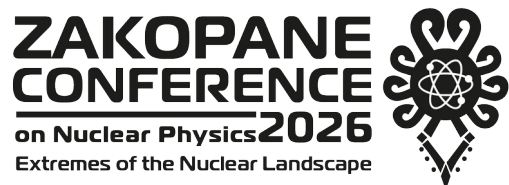




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PARIS-SACLAY

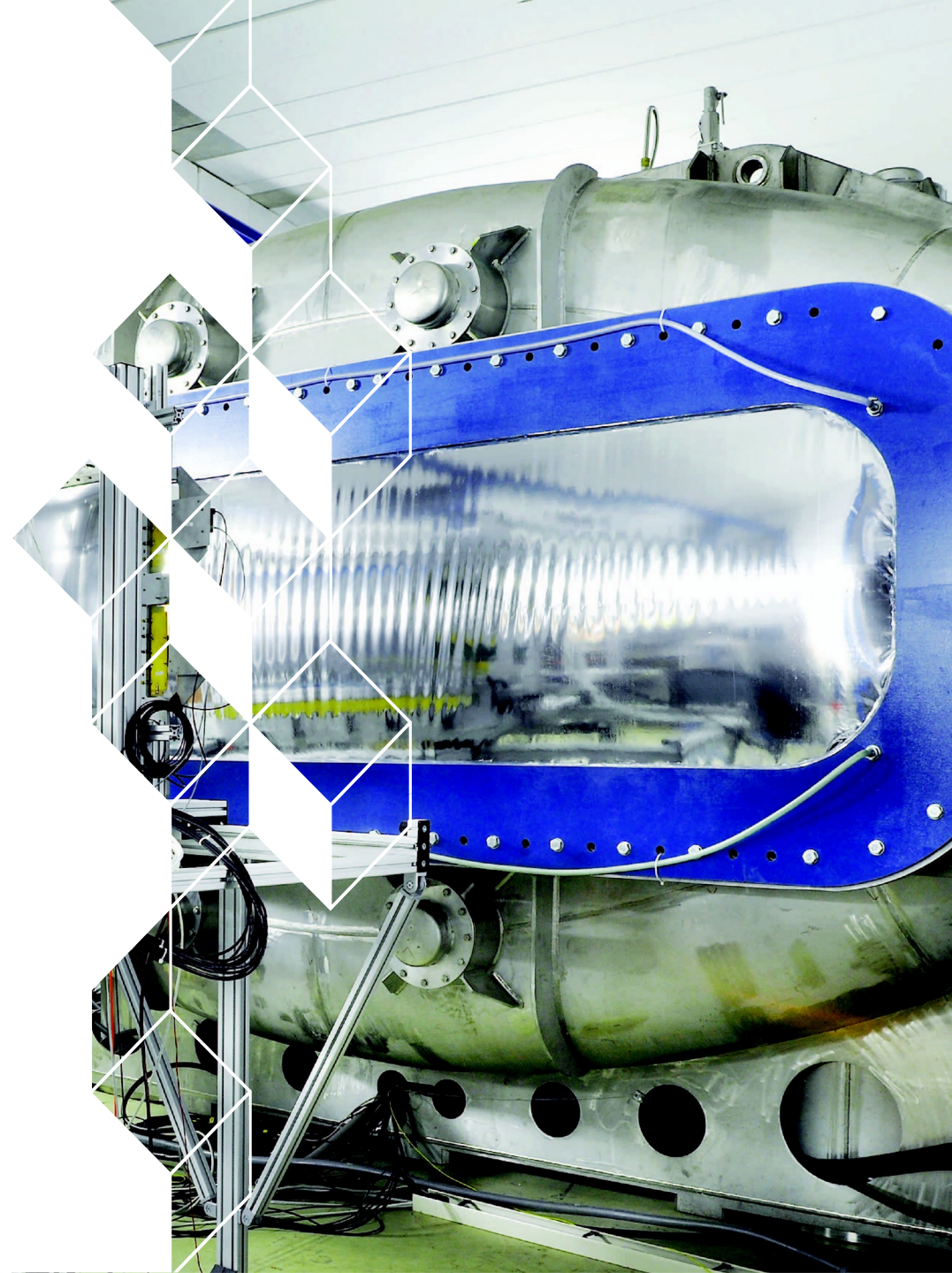
Mapping the new asymmetric fission island



Pierre Morfouace^{1,2}, Julien Taieb^{1,2}, Audrey Chatillon^{1,2} for the R³B collaboration

¹ CEA, DAM, DIF, 91297 Arpajon, France

² Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France



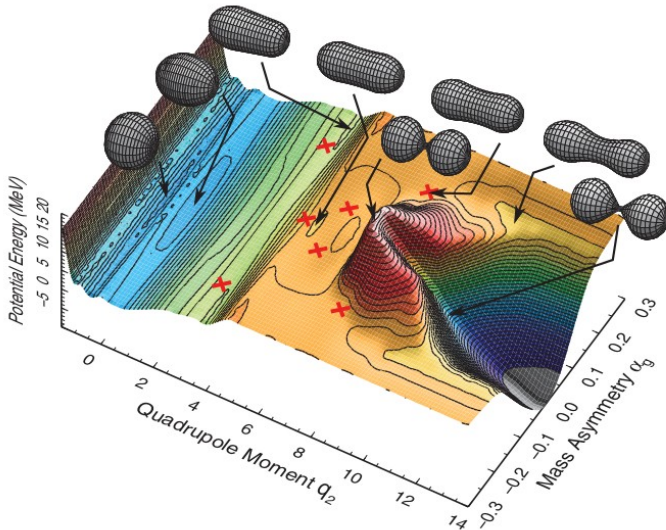


1 ■ Introduction & Motivations

Nuclear fission: a many-body quantum process

Static properties

Where can it go ?

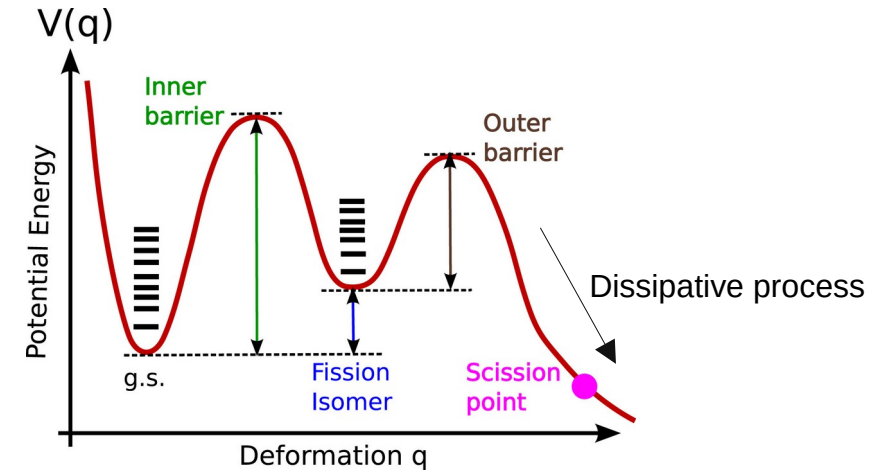


T. Ichikawa et al. Phys. Rev. C **86**, 024610 (2012)

- 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.

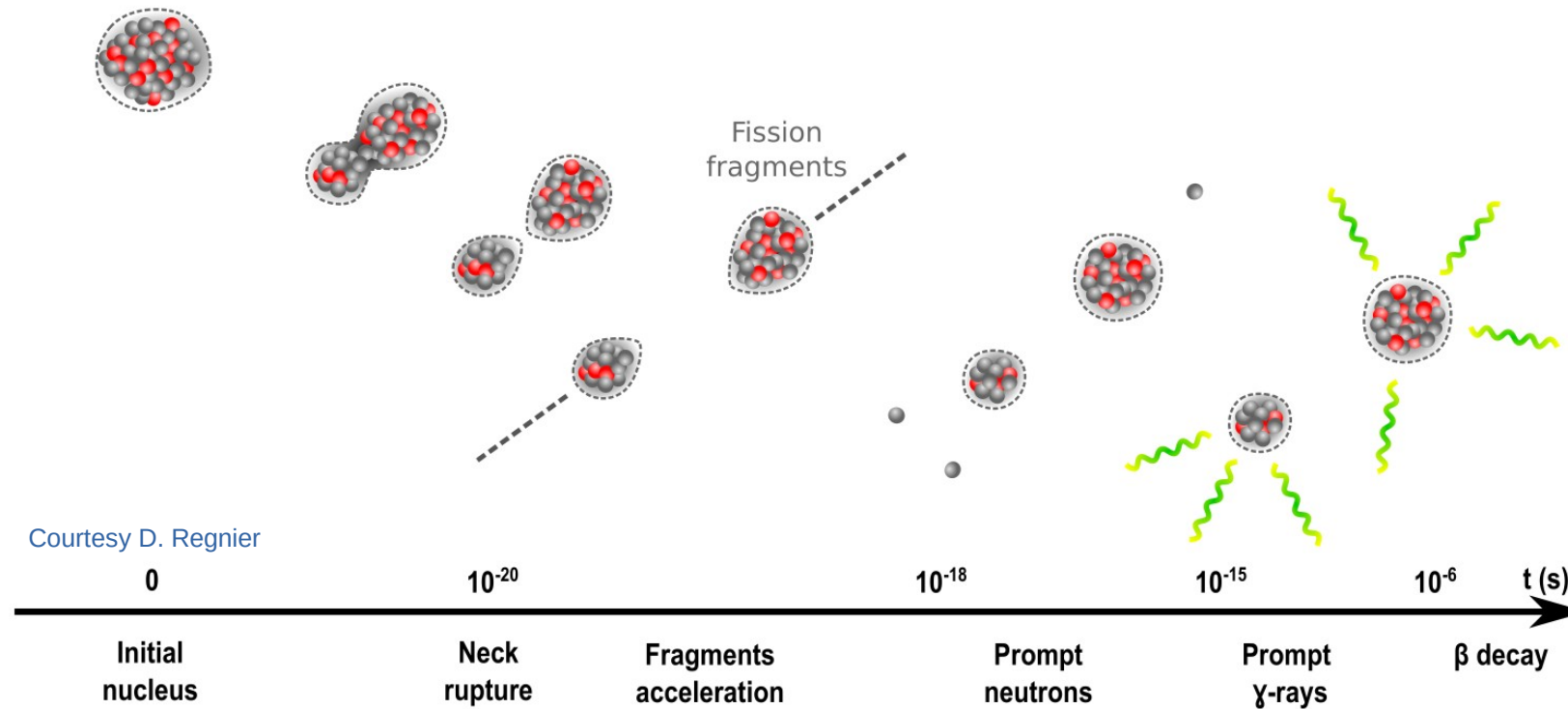
The fission outcome : The fragment distribution
It results from the interplay between the microscopic structure of the PES and the dynamics of the system evolving towards scission.

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

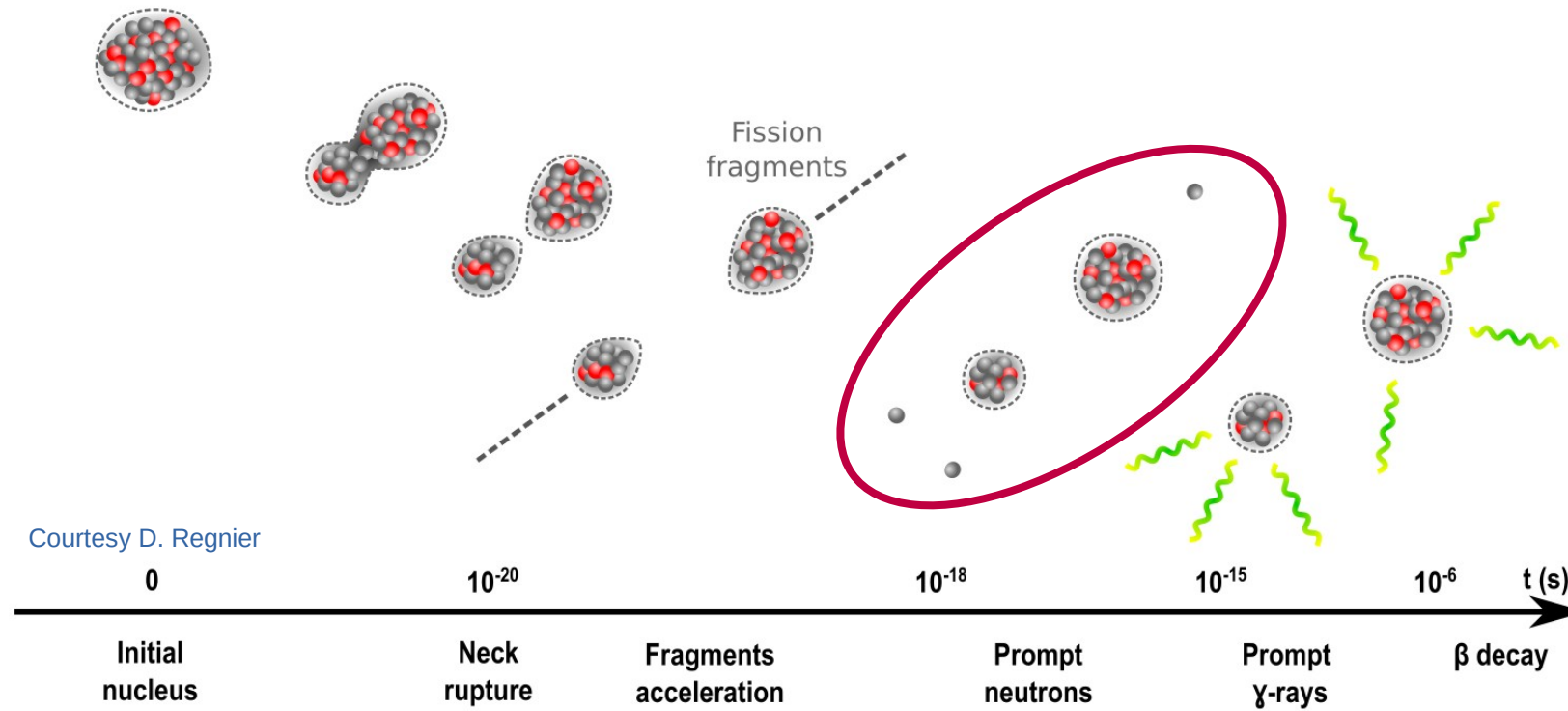


Measuring fission fragments



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

Measuring fission fragments



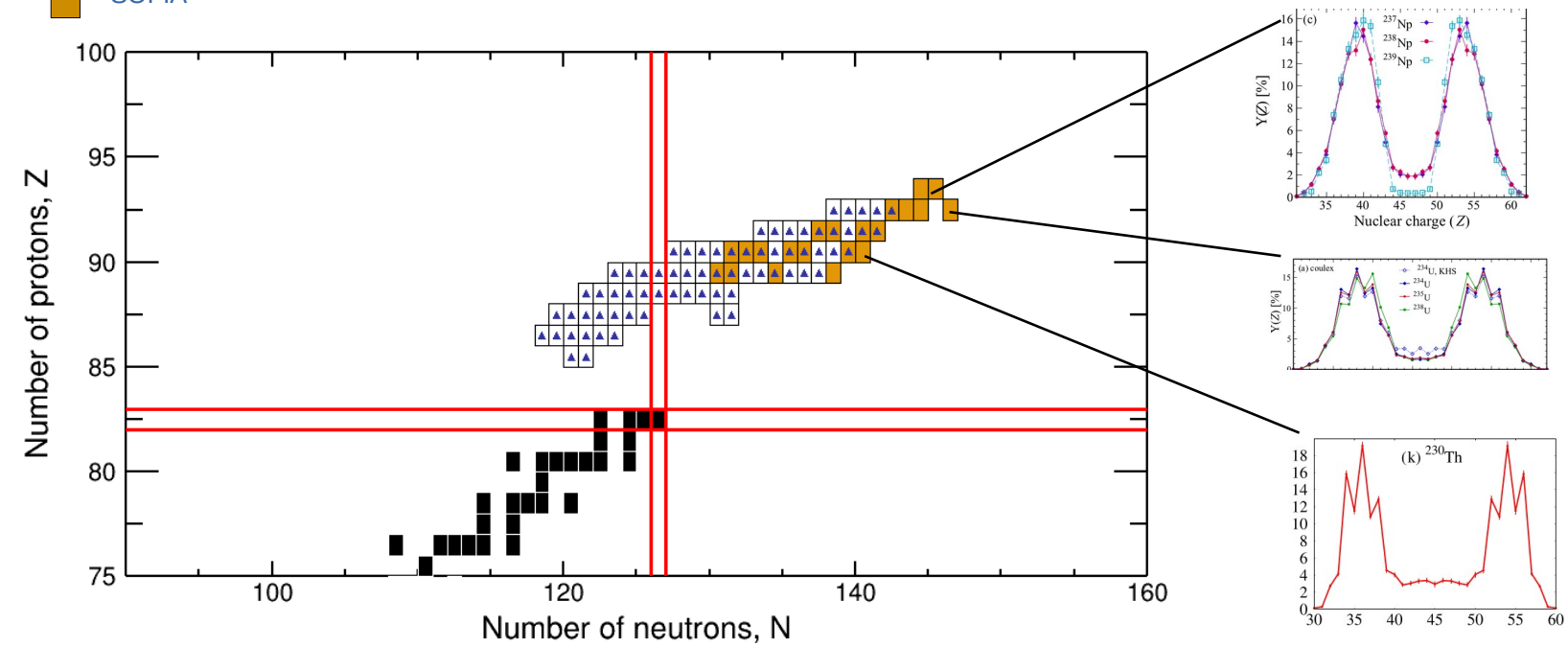
- The experiments at GSI using inverse kinematics at relativistic energy measure secondary fission fragments, typically 10s of nanoseconds after scission.

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)



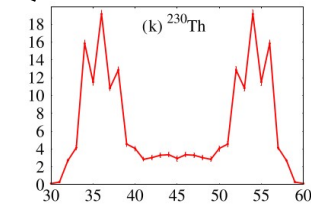
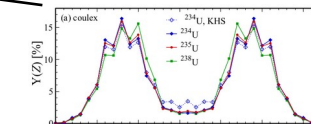
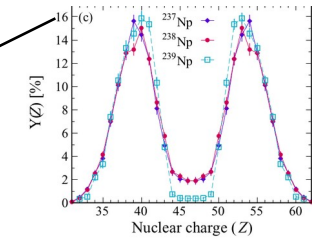
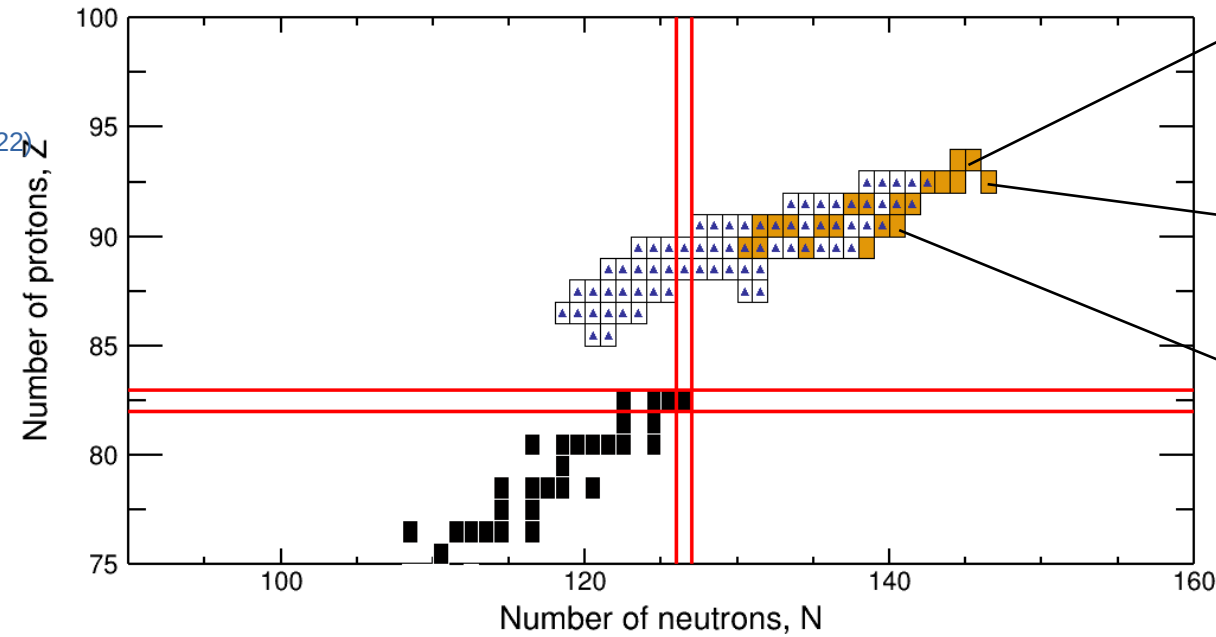
Fission yields to probe fission modes

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

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

■ SOFIA

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



In this region : $Z \approx 54$ (Xe) stabilisation

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

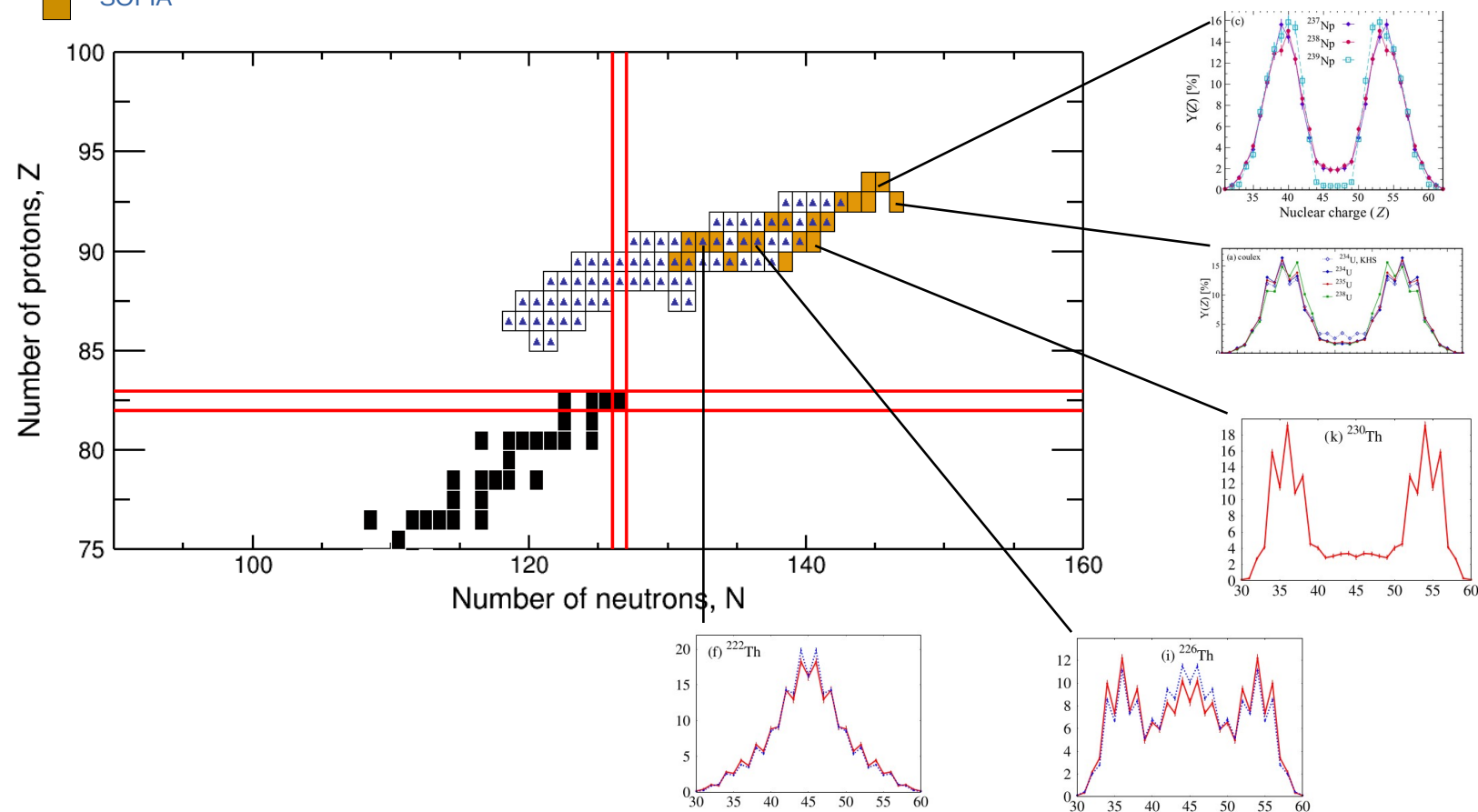
Driven by octupole shape in the fragments.

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)



A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)

A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

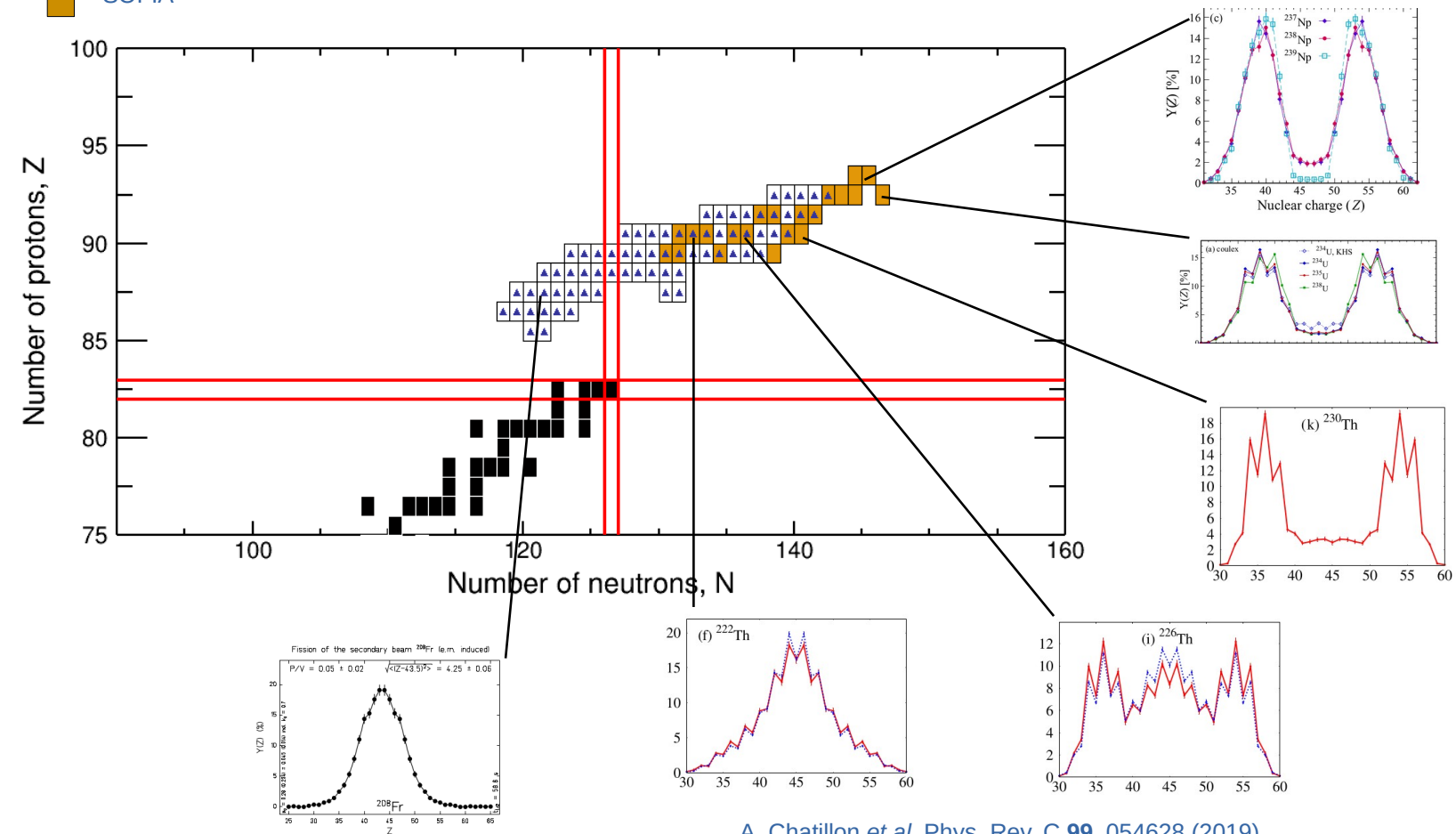
New symmetric compact fission mode.

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

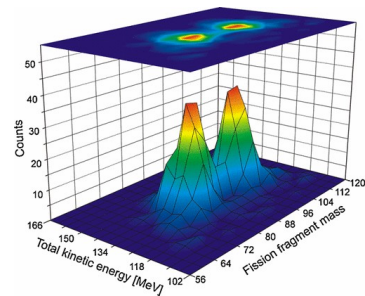
A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)
A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

Fission yields to probe fission modes

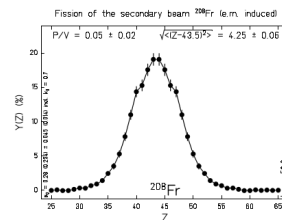
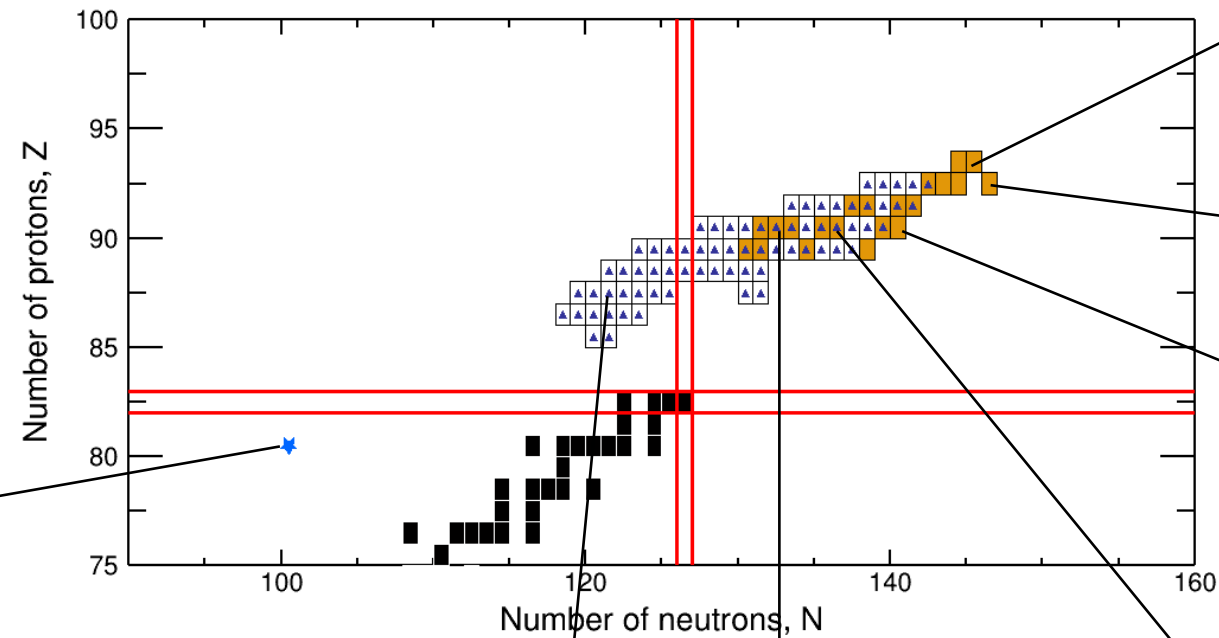
▲ K.-H. Schmidt *et al.* NPA **665** (2000) 221

■ SOFIA

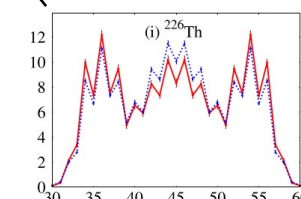
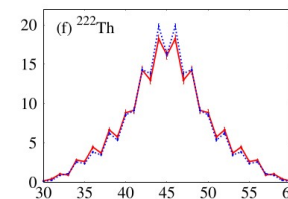
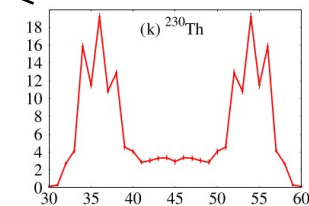
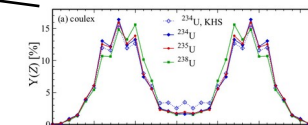
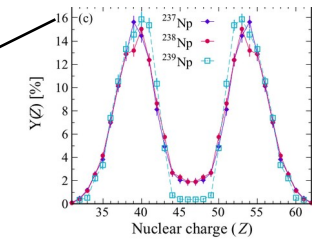
J.-F. Martin *et al.* Phys. Rev. C **104**, 044602 (2021)



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



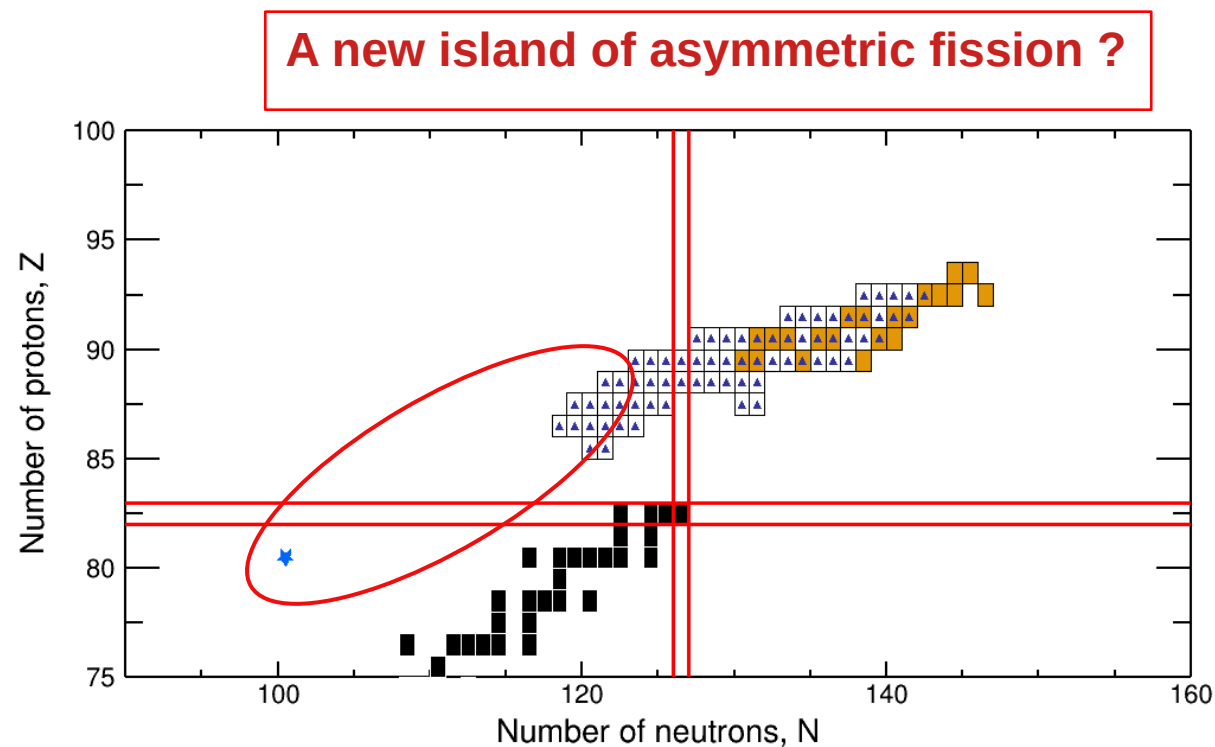
S. Steinhauser *et al.* Thesis work



A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)

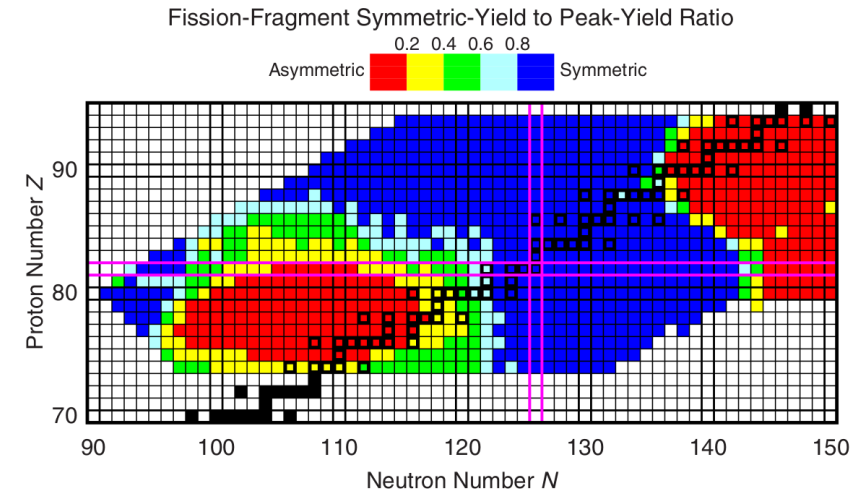
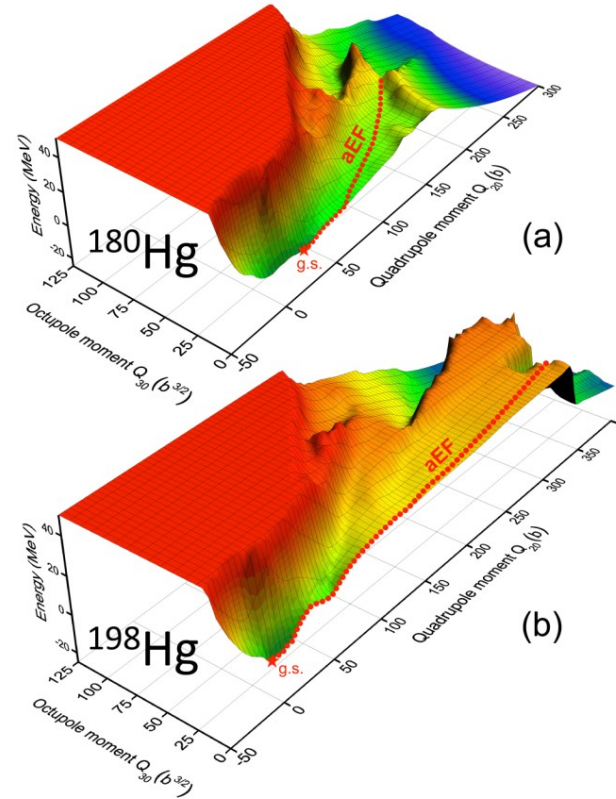
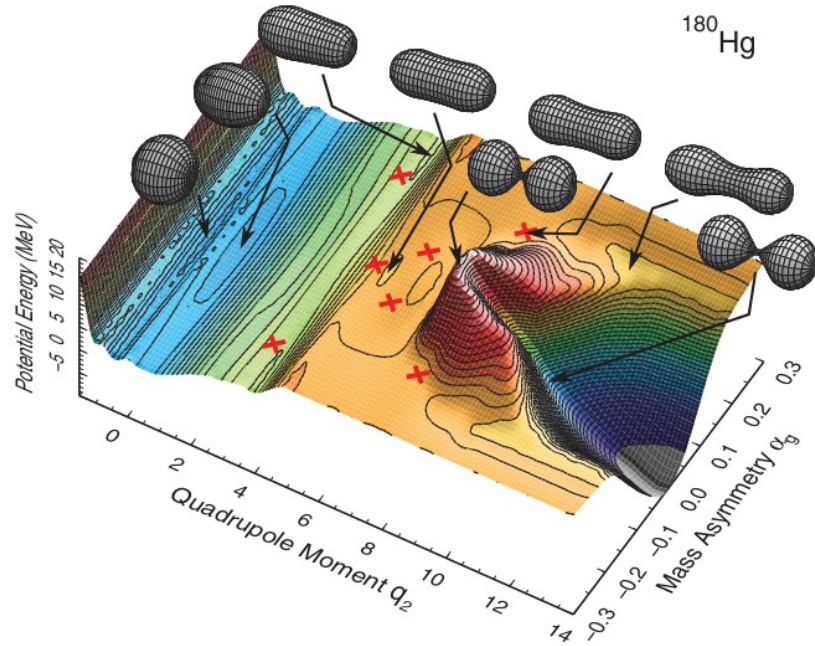
A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

Fission yields to probe fission modes



- 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 effects 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

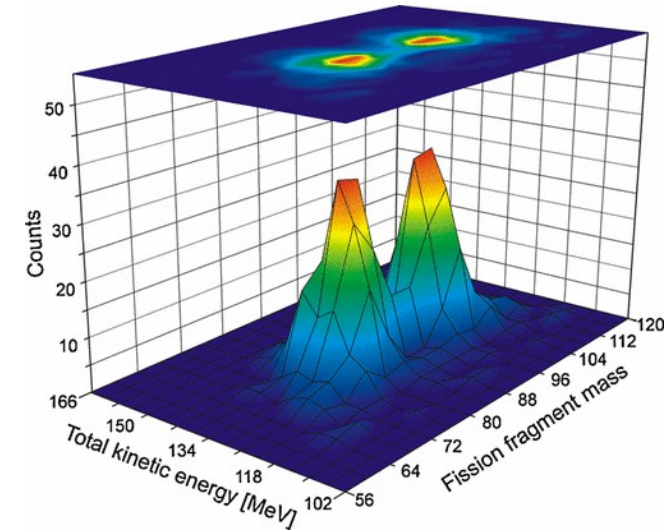
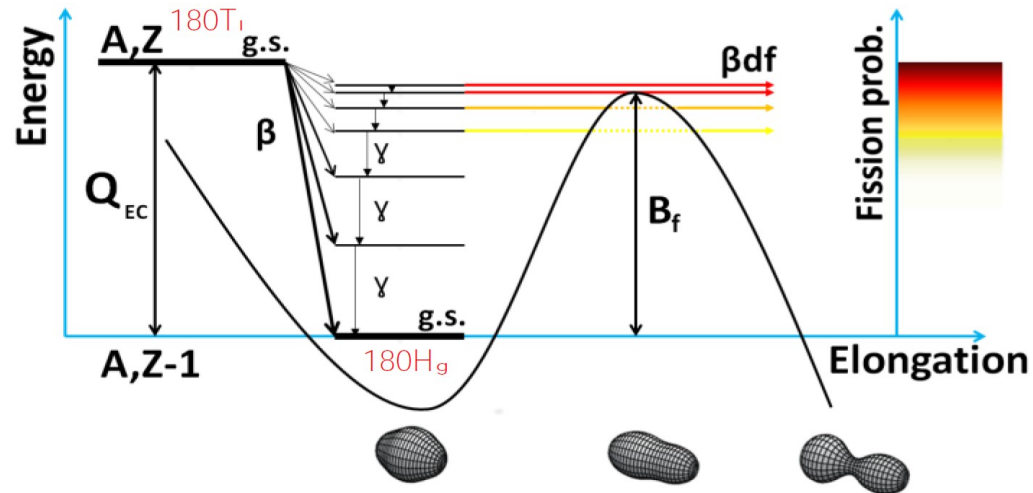
P. Moller *et al.* Phys. Rev. C **91**, 044316 (2015)

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.



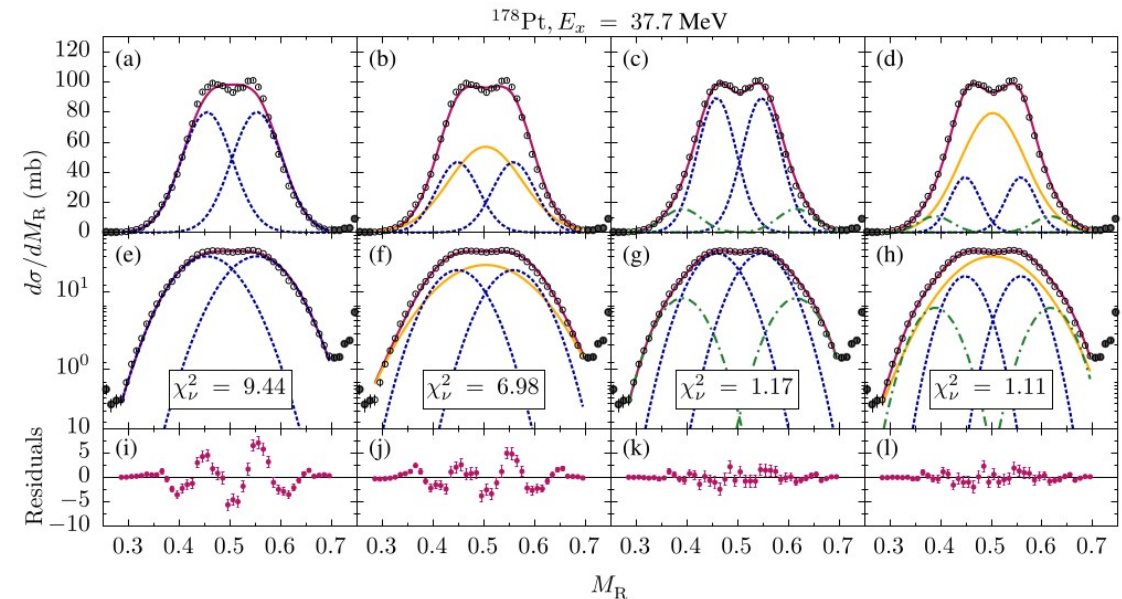
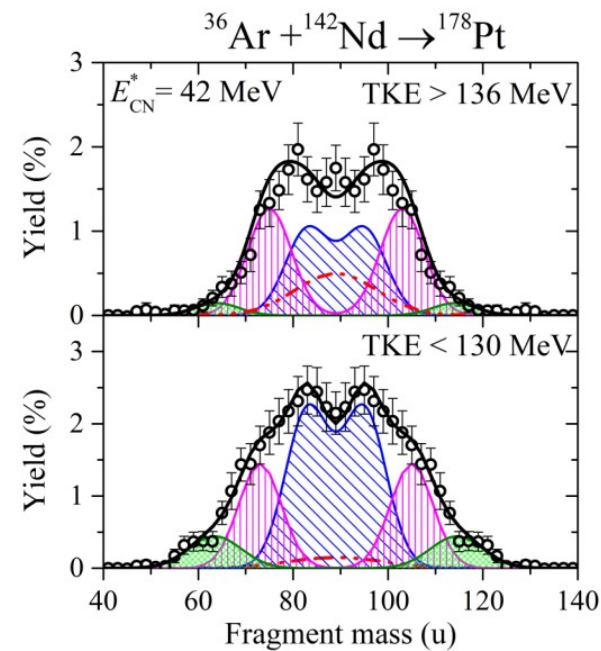
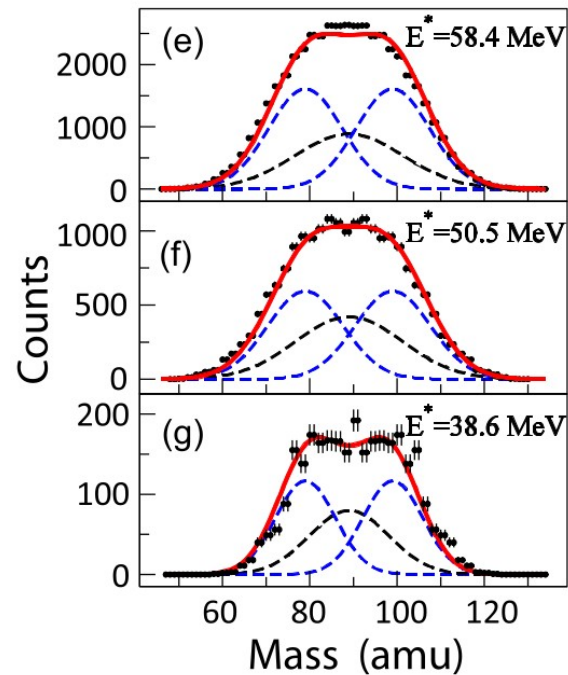
A. N. Andreyev *et al.* Phys. Rev. Lett. **105**, 252502 (2010)

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 resolution of $\sigma \approx 3\text{-}5$ 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).



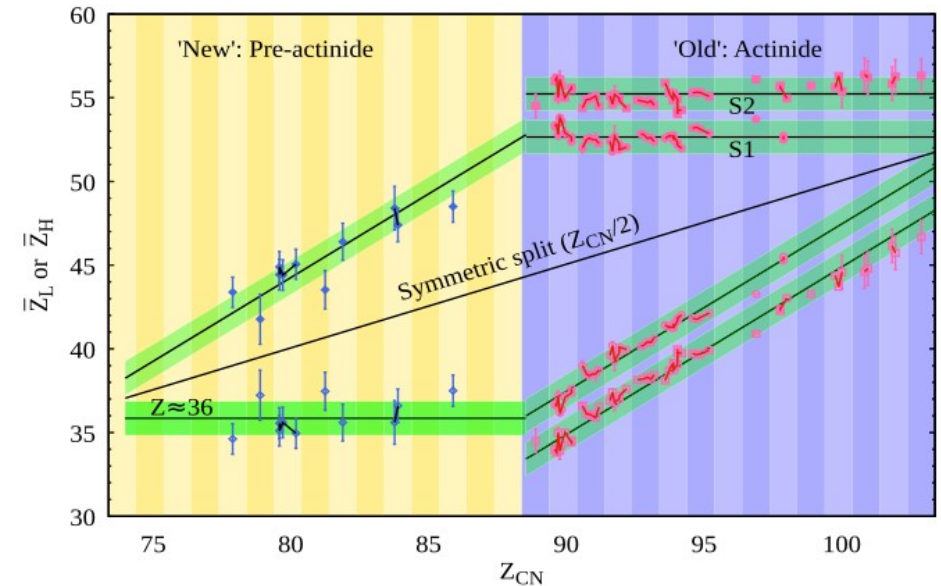
I. Tsekhanovich *et al.* Phys. Lett. B **790**, 583-588 (2019)

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.

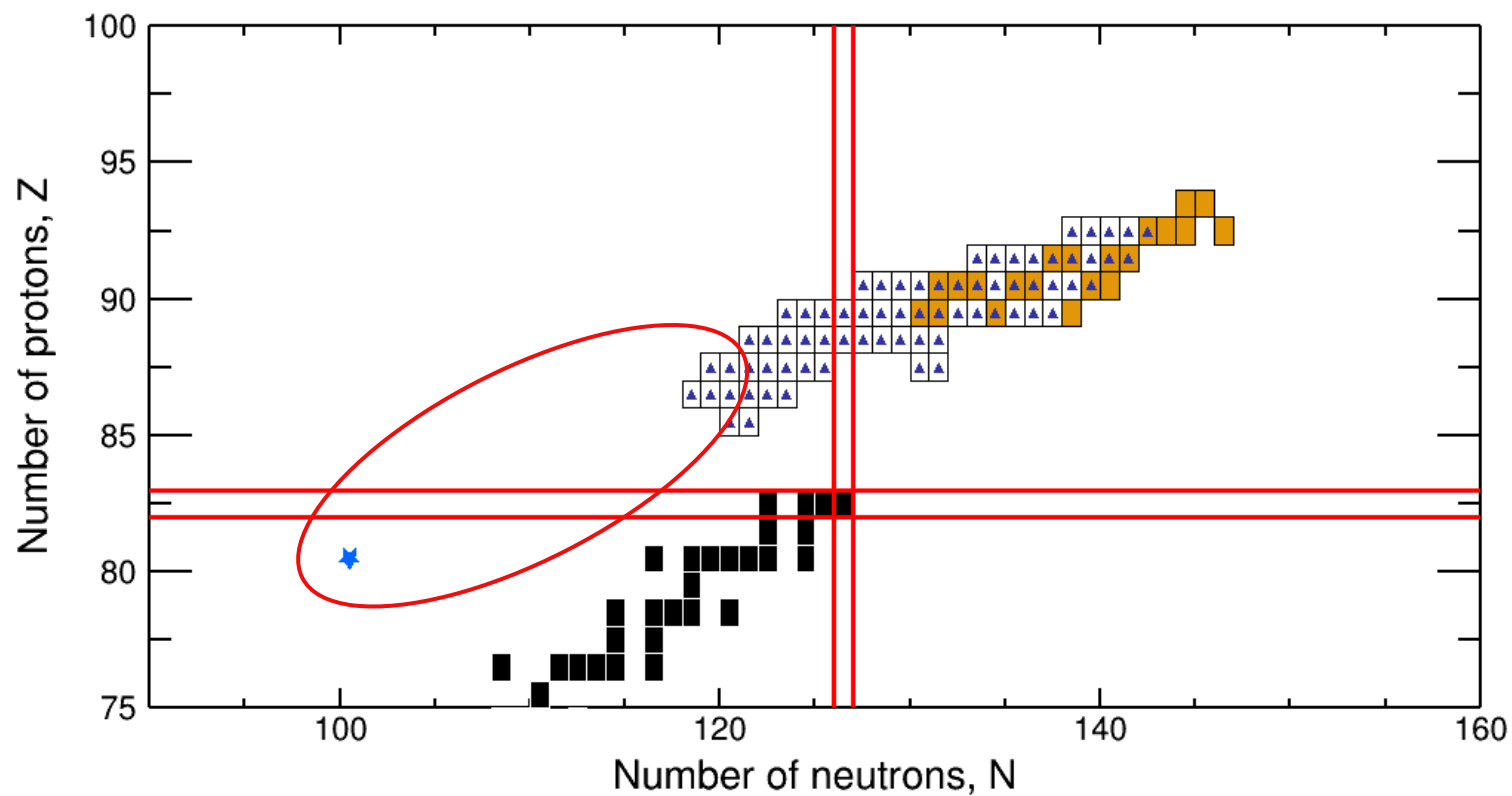


K. Mahata, C. Schmitt *et al.* Phys. Lett. B **825**, 136859 (2022)

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

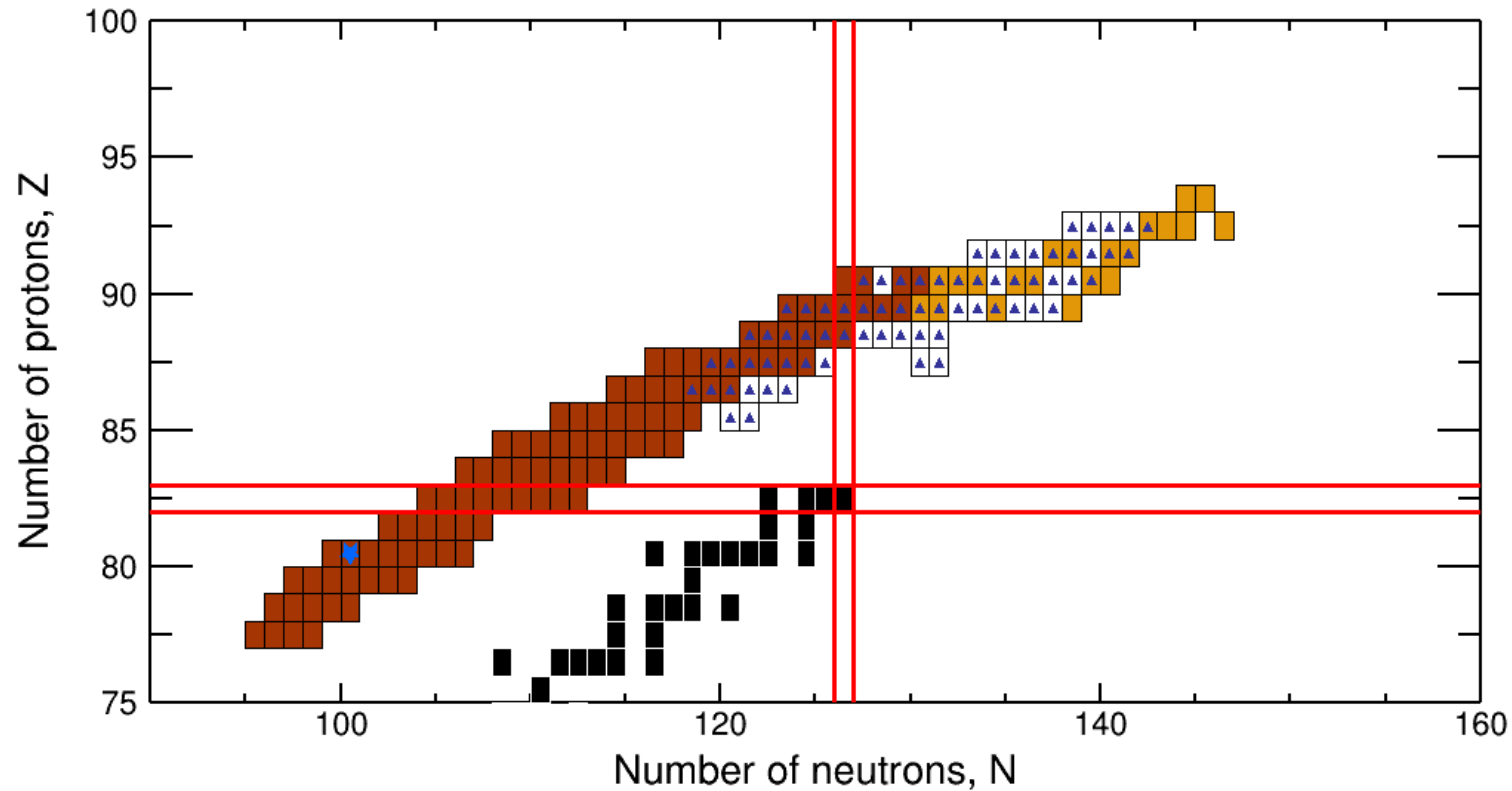
New R³B/SOFIA experiment in 2021

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 sublead region and the actinide region.



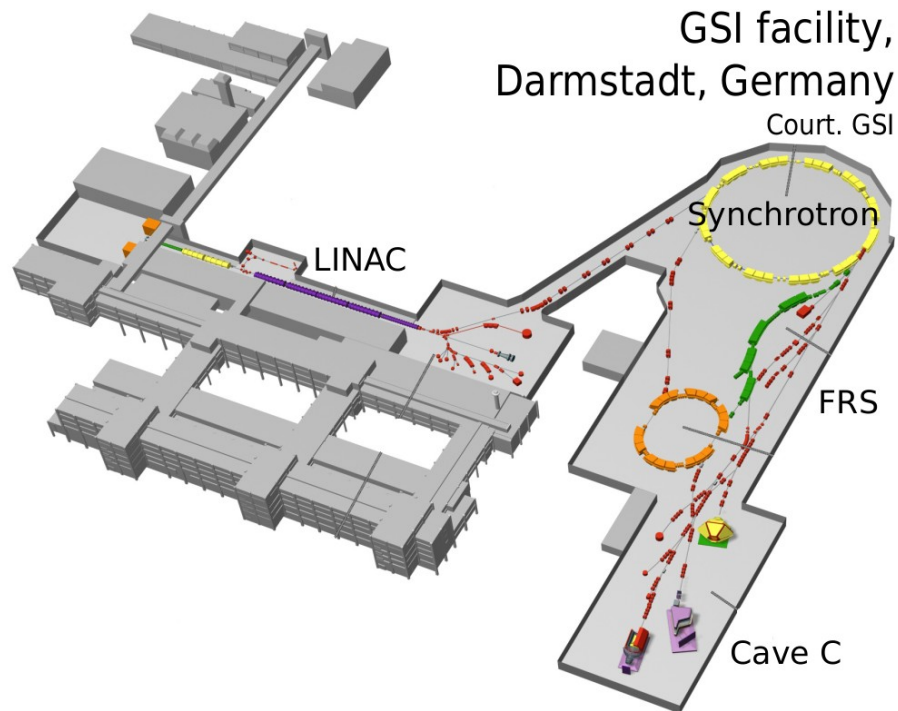


2. ■ SOFIA/R³B setup at GSI

Inverse kinematics at GSI



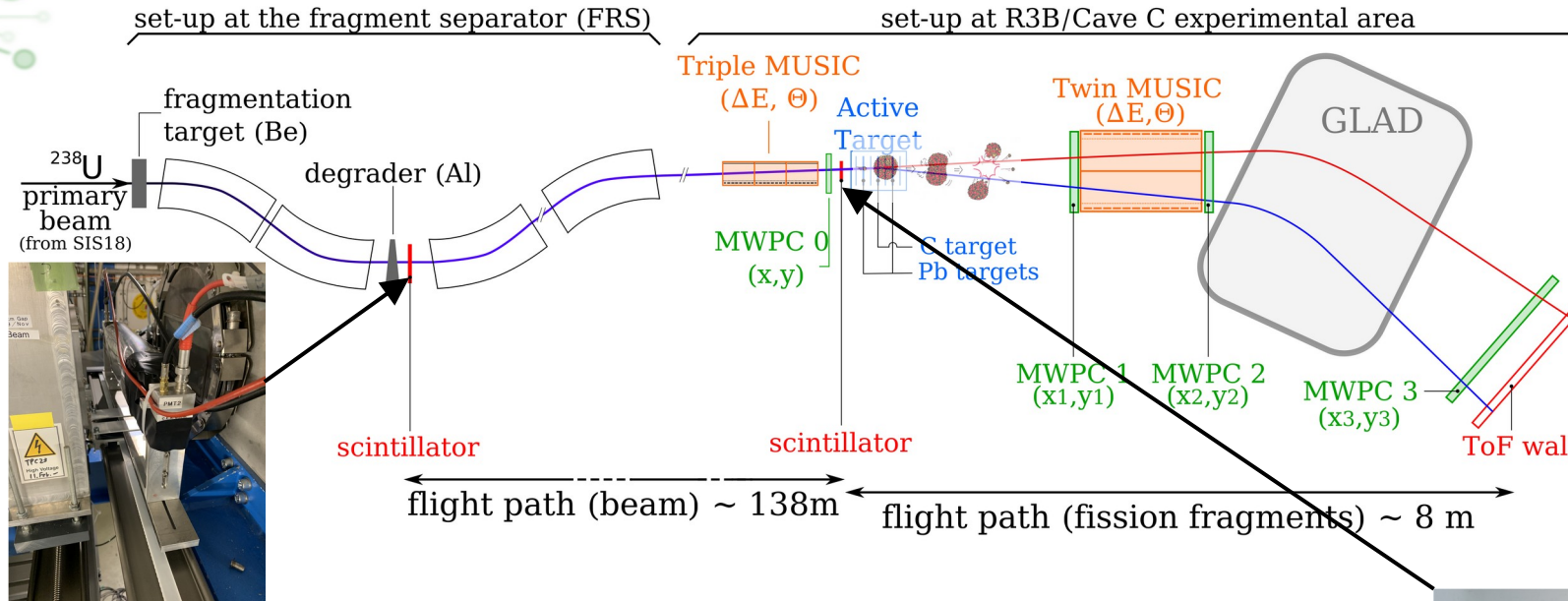
New SOFIA campaign in 2021 to map the fission modes in the neutron-deficient region around lead.



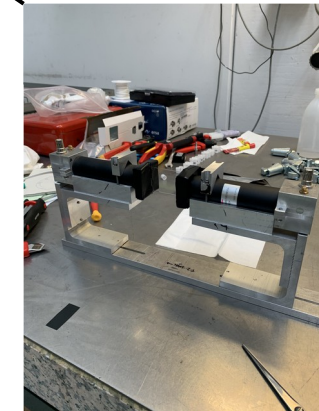
- Primary beam of ^{238}U at 1 GeV/u.
- Production and identification of the secondary beam through the FRS.
- Fission in cave C and identification of both fission fragments
- 12 FRS settings from ^{175}Pt up to ^{221}Pa



Experimental setup



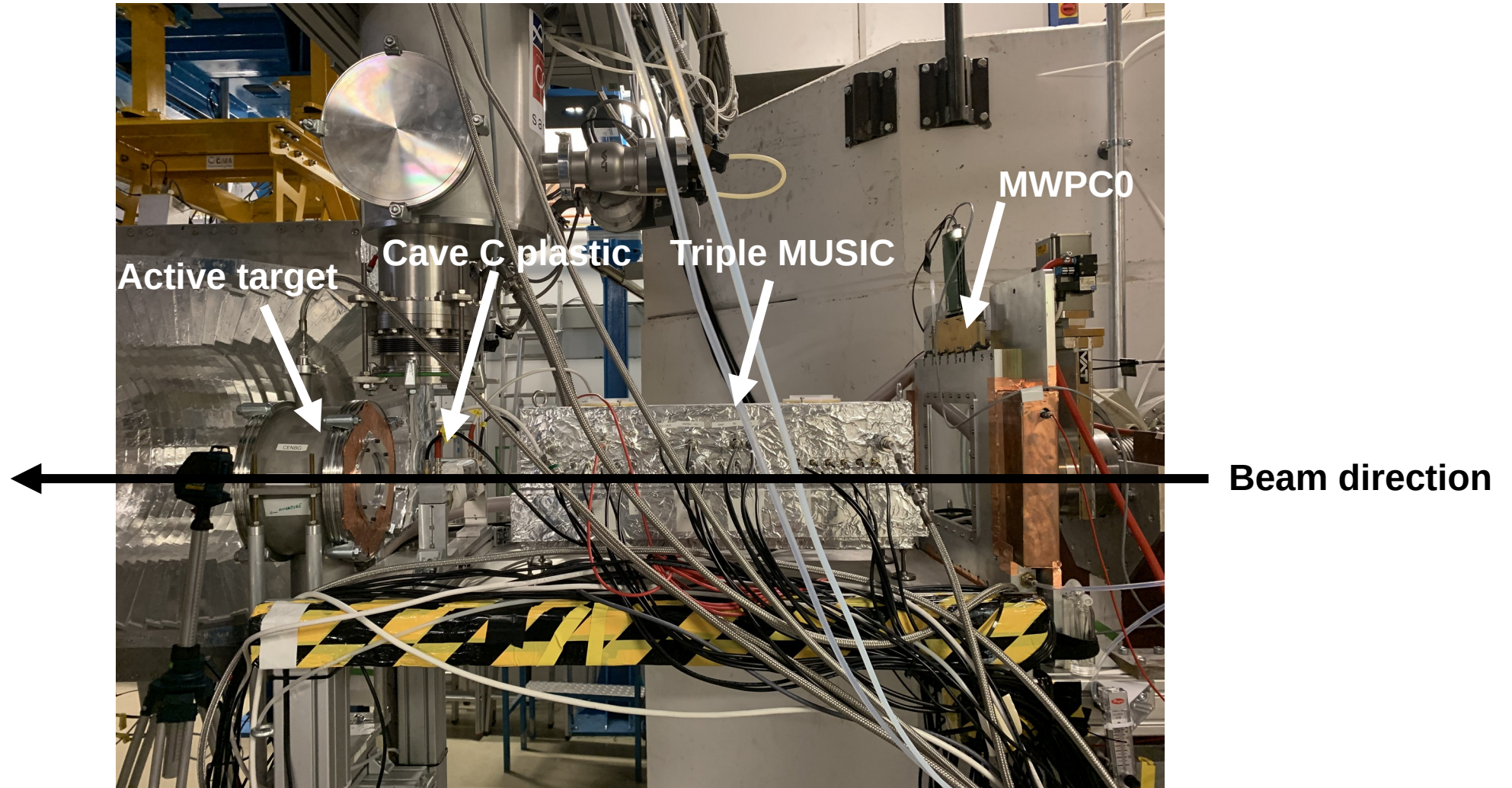
- Plastic at S2 for time and position measurement.
- Plastic at Cave C for start and ToF.
- Triple-MUSIC for charge identification of the secondary beam.
- Active target with three cathodes (2 lead + 1 carbon) to induced fission.
- MWPC for (x,y) measurements of the beam and the fission fragments.
-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



$$B\rho = B\rho_0(1 - X_{S_2}/D_{S_2})$$

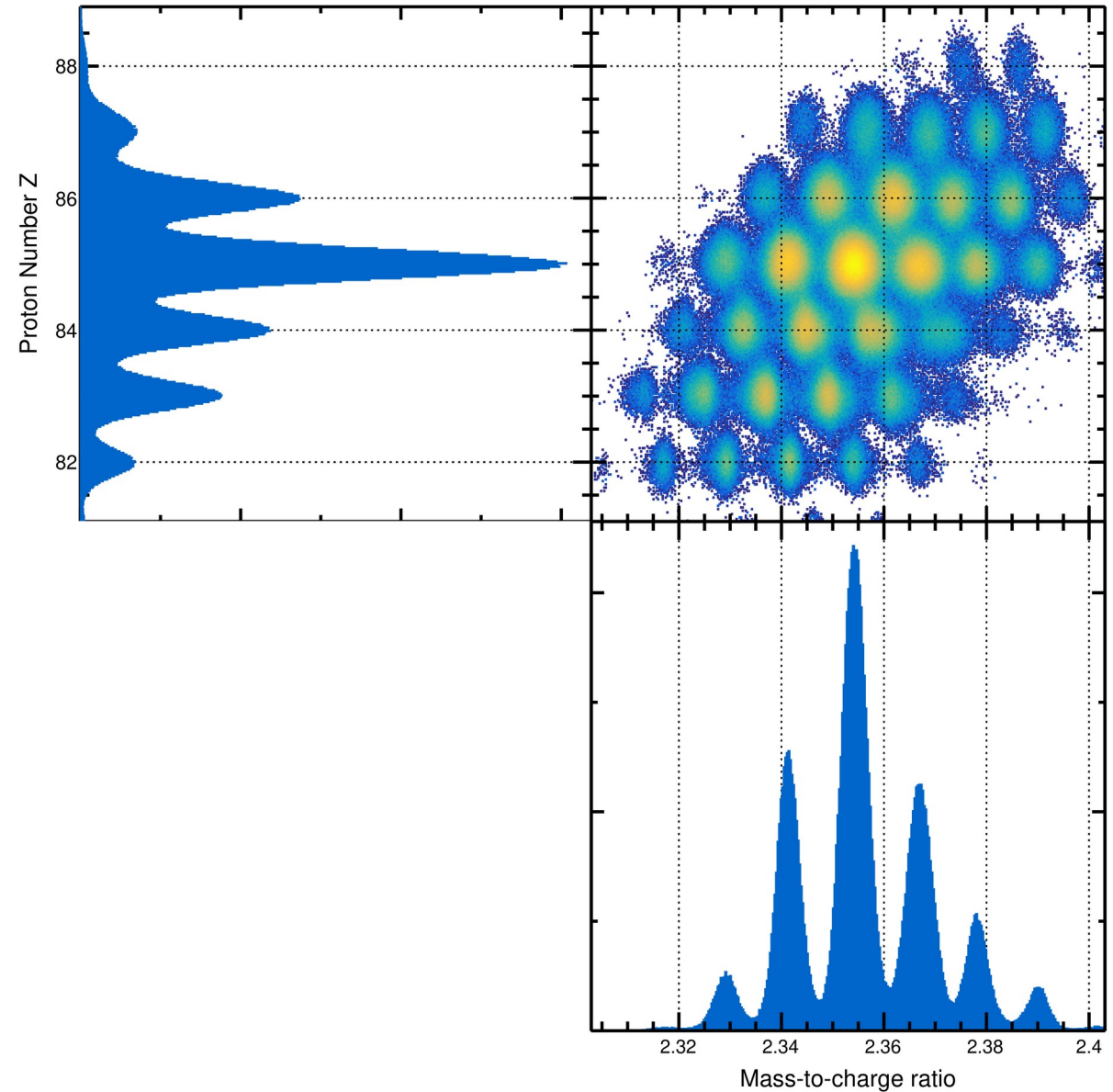
$$A/Q = B\rho/(3.10716 \cdot \gamma \cdot \beta)$$

Secondary beam identification

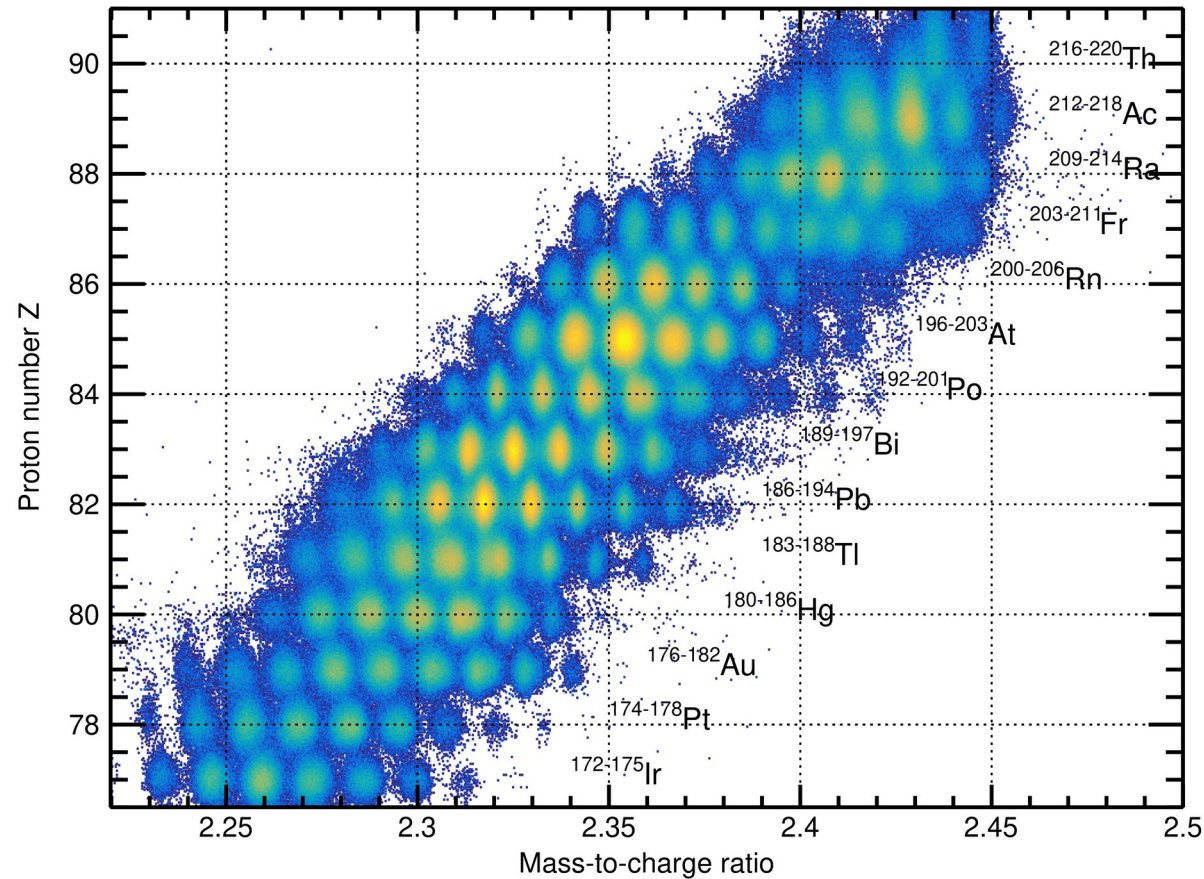


Secondary beam identification

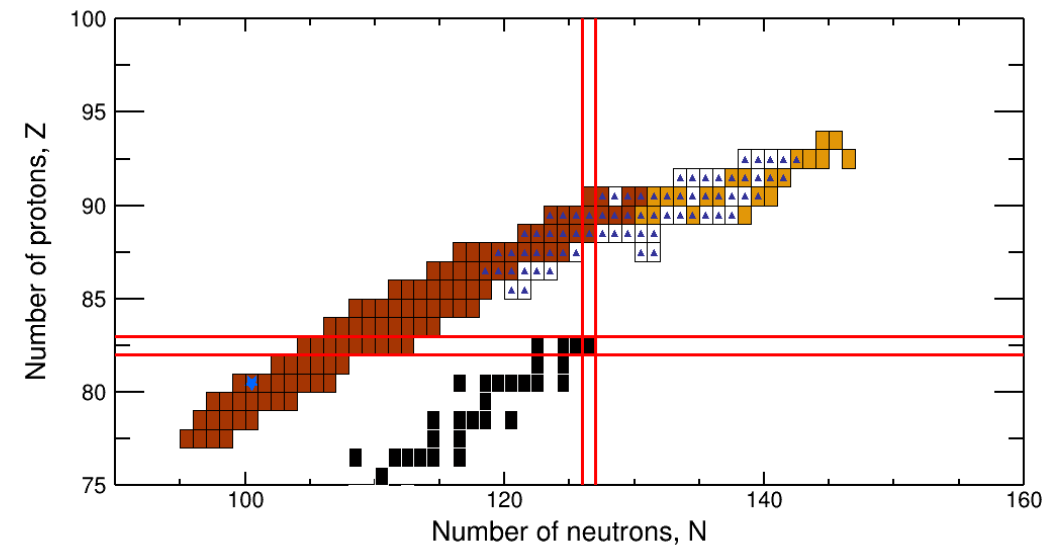
- Secondary beams produced around 700 MeV/u.
- Identified through the Brho – TOF – ΔE technique
- $\Delta A/A = 7.7 \times 10^{-4} \rightarrow \Delta A = 0.14$ uma
- $\Delta Z/Z = 2.5 \times 10^{-3} \rightarrow \Delta Z = 0.11$ charge unit



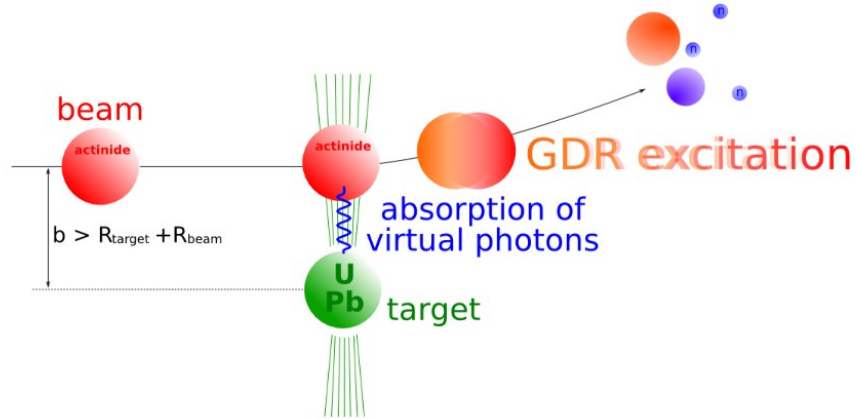
Global view of the studied systems



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



Coulomb induced fission at relativistic energies

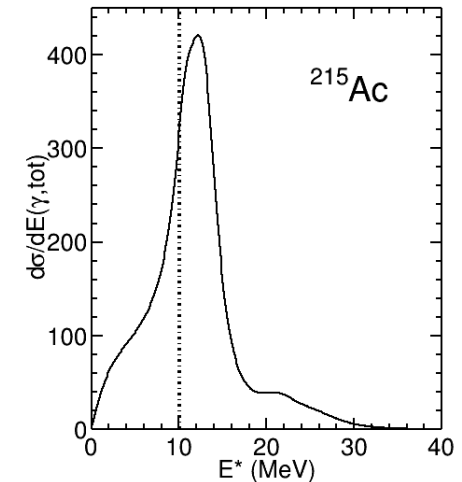
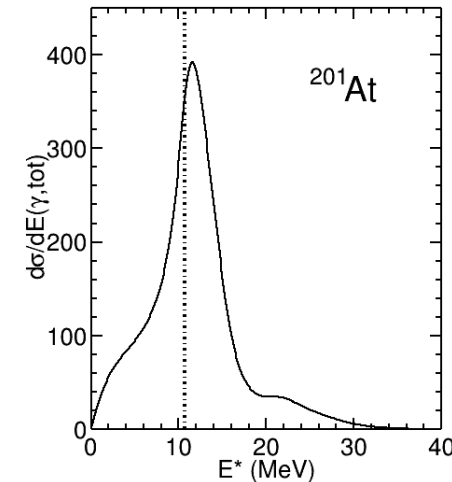
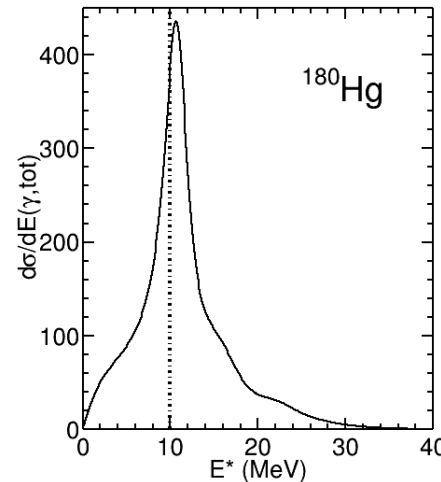
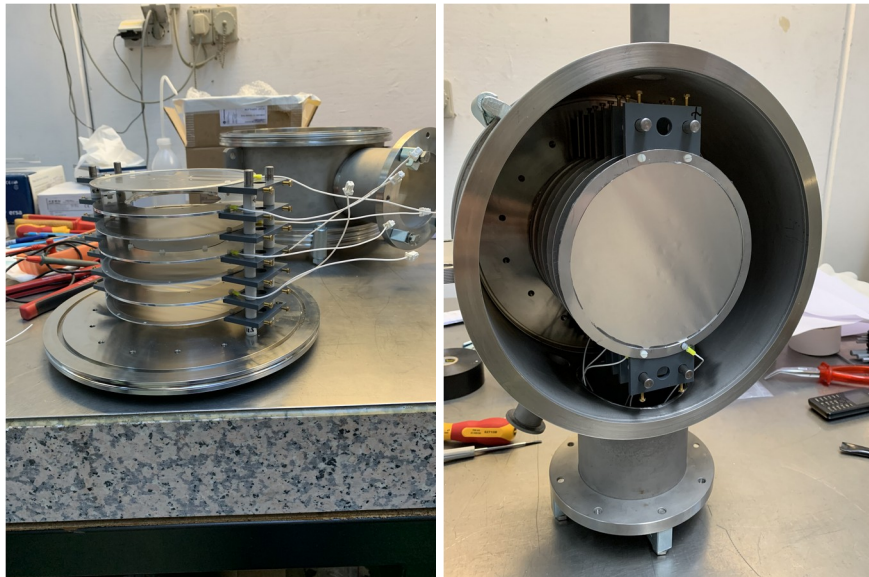


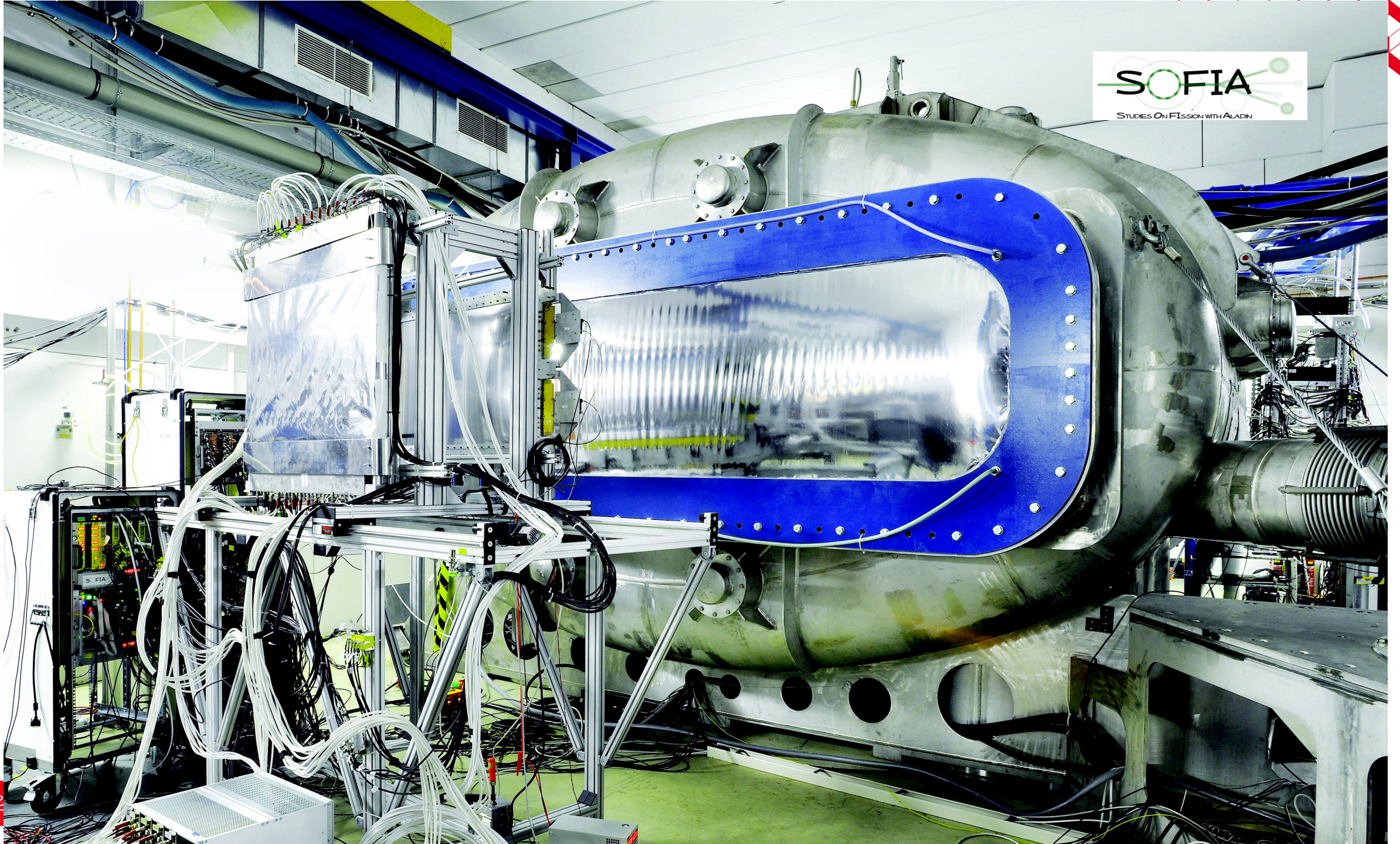
- **Coulomb induced fission**

- ✓ Large cross section (around de 3 barns)
- ✓ $\langle E^* \rangle$ 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

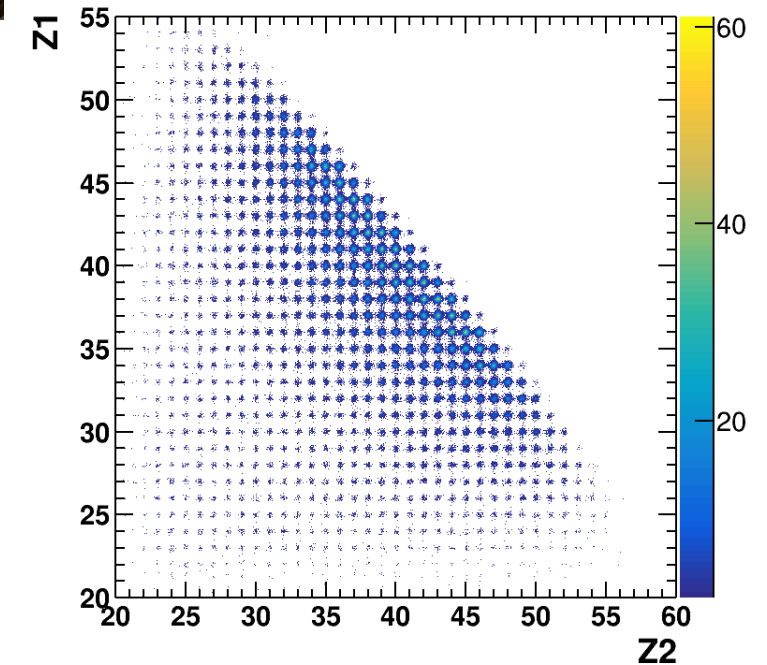
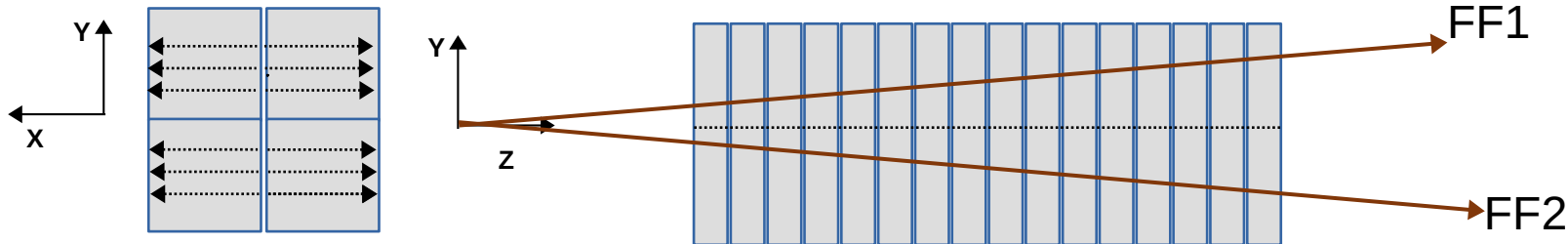
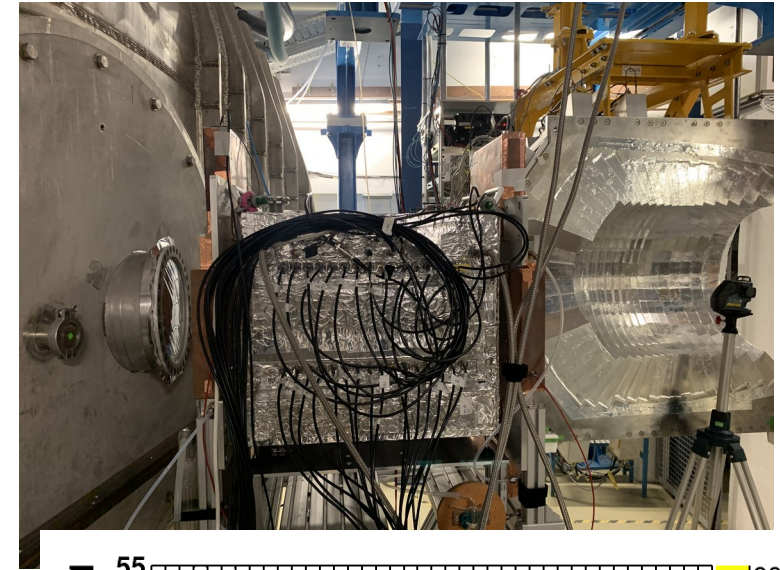




Fission fragment charge identification

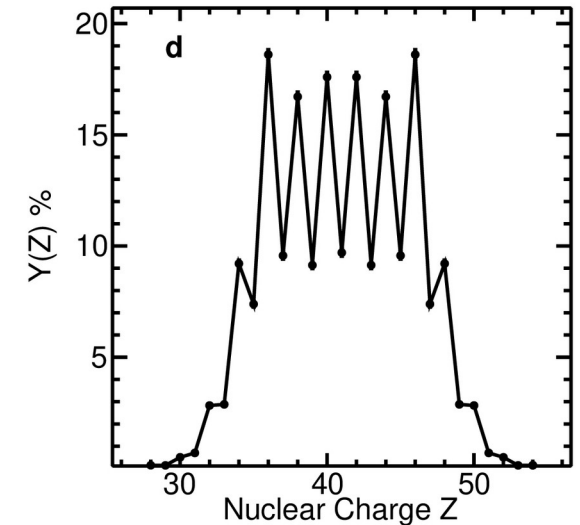
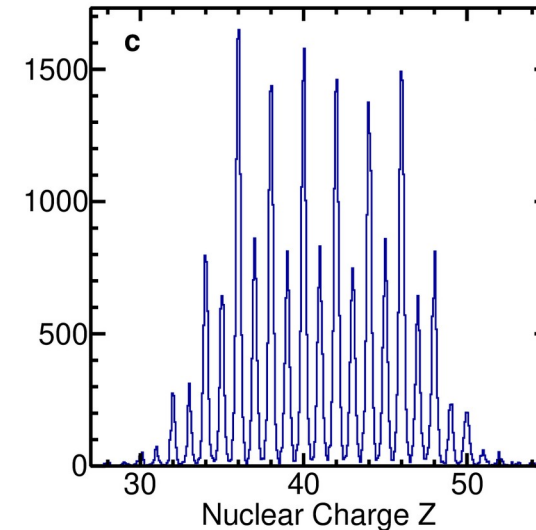
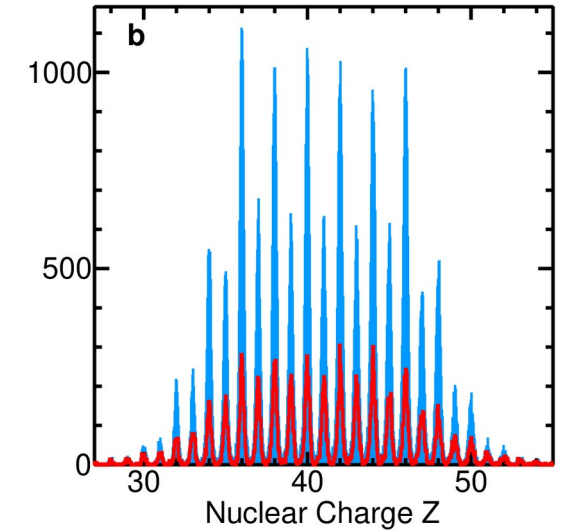
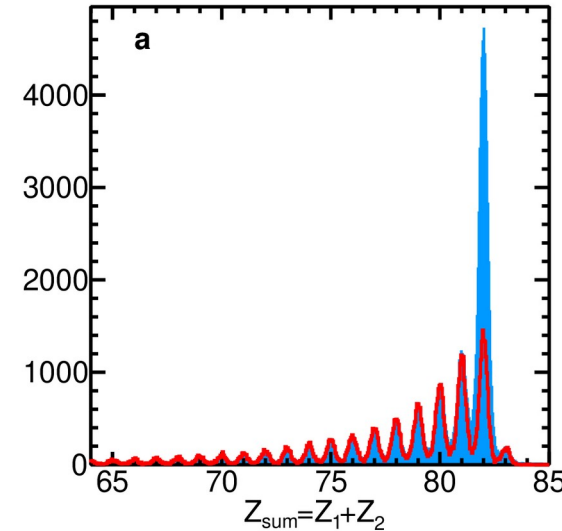
Twin MUSIC

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



Fission fragment charge identification

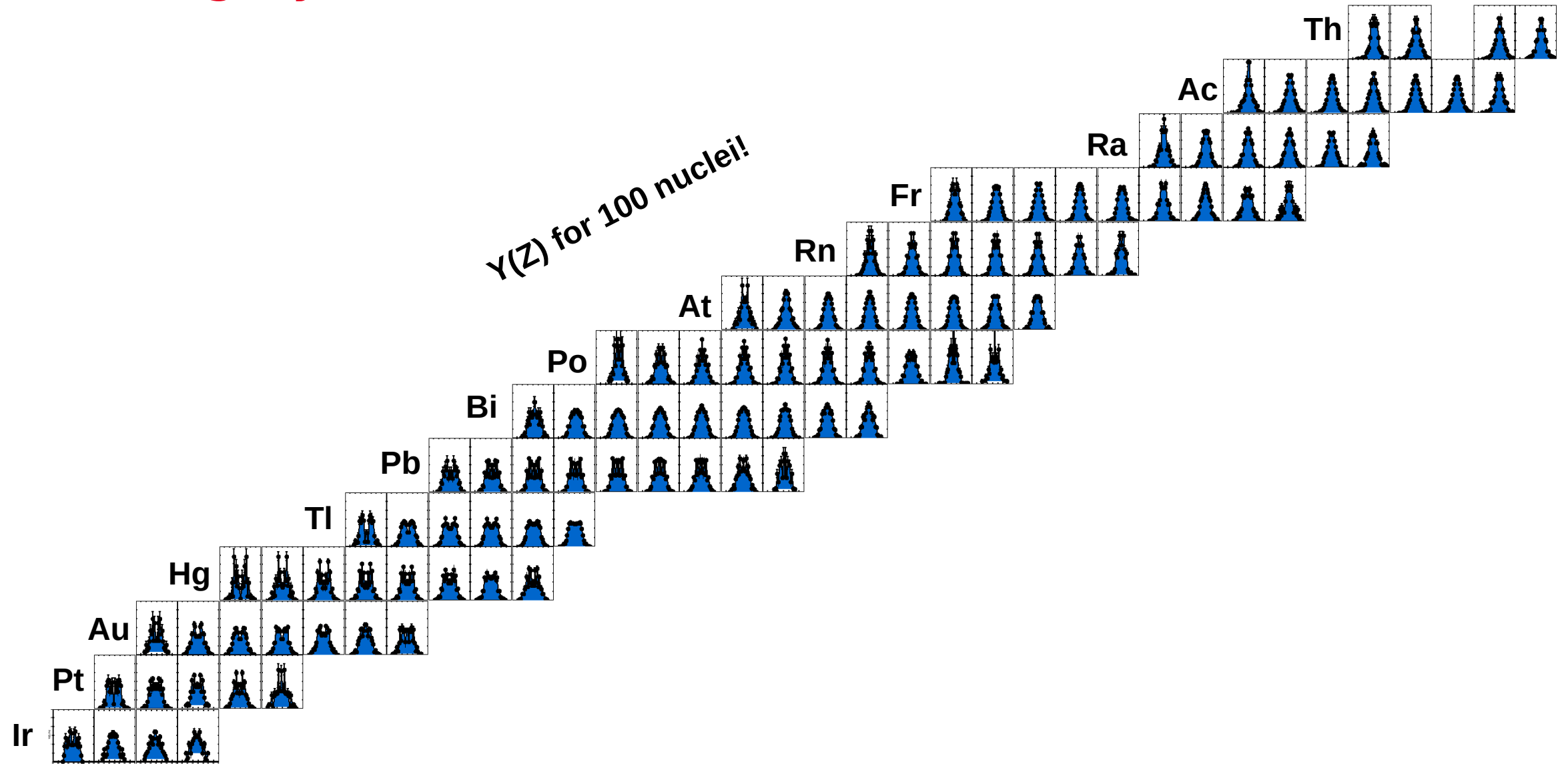
- Selection of a fissioning system (here ^{190}Pb)
- Charge identification of both fission fragments in coincidence using the Twin-MUSIC.
- $Z_1 + Z_2 = Z_{\text{beam}}$
- When $Z_1 + Z_2$ different from $Z_{\text{beam}} \rightarrow$ Nuclear excitation
- Event selection « Coulomb excitation » ($Z_{\text{sum}} = Z_{\text{beam}}$)
- 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.



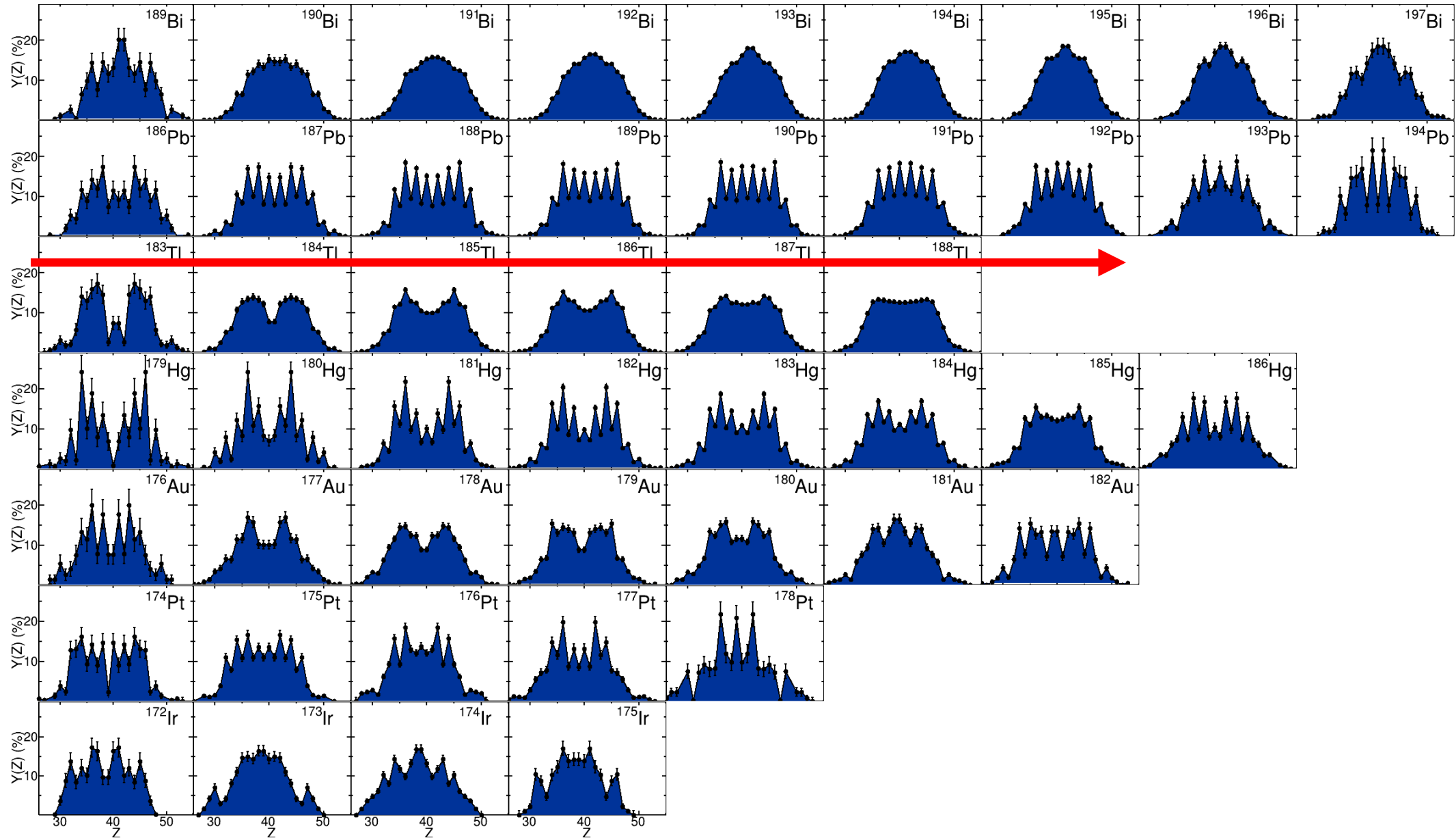


3 ■ Results

Charge yields



Charge yields

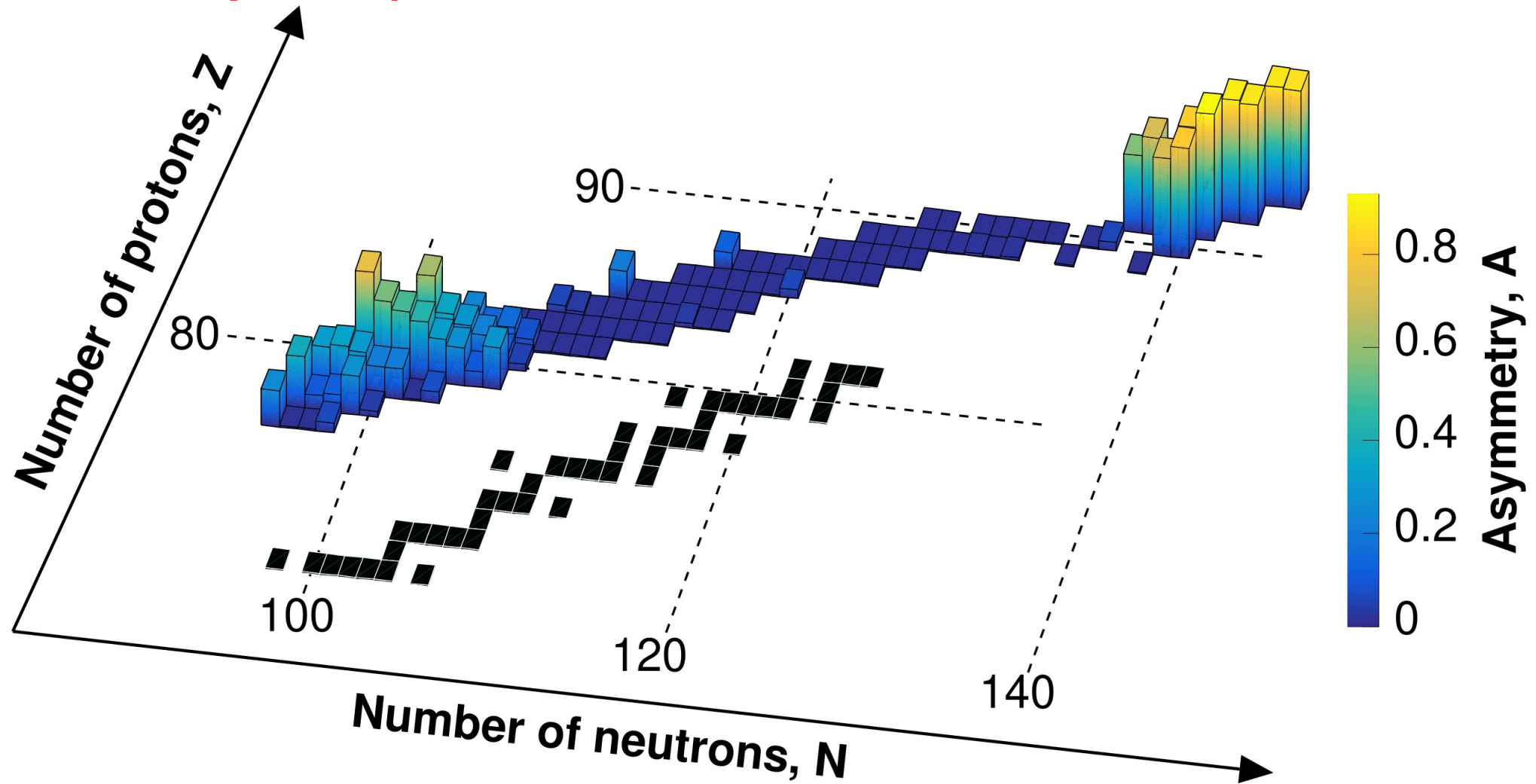


Asymmetry evolution

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

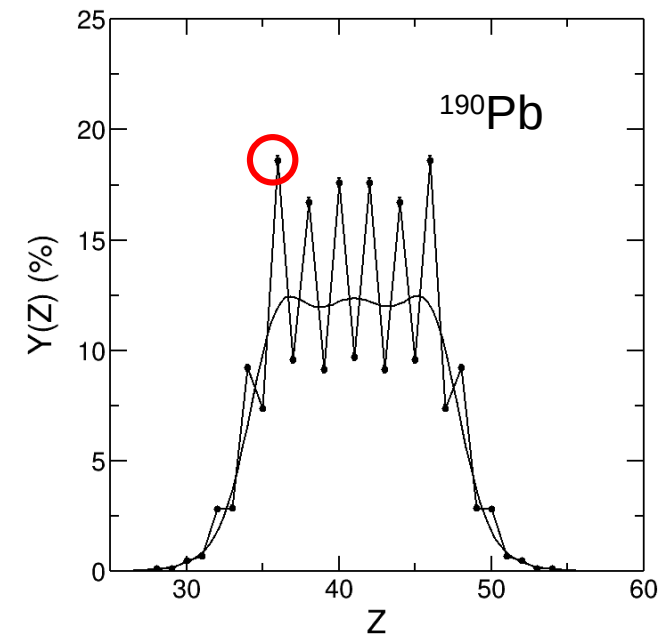
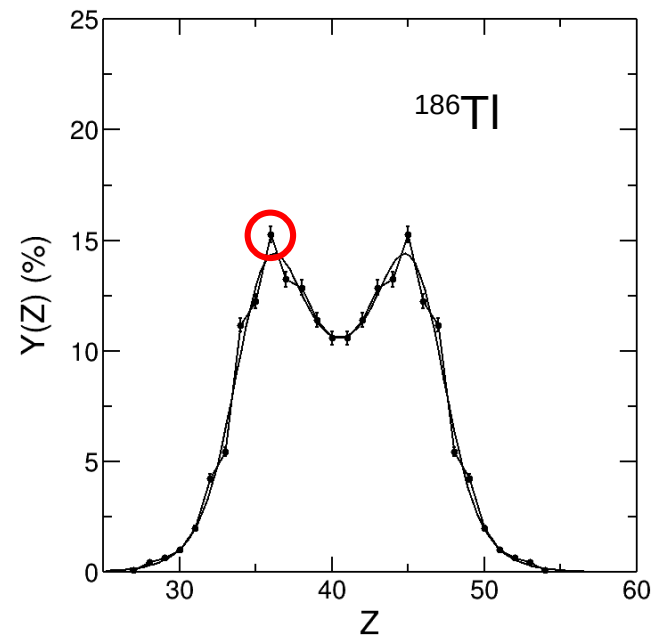
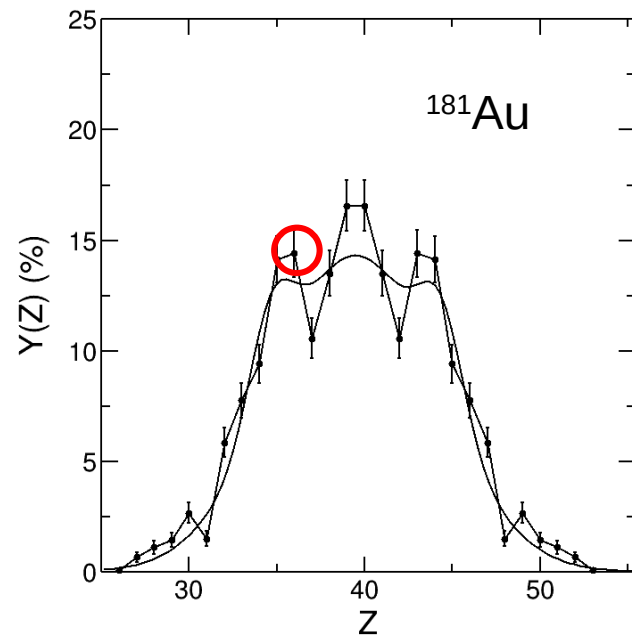
$$\mathcal{A} = 1 - \frac{Y(Z_{\text{sym}}) + \frac{Y(Z_{\text{sym}}-1) + Y(Z_{\text{sym}}+1)}{2}}{Y(Z_{\text{max}}) + \frac{Y(Z_{\text{max}}-1) + Y(Z_{\text{max}}+1)}{2}}$$

Asymmetry map



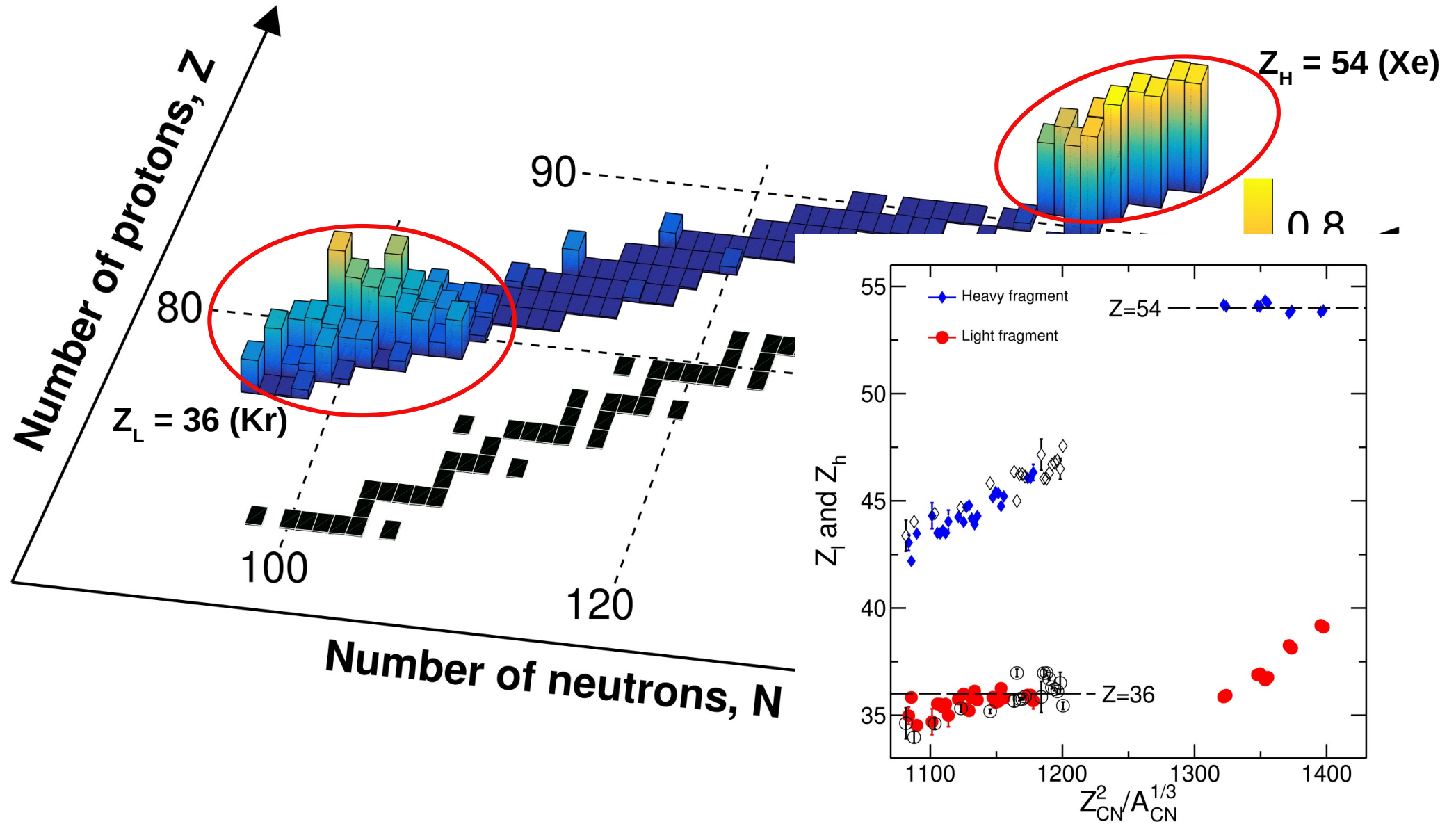
The data demonstrate a transition to more asymmetric fission as we move toward neutron-deficient systems.

Z=36 stabilization in the light fragment

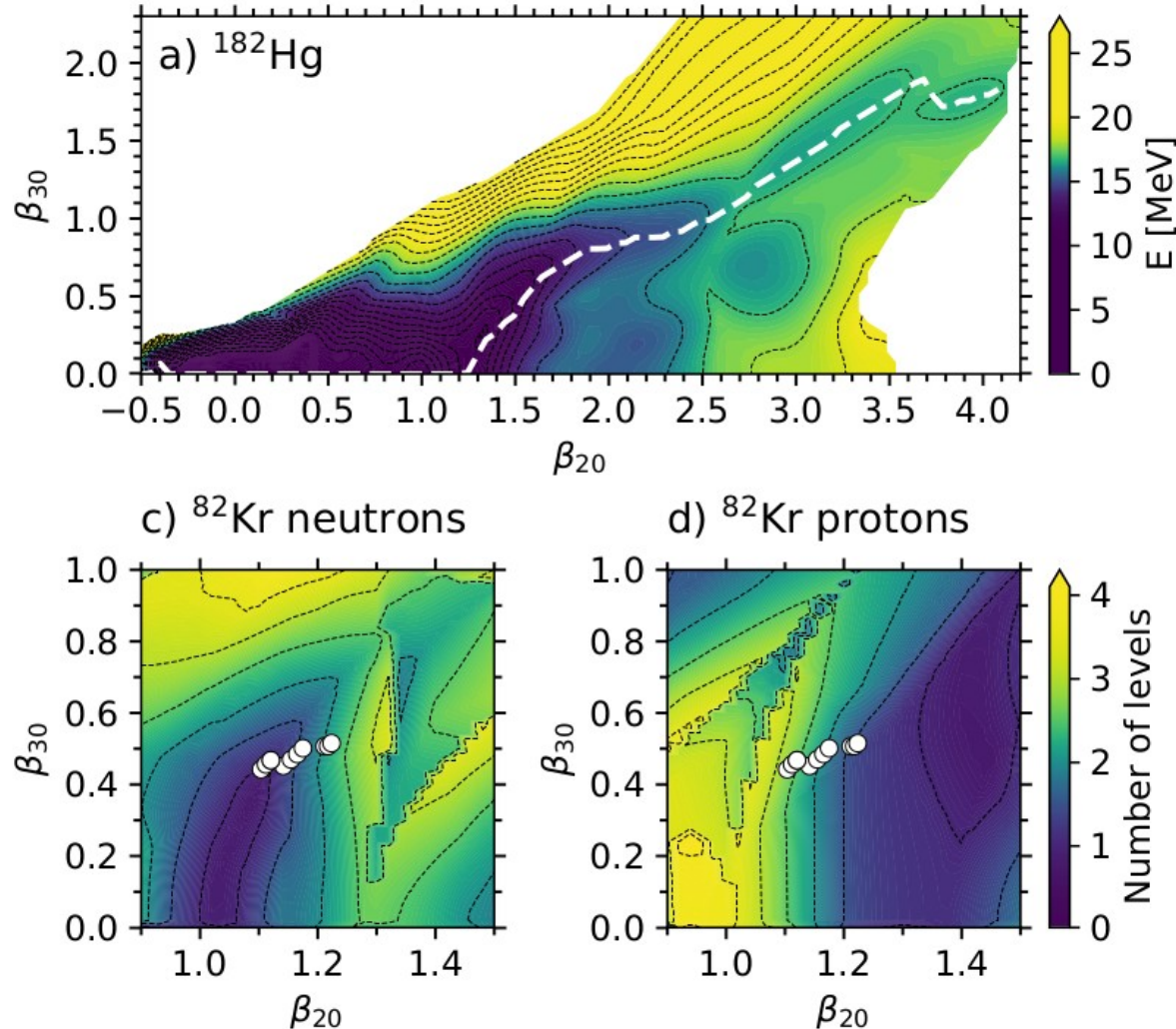


- The population of the light fragment $Z=36$ is favored in this new asymmetric fission island.
- The associated heavy partners exhibit a range from $Z=42$ to 46.

Asymmetry map



Microscopic calculations using Gogny D1S



- Extended HFB calculations of even-even nuclei in the island of asymmetric 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.

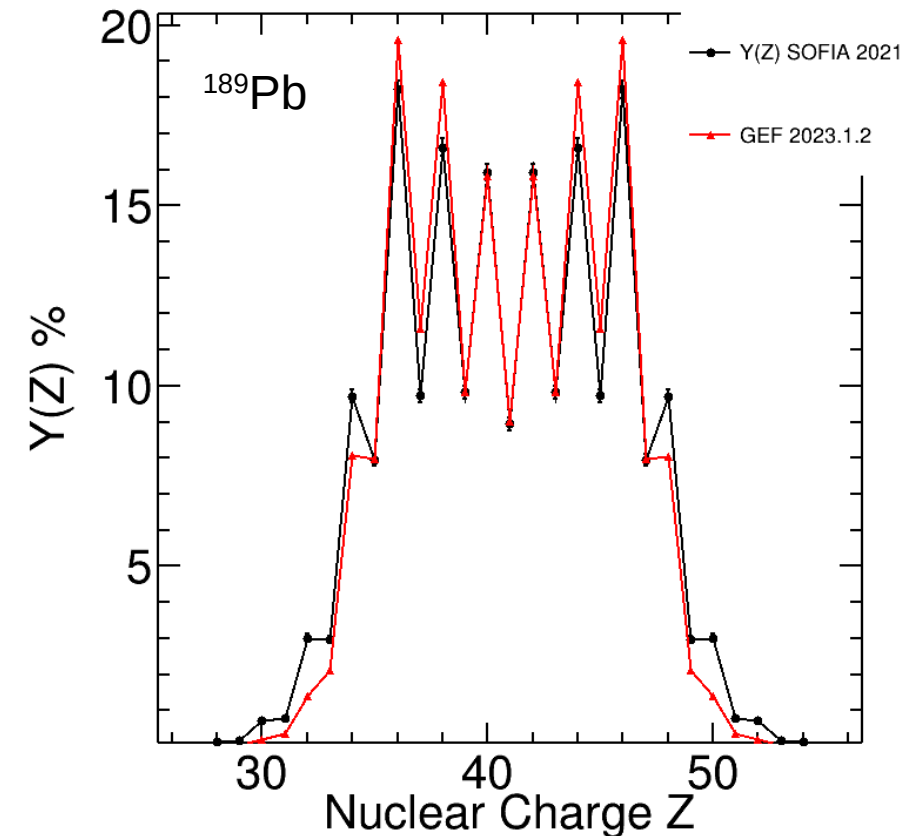
- ✓ **Z=36 Kr isotopes favored in the scission path in numerous cases.**
- ✓ **Shell effect in the light fragment.**
- ✓ **No shell effect visible in the associated heavy fragment.**

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.

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

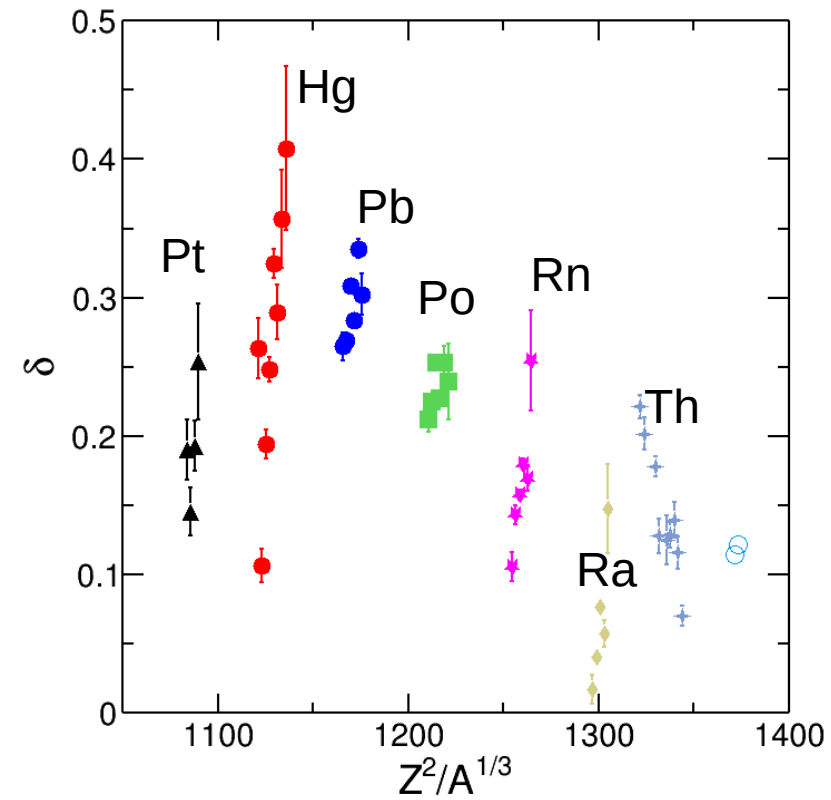
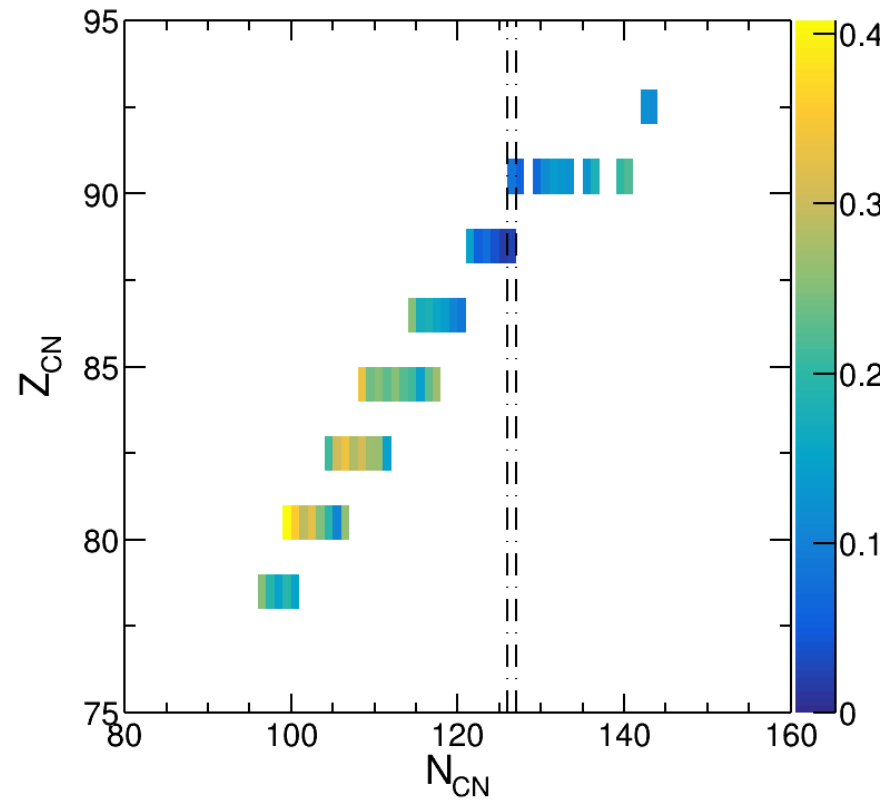
- How does the global odd-even staggering evolve with the fissioning system ?



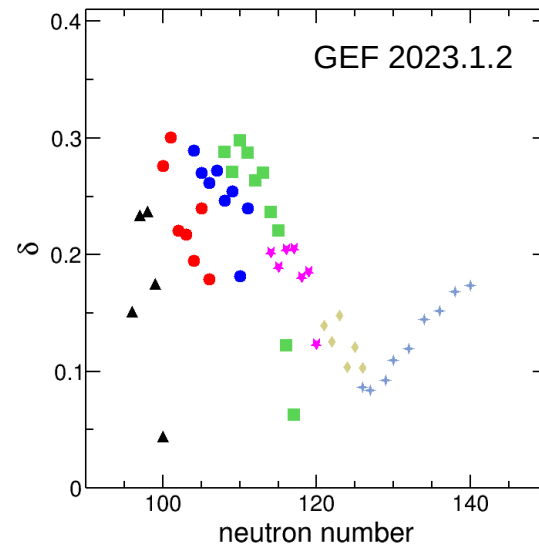
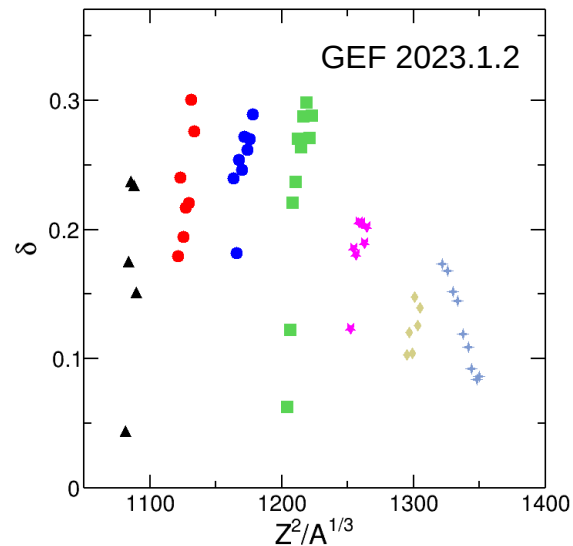
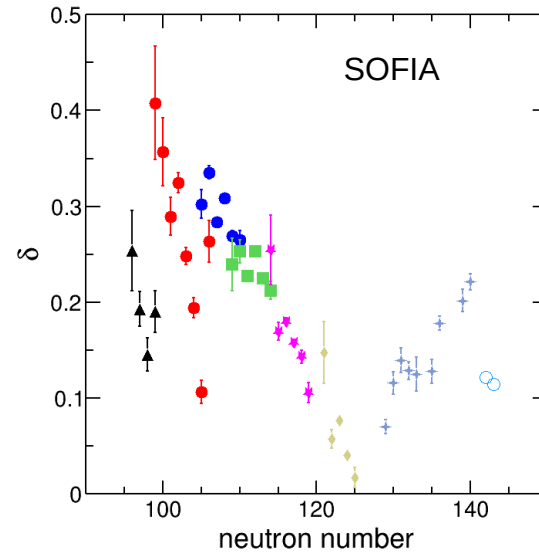
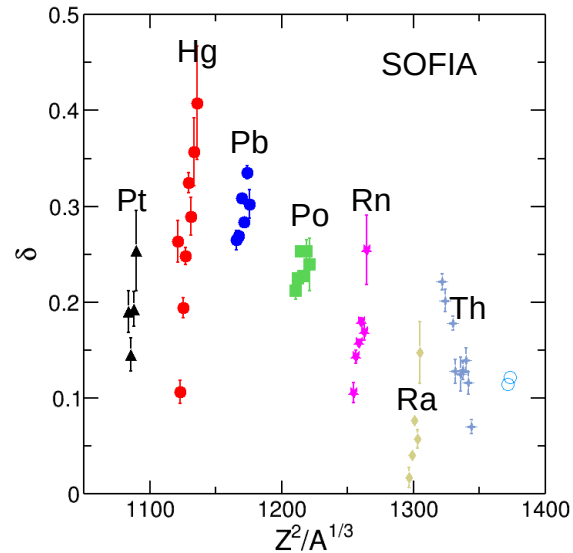
Global odd-even effect

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

- 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 ?



4 ■ Conclusion

Conclusion

- 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 !
 - ✓ Important data set to test and constrain theoretical models.
 - ✓ The evolution of the global odd-even effect needs to be investigated more deeply.
- 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 $Z=36$.
- Perspective:
 - Extend the measurement around the island
 - (p,2p) reaction to probe the excitation energy degree of freedom (shell damping, fission barrier...)

Thank you

R³B



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An asymmetric fission island driven by shell effects in light fragments

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