DE LA RECHERCHE À L'INDUSTRIE

SOFIA

STUDIES ON FISSION WITH ALADIN

Theoritician dreams /nightmares come true

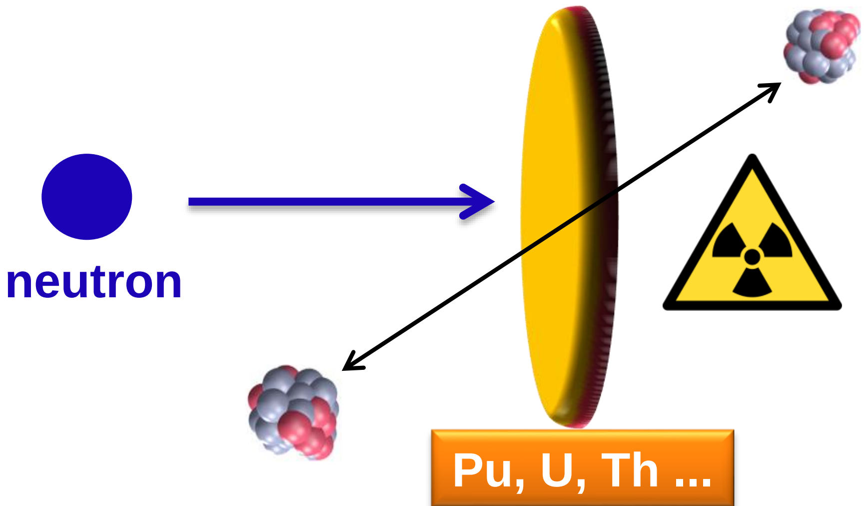
Julien TAIEB

For the SOFIA Collaboration

Fiesta workshop, Sept. 13th, 2014

www.cea.fr

THE EXPERIMENTAL TECHNIQUES



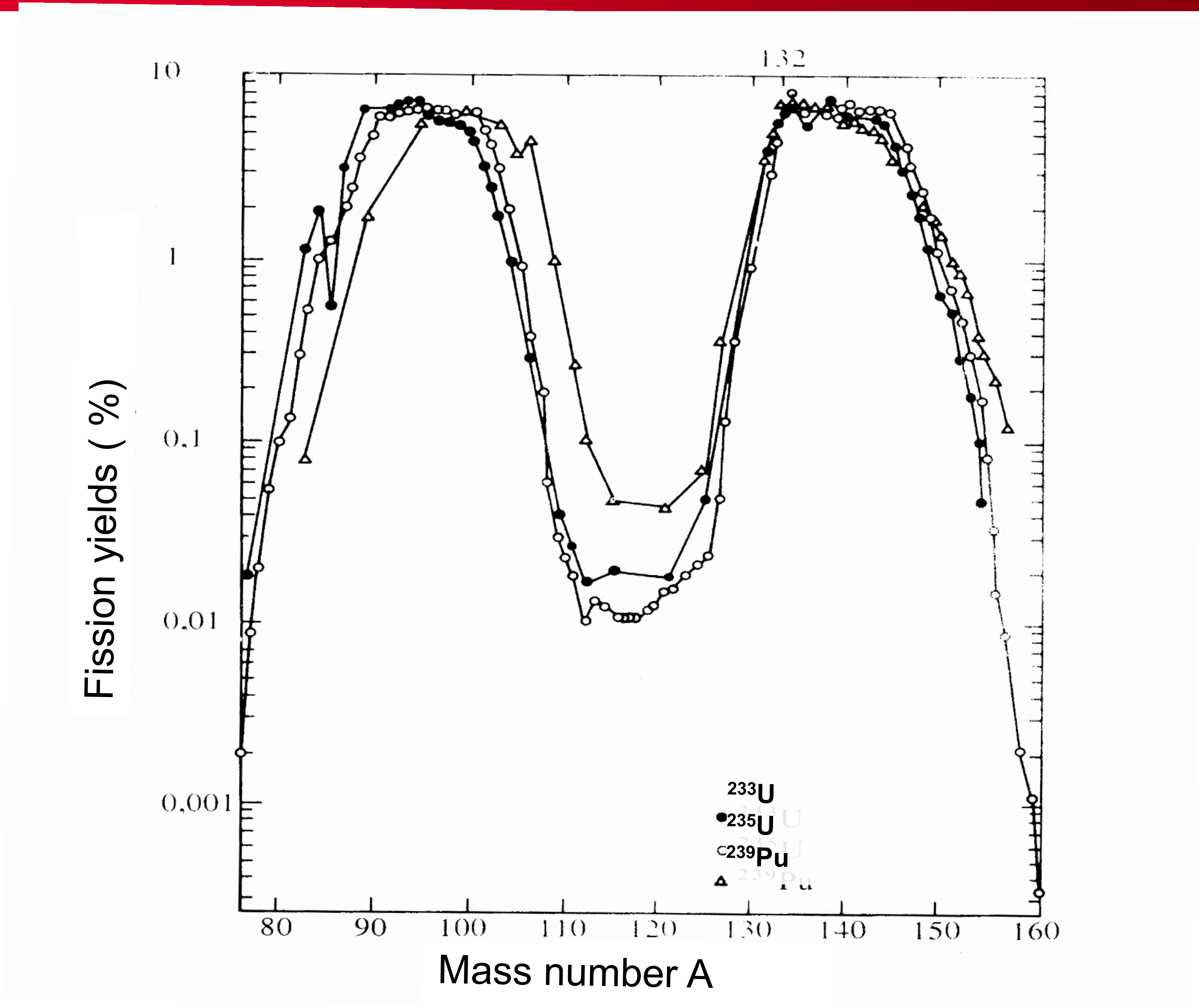
- 1 or 2 FF detected
- Identified in A or Z

Major difficulties

- (Thin))Target usually radioactive
- Low detection efficiency
- Mass number only measured in most experiments
- Atomic number very hard to get

Despite 75 years of effort, there is no way to identify all FF

THE FF MASS YIELDS MAJOR ACTINIDES

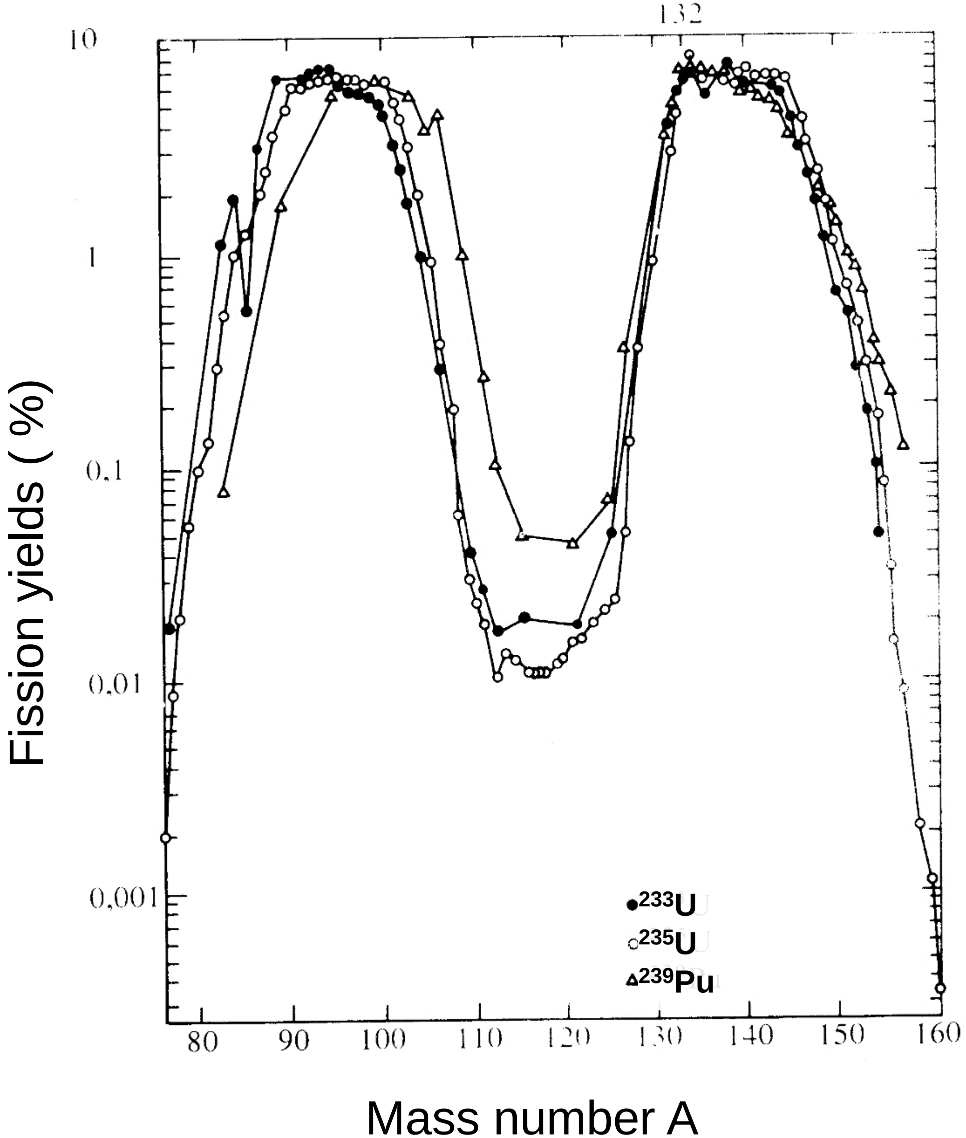


THE NUCLEAR CHARGE MEASUREMENT ISSUE

Measurement of the nuclear charge of FF

- Full ID needed for applications and for underatanding of the process
  - Mass number doesn't mean much
- How to measure the Z ?
  - Specific methods
    - Chemical separation + Gamma spectroscopy
    - X-ray identification
  - General method : energy loss (ΔE)
    - $\Delta E \propto Z^2$
    - Does work for the light FF
    - No separation for the heavy FF
    - Very low recoil velocity
      - Strong fluctuation in mean charge state
- **Only light fission fragments can be identified in Z and A**

THE FF MASS YIELDS MAJOR ACTINIDES



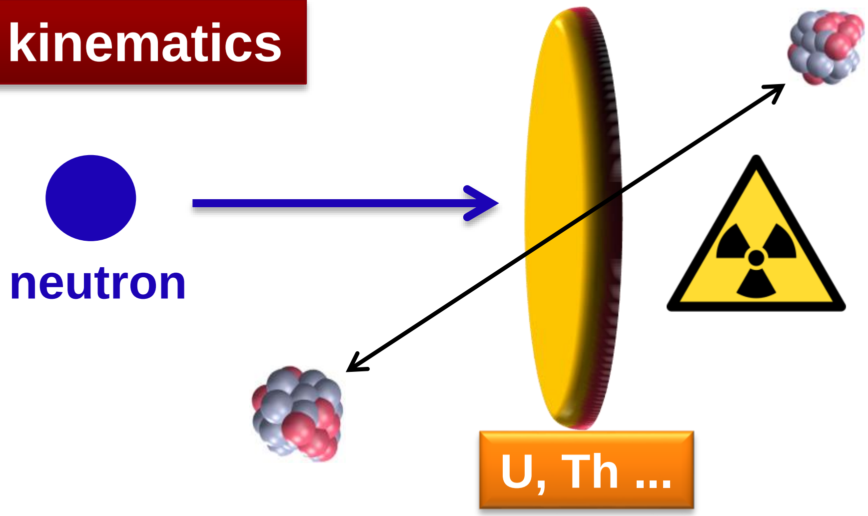
Heavy peak seems to stay

Light peak seems to adjust

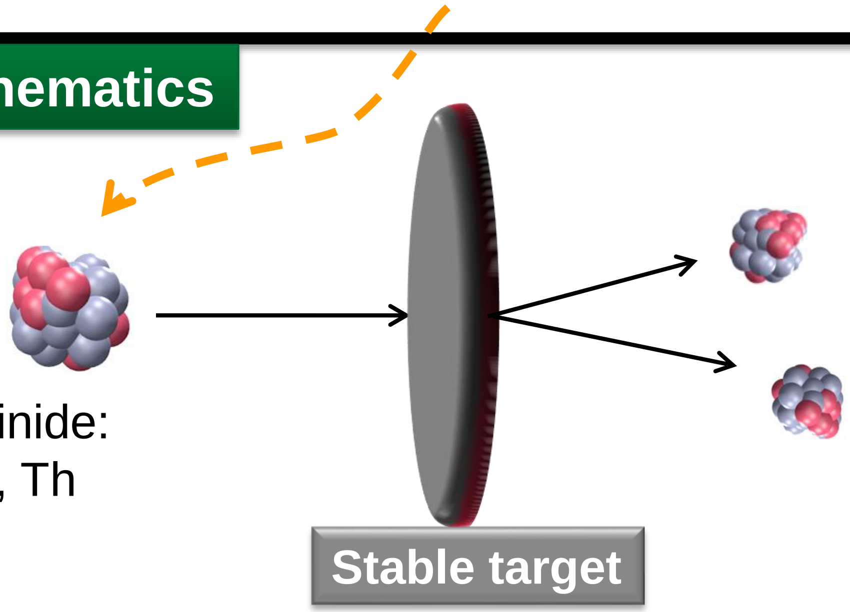
We would like to have a deeper look at the heavy peak

NEW EXPERIMENTAL APPROACH (K.H. SCHMIDT 96)

direct kinematics

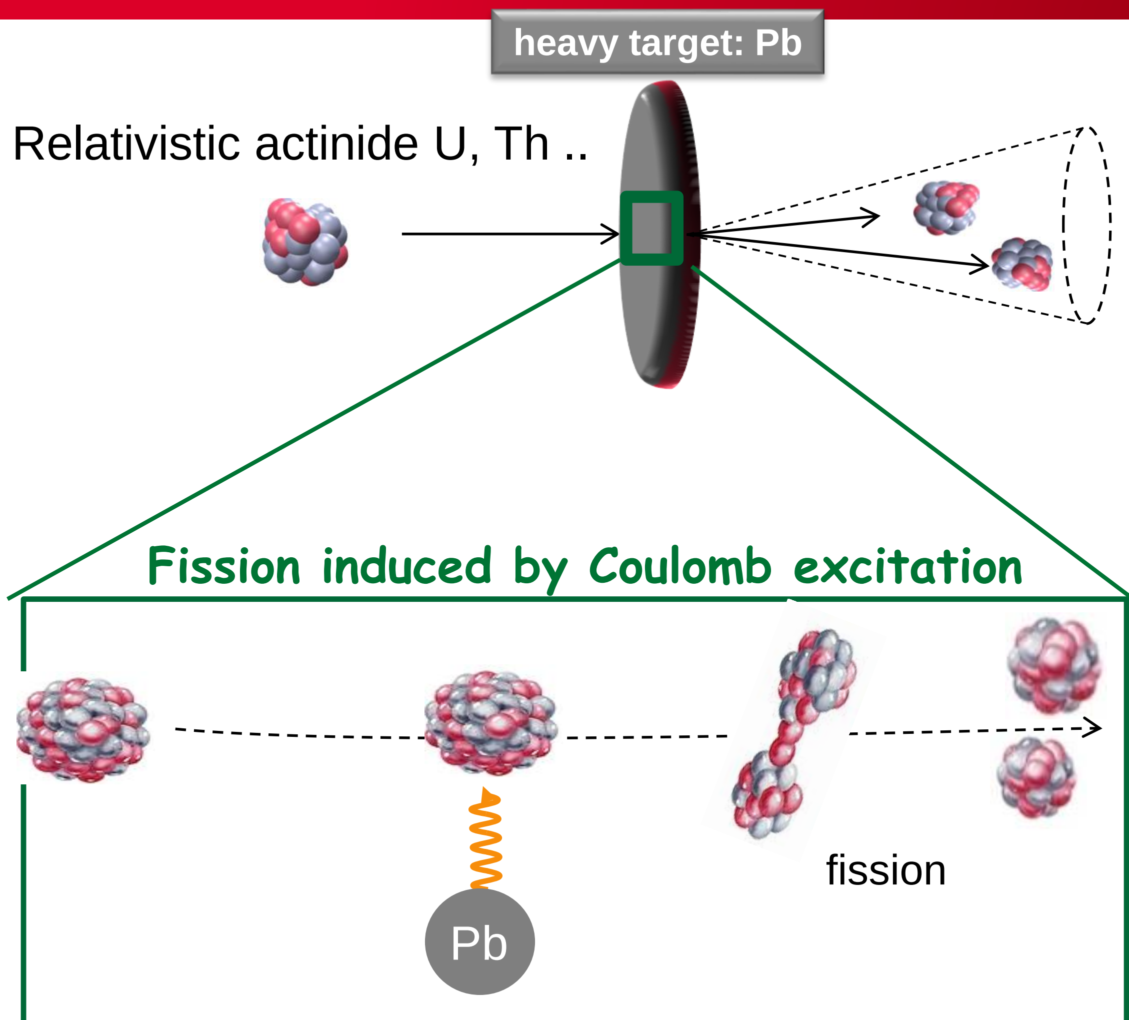


Reverse kinematics



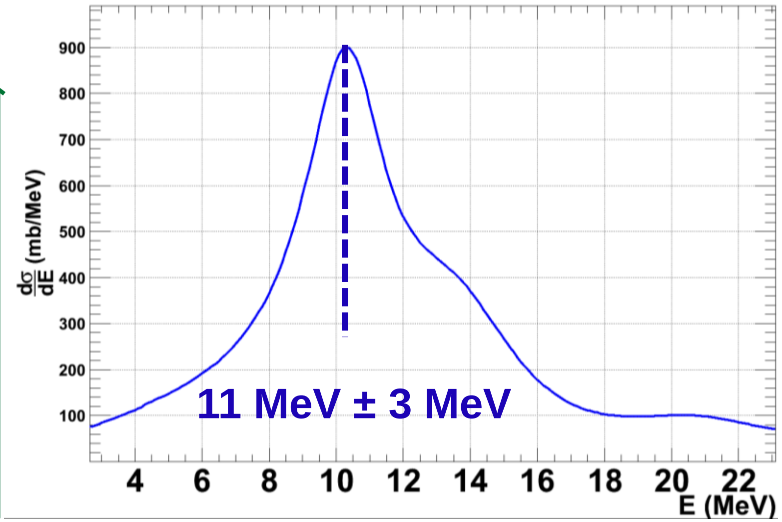
- Study the fission of radioactive nuclides
- Two FF emitted in forward direction : ϵ_{geom}
- Centre of mass boost: easier identification of FF
- Nuclear charge measured

FISSION IN REVERSE KINEMATICS AT GSI



The Giant Dipole Resonances (GDR) are populated

E* distribution



→ <E*> =12.5, similar to
7 MeV neutron induced fission

THE SOFIA EFFORT

- Follow K.-H. Schmidt pioneering idea
  - Improve precision
  - Measure the mass number
    - Get the number of emitted neutrons

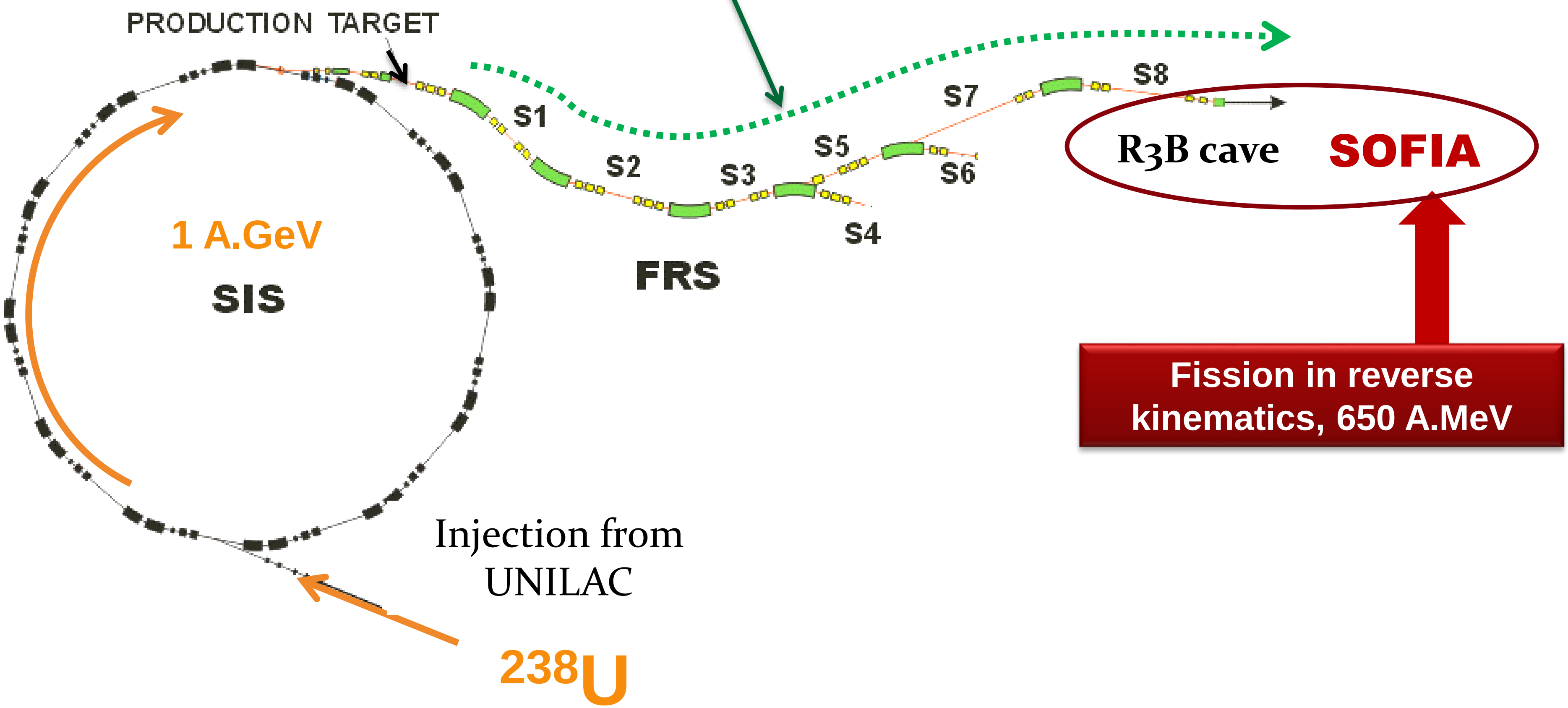
- Get unprecedented mass and charge resolutions
- Study the fission of many actinides and preactinides

- 8 european labs involved
- 5 years of technical developments
- 5 million euros invested
- 1st experiment in august 2012

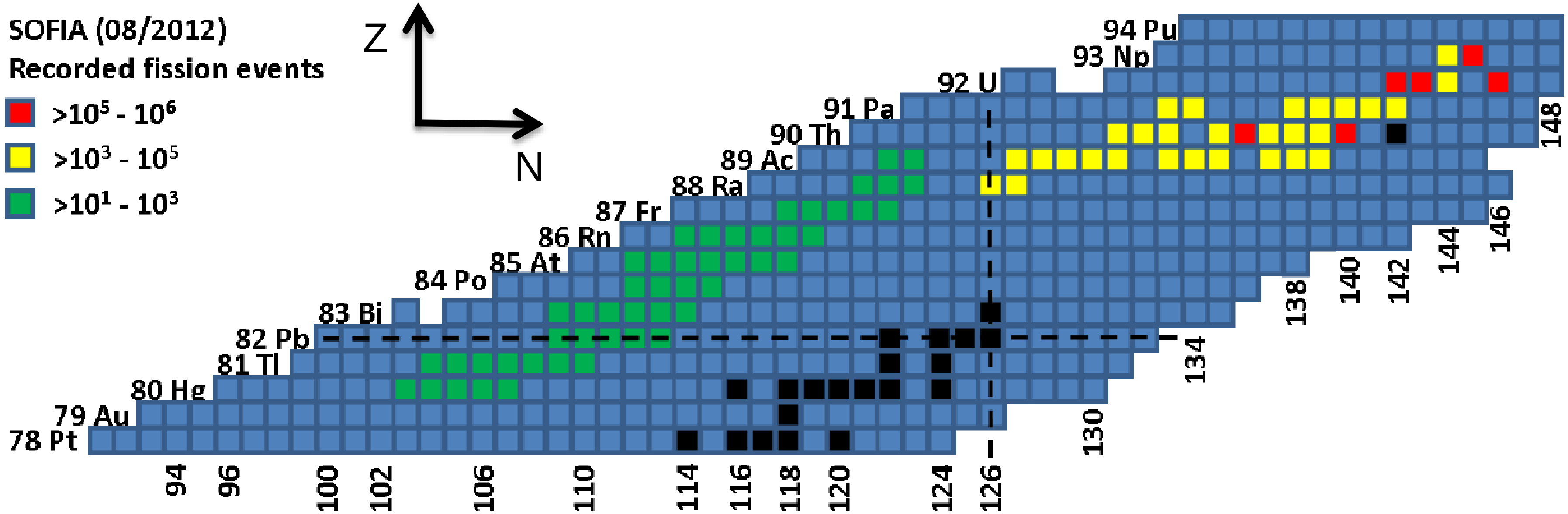
- Provide new data usable for :
  - Current nuclear reactors operation
  - Next generation nuclear reactor design
  - simulation of accidental configurations

- Improve the understanding of the process
- Contribute to the qualification of theoretical codes
- Improve the r-process modelling

Actinide secondary beams from fragmentation reactions of ^{238}U



1ST SOFIA EXPERIMENT, 08/2012



For both fragments, we measure

Z and A

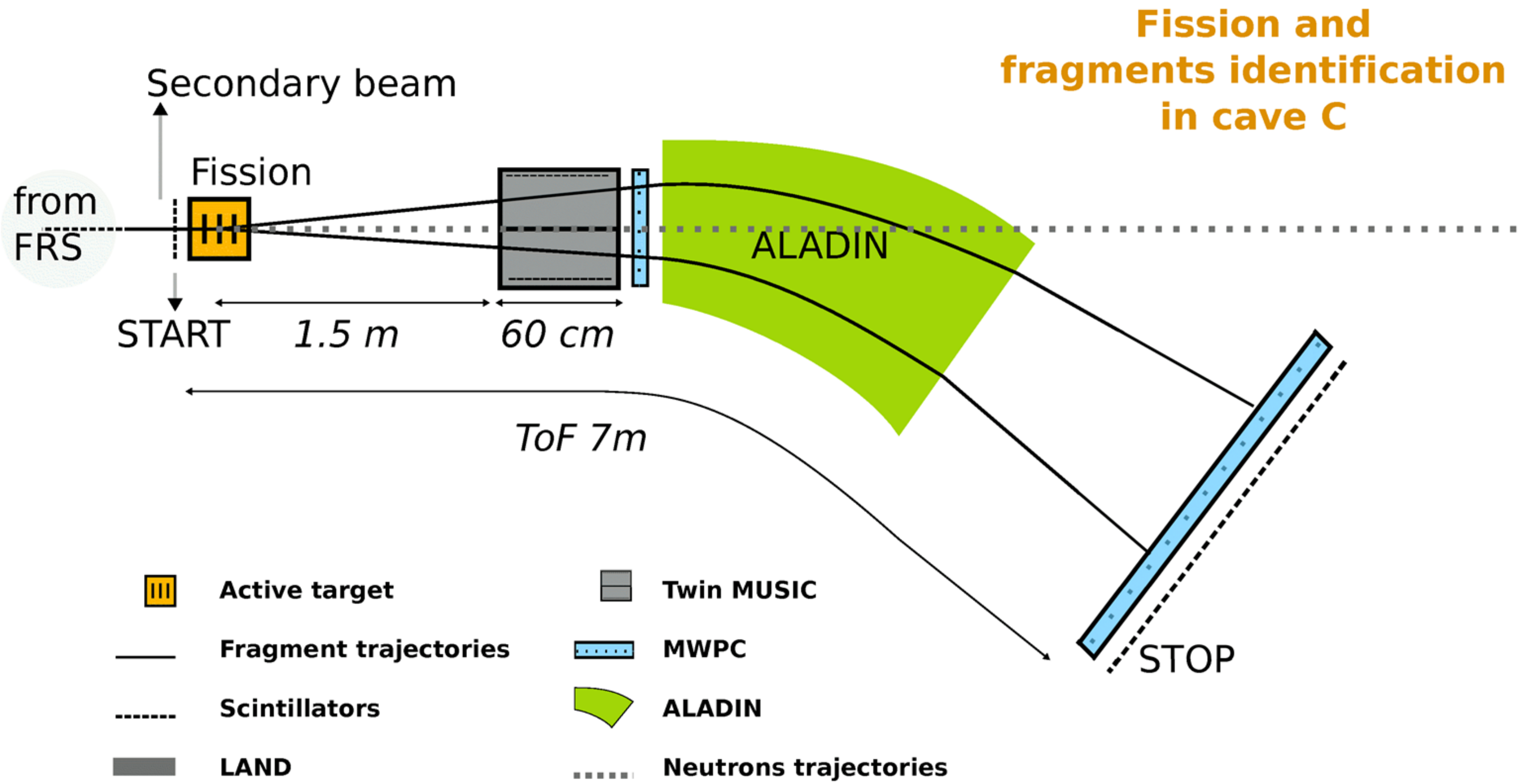
Target : resolution < 1 (FWHM) over the full FF range

<u>In addition</u>:

- **Number of emitted neutrons $\overline{\upsilon}$ = A_{fiss} – (A1 +A2)**
- **TKE**

The SOFIA set up

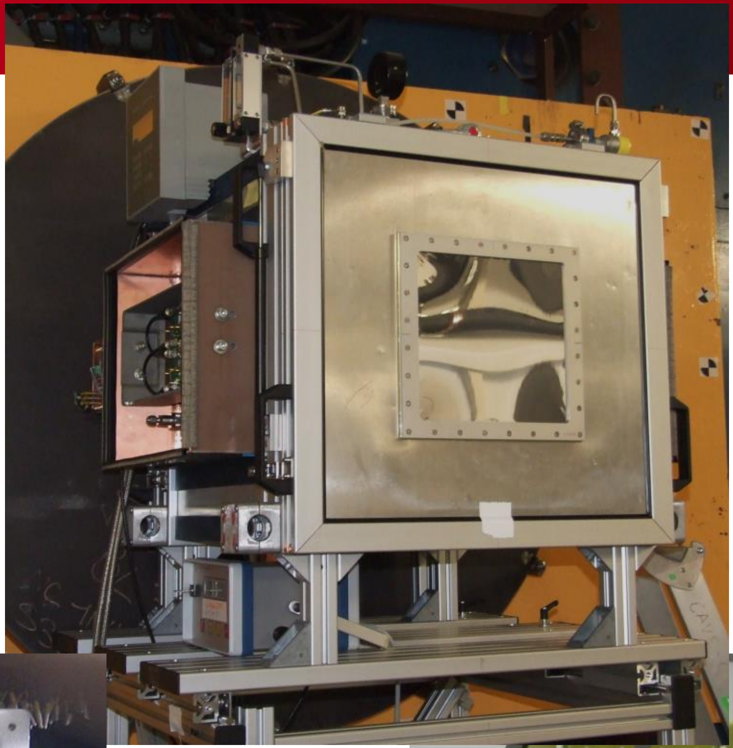
THE SOFIA SET UP

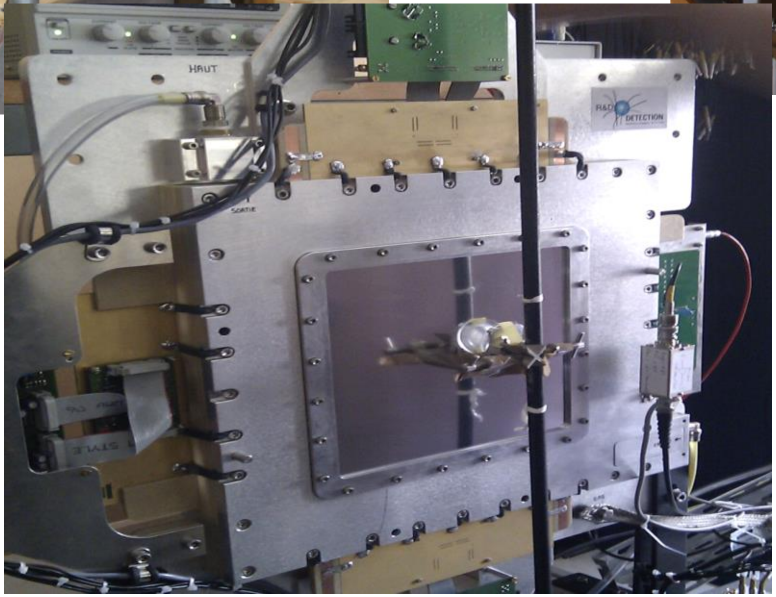


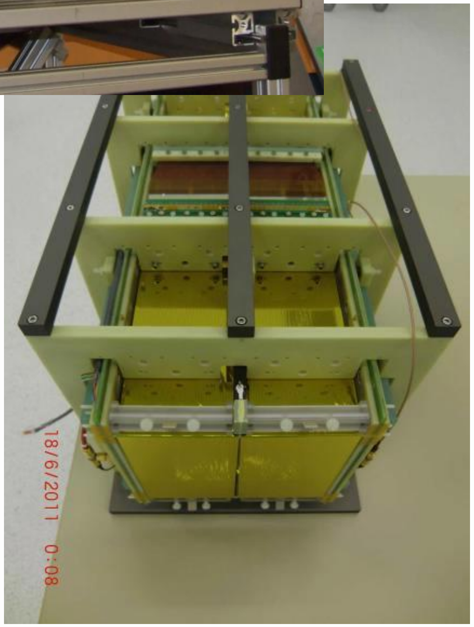
all detectors developed for that experiment

Challenge : mass identification in the FF region


← BEAM ←




HAUT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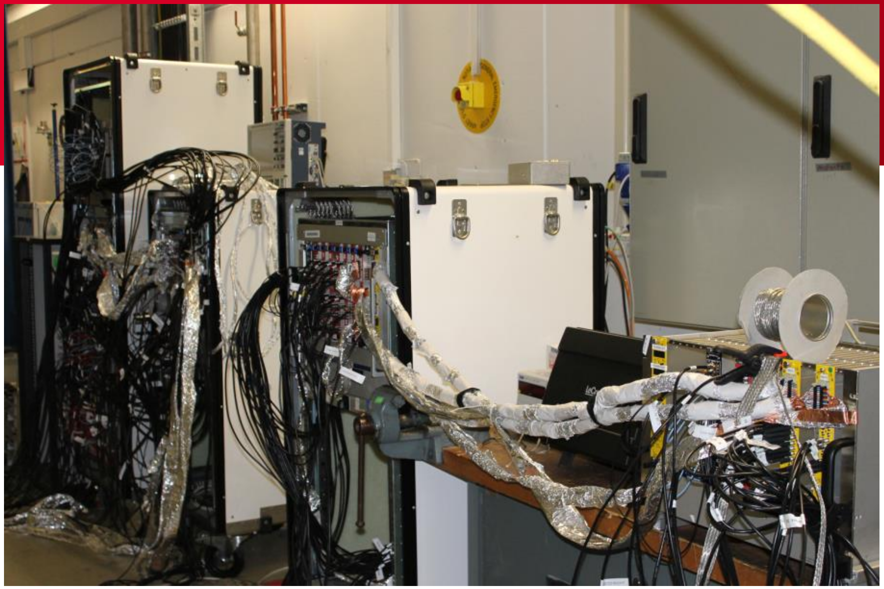
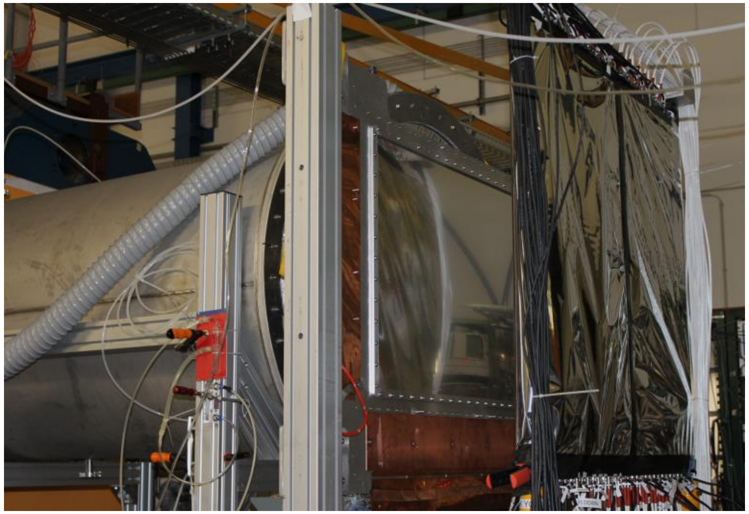
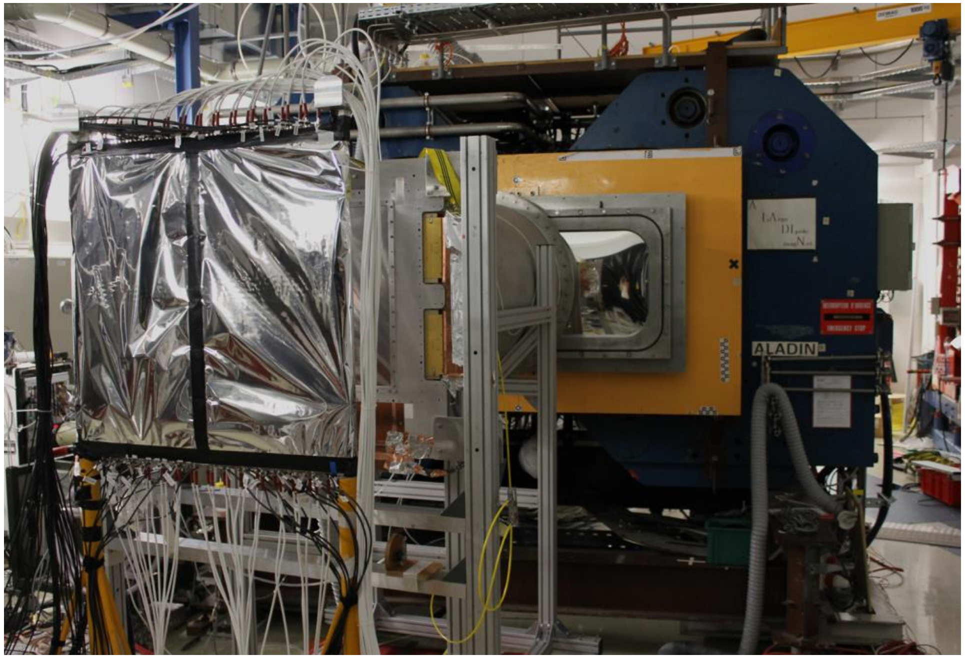


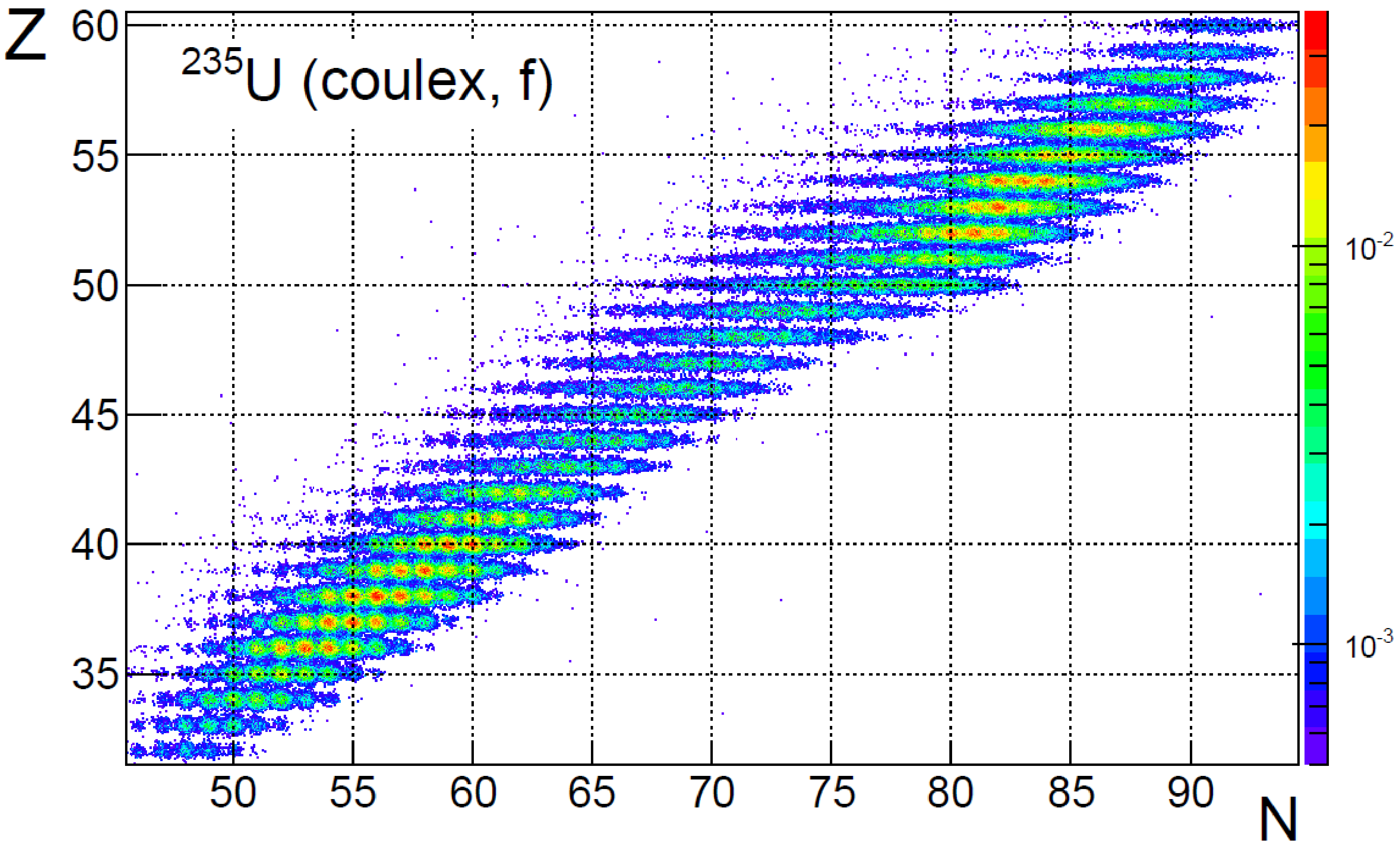



ALADIN

Spectra

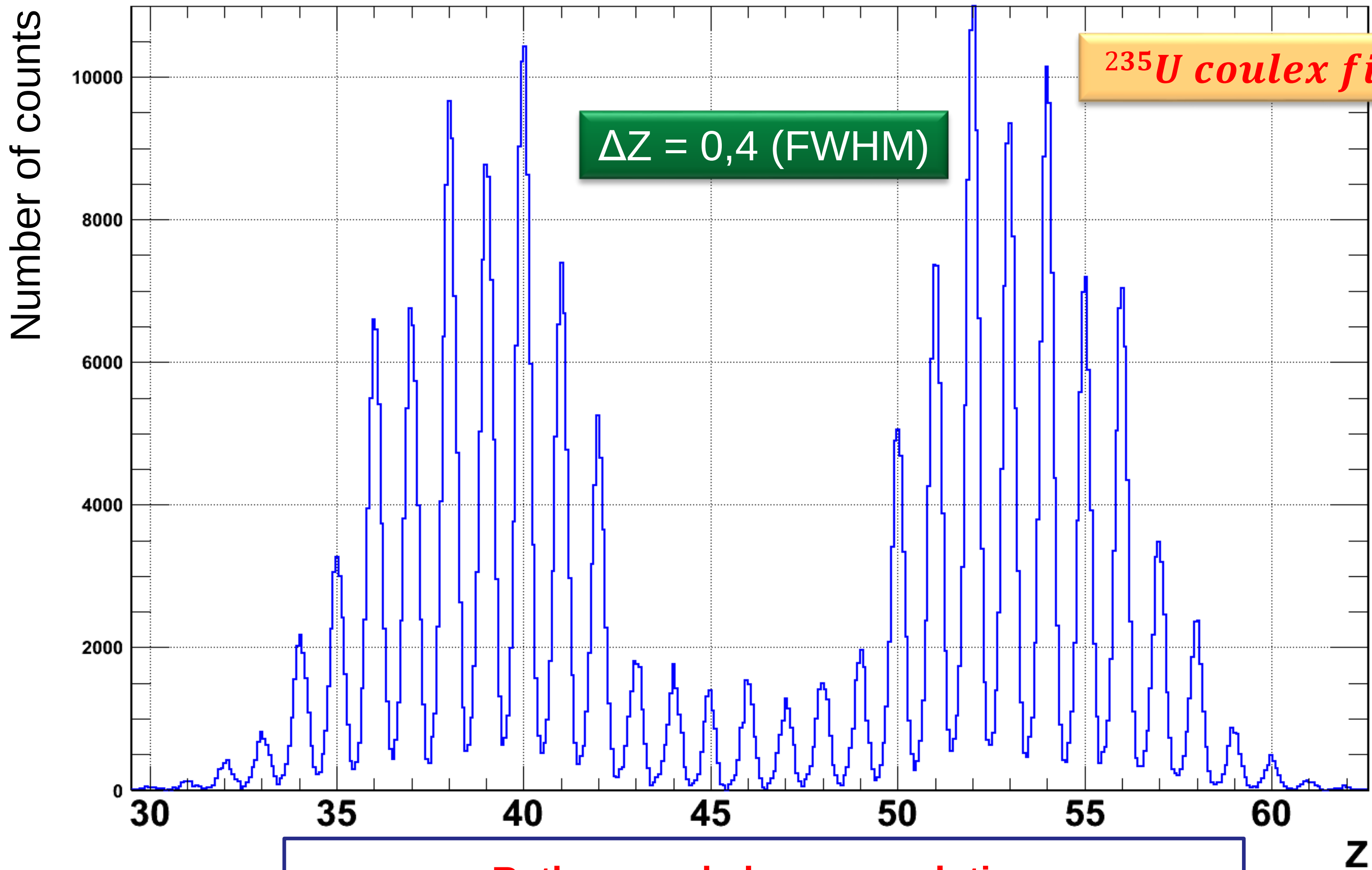
1) Chart of nuclide
2) Nuclear Charges
3) Masses

CHART OF MEASURED FF



PhD thesis : Julie Martin

NUCLEAR CHARGE SPECTRUM.



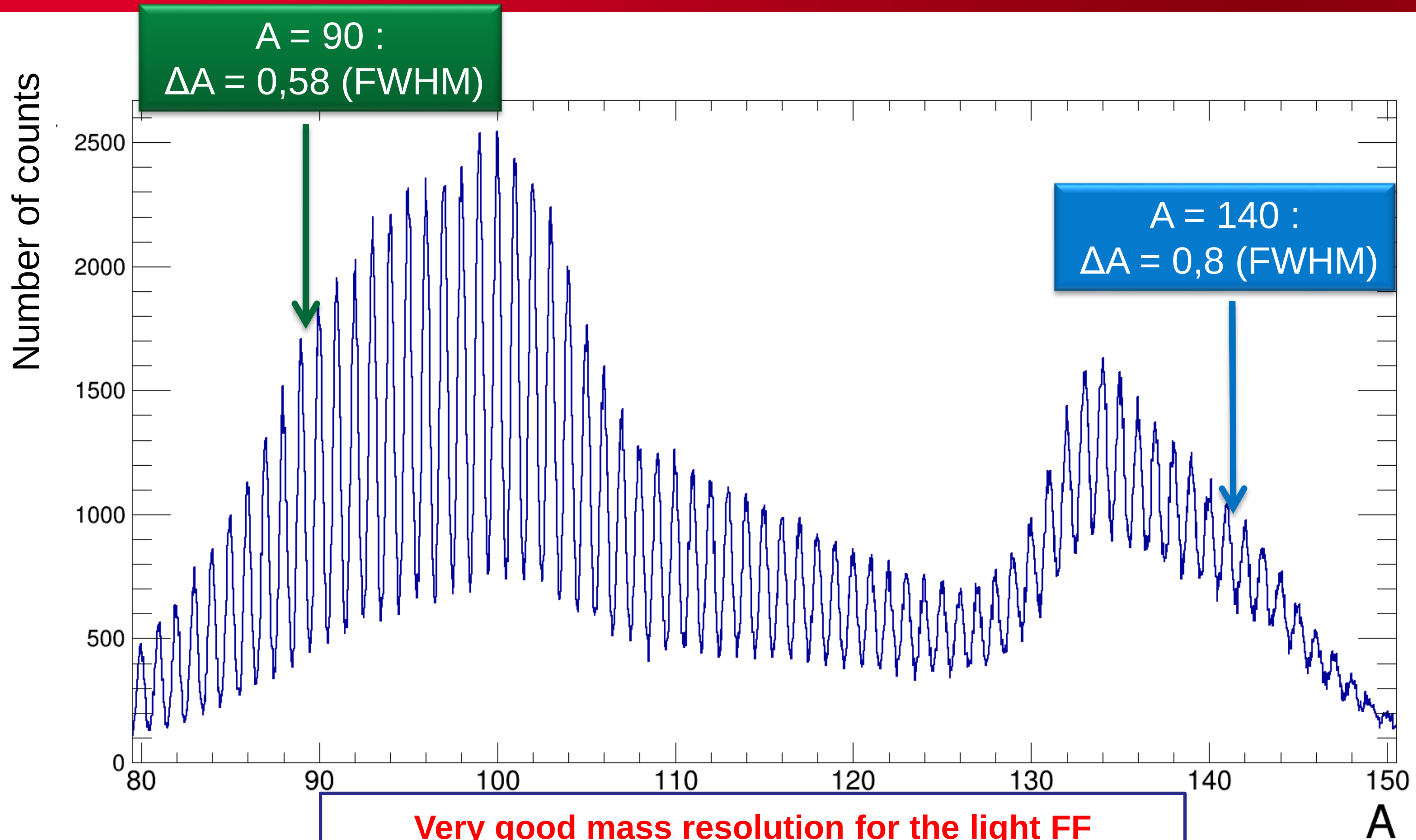
^{235}U coulex fission

Rather good charge resolution

Visible odd-even staggering

PhD thesis : Julie Martin

MASS NUMBER SPECTRUM



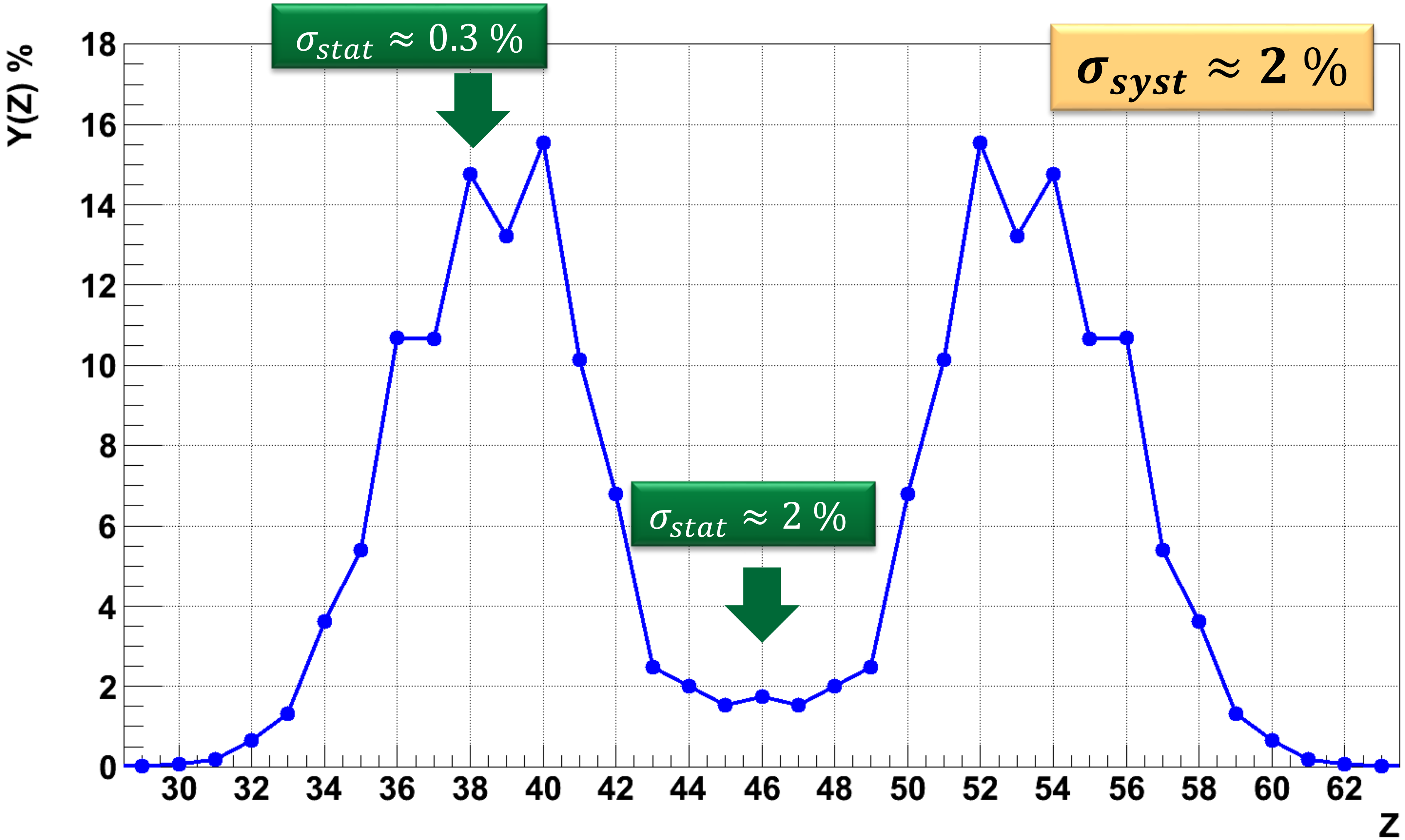
Very good mass resolution for the light FF

Degrades for the heavy FF, still neighbouring isotopes disantangled

Fission yields

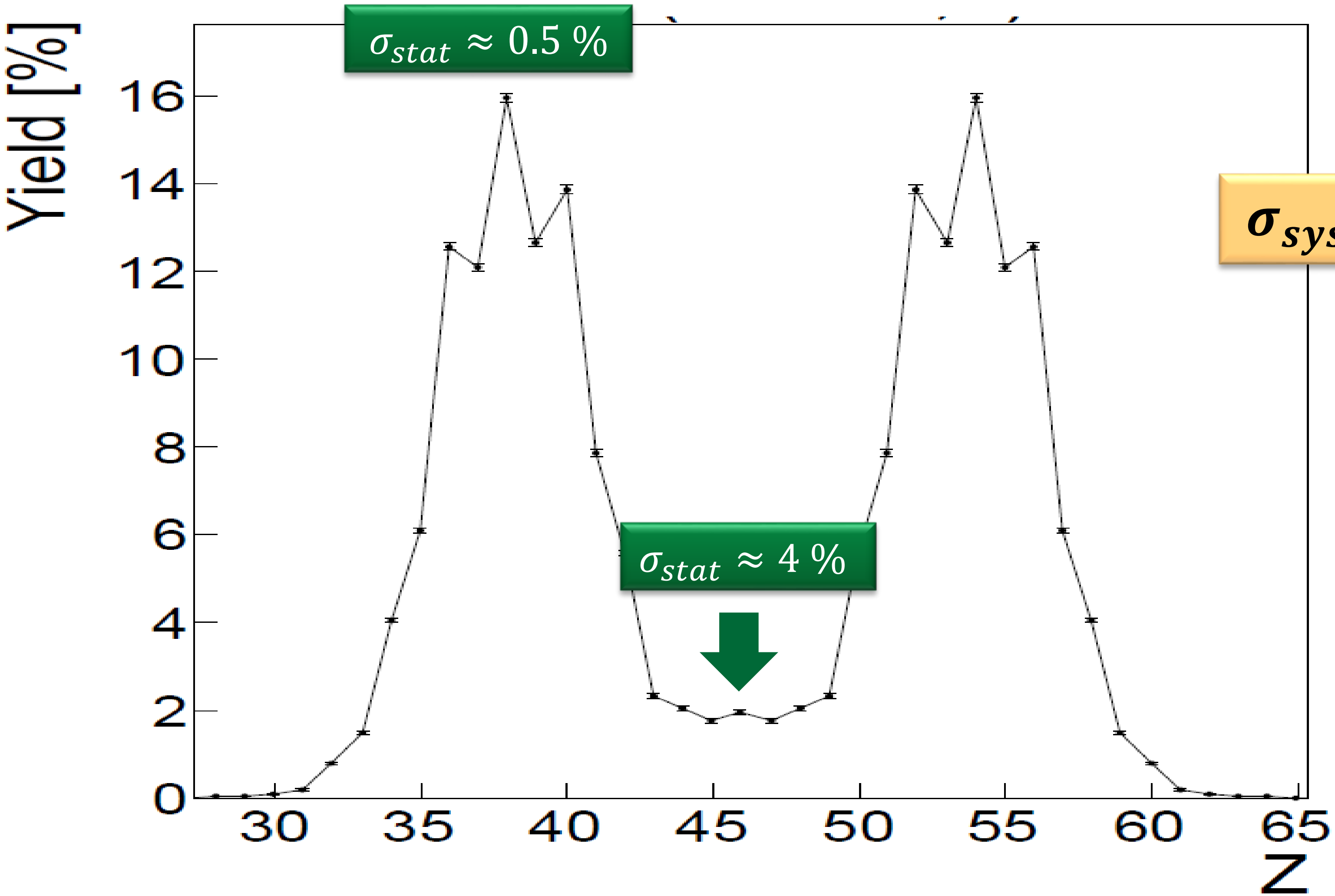
1) Element
2) Isotonic
3) Isotopic
4) Mass
5) Prompt Neutrons $\overline{\nu}$

^{238}U, CHARGE YIELDS



PhD thesis : Eric Pellereau

^{235}U, CHARGE YIELDS

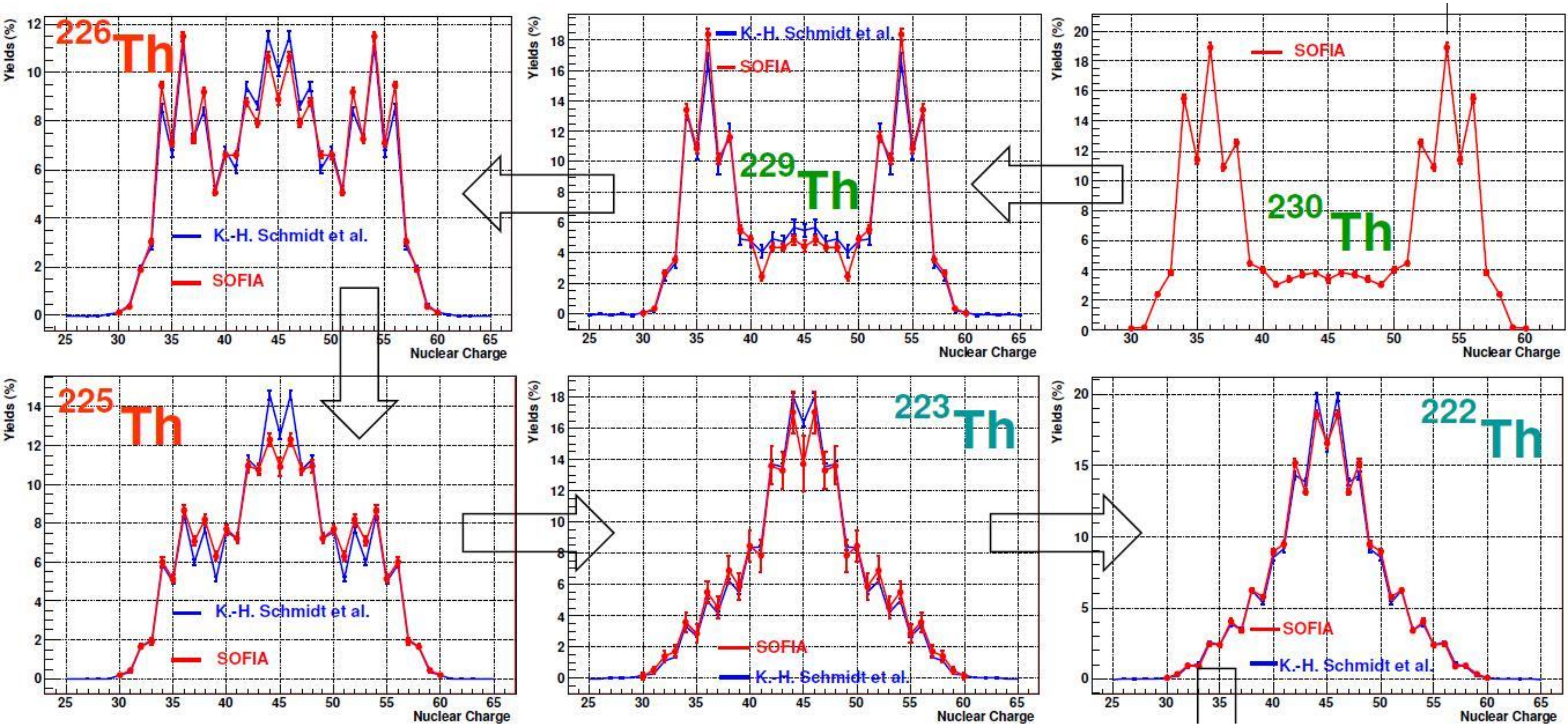


$\sigma_{syst} \approx 1$ %

Most produced element moves from 52 to 54

PhD thesis : Julie Martin

THE THORIUM CHAIN, K.-H. SCHMIDT ET AL VS SOFIA

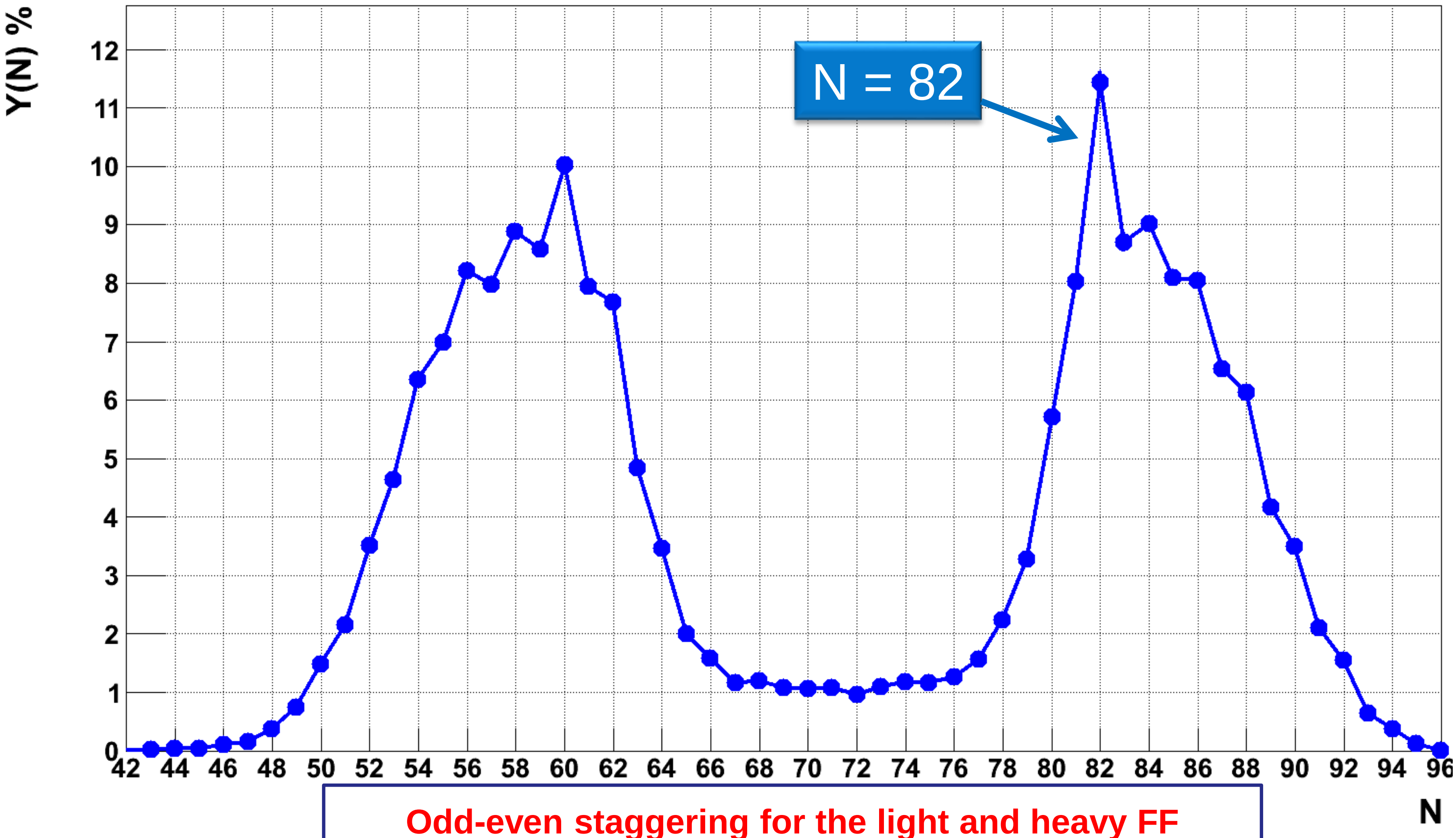


Courtesy : Audrey Chatillon

Fission yields

1) Element
2) Isotonic
3) Isotopic
4) Mass
5) Prompt Neutrons $\overline{\nu}$

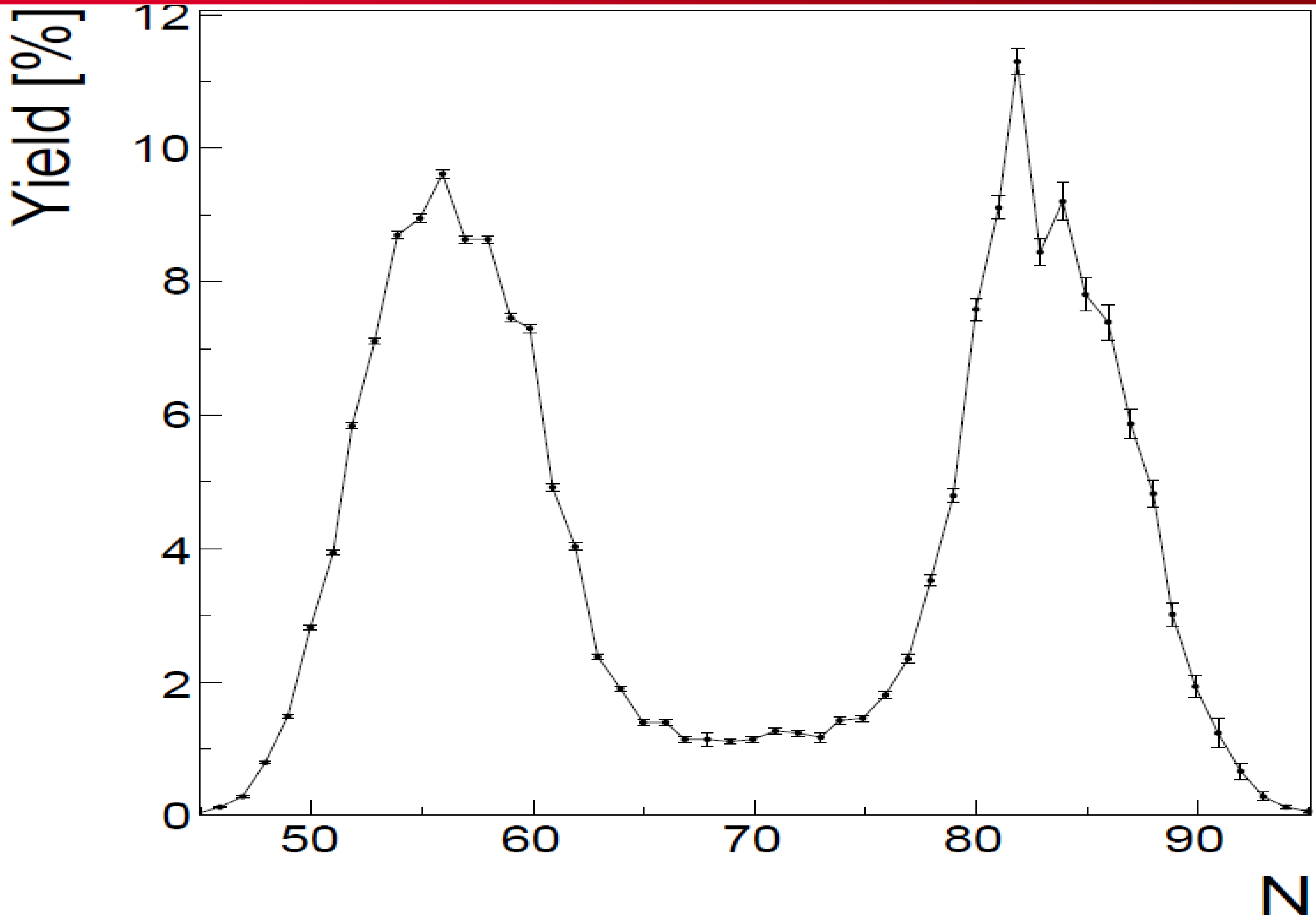
ISOTONIC YIELDS: N = A – Z, FISSION OF ^{238}U



Odd-even staggering for the light and heavy FF

Proeminent peak at N=82

ISOTONIC YIELDS: N = A – Z, FISSION OF ^{235}U



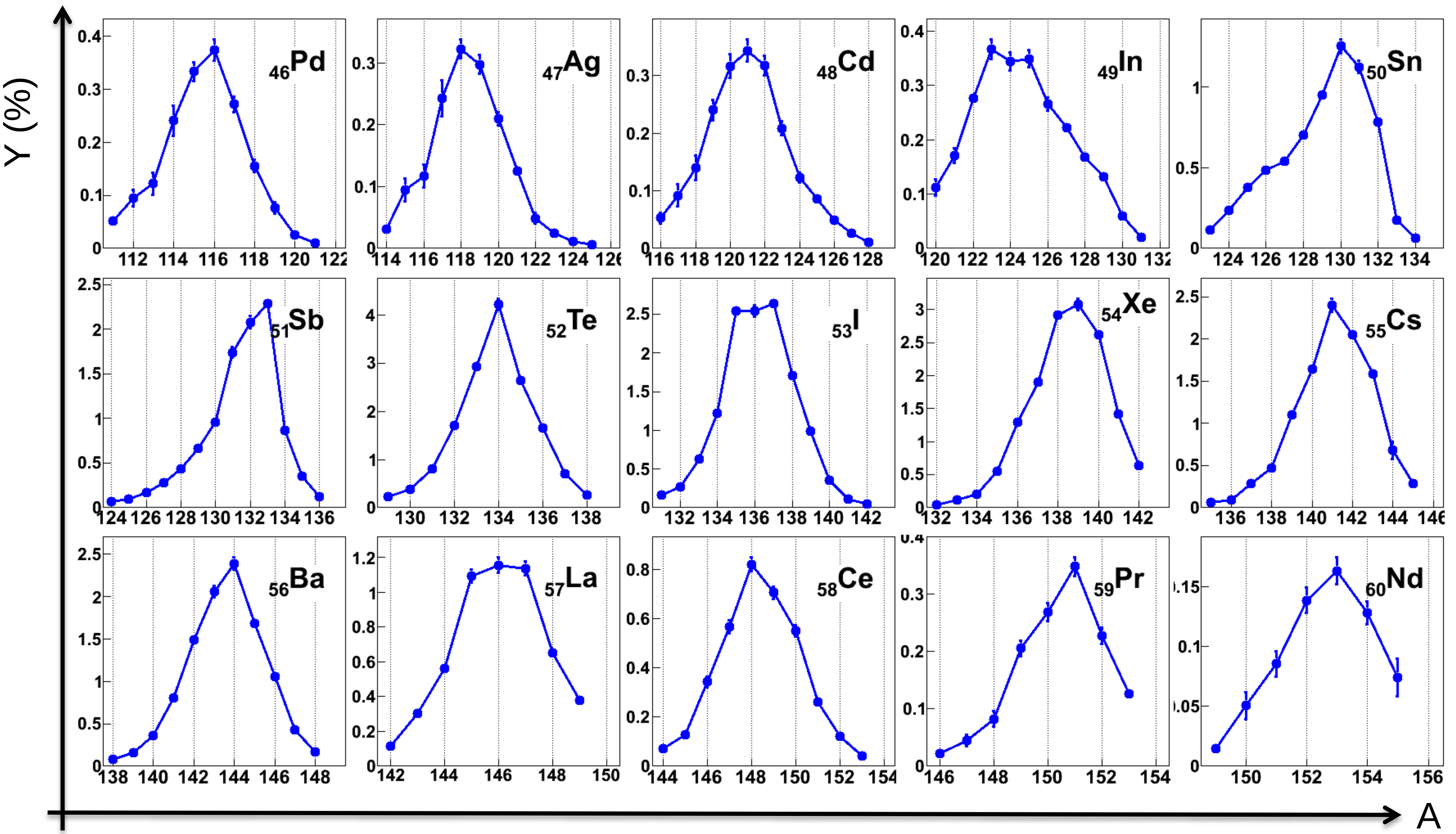
Odd-even staggering for the light and heavy FF

Proeminent peak at N=82

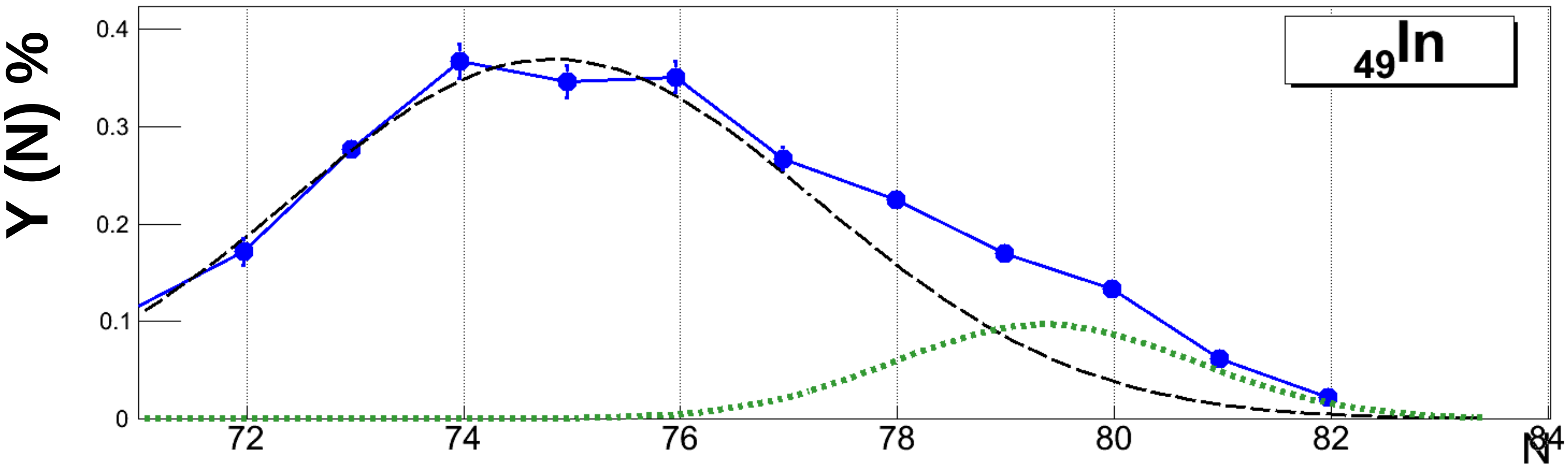
Fission yields

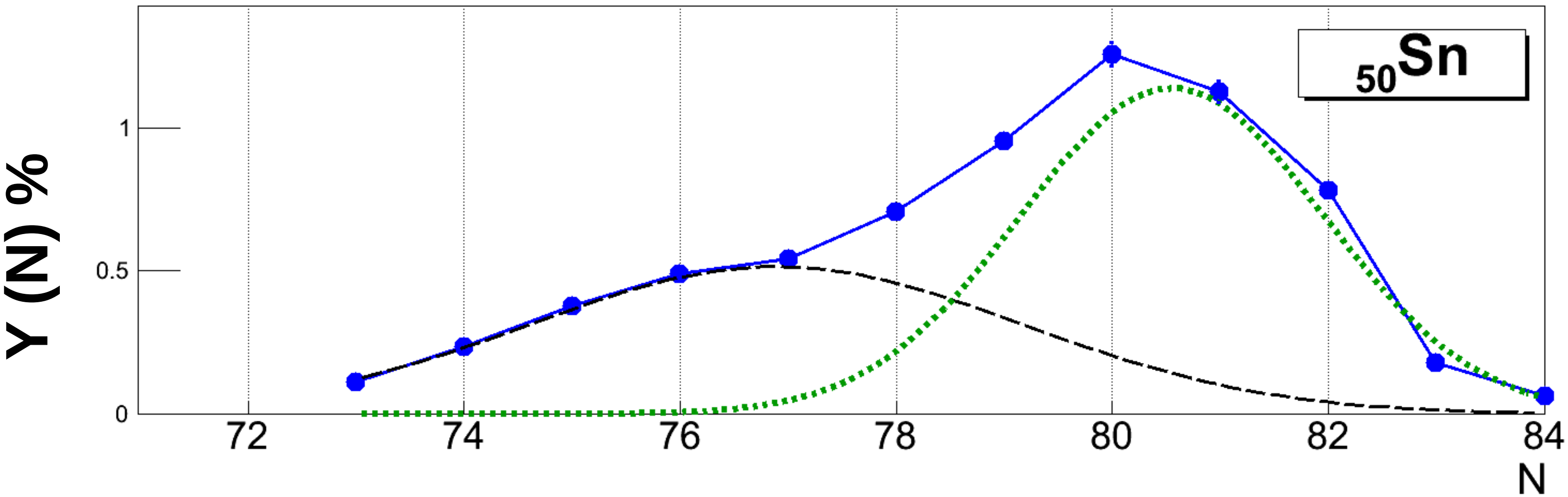
1) Element
2) Isotonic
3) Isotopic
4) Mass
5) Prompt Neutrons $\overline{\nu}$

ISOTOPIC YIELDS (HEAVY FF)

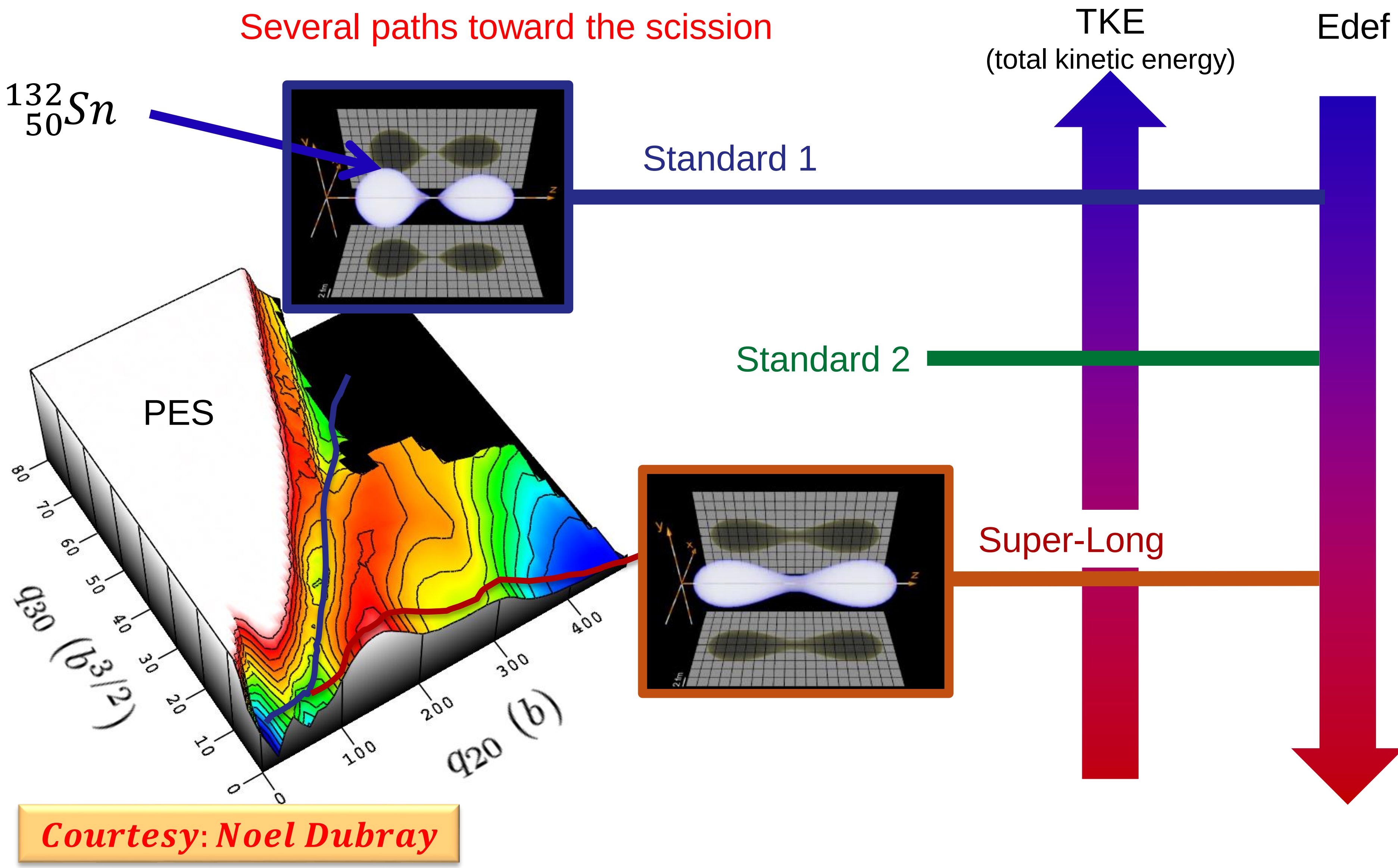


ISOTOPIC YIELDS ; ZOOM Z = 49-50

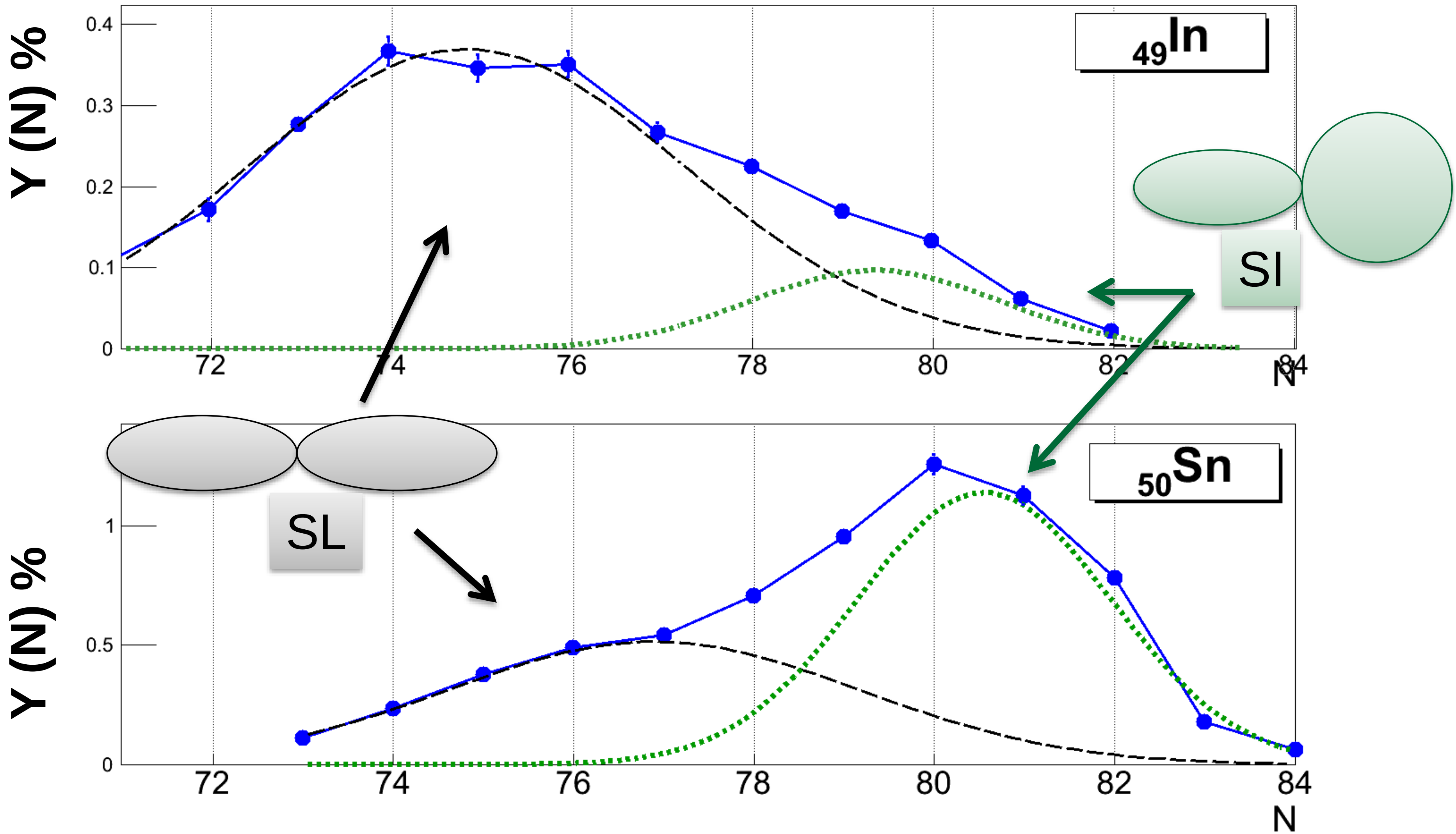




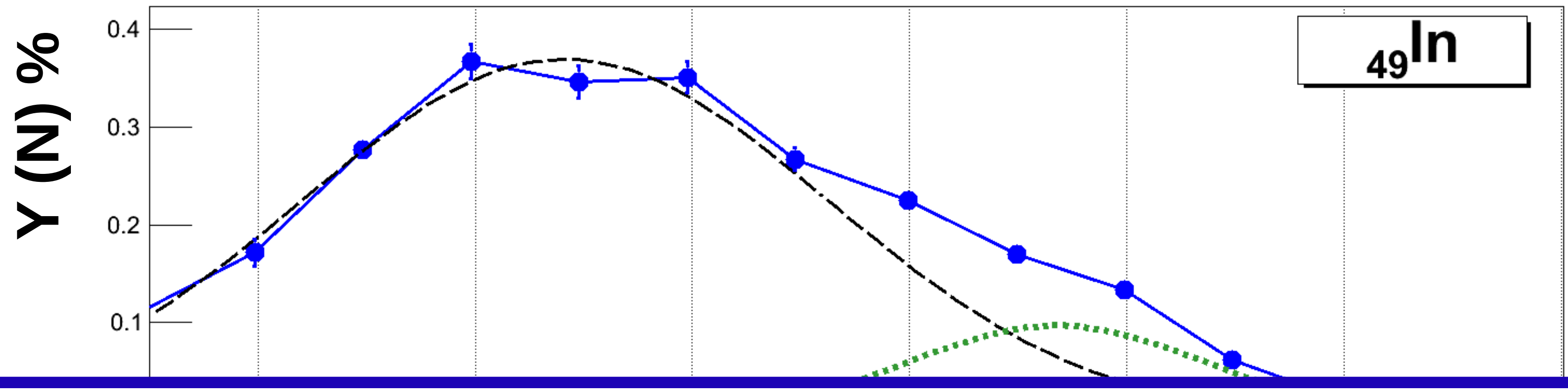
FISSION MODES

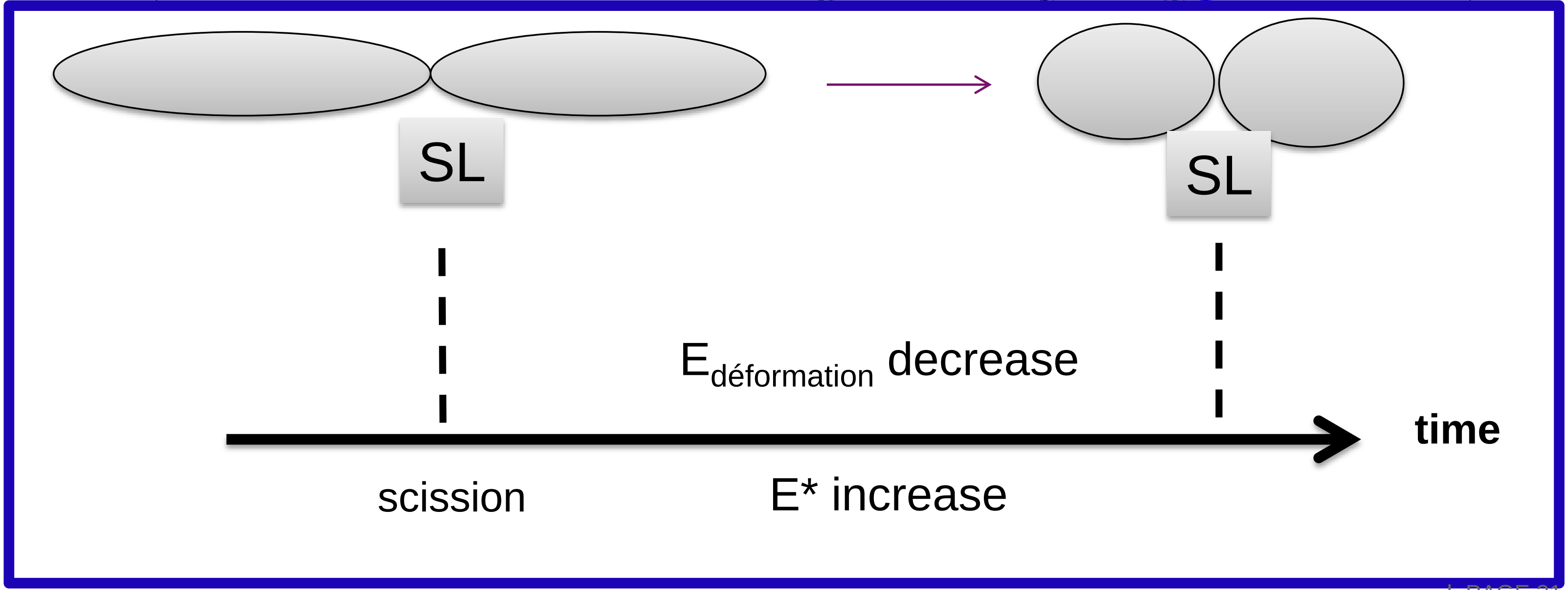


ISOTOPIC YIELDS; Z = 49-50



ISOTOPIC YIELDS; Z = 49-50

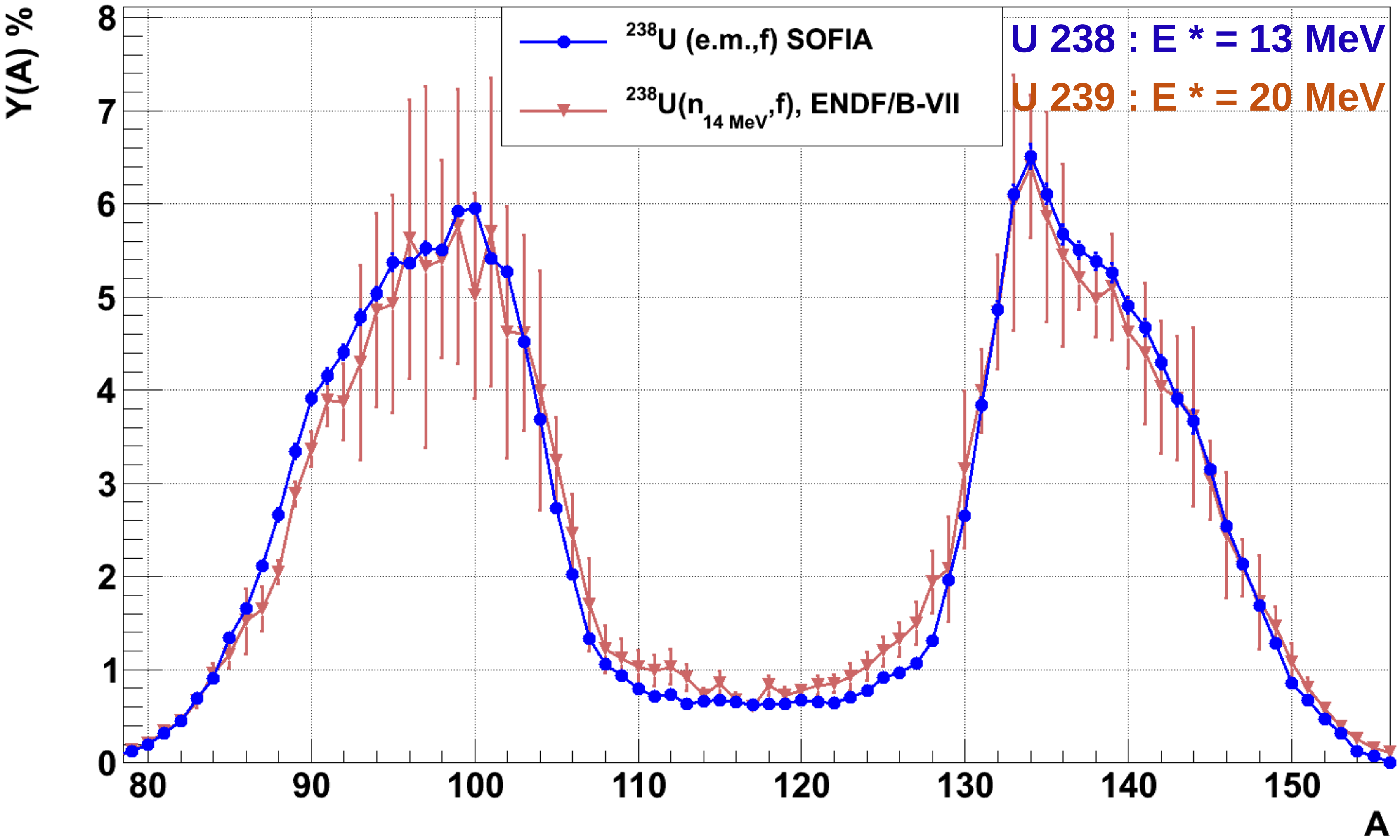




Fission yields

1) Element
2) Isotonic
3) Isotopic
4) Mass
5) Prompt Neutrons $\overline{\nu}$

MASS YIELDS, COMPARISON TO THE EVALUATION

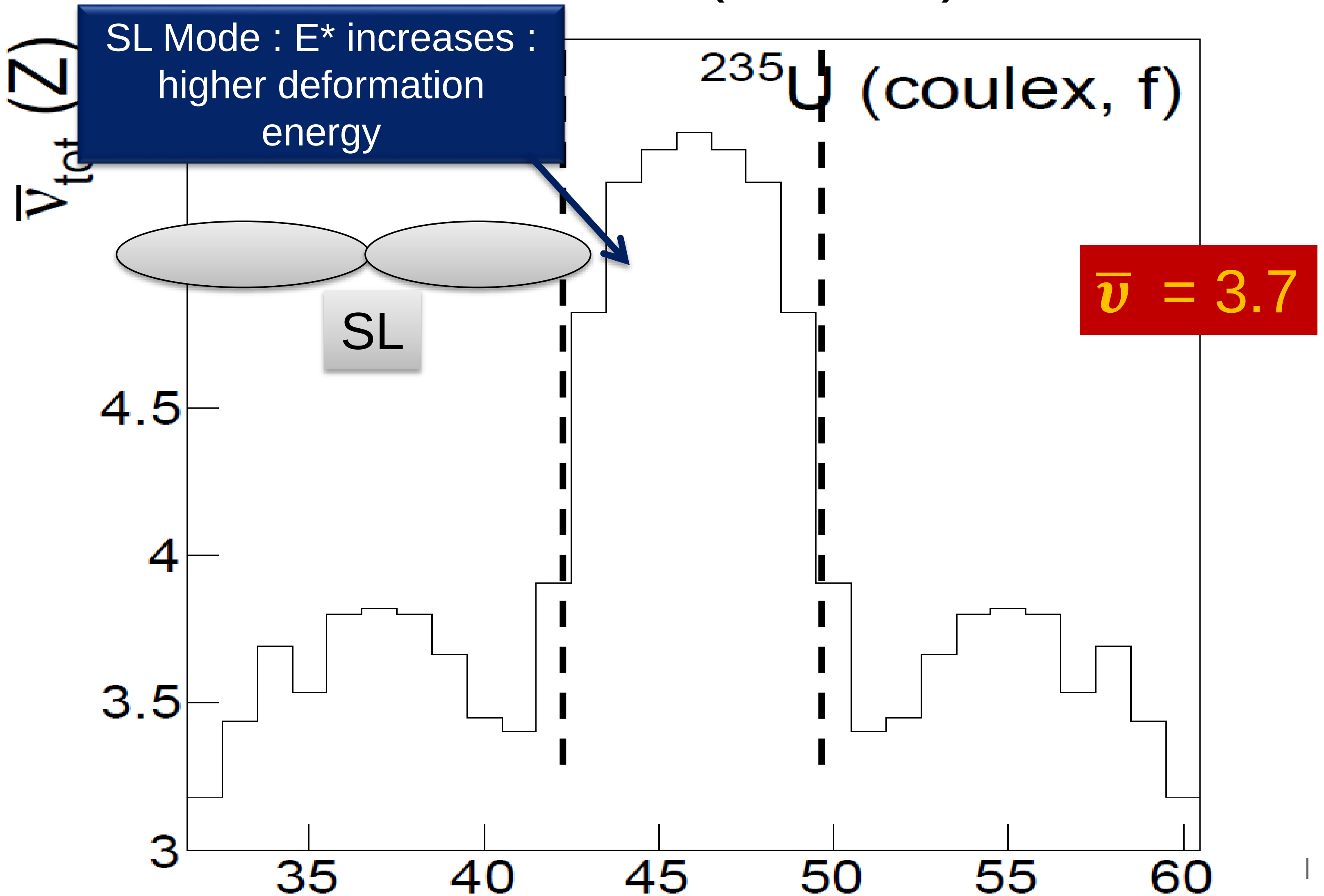


Fission yields

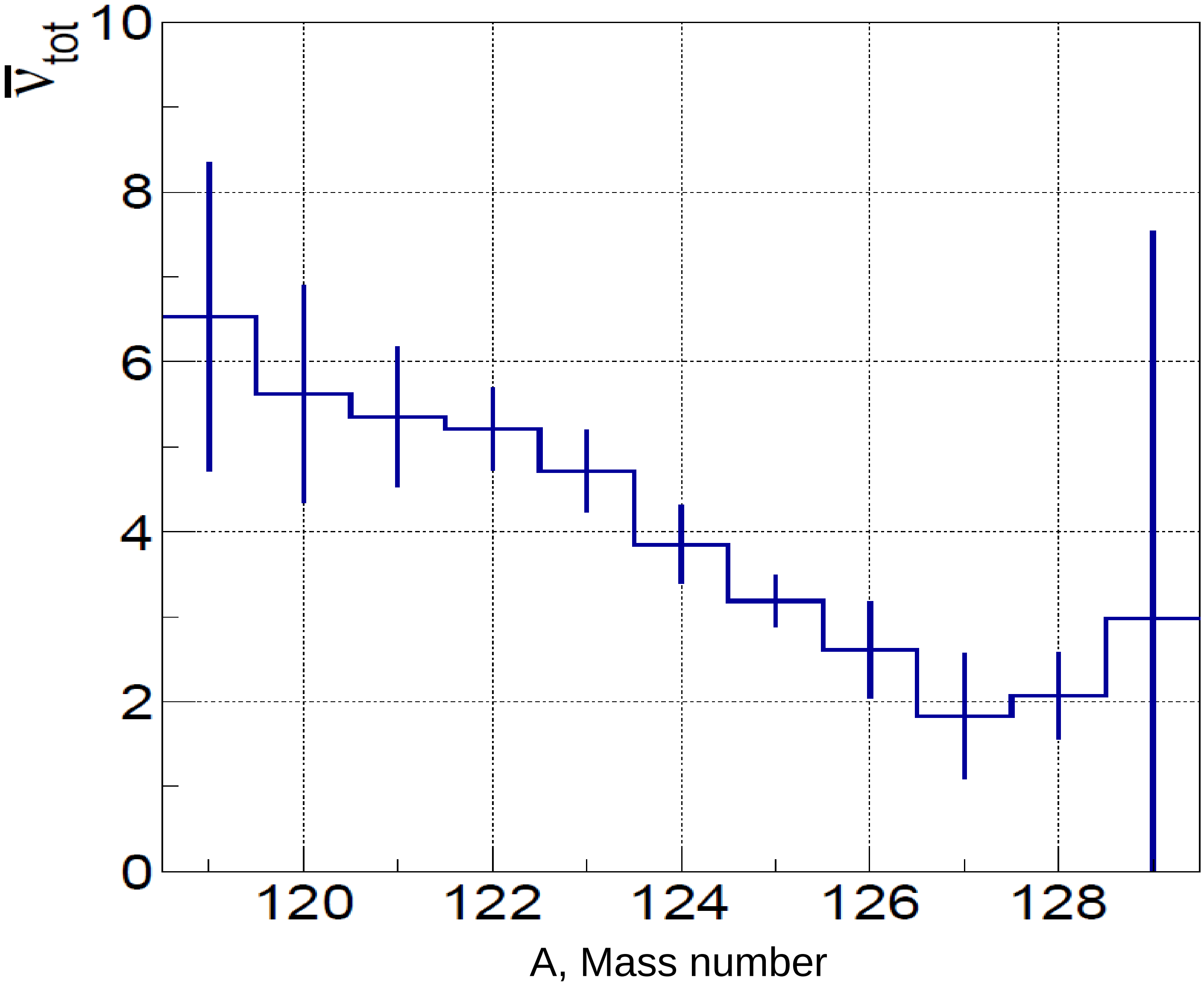
1) Element
2) Isotonic
3) Isotopic
4) Mass
5) Prompt Neutrons $\overline{\nu}$

$\bar{\upsilon}$ VS Z , FISSION OF ^{235}U

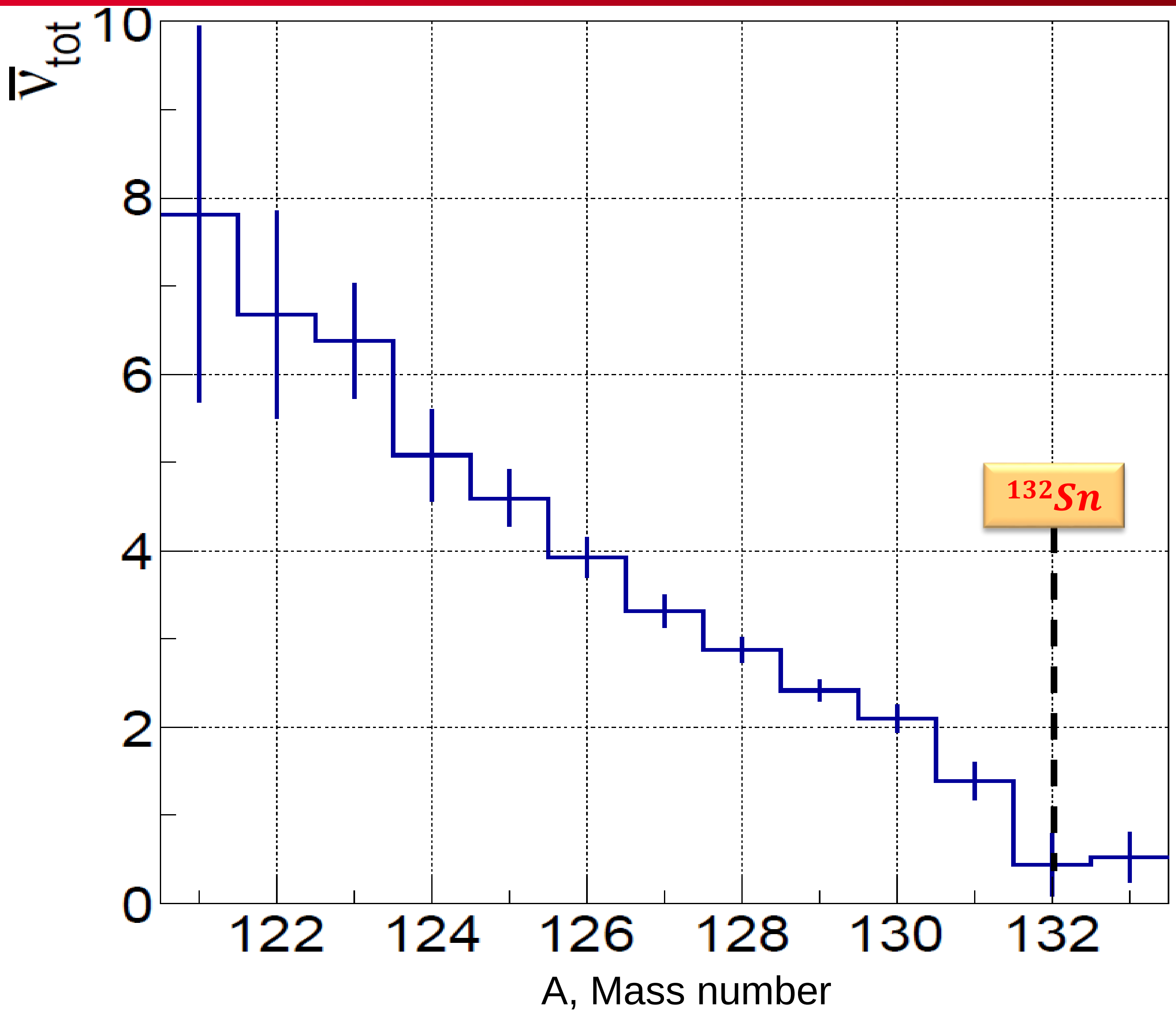
$\bar{\upsilon}$ = 235 – (A1 + A2)



$\overline{\nu}$ VS A FOR Z = 49, , FISSION OF ^{235}U



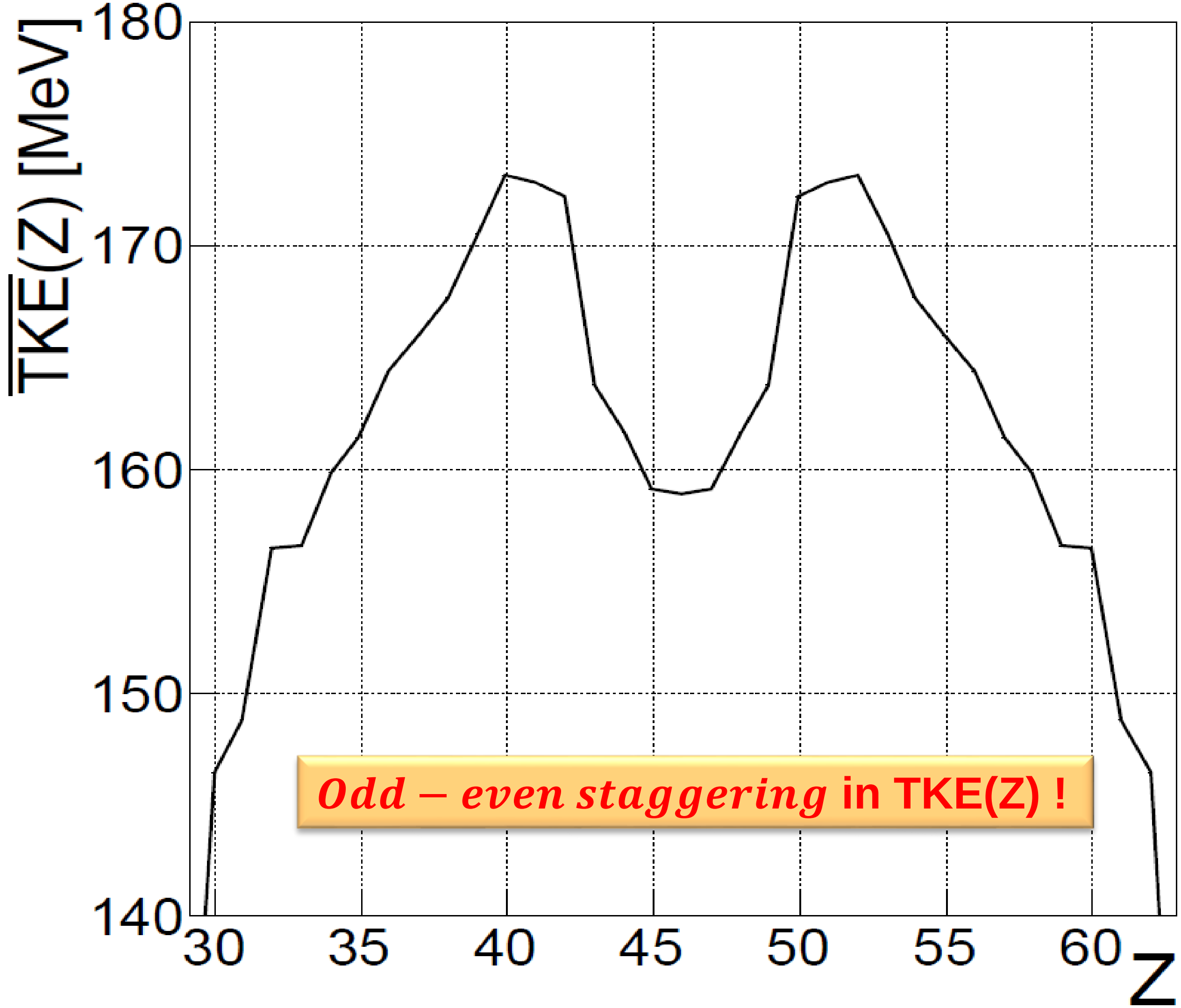
$\overline{\upsilon}$ VS A FOR Z = 50, , FISSION OF ^{235}U



Fission yields

1) Element
2) Isotonic
3) Isotopic
4) Mass
5) Prompt Neutrons $\overline{\nu}$
6) TKE

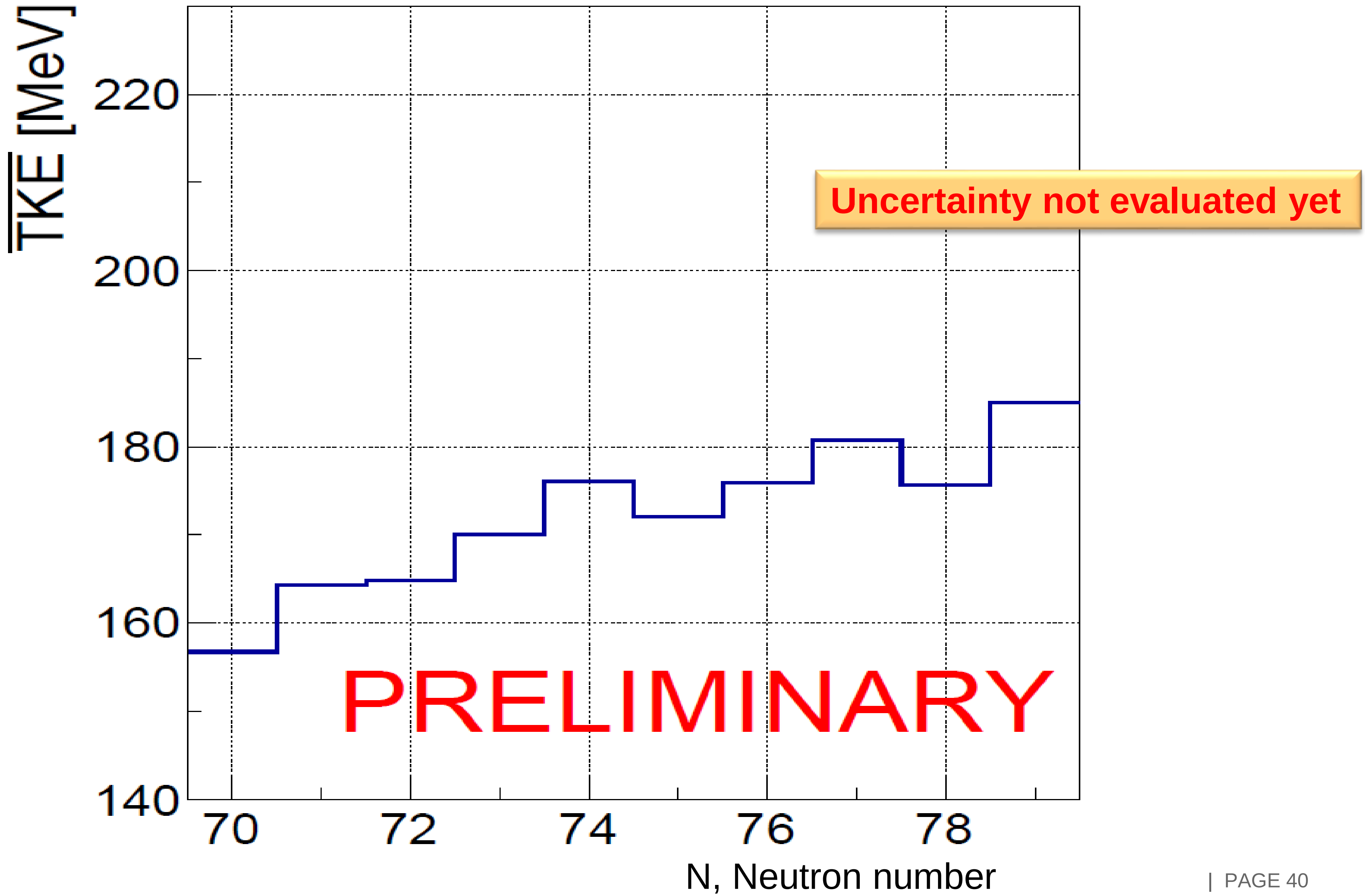
TKE VS Z , FISSION OF ^{235}U



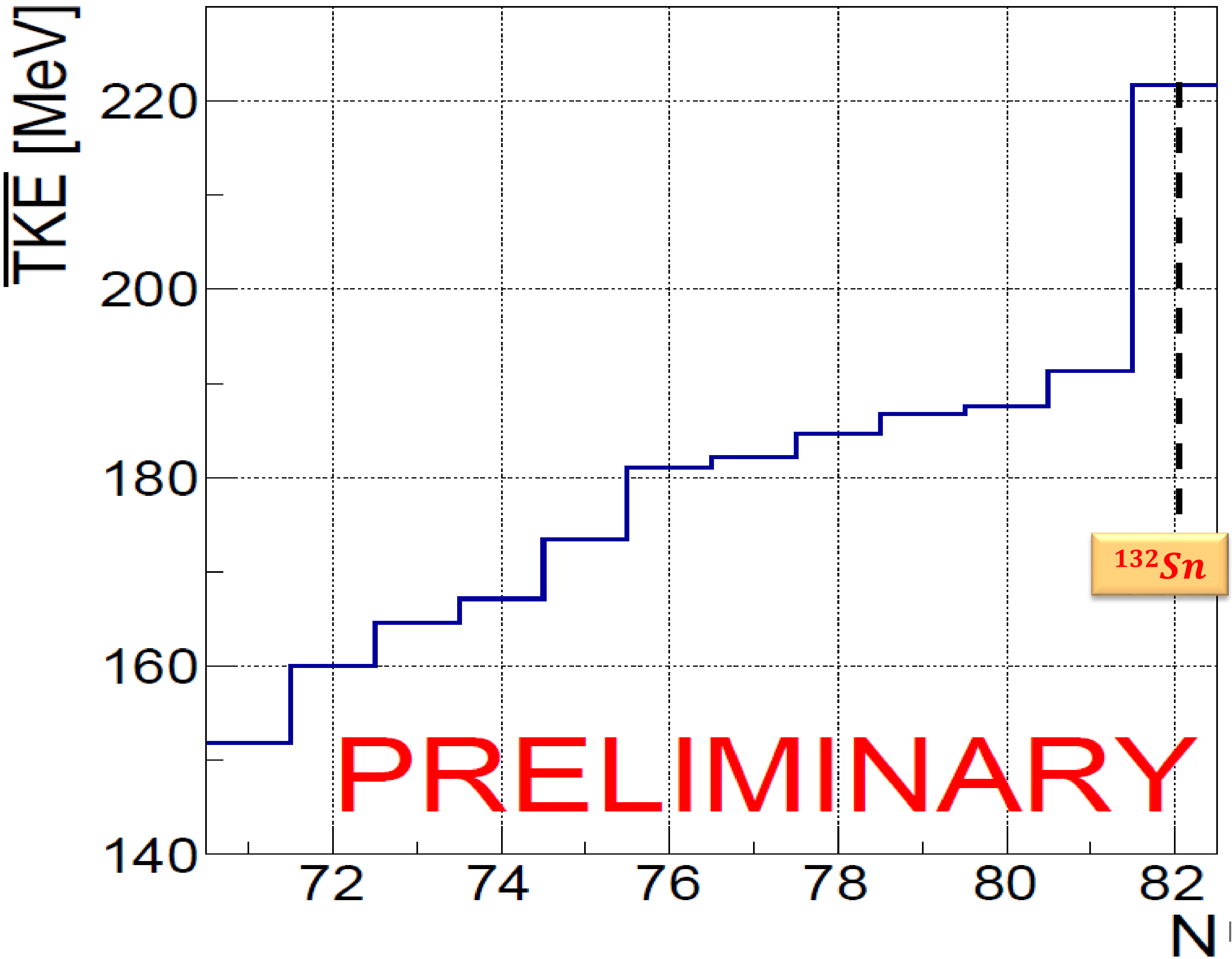
Odd – even staggering **in TKE(Z) !**

Harder to extract that in neutron induced fission
=> Hier uncertainty

TKE VS A FOR Z = 49, , FISSION OF ^{235}U



TKE VS A FOR Z = 50, FISSION OF ^{235}U



CONCLUSIONS

SOFIA1 provides new results :

- Fission of tens of nuclide studied in one experiment
- All fission fragments identified unambiguously for the 1st time in low energy fission

- Nuclear charge resolution = 0,4 u FWHM
- Mass resolution = 0,8 u FWHM for A = 140
- Typical uncertainty on isotopic yields < 5 %
- Big step forward w/ respect to previous knowledge

- Detailed information on fission modes
- New data on the scission configurations
  - Total kinetic energy
  - Number of emitted neutrons

The SOFIA collaboration

CEA

GSI

IPN – INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

CENBG

GANIL spiral2 – laboratoire commun CEA/DSM CNRS/IN2P3

USC – UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

UNIVERSIDADE DE VIGO

CHALMERS UNIVERSITY OF TECHNOLOGY

PERSPECTIVES

- L'^{238}U : 1 noyau sur les 80 mesurés → Intérêt aussi dans les systématiques
- SOFIA 2 en 2014

Futur 1 : R3B

- Aimant GLAD : 4,8 T.m. (ALADIN 2,2 T.m.)
- CALIFA : Mesure des gammas
- NEULAND : Mesure des neutrons (par fragment ?)
- Répartition de l'énergie dans la fission

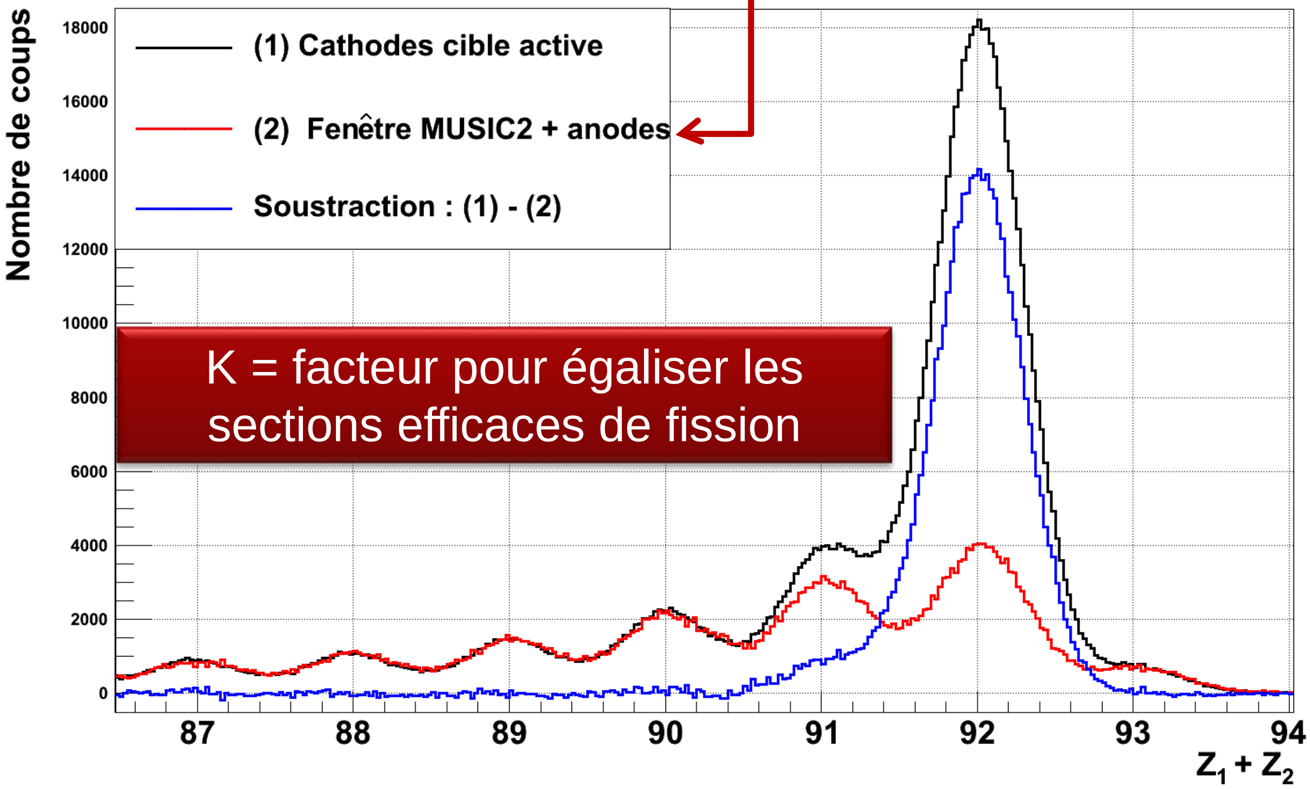
Futur 2 : FELISE @ FAIR

- Fission at ELISE : excitation électromagnétique par des e- : E* mesurée

SOUSTRACTION DE LA COMPOSANTE RÉSIDUELLE

La Sélection Z1+Z2 = 92 : n'élimine que les fissions de haute énergie ou des **PROTONS** sont enlevés

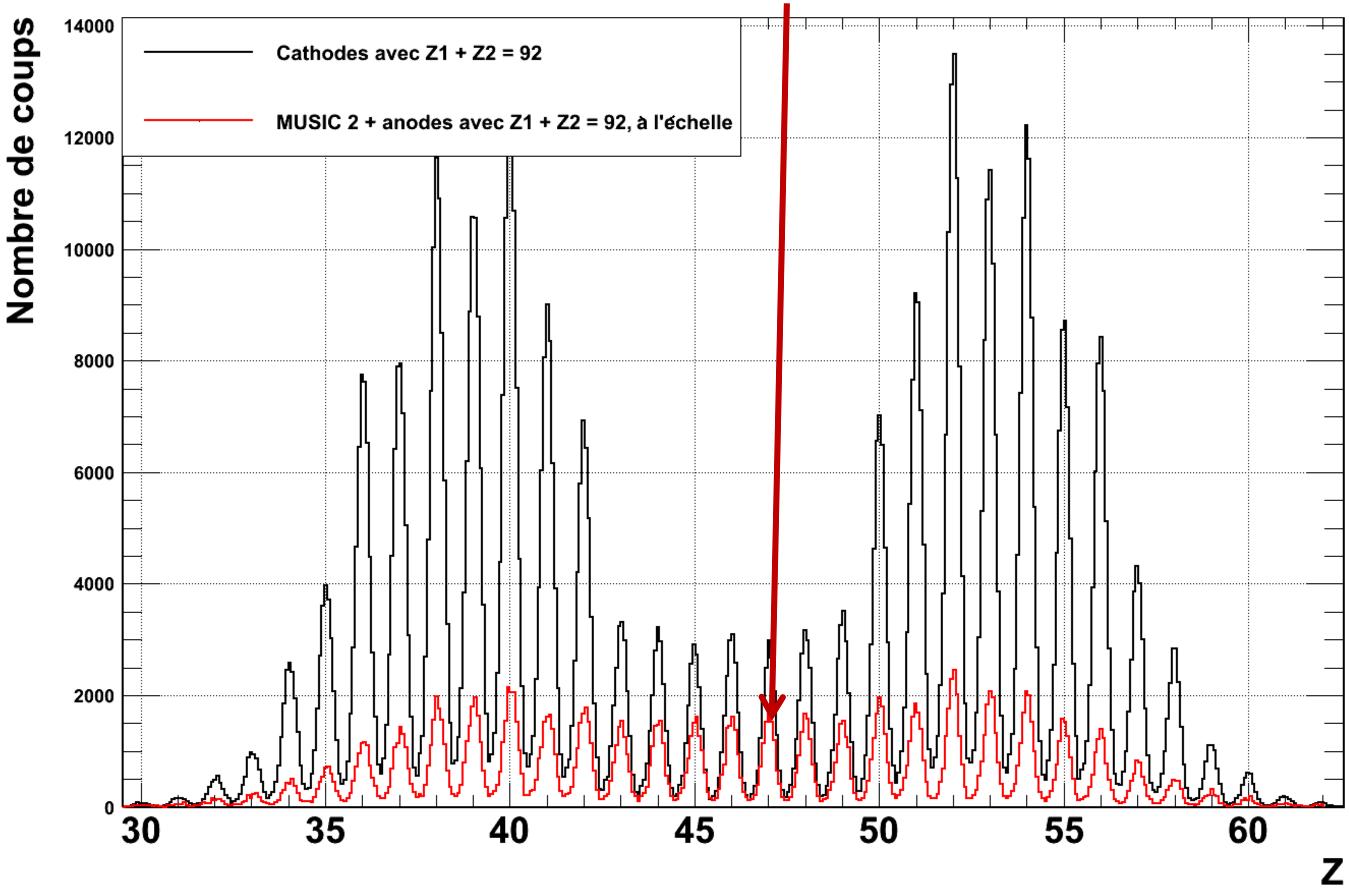
Suppression de la composante ou seuls des **NEUTRONS** sont enlevés ? → Utilisation des fissions dans les matériaux légers (pas de fission e.m.)



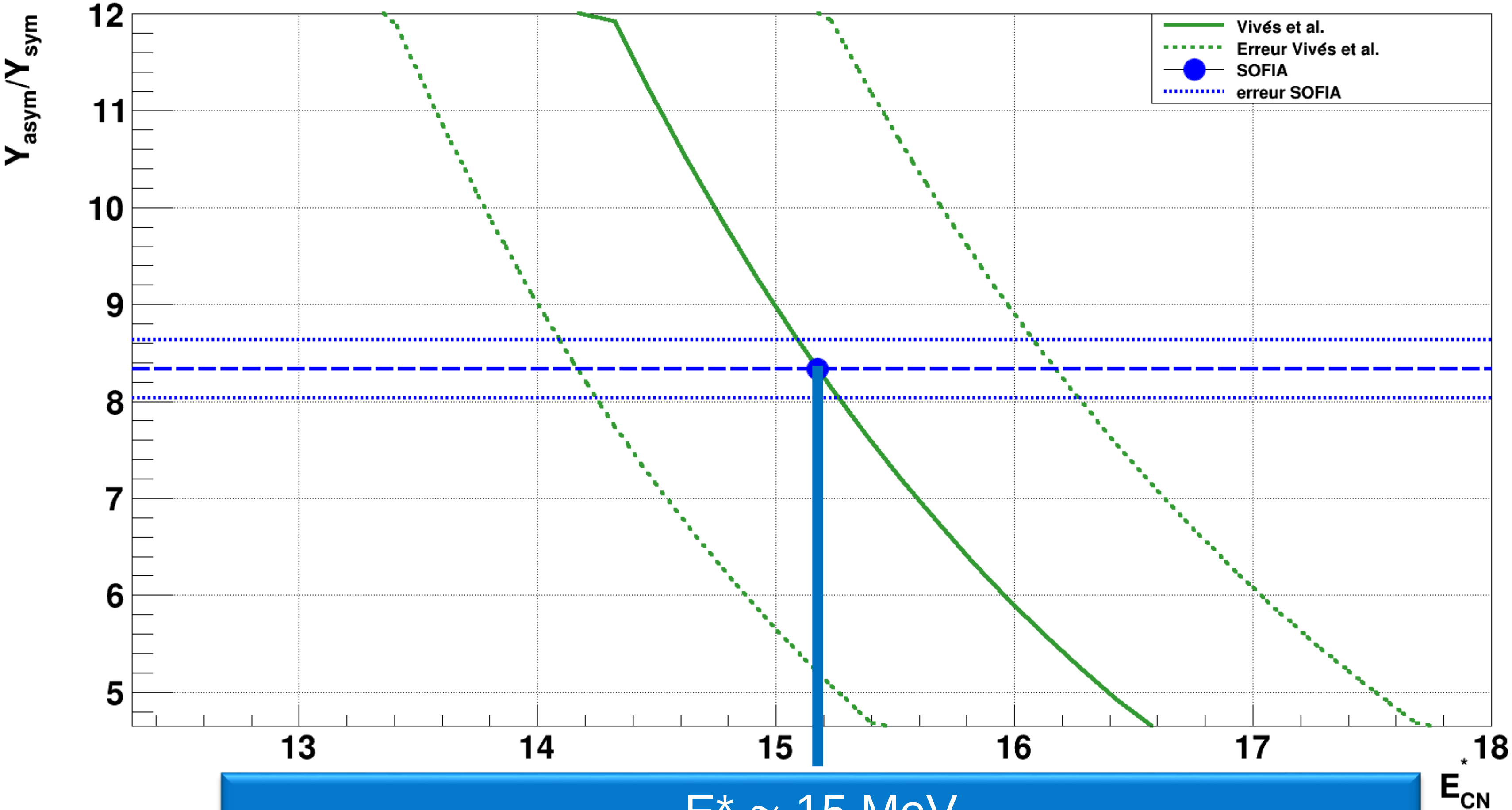
SOUSTRACTION DE LA COMPOSANTE RÉSIDUELLE

La Sélection Z1+Z2 = 92 : n'élimine que les fissions de haute énergie où des **PROTONS** sont enlevés

Suppression de la composante où seuls des **NEUTRONS** sont enlevés ? → Utilisation des fissions dans les matériaux légers (fissions nucléaires uniquement)



MASSES - PIC/VALLÉE VS E*



E* ≈ 15 MeV
Consistant avec la valeur de 14 MeV attendue (calculs)

Fission induite par neutron

n → A (J_i,π_i) = A+1 (J_f,π_f)

$J_f = J_i + 0.5$ si neutron thermique

$J_f = J_i + 0.5 + L$, avec L = f(E neutron)

$\pi_f = \pi_i$ si neutron thermique

$= \pi_i \times (-1)^L$

Fission induite par e.m.

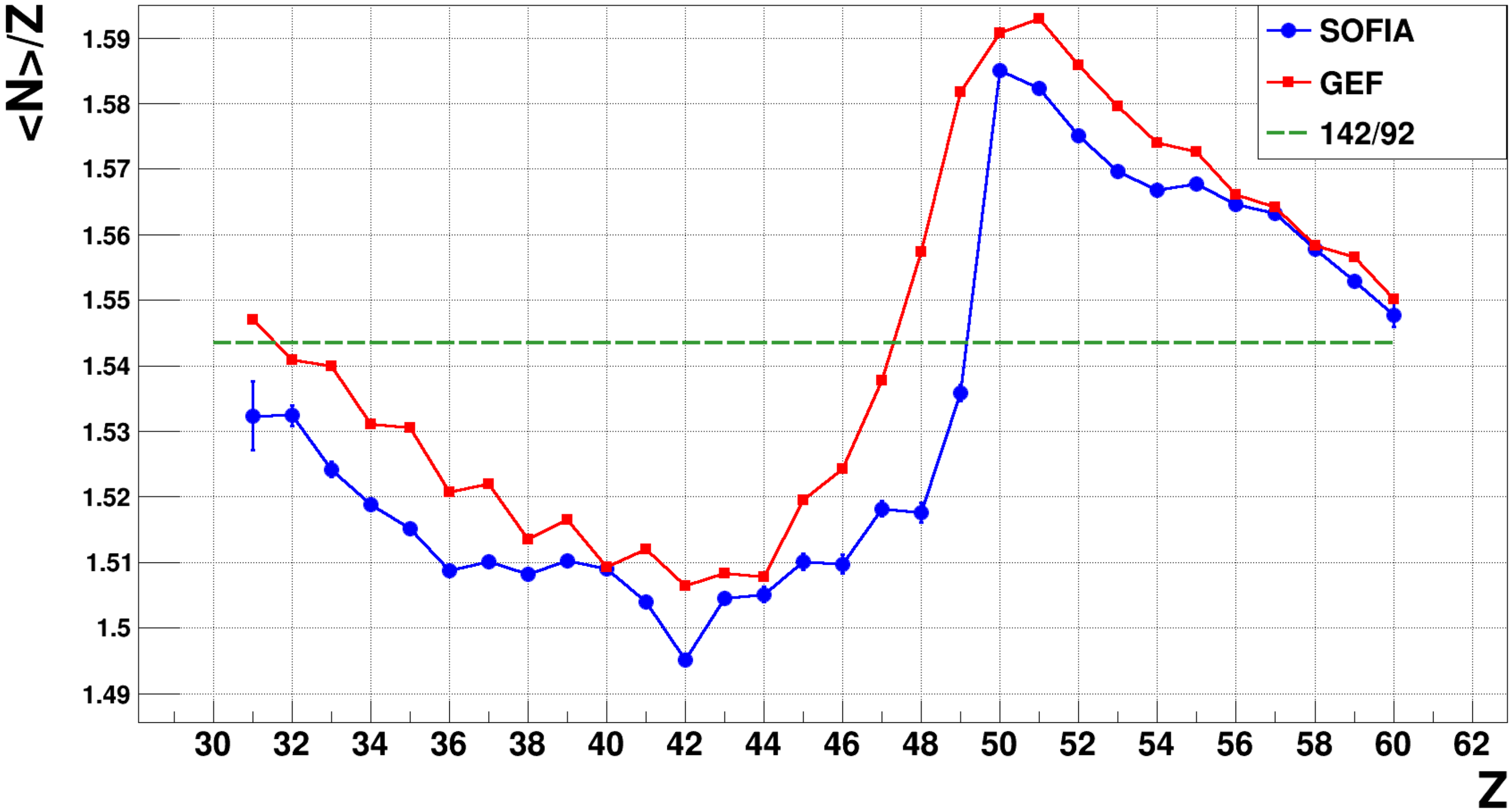
A+1 (J_i,π_i) + GDR : T = 1, L = 1, S = 0 = A+1 (J_f,π_f)

$J_f = J_i + 1$

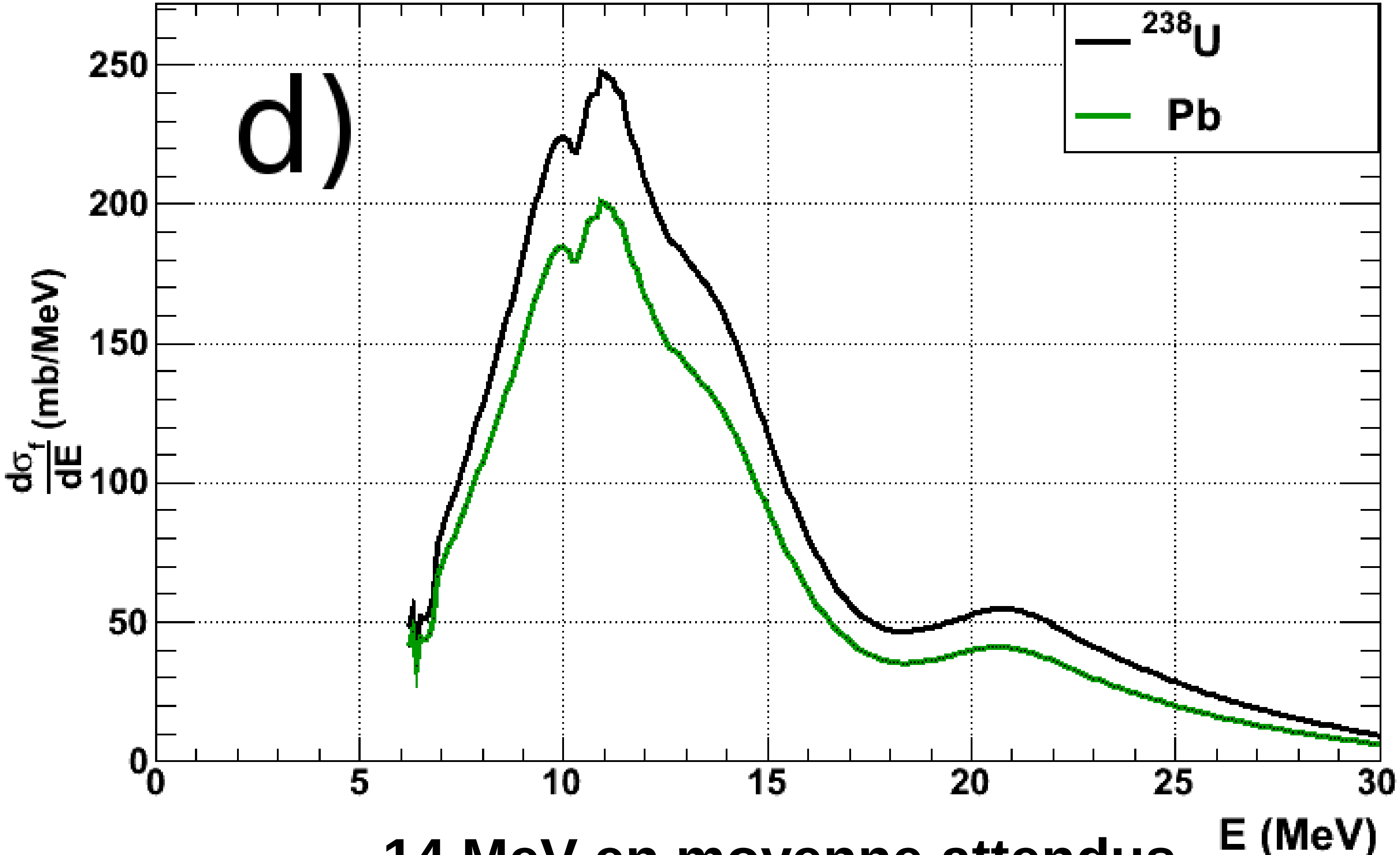
$\pi_f = -\pi_i$

Exemple : fission de l'U8 sur SOFIA :
U8 : GS = 0+ ; apres e.m. GDR : U8 : 1-
U7 : GS = 1/2+

POLARISATION EN CHARGE

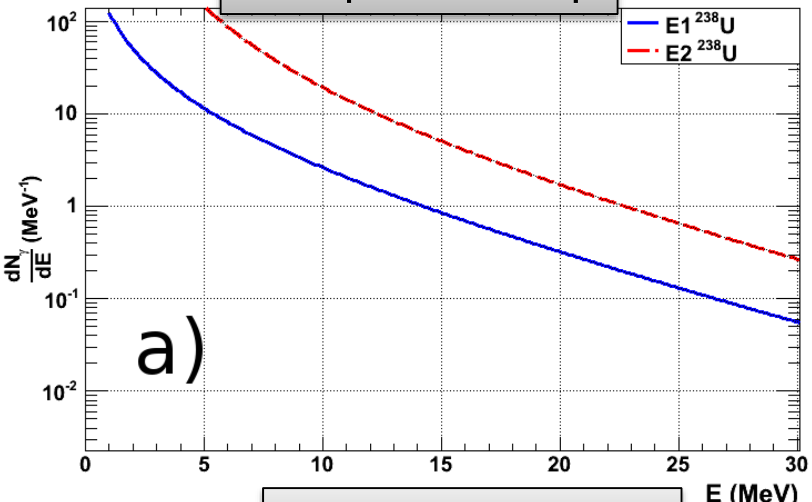


SPECTRE D'EXCITATION À LA FISSION

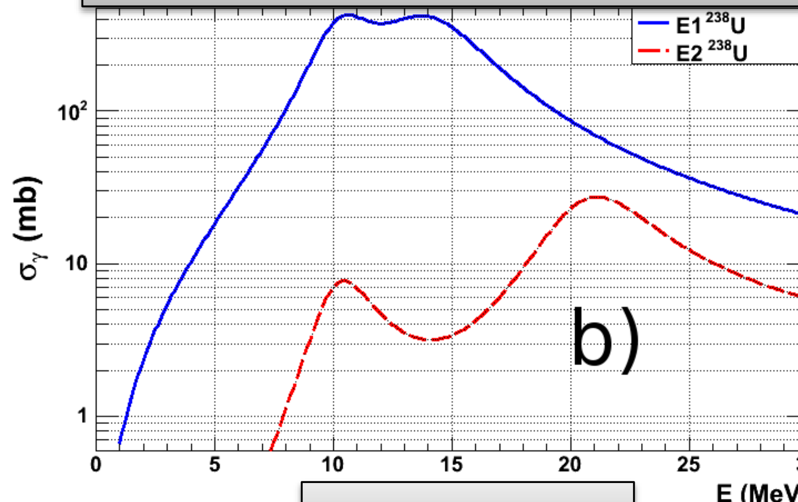


14 MeV en moyenne attendus

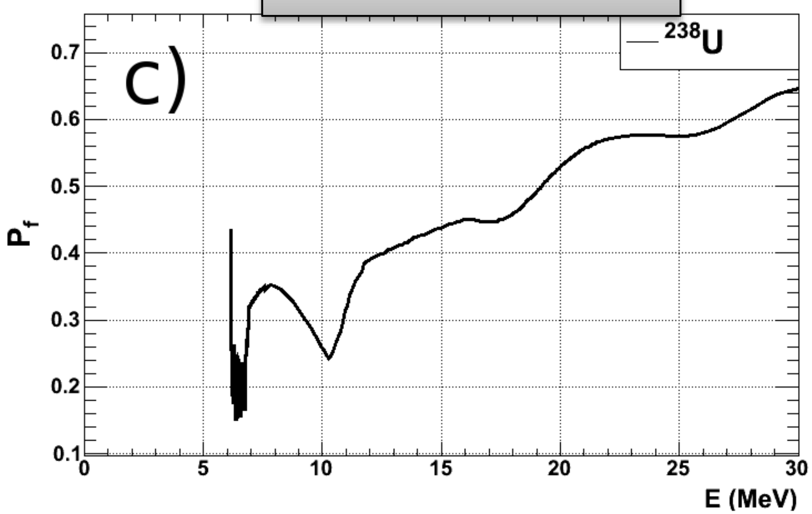
Flux photons eq.



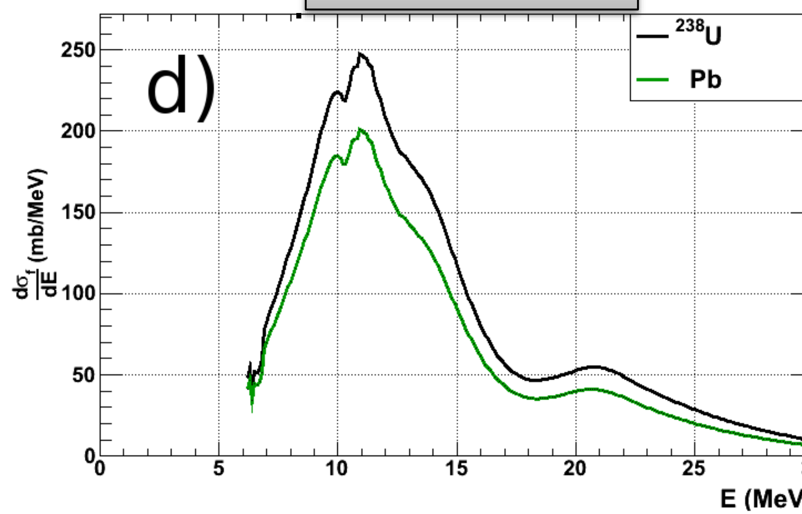
Flux photons eq. x (GDR , GQR)

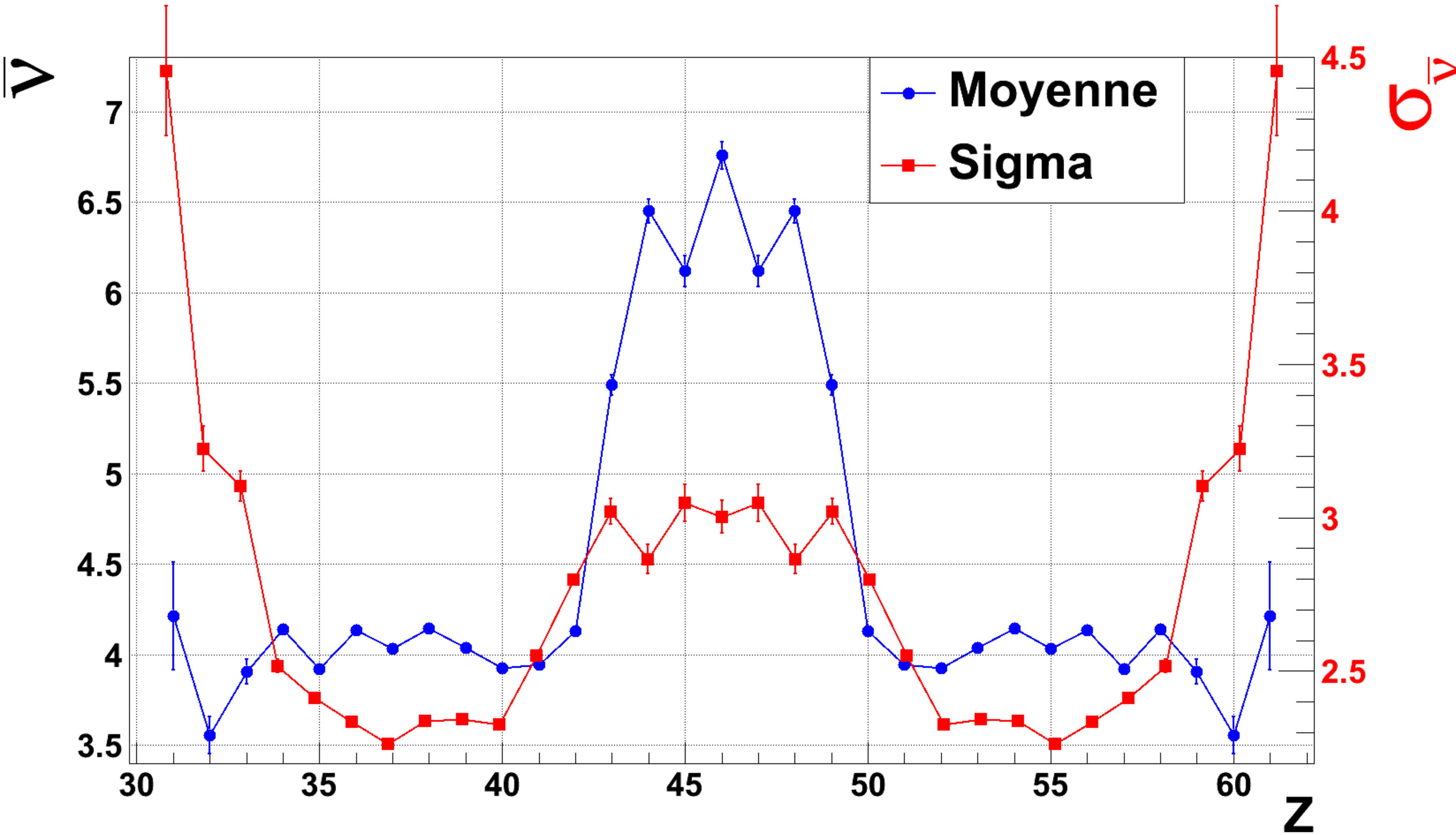


Probabilité fission



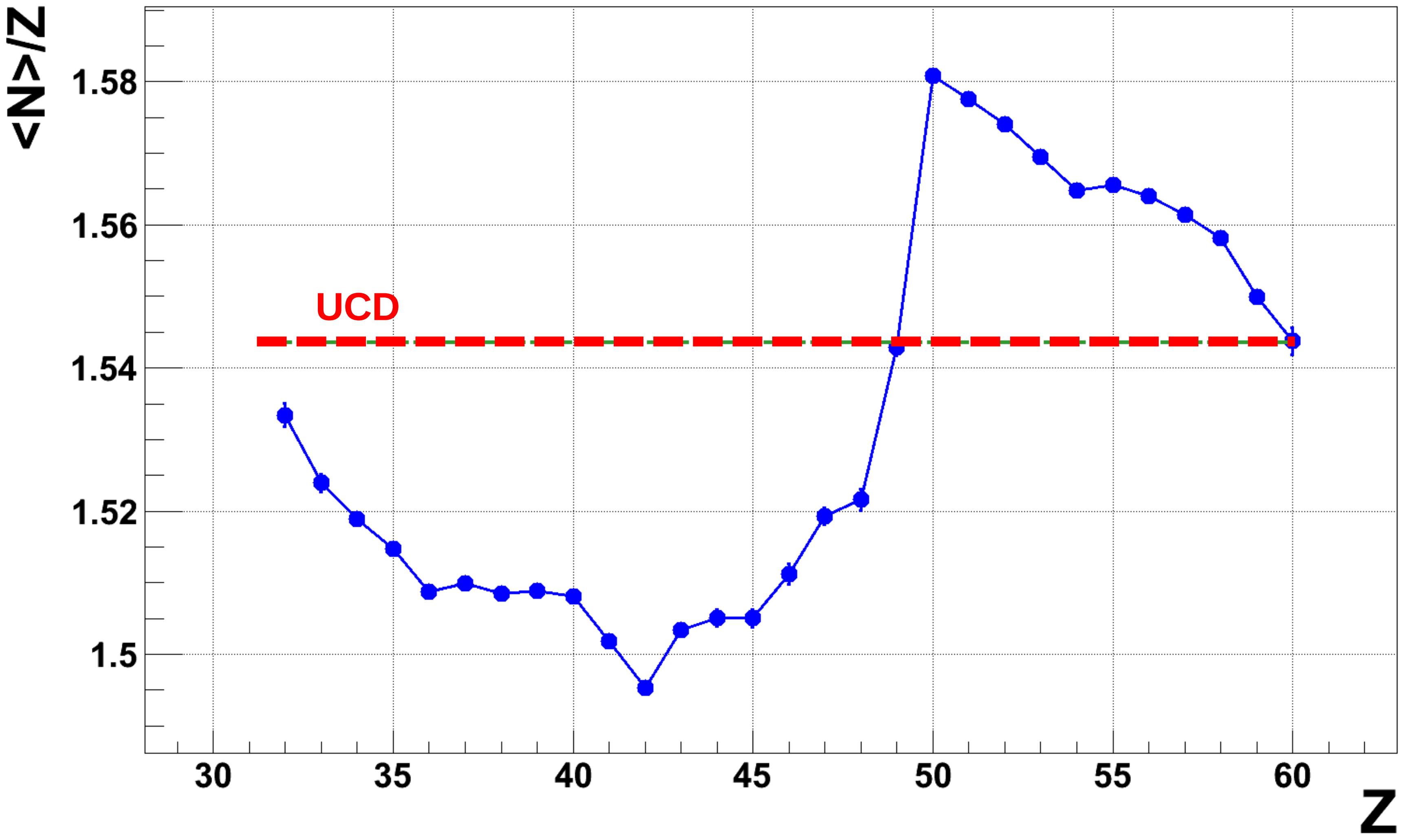
E* a la fission



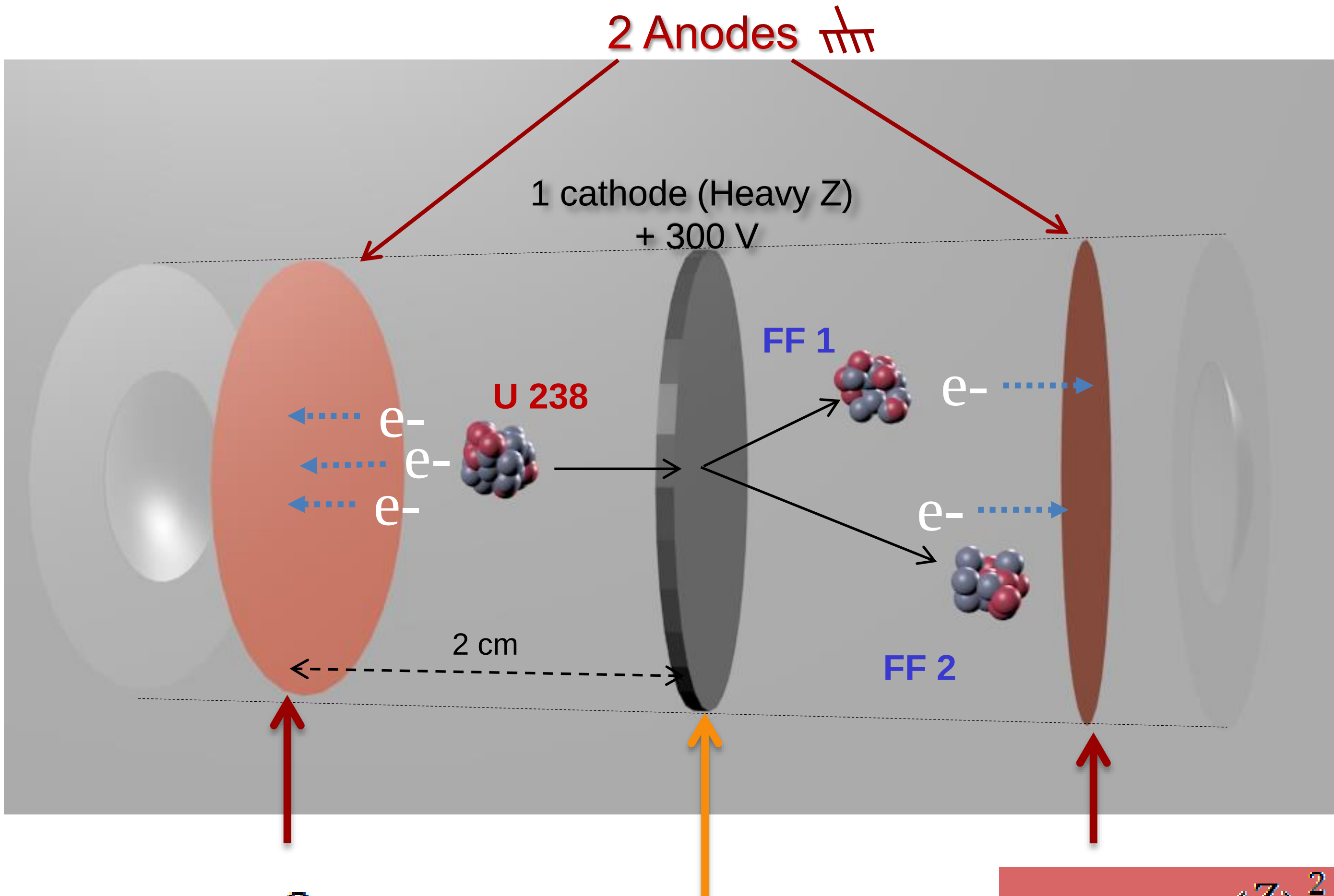


$\bar{\nu}$
7
6.5
6
5.5
5
4.5
4
3.5
30
35
40
45
50
55
60
Z
4.5
4
3.5
3
2.5
$\sigma_{\bar{\nu}}$
Moyenne
Sigma

CHARGE POLARIZATION



ACTIVE TARGET

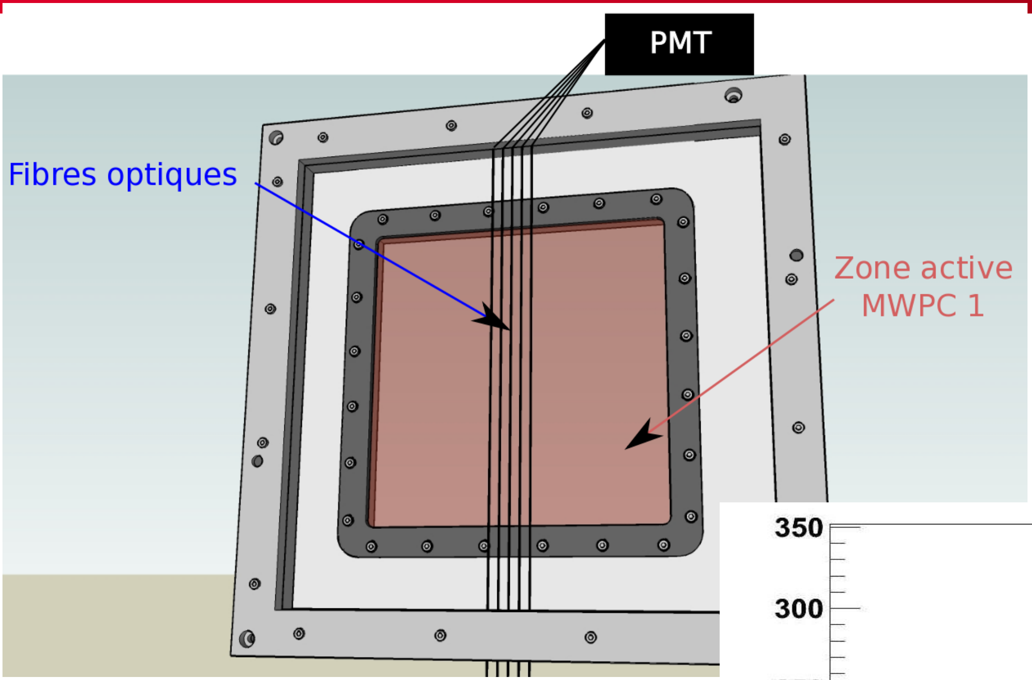


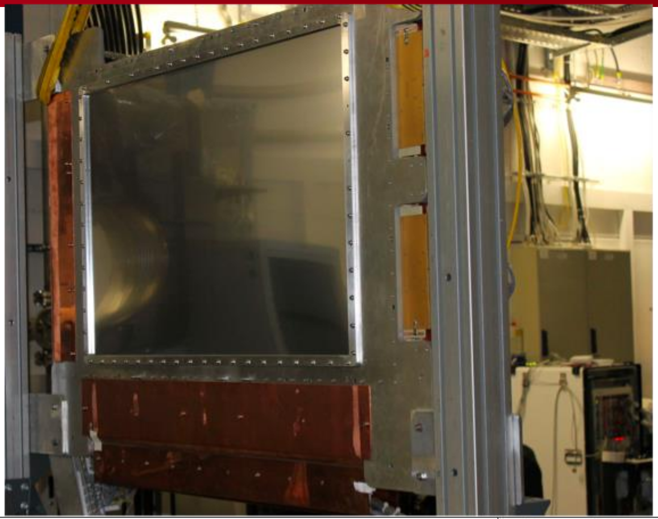
$$A1 \propto Z^2$$

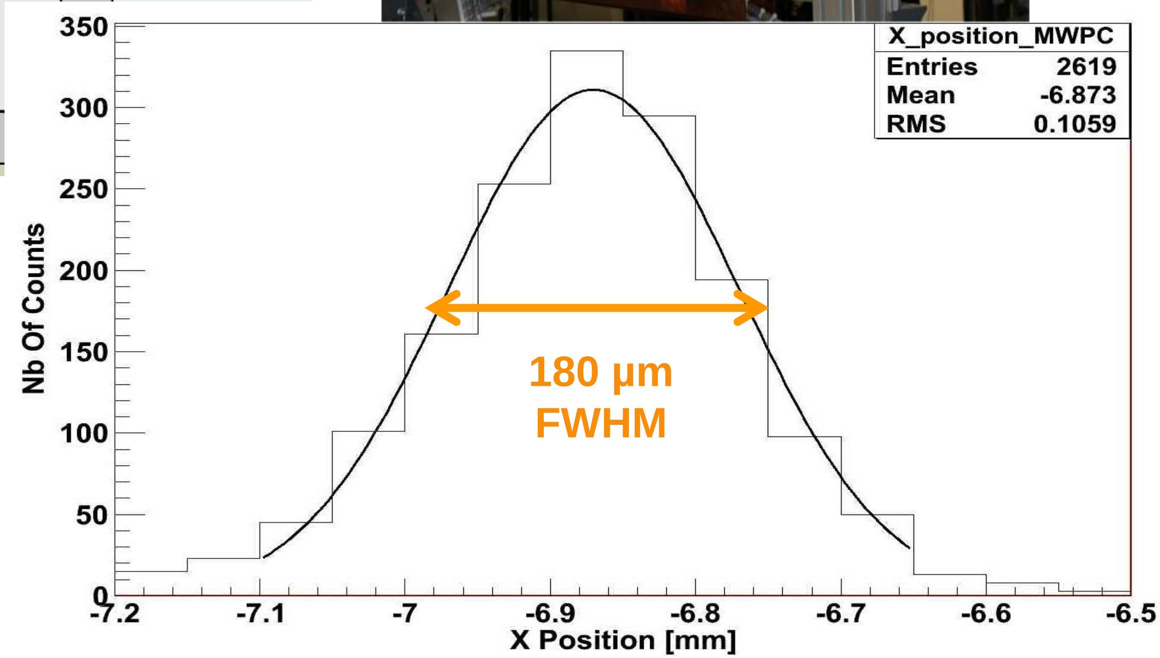
Coulomb excitation
(photon exchange)

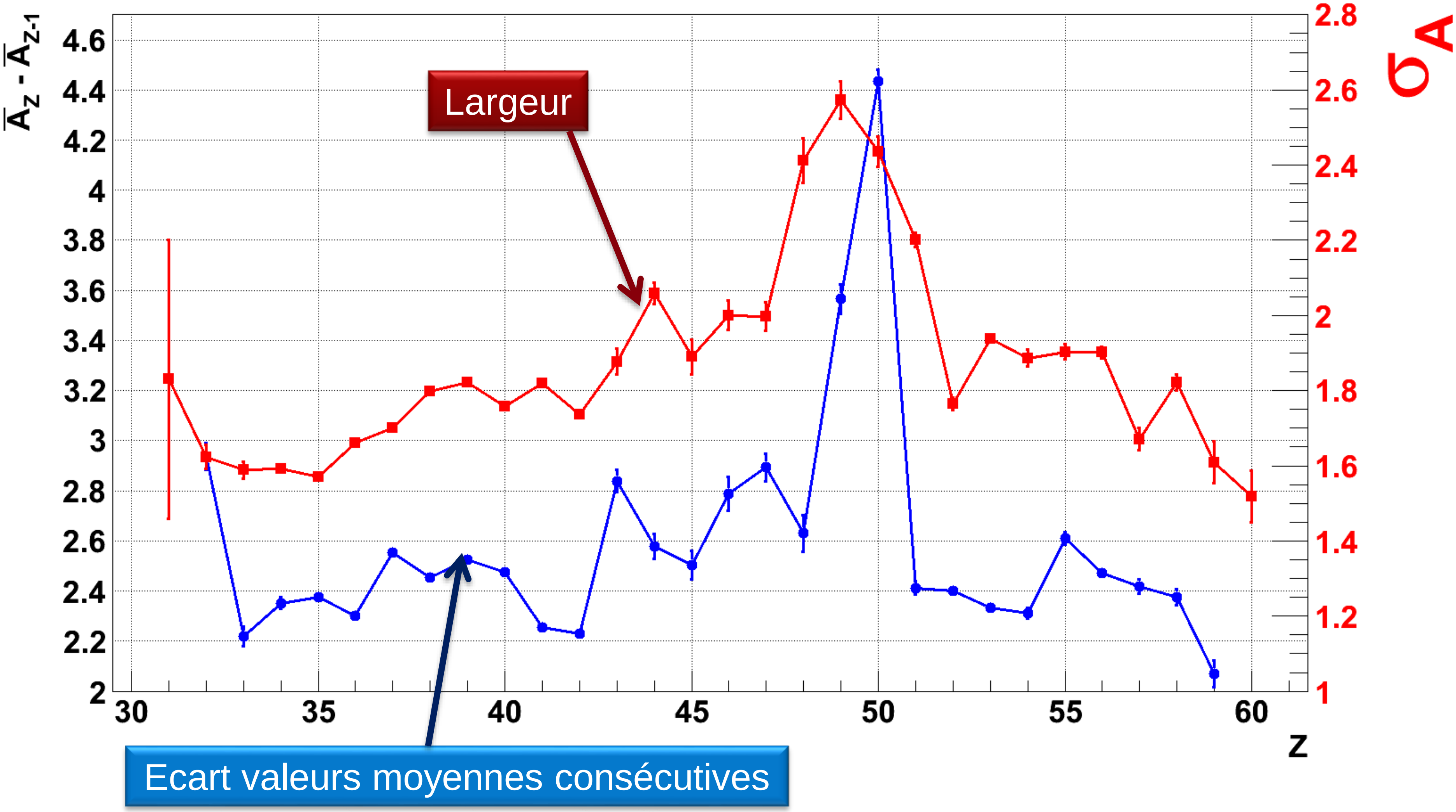
$$A2 \propto 2 * \left(\frac{Z}{2}\right)^2 = \frac{Z^2}{2}$$

MWPC : RÉSOLUTION EN POSITION

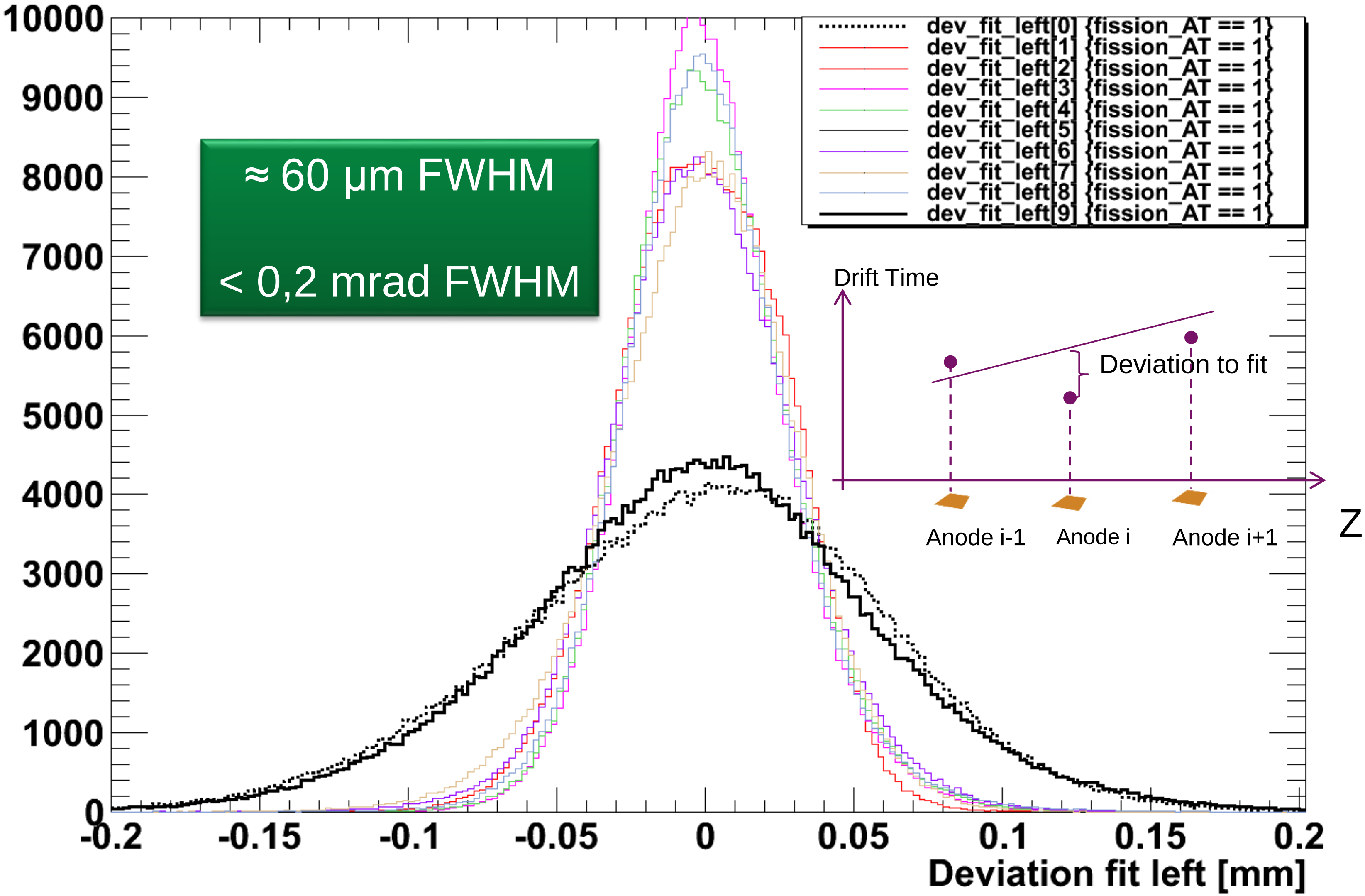






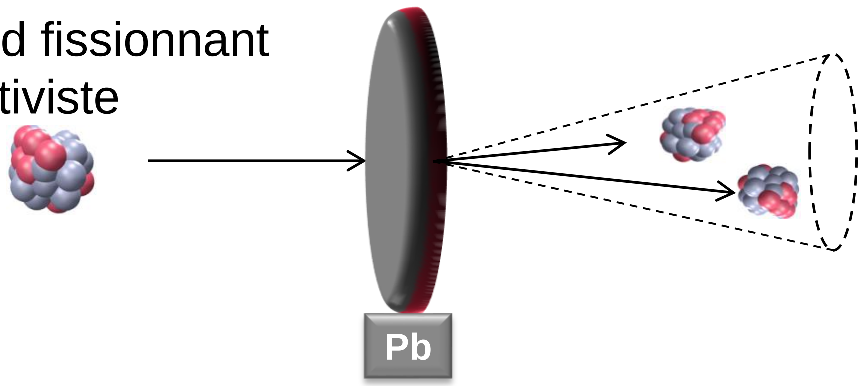

$\bar{A}_Z - \bar{A}_{Z-1}$
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
30
35
40
45
50
55
60
Z
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
σA
Largeur
Ecart valeurs moyennes consécutives

MUSIC : ANGLE RESOLUTION

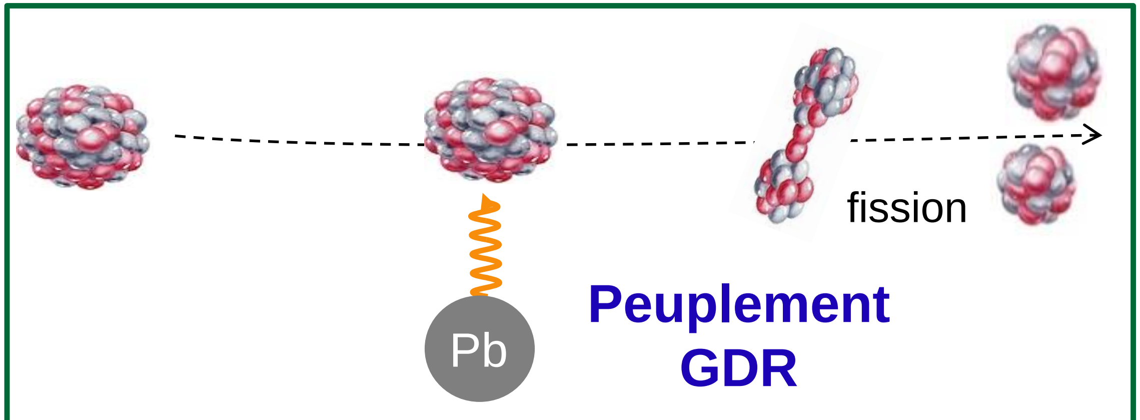


FISSION EN CINÉMATIQUE INVERSE RELATIVISTE

Noyau lourd fissionnant relativiste



- Etude de noyaux radioactifs
- Q = Z
- ϵ_{geom} importante



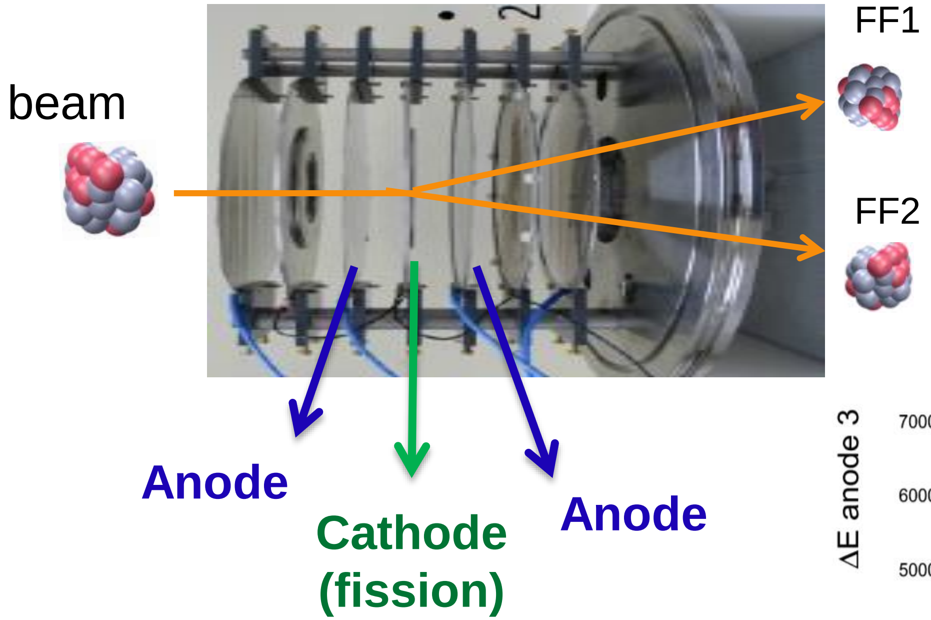
Excitation électromagnétique

E* ≈11 MeV

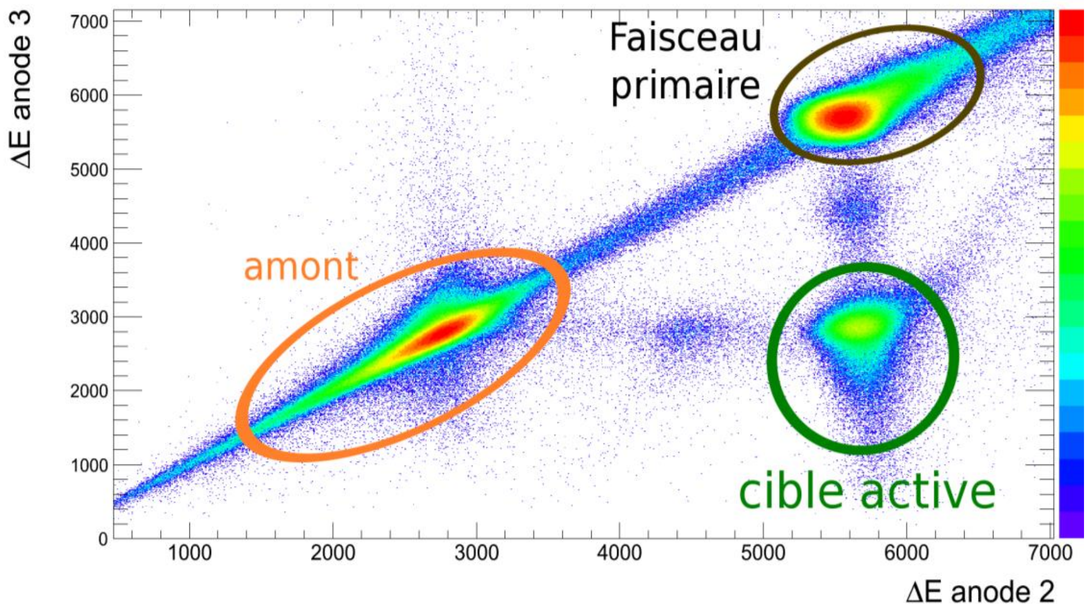
Fission de l'^{238}U en cinématique inverse ⬄ n (≈6 MeV) + ^{237}U

The detectors

Stack of ionisation chambers



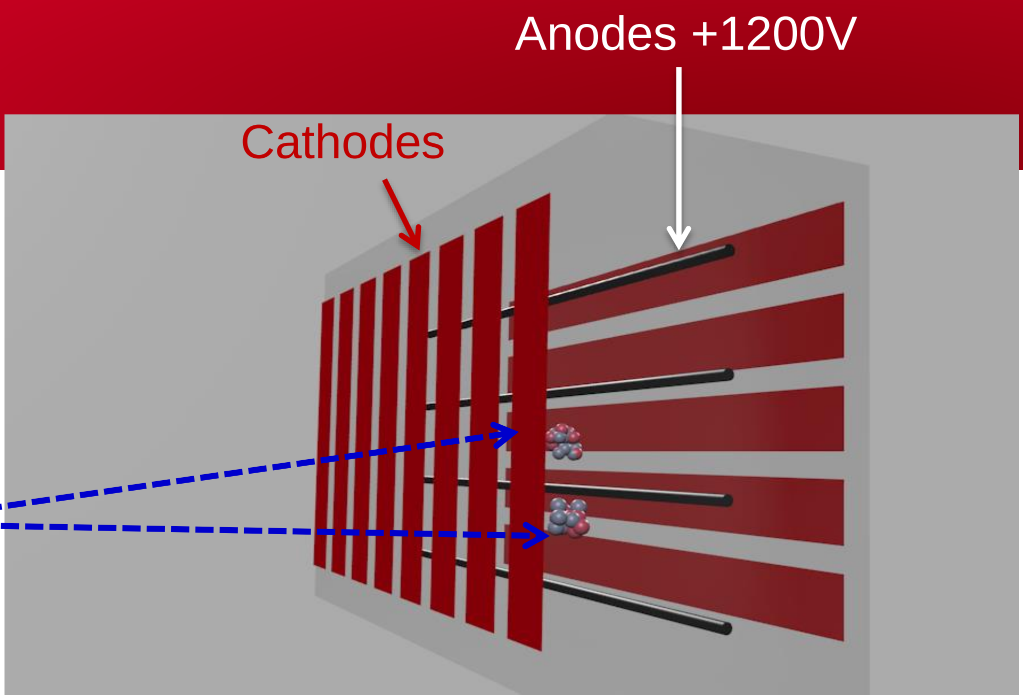
$$\Delta E(FF1) + \Delta E(FF2) \approx \frac{\Delta E(^{238}U)}{2}$$



- ❑ **Fission in the cathodes**
- ❑ **Anodes : provide ΔE**

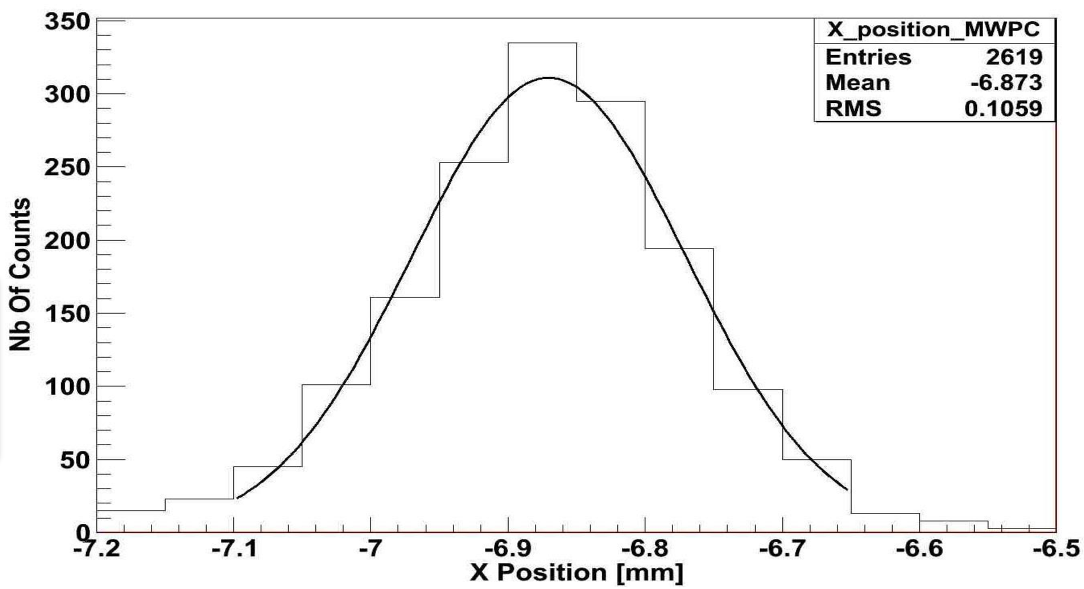
MWPCs

1) Création d'e- d'ionisation
2) Avalanche d'e- autour des fils d'anodes
3) Influence sur les pistes de cathode



INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

200 μm requis en X
135 μm mesures FWHM



DISPOSITIF TEMPS DE VOL

Haute énergie et base de vol courte (7.5 m) :

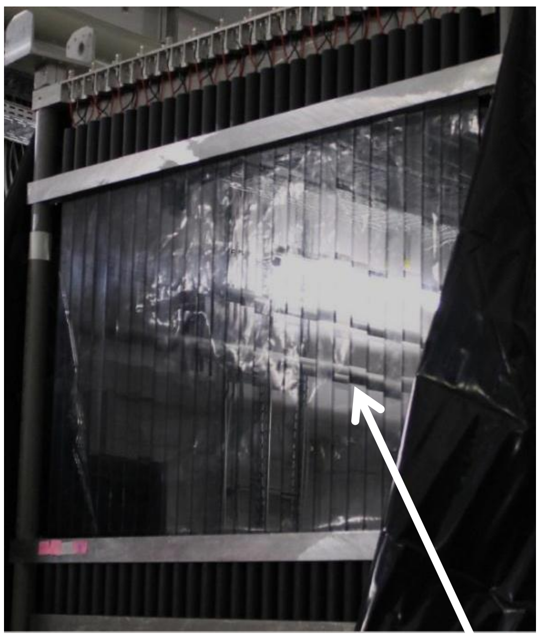
Nécessaire pour séparer A lourds : **40 ps FWHM**

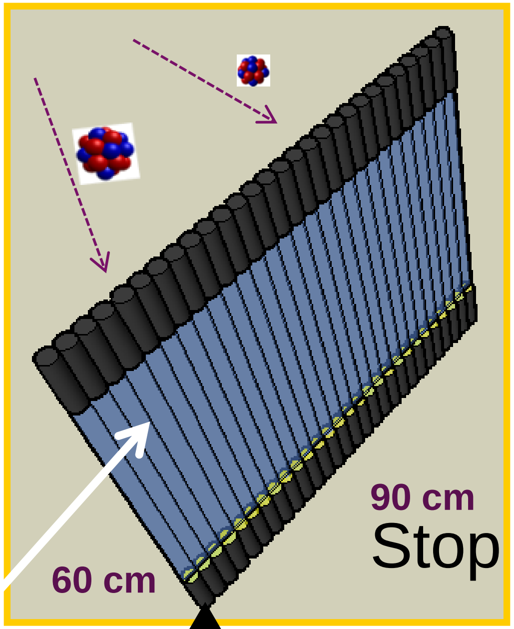
Au GSI : 100 ps **FWHM au mieux**

Bruyères-Le-Châtel

Stop : contrainte de taille :

- Dimensions : 90 * 60 cm^2 (dispersion du dipôle)

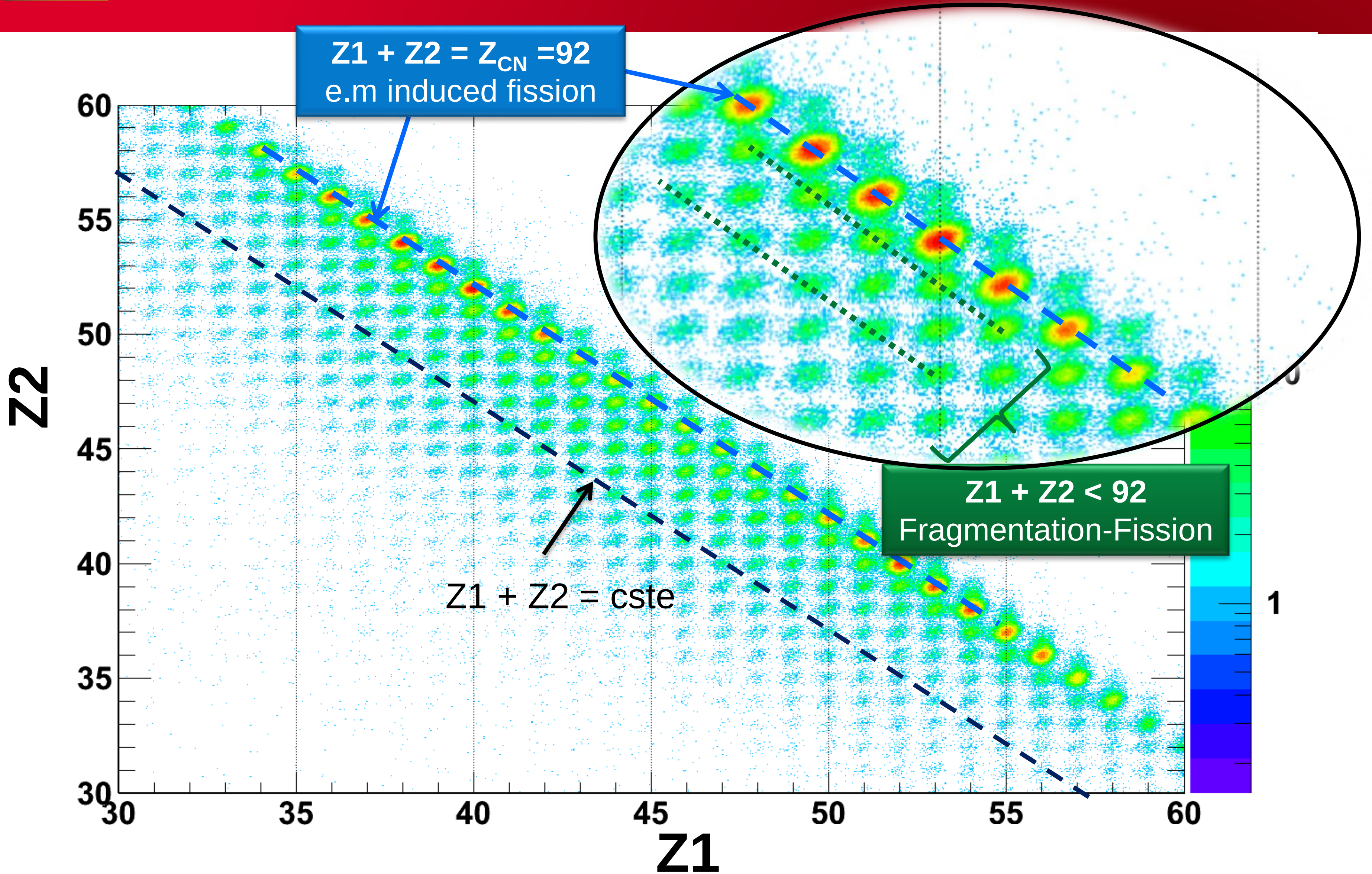




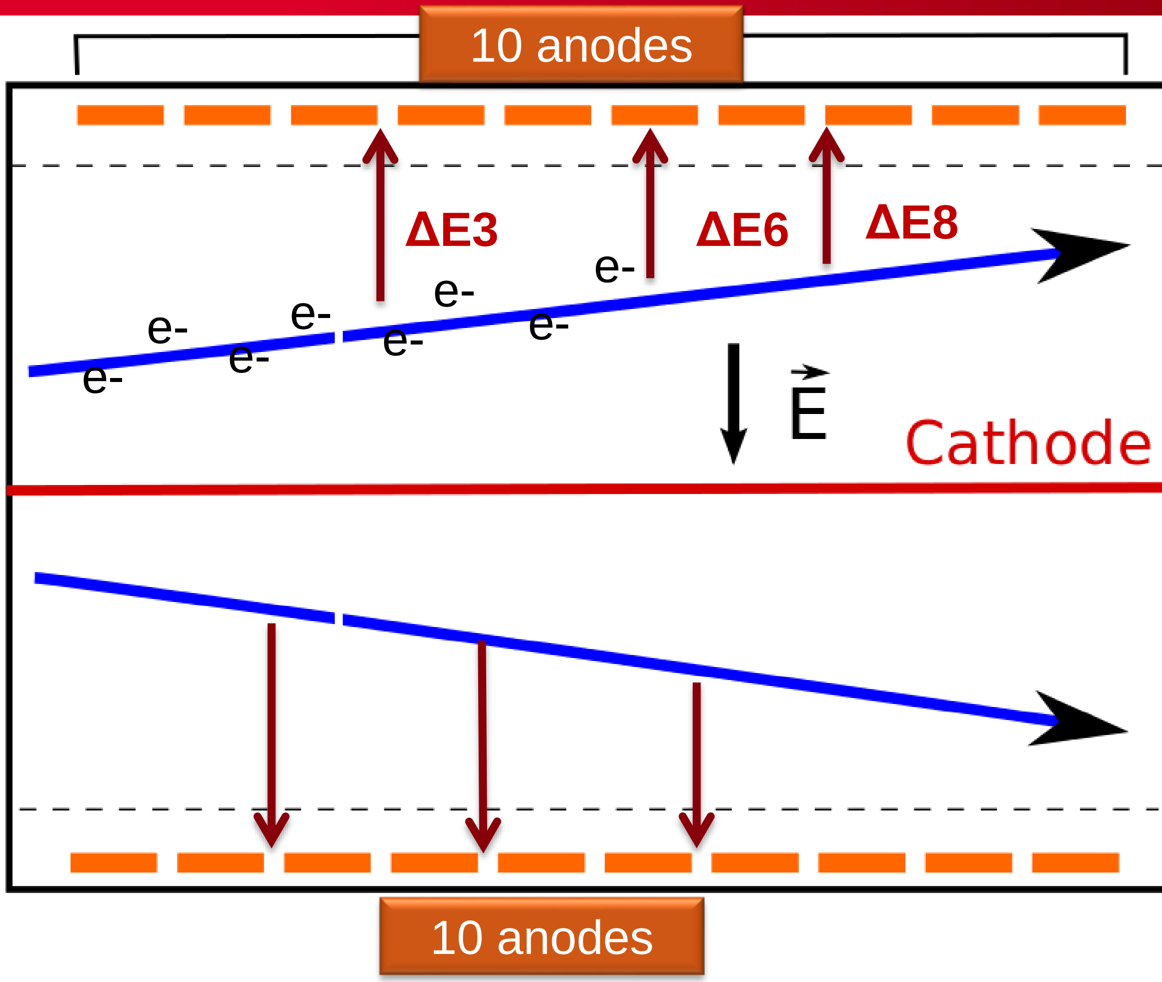
A. Ebran *et al.*, NIM A 728 (2013) 40-46

28 scintillateurs ⬄ 56 PMTs

Z2 VS Z1


Z1 + Z2 = Z_{CN} =92
e.m induced fission
Z1 + Z2 < 92
Fragmentation-Fission
Z1 + Z2 = cste
Z2
Z1
60
55
50
45
40
35
30
1

TWIN MUSIC : MULTI-SAMPLE IONISATION CHAMBER

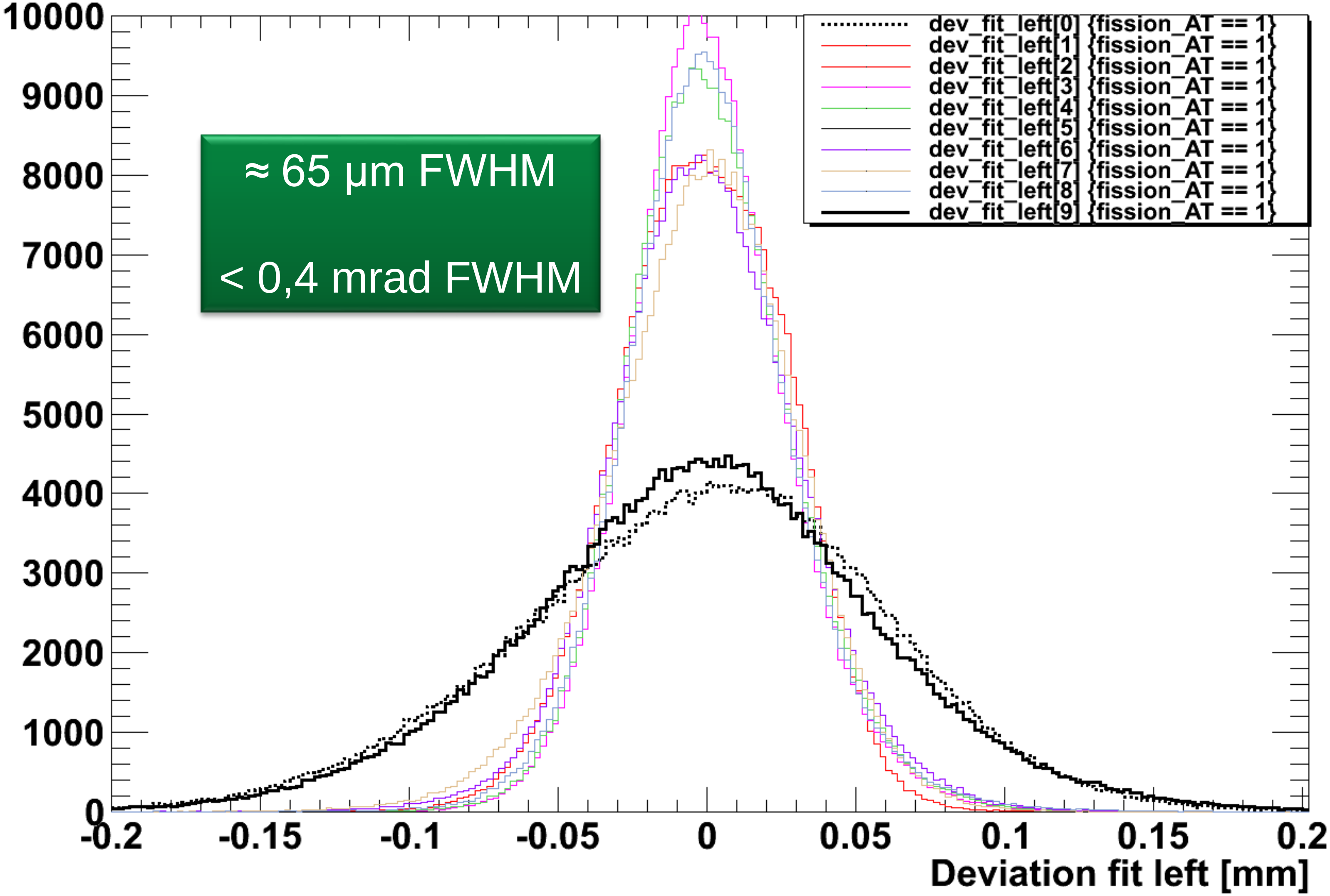


Upper view

ΔEi : energy losses → Z

ΔTi : drift time → θ

MUSIC : ANGLE RESOLUTION



TOF RESOLUTION