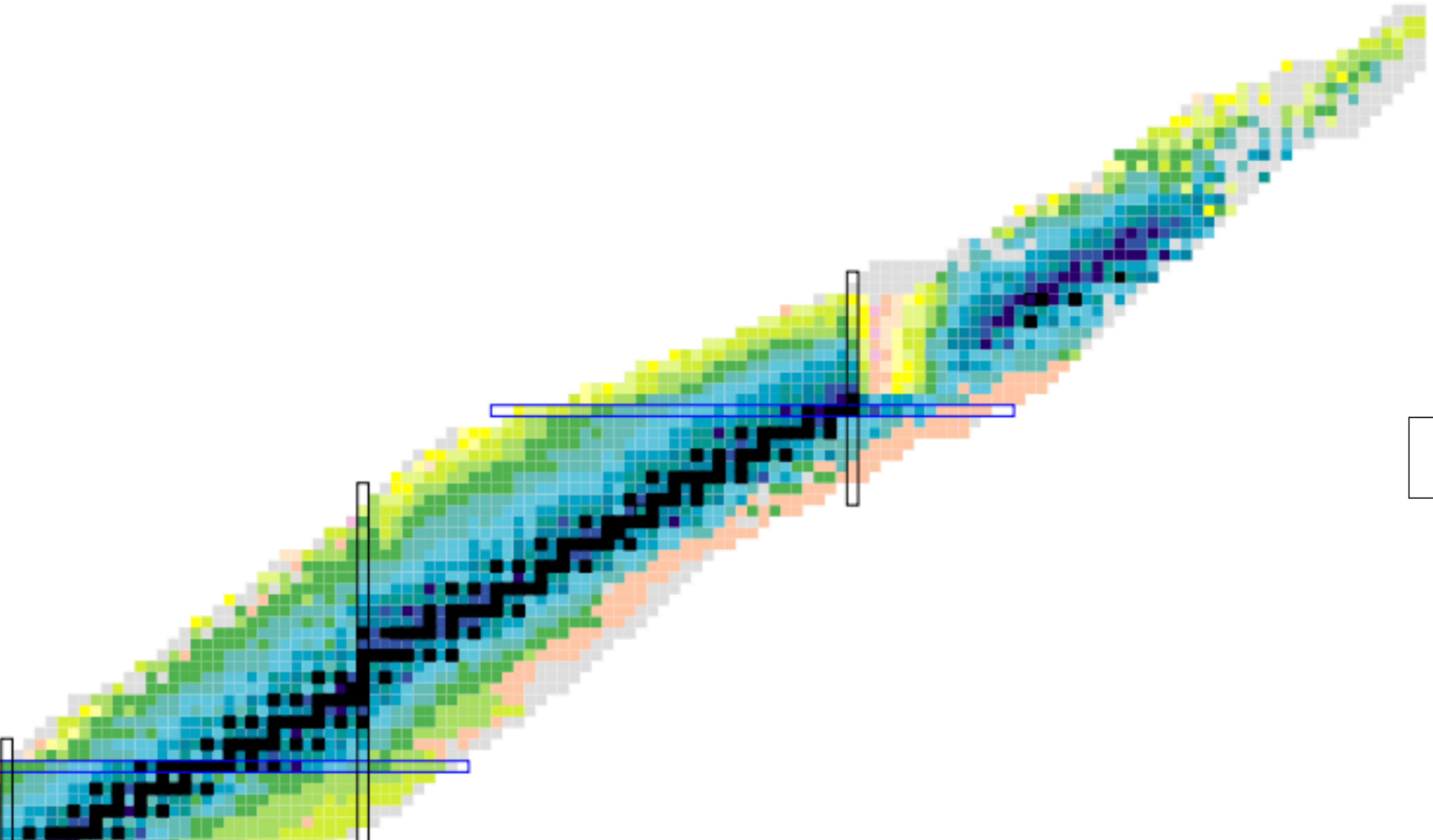
Structure and limits of the superheavy nuclear quantum building



Presentation : Martin BORDEAU
Supervisor : Benoît GALL
« From Nuclei to Stars » group

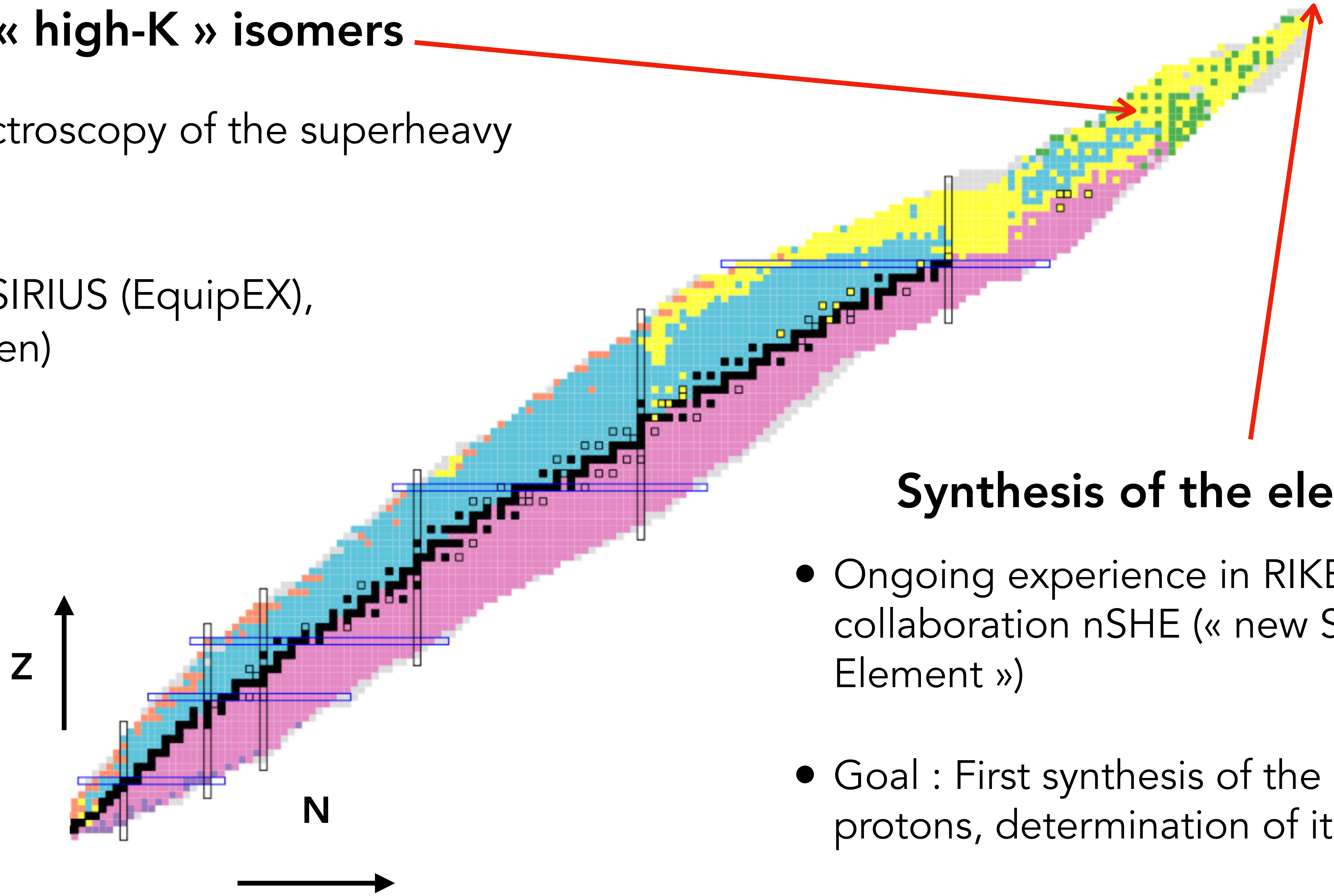
Université de Strasbourg
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
cnrs

Wednesday 21st of June 2023 / Master 2 PSA

Outline

Study of ^{256}Rf « high-K » isomers

- Goal: delayed spectroscopy of the superheavy nucleus of ^{256}Rf
- Facilities : S^3 and SIRIUS (EquipEX), GANIL, France (Caen)

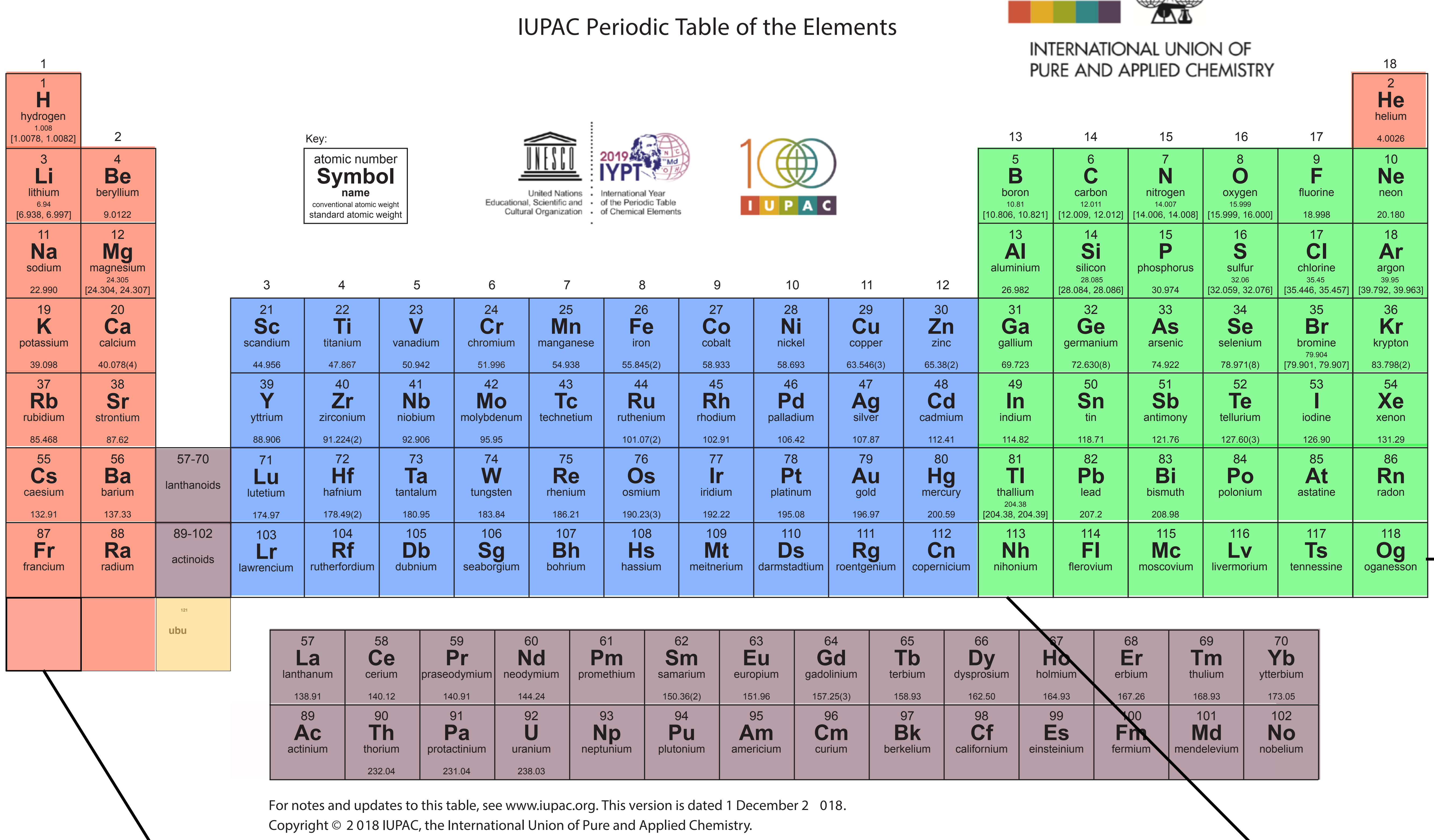


Synthesis of the element Z=119

- Ongoing experience in RIKEN, Japan, through collaboration nSHE (« new Super Heavy Element »)
- Goal : First synthesis of the element with 119 protons, determination of its lifetime and mass

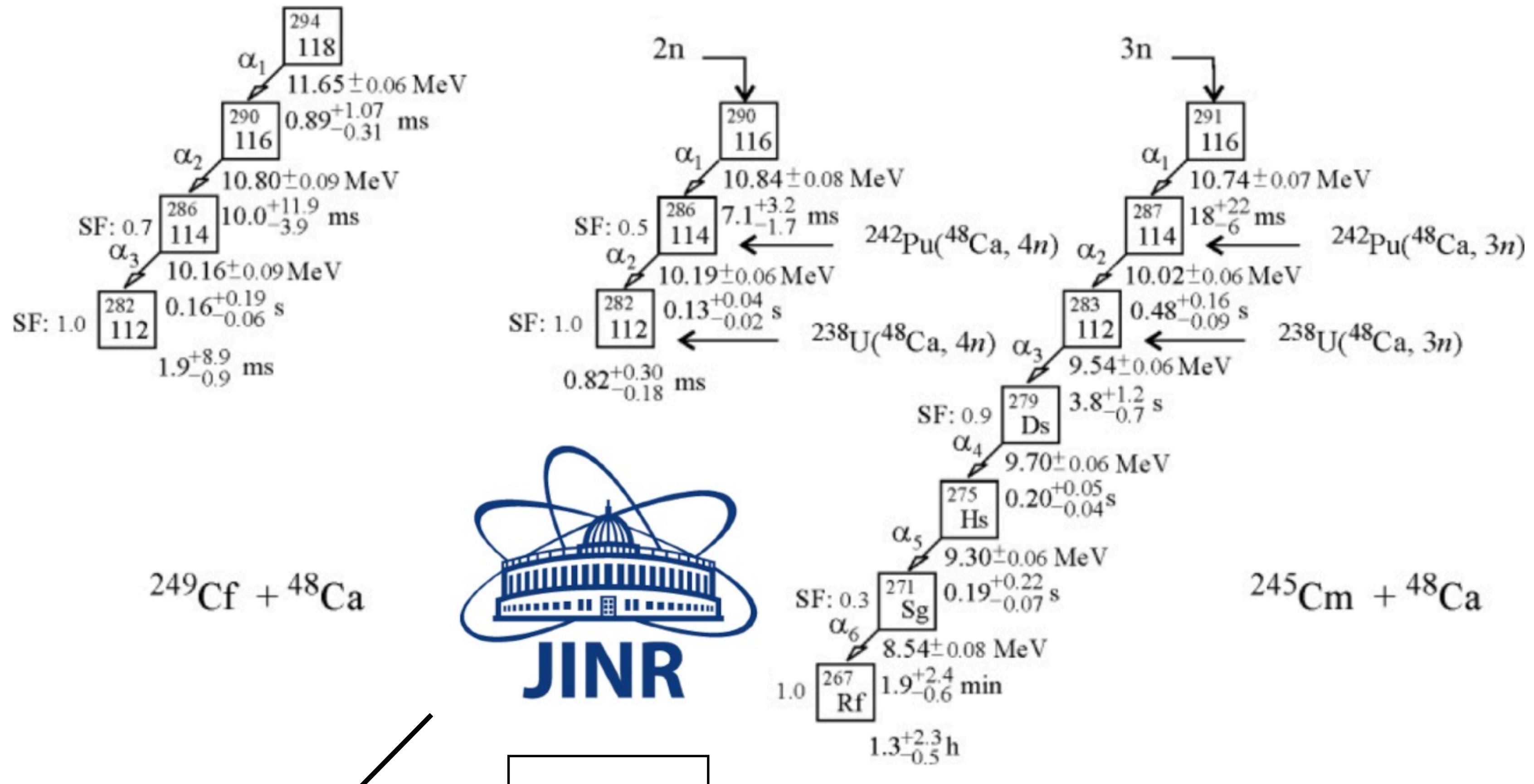
Synthesis of element 119

State-of-the-art

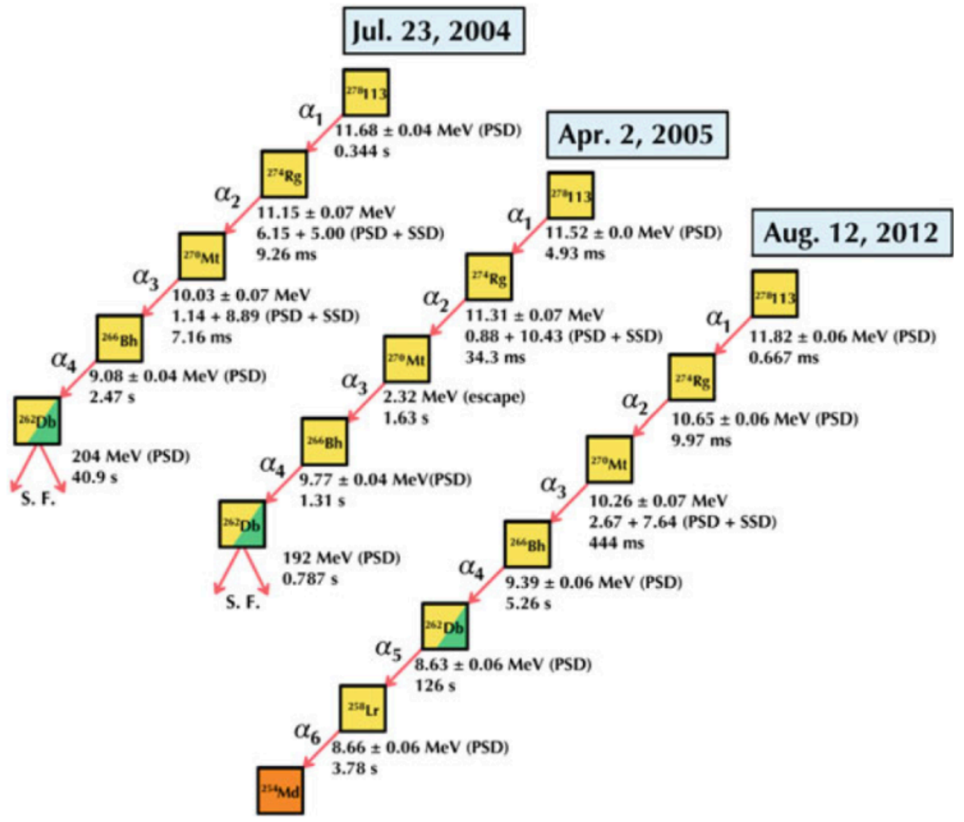


119 or Uue

Og
2006

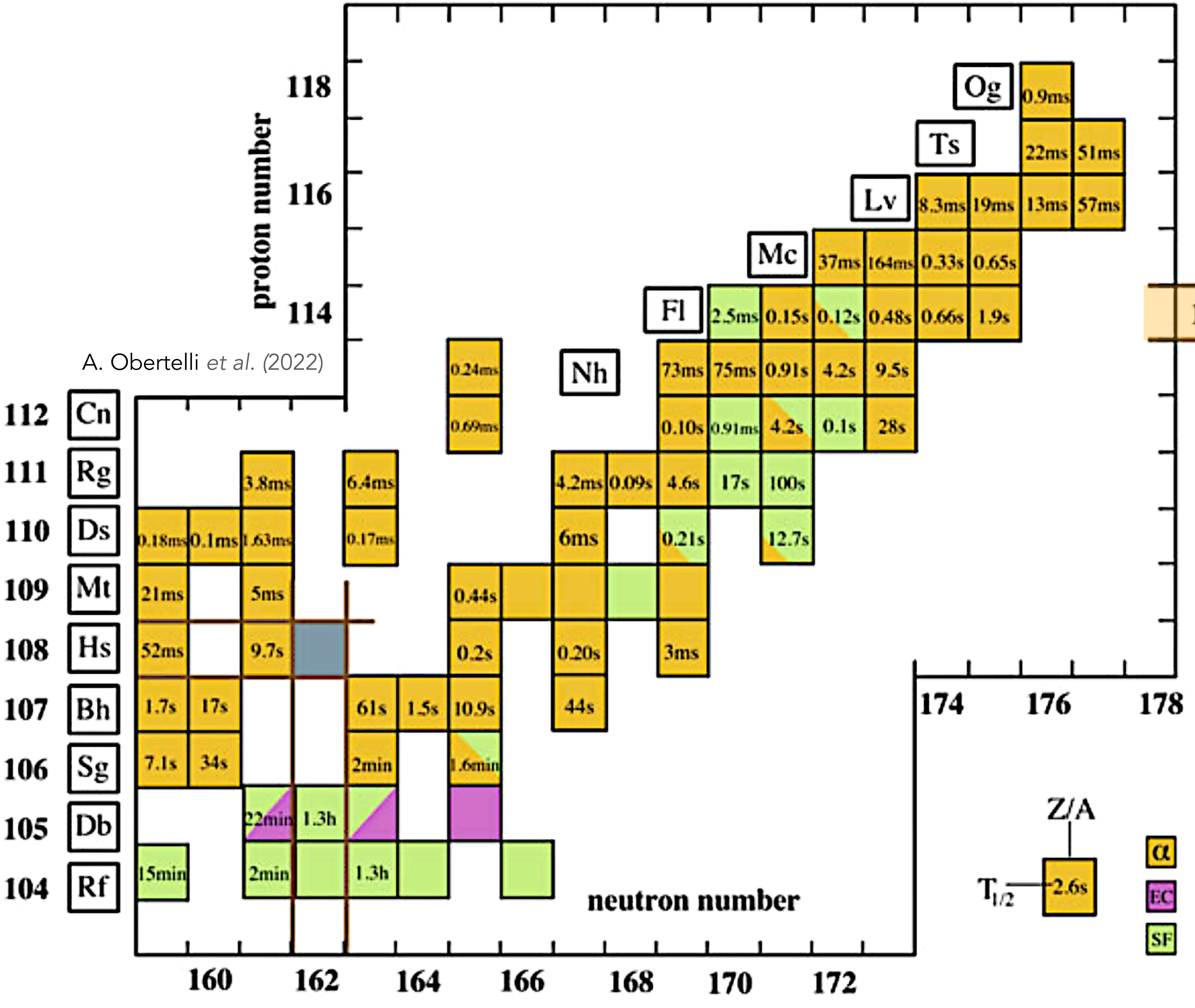


Nh
2012

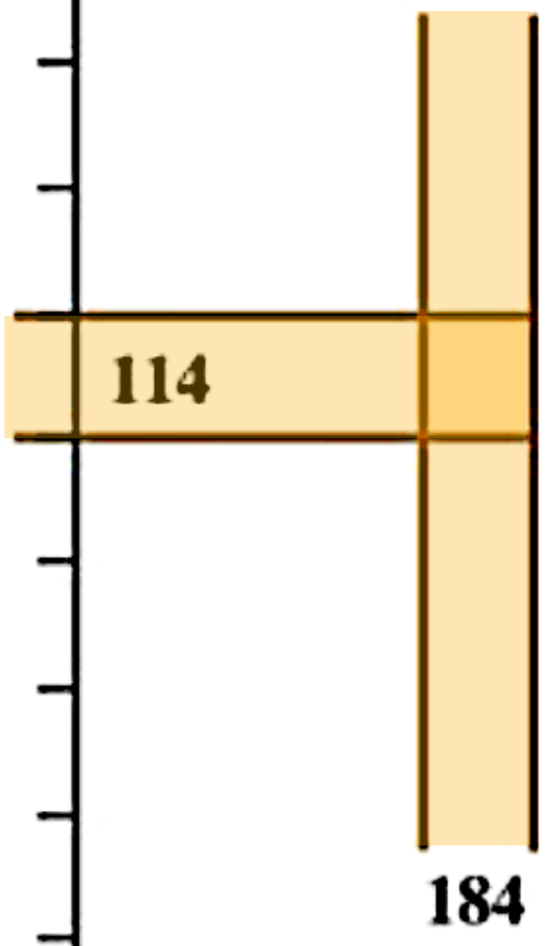


RIKEN

Synthesis of element 119



A. Obertelli *et al.* (2022)



- What is the heaviest nucleus that can be created? How many elements are there?
- New evidence of the existence of the "island of stability"
- New anchor point for theory (constraints thanks to mass and life time)

Model	Z	N
Nilsson	114	184
Wood-Saxon	114	184
Wood-Saxon Universal	126	184
Hartree-Fock-Bogoliubov	126	184
Relativistic Mean Field	120	172

K. Kessaci, Thèse de l'Unistra (2021)

Synthesis of element 119

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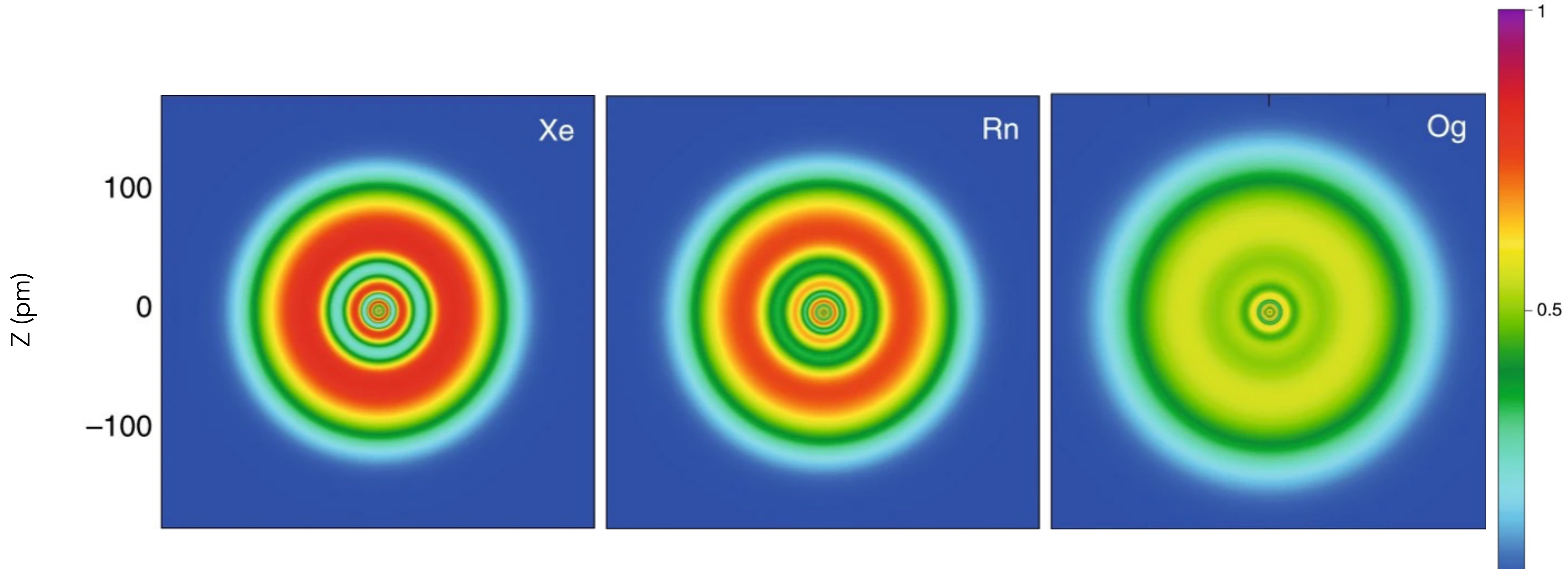
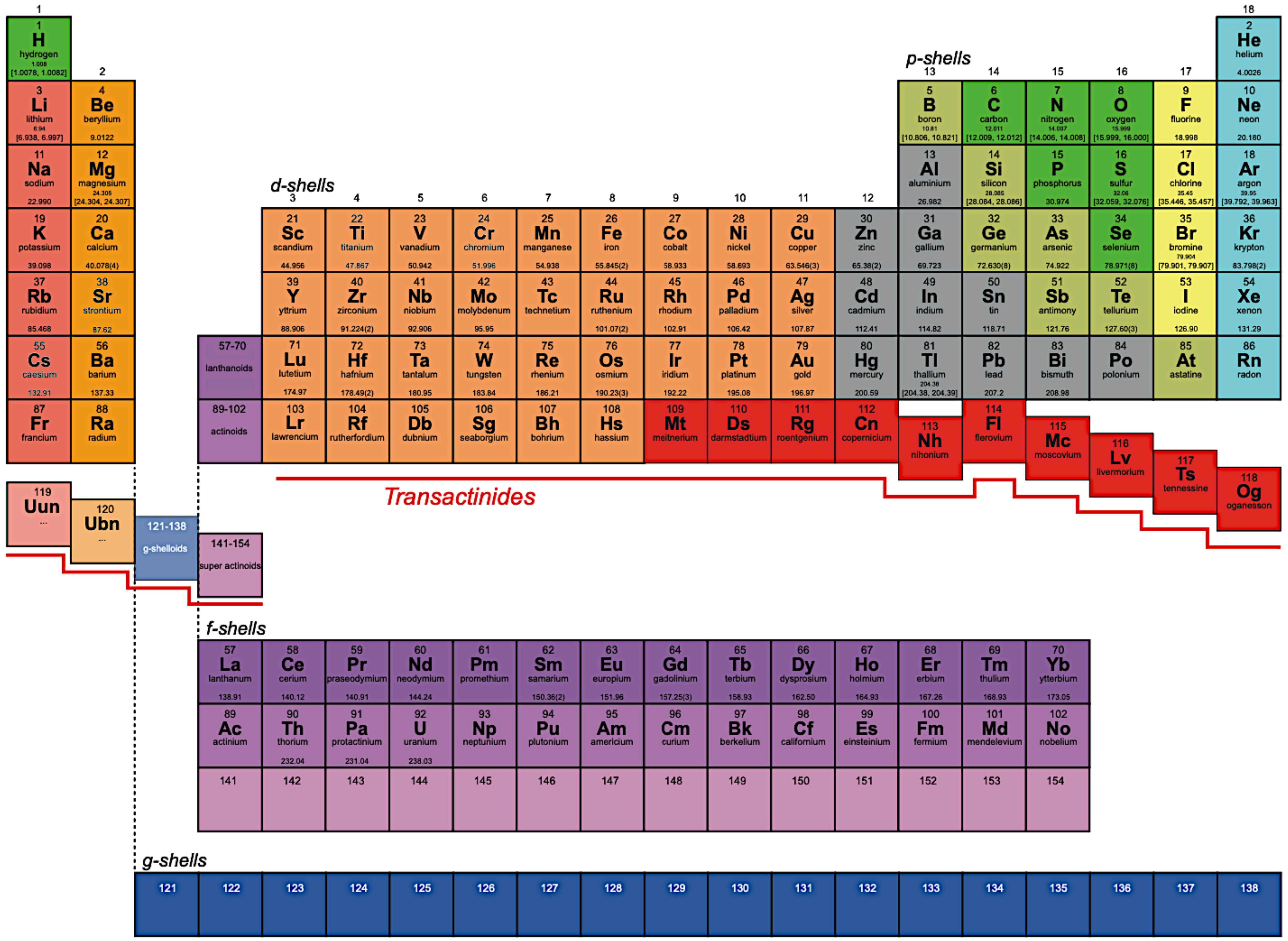
- 7th period completed → Oganesson (Z=118)
- Chemistry of the nuclei *g* electronic layer?
- Not negligible relativistic effects from Z=112
  → what about the classification of the elements?



P. Jerabek *et al.* (2018)



Cf. B. Gall

Synthesis of element 119

Experimental setup @ RIKEN, Japan

- Fusion-evaporation reaction :

$$^{51}\text{V} + ^{248}\text{Cm} \rightarrow ^{299-x}119^{*} + xn$$

- Production cross-section ~ fb !

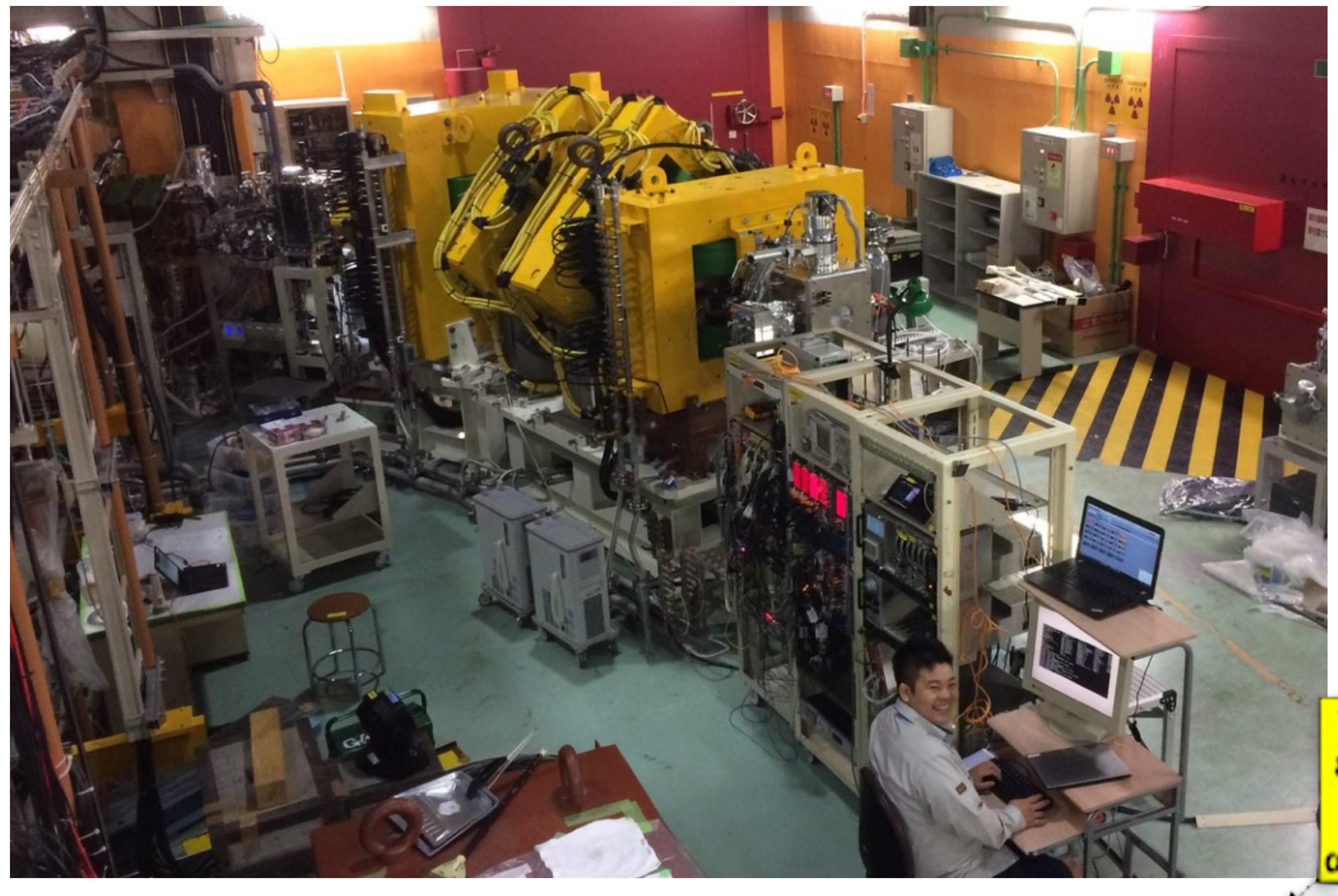
I (pμA)	σ (fb)	Event every:
1	50	2 months
10	50	6 months
1	3	12 years
10	3	15 months

($1 p\mu A \approx 6 \times 10^{12}$ particles/s)

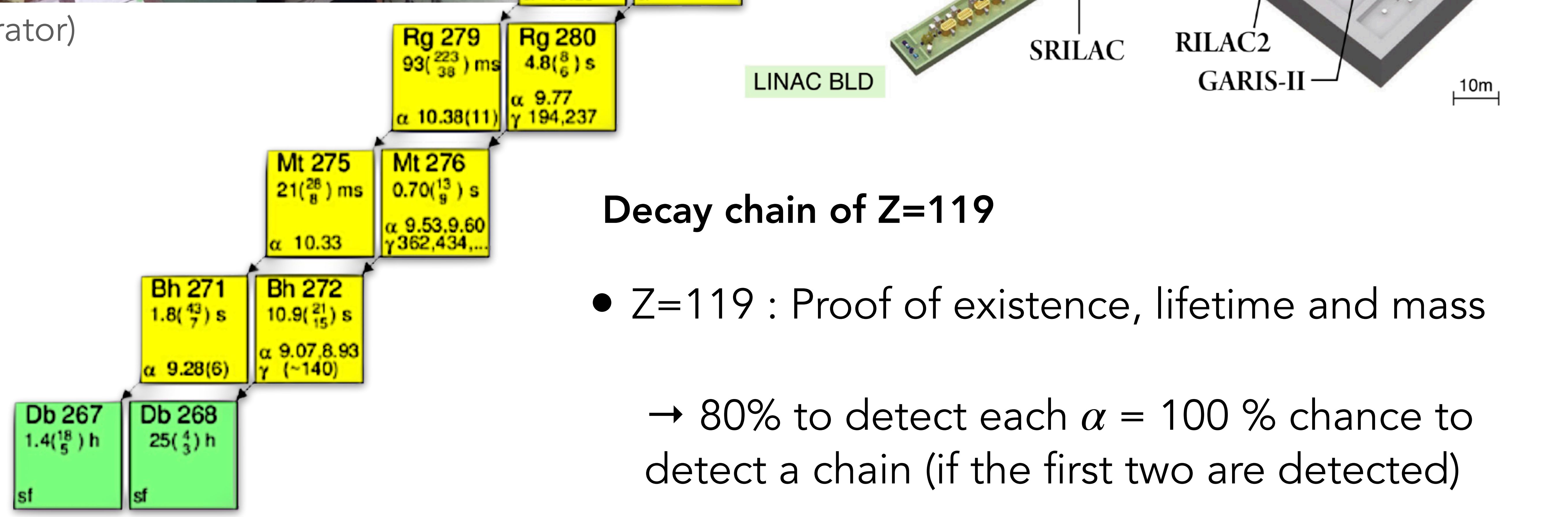
- High intensity

→ Superheavy factory: SRILAC, SHE factory, LINAG

→ New separators : GARIS III, DGFRS II & III, S^3



GARIS II (separator)
Cf. B. Gall



Decay chain of Z=119

- Z=119 : Proof of existence, lifetime and mass

→ 80% to detect each α = 100 % chance to detect a chain (if the first two are detected)

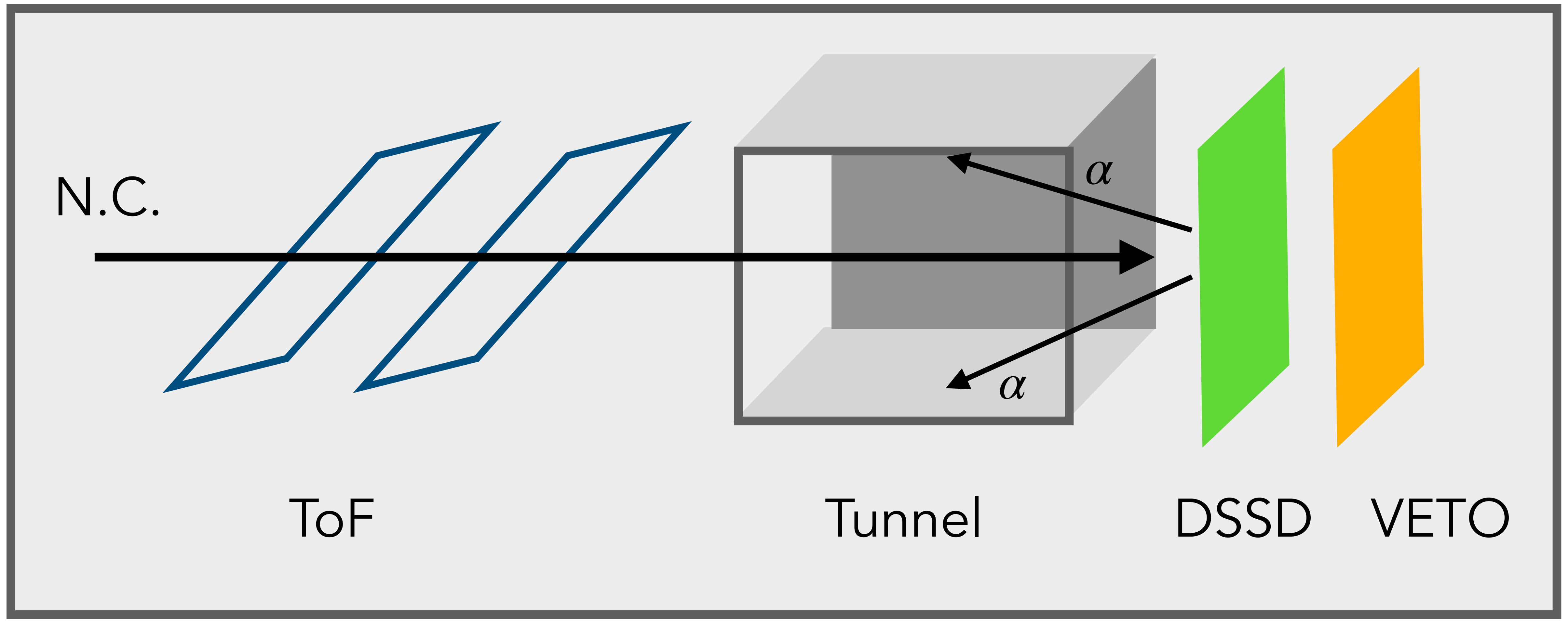
→ isotopes known except Z=117 (Ts)

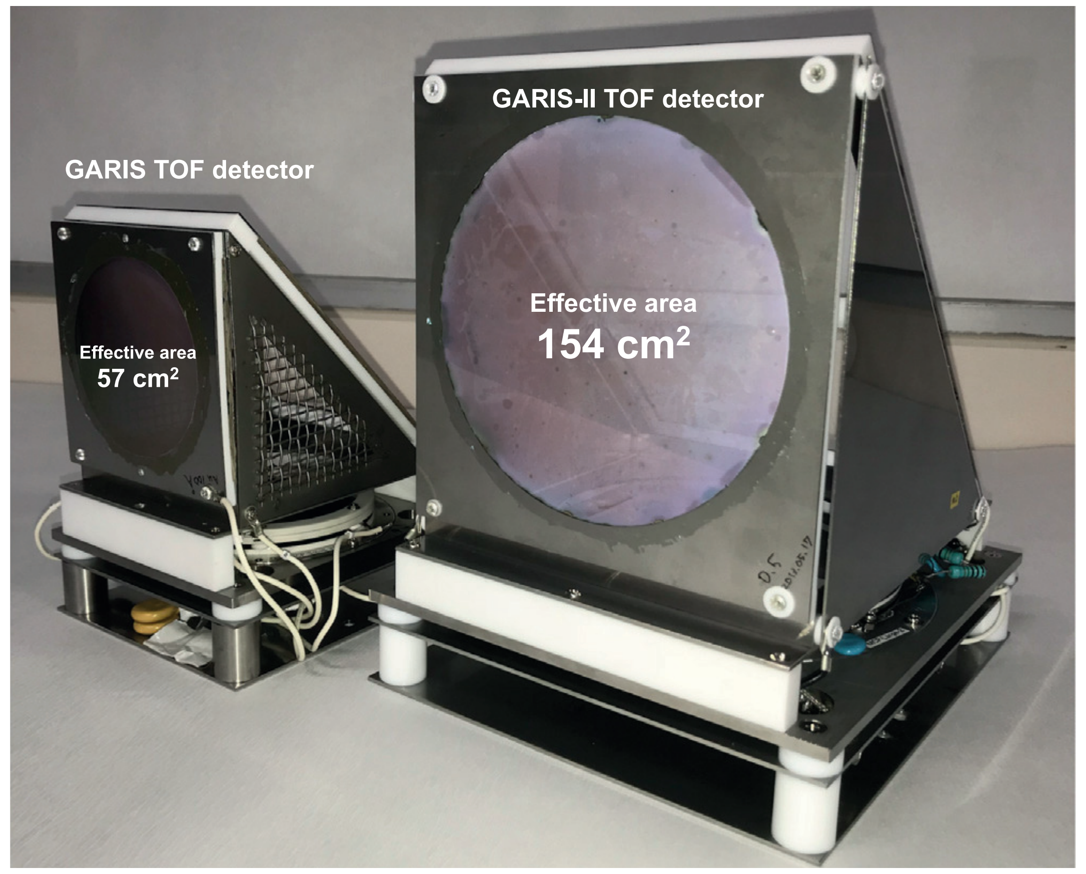
Synthesis of element 119

Experimental setup @ RIKEN, Japan

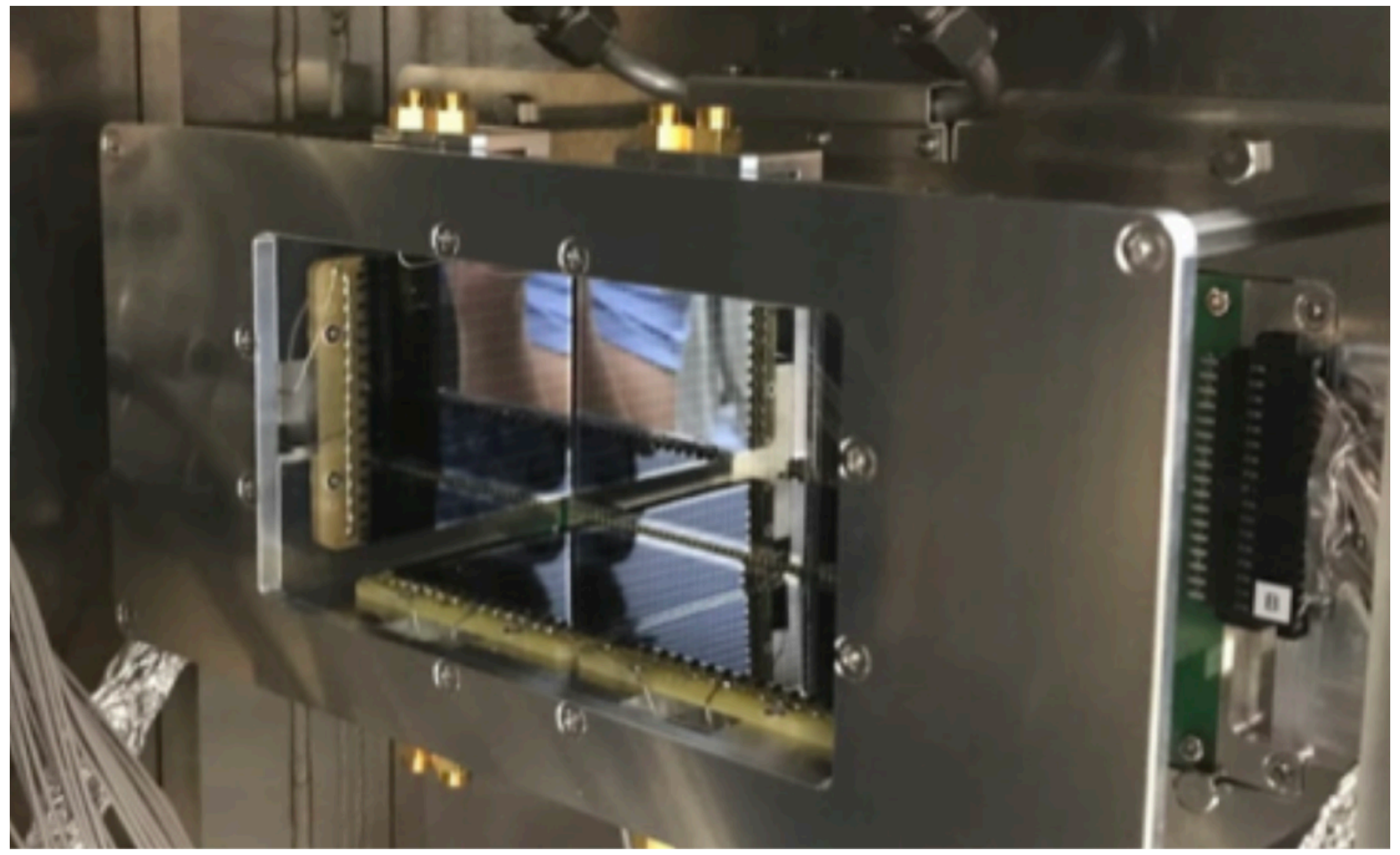
Detection system:

- Time of Flight detector (ToF)
- Double-sided silicon strip detector (DSSD) (reculs, e^- and α)
- non-pixelized silicon Tunnel (e^- and α)
- non-pixelized silicon VETO





ToF detector



Detection chamber

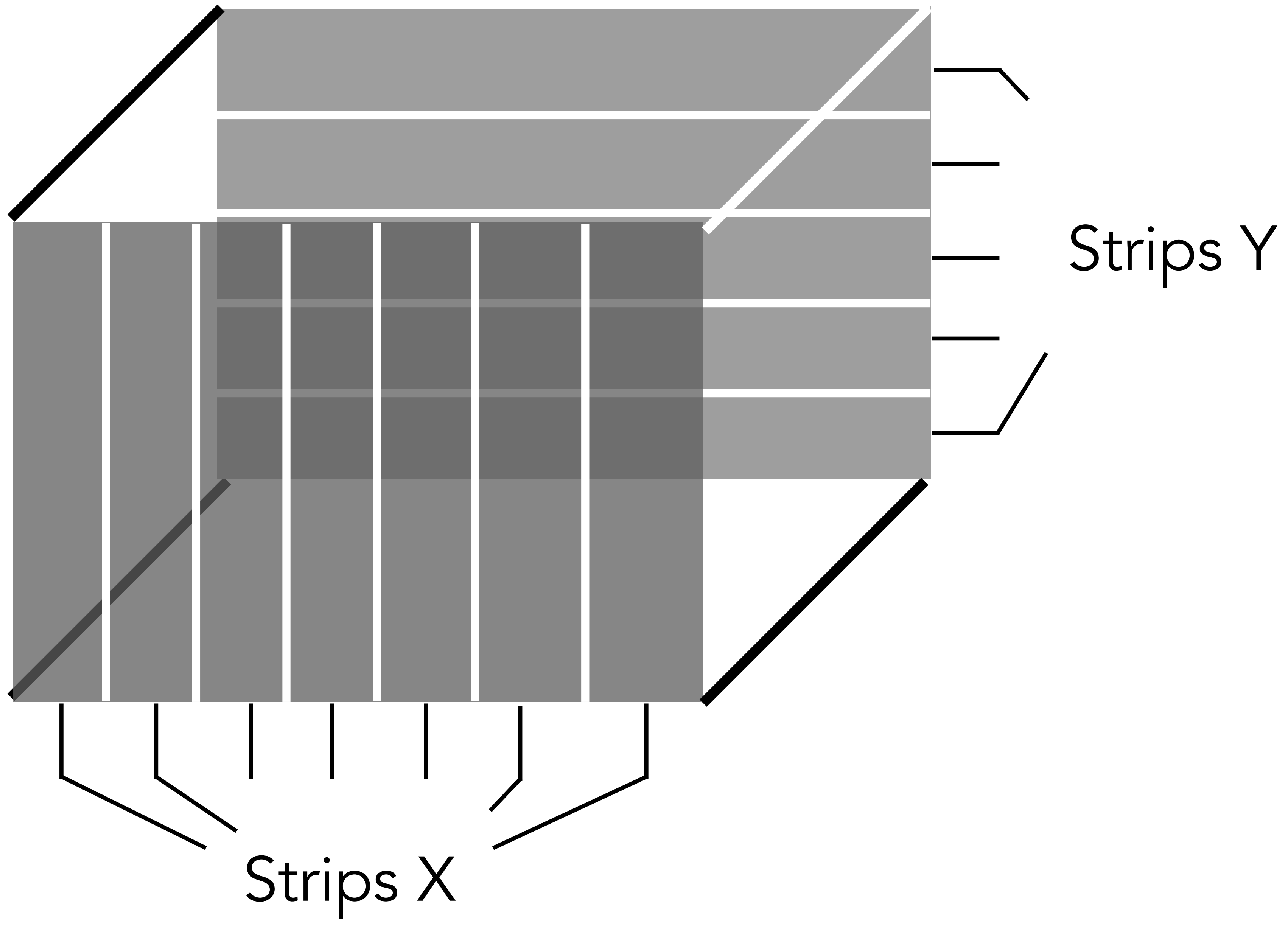
Internship: production of $^{257/258}$Db

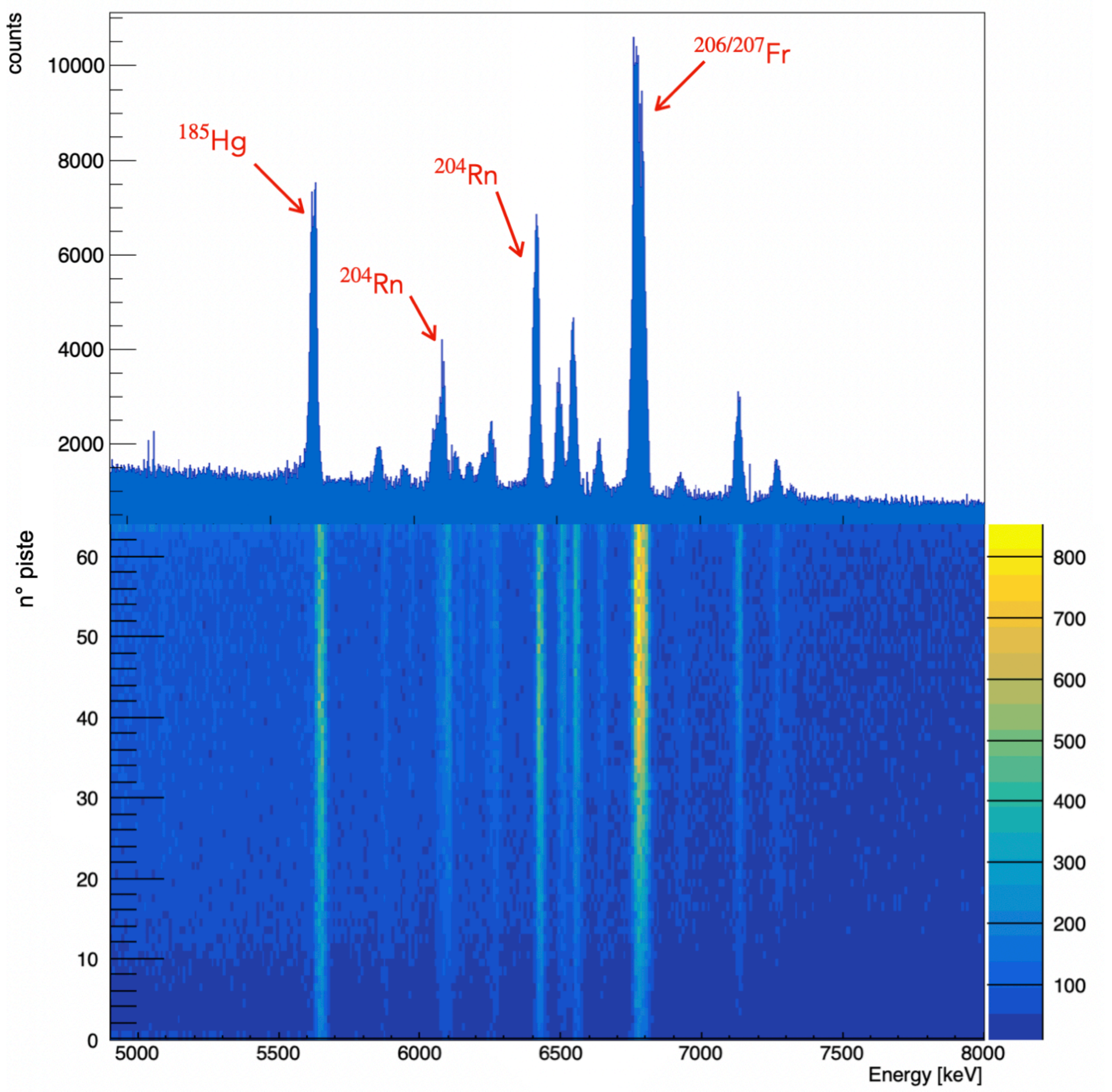
Calibration of an experiment and search for α-decay chains

- Calibration of detectors from reactions →
  $^{51}\text{V} + ^{159}\text{Tb} \rightarrow ^{210-x}\text{Ra} + xn$ and $^{51}\text{V} + ^{135}\text{La} \rightarrow ^{185}\text{Hg} + 5n$

DSSD

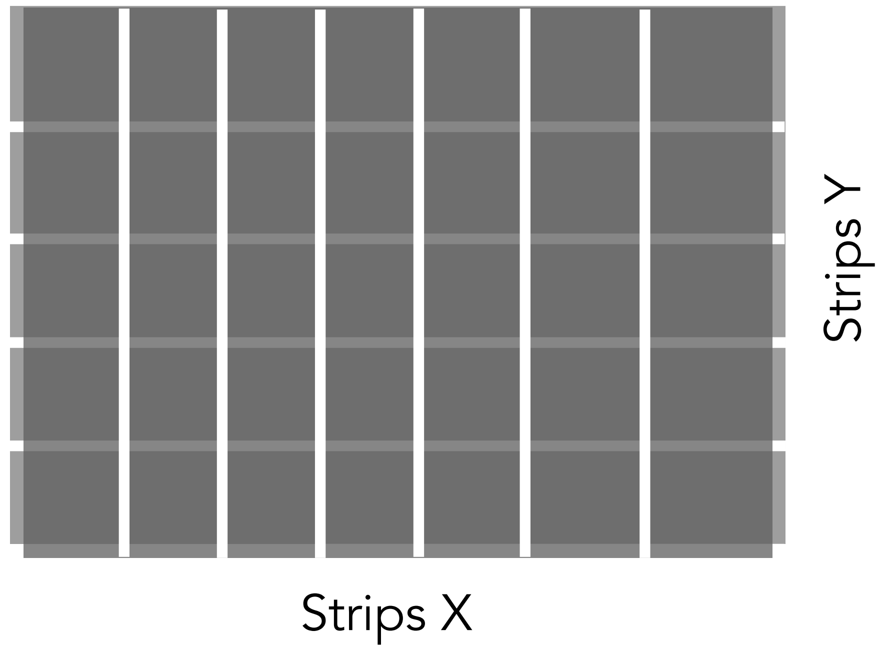
64 x 32 x 2 = 4096 pixels





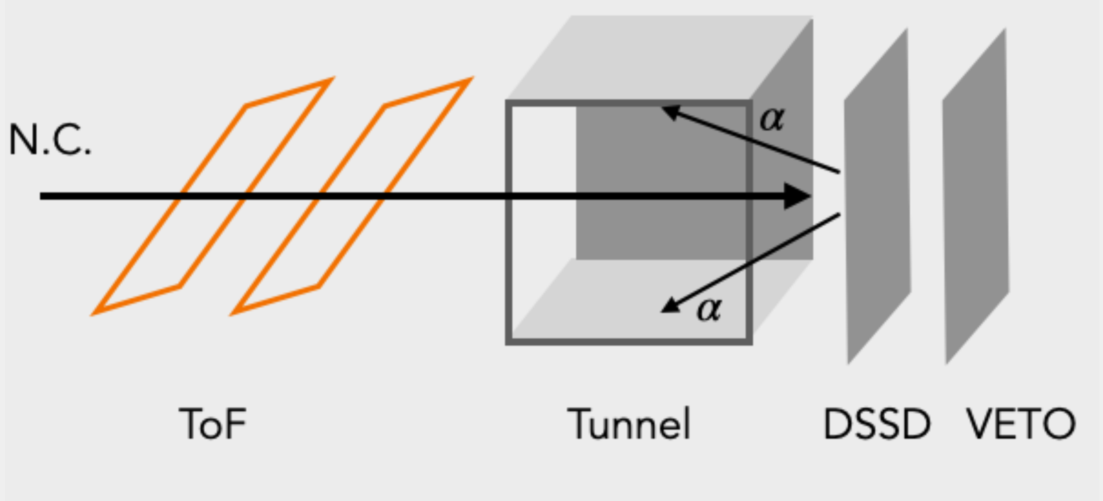
Internship: production of $^{257/258}$Db

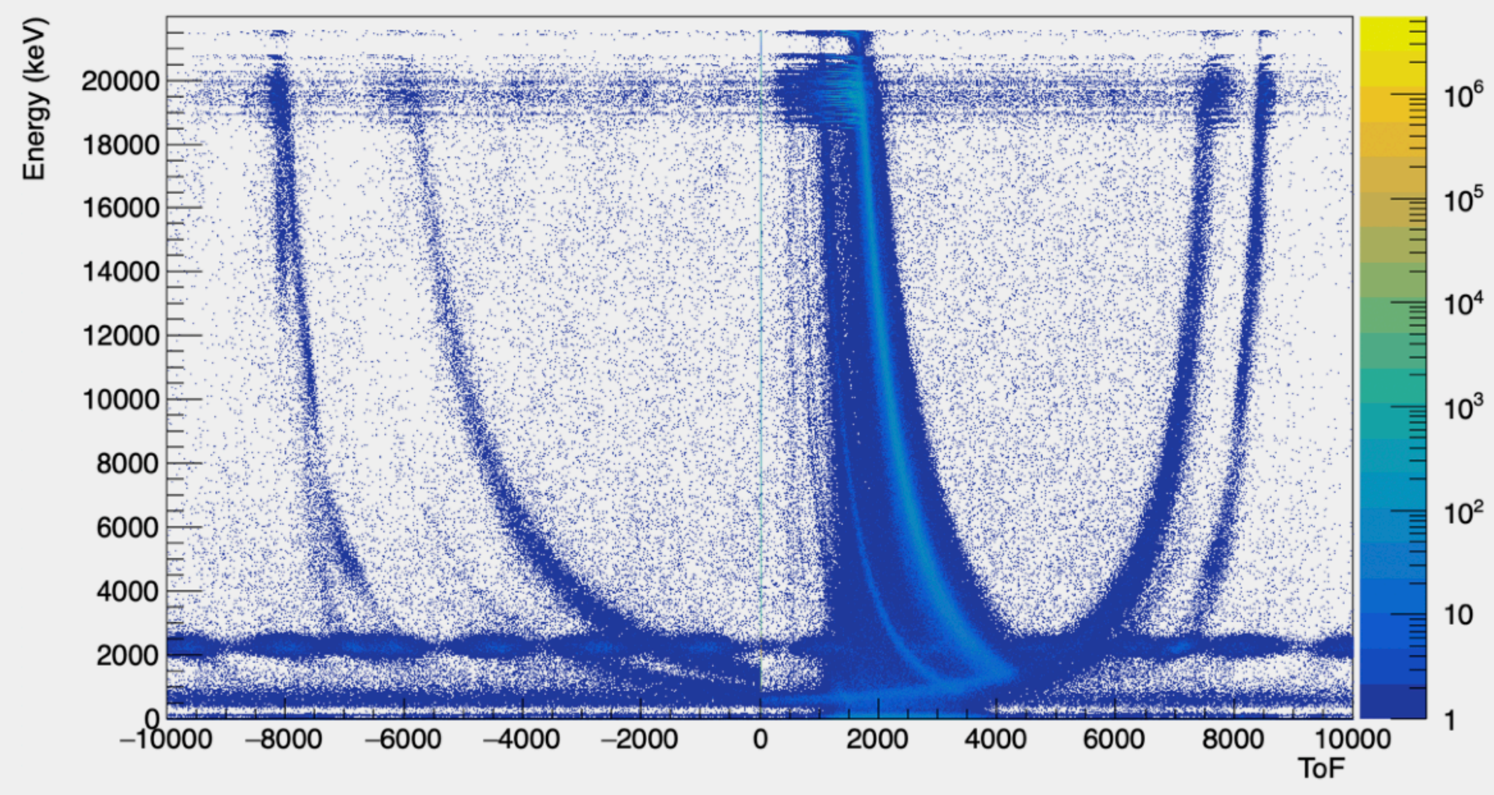
Calibration of an experiment and search for α-decay chains

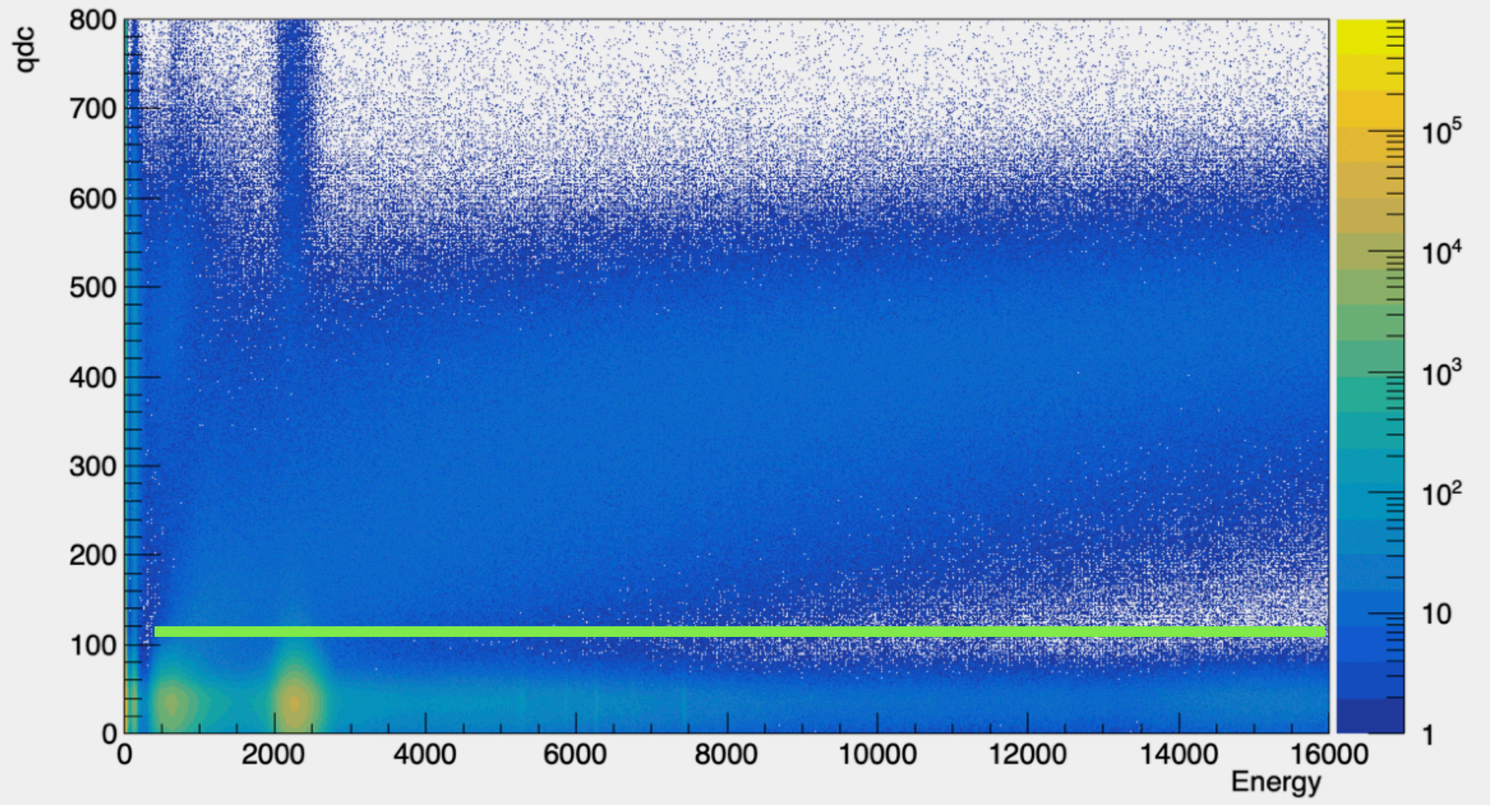


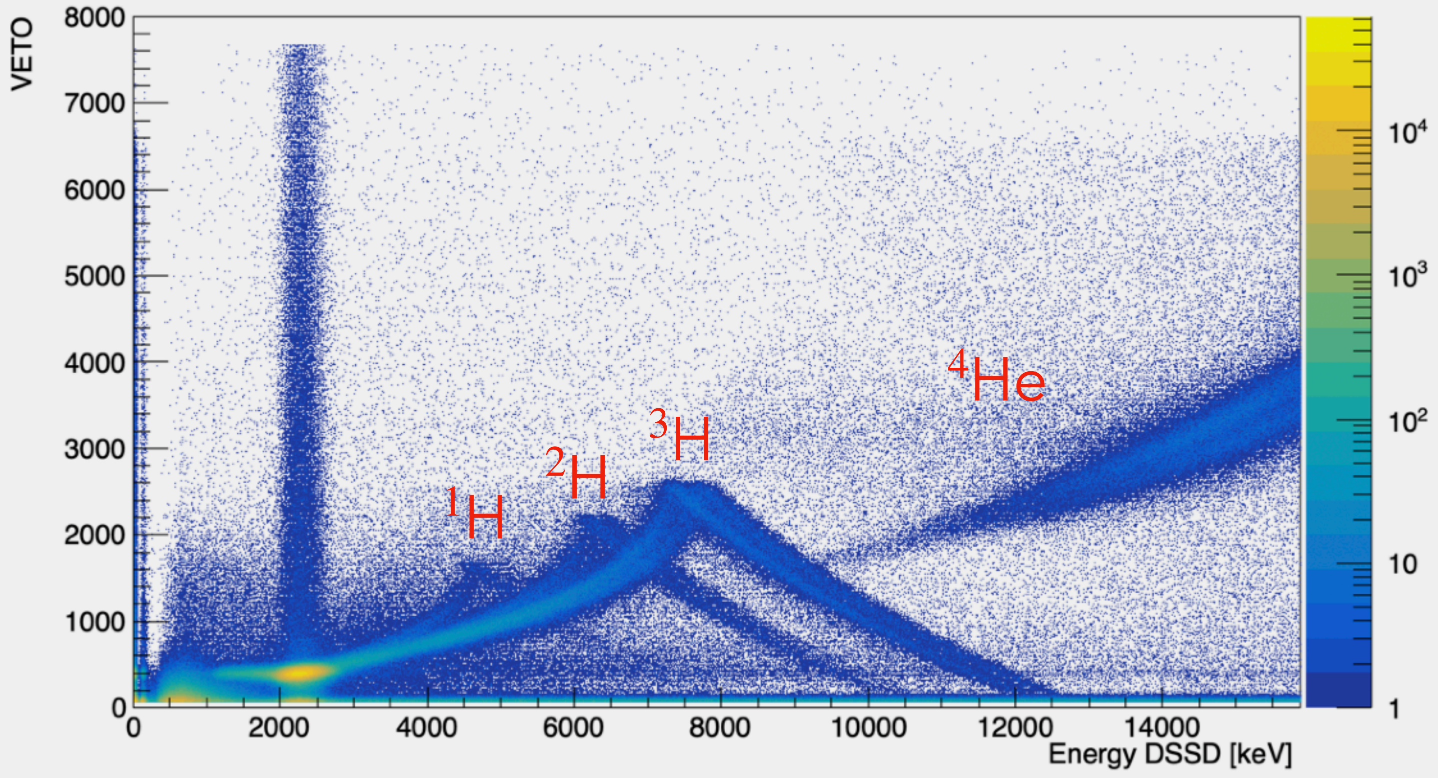
Data flow $\longrightarrow$ RαRA$\alpha\alpha$AαAR$\alpha\alpha$AαAαRR$\alpha\alpha$RAα

- ^{51}V $+^{208}$Pb $\rightarrow^{259-x}$Db $+$ xn
- Filtering using ToF, QDC et VETO



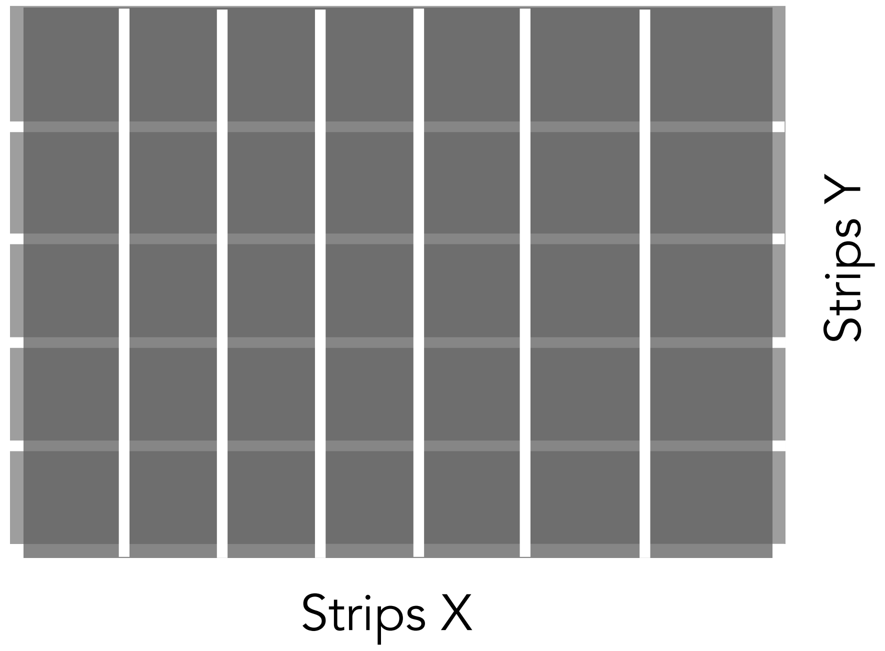






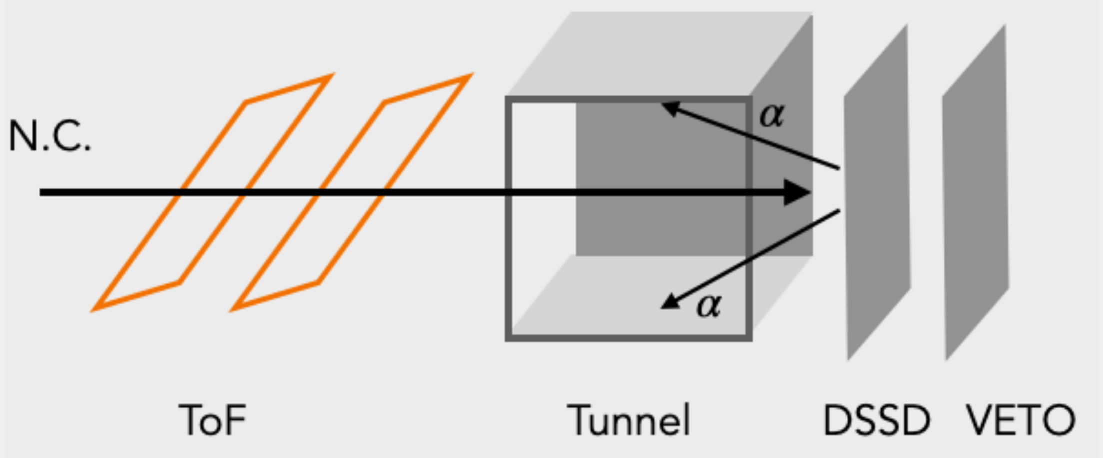
Internship: production of $^{257/258}$Db

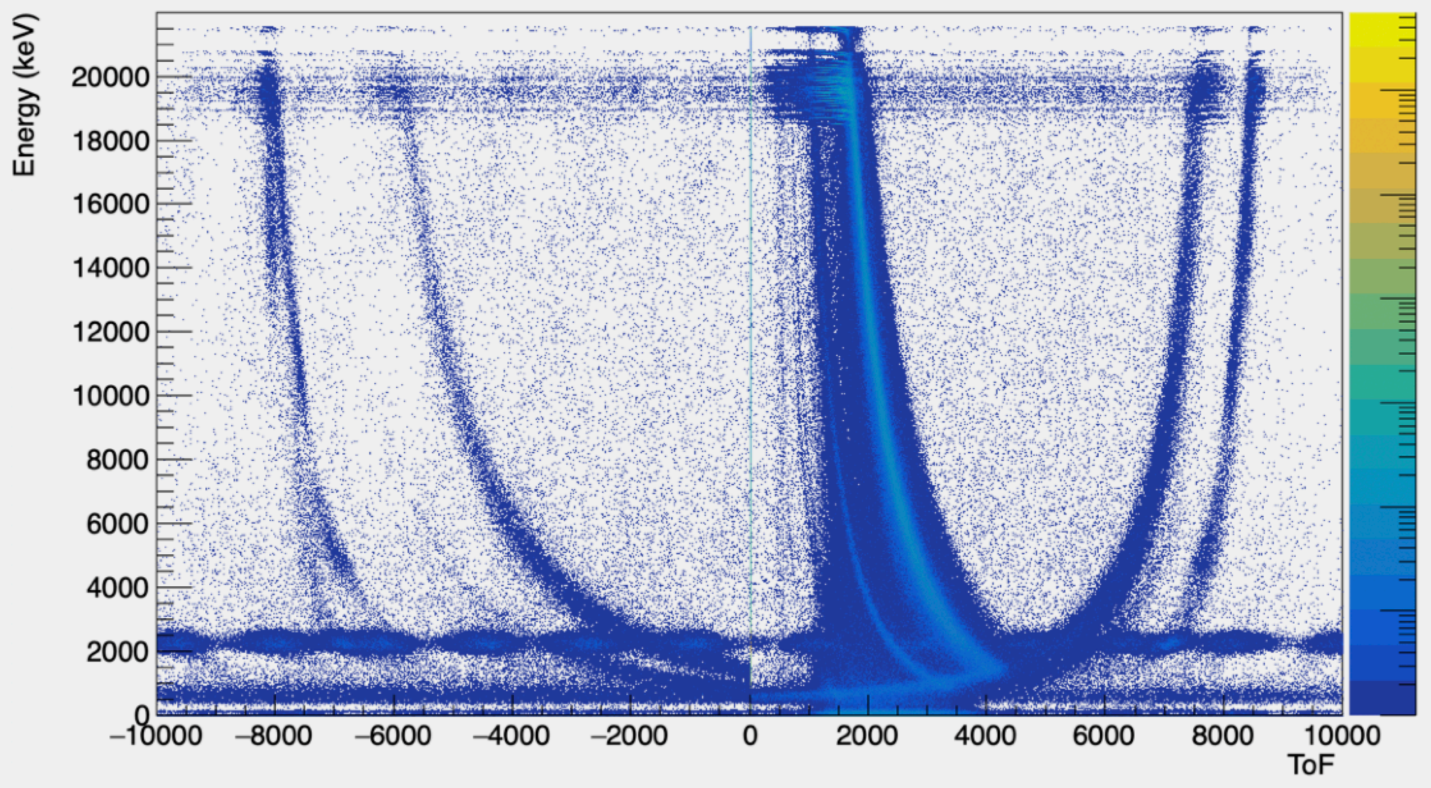
Calibration of an experiment and search for α-decay chains

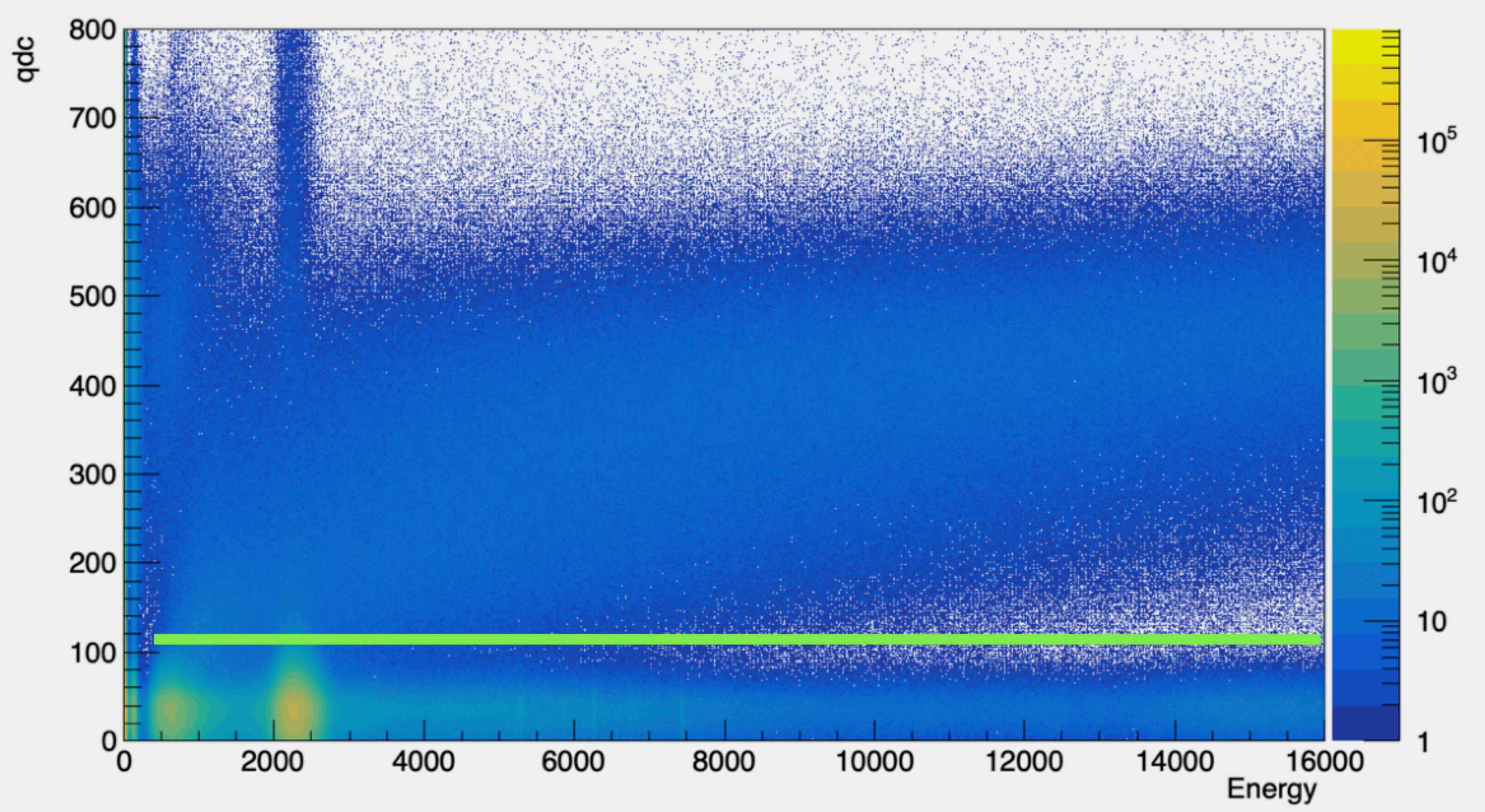


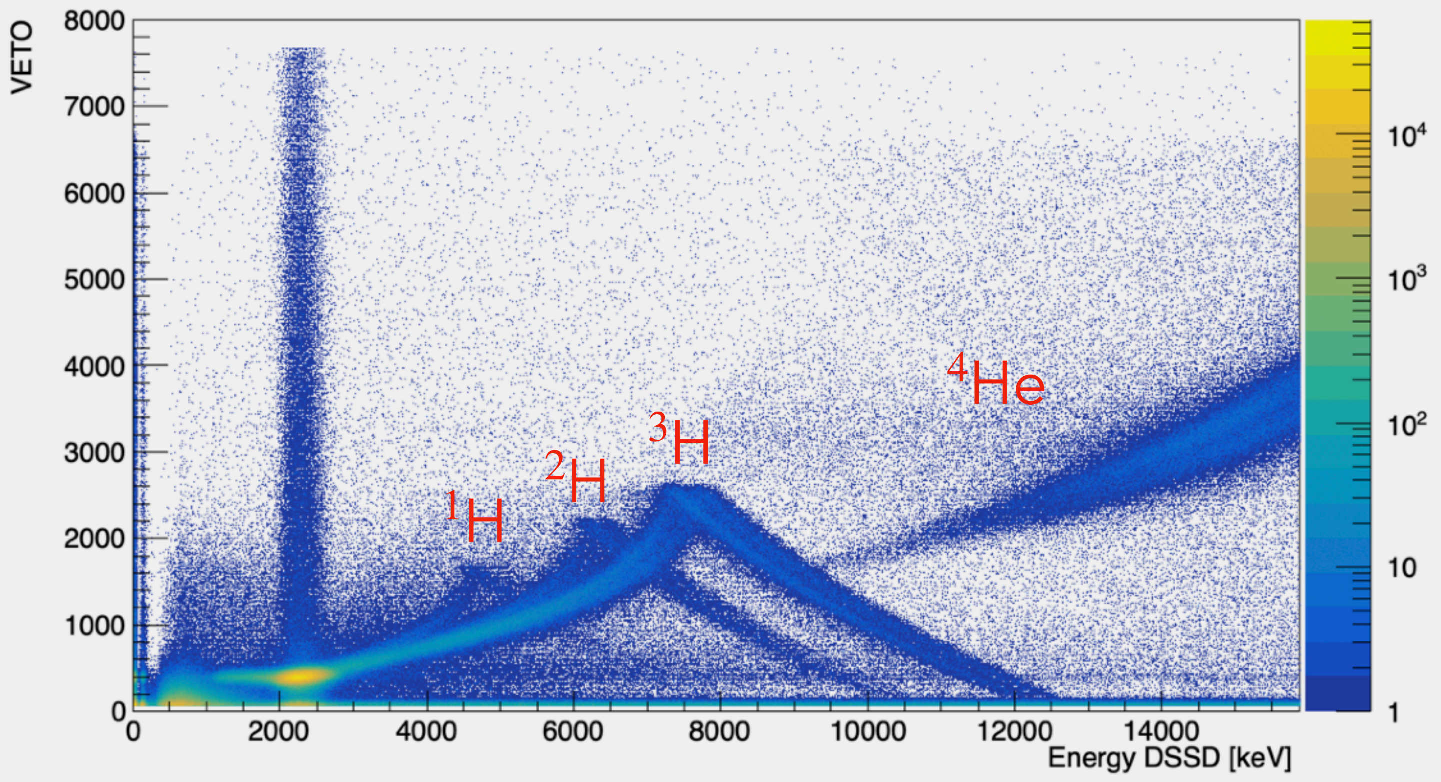
Data flow ⟶ $\mathrm{R}\alpha\mathrm{RA}\alpha\alpha\mathrm{A}\alpha\mathrm{AR}\alpha\alpha\mathrm{A}\alpha\mathrm{A}\alpha\mathrm{RR}\alpha\alpha\mathrm{RA}\alpha$

- $^{51}\mathrm{V} + ^{208}\mathrm{Pb} \rightarrow ^{259-x}\mathrm{Db} + xn$
- Filtering using ToF, QDC et VETO





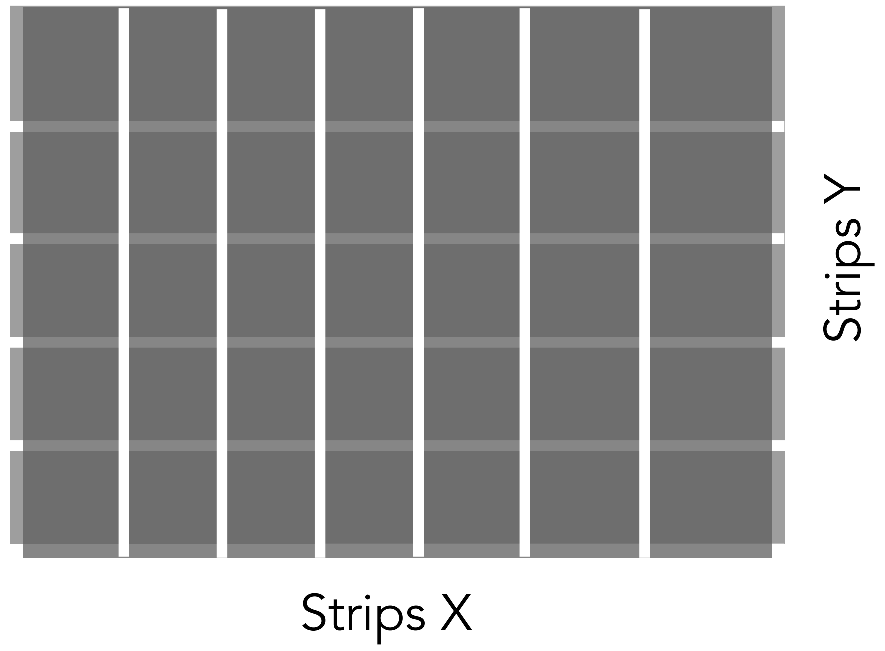




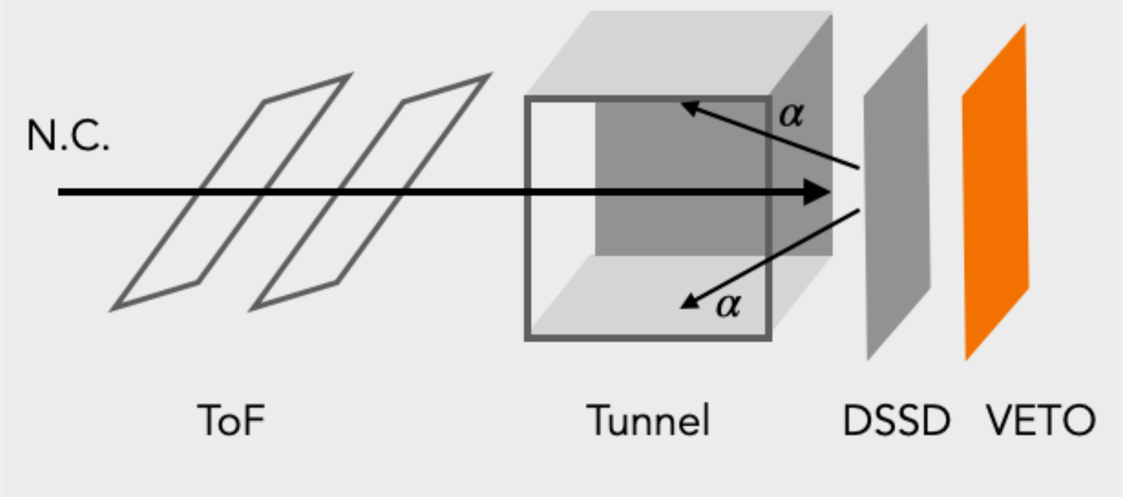
Internship: production of $^{257/258}$Db

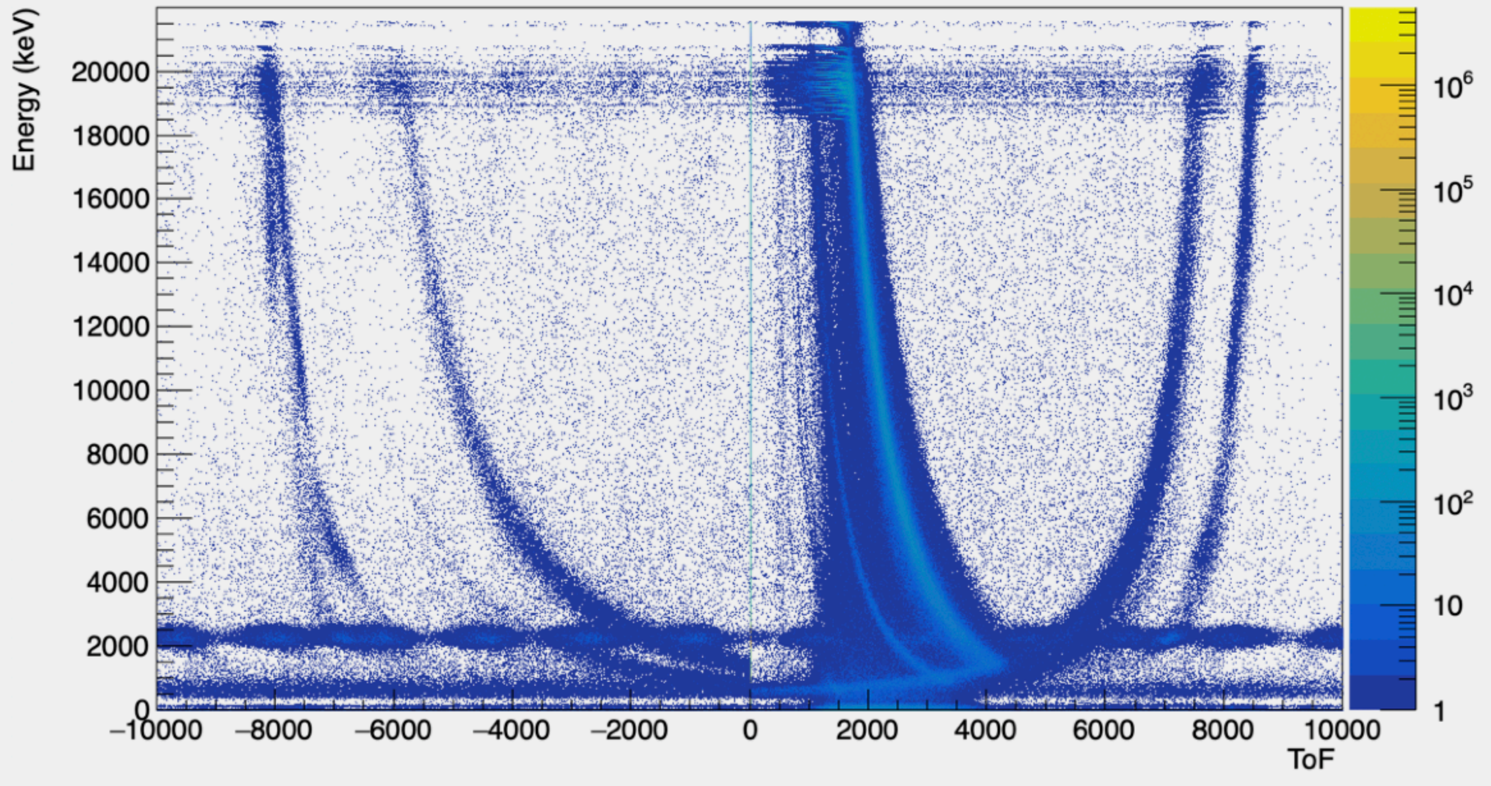
Calibration of an experiment and search for α-decay chains

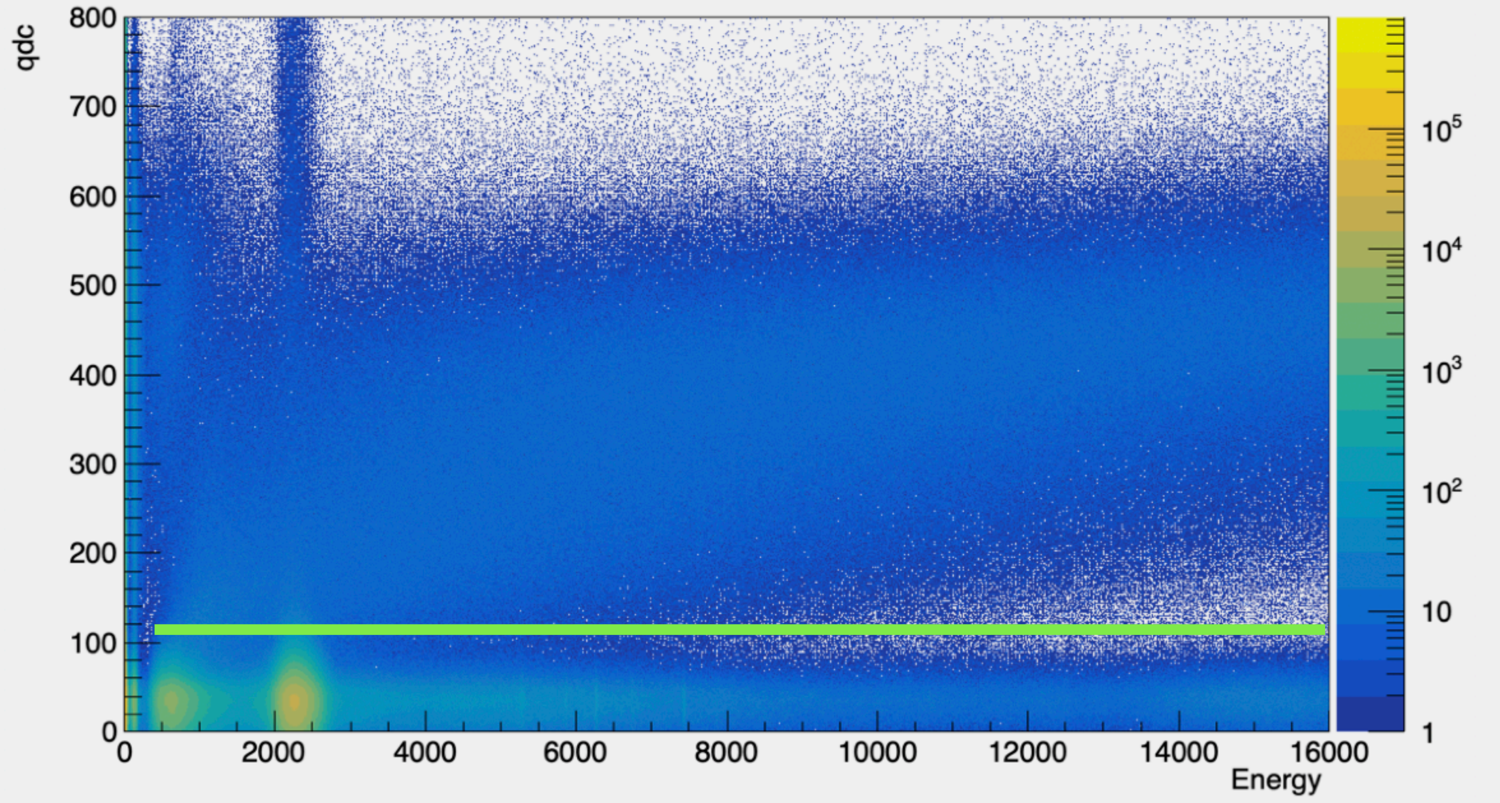
Data flow ⟶ RαR $\alpha\alpha$ α R$\alpha\alpha$Aα αRR$\alpha\alpha$R α

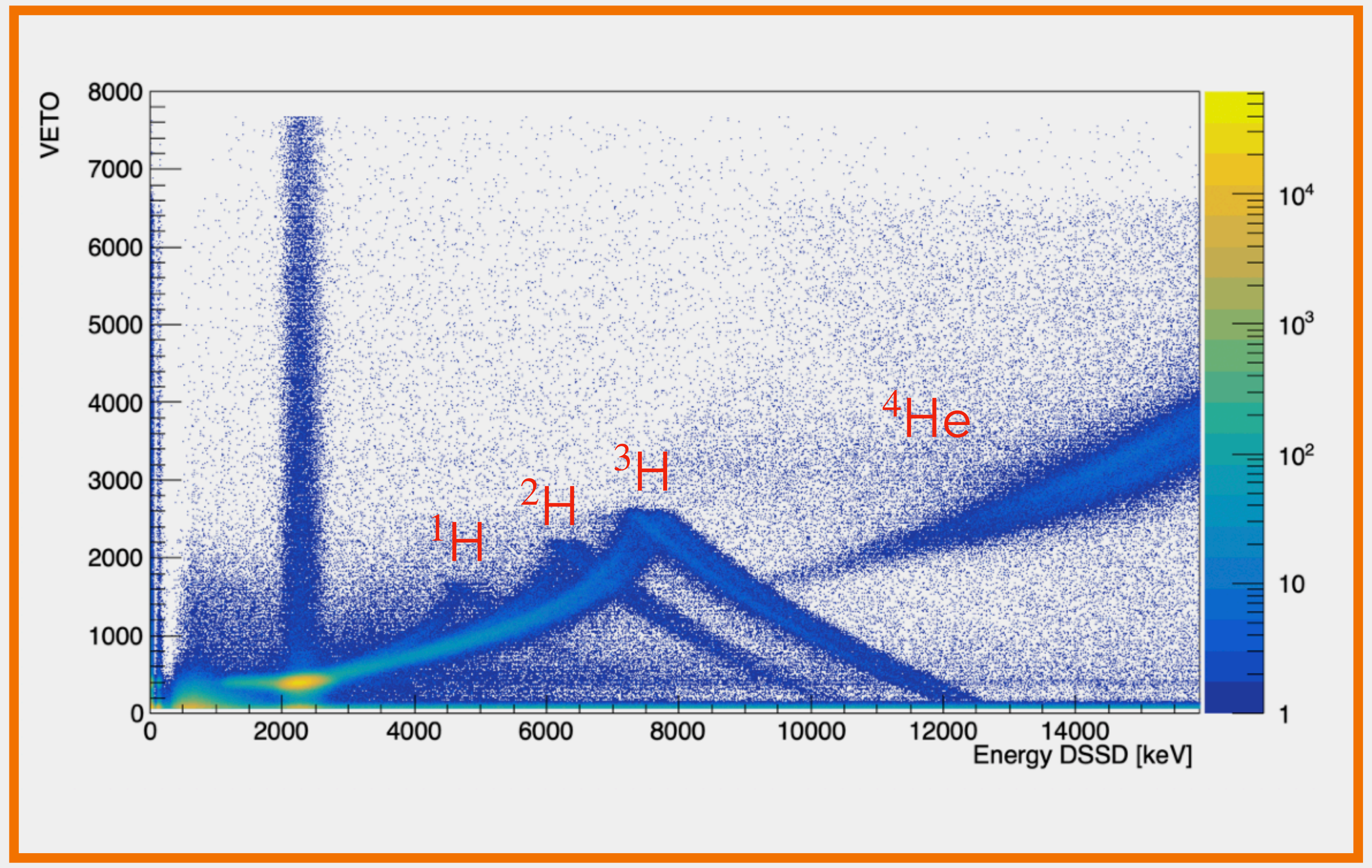


- ^{51}V $+^{208}$Pb $\rightarrow^{259-x}$Db $+$ xn
- Filtering using ToF, QDC et VETO







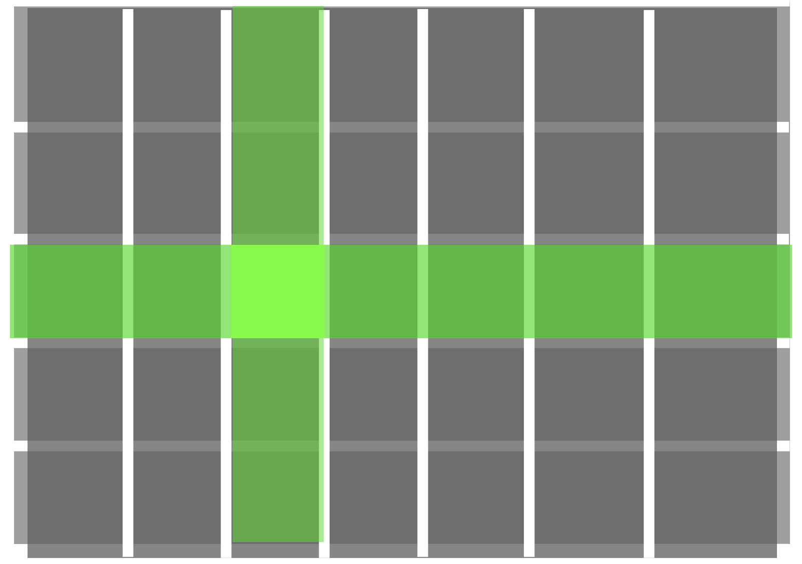


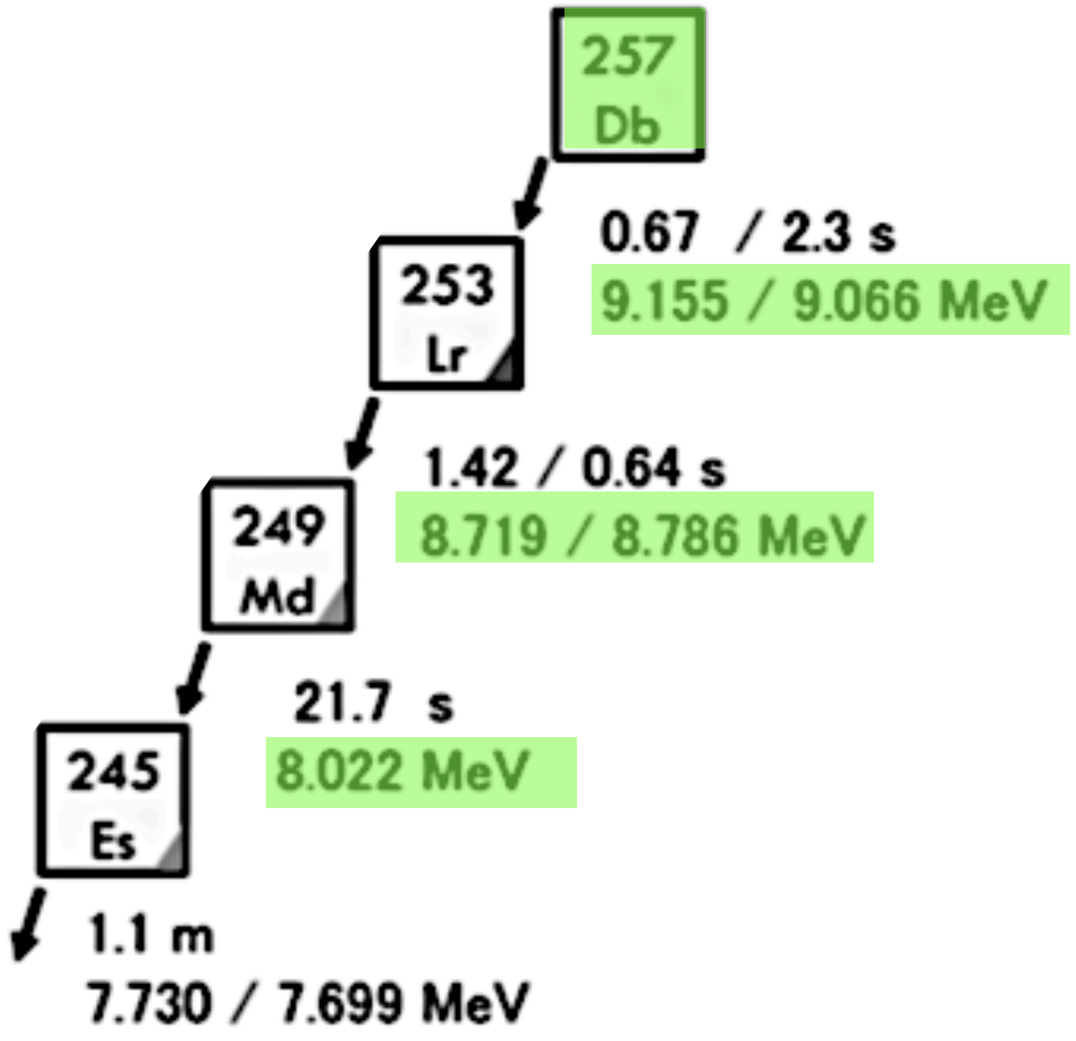
Internship: production of $^{257/258}$Db

Calibration of an experiment and search for α-decay chains

Data flow ⟶ $R\alpha R \quad \alpha_1\alpha \quad \alpha \quad R\alpha\alpha_2 A\alpha \quad \alpha_3 RR\alpha\alpha R \quad \alpha$

$\Delta t_{R-\alpha}$





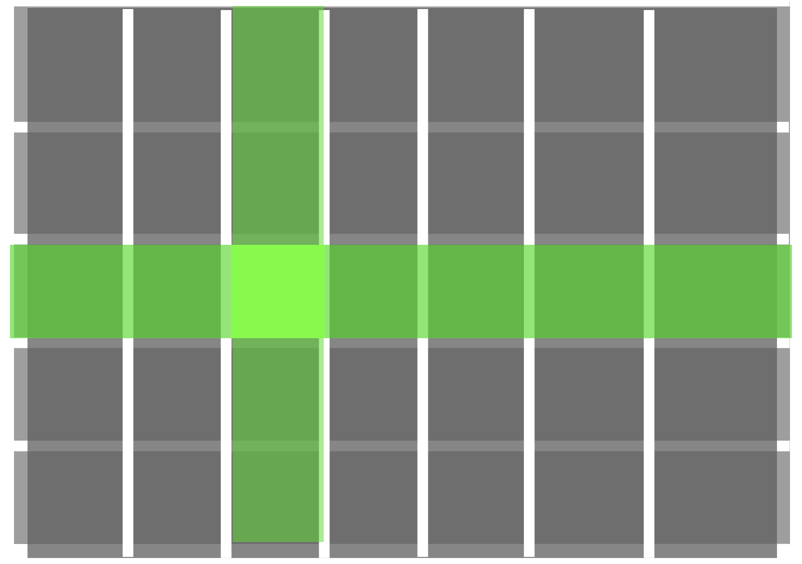
^{257}Db decay chain

Internship: production of $^{257/258}$Db

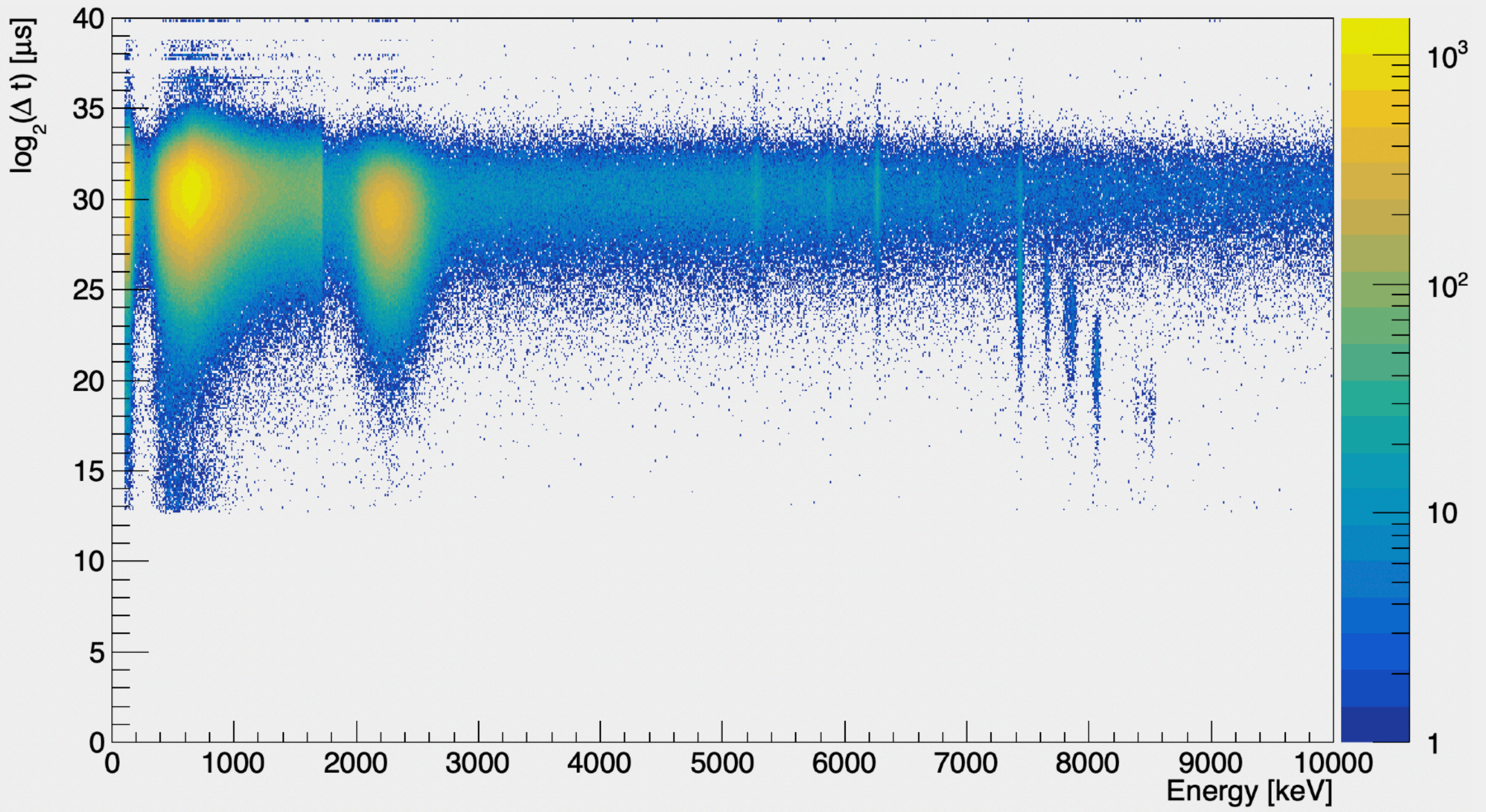
Calibration of an experiment and search for α-decay chains

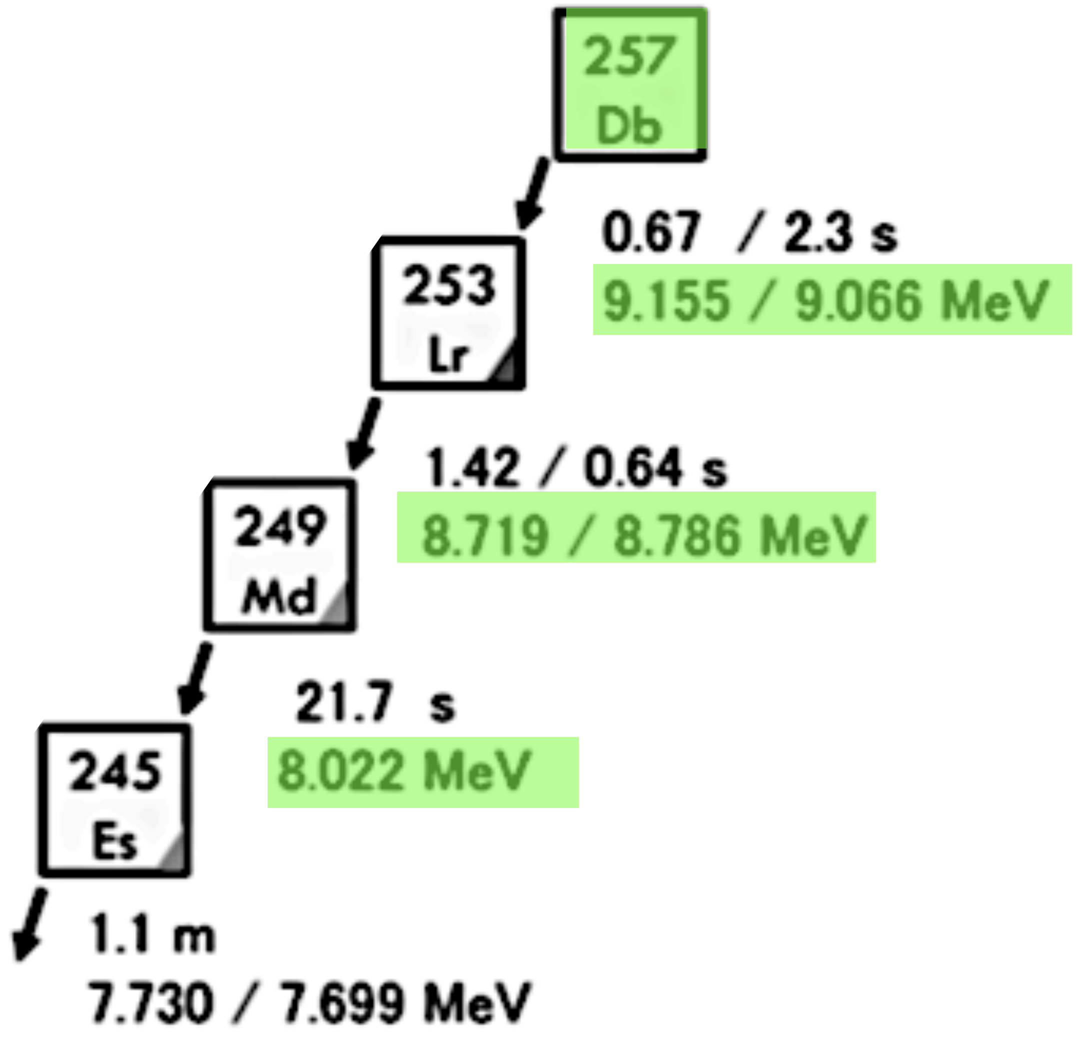
Data flow → $R\alpha R \quad \alpha_1\alpha \quad \alpha \quad R\alpha\alpha_2 A\alpha \quad \alpha_3 RR\alpha\alpha R \quad \alpha$

$\Delta t_{R-\alpha}$



- Recoils lifetimes as function of E_α



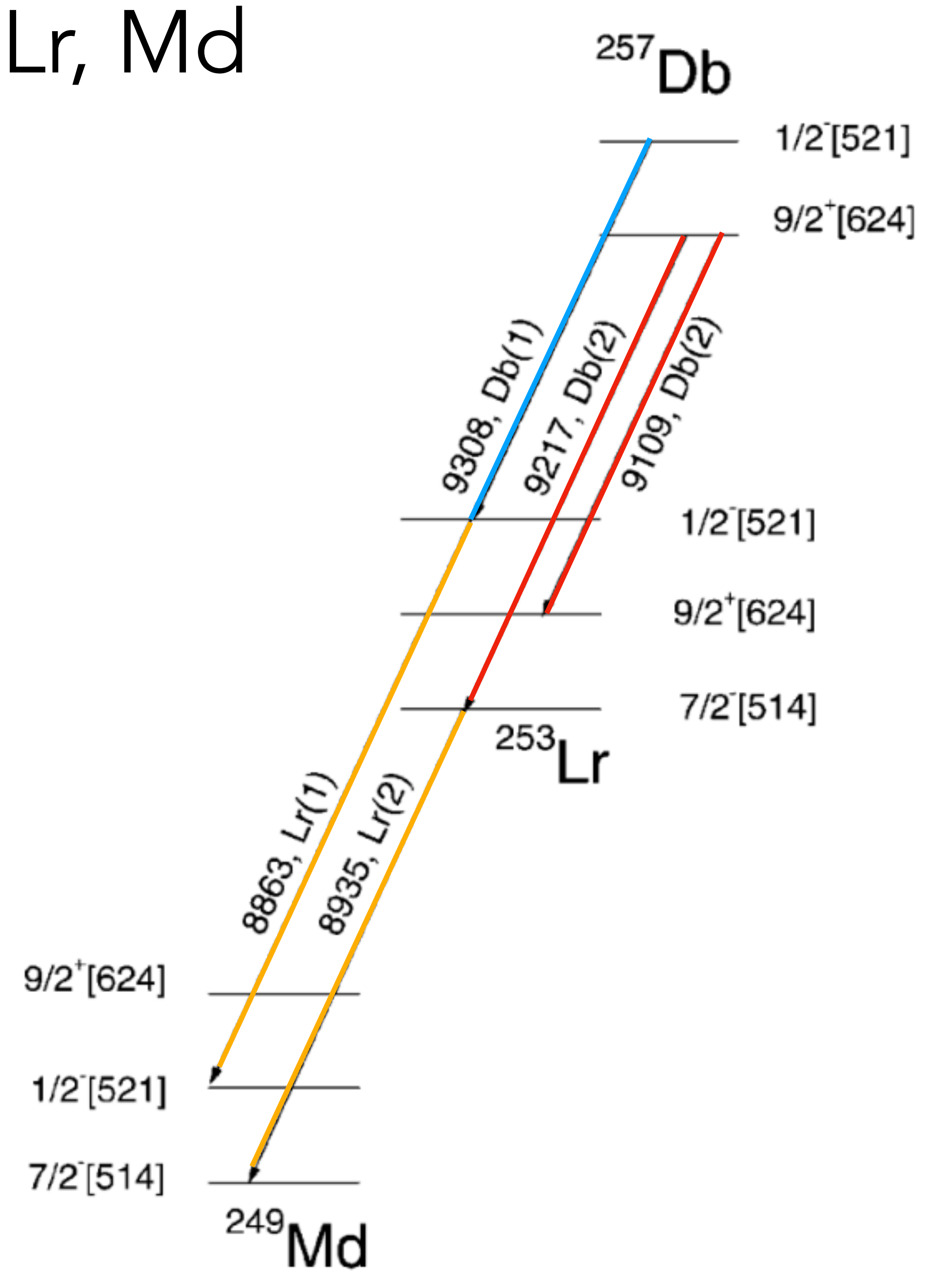


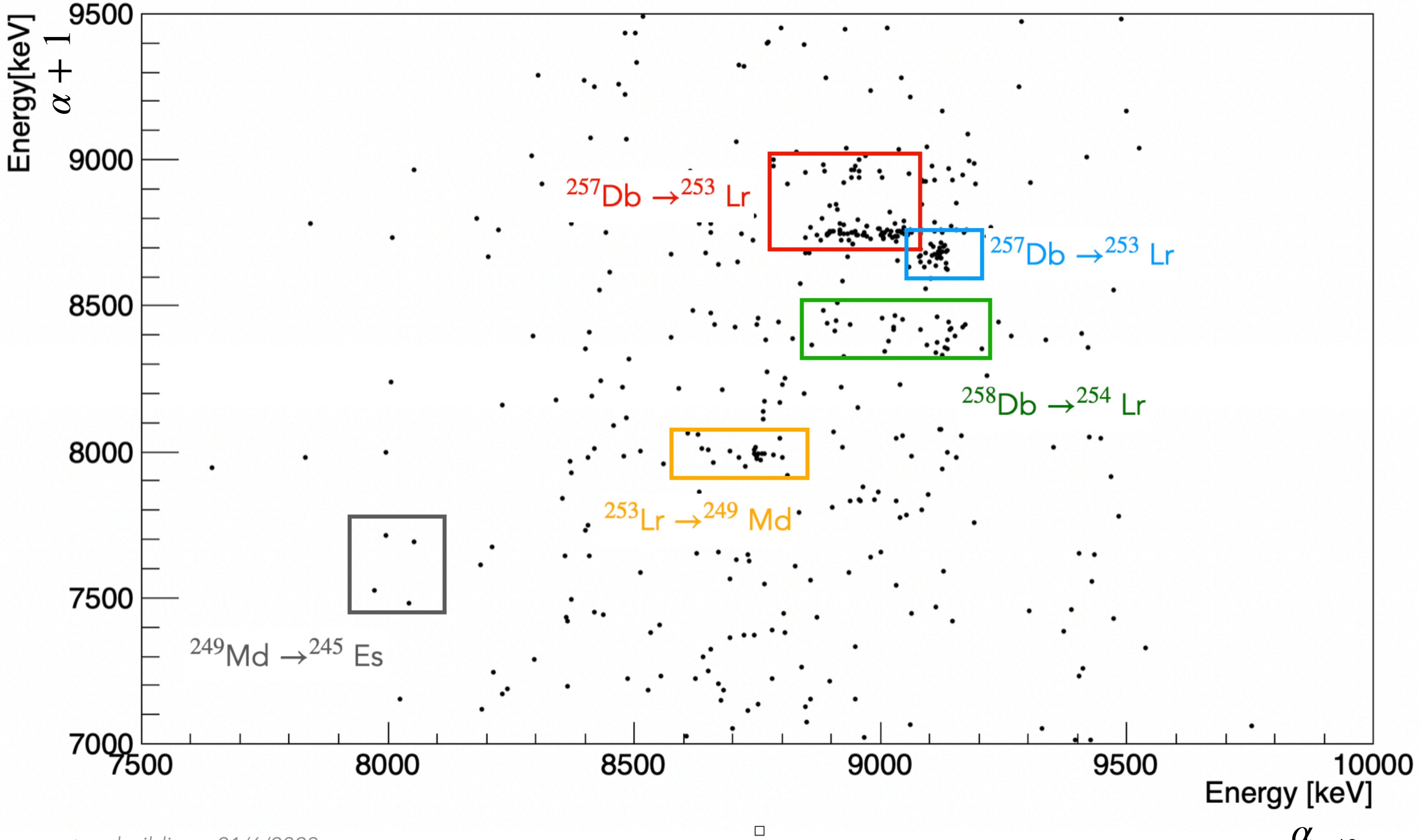
^{257}Db decay chain

Internship: production of $^{257/258}$Db

Analysis of decay chains and delayed spectroscopy

- Reconstruction of decay chains
- Delayed spectroscopy for Db, Lr, Md

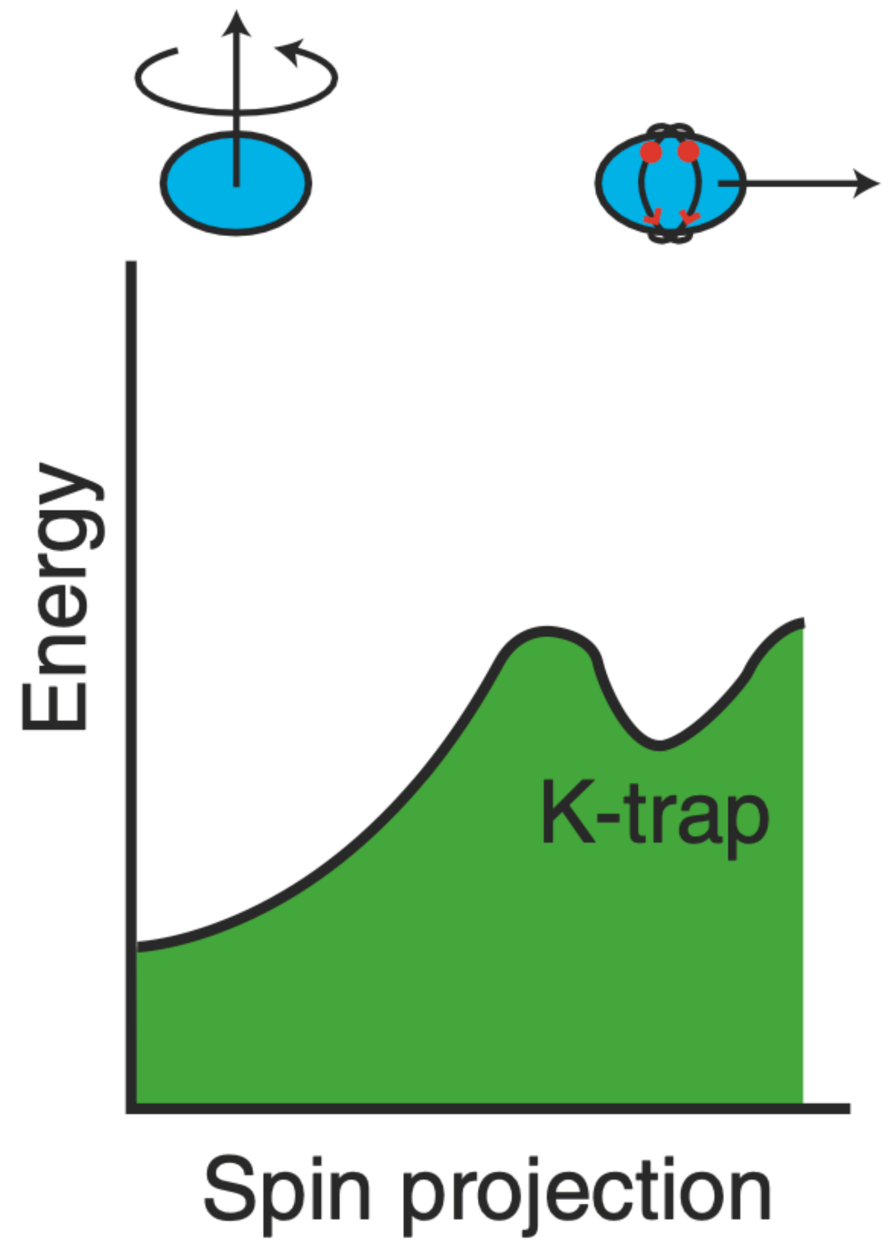




Study of ^{256}Rf « high-K » isomers

- Metastable excited state of a nucleus
- SHE region → "high-K" isomers

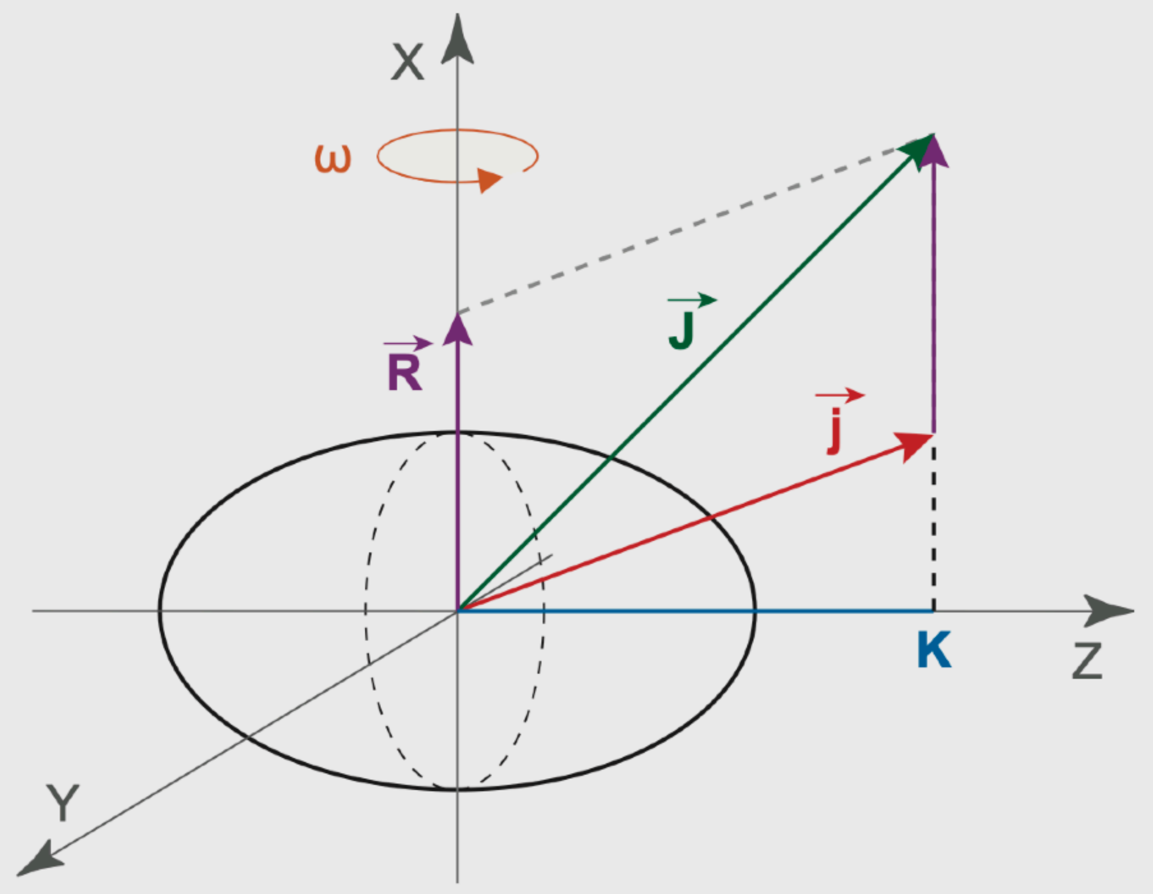
→ Useful to probe the quantum structure of the nucleus



P. Walker & G. Dracoulis, Nature, 1996

« high-K » isomers

- K: Projection of the total angular moment along the axis of deformation of the nucleus
- If $|\Delta K| > \lambda$ (Multipolarity of the transition), the transition is "forbidden" but possible decay by tunnel effect



Deformed nucleus with quantum numbers K, j, J

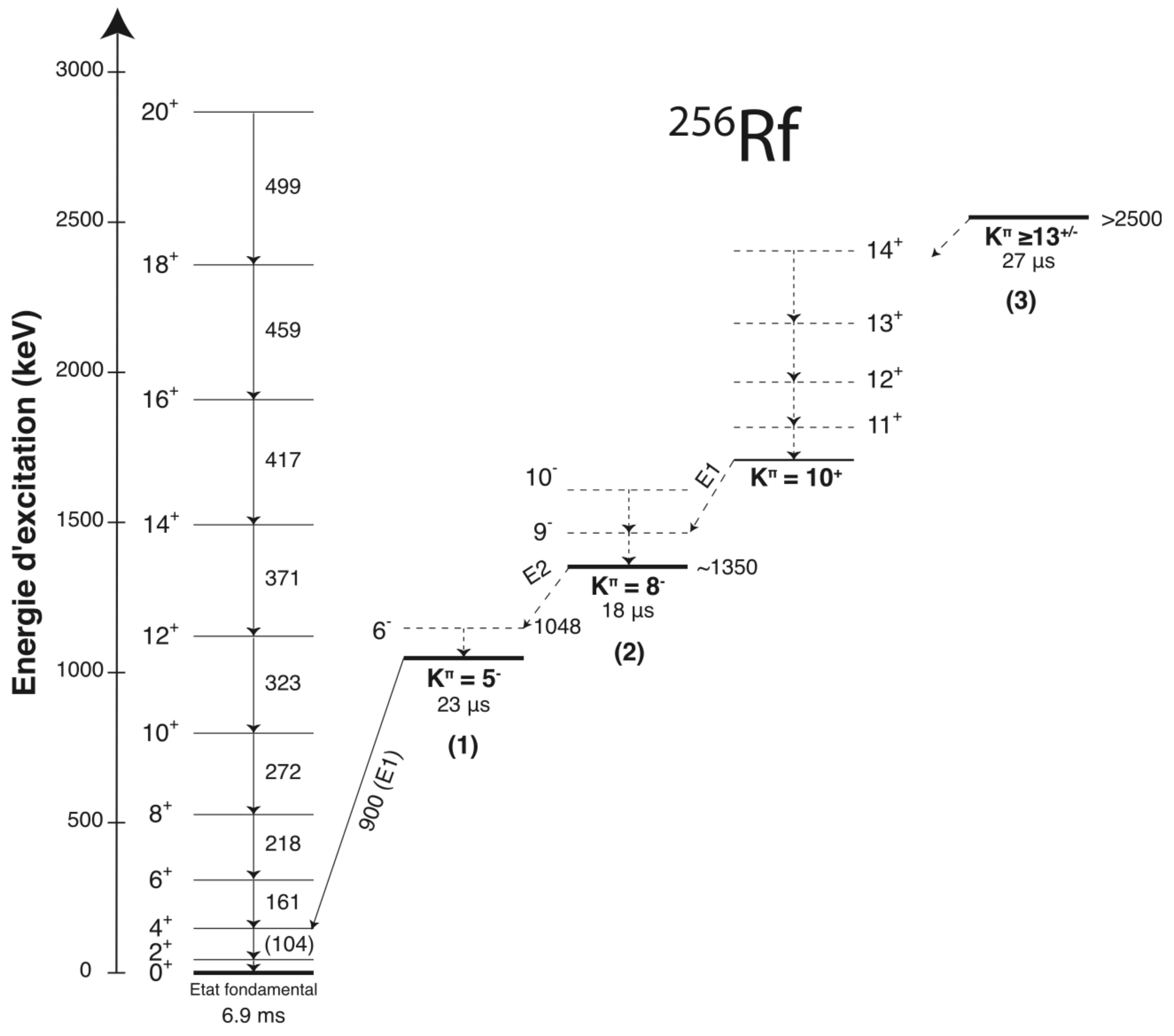
Study of ^{256}Rf « high-K » isomers

- Before 2011: several discordant delayed spectroscopy experiments
- 2011: experiments by IPHC and JYU physicists

$$^{50}\mathrm{Ti} + ^{208}\mathrm{Pb} \rightarrow ^{256}\mathrm{Rf} + 2n$$

↳ low cross-section = 17 nb

↳ **Important statistics with S^3 separator and the SIRIUS detection system**



J. Rubert, Thèse de l'Unistra (2013)

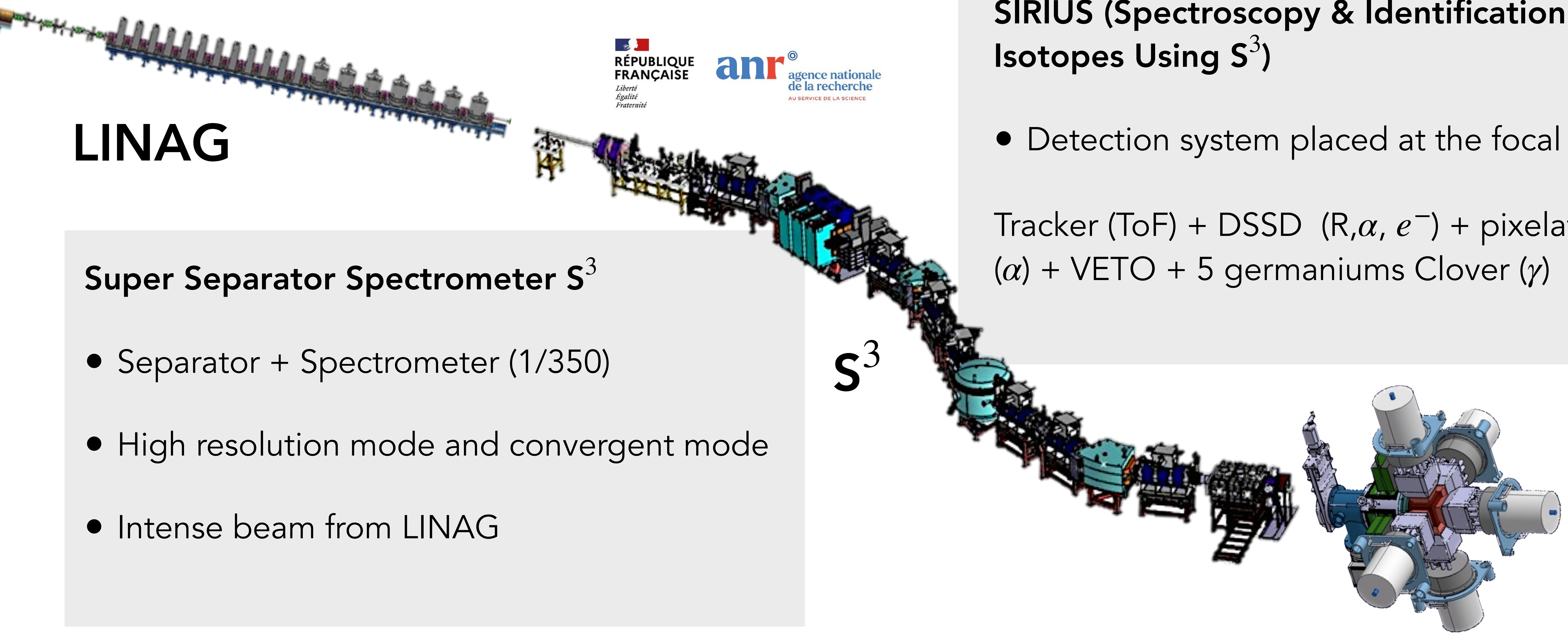
Study of ^{256}Rf « high-K » isomers

Experimental setup @ GANIL

SIRIUS (Spectroscopy & Identification of Rare Isotopes Using S^3)

- Detection system placed at the focal plane:

Tracker (ToF) + DSSD (R,α, e^-) + pixelated Tunnel (α) + VETO + 5 germaniums Clover (γ)



Super Separator Spectrometer S^3

- Separator + Spectrometer (1/350)
- High resolution mode and convergent mode
- Intense beam from LINAG

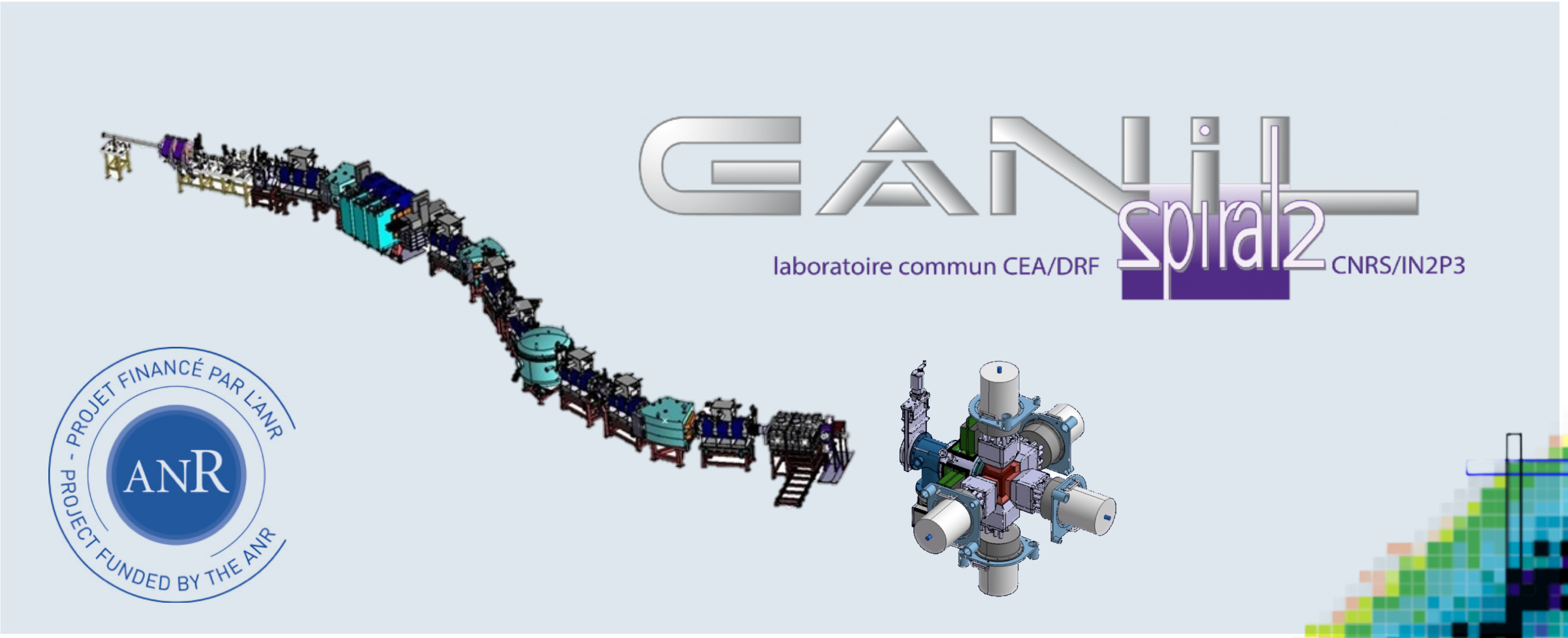
Conclusion

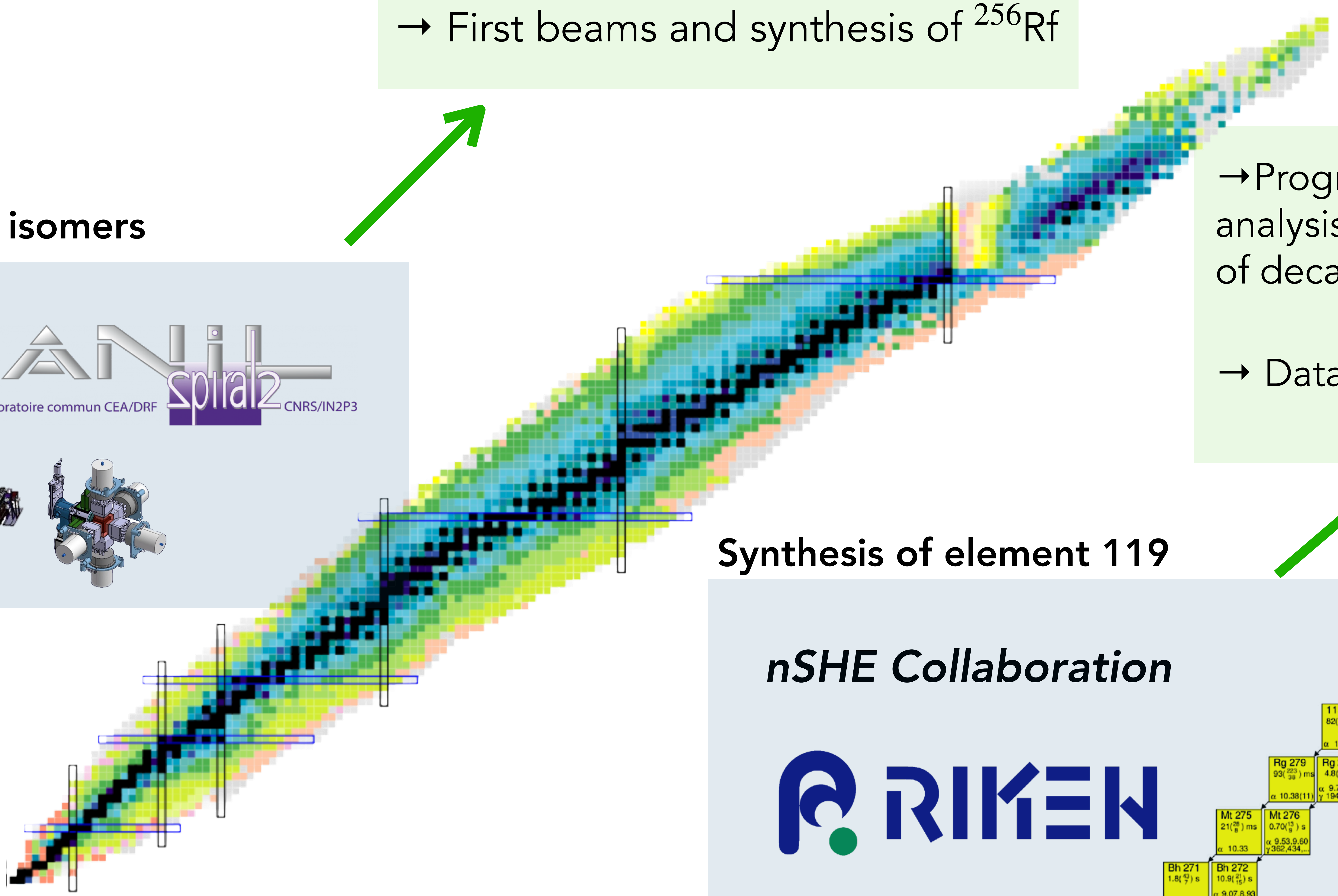
From internship to thesis ...

→ Installation and testing of S^3 and SIRIUS at GANIL, Caen

→ First beams and synthesis of ^{256}Rf

Study of ^{256}Rf « high-K » isomers





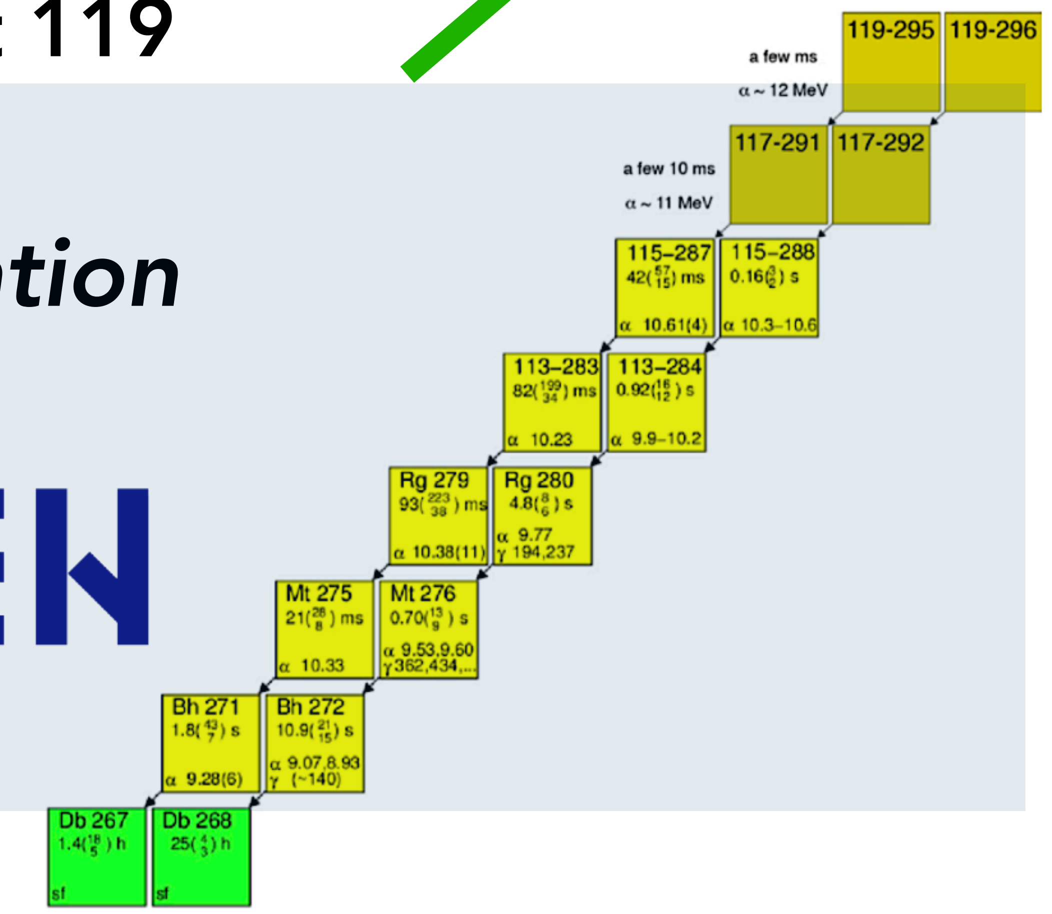
→ Programming of the analysis code for the search of decay chains of the Z=119

→ Data taking at RIKEN

Synthesis of element 119

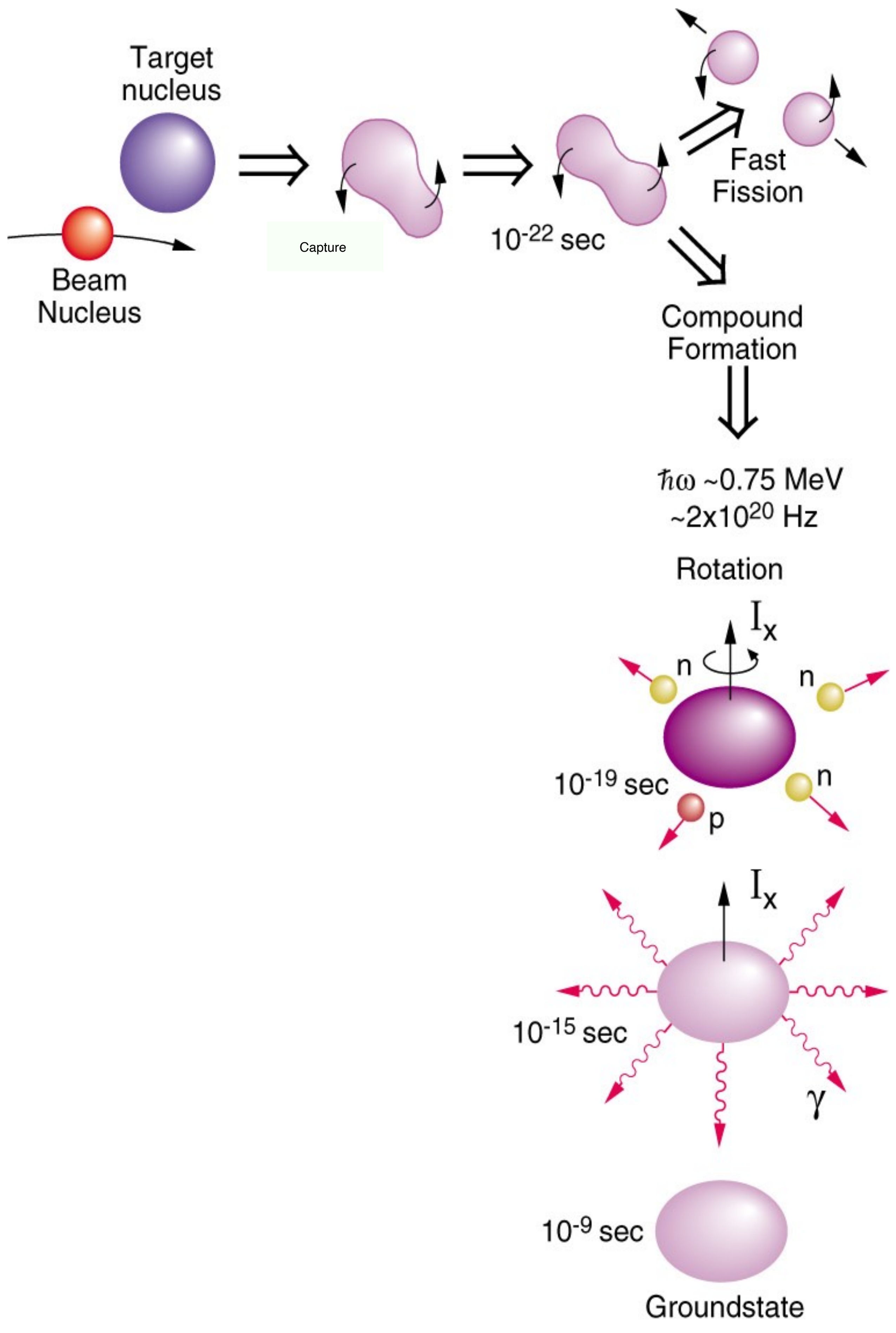
nSHE Collaboration

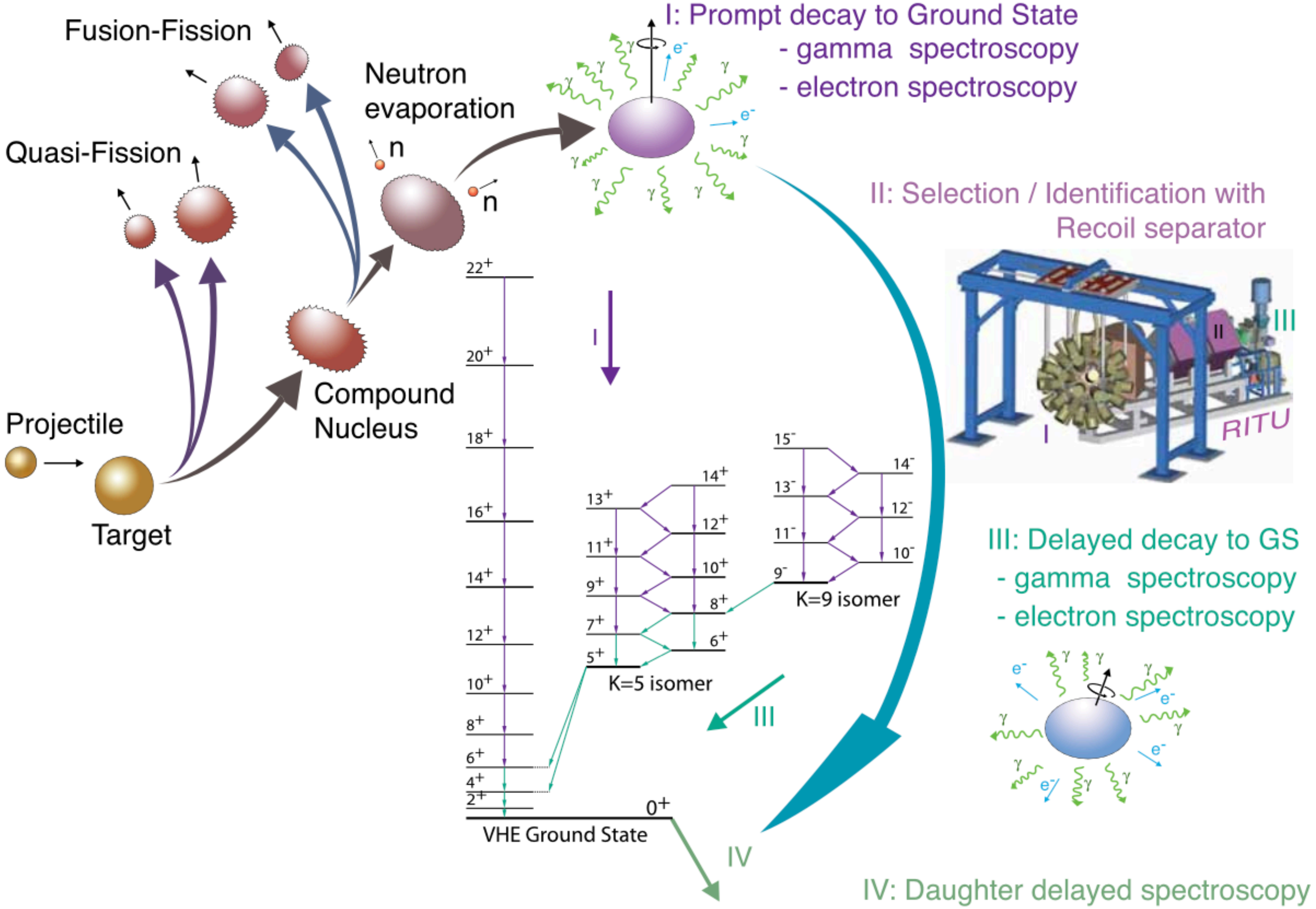
RIKEN



Backup slides

Reaction mechanisms.





Deformed nucleus

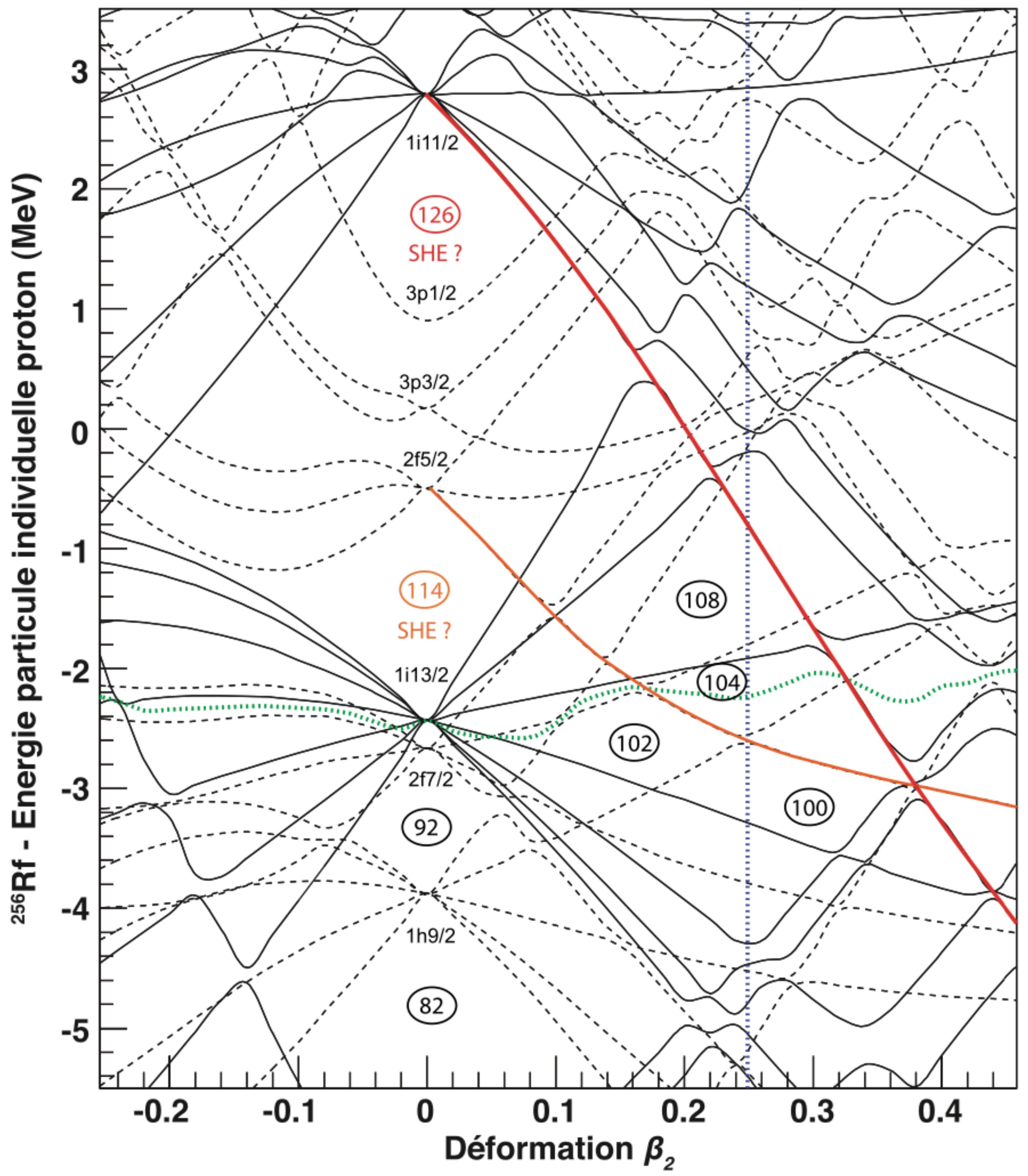


Figure 1.6: Schéma des orbitales des particules individuelles protons pour le noyau de ^{256}Rf en fonction du coefficient de déformation quadrupolaire β_2. Il a été calculé grâce au modèle "Woods-Saxon Universal" [Rou13]. Des gaps candidats superlourds sont situés à $Z = 114$ et à $Z = 126$. Par l'action de la déformation, les orbitales fermant ces gaps sont rapprochées de la surface de Fermi des noyaux transfermia.

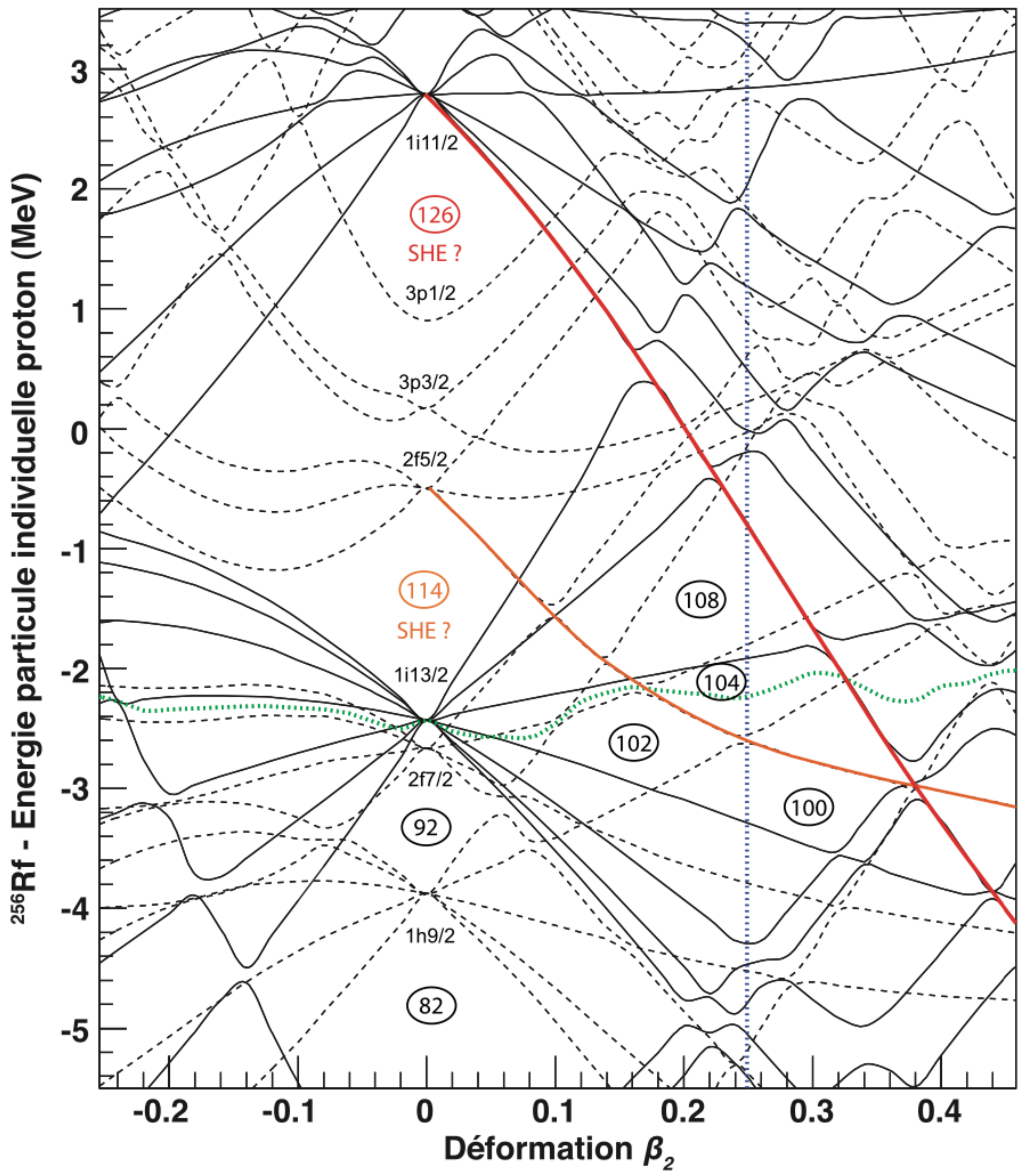
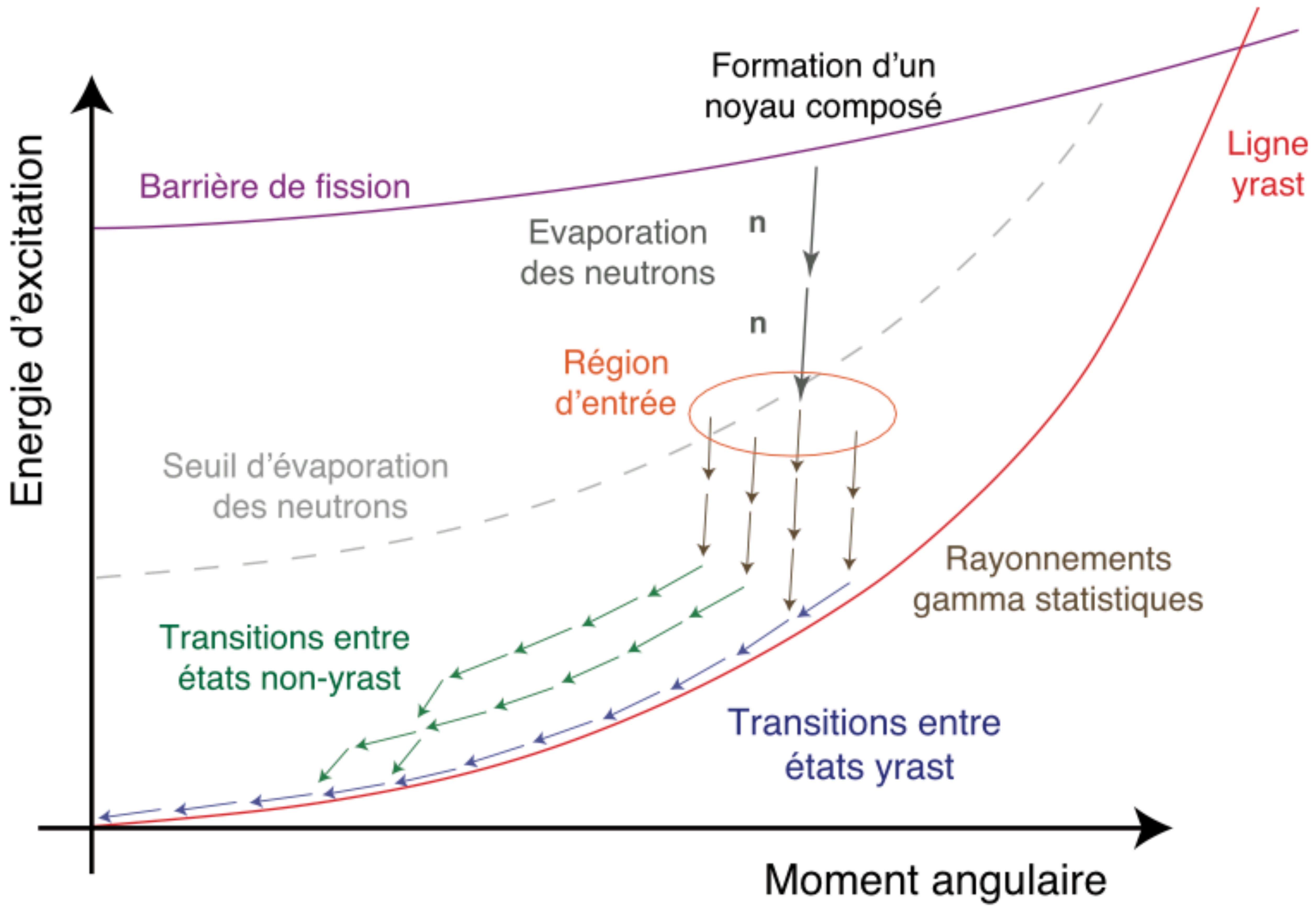
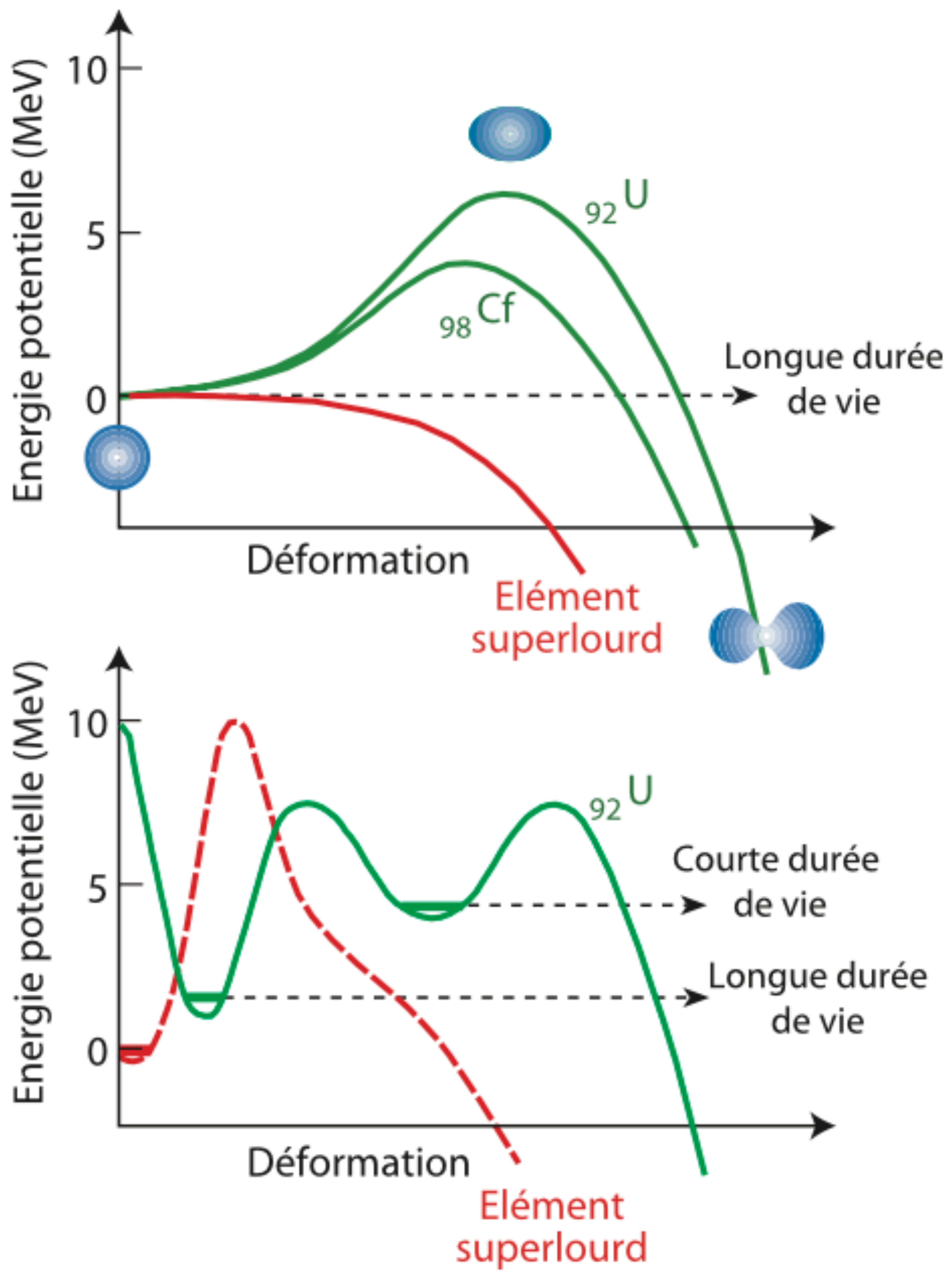


Figure 1.6: Schéma des orbitales des particules individuelles protons pour le noyau de ^{256}Rf en fonction du coefficient de déformation quadrupolaire β_2. Il a été calculé grâce au modèle "Woods-Saxon Universal" [Rou13]. Des gaps candidats superlourds sont situés à $Z = 114$ et à $Z = 126$. Par l'action de la déformation, les orbitales fermant ces gaps sont rapprochées de la surface de Fermi des noyaux transfermia.

Desexcitation of a CN

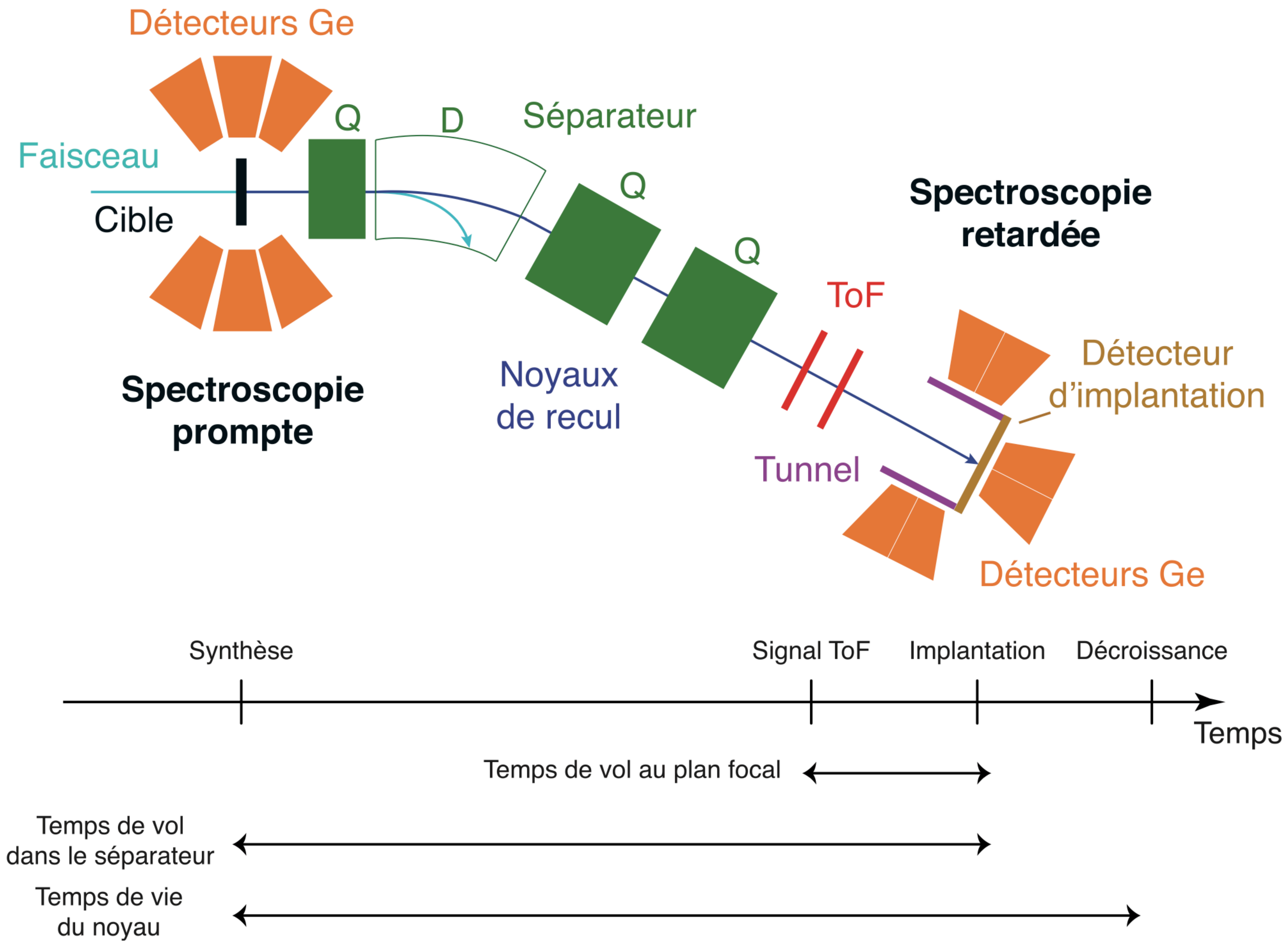


Shell Model



Energie potentielle (MeV)
10
5
0
$_{92}$U
$_{98}$Cf
Longue durée de vie
Déformation
Elément superlourd
Energie potentielle (MeV)
10
5
0
$_{92}$U
Courte durée de vie
Longue durée de vie
Déformation
Elément superlourd

prompte vs delayed Spectroscopy



SHE elements

Table 1
Decay properties of nuclei.

	Z	N	A	No. observed[a]	Decay mode, branch (%)[b,c]	Half-life[c]	E_α (MeV)	Q_α^{exp} (MeV)	Refs.
Og	118	176	294	d:4	α	$0.69^{+0.64}_{-0.22}$ ms	11.66 ± 0.06	11.82 ± 0.06	[71,73,74]
Ts	117	177	294	d:3, t:2	α	51^{+38}_{-16} ms	10.81–11.07	11.18 ± 0.04	[74,86–89]
		176	293	d:15	α	22^{+8}_{-4} ms	10.60–11.20	11.32 ± 0.05	[74,86–88]
Lv	116	177	293	d:4, s:1	α	57^{+43}_{-17} ms	10.56 ± 0.02	10.71 ± 0.02	[68–70,72]
		176	292	d:5, s:4	α	13^{+7}_{-4} ms	10.63 ± 0.02	10.78 ± 0.02	[70,72]
		175	291	d:3, s:1	α	19^{+17}_{-6} ms	10.74 ± 0.07 10.50 ± 0.02	10.89 ± 0.07	[49,71,72]
		174	290	d:11	α	$8.3^{+3.5}_{-1.9}$ ms	10.85 ± 0.07	11.00 ± 0.07	[49,71,73,74]
Mc	115	175	290	d:4, t:2	α	650^{+490}_{-200} ms	9.78–10.31	10.41 ± 0.04	[74,86–89]
		174	289	d:16	α	330^{+120}_{-80} ms	10.15–10.54	10.49 ± 0.05	[74,80,81,86–88]
		173	288	d:27, t:19	α	164^{+30}_{-21} ms	10.29–10.58	10.63 ± 0.01 ≈ 10.7 [83]	[75,76,80,81,83,84]
		172	287	d:2, t1	α	37^{+44}_{-13} ms	10.61 ± 0.05	10.76 ± 0.05	[75,76,81,83,84]
Fl	114	175	289	d:10, s:1, t:4, tc:1	α	$1.9^{+0.7}_{-0.4}$ s	9.84 ± 0.02 9.48 ± 0.08	9.98 ± 0.02	[45,48,49,62,65,68–70,72]
		174	288	d:17, s:4, t:11, ic:2, tc:1	α	$0.66^{+0.14}_{-0.10}$ s	9.93 ± 0.03	10.07 ± 0.03	[45,49,56,61,62,65,70,72]
		173	287	d:16, s:1, b:1, ic:1	α	$0.48^{+0.14}_{-0.09}$ s	10.03 ± 0.02	10.17 ± 0.02	[46,49,56,61,70–72]
		172	286	d:25, b:2	α: 60^{+10}_{-11}	$0.12^{+0.04}_{-0.02}$ s	10.21 ± 0.04	10.35 ± 0.04	[46,47,49,56,70,71,73,74]
		171	285	b:1	α	$0.13^{+0.60}_{-0.06}$ s			[47]
Nh	113	165	278	d:3	a	2 ms	11.52 -		
	113	173	286	d:4, t:2	α	$9.5^{+6.3}_{-2.7}$ s	9.61–9.75	9.79 ± 0.05	[74,86–89]
		172	285	d:17	α	$4.2^{+1.4}_{-0.8}$ s	9.47–10.18	10.01 ± 0.04	[74,80,81,86–88]
		171	284	d:27, t:20	α	$0.91^{+0.17}_{-0.13}$ s	9.10–10.11	10.12 ± 0.01 ≈ 10.3 [83]	[75,76,80,81,83,88,84]
		170	283	d:1, t1	α	75^{+136}_{-30} ms	10.23 ± 0.01	10.38 ± 0.01	[75,76,81,83,84]
		169	282	d:2	α	73^{+134}_{-29} ms	10.63 ± 0.08	10.78 ± 0.08	[82]
Cn	112	173	285	d:10, s:1, t:4, ic:1, tc:1	α	28^{+9}_{-6} s	9.19 ± 0.02	9.32 ± 0.02	[45,48,49,60,62,65,68–70,72]
		172	284	d:19, s:4, t:11, ic:2, tc:1	SF	98^{+20}_{-14} ms			[45,49,56,61,62,65,70,72]
		171	283	d:22, s:4, b:1, ic:6	α: ≥ 93	$4.2^{+1.1}_{-0.7}$ s	9.53 ± 0.02 9.33 ± 0.06 8.94 ± 0.07	9.66 ± 0.02	[46,49,56–59,61,63,70,71]

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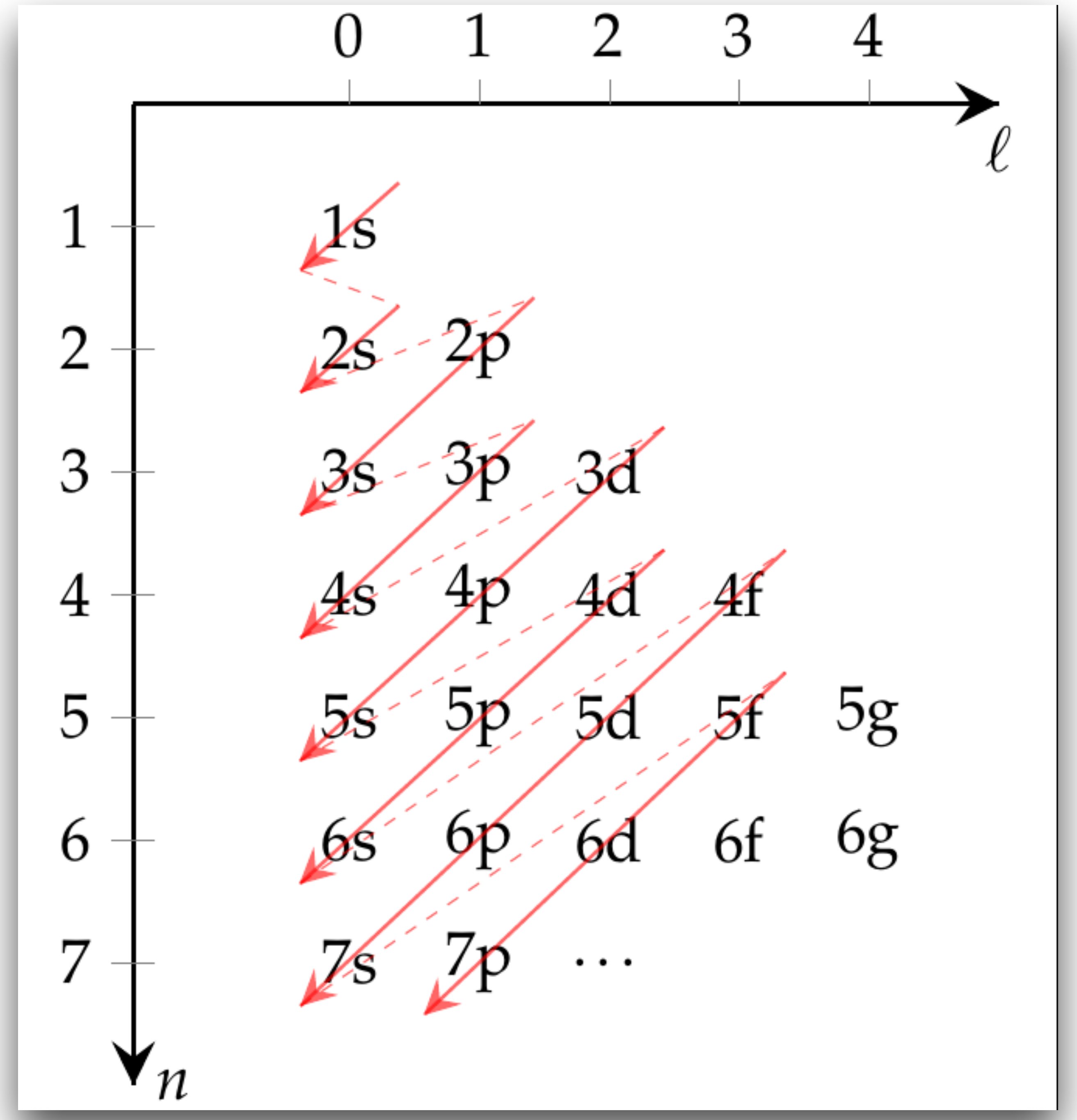
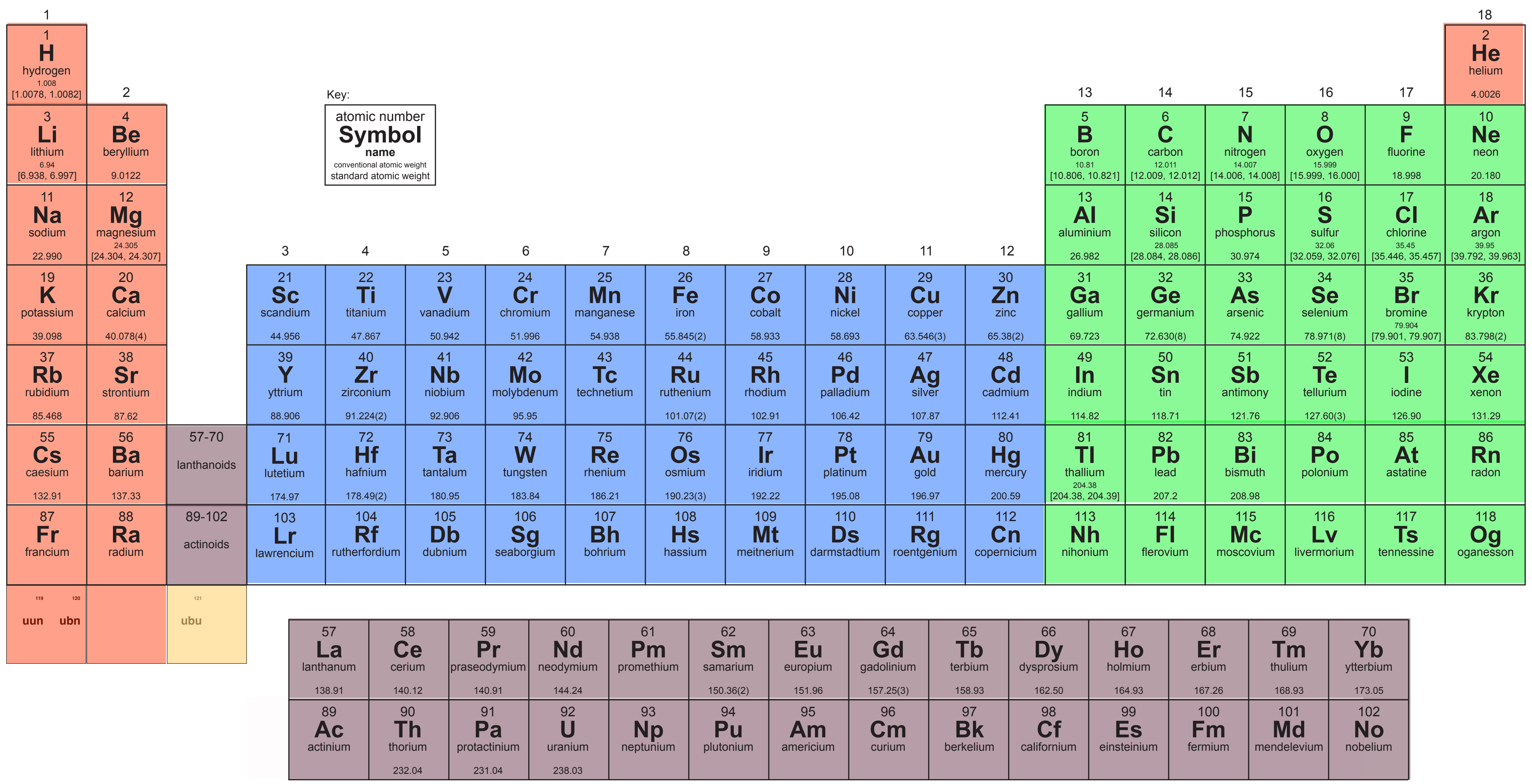
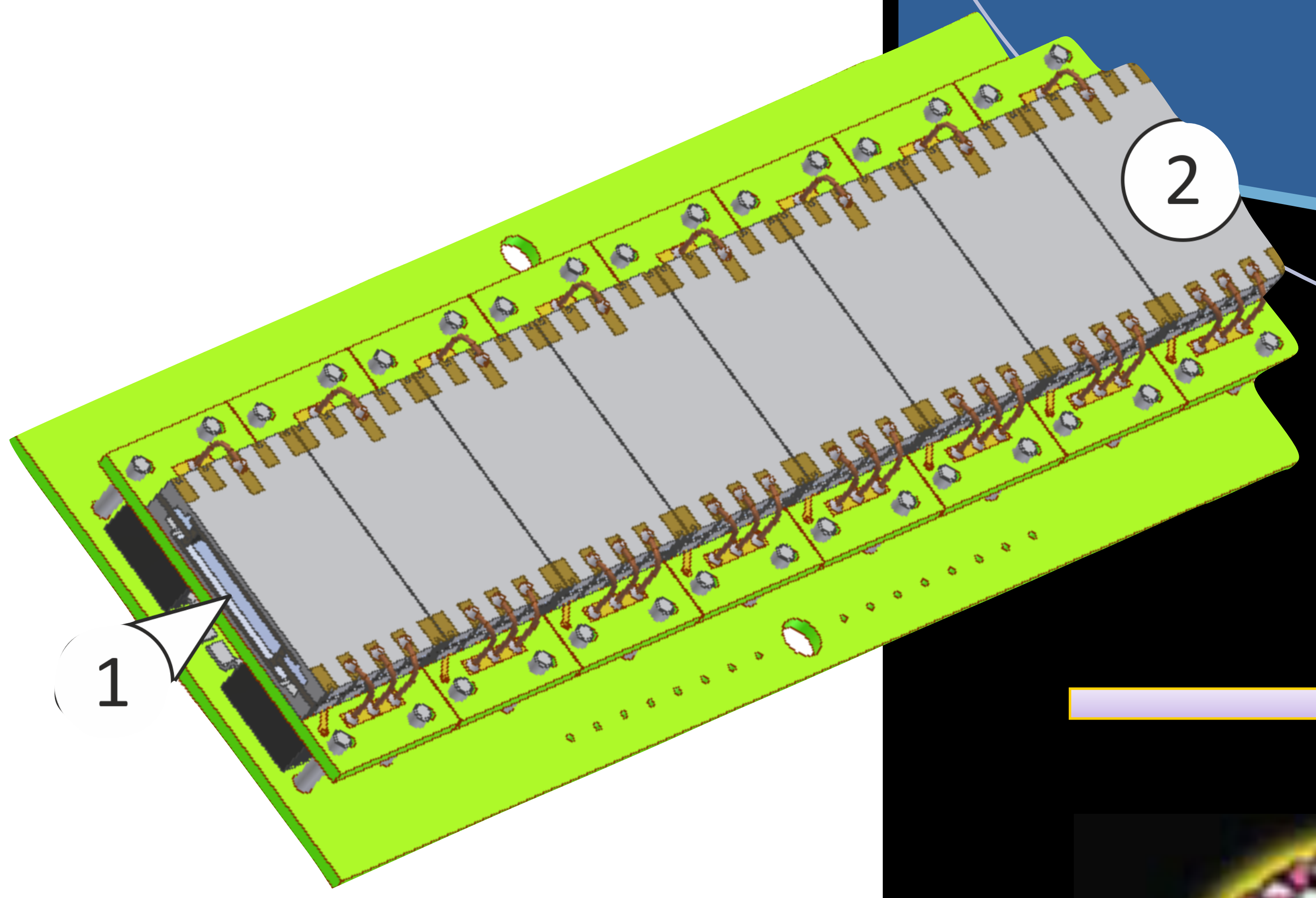
Relativistic effects

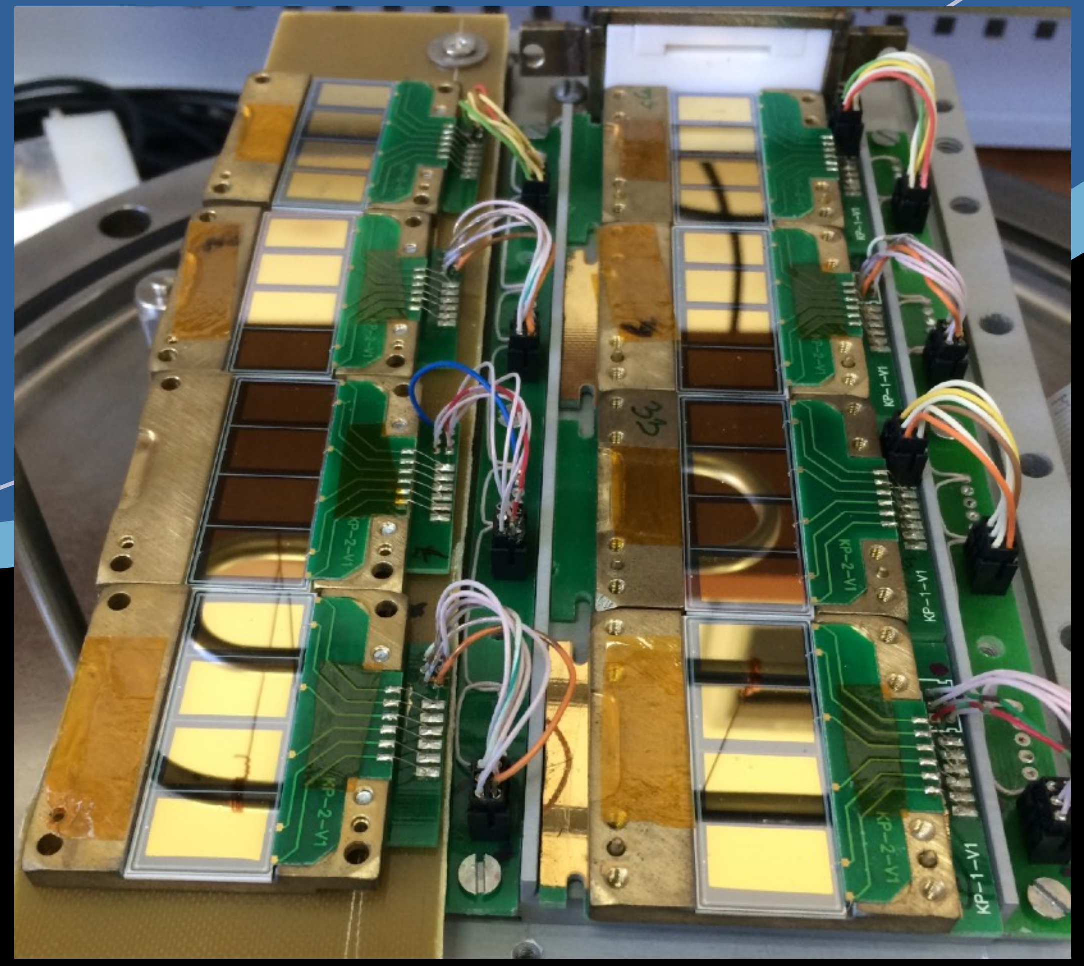


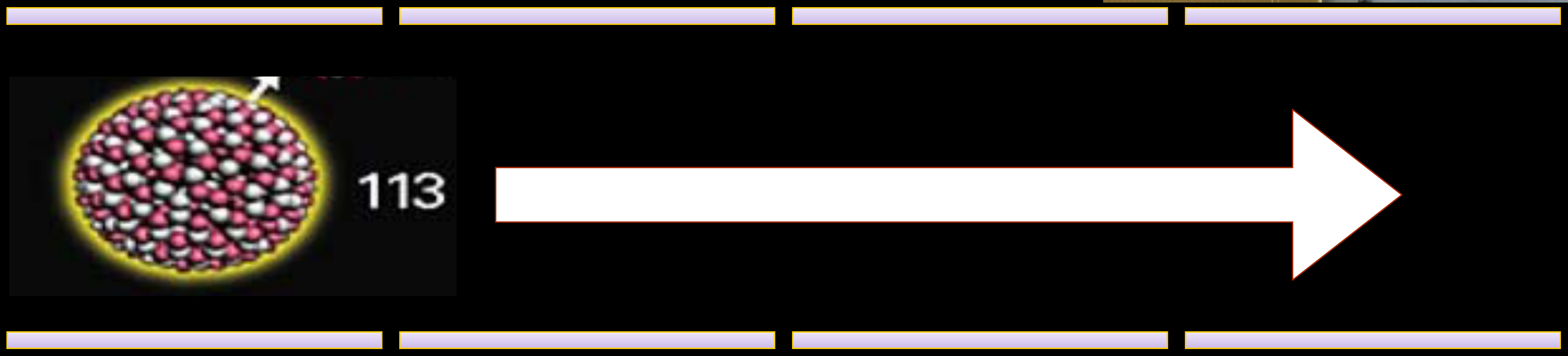


Chimie des SHE

Mesure de volatilité



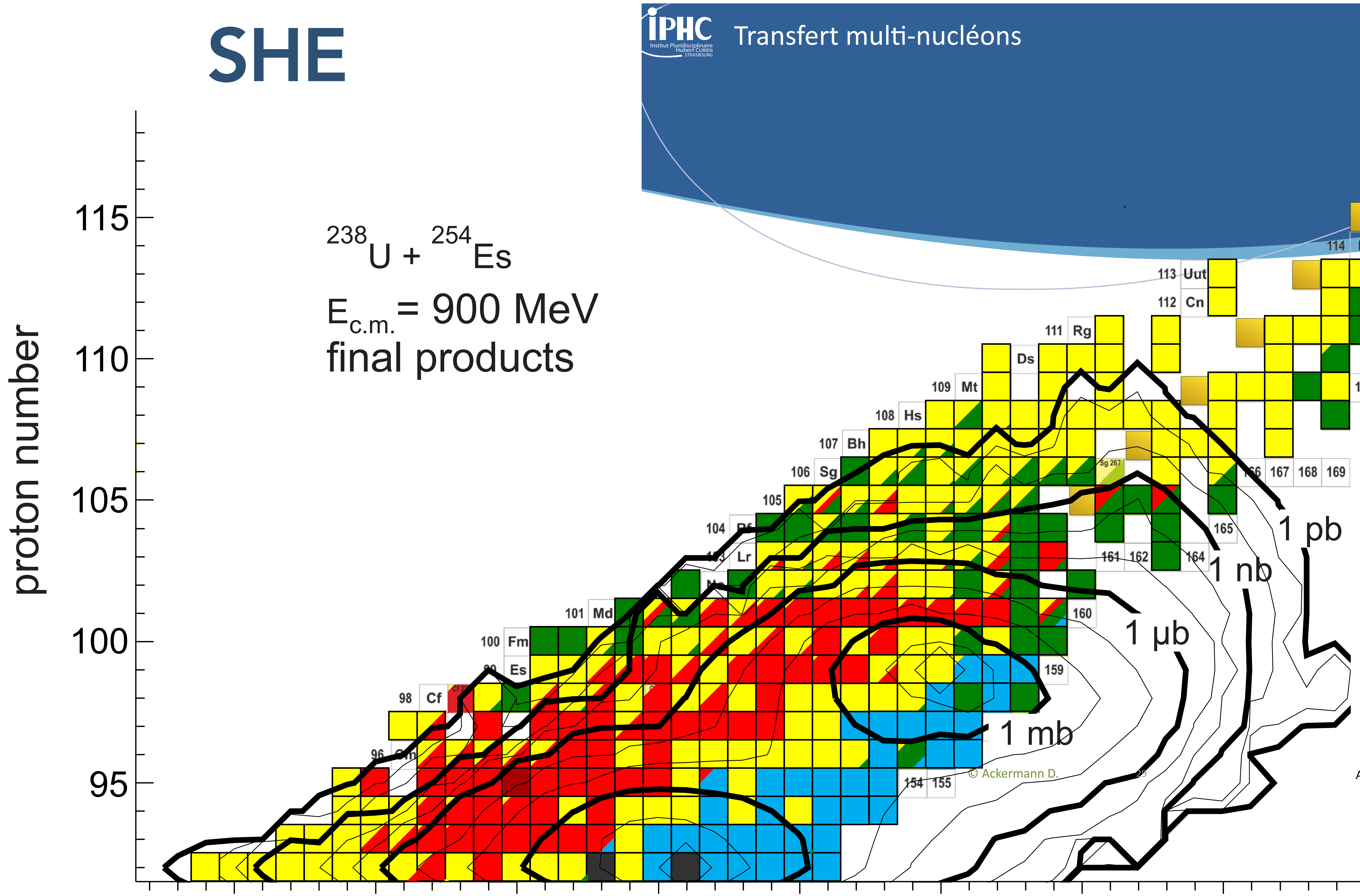




T   T-ΔT   T-2ΔT   T-3ΔT

à l'échelle de l'atome

SHE



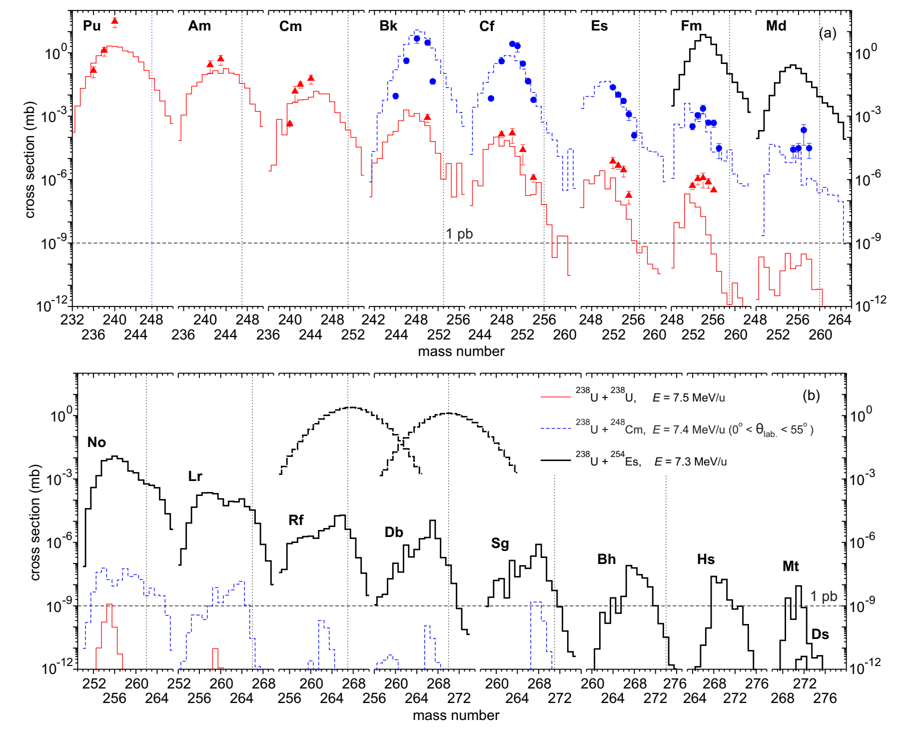


FIG. 9. Isotopic distributions of final above-target products obtained in collisions of actinides. The thin, dashed, and thick histograms correspond to the results of the calculations for the reactions $^{238}U + ^{238}U$ ($E = 7.5$ MeV/u), $^{238}U + ^{248}Cm$ ($E = 7.4$ MeV/u), and $^{238}U + ^{254}Es$ ($E = 7.3$ MeV/u), respectively. The experimental data for the $^{238}U + ^{238}U$ reaction (triangles) are taken from Ref. [17], and for $^{238}U + ^{248}Cm$ (circles) are from Ref. [18]. For more details see the text. The heaviest known isotopes of given chemical elements are indicated by the vertical dotted lines. The thick dashed curves show primary isotopic distributions of Rf and Db.

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SHE production in nature

SHE Barrier distribution study

Measurement of target like particle through GARIS I

In order to study the nucleus–nucleus interactions for syntheses of superheavy nuclei, we measured excitation functions for the quasielastic scattering of ^{48}Ca+^{208}Pb, ^{50}Ti+^{208}Pb, and ^{48}Ca+^{248}Cm using the gas-filled-type recoil ion separator GARIS. The quasielastic scattering events were clearly separated from deep-inelastic events by using GARIS and its focal plan detectors, except for high-incident-energy points. The quasielastic barrier distributions were successfully extracted

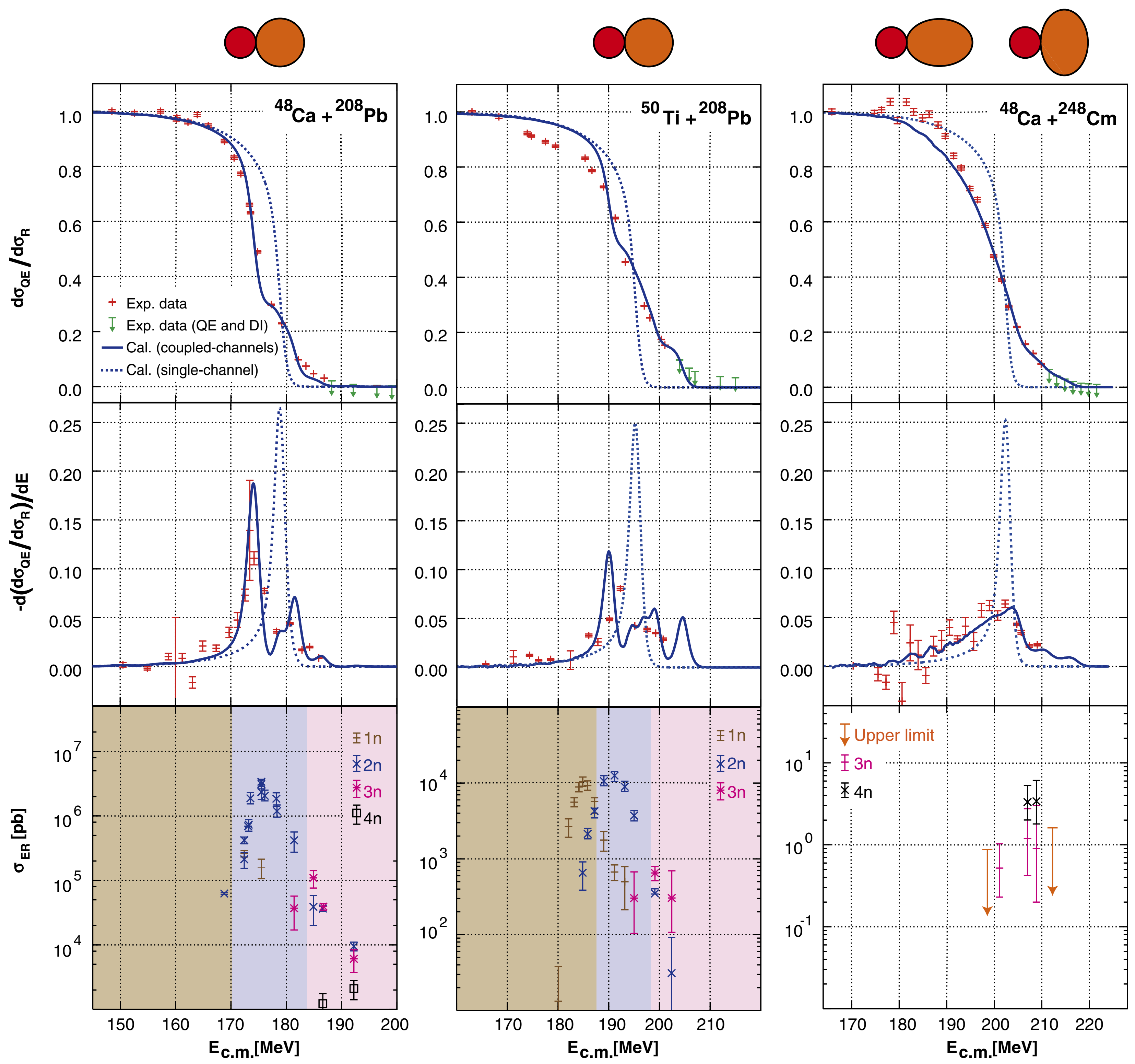

Fig. 7. (Color online) Measured excitation function for the QE scattering cross section relative to the Rutherford cross section (top panels). Left, middle, and right panels are for the ^{48}Ca+^{208}Pb, ^{50}Ti+^{208}Pb, and ^{48}Ca+^{248}Cm systems, respectively. The corresponding QE barrier distribution (middle panels) and the evaporation residue cross sections reported at different center-of-mass energies from the syntheses of No, Rf, and Lv evaporation residues[15,16,38–40] (lower panels) are also shown. Red symbols indicate the experimental data from this work, for which the error bars include only the statistical uncertainty. Green symbols indicate the experimental data of mixed QE and DI events. These data points provide an upper limit for $d\sigma_{QE}/d\sigma_R$ (see Sect. 2.3). Blue solid curves indicate the best fit of the coupled-channels calculation with the parameters shown in Table II. Blue dashed curves show the results of the single-channel calculations with the same internuclear potential as that used for the blue solid lines.

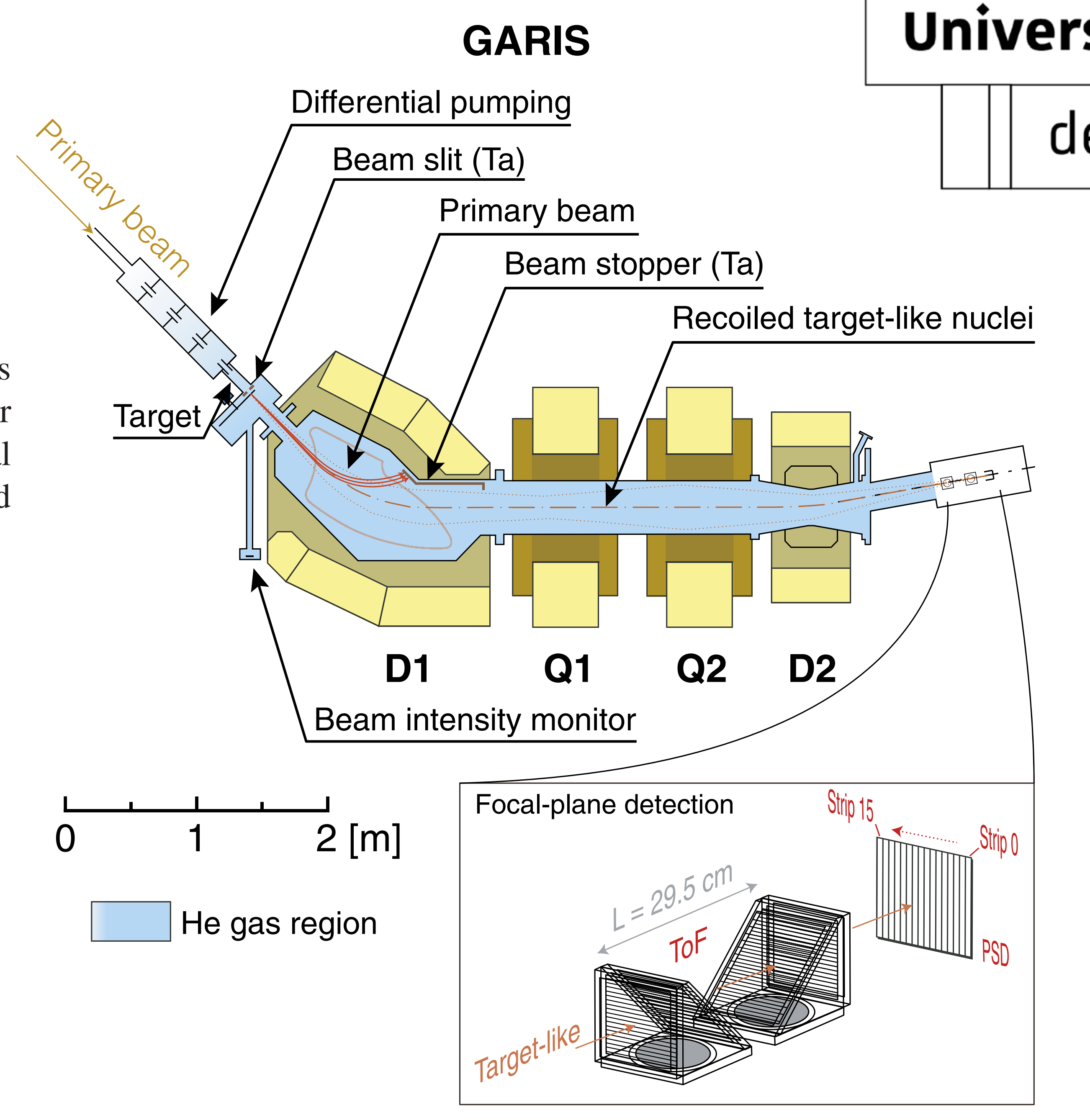

Fig. 1. (Color online) Schematics of GARIS and detectors. GARIS consists of a first dipole magnet (D1), followed by two quadrupole magnets (Q1) and (Q2), and a final dipole (D2) magnet. The lower figure shows the focal plane detector system composed of two ToF detectors and a 16-strip PSD.

One measures the barrier distribution
and determine E_{cm} for side collision
(=optimal bombarding energy for synthesis)

—> get optimal energy