Física Nuclear

Nuclear Physics

Instituto de Estructura de la Materia – Consejo Superior de Investigaciones Científicas

Single particle versus collectivity, shapes of exotic nuclei

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Rewriting Nuclear Physics textbooks

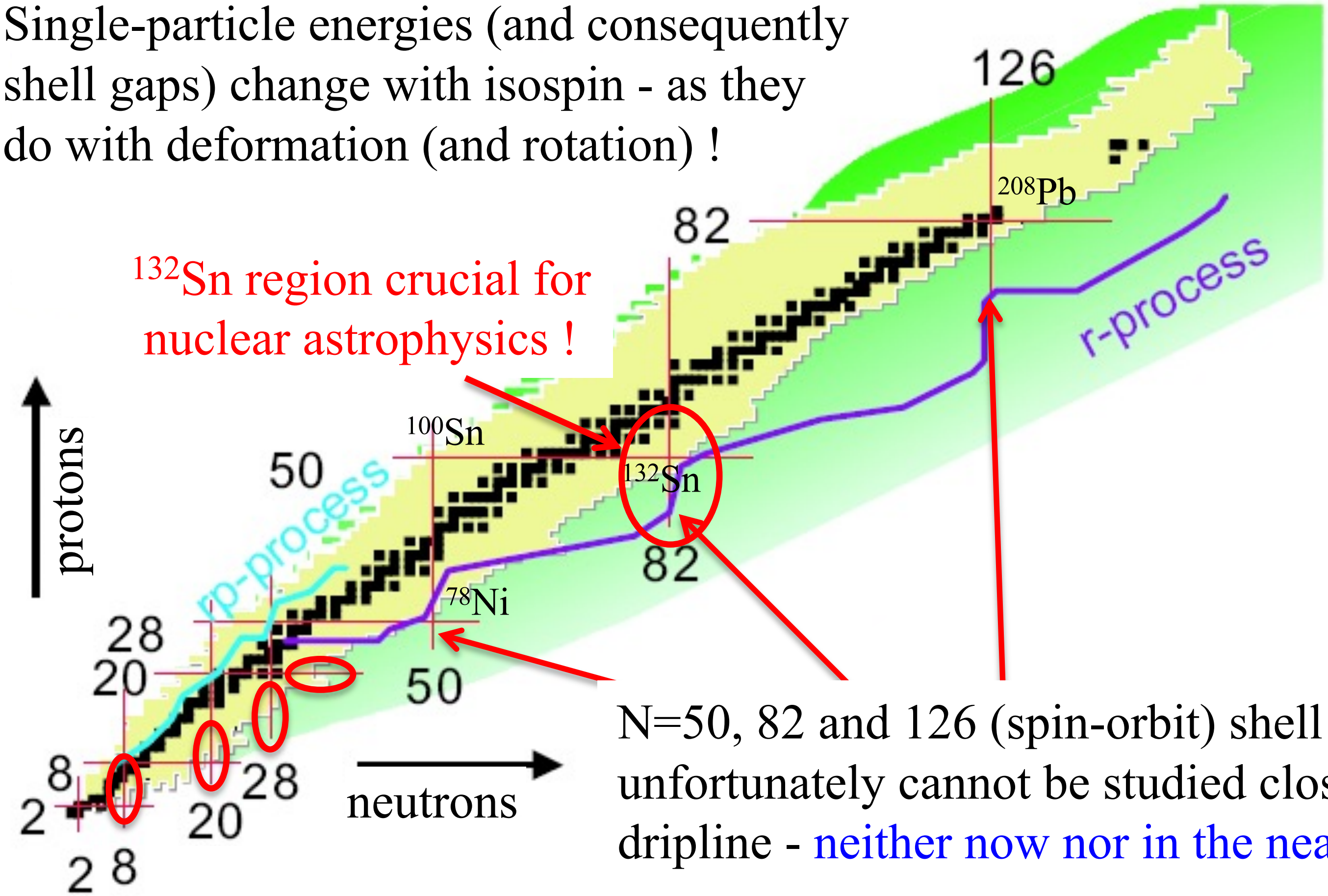
30 years with Radioactive Ion Beam Physics

Pisa (Italy), July 20th – 24th, 2015

The heavier neutron-rich region

Single-particle energies (and consequently shell gaps) change with isospin - as they do with deformation (and rotation) !

^{132}Sn region crucial for nuclear astrophysics !

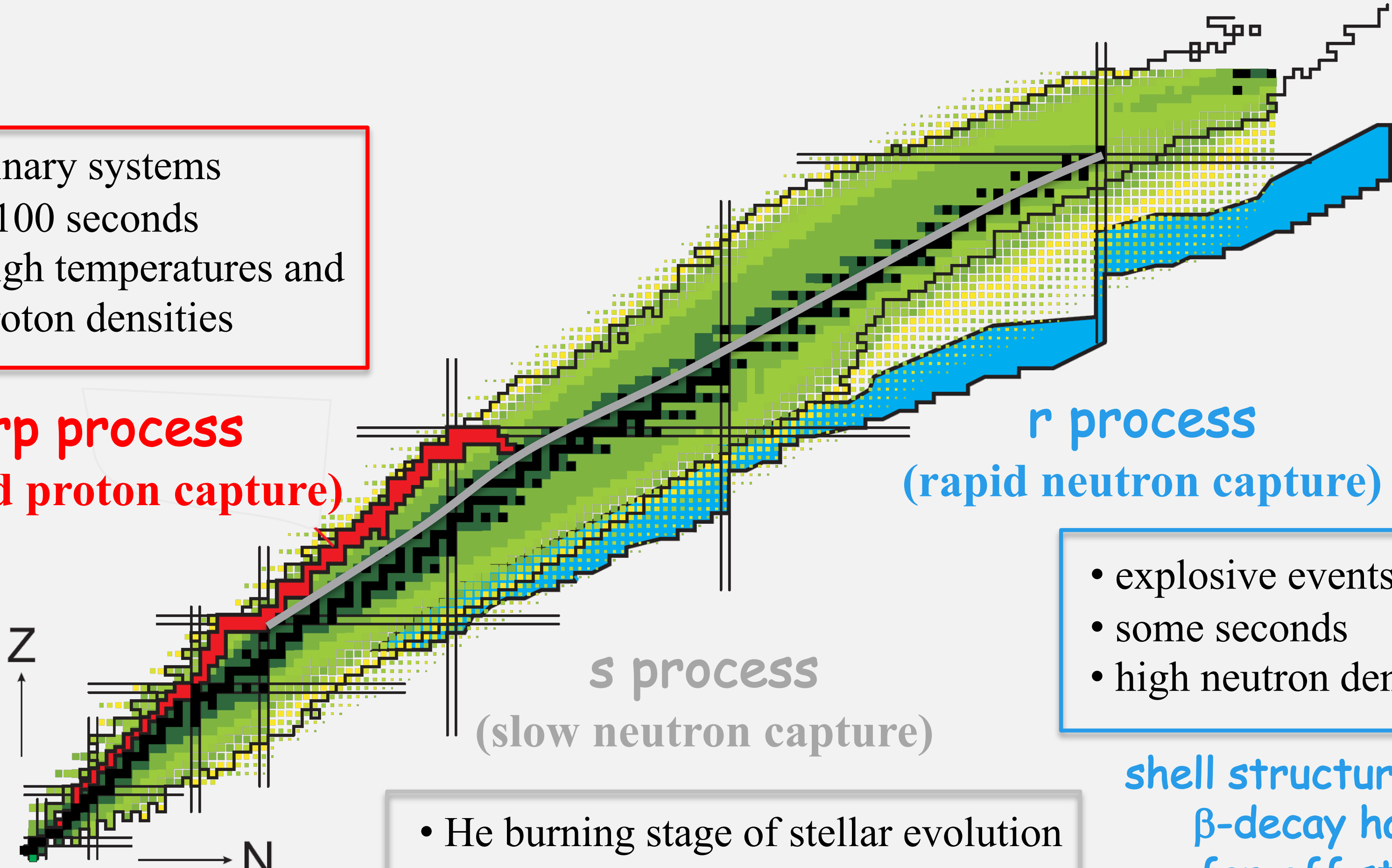


N=50, 82 and 126 (spin-orbit) shell closures unfortunately cannot be studied close to the dripline - neither now nor in the near future.

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

The importance of the N=82,126 shell closures

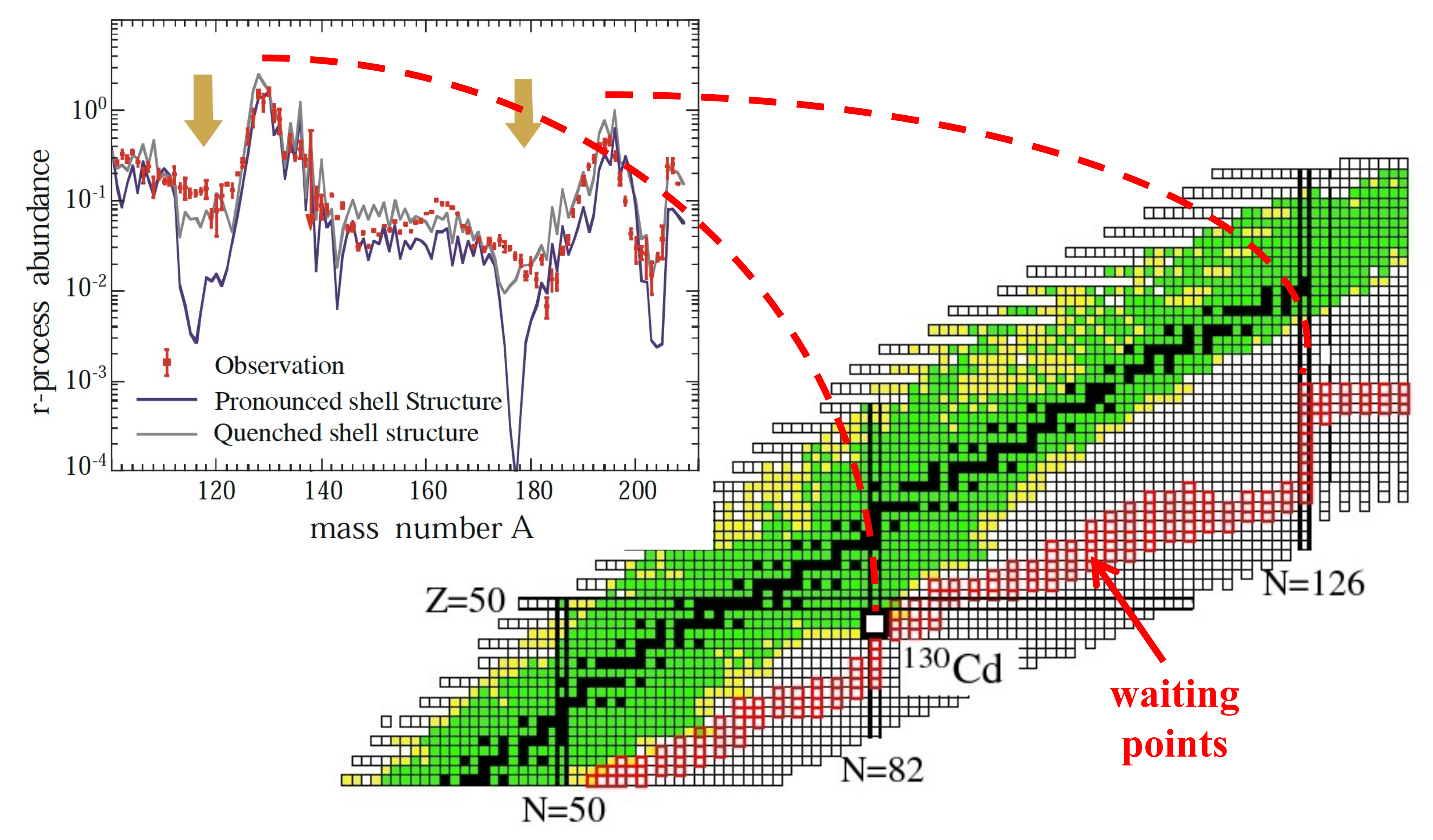
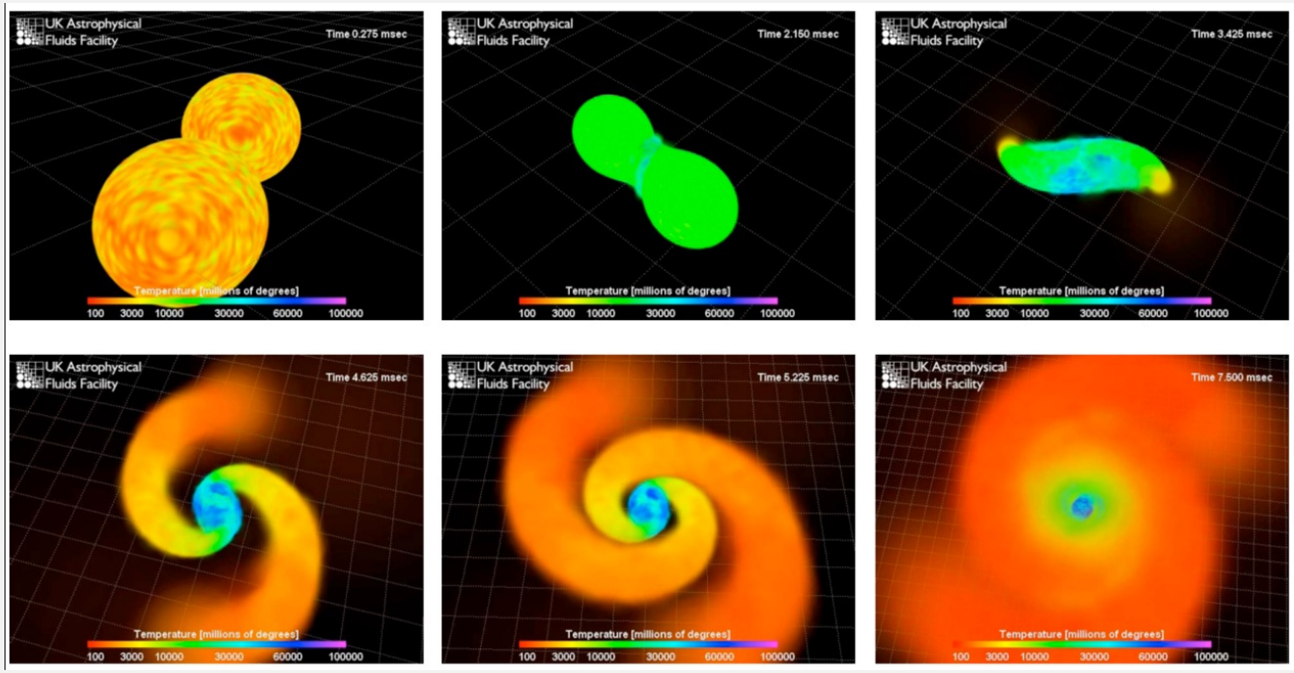


Figure shown in nearly all glossy brochures for future facilities …

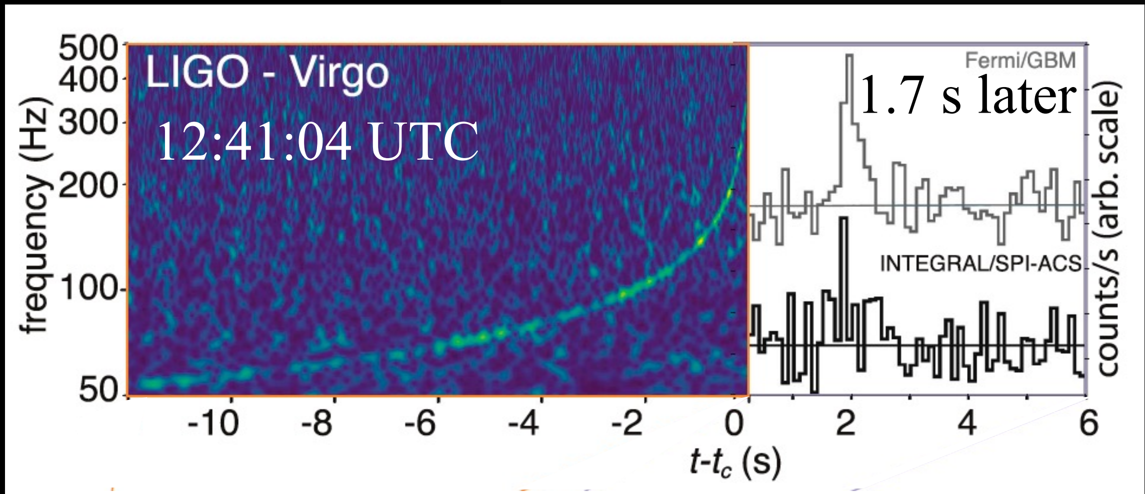
Supernovae remnant Crab nebula

Site of r-process still an open question !

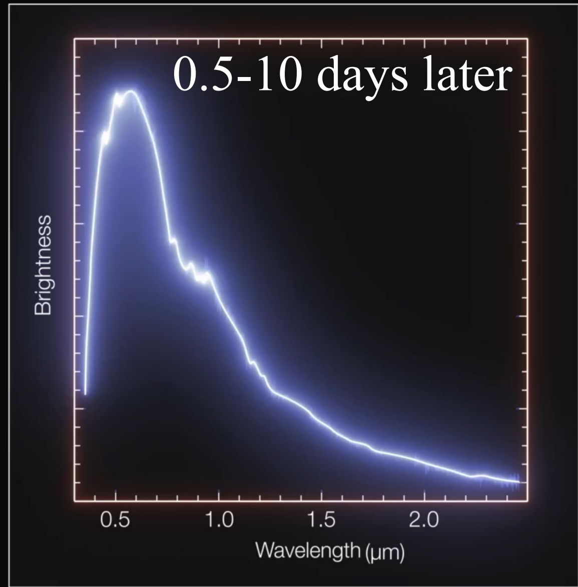
Merging neutron stars



On August 17, 2017 a new era started: GW170817



Abbott et al., Astrophysical Journal Letters 848:L12 (2017)



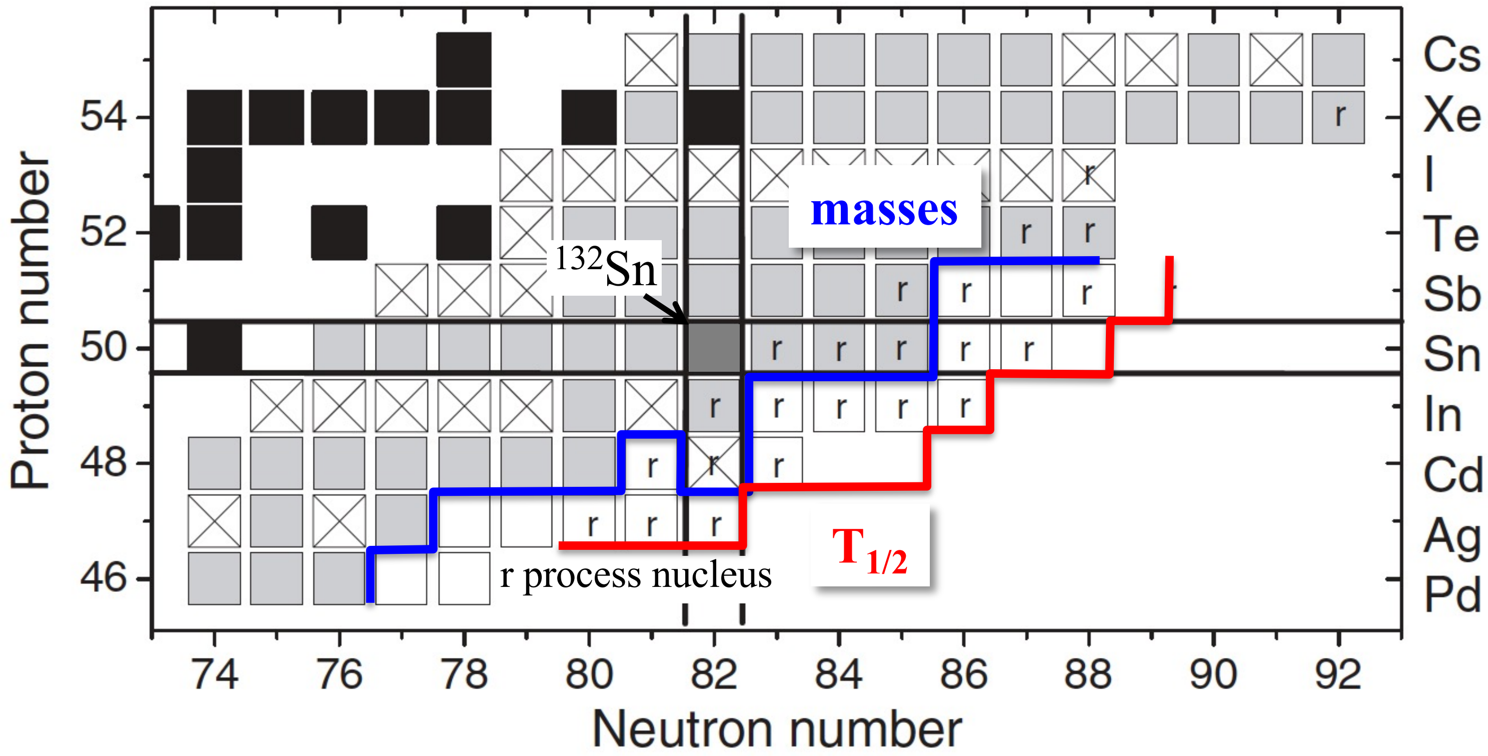
E. Pian et al., Nature 551, 67 (2017)
adopted by G. Martínez-Pinedo

Maura McLaughlin, Physics 10, 114 (2017)

Gravitational waves, γ-ray burst and optical transient ("Kilonova") observed from the same source:

Binary neutron star mergers are the dominant site of *r*-process nuclear synthesis !

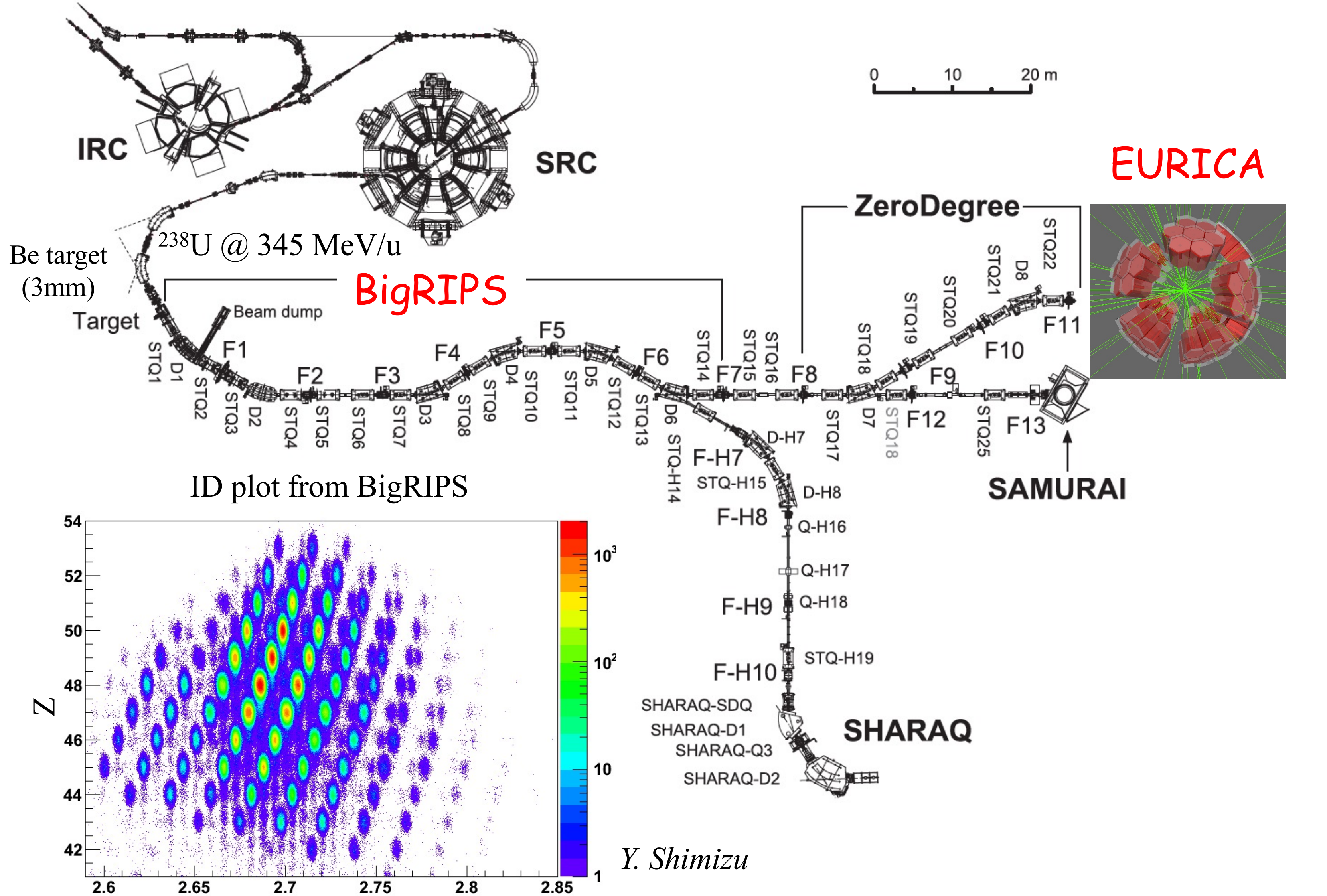
Experimental status of the ^{132}Sn region



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

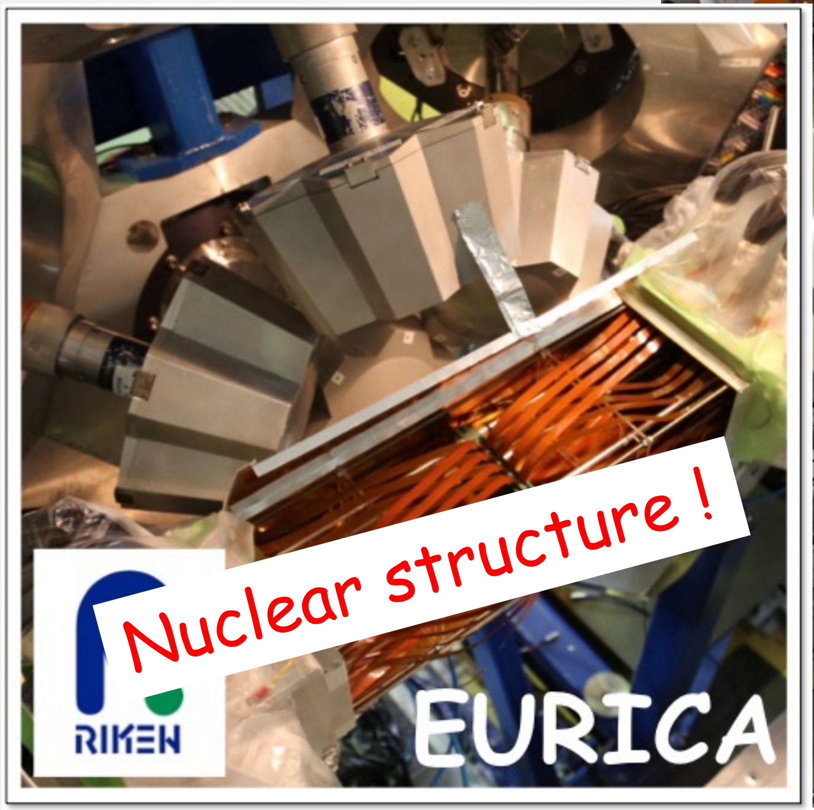
Need many more experimental half-lives and masses !

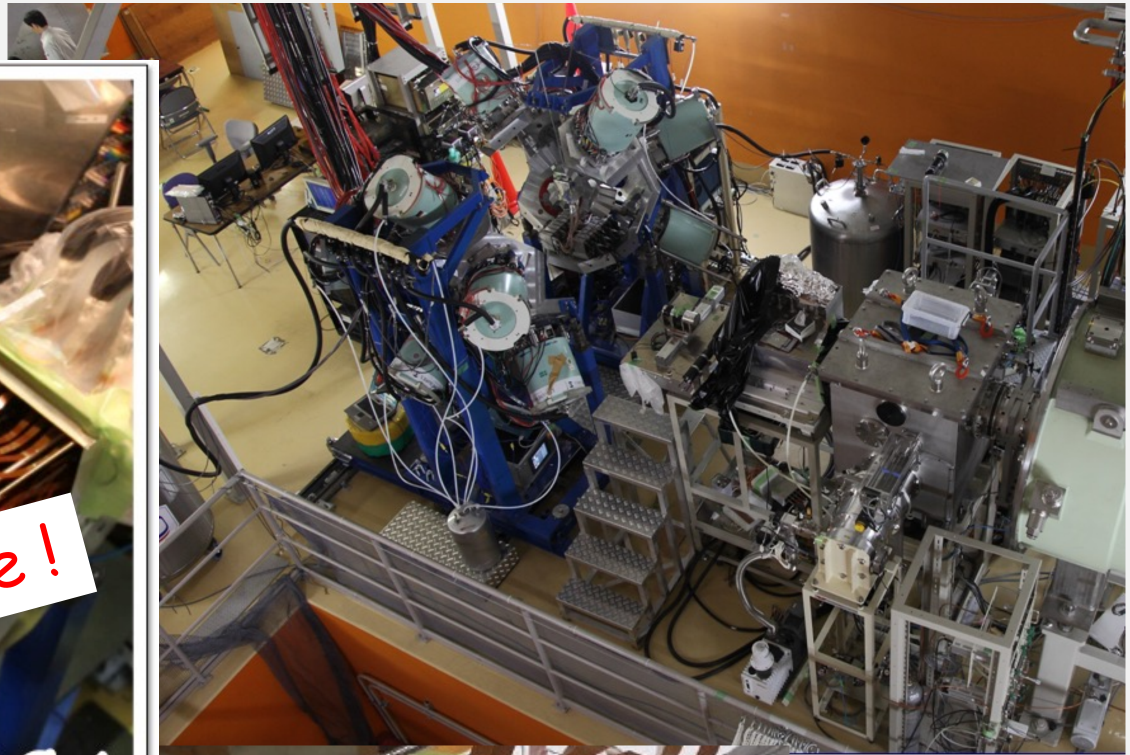
The EURICA project at RIKEN – since 2012

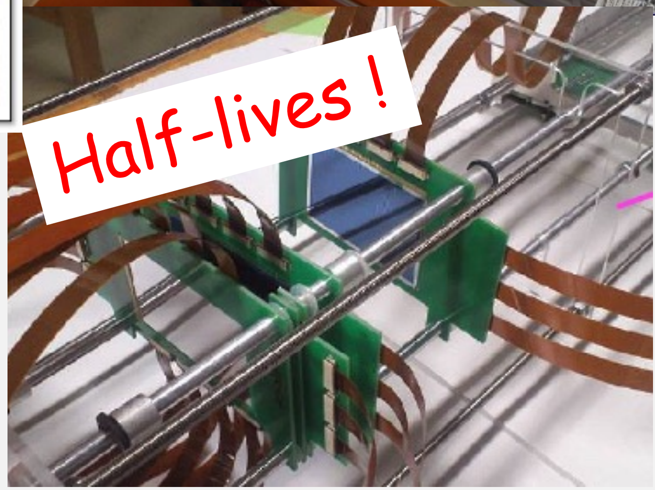


T. Kubo et al., PTEP 2012, 03C003

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

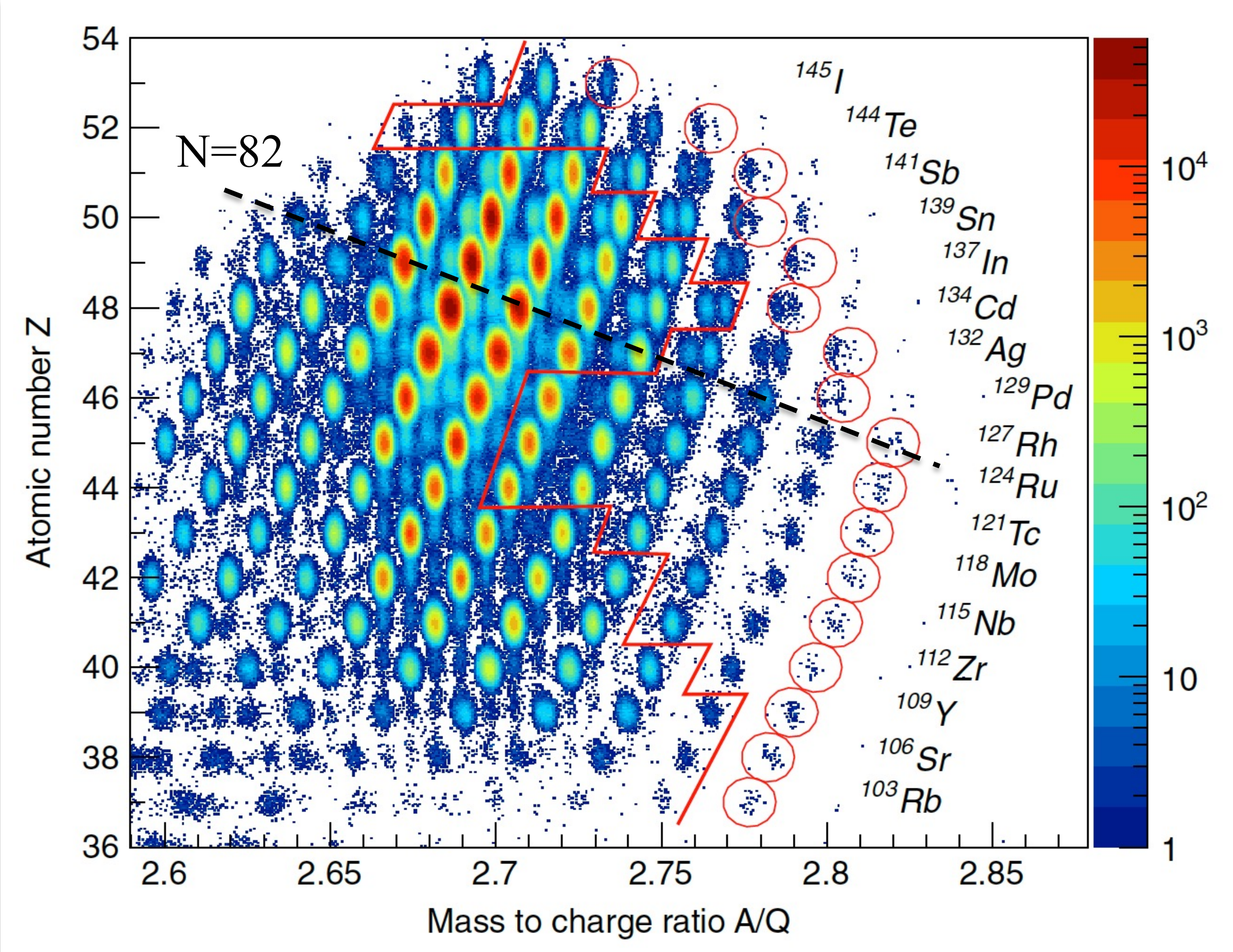
WAS3ABi

Stack of segmented Si detectors

ion implantation

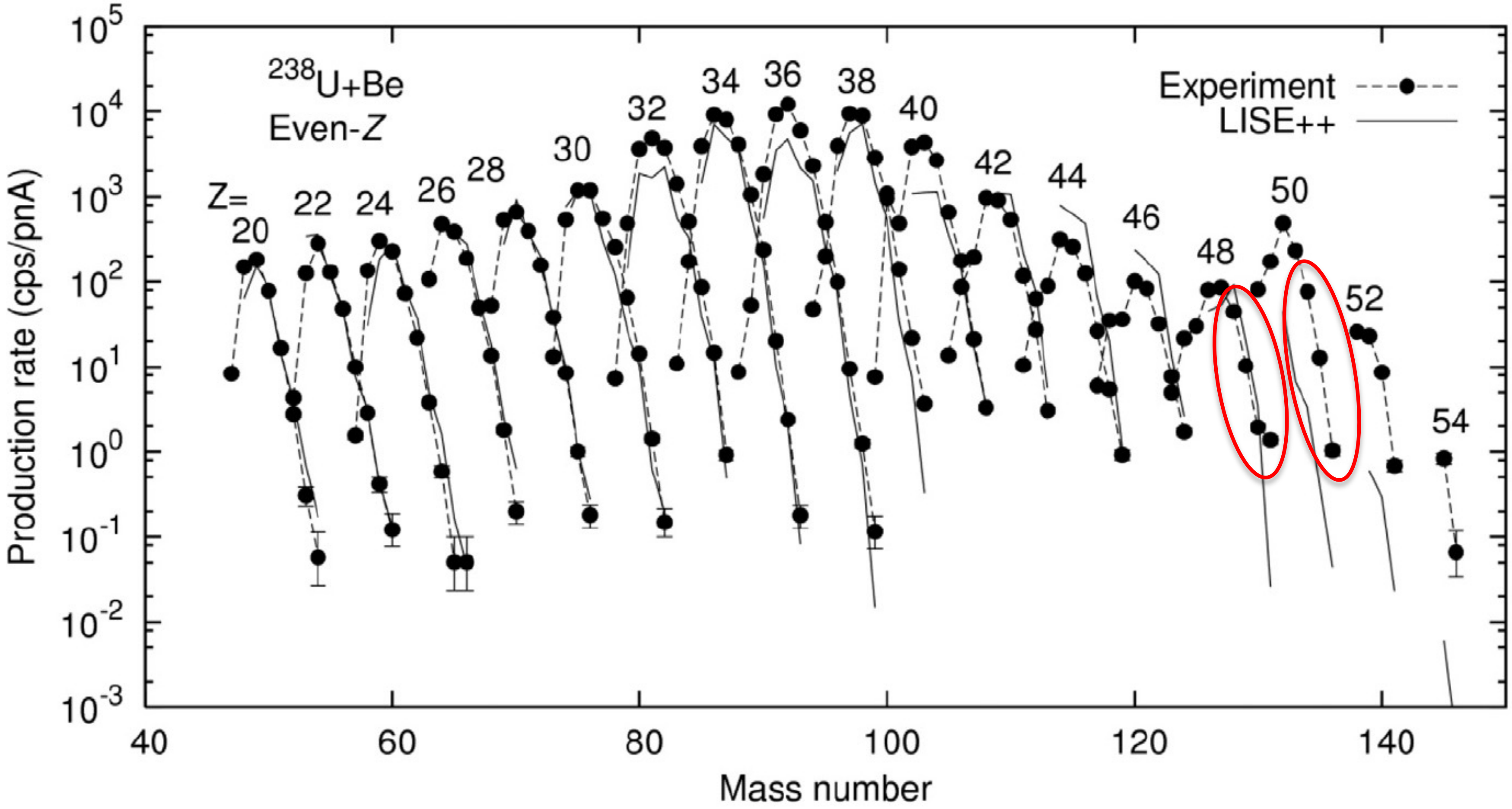
β decay

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



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

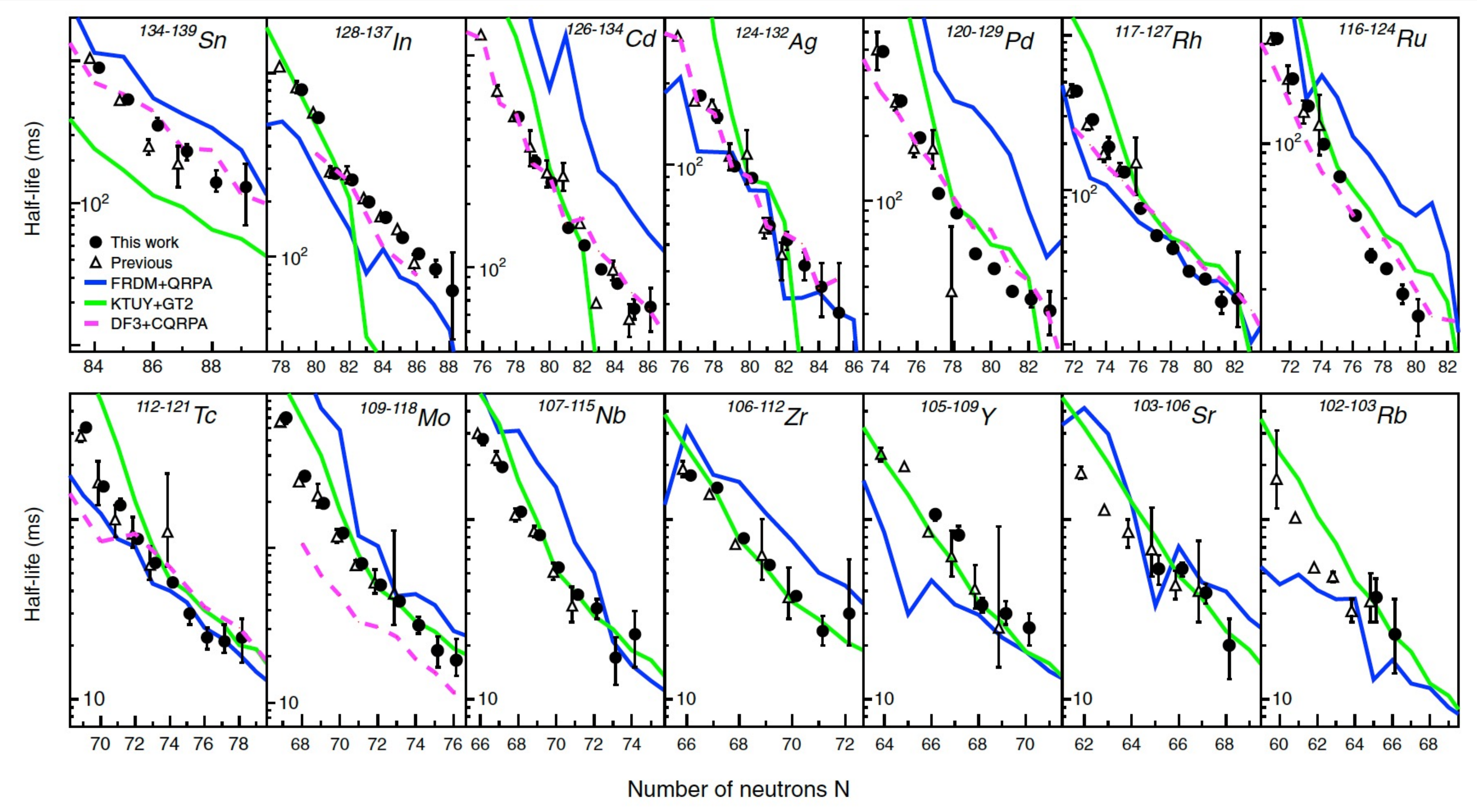
Production cross sections for ^{238}U+Be @ 345 MeV



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 !

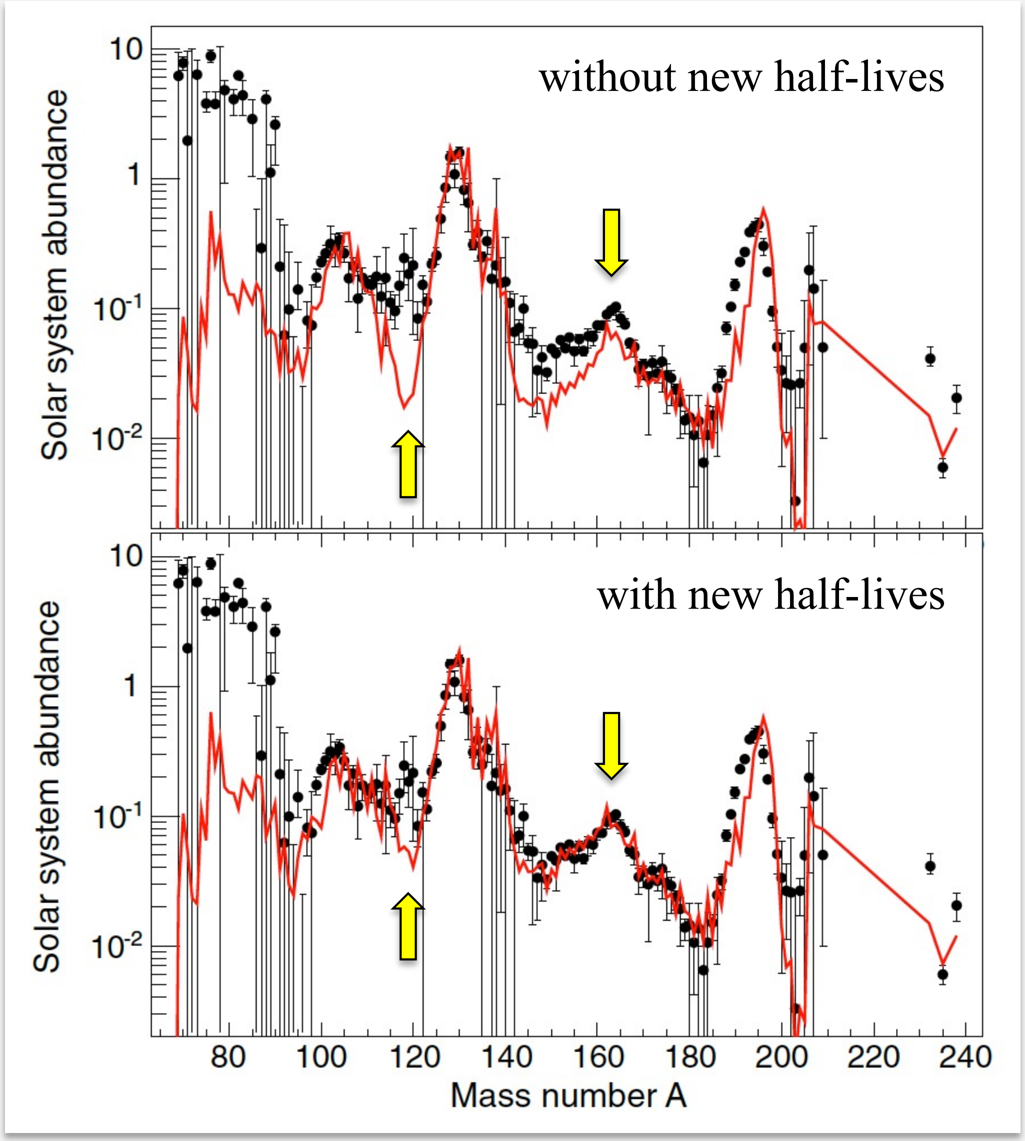
Systematic half-life measurement in the ^{132}Sn region



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 !

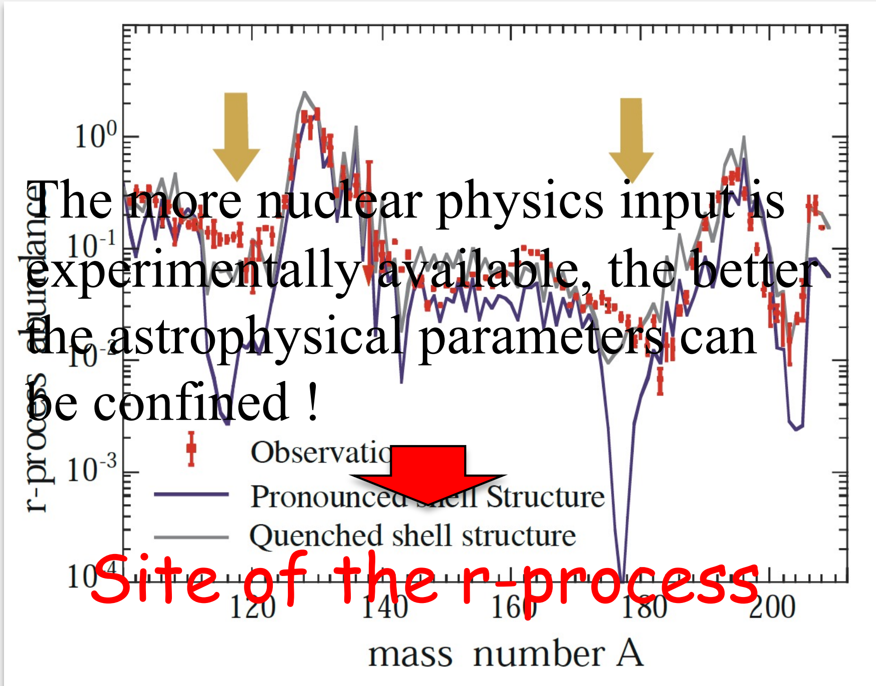
The r-process solar system abundance pattern



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.

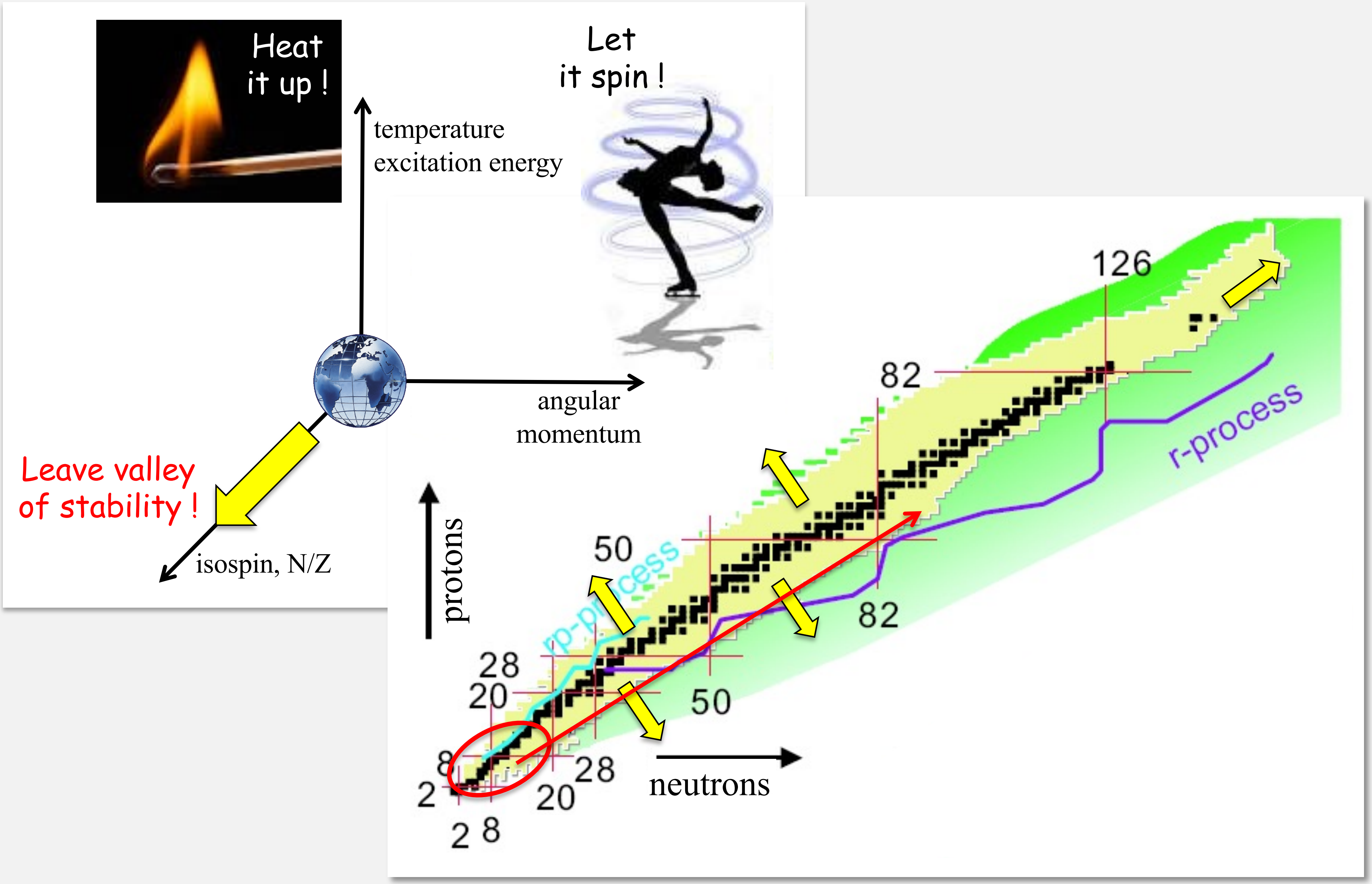


The more nuclear physics input is experimentally available, the better the astrophysical parameters can be confined !

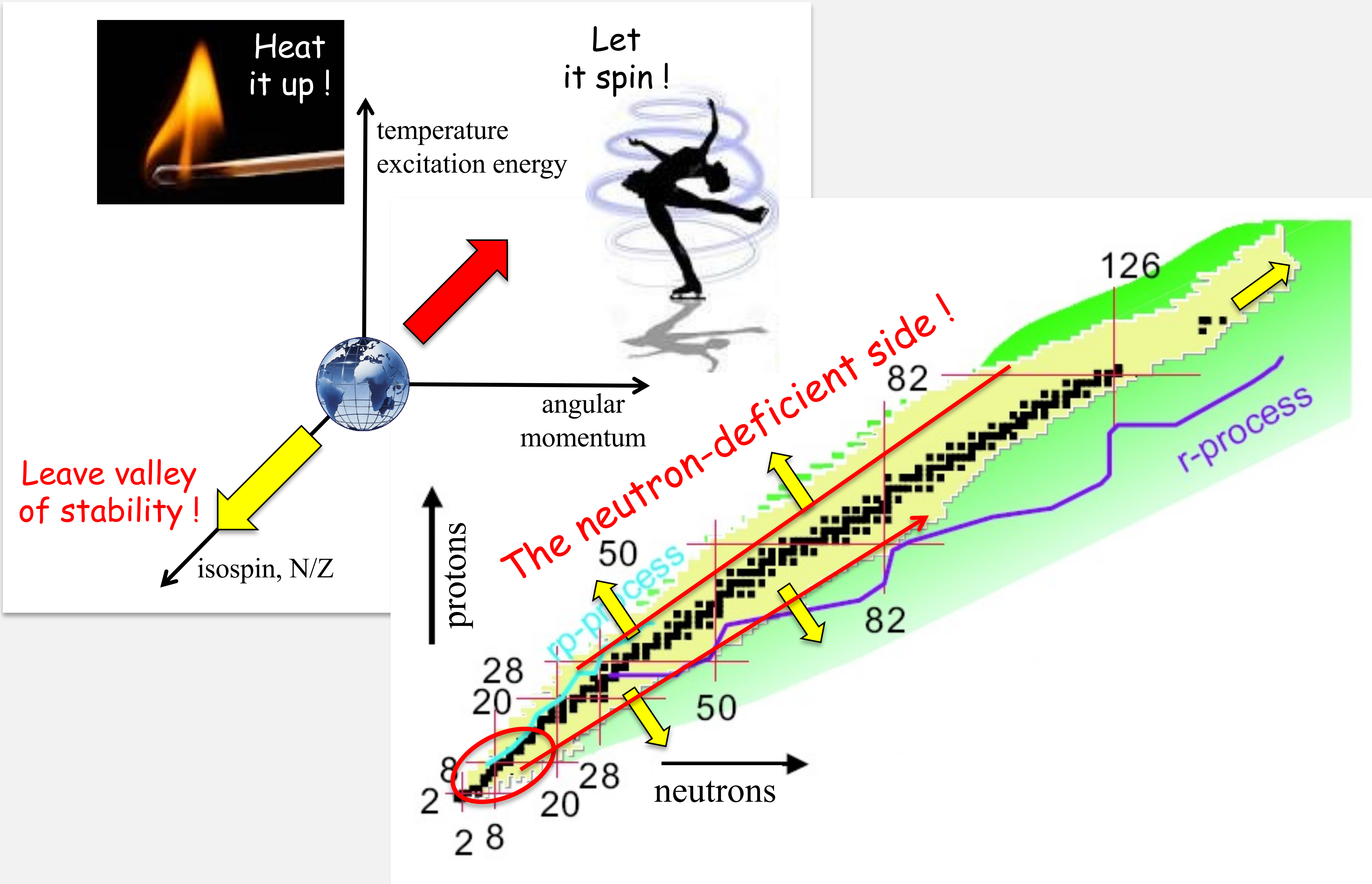
Site of the r-process

No need for fancy explications !

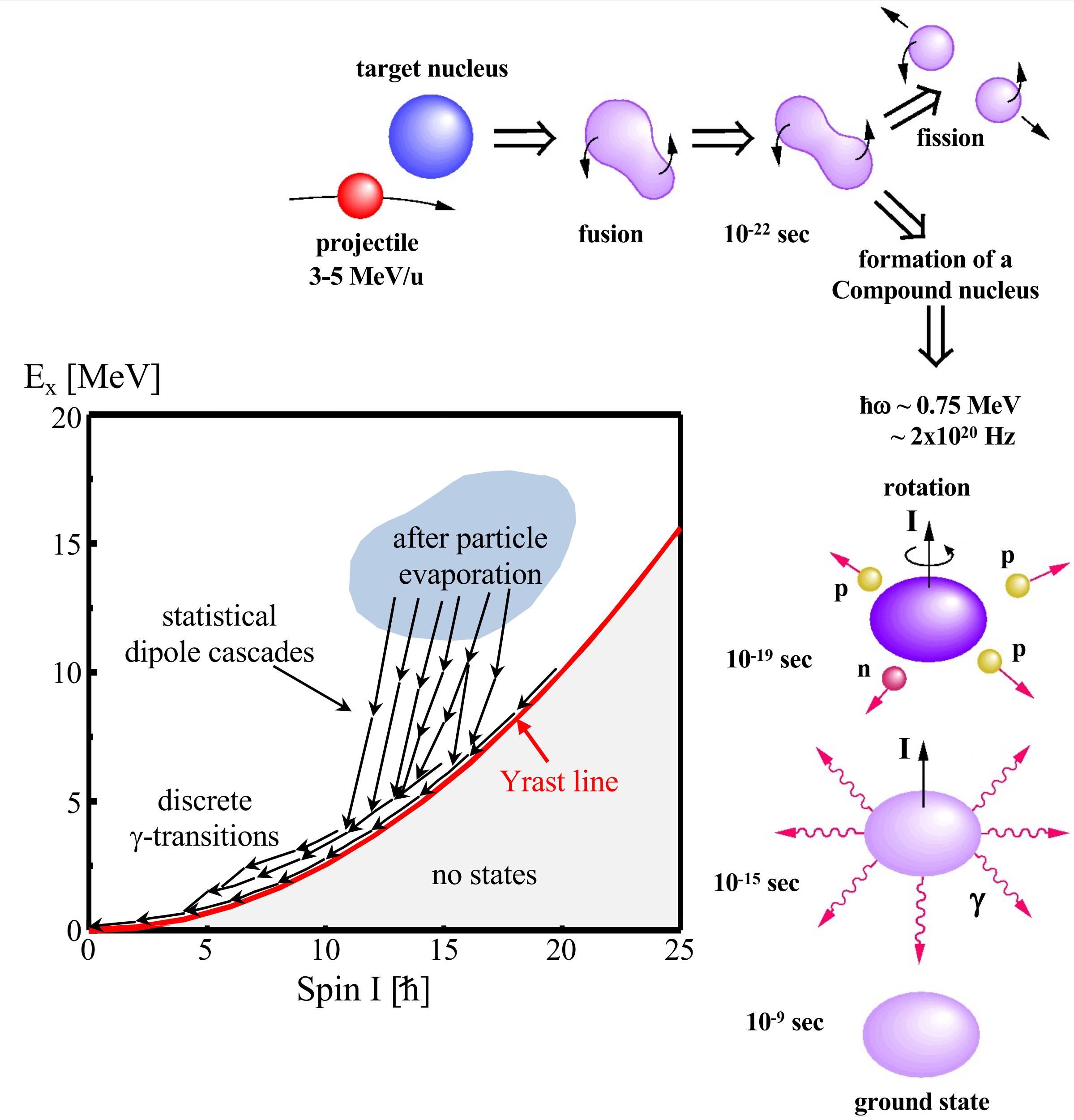
Let's play with all degrees of freedom



Let's play with all degrees of freedom



The heavy-ion induced fusion-evaporation reaction



- neutron-deficient nuclei
- high spin and excitation energy
- needs heavy-ion accelerator
- many different reaction products
- large range of cross sections
- recoil velocity of reaction products $v/c \approx$ 1-5%

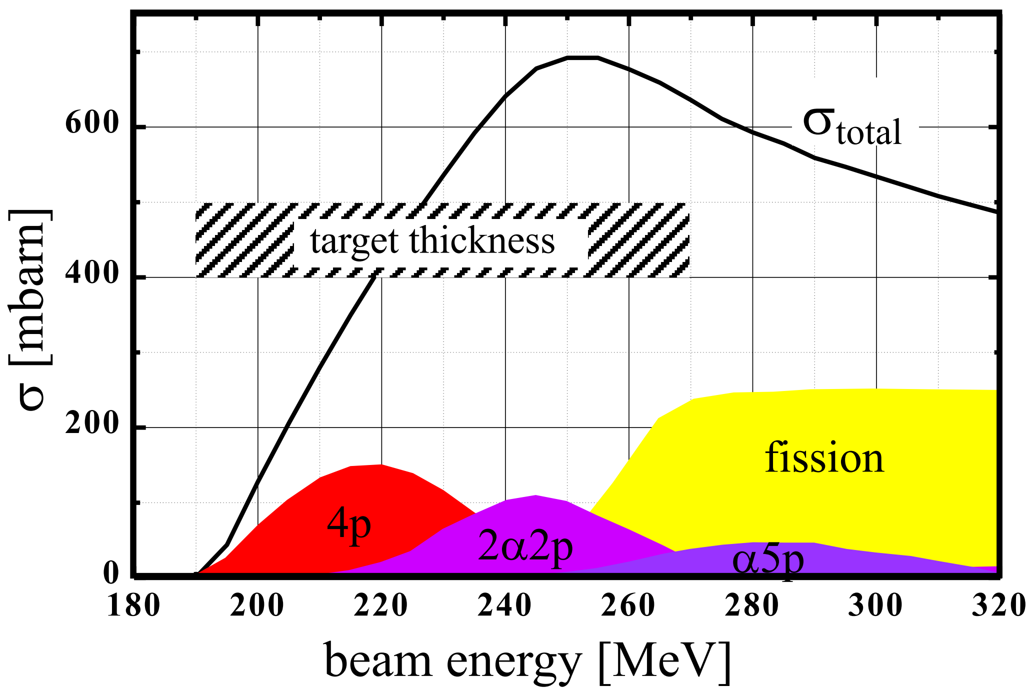
Use highly efficient γ-ray spectrometer to explore the E_x vs. I plane !

Recoil velocity crucial for many techniques to measure lifetimes, moments etc.

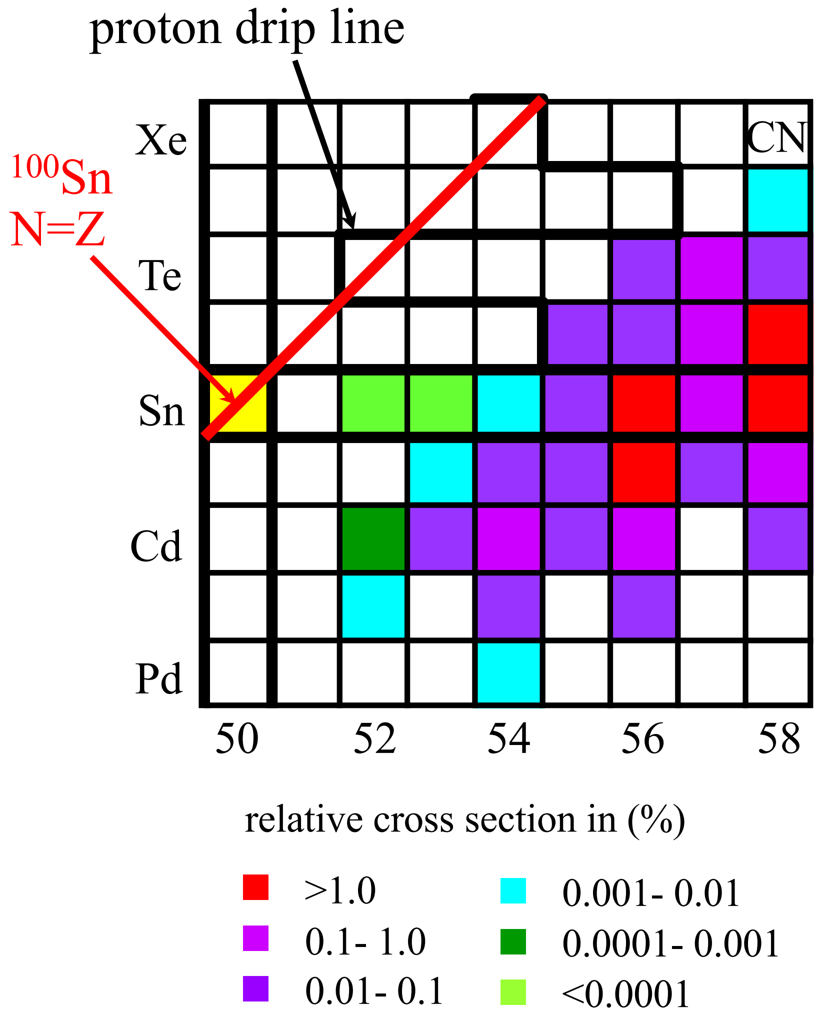
No time to talk about all that …

The importance of channel identification

Example: $^{58}Ni + ^{54}Fe$



- many different reaction products
- large dynamical range

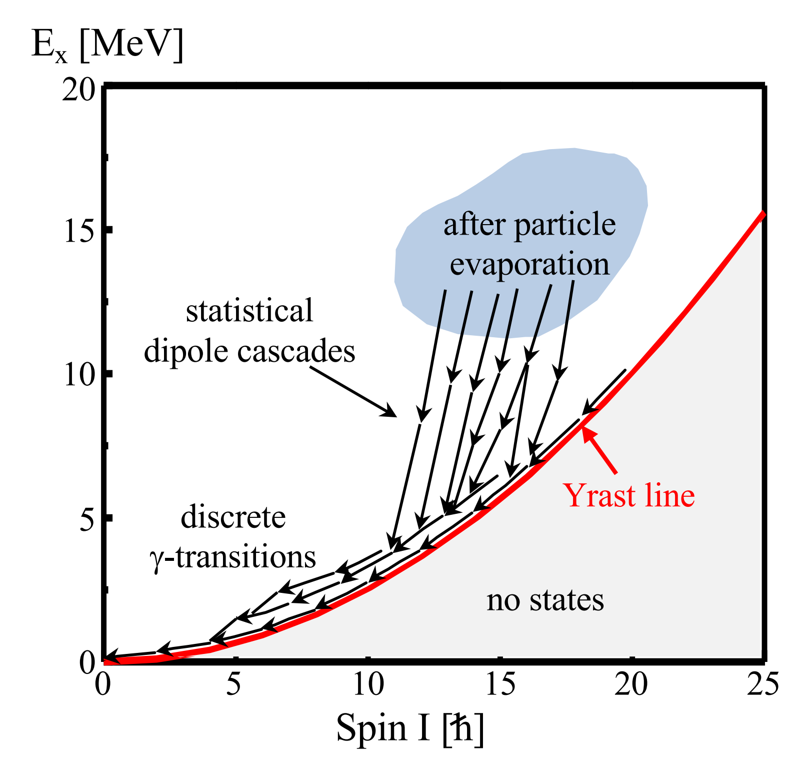


We need magnetic spectrometer, neutron detectors, charged particle detectors etc.

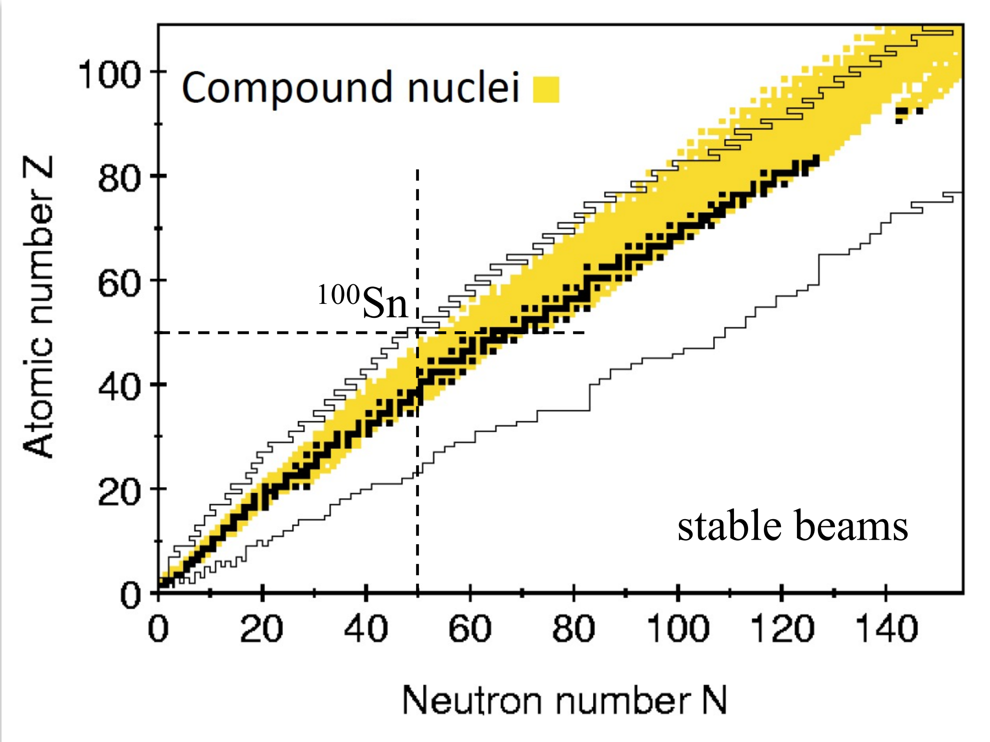
… or decay tagging !

No time to talk about all that …

The playground of fusion-evaporation reactions



Strongly populated reaction channels:
High-spin physics !

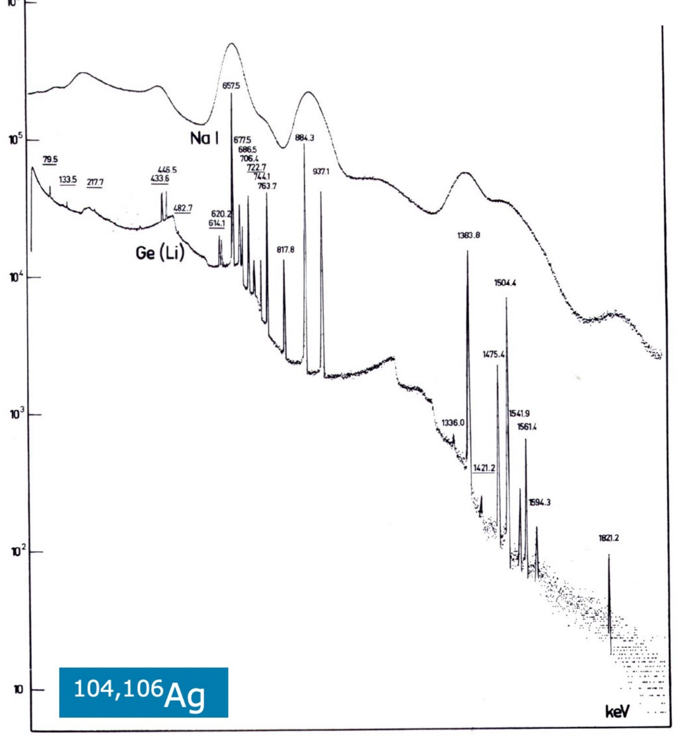


Weakly populated reaction channels:
New physics at the extremes of isospin !

How high-spin physics started …

Energy Resolution

From **Sodium Iodide** to **Germanium detectors**



Response function = differential spectrum obtained with a detector when hit by monochromatic radiation

60's → Use of Ge(Li) detectors marks the beginning of high-resolution in-beam γ-ray spectroscopy

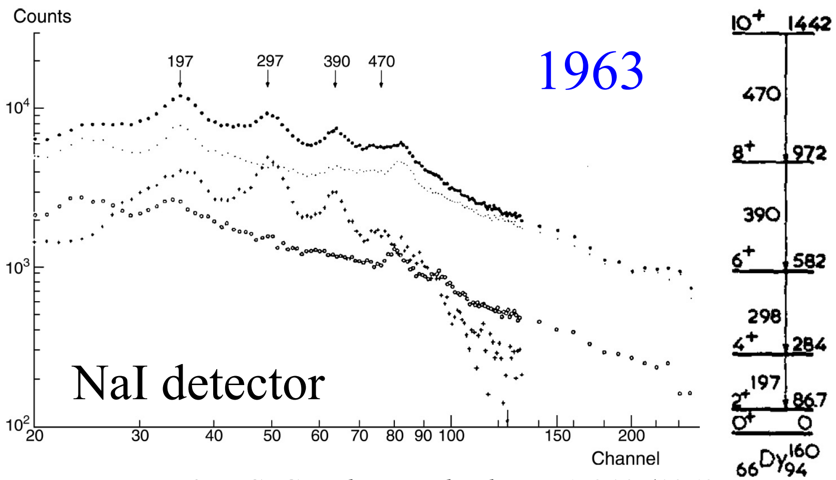
70's → Only few detectors , operated in γ–γ coincidence. Development of the HP-Ge detector.

Use of Germanium detectors = breakthrough in nuclear structure

FWHM ~2 keV at 1.3 MeV

How high-spin physics started ...

α-induced fusion-evaporation reactions - ^{160}Gd(α,4n)^{160}Dy



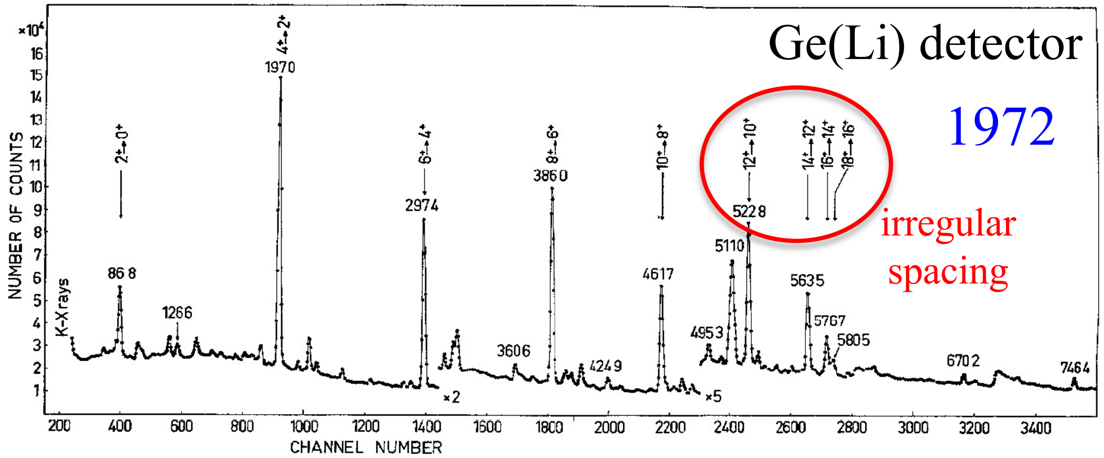
First 10^+ state !

H. Morinaga & P.C. Gugelot, Nucl. Phys. 46, 210 (1963)

Remember:

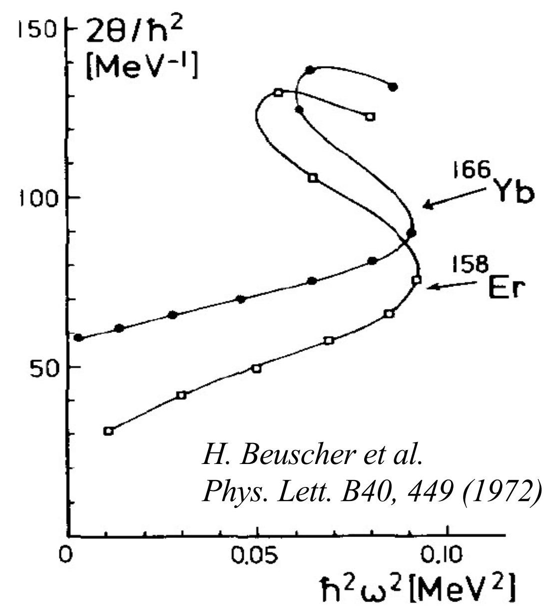
$$E_x = I(I+1)\frac{\hbar^2}{2J}$$

ΔE_γ=const.

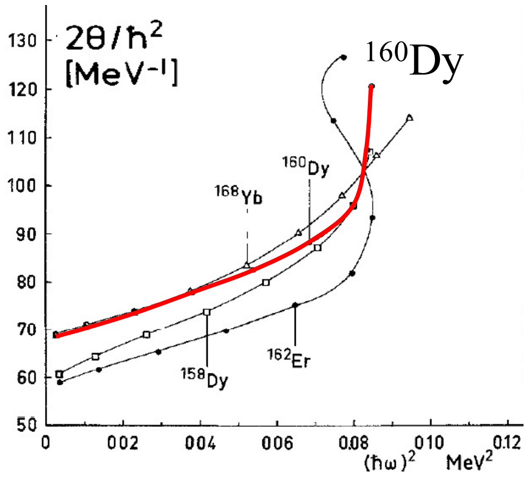


irregular spacing

A. Johnson, H. Ryde & S.A. Hjorth, Nucl. Phys. A179, 753 (1972)

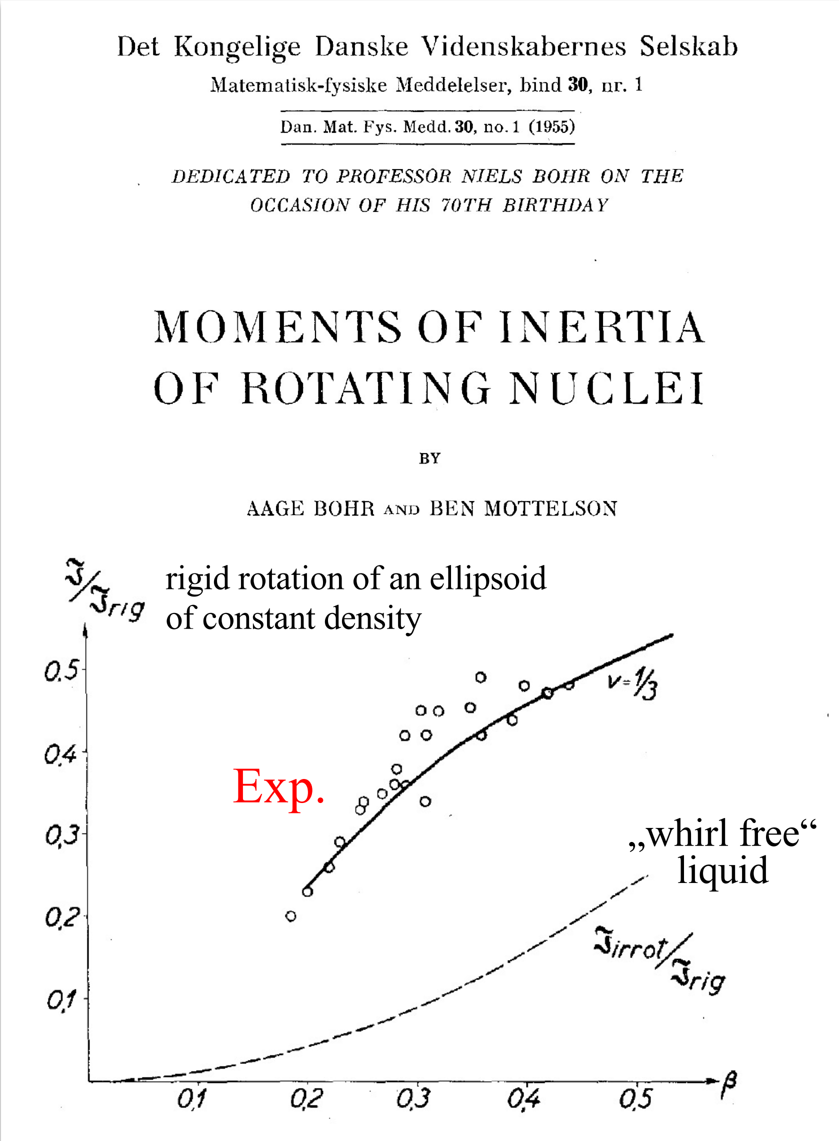


H. Beuscher et al.
Phys. Lett. B40, 449 (1972)



The discovery of backbending !

The problem of the "wrong" moment of inertia



Det Kongelige Danske Videnskabernes Selskab

Matematisk-fysiske Meddelelser, bind **30**, nr. 1

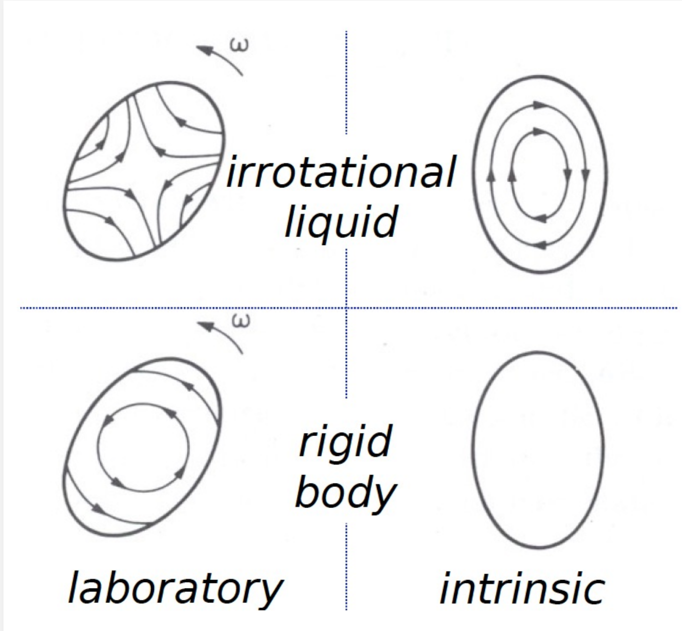
Dan. Mat. Fys. Medd. **30**, no. 1 (1955)

DEDICATED TO PROFESSOR NIELS BOHR ON THE OCCASION OF HIS 70TH BIRTHDAY

MOMENTS OF INERTIA OF ROTATING NUCLEI

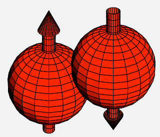
BY

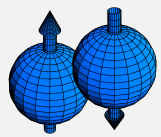
AAGE BOHR AND BEN MOTTELSON



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

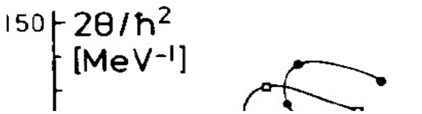
Super conductivity due to **pairing forces** in analogy to the Cooper pairs (electrons) in super conductors.





The backbending phenomenon

$^{162}Dy(\alpha,8n)^{158}Er$



Possible explanations:

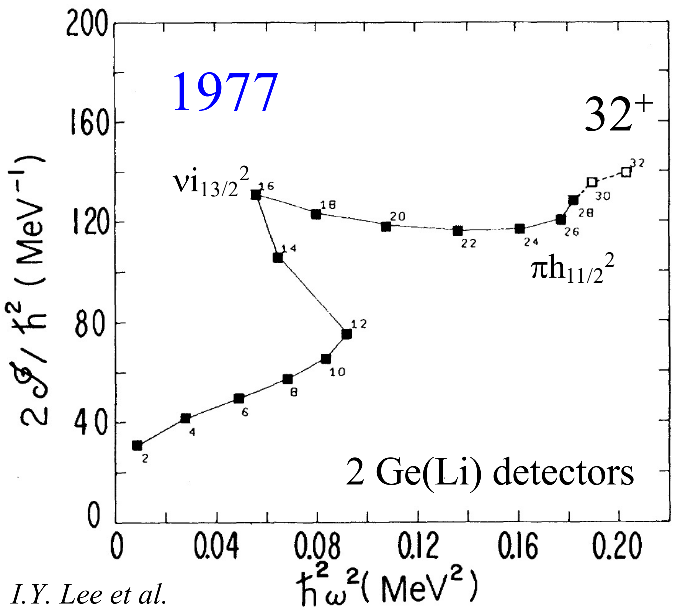
Mottelson-Valatin Coriolis antipairing effect
coherent collapse of pairing correlations,
phase transition from the superfluid to a non-superfluid state

neutrons

This work has demonstrated the feasibility of observing discrete yrast transitions of spin up to at least 30$\hbar$ in (HI,xn) reactions. Three developments have made these high spins accessible. These are (1) ^{40}Ar projectiles to bring in high angular momentum; (2) the elimination of the Doppler broadening by using thin targets and observing in the forward direction; and (3) the enhancement of a particular reaction channel using γ-ray multiplicities. The observed second discontinuity in the yrast levels of ^{158}Er around $I = 28\hbar$ may be due to several possible effects, with alignment of a second pair of particles appearing most likely to us. It will be interesting to find out whether such discontinuities are a general phenomenon and also whether there is a connection between them and the population pattern in (HI,xn) reactions.

LBL, 2 Ge(Li) detectors

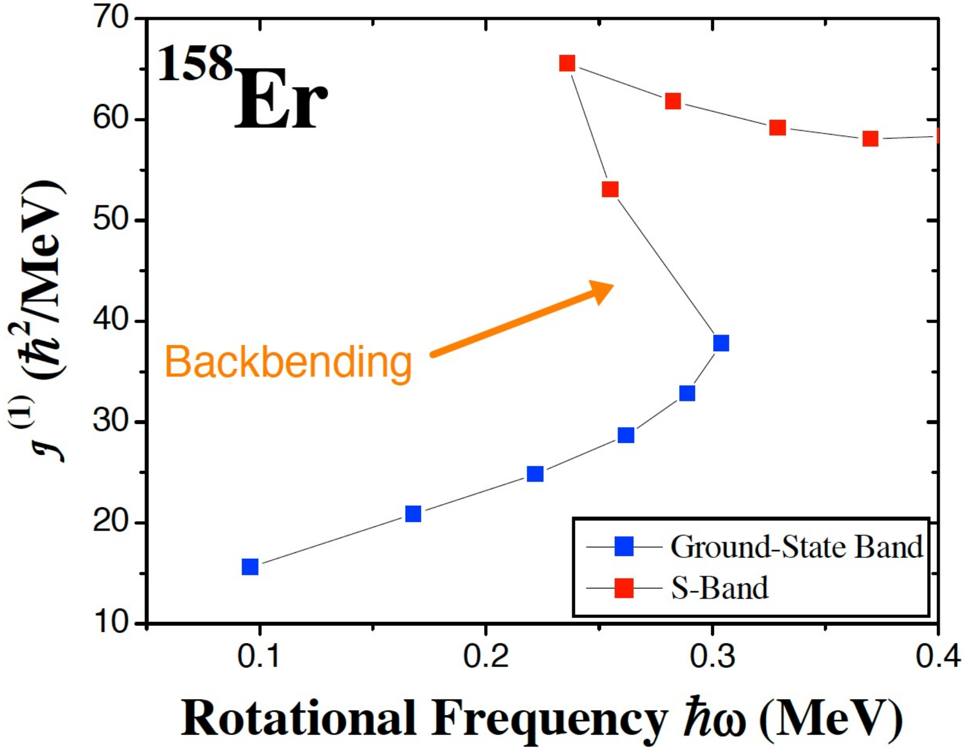
$^{122}Sn(^{40}Ar,4n)^{158}Er$



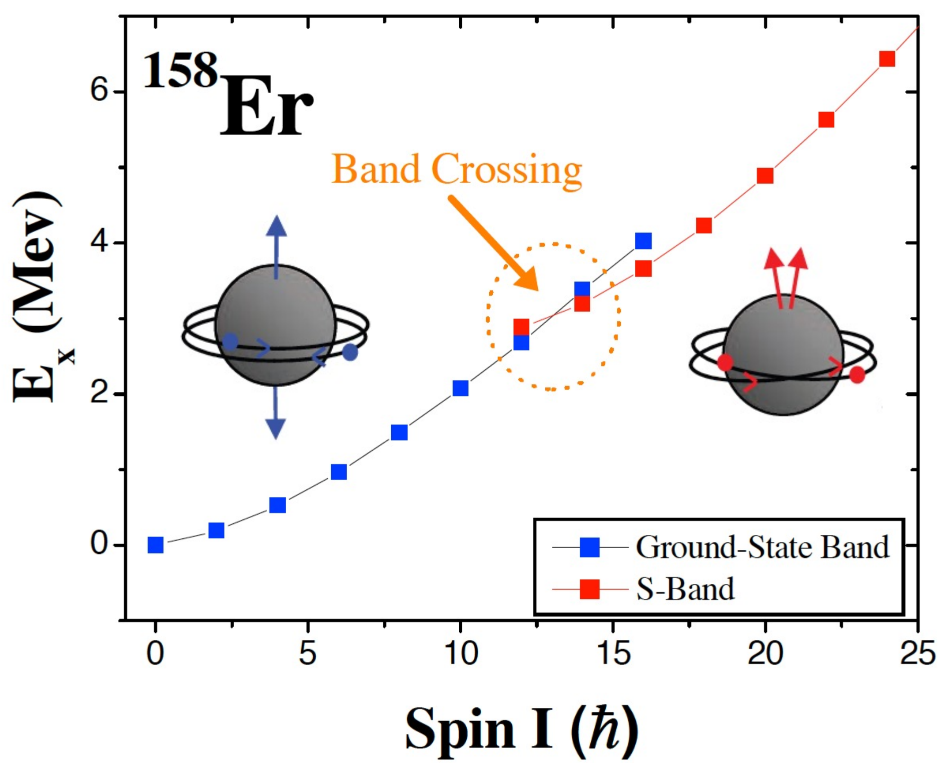
I.Y. Lee et al.
Phys. Rev. Lett. 38, 1454 (1977)

Band crossings along the Yrast line

Moment of inertia vs. rot. frequency

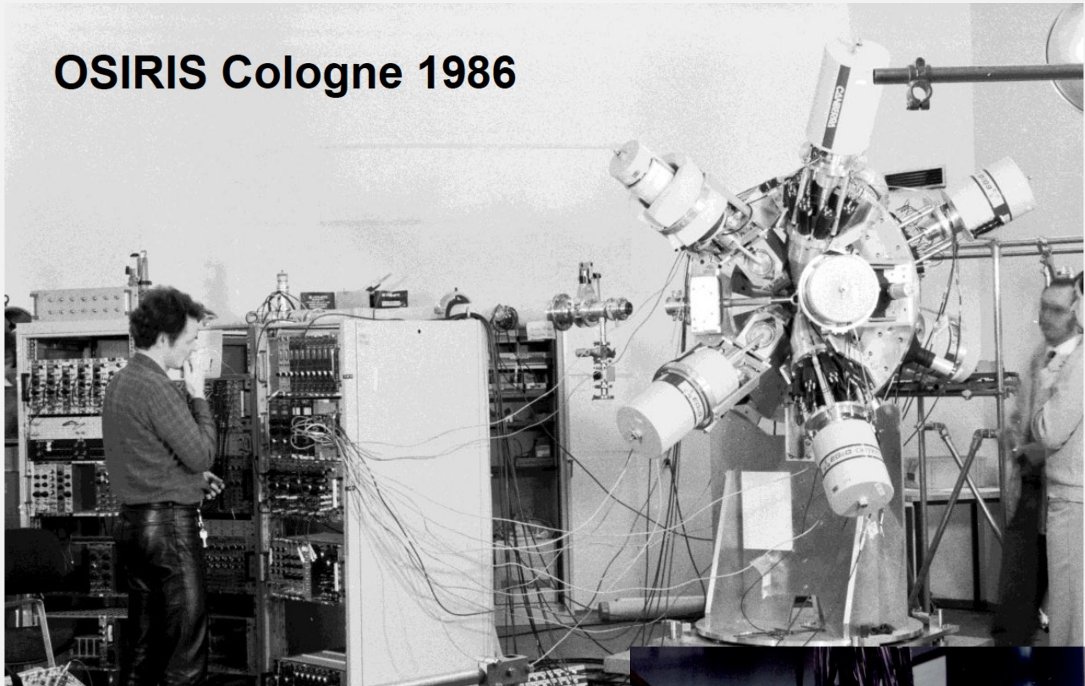


Excitation energy vs. spin

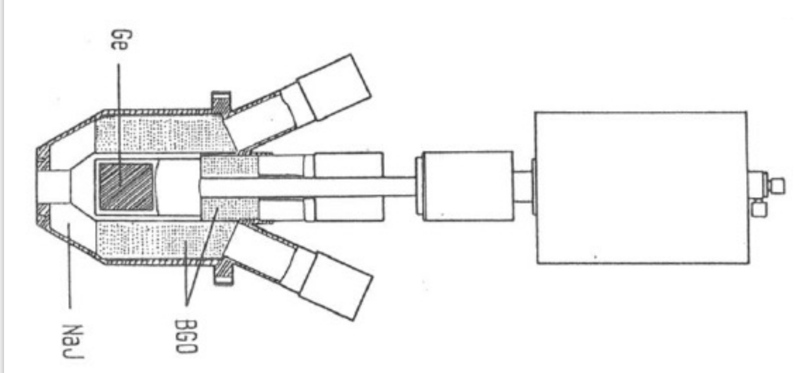


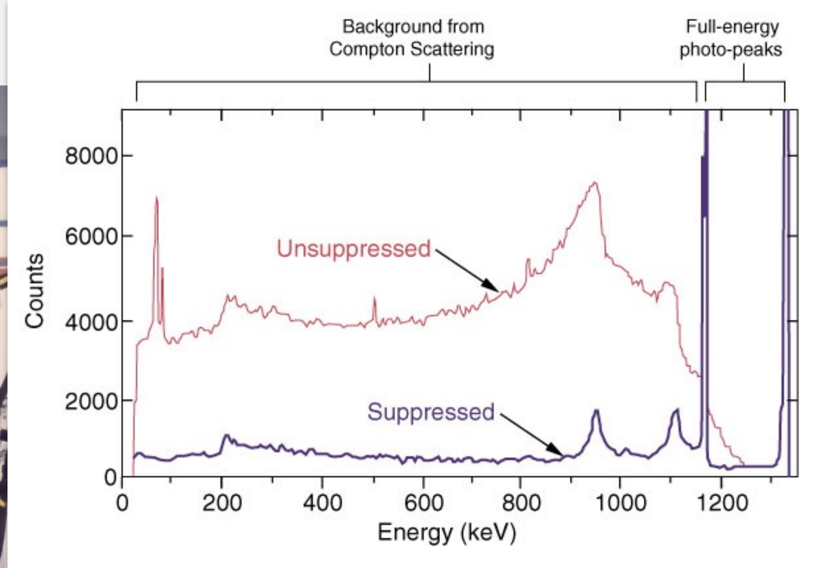
First back(up)bending corresponds to the crossing of the Stockholm band with the ground state band !

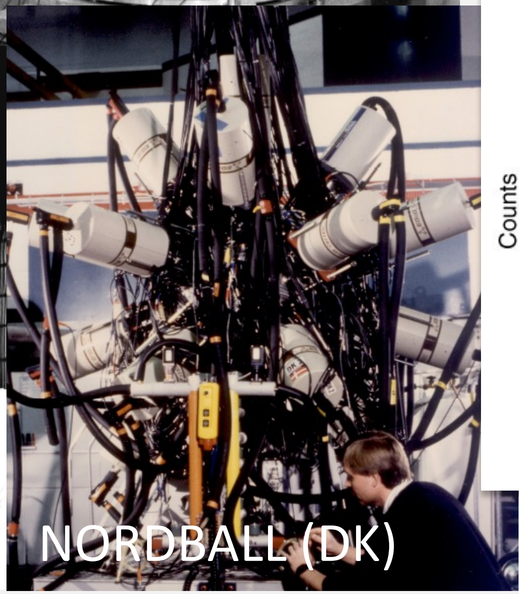
The 1980's: National arrays of HPGe detectors



Compton-suppression shields

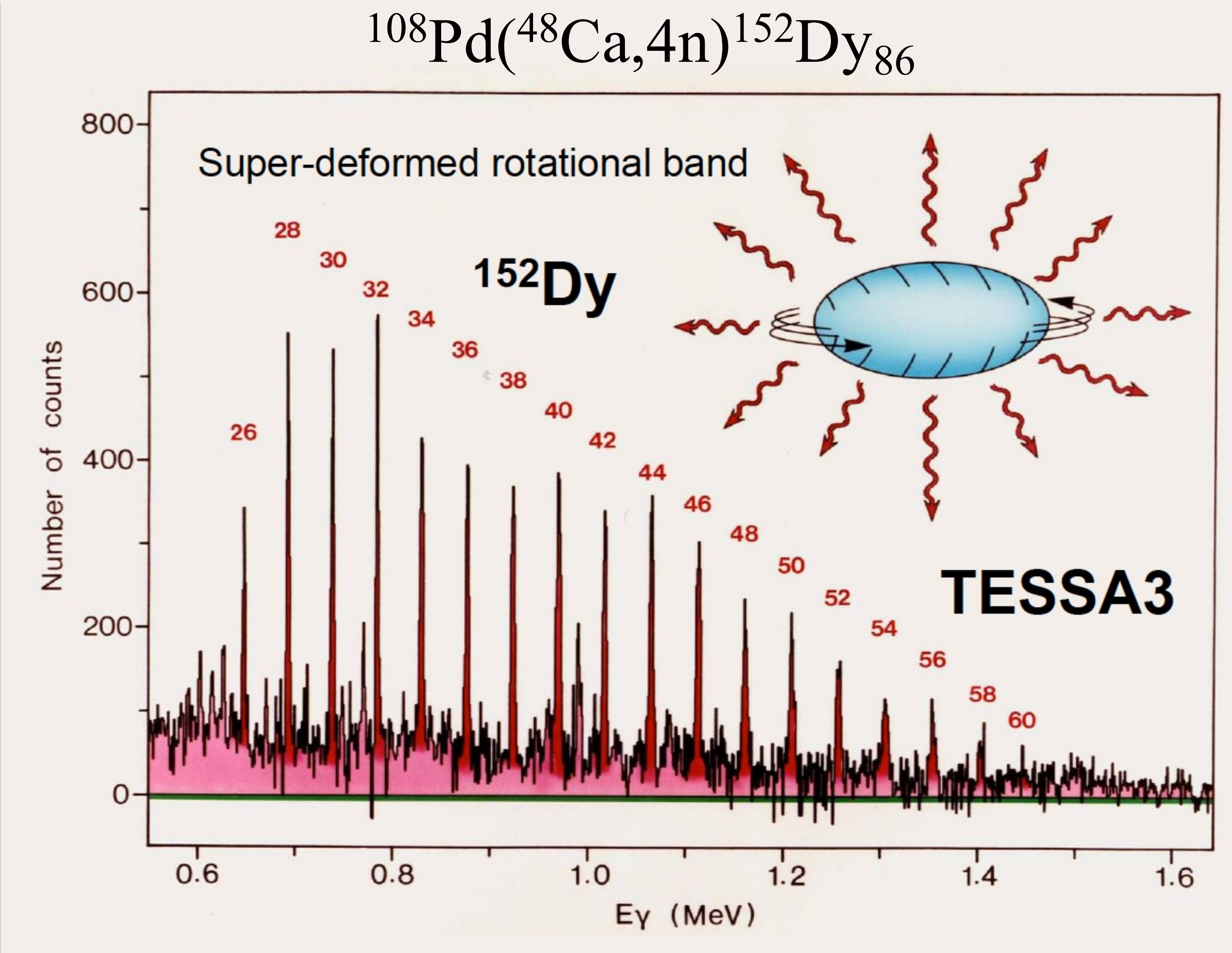






Nuclear Superdeformation: A major discovery

TESSA2: 12 escape-suppressed Ge detectors at the Daresbury Laboratory (UK)



Nearly constant spacing of 47 keV !

moment of inertia

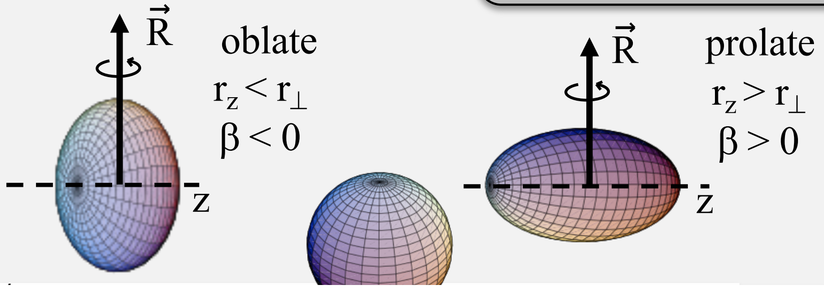
deformation

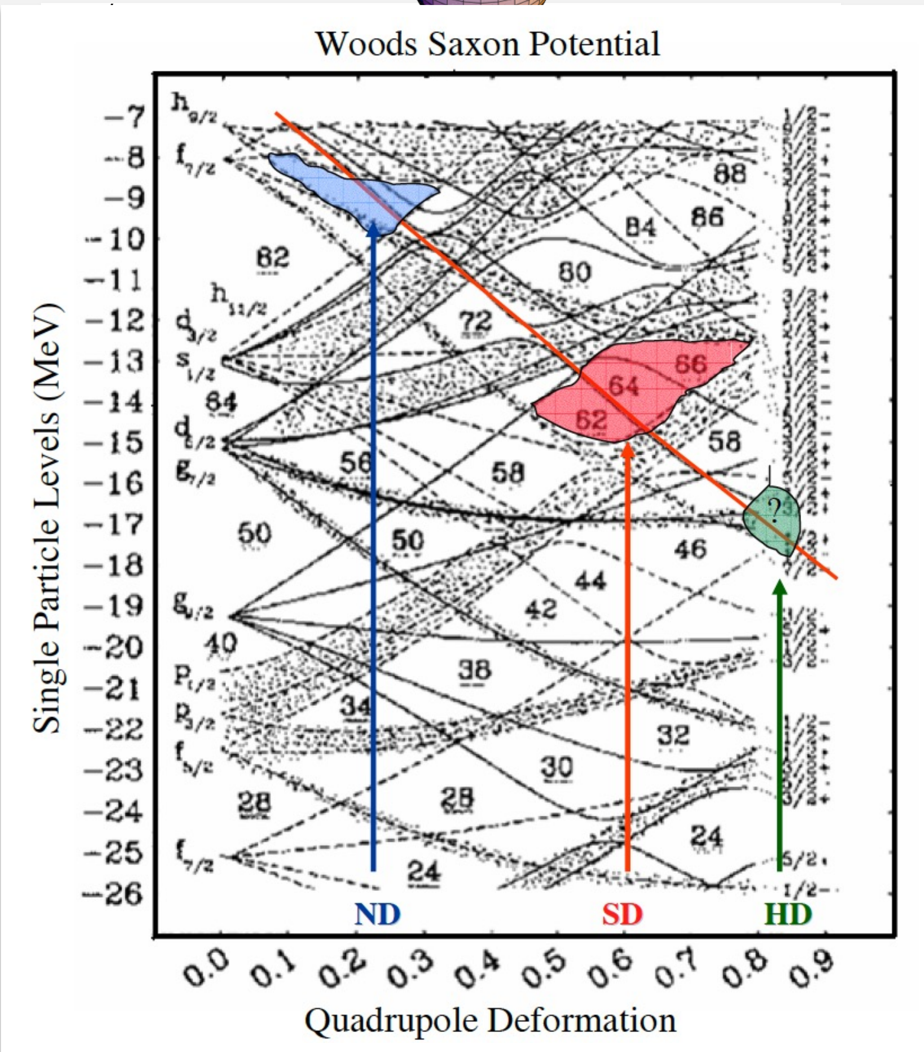
Axis ratio ~2:1 !

P. Twin et al., Phys. Rev. Lett. 57, 811 (1986)

Superdeformed bands in the γ-ray continuum observed before (E2 bump).

Deformed shell gaps



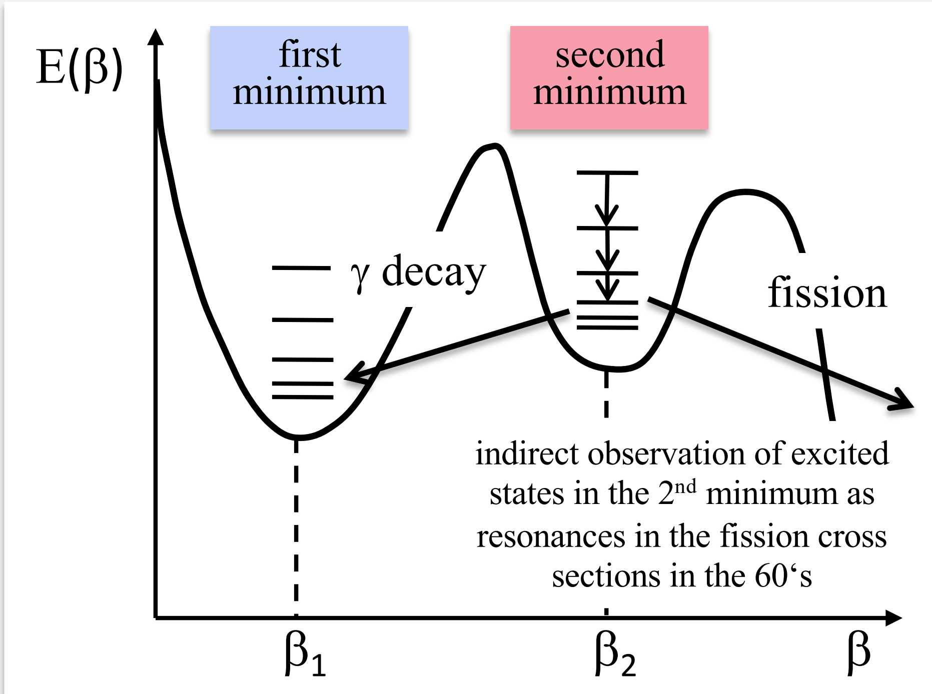


Potential energy of the nucleus as a function of the deformation:

$$E(\varepsilon) = \sum e_i(\varepsilon)$$

sum over the single-particle energies of all A nucleons

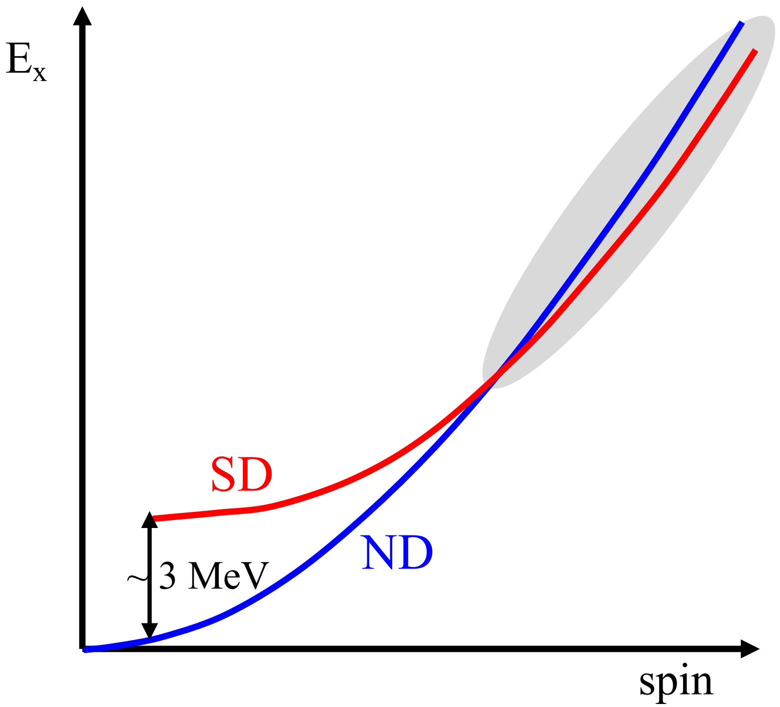
Due to the different slopes of the single-particle orbitals there might be more than one minimum for certain nucleon numbers !



Normal and superdeformed bands in the E_x vs. I plane

Moment of inertia larger for larger deformation

⇒ Superdeformed rotational states energetically favoured and therefore observable at high spin !



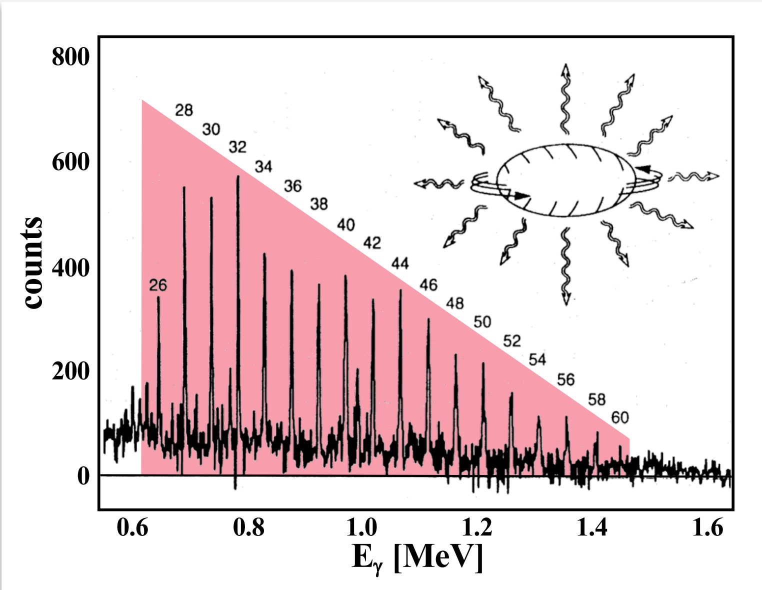
Rotational band:

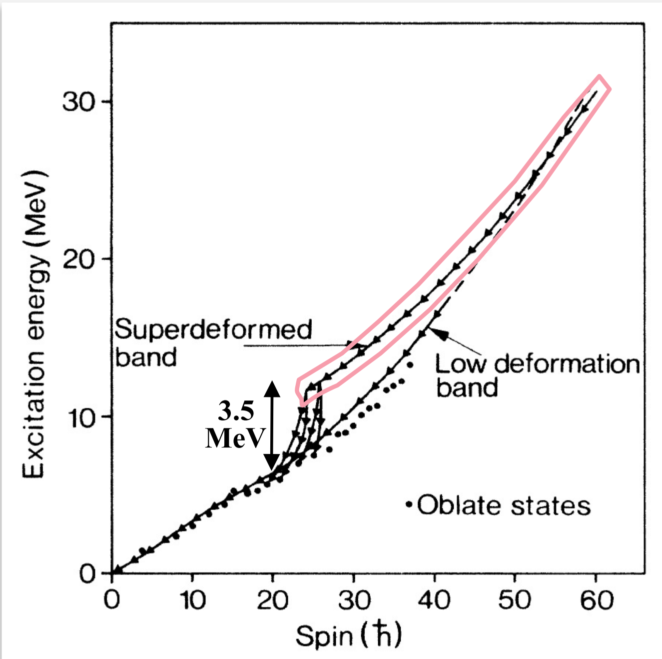
$$E_x = \frac{\hbar^2}{2J} I(I+1)$$

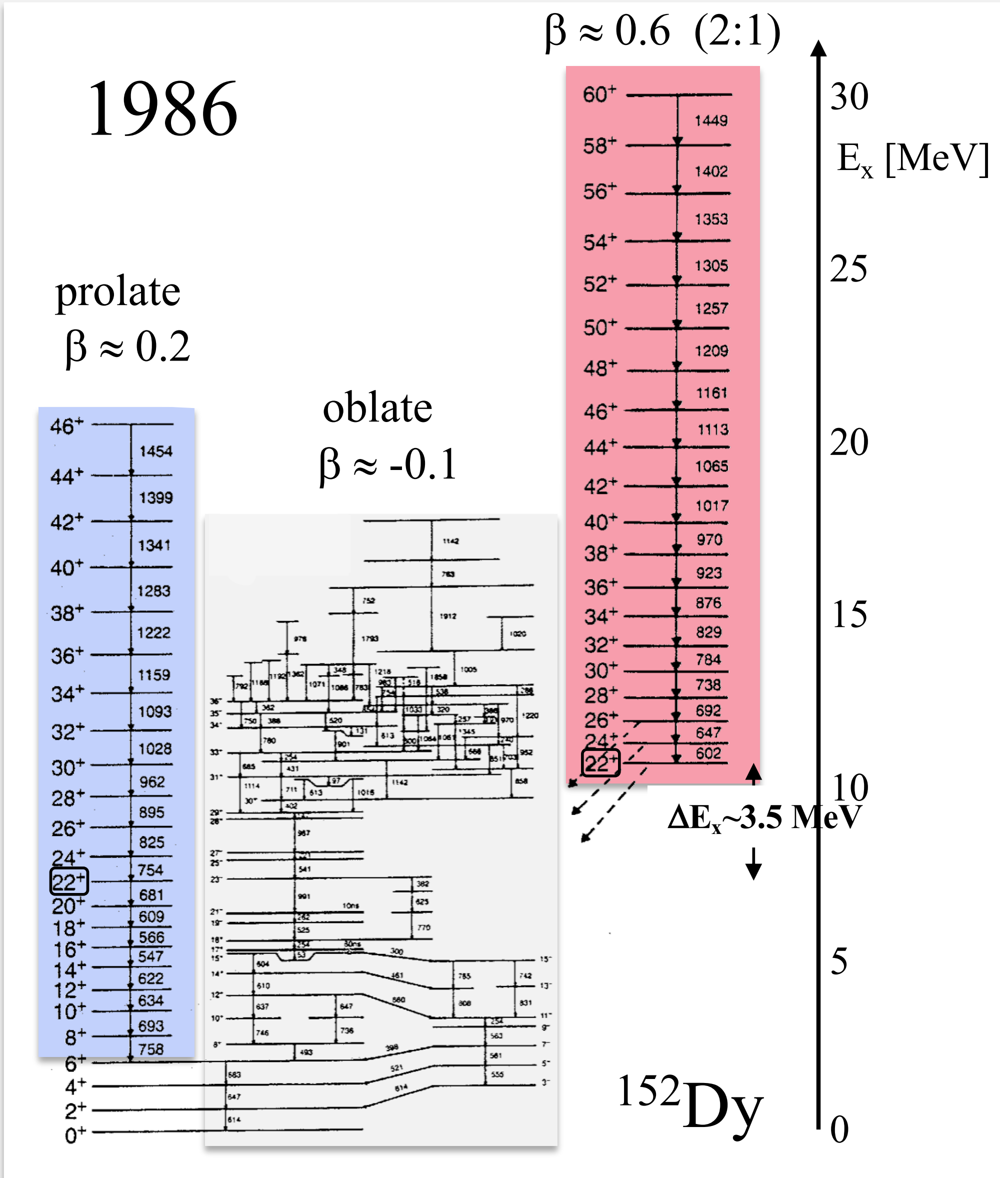
J : Moment of inertia

$J_{SD} > J_{ND}$

Discovery of superdeformation in $^{152}Dy_{86}$

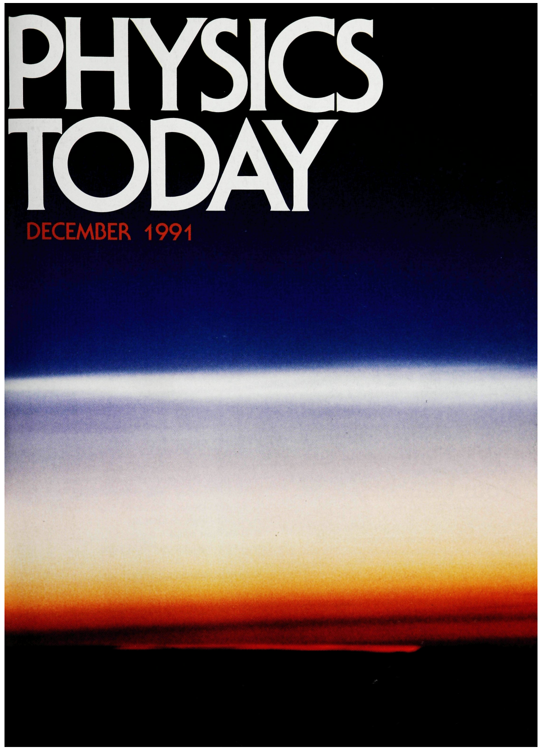






How does the SD band decay ?

Superdeformation as major physics discovery



"Top unexpected physics discoveries of the last five years!"

PHYSICS TODAY December 1991

Daniel Kleppner
Lester Wolfe Professor of Physics at MIT

High temperature superconductivity

Atom cooling and atom optics

Large-scale structure of the universe

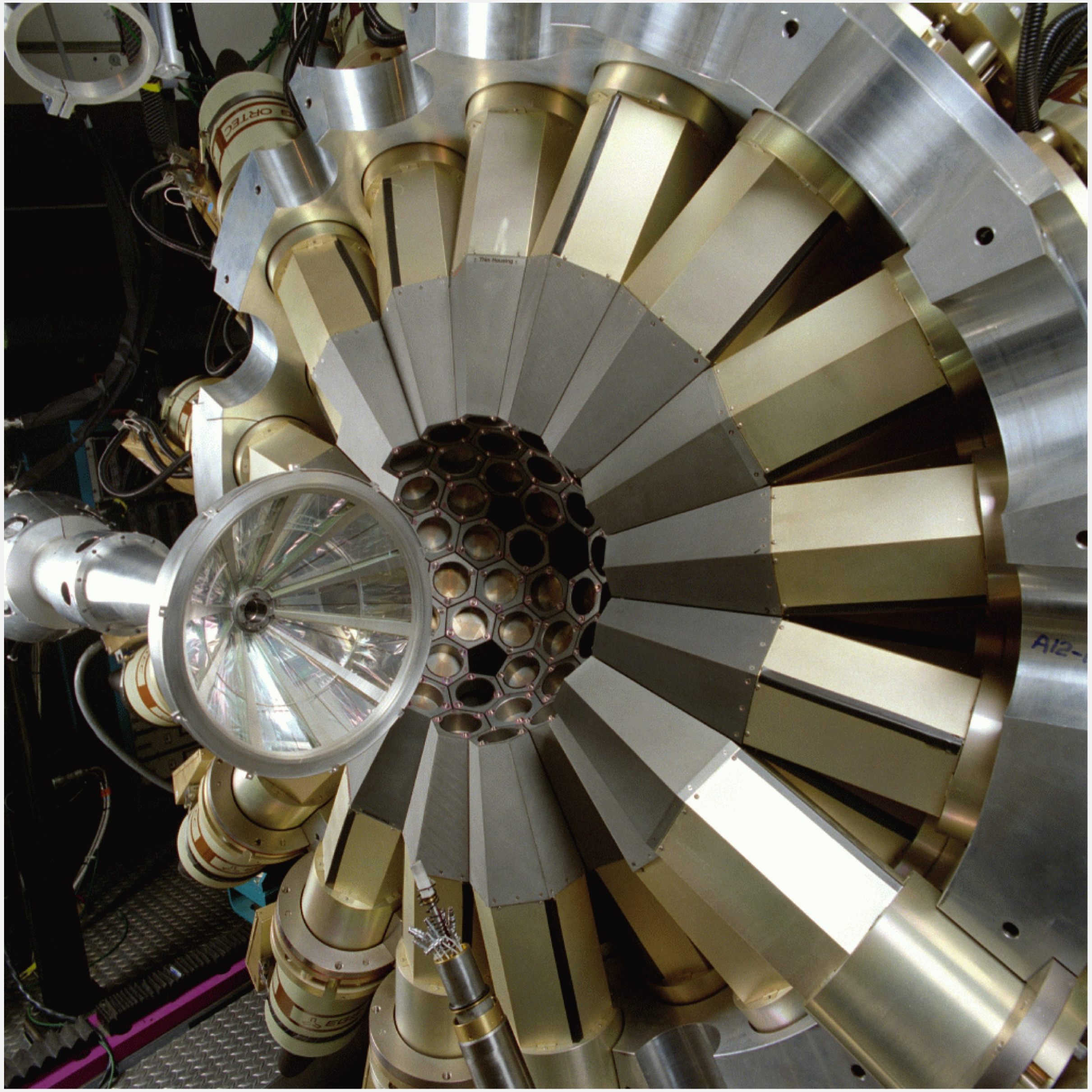
Supernova 1987A

<u>Superdeformed nuclei</u>

Buckyballs

Starting shot for the development of larger 4π γ-ray spectrometer !

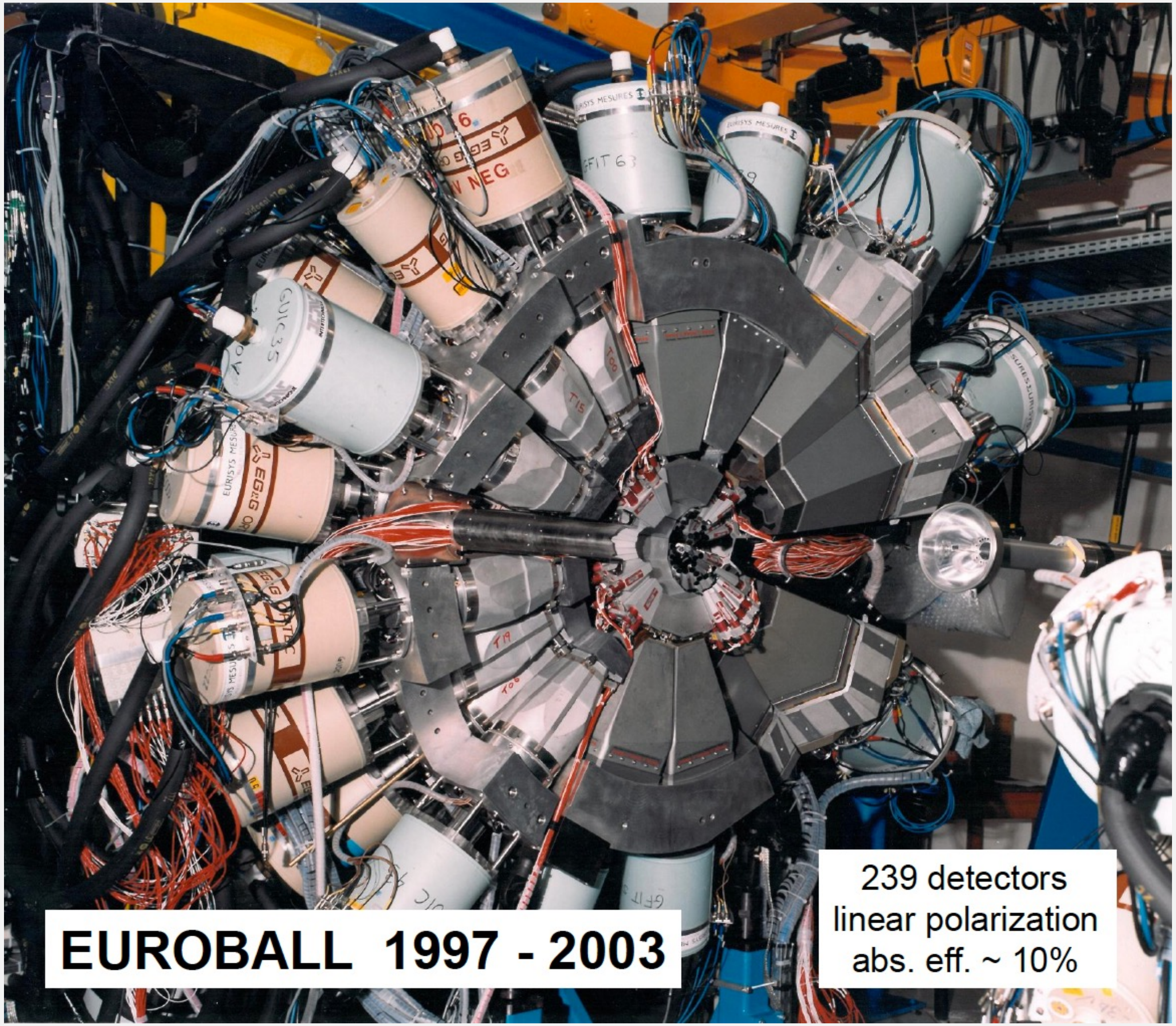
The American Gammasphere



Total photopeak efficiency around 10% !

1993-1995 :
preliminary (30 + ... Ge)
since 1996:
110 individual Ge
Berkeley - Argonne - Berkeley

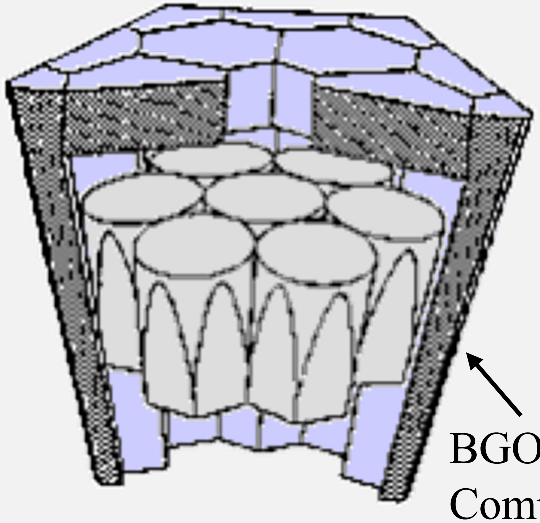
The European EUROBALL

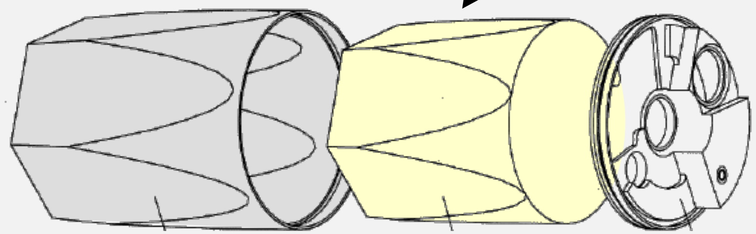


Total photopeak efficiency around 10% !

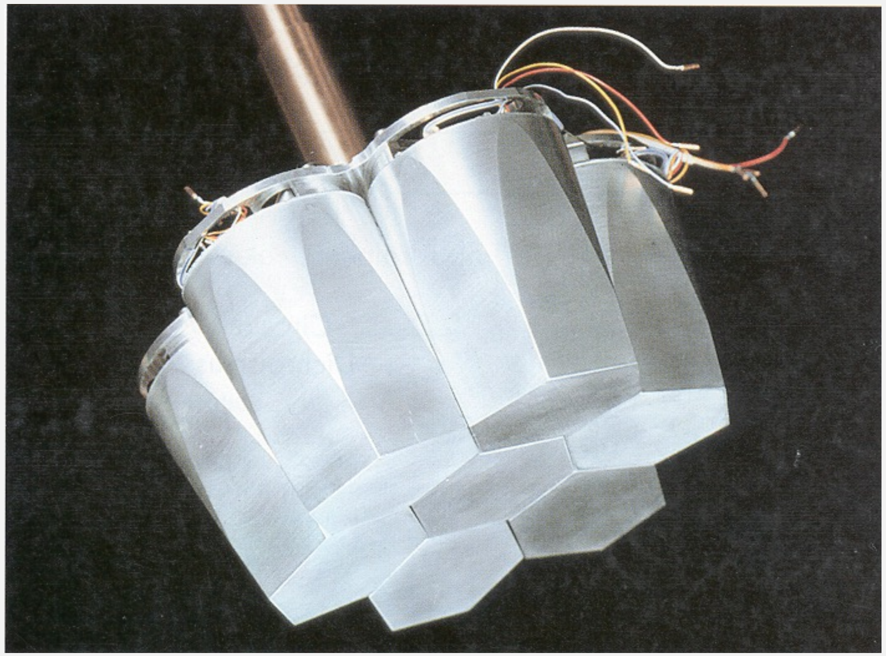
Three different types of detectors !

The composite CLUSTER detector of EUROBALL

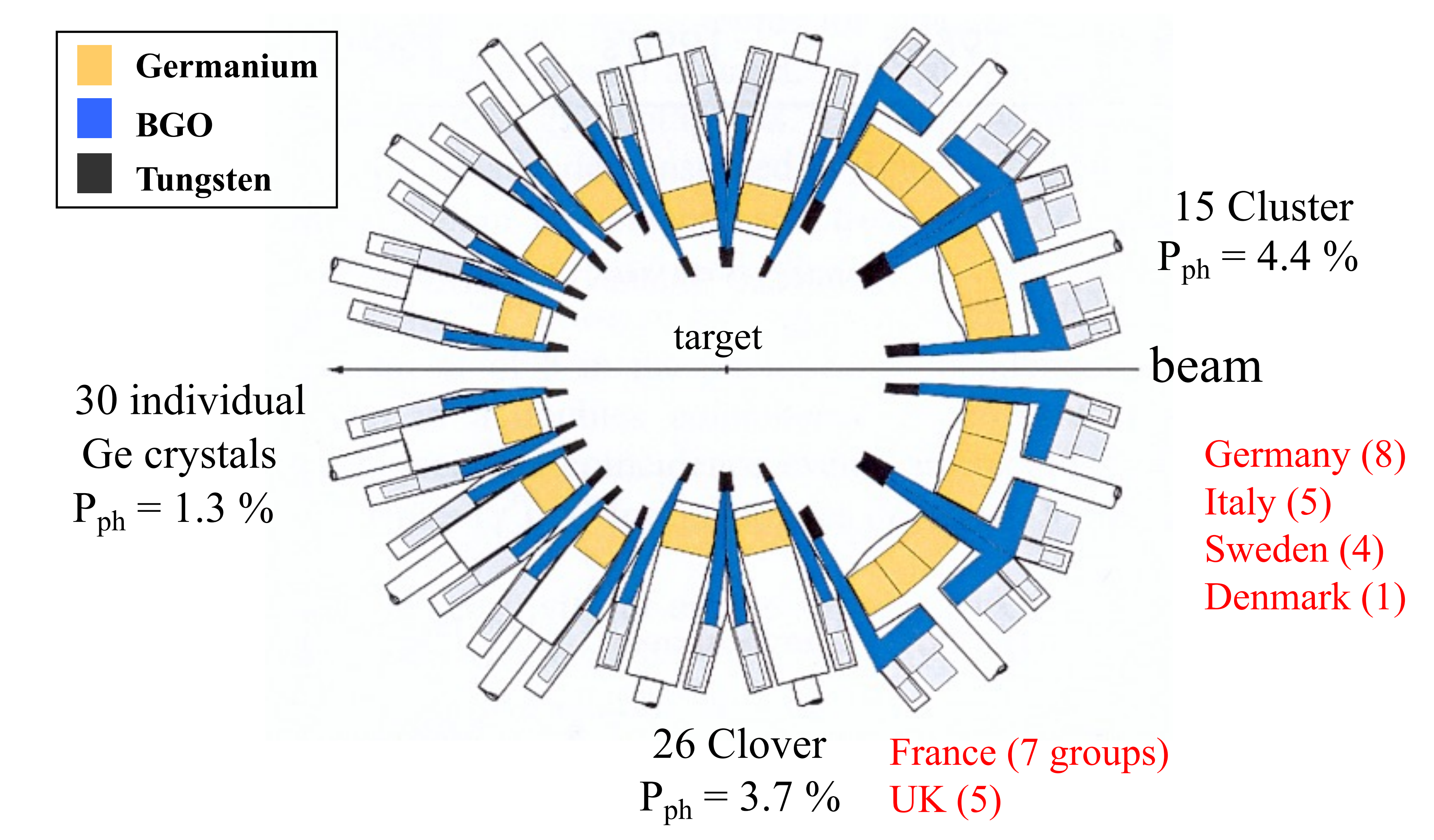




1.5 kg of Ge each crystal



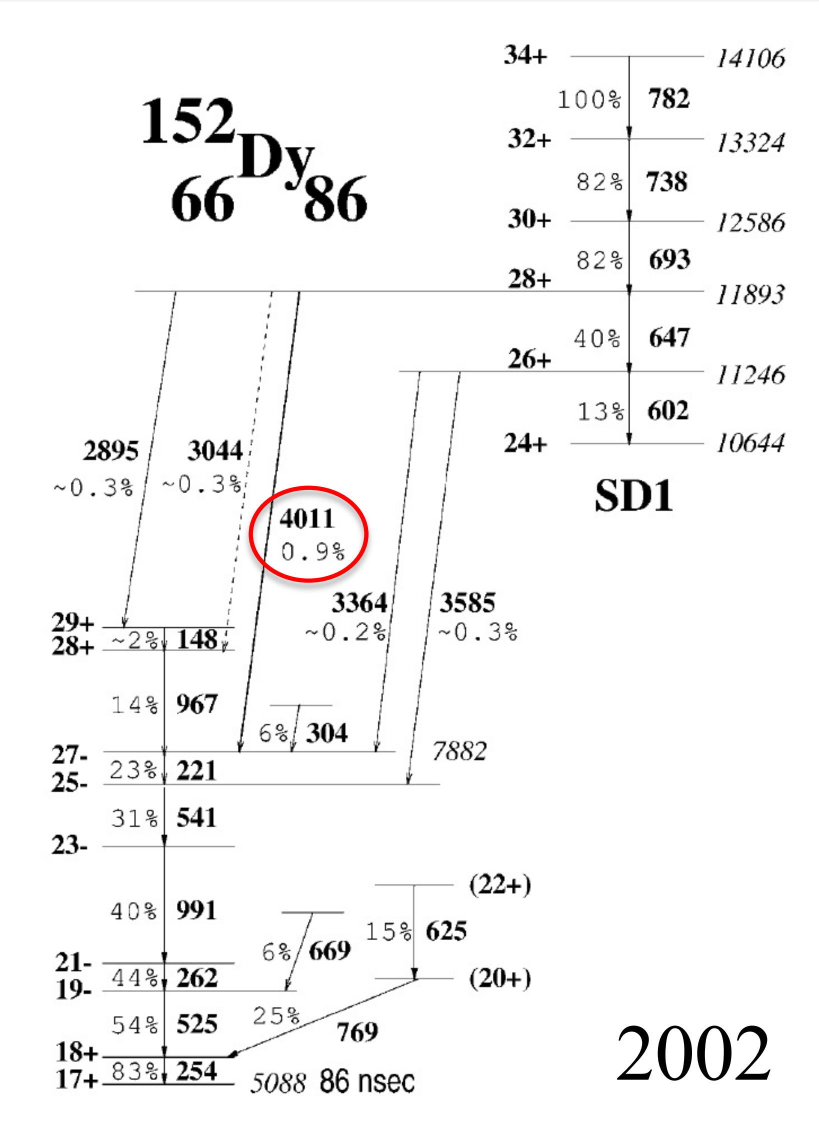
The European EUROBALL (1997-2004)



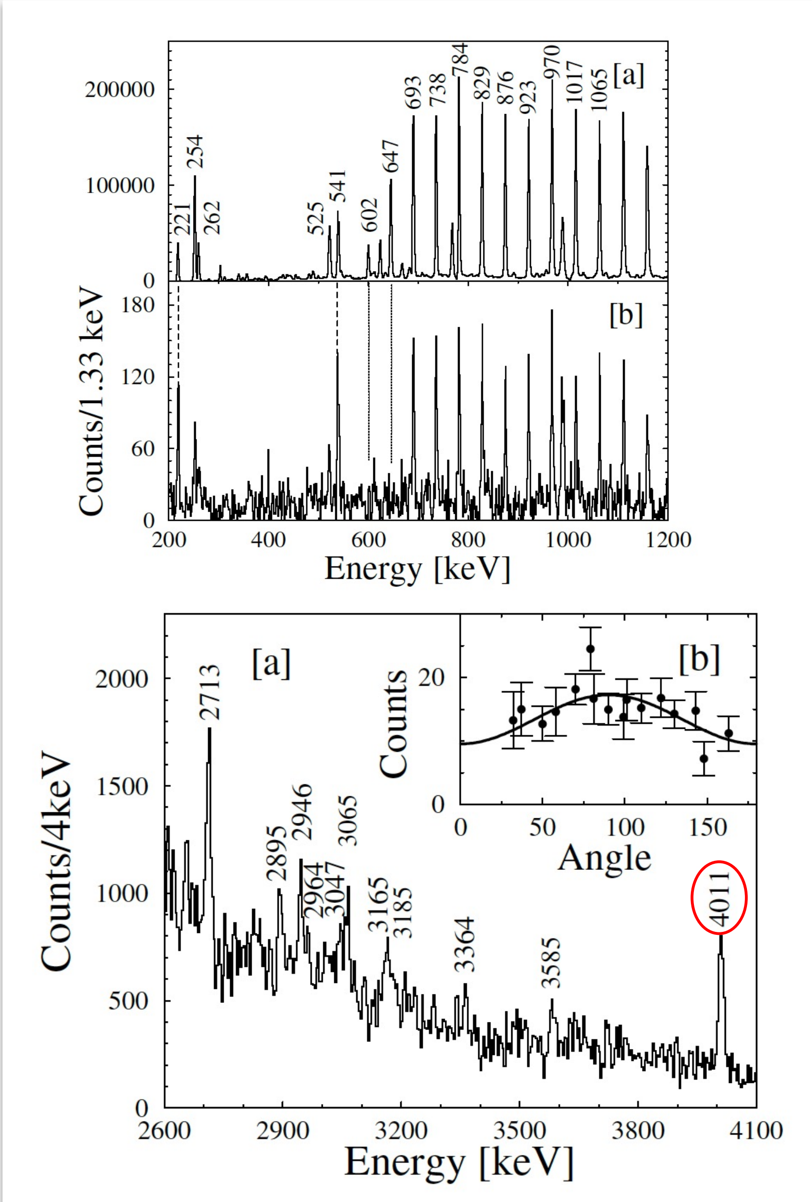
In operation at the LNL Legnaro (Italy)
and the IReS Strasbourg (France)

→ 239 individual Ge crystals !

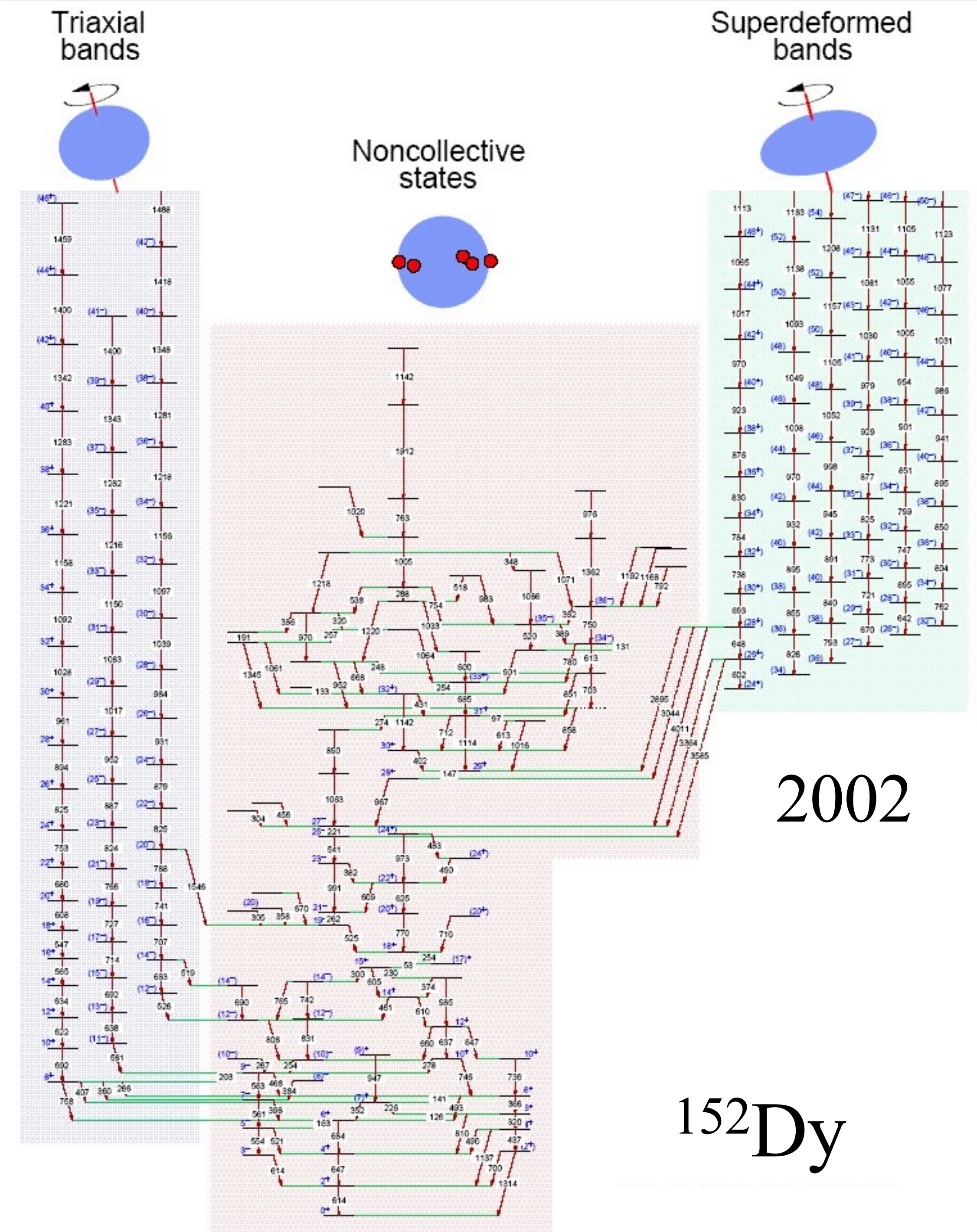
The decay-out in the case of ^{152}Dy - 16 years later



T. Lauritsen et al., Phys. Rev. Lett. 88, 042501 (2002)

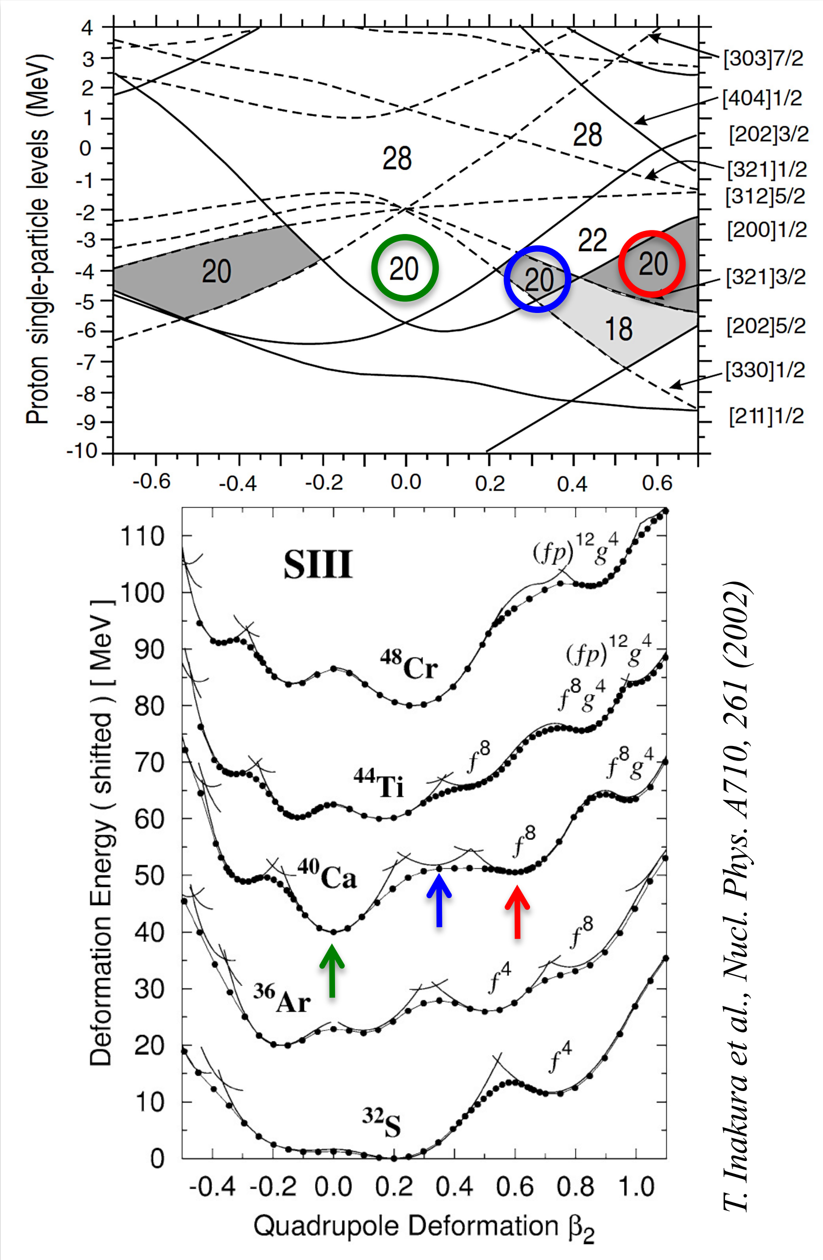


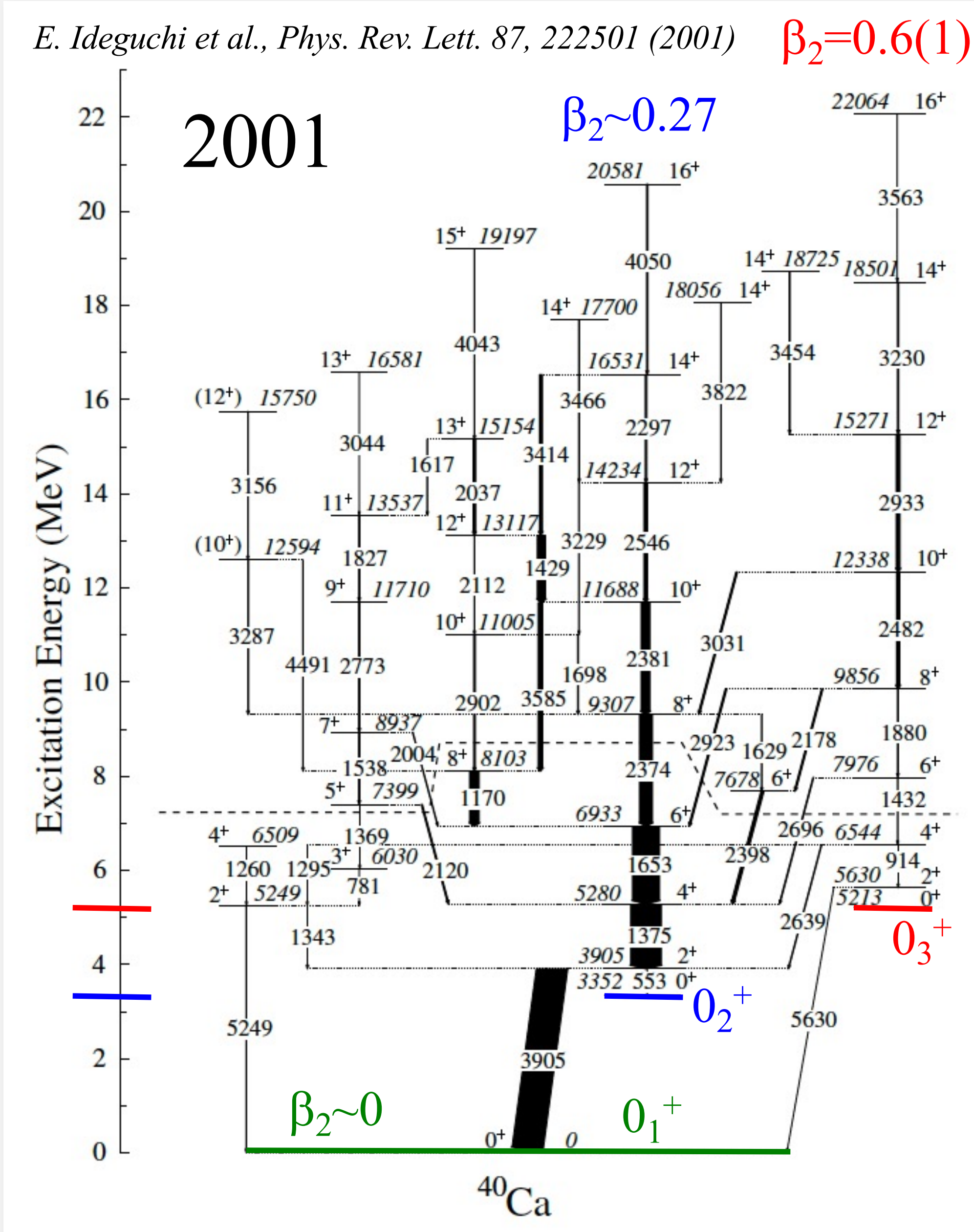
Coexistence of collective and non-collective motion



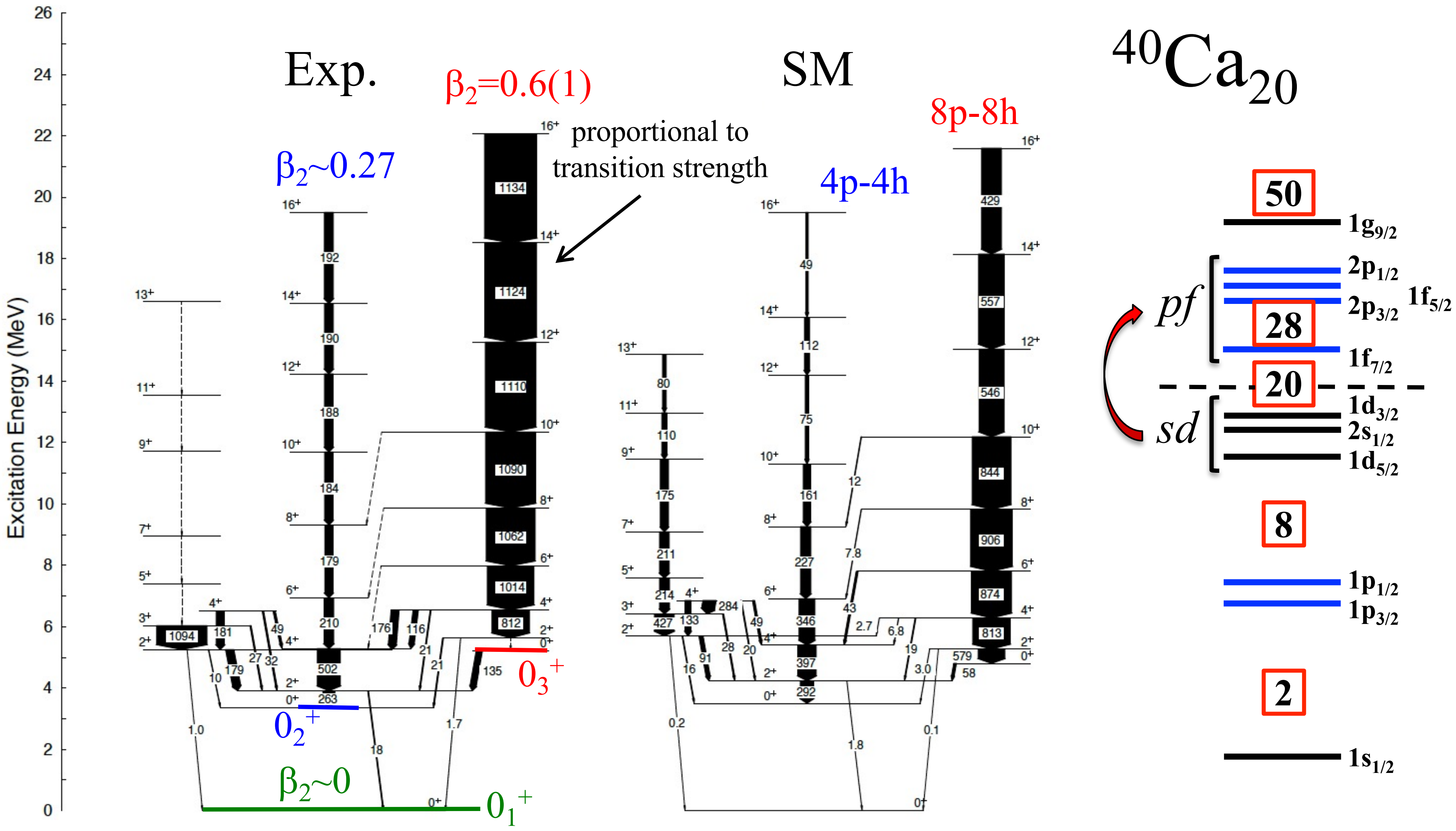
From 1986 to 2006: >250 SD bands all over the chart of nuclei

Superdeformation in doubly-magic ^{40}Ca



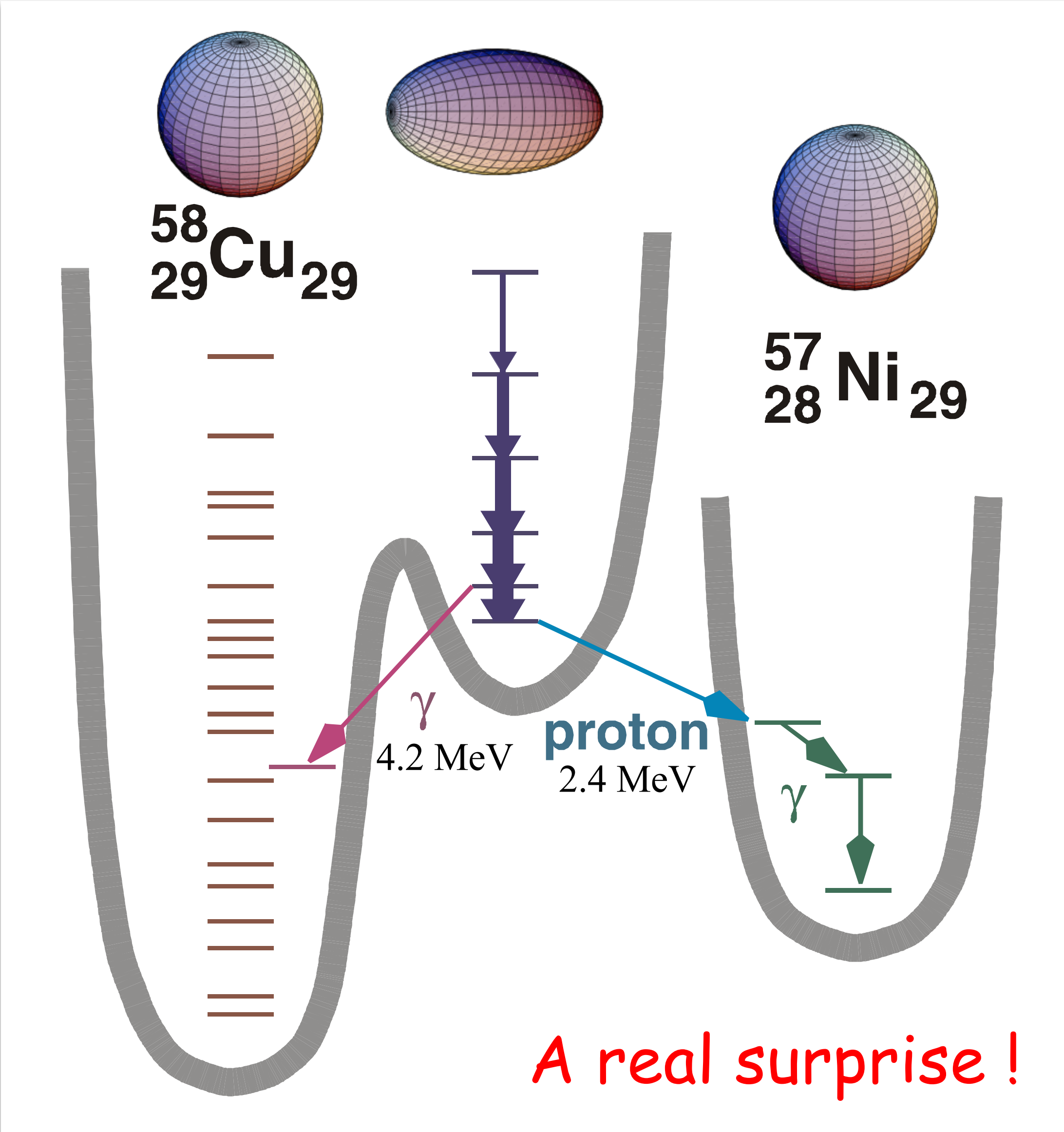


Superdeformation in the nuclear shell model



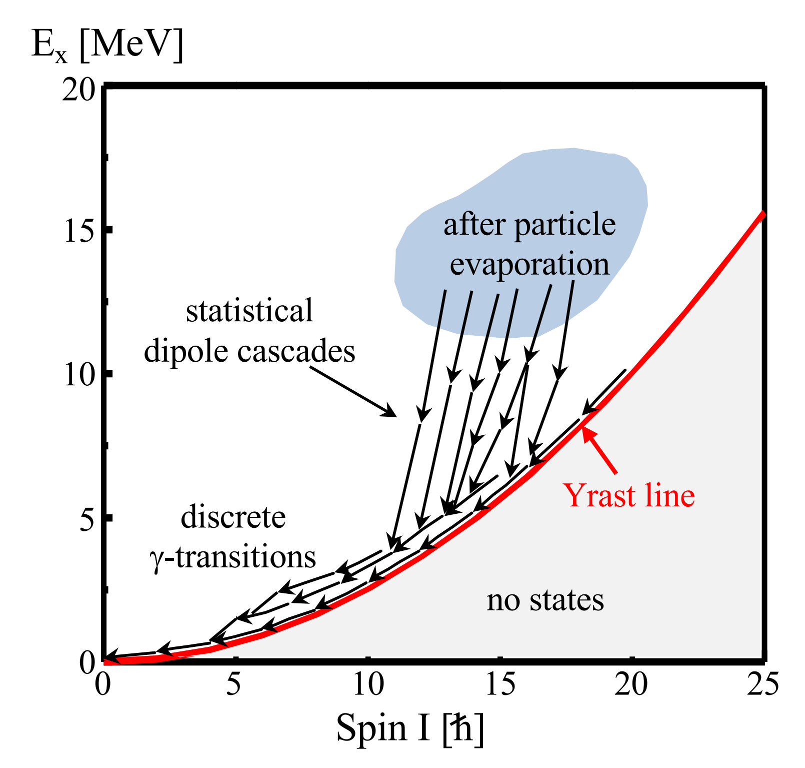
It is just a matter of configuration space …

Prompt proton decay out of the 2nd minimum

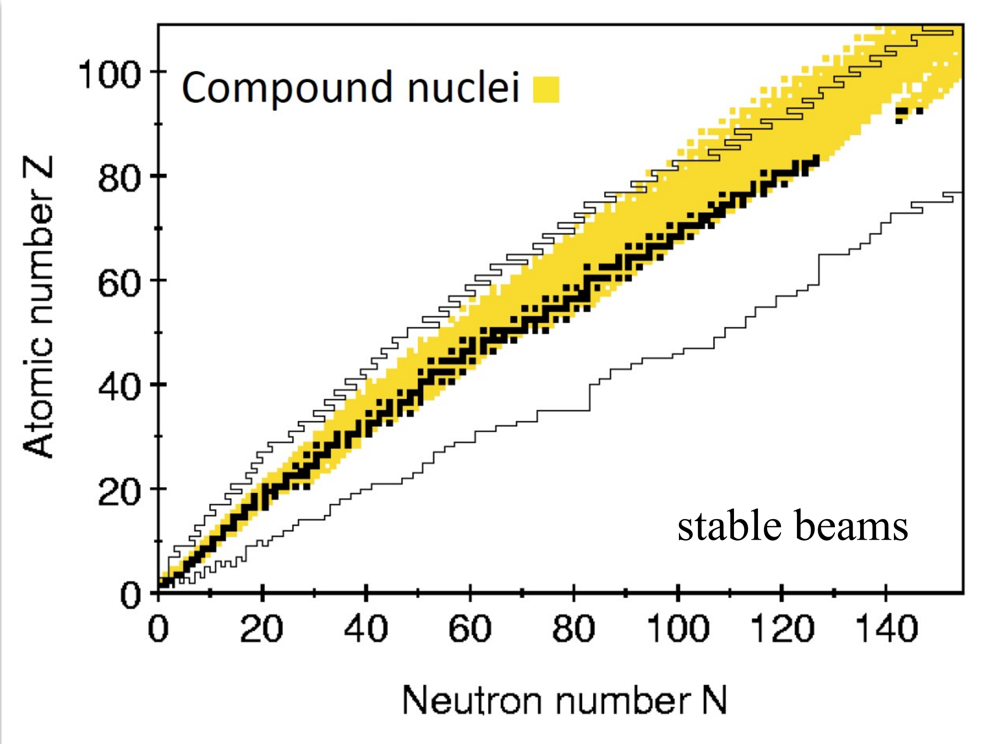


D. Rudolph et al., Phys. Rev. Lett. 80, 3018 (1998)

The playground of fusion-evaporation reactions

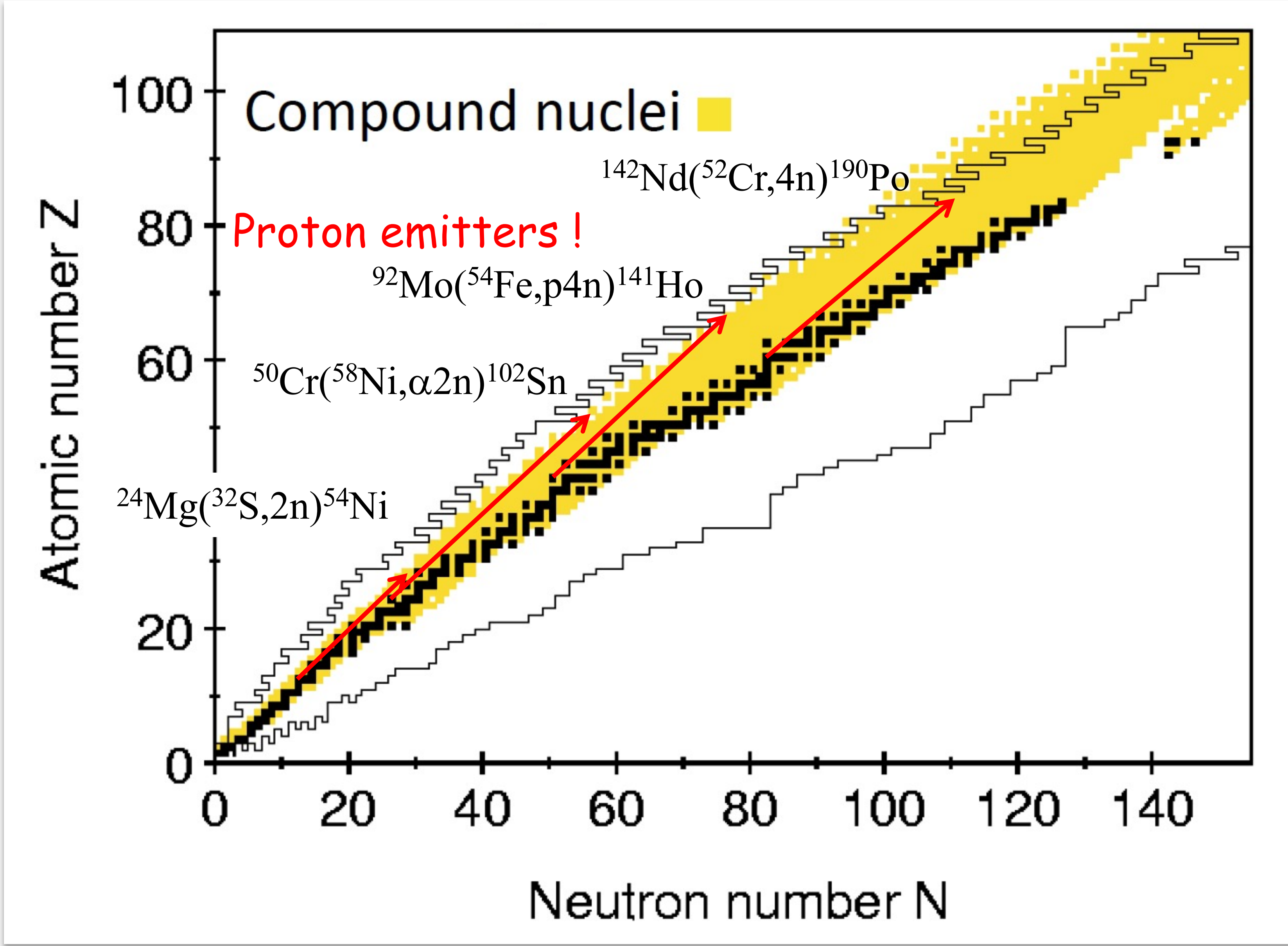


Strongly populated reaction channels:
High-spin physics !



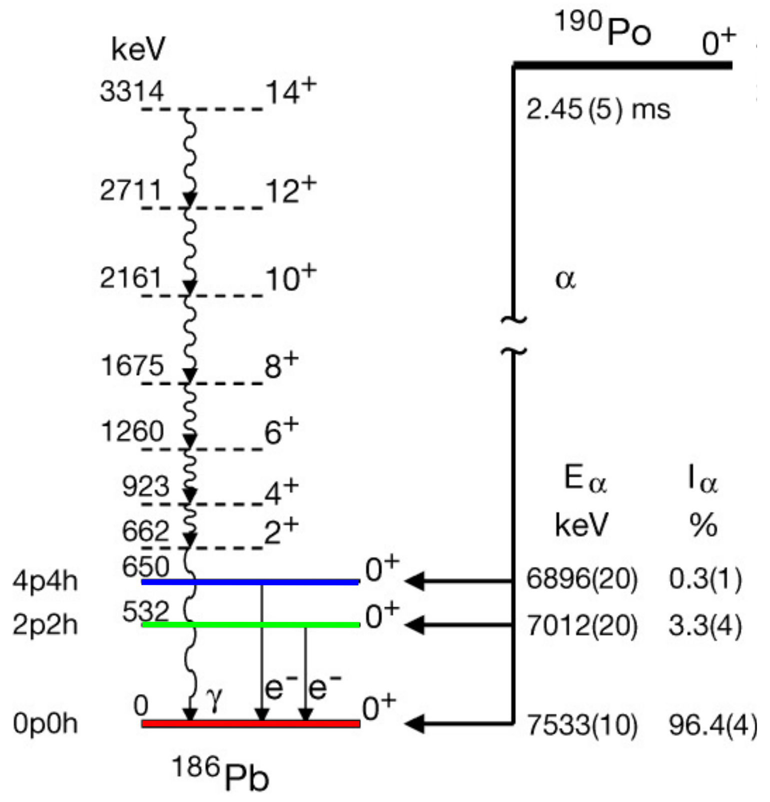
Weakly populated reaction channels:
New physics at the extremes of isospin !

The playground of fusion-evaporation reactions



Shape coexistence close to the ground state

Level scheme of ^{186}Pb

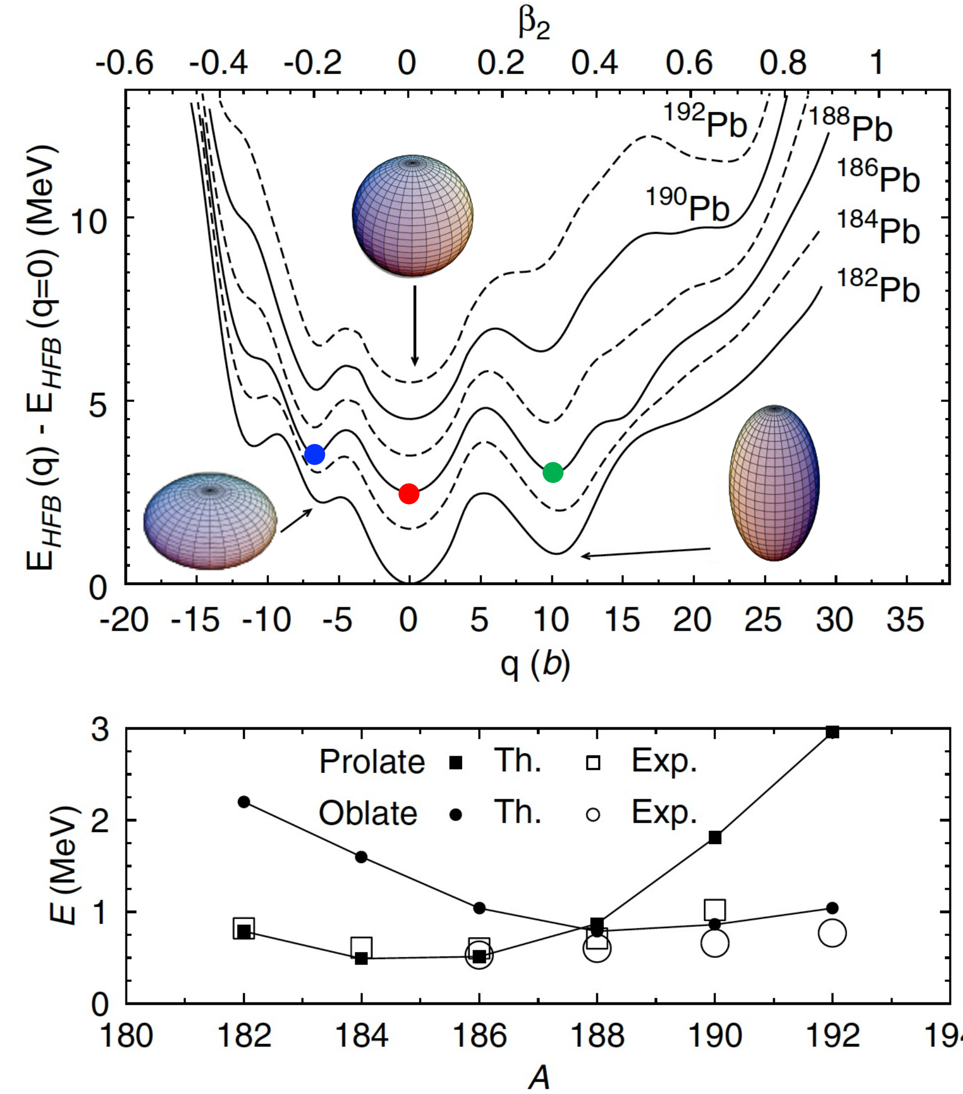


A. Andreyev et al., Nature 405,430 (2000)

^{142}Nd(^{52}Cr,4n)^{190}Po

σ~300 nbarn ~300 atoms per hour

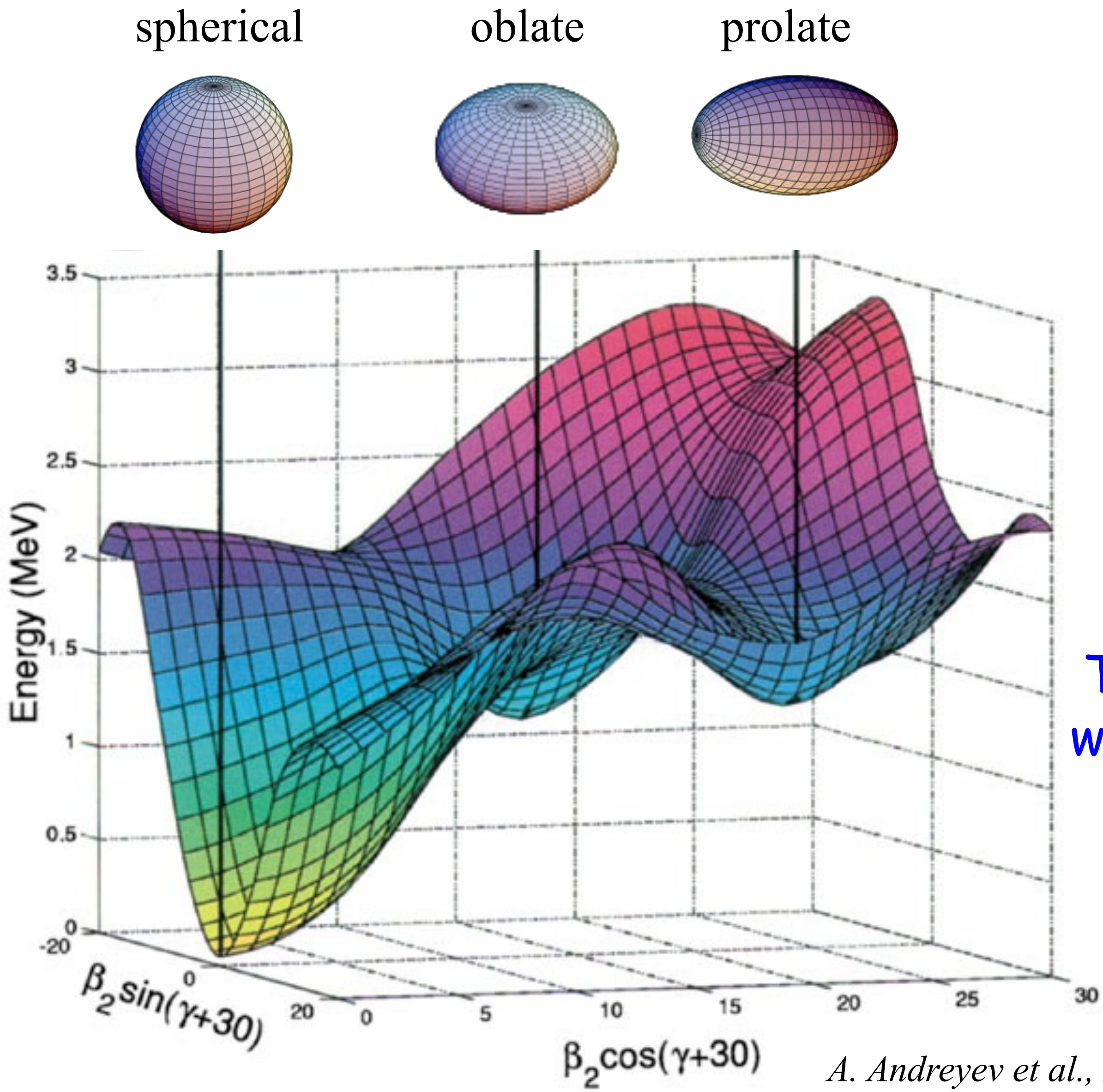
background ~10^6



J.L. Egido et al., Phys. Rev. Lett. 93, 082502 (2004)

Well described by mean field theory !

Shape coexistence close to the ground state



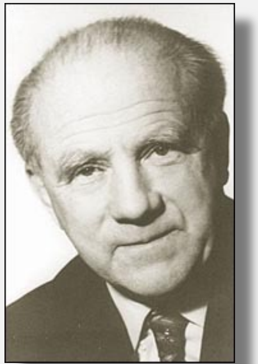
$^{186}_{82}Pb$

Three minima within ~1MeV !

I=0ħ

A. Andreyev et al., Nature 405,430 (2000)

Does the strong interaction conserve isospin ?

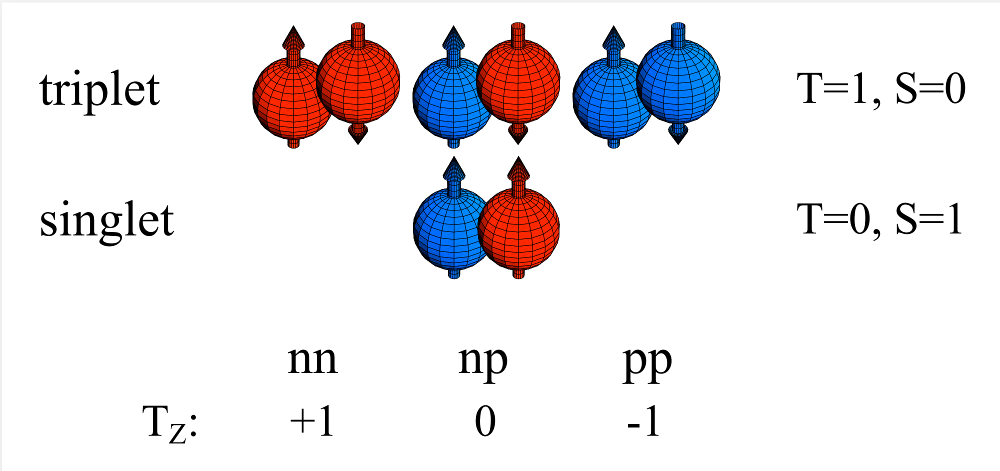


Heisenberg 1932

The strong interaction is charge symmetric and charge independent:

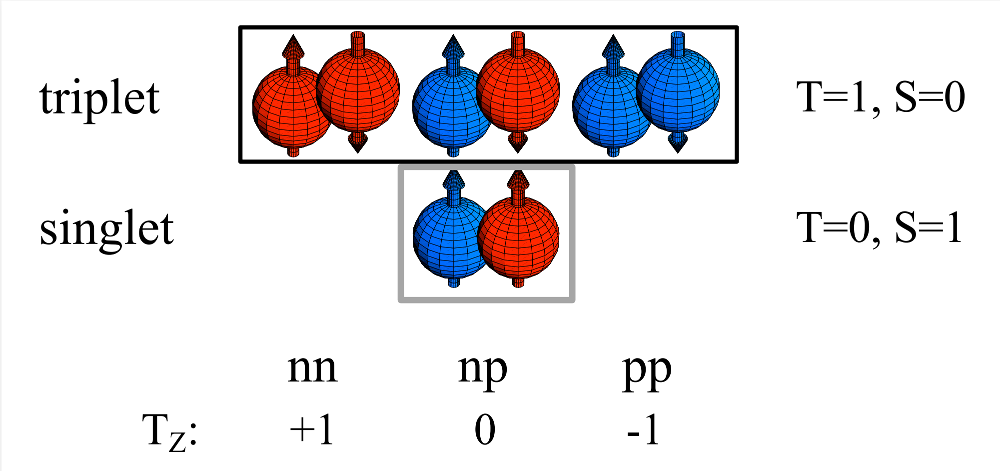
$$V_{pp} = V_{nn} = V_{pn}$$

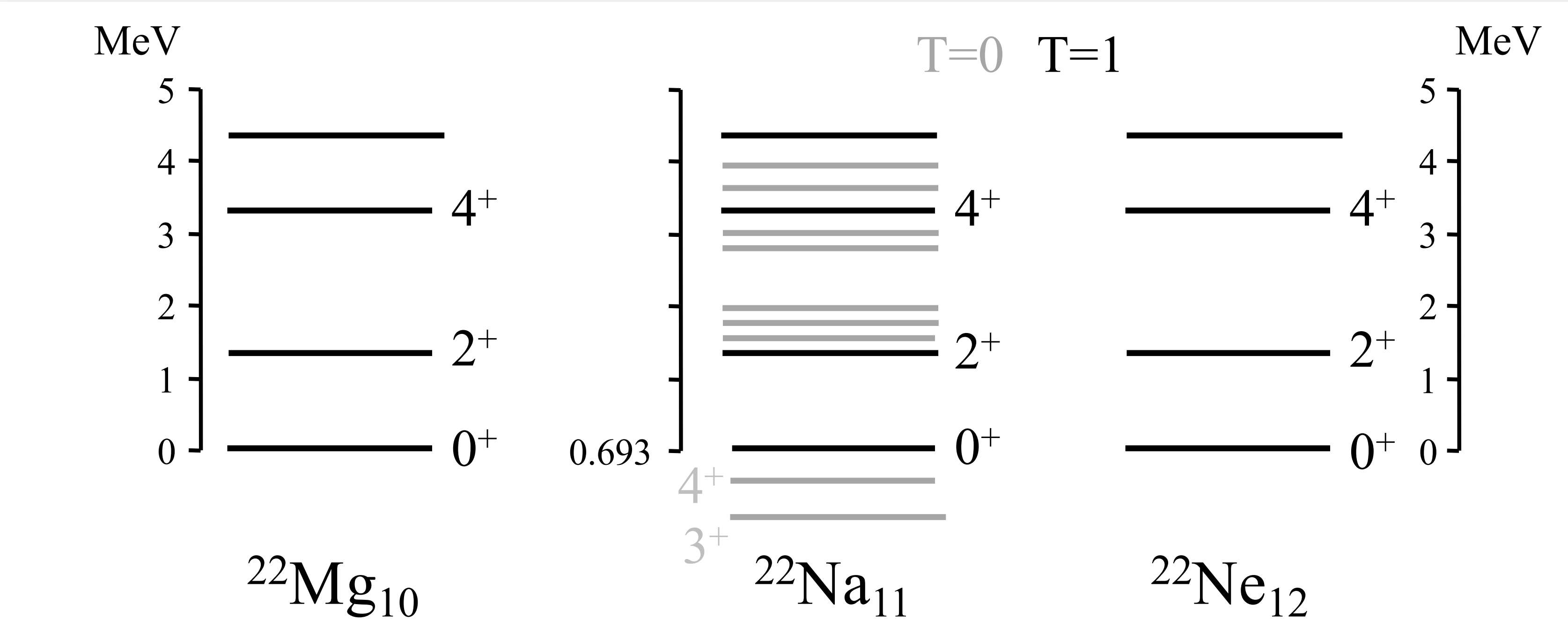
Proton and neutron can be viewed as two states of the same particle: the nucleon



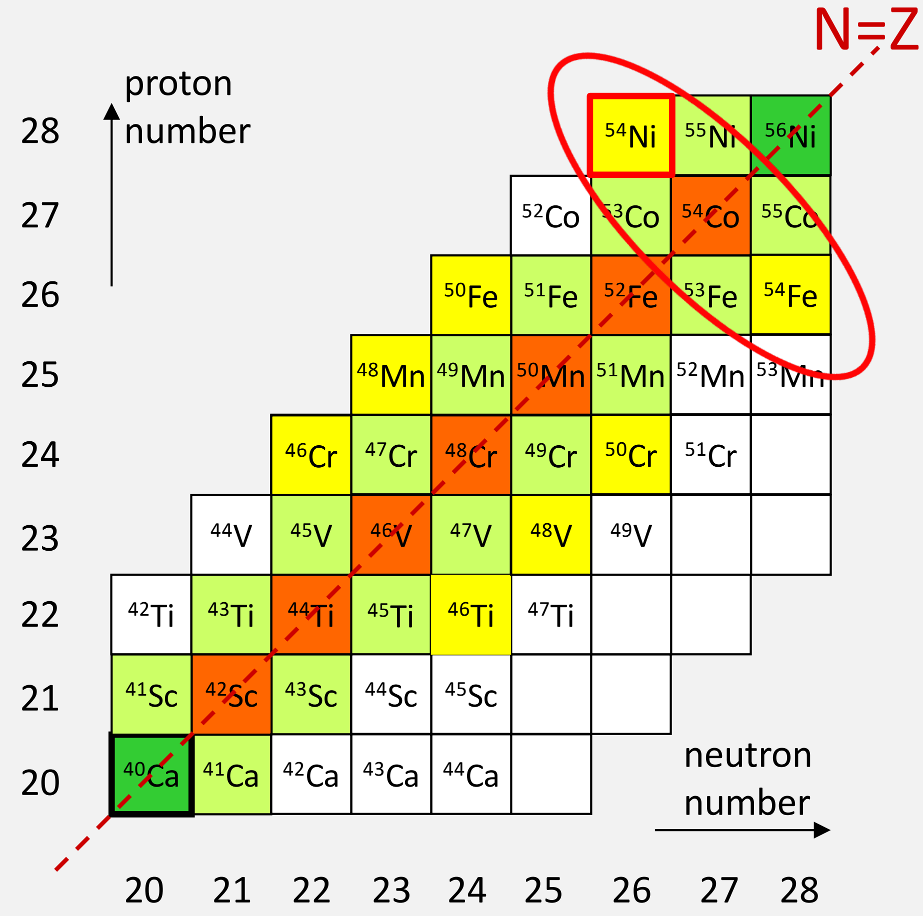
Study T=1 isobaric triplets to search for isospin breaking contributions !

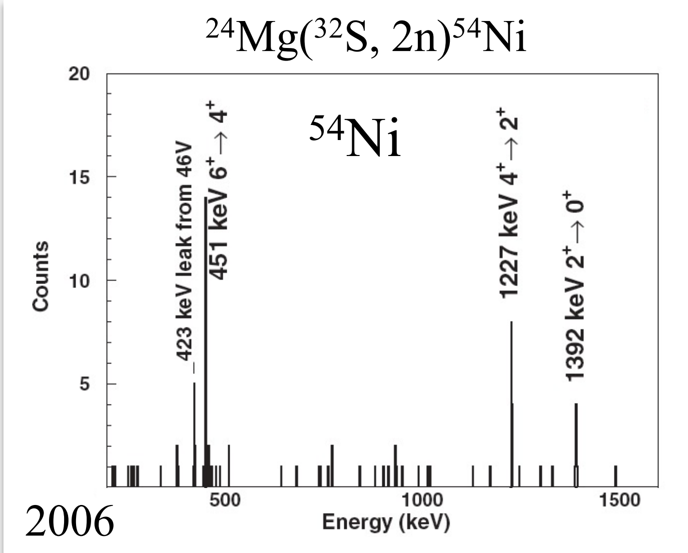
Isospin concept is known to work for light nuclei



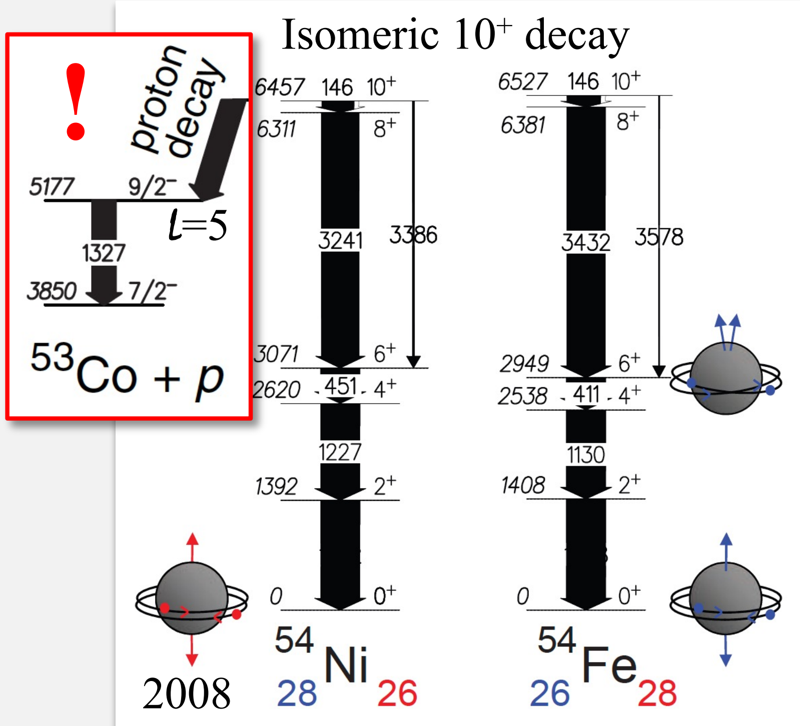


The example of the A=54 isospin triplet



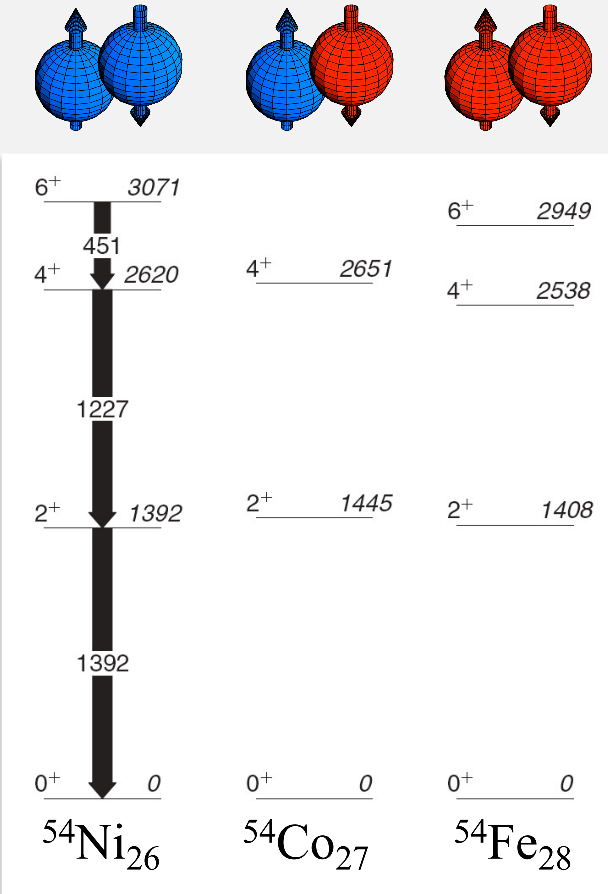


A. Gadea et al.
Phys. Rev. Lett. 97, 152501 (2006)



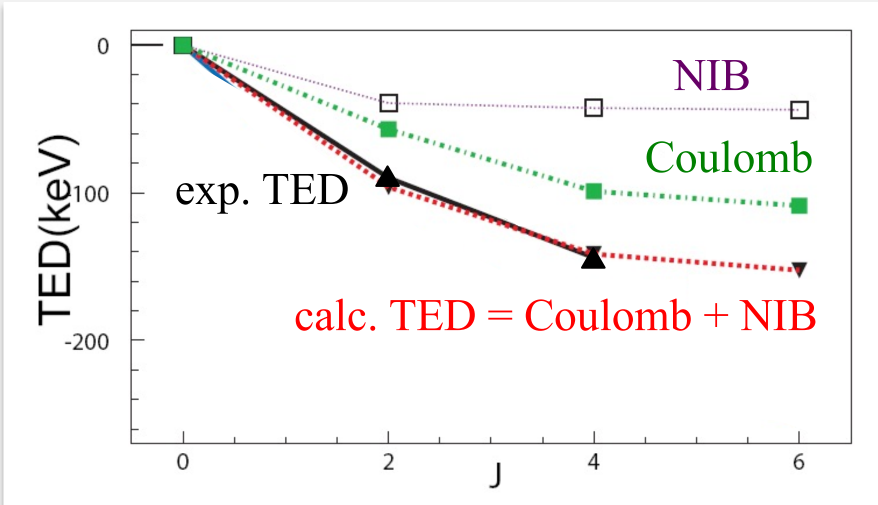
D. Rudolph et al.
Phys. Rev. C78, 021301(R) (2008)

Triplet energy differences for $^{54}Ni_{26}$-$^{54}Co_{27}$-$^{54}Fe_{28}$



Triplet energy difference:

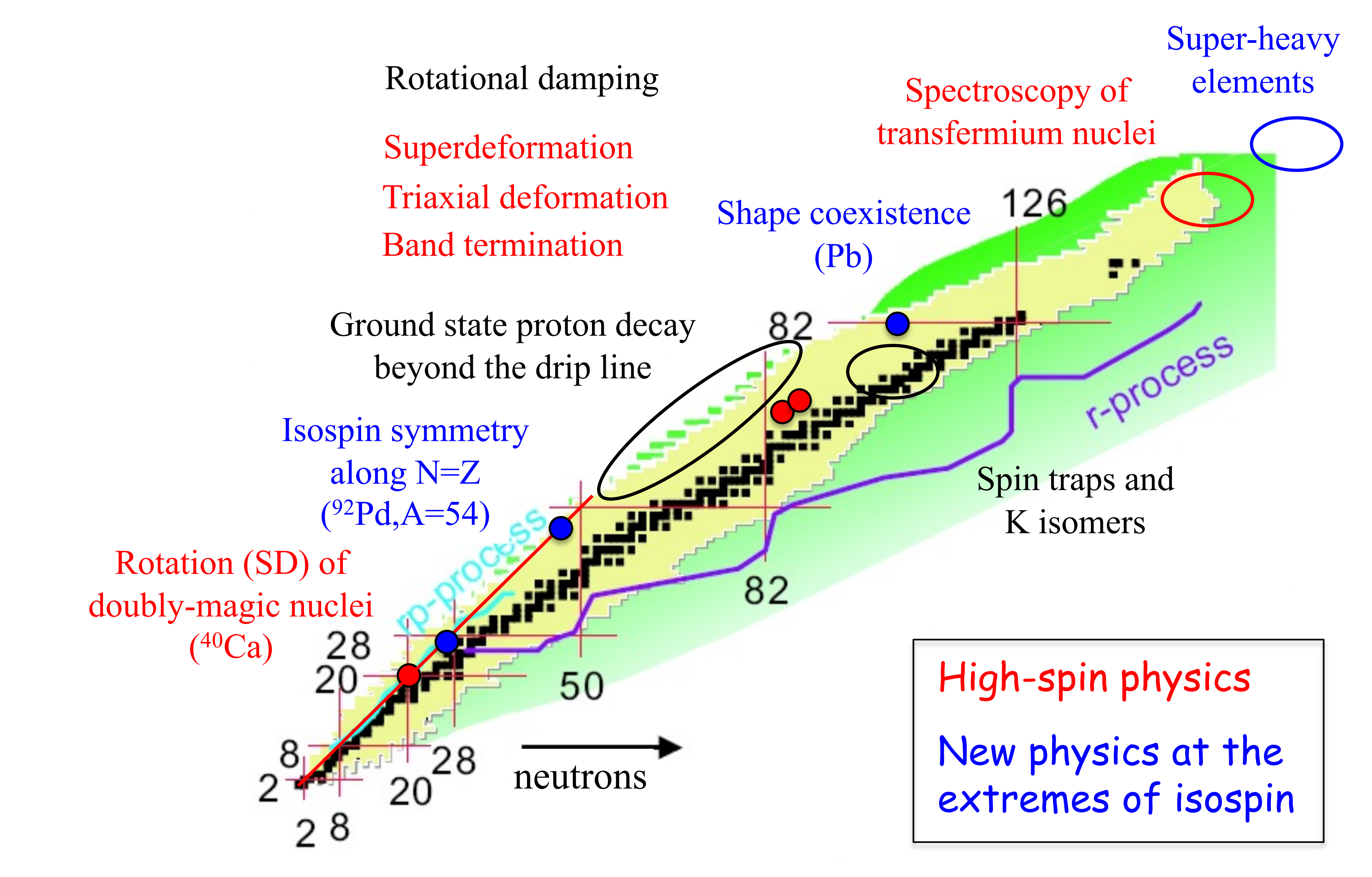
$$TED(J) = E_J(^{54}Ni) + E_J(^{54}Fe) - 2E_J(^{54}Co)$$



A. Gadea et al., Phys. Rev. Lett. 97, 152501 (2006)

Nuclear isospin-breaking (NIB) terms are of the same order as the Coulomb contributions !

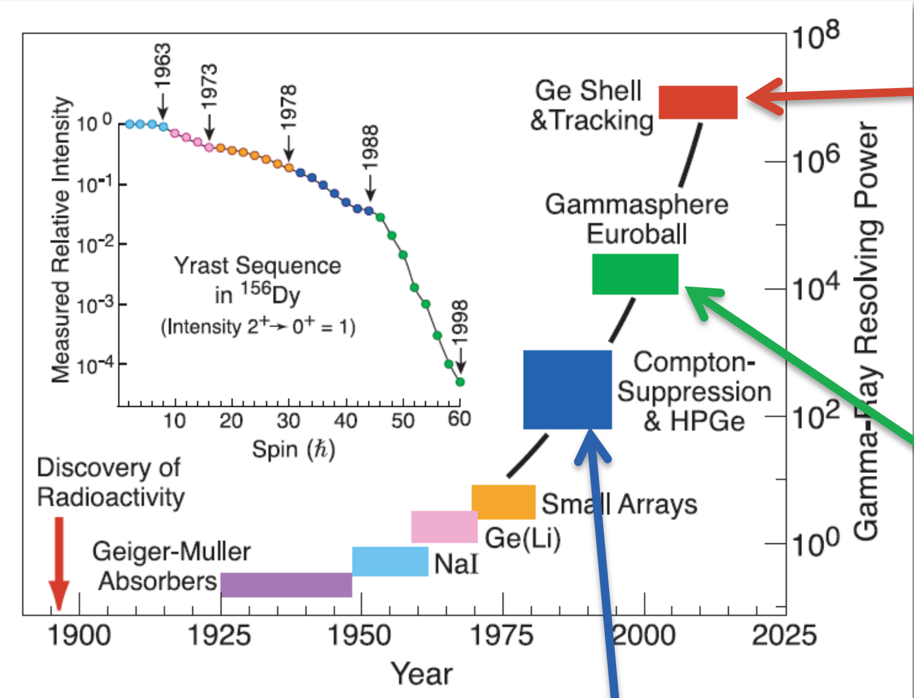
The nuclear landscape – neutron-deficient side
(with stable-beam induced fusion-evaporation reactions)

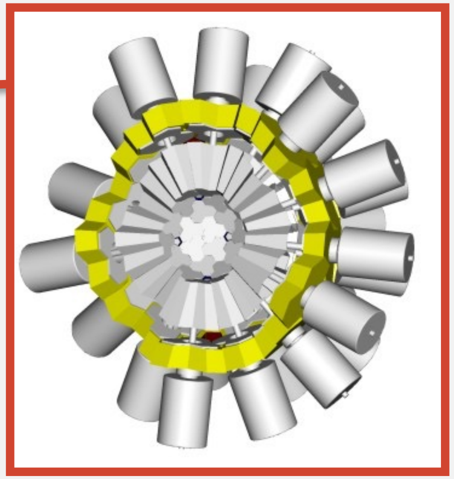


High-spin physics

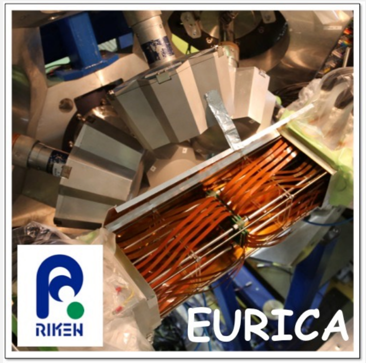
New physics at the extremes of isospin

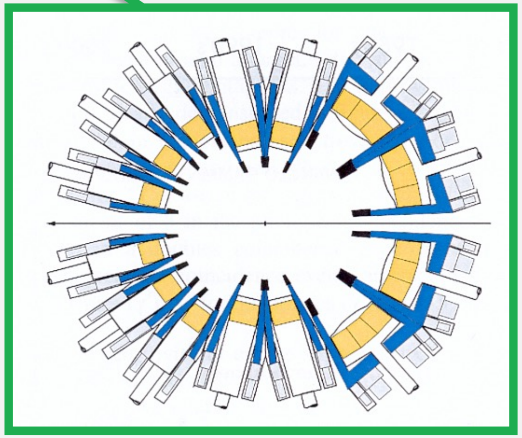
The future of γ-ray spectroscopy: Tracking arrays



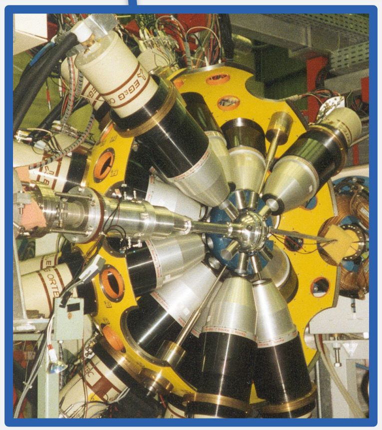


AGATA



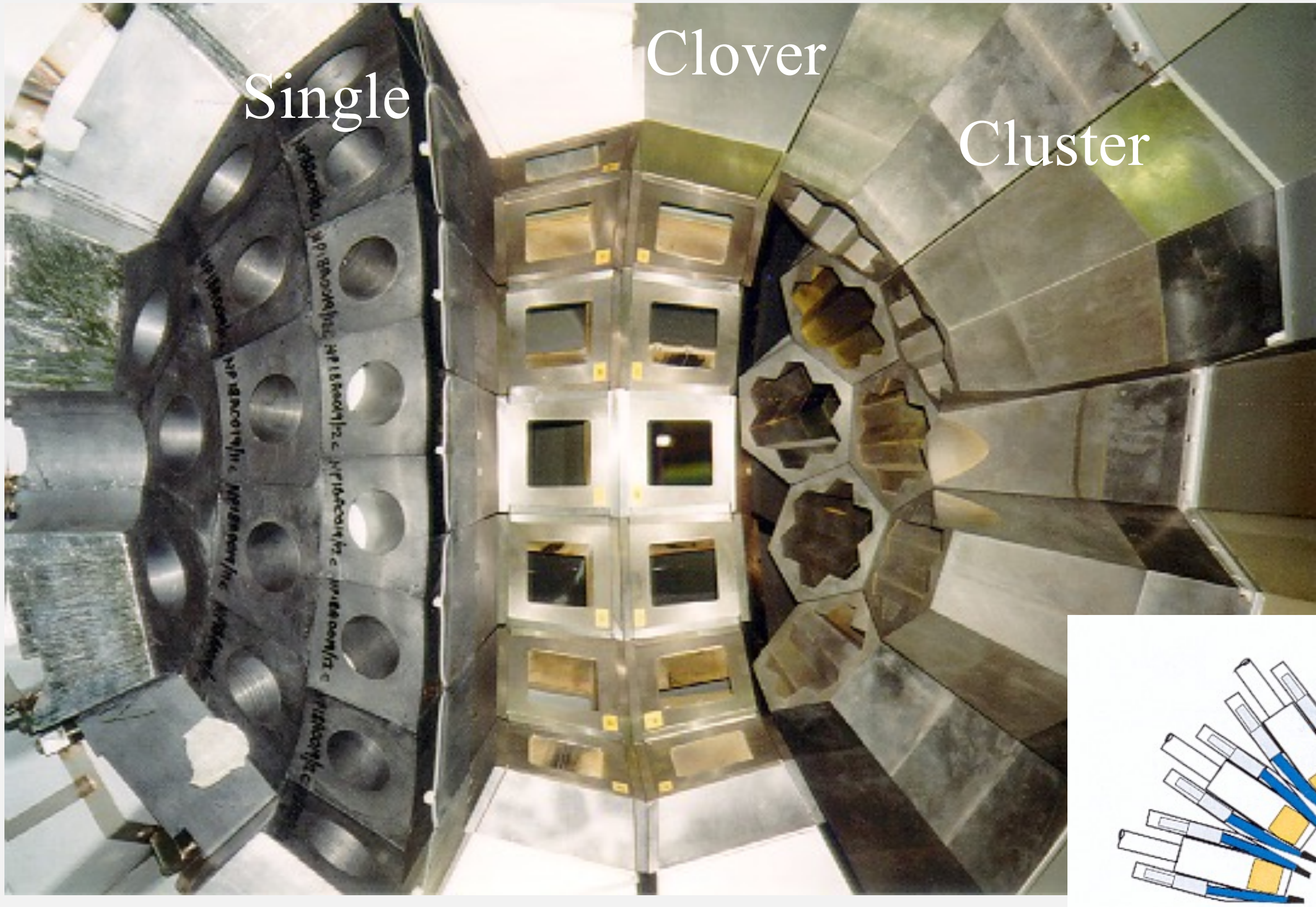


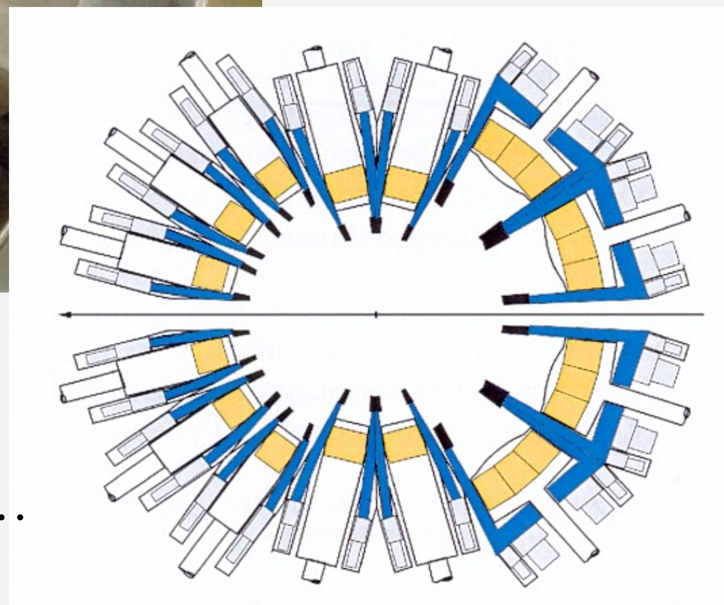
EUROBALL (1997-2003)



GASP

Target view into the collimators of EUROBALL





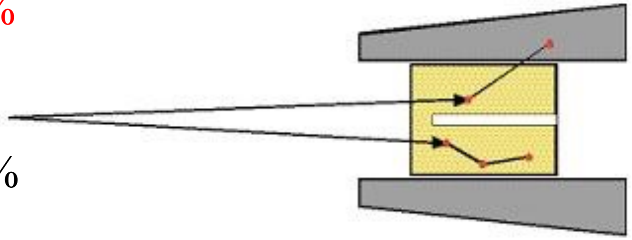
Large fraction of dead solid angle !

Get rid of Compton-suppression shields …

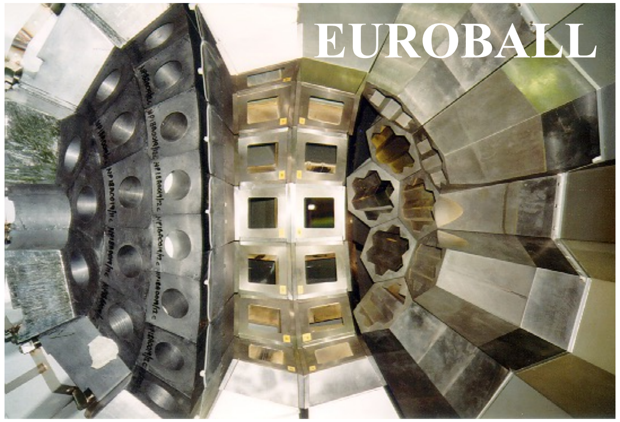
The idea of γ-ray tracking

Compton Shielded Ge

ε_{ph} ~ 10%
N_{det} ~ 100
Ω ~ 40%
Δθ ~ 8°

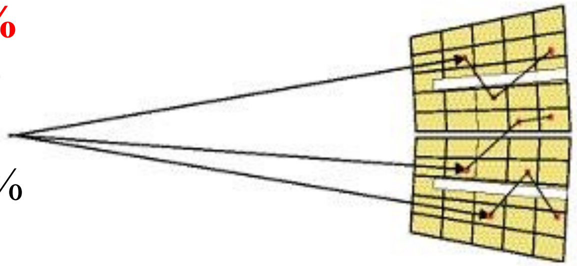


- scattered γ-rays lost
- poor definition of angle of incidence
- solid angle coverage limited by CS shields



Ge Tracking Array

ε_{ph} ~ 50%
N_{det} ~ 100
Ω ~ 80%
Δθ ~ 1°



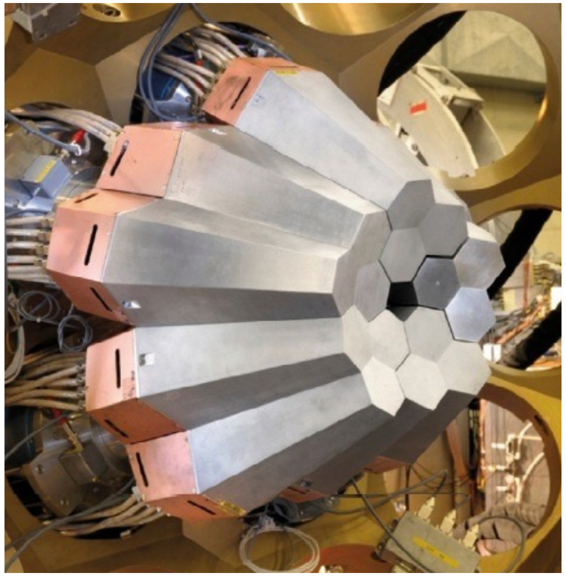
Combination of:

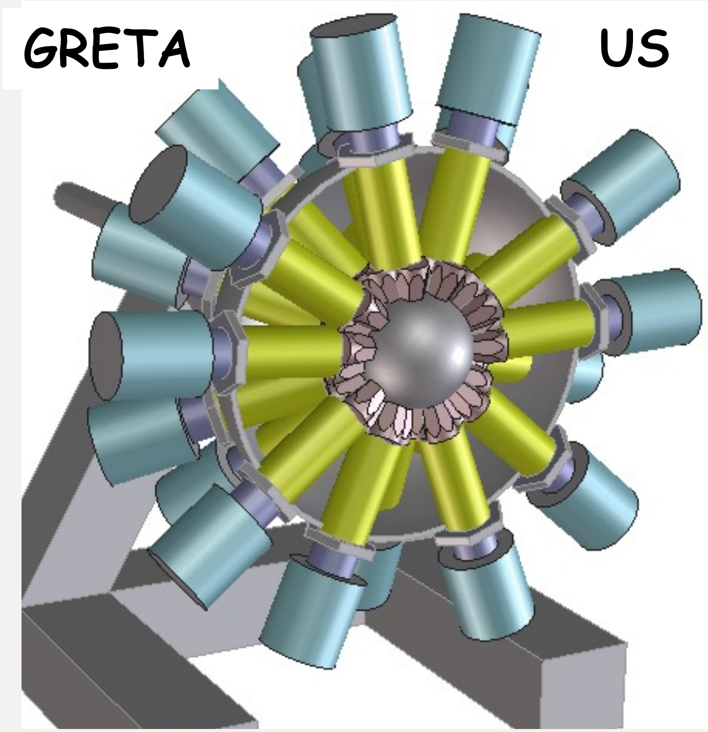
- segmented detectors
- digital electronics
- pulse shape analysis
- γ-ray tracking

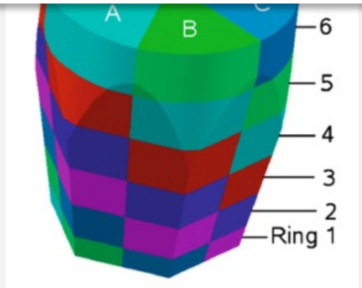
➡ much improved efficiency and angle definition

Previously, scattered gammas were wasted.
Technology is available now to track them !

The tracking arrays AGATA and GRETA







60 triple clusters = 180 crystals

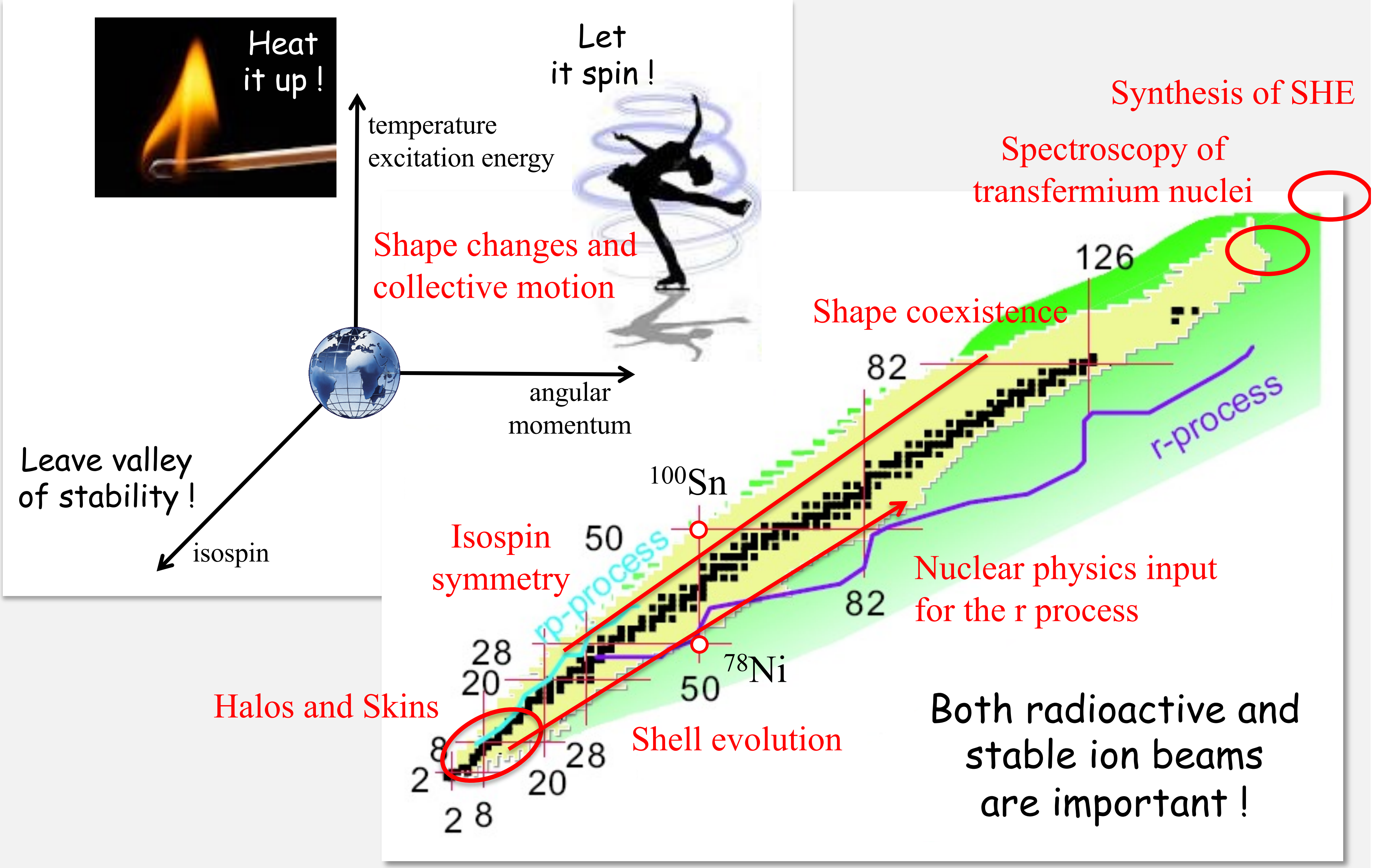
36-fold segmentation

360 kg of Ge
200 kEuro/crystal
6660 electronics channels

Caterina Michelagnoli
Lectures 2 & 3

AGATA and GRETA will open a new era in γ-ray spectrocopy
- with stable and radioactive ion beams !

Overview and summary



Nuclear structure research in the future

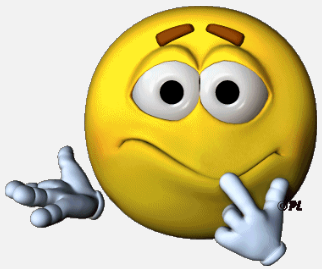
Exciting new facilities and instrumentation currently under construction – very attractive perspectives.

Still enough interesting new physics to be discovered.

✓

<u>But:</u> Fewer facilities, less beamtime, experiments more and more complex, data more and more precious (and expensive).

Nuclear physics became a very diverse and highly spezialized field.



It's time to rethink our way of working !

Try to get a more global view, define clear goals, set priorities etc.

Field must stay attractive for young researchers and financing agencies !