Physics-8140 course overview:

low-energy nuclear structure and reactions

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Topics

- Nuclear chart, the frontiers of neutron-rich and superheavy nuclei, astrophysics connection (r- and rp- process)

- low-energy accelerators: radioactive ion beam (RIB) facilities

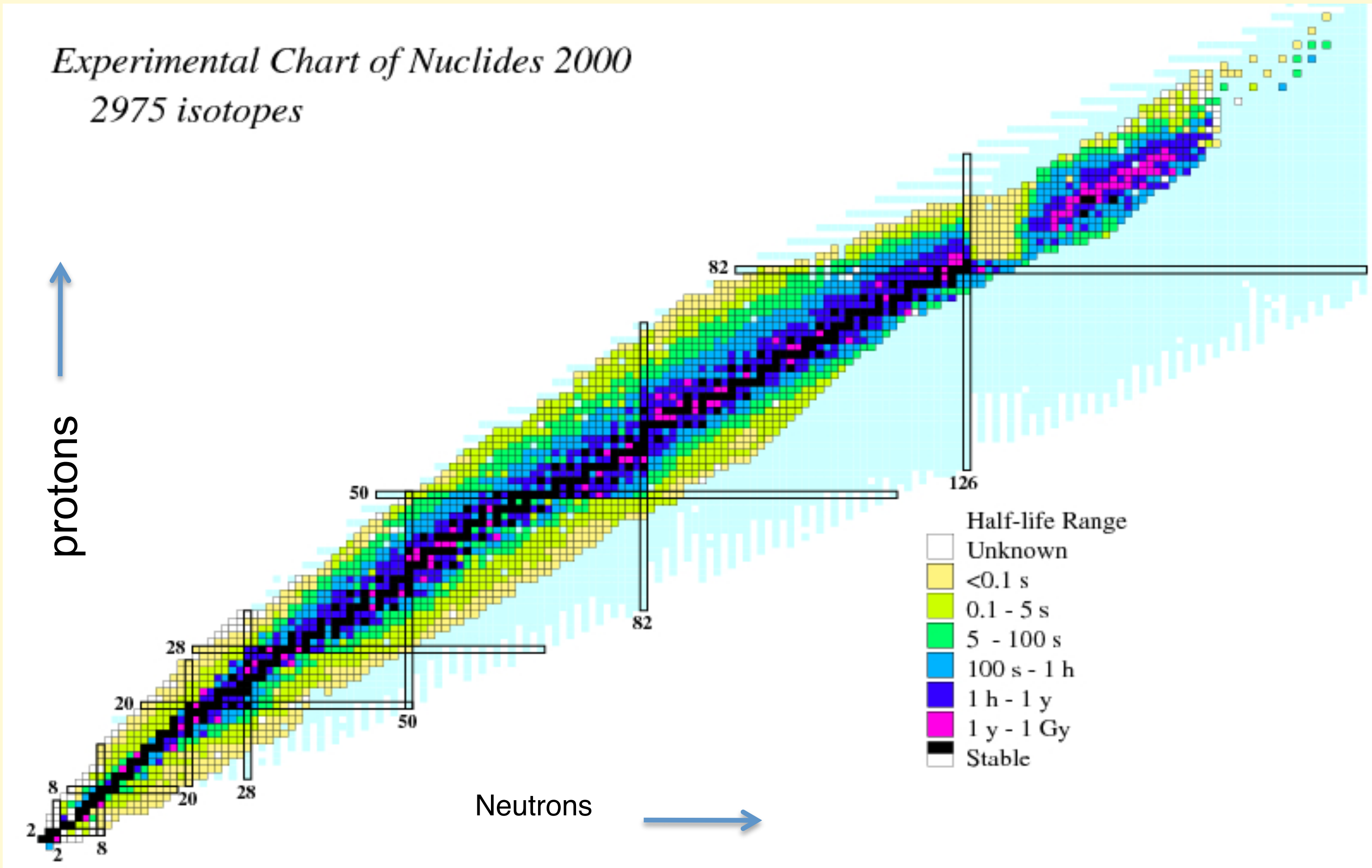
- The nucleus as a quantum many-body problem,
  static nuclear structure theory (HF),
  nuclei at the neutron dripline (HFB)

- Time-dependent mean field theory for nuclear reactions (TDHF)
  studies of deep-inelastic reactions and fusion of exotic neutron-rich nuclei

Topic 1

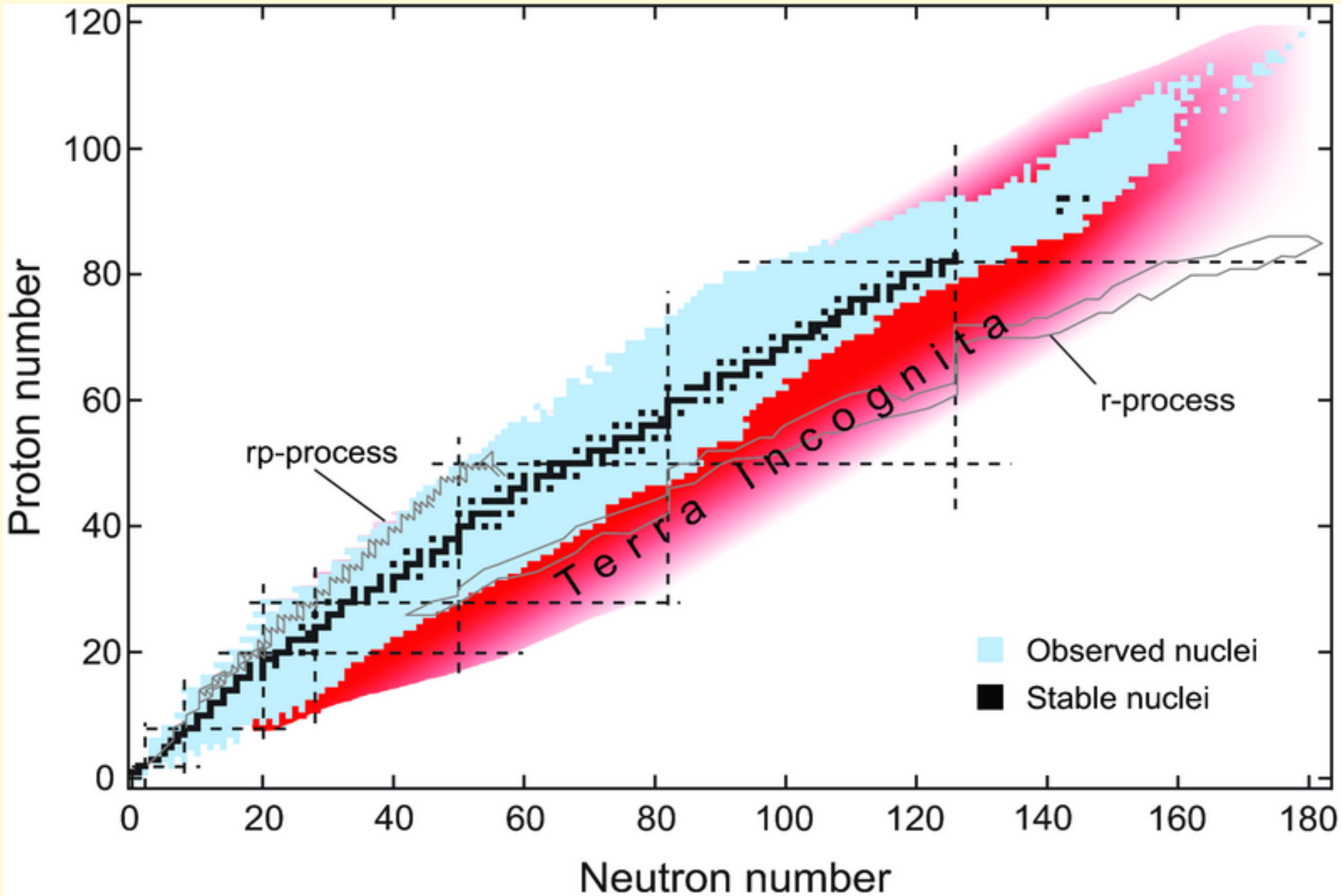
- Nuclear chart, the frontiers of neutron-rich and superheavy nuclei, astrophysics connection (r- and rp- process)

Nuclear chart, "magic" proton and neutron numbers, measured half-life ranges



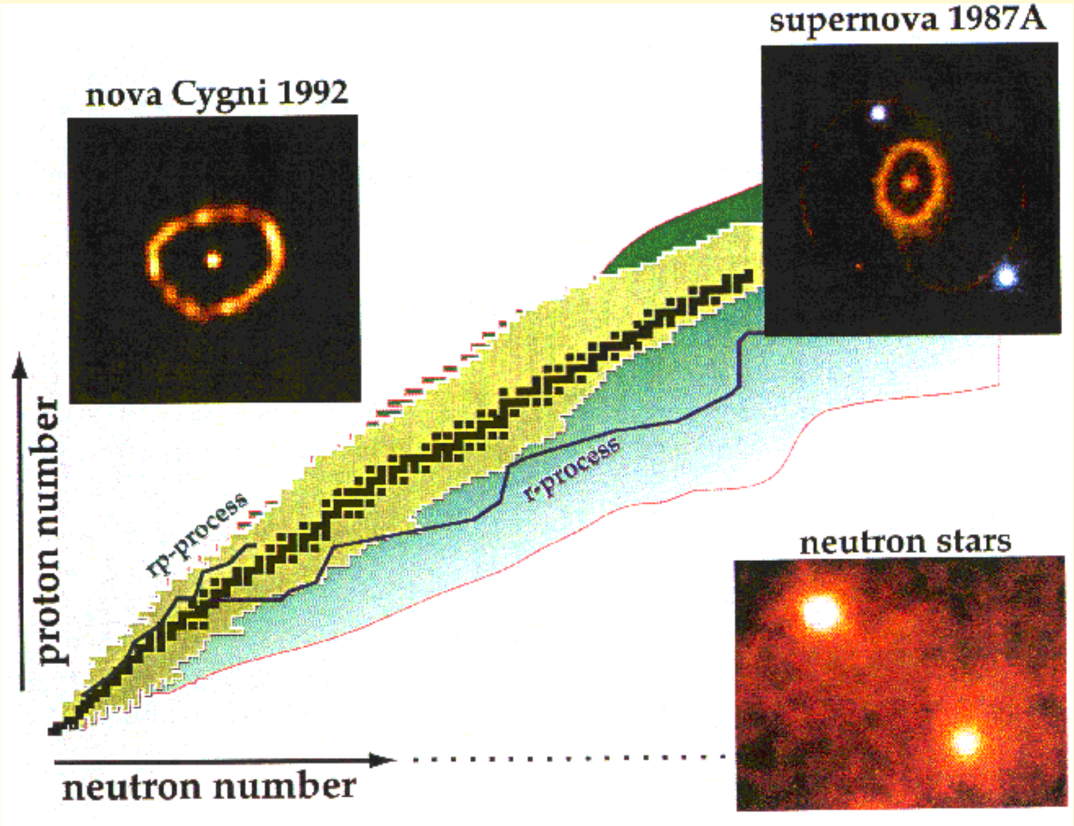
Nuclear chart and the frontier of neutron-rich nuclei

Ref: Isotope Science Facility proposal, MSU (Nov. 2006)



Nuclear astrophysics connection

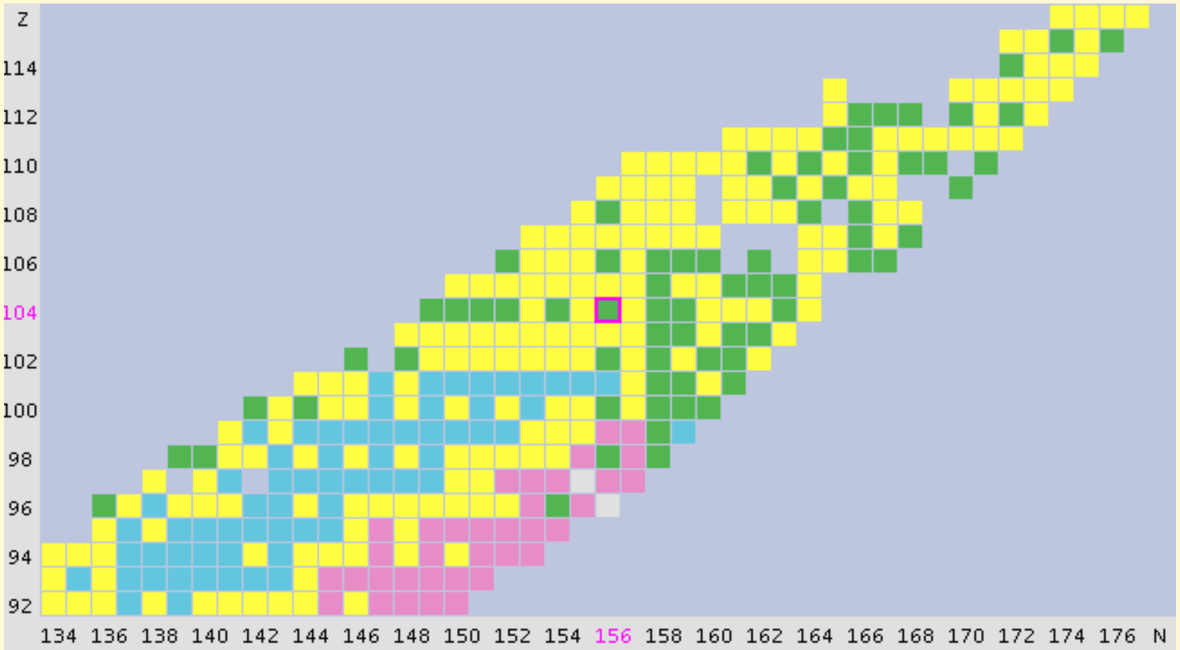
Rapid neutron capture process (= r-process) following supernova explosion goes through “terra incognita” of very neutron-rich nuclei



Second frontier: superheavy elements in heavy-ion fusion reactions

Ref: National Nuclear Data Center, Brookhaven

http://www.nndc.bnl.gov/index.jsp



Topic 2

- low-energy accelerators: radioactive ion beam (RIB) facilities

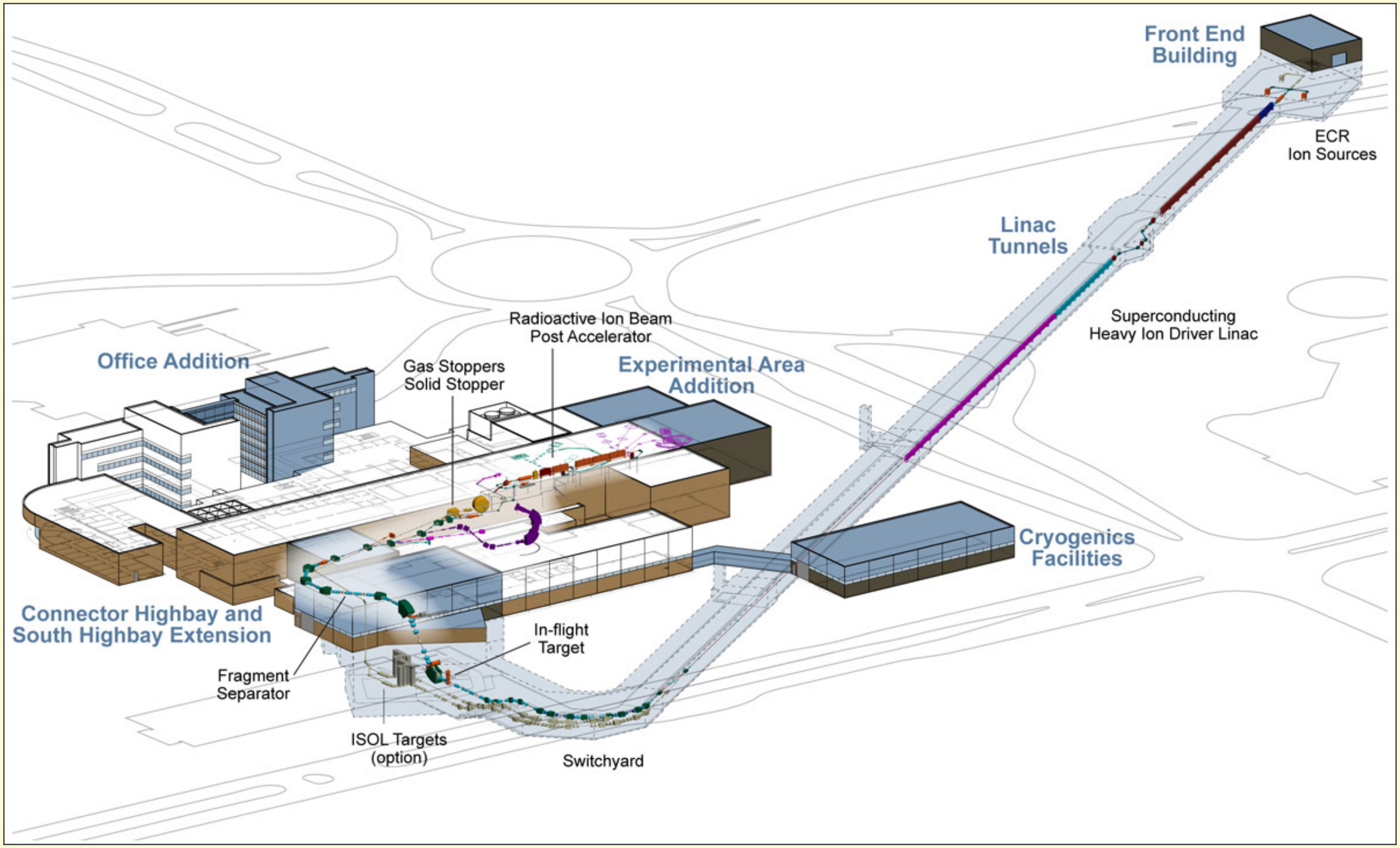
Radioactive Ion Beam Facilities worldwide

Figure 4.6. Representative distribution of projected major facilities for RI beams. The location of a FRIB within the United States has not been determined and is therefore placed arbitrarily in the center of the country.

Facility for Rare Isotope Beams (FRIB)

under construction at Michigan State University

http://www.frib.msu.edu/



Topic 3

- The nucleus as a quantum many-body problem,
  static nuclear structure theory,
  nuclei in vicinity of neutron dripline

Nuclear many-particle Hamiltonian (in coordinate representation)

$$H = \sum_{i=1}^{A} \frac{-\hbar^2}{2m} \nabla_i^2 + \frac{1}{2} \sum_{i,j=1}^{Z} v_{ij}^{(2)Coul} + \frac{1}{2} \sum_{i,j=1}^{A} v_{ij}^{(2)nucl} + \frac{1}{6} \sum_{i,j,k=1}^{A} v_{ijk}^{(3)nucl}$$

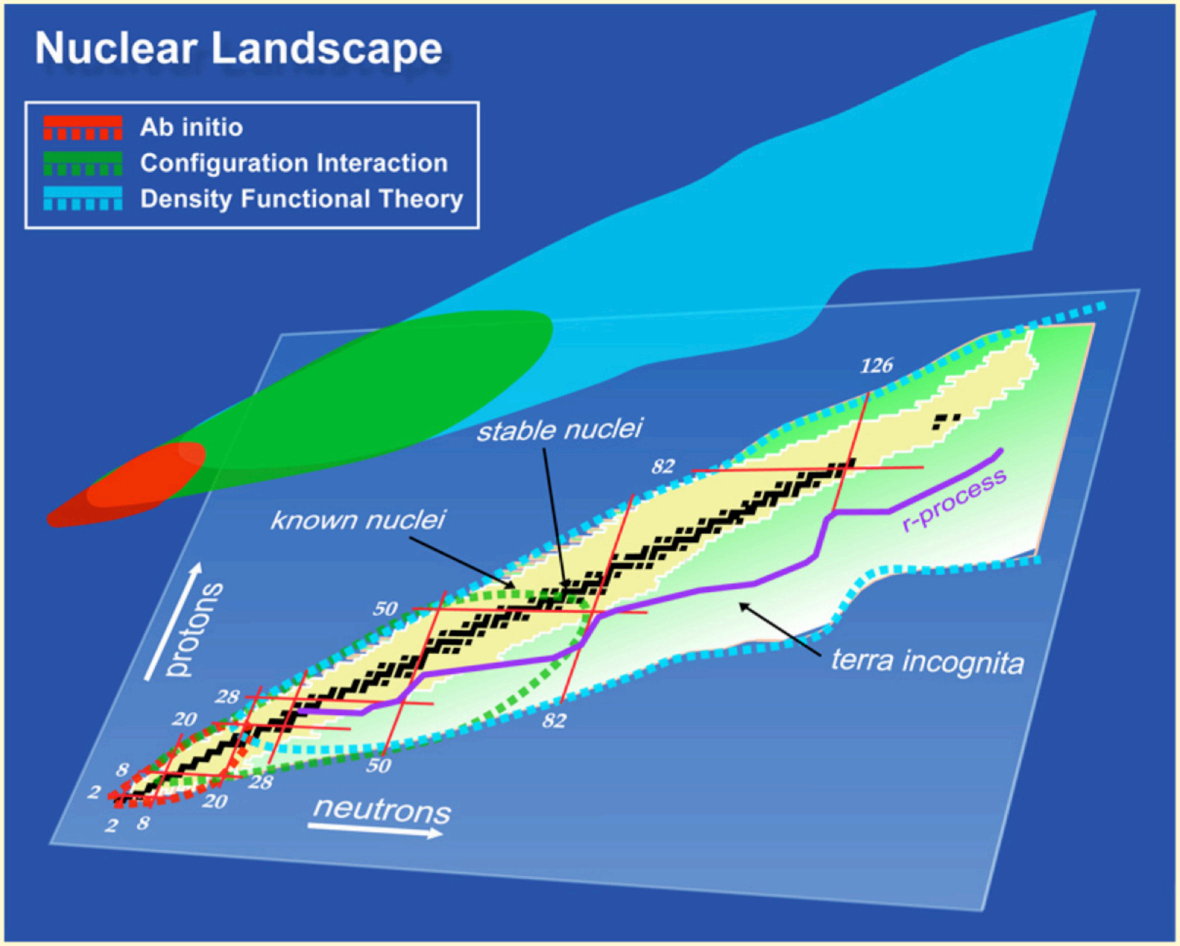
Formal structure $H = T^{(1)} + V^{(2)} + V^{(3)}$

- kinetic energy of all nucleons (1-body operator)
- 2-body Coulomb interactions between protons
- 2-body and 3-body strong nuclear interactions

many-particle Schrödinger equation (in coordinate representation)

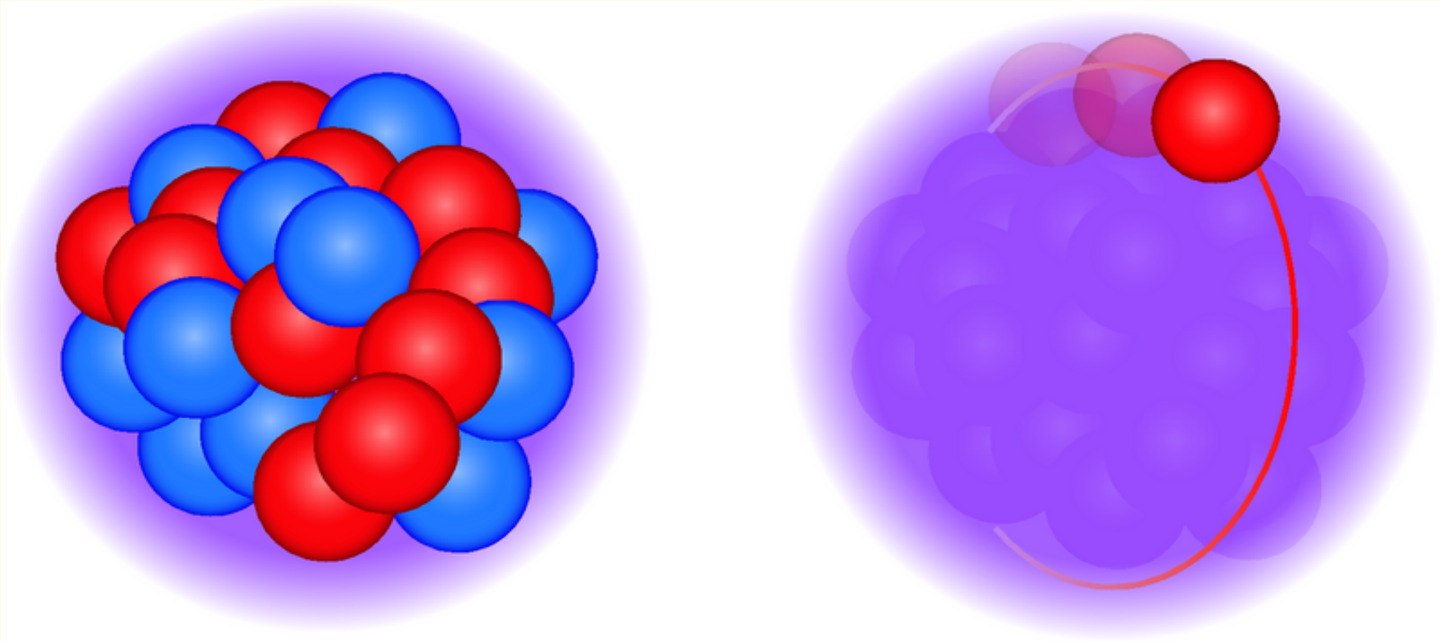
$$(H - E_n)\Psi_n(x_1, x_2, ..., x_A) = 0$$ with $$x = (\vec{r}, s_z, t_z)$$

Microscopic theories of nuclear structure



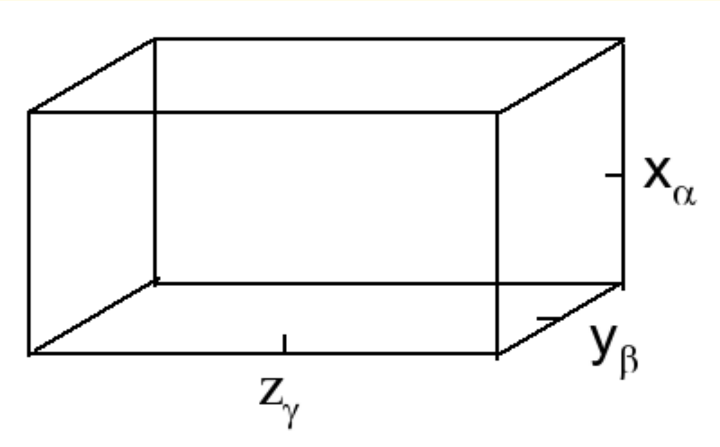
Mean-field concept

(Ref: Isotope Science Facility at Michigan State University,
MSUCL-1345, p. 41, Nov. 2006)



Static Hartree-Fock: numerical implementation

Represent wave functions for all A nucleons on 3-D Cartesian lattice



Grid points:

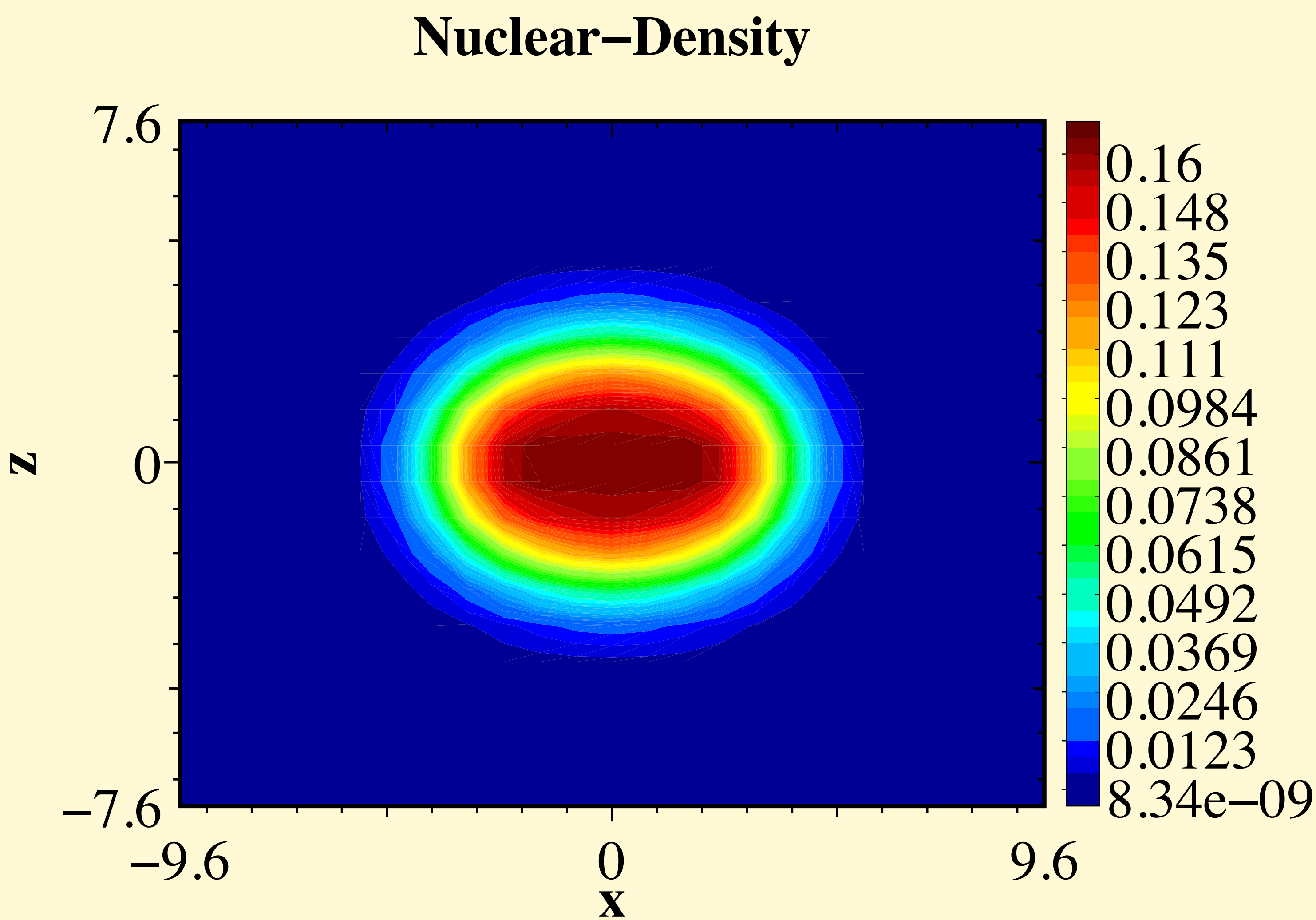
$$x_\alpha \quad (\alpha = 1, ..., N_x)$$
$$y_\beta \quad (\beta = 1, ..., N_y)$$
$$z_\gamma \quad (\gamma = 1, ..., N_z)$$

$$\psi(x, y, z; \sigma_z, t_z) \rightarrow \psi(x_\alpha, y_\beta, z_\gamma; \sigma_z, t_z)$$

Wave function on the lattice becomes a complex-numbered array of dimension

$$psi(N_x, N_y, N_z, 2, 2)$$

^{22}Ne: note prolate quadrupole deformation
140 iterations, CPU time = 15 s



Nuclear structure theory

Main Goal

Input: nucleon-nucleon 2-body and 3-body interaction

Output: quantum many-body calculation of all observables, e.g.

1) Properties of nuclear ground state

total binding energy energy

n/p separation energies ➞ dripline location, Q-values for nuclear reactions

Proton and neutron density distribution

equi-density contours ➞ “nuclear shape” (spherical or deformed)

moments of the density (root mean square radii)

n/p single-particle energy levels

pairing density ➞ pairing gap, pairing energy

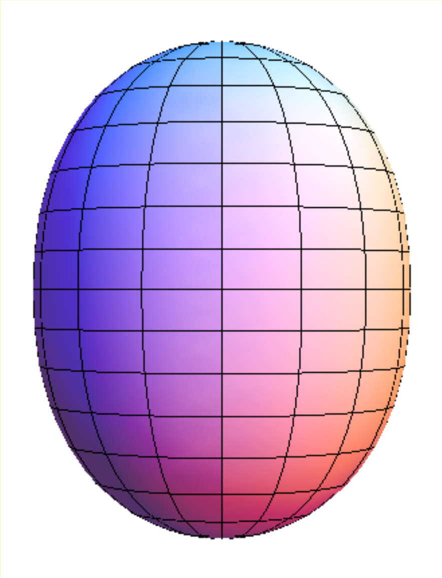
2) Excited states, in particular “collective” states

surface vibrations, rotations, giant multipole resonances, pygmy resonance, …

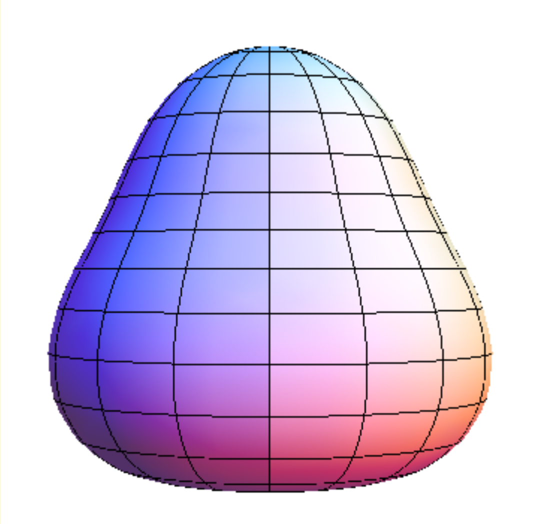
quasiparticle excitations (pairing)

Nuclear collective excitations: surface vibrations

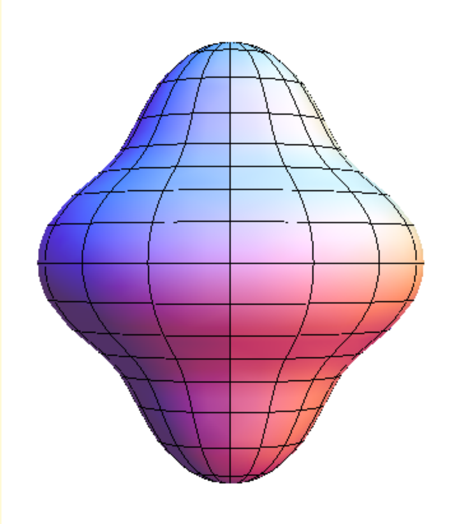
vibr. energy $\hbar\omega \approx 1.5\,MeV$ $\longrightarrow$ vibr. frequency $\omega \approx 2 * 10^{21}\,s^{-1}$



quadrupole



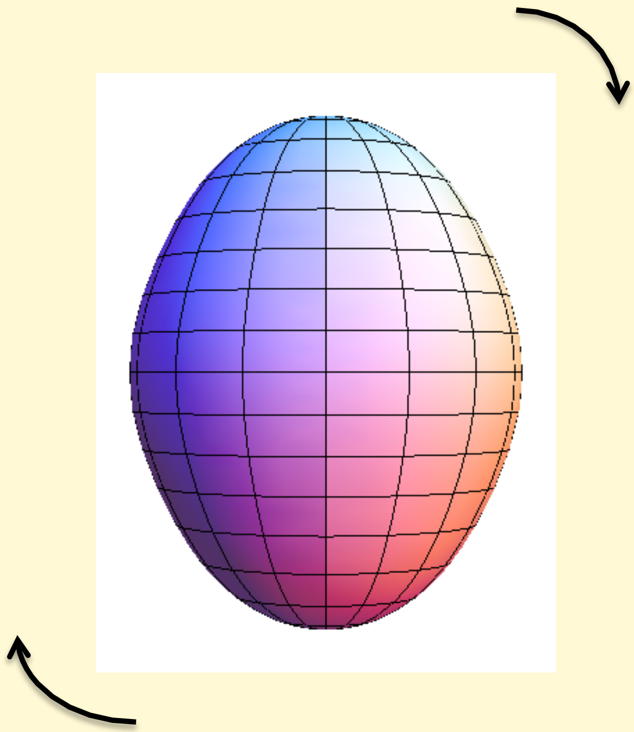
octupole



hexadecapole

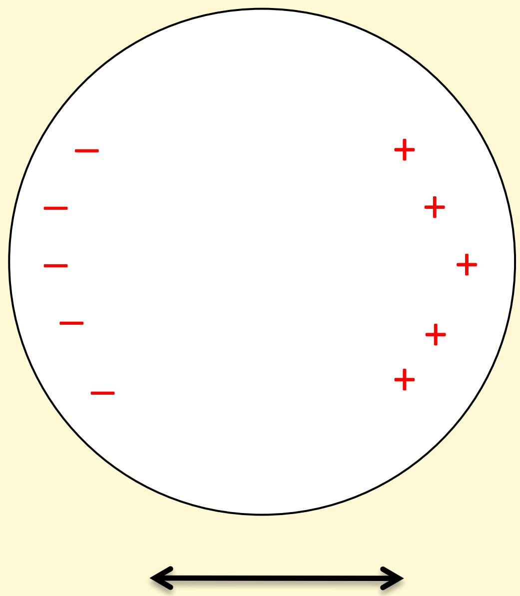
Nuclear collective excitations: rotations

rot. energy $\hbar\omega \approx 100 keV$ $\longrightarrow$ rot. frequency $\omega \approx 1.5 * 10^{20} s^{-1}$



Nuclear collective excitations: giant multipole resonances

proton / neutron density oscillations

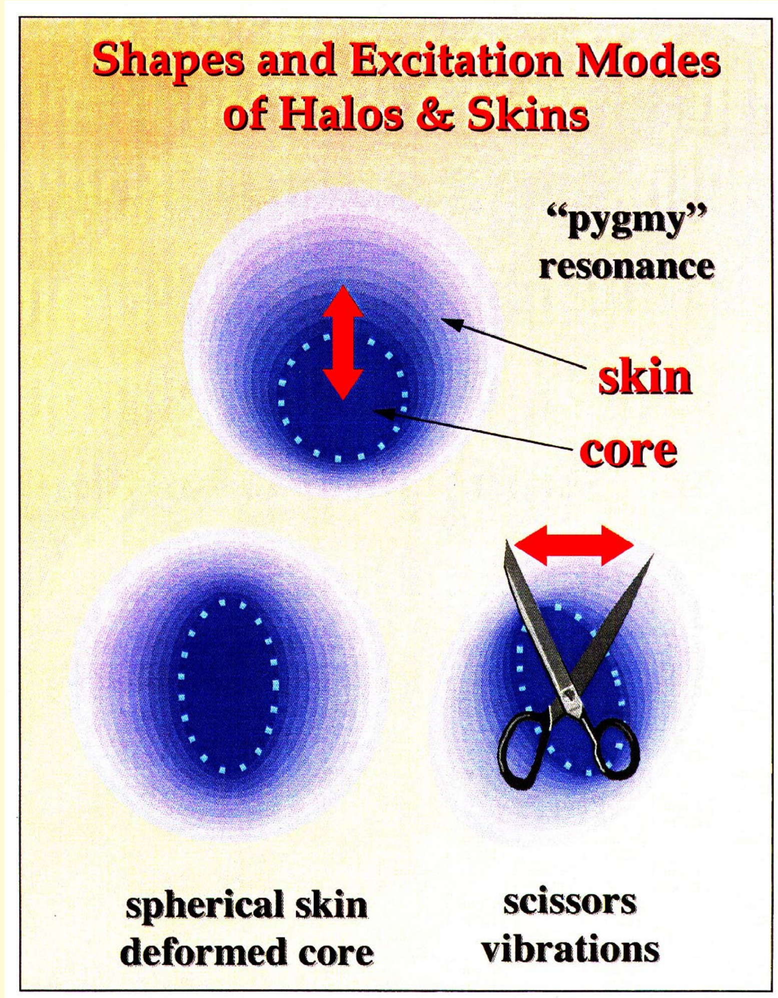


isovector giant
dipole resonance

proton deficiency

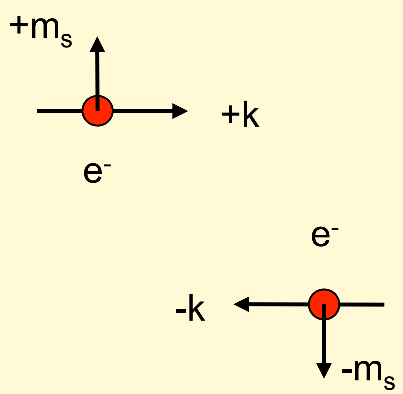
proton surplus

Exotic collective modes (neutron-halo and neutron-skin nuclei)
"pygmy" resonance and "scissors" mode

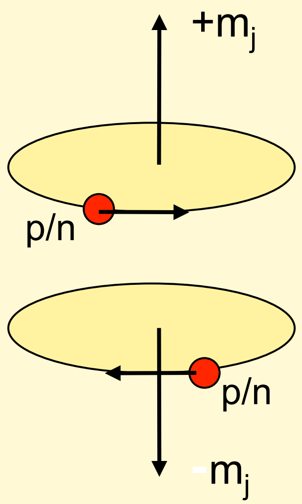


Cooper pair formation

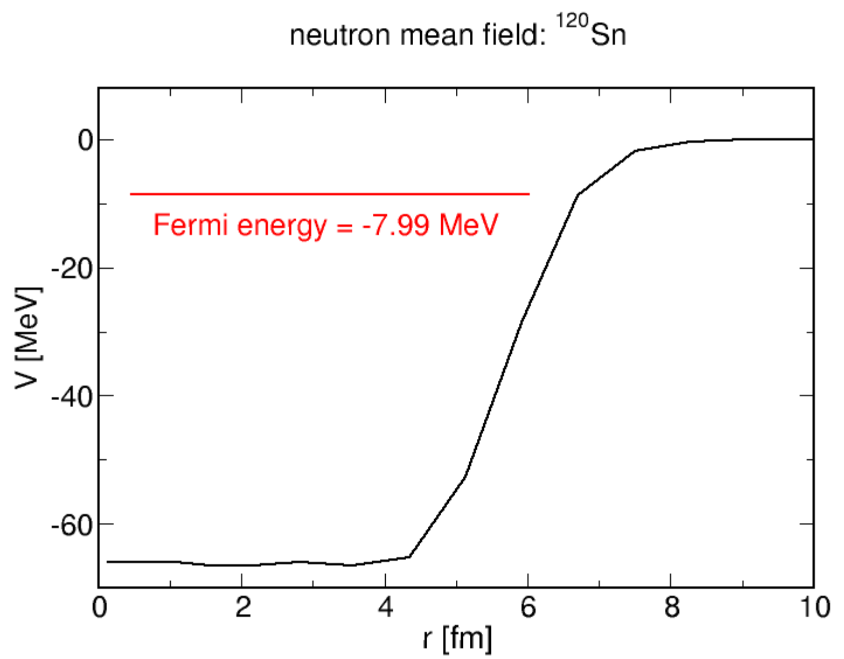
Condensed matter physics:
electron-phonon interaction

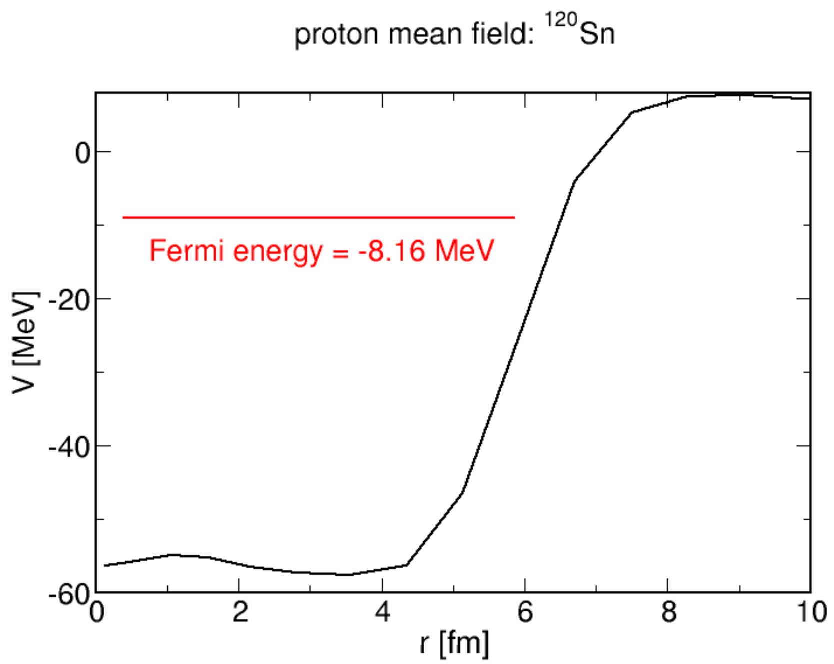


Nuclear physics:
short-range residual interaction



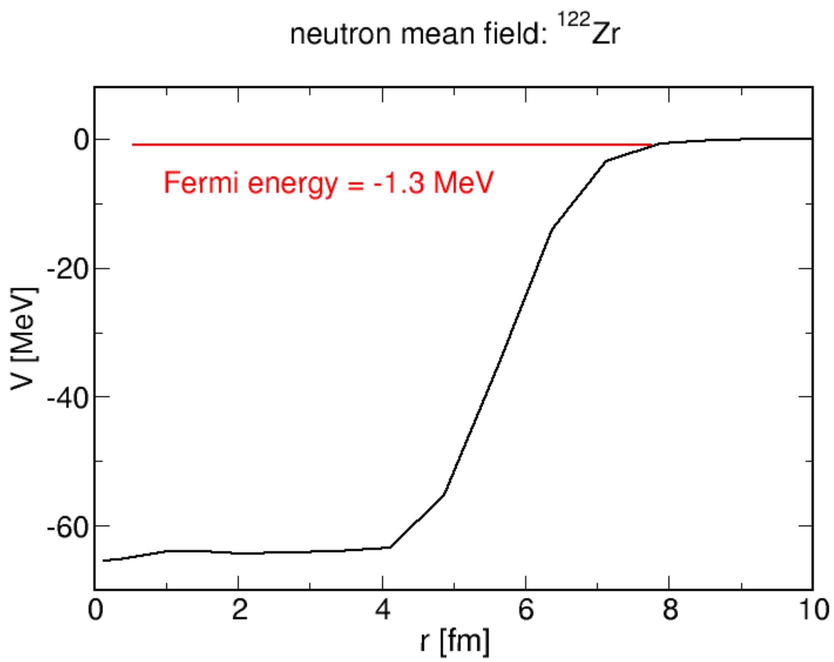
Stable isotope ^{120}Sn (Z=50, N=70)
VU-HFB code (2-D grid)

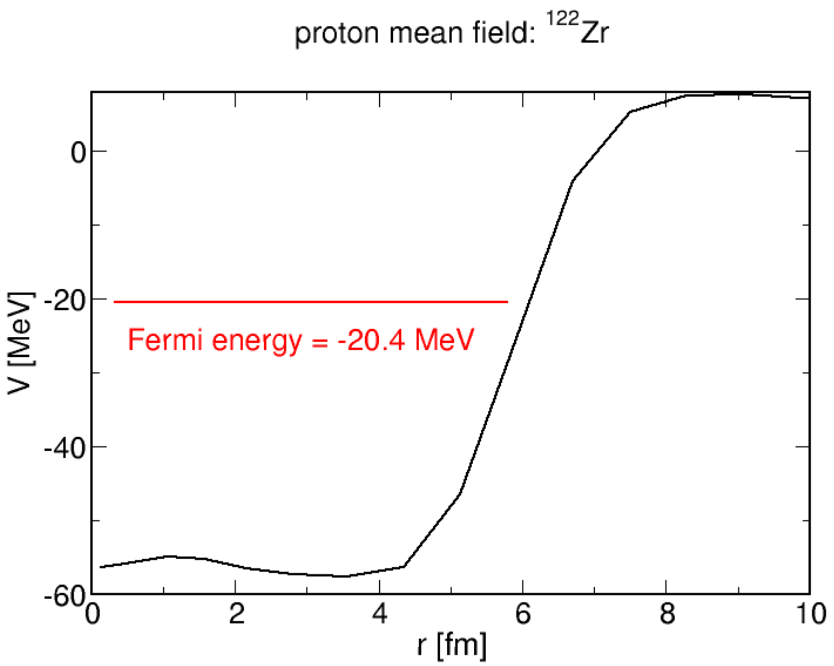




2n-dripline nucleus ^{122}Zr (Z=40, N=82), HFB on 2-D grid

Artur Blazkiewicz, Ph.D. thesis results (2005)





Neutrons at Fermi energy are almost unbound. Neutron wave functions spread out much more than those of protons: “neutron skin” (“neutron halo” for light nuclei)

Strong continuum coupling near the neutron dripline

Matsuo & Nakatsukasa, Journal of Physics G, May 2010

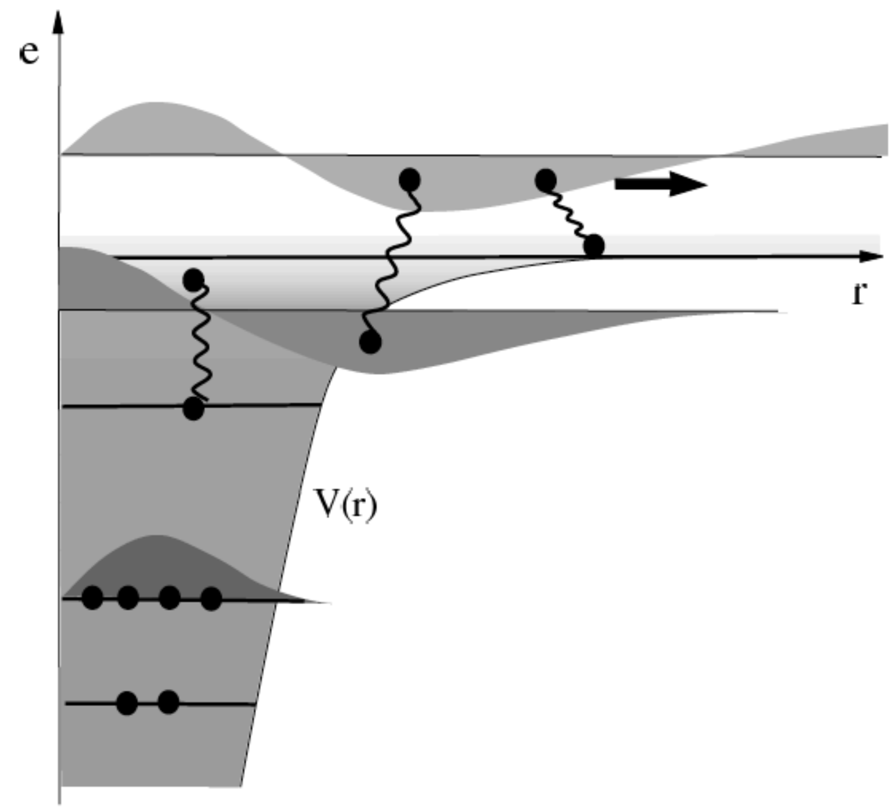
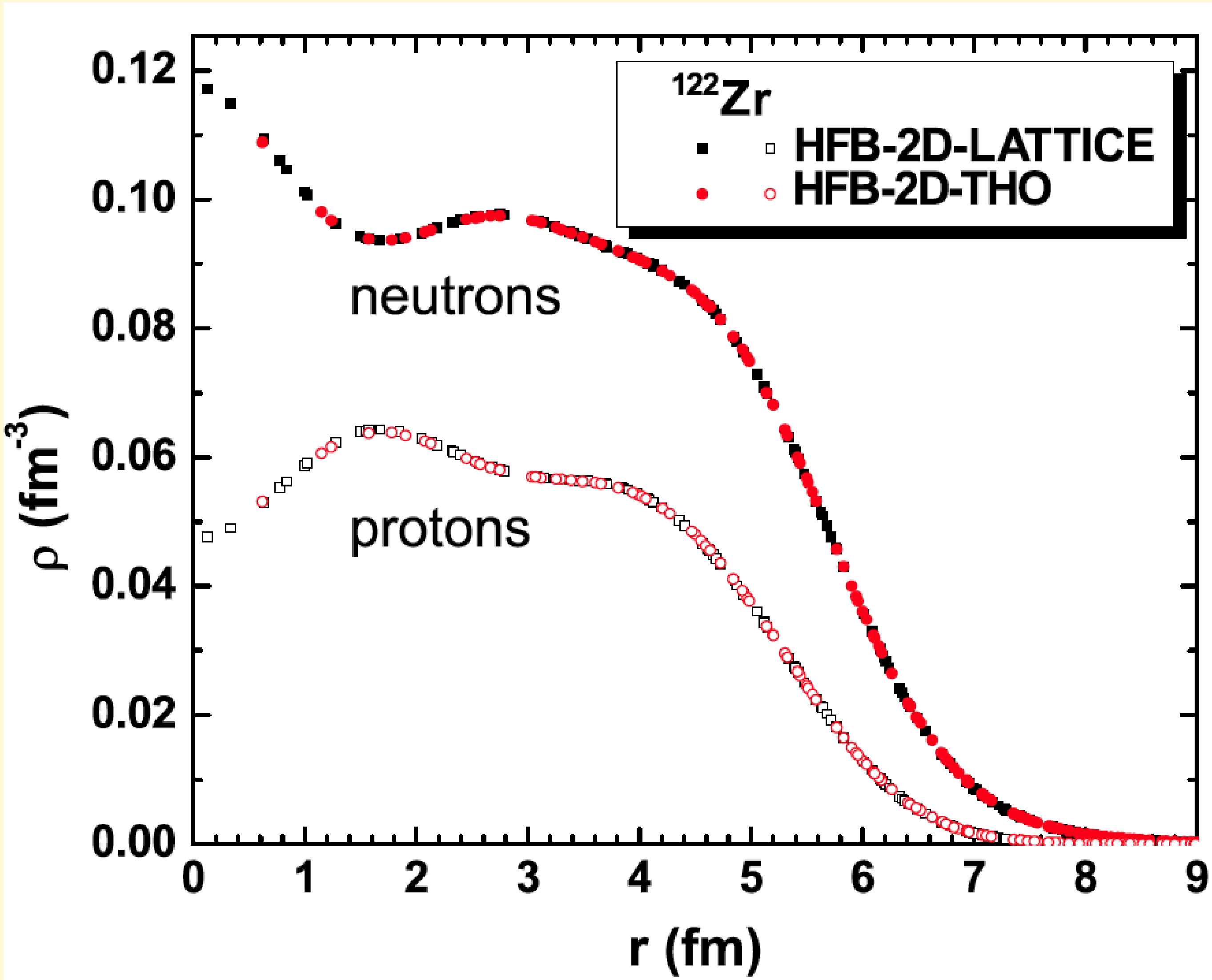


Figure 2. Schematic picture depicting correlations in nuclei near the drip-line, for which correlations involving the loosely bound and unbound continuum orbits play essential roles.

2n-dripline nucleus ^{122}Zr (Z=40, N=82), HFB on 2-D grid

Blazkiewicz, Oberacker, Umar & Stoitsov, Phys. Rev. C71, 054321 (2005)



Topic 4

- Time-dependent mean field theory for nuclear reactions (TDHF), studies of deep-inelastic and fusion reactions of exotic neutron-rich nuclei

Heavy-ion reactions as function of impact parameter b

impact
parameter b

large — Elastic collision, inelastic collision (Coulomb excitation)

Coulomb + nuclear inelastic excitation
few-nucleon transfer

medium

Multi-nucleon transfer

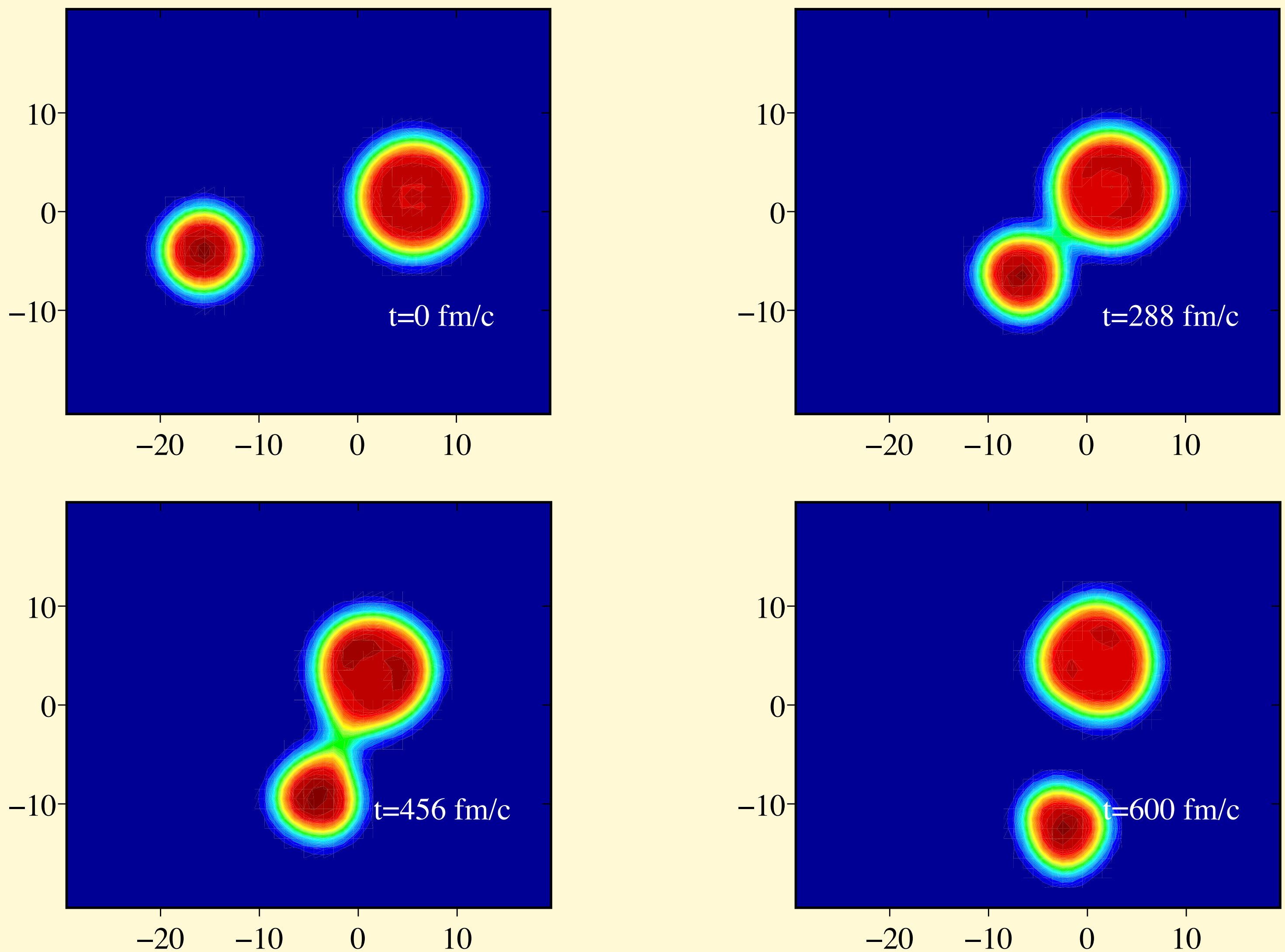
Deep-inelastic collisions ($E^* \approx 30$ MeV), 2 fragments emerge

small

Fusion reactions, 1 fragment in exit channel

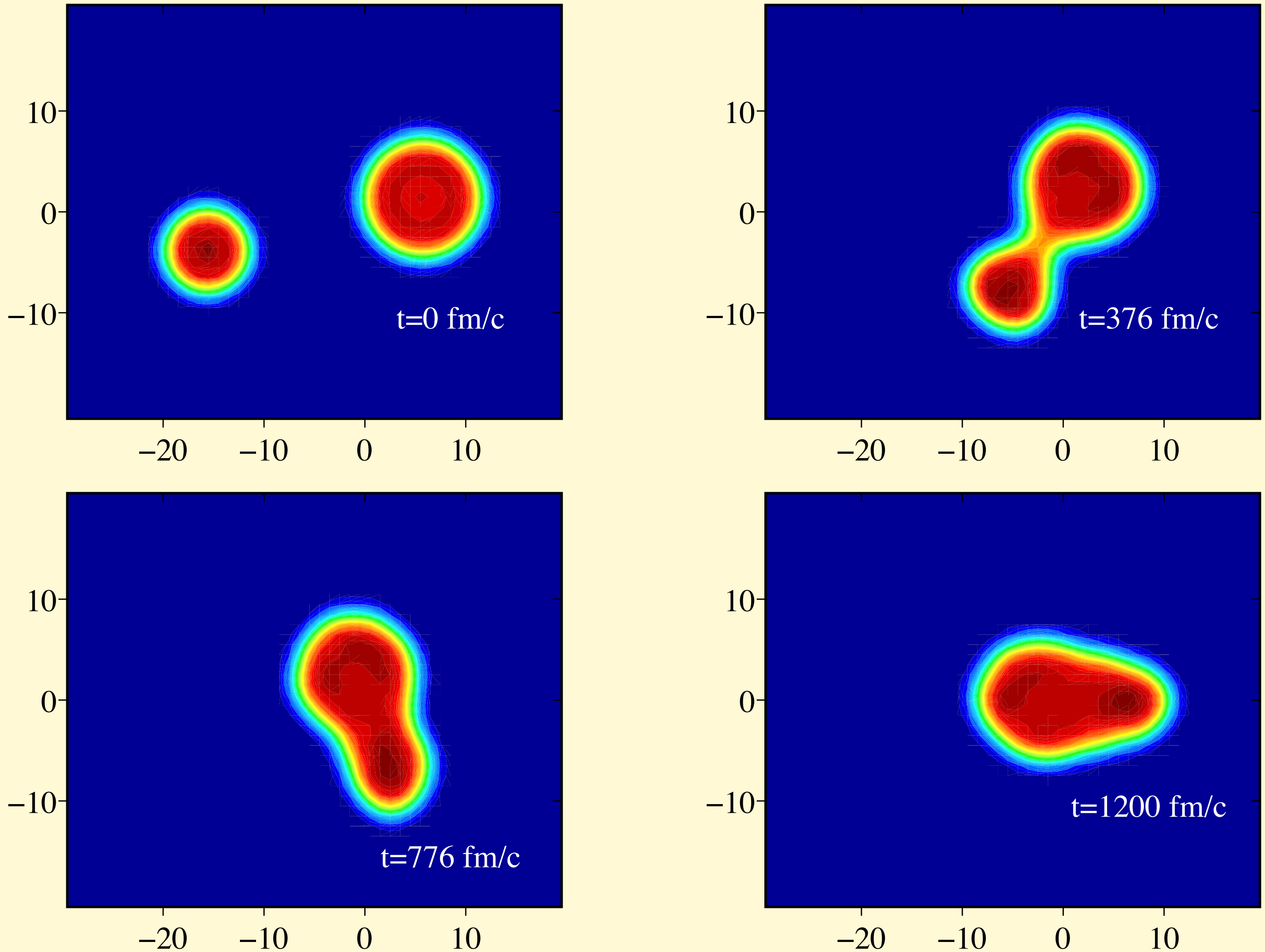
$^{48}Ca + ^{132}Sn$, E_{cm} = 130 MeV, b = 4.6 fm (deep-inelastic)

TDHF, SLy4 interaction, 3-D lattice (50*42*30 points)



^{48}Ca + ^{132}Sn, E_{cm} = 130 MeV, b = 4.45 fm (fusion)

TDHF, SLy4 interaction, 3-D lattice (50*40*30 points)



Heavy-ion fusion leading to superheavy element Z=112

spherical + spherical:
“cold fusion” (E* small)

spherical + deformed:
“hot fusion” (E* large)