Fission In Inverse Kinematics at GANIL

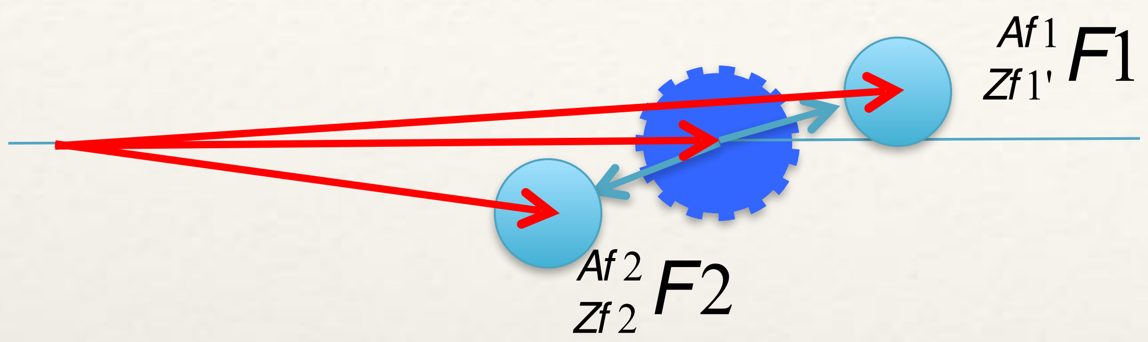
Diego Ramos

ISS Workshop

Liverpool, 27th -28th August 2019

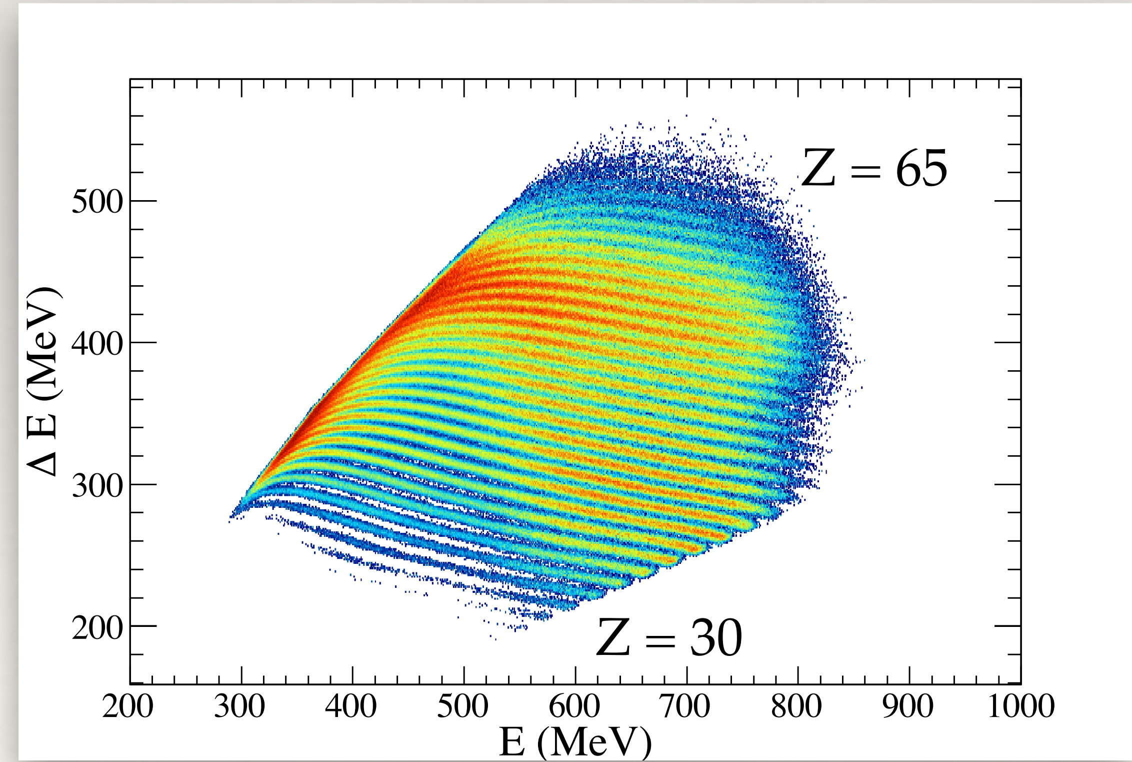
Inverse Kinematics

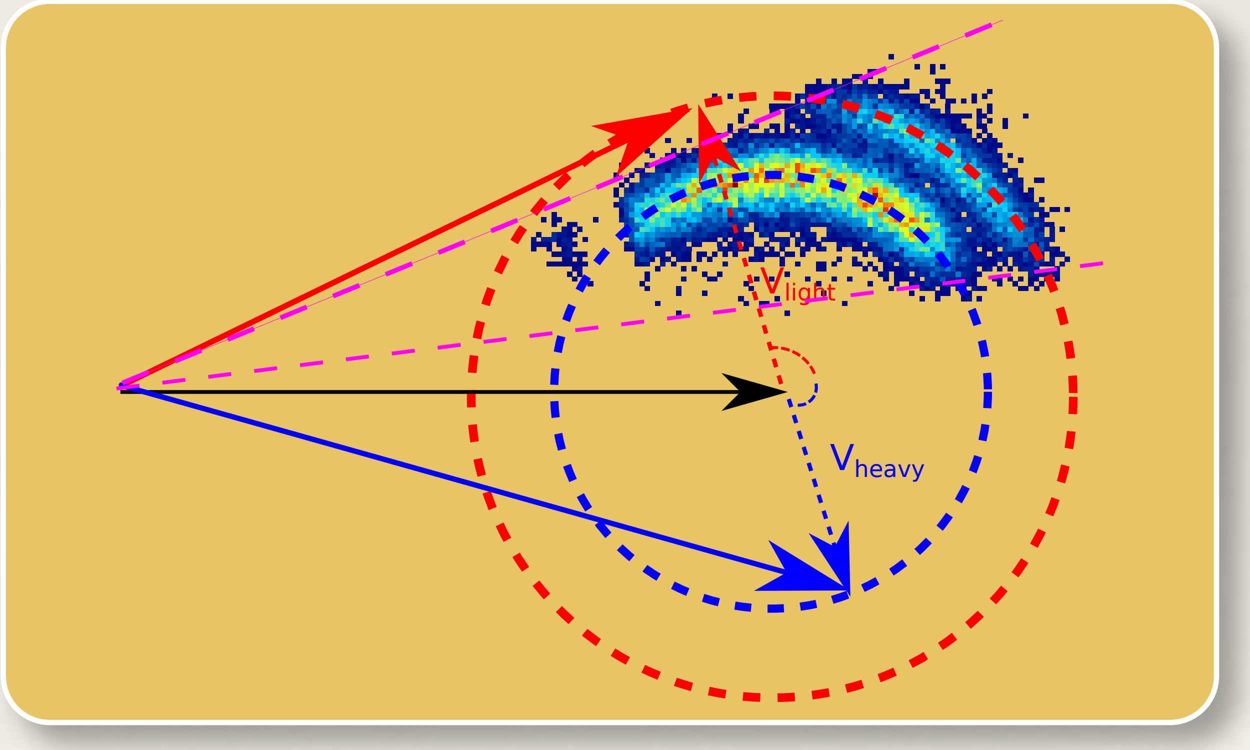
Beam: ^{238}U @ ~6 MeV/u



Coulomb energies provide low angular straggling and small Lorentz boost: **good velocity resolution in CM**

Inverse kinematics provide the capability of fission-fragments **nuclear-charge** identification

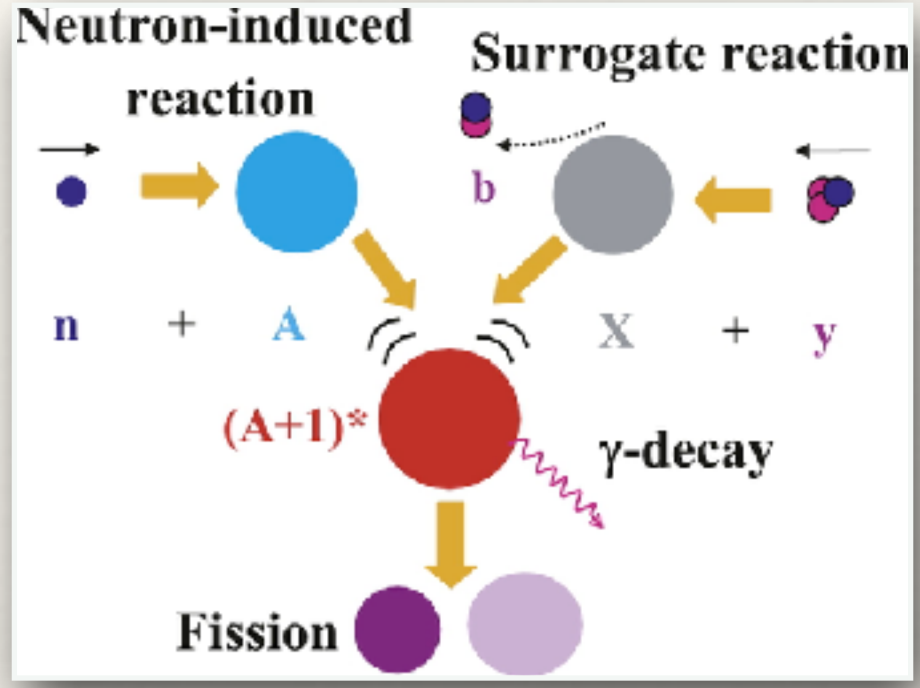




^{240}Pu ($\langle E_x \rangle = 10$ MeV)

Surrogate Reactions

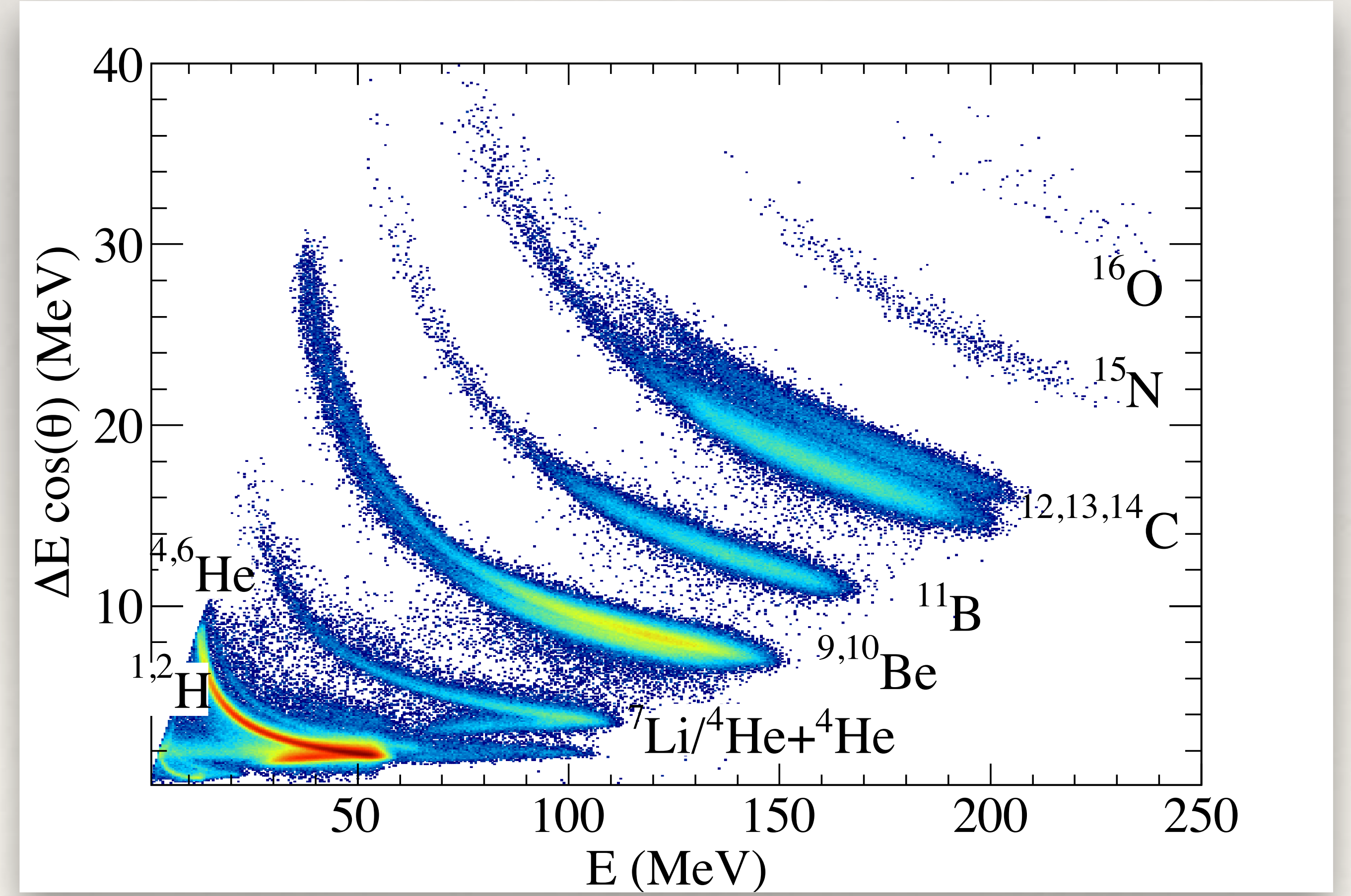
Target: ^{12}C, ^{9}Be, ^{7}Li (~200 μg/cm²)



Surrogate reactions give access to **exotic fissioning systems**, impossible to produce through n-induced reactions

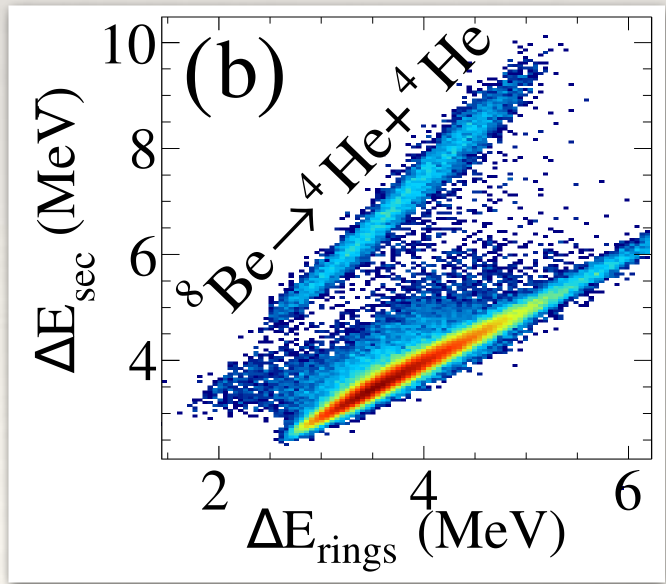
$^{238}U\ (^{12}C,\ ^{11}B)\ ^{239}Np^*$

$^{238}U\ (^{12}C,\ ^{6}He)\ ^{244}Cm^*$

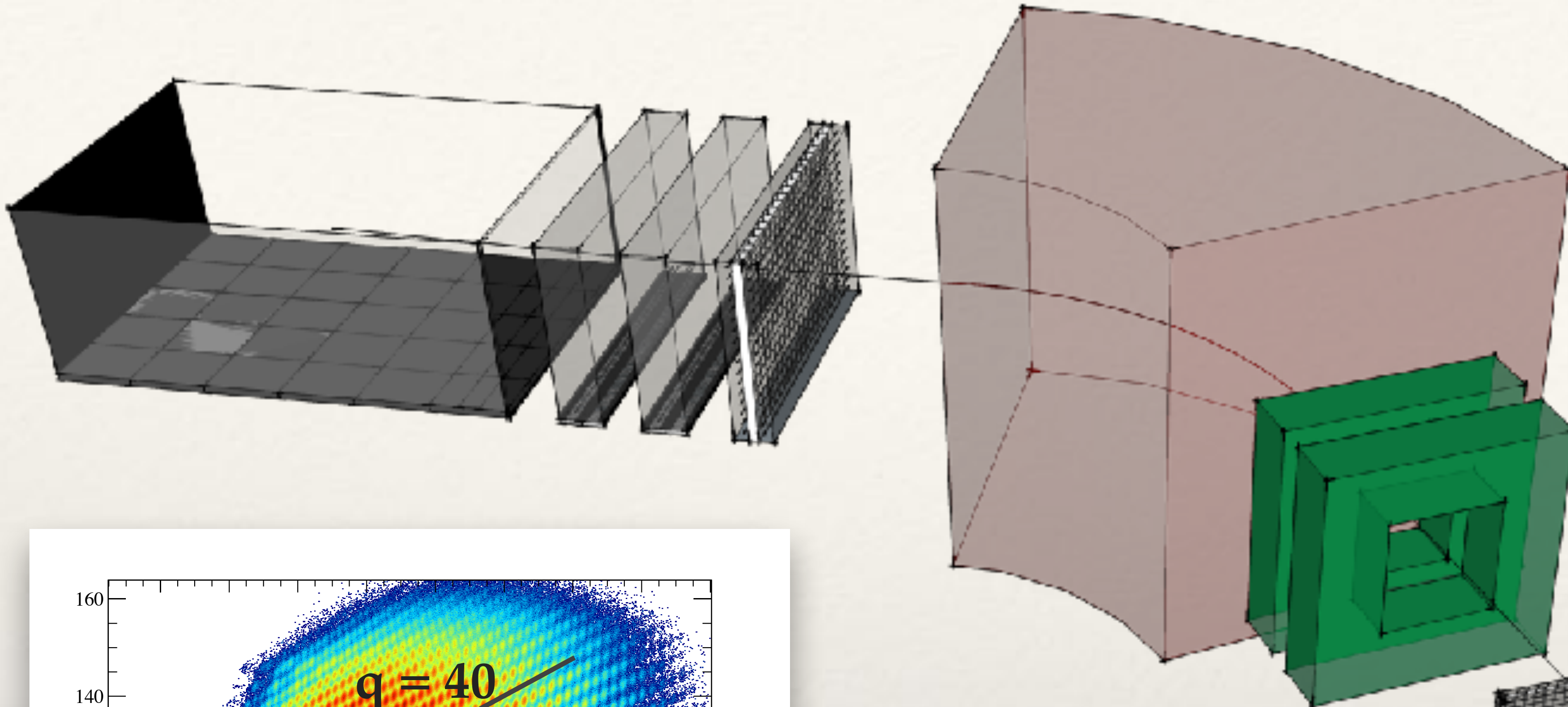


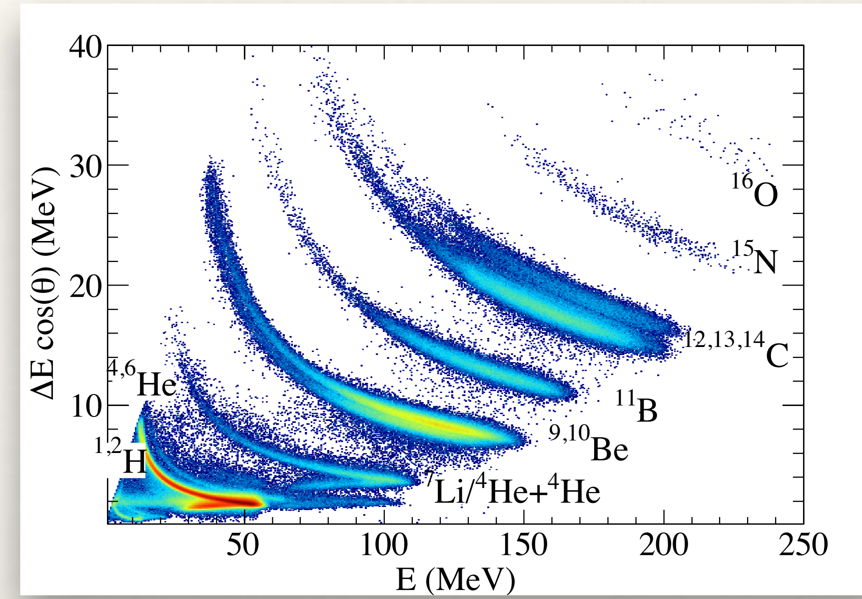
Surrogate reactions permit to explore the **impact of the incoming channel** into the final fission-fragment distributions

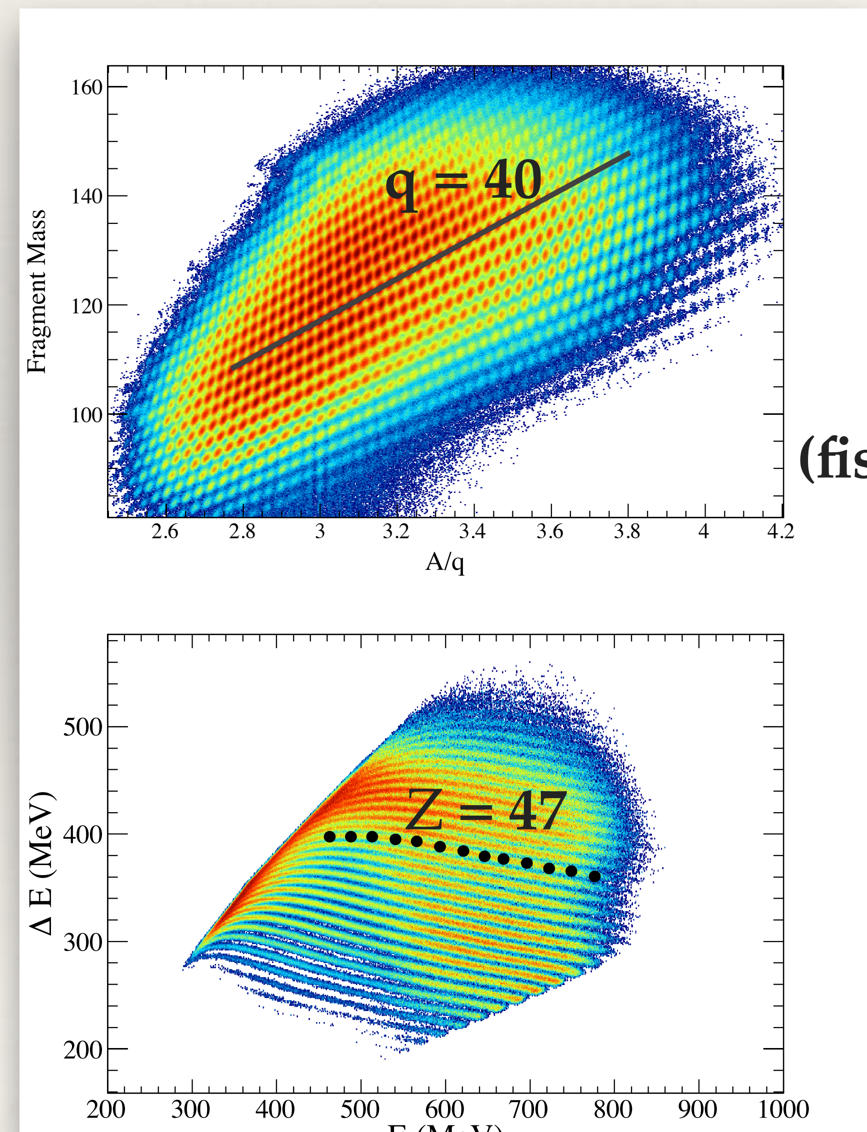
$^{238}U\ (^{9}Be,\ ^{8}Be)\ ^{239}U^*$



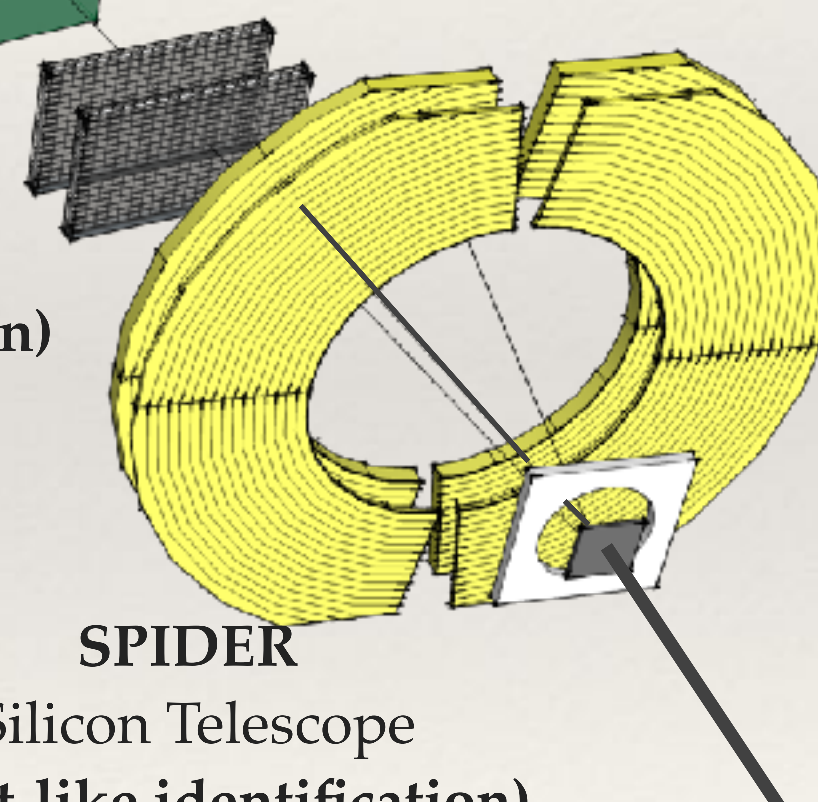
Experimental Setup







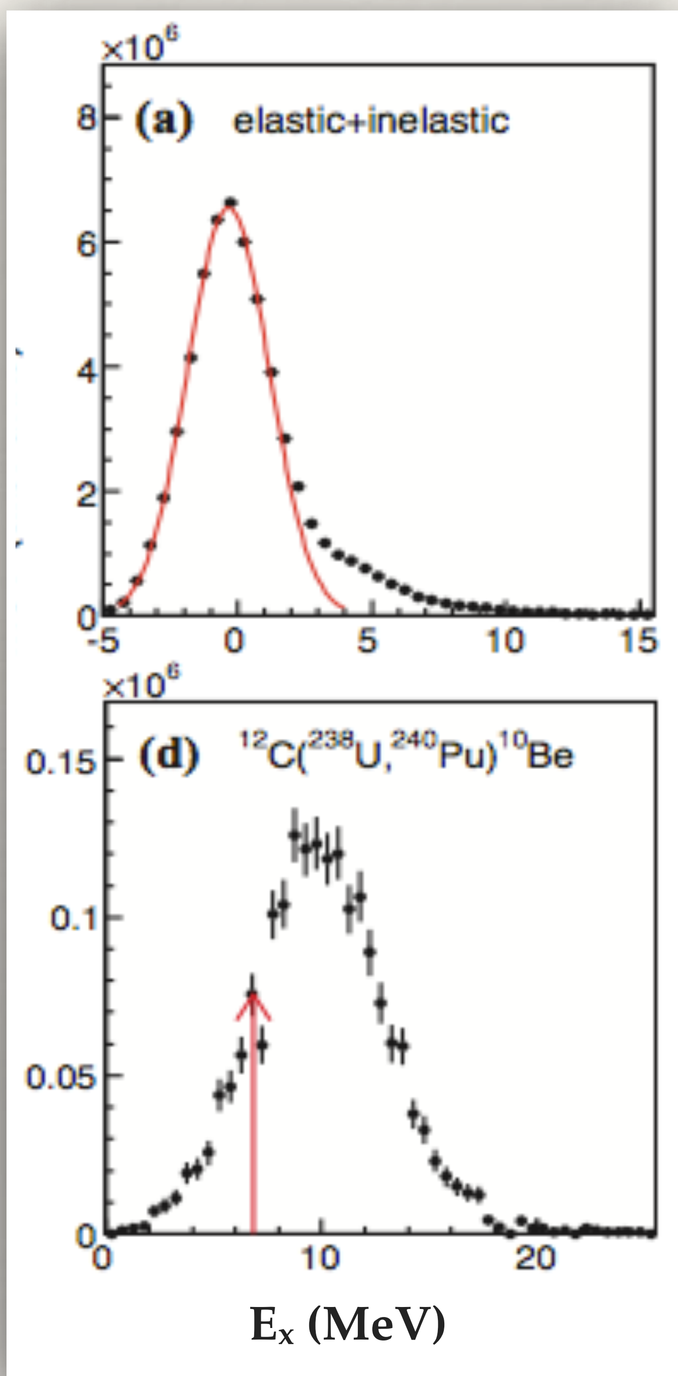
VAMOS
Magnet Spectrometer
(fission-fragments identification)

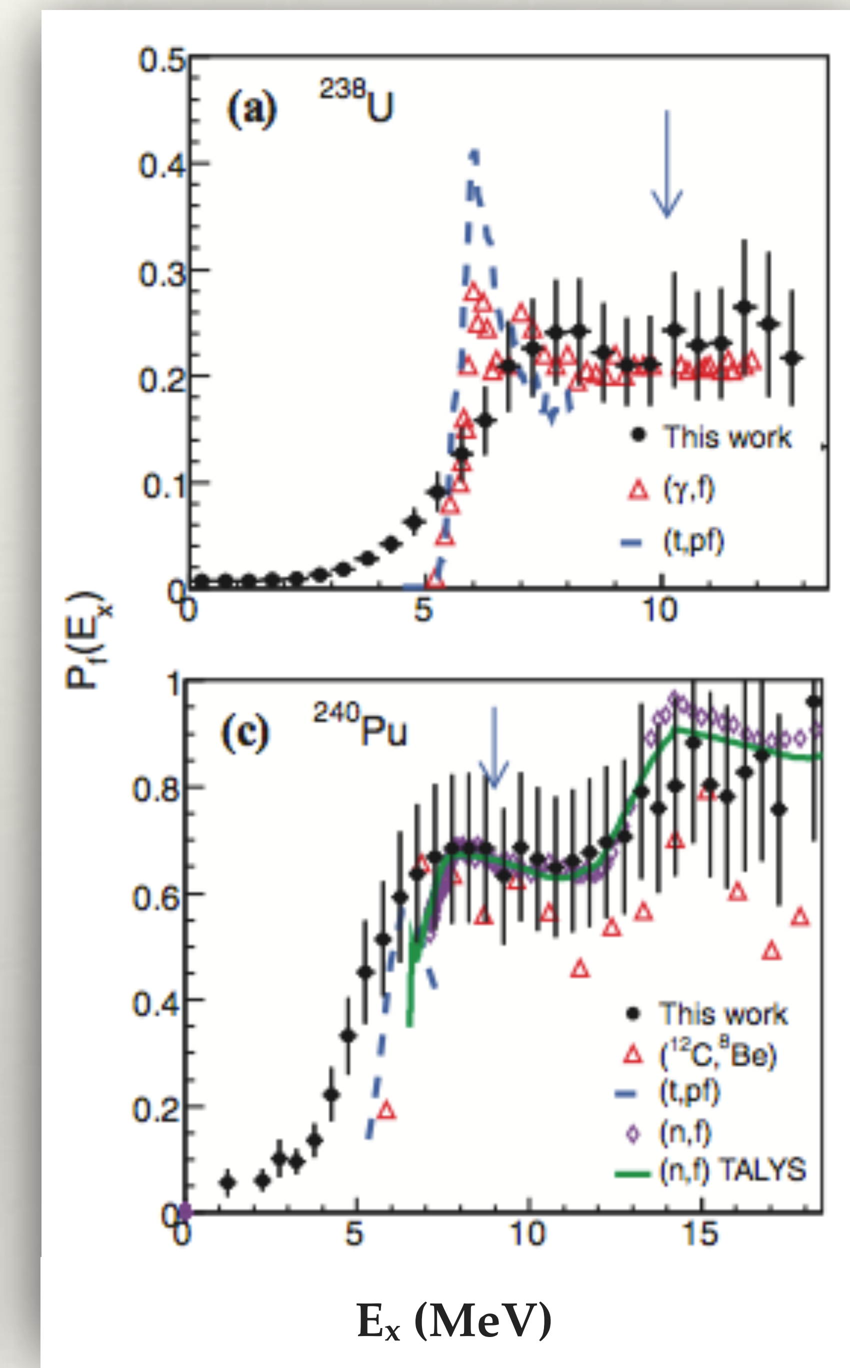


SPIDER
Silicon Telescope
(target-like identification)

^{238}U @ 6 MeV/u

Experimental Setup

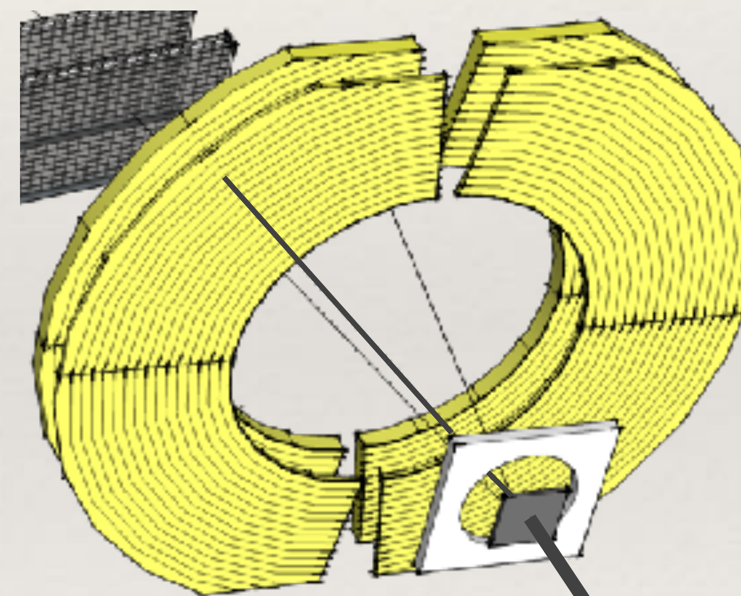




C. Rodríguez-Tajes *et al*., Phys. Rev. C **89**, 024614 (2014)

- ΔE = 70 µm thickness
- E = 1000 µm thickness
- 1.5 mm strips
- 22.5 deg sectors
- 4 cm downstream from target

Angular coverage: 30 - 47 deg



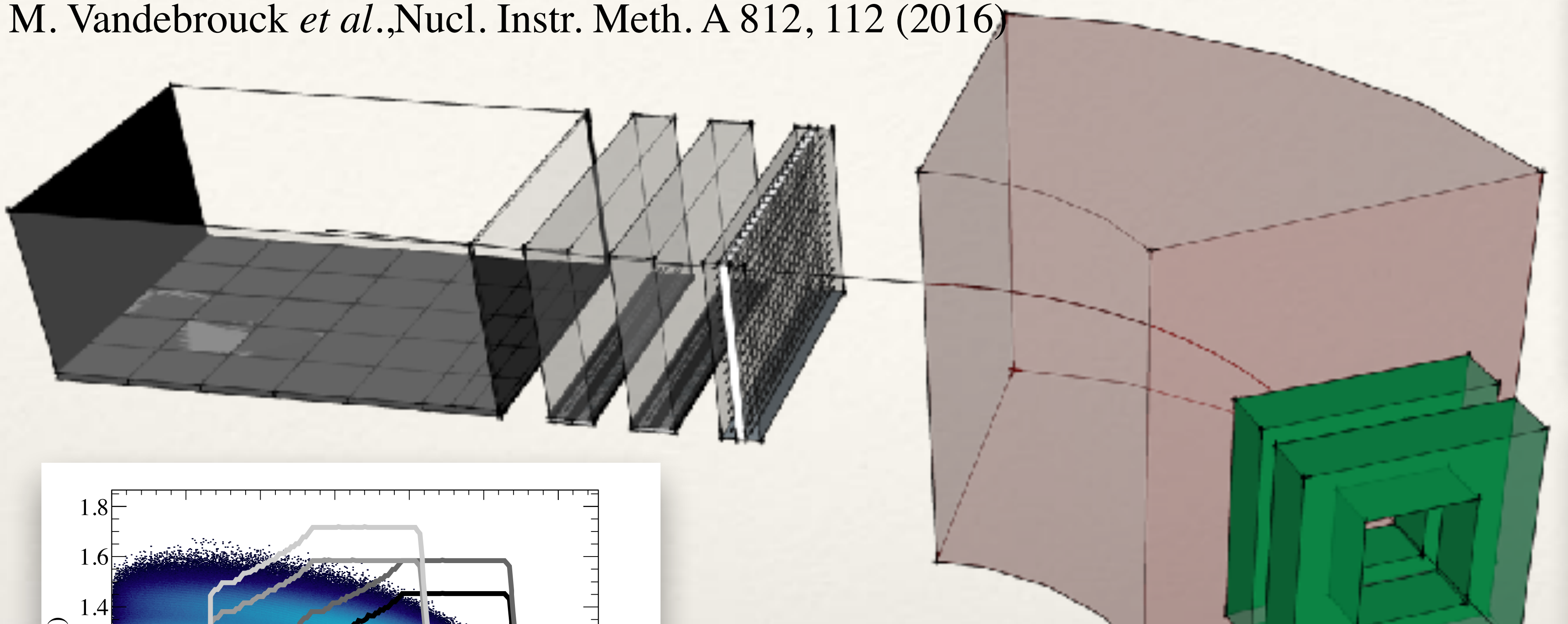
^{12}C 100 µg/cm^2

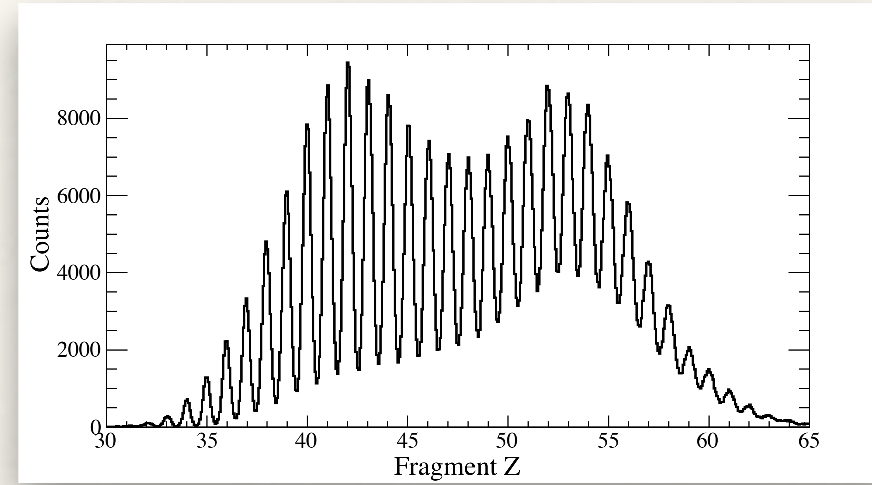
^{238}U @ 6 MeV/u

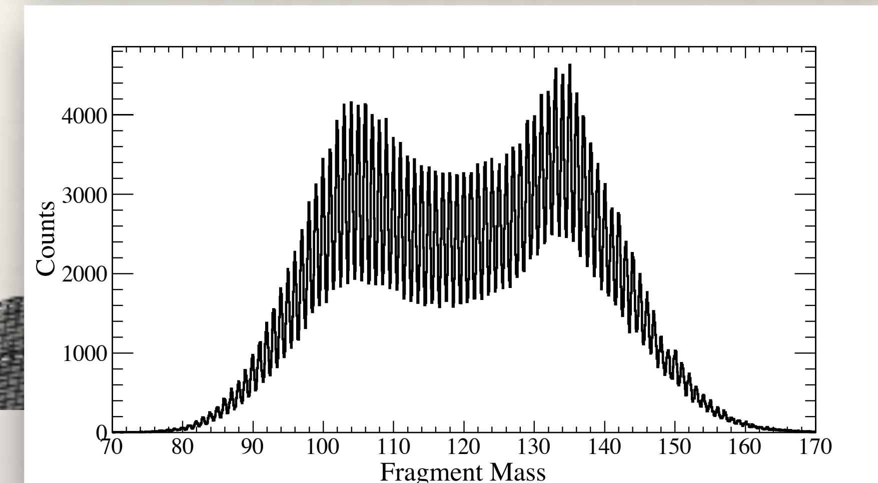
The target-like recoil identification and the angular segmentation permit to determine, event by event, **the excitation energy of the fissioning system with a resolution of FWHM = 2.7 MeV**

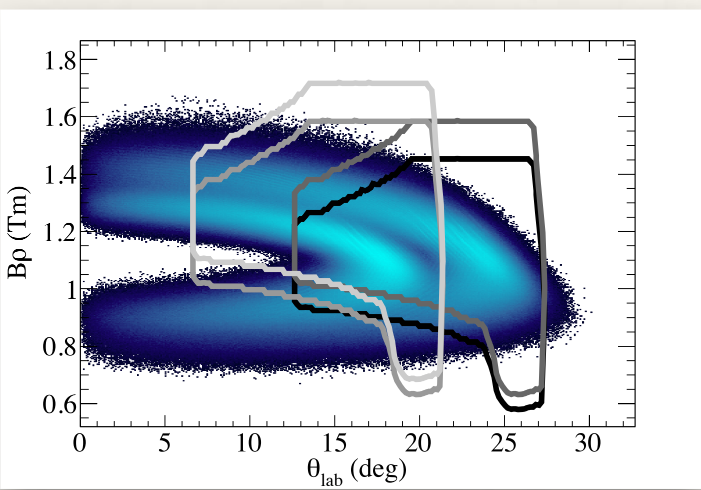
Experimental Setup

M. Rejmund *et al*., Nucl. Instr. Meth. A 646, 184 (2011)
M. Vandebrouck *et al*.,Nucl. Instr. Meth. A 812, 112 (2016)









VAMOS acceptance:

$\Delta B\rho$ ~20%

$\Delta\theta_x = \pm 7$ deg

$\Delta\theta_y = \pm 11$ deg

Despite the large spectrometer acceptance, **different settings are needed to cover from lighter to heavier fragments**

Identification based on:

ToF (~300 ps)

$B\rho$ (1/1000)

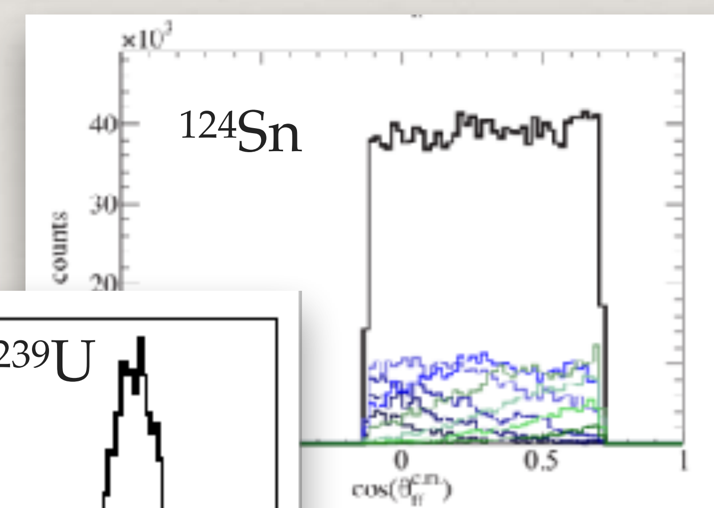
(θ,φ) angles (FWHM ~ 2.5 mrad)

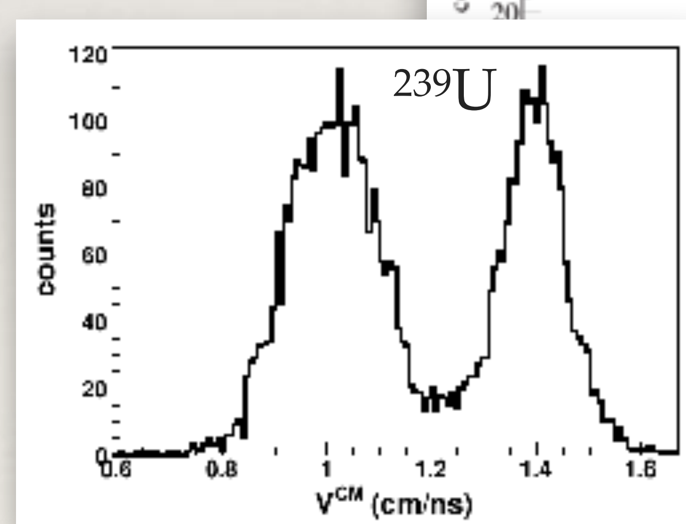
A (FWHM/A ~ 0.8-0.5 %)

Z (FWHM/Z ~ 1.2 %)

q (FWHM/q ~ 1.4 %)

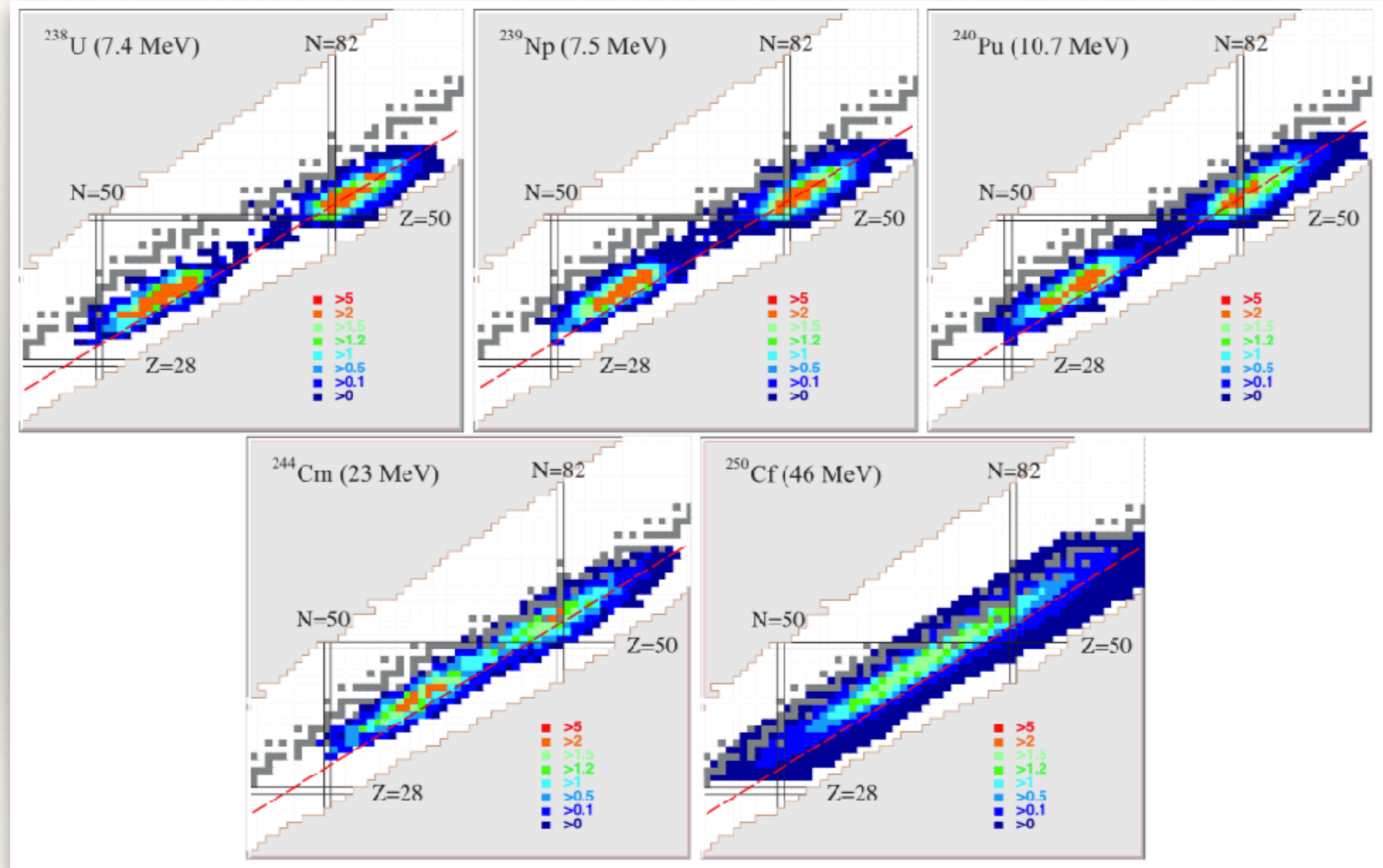
The angular distribution and velocity in CM are obtained from ToF and LAB angles





Isotopic Fission Yields

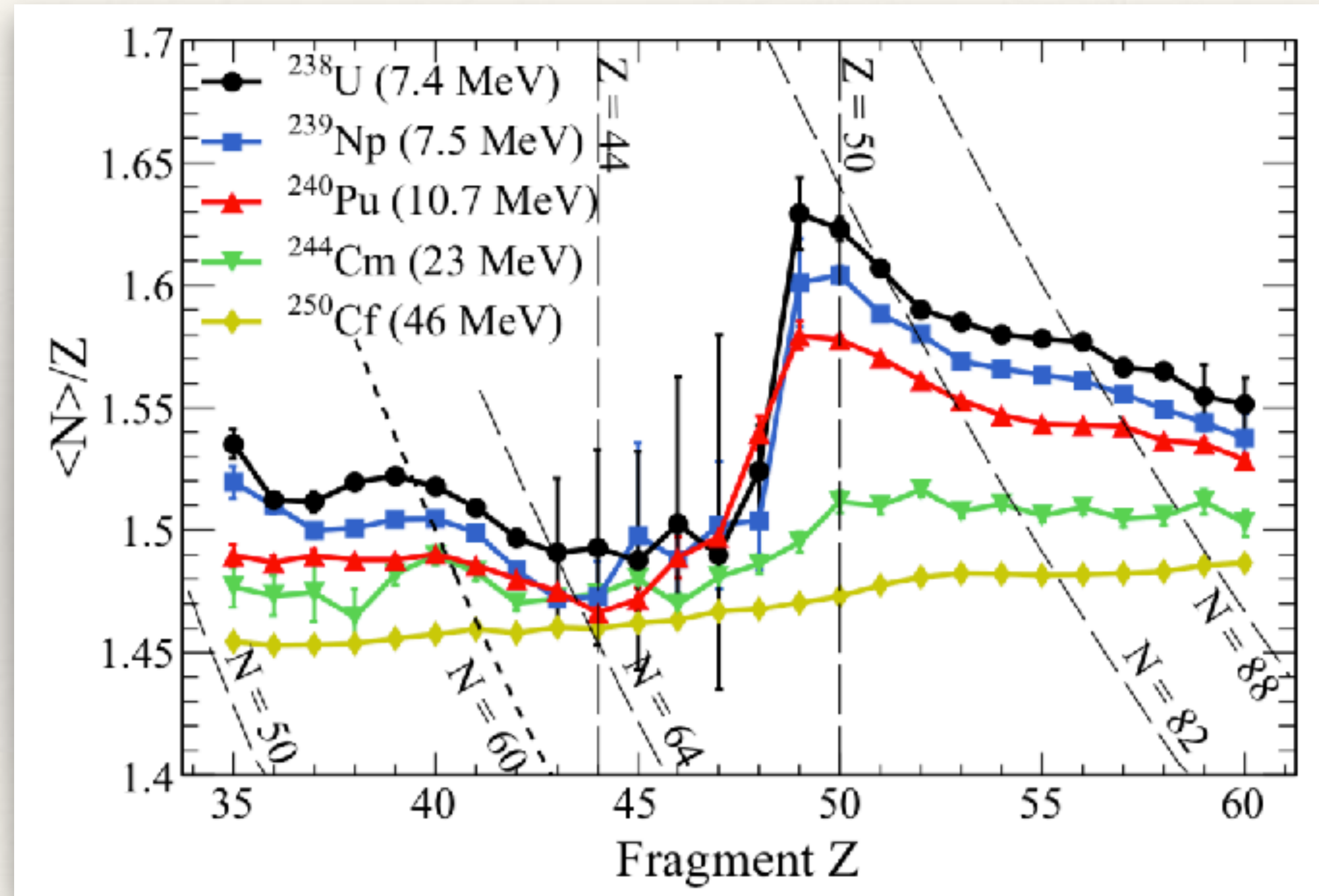
$^{238}U + ^{12}C$



D. Ramos *et al*., Phys. Rev. C **97**, 054612 (2018)

Neutron Excess

$$\frac{\langle N \rangle}{Z}(Z) = \frac{1}{Z}\sum_N N \frac{Y(N,Z)}{Y(Z)}$$



D. Ramos *et al*., Phys. Rev. C **99**, 024615 (2019)

Post-neutron-evaporation neutron content of fragments

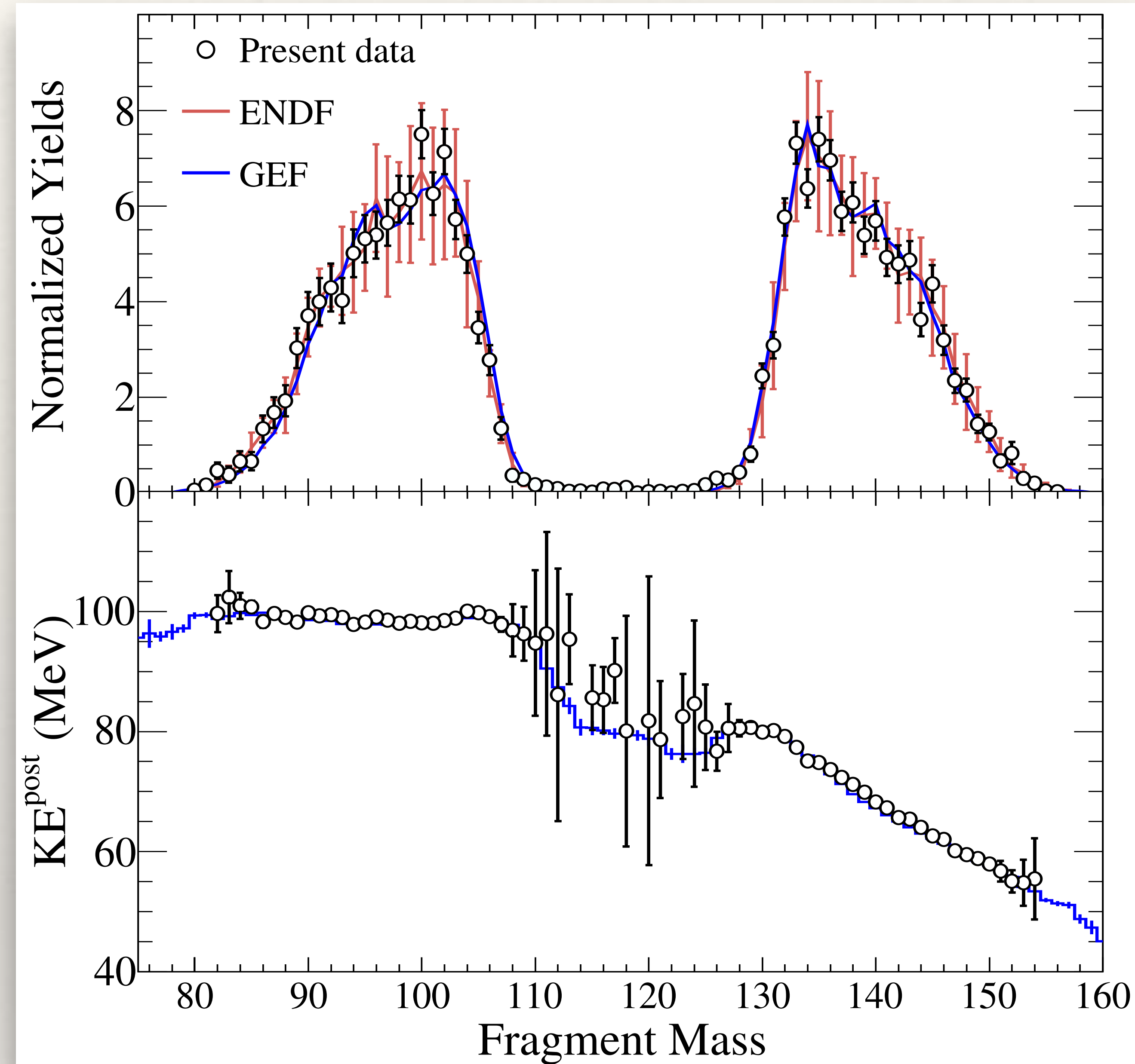
The charge polarization with the **increase of the neutron content around Z~50,** driven by the doubly-magic nucleus ^{132}Sn **reflects structural effects at low excitation energy**

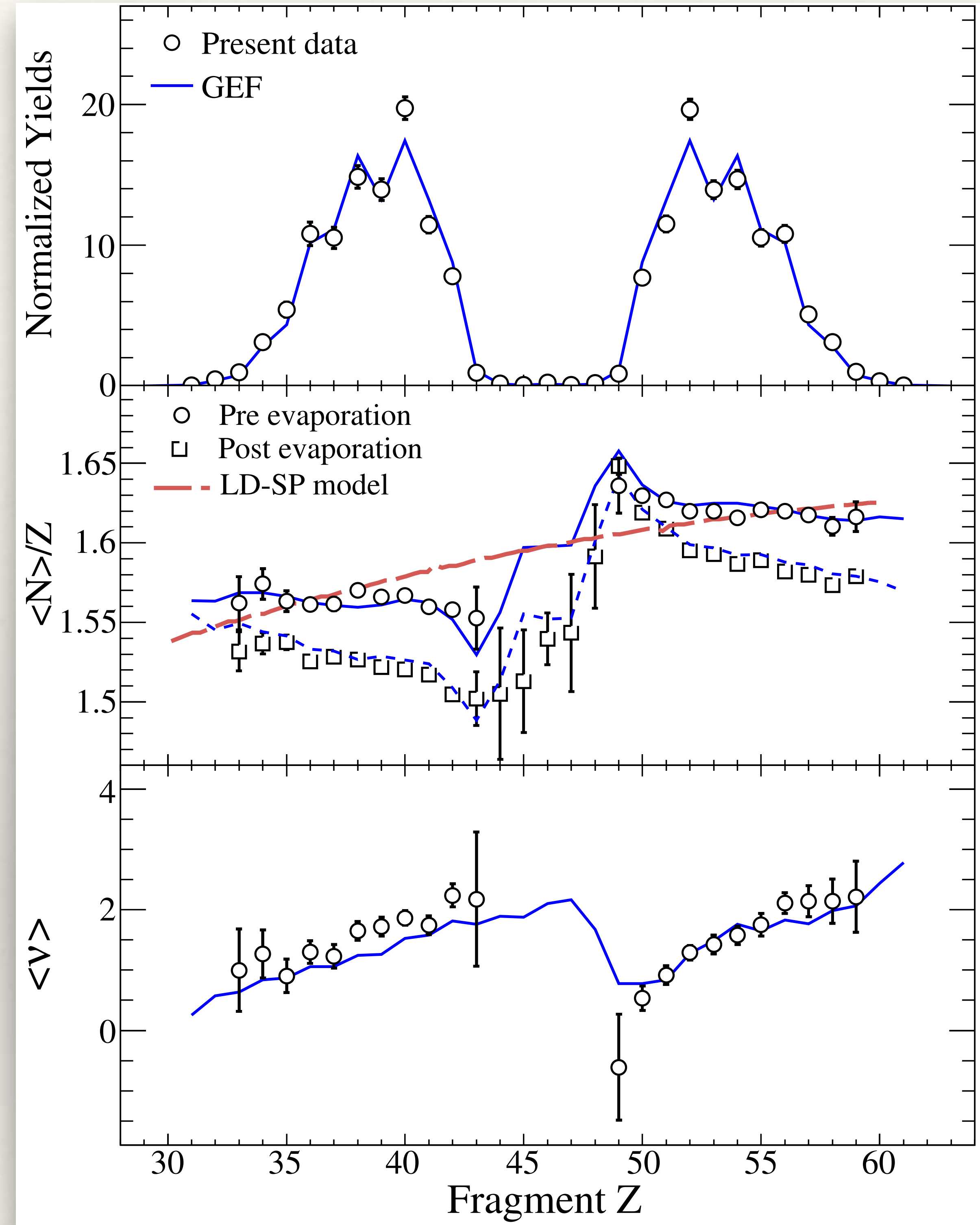
Structural effects vanish at higher excitation energy

^{239}U

^{238}U (^{9}Be, ^{8}Be) ^{239}U($\langle E_x \rangle = 8.3$ MeV)

D. Ramos *et al.*, Phys. Rev. Letters 123, 092503 (2019)





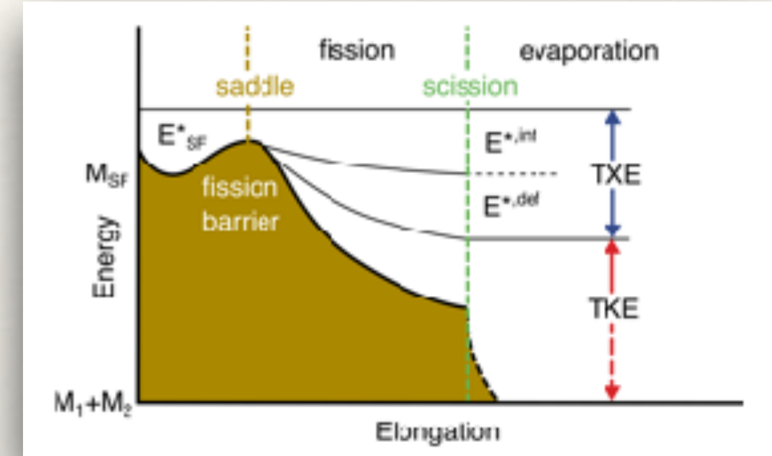
Important new data for evaluations

Pre n-evaporation data obtained from momentum conservation

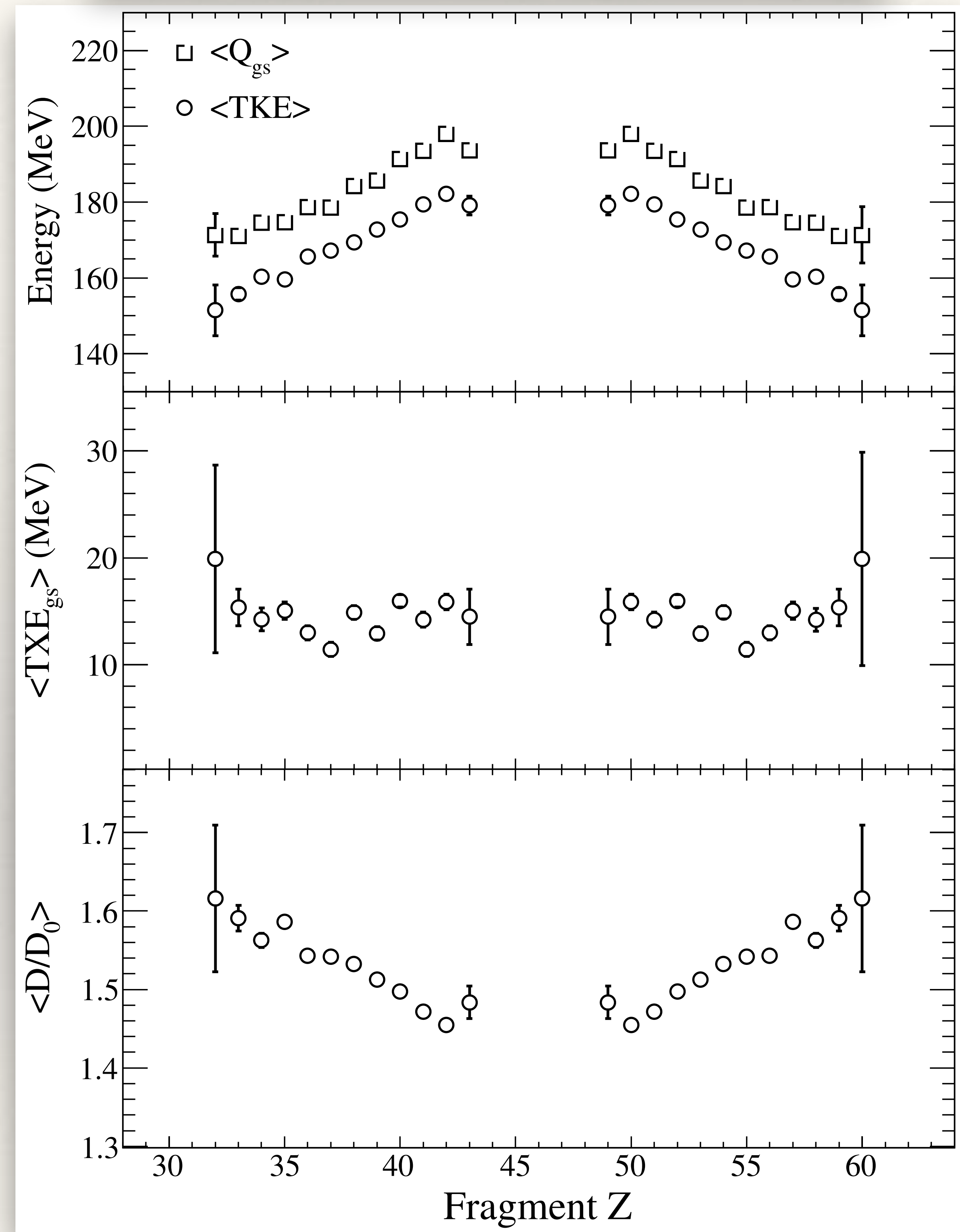
$$\langle A_1^* \rangle = A_{FS} \frac{\langle V_2 \gamma_2 \rangle}{\langle V_1 \gamma_1 \rangle + \langle V_2 \gamma_2 \rangle}$$

Direct measurement disproves the Sn anomaly of ^{239}U

Scission point configuration



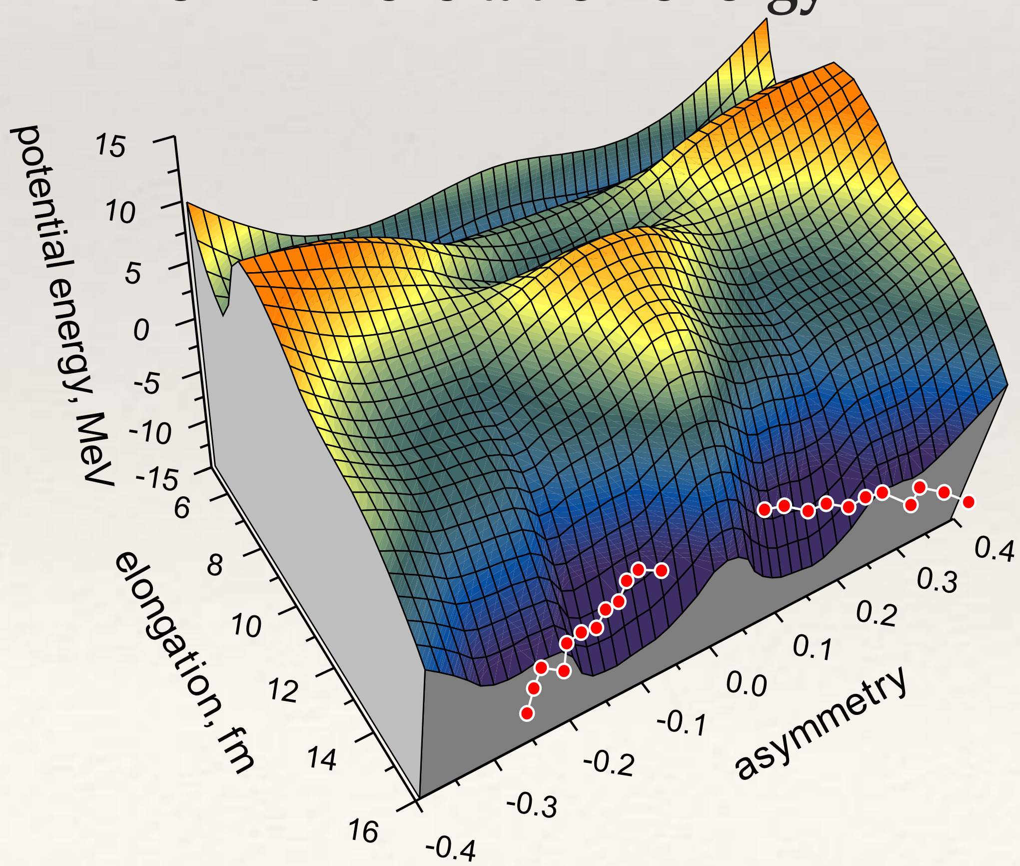
$$\langle TKE^*\rangle = u\langle A_1^*\rangle(\langle\gamma_1\rangle - 1) + u\langle A_2^*\rangle(\langle\gamma_2\rangle - 1)$$



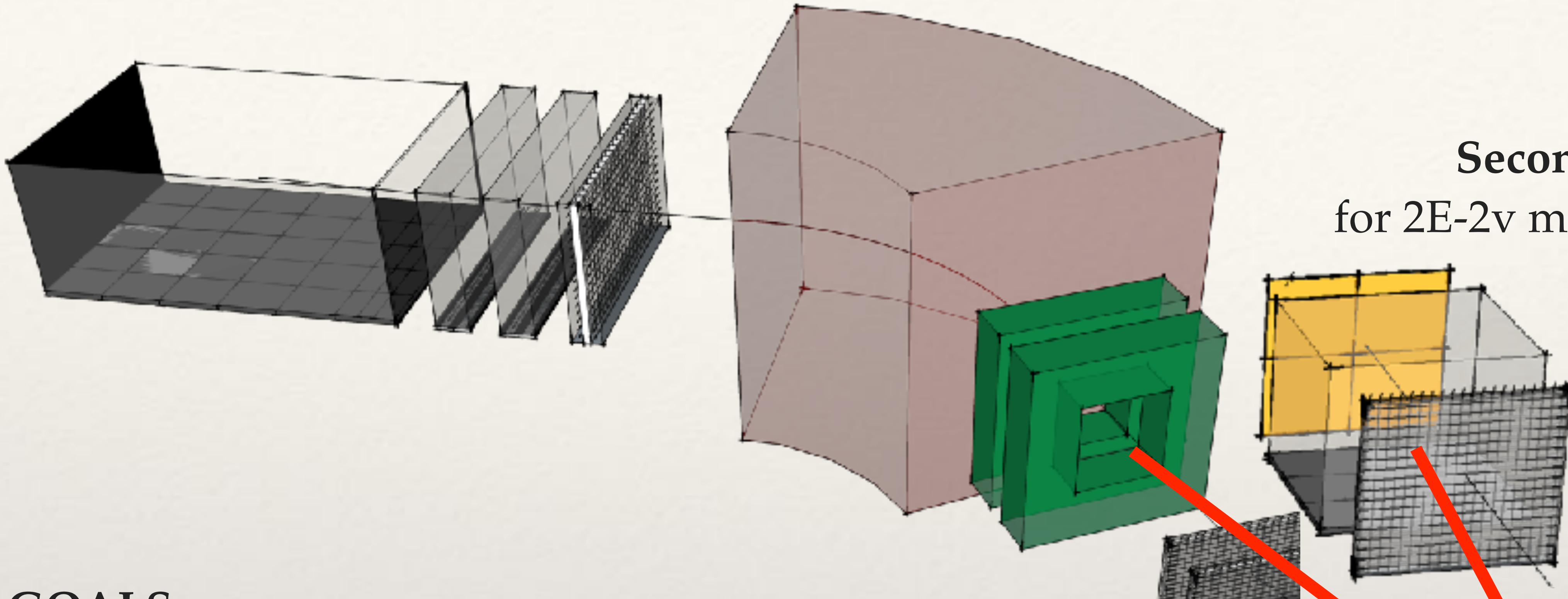
$$\langle D/D_0\rangle = 1.44\frac{Z_1 Z_2}{\langle TKE^*\rangle}\left(\frac{1}{r_0\langle A_1^*\rangle^{1/3} + r_0\langle A_2^*\rangle^{1/3}}\right)$$

The kinetic properties of the fragments gives scission-point information

Splits around Z~50 take place at lower elongation than more asymmetric splits but similar excitation energy



Perspectives

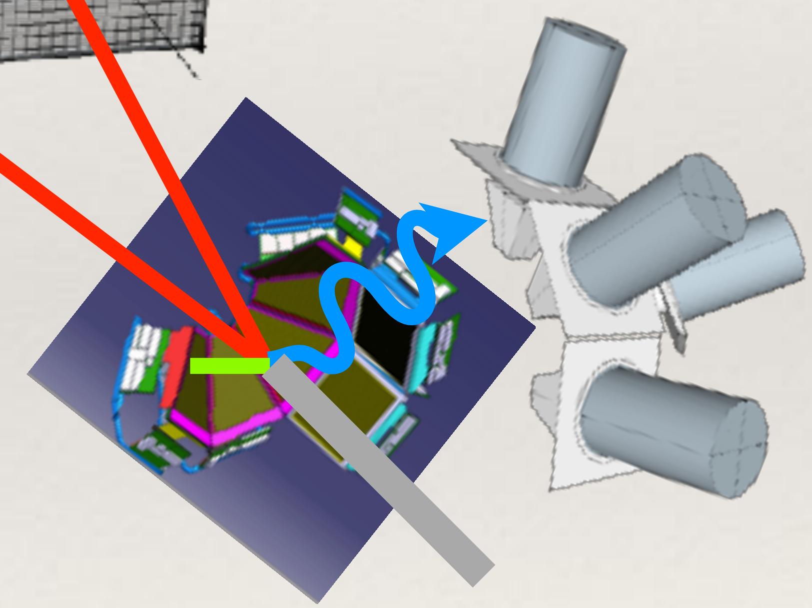


Second arm
for 2E-2v measurements

GOALS:

- Isotopic distributions at scission
- Isotopic TKE
- Precise initial E_x evolution
- Precise scission information:
    - gamma-emission
    - neutron-evaporation
    - fragment excitation energy

High-granularity
Silicon Telescope
200 KeV-resolution in E_x



Gamma Calorimeter
for fragment-decay measurements

Conclusions

- The use of inverse kinematics with the VAMOS spectrometer allowed the complete characterization of fissioning system in terms of Z, A, and E_x, and the isotopic identification of their full fragment distribution and their TKE.

- The correlation between N and Z reveals the effect of structure: a charge polarization with a saw-tooth behavior appears with a maximum governed by ^{132}Sn. Increasing E_x reduces this structure effect, but mainly on the heavy fragment.

- For first time the scission point configuration is accessible from the experimental point of view, measuring the neutron content and the separation of the fragments at scission.

- Further steps in the setup improvement are in mind, such as a second arm in order to measure simultaneously both fission fragments. Improvements in the detection of the target-like recoil and in the excitation energy resolution are other requirements to successfully continue the fission program at VAMOS/GANIL

Collaboration

GANIL, France

- D. Ramos, A. Lemasson, M. Rejmund, J.D. Frankland, J. Piot, D. Ackermann, E. Clement, B. Jacquot, T. Roger

IGFAE, University of Santiago de Compostela, Spain

- M. Caamaño, H. Álvarez-Pol, B. Fernández-Domínguez

IPHC Strasbourg, France

- C. Schmitt

LPC Caen, France

- F. Farget, D. Durand

IPN Orsay, France

- L. Audouin

CENBG Bordeaux, France

- A. Henriques, B. Jurado, I. Tsekhanovich

LIP Lisboa, Portugal

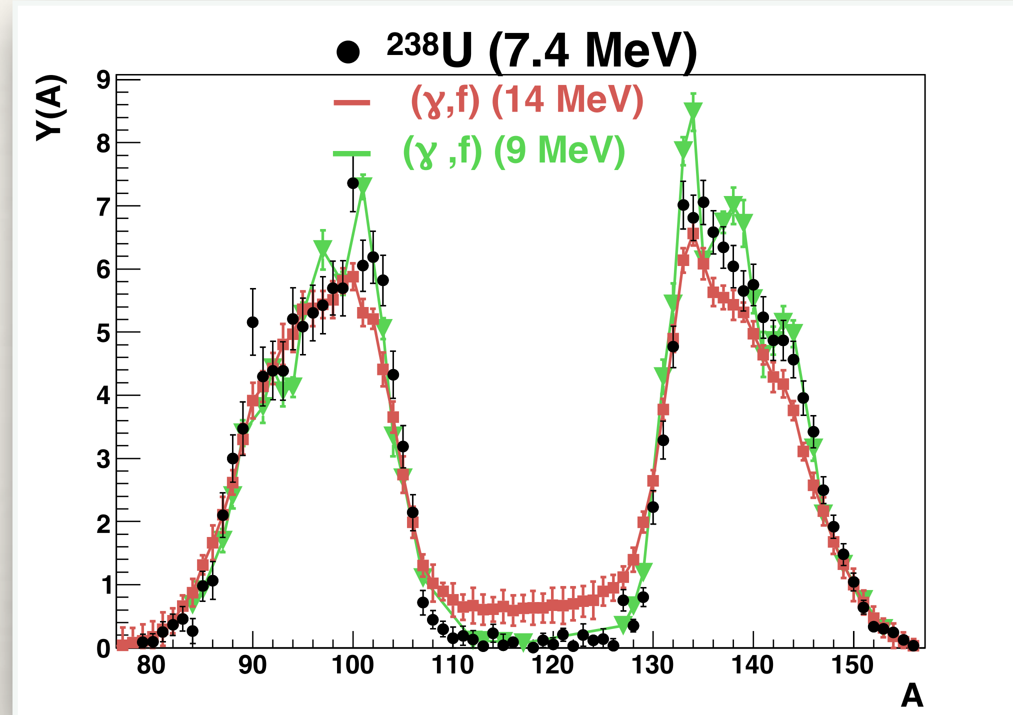
- D. Galaviz, P. Teubig

Chalmers University of Technology, Sweden

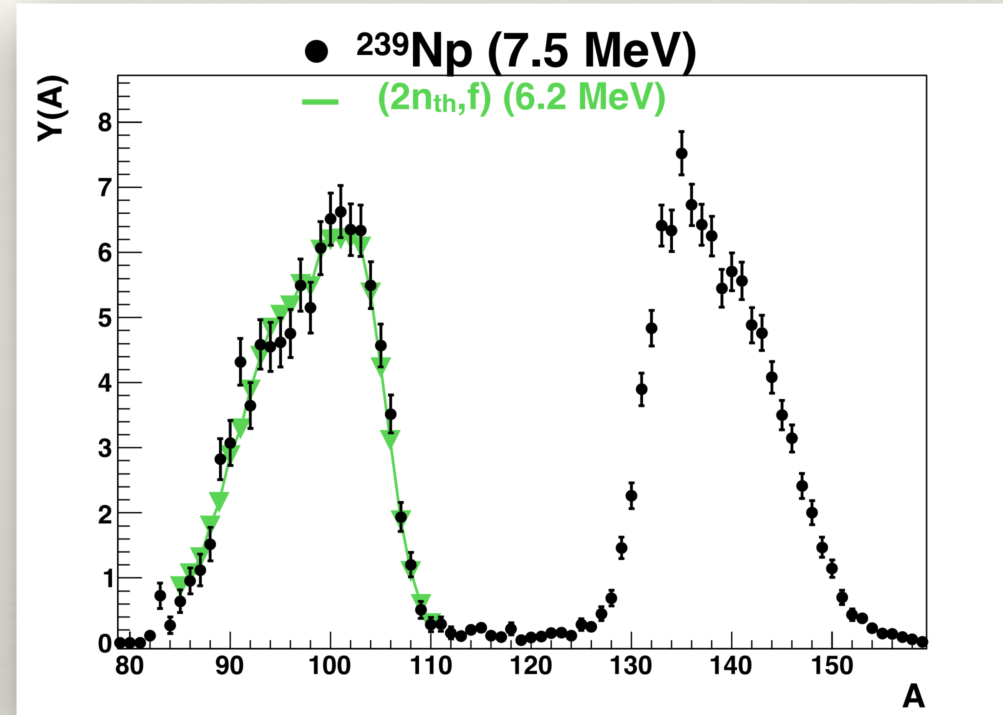
- A. Heinz

Backup

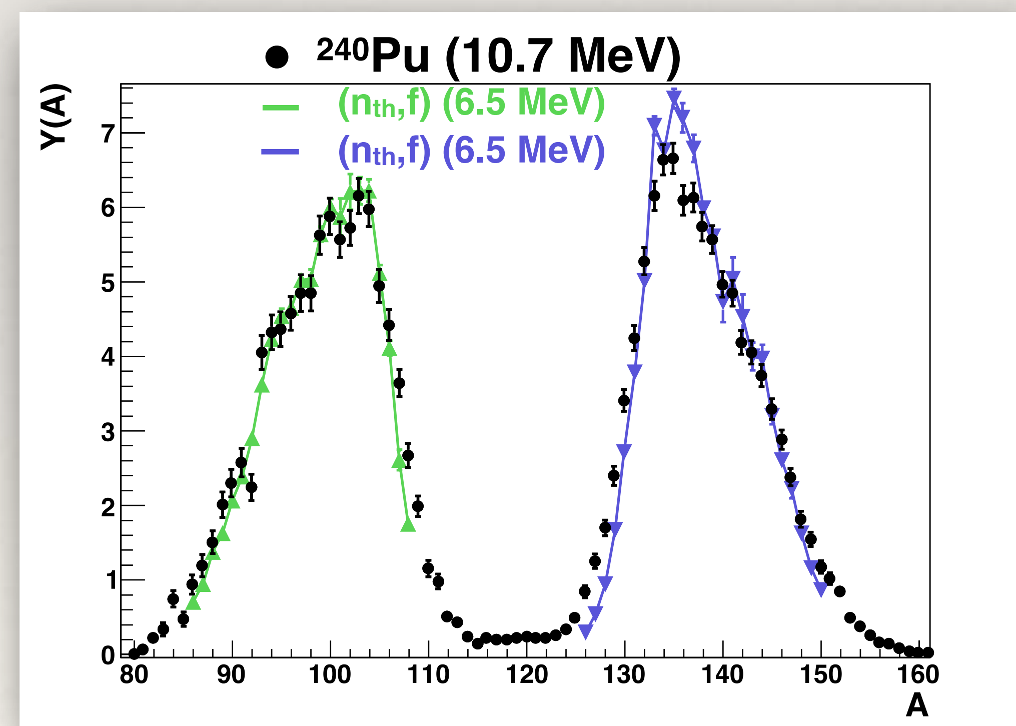
MASS FISSION YIELDS



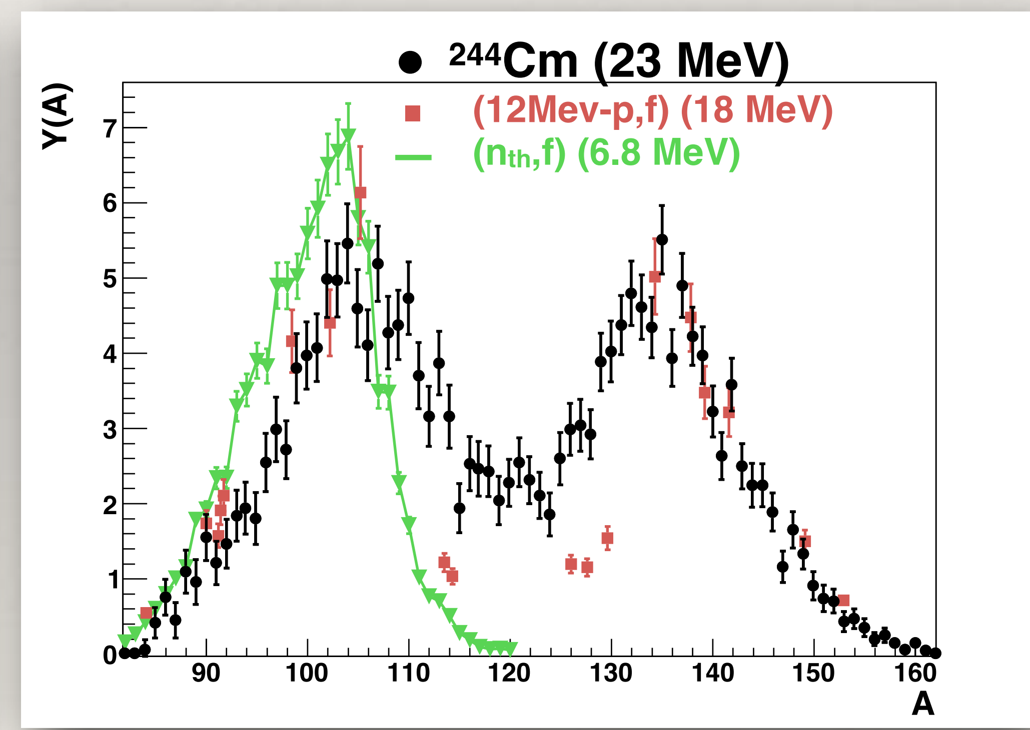
E. Pelleareau et al. PRC 95 (2017) 054603
H. Naik et al. EPJA 49 (2013) 94



G. Martinez et al. NPA 515 (1990) 433



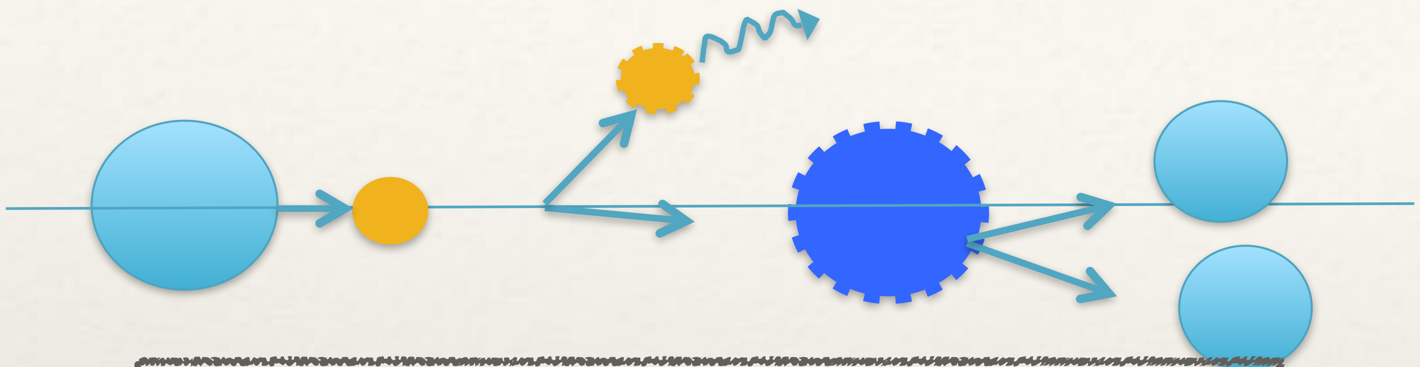
C. Schmitt et al. NPA 430 (1984) 21
A. Bail et al. PRC 84 (2011) 034605

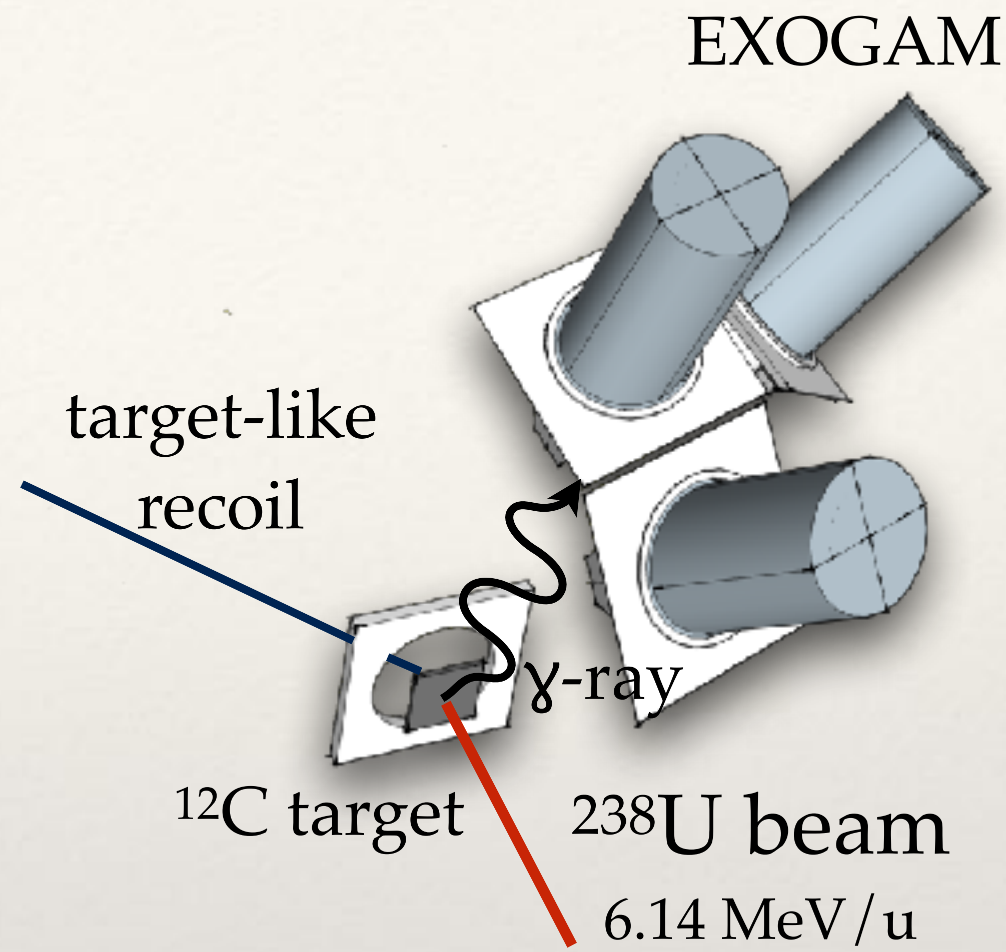


T. Ohtsuki et al. PRC 40 (1989) 2144
I. Tsekhanovich et al. PRC 70 (2004) 044610

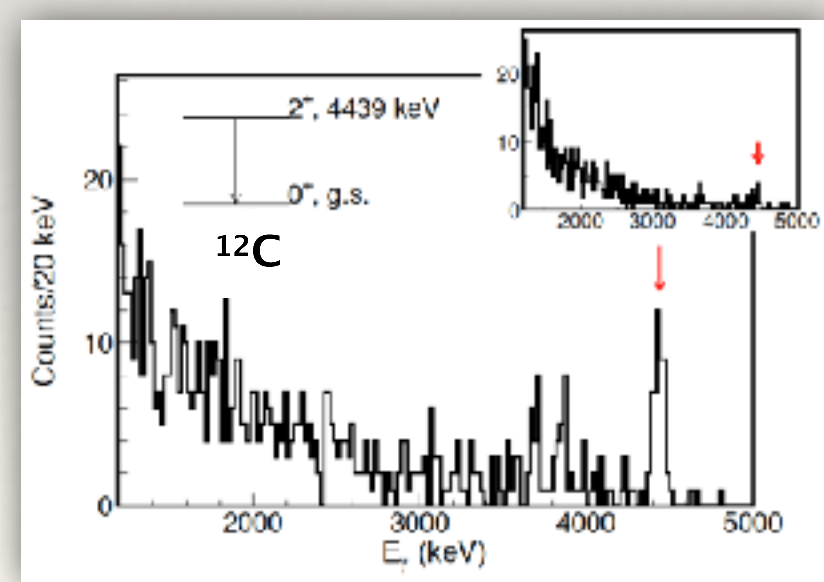
Excitation of the target-like recoil

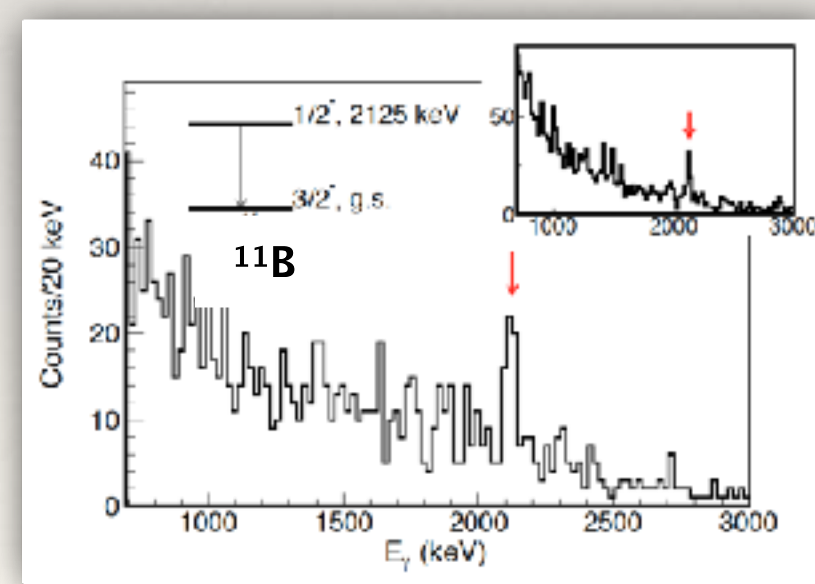
EXOGAM detector allow us to evaluate the excitation probability of the target-like nuclei

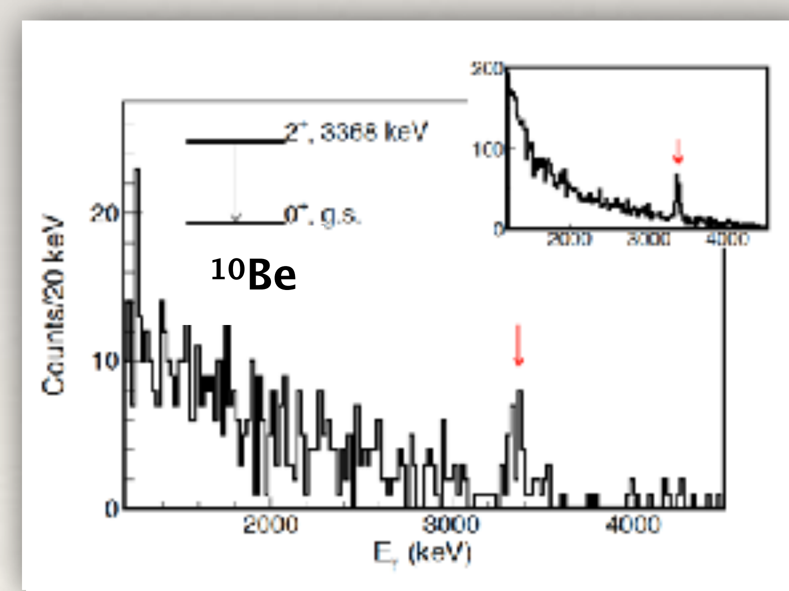




γ-rays measurements show excited states in ^{12}C, ^{11}B and ^{10}Be **in coincidence with fission with P_γ = 0.12-0.14**







C. Rodriguez-Tajes et al. PRC 89 (2014) 024614

Deformation at Scission

The CM reconstruction together with the Z,A identification permits to determine, for first time, the deformation of the fragments at Scission

^{240}Pu

$$\sum_{i=1}^{2} E_i^{*,int} = E^{*,Bf} + F^{dis}(TXE - E^{*,Bf})$$

$$E_i^* = Q_i^n + \nu_i \varepsilon + E_i^\gamma$$

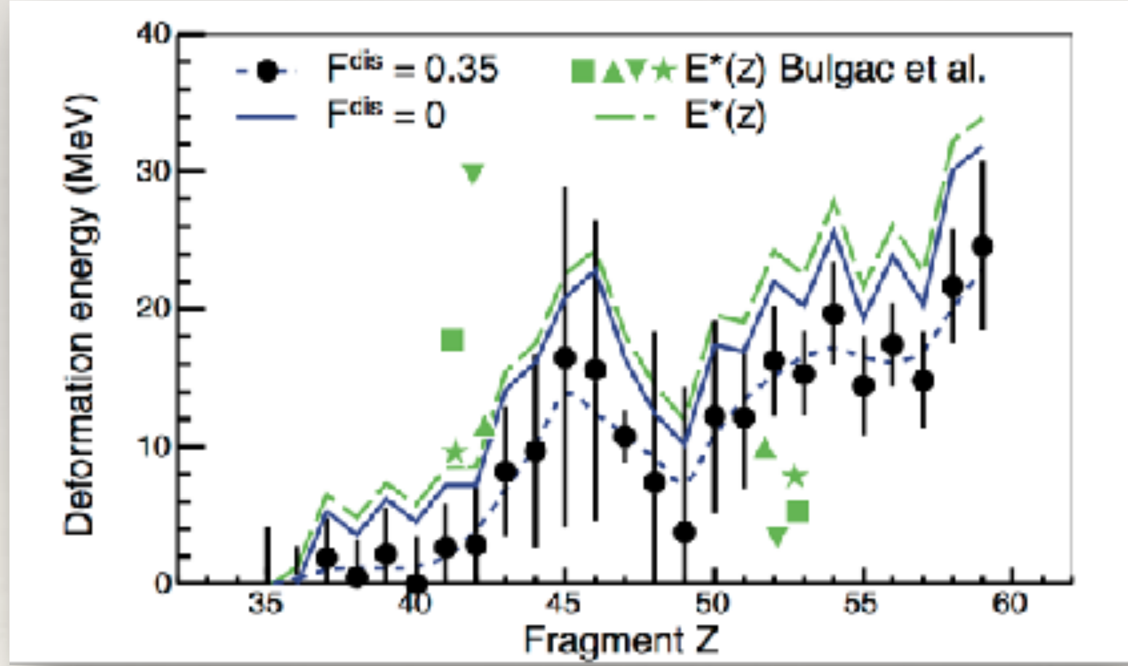
Key points:

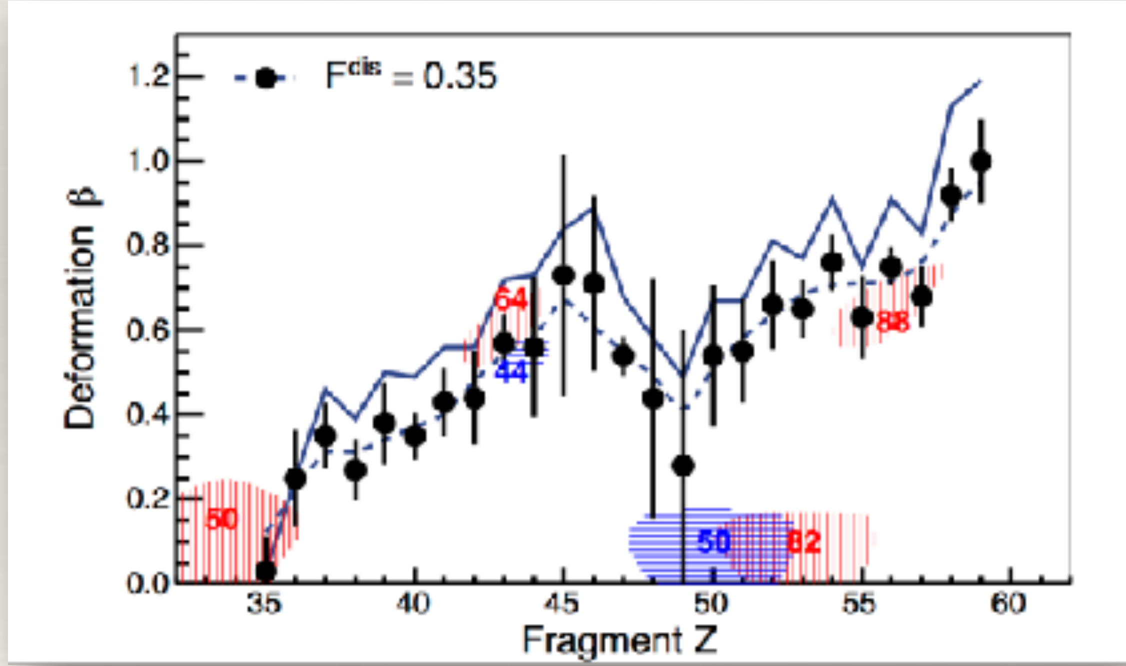
Dissipated energy = 35% (TXE-$E^{*,Bf}$)

$$E_i^\gamma = Sn_i^{\text{post}} \frac{\nu_i}{\nu_1 + \nu_2}$$

$$E_i^{*,def} = E_i^* - E_i^{*,int}$$

$$E_i^{*,def} = B(\langle A \rangle_i, Z_i, \beta_i) - B(\langle A \rangle_i, Z_i, \beta_i^{g.s.})$$

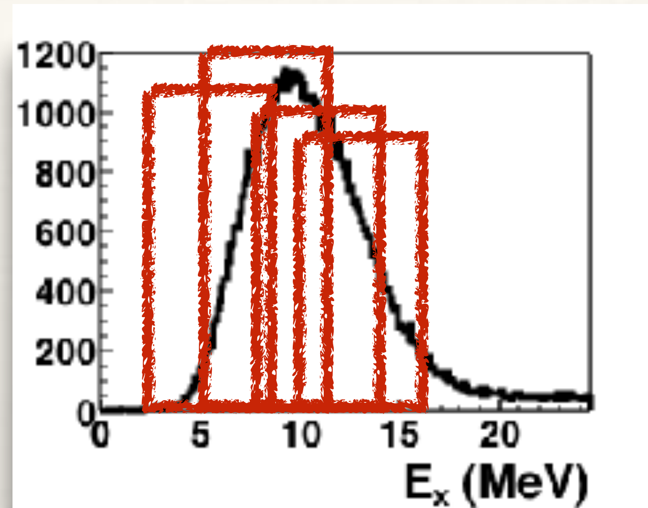




- The deformation at scission follows the deformed shell N=64,88 and Z=44

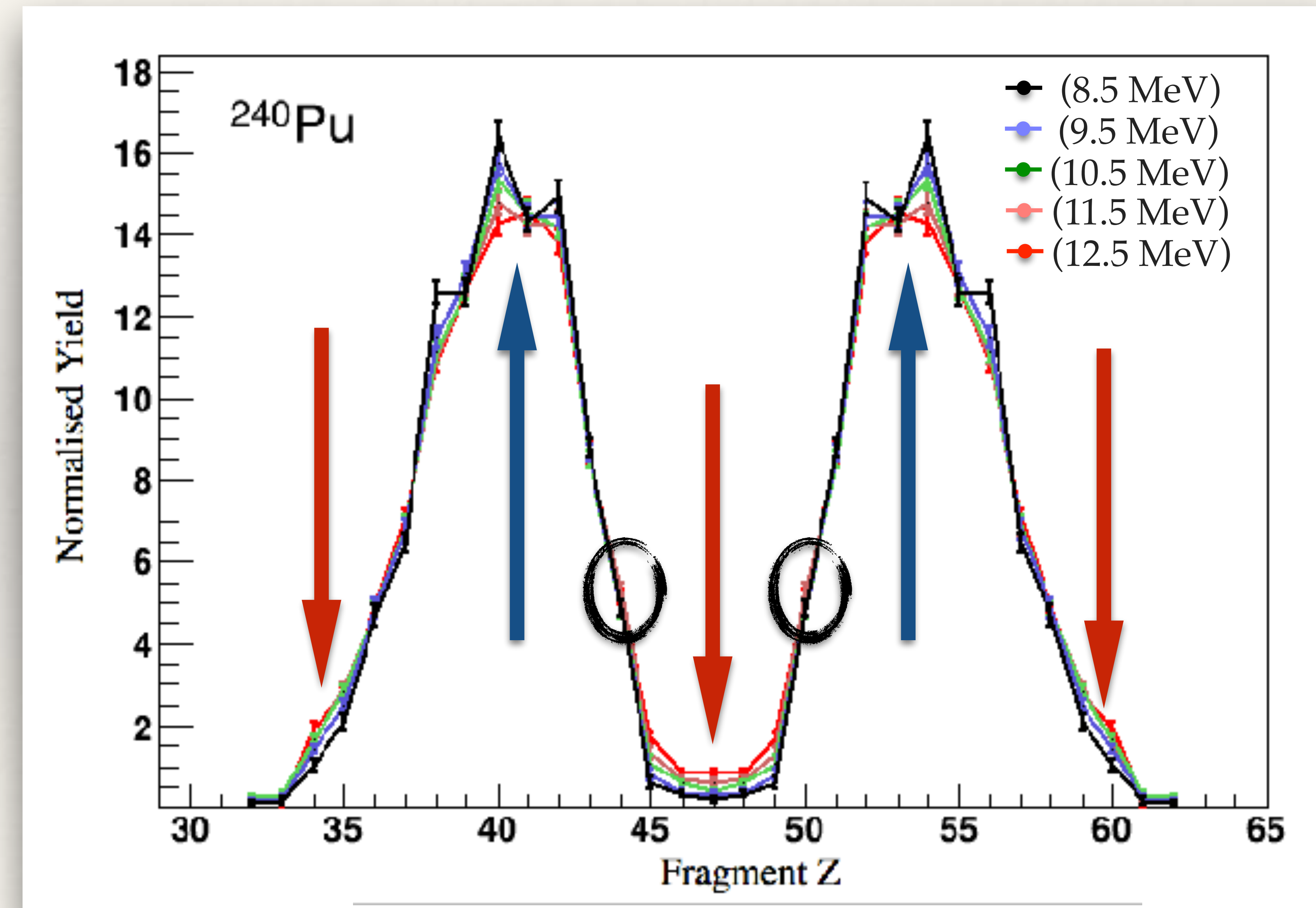
M. Caamaño and F. Farget, PLB 770, 72 (2017)

Excitation Energy Effect



Gates on E_x

- $\Delta\langle E_x \rangle$ = 1MeV
- STD(E_x)~1.5 MeV



- Additional E_x favors symmetric fission
- Very asymmetric splits are enhanced
- Even-odd staggering gets reduced
  - **Unexpected almost invariant value appears in Z=50**