

# Isotopic fission yields experiments

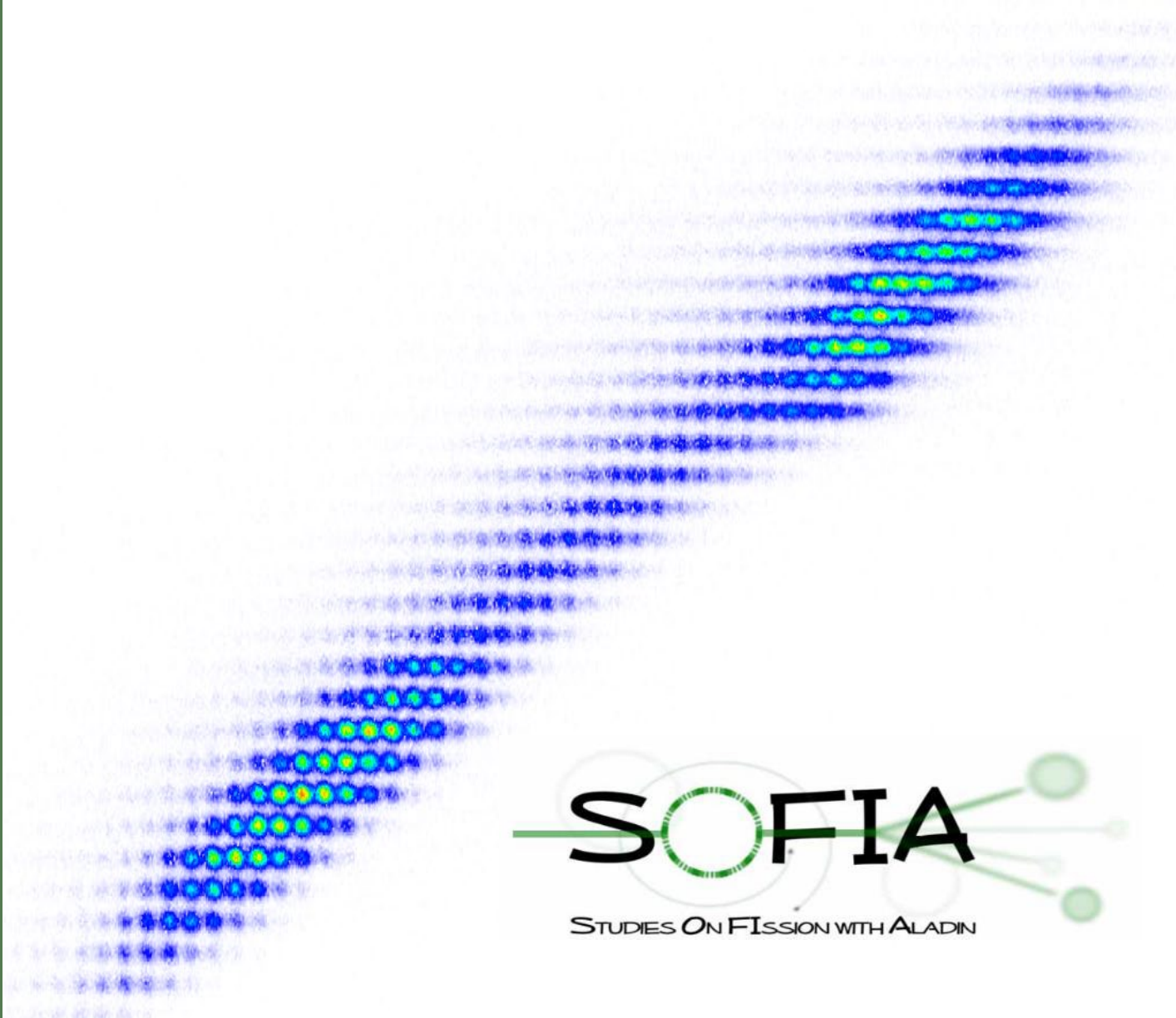
at GSI  
(and GANIL...?)

*L. Audouin*

*SOFIA collaboration*

*Preliminary SOFIA data analysis :*

*P. Morfouace*



# Fission fragment yields : applied physics

- Nuclear reactors: core dynamics
  - Delayed neutrons
  - Neutronic poisons
  - Increased influence with larger burn-ups
- Nuclear fuel: inventory
  - Used fuel handling and reprocessing
  - Residual (decay) heat

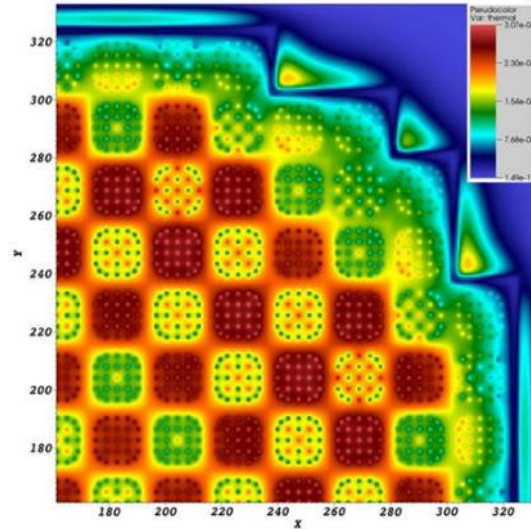
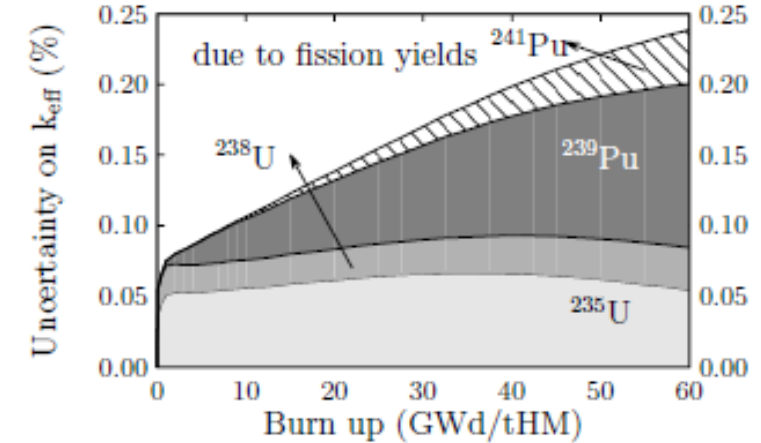
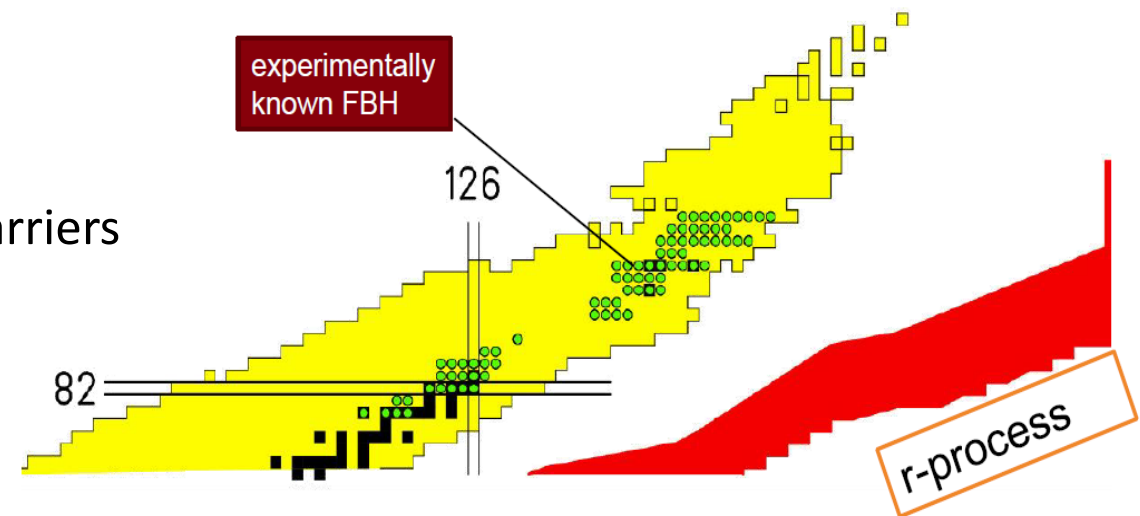


Figure 1 2D Slice of Thermal Flux Distribution near the Core Mid-plane

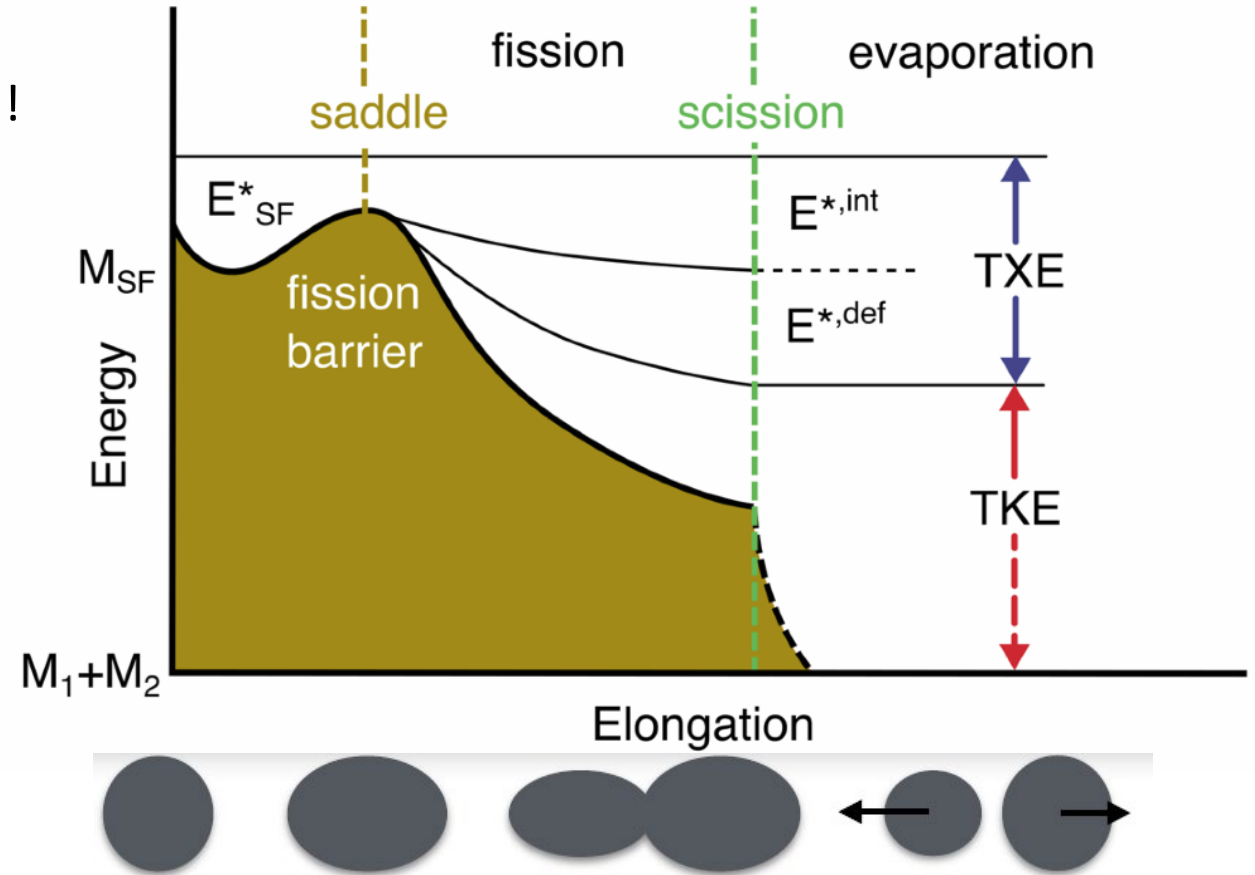


- Nuclear astrophysics: material cycling
  - Fission is the termination of the r-process
  - Nucleosynthesis calculations depend on fission barriers



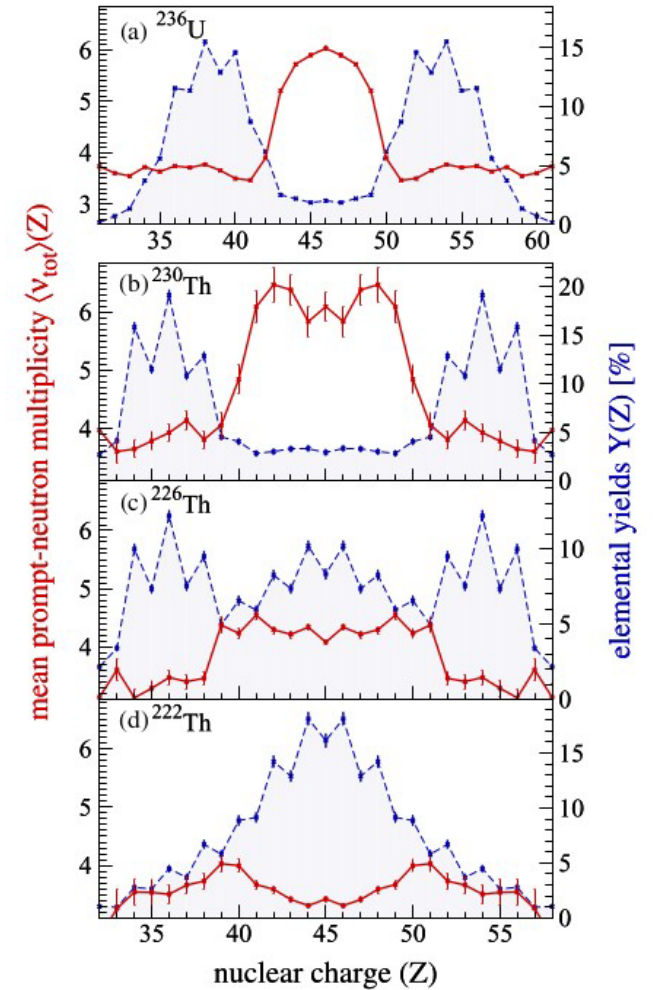
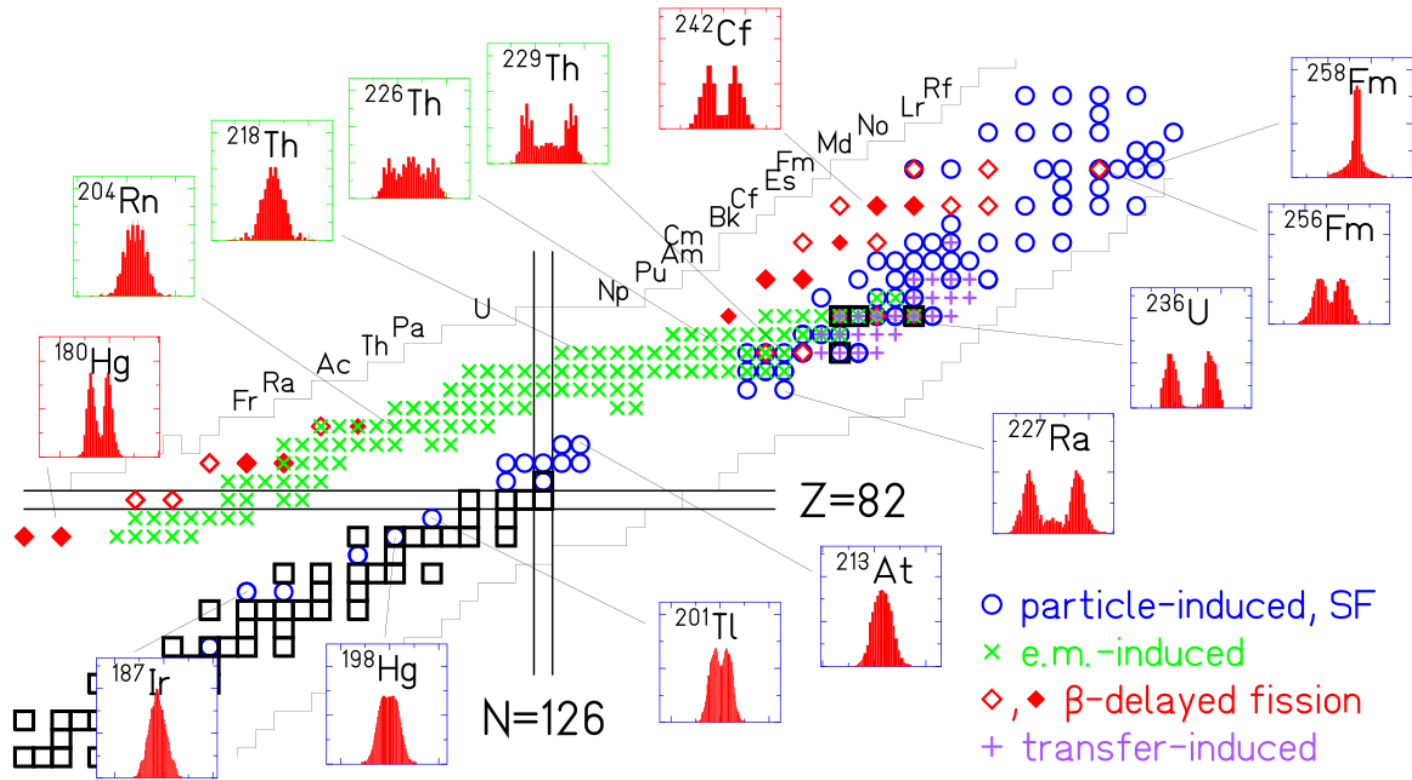
# Fission fragment yields : basic science

- Slow process (at nuclear scale...)
  - Actually... we don't know how long it takes!!
- Elongation...
- ... break-up ...
- ... cross-repulsion of fragments ...
- ... cooling of fragments
- Modelling fission is an enduring challenge!
  - Elongated nuclei
  - Dynamic process
  - Most intermediate states are unknown



# Fission modes

- Asymmetric fission in actinides due to shell effects.
- Transition toward symmetric fission in Th isotopes
- ✓ New fission mode : symmetric compact in n-deficient Th



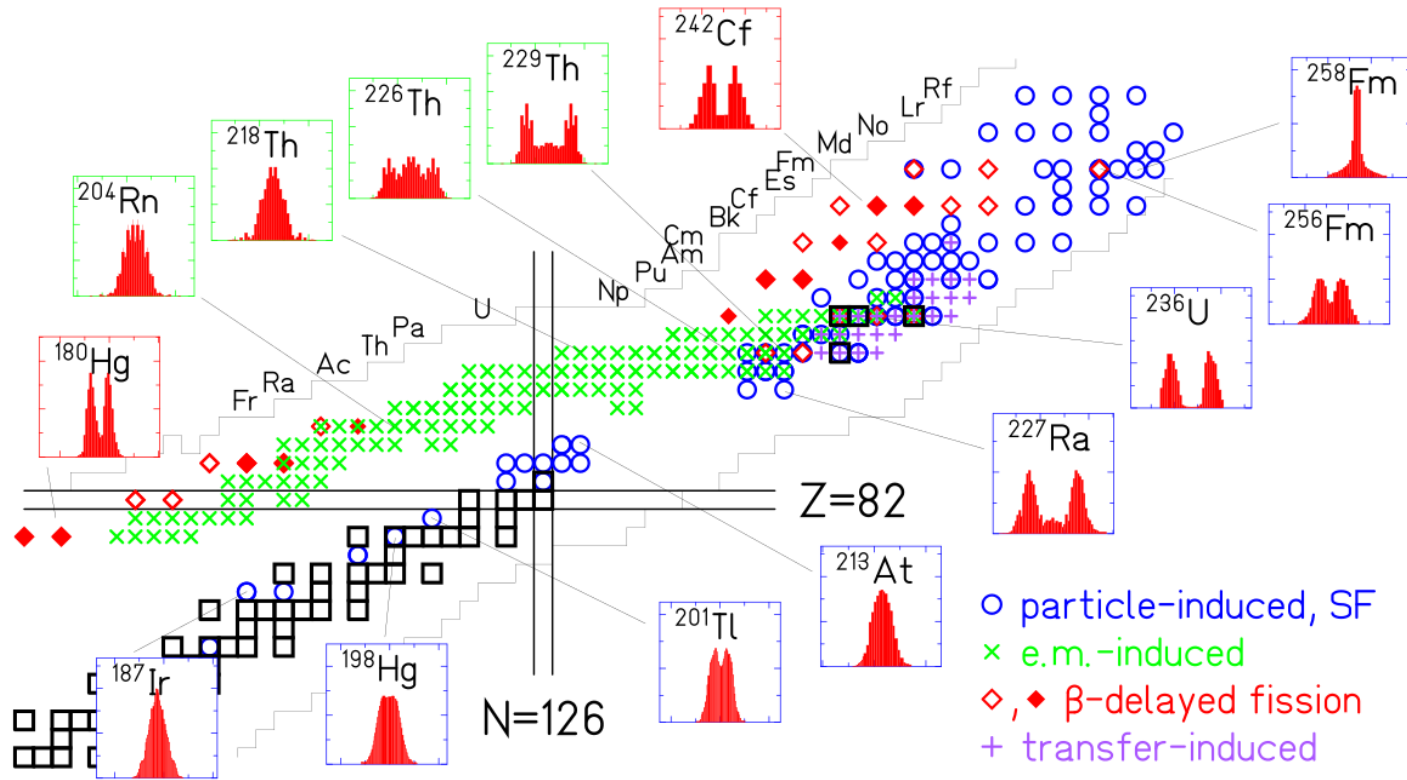
A. N. Andreyev *et al.* Rep. Prog. Phys. **81**, 016301 (2018)

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

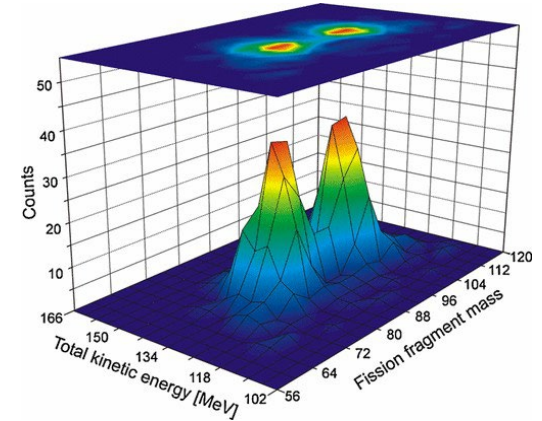
A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)

# Fission modes

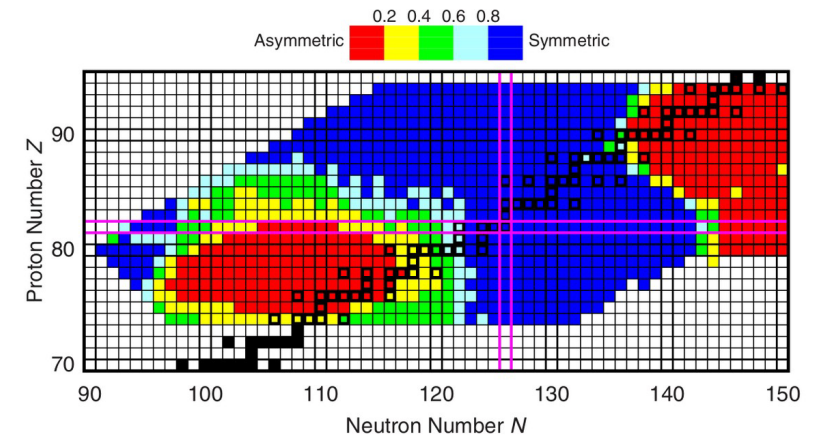
- Asymmetric fission in actinides due to shell effects.
- Transition toward symmetric fission in Th isotopes
- ✓ New fission mode : symmetric compact in n-deficient Th
- ✓ New fission mode : asymmetric in very light Hg



A. N. Andreyev *et al.* Rep. Prog. Phys. **81**, 016301 (2018)



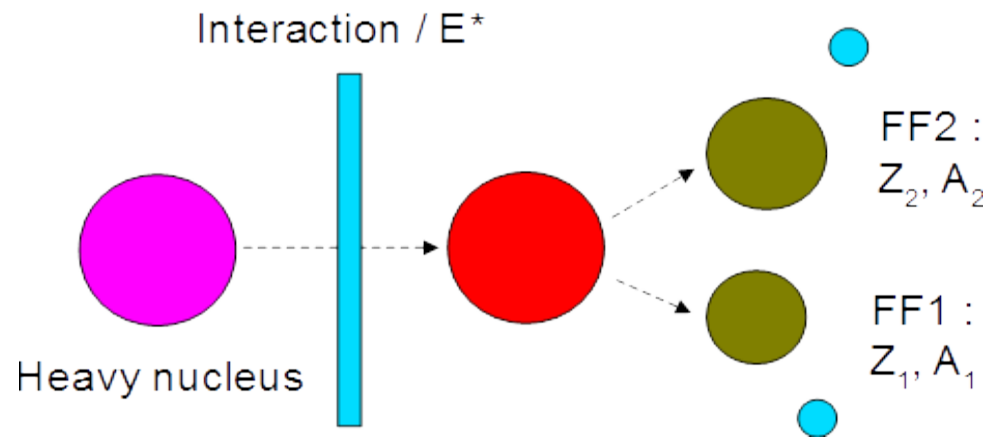
A. N. Andreyev *et al.* Phys. Rev. Lett. **105**, 252502 (2010)



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

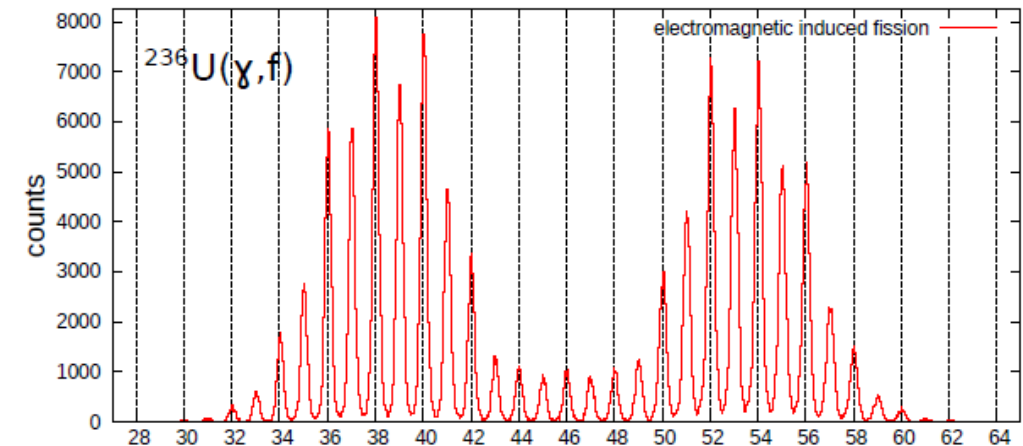
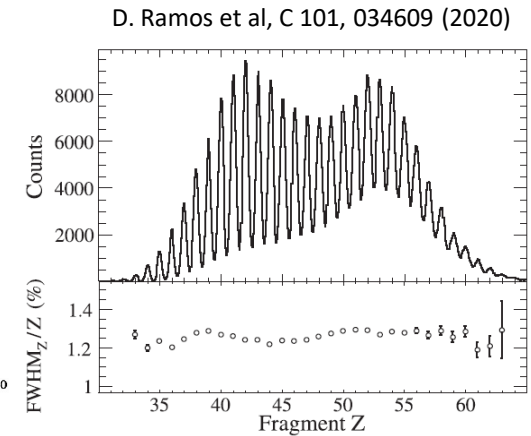
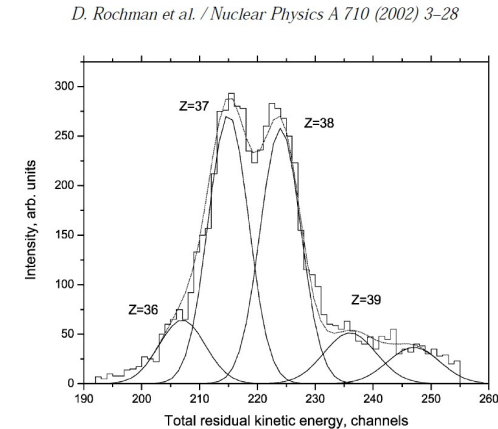
# Inverse Kinematics

- Heavy partner (fissioning system) as projectile
- In-flight fission



- ✓ Access to very short-lived nuclei
- ✓ Direct, precise Z measurement

- Identification of the fragments: recoil spectrometer
- Pioneer experiment : Schmidt et al. (1996) : Z of both FFs
- 2010s : SOFIA@GSI, transfer@GANIL, RIKEN



# The SOFIA program

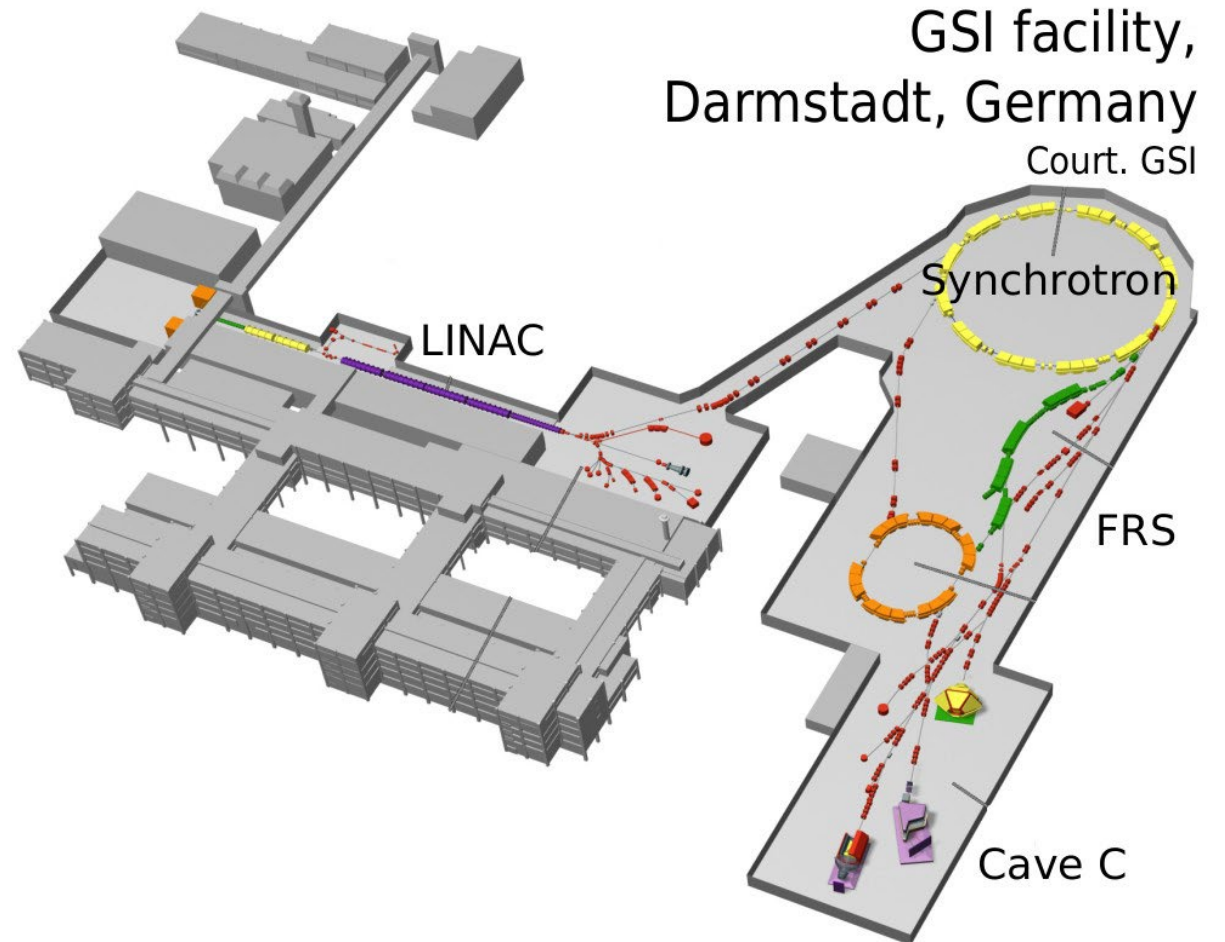
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- Direct identification of both fission fragments : A & Z
  - Data on Z are scarce
  - + Kinetic energy (fragments shapes)
  - + Total prompt neutron multiplicity (fragments excitation)
- Wide range of fissioning systems
  - U region for applications
  - Th and even lighter systems for structure study
- High-precision measurement (~ % on isotopic yields)
- Low  $E^*$ 
  - Maximum sensitivity to nuclear structure effects
  - Somehow close to excitation in reactors

# 2021 : “SOFIA 3” experiment

Fission modes in the neutron-deficient region around Lead

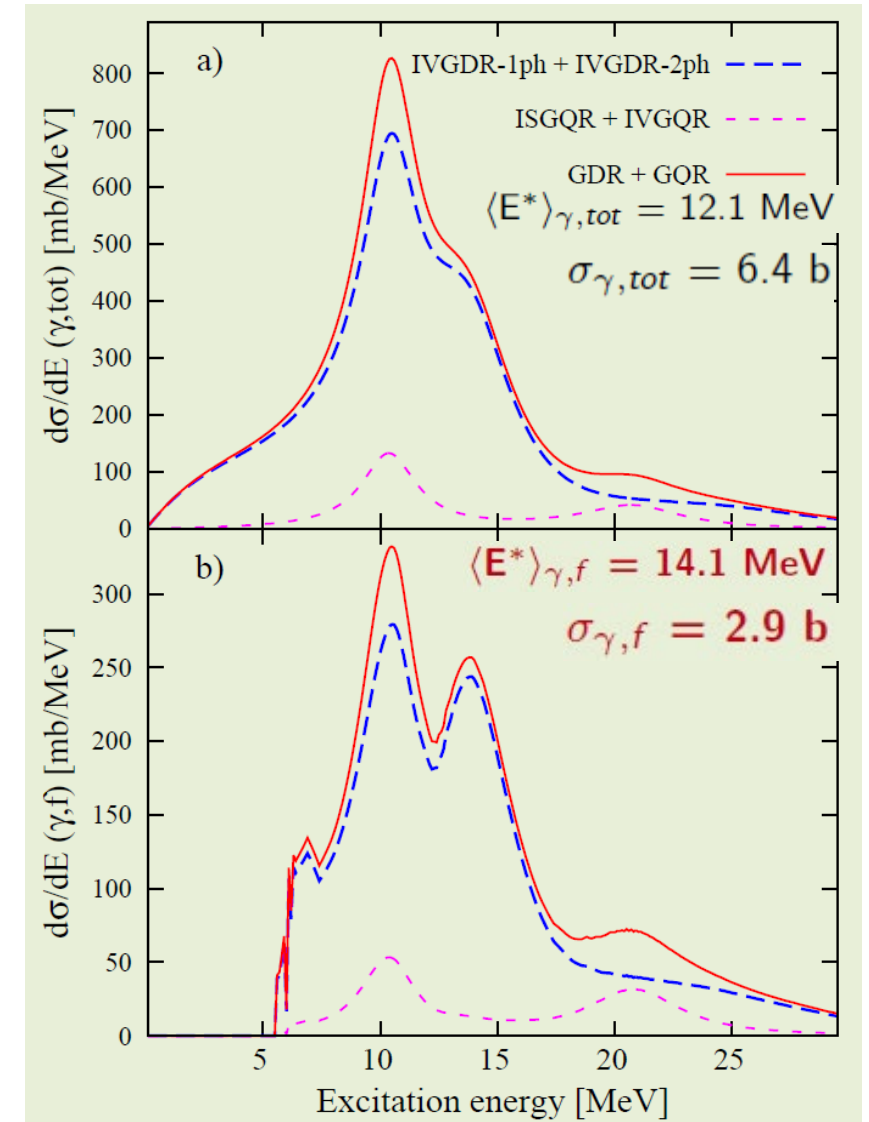
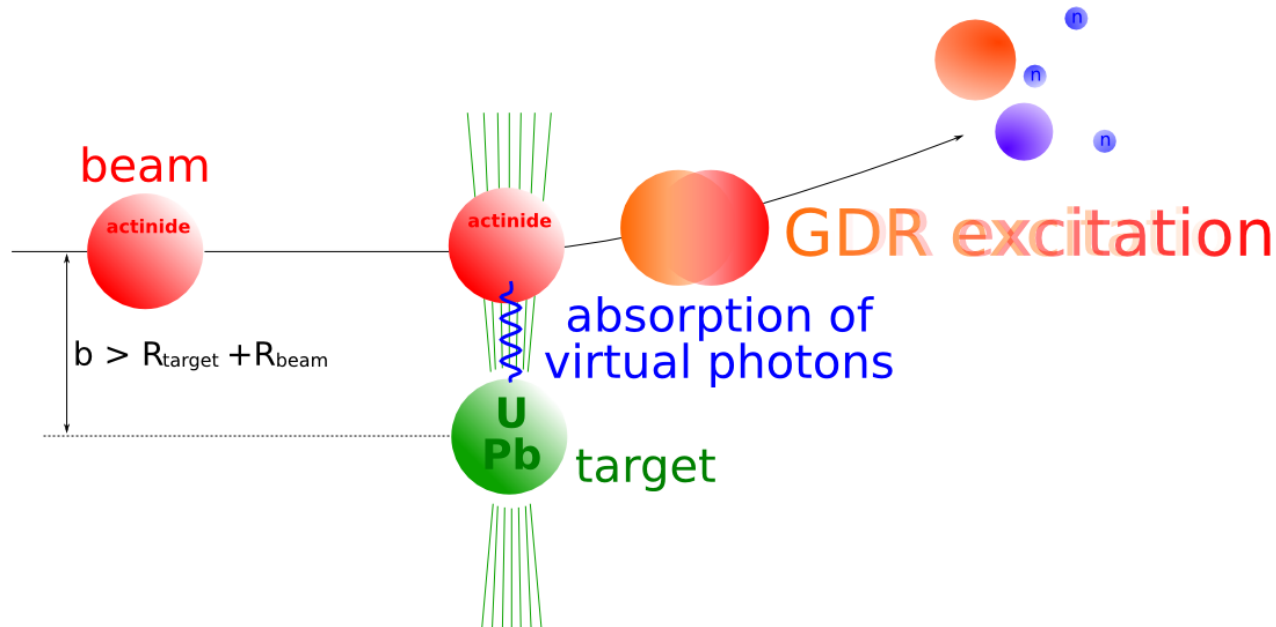
- Primary beam of  $^{238}\text{U}$  at 1 GeV/u
- Production and identification of the secondary beam through the FRS
- Fission in cave C and identification of both fission fragments.
- 12 FRS settings from  $^{175}\text{Pt}$  up to  $^{221}\text{Pa}$





# Coulomb-induced fission

- Large cross section ( $\sim b$ )
- Small  $E^*$  : excitation of the GDR ( $\langle E \rangle \sim 14$  MeV)
  - $^{236}\text{U} (\gamma, f) \sim ^{235}\text{U} (n, f)$  @ 8.2 MeV
  - 75% of first chance fission (23% 2<sup>nd</sup> chance)
- Significant dispersion of  $E^*$ : no info event-by-event
- Need to subtract nuclear contribution



# Identification of nuclei : principles

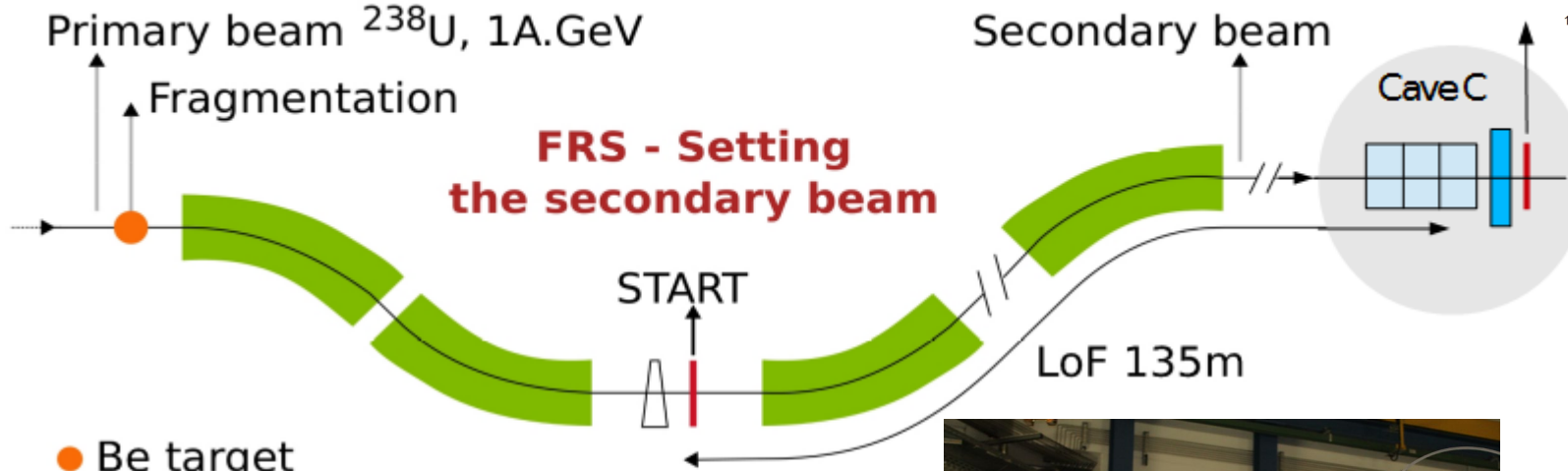
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- Z obtained directly from energy lost in a detector :  $dE/dx \propto Z^2$
- Magnetic rigidity deduced from positions
- Mass deduced from mag. rig. and Z :  $B\rho = p/q \propto A/q \cdot \beta\gamma$
  
- Hundreds of MeV per nucleon : nuclei mostly stripped
  
- Many detectors combined + extreme precision
  - Ionization chambers: Z (and position)
    - $dE/E \sim 1\%$  FWHM
  - Plastic detectors: time signals (velocities) + rough position
    - $dt \sim 40$  ps FWHM
  - MWPC: positions
    - $dx \sim 200$   $\mu$ m FWHM
  - One huge magnet.
    - The new one is gorgeous but troublesome

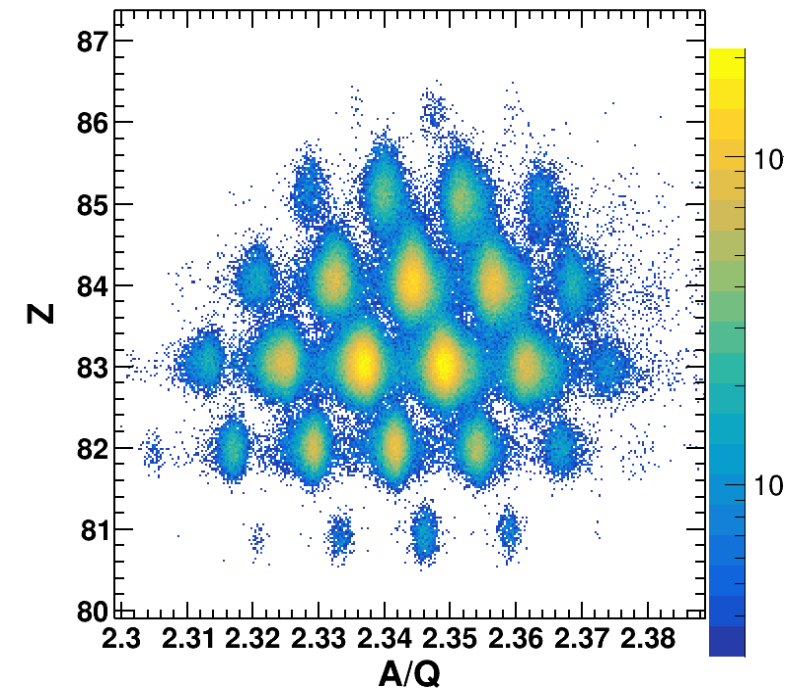
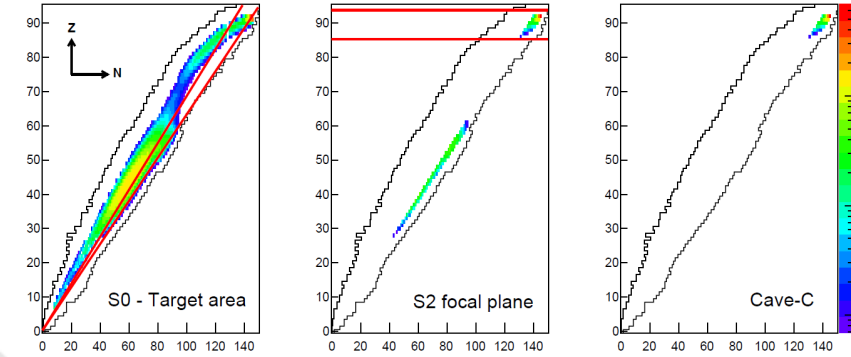
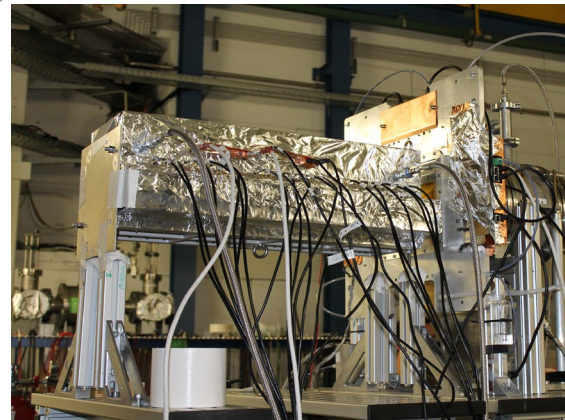


# Secondary beam: selection & identification

- Fragments from  $^{238}\text{U}$  @ 1A GeV
- In-flight selection (2 steps)
- Challenging identification (variable charge states)

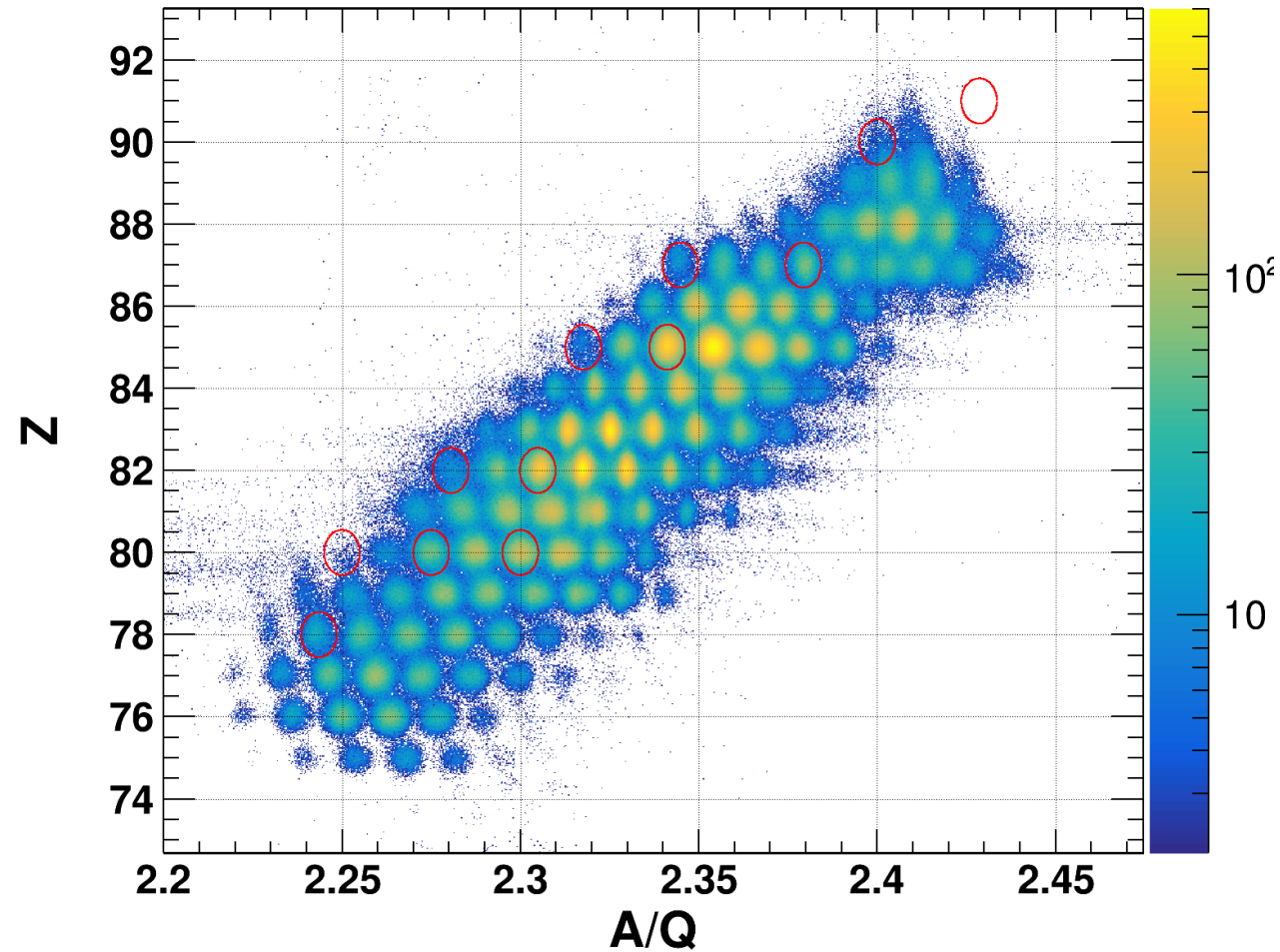


- Be target
- Dipoles
- Scintillators
- Degrador
- MWPC
- TripleMUSIC



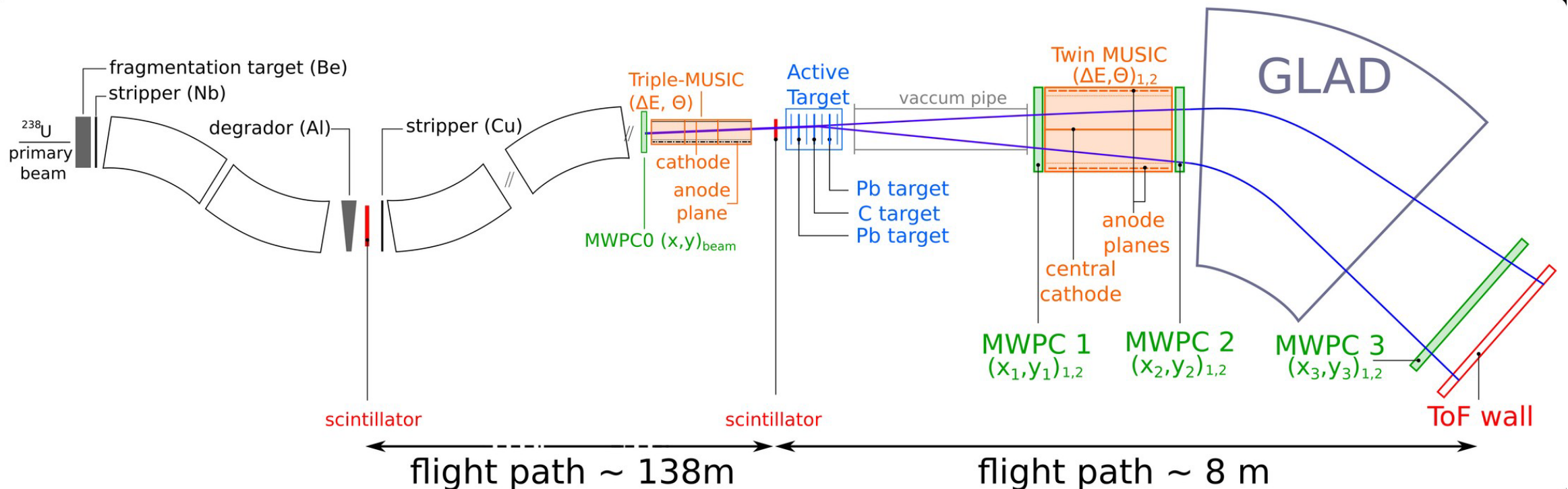
# Studied fissioning systems

- Summary of most of the FRS settings from  $^{175}\text{Pt}$  to  $^{216}\text{Th}$
- Coulomb-induced fission of about 60 isotopes.



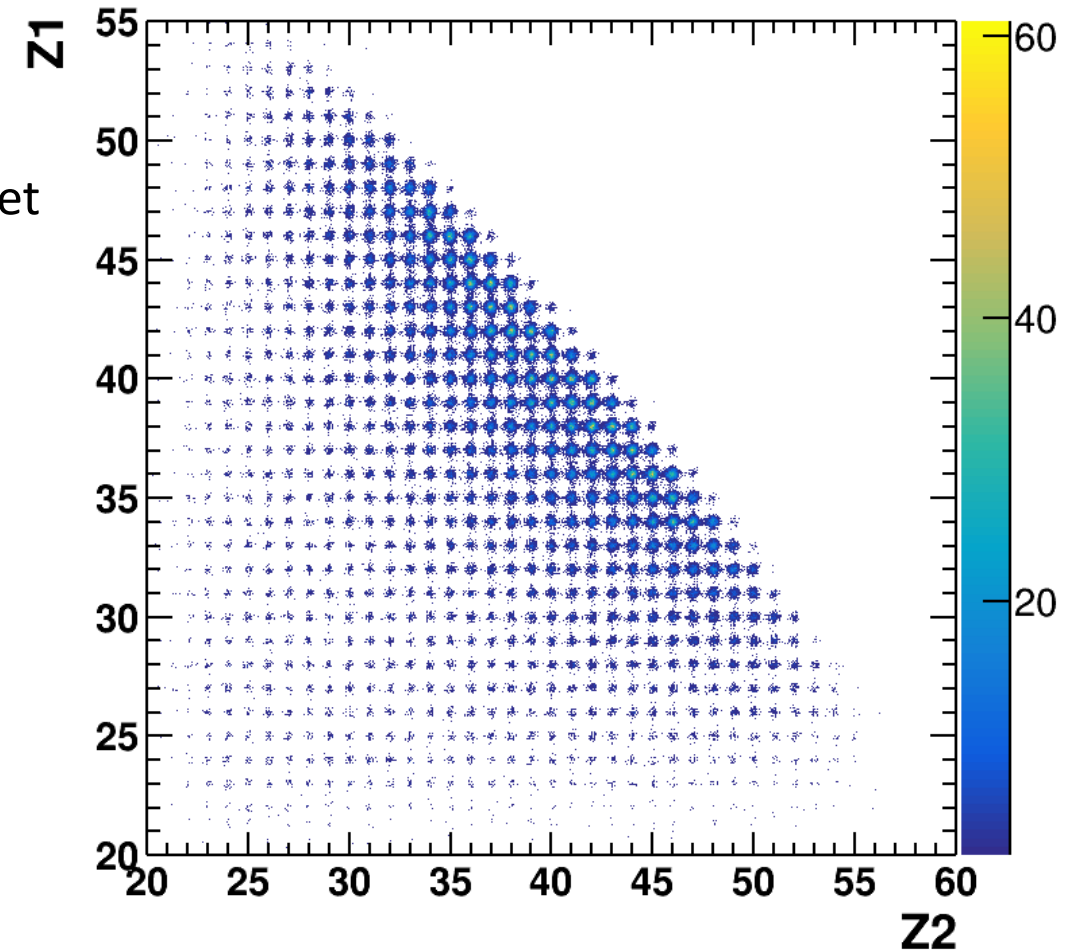
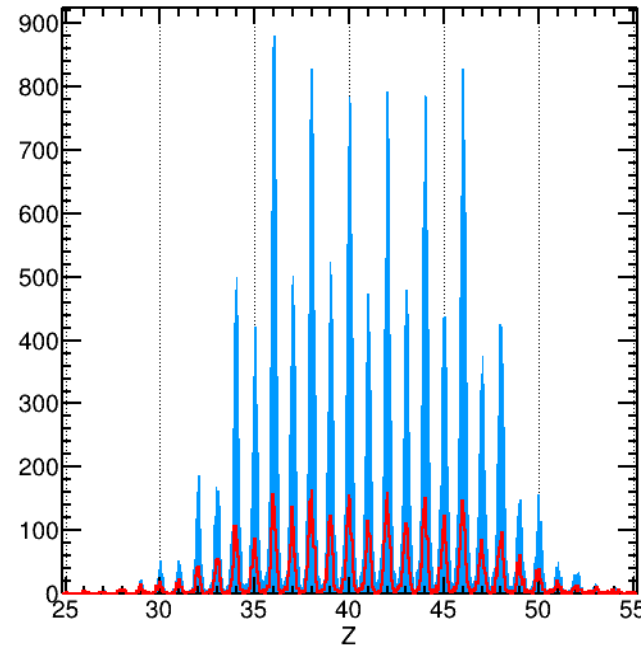
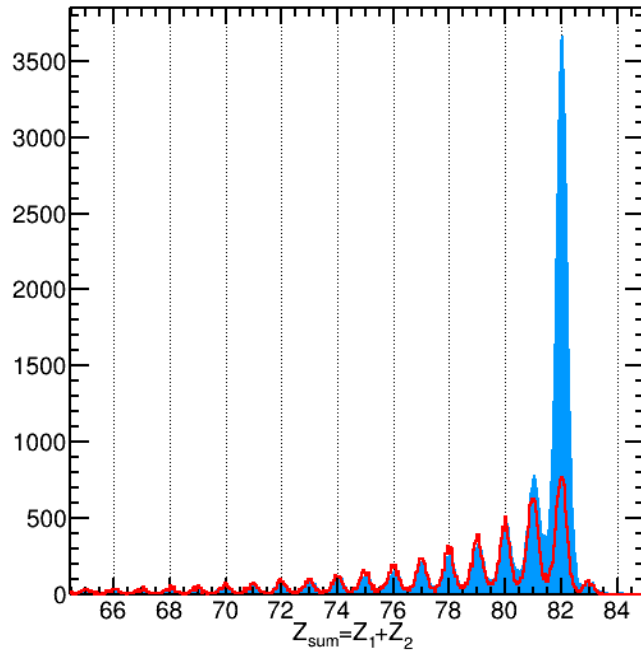
# The whole setup

- Plastic at S2 & cave C for time and position measurement.
- Triple-MUSIC for charge identification of the secondary beam.
- Active target with three cathodes (2 Lead + 1 Carbon).
- MWPC:  $(x,y)$  measurement of the beam and the fission fragments.
- Twim-MUSIC: charge identification of the fission fragments.
- ToF Wall: time of flight of fission fragments

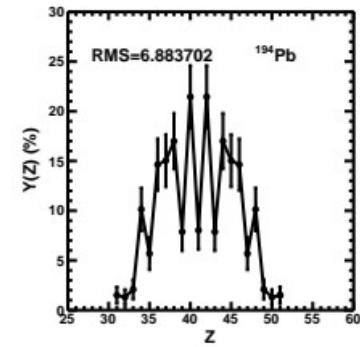
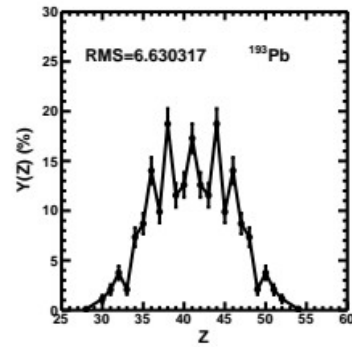
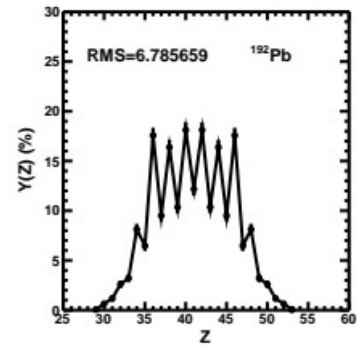
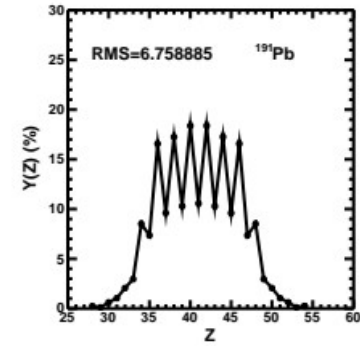
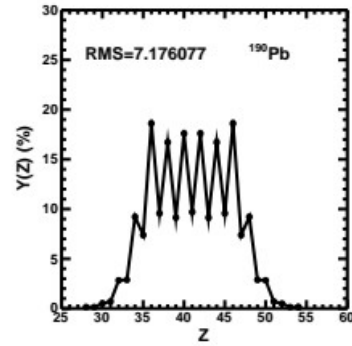
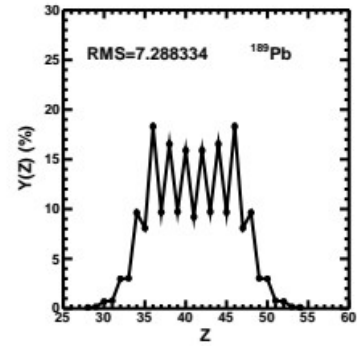
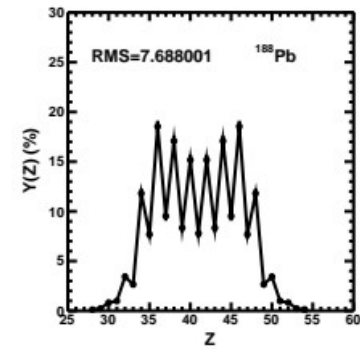
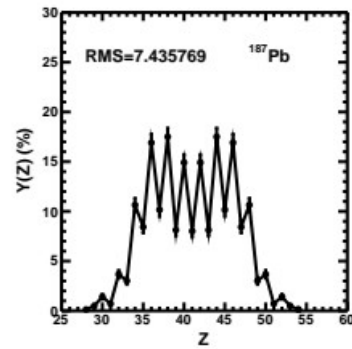
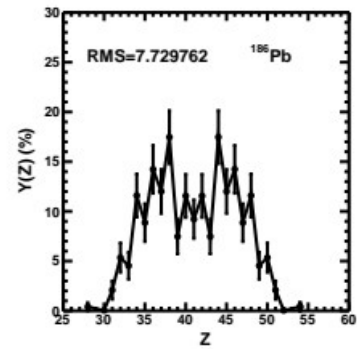


# Rejection of the nuclear contribution

- Selection of events  $Z_1 + Z_2 = Z_{\text{beam}}$
- Limiting fragmentation regime :
  - The reaction mechanism does not depend on the target
  - Subtraction of yields obtained on C target



# Preliminary results on Pb



# “Short-term” perspective ?

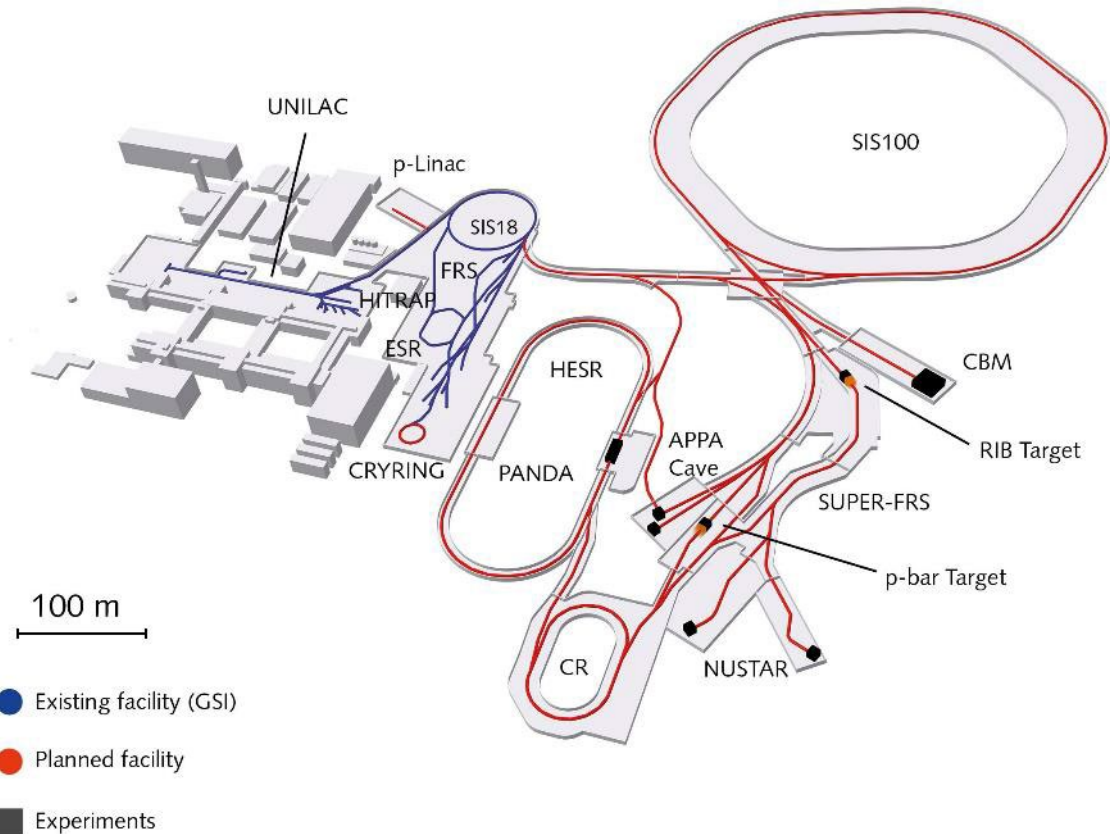
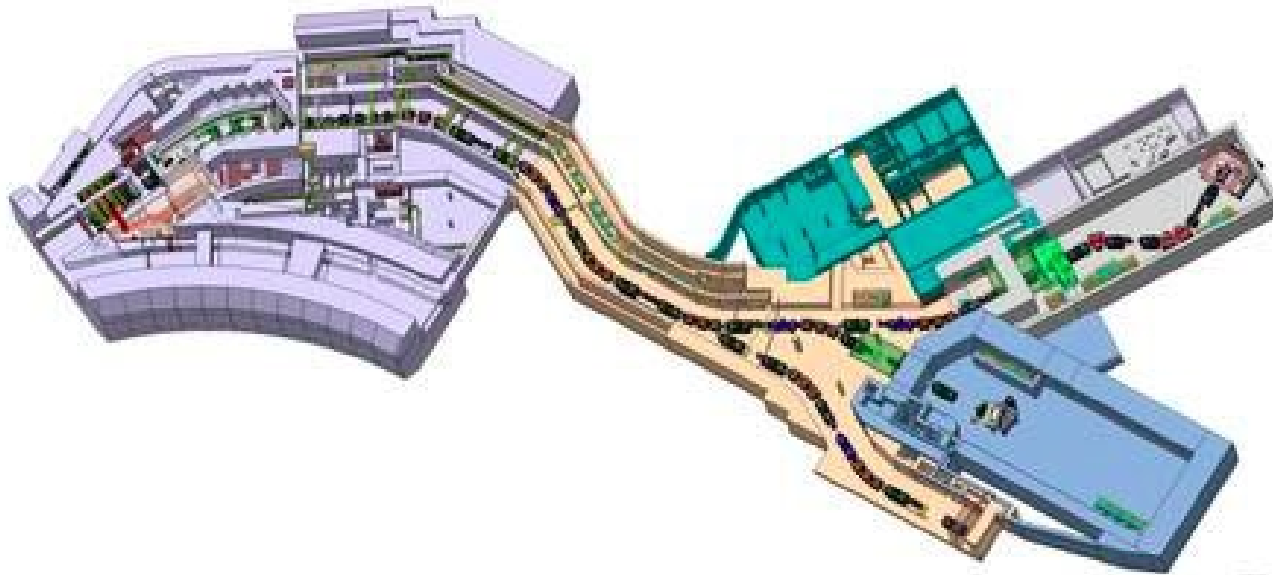
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- On-going participation to R3B experiments (no link with nuclear data)
- Complementary experiment in 2024 : fission close to the proton drip-line ?



# Mid-term perspectives: the FAIR facility

- Increased primary beam : up to  $5 \cdot 10^{11}$  U
- Super-FRS : better selection/transmission
- More exotic settings (neutron-rich beams)
- Exclusive experiments (neutron tagging)



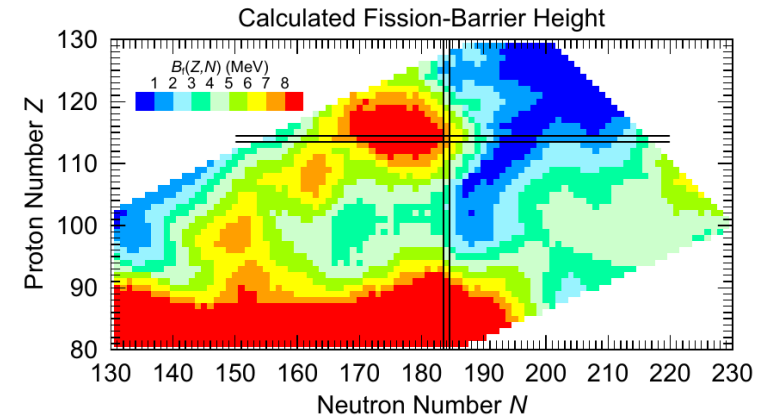
# The FAIR facility: yes, it's happening

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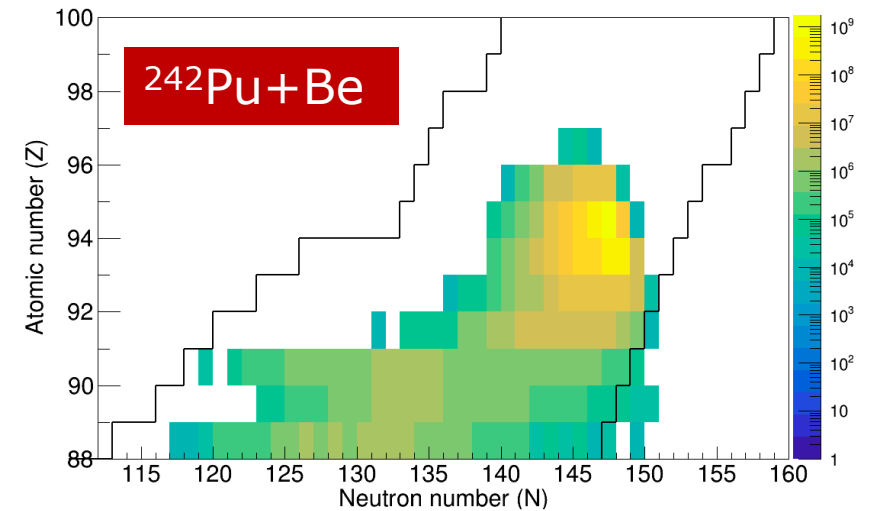
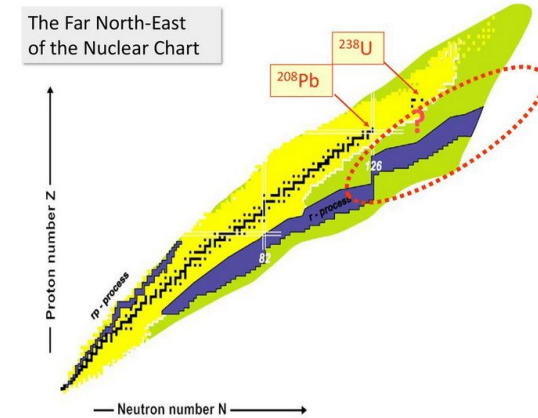


# $^{242}\text{Pu}$ beam

- Direct access to key systems (esp.  $^{240}\text{Pu}^*$ )
- New neutron-rich systems
  - Fission modelling
  - Also interesting for nuclear astrophysics
- Dedicated ion source
- Full decontamination of the injector
  
- GSI expresses interest
- Opportunity not just for « fissionists »
  - Nuclear structure
  - Possibly atomic physics
  - (not SH)



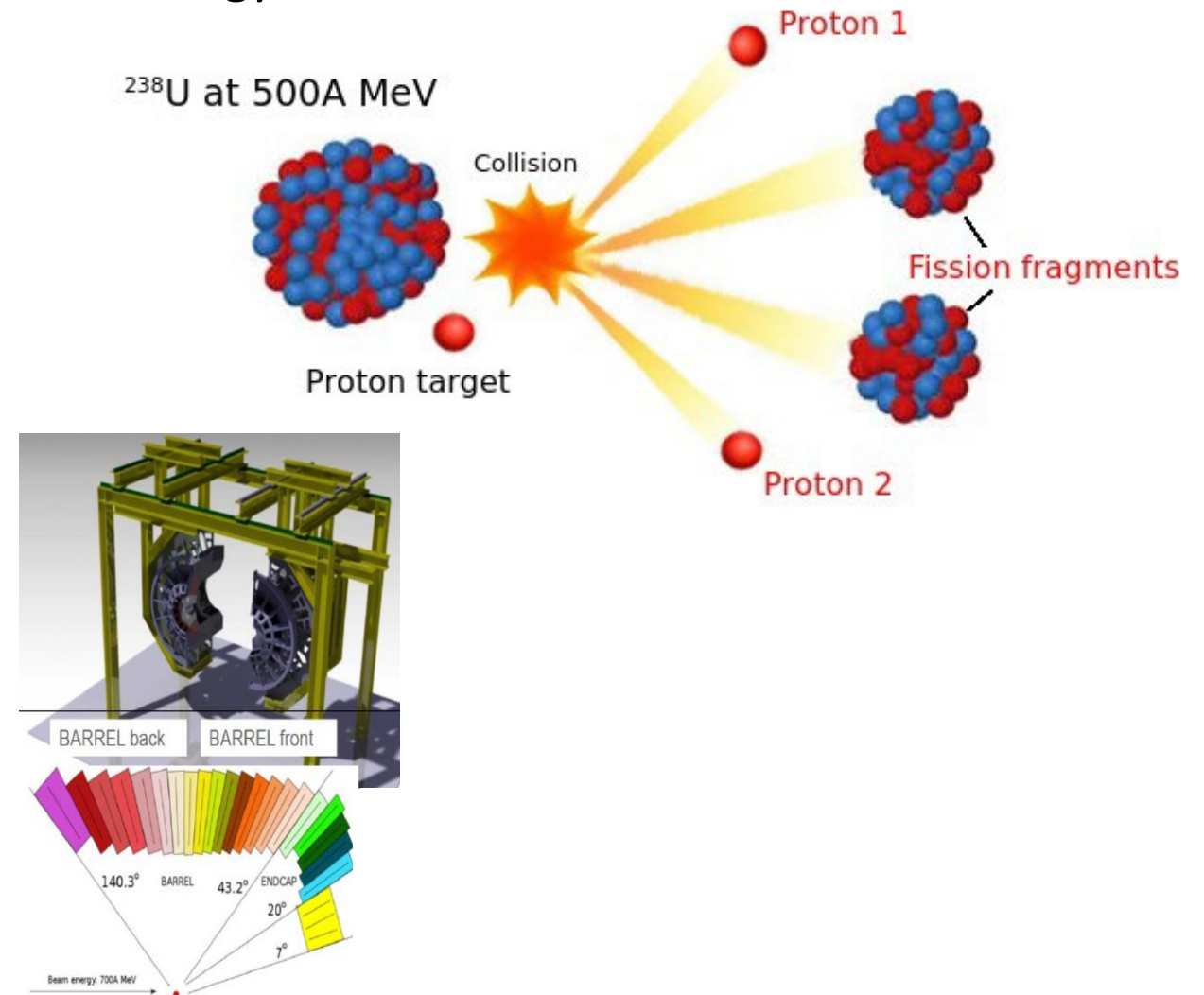
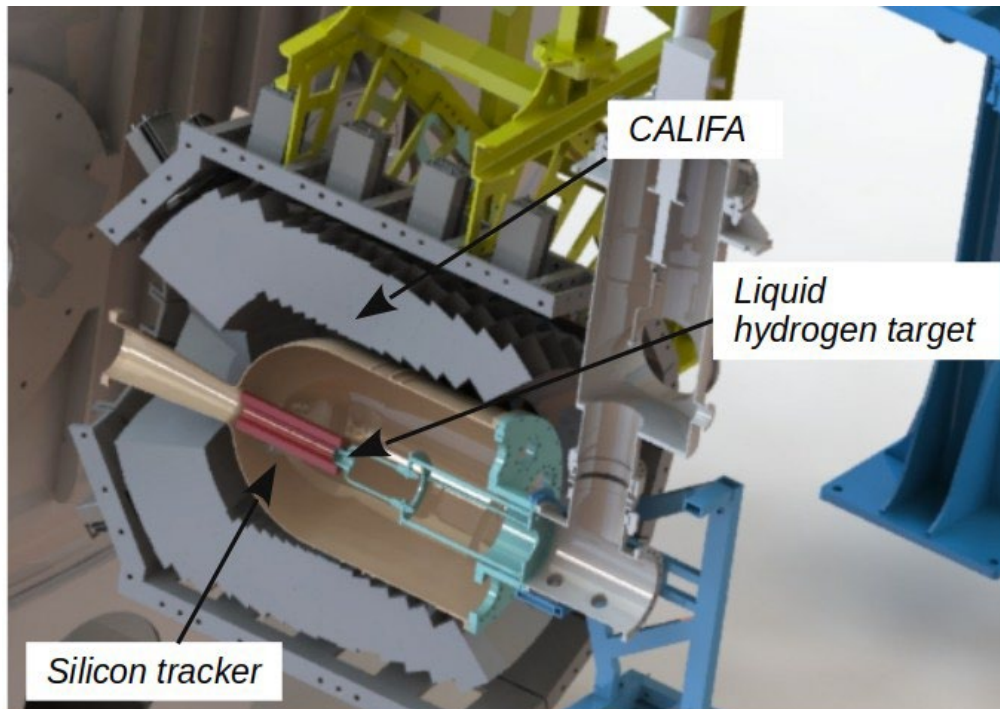
*P. Möller et al., Phys. Rev. C 79, 064304 (2009)*



*H. Alvarez-Pol et al., PRC 82, 041602(R) (2010)*

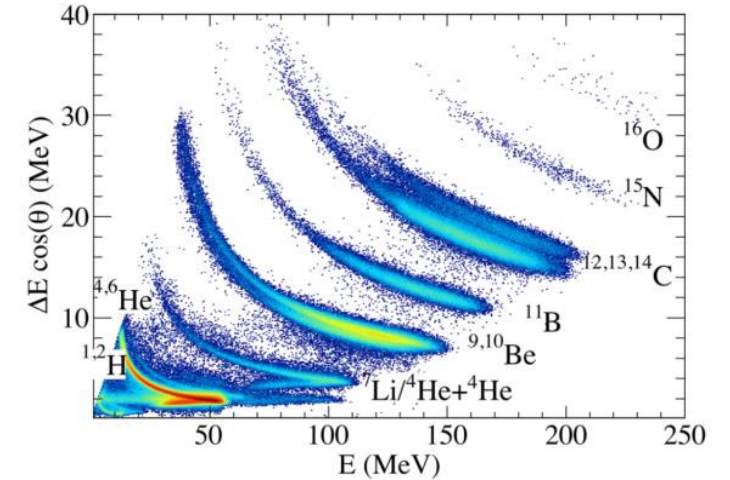
# (p,2p) fission : energy-dependant yields

- Complete kinematics : event-by-event excitation energy
- Liquid H<sub>2</sub> target + Califa calorimeter
- Aim : 2 MeV FWHM on E\*
- Low cross section (/100 w.r. GDR)



# GANIL activities: fission@VAMOS

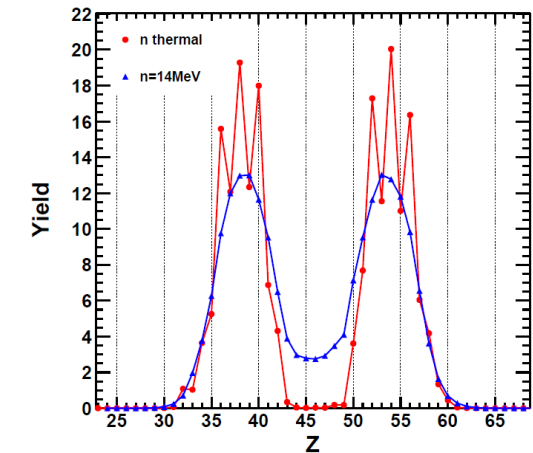
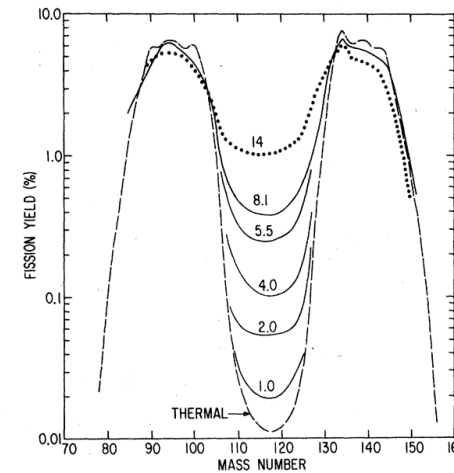
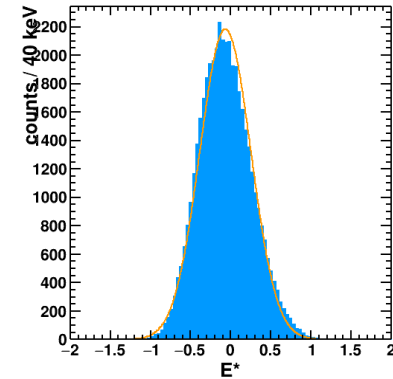
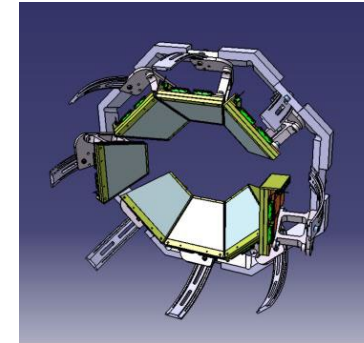
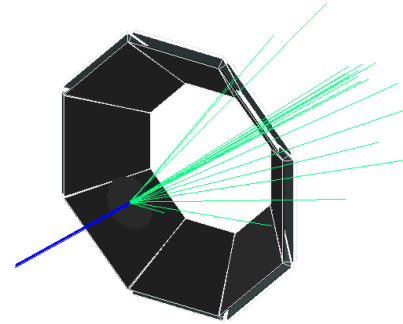
- Transfer-induced fission experiments
- Full identification of one fragment only
  - Kinematics reconstruction allows to bypass this
- Estimation of excitation energy (event-by-event)
- Previous campaigns :  $^{238}\text{U}$  primary beam, SPIDER Si array, VAMOS
  - Successful measurements, plenty of papers
  - Limited resolution in energy, limited statistics



D. Ramos *et al.* Phys. Rev. C  
97054612 (2018)

# GANIL activities: fission@VAMOS

- New PISTA Si array
  - Improved segmentation and resolution
  - Expected  $E^*$  resolution : 750 keV (FWHM)
- Latest improvements of VAMOS
- $^{232}\text{Th}$  beam
- Measurement of the dampening of shell effects
  - Long-pending theory question
  - Improvement of yields prediction in fast systems
  - High-quality data on  $^{236}\text{U}^*$  and  $^{240}\text{Pu}^*$
- Measurement of the Th region
  - High-quality data on  $^{234}\text{U}^*$
  - Rapidly-changing fragment split



# Outlook and status : NACRE in general / the 2.1.2 action

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- + NACRE is very useful for scientific animation
- + Helps the activity to be “readable” at the IN2P3 level
- Doesn't provide political traction (nTOF...)
- Good money, but not enough

Concerning the action, future is a bit blurry at the moment !

- No activity related to NACRE at GSI in 2023
- Possible experiment in 2024
- GSI/FAIR transition : SFRS / Pu beam experiments in 2026+ ...?
  
- Accepted proposals at GANIL
  
- Change of the action perimeter, new NACRE action...?