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The fundamental role of fission during the r-process nucleosynthesis

Part II:

The rapid neutron-capture process

- Astrophysical aspects
- Nuclear physics aspects & fission
  - Nuclear physics uncertainties
  - Models of relevance for r-process calculation
  - Role of fission
  - Calculation of fission observables & their impact

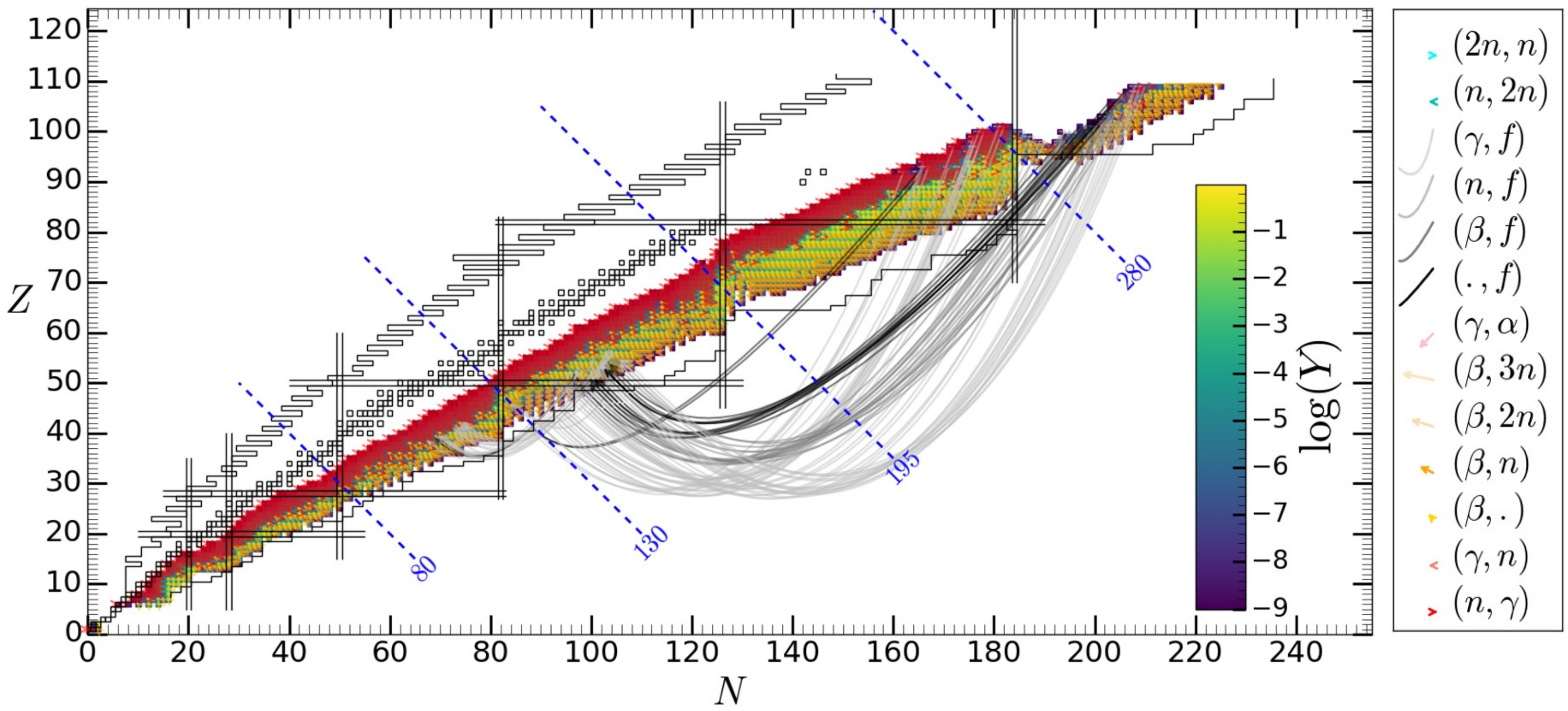
Another uncertainty: nuclear physics input

(n,γ) – (γ,n) – β competition & Fission

- β-decay rates
- (n,γ) and (γ,n) rates
- Fission (nif, sf, βdf) rates
- Fission Fragments Distributions

} Still many open questions

some 5000 nuclei with $Z \leq 110$ involved on the n-rich side



Nuclear physics input

(n,γ) – (γ,n) – β competition & Fission

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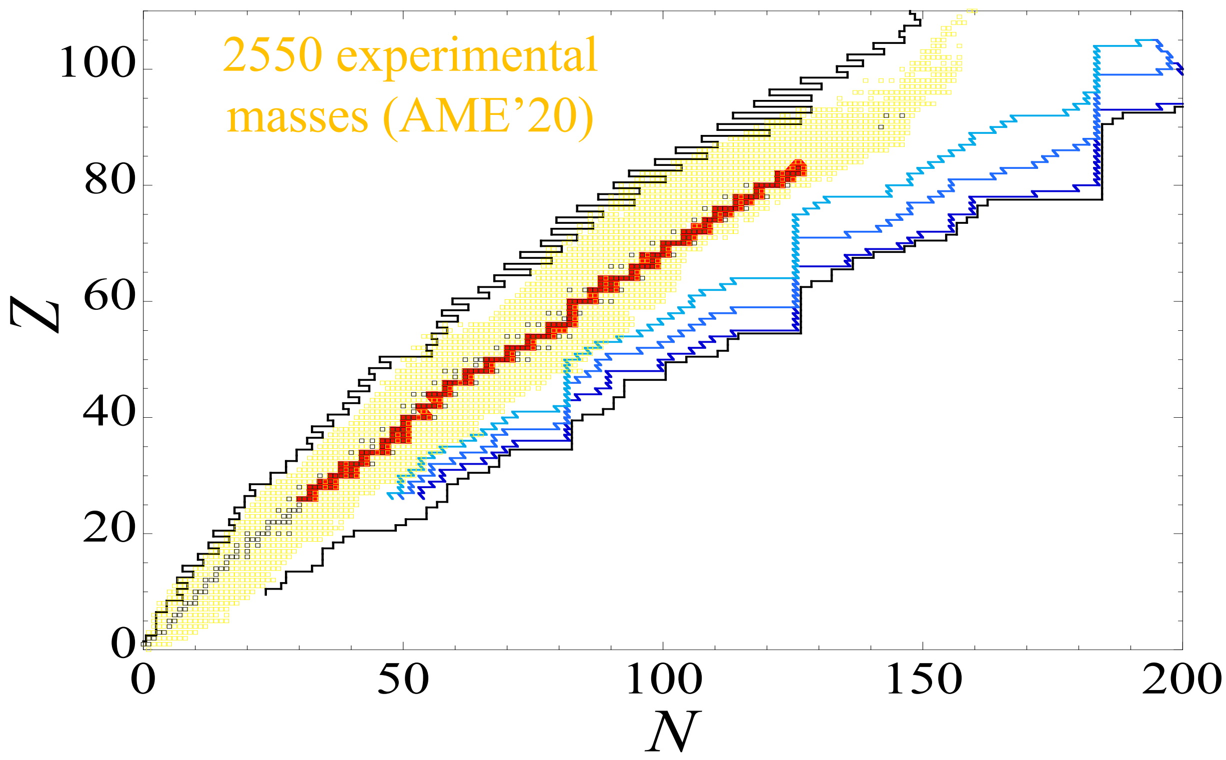
some 5000 nuclei with $Z \leq 110$ involved – essentially no exp. data



Nuclear physics input

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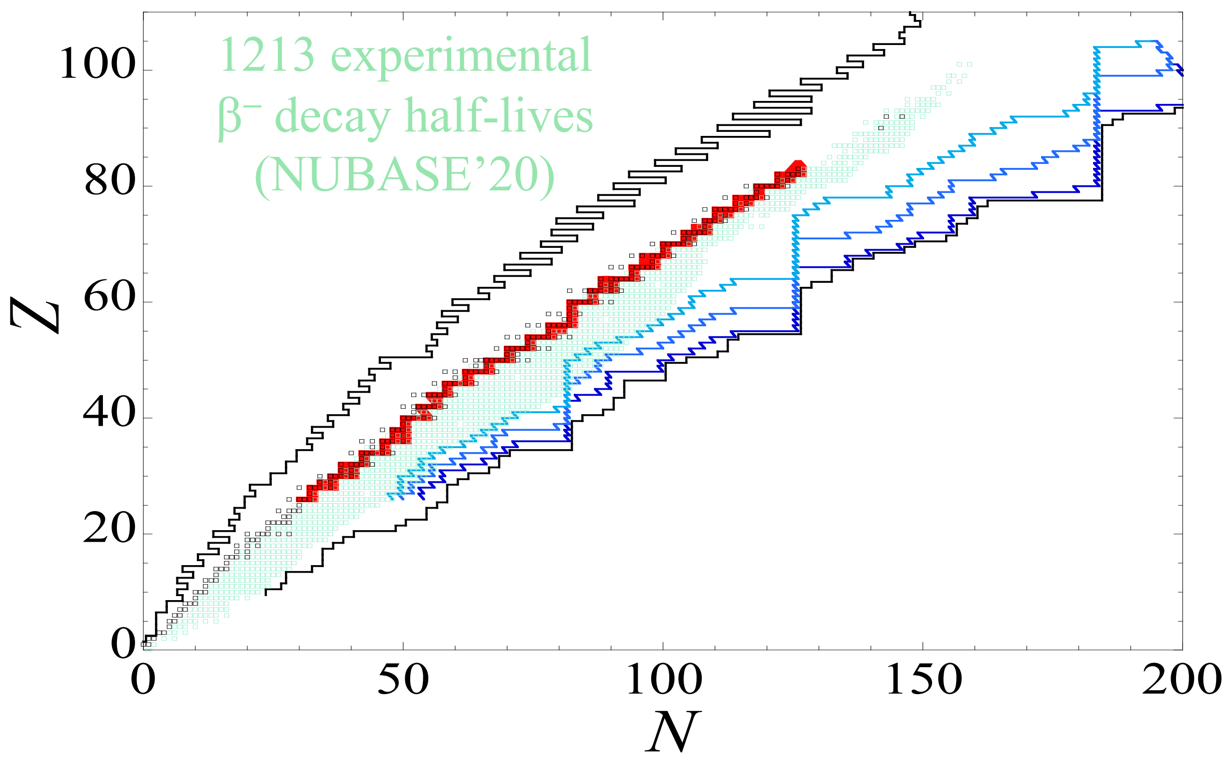
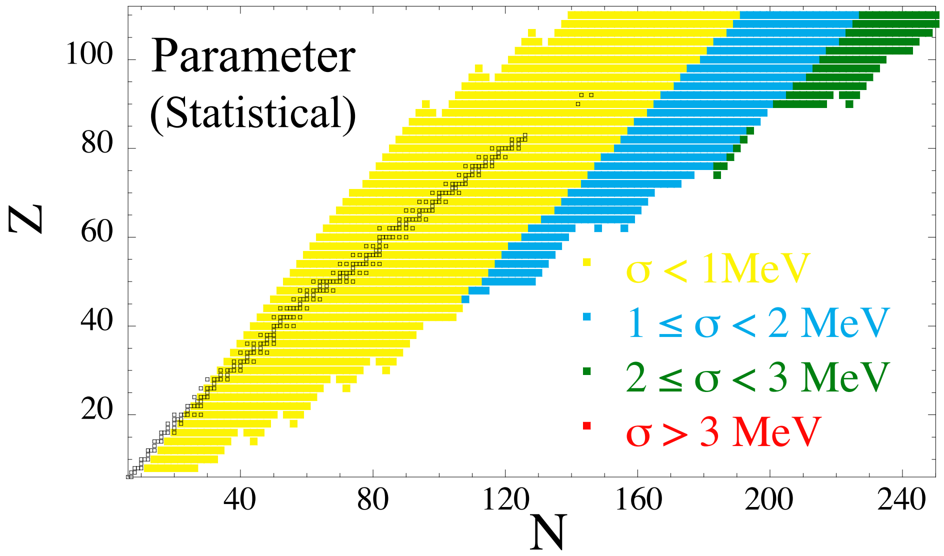
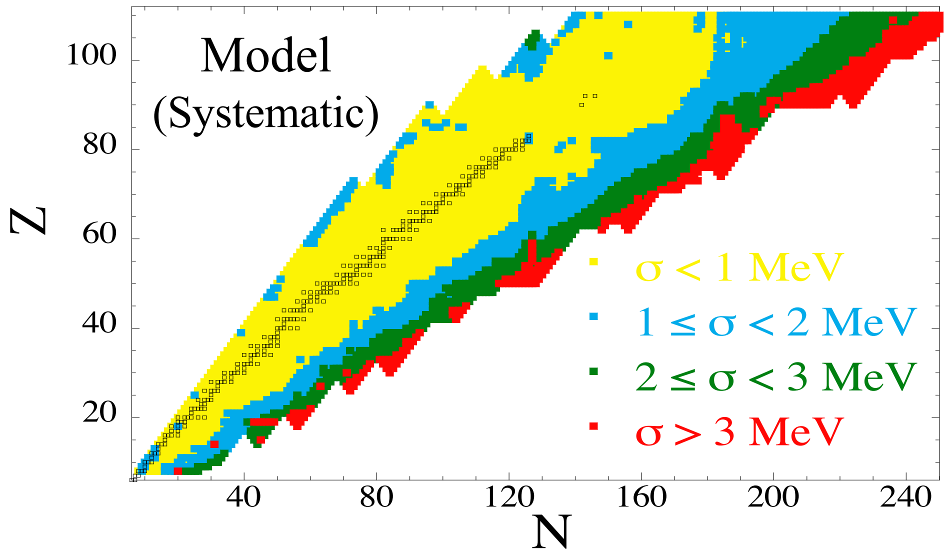


Nuclear uncertainties

Some Progress in considering "theoretical uncertainties" in NA

Two types of uncertainties affecting nuclear inputs (e.g Masses)



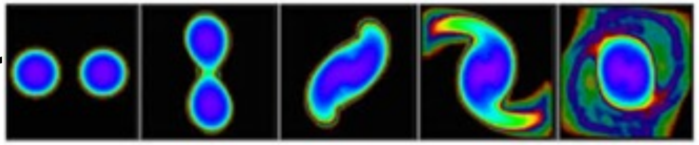


Model or parameter variations must be constrained by experimental data

e.g. mass models with $\sigma_{rms} < 0.8$ MeV or (n,γ) models with $f_{rms} \leq 2$

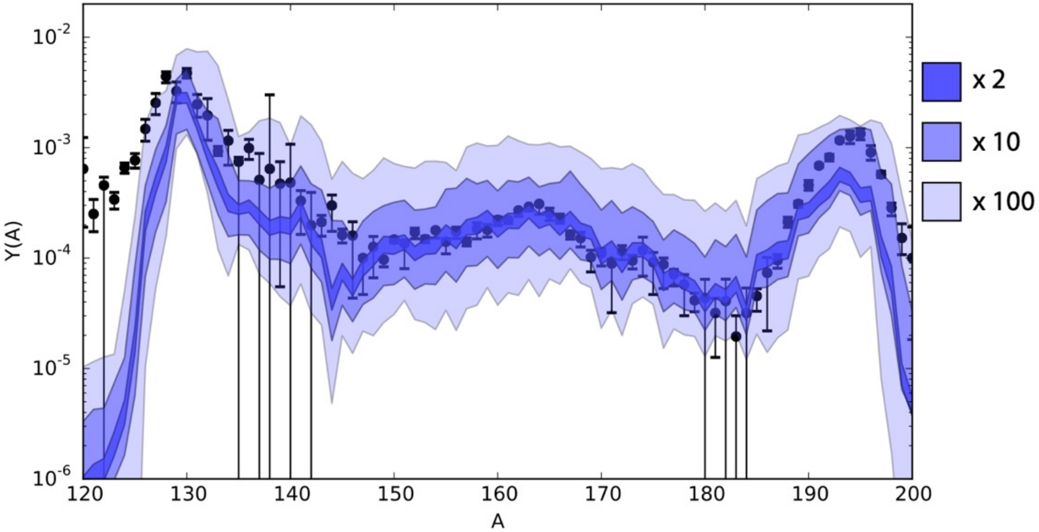
But what about their impact on astrophysical observables ?

How to propagate such NP uncertainties into astrophysics simulations ??



Uncorrelated MC approach

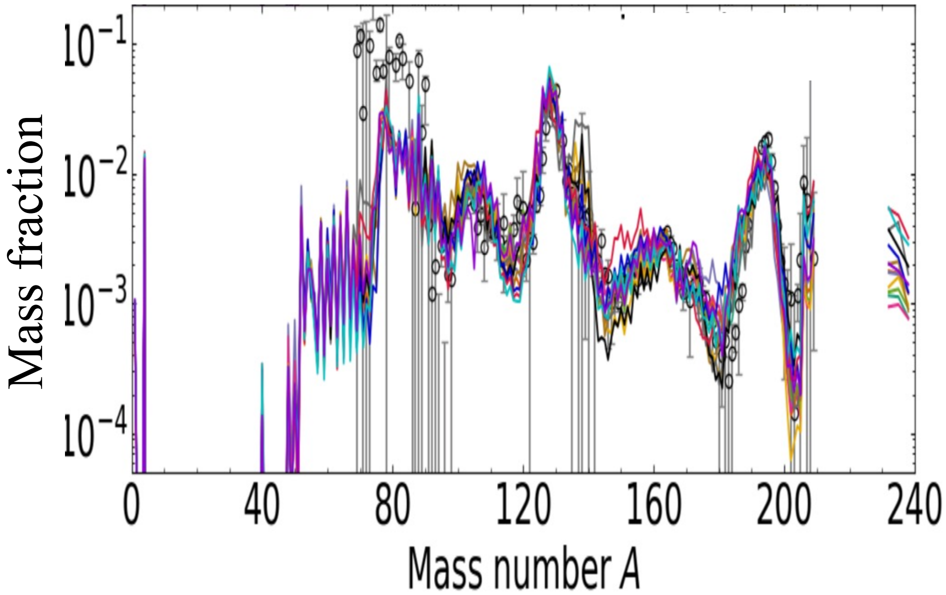
Mumpower et al. (2016); Nikas et al. (2020)



- Rates within an arbitray factor of 2, 10, 100
- Neglect correlations between uncertainties
- Overestimates impact if not exp-constrained

Model-correlated approach

Sprouse et al. (2020); Kullmann et al. (2022)



- Coherent model-correlated uncertainties
- Only parameter or model uncertainties
- Overestimates impact if not exp-constrained

In all cases, propagation must be applied to a large representative sample of trajectories

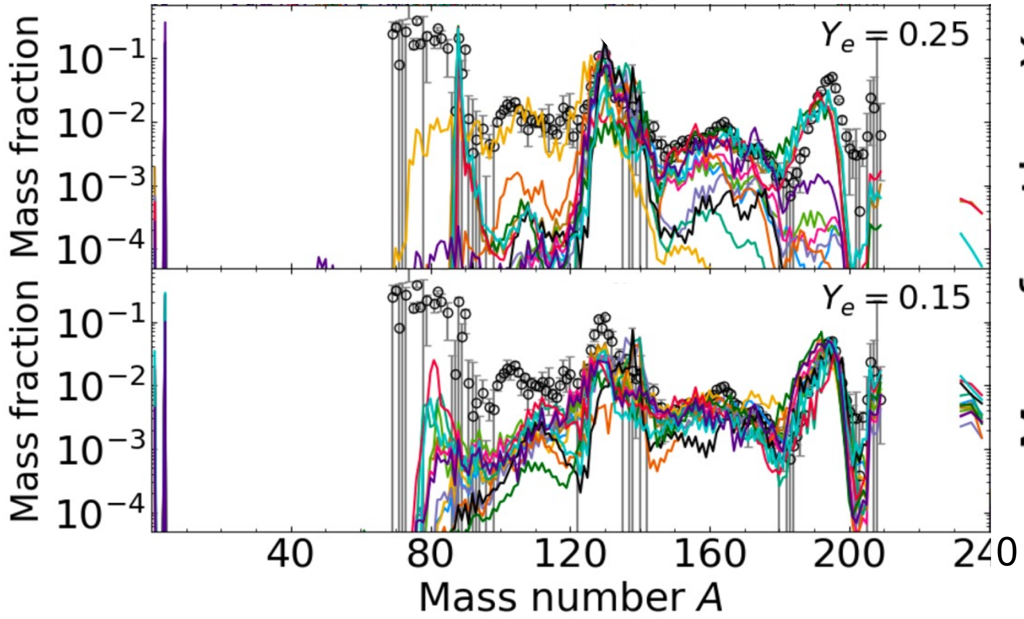
Impact of nuclear *model* uncertainties on the composition of NSM ejecta

15 different "acceptable" sets of nuclear inputs (masses, β-decay, n-capture, fission)

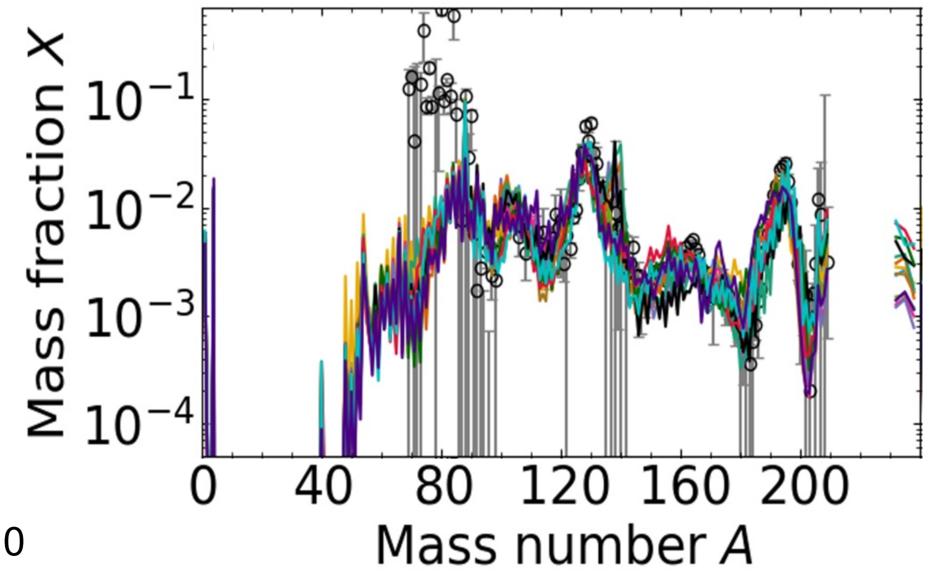
Kullmann et al. (2022)

Prompt dynamical ejecta: SFHo 135-135

Single trajectory



Multiple trajectories

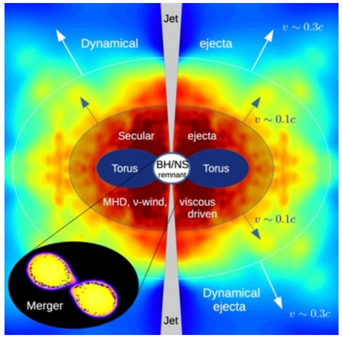


Global & Local discrepancies

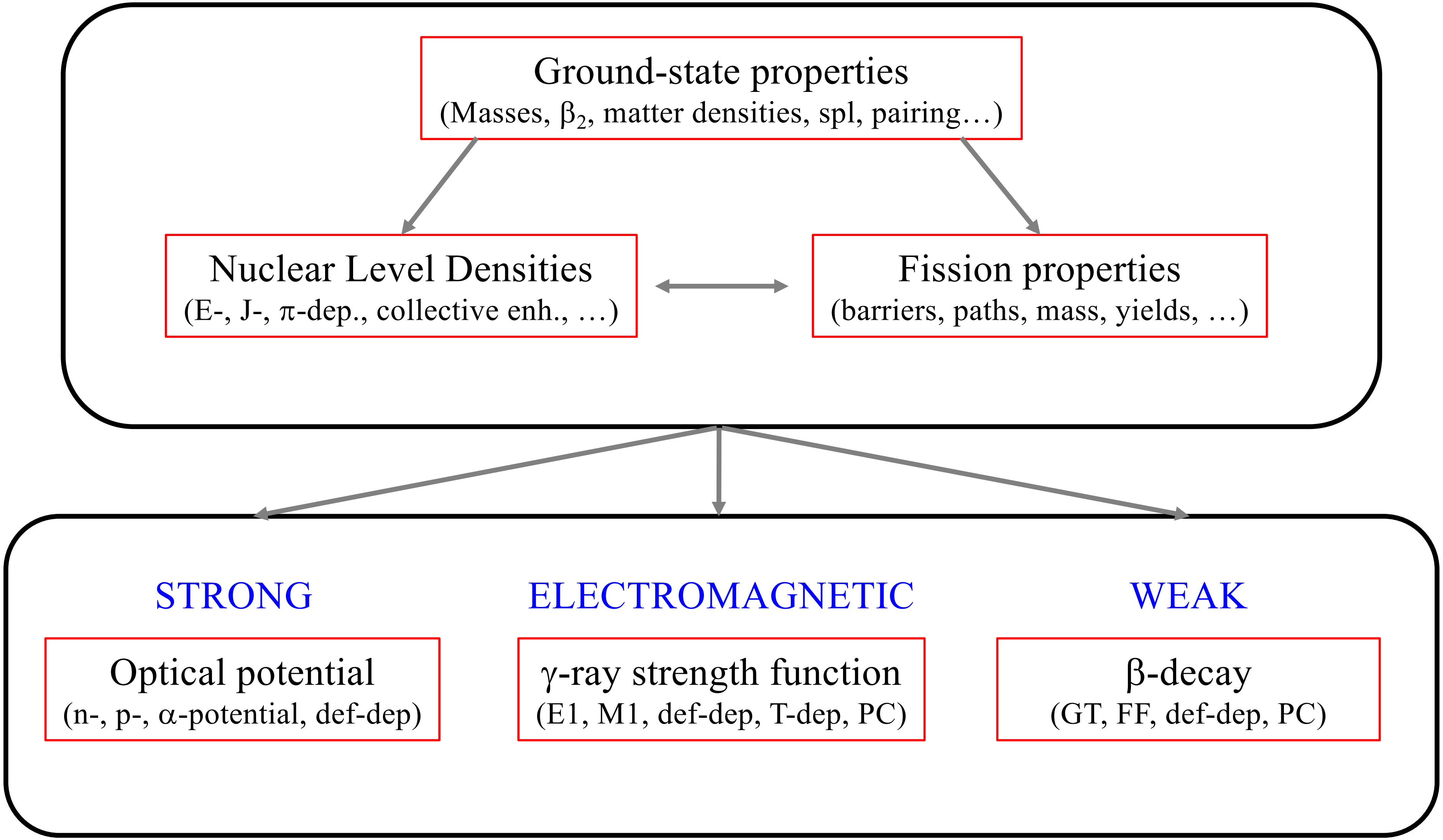
Local (correlated) discrepancies

Astrophysical models evolve and may still not be robust
(what is "important" today may not be next year)

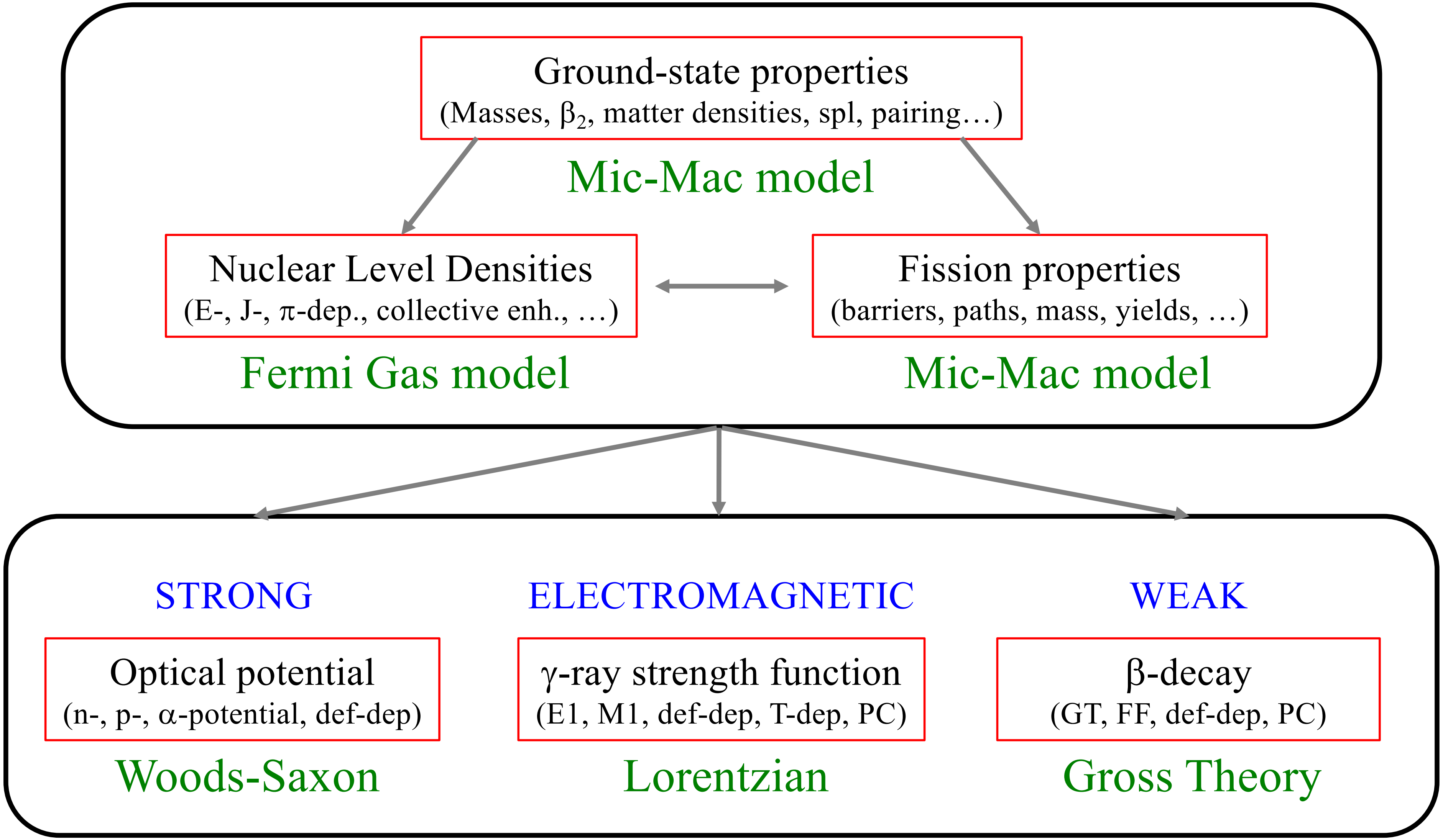
→ Remain extremely critical about propagation of nuclear uncertainties into astrophysical models



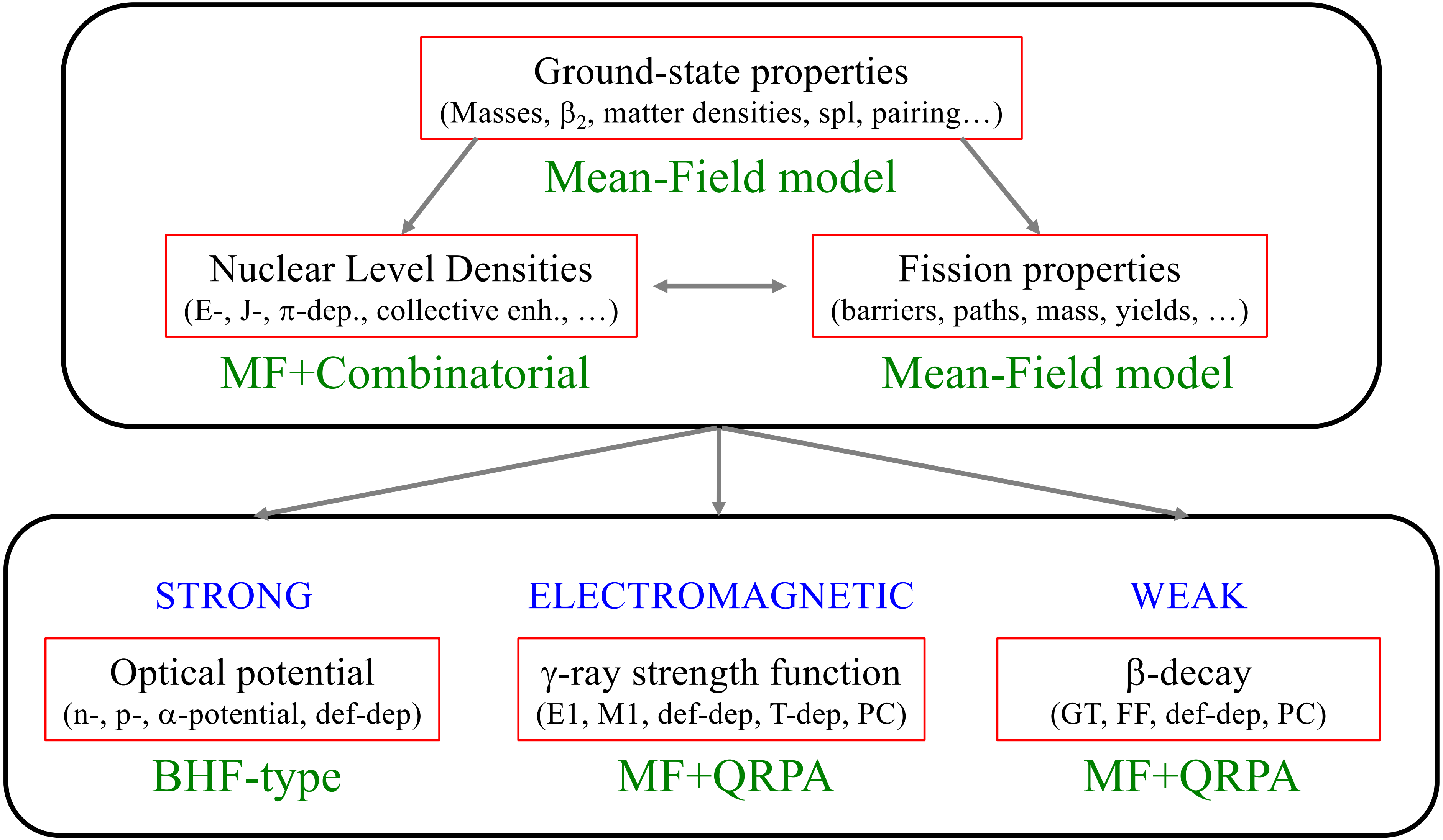
Nuclear inputs to nuclear reaction & decay calculations



Nuclear inputs to nuclear reaction & decay calculations



Nuclear inputs to nuclear reaction & decay calculations

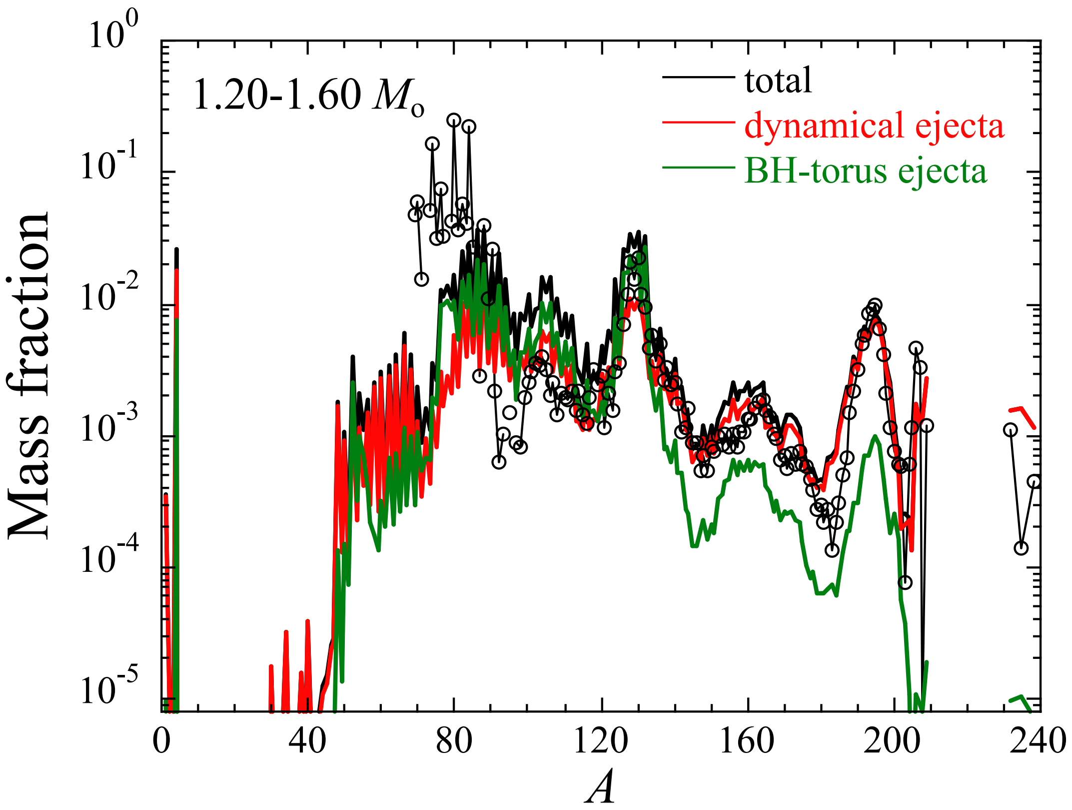


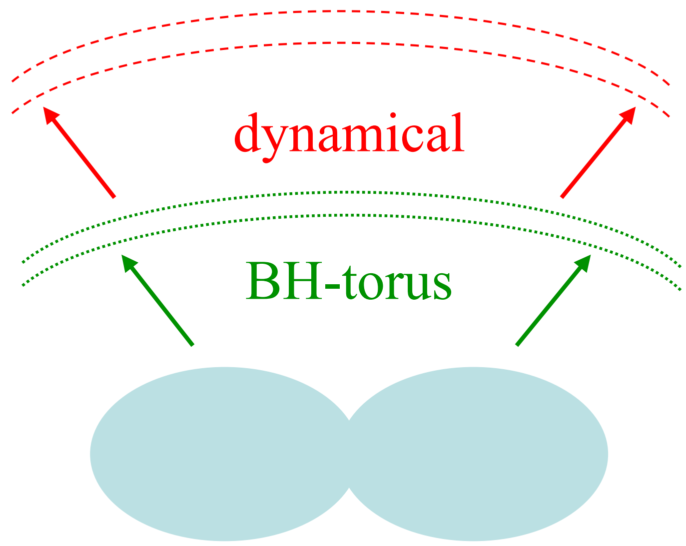
"Microscopic" approach is a necessary but not a sufficient condition !

"(Semi-)Microscopic" models must be competitive in reproducing exp. data !

Role of fission in the *dynamical* ejecta of NS-NS Merger

using multiple (~500) trajectories and correlated model uncertainties





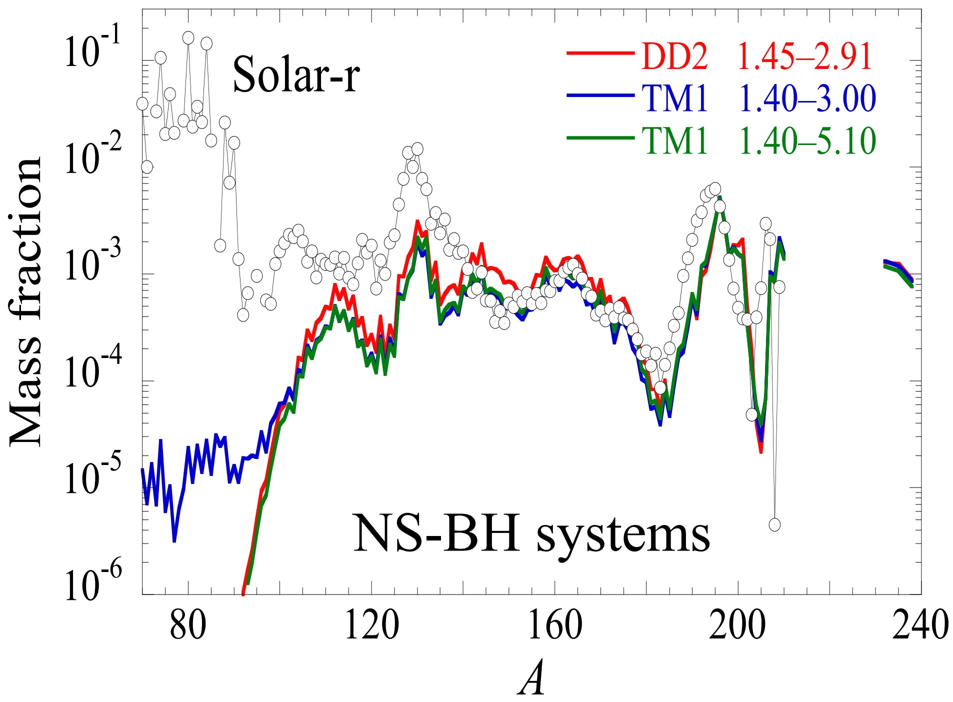
	total	dynamical	NS-torus	BH-torus
M_{ej} [M_o]	0.024	0.012	0.0	0.012
$\langle Y_e \rangle$	0.27	0.26	0.0	0.28
v_{ej} [c]	0.14	0.24	0.0	0.05

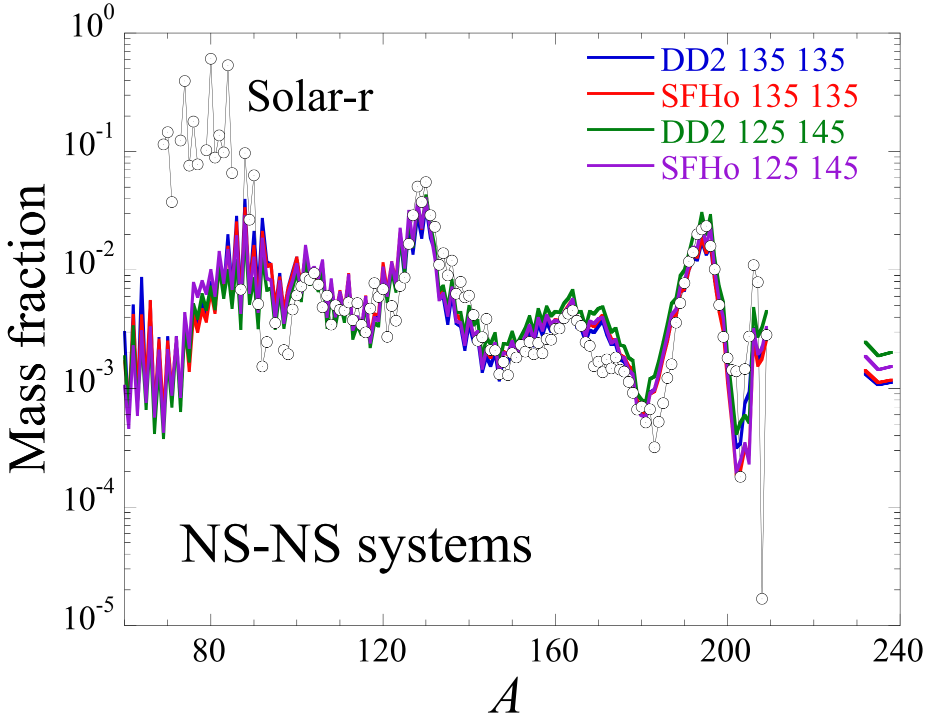
Role of fission in the *dynamical* ejecta of NS-BH Merger

Fission expected to be even more important in the dynamical ejecta of NS-BH merger

NS-BH (no weak interaction)

NS-NS (with weak interactions)



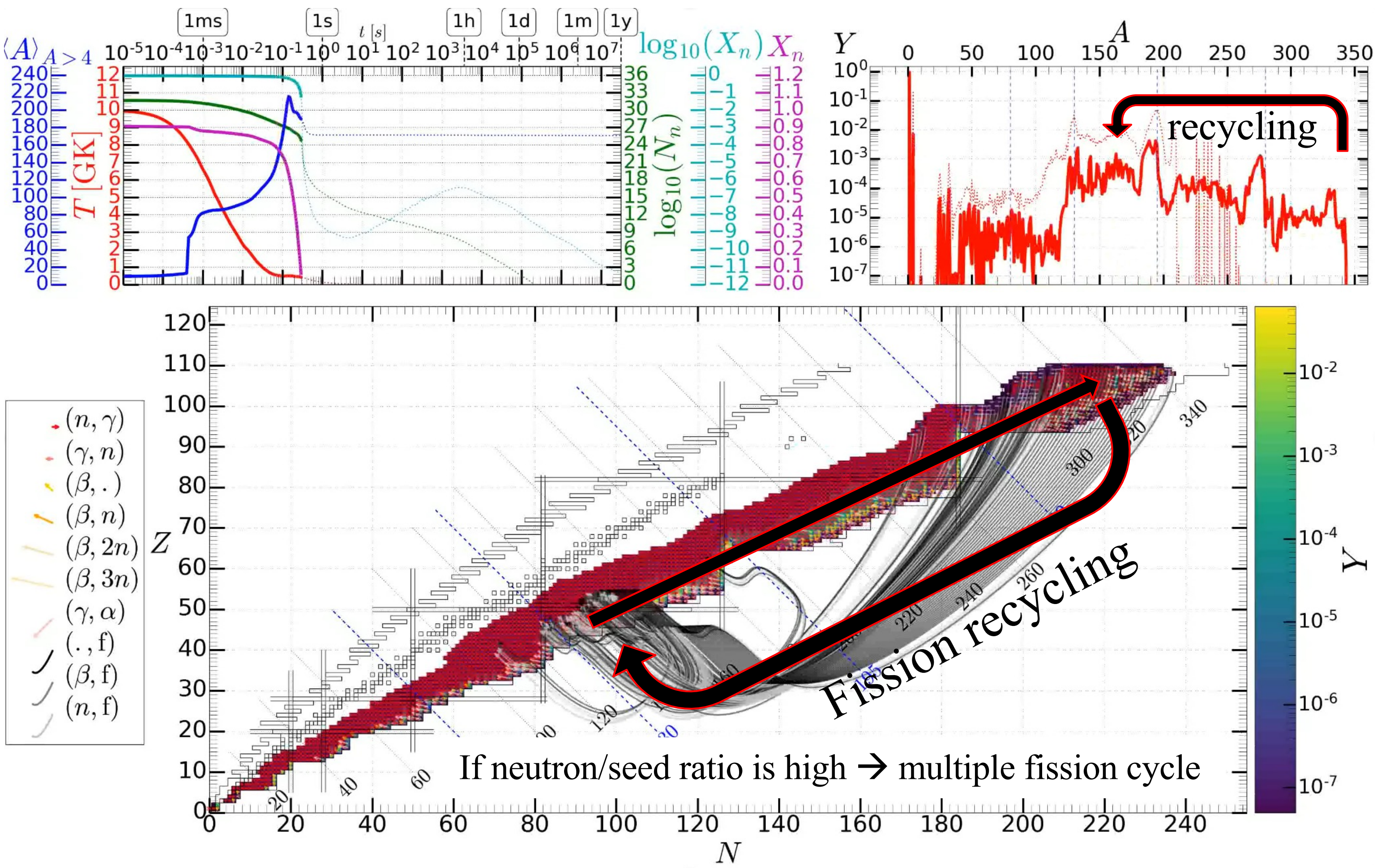


Fission and the production of actinides

Fission processes and fission fragment distribution of relevance for estimating the

1. termination point of the r-process (recycling, prod of SH, Universality ?)

After a few hundred ms in the dynamical ejecta

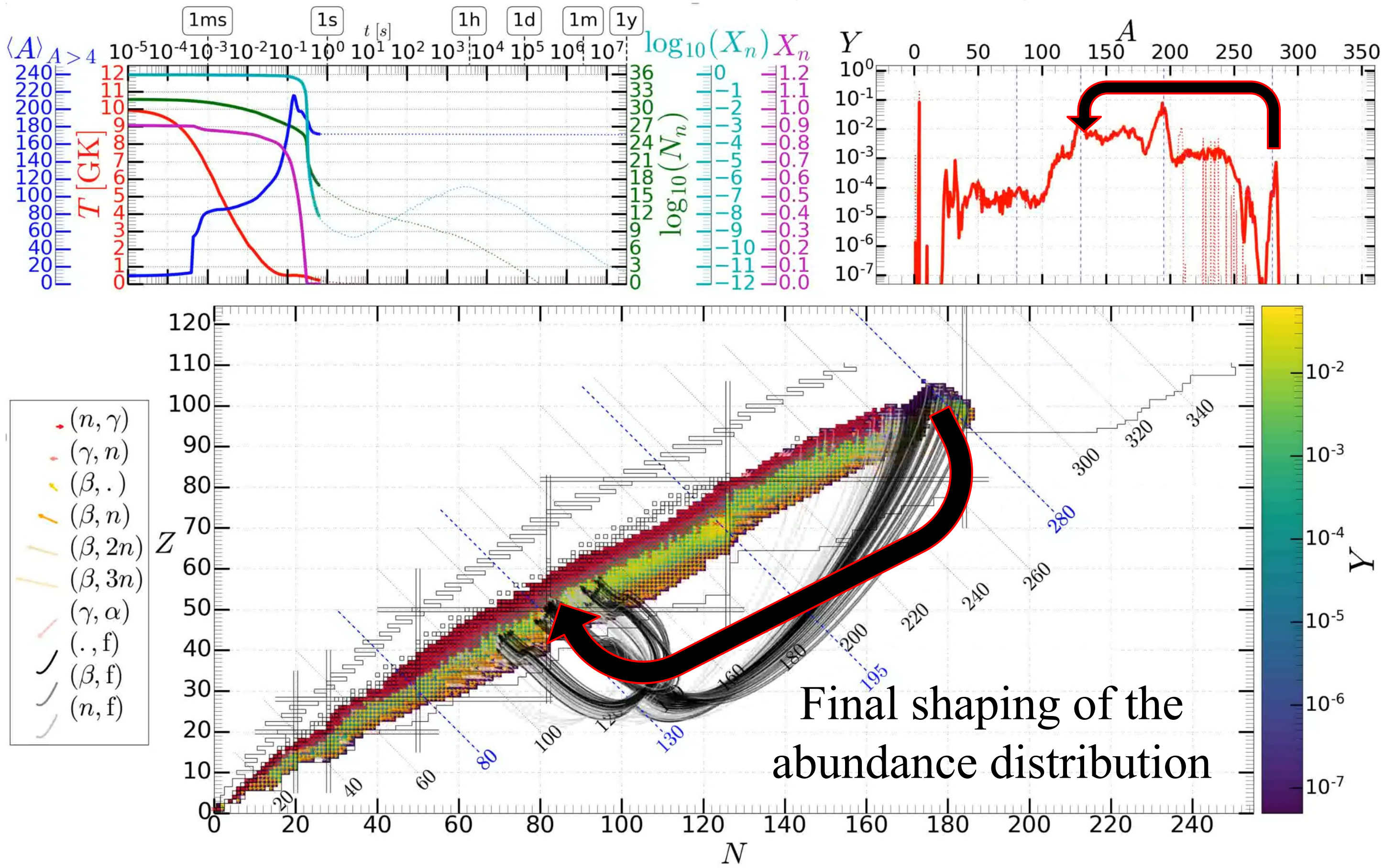


Fission and the production of actinides

Fission processes and fission fragment distribution of relevance for estimating the

1. termination point of the r-process (recycling, prod of SH)
2. production of light species (A~110-160) by fission recycling

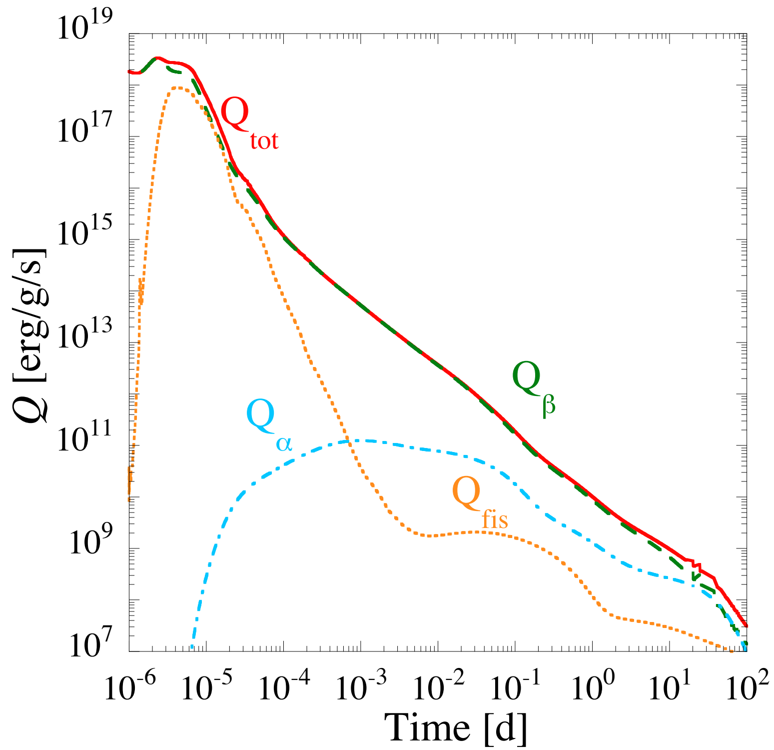
After about 1s in the dynamical ejecta



Fission and the production of actinides

Fission processes and fission fragment distribution of relevance for estimating the

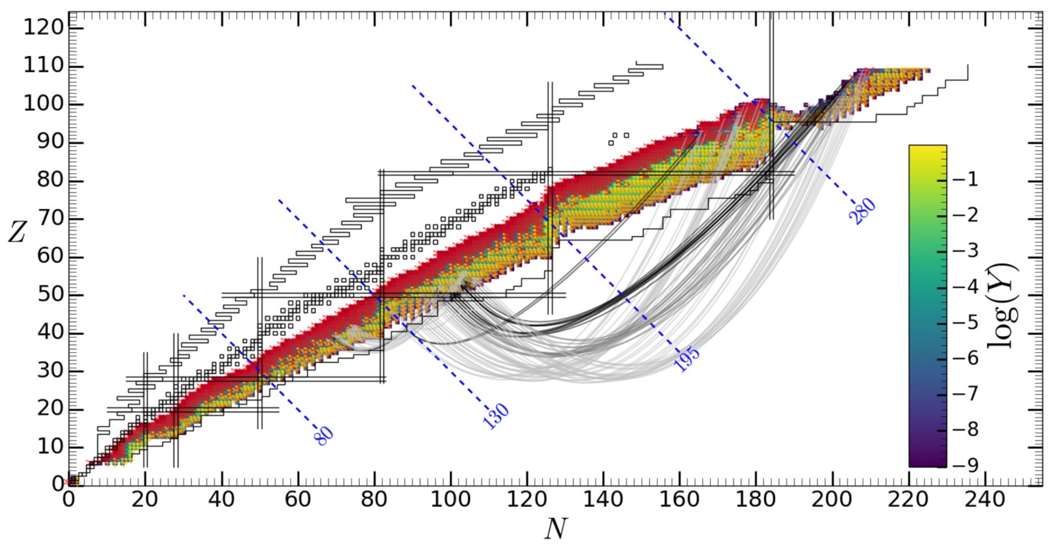
1. termination point of the r-process (recycling, prod of SH)
2. production of light species (A~110-160) by fission recycling
3. heating of the ejecta during the expansion

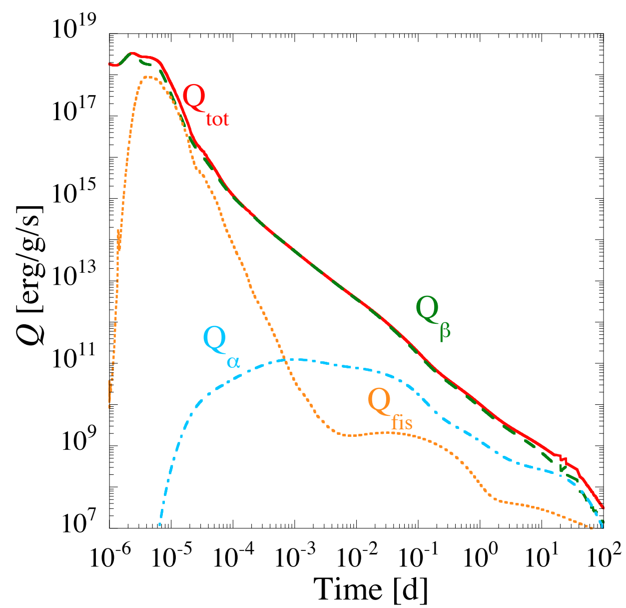


Fission and the production of actinides

Fission processes and fission fragment distribution of relevance for estimating the

1. termination point of the r-process (recycling, prod of SH)
2. production of light species (A~110-160) by fission recycling
3. heating of the ejecta during the expansion
4. production of Pb-peak elements
5. production of radiocosmochronometers (U, Th)

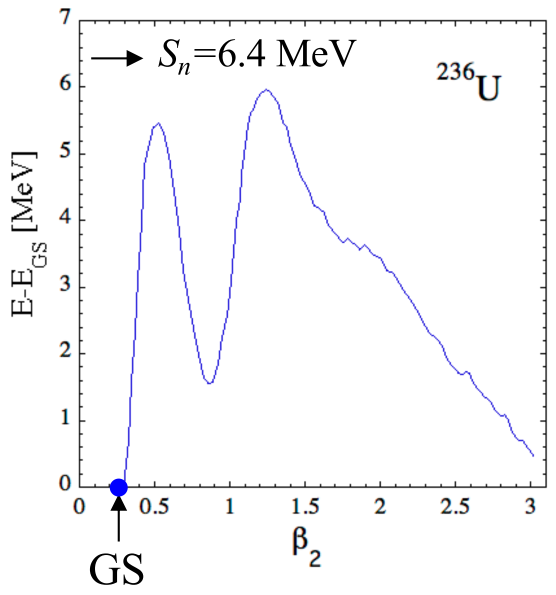


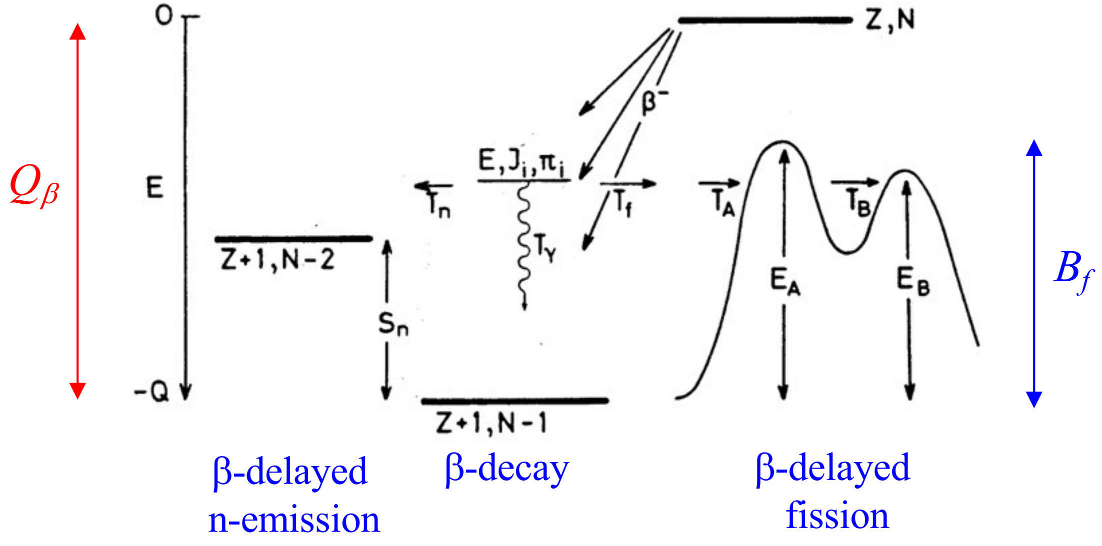


Nuclear fission

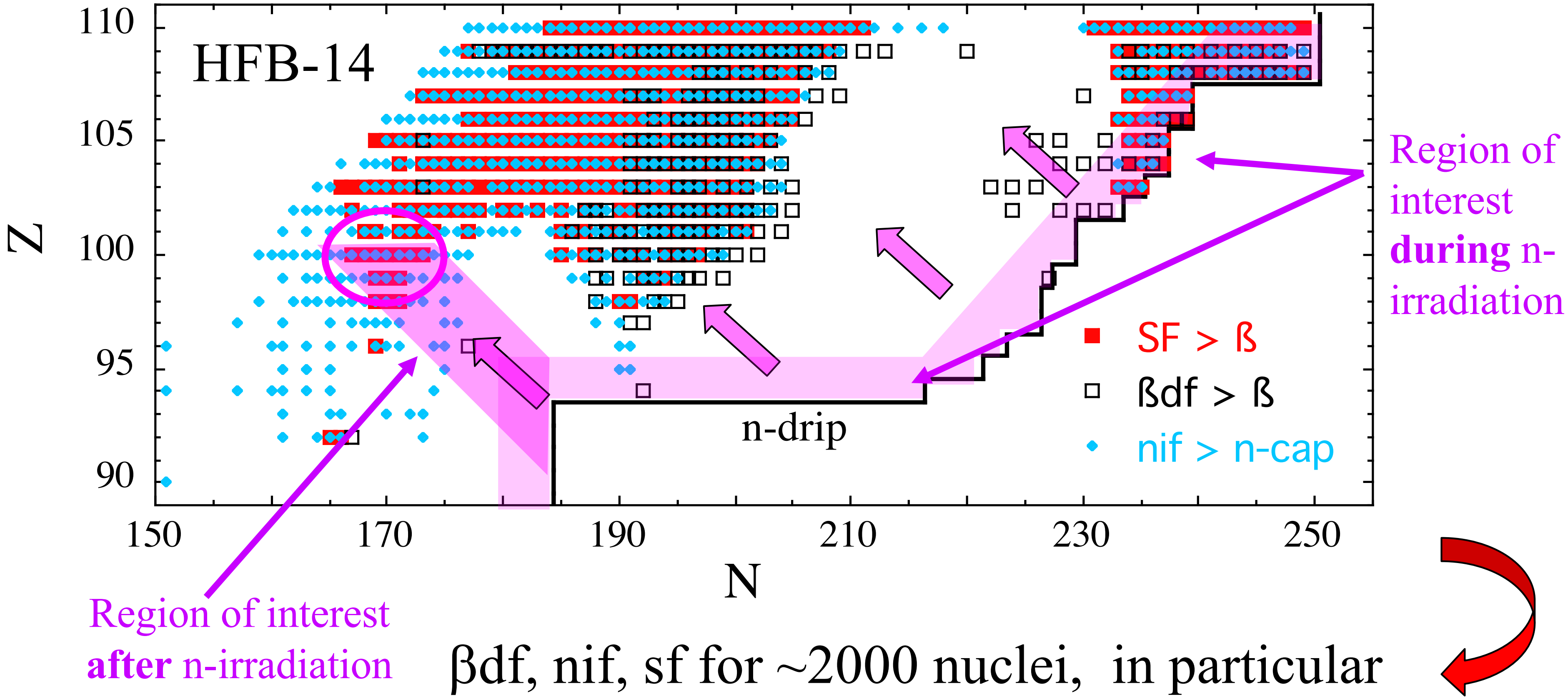
Three fission modes play an important role during the r-process nucleosynthesis:

- spontaneous fission: strongly depends on the fission barrier height
- neutron-induced fission: strongly depends on S_n–B_f (for E_n=kT ~ 100 keV)
- β-delayed fission, *i.e.* fission following a β-decay: strongly depends on $Q_\beta - B_f$





Fission properties and the r-process in NSM



βdf, nif, sf for ~2000 nuclei, in particular along the n-drip line

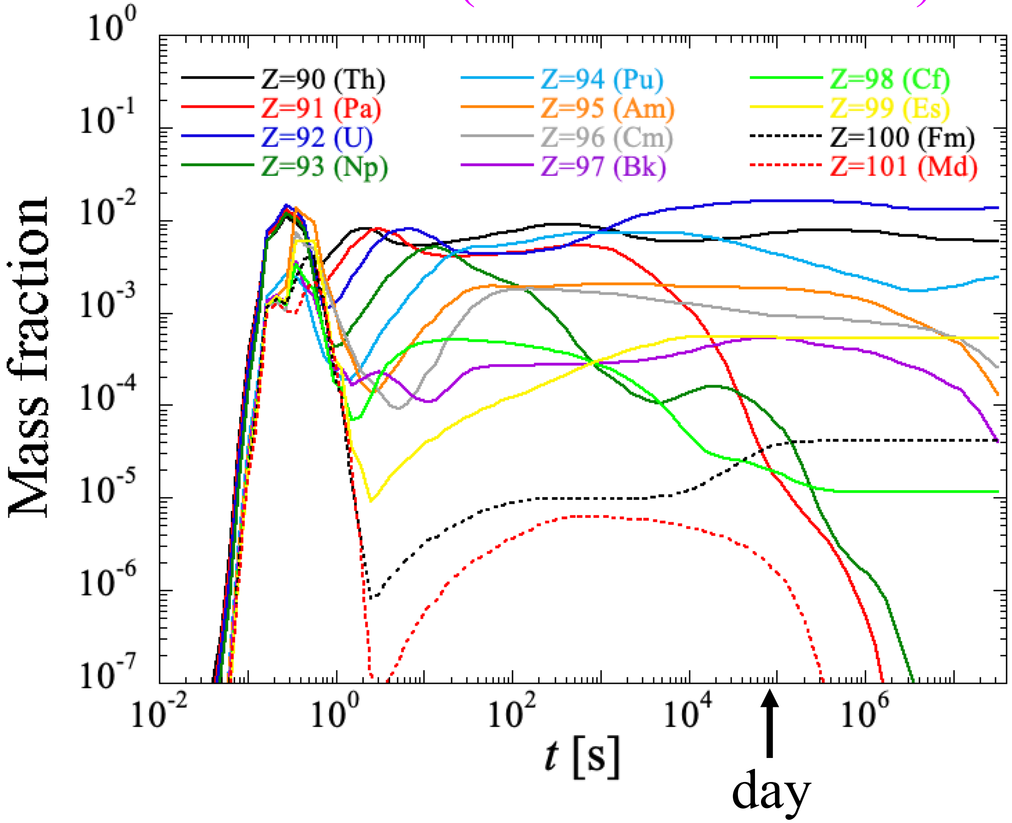
Production of Super-Heavy nuclei ?

Special emphasis on Fission & FFD for *A*~278

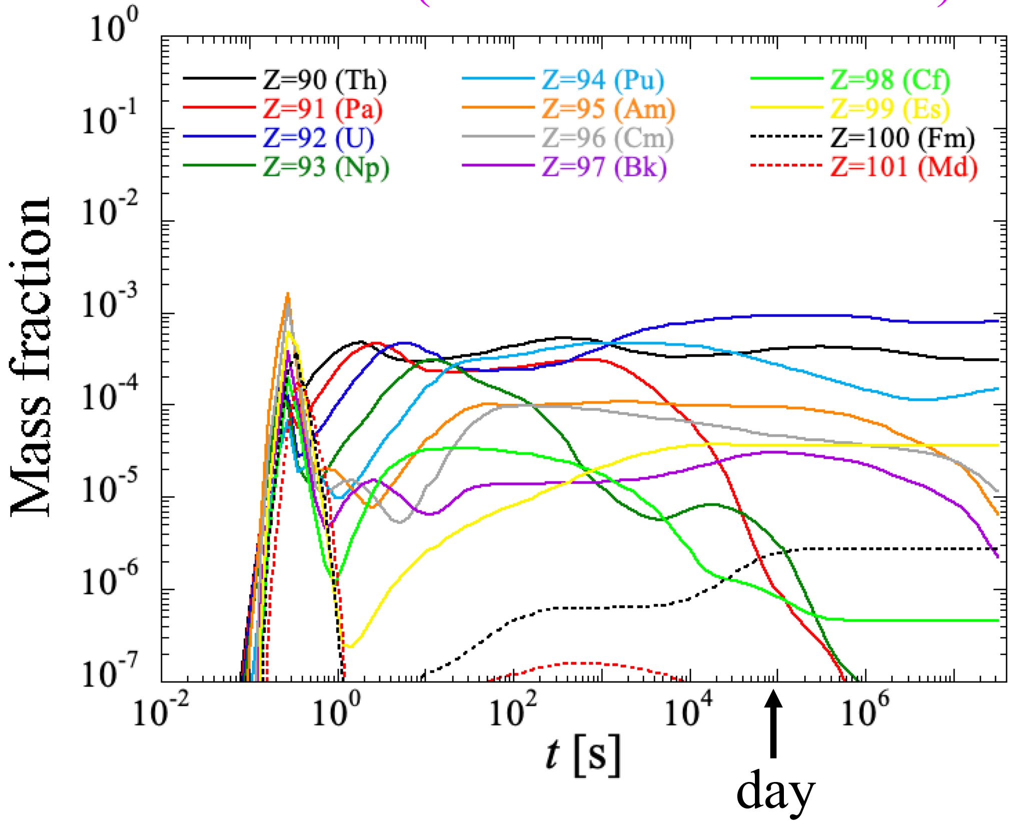
$90 \leq Z \leq 101$ Elemental abundances expected in the dynamical ejecta

HFB-14 fission barriers

NS-BH (no weak interaction)



NS-NS (with weak interactions)



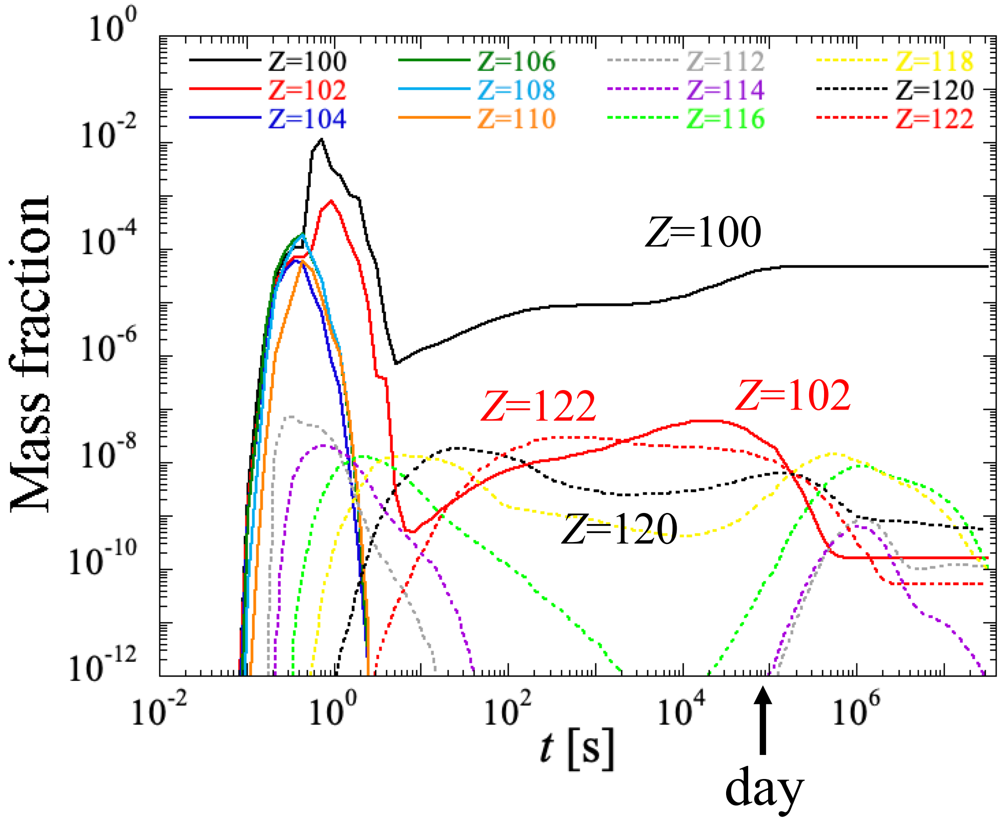
Significant production of actinides up to Z ~ 100

P.S. overall yields mass-averaged over hundreds of ejected mass elements

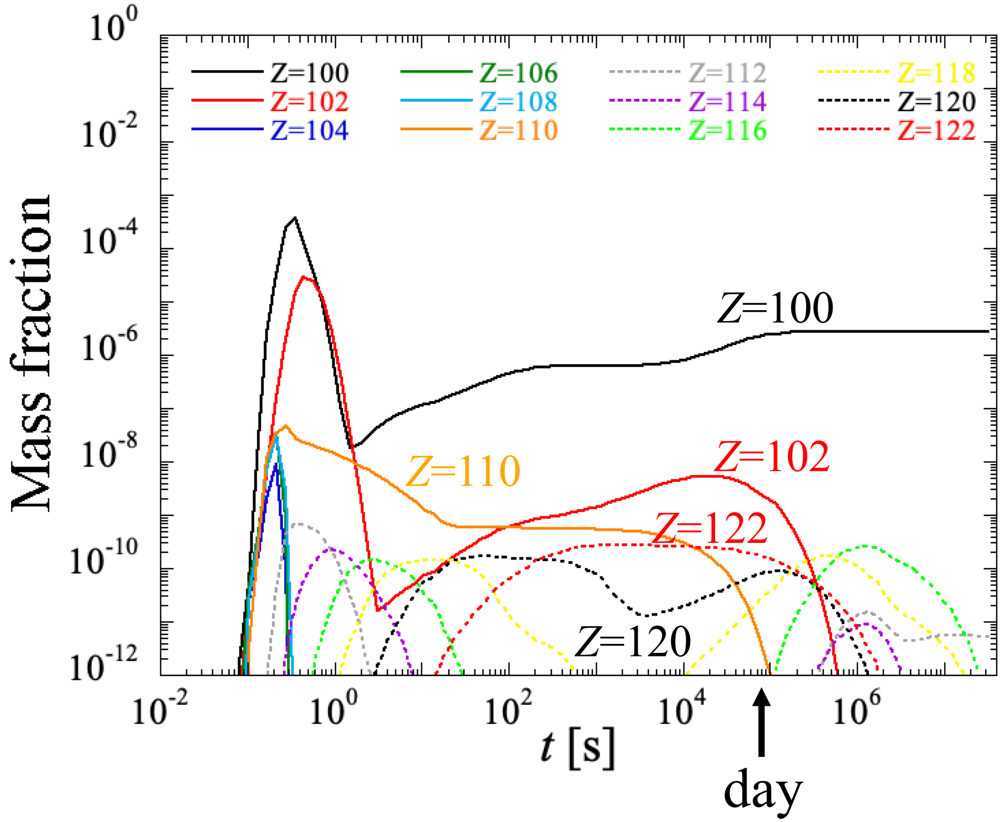
$100 \leq Z \leq 122$ elemental abundances expected in the dynamical ejecta

HFB-14 fission barriers

NS-BH (no weak interaction)



NS-NS (with weak interactions)



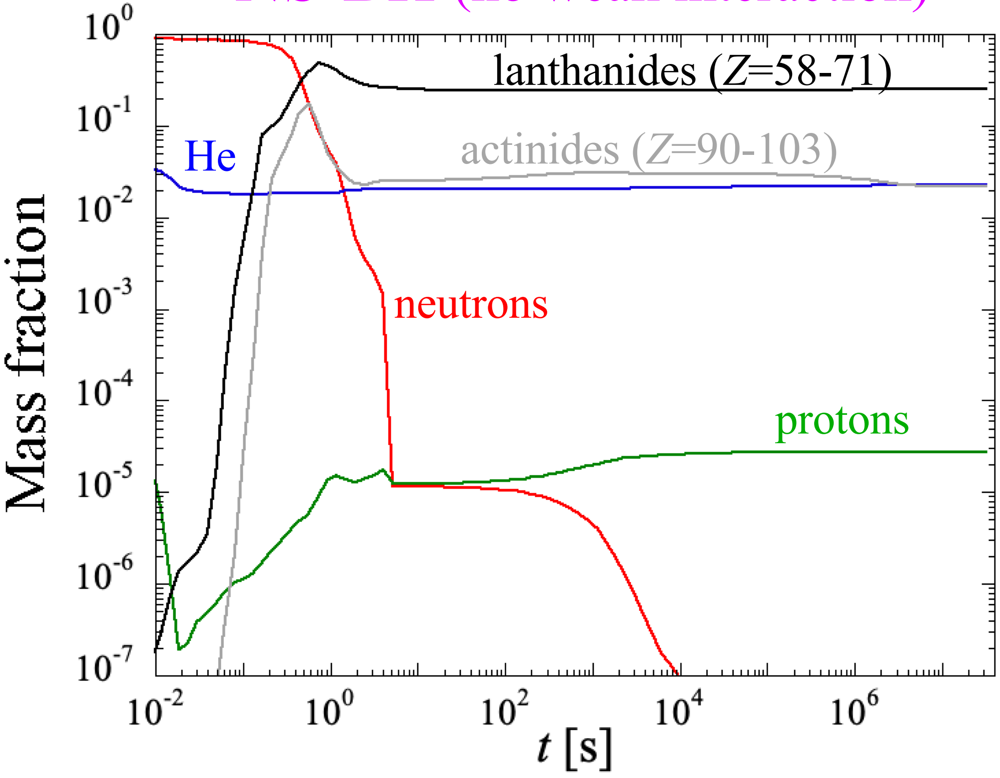
Significant production of actinides up to $Z \sim 100$

Non-zero production of super-heavies up to $Z \sim 120$

... if fission allows it ...

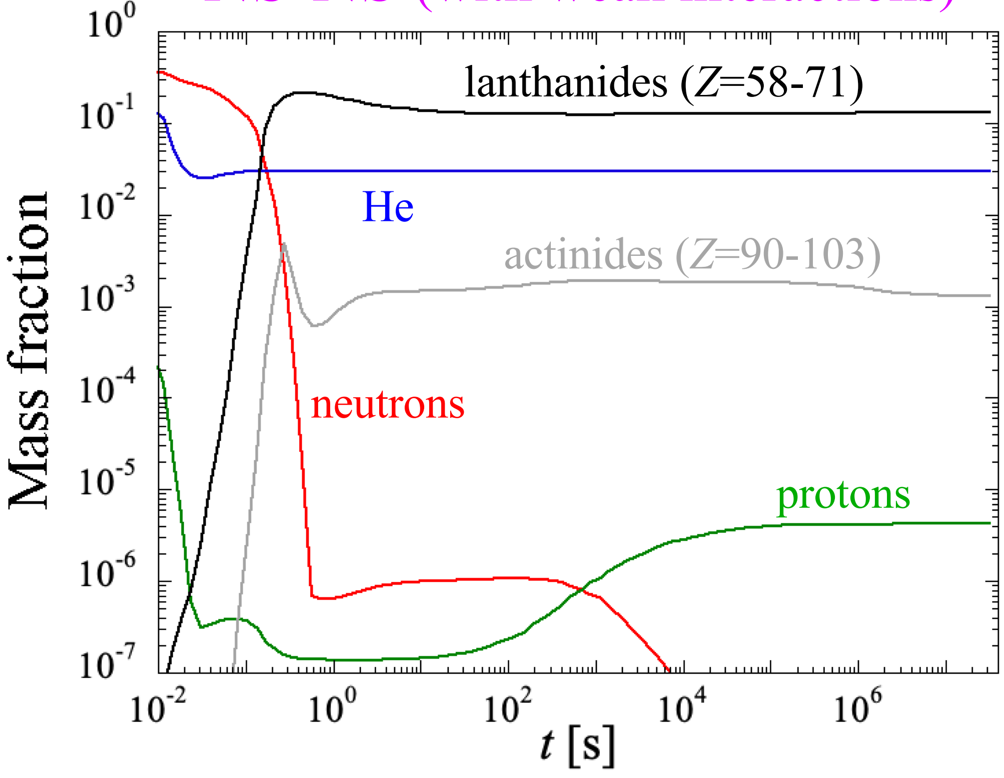
Elemental abundances expected in the dynamical ejecta

NS-BH (no weak interaction)



100% of matter experiences fission

NS-NS (with weak interactions)



~10% of matter experiences fission

Significant production of lanthanides and actinides

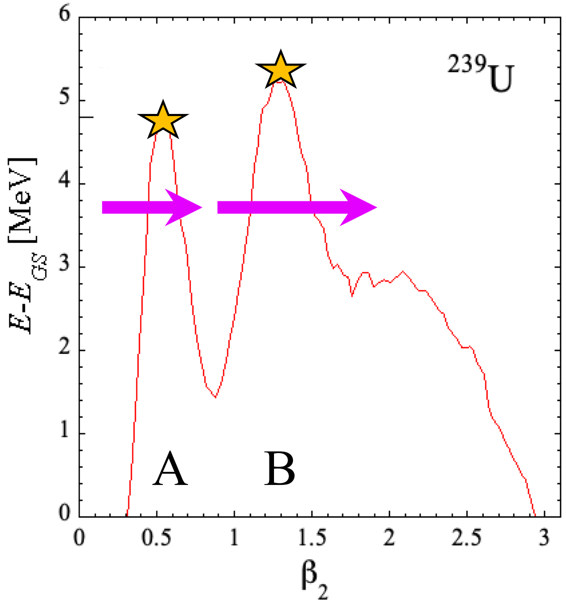
P.S. overall yields mass-averaged over hundreds of ejected mass elements

Calculation of the fission probability

cf talk of D. Regnier

full damping limit:

$$T(E,J,\pi) = \frac{T_A T_B}{T_A + T_B}$$



$$T(E,J,\pi) = \sum_d P(E-\varepsilon_d^{J,\pi}) + \int_{E_d}^{E} P(E-\varepsilon)\rho(\varepsilon,J,\pi)d\varepsilon$$

$$P_j(E) = \frac{1}{1+\exp(2K_j)} \qquad \text{WKB}$$

$$K_j = \pm \int_{a_j}^{b_j} [2\mu(E - V_j(\beta))/\hbar^2]^{1/2} d\beta \qquad \begin{matrix} + \text{ for } E > B_j \\ - \text{ for } E < B_j \end{matrix}$$

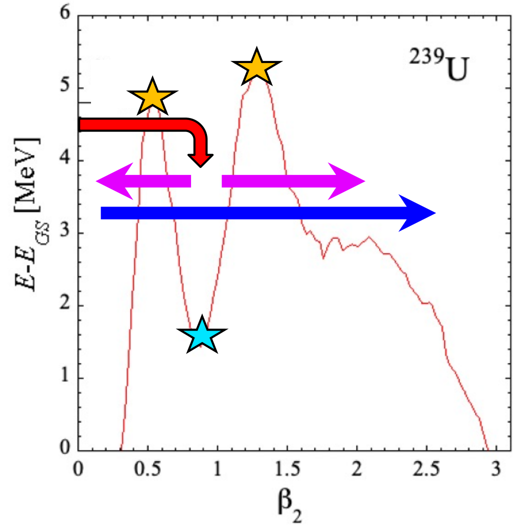
$\mu \sim 0.054\ A^{5/3}$ (inertial mass) often assumed deformation-independent

Fission in the Nucleosynthesis Context

Complicate NP input associated with HFB-type calculation of

- Potential Energy Surface → fission path, inertial mass
- NLD at the saddle points (& isomeric wells)

→ WKB Fission probability



- Spontaneous fission: Least-action path integral (2D HFB PES)

  + coupling with competitive n-, γ-, β-channels

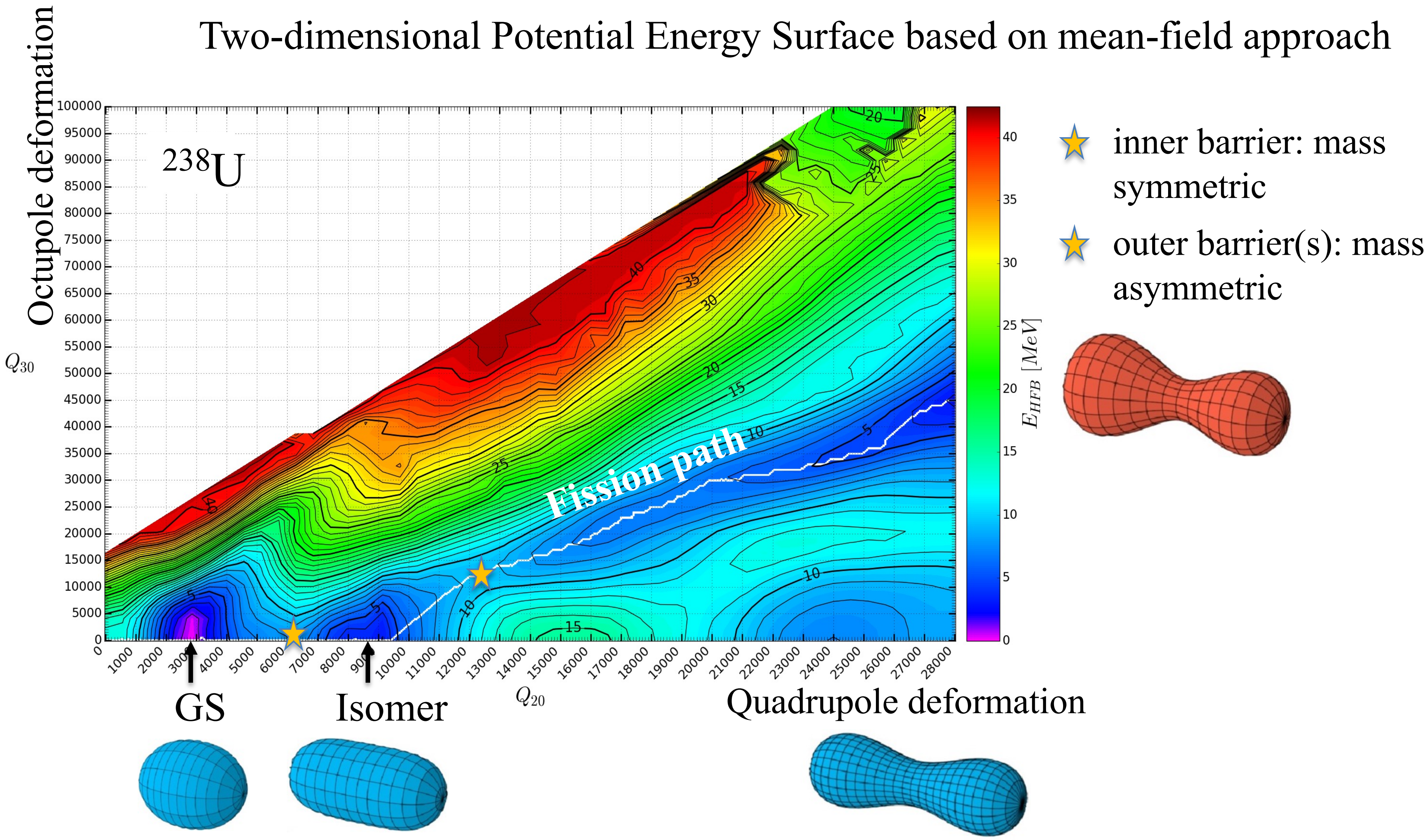
- Neutron-induced fission: HF reaction code
- β-delayed fission probability: QRPA GT β-strength + HF reaction code

→ Real effort needed to improve *predictions* of fission properties
(Still far from being achieved, even for U and Th !)

Calculation of the fission path and barriers

The fundamental role of octupole deformations

Two-dimensional Potential Energy Surface based on mean-field approach



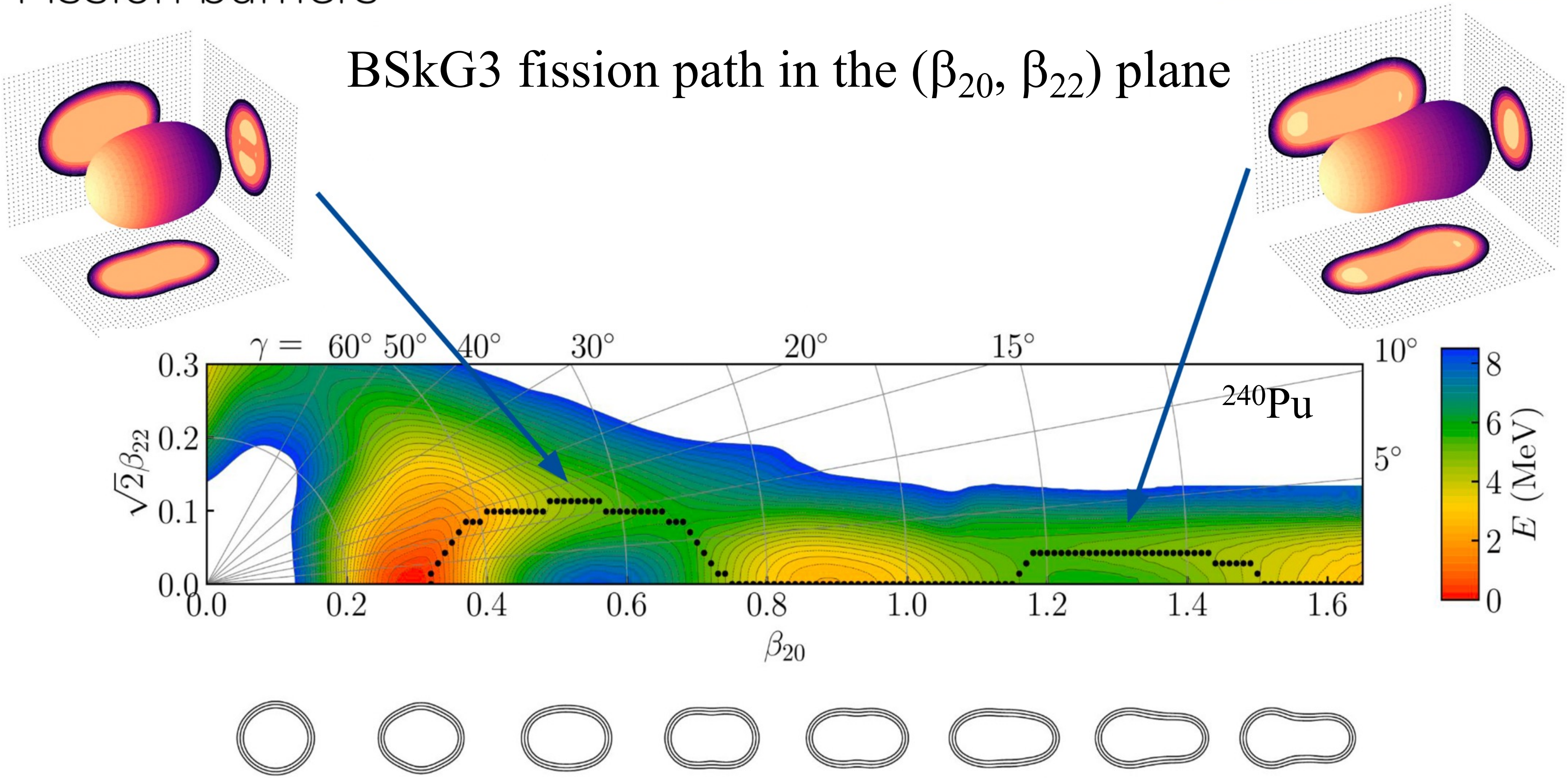
The fundamental role of triaxiality

Degrees of freedom: β_{20}, β_{22}, β_{30}

W. R. et al., EPJA **59**, 96 (2023).

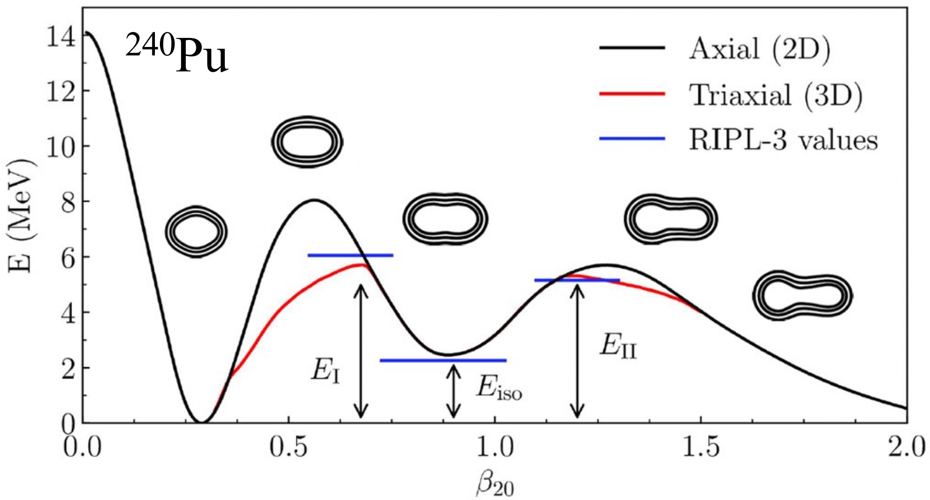
Fission barriers

BSkG3 fission path in the (β_{20}, β_{22}) plane



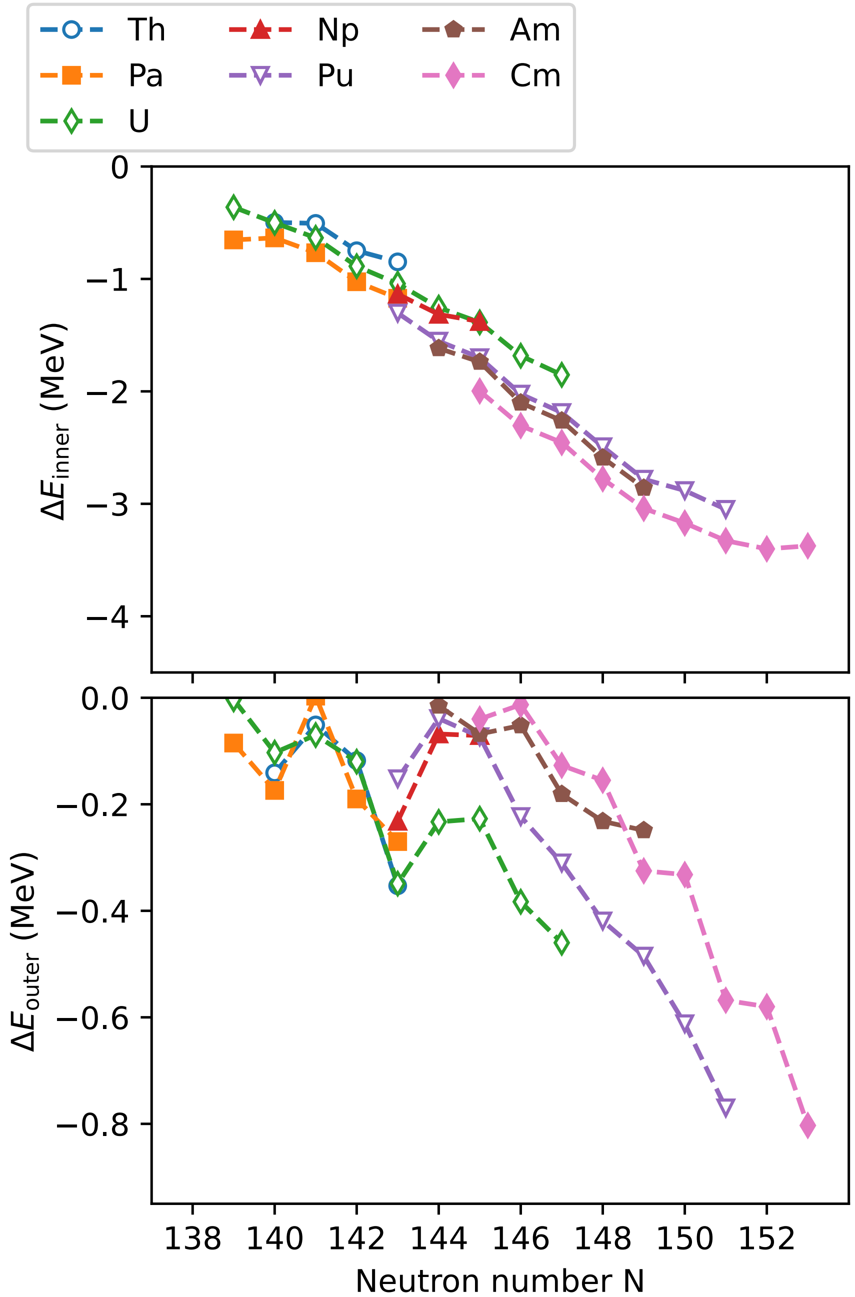
Effects of triaxiality on ***both***

- Triaxial inner barrier



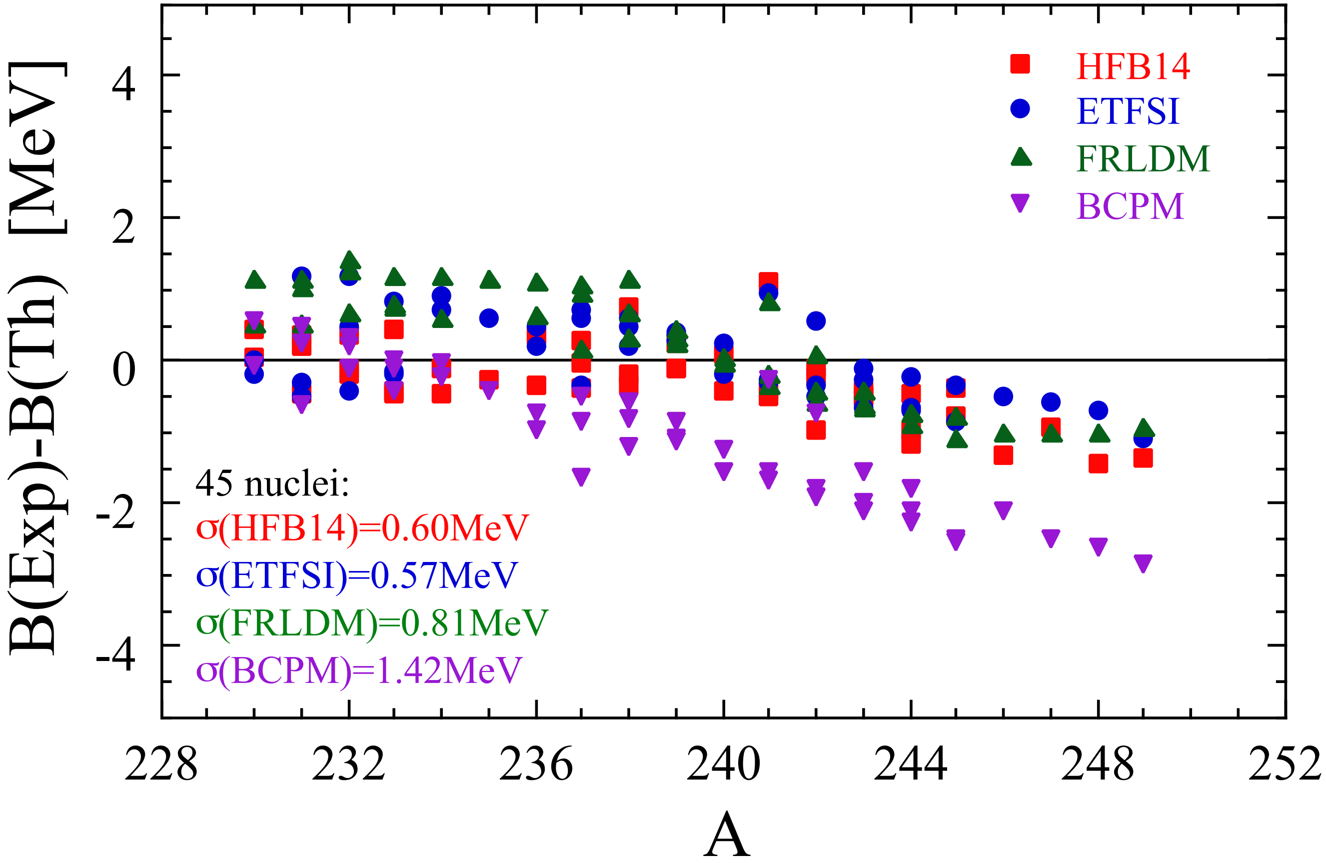
- Triaxial- and octupole-deformed outer barrier

(also for odd-A and odd-odd nuclei)



Only a few models applied to the ~ 2000 nuclei of r-process interest

Comparison between large-scale models and RIPL-3
primary fission barriers



$\sigma(45\ B_f) > 0.6$ MeV

New BSkG3 predictions

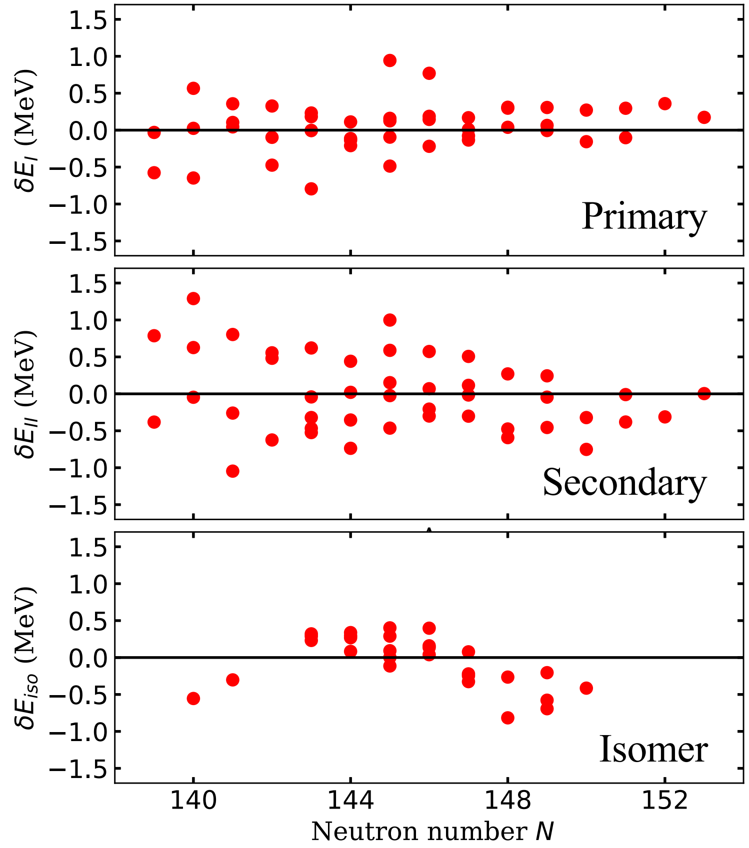
Grams et al. (2023)

New Skyrme-HFB mass model: BSkG3

- Triaxiality, time-reversal symmetry breaking & octupole GS deformation
- Microscopic pairing from "realistic" calc.
- Stiff EoS (NS M_{max}~$2.26M_o$)
- Accurate masses: σ(2457*M*)=0.63MeV
- Accurate fission barriers σ(45B_f)=0.33MeV including triaxial & octupole deformations **simultaneously**

	BSkG3
σ(*M*) [MeV]	0.63
σ(E_I) [MeV]	**0.33**
σ(E_{II}) [MeV]	0.51
σ(E_{iso}) [MeV]	0.36

B_f(BSkG3)- B_f(exp)

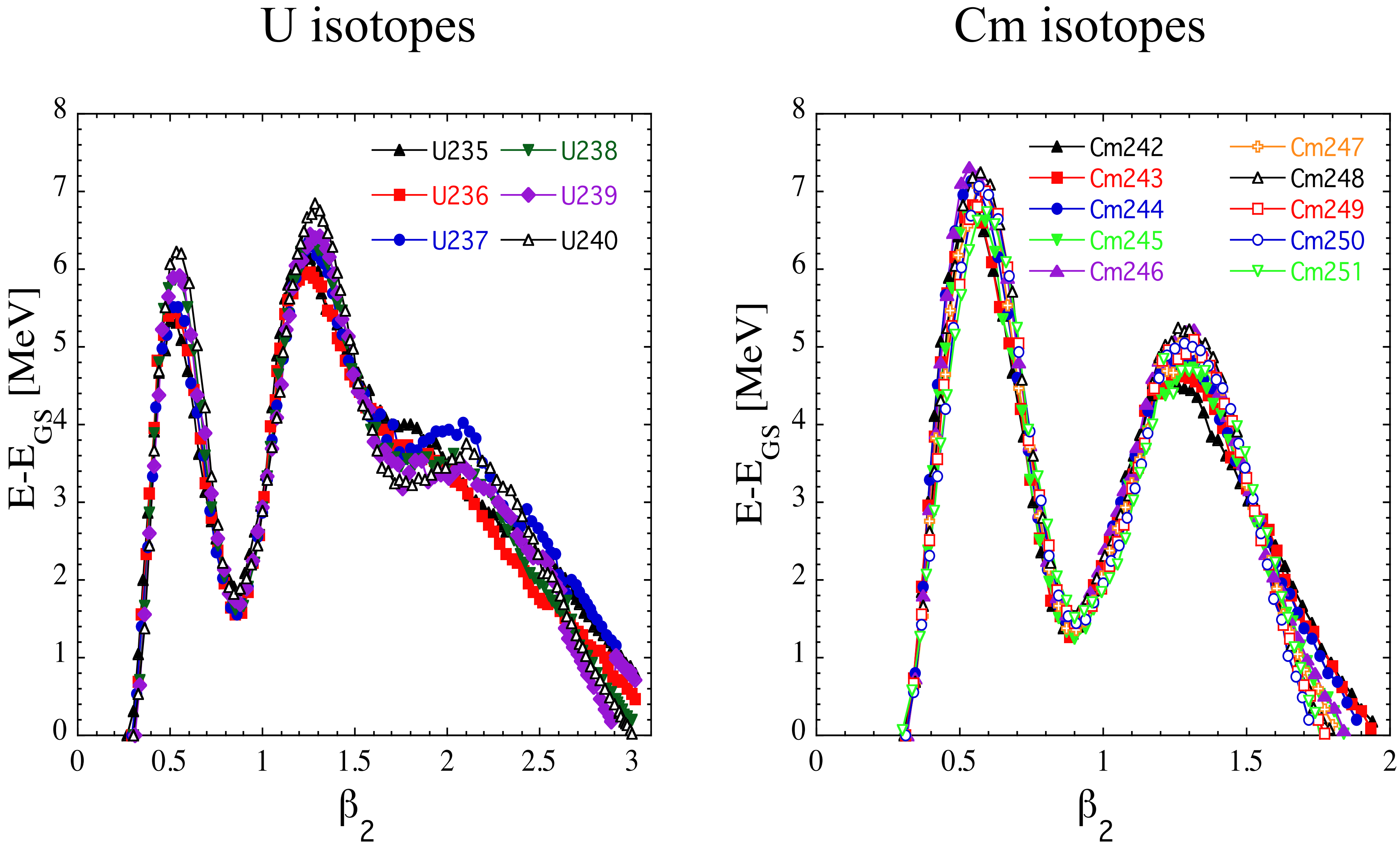


Including odd-*A* & odd-odd

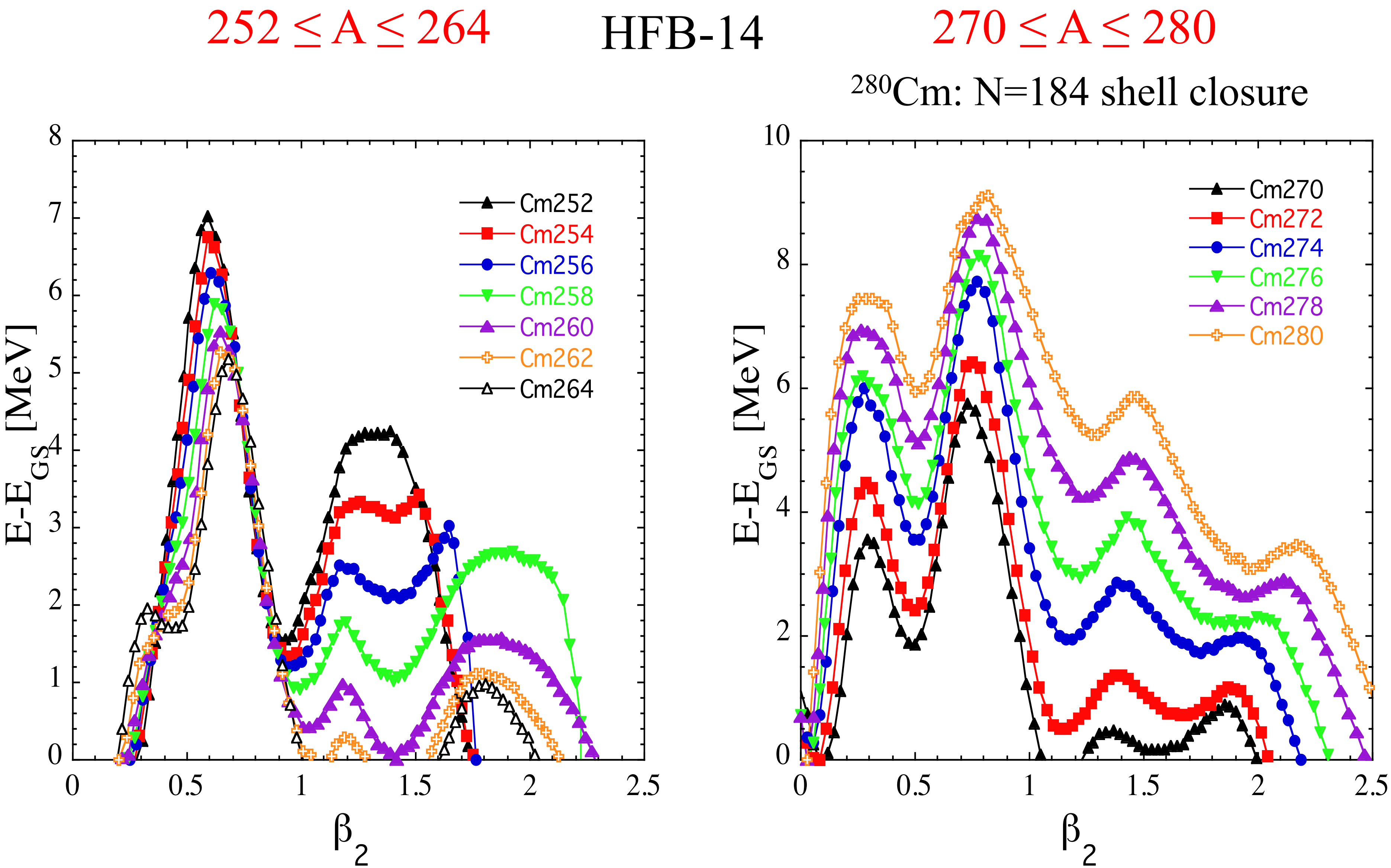
→ being extended now to the calculation of 2000 nuclei...

Projection of the static path along the quadrupole deformation parameter β_2

HFB-14

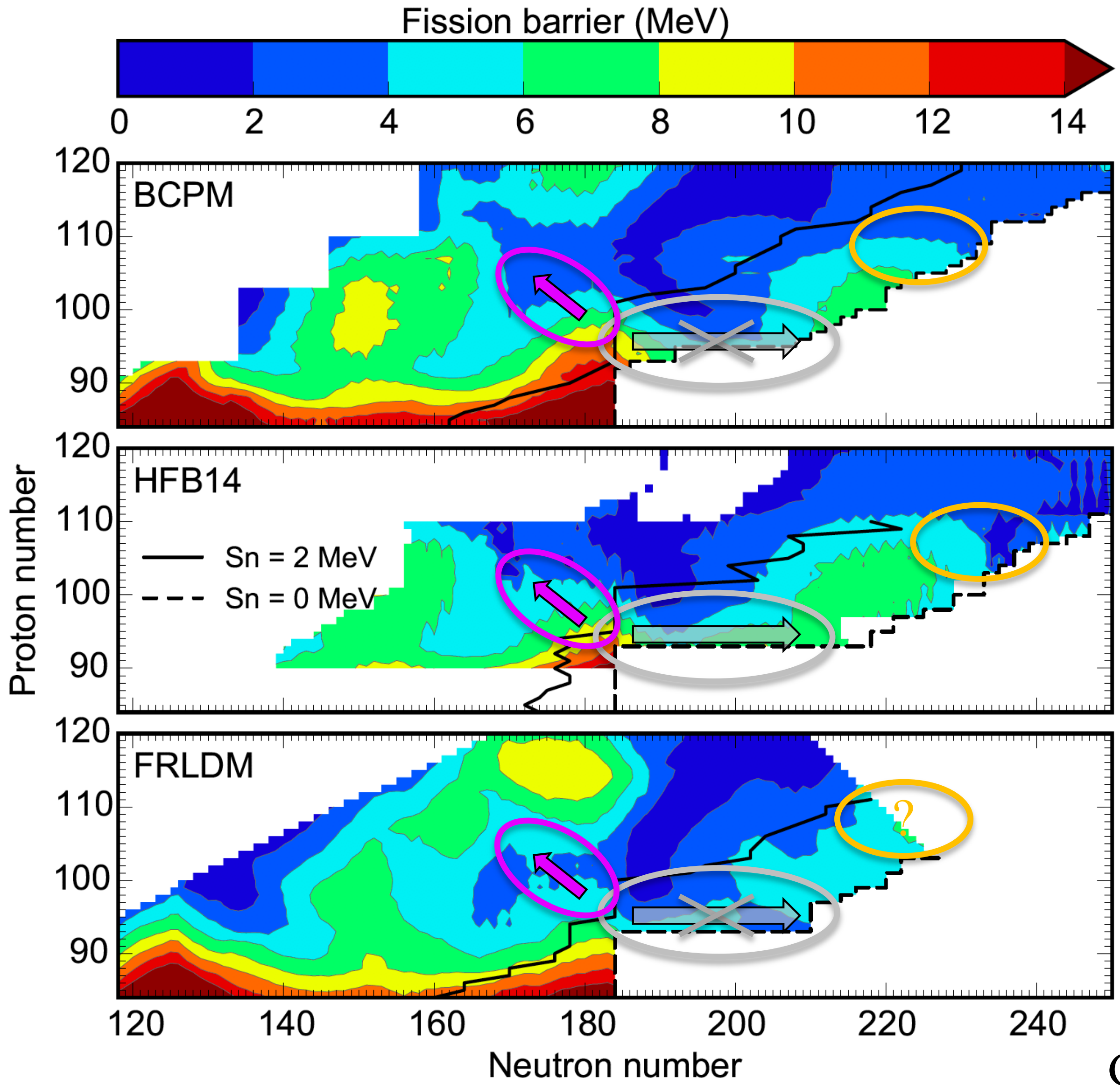


The Cm isotopes in the n-rich region



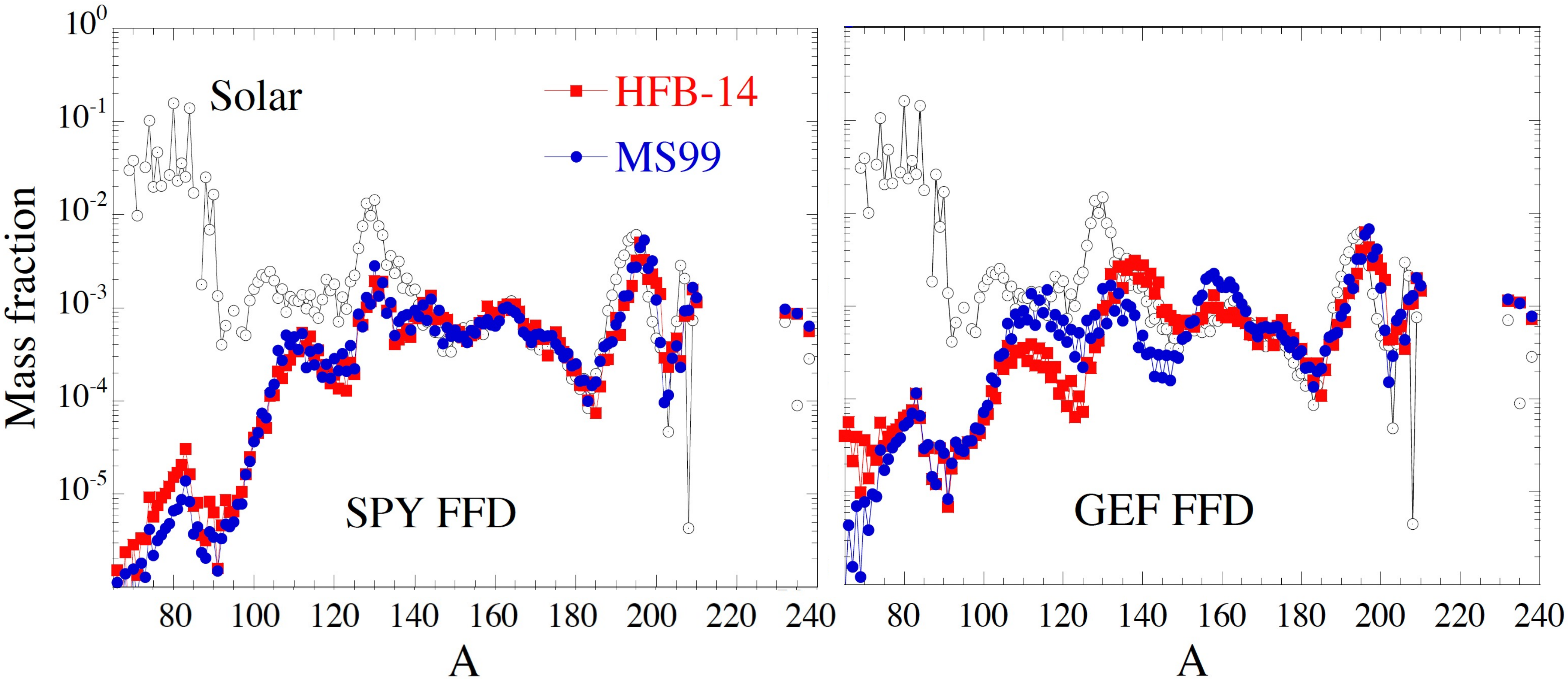
Fission properties mainly depend on the primary fission barriers

Fission barriers calculated for all nuclei with $90 \leq Z \leq 120$



Giuliani et al. (2018)

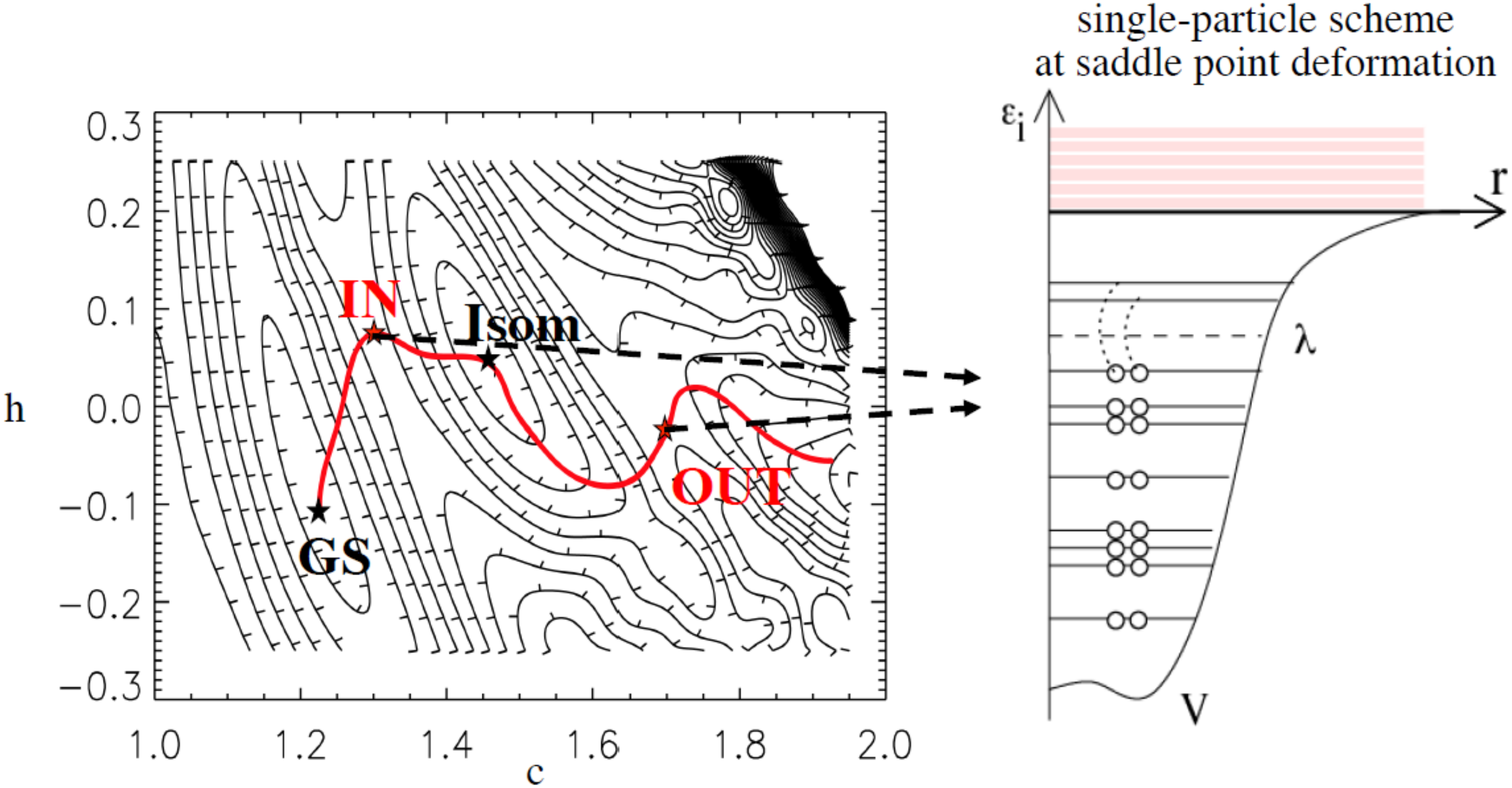
Impact of the barrier height on the r-process on the composition of the dynamical NS-BH ejecta



FISSION CROSS SECTIONS
(Microscopic approaches)

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

FISSION CROSS SECTIONS
(Microscopic approaches)
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

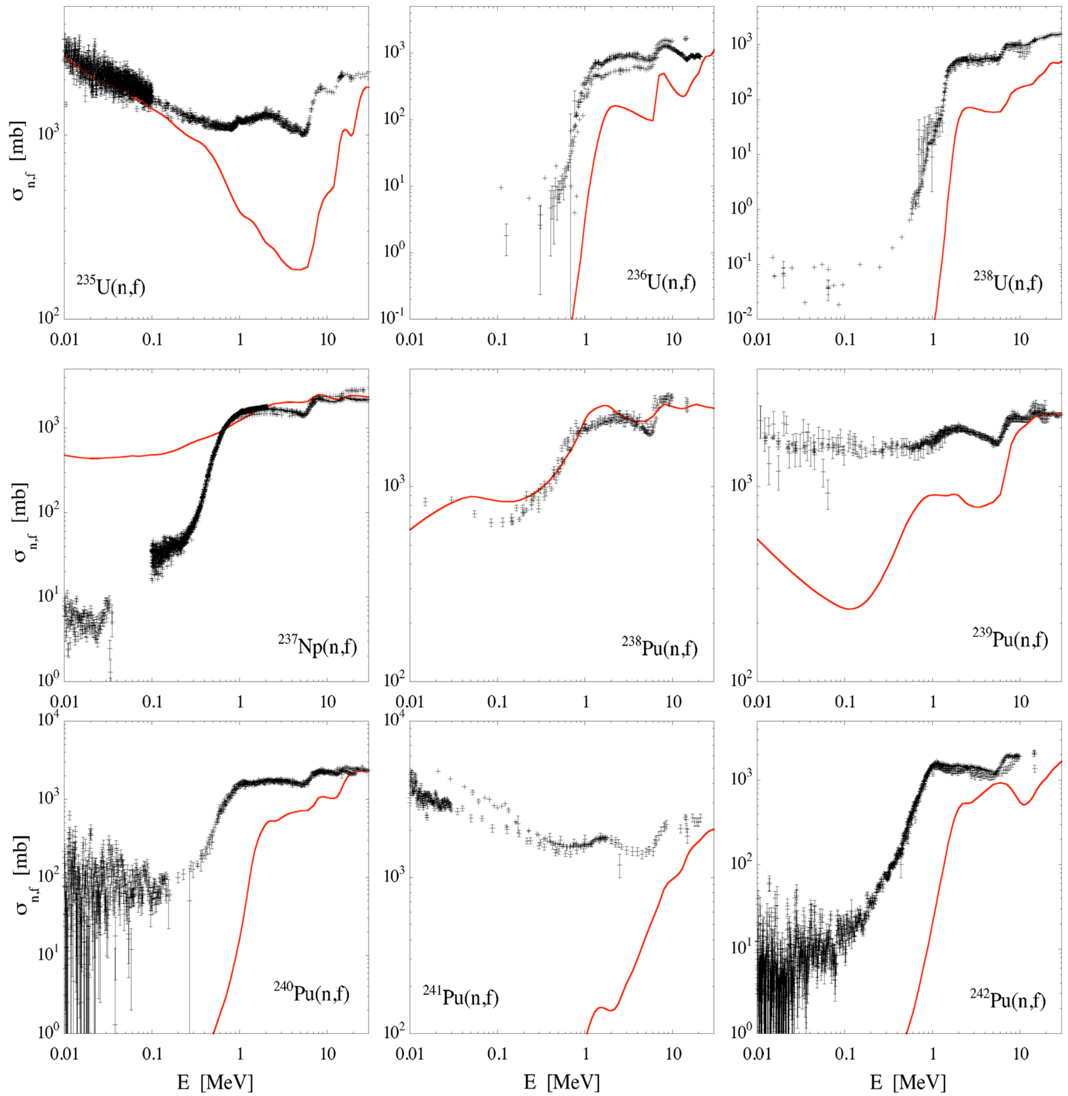
→ **NLD in a table format at inner and outer saddle points**

(~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: $\rho_{asym} = 2 \times \rho_{Comb}$

FISSION CROSS SECTIONS
(HFB-14 fission path & NLD)



Fission barriers
adjusted for
each target

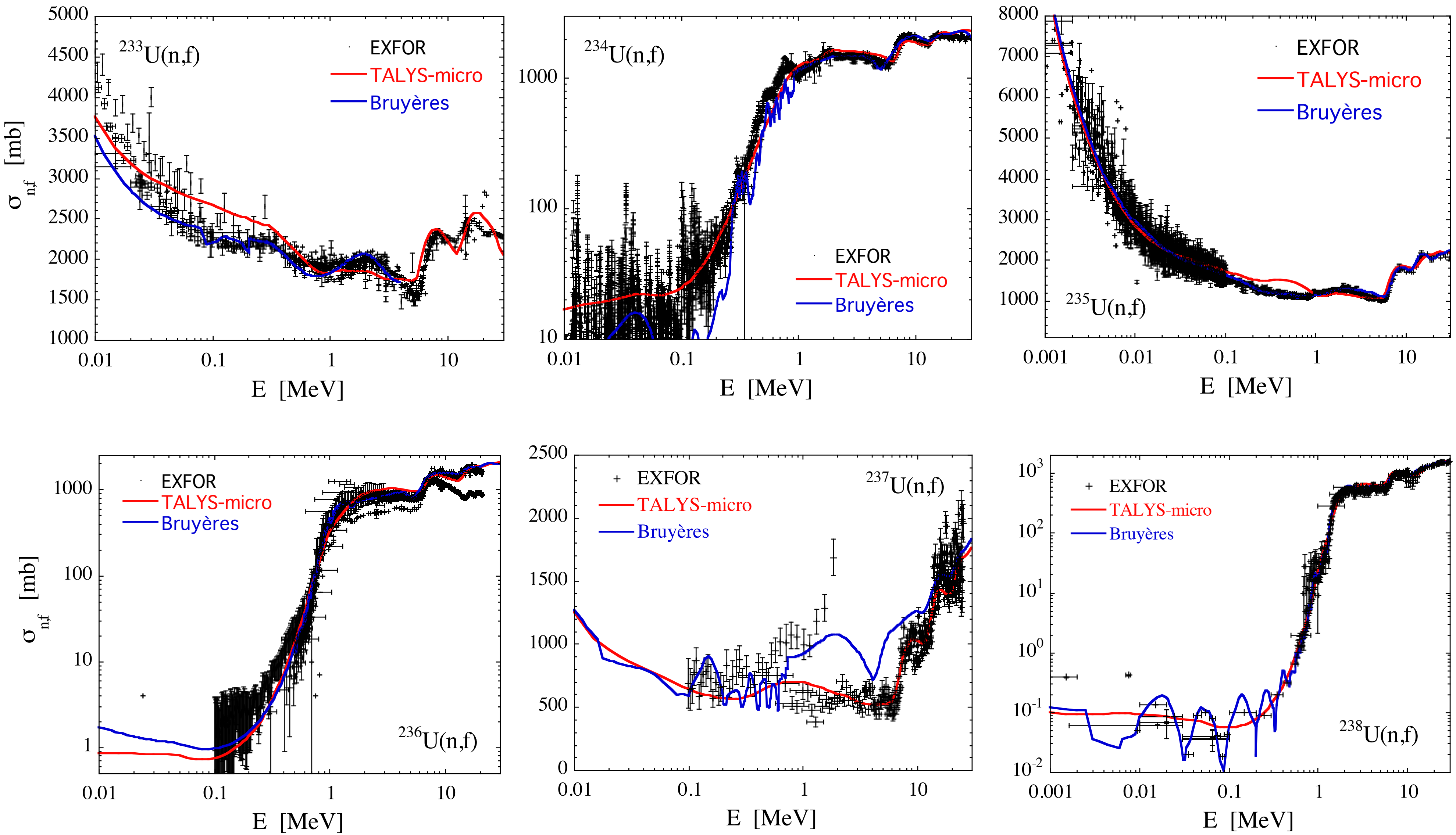
Fission barriers
adjusted for
each type of target
- odd-odd
- odd-even
- even-odd
- even-even

⇒ Quite "decent" (astrophysically speaking) after few adjustments.

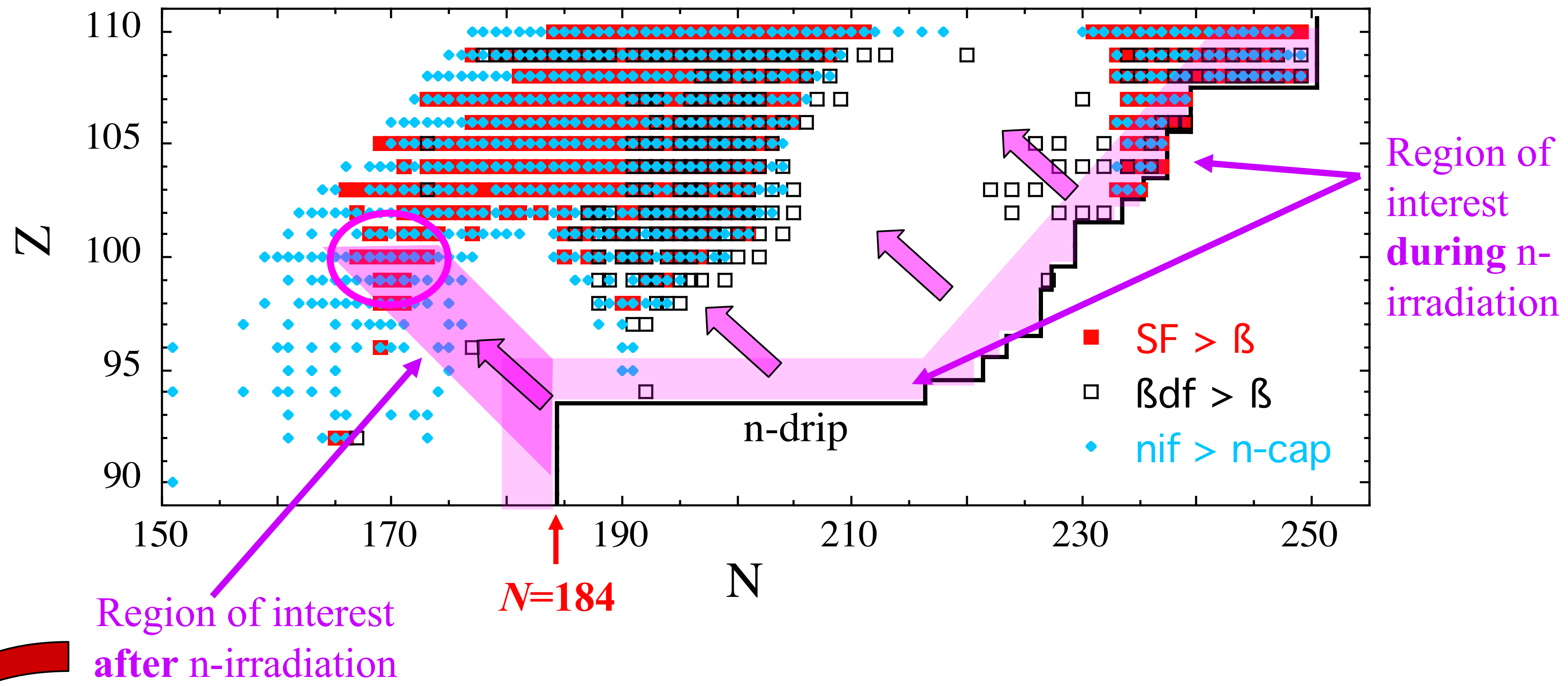
⇒ Default calculations not sufficient for applications.

Fit to ^{23x}U+n cross sections in the 0.001 – 30 MeV range

1 UNIQUE set of “microscopic” nuclear ingredients



Fission properties and the r-process



Accumulation of material at the *N*=184 closed shell
→ Special emphasis on the Fission Fragment Distribution for the *A*~278 isobars

Fission Fragment Distributions

GEF (ABLA): semi-empirical macroscopic-microscopic scission point model

- microscopic properties are essentially determined by the shell effects of the fragments
- only the macroscopic properties of the fissioning system are taken into account.
- inclusion of dynamical effects to include the impact of inertia along the fission trajectory

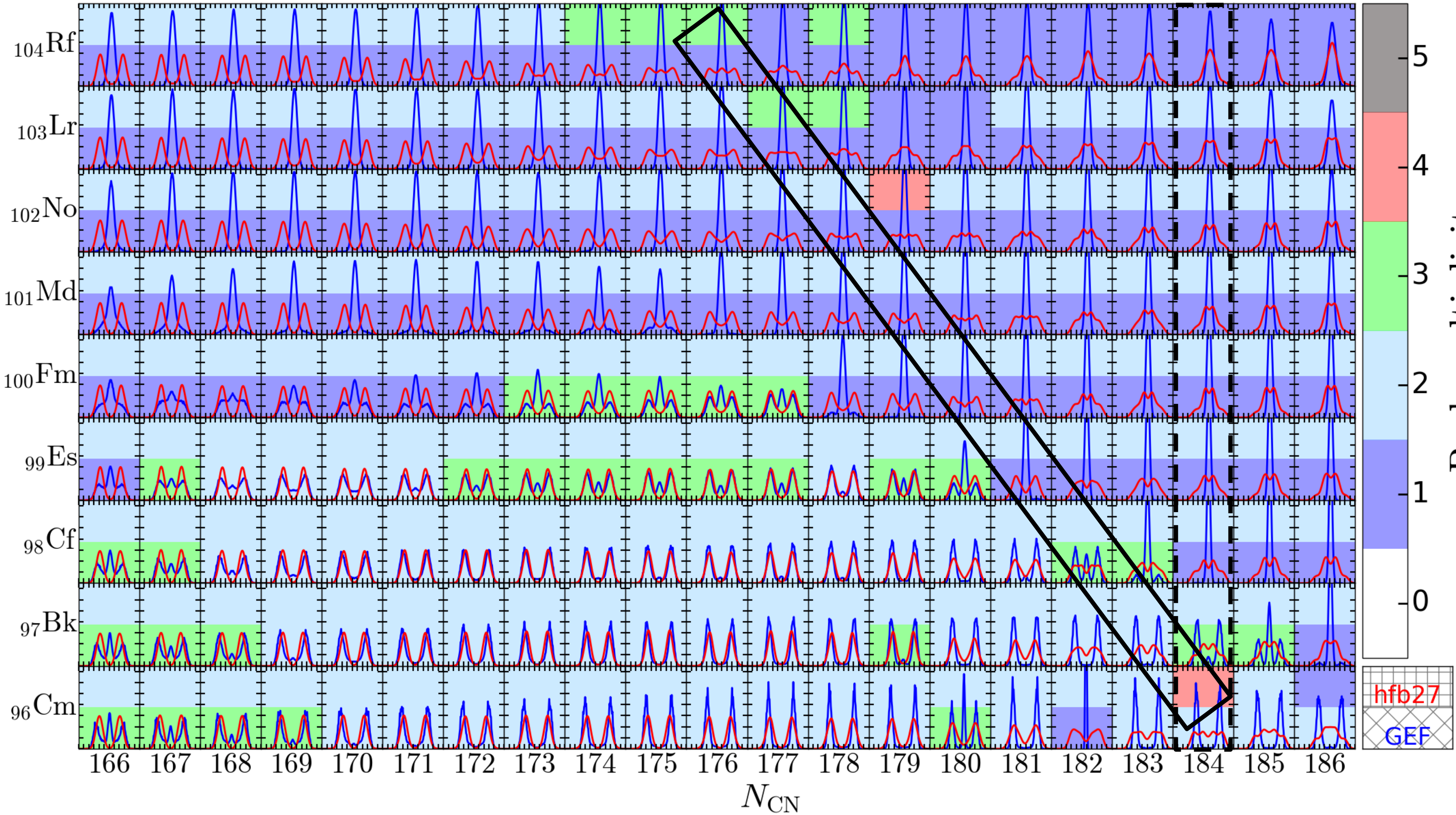
Schmidt and Jurado (2010-2012)

SPY: Scission Point model based on Gogny potential energy surfaces and NLD

- ONLY based on fission fragments & first-chance fission
- Evolution (quasi-static) from saddle to scission point is neglected
- Isolated fragments at rest
- Well-defined fragments properties (Z, N, β)
- Fragmentation probability $\propto$ number of available states

Lemaitre et al. (2015, 2018)

SPY vs GEF predictions of the FFD



$Y(A)$: 0 —> 15%

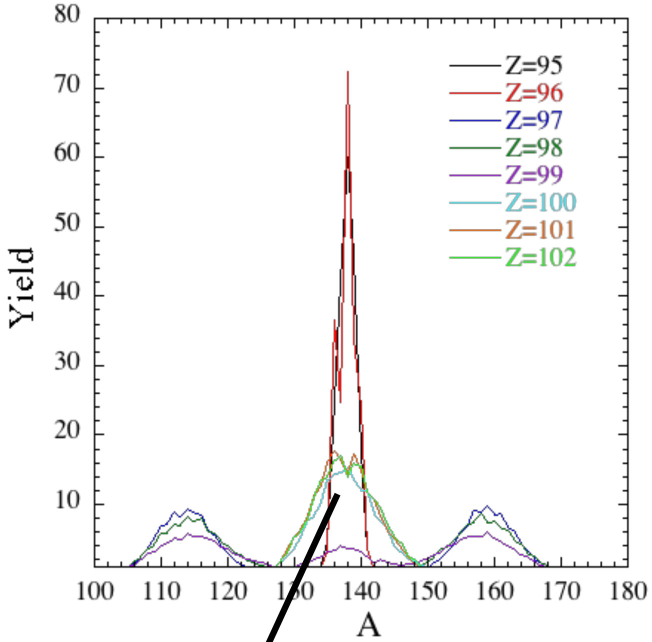
A : 70 —> 190

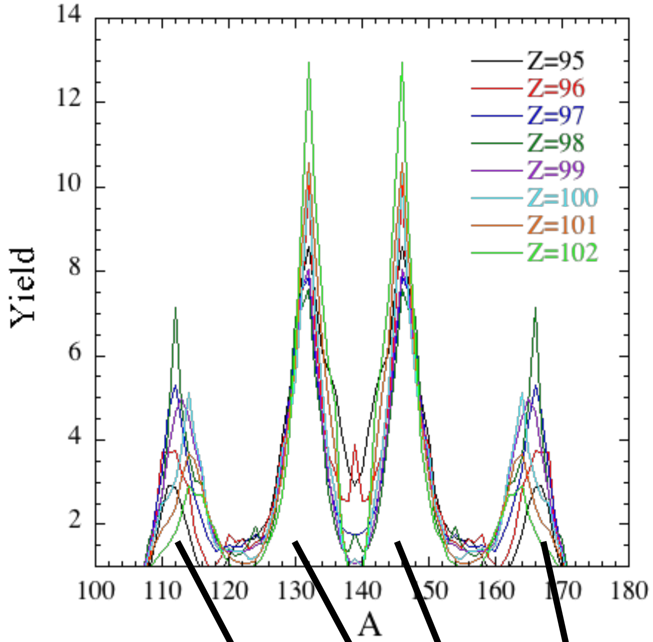
Sensitivity of dynamical composition to the fission fragment distribution

along the *A*=278 isobar (from the *N*=184 closed shell)

GEF v1.4
K. Schmidt et al. (2013)

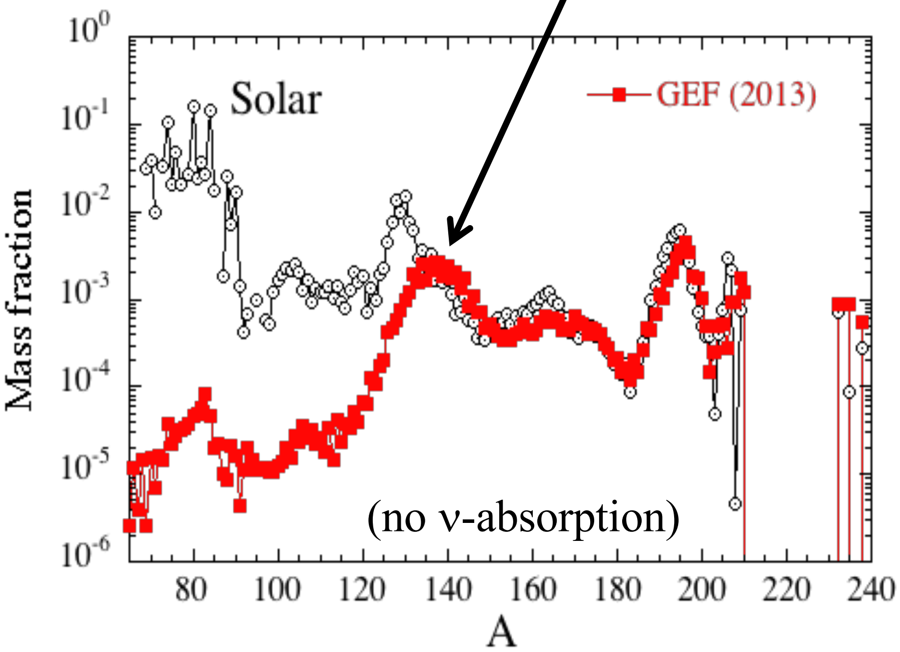
Semi-empirical mic-mac Scission Point model

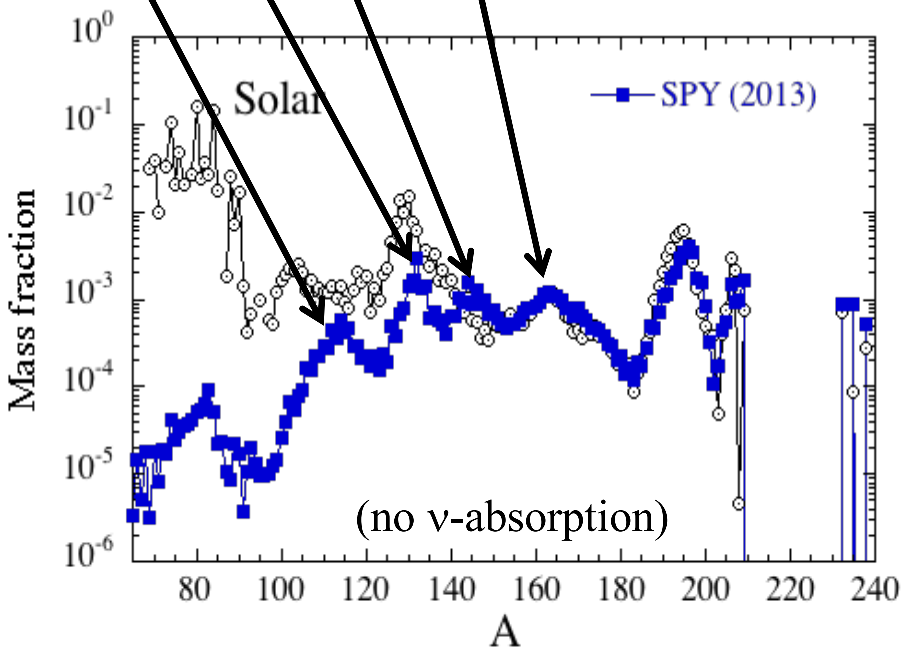




SPY:
S. Panebianco et al. (2013)

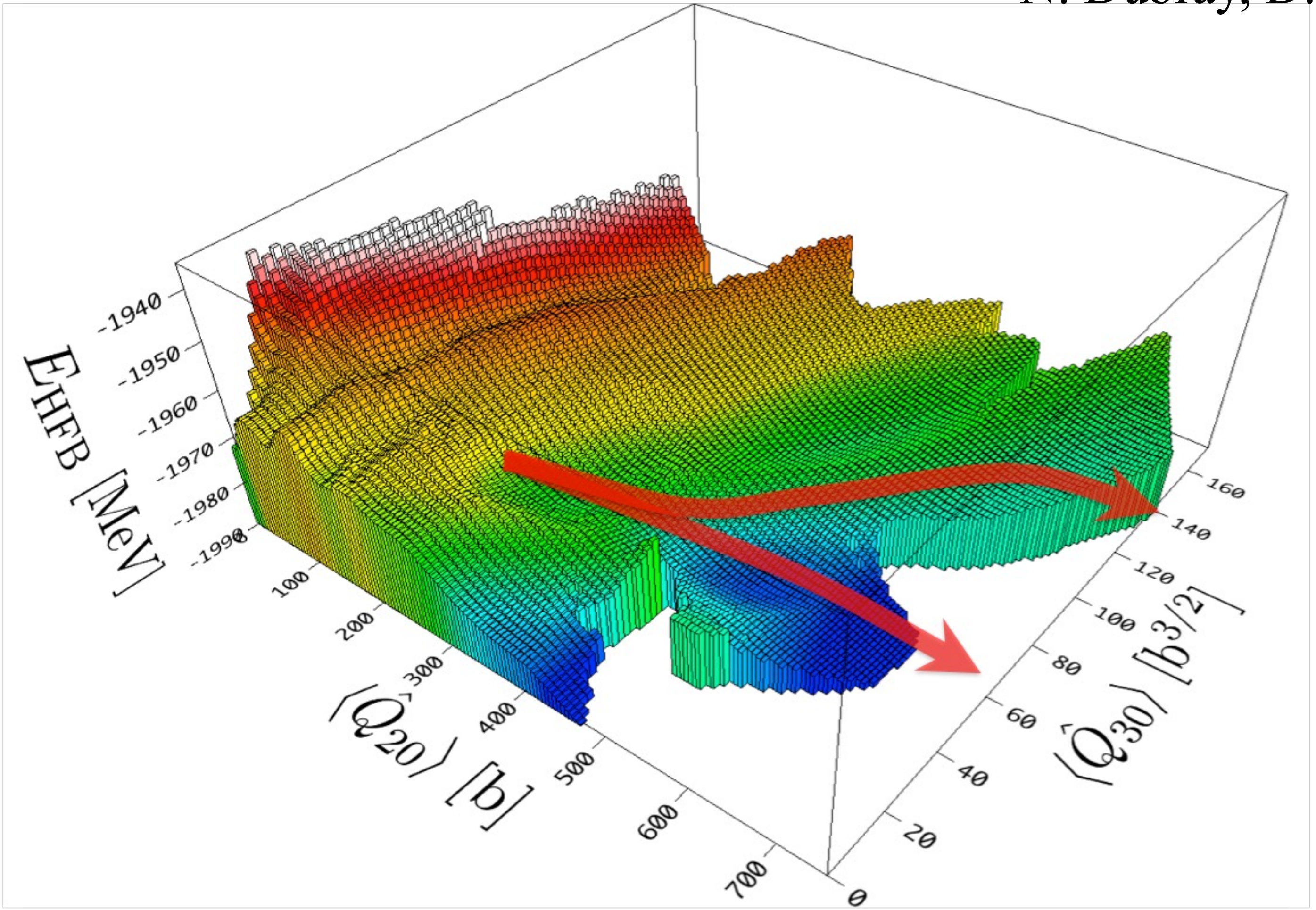
Scission Point model based on D1S potential energy surfaces





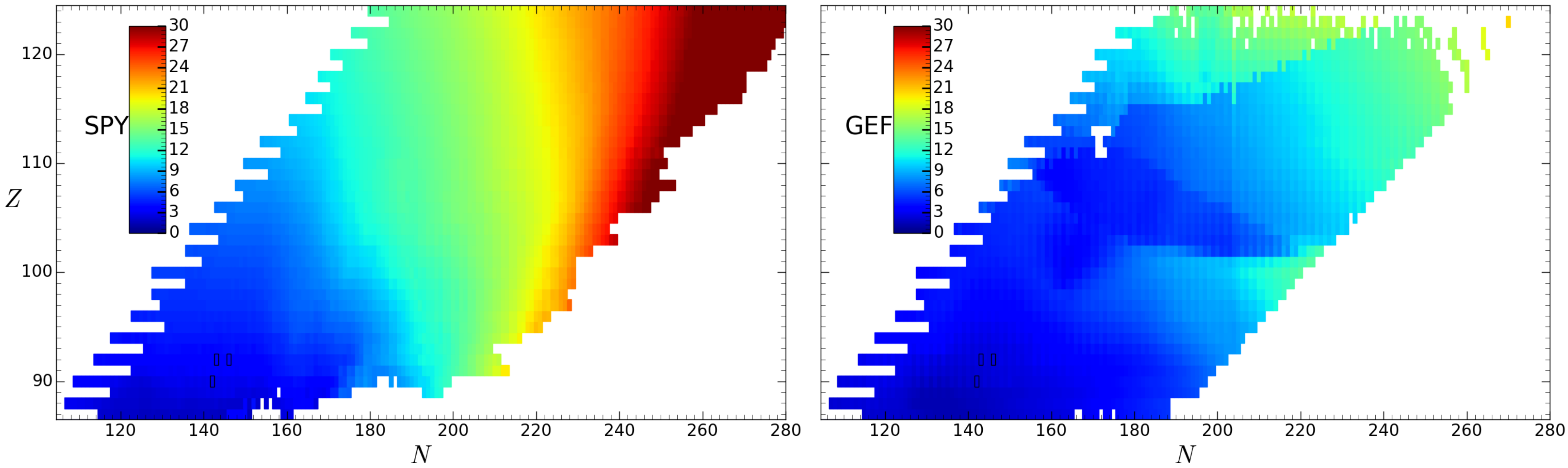
Gogny-HFB calculation of ^{278}Cf PES

N. Dubray, D. Regnier, N. Pillet



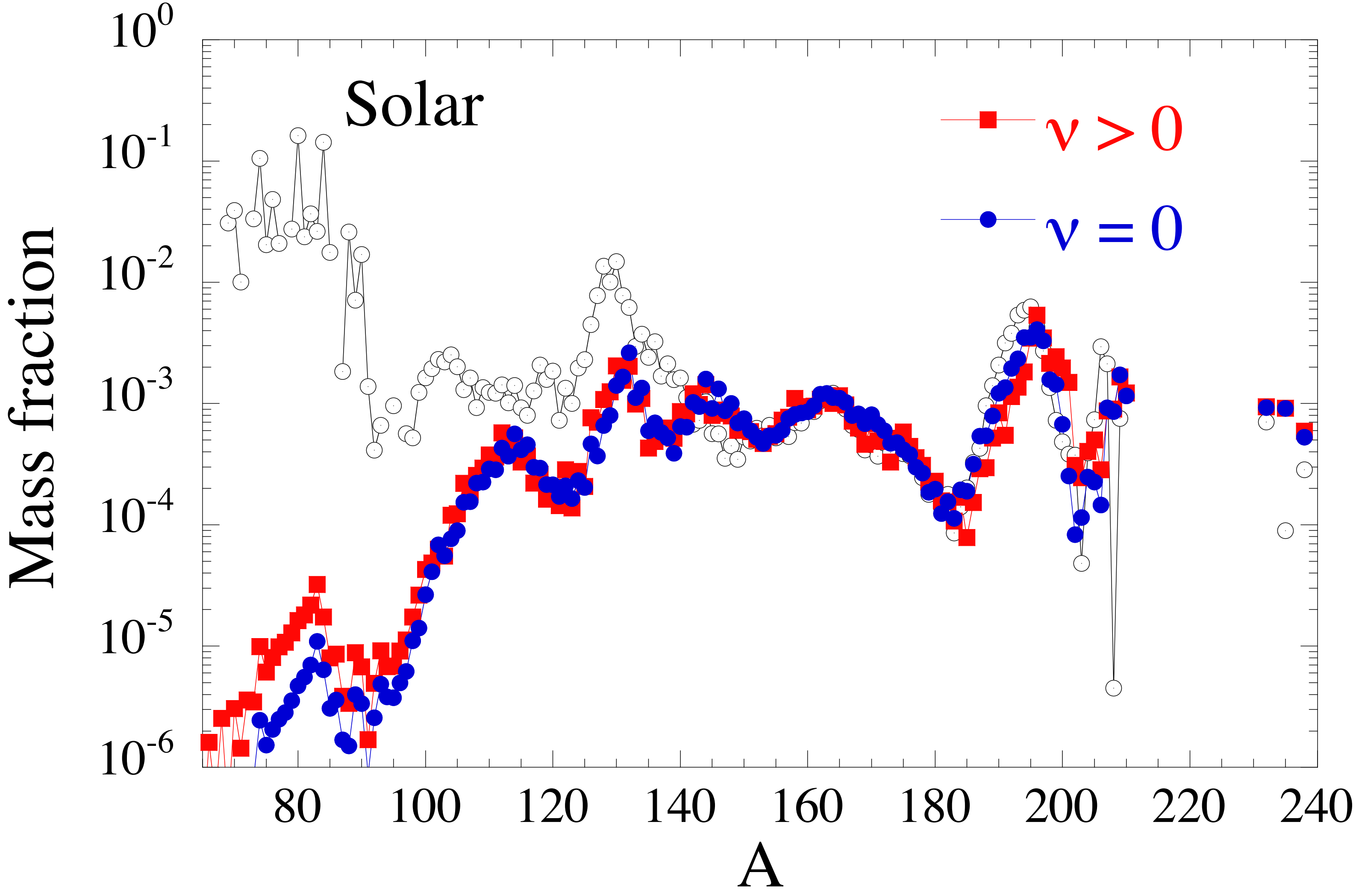
Missing dynamical calculations (Goutte et al. 2005, Bernard et al. 2011, Scamps et al. 2018)
(e.g. the time-dependent GCM; cf talks Regnier & Pillet)

Mean number of emitted neutrons



- during n-irradiation:
  - Neutrons emitted are rapidly recaptured by existing nuclei
    → no major impact on the final abundance distribution
- after n-irradiation:
  - Neutrons add up to β-delayed neutrons
  - Neutrons are captured by the most abundant species (N~126)
  - Possible shift of the abundances by a few units

Impact of the neutron emission on the r-process on the composition of the dynamical NS-BH ejecta

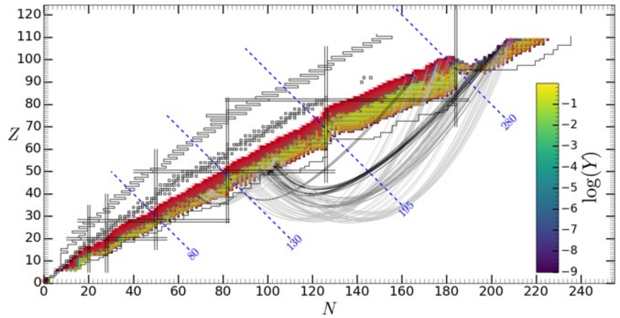


Conclusions

The role of fission remains important: 10 to 100% of ejected matter experience fission in compact object mergers

but quantitatively conclusions remain sensitive to the complex and still uncertain

- r-process site & weak interaction processes
  - define the nbr of free neutrons available
  - possible actinide/SH production
  - fission recycling & heating



- prediction of fission probabilities (sf, βdf, nif) & FFD !
  - potential energy surface for ~2000 nuclei
  - nuclear level densities at saddles/wells
  - fission fragment distributions
  - neutrons emitted