Low-energy heavy-ion physics: glimpses of the future

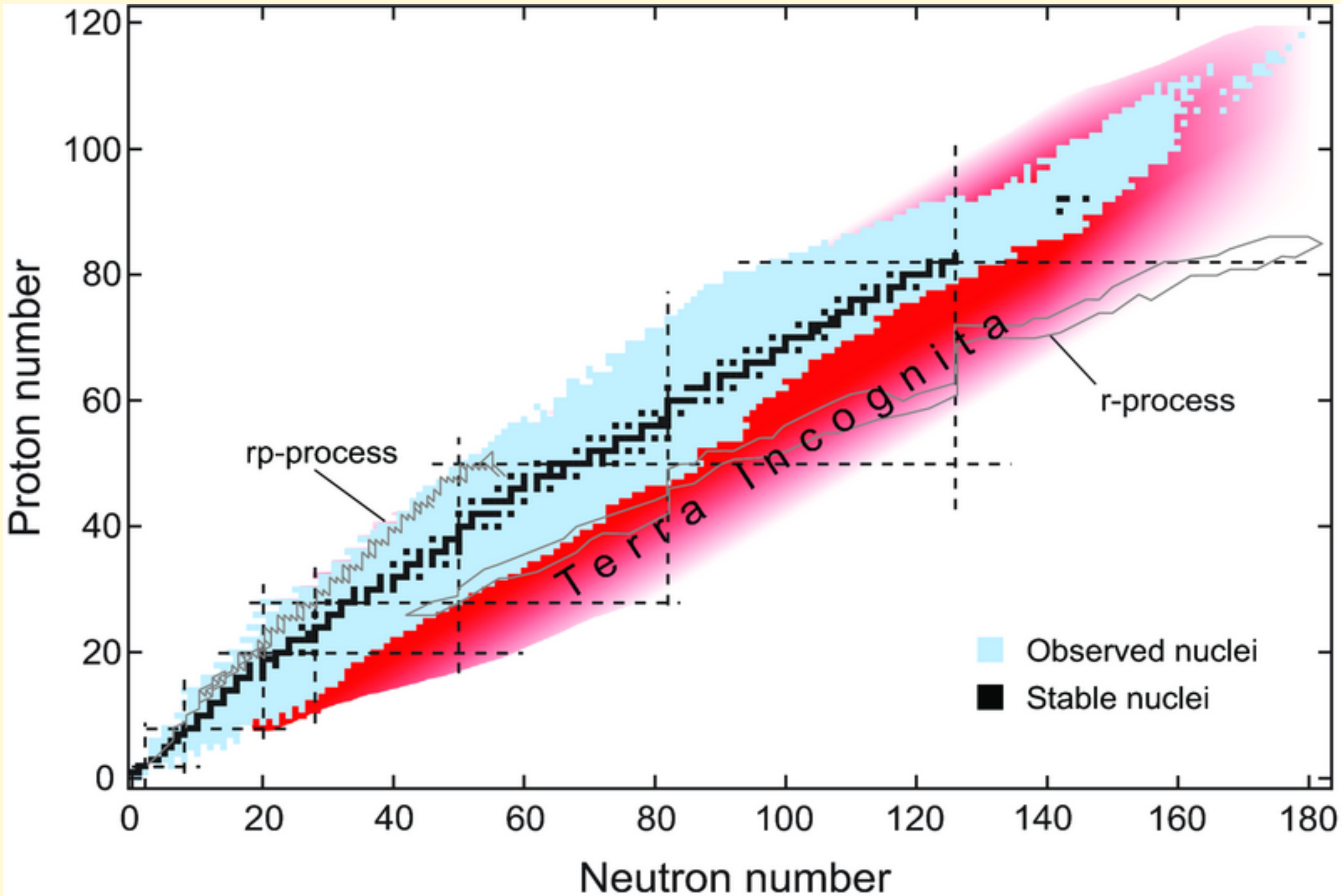
There are two frontiers for low-energy heavy-ion physics:

- explore "terra incognita" of thousands of new neutron-rich isotopes, investigate physics of neutron-dripline, astrophysics connection: r-process path (Supernovae)

- extension of periodic table: synthesis of new superheavy elements (currently up to Z=117)

Nuclear chart and the frontier of neutron-rich nuclei

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



Exp. data: neutron dripline for light nuclei (up to Z=8)

Ref: RIA Physics White Paper, Raleigh, NC conference (2000)

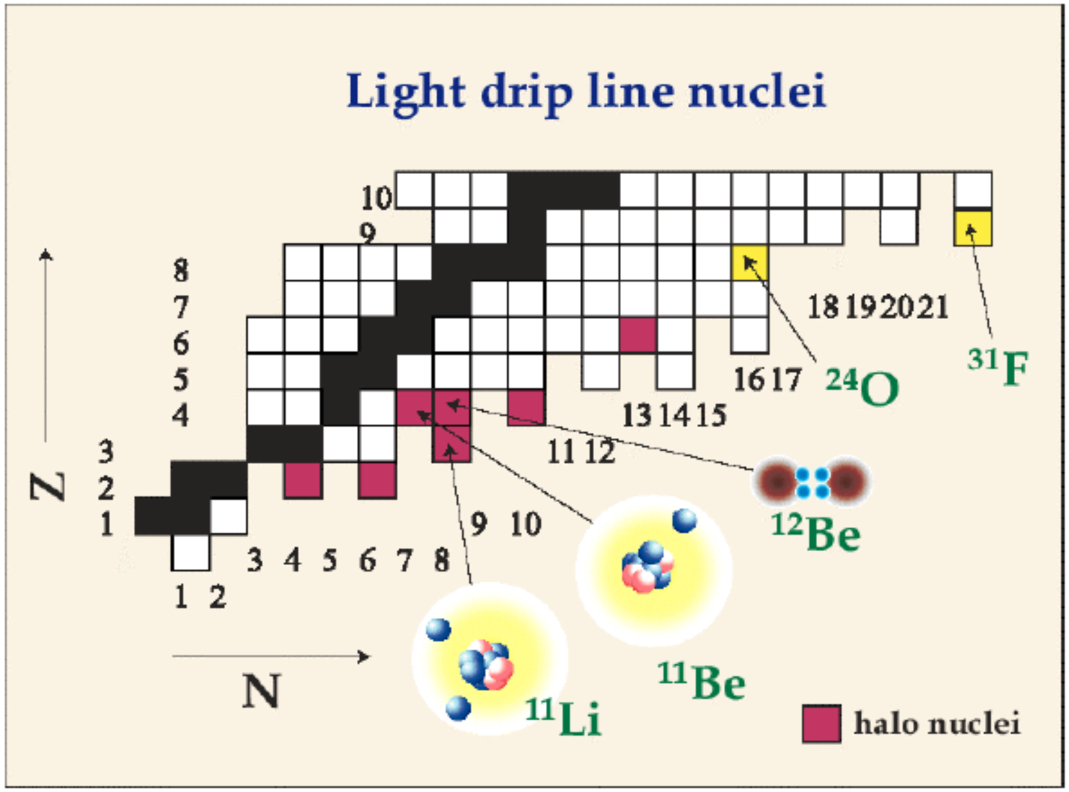


Figure 5: The part of the (N,Z) chart for the lightest nuclei. The neutron drip line has been reached only up to oxygen (Z = 8) where the heaviest particle-stable isotope has 16 neutrons. Interestingly, the heaviest isotope of flourine (Z=9) known has 22 neutrons. That is, one additional proton binds at least six neutrons. Known halo nuclei are marked by red squares. A very elongated "dimer" configuration in ^{12}Be has recently been found at higher excitation energies.

RIB production from CARIBU upgrade at ATLAS

http://www.phy.anl.gov/atlas/caribu/Cf252_upgrade_proposal_final_Rev4.pdf

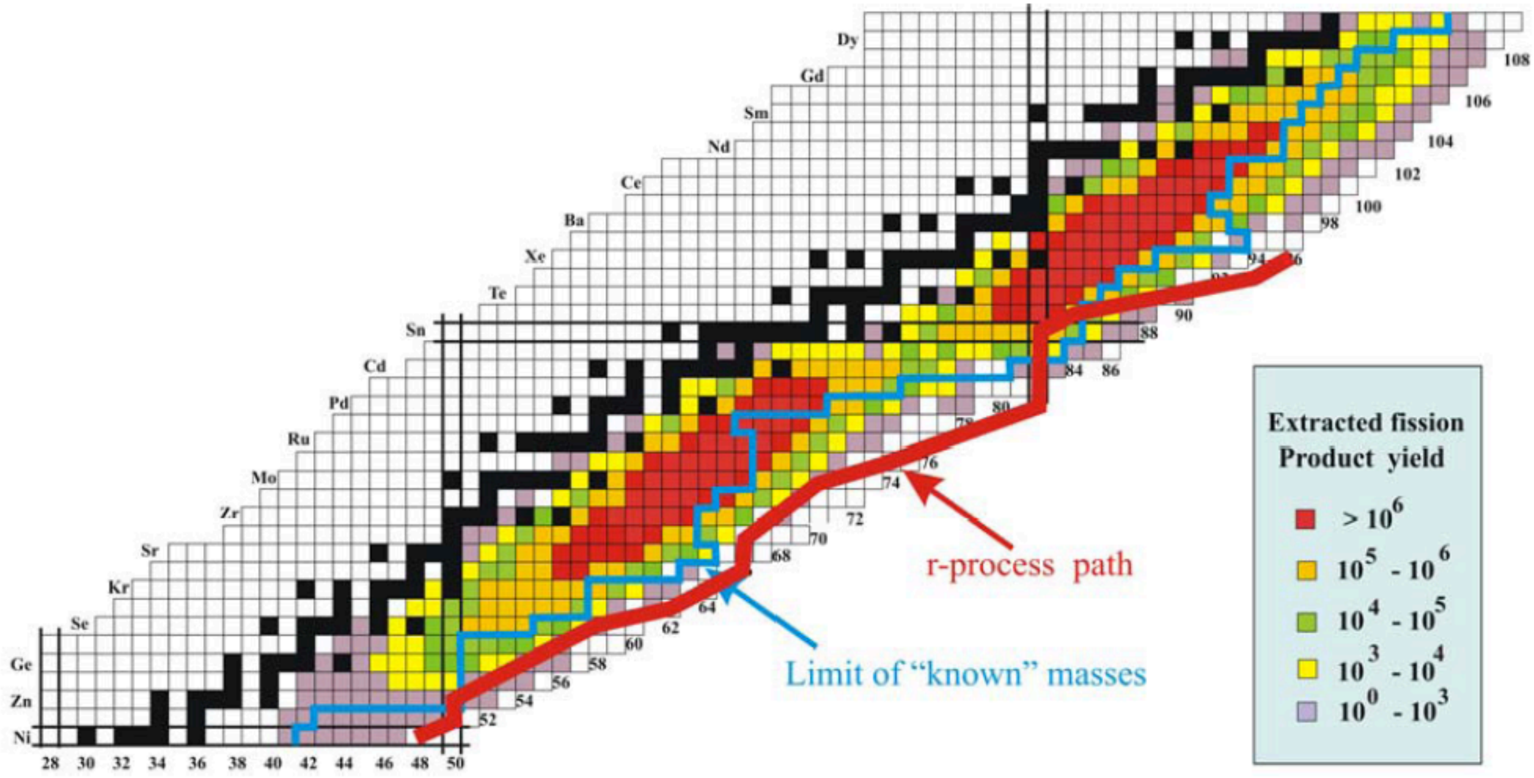
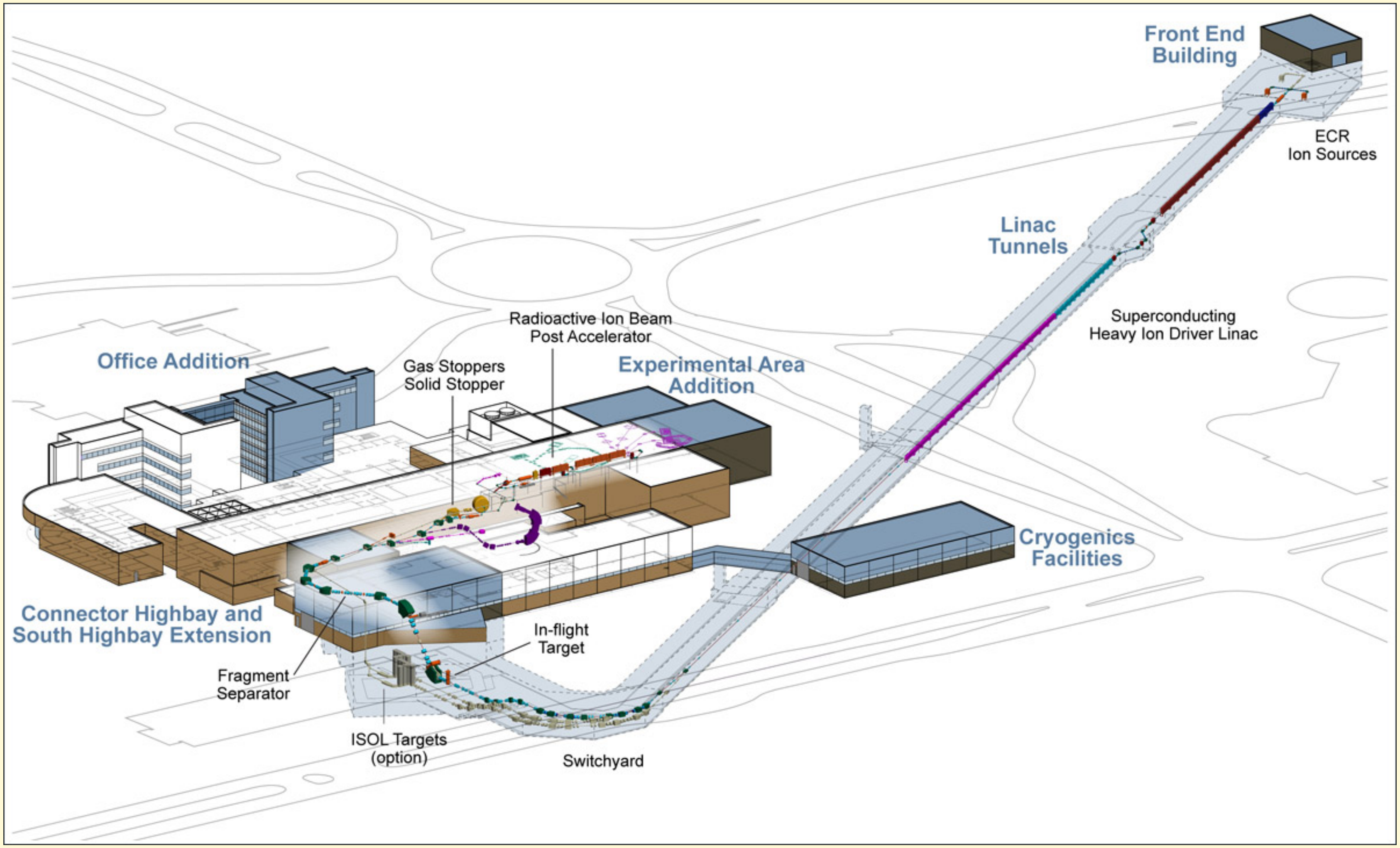


Figure 4. The r-process path together with the yield expected from an ion source system based on a 1 Ci californium fission source and the limit of known masses.

Facility for Rare Isotope Beams (FRIB)

under construction at Michigan State University

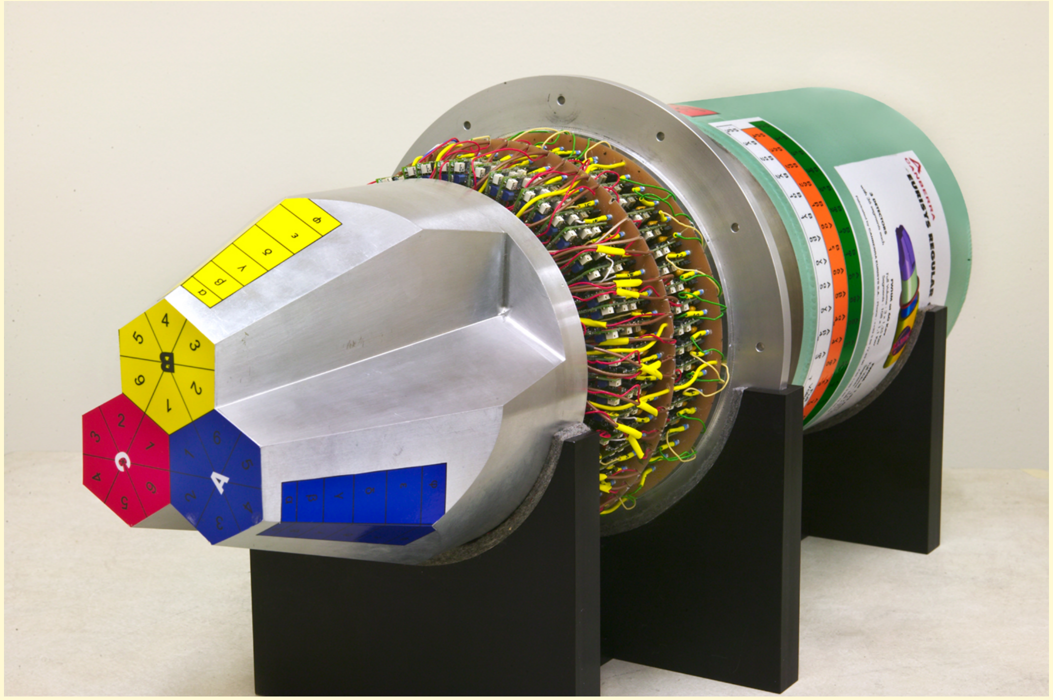
http://www.frib.msu.edu/



Major new gamma ray detectors in the U.S.

GRETA = Gamma Ray Energy Tracking Array
GRETINA = smaller version of GRETA
GRETINA consists of 28 highly segmented hyper-pure germanium crystals.
Each crystal is segmented into 36 electrically isolated elements.

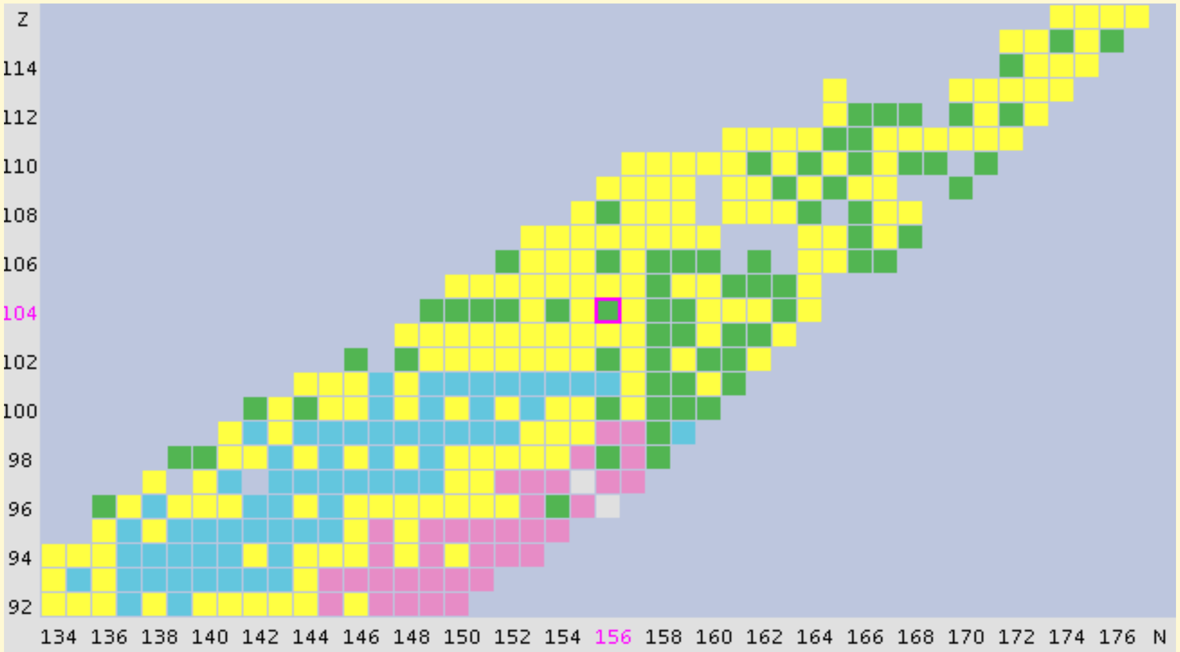
Gretina Website http://grfs1.lbl.gov/



Second frontier: superheavy elements in heavy-ion fusion reactions

Ref: National Nuclear Data Center, Brookhaven

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



Exp. discovery of superheavy element Z=117 at Dubna (Russia)

Vanderbilt physicists involved: Professors Hamilton and Ramayya

Phys. Rev. Lett. 104, 142502 (2010)

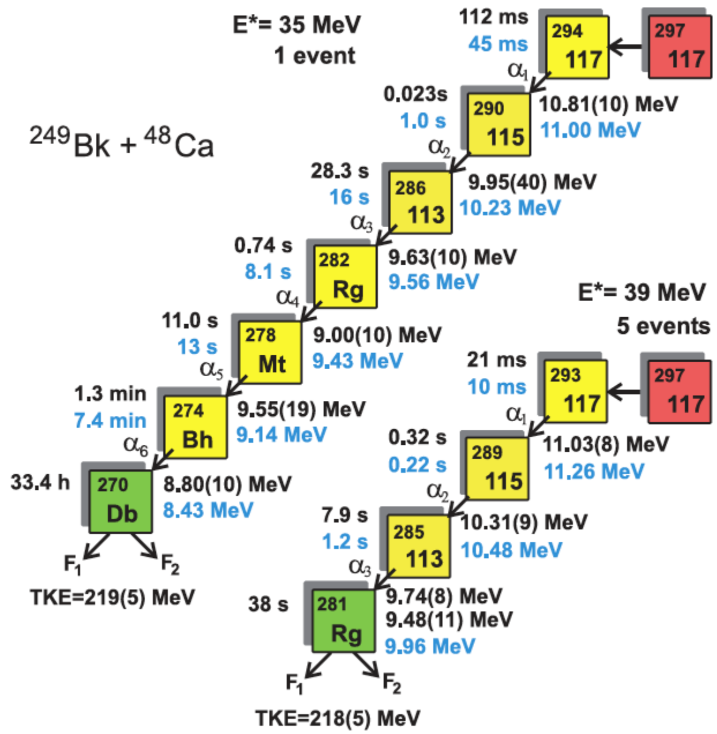


FIG. 1 (color). Observed decay chains interpreted as originating from the isotopes $A = 294$ (single event) and $A = 293$ (average of five events) of the new element $Z = 117$. The deduced and predicted [9] lifetimes ($\tau = T_{1/2}/\ln 2$) and α-particle energies are shown in black and blue, respectively.

The isotopes $^{293}117$ and $^{294}117$ were produced in fusion reactions between $^{48}_{20}$Ca and $^{249}_{97}$Bk. Decay chains involving 11 new nuclei were identified by means of the Dubna gas-filled recoil separator. The measured decay properties show a strong rise of stability for heavier isotopes with Z ≥111, validating the concept of the long sought island of enhanced stability for superheavy nuclei.

Current state-of-the-art microscopic theories of nuclear structure and reactions

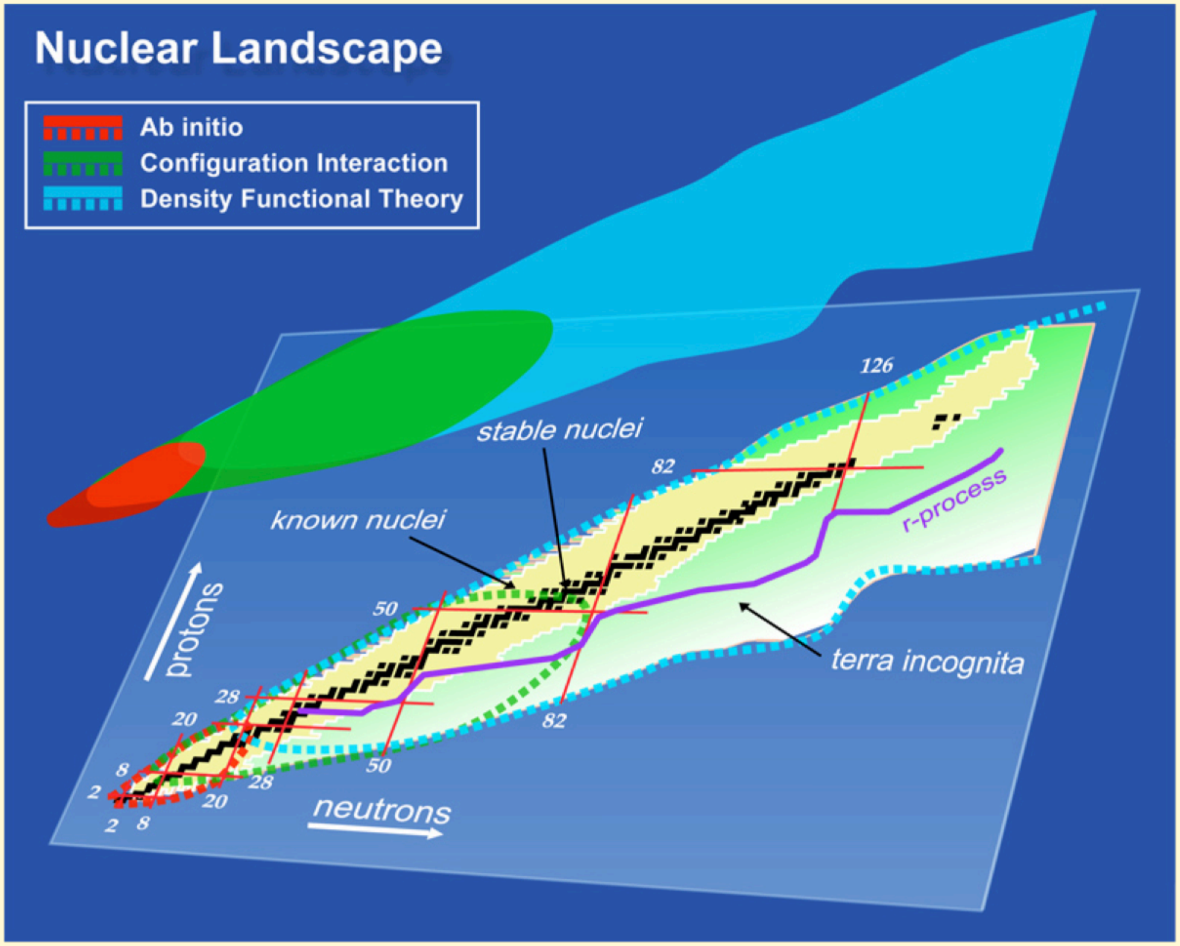
Nuclear structure

- Ab initio nuclear structure calculations for light nuclei
- HFB calculations: ground state properties
- HFB with constraints (cranking, Q_{20}, Q_{30}): rotational bands, collective potential energy surfaces
- RPA / QRPA calculations (excited states: surface vibrations and giant resonances)

Nuclear reactions

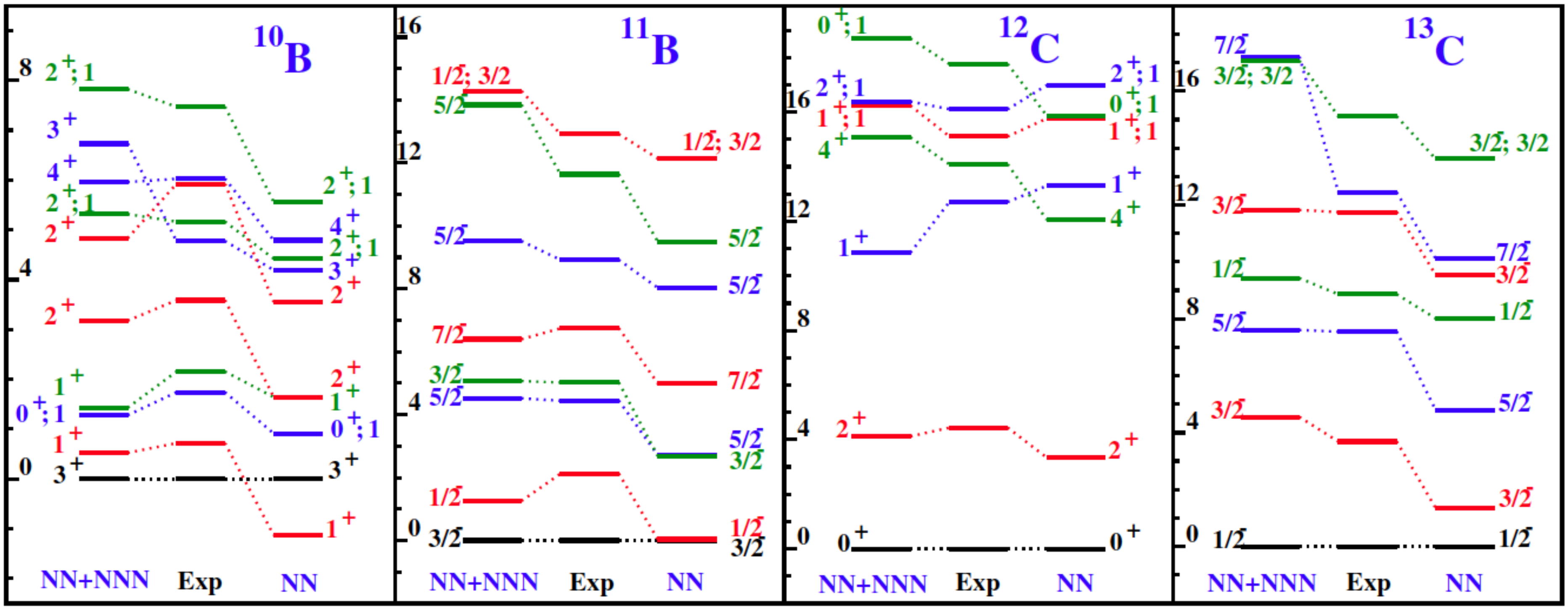
- Reaction theory that incorporates relevant degrees of freedom for weakly bound nuclei, including ab initio approaches
- TDHF / DC-TDHF calculations of heavy-ion reactions

Microscopic theories of nuclear structure



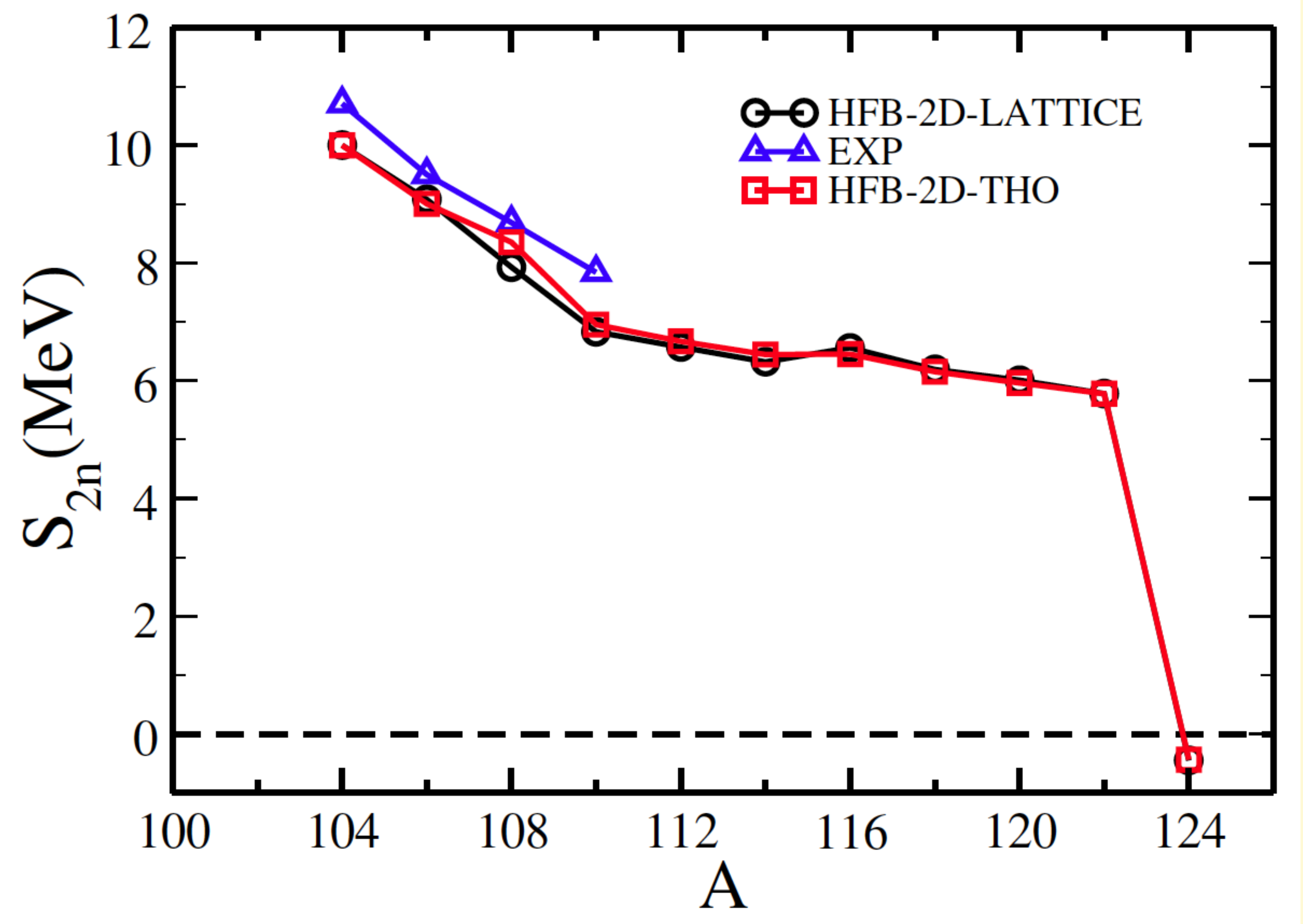
No-core shell model

Ref: Navratil, Gueorguiev, Vary, Ormand and Nogga, Phys. Rev. Lett. 99, 042501 (2007)



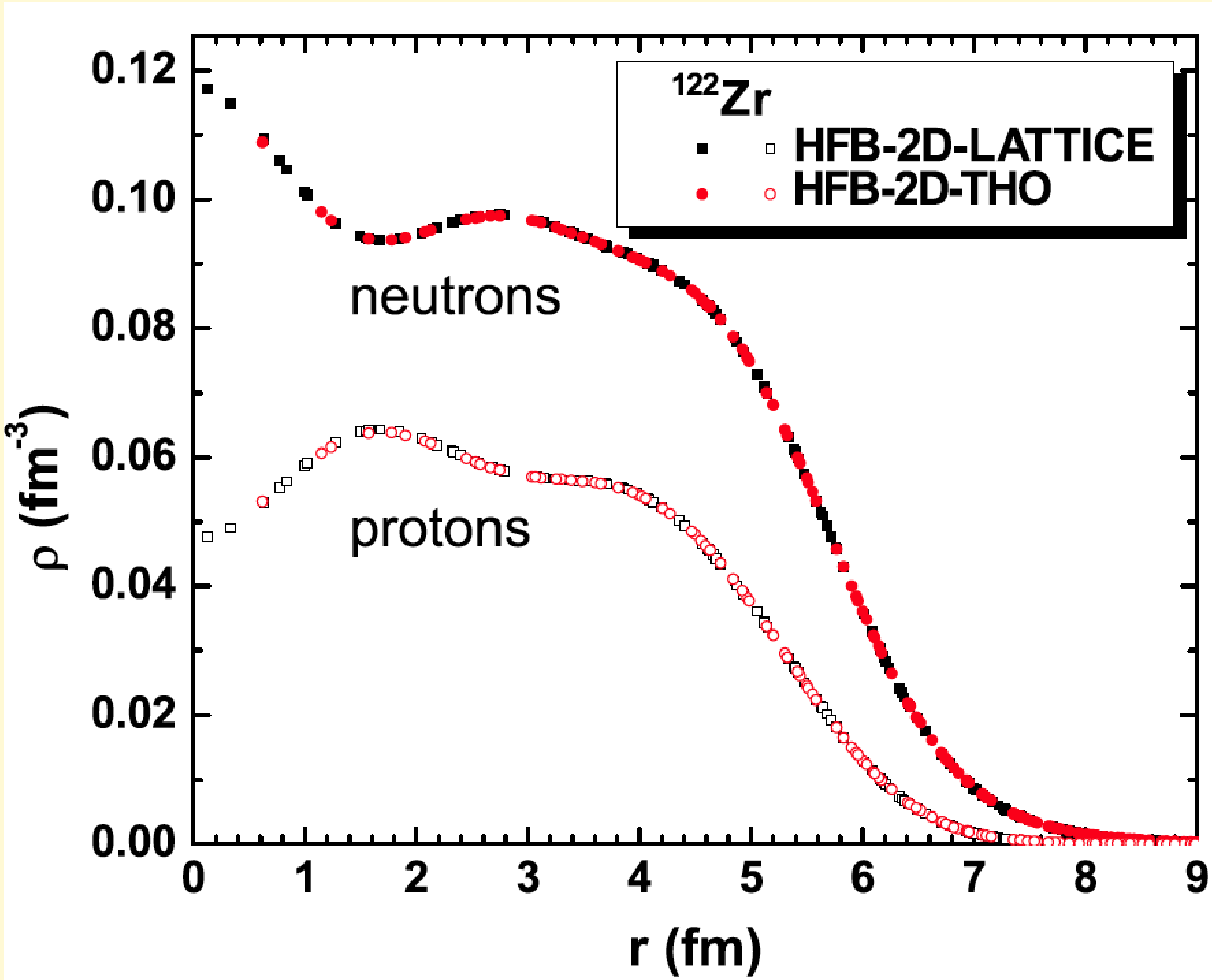
Zirconium isotopes (Z=40), HFB+SLy4 on 2D-grid

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



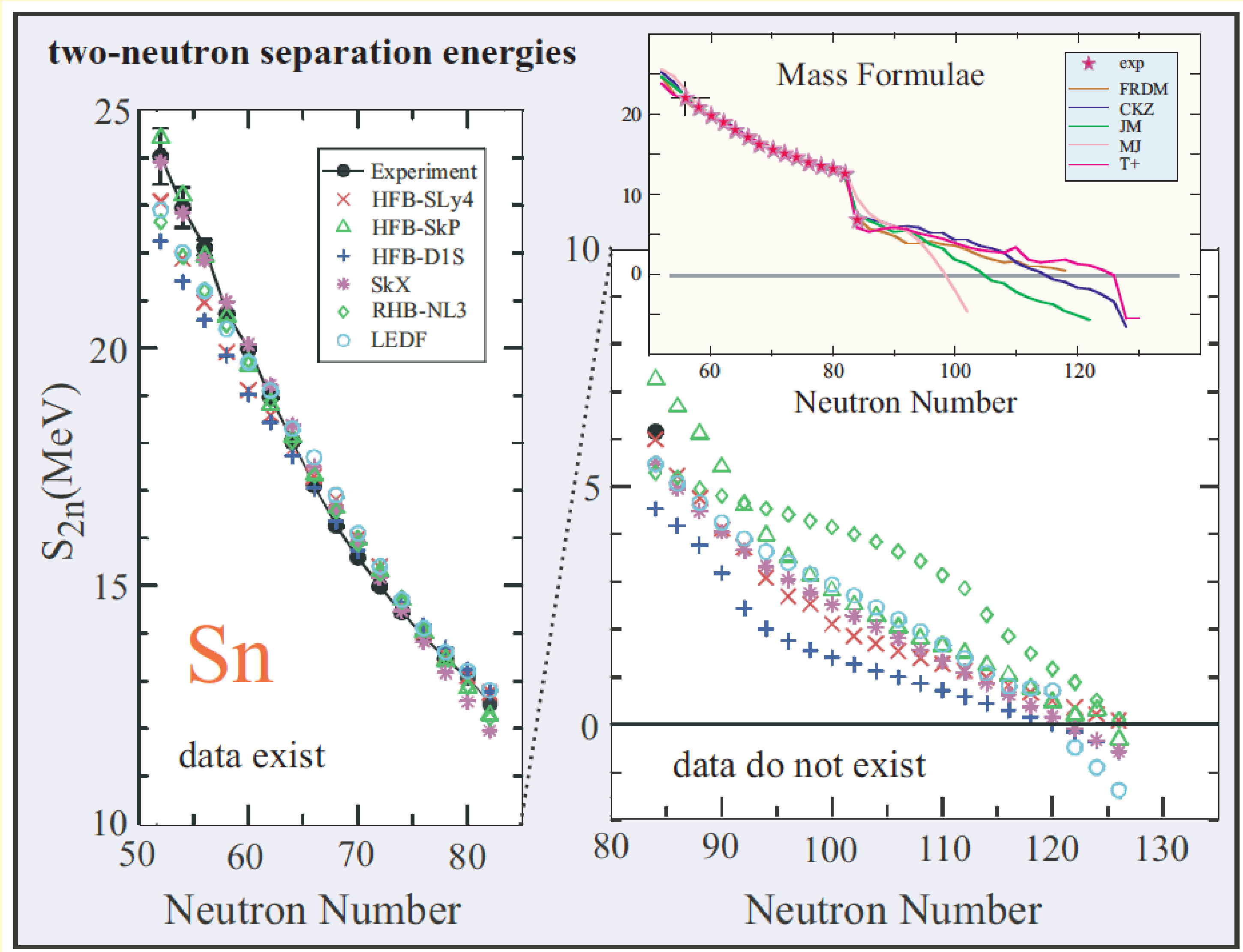
2n-dripline nucleus ^{122}Zr (Z=40, N=82), HFB on 2-D grid

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



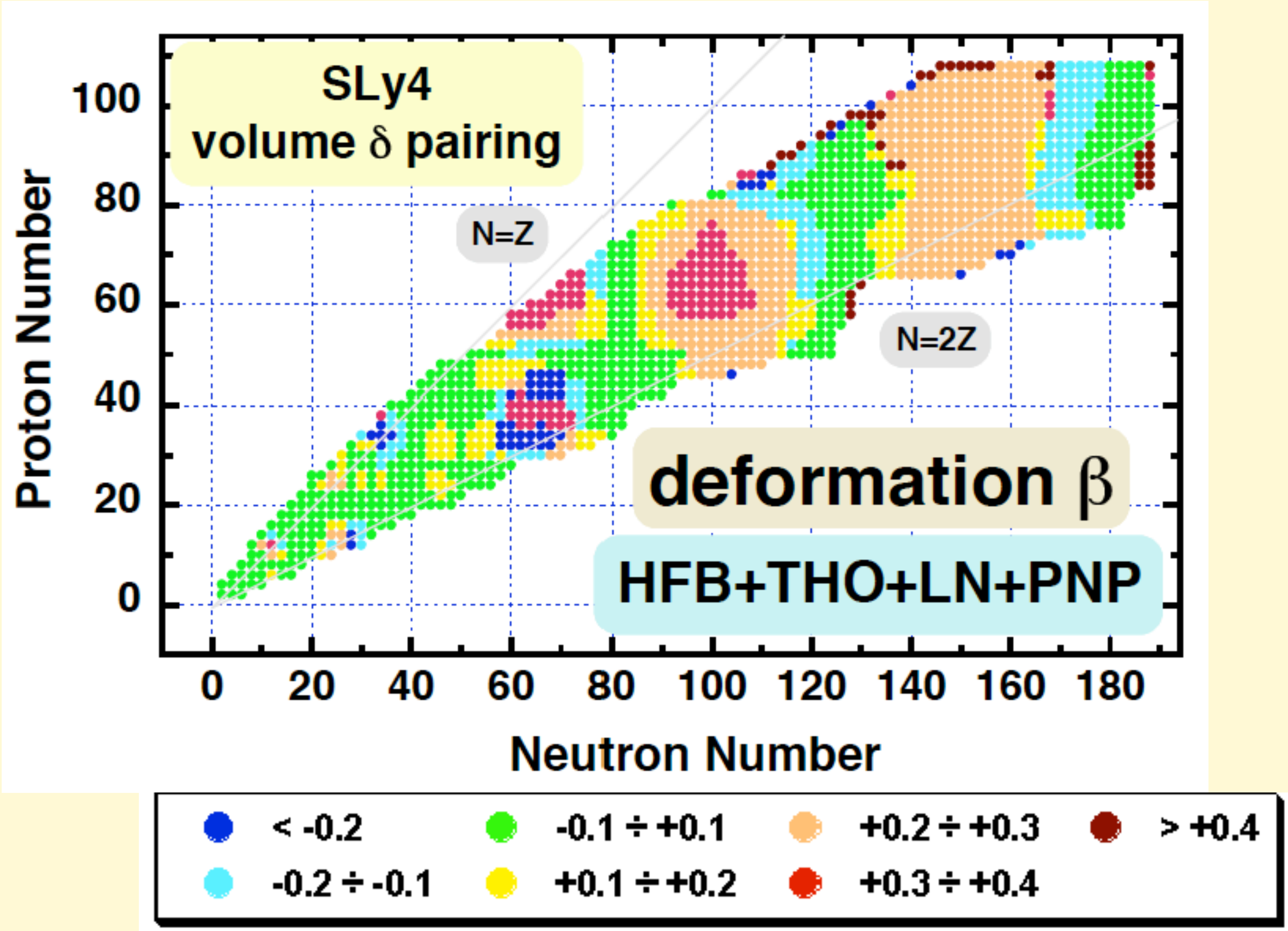
Tin isotopes (Z=50), HFB-1D for several Skyrme interactions

RIA Theory Bluebook (Sep. 2005), calculations by Dobaczewski et al.



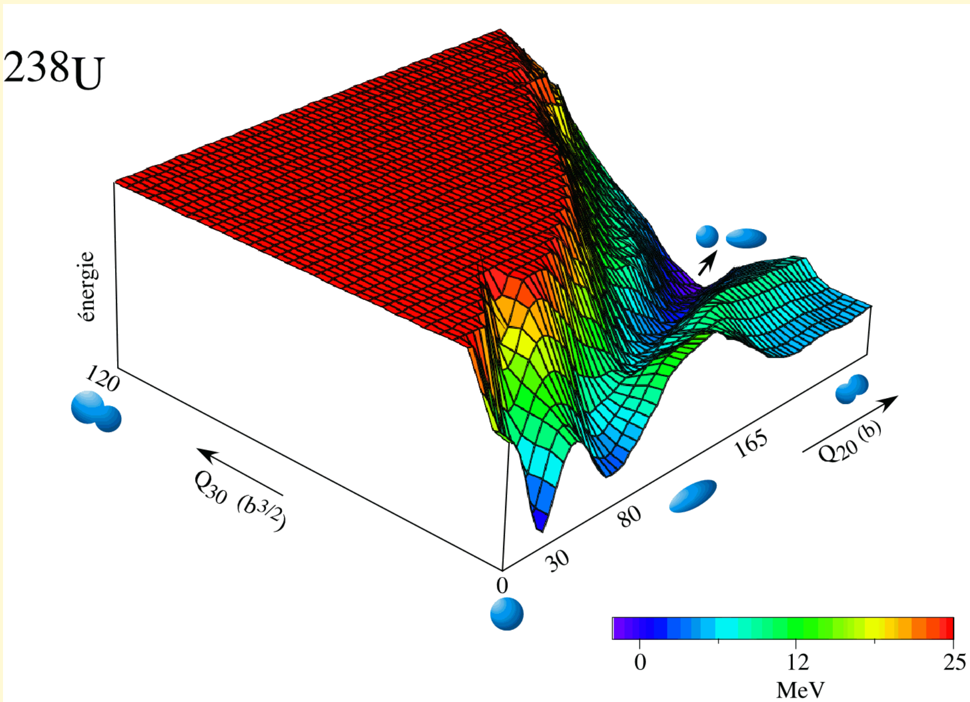
Nuclear ground state deformations (2-D HFB)

Dobaczewski, Stoitsov & Nazarewicz (2004)   arXiv:nucl-th/0404077



HFB with quadrupole + octupole constraints

H. Goutte, P. Casoli, and J.F. Berger, Nucl. Phys. A734 (2004) 217



microscopic potential energy surface $E(Q_{20}, Q_{30})$ for nuclear fission:

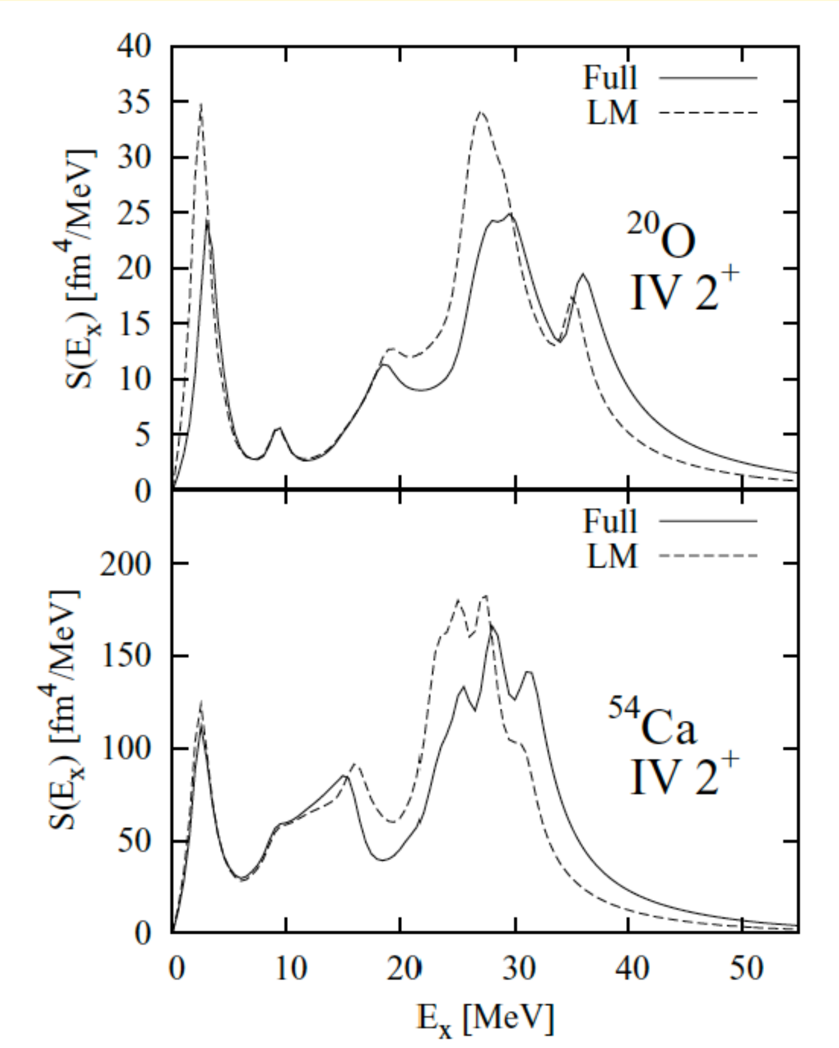
Q_{20} – elongation

Q_{30} – mass asymmetry

Notice double-humped fission barrier in Q_{20} – direction !

Continuum quasi-particle linear response theory for neutron-rich isotopes

Mizuyama, Matsuo & Serizawa, Phys. Rev. C79, 024313 (2009)



Strength function of isovector (T=1) quadrupole (L=2) response.

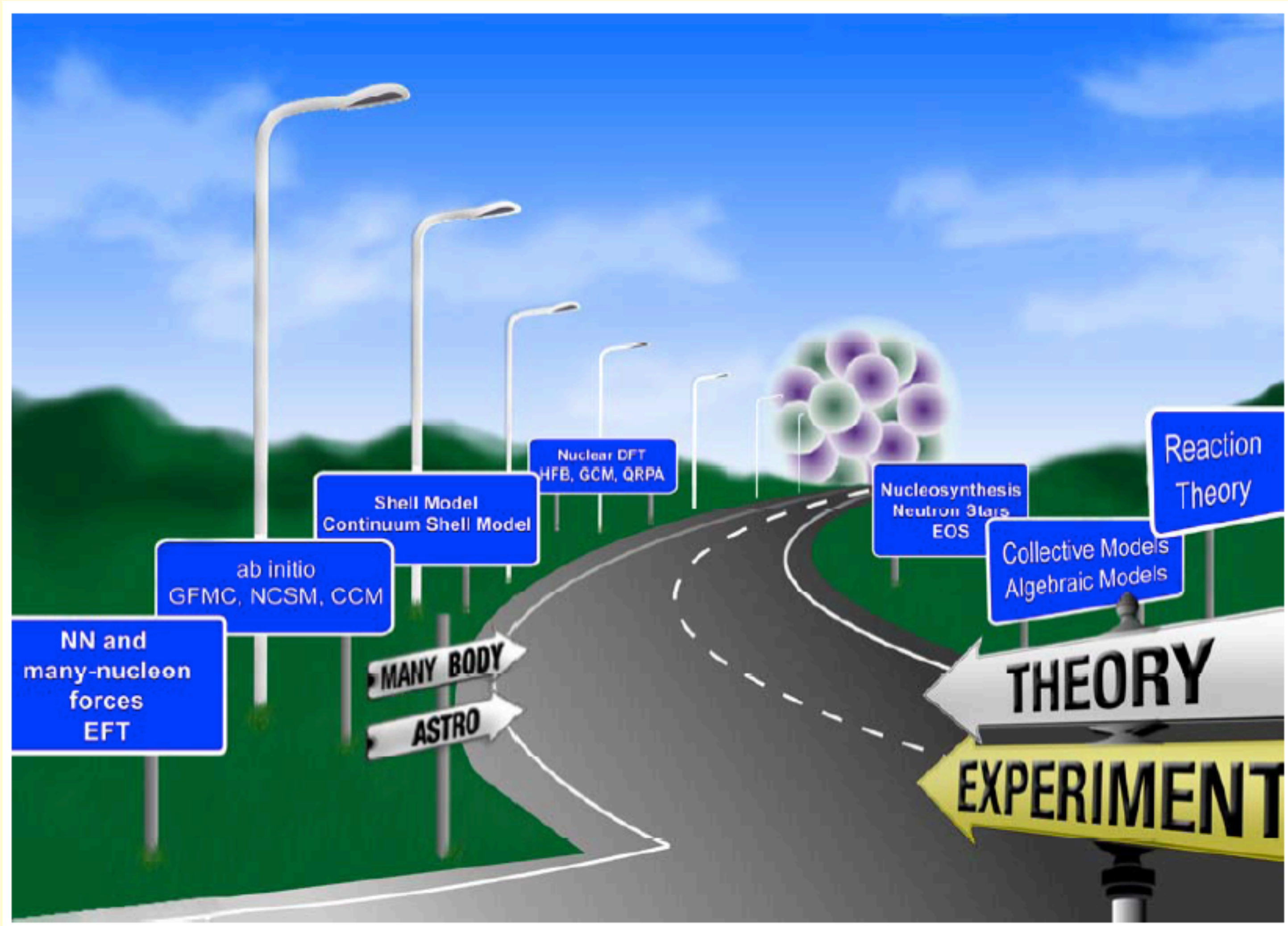
(LM = Landau-Migdal approx.)

Theory yields both low-energy and high-energy collective vibrations

Skyrme (SkM*) interaction for HFB mean field, and density-dependent delta interaction for pairing

Theoretical road map

Ref: RIA Theory Bluebook (Sep. 2005)



Theoretical / computational challenges for the future

Ref: RIA Theory Bluebook (Sep. 2005)

- Extend ab initio nuclear structure calculations to medium mass nuclei.
- Self-consistent nuclear density functional methods for static and dynamic problems.
- Reaction theory that incorporates relevant degrees of freedom for weakly bound nuclei, including ab initio approaches.
- Isospin degrees of freedom of the density-dependent nuclear interaction.
- Synthesis between nuclear theory and various astrophysical models to determine the nucleosynthesis in stars.