Mapping the fission modes with the SOFIA/R^{3}B setup at GSI

24ème COLLOQUE GANIL
21 au 25 septembre 2026
Bussang, France

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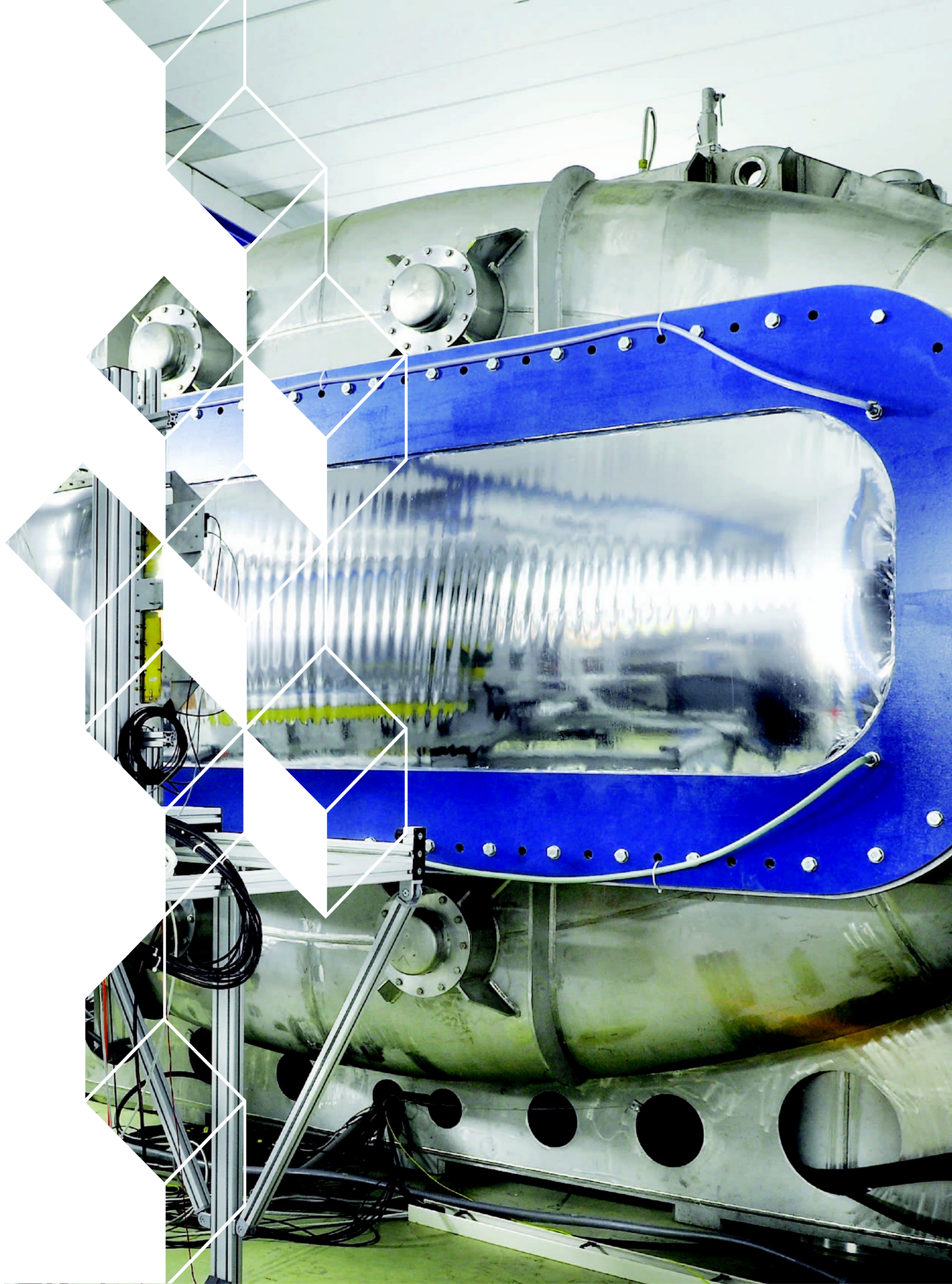
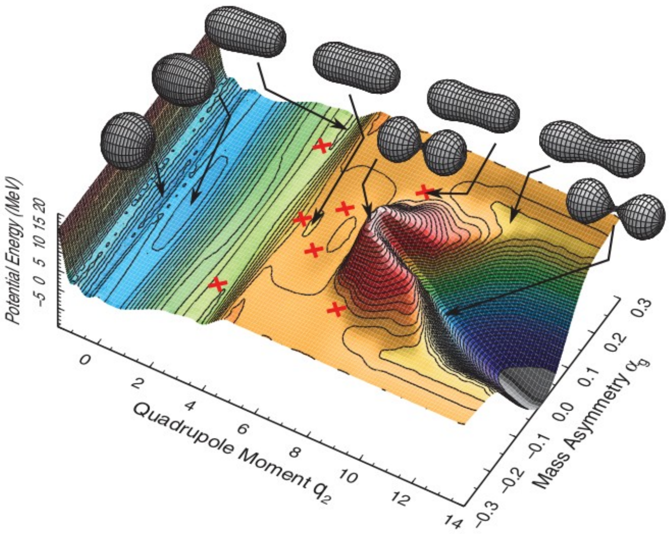


1. Introduction & Motivations

Nuclear fission: a many-body quantum process

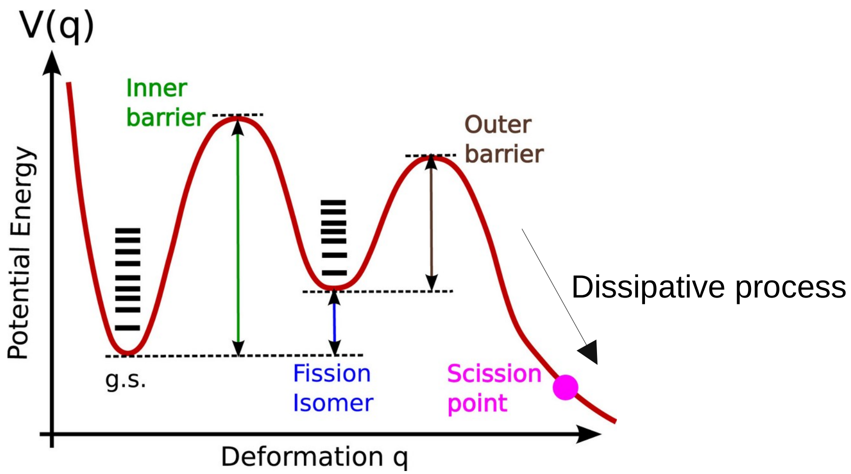
Static properties
Where can it go ?



T. Ichikawa *et al.* Phys. Rev. C **86**, 024610 (2012)

- Potential energy surface with deformation and mass asymmetry.
- Valley/barriers.
- Role of shell effects at large deformation.

Dynamics
How does it evolve ?



N. Schunck and D. Regnier
Progress in Particle and Nuclear Physics **125**, 103963 (2022)

- Coupling between collective (*how the nucleus moves and deforms as a whole*) and intrinsic (*how its individual nucleons are internally excited*) degrees of freedom.

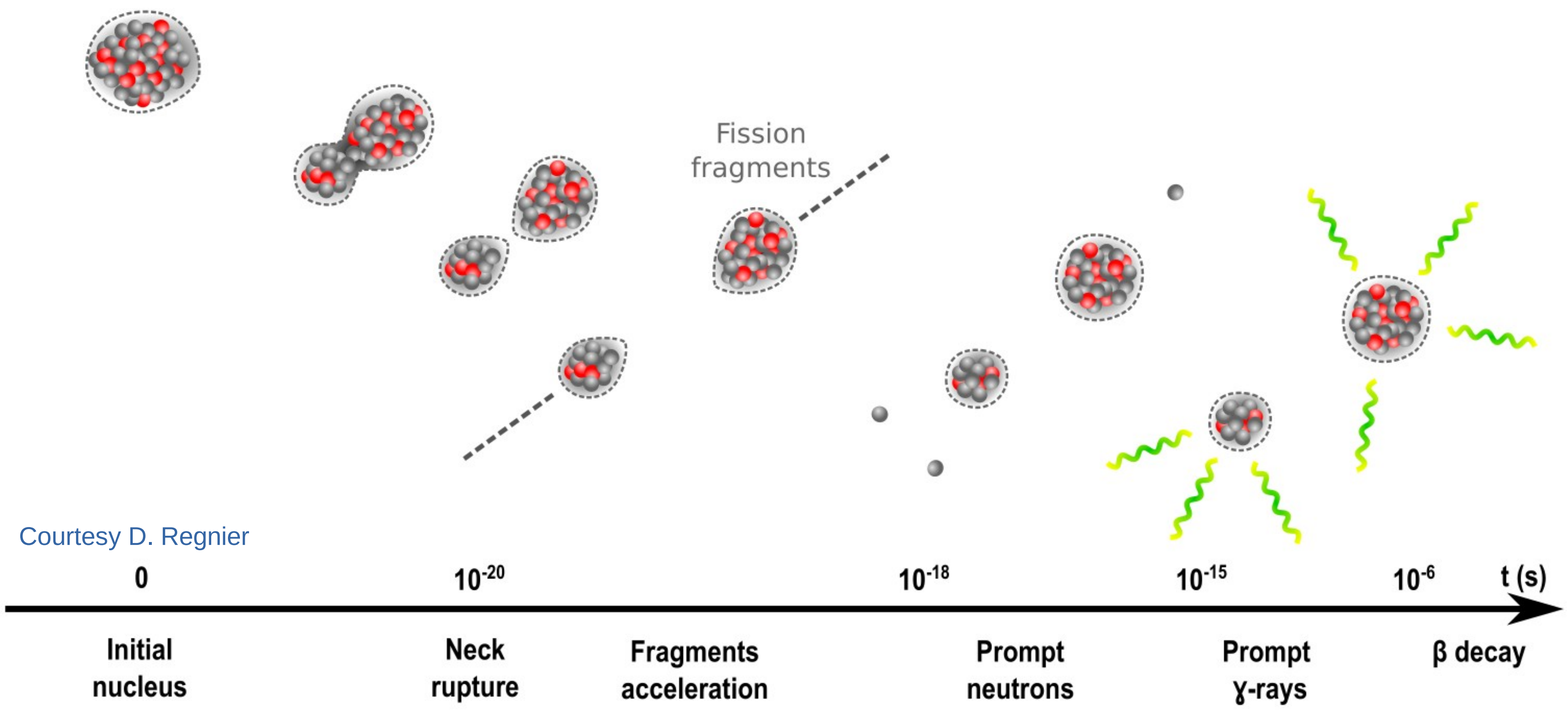
The fission outcome : The fragment distribution
It results from the interplay between the microscopic structure of the PES and the dynamics of the system evolving towards scission.

Why measure fission fragments?

- **Fission fragments are the fingerprints of the fission process**
  - Signatures of the underlying nuclear structure effects in the fission process.
  - Reveal shell effects in the fragments
  - Probe the dynamics toward scission
  - Constrain fission models
  - Mapping the fragments allows us to map the asymmetric-fission landscape.

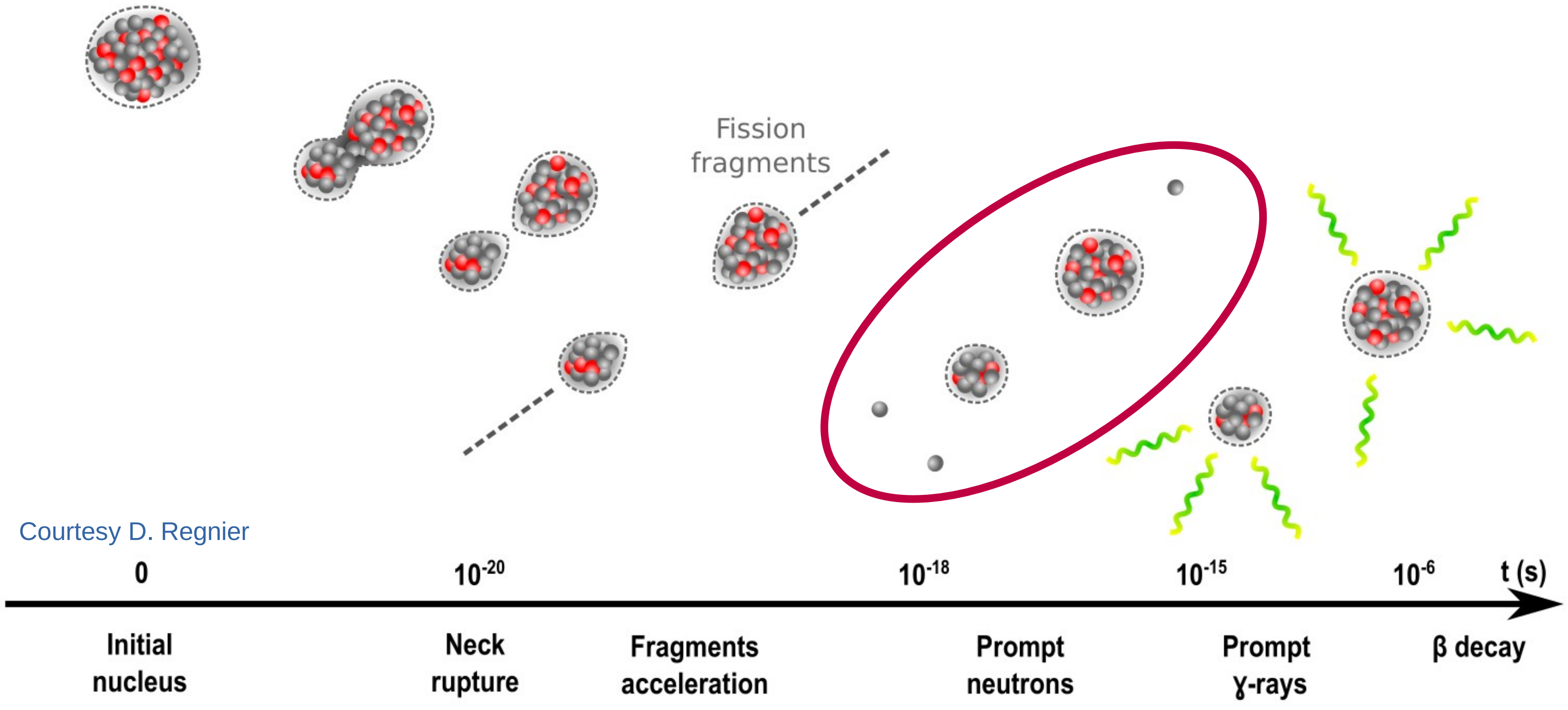
- **A lot of applications**
  - Nuclear science and applications
    - Energy production
    - Medecine
    - Defense
  - Nuclear astrophysics
    - *r*-process : Fragment yields determine how material is recycled towards lighter/heavier nuclei

Measuring fission fragments



- Primary fission fragments : before prompt neutron emission
- **Secondary fission fragments**: after neutron evaporation → *independent yields*
- Fission products: after β-decay → *cumulative yields*

Measuring fission fragments



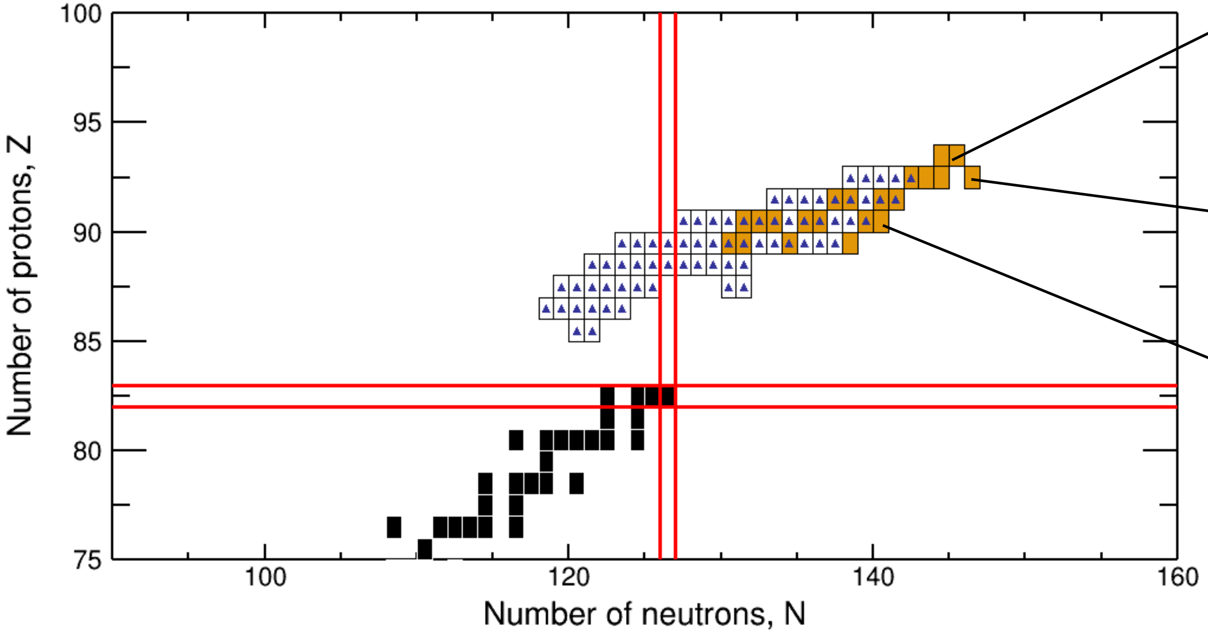
- The experiments at GSI using inverse kinematics at relativistic energy measure secondary fission fragments, typically 10s of nanoseconds after scission.

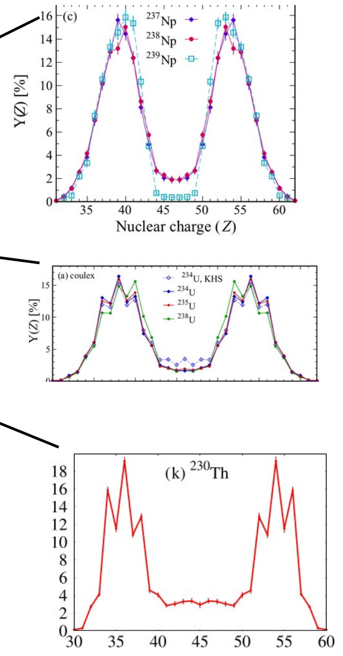
Fission yields to probe fission modes

▲ K.-H. Schmidt *et al.* NPA **665** (2000) 221

■ SOFIA

J-.F. Martin *et al.* Phys. Rev. C **104**, 044602 (2021)





Fission yields to probe fission modes

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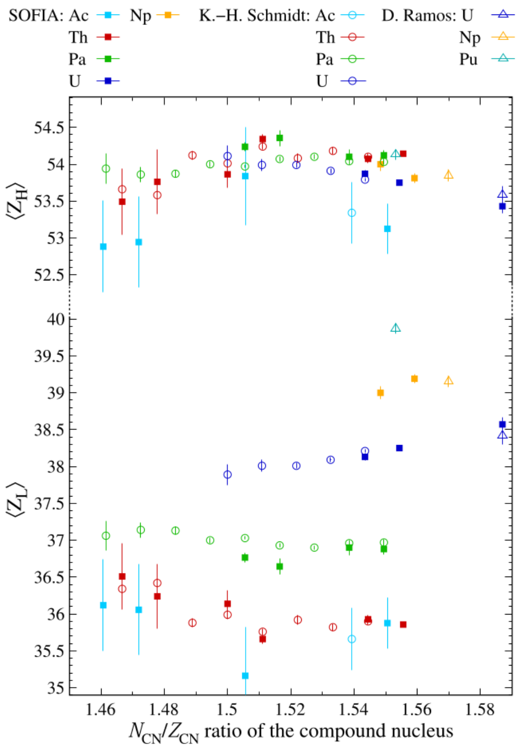
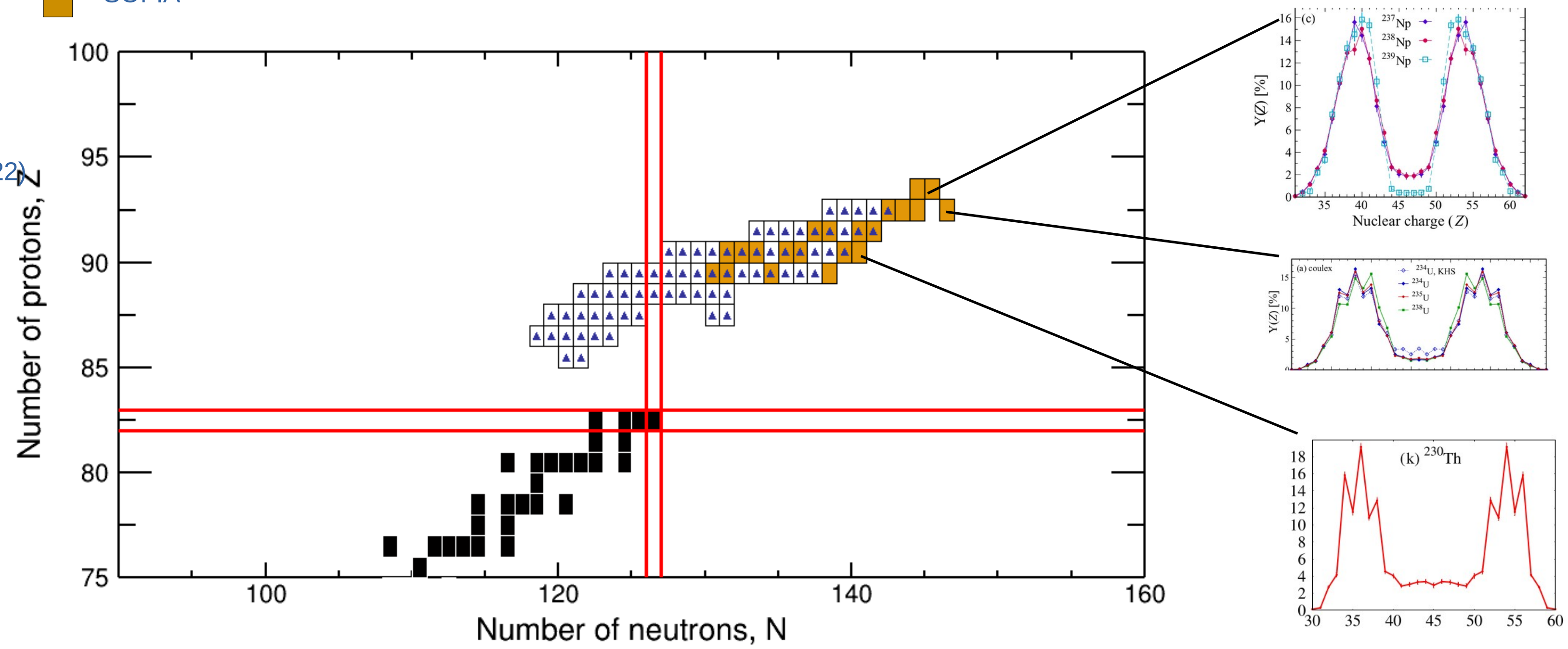
SOFIA

J.-F. Martin *et al.* Phys. Rev. C **104**, 044602 (2021)

A. Chatillon *et al.* Phys. Rev. C **106**, 024618 (2022)



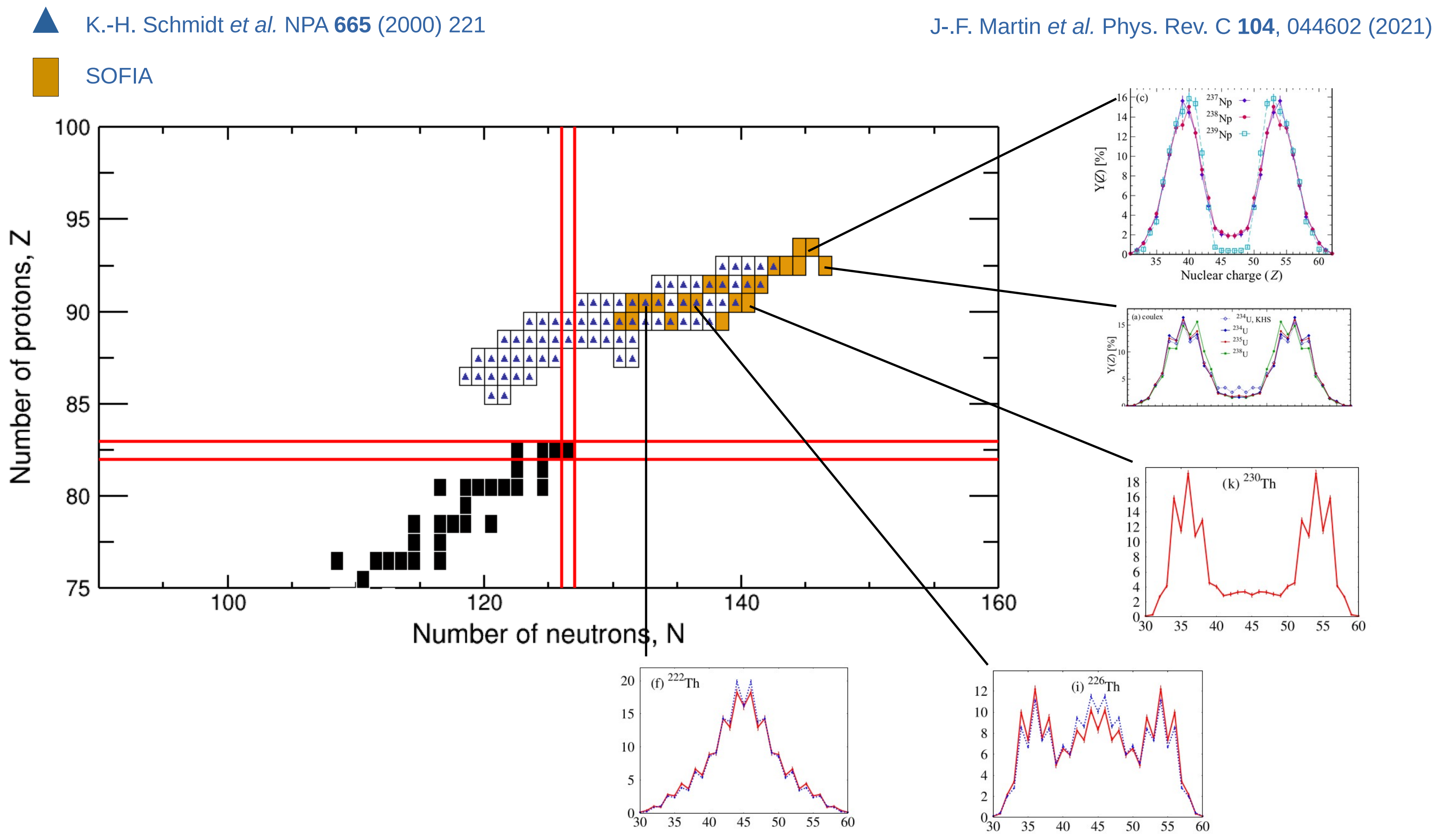


In this region : Z≈54 (Xe) stabilisation

G. Scamps and C. Simenel Nature **564** (2018)

Driven by octupole shape in the fragments.

Fission yields to probe fission modes



A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)
A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

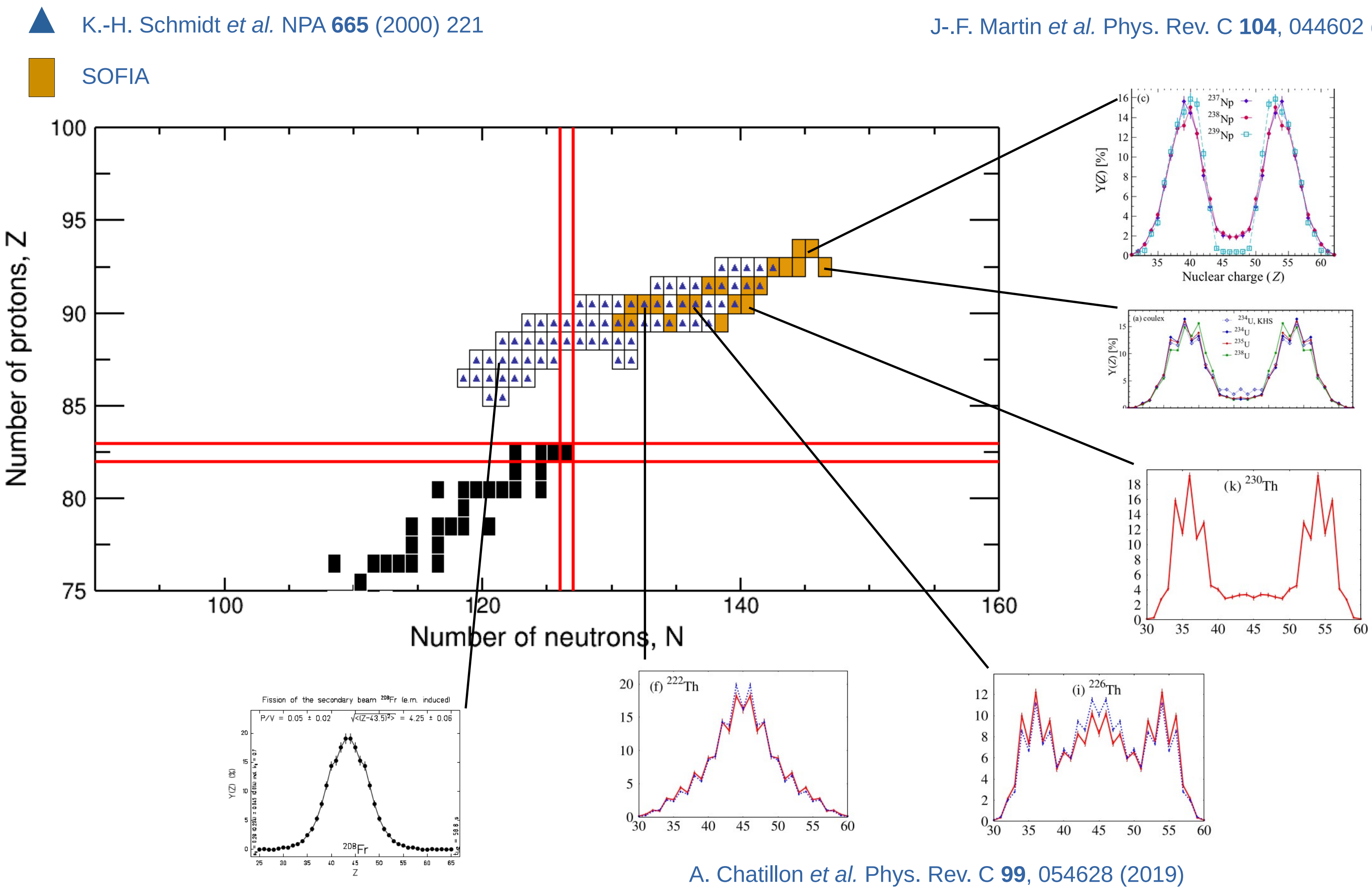
New symmetric compact fission mode.

Fission yields to probe fission modes

K.-H. Schmidt *et al.* NPA **665** (2000) 221

SOFIA

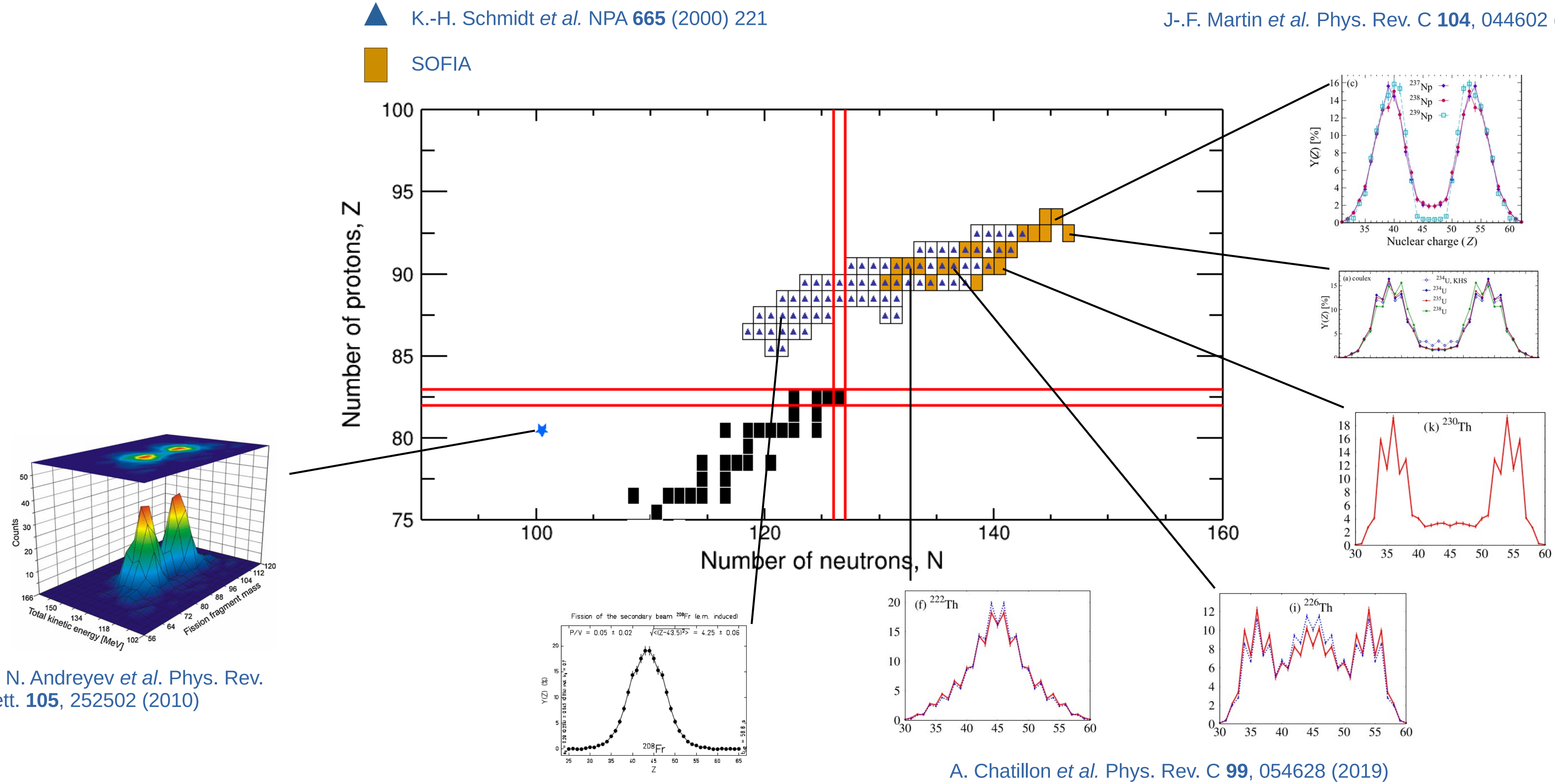
J.-F. Martin *et al.* Phys. Rev. C **104**, 044602 (2021)



S. Steinhauser *et al.* Thesis work

A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)
A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

Fission yields to probe fission modes



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A. N. Andreyev *et al*. Phys. Rev. Lett. **105**, 252502 (2010)

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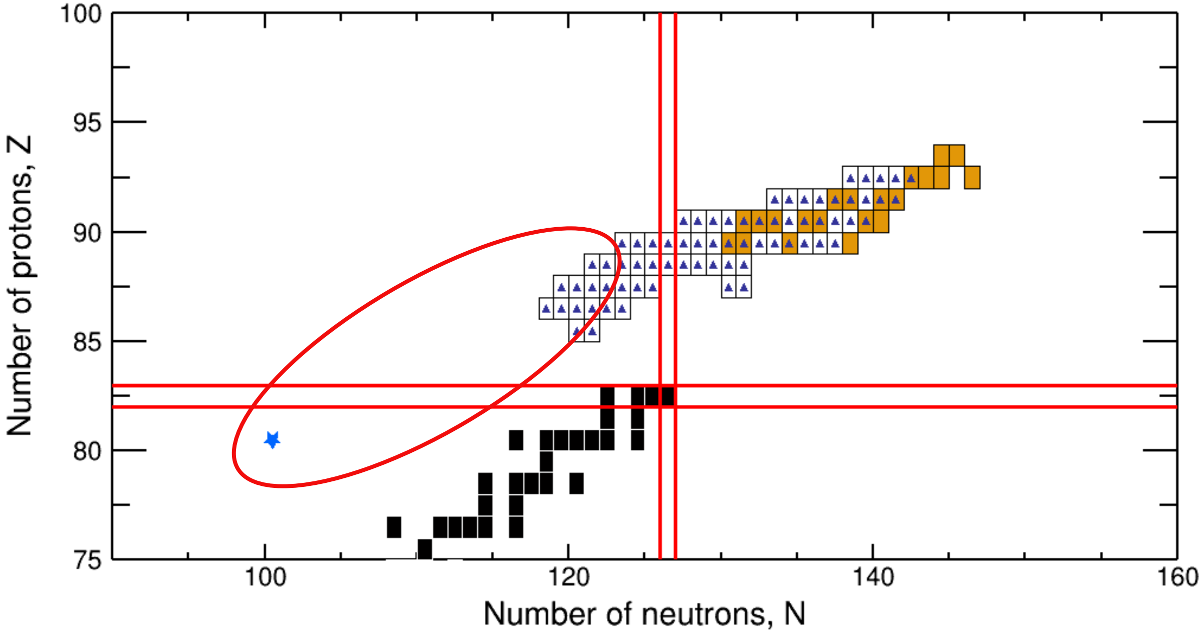
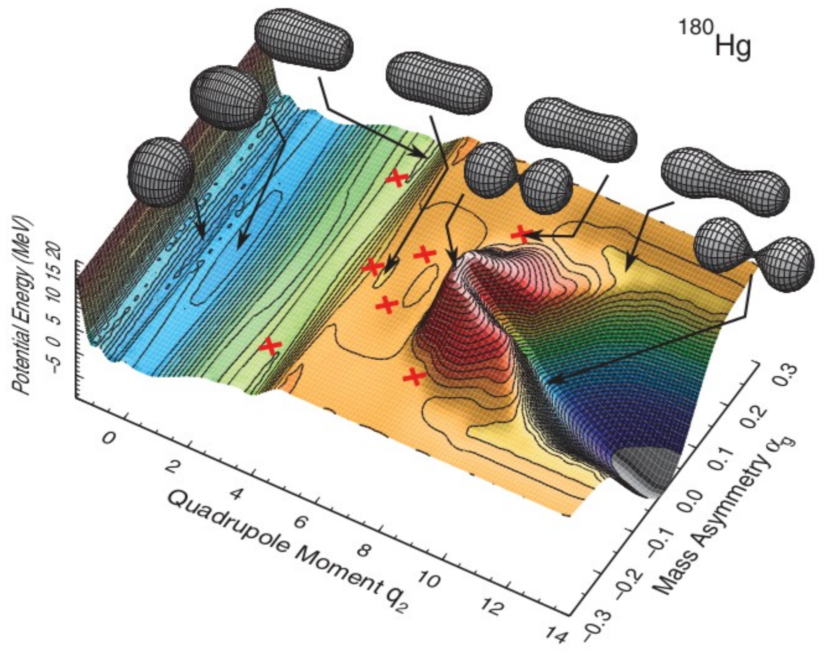
Fission yields to probe fission modes

A new island of asymmetric fission ?



- What mechanism responsible of this new asymmetric split ?
- What shell effect ?
- What are the boundaries?
- ...

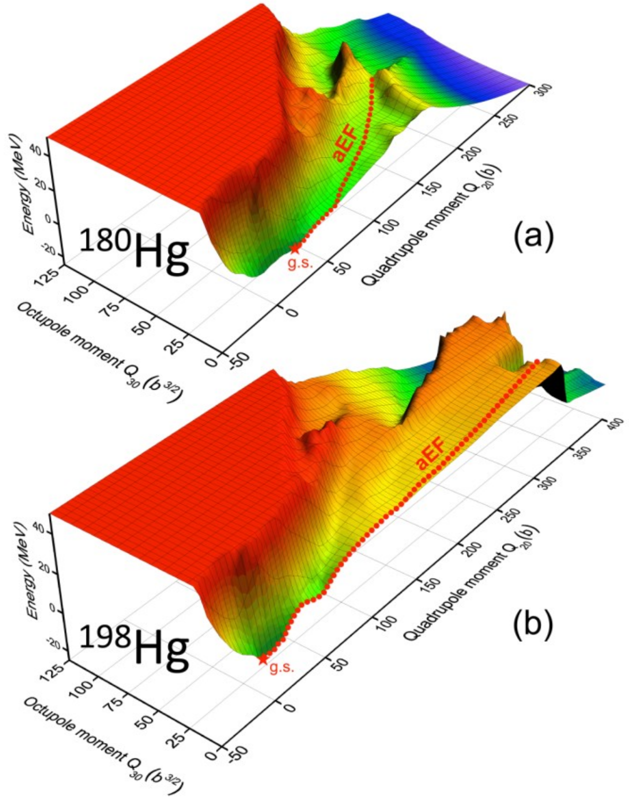
Triggered a lot of theoretical activities…



T. Ichikawa *et al.* Phys. Rev. C **86**, 024610 (2012)

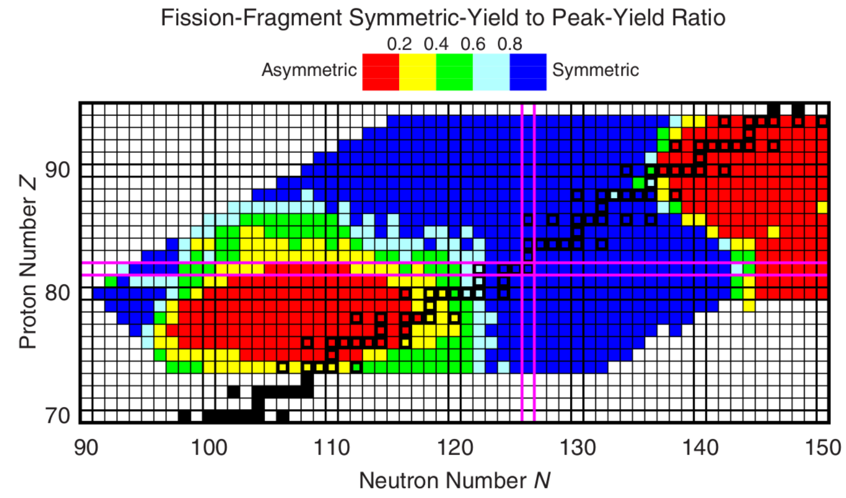
Macro-micro calculations in a 5D space

- Barrier blocked in the symmetric valley.
- Fission independent of structure effetc in the fragments?



M. Warda *et al.* Phys. Rev. C **86**, 024601 (2012)
J. D. McDonnell *et al.* Phys. Rev. C **90**, 021302(R) (2014)

- Mean field calculations using Skyrme SkM* or Gogny D1S interaction

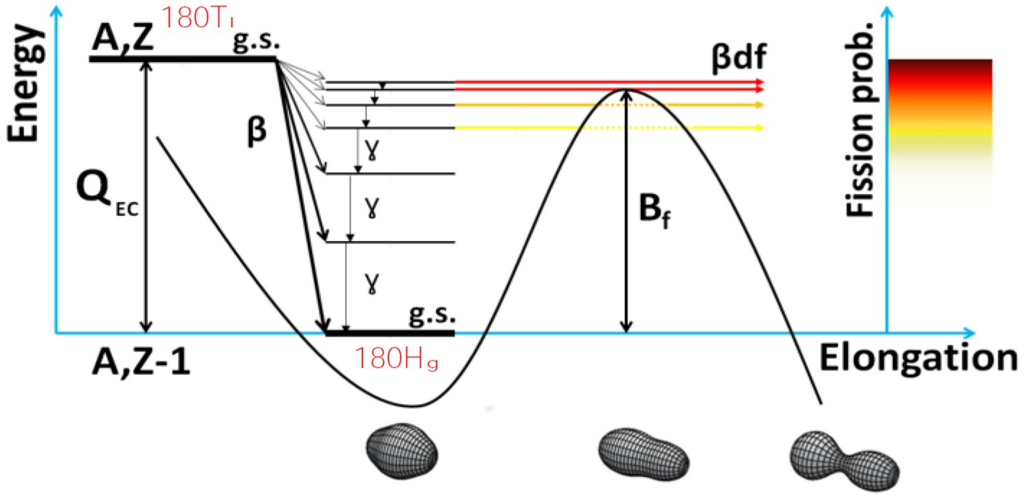


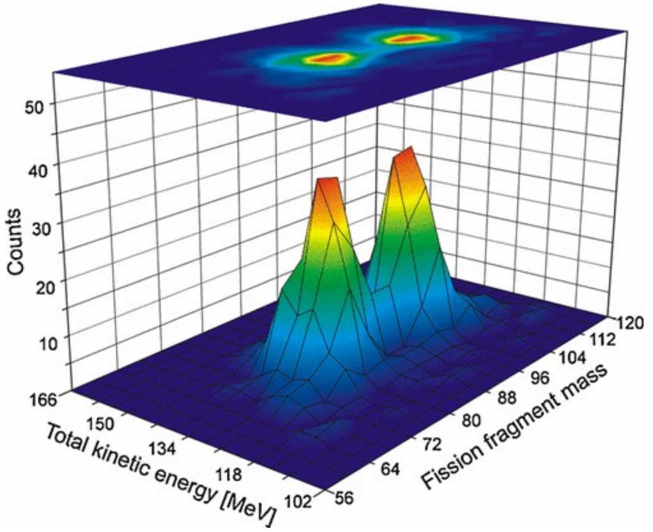
P. Moller *et al.* Phys. Rev. C **91**, 044316 (2015)

stochastic calculations giving a theoretical map of the evolution of the fission.c

Triggered a lot of experimental activities

- **β-decay delayed fission**
  - Only a few nuclei accessible with this technique
  - We need $Q_{\beta} > B_f$
  - Probe low energy fission
  - Measure mass ratio M1/M2 only.



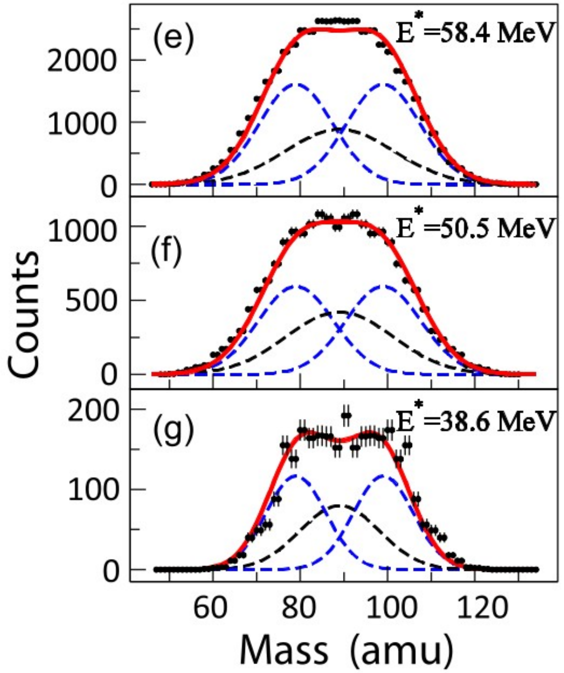


A. N. Andreyev *et al*. Phys. Rev. Lett. **105**, 252502 (2010)

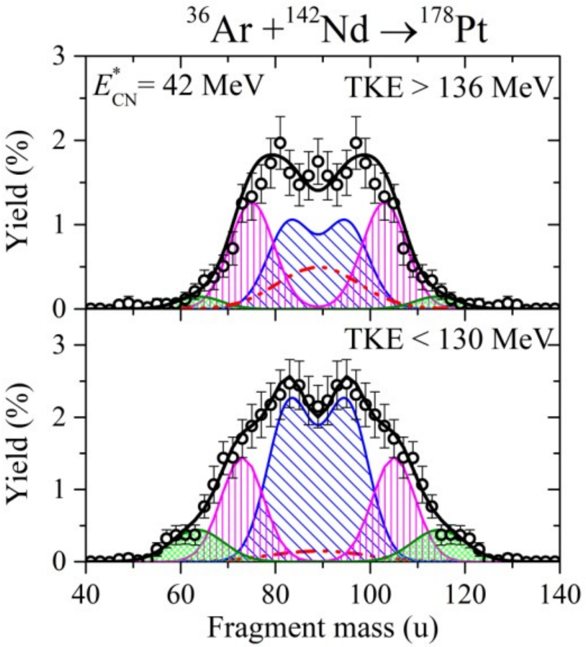
Triggered a lot of experimental activities

- **Fusion-fission**
  - A selection of beam and target to access neutron-deficient systems.
  - Large excitation energy => vanishing of structure effects
  - Only mass distribution with a resoltuion of σ ≈ 3-5 u.
  - Gaussian fit to extract different fission modes (not easy).

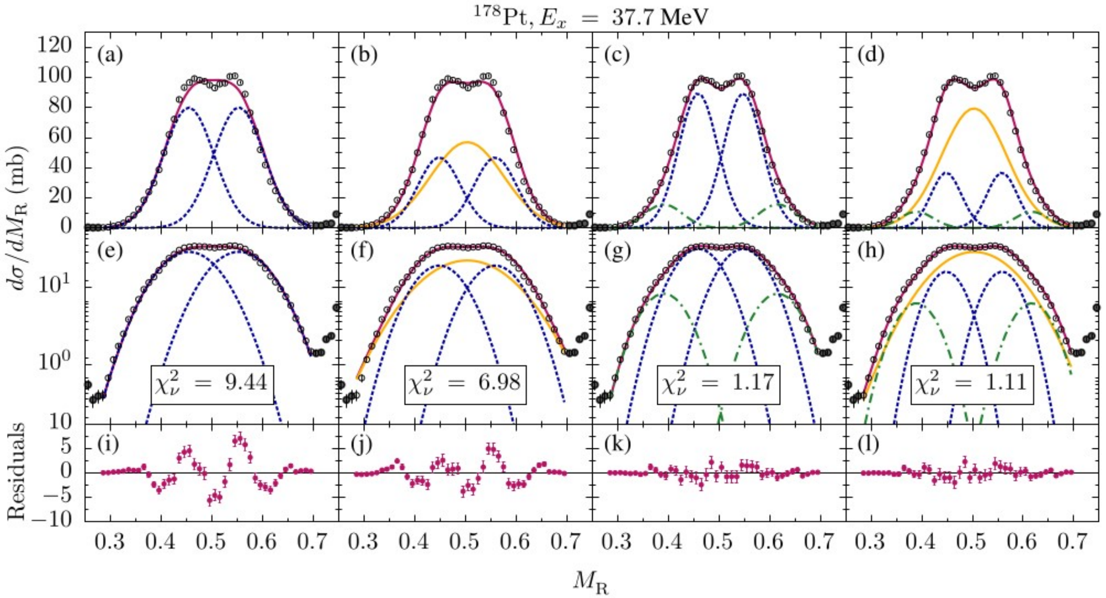
- ^{178}Pt fissioning system example
  - 3 different experiments
  - 3 different interpretation for the number of modes (2, 3 or 4 modes).



I. Tsekhanovich *et al.* Phys. Lett. B **790**, 583-588 (2019)



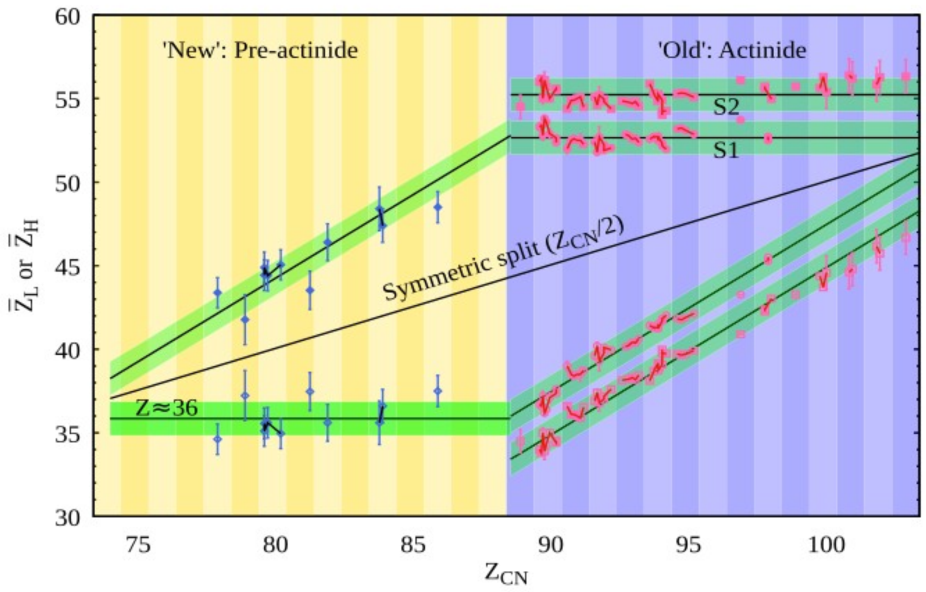
E. M. Kozulin *et al.* Phys. Rev. C **105**, 014607 (2022)



B.M.A. Swinton-Bland *et al.* Phys. Lett. B **837**, 137655 (2023)

Proton-shell responsible for it?

- Mahata et al.
  - Systematic and wide analysis of mass distribution using UCD (Unchanged Charge Density) hypothesis to extract the Z information.
  - This result points to a proton stabilization in this pre-actinide region.

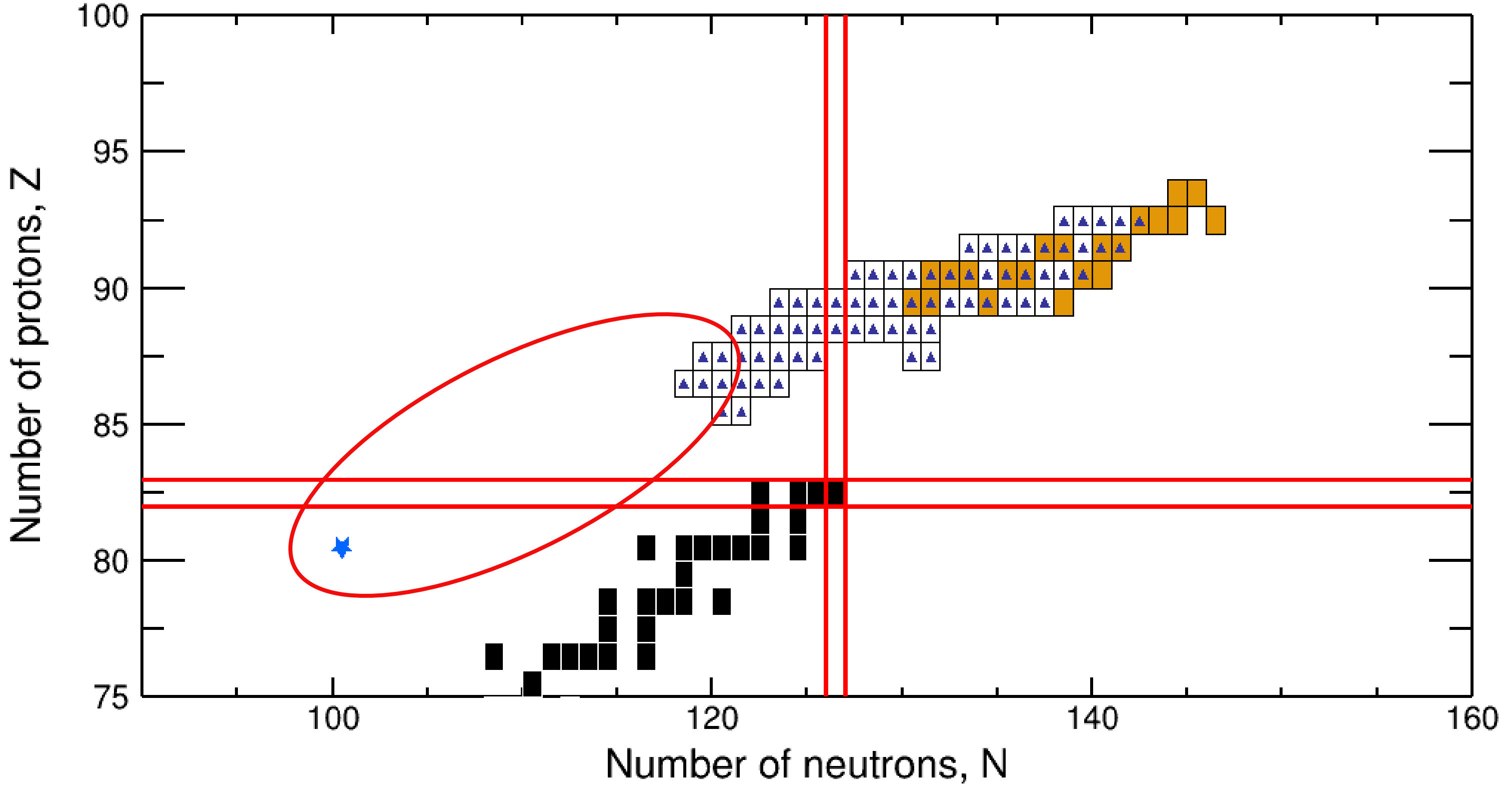


K. Mahata, C. Schmitt *et al.* Phys. Lett. B **825**, 136859 (2022)

- ✗ **Z information is missing, never measured.**
- **Charge distribution is important to understand the origin of this new asymmetric fission.**

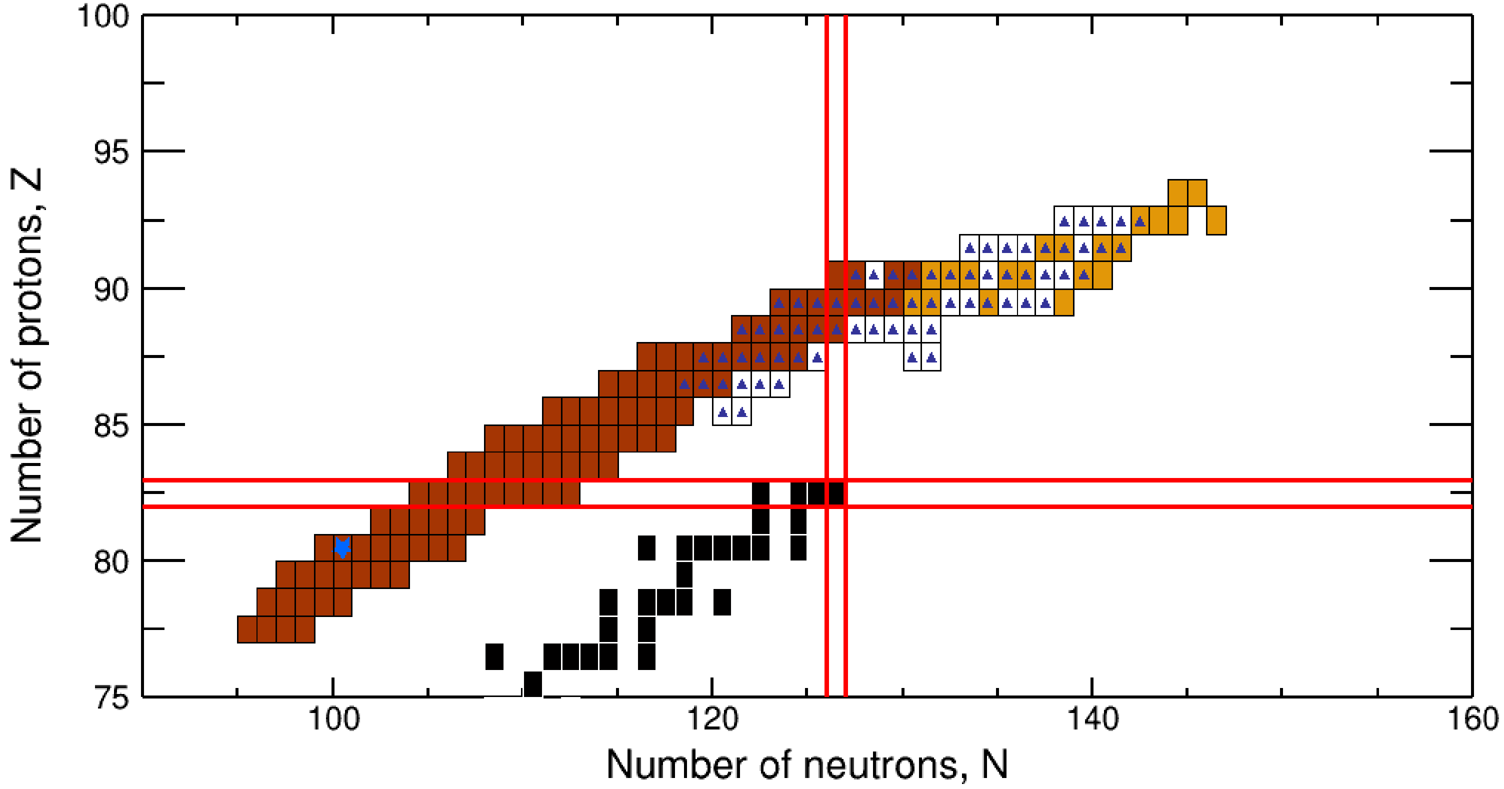
New R^{3}B/SOFIA experiment in 2021

Proposal: J. Taieb
Mapping this new asymmetric fission island



New R³B/SOFIA experiment in 2021

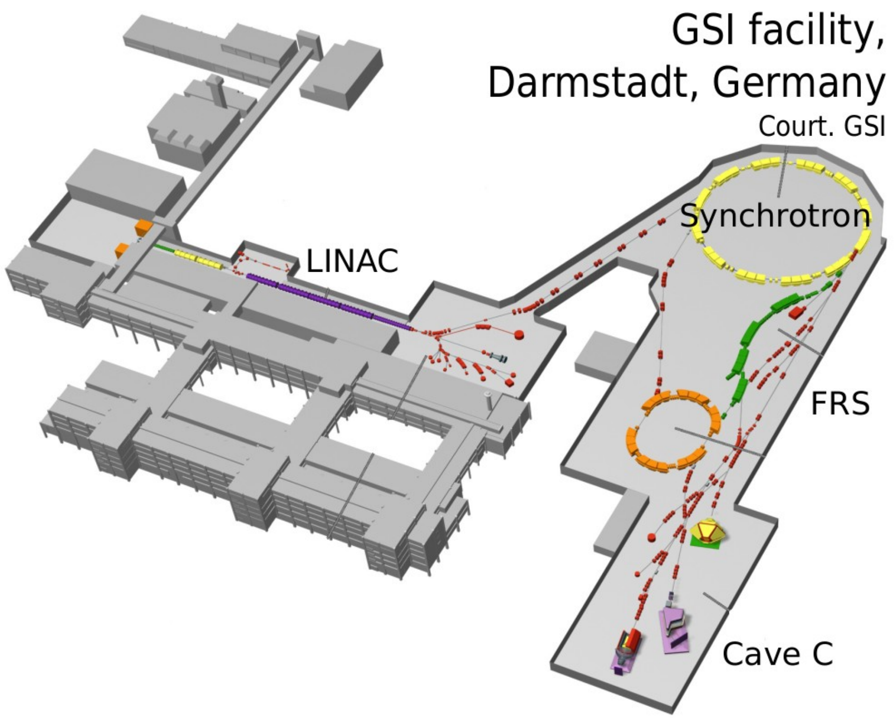
- **100 fissioning systems in one experiment !**
- **Establishing a connection between the neutron-deficient subleab region and the actinide region.**



2. SOFIA/R^{3}B setup at GSI

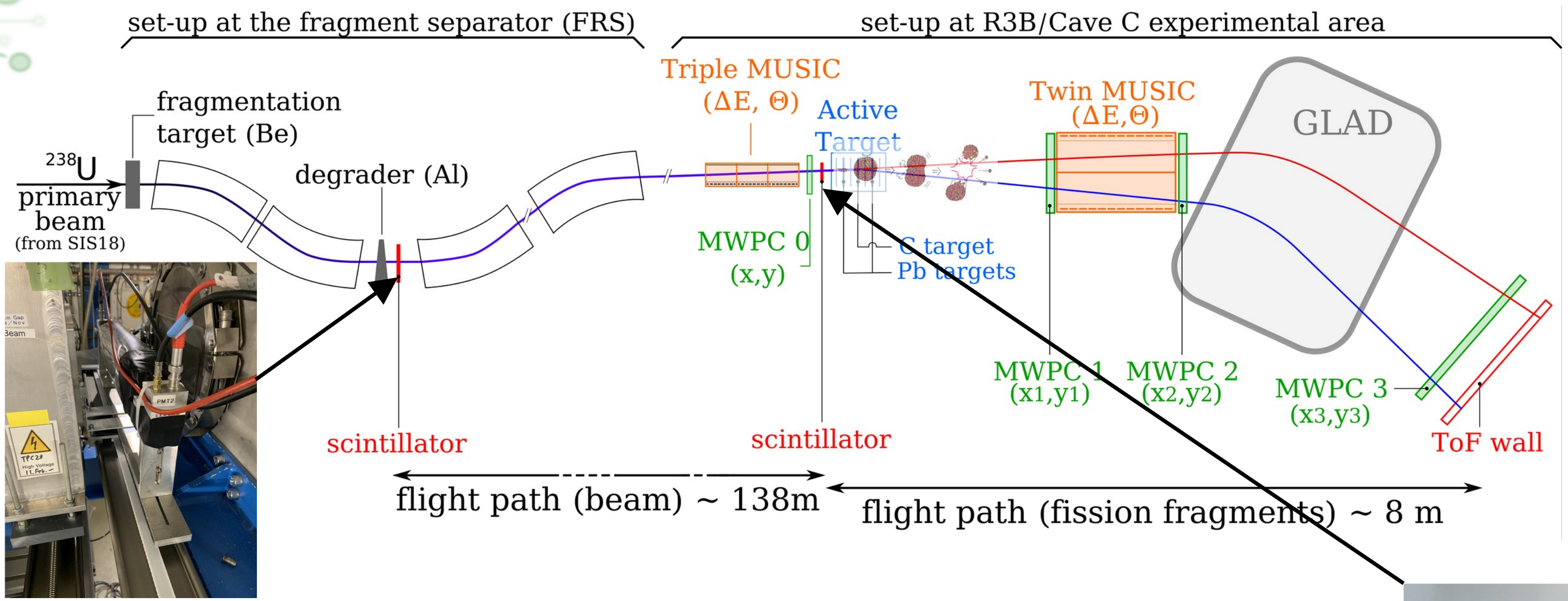
Inverse kinematics at GSI

New SOFIA campaign in 2021 to map the fission modes in the neutron-deficient region around lead.



- Primary beam of ^{238}U at 1 GeV/u.
- Production and identification of the secondary beam through the FRS.
- Fission in cave C and identification of both fission fragments
- 12 FRS settings from ^{175}Pt up to ^{221}Pa

Experimental setup

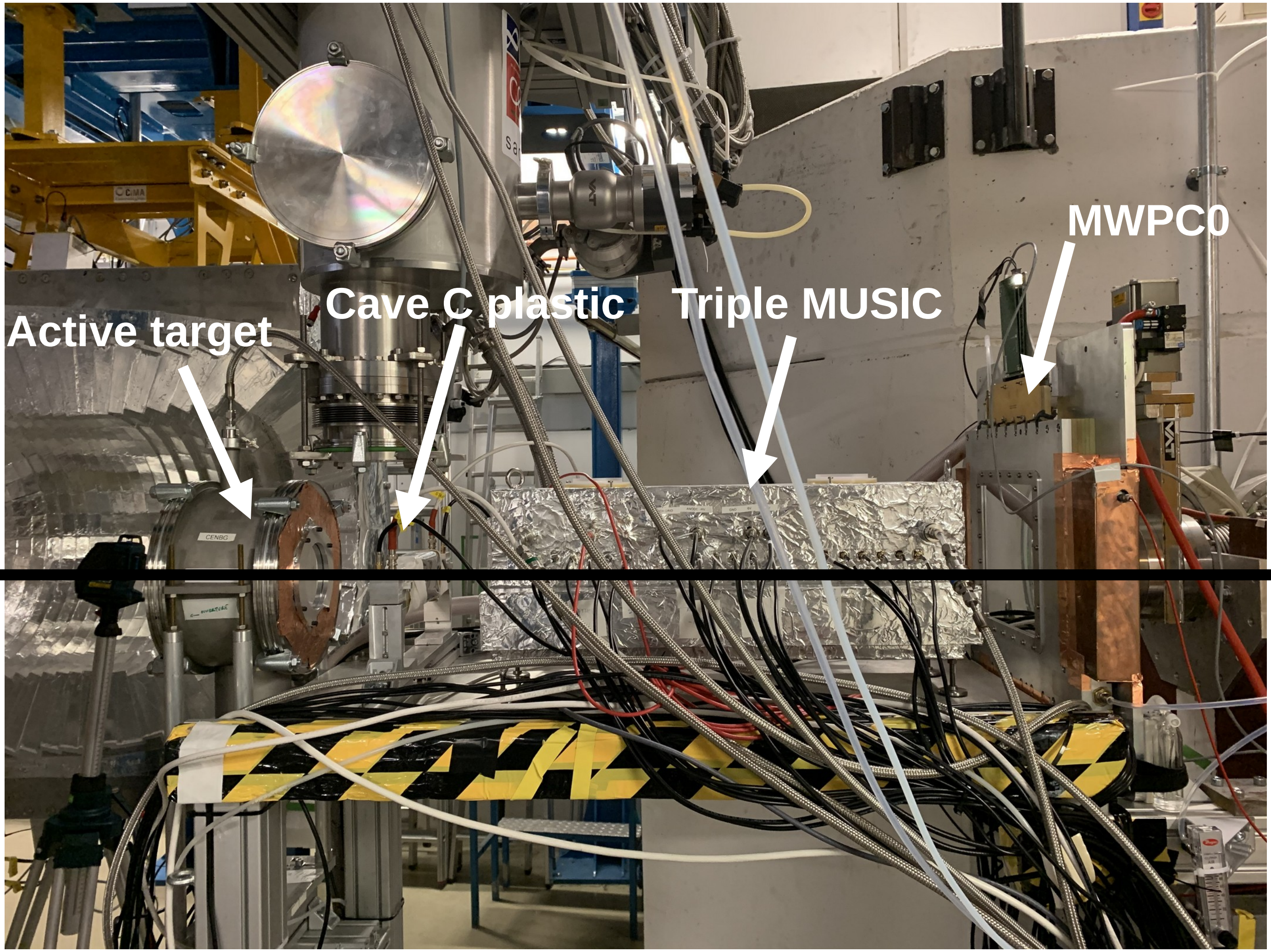


- Plastic at S2 for time and position measurement.
- Plastic at Cave C for start and ToF.
- Triple-MUSIC for charge identification of the secondary beam.
- Active target with three cathodes (2 lead + 1 carbon) to induced fission.
- MWPC for (x,y) measurements of the beam and the fission fragments.
- Twim-MUSIC for charge identification of the fission fragments.
- Tof Wall frotime of flight of the fission fragments.

$B\rho = B\rho_0(1 - X_{S2}/D_{S2})$

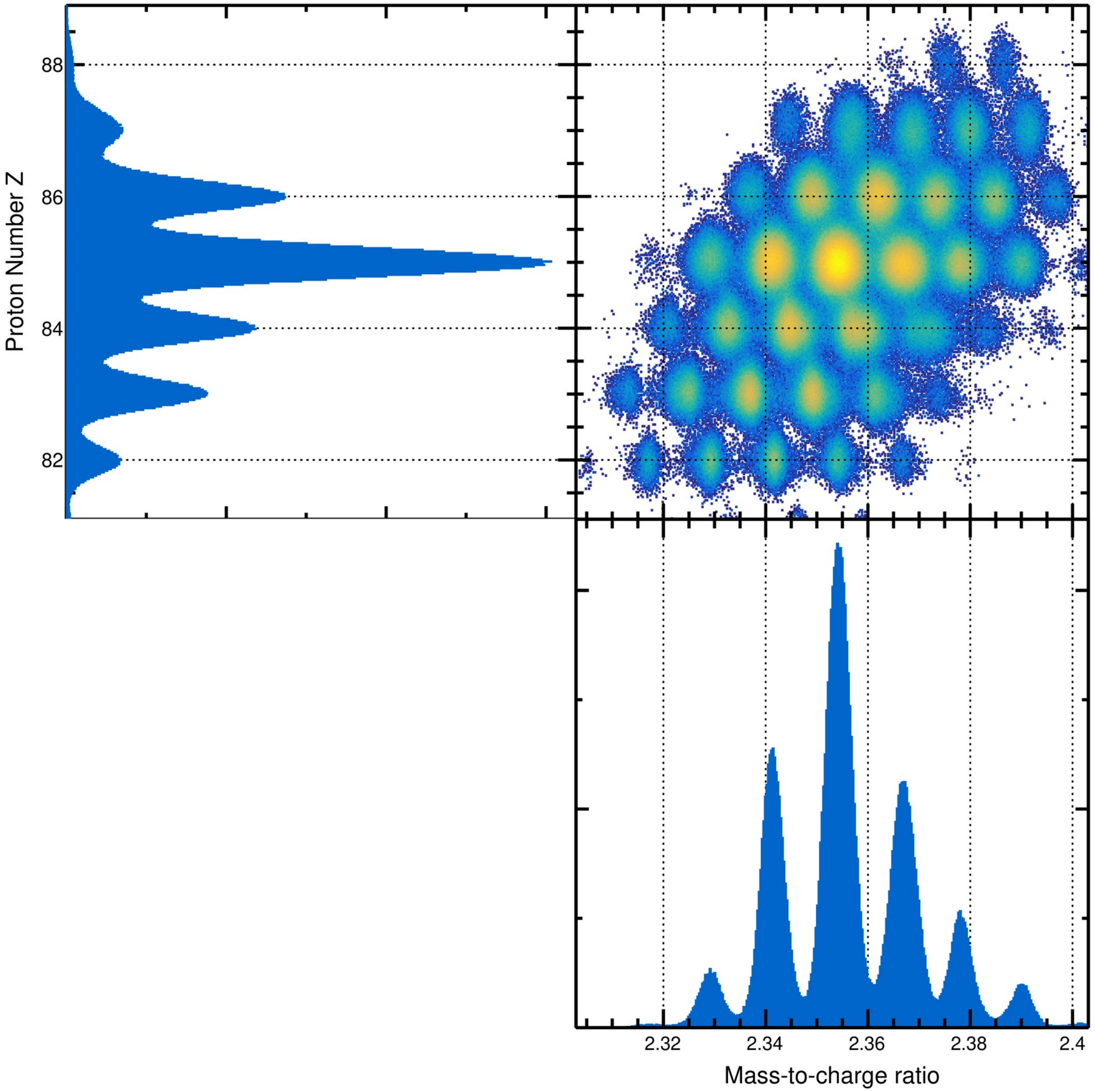
$A/Q = B\rho/(3.10716*\gamma*\beta)$

Secondary beam identification

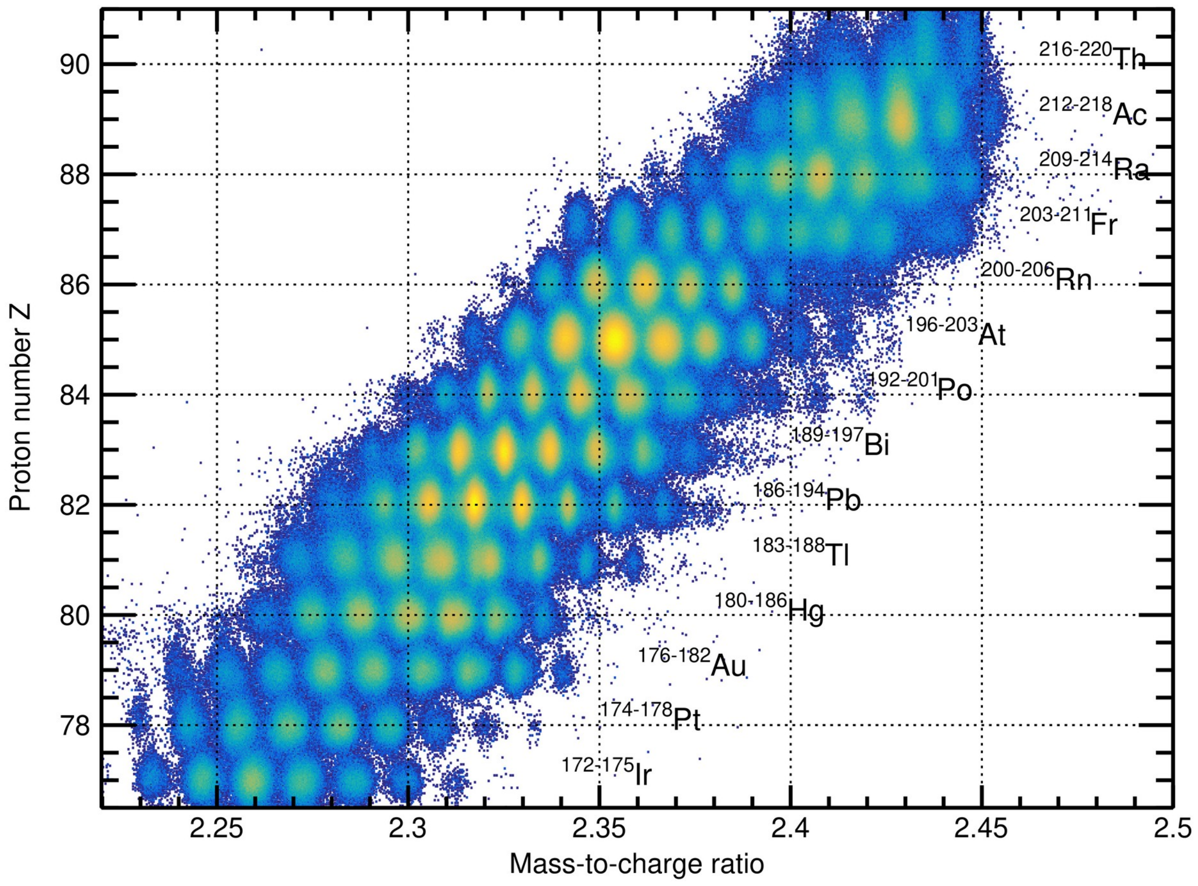


Secondary beam identification

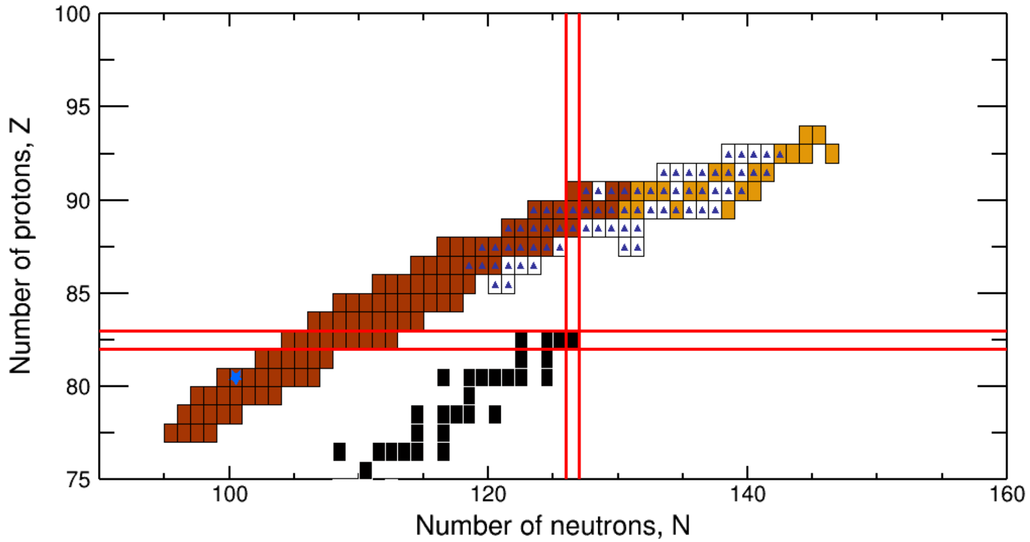
- Secondary beams produced around 700 MeV/u.
- Identified through the Brho – TOF – ΔE technique
- $\Delta A/A = 7.7\times10^{-4} \rightarrow \Delta A = 0.14$ uma
- $\Delta Z/Z = 2.5\times10^{-3} \rightarrow \Delta Z = 0.11$ charge unit



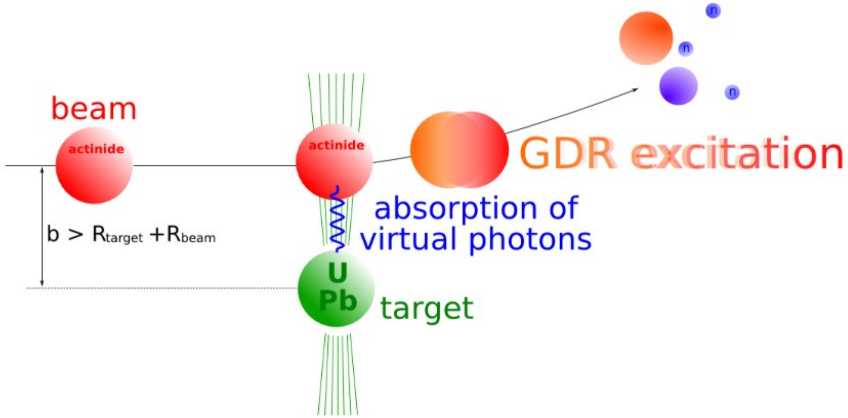
Global view of the studied systems

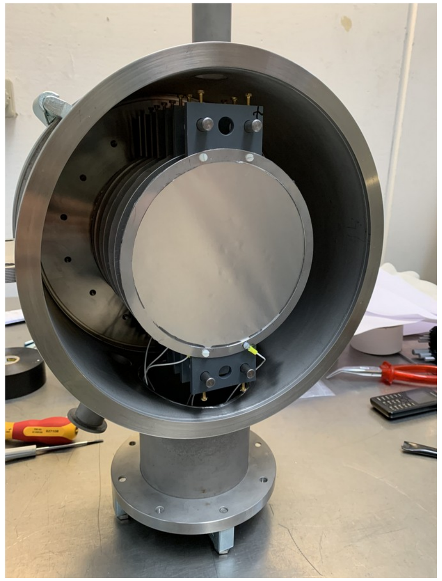


- 100 fissioning systems in one experiment
  - 12 FRS settings
  - From ^{175}Pt up to ^{220}Th
  - Very exotic systems
  - Bridge between the neutron-deficeint sub-lead region and the actinide region.



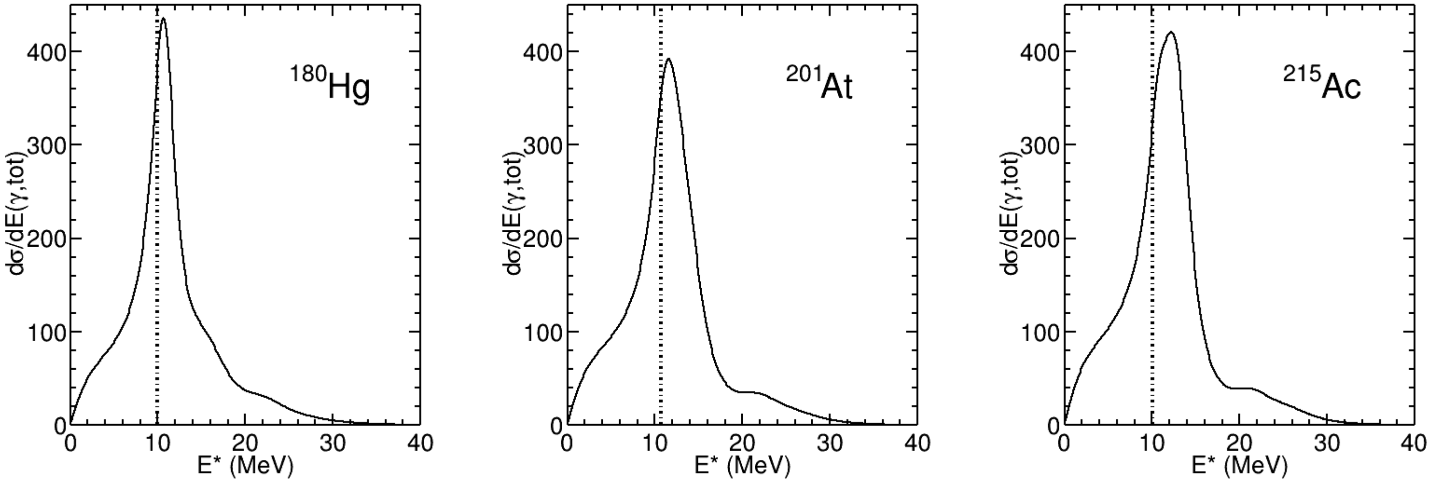
Coulomb induced fission at relativistic energies

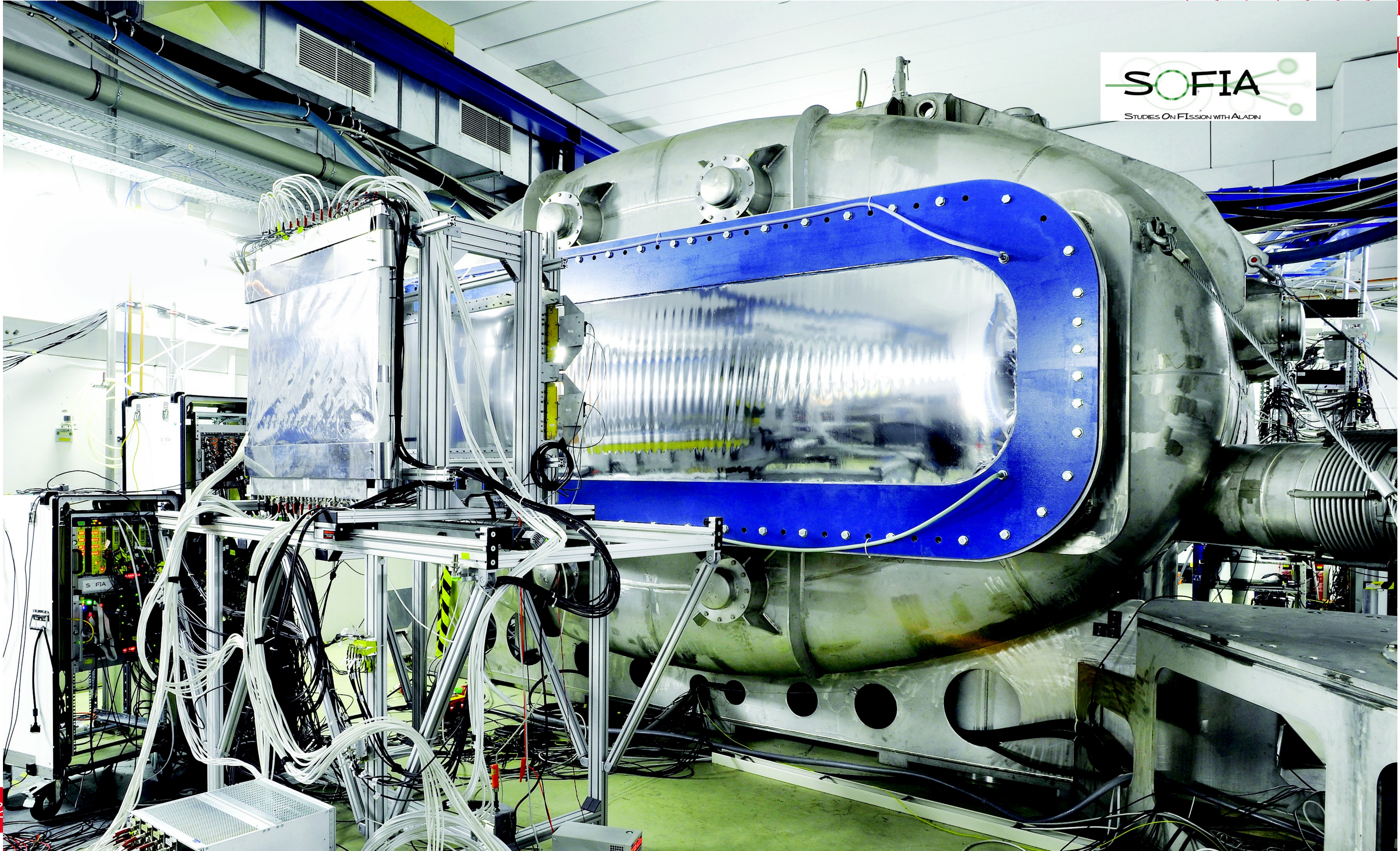




- **Coulomb induced fission**
  - ✓ Large cross section (around de 3 barns)
  - ✓ <E*> around de 14 MeV (excitation mainly through the GDR) → Sensitive to shell effects

- **Active target**
  - ✓ 2 lead cathodes (1.5 mm thick)
  - ✓ 1 carbon cathode (0.5 mm thick) to subtract the nuclear contribution

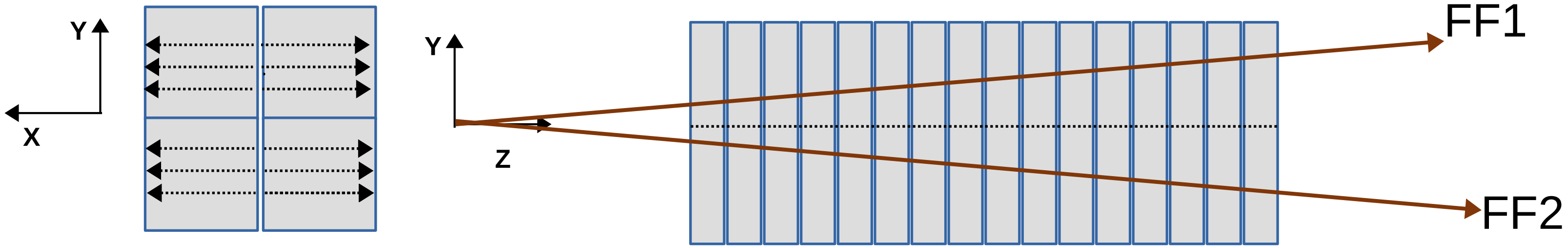


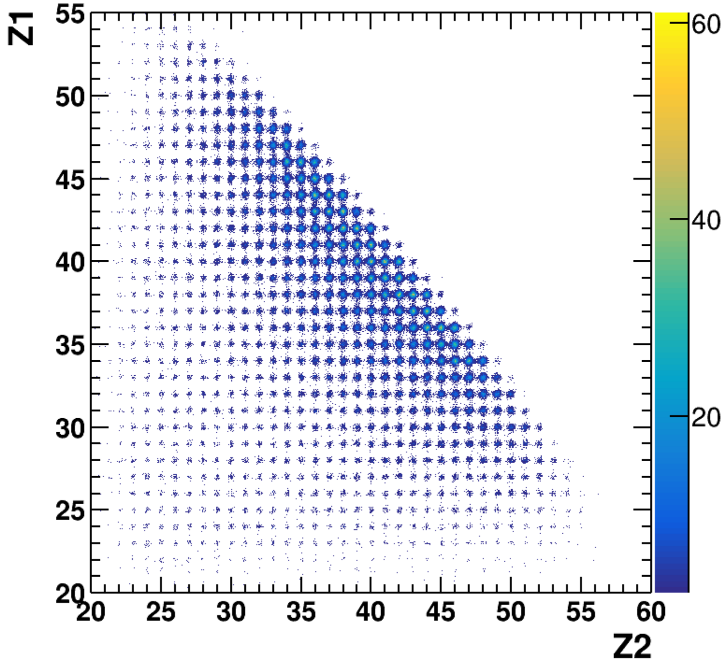

SOFIA
STUDIES ON FISSION WITH ALADIN

Fission fragment charge identification

Twin MUSIC

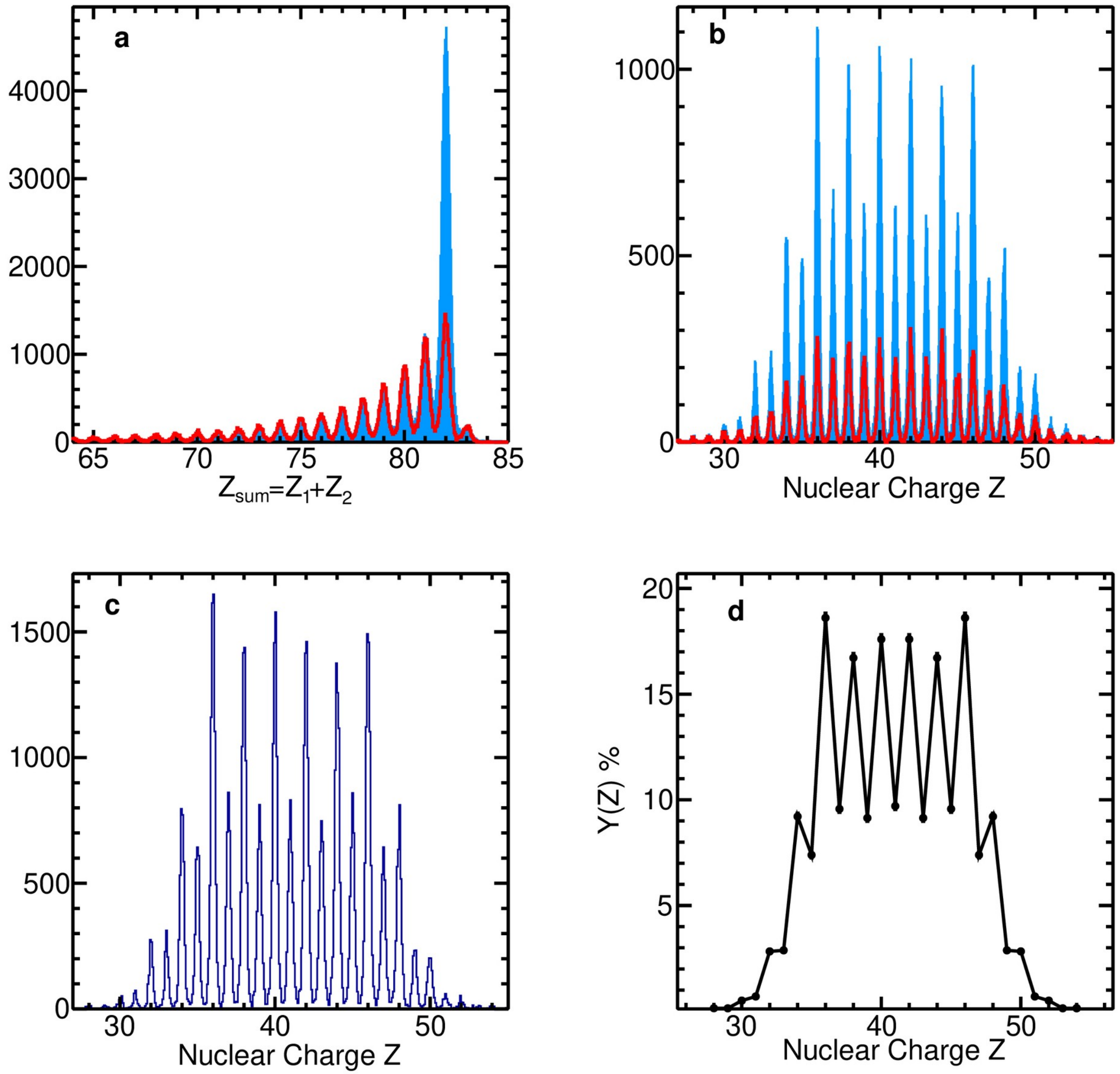
- 4 sections
- We measure both fragment in coincidence.
- Horizontal drift time.
  - ➔ X and θ measurement





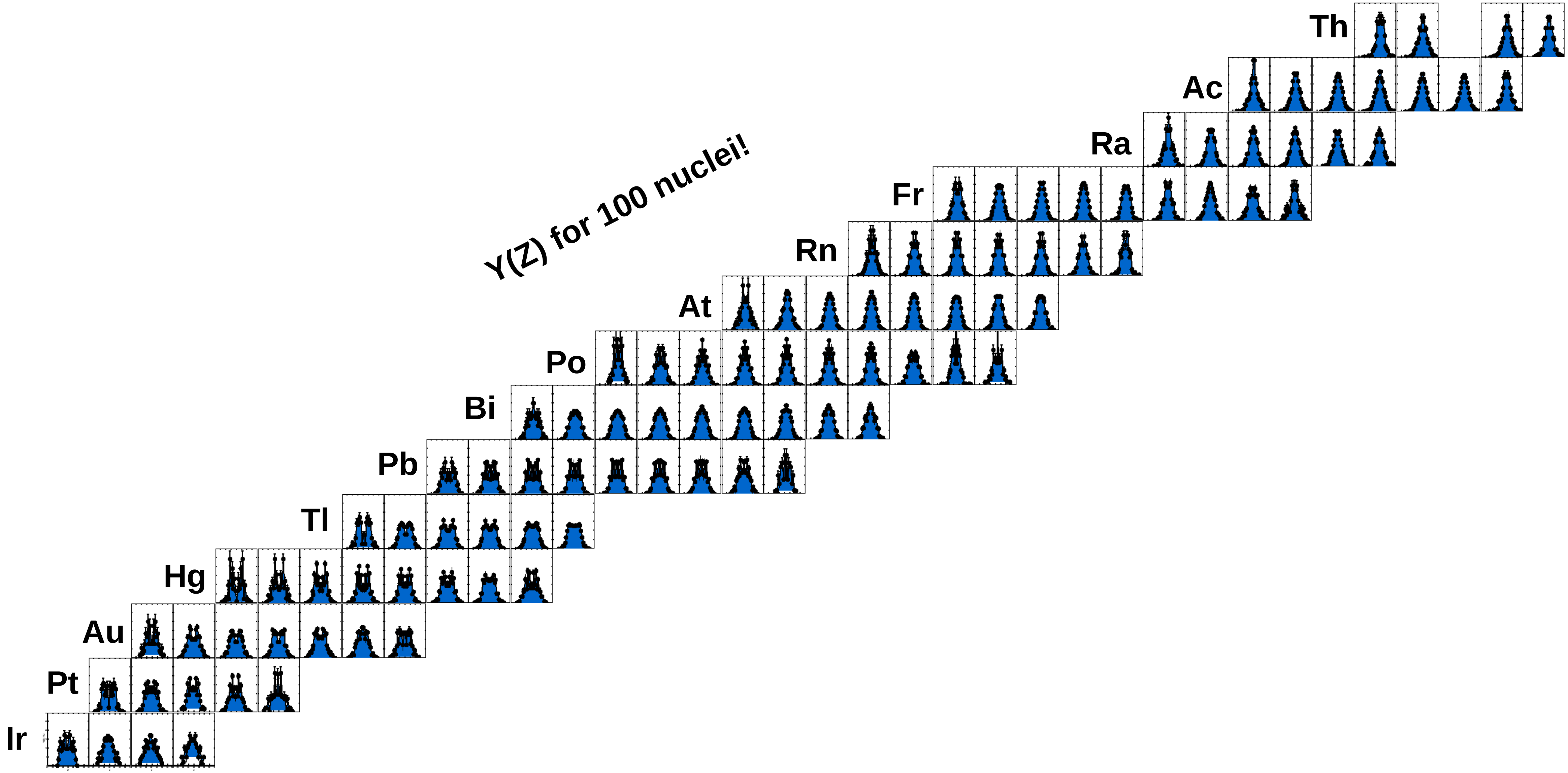
Fission fragment charge identification

- Selection of a fissioning system (here ^{190}Pb)
- Charge identification of both fission fragments in coincidence using the Twin-MUSIC.
- $Z_1 + Z_2 = Z_{beam}$
- When Z_1+Z_2 different from Z_{beam} → Nuclear excitation
- Event selection « Coulomb excitation » ($Z_{sum} = Z_{beam}$)
- Nuclear subtracted charge distribution of the Coulomb-induced fission
- Extraction of the fission charge yields for 100 fissioning systems in a systematic and coherent way.

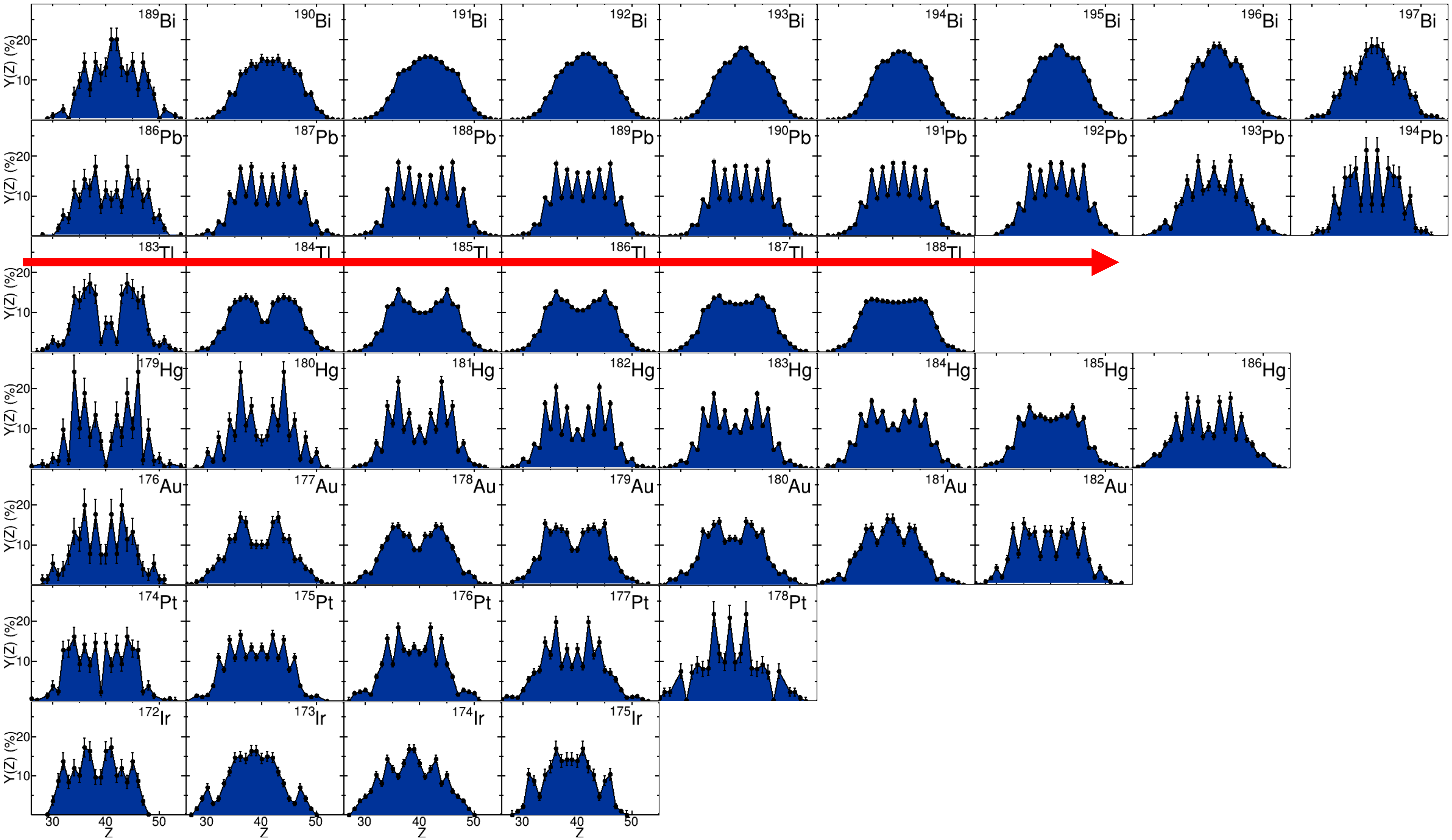


3. Results

Charge yields



Charge yields

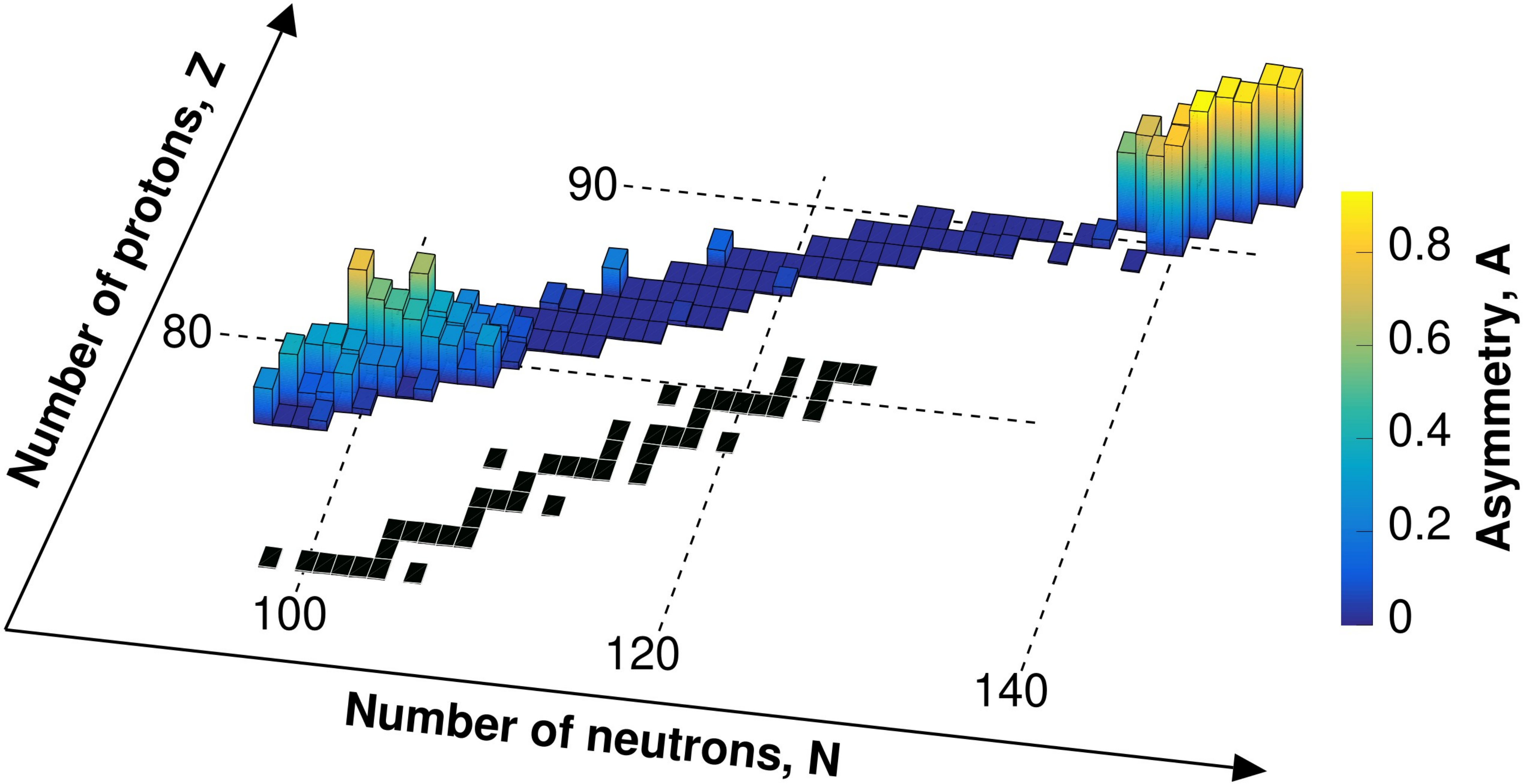


Asymmetry evolution

- Determination of an asymmetry variable to extract a global view of the evolution

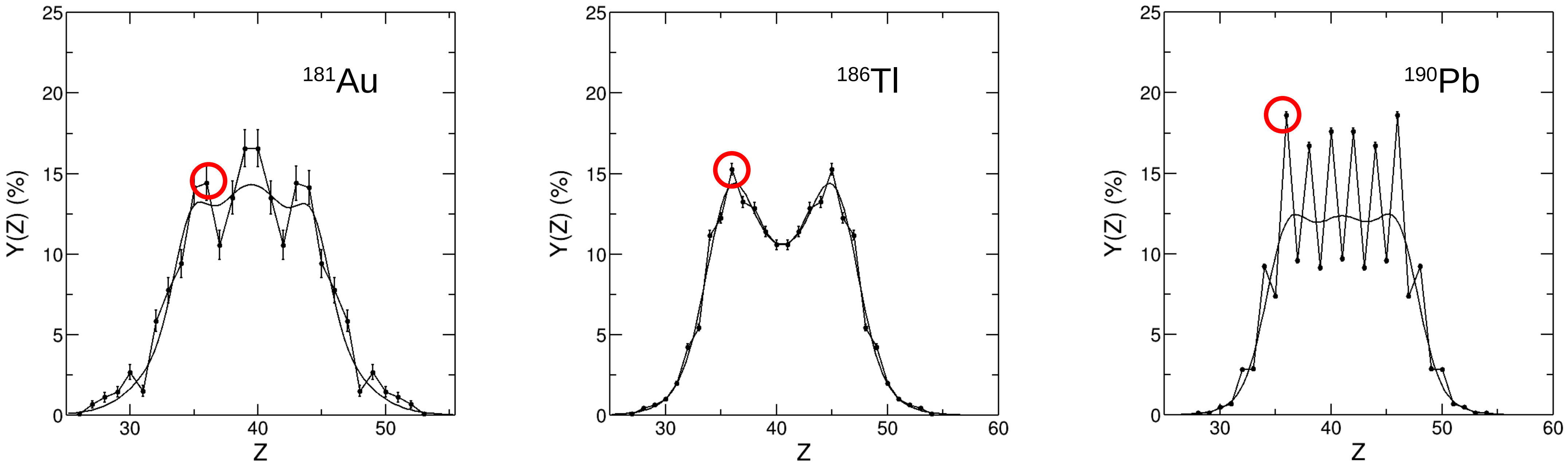
$$\mathcal{A} = 1 - \frac{Y(Z_{\text{sym}}) + \frac{Y(Z_{\text{sym}}-1)+Y(Z_{\text{sym}}+1)}{2}}{Y(Z_{\text{max}}) + \frac{Y(Z_{\text{max}}-1)+Y(Z_{\text{max}}+1)}{2}}$$

Asymmetry map



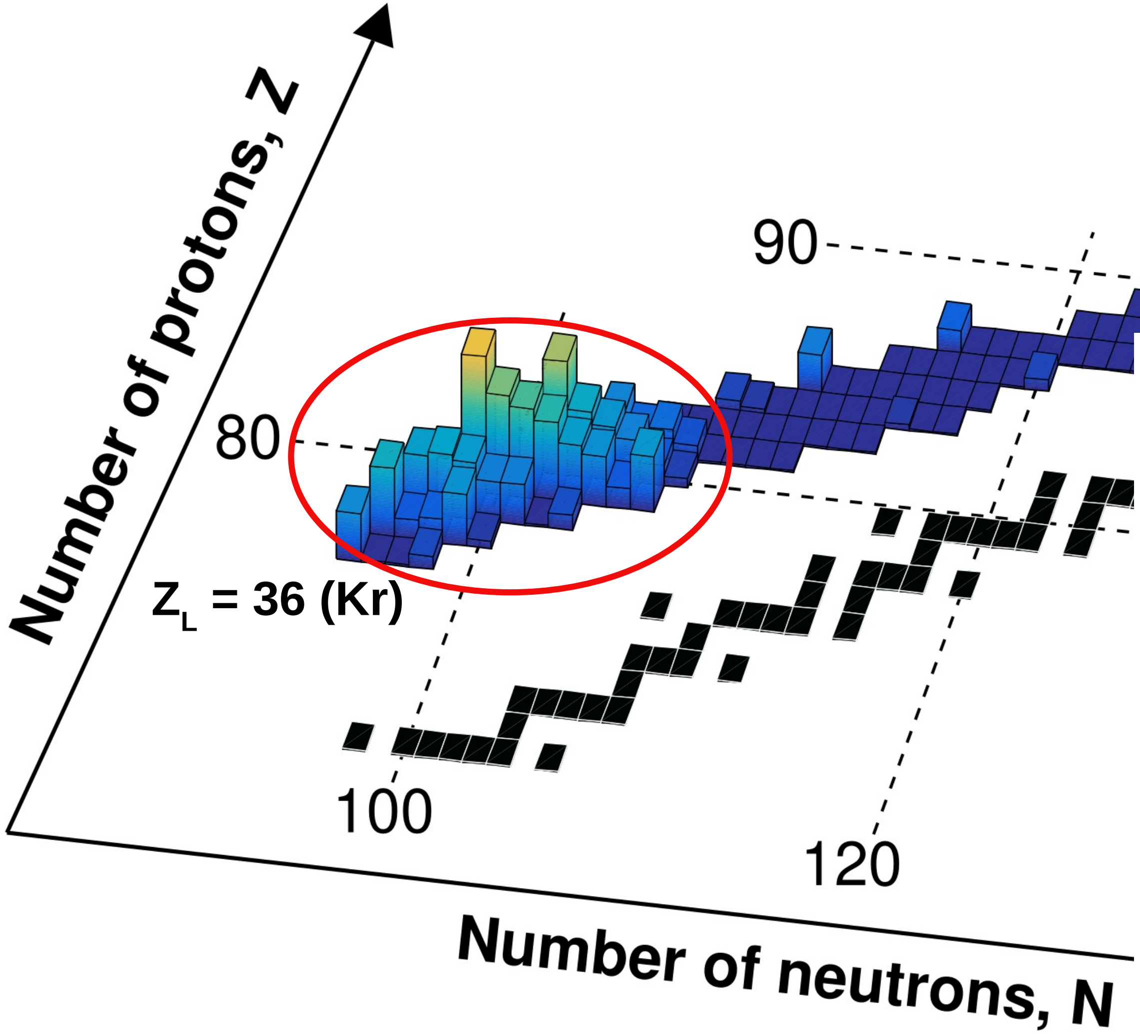
The data demonstrate a transition to more asymmetric fission as we move toward neutron-deficient systems.

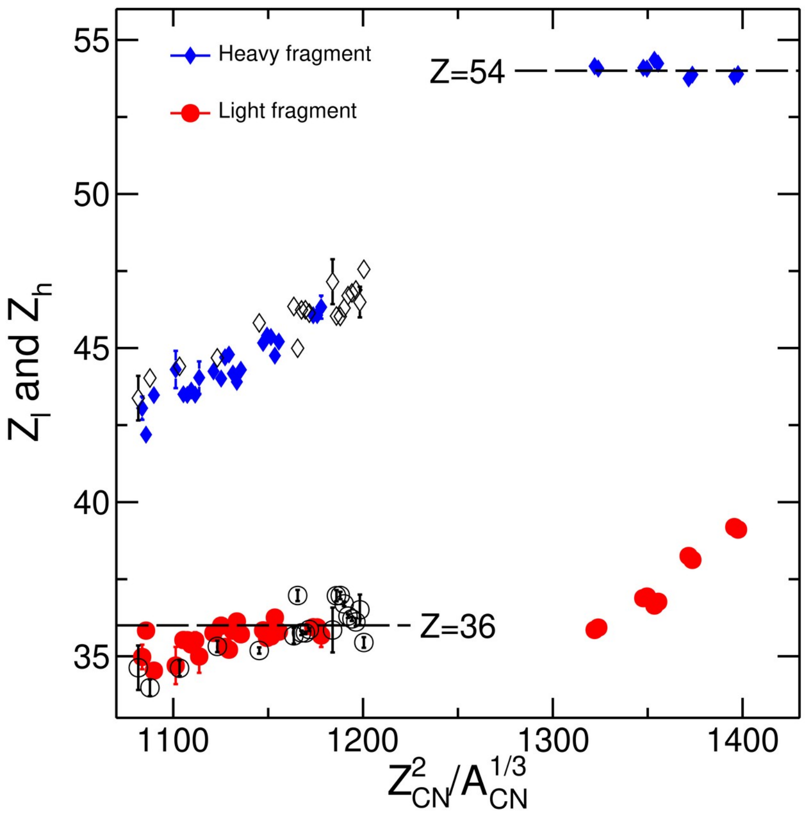
Z=36 stabilization in the light fragment



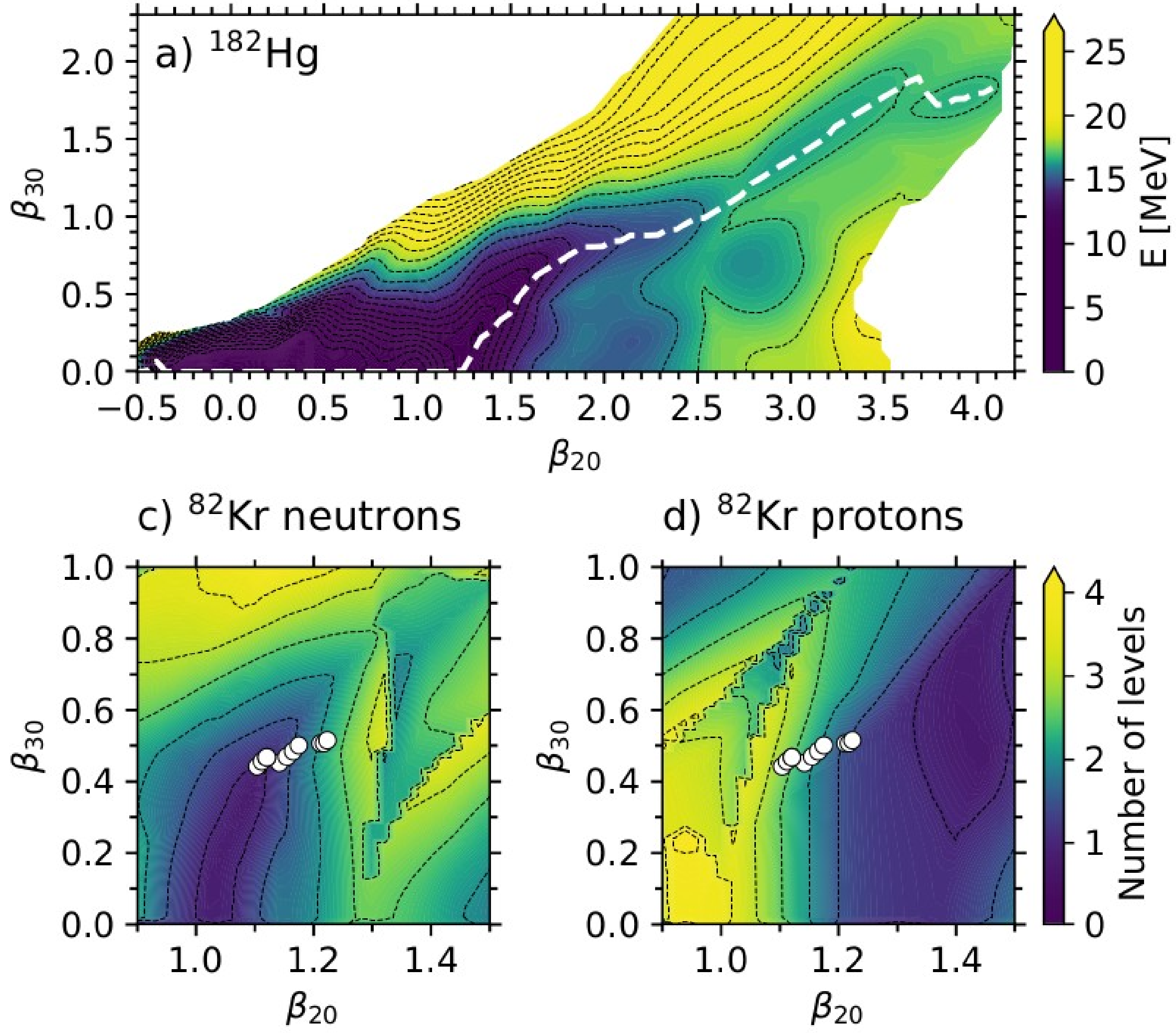
- The population of the light fragment Z=36 is favored in this new asymmetric fission island.
- The associated heavy partners exhibit a range from Z=42 to 46.

Asymmetry map





Microscopic calculations using Gogny D1S



- Extended HFB calculations of even-even nuclei in the island of asymmetic fission (Theoretician colleagues CEA-DAM and CEA-DES).
- Potential Energy Surface (PES) generated.
- Favored pre-fragments determined in the path before scission.
- Systematic study of possible shell effects in these light pre-fragments looking at Q_2-Q_3 deformation along the scission path.

  - ✓ **Z=36 Kr isotopes favored in the scission path in numerous cases.**
  - ✓ **Shell effect in the light fragment.**
  - ✓ **No shell effect visible in the associated heavy fragment.**

4. Conclusion

Conclusion

- Coulomb induced fission at relativistic energy is a powerful tool to probe the fission modes.

- Measurement of fission charge yields of 100 neutron-deficient nuclei through Coulomb excitation.
  - ✓ We delineate the boundaries of the new island of asymmetric fission.
  - ✓ Direct experimental evidence of proton-shell stabilization at Z=36 in this new asymmetric split.
  - ✓ Asymmetric fission driven by light fragment !

- Large scale microscopic calculations (HFB3 with the D1S Gogny interaction) (G. Blanchon, N. Dubray, N. Pillet, D. Regnier, R. Bernard)
  - ✓ Challenging calculations in this neutron-deficient region.
  - ✓ Evidence of deformed shell effect in the light fragment at Z=36.

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An asymmetric fission island driven by shell effects in light fragments

P. Morfouace, J. Taieb, A. Chatillon, L. Audouin, G. Blanchon, R. N. Bernard, N. Dubray, N. Pillet, D. Regnier, H. Alvarez-Pol, F. Amjad, P. André, G. Authelet, L. Atar, T. Aumann, J. Benlliure, K. Boretzky, L. Bott, T. Brecelj, C. Caesar, P. Carpentier, E. Casarejos, J. Cederkäll, A. Corsi, … M. Zhukov + Show authors

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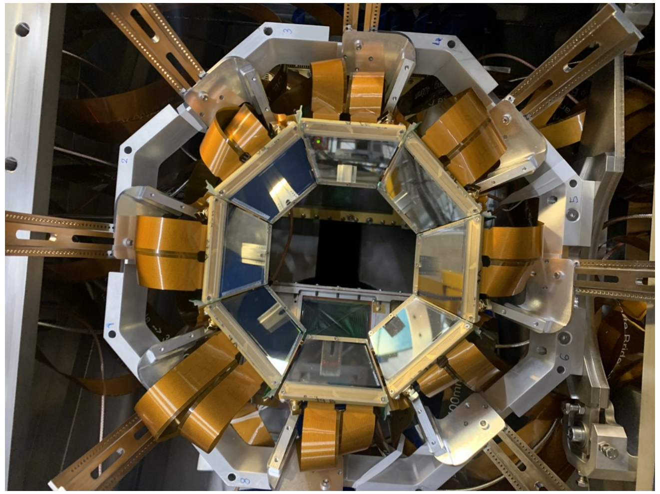
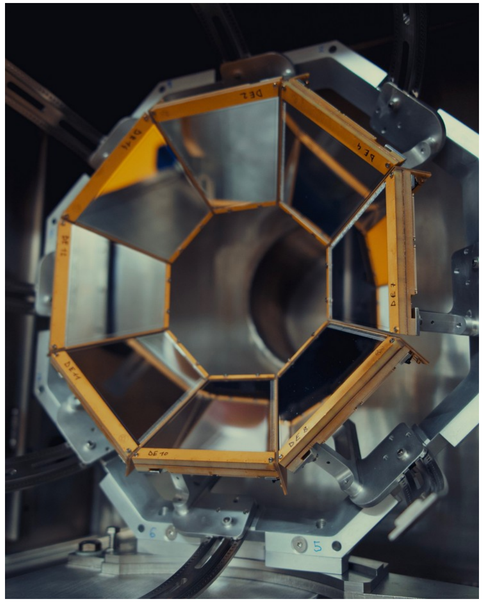
Perspectives

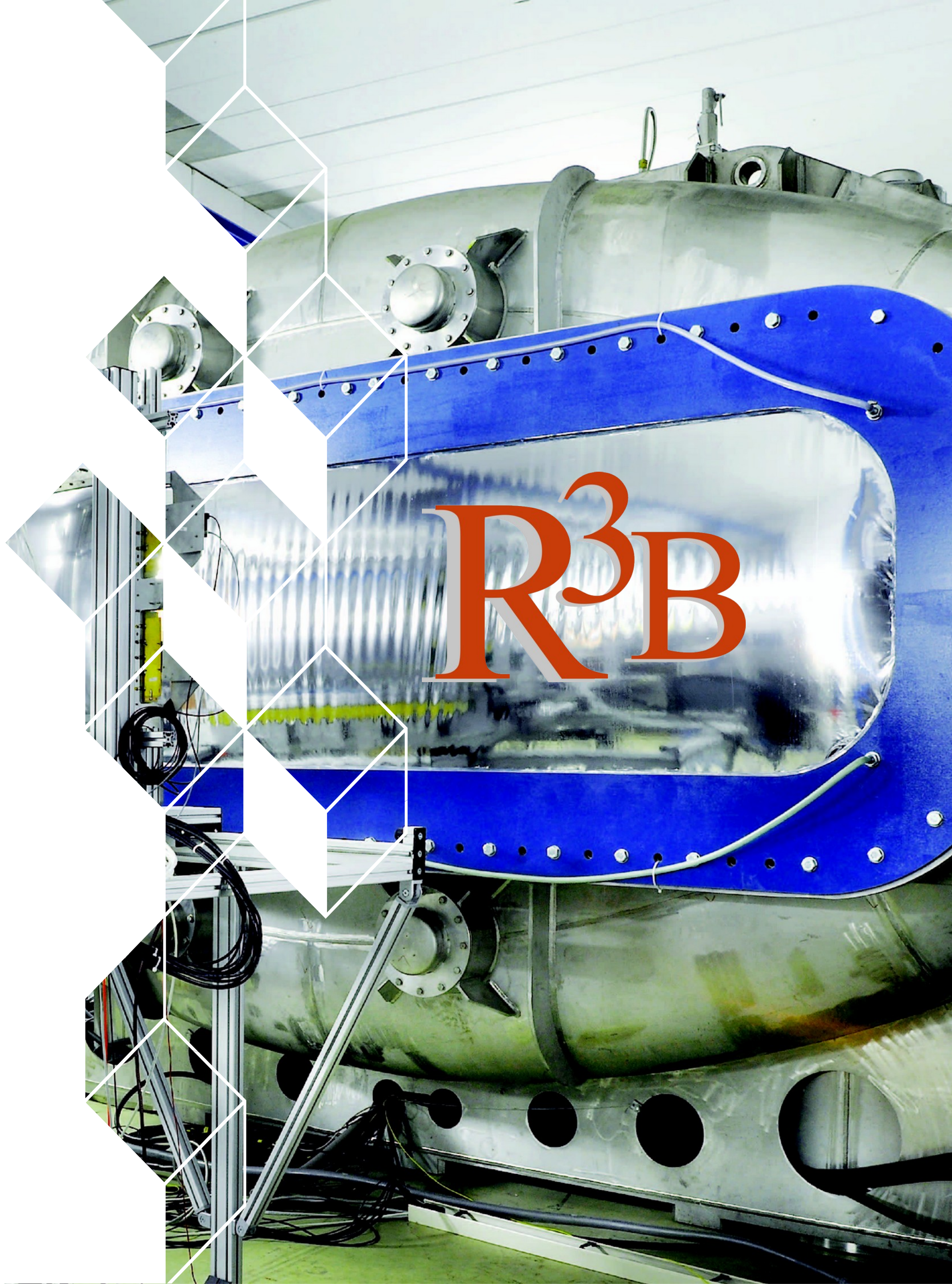
- GSI:
  - Extend the measurement around the island
  - (p,2p) reaction to probe the excitation energy degree of freedom (shell damping, fission barrier...)

- GANIL:
  - Unique place: VAMOS + Pista/Pista-2
  - Multi-nucleon transfer to access different fissioning systems
  - Probe the excitation-energy degree of freedom.
  - See talks: D. Ramos, T. Efremov, A. Cobo, B. Errandonea





Thank you !

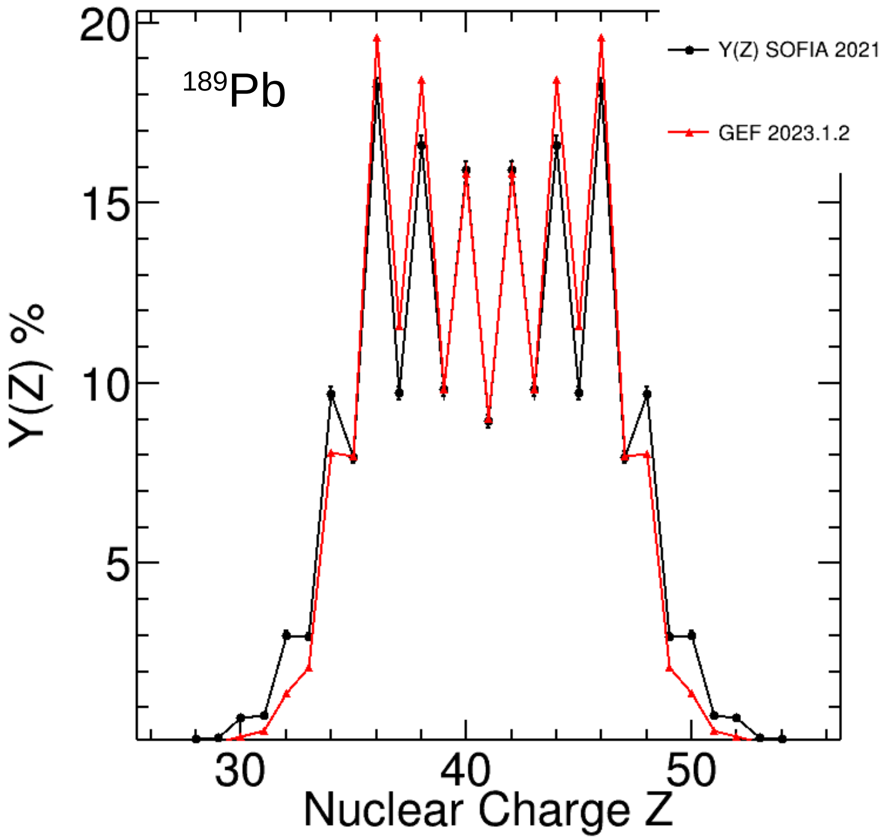


Global odd-even effect

- The global odd-even staggering connects the measured charge distribution directly to the pairing correlations and the excitation energy at scission.
- For even-Z fissioning systems, the charge yield shows an enhancement of even-Z fragments.
- It reflects the fact that protons tend to remain paired during the fission process. Producing odd-Z fragments require to break a pair.

$$\delta = \left(\sum_e Y_e - \sum_o Y_o\right) / \sum_{e,o} Y$$

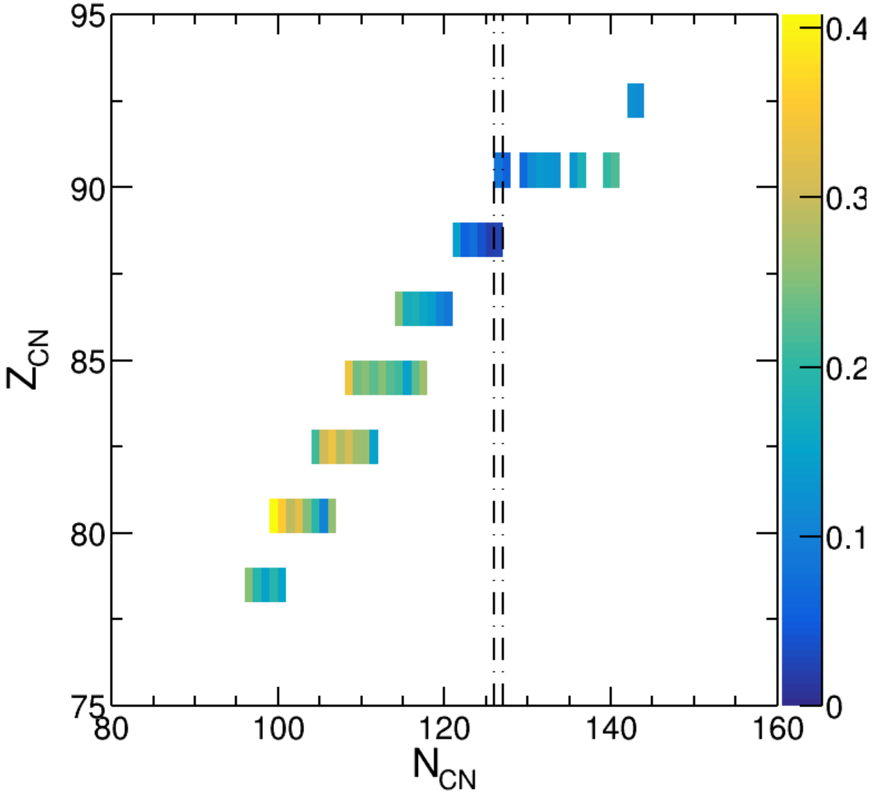
- How does the global odd-even staggering evolve with the fissioning system ?

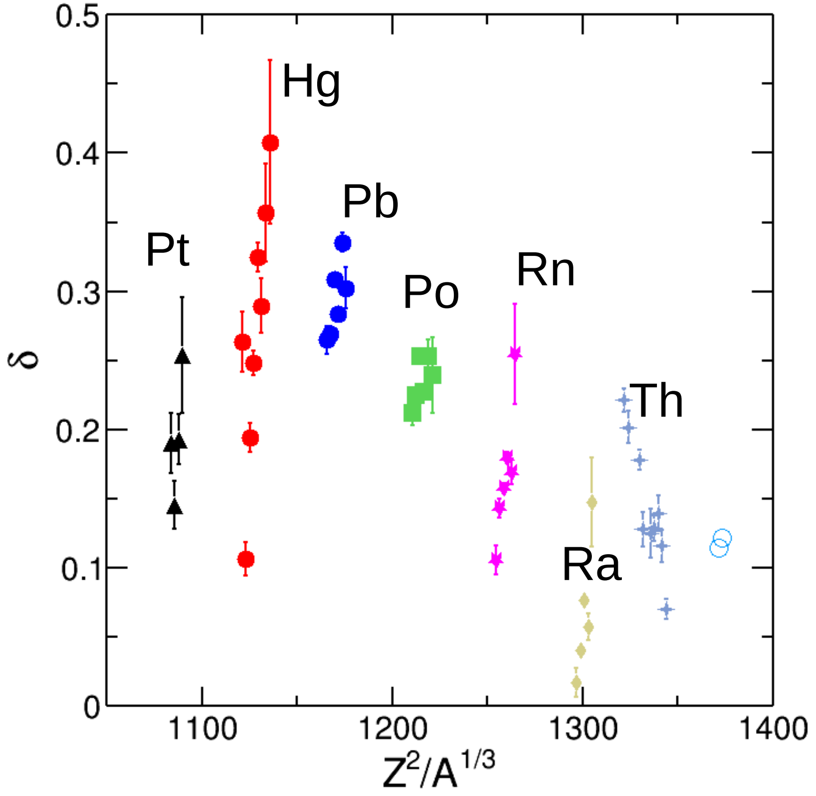


Global odd-even effect

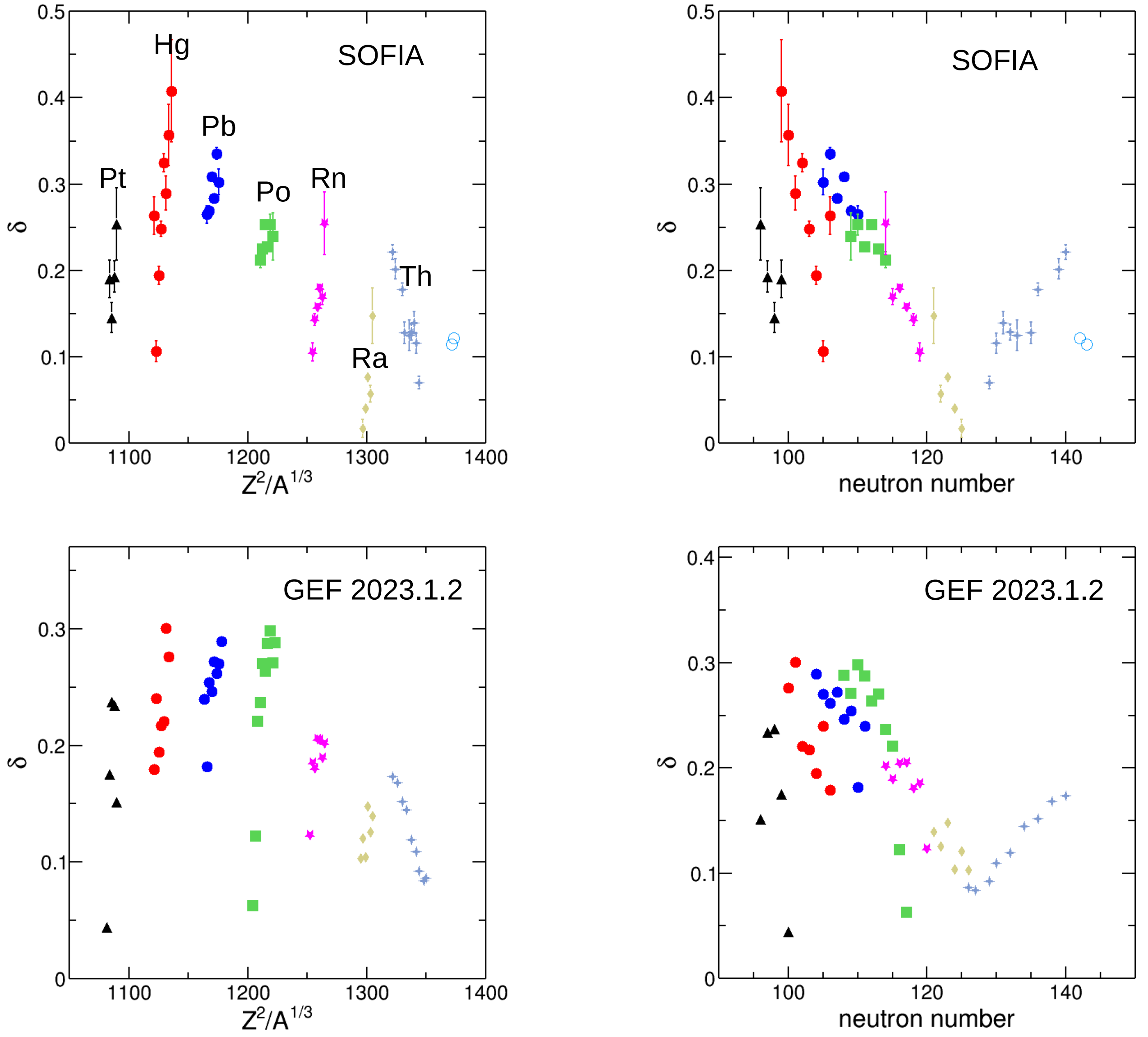
$$\delta = \left(\sum_e Y_e - \sum_o Y_o\right) / \sum_{e,o} Y$$

- Systematic decrease of δ toward N=126.
- A minimum seems to be reached for N=126 (fissioning system).





Global odd-even effect



- Comparison using GEF 2023.1.2
  - Systematic decrease toward N=126.
  - GEF 2023.1.2 captures very well the behaviour of the evolution.
  - However, recent versions of GEF do not reproduce it

- The global odd-even effect exhibits a pronounced minimum around N=126.
- Why should the pairing signature in the fragments know that the fissioning nucleus is approaching the N=126 shell closure ?