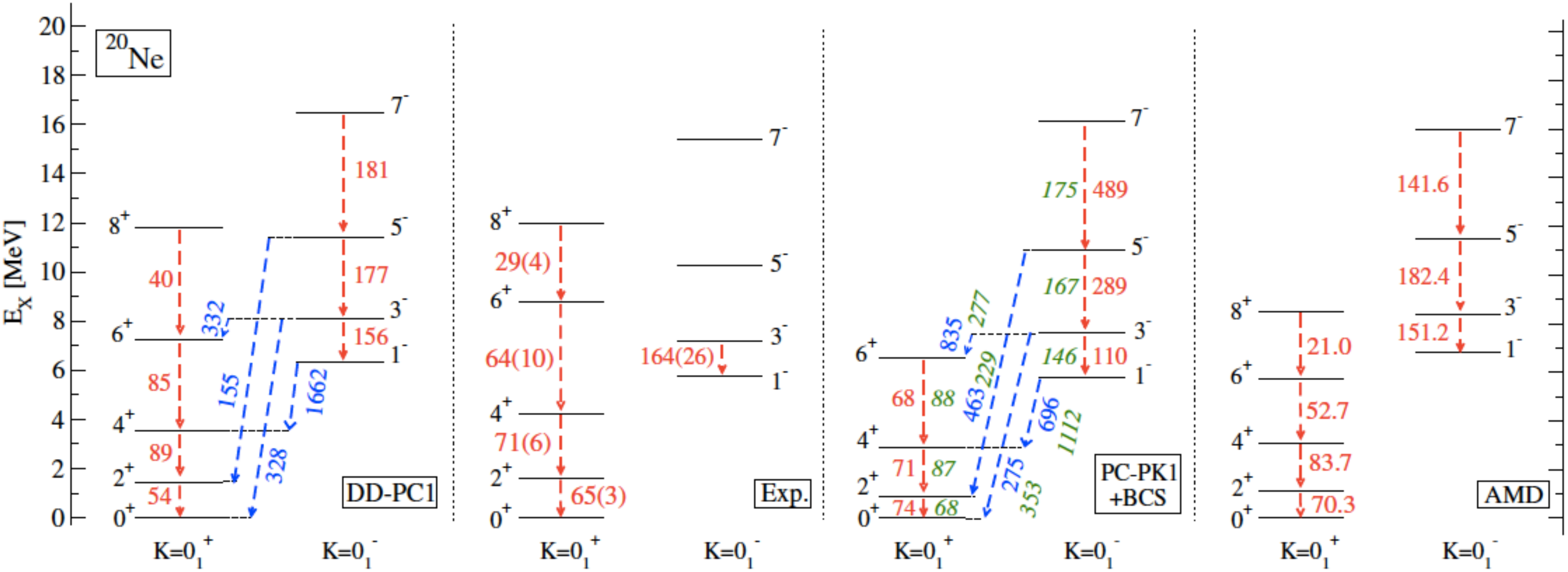






Comparison to experiment:
spectrum and (exotic) decays

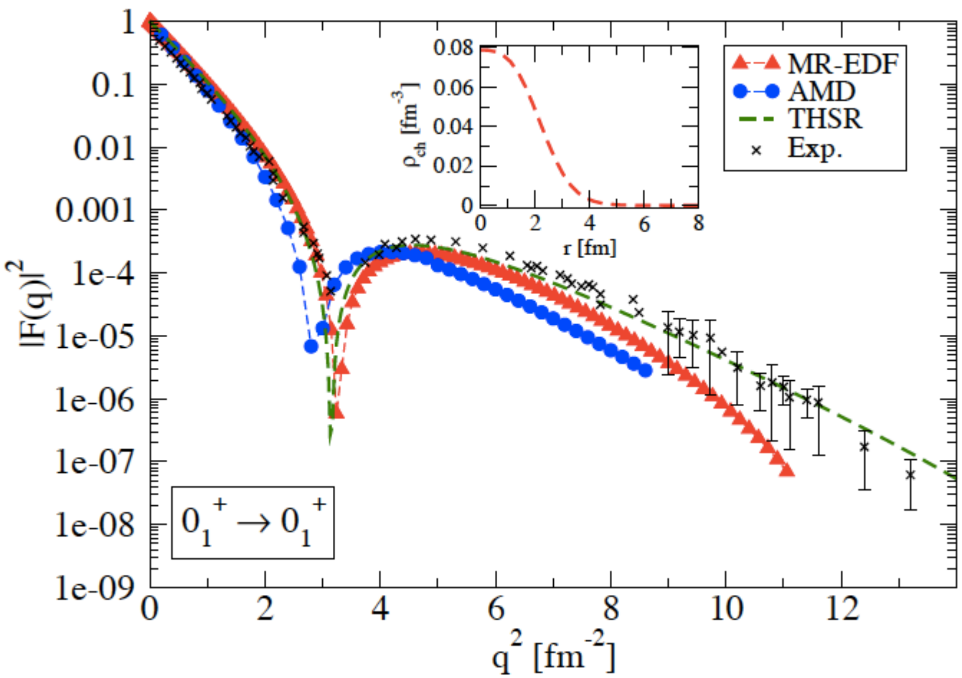
Comparison with the exp. spectrum on ^{20}Ne



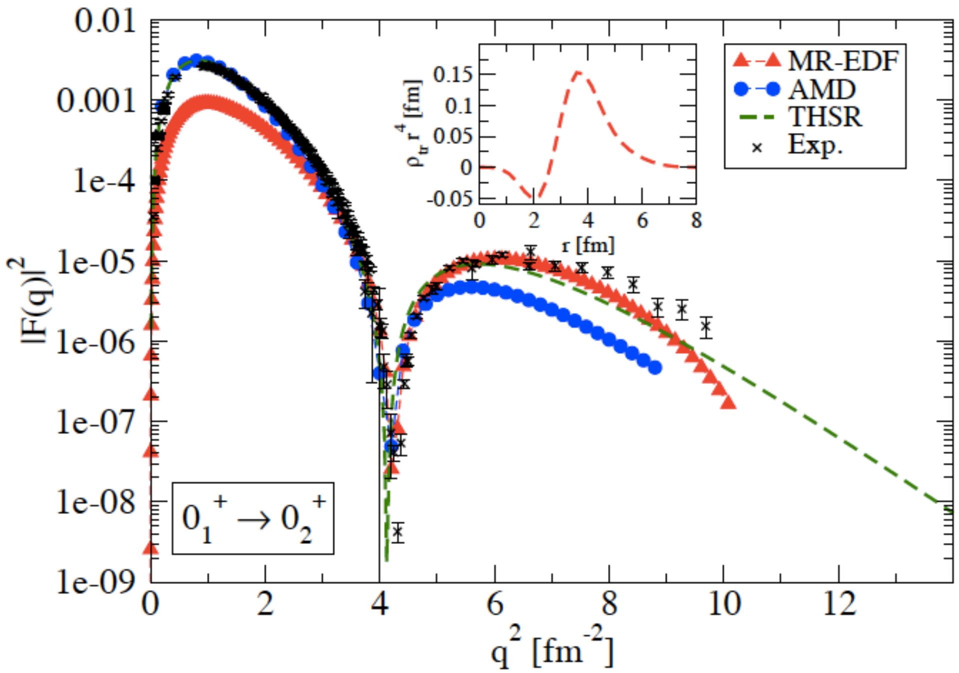
P. Marević , J.-P. Ebran, E. Khan, T. Nikšić, and D. Vretenar, PRC 97, 024334 (2018)

- GCM on top of axially symmetric /reflection asymmetric RHB (DD-PC1) :
- Angular momentum, parity and particle number projections

Comparison with exp. form factors on ^{12}C



g.s.



Hoyle

P. Marević , J.-P. Ebran, , E. Khan, T. Nikšić, and D. Vretenar, PRC 99, 034317 (2019)

A microscopic approach to α decay

Potential energy surfaces calculated with covariant EDF

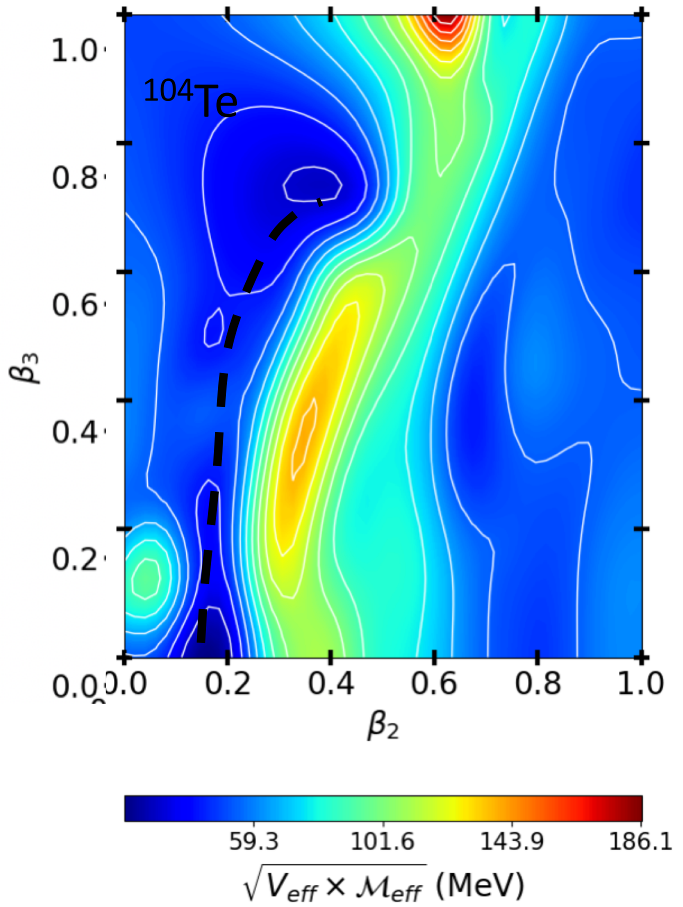
$$S(L) = \int_{s_{in}}^{s_{out}} \frac{1}{\hbar}\sqrt{2\mathcal{M}_{eff}(s)[V_{eff}(s) - E_0]}ds$$: minimization of the action integral

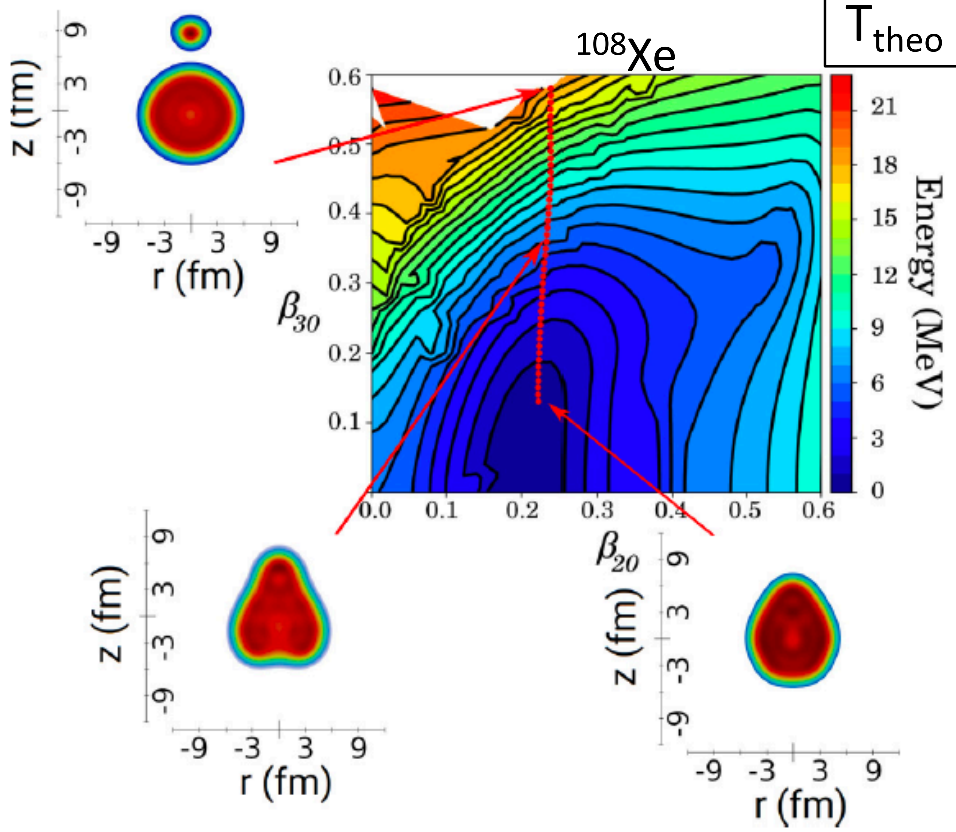
$$P = \frac{1}{1+\exp[2S(L)]}$$: barrier penetration probability (WKB)

$$T_{1/2} = \ln 2/(nP)$$ n: number of assaults per unit of time

Light α emitters:

	^{104}Te	^{108}Xe
T_{exp}	<18ns	58 μs
T_{theo}	197ns	50 μs

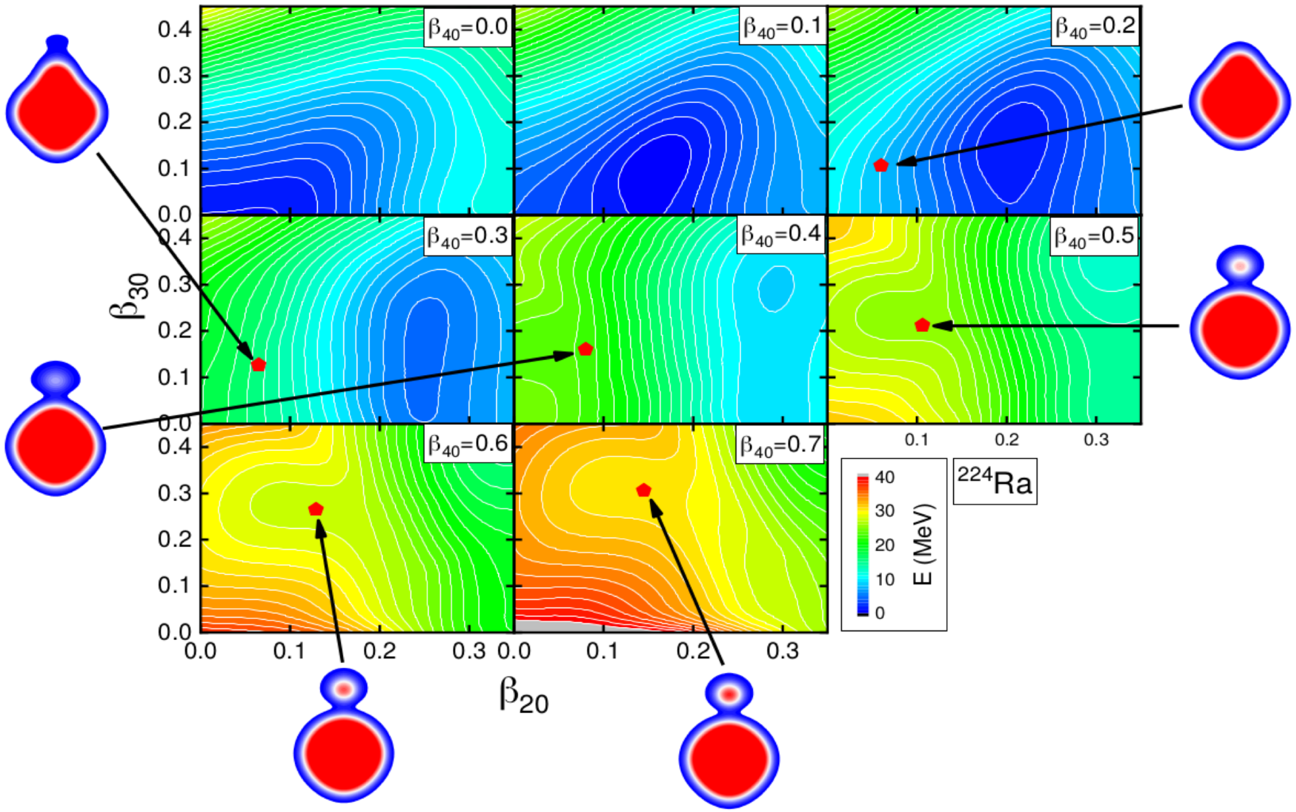


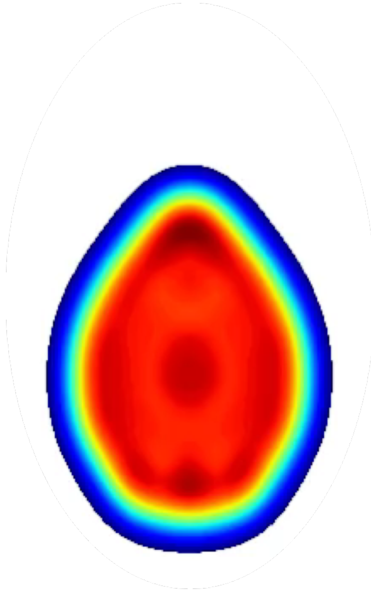


F. Mercier, J. Zhao, R.-D. Lasseri, J. P. Ebran, E. Khan, T. Nikšić, and D. Vretenar, Phys. Rev. C 102, 011301(R) (2020)

α decay in ^{224}Ra

^{224}Ra	
T_{exp}	3.6 d
T_{theo}	5.7 d



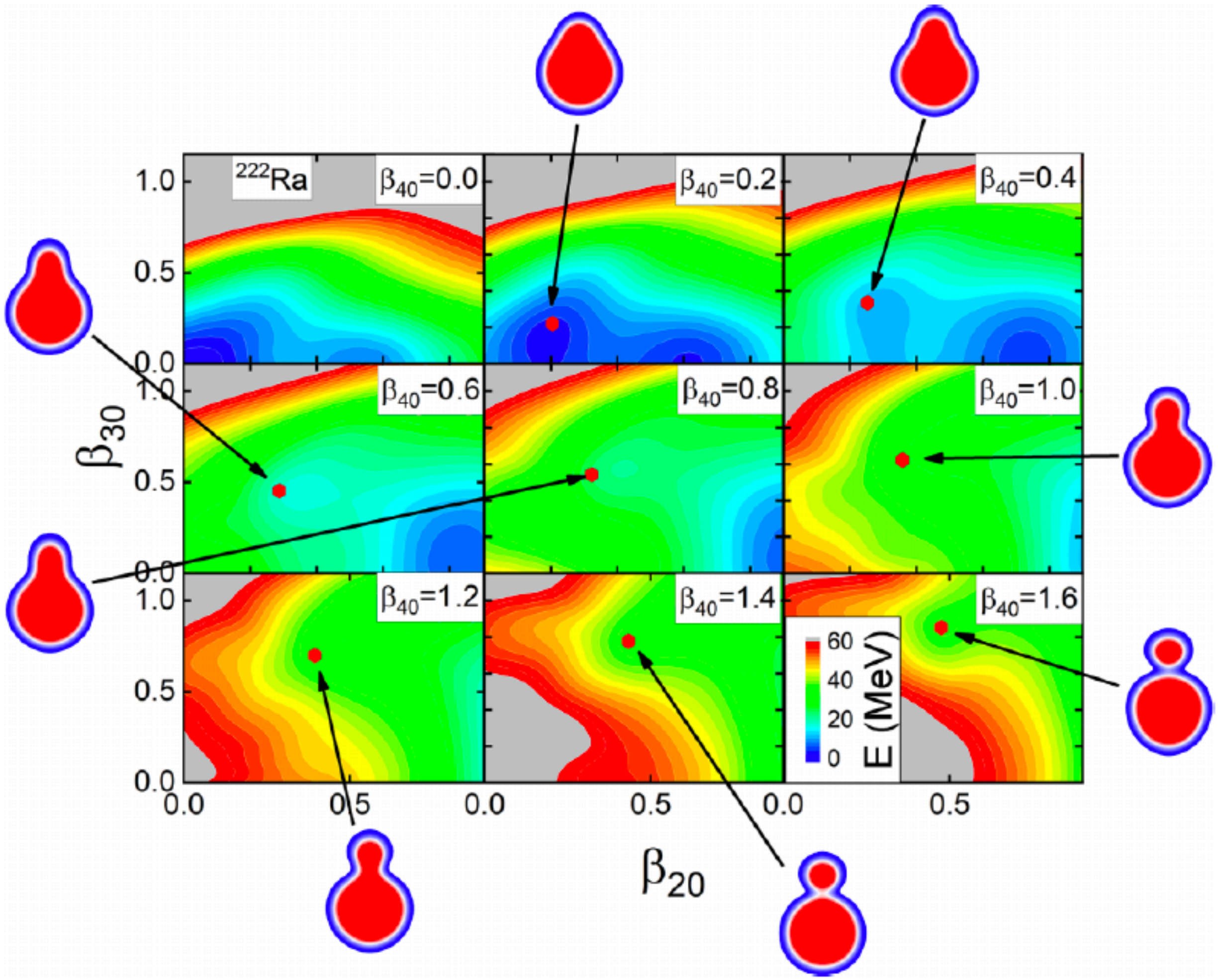


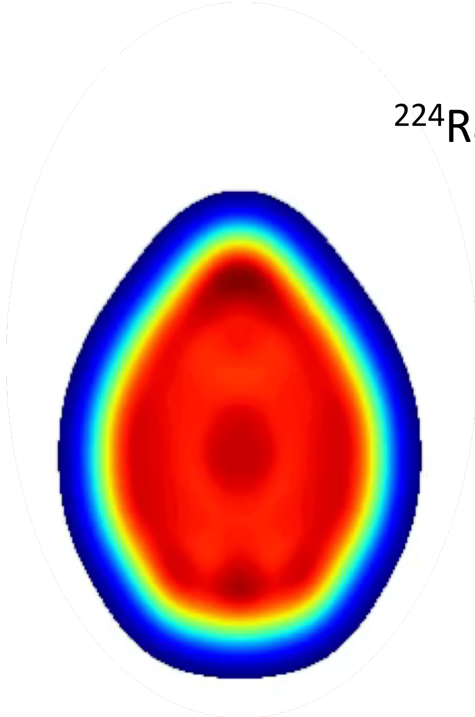
RHB density plots

For heavy nuclei, the hexadecapole constraint β_4 is necessary to form the neck for alpha-particle emission

J. Zhao, J. P. Ebran, L. Heitz, E. Khan, F. Mercier, T. Nikšić, and D. Vretenar, Phys. Rev. C 107, 034311 (2023)

^{14}C cluster decay in $^{222,224}Ra$



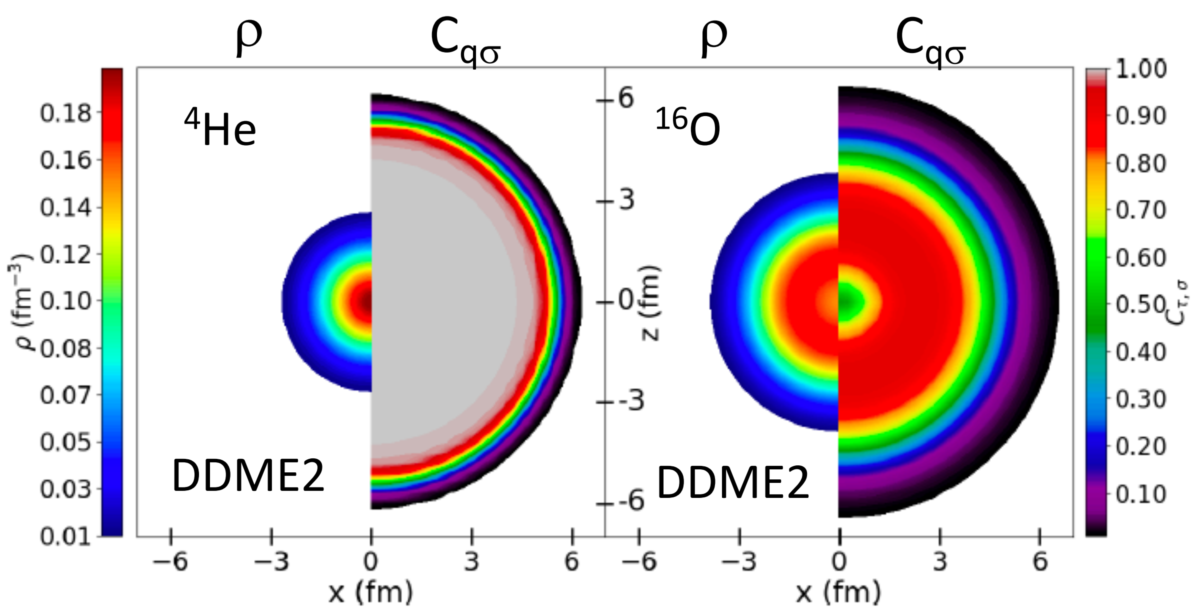


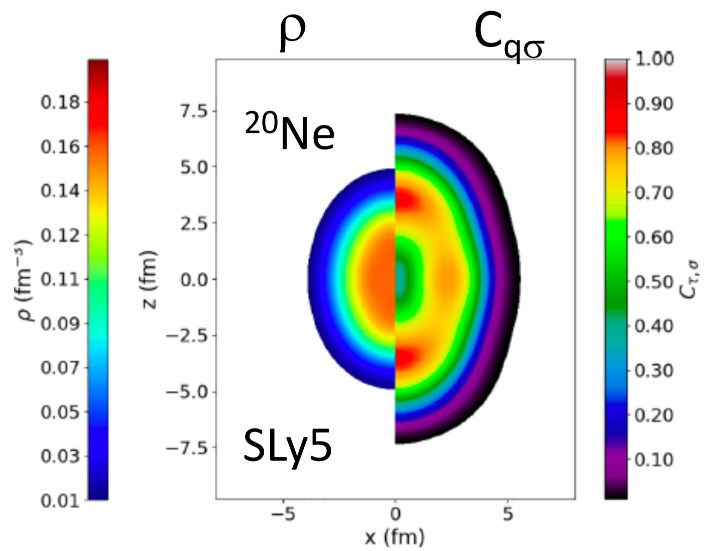
RHB density plots

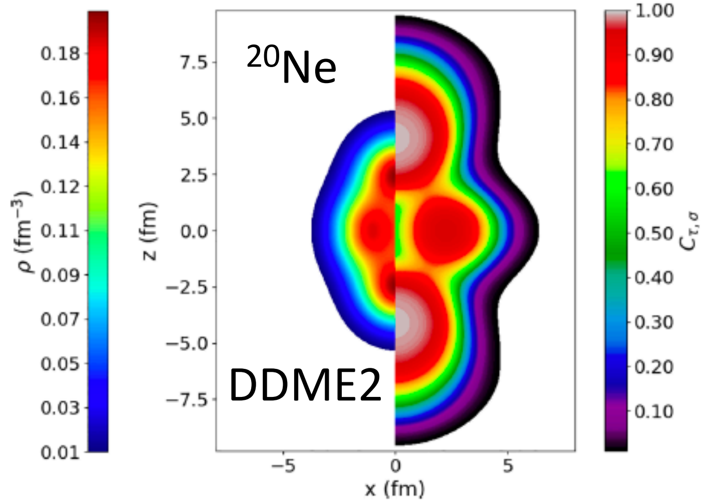
	T_{expt}	T_C^{2D}	T_C^{3D}
^{222}Ra	11.01	13.61	14.82
^{224}Ra	15.86	15.87	

Cluster decay more complex than α one: collective inertia, etc.

Criteria for alpha clusterization in nuclei







3 criteria required for alpha cluster:

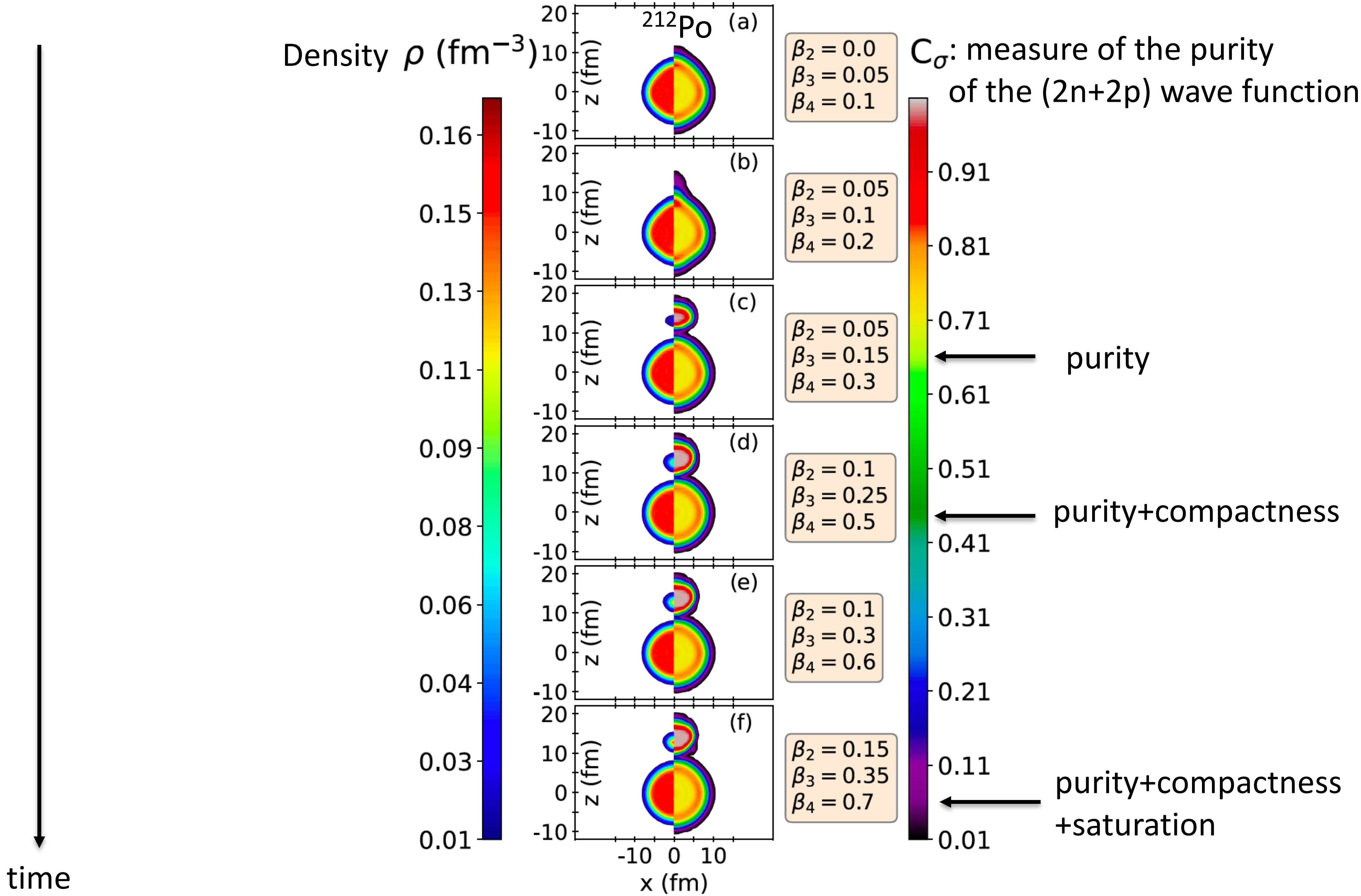
	$C_{q\sigma}$	$\rho/\rho_{\max}$	$F(R_\alpha)_\parallel$	$F(R_\alpha)_\perp$
Criteria for cluster	>0.9	>0.8	>0.6	>0.6
^{4}He (DD-ME2)	1	1	0.82	0.82
^{20}Ne (DD-ME2)	0.95	1	0.75	0.70
^{20}Ne (SLy5)	0.6	1	0.45	0.25
^{16}O (DD-ME2)	0.9	1	0.79	0.41
	Purity	Saturation	Compactness	

with $F(r) = \dfrac{\rho_{\max} - \rho(r)}{\rho_{\max}}$

(see bubble nuclei)

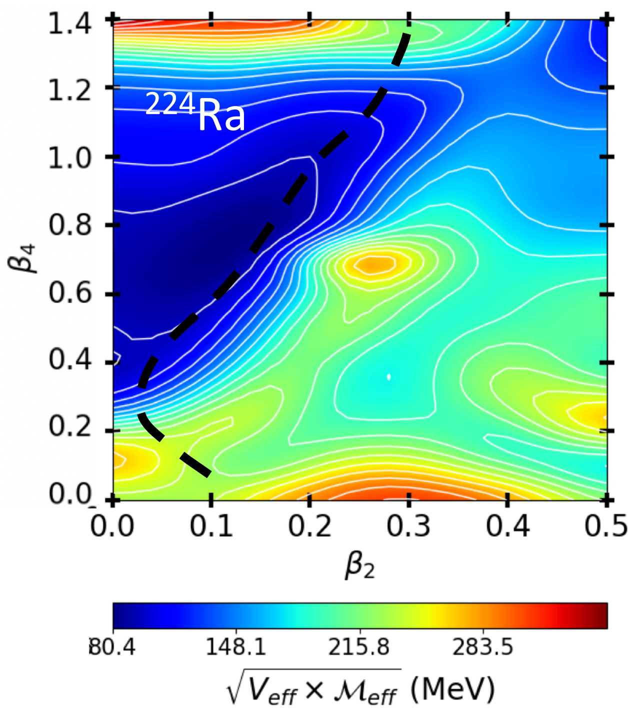
E. Khan, L. Heitz, F. Mercier, J. P. Ebran, PRC 106, 064330 (2022)

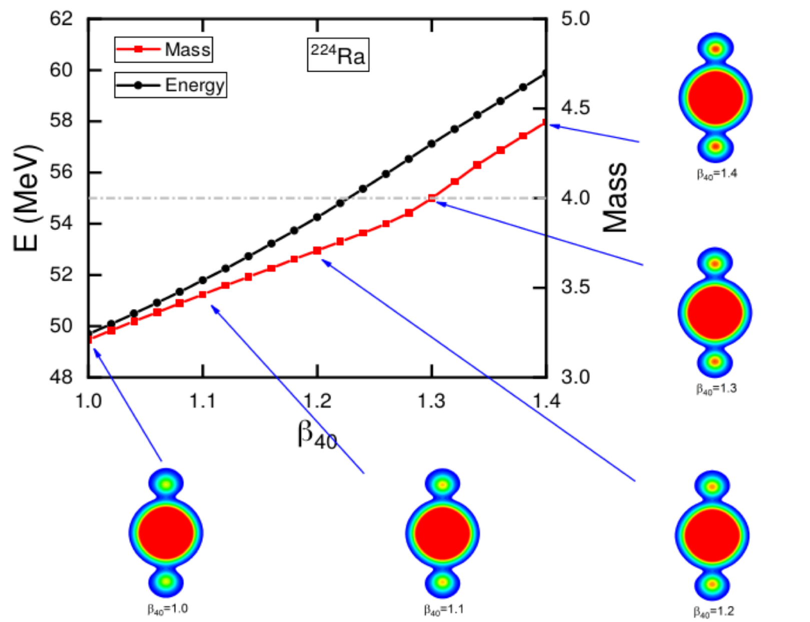
Microscopic insight on the α decay

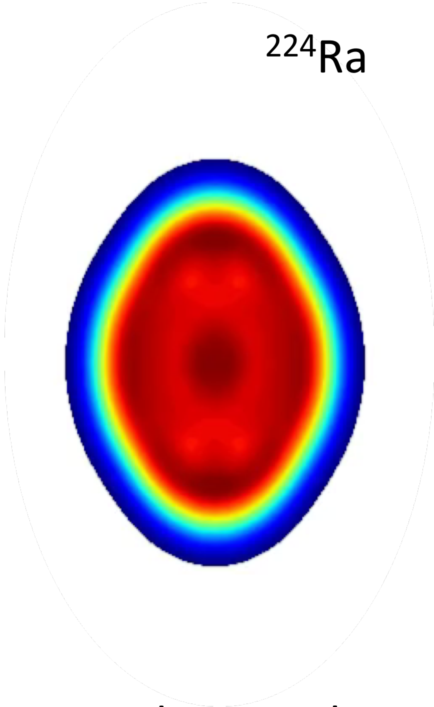


The symmetric 2α decay

	^{14}C	^{8}Be	2α
T_{theo}	$10^{15.87}$ s	$10^{27.87}$ s	$10^{13.03}$ s
T_{exp}	$10^{15.86}$ s	??	??





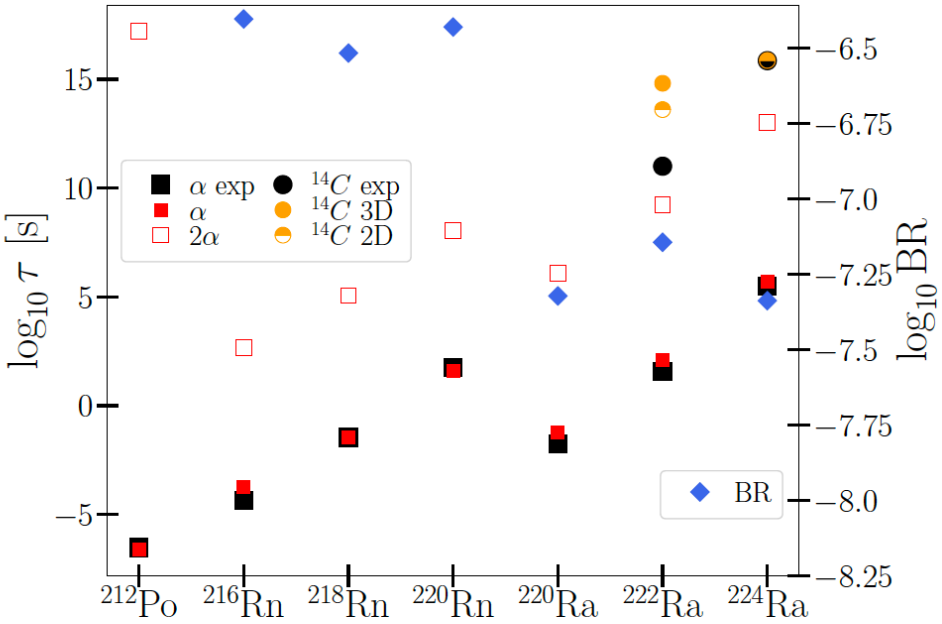


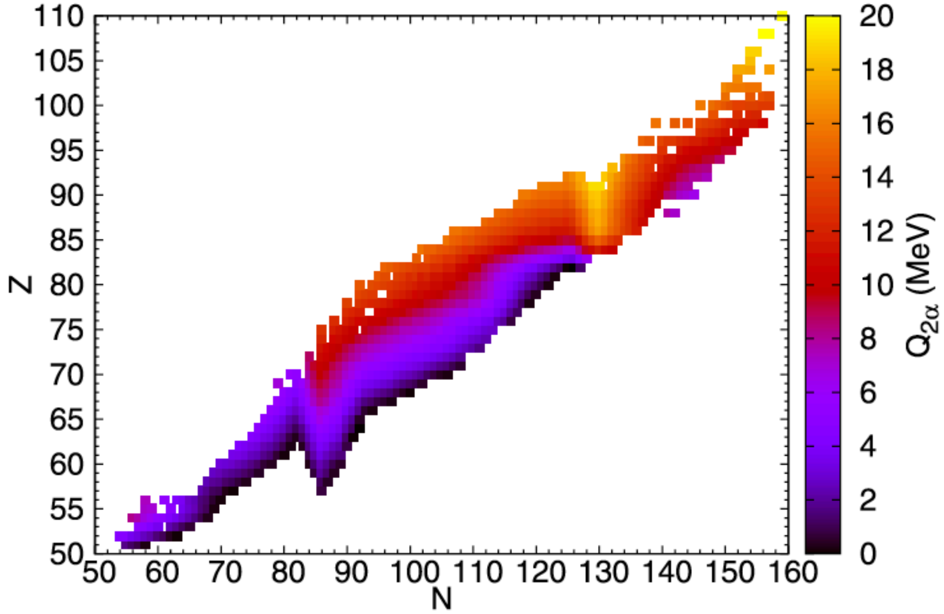
RHB density plots

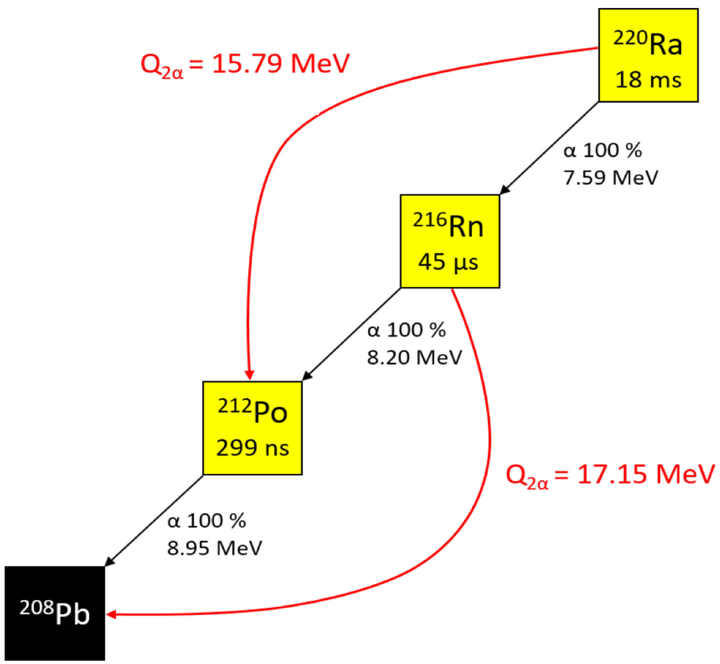
- Unobserved for now
- 2α decay predicted since several decades as ^{8}Be cluster emission: negligible BR
- Here, separate emissions of the 2 α , BR larger than observed ^{14}C cluster emission

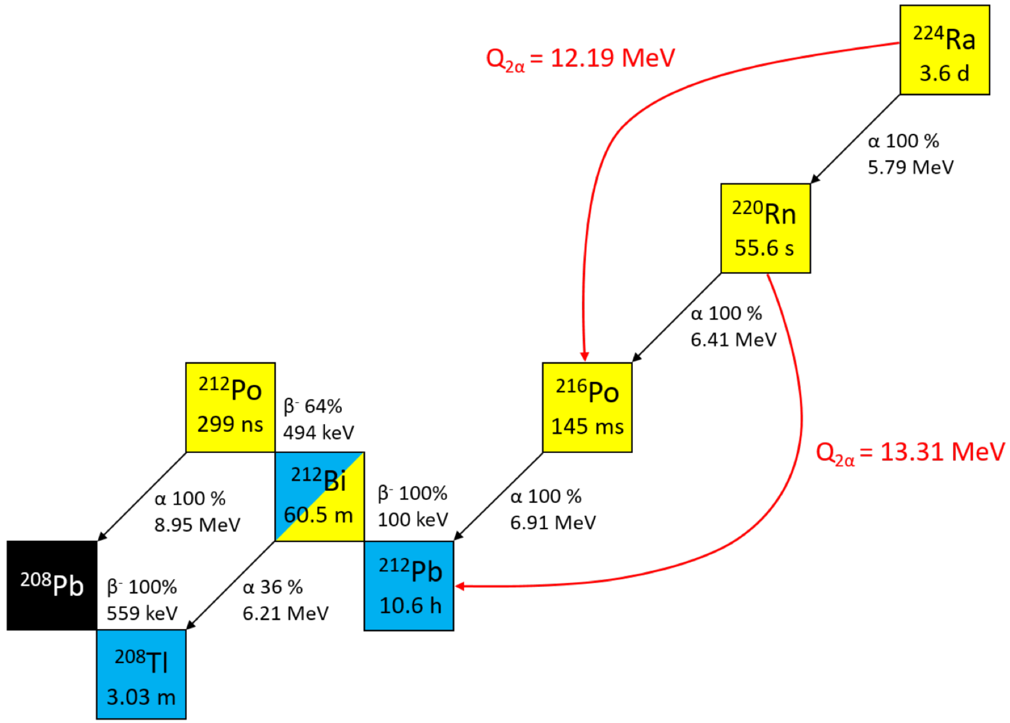
F. Mercier, J. Zhao, J. P. Ebran, L. Heitz, E. Khan, T. Nikšić, and D. Vretenar, Phys. Rev. Lett. 127, 012501 (2021)

Best 2α decay candidates ?









2α decay exp. collaboration

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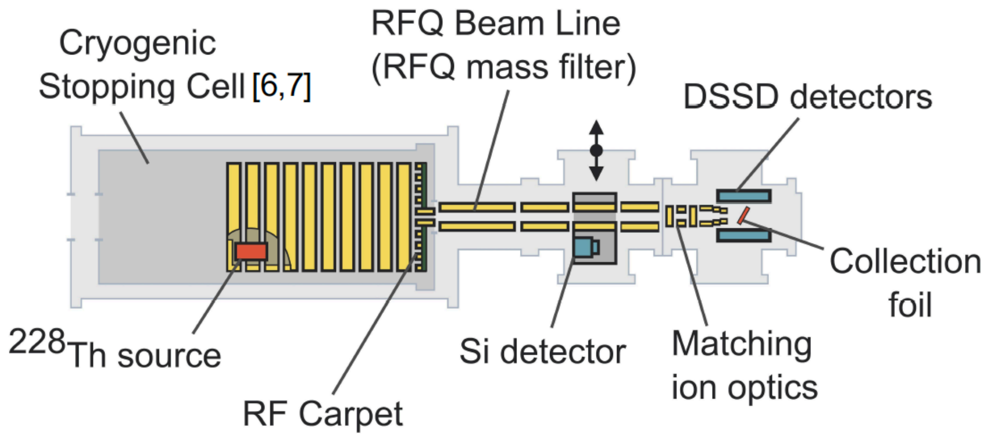
3 experiments under analysis

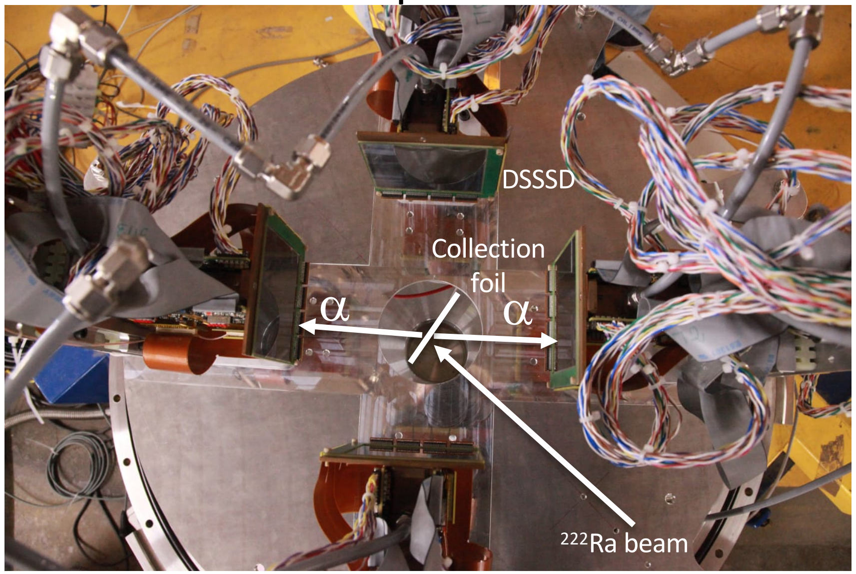
^{224}Ra@FRS-Ion catcher, GSI (2022)



+ ^{220}Rn@FRIB (2024) with GADGET II TPC

^{220,222}Ra@Isolde (June 2023)

Topview



L. Heitz, PhD Thesis (2025), Paris-Saclay University

Conclusions

- Quantality drives the scattering length and the packing vs. actual density (nuclei)
- Finite systems $\longrightarrow$ localisation parameter = quantality x size effects
- Nuclei: from quantum liquid to clusters transitional phase. Nuclear crystal ?
- Control parameters of the cluster phase: density
number of constituents
excitation energy
deformation
temperature
- Alpha and cluster decays are related to the existence of a nuclear cluster phase
- Localisation+saturation+compactness required for pinpointing an alpha cluster
- Spin-orbit effect: driven by the quantality and the coupling constant = inertia parameter
- Role of pseudo-spin in magic numbers and their evolution in exotic nuclei

Thank you !