"New aspects and properties of atomic nuclei using reactions with radioactive beams"

A contribution to the
Inspyre 2025 School INFN LNL, Legnaro

July 15-18 2025

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INFN Sezione di Firenze

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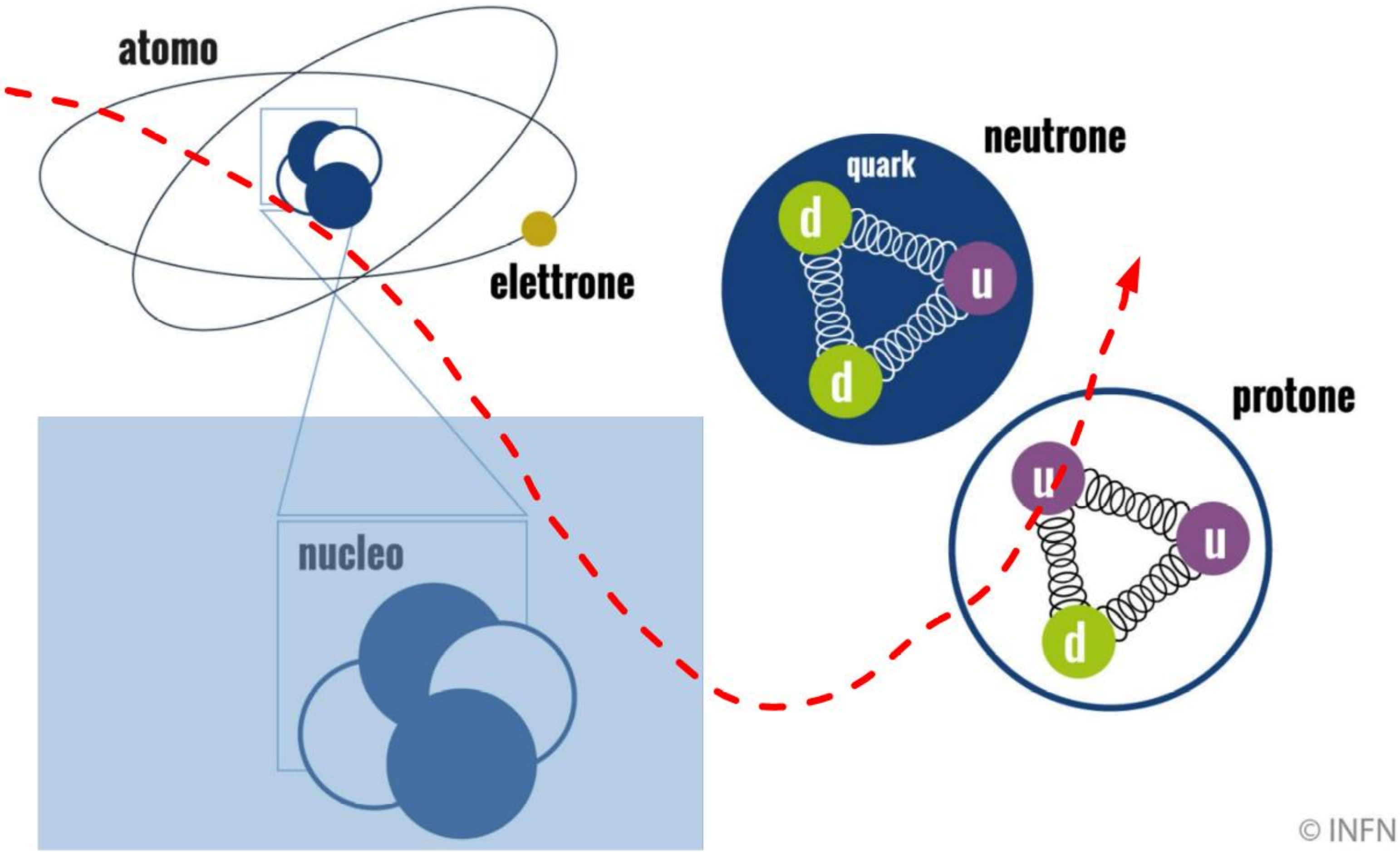
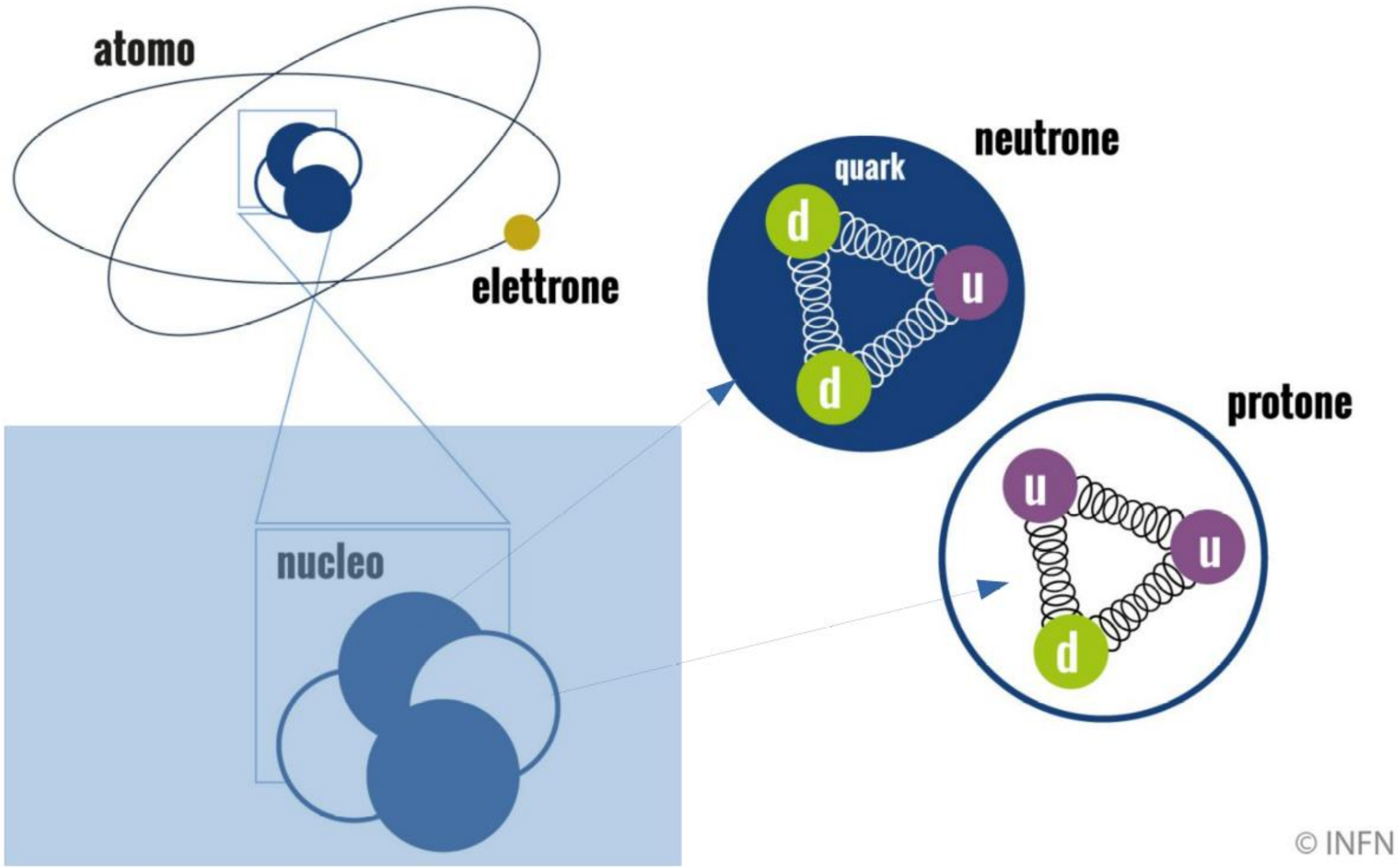
$\hbar c$ = 200 MeV*fm

Nuclear typical scale: **0.4-10 fm**

Typical energy range **20-500MeV**



“New aspects and properties of atomic nuclei using reactions with radioactive beams”

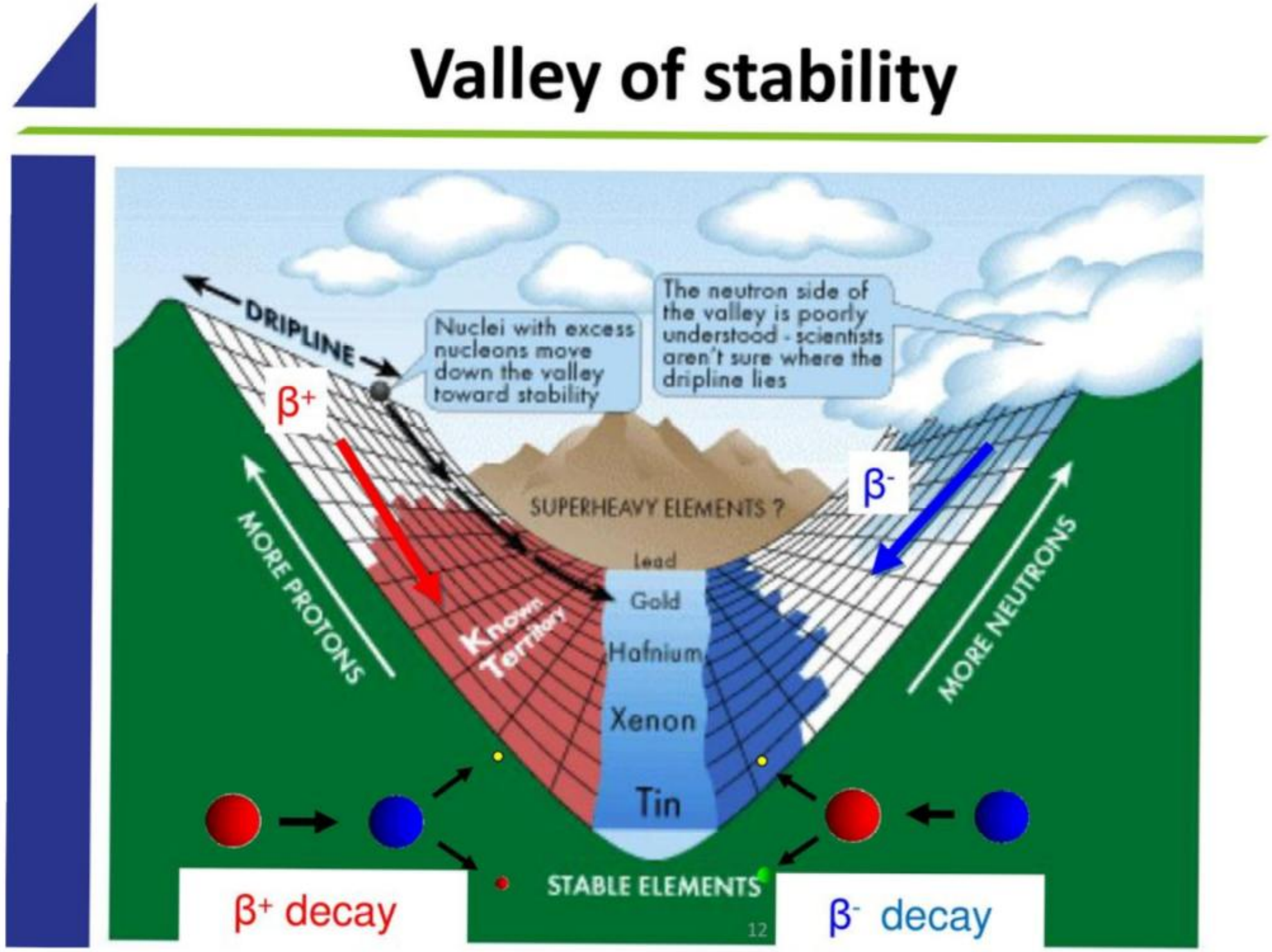


Last 40 years (anniversary!) of studies changed and are changing the nuclear Physics textbooks

An adventure in a Canyon region

From an old conversation with my colleague Nanni Pollarolo

The nuclear Canyon:
the action of the nuclear potential

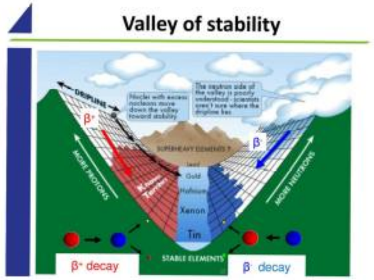


Jebel Shams Canyon, OMAN

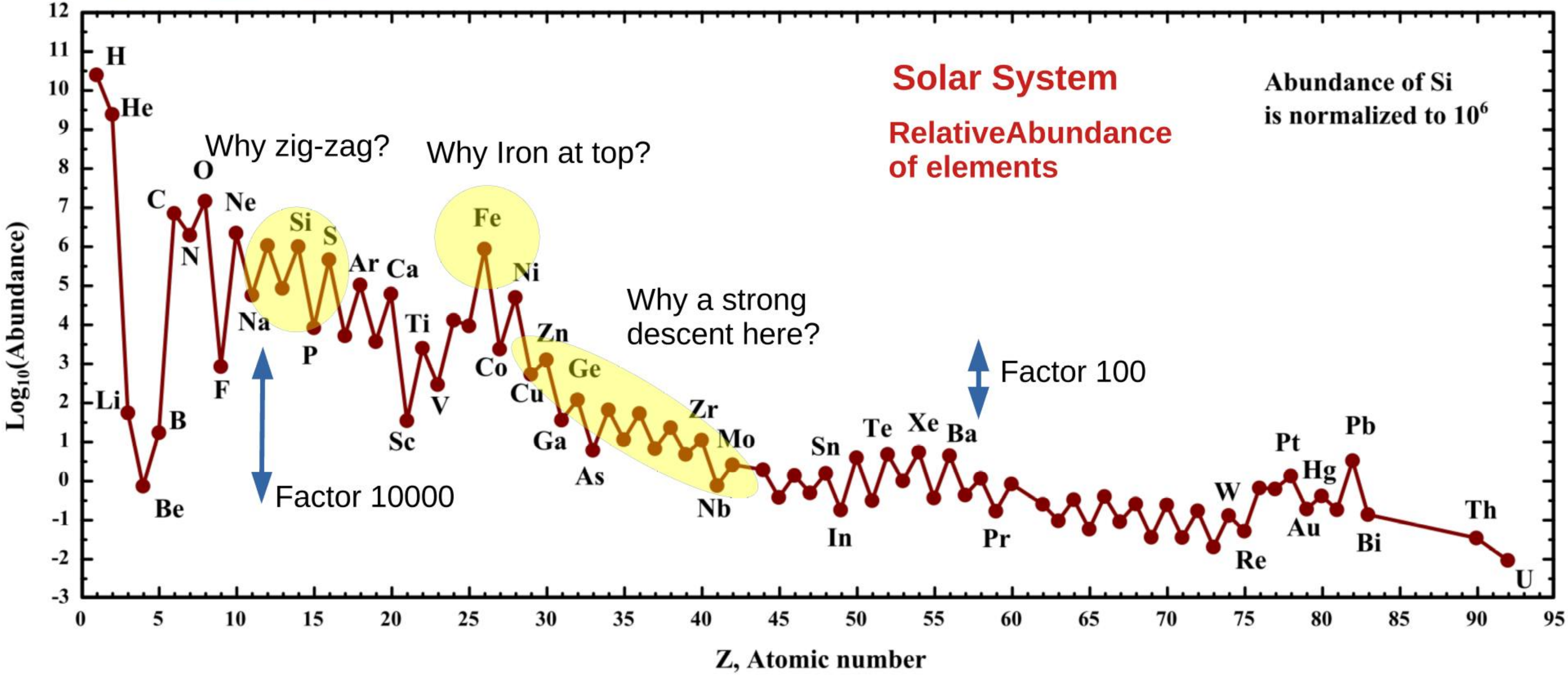
Summary

- 1900-1980 Nuclear physics, down in the canyon (stability)
- Where/How Nature explores the whole landscape
- 1980-now: exotic beam facilities and the journey far from stability
- Physics cases, fascinating nuclei

INSPYRE
INternational School on modern PhYsics and REsearch



Masses, bonds, stability, abundances



Nuclear mass *m* and binding energy

$$m = Zm_p + Nm_n - \frac{E_B}{c^2}$$

final total mass =mass of components - Binding energy (E_B)

- Equivalence $mc^2=E$
- “To bind” means transforming part of the mass in energy.
- Binding energy and mass excess (change of sign plus-minus)
- Valid for every bound systems in nature

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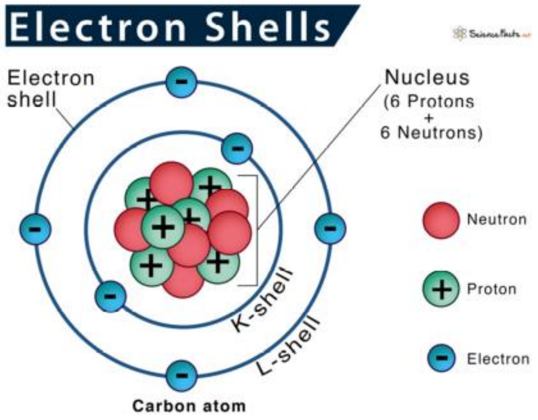
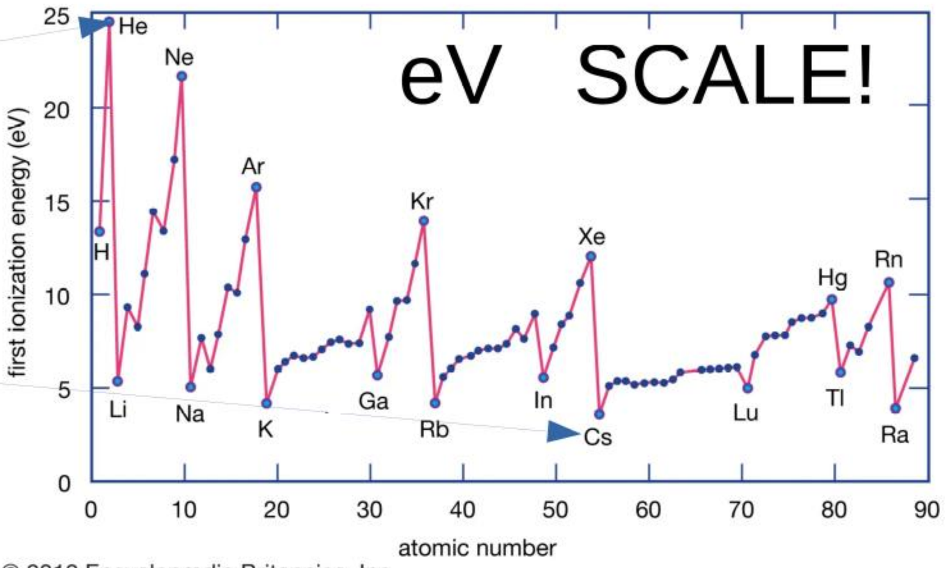


Noble elements: last electrons deeply bound

Alcaline elements: last electron almost free

EXAMPLE: ATOMIC SYSTEMS and the world of CHEMISTRY



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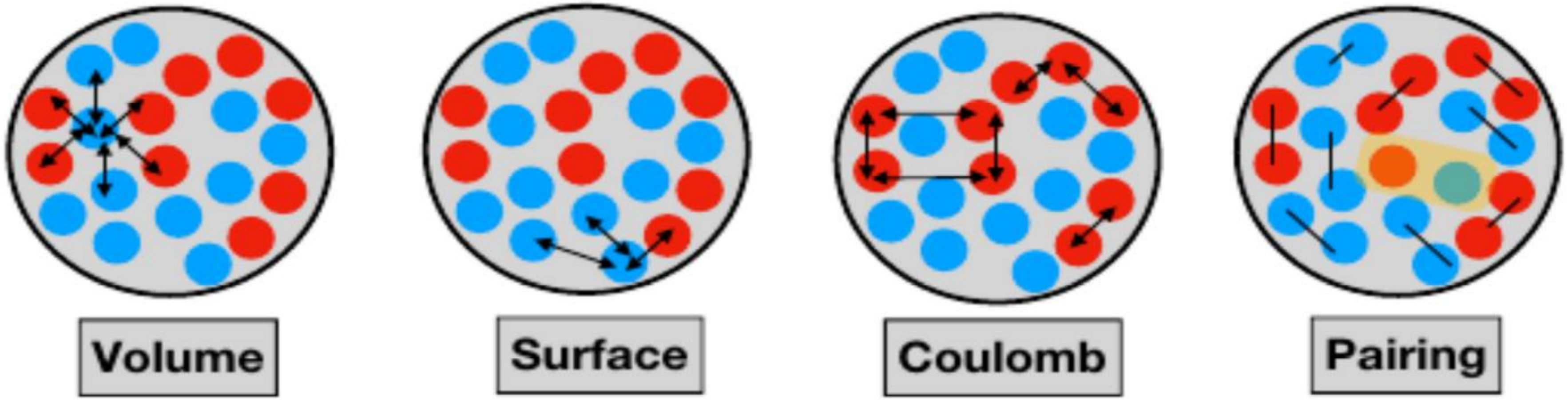
Various contributions of the nuclear potential produce the binding energy and thus the nuclear masses:

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

volume	surface	Electric energy (Coulomb potential)	Symmetry energy (neutron-proton symmetry)	Pairing term
+	-	-	-	+

Nuclear mass *m* and binding energy



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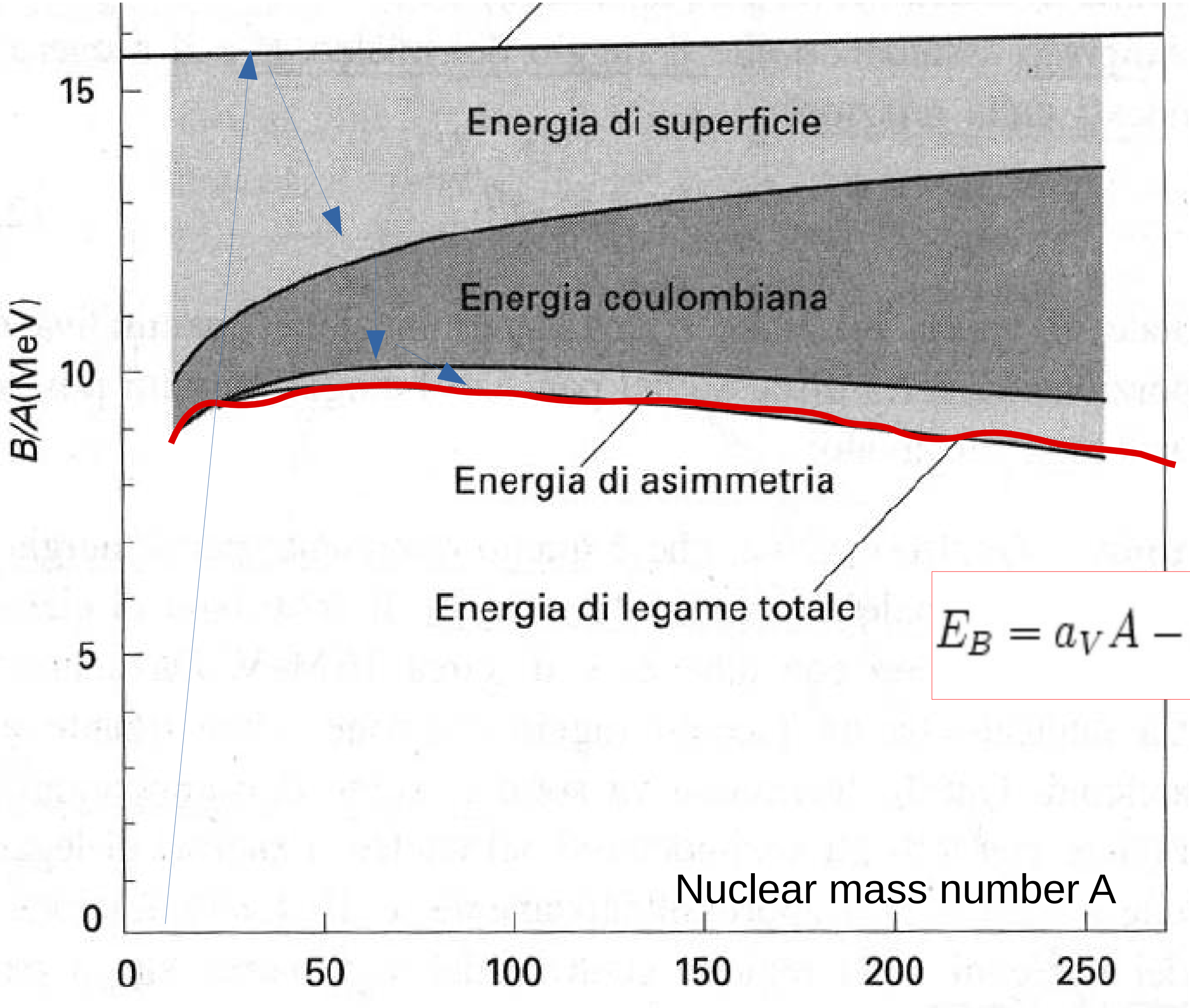
volume	surface	Electric (Coulomb potential)	Symmetry energy (neutron-proton symmetry)	Pairing term
+	-	-	-	+/-

Various contributions to E_B (or B/A, MeV scale)



90 years of predictions

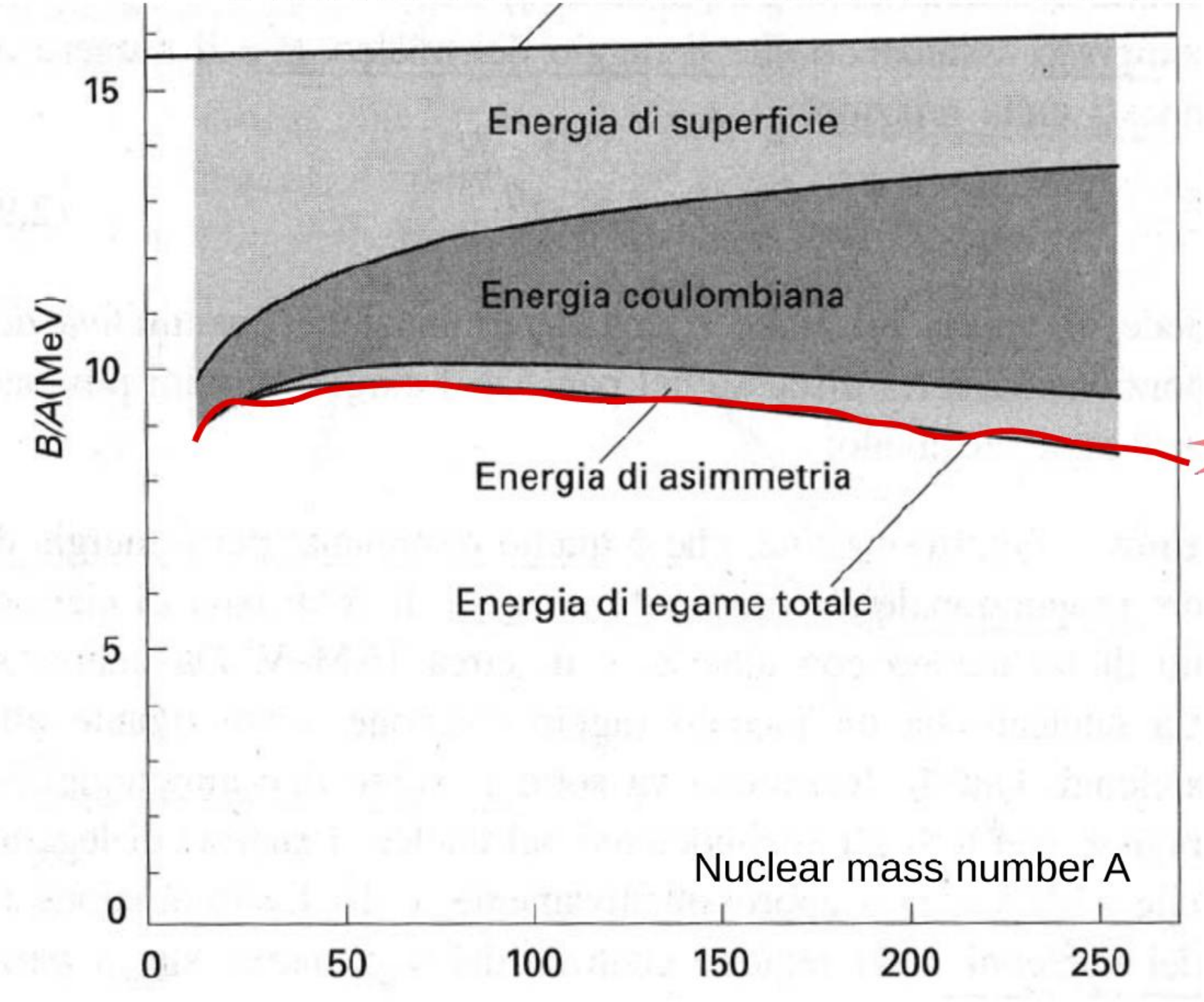
Semi-empirical nuclear mass formula

Von Weitzäcker, 1935

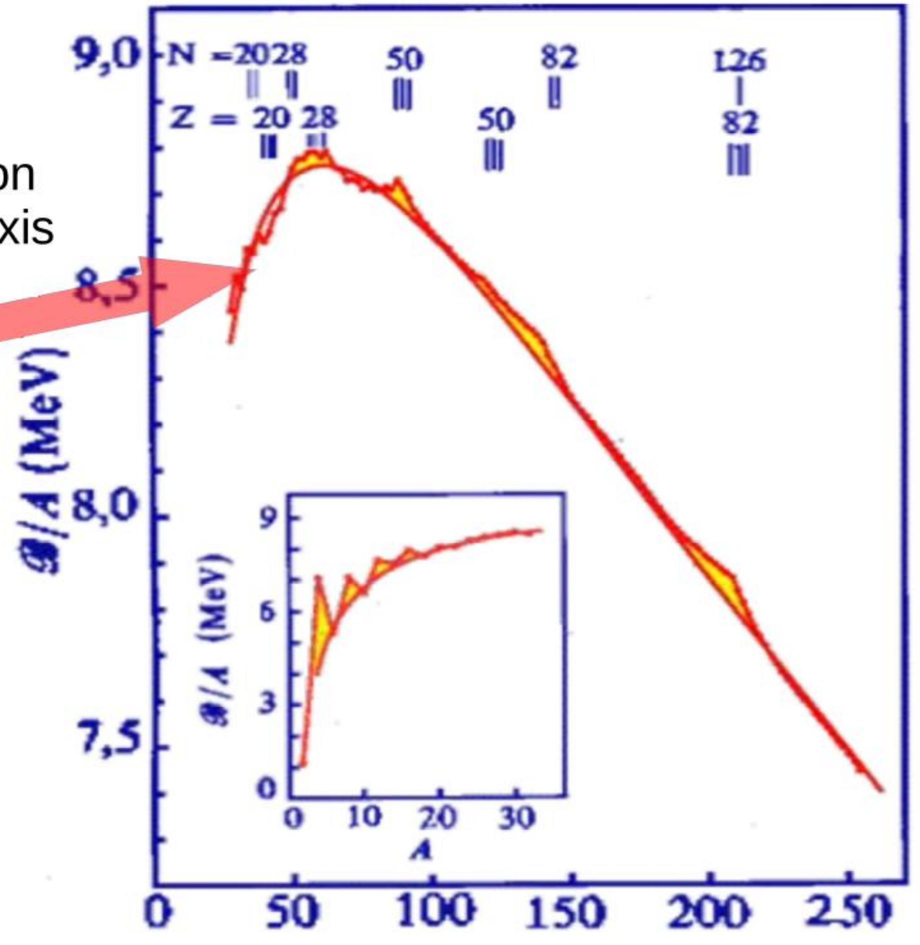
$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{ even } (A \text{ even}) \\ 0 & A \text{ odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases} \qquad \delta_0 = \frac{a_P}{A^{1/2}}$$

Various contributions to E_B (or B/A, MeV scale)

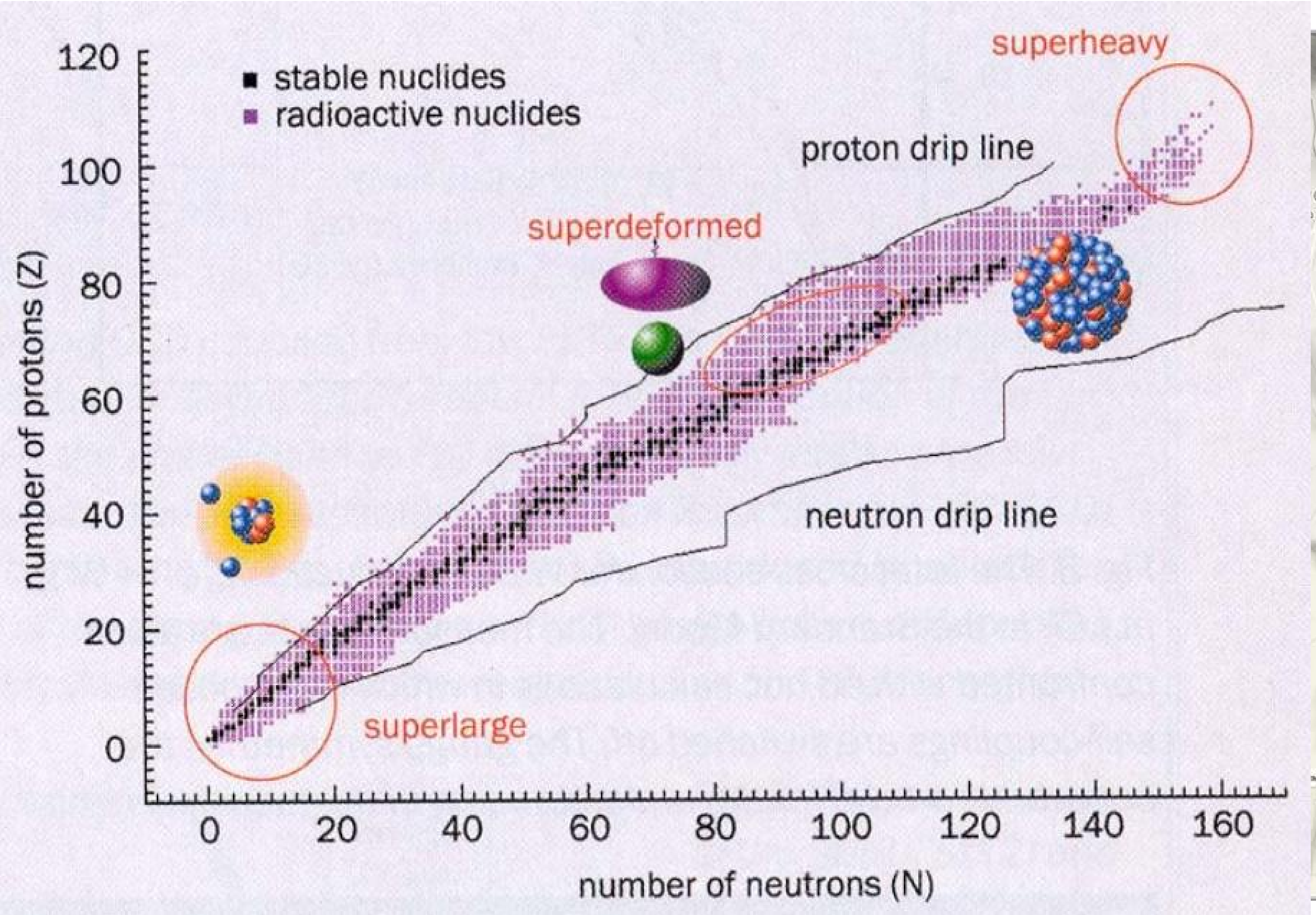


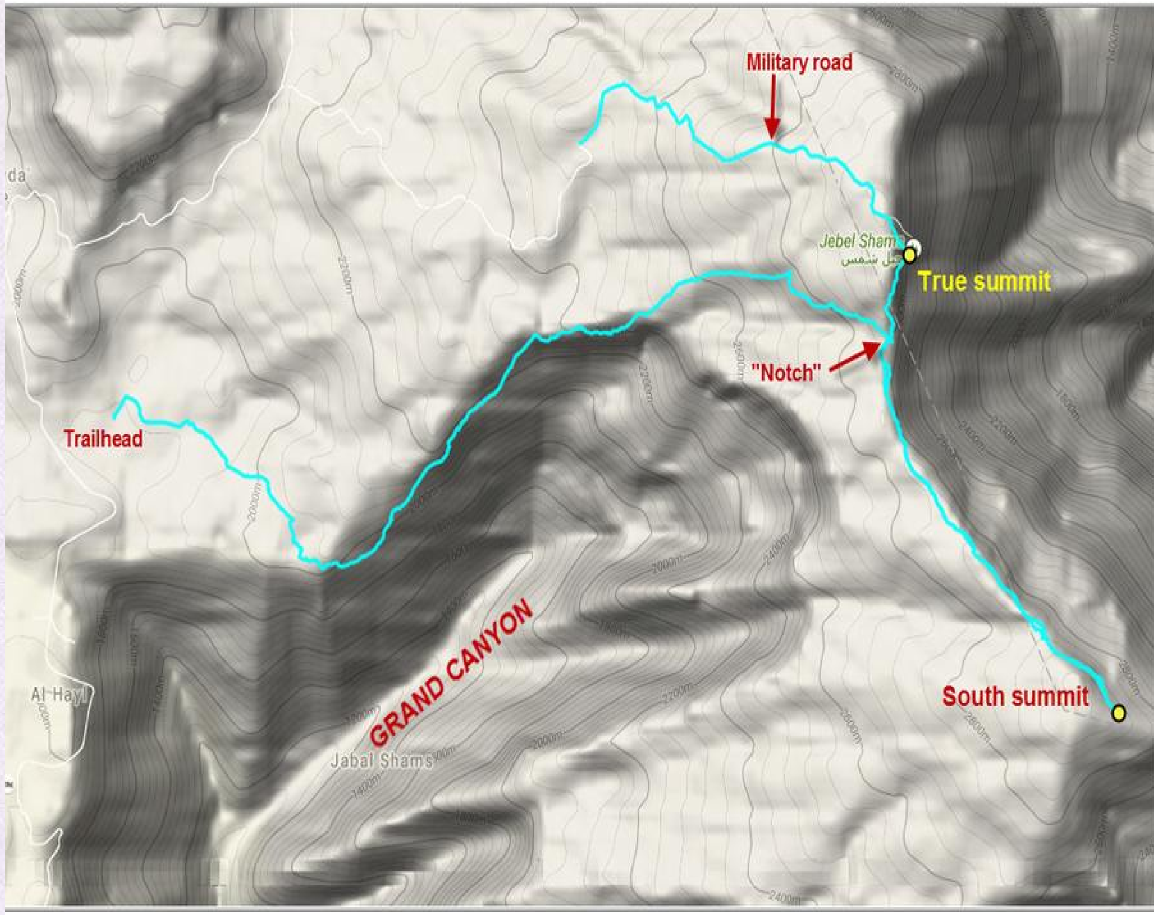
Zoom on the Y-axis



Nuclear mass number A

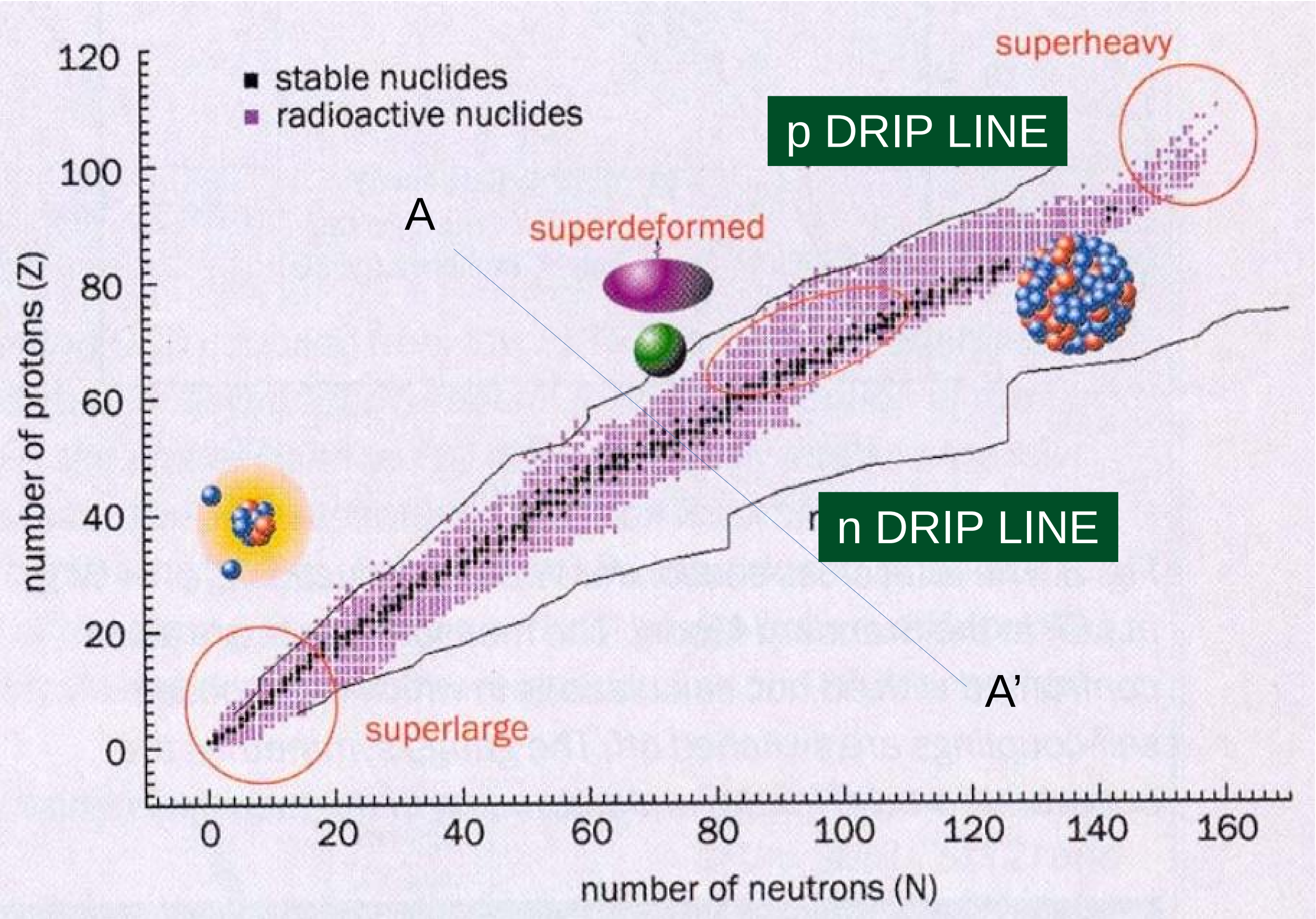
Stronger bonds, larger stability: the canyon

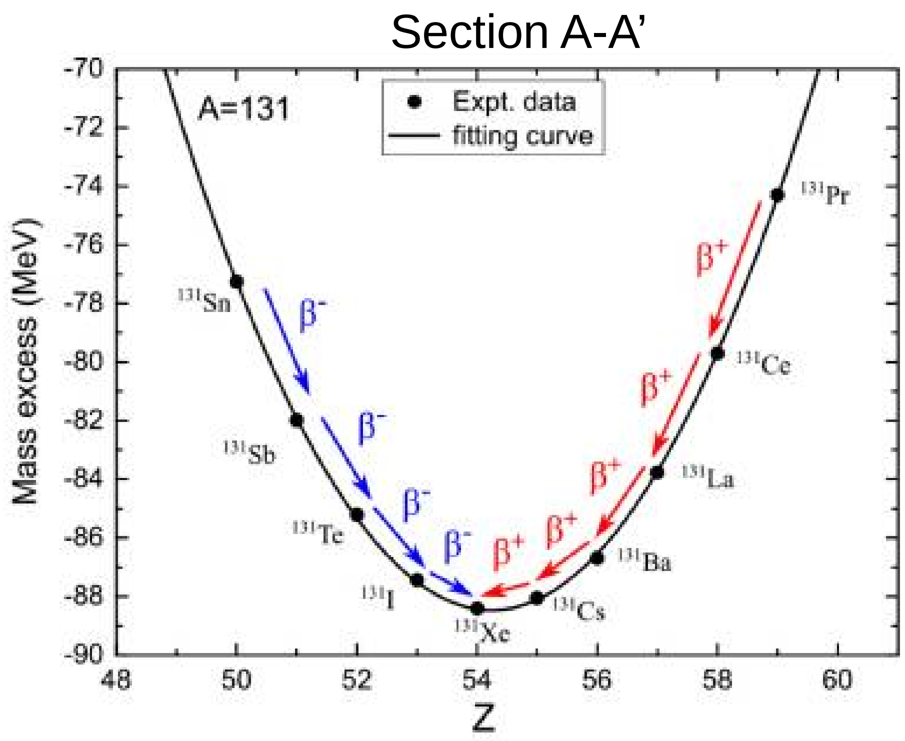




The interplay of the various nuclear potential terms produces a narrow region in the bidimensional map Z vs A (Chart of Segré), where most nuclei are located: this is the **VALLEY of (nuclear) STABILITY (where about 300 nuclides are sitting)**

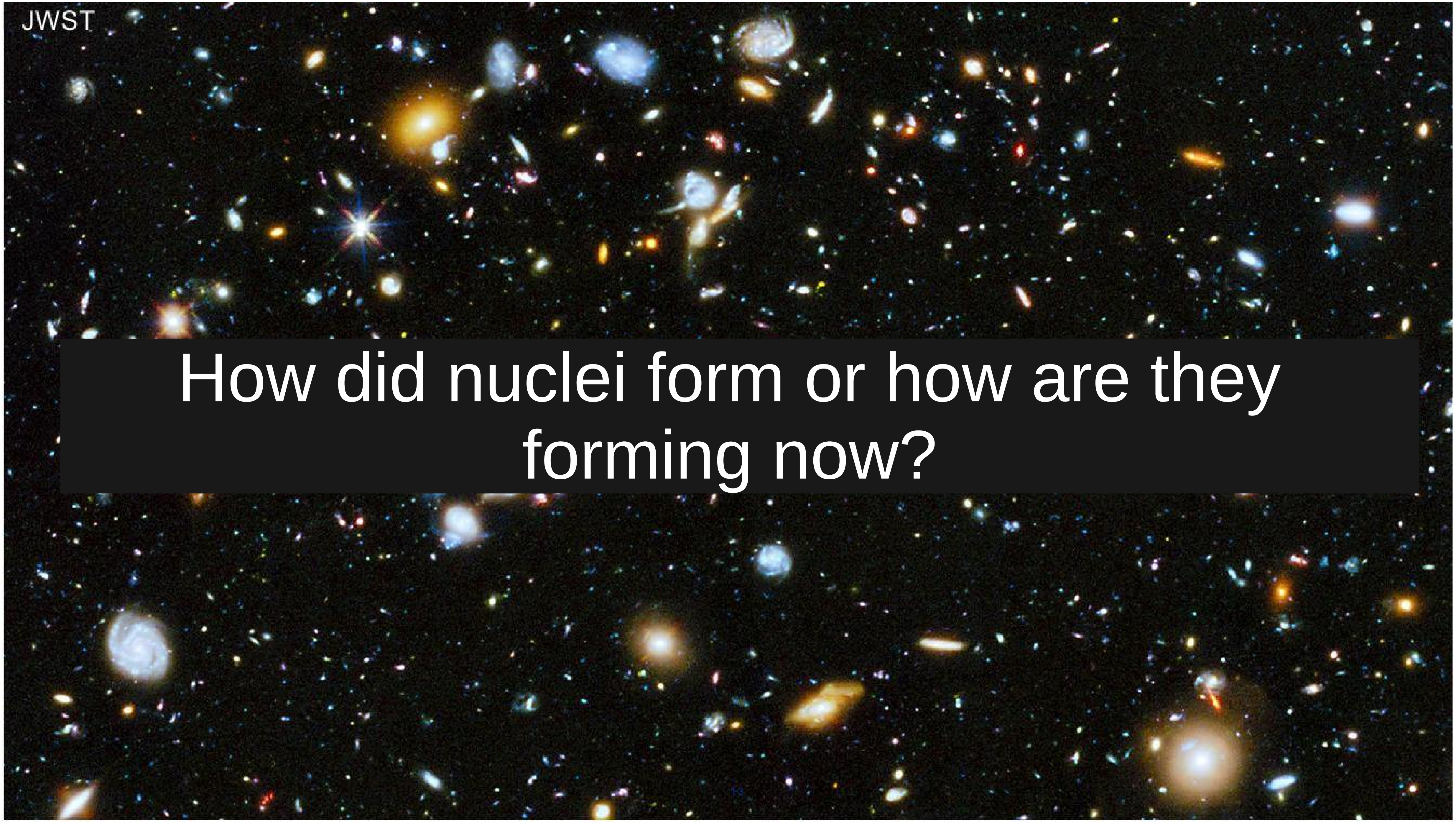
Stronger bonds, larger stability





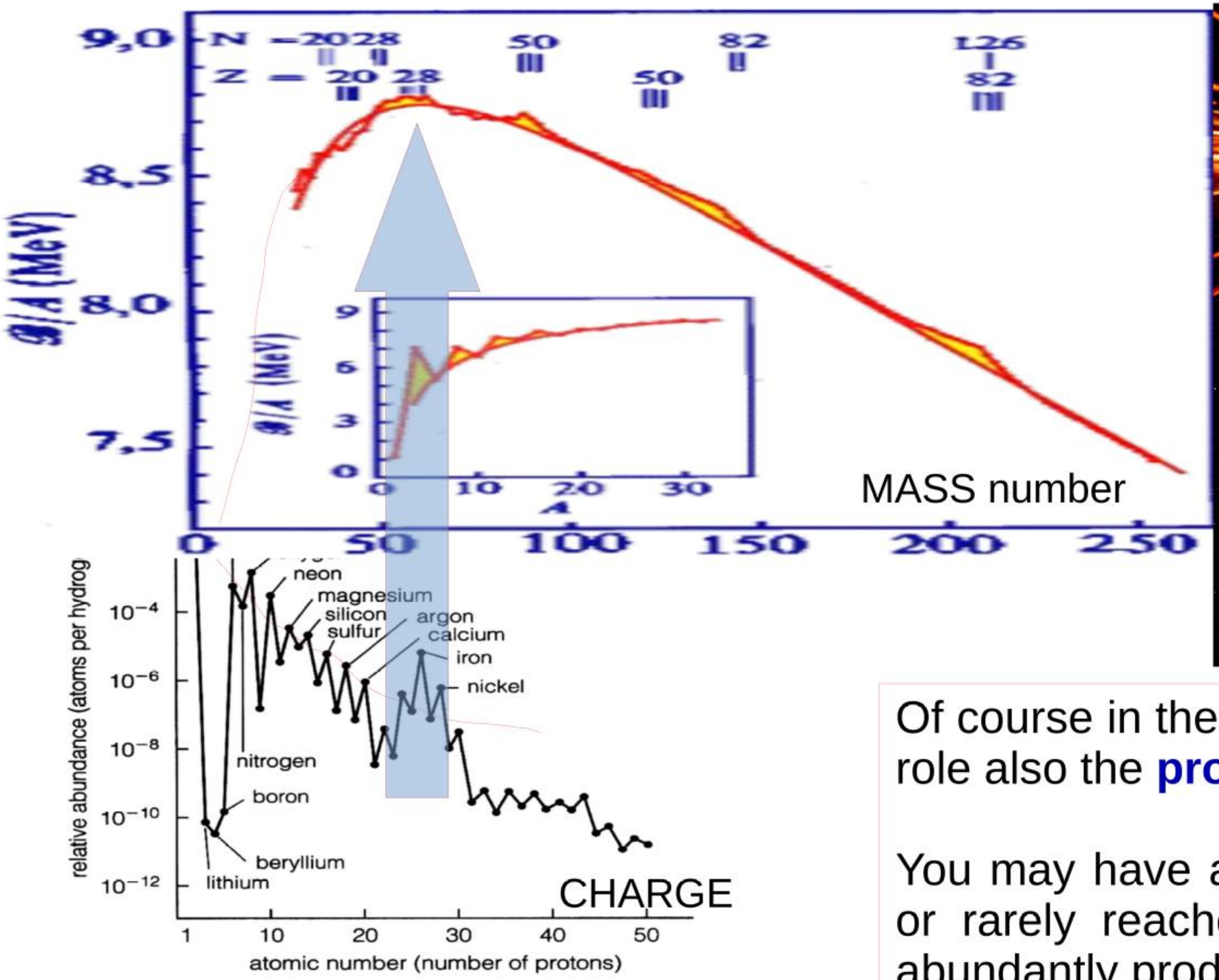
The interplay of the various nuclear potential terms produces a narrow region, in the bidimensional map Z vs A (Chart of Segré), where most nuclei are located: this is the **VALLEY of (nuclear) STABILITY**

Drip lines: are the tops of the canyon, at both sides, where separation energy for p and n goes to zero.



How did nuclei form or how are they forming now?

Bonds, sources, abundances



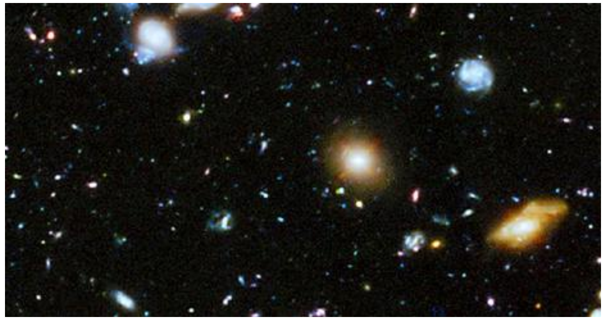
Cosmological origin
BIG BANG

Astrophysical origin
Novae, micronovae, ...

Of course in the observed abundances there play a strong role also the **production sites and production sources**.

You may have a possible stability region never accessed or rarely reached and v.v. less bound systems very abundantly produced

How did nuclei form or how are they forming, now ?



Nucleosynthesis

- Cosmological origin: BIG BANG
- Stellar main sequence (p-p chain, basically is fusion of 4*H into 4He)
- Stars (old and/or heavy) from He+He+He to 12C and over (16O,20Ne…)
- Stars: Neutron “candles” at a certain stellar life phase; the slow process
- Stars: Final (explosive) phases; the rapid process
- Giant explosions or collisions: micronovae, novae, black hole mergers or other pair collapses

How did nuclei form or how are they forming, now ?

Nucleosynthesis

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- **And in laboratories? Can we do something similar on Earth?**

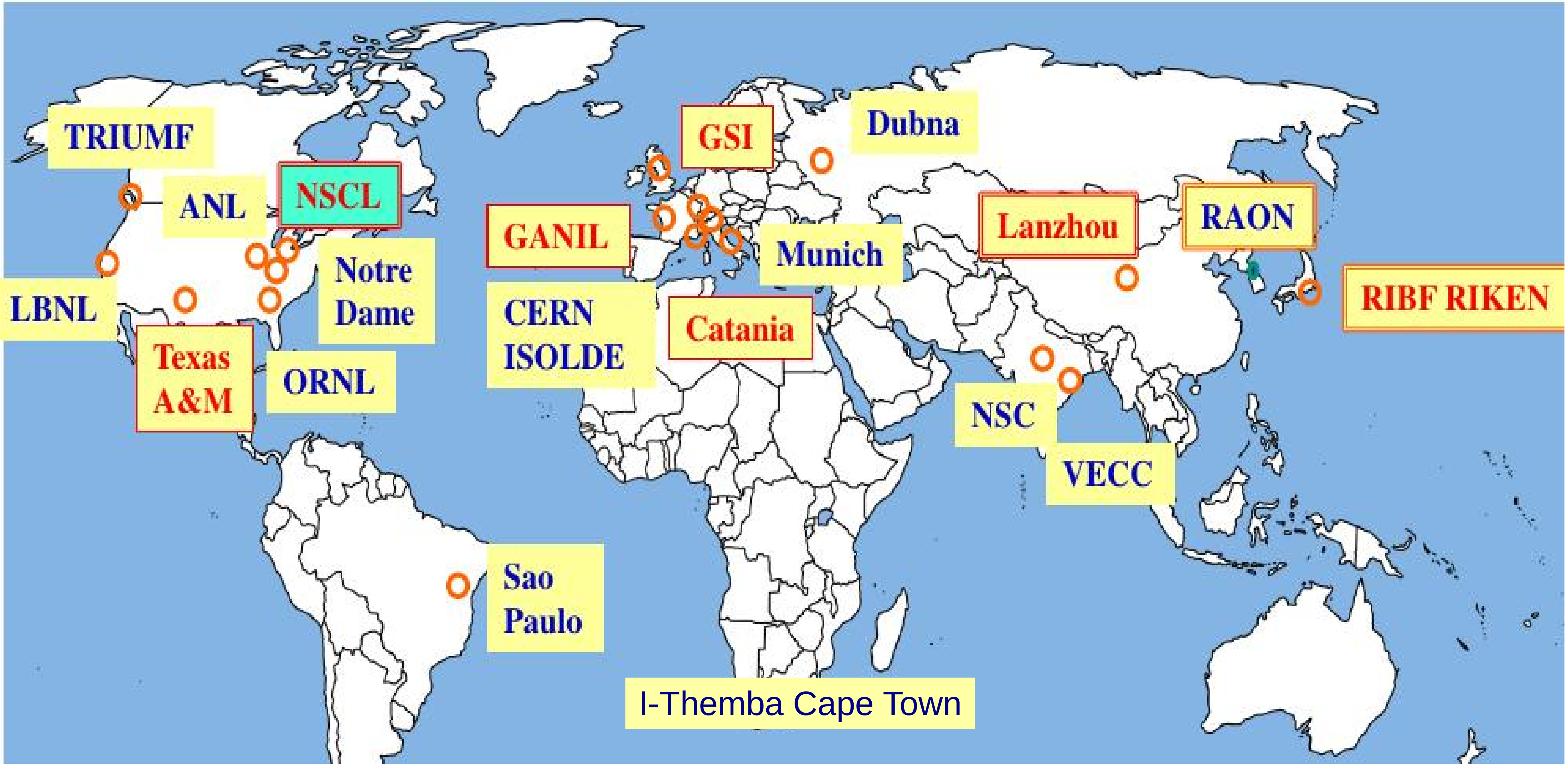
Going to the analogy:
how to climb the Canyon sides?

- Fragmentation in flight
- ISOL (isotope separation on line)
- Where in the world
- A matter of final energy, purity, precision
- Low energy: nuclear structure
- High energy: Equation Of State and nuclei at extreme environments
- *Relativistic energy (back to Big Bang and up to nucleon structure)*
- **SPES** at LNL (Legnaro)

Radioactive ion beam (RIB) facilities

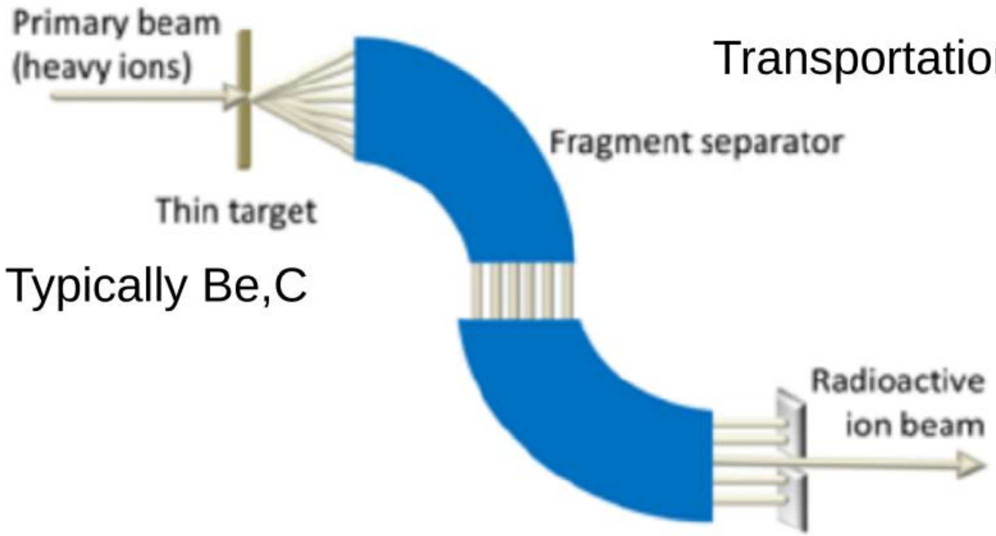
you are here!

RIB labs in the world

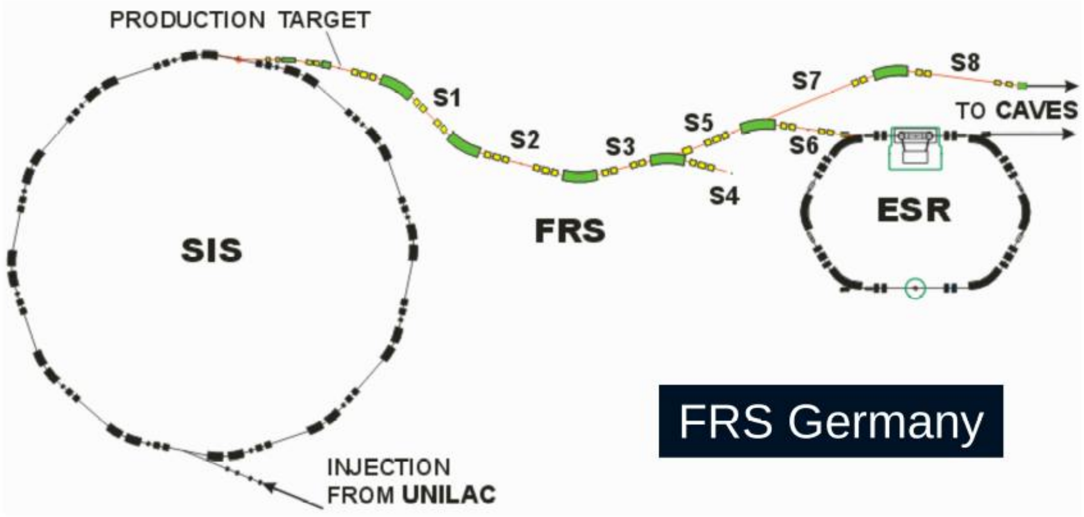


IN-FLIGHT (IF) Technique

Transportation & selection

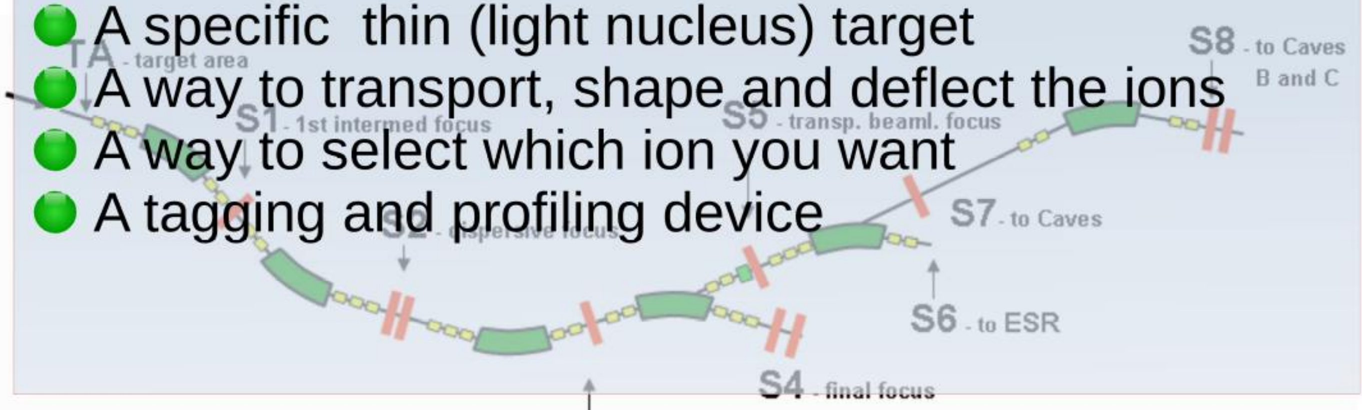


Typically Be,C



Ingredients for a well performing IF beam lab

- An injecting accelerator, powerful
- A specific thin (light nucleus) target
- A way to transport, shape and deflect the ions
- A way to select which ion you want
- A tagging and profiling device



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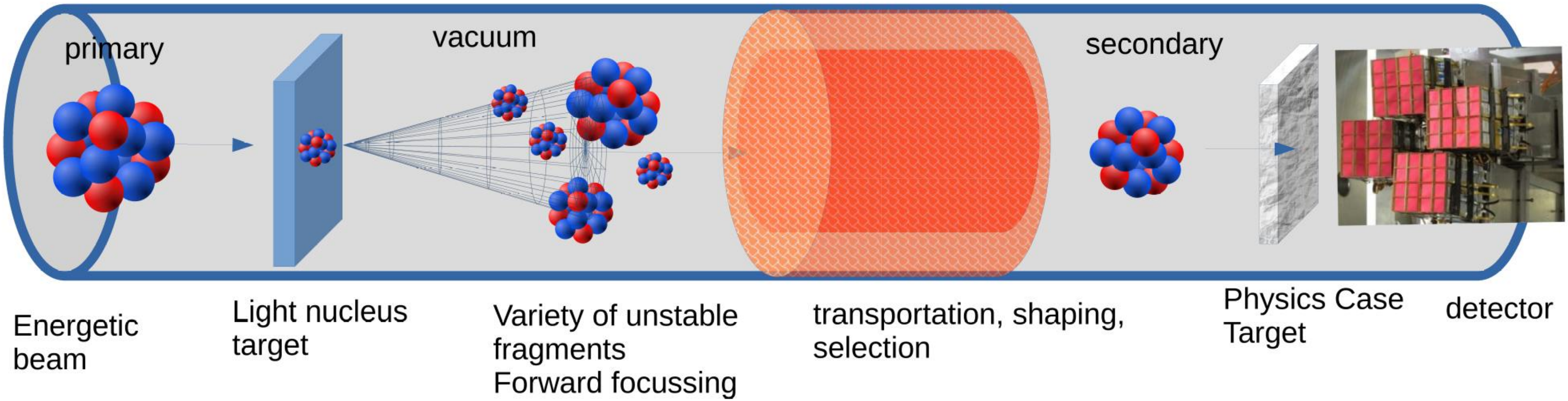
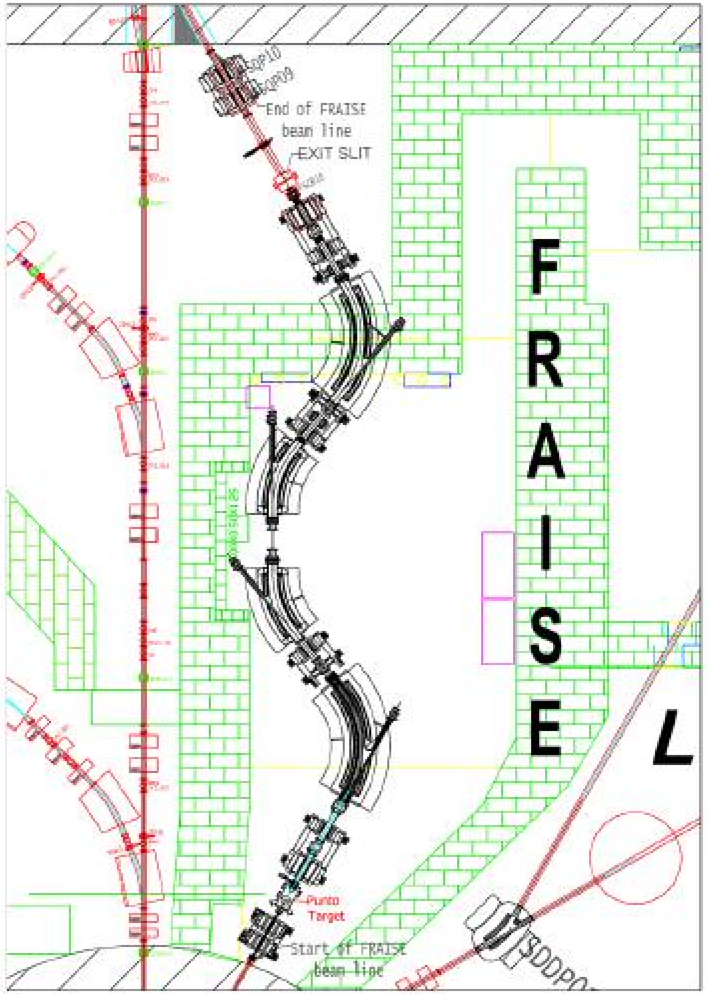


IN-FLIGHT Technique

In ITALY
FRAISE Fragment IN-flight Separator
@ LNS, INFN Catania

Driver: Superconducting Cyclotron (upgraded to 10kW)
Primary Ions: from C to Ar
Production Target: Be,C (max power 2-3kW)



$^{12}C^{6+}$ @ 60 AMeV $^{18}O^{8+}$ @ 70 AMeV $^{20}Ne^{10+}$ @ 70 AMeV
on 1-2mm ^{9}Be target

				^{17}Ne 8.7E5 53	^{18}Ne 3.1E7 51	^{19}Ne 6.0E8 52	^{20}Ne	^{21}Ne	^{22}Ne	^{23}Ne
					^{17}F 1.7E8 50	^{18}F	^{19}F	^{20}F 9.5E6 55	^{21}F	^{22}F
		^{13}O 7.2E4 54	^{14}O 1.4E6 40	^{15}O 2.8E7 54	^{16}O	^{17}O	^{18}O	^{19}O 4.4E6 50	^{20}O	^{21}O
		^{12}N 1.2E6 49	^{13}N 2.3E7 50	^{14}N	^{15}N	^{16}N 6.9E8 53	^{17}N 3.2E8 57	^{18}N 3.7E6 57		
^{9}C 4.0E5 45	^{10}C 1.1E7 43	^{11}C 2.2E8 44	^{12}C	^{13}C	^{14}C 1.1E8 59	^{15}C 4.0E7 59	^{16}C 1.4E7 60	^{17}C 1.2E5 58	^{18}C 4.8E2 55	^{19}C
^{8}B 3.1E6 42		^{10}B	^{11}B	^{12}B 2.6E7 57	^{13}B 7.5E6 58	^{14}B 1.4E6 60	^{15}B 2.6E5 51		^{17}B	
^{7}Be 1.5E7 43		^{9}Be	^{10}Be 1.6E7 50	^{11}Be 1.5E6 58	^{12}Be 2.8E5 60		^{14}Be 3.0E3 63			
^{6}Li	^{7}Li	^{8}Li 4.2E6 50	^{9}Li 8.9E5 51		^{11}Li 3.3E3 60					
	^{6}He 2.1E6 51		^{8}He 1.8E4 51							

Proton rich

neutron rich

EXPECTED (calculations)

IN-FLIGHT Technique

Superconducting magnet for SFS

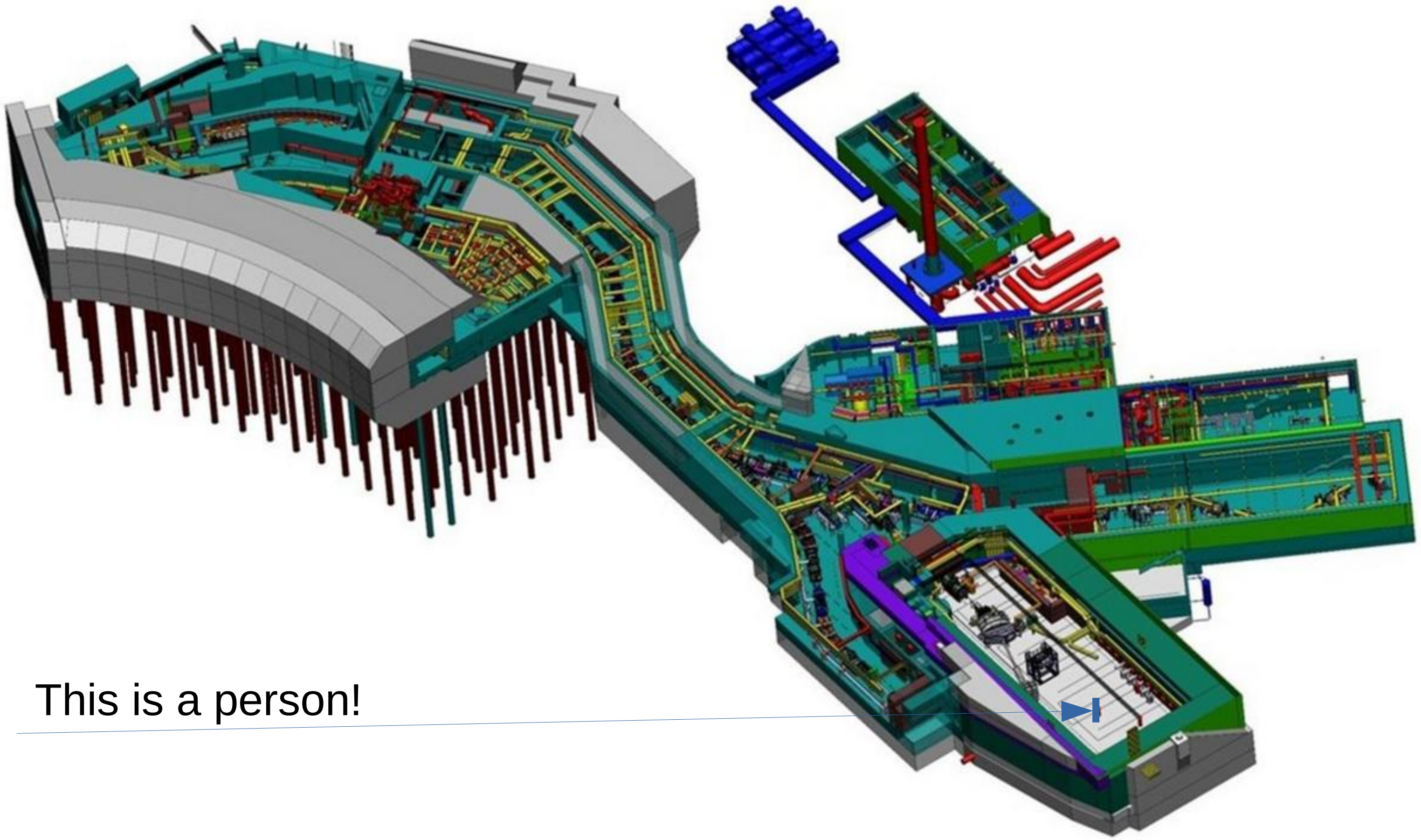
FEATURES

Intensities up to **1000 billions per second**

Elements from **p – U**

Energies up to **1.5 GeV/nucleon**

SFS **Super Fragment Separator @ GSI**



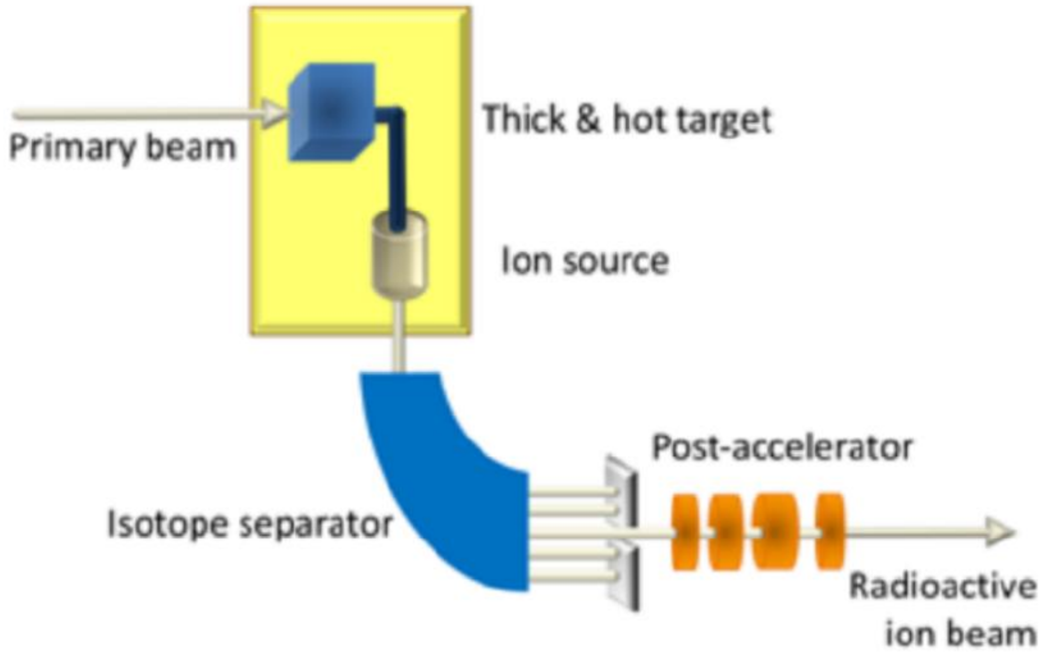
This is a person!

@DMU-GSI, @FSB-FAIR

A GIANT IN GERMANY

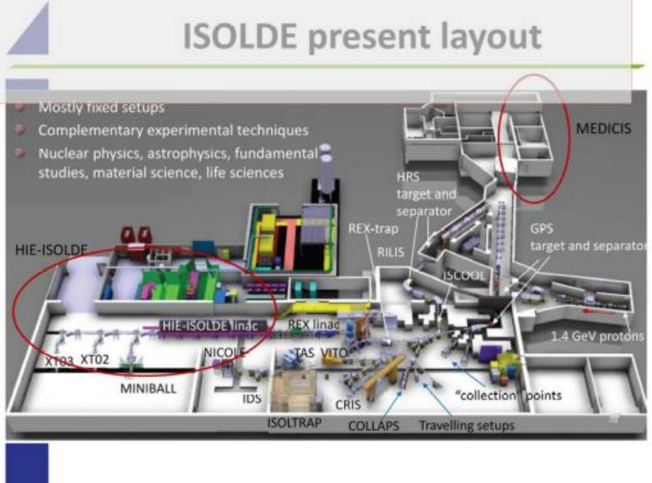
ISOL TECHNIQUE

isotope separation on line



Ingredients for a performing exotic beam lab

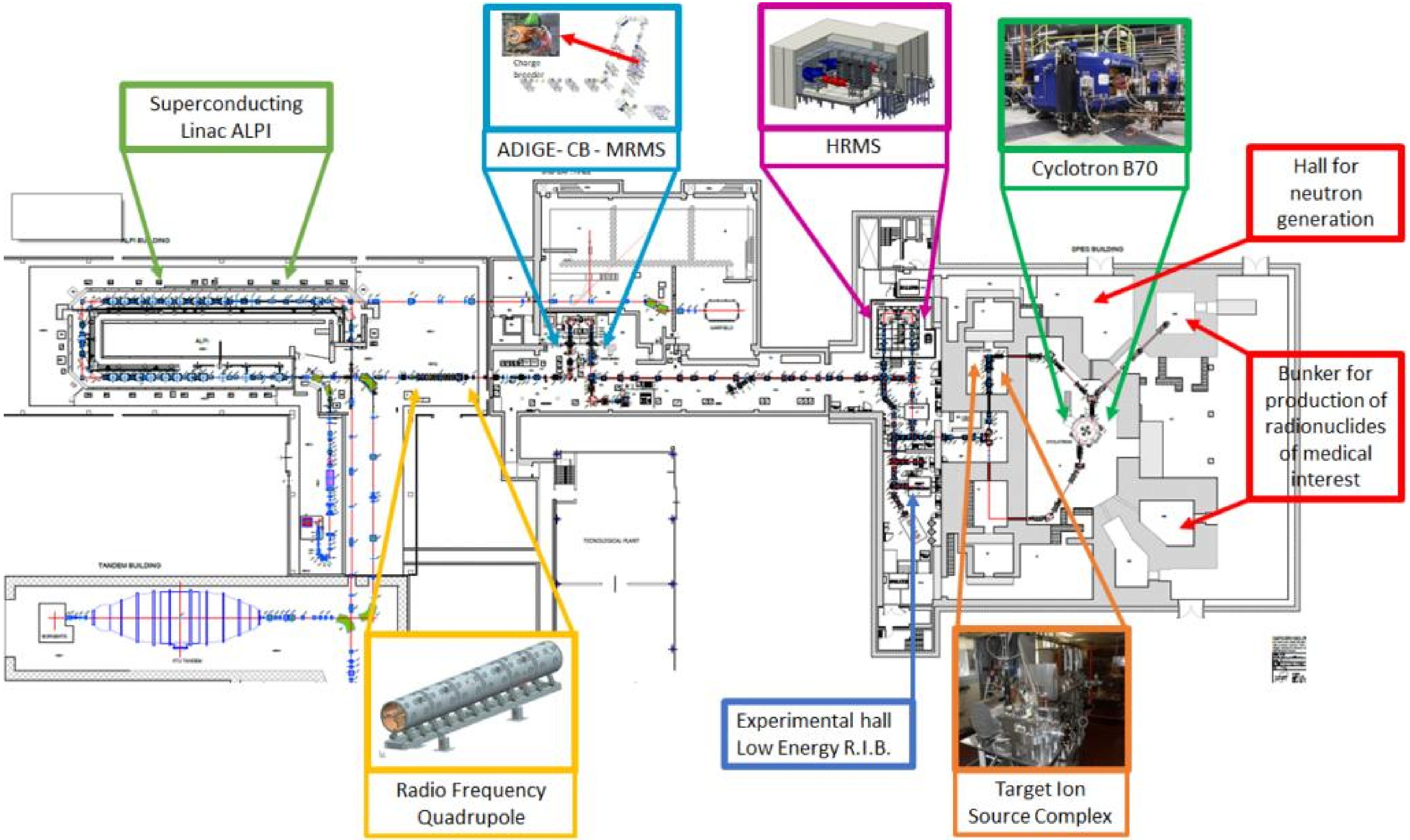
- An injecting accelerator, powerful
- A special 'robust' target
- A way to extract formed produced (slow) nuclei (atomic form)
- A way to give charge to atoms (getting ions)
- A way to select which ion you want
- A post-accelerator to achieve useful energy for physics
- All above, very quick!



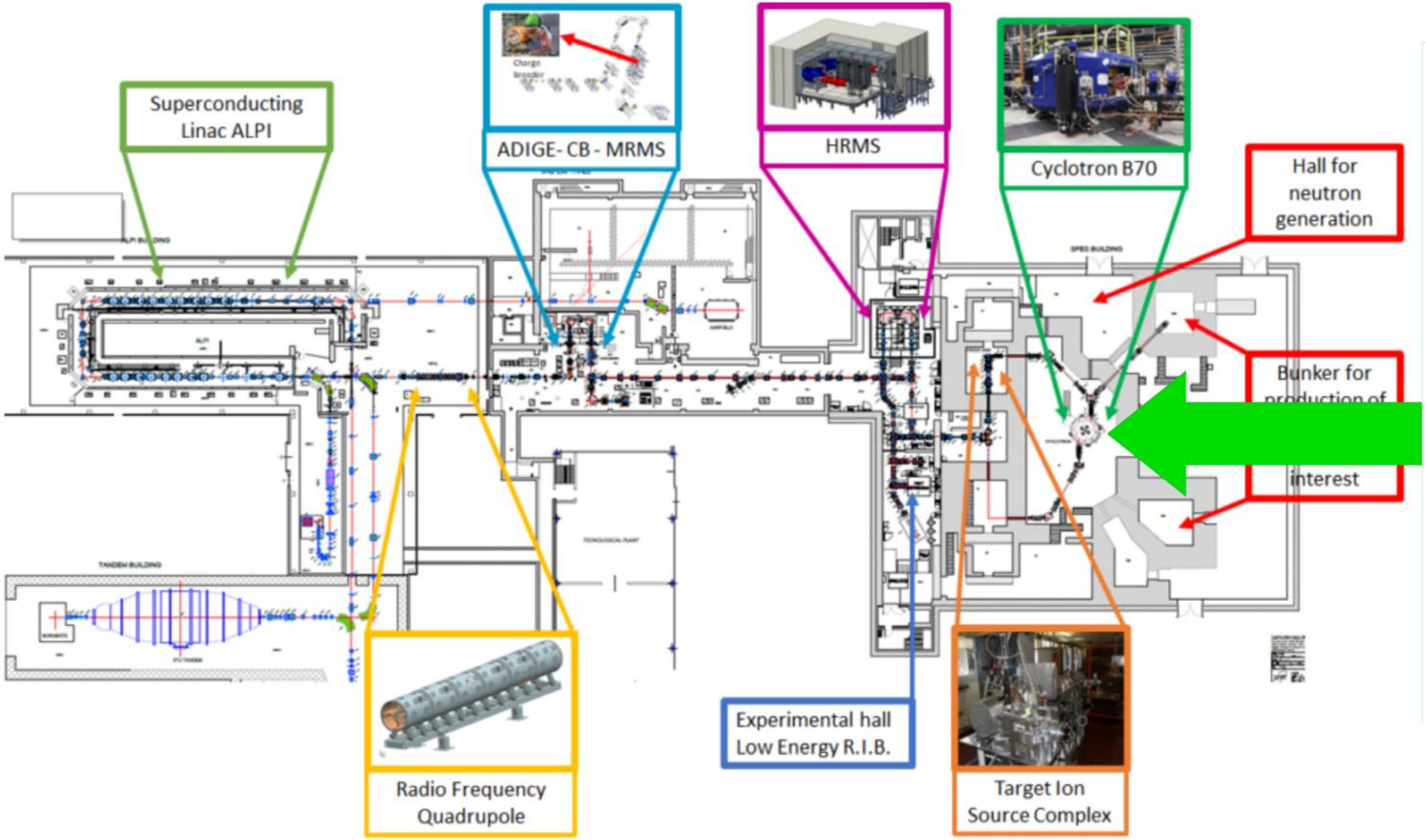
Among various examples:

Historical Facility, great expertise: ISOLDE, CERN
Then also Triumf (Canada)
In progress: **SPES, here at LNL**

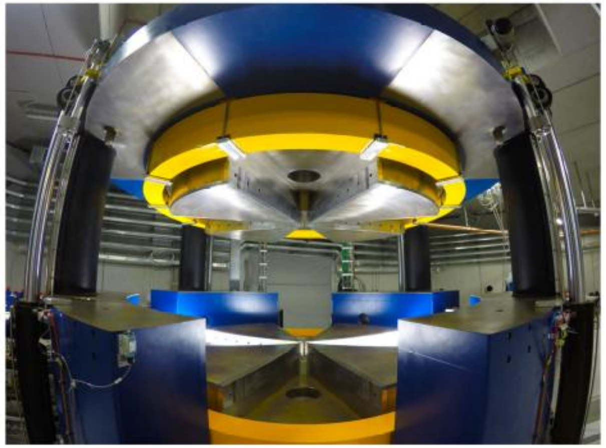
The italian ISOL laboratory: SPES at LNL



The italian ISOL laboratory: SPES at LNL



All starts here



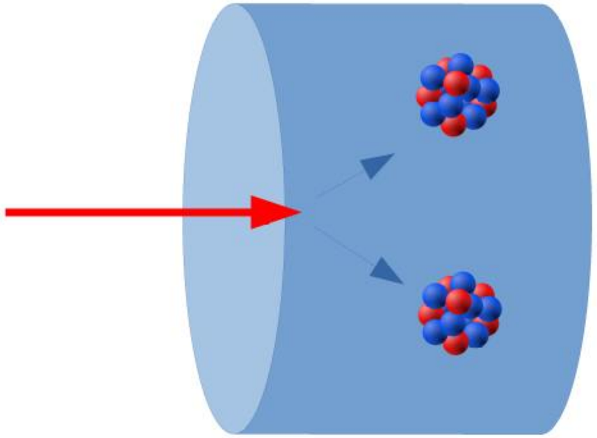
B70 **cyclotron**
150 tons
Proton beams up to 0.75mA
Energy 20-70 MeV
Max power 52kW

The Target Ion Source (TIS) at SPES

From the cyclotron
Proton beam

Up to
some 10^{15} pps

Sliced target (disks of e.g. SiC, BeC, Ucx, refractory compounds)

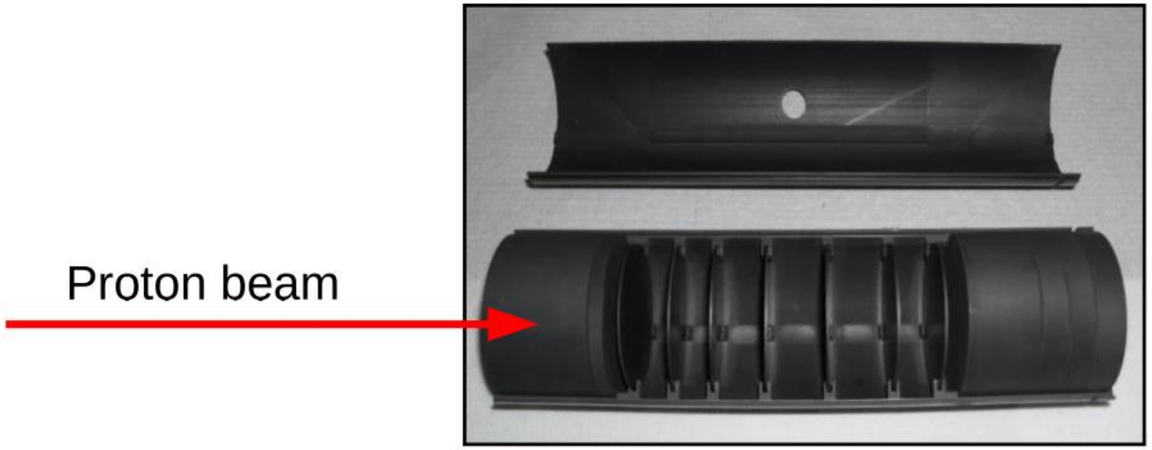


UCx

The exotic slow fragments soon stop within the disk

We must extract them!

The Target Ion Source (TIS) at SPES



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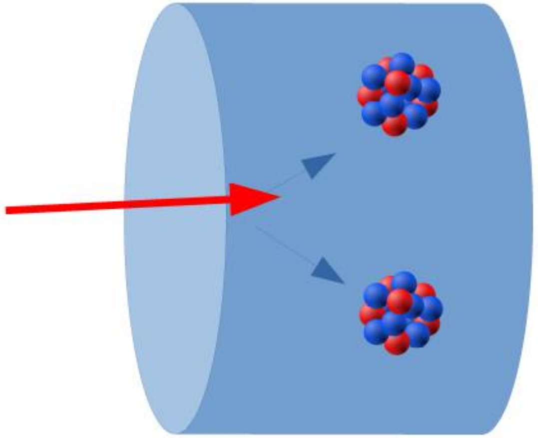

UCx

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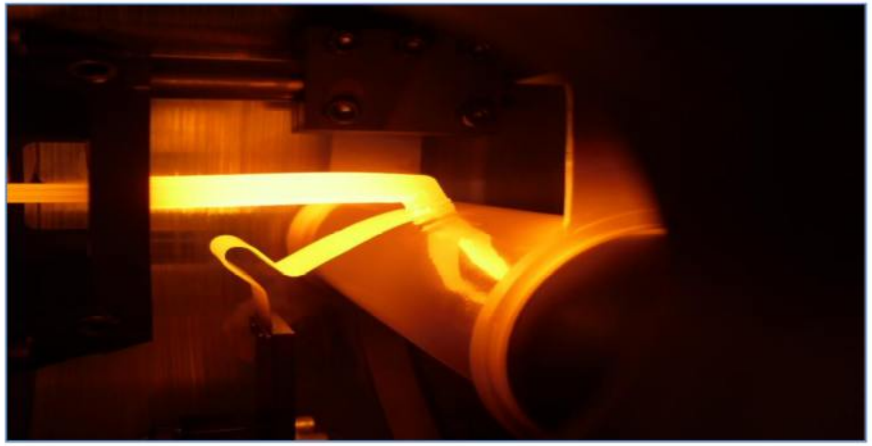
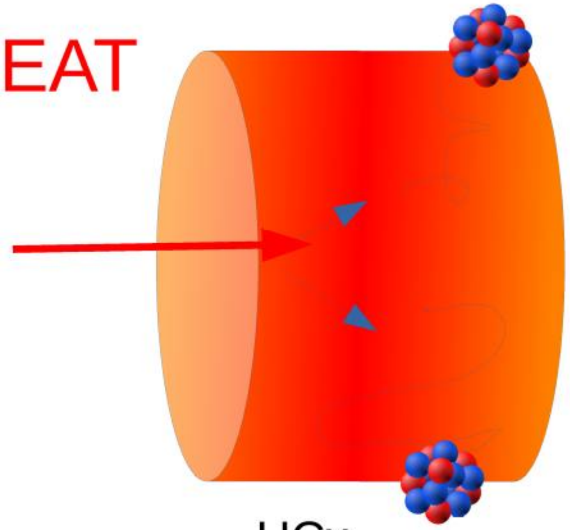
Use of HEAT



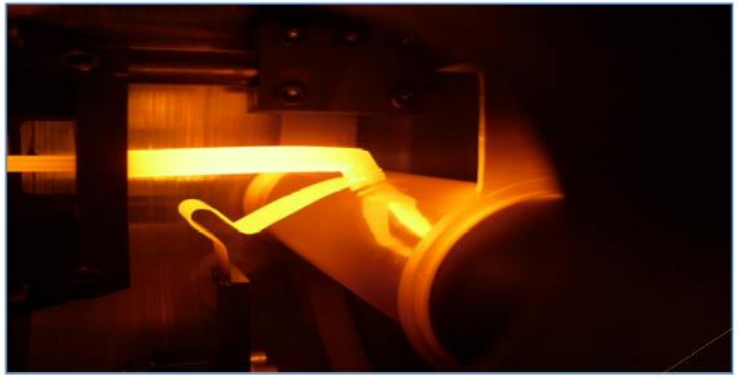
Strong heating at T=2000-2200°C

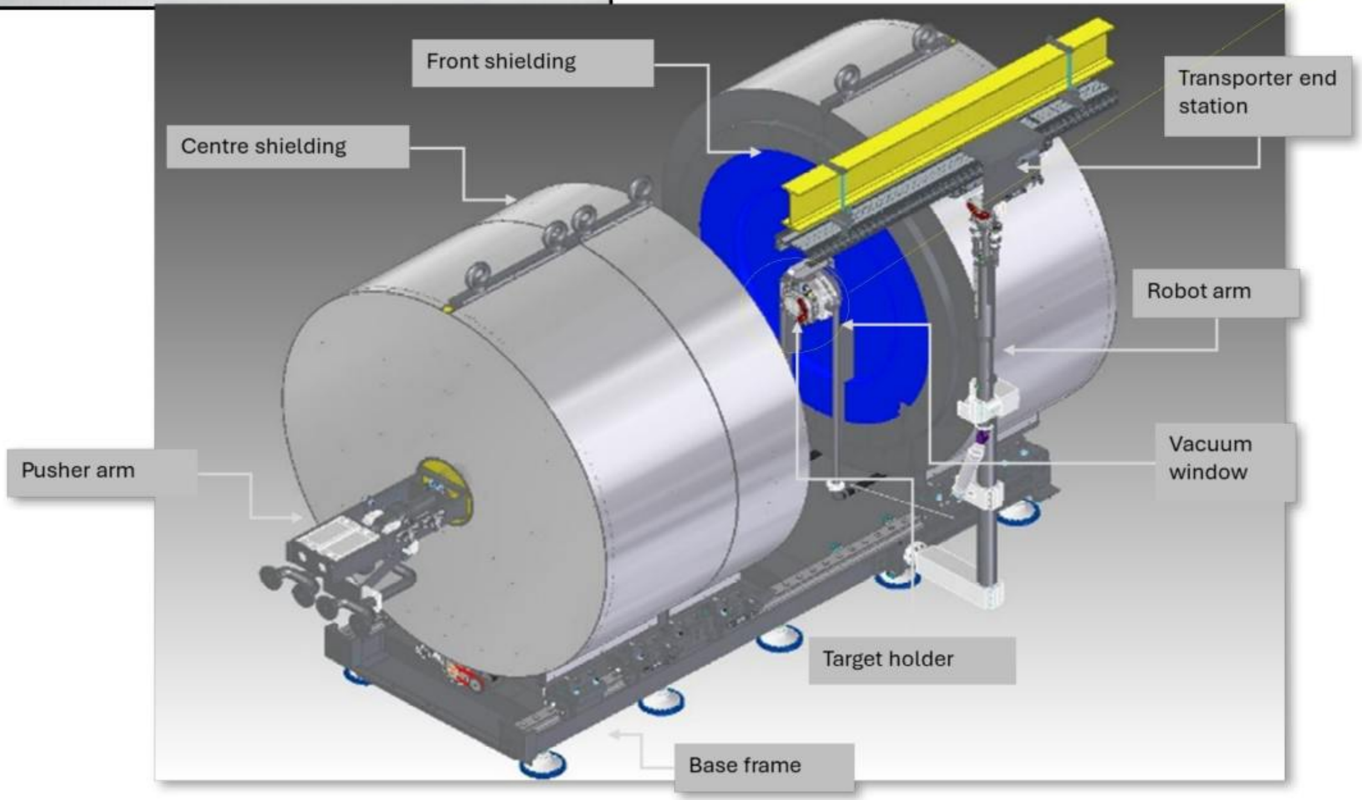


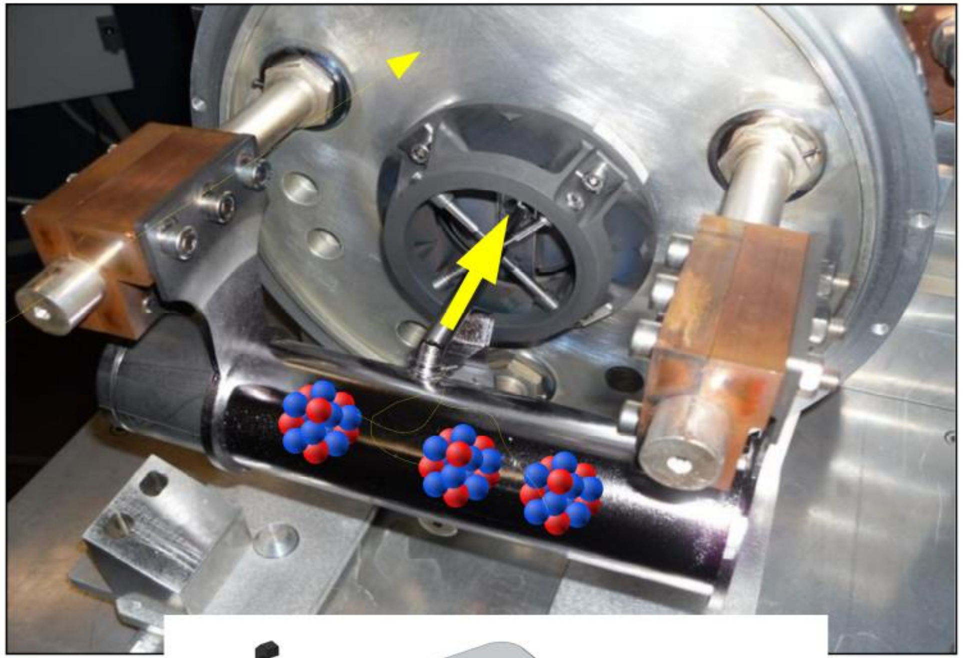
UCx

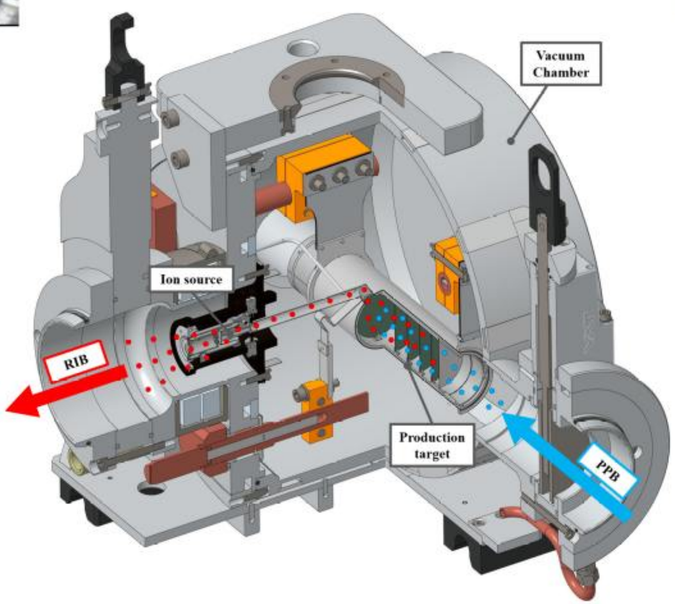
The unstable species **effuse** out of the target disk (with a certain efficiency, of course)

The Target Ion Source (TIS) at SPES

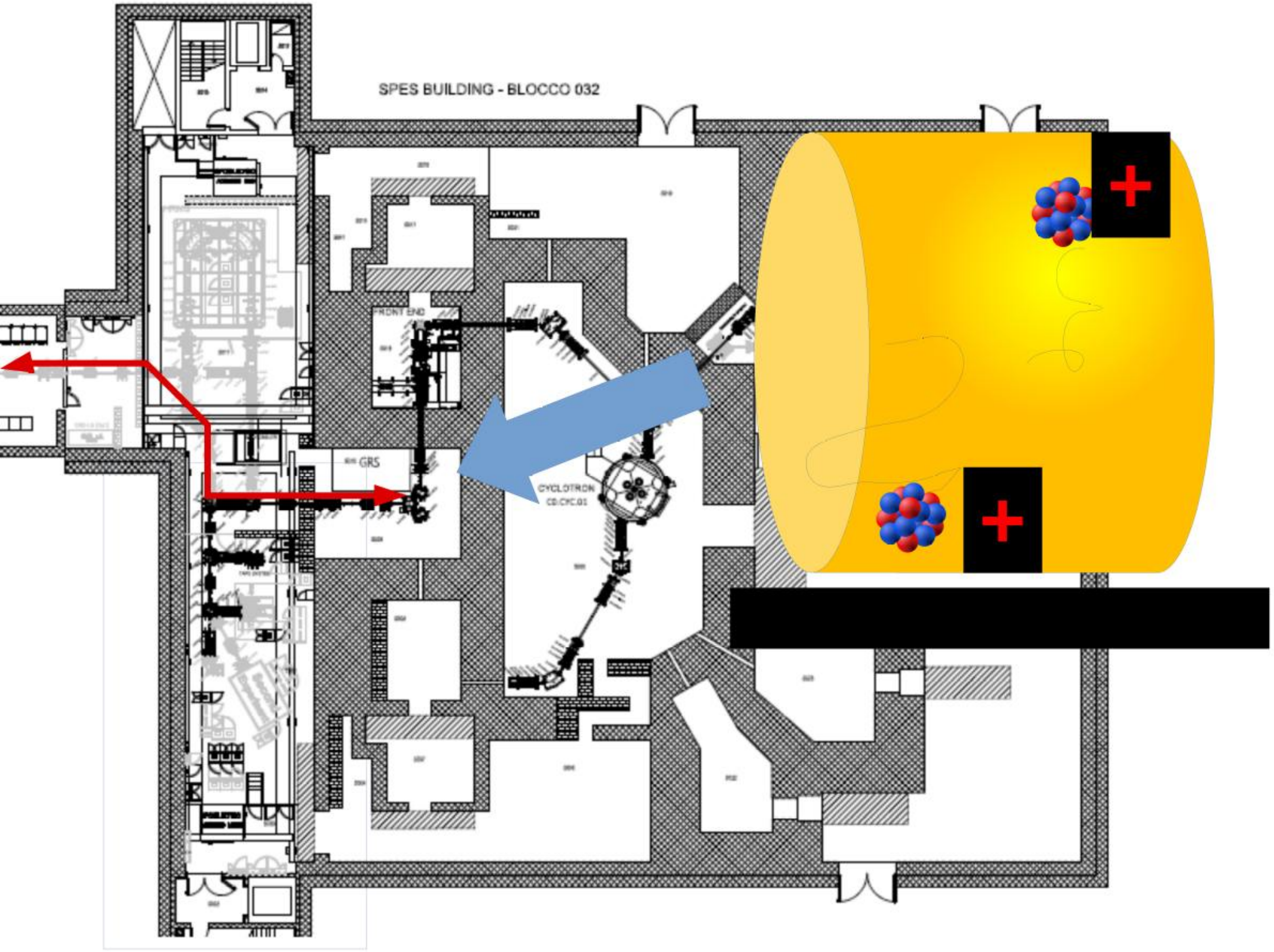




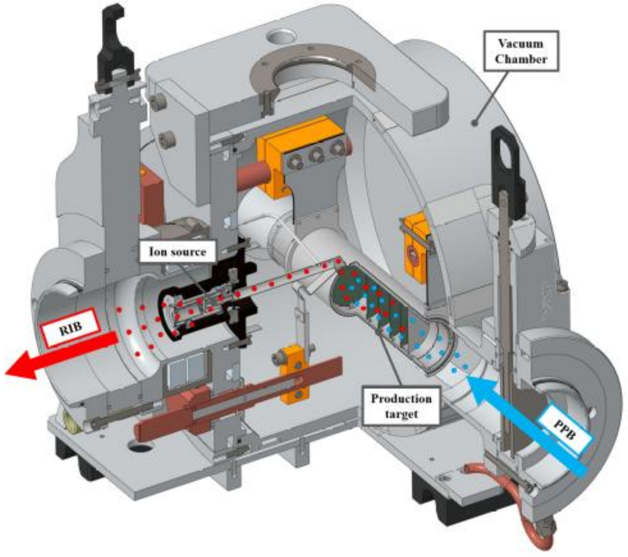




From atoms to ions, from slow to fast ions



Low Energy RIB area



After the extraction from the target, in fractions of second, ions must be produced (1+), must be preliminarly accelerated (with static HV), then enriched in charge (Charge Breeder) and accelerated more with specific RadioFrequency sections. Also the isotope separation must be done with efficient spectrometers

Which are the most intriguing physics subjects?

Nuclear geography: interplay of energies and potentials (typical of all physical systems)

- Nuclear radius: a clear cut definition?
- Atomic nuclei become nuclear atoms...
- Nuclei: not only single protons and neutrons
- Weakly bound systems and their wonderful periphery
- Strange radioactivity modes
- Shapes: not only spherical droplets
- From old Magic to new Magic
- ...and much more; if you're curious, please follow Nuclear Physics Academic courses!

To stimulate your curiosity

What is the nuclear radius?

Till the ‘80s there was consensus about the “macroscopic” nucleus description in terms of a **drop of incompressible liquid** with **constant density.** This implies that the radius R of the nucleus **weakly** increases with its mass m.

$$V=(4/3)\pi R^3$$

$$m=\rho V\,;\,\rho=constant\,(incompressible\,liquid\,drop)$$

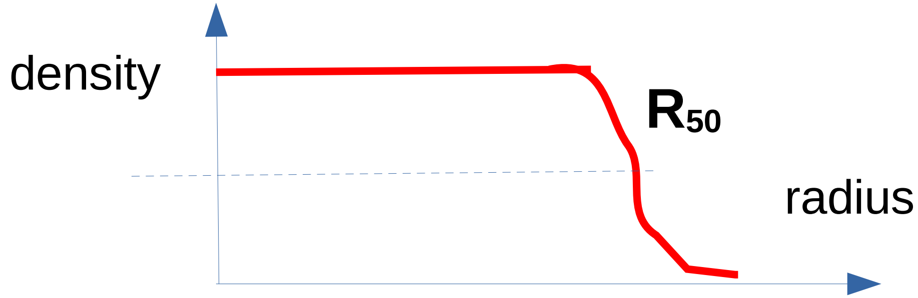
From these formulas, it simply follows:

$$R=a\,m^{(1/3)}=r_0\,A^{(1/3)}$$

Where r_0 is a ‘constant’ in (fm) and A is the mass number. Typically r_0=1.2fm

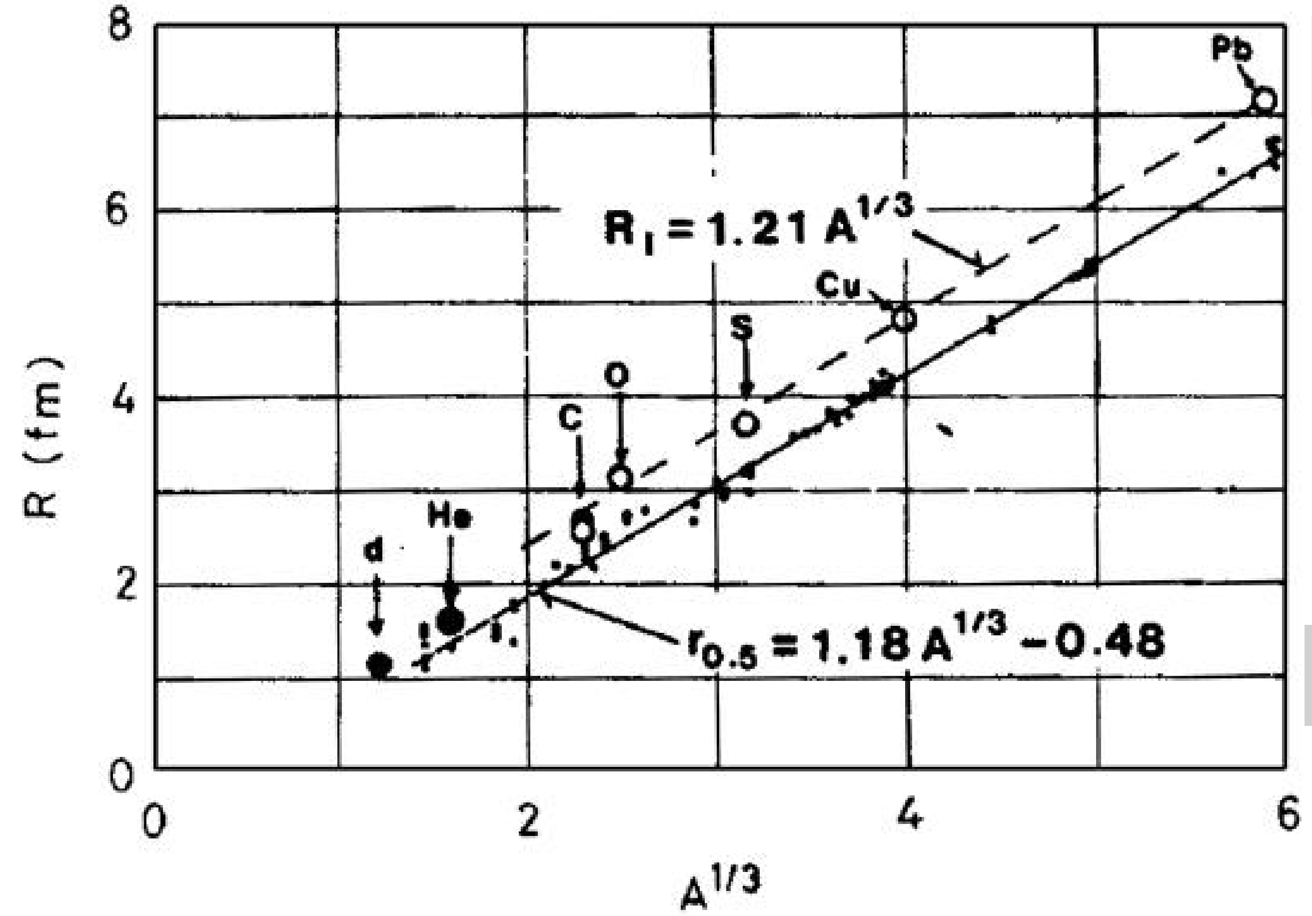
But: *Natura non facit saltus*! Experiments using electron diffusion on nuclei revealed some diffuseness, i.e. some surface detail:

$$R_{50}=r_0\,A^{(1/3)}-\delta$$



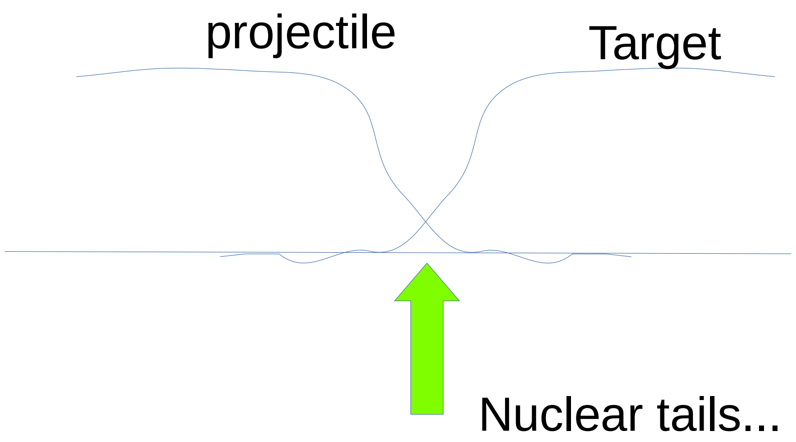
What is the nuclear radius?

Measurements of cross sections in reactions with stable nuclei put in evidence small surface effects (diffuseness); **however**, the main view/description of the nuclear droplets was retained.



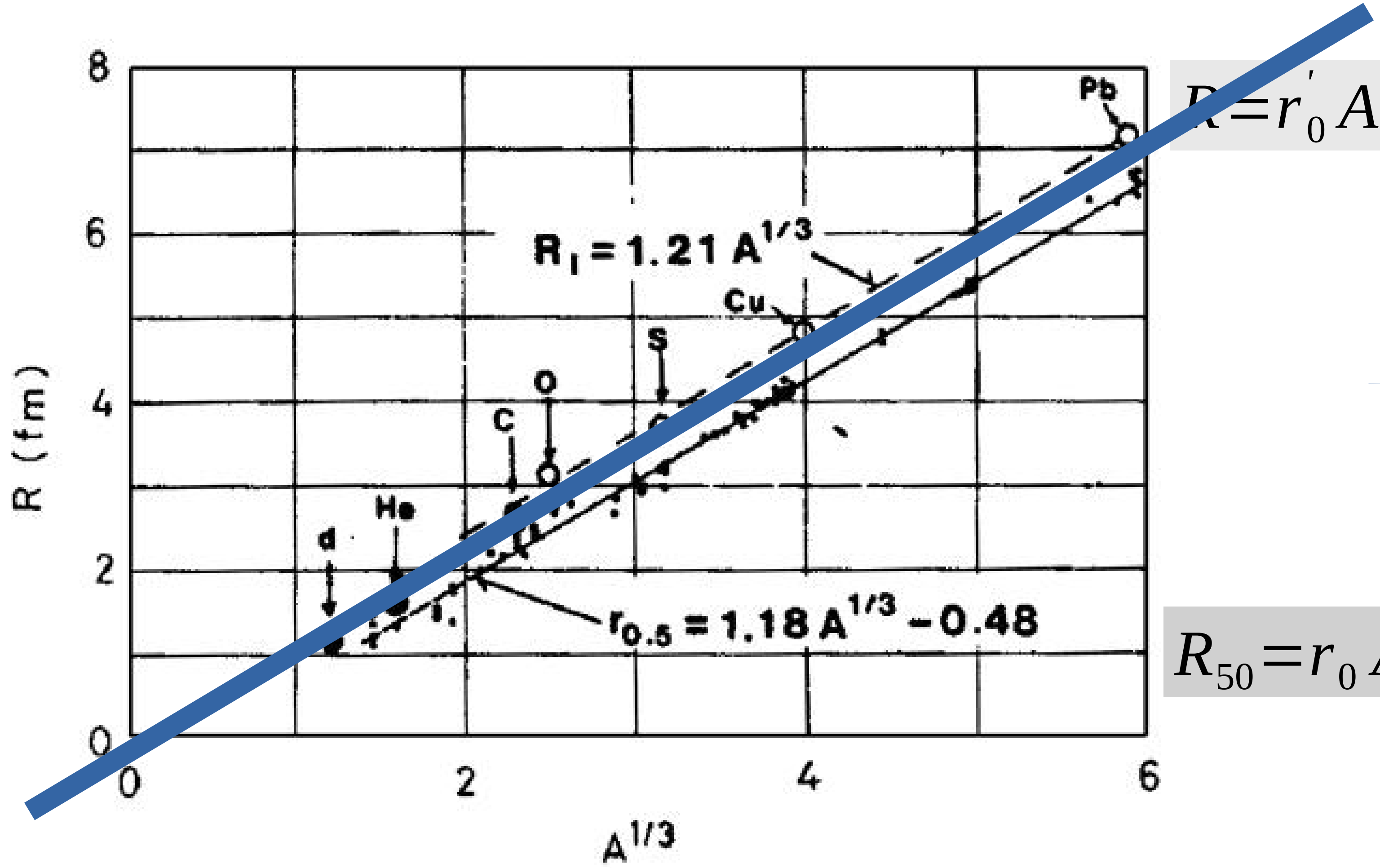
$$R = r_0^{'} A^{(1/3)}$$

$$R_{50} = r_0 A^{(1/3)} - \delta$$



What is the nuclear radius?

Measurements of cross sections in reactions with stable nuclei put in evidence small surface effects (diffuseness); **however**, the main view/description of the nuclear droplets was retained.



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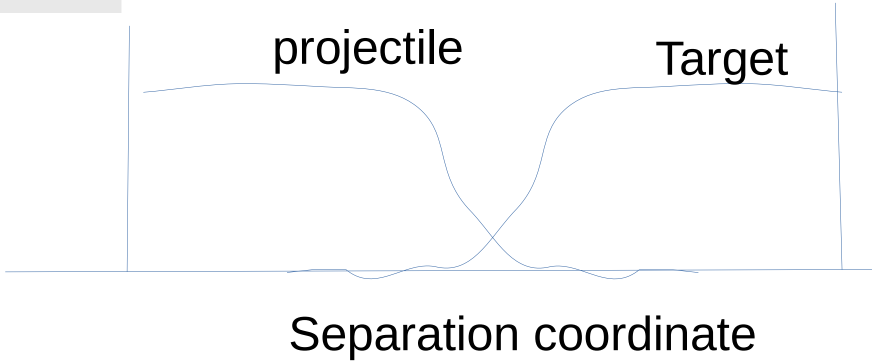
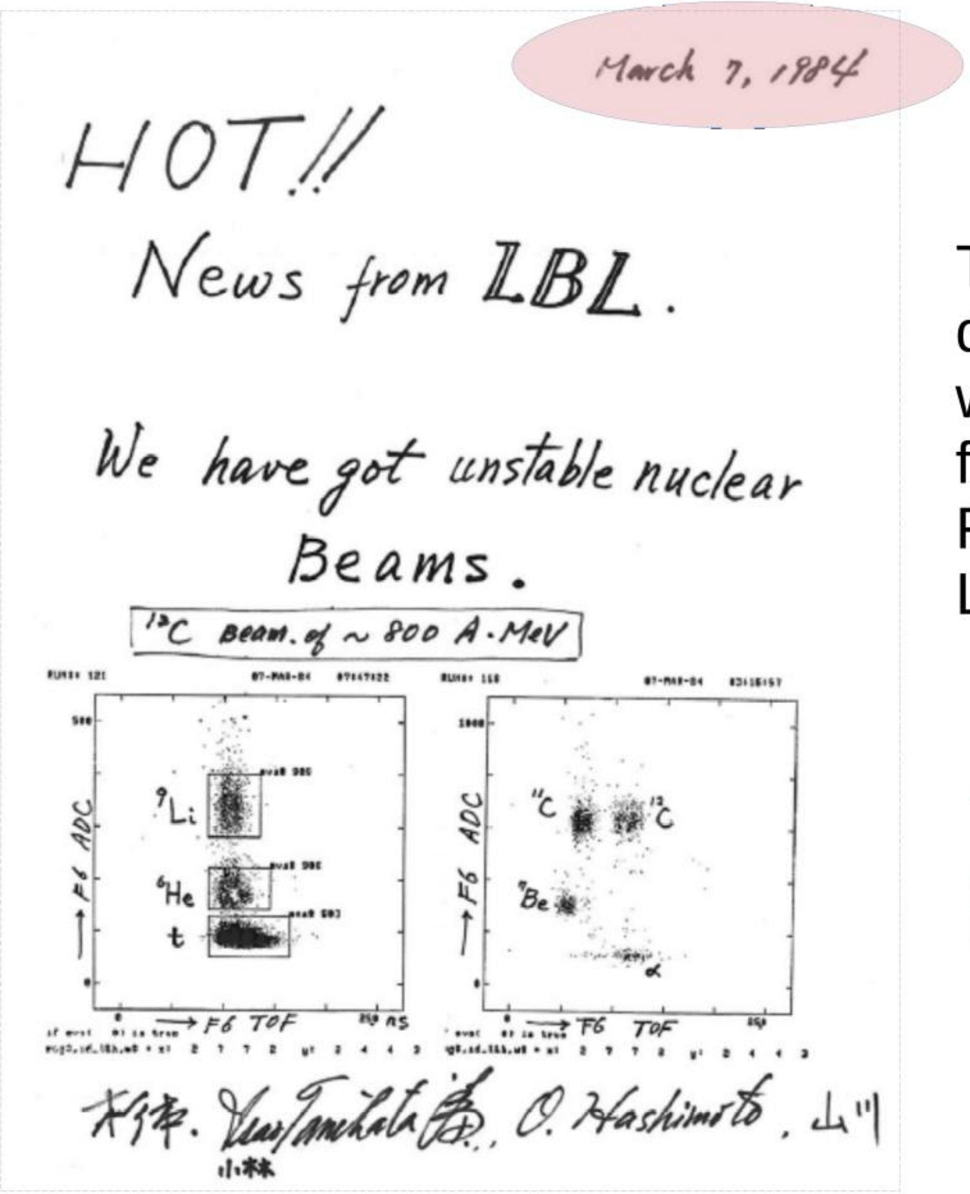
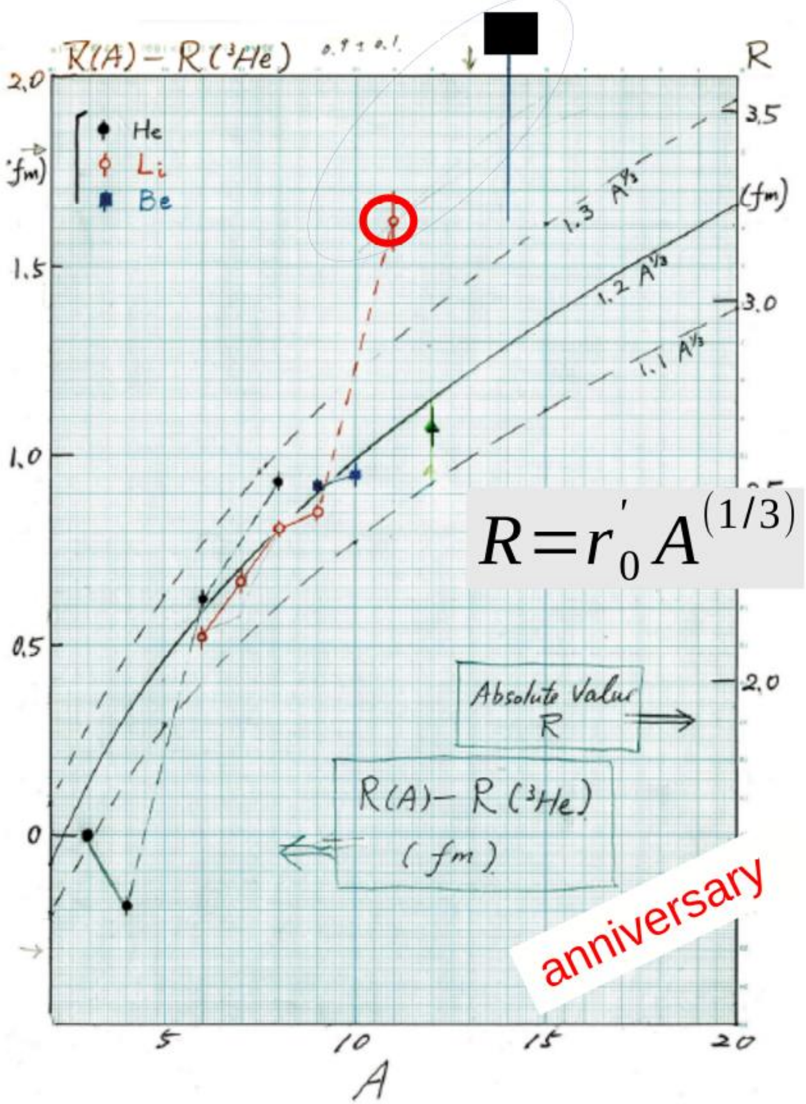


The discovery of halo in nuclei



This paradigm was dramatically changed with the advent of the first **unstable beams**. First attempts at the LBL, USA (early 80s)

The strange radii of 11Li and 14Be



$$R = r'_0 A^{(1/3)}$$

An unexpected variety of configurations

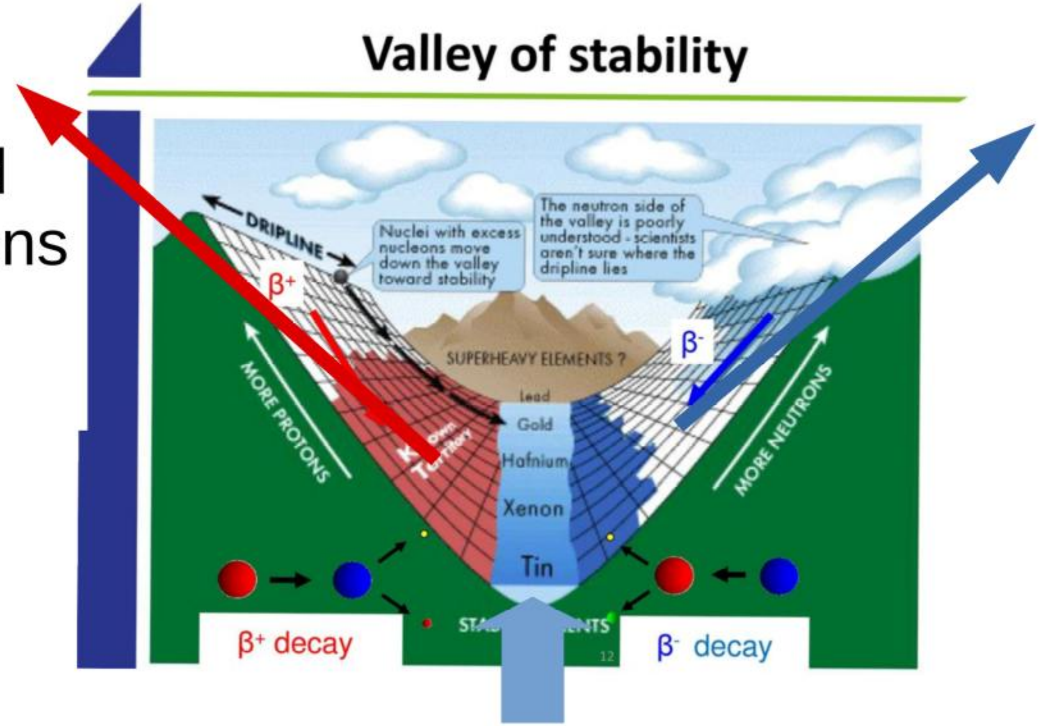
- Mass scaling not fully valid!
- Radius also depends on the isospin degree of freedom, i.e. the difference in neutron N and proton Z numbers
- Isobars (same A) with different ratios N/Z have not same radius.

The diffuseness **is not *almost* equal i**n all nuclei. The spatial distributions of neutrons and protons, similar for stable nuclei, may differ far from the *Canyon valley;* their separation energies can change a lot, accordingly, for protons and neutrons

If you climb this side

- protons loosely bound
- Extended p-distributions
- large radii
- Short lifetimes

"Only" this?



n,p similar binding energies

If you climb this side

- Neutrons loosely bound
- Extended n-distributions
- Very large radii
- Short lifetimes

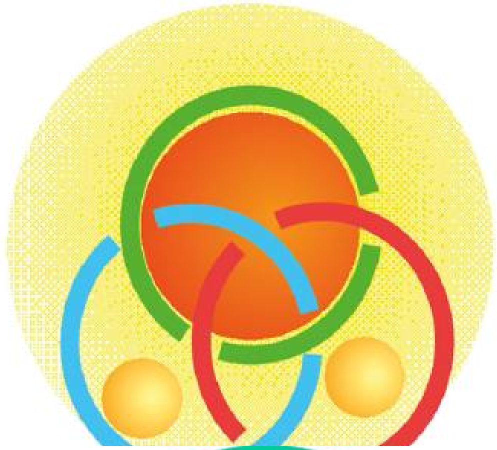
"Only" this?

An unexpected variety of configurations

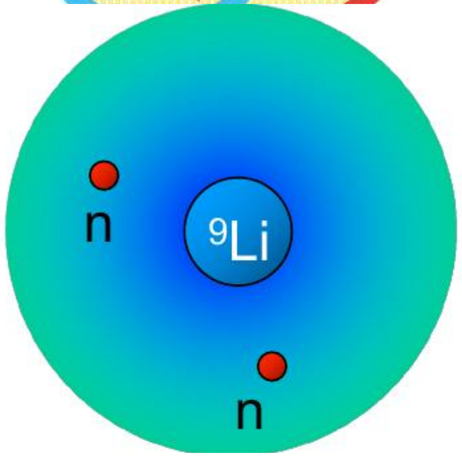
Other phenomena have been put in evidence and are currently under study using reactions with exotic beams. The **drip lines** have been reached with these investigations f**or the light systems** because they are closer to the Valley.

Examples of new nuclear phenomena

- Only in three guys together, we survive!
- Neutrons as electrons in molecules
- Not only halos but also Neutron skins
- Towards the Equation of State of nuclei and neutron stars
- The world of clusters



^{11}Li



^{9}Li + neutron doesn't exist

2-neutron pair doesn't exist

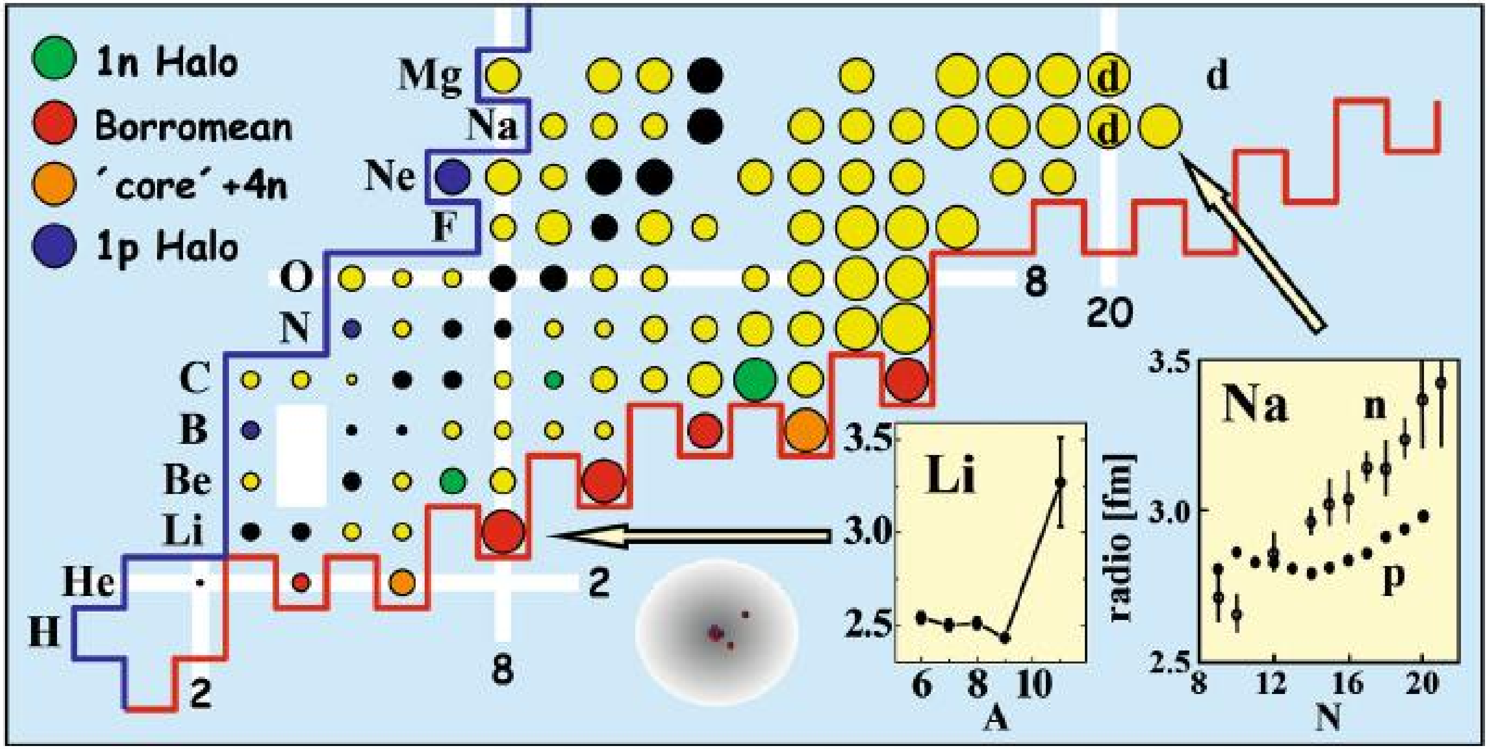
^{9}Li+2n does exist, it's ^{11}Li

Rare quantum case of a system bound via three-body correlations

Borromean nuclei
(from araldic logo)

An unexpected variety of configurations

Other phenomena have been put in evidence and are currently under study using reactions with exotic beams. The **drip lines** have been reached with these investigations f**or the light systems** because they are closer to the Valley.



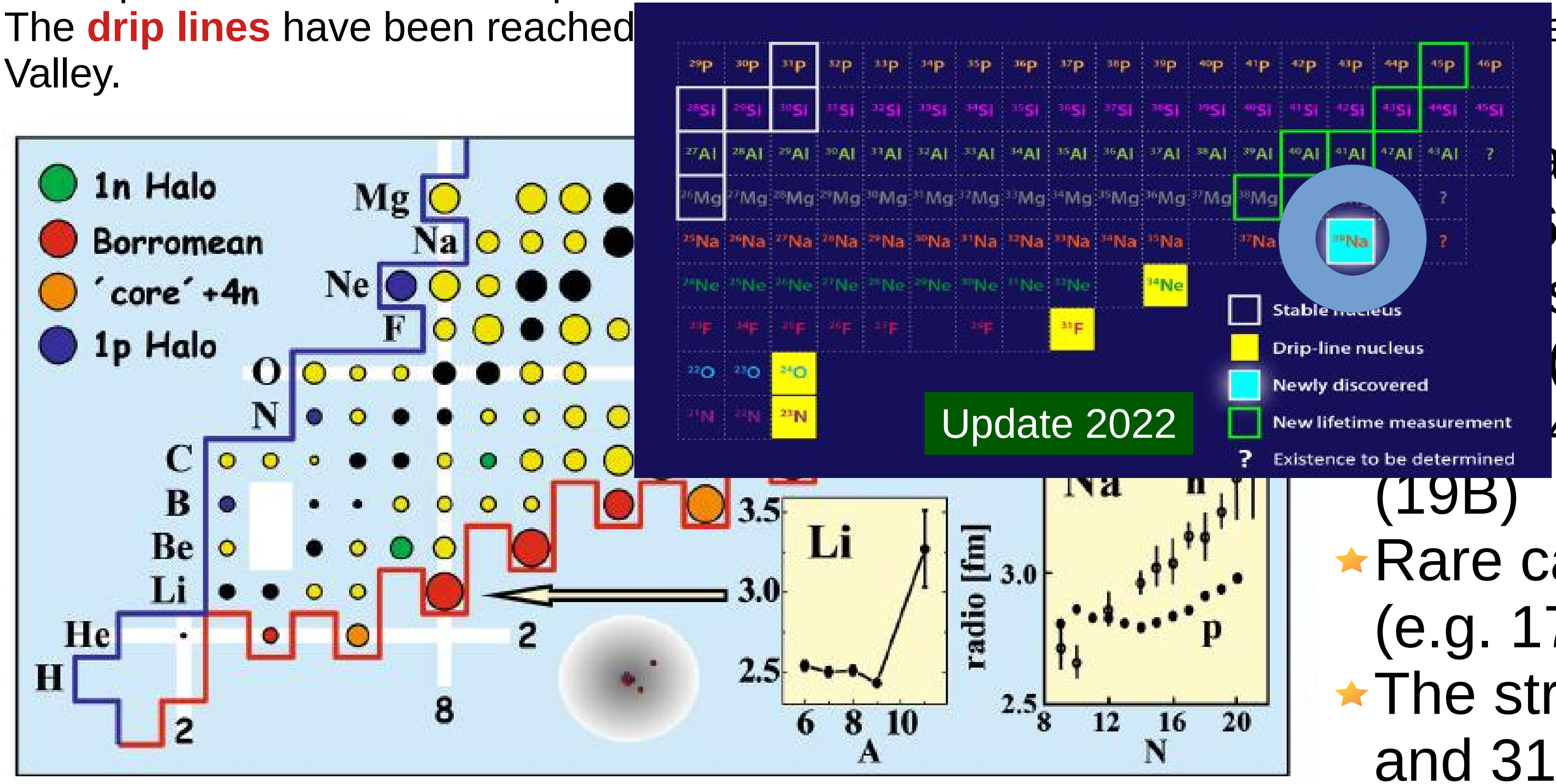
- Several Borromean nuclei (e.g. 6He, 14Be, 22C)
- Some single-neutron halo nuclei (e.g.11Be, 19C)
- Some 4n correlations (19B)
- Rare cases of proton halo (e.g. 17Ne)
- The strange case of 24O and 31F limiting species

2015: n-drip line was reached up to Z=11 (Sodium)

What next?

An unexpected variety of configurations

Other phenomena have been put in evidence and are currently under study using reactions with exotic beams.
The **drip lines** have been reached … ecause they are closer to the Valley.



- …al Borromean nuclei (…He, 14Be, 22C)
- …single-neutron halo (e.g.11Be, 19C)
- …4n correlations (19B)
- ★ Rare cases of proton halo (e.g. 17Ne)
- ★ The strange case of 24O and 31F border guys

2015: n-drip line was reached up to Z=11 (Sodium)

What next?

An unexpected variety:clusters

Archaeologists are careful when they suspect that some nice hidden structure and configuration can emerge from the gross region they excavate.

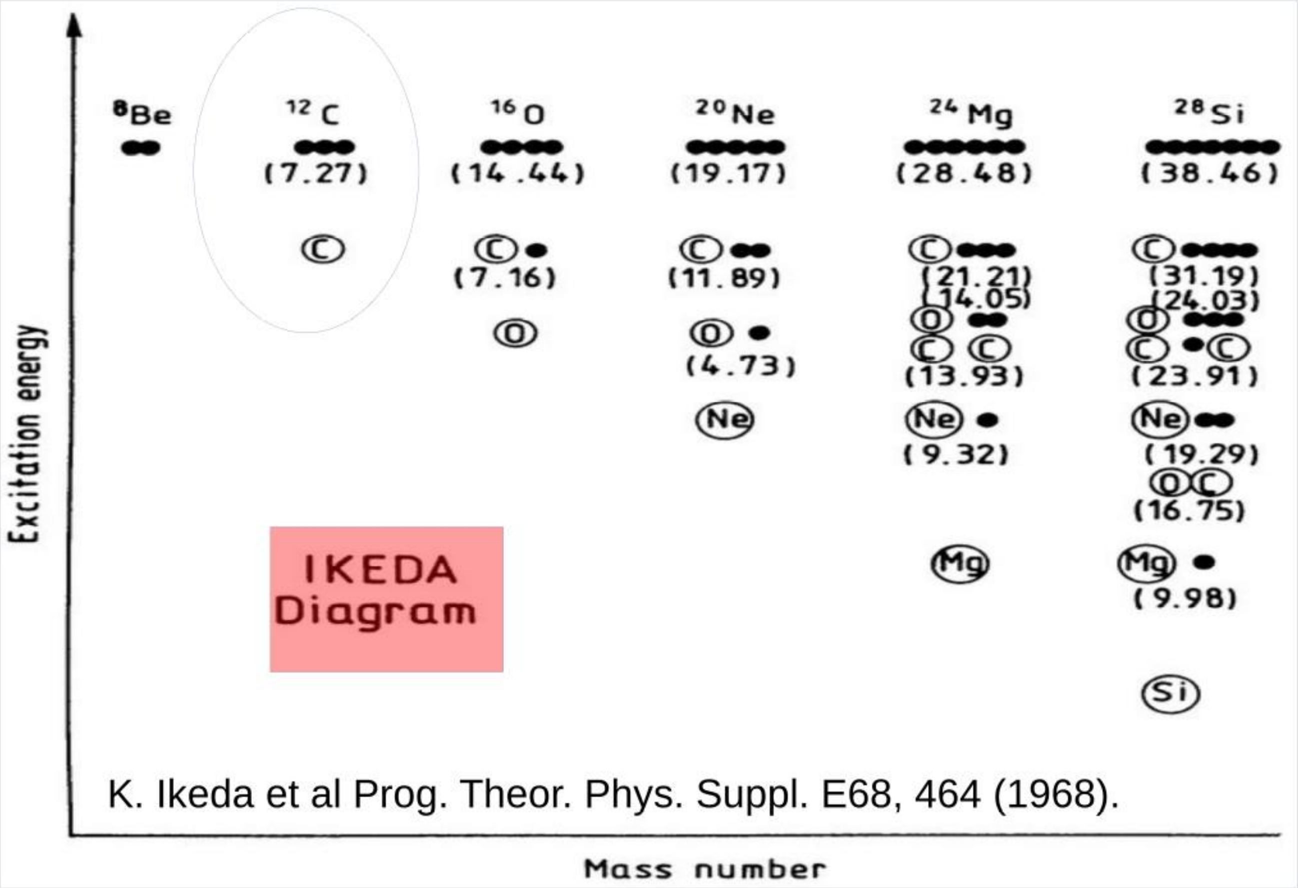
Similarly, nuclear physicists for many decades were supposing that in some nuclei the wave function may have contribution from **cluster configurations (i.e. groups of strictly correlated nucleons in the medium)**

In particular, (due to their high binding energy) nucleon quartettos of alpha-particles were expected.

As in archaelogy discovery, the underlying structure can manifest when the nucleus is *gently* excited just close to the separation energy (at the threshold)

An unexpected variety

60 years ago, it was proposed that in N=Z nuclei, a hidden structure made of alpha particles could be evidenced when light (stable) nuclei are excited close to the separation energy

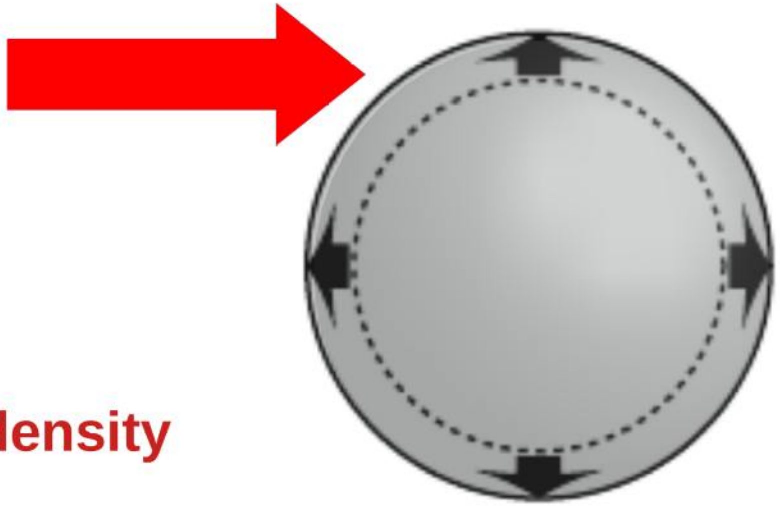


K. Ikeda et al Prog. Theor. Phys. Suppl. E68, 464 (1968).

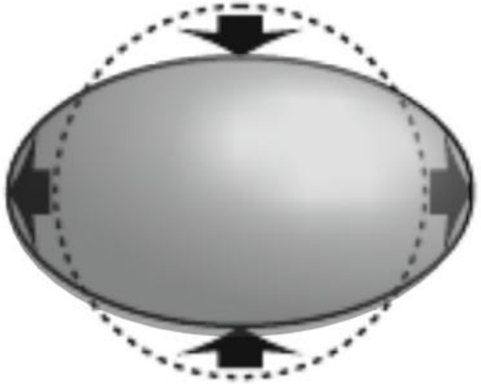
An unexpected variety

Nuclei don’t like to change density (incompressible to a large extent) so that other modes are excited when you start to put energy

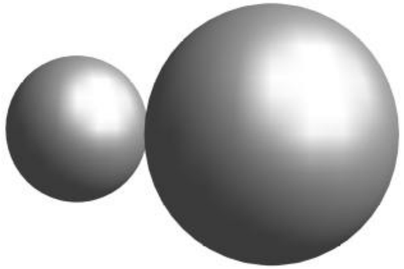
unfavourable



Shape oscillations are more favoured and also cluster formation because **they both don’t change the density**



Shape oscillation



clustering

favourable

An unexpected variety

The saturation property of nuclei at the drip lines breaks up and many associated features change a lot. Thus the cluster structures, when "*climbing the canyon*", can reveal unexpected phenomena

Consider a very neutron rich nucleus: does this unbalance favour or disfavour clustering?

An unexpected variety

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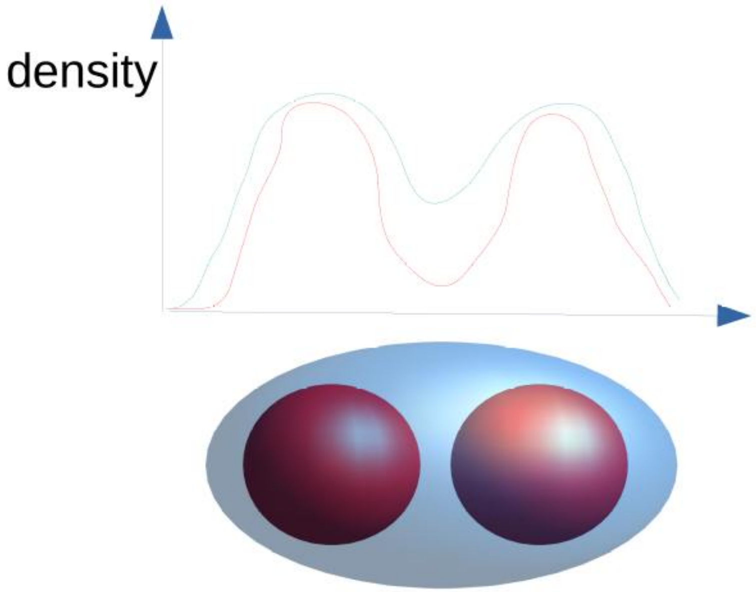
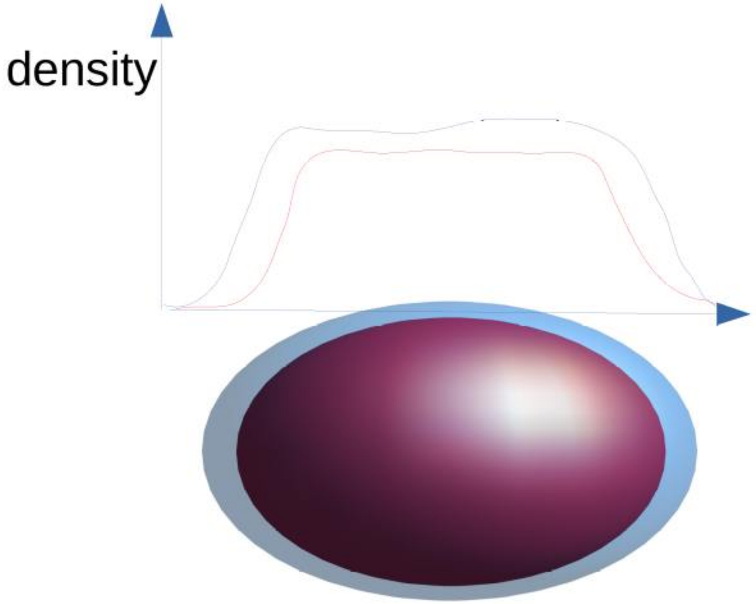


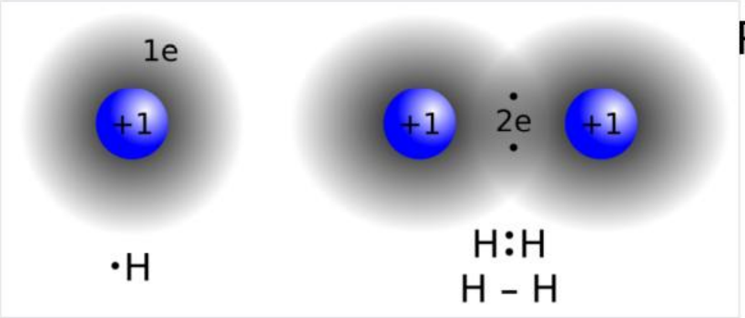
Clustering favoured because the symmetry Energy is *locally* reduced



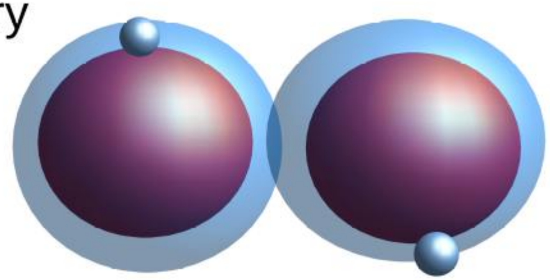
Clustering disfavoured because the symmetry Energy is *globally* reduced

An unexpected variety

Also the shell structure of nuclei, due to their quantum nature, comes to play and changes with strong p-n unbalance; the shells are built in a non spherical well

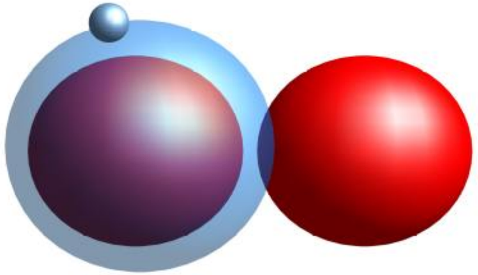


Remind chemistry



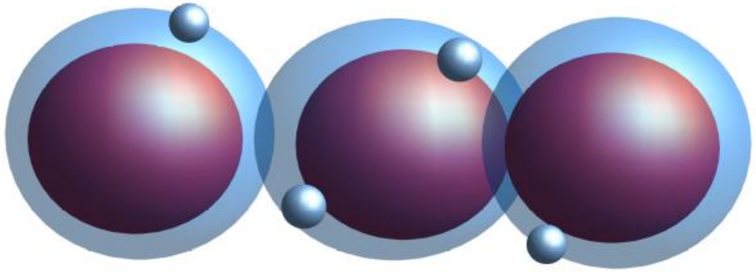
Molecular configuration with a kind of **covalent** bond

Configurations appear looking like atomic or molecular systems where valence hadrons are exchanged or shared to establish the (weak) bond



Atomic configuration with a kind of **ionic** bond

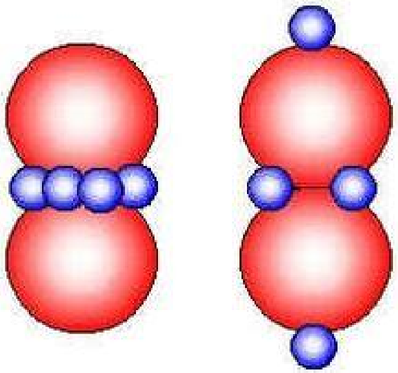
Many shapes manifest for exotic nuclides that cannot exist in stable species



Peculiar configurations allowed by the excess nucleons acting as valence electrons

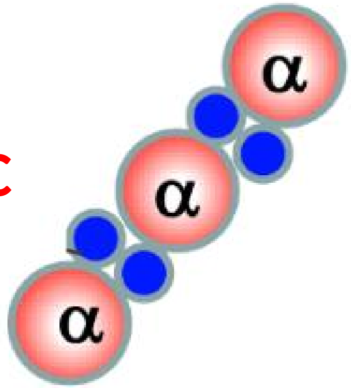
An unexpected variety

^{12}**Be**



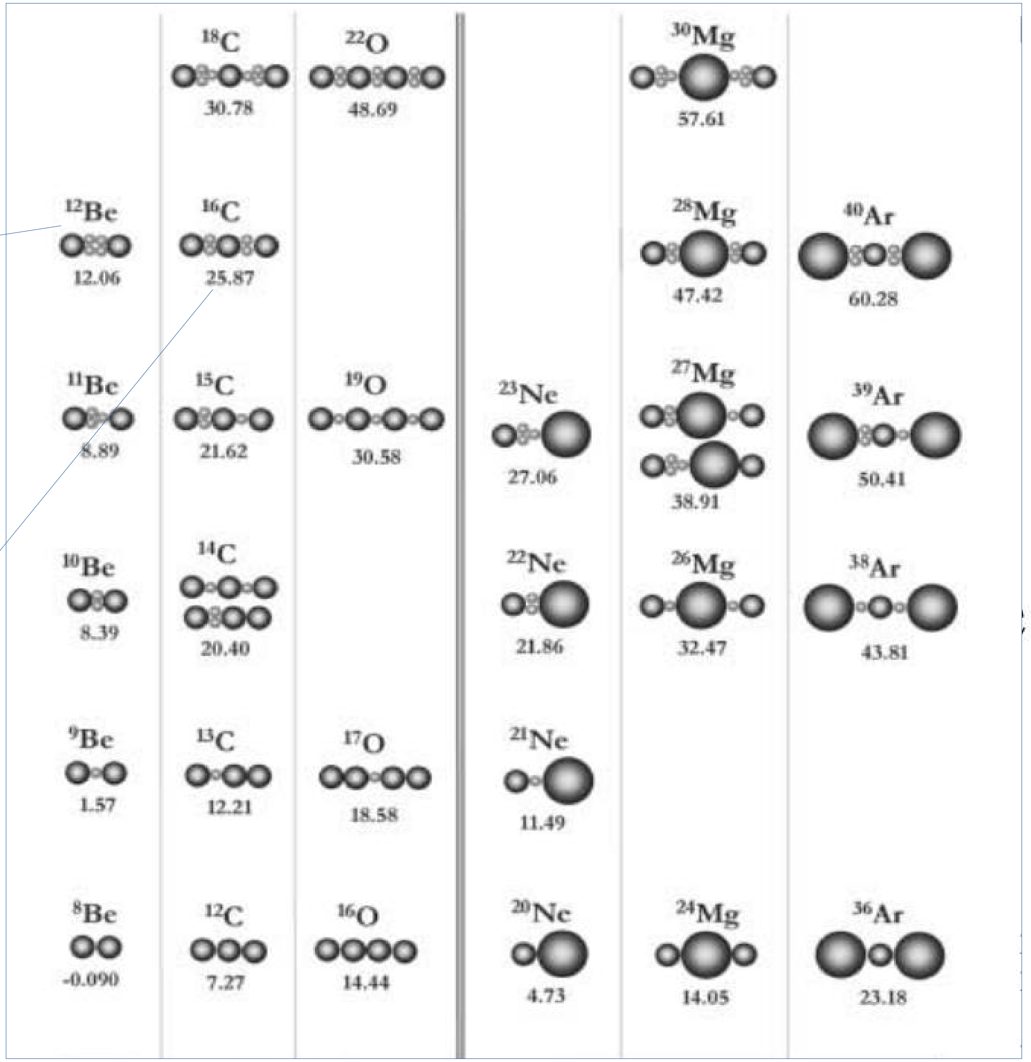
Cartoons for dimers and trimers

^{16}**C**



linear chain

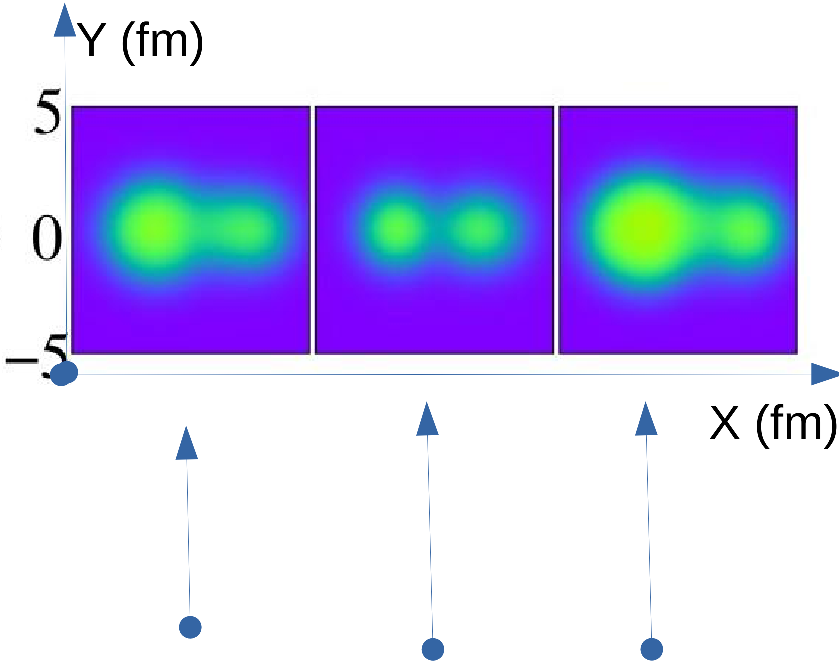
^{10}Be, $^{13\text{-}14}$C, ^{16}C(?),…



A proposed **new IKEDA diagram**

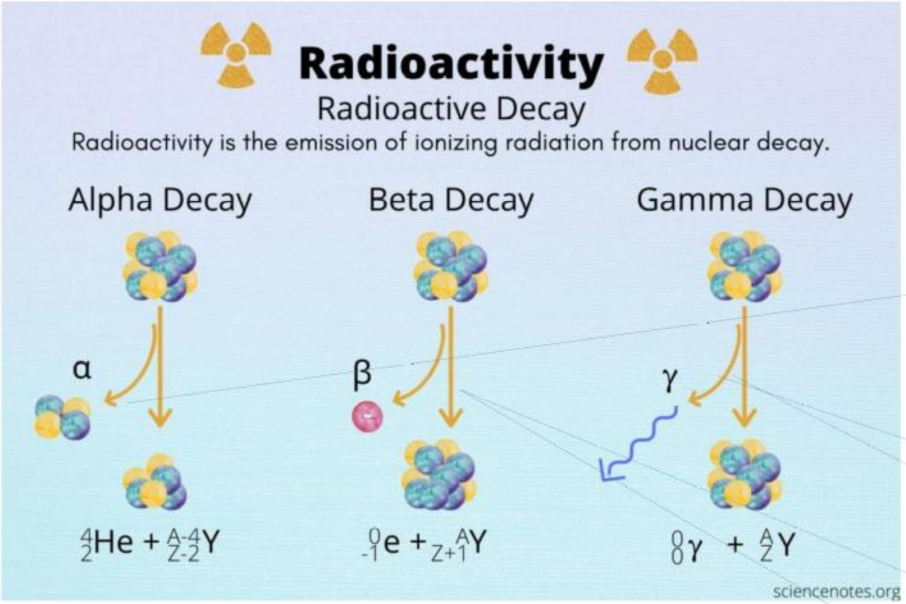
^{12}**Be**

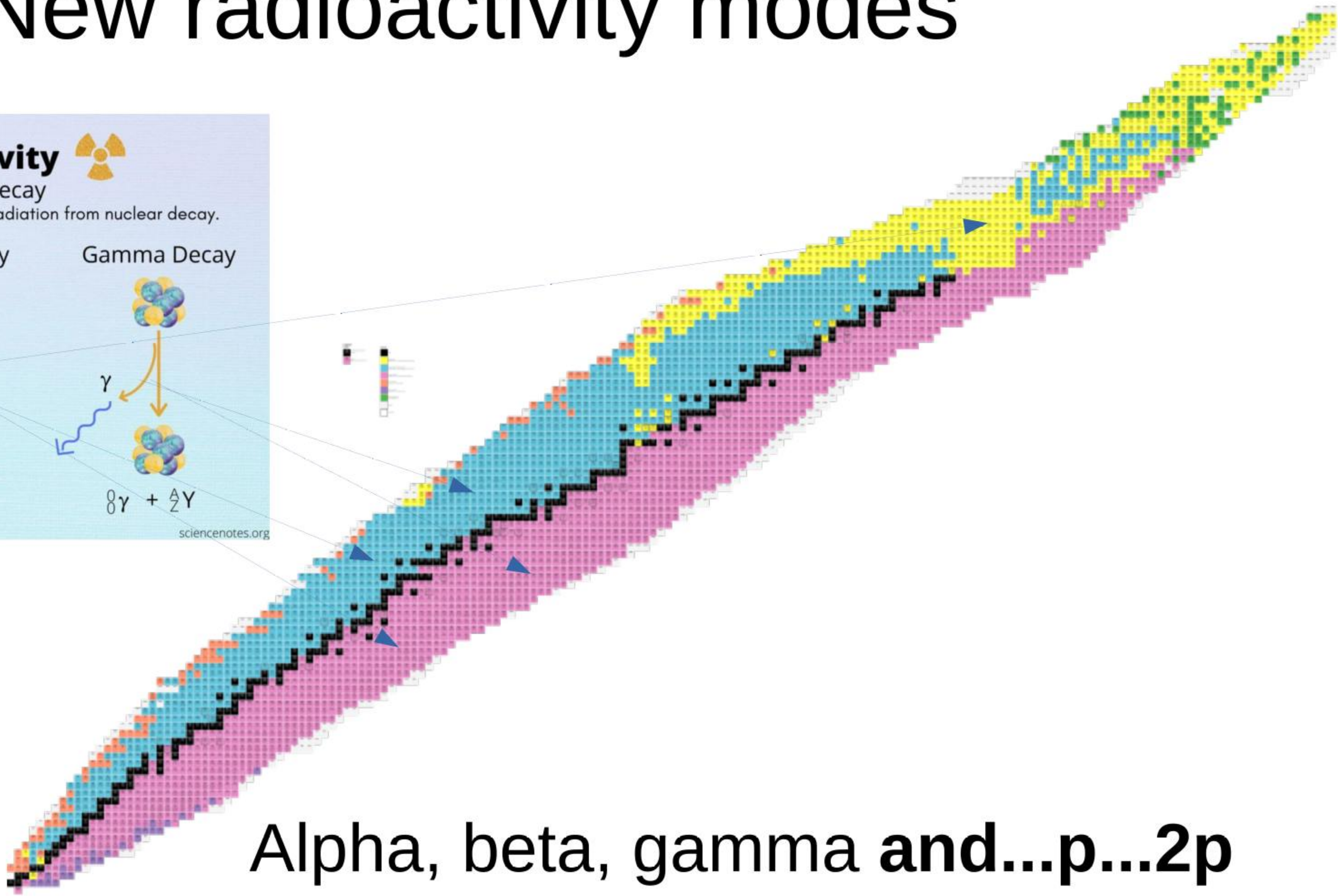
Density plots from a sophisticated quantum model (Antisymmetrized Molecular Dynamics AMD)



Matter proton neutron

New radioactivity modes





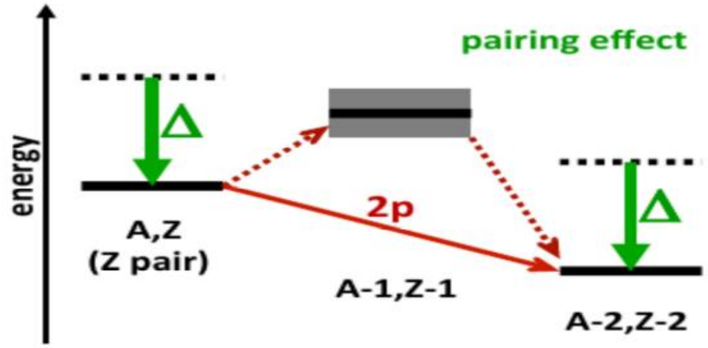
Alpha, beta, gamma **and...p...2p**

New radioactivity modes

- Close to the p-drip line the proton excess is high and the instability grows
- nuclei can decay from ground state via one-proton (if odd-Z) or two-proton emission (if even-Z)

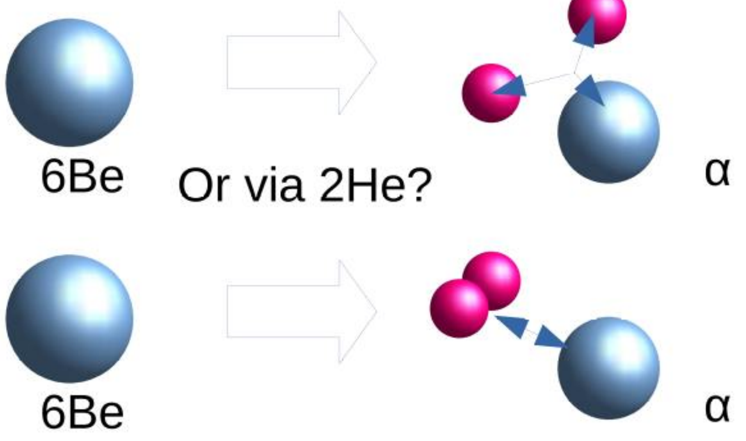
1 proton decay
Already **observed the first time at GSI in 1980** via fusion reaction with stable beams (fusion reactions with **stable** beam-target pair typically produce nuclei toward the p-rich side of the valley)

2 proton decay
difficult experiments but feasible without radioactive beams. The latter, however, allow for a deeper investigation towards the p-drip region and to access very exotic decay.



In particular **2-proton decay from ground state**

ok...but
Prompt 3body



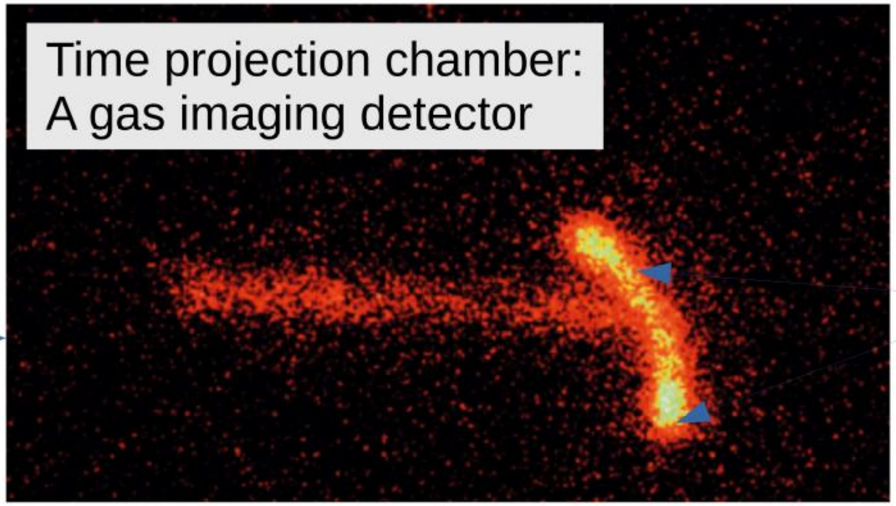
New radioactivity modes

2 proton from the ground state: expected when the binding energy of a proton pair is less than that of one proton. This can occur for nuclei close to the drip line

First observation of a correlated two-proton decay from g.s.
2002 at GANIL

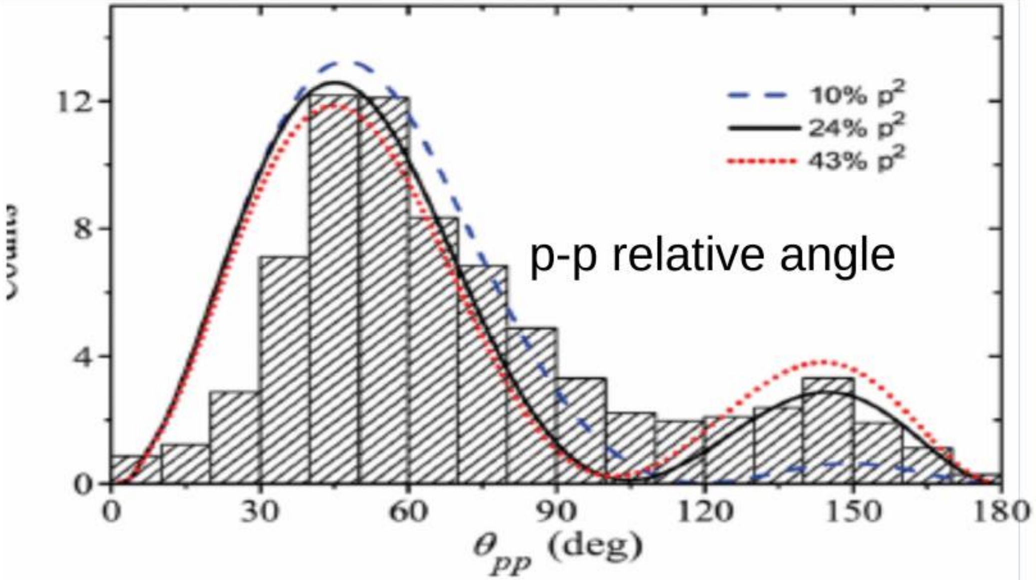
TPC photographs of the 2p decay from g.s. of ^{45}Fe taken in **2007 at MSU**

^{45}Fe ion
26 protons
19 neutrons
T1/2=2.6ms



Proton tracks

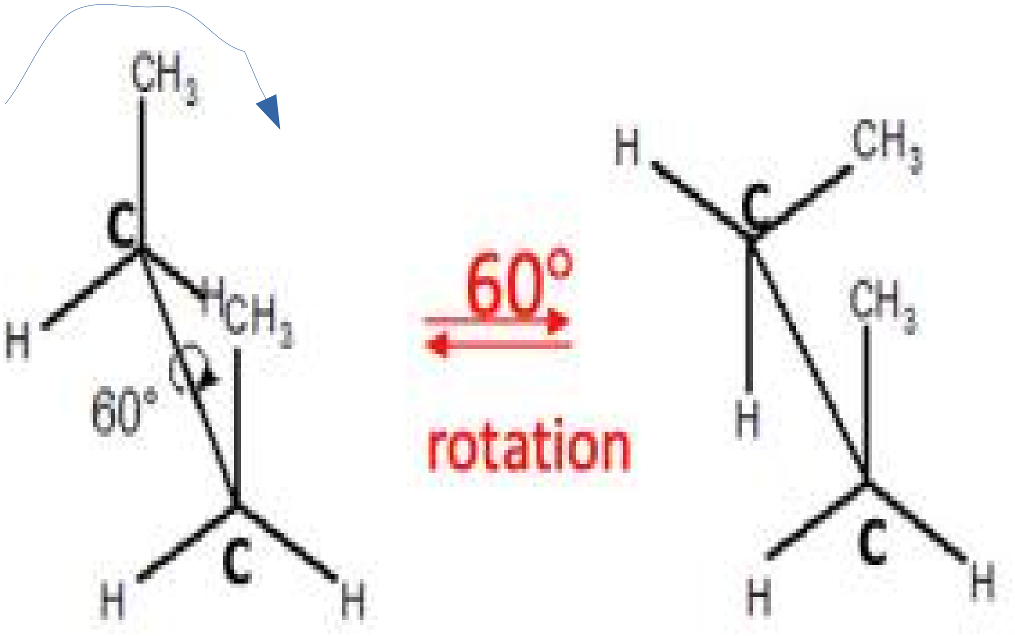
Angular correlation demonstrate it's **direct 3 body** decay!



Shape Coexistence
one chemistry, various shapes

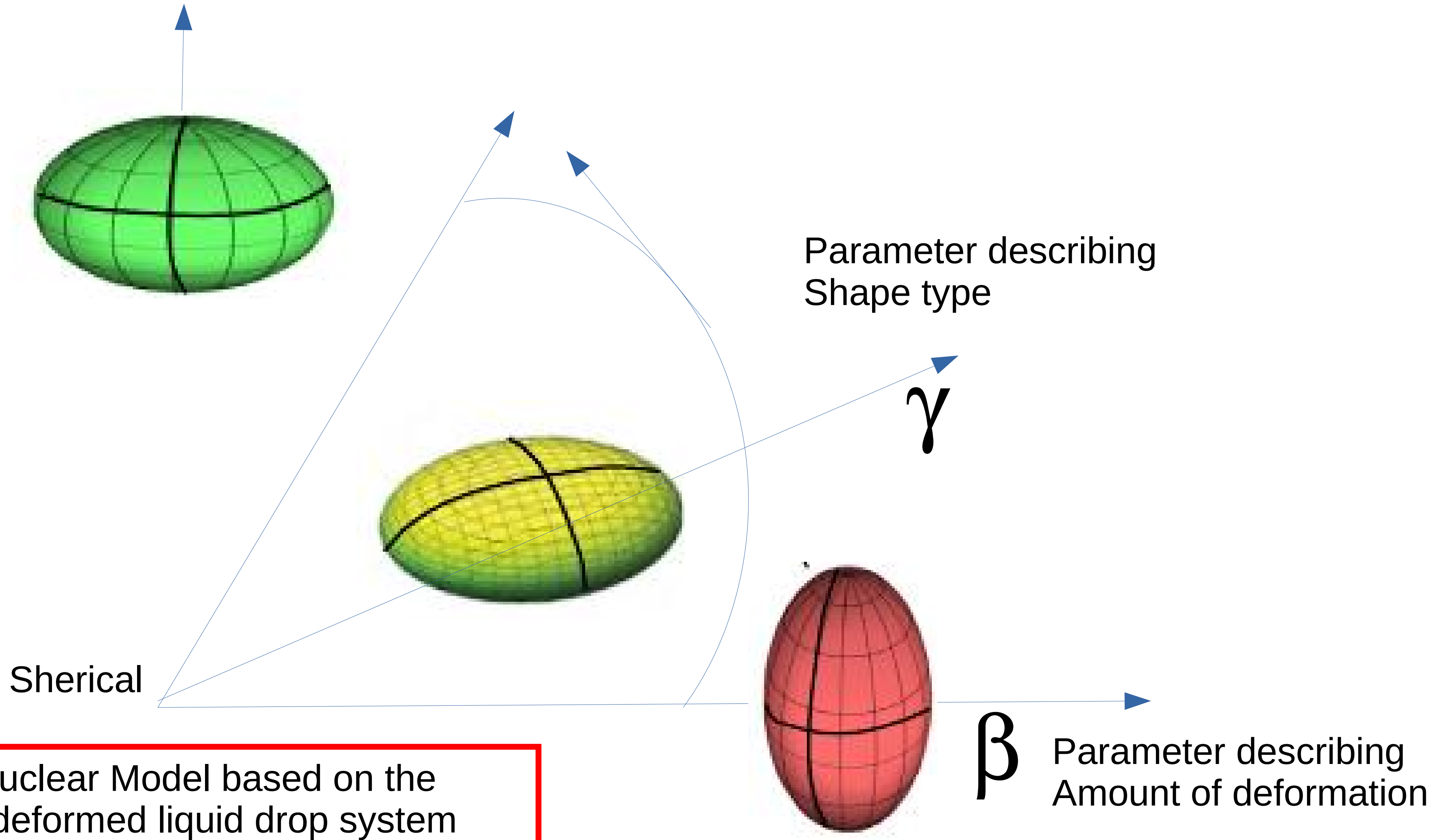
Again in analogy with chemistry

Quantum system phenomenon:
The system can assume various shapes (rearrangements of the constituents) having close energetic levels. The constituents can be arranged differently



MOLECULES, ISOMERS

Nuclear Shape in two parameters
(for the class of quadrupole deformation)

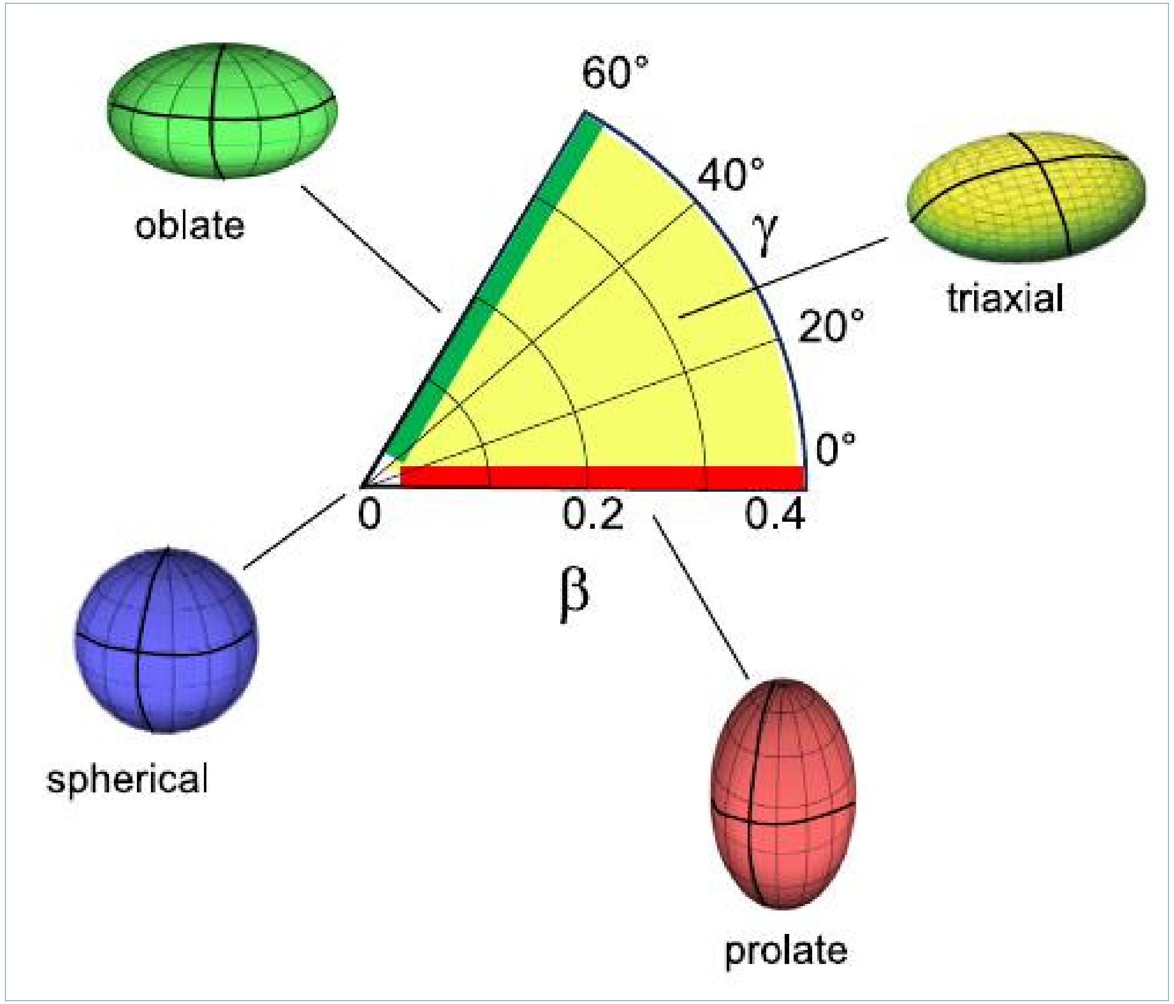


Semiclassical nuclear Model based on the analogy with a deformed liquid drop system

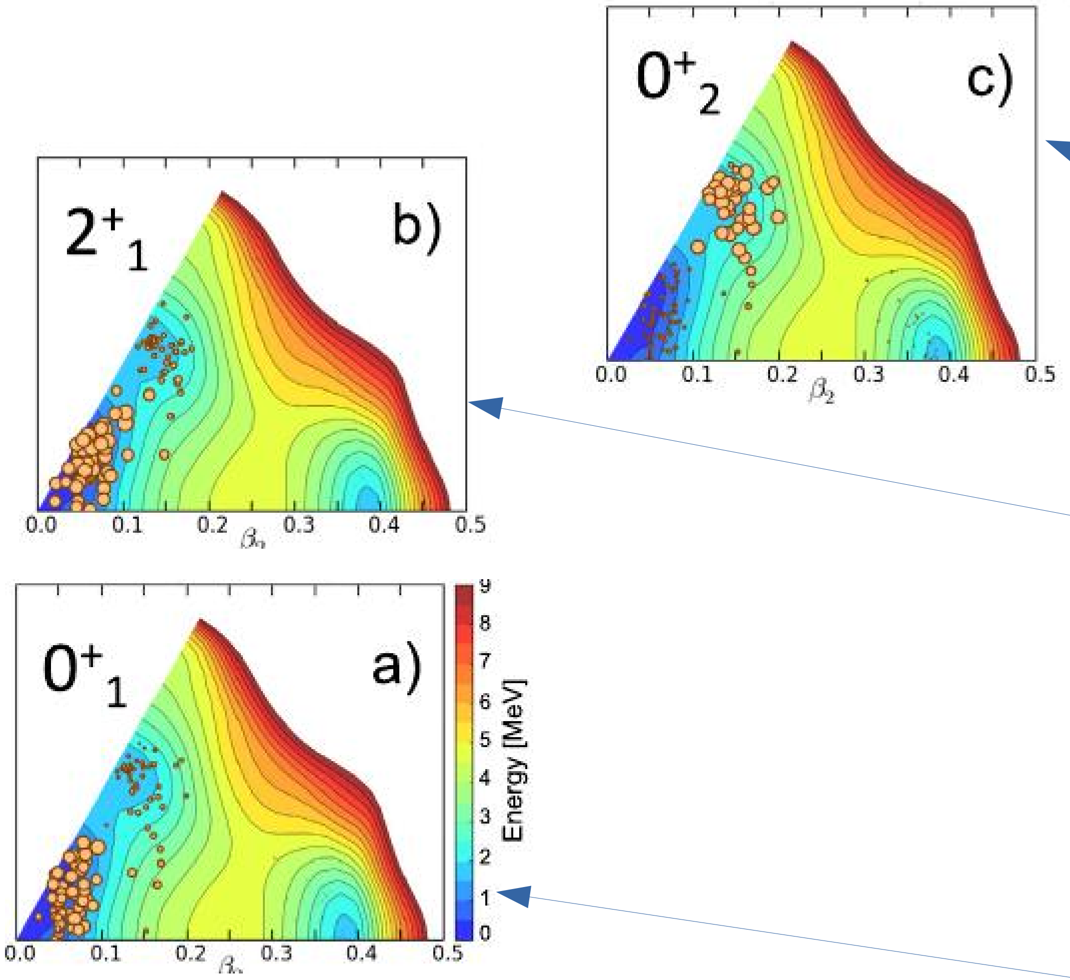
Shape Coexistence in nuclei
the discovery in the ‘70s

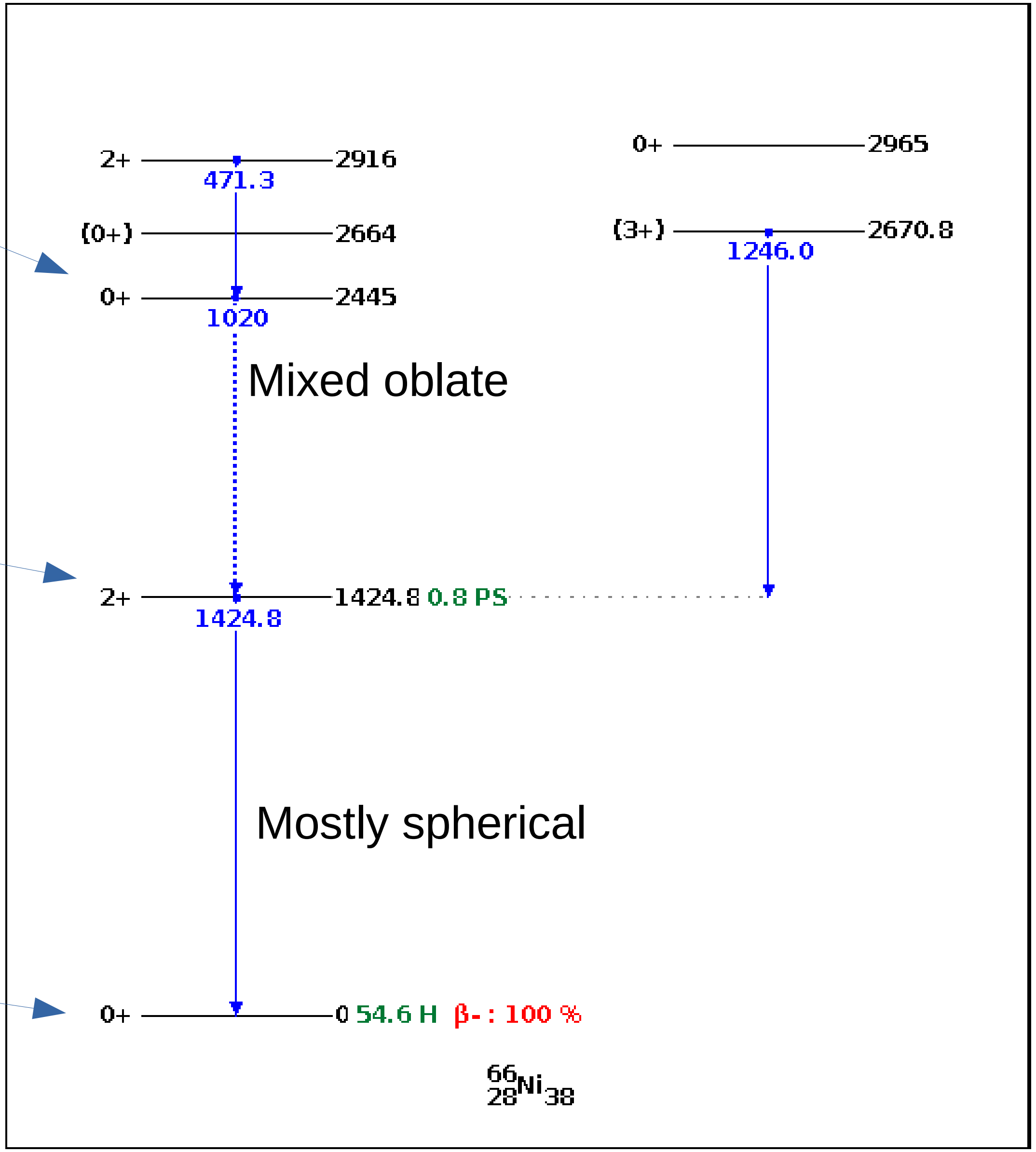
At ISOLDE-CERN, the study of neutron deficient **Hg and Pb** isotopes, showed this new facet of nuclear structure

Similarly, **Kr isotopes** were soon found to present almost *degenerate* (i.e. same energy) prolate and oblate configurations



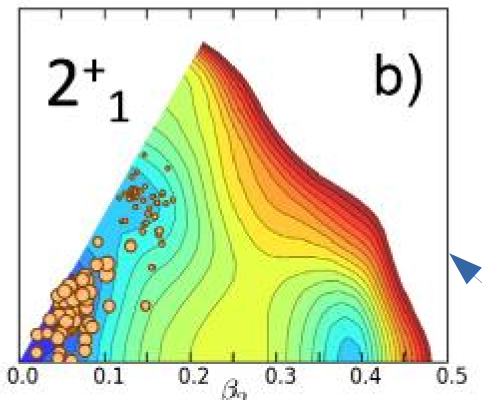
The example of $^{66}_{28}Ni$ (unstable)

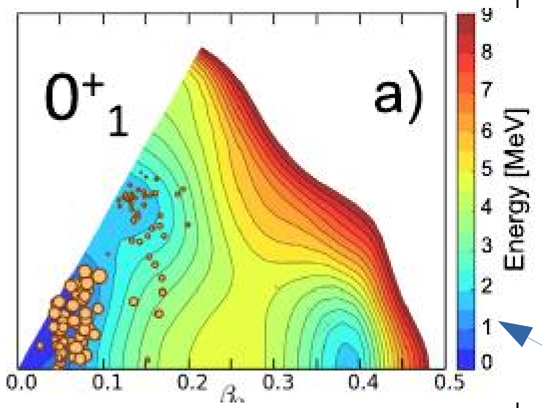


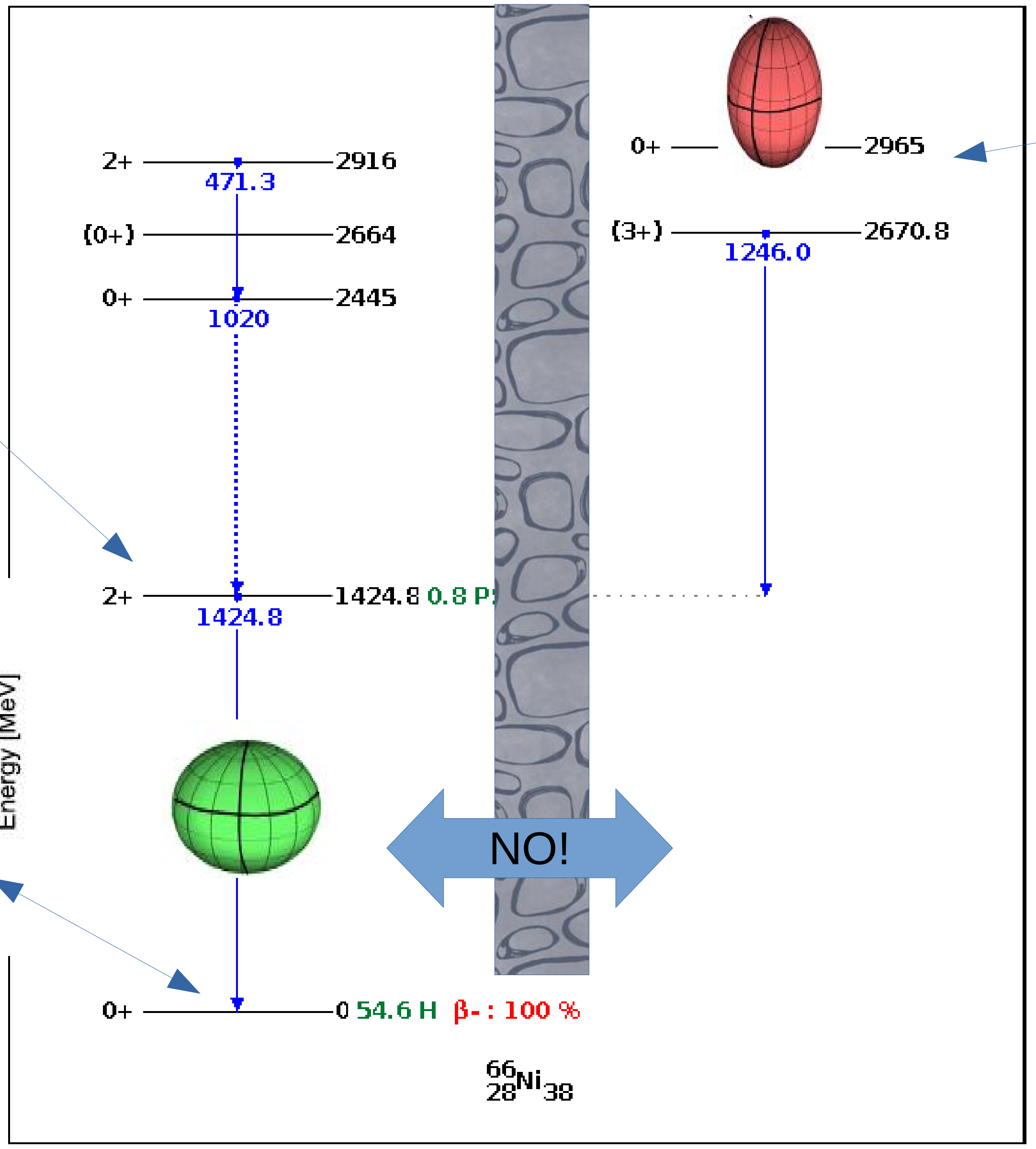


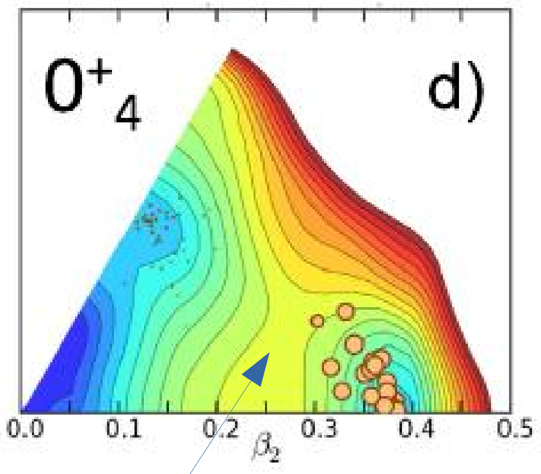
At the ground state an almost spherical shape energy band is found

The example of ^{66}Ni (unstable)





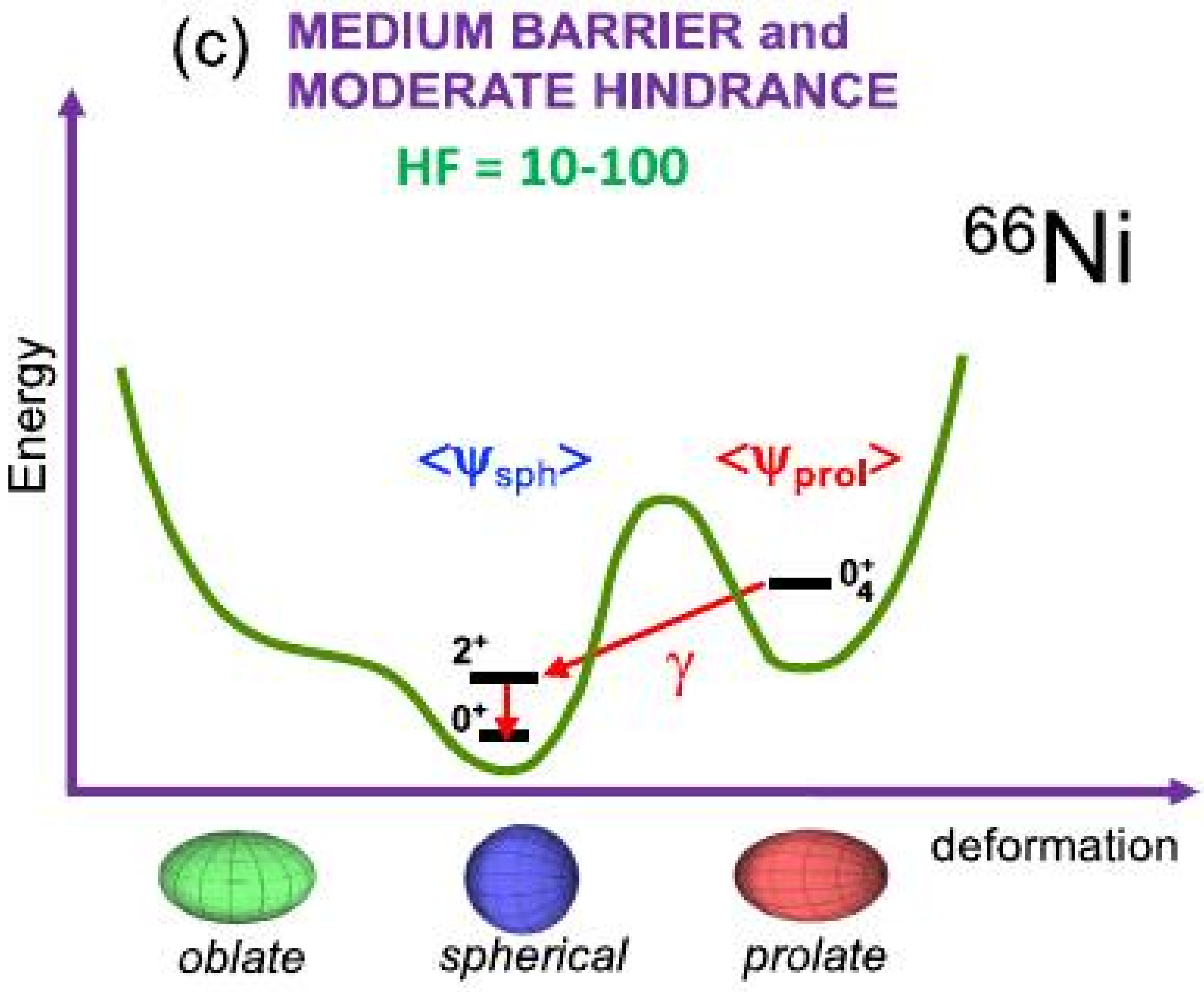


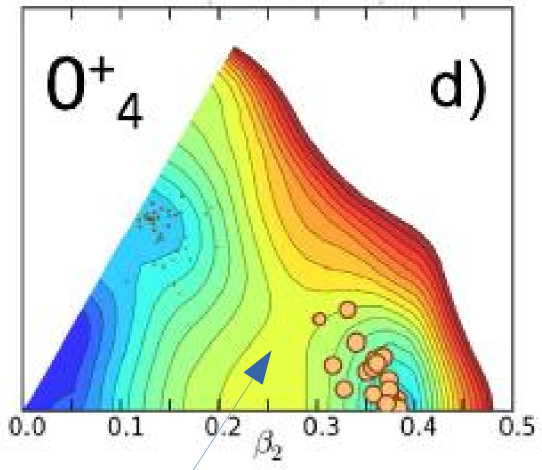


You must climb the barrier if you would go from spherical to prolate

Transitions from different shape bands are strongly suppressed

The example of ^{66}Ni (unstable)





You must climb the barrier if you would go from spherical to prolate

Transitions from different shape bands are strongly suppressed

A very rich information exploring the "canyon" slope

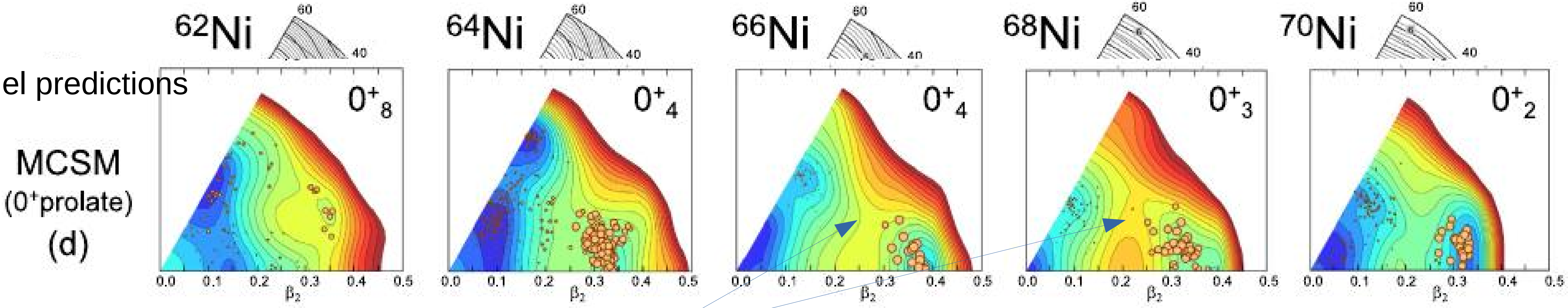
Even-even
$_{28}$Ni chain

Unstable isotopes

Stable isotopes

54h | 29 s | 6 s

Model predictions



Developping the barrier in deformed excited 0+ band

(MCSM = MonteCarlo Shell Model)

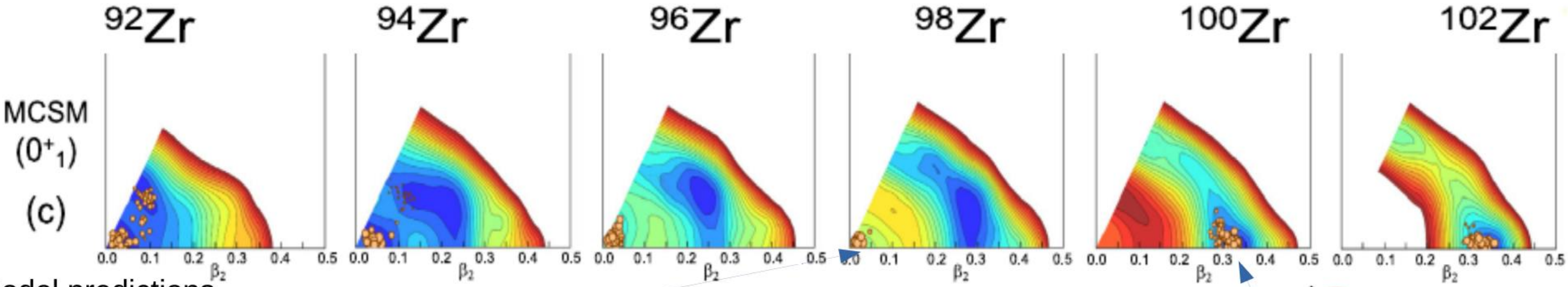
A very rich information exploring the “canyon” slopes

Even-even
$_{40}$Zr chain

Unstable isotopes

31 s 7 s 2 s

Stable isotopes

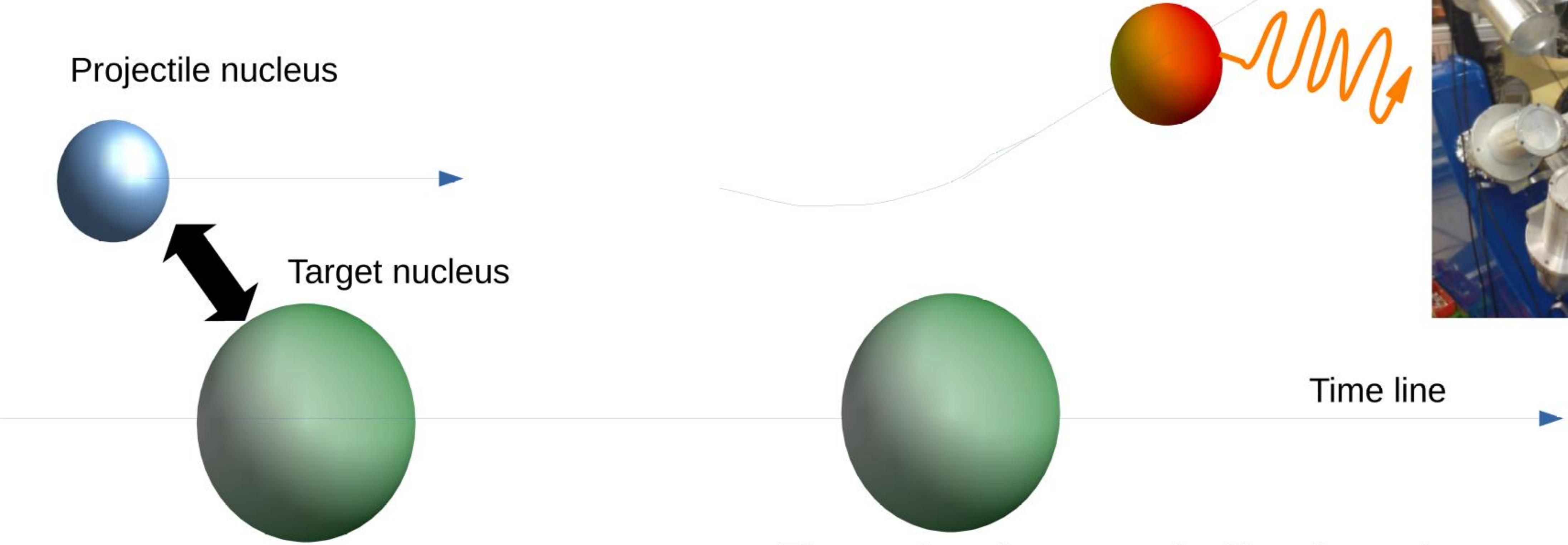


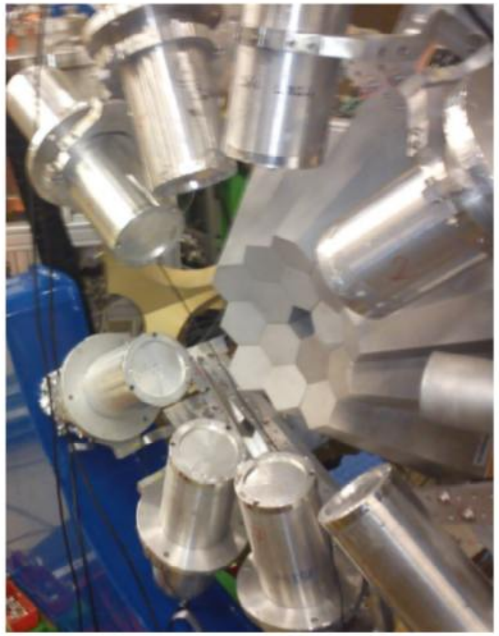
Model predictions

Sudden change of the shape of first excited 0+ level with increasing neutron number

Coulomb Excitation:
nuclear electric fields to gently excite nuclei

An excellent experimental technique also for **SPES**

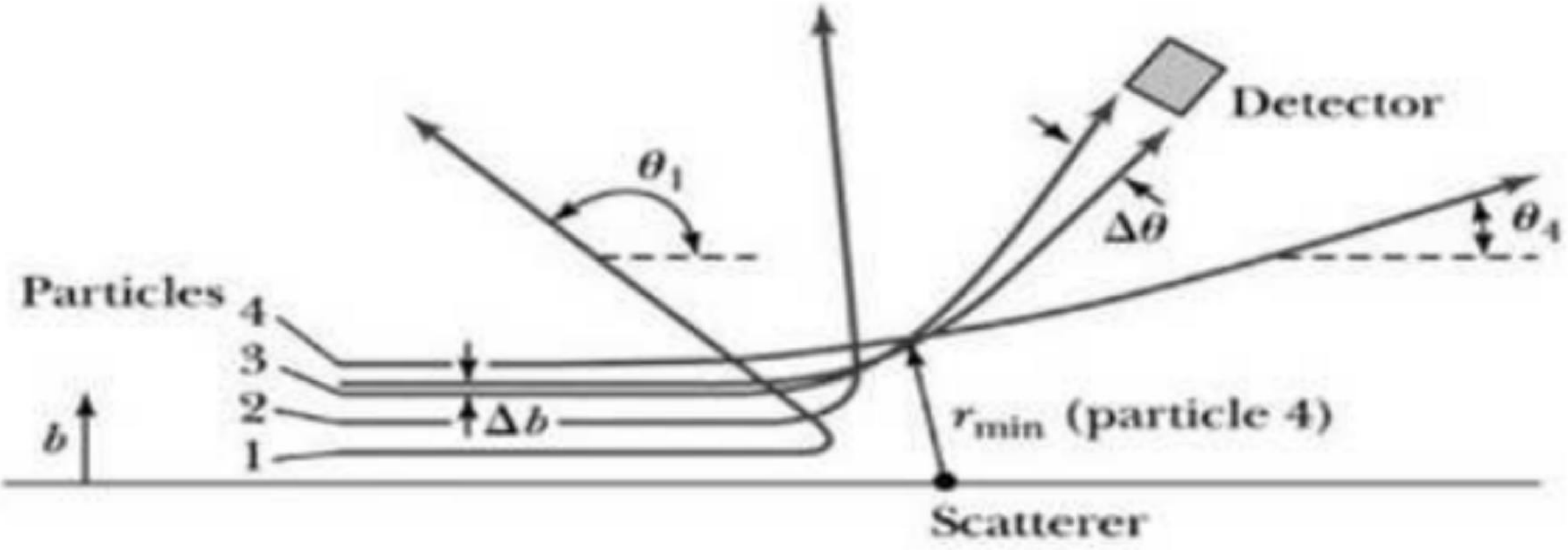




Far distance:
Coulomb interaction only

The nucleus is not a point like charge but a complex system
It gets excited and one studies its decay to ground state

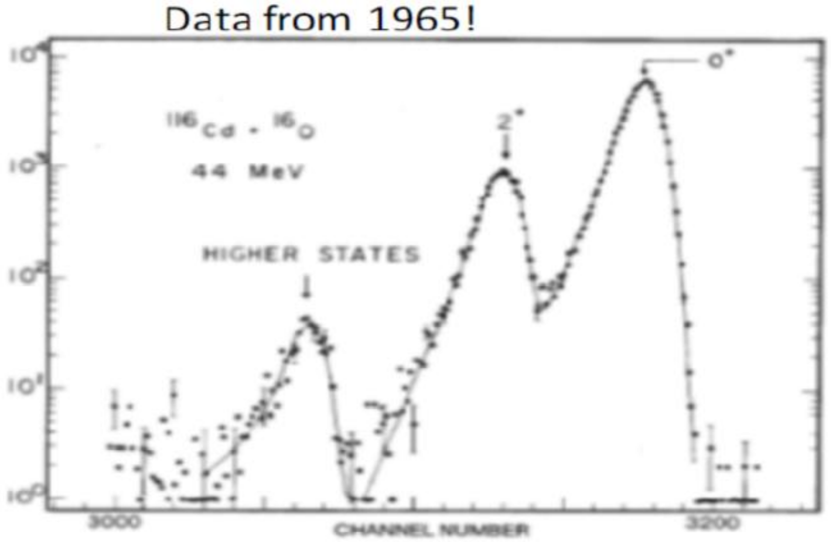
Coulomb Excitation:
nuclear electric fields to gently excite nuclei



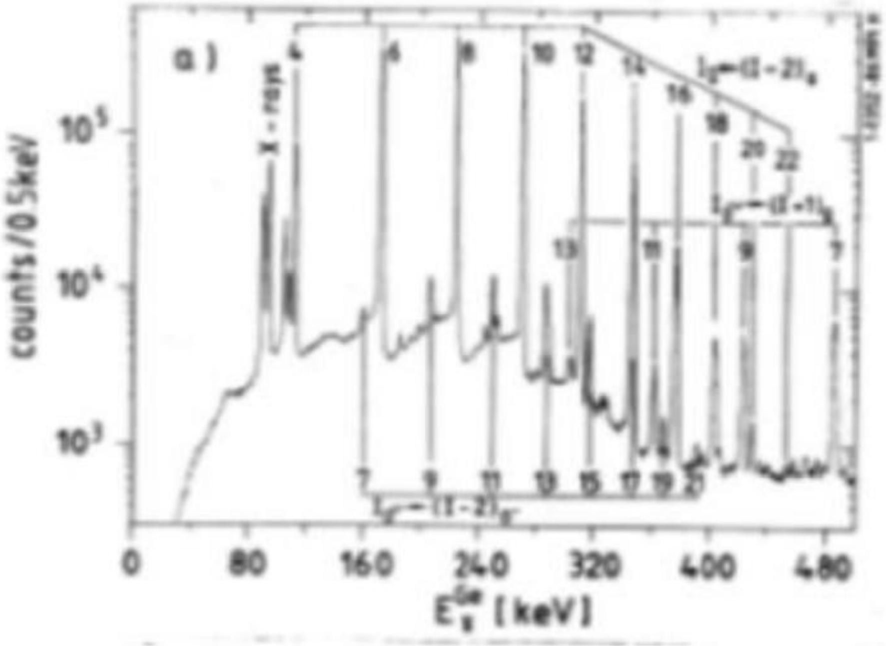
Far distance:
Coulomb interaction only

The projectile is not a point like charge but a complex system
It gets excited and one studies its decay to ground state

Coulomb Excitation with stable light beams



- First experiments ('60)
- light (and stable) ion beams
- Spectrometers
- no gamma-detectors



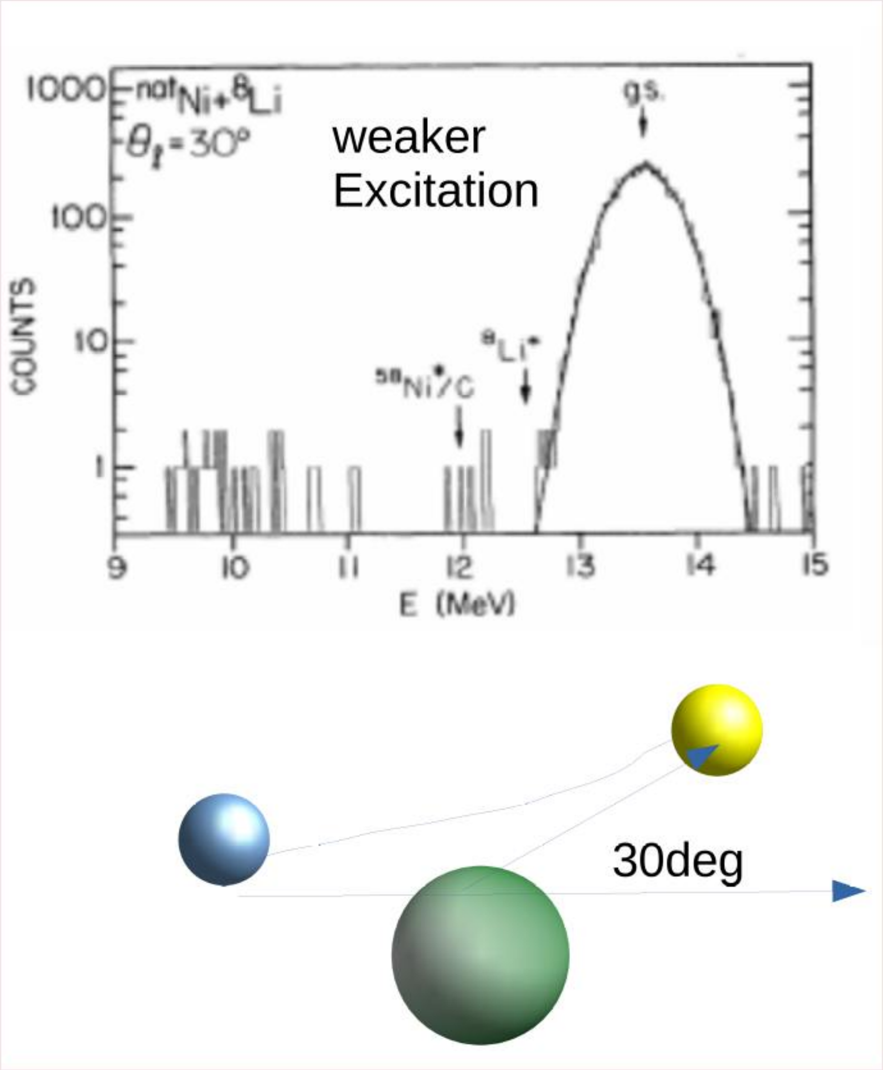
- Experiments from the '70s
- Also Germanium gamma-detectors
- excellent gamma-E resolution
- unprecedented details of nuclear structure

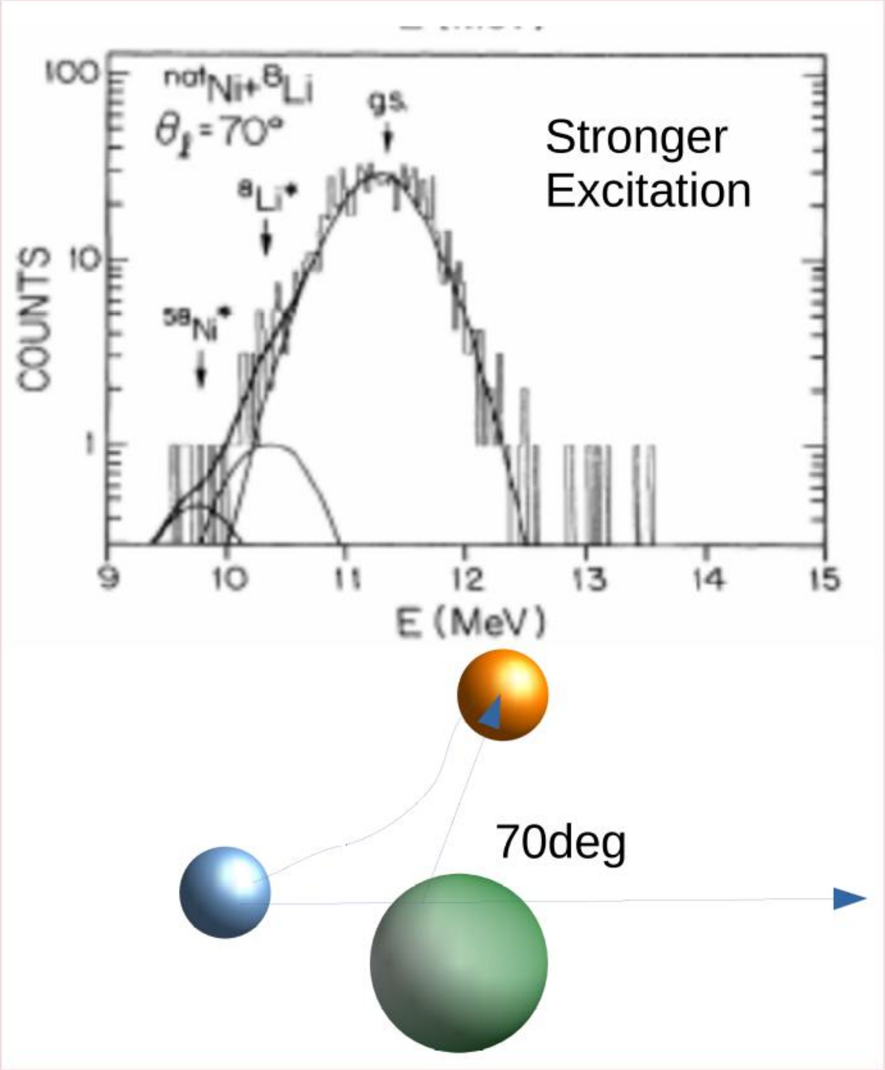
Coulomb Excitation
1991: first experiment with unstable ions

J.A. Brown
FIRST EXPERIMENT WITH a Radioactive beam (USA)
8Li from n-pickup of 7Li on a thick Be target

^{8}Li+^{nat}Ni at 15 MeV

- T1/2 for 8Li=870 ms
- NO GAMMA DETECTOR
- ONLY DEFLECTED Lithium was detected

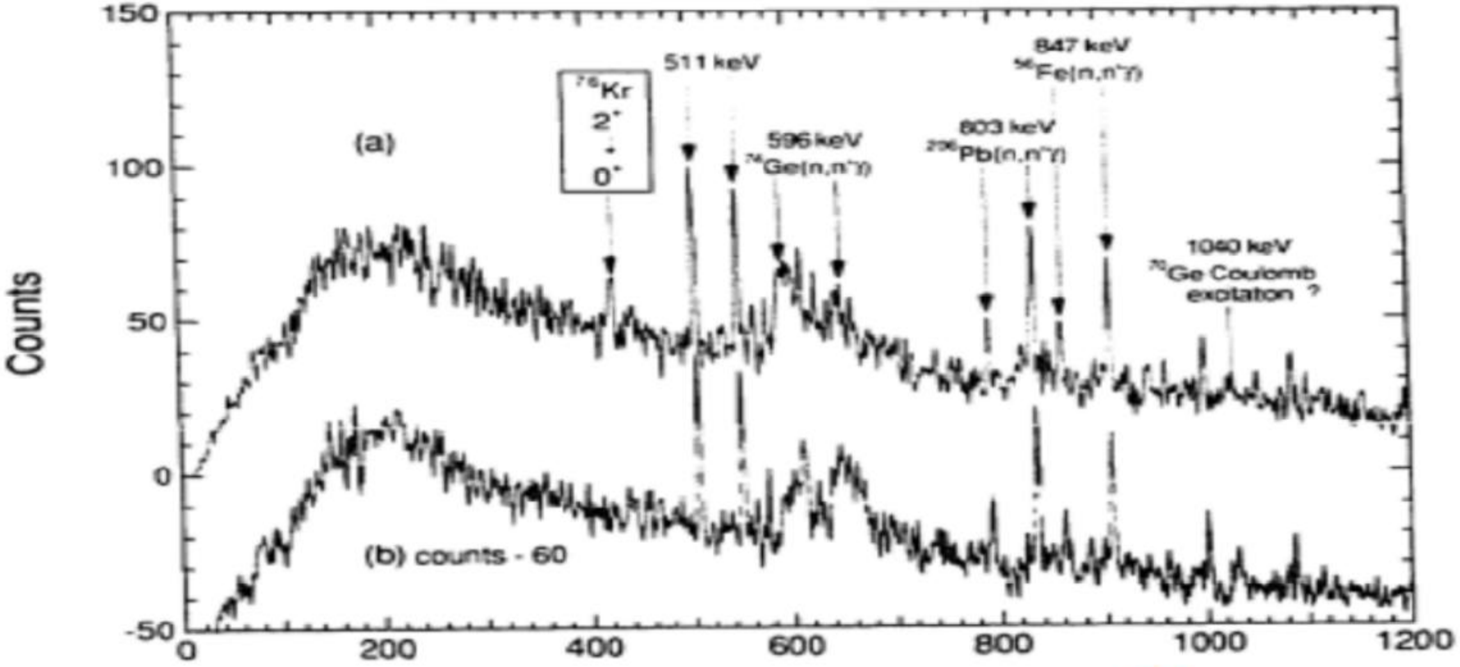


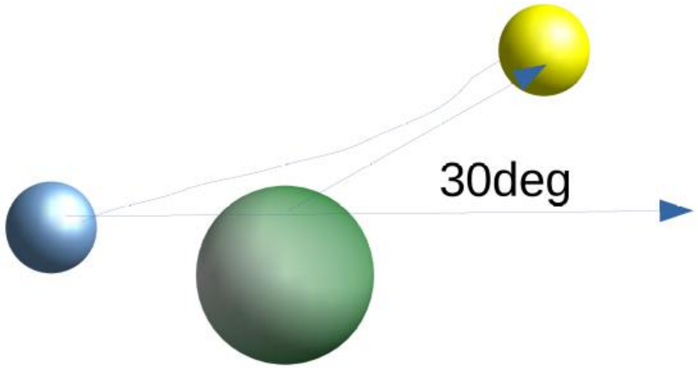


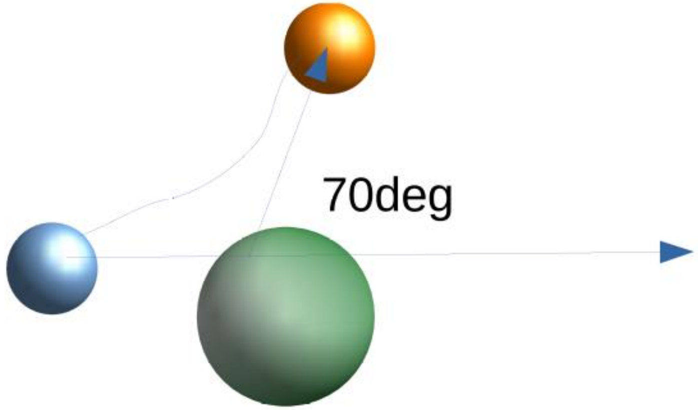
Coulomb excitation:
1992: exotic beams, gamma and particle detectors

M.Oshima
FIRST EXPERIMENT WITH a Radioactive beam AND GAMMA DETECTOR (JAPAN)

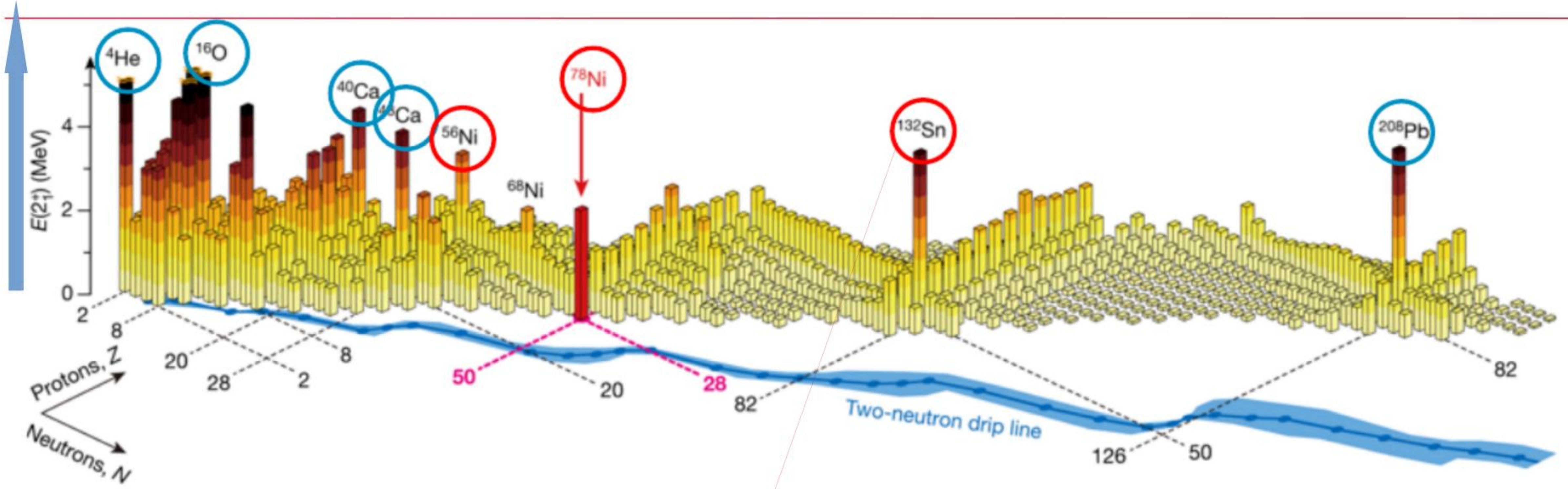
^{76}**Kr** from 3n-stripping of 70Ge on a thick Be target







Coulomb excitation:
a strong method to explore the canyon



tor

- For double-magic nuclei the gap of the 2+ excited state and g.s. is large
- nuclei are in this case spherical

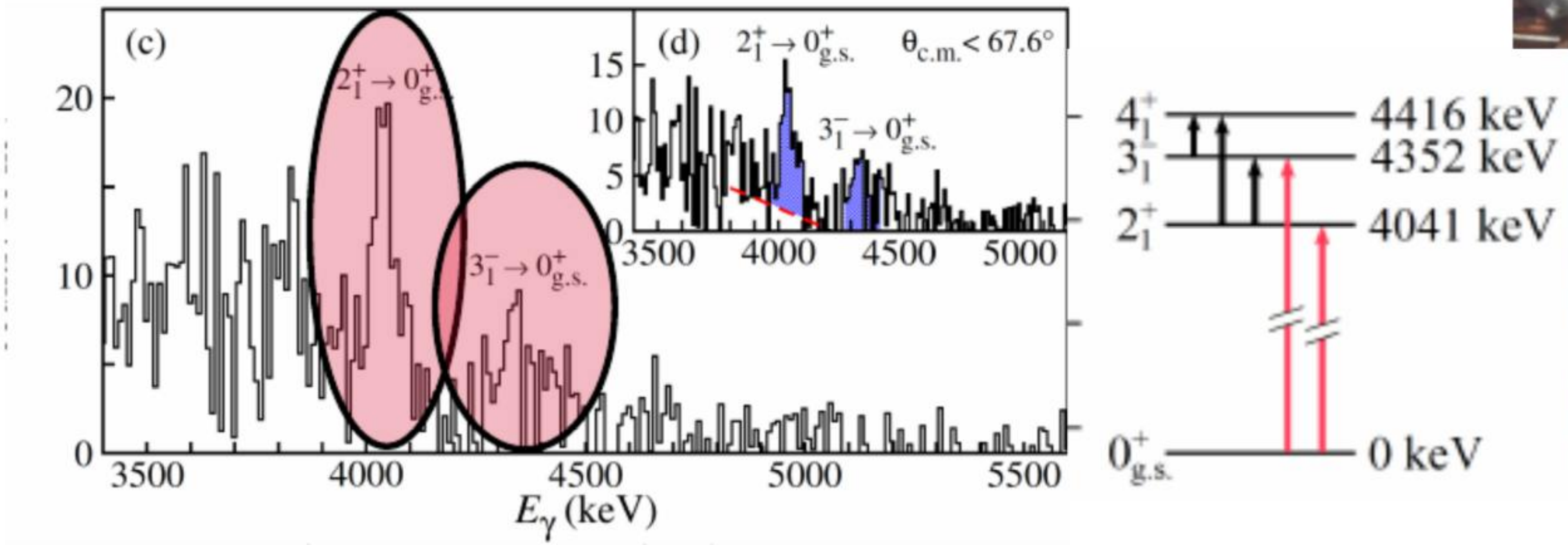
  BUT:
- Is this still valid towards the n-drip line?
- The ‘reference’ case of **132Sn** (also at SPES)

The reference case of ^{132}Sn (also at SPES)

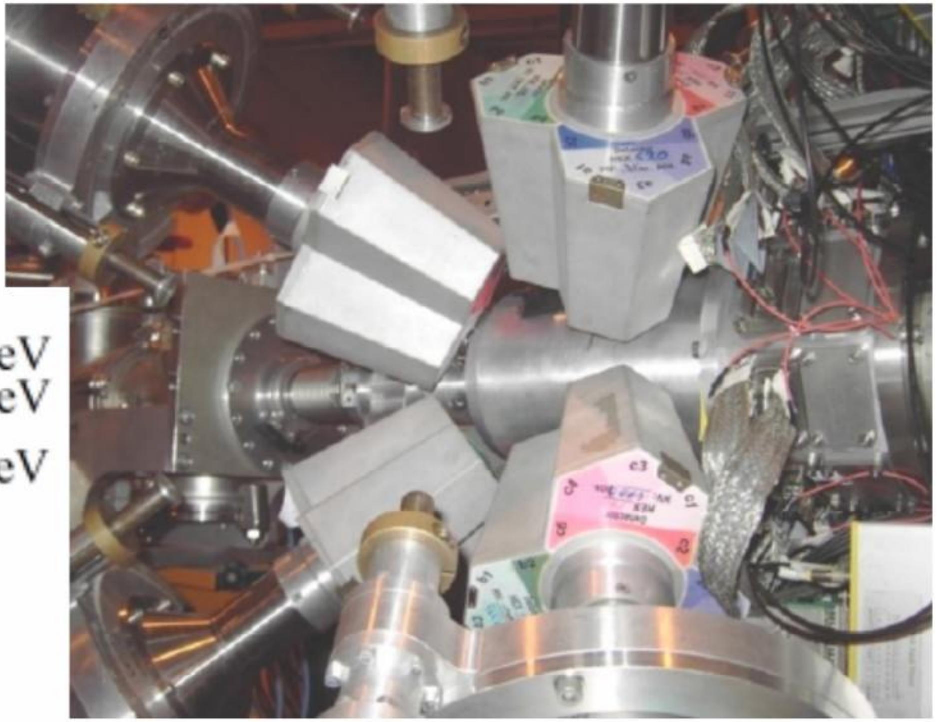
- First study at ISOLDE with the MINIBALL array
- Very good experiment published in 2018

Low energy Coulomb excitation

$^{206}Pb + ^{132}Sn^{31+}$ @ 5.49 MeV/u



MINIBALL Gamma detector @ CERN



- First determination of the lowest energy level of 132Sn
- Comparison with Shell model advanced calculations
- Strong hint to confirm the spherical shape
- Still low statistics
- Rather big background of contaminants

A top-10 physics case for the SPES facility promising high-rate and high-purity ^{132}**Sn** beam at right energy

Some References and credits

1 Kosai Tanabe and Kazuko Sugawara-Tanabe
Top-on-top mechanism and the electromagnetic transitions for the triaxial strongly deformed bands in odd mass nuclei
2 Tommaso Marchi, INFN LNL
Presentation of the LNL delegation at PSI, Suisse, july 2025
3 Marco Rocchini, INFN FI
Presentation of the Gr3 nuclear phys group, CdS Firenze, june 2025
4 Andrea Jungclaus
Single particle versus collectivity, shapes of exotic nuclei https://link.springer.com/article/10.1140/epjp/i2016-16059-9
5 Isaho Tanihata
Nuclear Physics with RIB's: How it all started https://link.springer.com/article/10.1140/epjp/i2016-16090-x
6 *N.S. Martorana 2023 J. Phys.: Conf. Ser. 2586 012149*
7 *P. Russotto 2024*
8 *W. Korten – AGATA – The Advanced Gamma Tracking Array - CPAN Days october 2019*
9 *W. Von Oertzen Eur. Phys. J. A 11, 403–411 (2001)*
10 *M. Kimura Eur. Phys. J. A (2016) 52: 373*
11 *Y. Blumenfeld Physics 15 177 2022*

Conclusions

Heavy and SuperHeavy nuclei

Unknown regions for Young researchers

Proton drip line

Valley of Stability

Neutron Drip line

Light nuclei

The discovery of halo in nuclei

- 11Li
- Dimensions
- Weakly bound systems
- Diffuse surfaces
- New collective modes
- Strange shapes (not only spherical: pear, chain, bubble, coexistence)
- Exotic radioactivity e.g. proton decay!
- New magic numbers
- From ‘normal’ collective modes to exotic modes
- Pigmy
- Dynamical dipole

Coulomb excitation:
electric fields to gently excite nuclei

J.A. Brown 1991
FIRST EXPERIMENT WITH a Radioactive beam (USA)
8Li from n-pickup of 7Li on a thick Be target

8Li+Ni at 15MeV

Strong actual interest: perfect technique for ISOL laboratories

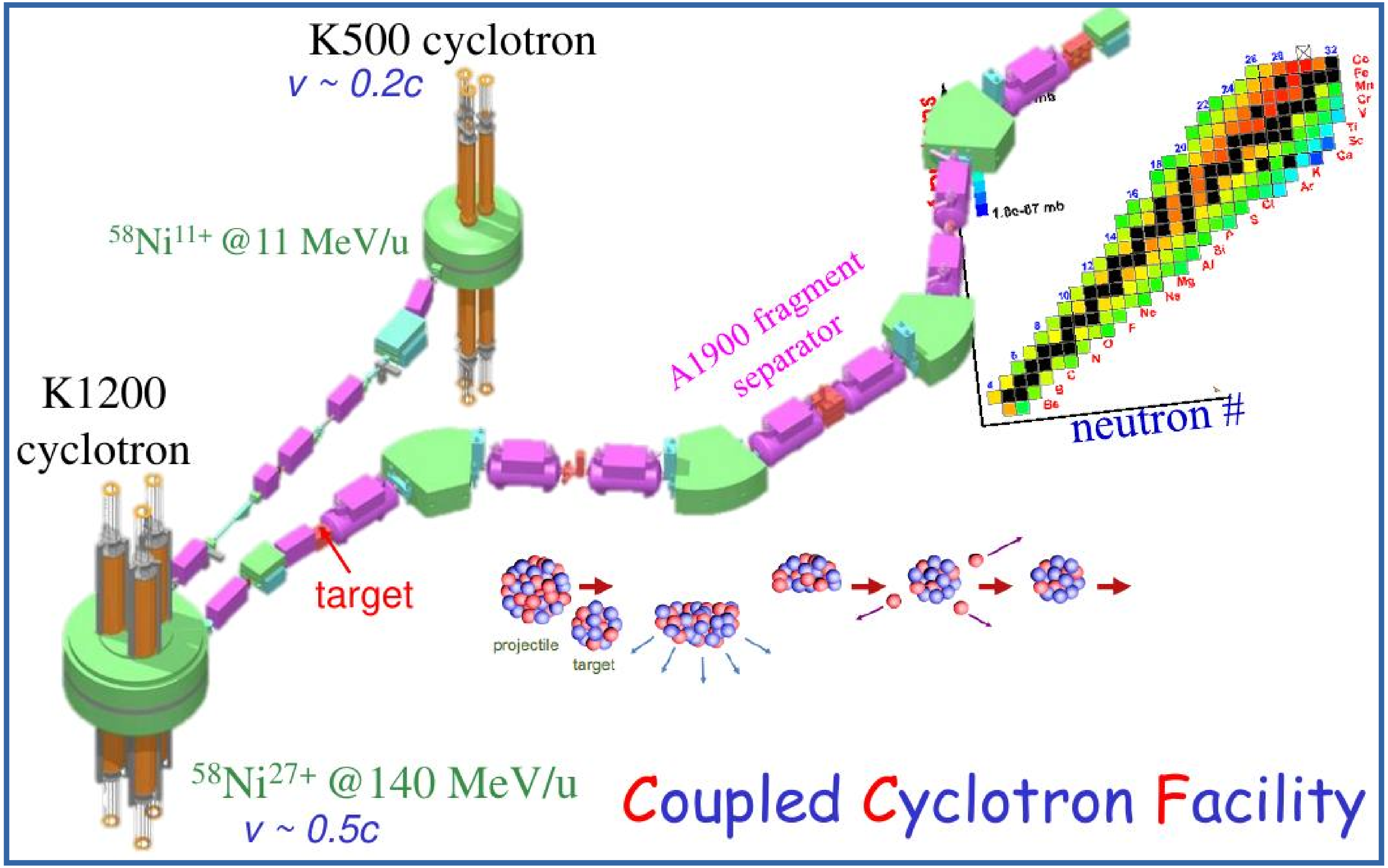
ISOL: low energy beams
ISOL: pure beam species (low contamination)
ISOL: suitable beam (even low) currents, CE has large cross sections

OPTIMUM experimental conditions to investigate more the nuclear structure far from the stability line (“climb the canyon cliff”)

OF COURSE:
The more you climb the more you suffer! (low statistics, large isotopic contaminations, less robust complementary information)

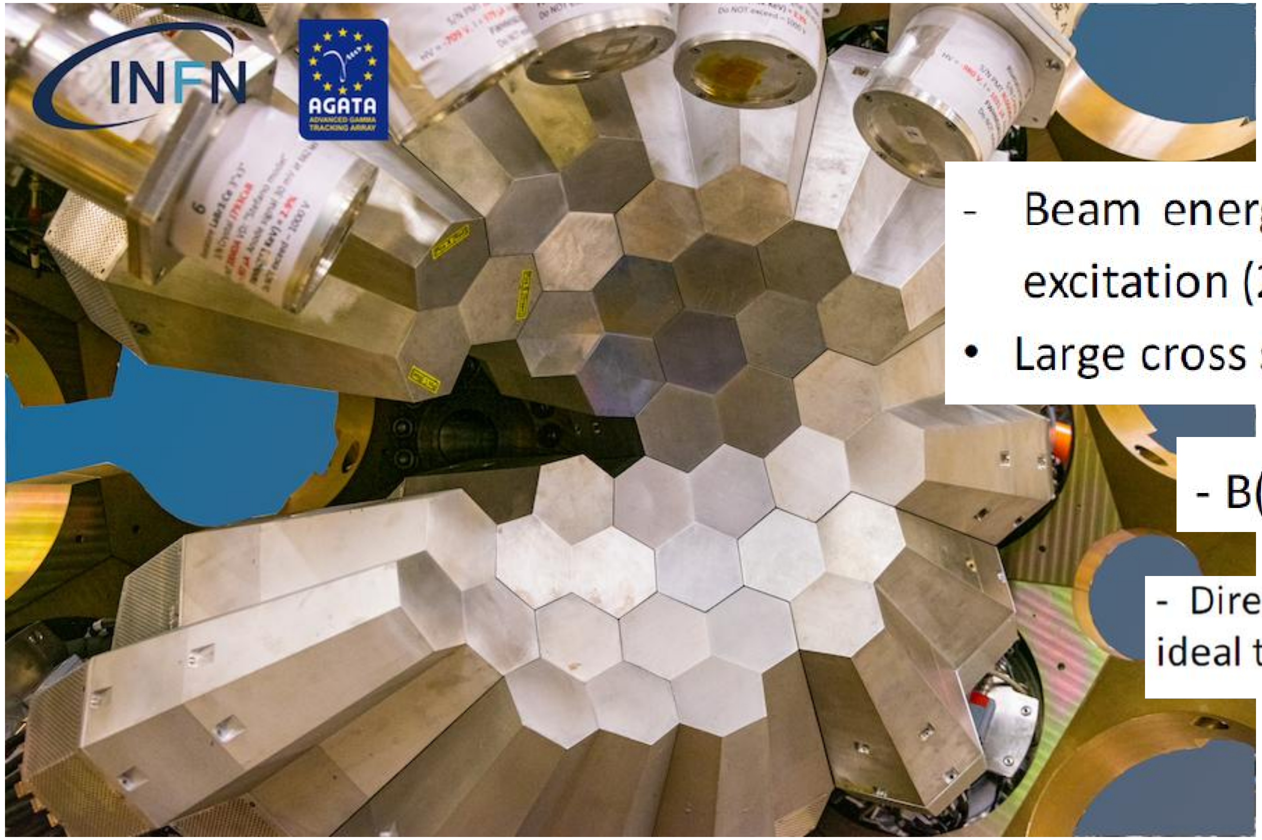
Collectivity in nuclei
Shape coexistence

Example of IF facility NSCL (USA)



Se serve vedi
Btsang nella
cartella talk
nusym15
DeAngelis
vitainfn/csn3/2017
Prete
vitainfn/cns3/
lns2017

Gamma side



Coulomb excitation
Vedi indico page feb 2025, Firenze

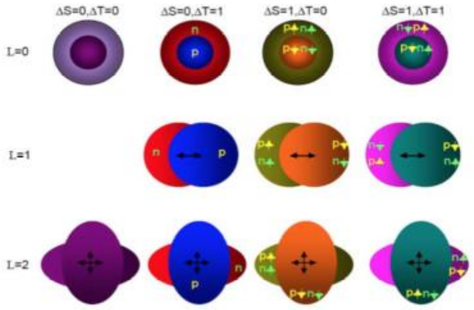
- Beam energies available at ISOL facilities perfect for Coulomb excitation (2-5 MeV/A)
- Large cross sections (excitation of 2^+_1 ~ barns)

- B(E2) transition probabilities – measure of collectivity

- Direct measurement of quadrupole moment including sign – ideal tool to study shapes and shape coexistence

GMR study: Physics Motivation

Giant Resonances in Exotic Nuclei

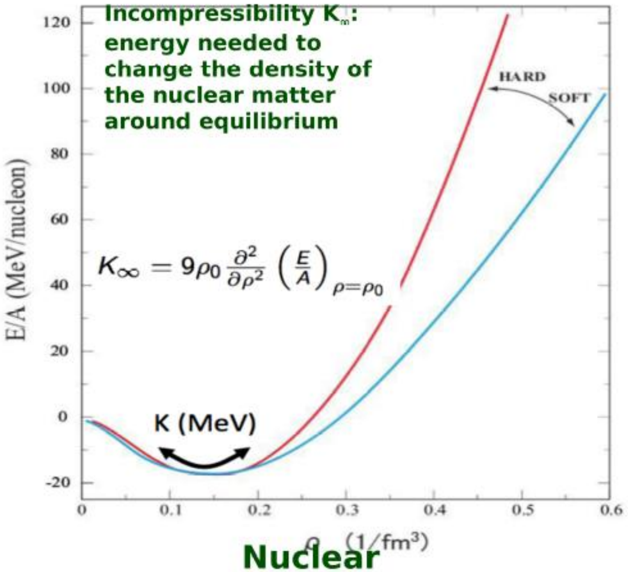


Constrain the Nuclear Matter Equation of State

Investigation of the GMR

$$E_{GMR} = \hbar\sqrt{\frac{K_A}{m < r^2 >}}$$

its energy is directly related to the compressibility of nuclear matter ($K\infty$)



Nuclear incompressibility

$$K_A = K_\infty + K_{surf}A^{-1/3} + K_\tau\delta^2 + K_{Coul}\frac{Z^2}{A^{4/3}}$$

Nucleus (mass A) — *Nuclear Matter* — *Isospin Dependence*

K_τ = -500 ± 100 MeV

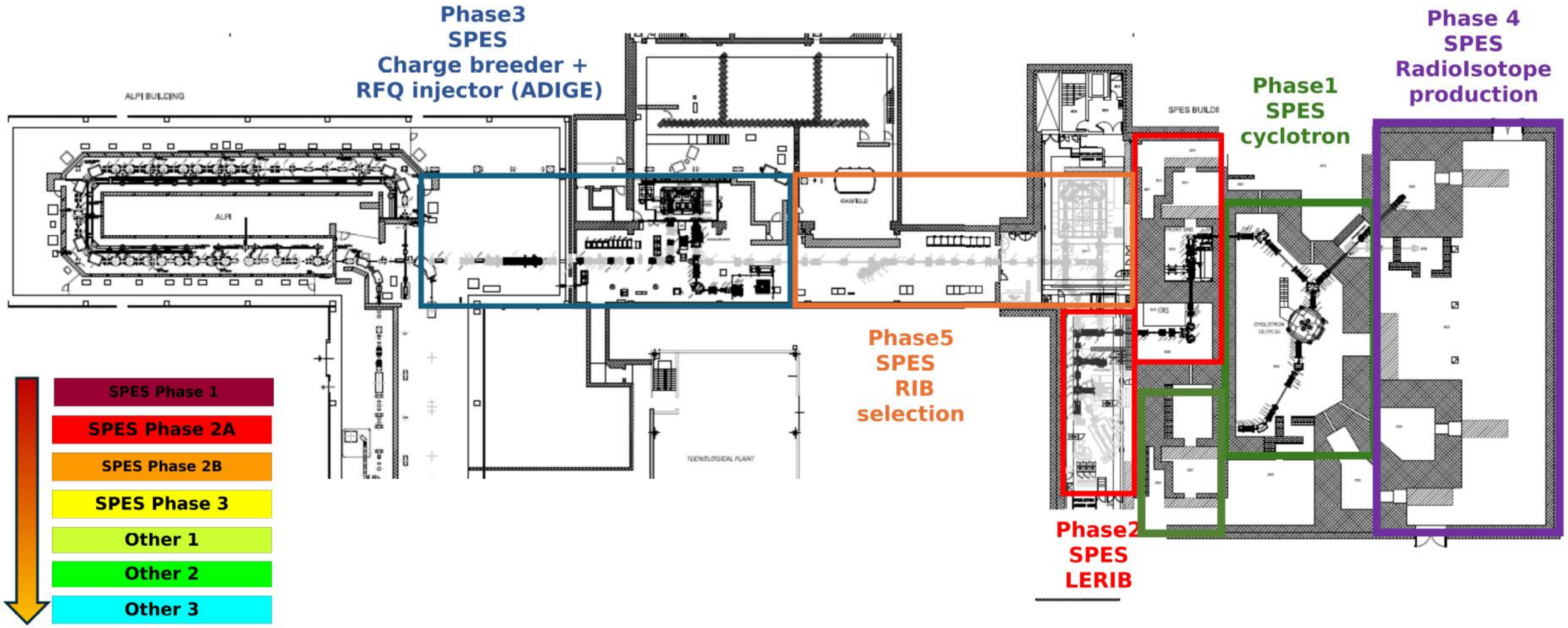
T. Li, U. Garg et al., Phys. Rev. C 81, 034309 (2010)

K_∞ = 240 ± 10 MeV

J. Li, G. Colò and J. Meng, Phys. Rev. C 78, 064304 (2008)

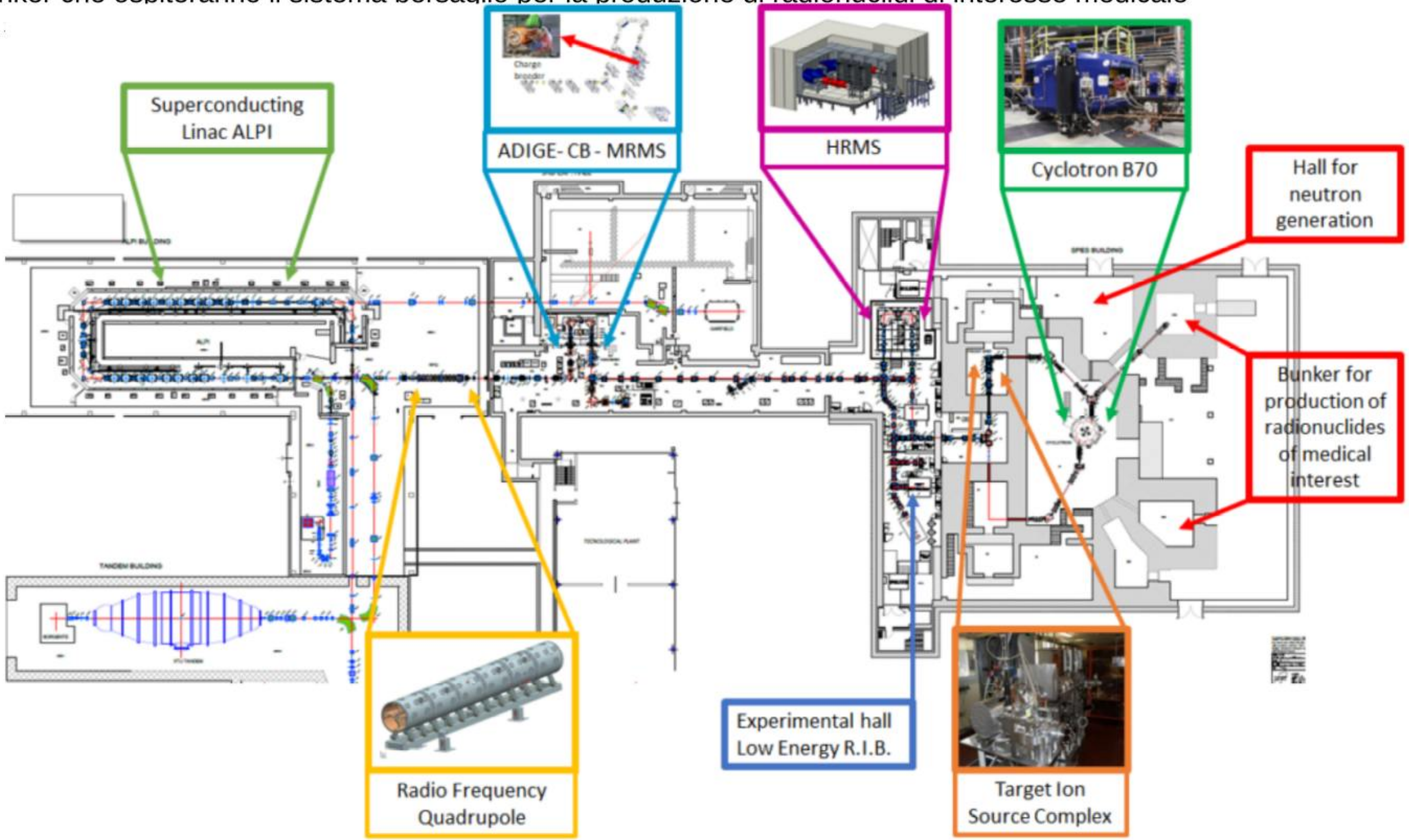
Part of this uncertainty is due to our poor knowledge of the Isospin dependence K_τ

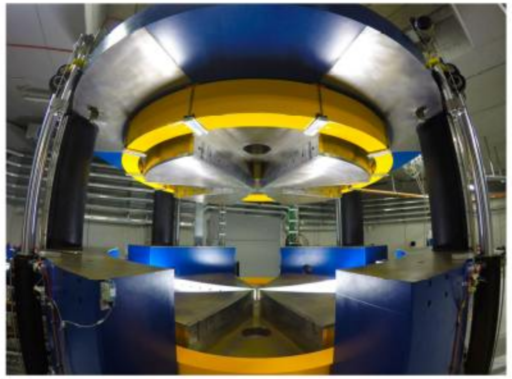
SPES – Phased Approach



SPES, LNL

a sala sperimentale per gli esperimenti con fasci di ioni radioattivi non riaccelerati (Low Energy R.I.B.)
o Spettrometro di massa ad Alta Risoluzione HRMS per la separazione di massa dei fasci di ioni radioattivi
niettore ADIGE, che comprende lo Spettrometro di massa a Media Risoluzione MRMS e il Charge Breeder
per l'aumento dello stato di carica
fasci di ioni radioattivi
RFQ (Radio Frequency Quadrupole) per la preaccelerazione dei fasci di ioni radioattivi
acceleratore lineare superconduttivo ALPI per l'accelerazione dei fasci di ioni radioattivi
bunker che ospiteranno il sistema bersaglio per la produzione di radionuclidi di interesse medicale
a





B70 cyclotron
150 tons
Proton beams up to 0.75mA
Energy 20-70 MeV
Max power 52kW

The discovery of halo in nuclei

- 11Li
- Dimensions
- Weakly bound systems
- Diffuse surfaces
- New collective modes
- Strange shapes (not only spherical: pear, chain, bubble, coexistence)
- Exotic radioactivity e.g. proton decay!
- New magic numbers
- From ‘normal’ collective modes to exotic modes
- Pigmy
- Dynamical dipole

Coulomb excitation:
still a stimulating method

J.Henderson and others PRL 2025

The strange case of lead (208Pb) which is the heaviest DM nucleus
Confirmed shape deformation (prolate dominant) in double-magic nuclei
No model reproduces this so strong behaviour
Why unexpected? Because magic nuclei (and more double magic one) are particularly stable and supposed to spherical