# The Challenges of Nuclear Physics


W.Gelletly

CENTRE FOR NUCLEAR & RADIATION PHYSICS

Physics Department,University of Surrey


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# Outline

1.Introduction

2.Main themes and questions

3.Structure of nucleons and other hadrons
-The non-perturbative regime of QCD

4.The Nuclear Phase Diagram
-Exploring the diagram
-Nuclear matter at high net baryon densities.

5.Nuclear Theory:-
From ab-initio calcs. to the Shell Model to Mean Field Theories

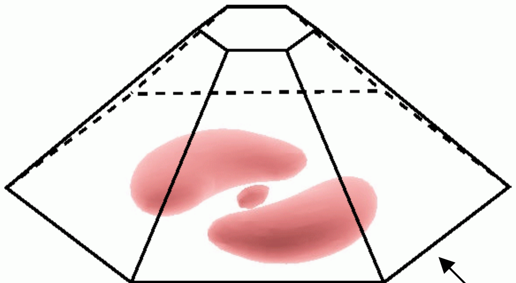
6.The structure of nucleonic matter
Many questions need radioactive ion beams to answer them.

7.Nuclei and the Cosmos

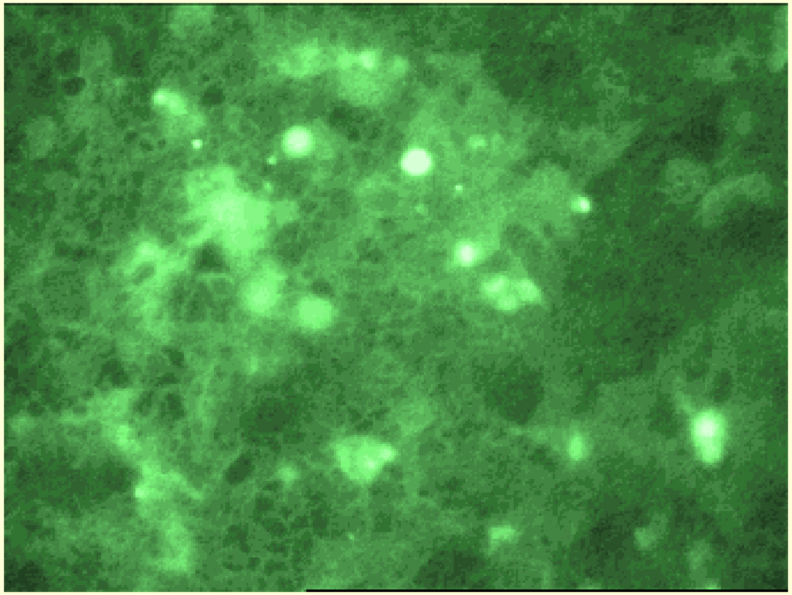
8.Conclusions

# Nuclear Physics at the heart of modern science

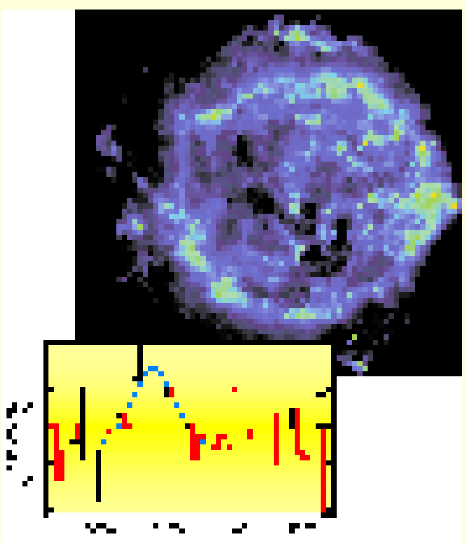
**Nuclear Physics**



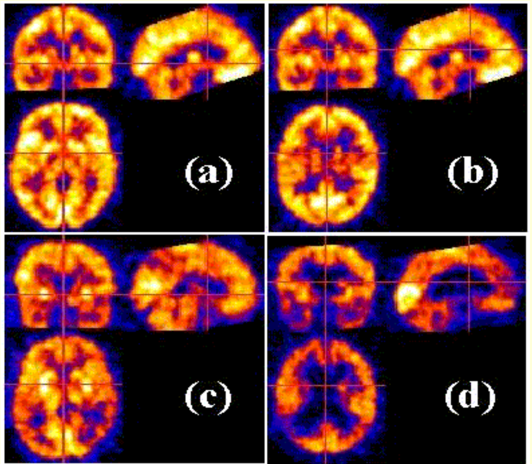
Quantum Dots



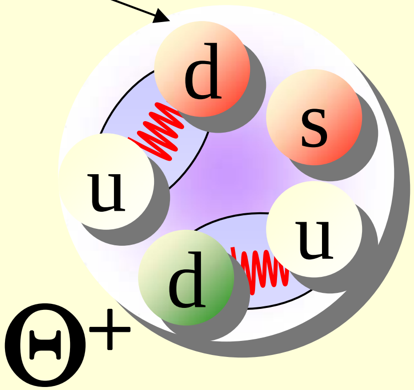
Bystander Effect



Cassiopiea

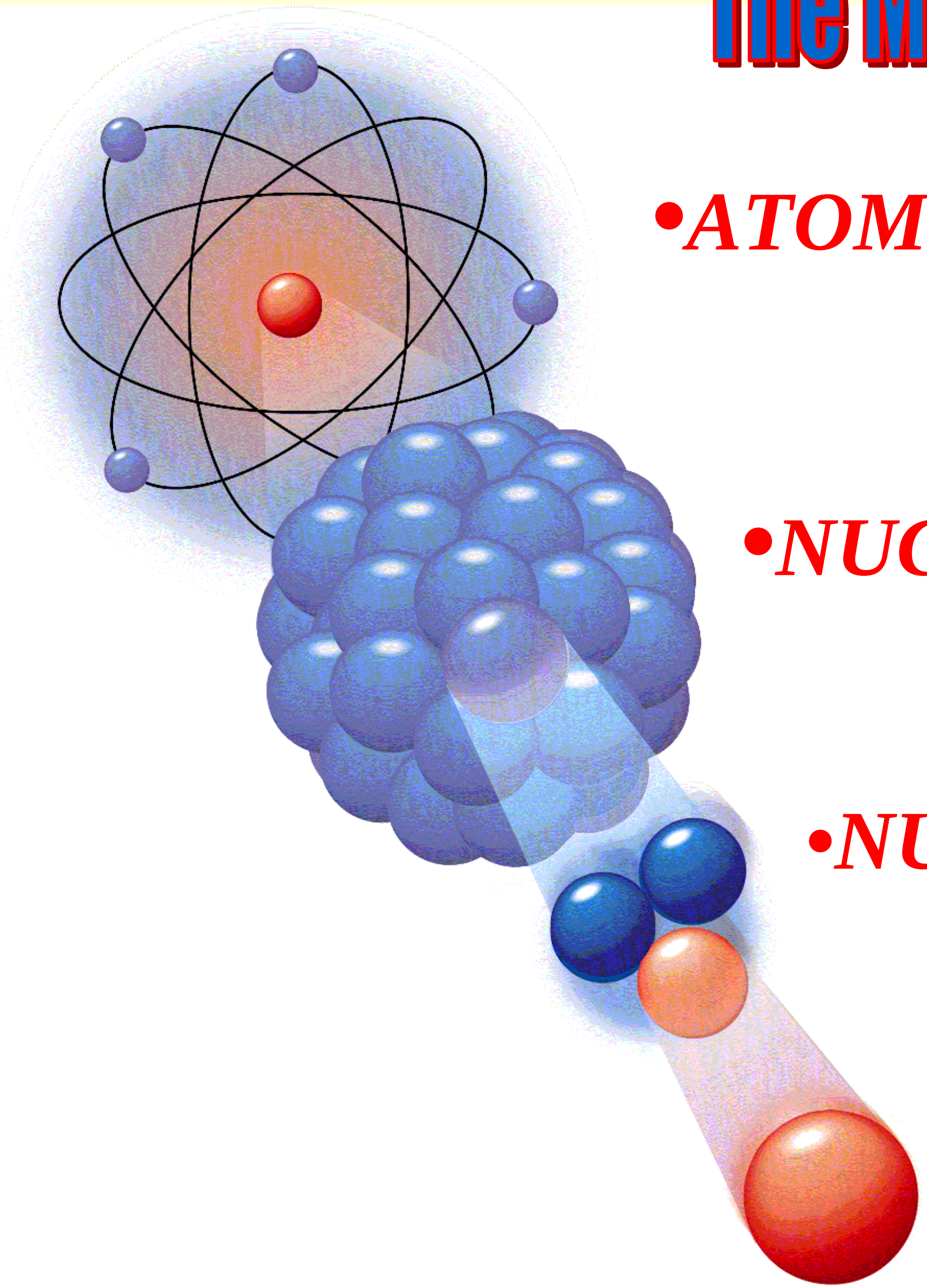



PET




Pentaquark

# The Microscopic world



- *ATOMS--$10^{-10}$ m*
- *NUCLEI--$10^{-14}$ m*
- *NUCLEONS-$10^{-15}$ m*
- *QUARKS--*

# The present main themes and questions in nuclear science

(as defined by NUPECC : **Nu**clear **P**hysics **E**uropean **C**ollaboration **C**ommittee
and the DOE/NSF NSAC: **N**uclear **S**cience **A**dvisory **C**ommittee)

- **What is the structure of the nucleon and other hadrons ?**
  observed properties → **QCD**

- **What is the structure of nucleonic matter ?**
  central goal of nuclear physics: **nuclear structure**

- **What are the properties of hot and dense nuclear matter ?**
  various phases → quark-gluon plasma: a new state of matter in which quarks and gluons are deconfined

- **What is the rôle of nuclei in the universe ?**
  nuclear astrophysics → combination of astronomical observations and astrophysical modelling and of nuclear structure and theory

- **What are the limits of the present Standard Model ?**
  nucleus as laboratory for fundamental interactions, neutrinos and their masses, magnetic anomaly g-2 of the muon, . . .

# Structure of the nucleon and other hadrons
# The femtoscale frontier

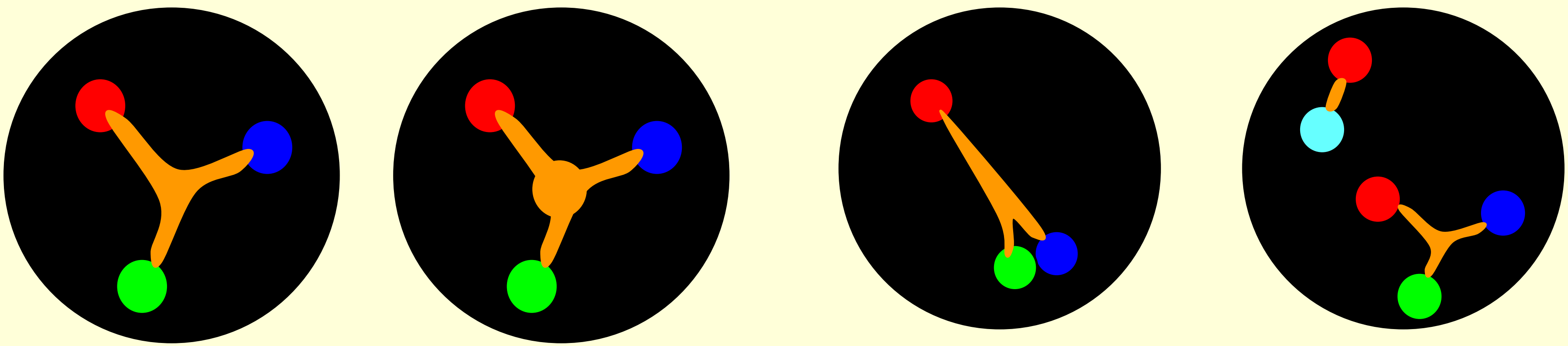
Goal:- To understand the structure and properties of protons and neutrons and ultimately nuclei, in terms of the quarks and gluons of QCD

There are many unanswered questions:-

- What is the non-perturbative nature of QCD?
- What is the origin of the mass of the nucleon?
- What is the origin of the spin of the nucleon?
- Why do only two colourless configurations of quarks prevail?
- Do glueballs or quark-gluon hybrids exist?
- …………..?????

# Problems in baryon spectroscopy

A. Theoretical problem:  What are  effective degrees of freedom ?

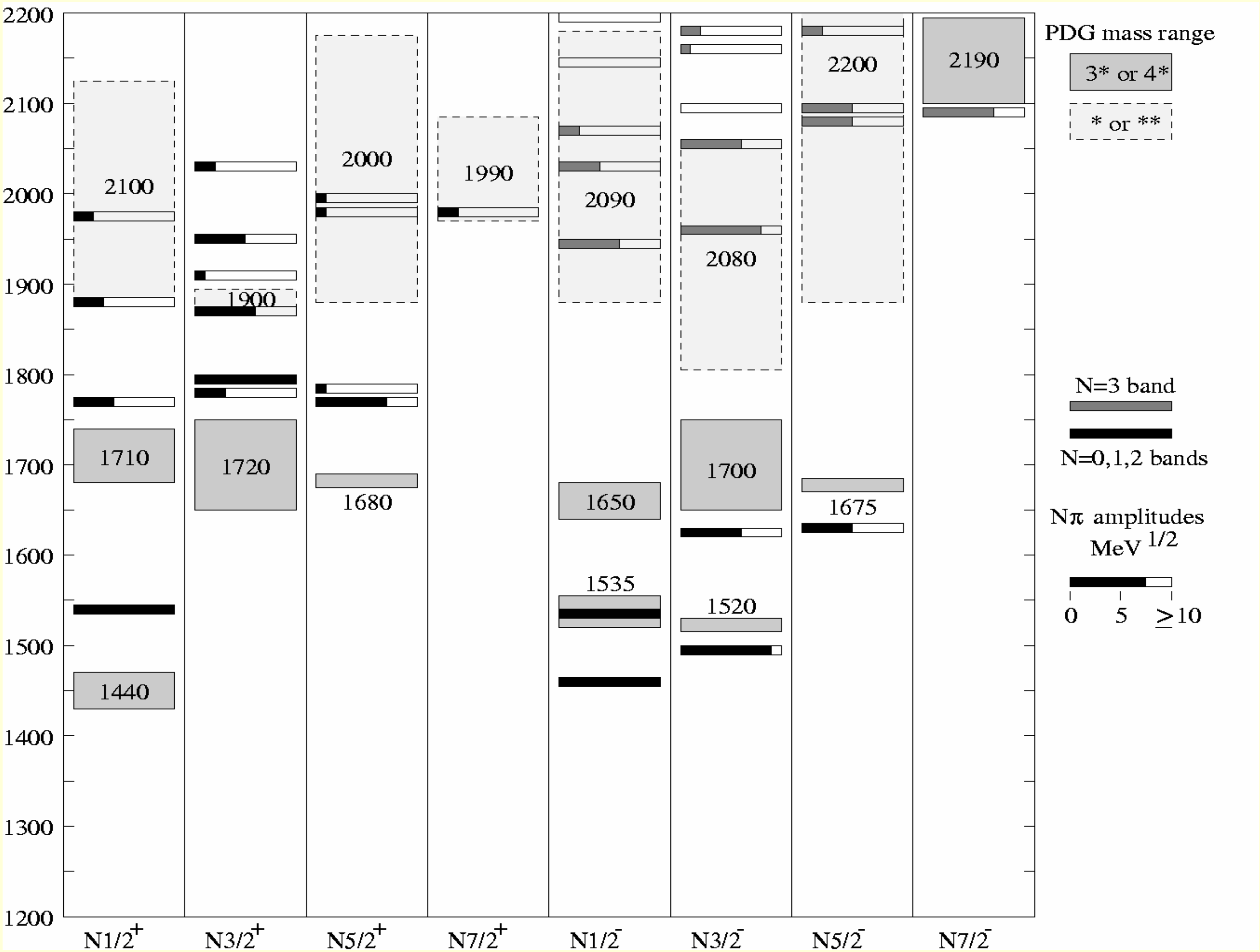


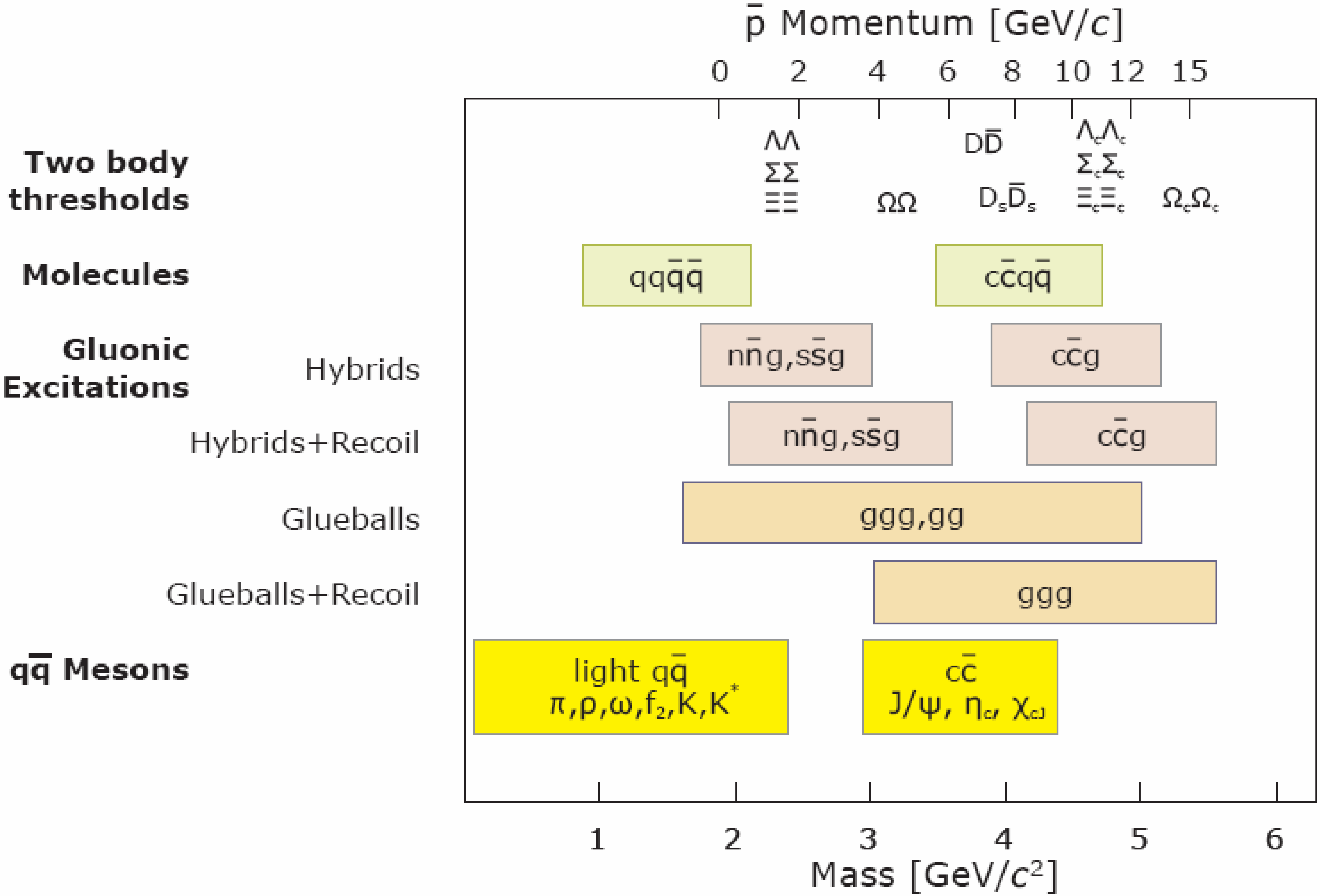
(a) 3q  (b) hybrid  (c) diquark  (d) multi-quark

Predicted states:  (d) > (b) > (a) > (c)

“missing” baryon problem: observed states < (a) predicted states

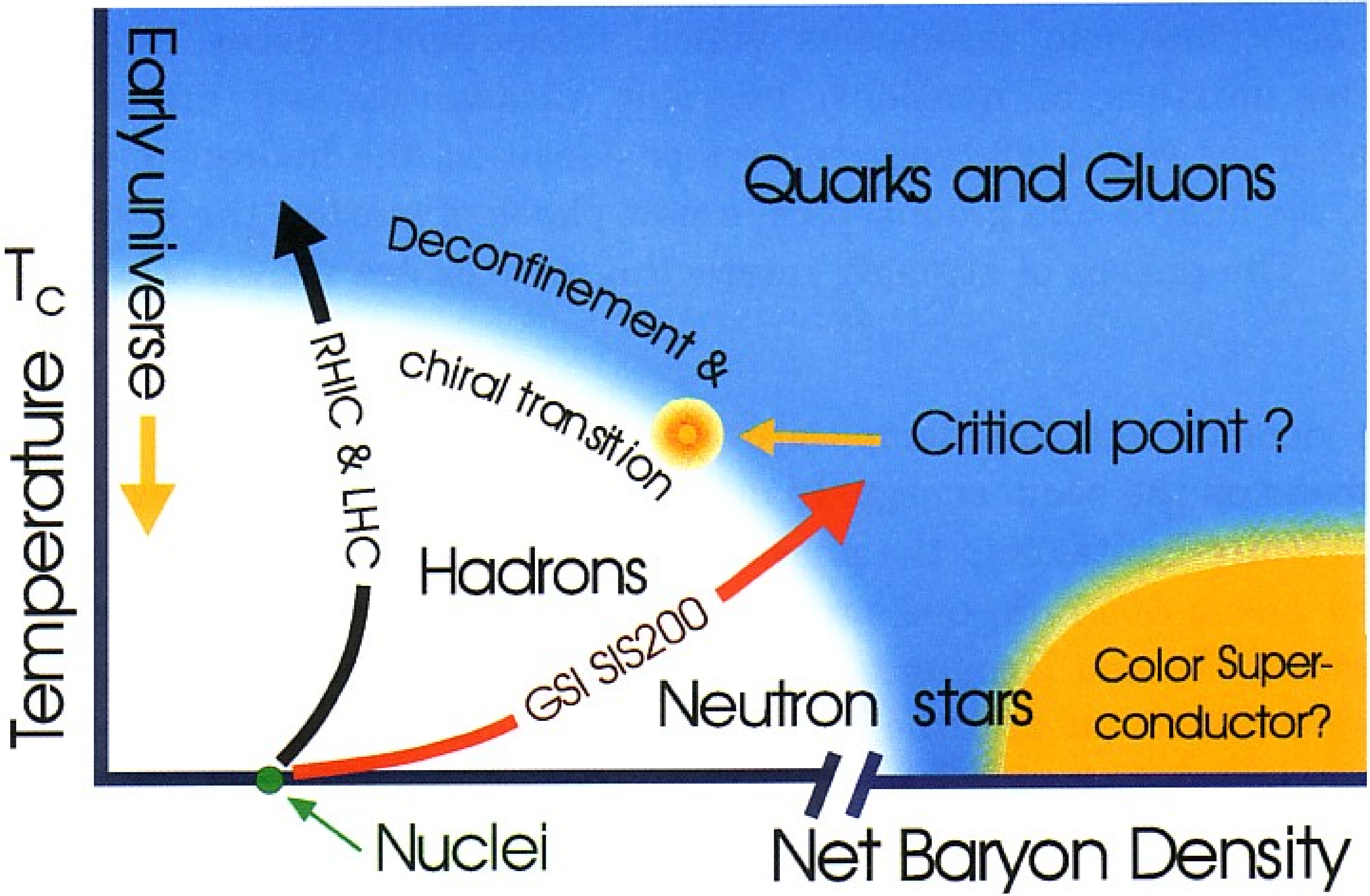
# “Missing” N* Problem Capstick et al.





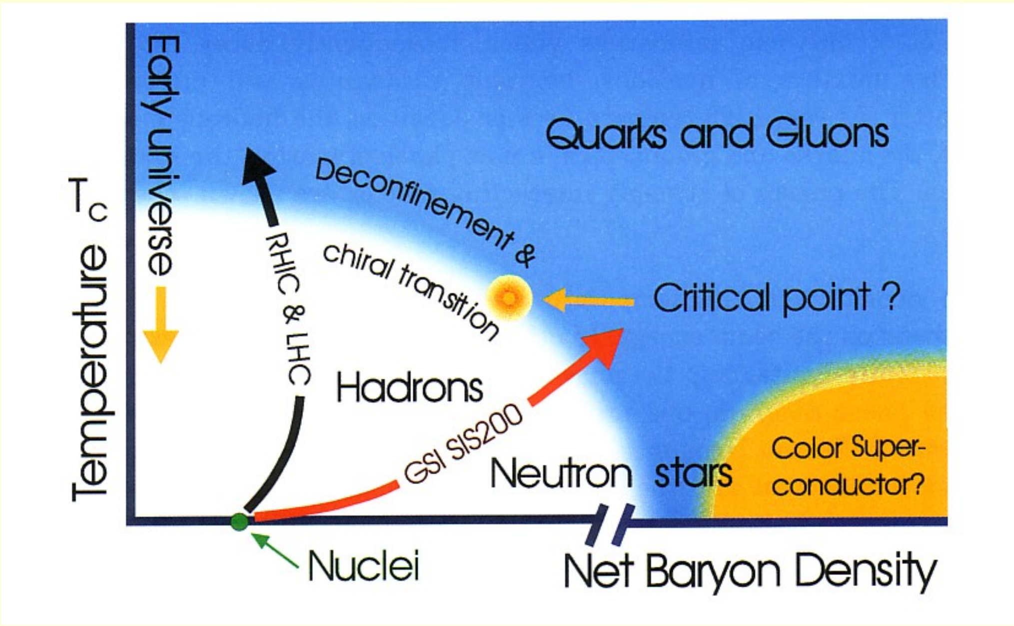
p̄ Momentum [GeV/c]
0 2 4 6 8 10 12 15
Two body thresholds
ΛΛ ΣΣ ΞΞ
ΩΩ
DD̄
D_sD̄_s
Λ_cΛ_c Σ_cΣ_c Ξ_cΞ_c
Ω_cΩ_c
Molecules
qqq̄q̄
cc̄qq̄
Gluonic Excitations
Hybrids
nn̄g,ss̄g
cc̄g
Hybrids+Recoil
nn̄g,ss̄g
cc̄g
Glueballs
ggg,gg
Glueballs+Recoil
ggg
qq̄ Mesons
light qq̄
π,ρ,ω,f_2,K,K*
cc̄
J/ψ, η_c, χ_cJ
1 2 3 4 5 6
Mass [GeV/c²]

# A Phase Diagram for Nuclear Matter

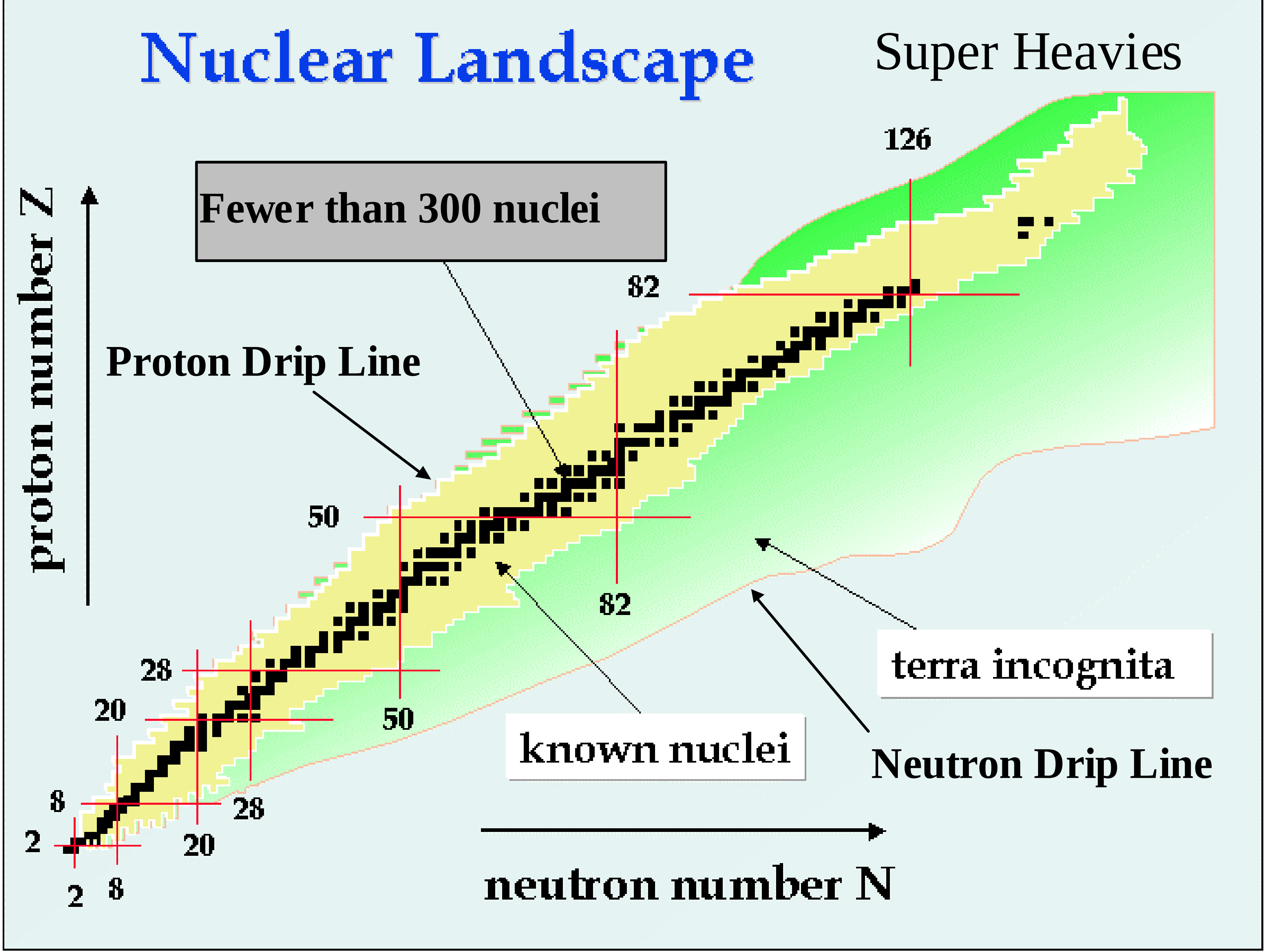


# Nuclear Matter at High Net Baryon Densities

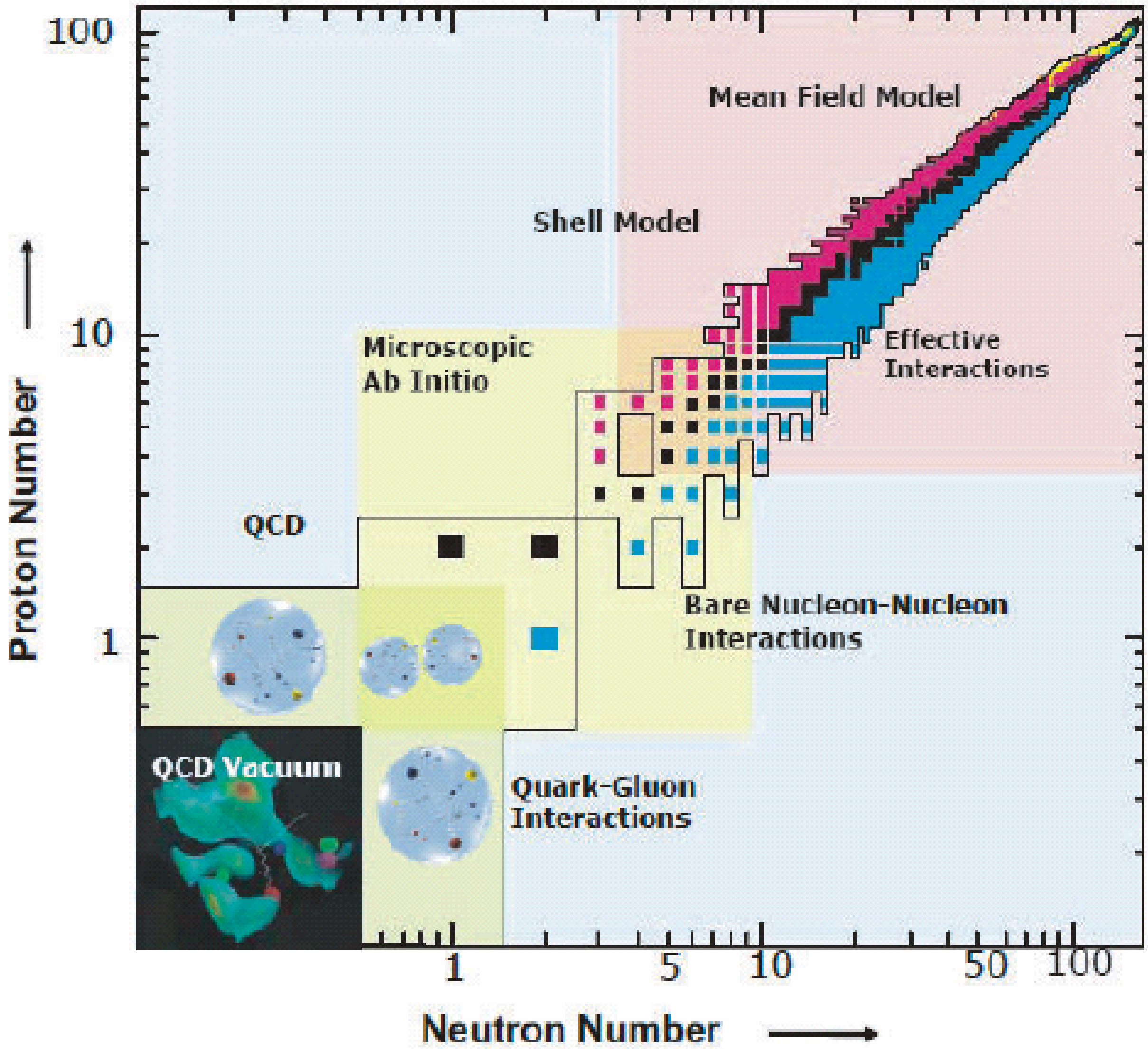
- Our aim has to be to map out this phase digram. The region of high net baryon densities is TERRA INCOGNITA-theoretically and experimentally.
- We can reach it in HI collisions at intermediate energies-moderateT and $\rho$ = 2-5$\rho_{nucl.}$
  - -This is one main focus of theFAIR project where we can study the collisions of heavy nuclei at 2-30 A.GeV
  - -Key observables are electromagnetic probes giving information from centre of the fireball, particularly in-medium properties of hadrons.
- Many questions:-Is modification of hadron properties in dense nuclear medium due to the onset of deconfinement and/or chiral symmetry restoration?
  Is there a phase boundary between hadronic and deconfined matter or is there a smooth cross-over?




- Is there a critical point separating a cross-over transition from a first-order transition?
- Is cold, deconfined matter a colour superconductor?
- What is the effect of high isospin densities?
- ……..???


Nuclear Landscape
Super Heavies
126
Fewer than 300 nuclei
82
proton number Z
Proton Drip Line
50
82
28
50
20
terra incognita
known nuclei
Neutron Drip Line
8
28
2
20
2
8
neutron number N

# The chart of nuclei – a theoretical perspective




- From QCD → effective field theories → nucleon-nucleon forces and mean-field models with effective interactions: small and tedious steps

# Ab-initio Calculations

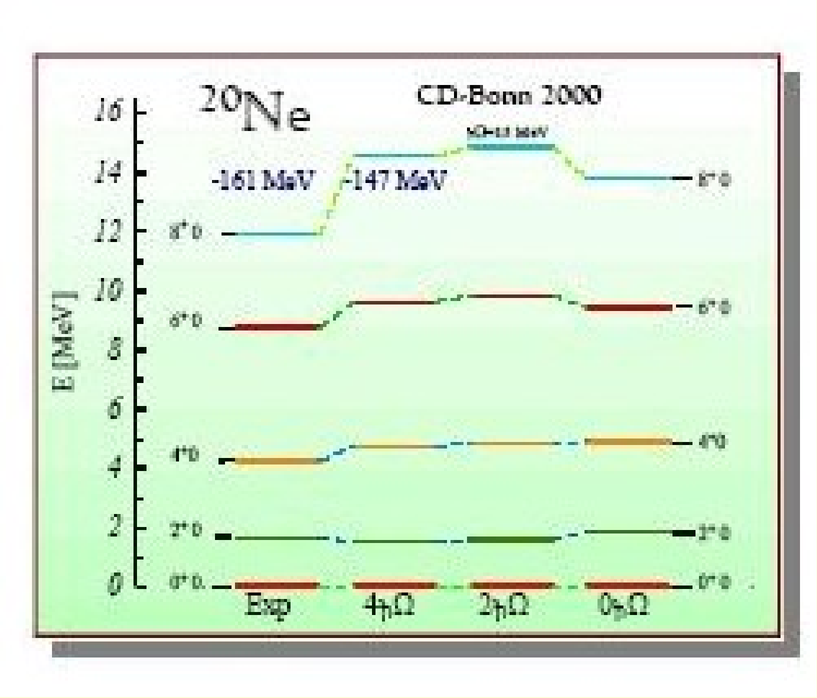
- Goal:-To compute properties of A-nucleon system as an A-body problem with free space interactions that describe nucleon-nucleon(NN) scattering.

They use the fit to large number of measurements of nucleon-nucleon scattering to determine NN interaction

Several approaches needed:
- No direct comparison with experiment
- Need several methods for comparison
- Internal consistency
- Convergence checks for precision.

Three methods so far:
- No Core Shell Model
- Green's function Monte Carlo
- Coupled Cluster Expansion

Next Generation:
- Chiral Effective Field Theories
  (Closer relation to underlying QCD)



# Ab-Initio Calculations

- Realistic two-nucleon potentials highly accurate
  - Coordinate space potentials
    - Local: AV18, AV8', Nijmegen II
    - Nonlocal: Nijmegen I
  - Momentum space nonlocal potentials
    - Boson-exchange potentials: CD-Bonn
    - Effective field theory potentials: $N^3LO$

☜ High Quality

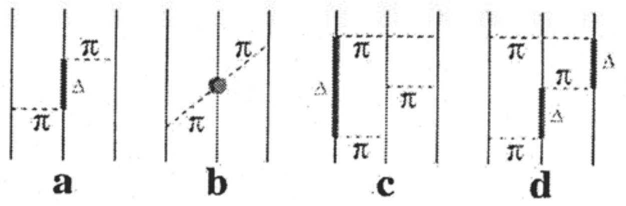
- Exact few-body calculations with these potentials show that $^3$H, $^3$He, $^4$He underbound by 5-10%
- Problems in $A$=3 scattering: p+d, n+d, $A_y$ puzzle
- Nuclear structure calculations with realistic two-nucleon potentials in the $p$-shell
  - GFMC, NCSM, CCM
  - Underbinding
  - Level spacing not quite right
  - Ordering of lowest states not correct for some nuclei

**Regardless of which realistic two-nucleon potential used problems remain:**

**Need to include a three-nucleon interaction**

# $V = V_{ij} + V_{jik}$

$V_{ij}$ = 2 body forces
$V_{ijk}$= 3 body forces

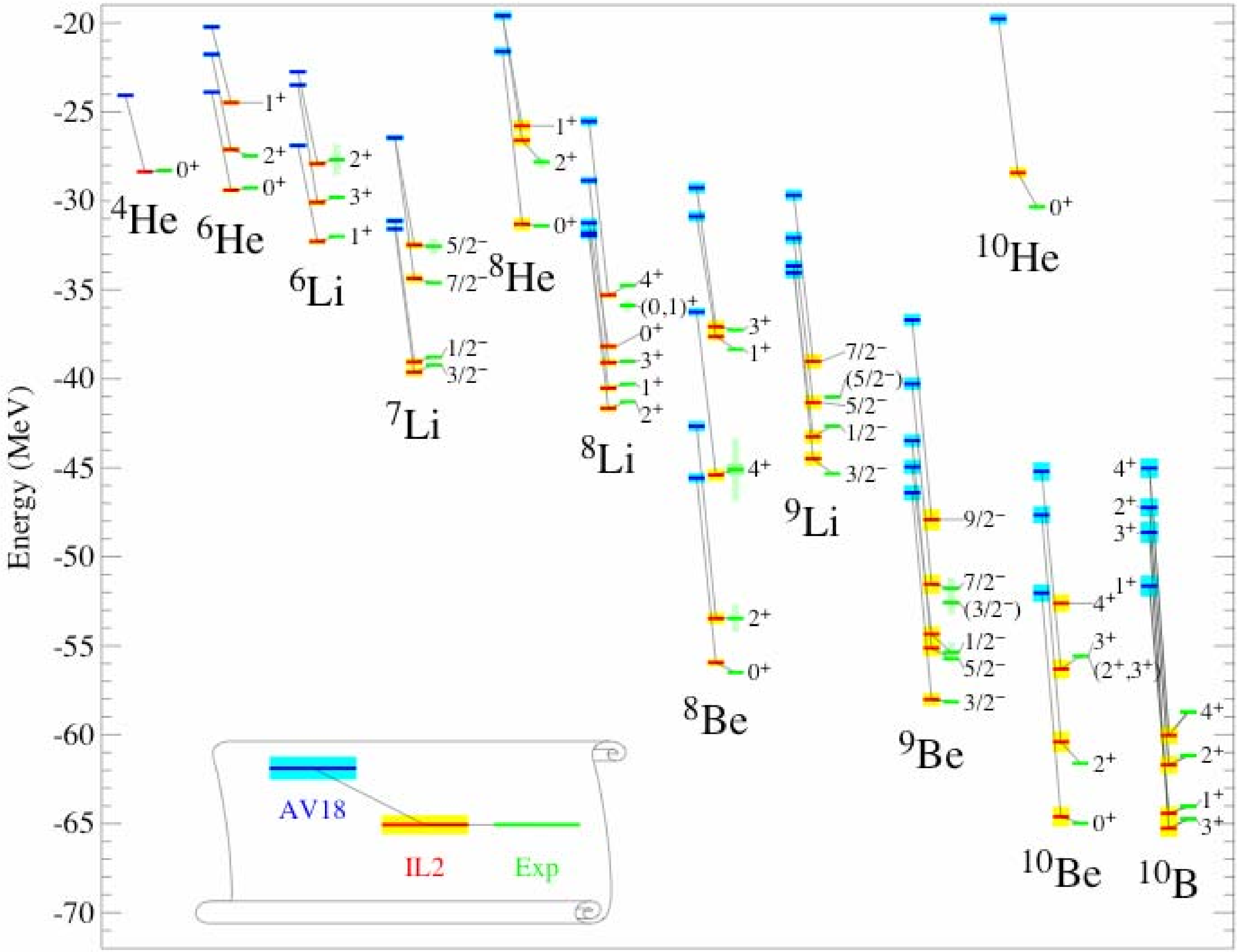



$^4$He : $E_B$ = 24.2-24.5 MeV calculated with 2-body
$E_B$ = 28.3 MeV exp.

Difference 15% !!

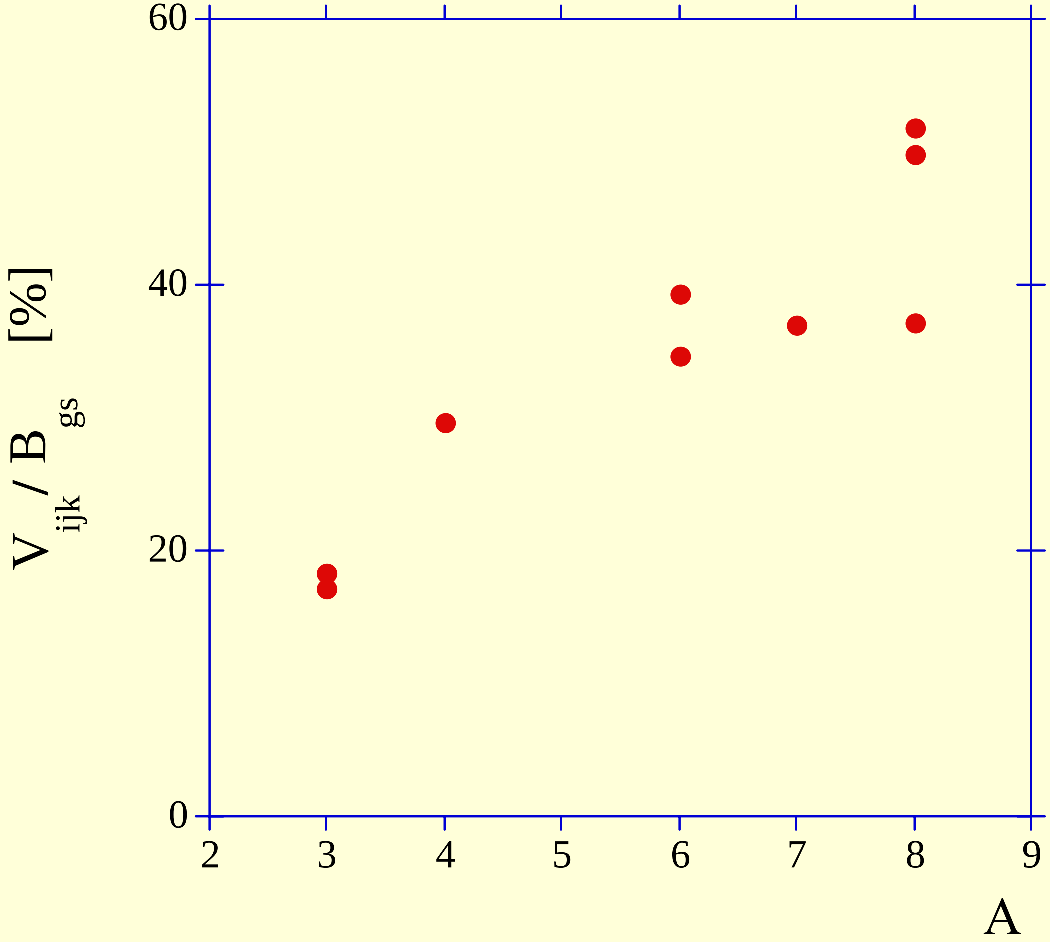
$^4$He : $E_B$ = 28.3-28.8 MeV calculated with 3 body
$E_B$ = 28.3 MeV exp.

Difference ≤1% !!

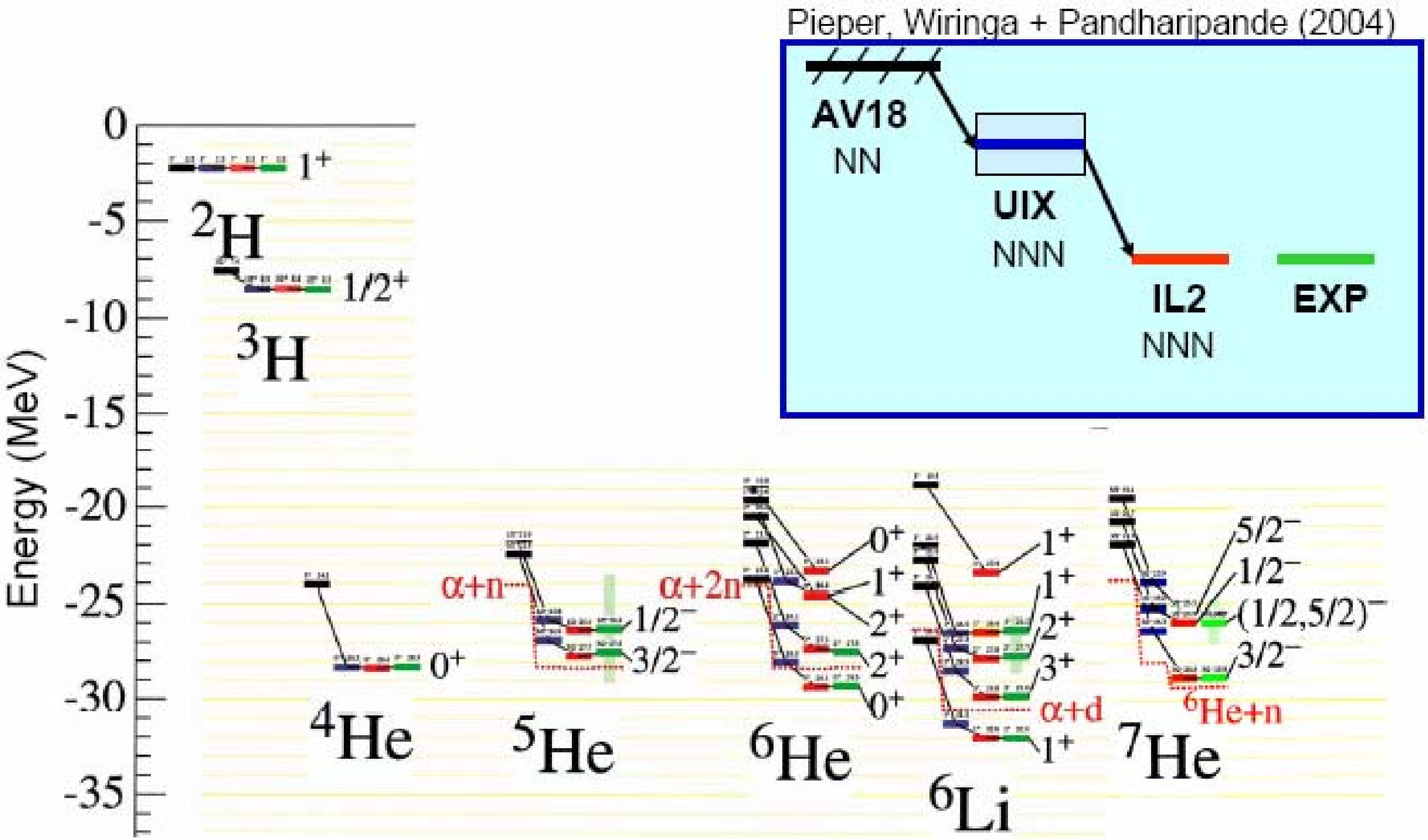


Energy (MeV)
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
4He
6He
6Li
7Li
8He
8Li
8Be
9Li
9Be
10He
10Be
10B
AV18
IL2
Exp

Ratio of three-nucleon potential energies
to experimental binding energies
PRC 64 (2001) 014001



# Today: ab initio quantum Monte Carlo calculations for A ≤ 12



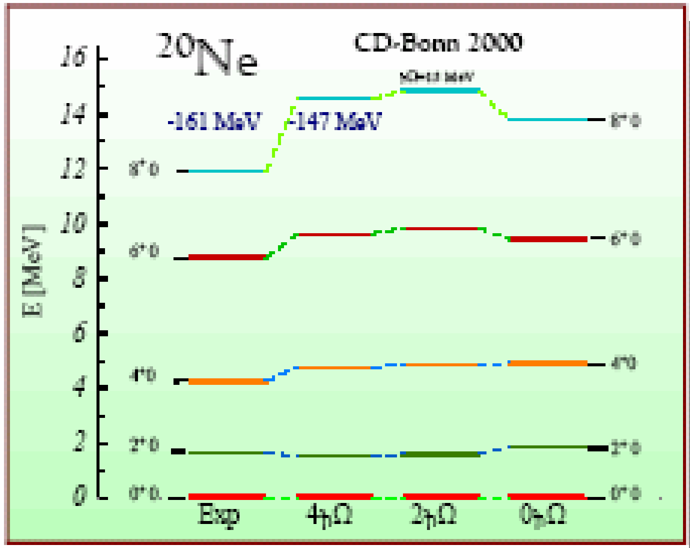

- Effect of NNN forces

# Present Status of Ab-initio Calculations

- *Ab initio* no-core shell model
  - Method for solving the nuclear structure problem for light nuclei
  - Apart from the GFMC the only working method for $A$>4 at present
  - Advantages
    - applicable for any NN potential
    - Effective field theory
    - Easily extendable to heavier nuclei
    - Calculation of complete spectra at the same time
  - Success - importance of three-nucleon forces for nuclear structure

**Work in progress**

- Calculations with realistic three-body forces in the *p*-shell
  - Better determination of the structure of the three-body force itself
- Coupling of the NCSM to nuclear reactions theories
  - Direct reactions
    - Density from NCSM plus folding approaches
  - Low-energy resonant and nonresonant reactions
    - RGM-like approach
      - Exotic nuclei: RIA
      - Thermonuclear reaction rates: Astrophysics




**Future plans**

- Extensions to heavier nuclei
  - Effective interaction for valence nucleons
    - RIKEN, RIA

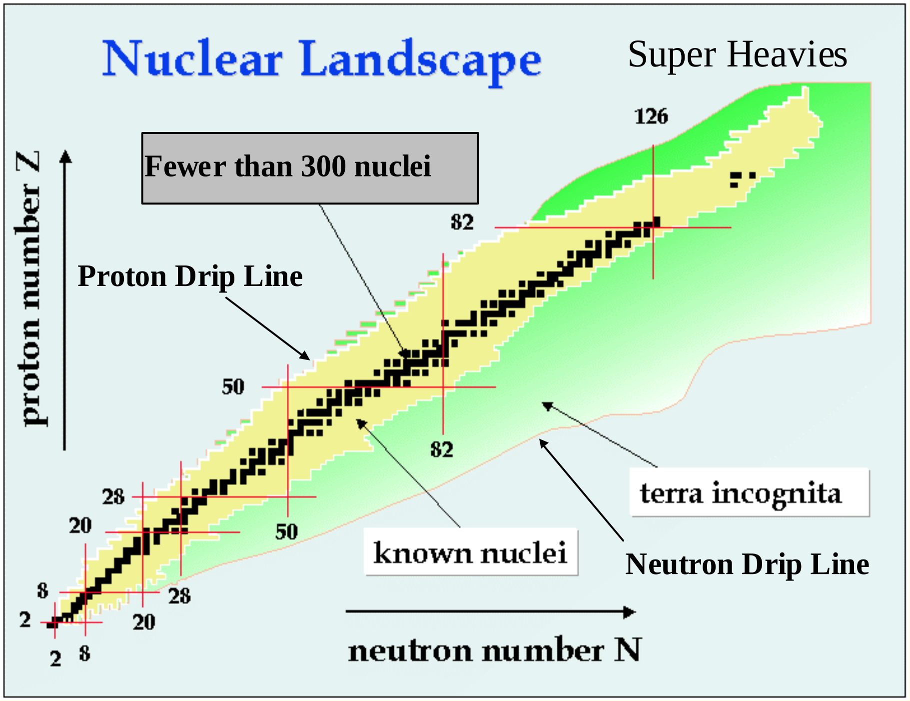
# What is the structure of nucleonic matter?

Goal: to determine nuclear properties over a wide range of N,Z,I,T,$\omega$ and find a consistent theoretical framework to describe the phenomena observed.

There are many unanswered questions:

- The Limits of nuclear existence?
- The emergence of new quantum ordering in highly dilute, neutron-rich matter.
- The emergence of new forms of nuclear matter in very loosely bound systems
- Can we find a consistent theoretical framework that spans from few-body-many body systems of nucleons?
- Do the symmetries seen in near-stable nuclei appear far from stability?
- …..????

# The Limits of Nuclear Existence




- Challenge: What are the limits of of nuclear existence?Where are the drip-lines? What is the last element we can make?

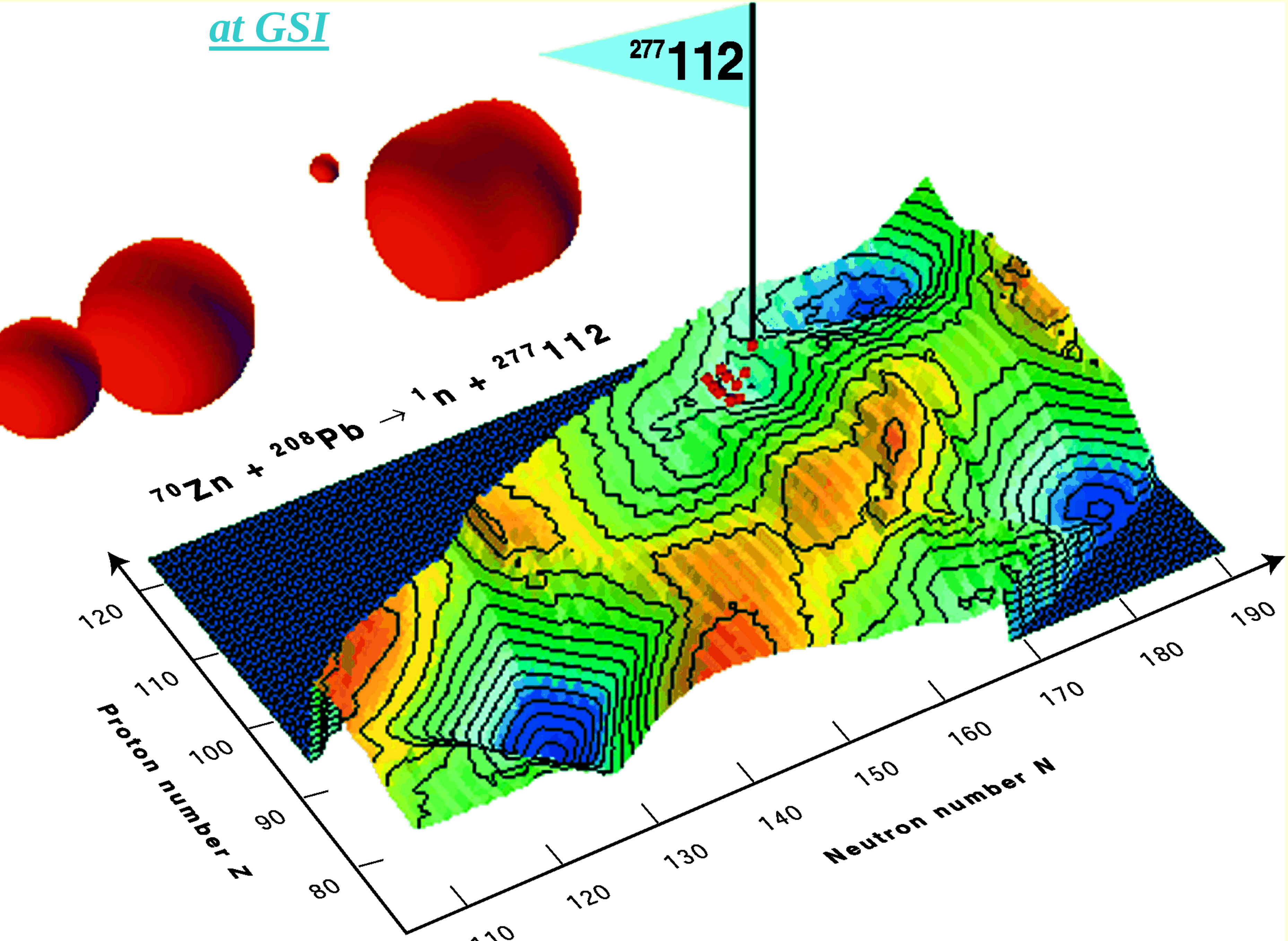
- We know that Shell structure stabilises the heaviest elements against fission and alpha decay.

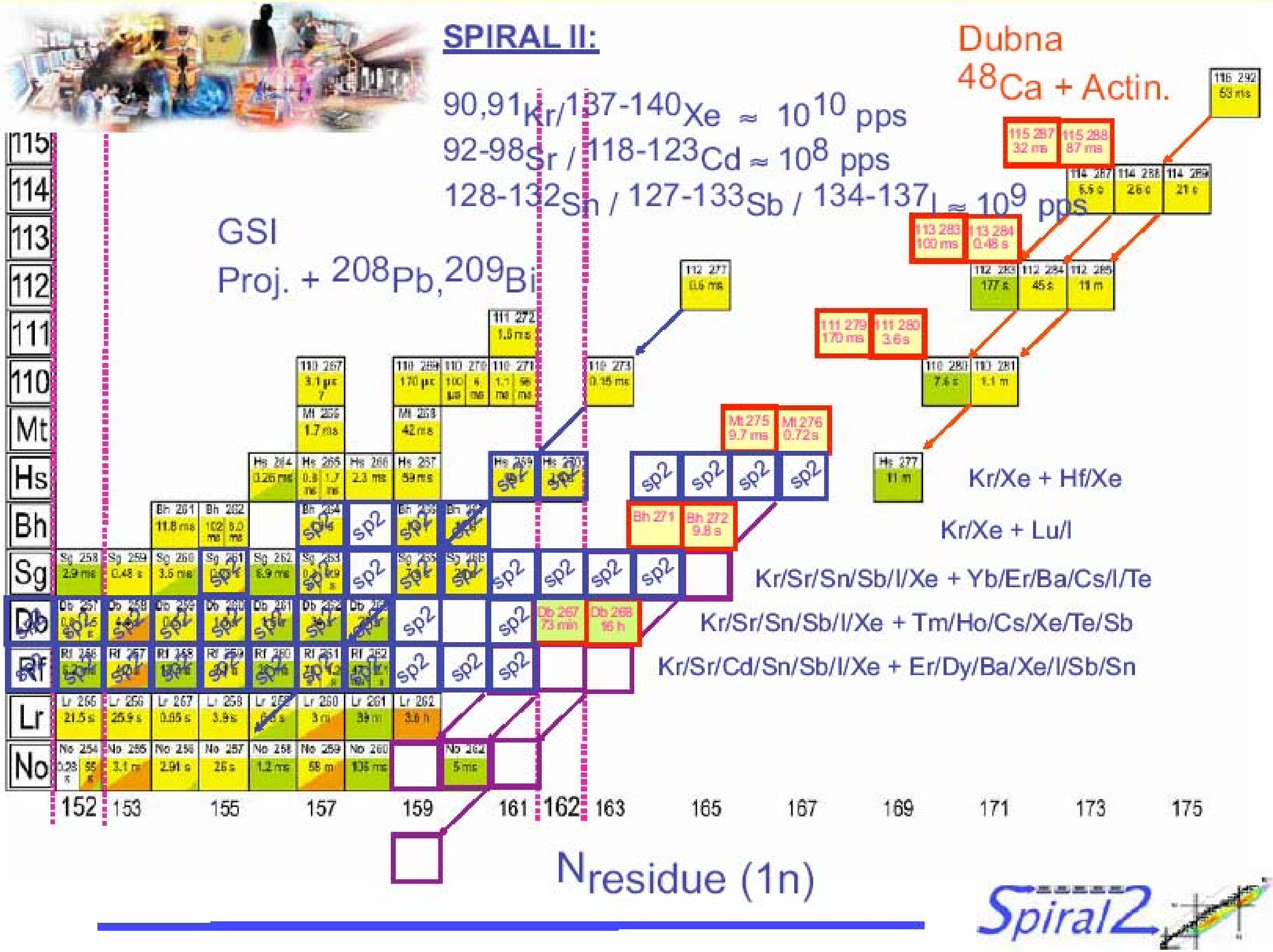
- We have solid evidence of the elements up to 112 and over the last couple of years the Russians have produced evidence of Z = 113-116 in reactions such as $^{244}$Pu($^{48}$Ca,xn), $^{245}$Cm($^{48}$Ca,xn), and $^{243}$Am($^{48}$Ca,xn).

- Oganessian et al.Phys.Rev.C69 (2004)054607--Z = 114 & 116

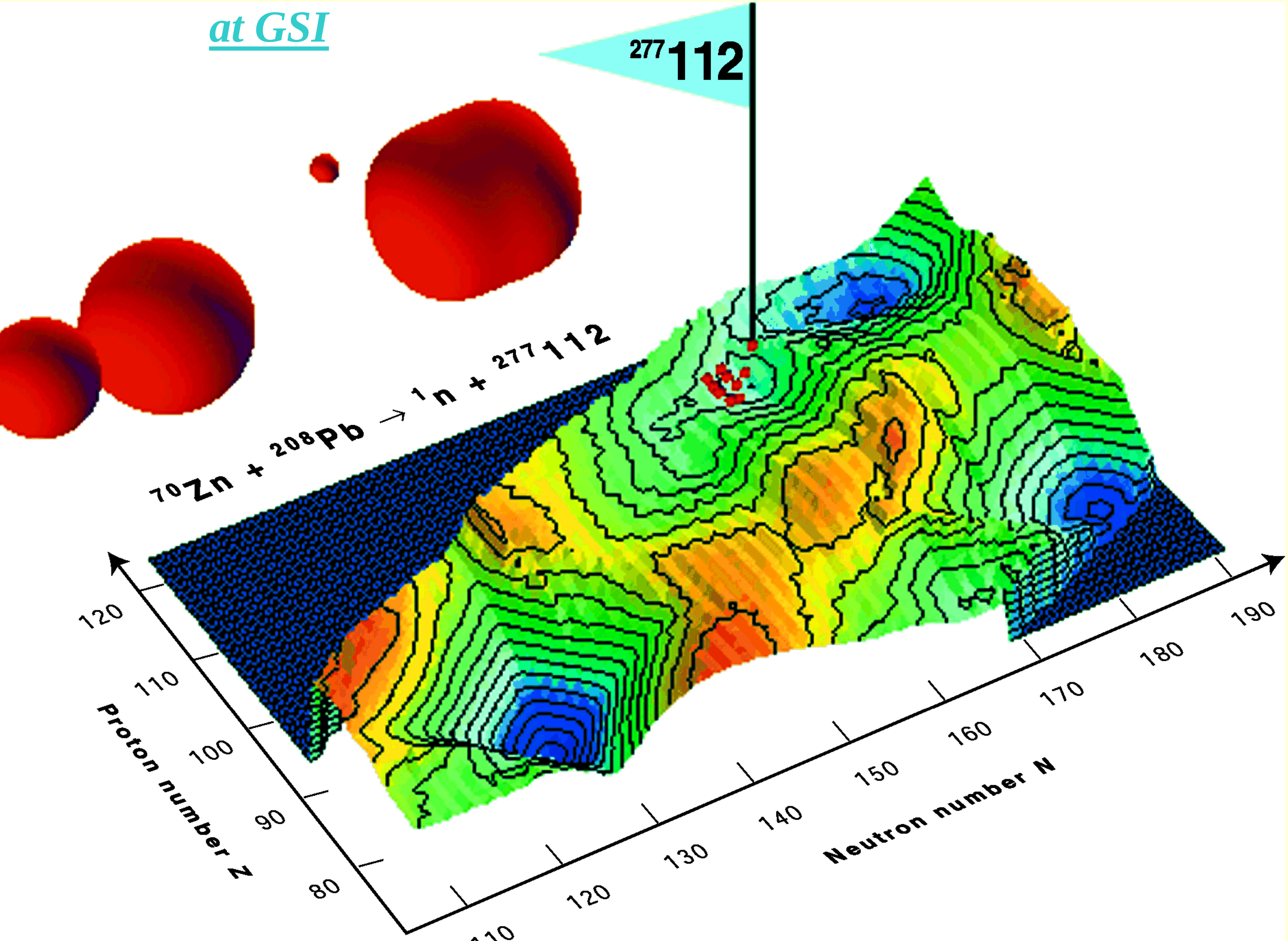
- Oganessian et al.Phys.Rev.C69 (2004)021601--Z = 113 & 115

# Creeping up on the Superheavies at GSI



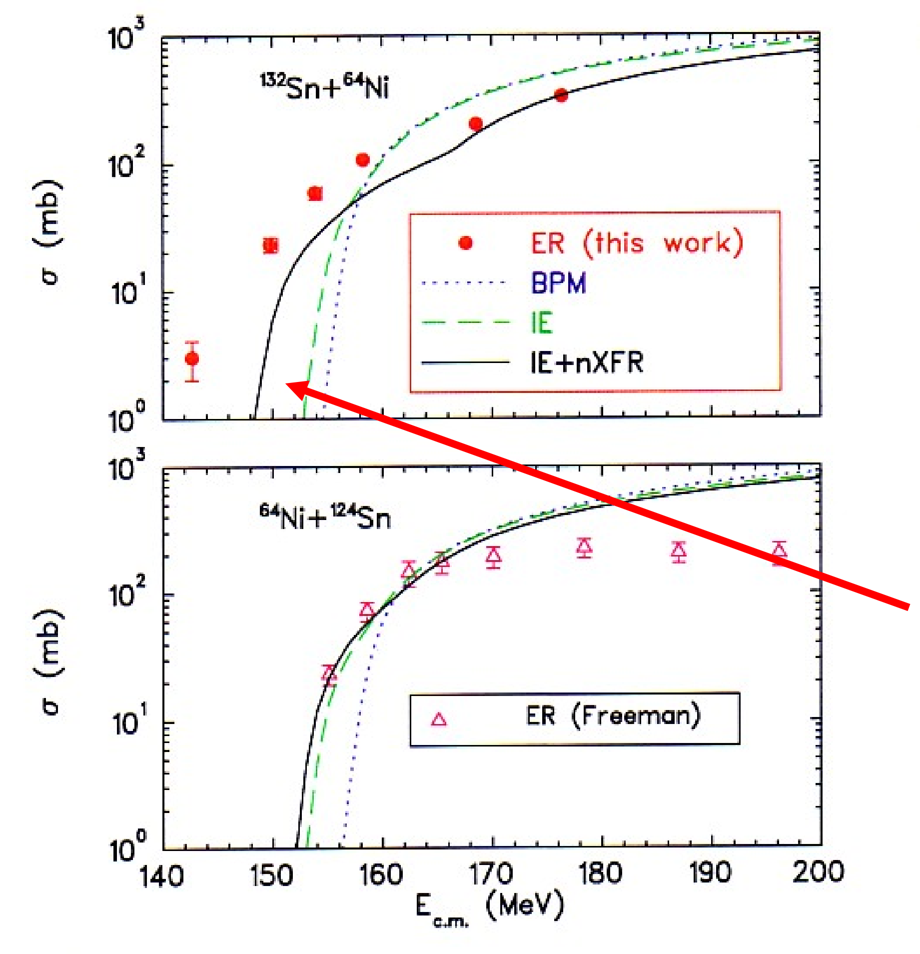

SPIRAL II:
90,91Kr/137-140Xe ≈ 10^10 pps
92-98Sr / 118-123Cd ≈ 10^8 pps
128-132Sn / 127-133Sb / 134-137I ≈ 10^9 pps
GSI
Proj. + 208Pb,209Bi
Dubna
48Ca + Actin.
Kr/Xe + Hf/Xe
Kr/Xe + Lu/I
Kr/Sr/Sn/Sb/I/Xe + Yb/Er/Ba/Cs/I/Te
Kr/Sr/Sn/Sb/I/Xe + Tm/Ho/Cs/Xe/Te/Sb
Kr/Sr/Cd/Sn/Sb/I/Xe + Er/Dy/Ba/Xe/I/Sb/Sn
115
114
113
112
111
110
Mt
Hs
Bh
Sg
Db
Rf
Lr
No
152
153
155
157
159
161
162
163
165
167
169
171
173
175
sp2
116 292 53 ms
115 287 32 ms
115 288 87 ms
114 287 5.5 s
114 288 2.6 s
114 289 21 s
113 283 100 ms
113 284 0.48 s
112 277 0.6 ms
112 283 177 s
112 284 45 s
112 285 11 m
111 272 1.8 ms
111 279 170 ms
111 280 3.6 s
110 267 3.1 µs
110 269 170 µs
110 273 0.15 ms
110 280 7.6 s
110 281 1.1 m
Mt 266 1.7 ms
Mt 268 42 ms
Mt 275 9.7 ms
Mt 276 0.72 s
Hs 264 0.26 ms
Hs 266 2.3 ms
Hs 267 59 ms
Hs 277 11 m
Bh 261 11.8 ms
Bh 271
Bh 272 9.8 s
Sg 258 2.9 ms
Sg 259 0.48 s
Sg 260 3.6 ms
Sg 262 6.9 ms
Db 267 73 min
Db 268 16 h
Lr 255 21.5 s
Lr 256 25.9 s
Lr 257 0.65 s
Lr 258 3.9 s
Lr 260 3 m
Lr 261 39 m
Lr 262 3.6 h
No 254
No 255 3.1 m
No 256 2.91 s
No 257 25 s
No 258 1.2 ms
No 259 58 m
No 260 106 ms
No 262 5 ms
Nresidue (1n)
Spiral2

# Creeping up on the Superheavies at GSI



# The Limits of Nuclear Existence

- Challenge: To create elements 112-116 and beyond.




J.F.Liang et al.,PRL91(2003)152701

- Two routes:Cold and hot fusion

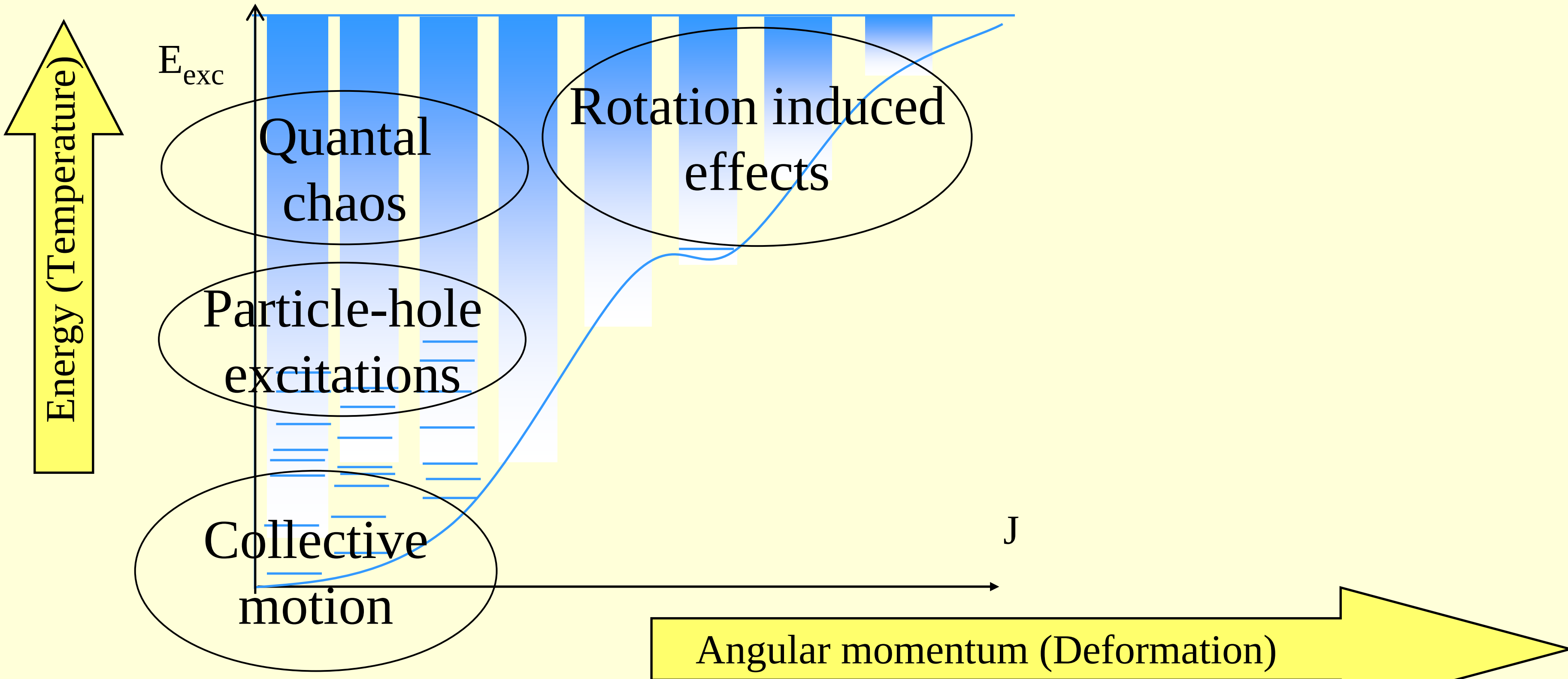
- Question:Will n-rich projectiles allow us to approach closer to the anticipated centre of the predicted Superheavy nuclei.

- There is some evidence that extra neutrons enhance fusion below the barrier.The figure shows studies at Oak Ridge with 2 x $10^4$ pps where it is clear that there is a large enhancement below the barrier.

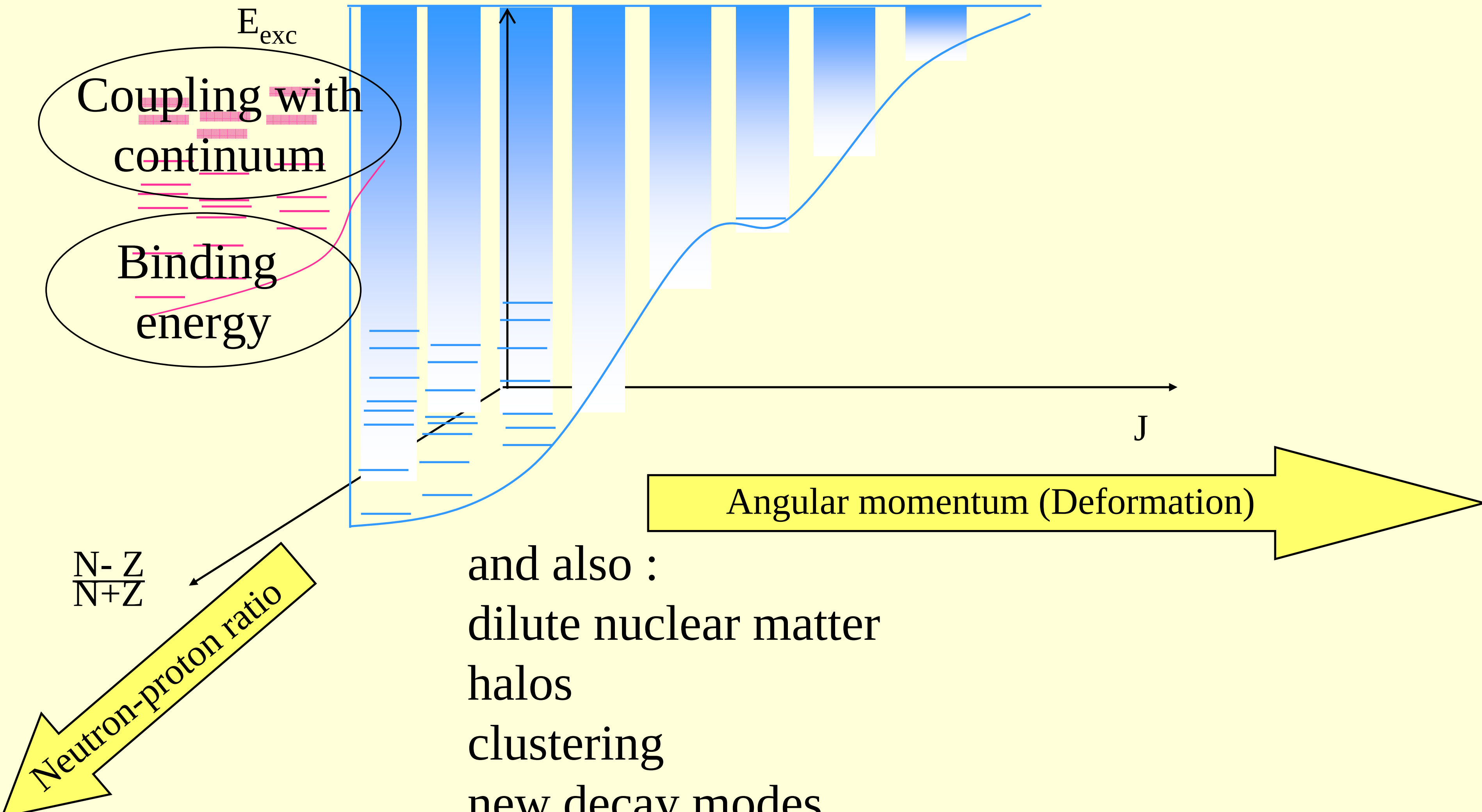
- RNBs may allow us to approach the spherical N=184 shell.

In contrast to other mesoscopic systems the atomic nucleus can be excited and observed in a very clean way.

Chart of nuclear excitations.



Radioactive Ion Beams (RIBs) add a new axis to this chart. It will allow the manipulation of one important degree of freedom in atomic nuclei.



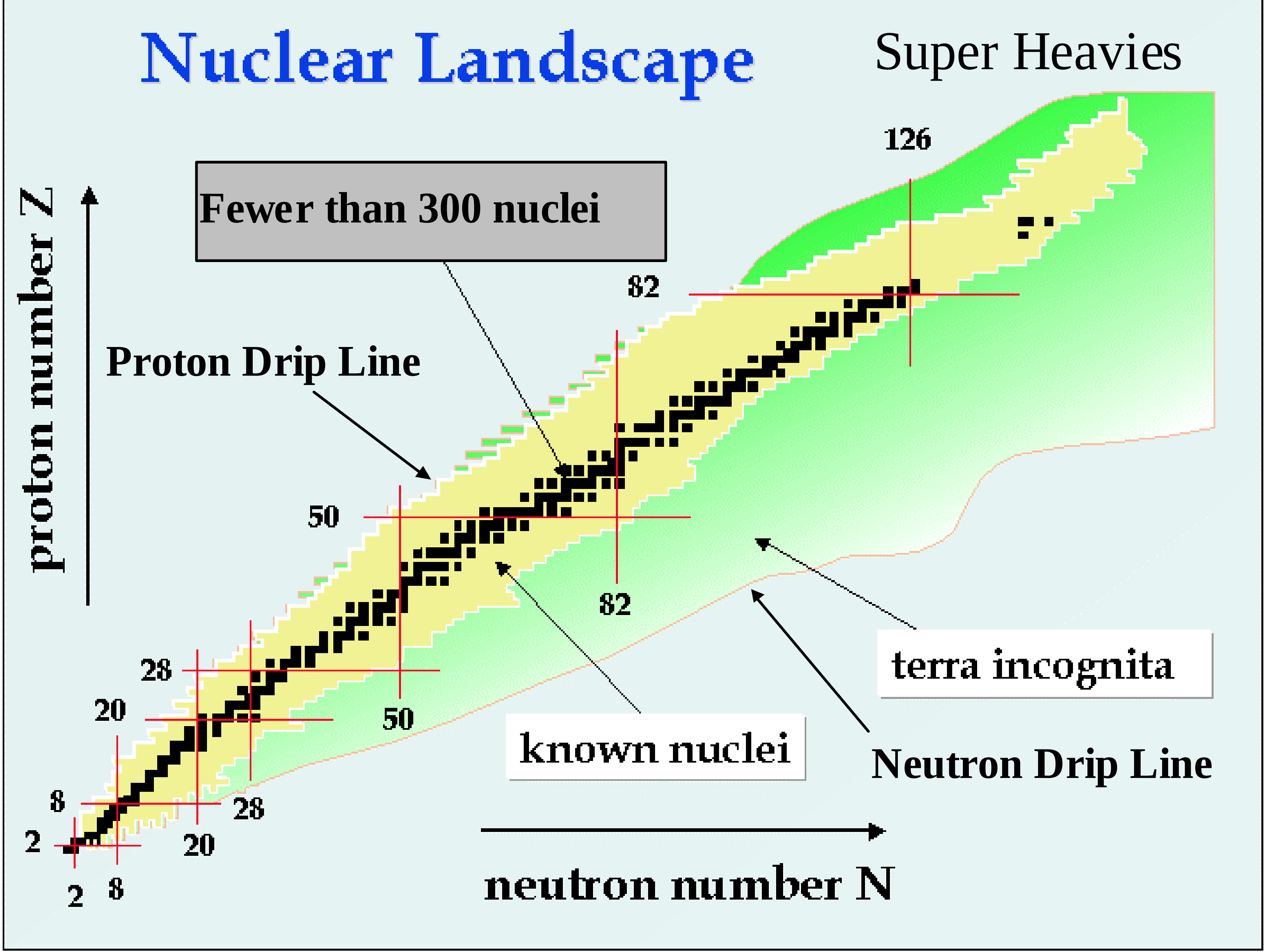

and also :

dilute nuclear matter

halos

clustering

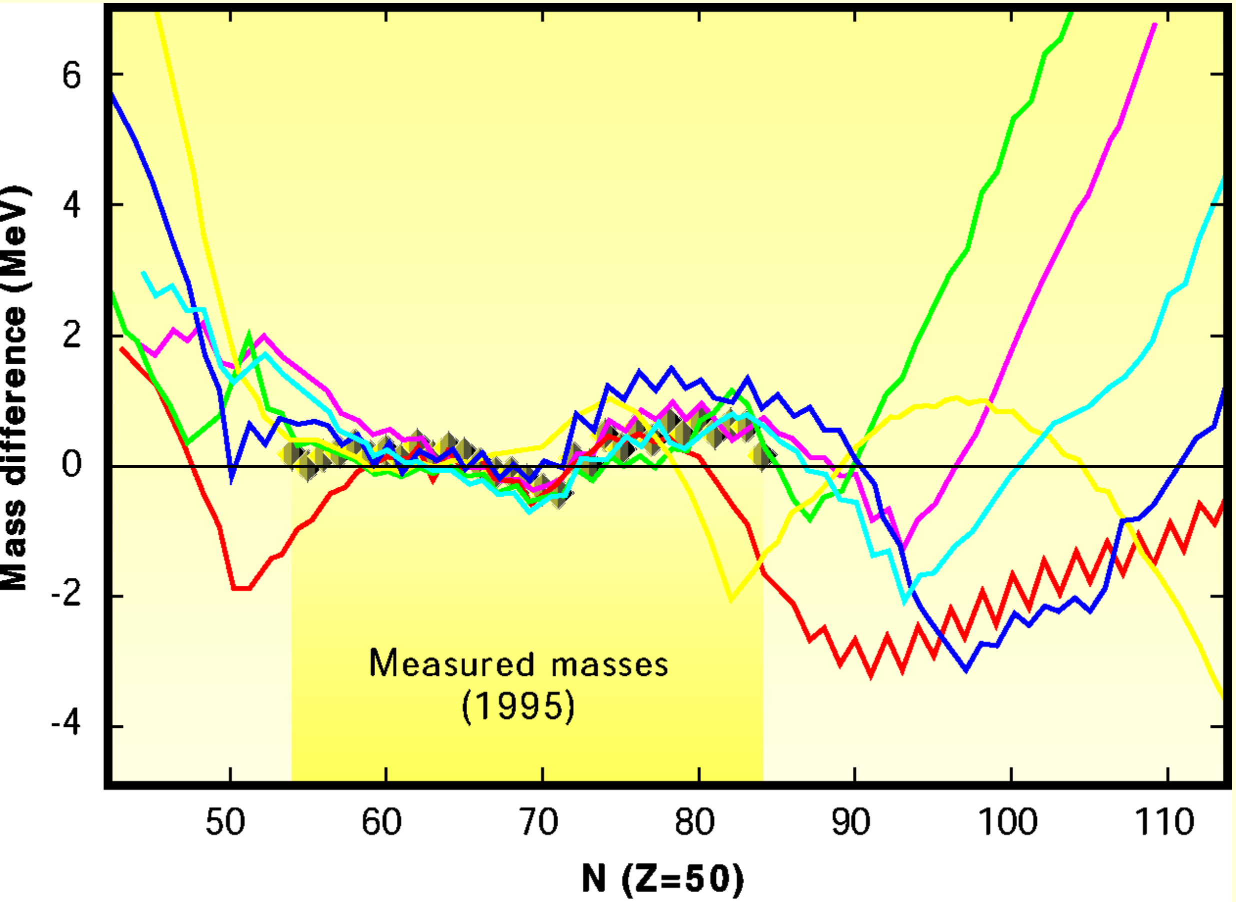
new decay modes


Nuclear Landscape
Super Heavies
126
Fewer than 300 nuclei
82
proton number Z
Proton Drip Line
50
82
28
20
50
8
28
2
20
2
8
terra incognita
known nuclei
Neutron Drip Line
neutron number N

# ***The Drip-lines-Where are they?***

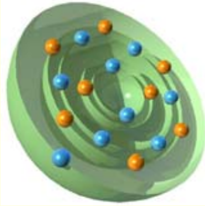
• We now have a reasonably good idea of where the proton drip-line lies but we still have little idea about the neutron drip-line.

• The figure shows the masses of the Sn(Z = 50) isotopes fitted to a range of different mass formulae.all is well where we have measured masses but we get widely differing predictions for the drip-lines.

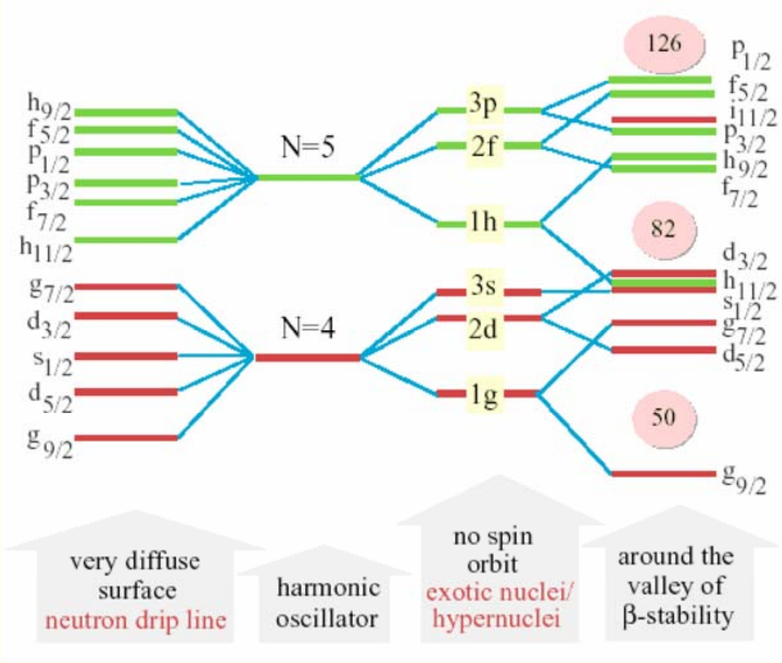



CHALLENGE:
To measure the masses as far from stability as possible to try to determine where the drip-line lies.

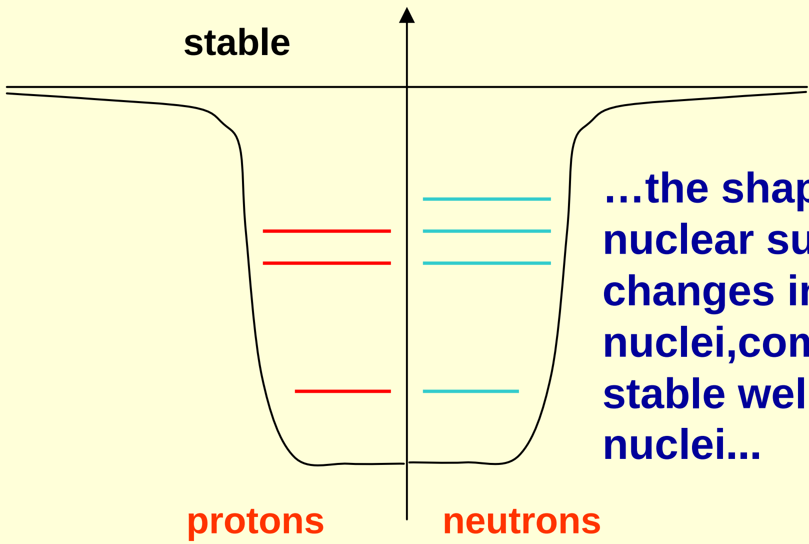
# Evidence for shell structure



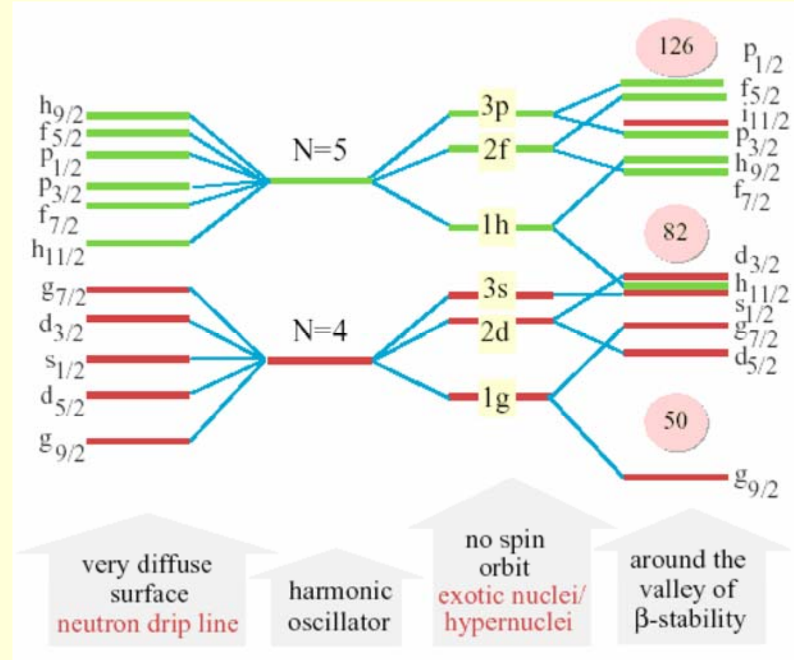
- Evidence for nuclear shell structure from
  - $2^+$ in even-even nuclei [$E_x$, $B(E2)$].
  - Nucleon-separation energies & nuclear masses.
  - Nuclear level densities.
  - Reaction cross sections.
- *Is nuclear shell structure modified away from the line of stability?*



# Shell Structure far from Stability

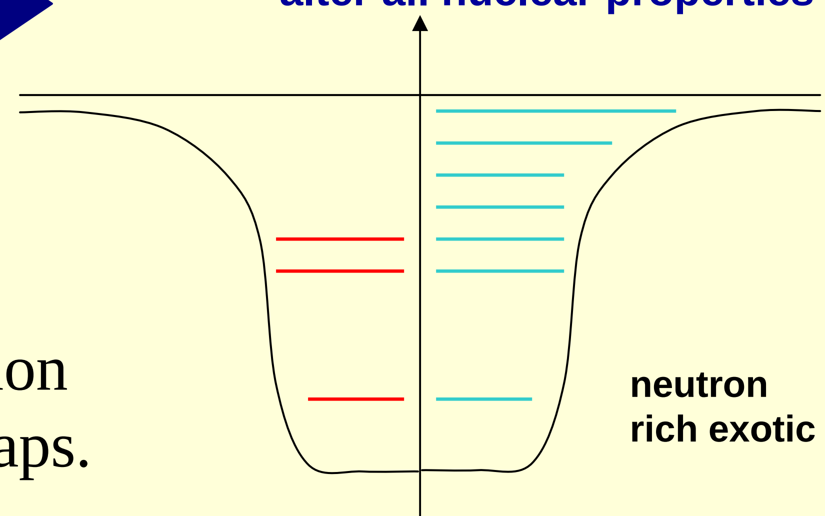



**…the shape of the nuclear surface changes in exotic nuclei,compared to stable well-known nuclei…**



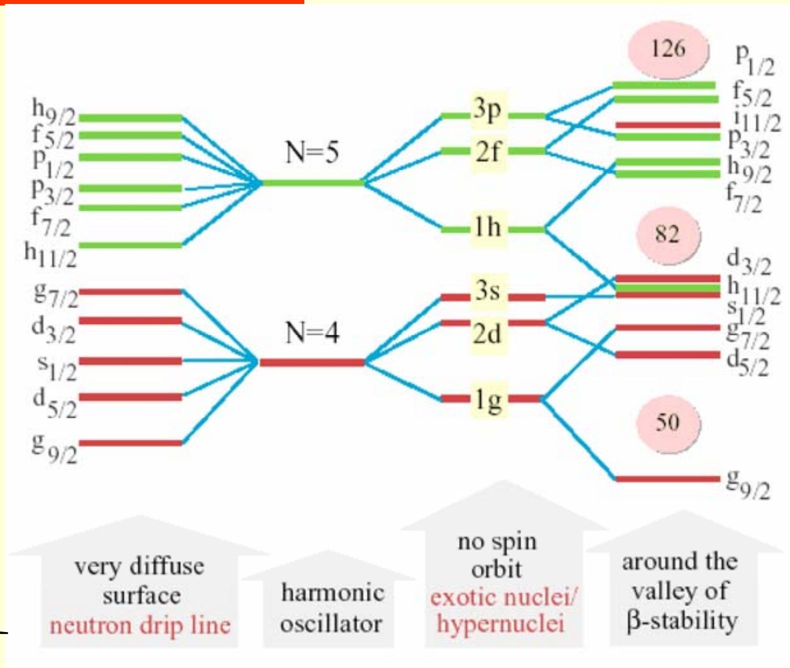

**…this changes the quantum levels and hence can radically alter all nuclear properties**

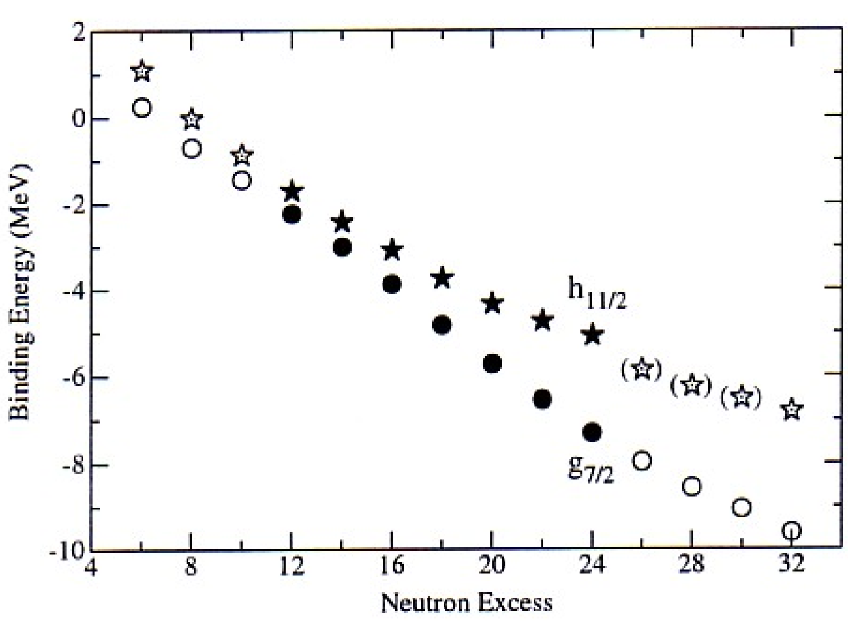
The “Magic Numbers” in heavy nuclei are due to the l.s interaction which pushes down the higher ang. mom. State. In the n-rich nuclei the lower surface density means that we anticipate a weakening of this interaction and, hence, a weakening of the shell gaps.



# *Shell Structure far from Stability*

- Do we have any evidence for the weakening of shell structure with neutron excess?
- The Sn(Z = 50) nuclei have a long range of stable isotopes. The (α,t) reaction has been studied by J.P.Schiffer et al,PRL92(2004)162501




- They measured the positions and purity of the single proton states outside the $^{132}$Sn (Z = 50)closed shell.
- They observe a widening gap and hence a reduction in shell gap.

- Challenge:Can we determine and understand the s.p. structure in n-rich nuclei.

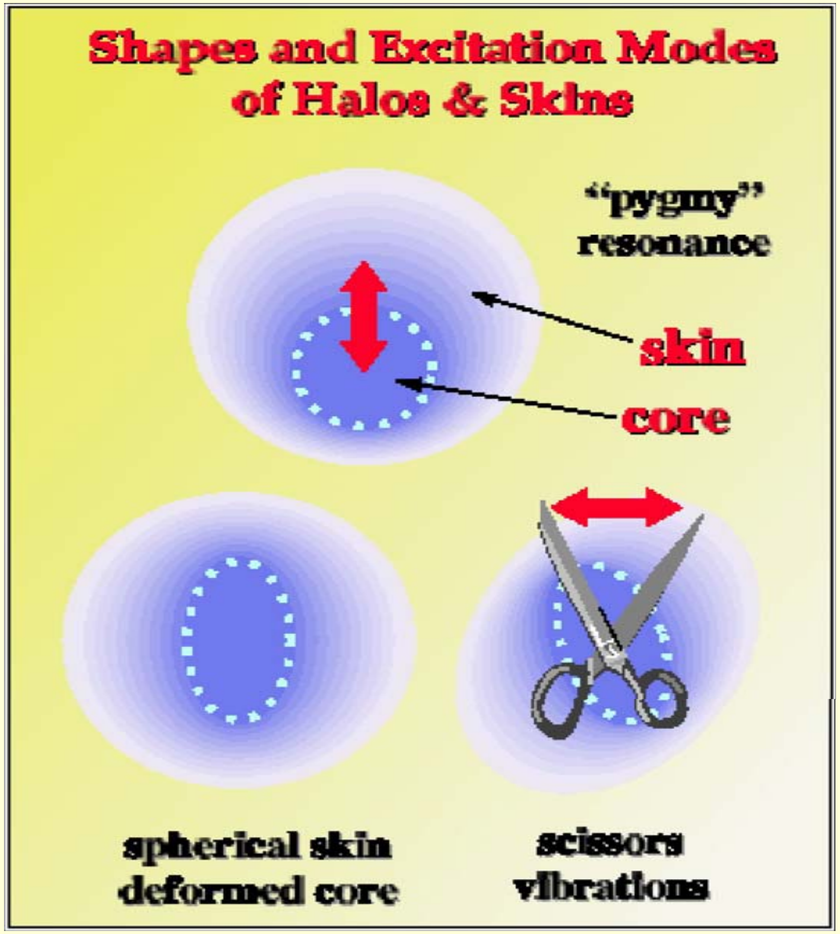
# *Collective Modes*

- Atomic nuclei display a variety of collective modes in which an assembly of neutrons moves coherently [e.g Low-lying vibrations and rotations.

- **Challenge**:Will new types of collective mode be observed in neutron-rich nuclei in particular?

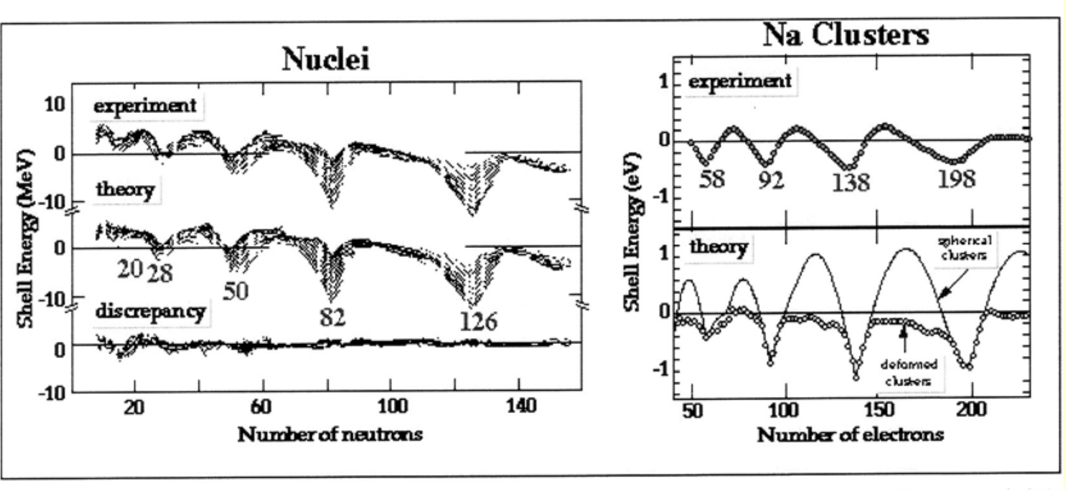
- Will the nucleus become a three-fluid system-made up of a proton and neutron core plus a skin of neutrons?

We will then get collective modes in which the skin moves relative to the core.



# Nuclei seen from a different point of view-Common themes and challenges

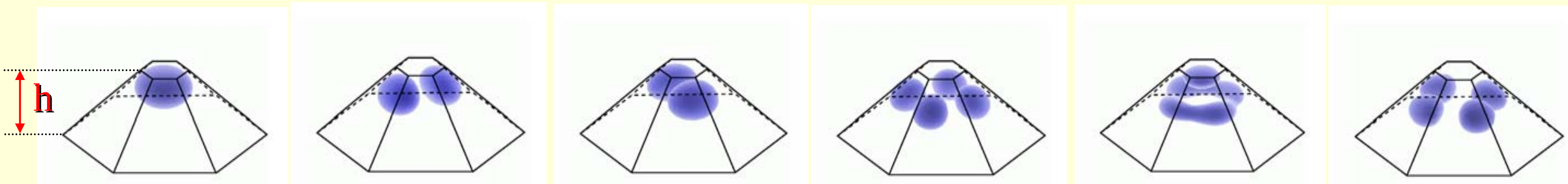
- ***How are complex systems built from a few,simple ingredients?***
  **-Universe appear complex but is made from a small no. of objects**
  **-They obey simple physical laws and interact via a few forces.**
- Nuclei are femtostructures but share much with quantum nanostructures
- Nuclei have much in common with metallic clusters,quantum dots and grains, atom condensates, droplets and surface structures etc.
- These quantum systems share common phenomena although they are on different energy scales-nuclear MeV,molecular eV,solid state meV
- Among the common topics we find Shell structures, pairing and the existence of collective modes of motion




- Nuclei=Two-fluid system,finite N interacting via strong,short-range force

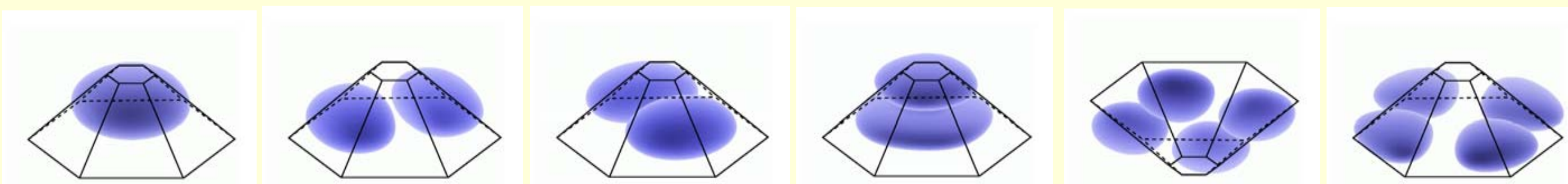
# Electron States

## Large dot   h=3.6 nm




| | | | | | |
|---|---|---|---|---|---|
| E1=3.222 eV | E2=3.395 eV | E3=3.400 eV | E4=3.556 eV | E5=3.575 eV | E6=3.621 eV |
| [3.231] | [3.405] | [3.409] | [3.564] | [3.584] | [3.630] |

## Small dot   h=1.8 nm



| | | | | | |
|---|---|---|---|---|---|
| E1=3.798 eV | E2=4.145 eV | E3=4.161 eV | E4=4.312 eV | E5=4.445 eV | E6=4.572 eV |
| [3.822] | [4.173] | [4.179] | [4.333] | [4.466] | [4.591] |

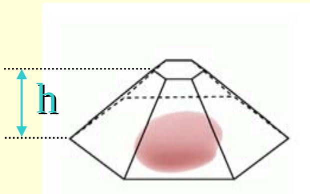
Surfaces correspond to $|\Psi|^2$=const=0.01 nm$^{-3/2}$

Energies  in brackets are for the dot without dislocation

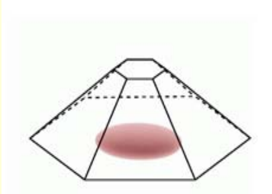
Alexei Andreev(University of Surrey)

# Hole States

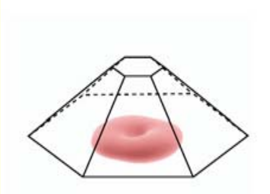
## Large dot h=3.6 nm



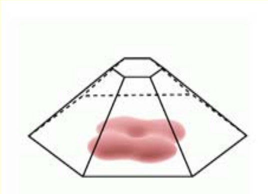

H1=0.501 eV [0.497]



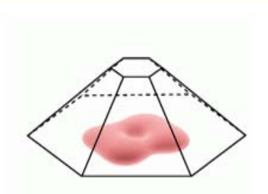
H2=0.497 eV [0.494]



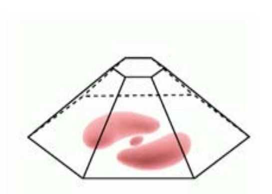
H3=0.475 eV [0.472]



H4=0.452 eV [0.448]

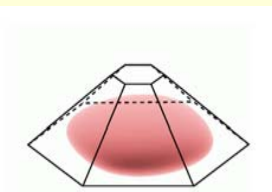


H5=0.445 eV [0.441]

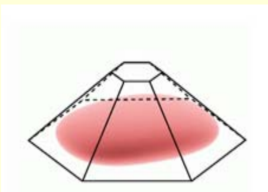


H6=0.424 eV [0.421]

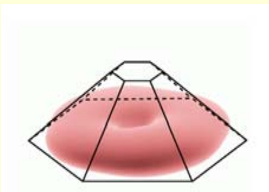
## Small dot h=1.8 nm



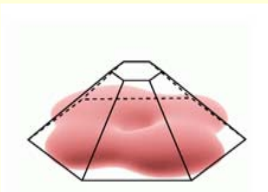
H1=0.063 eV [0.053]



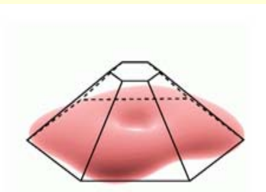
H2=0.058 eV [0.049]



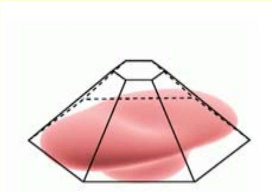
H3=0.015 eV [0.008]



E4=-0.011 eV [-0.020]



H5=-0.019 eV [-0.030]



H6=-0.034 eV [-0.043]

Surfaces correspond to $|\Psi|^2$=const=0.01 $nm^{-3/2}$

Alexei Andreev(University of Surrey)

## *Simple excitations and regularities in complex systems*

## *-A second theme*

- Complex,many-body systems display surprising regularities and simple excitation patterns. Challenge is to understand how a nucleus containing hundreds of strongly interacting particles can display such regularities.

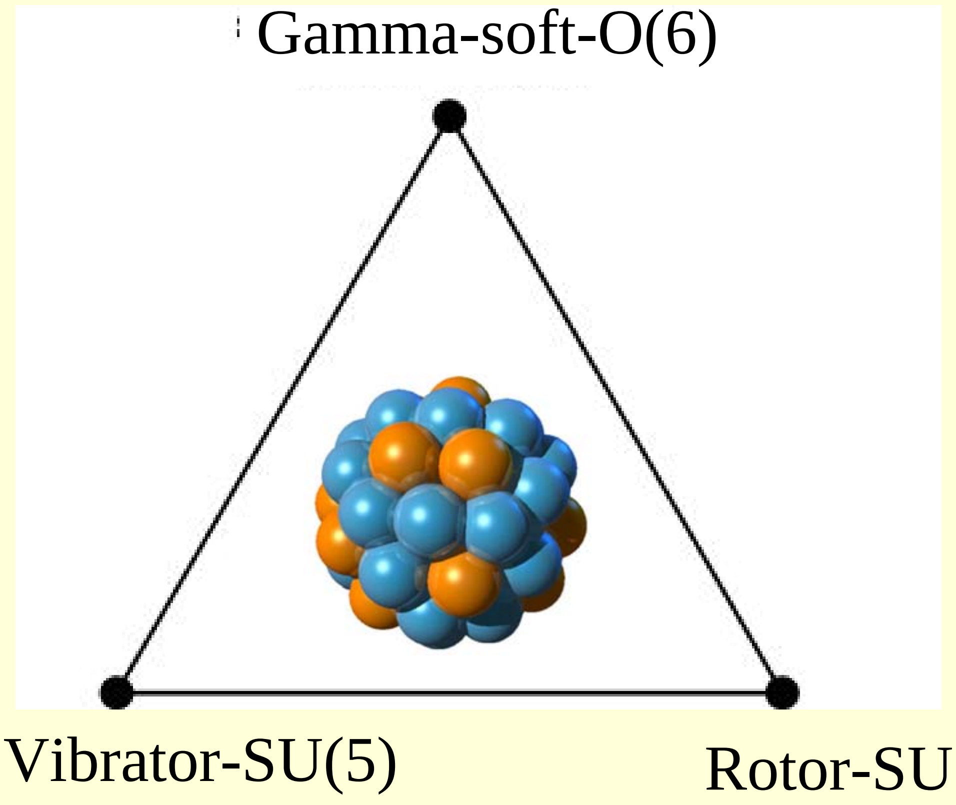
- Regularities are associated with symmetries, in particular symmetries of interactions, called Dynamical symmetries,based on group theory.

- A variety of Dynamical Symmetries have been observed in nuclei, based on the Interacting Boson Model(correlated pairs of fermions ≡ Cooper pairs in an electron gas)
- Challenge: Will these symmetries persist in nuclei far away from stability and will new symmetries appear?

# *Dynamical symmetries*

- Within the framework of the Interacting Boson Model-a model in which nuclei consist of pairs of protons and neutrons.We can have s- and d-pairs with L = 0 and 2.We have found empirically examples of spherical, ellipsoidally deformed and asymmetric nuclei.

- This is a one-fluid system.

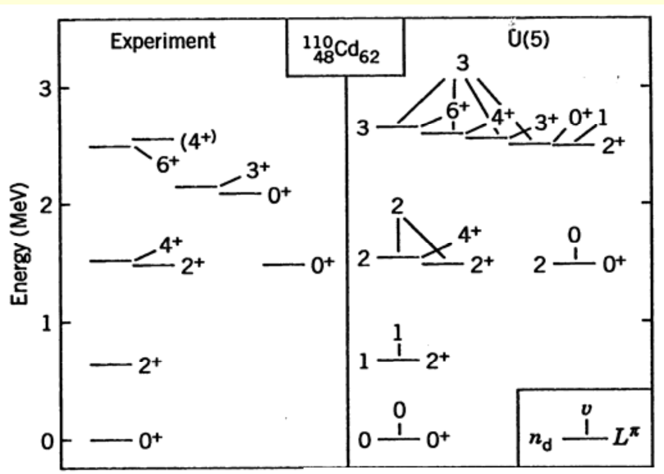


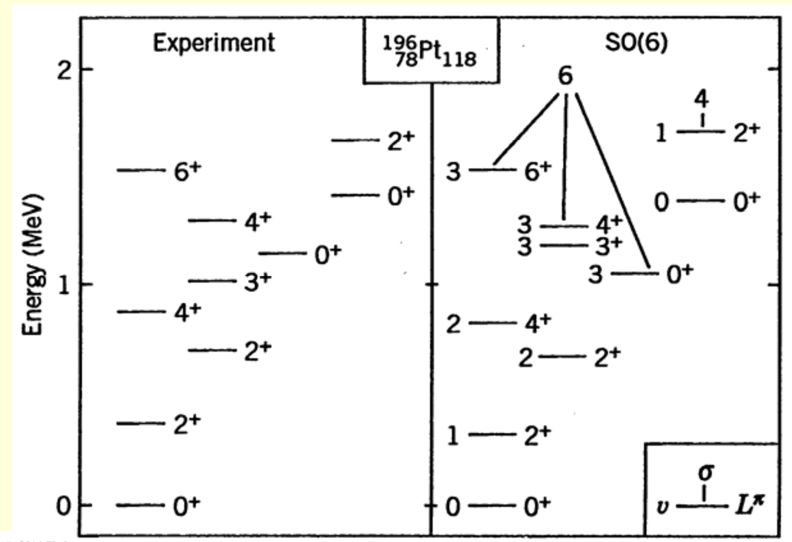

- The dynamical symmetries are shown at the vertices of the triangle.Almost all even-even nuclei can be placed in or on the triangle.

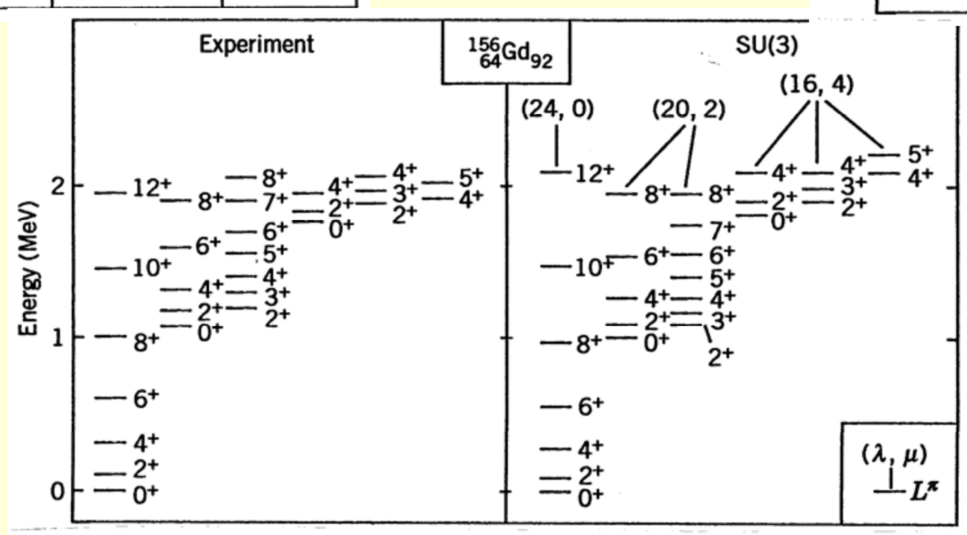
- Will we see dynamical symmetries of a 2-fluid for large n-excess?

# The IBM symmetries

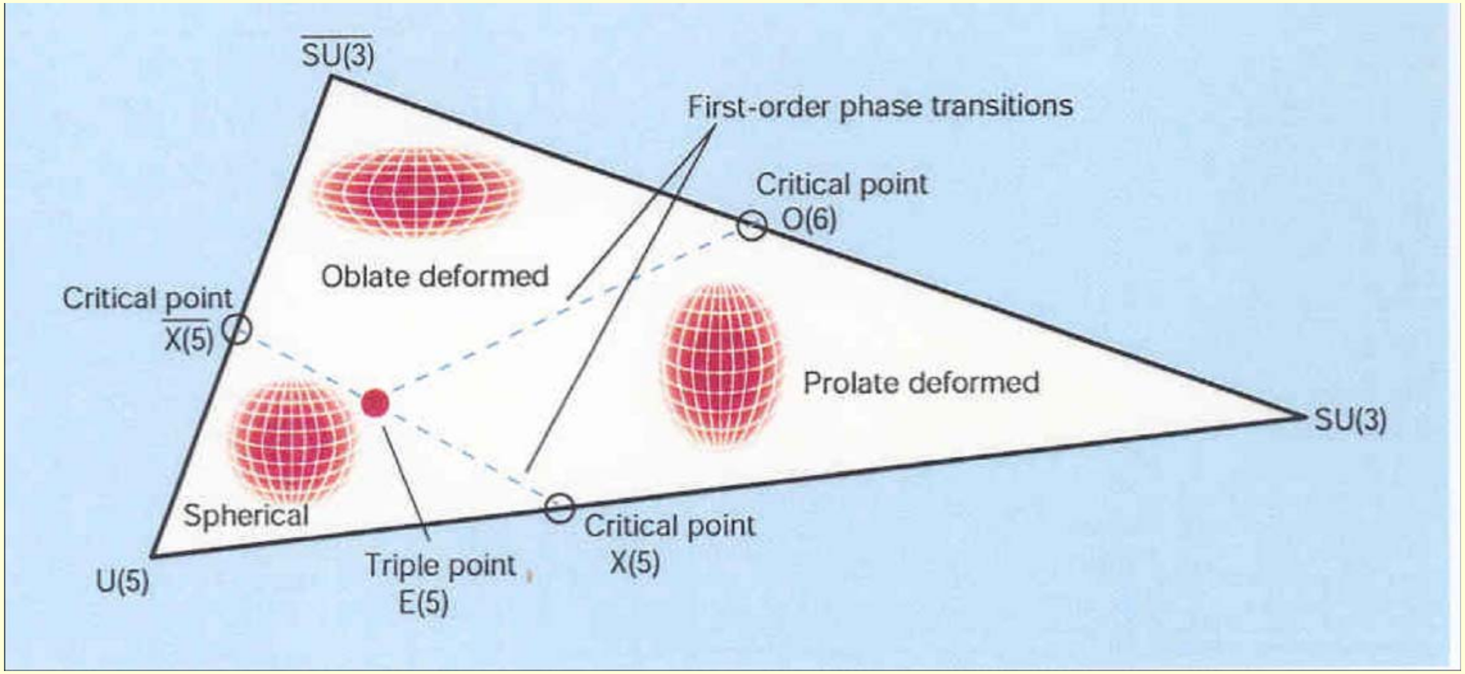
- Three analytic solutions: U(5), SU(3) & SO(6).



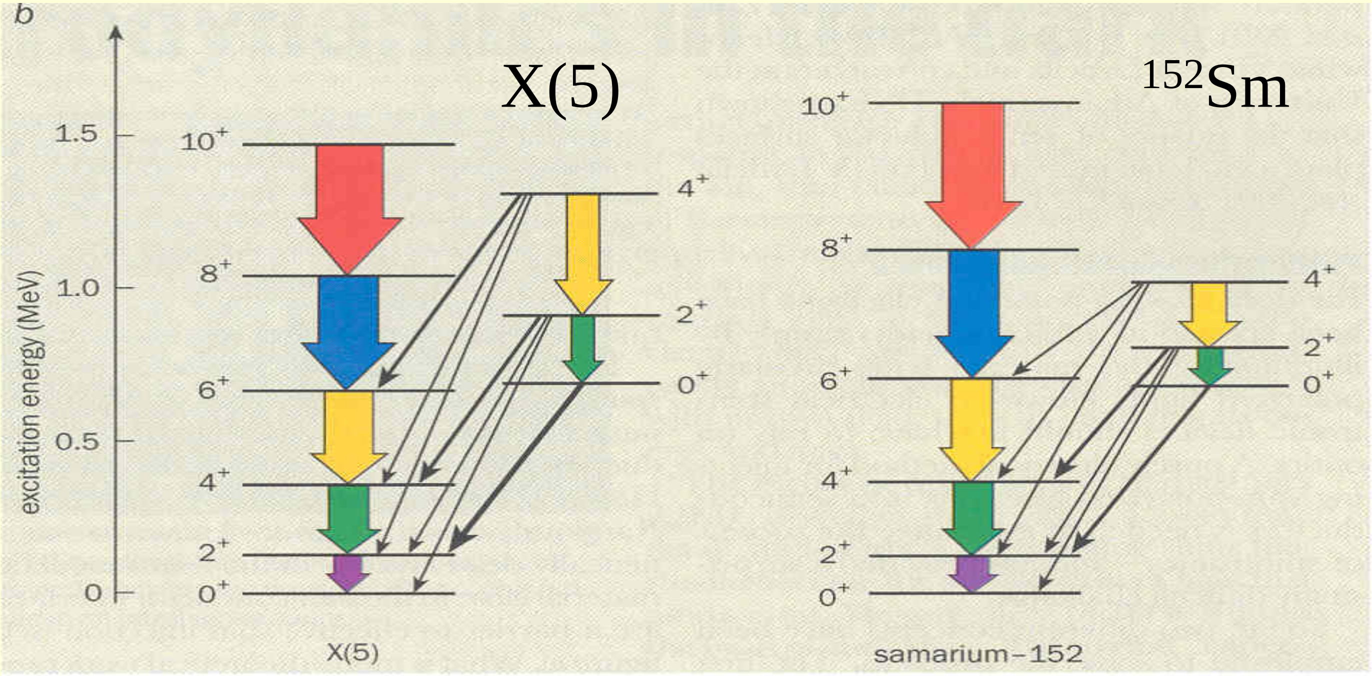
# IBM symmetries and phases




- Open problems:
  - Symmetries and phases of two fluids (IBM-2).
  - Coexisting phases?
  - Existence of three-fluid systems?

D.D. Warner, Nature **420** (2002) 614

# *Critical Point Symmetries - an example*




- An example of the critical point symmetries predicted by Iachello. The experimental and theoretical E(4)/E(2) ratios both equal 2.91 and the E(0)/E(2) ratios are 5.65.The measured transition probabilities also agree.This picture can be developed from Landau's theory of phase transitions[L.Landau,Phys.Sowjet 11(1937)26]

F.Iachello,PRL85(2000)3580;ibid 87(2001)052502

# The role of nuclei in the Universe

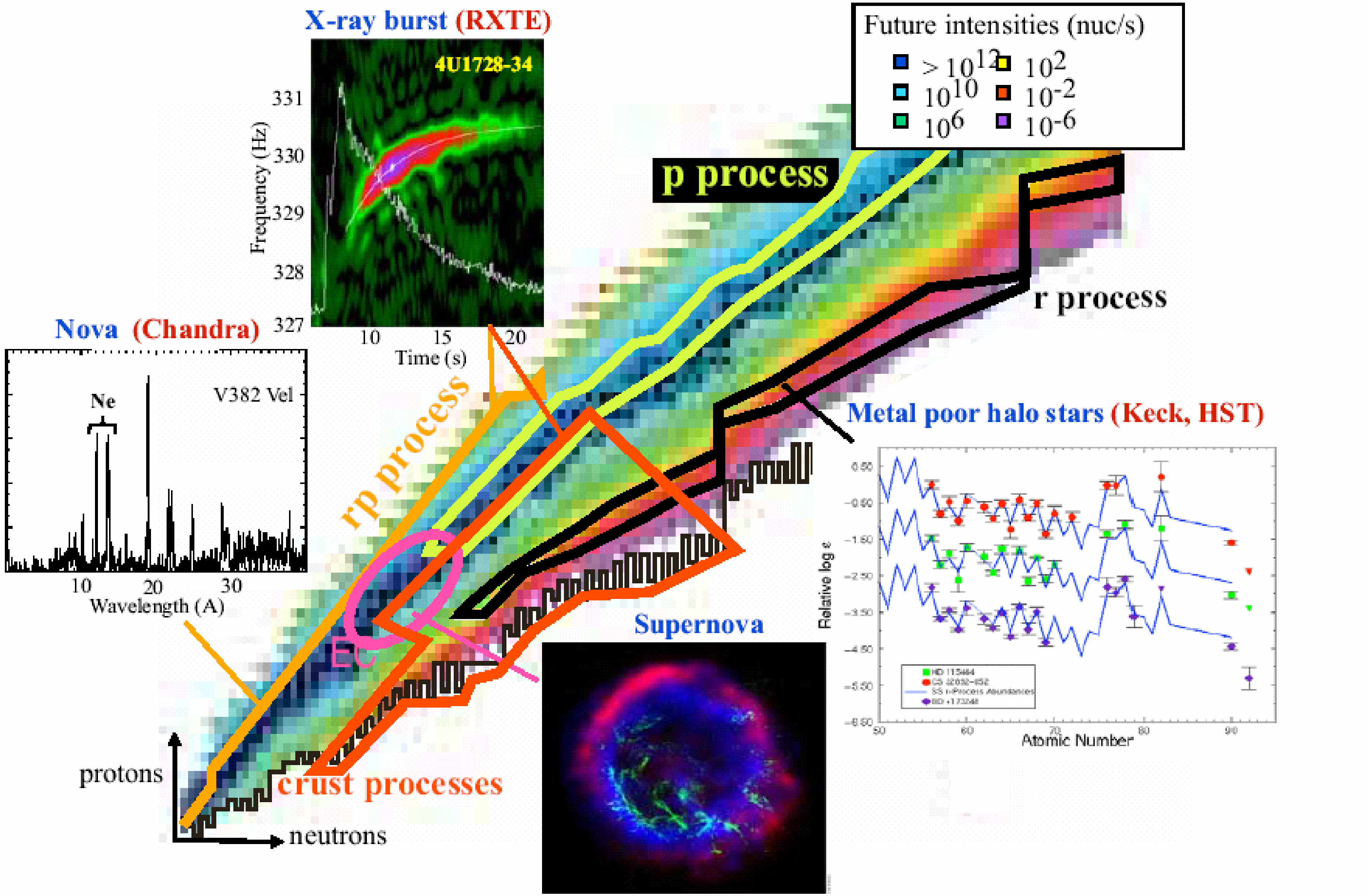
Goal: to combine our knowledge of nuclear structure and theory
with astronomical observations to model
astrophysical processes.

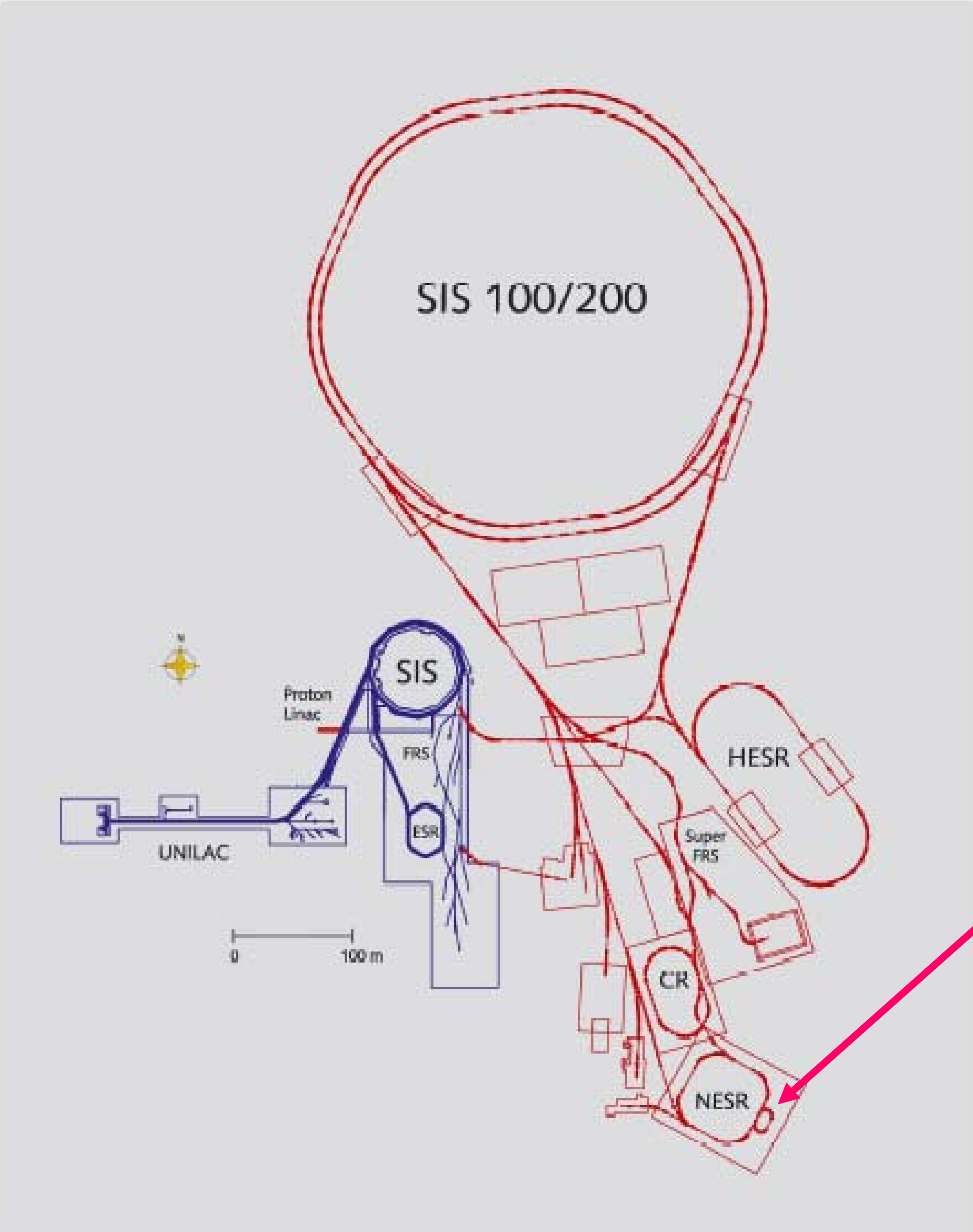
Many unanswered questions or badly understood processes:

- The nuclear astrophysical origins of the chemical elements
- The manipulation of nuclear decay rates by controlling the nuclear medium
- The mechanisms by which supernovae explode
- The dynamics of explosive stellar processes
- Nuclear processes in the Early Universe
- ……????

# Rare Isotopes in Nuclear Astrophysics

*Courtesy of H. Schatz*






# FAIR

- Main features:-
  Intense,high quality sec. beams of radioactive ions and anti-protons.
- Increase in primary beam energy by 15.
- Increase in RIB intensity by $10^4$
- Storage rings for heavy ions(NESR) and anti-protons(HESR).
- Electron ring intersecting NESR to allow $e^-$-RIB interactions

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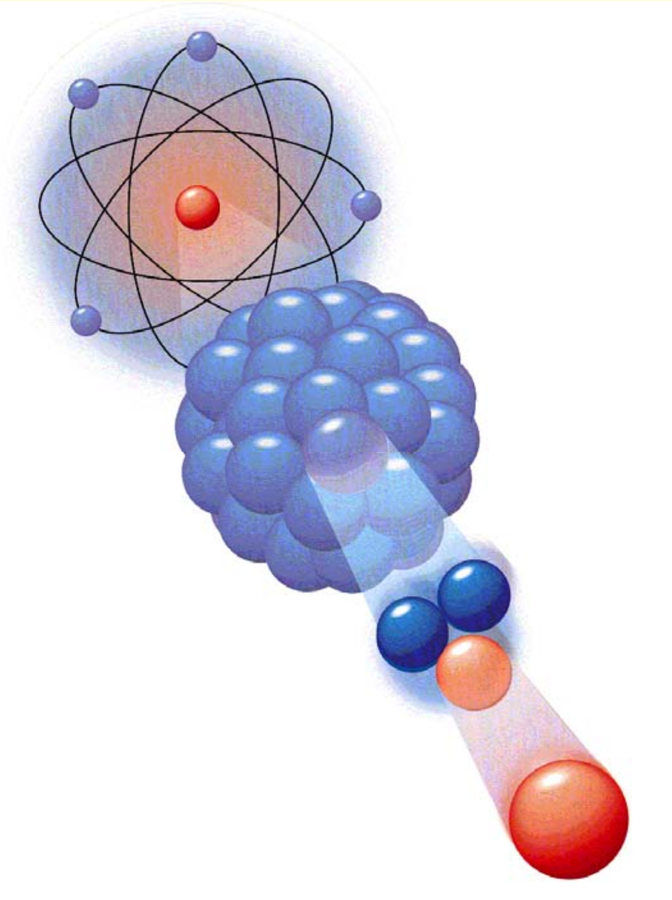
- Blue-present facility
- Red-future additions

# Summary

- Nuclear physics faces many challenges ranging from questions relating to the non-perturbative regime of QCD and the various phases of nuclear matter through the structure of nucleonic matter to the role of nuclear reactions and decay in the Early Universe and in stellar processes.



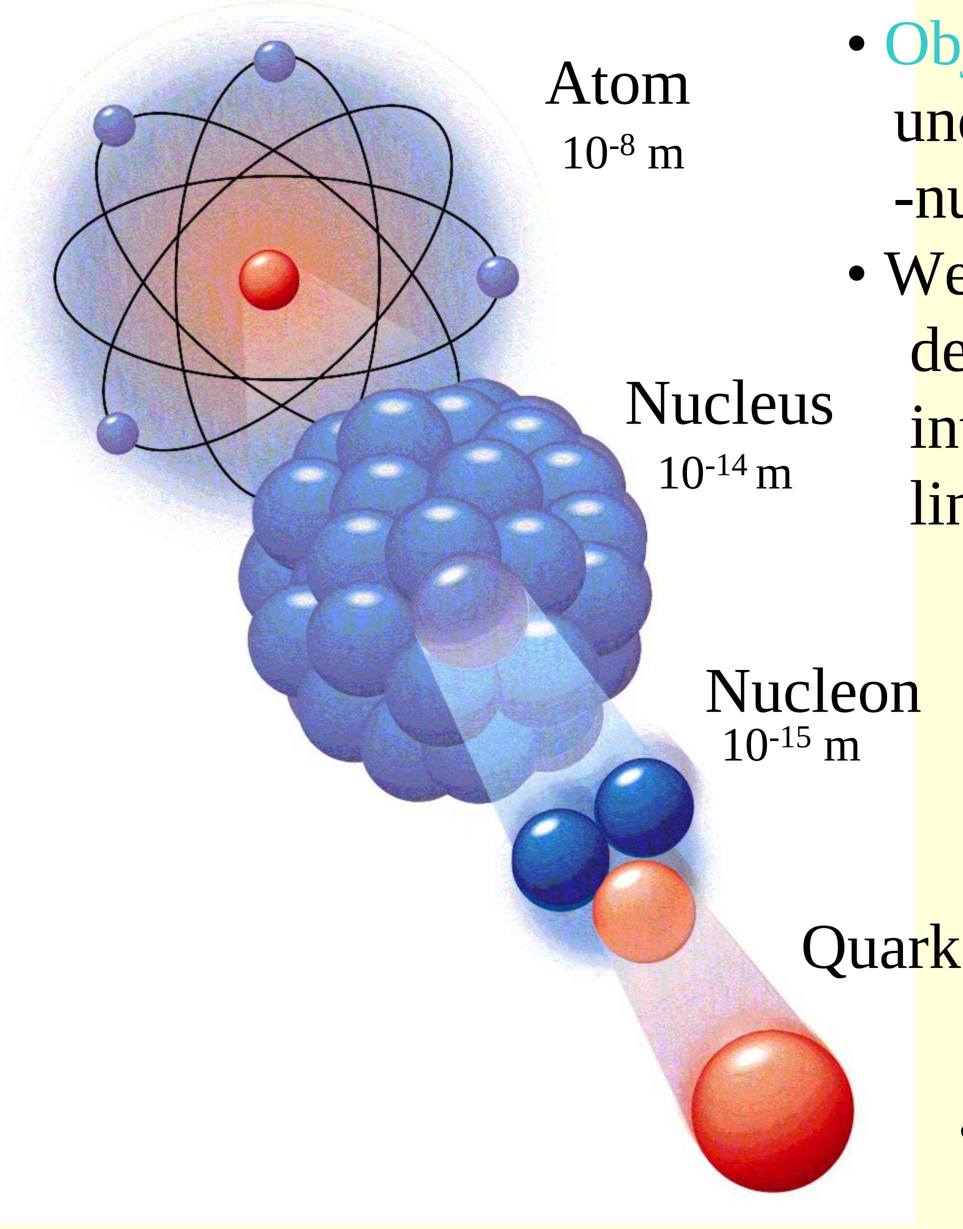
- Not all of the tools we need to attack these questions are yet available but those we lack are on the way.

- In particular we need intense beams of radioactive ions to explore many facets of the structure of nucleonic matter.

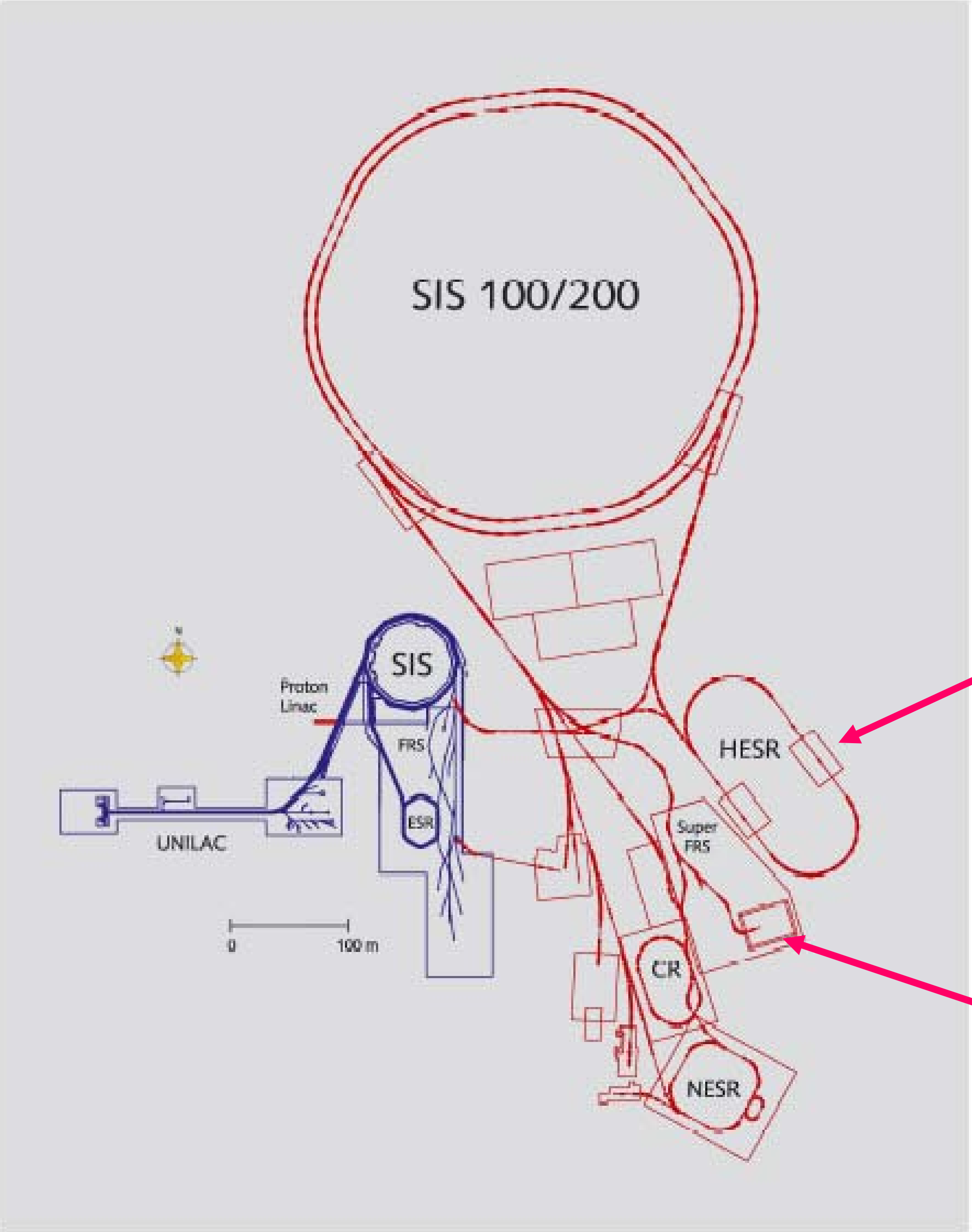
- We have found two main, complementary ways of producing such beams-the ISOL or two-step method and high energy fragmentation.In the longer term Europe will have one major facility of each type -FAIR and EURISOL.

- EURISOL and other such ISOL facilities open the prospect of joint RIB and Beta-beam facilities.

# FAIR and the Microscopic World




- Objective-comprehensive, quantitative understanding of matter -nuclei,nucleons,quarks and gluons
- We have been very successful probing deeper and deeper ***but*** matter has an intrinsic complexity, more than just the linear superposition of the components.
  - Many-body aspects play a decisive role at all levels of the hierarchical structure of matter.
    Hence strong connexions with nanosystems such as Quantum dots metallic clusters,Fermionic condensates, superconductors etc
- Applications in many areas-Nucl. Astro,Medicine,Radiobiol. etc




# FAIR

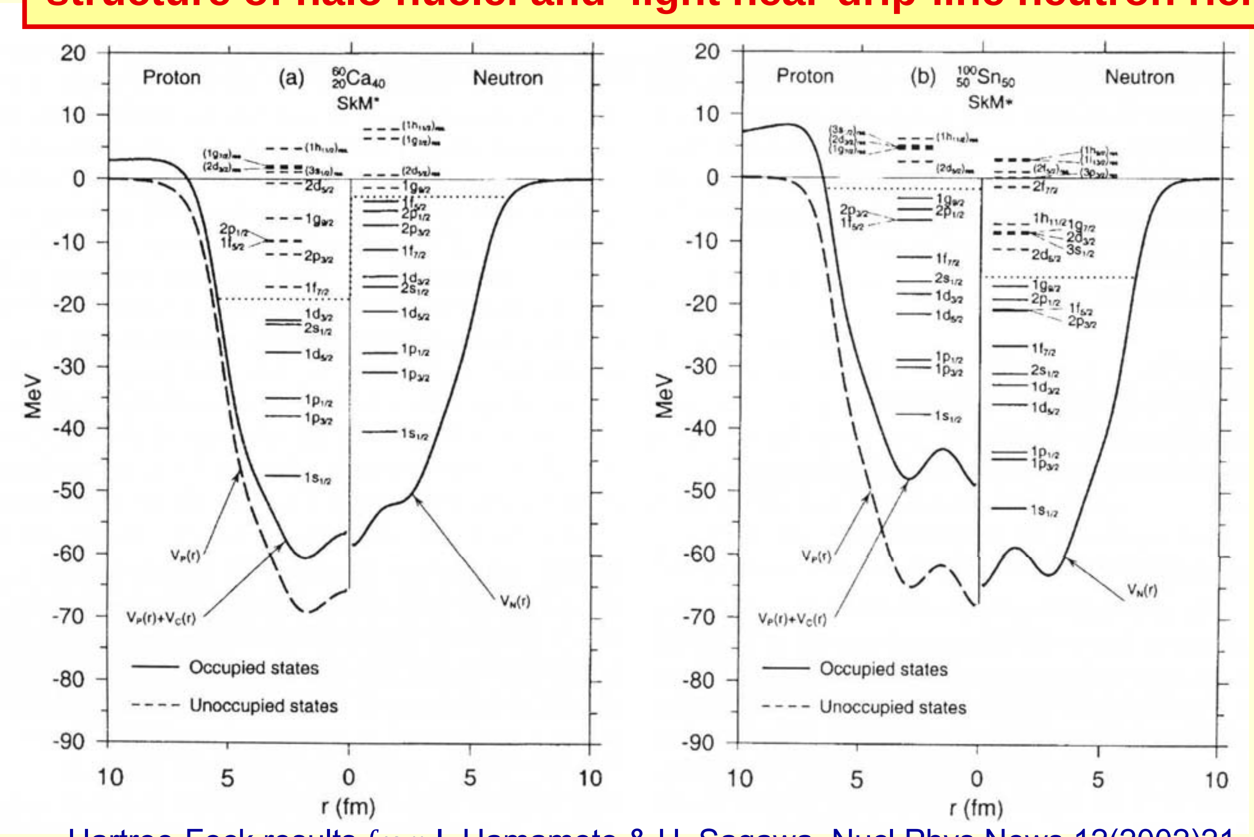
- Blue-present facility
- Red-future additions
- UK interest focussed on PANDA and NUSTAR.
- PANDA is aimed at the structure of hadrons and their interaction with the nuclear medium using cooled anti-proton beams
- NUSTAR aims to exploit RIBs from the Super-FRS to study Nuclear Structure

# Physics Issues addressed by transfer and knockout

**evolution and changes in shell structure, away from stability:**

- identify single particle states, by measuring $J^{\pi}$ or even just $\ell$ as well as possible
- identify if they pure or are mixed with states of more complicated parentage,
- characterise the degree of purity (of pure single particle nature)
- measure the mixing/spreading of the simple wavefunction across states,
- in regions of deformation, identify Nilsson orbitals from "fingerprints" of s.p. content

**structure of halo nuclei and light near-drip-line neutron rich nuclei**




Hartree-Fock results *from* I. Hamamoto & H. Sagawa, Nucl Phys News 12(2002)21

The single particle levels for an exotic neutron-rich nucleus are different in energy and relative spacings compared ot those of an exotic proton-rich nucleus…

this is of interest in itself and leads to new structure properties like altered collectivity…

and also requires to be known, to enable shell model calculations