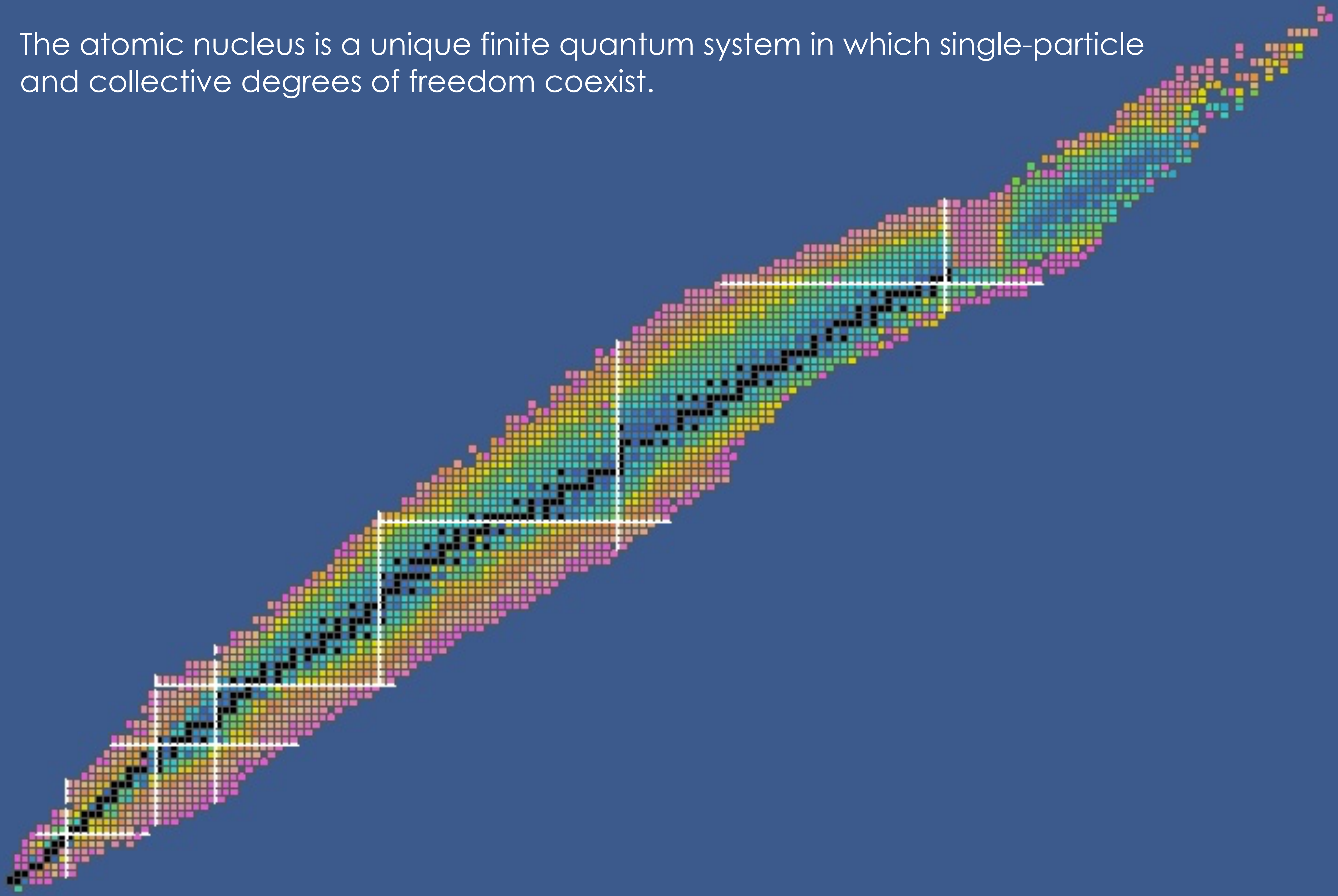
Static and dynamic aspects of exotic nuclear structure

Dario Vretenar
University of Zagreb

The atomic nucleus is a unique finite quantum system in which single-particle and collective degrees of freedom coexist.



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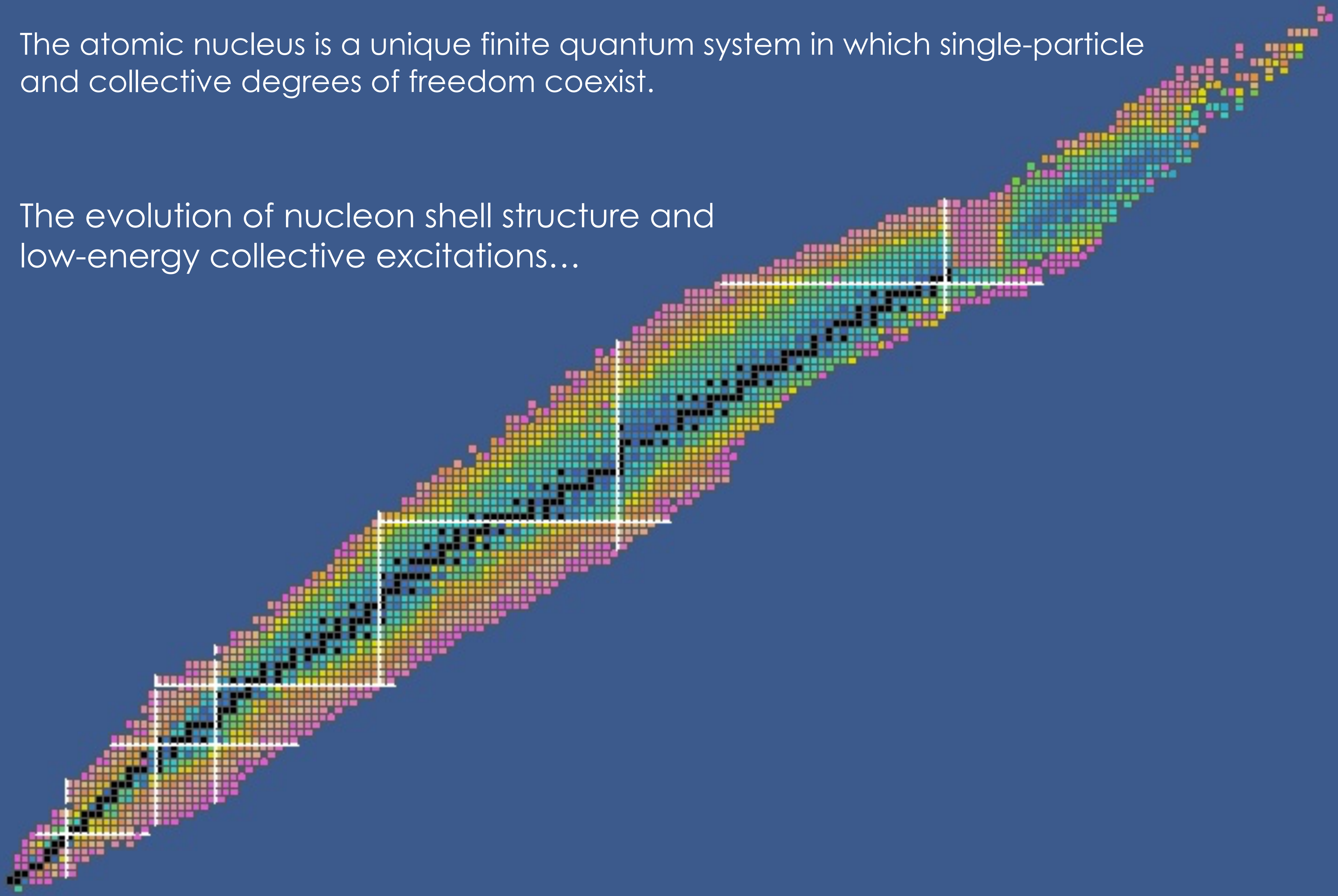
The evolution of nucleon shell structure and low-energy collective excitations…



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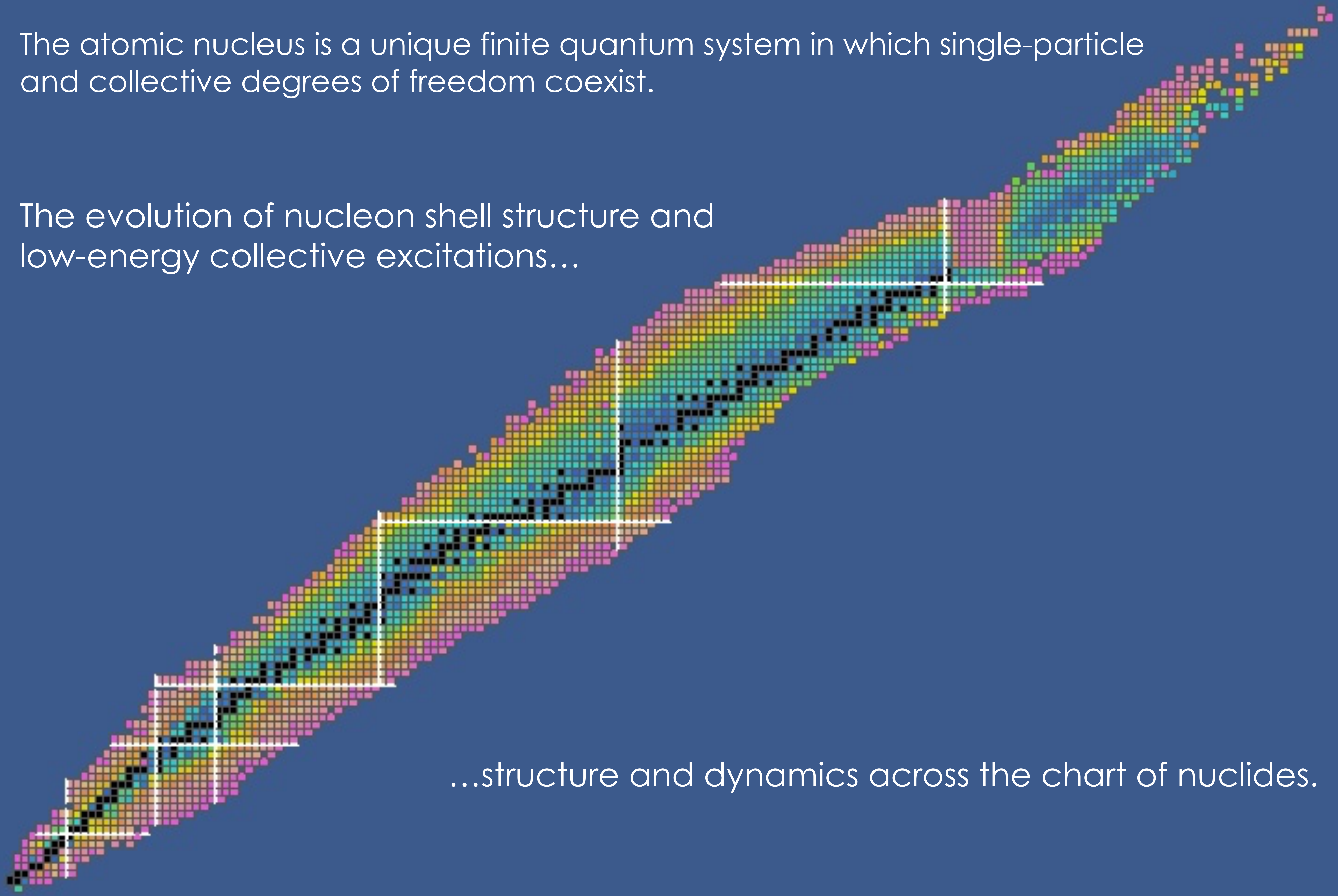
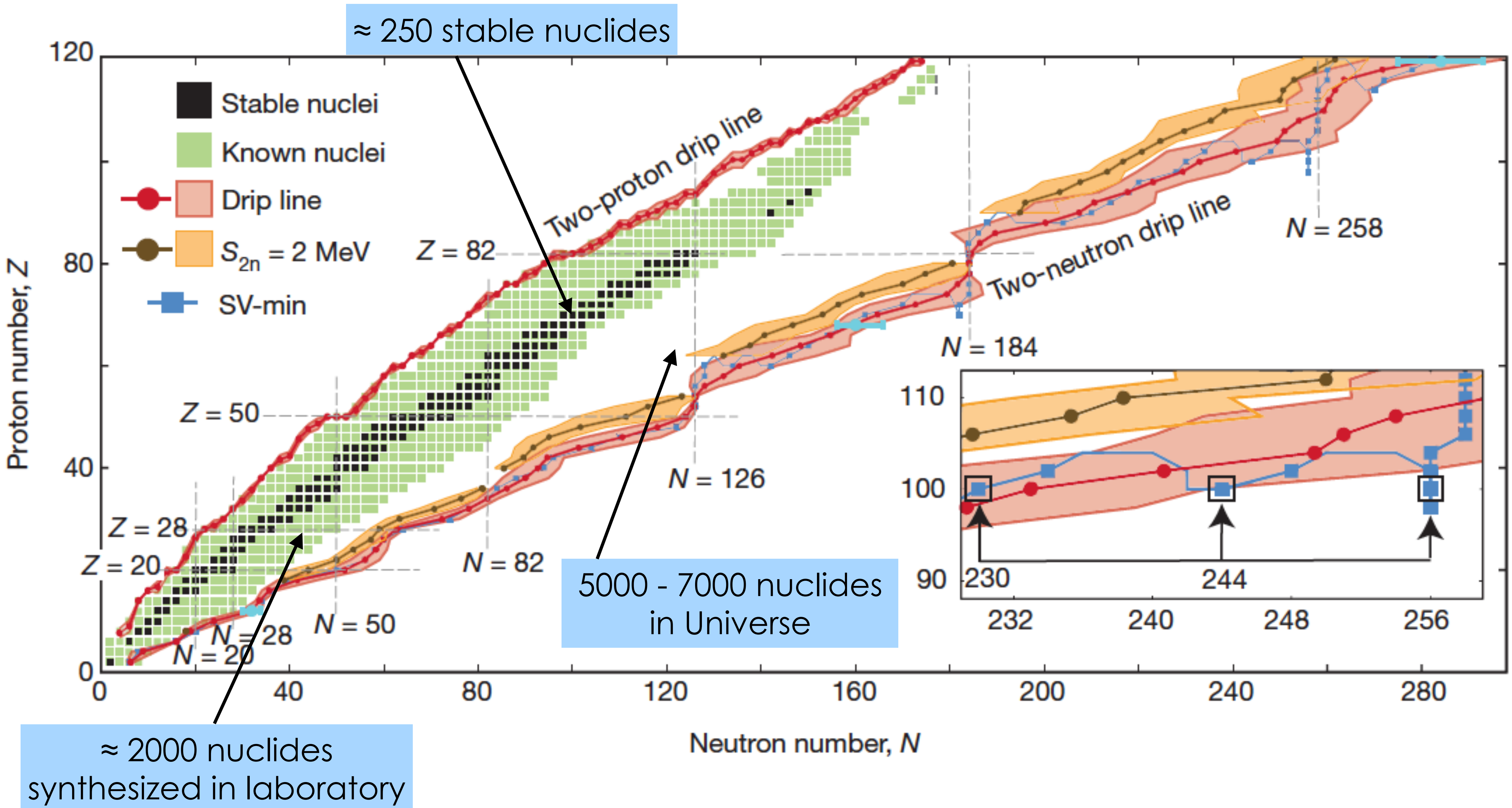
The evolution of nucleon shell structure and low-energy collective excitations…



…structure and dynamics across the chart of nuclides.

Chart of Nuclides



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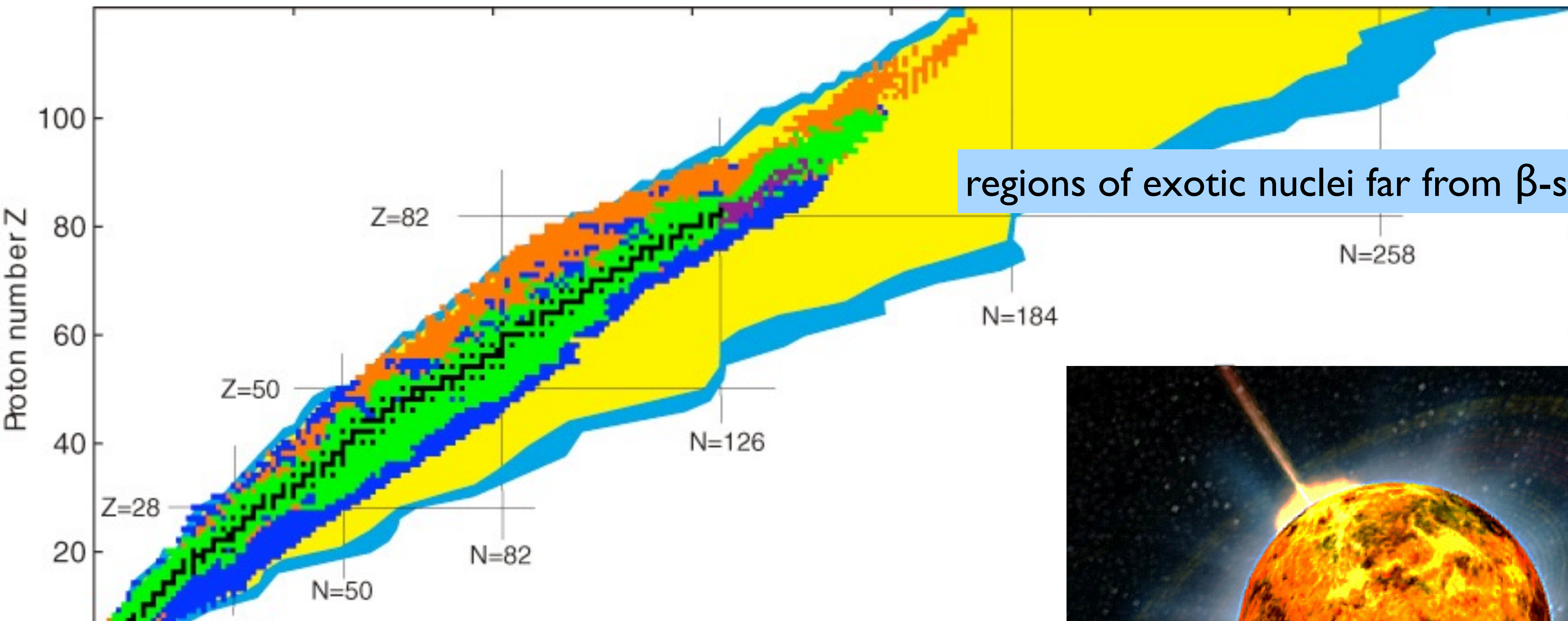
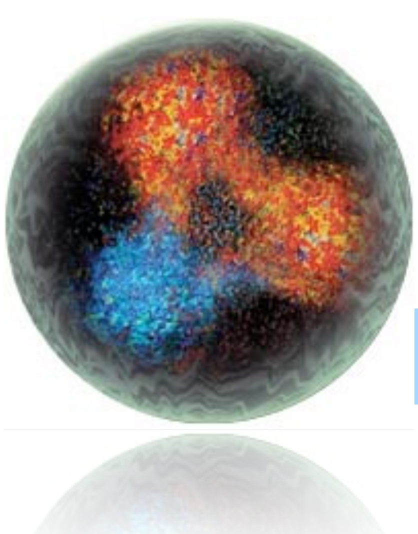
510 | NATURE | VOL 486 | 28 JUNE 2012

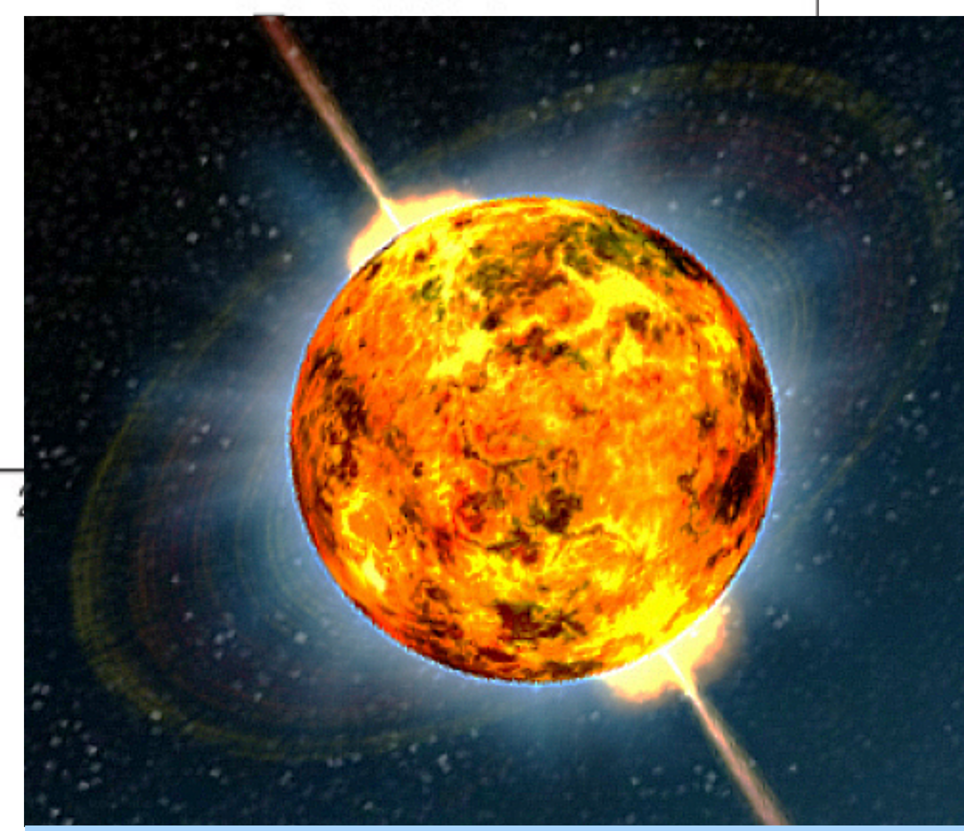
Low-energy Nuclear Theory



regions of exotic nuclei far from β-stability

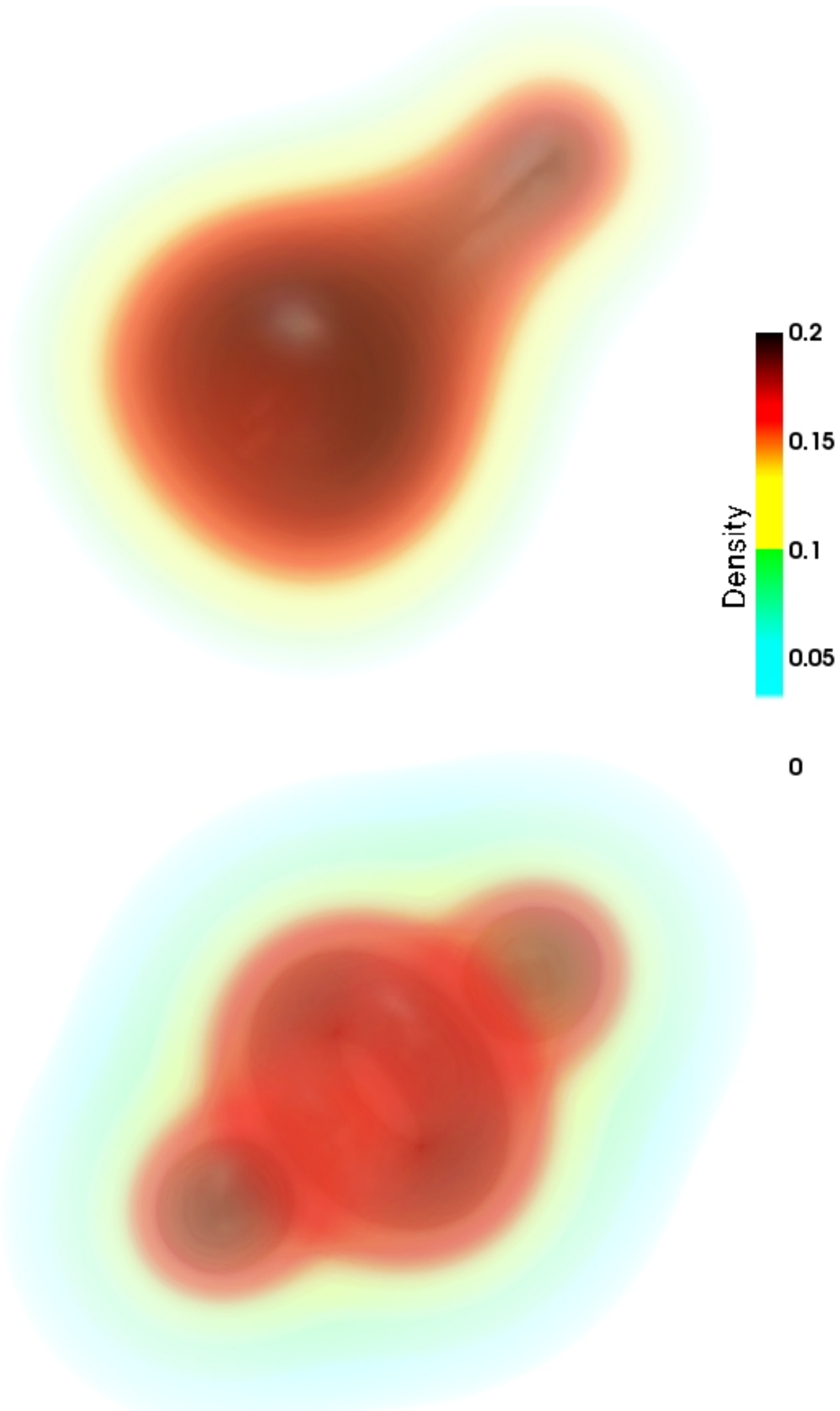


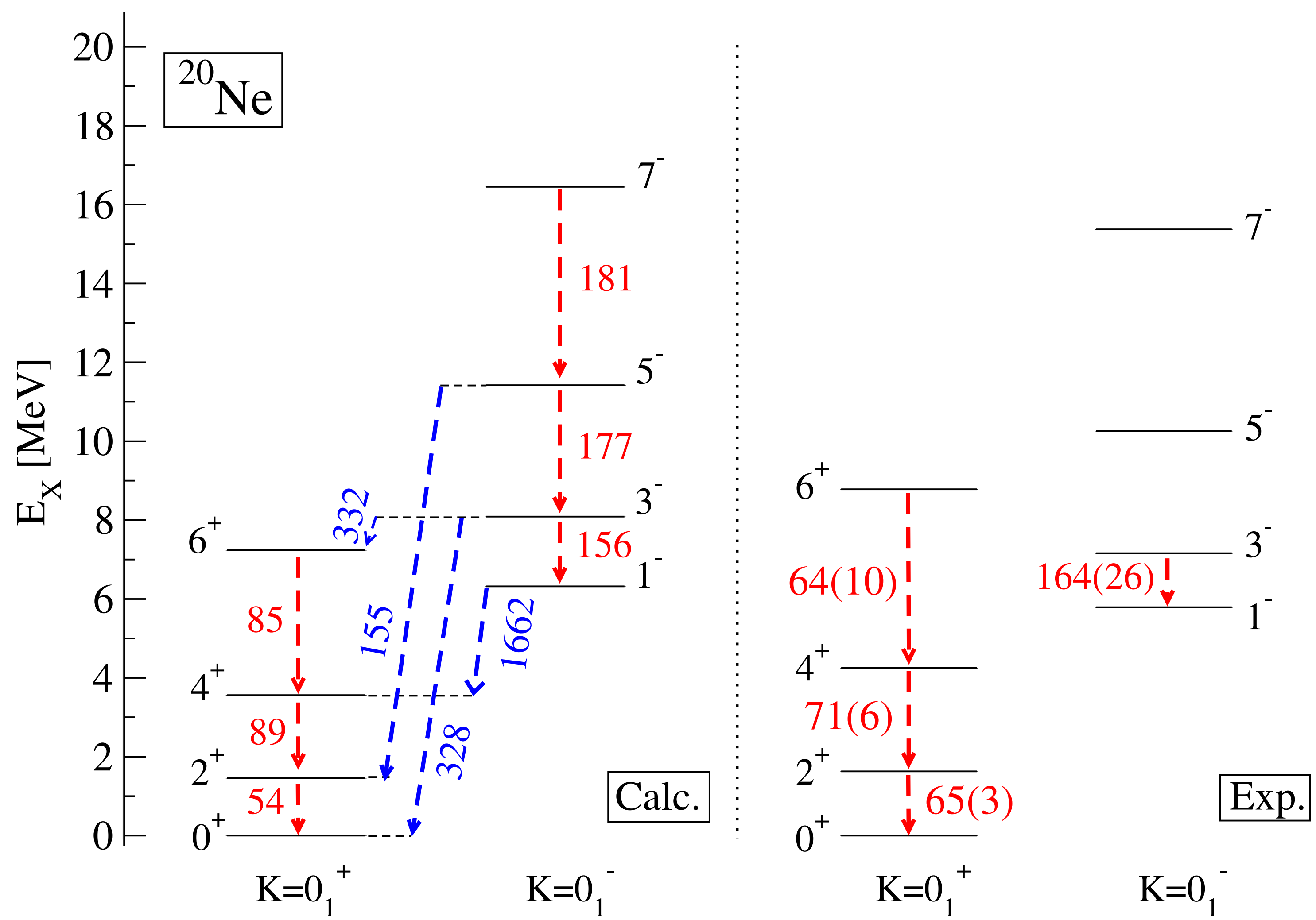
connection to low-energy QCD



nuclear astrophysics applications

Localization and clustering in atomic nuclei:





How atomic nuclei cluster

J.-P. Ebran[1], E. Khan[2], T. Nikšić[3] & D. Vretenar[3]

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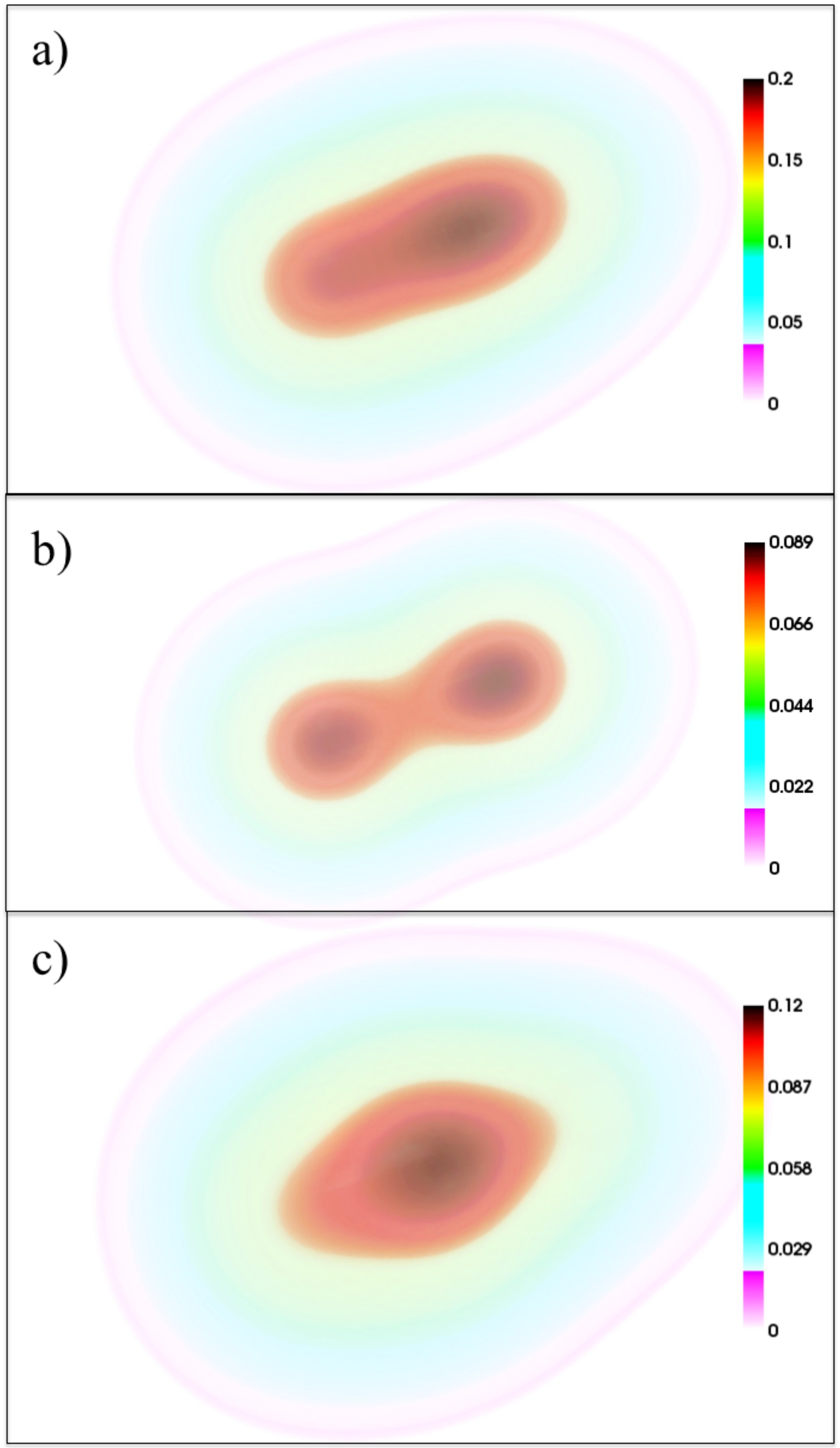
19 JULY 2012 | VOL 487 | NATURE | 341

Clustering in neutron-rich nuclei ⇒ molecular bonding of α-particles by the excess neutrons.

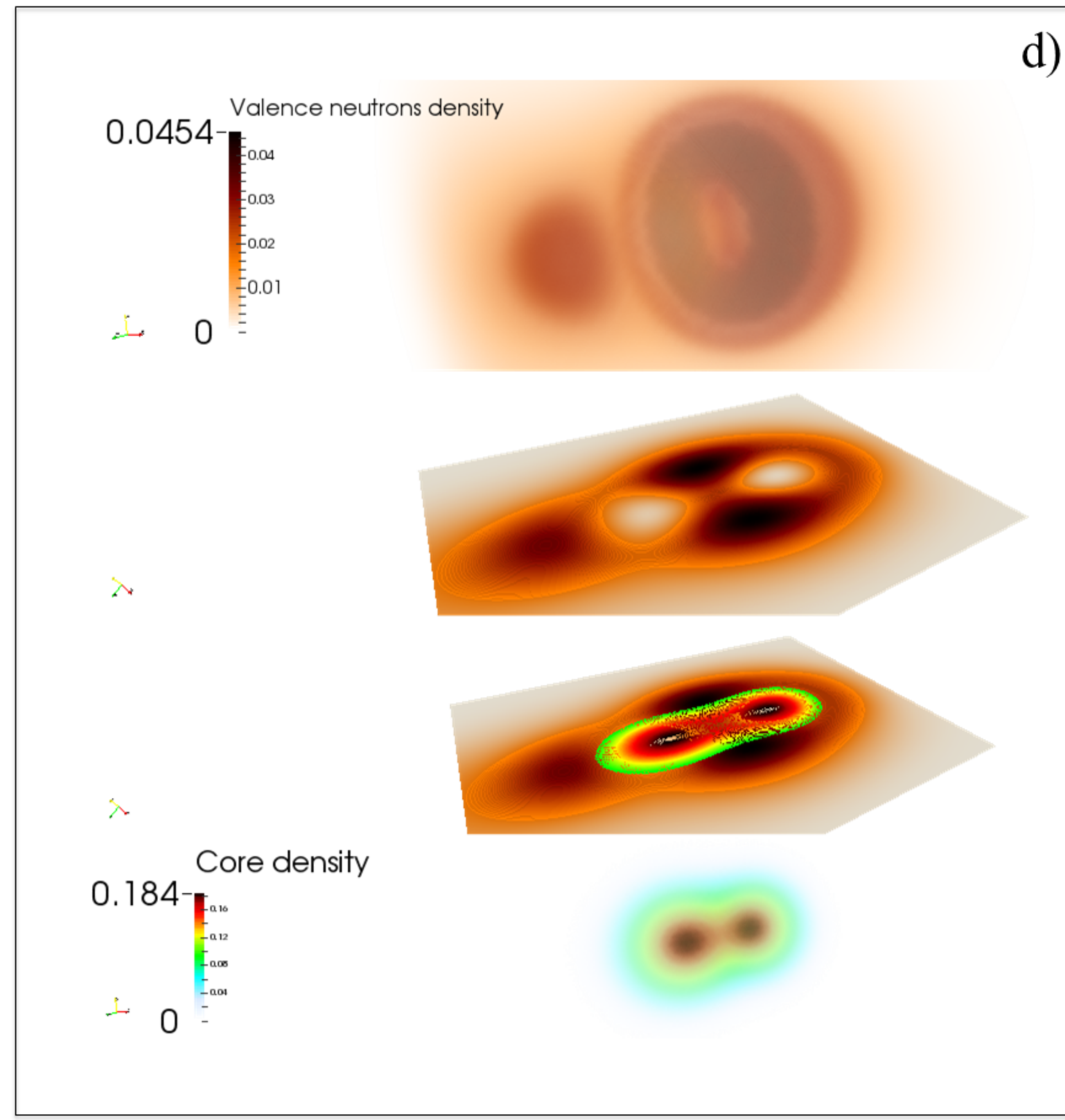
Total nucleon density

Proton density

Neutron density

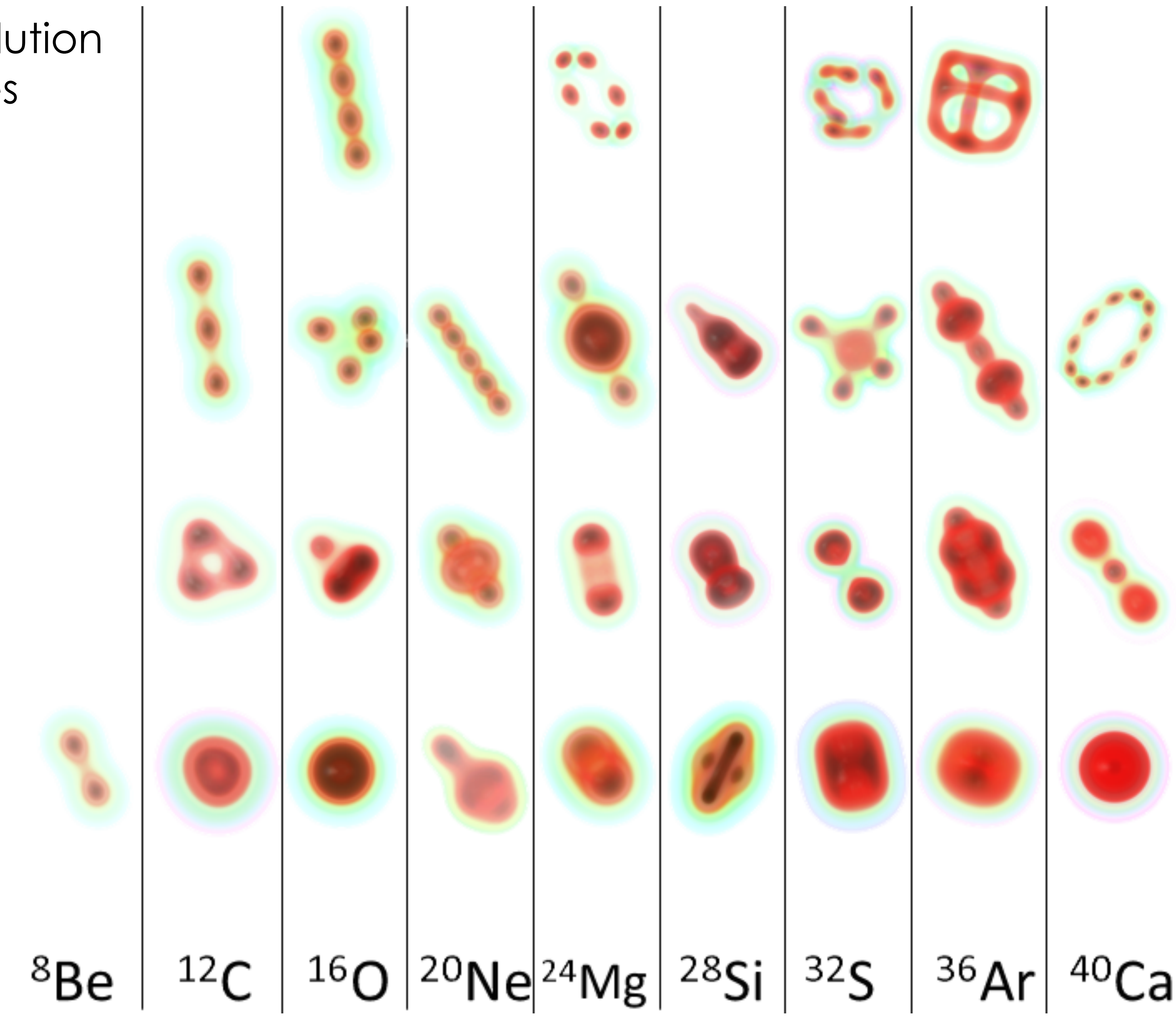


^{14}Be



J.-P. Ebran, E. Khan, T. Nikšić, and D. Vretenar
Phys. Rev. C **90**, 054329

…formation and evolution of exotic cluster states



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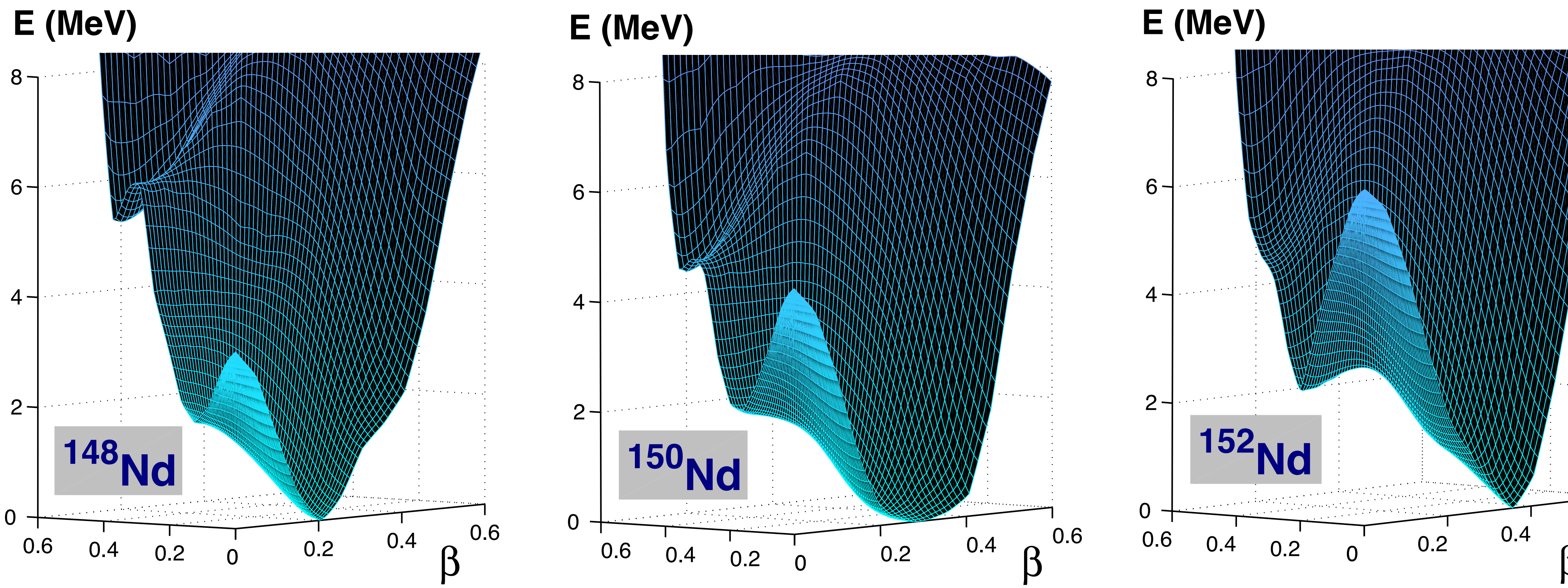
PHYSICAL REVIEW C **90**, 054329 (2014)

Shape Quantum Phase Transitions

…evolution of nucleonic shells ⇒ phase transitions in equilibrium shapes (QPT)

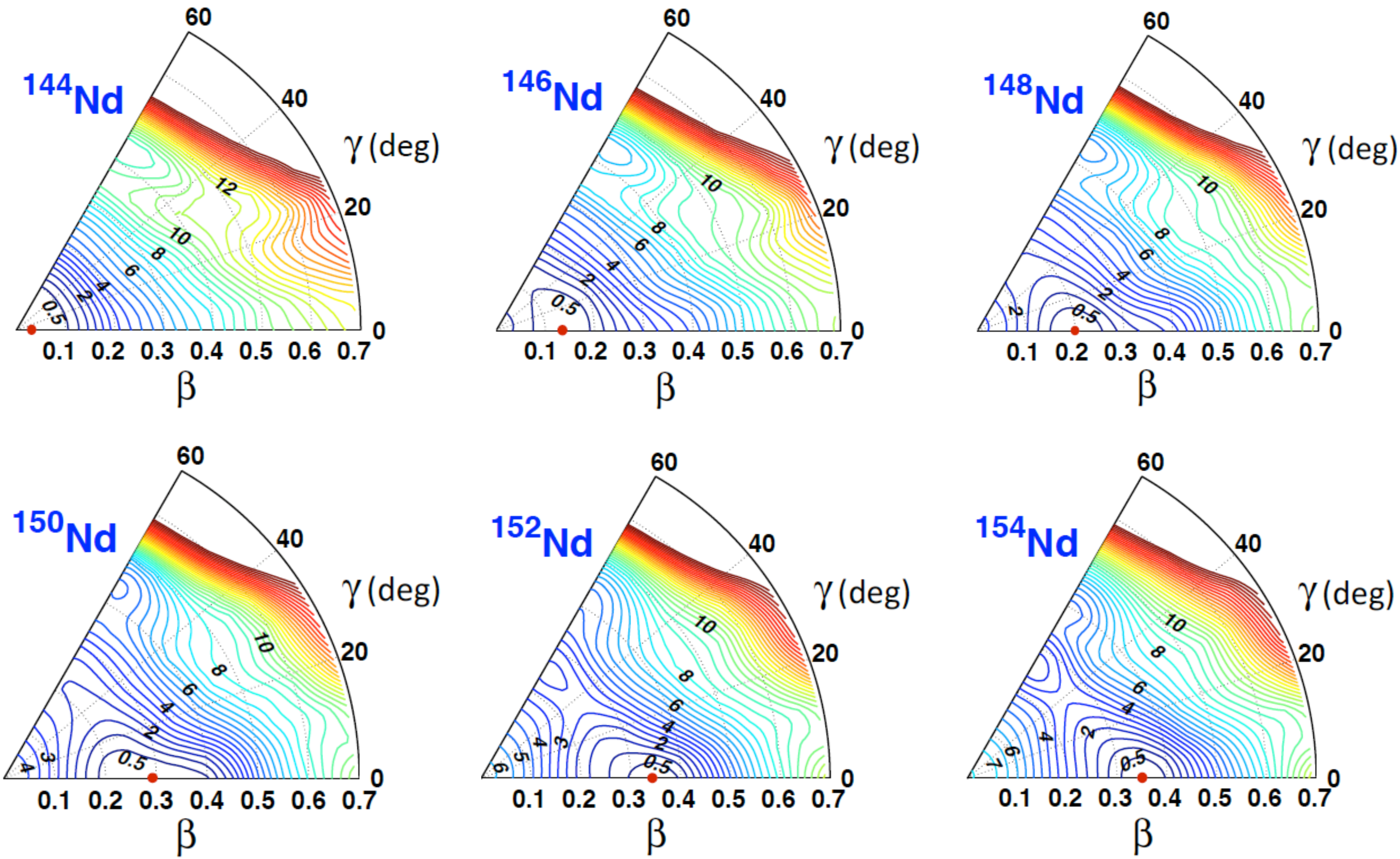


Nuclear Quantum Phase Transitions:

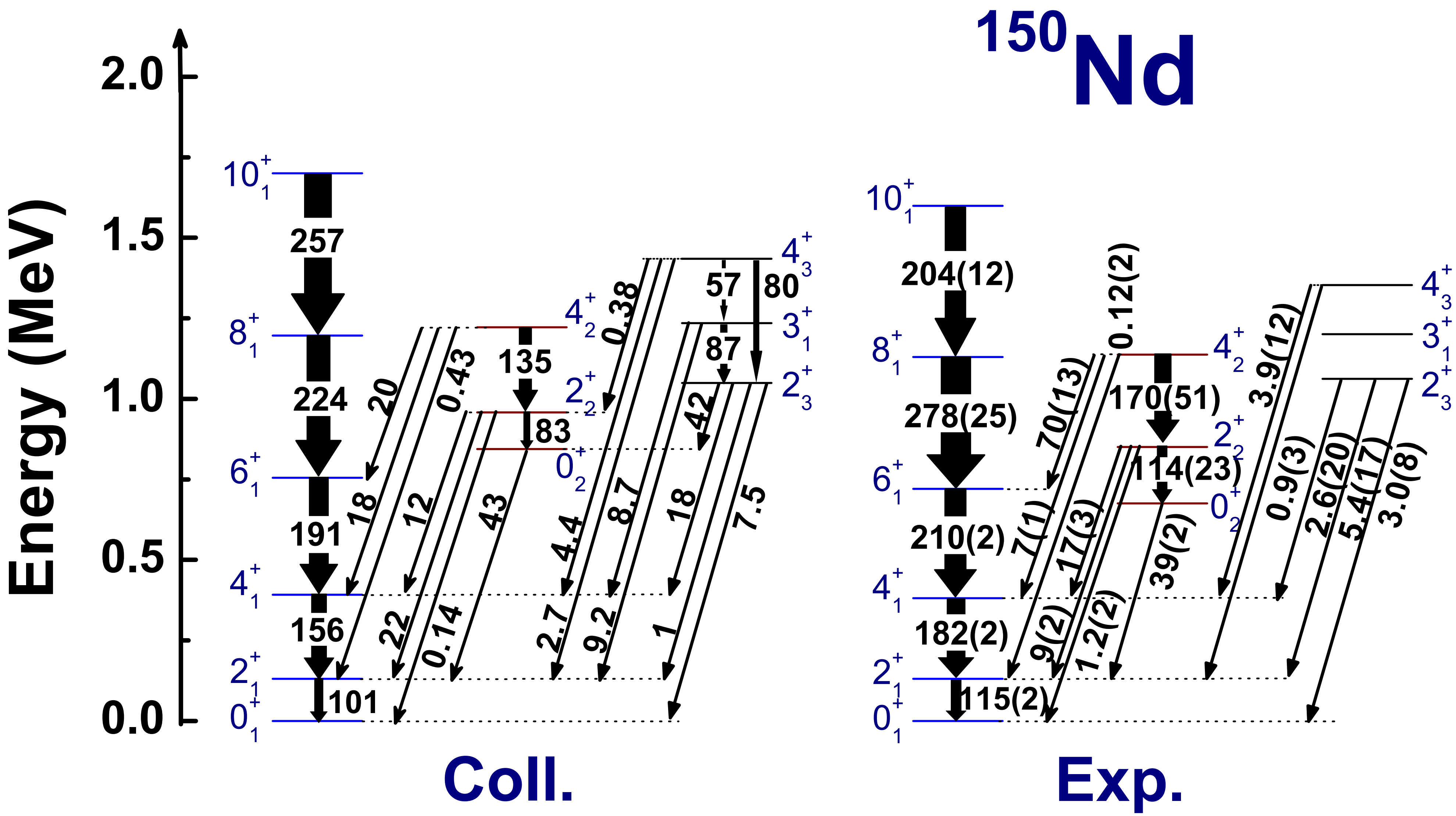
⇒ the physical control parameter - nucleon number

⇒ order parameters - expectation values of operators that as observables characterize the state of a nuclear system.

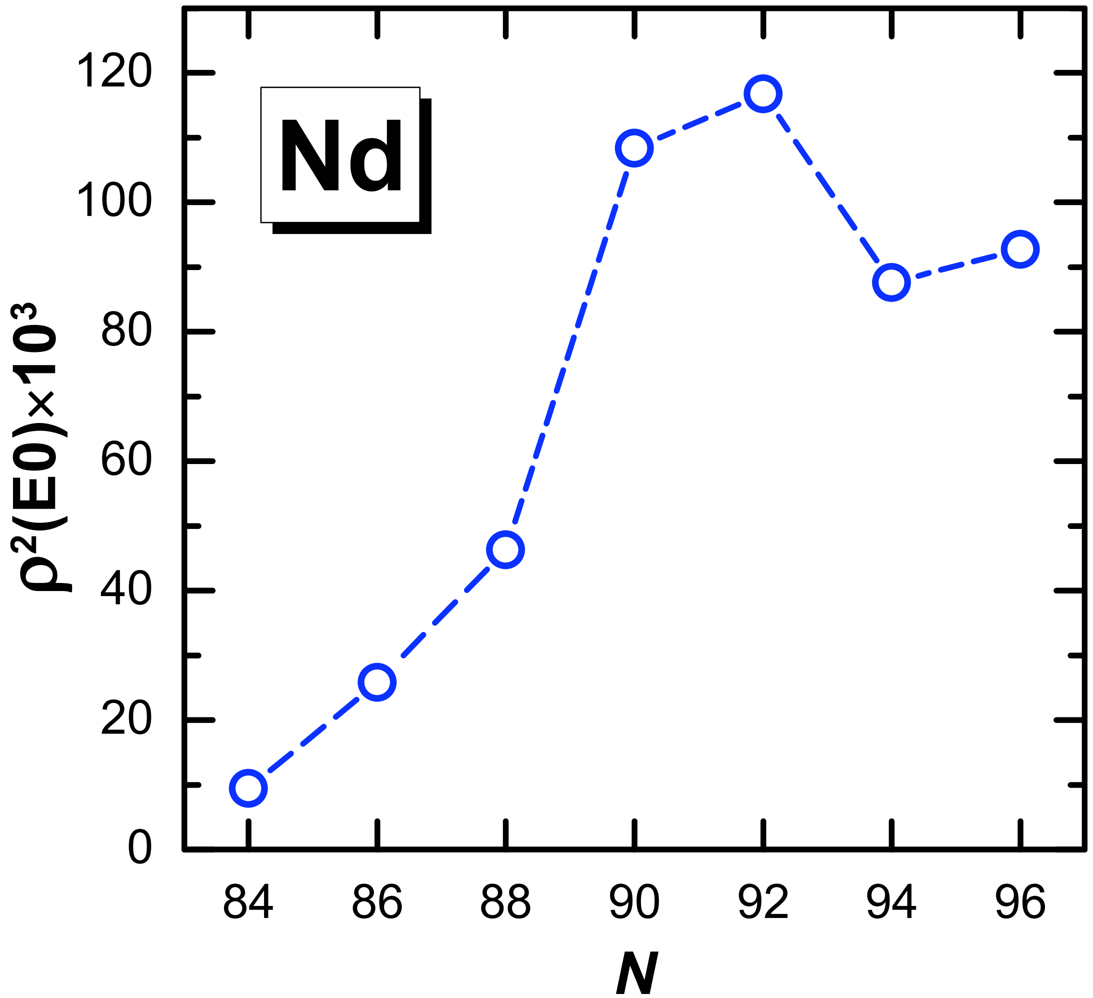
Transitions between spherical and axially deformed shapes in the chain of Nd-Sm-Gd isotopes.



Experimental evidence for a first-order shape phase transition at N≈90



Nikšić, Vretenar, Lalazissis, Ring, Phys. Rev. Lett. **99**, 092502 (2007)
Li, Nikšić, Vretenar, Meng, Lalazissis, Ring, Phys. Rev. C **79**, 054301 (2009)

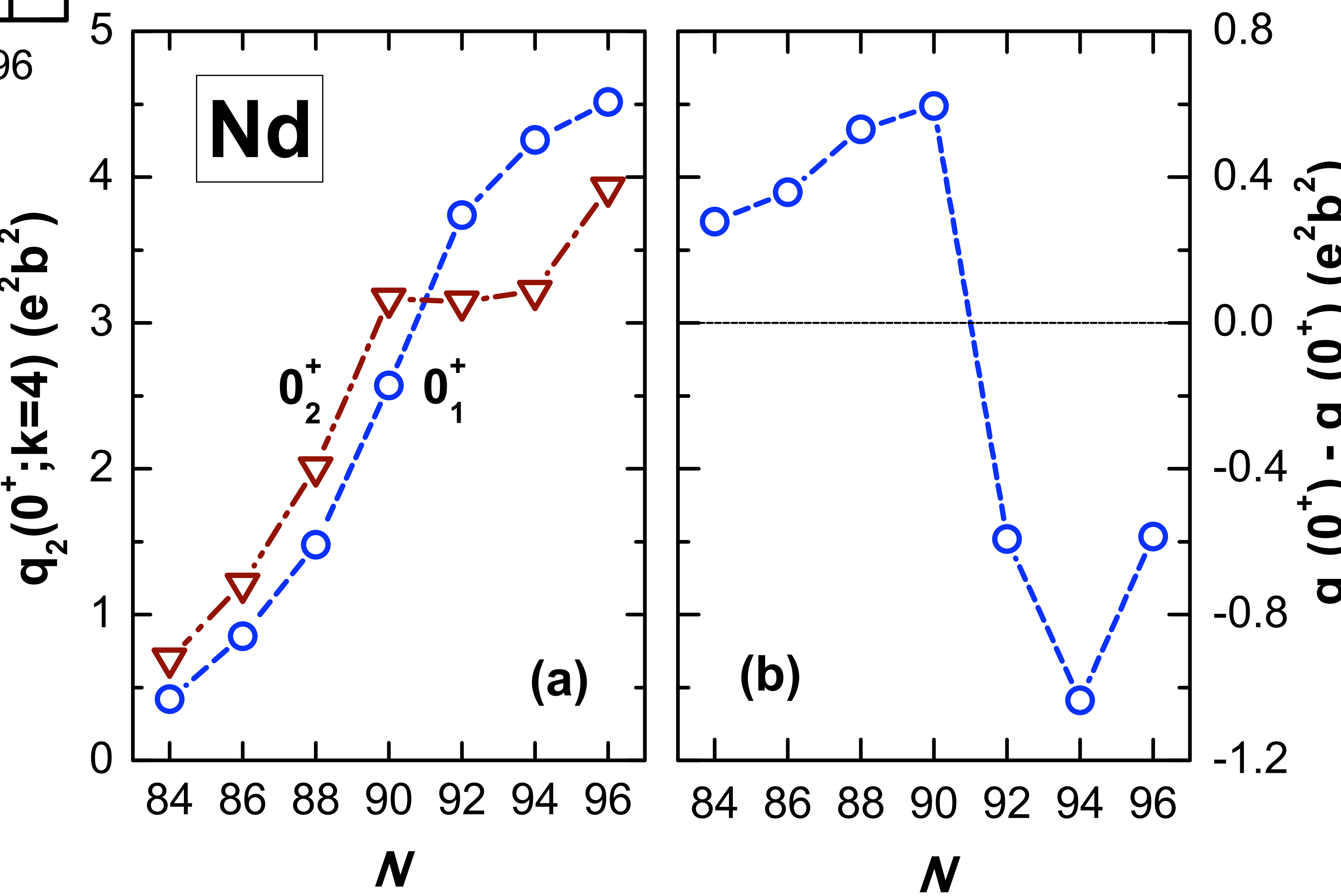


$$\hat{T}(E0) = \sum_k e_k r_k^2$$

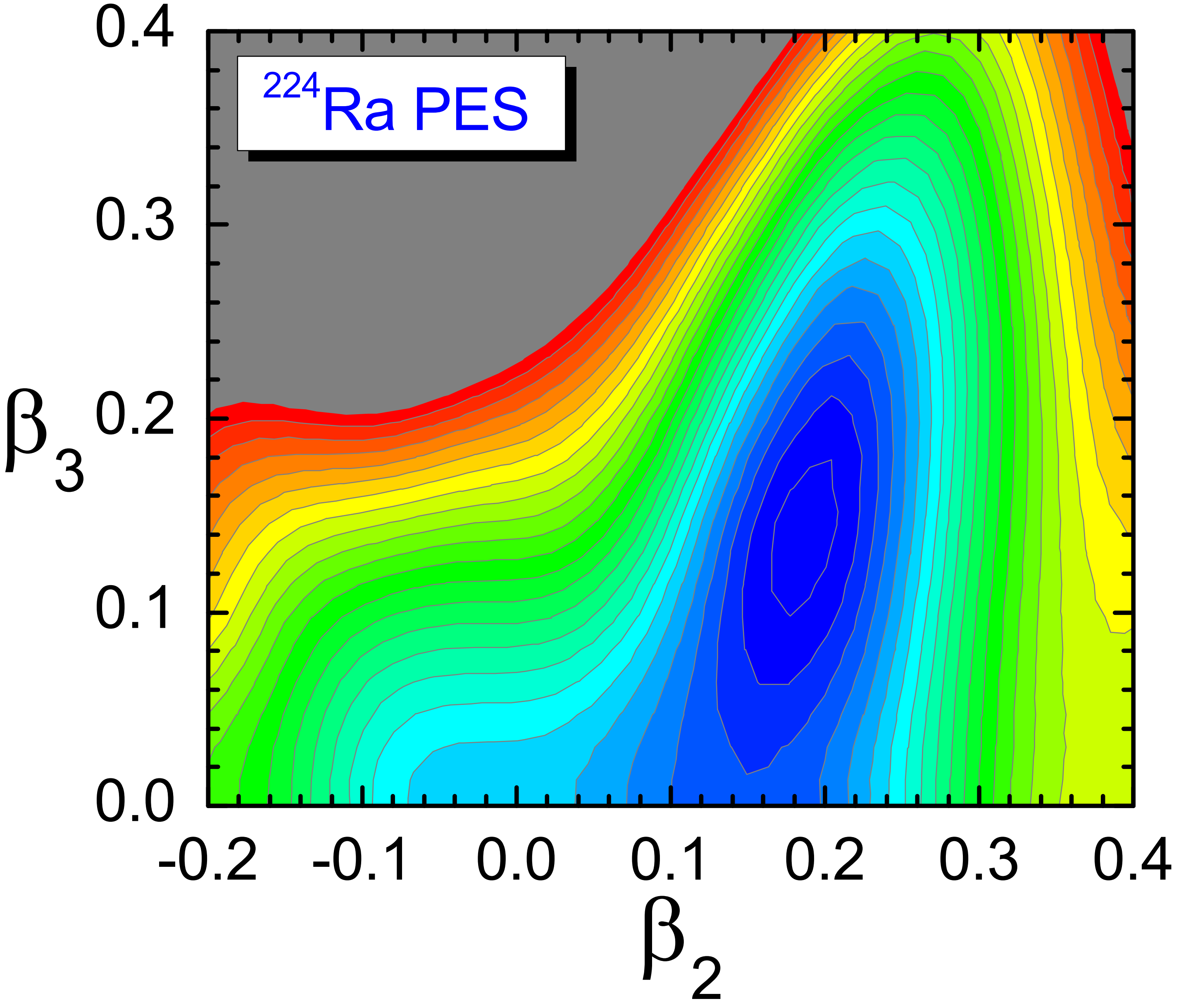
$$\rho^2(E0; 0_2^+ \rightarrow 0_1^+) = \left| \frac{\left\langle 0_2^+ | \hat{T}(E0) | 0_1^+ \right\rangle}{eR^2} \right|^2$$

q shape invariants:

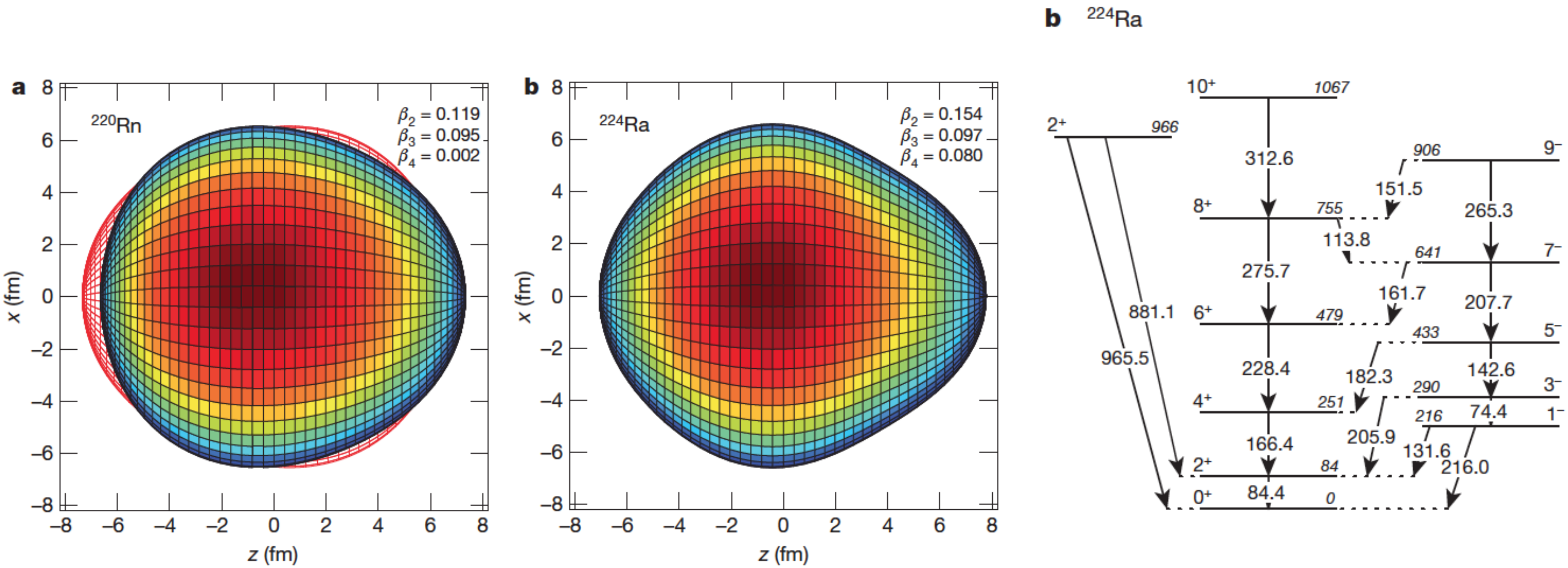
$$q_2(0_n^+; k) = \sum_{j=1}^{k} B(E2; 0_n^+ \rightarrow 2_j^+)$$



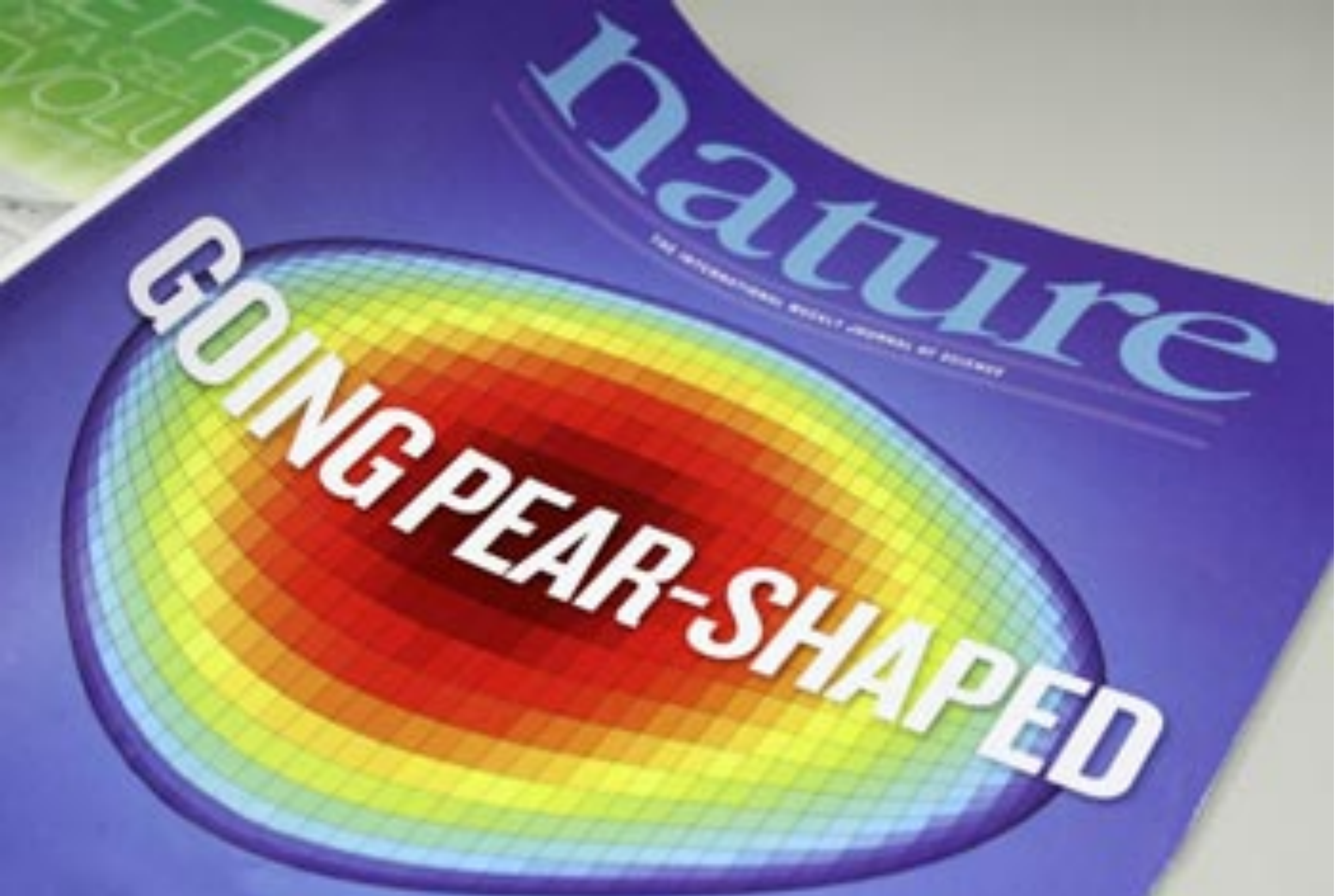
Spectroscopy of quadrupole and octupole deformed heavy nuclei



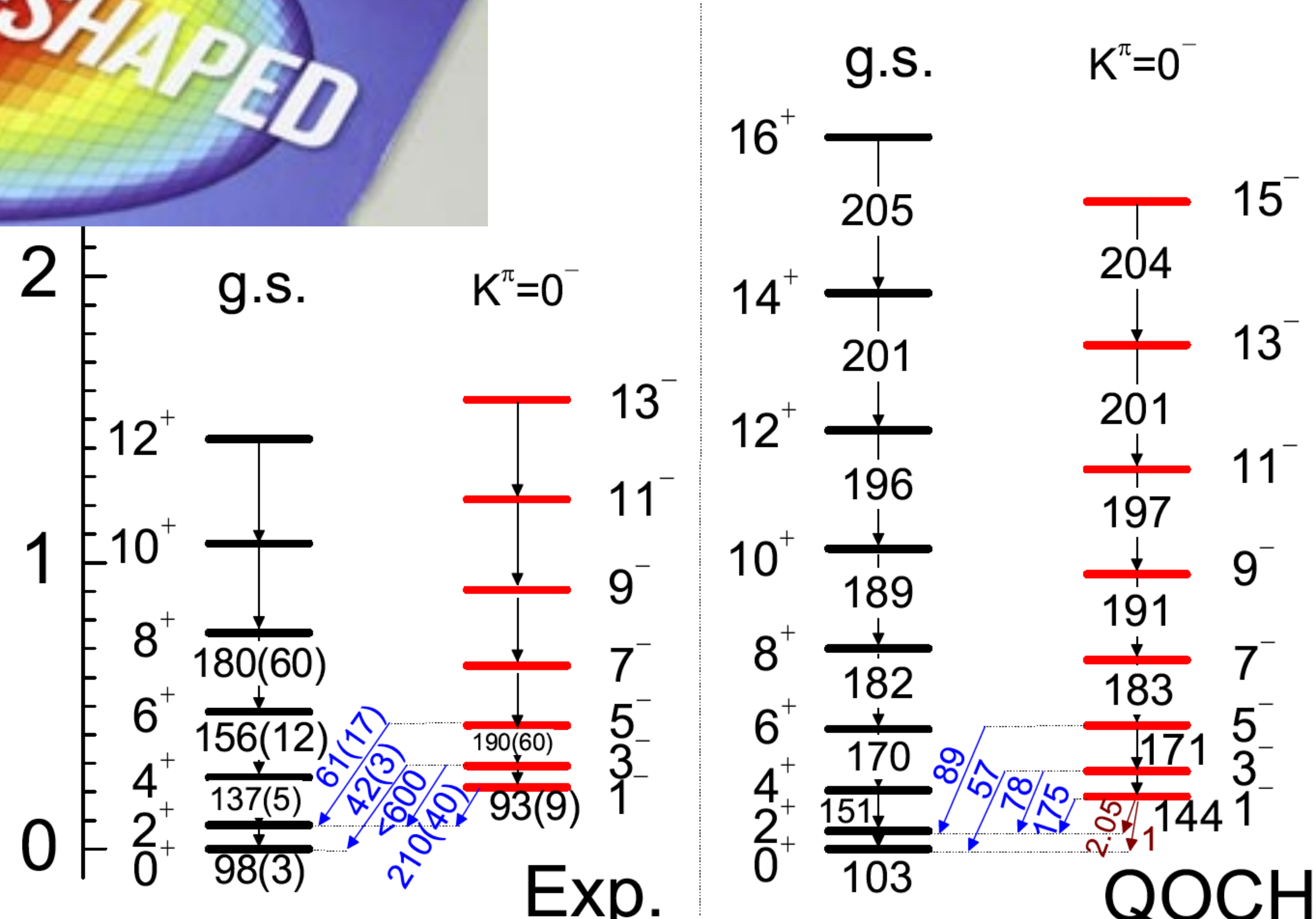
Octupole deformed (pear-shaped) heavy nuclei:



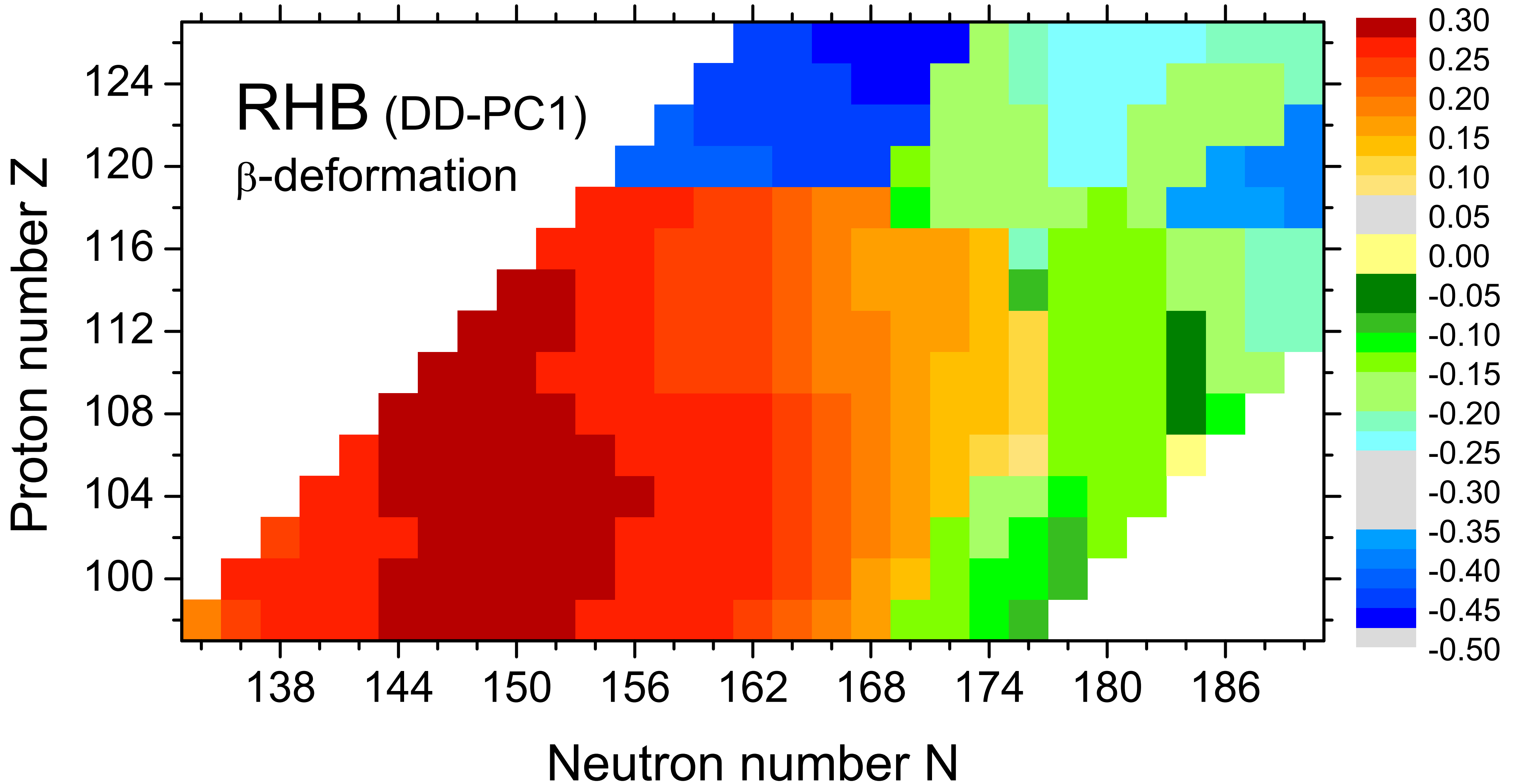
RESEARCH ARTICLE 202 | NATURE | VOL 497 | 9 MAY 2013


nature
GOING PEAR-SHAPED

^{224}Ra

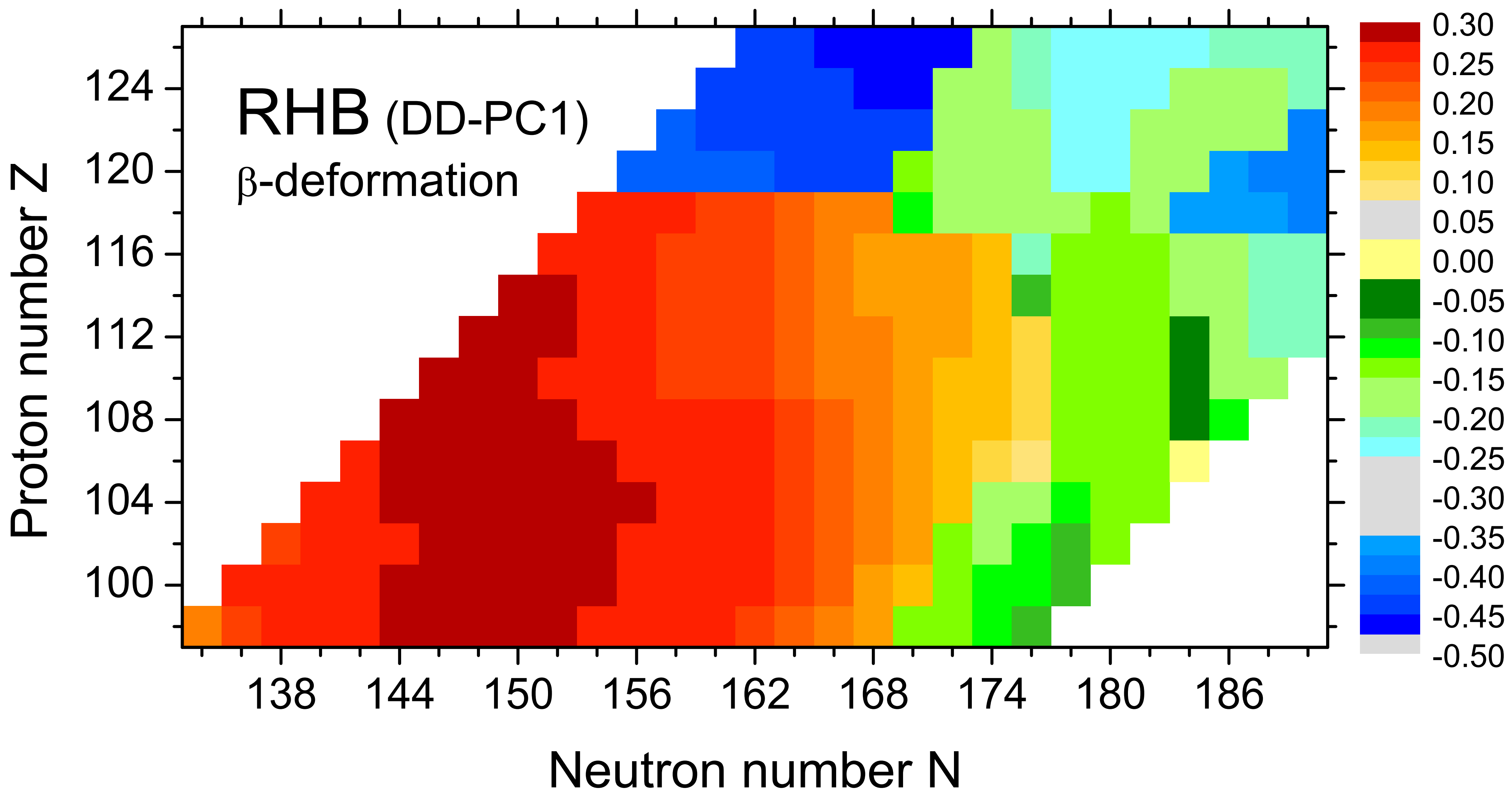

g.s.
$K^{\pi}=0^{-}$
Exp.
QOCH
0
1
2
0^{+}
2^{+}
4^{+}
6^{+}
8^{+}
10^{+}
12^{+}
14^{+}
16^{+}
1^{-}
3^{-}
5^{-}
7^{-}
9^{-}
11^{-}
13^{-}
15^{-}
98(3)
137(5)
156(12)
180(60)
190(60)
93(9)
61(17)
42(3)
<600
210(40)
103
151
170
182
189
196
201
205
144
171
183
191
197
201
204
89
57
78
175
2.05
1

Extrapolation to Superheavy Nuclei



Extrapolation to Superheavy Nuclei

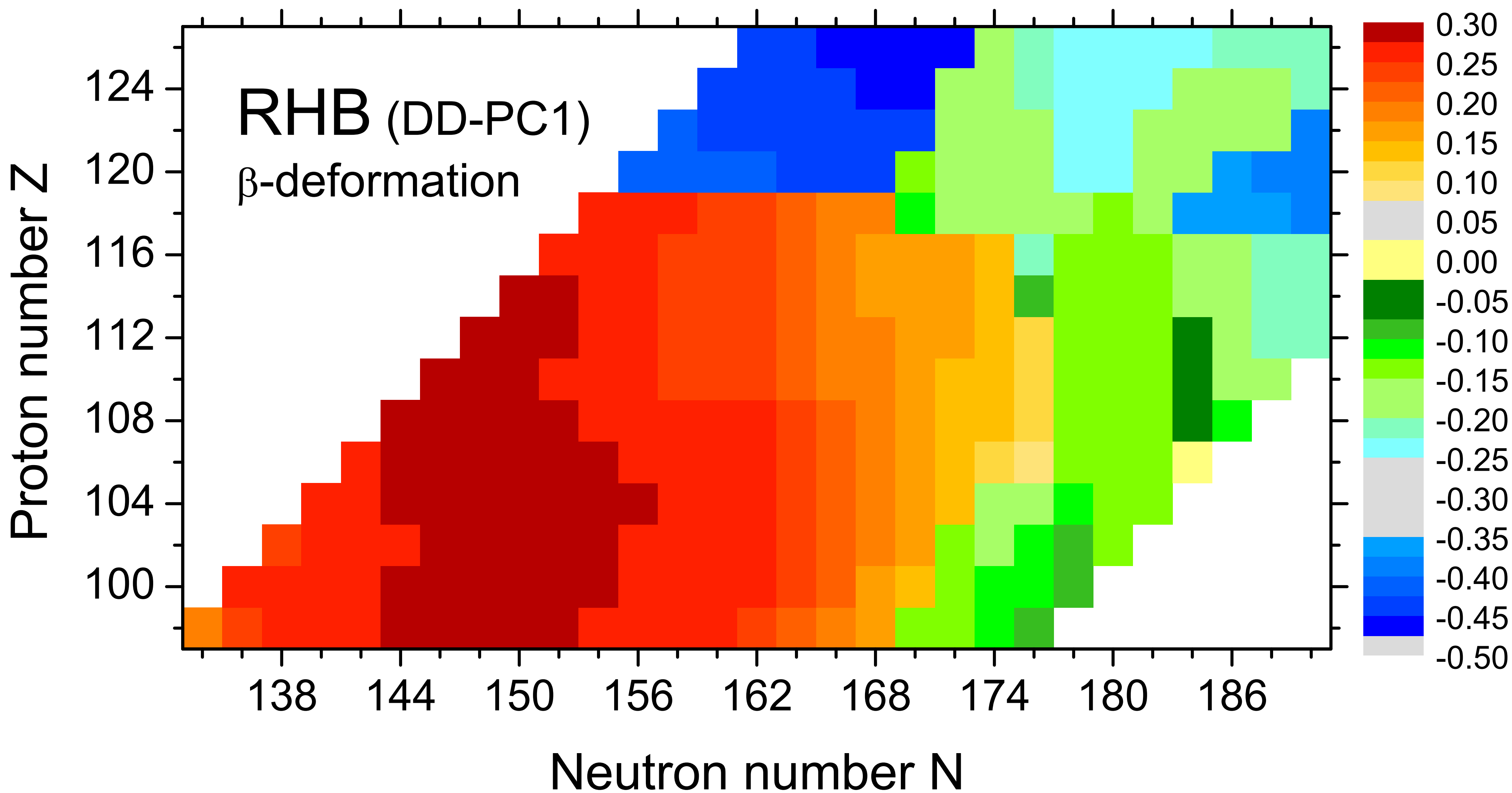
Higher density of single-particle states ➠ the evolution of deformed shells with nucleon number will have a more pronounced effect on energy gaps, separation energies, Q_{α}-values …



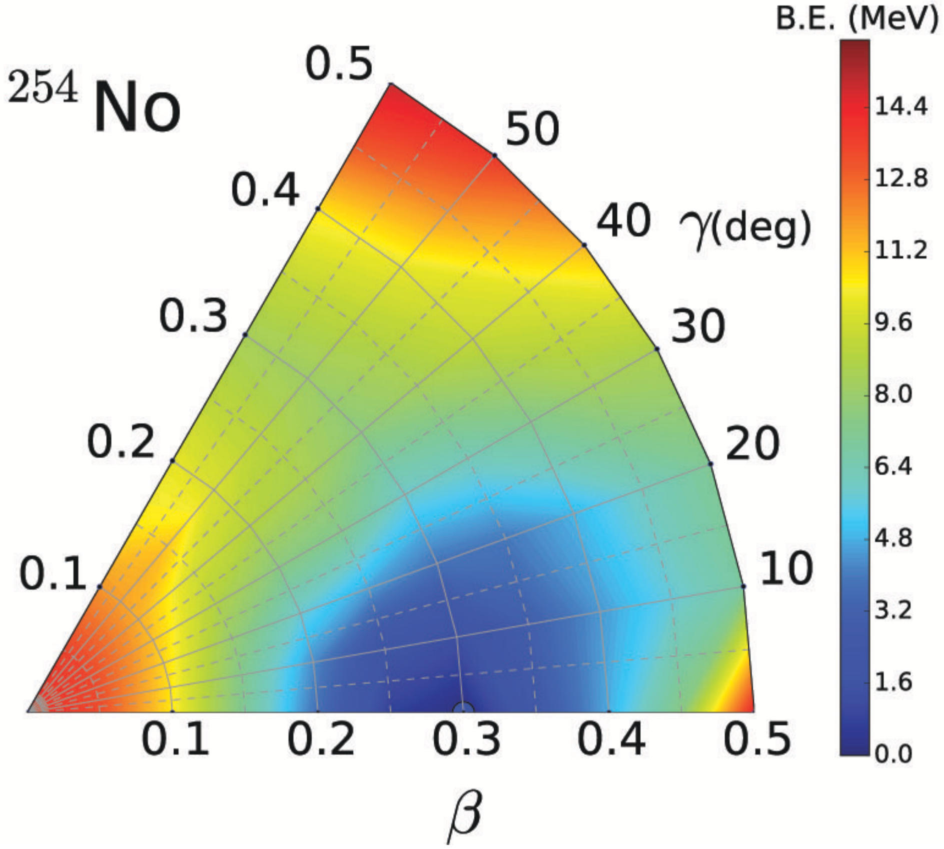
Extrapolation to Superheavy Nuclei

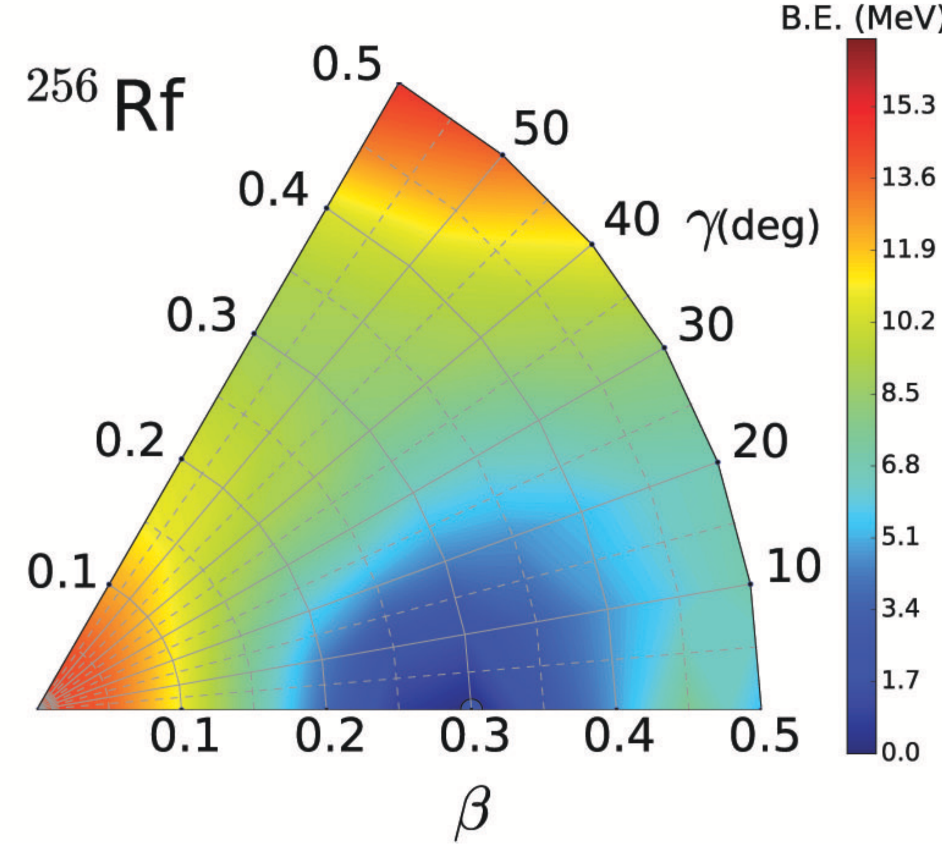
Higher density of single-particle states ➠ the evolution of deformed shells with nucleon number will have a more pronounced effect on energy gaps, separation energies, Q_α-values …

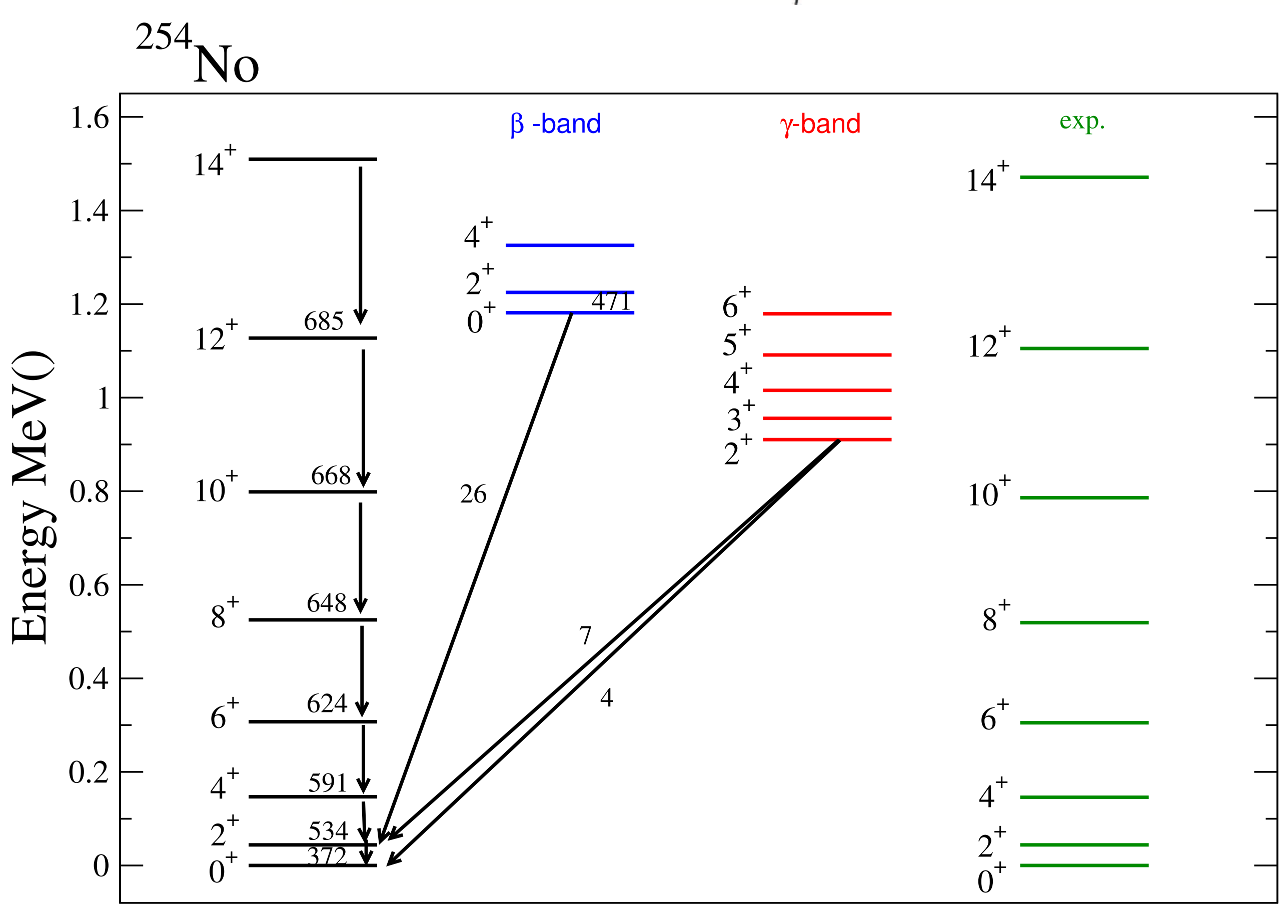
Stronger competition between the attractive short-range nuclear interaction and the long-range electrostatic repulsion ➠ Shape transitions! Exotic shapes!

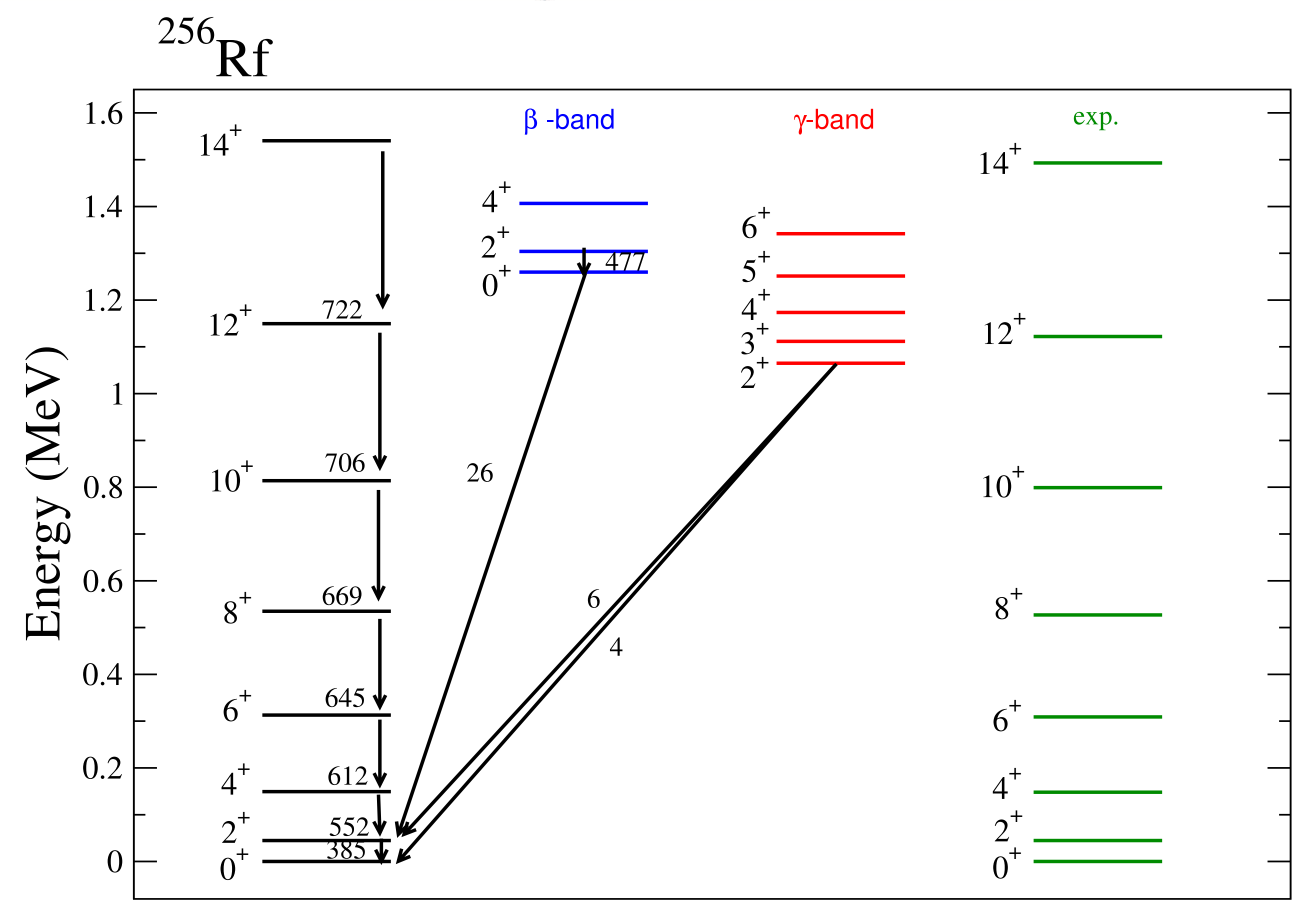


Triaxial energy maps of ^{254}No and ^{256}Rf isotopes in the β–γ plane (0 ≤ γ ≤ 60°).

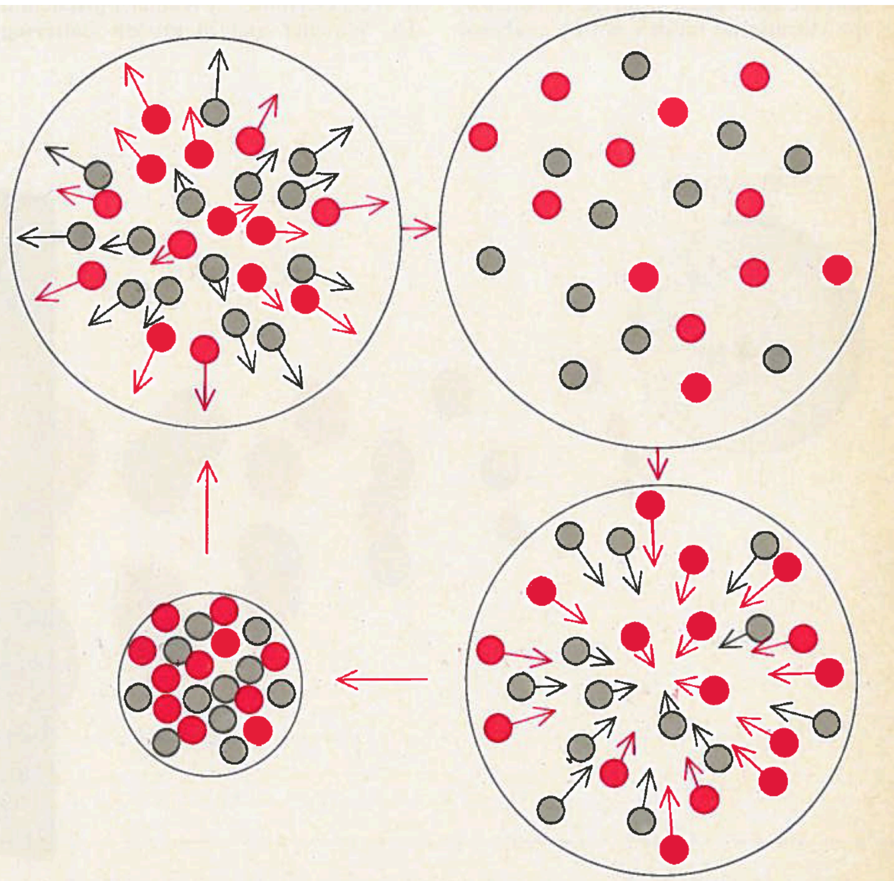




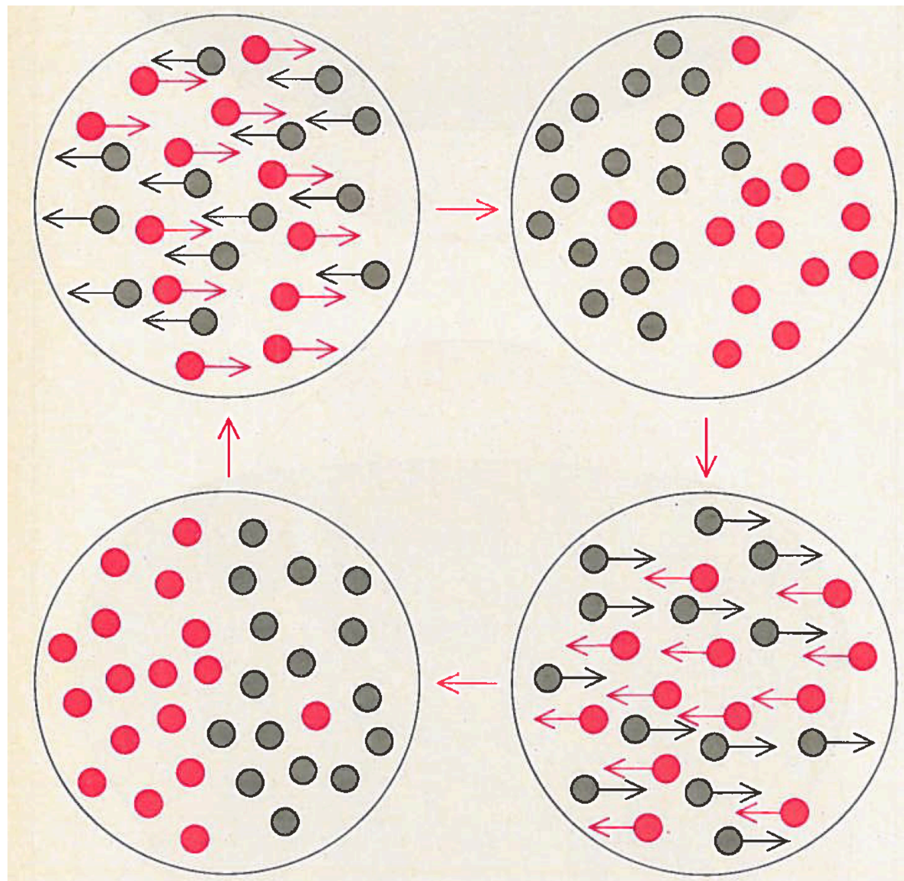




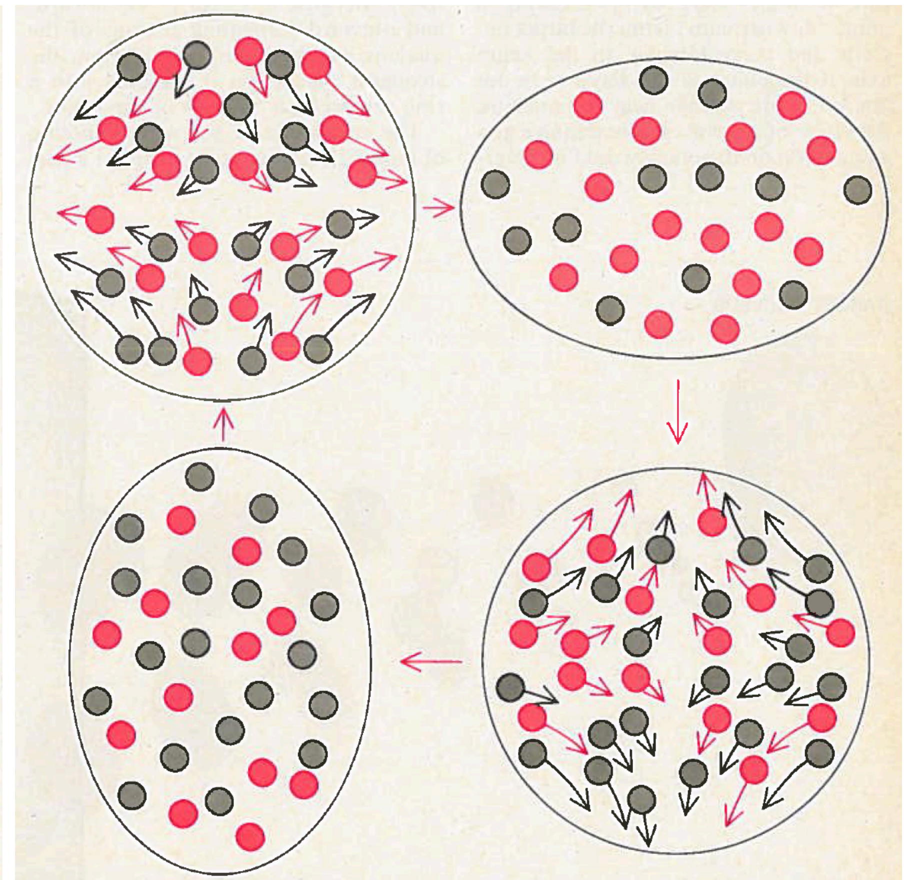
Harmonic vibrations



Isoscalar monopole resonance



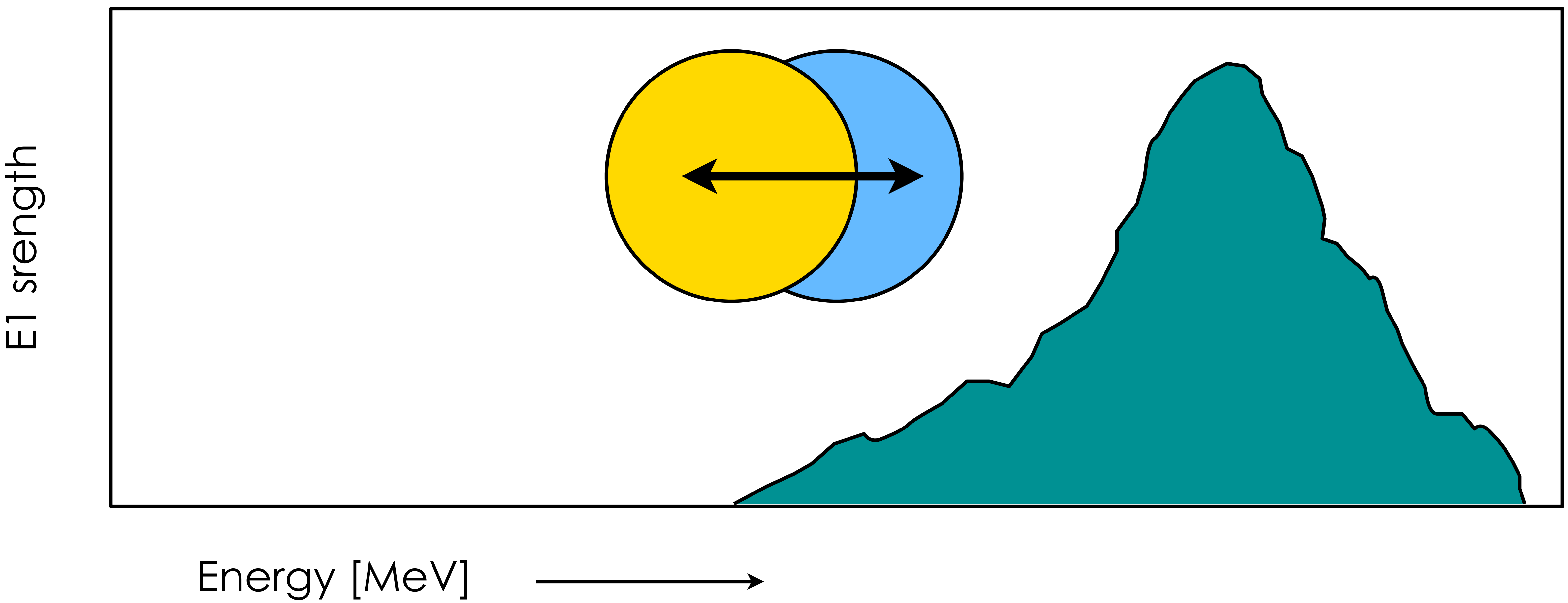
Isovector dipole resonance



Isoscalar quadrupole resonance

Exotic modes of excitations

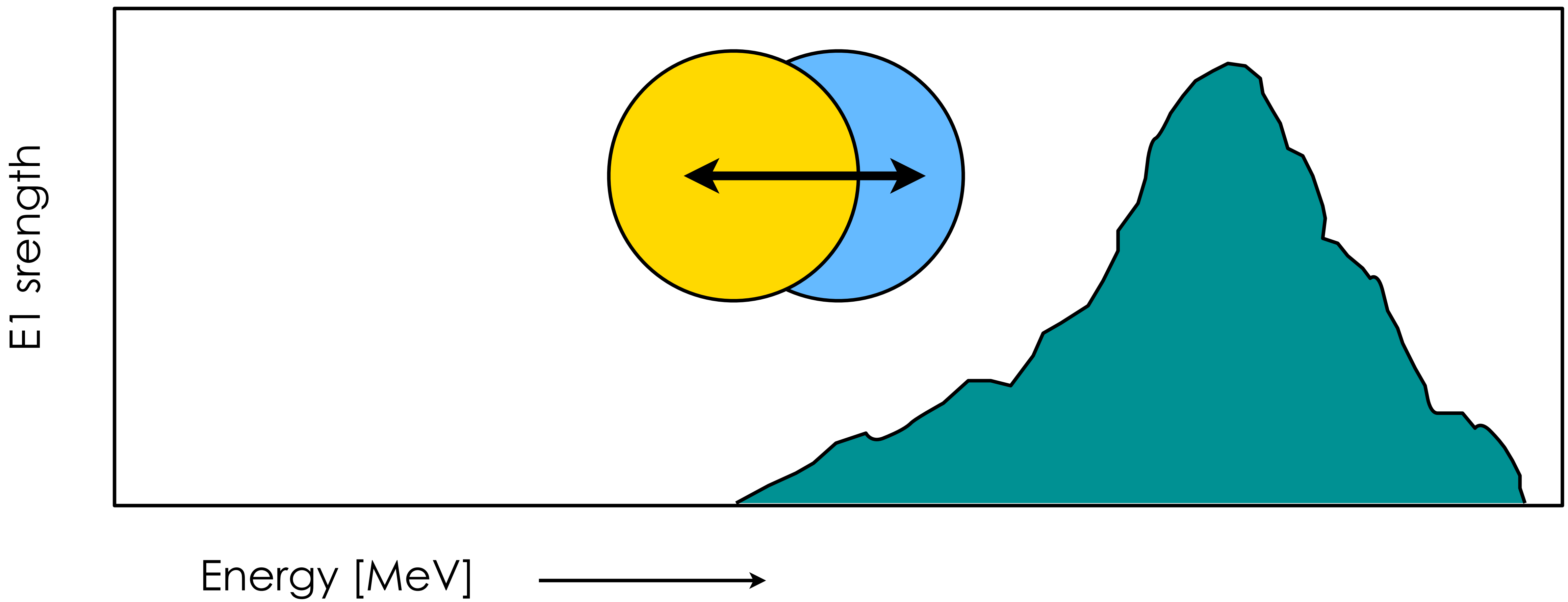
Dipole response of neutron-rich nuclei



Paar, Vretenar, Khan, Colò, Rep. Prog. Phys. **70**, 1 (2007)

Exotic modes of excitations

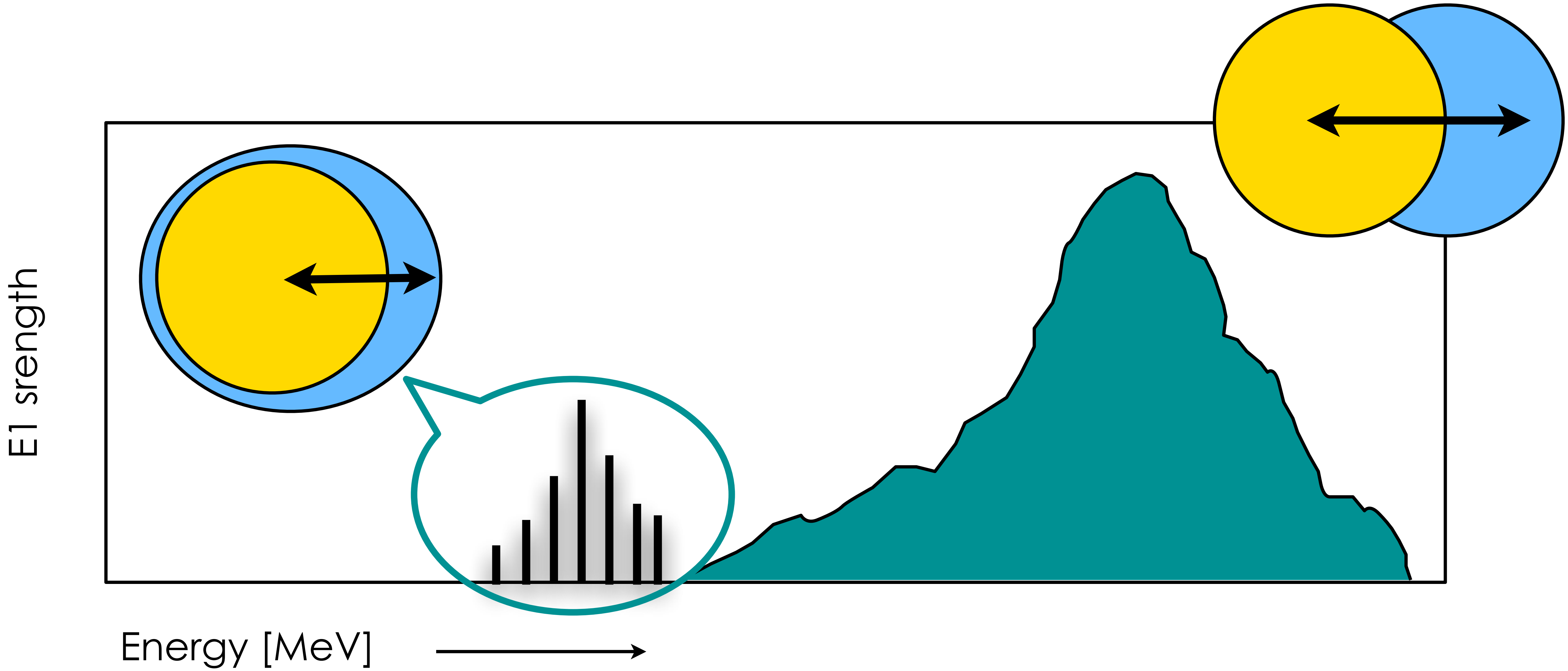
Dipole response of neutron-rich nuclei



In stable nuclei 100% of the E1 strength is absorbed in the Giant Dipole Resonance.

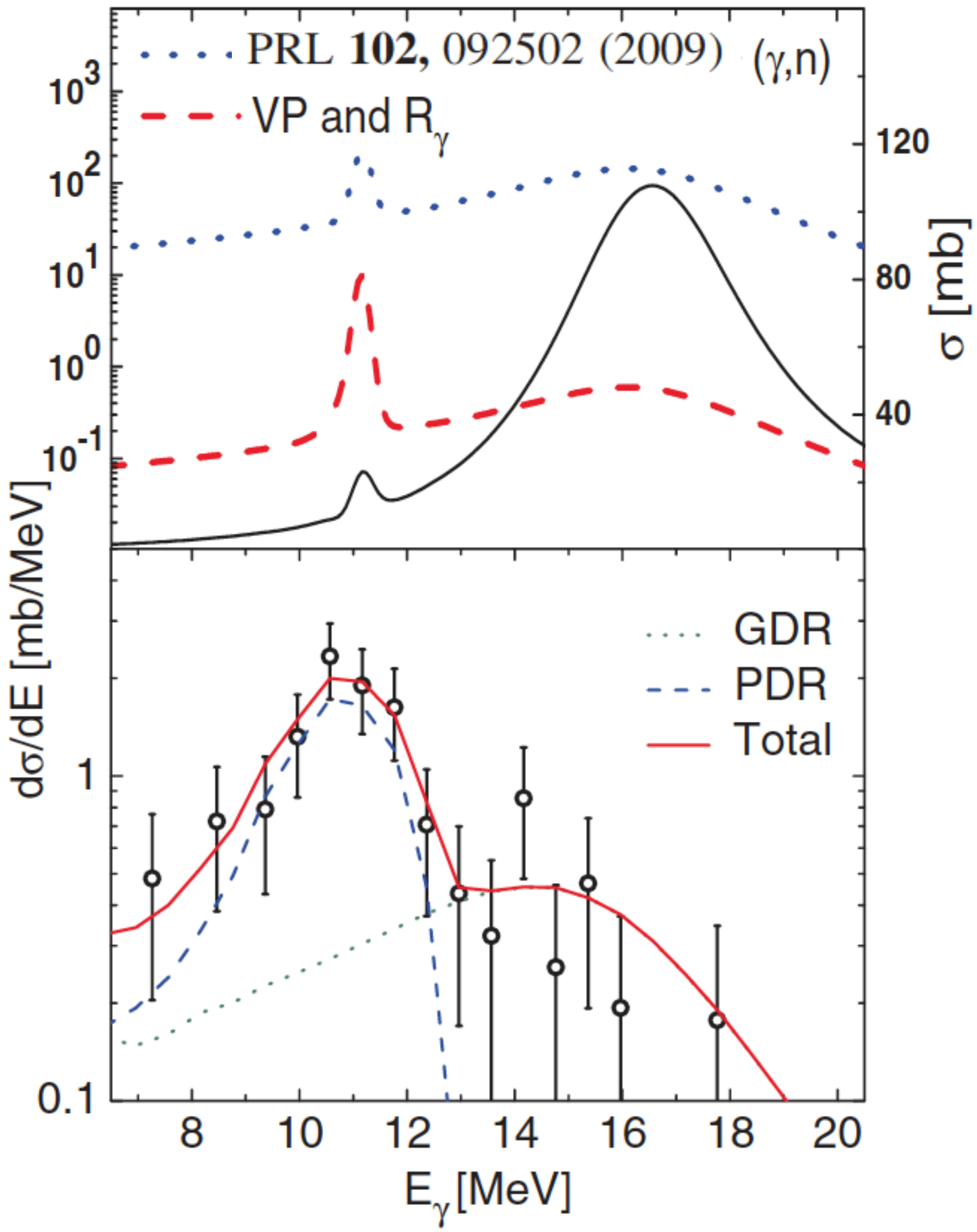
Paar, Vretenar, Khan, Colò, Rep. Prog. Phys. **70**, 1 (2007)

Neutron-rich nuclei → weak binding of the excess neutrons, diffuse neutron densities, formation of a neutron skin.

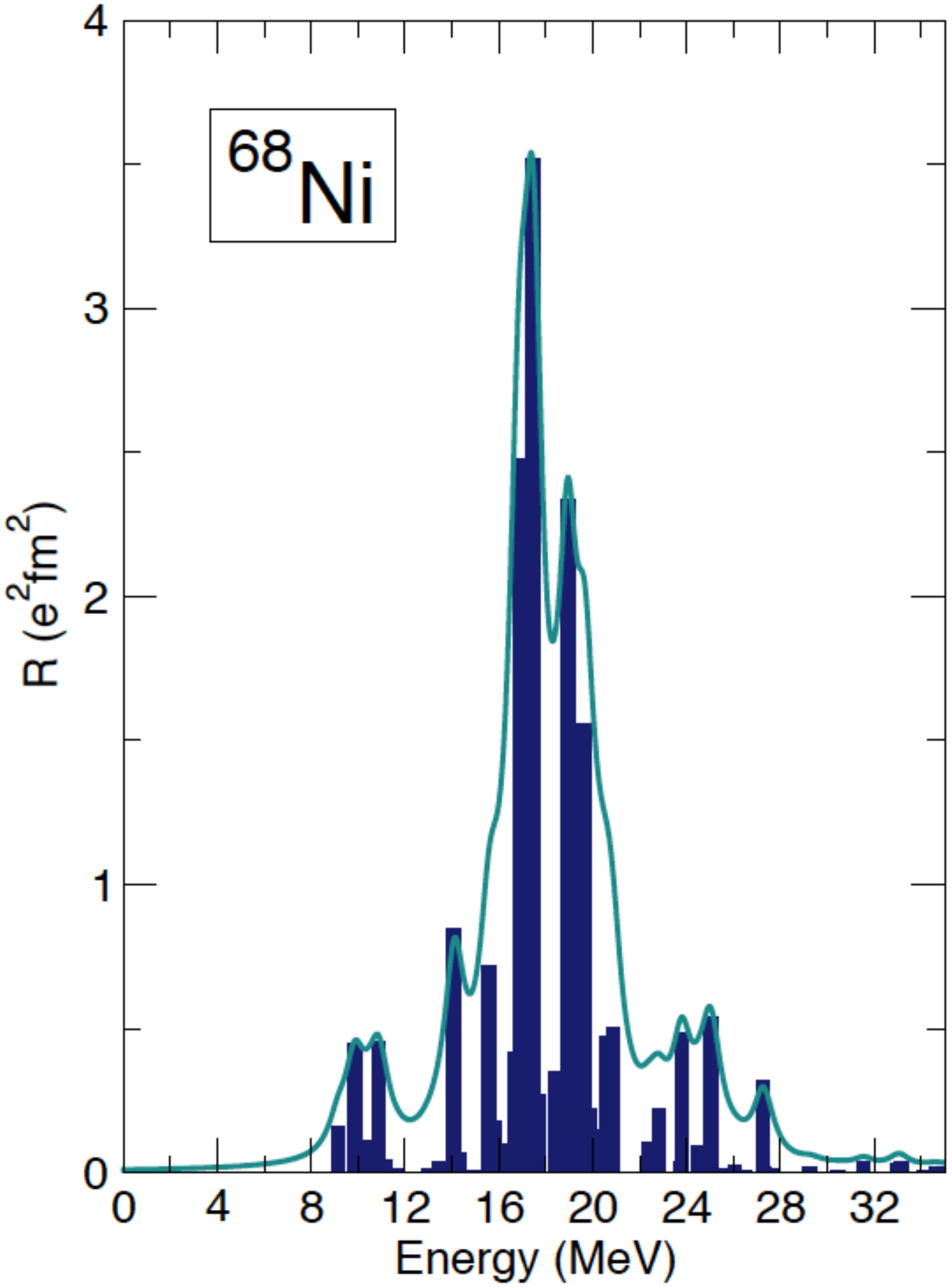


Neutron-rich nuclei → predicted occurrence of a collective soft dipole mode (Pygmy Dipole Resonance)

^{68}Ni photoabsorption cross section



E1 strength function

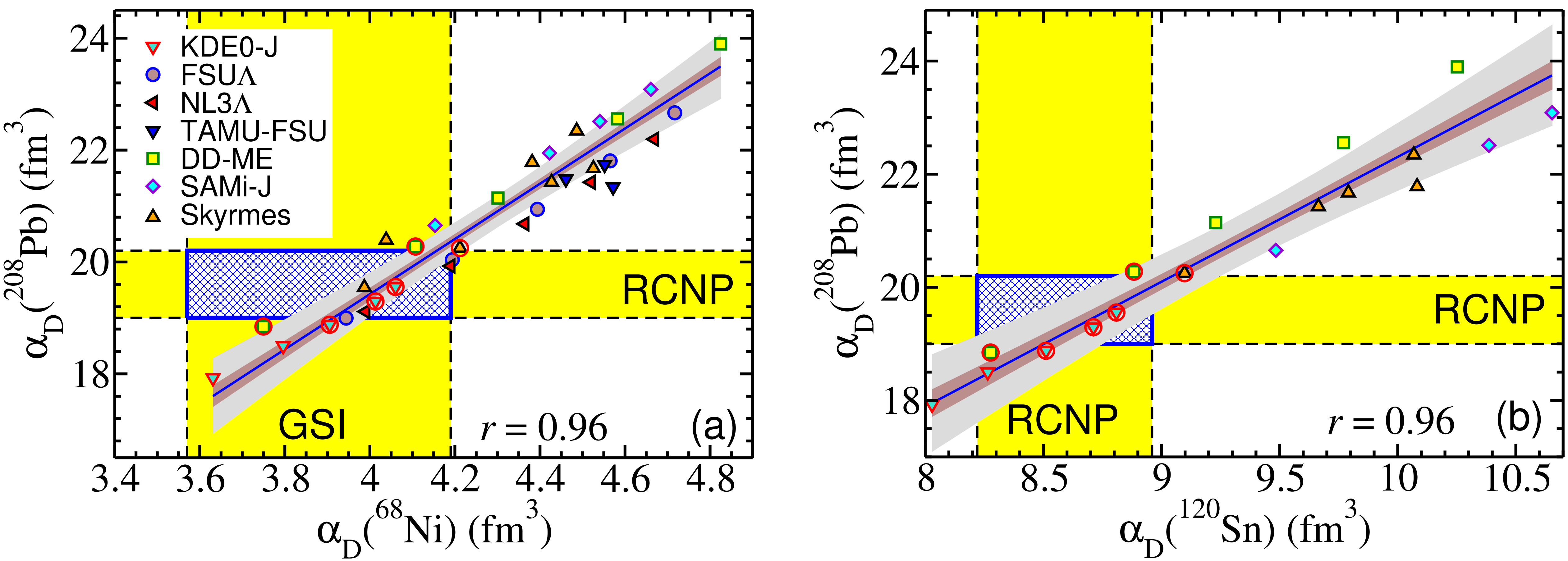


Editors' Suggestion

Neutron skin thickness from the measured electric dipole polarizability in Ni 68 , Sn 120 , and Pb 208

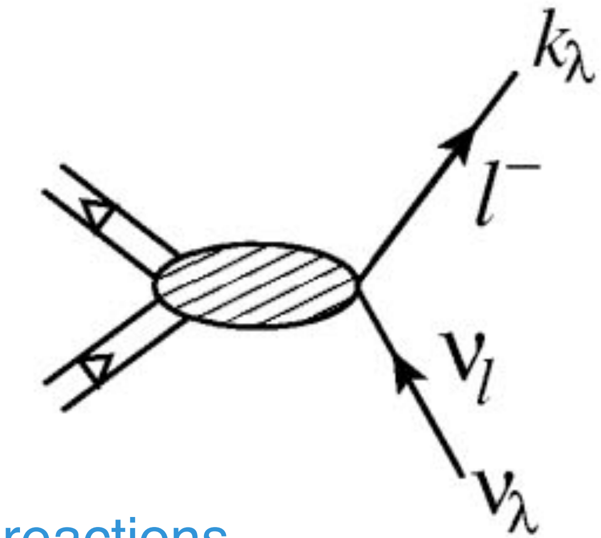
X. Roca-Maza, X. Viñas, M. Centelles, B. K. Agrawal, G. Colò, N. Paar, J. Piekarewicz, and D. Vretenar

Phys. Rev. C **92**, 064304 (2015)



Neutrino-nucleus reactions

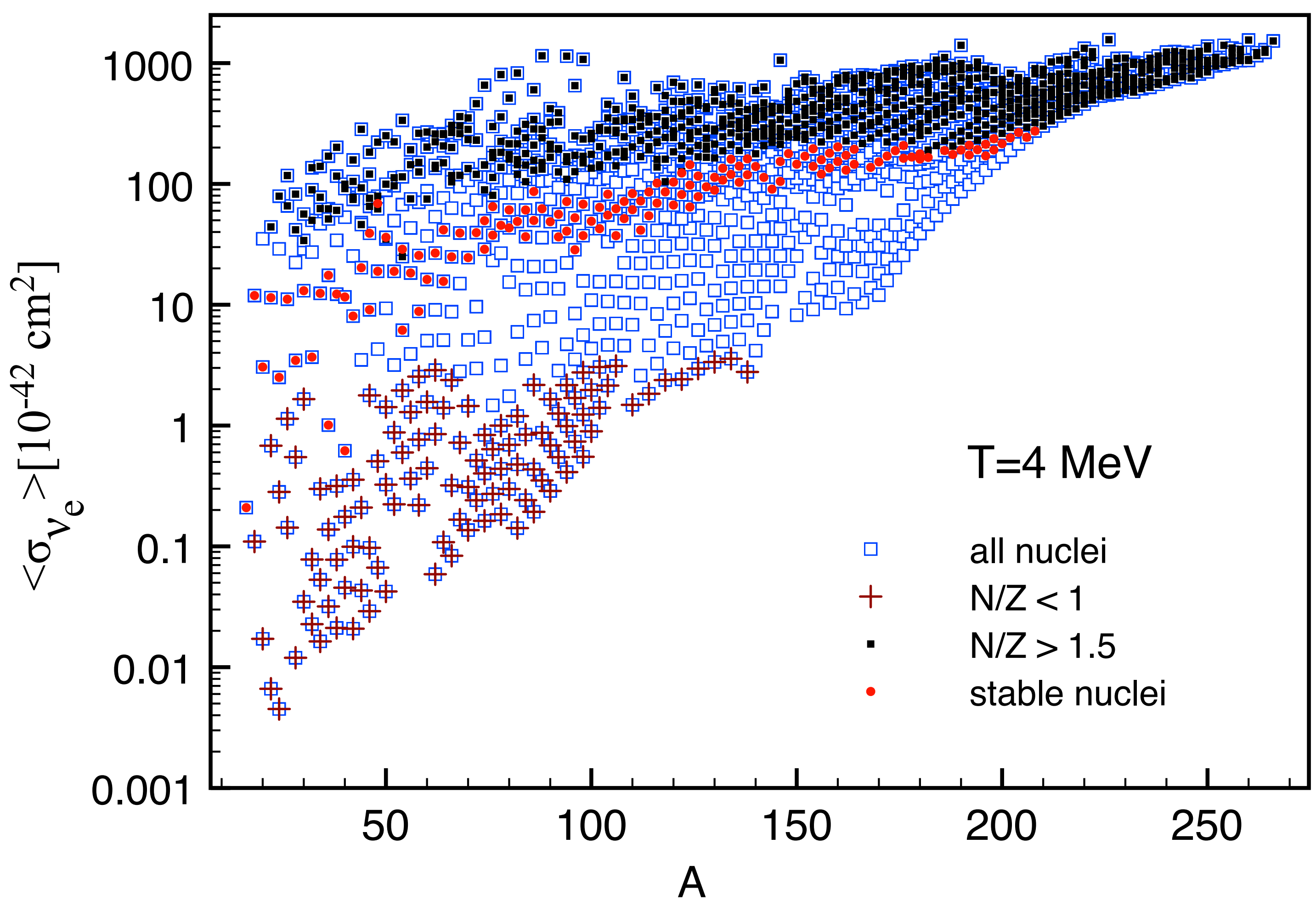
$$\nu_e +_Z X_N \rightarrow \quad _{Z+1}X^*_{N-1} + e^-$$



Large-scale calculations of supernova neutrino-induced reactions

N. Paar, H. Tutman, T. Marketin, and T. Fischer

Phys. Rev. C **87**, 025801 (2013)



Uncertainties in modeling low-energy neutrino-induced reactions on iron-group nuclei

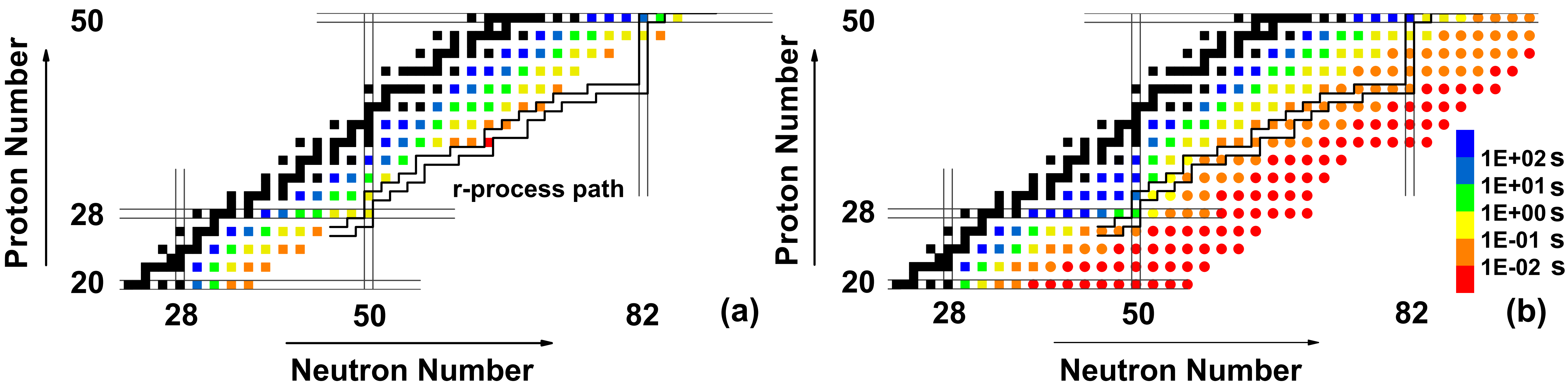
N. Paar, T. Suzuki, M. Honma, T. Marketin, and D. Vretenar

Phys. Rev. C **84**, 047305 (2011)

Table 1. Comparison of the inclusive ν_e–^{56}Fe cross sections averaged with the Michel flux.

	$\langle\sigma\rangle$ $[10^{-42}$ cm$^2]$
RNEDF (DD-ME2)	263
SM (GXPF1J) + RPA (SGII)[28,41]	259
RPA (Landau–Migdal)[67]	240
QRPA (SIII)[68]	352
QRPA (G-matrix)[69]	173.5
Theoretical average	258 ± 57
Exp. (KARMEN)[59]	$256 \pm 108 \pm 43$

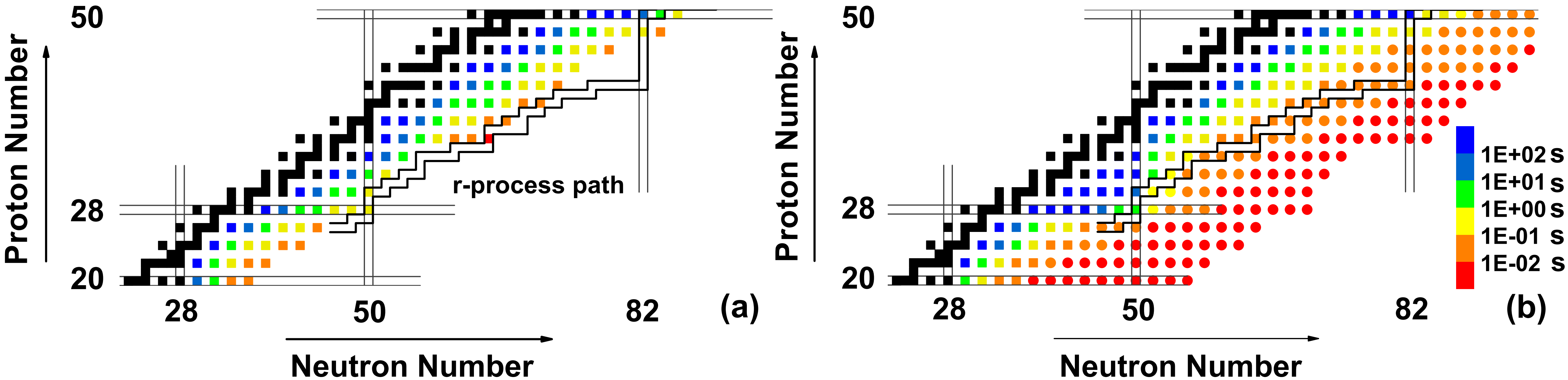
β-decay half-lives of neutron-rich nuclei and matter flow in the r-process



Contour maps of experimental and theoretical β-decay half-lives for the Z = 20–50 even–even nuclei.

Niu, Niu, Liang, Long, Nikšić, Vretenar, Meng, Phys. Lett. B **723**, 172 (2013).

β-decay half-lives of neutron-rich nuclei and matter flow in the r-process

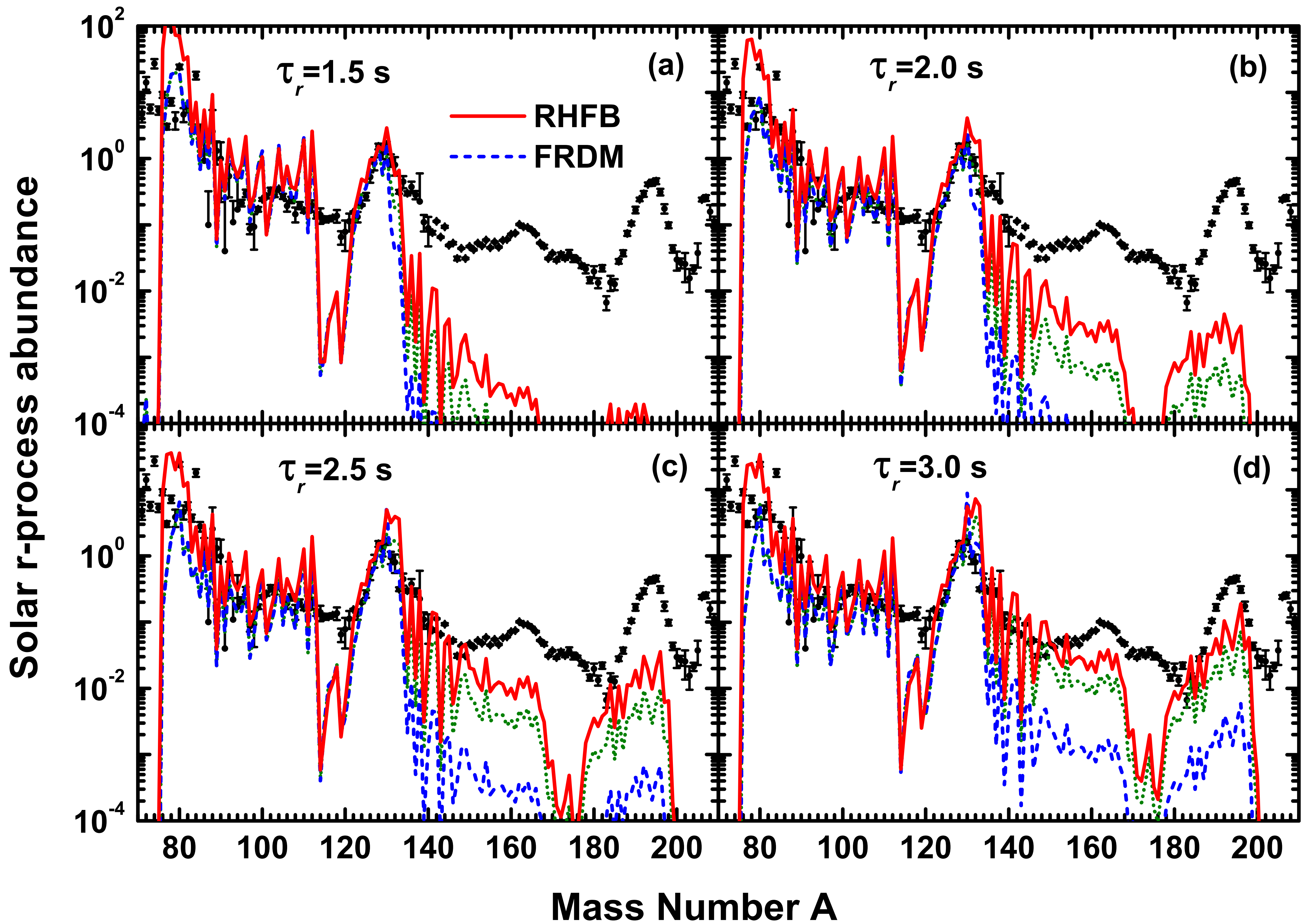


Contour maps of experimental and theoretical β-decay half-lives for the Z = 20–50 even–even nuclei.

⇒ impact of the predicted β-decay half-lives on r - process abundances:

Niu, Niu, Liang, Long, Nikšić, Vretenar, Meng, Phys. Lett. B **723**, 172 (2013).

The impact of nuclear β-decay half-lives on the r-matter flow.



How does the nuclear chart emerge from the underlying fundamental interactions?

Where are the limits of stability and what is the heaviest element that can be created?

How does nuclear structure evolve across the nuclear landscape and what shapes can nuclei adopt?

How does nuclear structure change with temperature and angular momentum?

How can nuclear structure and reaction approaches be unified?

How complex are nuclear excitations?

How do correlations appear in dilute neutron matter, both in structure and reactions?

What is the density and isospin dependence of the nuclear equation of state?