Fission yields measurements and fission study in inverse kinematics

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on behalf of the SOFIA collaboration

Fission fragment yields : applied and basic physics

- FF impact the reactor neutronics :
  - Delayed neutrons, neutronic poisons
  - Increased influence with larger burn-ups (30 MWd/T originally, then 60... 90 tomorrow?)
  - Criticity excursions : quick accumulation of FF
- FF are the main source of residual power and radioactivity :
  - Shielding for used fuel handling and reprocessing
  - Loss Of Coolant Accident (LOCA)
- Decay heat simulations require better fragment yields

- FF are also a remarkable probe for nuclear structure
  - N- and Z-shell effects on fission partition
  - Shell effects at large deformation
  - Influence of the pairing : even-odd staggering in the yields
  - Distribution of the fission energy : fragments deformation

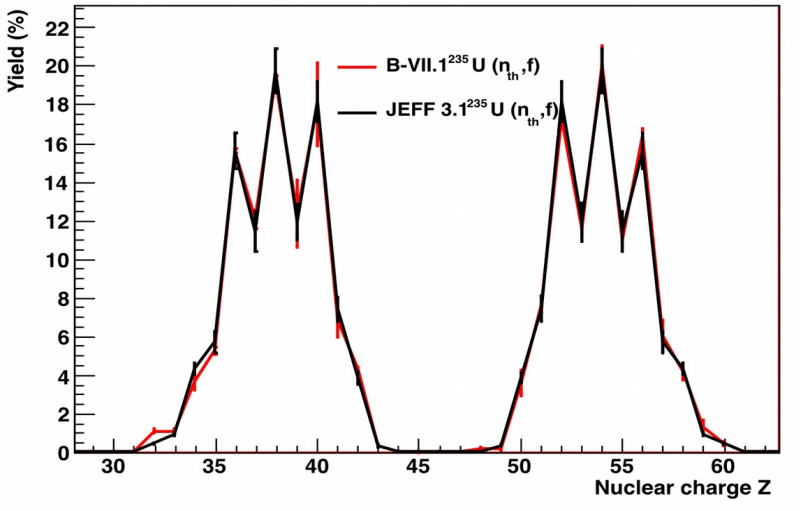
Fission modes in the actinides region

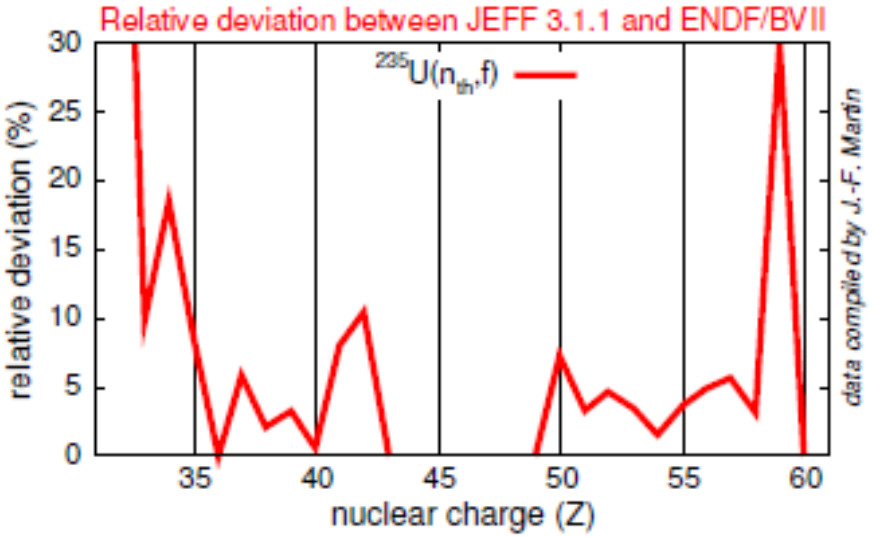
- 3 fission modes in the U region :
  - 2 asymmetric modes
  - 1 symmetric mode
  - Each mode is associated to different scission configurations
  - The Total Kinetic Energy (TKE) is a good probe of these configurations

standard 1 (ST1)	standard 2 (ST2)	superlong (SL)
○ asymmetric 2ndhamp	○ asymmetric 2ndhamp	○ symmetric 2ndhamp
○ short path: compact	○ long path	○ large elongation
○ quasi-spherical heavy FF	○ deformed heavy FF	○ less shell influence (LDM)
$\Rightarrow A_H \sim 132, Z_H \sim 50, N_H \sim 82$	$\Rightarrow A_H \sim 140, Z_H \sim 54, N_H \sim 88$	○ increases with E*
HIGH TKE	INTERMEDIATE TKE	LOW TKE

Where are we now ?

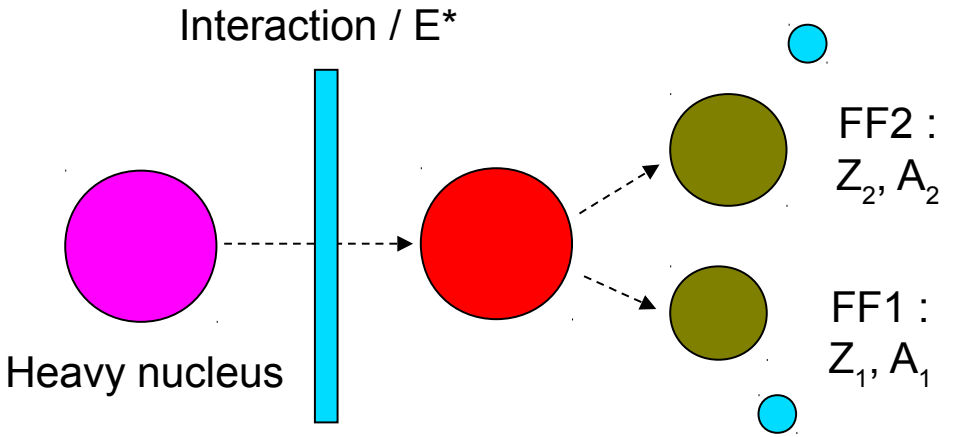
- Data are generally imprecise and/or limited
- Only a handful of fissioning systems were studied
- Even for the most-studied system $^{235}U(n_{th},f)$: 10% uncertainties





- Direct kinematics measurements face limitations :
  - Large-Z yields can hardly be measured (kinetic energy)
  - Only a few actinides can be used as targets

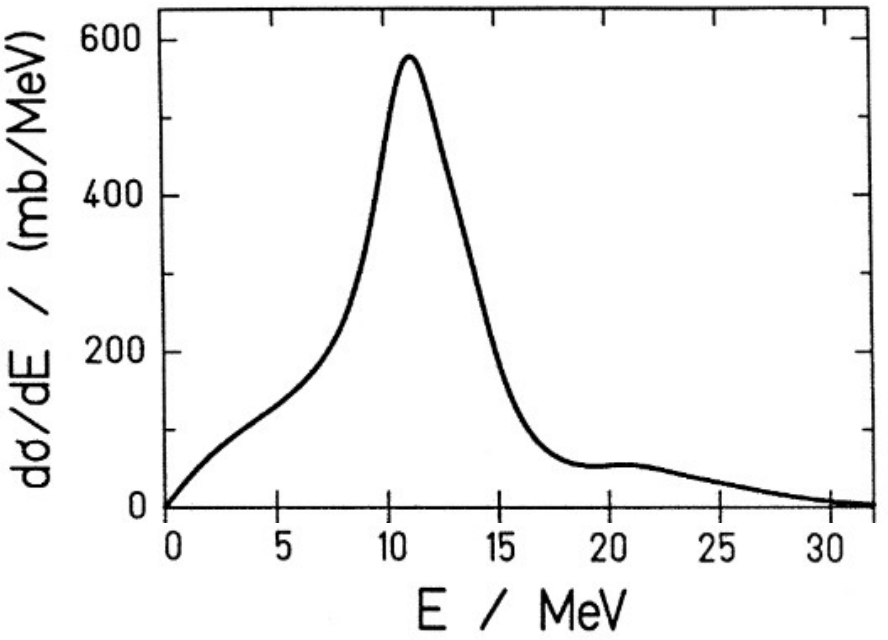
Inverse kinematics



- The actinide is the projectile
- Identification of the fragments in a recoil spectrometer
- Secondary beam : tens of different nuclei become accessible
- No neutron target :
  - Collision : large average E* for a relativistic beam
  - Transfer : reduced beam energy, only 1 fragment in the spectrometer
  - Electro-magnetic interaction : relativistic beam, 100% acceptance
- Pioneer experiment : K.-H. Schmidt et al. (1996) : both FFs, only Z
- 2010s : SOFIA@GSI

Concept and aims of SOFIA

- Identification of both fission fragments : isotopic yields !
  - Nuclear charge
  - Mass number
  - Kinetic energy
  - Deduced total prompt neutron multiplicity
  - Measurement before beta decay
- New recoil spectrometer (Aladin magnet)
- Coulomb-induced fission :
  - Excitation of the GDR (<E> ~ 12 MeV)
  - ^{236}U (gamma,f) ~ ^{235}U ($n_{6\ MeV}$,f)
- Broad range of fissioning systems : actinides and neutron deficient pre-actinides (^{238}U fragmentation)



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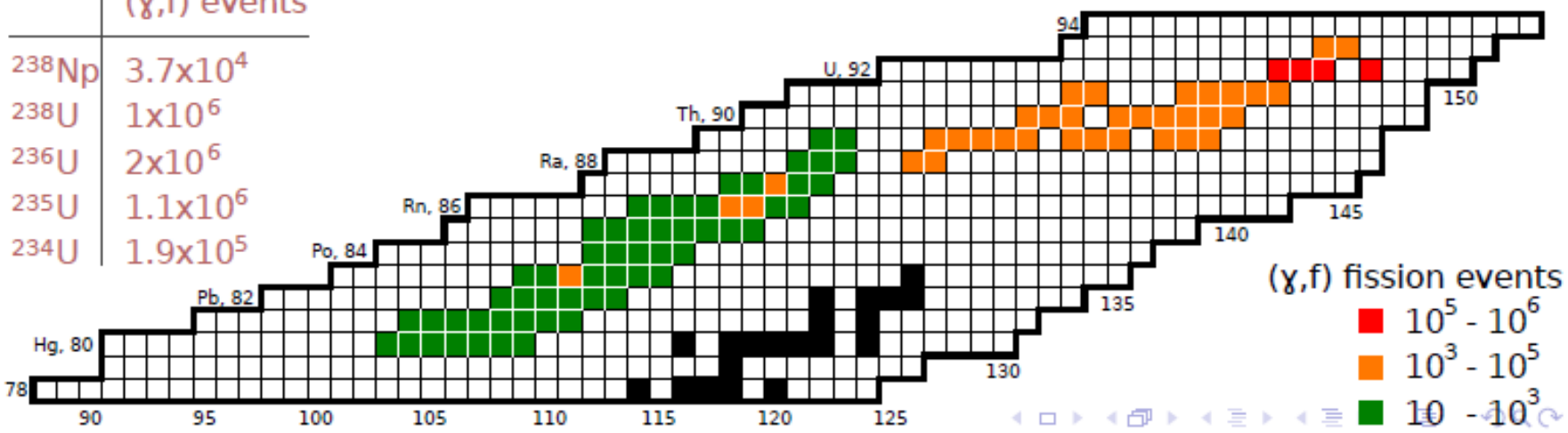
2 campaigns of SOFIA

- First run : 2012
  - Measurement of ^{234,235,238}U and ^{237,238}Np (10^5 – 10^6 fission events per system)
  - Transition from symmetric to asymmetric in $^{221\text{-}230}$Th (10^3 – 10^5 / system)
  - Fission of very neutron-deficient pre-actinides from Hg to Ra : low statistics (10 – 10^3 / system)
- 2014 run : main objective → ^{236}U
  - Improved set-up to get high statistics : 2.10^6 fission events (in 20 hours only!)
  - Few hours devoted to lighter nuclei for calibration purpose

	(γ,f) events
^{238}Np	3.7×10^4
^{238}U	1×10^6
^{236}U	2×10^6
^{235}U	1.1×10^6
^{234}U	1.9×10^5



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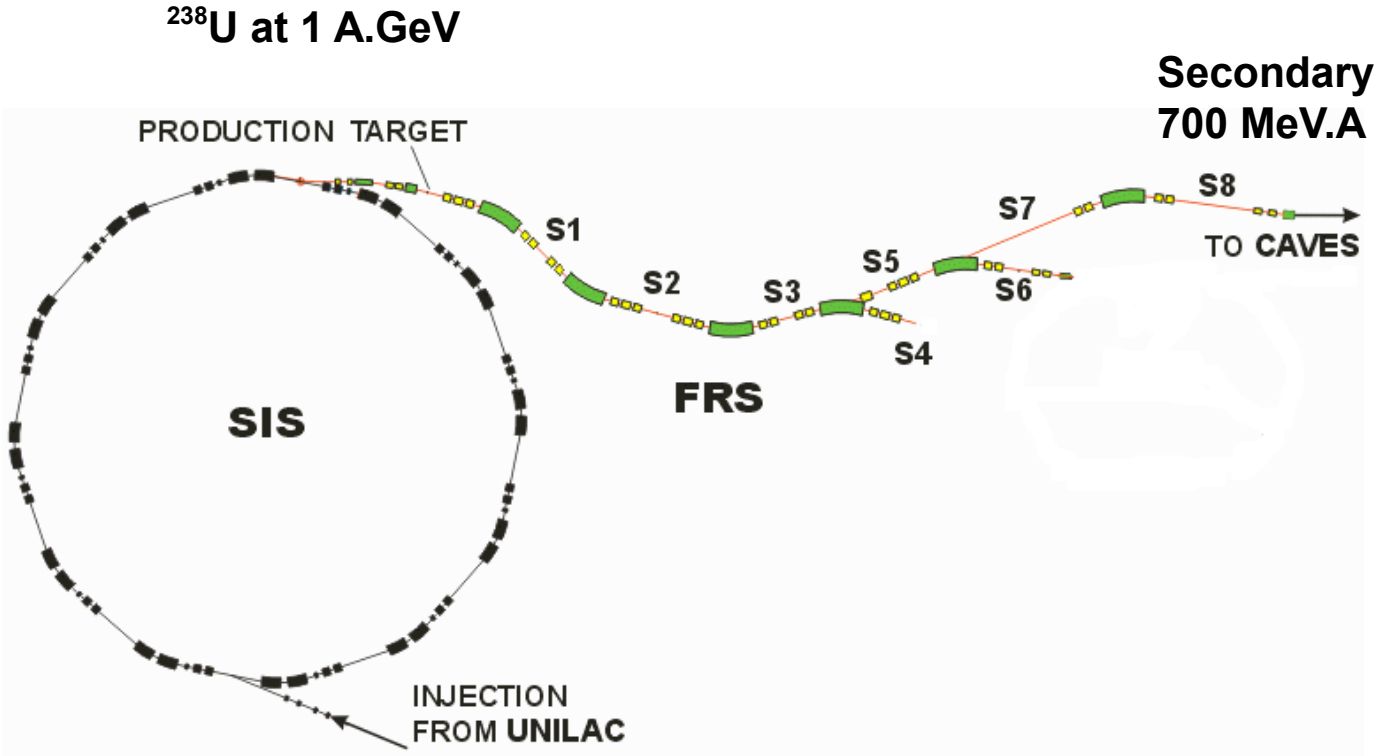
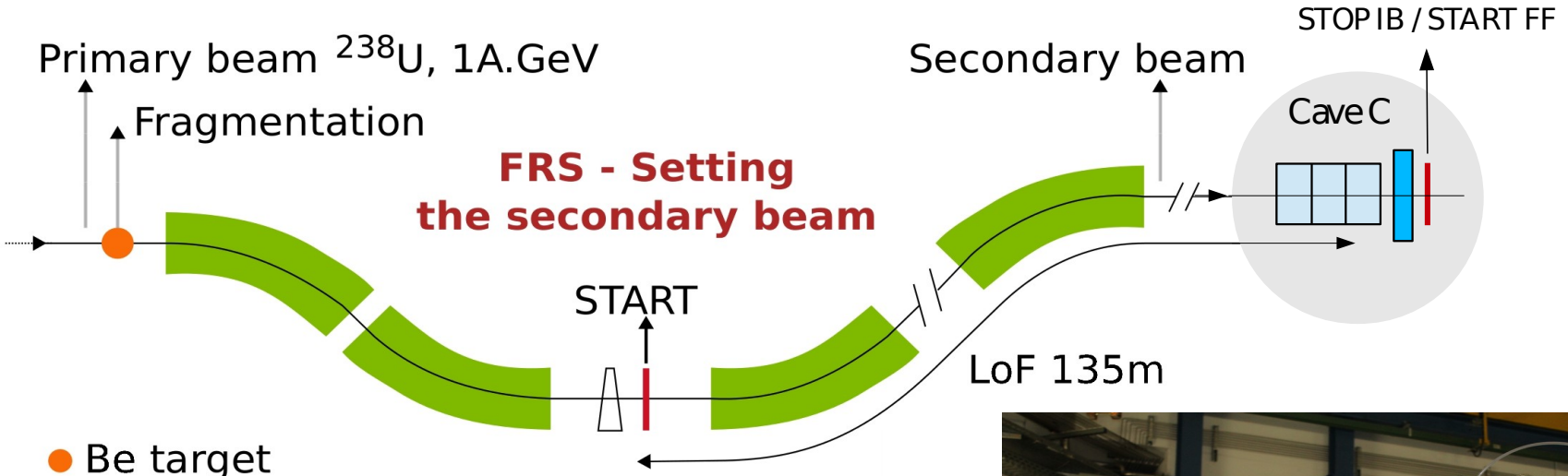
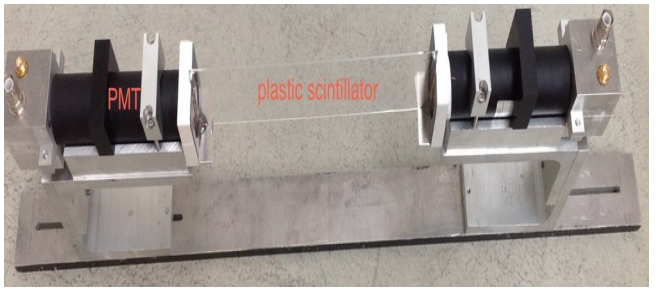
Secondary beam production

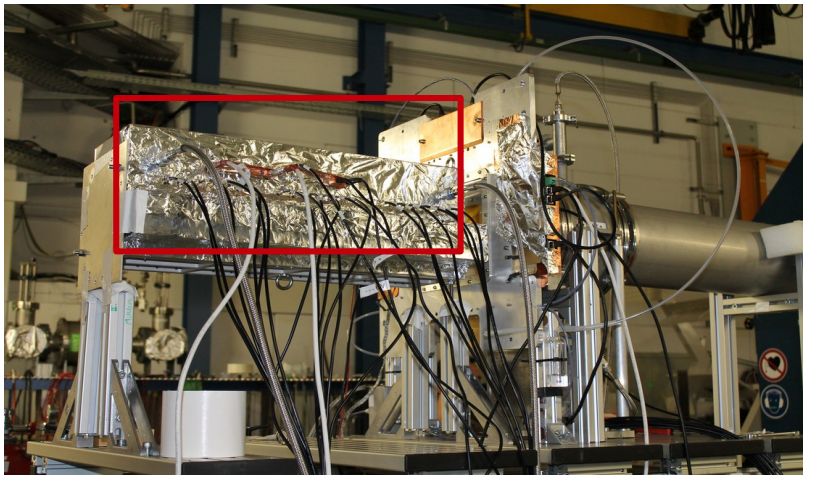
- Fragmentation of ^{238}U on Be target
- Selection and identification of the secondary beam in the FRagment Separator (FRS)



Secondary beam identification: 2014 setup

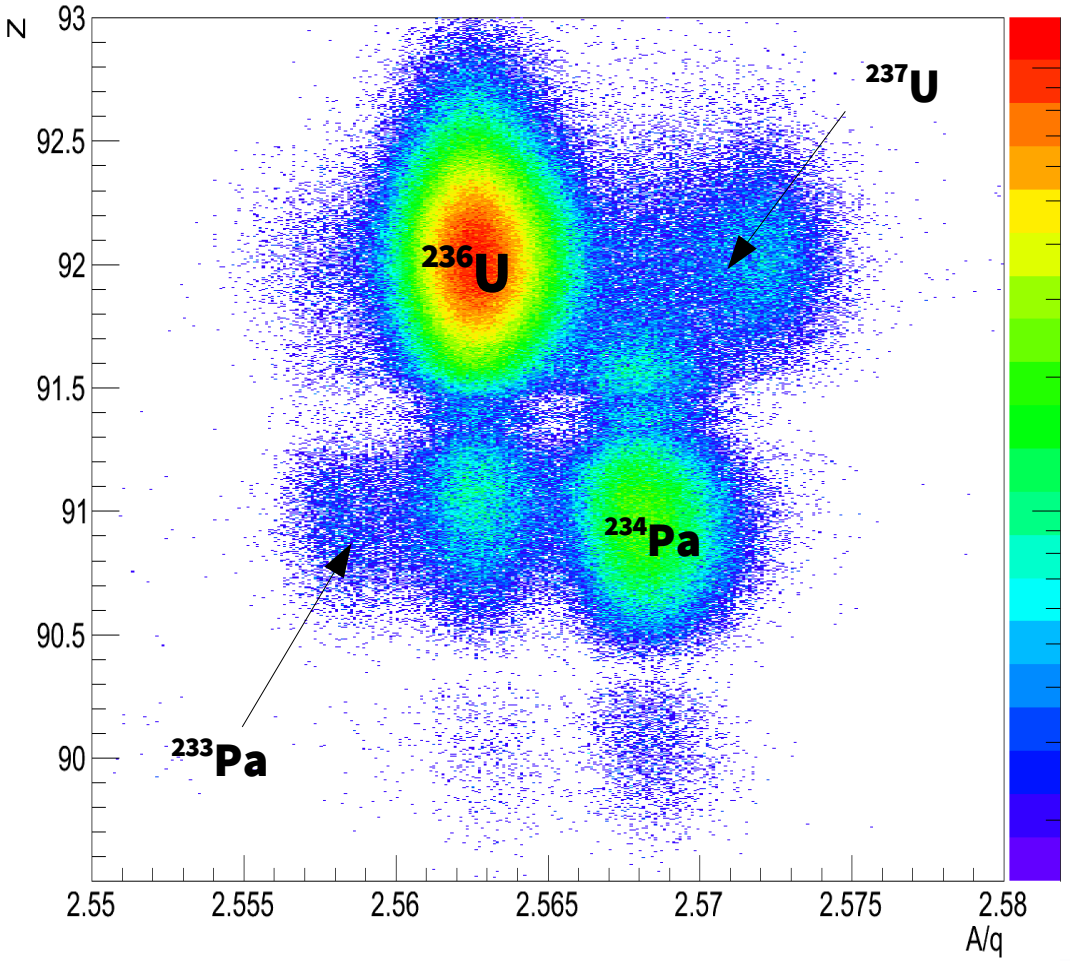


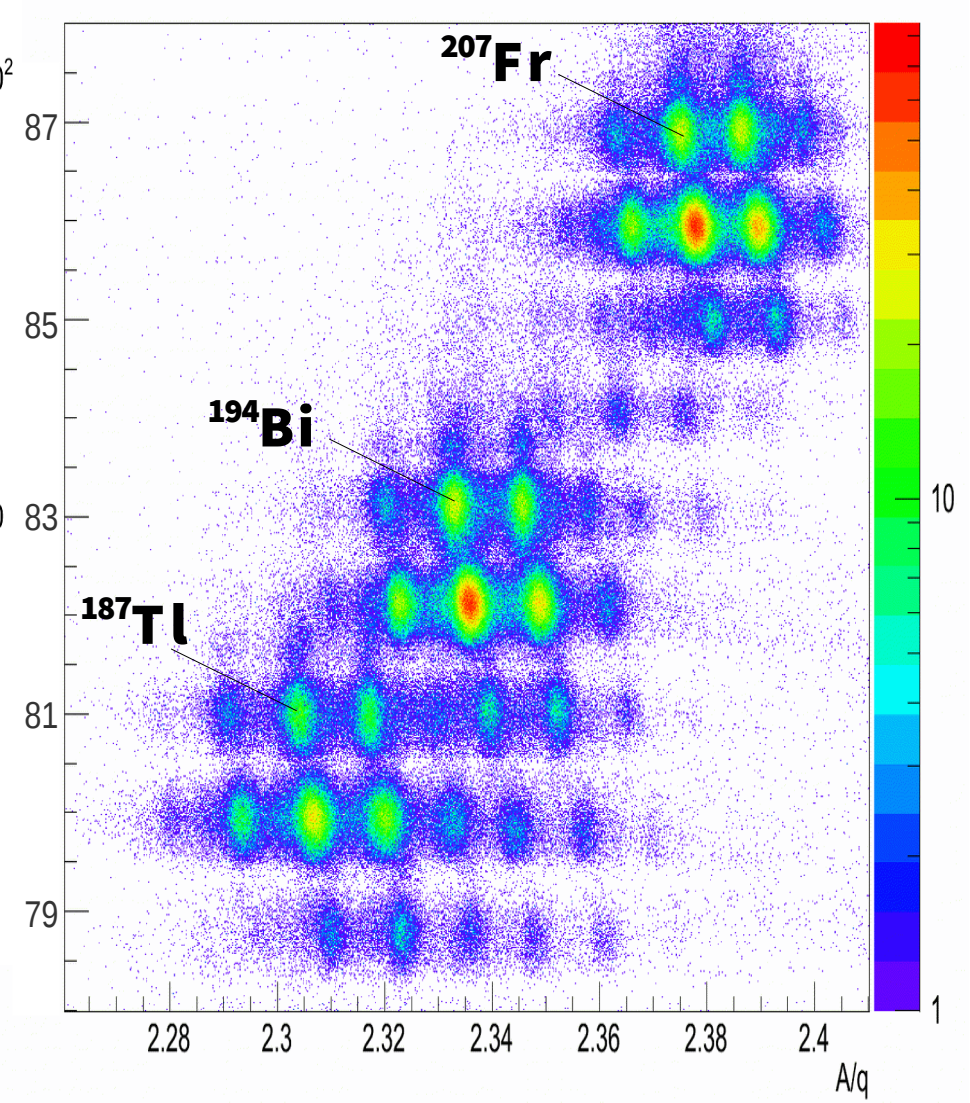




- Standard Bρ – ΔE – ToF method
- High-Z fragments have a large probability to carry electron(s)

Secondary beam identification: 2014 results





Analysis : Yiman Yan

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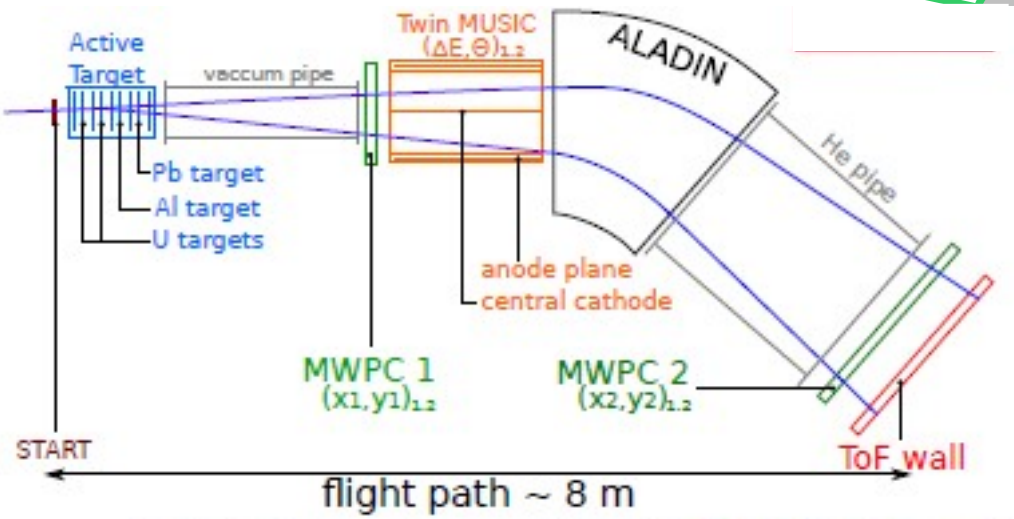
Fission fragments identification

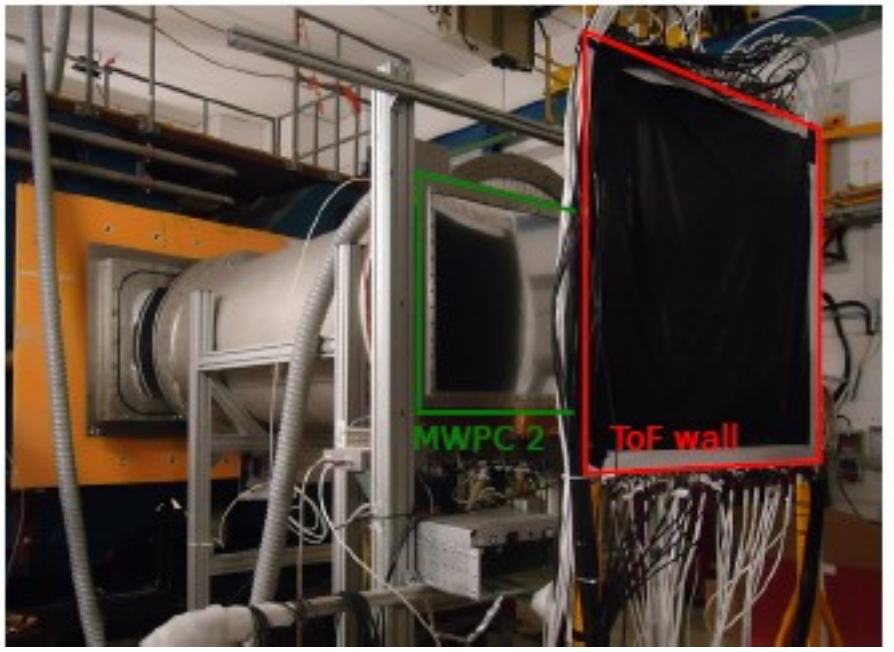
ΔE - Bρ - ToF method
A/Z = Bρ / ßγ

Bρ: position from MWPCs
Θ from the Twin-MUSIC

ΔE: from the Twin-MUSIC

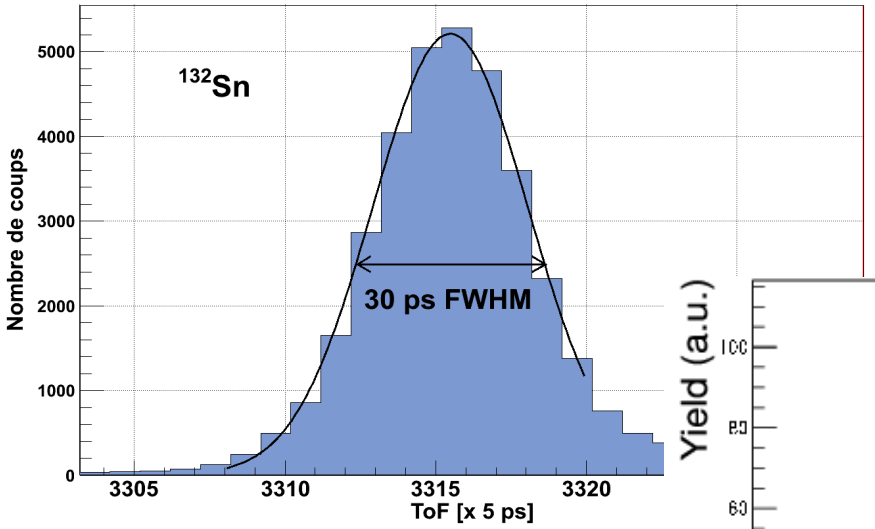
ToF: between START and ToF-wall

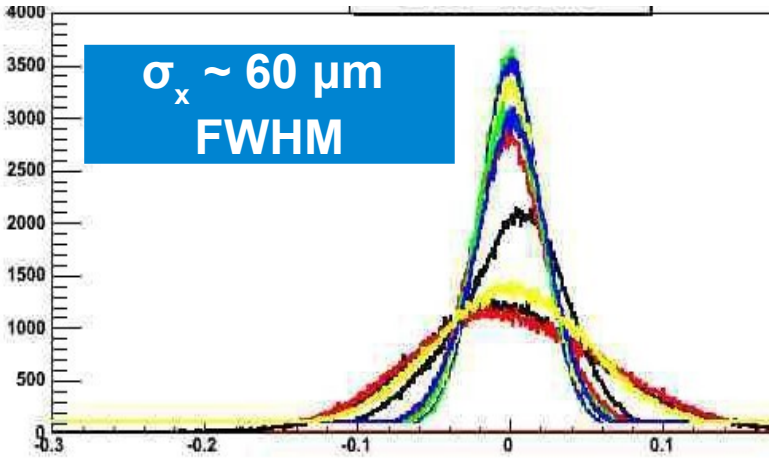


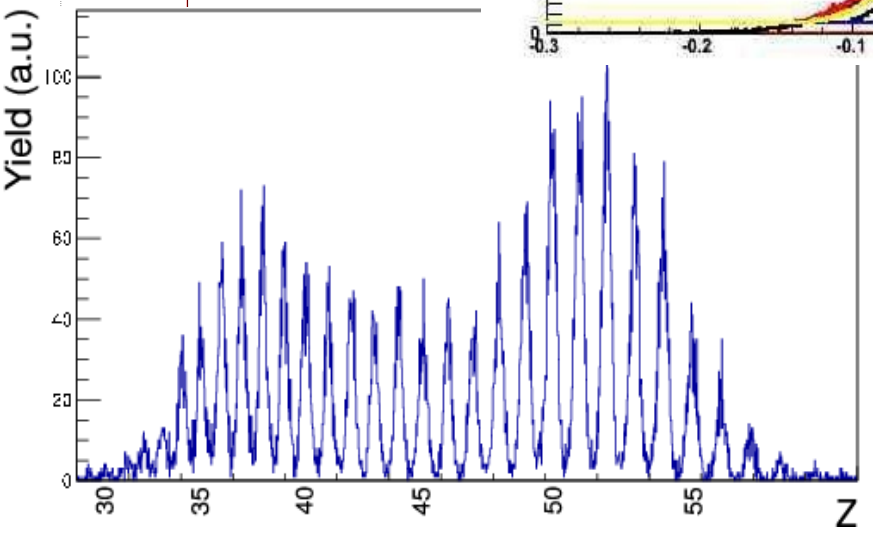


Technical challenges!

- Complete Z discrimination: resolution better than 1% FWHM
- Mass discrimination (Bρ): position resolution < 200 µm FWHM
- The 8 m flight path requires a ToF resolution ~ 40 ps FWHM







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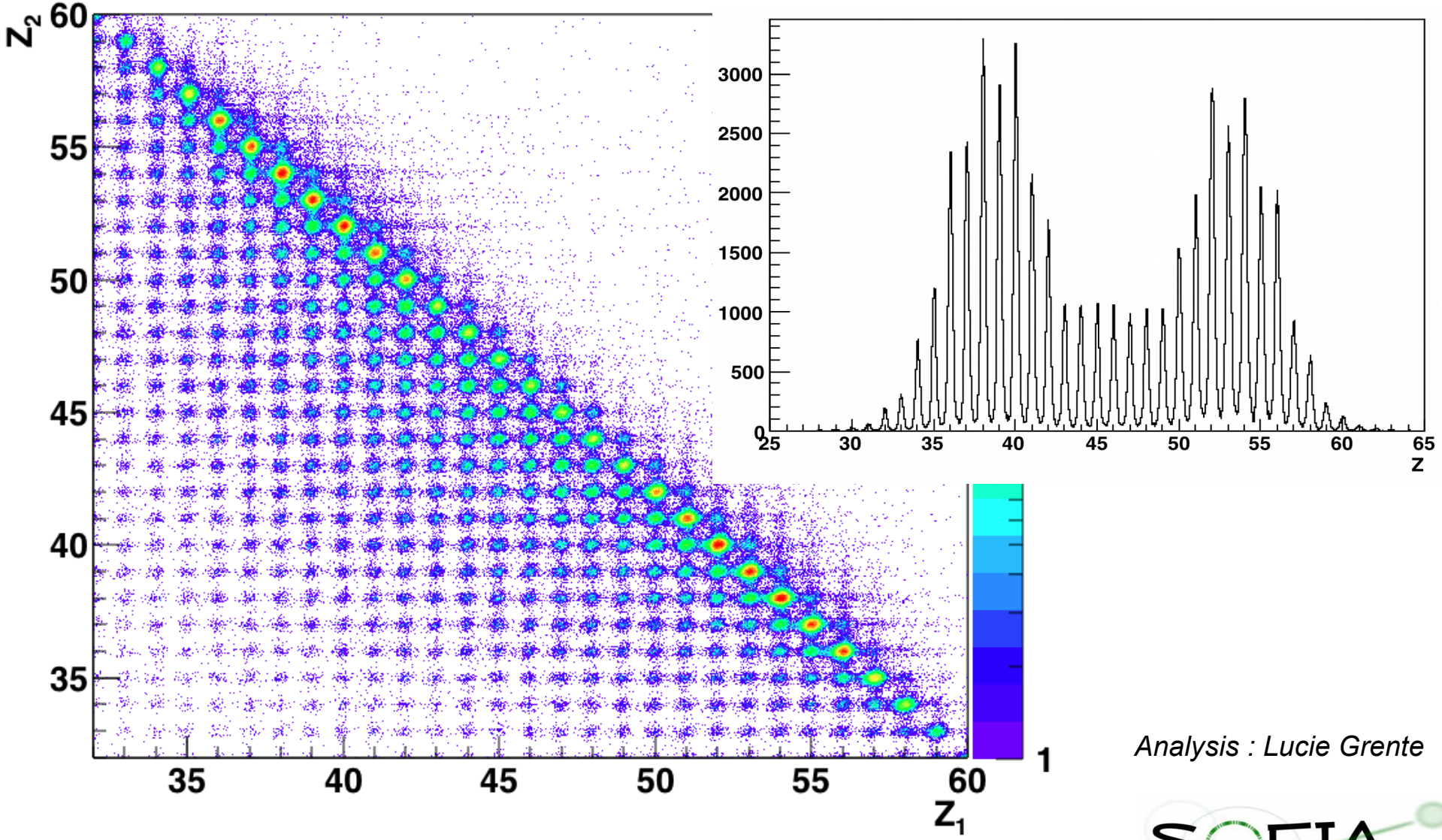
Nuclear charge distribution

- Excellent nuclear charge resolution : δZ = 0,35 FWHM



Analysis : Lucie Grente

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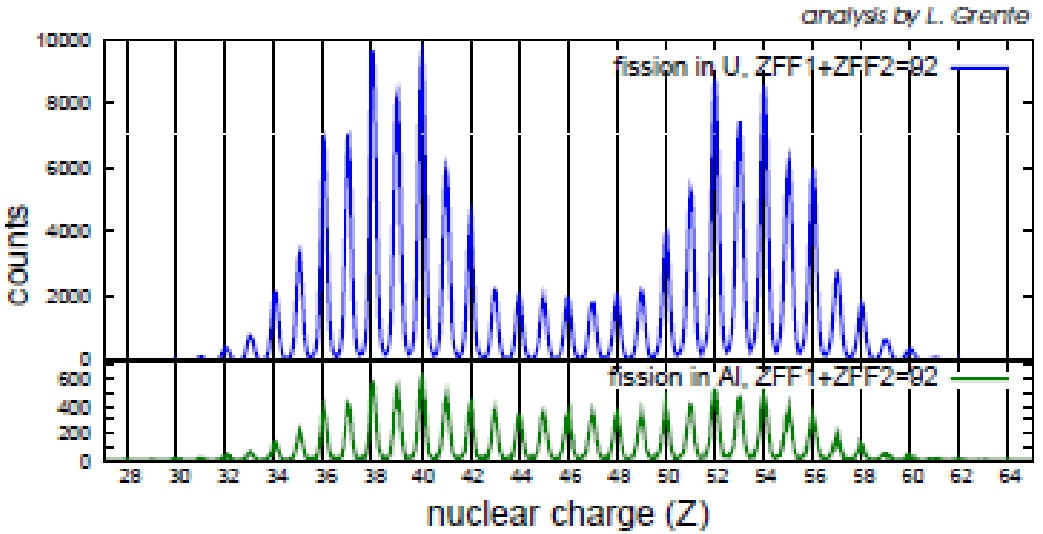
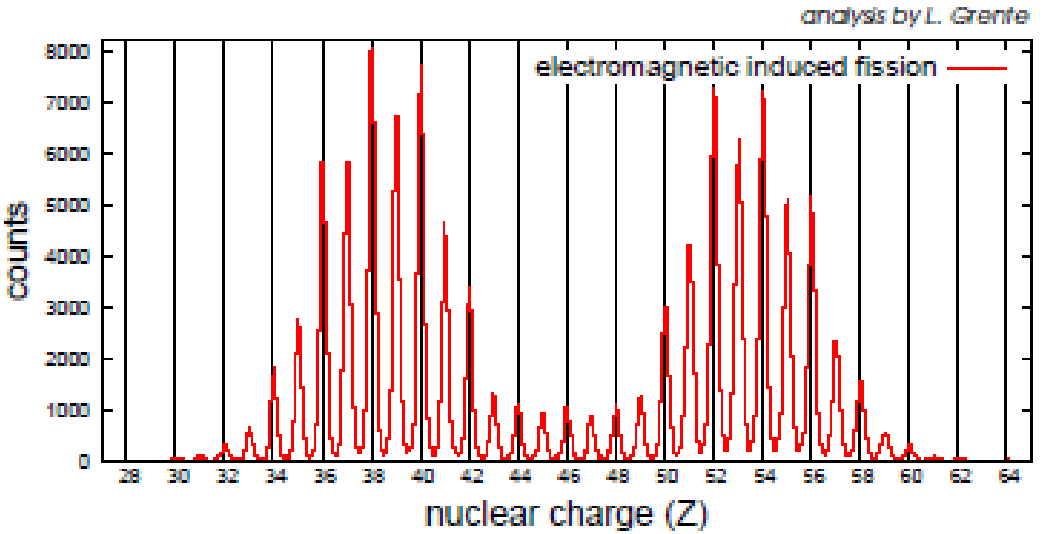
Rejection of the nuclear contribution

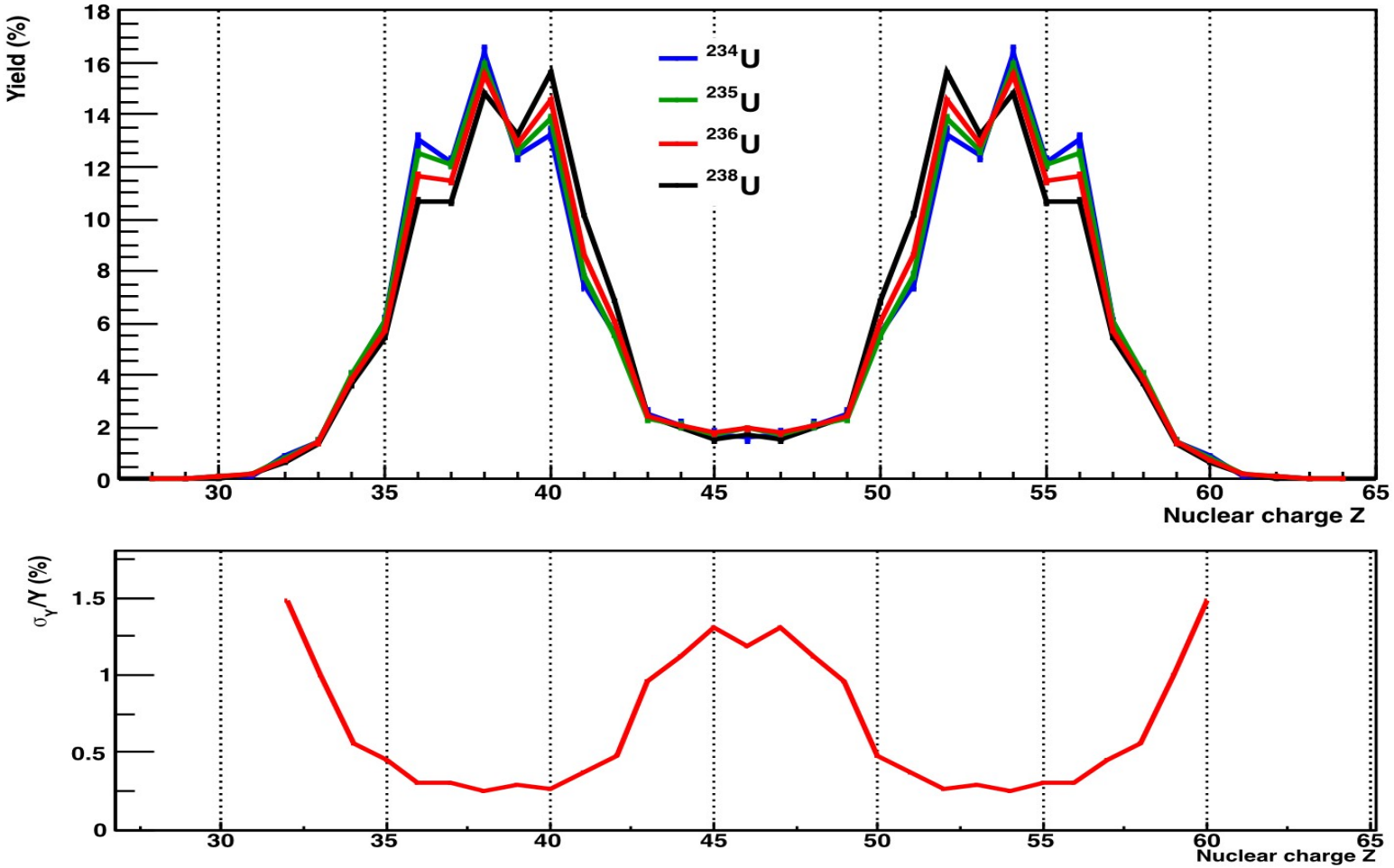
- Selection of events $Z_1+Z_2 = Z_{beam}$
- Limiting fragmentation regime :
  - ✔ The reaction mechanism does not depend on the target
  - ✔ Subtraction of yields obtained on Al target (renormalization)





Charge yields and proton even-odd effect : U

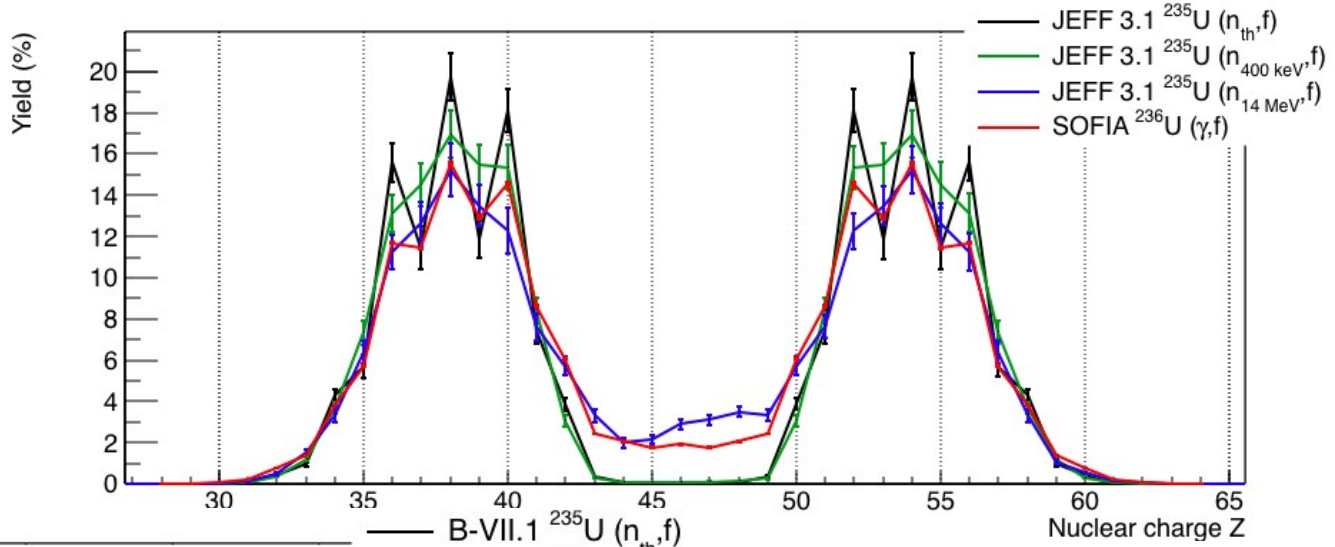
- Unprecedented resolution
- Role of ST1 (heavy fragment around ^{132}Sn) increases with mass

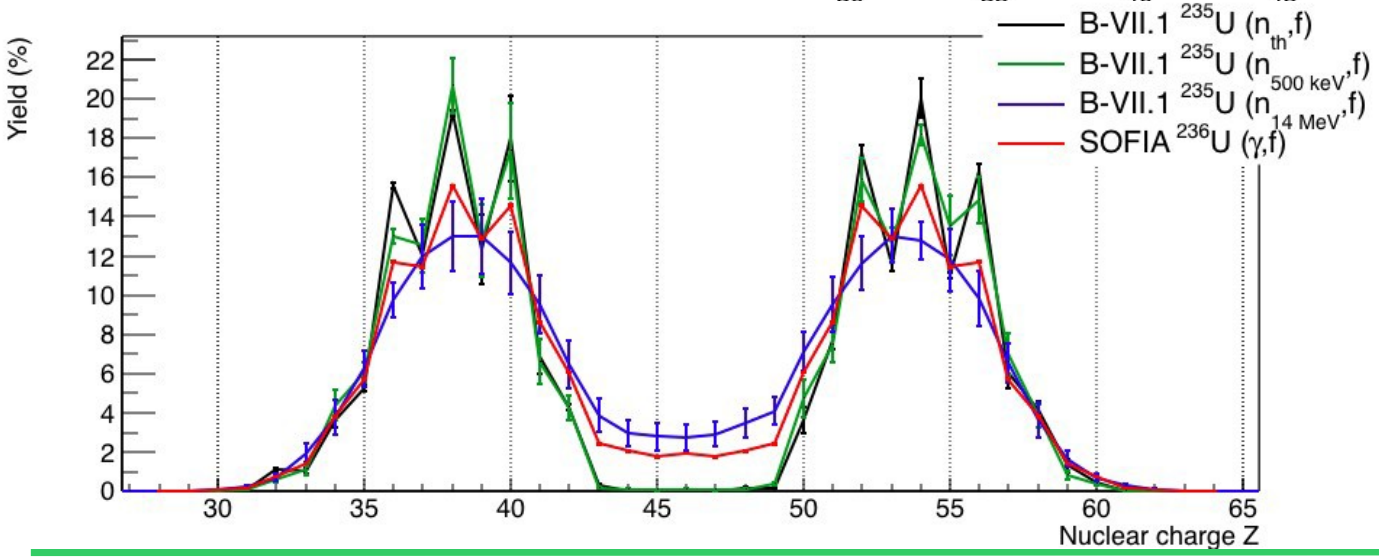


Analysis : Eric Pelereau, Julie Martin, Lucie Grente

Comparison to libraries

- Underestimation of e-o effect at 400 keV in JEFF
- High-energy damping of e-o effect too strong in ENDF





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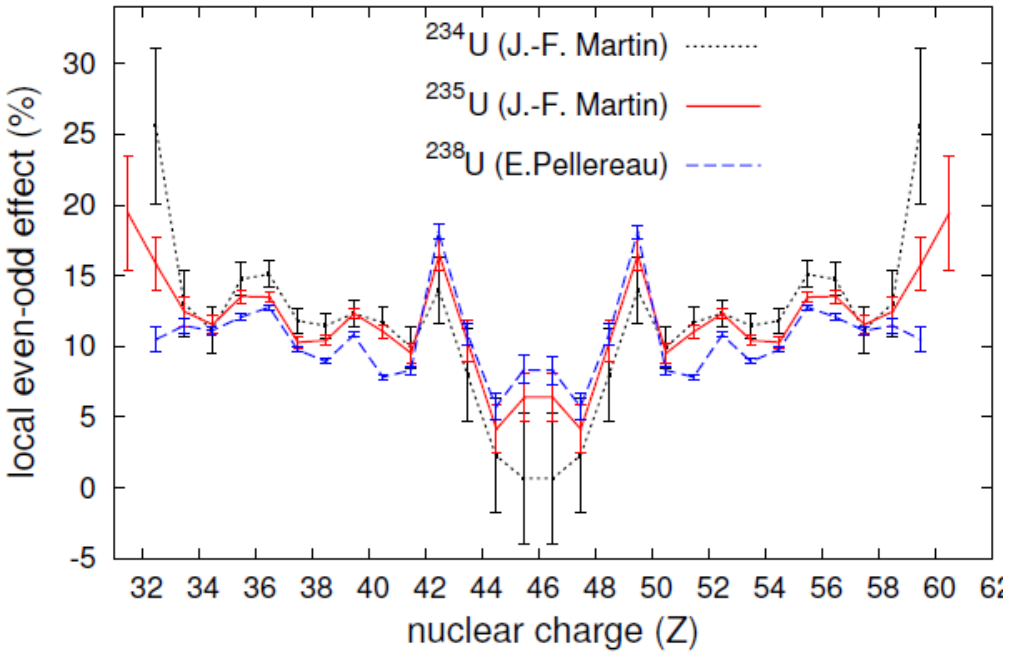
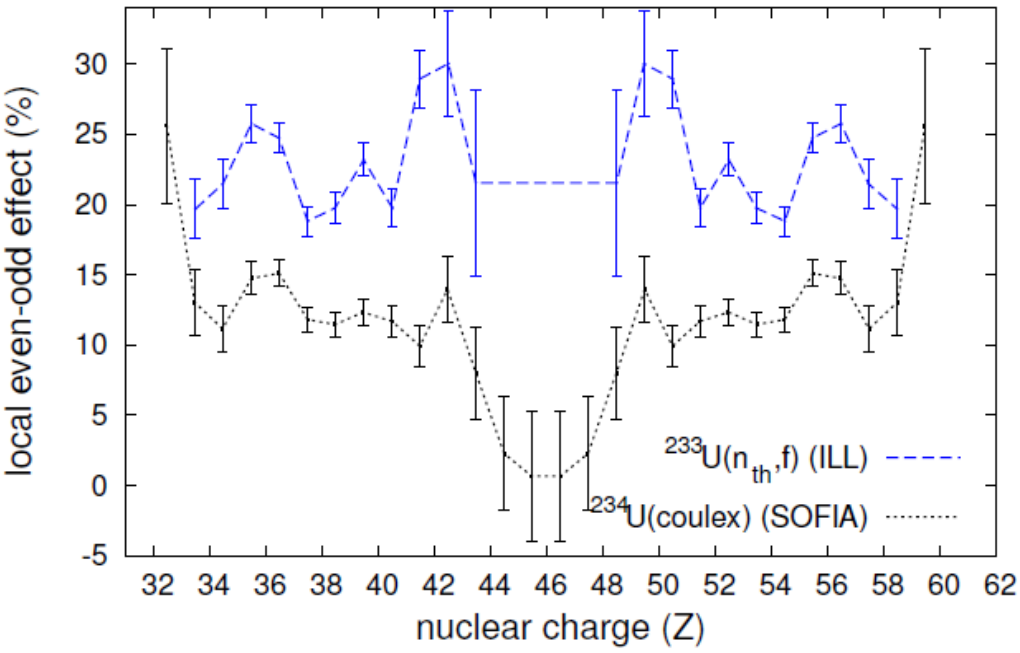
Protons even-odd effect : systematics

- Varies weakly with the mass of the system
- Slight increase with asymmetry in SOFIA data
- Reduced by increasing excitation energy





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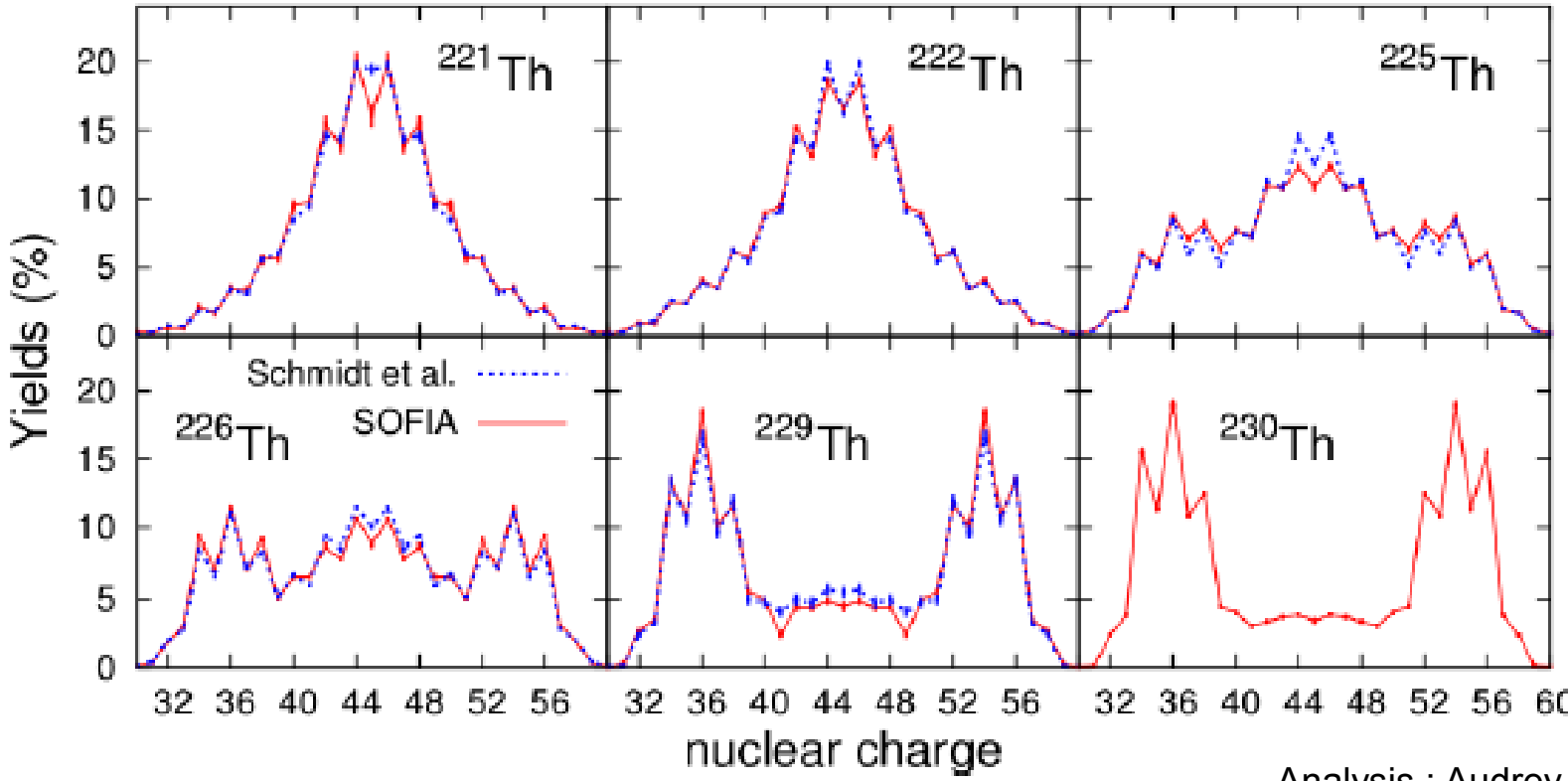
Charge yields and proton even-odd effect : Th

- Transition from asymmetric to symmetric splitting
  - Enhancement of the 36-54 splitting in asymmetric cases
- Strong even-odd staggering even for symmetric splitting
- Excellent agreement with Schmidt et al.



Analysis : Audrey Chatillon

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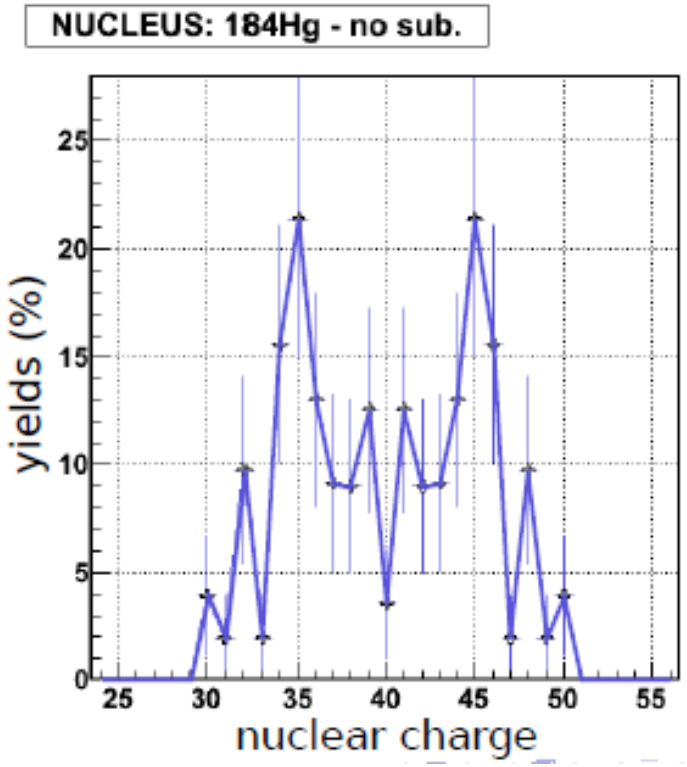
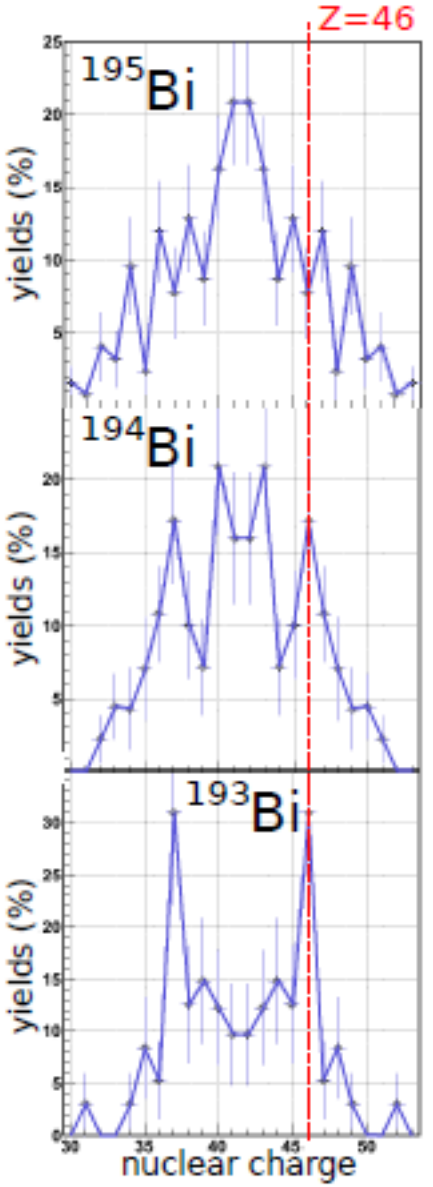
Charge yields and proton even-odd effect : Bi & Hg

- Confirmation of asymmetric fission in Hg
- Transition in Bi, much faster than in Th
- 46-37 strongly favored in light Bi isotopes
  - Shell effect for Z = 46 in neutron-deficient region ?

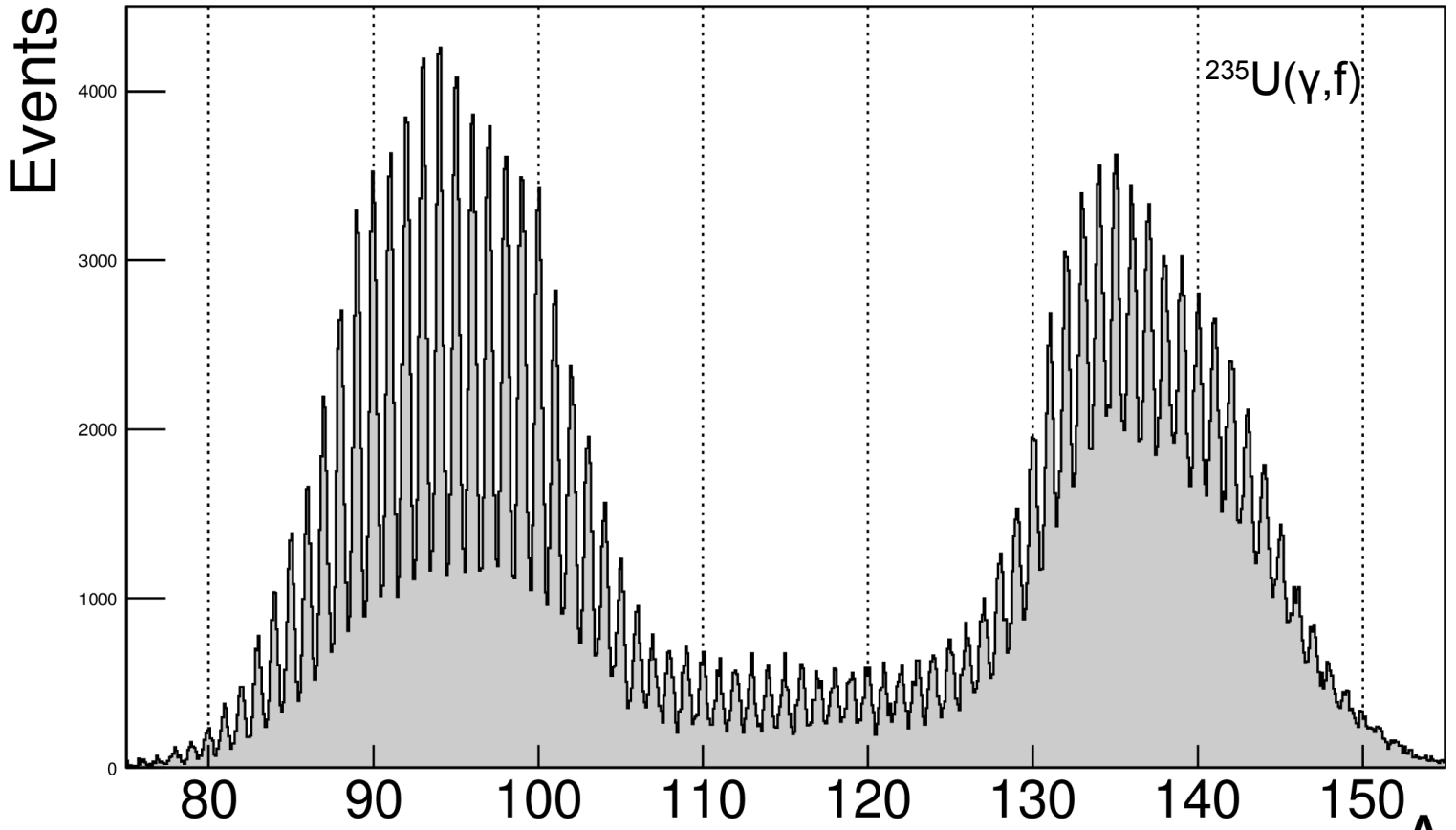




Analysis : Thomas Gorbinet

Mass separation

- Unique performance in ToF and position measurement
- Mass resolution : 0.6 to 0.8 FWHM
- Statistical uncertainty 1.6% to 3%



Analysis : Julie Martin

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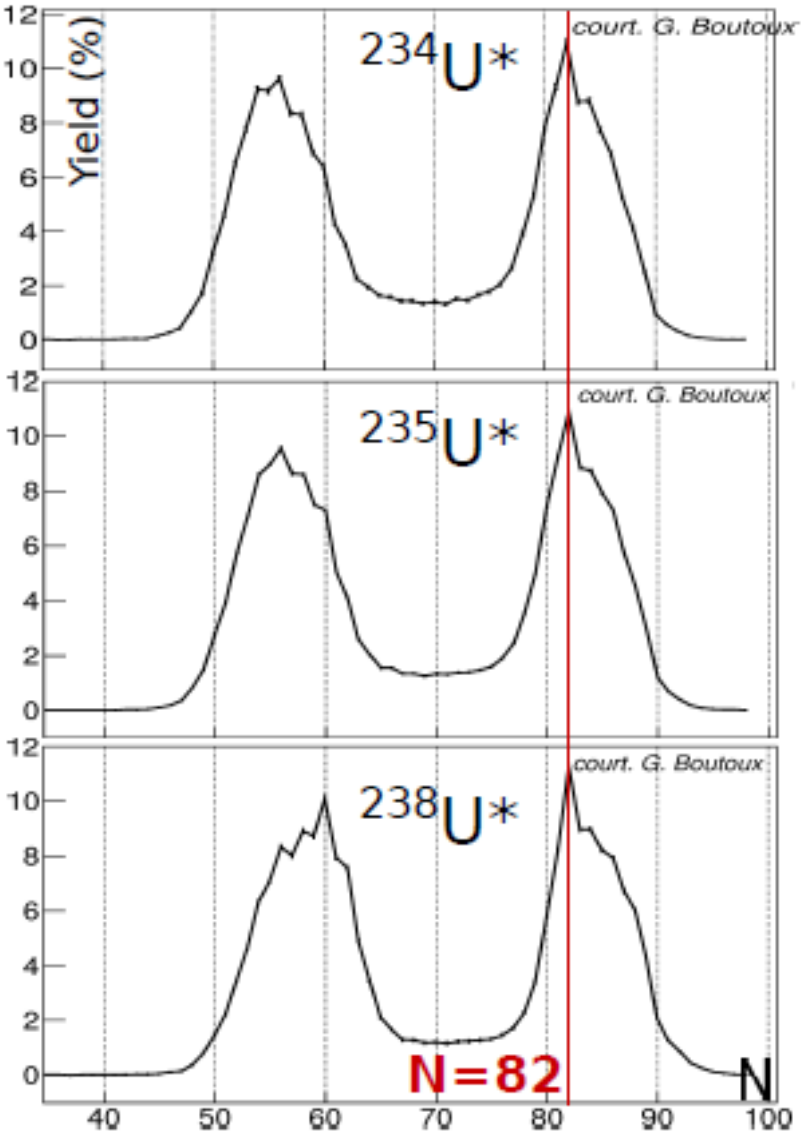
Isotonic yields

- N=82 is a driving force in scission
- Limited even-odd effect



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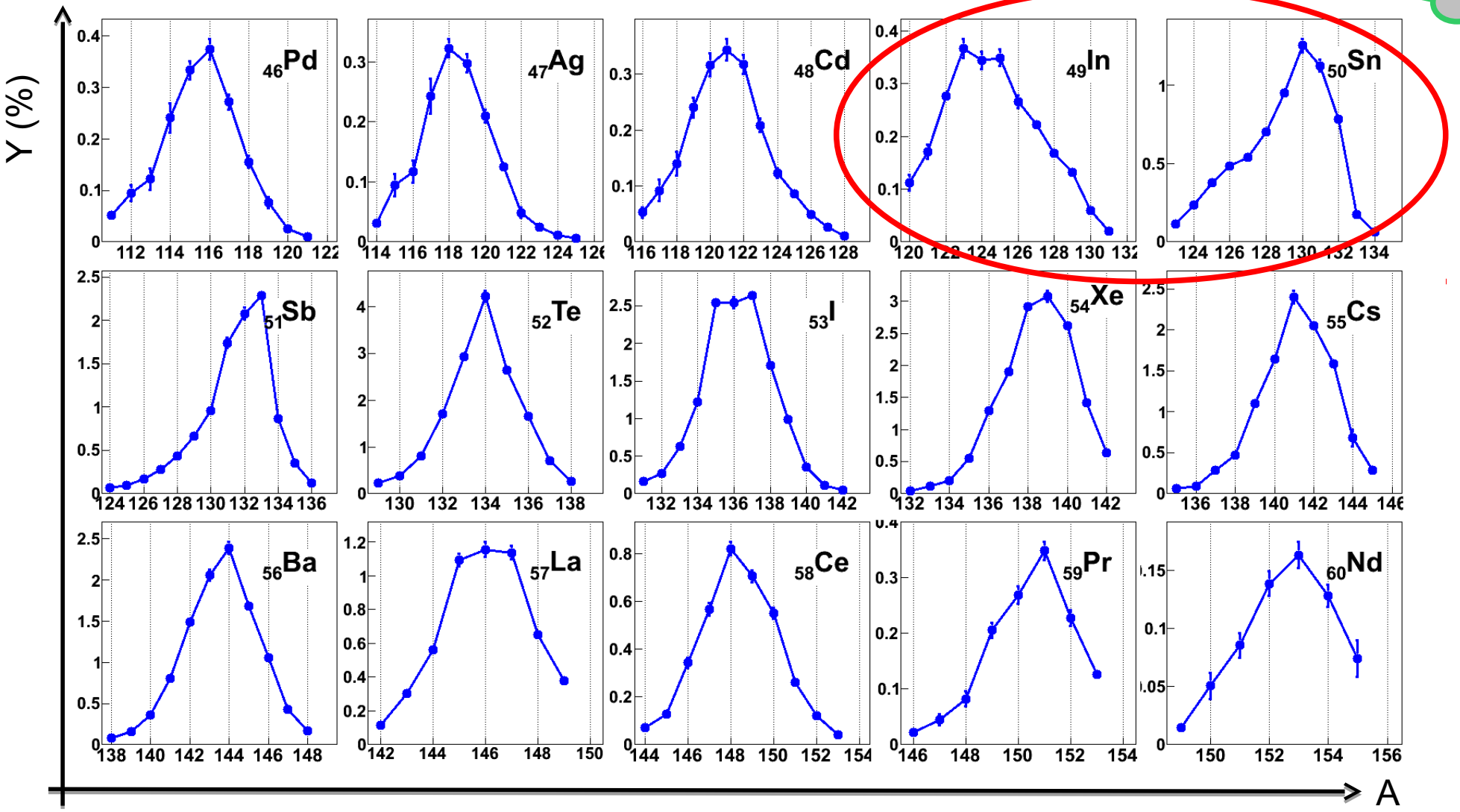
Isotopic distributions



- Dramatic change in favored fission mode : SL to ST1

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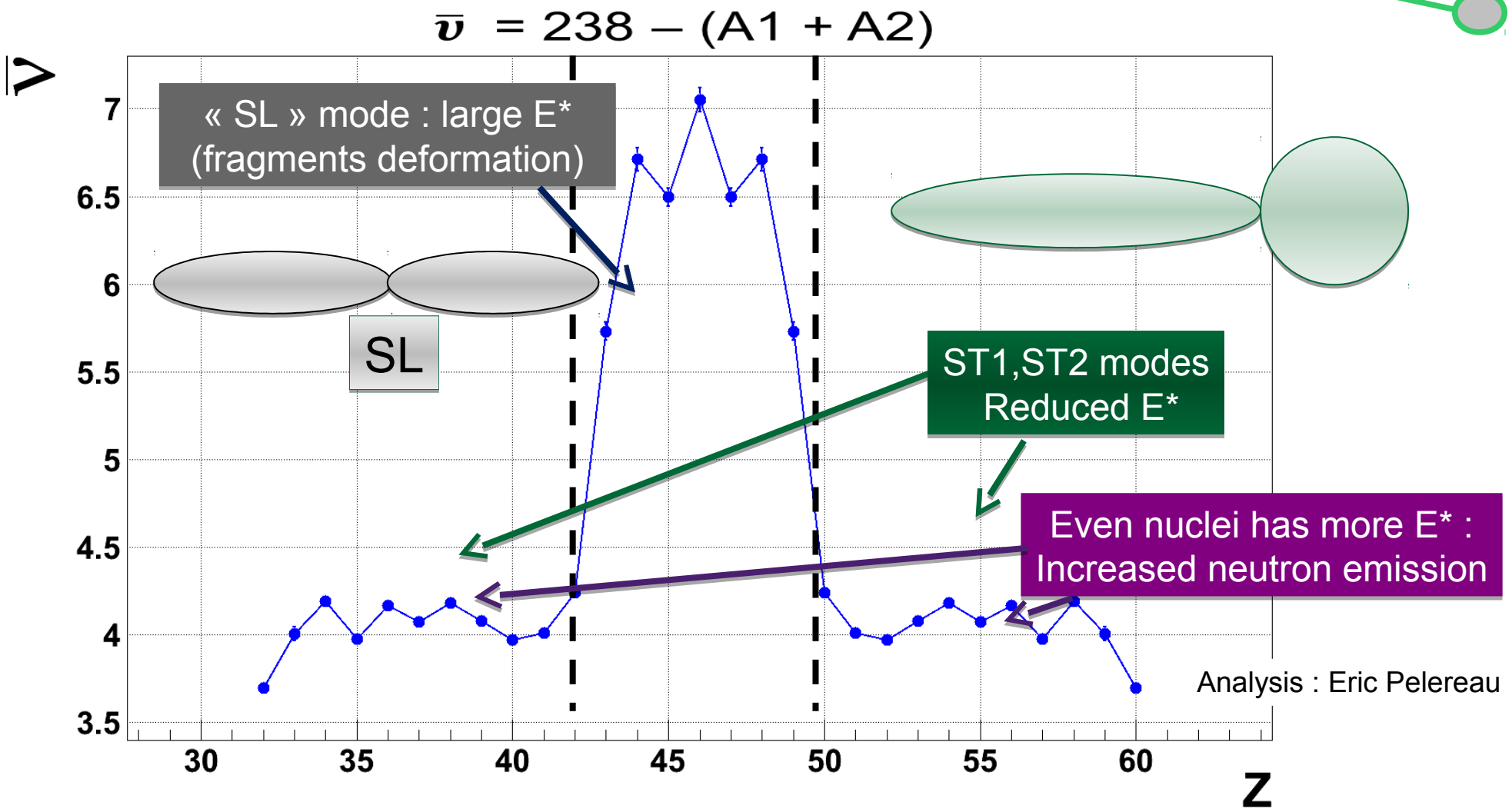
Prompt neutrons

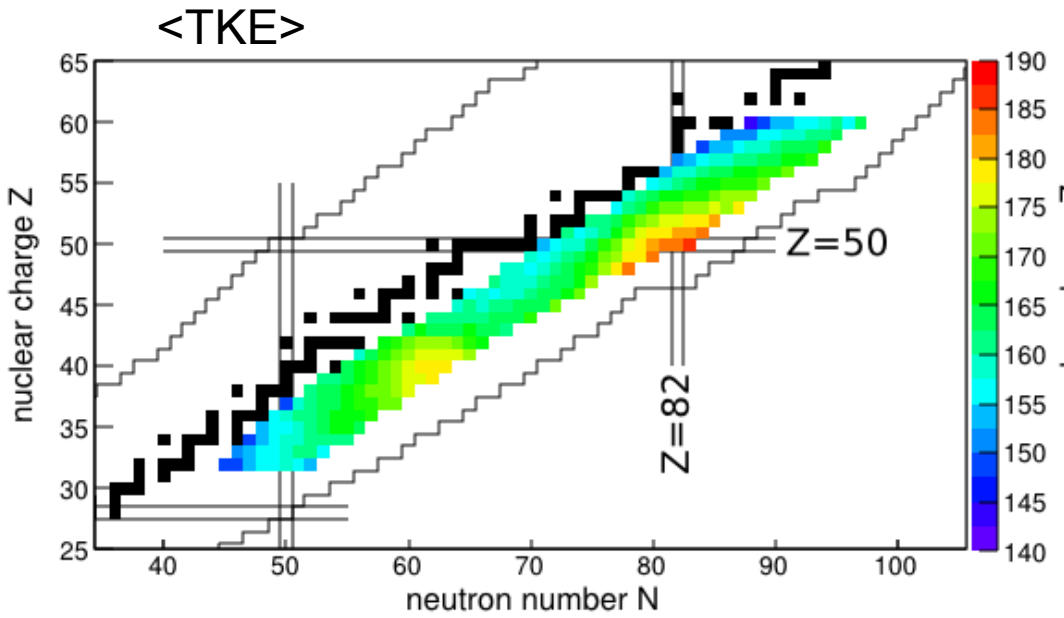


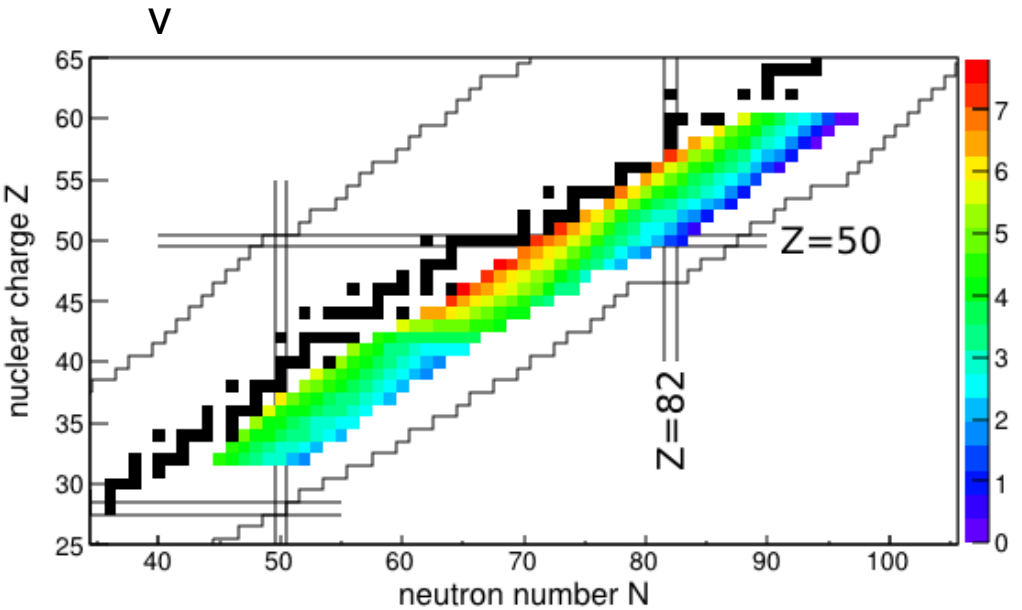
- Deformation directly impacts on ν :
  E_{def} relaxes into E* which is released by neutron emission

Total kinetic energy

- Transition in modes is reflected in TKE :
  - ✓ High TKE for ST1 mode (compact scission configuration)
  - ✓ Low TKE for SL mode (large deformation)

- Conversely, ν is large when TKE is small





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Summary

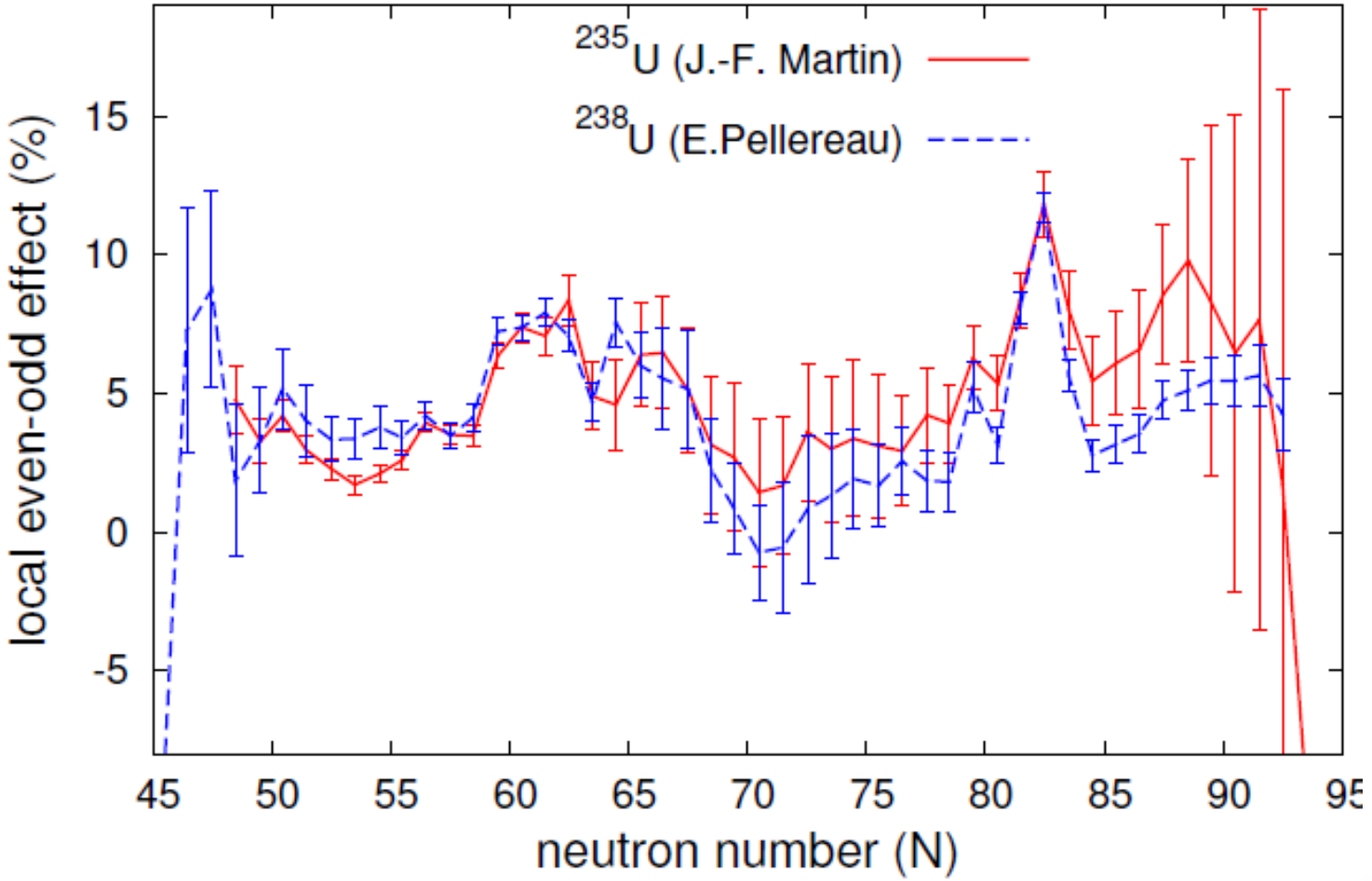
- SOFIA has met technical challenges to provide high-quality data
  - Full identification of both FF, TKE, prompt neutrons
  - High-precision yields
  - Large range of nuclei
- Coulomb-induced fission is an efficient tool for low-energy fission

- Data consistent with existing measurements
- New constraints for modeling
- Reduction of uncertainties in evaluated libraries

- The question of Z vs N shell for fission stabilization remains open
- Large perspectives within the R3B program @ FAIR
  - Neutron multiplicity per fragment
  - ^{242}Pu beam : isotopic yields for Pu and Am isotopes
  - Continued exploration of the NW of the map
  - e^--induced fission ? Yields as a function of E*…

Neutron even-odd effect

- Much more limited than the proton even-odd effect



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