Single particle versus collectivity, shapes of exotic nuclei

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Rewriting Nuclear Physics textbooks
30 years with Radioactive Ion Beam Physics
Pisa (Italy), July 20th – 24th, 2015

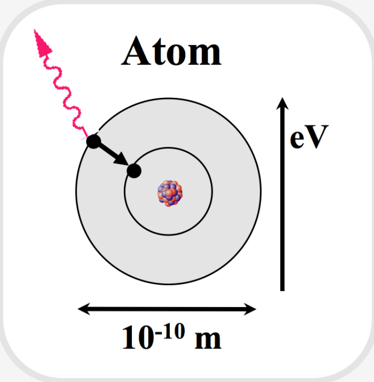
Single particle versus collectivity, shapes of exotic nuclei

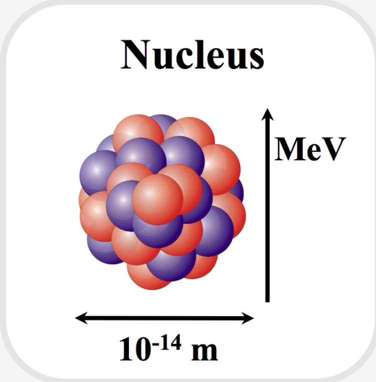
- What a title !   A bit of everything …
- Start with some reminders of "classical" nuclear physics
- What's new over the last 30 years ?
  From the perspective of an observer of the field since 1989 …
  (pure experimentalist, γ-ray spectroscopist interested in A>70 nuclei)

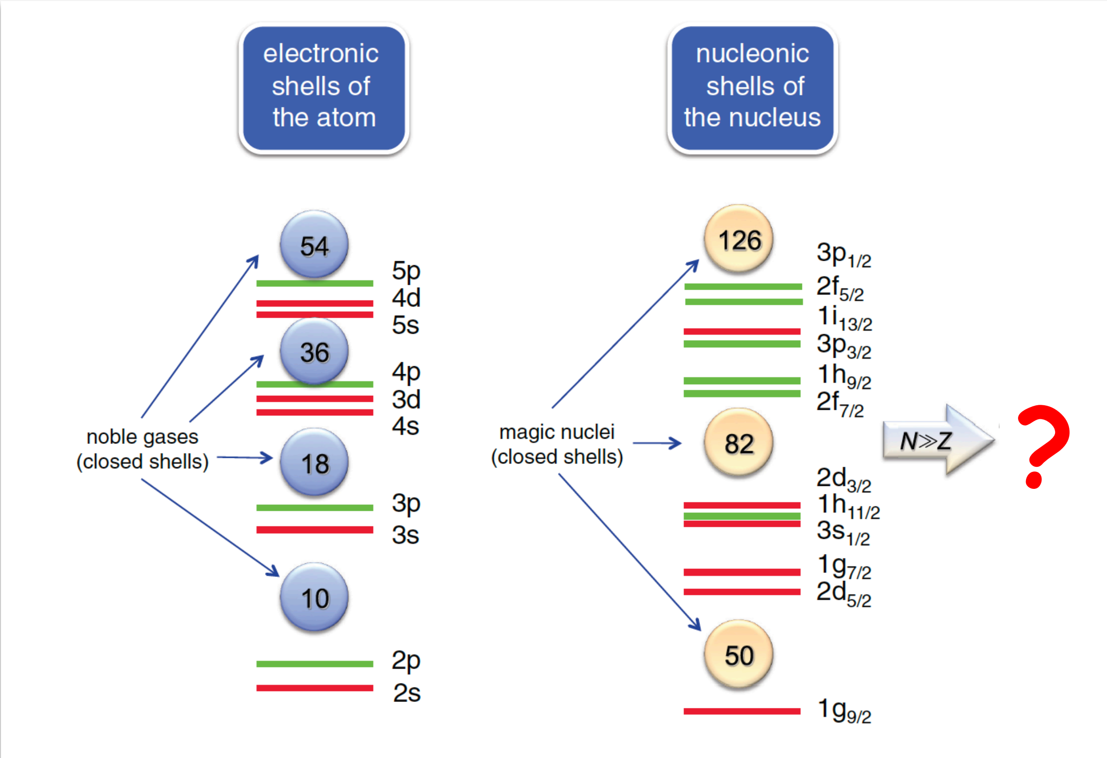
Rewriting Nuclear Physics textbooks
30 years with Radioactive Ion Beam Physics

- Radioactive ion beams are an important part, but not the whole story !
- Small selection of examples – only limited time …
- I will simplify (hopefully without getting things wrong), omit, not always show latest etc.
- Try to avoid topics which others may already have shown

The shell structure of atomic nuclei



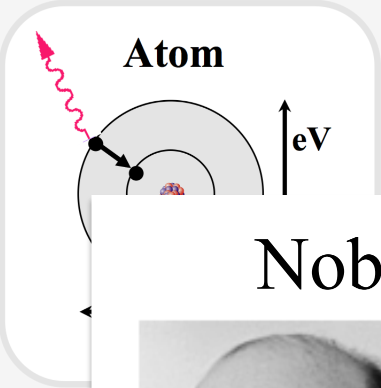


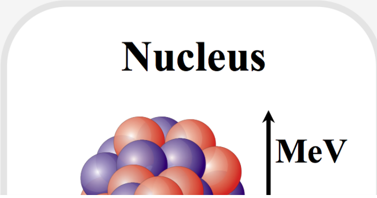


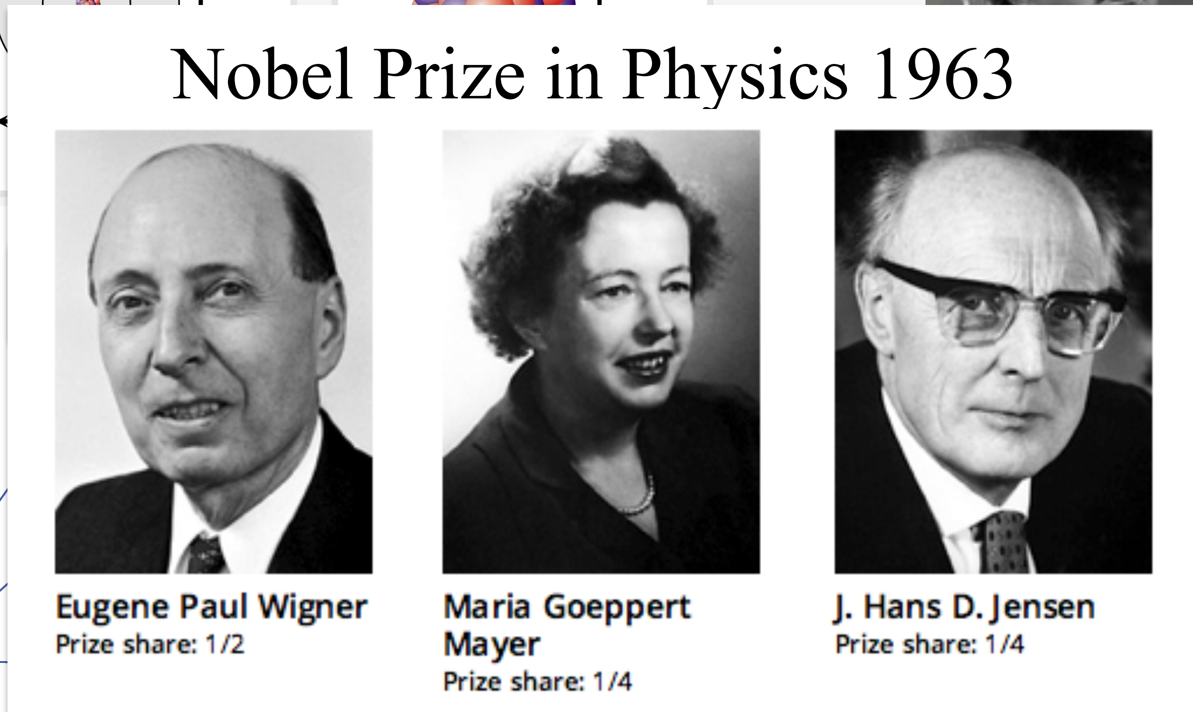
Remember:
Two independent parameters in atomic nuclei, Z and N !

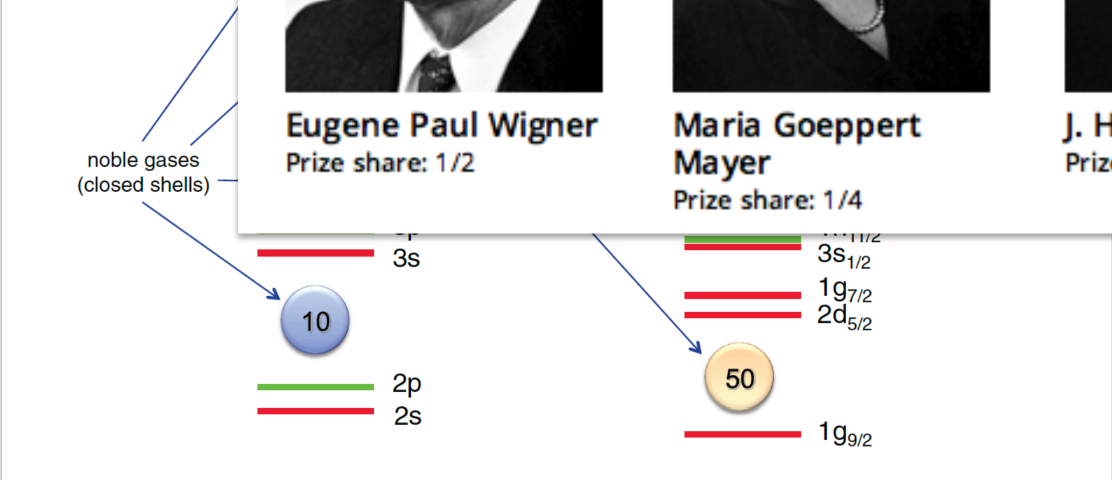
"Shell evolution":
Next part of my talk …

The shell structure of atomic nuclei









nt parameters
i, Z and N !

"Shell evolution":
Next part of my talk ...

The birth of the collective models in 1952

Interpretation of Isomeric Transitions of Electr

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Institute for Theore
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IN the recent classificat
electric quadrupole
examples of lifetimes ap
basis of the shell model. I
more than a factor of a h
we have here the effect
motion.[1]

A natural interpretatio
model describing the nucl
motion and nuclear surf
model, the low-lying state
of the particle structure
the surface, or by an exci
the particle quantum nun
states are of the former ch
means of the shell model.
however, that transition p

Nov. 1952

Rotational States in Even-Even Nuclei

AAGE BOHR AND BEN R. MOTTELSON*
Institute for Theoretical Physics, Copenhagen, Denmark
(Received March 24, 1953)

IN a recent note,[1] an interpretation of the short-lived $E2$ isomers has been suggested in terms of rotational states of the deformed nucleus. Empirical evidence is rapidly accumulating on the low energy spectra of even-even nuclei;[2–4] the purpose of the present note is to call attention to the extensive support which exists in these data for the above interpretation, and to suggest its usefulness in the analysis of decay schemes.

In the model describing the nucleus in terms of the coupled particle motion and surface oscillations, low-lying rotational states are associated with the large deformations expected in regions with many particles outside of closed shells. In such regions, the rotational spectrum is expected to be given rather accurately by the simple expression[1]

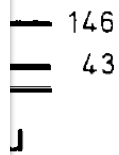
$$E_I = \frac{\hbar^2}{2\mathcal{J}} I(I+1), \quad I = 0, 2, 4, 6, \text{ even parity} \tag{1}$$

March 1953

First observation of rotational bands

Three examples from 1953:

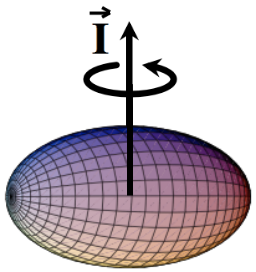
Fine structure in α decay



Nobel Prize in Physics 1975

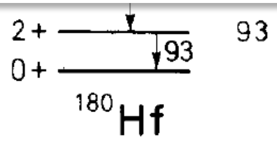
Aage Niels Bohr | Ben Roy Mottelson | Leo James Rainwater

rotations –

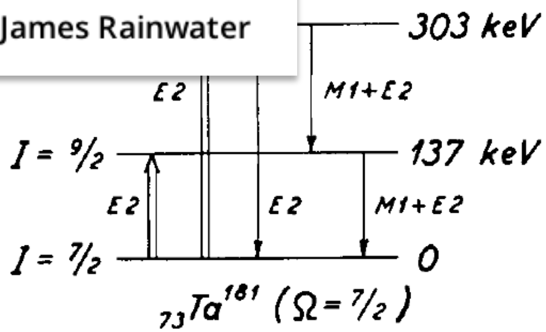


even-even nucleus

$E(4^+)/E(2^+) \sim 3.3$

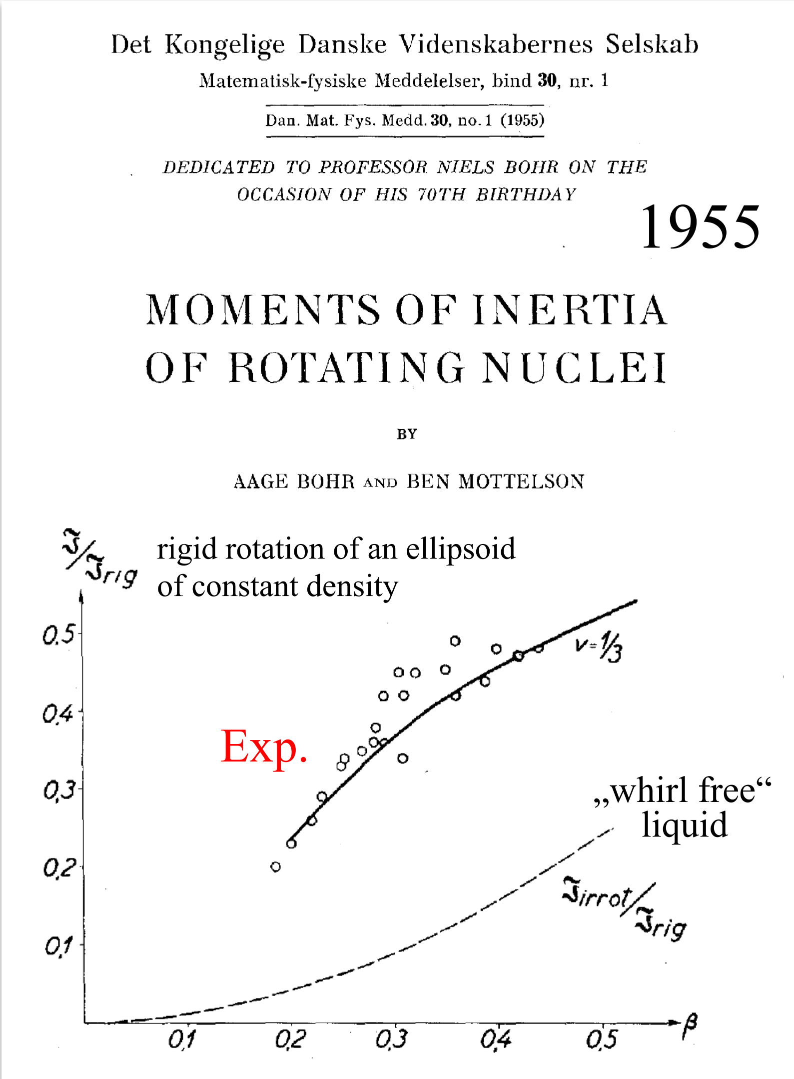


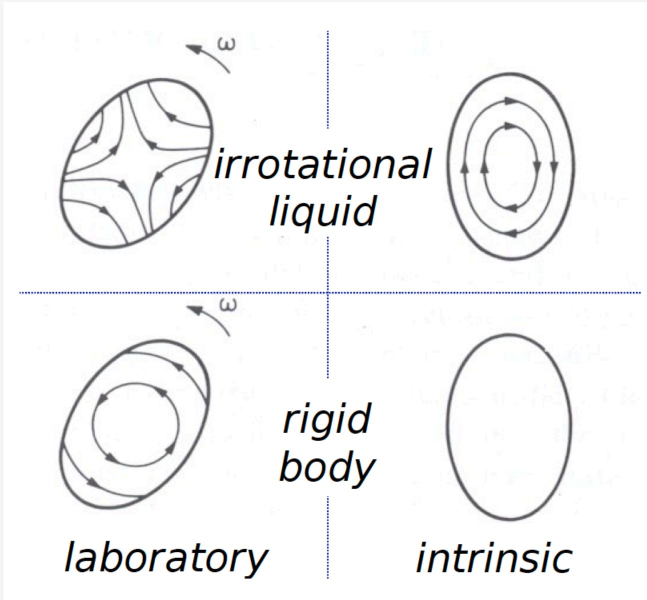
experiment



Bohr Nobel Lecture

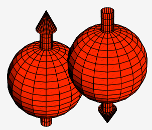
The problem of the "wrong" moment of inertia

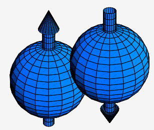




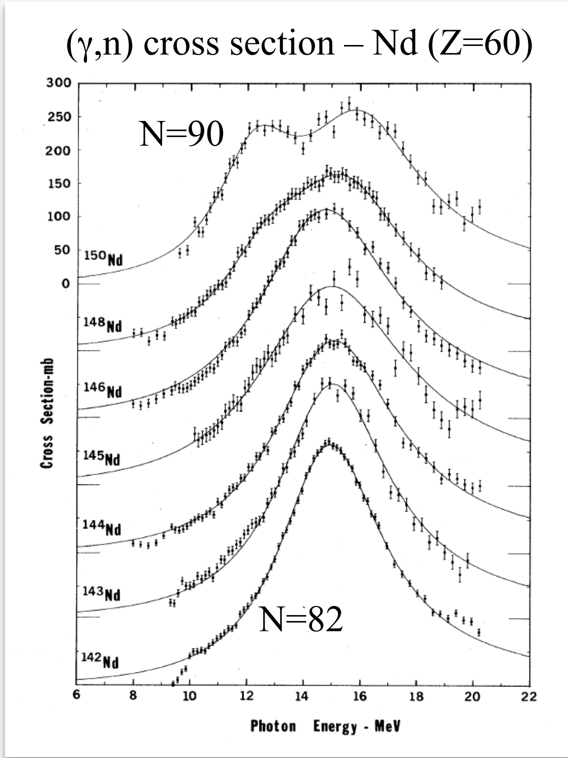
„Nuclei are like egg shells which are filled with a mixture of a normal and a super-conducting liquid !"

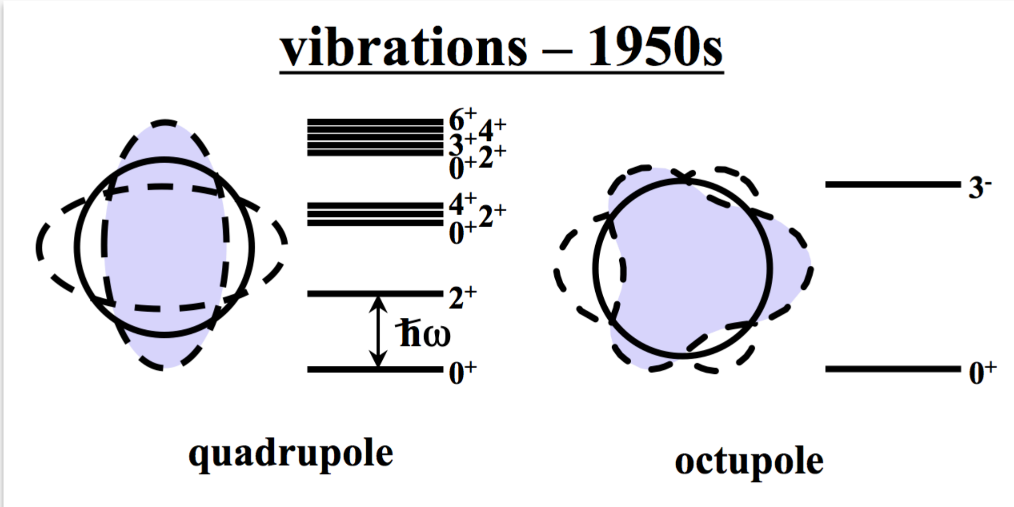
Super conductivity due to **pairing forces** in analogy to the Cooper pairs (electrons) in superconductors.

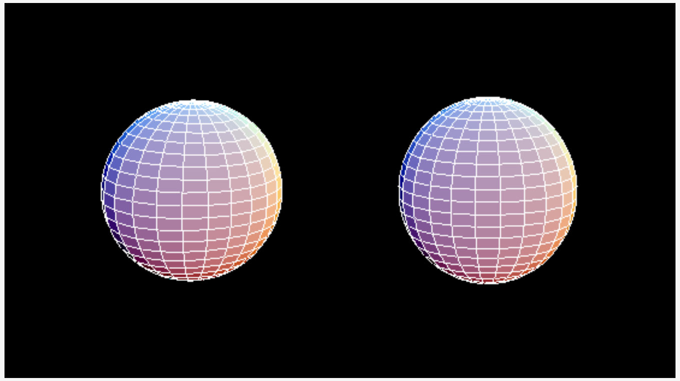


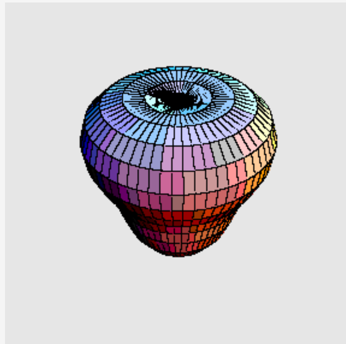


The vibrational degree of freedom

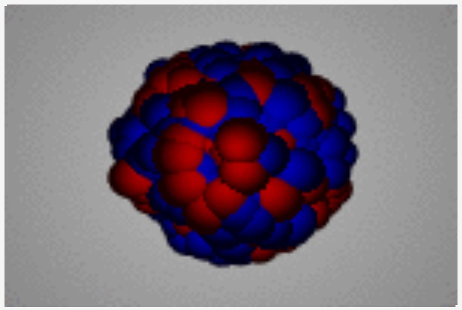




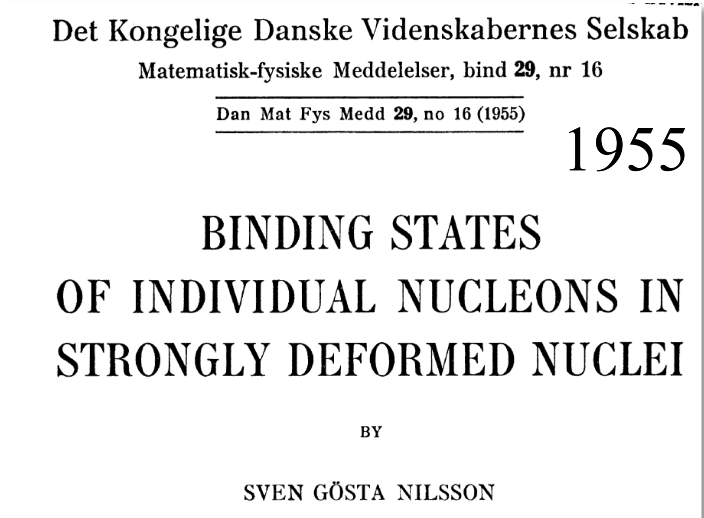




Giant Dipole Resonance



Deformed nuclei in the Nilsson model



Det Kongelige Danske Videnskabernes Selskab
Matematisk-fysiske Meddelelser, bind **29**, nr 16

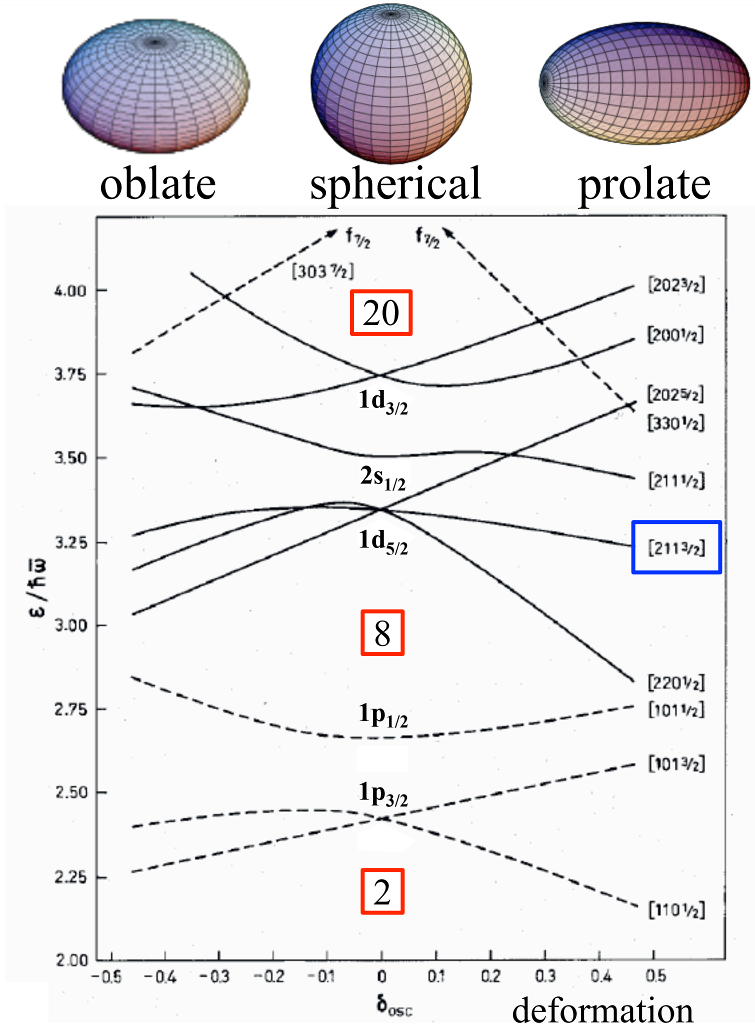
Dan Mat Fys Medd **29**, no 16 (1955)

1955

BINDING STATES
OF INDIVIDUAL NUCLEONS IN
STRONGLY DEFORMED NUCLEI

BY

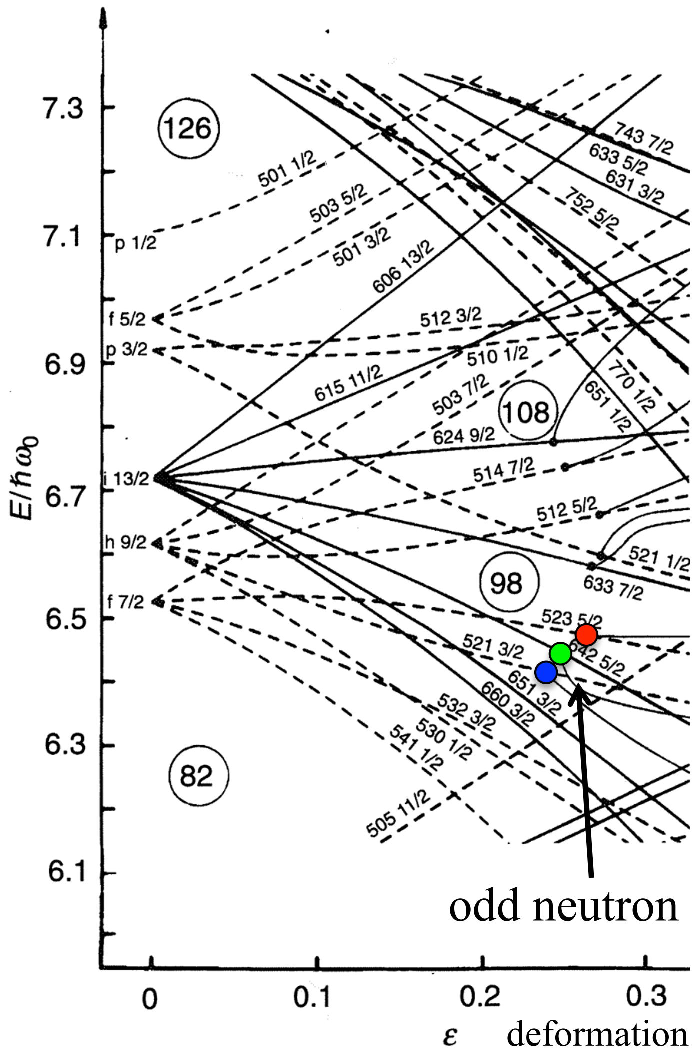
SVEN GÖSTA NILSSON

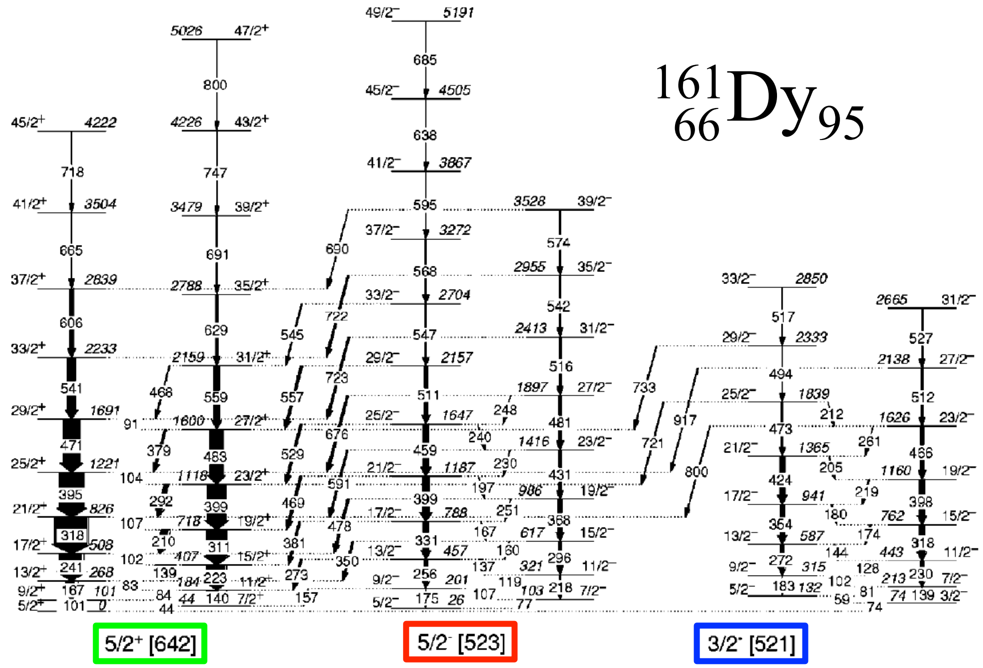


new asymptotic quantum numbers

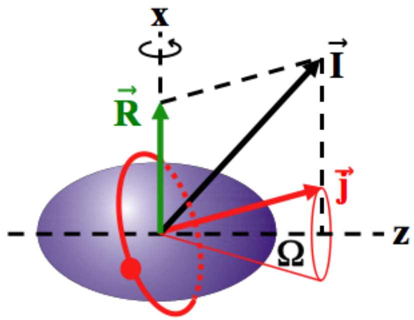
2j+1-fold degeneration is removed,
states with +m and –m still degenerate !

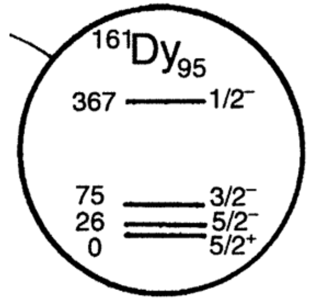
Single-particle motion in a deformed field





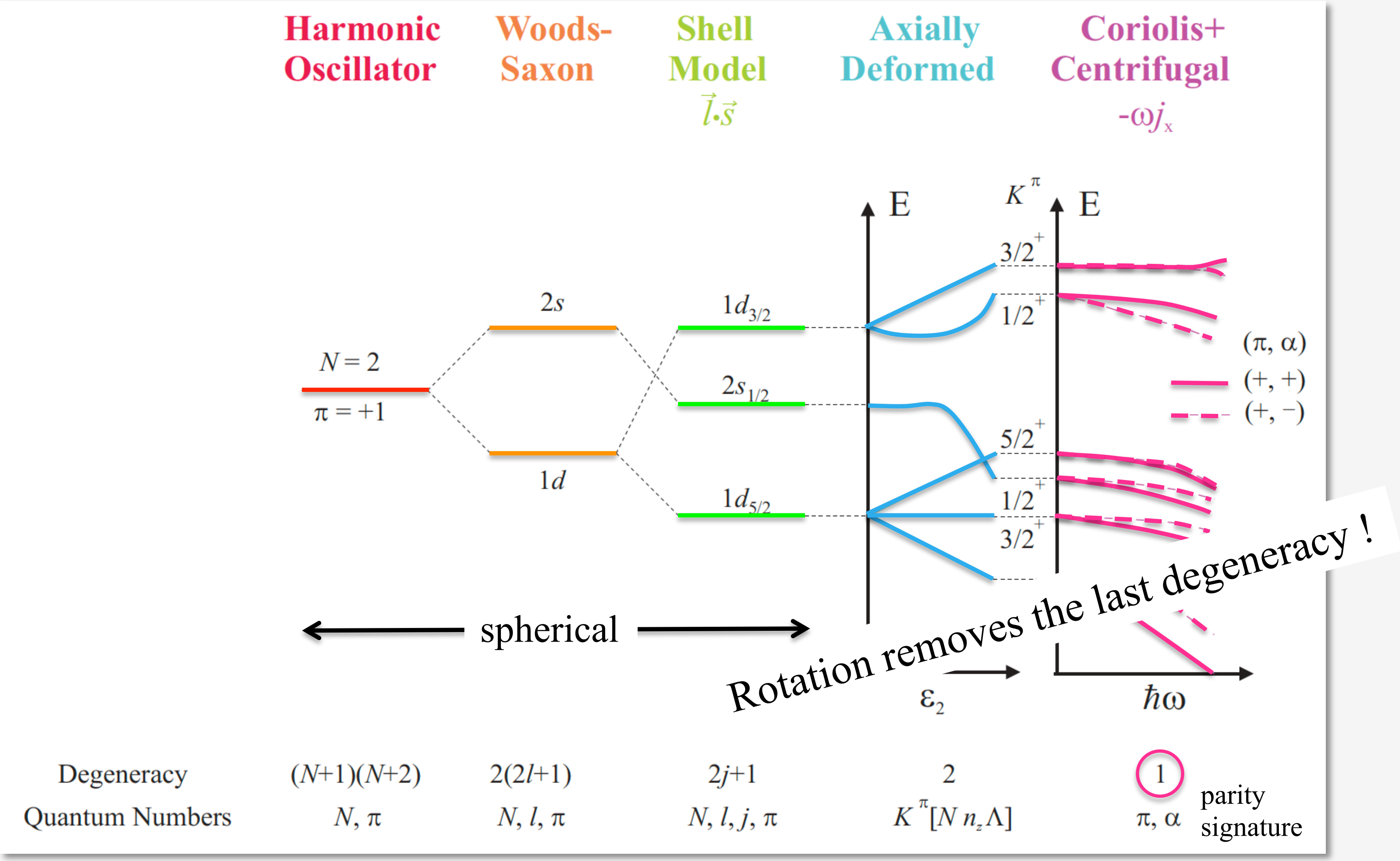
A. Jungclaus et al., Phys. Rev. C67, 034302 (2003)





Three rotational band heads within 75 keV !

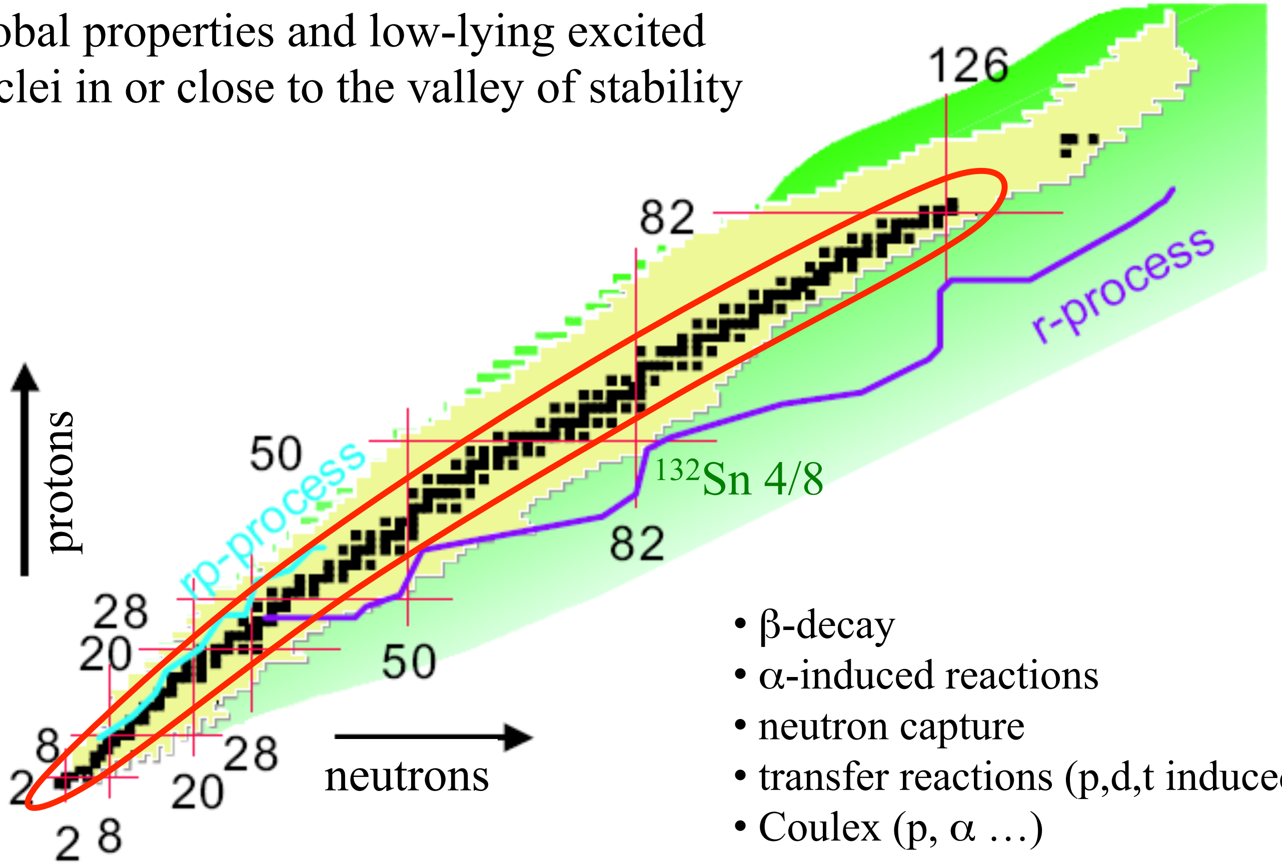
Single-particle motion in a rotating deformed field



Single-particle energies depend on deformation and rotational frequency !

Over the next twenty years ...

Study of global properties and low-lying excited states of nuclei in or close to the valley of stability

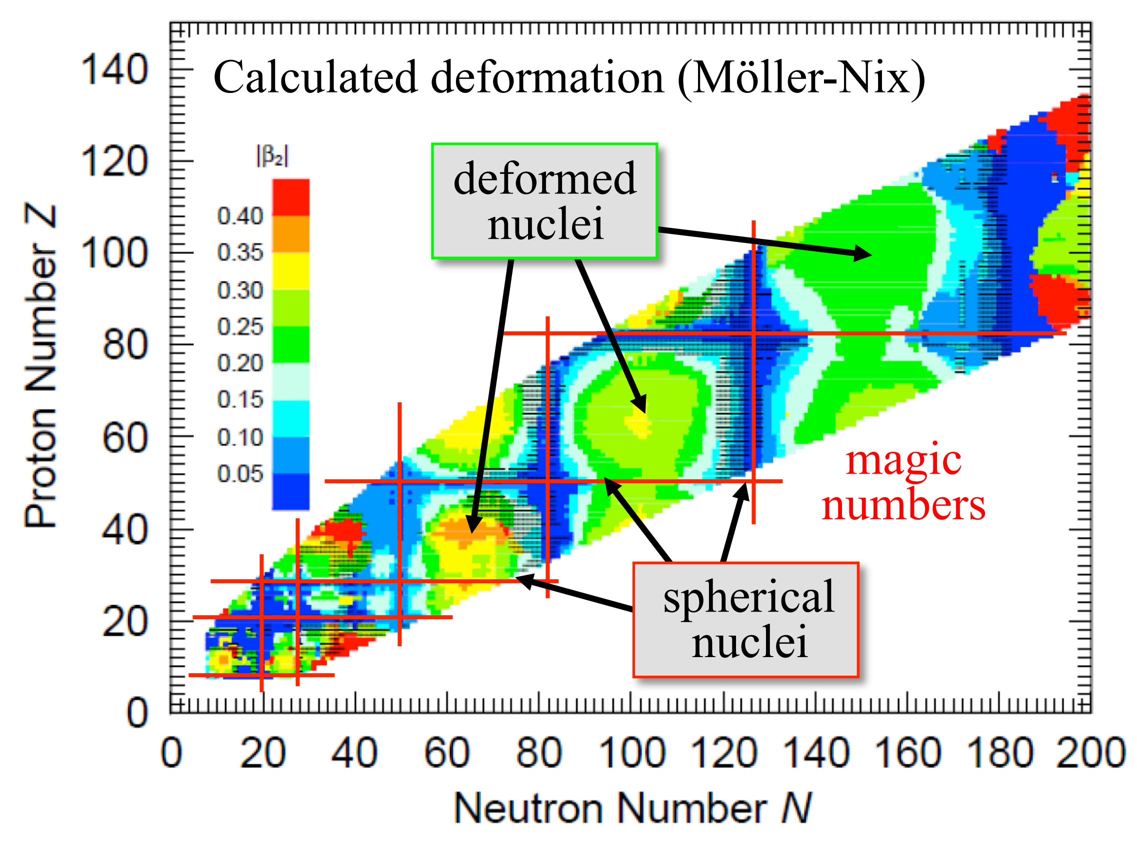


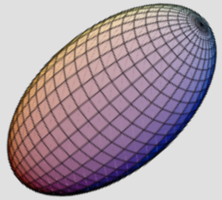
- β-decay
- α-induced reactions
- neutron capture
- transfer reactions (p,d,t induced)
- Coulex (p, α …)
- γ-induced neutron emission

- <u>scattering experiments (e, p …)</u>

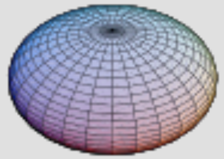
Radii and density distributions !

„Classical" nuclear physics



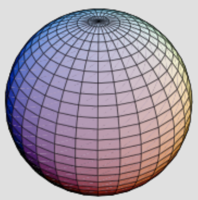


prolate nucleus



oblate nucleus

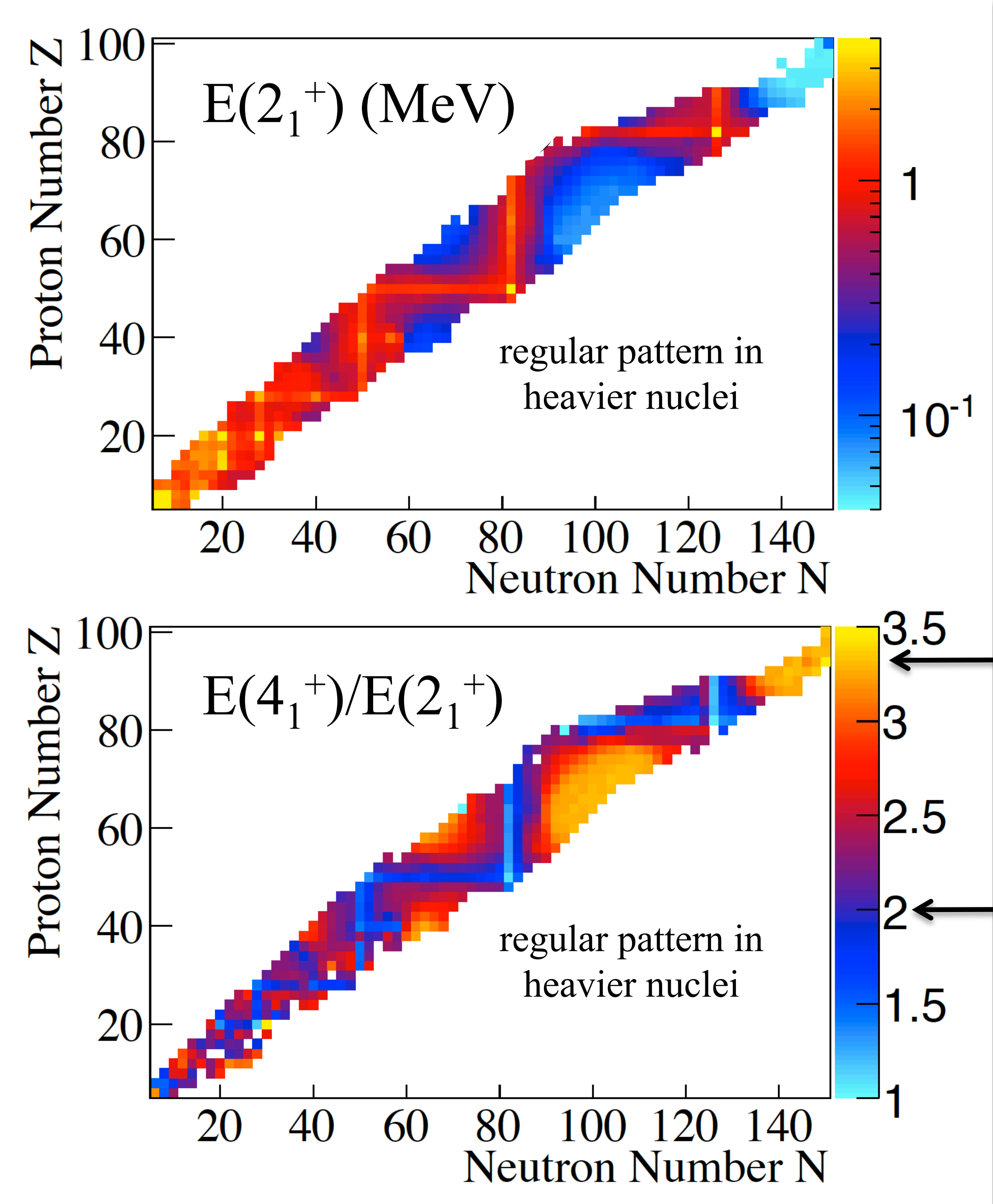
rotations and vibrations
→ collective models

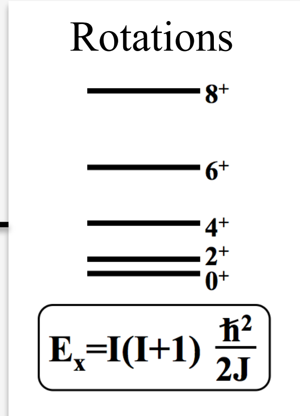


spherical nucleus

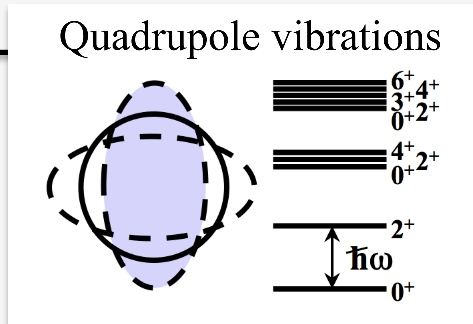
Single-particle excitations
→ nuclear shell model
vibrations → collective models

$E(2^+)$ and $E(4^+)/E(2^+)$ as global indicators in even-even nuclei



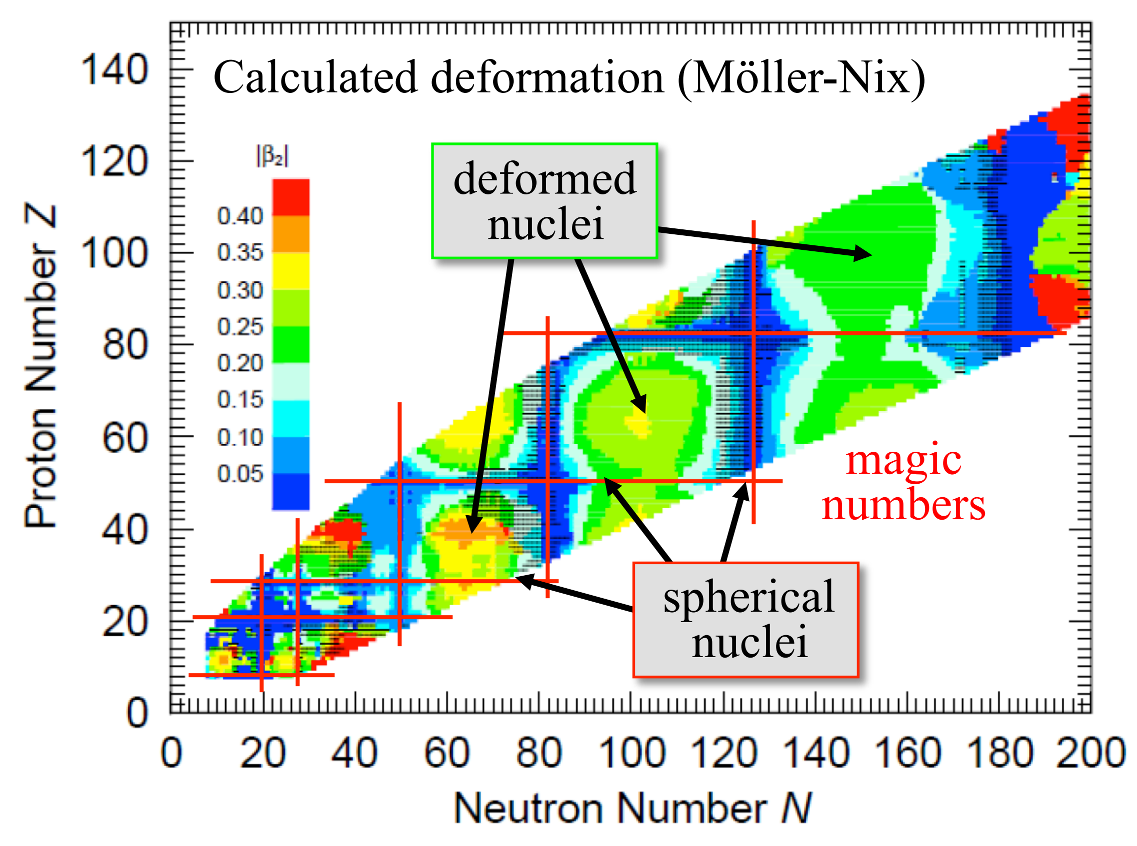


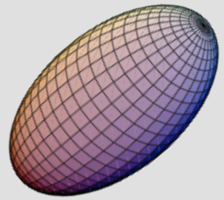
$E(4_1^+)/E(2_1^+)$
$=(4*5)/(2*3)$
$=20/6=$**3.3**



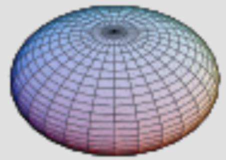
$E(4_1^+)/E(2_1^+)$
$=2h\omega/h\omega=$**2**

„Classical“ nuclear physics



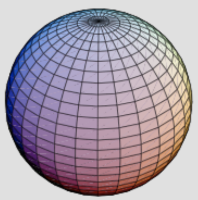


prolate nucleus



oblate nucleus

rotations and vibrations
→ collective models



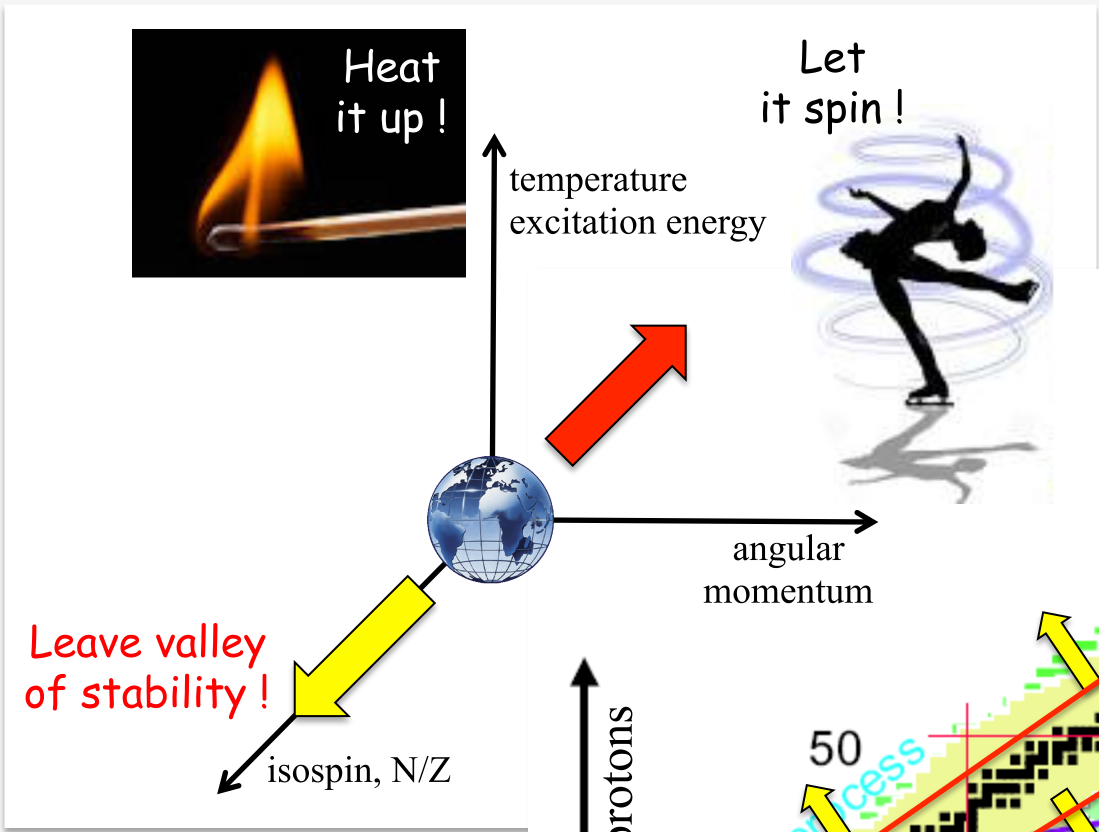
spherical nucleus

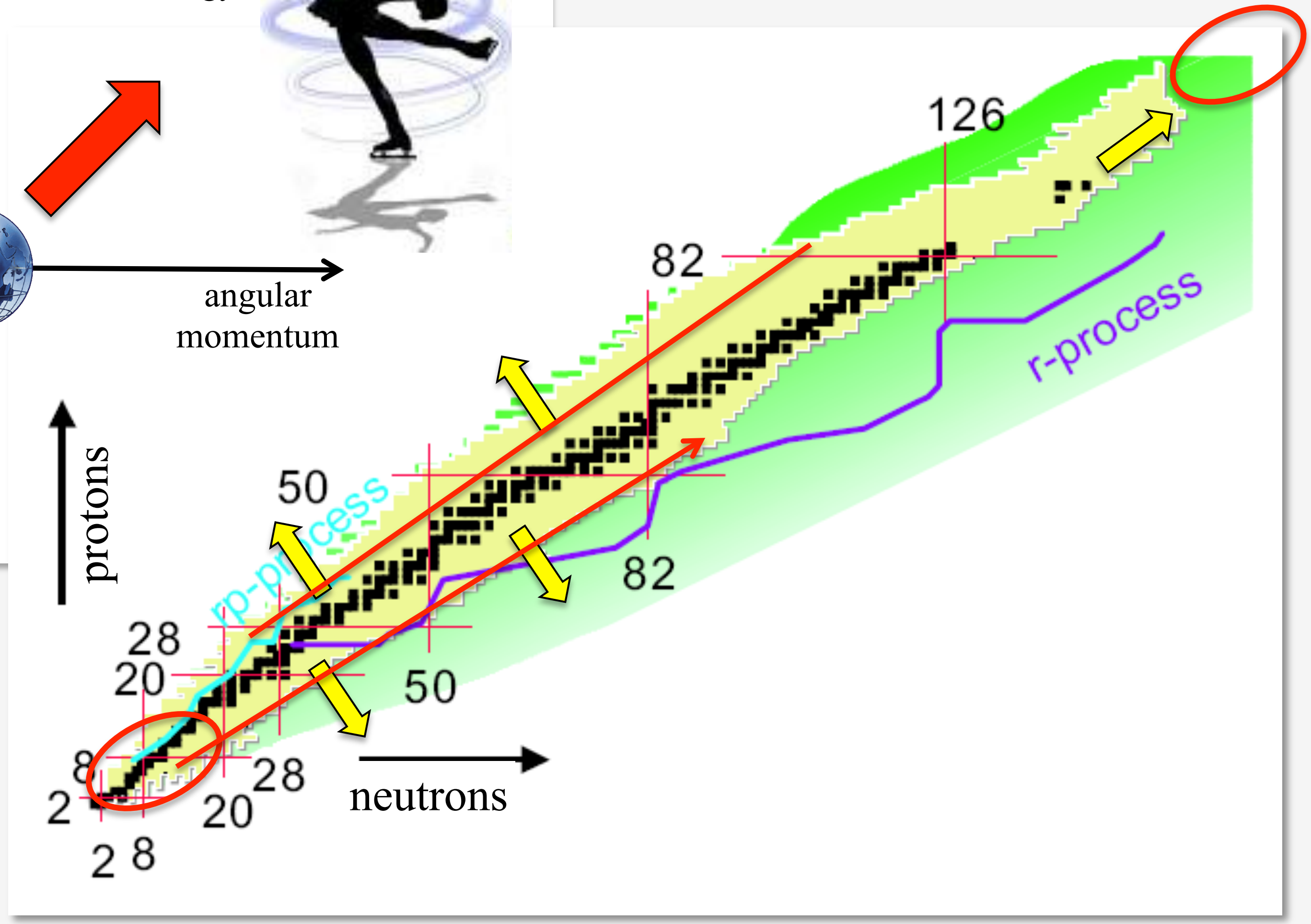
Single-particle excitations
→ nuclear shell model
vibrations → collective models

Is that already the full story ?

No !!!!!!!!!!!!!!!

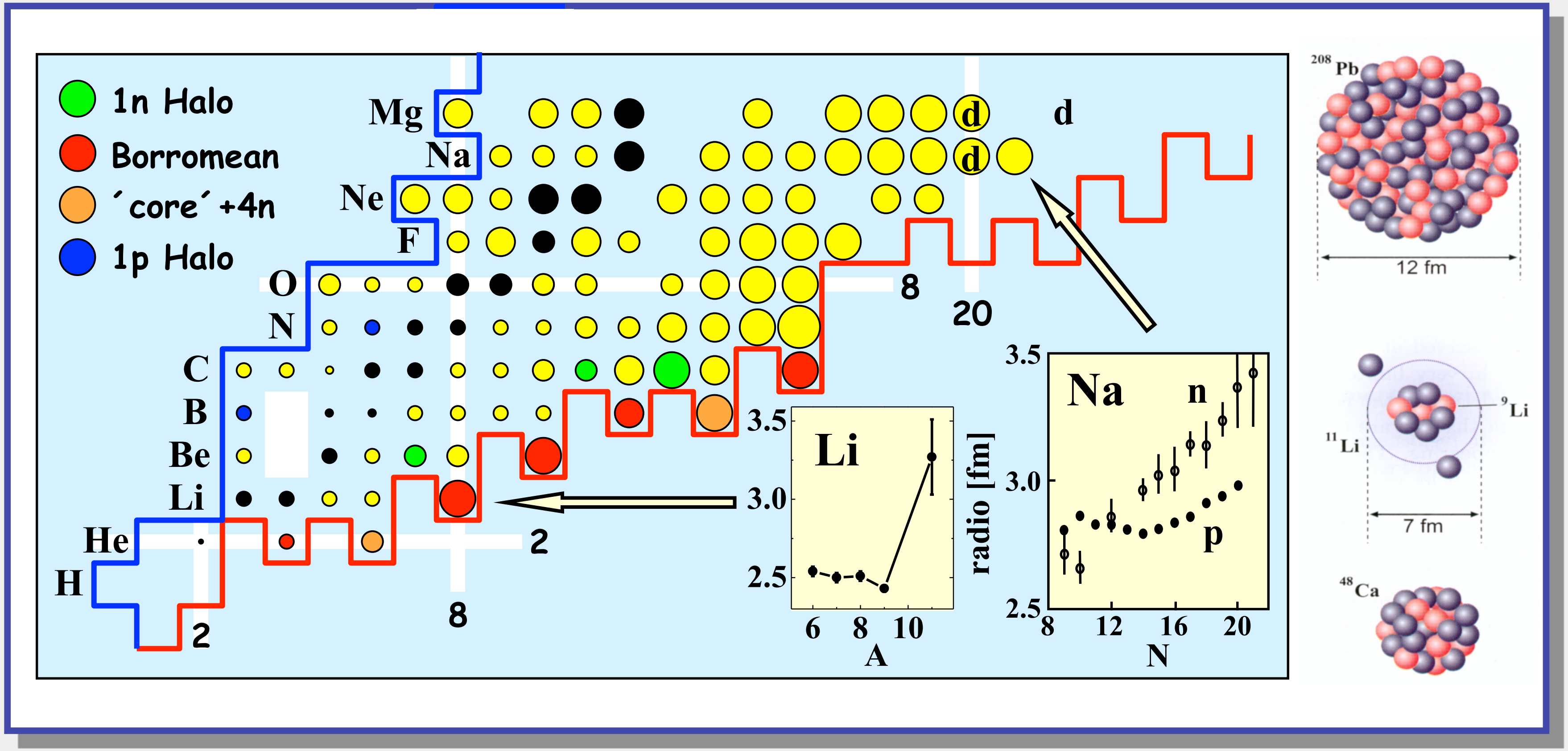
Let's play with all degrees of freedom





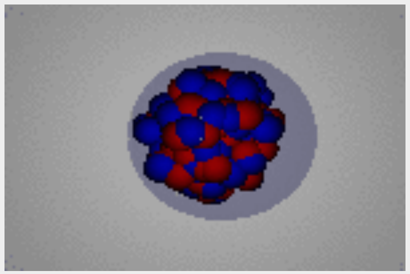
Let's start with the light nuclei !

Nuclear radii – halos and neutron skins

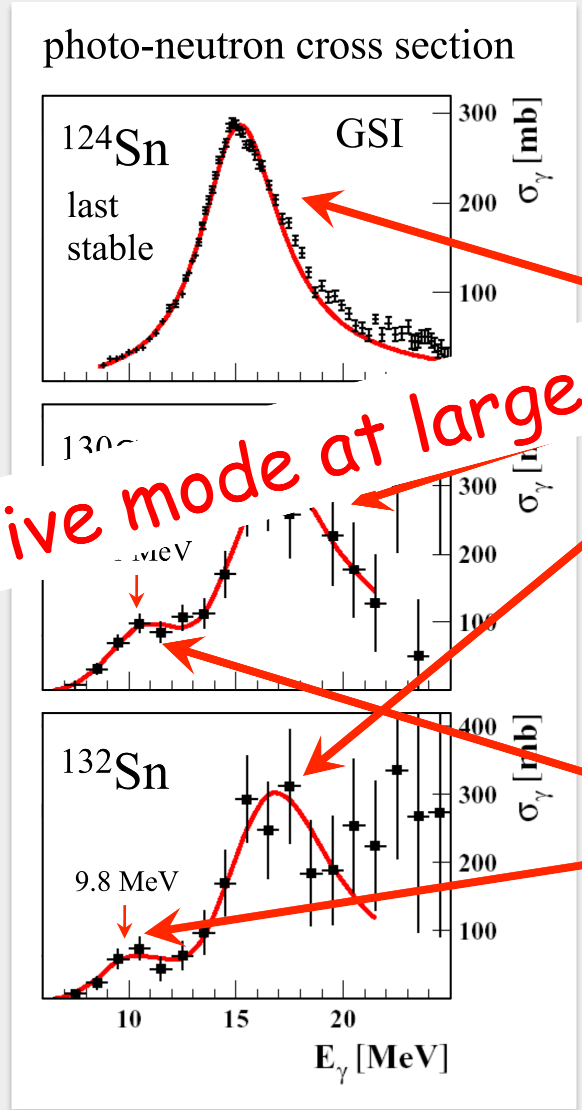


Remember:

- $R = r_0 \cdot A^{1/3}$ $r_0 = 1.1\text{-}1.2$ fm
- The thickness t of the nuclear surface is constant.
- Protons and neutrons are uniformly mixed.

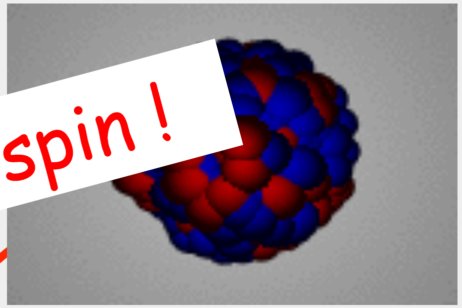


The Pygmy resonance in neutron-rich Sn isotopes

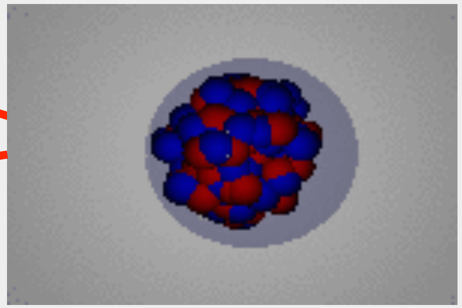


A new collective mode at large isospin !

Giant Dipole Resonance

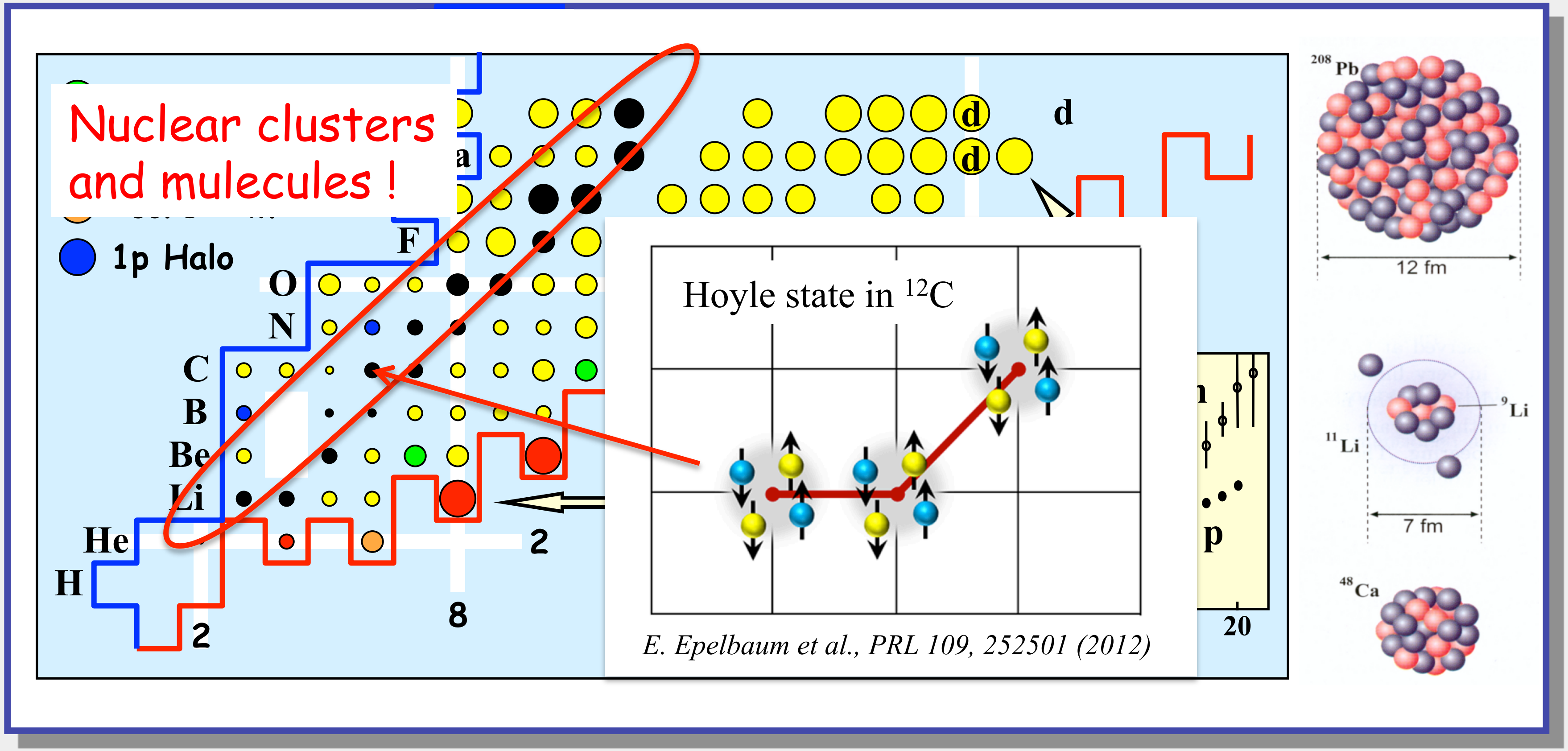


Pygmy Resonance



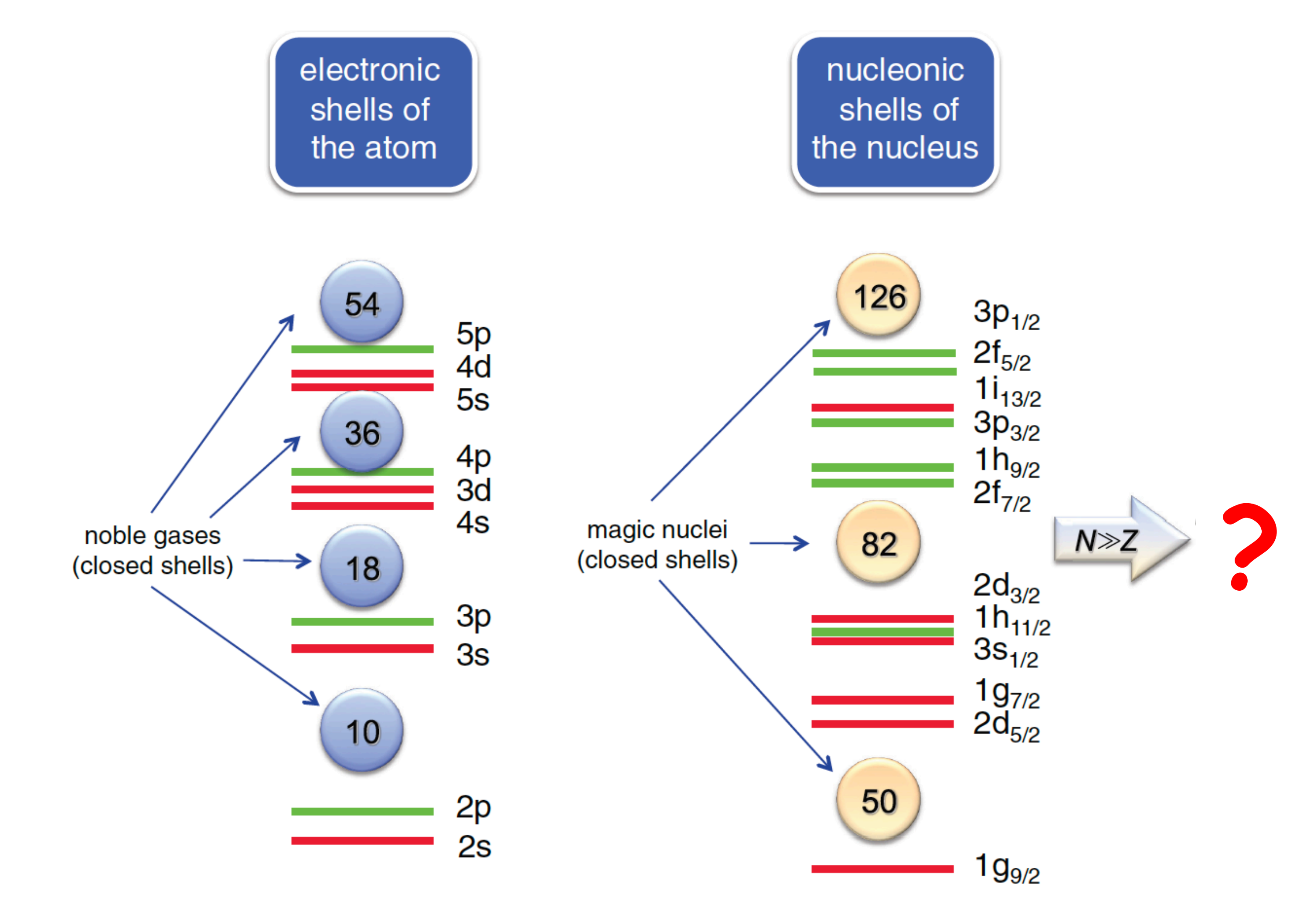
P. Adrich et al.
Phys. Rev. Lett. 95 (2005) 132501

Nuclear radii – halos and neutron skins

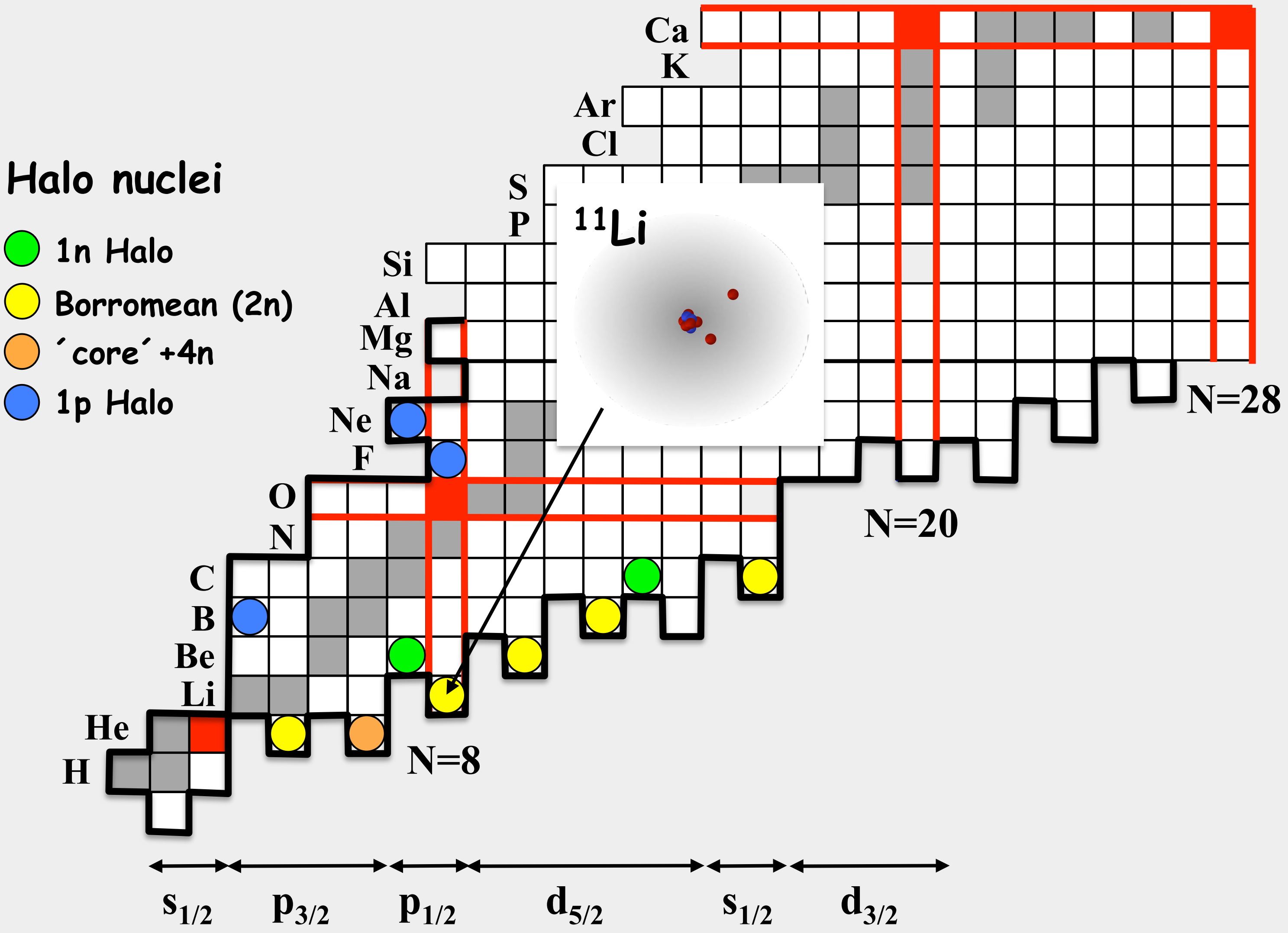


Light nuclei are indeed a rich playground !

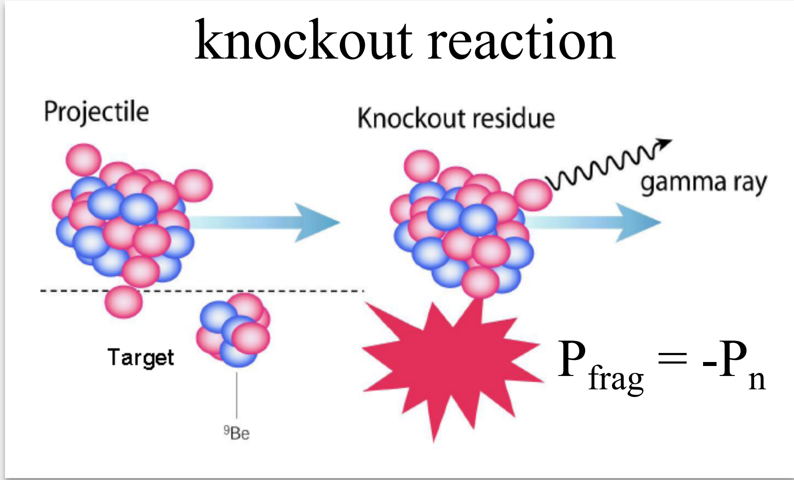
“Shell evolution” on the neutron-rich side



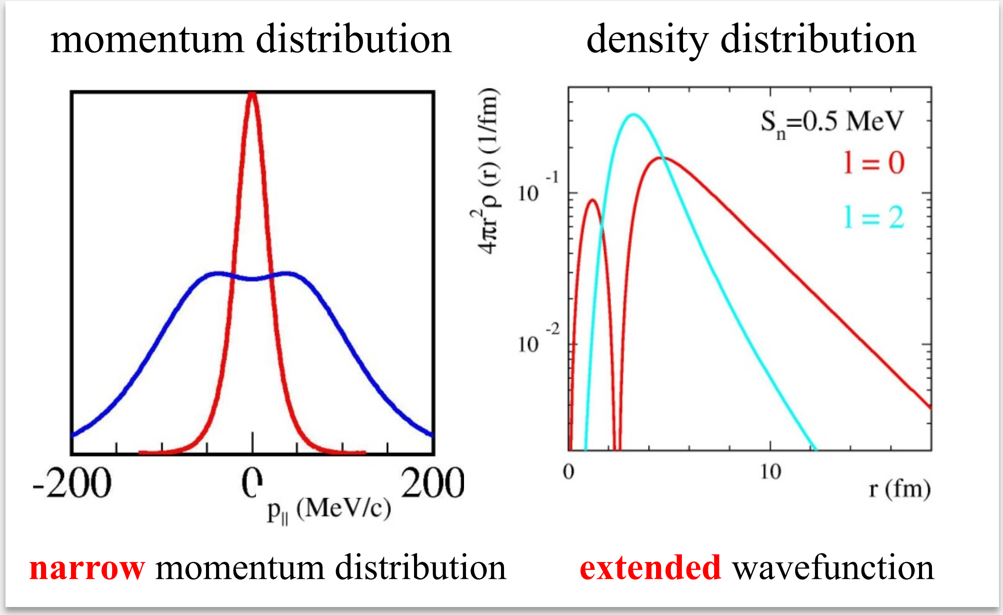
Neutron halos and the N=8 shell closure



Knockout reactions at relativistic energies

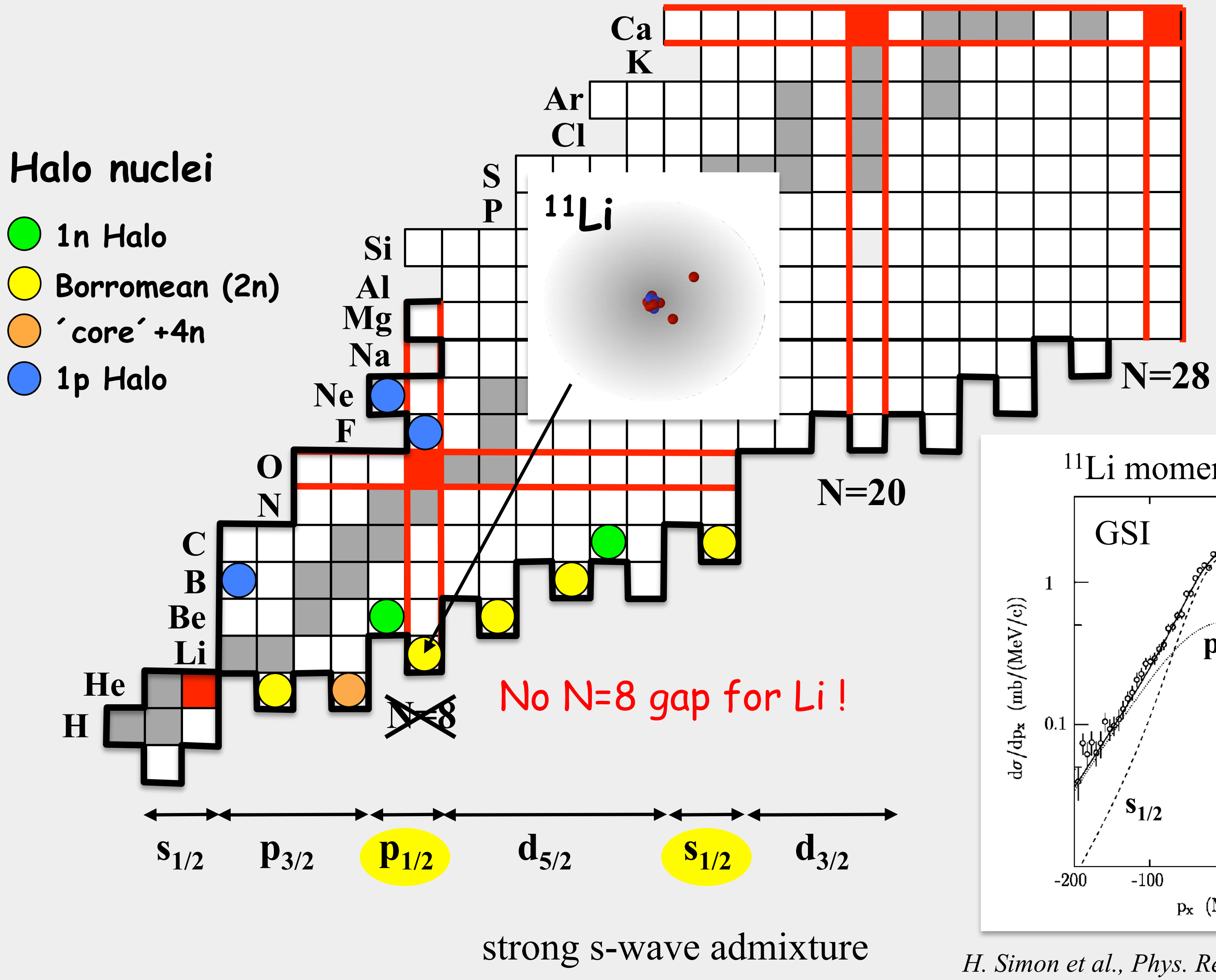


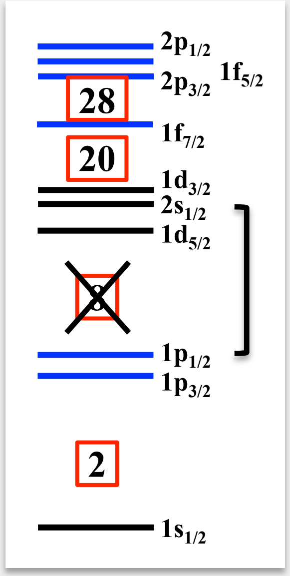
Heisenberg's uncertainty principle

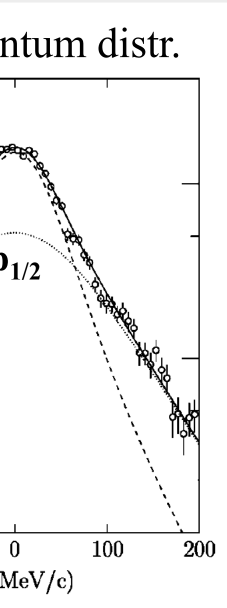


➡ angular momentum ℓ of the removed nucleon

Neutron halos and the N=8 shell closure





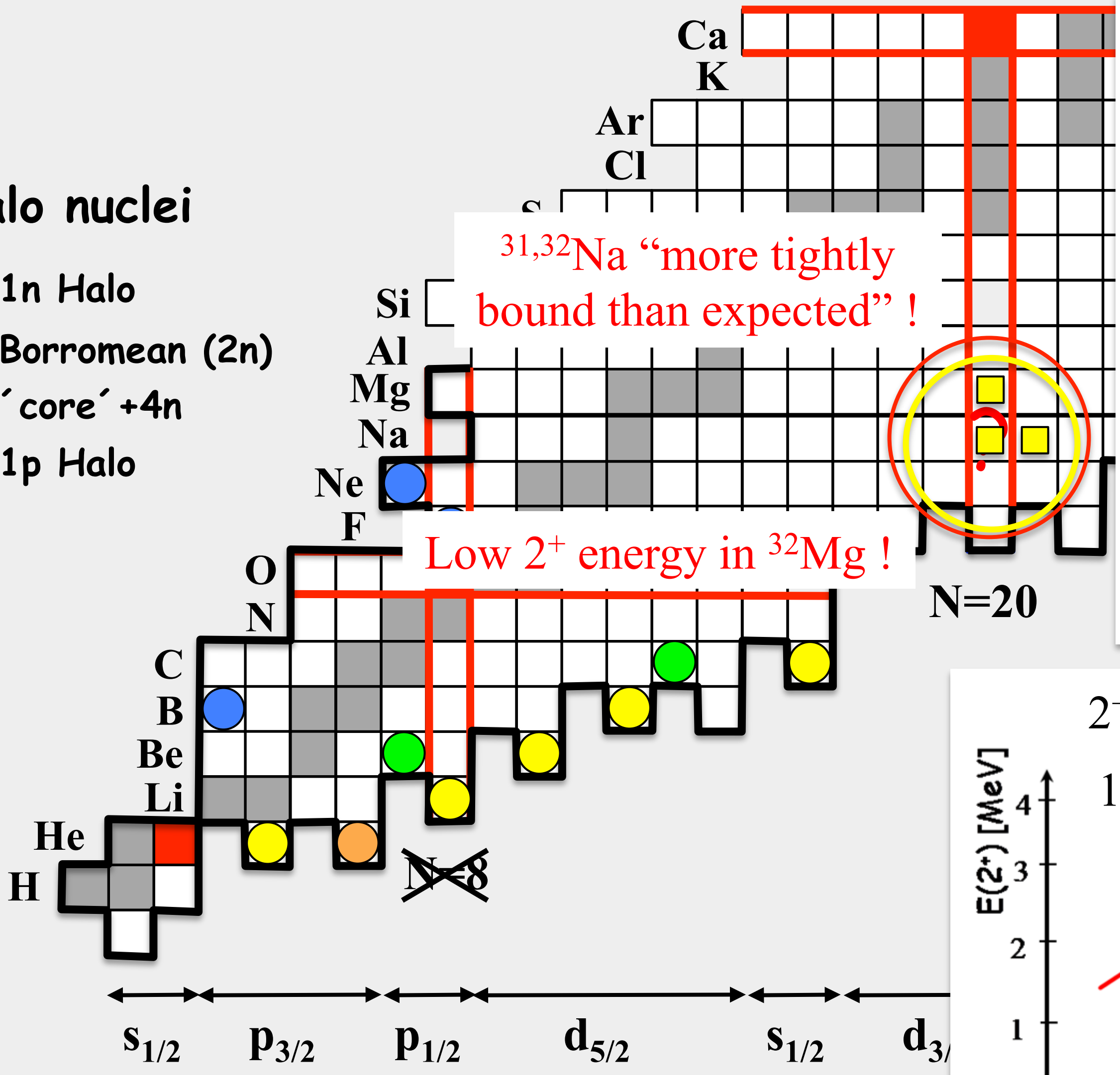


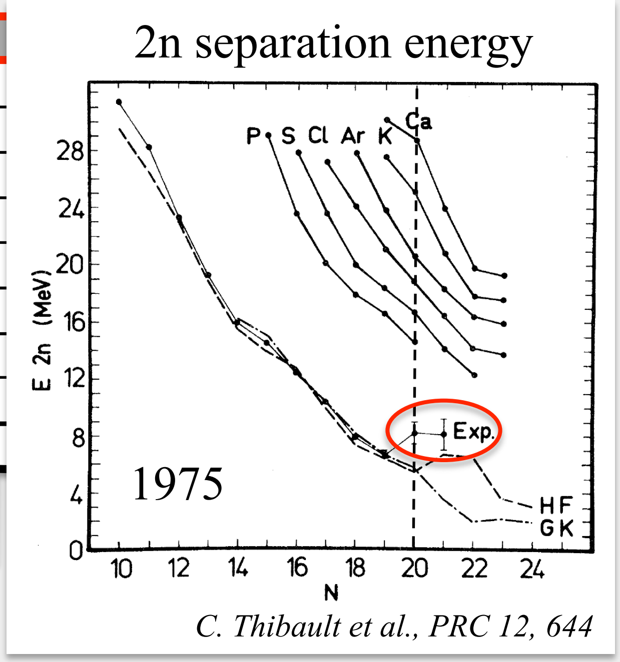
H. Simon et al., Phys. Rev. Lett. 83, 496 (1999)

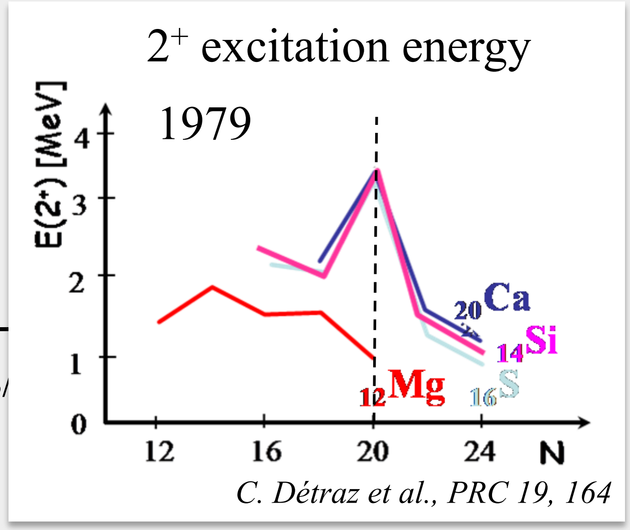
What about the N=20 shell closure ?

Halo nuclei

- 1n Halo
- Borromean (2n)
- ´core´ +4n
- 1p Halo

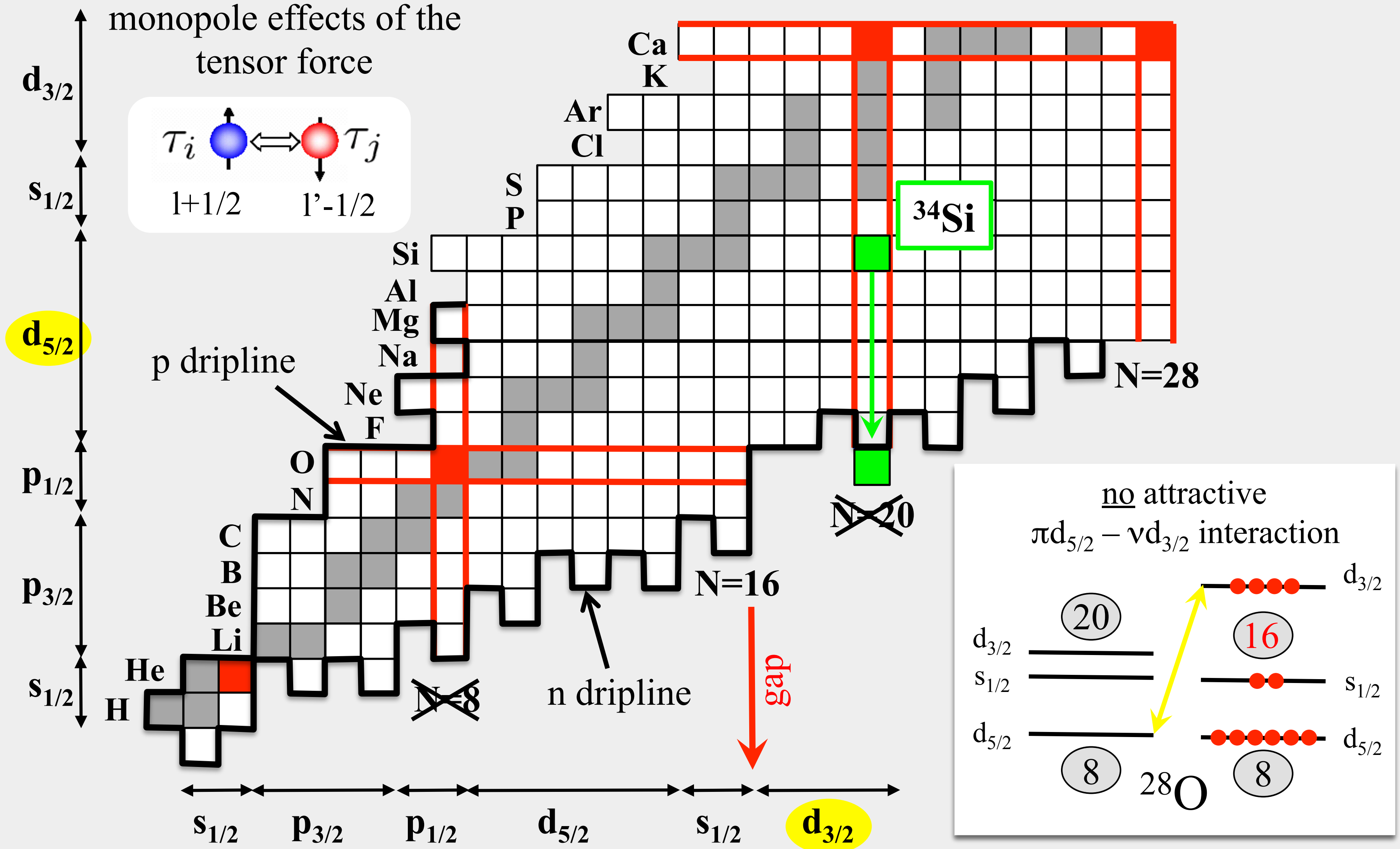




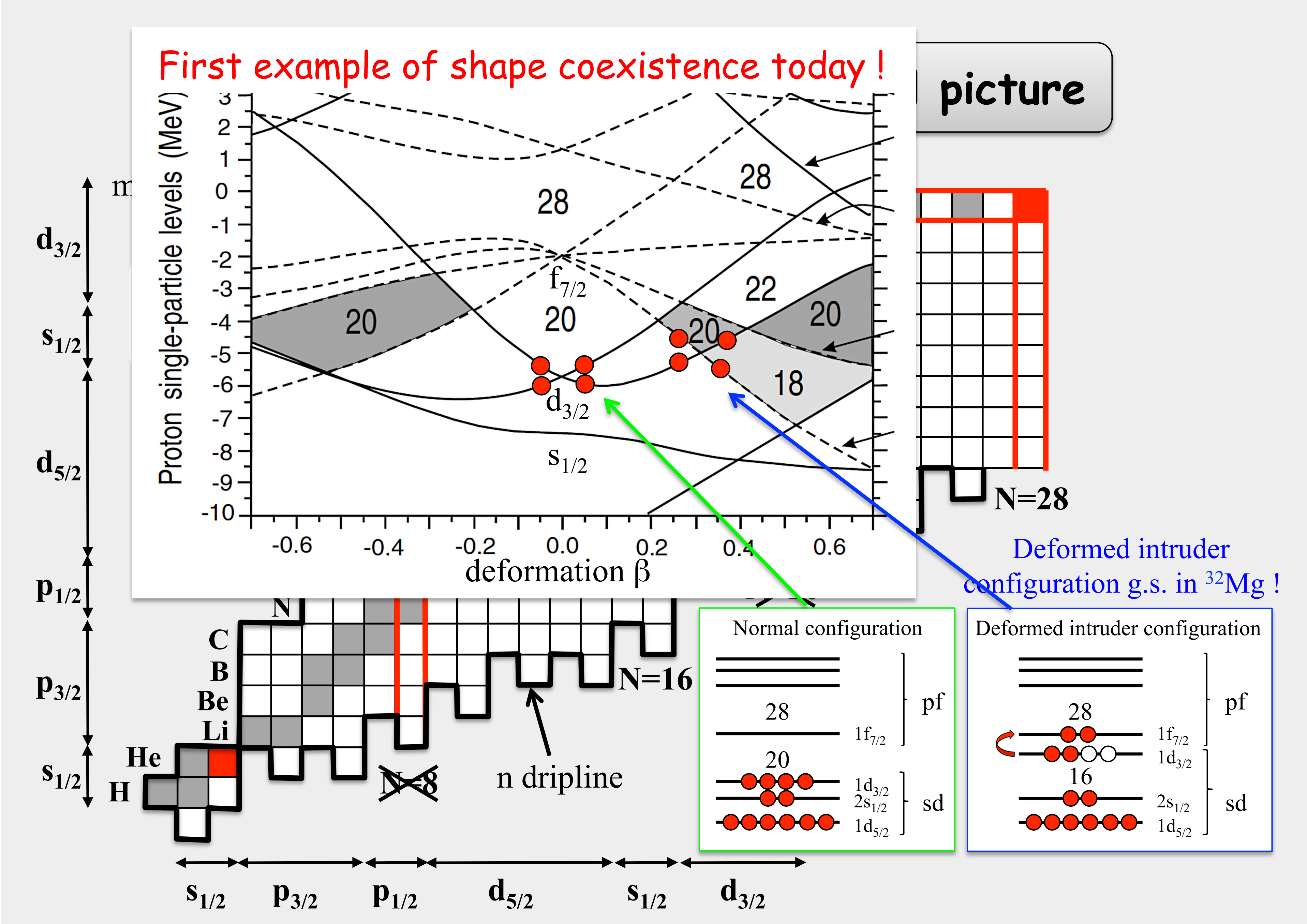


Since then a wealth of information in this region

Explanation within the shell model picture

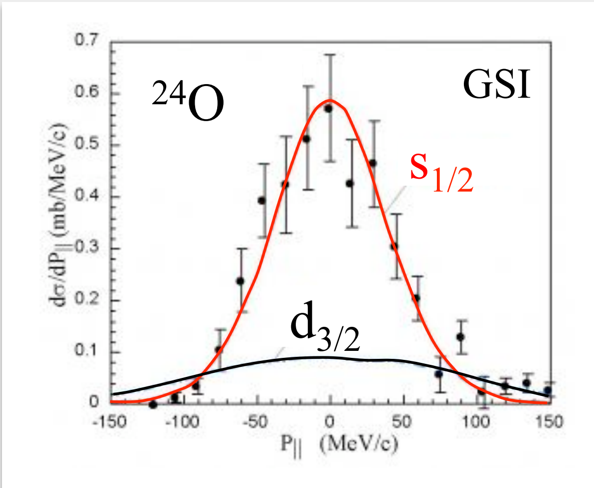


T. Otsuka et al., Phys. Rev. Lett. 87, 082502 (2001); Phys. Rev. Lett. 95, 232502 (2005)



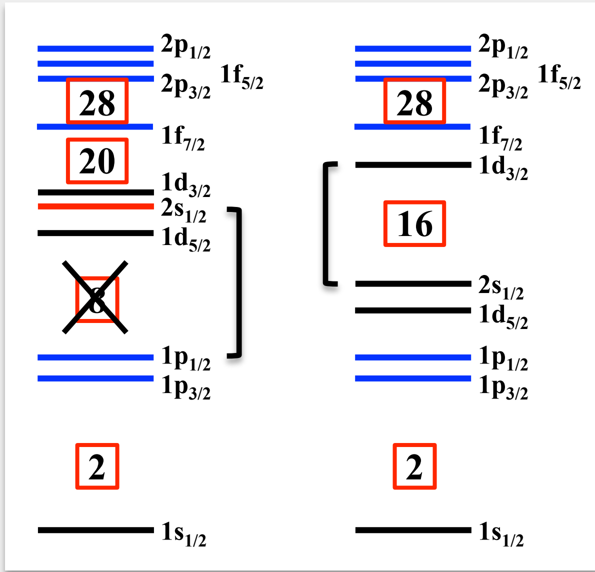
T. Otsuka et al., Phys. Rev. Lett. 87, 082502 (2001); Phys. Rev. Lett. 95, 232502 (2005)

Momentum distributions in $^{23,24}O$



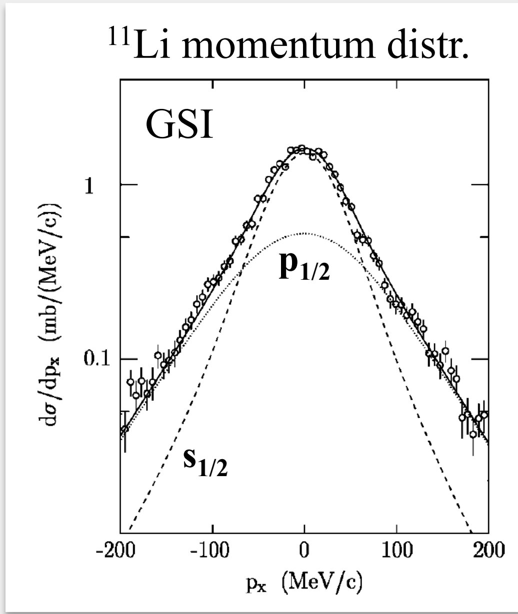
R. Kanungo et al., PRL 102, 152501 (2009)

Last neutron occupies $s_{1/2}$ orbital, no $d_{3/2}$ component !



$s_{1/2}$ and $d_{3/2}$ close in energy, mixing to be expected

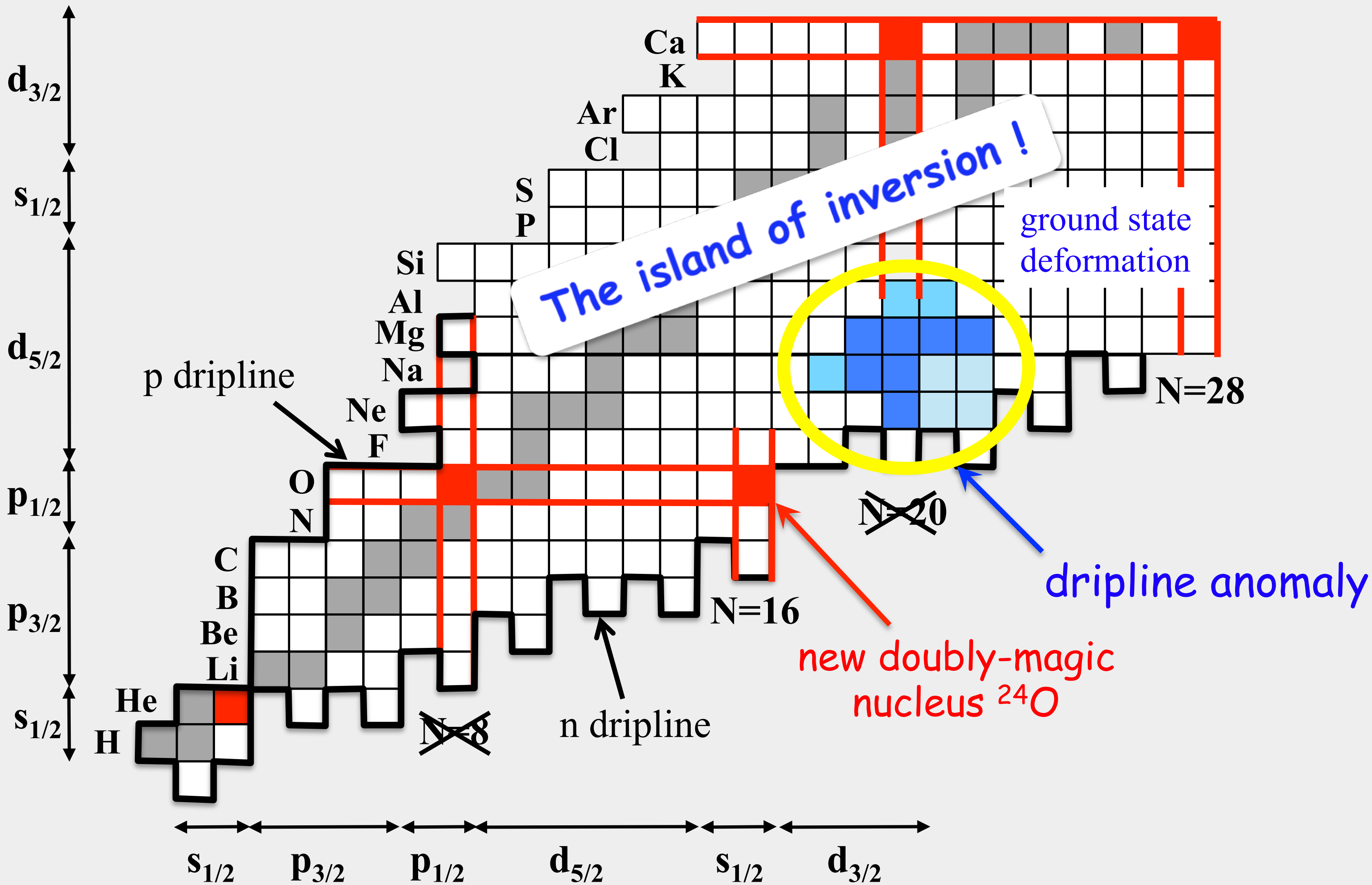
No mixing → N=16 gap !



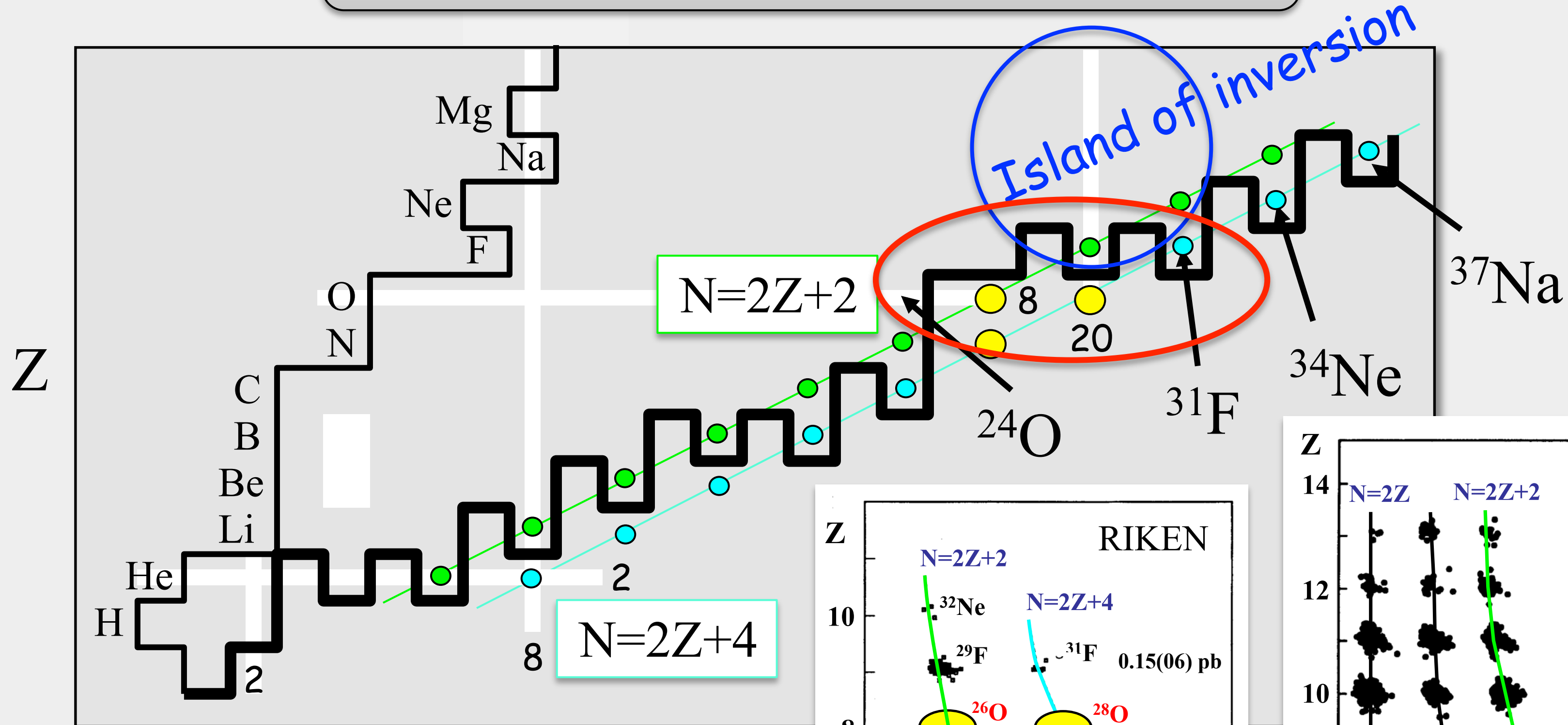
Spherical magic number at N=16,

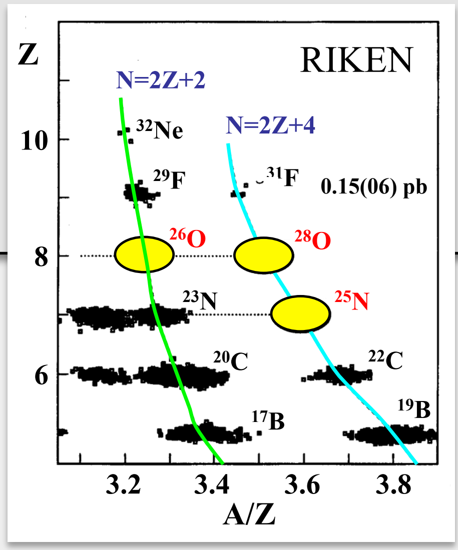
^{24}O doubly magic !

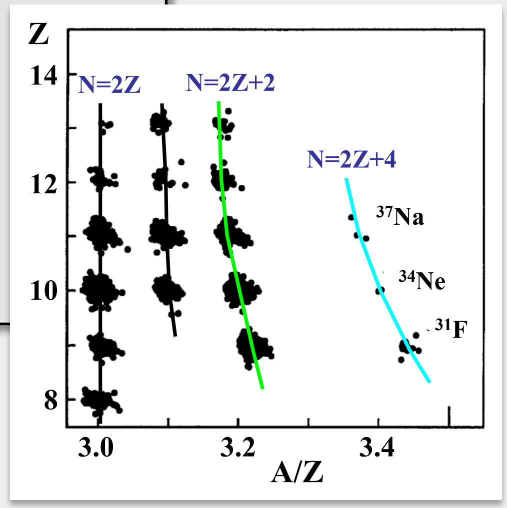
New magic number and the island of inversion



The neutron dripline up to Na







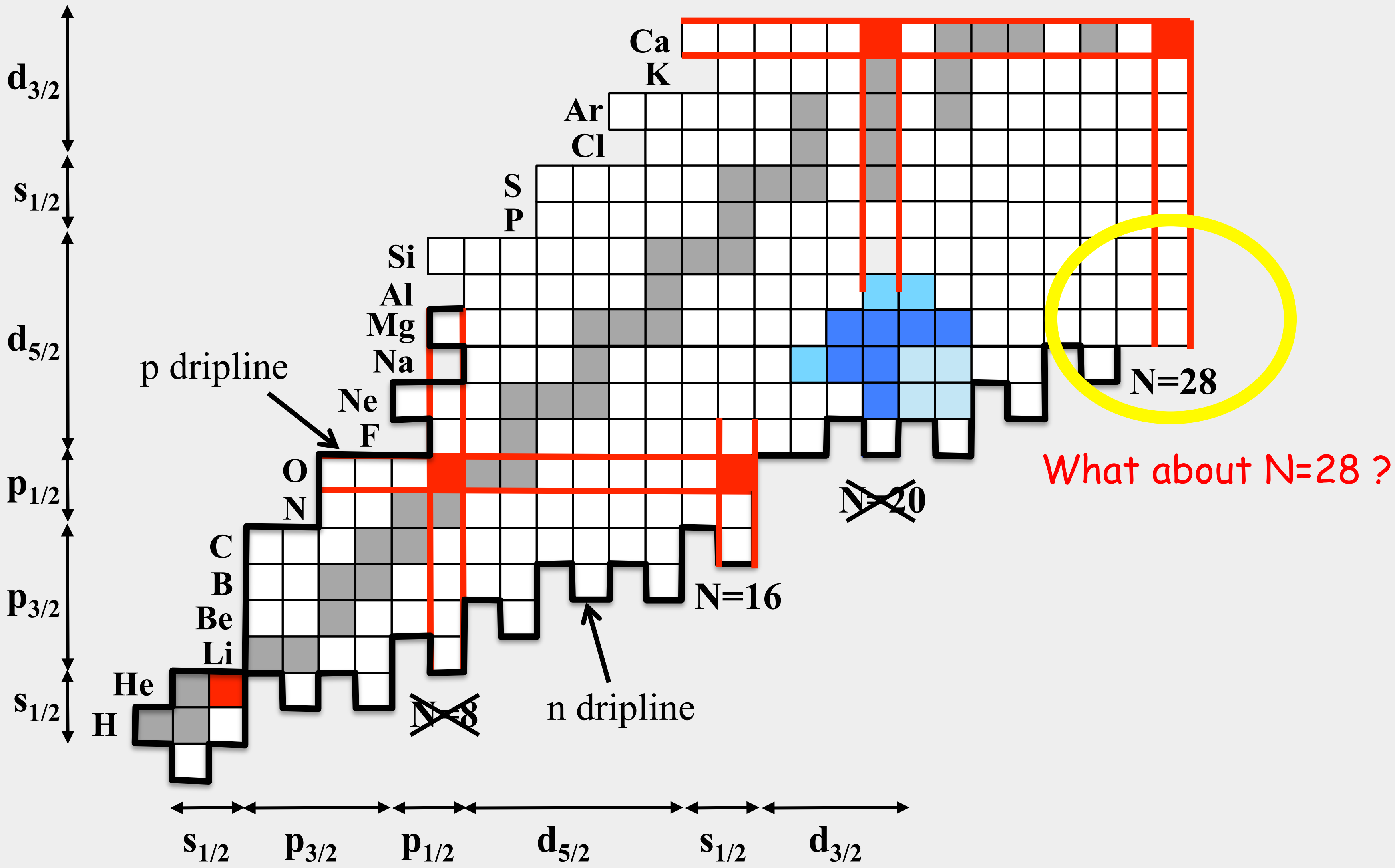
H. Sakurai et al., PLB 448 (1999) 180
M. Notani et al., PLB 542 (2002) 49

In F (Z=9) six more neutrones are bound as compared to O (Z=8) !

Additional binding due to deformation !!!

The mere existence of a nucleus already tells us something …

New magic number and the island of inversion



nature Vol 449|25 October 2007|doi:10.1038/nature06213

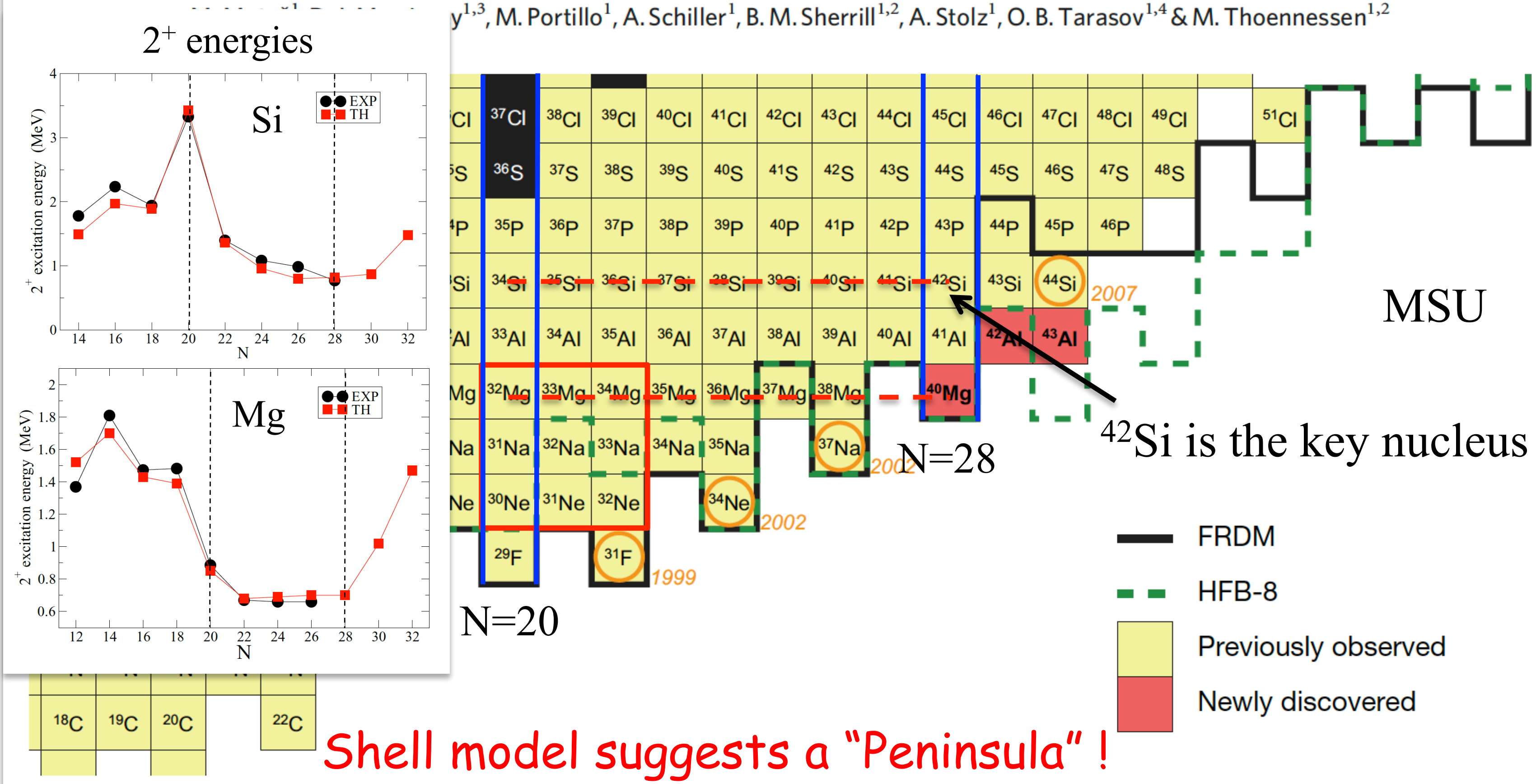
LETTERS

A second "island of inversion" at N=28 ?

Discovery of ^{40}Mg and ^{42}Al suggests neutron drip-line slant towards heavier isotopes

2007

T. Baumann[1], A. M. Amthor[1,2], D. Bazin[1], B. A. Brown[1,2], C. M. Folden III[1], A. Gade[1,2], T. N. Ginter[1], M. Hausmann[1], ... y[1,3], M. Portillo[1], A. Schiller[1], B. M. Sherrill[1,2], A. Stolz[1], O. B. Tarasov[1,4] & M. Thoennessen[1,2]



Shell model suggests a "Peninsula" !

What about the N=28 shell closure ?

More complete experimental information needed !

nature Vol 435|16 June 2005|doi:10.1038/nature03619

LETTERS 2005

'Magic' nucleus ^{42}Si

J. Fridmann[1], I. Wiedenhöver[1], A. Gade[2], L. T. Baby[1], D. Bazin[2], B. A. Brown[2], C. M. Campbell[2], J. M. Cook[2], P. D. Cottle[1], E. Diffenderfer[1], D.-C. Dinca[2], T. Glasmacher[2], P. G. Hansen[2], K. W. Kemper[1], J. L. Lecouey[2], W. F. Mueller[2], H. Olliver[2], E. Rodriguez-Vieitez[3], J. R. Terry[2], J. A. Tostevin[4] & K. Yoneda[2]

PRL **99,** 022503 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

2007

Collapse of the $N = 28$ Shell Closure in ^{42}Si

B. Bastin,[2] S. Grévy,[1,*] D. Sohler,[3] O. Sorlin,[1
D. Baiborodin,[5] R. Borcea,[6] C. Bourgeois,[4] A. Buta,[6
Z. Elekes,[3] S. Franchoo,[4] S. Iacob,[6] B. Laurent,[2] M.
N. A. Orr,[2] Y. Penionzhkevich,[10] Z
M. G. Saint-Laur

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PHYSICS LETTERS B
Physics Letters B 649 (2007) 43–48
www.elsevier.com/locate/physletb

2007

Mass measurements of neutron-rich nuclei near the $N = 20$ and 28 shell closures

homaz [a], D. Baiborodin [c],
lbert [f], L. Giot [a], A. Khouaja [a],
h [h], S. Pita [a], M. Rousseau [a],

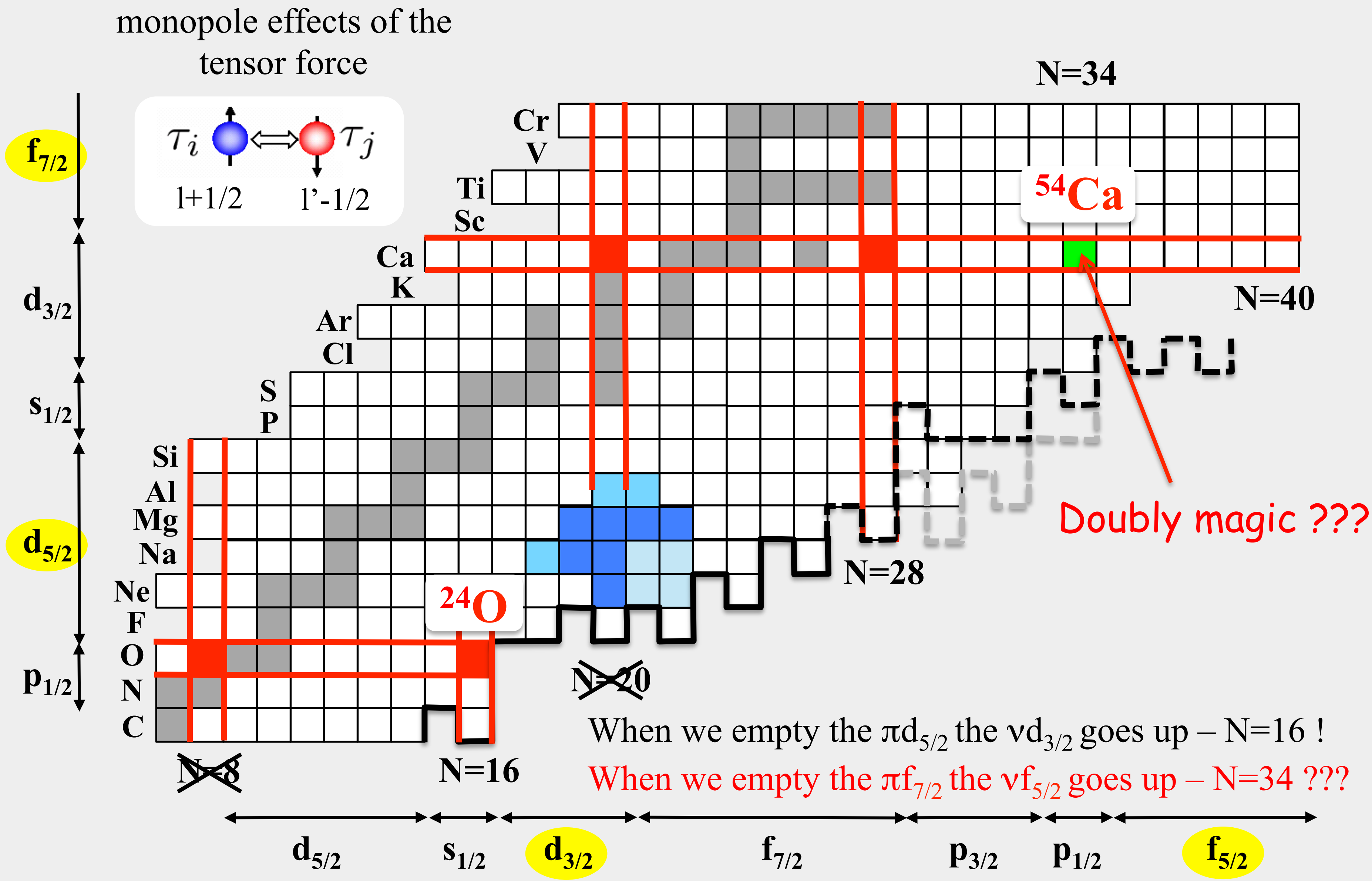
PRL **109,** 182501 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

2012

Well Developed Deformation in ^{42}Si

S. Takeuchi,[1,*] M. Matsushita,[1,2,†] N. Aoi,[1,‡] P. Doornenbal,[1] K. Li,[1,3] T. Motobayashi,[1] H. Scheit,[1,§] D. Steppenbeck,[1,†] H. Wang,[1,3] H. Baba,[1] D. Bazin,[4] L. Càceres,[5] H. Crawford,[6] P. Fallon,[6] R. Gernhäuser,[7] J. Gibelin,[8] S. Go,[9] S. Grévy,[5] C. Hinke,[7] C. R. Hoffman,[10] R. Hughes,[11] E. Ideguchi,[9,‡] D. Jenkins,[12] N. Kobayashi,[13] Y. Kondo,[13] R. Krücken,[7,||] T. Le Bleis,[14,15,¶] J. Lee,[1] G. Lee,[13] A. Matta,[16] S. Michimasa,[9] T. Nakamura,[13] S. Ota,[9] M. Petri,[6,§] T. Sako,[13] H. Sakurai,[1] S. Shimoura,[9] K. Steiger,[7] K. Takahashi,[13] M. Takechi,[1,**] Y. Togano,[1,**] R. Winkler,[4,††] and K. Yoneda[1]

Is N=34 a new magic number far-off stability ?



When we empty the $\pi d_{5/2}$ the $\nu d_{3/2}$ goes up – N=16 !

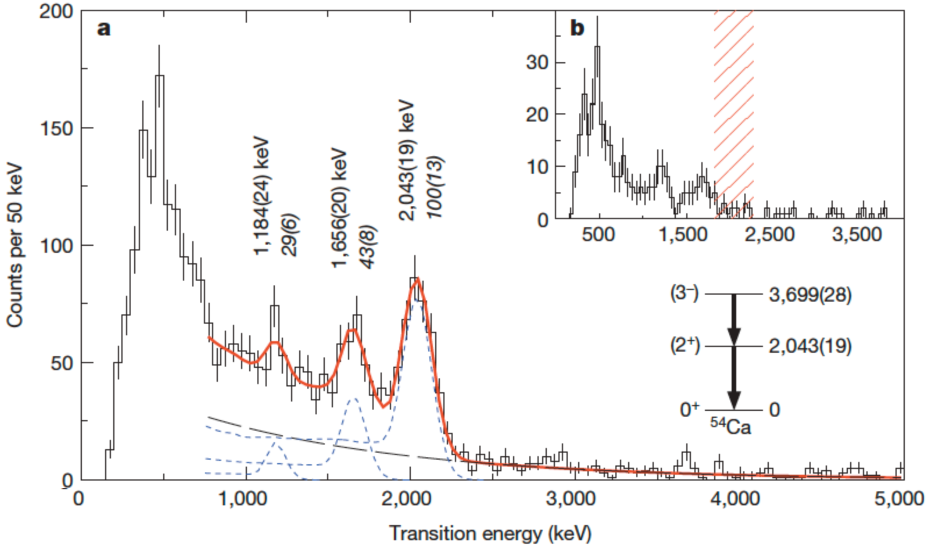
When we empty the $\pi f_{7/2}$ the $\nu f_{5/2}$ goes up – N=34 ???

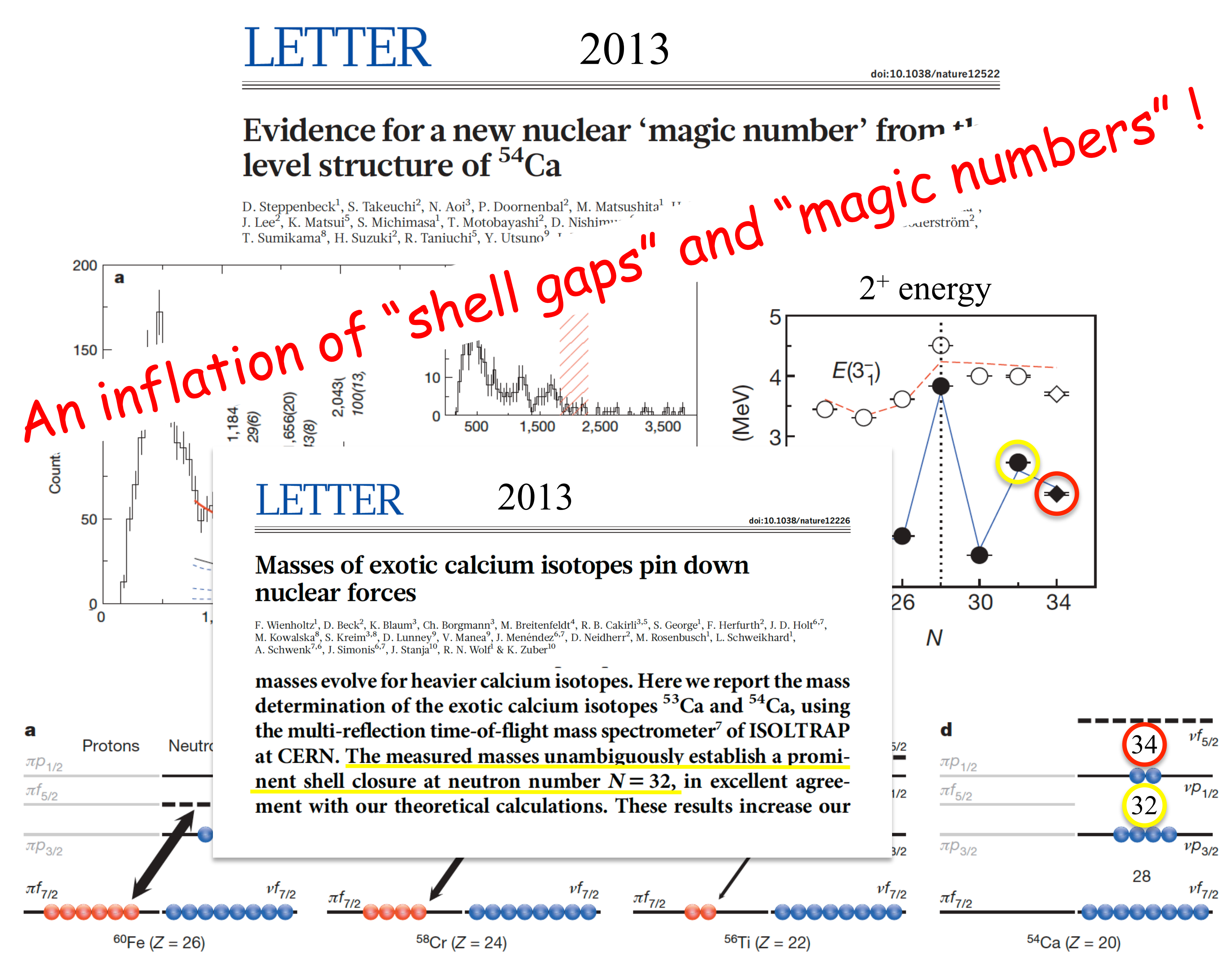
LETTER 2013

doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

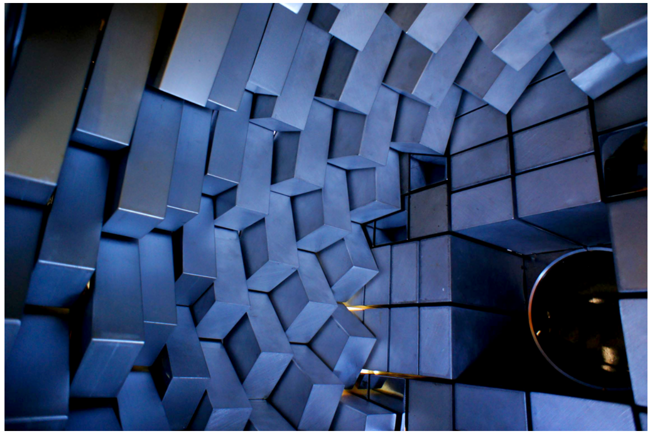
D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]



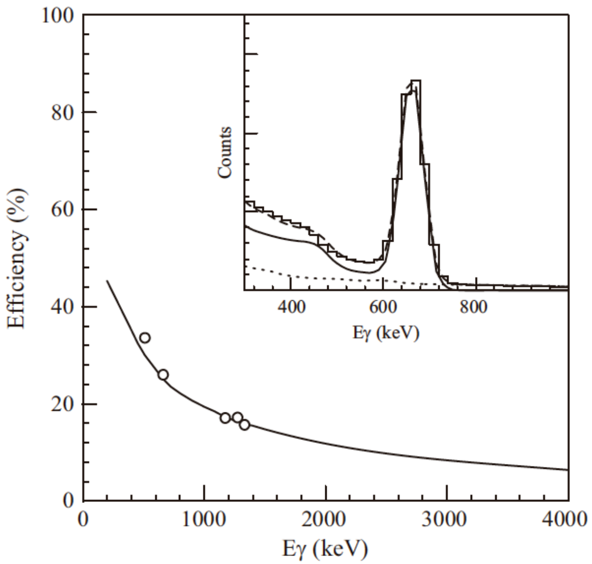


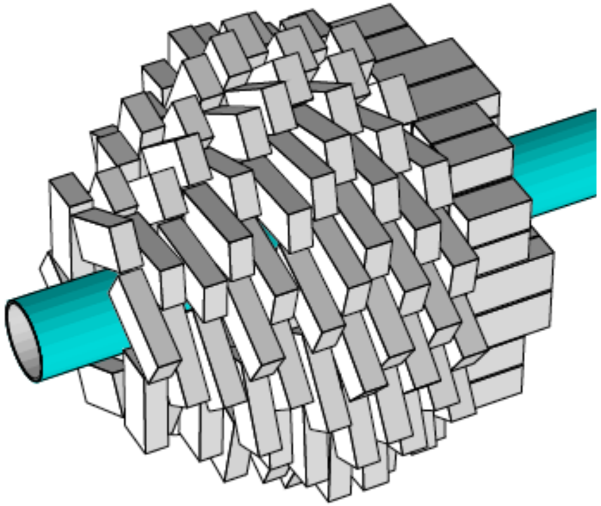
An inflation of "shell gaps" and "magic numbers" !
LETTER 2013
doi:10.1038/nature12522
Evidence for a new nuclear 'magic number' from the level structure of 54Ca
D. Steppenbeck, S. Takeuchi, N. Aoi, P. Doornenbal, M. Matsushita, J. Lee, K. Matsui, S. Michimasa, T. Motobayashi, D. Nishimura, T. Sumikama, H. Suzuki, R. Taniuchi, Y. Utsuno
2+ energy
E(3−1)
(MeV)
N
26
30
34
Count
a
Protons
πp1/2
πf5/2
πp3/2
πf7/2
νf7/2
νf5/2
νp1/2
νp3/2
34
32
28
60Fe (Z = 26)
58Cr (Z = 24)
56Ti (Z = 22)
54Ca (Z = 20)
d
LETTER 2013
doi:10.1038/nature12226
Masses of exotic calcium isotopes pin down nuclear forces
F. Wienholtz, D. Beck, K. Blaum, Ch. Borgmann, M. Breitenfeldt, R. B. Cakirli, S. George, F. Herfurth, J. D. Holt, M. Kowalska, S. Kreim, D. Lunney, V. Manea, J. Menéndez, D. Neidherr, M. Rosenbusch, L. Schweikhard, A. Schwenk, J. Simonis, J. Stanja, R. N. Wolf & K. Zuber
masses evolve for heavier calcium isotopes. Here we report the mass determination of the exotic calcium isotopes 53Ca and 54Ca, using the multi-reflection time-of-flight mass spectrometer of ISOLTRAP at CERN. The measured masses unambiguously establish a prominent shell closure at neutron number N = 32, in excellent agreement with our theoretical calculations. These results increase our

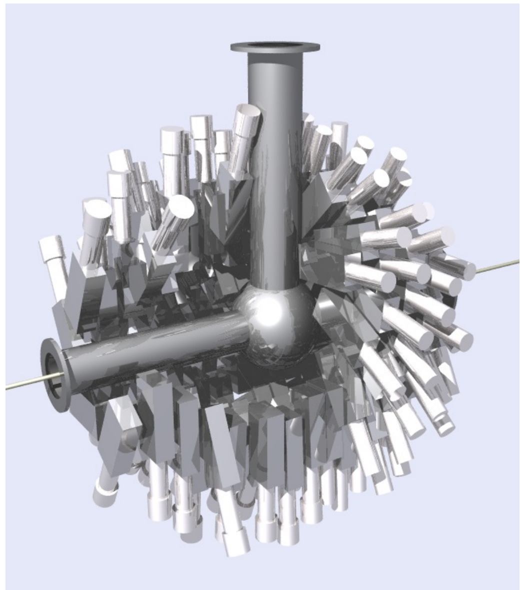
The γ-ray spectrometer DALI2 at RIKEN



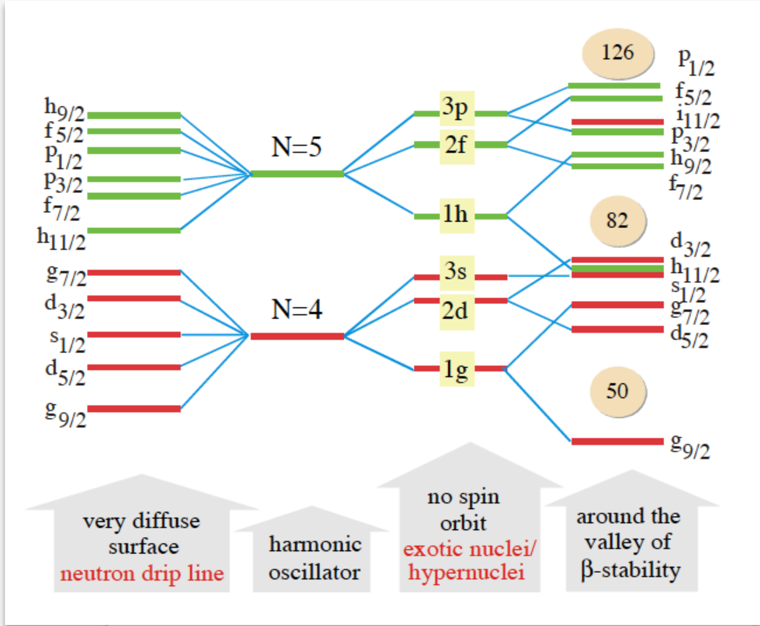
186 NaI (Tl)
scintillators



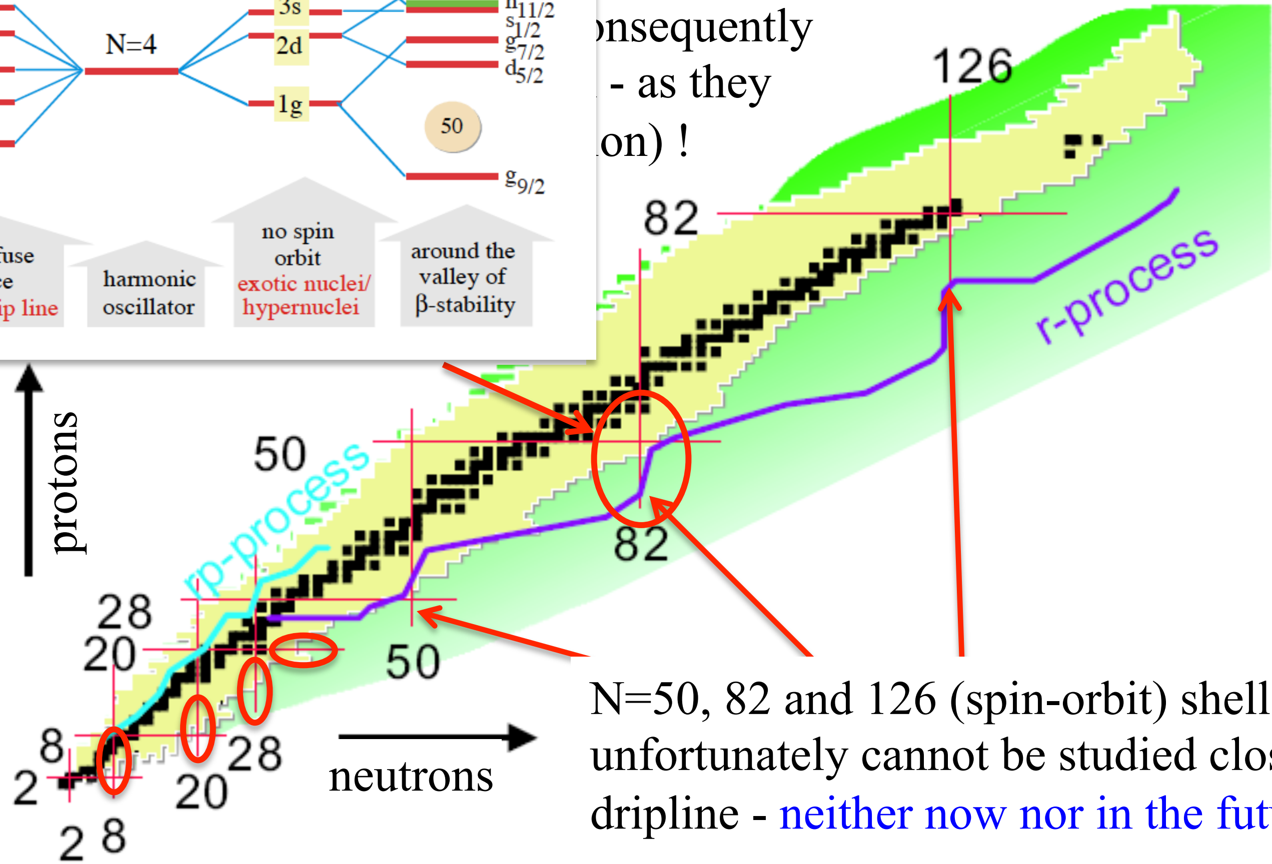




eutron-rich region



nsequently
- as they
on) !

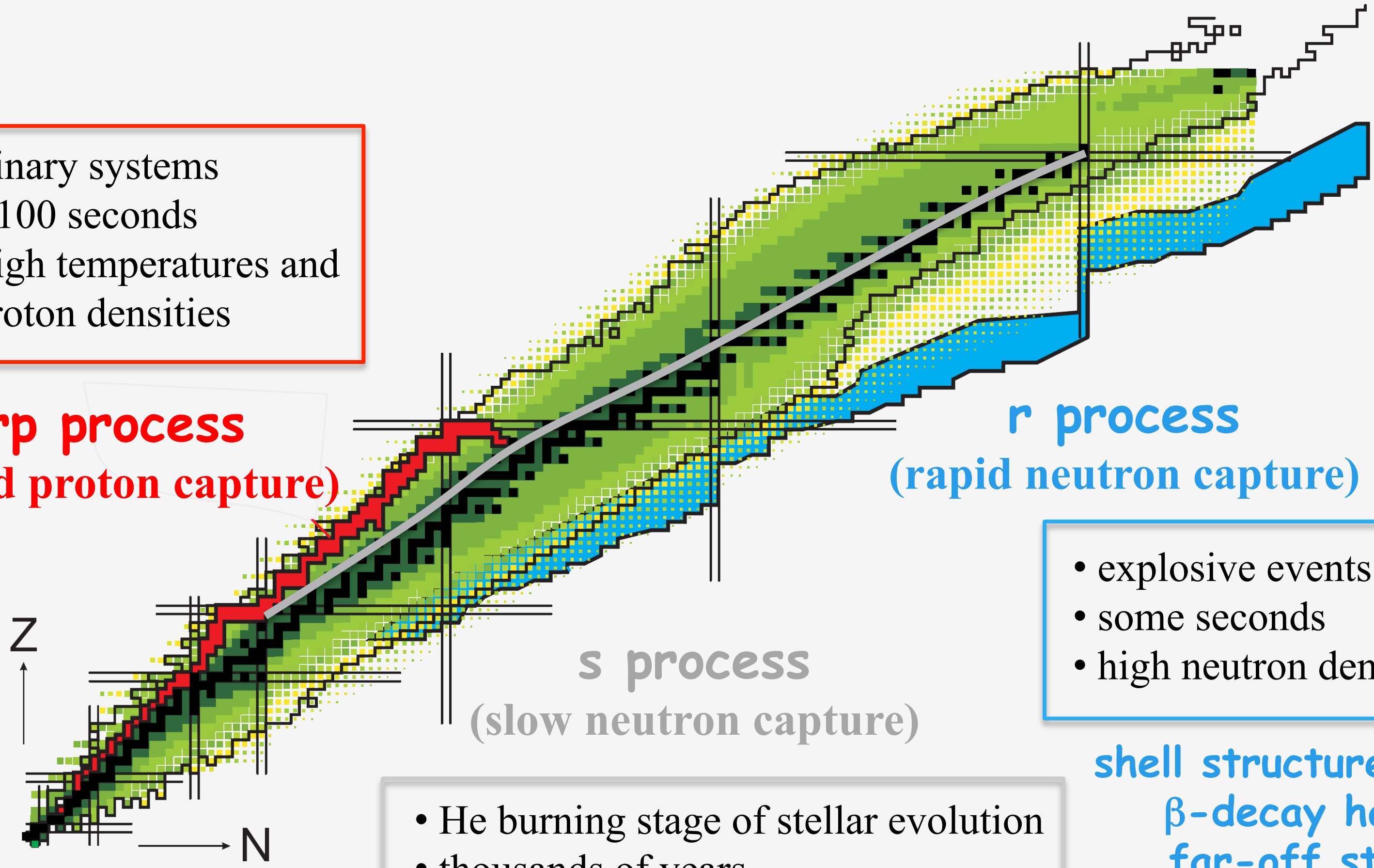


N=50, 82 and 126 (spin-orbit) shell closures unfortunately cannot be studied close to the dripline - neither now nor in the future.

Nucleosynthesis of the heaviest elements

- binary systems
- ~100 seconds
- high temperatures and proton densities

rp process
(rapid proton capture)



r process
(rapid neutron capture)

- explosive events
- some seconds
- high neutron densities

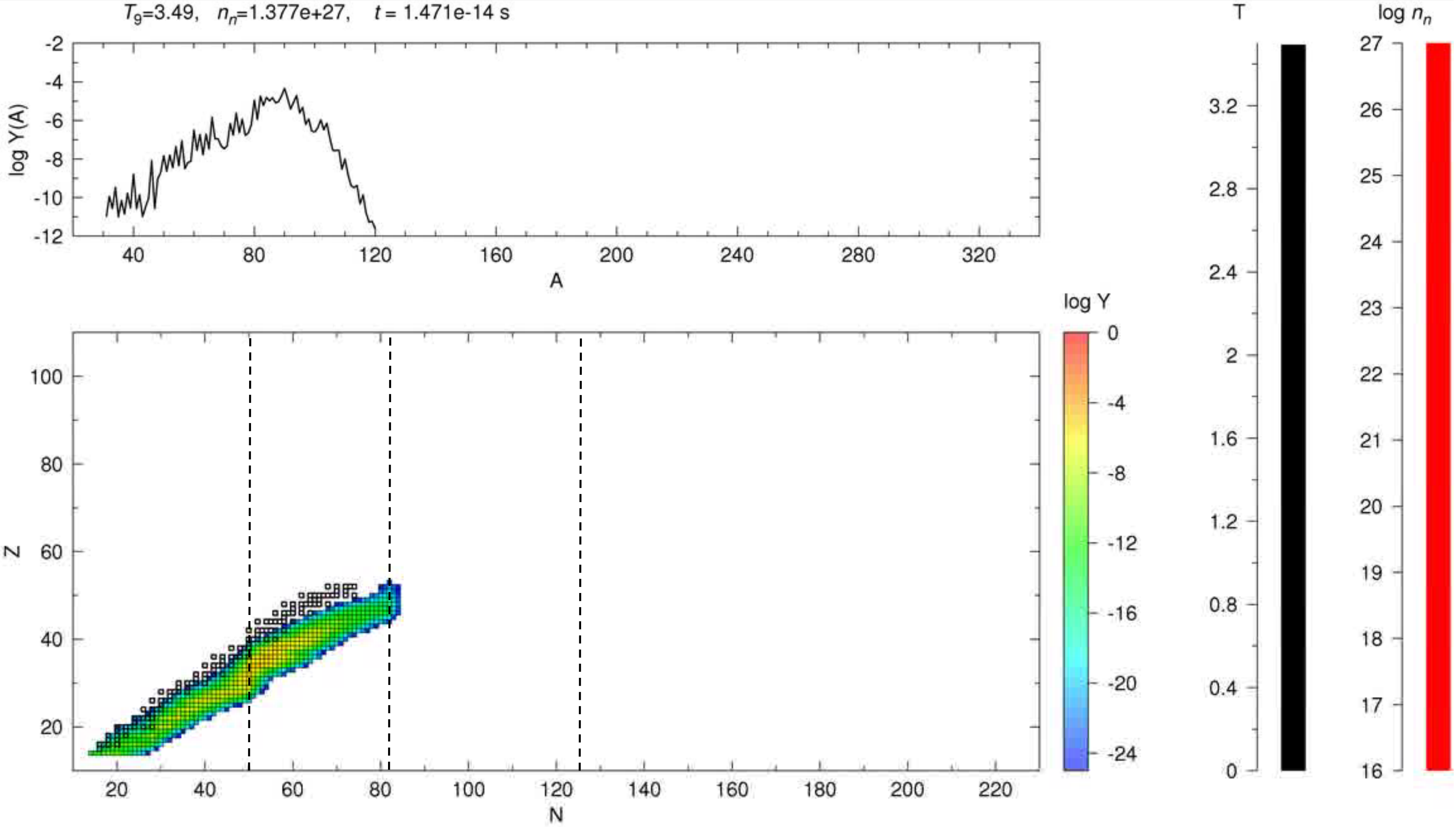
shell structure, masses, β-decay halflives far-off stability

s process
(slow neutron capture)

- He burning stage of stellar evolution
- thousands of years
- low neutron densities

n-capture cross sections of stable nuclei

Realistic r process calculations (G. Martínez Pinedo)



Most nuclear input data are theoretical estimates !

The importance of the N=82,126 shell closures

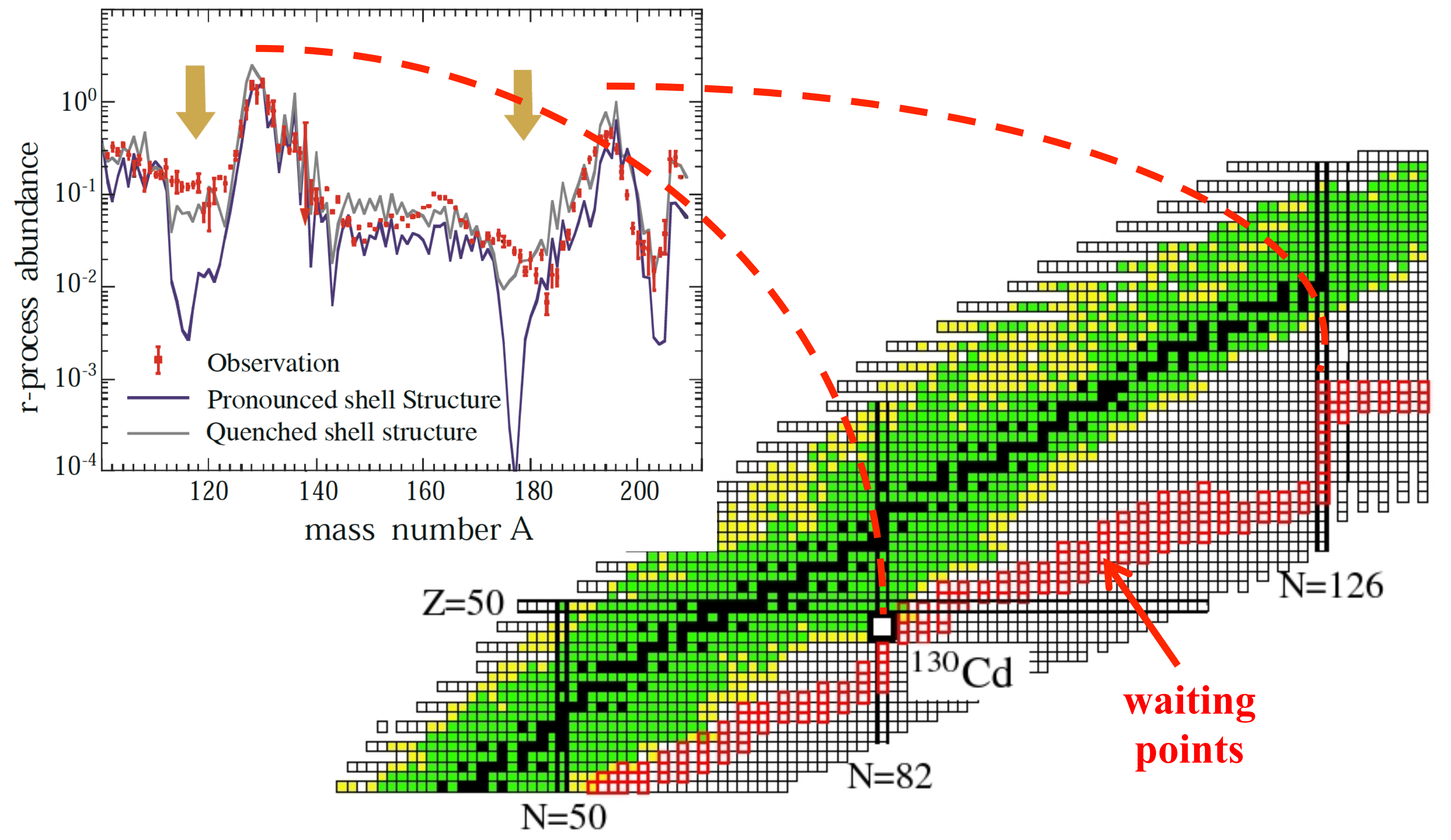
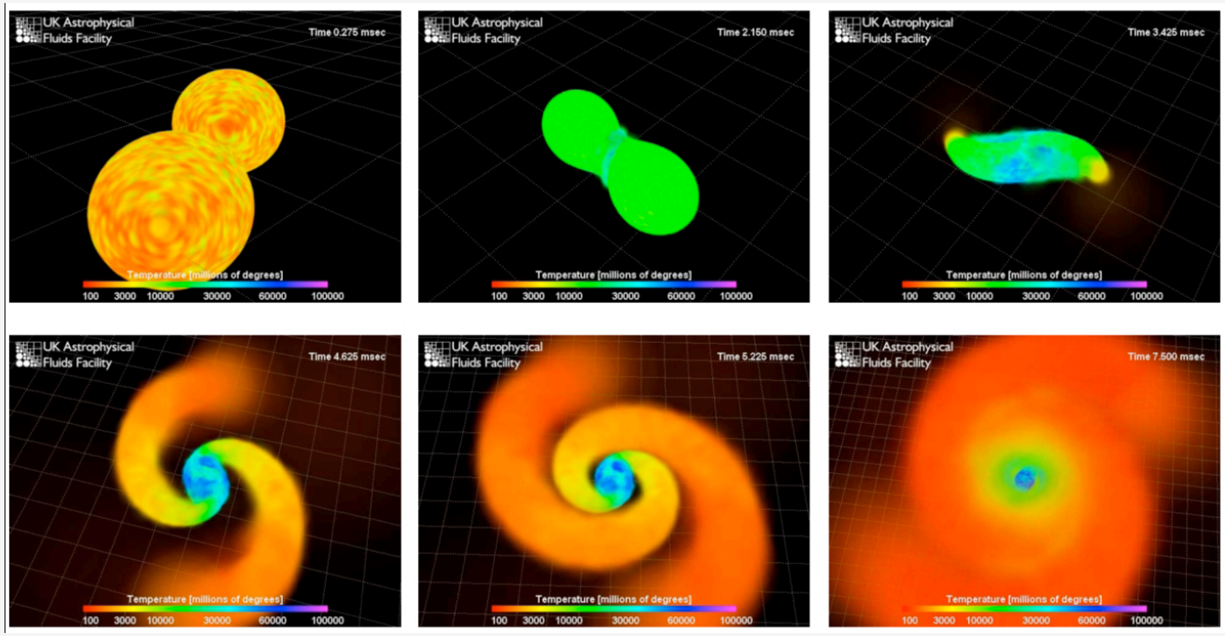


Figure shown in nearly all glossy brochures for future facilities …

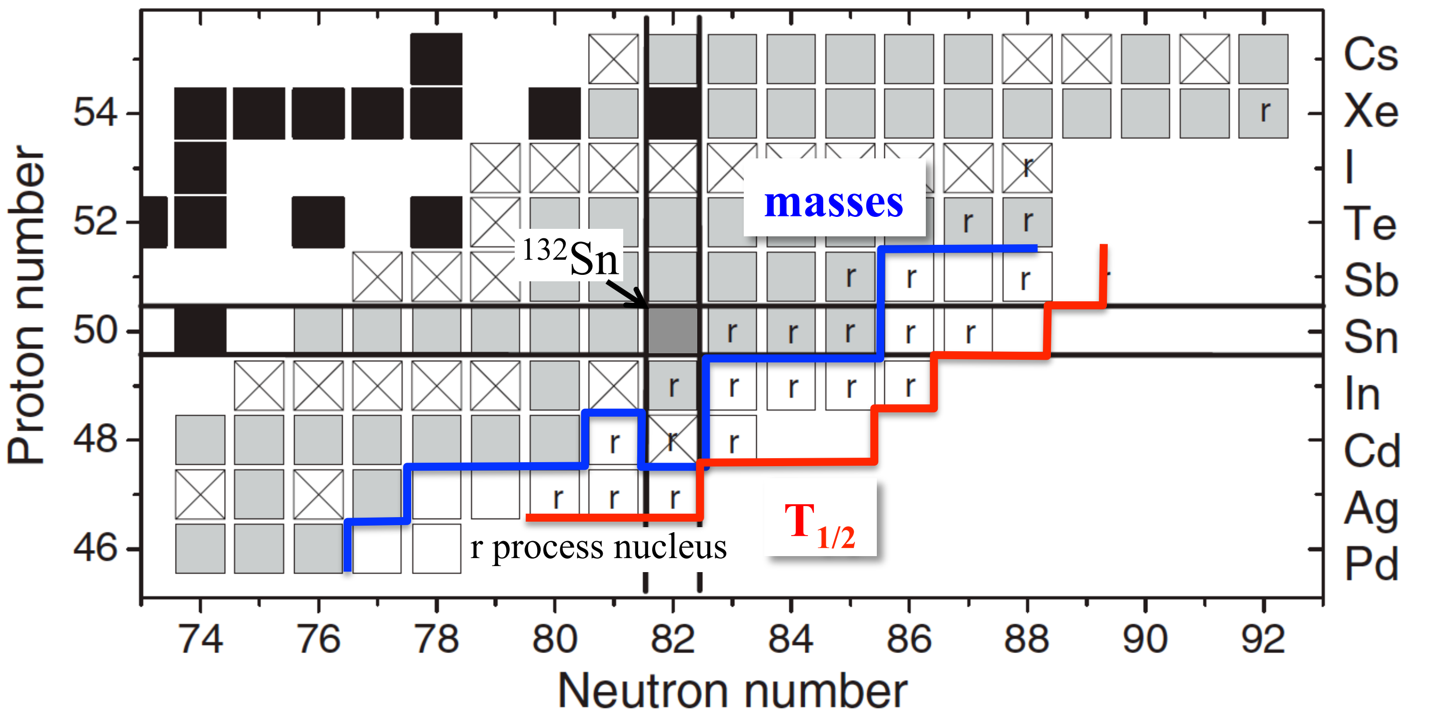
Supernovae remnant Crab nebula

Site of r-process still an open question !

Merging neutron stars



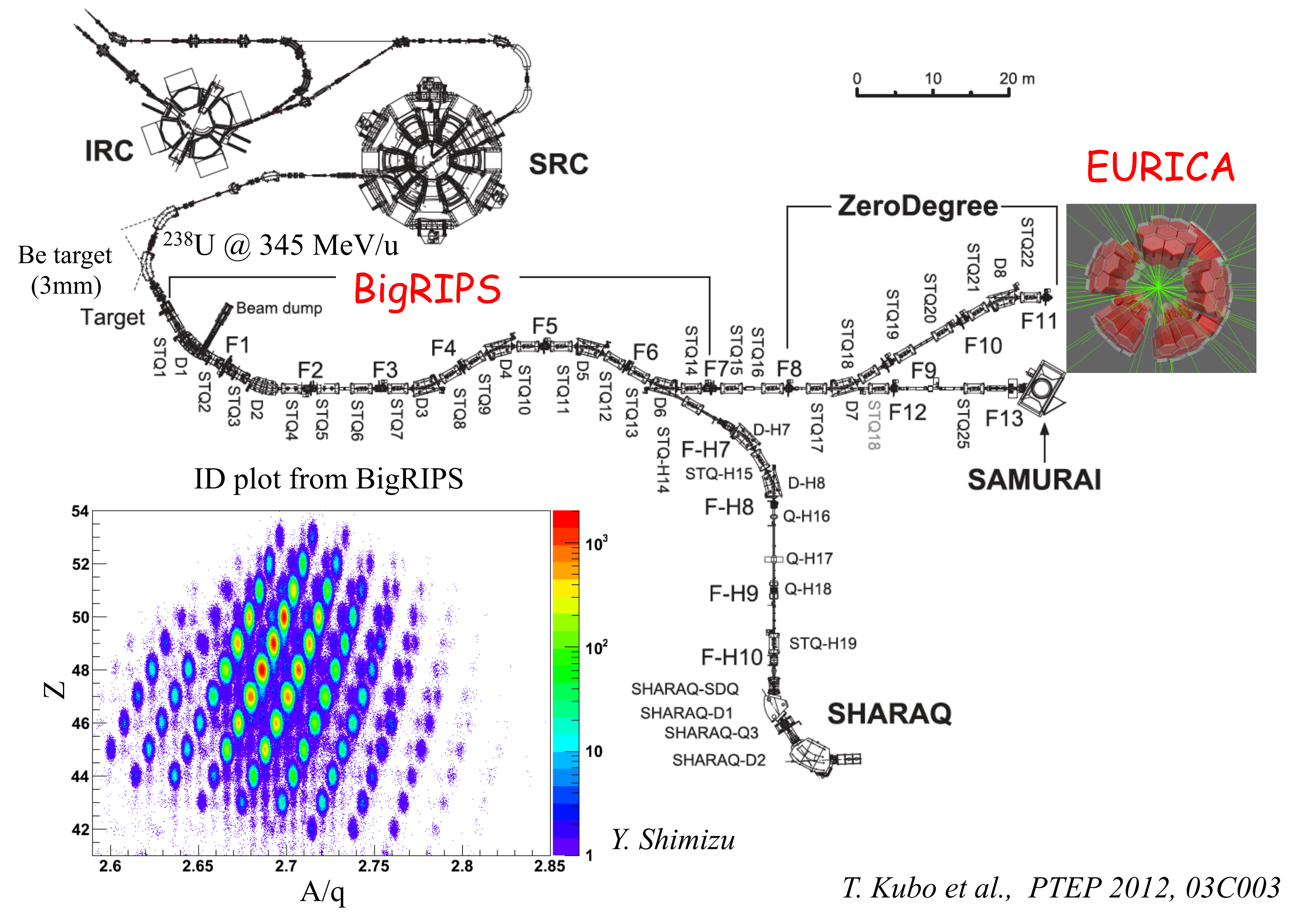
Experimental status of the ^{132}Sn region



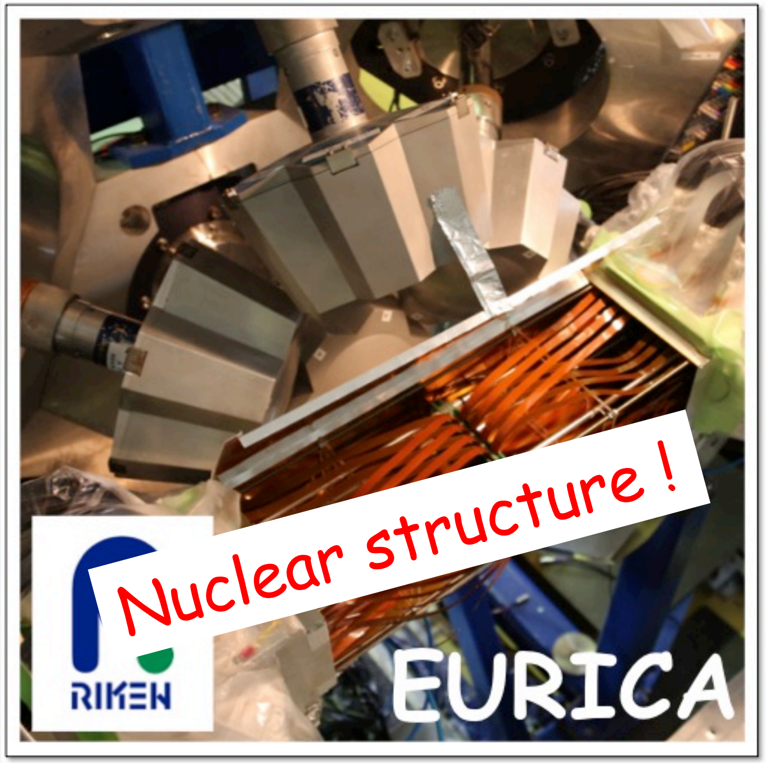
J. Hakala et al., Phys. Rev. Lett. 109 (2012) 032501

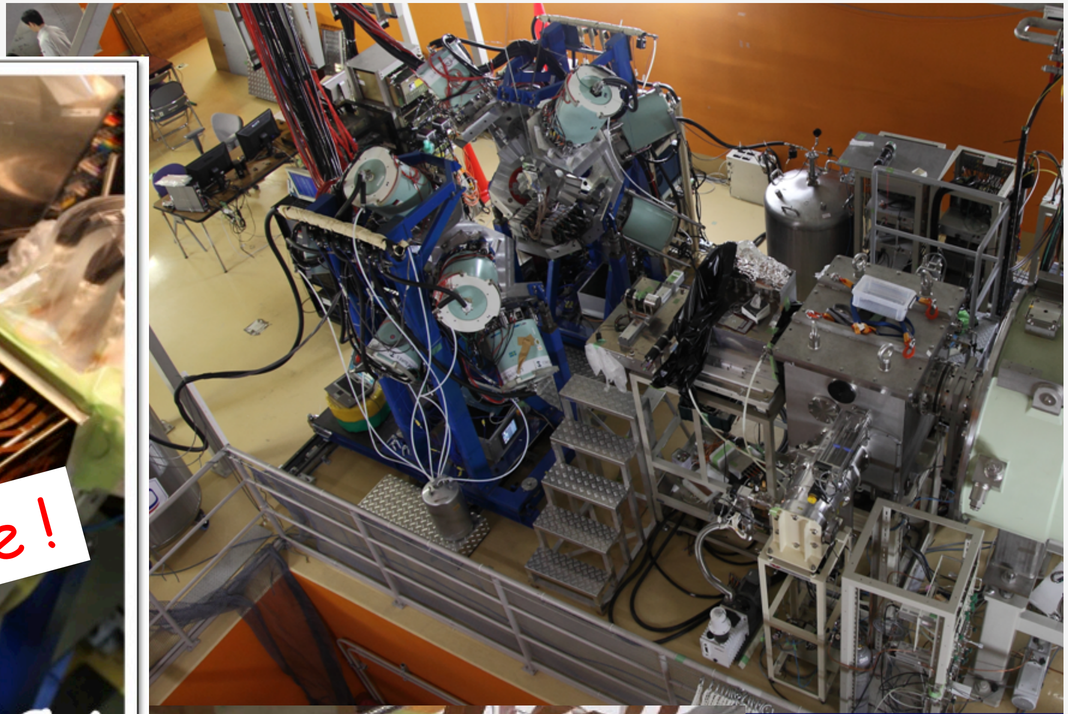
Need many more experimental half-lives and masses !

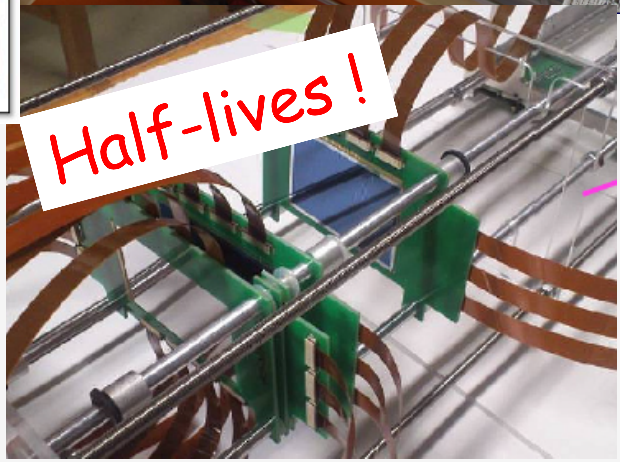
The EURICA project at RIKEN – since 2012



The EURICA project at RIKEN – since 2012







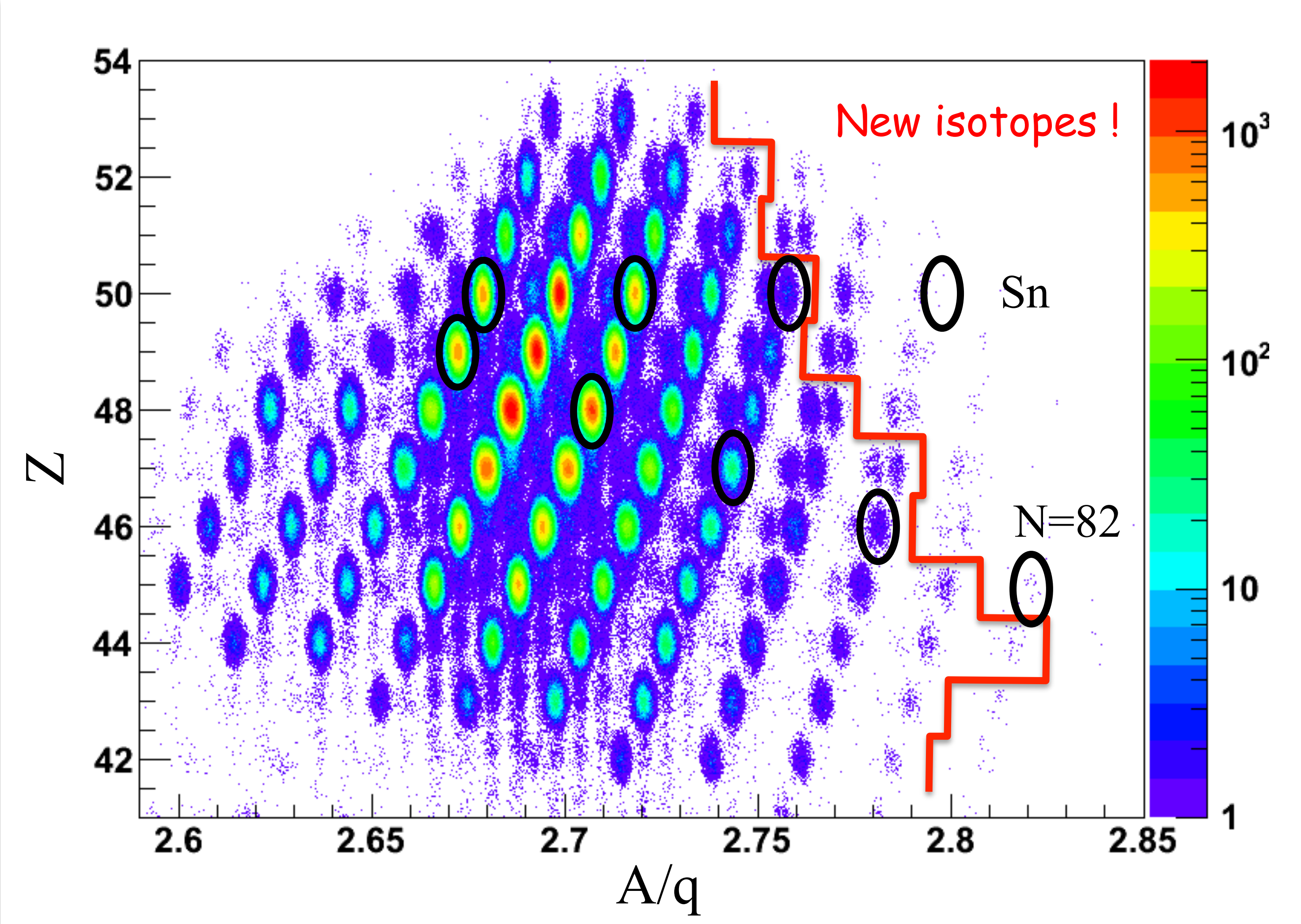
EURICA
12 EUROBALL Cluster detectors, i.e. 84 Ge crystals

γ decay of isomeric states or after β decay

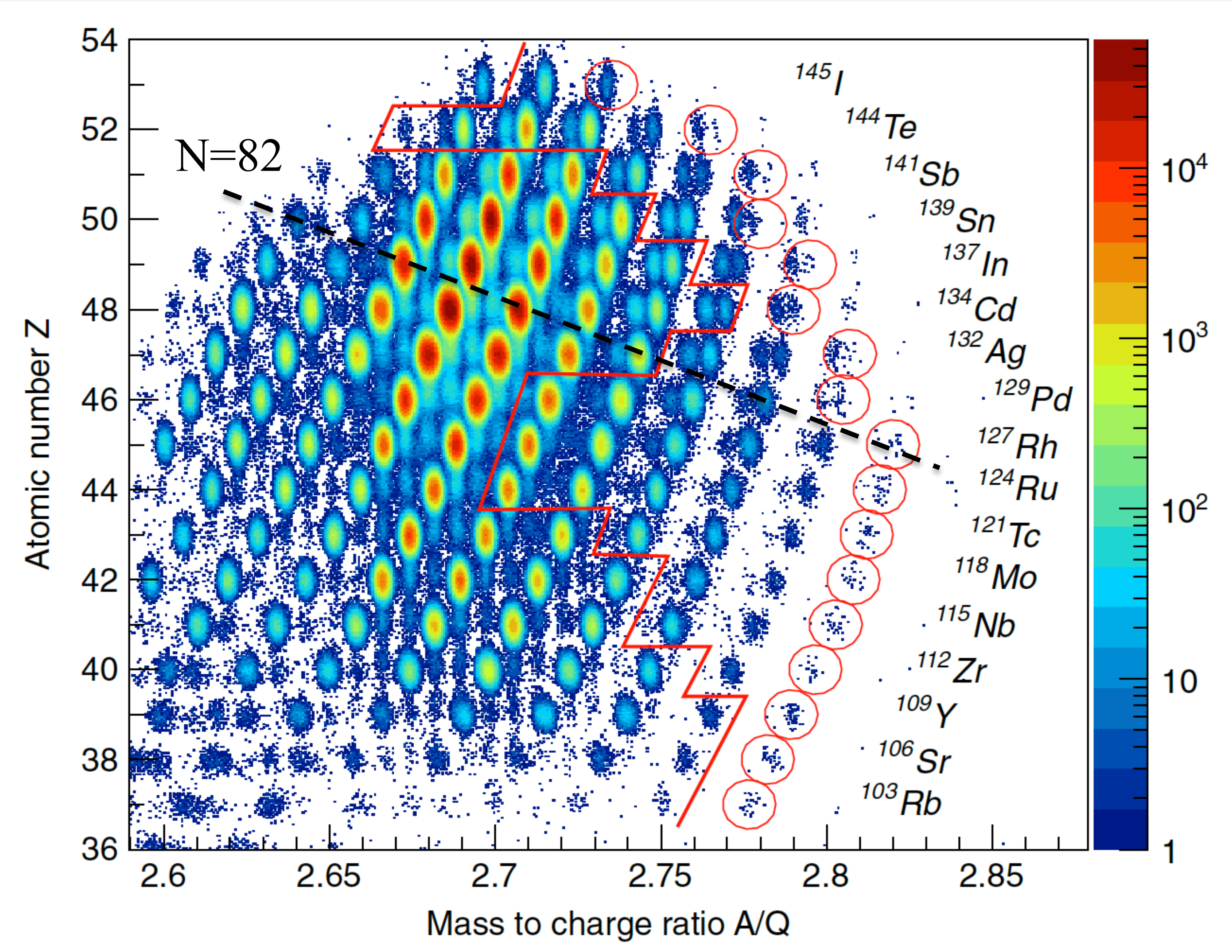
WAS3ABi
Stack of segmented Si detectors

ion implantation
β decay

BigRIPS ID plot: Sum of two settings

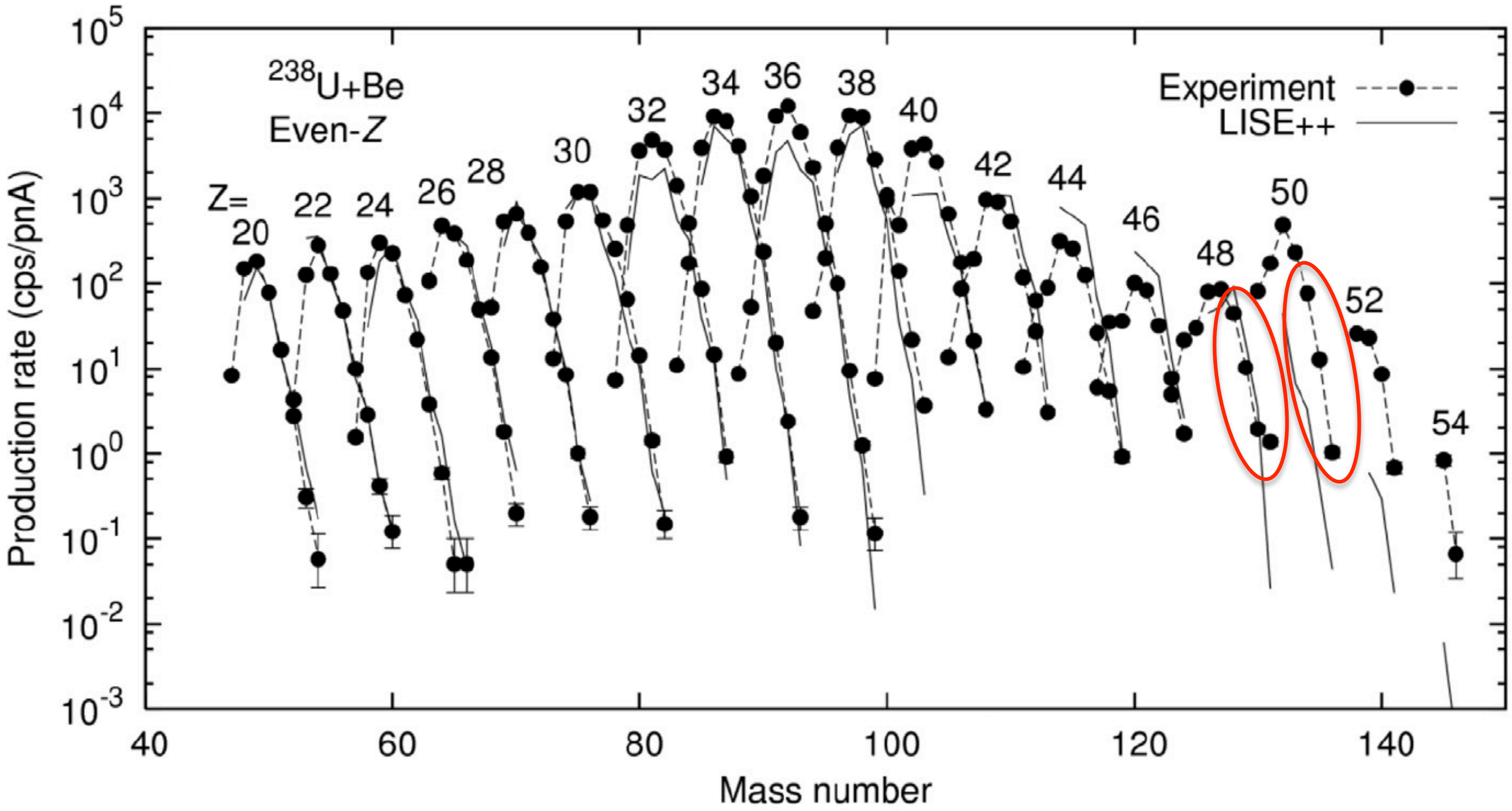


Systematic half-life measurement in the ^{132}Sn region



110 half-lives measured, 40 for the first time !

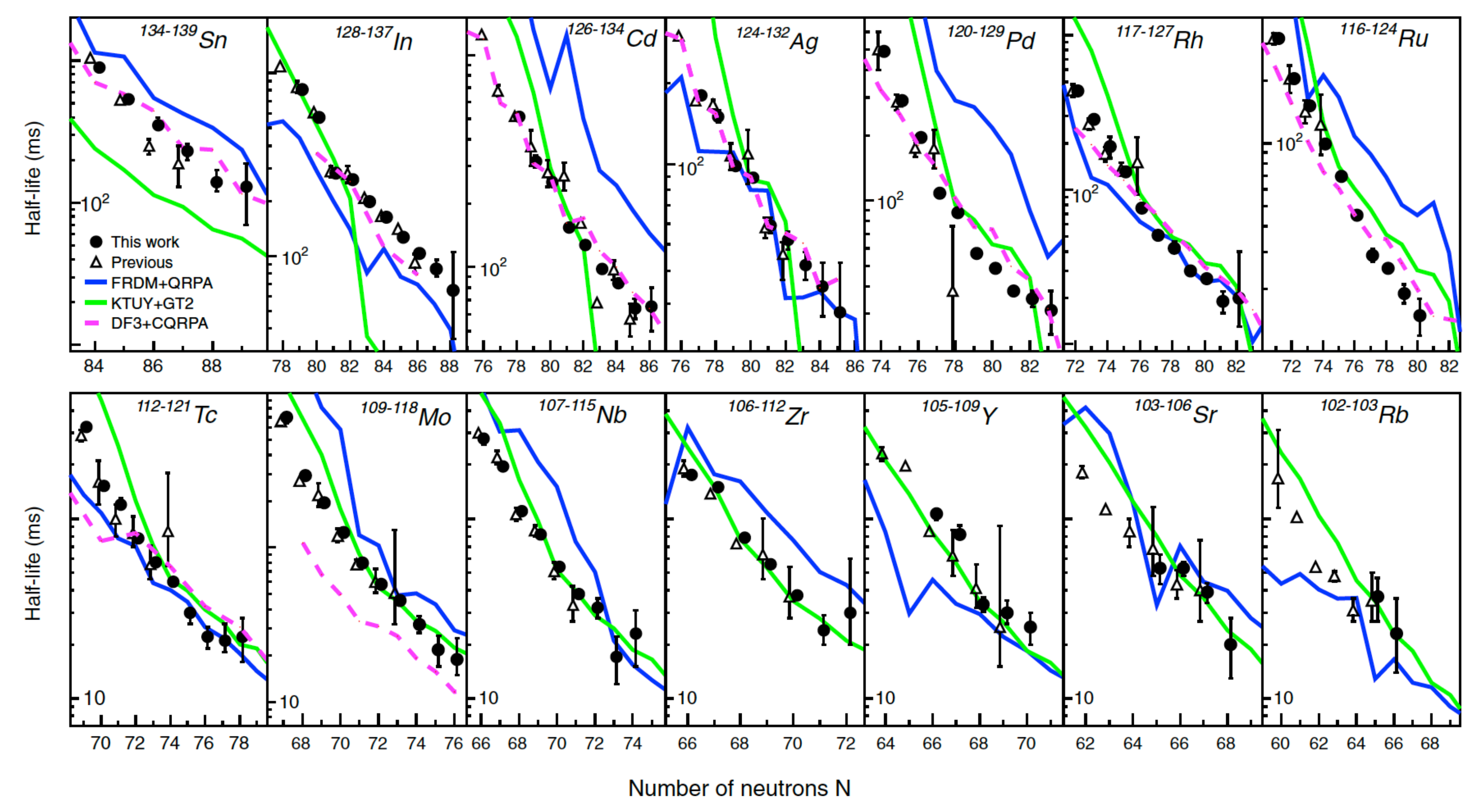
Production cross sections for ^{238}U+Be @ 345 MeV



H. Suzuki et al. / Nuclear Instruments and Methods in Physics Research B 317 (2013) 756–768

One order of magnitude in beam intensity means 1-2 neutrons further out !

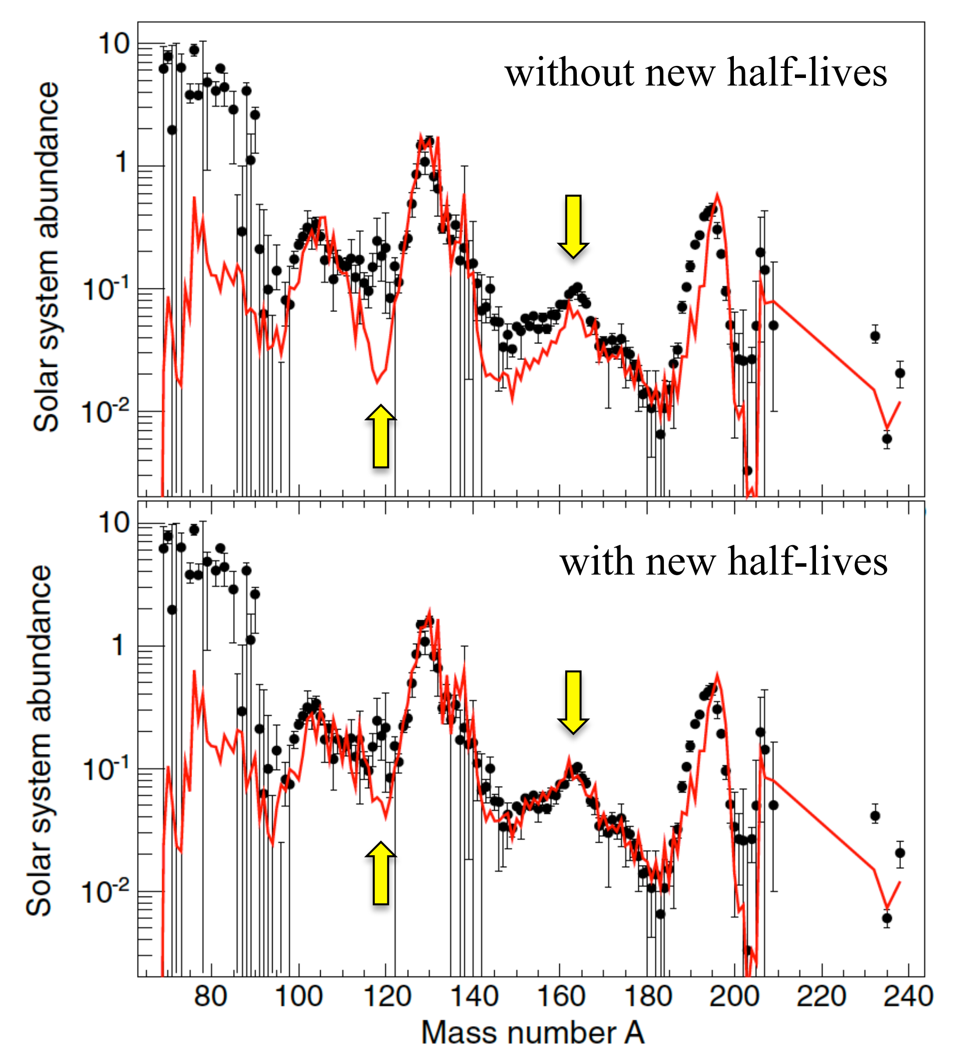
Systematic half-life measurement in the ^{132}Sn region



G. Lorusso et al., Phys. Rev. Lett. 114, 192501 (2015)

Systematic measurements crucial to test theoretical model predictions for unaccessible regions of the nuclear chart !

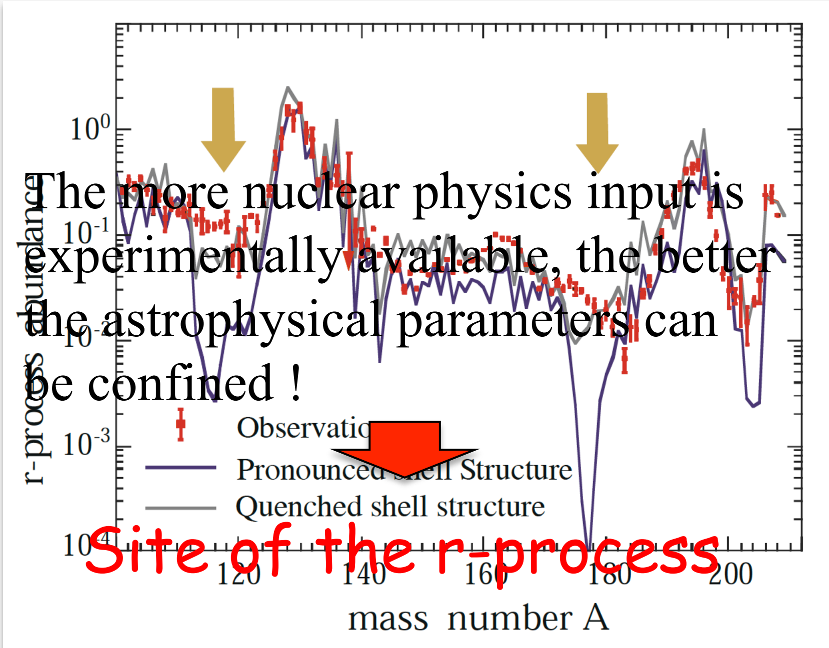
The r-process solar system abundance pattern



G. Lorusso et al., Phys. Rev. Lett. 114, 192501 (2015)

New experimental half-lives

- alleviate the underproduction just below the A~130 peak and
- greatly improve the description of the rare earth element abundances.



The more nuclear physics input is experimentally available, the better the astrophysical parameters can be confined !

Site of the r-process

No need for fancy explications !