DE LA RECHERCHE À L'INDUSTRIE

SHE factory at France

13 September 2021

Barbara Sulignano

Why to study SHE elements

- We can ask ourself if it is it worth studying superheavy nuclei considering the money, especially when those atoms are inherently unstable.

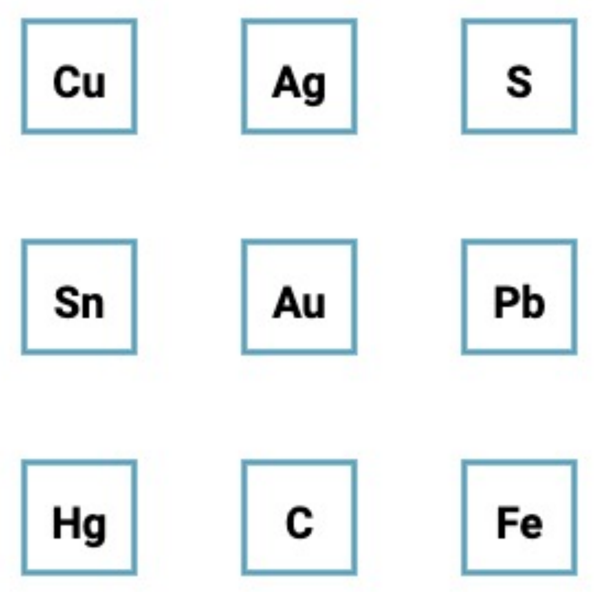
Yes… studying those nuclei we can learn so many things for example:

- How do nucleons organize themselves into an atomic nucleus?
- What are the forces that hold them together?
- How do nuclei and particles participate in the evolution of the Universe?

OUTLINE

- How many elements exists ?
- How to produce them ?
- How to produce them today
- What do we need to overcome the limits
- How to go heavier and heavier

Ancient Times



https://vis.sciencemag.org/periodic-table/

Middle Ages

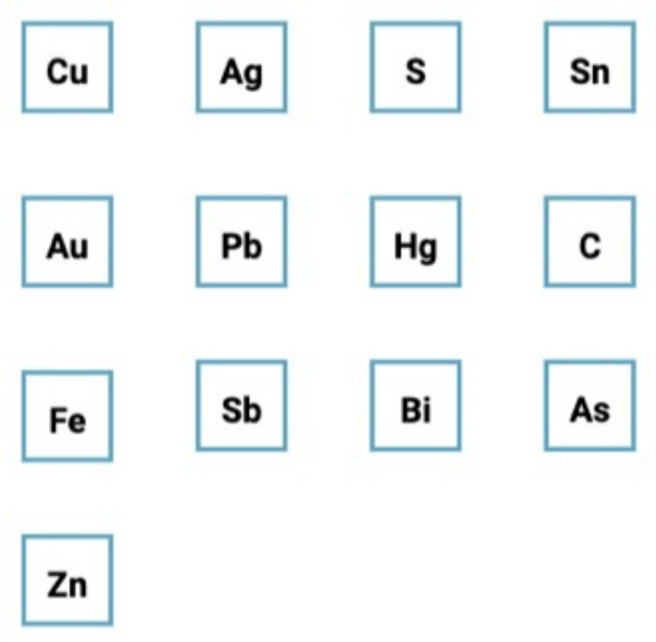


Table of isotopes

1789 Antoine Lavoisier

"Table of Simple Substances"

It was just one long column

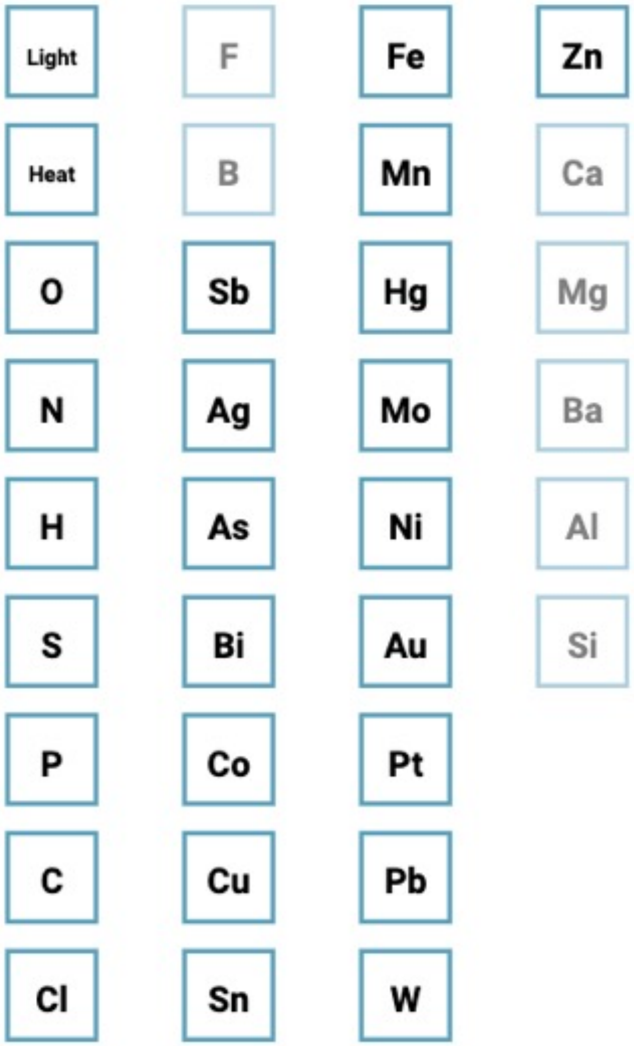


Table of isotopes

1945 Glenn Seaborg

The adventure remaining was synthesis of the short-lived radioactive elements, most of them heavier than actinium.

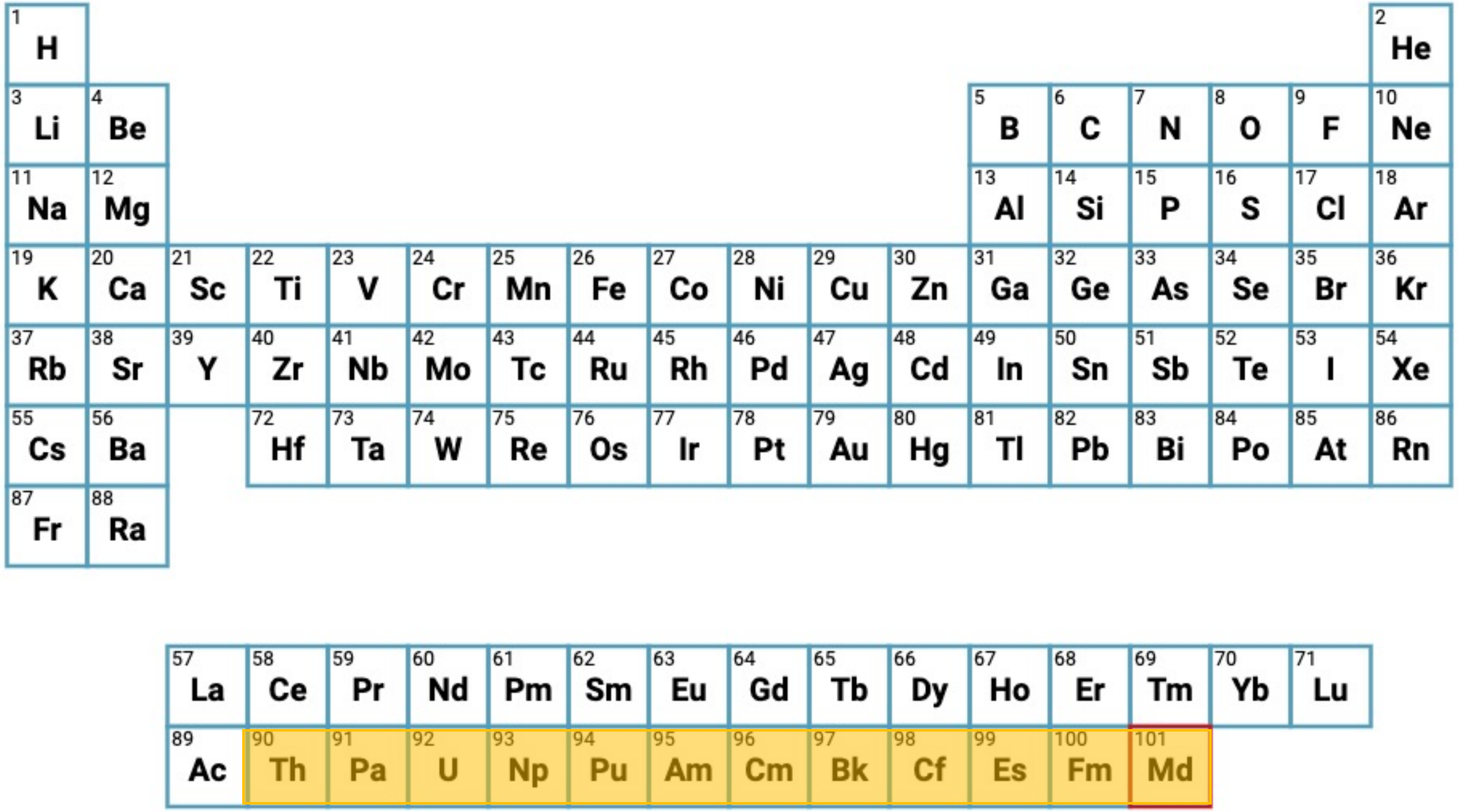
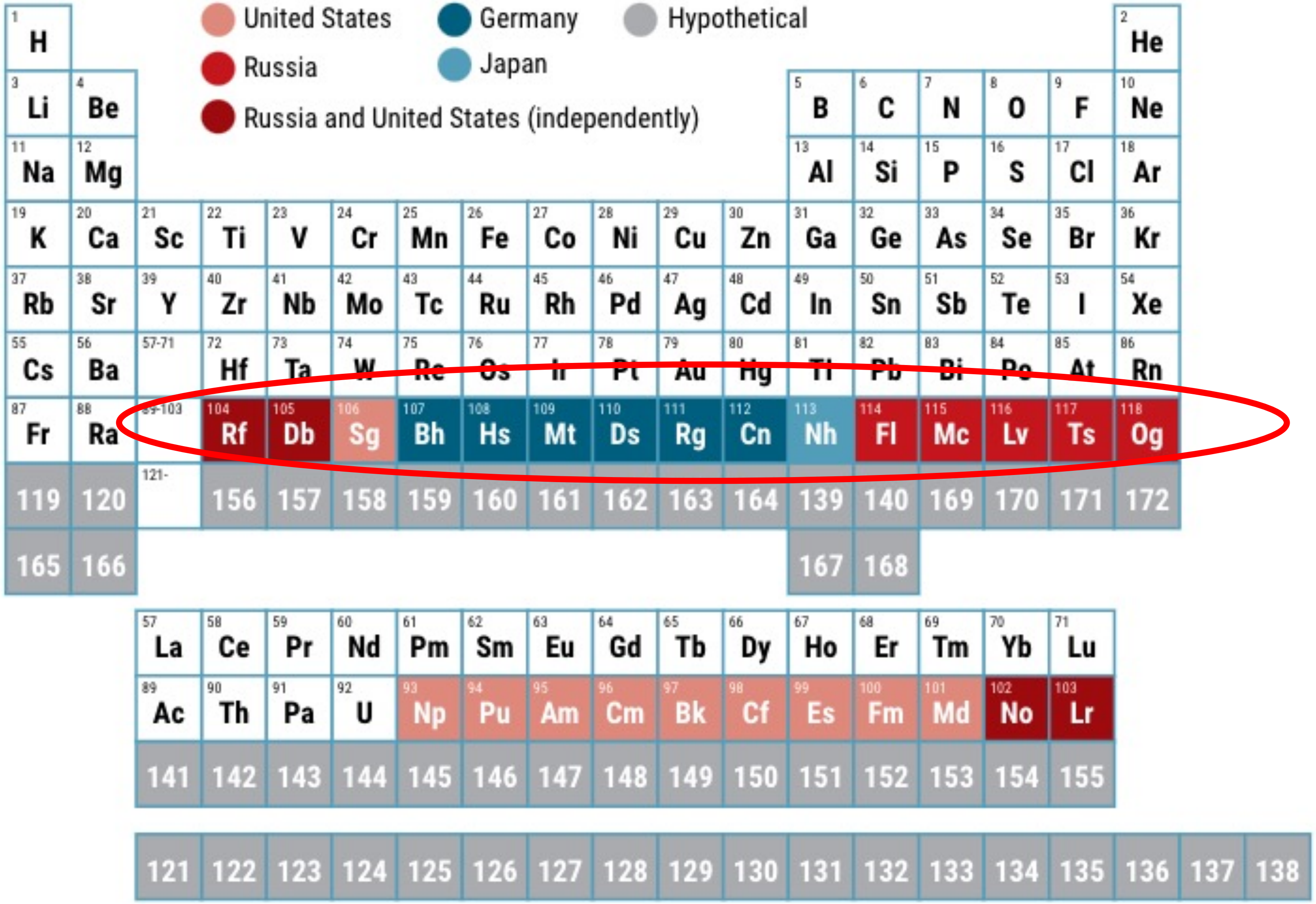


Table of isotopes

1958- 2016

- The current layout of the periodic table was finally settled in 2016.
- Physicist are working to push into an hypothetical eight row of the table of isotopes.

SHE includes elements 104 and beyond



See W. Lopez Martens's talk – GDR RESASANT

OUTLINE

- How many elements exists
- **How to produce them**
- How to produce them today
- What do we need to overcome the limits
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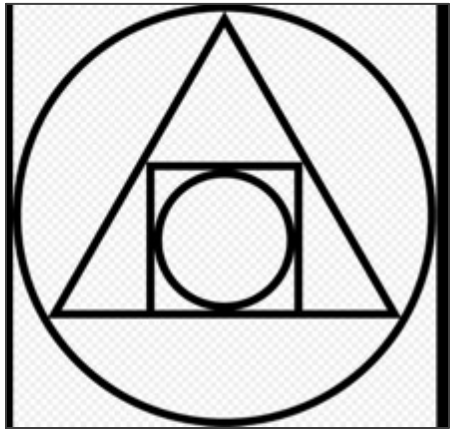
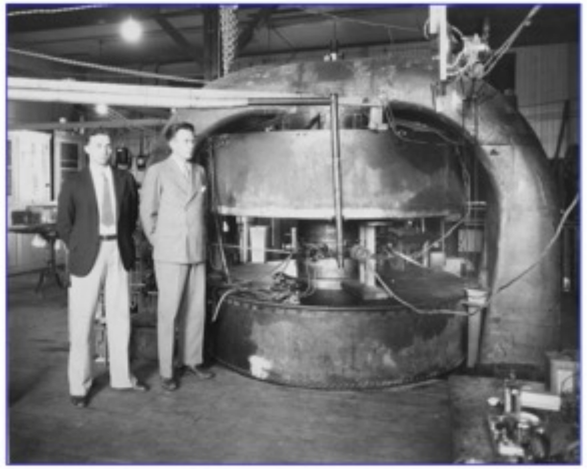
How we may produce SHE

- Medieval alchemists dreamed of turning lead (base metals) into gold, of transmuting one element into another with the help of the **philosopher's stones.**



- In modern time very heavy elements were first produce via nuclear reaction or investigating products from nuclear explosion.



Livingston and Lawrence, 27'' cyclotron

see Ch. Theisen's talk – GDR RESASANT

- How many elements exists
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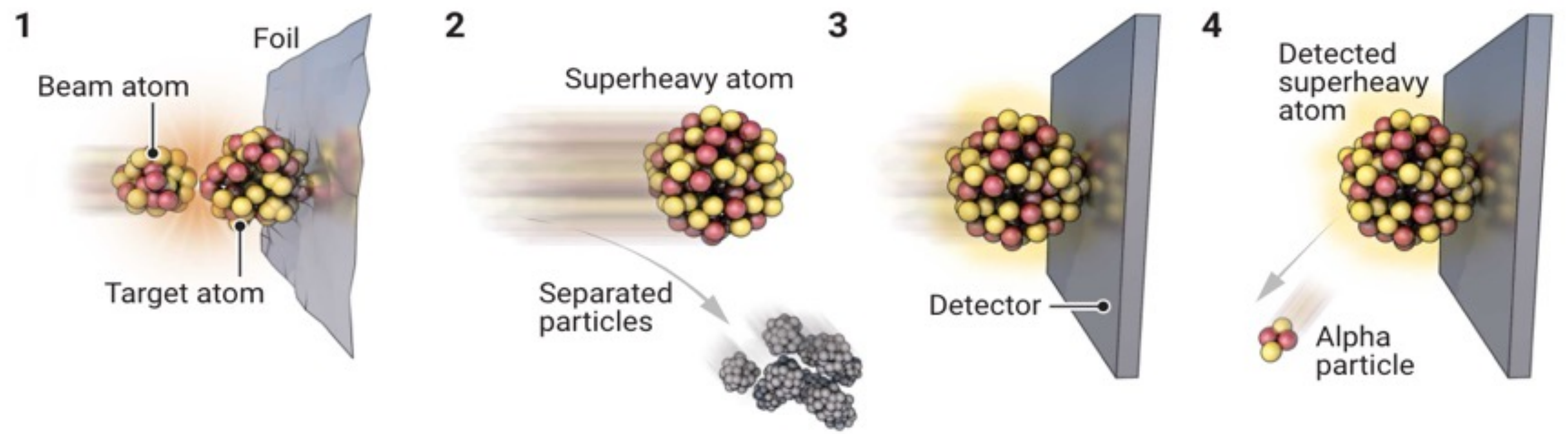
How to produce them today

SHE are synthesized one atom at a time in heavy ion-induced nuclear fusion reactions

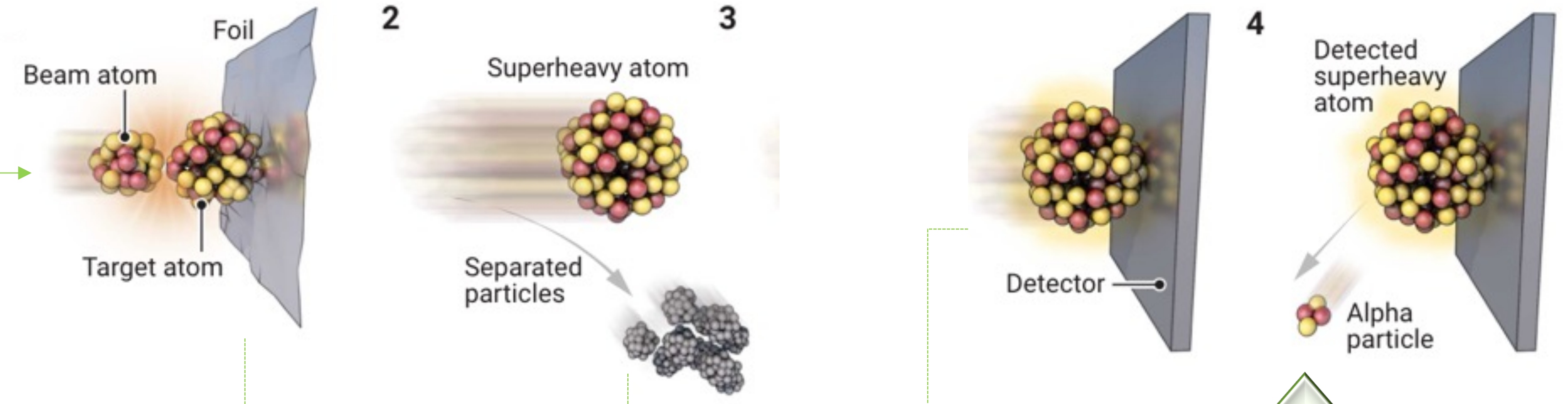
Beam atom



A projectile nucleus is accelerated	Bombard a target nucleus	The resulting superheavy atom flies through separator	The superheavy atom are implanted in a detector	Where its energy and that of its decay is measured

What we need to synthetize the SHE?

Beam atom



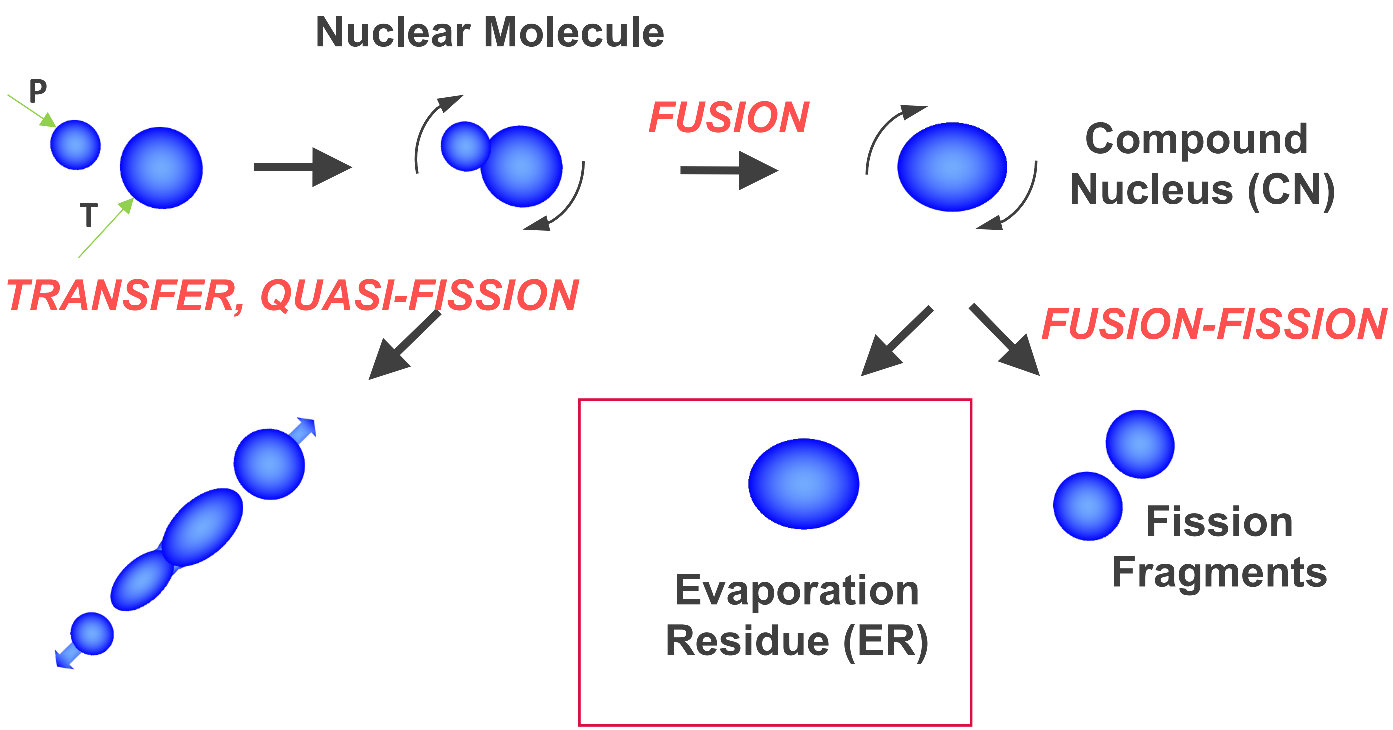
ACCELERATOR

TARGET

SPECTROMETER

DETECTOR

Why so difficult to produce SHE: Mechanism

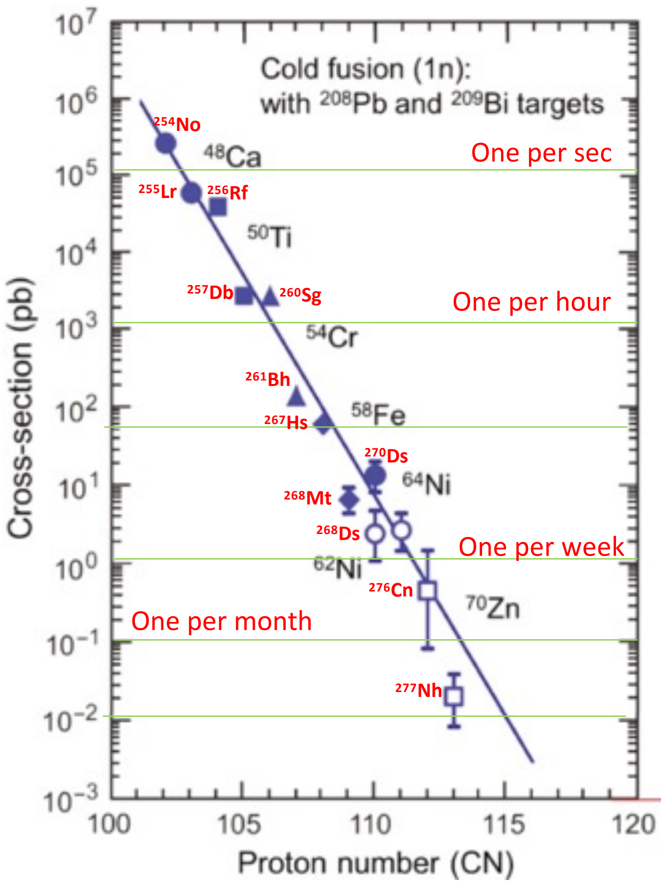


1) Collision projectile and target
2) Competition between quasi-fission and complete fusion;
3) De-excitation cascade of compound nucleus (CN) with evaporation residues (ER) and fusion-fission fragments.

- **The synthesis of SHE require to find favorable reactions (projectile and target pair)**
- **Optimal beam energy range increase the probability of ER formation**

Why so difficult to produce SHE: Cross sections

- At GSI six elements from bohrium to copernicium (107–112) were created;
- By fusion evaporation reactions using the projectiles of ^{54}Cr, ^{58}Fe, $^{62,64}Ni$ and ^{70}Zn
- Doubly magic target of ^{208}Pb and ^{209}Bi.

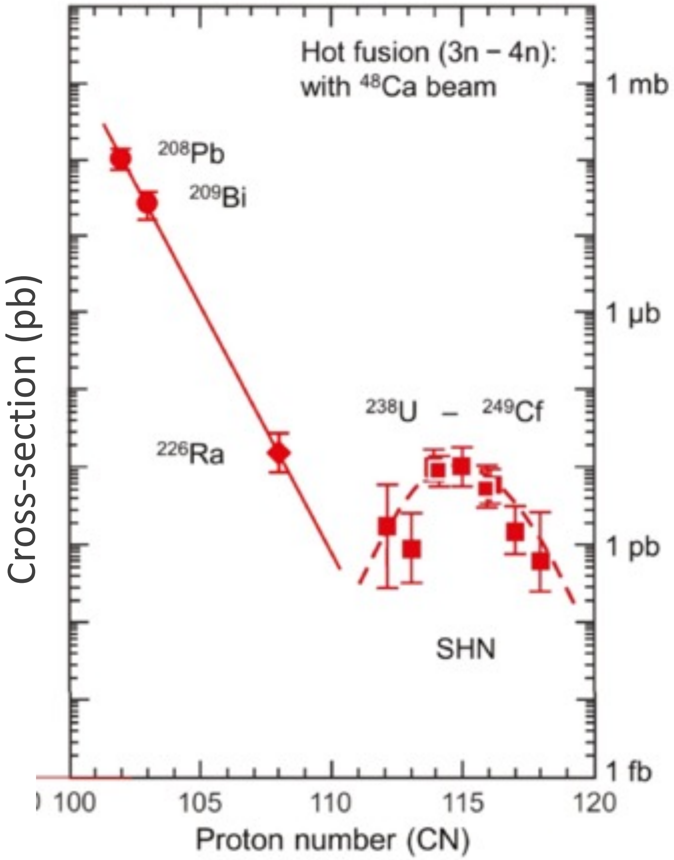


- In 2003 at RIKEN, ^{70}Zn on ^{209}Bi target to produce Z=113 (Nihonio ^{113}Nh)
- **3 atoms in 553 days**
- The method encountered limitations as the probability of fusion and survival fell precipitously

  →increasing Coulomb repulsion between target and projectile

Why so difficult to produce SHE: Cross sections

- **Getting beyond 113 required a different approach: hot fusion.**
- **Hot fusion uses higher beam energies and relies on a special isotope with a large excess of neutrons, calcium-48 on actinide targets (U, Cm,….)**



- Calcium-48 is expensive ($250,000 per gram)
- Dubna identified **4 atoms** of element 114 (^{114}Fl) within **6 months**.
- To produce heavier nuclei (Z=118) radioactive targets such as Cm or Cf where used.

OUTLINE

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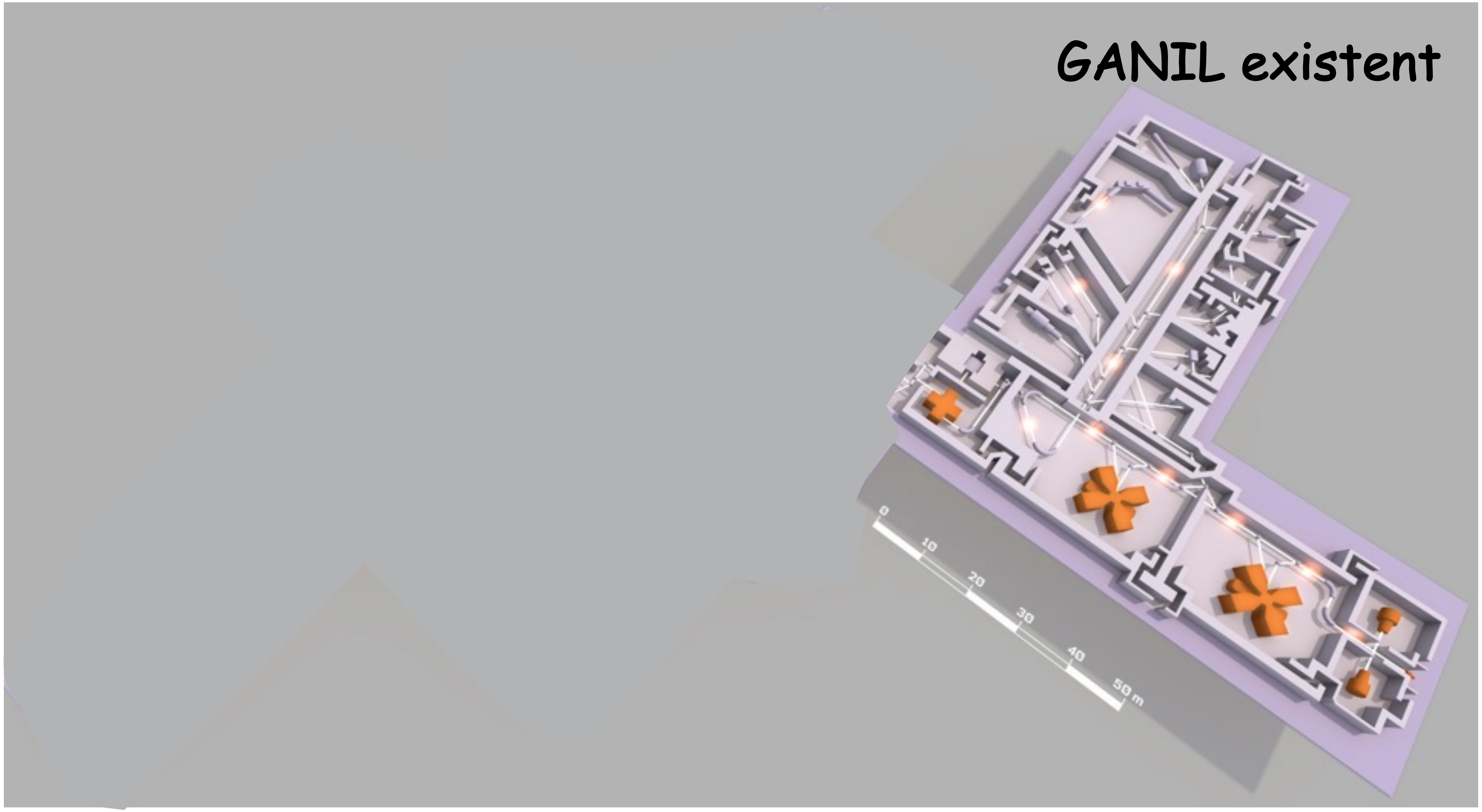
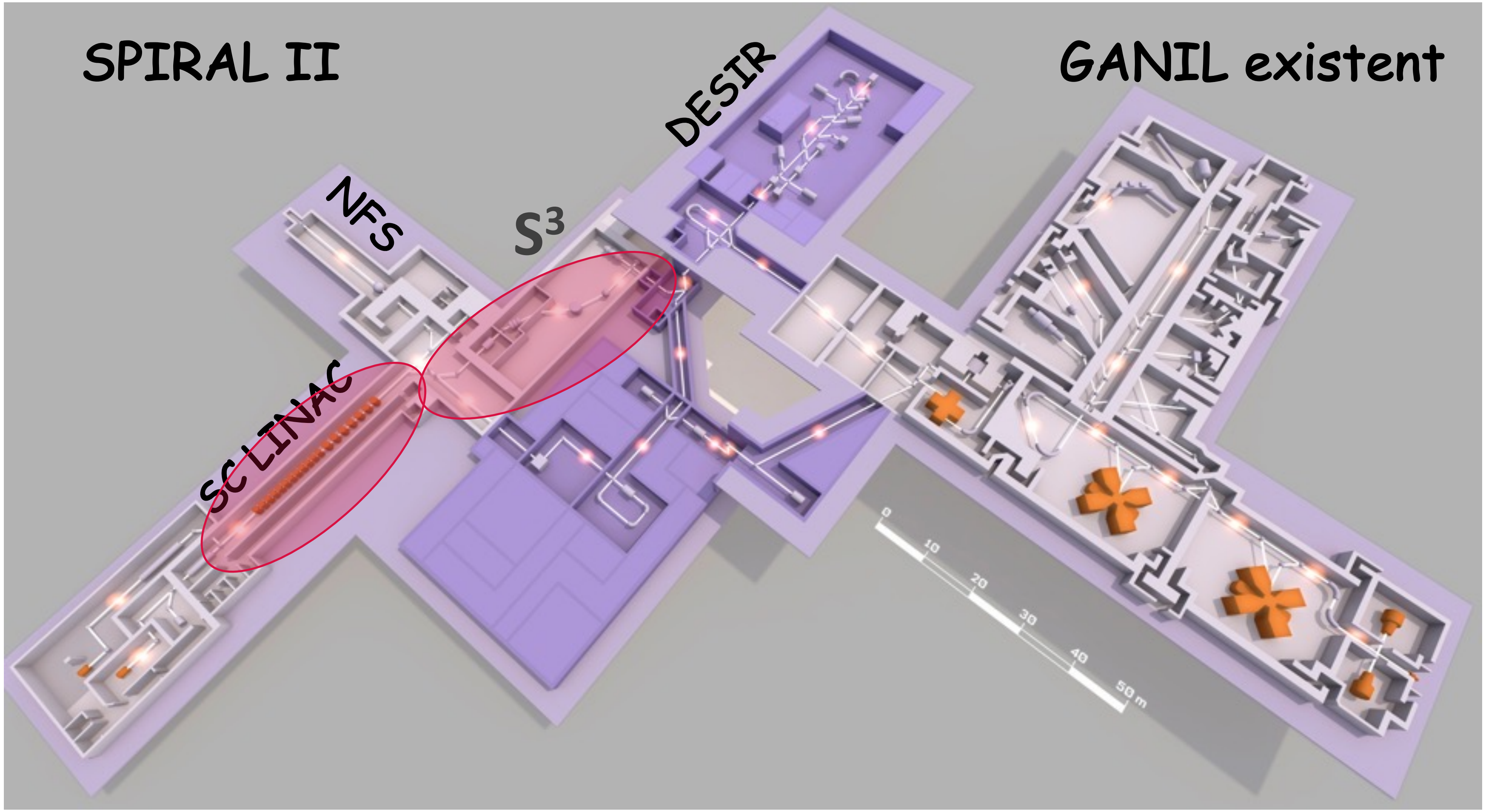
What do we need to overcome the limits ?

- More beam intensity to produce SHE nuclei
- High performance spectrometers
- Cutting-edge Focal plane detector
- Transfermium targets to go heavier and heavier



H. Savajols (GANIL)

SPIRAL II - the second generation System for On-Line Production of Radioactive Ions



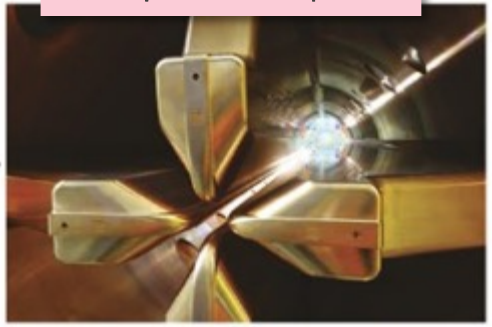
SPIRAL2 LINAC accelerator

Two ECR ion source:

1) 33 MeV protons and 40 MeV deuterons (Imax 5mA),
2) Heavy ion beam from He up to U

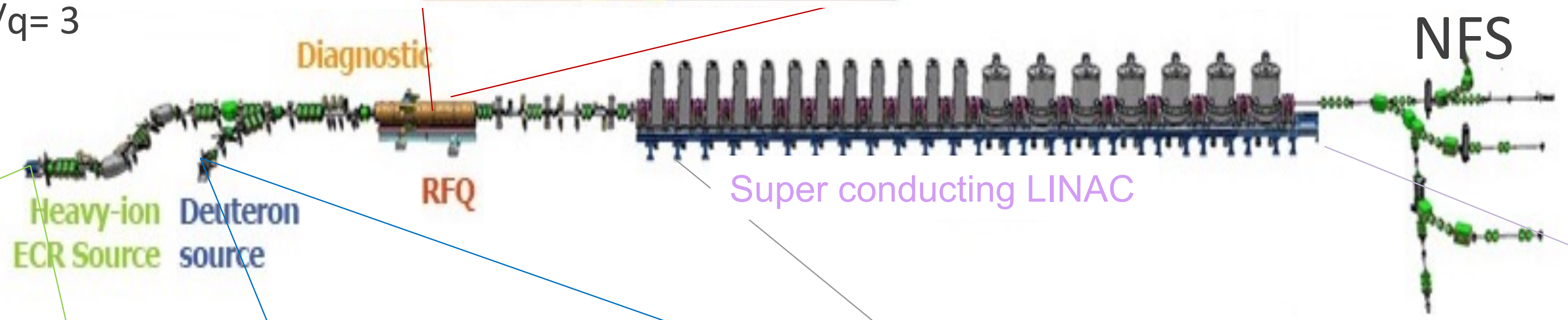
→Beam energies : 14.5 Mev/nucleons ($I=10^{14}$ ions per second) with A/q= 3

RFQ
Quadrupole Radio Frequencies



Status:

- ➢ 2019 first beam injected
- ➢ 2020 Proton beam @ 33 MeV
- ➢ 2021 Deuterons beam 40 MeV I=50 μA

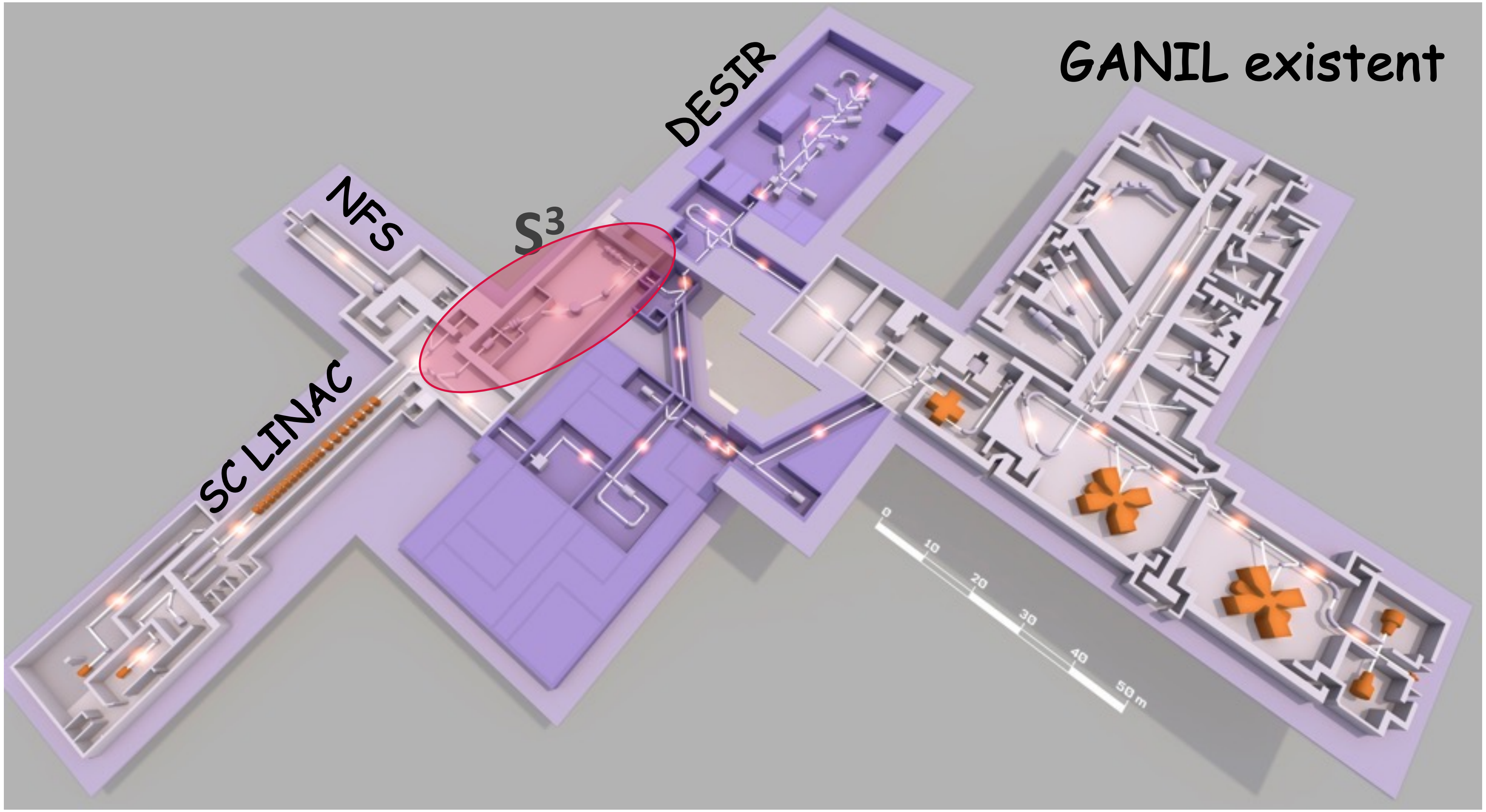


Heavy ion source

PROTONS AND DETORION ION SOURCE

Superconducting accelerator cryomodules A & B

SPIRAL II : S3

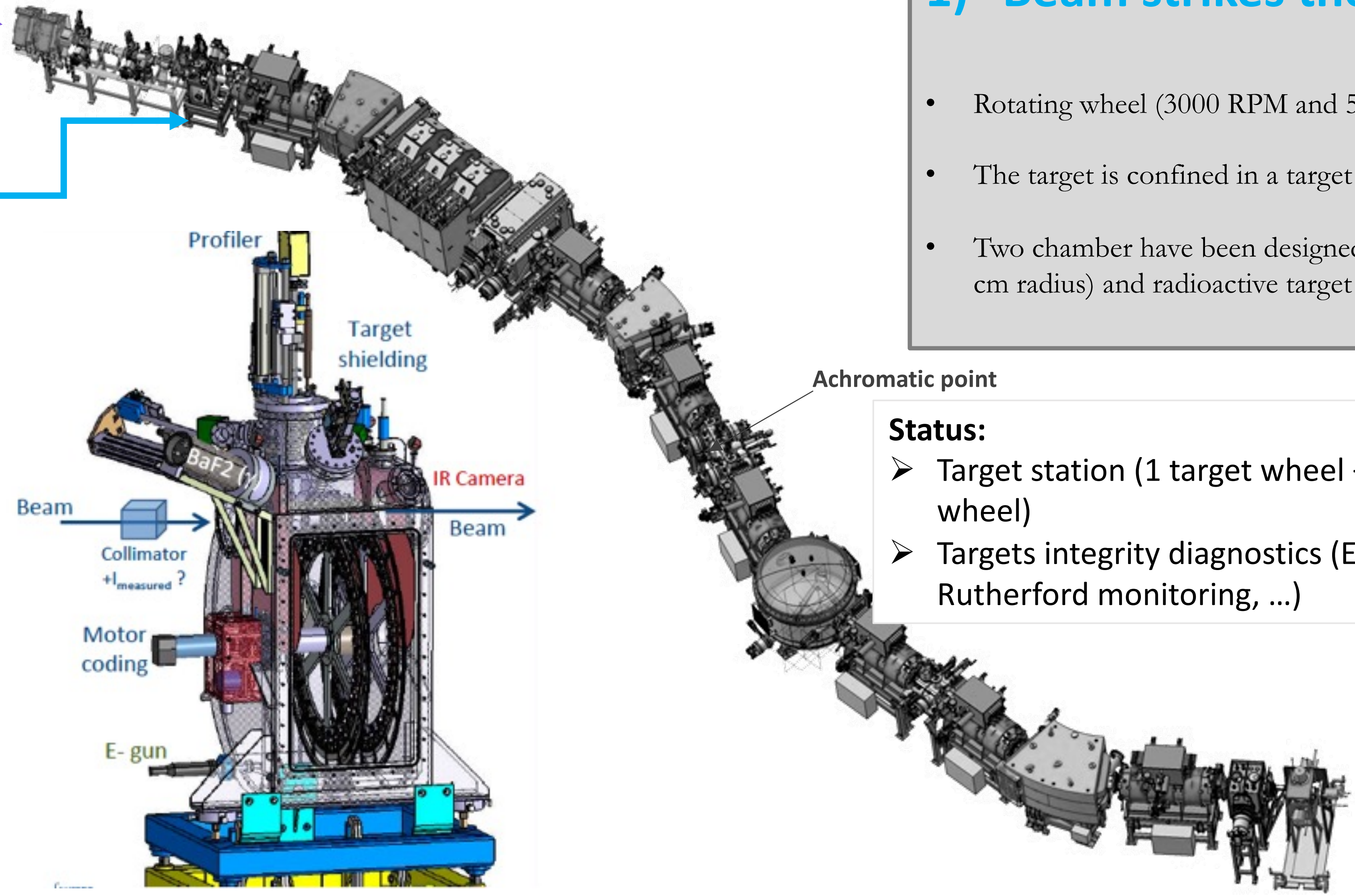


H. Savajols (GANIL)

Production of high-intensity heavy-ions beams at S^3

Characteristics:

- High selectivity > 10^{13}
- High efficiency 50%
- Mass resolution > 1/350
- Versatility



Target
Fusion-evaporation reaction

1) Beam strikes the target

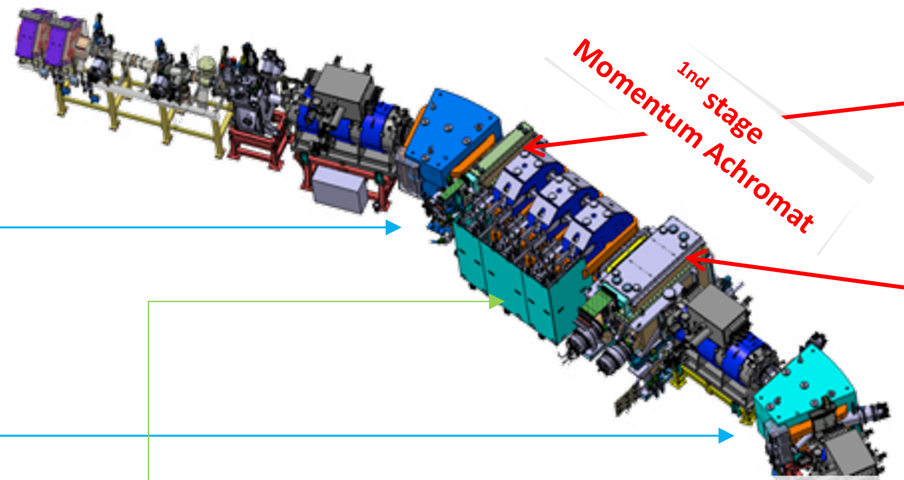
- Rotating wheel (3000 RPM and 5000 RPM)
- The target is confined in a target chamber
- Two chamber have been designed for stable (37 cm radius) and radioactive target (8 cm radius)

Status:

- ➢ Target station (1 target wheel + 1 stripper wheel)
- ➢ Targets integrity diagnostics (Electron gun, Rutherford monitoring, …)

S3 for decay spectroscopy studies : Momentum Achromat

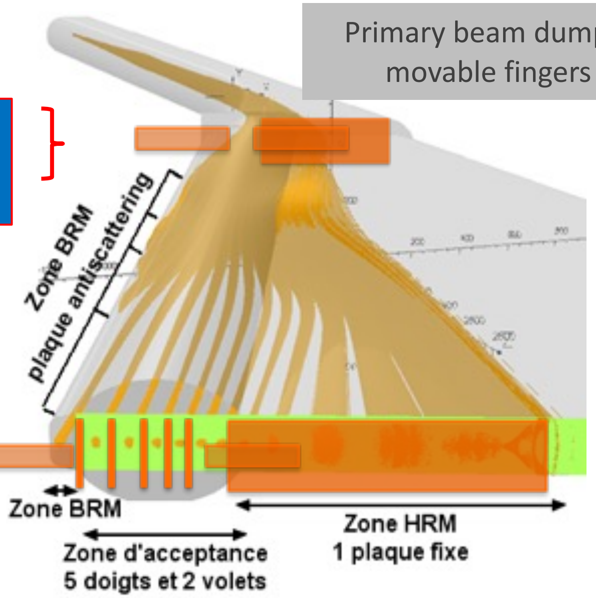
SPIRAL2 beam



Upstream BD
- 2 shutters
- 1 fixed plate

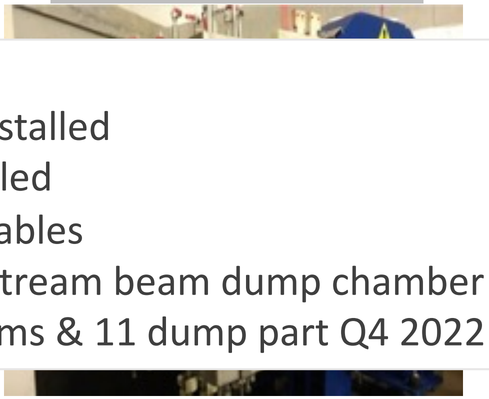
Downstream BD
- 5 fingers
- 2 shutters
- 1 fixed plate

Primary beam dump + movable fingers



2 Magnetic dipoles

Open triplet + primary beam dump + movable fingers



Status:

- 3 magnetic dipoles installed
- Open RT Triplet installed
- Power supplies and cables
- Upstream and downstream beam dump chamber installed on S3 line
- Translation mechanisms & 11 dump part Q4 2022

- Two **magnetic dipole** to produce p/q dispersive intermediate image (brhomax=1.8 Tm)
- **Open-sided triplet** to stop high intensity charge state outside the acceptance.
- **Beam dump and movable multi-finger** system to stop 99.9% of primary beam

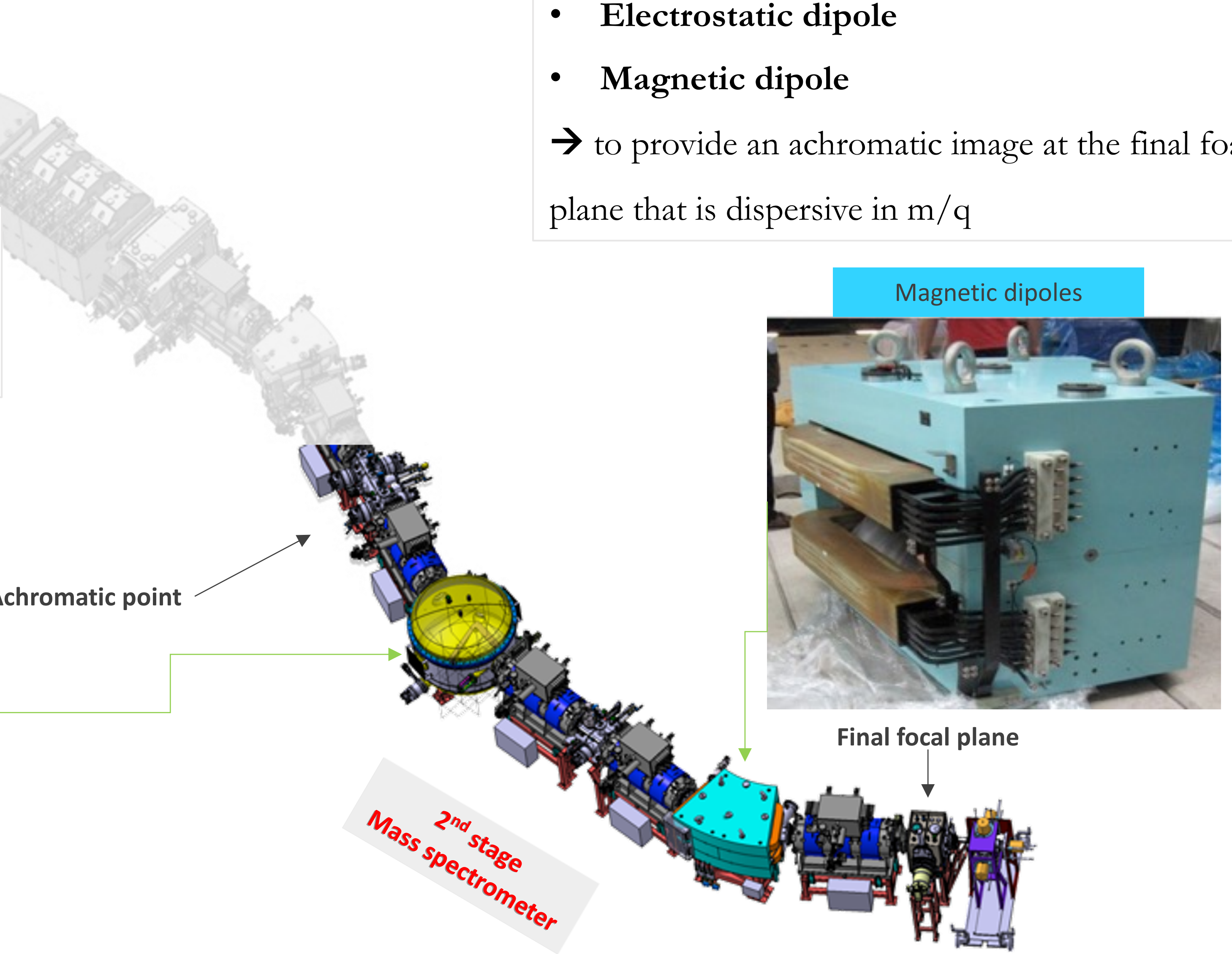
S3 FOR DECAY SPECTROSCOPY STUDIES : MASS SEPARATOR

- **Electrostatic dipole**
- **Magnetic dipole**

→ to provide an achromatic image at the final foal plane that is dispersive in m/q

Status:

- Chamber, Ti electrodes and all hardware completed at IJCLab
- E-Dipole installed on S^3 line Q4 2021



S3 FOR DECAY SPECTROSCOPY STUDIES

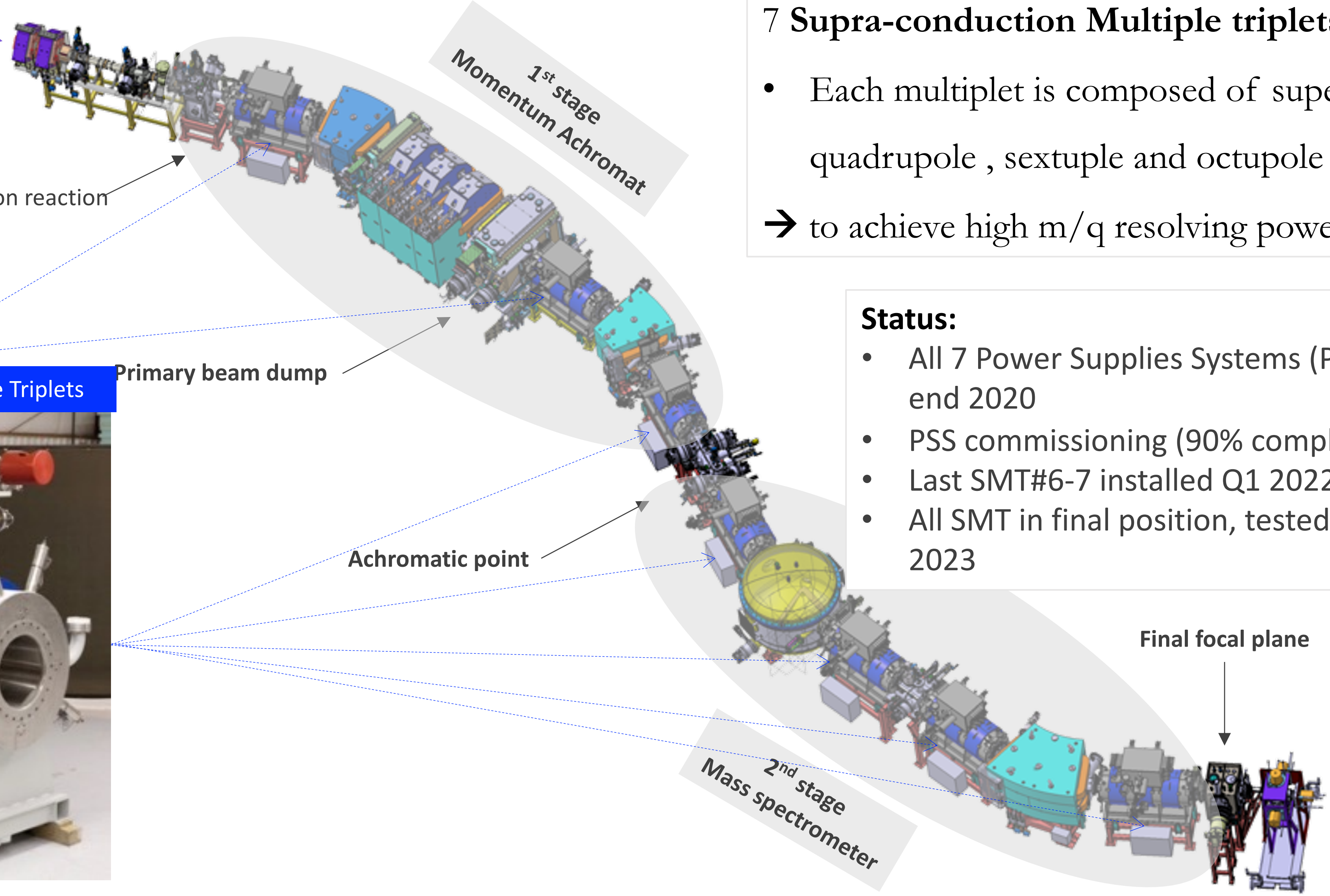
7 Supra-conduction Multiple triplets

- Each multiplet is composed of superimposed quadrupole , sextuple and octupole fields

→ to achieve high m/q resolving power

Status:

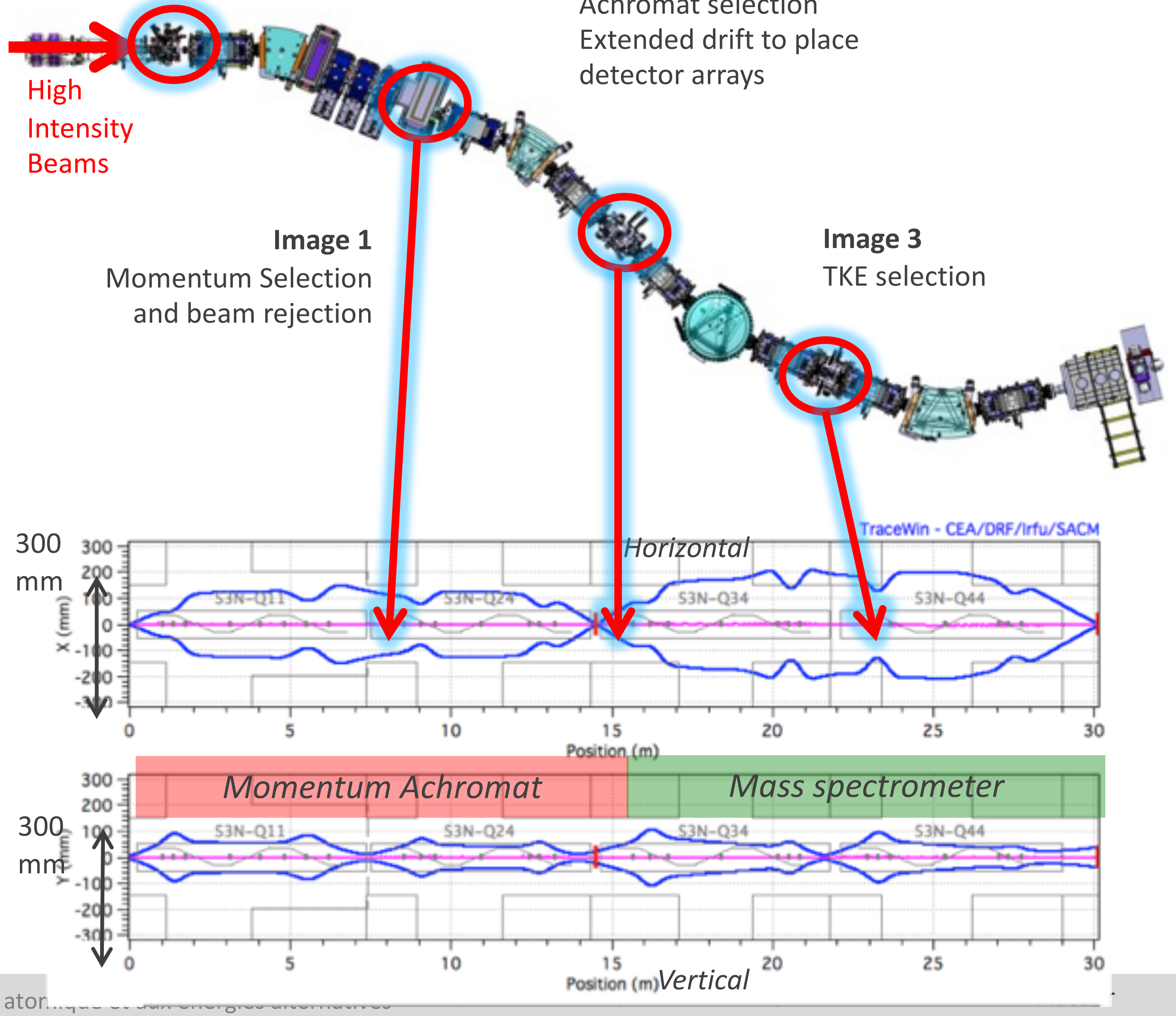
- All 7 Power Supplies Systems (PSS) installed end 2020
- PSS commissioning (90% completed)
- Last SMT#6-7 installed Q1 2022
- All SMT in final position, tested and plugged Q1 2023



7 Supra-conducting Multiple Triplets

Optical modes : Ultra High Resolution Mode

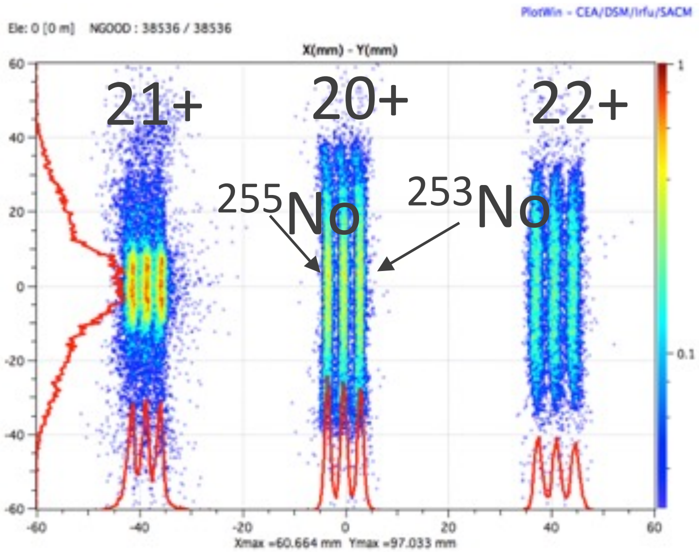
- Highest possible mass selectivity



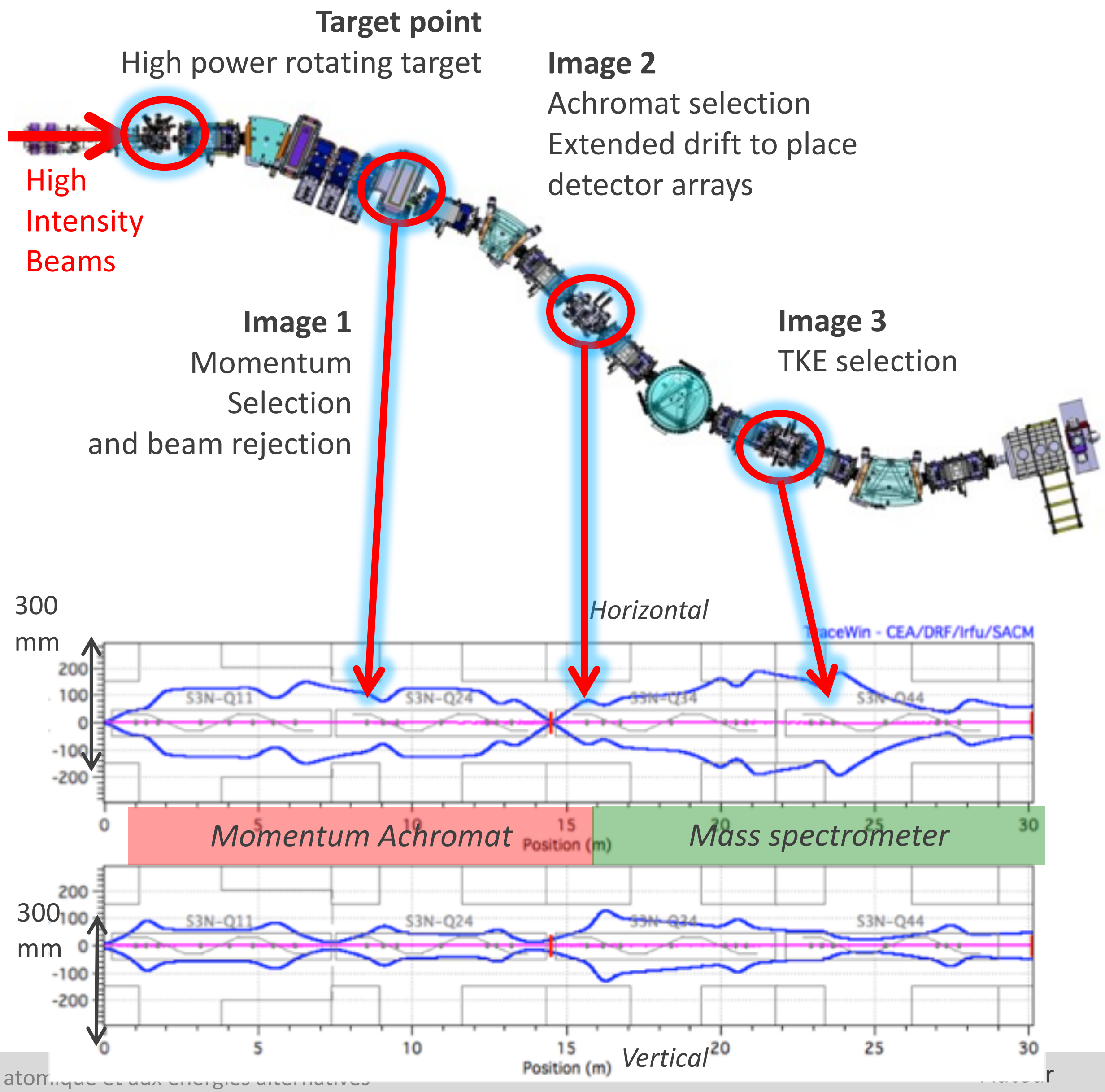
$^{48}Ca(^{208}Pb, 2n)^{254}No$

- Transmission (20%)
- *Acceptance σ_θ = 34mrad σ_p = 2.2%*
- Mass resolution (ΔM/M ≈ 500)
- Versatility ($B\rho_{max}$=1.6Tm; $E\rho_{max}$ = 12MV)

Mass selection



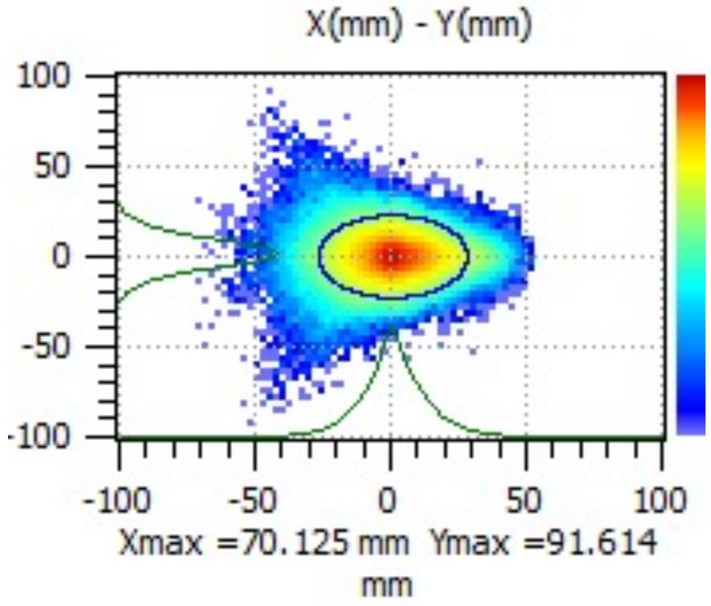
Optical modes : Converging Mode



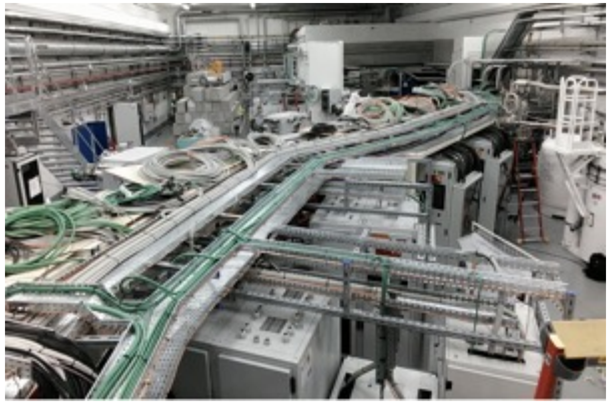
$^{48}Ca(^{208}Pb, 2n)^{254}No$

- Transmission (40%)
- *Acceptance σ_θ = 34mrad σ_p = 2.2%*
- Mass resolution ($\Delta M/M \approx 0$)
- Versatility ($B\rho_{max}$=1.6Tm; $E\rho_{max}$ = 12MV)

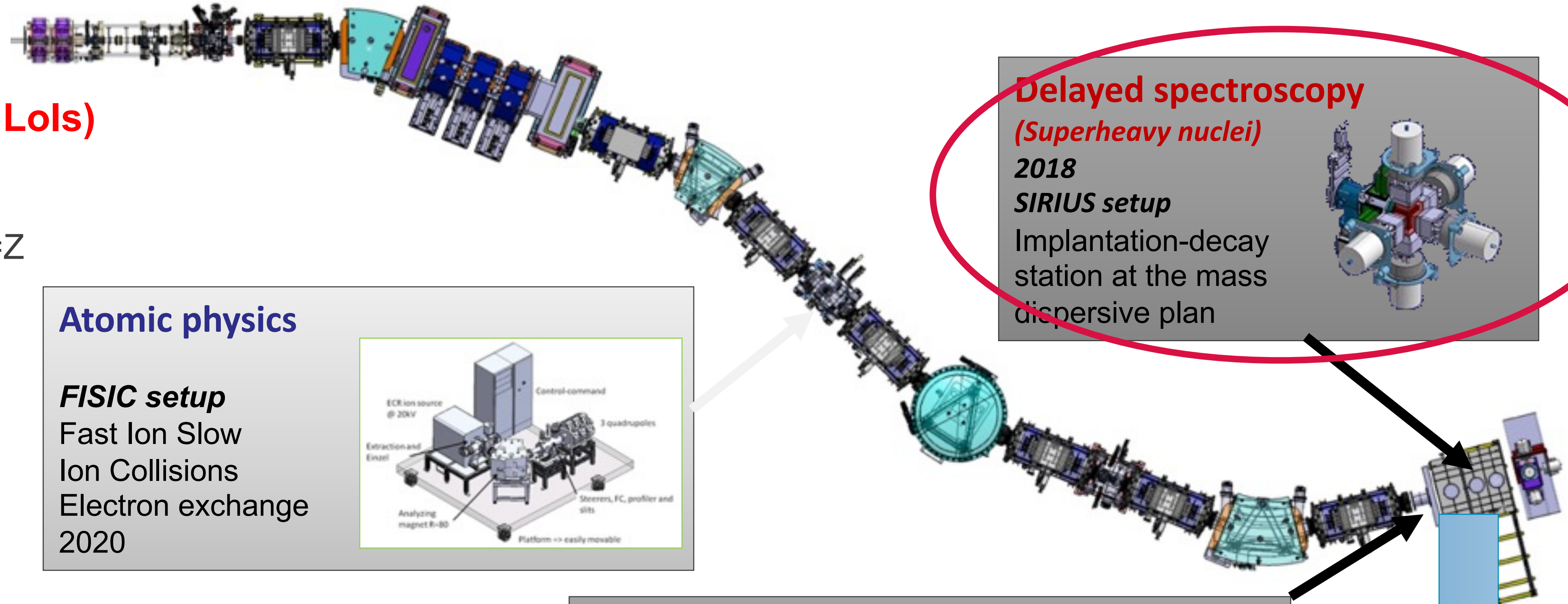
Converging mode – no mass resolution



S^3: Super Separator Spectrometer



S3 versatile instrumentation



S3 Physics case (26 LoIs)

- VHE-SHE nuclei
- Proton drip-line & N=Z
- Nuclear Astrophysics
- Atomic physics

Atomic physics

FISIC setup
Fast Ion Slow
Ion Collisions
Electron exchange
2020

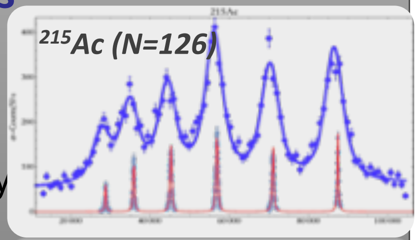
Delayed spectroscopy

(Superheavy nuclei)
2018
SIRIUS setup
Implantation-decay
station at the mass
dispersive plan

Ground state properties

(mass, size, moments, spins)

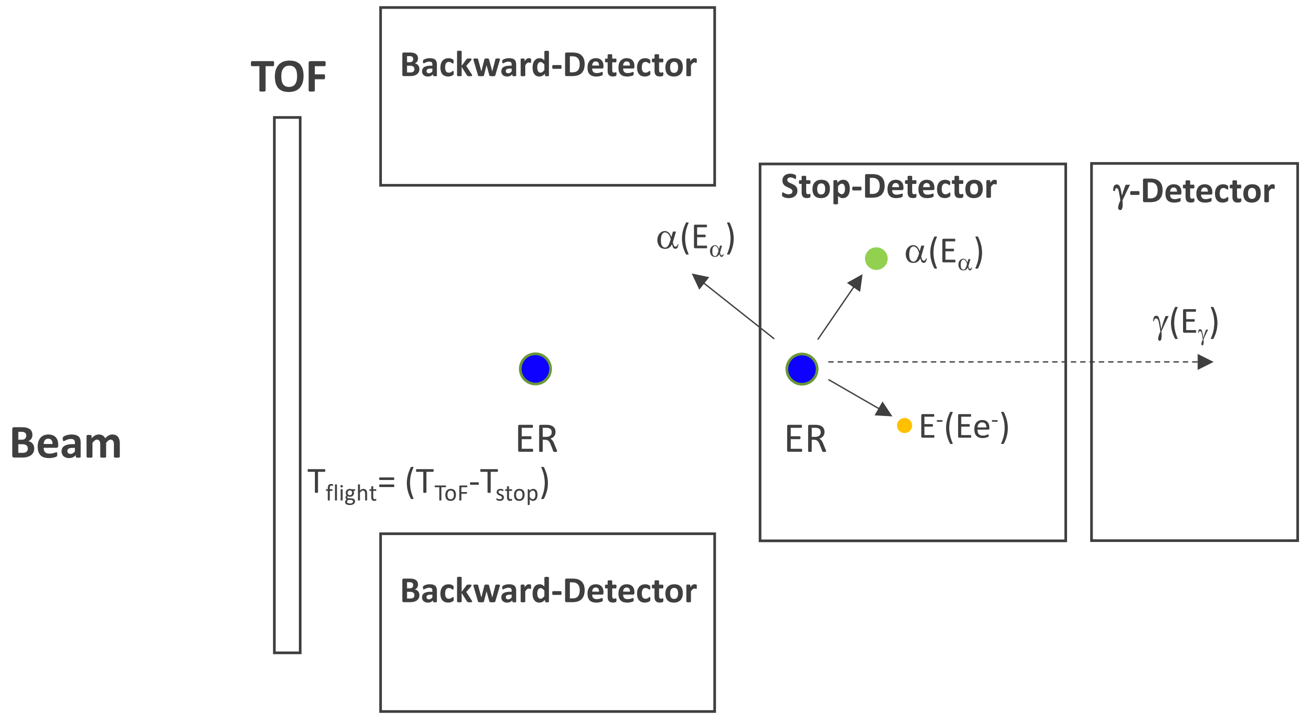
S3-LEB setup
In gas jet laser spectroscopy
-mass measurement
-decay spectroscopy pure beams

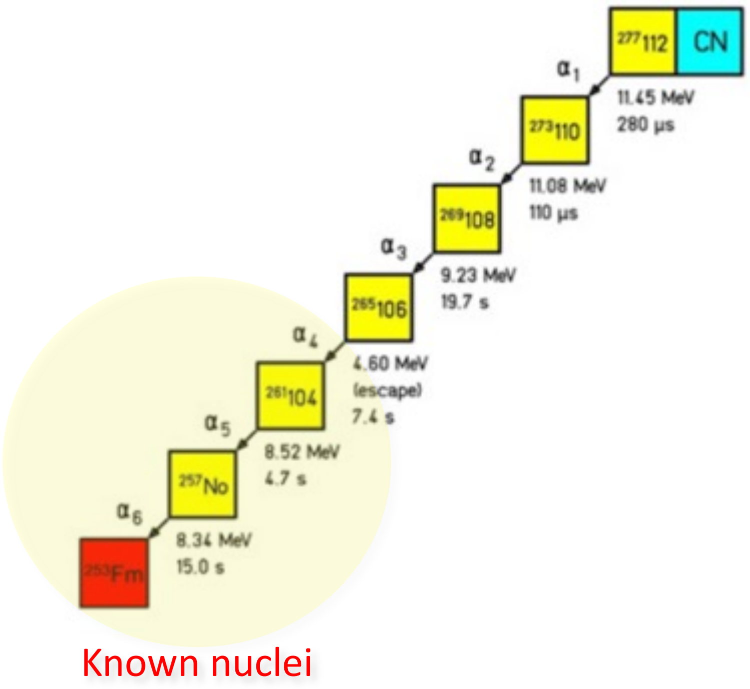


DESIR

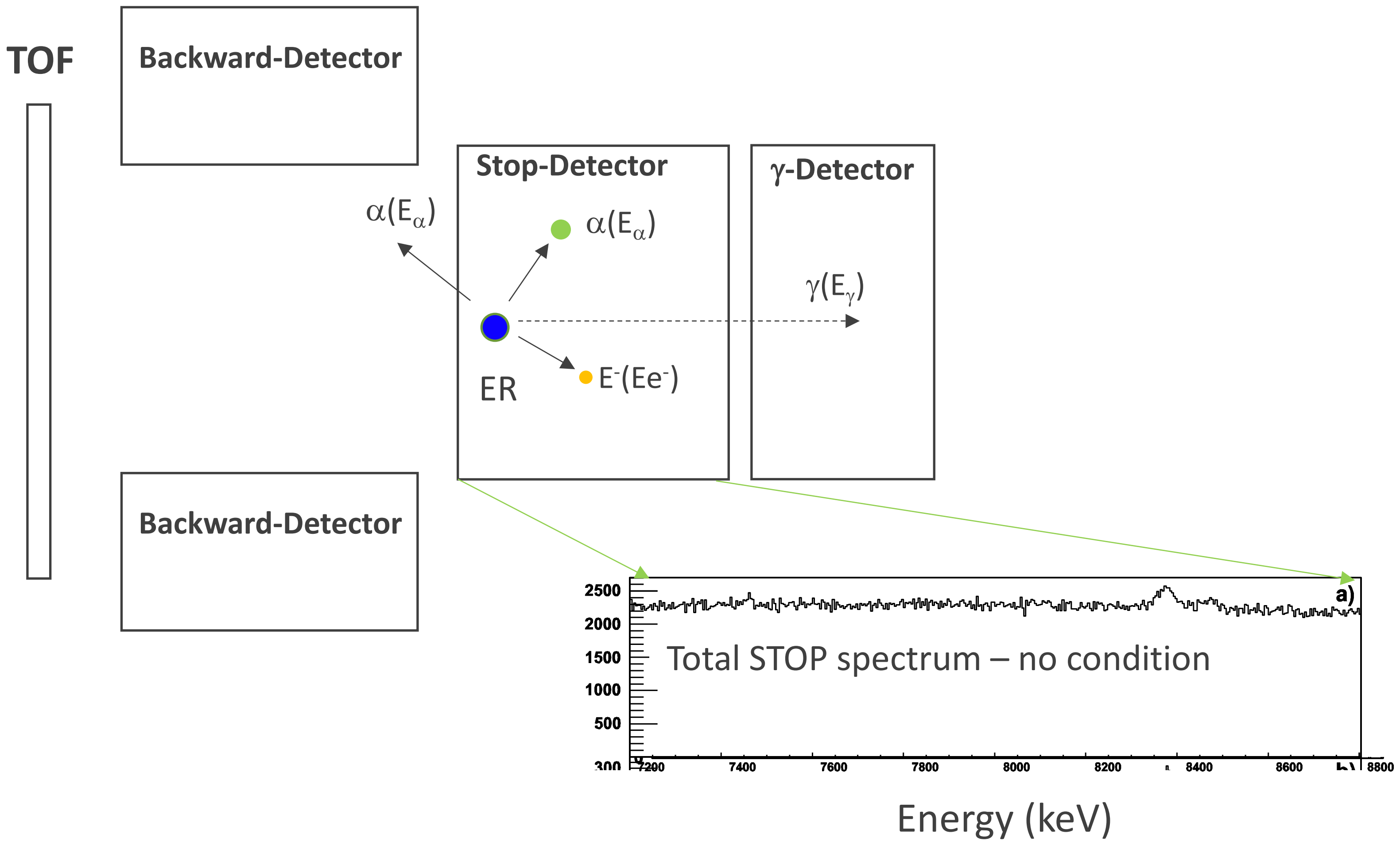
Courtesy of H. Savajols

Focal plane detector: recoil decay tagging technique

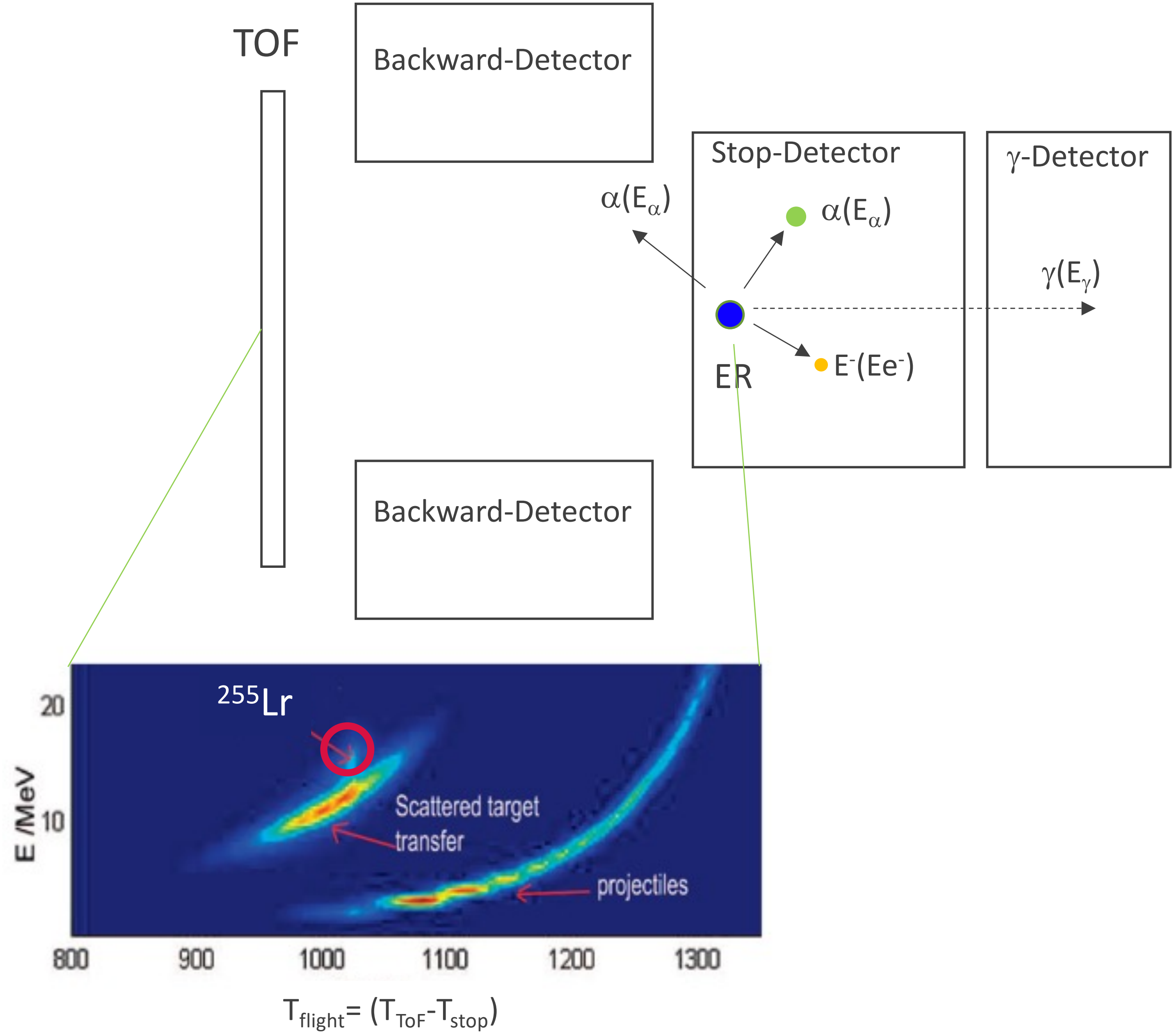




Focal plane detector: recoil decay tagging technique

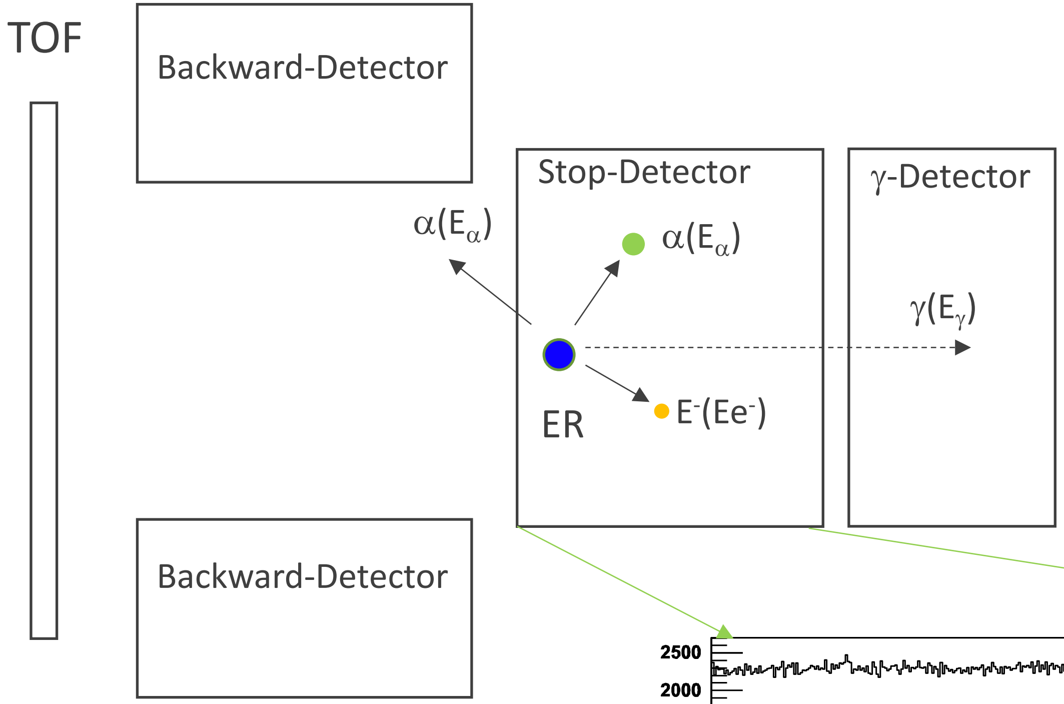


Focal plane detector: recoil decay tagging technique

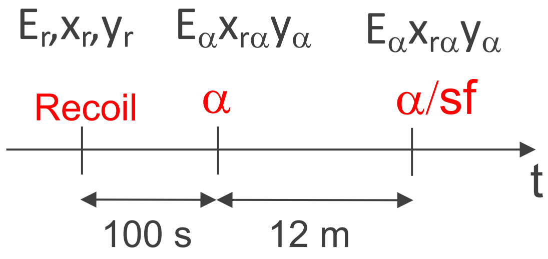


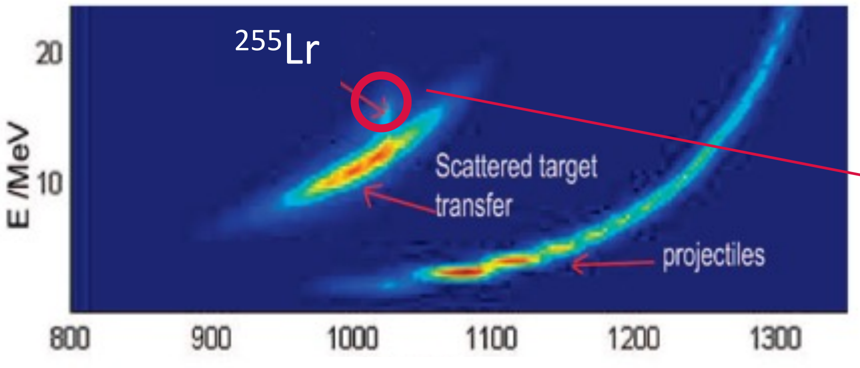
- The SHE nuclei are identified on the basis of kinematics (e.g. time of flight, implantation energy)

Focal plane detector: recoil decay tagging technique

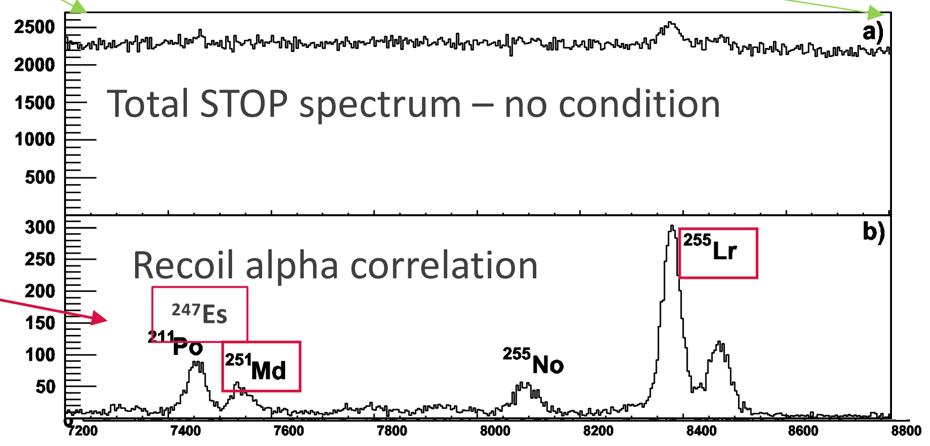


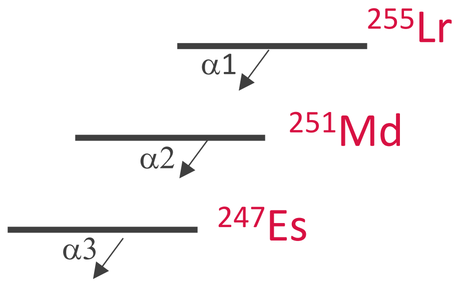
- The SHE nuclei are identified on the basis of kinematics (e.g. time of flight, implantation energy)
- Correlating in time and position in the same pixel with its decay.



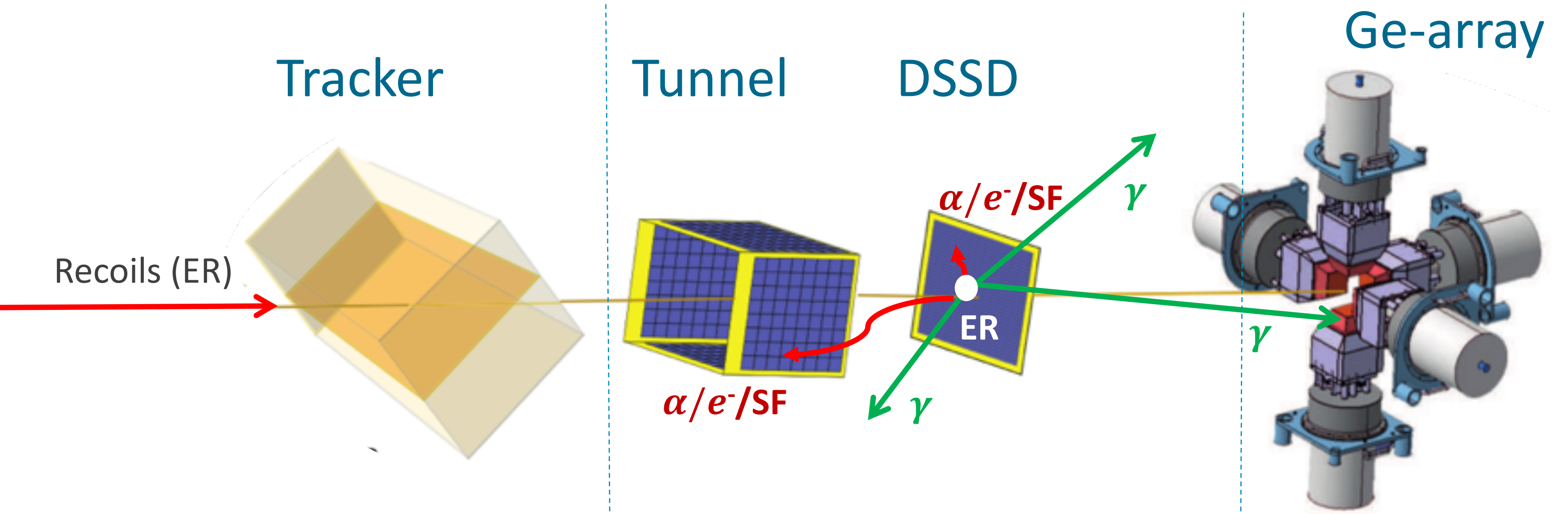


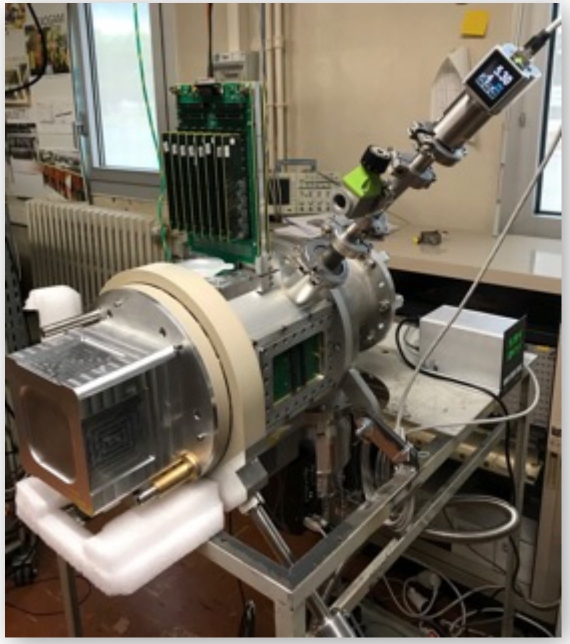
$T_{flight}= (T_{ToF}-T_{stop})$





Focal plane detector: SIRIUS





Time of Flight:

- Emissive foil
- Thin windows
- High Time resolution
- Mass Identification

A/ΔA ~300

Silicon detectors:

- Charged particle discrimination for recoil, beta and decay alpha

  High resolution alpha and conversion electron spectroscopy
- Access to short decay times
- Digital electronics to record the traces

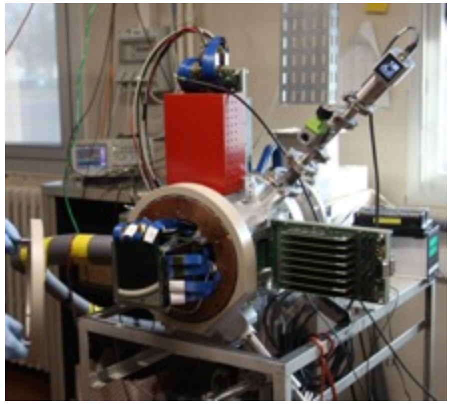
γ-ray detection :

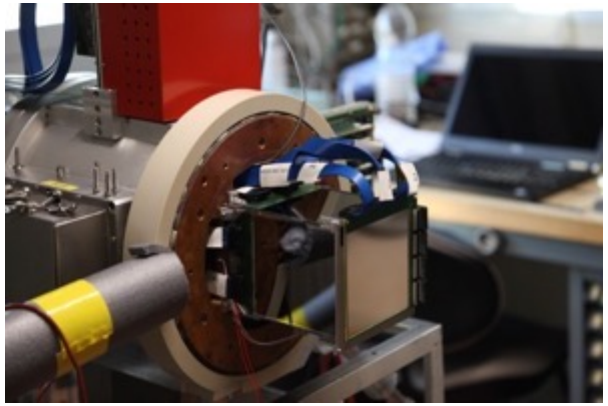
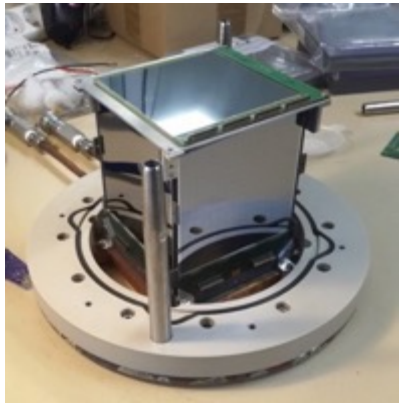
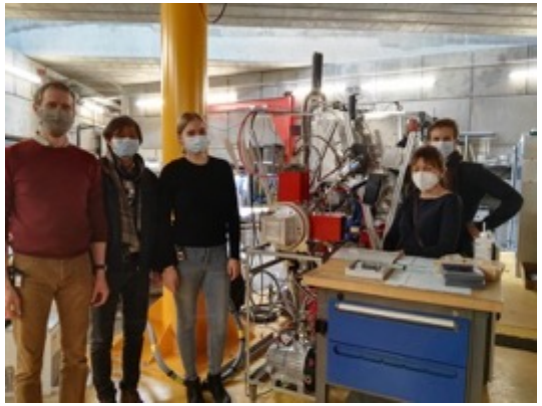
- 5 EXOGAM clover detectors
- Efficiency of 40% at 121 keV

Observables :

Decay mode
Half-life
Excitaion energy
Transition mixing

SIRIUS: highlights and next milestones



- March 2020: all parts of SIRIUS were built in the different laboratory (IPHC, IJClab, GANIL, IRFU)
- July 2020: Sirius arrived at IRFU where it was tested with the final electronics and the acquisition system.
- May 2021: SIRIUS arrived at GANIL, where it is now under test with all the electronics channels

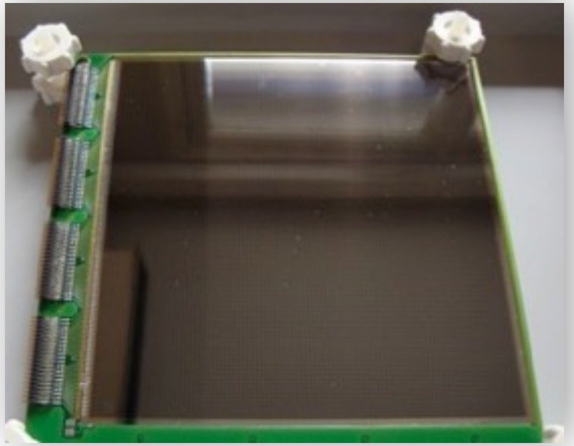
Next steps :

- **Test of SIRIUS coupled with tracker detector**
- **In-beam tests in a realistic implantation-decay experiment**
- **Installation at S3**

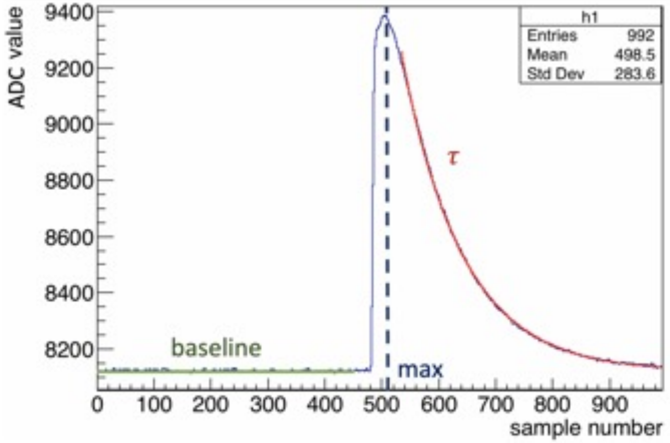
PERFORMANCE OF SIRIUS : DSSD

Physics Constraints DSSD

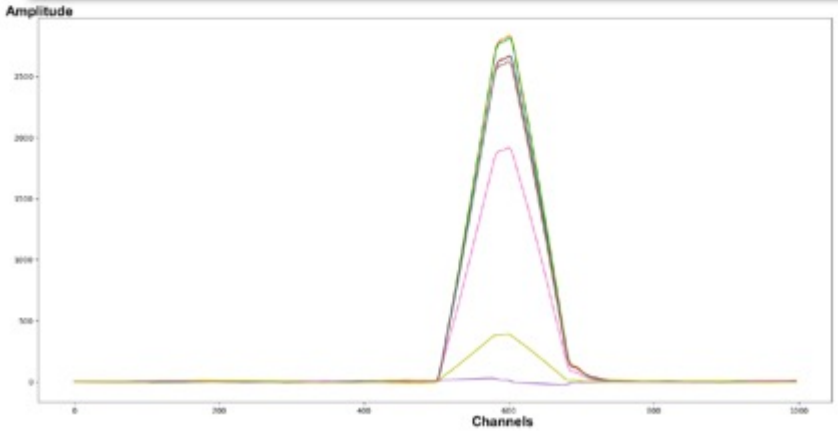
- Large size because of S^3 optics;100x100 mm^2; 128x128 strips
- Large dynamics: electrons, alpha, Heavy ions
- Energy range and resolution:
- Alpha/e⁻: 0÷20 MeV FWHM≈20 keV
- Heavy Ions: 50÷500 MeV FWHM<5-10 MeV
- Windowless detectors because slow and heavy recoils
- High implantation signal followed (10µs) by a small decay signal

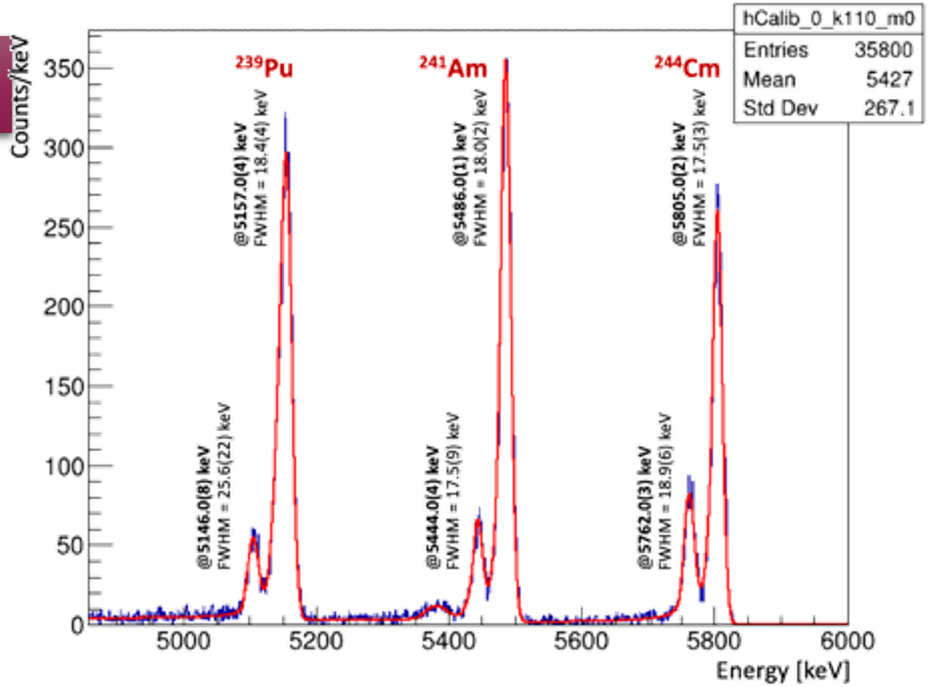


Alpha trace signal from digital electronics



A trapezoidal filter (Jordanov filter) applied to the signal to extract the energy and time

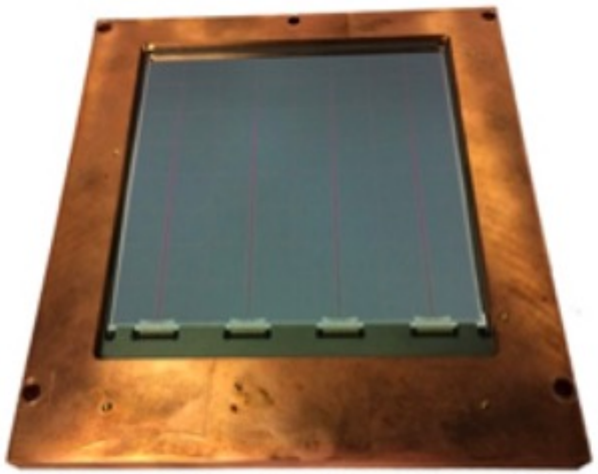


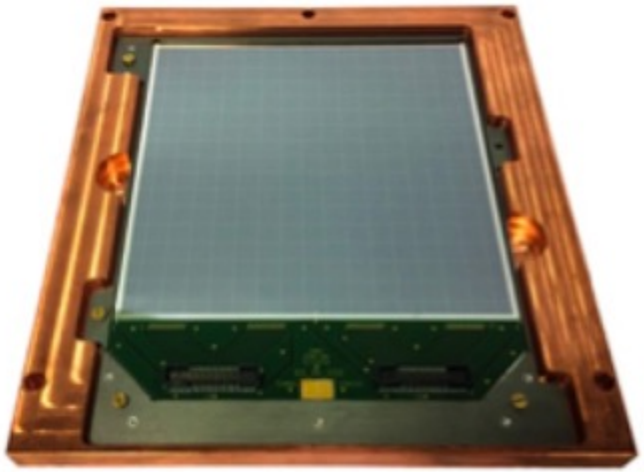


PERFORMANCE OF SIRIUS: TUNNEL

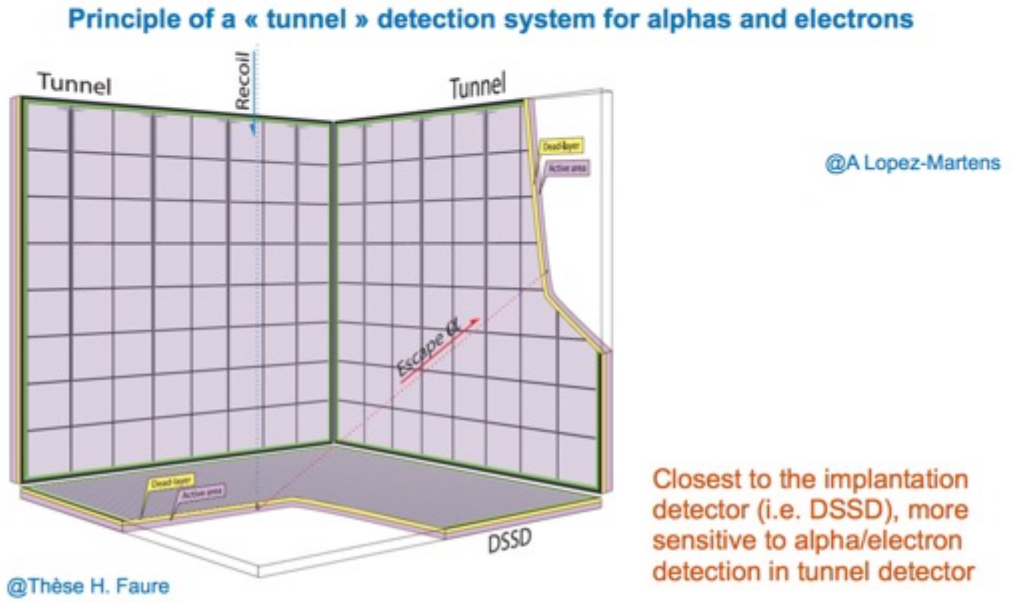
Physics Constraints TUNNEL

- Size : 10x10 mm^2
- Thickness: 1mm
- Window less
- Need for segmentation in the first centimeter of the tunnel Si !
- Counting rate < 10 kHz (total)
- Good energy resolution
- Detector type: SSSD (8x8 pads)



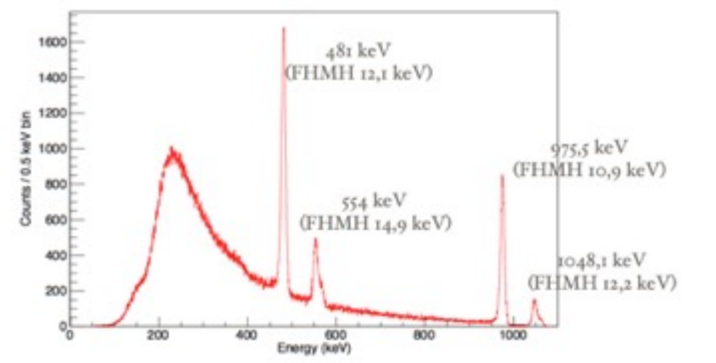


Physics Constraints TUNNEL

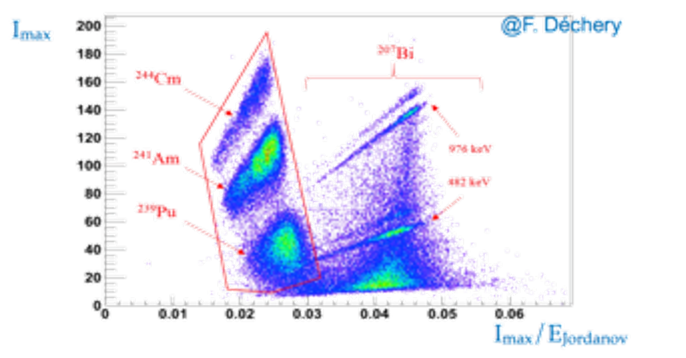


Closest to the implantation detector (i.e. DSSD), more sensitive to alpha/electron detection in tunnel detector

^{207}Bi electron sealed source



Possible to discriminate α/e⁻



Nuclear Inst. and Methods in Physics Research, A 1015 (2021) 165770

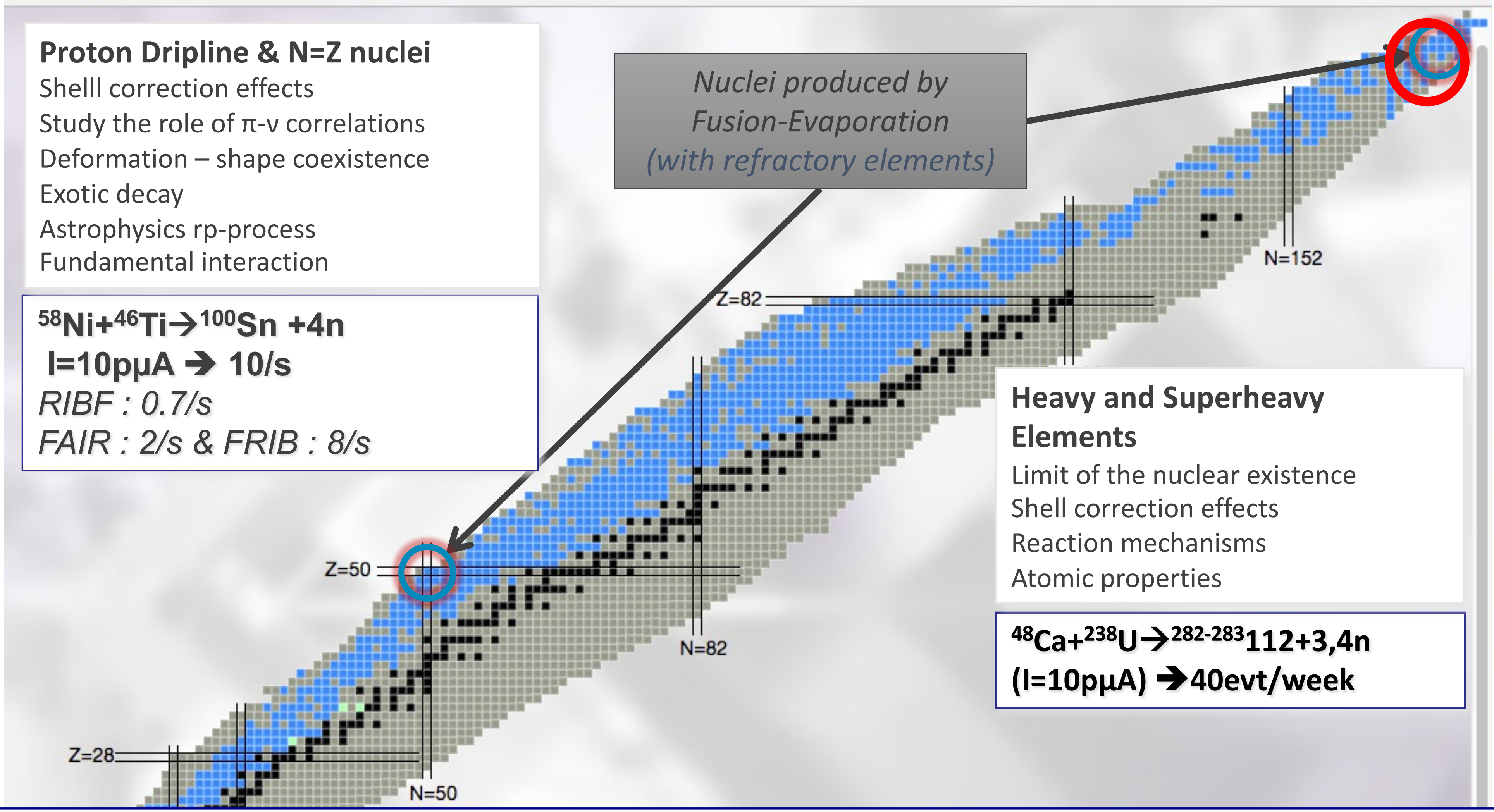
Physics goals

Study of rare events in nuclear and atomic physics

Proton Dripline & N=Z nuclei
Shelll correction effects
Study the role of π-ν correlations
Deformation – shape coexistence
Exotic decay
Astrophysics rp-process
Fundamental interaction

$^{58}Ni + ^{46}Ti \rightarrow ^{100}Sn$ +4n
I=10pμA ➔ 10/s
RIBF : 0.7/s
FAIR : 2/s & FRIB : 8/s

Nuclei produced by Fusion-Evaporation (with refractory elements)



Heavy and Superheavy Elements
Limit of the nuclear existence
Shell correction effects
Reaction mechanisms
Atomic properties

$^{48}Ca + ^{238}U \rightarrow ^{282\text{-}283}112$+3,4n
(I=10pμA) ➔40evt/week

➔ **test nuclear and atomic models and guide new theoretical development**

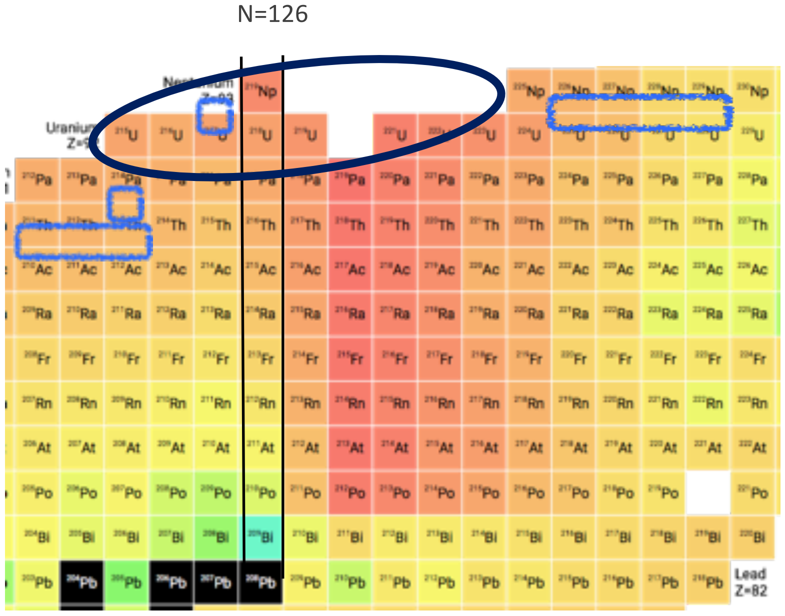
Heavy & Very Heavy Nuclei

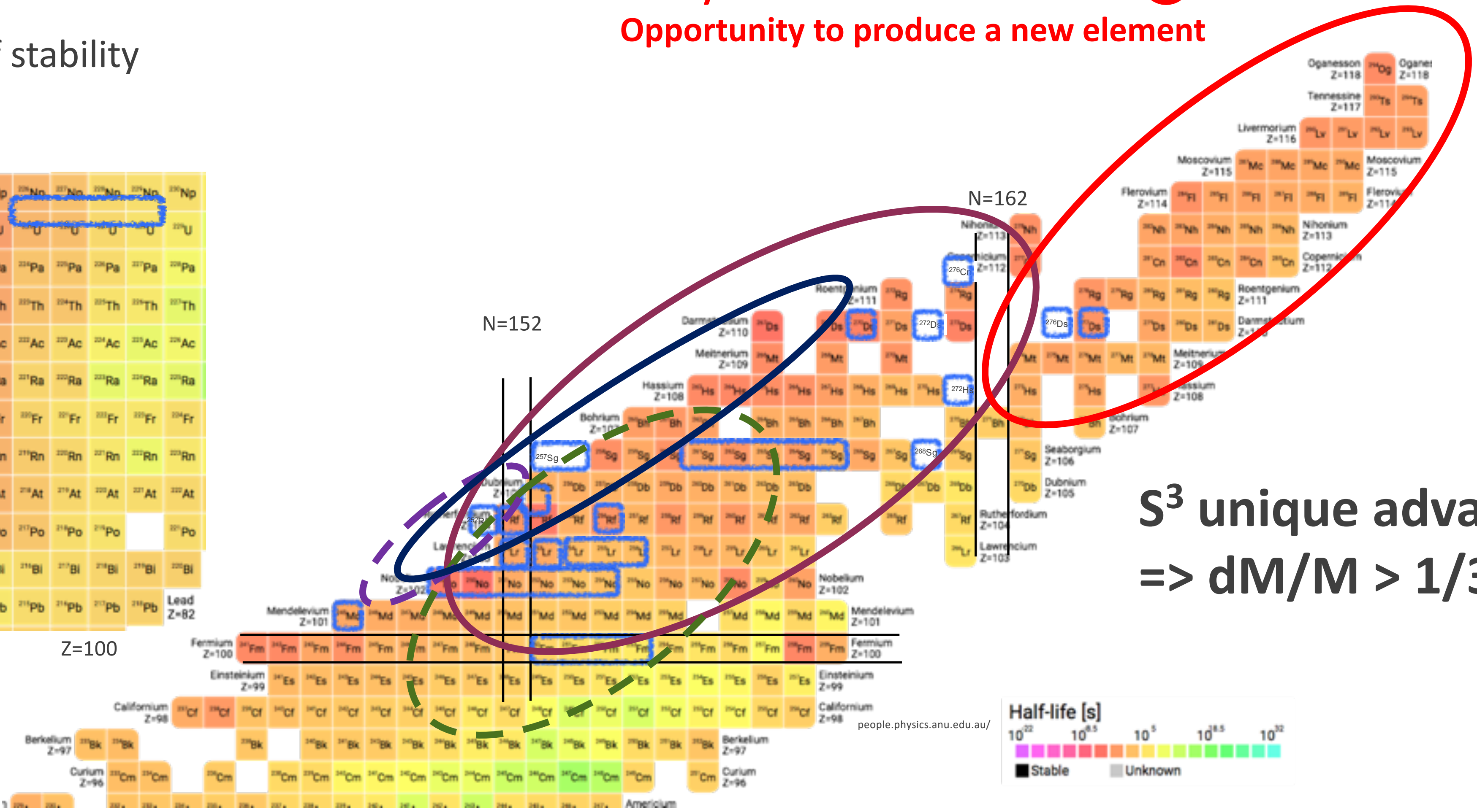
- Nuclear structure responsible for the shell stabilization
- Understand the influence of nuclear structure on fusion-evaporation for SHE
- K-isomers
- Single particle states
- New isotopes –limits of stability
- Reaction mechanism

Map nuclear structure
Bridge the gap between hot and cold fusion A/Q=3 A/Q=7

Probe the limits of stability A/Q=3 A/Q=7

SHE synthesis
Opportunity to produce a new element A/Q=7





S^3 unique advantage
=> dM/M > 1/350

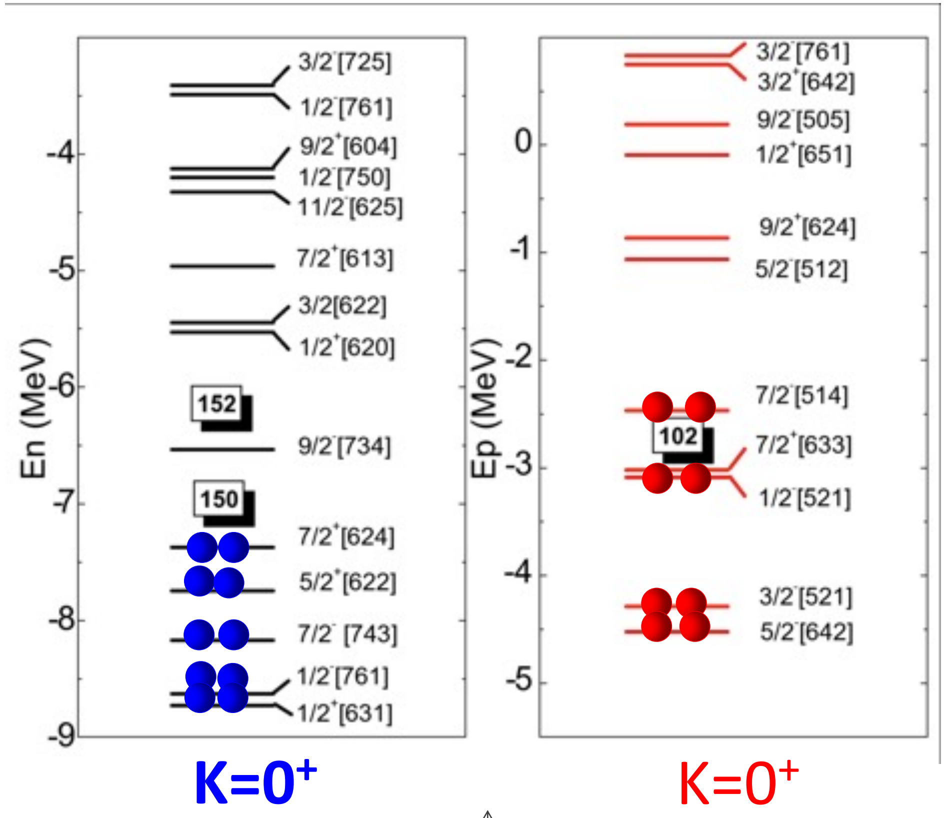
DAY 1 EXPERIMENT @ S3: ISOMERIC STATES IN EVEN EVEN NUCELI

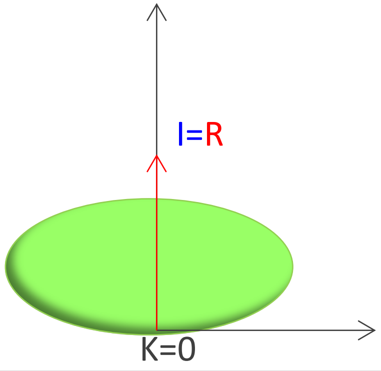
Why K isomers occur?

- Deformed nucleus
- Selection rule for electromagnetic transition λ ≥ ΔK is not fulfilled
- Breaking of particle pairs at Fermi Surface

What we can learn?

- Information about Nilsson level energy gaps
- Influence on stability of super heavy elements
- Constrains parameters that define nuclear mean filed → Benchmark nuclear theory





ISOMERIC STATES IN EVEN EVEN NUCELI

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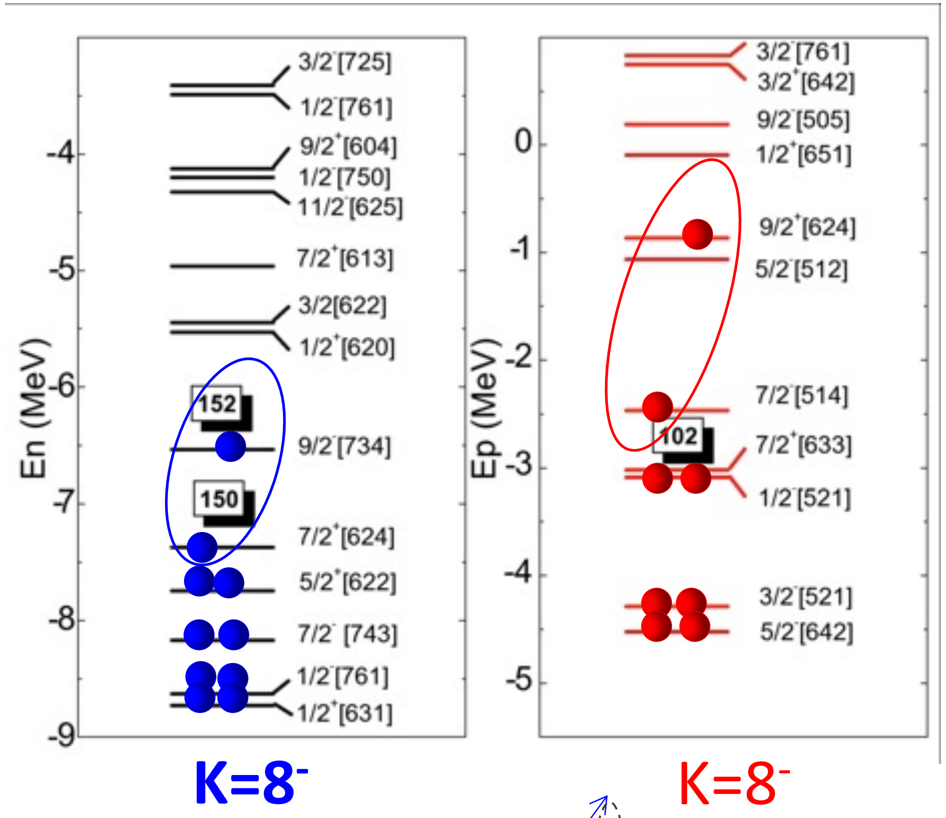

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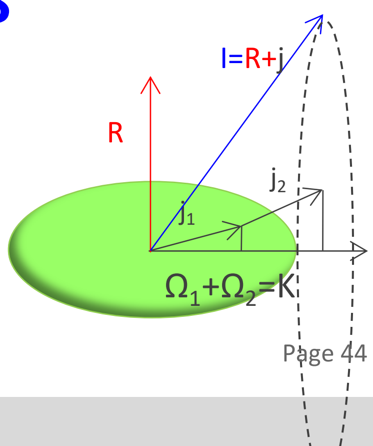
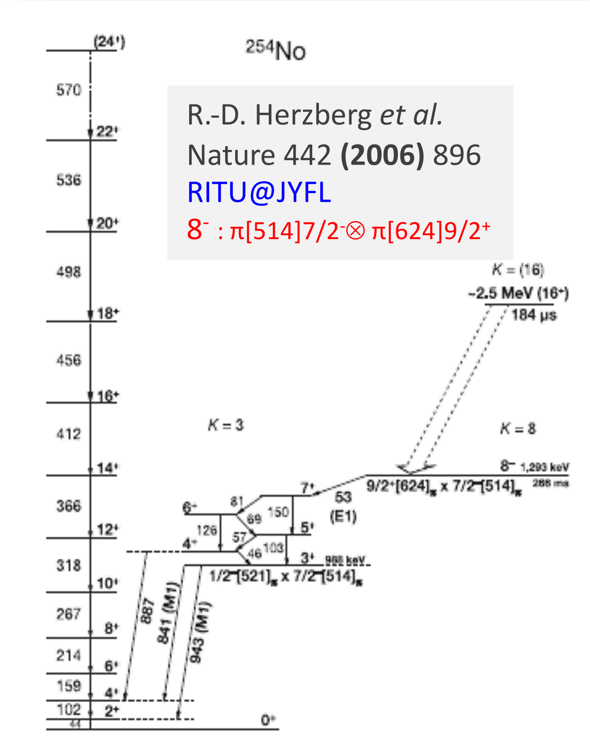


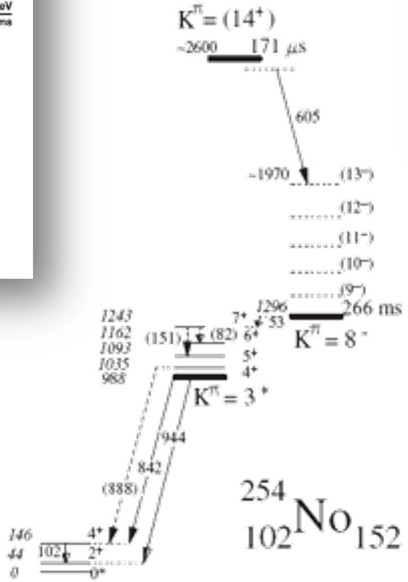
DAY 1 S3: DISAGREEMENT ON HIGH-K ISOMERS IN ^{254}NO

- For a long time, it was agreed that 8- isomer is a 2qp proton states.
- Berkeley suggest a new level scheme on the 8- isomer and a 2qp neutron state.
- Also evidences for a second isomer at ~ 2,5 MeV have been found.

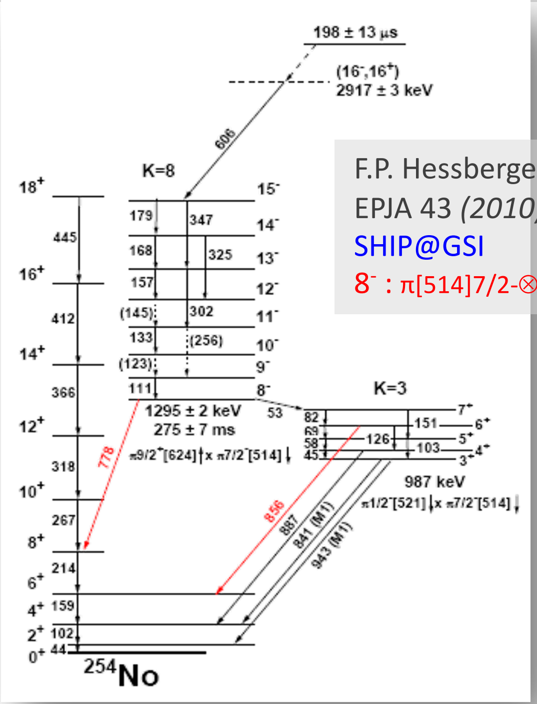


R.-D. Herzberg *et al.*
Nature 442 **(2006)** 896
RITU@JYFL
8^- : $\pi[514]7/2^- \otimes \pi[624]9/2^+$

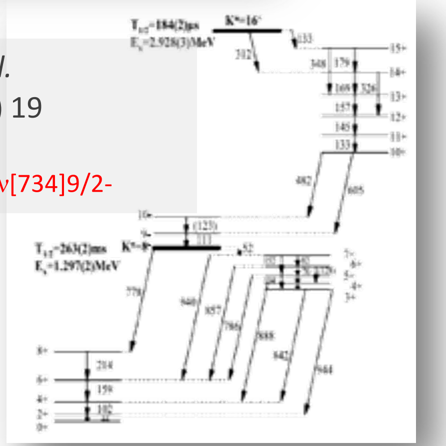
Cross sections
σ= 2μb



S.K. Tandel *et al.*
PLR 97 **(2006)** 082502
FMA@ANL
8^- : $\pi[514]7/2^- \otimes \pi[624]9/2^+$



F.P. Hessberger *et al.*
EPJA 43 *(2010)* 55
SHIP@GSI
8^- : $\pi[514]7/2^- \otimes \pi[624]9/2+$



R.M. Clark *et al.*
PLB 690 **(2010)** 19
BGS@LBNL
8^- : $\nu[613]7/2+ \otimes \nu[734]9/2-$

- no agreement concerning an 2qp K isomer at ~1,3 MeV
- More data are needed

Other installations

High intensity facilities

Present generation facilities (intensities around 1pµA) : Berkely, Dubna, GSI, Riken

Spiral2 phase1 do better for light ions, and slightly better for medium heavy ones

Other installations

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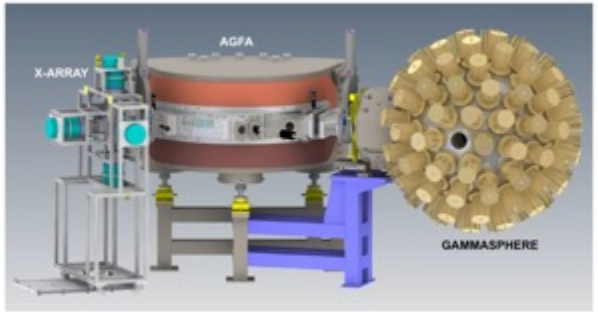


◎**ATLAS @ ANL** (Low-energy US facility focusing on experiment with stable beams)

◎**SHE Factory @ Dubna**

Other installations

High intensity facilities

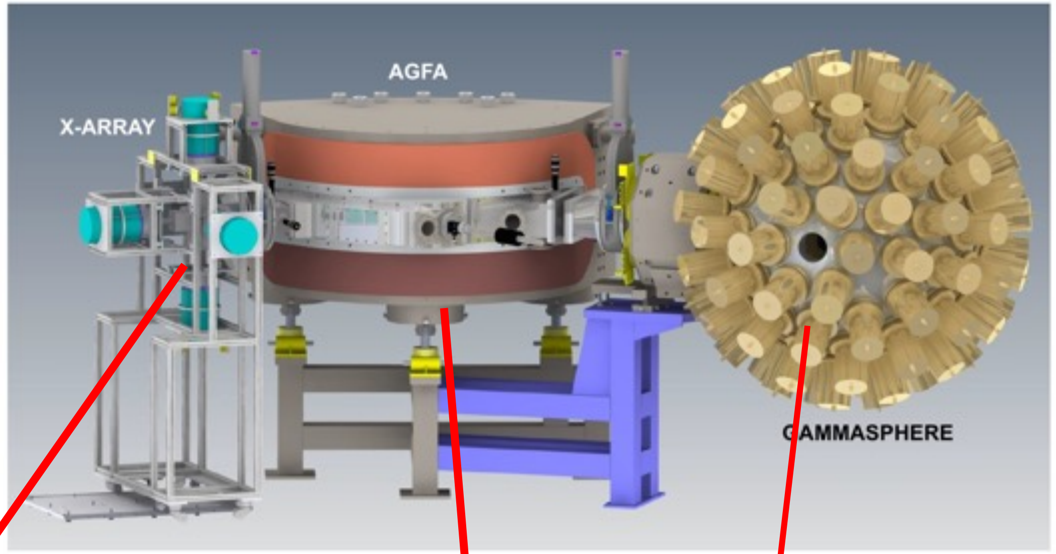
◎ATLAS @ ANL 2018

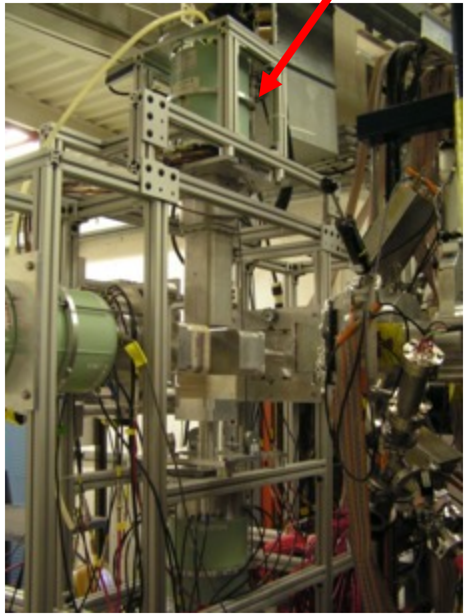
(Low-energy US facility focusing on experiment with stable beams)

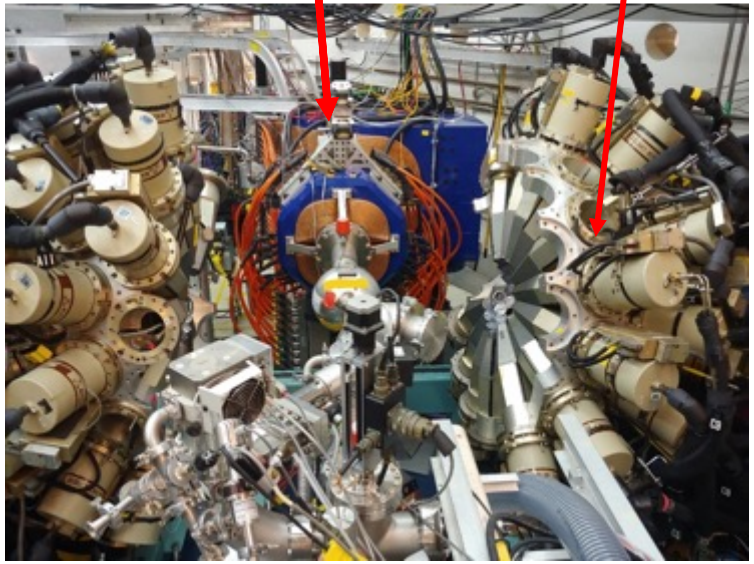
- Upgrade of beam intensities up to 10 pμA and energies (15MeV/u)
- AGFA new gas filled separator *N=Z, VHE*
- *New focal plane detector with digital electronics*

😀 Very short flight path : Short living isotopes
😀 High efficiency
😀 Very wide angular acceptance: MNT reactions

😟 Beam intensities of ^{48}Ca: 300 pnA
😟 No mass resolution
😟 No separation
😟 No suitable for asymmetric reactions







Other installations

◎SHE Factory @ Dubna

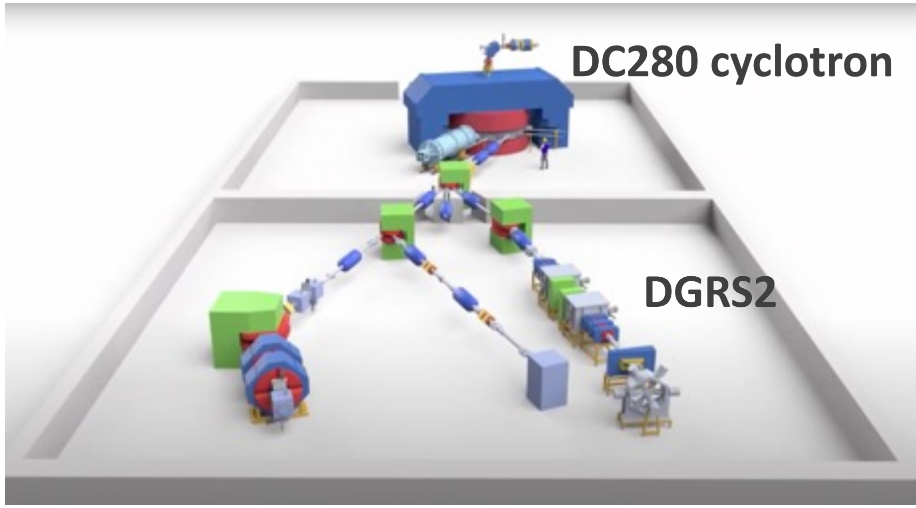
Dedicated facility

SC ion source and very high intensity cyclotron : 10-20pµA

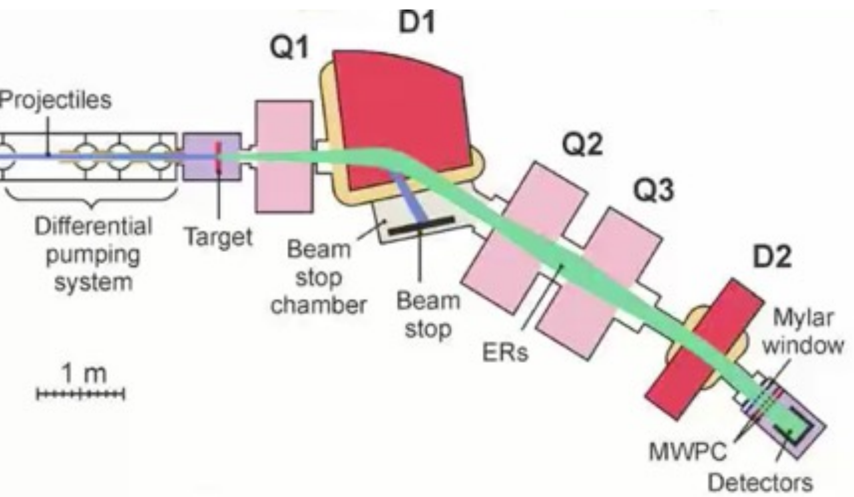
➔ 1^{st} commissioning experiments in 2018

➔ Construction of Dubna Gas filled recoil separator 2 DGFRS2

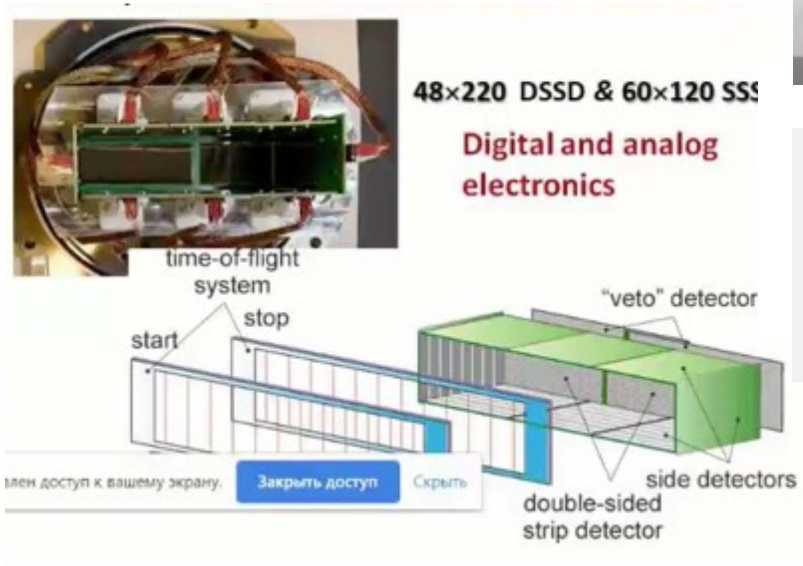
➔ New focal plane detectors 48x220 DSSD & 60x12 SSSD



DGRS 2



Focal plane detector



😀 Very high beam intensity 10 pµA for ^{48}Ca
😀 High transmission
😀 Very long beam time available
7000 h per year

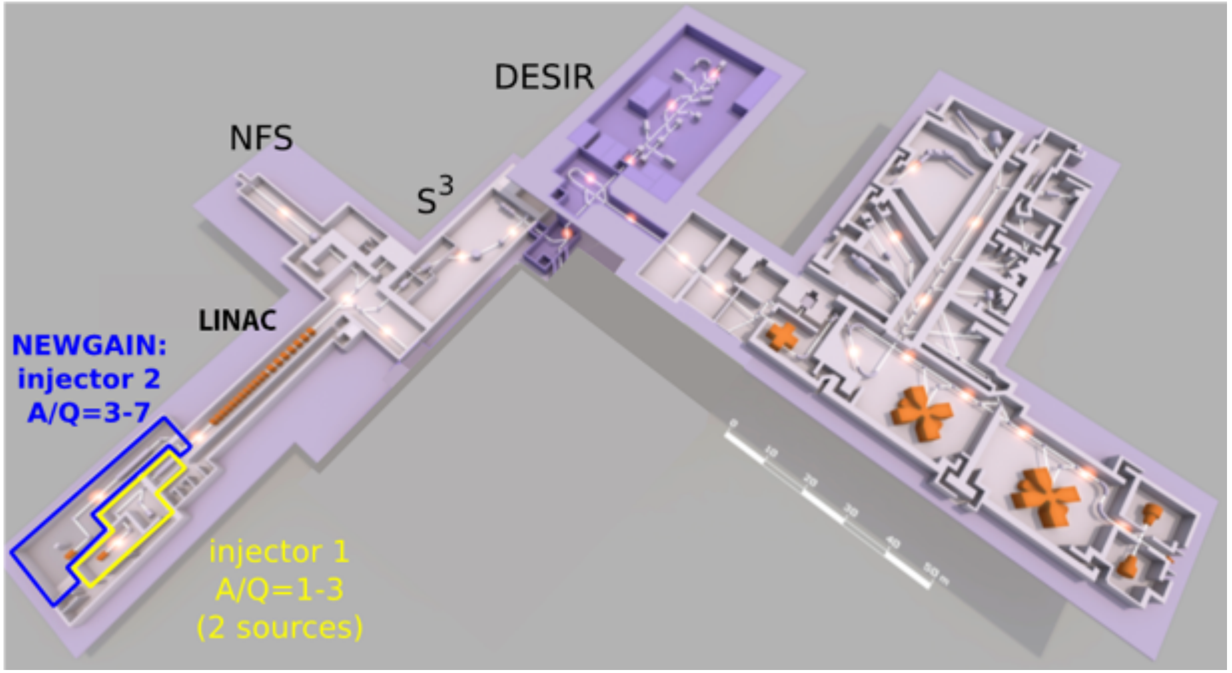
😟 No mass resolution
😟 No separation
😟 No U beams available

OUTLINE

- How many elements exists
- How to produce them
- How to produce them today
- Method used nowadays to sythetize SHE
- **How to go heavier and heavier**

→ projectile nuclei heavier than ^{48}Ca, such as ^{50}Ti, ^{51}V, and ^{54}Cr,^{208}U and transactinides targets Cf

FUTURE: NewGain project @ GANIL

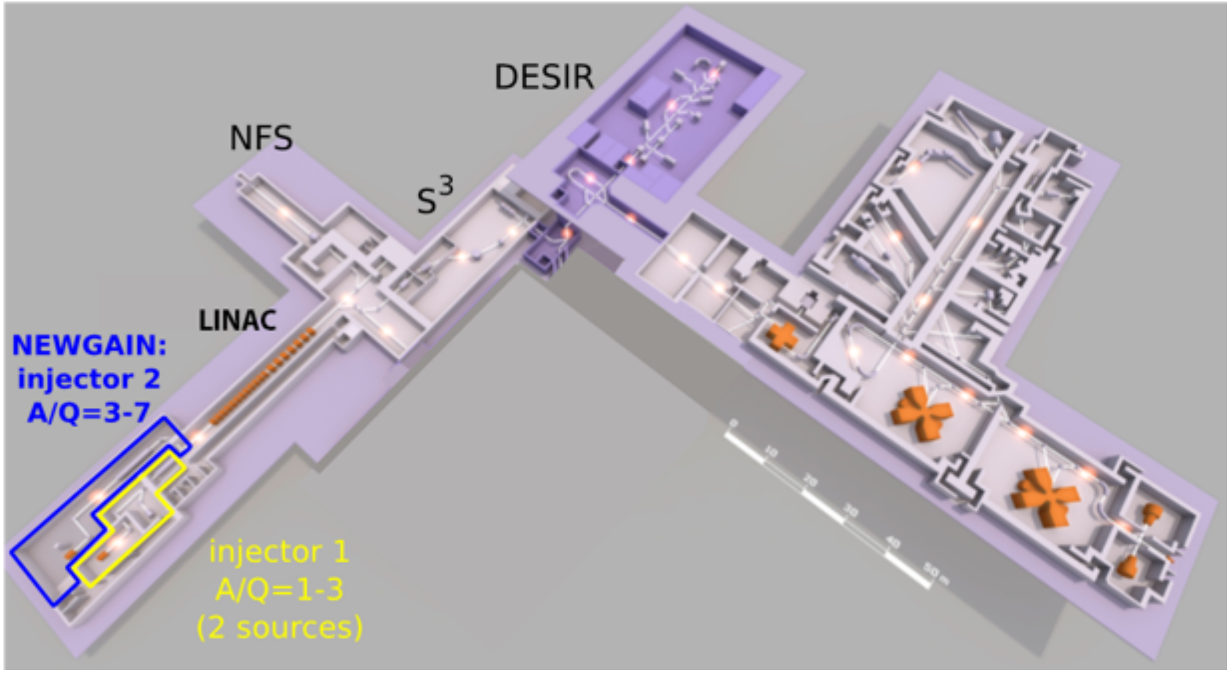


AIMS

- Second injector A/q=7
- Intense heavy ion beams up to Uranium
- Will be used by S3, Desir, NFS

GANIL,CENBG,USC,IPHC,CIMAP,INSP,IJCLab,IP2I,IRFU

FUTURE: NewGain project @ GANIL



AIMS

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- Intense heavy ion beams up to Uranium
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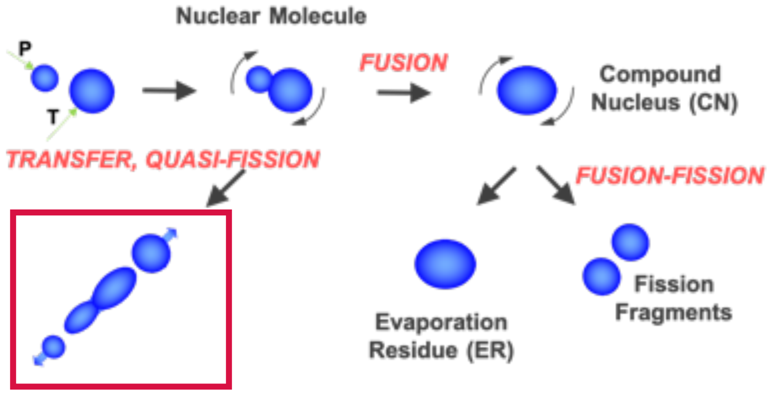
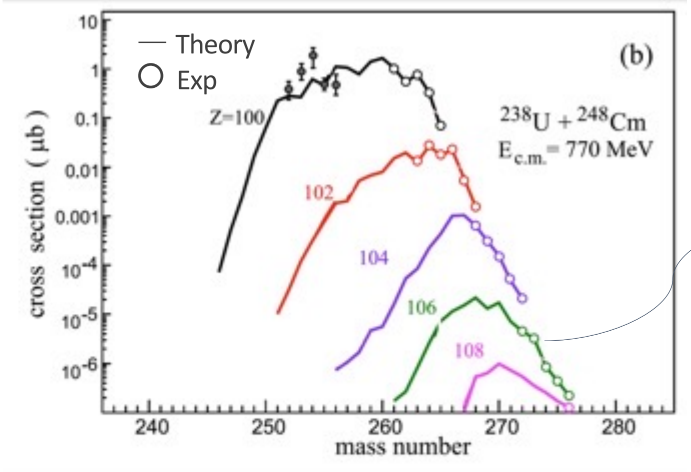
Beam intensities puA (6.2e+12 pps)	SPIRAL2 GANIL, Caen			
	LINAG A/q≤3 Phoenix v3	NEWGAIN A/q≤7 Phoenix v3	NEWGAIN A/q≤6 SC source	NEWGAIN A/q≤7 SC source
^{18}O	80	>64	300	300
^{40}Ar	16	56	56	56
^{36}S	2.3	30	30	30
^{40}Ca	2.9	16	16	16
^{48}Ca	1.2	8	16	16
^{58}Ni	1.1	3.2	6.4	6.4
^{86}Kr	0.1	8	16	16
^{136}Xe	0.001	5.6	>8	>8
^{238}U	<<0.001	0.06	0.4	4.8

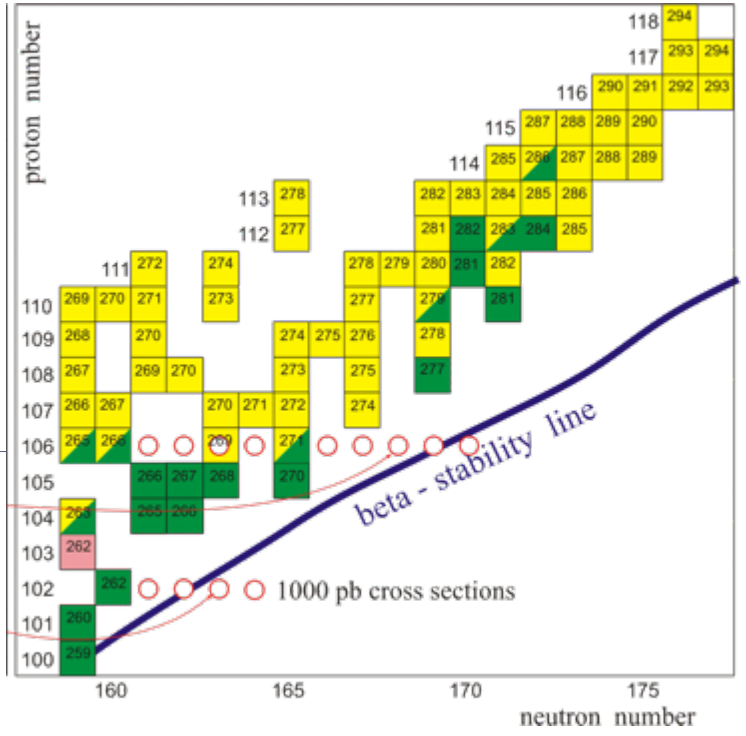
Studies of fission, deep-inelastic reactions and for future rare-isotope beam facilities….

FUTURE installation using NewGAIN: MNT studies



Cross sections for transfer reaction





V. Zagrebaev,W. Greiner, Nulc. Phys. A 944 (2015)

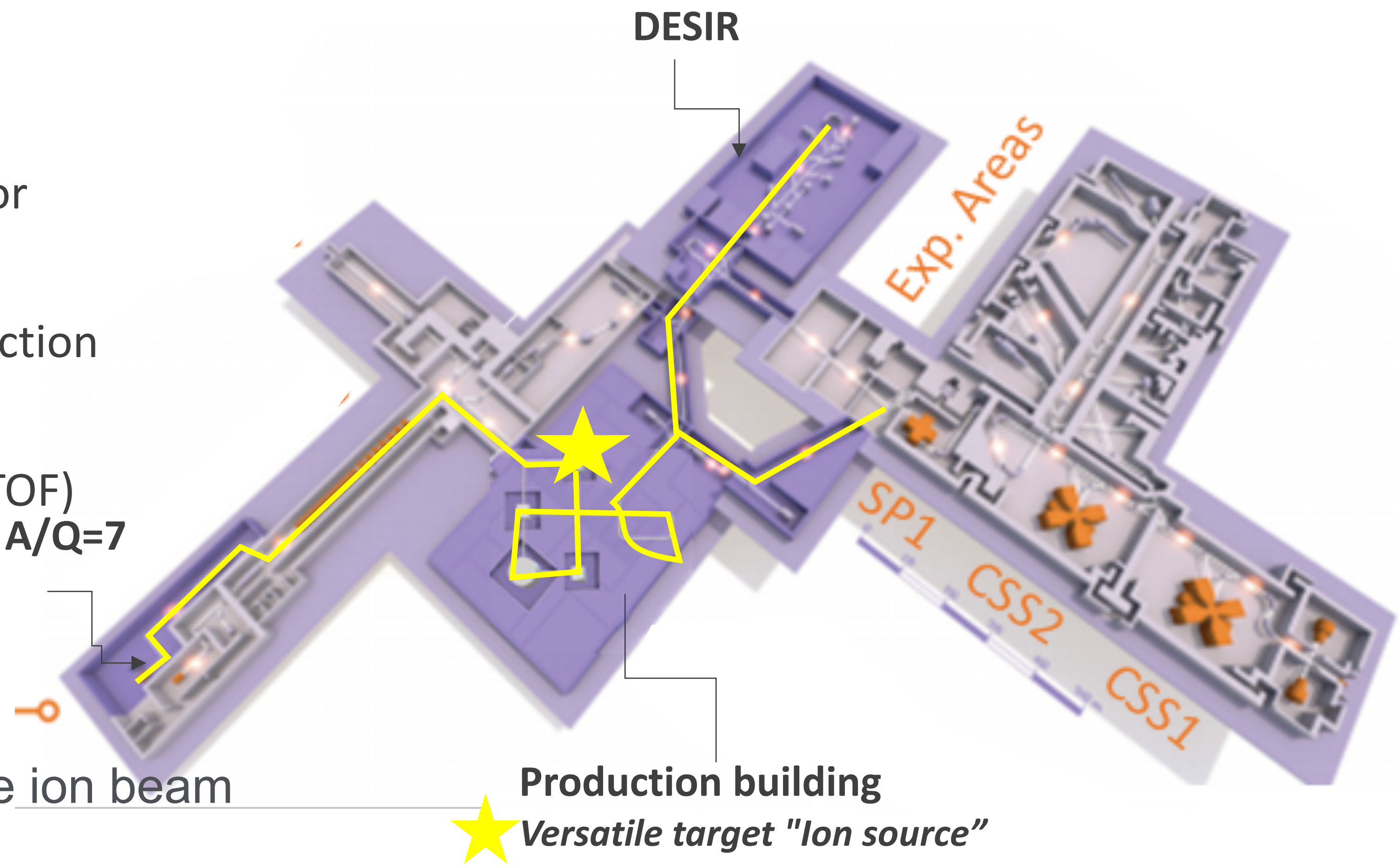
- ➢ Produce very heavy neutron rich nuclei
- ➢ Higher cross section at 0° for projectiles with high in A and Z
- → NewGain mandatory
- ➢ Large angular and momentum distribution of the fragment produced

- ➢ S3 usefulness due to kinematic limitation imposed by the electric dipole
- → Need a new separation selection device

Zagrebaev and Greiner pointed out role of shell structure in enhancing yields and utility of running reactions near the Barrier.

FUTURE installation using NewGAIN under investigation

- The high heavy beam from Newgain injector
- A new target ion source based on MNT reaction
- S3-Leb for separation (buncher, laser, MR-TOF)
- DESIR for spectroscopy after decay
- May be reaccelerated to use as radioactive ion beam



See for more details https://indico.in2p3.fr/event/20534/attachments/57082/89393/Report_ExoticBeamRe-Acceleration.pdf

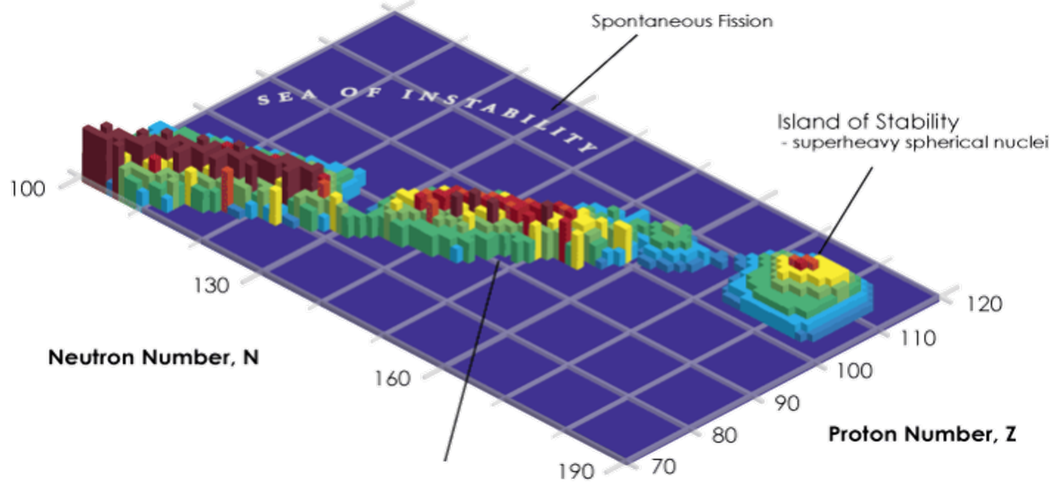
Conclusion

The voyage continues into the uncharted regions of the periodic table of elements

- S3 have been built and first experiment will be start in 2023

- SIRIUS focal plane detector for investigation

  SHE nuclei has been built and is now under test

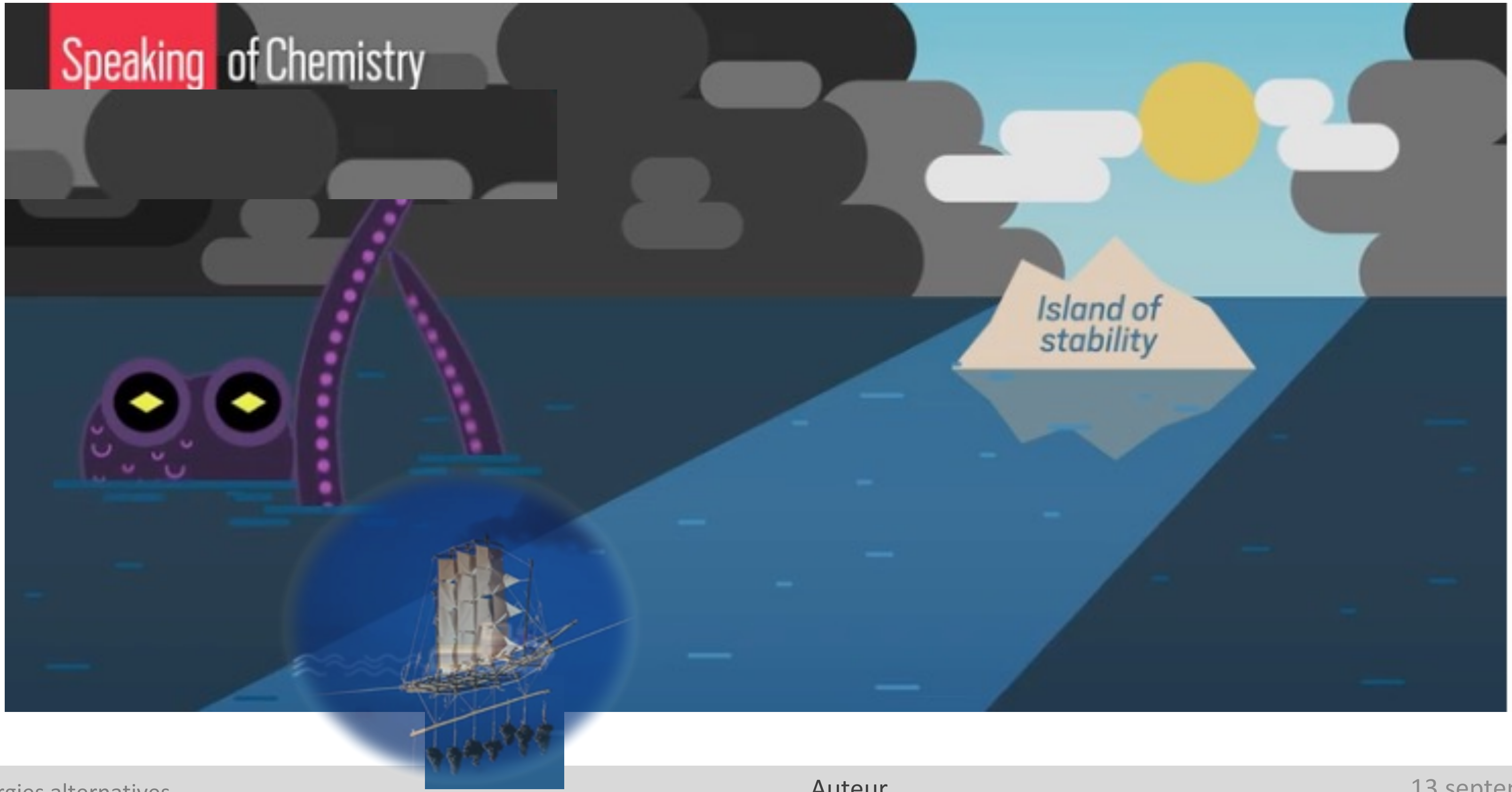


- NewGain ions source have been financed

- Several installation using NewGain beam intensities are under evaluation

- **The voyage continues into the uncharted regions of the periodic table of elements and table of nuclides. Based on the current progress, the prospects in the field of superheavy elements and nuclei are excellent**

(Witold Nazarewicz 2018 nature physics)



Merci de votre attention

13 September