Nucleosynthesis: a field with still many open nuclear physics questions

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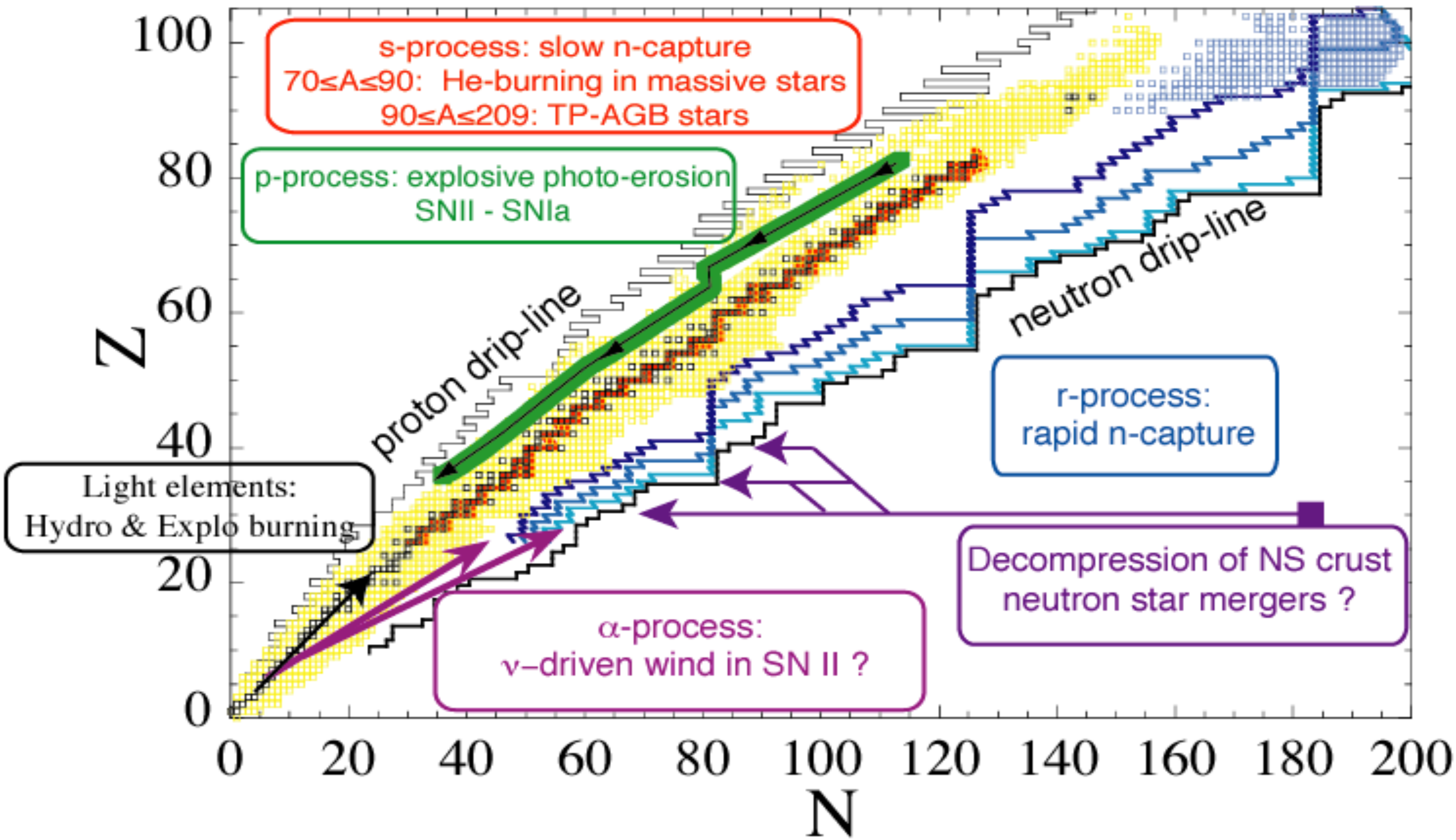
The s-, r- and p-processes of nucleosynthesis



Where do we stand today ?

	ASTRO	NUCLEAR	OBS
S-PROCESS	+ –	+	+ –
P-PROCESS	+ –	–	–
R-PROCESS	– –	– –	+ –

… the r-process site remains unknown ...

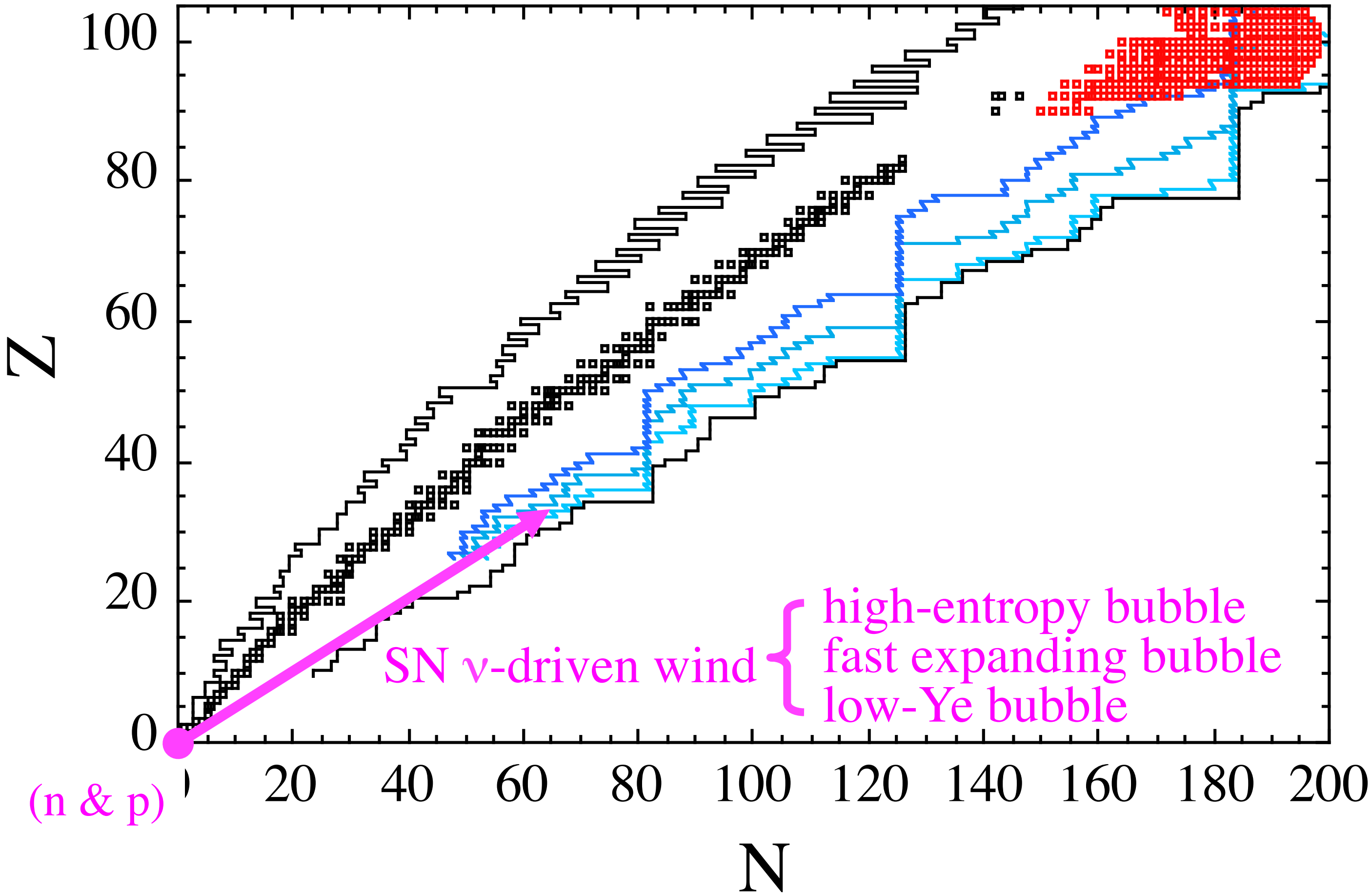
Our understanding of the r-process nucleosynthesis, i.e. the origin of about half of the nuclei heavier than Fe in the Universe is considered as

one of the top 11 questions in Physics and Astronomy

(“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”: 2003, National research council of the national academies)

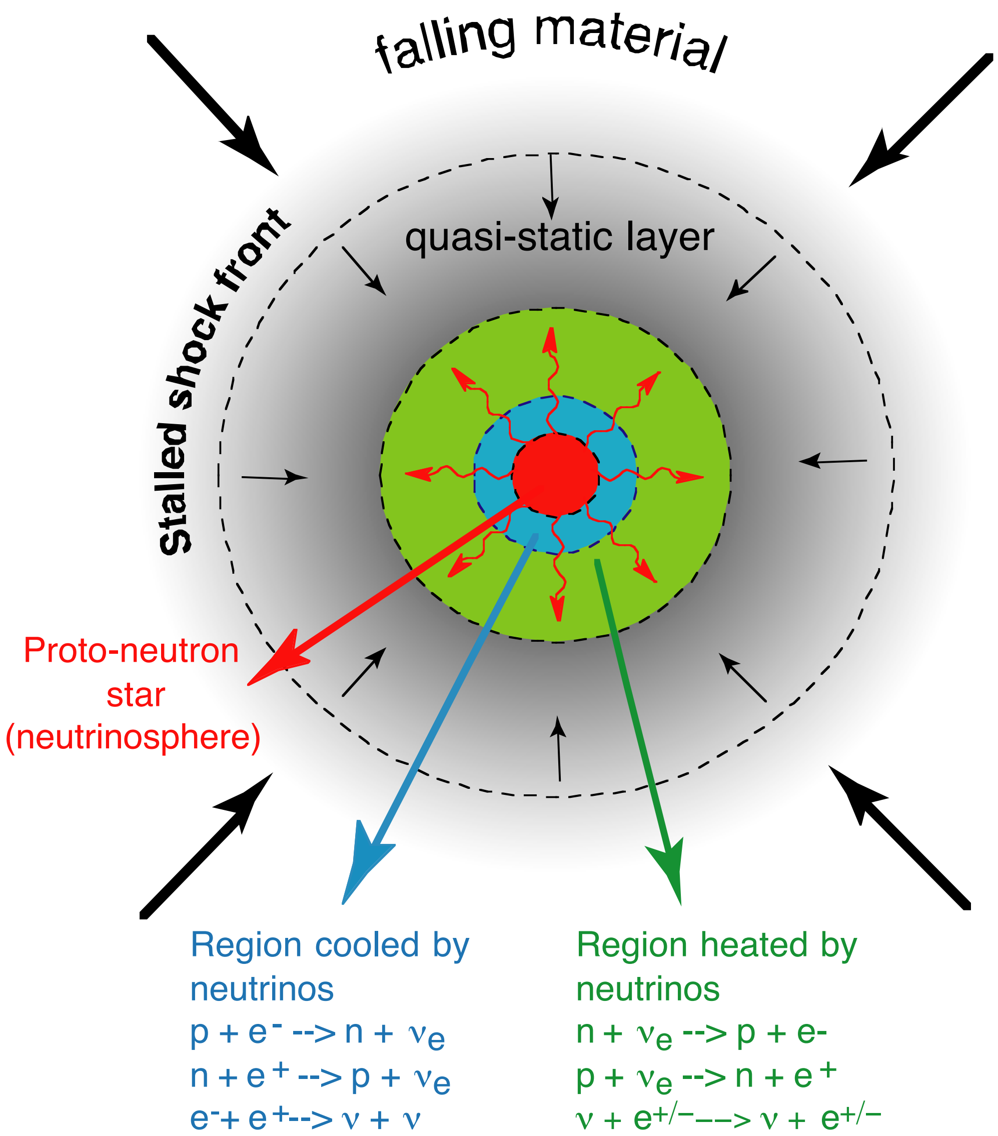
The r-process nucleosynthesis

one of the still unsolved puzzles in astrophysics
… the r-process site remains unknown ...



Supernovae: the favoured r-process site ??
Many subjective interpretations, unconfirmed speculations, fast conclusions, …

The favorite r-process site: the ν-driven wind in SNII



Decompression of hot material

n,p at $T_9 \approx 10$ $\rho \sim 10^6 g/cm^3$

↓ NSE

^4He recombination

↓ $\alpha\alpha n$-$^9Be(\alpha,n)$

^{12}C bottleneck

↓ (α,γ) & (α,n)

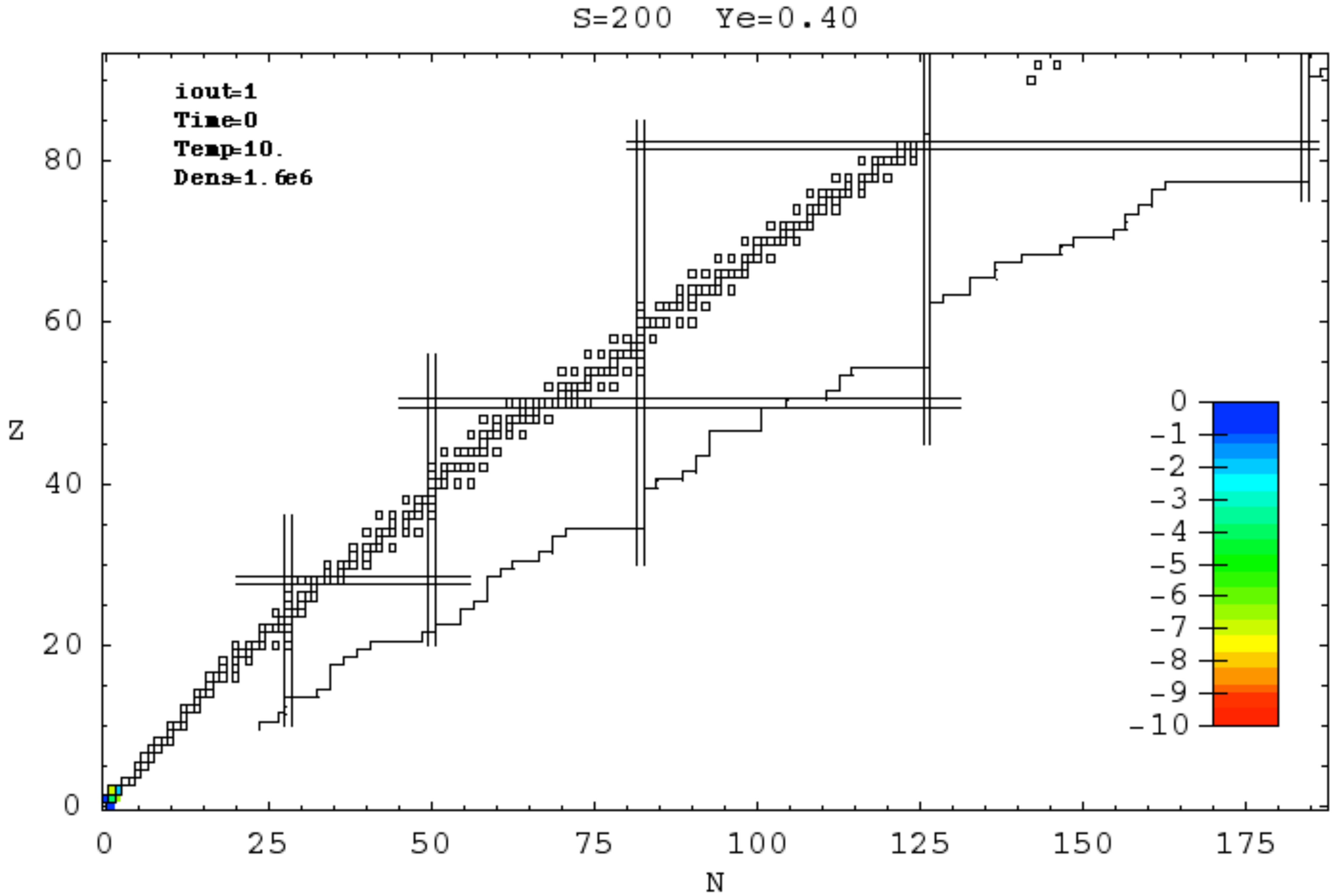
$60 \leq A \leq 100$ seed

↓ (n,γ) & (γ,n) + β-decays

r-process

if Y_n/Y_{seed} large enough !!

Artificially large S, small Y_e, τ_{ex}

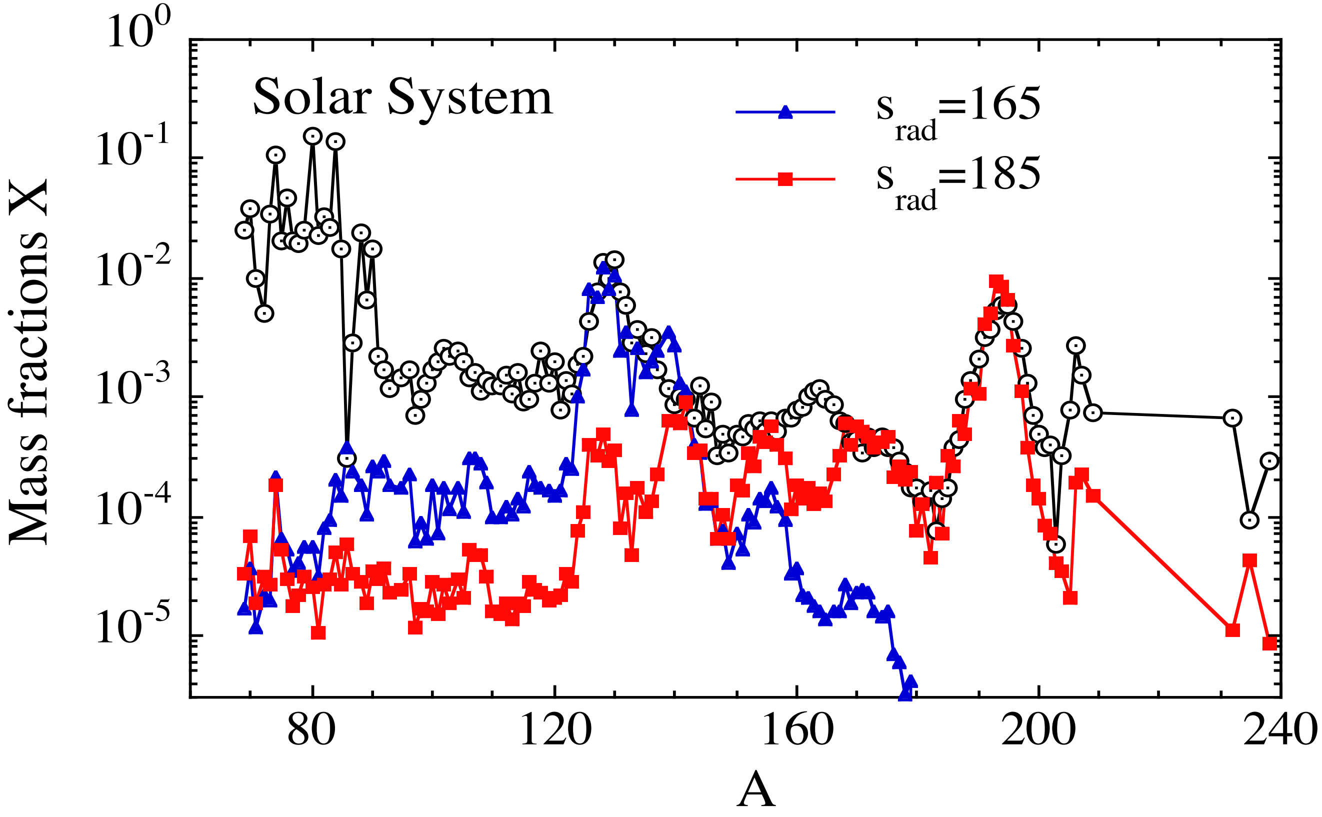


S=200 Ye=0.40
iout=1
Time=0
Temp=10.
Dens=1.6e6
Z
N
0
20
40
60
80
0
25
50
75
100
125
150
175
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

r-abundance distribution in the ν-driven wind

Wind model of Janka & Takahashi (1997): same initial Y_e=0.48

same mass loss rate: $dM/dt=6\ 10^{-6}\ M_o/s$ – different entropies



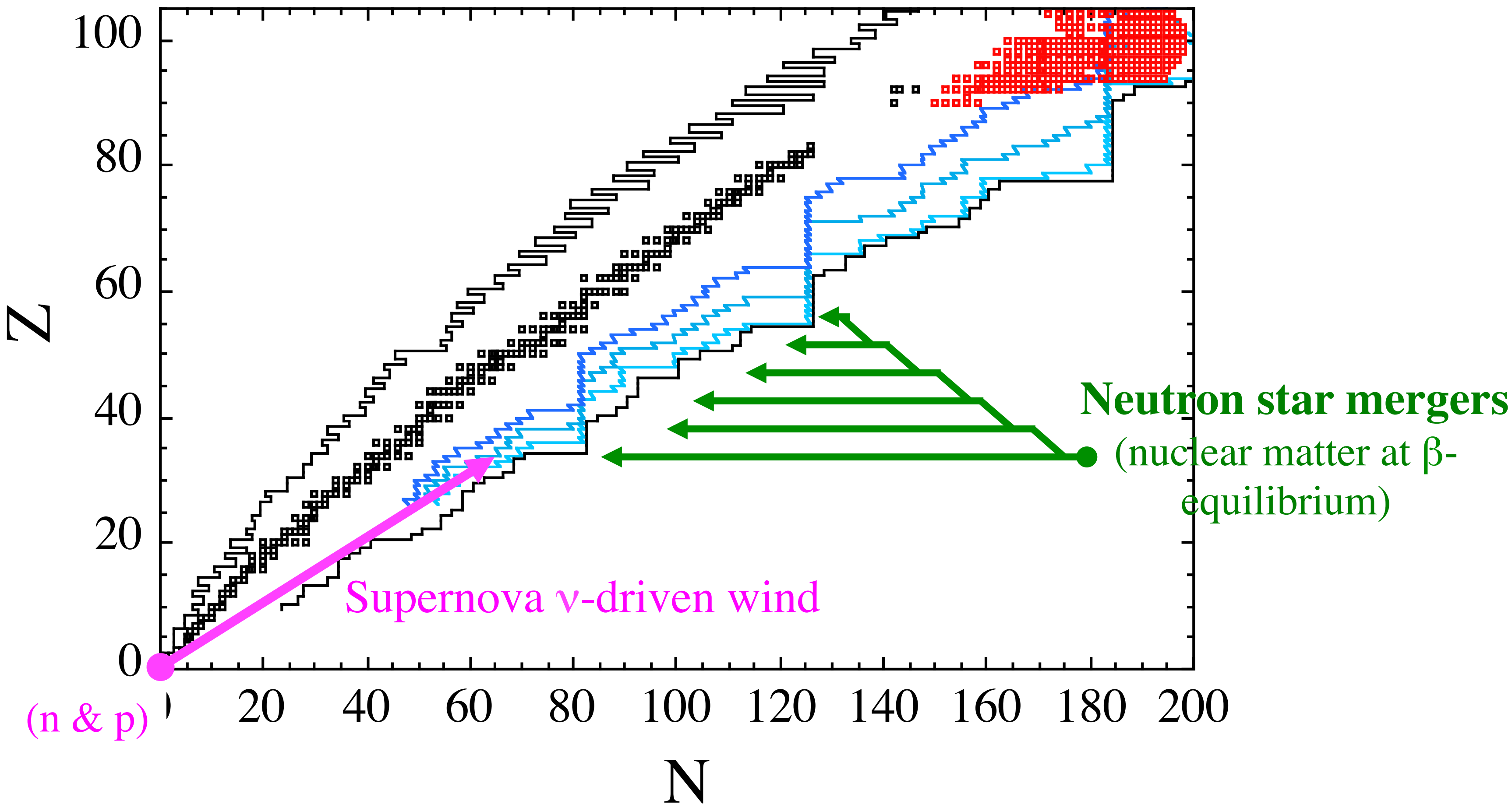
Extremely sensitive to the (unknown) thermodynamic profiles (S,Y_e,τ_{exp})

only hydrodynamic Supernova simulations can tell

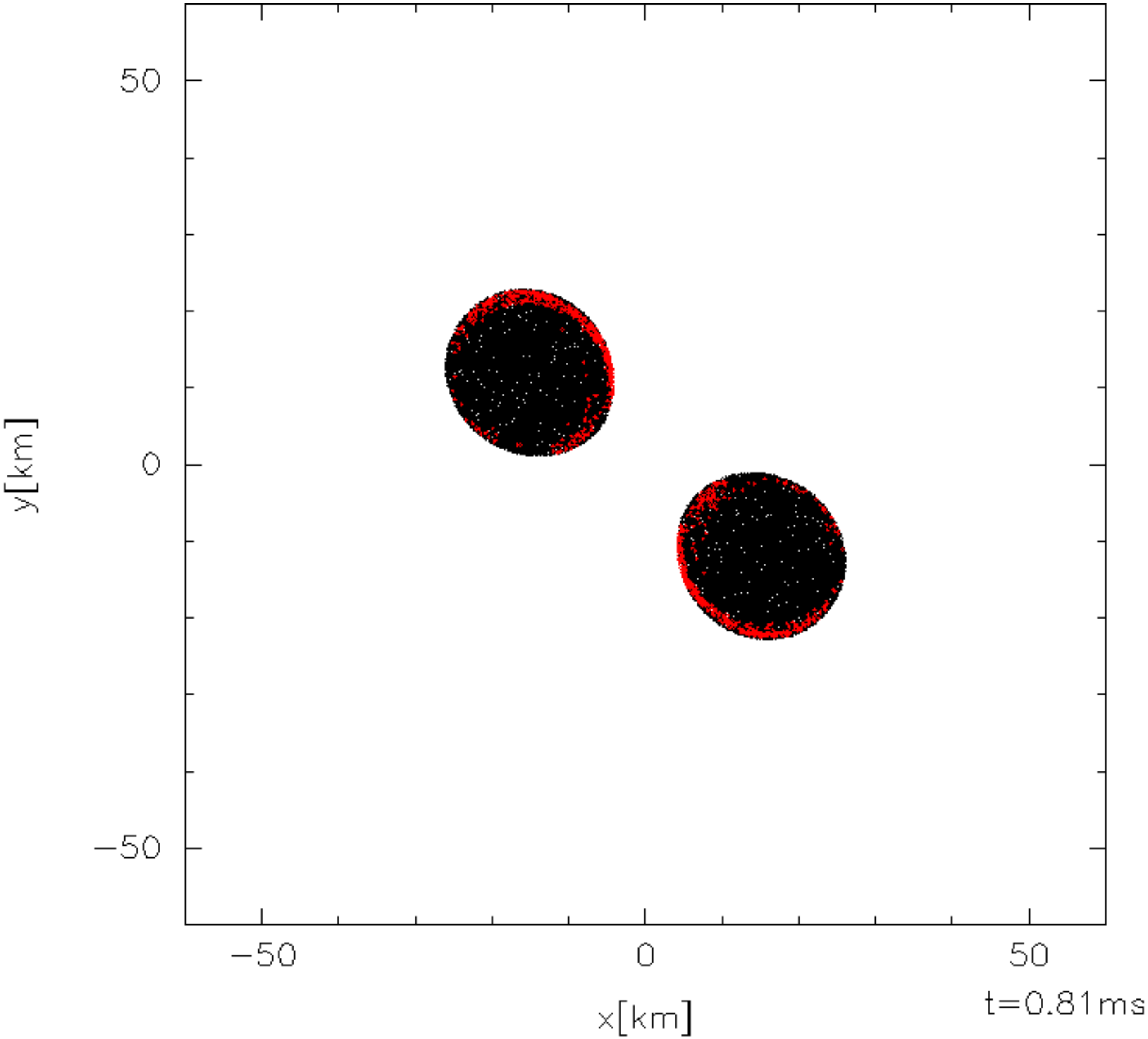
… but the explosion has to be under control first …

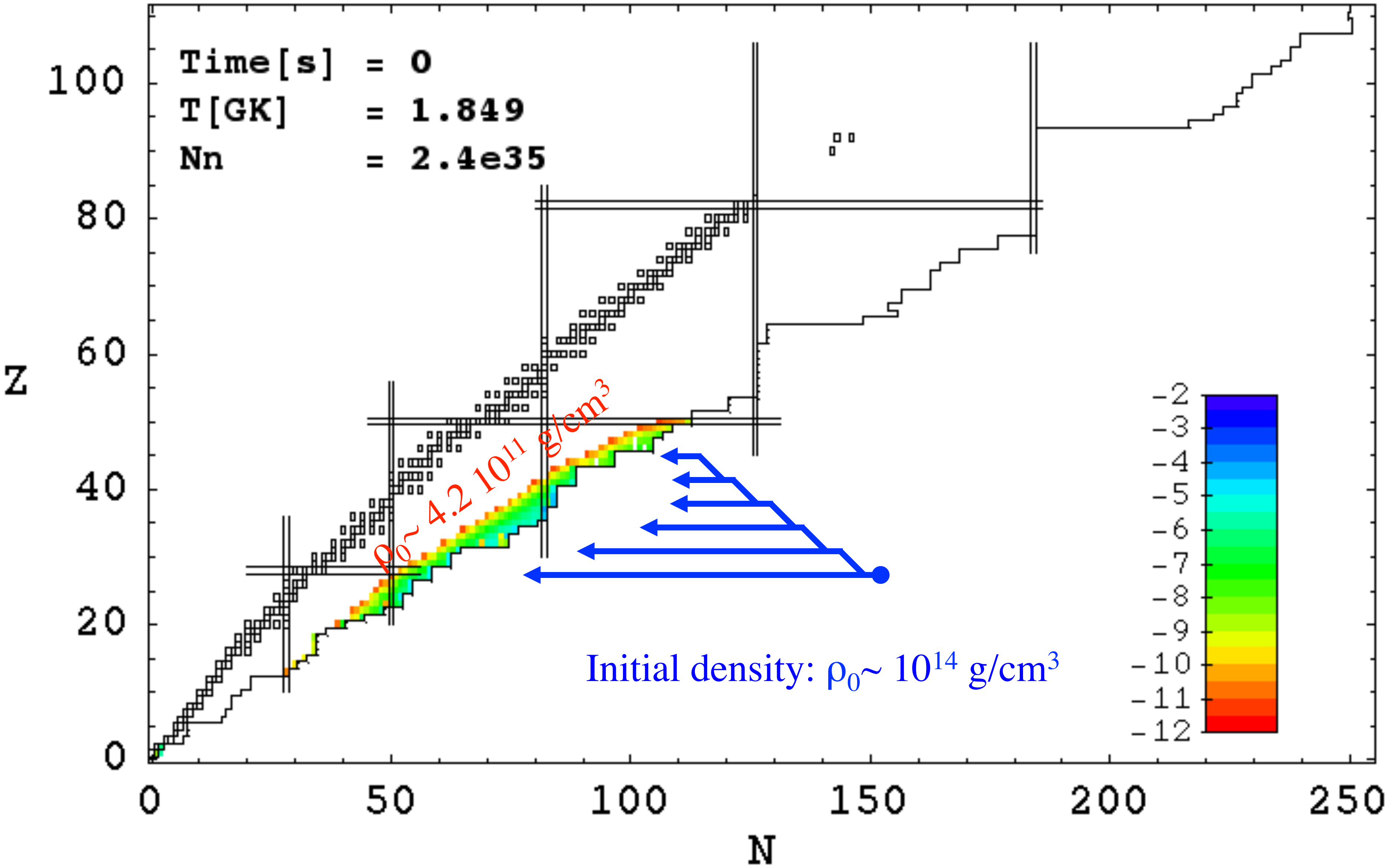
An alternative r-process scenario: the decompression of NS matter

(initial conditions: high-density matter)

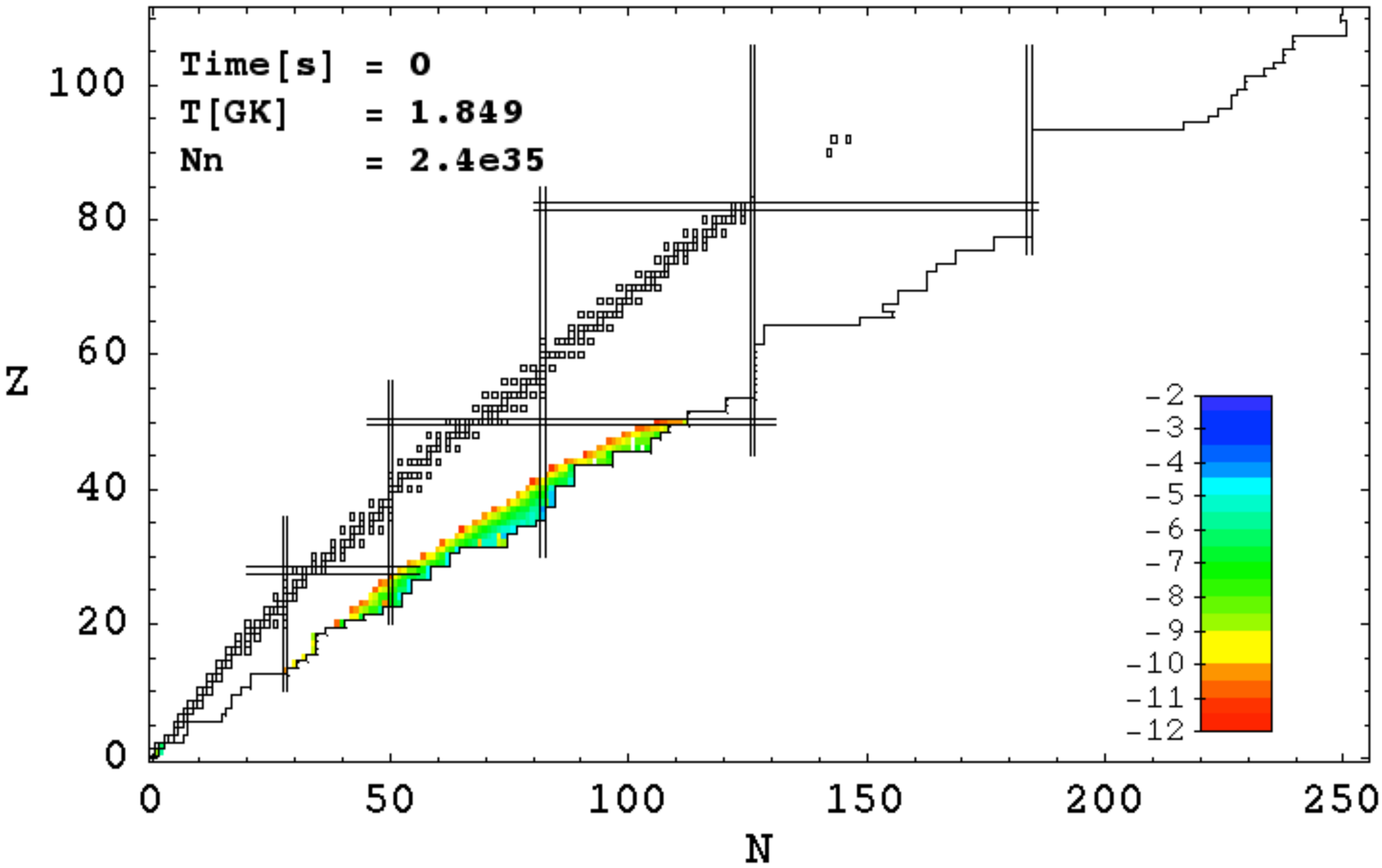


Neutron star mergers: $10^{-3} - 10^{-2}\ M_o$ ejected (Bauswein & Janka 2011)





Time[s] = 0
T[GK] = 1.849
Nn = 2.4e35
ρ_0~ 4.2 10^{11} g/cm^3
Initial density: ρ_0~ 10^{14} g/cm^3
Z
N
0
20
40
60
80
100
0
50
100
150
200
250
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12



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100
150
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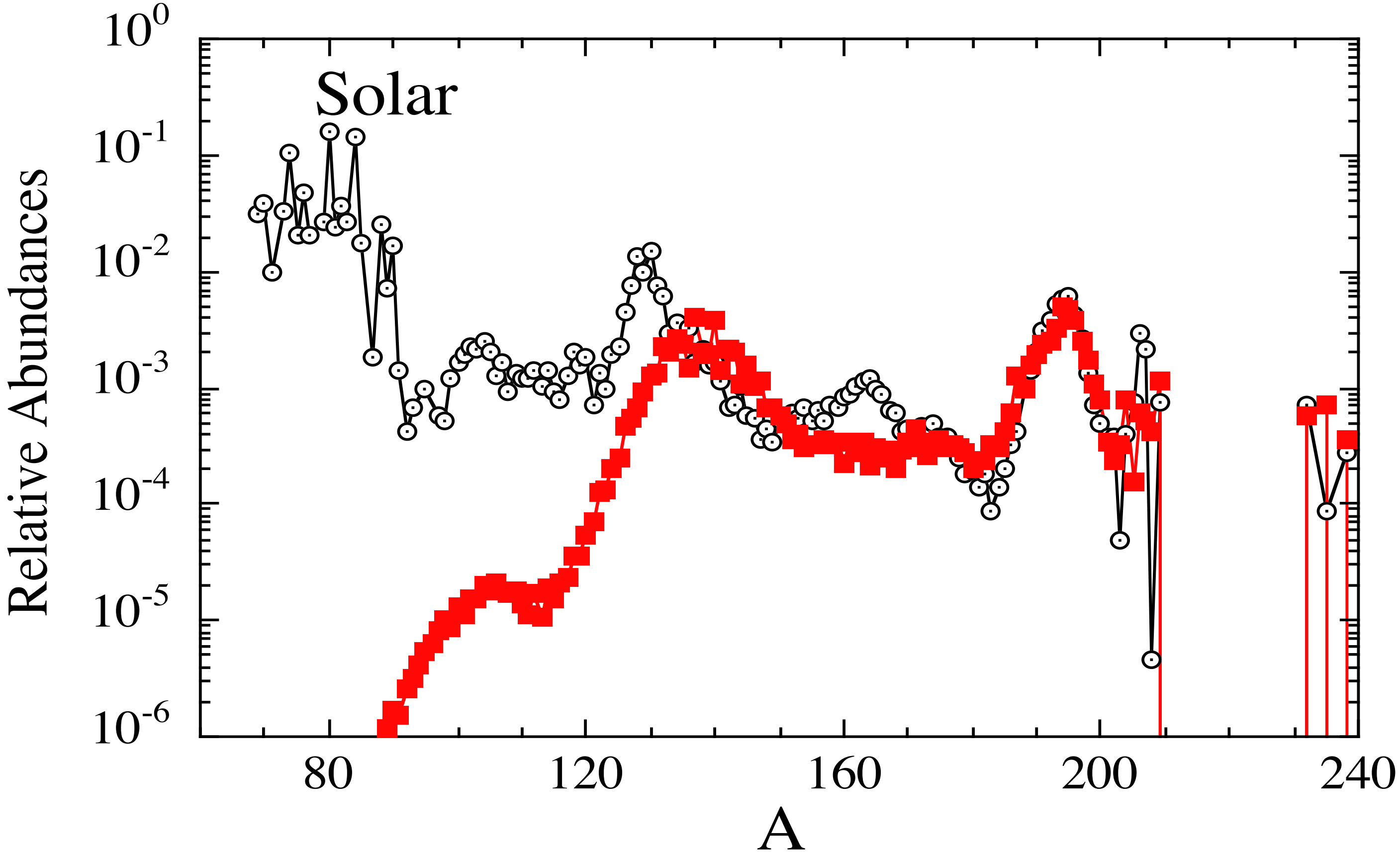
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12

Final ejected r-abundance distribution

1000 trajectories for a 1.35 –1.35 M_o NS merger



"robust" production of A>140 r-nuclei in solar distribution

Nuclear needs for r-process nucleosynthesis

ν-driven wind (cold or hot)	(n,γ)–(γ,n) *competition* (equilibrium for hot wind)	β-decays, (n,γ) & (γ,n) **rates** + *ν*-nucleus interaction + Fission (nif, sf, βdf) (? unlikely)
Inner crust of NS	(n,γ) <–> β competition & Fission recycling	β-decay & (n,γ) **rates** + Fission (nif, sf, βdf) rates + Fission products distribution (+ NP associated with initial cond.)

In all cases, nucleosynthesis requires RATES for some 5000 nuclei !

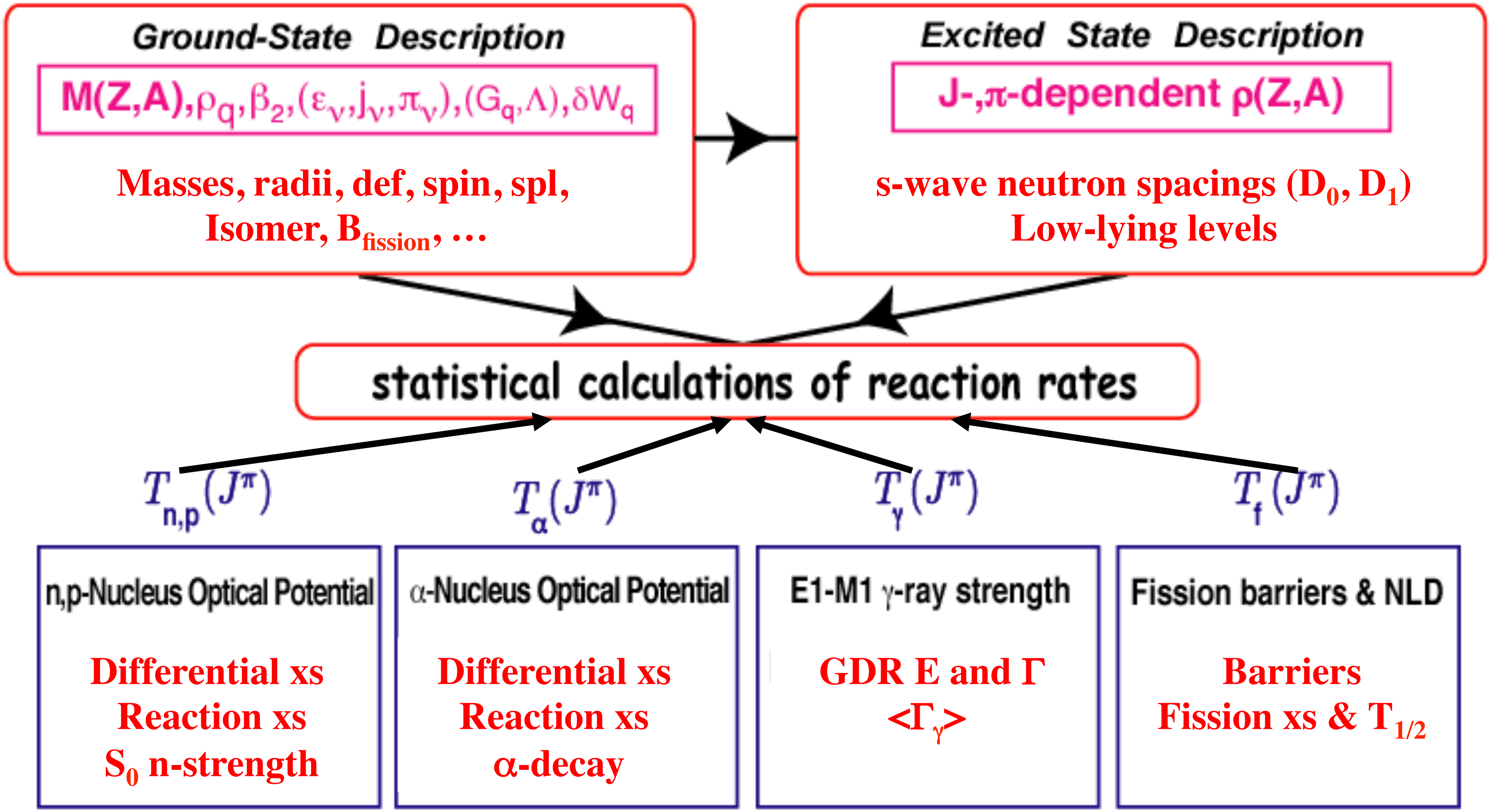
(and not only along the oversimplified so-called "r-process path")

→ simulations rely almost entirely on theoretical predictions

We know these quantities will enter the problem but as long as the r-process site will remain unknown, we cannot judge

- *quantitatively* about the *importance* of a given ingredient, hence
- even less about the *quality* of the nuclear input (from astro simulations)

Direct or indirect observables entering nuclear reaction models



Except masses, radii, Q and low-lying levels, almost no data available for n-rich nuclei

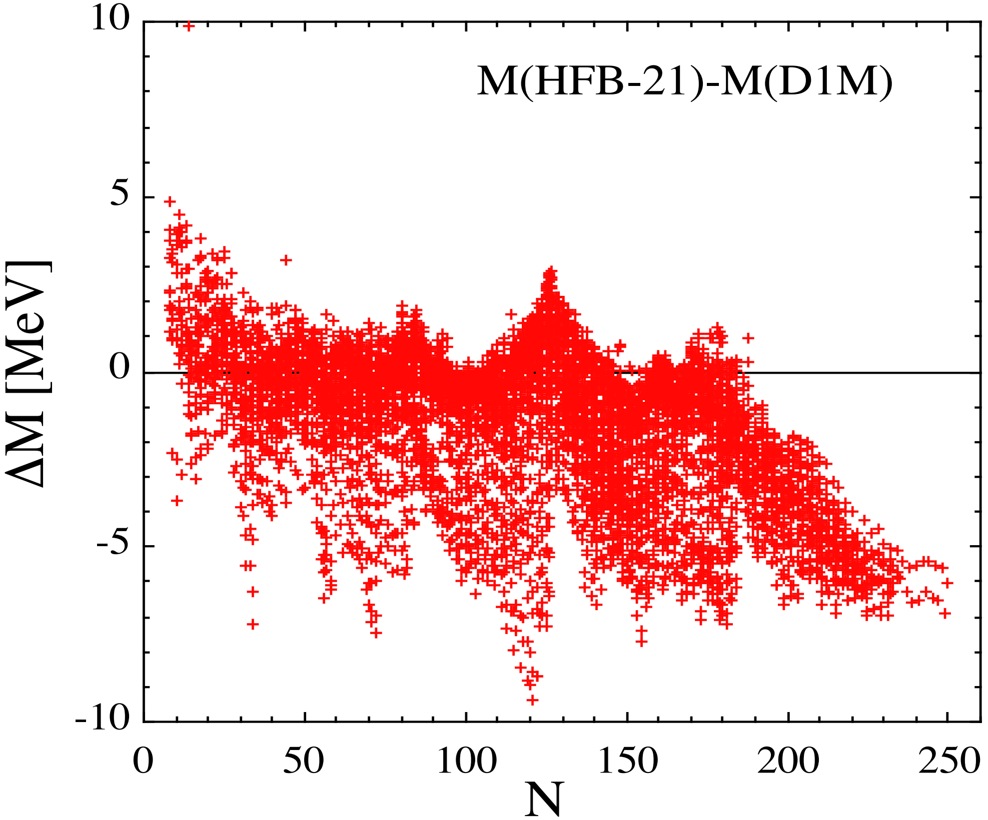
➡ Determination rely *entirely* on models fitted on the stable nuclei

Sensitivity to the masses and corresponding reaction rates

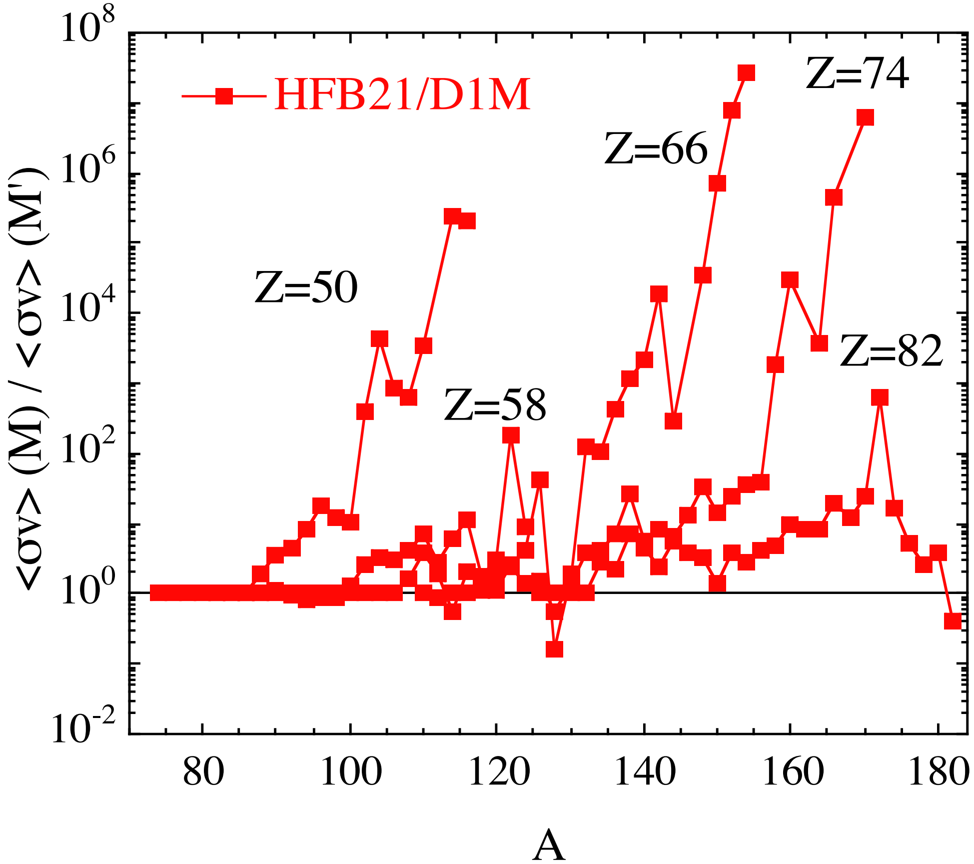
HFB-21: Skyrme HFB mass model — σ(2149 exp masses)=577keV

HFB-D1M: Gogny HFB mass model — σ(2149 exp masses)=798keV

Mass differences between HFB21 & D1M



TALYS(n,γ) rates at T_9=1 on Sn-Pb isotopes



Different trends due to different shell & correlation energies

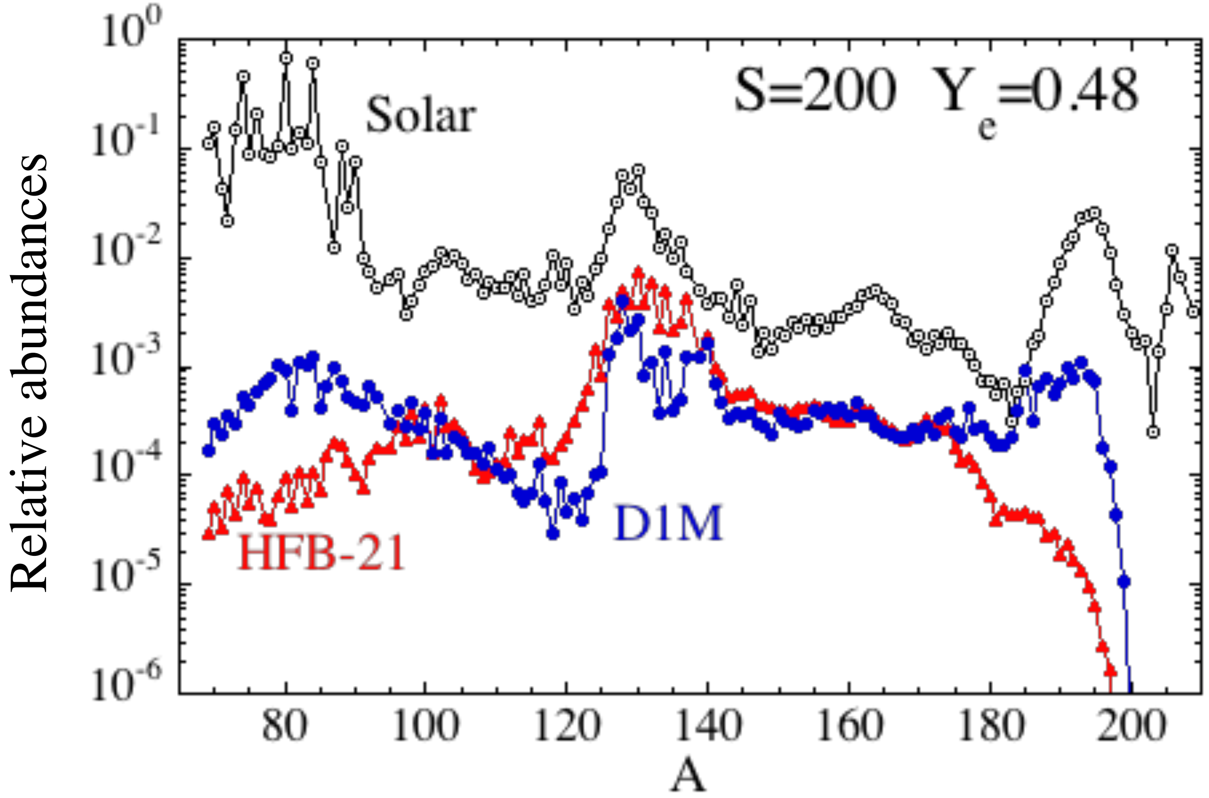
Sensitivity to nuclear masses and corresponding rates

Comparison for 2 different mass models:

HFB-21: Skyrme HFB mass model — σ(2149 nuclei)=577keV

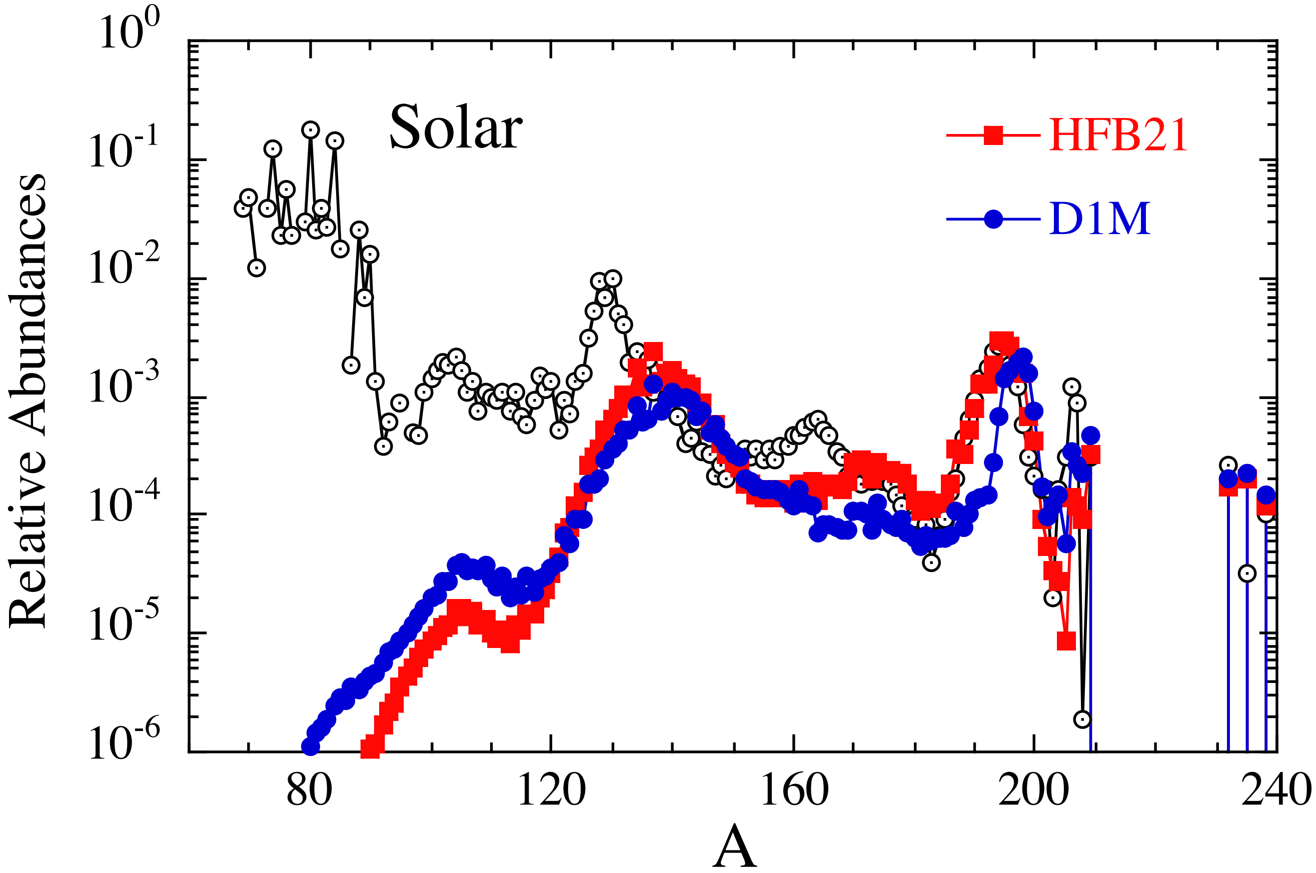
HFB-D1M: Gogny HFB mass model — σ(2149 nuclei)=798keV

r-abundance distribution from 1 specific ν-driven wind



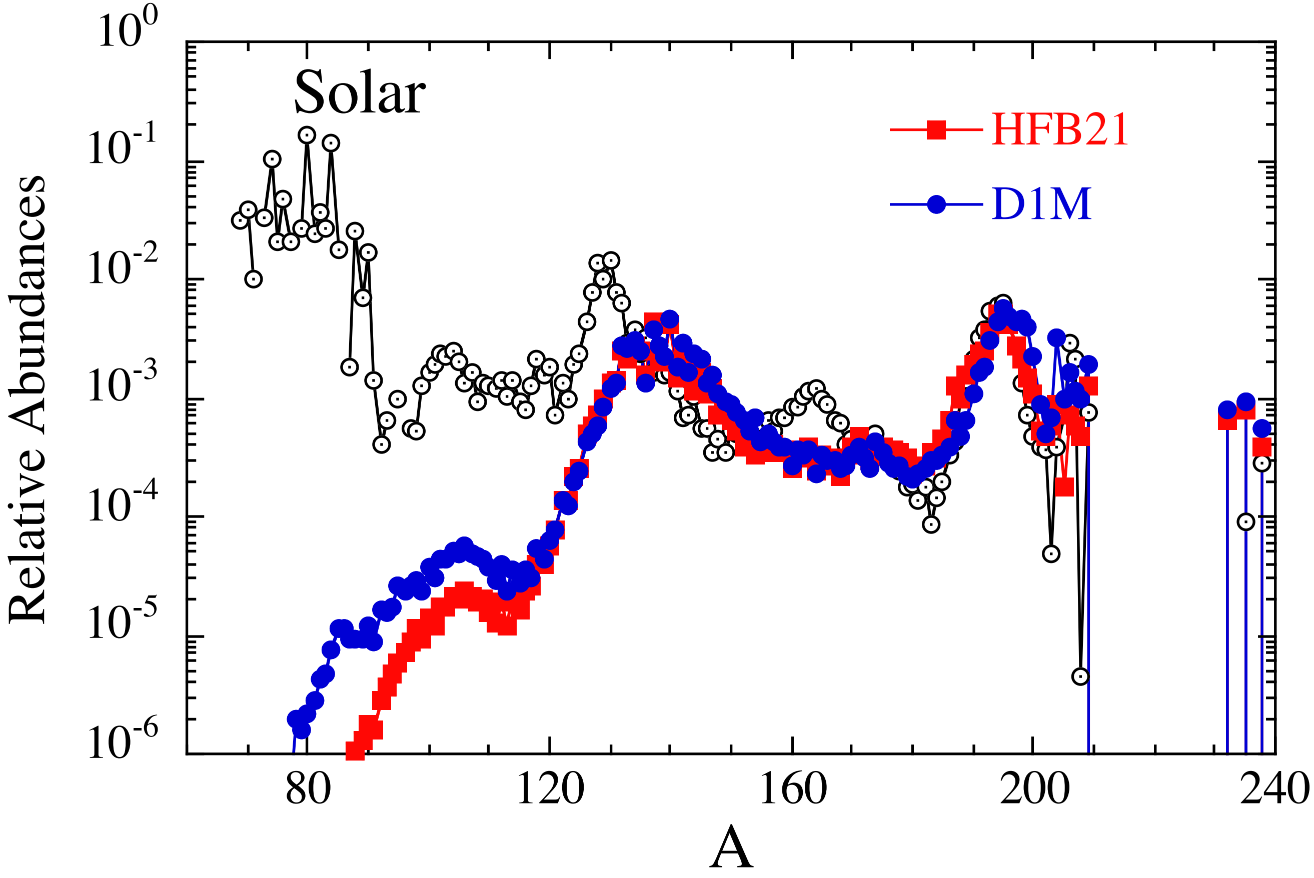
Impact of masses/rates on the r-process nucleosynthesis in NS mergers

r-abundance distributions from **1** typical ejected “mass element”



Impact of masses/rates on the r-process nucleosynthesis in NS mergers

r-abundance distributions from hundreds of “mass elements”)



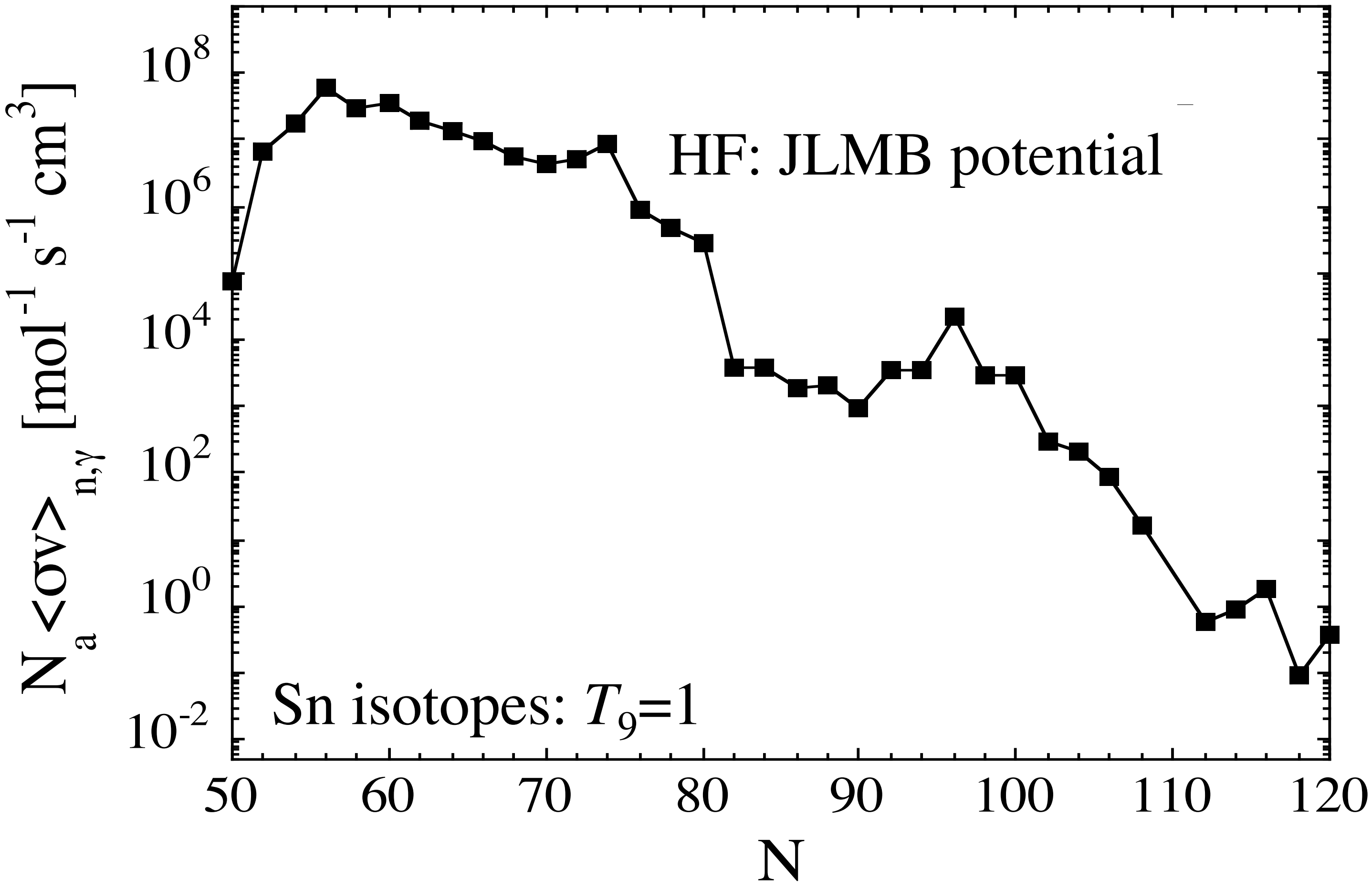
Local differences, but smoothed out by fission recycling and mass-averaging

But
the situation might be more complicated

STILL MANY OPEN QUESTIONS:

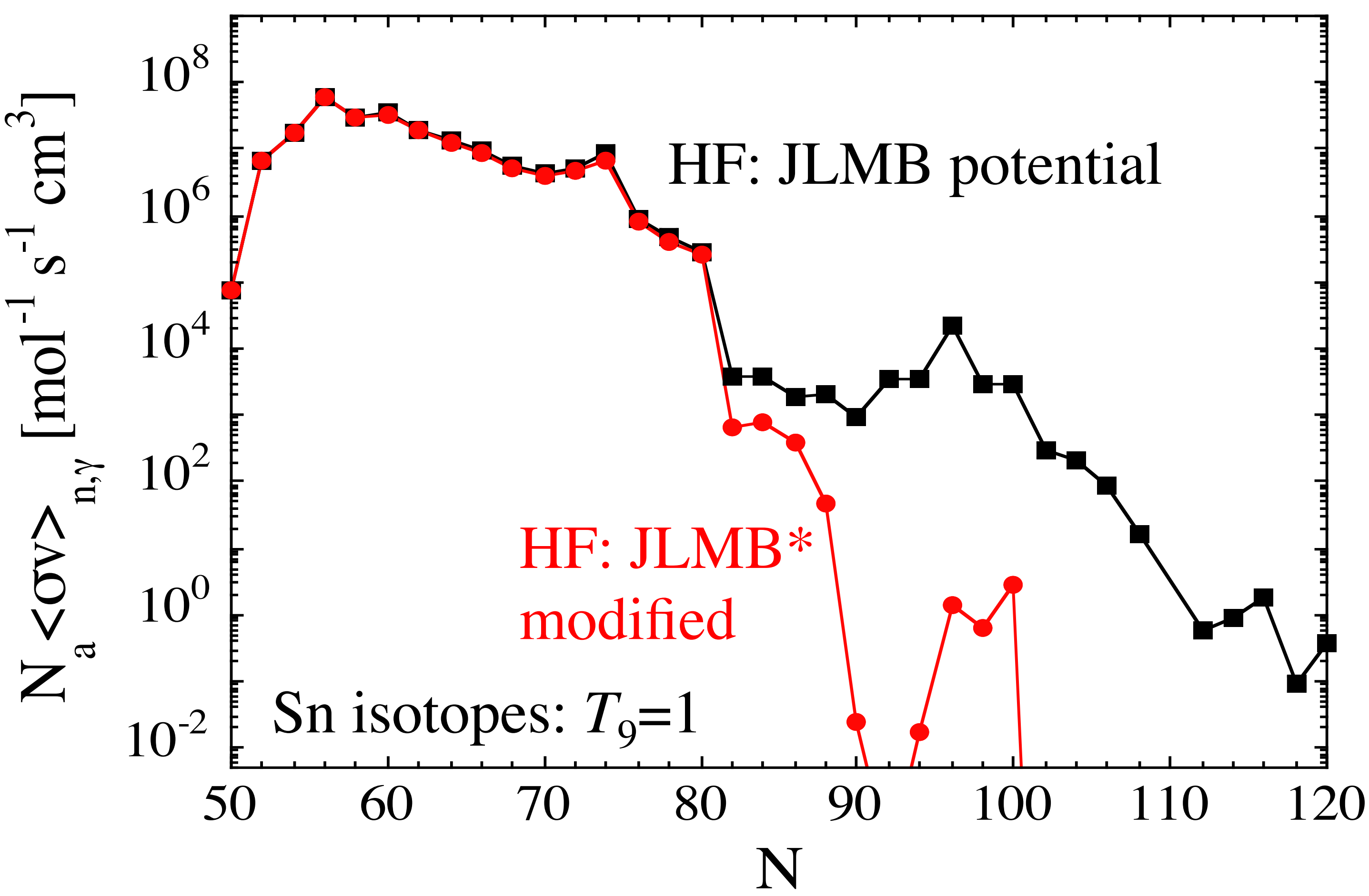
- **The nuclear inputs for exotic n-rich nuclei** (almost no exp. data !)
  - **E1-strength function: GDR tail, PR, ε=0 limit, T-dep**
  - **Nuclear level Densities (at low *E*): J- and π-description, pairing, shell and collective effects**
  - **Optical potential and its isovector component**
- **The reaction model**
  - **Pre-equilibrium effects in the n-rich region**
  - **Direct capture for low-Sn reactions**

Uncertainties in the prediction of (n,γ) rates far away from stability



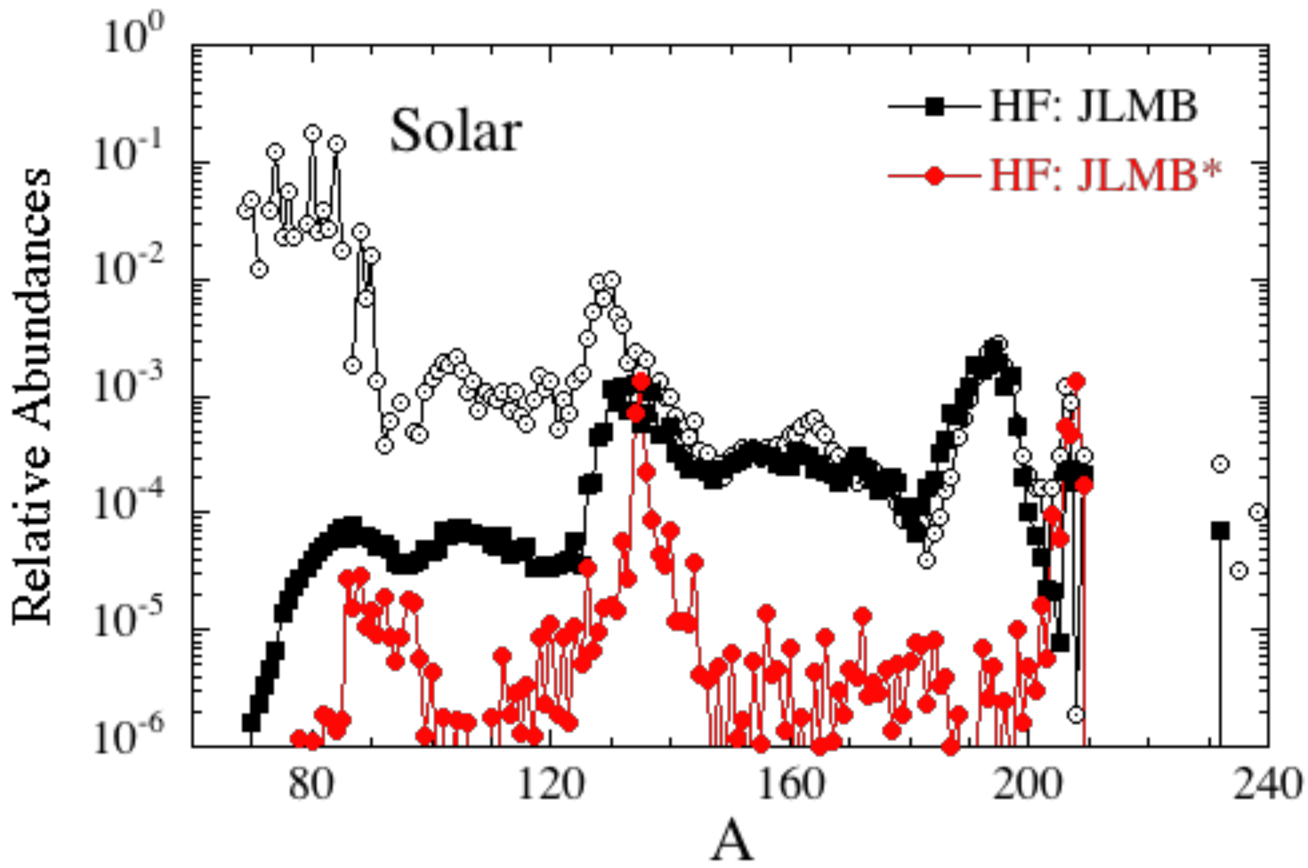
Optical potential: JLM (Jeukenne, Lejeune & Mahaux) – B (Bruyeres-le-Chatel)

JLMB*: modification of the JLMB isovector component of the Imaginary potential to reproduce isospin dependence of the neutron strength data in Sn and Te isotopic chains



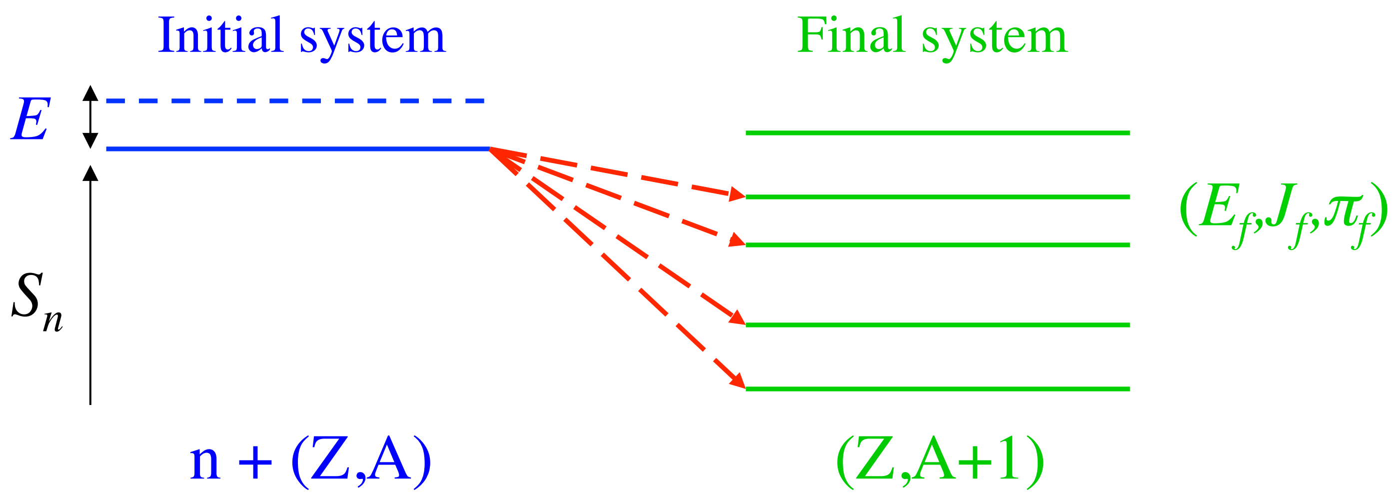
Impact of rates on the r-process nucleosynthesis in NS mergers

r-abundance distributions from **1** typical ejected "mass element"



Direct captures

Direct scatter of incoming neutrons into a bound state without formation of a Compound Nucleus (particularly important for light and low-S_n n-rich nuclei)



Direct capture cross section calculated within the potential model

$$\sigma_f^{DC}(E) = \frac{16\pi}{9\hbar}\, k_\gamma^3\, \bar{e}^2 \; | \, Q^{E1}_{i\rightarrow f}(E) \, |^2 \quad \text{with} \quad Q^{E1}_{i\rightarrow f}(E) = \langle \Psi_f \, | \, T^{E1} \, | \, \Psi_i(E) \rangle$$

→ reliable model, but requires a proper description of

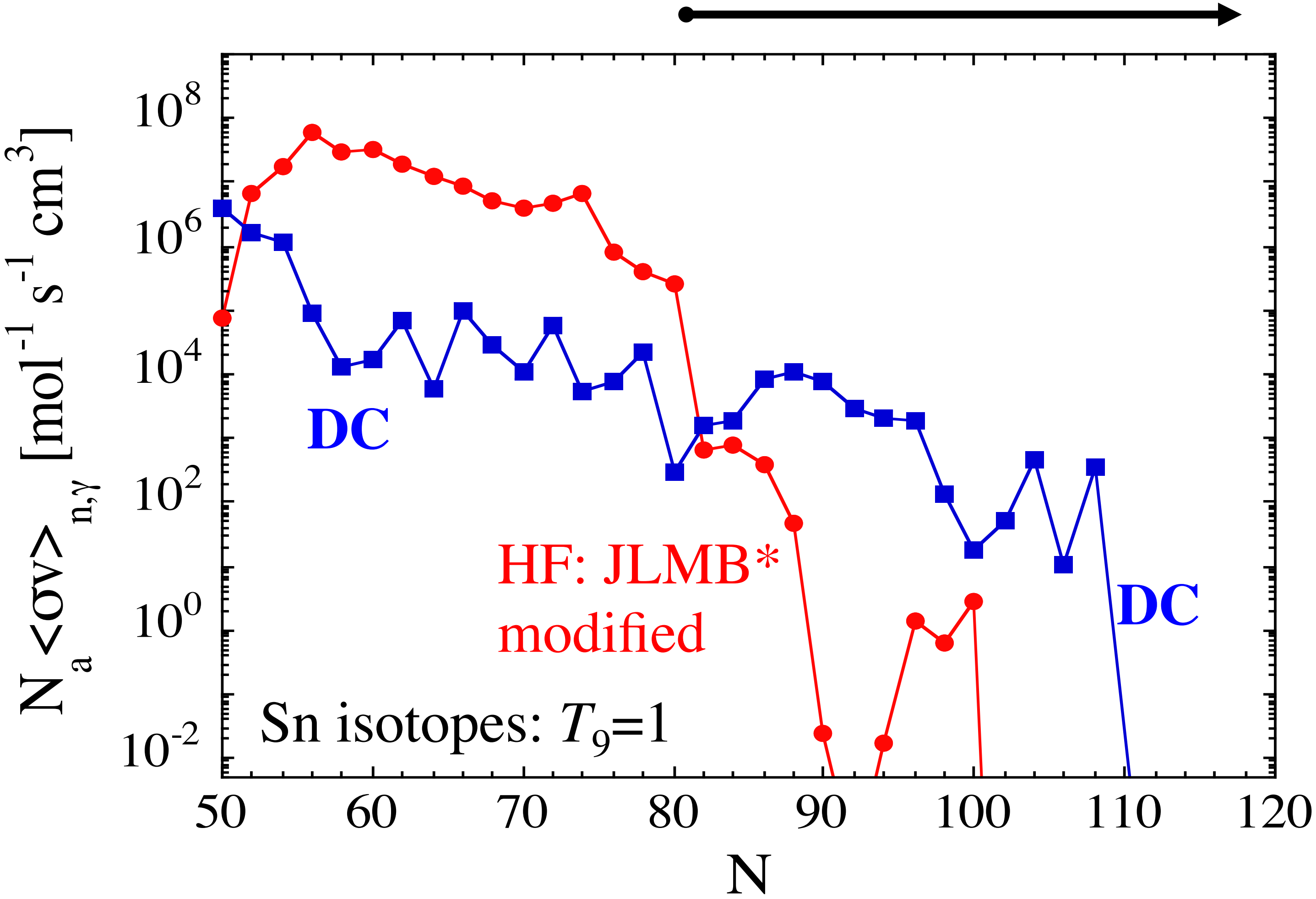
– n-nucleus potential

– excitation spectrum (E_f, J_f, π_f)

– spectroscopic factor C^2S

Lane, Lynn, Satcher, Christy, Duck, Baye, Descouvemont, Mengoni, …

(n,γ) rates essentially given by DC processes



Still many questions regarding the predictions of n-capture by exotic nuclei reliably

Fission and the production of actinides

Fission processes (**spontaneous, β-delayed, neutron-induced**) and fission fragment distribution of relevance (depending on the astrophysical site !?!) for estimating the

- termination point of the r-process (recycling, heating)
- production of Pb-peak elements
- production of radiocosmochronometers (U, Th)
- production of light species (A~110-160) by fission recycling

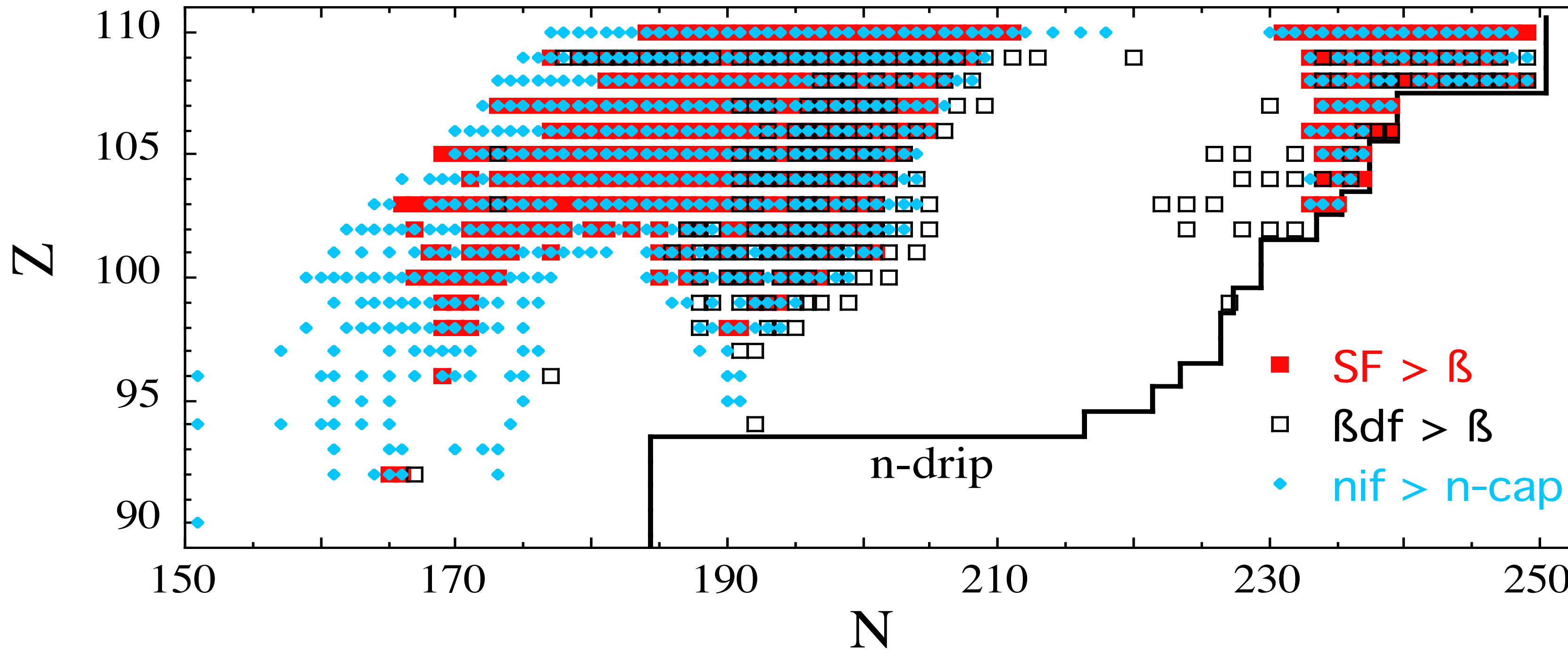
Complicate nuclear physics associated with

- Full Potential Energy Surfaces (fission barriers, saddle points, fission path)
- Nuclear level densities at the saddle points
- Fission fragment distributions

for some 2000 heavy exotic n-rich nuclei with $90 \leq Z \leq 110$

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

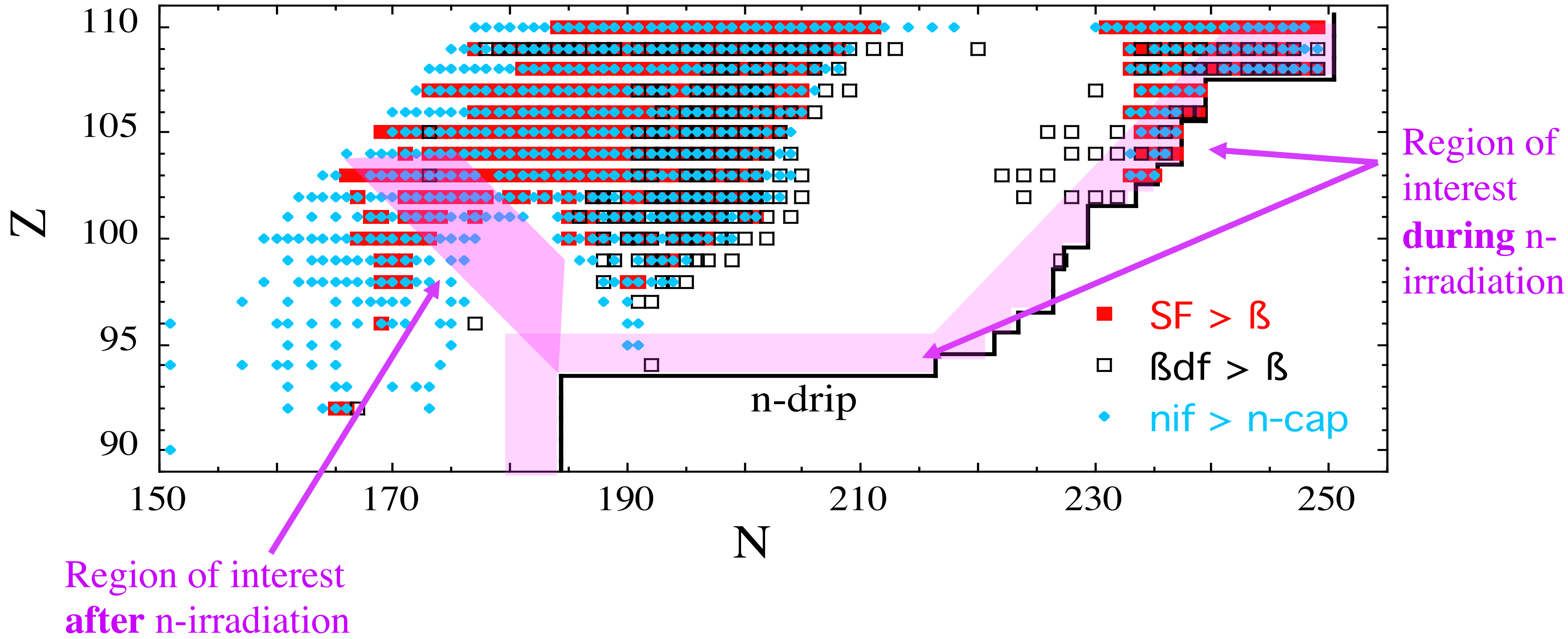
Prediction of fission probabilities



Detailed calculation of fission probabilities (sf, nif, βdf) for about 2000 nuclei (Z≤110)

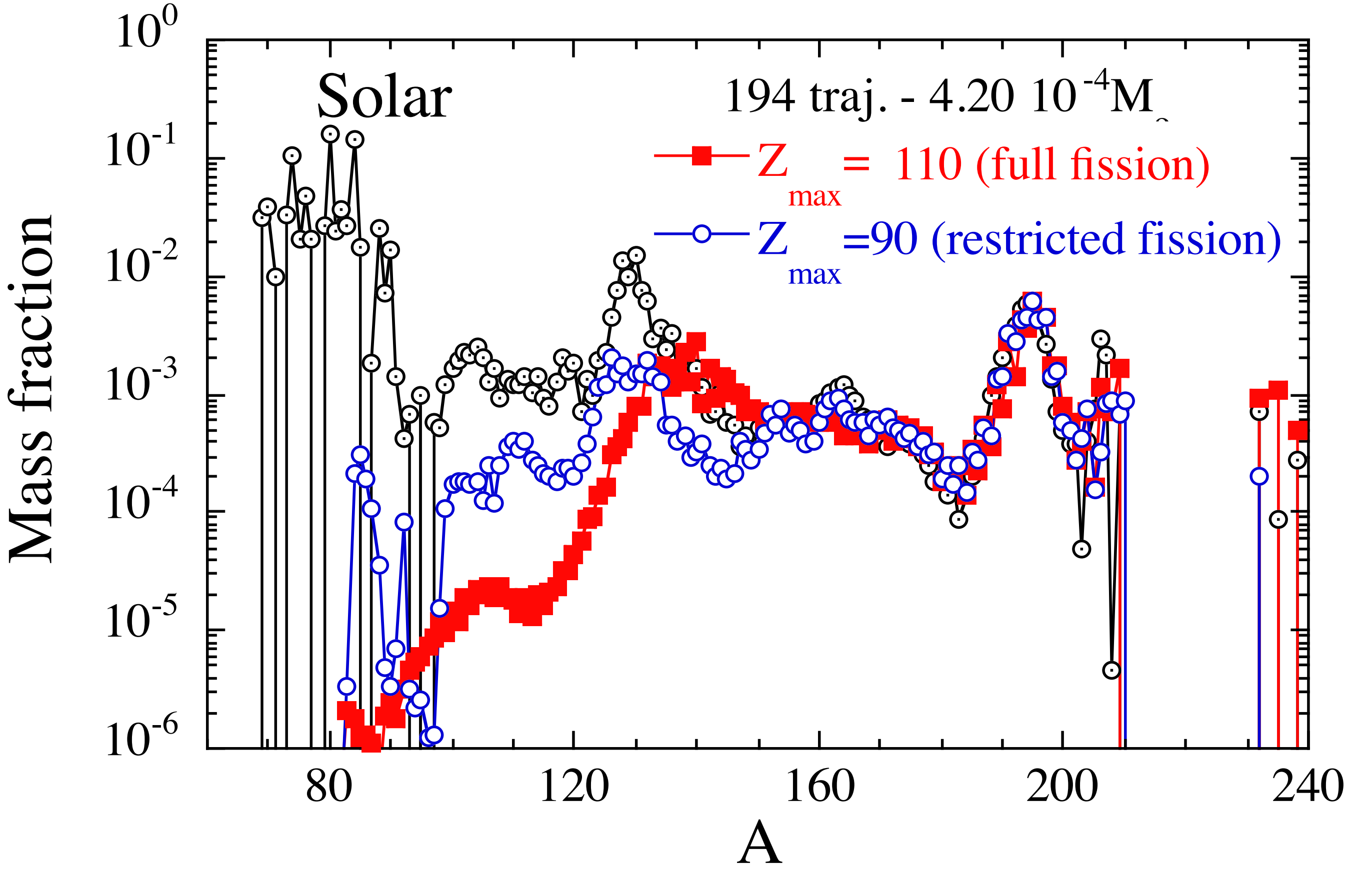
- sf: HFB-14 fission path and barrier penetration (based on TALYS T_f)
- βdf: HFB-14 fission path and GT β-strength function (based on TALYS T_f)
- nif: HFB-14 fission path and NLD included in TALYS
- fission fragment distribution (mass-symmetric or asymmetric ?) … to be followed

Prediction of fission probabilities

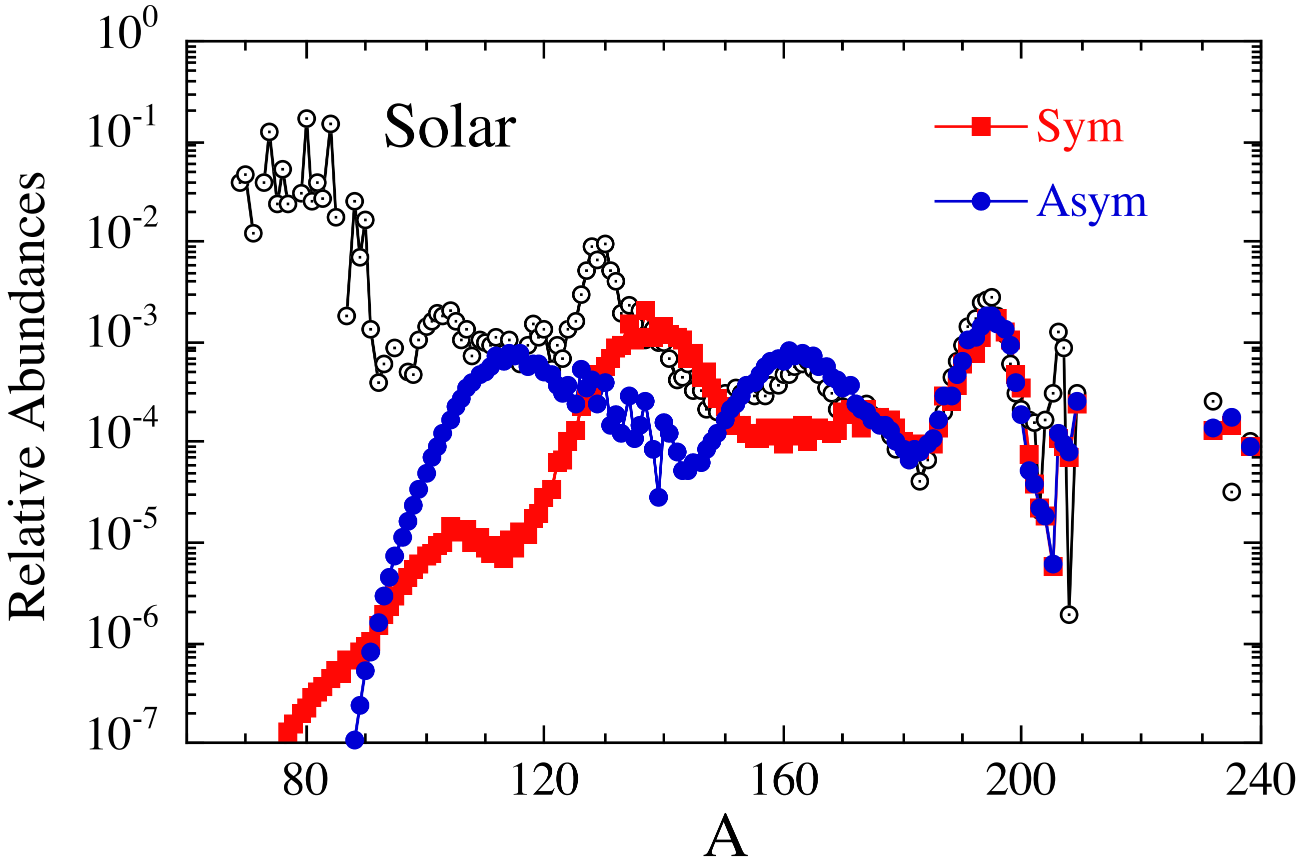


Still many uncertainties affecting the prediction of the input physics necessary to estimate the (sf, βdf, nif) rates & fission fragment distribution

Impact of the fission scheme on the abundance predictions in NS mergers



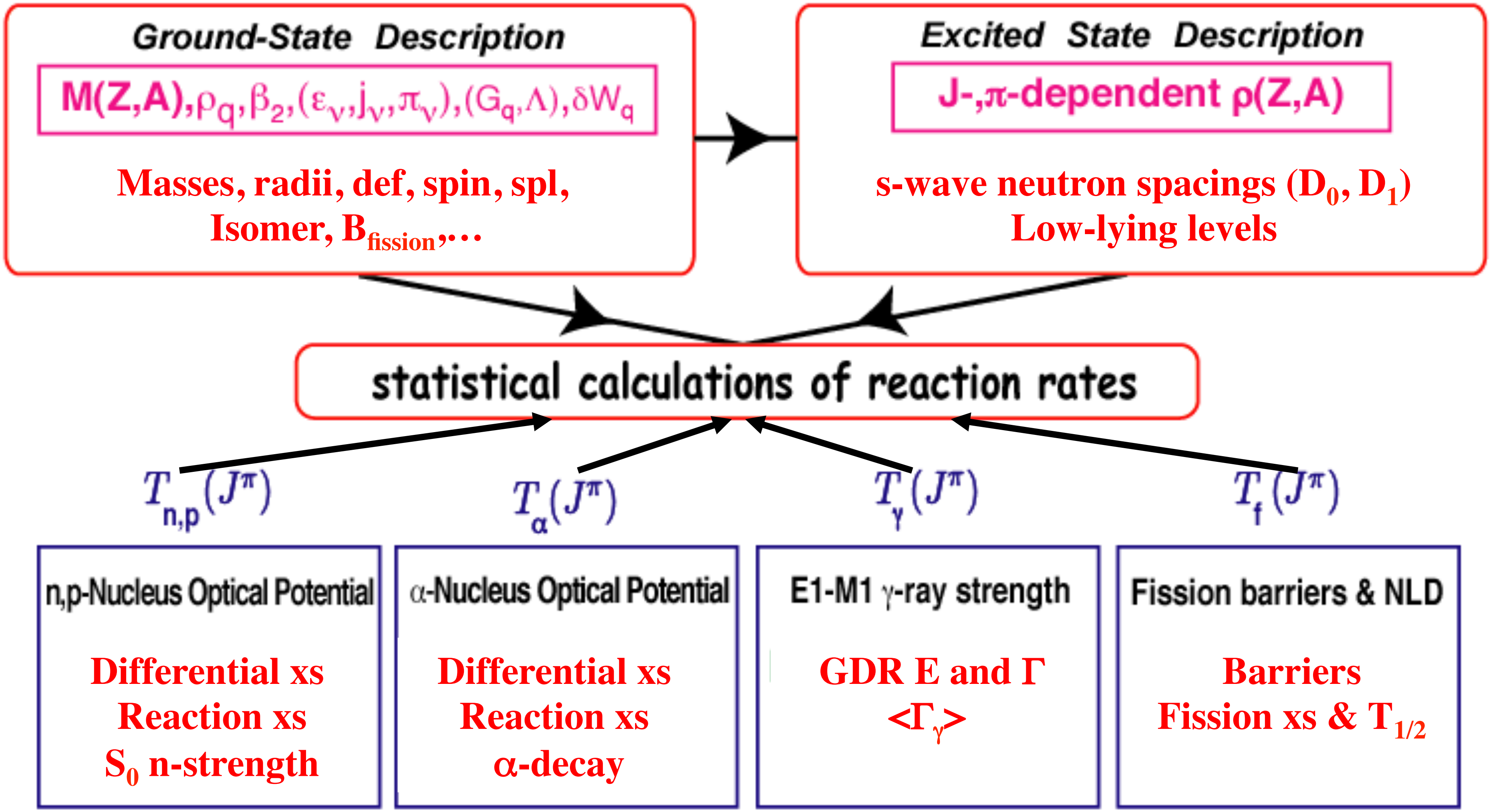
Impact of the fission fragment distribution on the r-process abundances



How can experimental nuclear physics help ?

1) Measurement of given properties for a large set of nuclei:

to constrain global models that should be as “microscopic” as possible



2) Specific measurements to bring insights on a given physical property (or parametrization) that could have a significant impact on the extrapolation of the predictions

(in particular far away from the valley of stability)

Any property that can *potentially* have an impact on the reaction or β-decay rates, hence *potentially* on the r-abundance predictions

- Specific nuclear structure properties (e.g neutron skin, N=82 & 126 shell effects, …)
- Nuclear Level Densities in exotic nuclei
- Dipole strength at low energies (pygmy resonance, $\varepsilon_\gamma=0$ limit)
- Imaginary component of the neutron optical potential for n-rich nuclei
- Pre-equilibrium contribution to the reaction mechanism of exotic n-rich nuclei

Conclusions

A continued effort is required

- **to get experimental data for neutron-rich nuclei to constrain the various input of relevance in the determination of reaction and β-decay rates**
- **to improve, in the framework of "microscopic" models, the predictions of**
  - **nuclear structure properties (masses, deformations, …)**
  - **reaction cross sections (rates) for experimentally unknown nuclei**
    - **Reaction model: equilibrium, pre-equilibrium, Direct Capture**
    - **Nuclear ingredients**
      - **ground state properties**
      - **nuclear level densities & low-lying level scheme**
      - **optical potentials**
      - **γ-ray strength functions**
      - **fission properties**
      - **spectroscopic factors**

We are still not capable of estimating reliably
the radiative neutron capture by exotic neutron-rich nuclei !

Experimental as well as Theoretical works are needed