The GEneral Fission code (GEF)

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Motivation:
Accurate and fast fission code for nuclear technology.
(Not possible with current theoretical models)

Structure of GEF

A, Z, E* of fissioning nucleus
& number of events

From Po to Sg
and E* <=100 MeV

Competition fission/particle
emission for excited nucleus

Random sample of the properties of the
fission fragments at scission:
$A_1, Z_1, E^*_1, E^k_1, J_1, A_2, Z_2, E^*_2, E^k_2, J_2$

Sampling from distributions that are obtained from a physical model!!!

Desexcitation of fission fragments:
Prompt neutron multiplicity, E_n, angle
Prompt gamma multiplicity, $E\gamma$

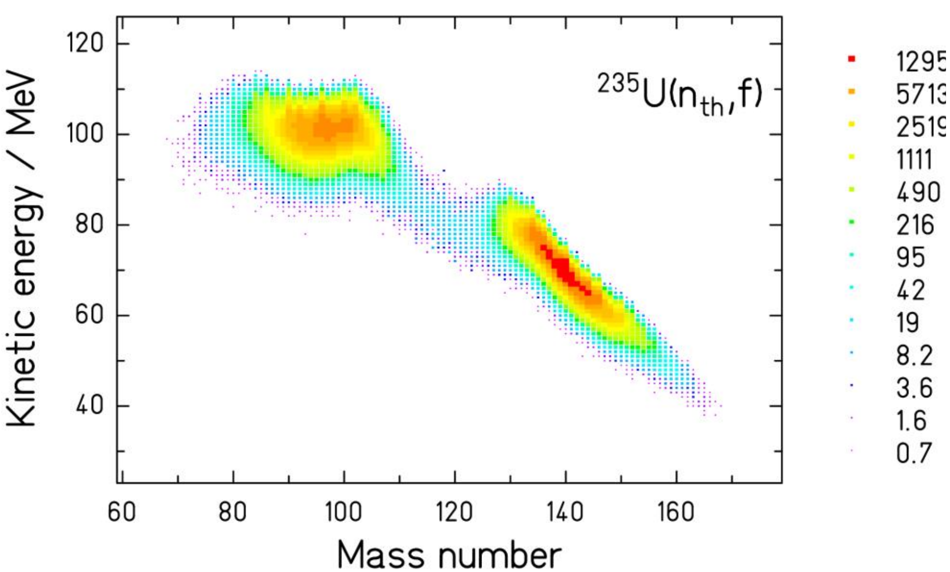
Loop
over
events

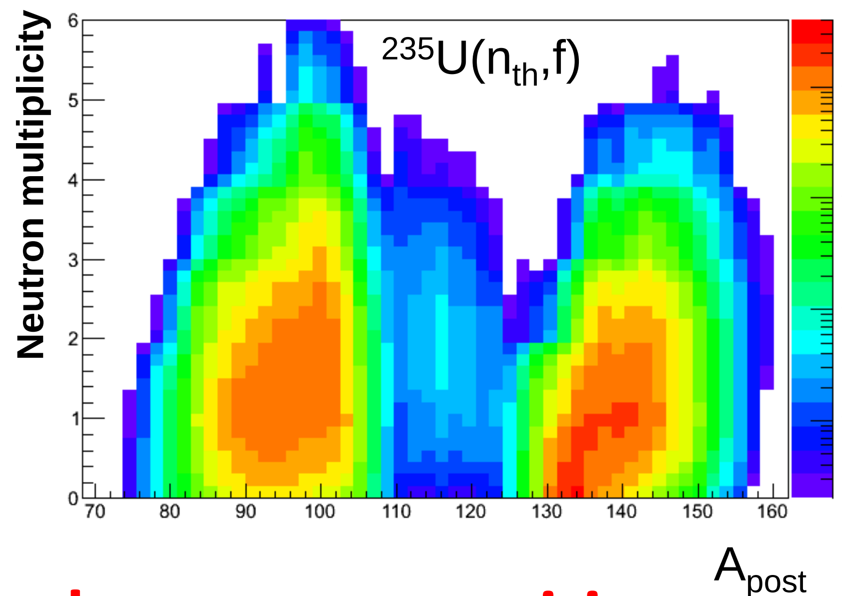
Output of GEF

Results for essentially all fission observables

List-mode output
can be used as an event generator

```
Fichier  Edition  Format  Affichage  ?
* Z1 Z2 A1post A2post I1pre I2pre n1 n2 TKEpre TKEpost
* Calculation with nominal model parameters
 38  54  94  139  1.5  7.5  1  2  169.3808  167.3484
 37  55  92  140  3  0  2  2  161.8703  158.89
 35  57  88  146  4.5  8.5  1  1  161.9046  160.3561
 35  57  90  143  0.5  14.5  1  2  158.5806  156.6665
 36  56  90  145  3  4  0  1  177.1083  176.6457
 36  56  92  143  4  11  0  1  174.0105  173.5394
 35  57  88  147  2  16  0  1  169.2923  168.8658
 37  55  93  141  5  8  1  1  172.1861  170.601
 40  52  98  135  3.5  3.5  1  2  178.0875  175.9526
 40  52  102  132  7.5  13.5  1  1  171.735  170.2318
 38  54  97  137  5  5  1  1  180.9156  179.2917
```





All possible correlations between quantities, also for nuclei where no data are available, UNIQUE!

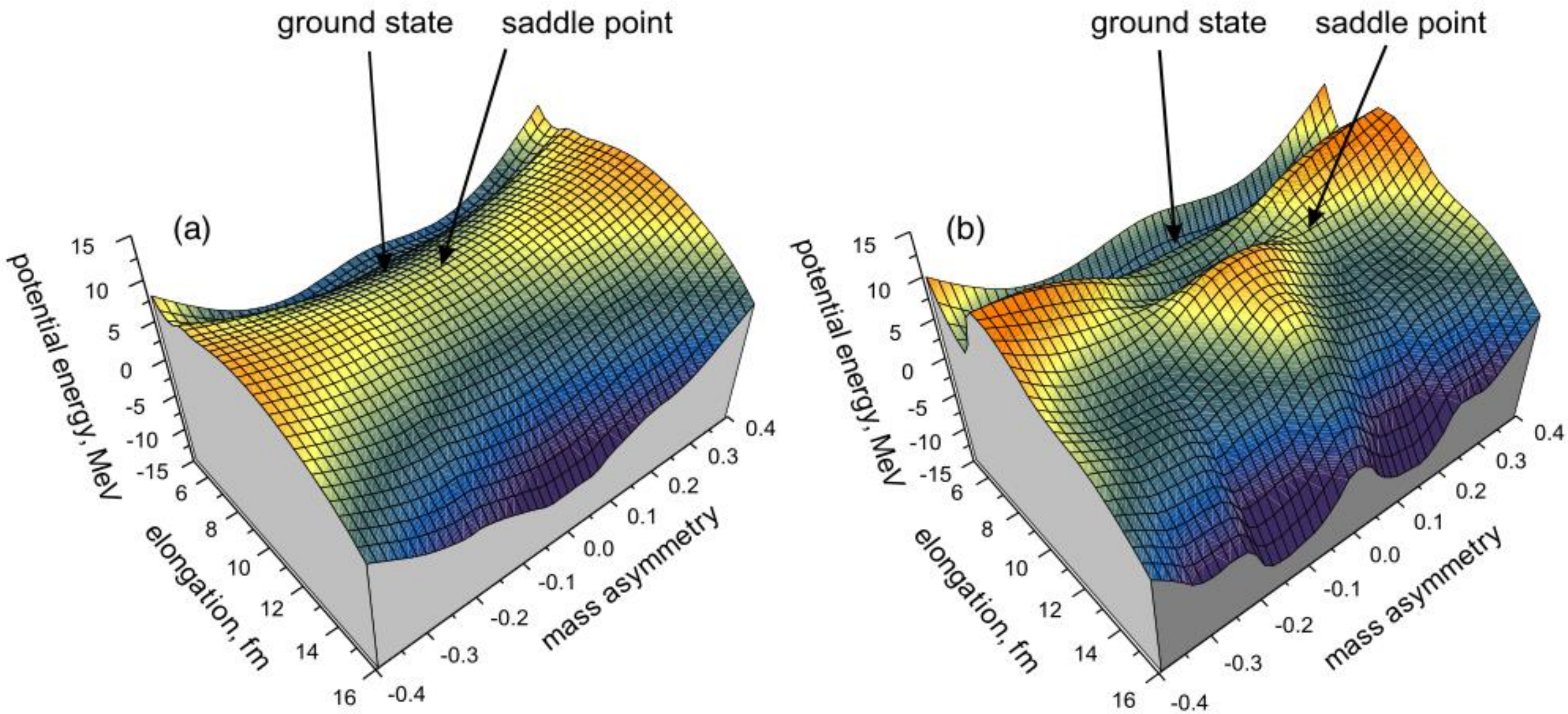
Ideas behind GEF

Combination of physical concepts and experimental information

An example: determination of fission-fragment yields

Macroscopic-microscopic model

Two-center shell model calculation by A. Karpov, 2008

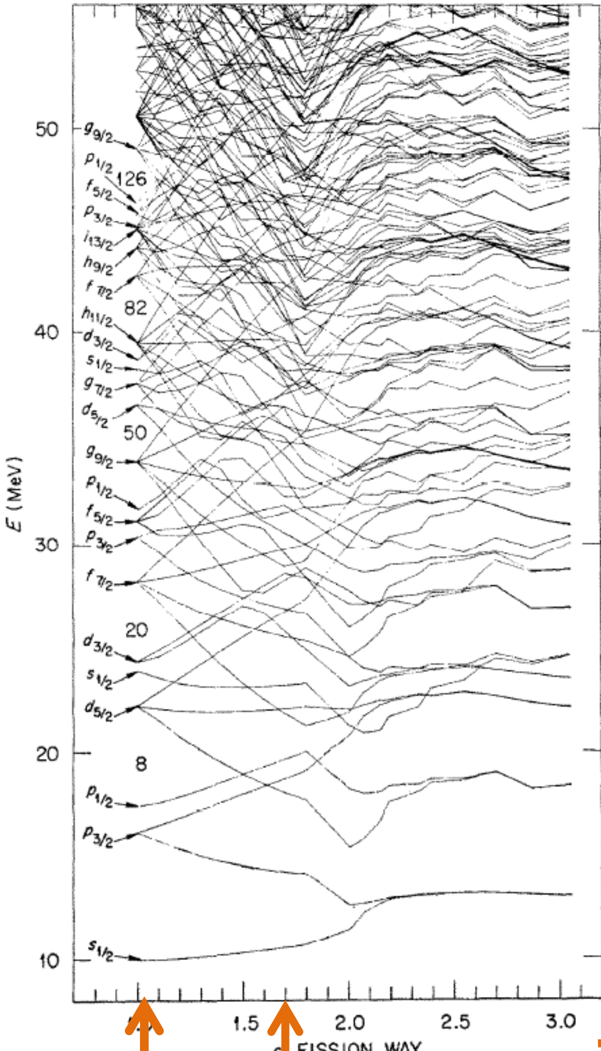


Liquid-drop potential

With shell effects

Influence of fragment shells on the fission process

Neutron shell-model states of 236U
(U. Mosel, H. W. Schmitt, Nucl. Phys. A 165 (1971) 73)



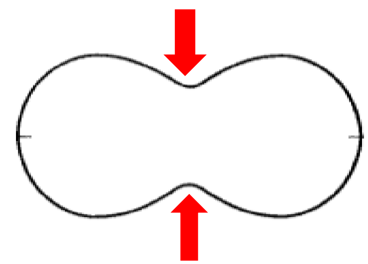
Ground state

Second barrier

... Scission

The shell effects that modulate the potential already near saddle are those of the fission fragments!

Quantum-mechanical effect caused by the neck!



Confirmed by recent HF + BCS calculations

C. Simenel et al., PRC 89 (2014) 031601 (R)

The separability principle

Separability principle

- Macroscopic potential depends on fissioning nucleus
- Shell effects depend essentially on the fission fragments

Stiffness of macroscopic potential

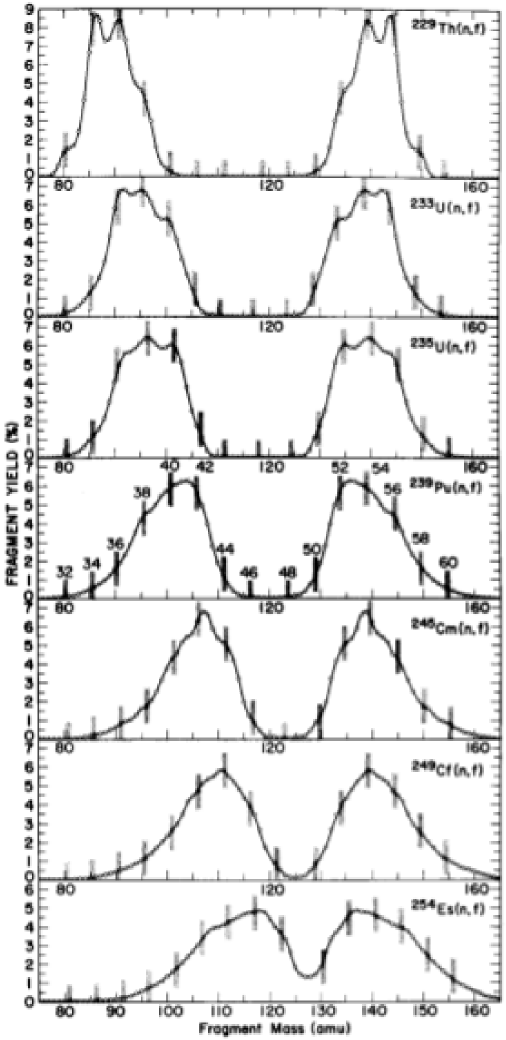
→ Deduced from experimental yields of symmetric mode for each fissioning nucleus

Position, strength and curvature of shells

→ Deduced from experimental yields and shapes of asymmetric modes, essentially the same for all fissioning nuclei

Description of a large variety of fissioning systems with the same set of parameters!!

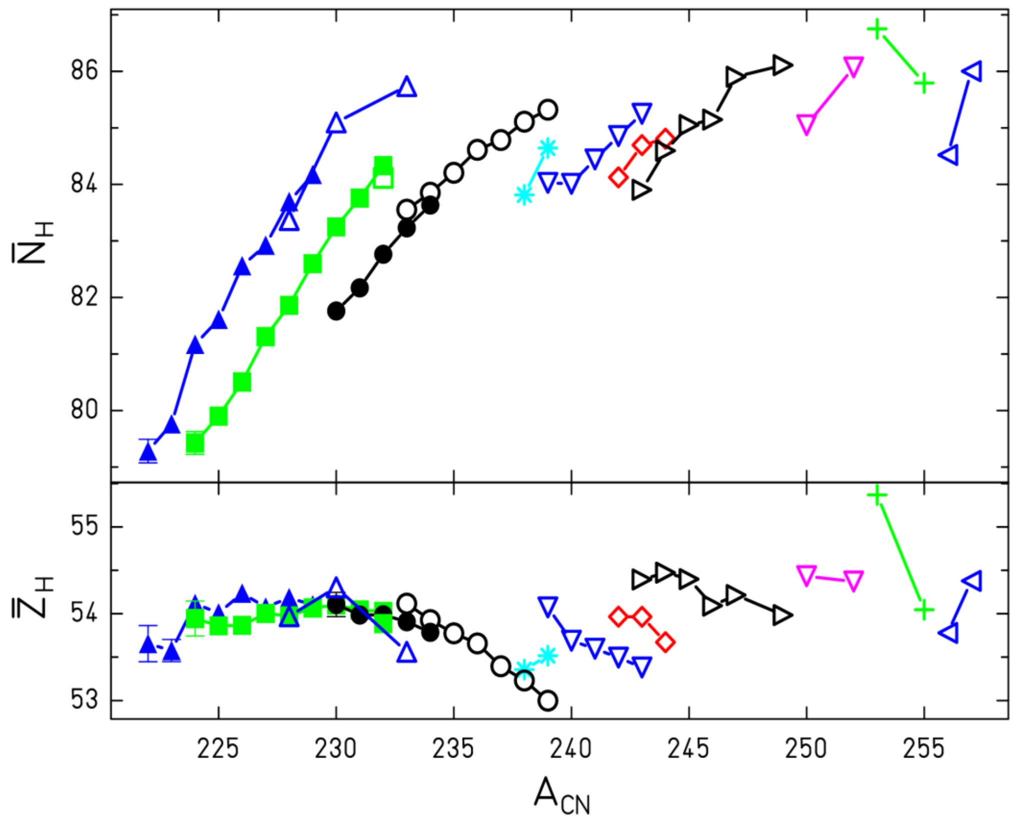
Empirical information on the main shells



Unik et al., 1973

<A> ≈ 140

Shell effects in neutron number

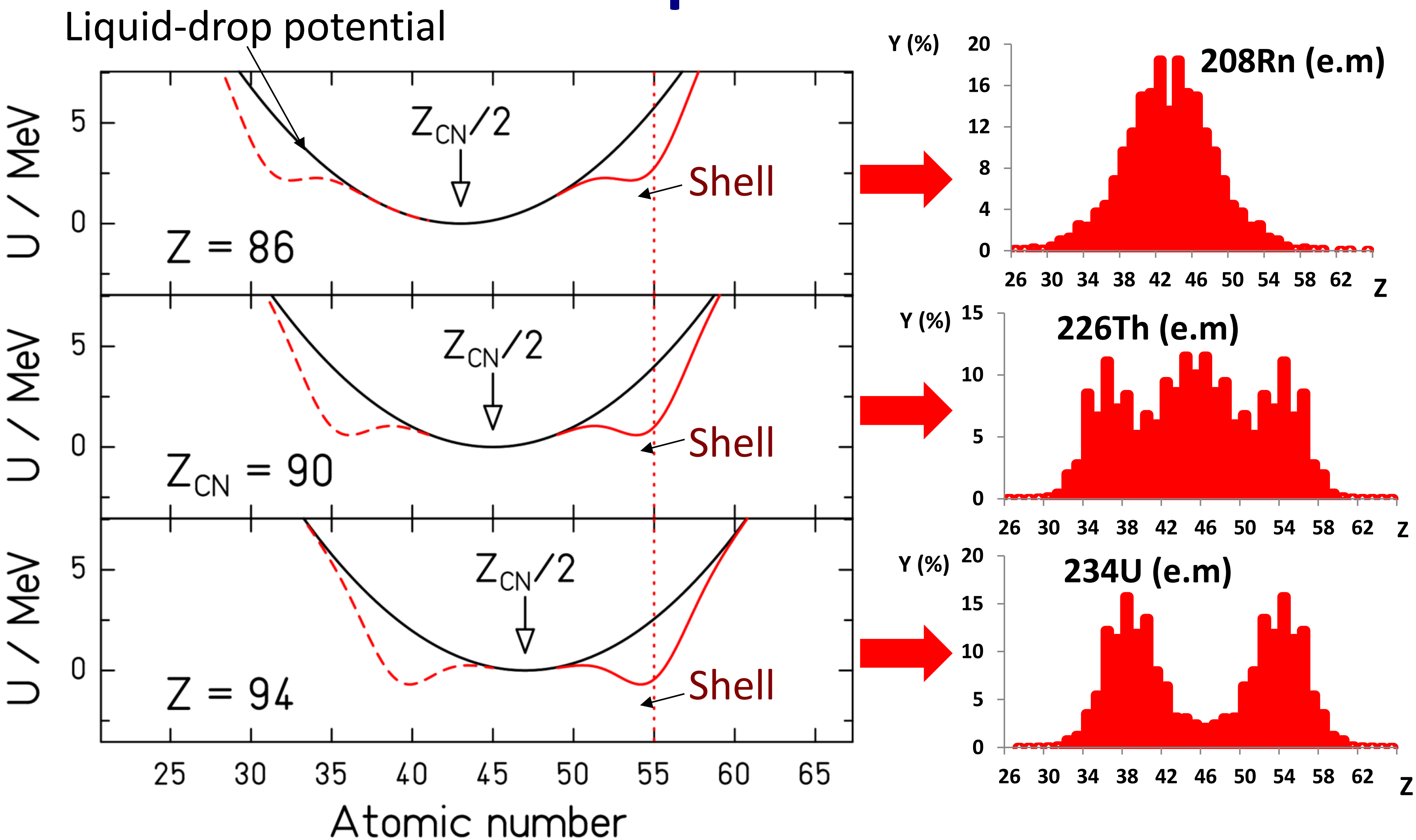


Böckstiegel et al., NPA 802 (2008) 12

GSI data with long isotopic chains:

New empirical result: <Z> ≈ 54

Final potential



Interplay between liquid-drop potential and shells explains observed transition from symmetric to asymmetric fission

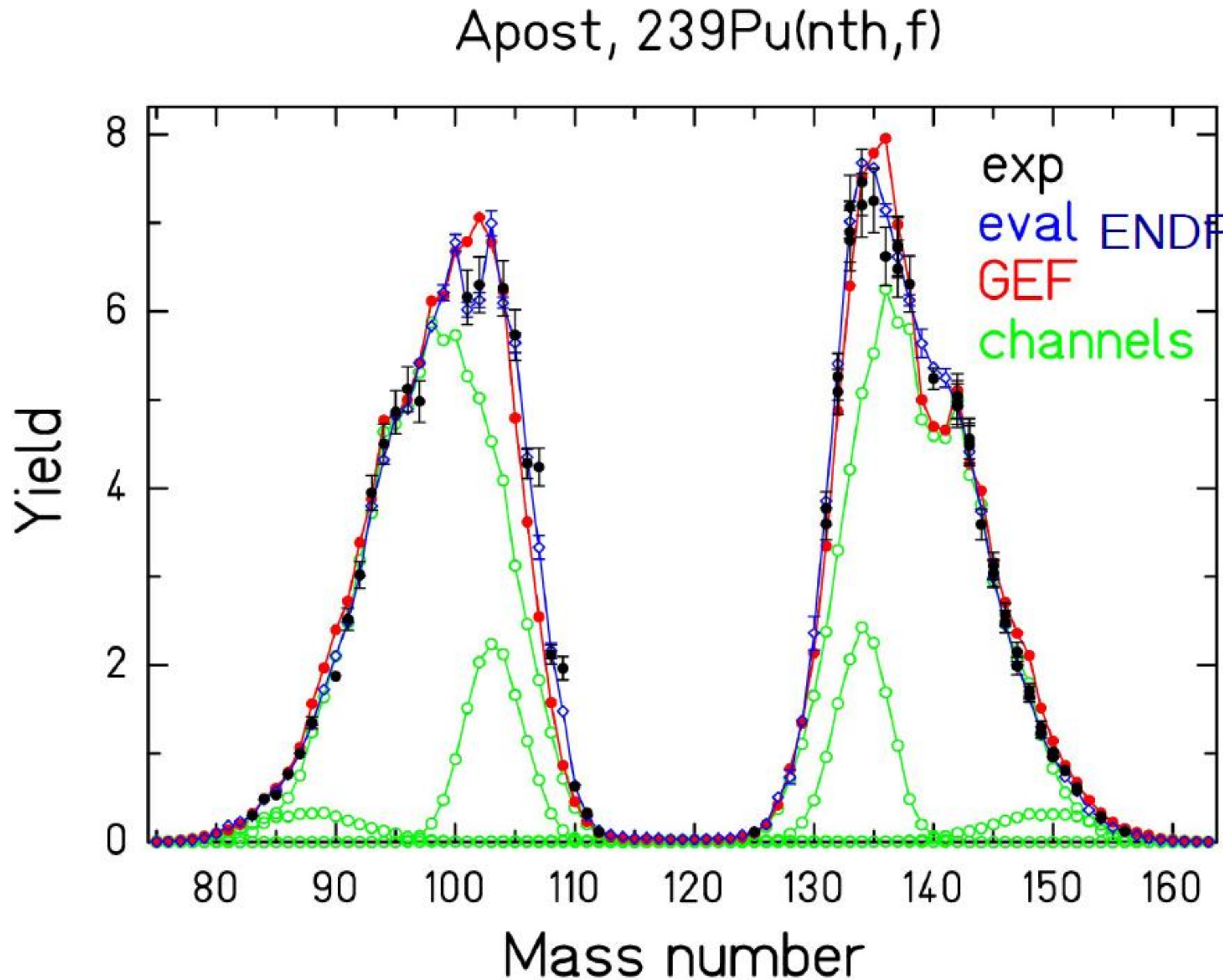
Comparison with experimental data and evaluations

See:

K.-H. Schmidt, B. Jurado, Ch. Amouroux, JEFF-Report 24 (June 2014)
https://www.oecd-nea.org/databank/docs/2014/db-doc2014-1.pdf
for comprehensive comparison of GEF with all possible fission observables

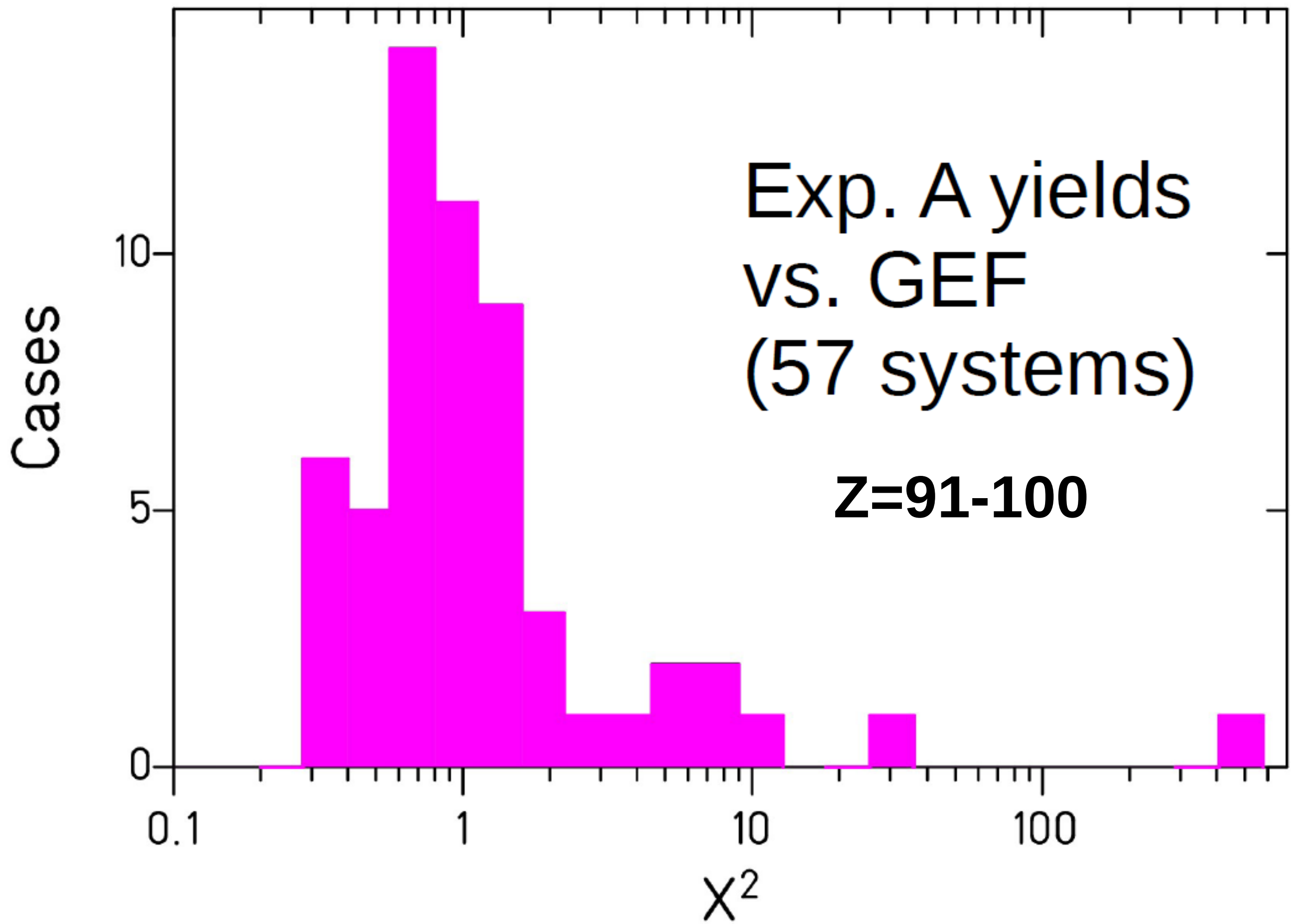
All the results obtained with a single parameter set!

An example...



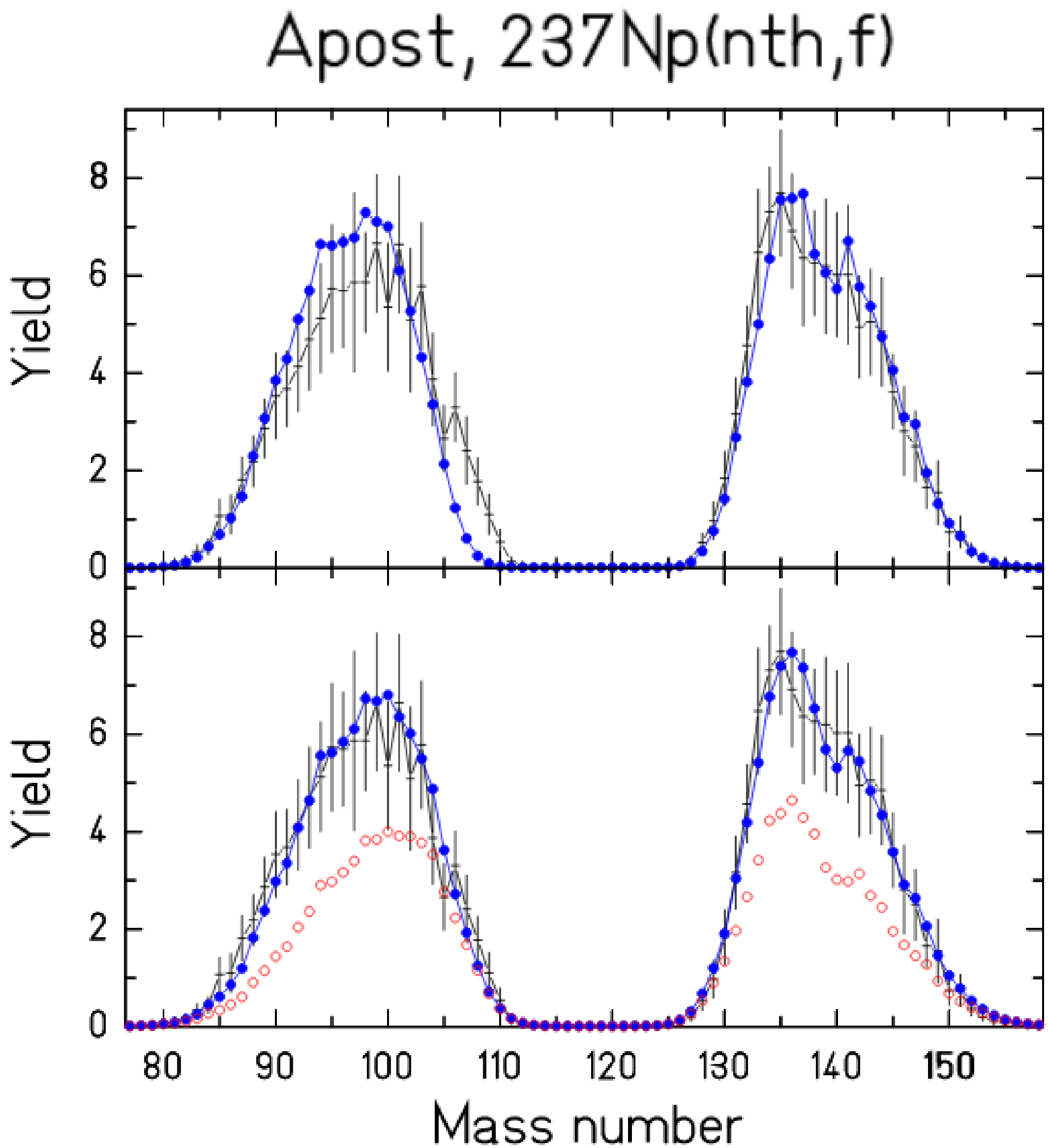
Apost, 239Pu(nth,f)
exp
eval
ENDF
GEF
channels
Yield
Mass number
0
2
4
6
8
80
90
100
110
120
130
140
150
160

χ^2 deviations between GEF and experimental data



Amongst the 9 discrepant cases only 1 (229Th(n_{th},f)) can be clearly attributed to a deficiency in the model!

GEF a tool to identify anomalies



ENDF
GEF

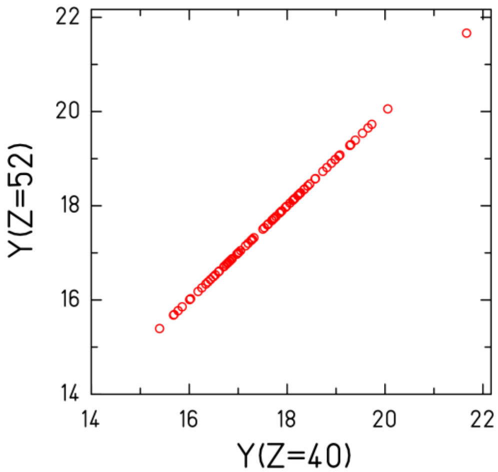
ENDF
GEF:
239Pu(nth,f) 60%
237Np(nth,f) 40%

Data spoiled by 239Pu target contaminant!

GEF provides covariance matrices

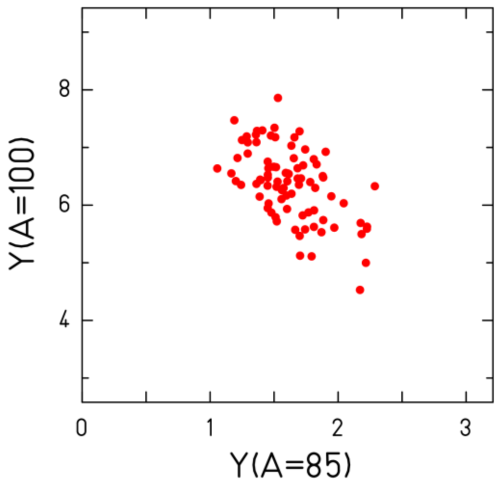
Interdependence between fragment yields

- Interdependence required by physics



Two complementary fragments (Strictly correlated)

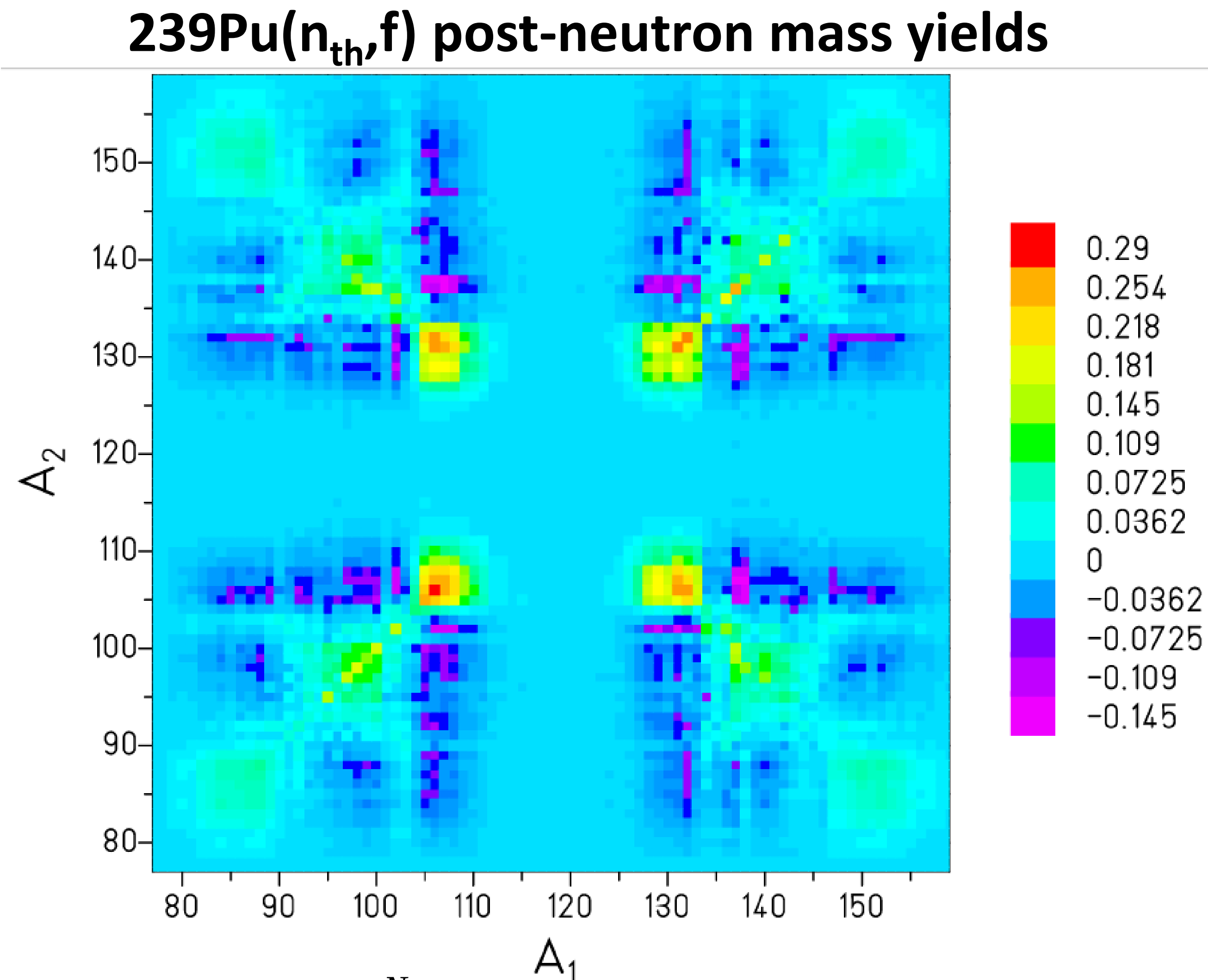
- Interdependence required by the model



Two fragments from different modes. (Slightly anti-correlated, normalisation to 200%)

Result of perturbed GEF calculations for 235U(n_{th},f)

Covariance matrix of yields of one fissioning nucleus

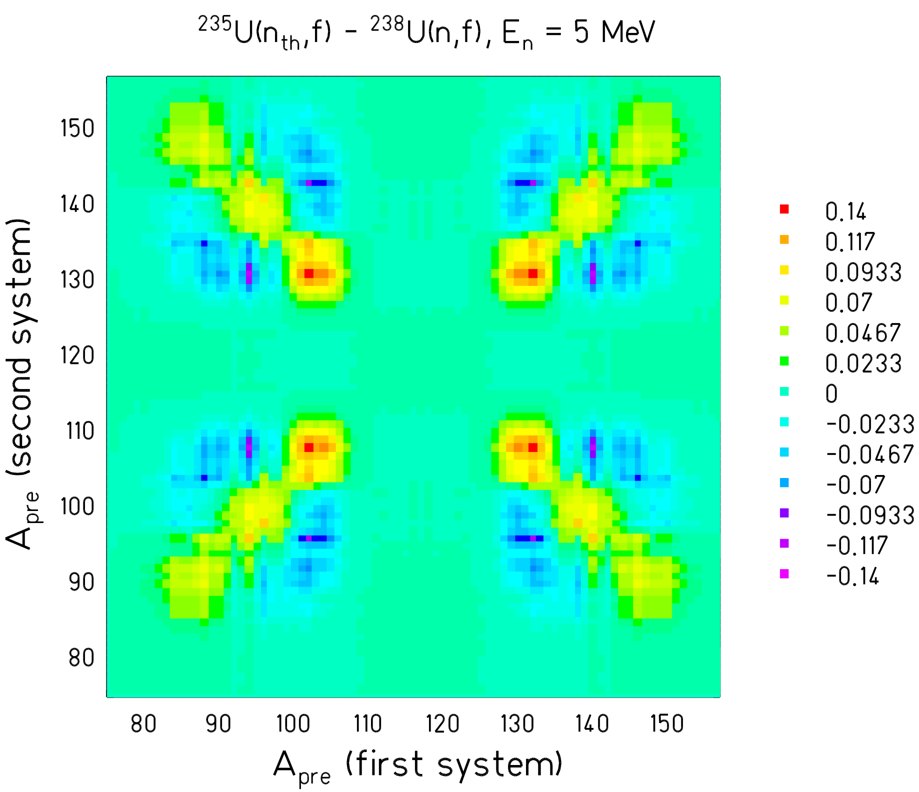


$$Cov\left(A_{1,i};A_{2,i}\right)=\frac{1}{N-1}\sum_{i}^{N}\left(Y(A_{1,i})-\left\langle Y(A_{1,i})\right\rangle\right)\left(Y(A_{2,i})-\left\langle Y(A_{2,i})\right\rangle\right)$$

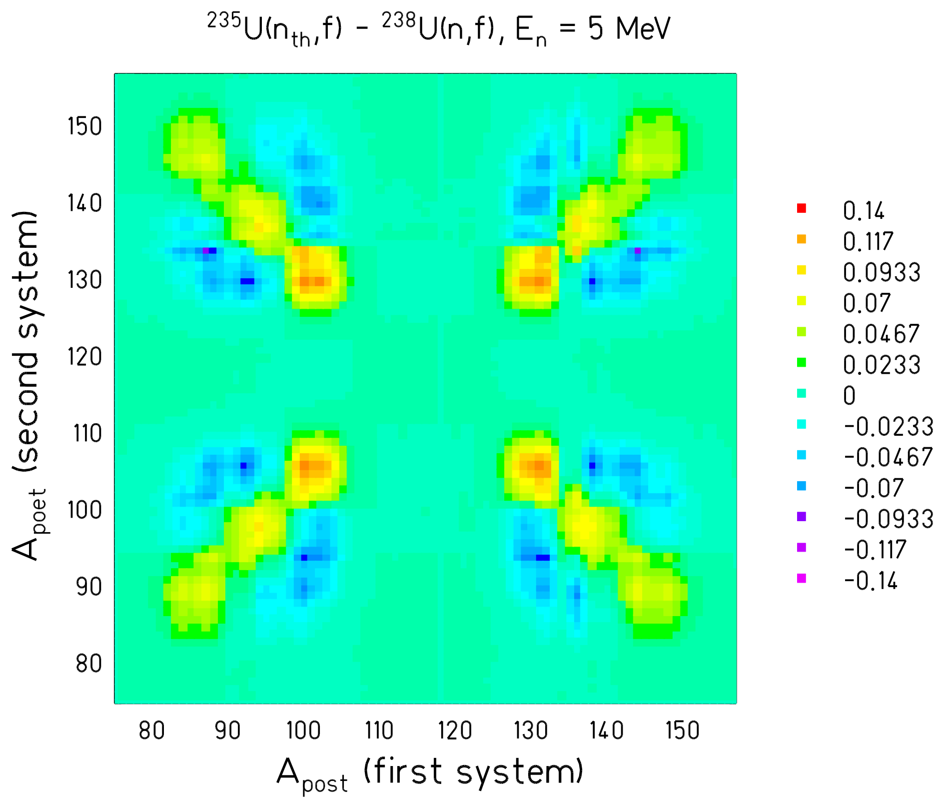
Covariance matrix of yields of two fissioning nuclei

The same parameters for all fissioning nuclei→possibility to determine the covariance matrix for two fissioning nuclei!

Pre-neutron mass yields



Post-neutron mass yields



Conclusions

→GEF: **combination of fundamental physics and specific experimental information within a general approach**

→GEF a useful tool for evaluation and applications in other domains
GEF is unique in preserving the correlations between all the quantities!

→GEF a useful tool for fundamental physics
*The assumption of a universal set of shells for all fissioning nuclei gives an excellent description of the fission-fragment yields. This remarkable finding can be useful in the development of microscopic theories.
*Etc…

…and perspectives

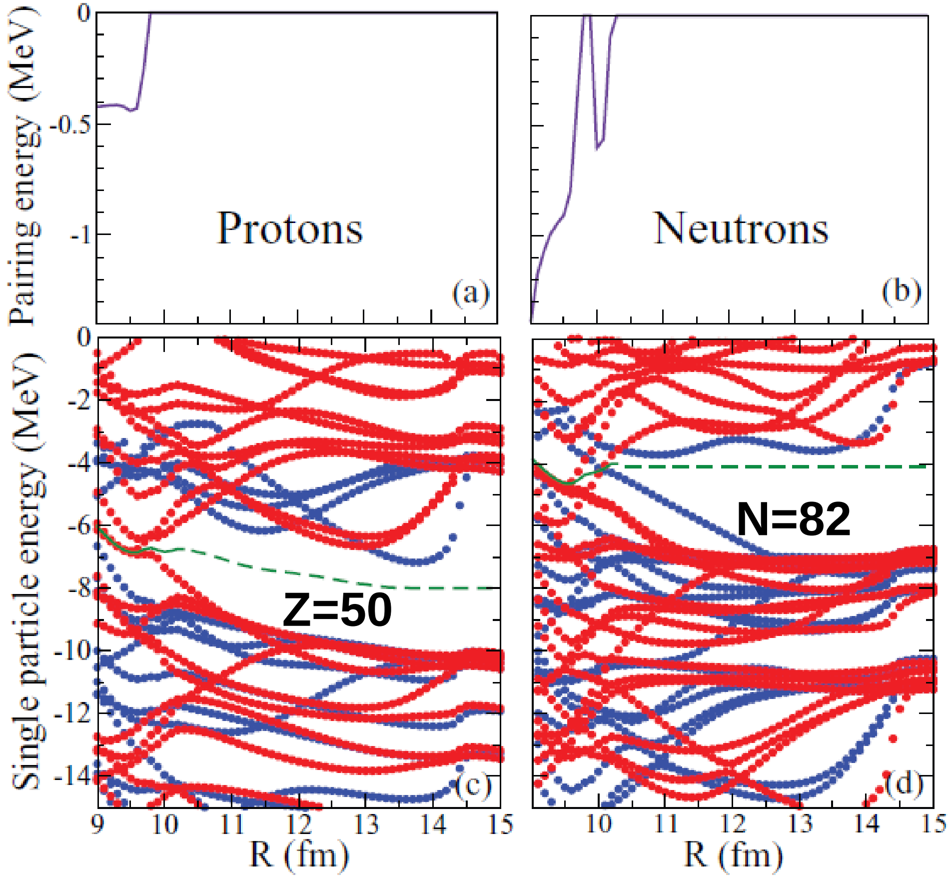
→Use of new fission data (SOFIA(GSI) & GANIL) to improve GEF
→Inclusion of ternary fission
→Extension to very exotic neutron-rich fissioning nuclei of interest for the r-process in stellar nucleosynthesis
→etc…

Download and further information can be found in :
www.khs-erzhausen.de or www.cenbg.in2p3.fr/GEF

Early influence of fragment shells

HF + BCS calculations for fission of ^{264}Fm

C. Simenel and A. S. Umar, Phys. Rev. C 89 (2014) 031601 (R)

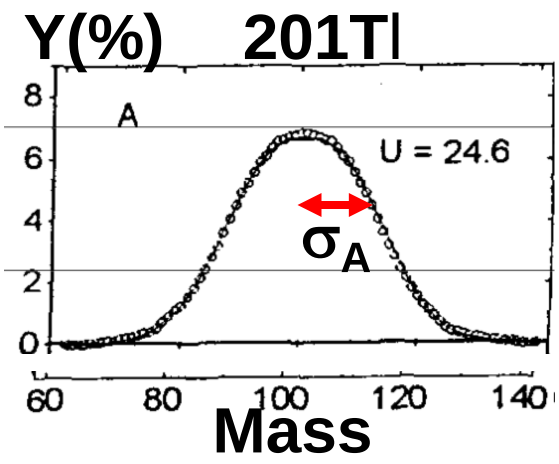


Saddle → R=7.3 fm

Scission → R=15 fm

Shells of double magic ^{132}Sn fragments set in at R=9.5 fm, very close to saddle!!

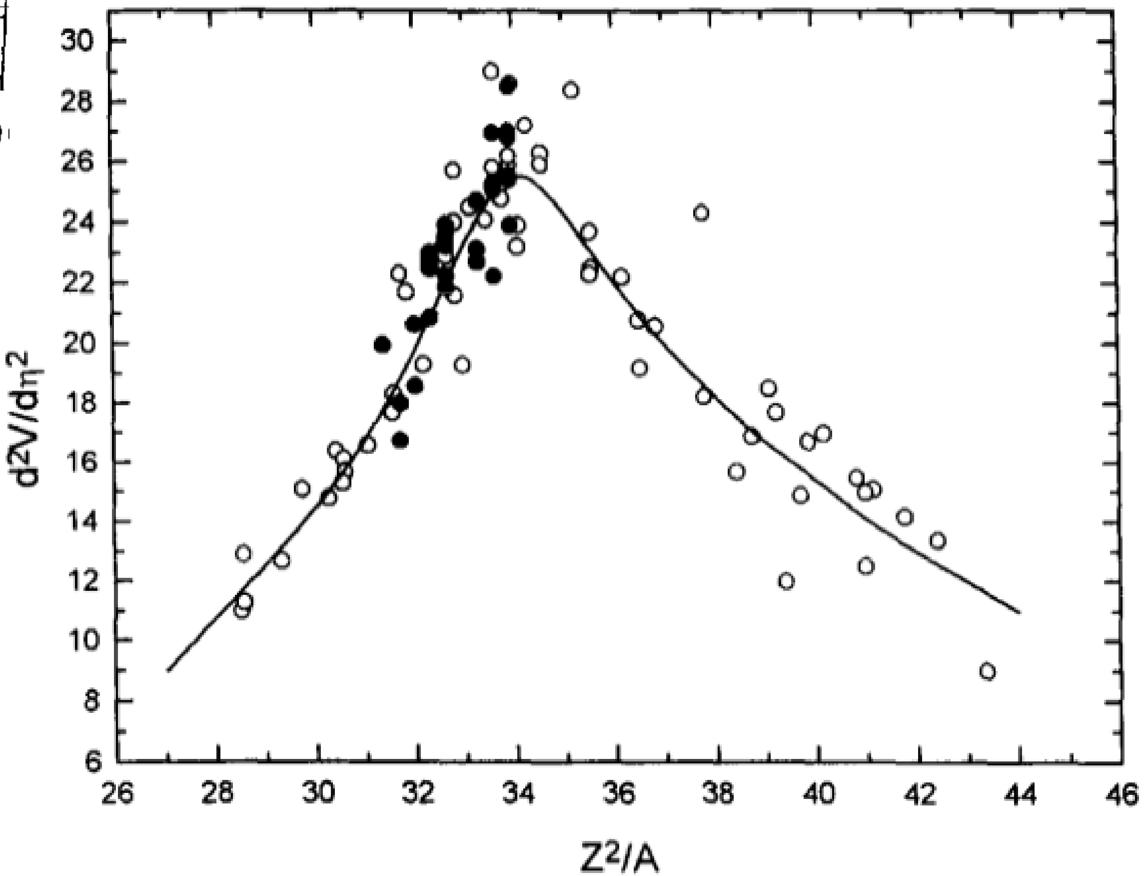
Empirical information on the macroscopic potential



Mulgin et al., NPA 640 (1998) 375

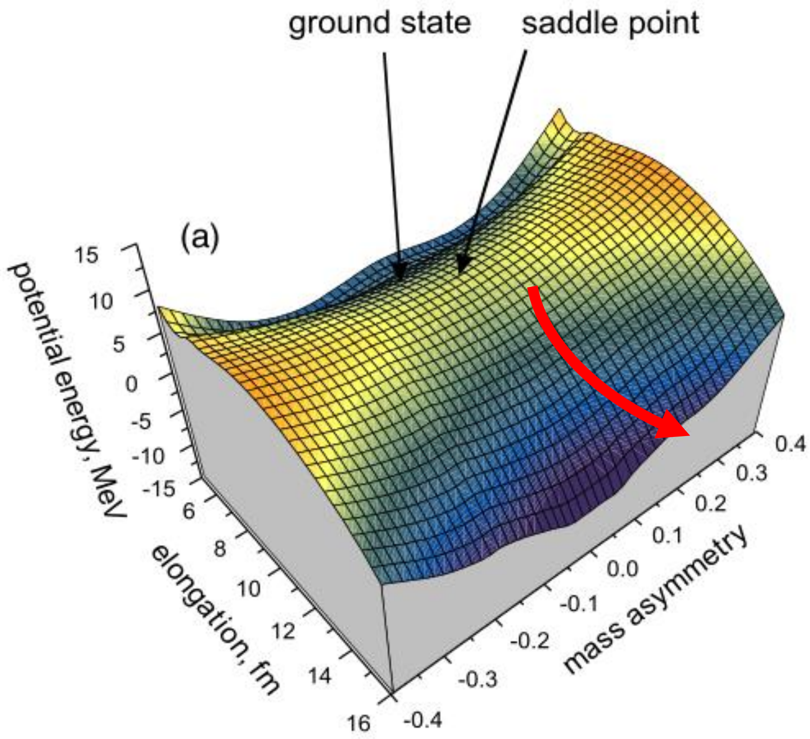
Assuming a harmonic oscillator in a heat bath

$$\sigma_A^2 = \frac{T}{stiffness}$$



Stiffness of the macroscopic potential is a unique function of the fissility of the fissioning nucleus!

How about dynamics?



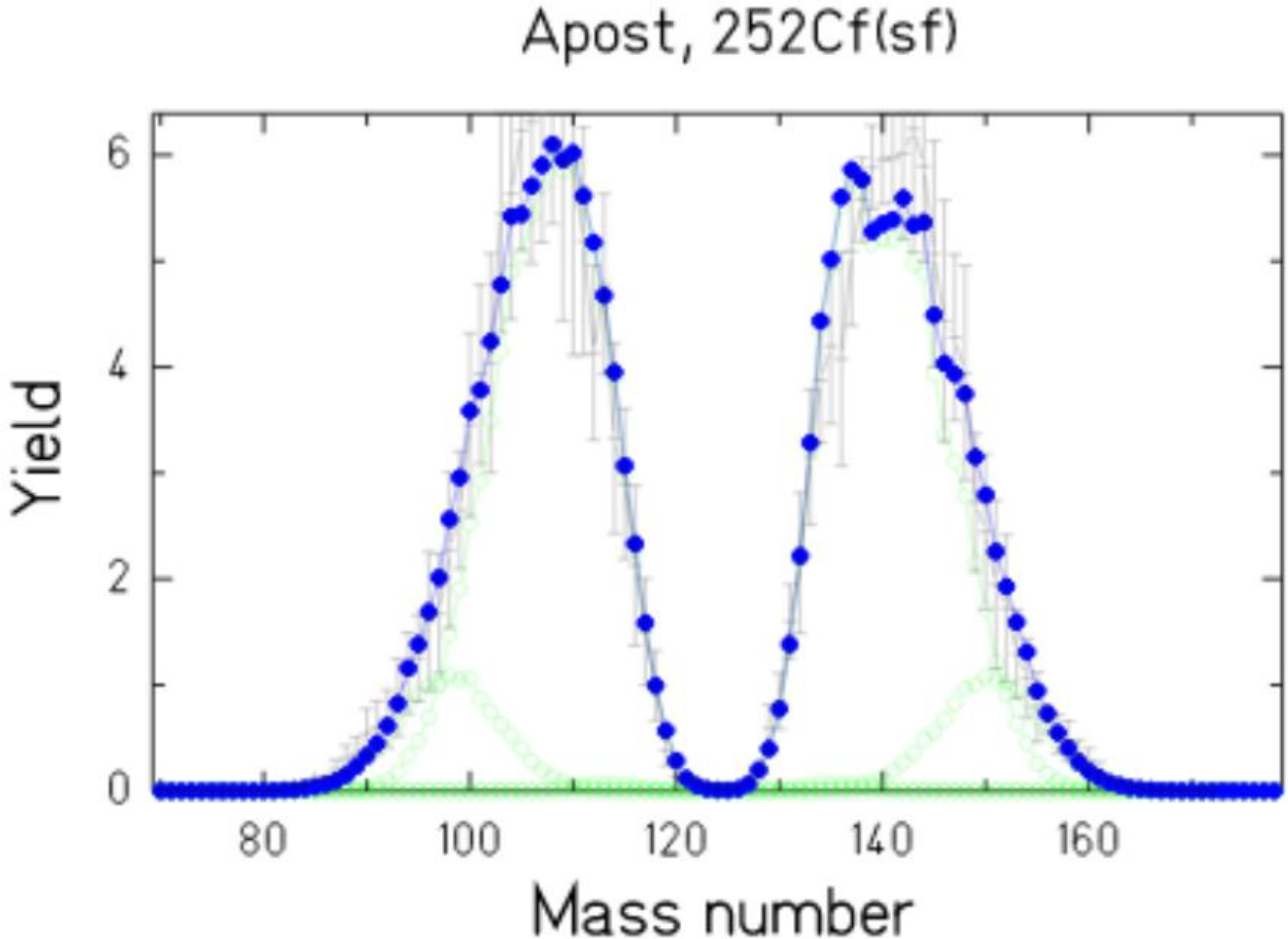
Shell effects are fixed but the stiffness of the macroscopic potential changes on the way to scission.

Mass asymmetry is influenced by the potential at earlier stages of the descent.
"Memory" effect!
Andreyev et al. Sov. J. Nucl. Phys. **43** (1986) 727 and Nucl. Phys. A **502** (1989) 405c

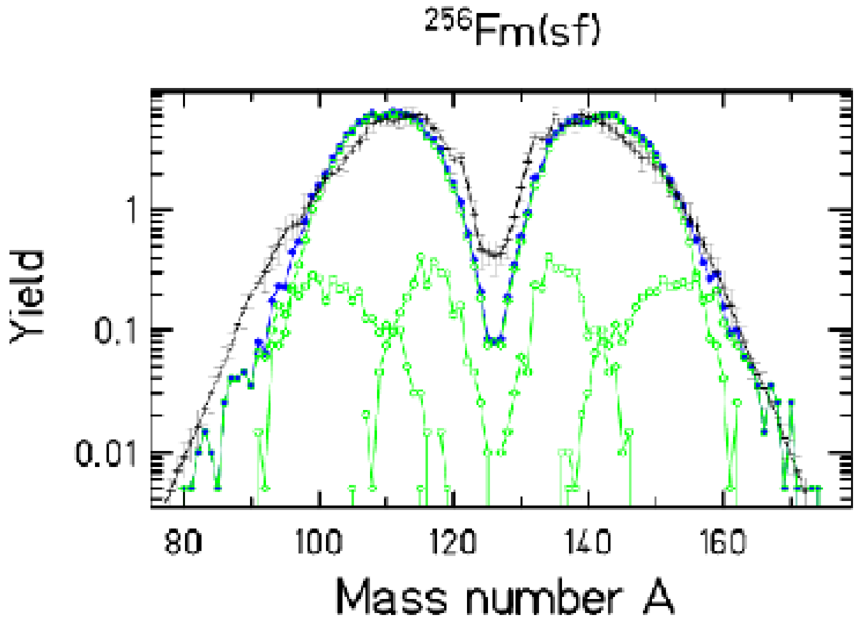
Experimental symmetric yields reflect an effective potential!

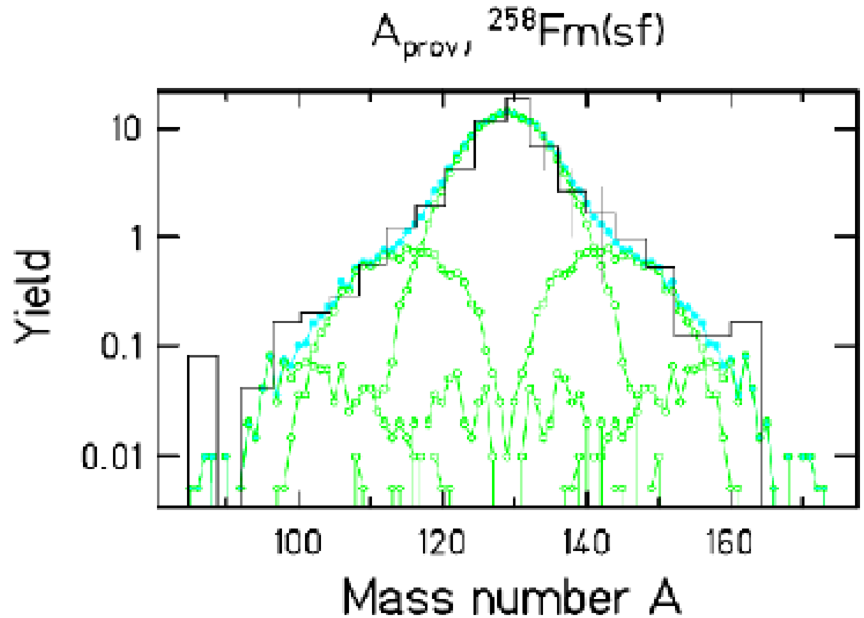
Because of the use of the stiffness from experimental data, dynamical effects are automatically included!

Yields, spontaneous fission

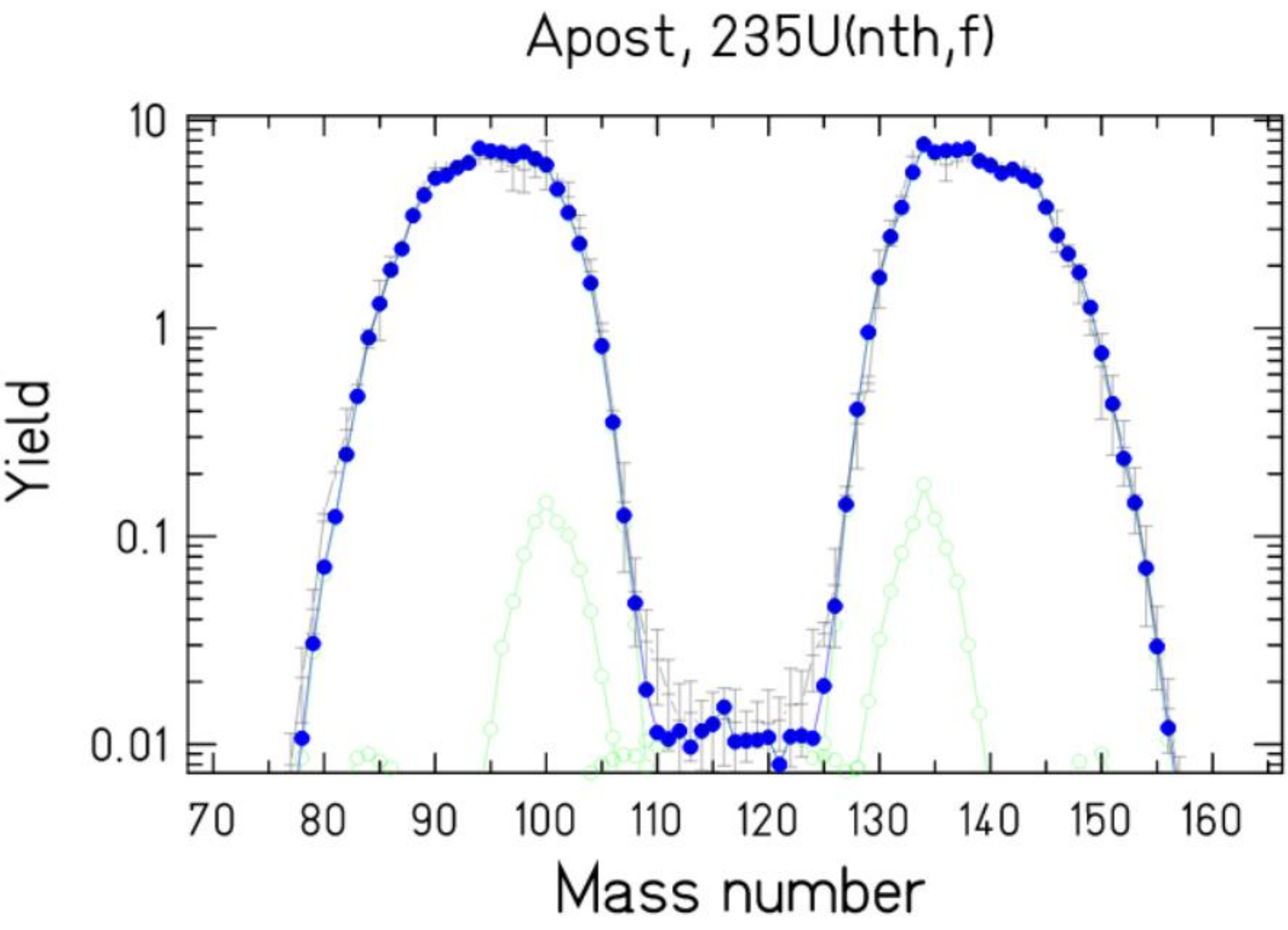


Yields, spontaneous fission

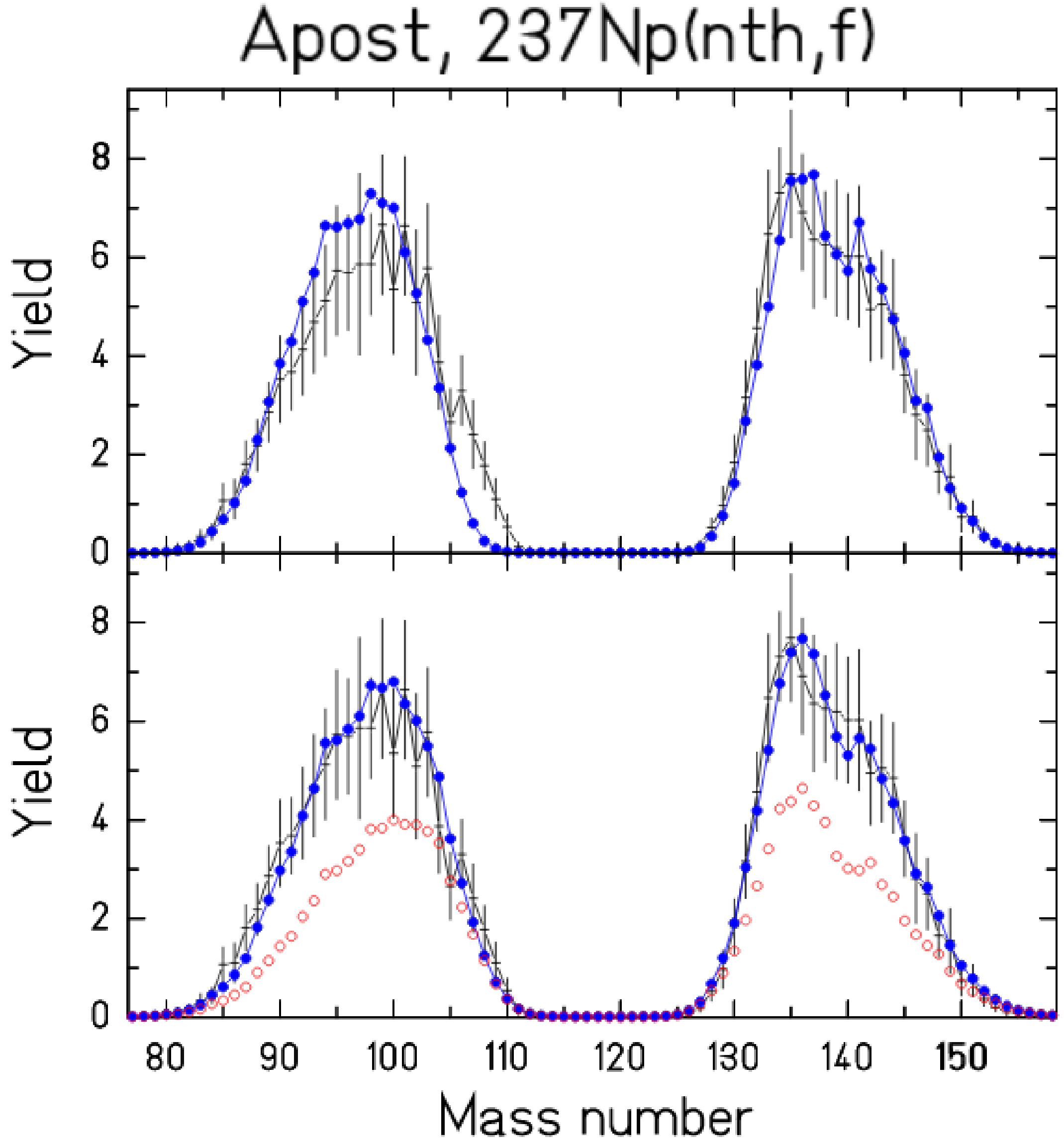




Yields, thermal-neutron-induced fission

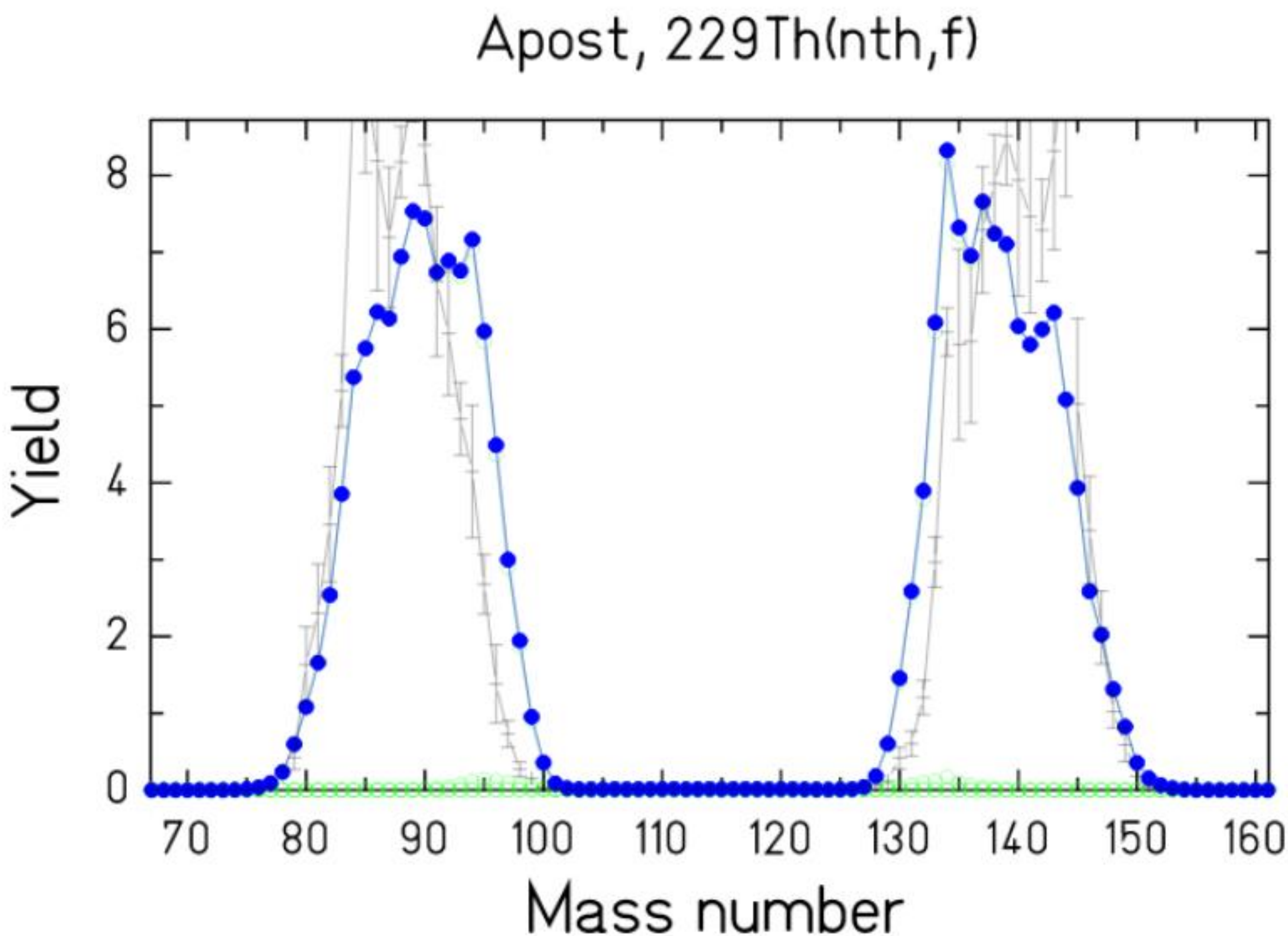


Yields, thermal-neutron-induced fission

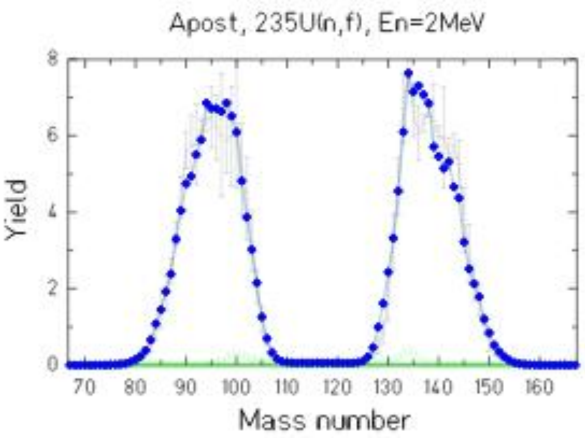


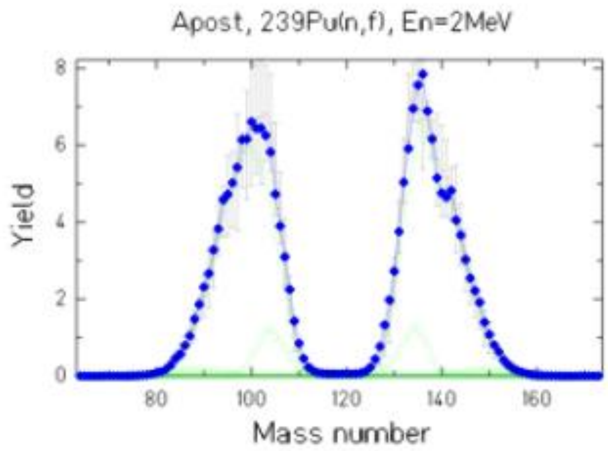
Data spoiled by 239Pu target contaminant!

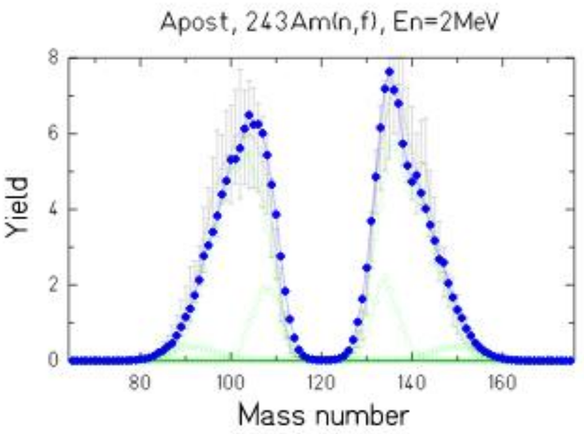
Yields, thermal-neutron-induced fission

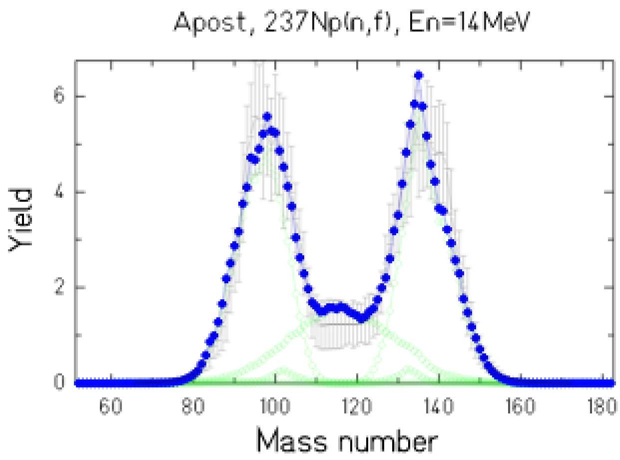


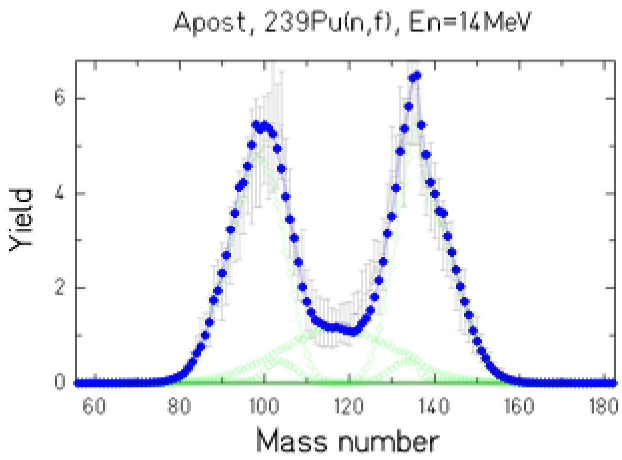
Yields, higher energies



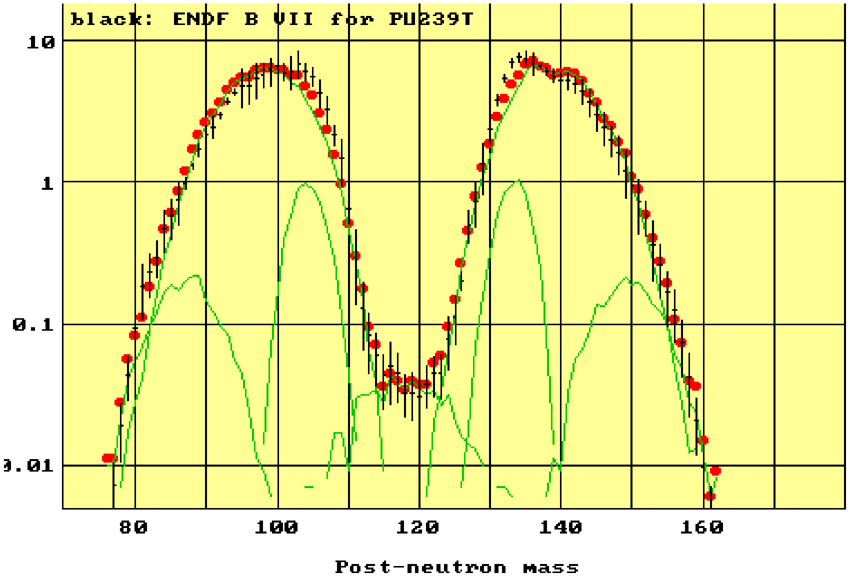


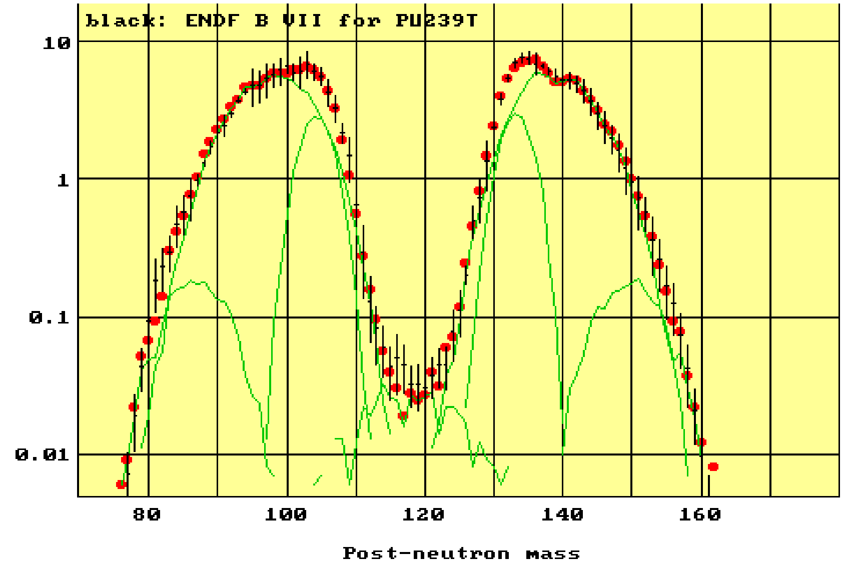




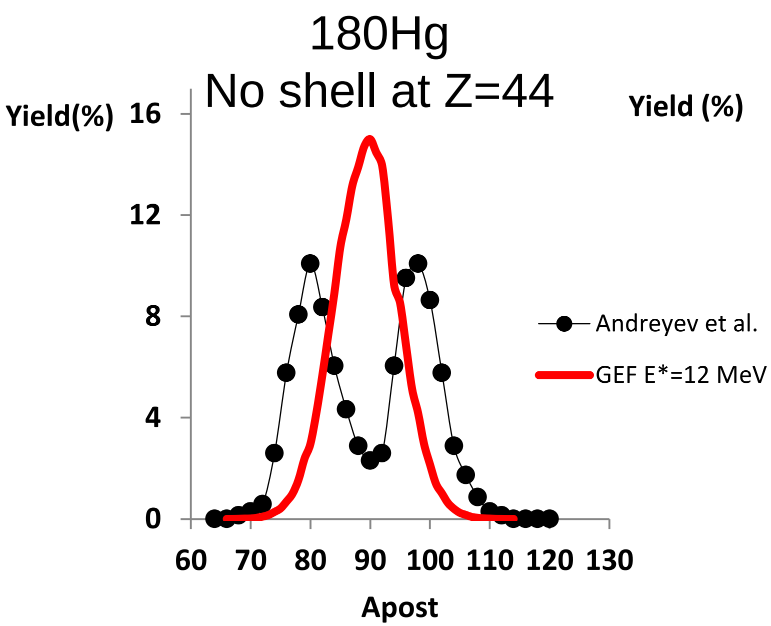


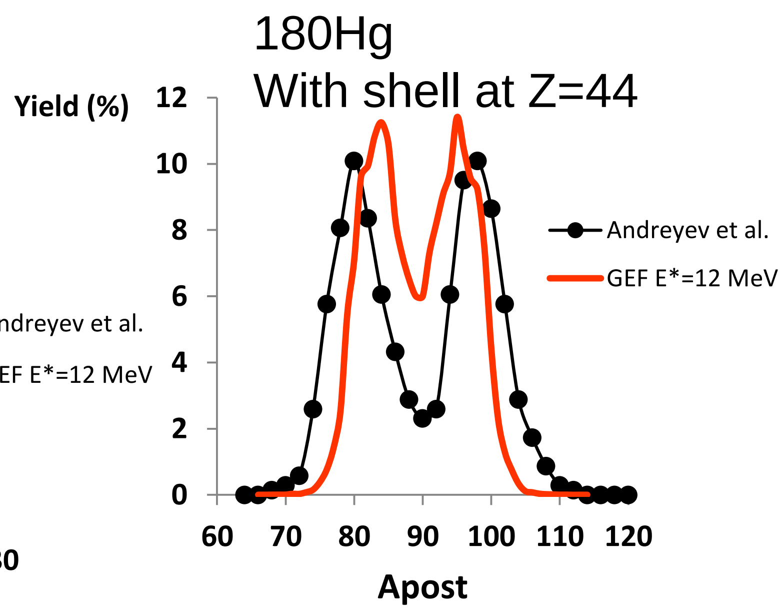
GEF: a useful tool for fundamental physics



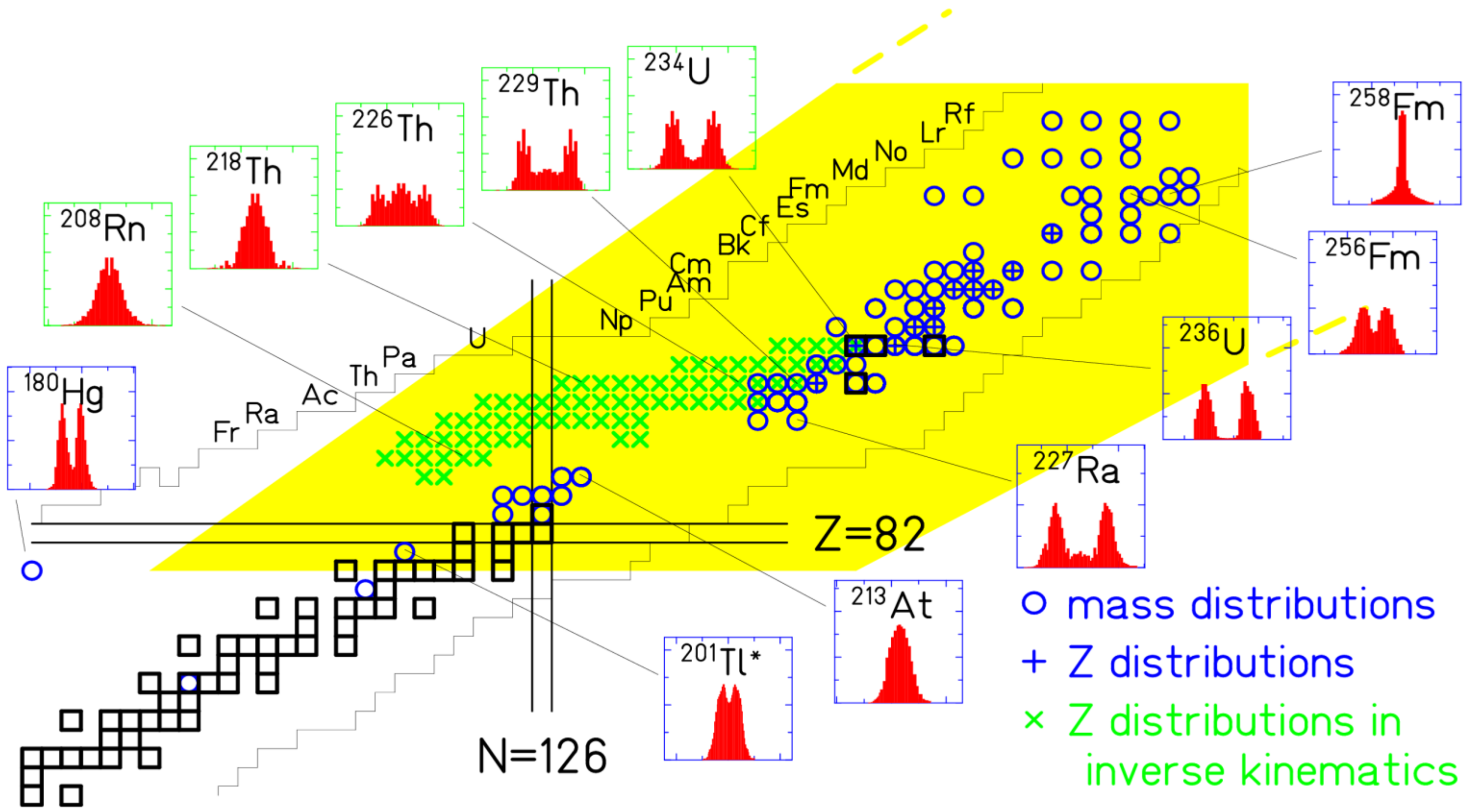


Shell effect at Z=44 needed to reproduce all the data in a coherent way!





This shell is responsible for the asymmetric fission observed for light, neutron-deficient fissioning nuclei!!!



^{208}Rn
^{218}Th
^{226}Th
^{229}Th
^{234}U
^{258}Fm
^{256}Fm
^{236}U
^{227}Ra
^{213}At
^{201}Tl*
^{180}Hg
Fr Ra Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr Rf
Z=82
N=126
○ mass distributions
+ Z distributions
× Z distributions in inverse kinematics