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EUROPEAN CENTRE FOR THEORETICAL
STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

TRENTO, ITALY

Institutional Member of the European Expert Committee NUPECC

ChETEC Action

Microscopic description of fission for the r-process in neutron-star mergers ejecta

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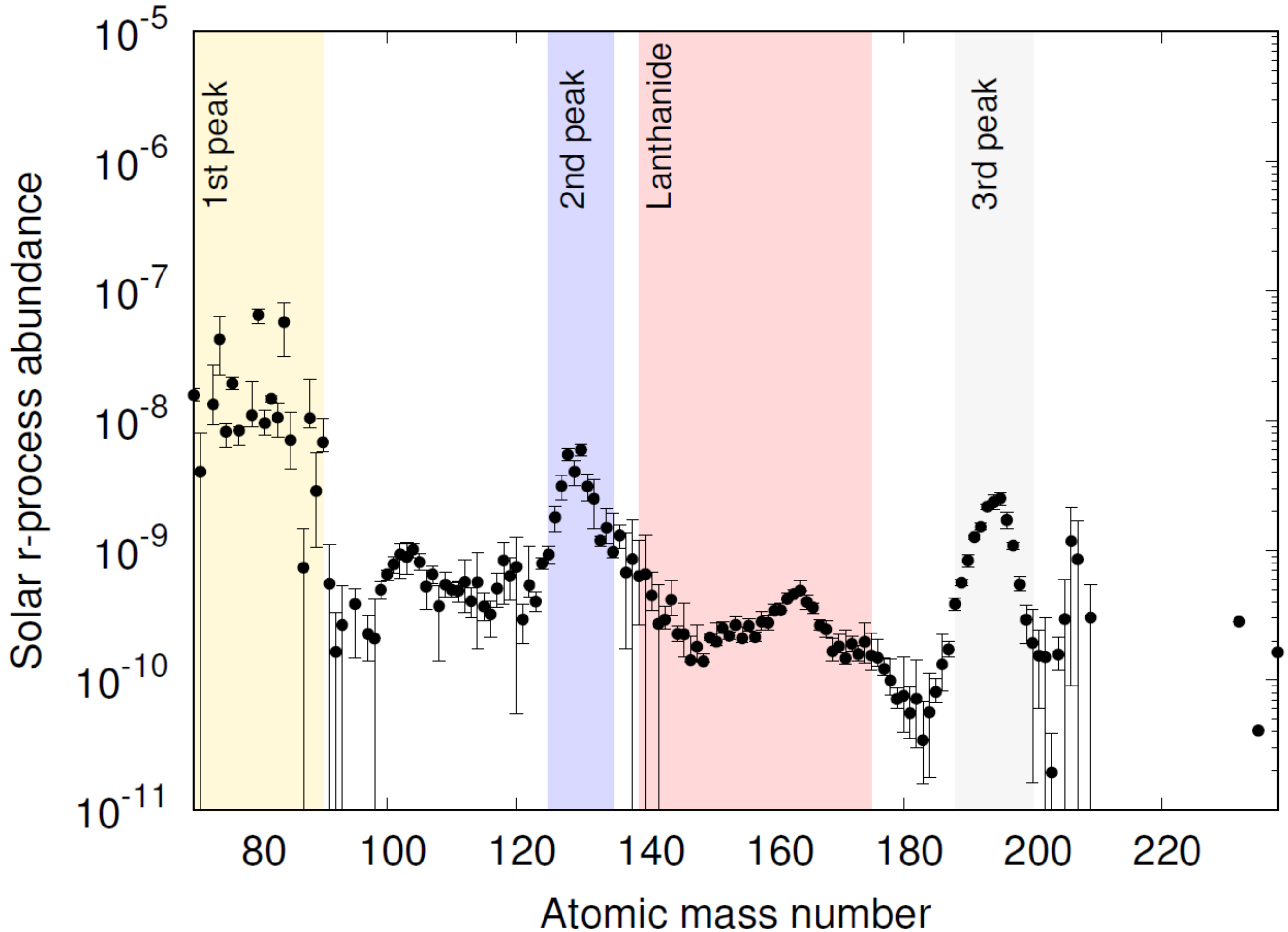
Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

Nuclear and astrophysics aspects for the rapid neutron capture process in the era of multimessenger observations

Trento, July 1-5, 2019

Understand the structure of solar r-process abundances

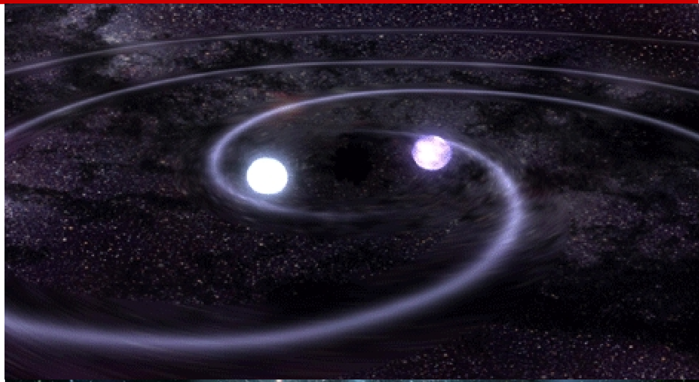


- From NS to r-process elements
- Fission in nucleosynthesis
- Fission process
- Fission path & fission barrier
- Fission fragments - SPY model

From NS to r-process elements

- **inspiral phase** (~ millions of years)
  gravitational-wave emission

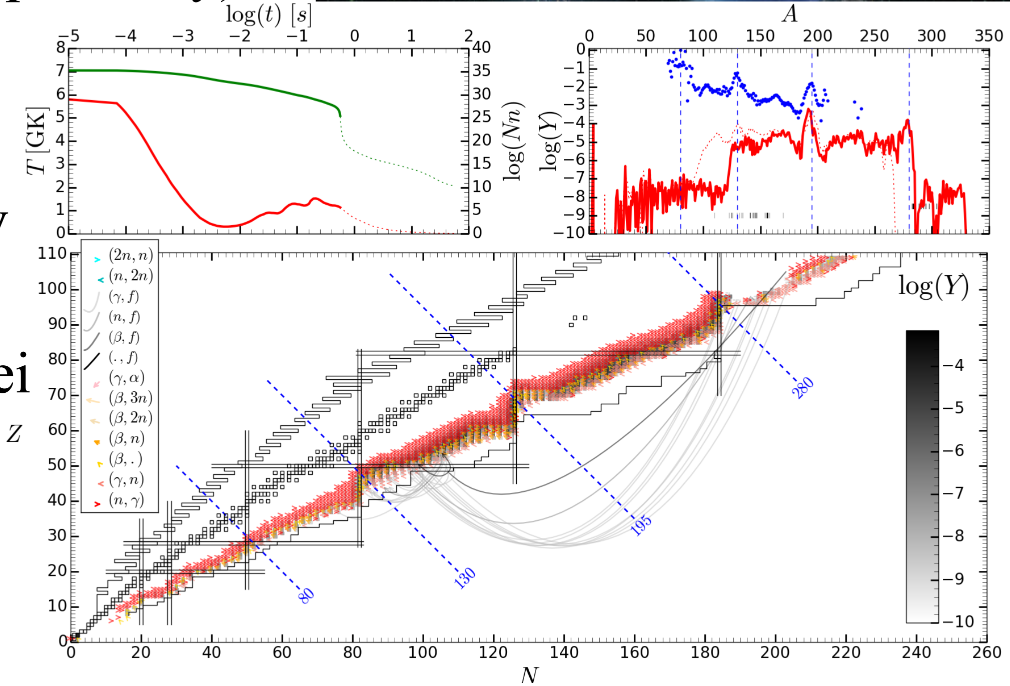
- **coalescence phase/dynamical ejecta** (~ ms)
  $0.001 - 0.02\ M_{\odot}$ nuclear matter are ejected
  from NS merger ($1.35M_{\odot}$ x2)
  initially cold, gets shock-heated during the ejection
  $T > 10^{10}$ K (1MeV) (see A. Bauswein's talk)



- **nucleosynthesis in ejected matter**
starts when $T<10^{10}$ K & $\rho < 4.2\ 10^{11}$ g/cm^3 (drip density)
many neutron captures

↳ neutron capture > β decay
  move away from the valley of stability

↳ neutron capture + β decay
  production of heavy neutron rich nuclei



Fission in nucleosynthesis

- **Fission of heavy elements** plays a fundamental role
- **Recycling the matter** during the neutron irradation

$\rightarrow$ (n,γ) + β + (γ,n) + βdn + βd2n + βd3n

2-3 cycles (0.1 → 1 s)

fission fragments ← (n,f) + βdf ← heavy neutron rich nuclei

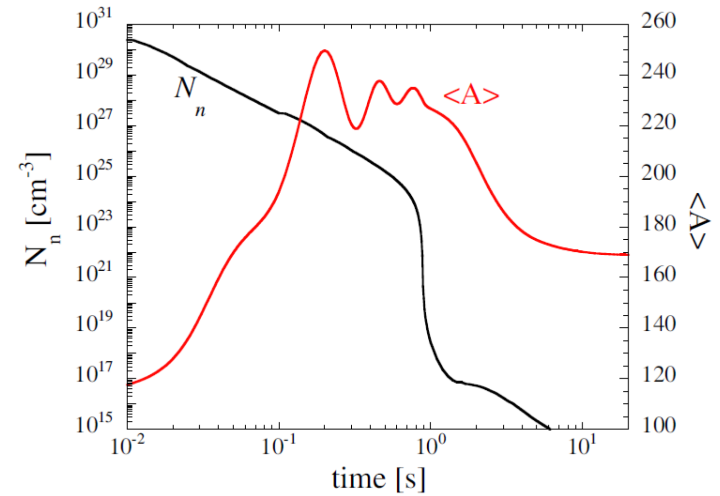


Fig. 13. (Color online) time evolution of the neutron density N_n and average mass number $\langle A \rangle$ for a specific representative mass element ejected from the 1.35–1.35$M_\odot$ NS merger.

S. Goriely, EPJ A (2015) 51:22

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2-3 cycles (0.1 → 1 s)

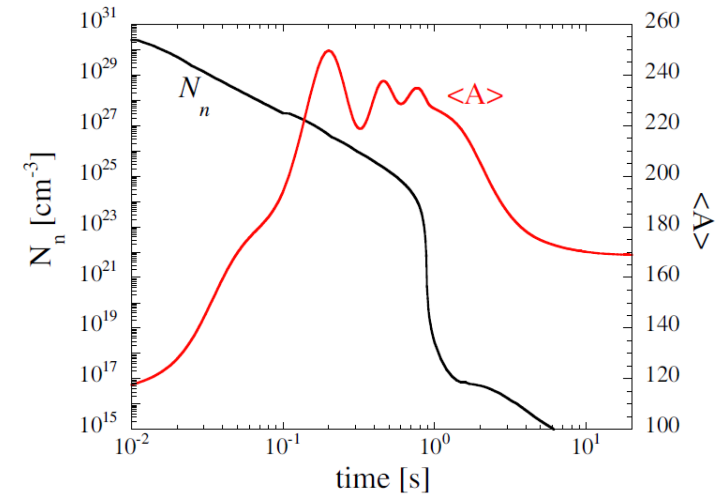
fission fragments $\leftarrow$ (n,f) + βdf $\leftarrow$ heavy neutron rich nuclei

- **Neutron density falls at t ~ 1s**
  no more neutron captures

- **Fission shapes the final r-abundance**
  distribution in 110 ≲ A ≲ 170 mass region :
  1→ 10 s (heating dominated by βdf & sf)

- **β decay for t > 10 s**

- Nuclear flow & abundances are affected by fission barriers & fission fragments distribution



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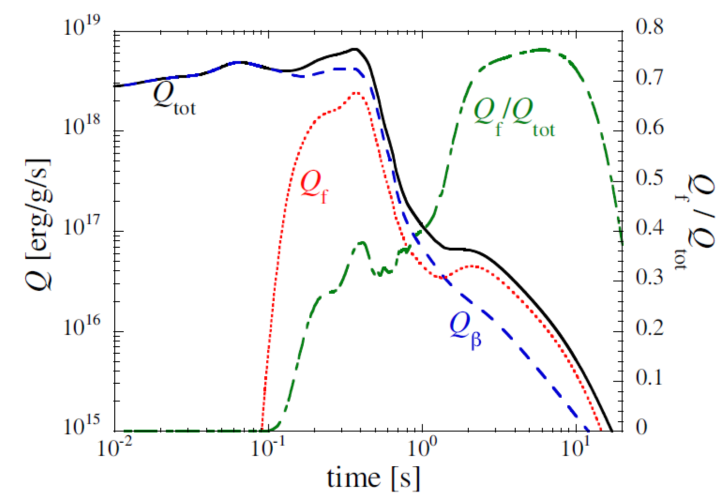
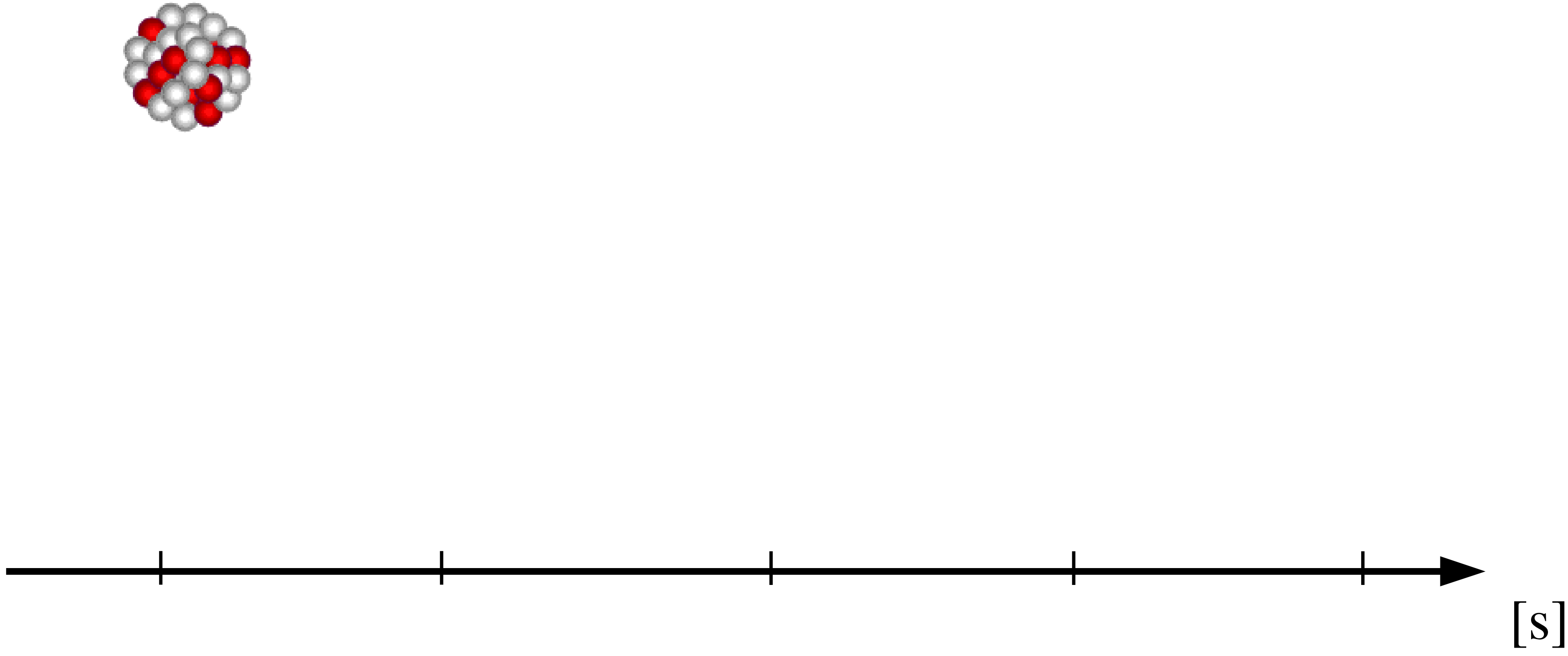


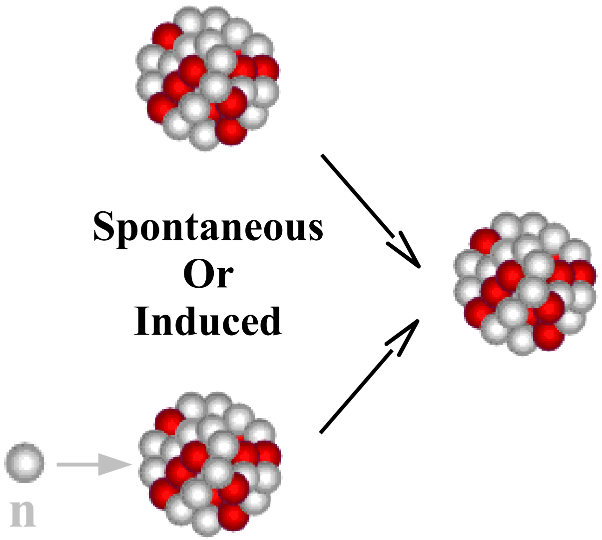
Fig. 14. (Color online) time evolution of the total mass-averaged radioactive heating rate per unit mass Q_{tot} (black solid line) and its β-decay Q_β (dashed line) and fission Q_f (dotted line) contributions for the matter ejected from the 1.35–1.35$M_\odot$ NS merger. The Q_f/Q_{tot} ratio is also given (dash-dotted line; right axis).

S. Goriely, EPJ A (2015) 51:22

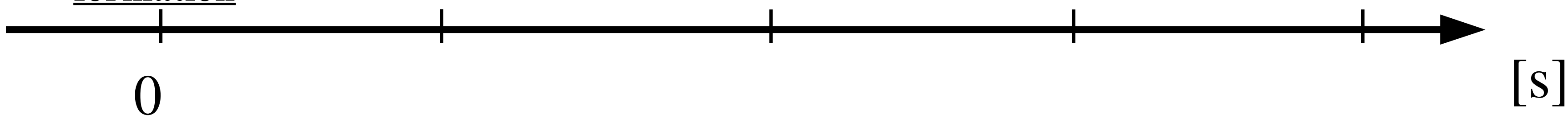
Fission process



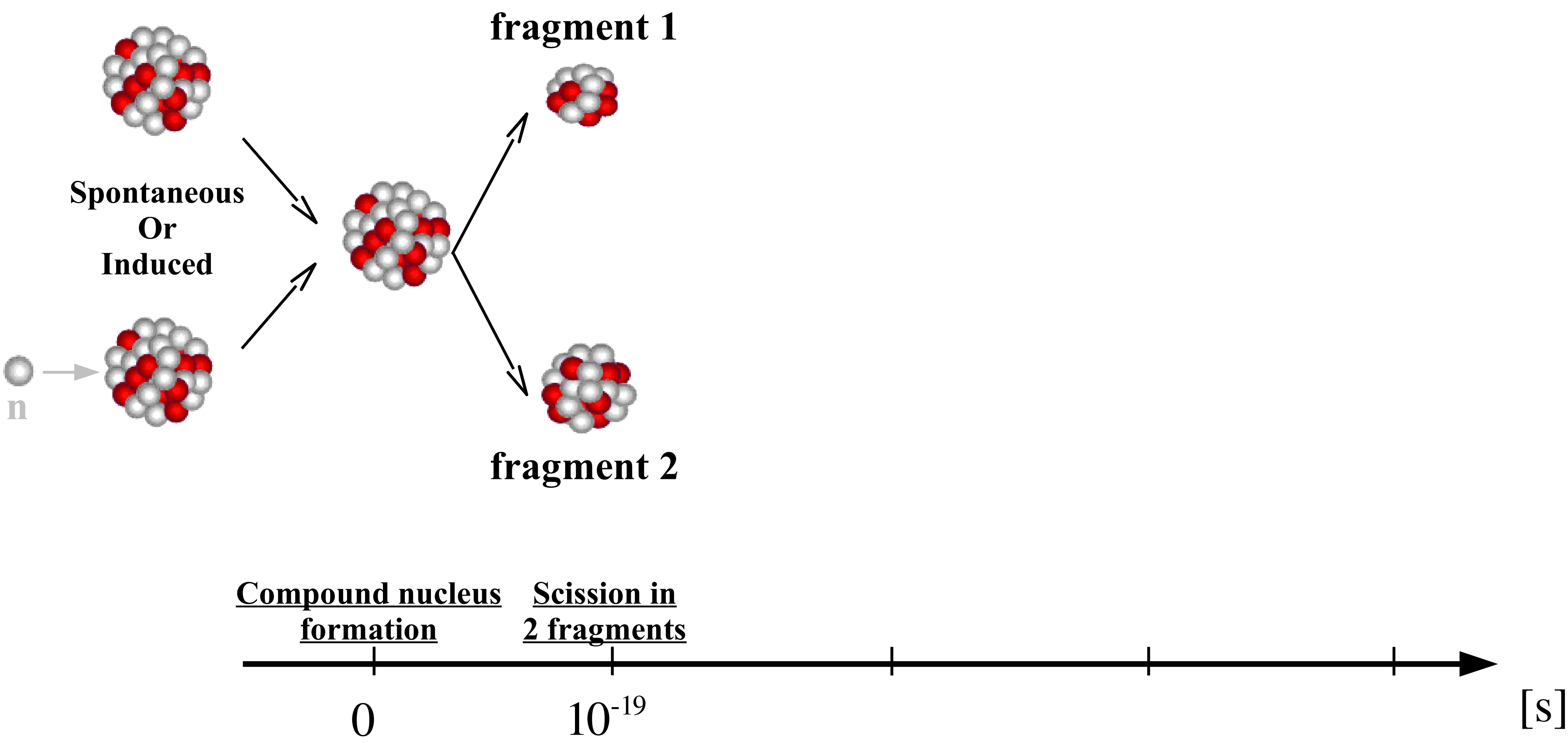
Fission process



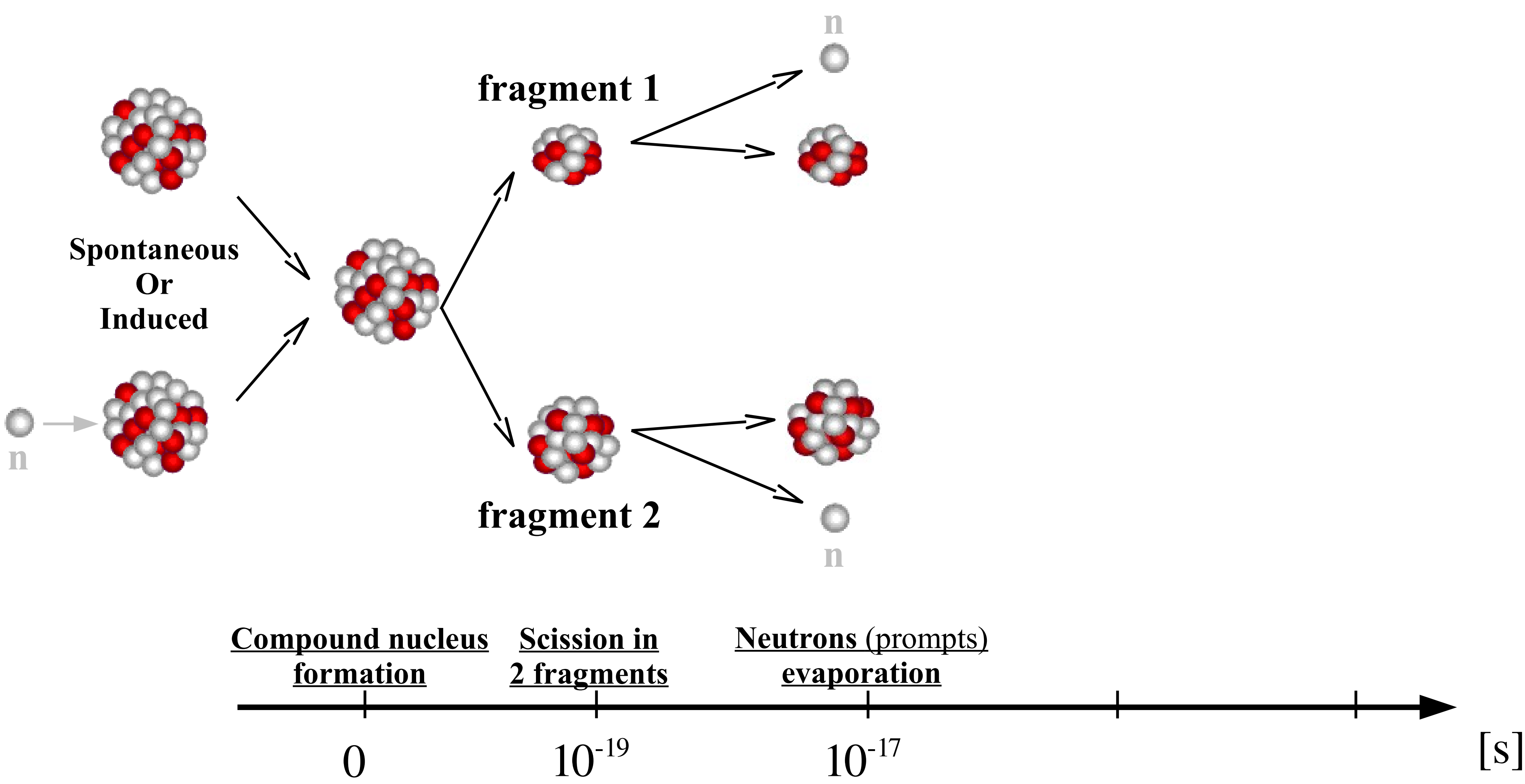
Compound nucleus formation



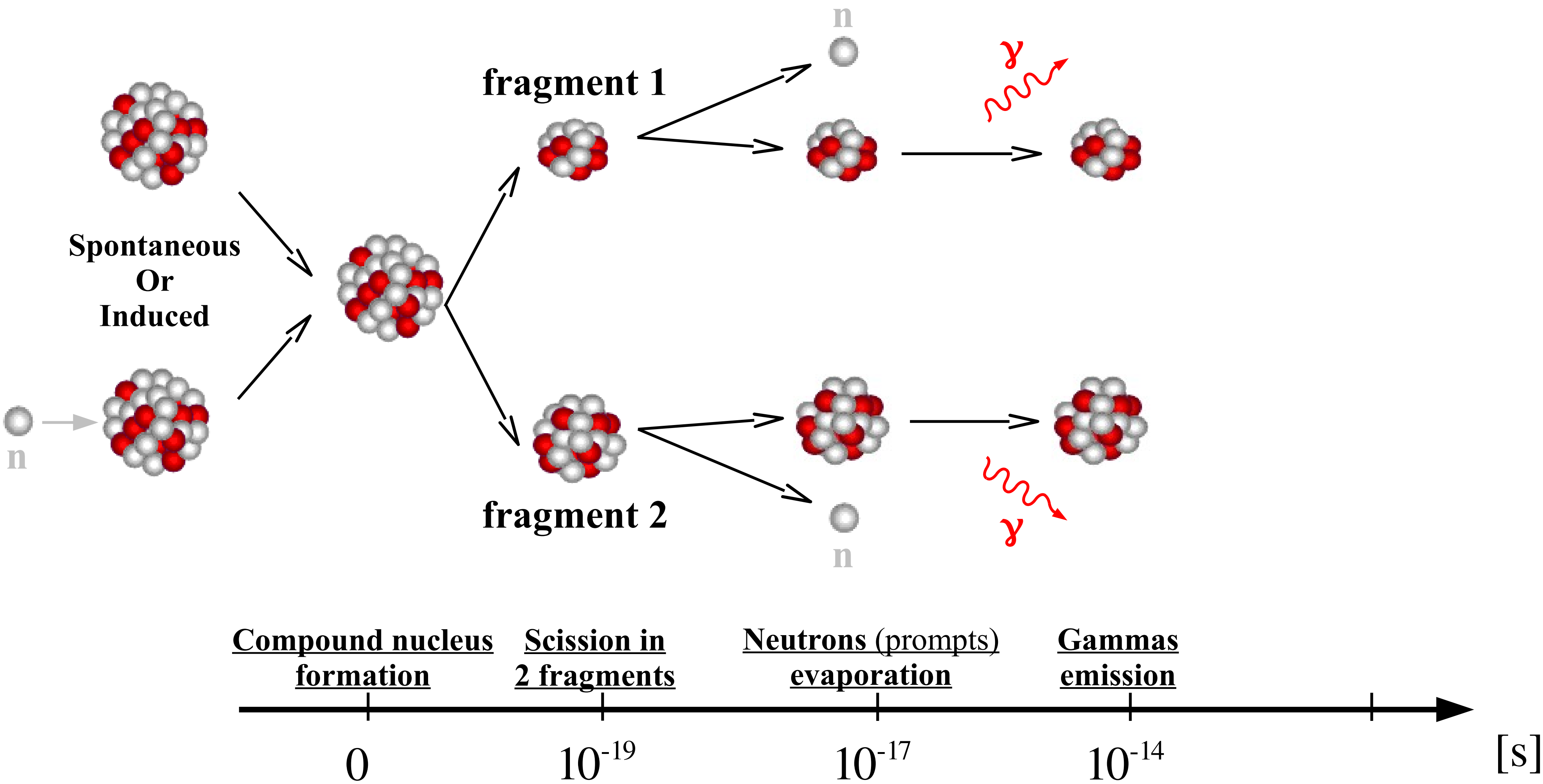
Fission process



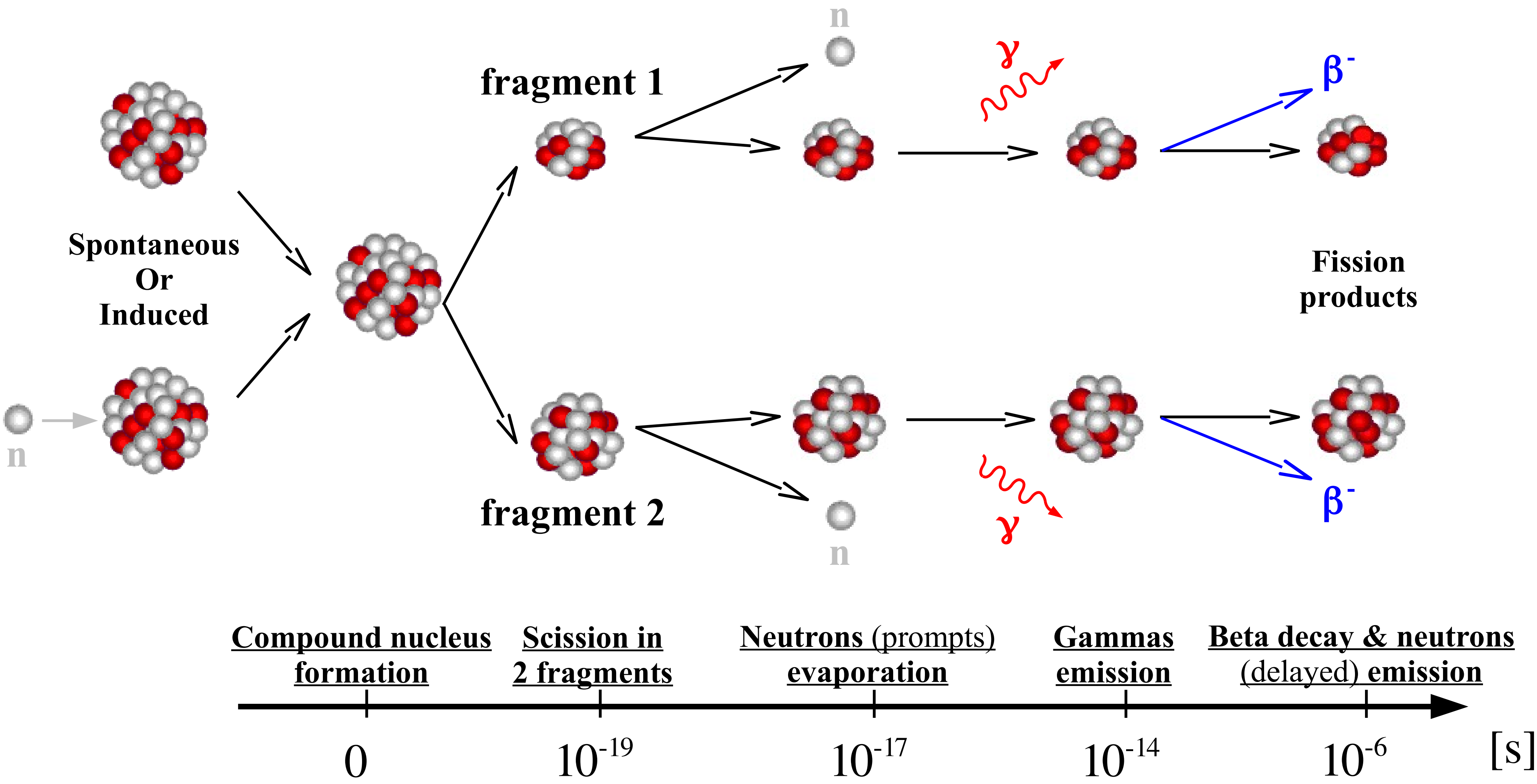
Fission process



Fission process

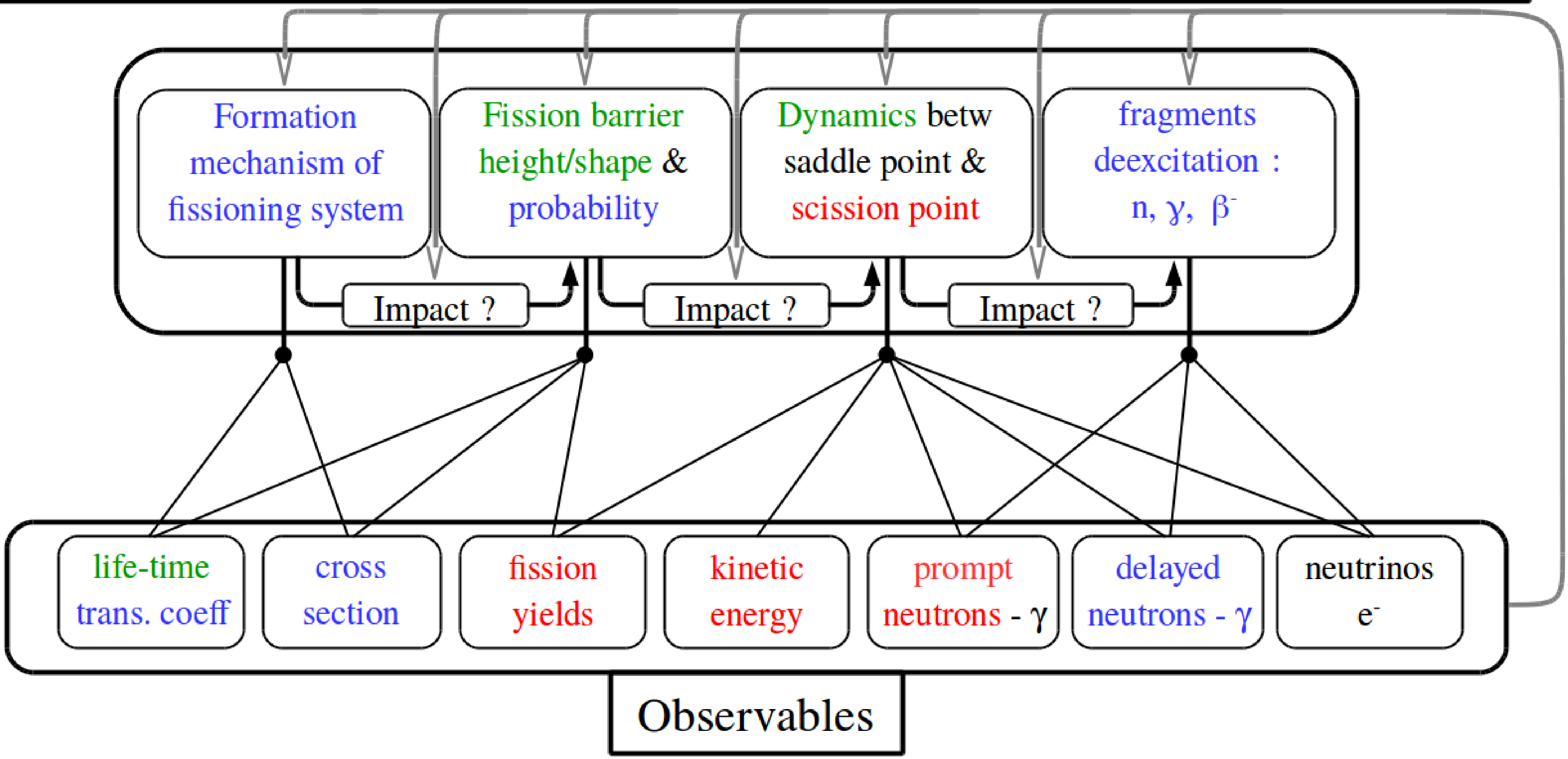


Fission process



Fission process

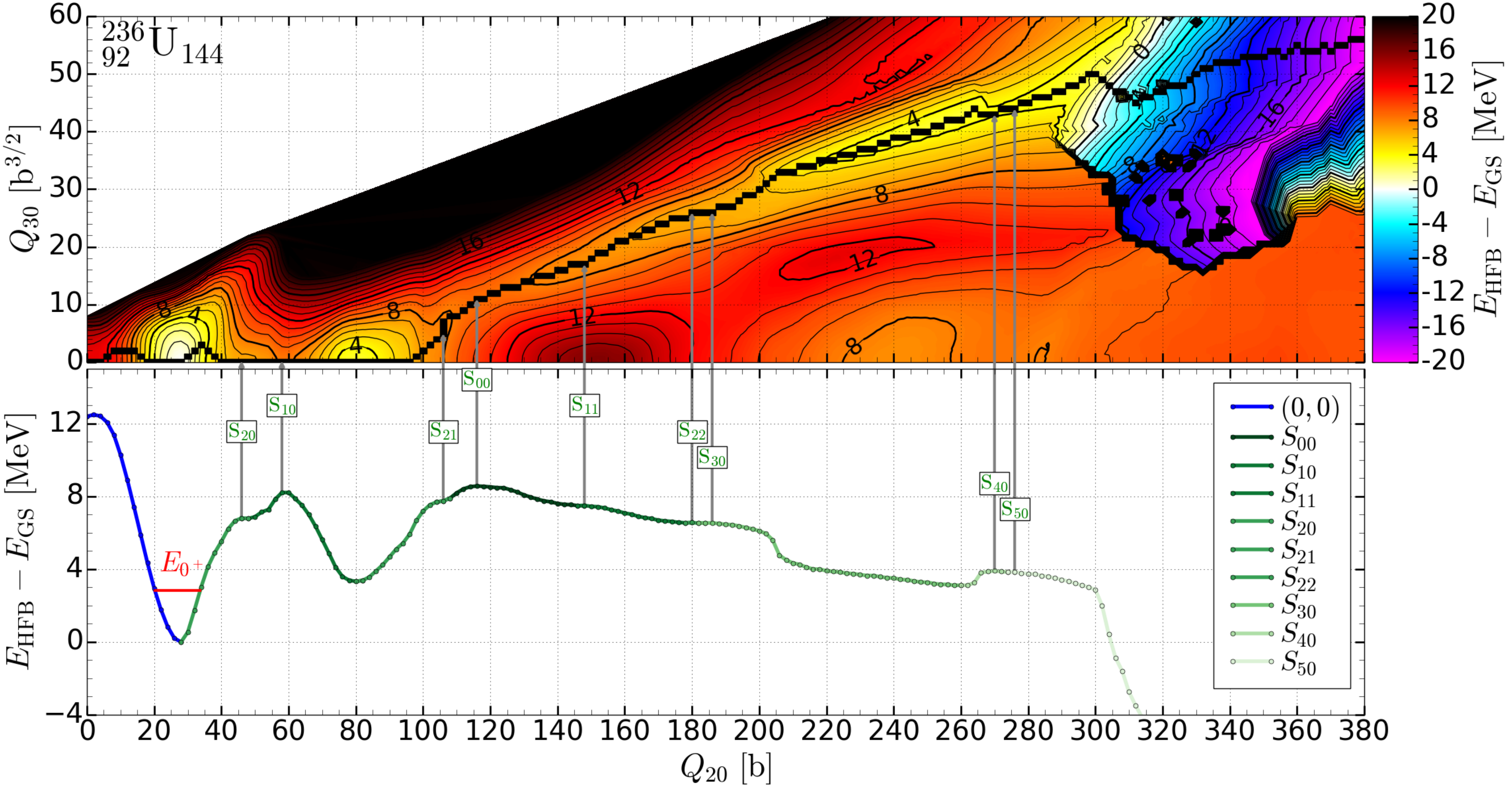
Fission process modelling : TALYS, PES (D1M+ATDHF), SPY (BSk27/D1M)



Fission path & fission barrier

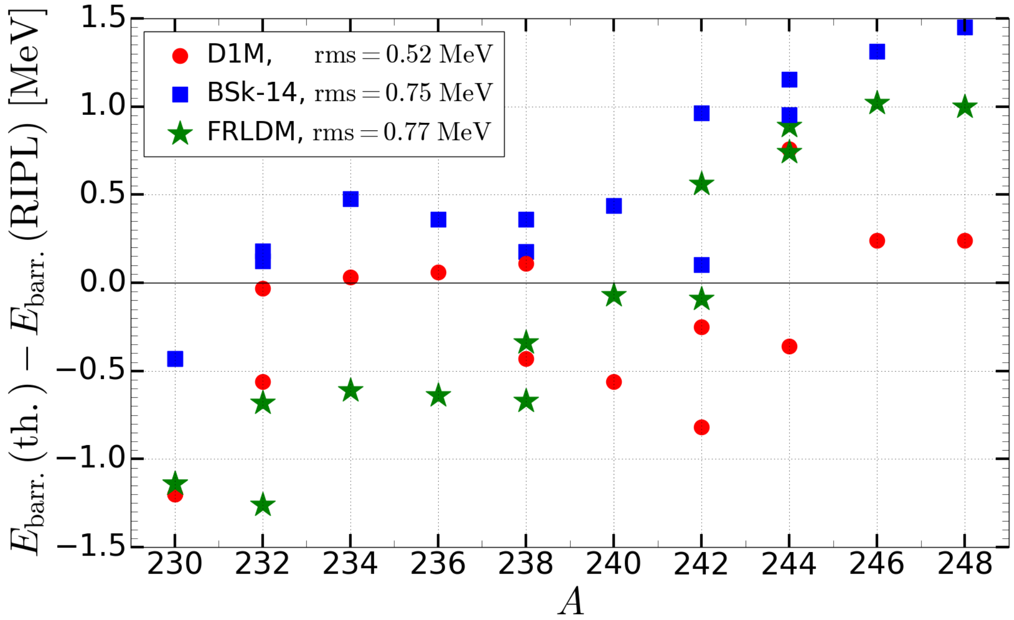
Potential Energy Surface

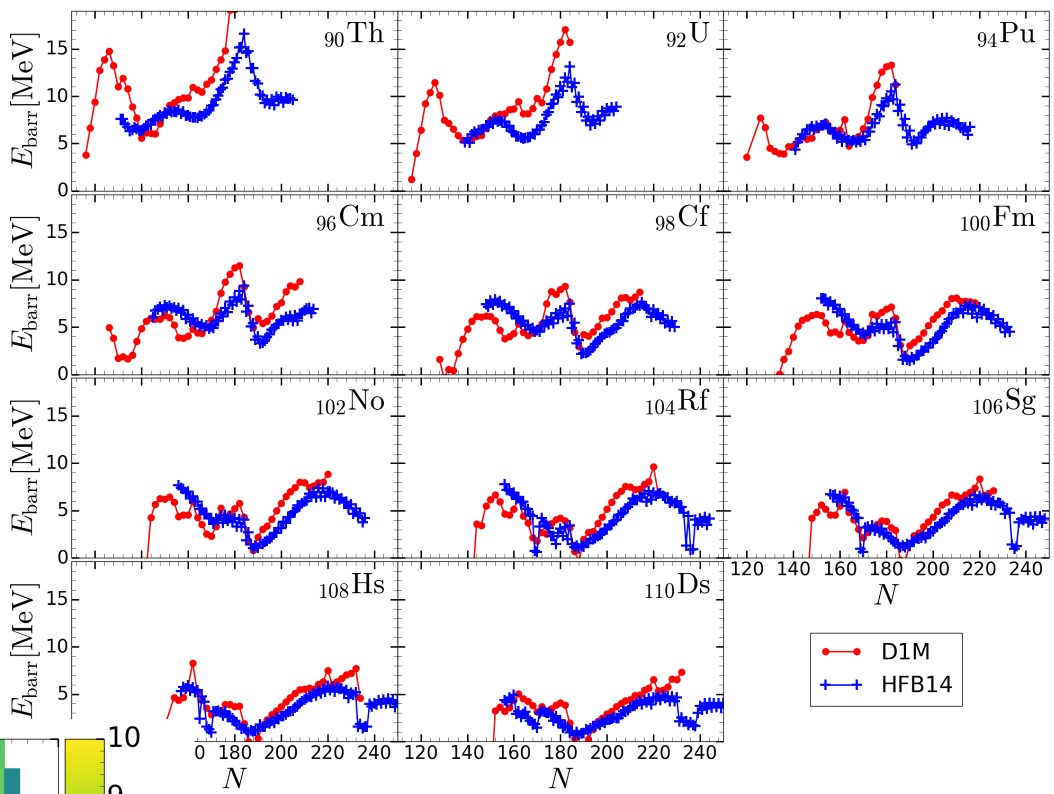
PES : constrainted HFB Gogny D1M (Q20,Q30) + triaxial correction + beyond mean-field correction (ATDHF)

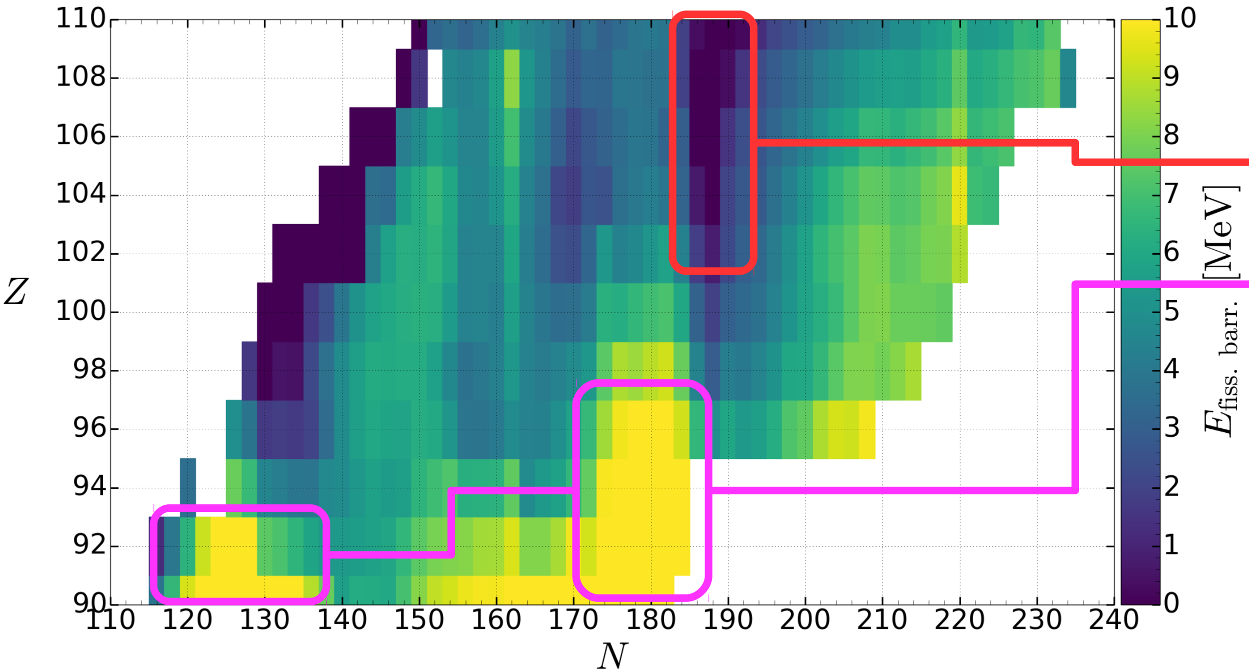


Fission path & fission barrier

Fission barrier (D1M)





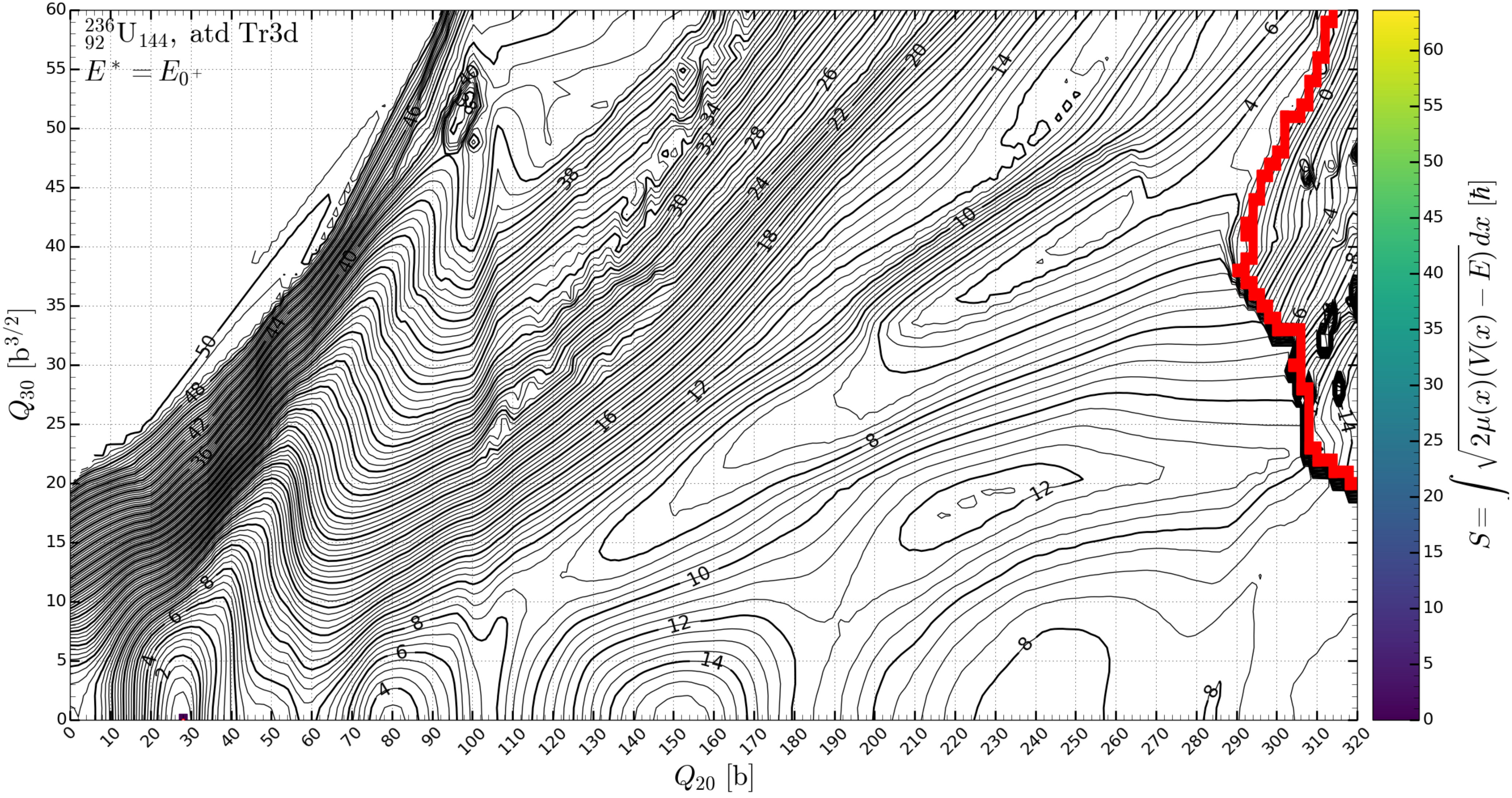


low fiss. barr.

$E_{\mathrm{barr}} > 10$ MeV

Strong neutron number influence
Weak proton number influence

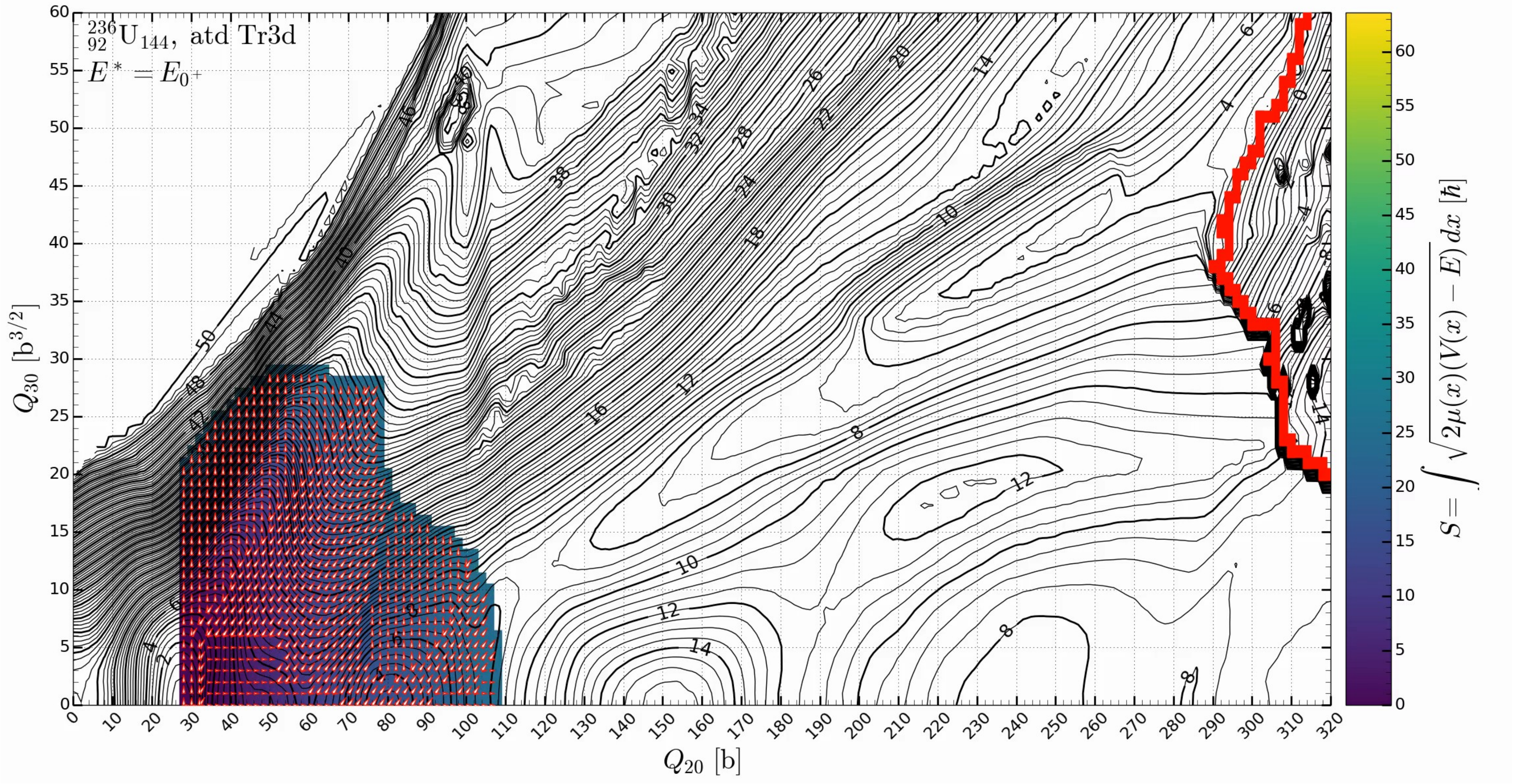
U236 ; shortest-path tree : red edged white arrows, LAP in black



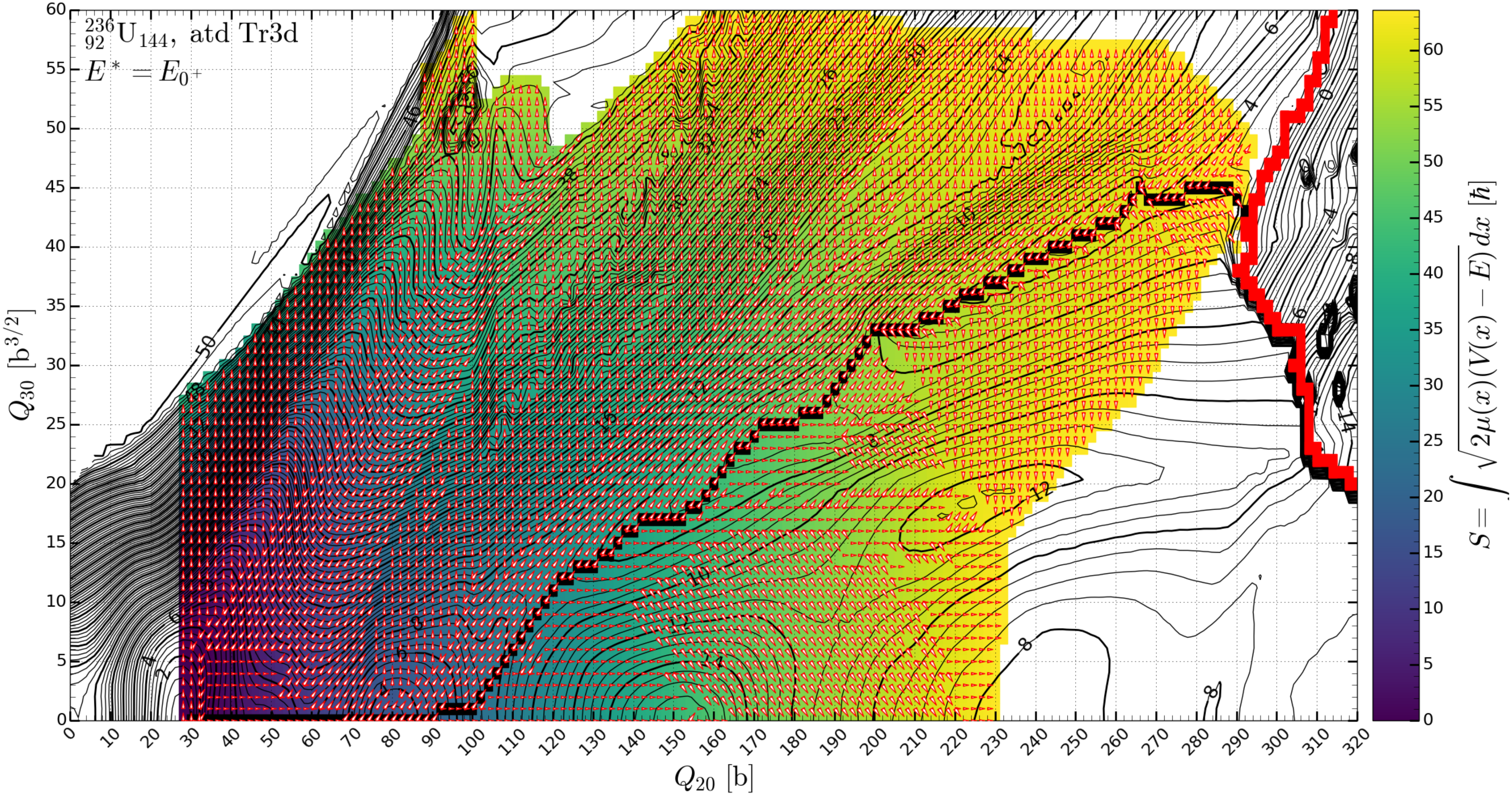
Fission path & fission barrier

Least action path

U236 ; shortest-path tree : red edged white arrows, LAP in black



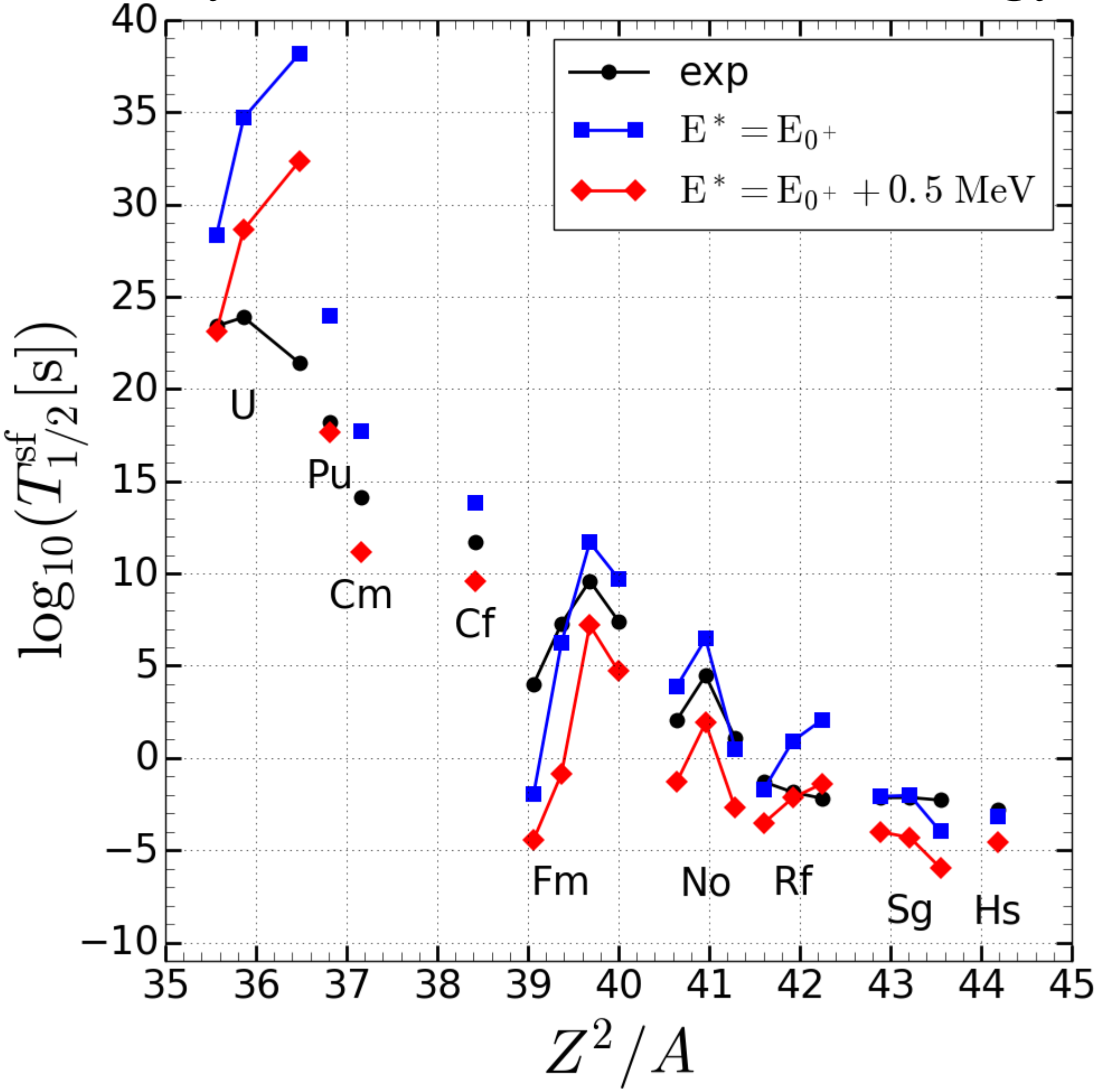
U236 ; shortest-path tree : red edged white arrows, LAP in black



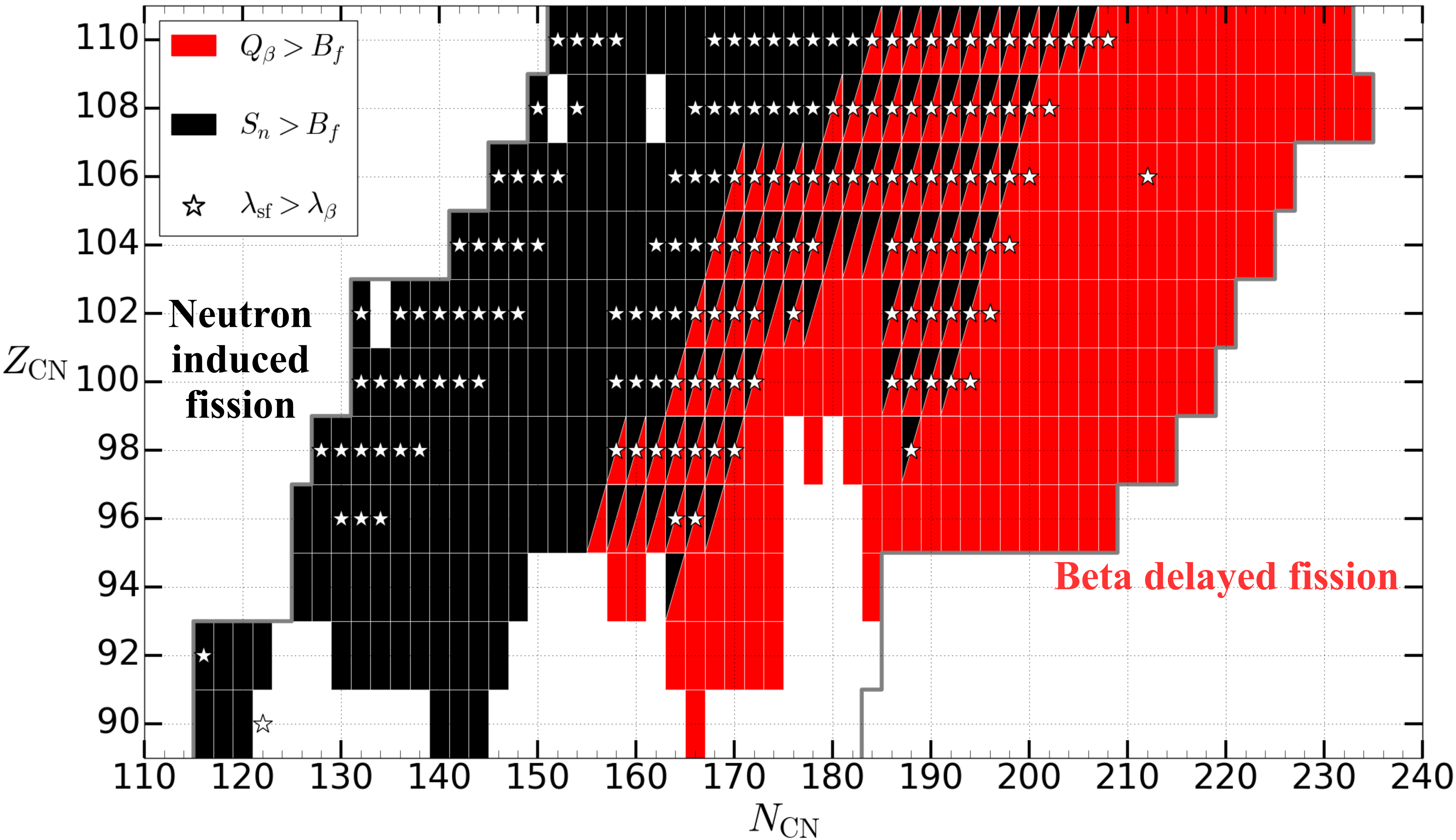
Fission path & fission barrier
Spontaneaous fission lifetimes

$$T^{sf}_{1/2} = 2.86\ 10^{-21}\left(1 + e^{2S(E)/\hbar}\right)\ [s]$$

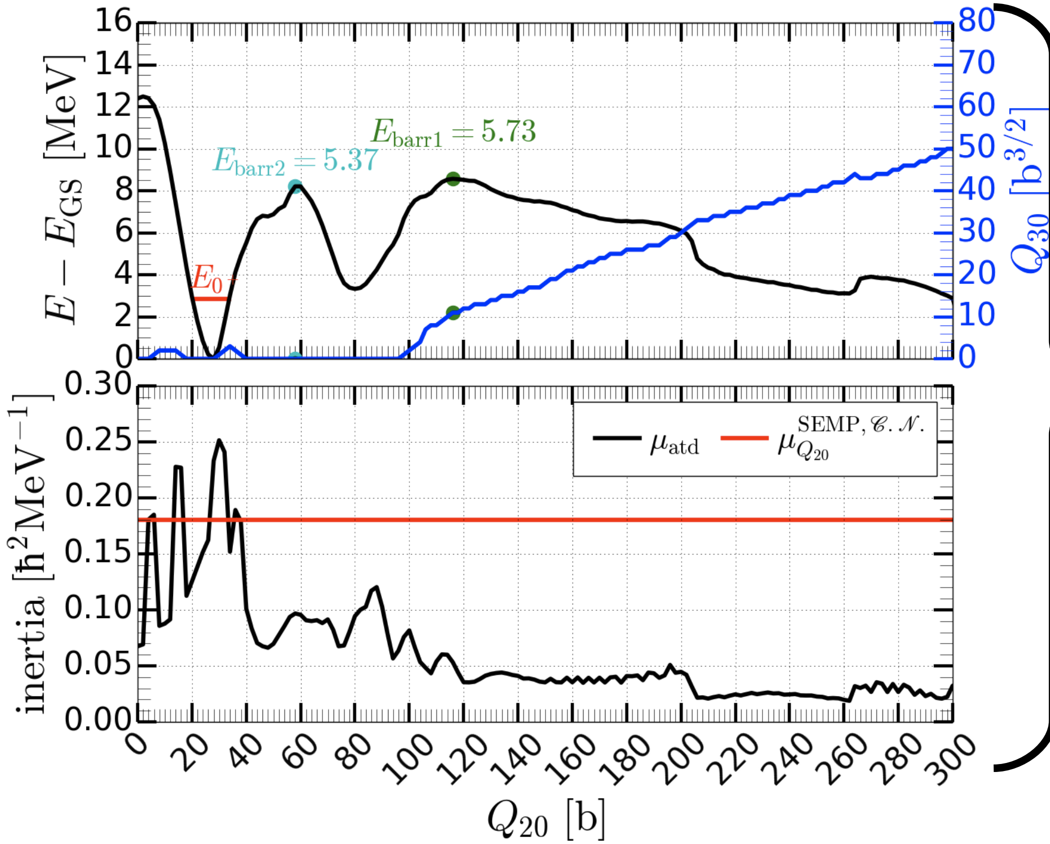
- Experimental half-lifes are fairly well reproduced
- Fission half-life are very sensitive to excitation energy



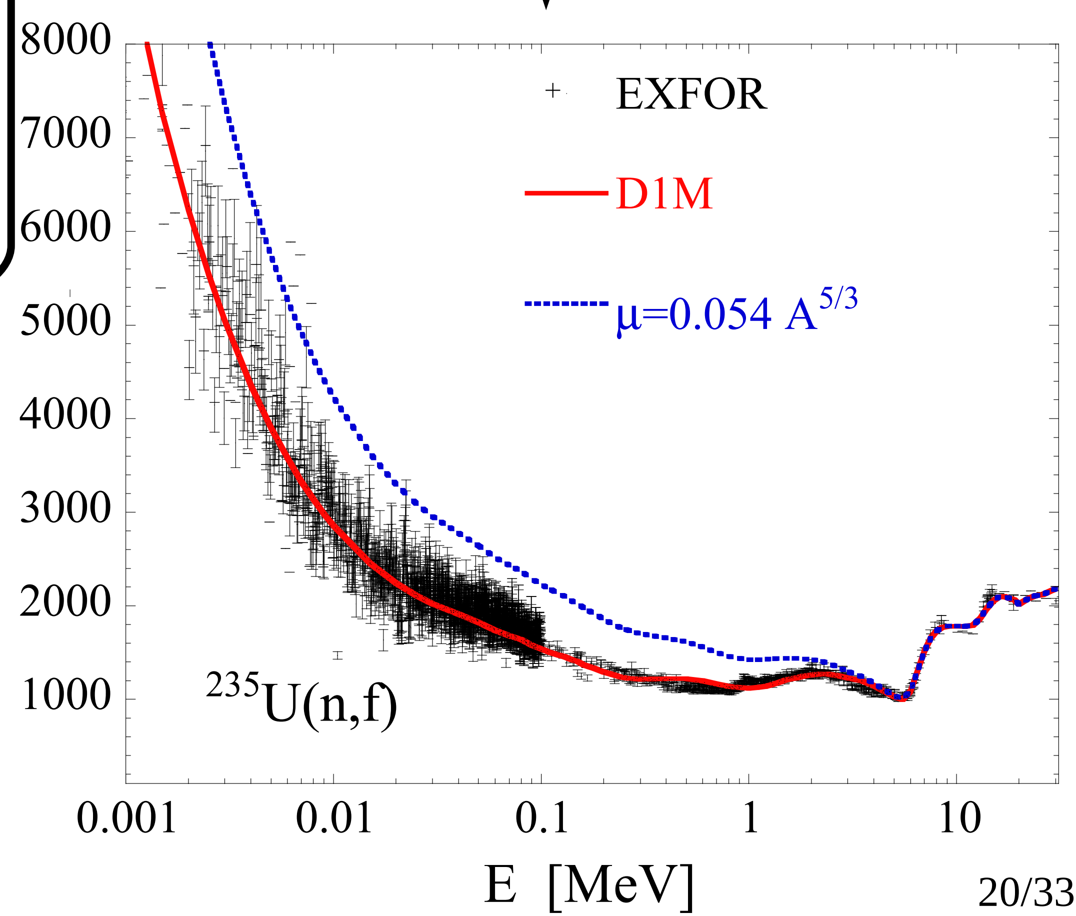
Fission path & fission barrier
$Q_\beta - S_n - B_f$ & sf – β (D1M)



Fission path & fission barrier
U235(n,f) cross section



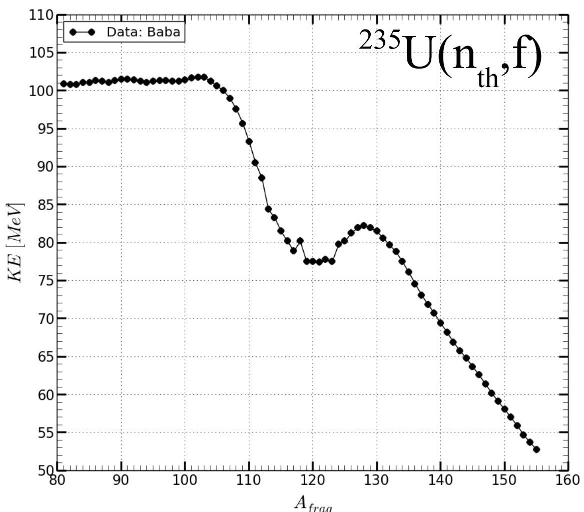
TALYS



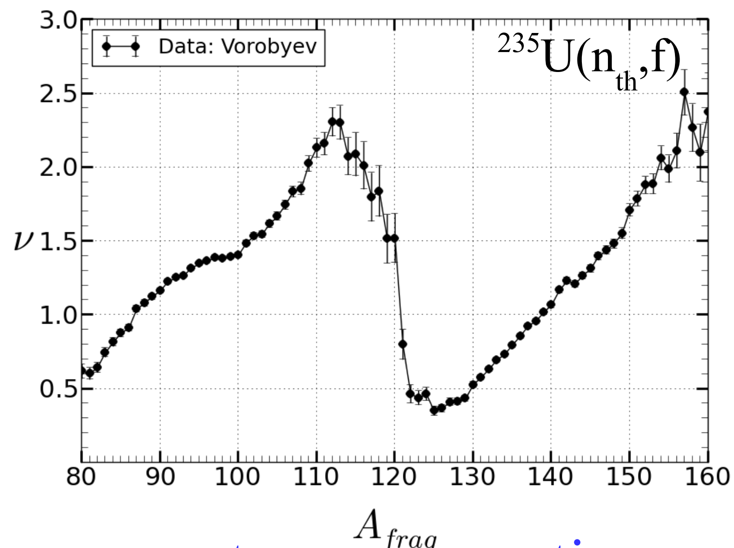
Fission fragments - SPY model
presentation

What is the role of the nuclear structure of fission fragments during the fission process ?

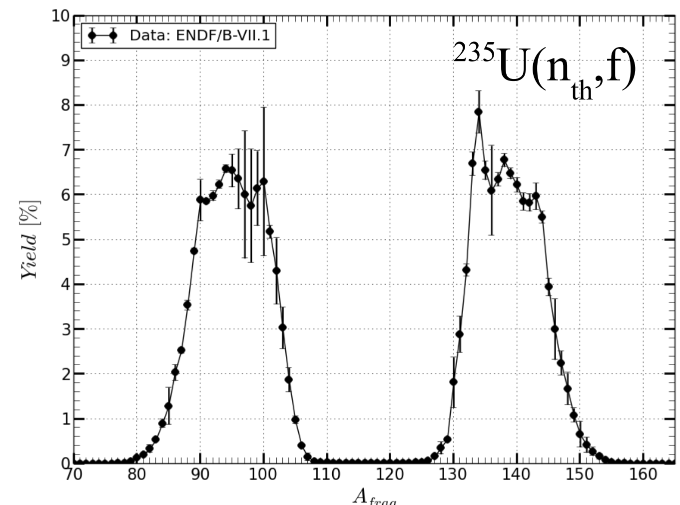
Can experimental data be understood/reproduced considering <u>only the nuclear structure of the fission fragments</u> ?



kinetic energy

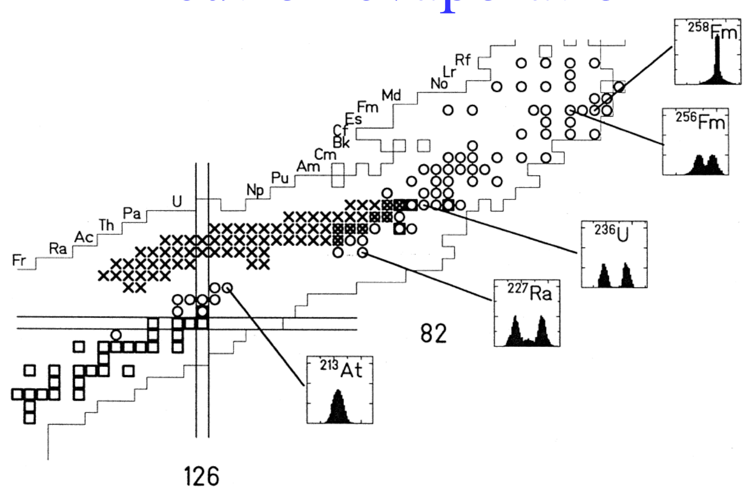


neutron evaporation



yields

symmetric/asymmetric fission

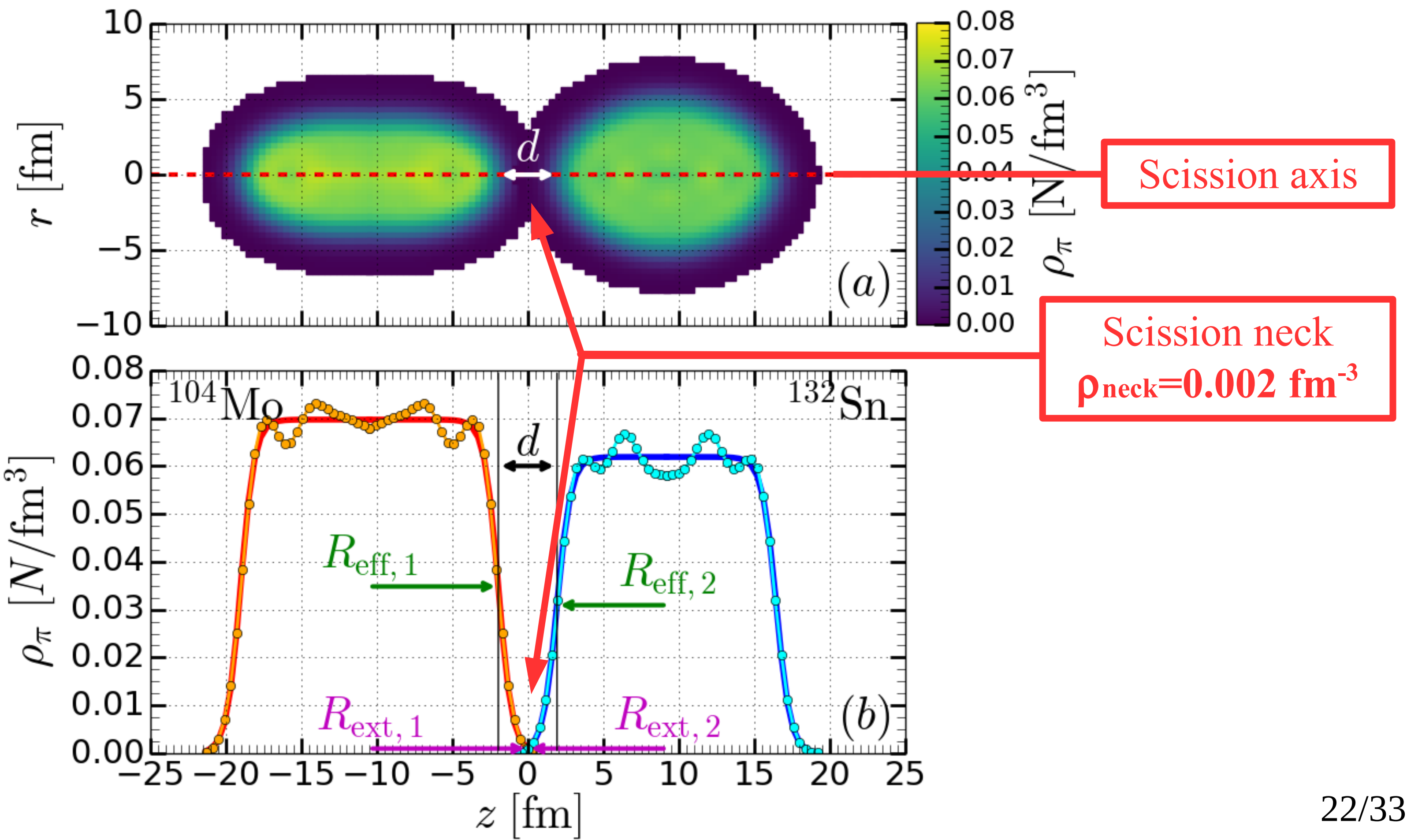


Fission fragments - SPY model
a scission point model

Hypo. to determine the frag. properties : fission process (CN→ frag.) ≈ scission line
Scission configuration : defined by the proton density at scission neck between 2 frag.
Fragments are at rest (no prescission kinetic energy)
Fragments are axially symmetric
Inputs : frag. E_{ind}, spl & proton density from HFB calculations (Gogny or Skyrme)

Proton density distribution
$^{104}Mo_{(\beta=1.2)}+^{132}Sn_{(\beta=0.4)}$

Proton density along scission axis



Fission fragments - SPY model

a statistical model

→ **ONLY based on fission fragments & first-chance fission**

→ Evolution (quasi static) between saddle point to scission point is neglected

→ Isolated fragments

→ Well defined fragments characteristics (Z, N, β)

→ Fragmentation probability $\propto$ number of available states

↳ Fragments observables

Fission fragments - SPY model
a statistical model

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Two quantities are needed to compute physical quantities

- available energy for each fragmentation of the system : AE
- the number of available states for each fragmentation of the system : AS

Fission fragments - SPY model
a statistical model

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$^{235}U(n_{th},f)$: ~500 fragmentations

1 fragmentation → 57 x 57 deformations

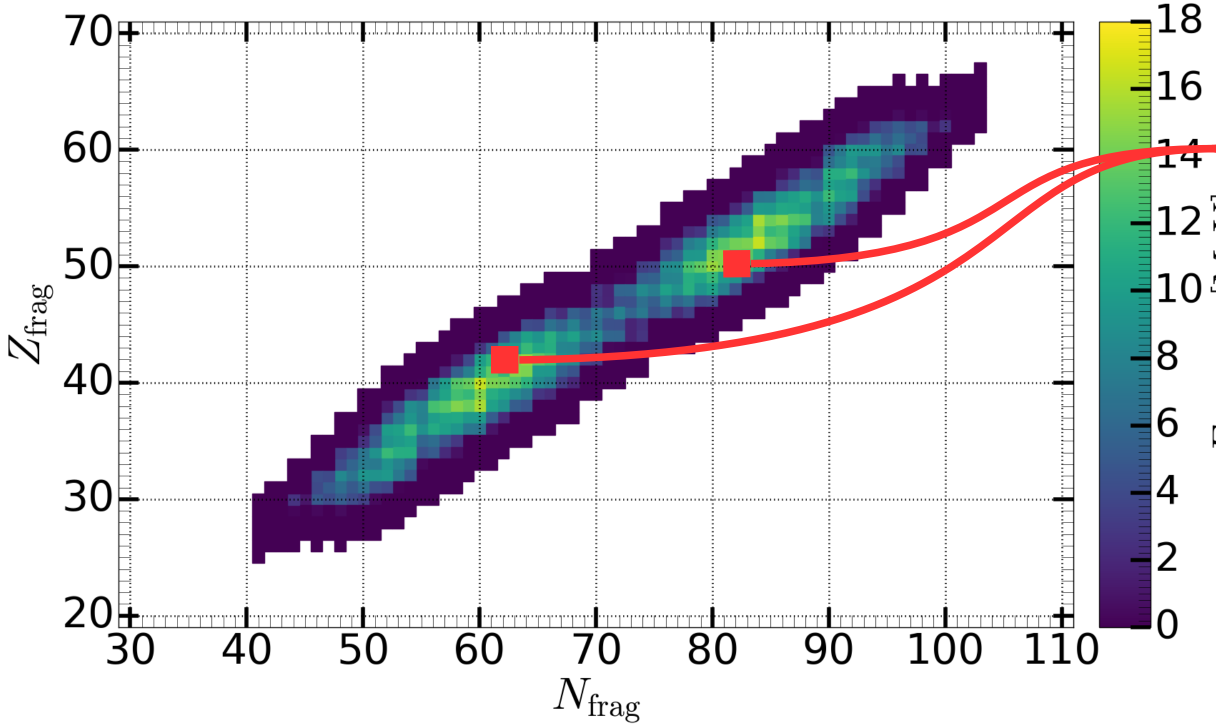
↥ Ecoul : the most time-consuming numerically computed

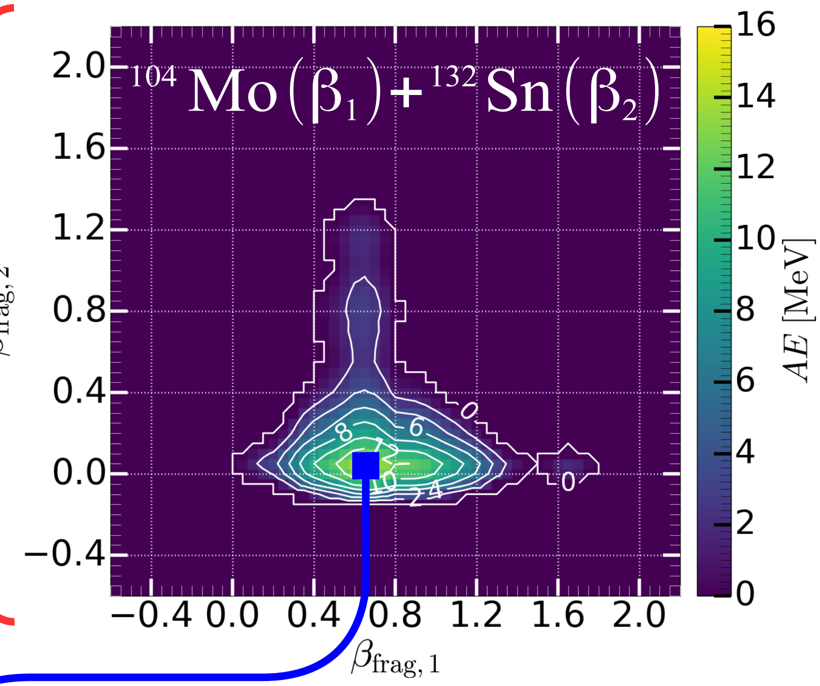
→ **1,6 million AE**

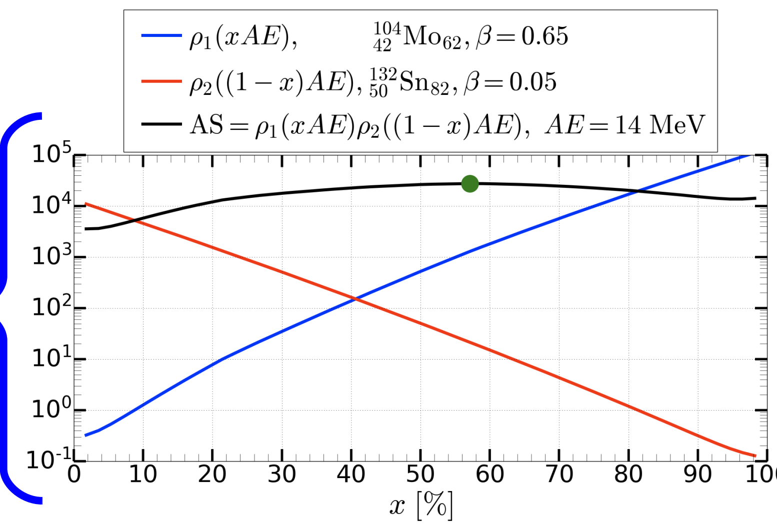
↳ AE ≈ 20 MeV → 20 AS/fragmentation

→ **32 million AS**

Fission fragments - SPY model
available energy & available states







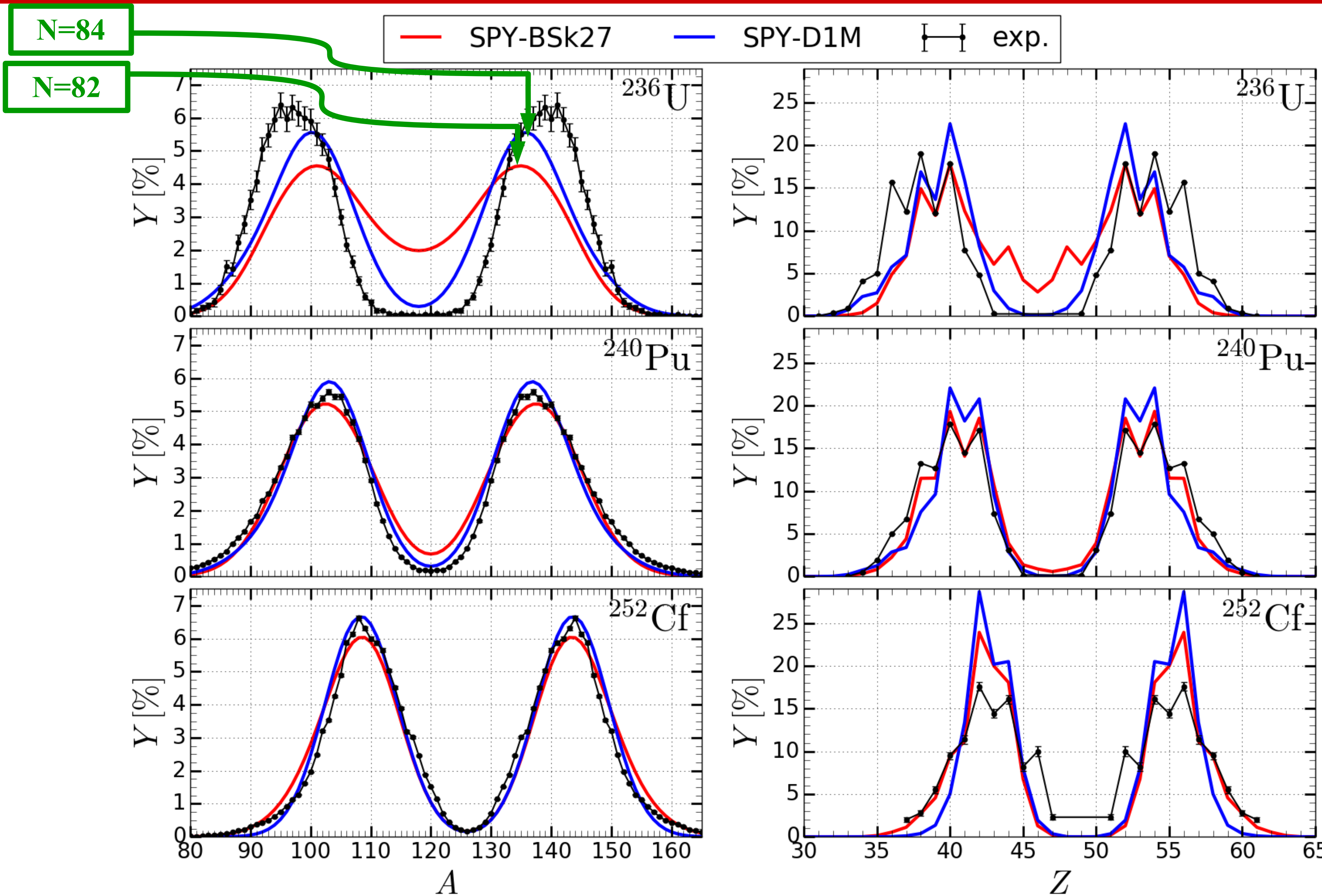
All deformation couples (β_1,β_2)

All energy shares

Probability of a given fragmentation

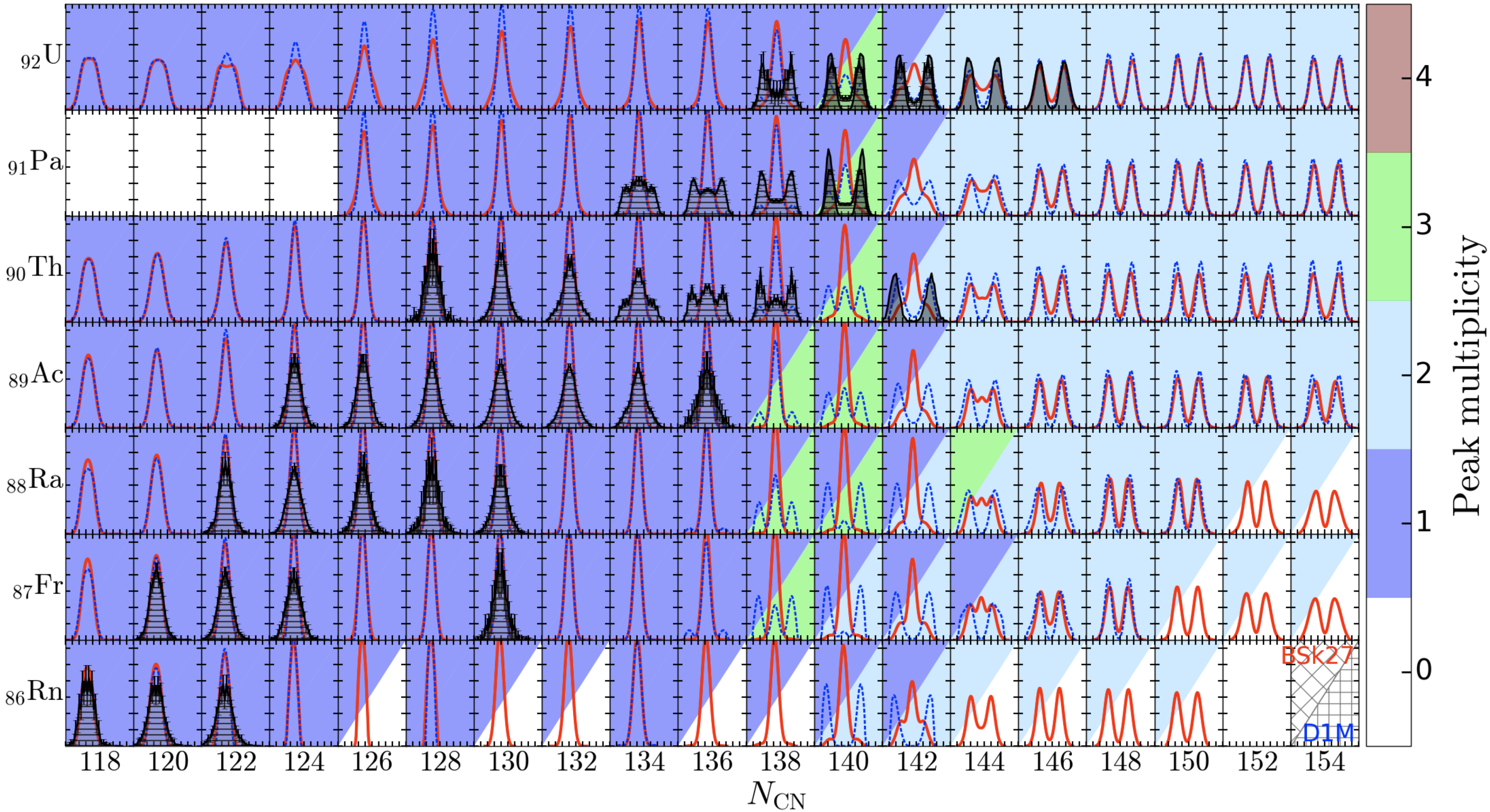
$$Y(Z_1,N_1,Z_2,N_2)=\iint_{\beta_1,\beta_2}\int_0^1 \rho_1\big(x\,\overbrace{AE}^{AE(\beta_1,\beta_2)},\beta_1\big)\,\rho_2\big((1-x)AE,\beta_2\big)\,\delta E^2\,dx\;d\beta_1\,d\beta_2$$

Fission fragments - SPY model
Fission of U236, Pu240 & Cf252



Exp data : U236 → C. Romano et al, PRC81, 014607 (2010) // W. Lang et al, NPA345, 34 (1980)
Pu240 → C. Tsuchiya et al , J. Nucl. Sci. Technol. 37, 941 (2000) // C. Schmitt et al, NPA430, 21 (1984)
Cf252 → Sh. Zeynalov et al, J. Korean Phy. Soc. 59, 1396 (2011) // G. Mariolopoulos et al, NPA361, 213 (1981)

Fission fragments - SPY model
Fission of « actinides »

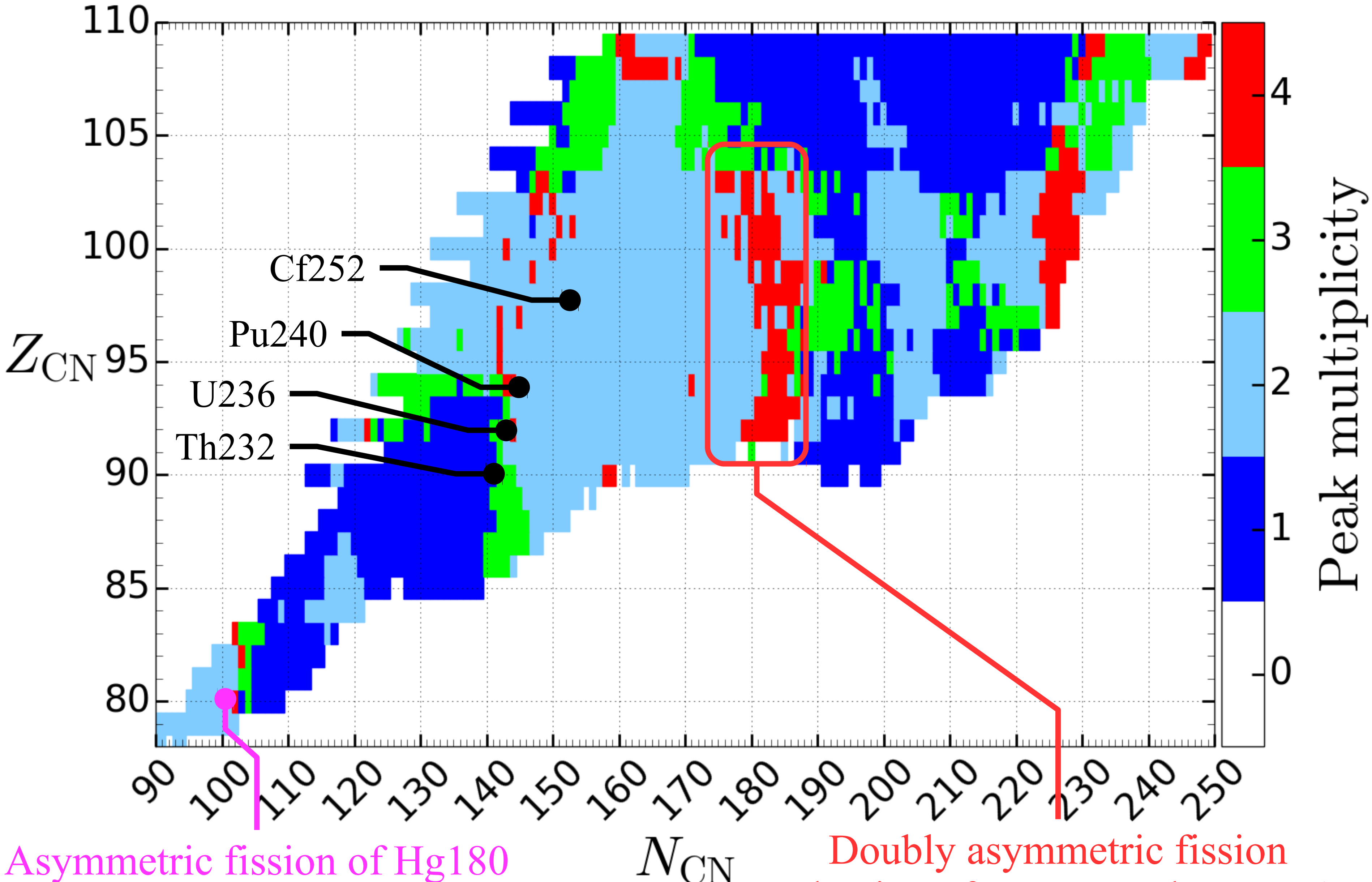


Disparity of the location of sym/asym fission for Fr, Rn (6 neutrons)

Transition sym/asym occurs for a too neutron rich isotope wrt exp. data

Exp. Data, curve with a striped filling : Coulex induced fission, E* around 11 MeV (GDR) (NPA655 p221(2000))

Fission fragments - SPY model
Peak multiplicity



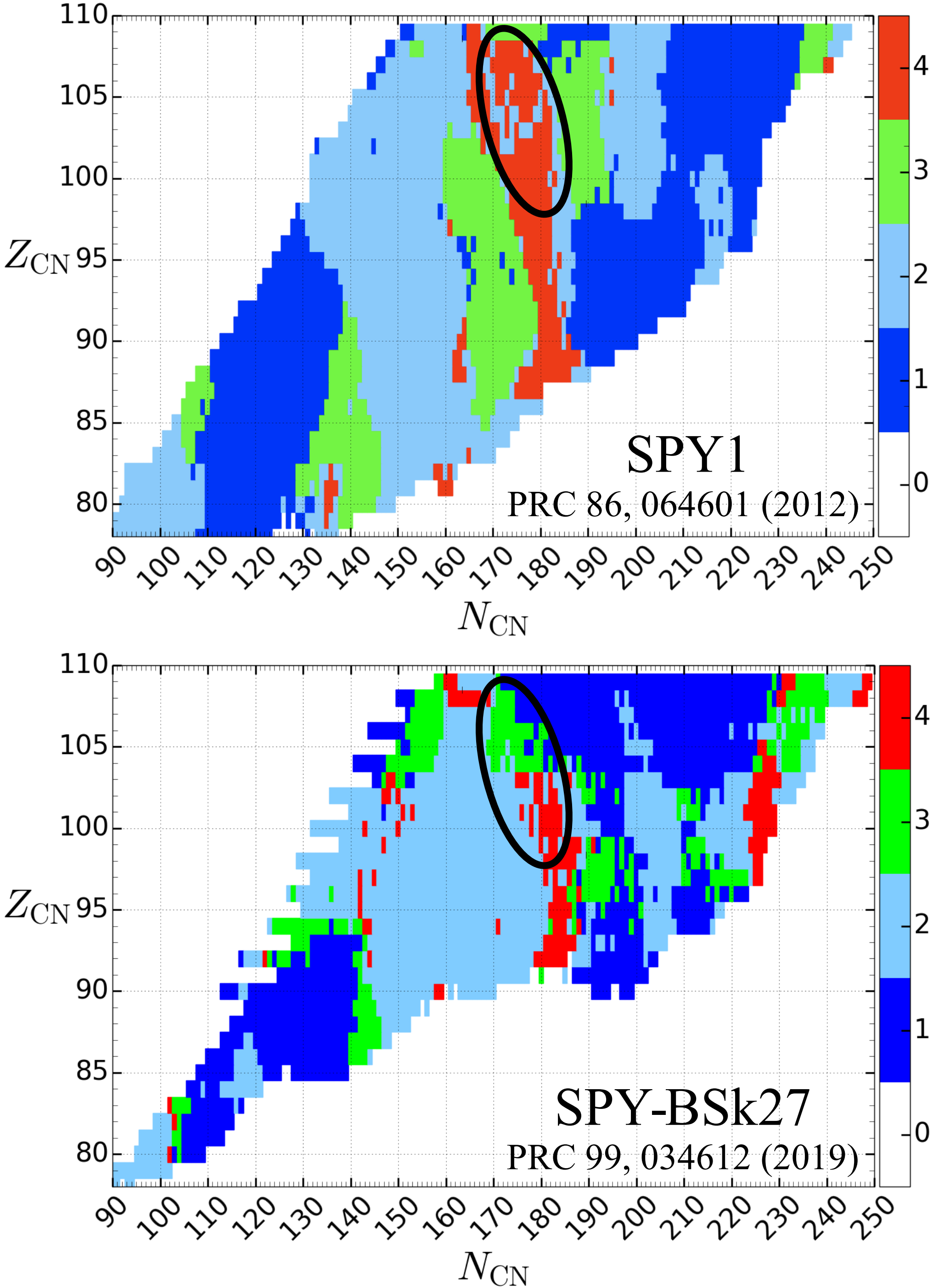
Asymmetric fission of Hg180
(S. Panebianco et al, Phys. Rev. C 86, 064601 (2012))

Doubly asymmetric fission
→ production of r-process elements A~165
(S. Goriely et al, Phys. Rev. Lett. 111, 242502 (2013))

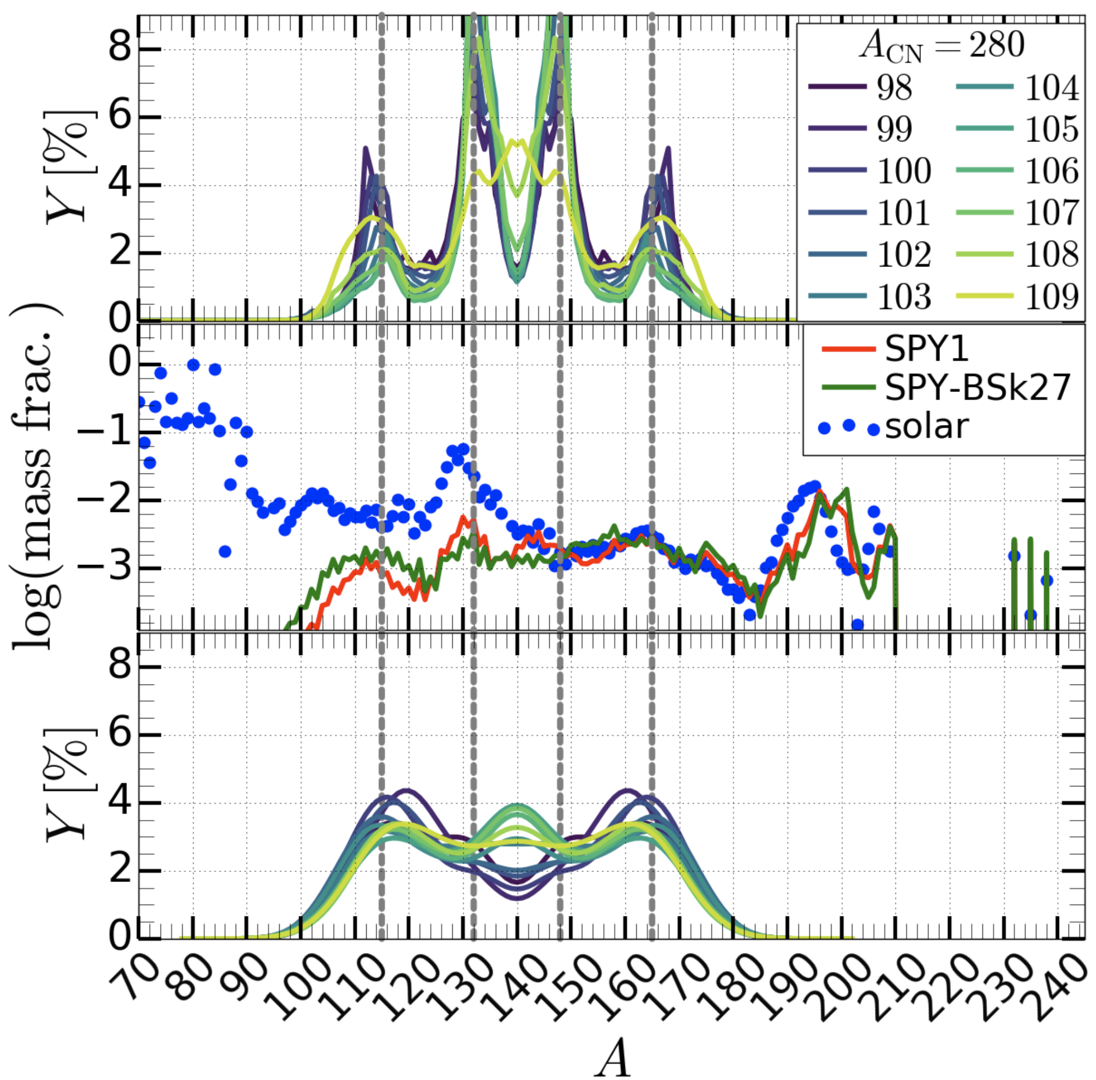
SPY-BSk27 * Q=8 MeV * ρ_{neck}=0.002 fm^{-3}

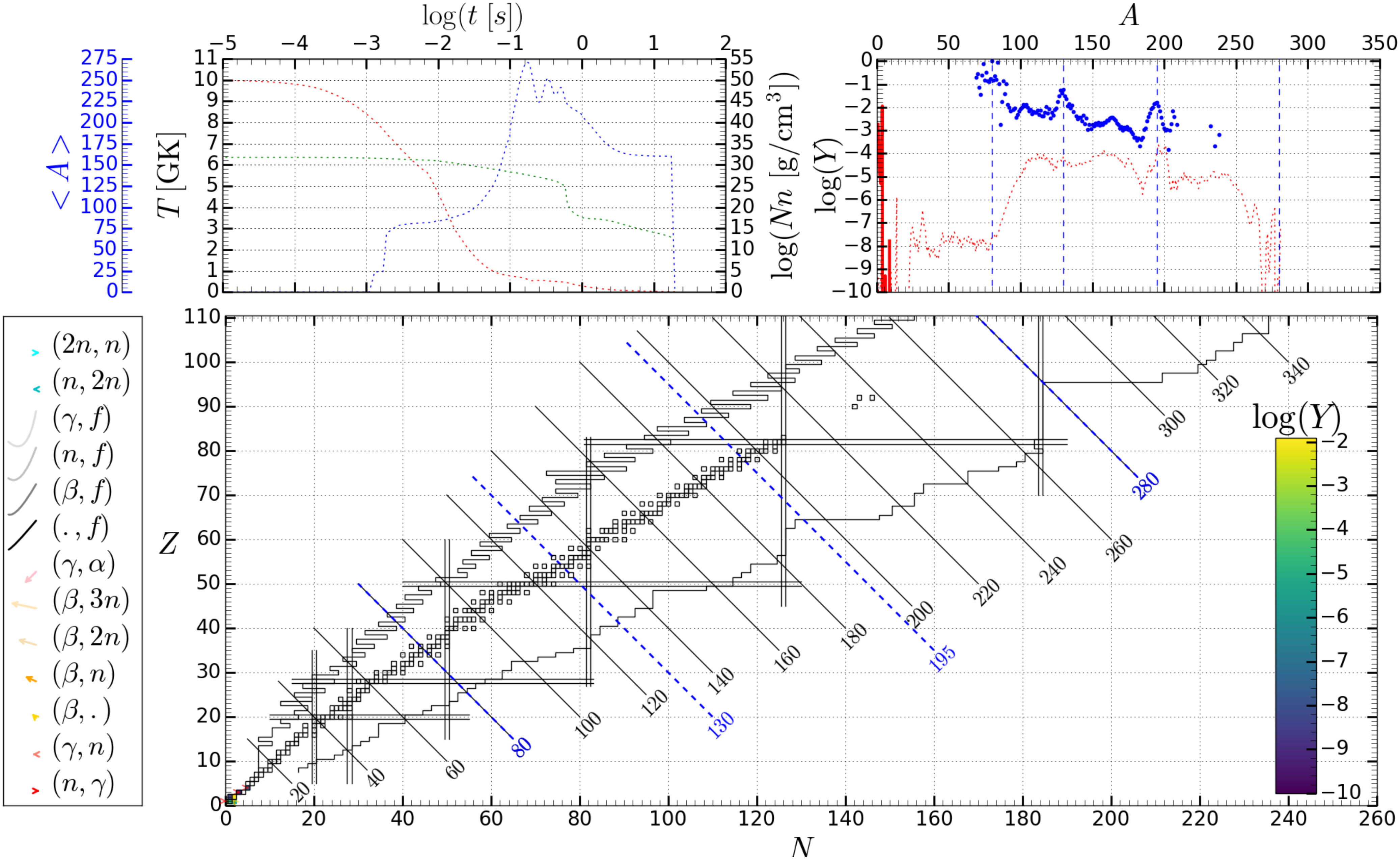
Fission fragments - SPY model

Doubly asymmetric fission & abundances

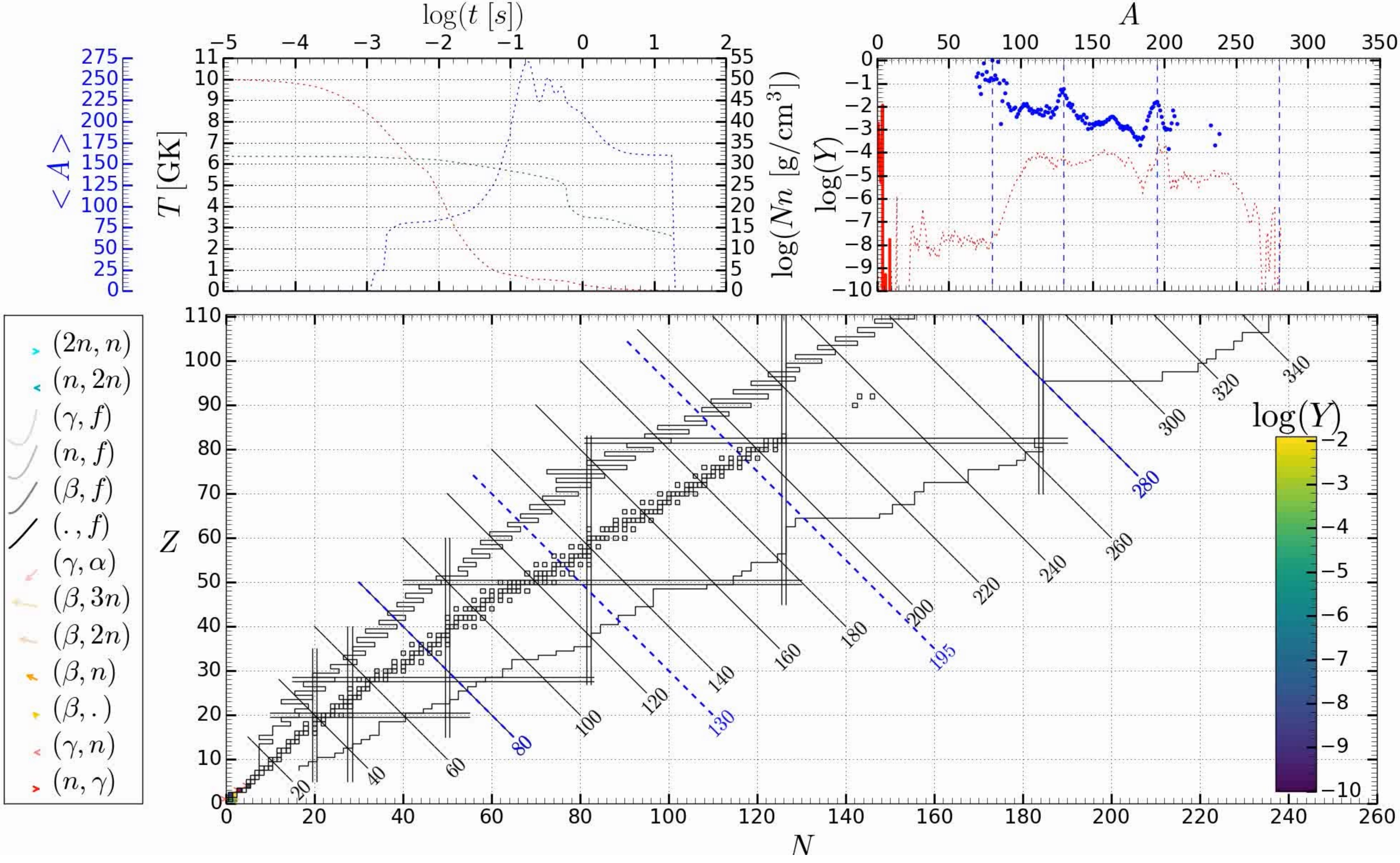


More details about dynamical ejecta in PRL 111, 242502 (2013) & A. Bauswein's talk





log(t [s])
A
$< A >$
$T\,[\mathrm{GK}]$
$\log(Nn\ [\mathrm{g/cm^3}])$
$\log(Y)$
$(2n,n)$
$(n,2n)$
(γ,f)
(n,f)
(β,f)
$(.,f)$
(γ,α)
$(\beta,3n)$
$(\beta,2n)$
(β,n)
$(\beta,.)$
(γ,n)
(n,γ)
Z
N
$\log(Y)$
20
40
60
80
100
120
130
140
160
180
195
200
220
240
260
280
300
320
340



$\log(t\ [s])$
$\langle A \rangle$
$T\,[\mathrm{GK}]$
$\log(Nn\ [\mathrm{g/cm^3}])$
A
$\log(Y)$
$(2n,n)$
$(n,2n)$
(γ,f)
(n,f)
(β,f)
$(.,f)$
(γ,α)
$(\beta,3n)$
$(\beta,2n)$
(β,n)
$(\beta,.)$
(γ,n)
(n,γ)
Z
N
$\log(Y)$

Conclusions & outlooks

Fission path

- Fission barriers for 500 e-e nuclei (J.-F. Lemaître et al, PRC 98, 024623 (2018))
- Half lives in good agreement with experimental data

* To be extended to odd nuclei
* LEP/LAP → Fission cross sections
* R-process in full Gogny D1M framework

Fission fragments

- Scission point, static frag., statistical (microcanonical description)
- Definition of the scission point based on realistic proton distribution
- All ingredients are calculated coherently in the same microscopic framework (Skyrme BSk27 eff. N-N interaction ; J.-F. Lemaître et al, Phys Rev C 99, 034612 (2019))
- Applied to the r-process, doubly asymm. fission (S. Goriely et al, Phys. Rev. Lett. 111, 242502 (2013))

* Improve the description of the kinetic energy, the neutron evaporation
* Octupole deformations
* New version with Gogny-D1M eff. N-N interaction → link with PES