Fission reactions

S. Hilaire

CEA, DAM, DIF

ICTP-IAEA Workshop on Simulation of Nuclear Reaction Data with the TALYS Code - TRIESTE - October 2023

Content

- **Introduction**
- **General features about nuclear reactions**
  - Time scales and associated models
  - Types of data needed
  - Data format = f (users)
- **Nuclear Models**
  - Basic structure properties
  - Optical model
  - Pre-equilibrium model
  - Compound Nucleus model
- **Model ingredients**
  - Level densities
  - Gamma-ray strengths
  - Fission transmission coefficients
- **Fission reactions**
  - Generalities about fission
  - Fission neutrons and gammas
  - Fission yields
  - Fission cross sections
- **Prospects**

Content

MONDAY

- **Introduction**
- **General features about nuclear reactions**
  - Time scales and associated models
  - Types of data needed
  - Data format = f (users)
- **Nuclear Models**
  - Basic structure properties
  - Optical model
  - Pre-equilibrium model
  - Compound Nucleus model
- **Model ingredients**
  - Level densities
  - Gamma-ray strengths
  - Fission transmission coefficients
- **Fission reactions**
  - Generalities about fission
  - Fission neutrons and gammas
  - Fission yields
  - Fission cross sections
- **Prospects**

Content

- **Introduction**
- **General features about nuclear reactions**
  - Time scales and associated models
  - Types of data needed
  - Data format = f (users)
- **Nuclear Models**
  - Basic structure properties
  - Optical model
  - Pre-equilibrium model
  - Compound Nucleus model
- **Model ingredients** TUESDAY
  - Level densities
  - Gamma-ray strengths
  - Fission transmission coefficients
- **Fission reactions**
  - Generalities about fission
  - Fission neutrons and gammas
  - Fission yields
  - Fission cross sections
- **Prospects**

Content

- **Introduction**
- **General features about nuclear reactions**
  - Time scales and associated models
  - Types of data needed
  - Data format = f (users)
- **Nuclear Models**
  - Basic structure properties
  - Optical model
  - Pre-equilibrium model
  - Compound Nucleus model
- **Model ingredients**
  - Level densities
  - Gamma-ray strengths
  - Fission transmission coefficients

TODAY

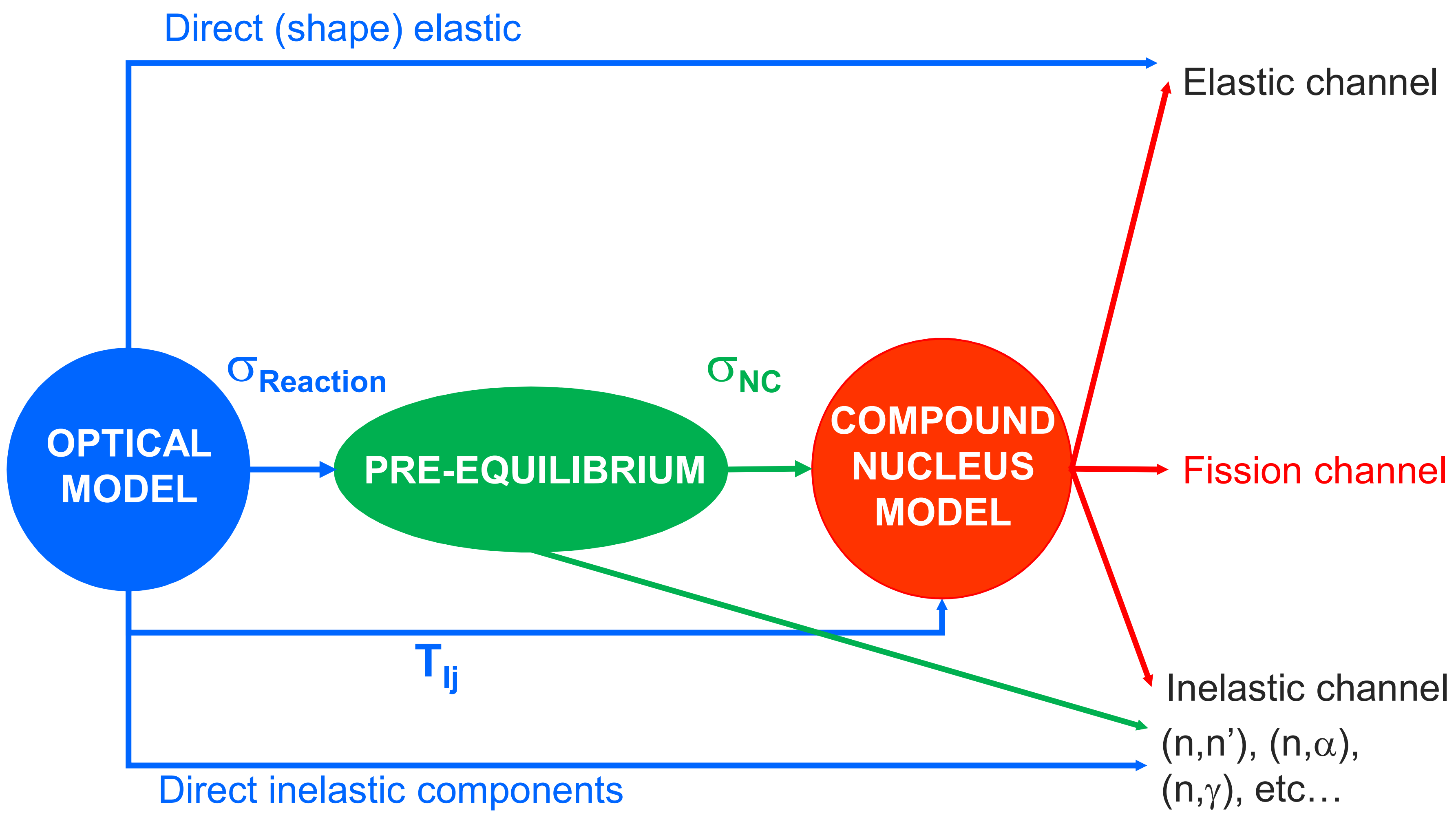
- **Fission reactions**
  - Generalities about fission
  - Fission neutrons and gammas
  - Fission yields
  - Fission cross sections
- **Prospects**

Content

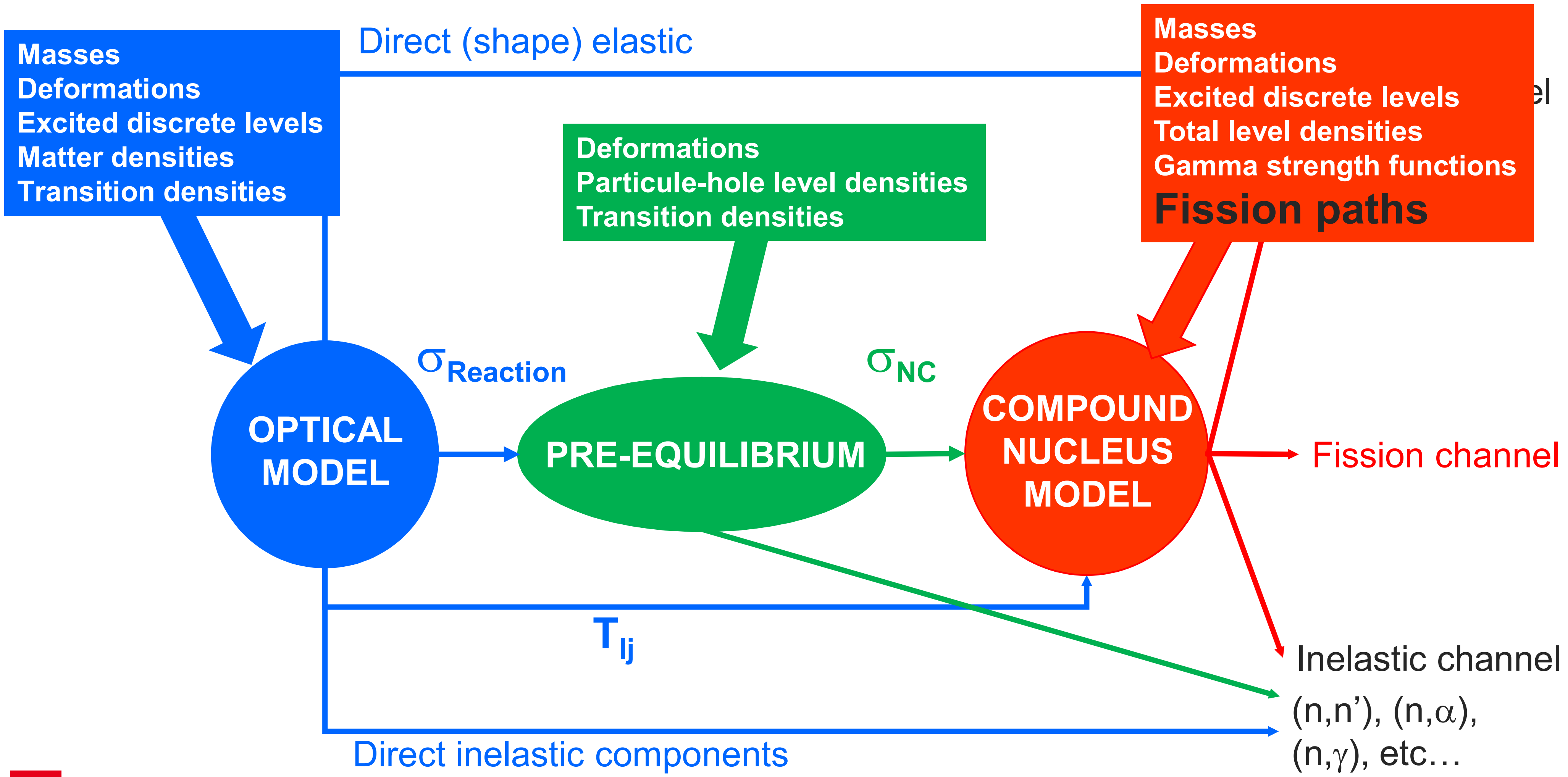
- **Introduction**
- **General features about nuclear reactions**
  - Time scales and associated models
  - Types of data needed
  - Data format = f (users)
- **Nuclear Models**
  - Basic structure properties
  - Optical model
  - Pre-equilibrium model
  - Compound Nucleus model
- **Model ingredients**
  - Level densities
  - Gamma-ray strengths
  - Fission transmission coefficients
- **Fission reactions**
  - Generalities about fission
  - Fission neutrons and gammas
  - Fission yields
  - Fission cross sections
- **Prospects**

1. FEW REMINDERS

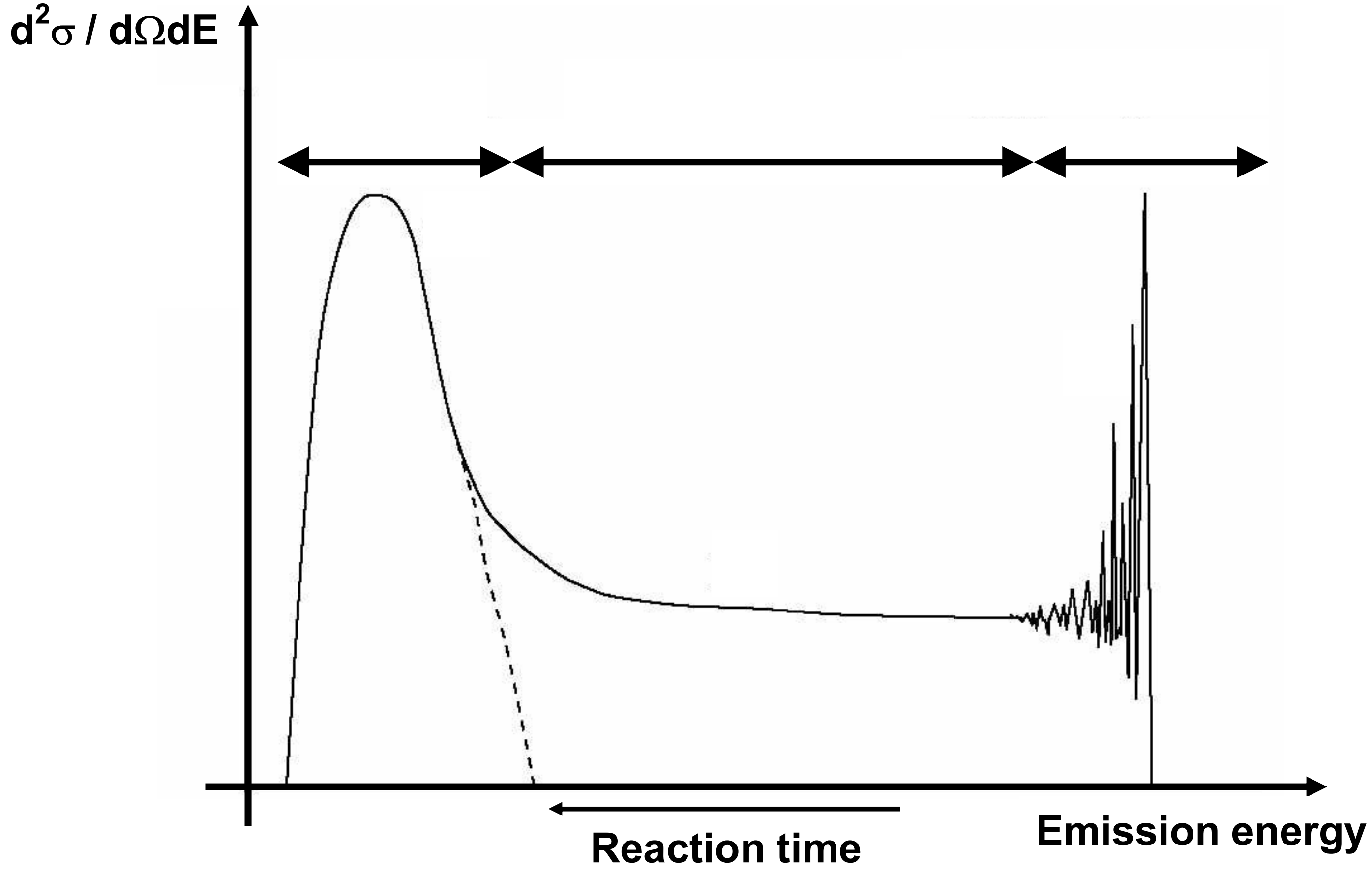
Models sequence and required ingredients



Models sequence and required ingredients

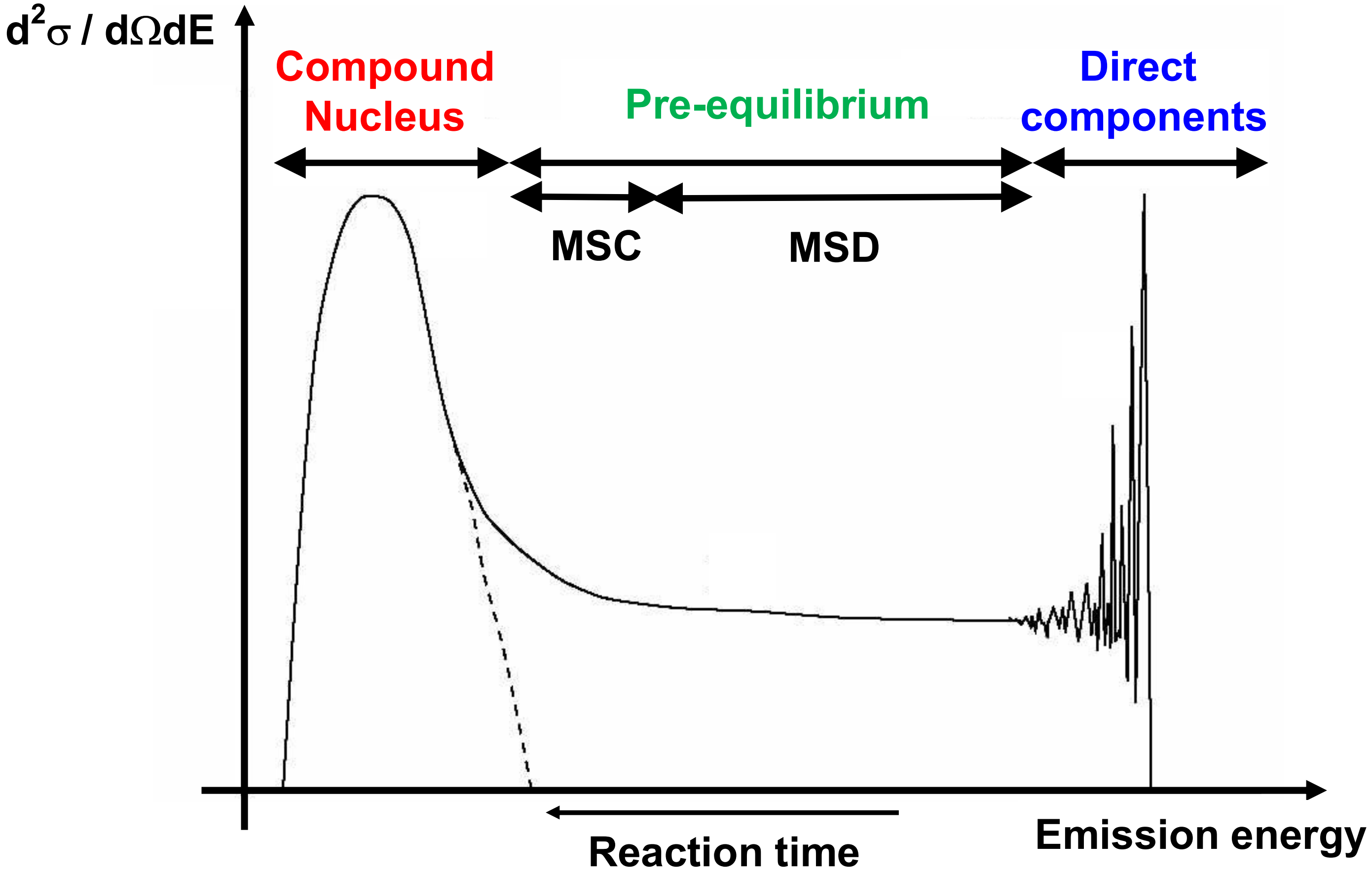


Time scales and associated models



Real scale : 10^{-15} s 10^{-22} s
Human scale : year s

Time scales and associated models



Real scale : 10^{-15} s 10^{-22} s

Human scale : year s

Fission reactions

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

- Conclusions

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

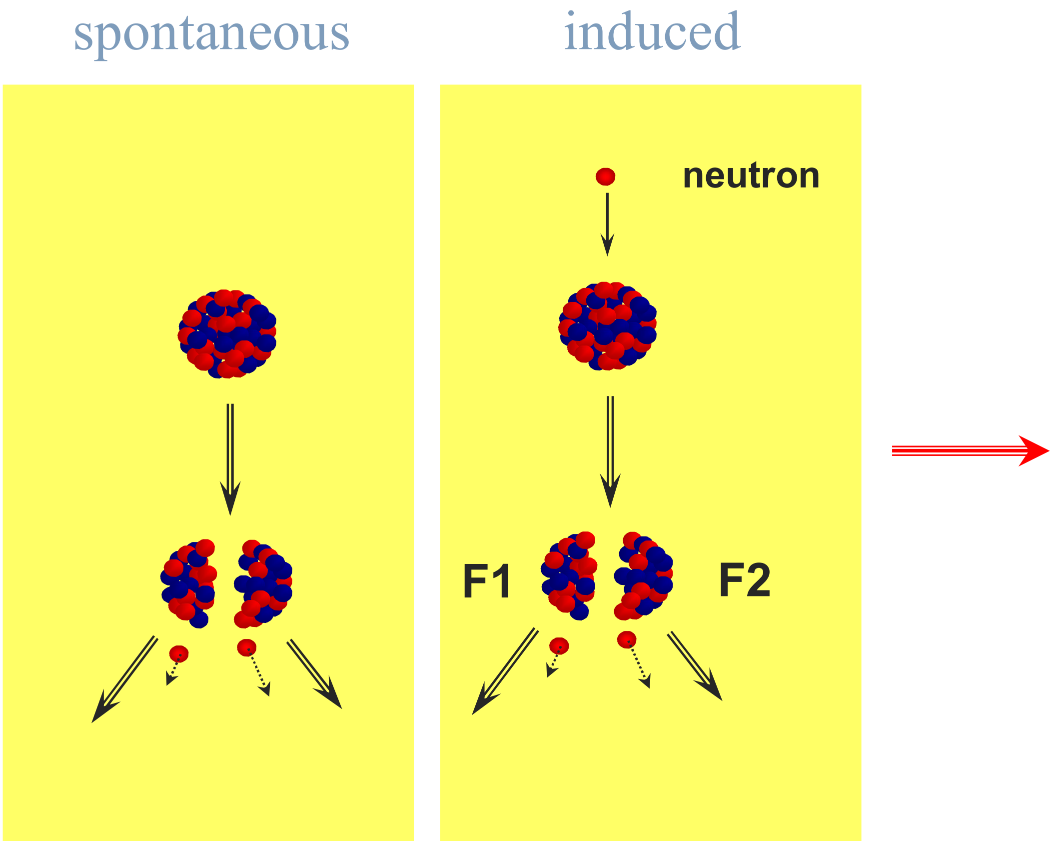
- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

- Conclusions

2. GENERALITIES

The fission process



Fragments (2+ε)

Prompt neutrons (ν)

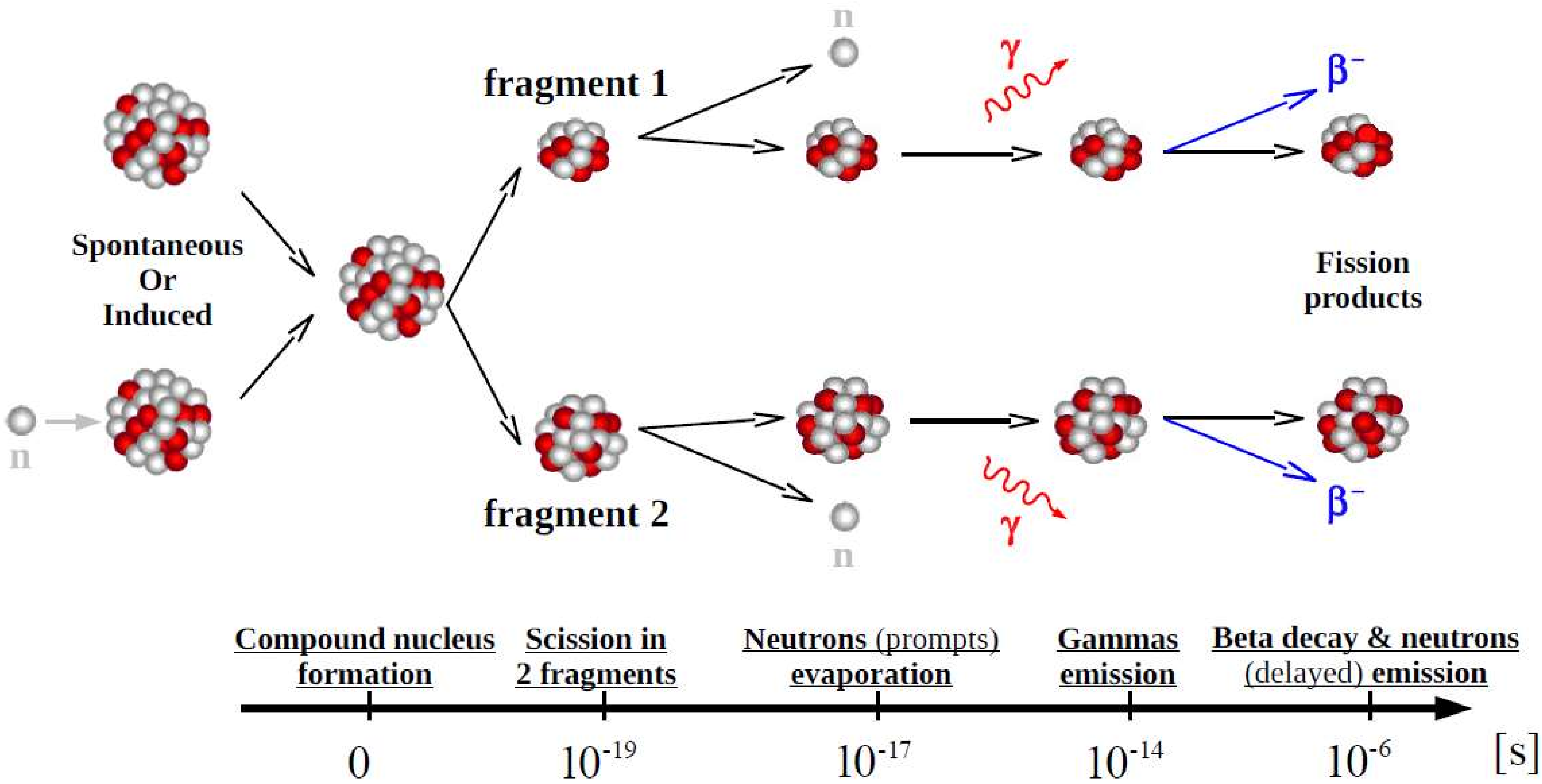
Delayed neutrons (ν/100)

Prompt gammas

Delayed gammas

...... Energy (200 MeV)

The fission process : sequence for induced fission



The fission process : typical energy balance

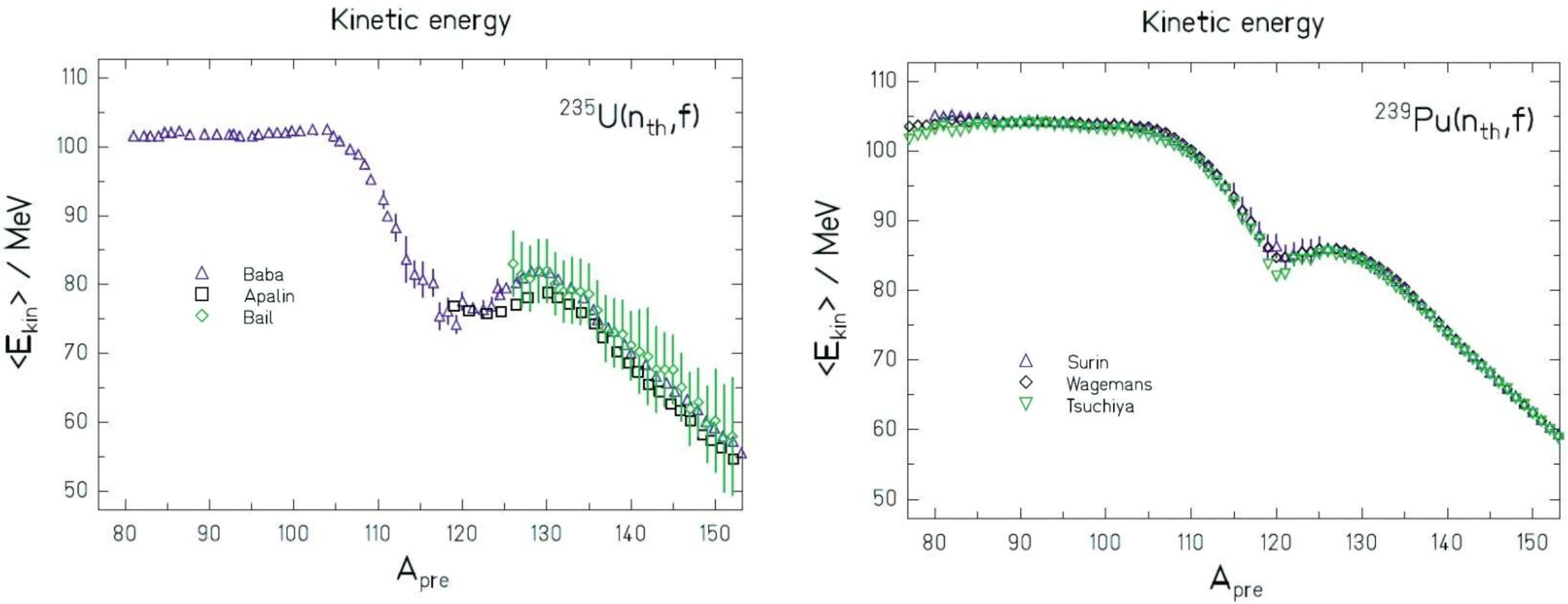
Fragments kinetic energy	**165 MeV**
prompt γ	**8 MeV**
β decay	**19 MeV**
delayed γ	**7 MeV**
prompts neutrons	**5 MeV**
TOTAL :	**204 MeV**

$n + {}^{235}U \rightarrow {}^{94}Sr + {}^{140}Xe + 2n$ => Q= 184.68 MeV

$\rightarrow {}^{94}Kr + {}^{139}Ba + 2n$ => Q= 177.46 MeV

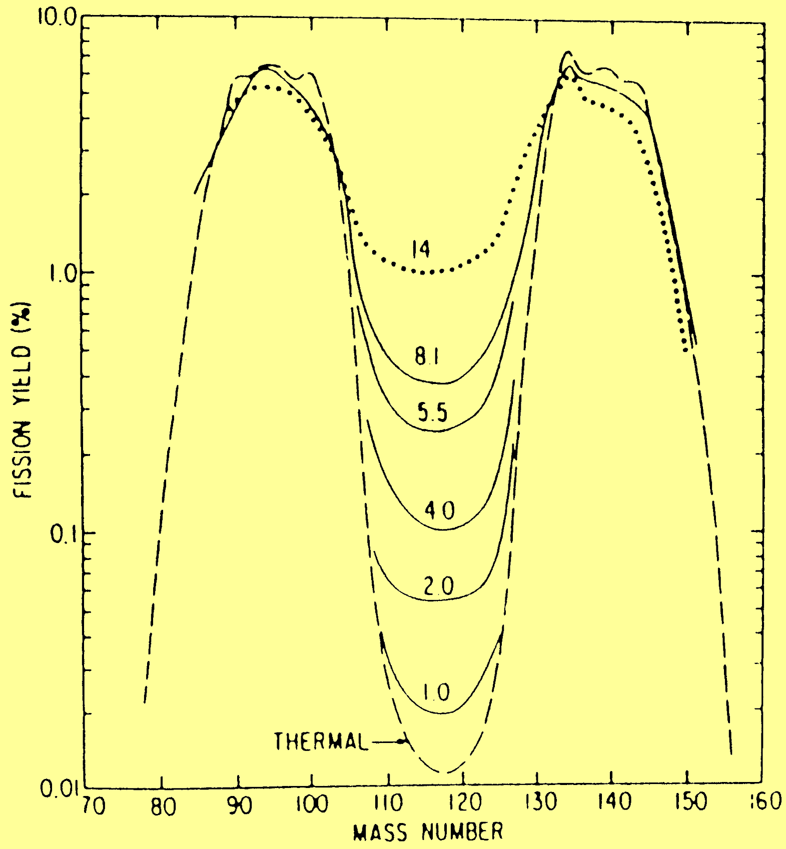
$\rightarrow {}^{118}Pd + {}^{117}Pd + 1n$ => Q= 192.73 MeV

The fission process : fragments kinetic energies



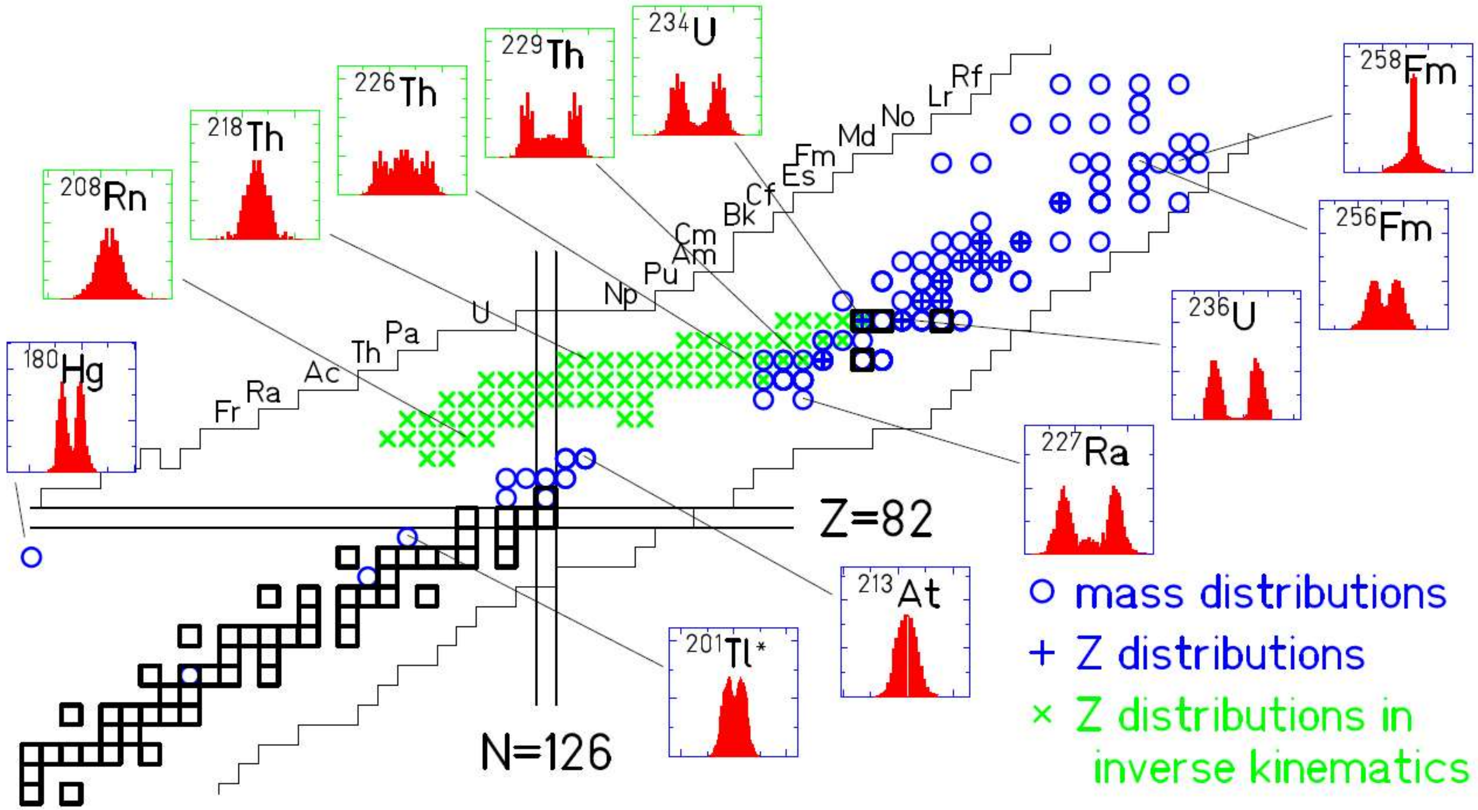
The fission process : yields variations with energy

$n_E + {}^{235}U$



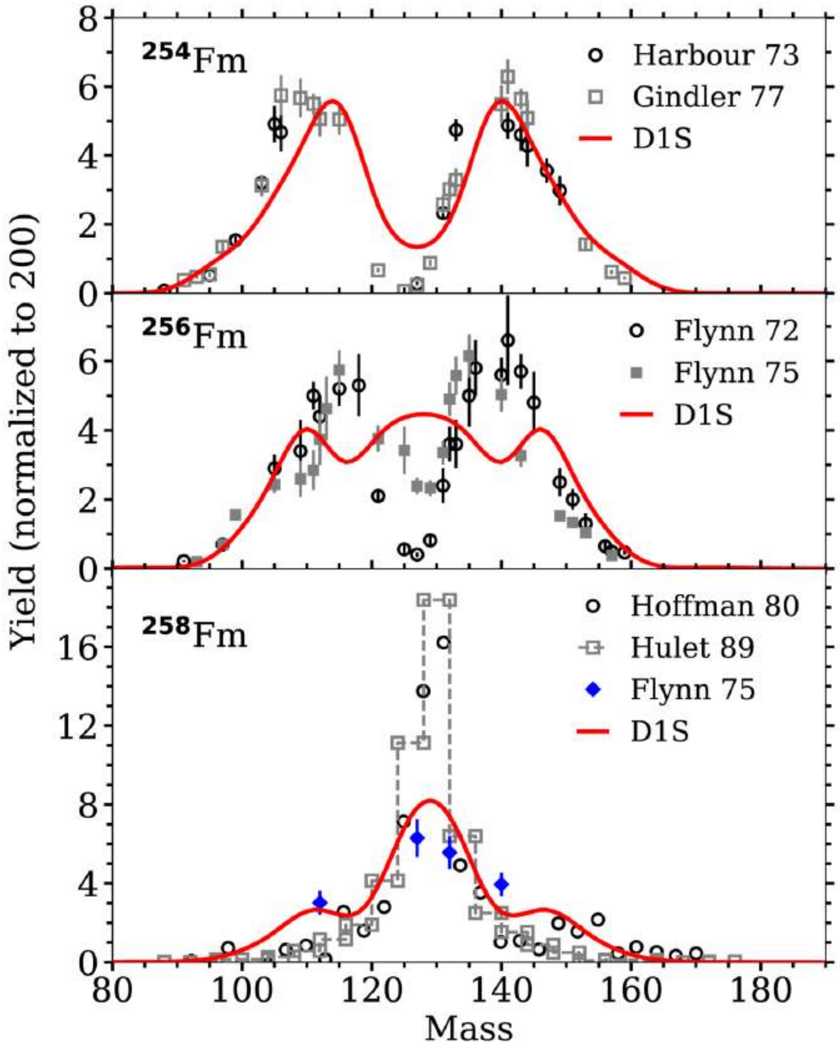
$\Rightarrow$ **Well filled with increasing incident energy**

The fission process : yields variations with targets

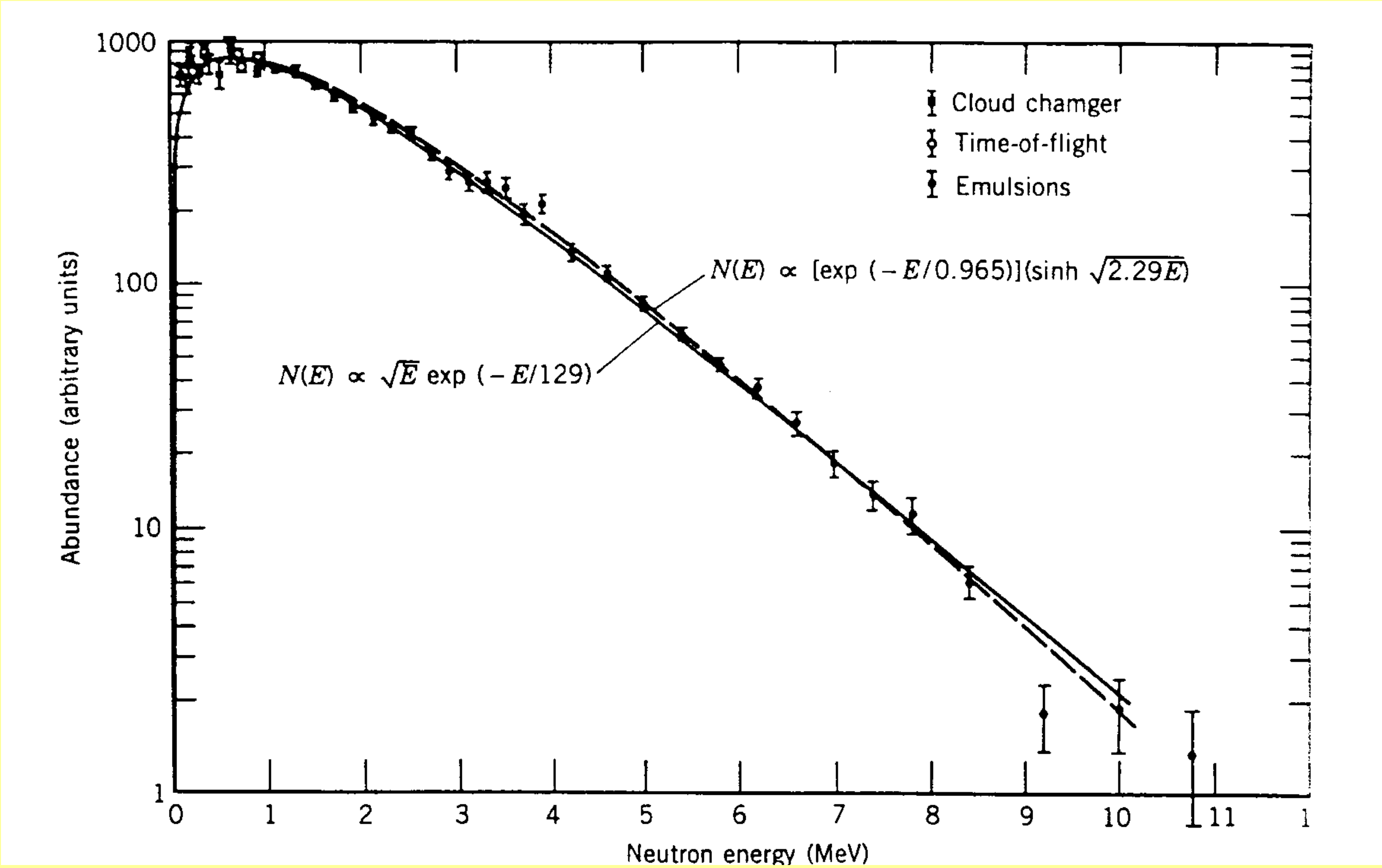


⇒ **FF distribution strongly modified with different targets**

The fission process : rapid yield variations

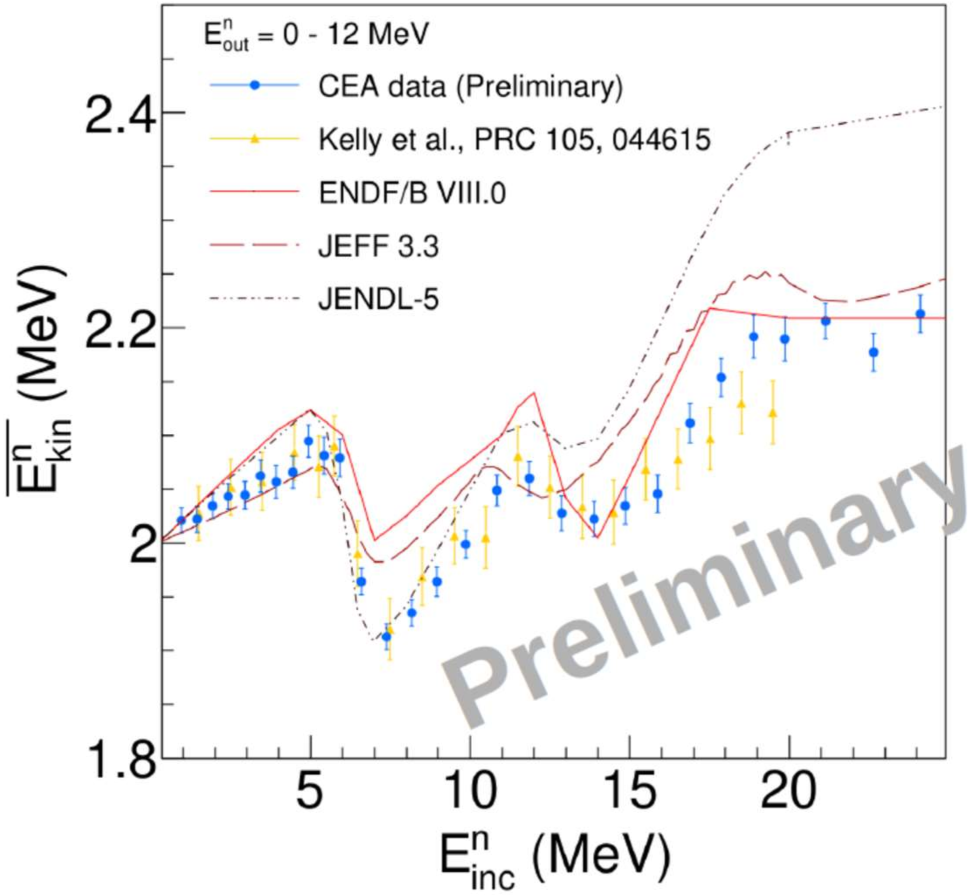


The fission process : emitted neutrons spectrum



⇒ **Maxwellian (evaporation) spectrum**

The fission process : mean energy of emitted neutrons



^{235}U

The fission process : neutron multiplicities

$\bar{\nu}$			
^{240}Pu	2.257	+/-	.045
^{238}Pu	2.33	+/-	.08
$^{235}U+n$	2.47	+/-	.03
^{242}Cm	2.65	+/-	.09
^{244}Cm	2.82	+/-	.05
^{252}Cf	3.86	+/-	.07
^{242}Pu	2.18	+/-	.09
$^{233}U+n$	2.585	+/-	.062

The fission process : neutron multiplicities and incident nrj

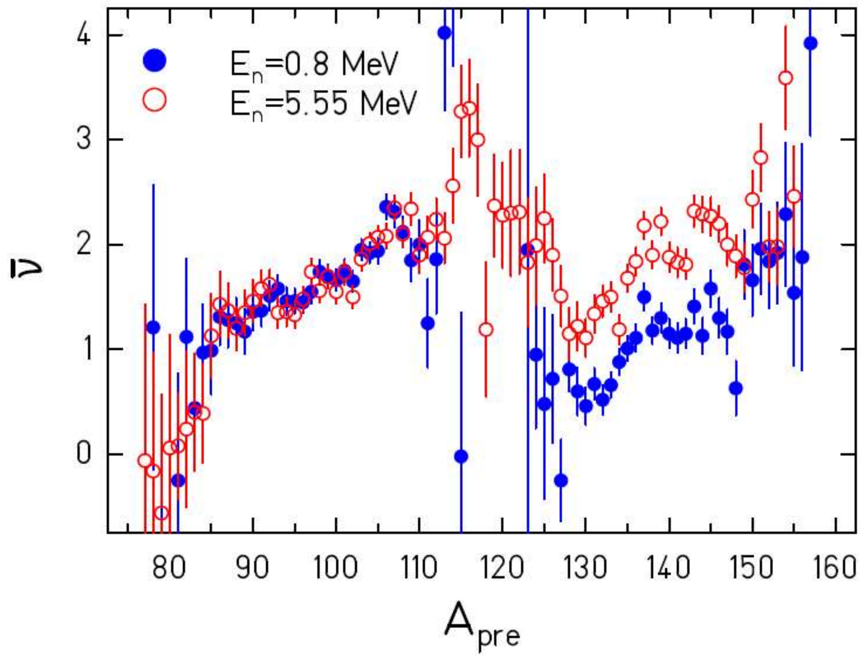
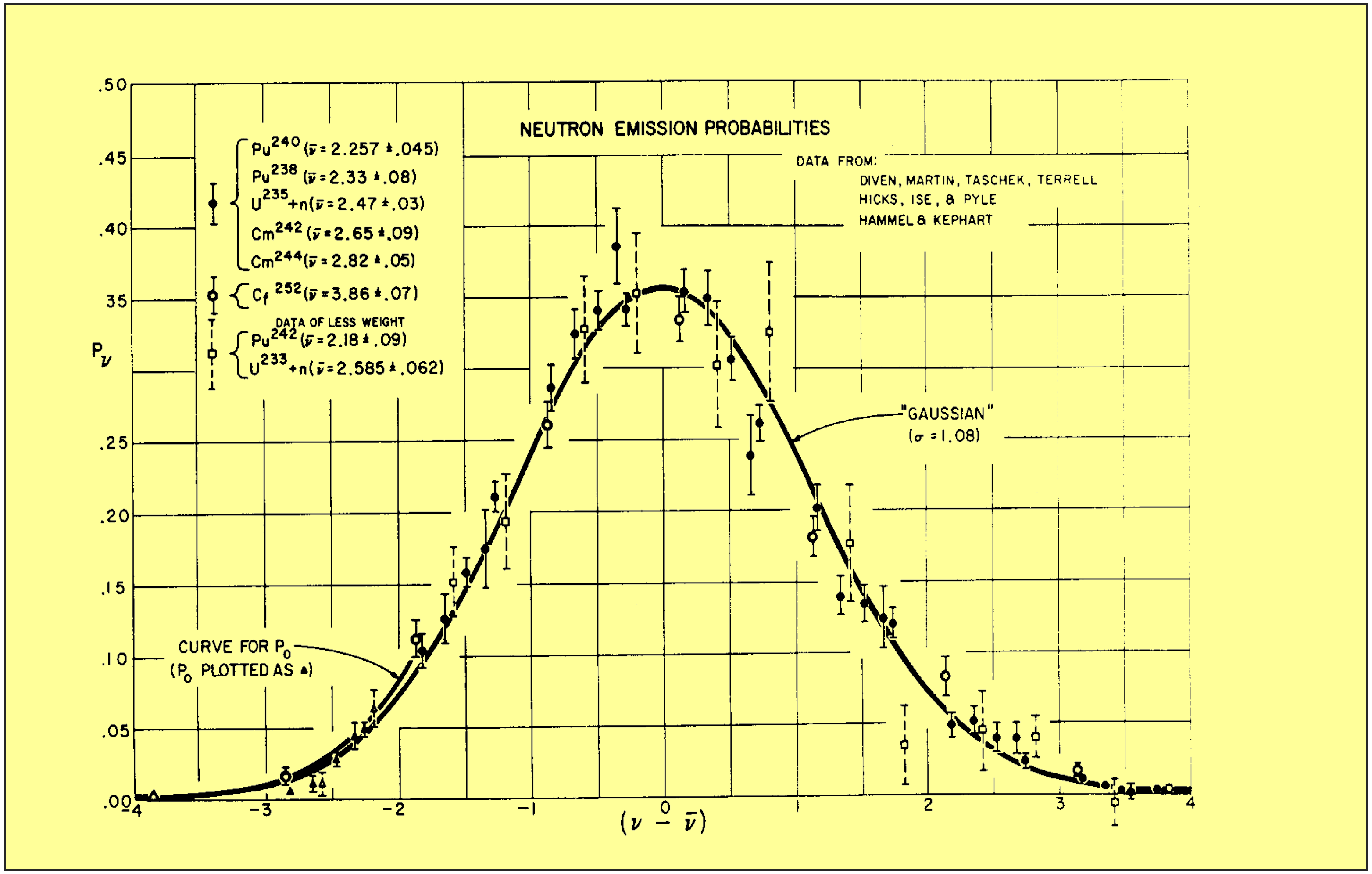
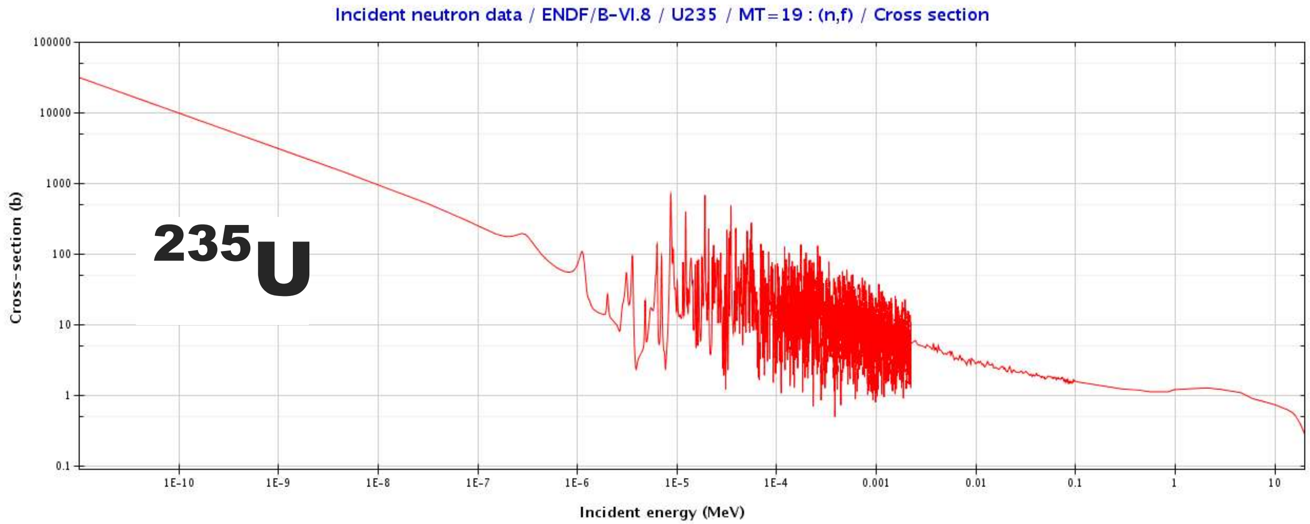


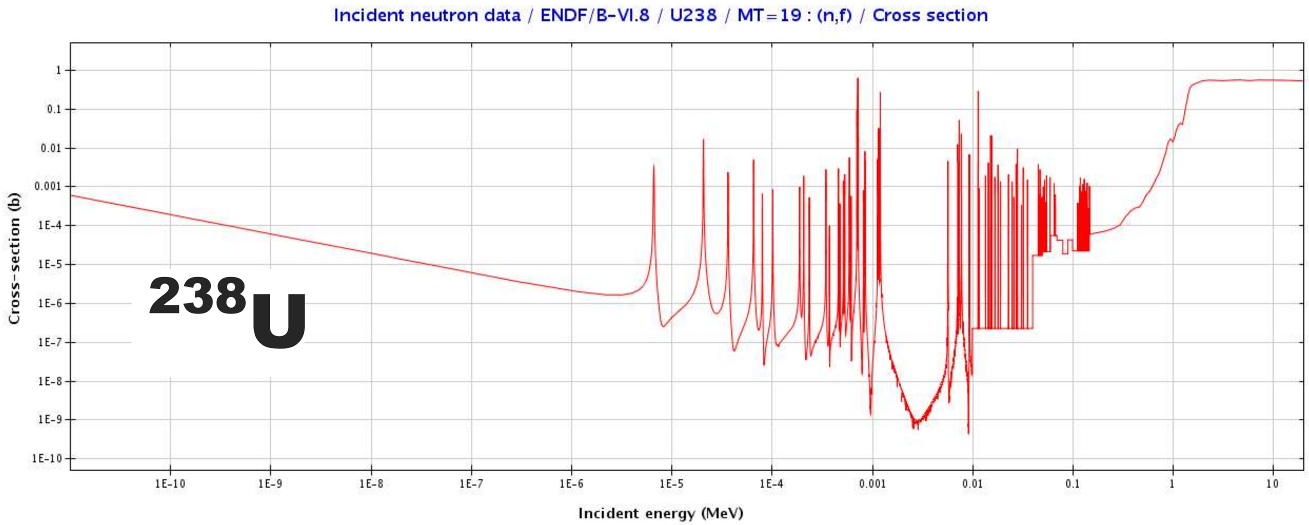
Figure 13: Prompt-neutron multiplicity as a function of the pre-neutron fragment mass for the system ^{237}Np(n,f) for $E_n = 0.8$ MeV and 5.55 MeV

The fission process : sequence for induced fission

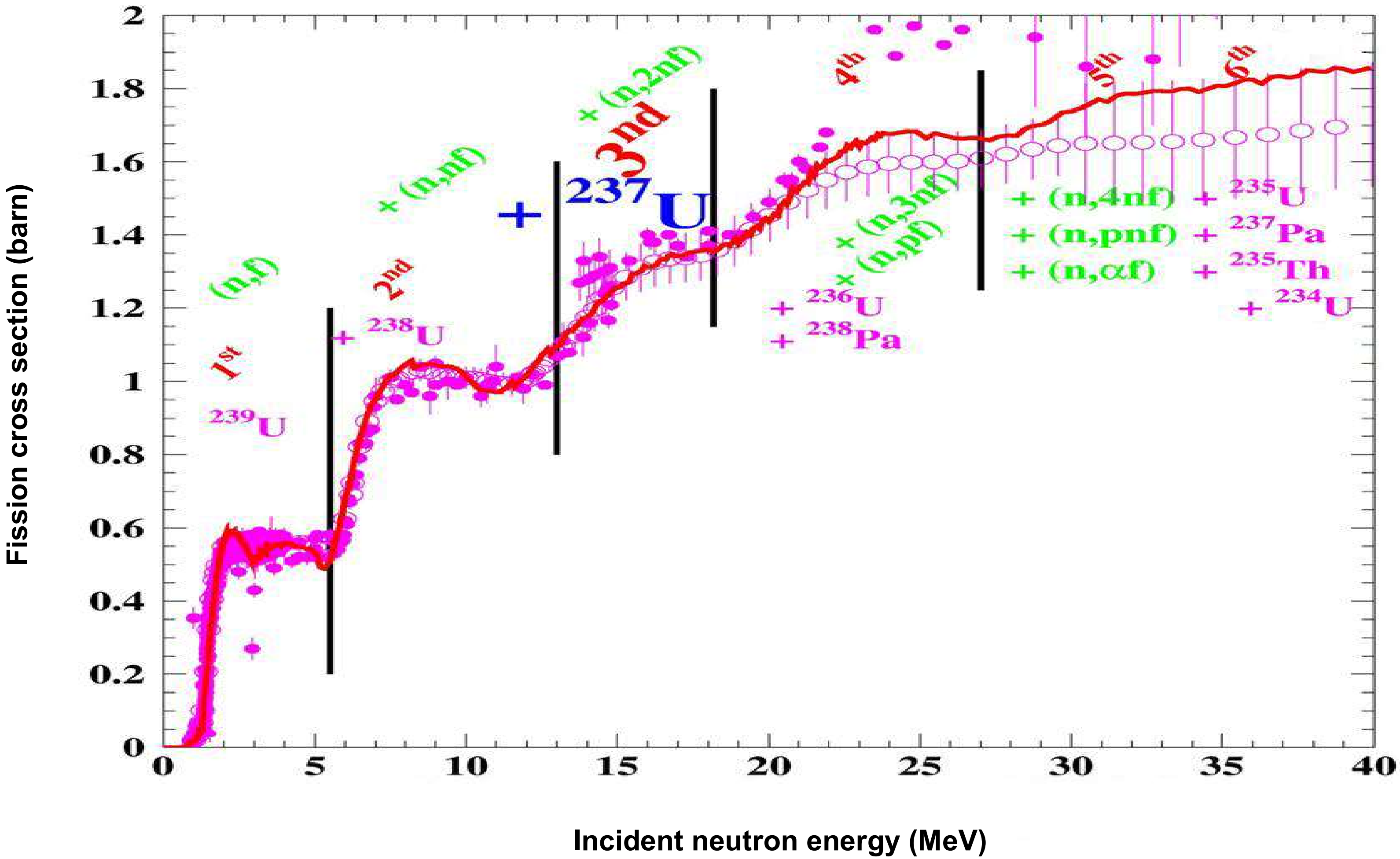


The fission process : fissile vs fertile





The fission process : fission chances



The fission process : sequence for induced fission

Describing all previously mentioned data is a real challenge for theoretical models.

Several phenomenological approaches are usually adopted to describe each type of data because of the flexibility they offer for measured nuclei.

- $\Rightarrow$ **Many models and parameters : extrapolation at your own risks !**
- $\Rightarrow$ **Clear lack of coherence or deep understanding of the underlying physics !**

3. FISSION YIELDS

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

- Conclusions

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

- Conclusions

GEF model

Details in Nucl. Data Sheets 131 (2016) 107-221
Code at www.khs-erzhausen.de/home.html

Phenomenological approach not intended to compete with fundamental microscopic approach, but aiming at producing data with the accuracy required for industrial application

⇒ many empirical laws fitted to data

GEF model

Details in Nucl. Data Sheets 131 (2016) 107-221
Code at www.khs-erzhausen.de/home.html

Phenomenological approach not intended to compete with fundamental microscopic approach, but aiming at producing data with the accuracy required for industrial application

⇒ many empirical laws fitted to data

The available measured fission barriers were used to deduce the following empirical function, which describes the difference between the inner and the outer barrier height:

$$E_A - E_B = 5.40101 - 0.00666175 \cdot Z^3/A + 1.52531 \cdot 10^{-6} \cdot (Z^3/A)^2. \quad (10)$$

GEF model

Details in Nucl. Data Sheets 131 (2016) 107-221
Code at www.khs-erzhausen.de/home.html

Phenomenological approach not intended to compete with fundamental microscopic approach, but aiming at producing data with the accuracy required for industrial application

⇒ many empirical laws fitted to data
⇒ range of application restricted close to experimentally accessible regions

GEF model

Details i
Code at

Phenomen
microscopi
the accurac

⇒ many er
⇒ range of

According to the concept of the GEF model, the range of validity is not strictly defined. Technically, the code runs for any heavy nucleus. However, the results of the model are more reliable for nuclei which are not too far from the region where experimental data exist. It is recommended not to use the code outside the range depicted in figure 1 on the chart of the nuclides.

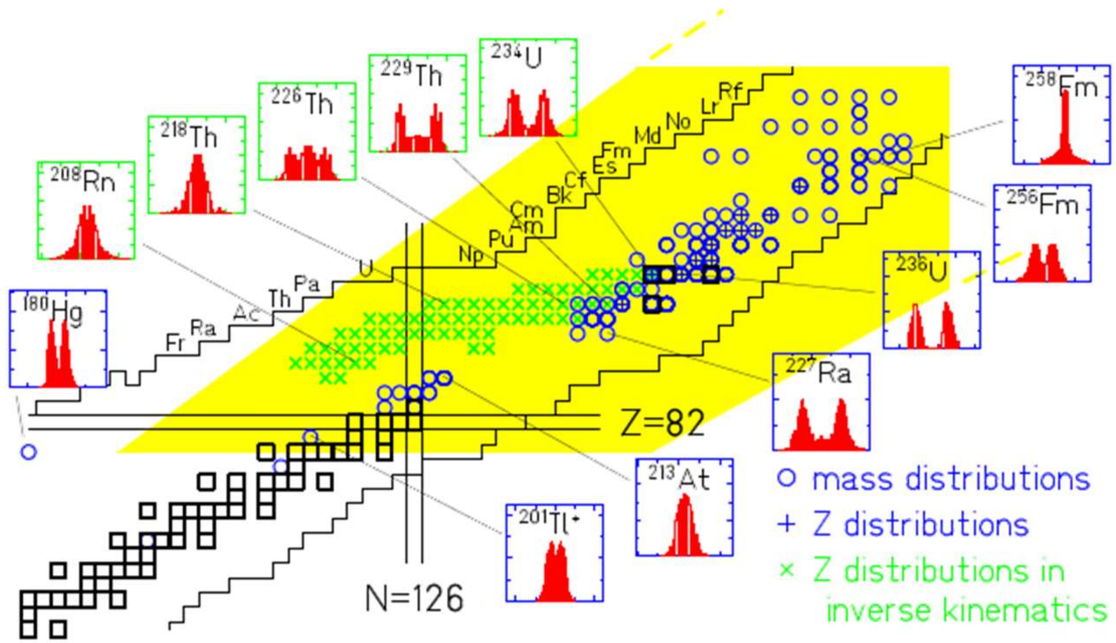


Figure 1: Validity range of the GEF model on a chart of the nuclides, marked in yellow. For a detailed description of the figure see figure 6.

GEF model

Details i
Code at

Phenomeno
microscopi
the accura

⇒ **many er**
⇒ **range of**

According to the concept of the GEF model, the range of validity is not strictly defined. Technically, the code runs for any heavy nucleus. However, the results of the model are more reliable for nuclei which are not too far from the region where experimental data exist. It is recommended not to use the code outside the range depicted in figure 1 on the chart of the nuclides.

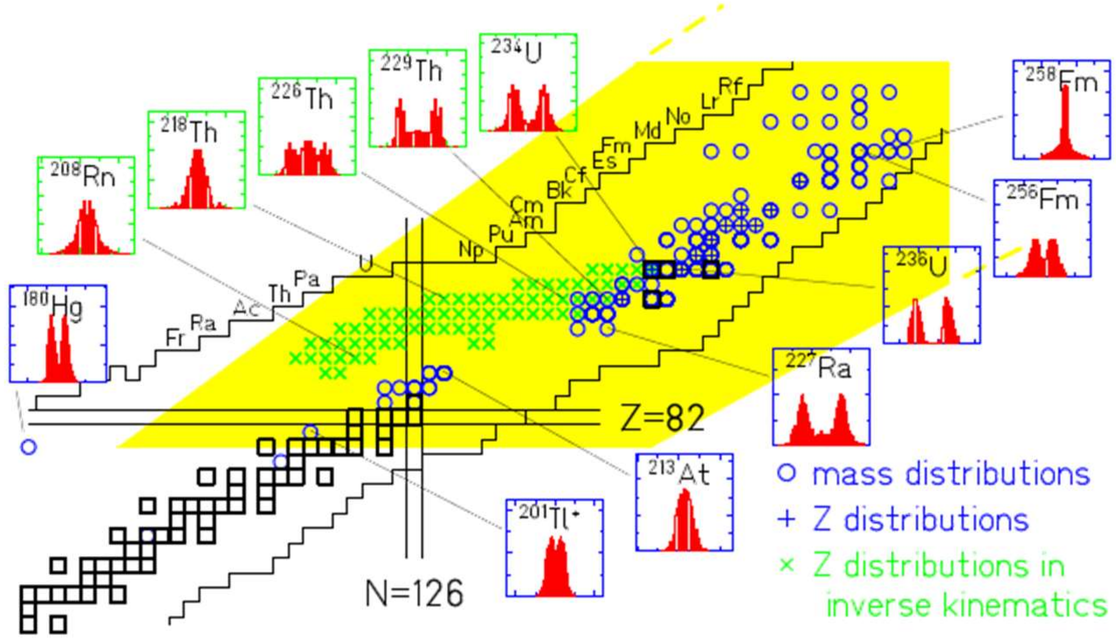
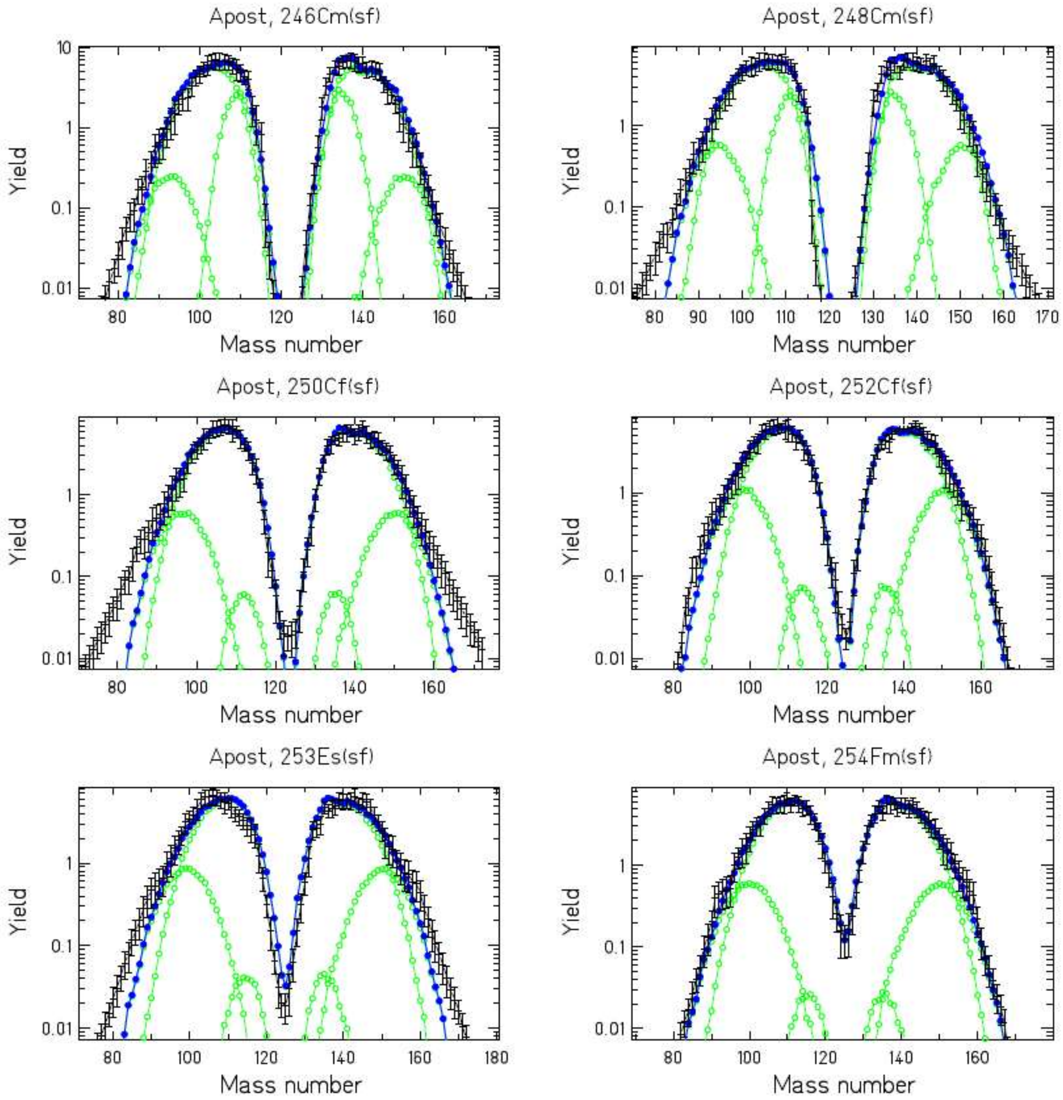


Figure 1: Validity range of the GEF model on a chart of the nuclides, marked in yellow. For a detailed description of the figure see figure 6.

The fission process : GEF results

The fis

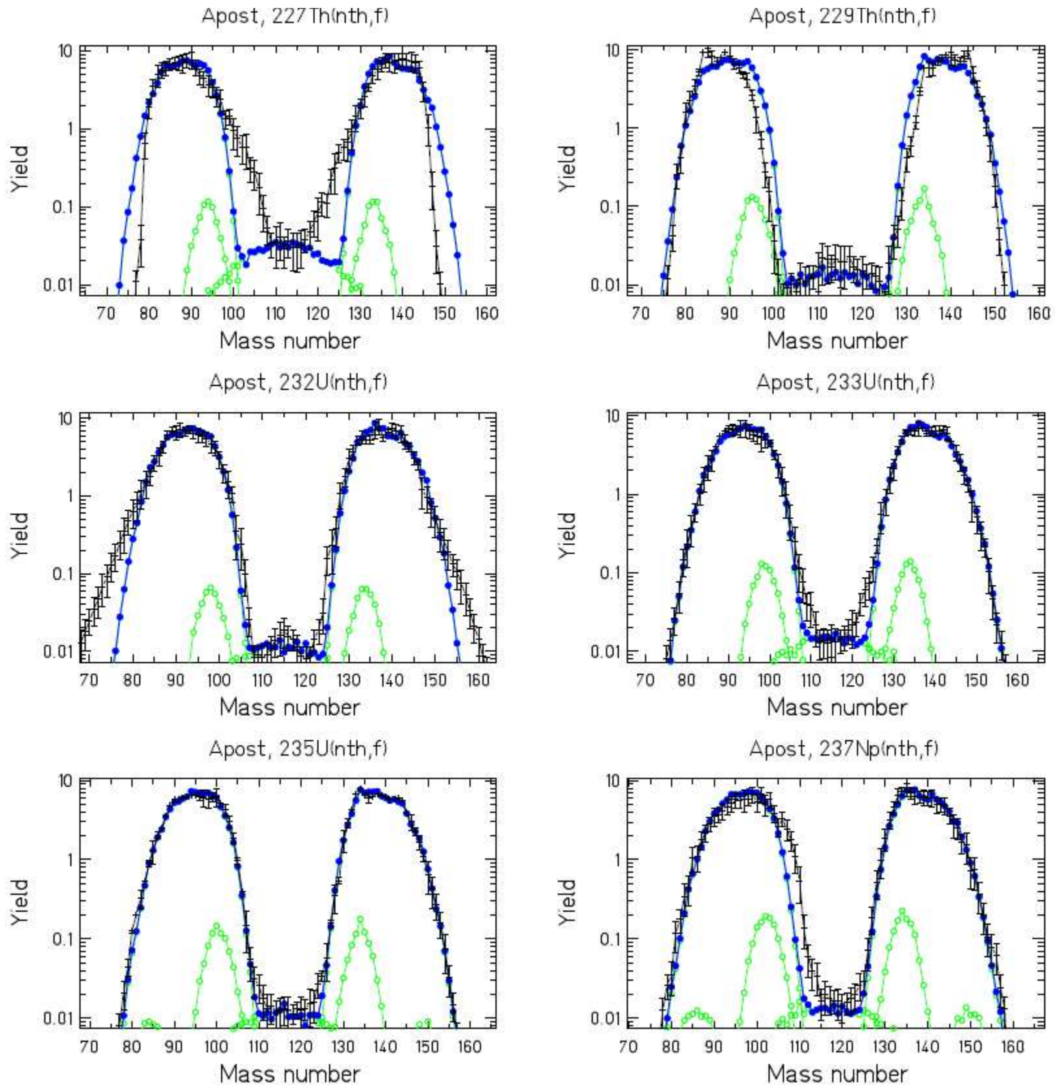
Spontaneous fission



The fission process : GEF results

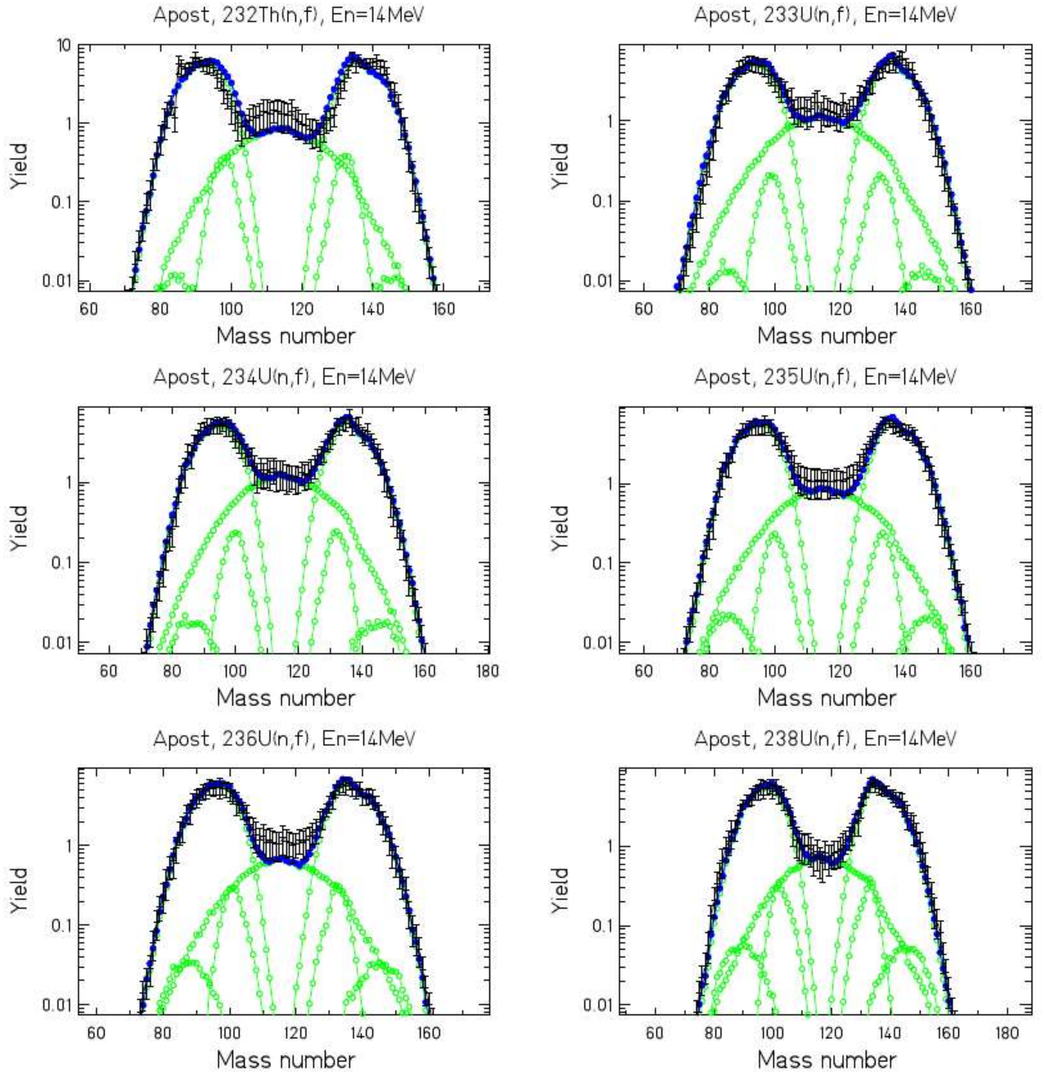
The fiss

thermal neutrons induced fission



The fissi

fast neutrons induced fission



SPY model

Details in Phys. Rev. C92 (2015) 034617 & Phys. Rev. C99 (2019)

Approach based on absolute energy balance based on HFB potential energy surfaces as function of axial deformation
⇒ Available energy at scission

Available energy (AE) shared between fragments : x (AE) and (1-x) (AE)

$$\pi(Z_1,N_1,Z_2,N_2,\tilde{q}_1,\tilde{q}_2,x)=\rho_1(x|AE|)\rho_2((1-x)|AE|)\delta E^2$$

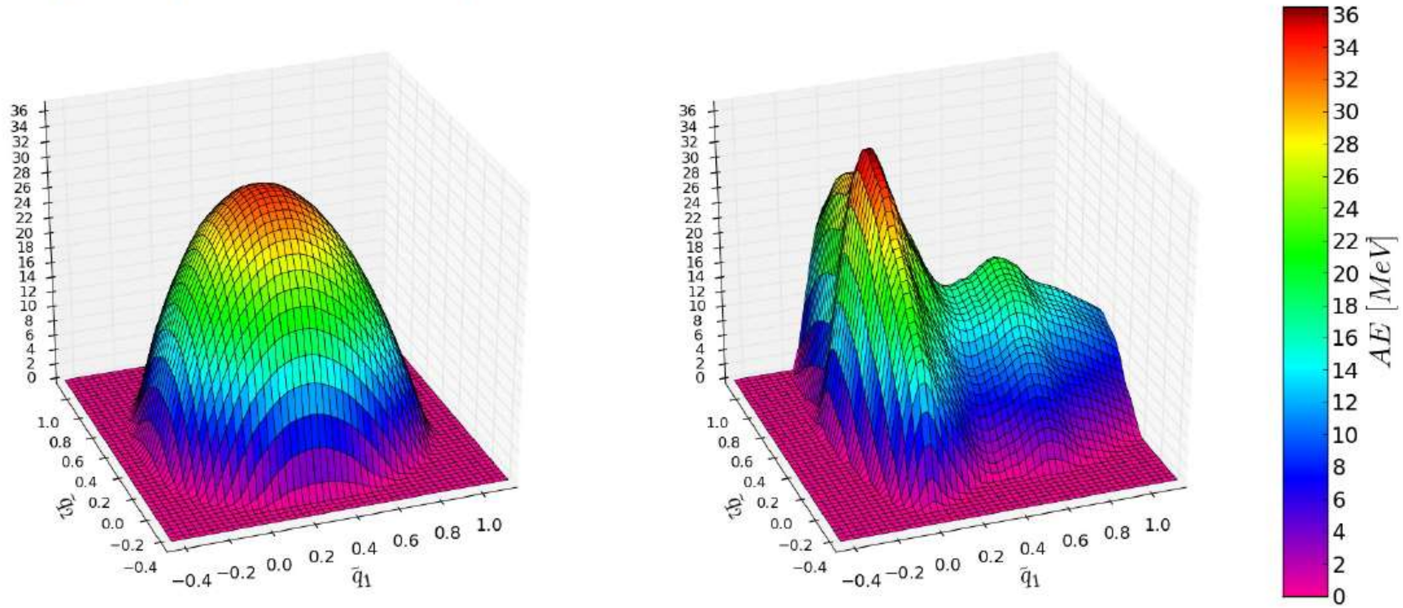
$$\Pi(Z_1,N_1,Z_2,N_2,\tilde{q}_1,\tilde{q}_2)=\int_0^1 \pi(Z_1,N_1,Z_2,N_2,\tilde{q}_1,\tilde{q}_2,x)dx$$

$$P(Z_1,N_1,Z_2,N_2)=\iint \Pi(Z_1,N_1,Z_2,N_2,\beta_1,\beta_2)d\tilde{q}_1 d\tilde{q}_2$$

SPY : available energy

Individual energy ($^{132}Sn+^{104}Mo$)

liquid drop model (macroscopic) *Amedee* data base : HFB+Gogny (microscopic)

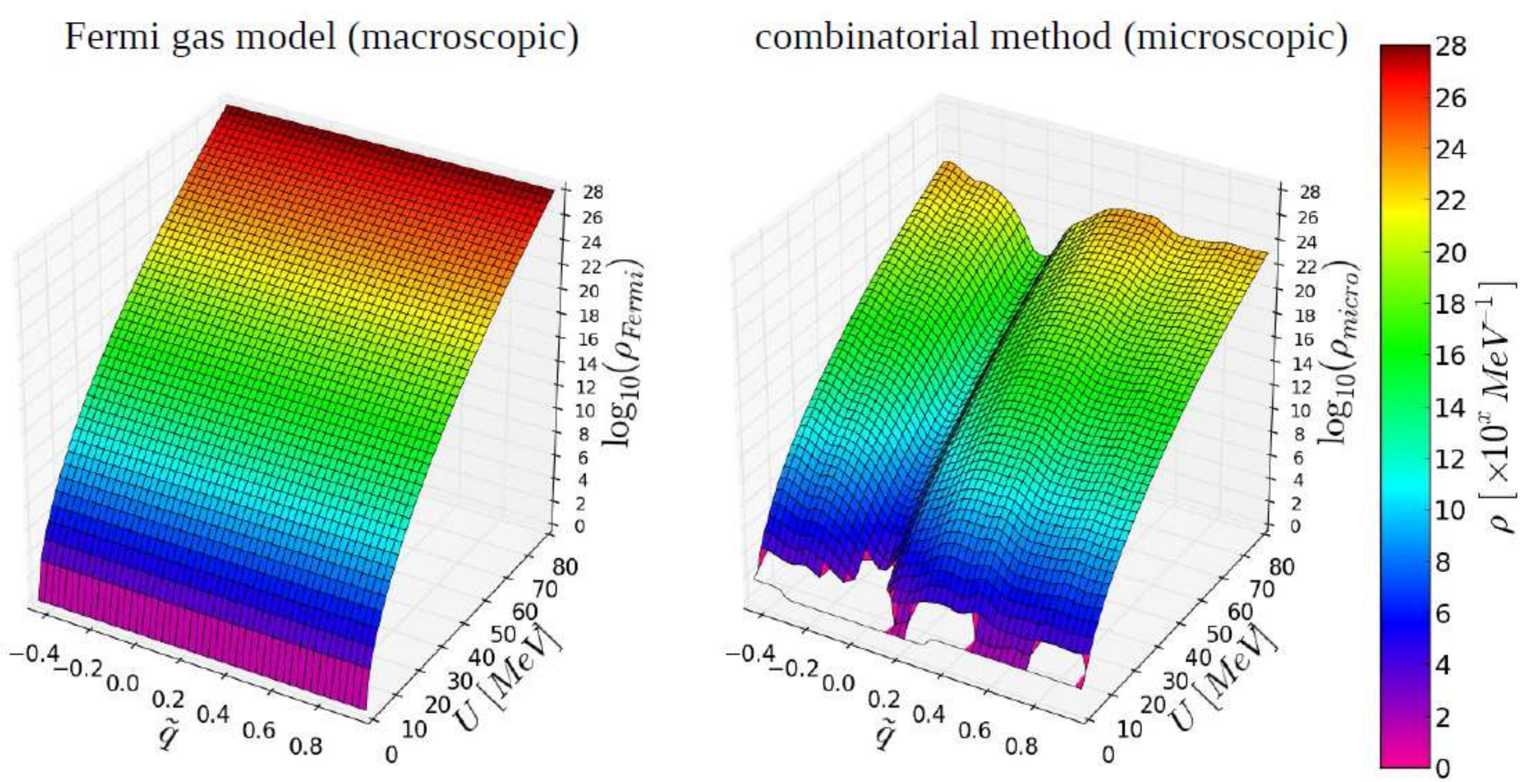


Courtesy J.F. Lemaitre

$$AE = \left| E_{ind1} + E_{ind2} + E_{coul} + E_{nucl} - E_{CN} \right|$$

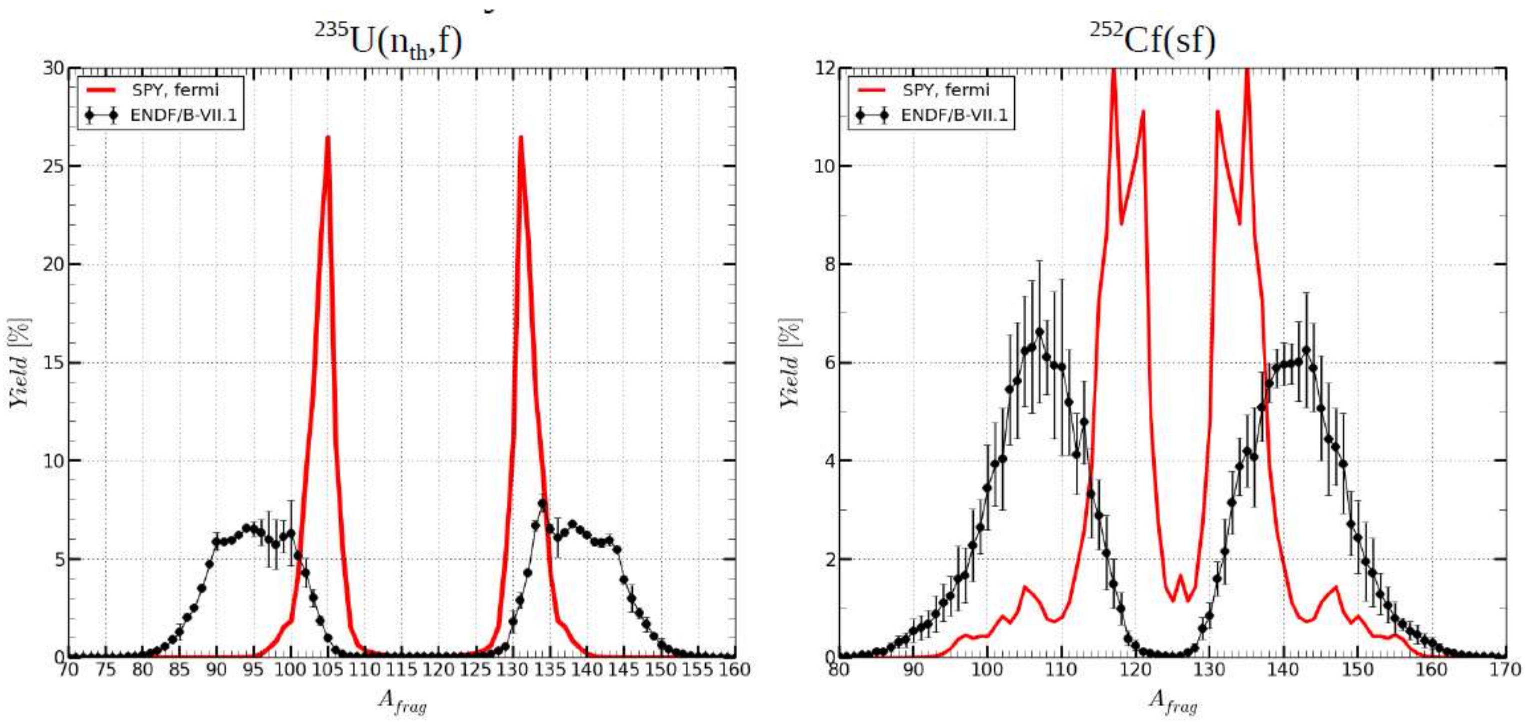
The fission process : energy sharing & level densities

State density of ^{132}Sn ; $\rho \propto e^{2\sqrt{aU}}$



Courtesy J.F. Lemaitre

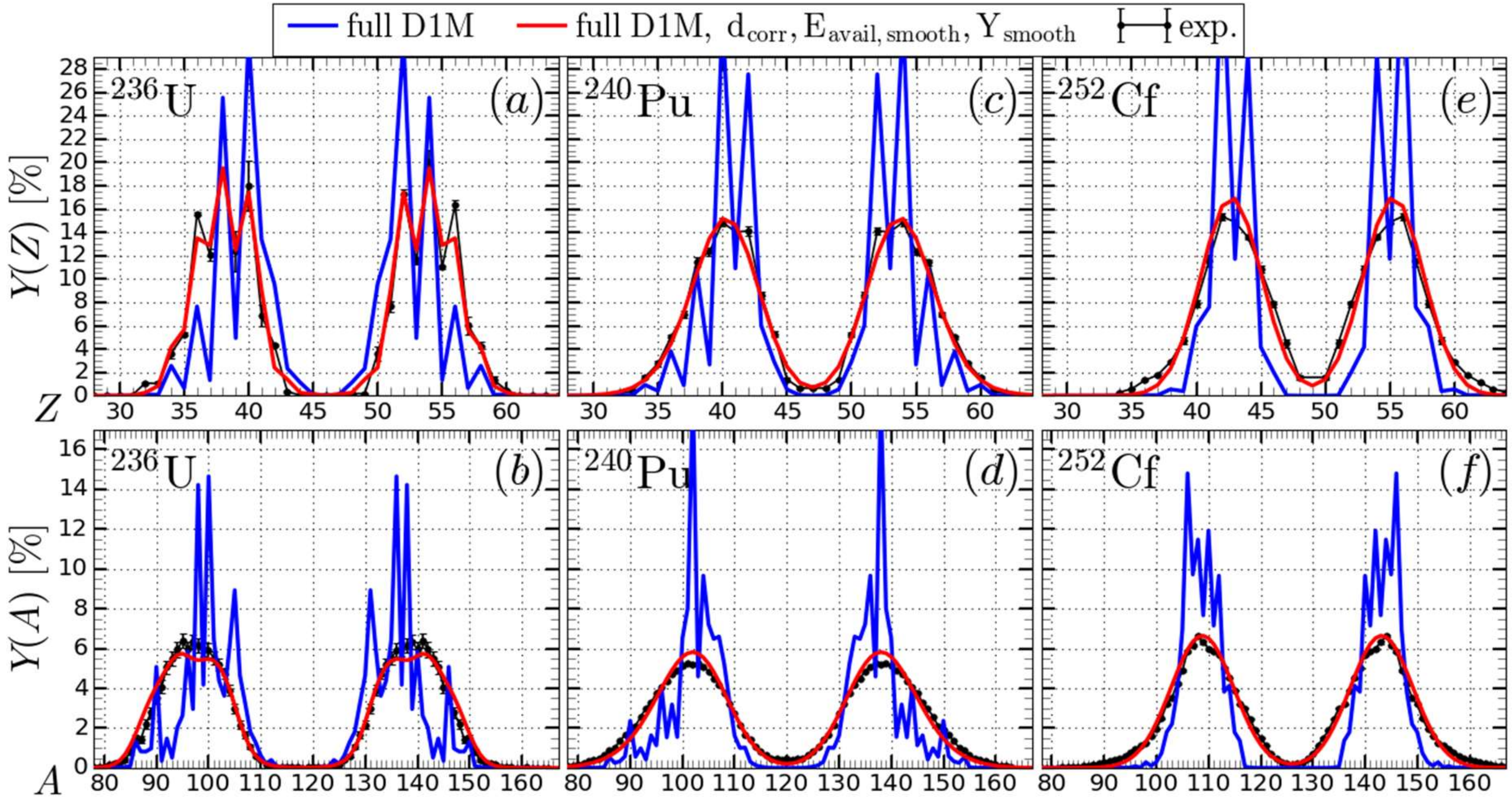
SPY model : raw results



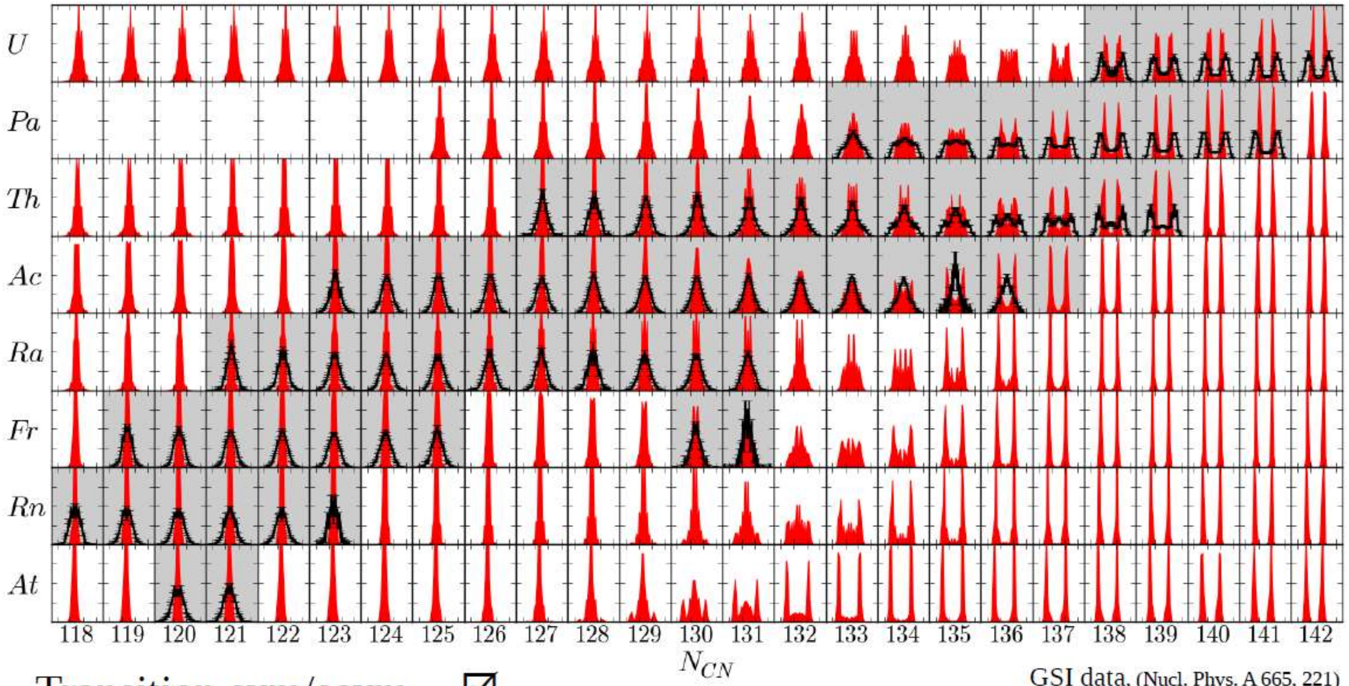
$\Rightarrow$ **Less accurate than GEF (only one parameter fixed !)**

SPY model : raw results

⇒ **Can be improved with smoothing methods (much more parameters)**



SPY model : systematic predictions rather easy



GSI data, (Nucl. Phys. A 665, 221)
SPY model

Transition sym/asym ☑

Good tendancy, with shift of sym/asym transition of few charges

Peak width ☒

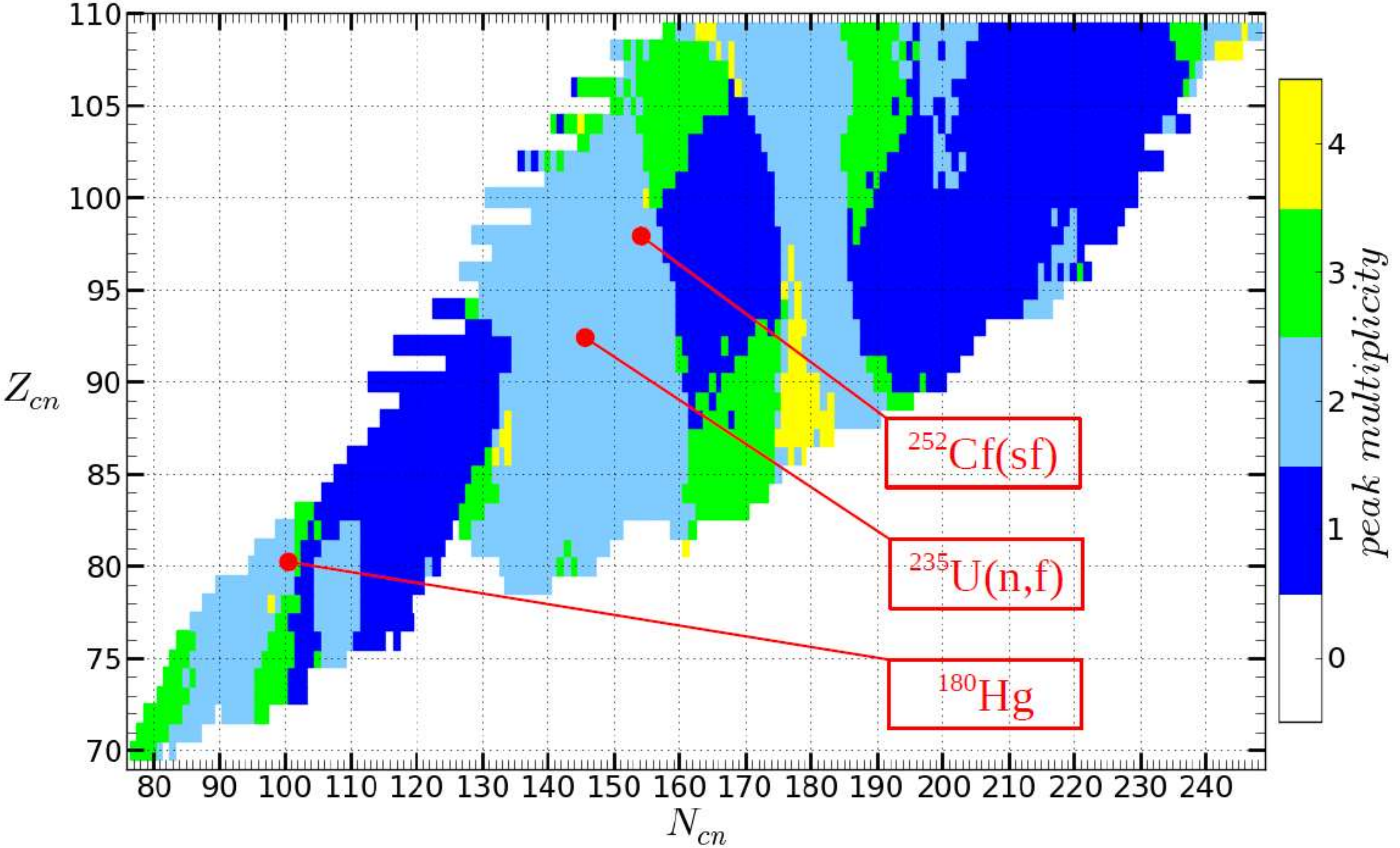
Too narrow due to strong influence of nuclear structure

21

Courtesy J.F. Lemaitre

⇒ **Rather good qualitative description**

SPY model : systematic predictions rather easy



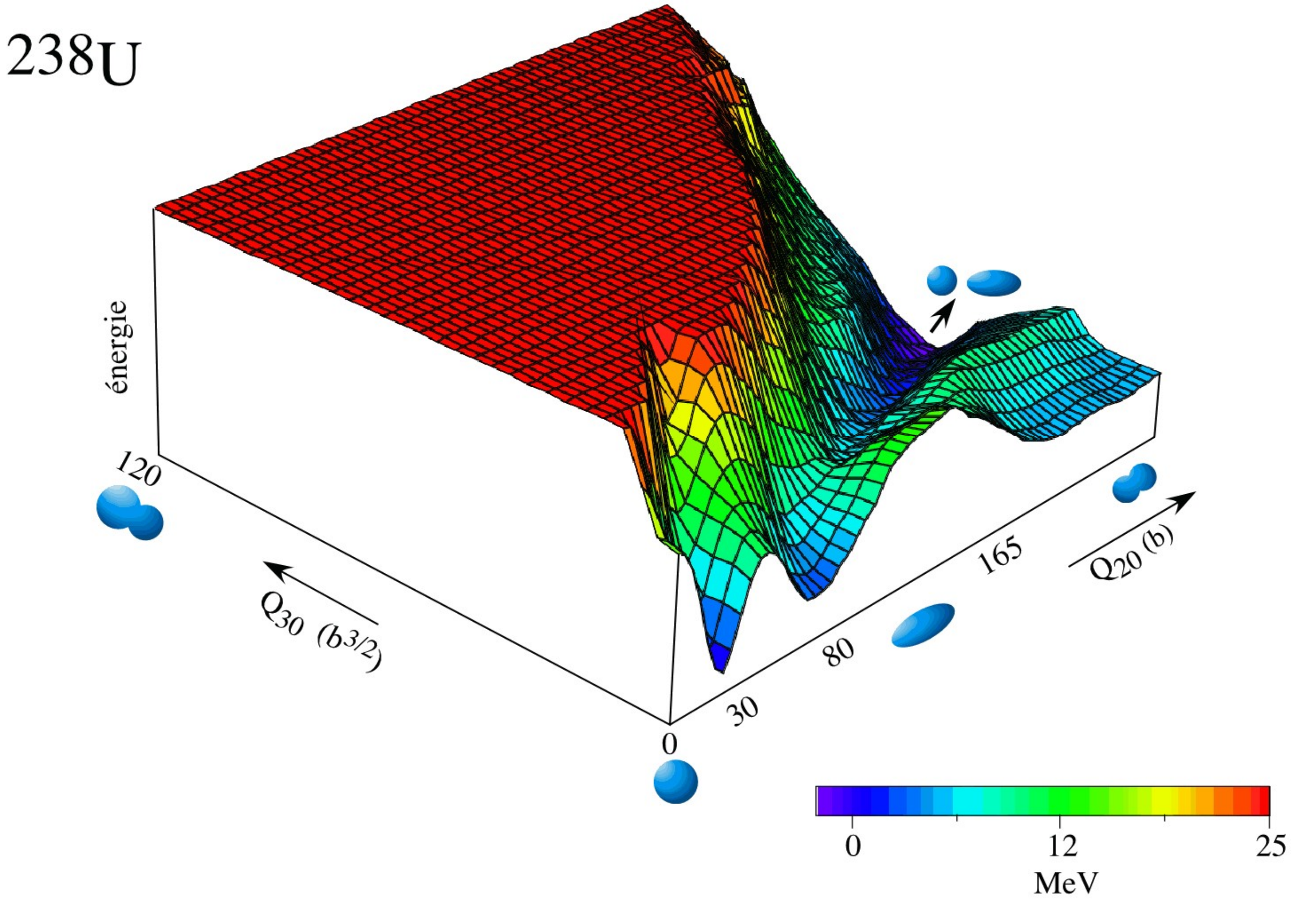
Courtesy J.F. Lemaitre

Based on microscopic grounds **⇒ predictive power even far from stability**

⇒ region with 4 peaks predicted !

Microscopic approach

1) PES calculation as function of elongation-asymmetry



Microscopic approach

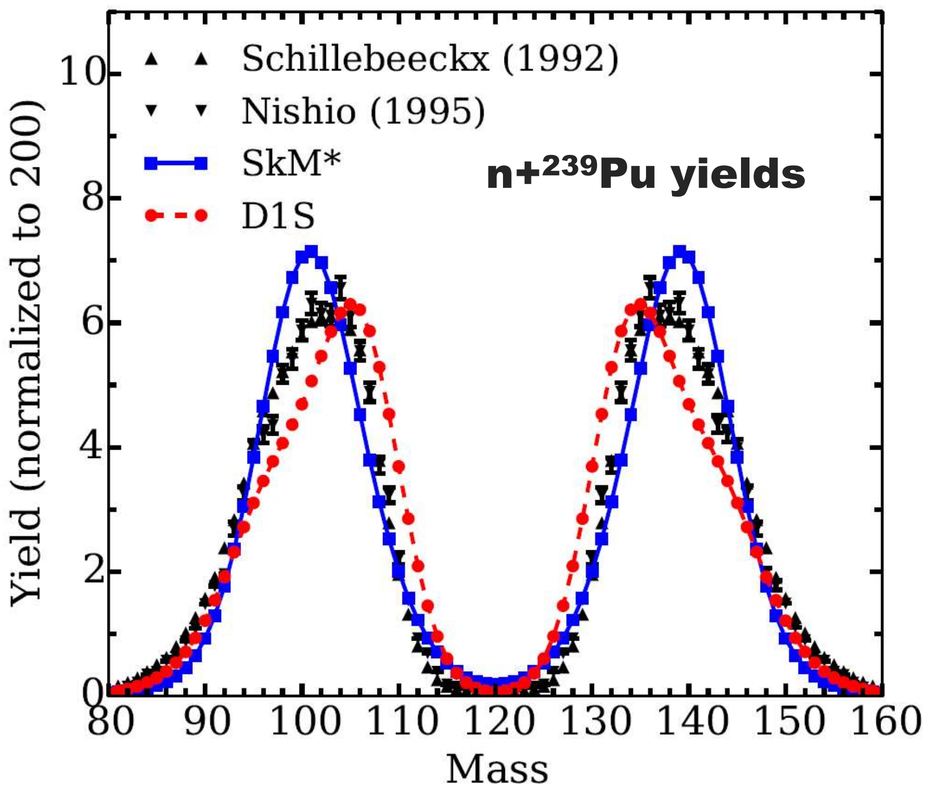
1) **PES calculation as function of elongation-asymmetry**
2) **Quantum mechanical Wave packet propagation in the computed PES (FELIX code)**

Microscopic approach

1) **PES calculation as function of elongation-asymmetry**
2) **Quantum mechanical Wave packet propagation in the computed PES (FELIX code)**

Microscopic approach

1) PES calculation as function of elongation-asymmetry
2) Quantum mechanical Wave packet propagation in the computed PES (FELIX code)
3) Extraction of the flux through a scission line (whose definition is not trivial)



⇒ Not accurate enough for applications
⇒ Time consuming (10000 h per nucleus on single CPU)
⇒ Extrapolations and systematics manageable with HPC
⇒ Limited to even-even

3. Neutrons and gammas from fission

Fission reactions

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

- Conclusions

Fission reactions

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

- Conclusions

Madland-Nix model : PFNS

Details in Nucl. Sci. Eng. 81 (1982) 213.

- Fission yields reduced to a light and a heavy fragment whose temperatures are distributed according to a triangular law

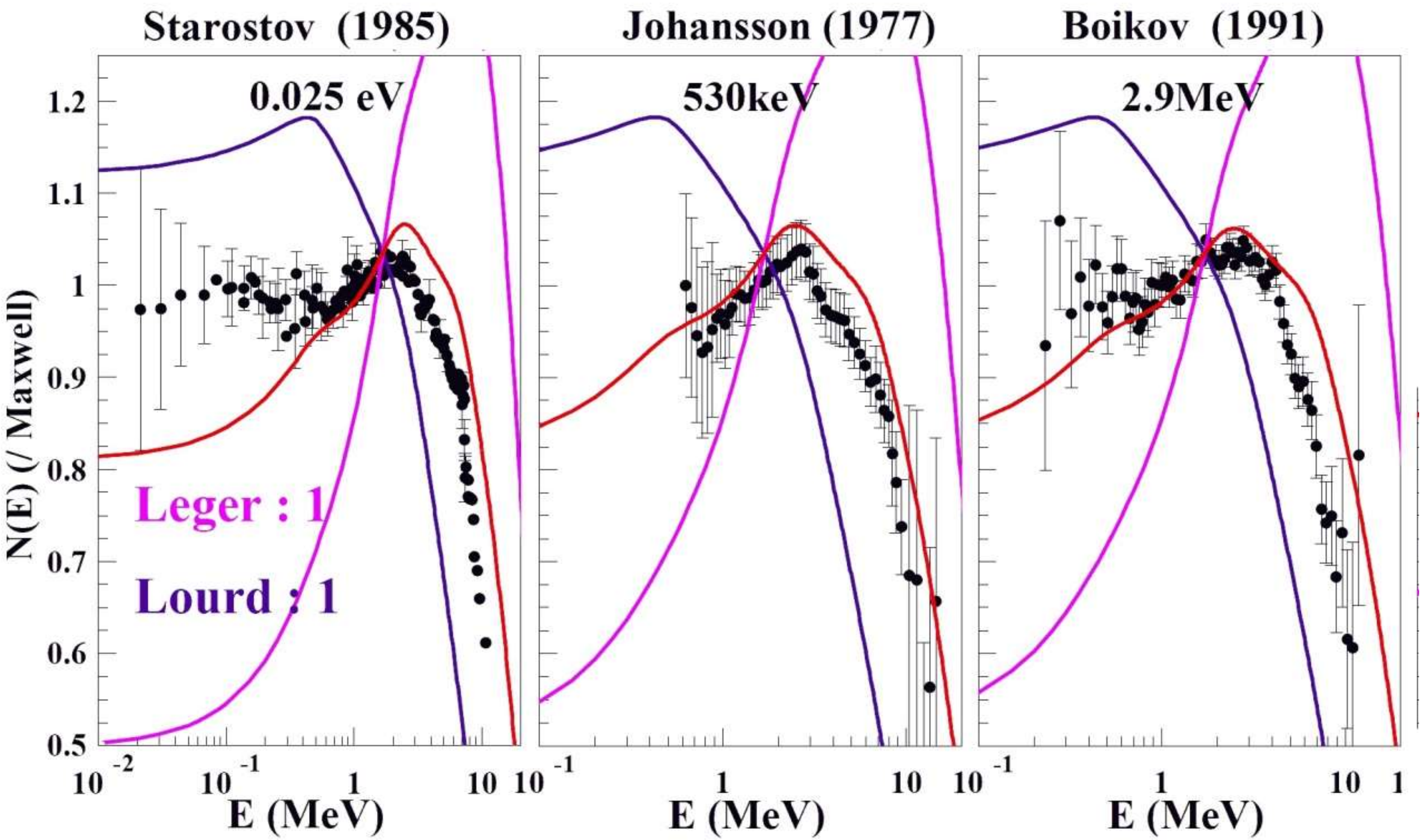
- For each temperature, each fragment neutron emission is modeled by the corresponding Weisskopf spectrum normalized by the fragment formation cross section by induced neutron reaction

- Multiple fission chances accounted for using fission cross sections

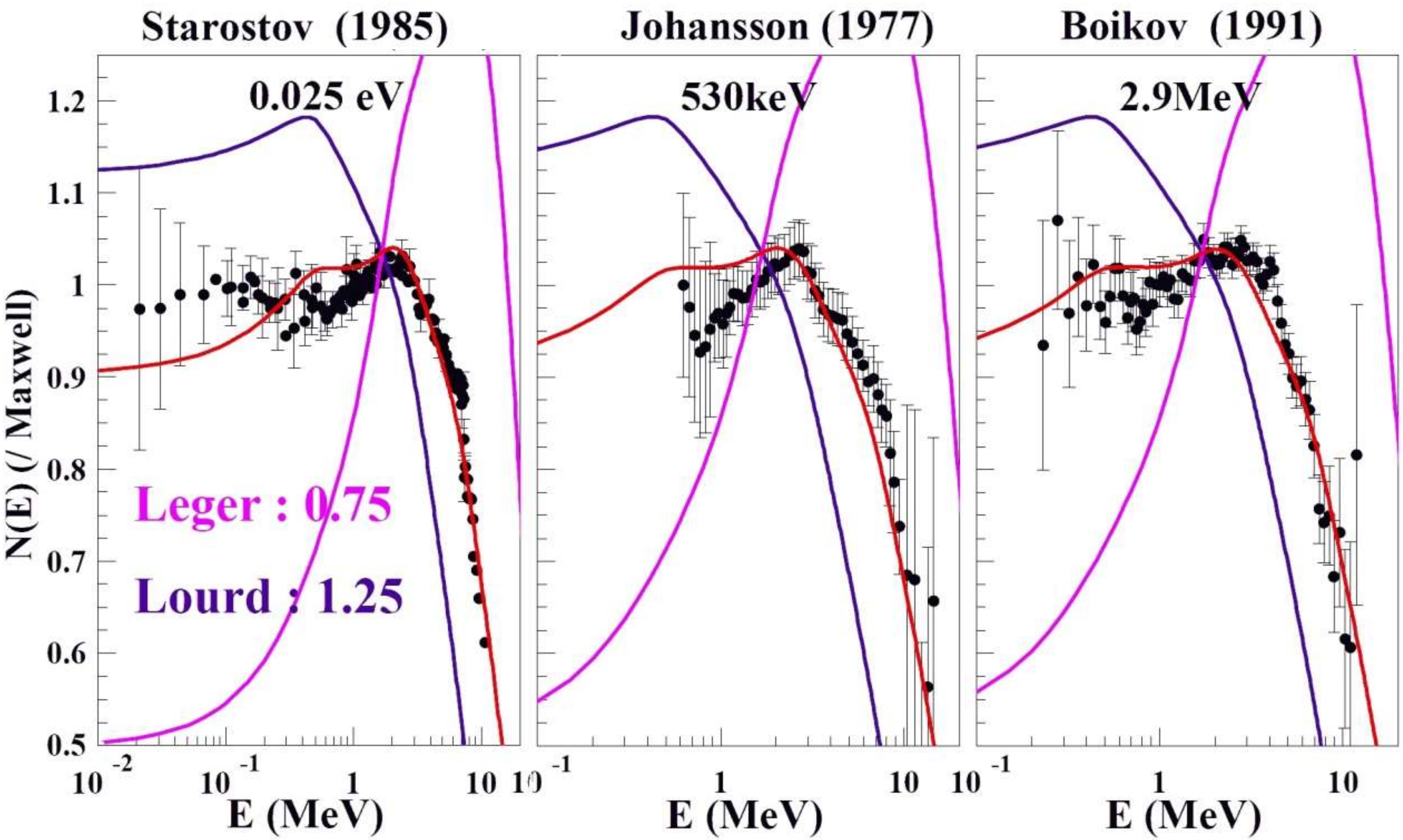
- Final neutron spectrum defined by an average of light and heavy fragment spectra

⇒ model with parameters designed to fit data

Madland-Nix model : PFNS



Madland-Nix model : PFNS



Madland-Nix model : PFNS

mean gamma energy parameterized (several options)

⇒ model with parameters designed to fit data

Madland-Nix model : PFNS

mean gamma energy parameterized (several options)

$$\overline{\nu_{p\,i}} = \frac{< E_i^* > - < E_\gamma^{tot}\,i >}{< S_{n\,i} > + < \epsilon_i >}$$

$\langle E_\gamma^{tot} \rangle$ mean prompt gamma energy

$\langle S_n \rangle$ mean neutron binding energy

$\langle \epsilon \rangle$ mean emitted neutron energy

⇒ model with parameters designed to fit data

Madland-Nix model : PFNS

mean gamma energy parameterized (several options)

$$\overline{\nu_{p\,i}} = \frac{< E_i^* > - < E_\gamma^{tot}\, i >}{< S_{n\,i} > + < \epsilon_i >}$$

$\langle E_\gamma^{tot} \rangle$ mean prompt gamma energy

$\langle S_n \rangle$ mean neutron binding energy

$\langle \epsilon \rangle$ mean emitted neutron energy

$$\overline{\nu}_p = \sum_{i=1}^{N} \frac{\sigma_{f\,i}}{\sigma_f} (i - 1 + \overline{\nu}_{p\,i})$$

$\sigma_{f\,i}$: i^{th} fission chance cross section.

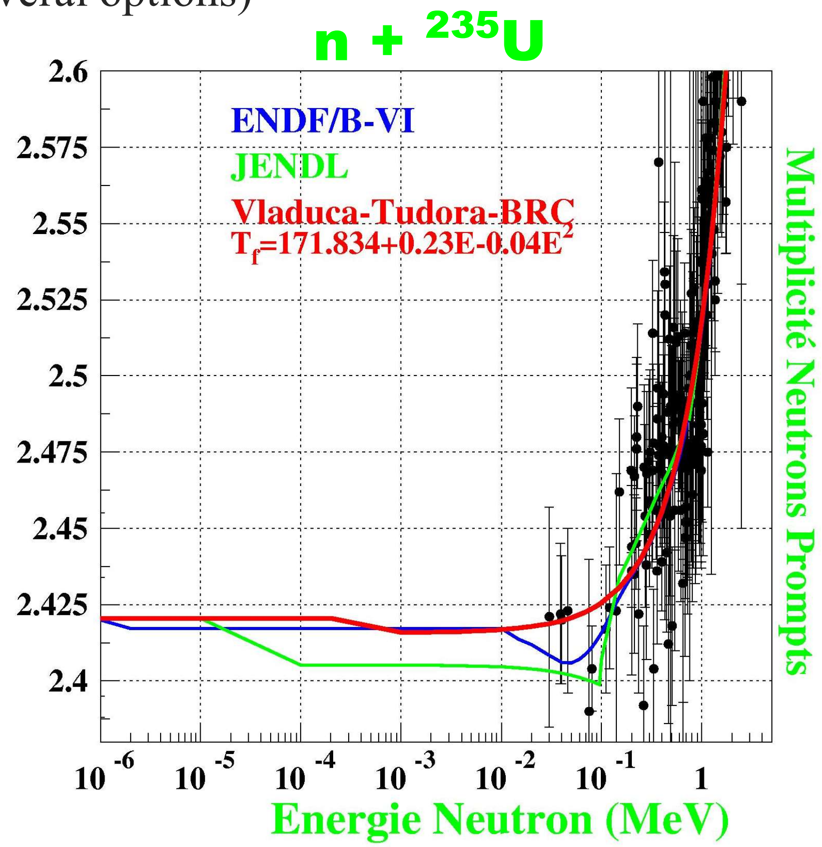
⇒ model with parameters designed to fit data

Madland-Nix model : PFNS

mean gamma energy parameterized (several options)

$$\overline{\nu}_{p\,i} = \frac{< E_i^* > - < E_\gamma^{tot}\, i >}{< S_{n\,i} > + < \epsilon_i >}$$

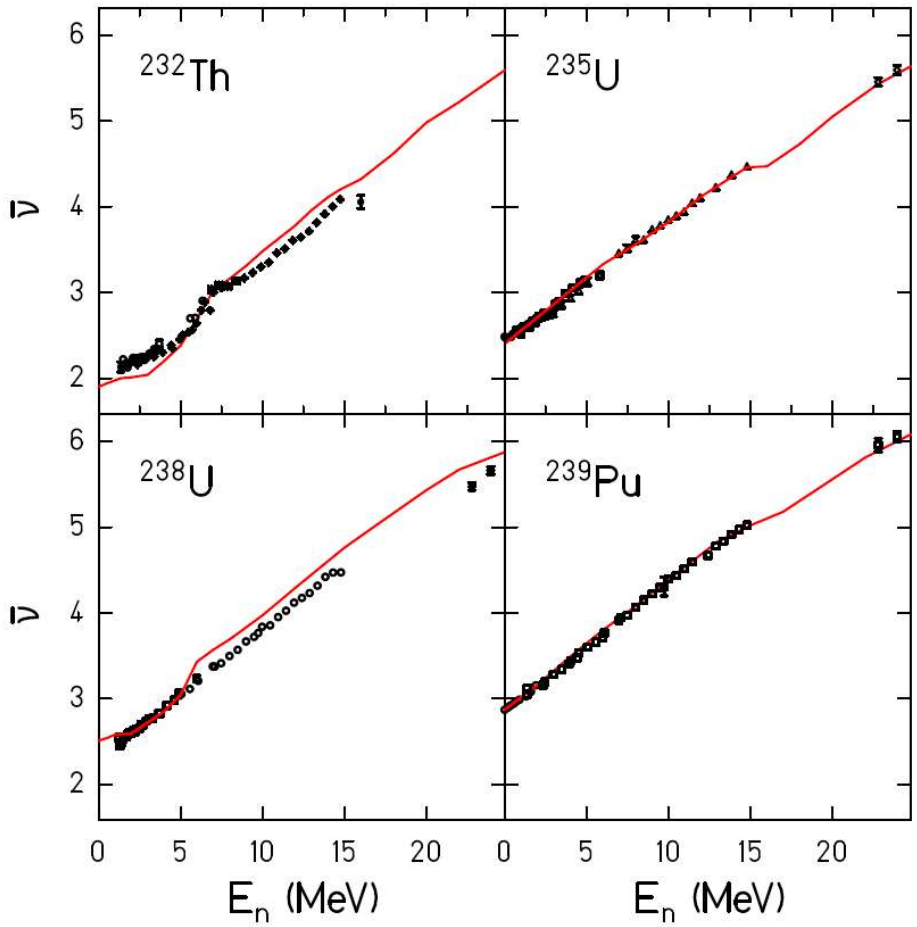
$$\overline{\nu}_p = \sum_{i=1}^{N} \frac{\sigma_{f\,i}}{\sigma_f} (i - 1 + \overline{\nu}_{p\,i})$$



⇒ **model with parameters designed to fit data**

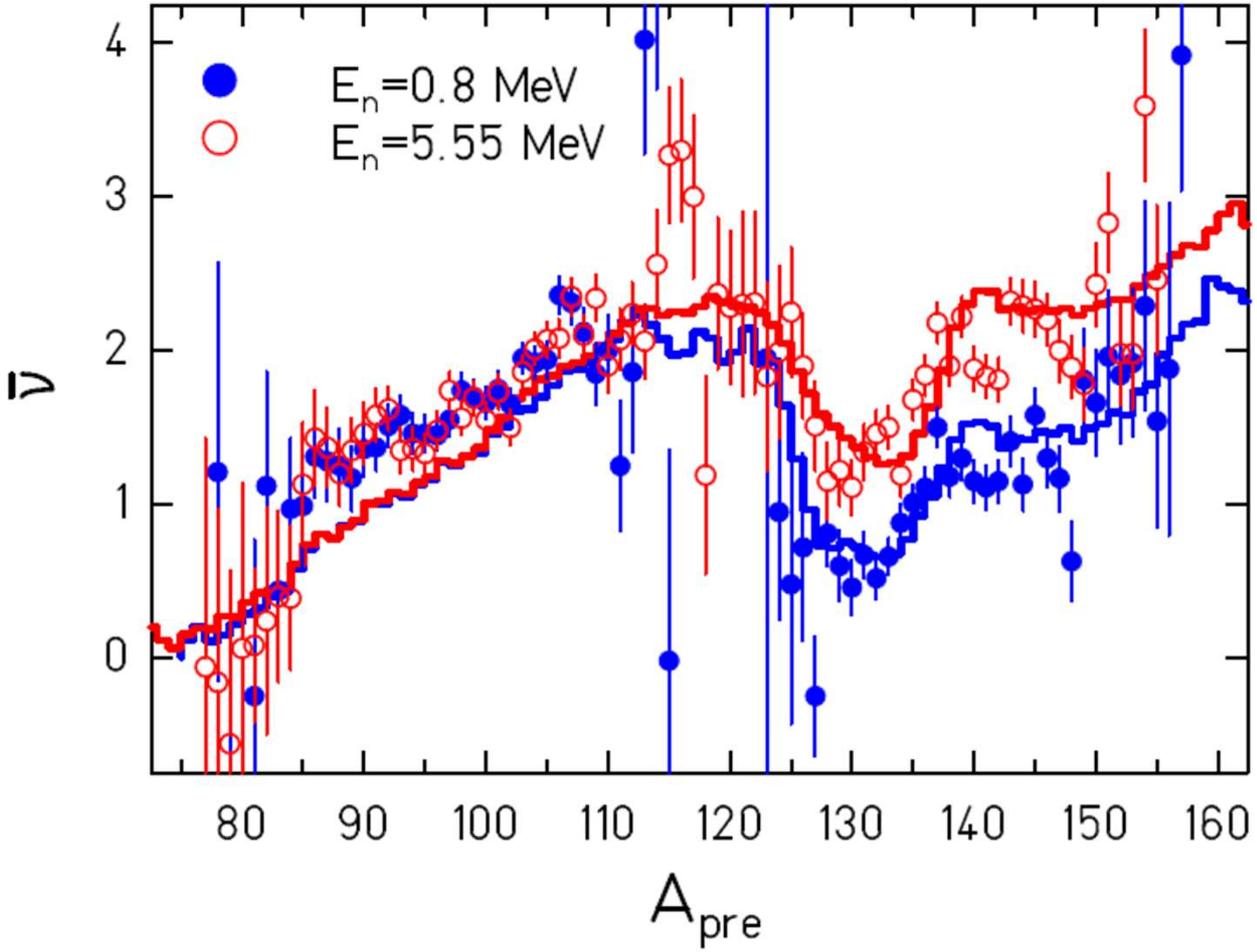
GEF model : neutron multiplicities

Details in Nucl. Data Sheets 131 (2016) 107-221
Code at www.khs-erzhausen.de/home.html



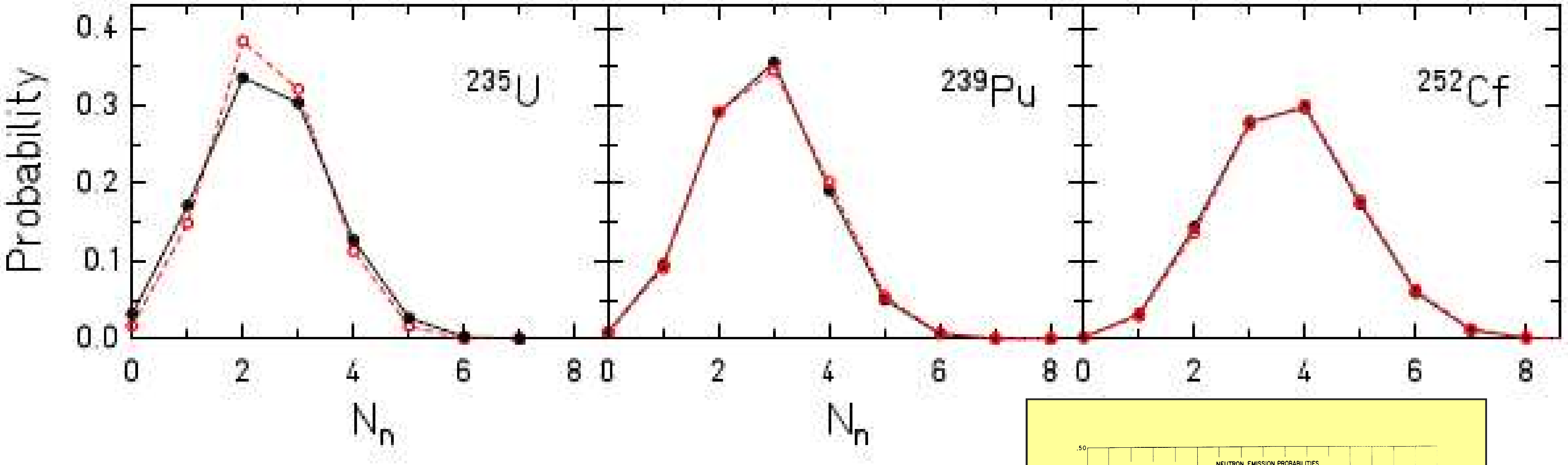
GEF model

Details in Nucl. Data Sheets 131 (2016) 107-221
Code at www.khs-erzhausen.de/home.html

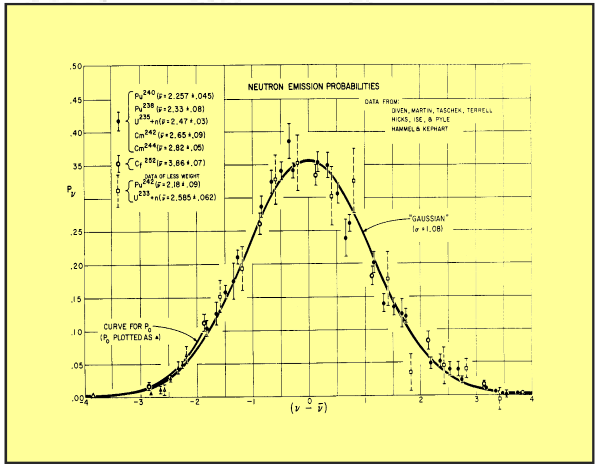


GEF model : neutron multiplicities distributions

Details in Nucl. Data Sheets 131 (2016) 107-221
Code at www.khs-erzhausen.de/home.html

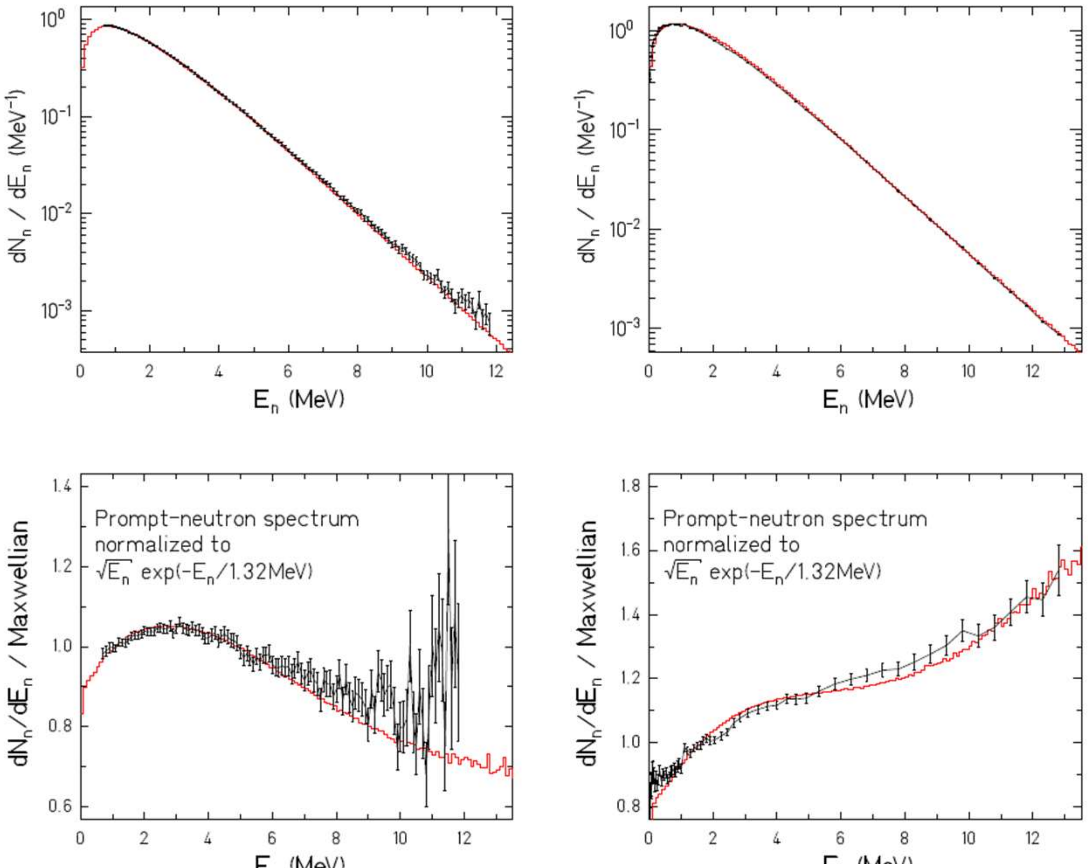


Derivative of a Gaussian
(remember slide 18)

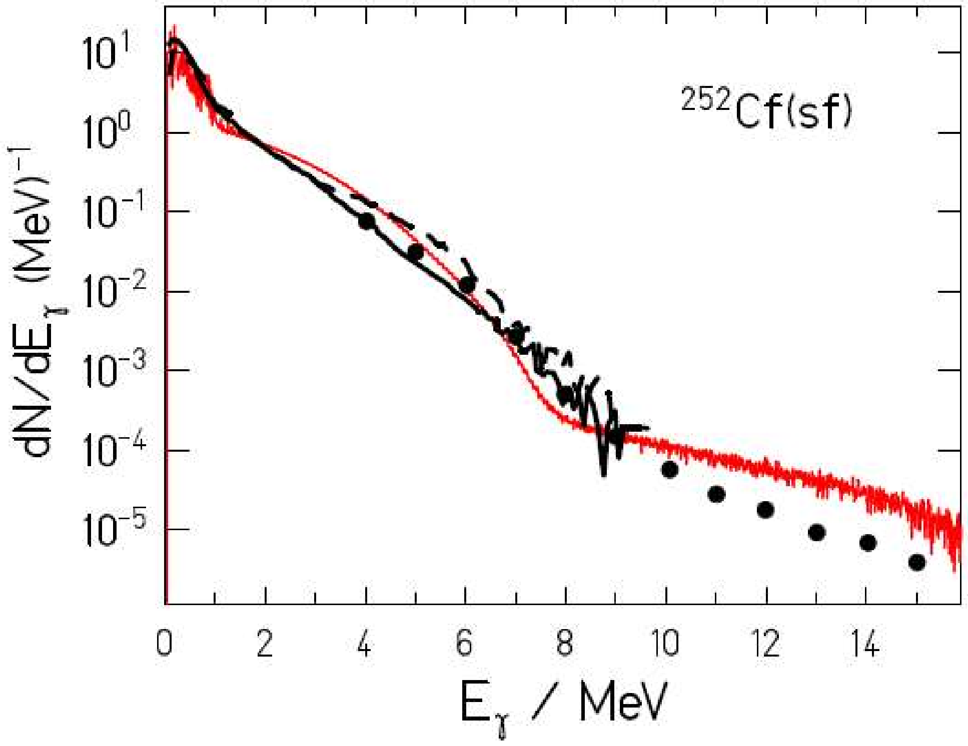


GEF model : neutron and gamma spectra

PFNS



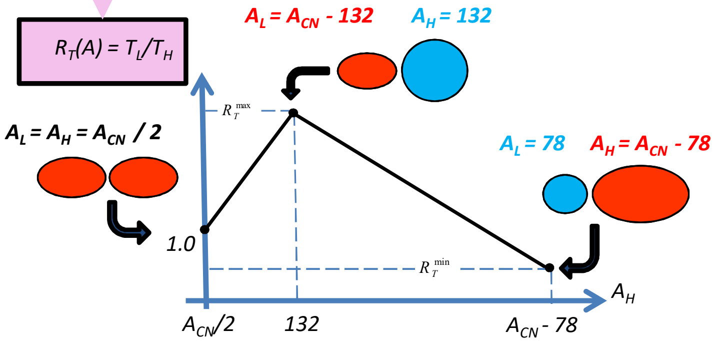
PFGS

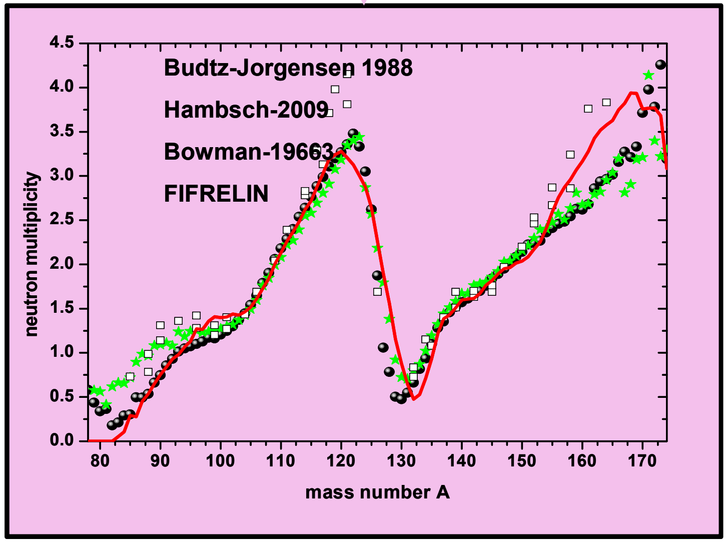


⇒ **GEF very efficient to fit data and fill the gaps for applications**

Monte Carlo approach designed to deal with fission fragment decay

⇒ fragment's mass sampled from exp. or theory (GEF)
⇒ fragment's kinetic energy sampled from exp. or theory
⇒ fragment's charge sampled from Wahl model ($Z=Z_{CN}/A_{CN} * A$)
⇒ fragment's spin distribution sampled from level density law
⇒ excitation energy sharing following temperature ratio law adjusted on saw tooth





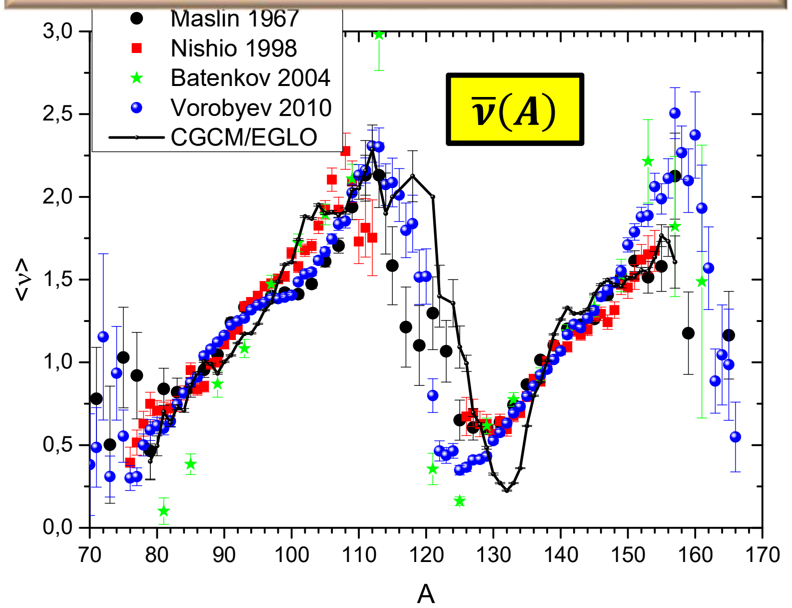
Details in Phys. Rev. C 82 (2010) 054616.

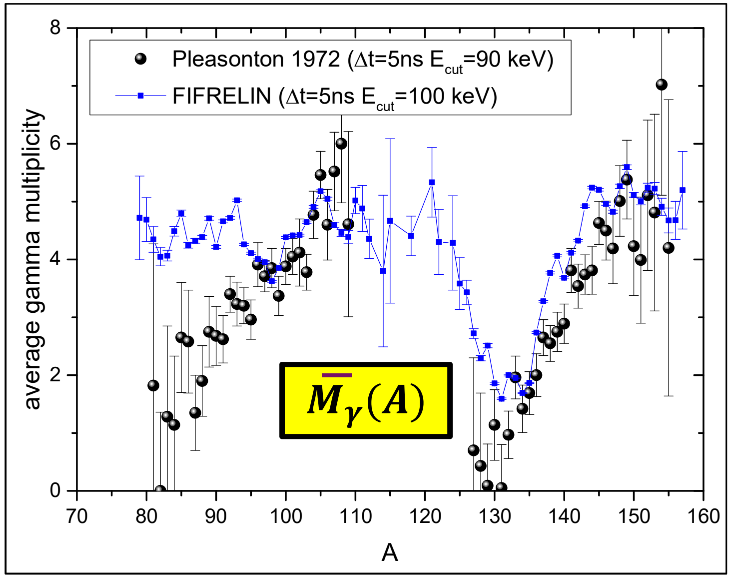
FIFRELIN : neutron multiplicities

Average prompt neutron multiplicity as a function of pre-neutron fragment mass

$^{235}U(n_{th},f)$

Average prompt gamma multiplicity as a function of pre-neutron fragment mass





Neutron average quantities

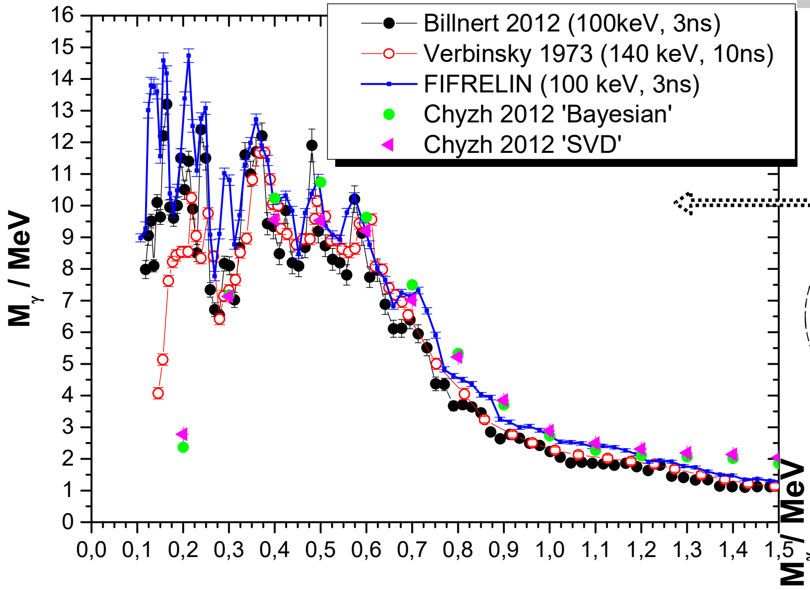
	$<\nu_L>$	$<\nu_H>$	$<\nu>$
Nishio 2004	**1.42**	**1.01**	**2.43 ± 0.03**
FIFRELIN	**1.41 ±** ***0.001***	**1.02±** ***0.001***	**2.43 ±** ***0.001***

Gamma average quantities

	Threshold	ΔT	$<M_\gamma>$ (γ/f)	$<E_\gamma^{tot}>$ (MeV)	$<\varepsilon_\gamma>$ (MeV)
Oberstedt 2013	**100 keV**	**5 ns**	**8.19 ± 0.11**	**6.92 ± 0.09**	**0.85 ± 0.02**
FIFRELIN	**100 keV**	**5 ns**	**8.04 ± 0.01**	**7.02 ± 0.01**	**0.875 ± 0.001**

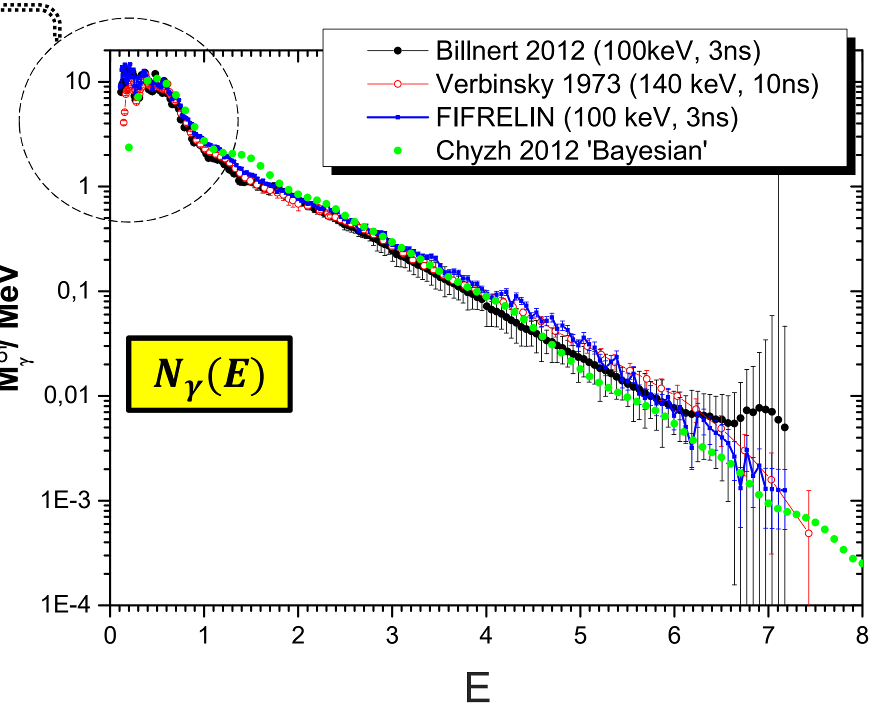
Courtesy O. Litaize

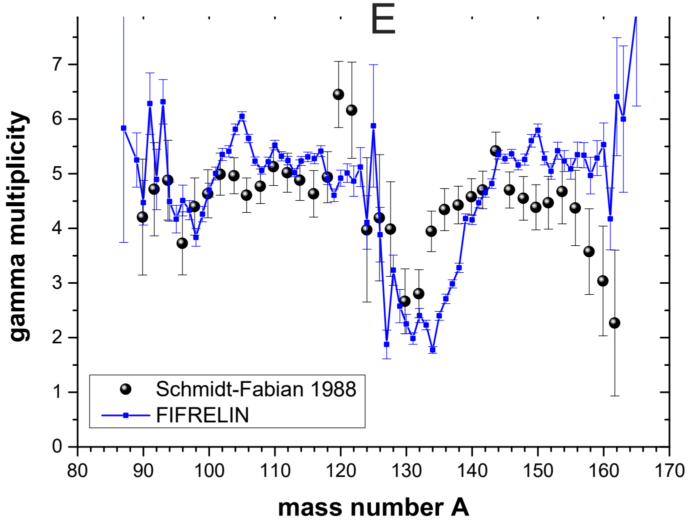
FIFRELIN : PFGS and spontaneous fission



Prompt fission gamma spectrum

^{252}Cf (sf)

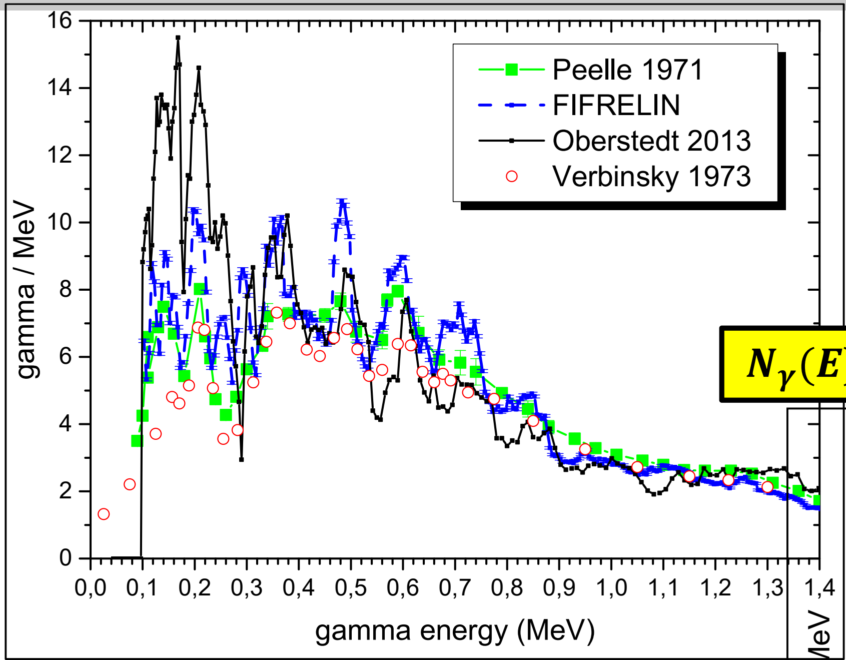




Average prompt gamma multiplicity as a function of pre-neutron mass

Courtesy O. Litaize

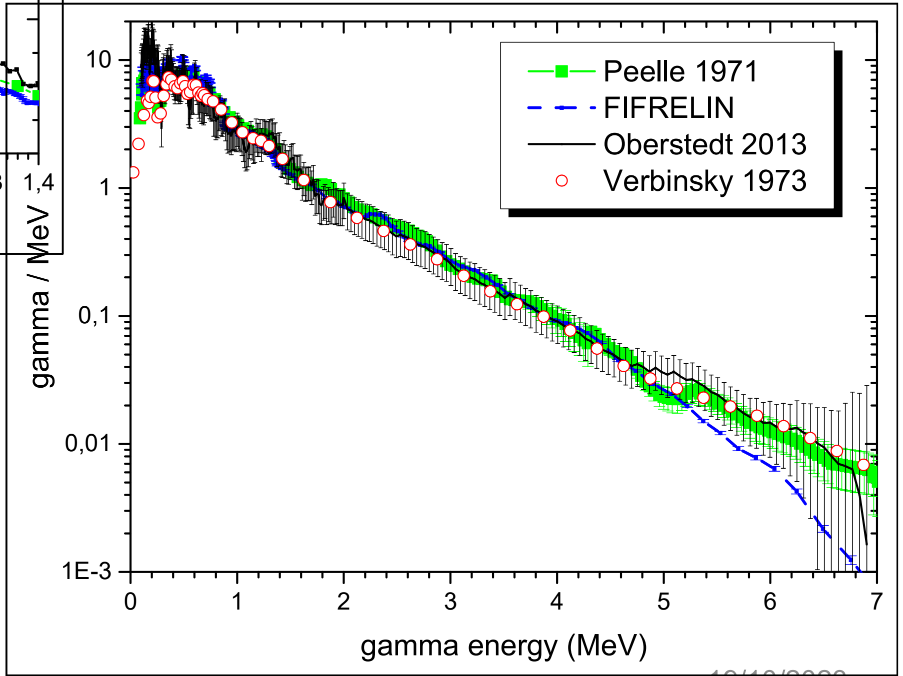
FIFRELIN : PFGS and neutron induced fission



Prompt fission gamma spectrum

$N_\gamma(E)$

- **Lower strength in the calculation above 6 MeV ?**



- **Position of the structures at low energy is reproduced by the calculation**

$^{235}U(n_{th},f)$

Courtesy O. Litaize

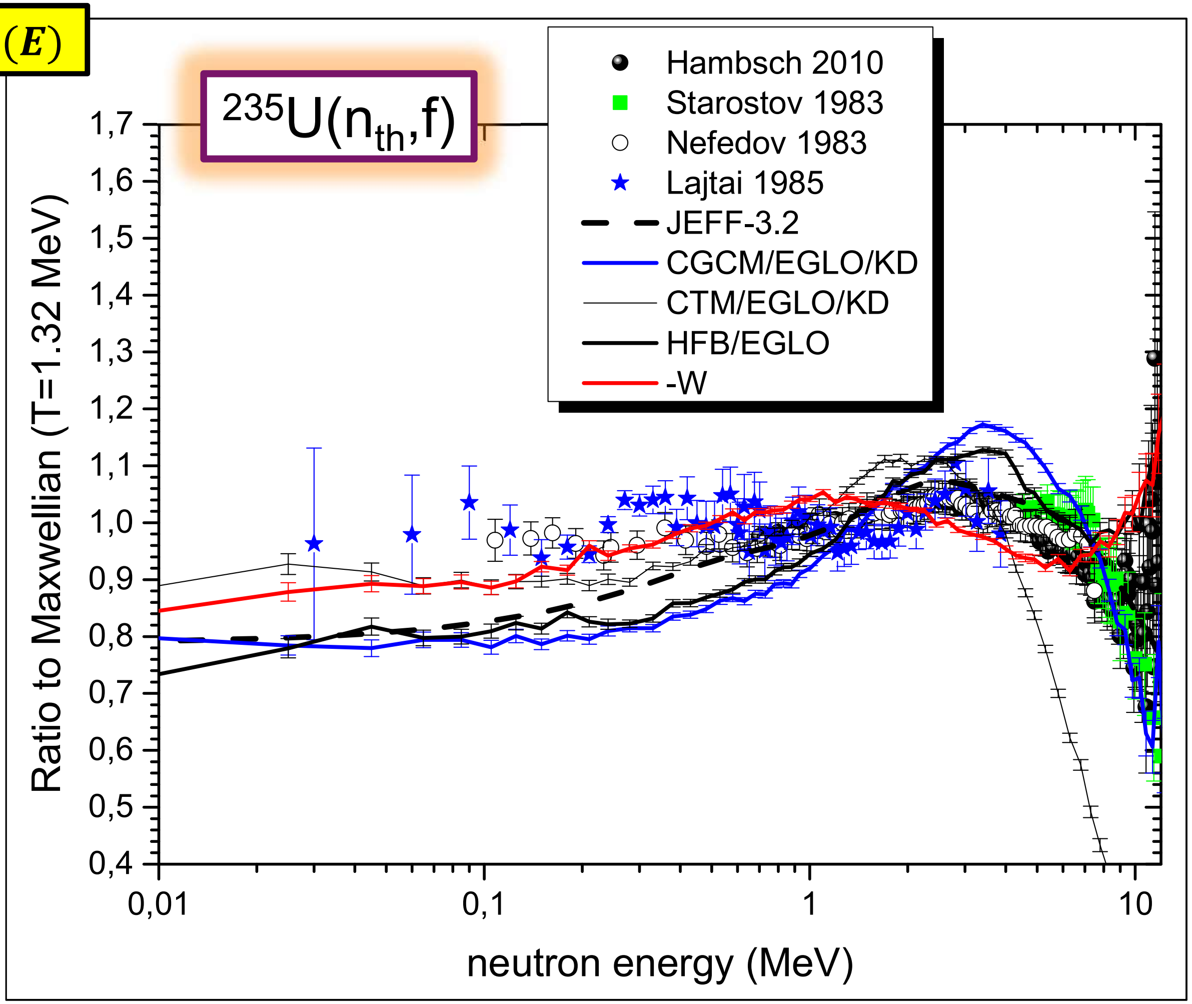
FIFRELIN : PFNS and neutron induced fission

Prompt fission neutron spectrum

FIFRELIN -HF (LDM)	<E> MeV	<ν>
(CGCM)	2.102(2)	2.424(2)
(CTM)	1.891(1)	2.444(1)
(HFB)	2.079(2)	2.397(2)
FIFRELIN -W	1.945(2)	2.430(3)
JEFF-3.2	2.03	2.42

Micro data	1.974(2)
Macro data	2.03

$N_\nu(E)$

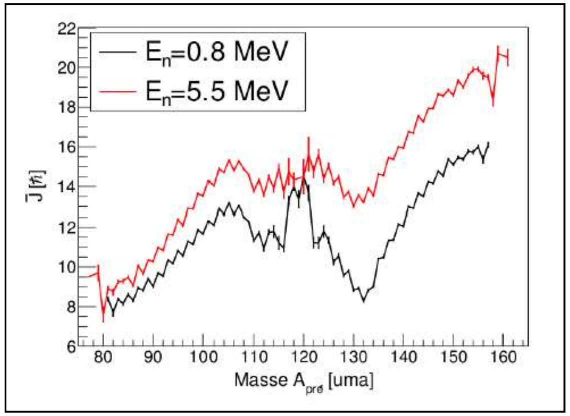


Courtesy O. Litaize

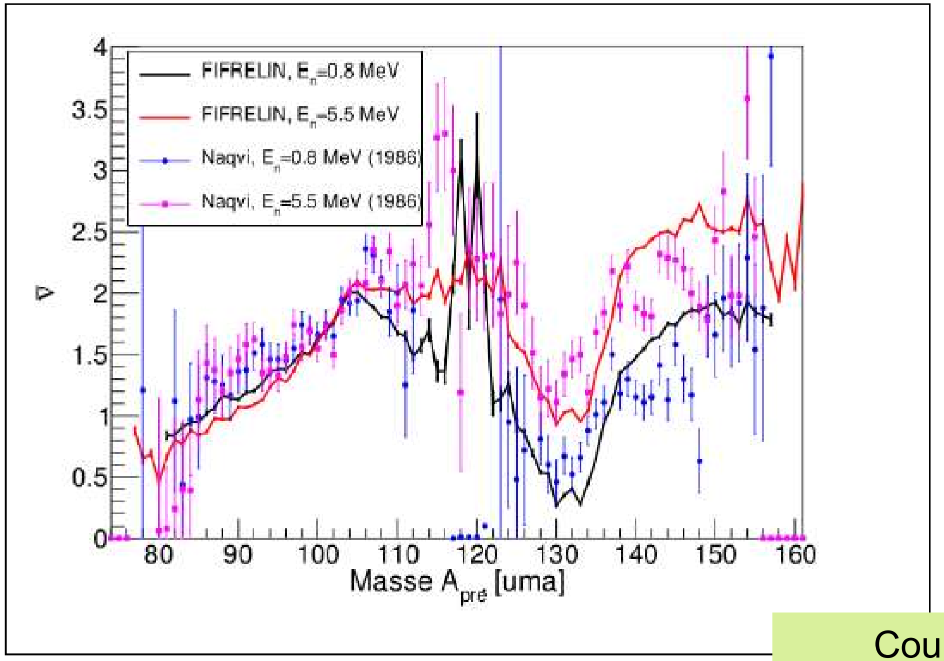
FIFRELIN : neutron multiplicities and incident energy

Constant temperature ratio
R_T=1 @ 0,8 MeV
R_T=0.8 @ 5,5 MeV

Energy dependent spin cut-off for initial spin



$^{237}Np(n,f)$



Courtesy L. Thulliez

MICROSCOPIC APPROACH

Details in Phys. Rev. C 77 (2008) 014310.

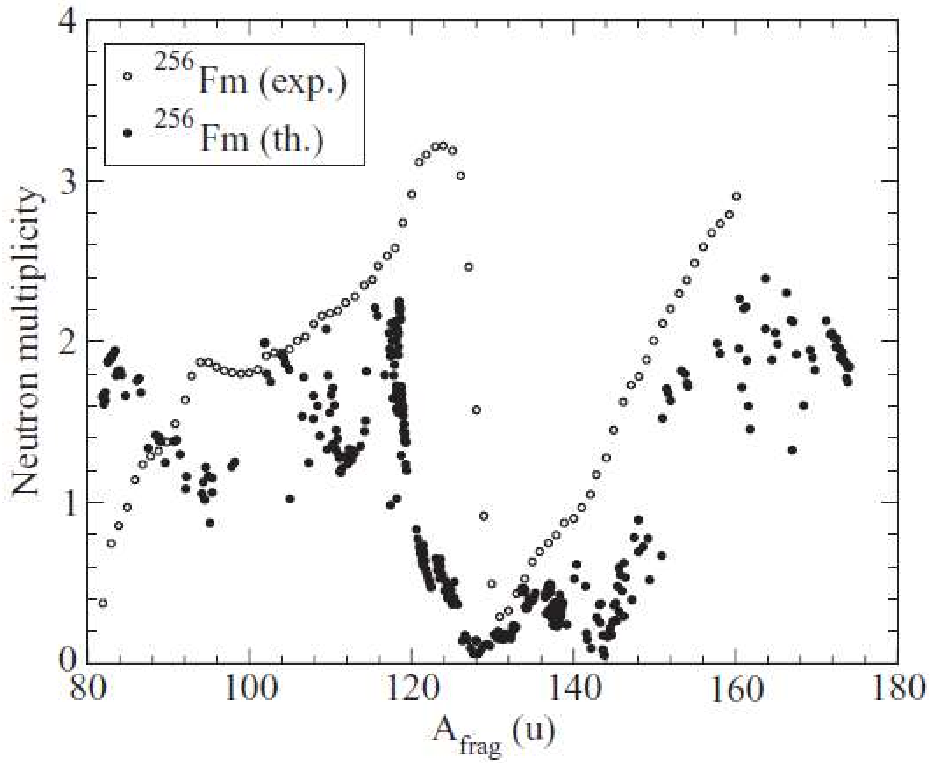


FIG. 15. ^{256}Fm. Neutron multiplicity versus fragment mass. Comparison between predictions (solid symbols) and data [47] (empty symbols).

⇒ **Not yet at the level**

4. Fission cross sections

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

- Conclusions

- Generalities about fission

Induced, spontaneous, energy balance, fission yields, PFNS, neutron multiplicities, cross sections, fission chances, Kinetic energies, …..

- Fission yields

- GEF model
- SPY model
- Microscopic approach

- Neutrons and gammas from fission

- Madland-Nix model
- GEF model
- FIFRELIN
- Microscopic approach

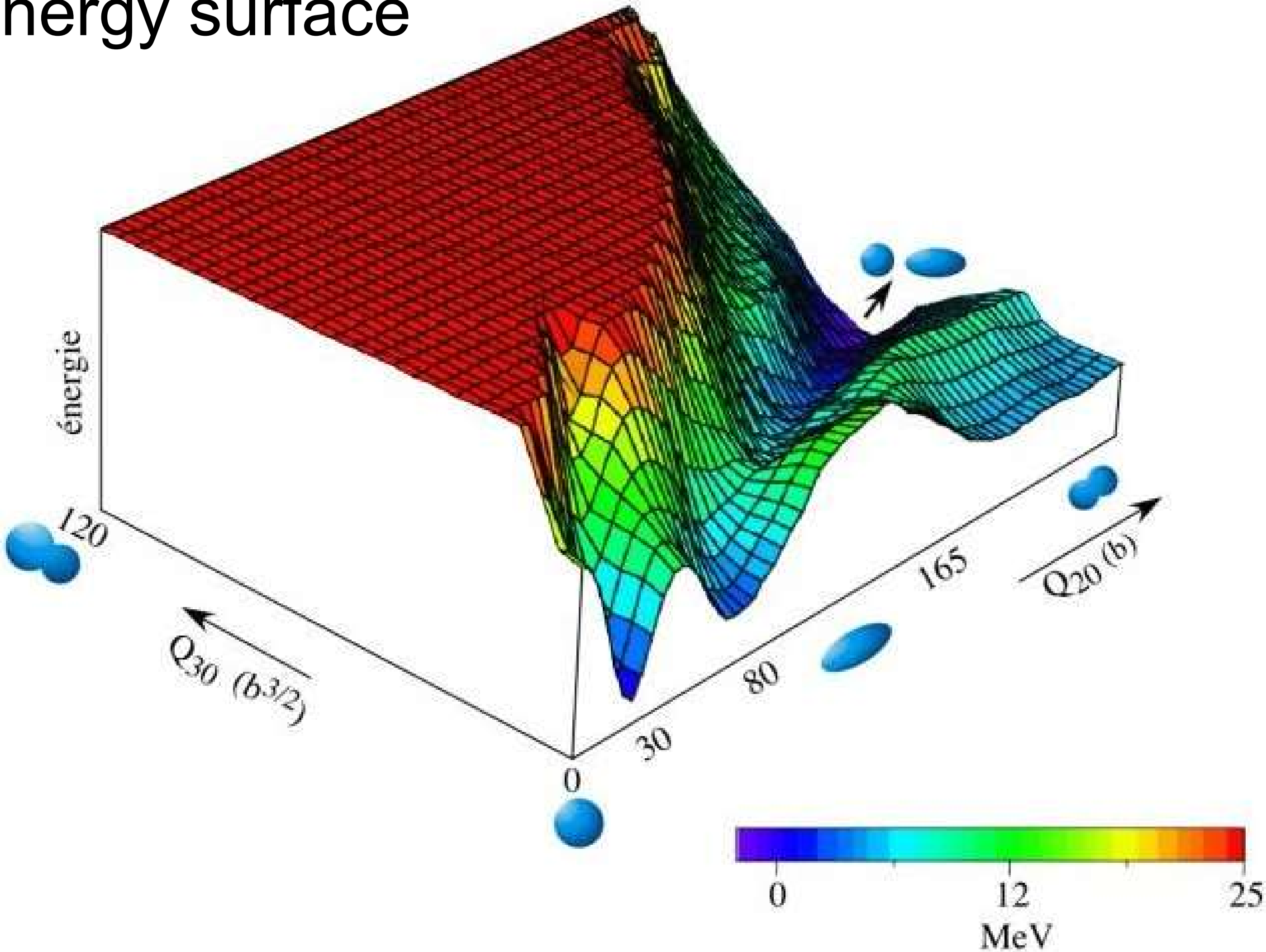
- Fission cross sections

- Phenomenological approaches
- Coherent fission cross sections
- Microscopic approaches
- Integral benchmark sensitivity

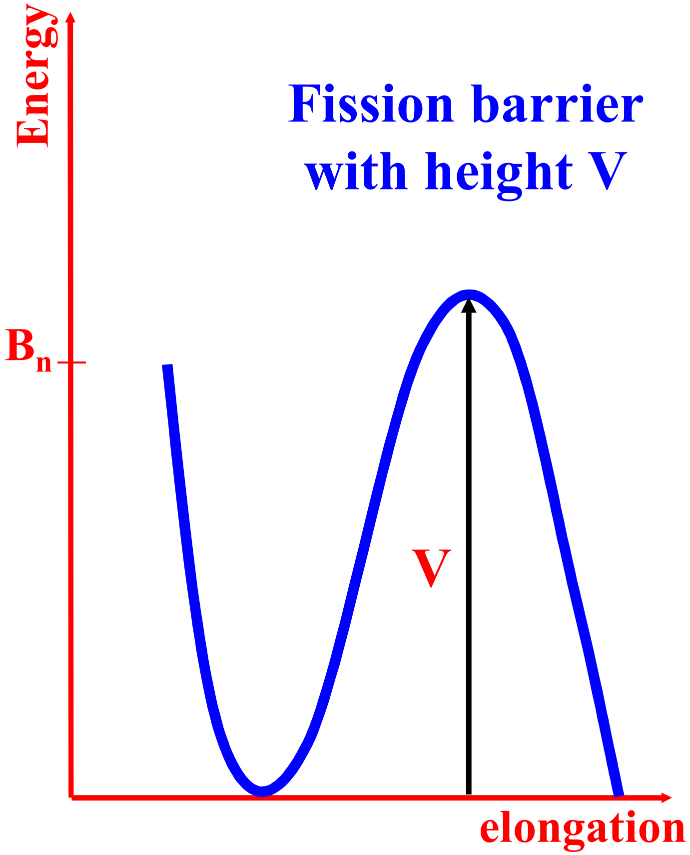
- Conclusions

Fission barriers and fission paths

^{238}U Potential energy surface

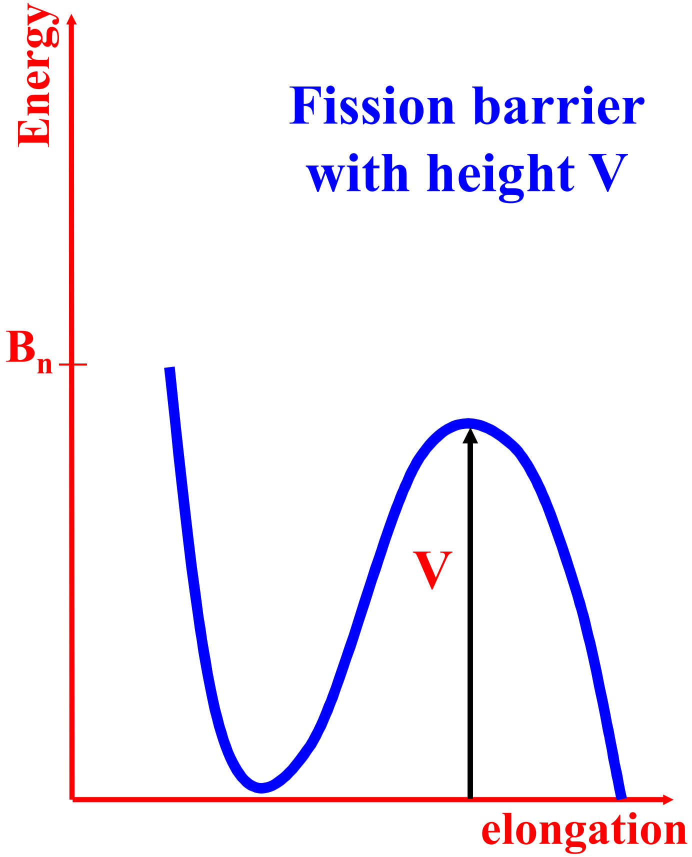


Fissile or fertile



$B_n < V$

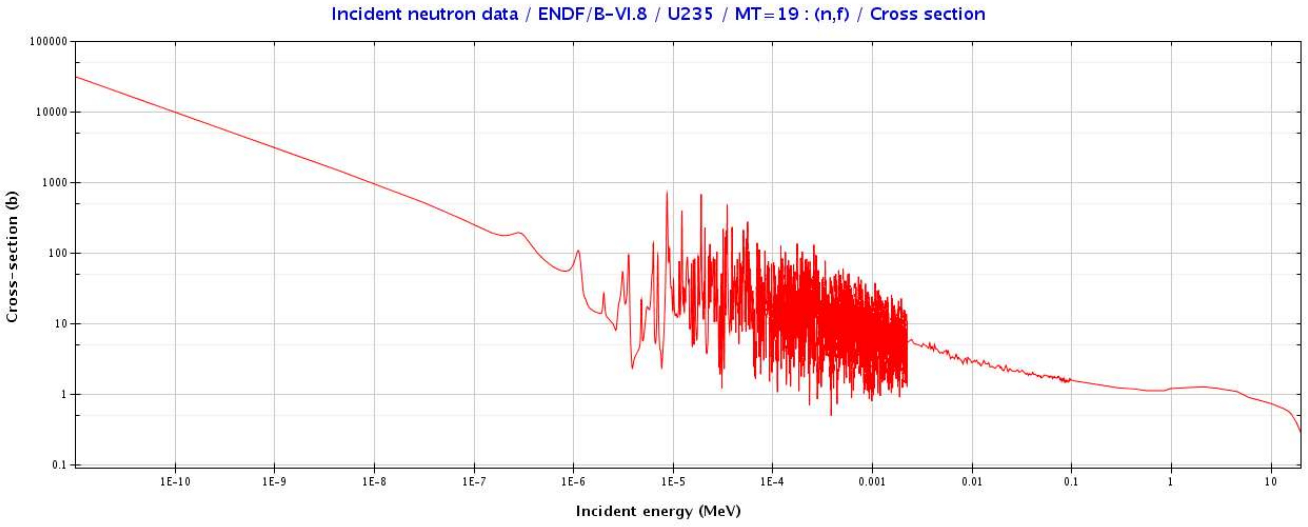
Fertile target (^{238}U)

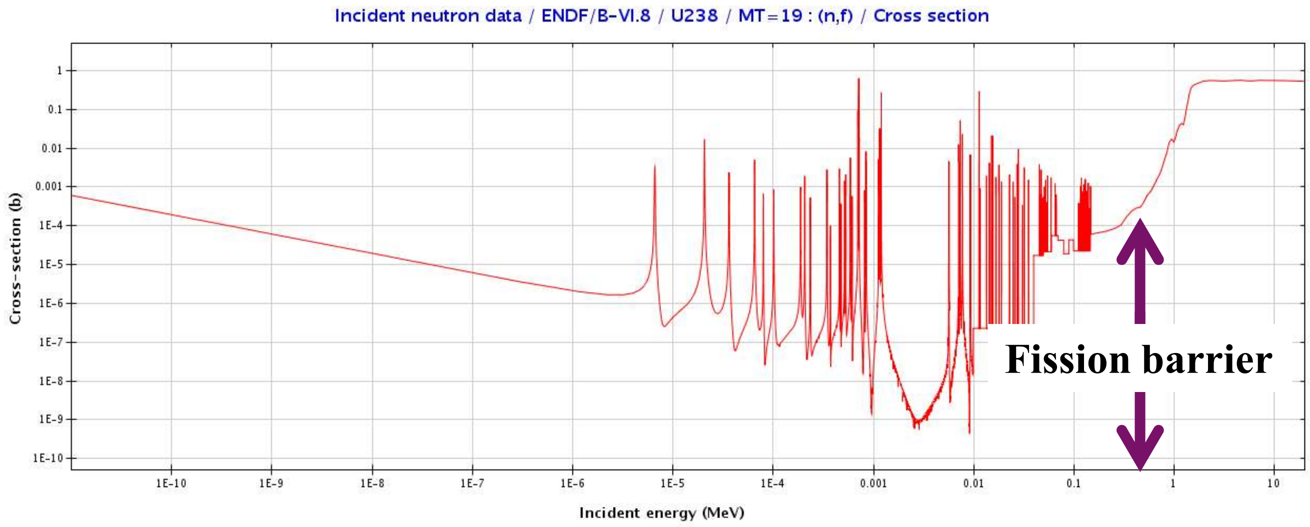


$B_n > V$

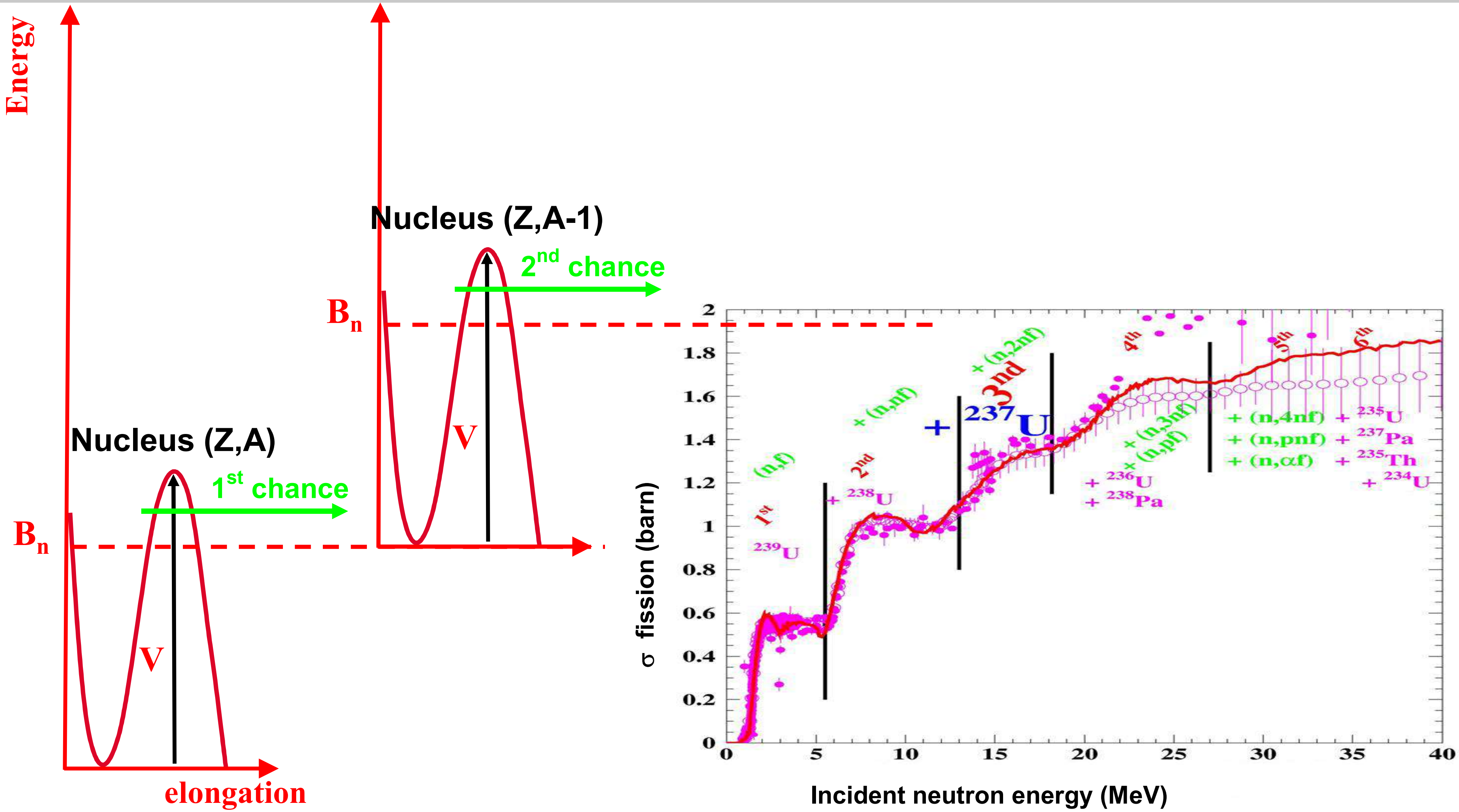
Fissile target (^{235}U)

Fissile or fertile

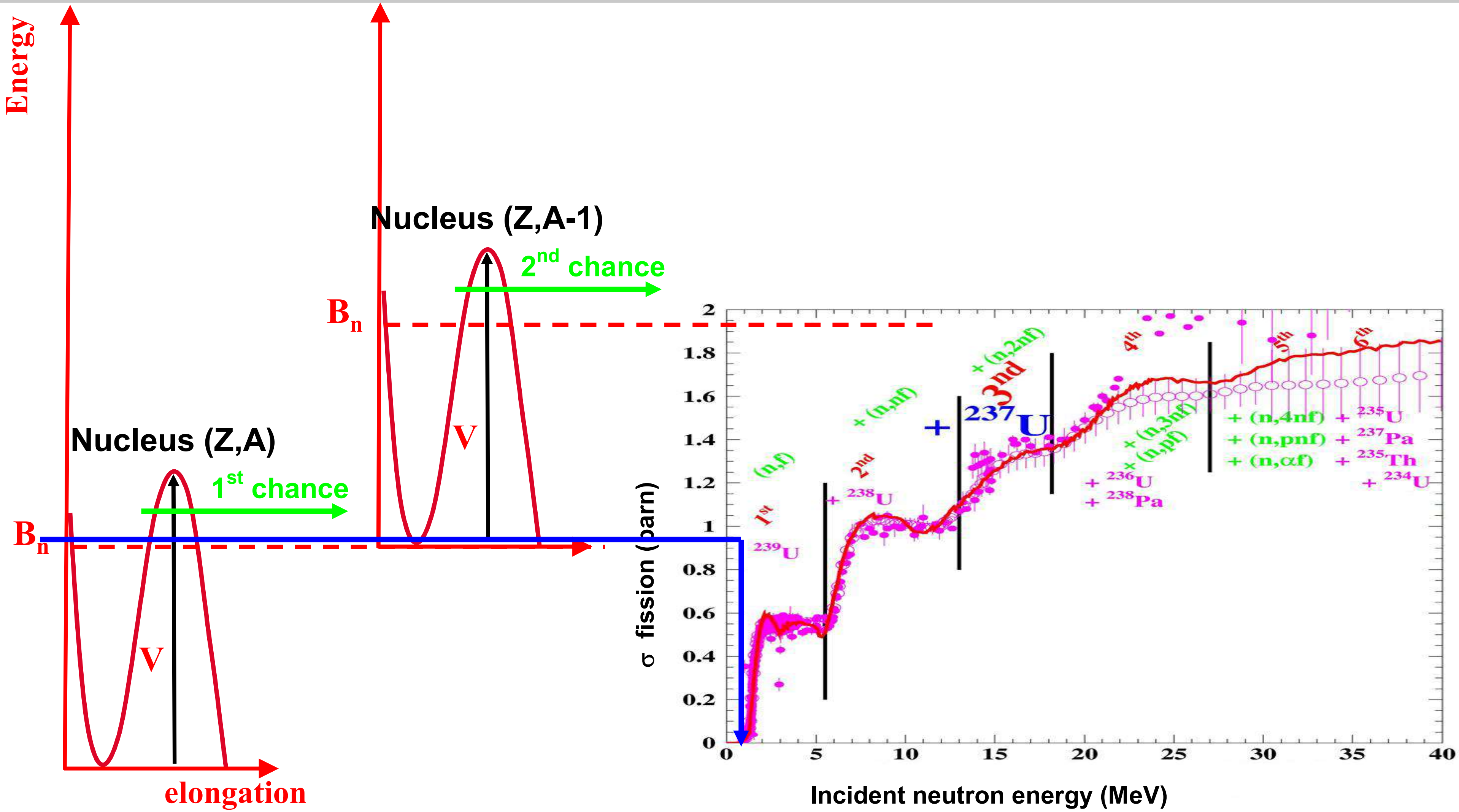




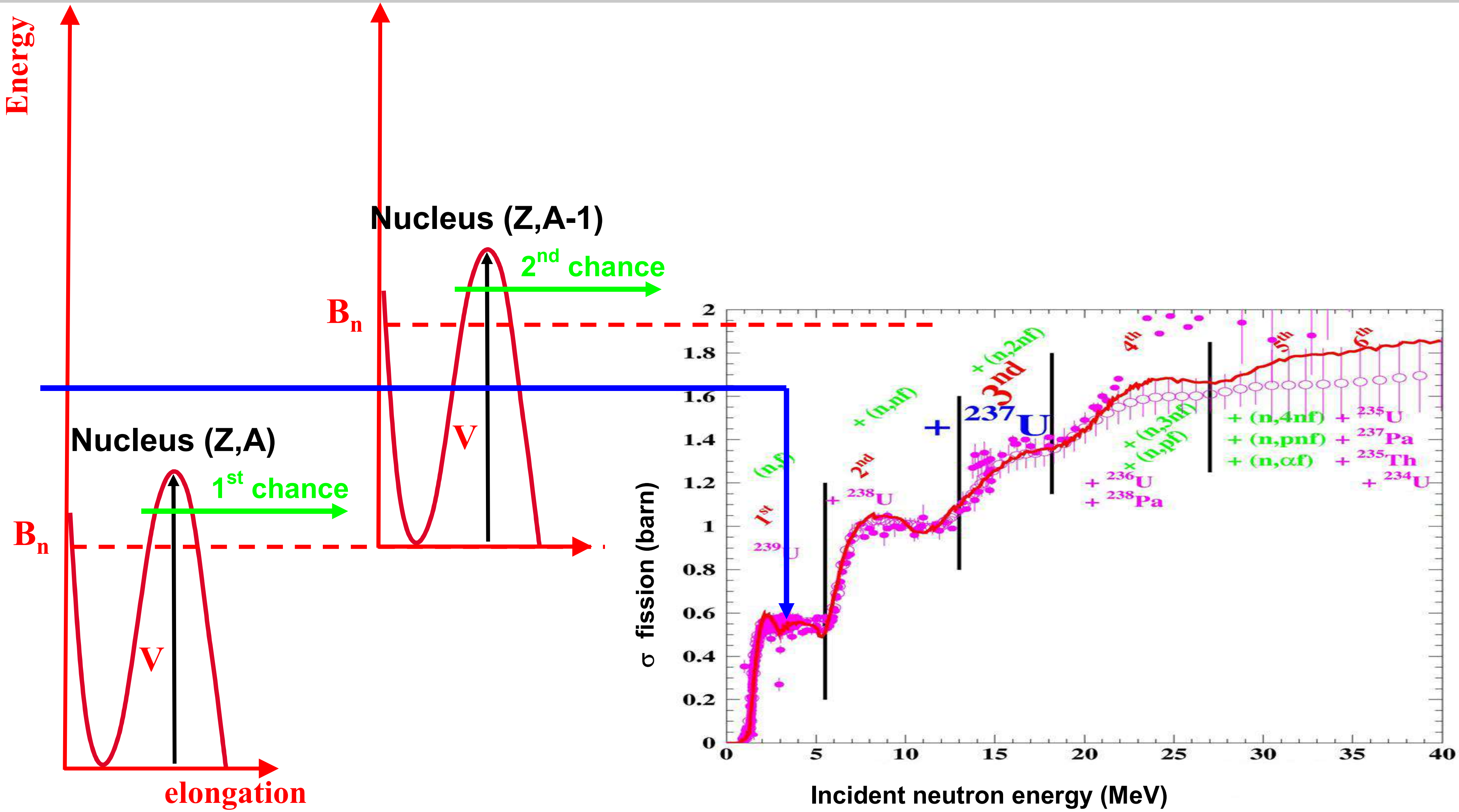
Multiple fission chances



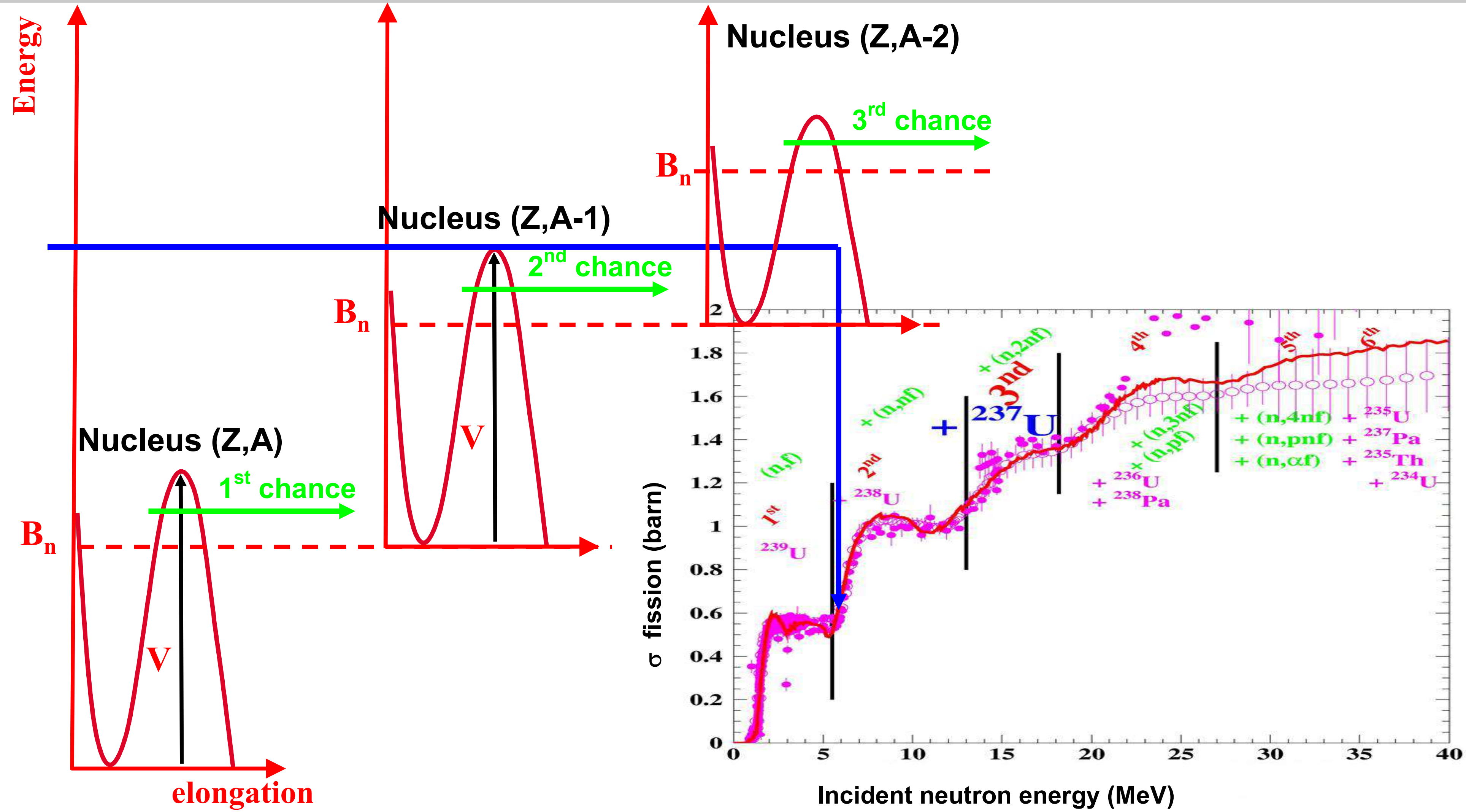
Multiple fission chances



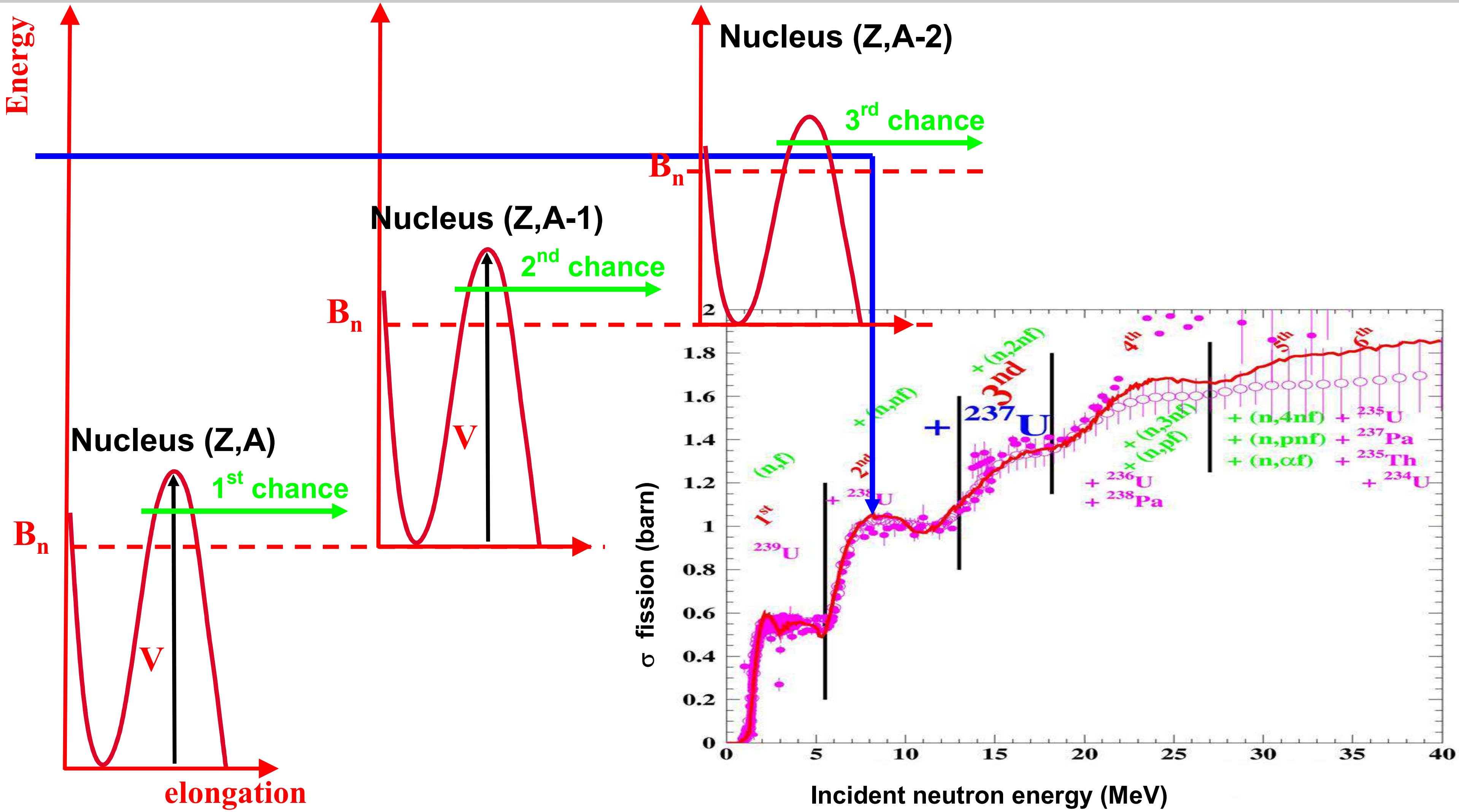
Multiple fission chances



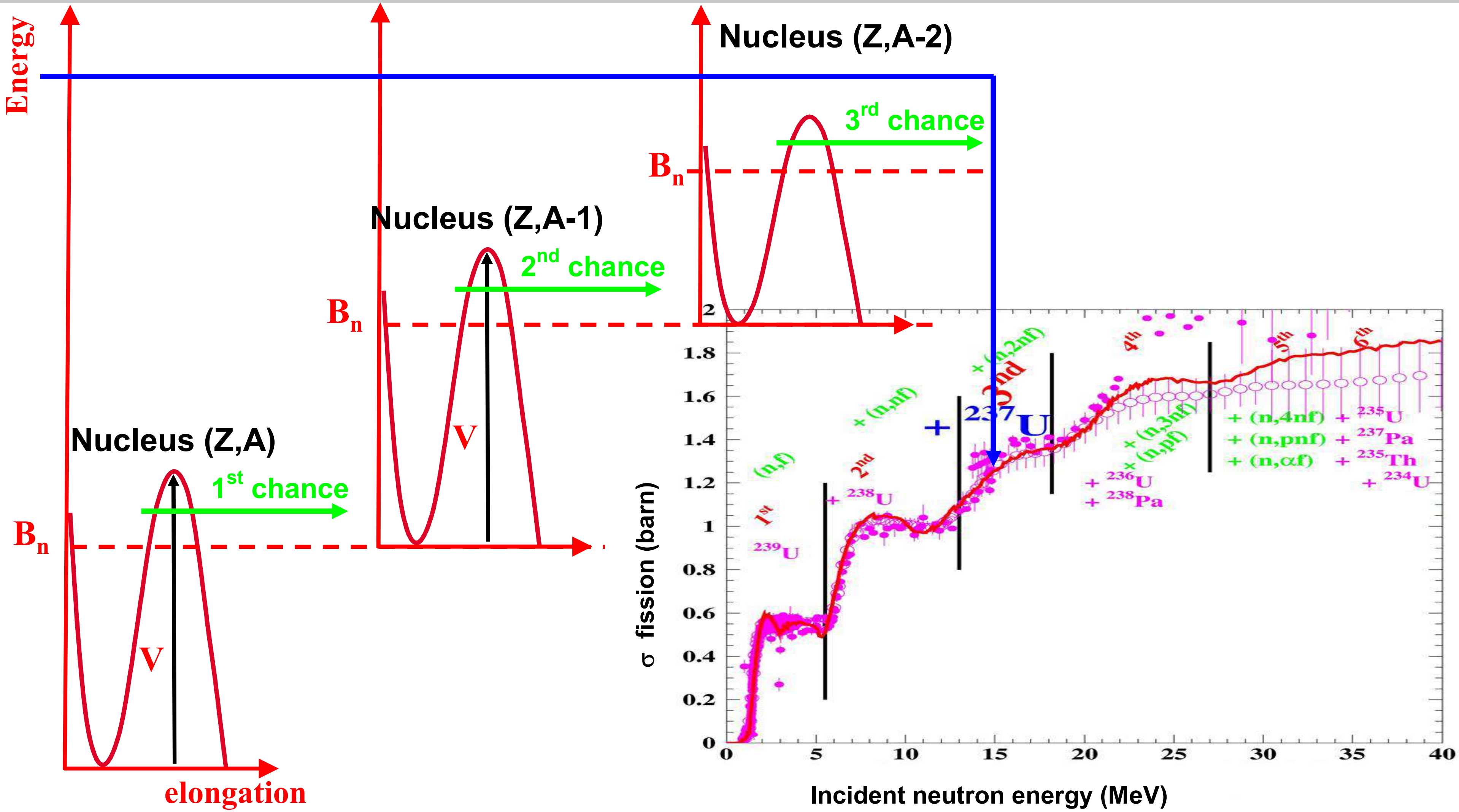
Multiple fission chances



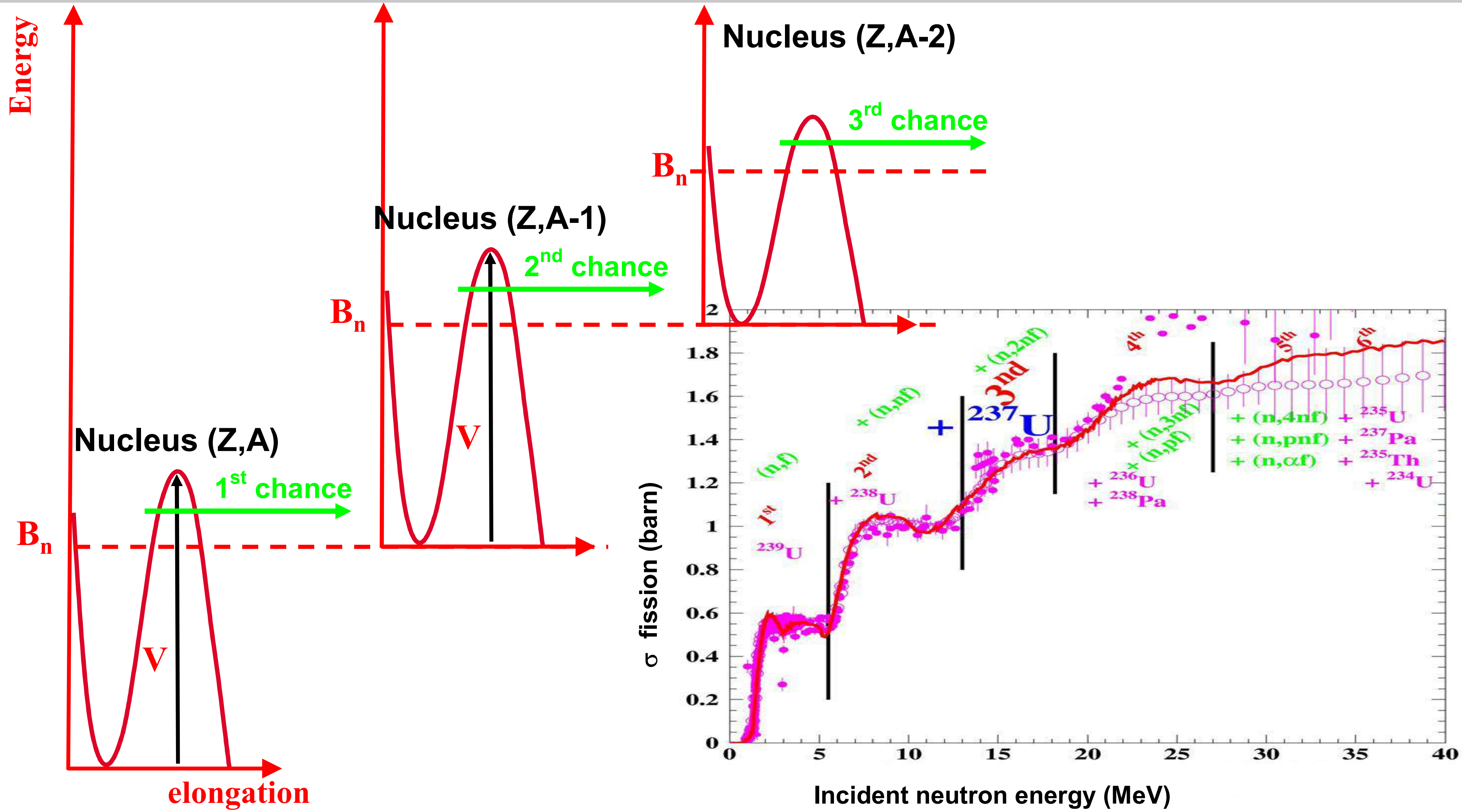
Multiple fission chances



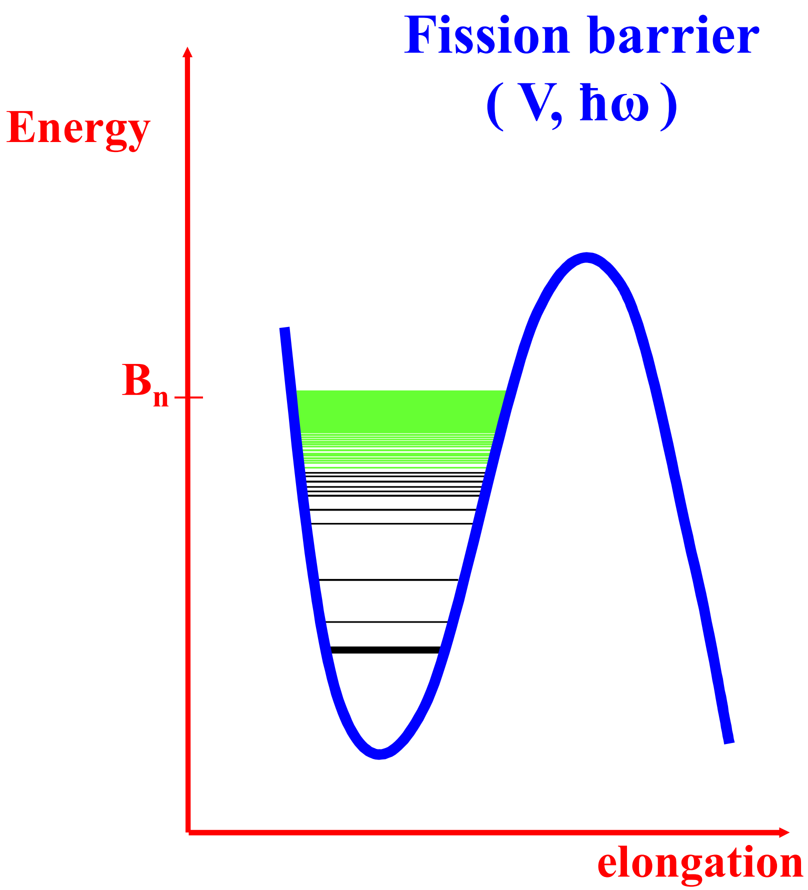
Multiple fission chances



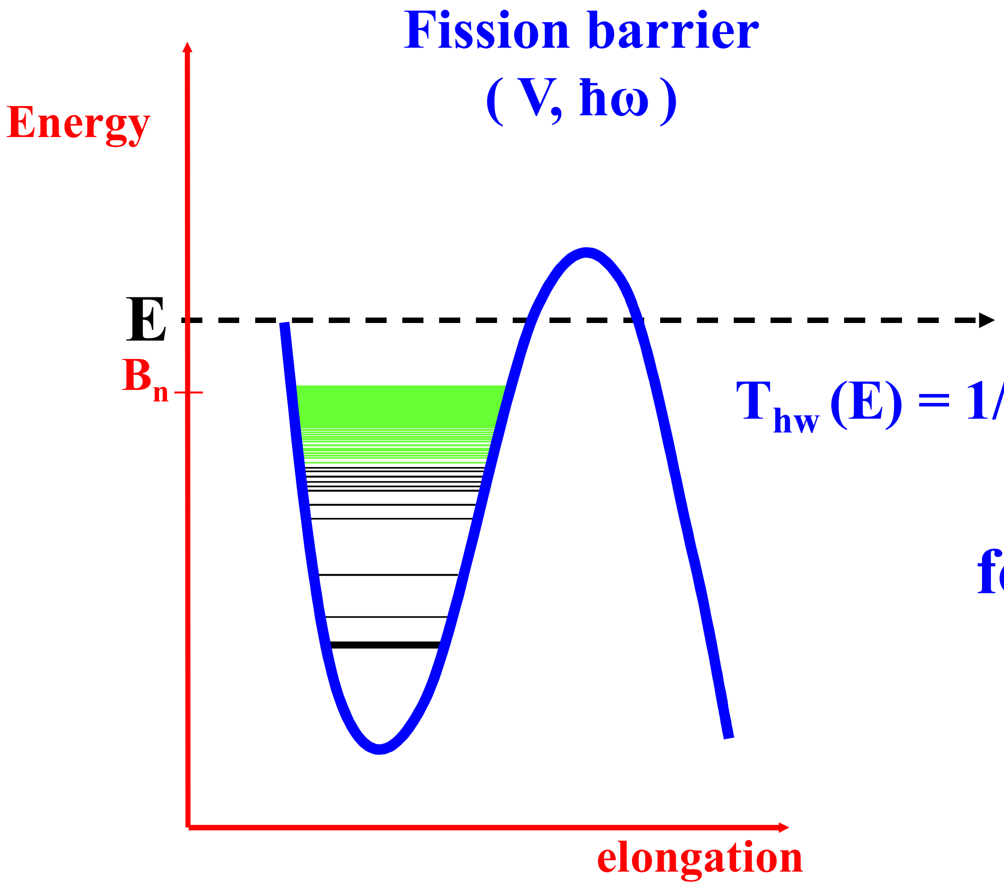
Multiple fission chances



Fission transmission coefficient :Hill-Wheeler penetrability



Fission transmission coefficient :Hill-Wheeler penetrability

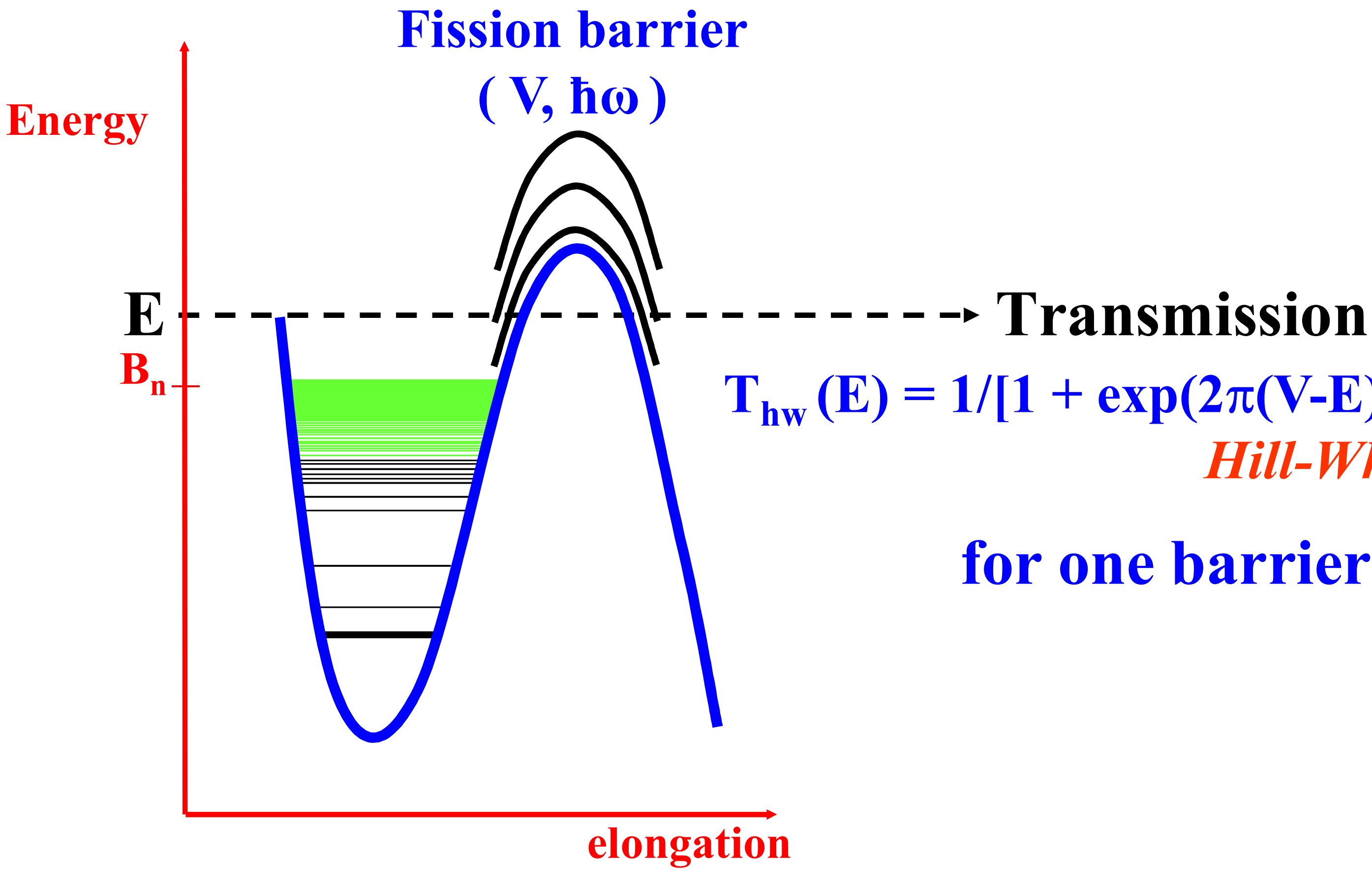


$$T_{hw}(E) = 1/[1 + \exp(2\pi(V-E)/\hbar\omega)]$$

Hill-Wheeler

for one barrier !

Fission transmission coefficient :Hill-Wheeler penetrability



$T_{hw}(E) = 1/[1 + \exp(2\pi(V-E)/\hbar\omega)]$

Hill-Wheeler

for one barrier !

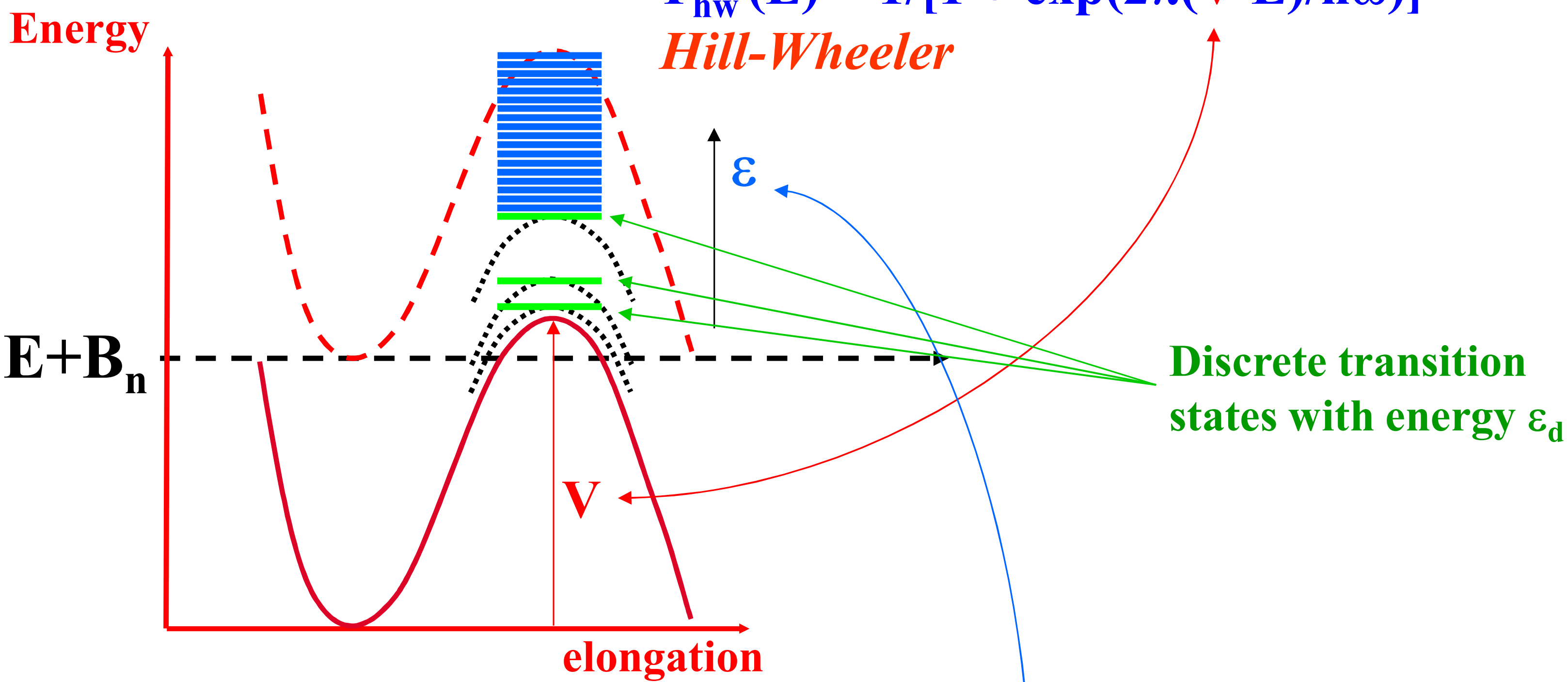
+ transition state on top of the barrier !

Bohr hypothesys

Fission transmission coefficient : single humped barrier

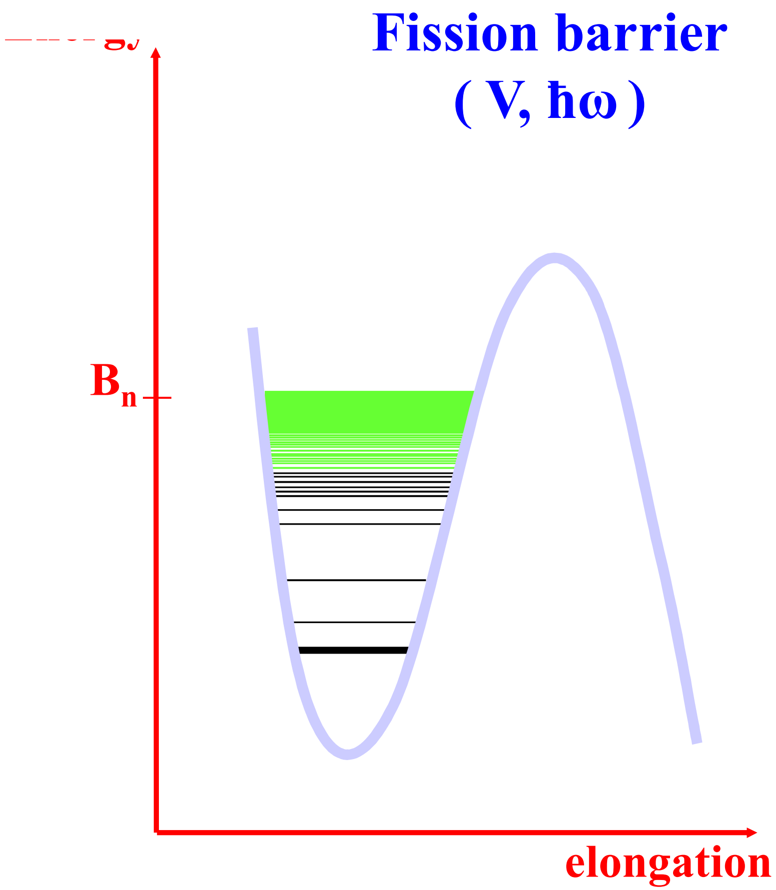
$$T_{hw}(E) = 1/[1 + \exp(2\pi(V-E)/\hbar\omega)]$$

Hill-Wheeler

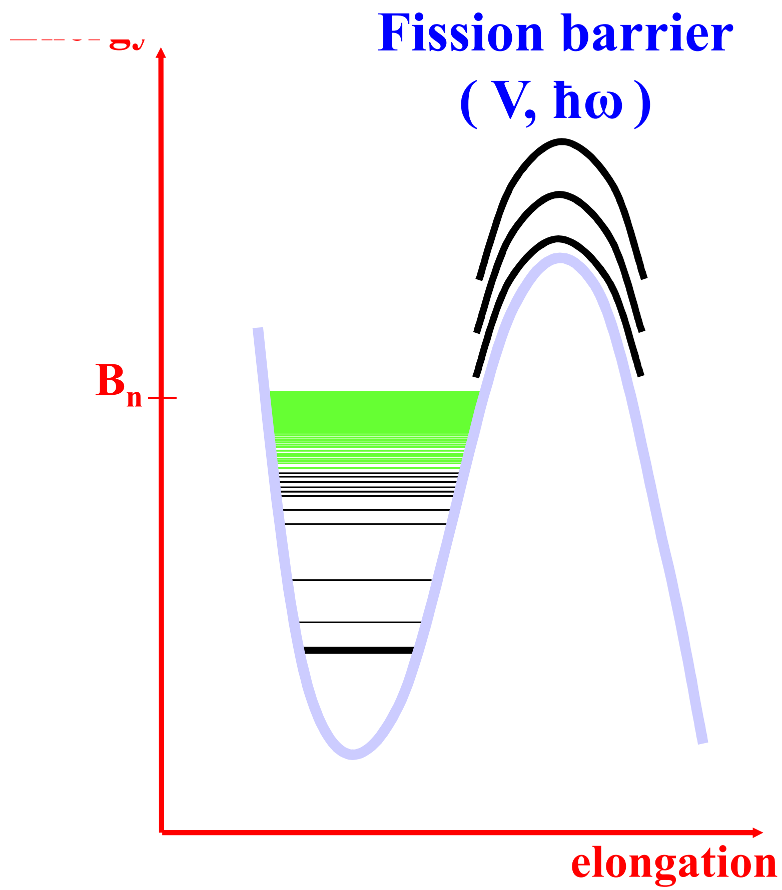


$$T_f(E, J, \pi) = \sum_{\substack{\text{discrete} \\ J,\, \pi}} T_{hw}(E - \varepsilon_d) + \int_{E_s}^{E+B_n} \rho(\varepsilon, J, \pi)\, T_{hw}(E - \varepsilon)\, d\varepsilon$$

Fission transmission coefficient : penetrability for double humped barrier

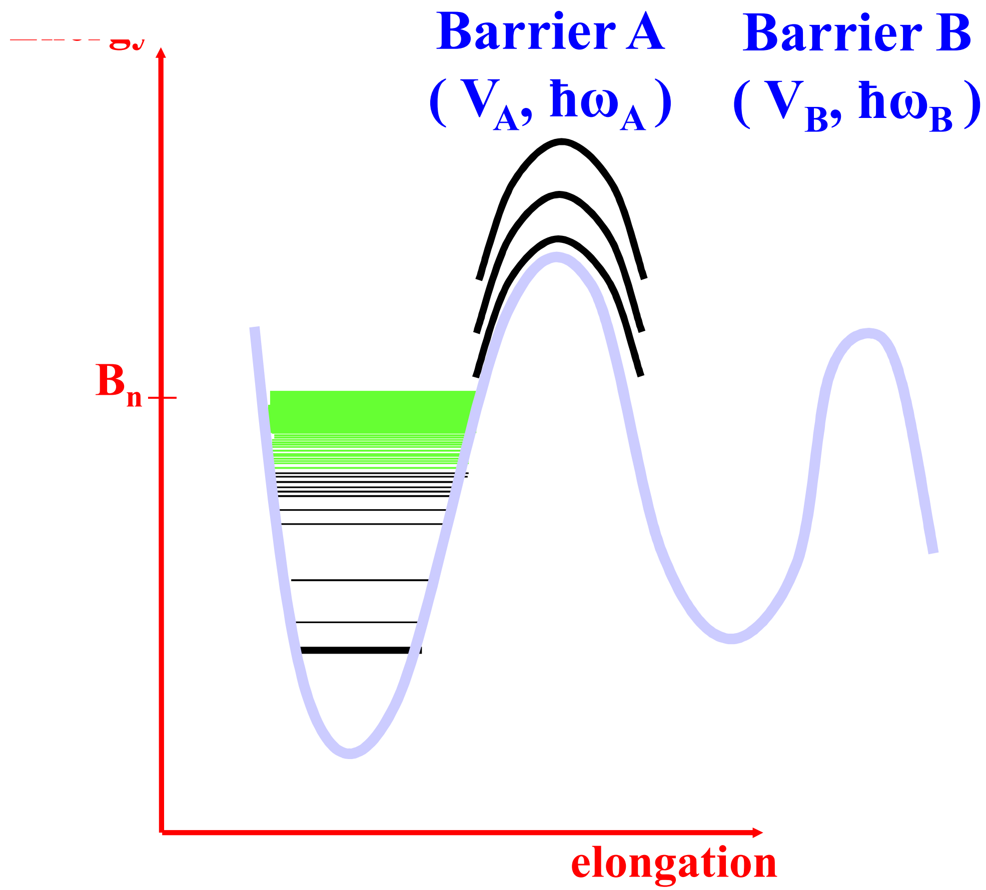


Fission transmission coefficient : penetrability for double humped barrier



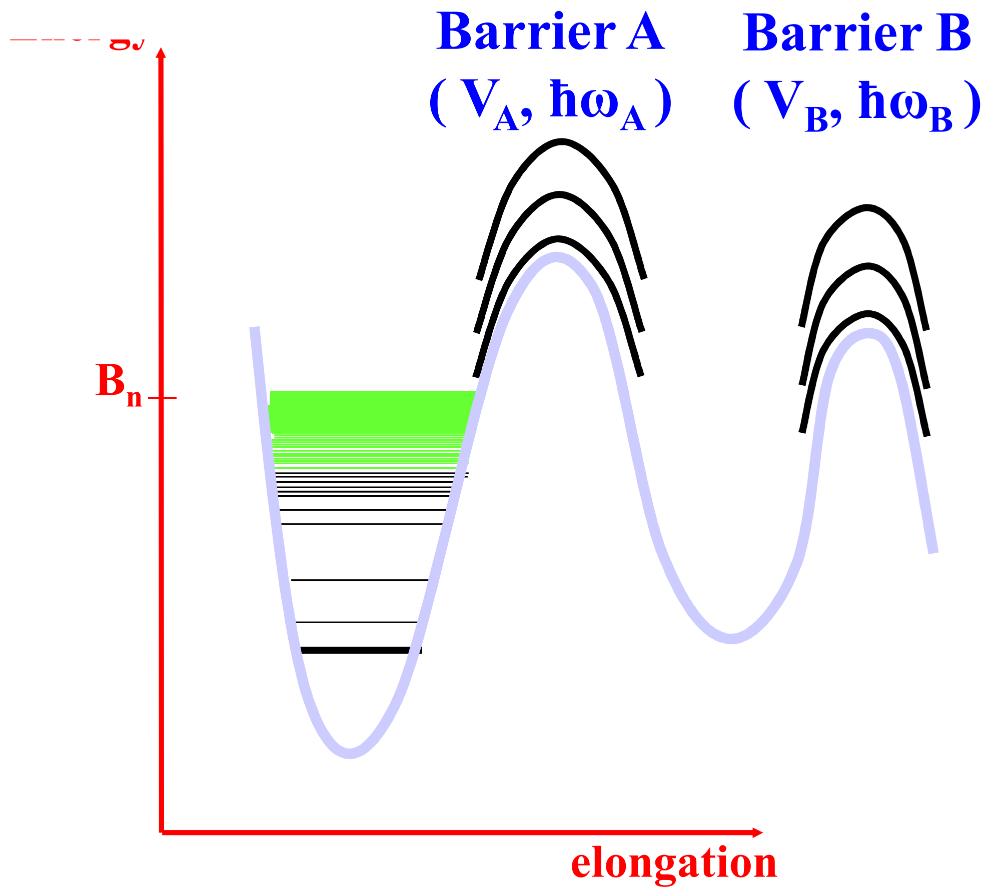
+ transition states on top of the barrier !

Fission transmission coefficient : penetrability for double humped barrier



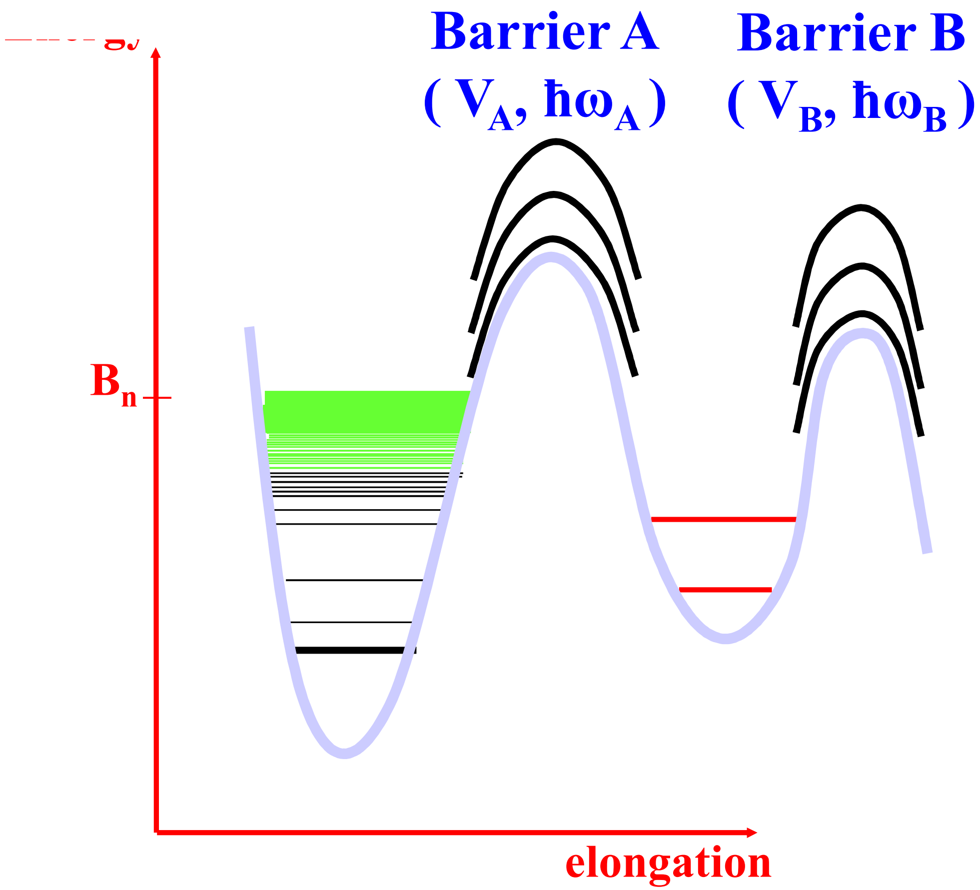
+ transition states on top of the barrier !

Fission transmission coefficient : penetrability for double humped barrier



+ transition states on top of each barrier !

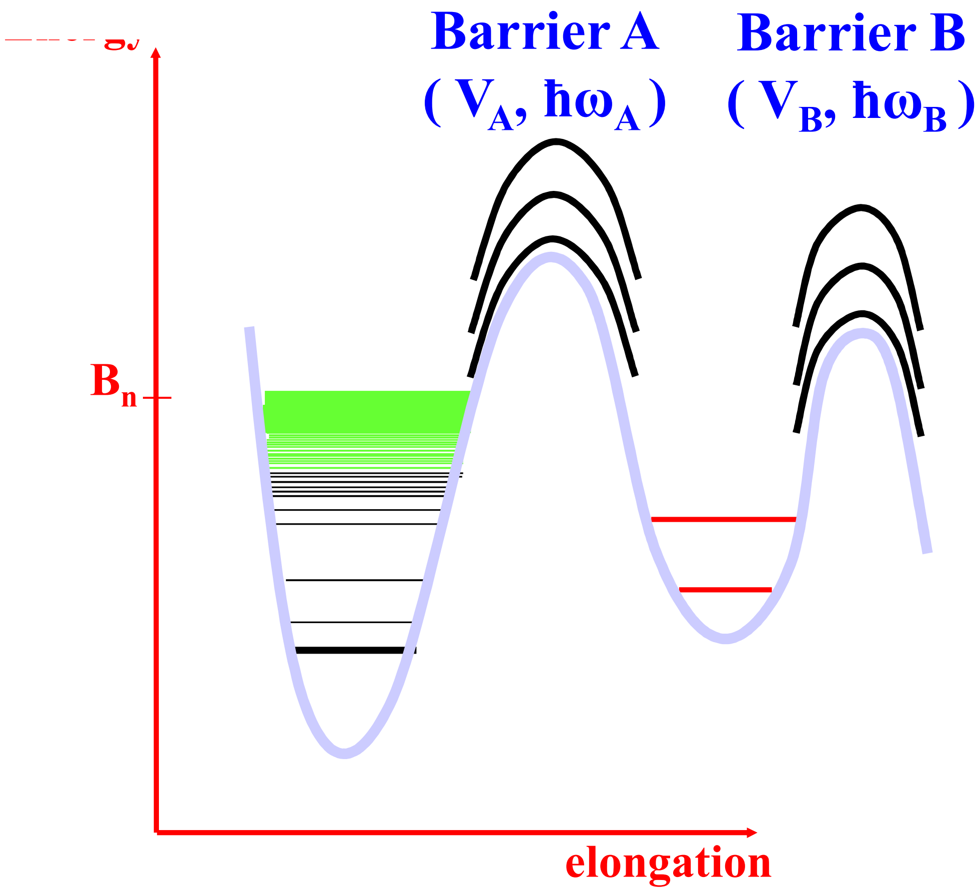
Fission transmission coefficient : penetrability for double humped barrier

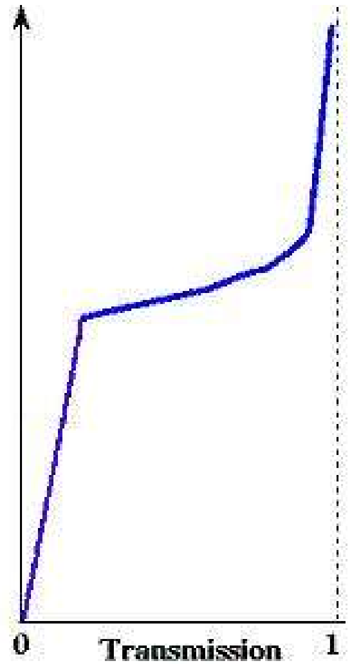


+ transition states on top of each barrier !

+ class II states in the intermediate well !

Fission transmission coefficient : penetrability for double humped barrier

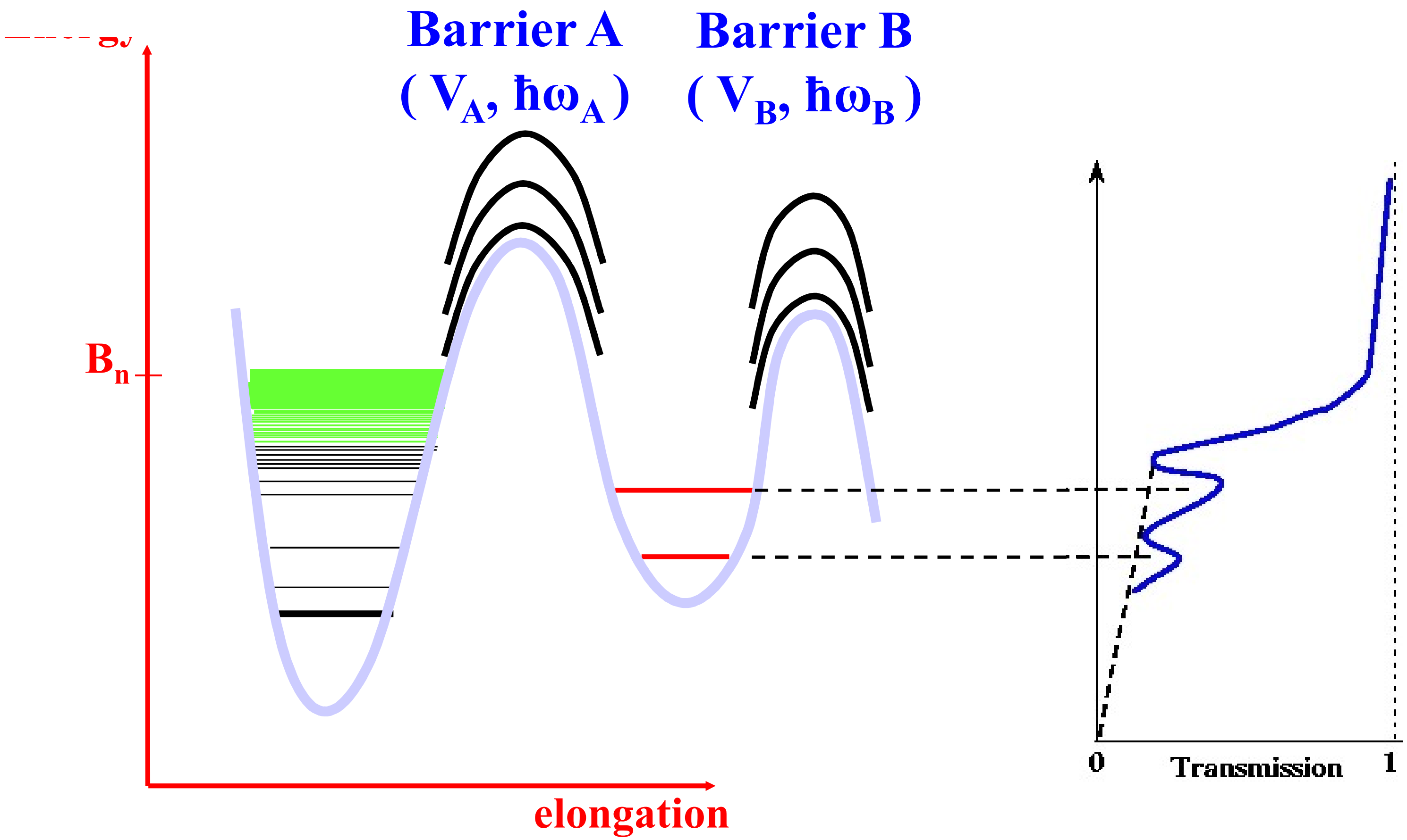




+ transition states on top of each barrier !

+ class II states in the intermediate well !

Fission transmission coefficient : penetrability for double humped barrier



+ transition states on top of each barrier !
+ class II states in the intermediate well !

Fission transmission coefficient : double/triple humped barrier

Two barriers A et B

$$T_f = \frac{T_A T_B}{T_A + T_B}$$

More exact expressions in Sin et al., PRC 74 (2006) 014608

Fission transmission coefficient : double/triple humped barrier

Two barriers A et B

$$T_f = \frac{T_A\, T_B}{T_A + T_B}$$

Three barriers A, B and C

$$T_f = \frac{\dfrac{T_A\, T_B}{T_A + T_B} \times T_C}{\dfrac{T_A\, T_B}{T_A + T_B} + T_C}$$

More exact expressions in Sin et al., PRC 74 (2006) 014608

Fission transmission coefficient : double/triple humped barrier

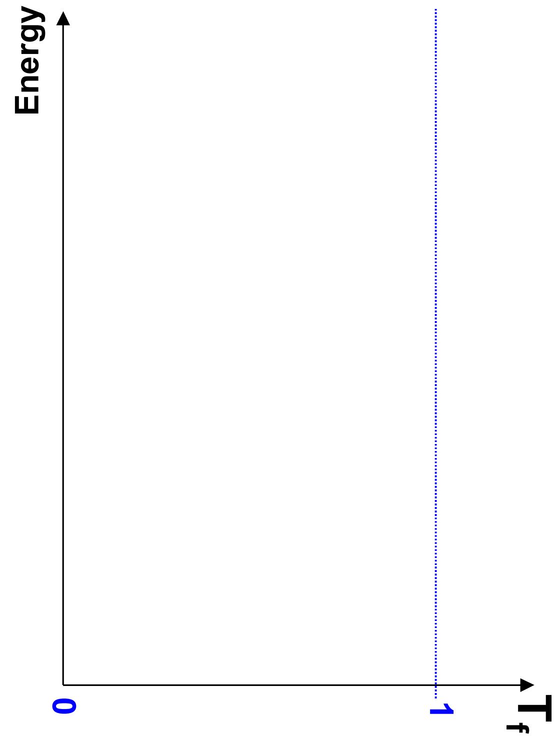
Two barriers A et B

$$T_f = \frac{T_A T_B}{T_A + T_B}$$

Three barriers A, B and C

$$T_f = \frac{\frac{T_A T_B}{T_A + T_B} \times T_C}{\frac{T_A T_B}{T_A + T_B} + T_C}$$

Resonant transmission



More exact expressions in Sin et al., PRC 74 (2006) 014608

Fission transmission coefficient : double/triple humped barrier

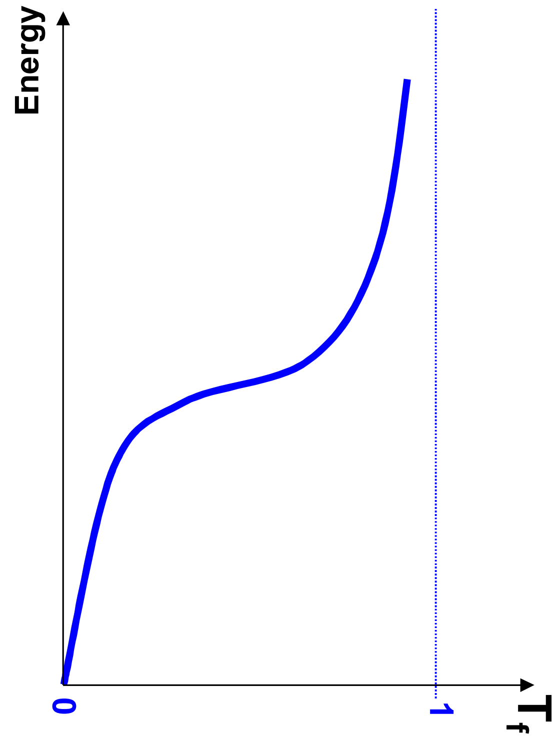
Two barriers A et B

$$T_f = \frac{T_A\, T_B}{T_A + T_B}$$

Three barriers A, B and C

$$T_f = \frac{\dfrac{T_A\, T_B}{T_A + T_B} \times T_C}{\dfrac{T_A\, T_B}{T_A + T_B} + T_C}$$

Resonant transmission



$T_f =$

More exact expressions in Sin et al., PRC 74 (2006) 014608

Fission transmission coefficient : double/triple humped barrier

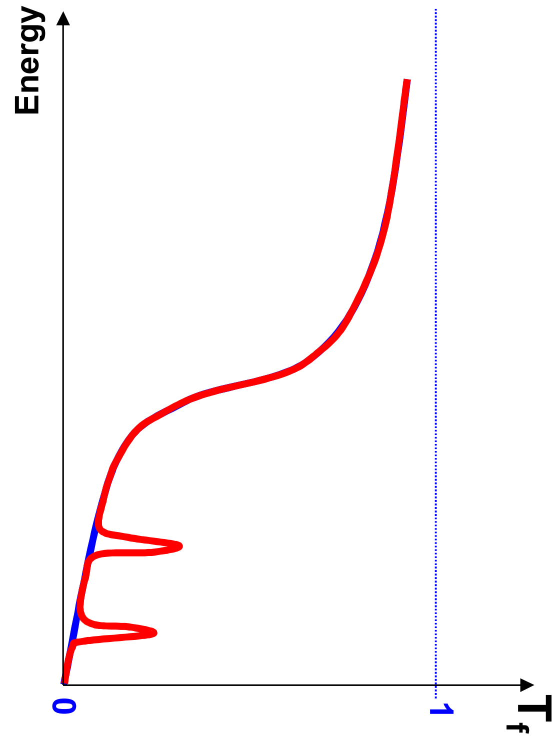
Two barriers A et B

$$T_f = \frac{T_A T_B}{T_A + T_B}$$

Three barriers A, B and C

$$T_f = \frac{\dfrac{T_A T_B}{T_A + T_B} \times T_C}{\dfrac{T_A T_B}{T_A + T_B} + T_C}$$

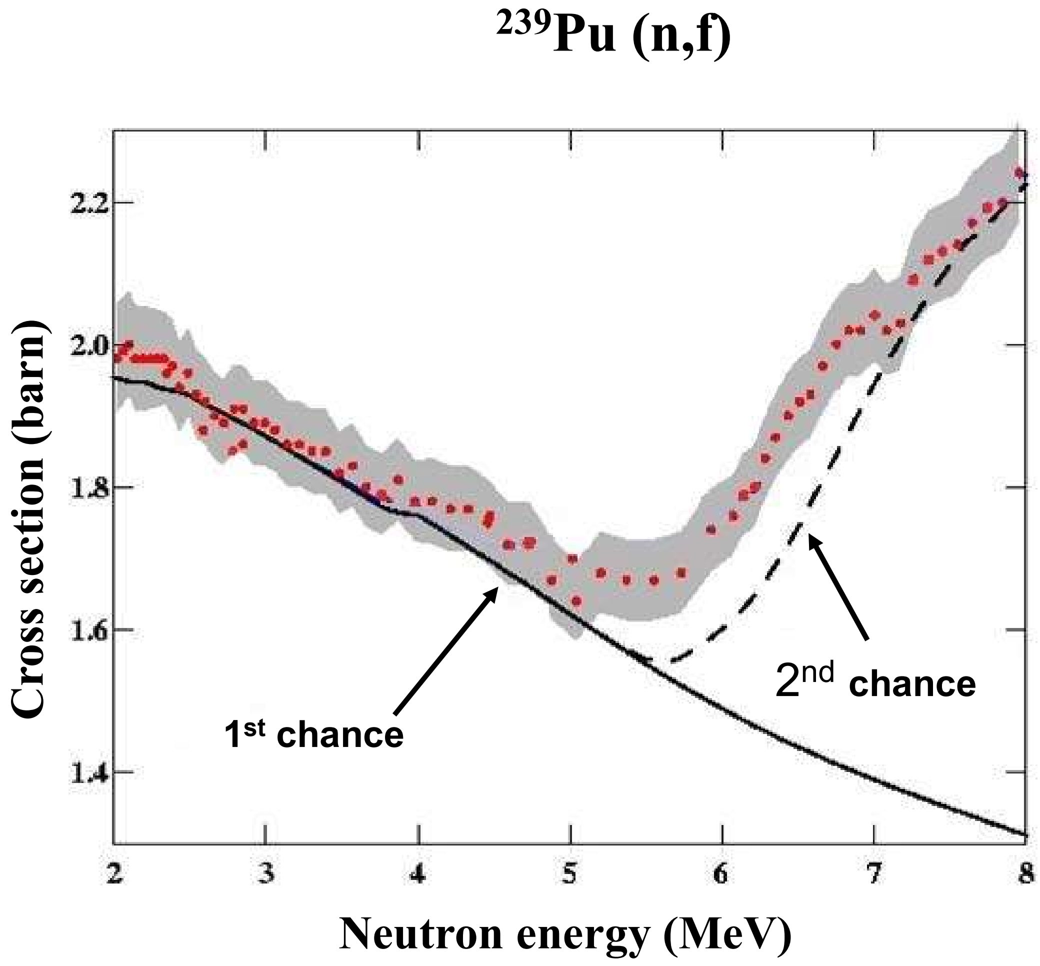
Resonant transmission



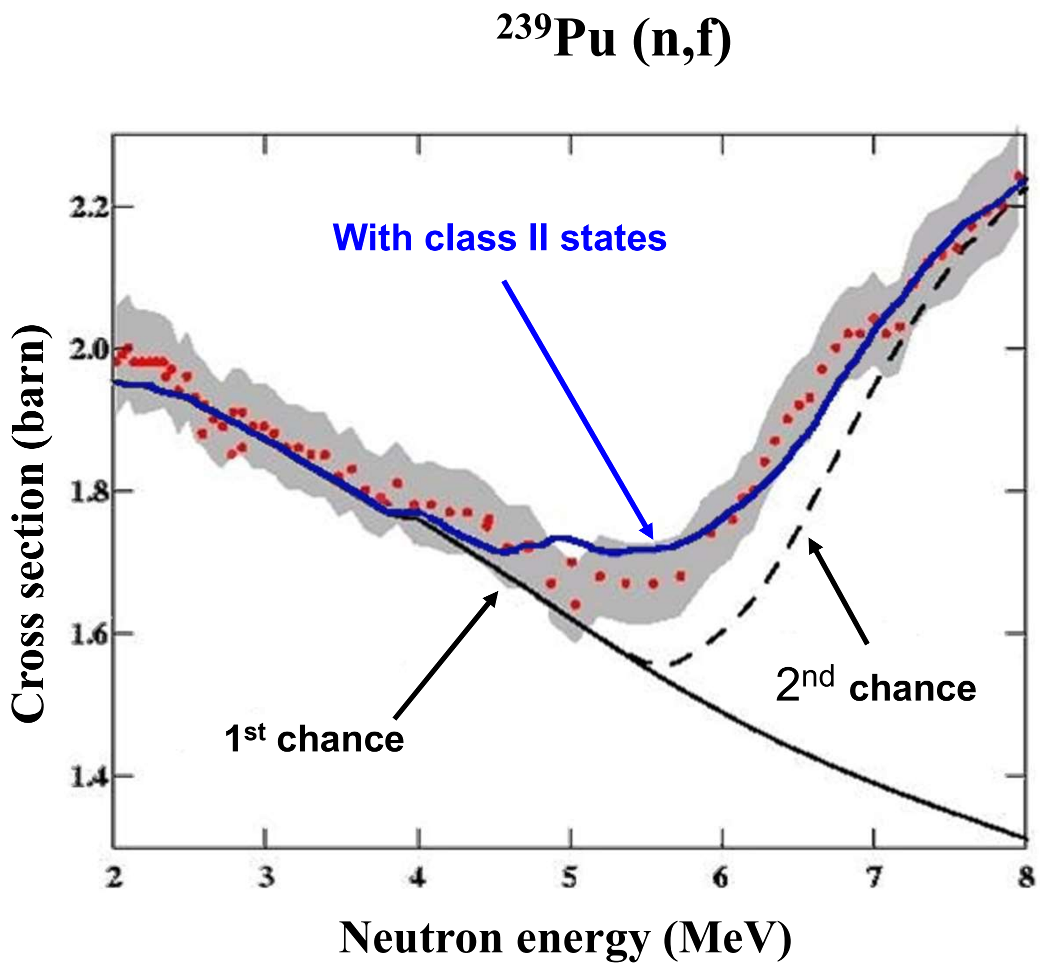
$T_f =$

More exact expressions in Sin et al., PRC 74 (2006) 014608

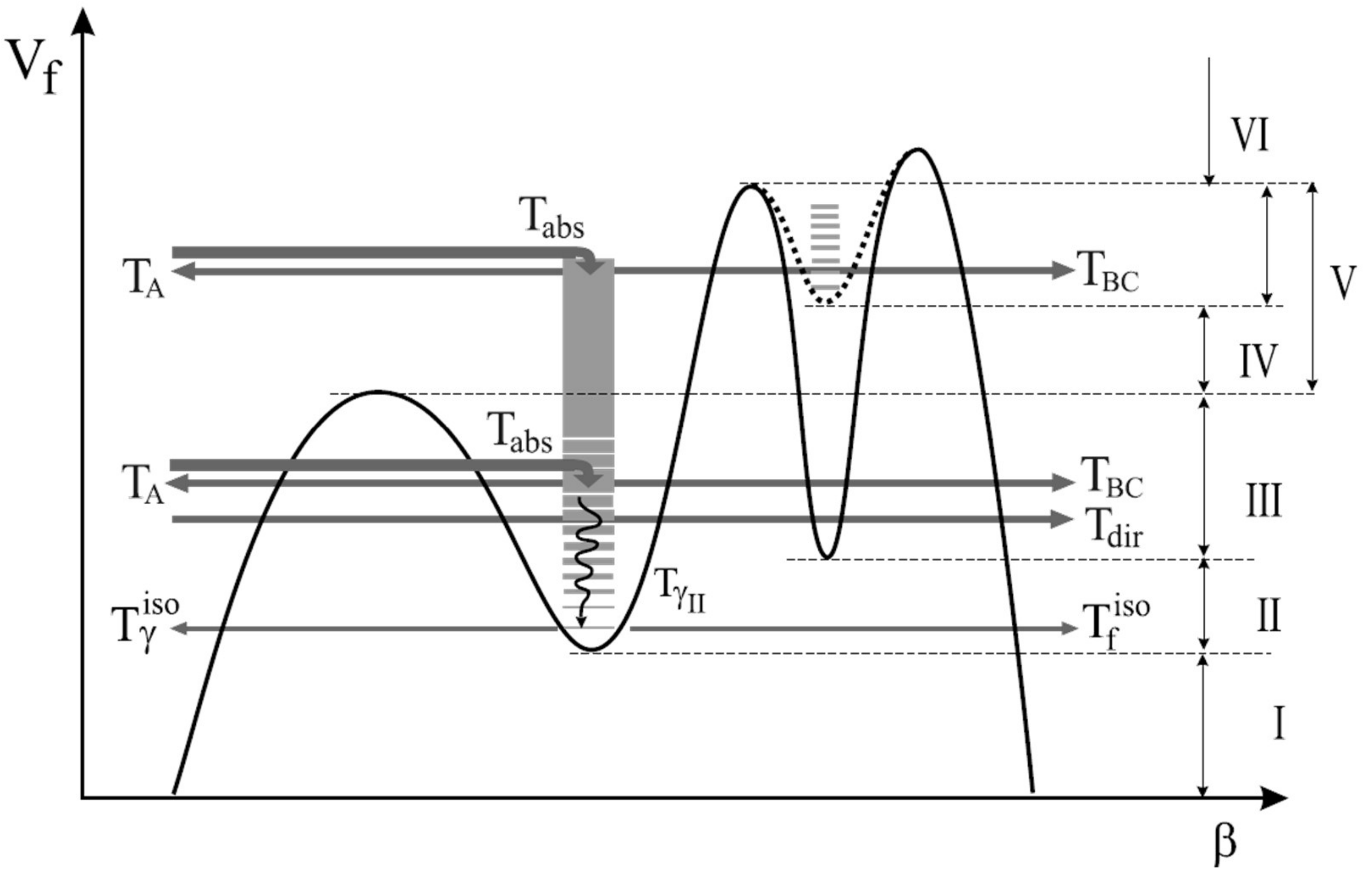
Fission transmission coefficient : role of class II states



Fission transmission coefficient : role of class II states



Fission transmission coefficient : maximum complexity

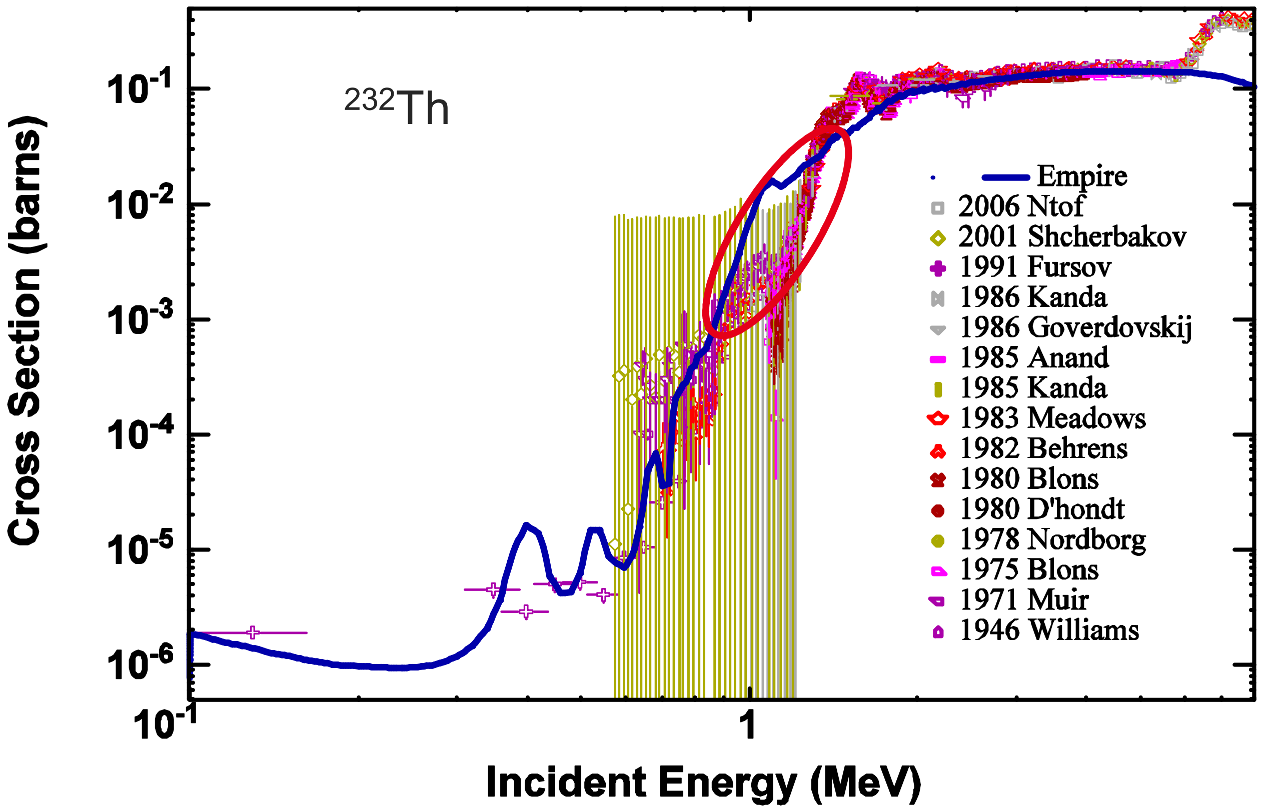


See in Sin et al., PRC 74 (2006) 014608
Bjornholm and Lynn, Rev. Mod. Phys. 52 (1980) 725.

Fission transmission coefficient : class II and class III states

Case of a fertile nucleus

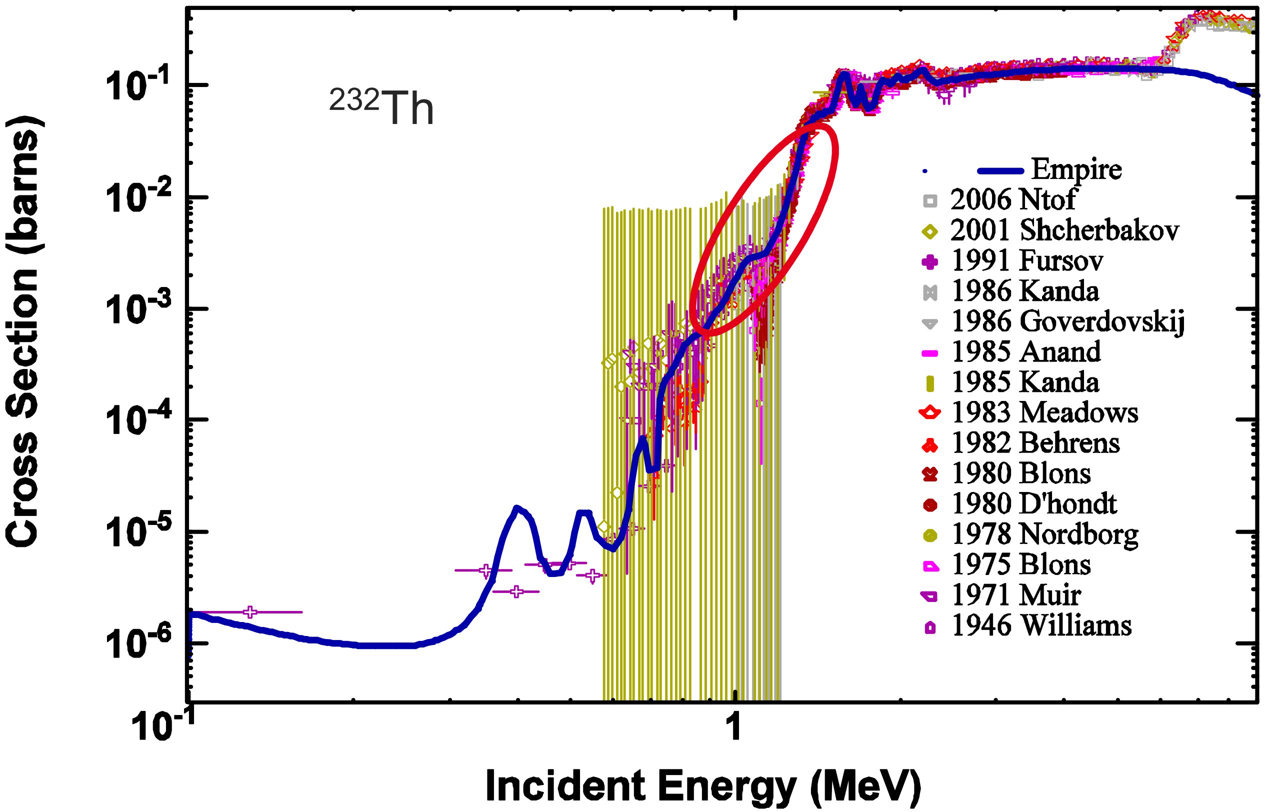
Partially damped class II states. No class III states



Fission transmission coefficient : class II and class III states

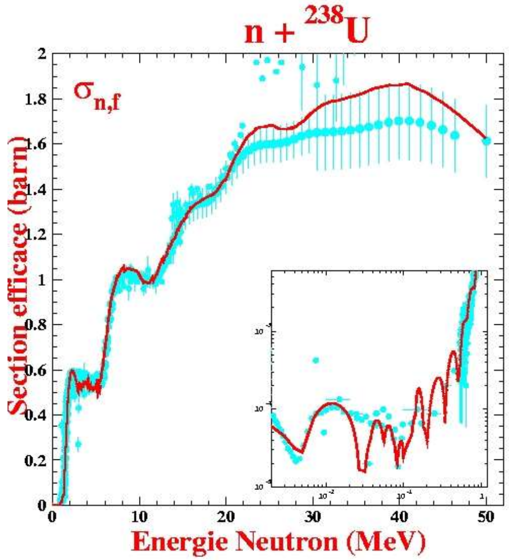
Case of a fertile nucleus

Class II + III states. Partial damping.

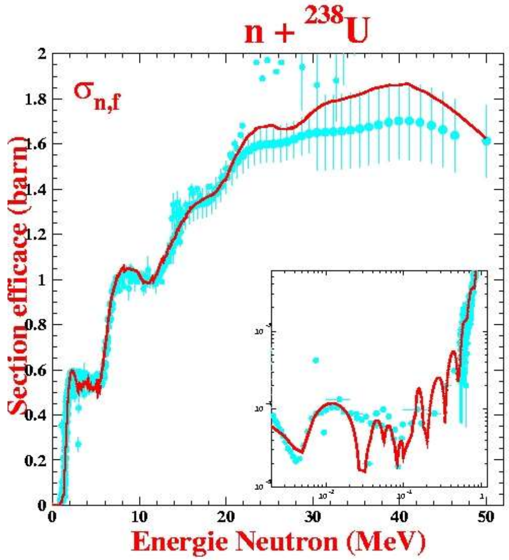


Coherent fission modeling : single target / several fissions

Coherent fission modeling : single target / several fissions



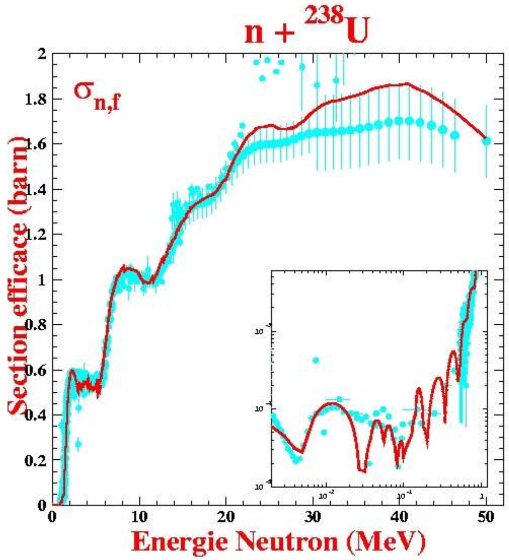
Coherent fission modeling : single target / several fissions



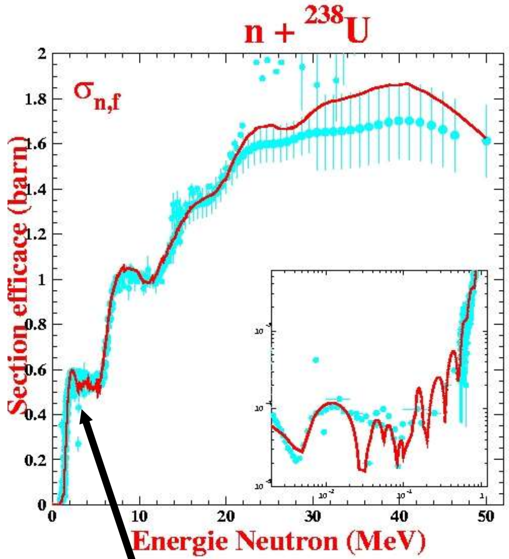
U9

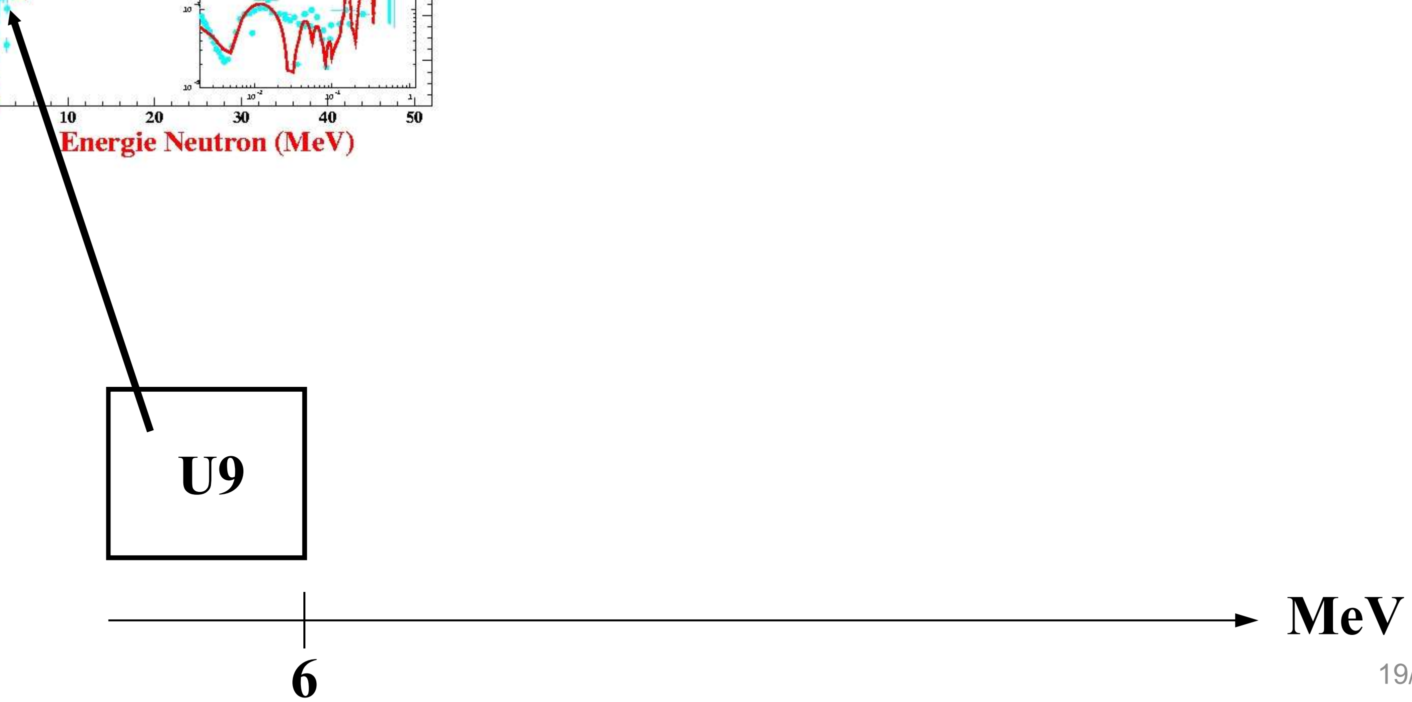
MeV

Coherent fission modeling : single target / several fissions

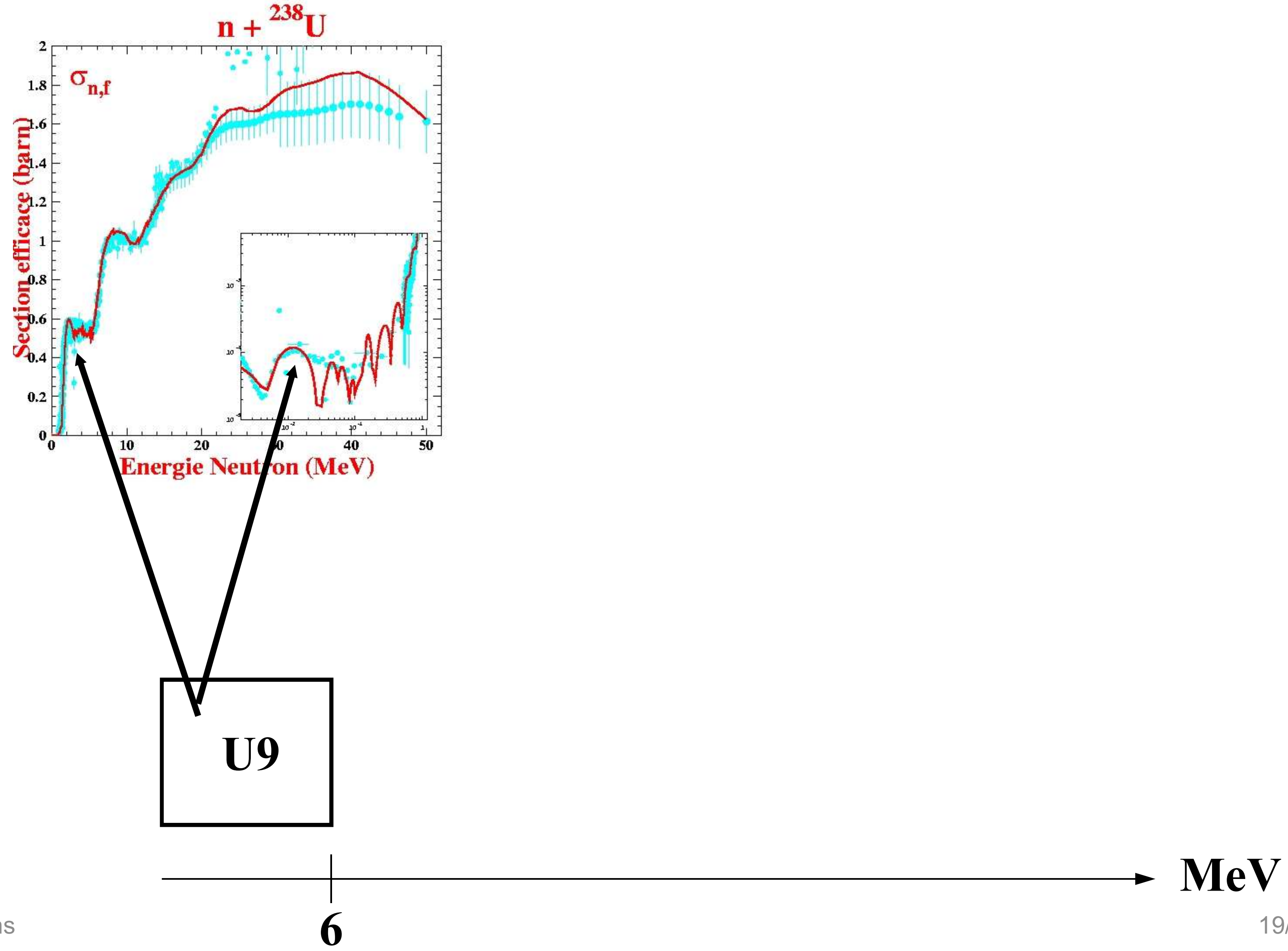


Coherent fission modeling : single target / several fissions

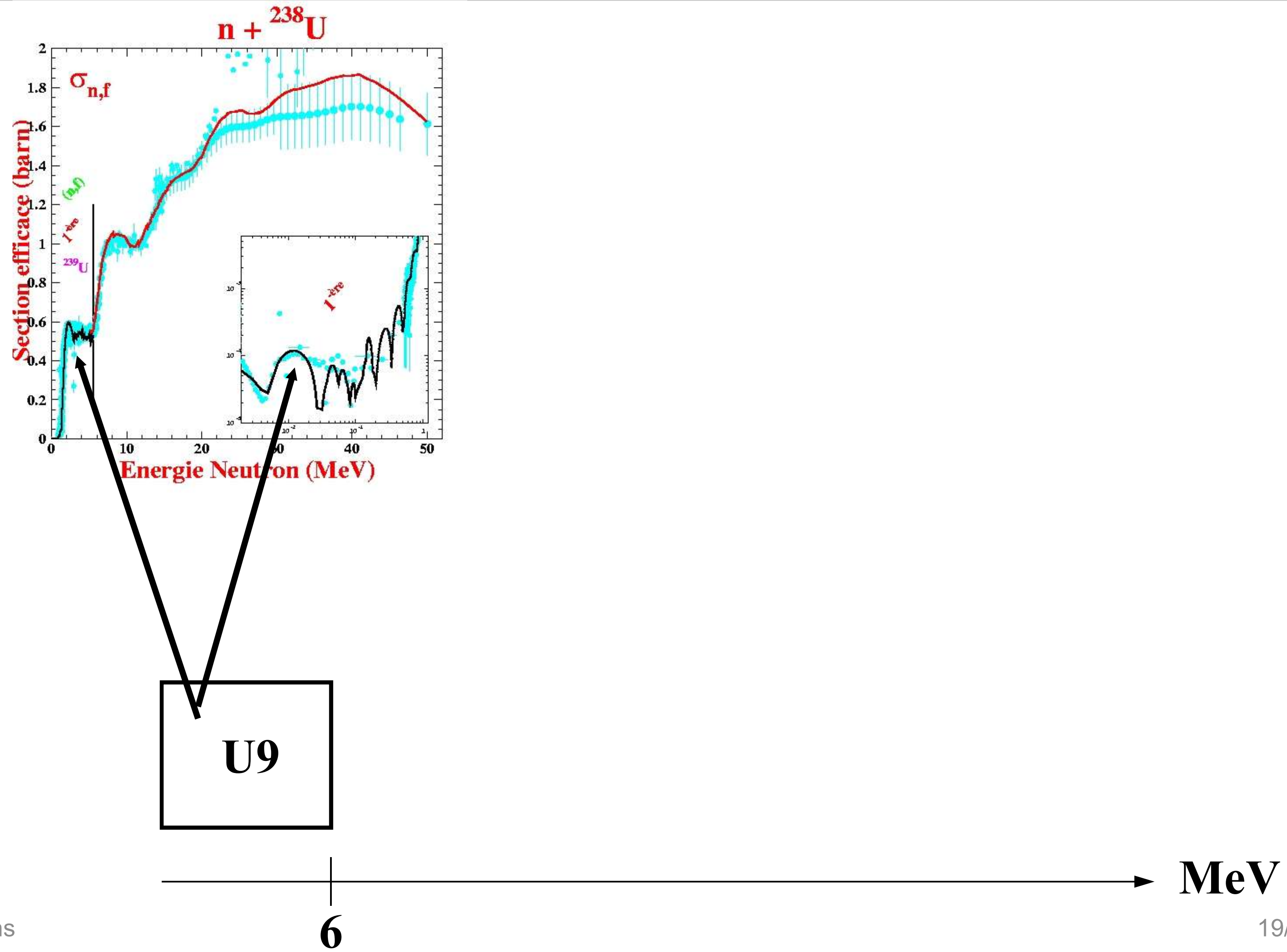




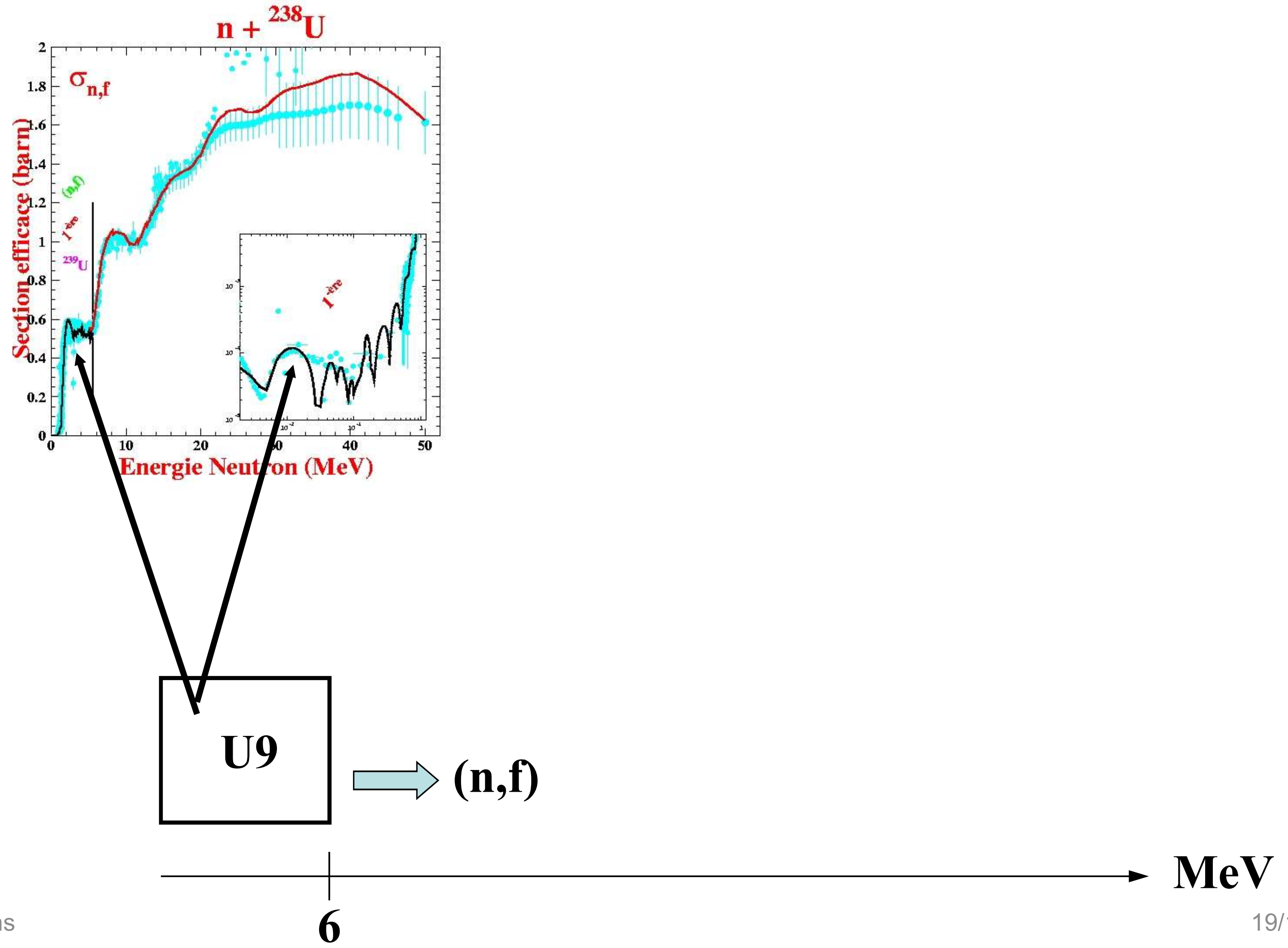
Coherent fission modeling : single target / several fissions



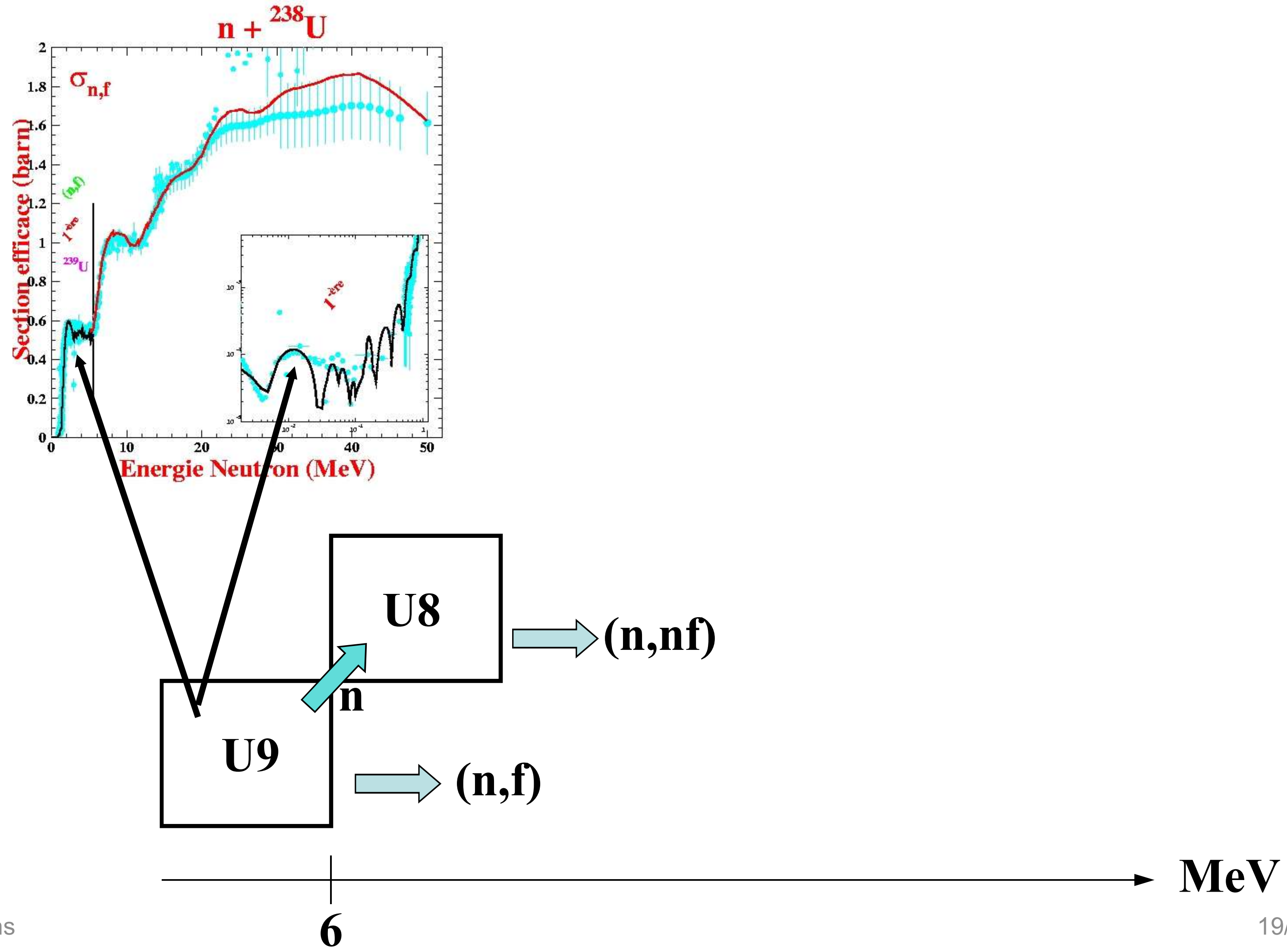
Coherent fission modeling : single target / several fissions



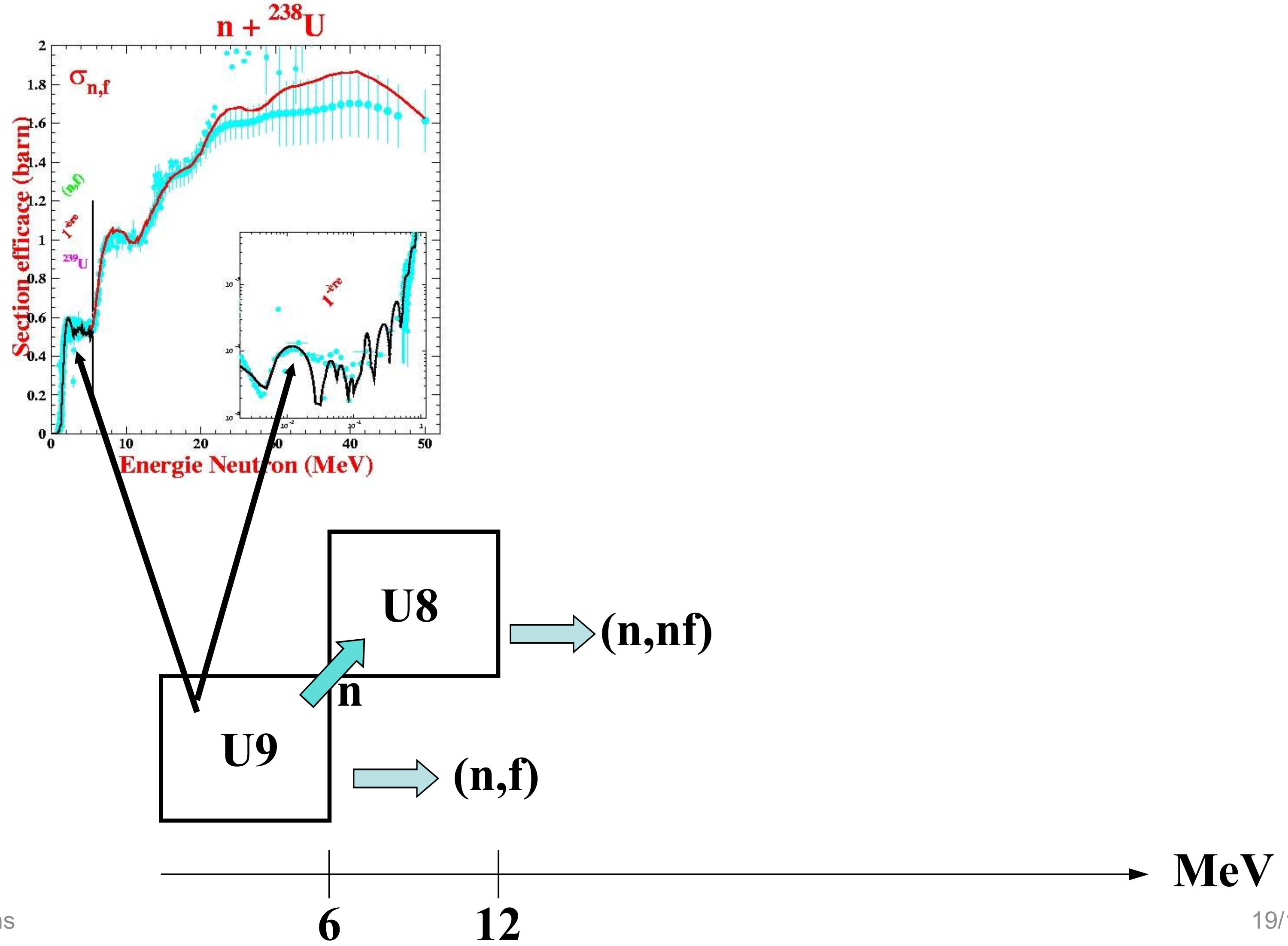
Coherent fission modeling : single target / several fissions



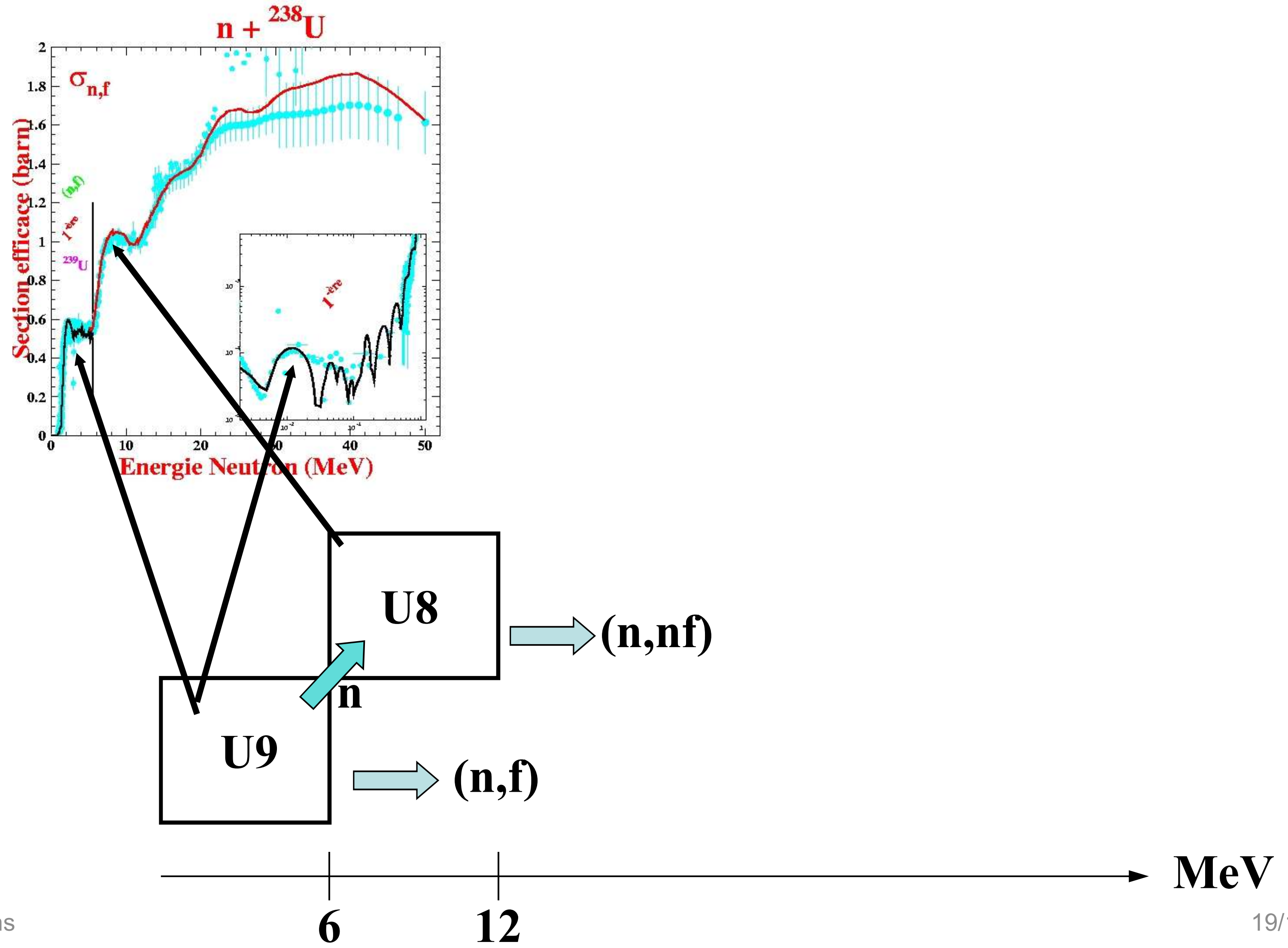
Coherent fission modeling : single target / several fissions



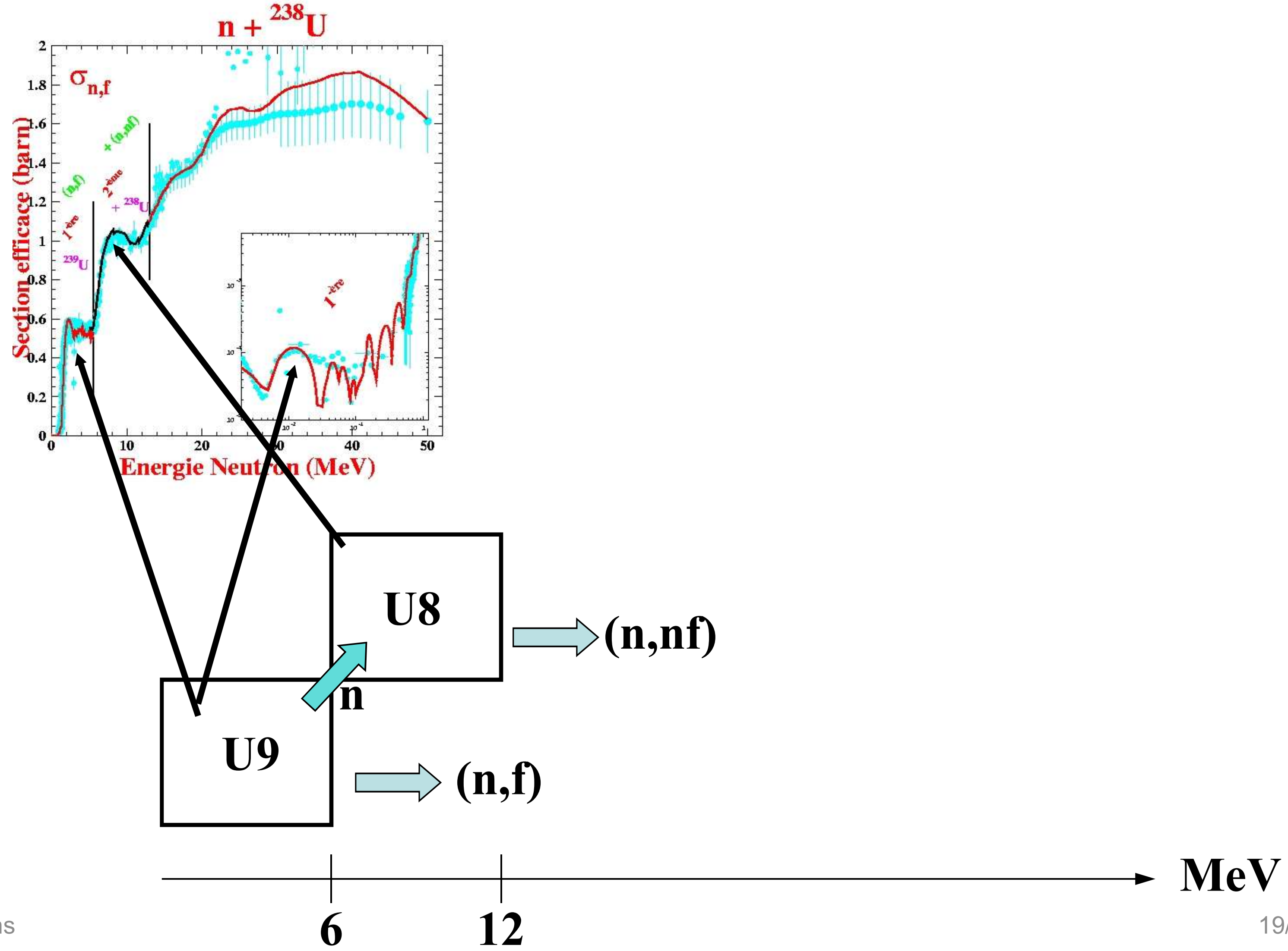
Coherent fission modeling : single target / several fissions



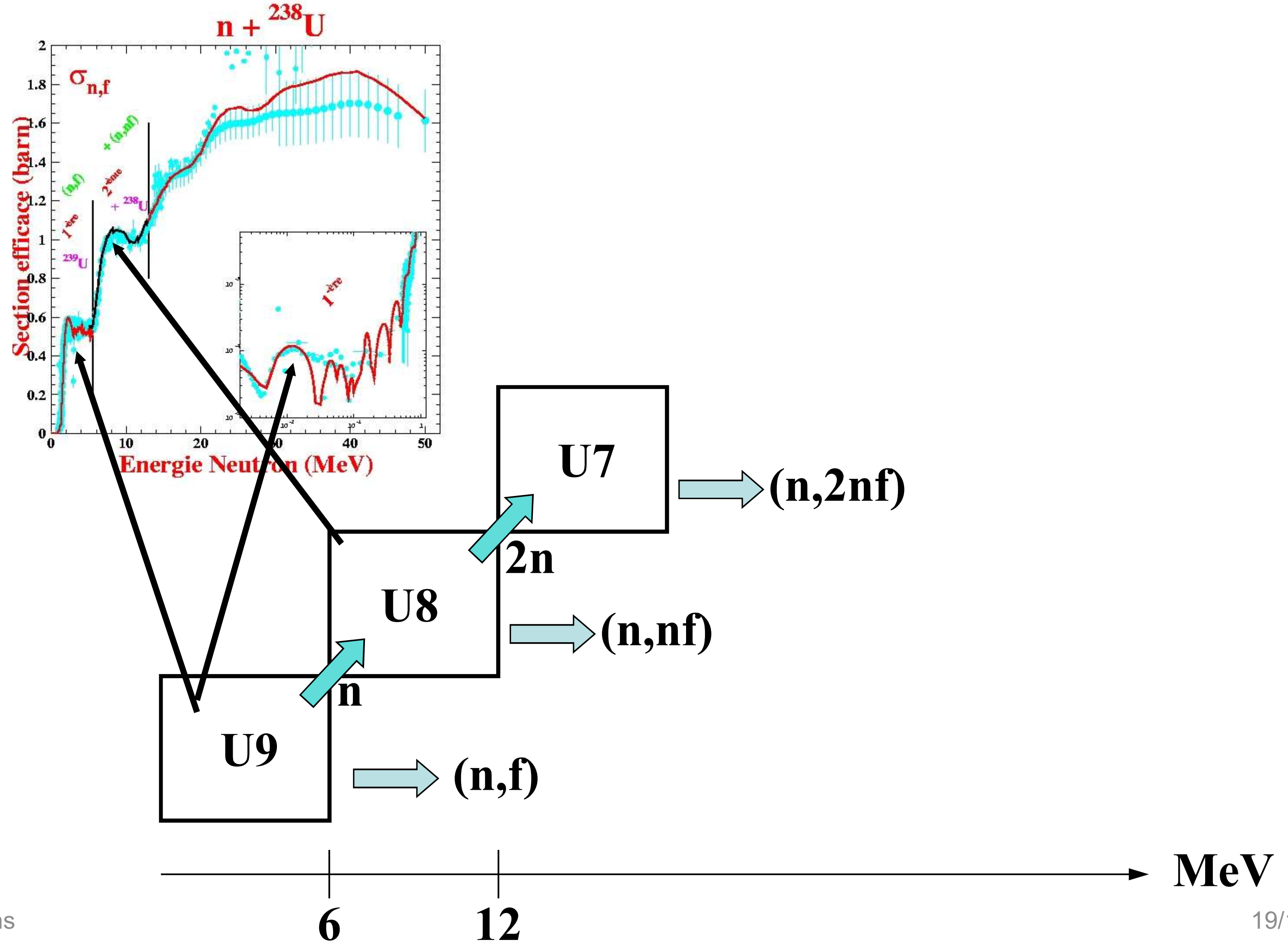
Coherent fission modeling : single target / several fissions



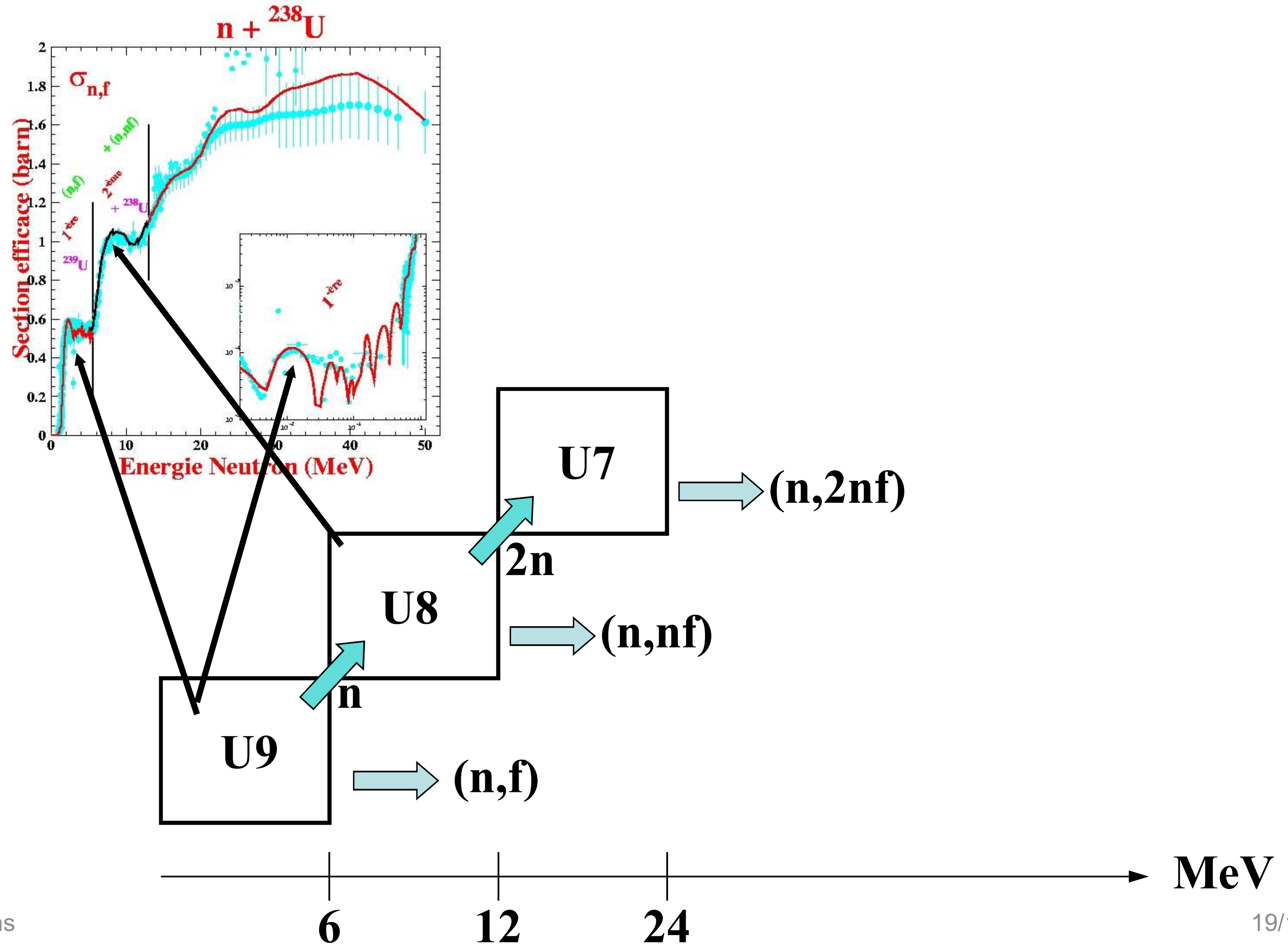
Coherent fission modeling : single target / several fissions



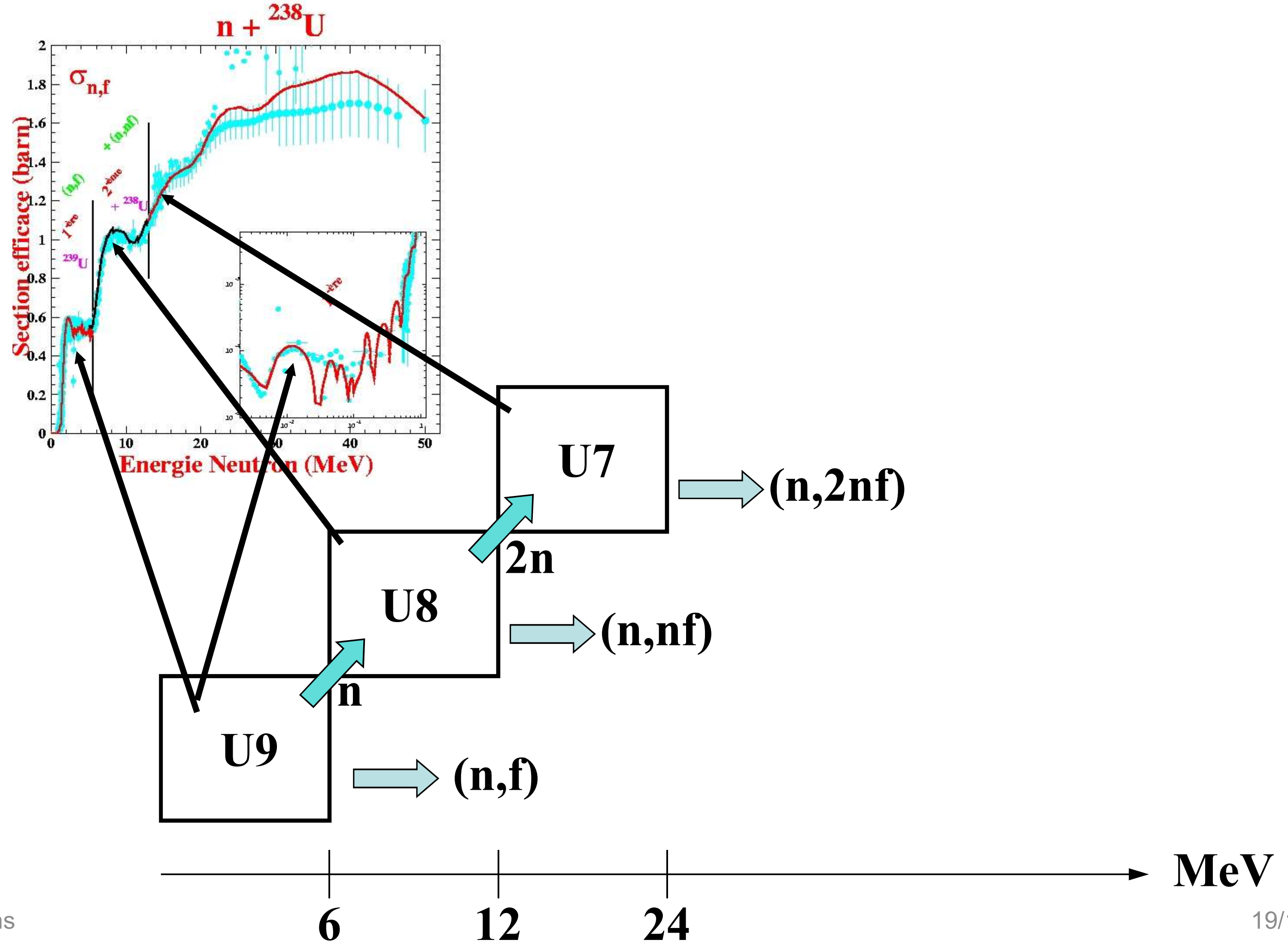
Coherent fission modeling : single target / several fissions



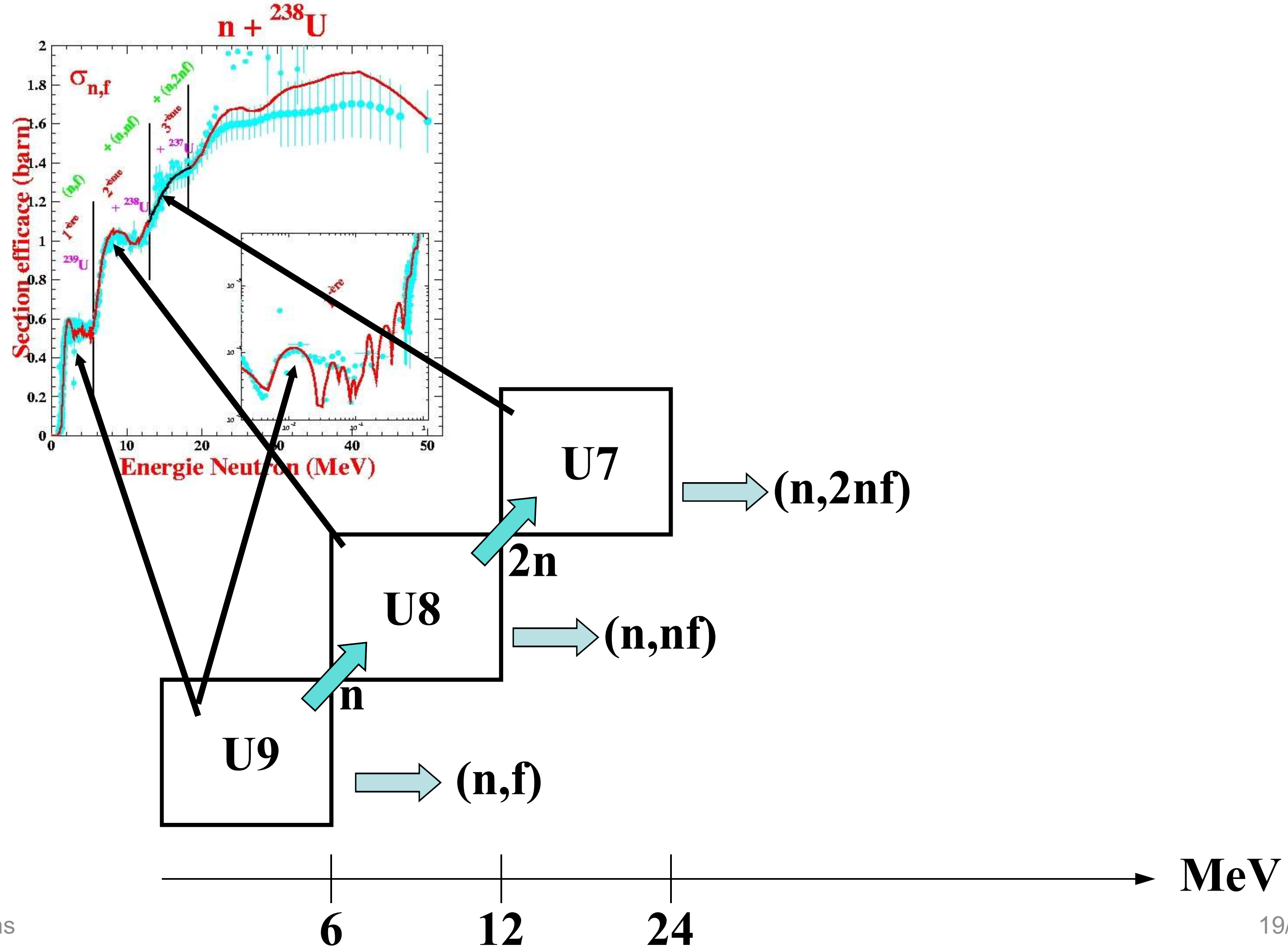
Coherent fission modeling : single target / several fissions



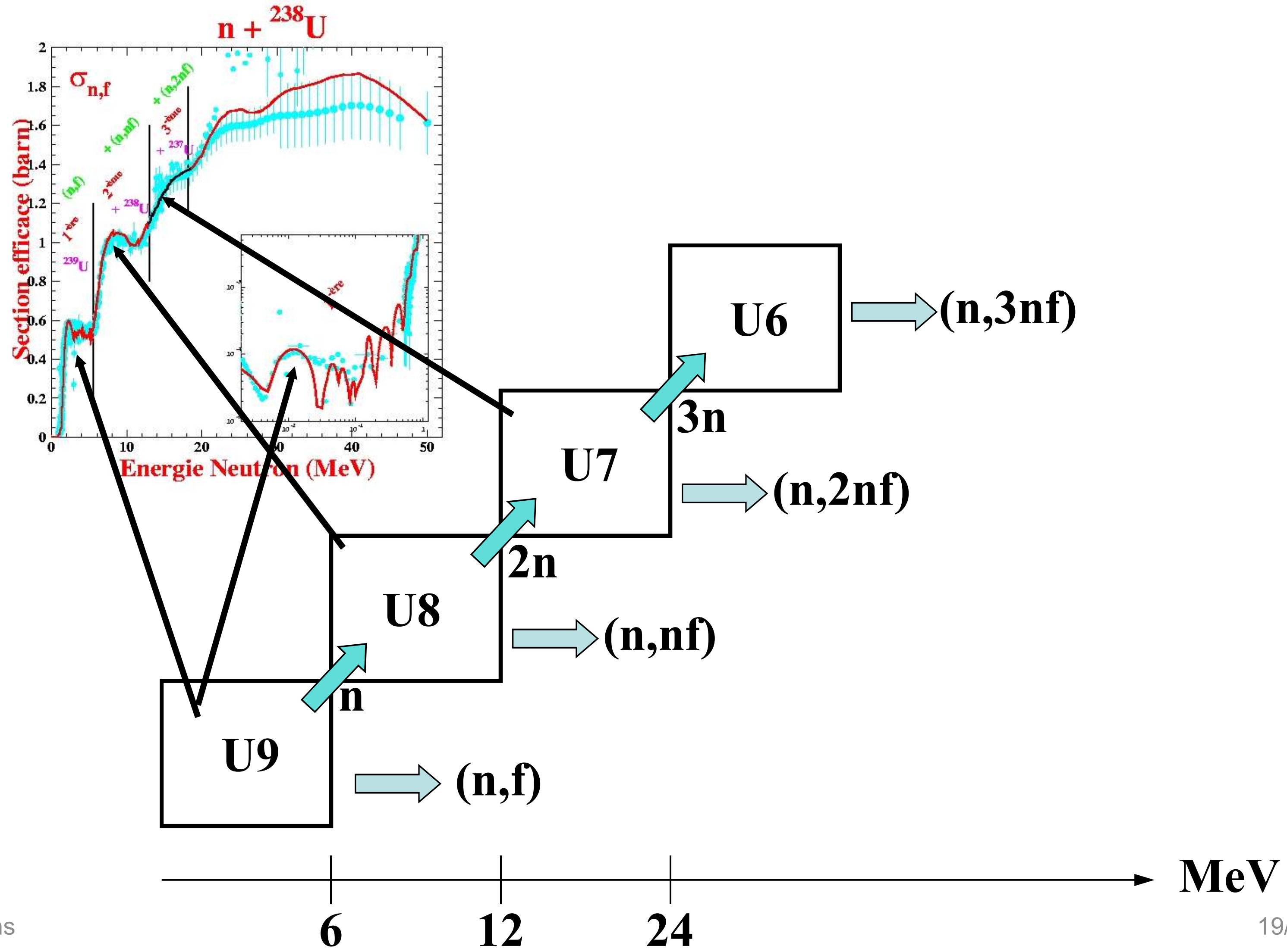
Coherent fission modeling : single target / several fissions



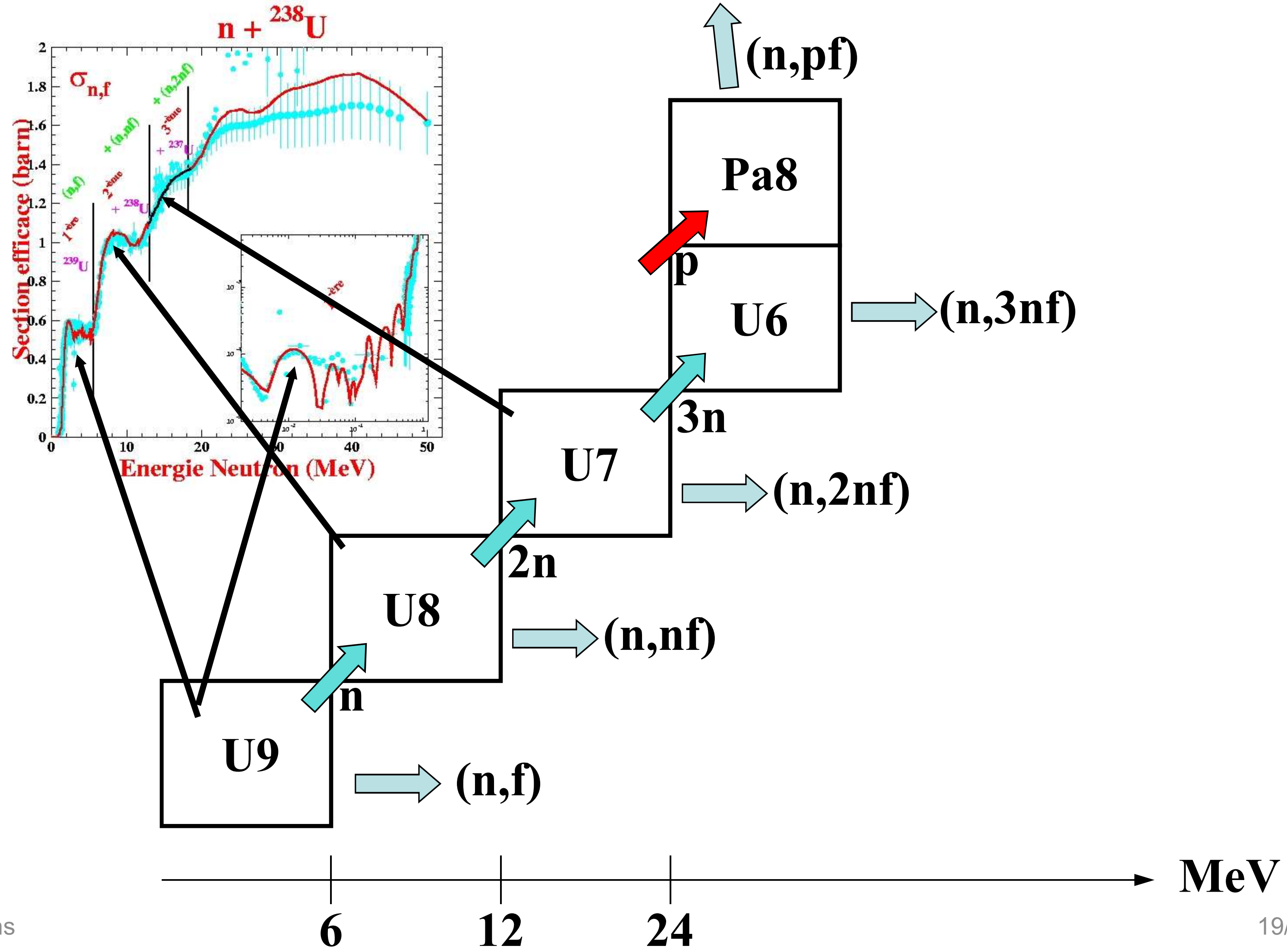
Coherent fission modeling : single target / several fissions



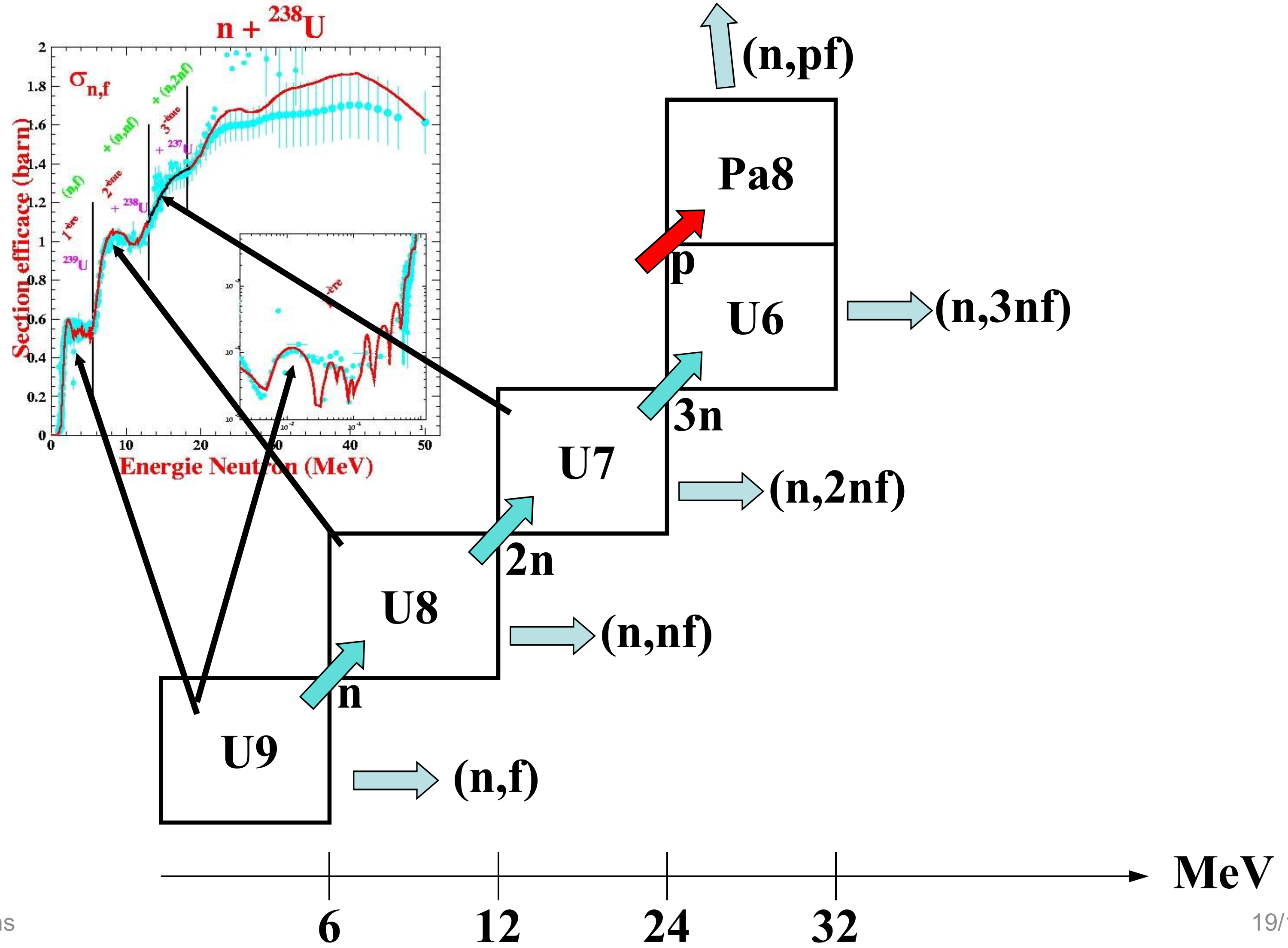
Coherent fission modeling : single target / several fissions



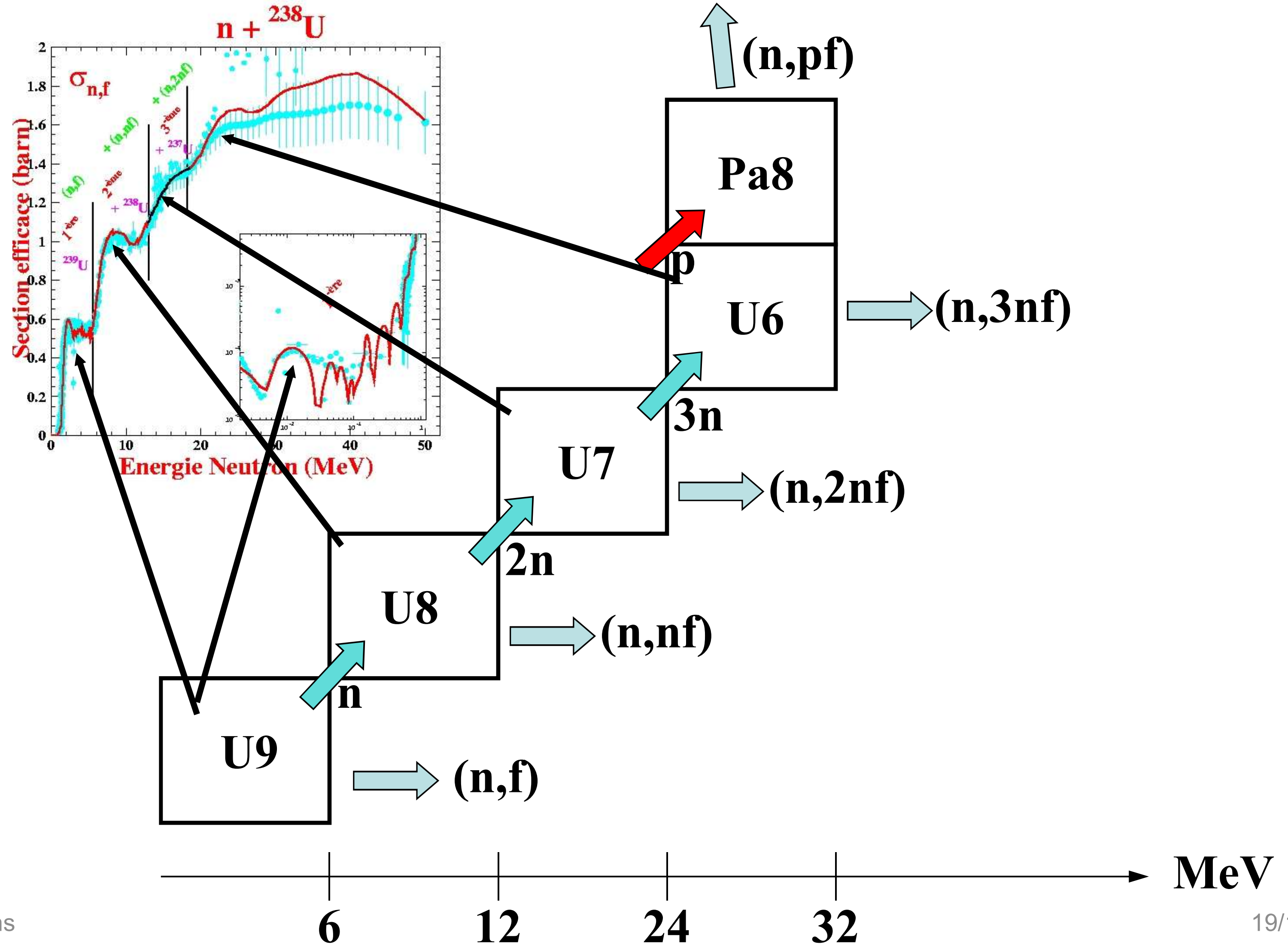
Coherent fission modeling : single target / several fissions



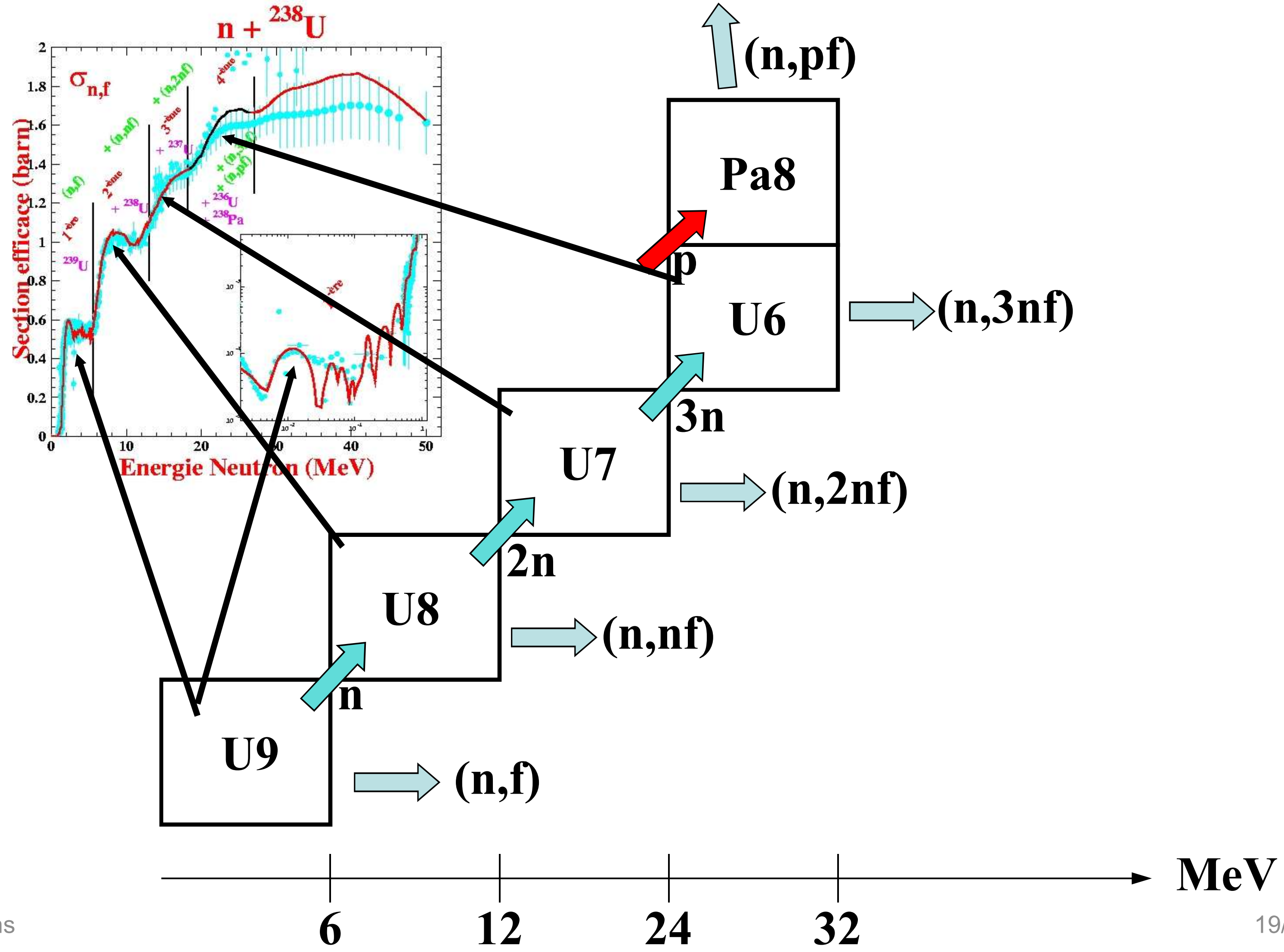
Coherent fission modeling : single target / several fissions



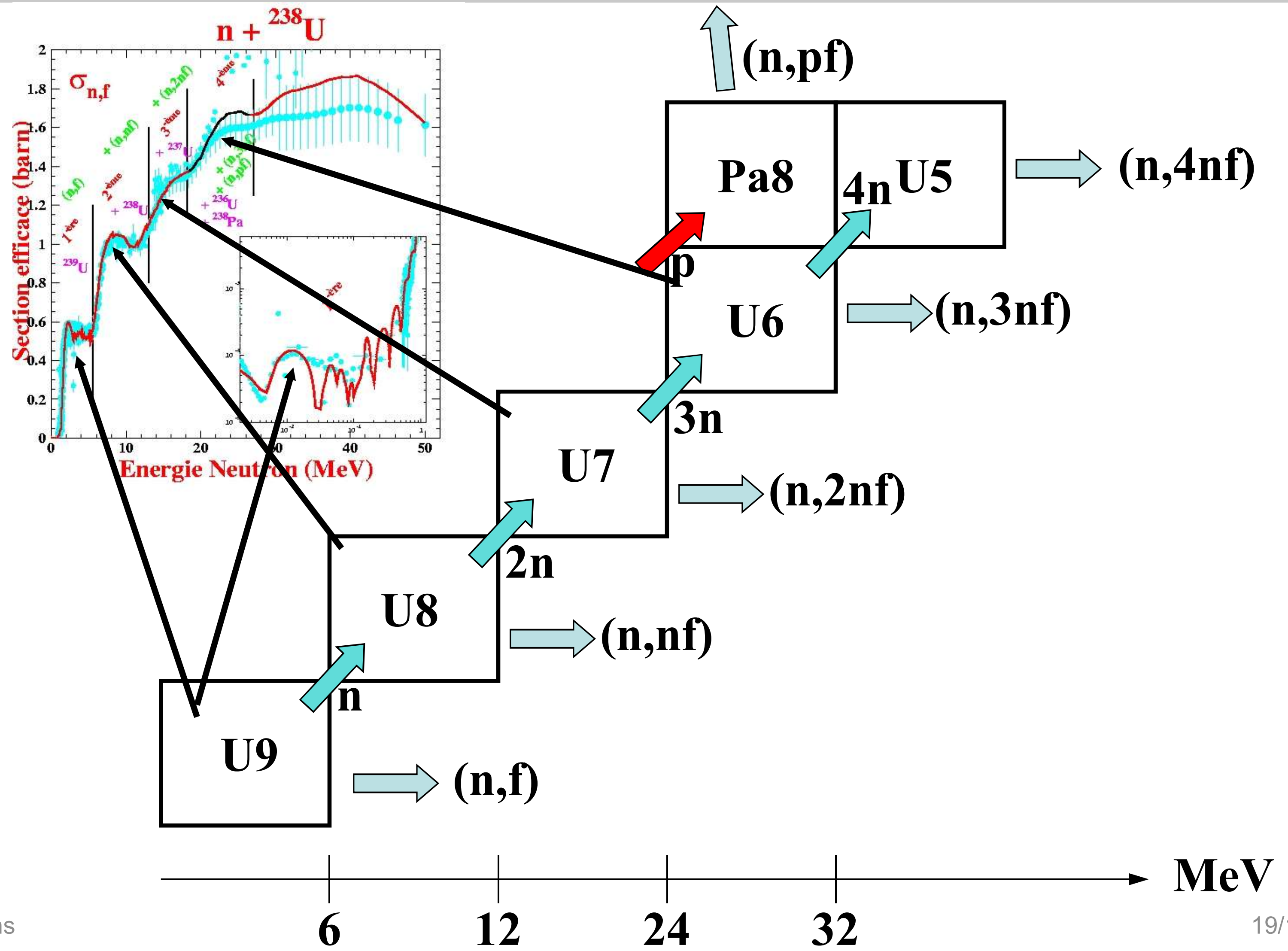
Coherent fission modeling : single target / several fissions



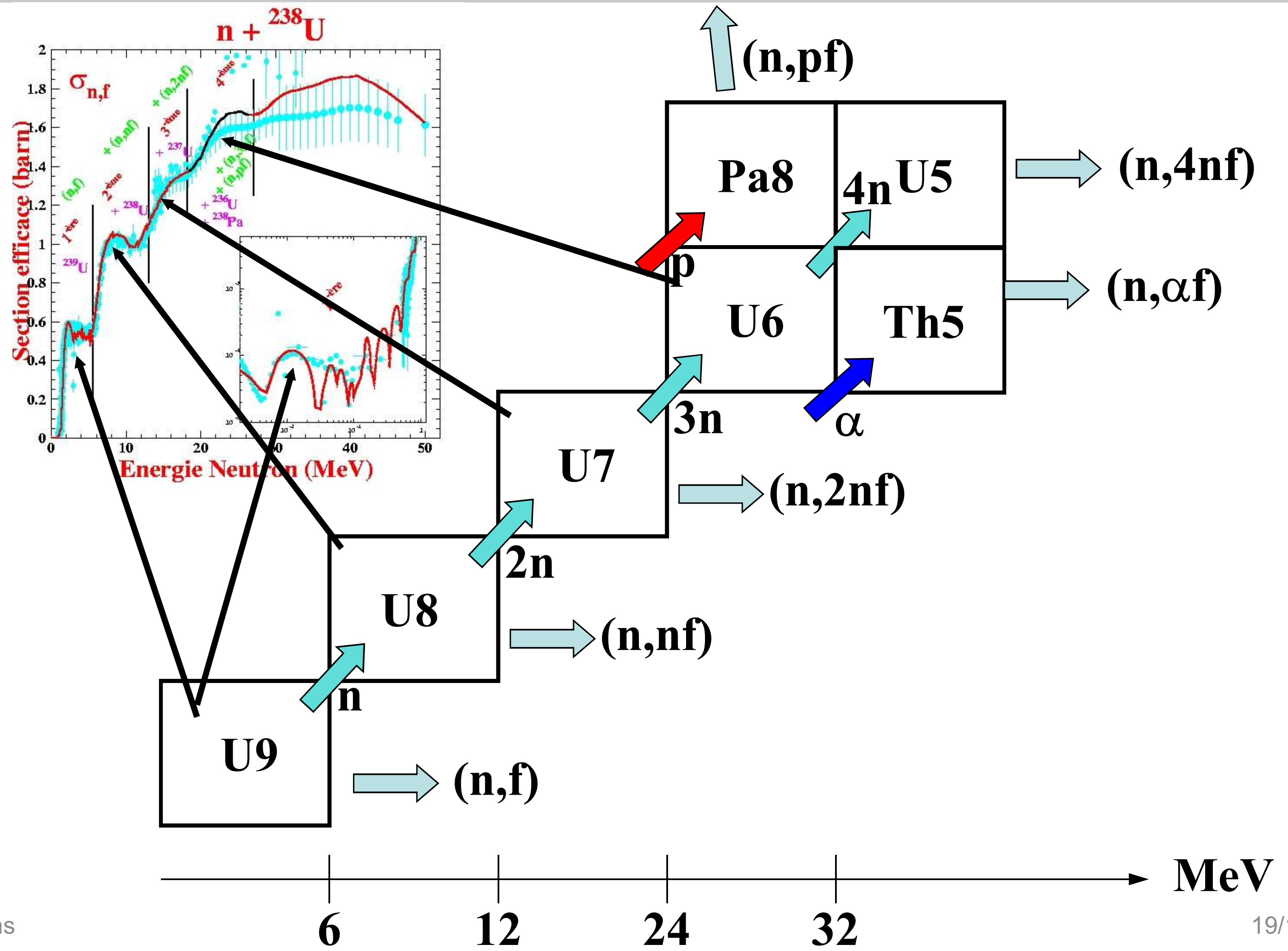
Coherent fission modeling : single target / several fissions



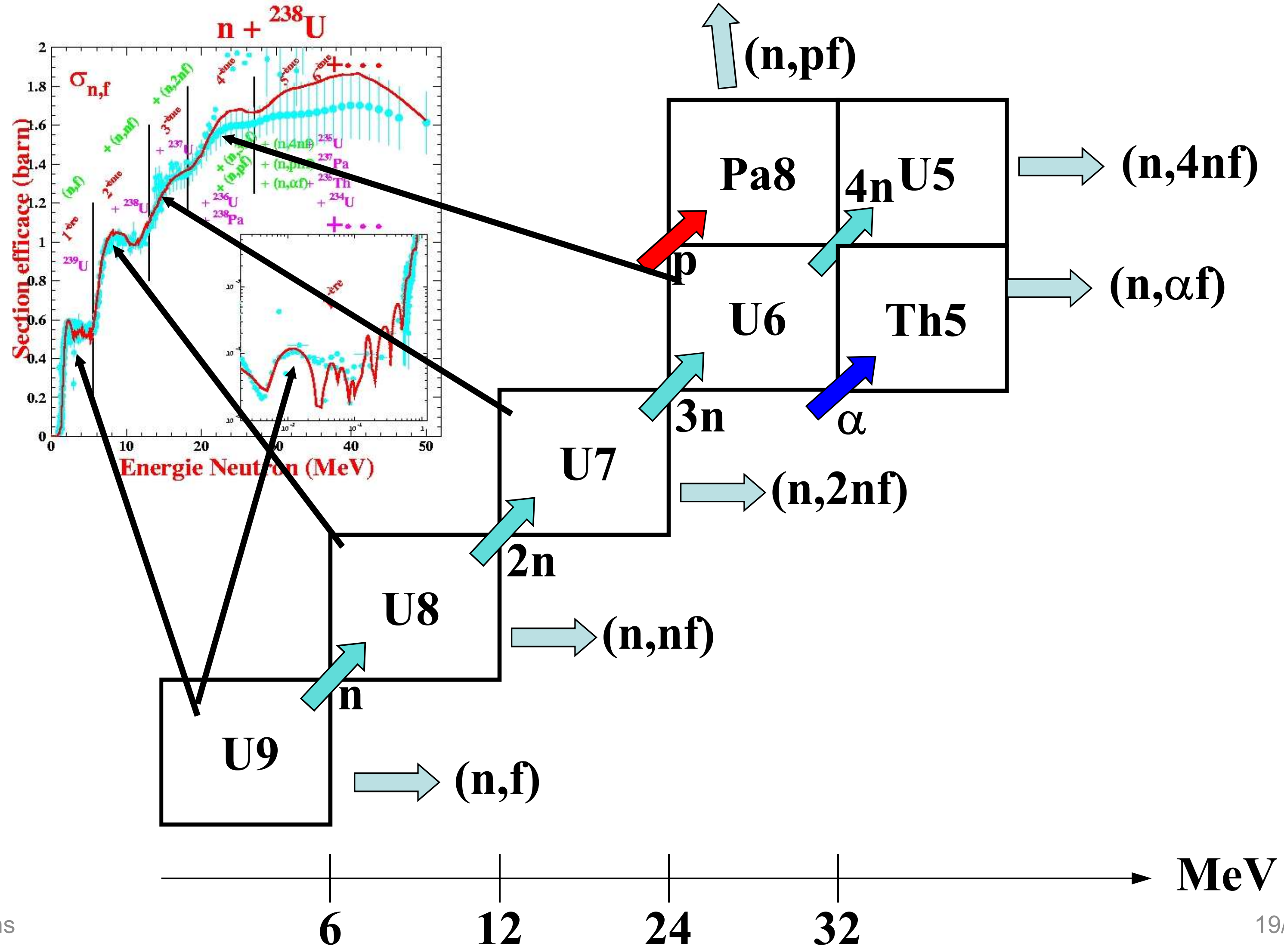
Coherent fission modeling : single target / several fissions



Coherent fission modeling : single target / several fissions

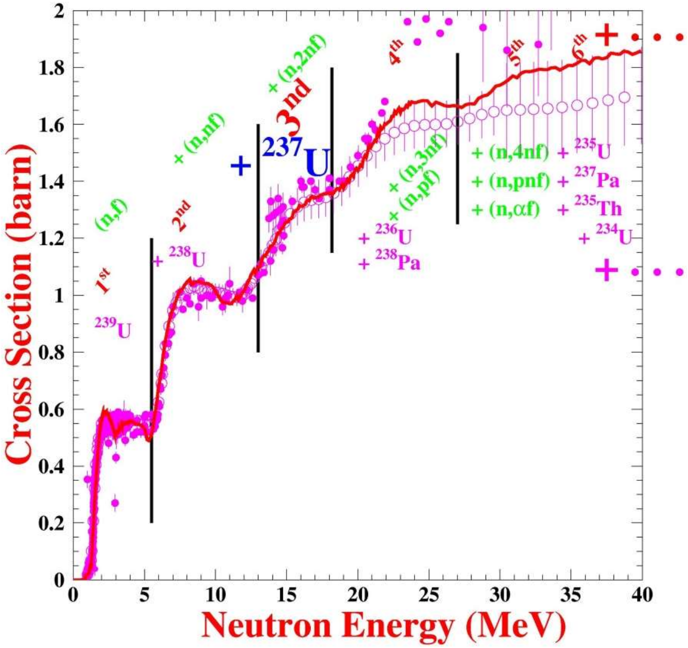


Coherent fission modeling : single target / several fissions

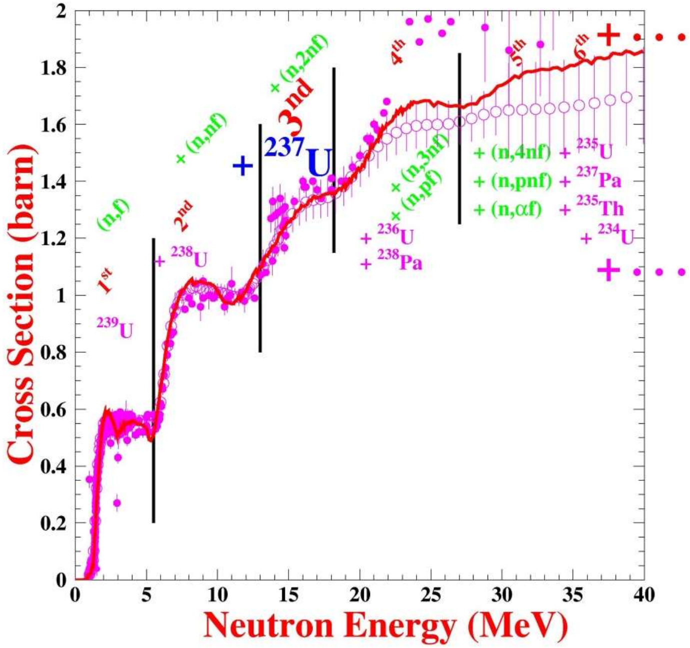


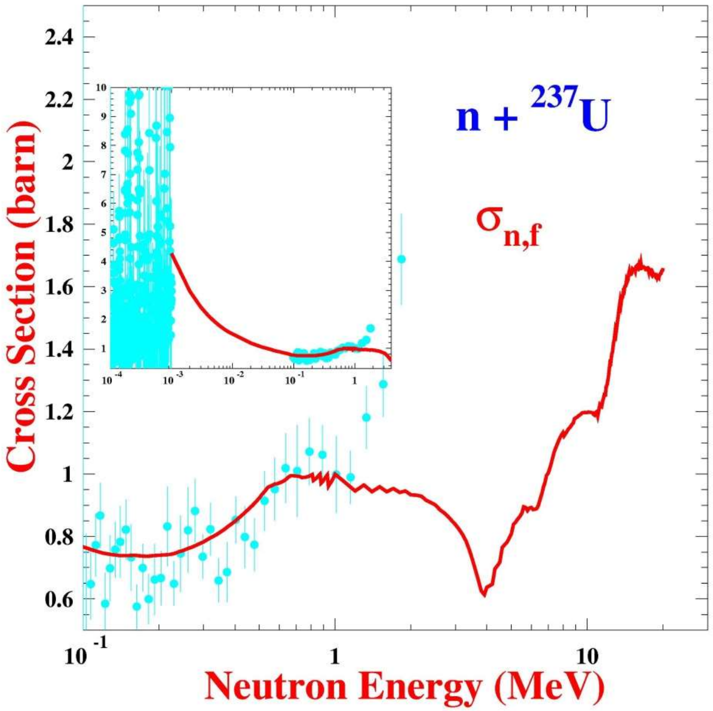
Coherent fission modeling : several targets / strong constraints

Coherent fis … nstraints

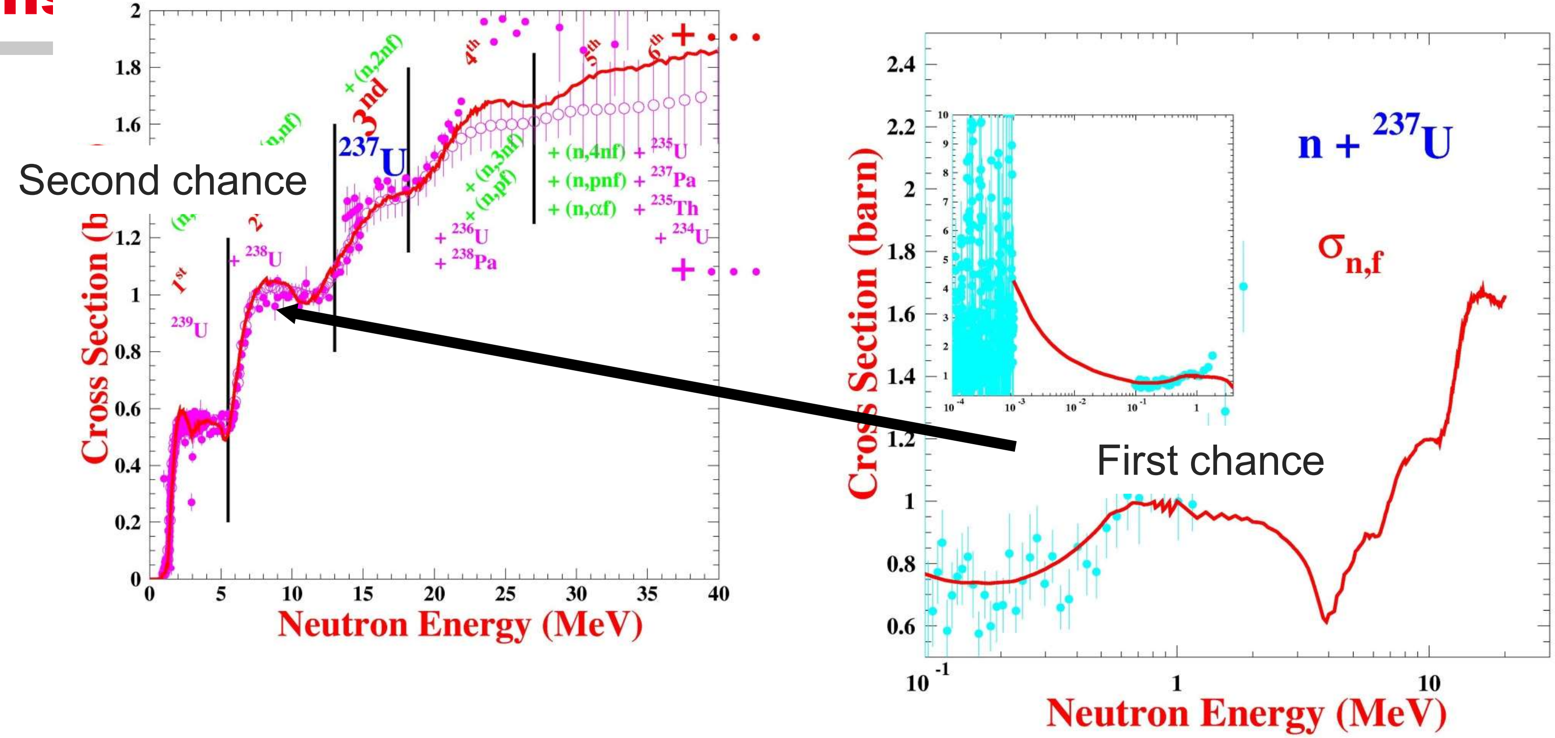


Coherent fis ... nts

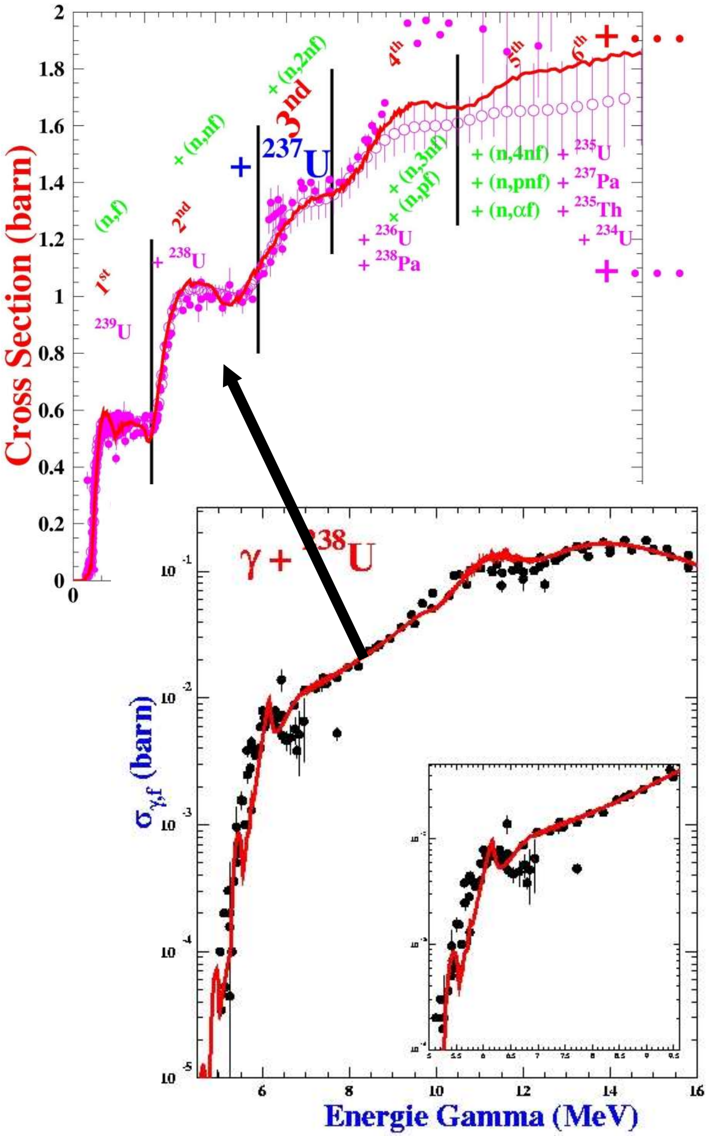


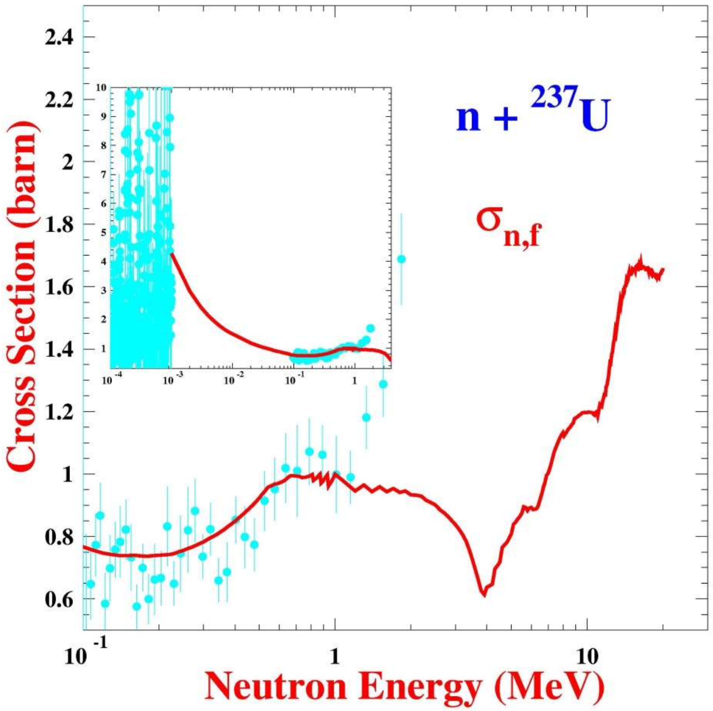


Coherent fi… nts

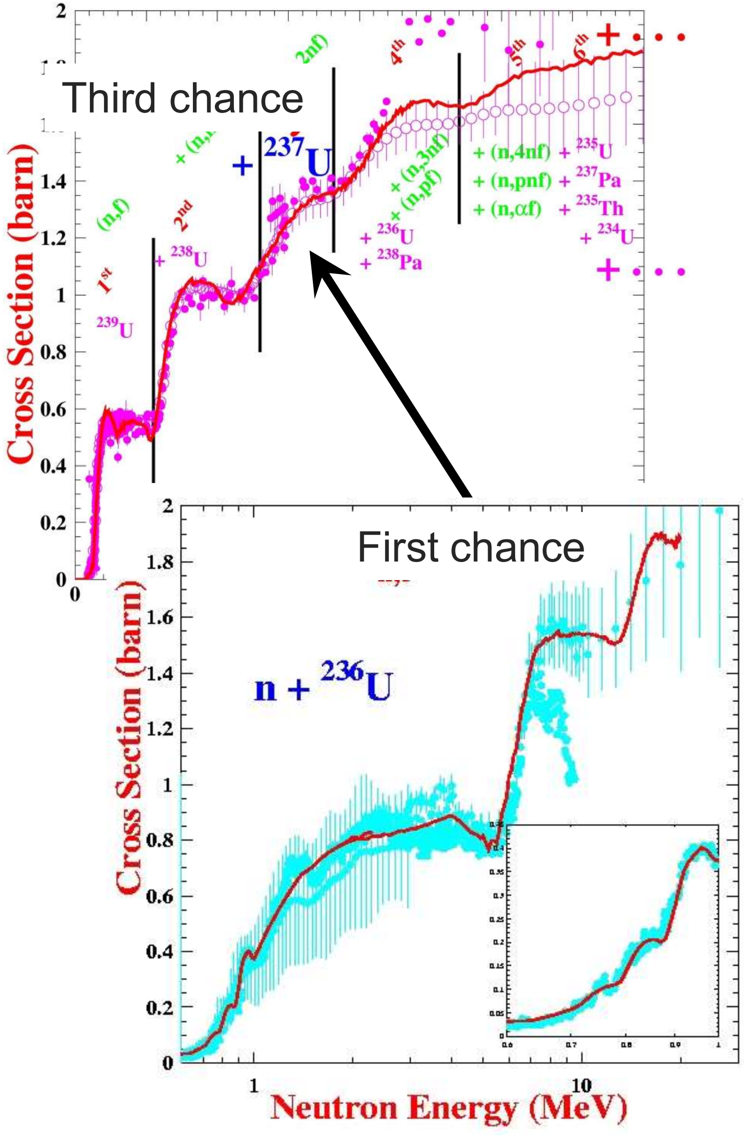


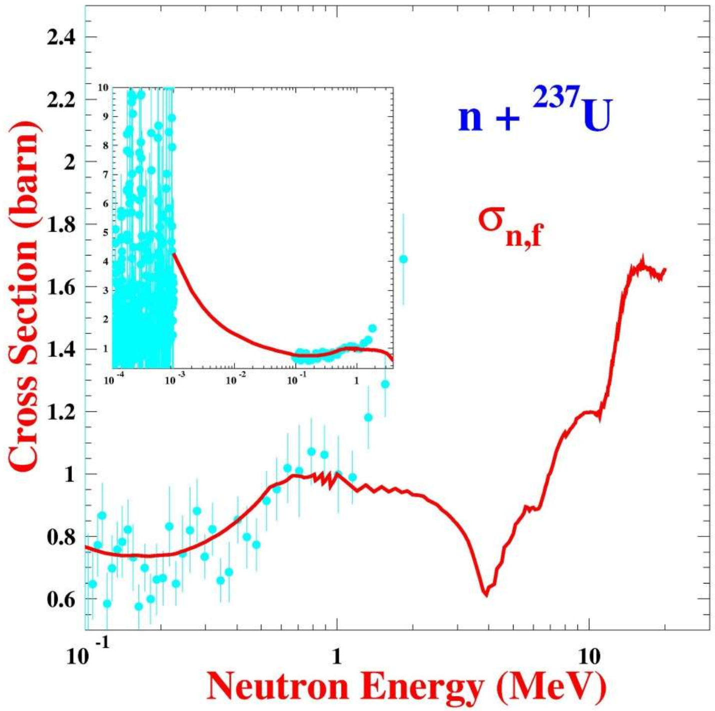
Coherent fis… …nts



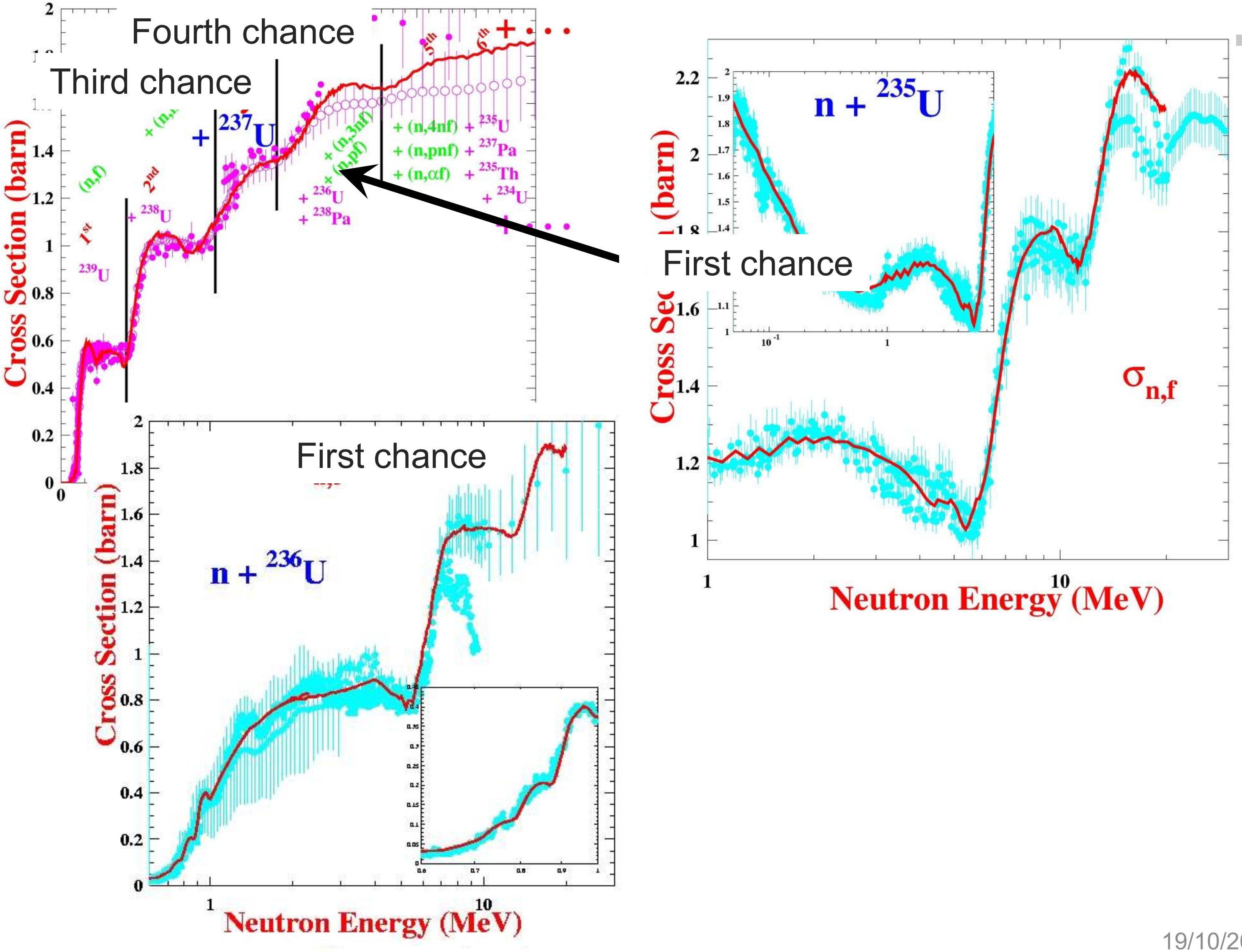


Coherent fis ... nts

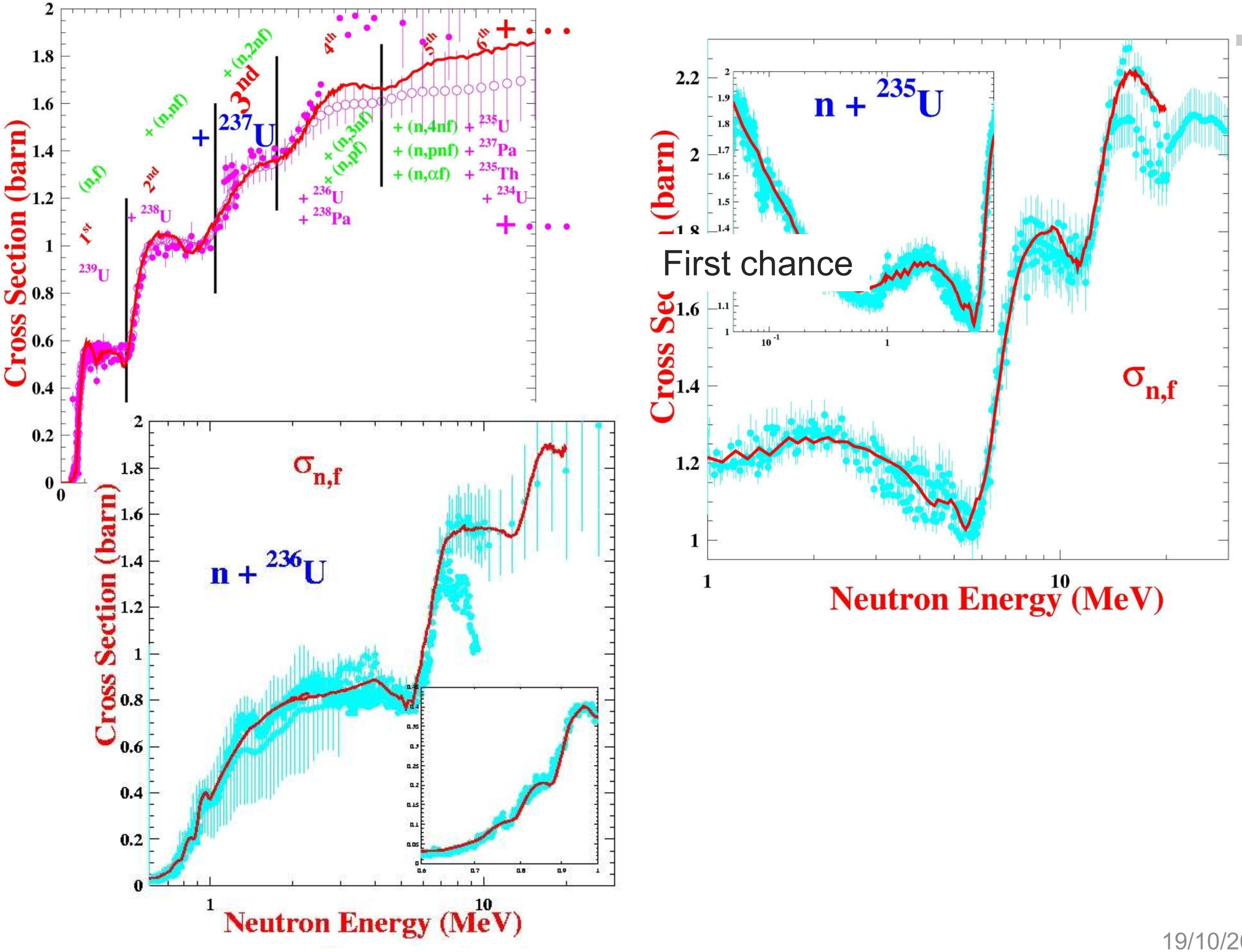




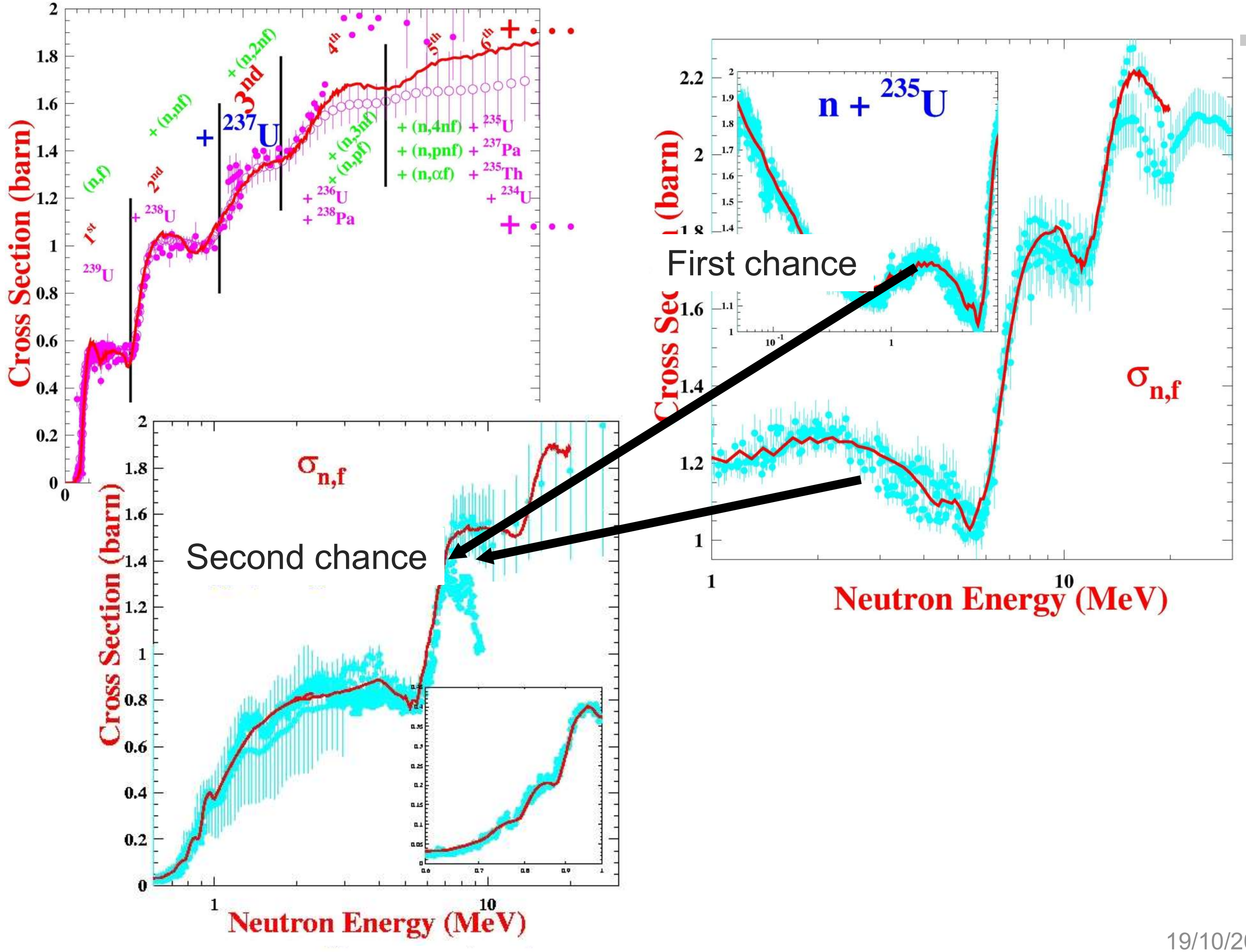
Coherent fis … nts



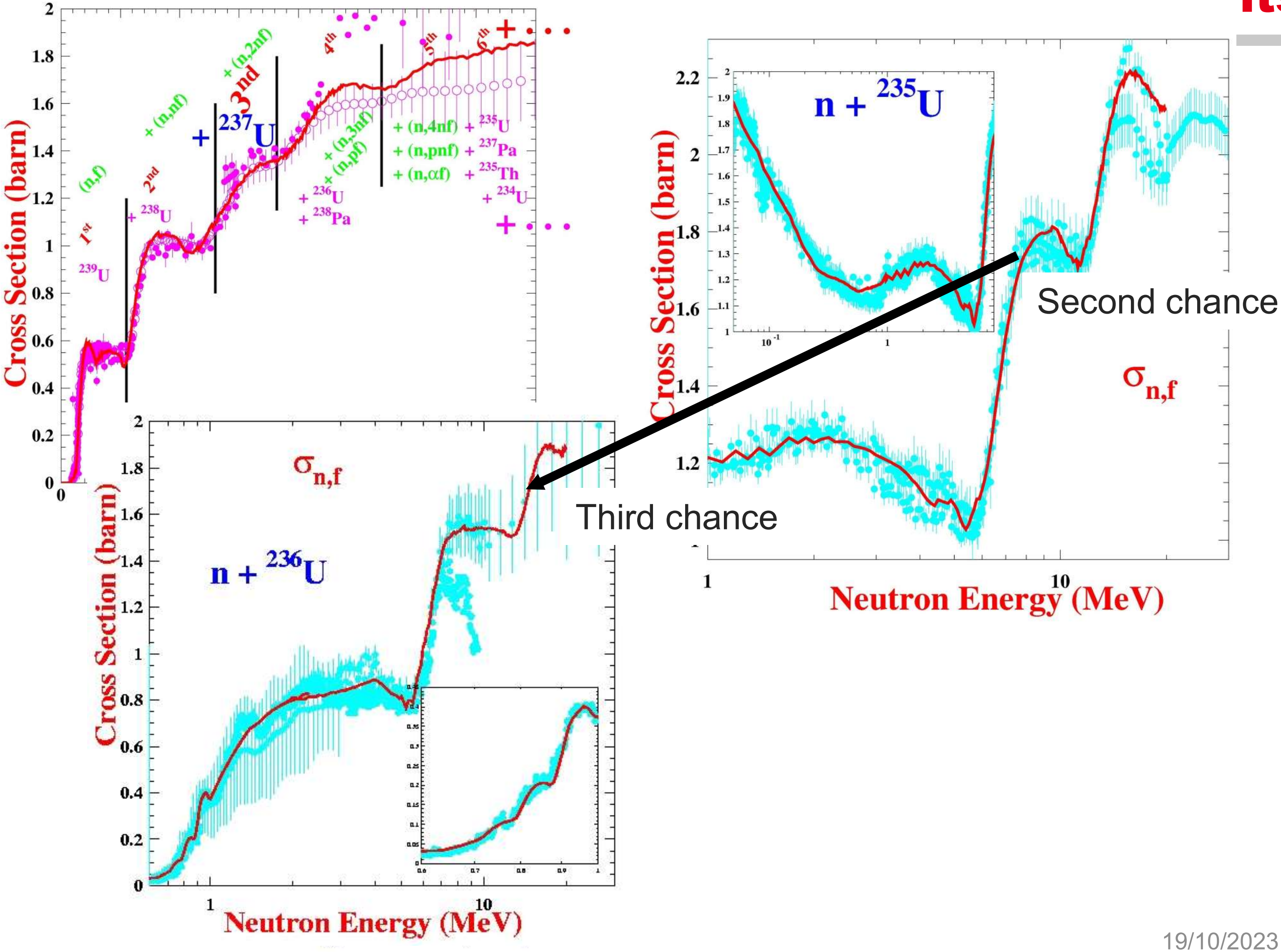
Coherent fis … nts



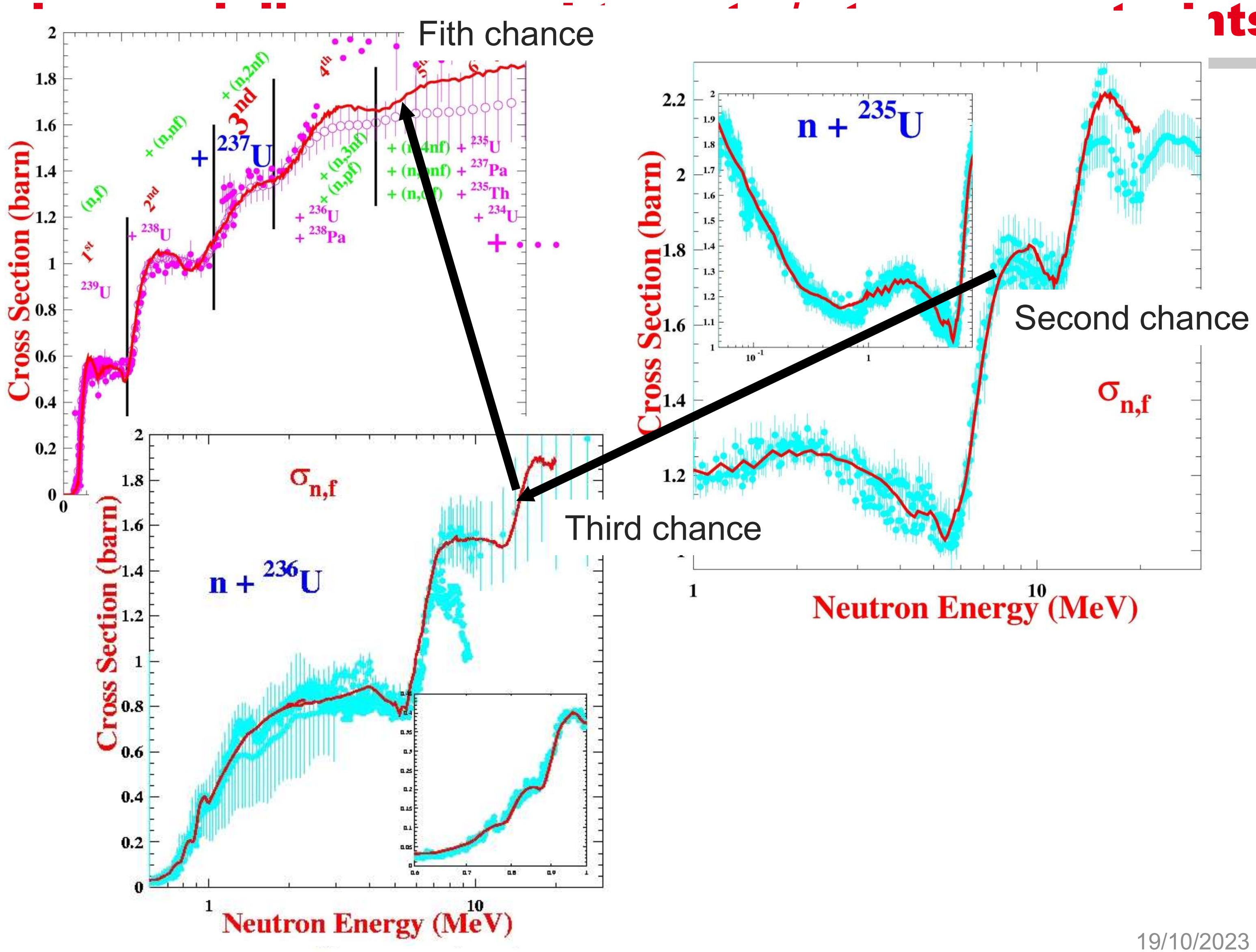
Coherent fis … nts



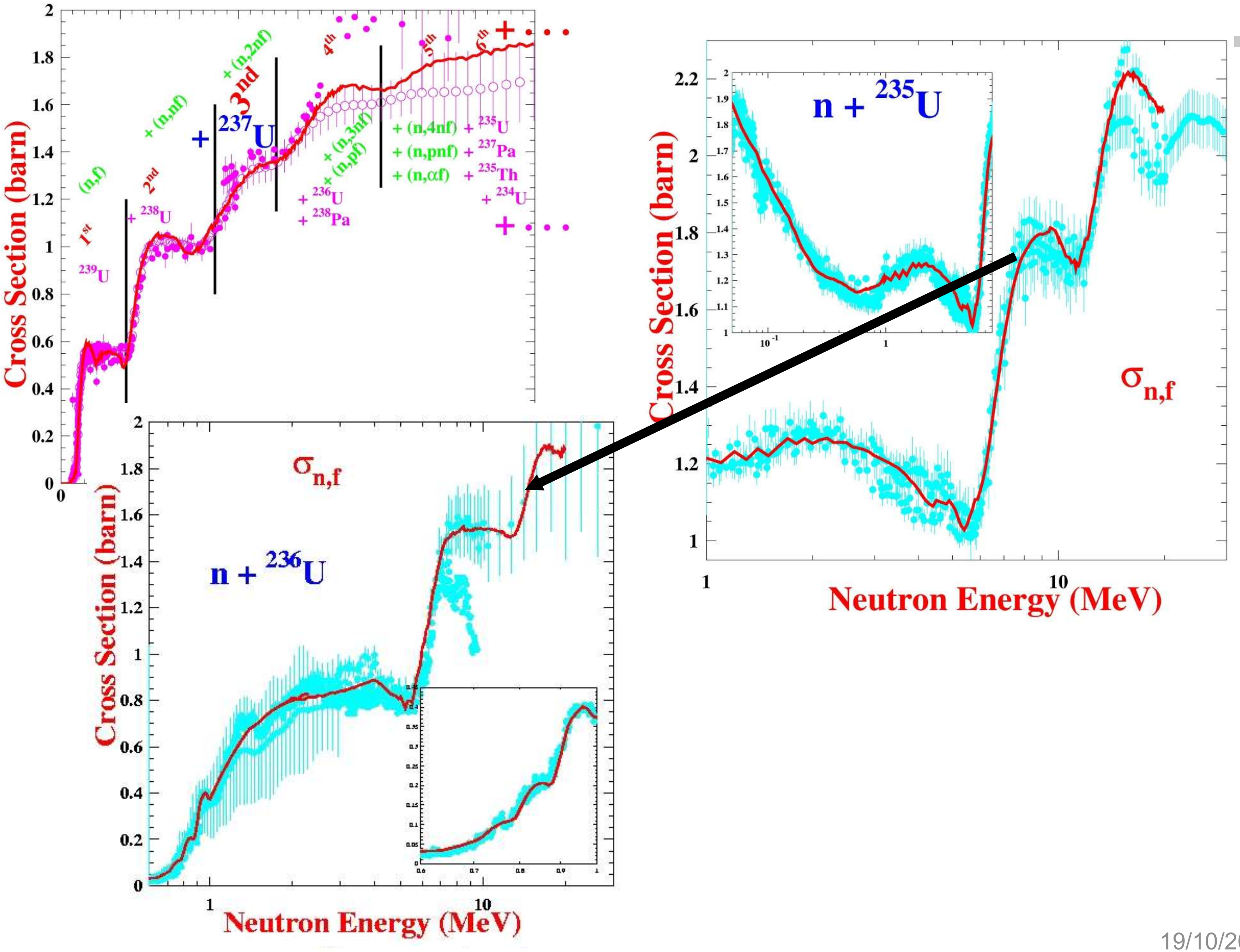
Coherent fis ... nts



Coherent fi… …nts



Coherent fis… …nts



Microscopic approach

Ingredients of relevance to estimate fission properties

$$T(E,J,\pi) = \int_0^E P(E-\varepsilon)\rho(\varepsilon,J,\pi)d\varepsilon \quad \begin{cases} P(E) = \dfrac{1}{1+\exp(2K)} \\ K = \pm \displaystyle\int_a^b [2\mu(E-V(\beta))/\hbar^2]^{1/2} d\beta \end{cases}$$

Hill-Wheeler approximation: $P^{HW} = \dfrac{1}{1+\exp[2\pi(V_0 - E)/\hbar\omega]}$

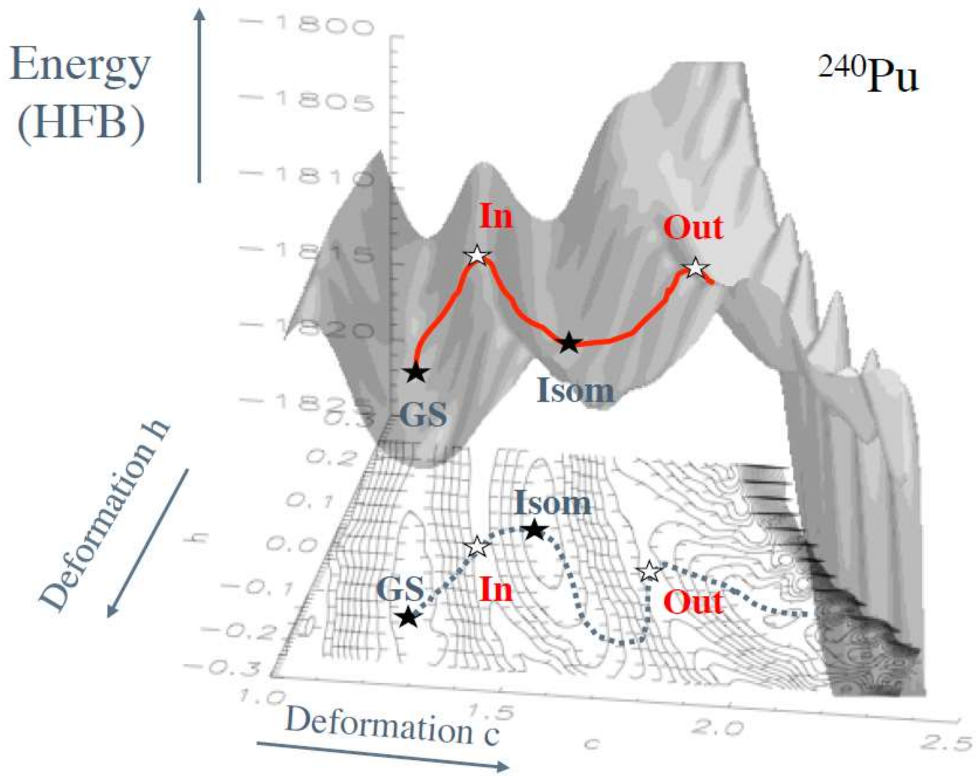
Fundamental ingredients:

- Fission barrier heights } Fission path
- Fission barrier widths }
- ***Nuclear Level Densities at saddle points***

MAJOR CHALLENGE: COHERENT PREDICTIONS OF ALL INPUTS

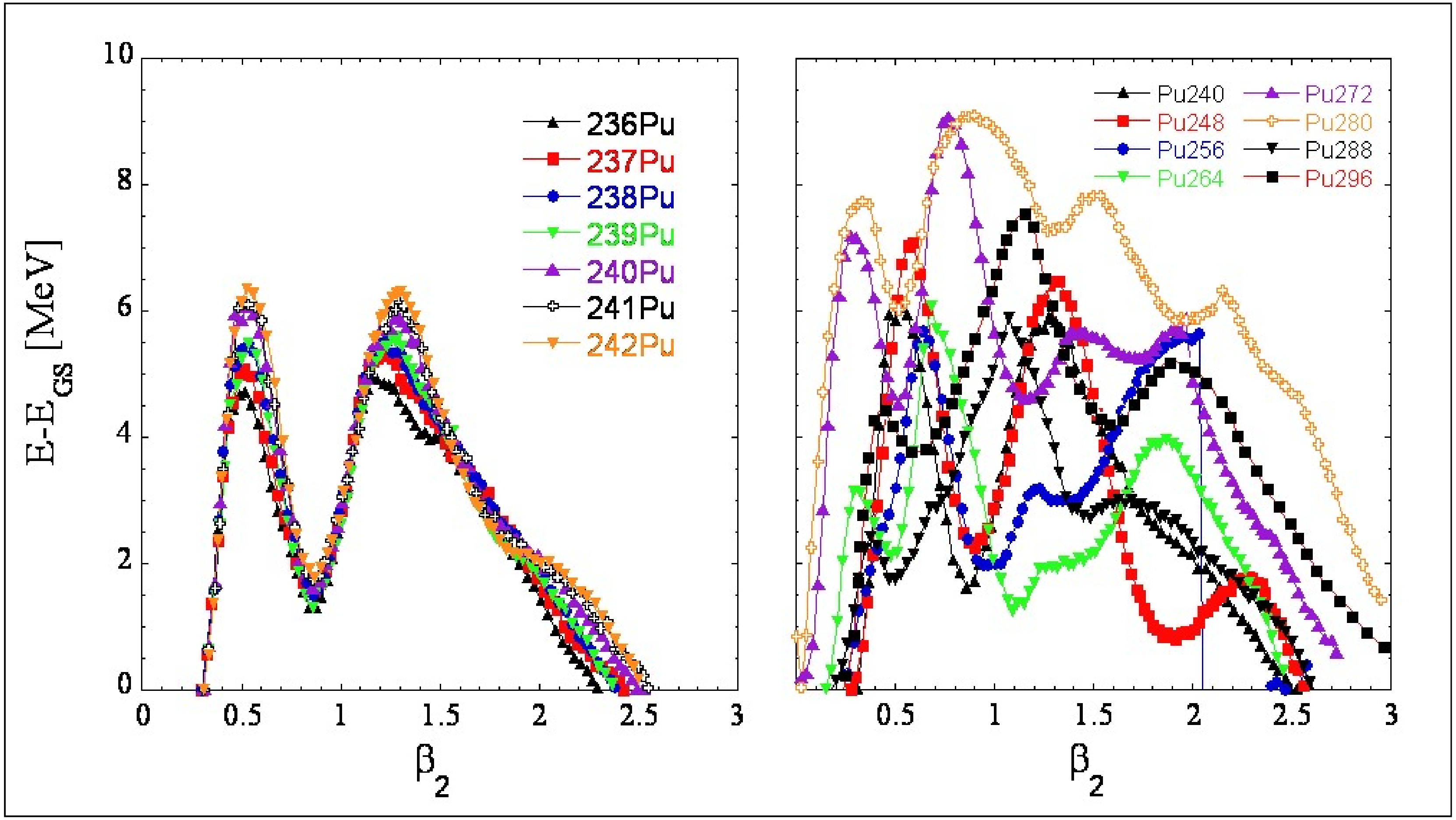
Microscopic approach

Determination of the fission path performing HFB calculation as function of appropriate deformation (collective) variables using ideally an effective interaction also adjusted on experimental masses



Also use the same effective interaction to calculate level densities (GS and top of each barrier)

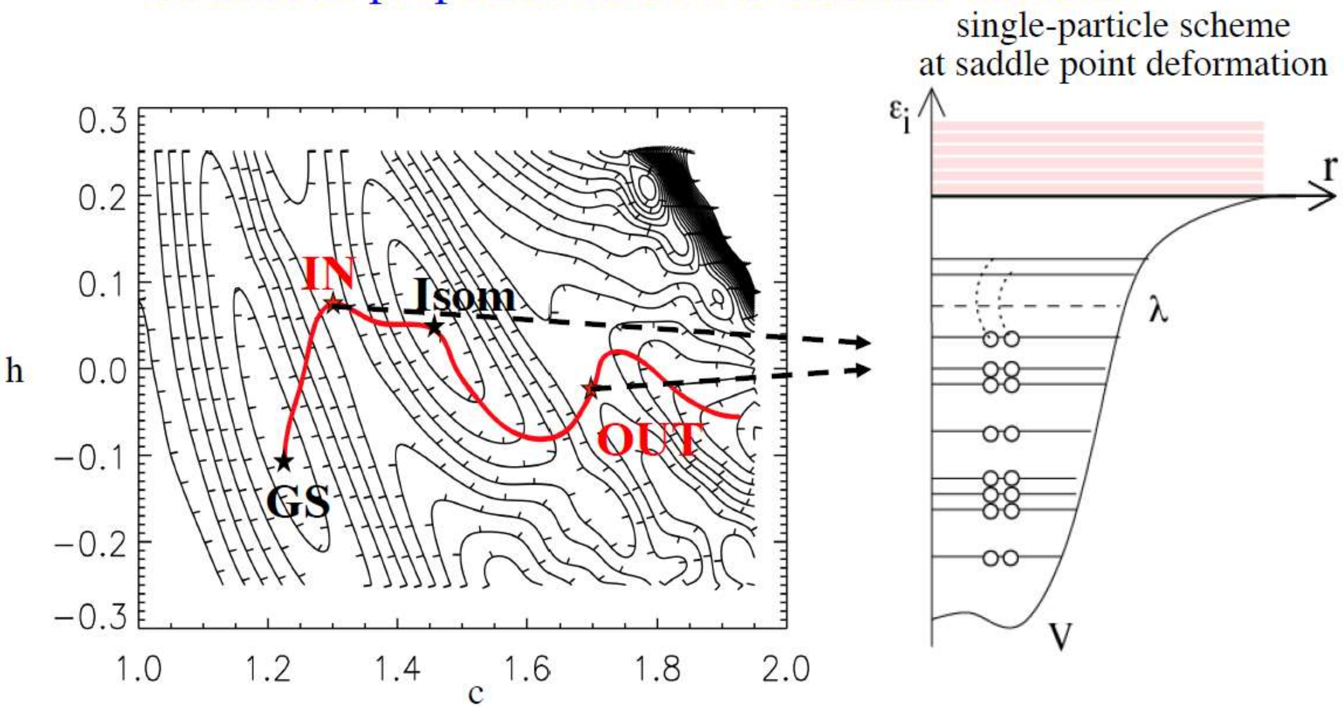
Microscopic approach : fission paths



⇒ For exotic nuclei : strong deviations from Hill-Wheeler.

Nuclear level densities at the saddle points

HFB model provides at each deformation (including saddle points)
all nuclear properties needed to estimate the NLD



Possibility to estimate NLD at the saddle point within the HFB+Combinatorial model

Nuclear Level Density at Saddle Points

- Fission Barriers and saddle point deformations (Q,O,H) determined within HFB method
- Nuclear properties (spl, pairing) at the inner and outer saddle points with constrained HFB model
- NLD in the framework of the microscopic combinatorial model based on HFB single-particle level and pairing predictions at the HFB saddle points (plus collective rotational and vibrational enhancement)

All ingredients described on the basis of the
same Skyrme effective interaction (BSk14) at GS and Saddle Points

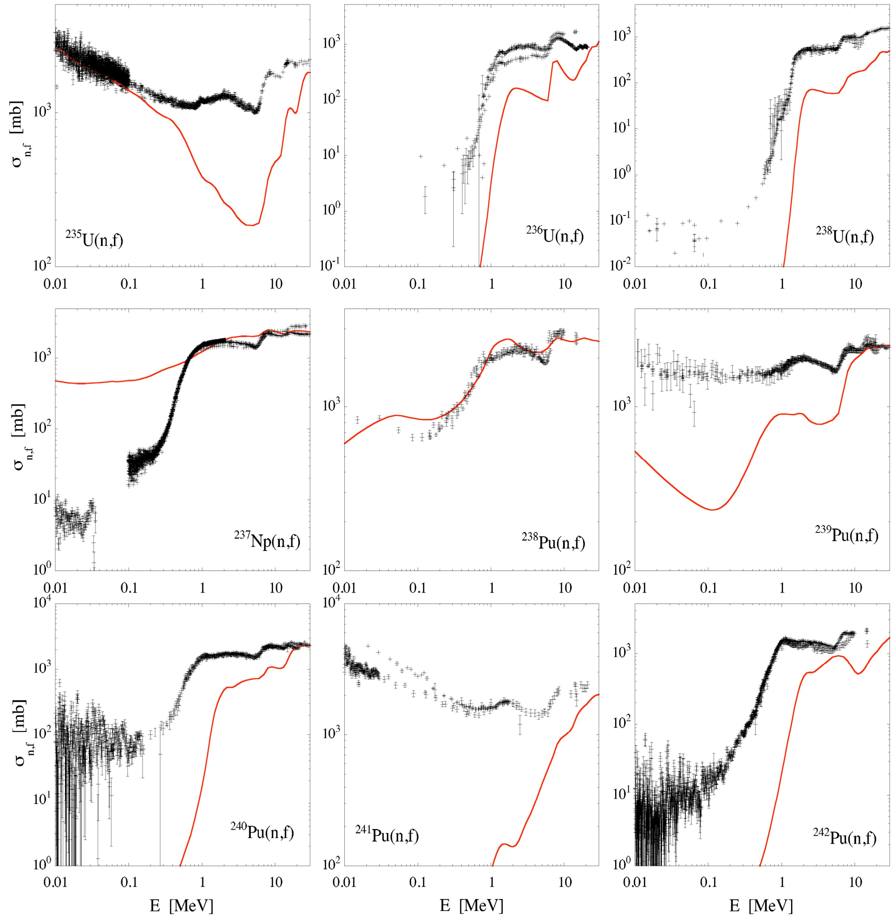
→ **NLD in a table format at inner and outer saddle points**

(~2000 nuclei : 2/3 saddle points & 1/2 shape isomers)

For inner barrier, usually predicted to be triaxial: $\rho_{triax} = \sqrt{\frac{\pi}{2}}\sigma_{\perp} \times \rho_{Comb}$ — Bjornholm & Lynn (1980)

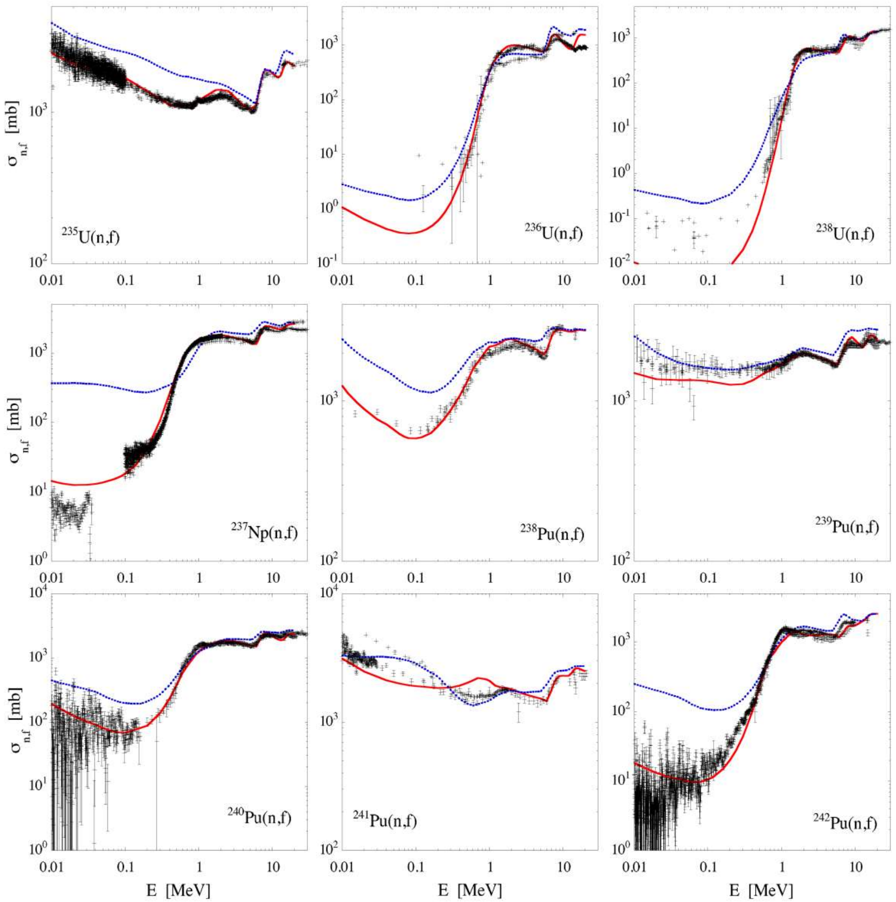
For outer barrier, usually predicted to be left-right asymmetric: $\rho_{asym} = 2 \times \rho_{Comb}$

Microscopic approach : results



⇒ **Default calculations not sufficient for applications.**

Microscopic approach : results



Fission barriers
adjusted for
each target

Fission barriers
adjusted for
each type of target
- odd-odd
- odd-even
- even-odd
- even-even

⇒ **Not ridiculous after few adjustments.**

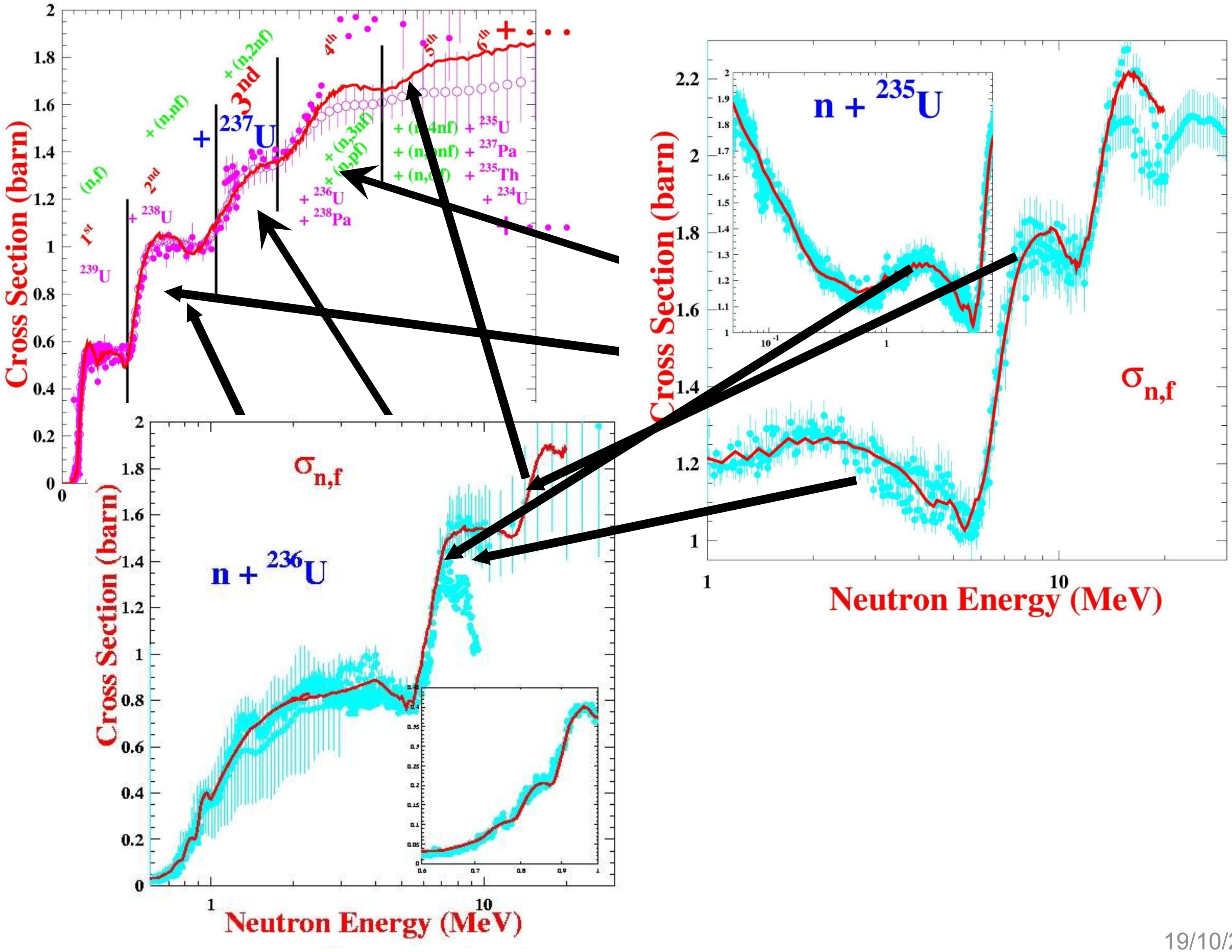
Microscopic approach

Coherent fission cross sections
with phenomenological approach

Neutron induced fission on ^{238}U

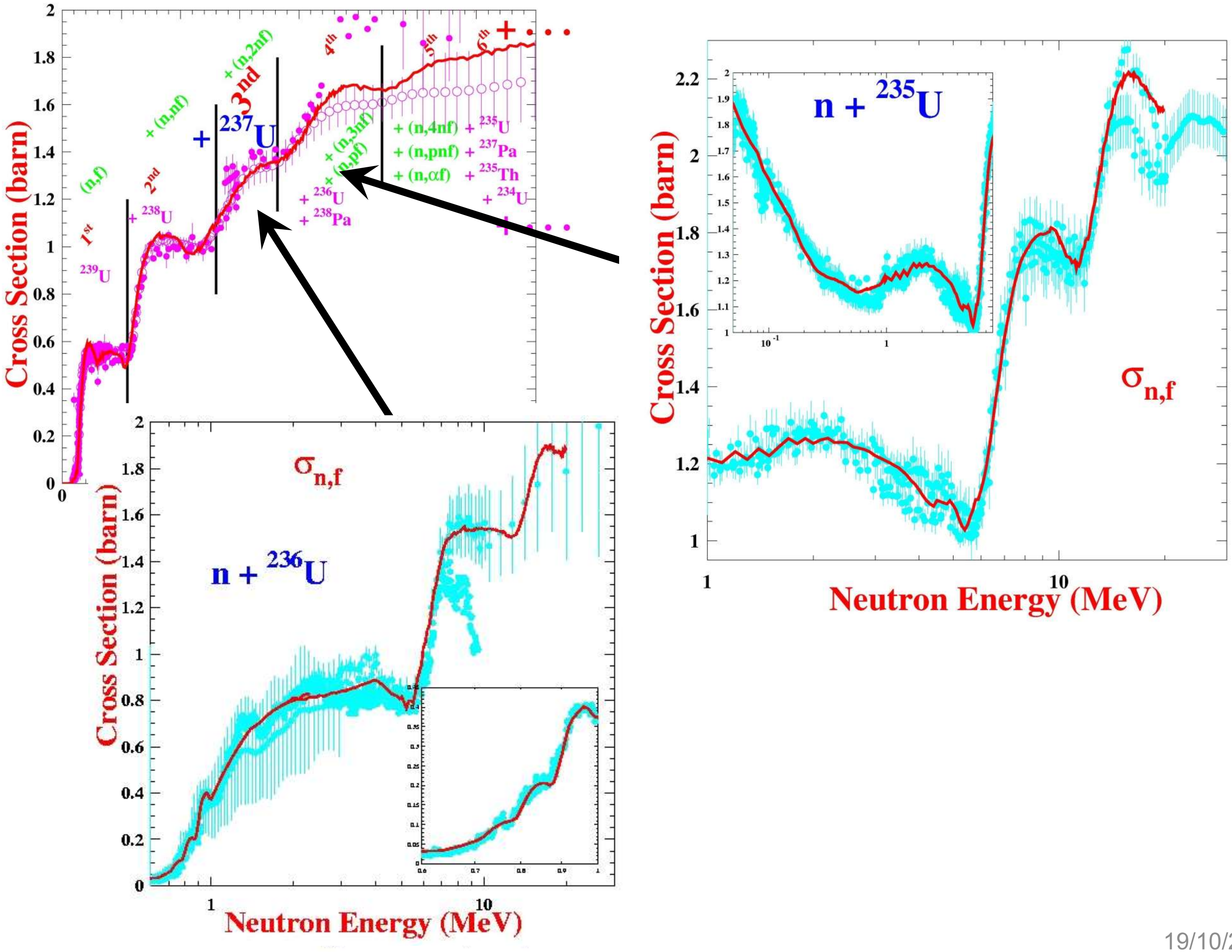
- several hundreds of parameters
- unique set for all fission chances or U targets

Microscopi



Cross Section (barn)
(n,f)
(n,nf)
(n,2nf)
1st
2nd
3nd
4th
5th
6th
^{239}U
+ ^{238}U
+ ^{237}U
+ ^{236}U
+ ^{238}Pa
+ (n,3nf)
+ (n,pf)
+ (n,4nf) + ^{235}U
+ (n,αnf) + ^{237}Pa
+ (n,αf) + ^{235}Th
+ ^{234}U
n + ^{236}U
$\sigma_{n,f}$
Cross Section (barn)
Neutron Energy (MeV)
n + ^{235}U
$\sigma_{n,f}$
Cross Section (barn)
Neutron Energy (MeV)

Microscopic



Can we do the same with microscopic ingredients ?

Microscopic approach

Microscopic approach

HFB-14 predictions of fission barriers and NLD at saddle points, including renormalization (max 5 parameters) of

- fission path height: $B_f'(\beta_2) = B_f(\beta_2) \times v_{corr}$
- NLD at 1st and 2d saddle points:

$$\rho'(U,J,P) = \rho(U-\delta,J,P)e^{\alpha\sqrt{U-\delta}}$$

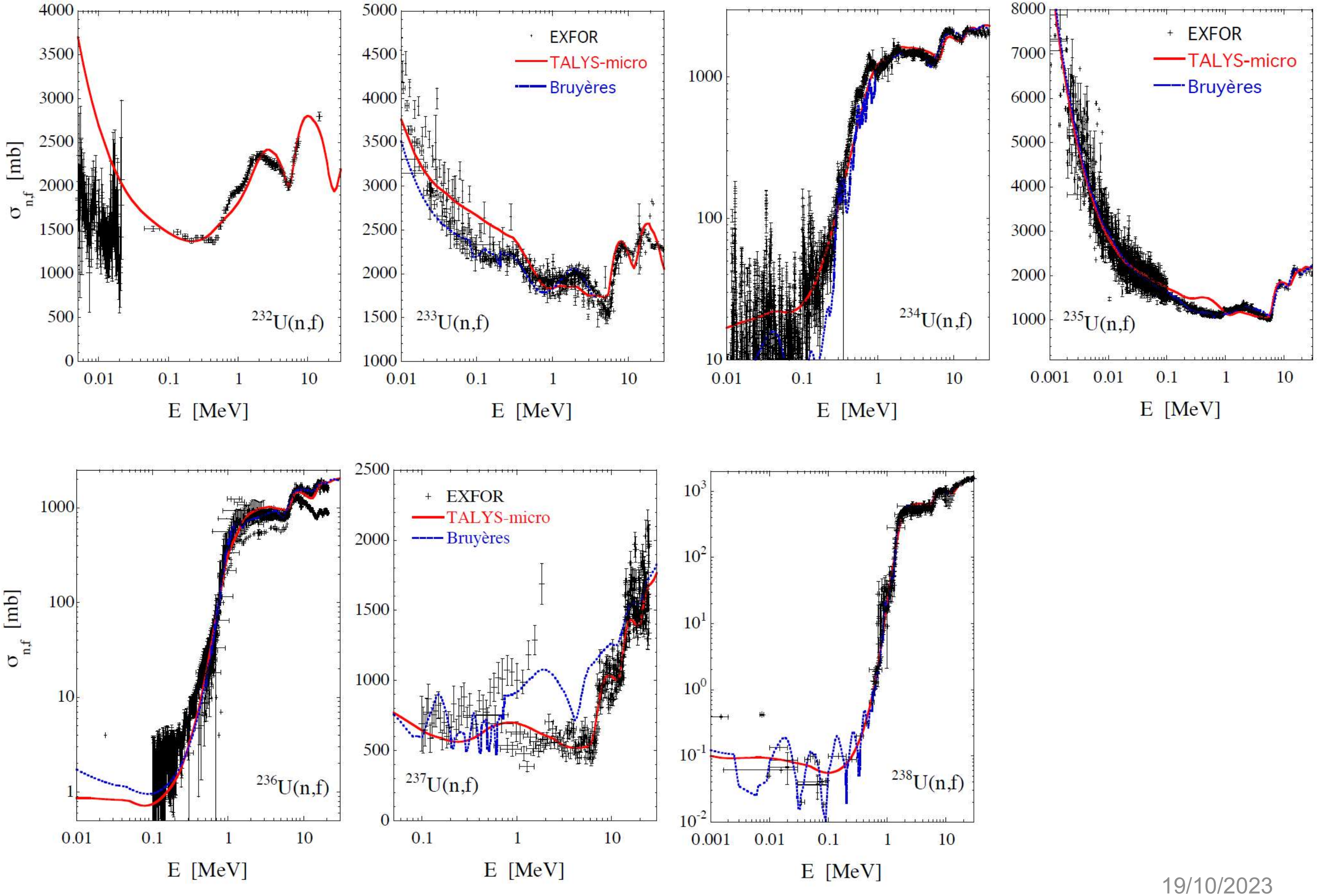
Additional nuclear inputs:

- Nuclear structure properties: HFB-14 (Goriely et al. 2007)
- Optical potential: Soukhovitskii et al. (2004)
- γ-ray strength: Hybrid model (Goriely, 1998)
- NLD: HFB-14 plus combinatorial model (Goriely et al., 2008) normalized on s-wave spacings and discrete excited levels

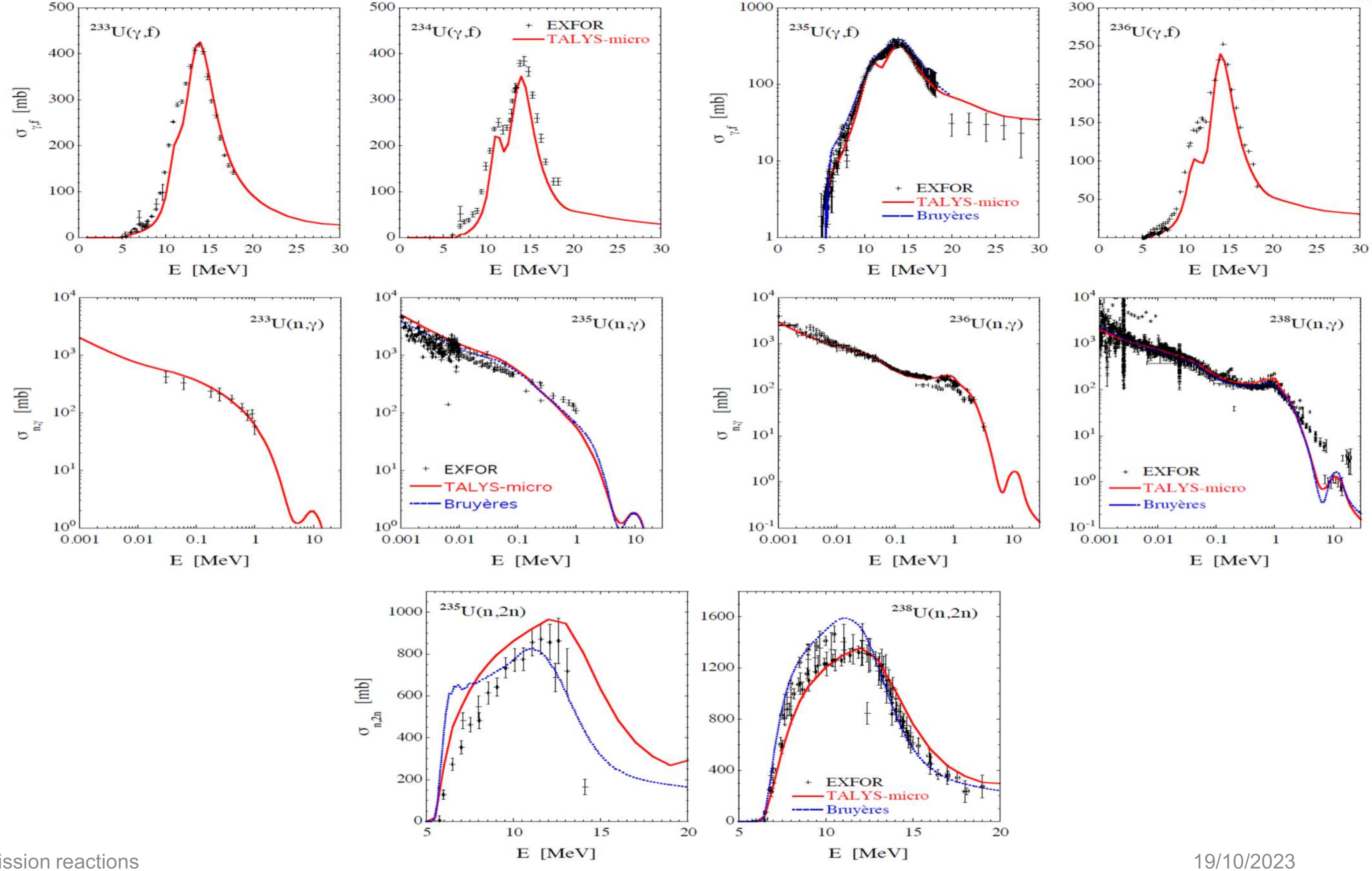
Note:

- 1 UNIQUE set of nuclear ingredients for all U isotopes
- no class 2 states included
- no discrete transition states included

Microscopic approach



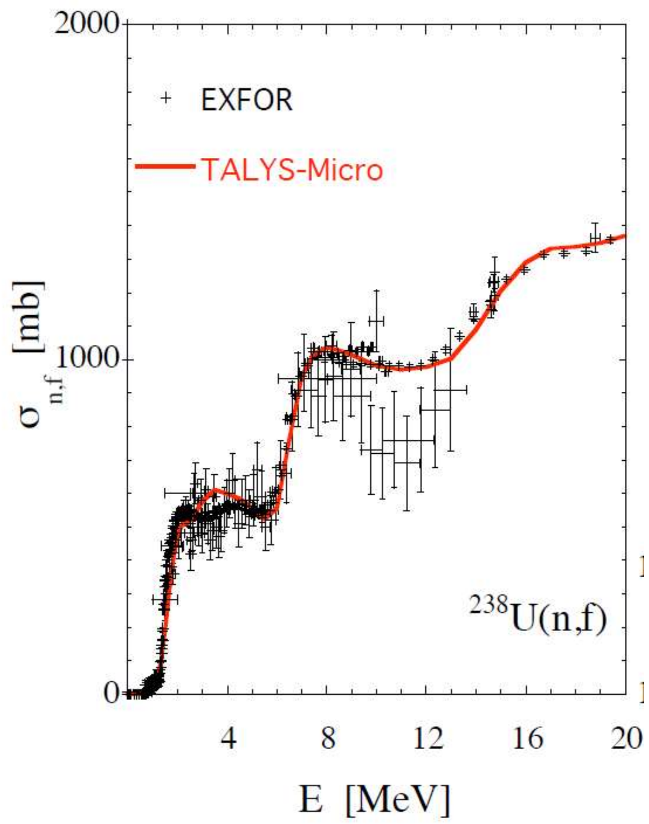
Mici



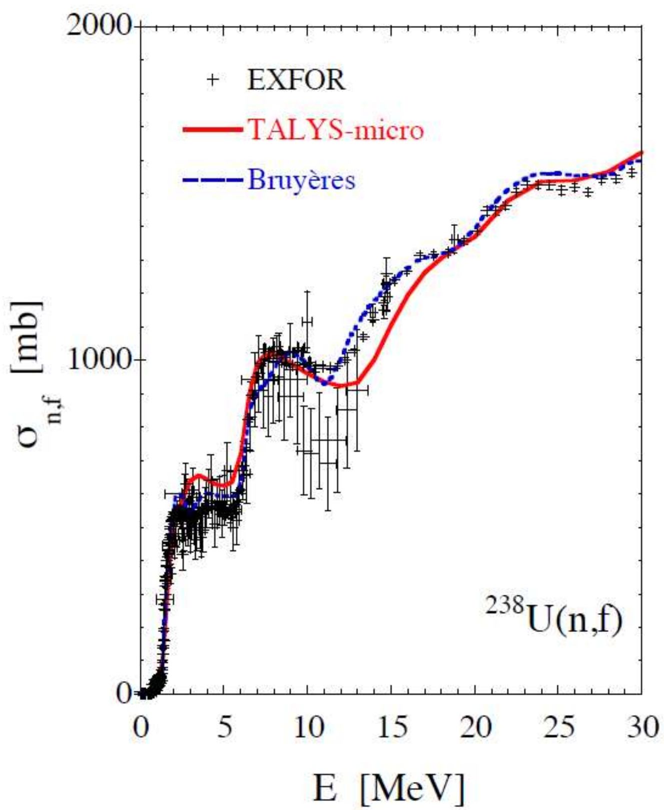
²³³U(γ,f)
²³⁴U(γ,f)
²³⁵U(γ,f)
²³⁶U(γ,f)
²³³U(n,γ)
²³⁵U(n,γ)
²³⁶U(n,γ)
²³⁸U(n,γ)
²³⁵U(n,2n)
²³⁸U(n,2n)
EXFOR
TALYS-micro
Bruyères
E [MeV]
σγ,f [mb]
σn,γ [mb]
σn,2n [mb]

Microscopic approach

Without Coherence



With Coherence

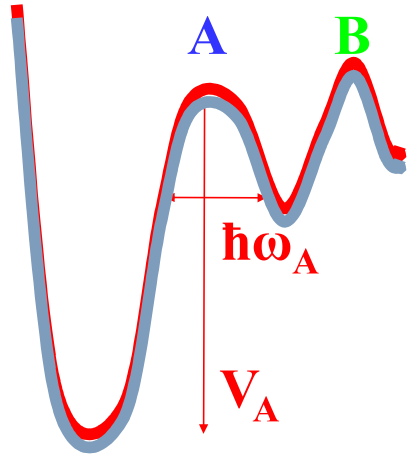


Coherence = more constraints = slightly worse fit

Integral benchmark / fission / parameter sensitivity

Integral benchmark / fission / parameter sensitivity

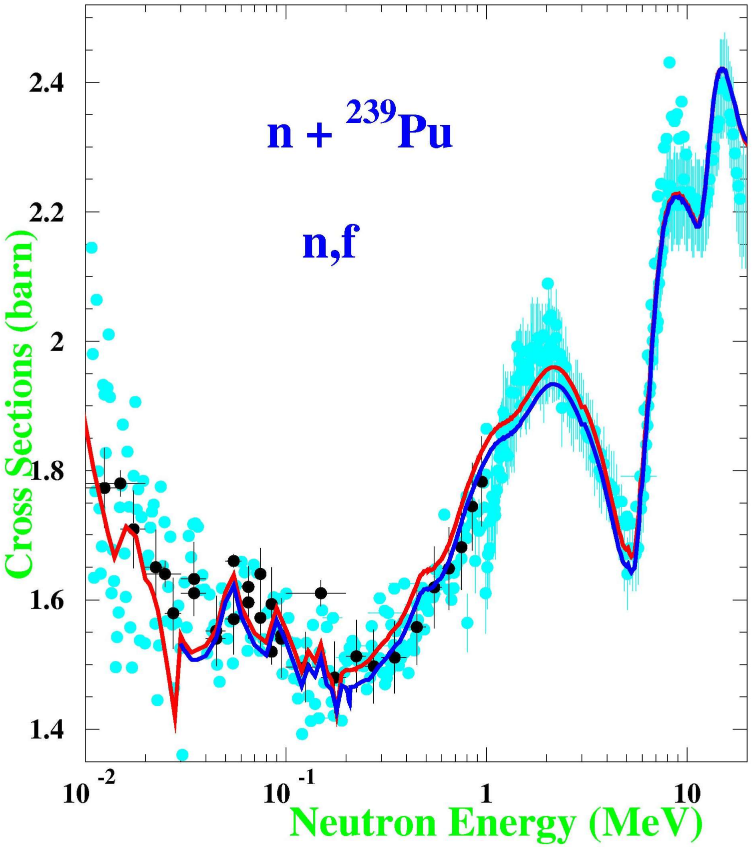
^{239}Pu (n,f)



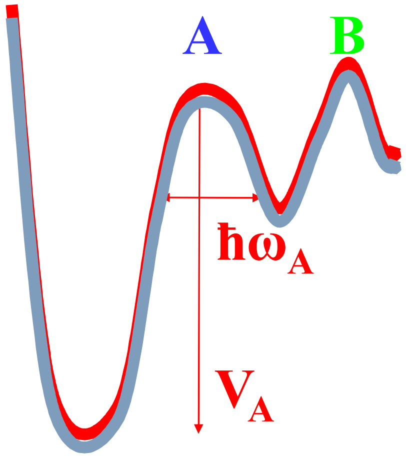
-20 keV sur V_A

≈ 0.34% !!

Integral benchmark / fission / parameter sensitivity

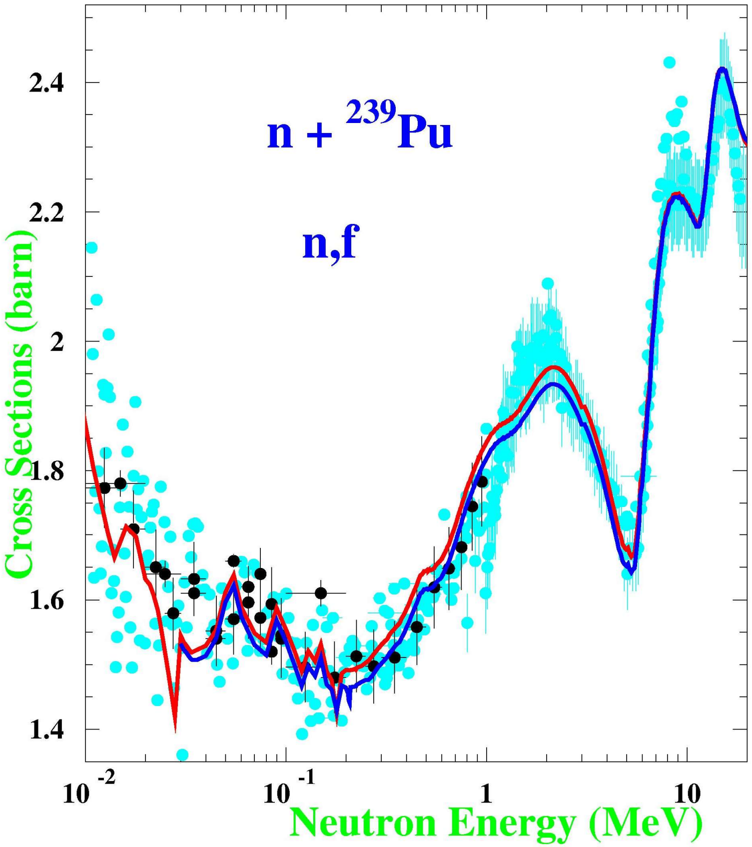


^{239}Pu (n,f)

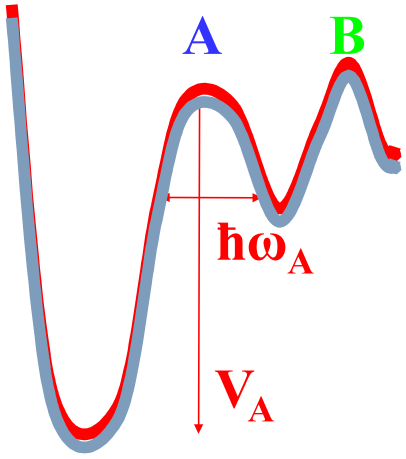


-20 keV sur V_A
≈ 0.34% !!

Integral benchmark / fission / parameter sensitivity

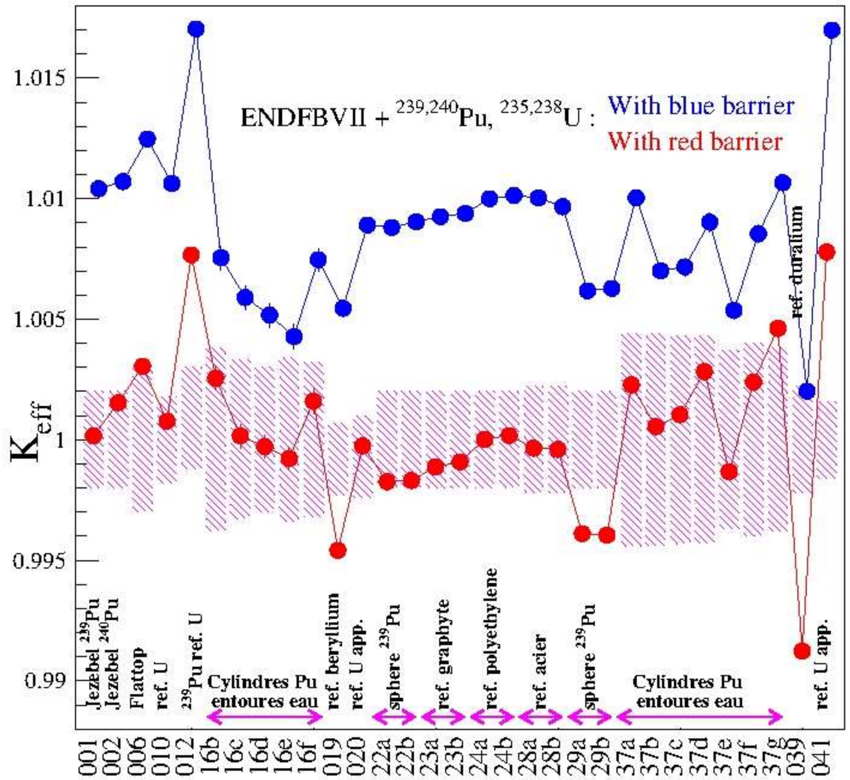


^{239}Pu (n,f)



-20 keV sur V_A

≈ 0.34% !!



4. Conclusions and Prospects

Conclusions

Nuclear reaction modeling : 2 complementary paths

Empirical / Analytical approaches

- Good (very) fitting power
- Weak (modest) computing time
- Weak predictive power
- Important human optimization

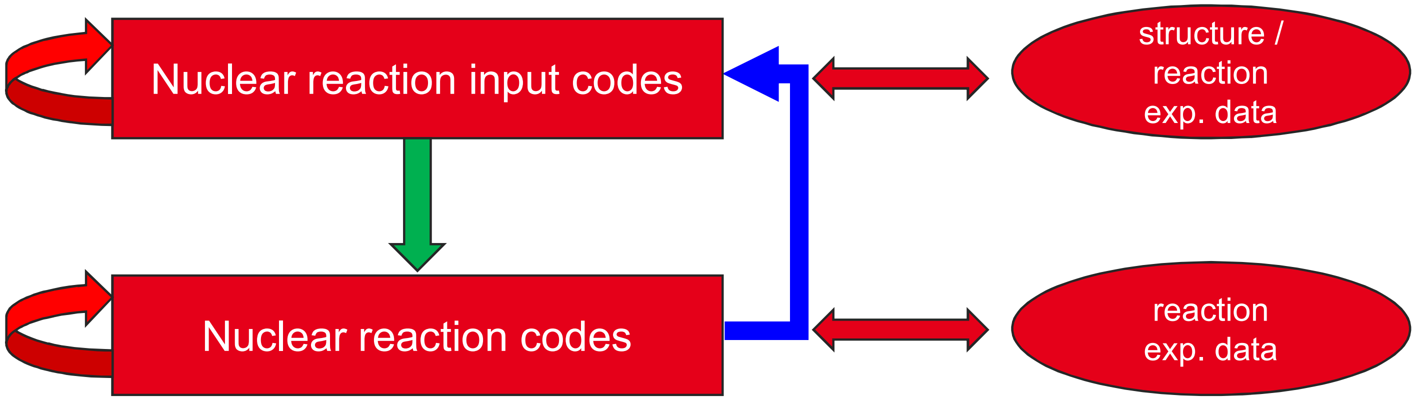
⇒ accurate evaluated files for applications (ENDF, JEFF, JENDL …)

Microscopic (semi-) approaches

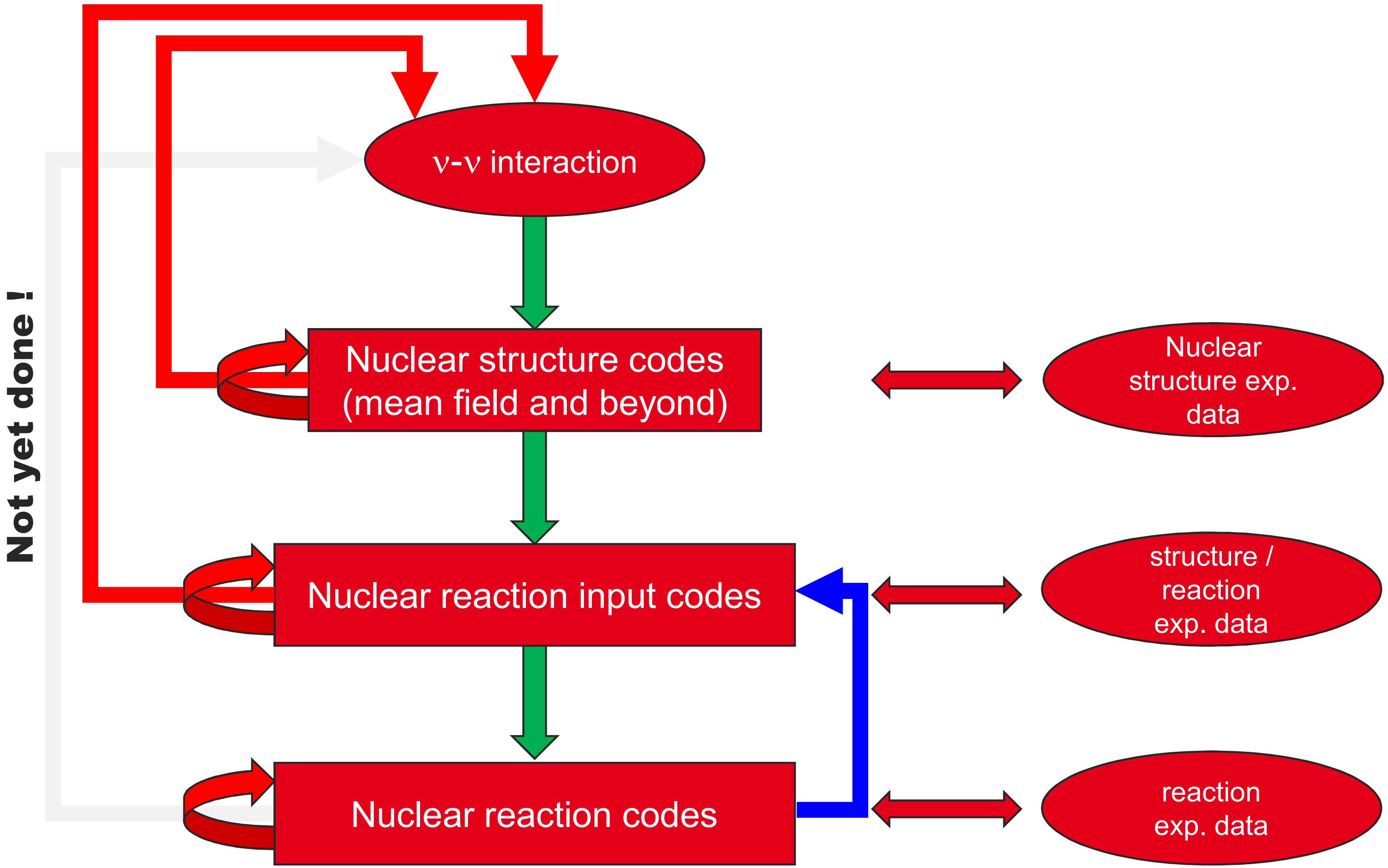
- Weak fitting power
- Important computing time
- Good predictive power
- Weak human optimization

⇒ astrophysical applications
⇒ fundamental research
⇒ guide for empical approaches

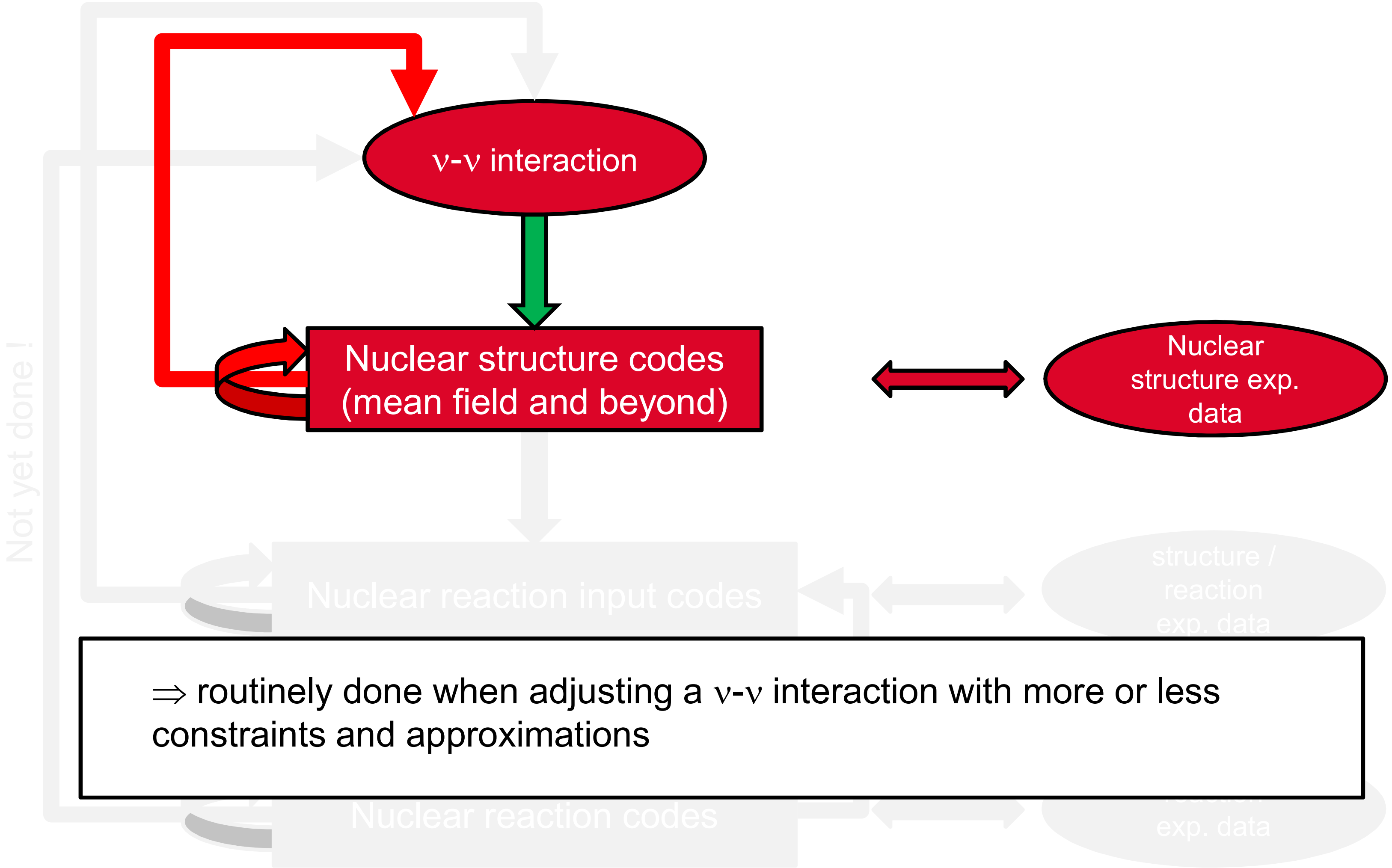
Phenomelogical approach : fitting loop



Microscopic approach : multiscale fitting loop

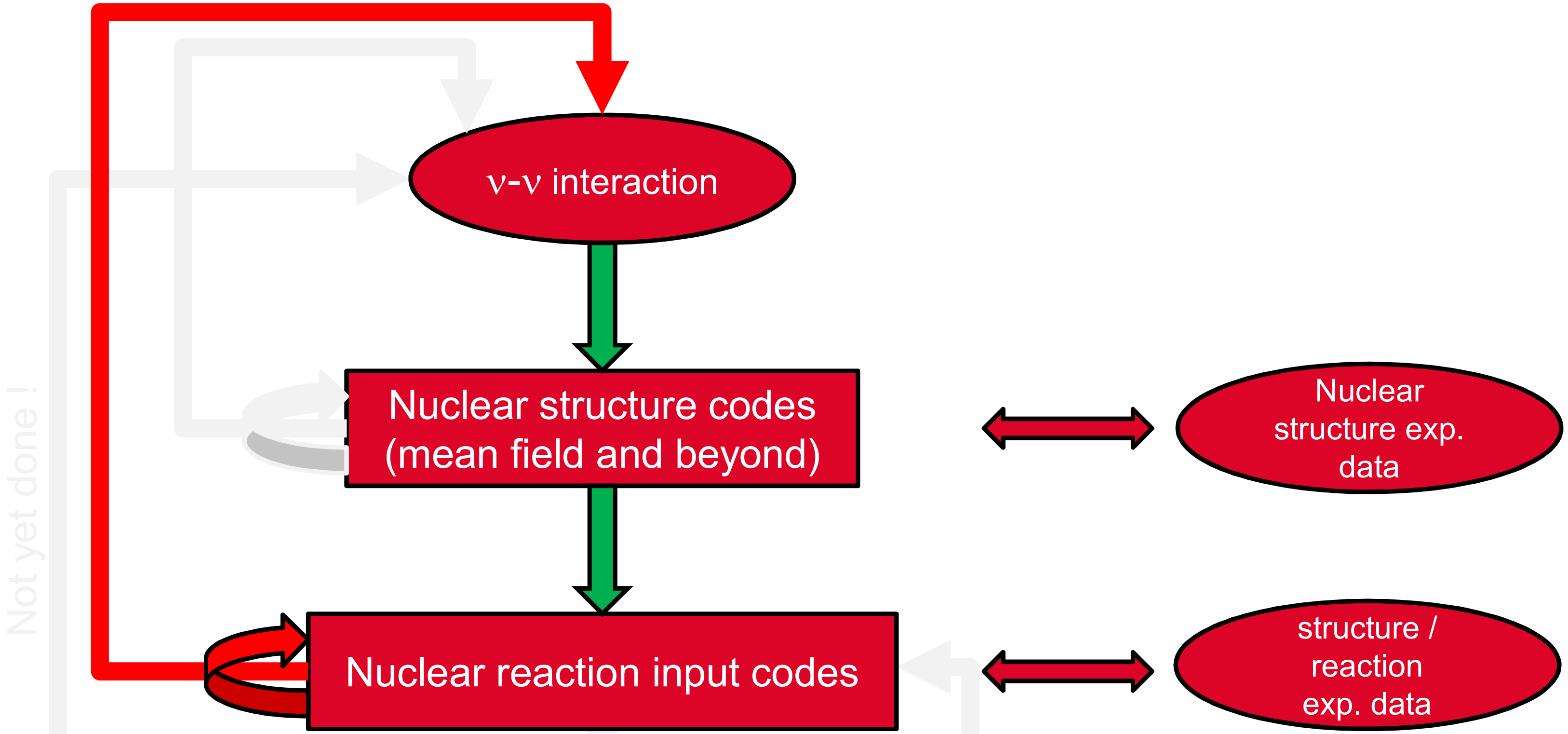


Microscopic approach : multiscale fitting loop



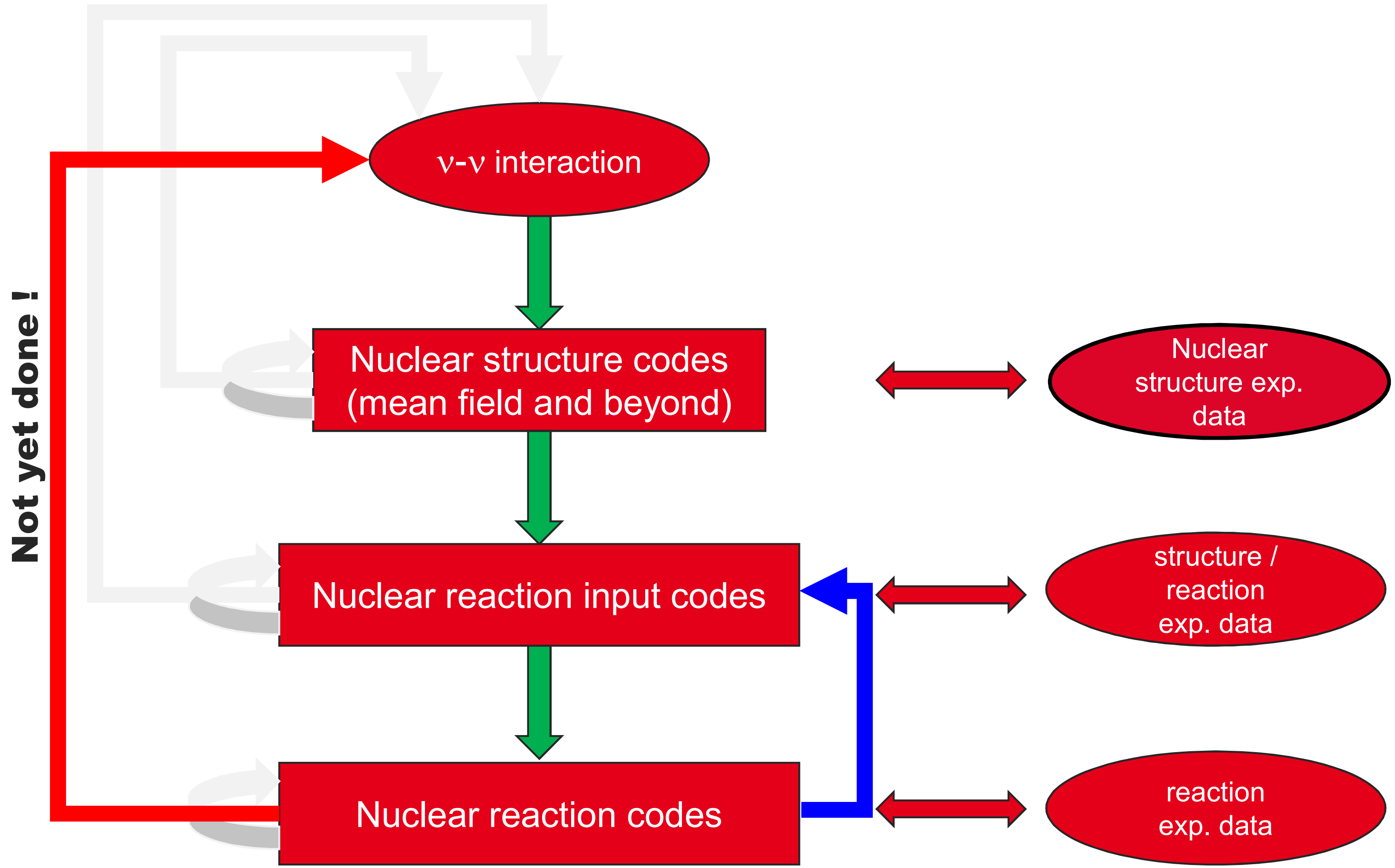
⇒ routinely done when adjusting a ν-ν interaction with more or less constraints and approximations

Microscopic approach : multiscale fitting loop

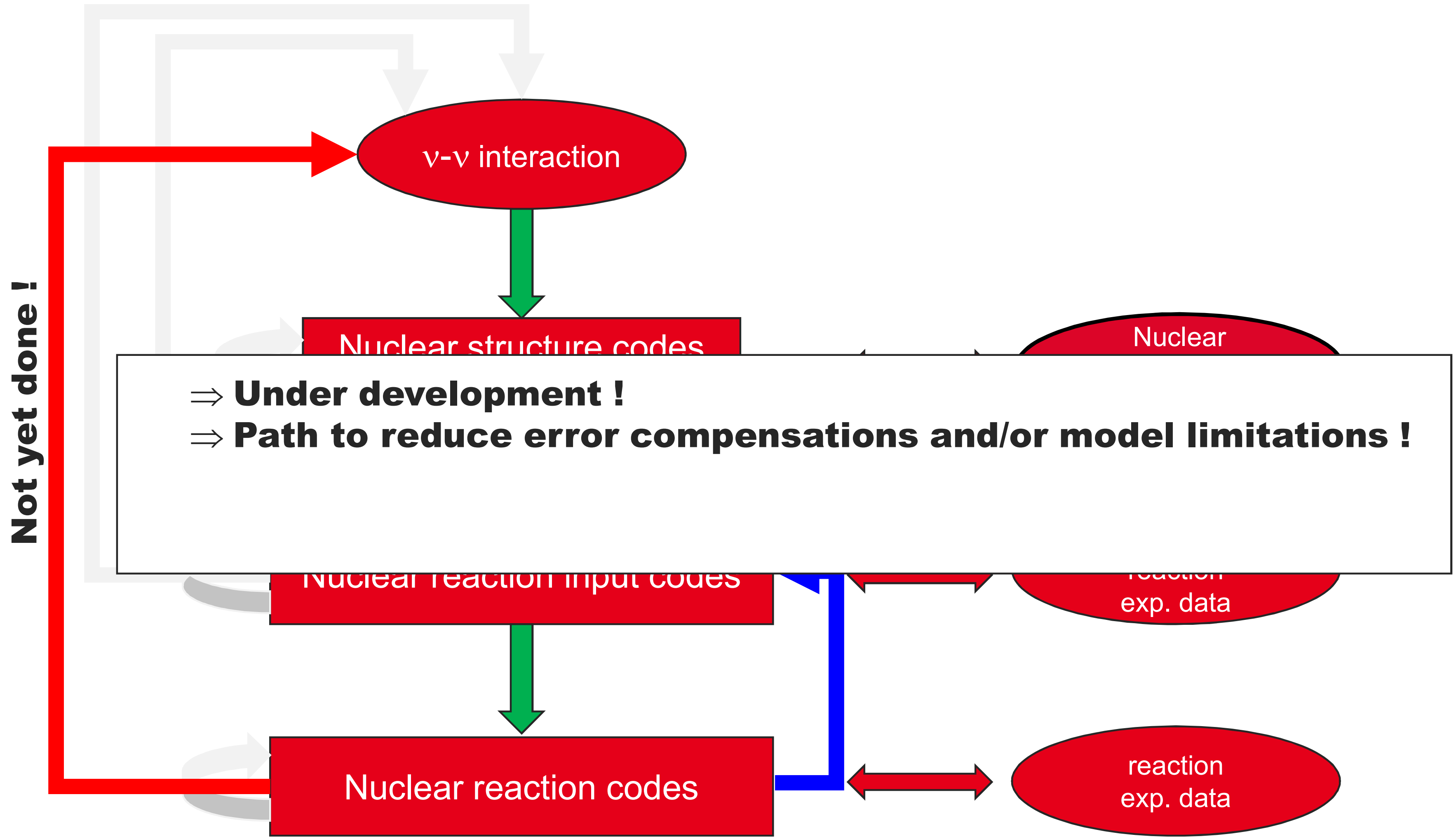


⇒ scarcely done because of the accumulation of approximations (few examples yet : D1M, BSk14)

Microscopic approach : multiscale fitting loop



Microscopic approach : multiscale fitting loop



⇒ **Under development !**
⇒ **Path to reduce error compensations and/or model limitations !**