Mesurer la fission: Défis et résultats récents

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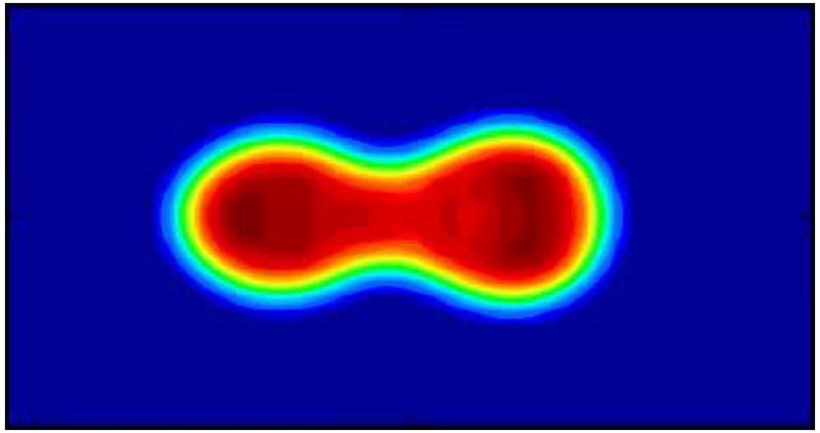
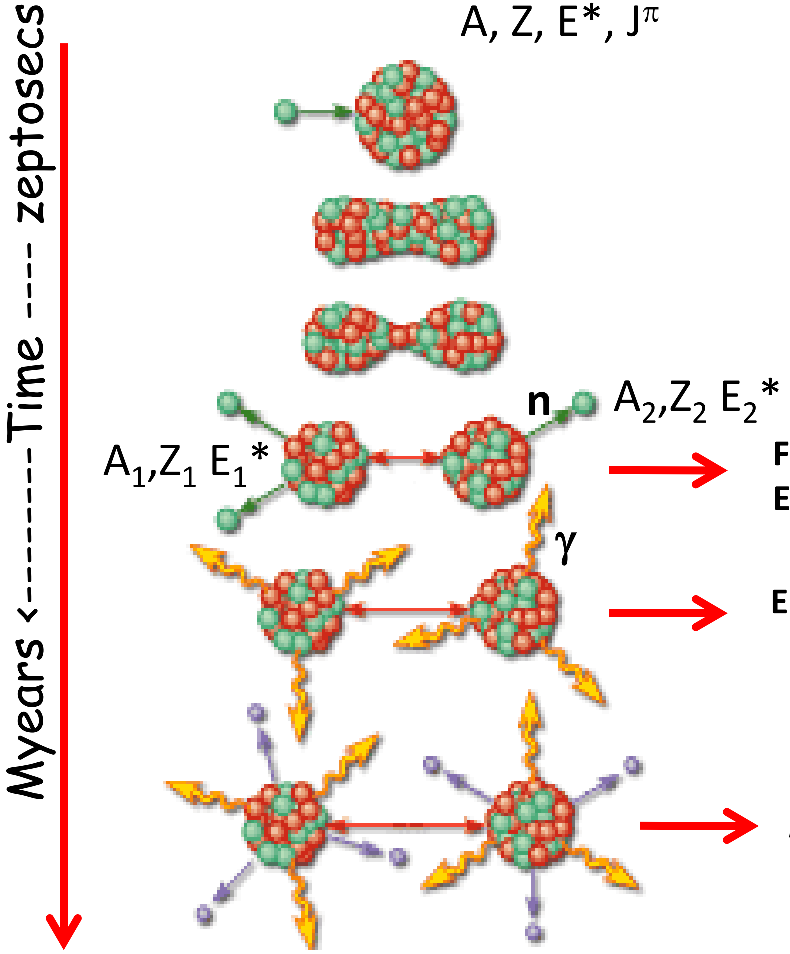
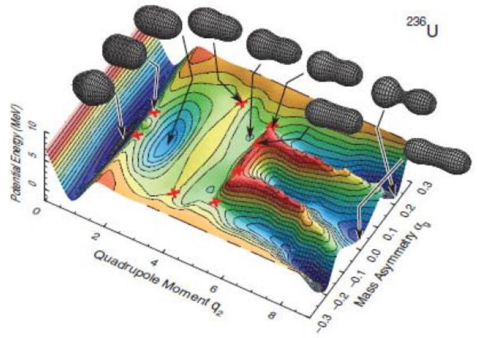
Grand Accélérateur National D'Ions Lourds, Caen

26ème Congrès Général de la SFP
Paris 3rd-7th July 2023



The Fission Process



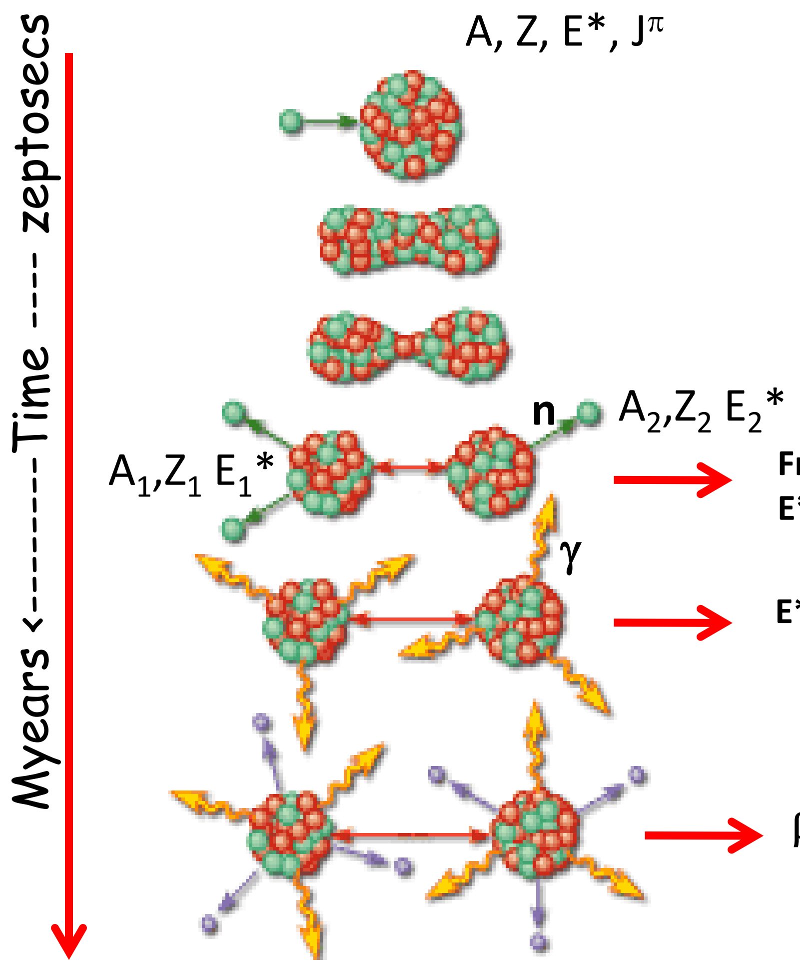


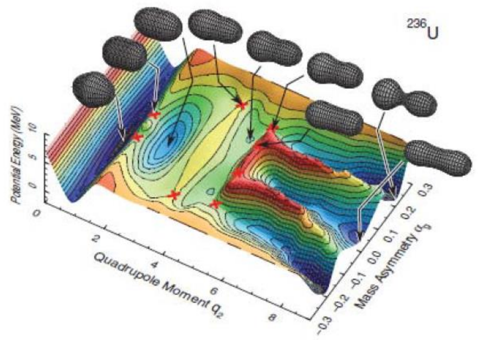
Fragments recover smaller deformation
E* release by prompt neutron emission

E* release by prompt gamma-ray emission

β decay

The Fission Process





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Chemical Identification of Ba (Z=56) in Uranium Samples (Z=92) irradiated by neutrons

Hahn and Strassmann (Dec. 1938)

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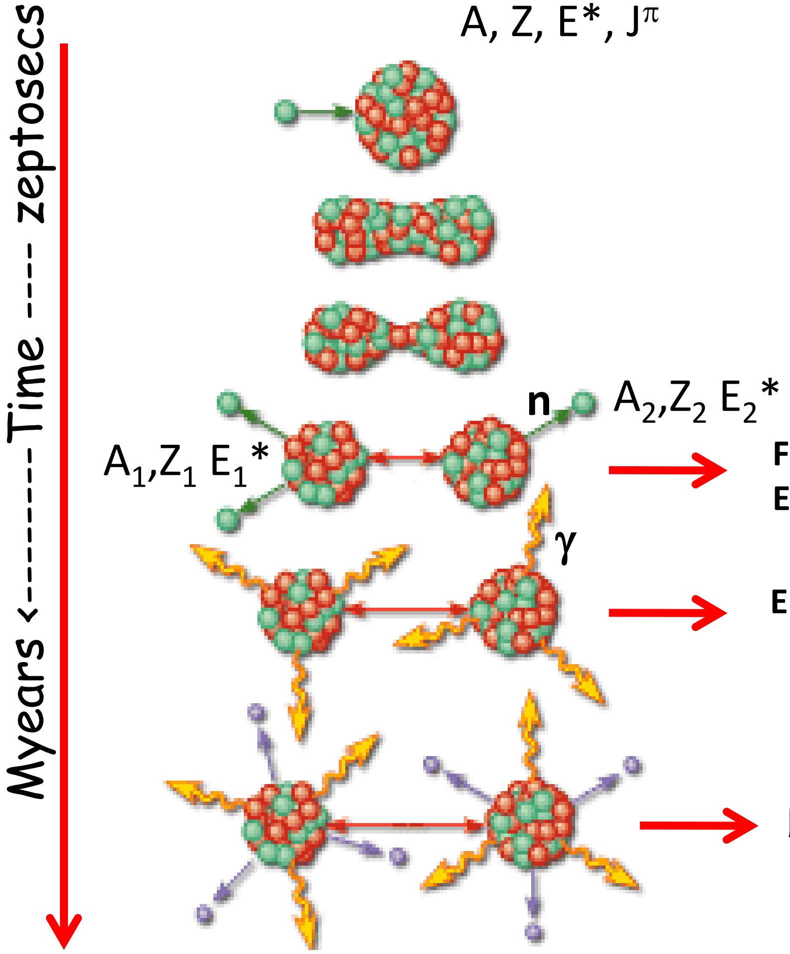

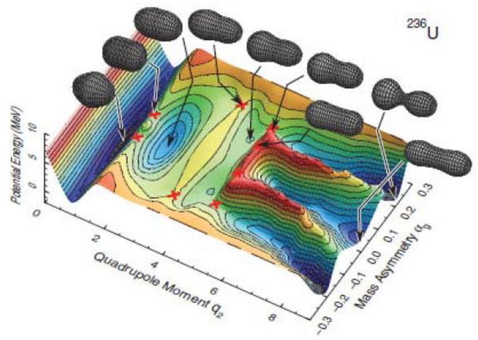

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Meitner and Frisch, Nature (1939)

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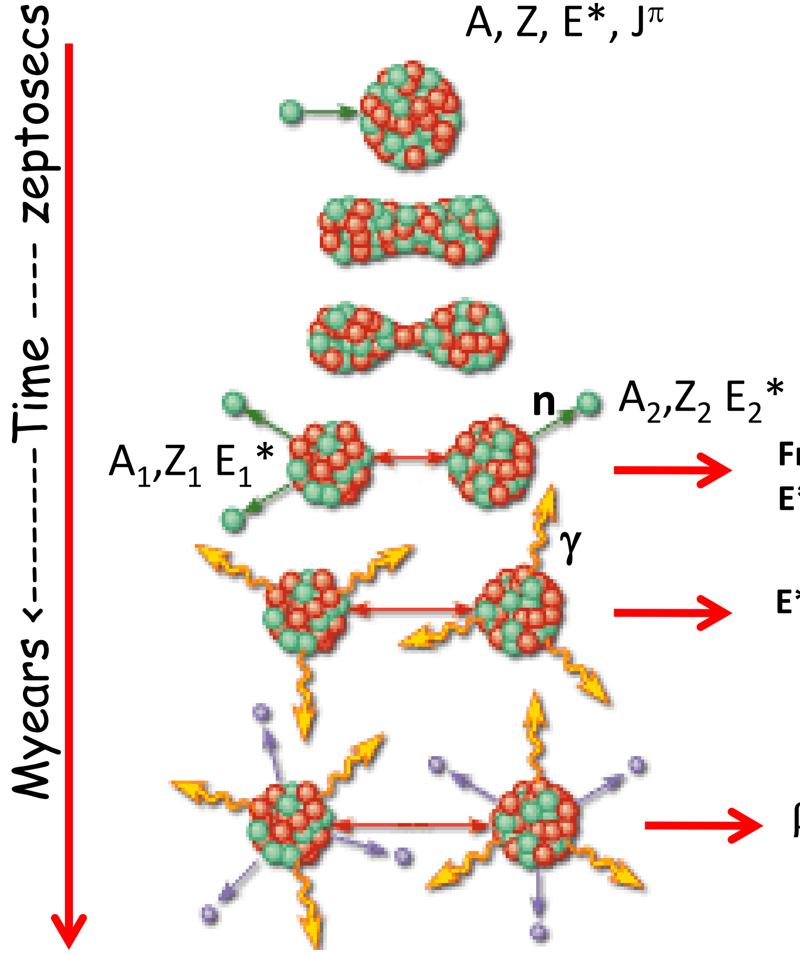

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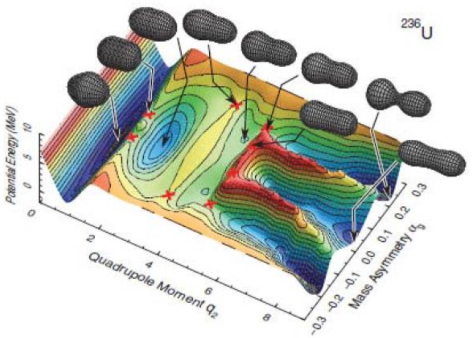

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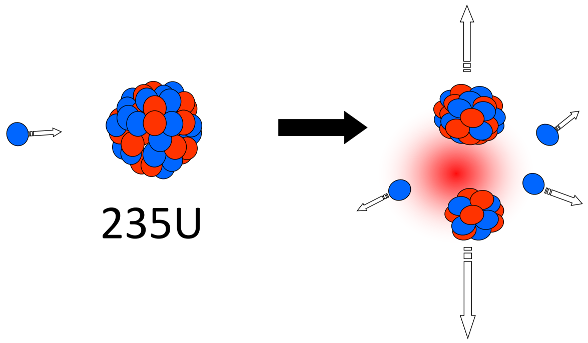
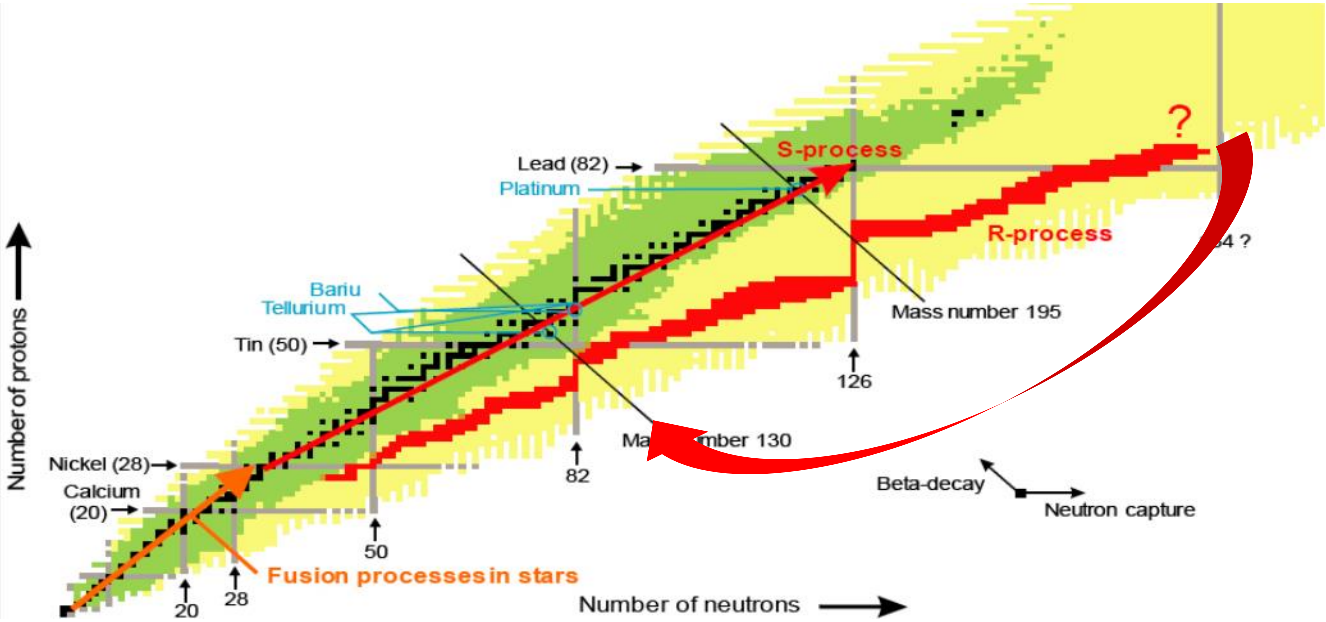
85 years of experimental and conceptual challenges

The importance of fission

Huge amount of energy released per fission event: ~ 200 MeV!
Few eV for combustion of a molecule of coal, gas or oil…



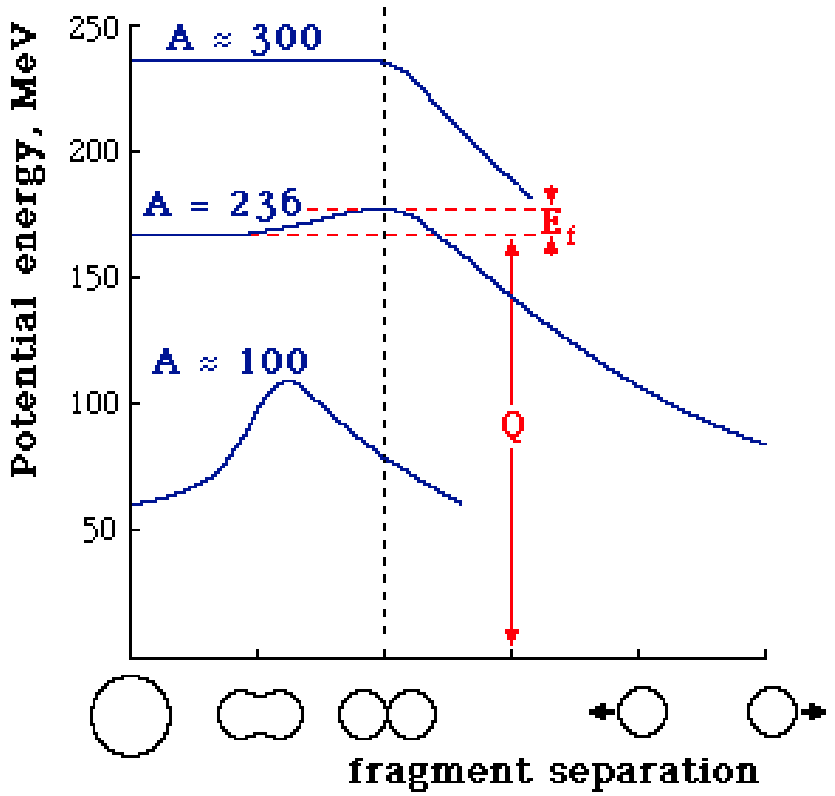
- **Nuclear technology => production of**
    - **electricity (~10% of present electricity production)**
    - **radio-isotopes for medecine**
    - **Radioactive Ions Beams**
- **Nuclear astrophysics, synthesis of elements via the r-process**

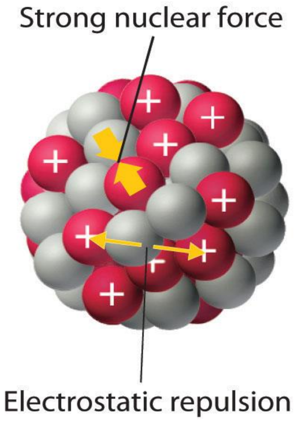


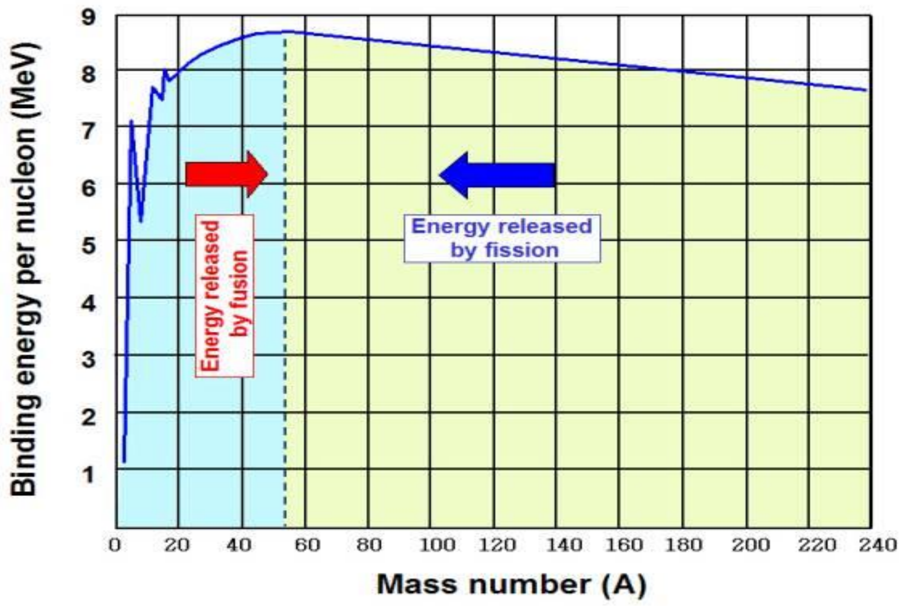
Fission sets the end point of the r-process and strongly influences the r-process abundances and light curves!

Why Nuclei Fission ?

- Competition between nuclear binding (neutrons and protons) and electrostatic repulsion (protons)
  -> Fission Barrier
- Once separated, the products "slide" of the electrostatic potential
- The energy released is found in their velocities



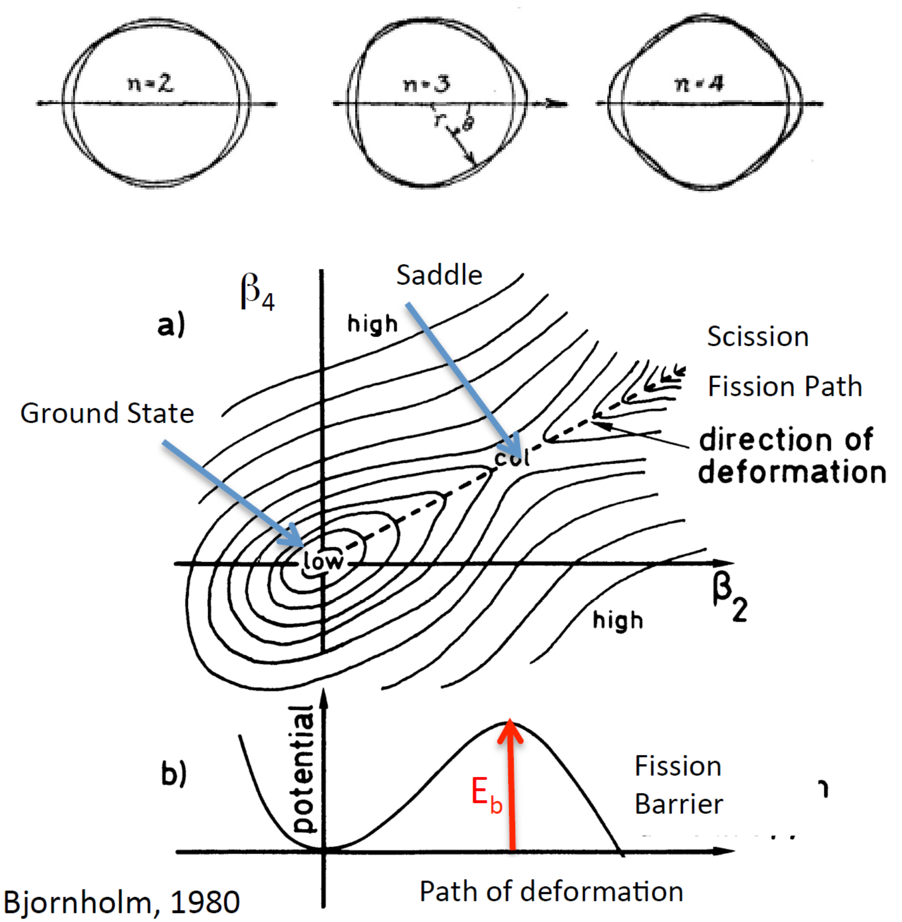




Fission can be :

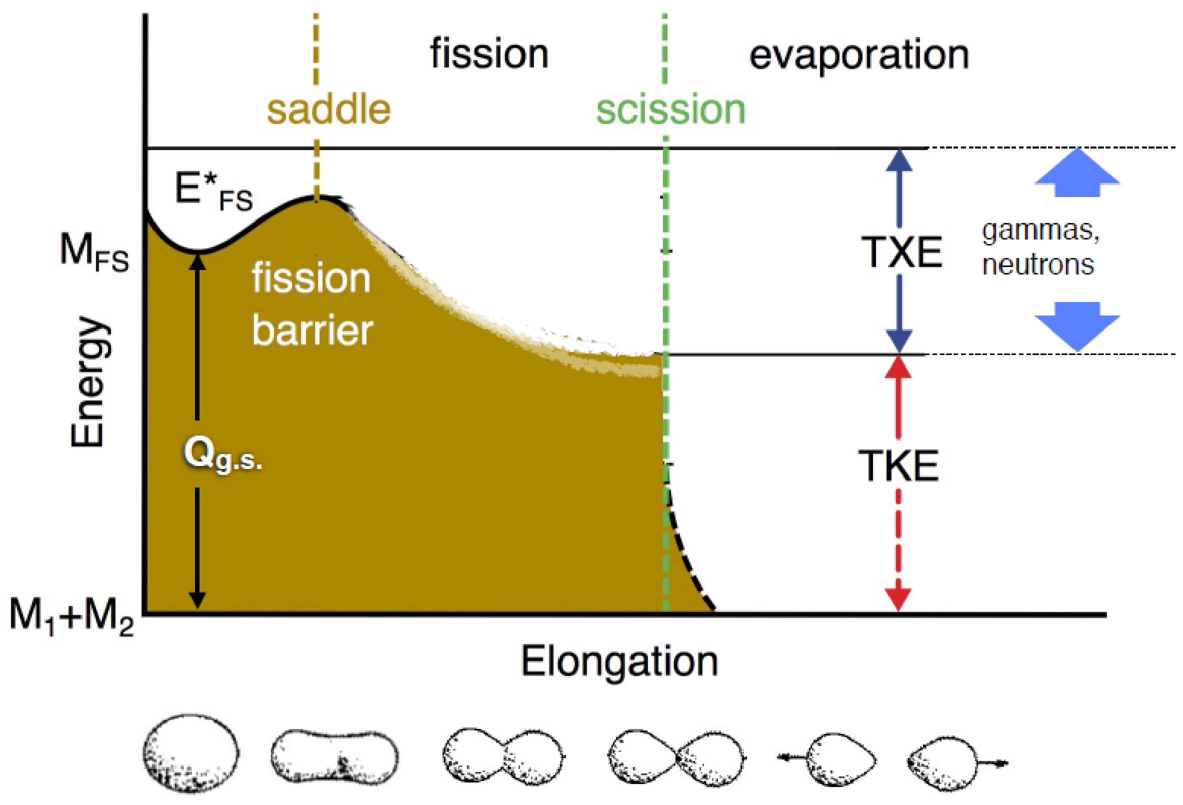
- spontaneous :
- induced :
  - By neutrons
  - By photo fission (γ)
  - By nuclear reactions

A Macroscopic point of view :
Fission of a liquid drop of nuclear matter



Bjornholm, 1980

N. Bohr, J.A. Wheeler, PR 56, 426 (1939)



Caamano *et al. (2013)*

Aren't nuclei quantum objects governed by the nuclear Force ?

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

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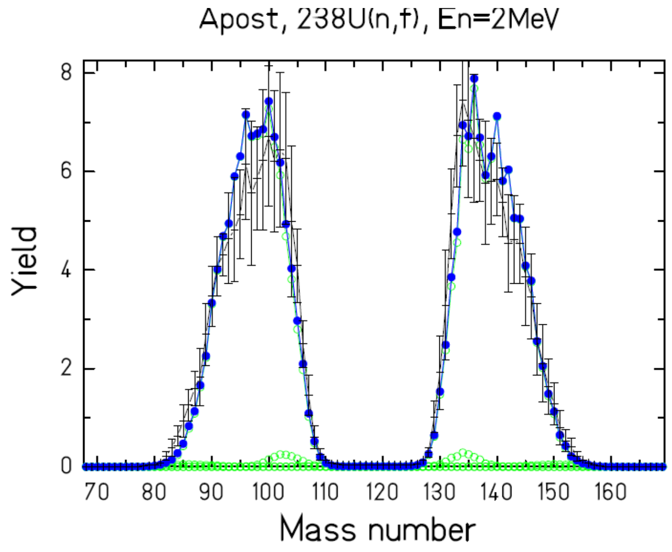

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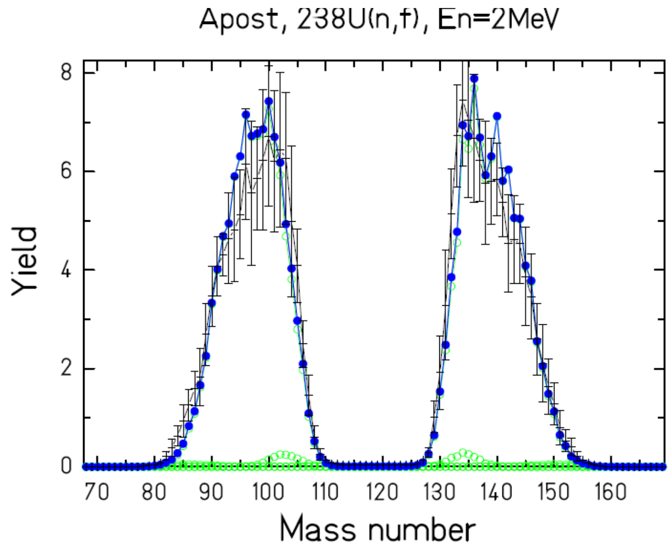


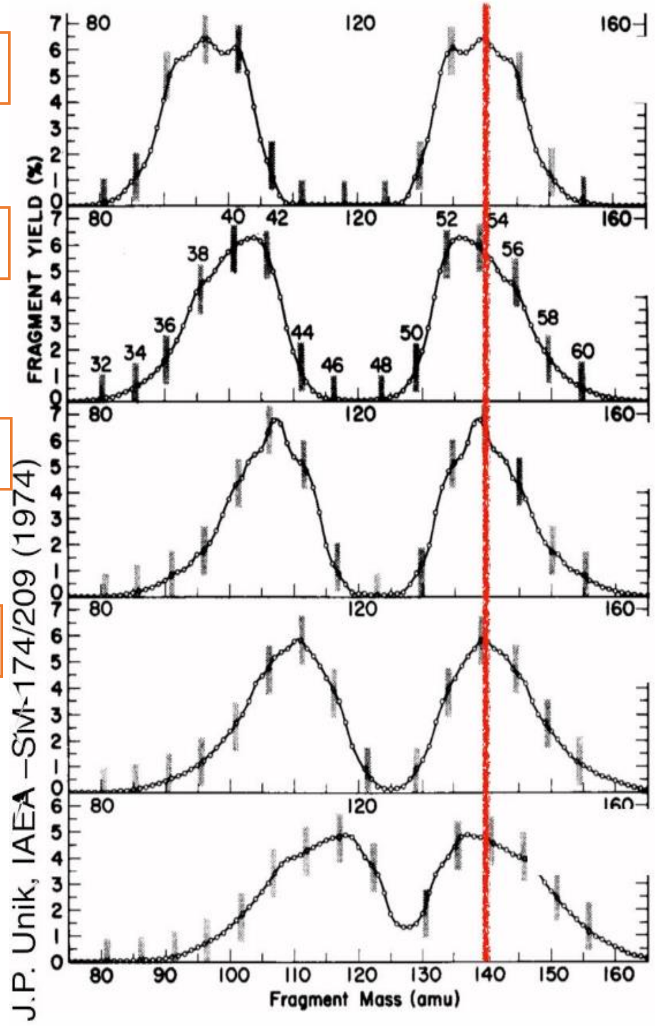
^{235}U

^{239}Pu

^{245}Cm

^{249}Cf

^{254}Es



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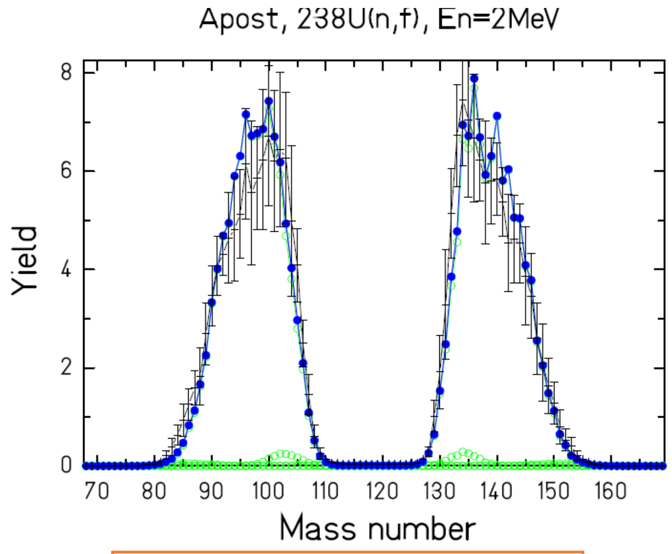
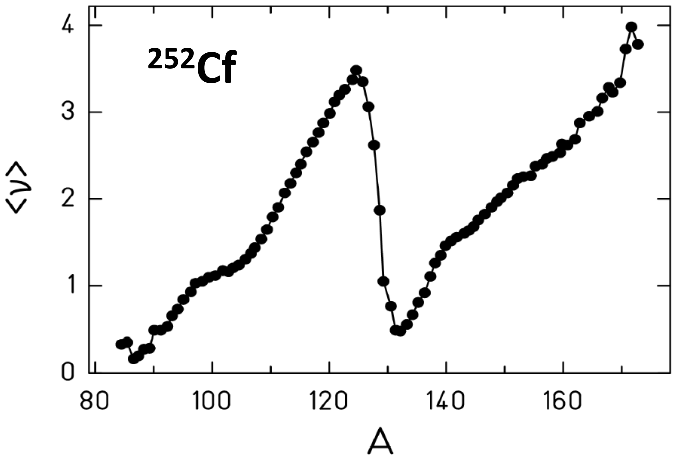
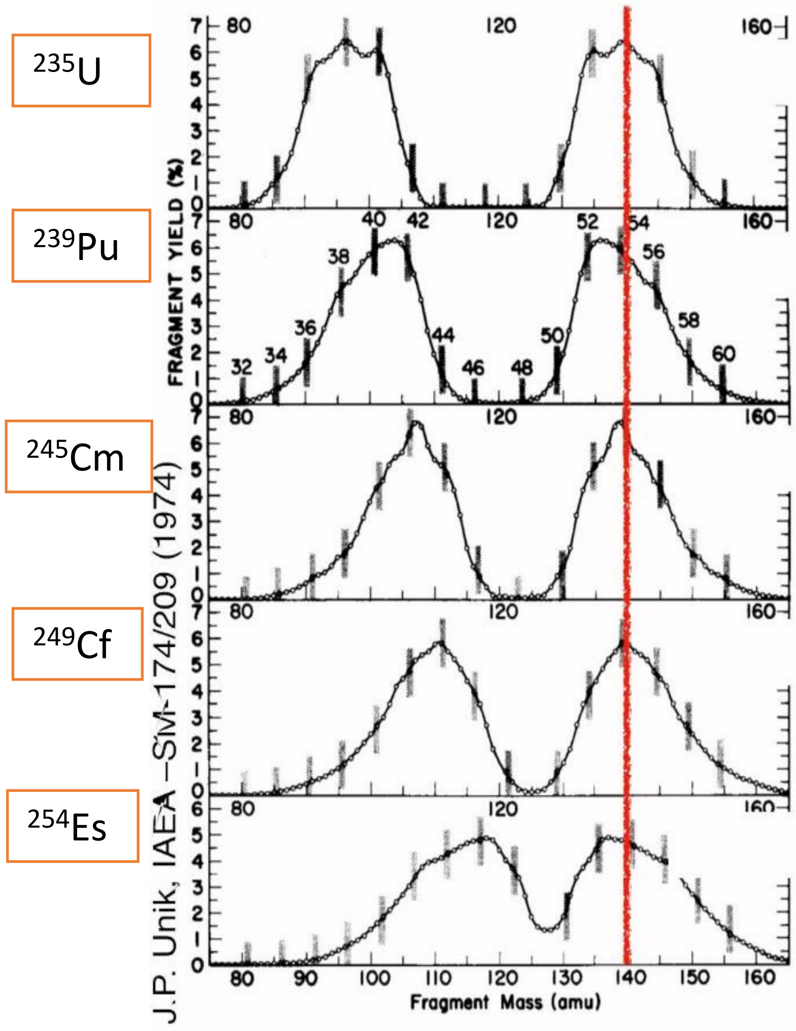


Neutrons Evaporation





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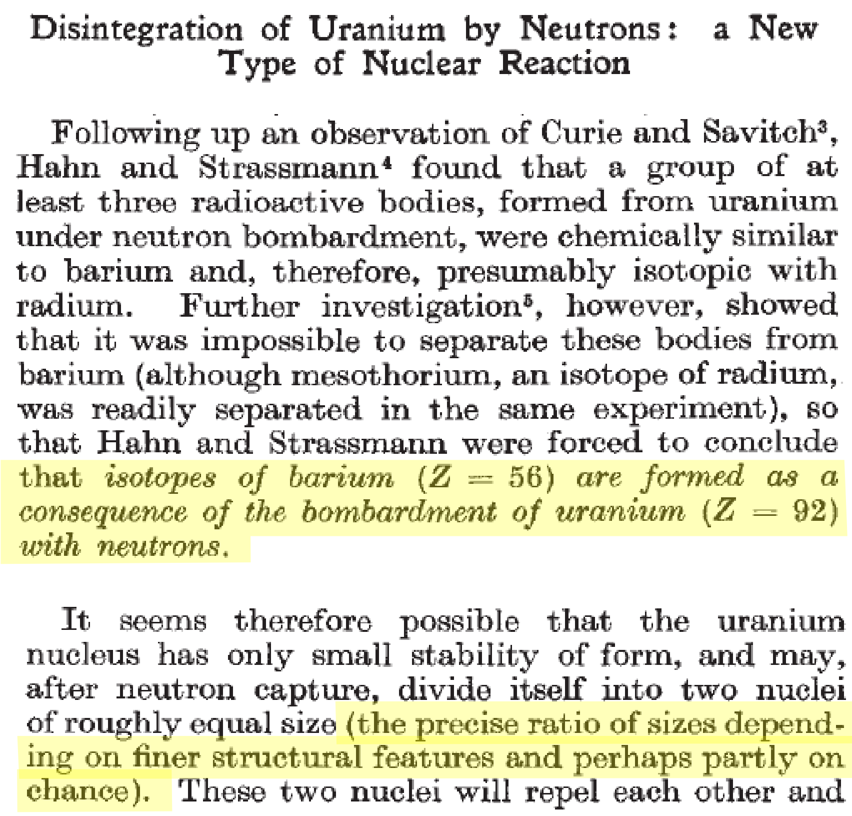
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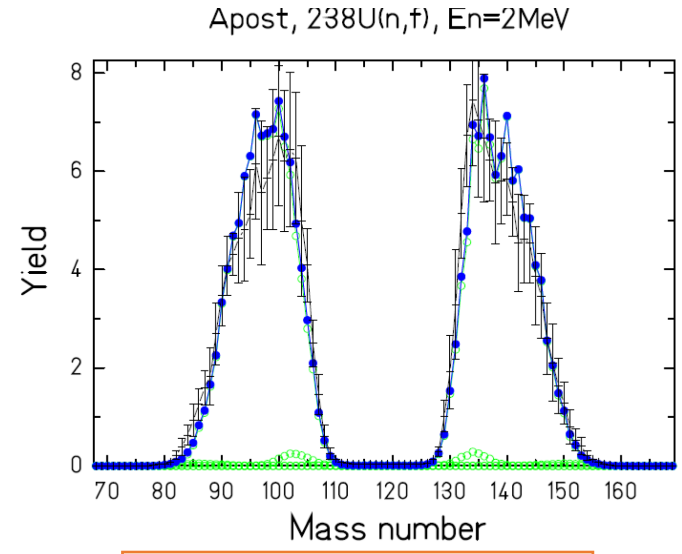

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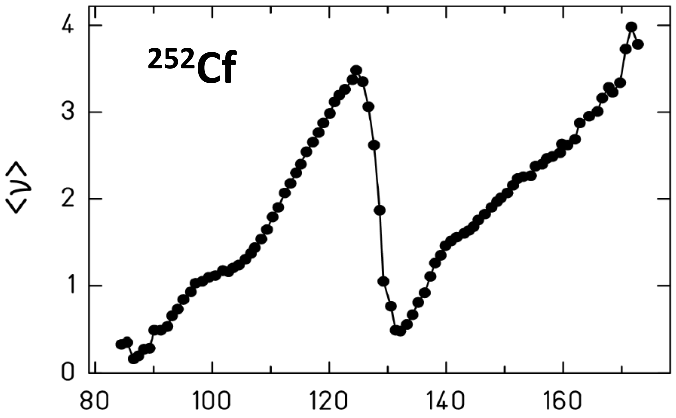

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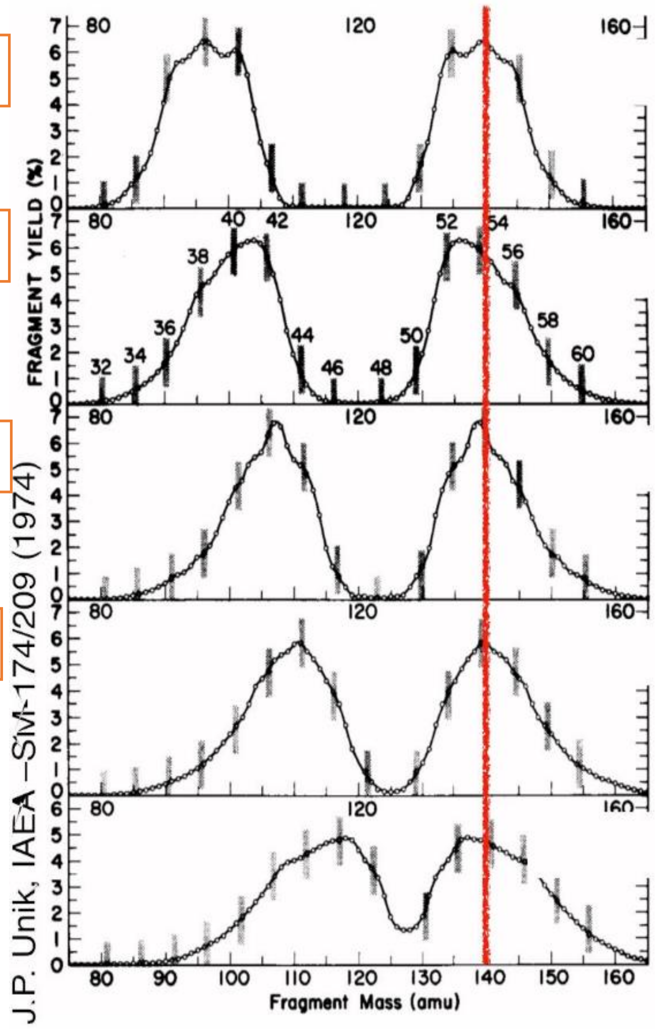
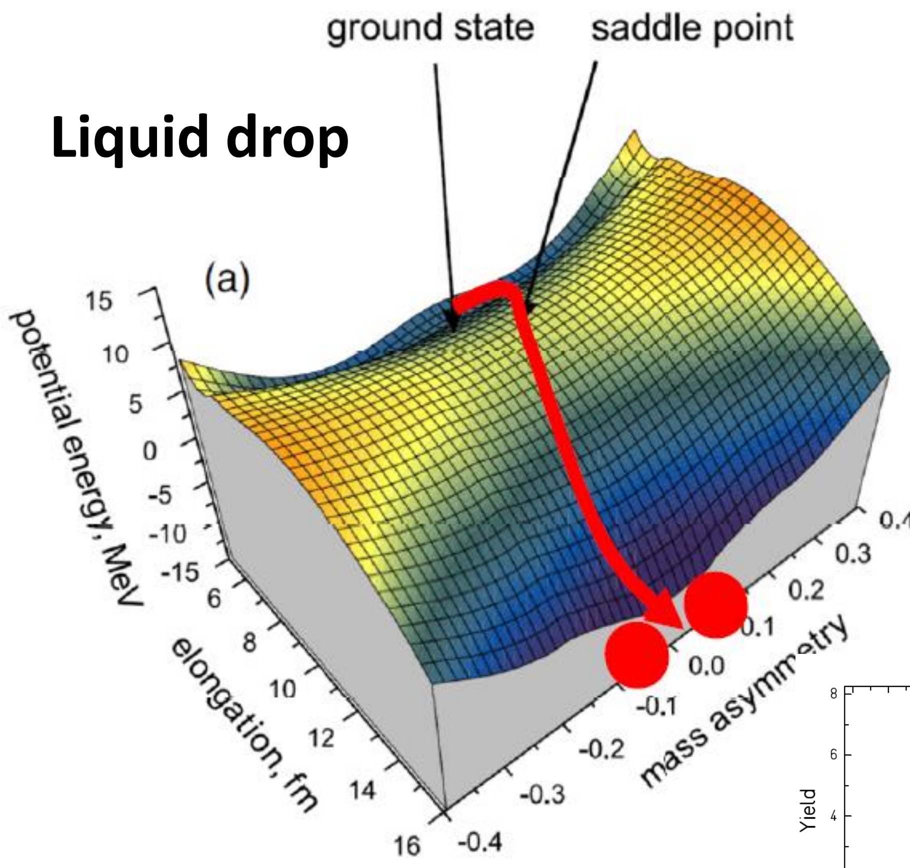
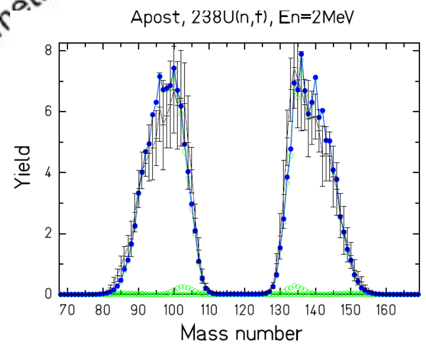


=> Microscopic / Structural effects

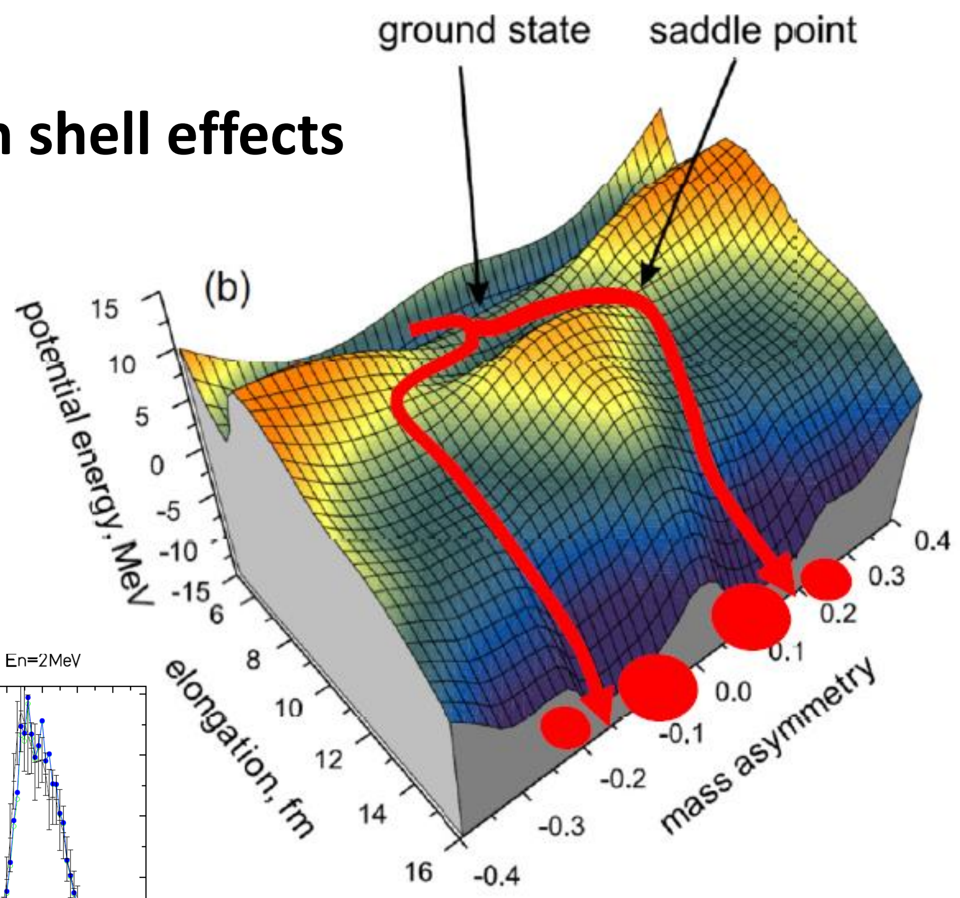
The importance of fission for fundamental nuclear physics

Liquid drop





With shell effects



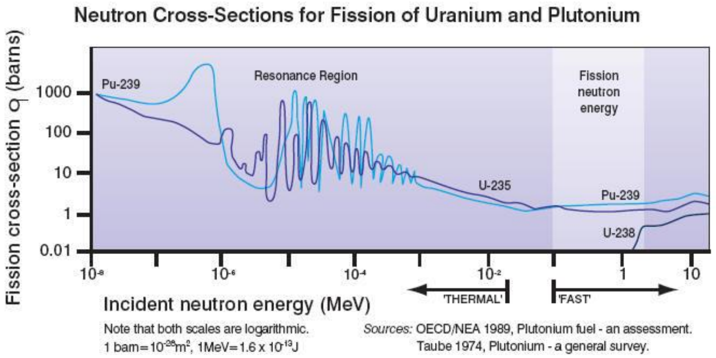
Fission is a complete laboratory for studying nuclear dynamics over a broad range of deformation under the influence of shell effects, correlations!

Many key fundamental nuclear properties have to be taken into account!

The richness of fission observables

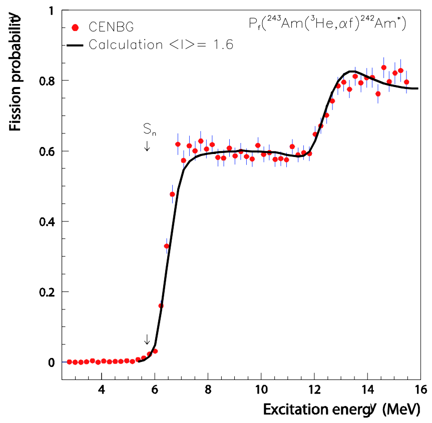
Formation :

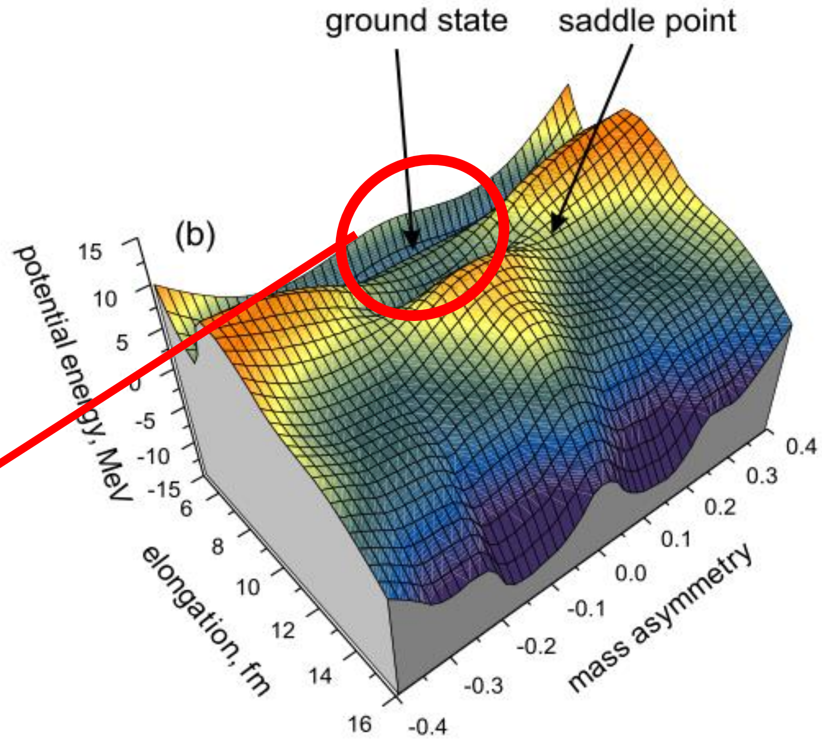
Capture cross sections



Ground-state to barrier :

Fission probability,





- neutron capture cross sections
- Fission Barrier (Fission probability)

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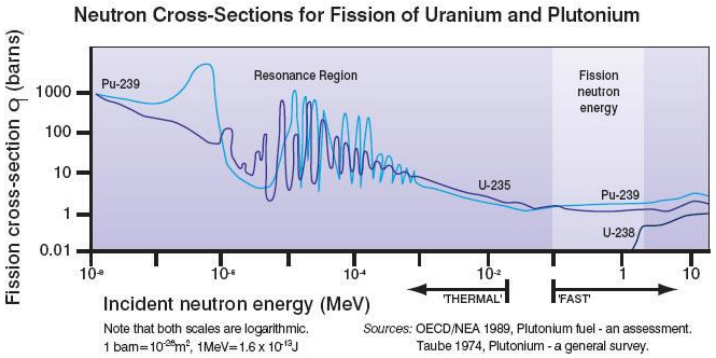

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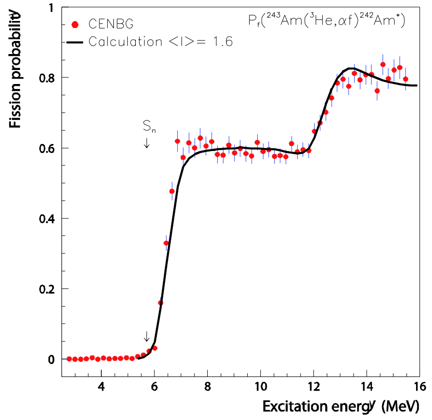
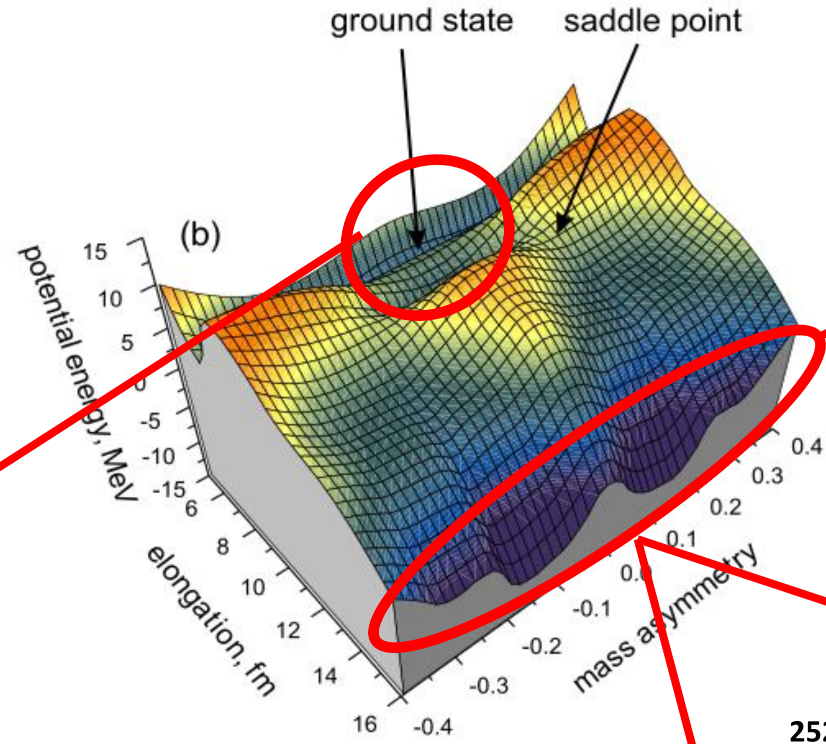
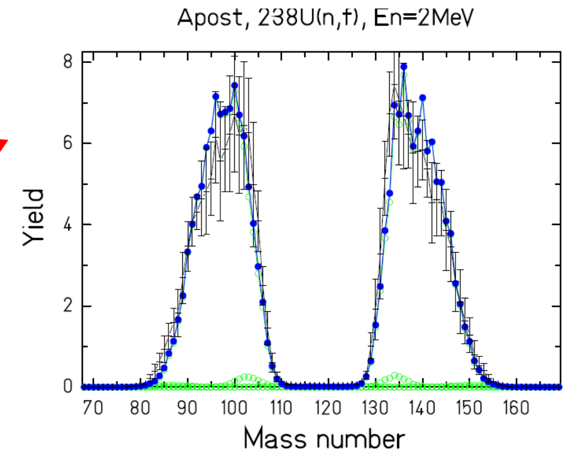




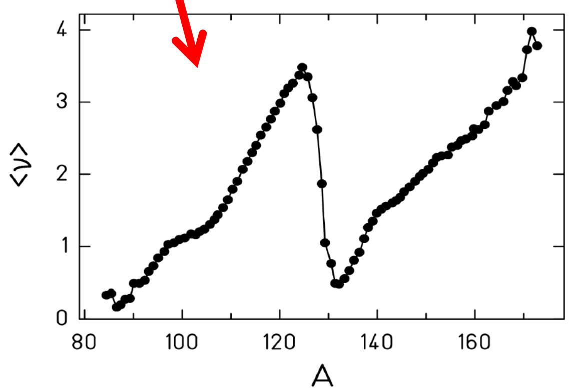
Barrier to well after scission:

Fission fragment yields



Prompt neutrons & gammas

^{252}Cf



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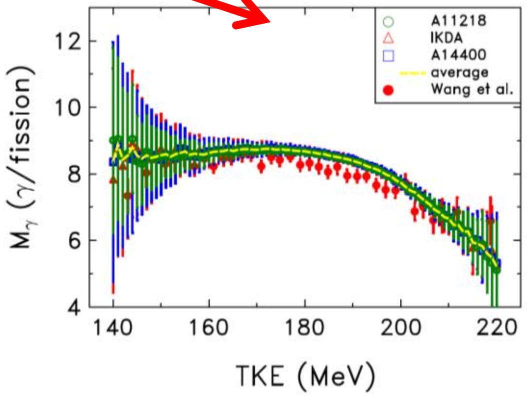

- neutron capture cross sections
- Fission Barrier (Fission probability)
- Fission Fragment Yields (A , (N,Z))
- Kinetic Energies
- Neutron multiplicities
- Gamma-ray Emission
- Cummulative yields

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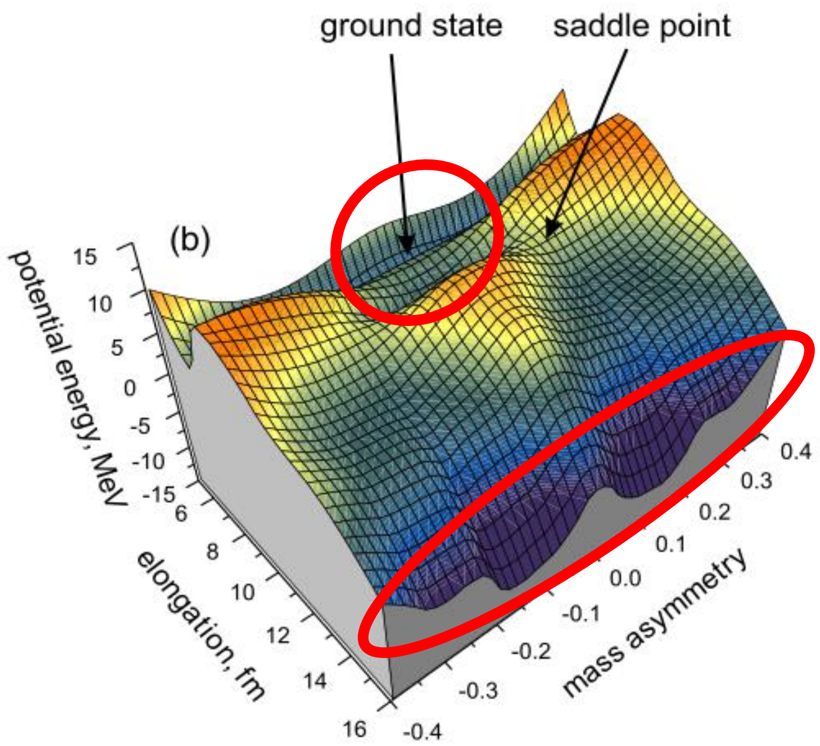
Capture cross sections

- L. Mathieu

Ground-state to barrier :
Fission probability,

- L. Audoin (Poster)
- C. Berthelot (Poster)



Barrier to well after scission:
Fission fragment yields

- P. Morfouace
- J-E Ducret (Poster)
- D. Treasa (Poster)

Prompt neutrons & gammas

- V. Piau
- C. Michelagnoli
- G. Soum

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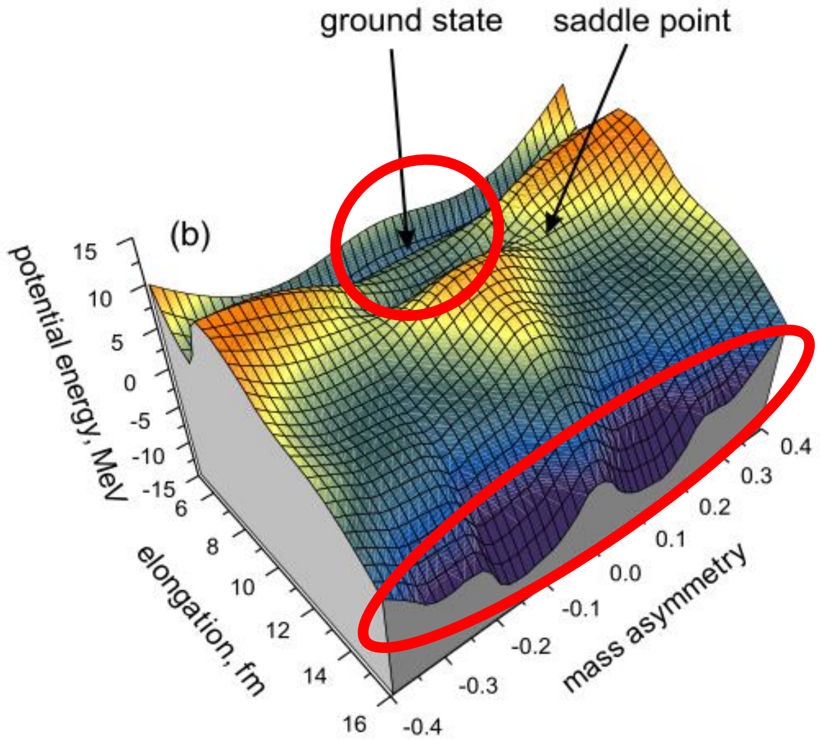

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When the system has a lot of energy !

- Q. Fable (Poster)

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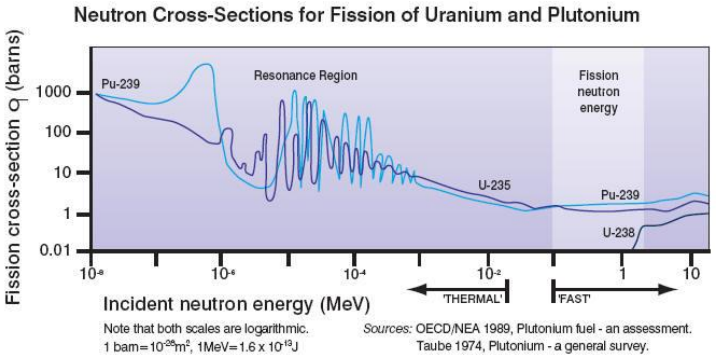

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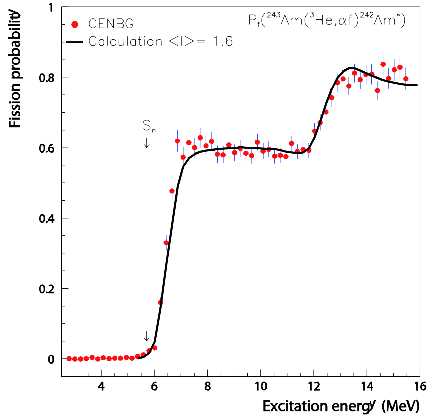

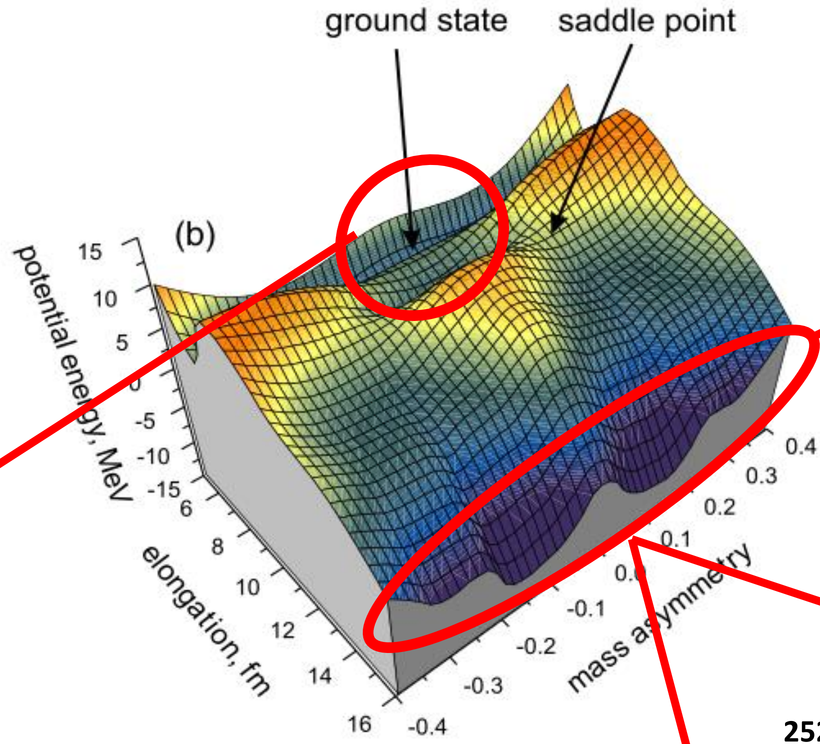

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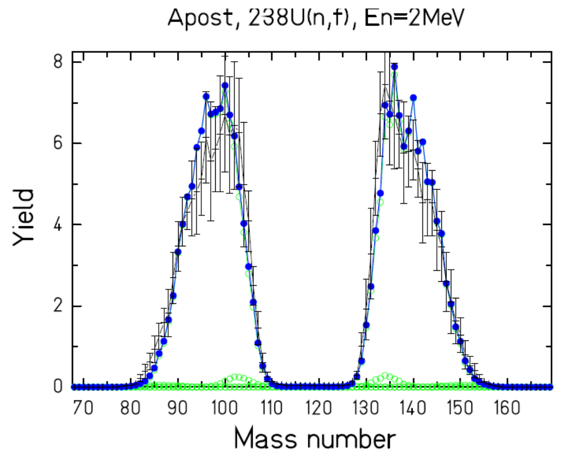

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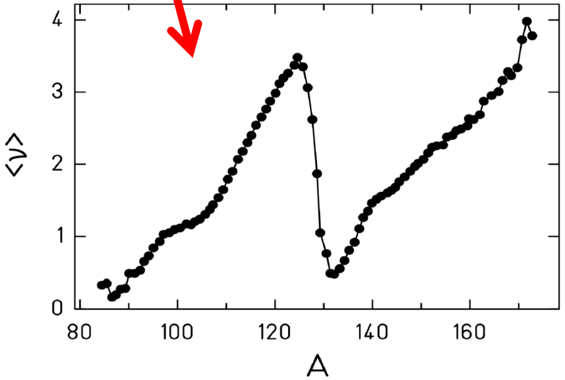

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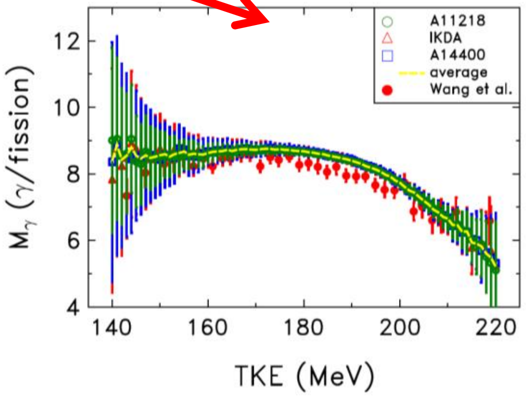

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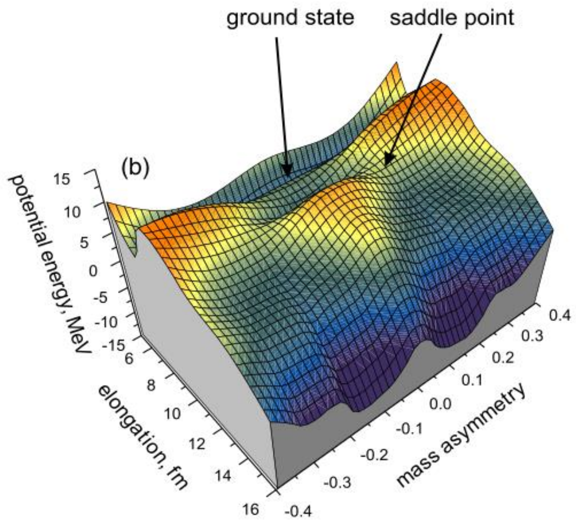
- Fission Barrier (Fission probability)
- Fission Fragment Yields (A , (N,Z))
- Kinetic Energies
- Neutron multiplicities
- Gamma-ray Emission
- Cummulative yields

New opportunities have revived the field of nuclear fission

- New experimental techniques to measure Fission Fragments yields
  (compared to spontaneous or n-induced fission)
  - Heavy ion reaction induced fission
    (fusion, transfer, inelastic excitation)
  - Inverse kinematics with magnetic spectrometers

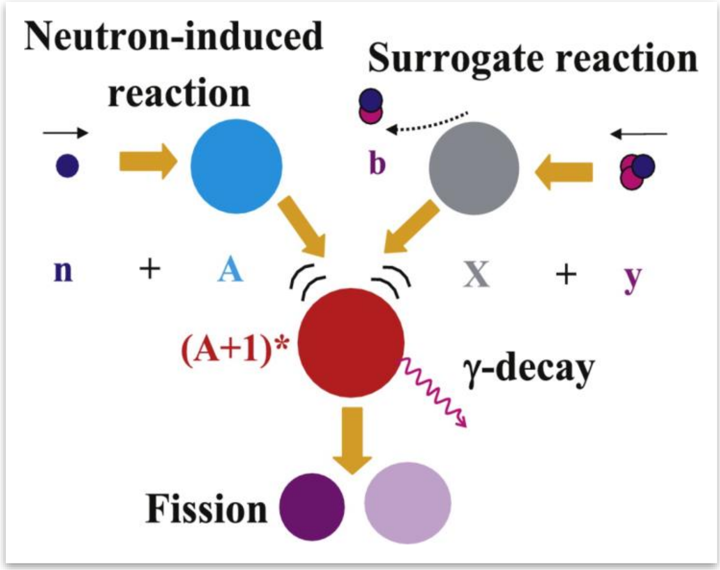
=> New Opportunities
  - Range of fissioning systems
    (A,Z, Excitation Energy domain)
  - Isotopic Identification of fission Fragments (A_{ff},Z_{ff})

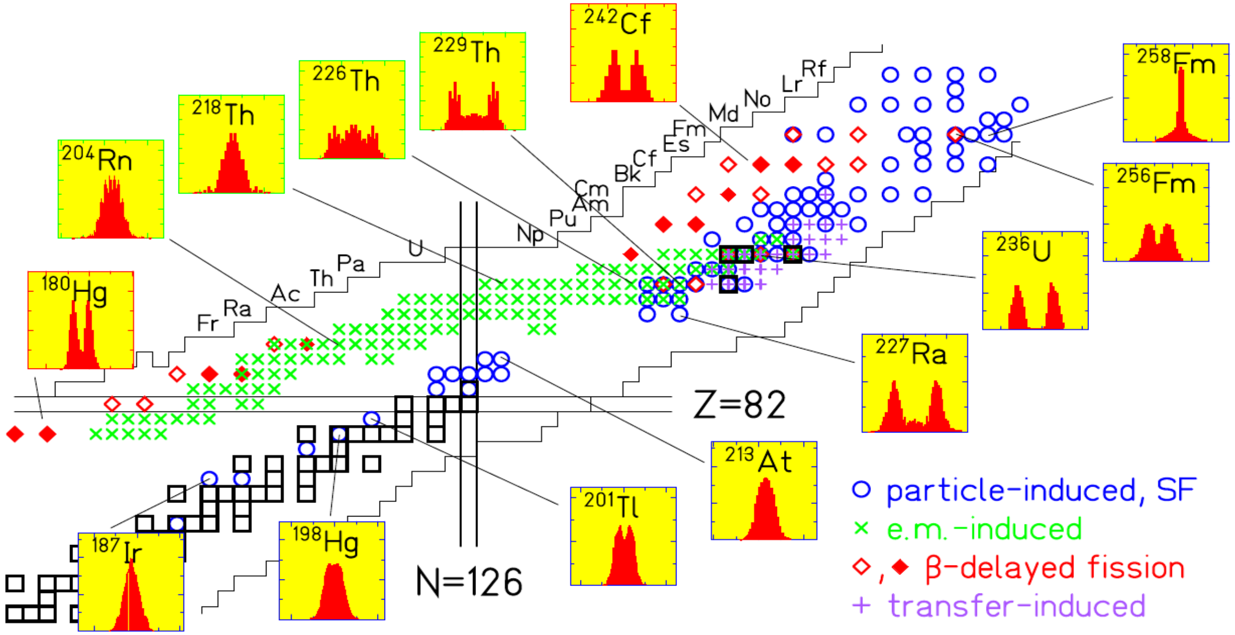


Heavy ions reactions fission studies

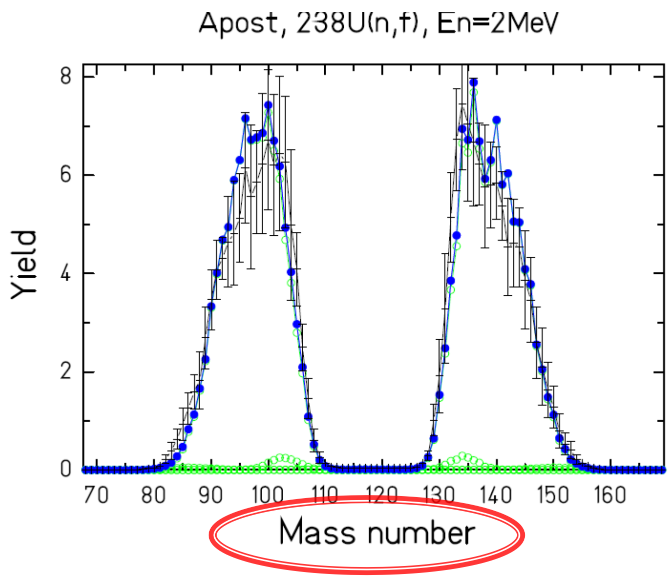
Studying « exotic » fissionning systems using heavy ion reactions (changing the content in number of protons and neutrons)

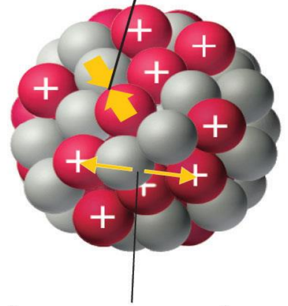
- Fusion (A+B-> C)
- Transfert of particules (A + B -> C + D)
- Electromagnetic excitation of Radioactive Beams (A+B->A*+B)
- Beta delayed fission

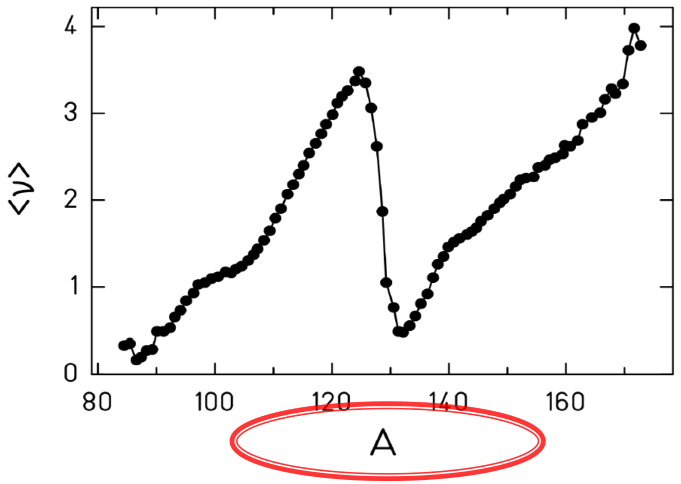




Decades of investigations based on the mass of fission fragments



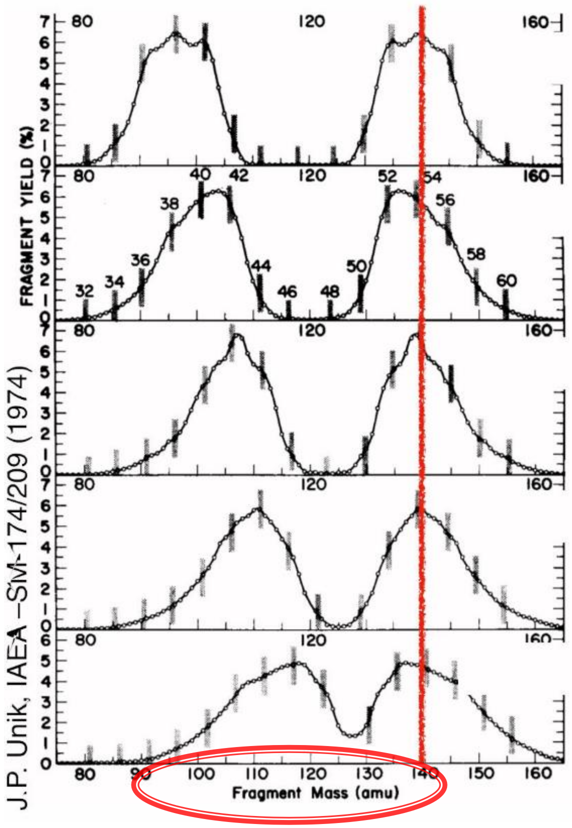




A = N + Z

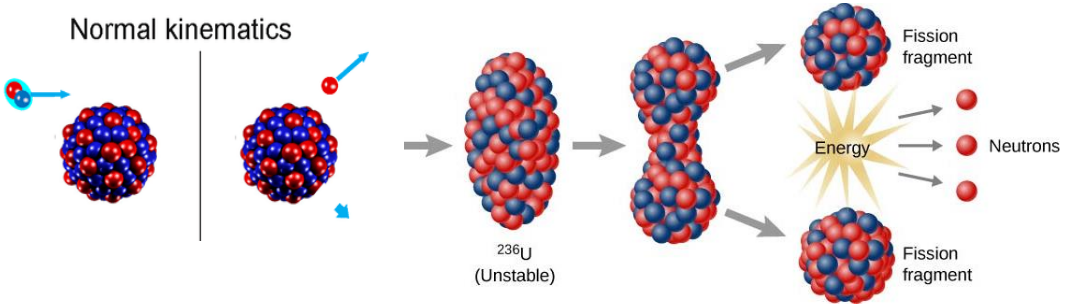
N and Z are the degrees of freedom of nuclei

Related to the challenge of measuring the charge (Z) of fission fragments



Fission under the inverse kinematics boost

Direct kinematics fission
Light beams + Actinide target → Fission almost at rest



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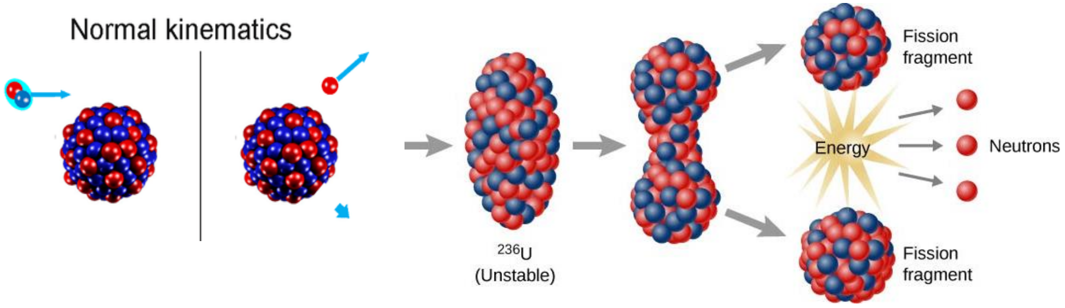

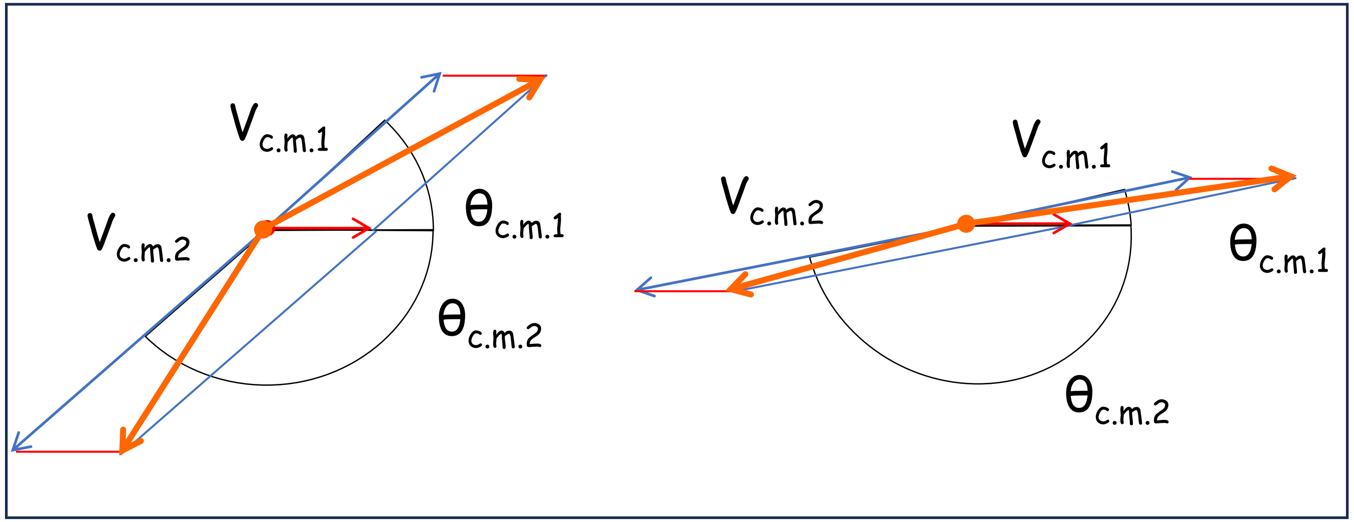

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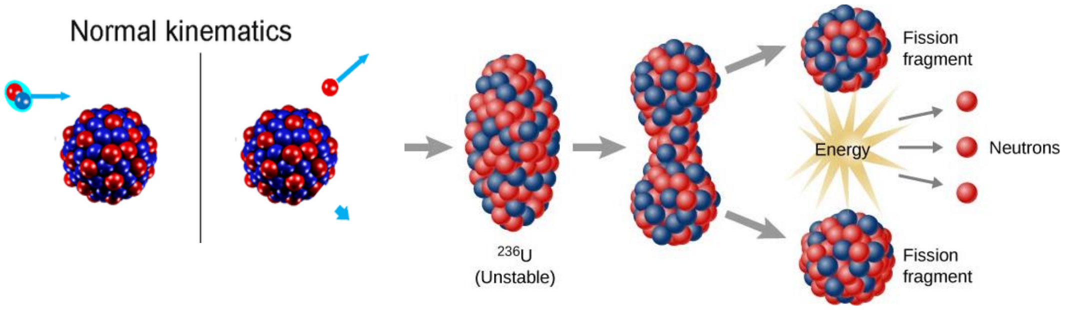
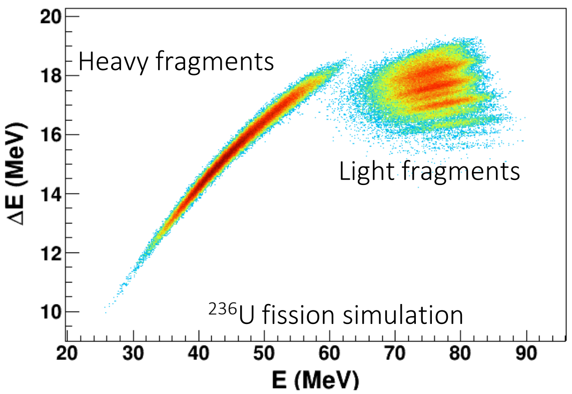


Atomic Charge (Z) identification
Exemple with ΔE/E



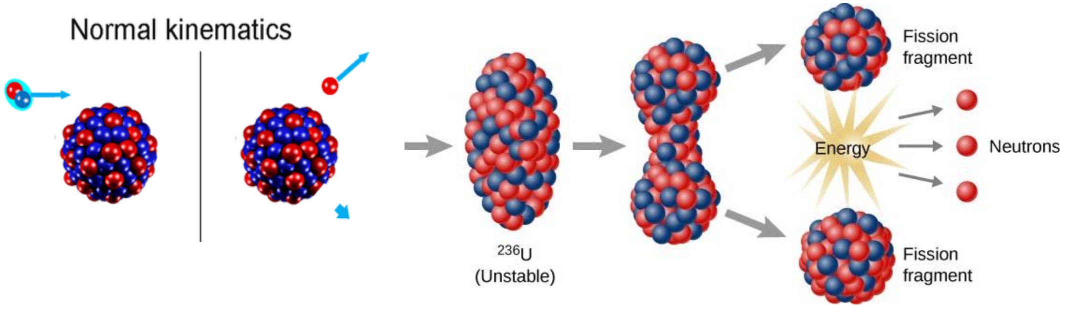
- Very **low** recoil energy of Fission Fragments (1cm/ns)
- Limited identification capabilities
  - Mass 2-4 amu
  - Z < 40
- Experimental challenge to overcome

=> Poster FALSTAFF @ NFS / **J-E Ducret**

Fission under the inverse kinematics boost

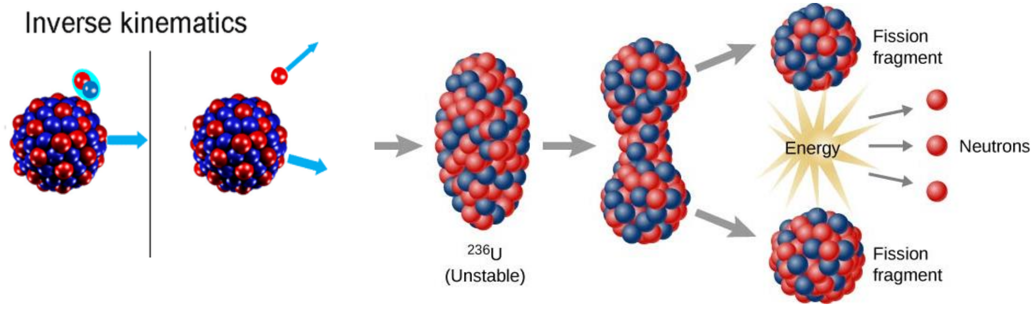
Direct kinematics fission

Light beams + Actinide target → Fission almost at rest



Inverse kinematics fission

Heavy beams + light target → Fission in motion / flight



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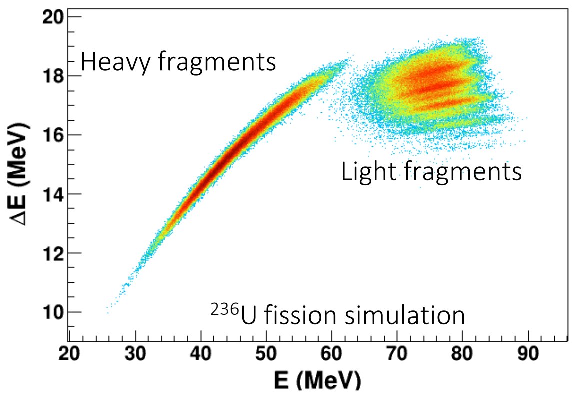

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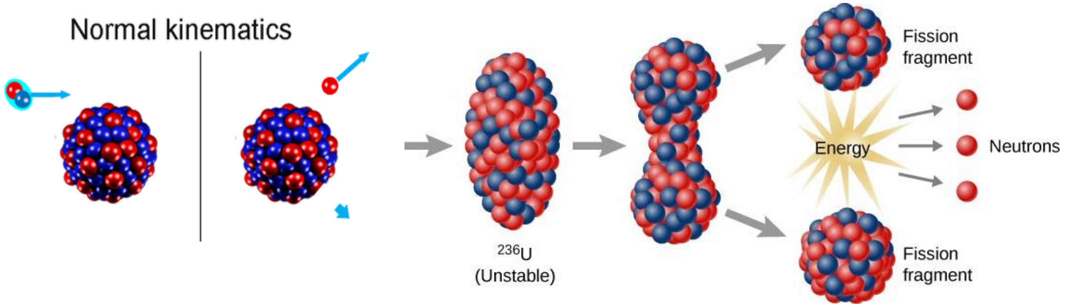

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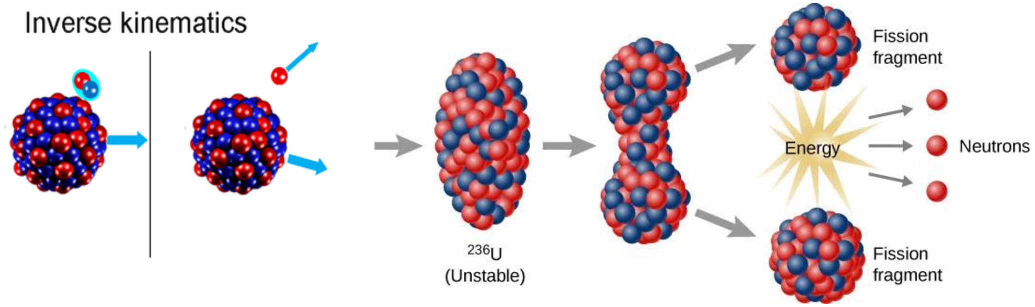

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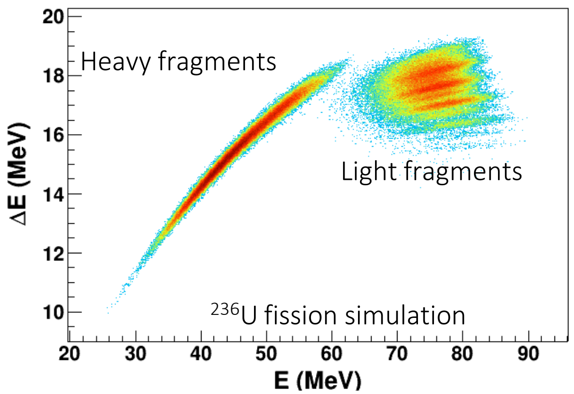

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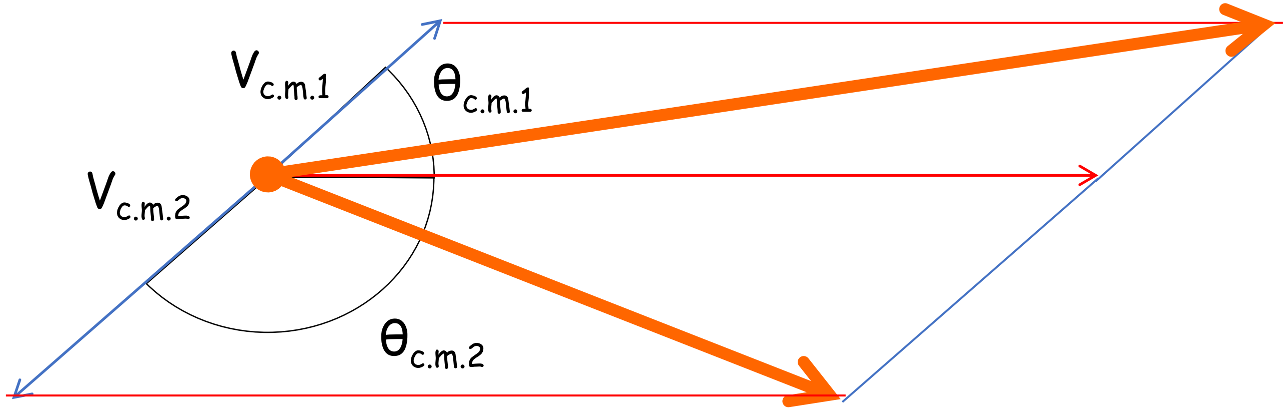

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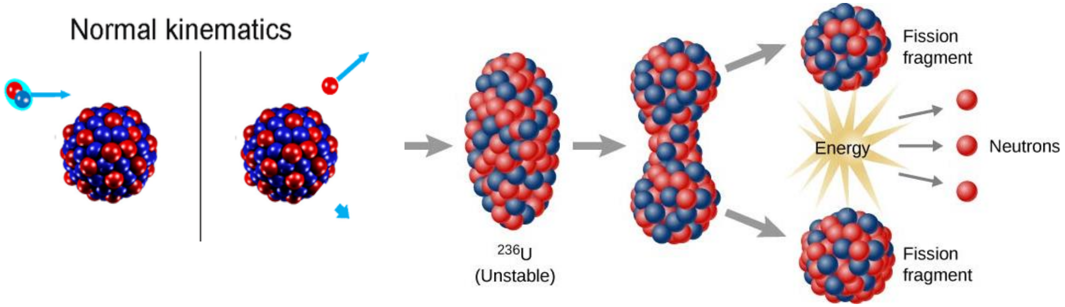

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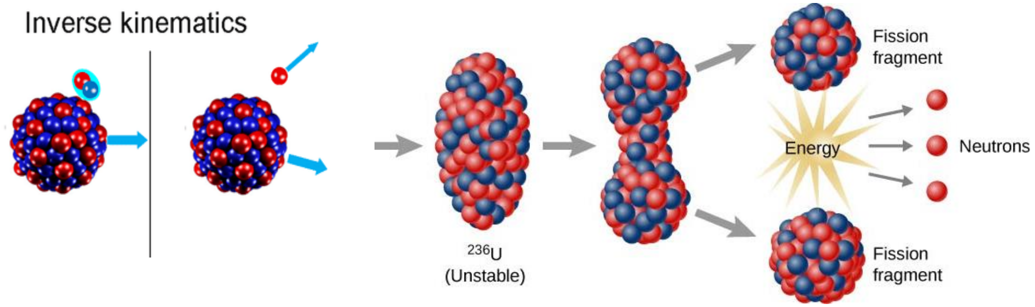

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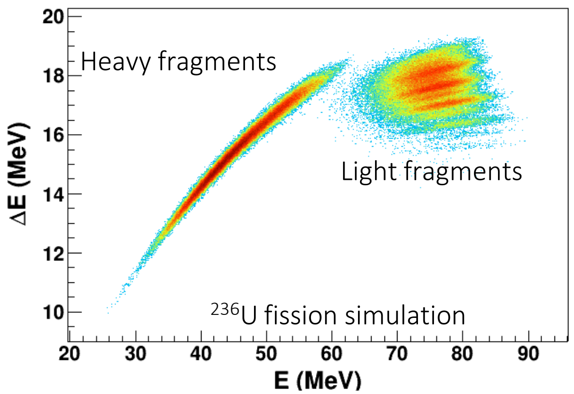

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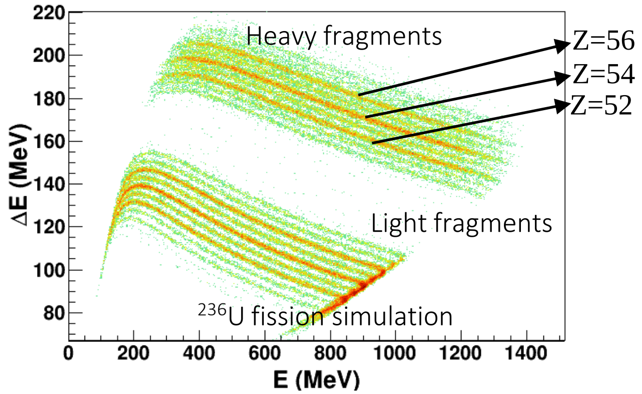
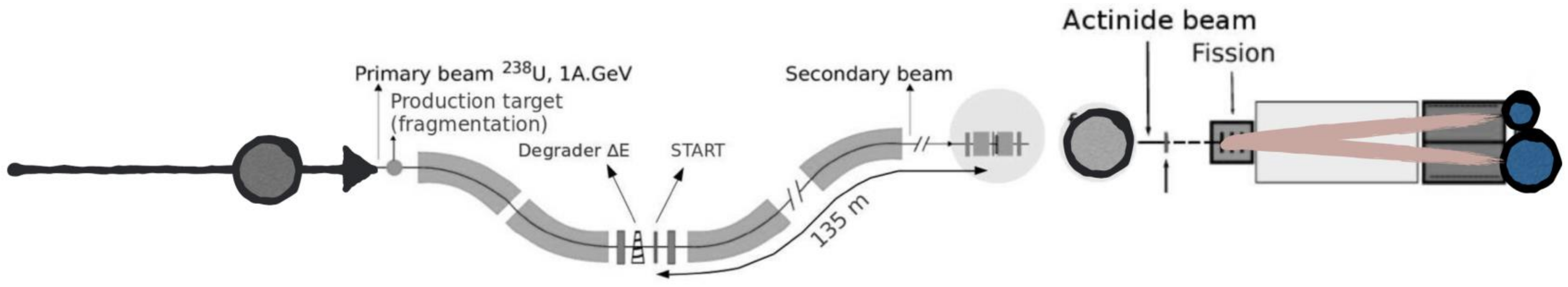


- Boosted Fission Fragments (> 3cm/ns)
- Favored identification capabilities
  - Mass 1/200 (with spectrometer)
  - Complete Z distributions
- Kinematical Focussing
  => Improved detection efficiency

Relativistic Fission in inverse kinematics at GSI

K.-H. Schmidt et al.



Fragmentation => cocktail beam of Radioactive Ions of actinides
Electromagnetic excitation (A+B->A*+B) induced fission

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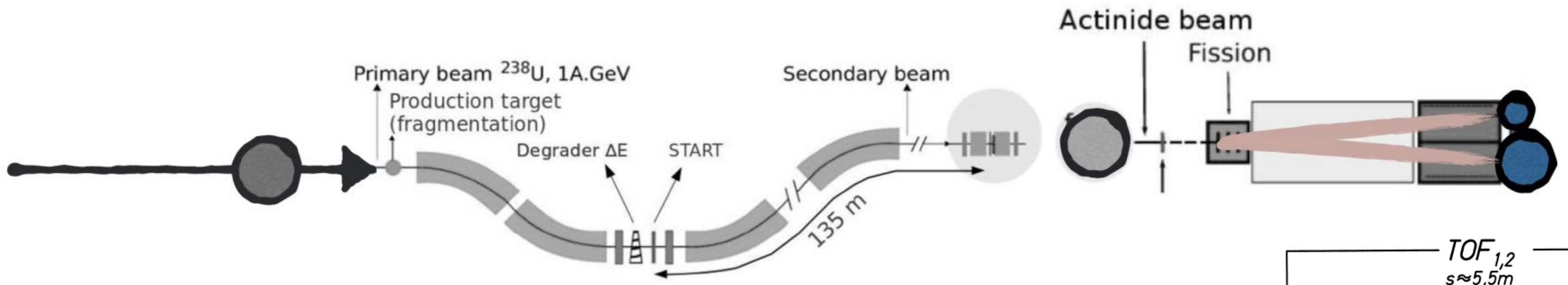

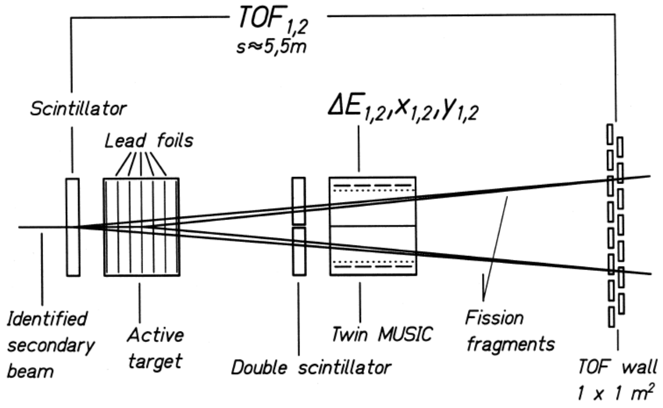

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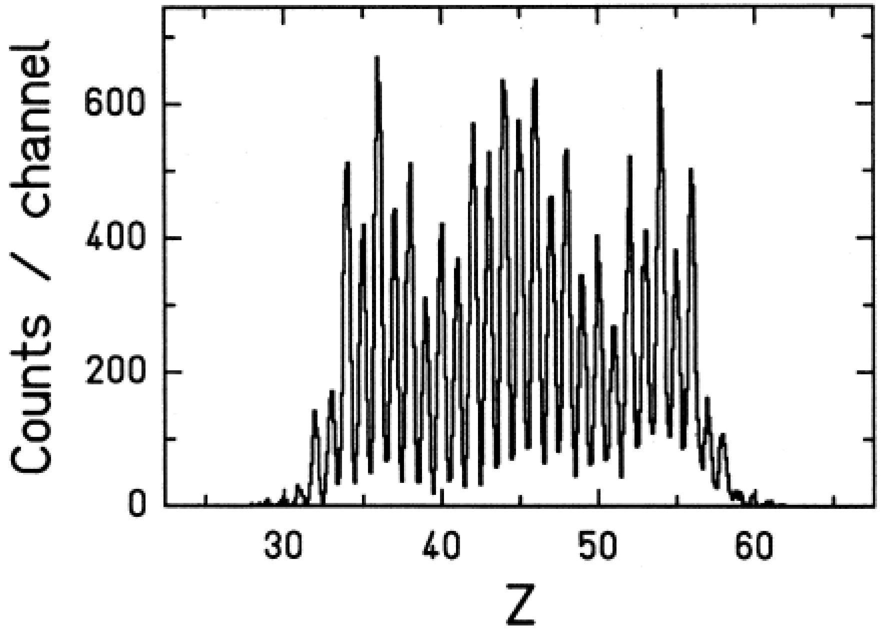

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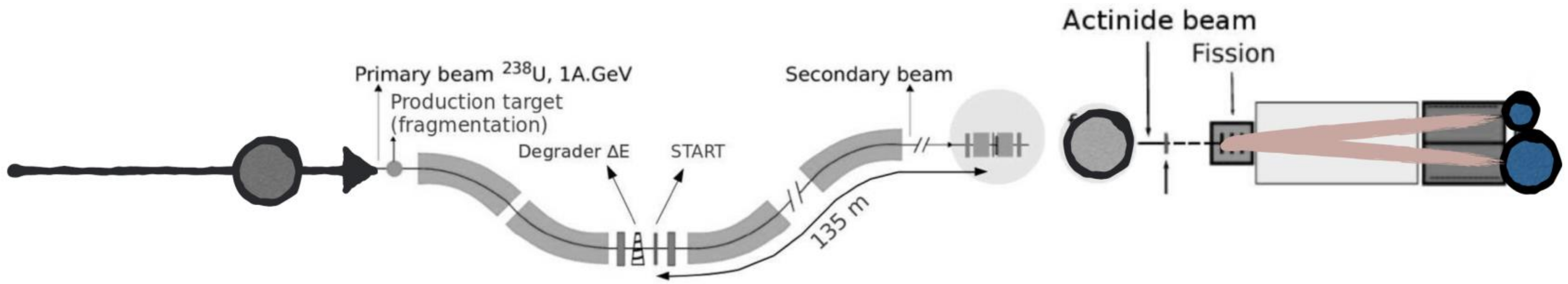

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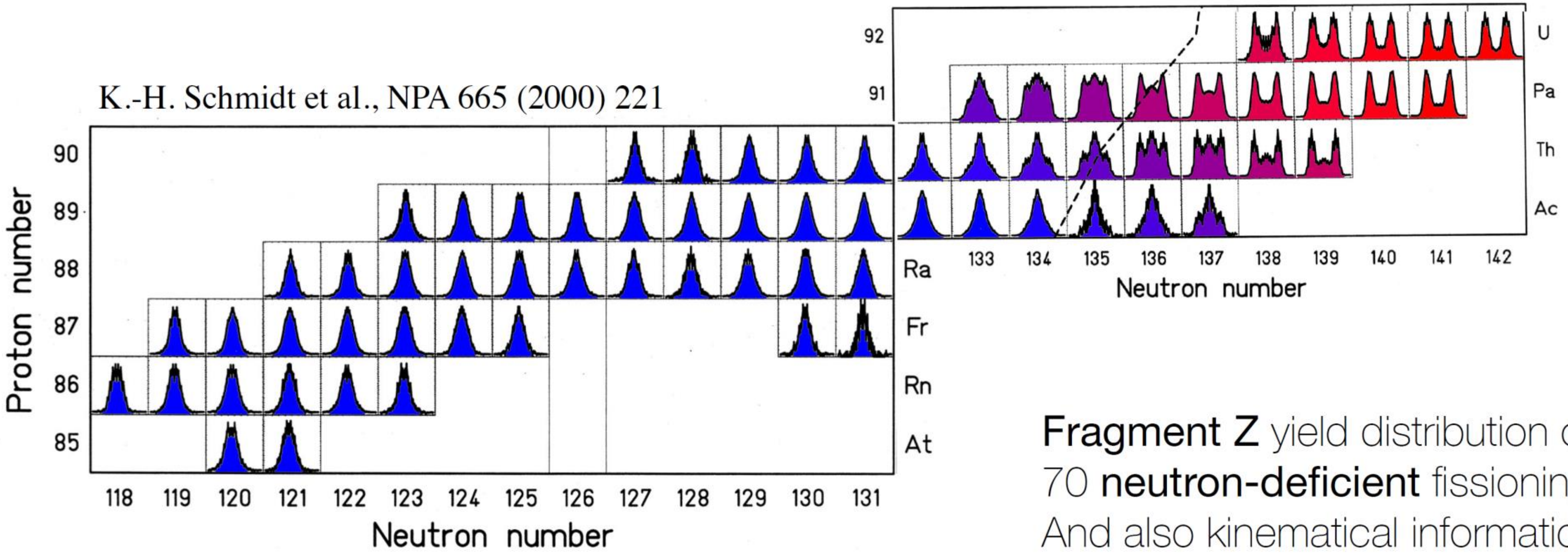
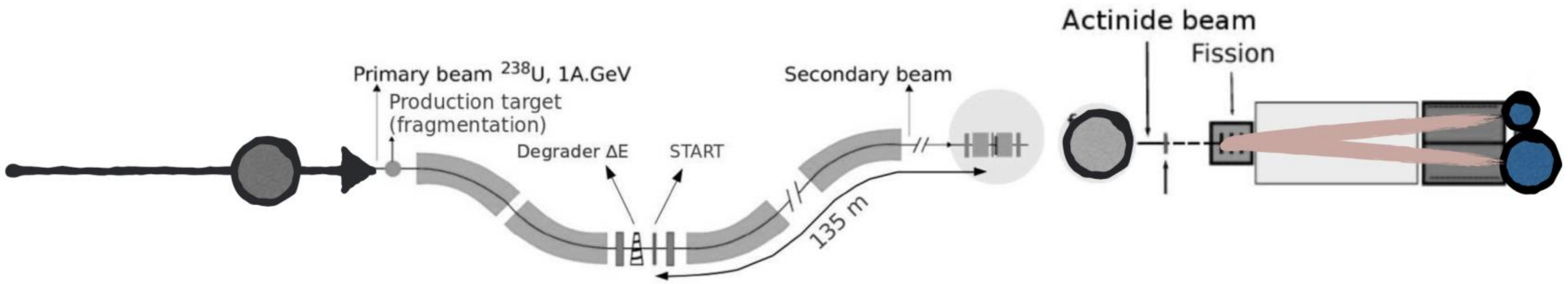
K.-H. Schmidt et al., NPA 665 (2000) 221



Fragment Z yield distribution of more than 70 **neutron-deficient** fissioning systems.
And also kinematical information…

Relativistic Fission in inverse kinematics at GSI

K.-H. Schmidt et al.



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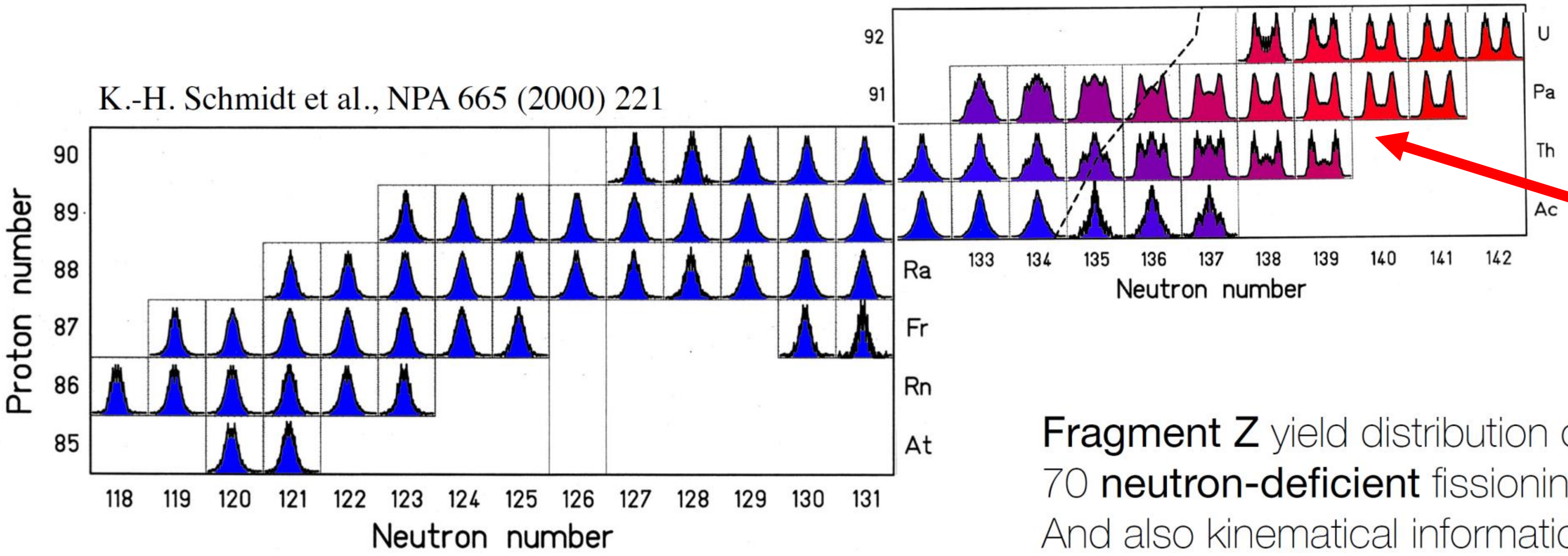
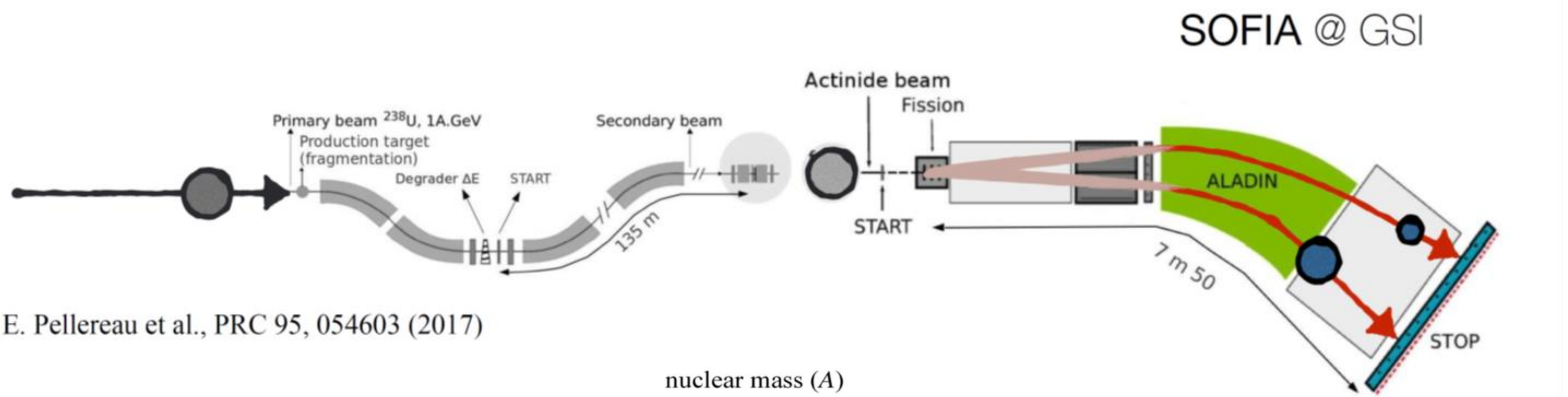


1) Stabilization in Z (while observed in A before)
2) Transition and competition between assymetric and symmetric fission

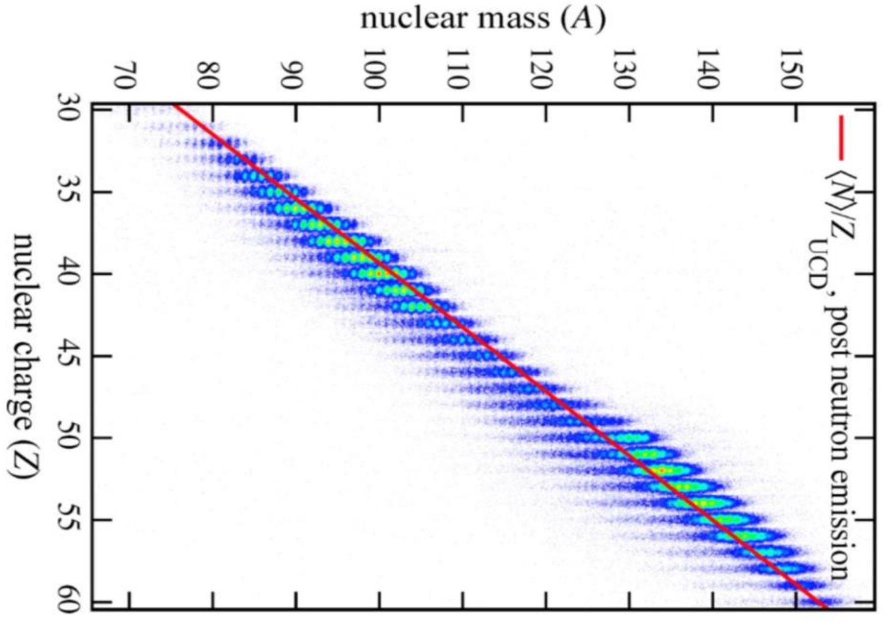
=> Competing structural effects

Fragment Z yield distribution of more than 70 **neutron-deficient** fissioning systems.
And also kinematical information…

Relativistic Fission in inverse kinematics at GSI



E. Pellereau et al., PRC 95, 054603 (2017)



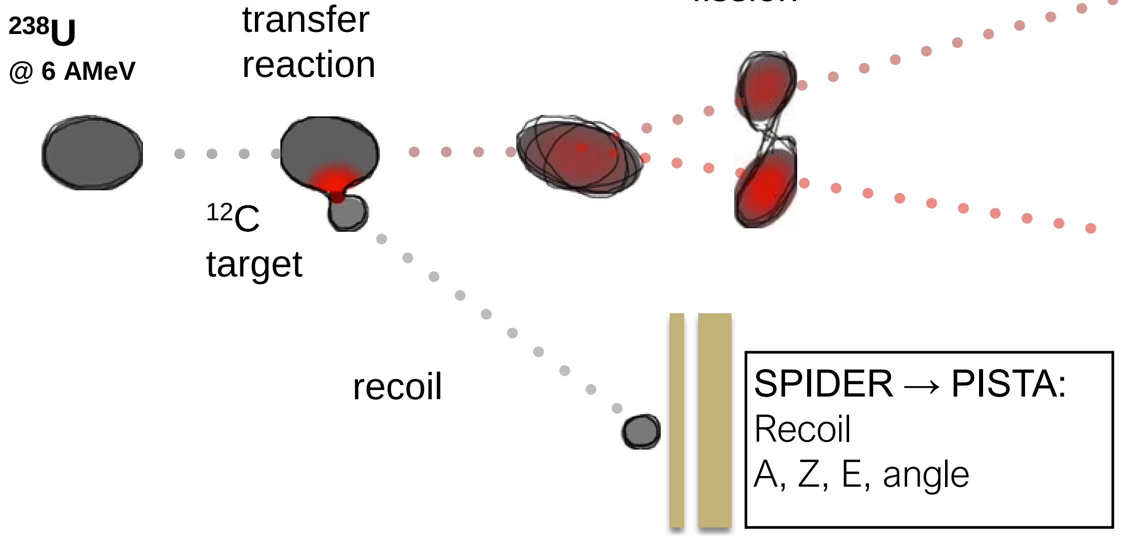
Recent results and perspectives @ SOFIA => Pierre Morfouace

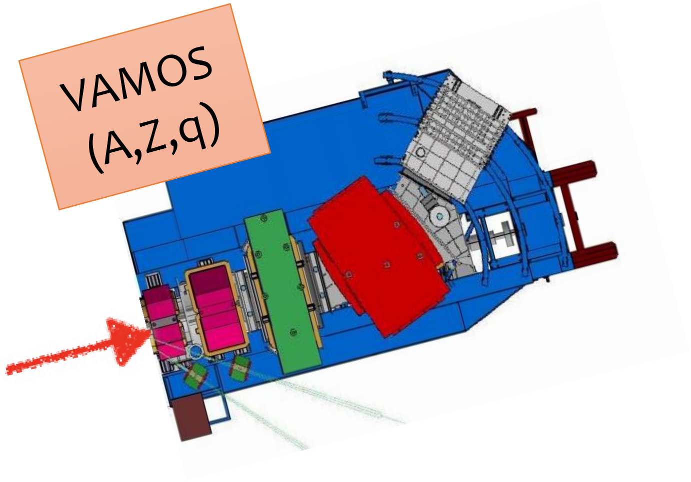
Accurate access to **Z and Mass**

Fission in inverse kinematics at VAMOS/GANIL

Inverse Kinematic using beams of ^{238}U around Coulomb Barrier

⇒ Access to « exotic » fissionning systems heavier than ^{238}U





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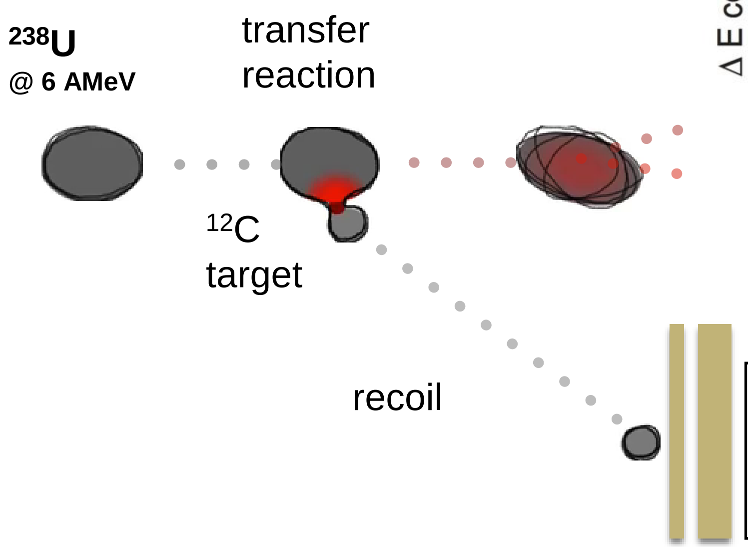
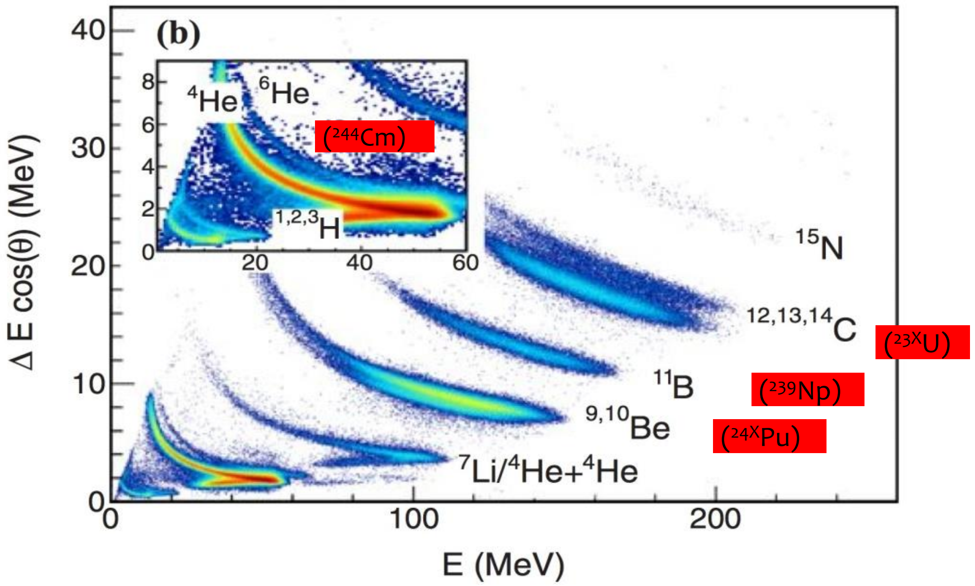
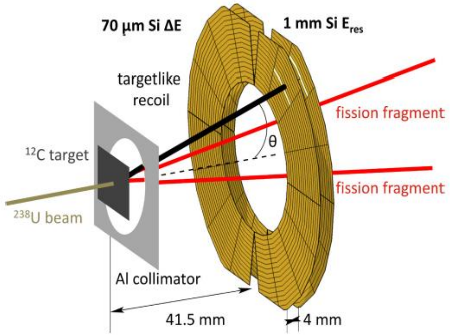




SPIDER → PISTA:
Recoil
A, Z, E, angle



The reconstruction of the binary reaction gives kinematical information and the identification of the fissioning system

Surrogate reactions
(transfer induced fission)

⇒ Selection of the fissionning system
⇒ Measurement of the excitation energy

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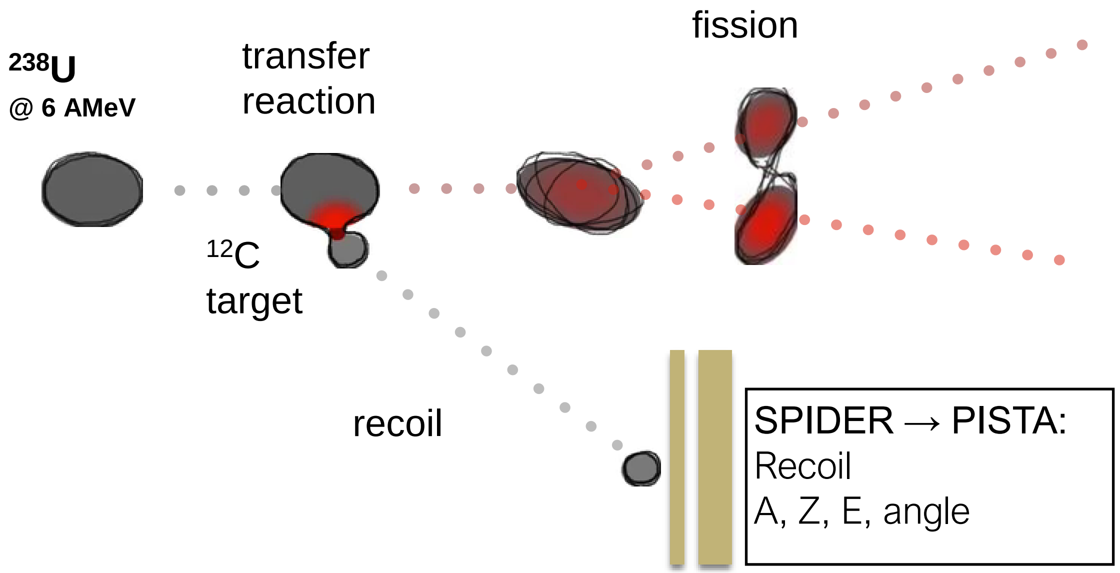

SPIDER → PISTA:
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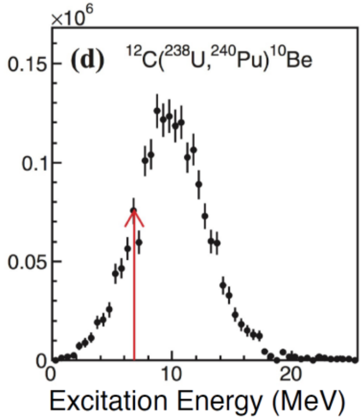
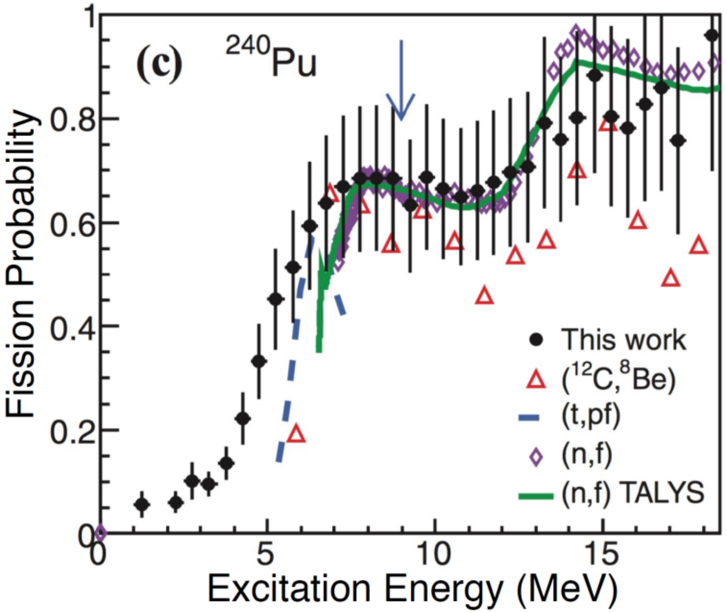
A, Z, E, angle

C. Rodríguez. Tajes et al., PRC 89 (2014) 024614



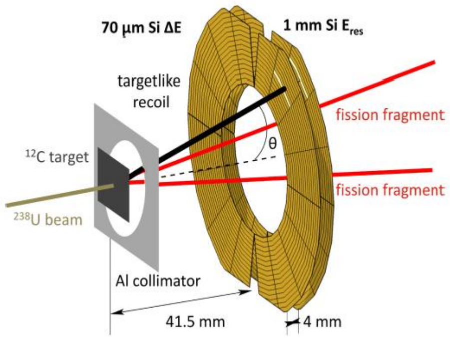
first and second chance barriers



The reconstruction of the binary reaction also provides information on the fission barrier

Surrogate reactions
(transfer induced fission)

⇒ Selection of the fissionning system
⇒ Measurement of the excitation energy



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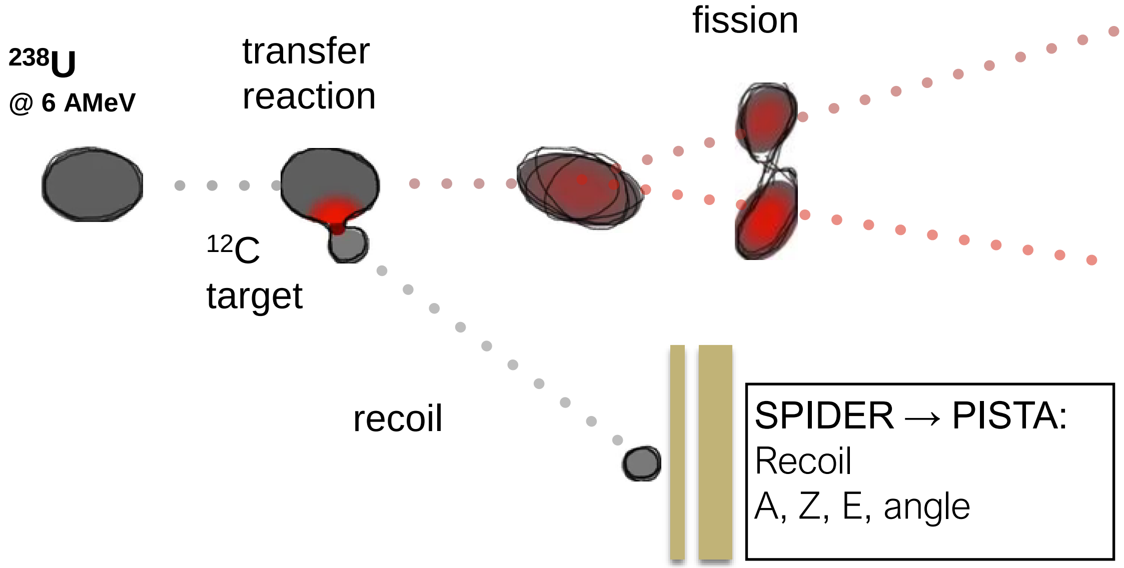
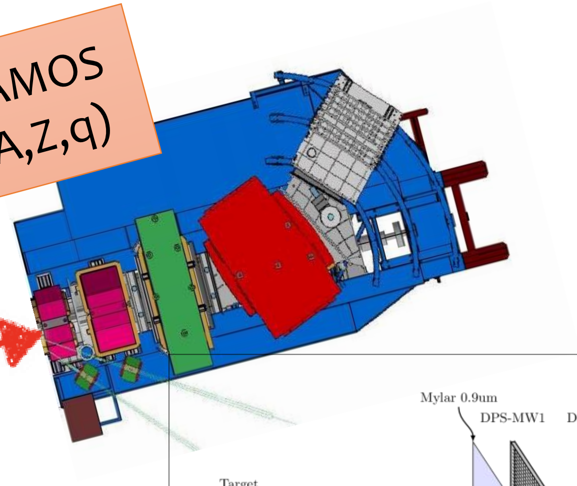
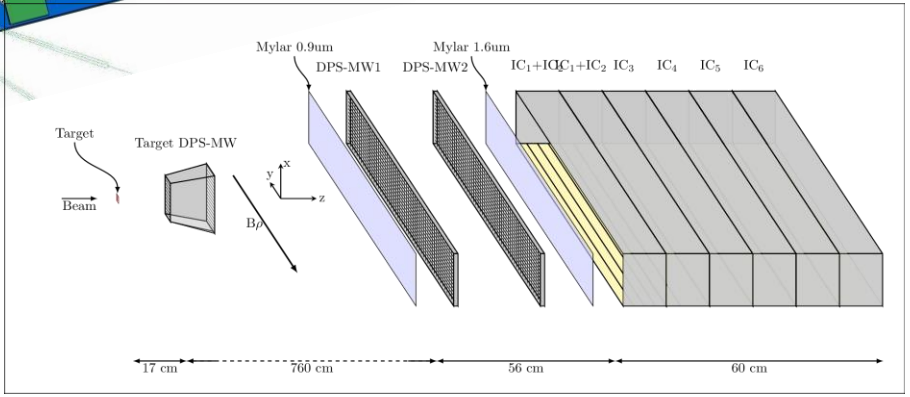


SPIDER → PISTA:
Recoil
A, Z, E, angle

VAMOS
(A,Z,q)





VAMOS Magnetic Spectrometer

⇒ Direct and Complete isotopic fission fragment yields

⇒ Precise center-of-mass fission fragment velocities isotopically (due to Coulomb barrier energies)

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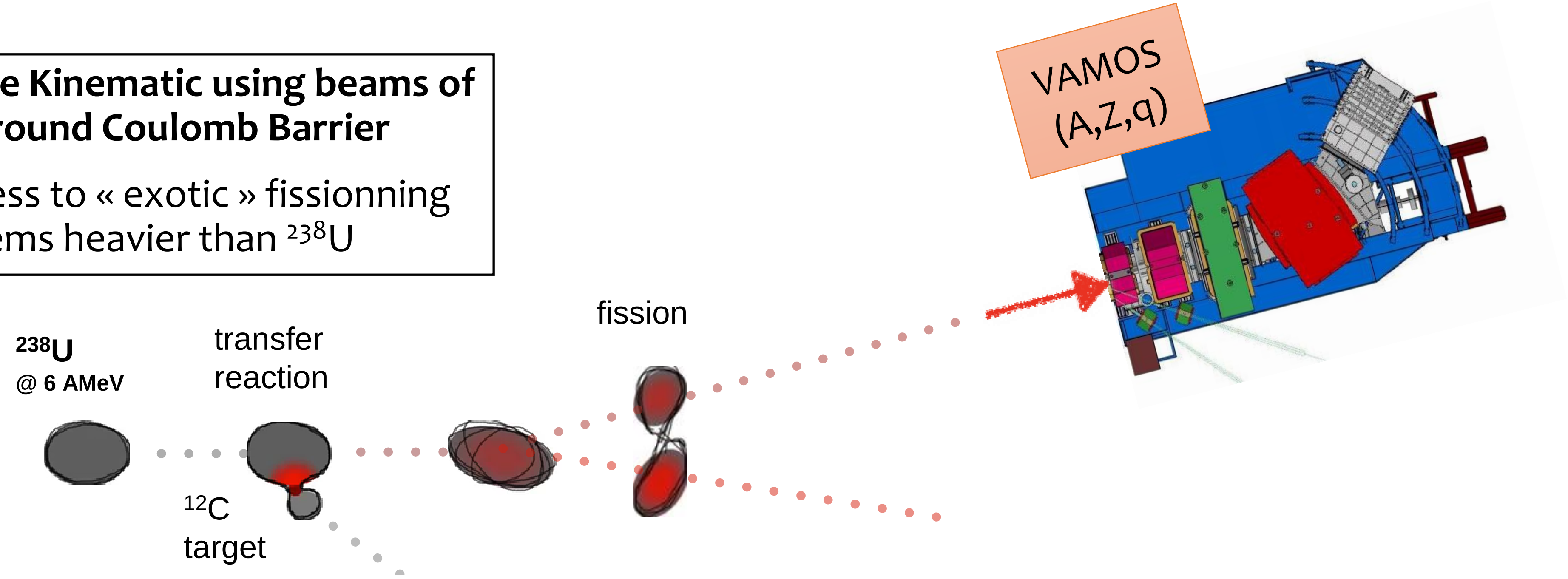

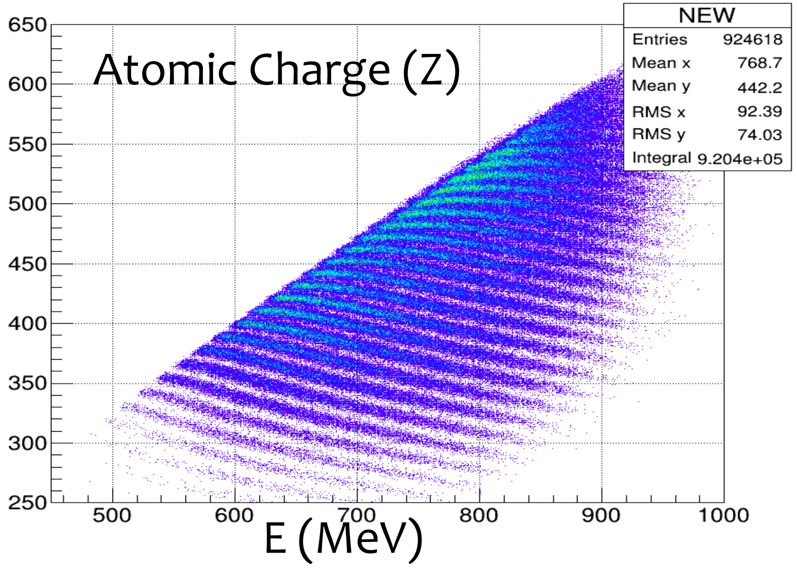

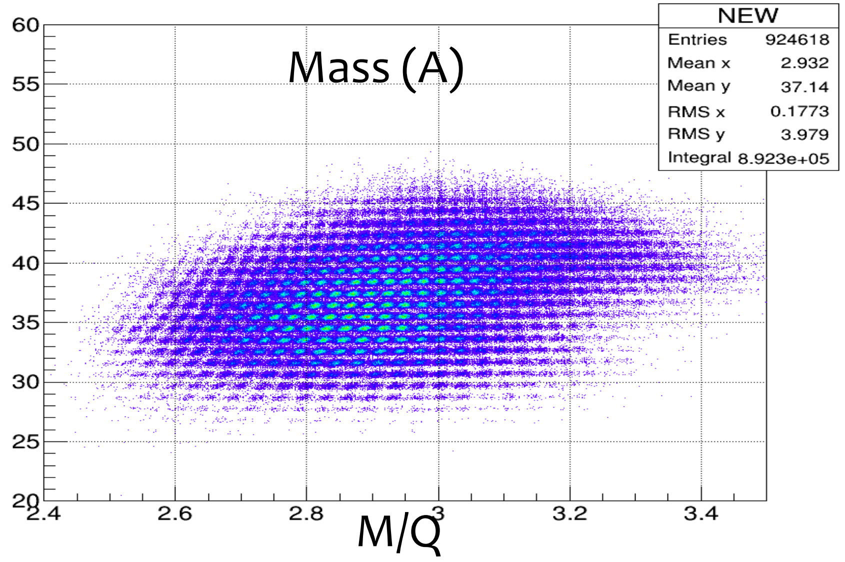

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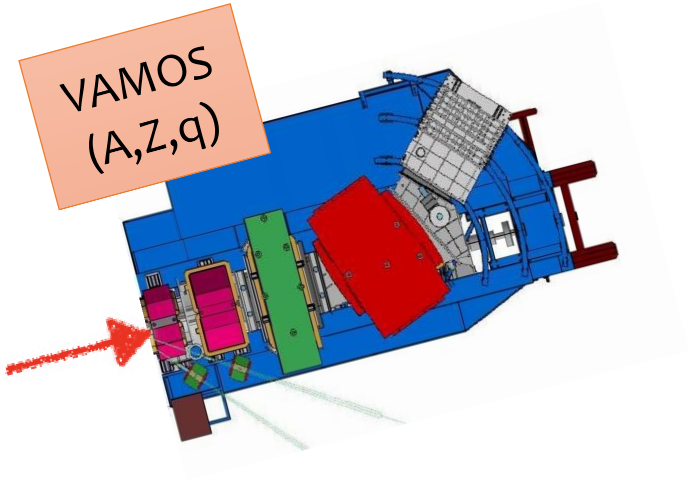

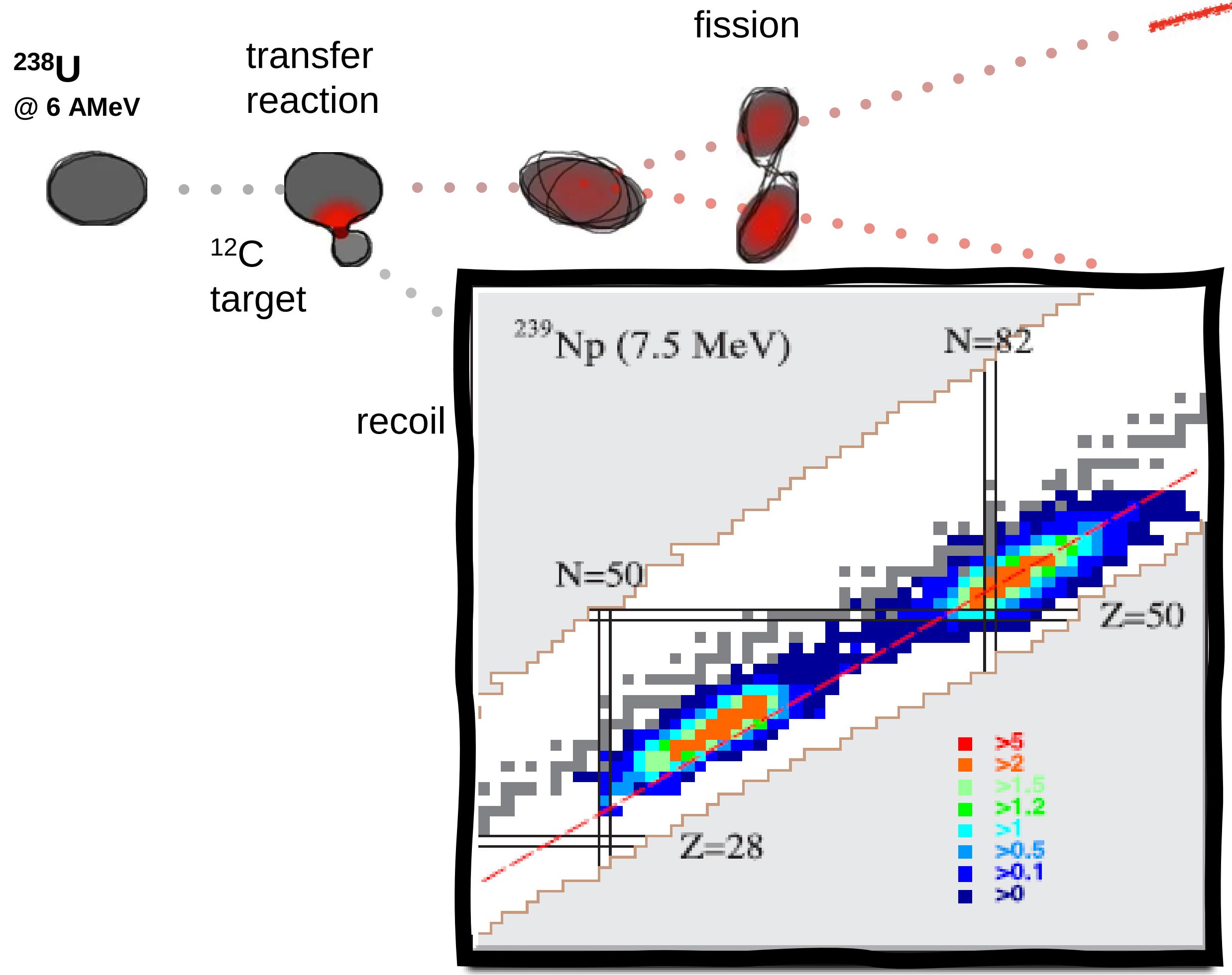

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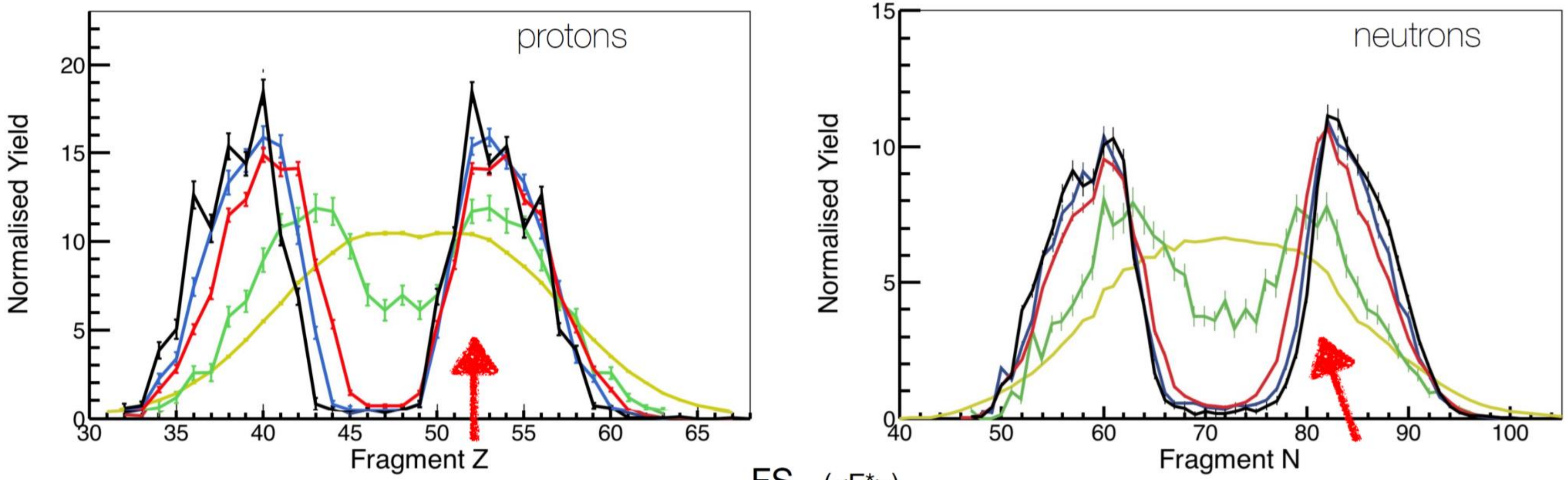
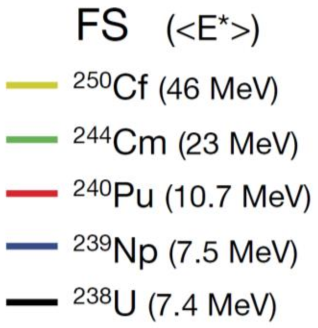
A set of revisited and new observables
Z and N distributions





The effect of the heavy group lasts until very high excitation energy.

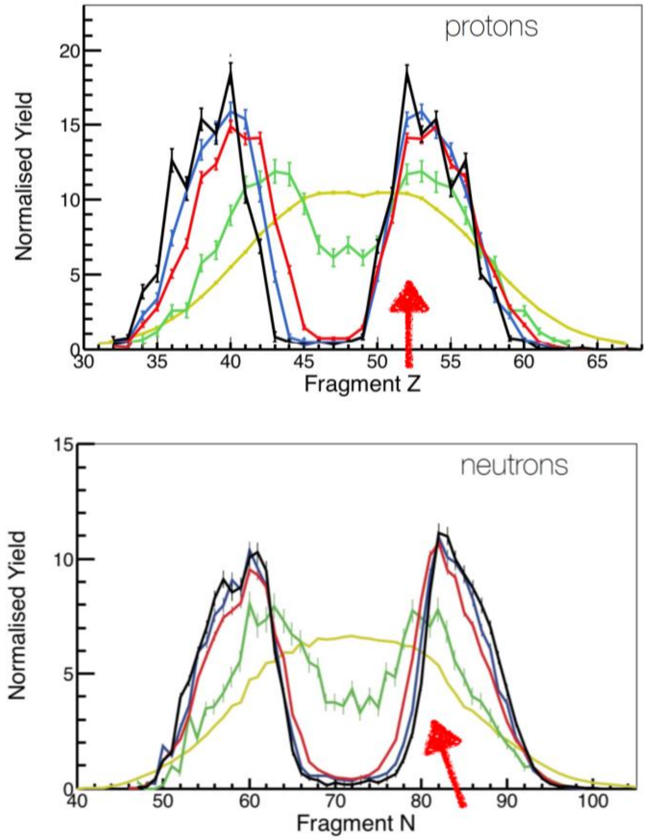
At ~46 MeV the distribution is not yet fully LD.

The measured neutron distribution is affected by post-scission evaporation.

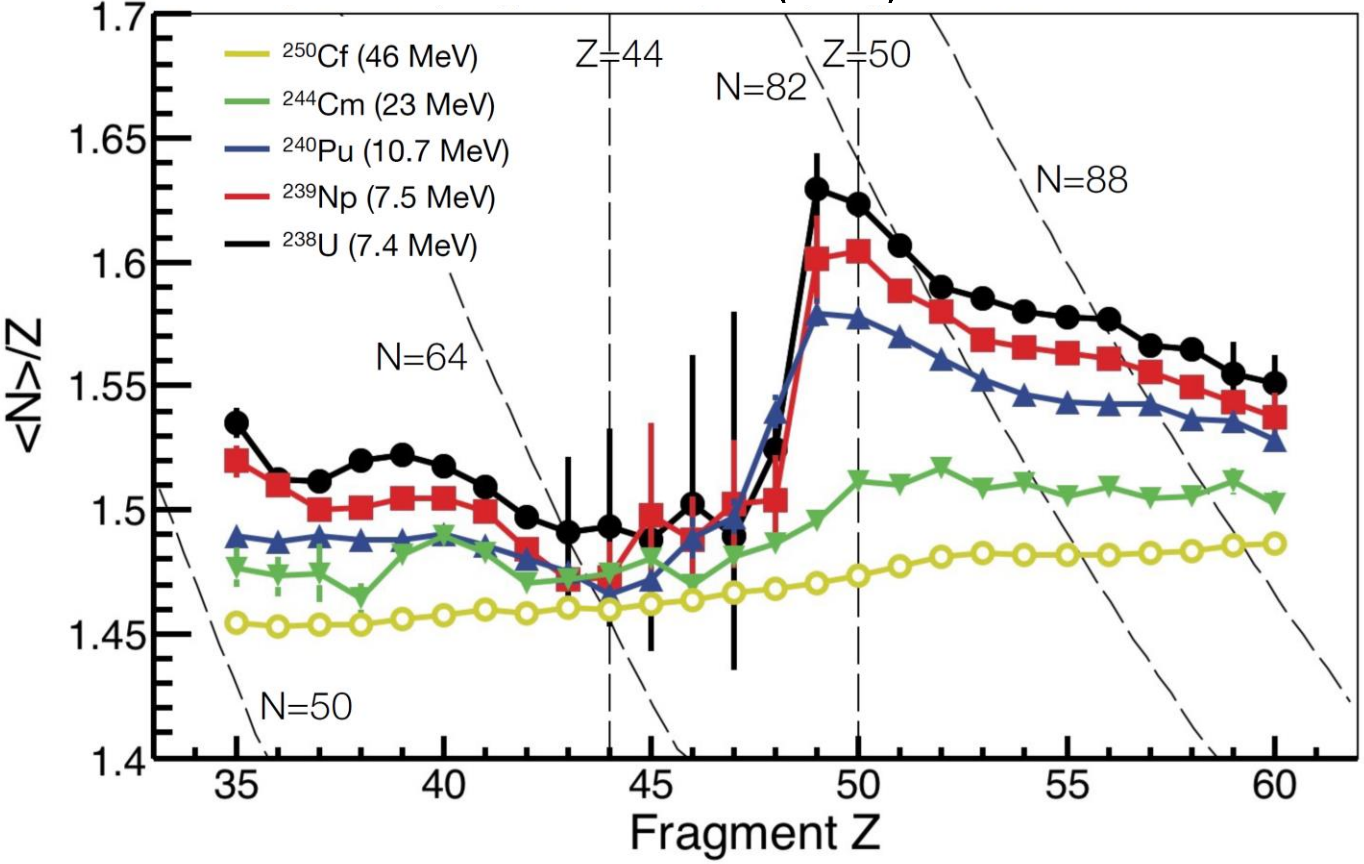
Even odd effect : pairing of nucleons in fission and damping with the excitation energy.

D. Ramos *et al.* (2019)

A set of revisited and new observables
Fragments N excess (<N>/Z)



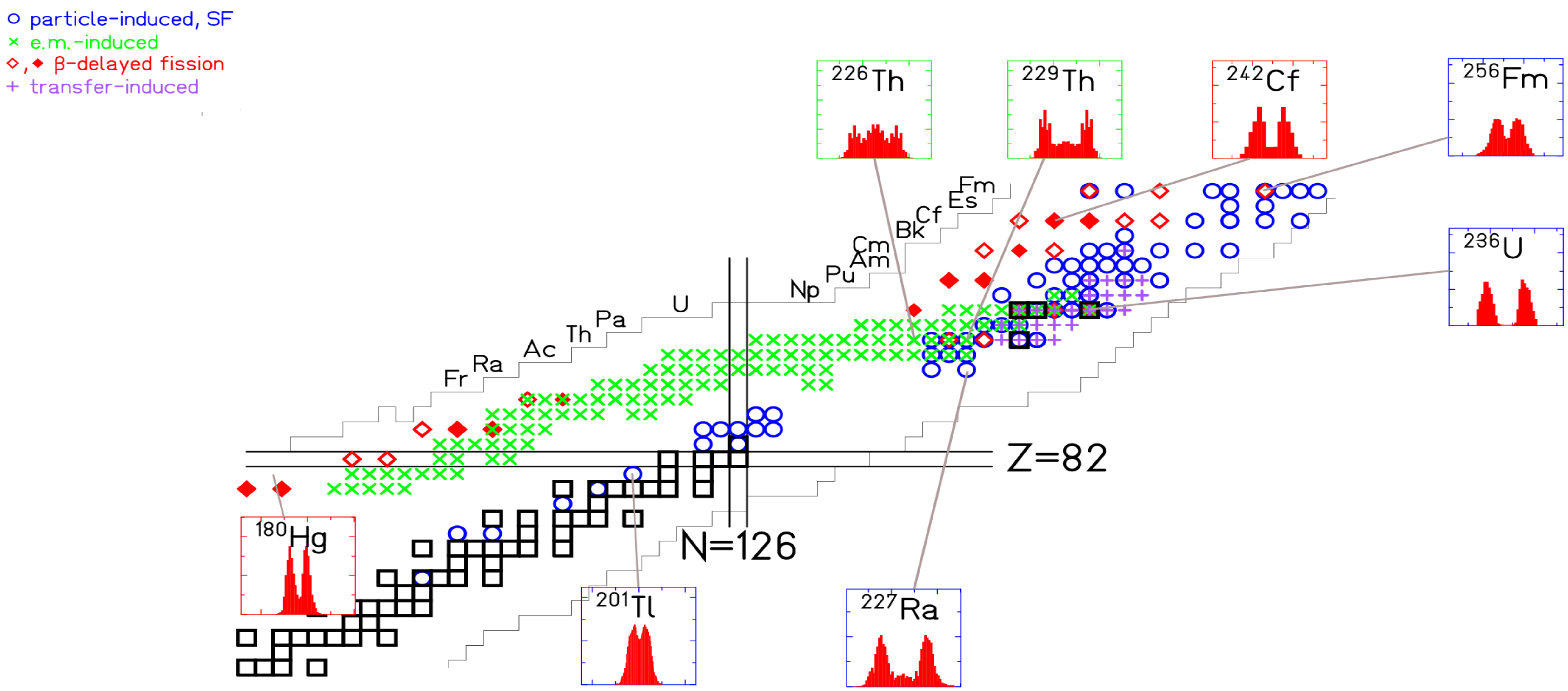
D. Ramos *et al.* (2019)



Reveals fine structural effects otherwise unnoticed

N=82 (~spherical) and N=88 (deformed / Octupolar)

Exploring further the fission landscape



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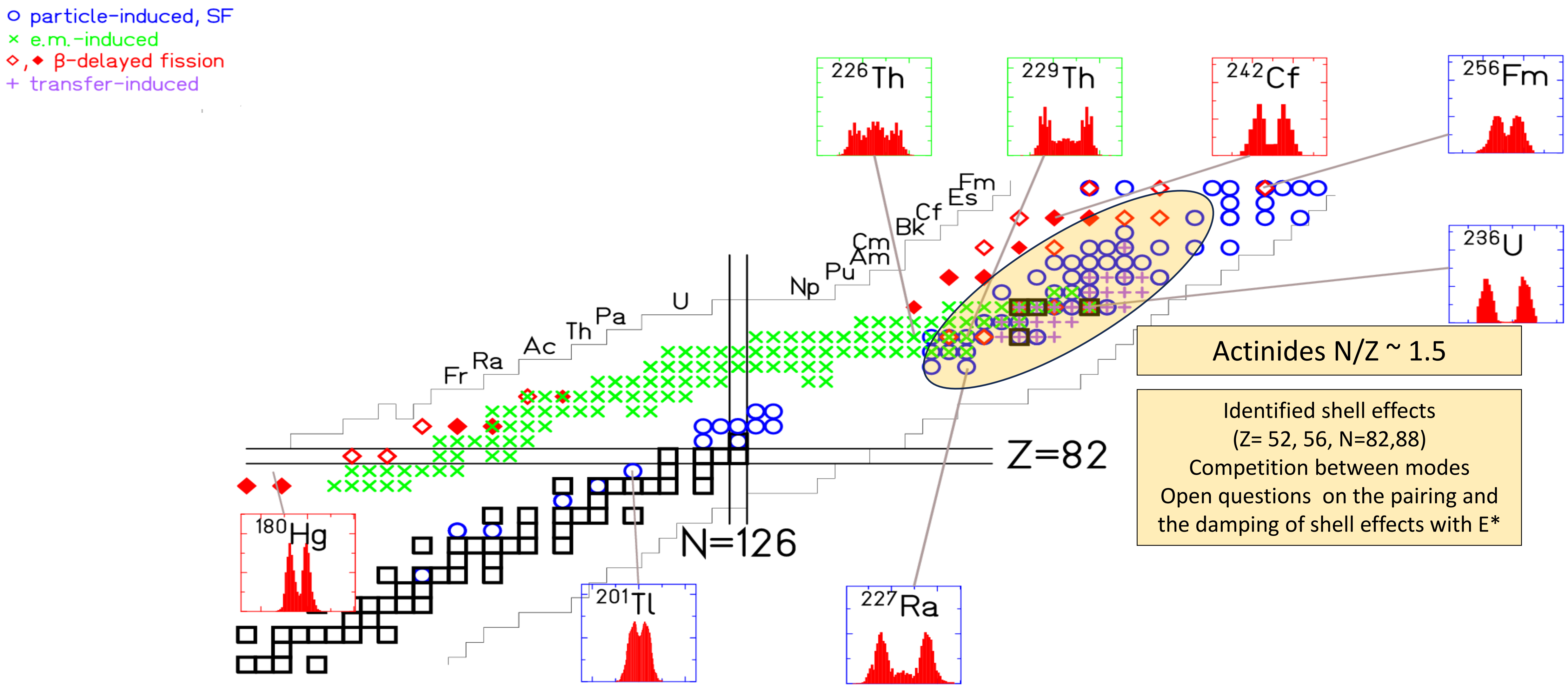
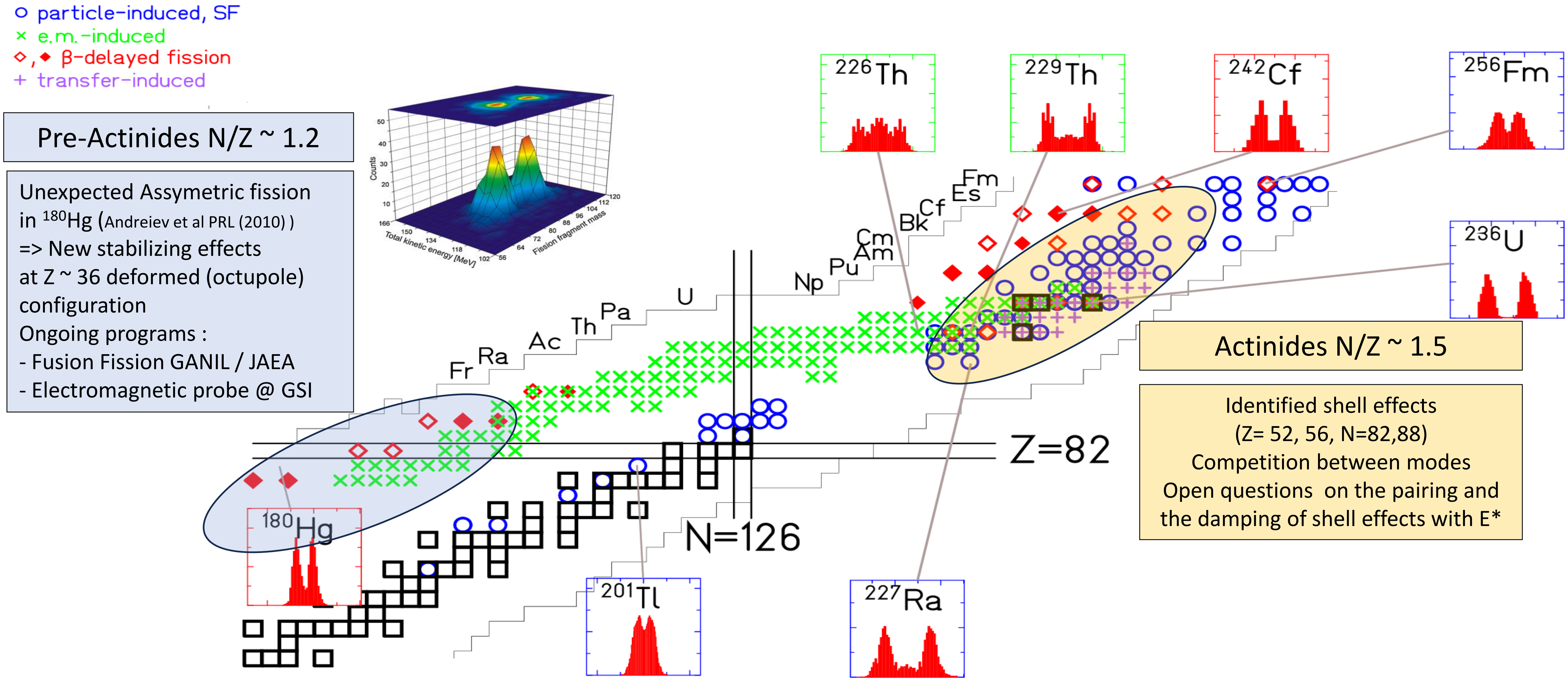


Actinides N/Z ~ 1.5

Identified shell effects
(Z= 52, 56, N=82,88)
Competition between modes
Open questions on the pairing and the damping of shell effects with E*

Exploring further the fission landscape



Pre-Actinides N/Z ~ 1.2

Unexpected Assymetric fission in ^{180}Hg (Andreiev et al PRL (2010))
=> New stabilizing effects at Z ~ 36 deformed (octupole) configuration

Ongoing programs :

- Fusion Fission GANIL / JAEA
- Electromagnetic probe @ GSI

Actinides N/Z ~ 1.5

Identified shell effects
(Z= 52, 56, N=82,88)
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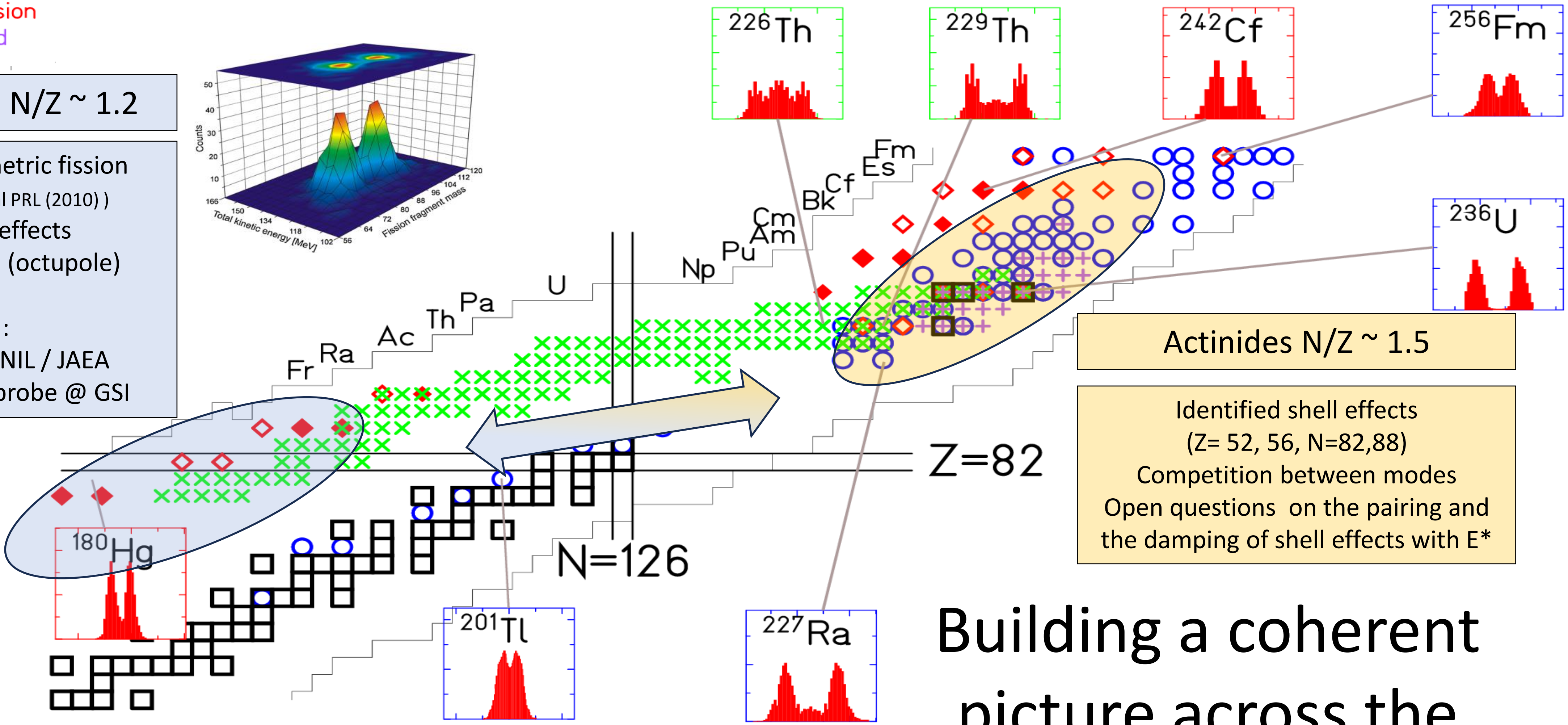
Open questions on the pairing and the damping of shell effects with E*

Exploring further the fission landscape



Pre-Actinides N/Z ~ 1.2

Unexpected Assymetric fission in ^{180}Hg (Andreiev et al PRL (2010))
=> New stabilizing effects at Z ~ 36 deformed (octupole) configuration

Ongoing programs :
- Fusion Fission GANIL / JAEA
- Electromagnetic probe @ GSI

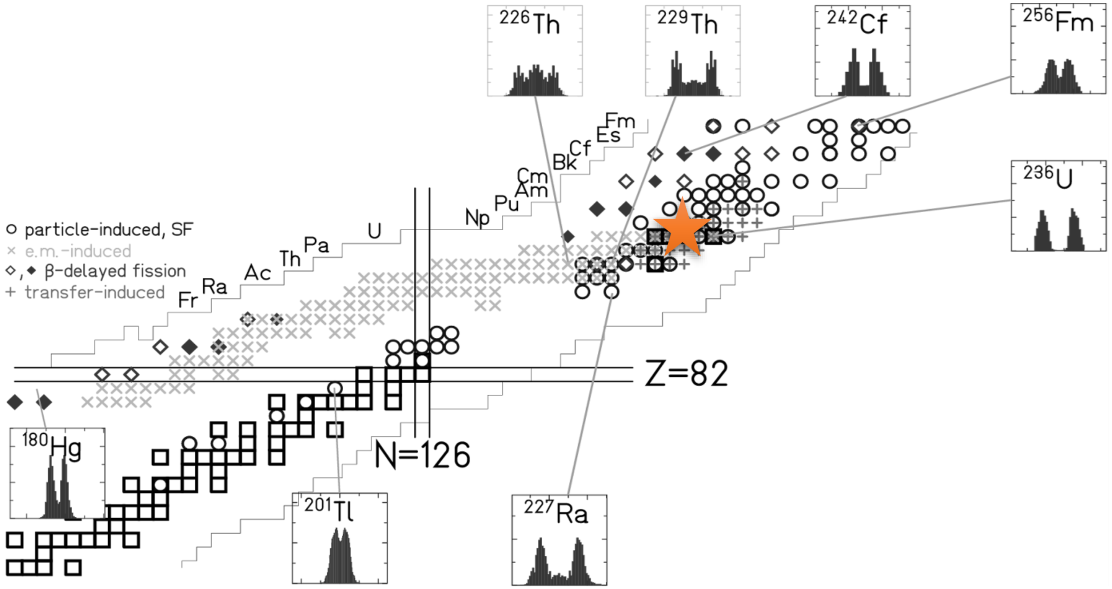
Actinides N/Z ~ 1.5

Identified shell effects
(Z= 52, 56, N=82,88)
Competition between modes
Open questions on the pairing and the damping of shell effects with E*

Building a coherent picture across the landscape

Fission : A long history and rich perspectives

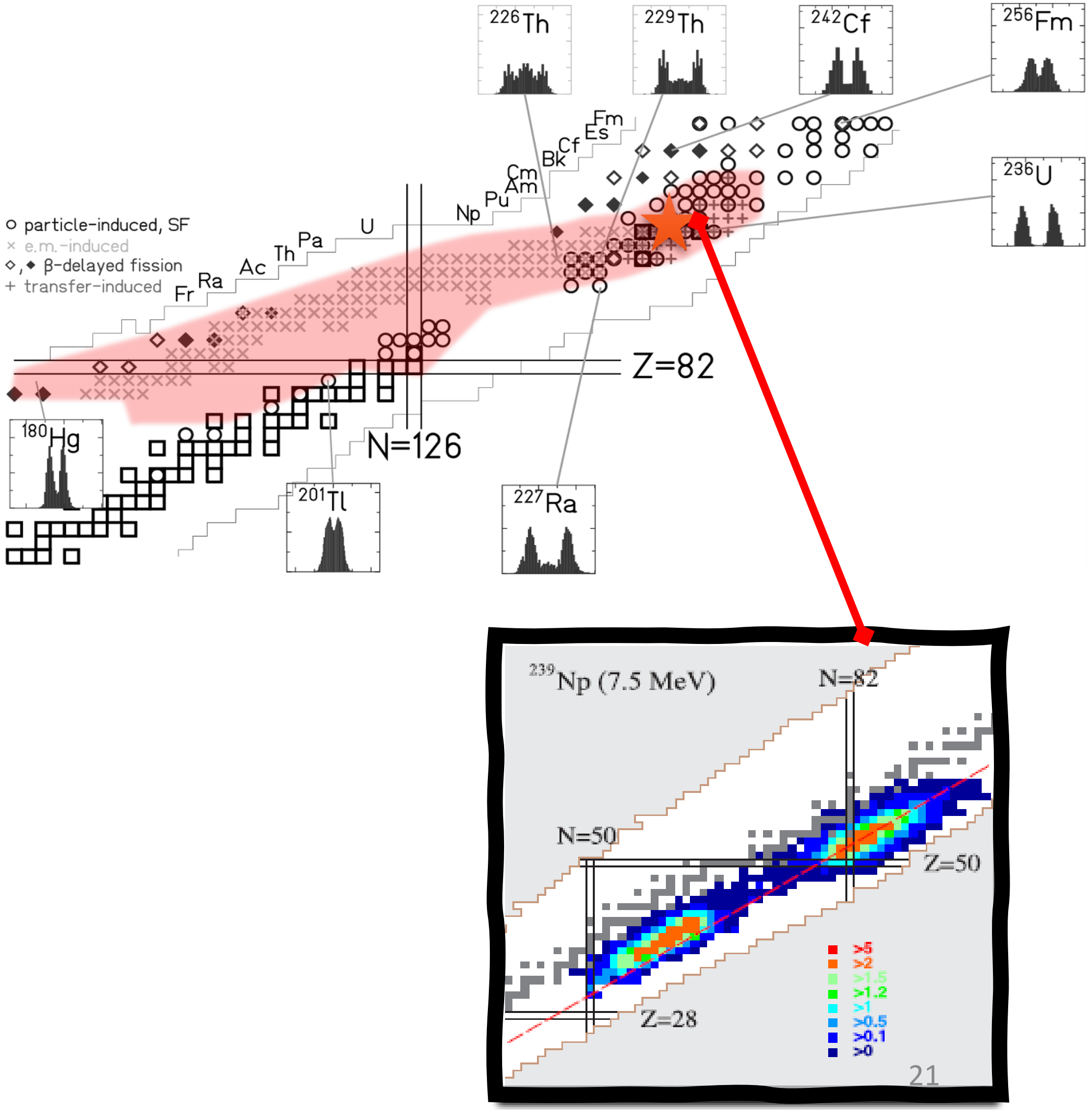
After 85 years of studies, fission remains a challenging topic



Fission : A long history and rich perspectives

After 85 years of studies, fission remains a challenging topic

- **In the last decade, experimental developments** opened new paths to probe the fission process for a wide range of systems (in terms of content (N/Z) and excitation energy E*)
- **Present and future exclusive measurements (A,Z,E*)** bring new constrains to models to explore the different underlying dynamical and structural mechanisms that drive the fission process **towards a coherent picture** of the fission process across the fission nuclear landscape.



Fission : A long history and rich perspectives

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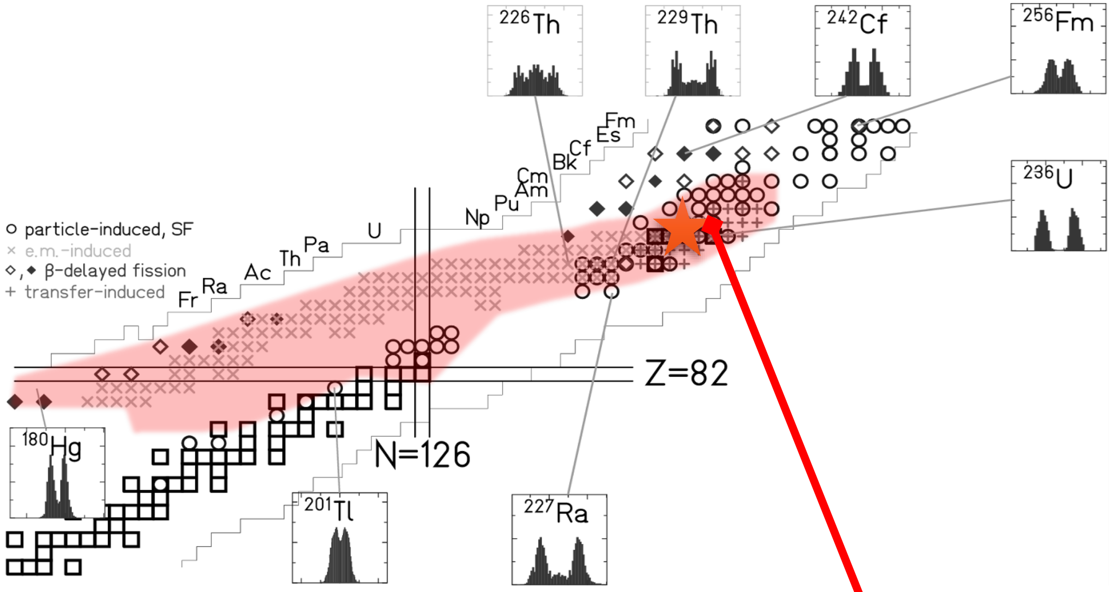
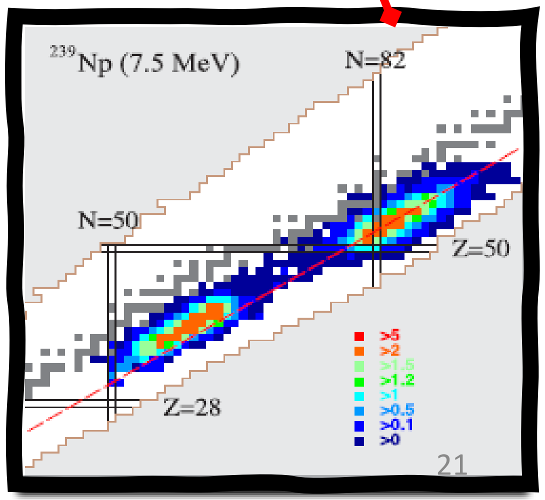
- **Contributions to nuclear data needs** and evaluation
- Beyond the fission yields (mostly shown today), a large number of observables (Kinetic Energies, neutron multiplicities, prompt gamma-ray spectra) plays a key role in gaining a deeper understanding of the process.
  => V. Piau, C. Michelagnoli
- **Ongoing intense theoretical developments** aiming at a microscopic description of the fission process
  => D. Regnier





Thank you for your attention !