Nuclear and astrophysics aspects of the heavy elements nucleosynthesis

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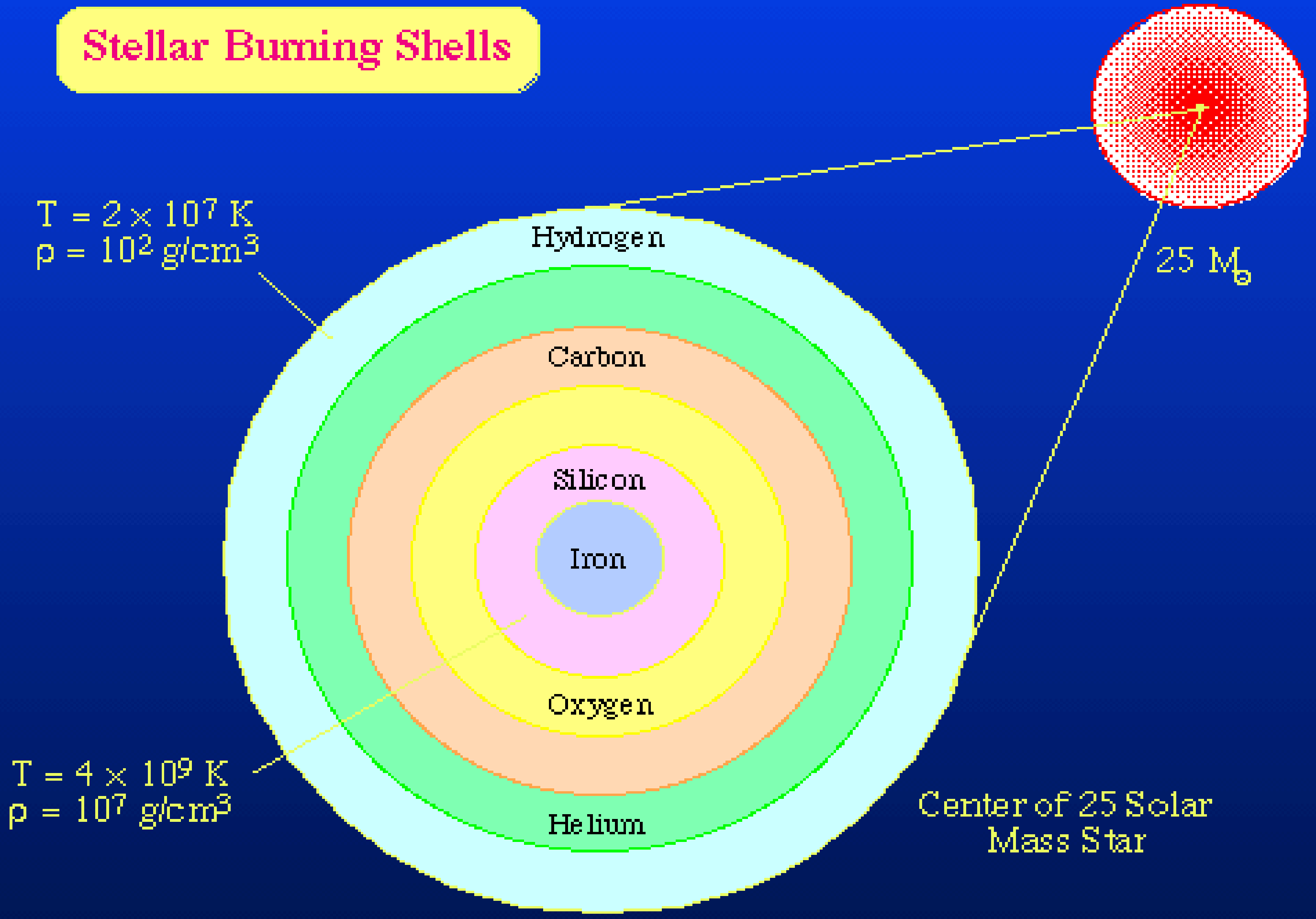
- Introduction
- The s-process nucleosynthesis
- The r-process nucleosynthesis
- The p-process nucleosynthesis

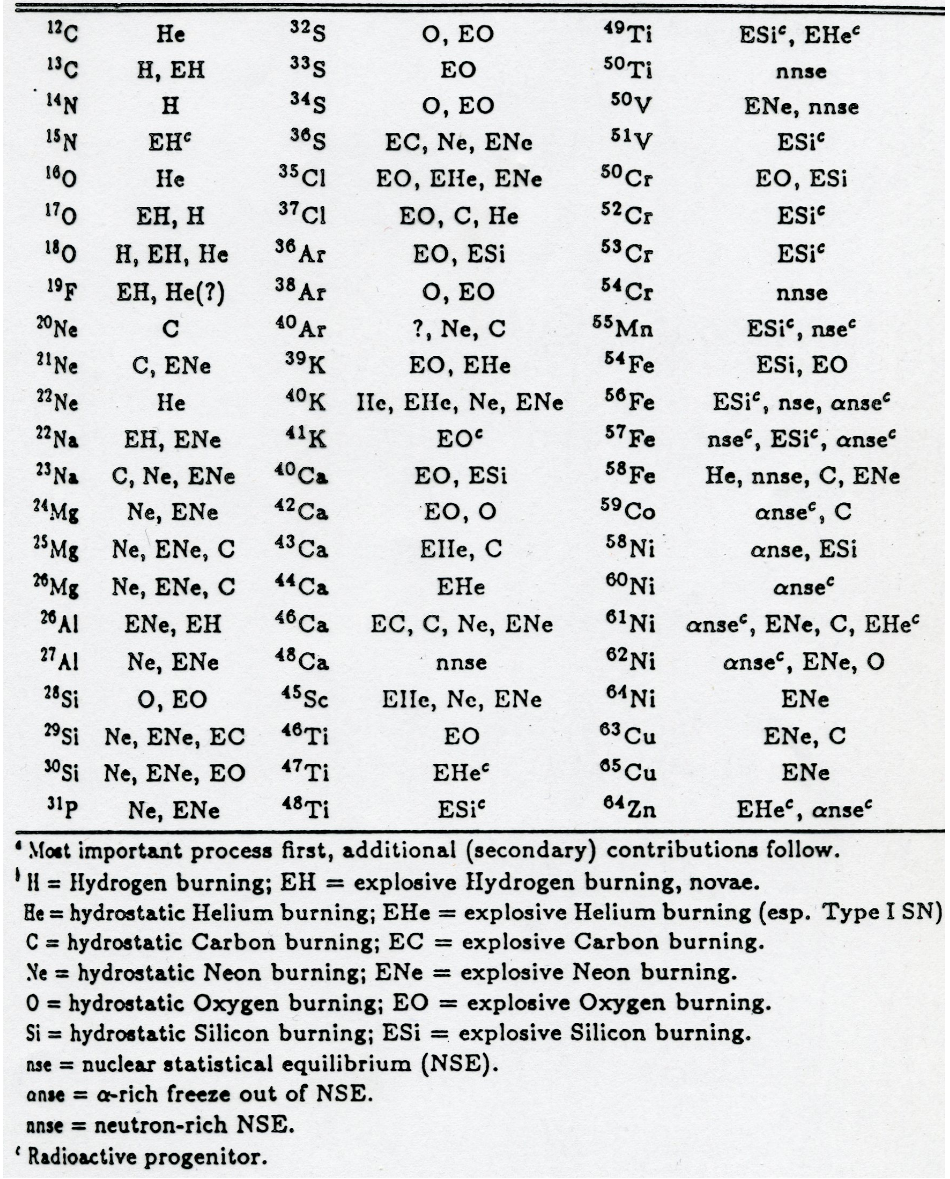
For each process

- – Some astrophysical aspects
- – Some nuclear physics aspects
- – Some observational aspects

Stellar Burning Shells



The different burning phases responsible for the nucleosynthesis of light elements



^{12}C	He	^{32}S	O, EO	^{49}Ti	ESi^c, EHe^c
^{13}C	H, EH	^{33}S	EO	^{50}Ti	nnse
^{14}N	H	^{34}S	O, EO	^{50}V	ENe, nnse
^{15}N	EH^c	^{36}S	EC, Ne, ENe	^{51}V	ESi^c
^{16}O	He	^{35}Cl	EO, EHe, ENe	^{50}Cr	EO, ESi
^{17}O	EH, H	^{37}Cl	EO, C, He	^{52}Cr	ESi^c
^{18}O	H, EH, He	^{36}Ar	EO, ESi	^{53}Cr	ESi^c
^{19}F	EH, He(?)	^{38}Ar	O, EO	^{54}Cr	nnse
^{20}Ne	C	^{40}Ar	?, Ne, C	^{55}Mn	ESi^c, nse^c
^{21}Ne	C, ENe	^{39}K	EO, EHe	^{54}Fe	ESi, EO
^{22}Ne	He	^{40}K	He, EHe, Ne, ENe	^{56}Fe	ESi^c, nse, αnse^c
^{22}Na	EH, ENe	^{41}K	EO^c	^{57}Fe	nse^c, ESi^c, αnse^c
^{23}Na	C, Ne, ENe	^{40}Ca	EO, ESi	^{58}Fe	He, nnse, C, ENe
^{24}Mg	Ne, ENe	^{42}Ca	EO, O	^{59}Co	αnse^c, C
^{25}Mg	Ne, ENe, C	^{43}Ca	EHe, C	^{58}Ni	αnse, ESi
^{26}Mg	Ne, ENe, C	^{44}Ca	EHe	^{60}Ni	αnse^c
^{26}Al	ENe, EH	^{46}Ca	EC, C, Ne, ENe	^{61}Ni	αnse^c, ENe, C, EHe^c
^{27}Al	Ne, ENe	^{48}Ca	nnse	^{62}Ni	αnse^c, ENe, O
^{28}Si	O, EO	^{45}Sc	EHe, Ne, ENe	^{64}Ni	ENe
^{29}Si	Ne, ENe, EC	^{46}Ti	EO	^{63}Cu	ENe, C
^{30}Si	Ne, ENe, EO	^{47}Ti	EHe^c	^{65}Cu	ENe
^{31}P	Ne, ENe	^{48}Ti	ESi^c	^{64}Zn	EHe^c, αnse^c

[a] Most important process first, additional (secondary) contributions follow.

[b] H = Hydrogen burning; EH = explosive Hydrogen burning, novae.
He = hydrostatic Helium burning; EHe = explosive Helium burning (esp. Type I SN)
C = hydrostatic Carbon burning; EC = explosive Carbon burning.
Ne = hydrostatic Neon burning; ENe = explosive Neon burning.
O = hydrostatic Oxygen burning; EO = explosive Oxygen burning.
Si = hydrostatic Silicon burning; ESi = explosive Silicon burning.
nse = nuclear statistical equilibrium (NSE).
αnse = α-rich freeze out of NSE.
nnse = neutron-rich NSE.

[c] Radioactive progenitor.

from ^{12}C to Fe-group nuclei

H = Hydrostatic H-burning
EH = Explosive H-burning
He = Hydrostatic He-burning
EHe = Explosive He-burning
C = Hydrostatic C-burning
EC = Explosive C-burning
Ne = Hydrostatic Ne-burning
ENe = Explosive Ne-burning
O = Hydrostatic O-burning
EO = Explosive O-burning
Si = Hydrostatic Si-burning
ESi = Explosive Si-burning
NSE = Nuclear Statistical Equilibrium

The production of elements heavier than iron

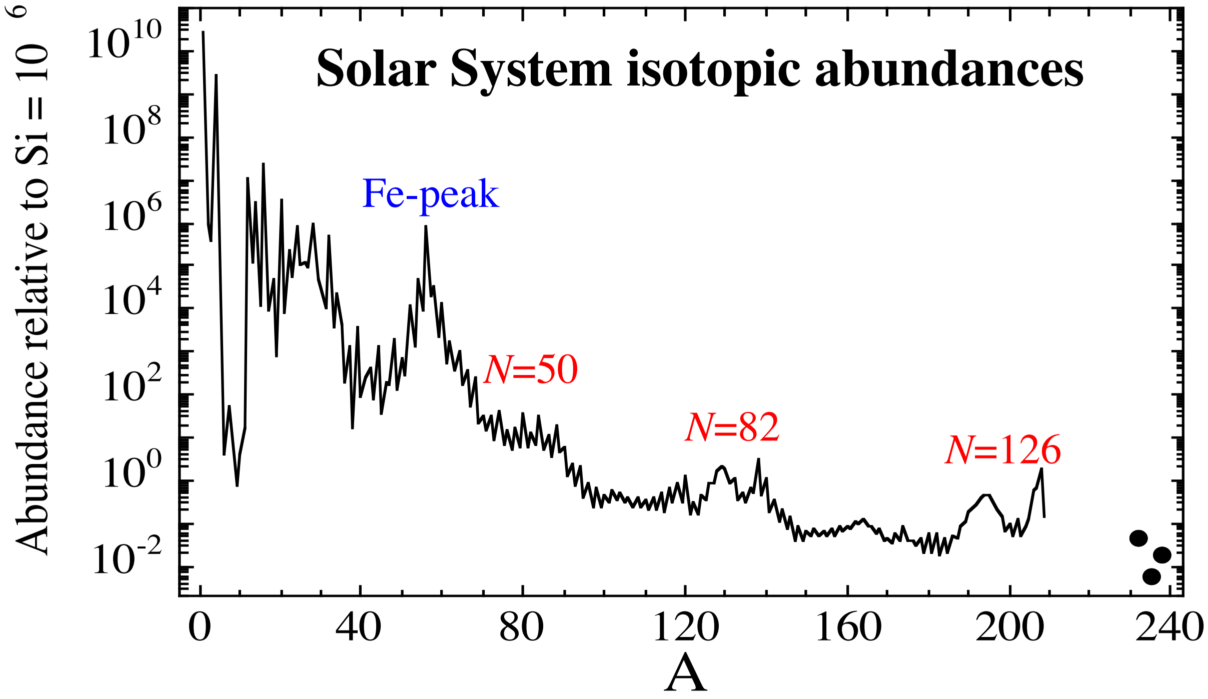
The concept of synthesis by neutron captures

$\tau_p(A>56)$ & $\tau_\alpha(A>56)$ >>> typical evolution lifetime of a star

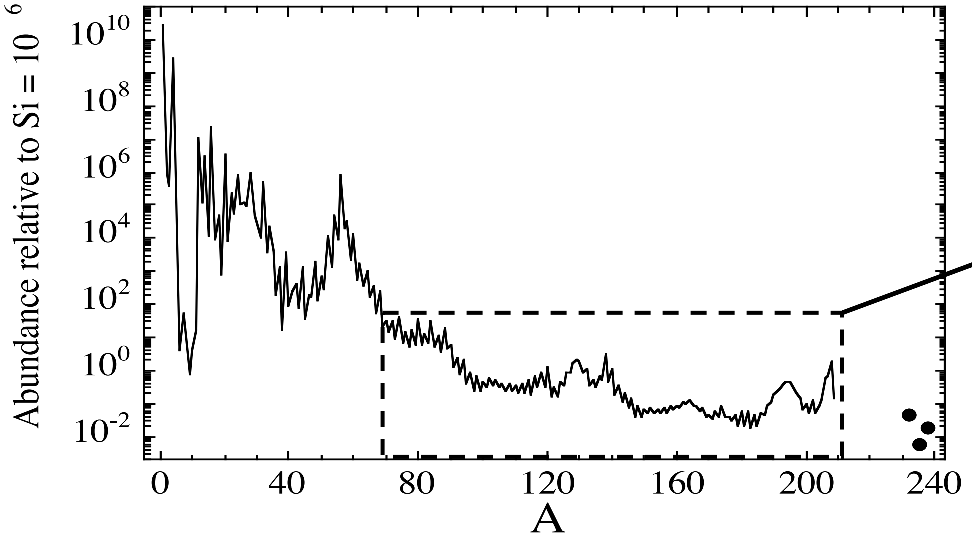
→ Charged-particle captures are inefficient to produce the bulk galactic $A > 56$ nuclei

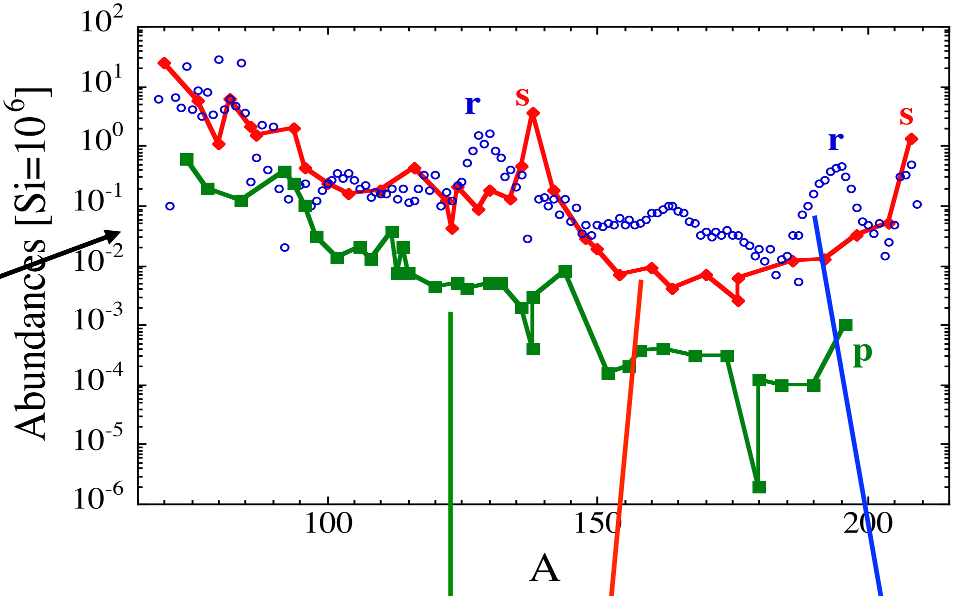
→ **Consider NEUTRONS instead !**

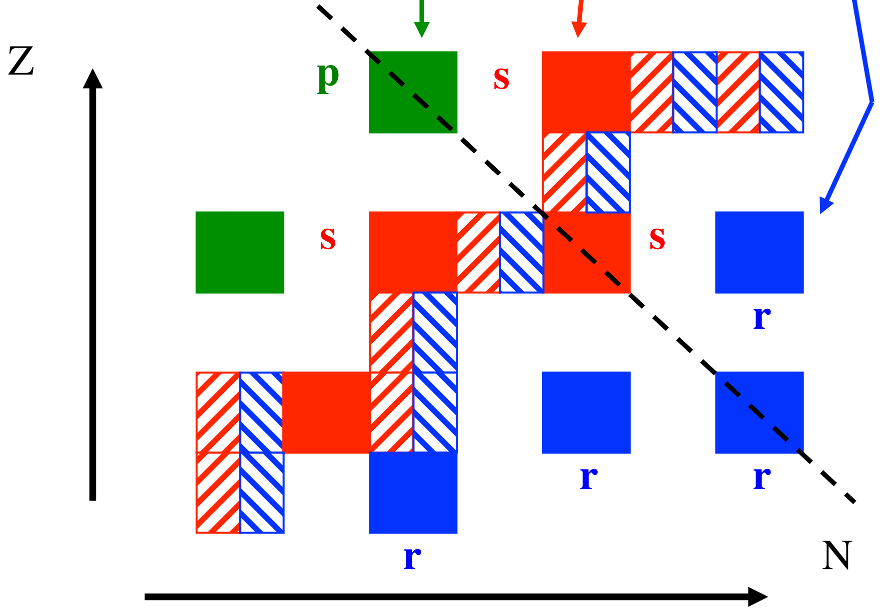
- **No coulomb barrier**
- **Natural explanation for the peaks observed in the solar system abundances at neutron magic numbers *N*=50, 82 and 126**



Decomposition of the solar abundances



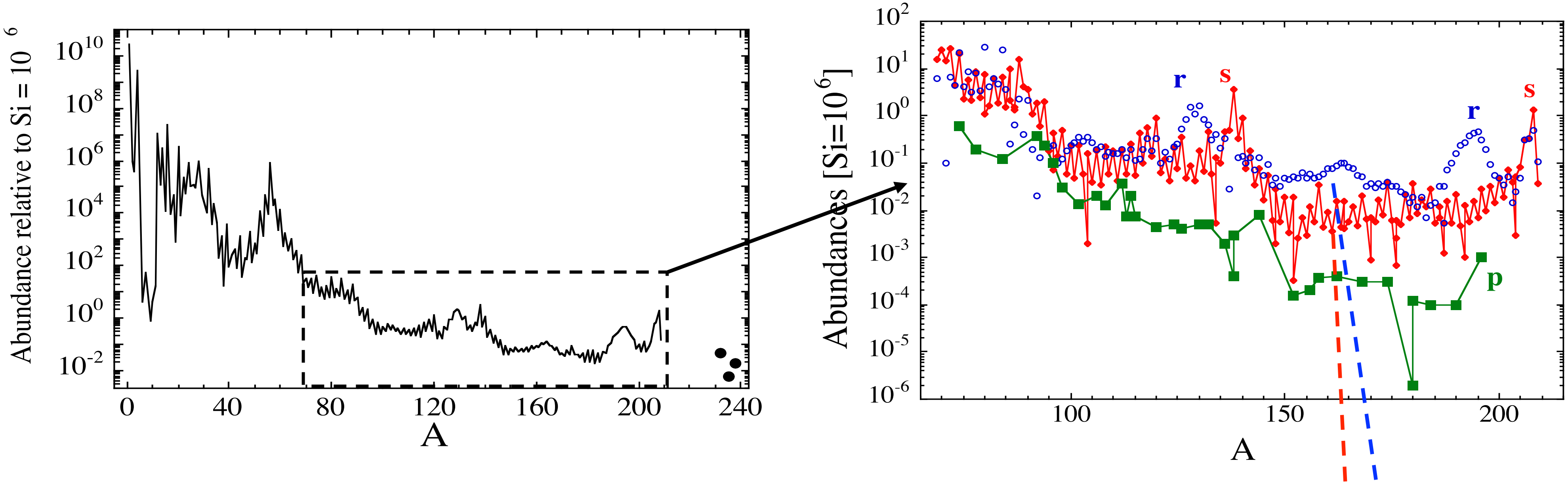


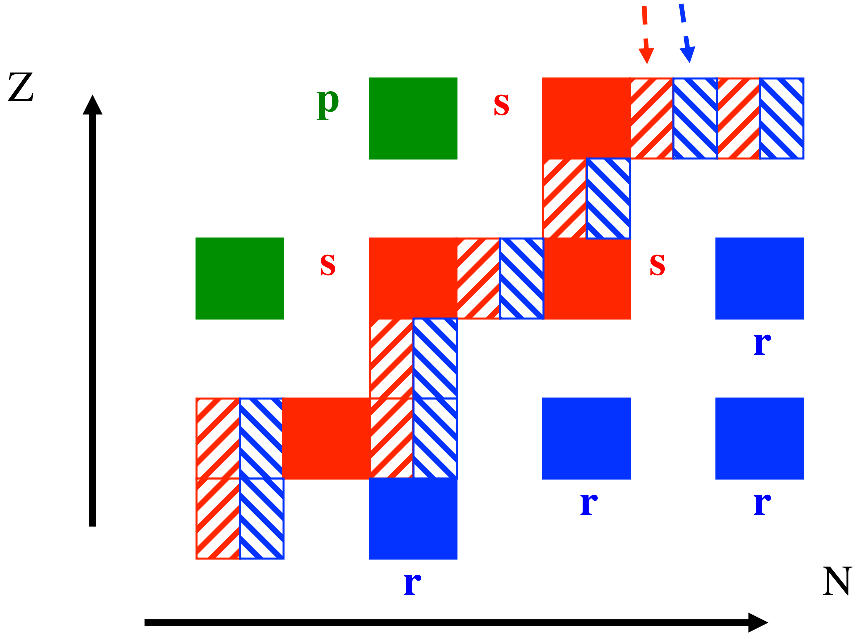


Separation of the stable nuclei into

- **Proton-rich isobars: p-nuclei**
- **Isobars at the bottom of the valley of β-stability: s-nuclei**
- **Neutron-rich isobars: r-nuclei**

Decomposition of the solar abundances





Separation of the stable nuclei into

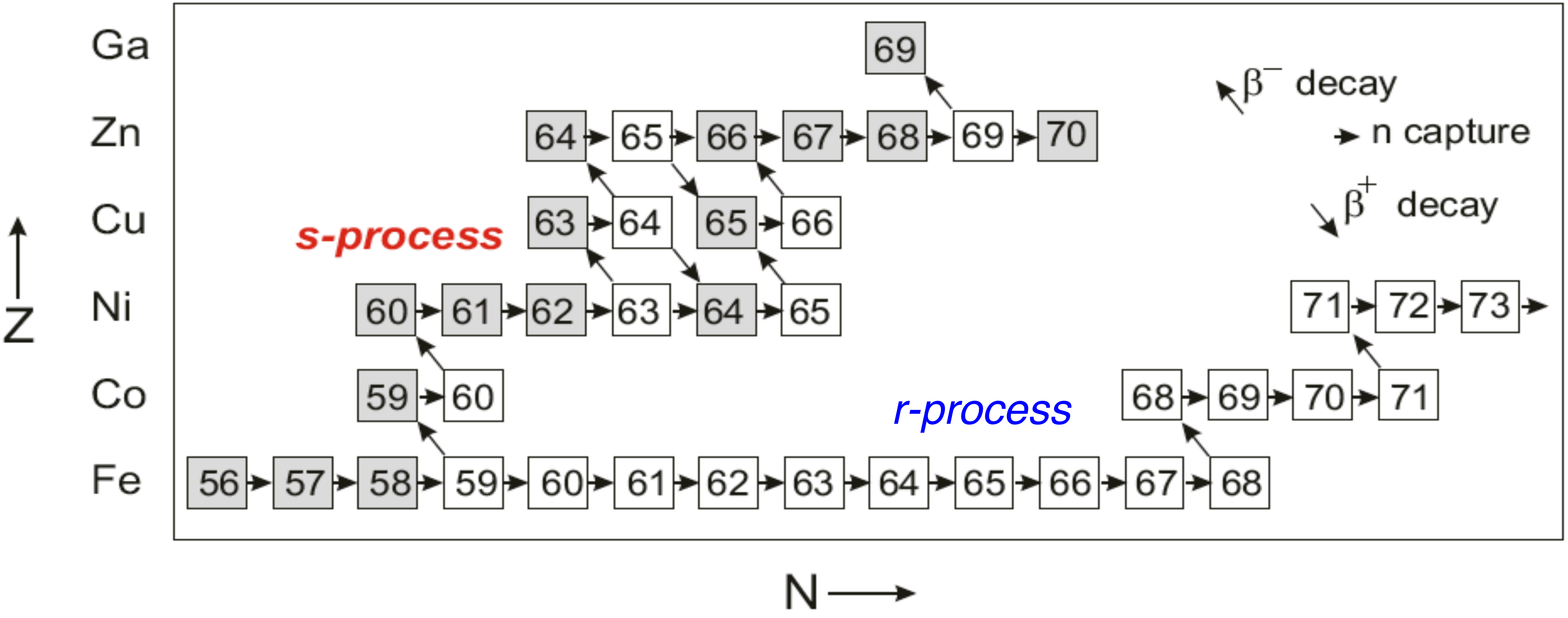
- **Proton-rich isobars: p-nuclei**
- **Isobars at the bottom of the valley of β-stability: s-nuclei**
- **Neutron-rich isobars: r-nuclei**

A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta << \tau_n$

Rapid neutron-capture process: $\tau_\beta >> \tau_n$

τ_n = lifetime against neutron capture
τ_β = lifetime against β⁻ decay



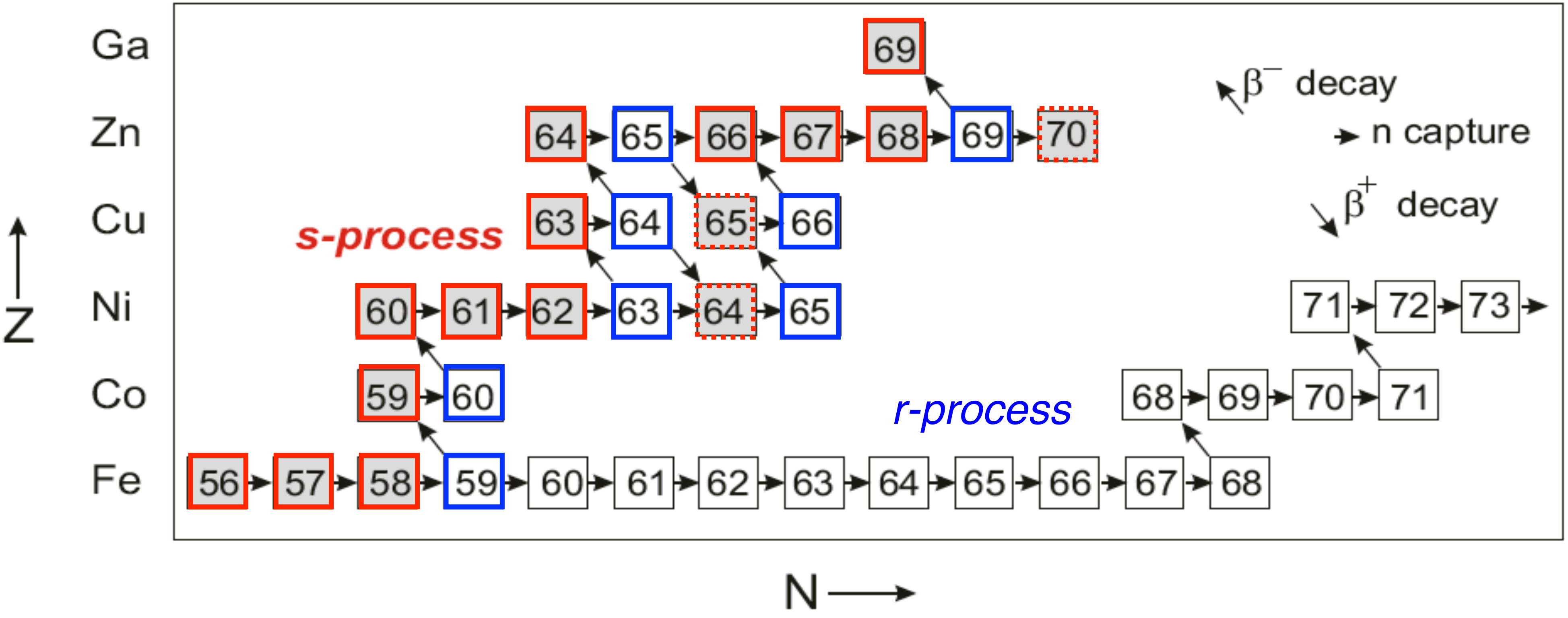
A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta << \tau_n$

$N_n \sim 10^7\text{-}10^{11}$ cm^{-3} $T \sim 1\text{-}3\ 10^8$K $t_{irr} \sim 10\text{-}10^4$yr

τ_n = lifetime against neutron capture

τ_β = lifetime against β^- decay



A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta \ll \tau_n$

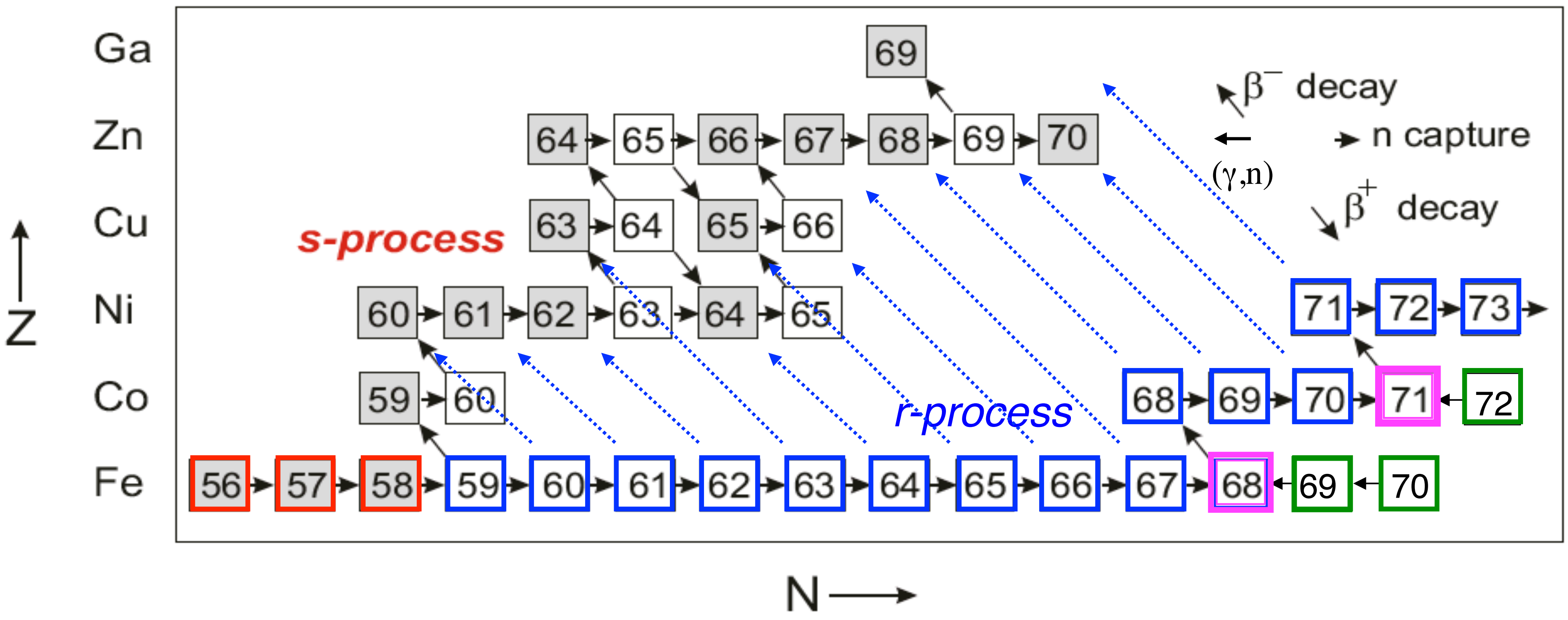
$N_n \sim 10^7\text{-}10^{11}\ \mathrm{cm}^{-3}$ $T \sim 1\text{-}3\ 10^8\,\mathrm{K}$ $t_{irr} \sim 10\text{-}10^4\,\mathrm{yr}$

Rapid neutron-capture process: $\tau_\beta \gg \tau_n$

$N_n \gg 10^{20}\ \mathrm{cm}^{-3}$ $T \sim 10^9\,\mathrm{K}$ $t_{irr} \sim 1\,\mathrm{s}$

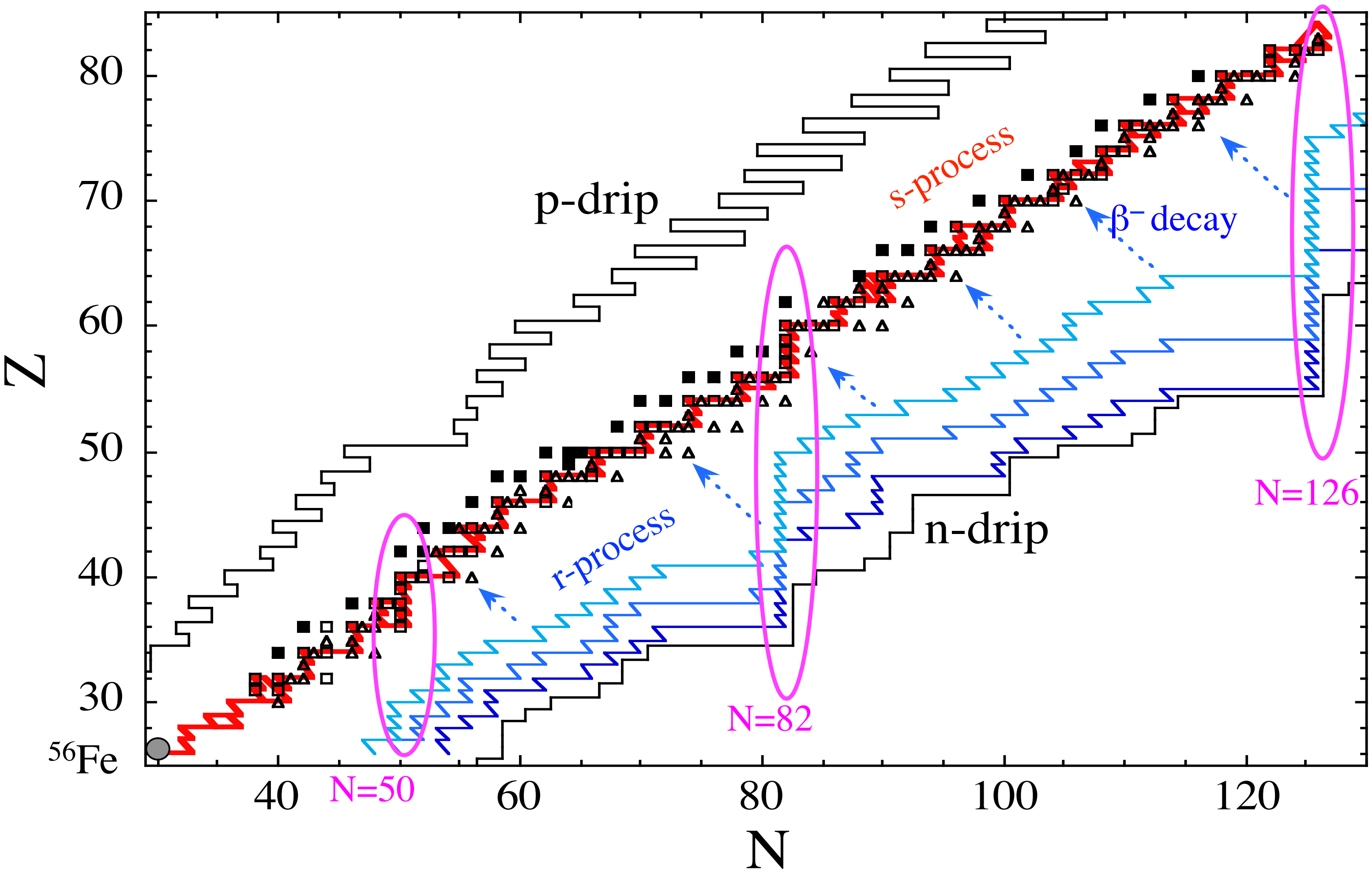
τ_n = lifetime against neutron capture

τ_β = lifetime against β⁻ decay

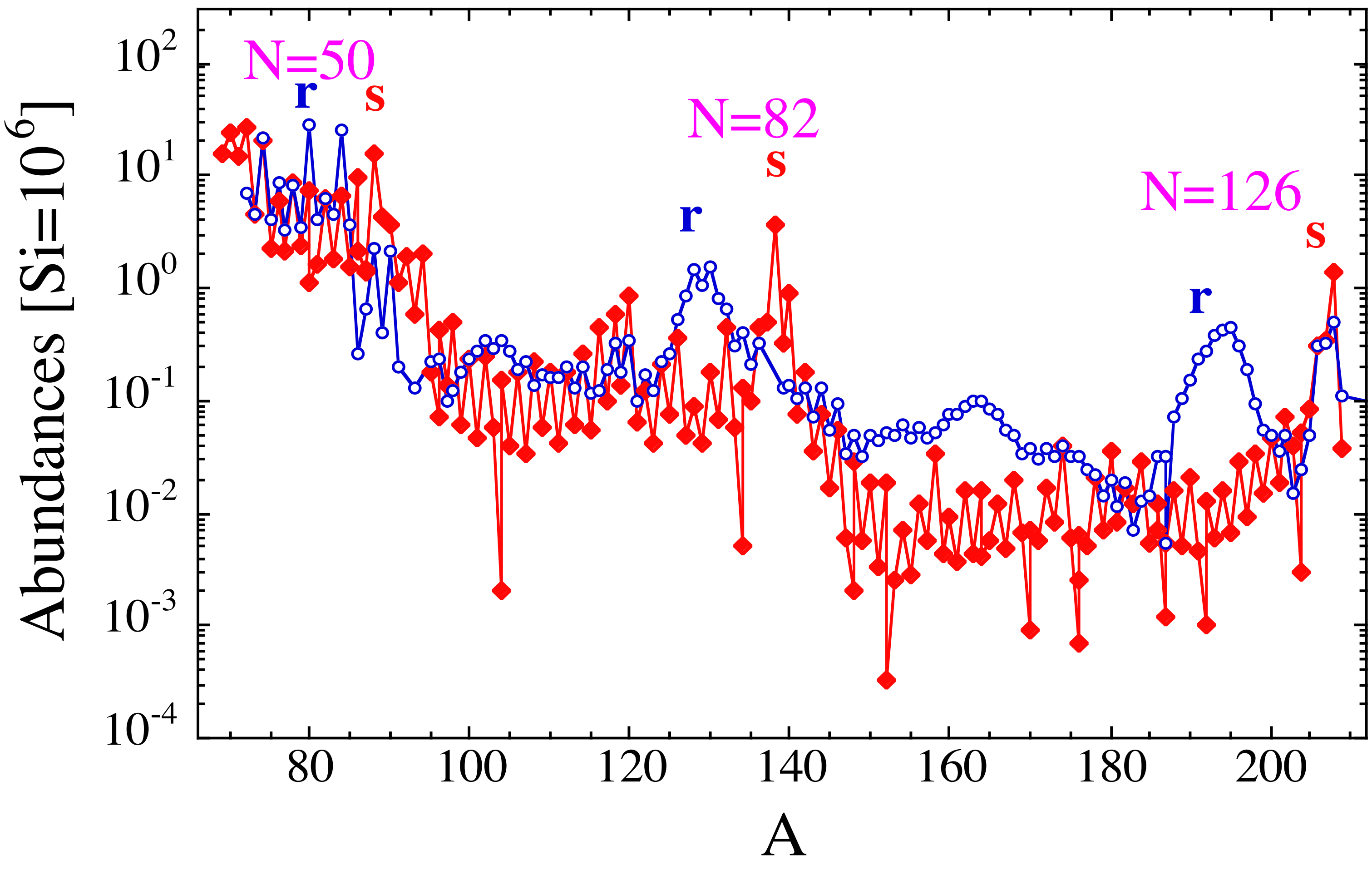


A schematic representation of the s- and r-processes

Closed shells at magic numbers N=50, 82, 126 --> slow n-capture



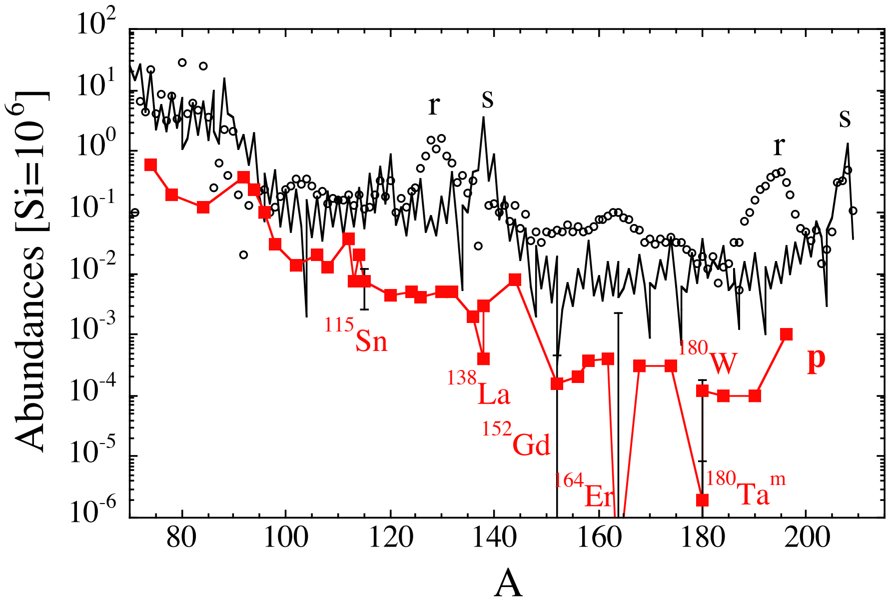
The signature of nuclear properties in the double-peak pattern of the solar abundance distribution

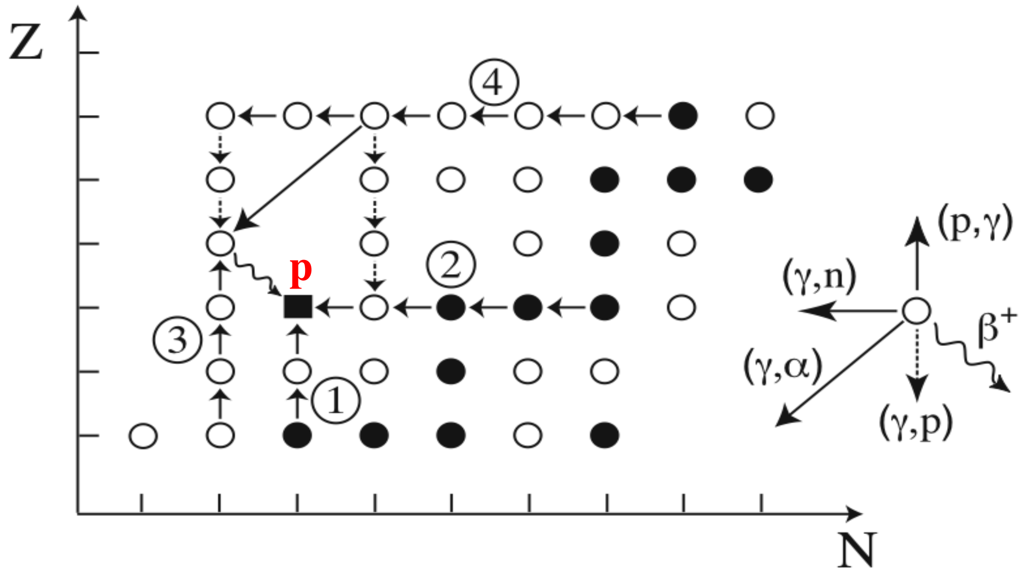


The nature of the p-process nucleosynthesis

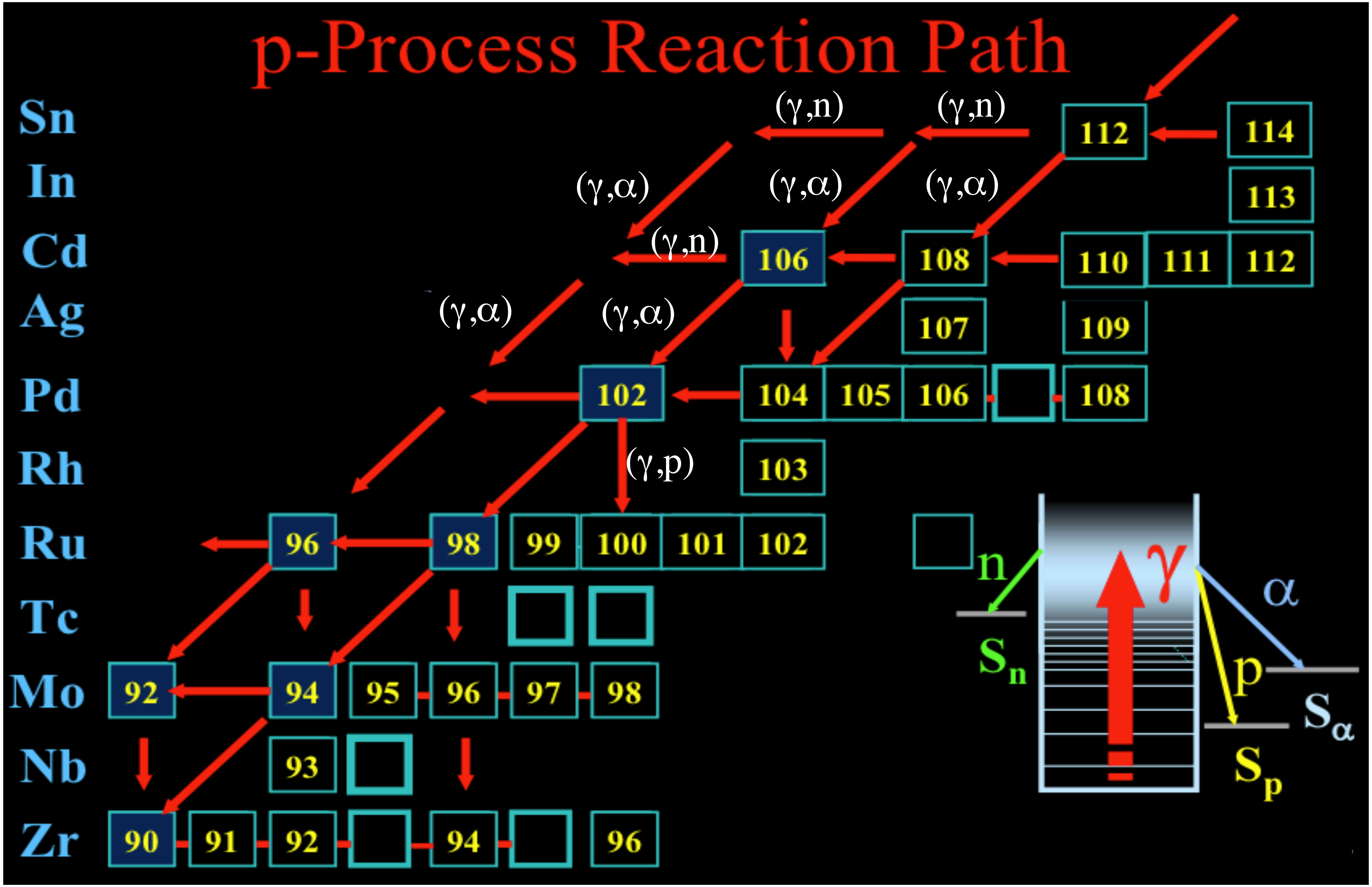
1. *Production of heavy seed nuclei* (s- and r-processes) in previous star generations. In particular the s-process during core He-burning leading to an increase of $70 \leq A \leq 90$ s-elements.
2. *Heating of the s-enriched and r-seeds* at a temperature of T=2-3 10^9 K for a few seconds leading to the photodissociation of the s- and r-nuclei into p-nuclei by (γ,n), (γ,p) and (γ,α) reactions. In some proton-rich environments, proton captures can be envisioned as contributing to the production of p-nuclei (but generally protons are absent in these environments).

p-nuclei are about 10 to 100 times less abundant than s and r-nuclei in the solar system

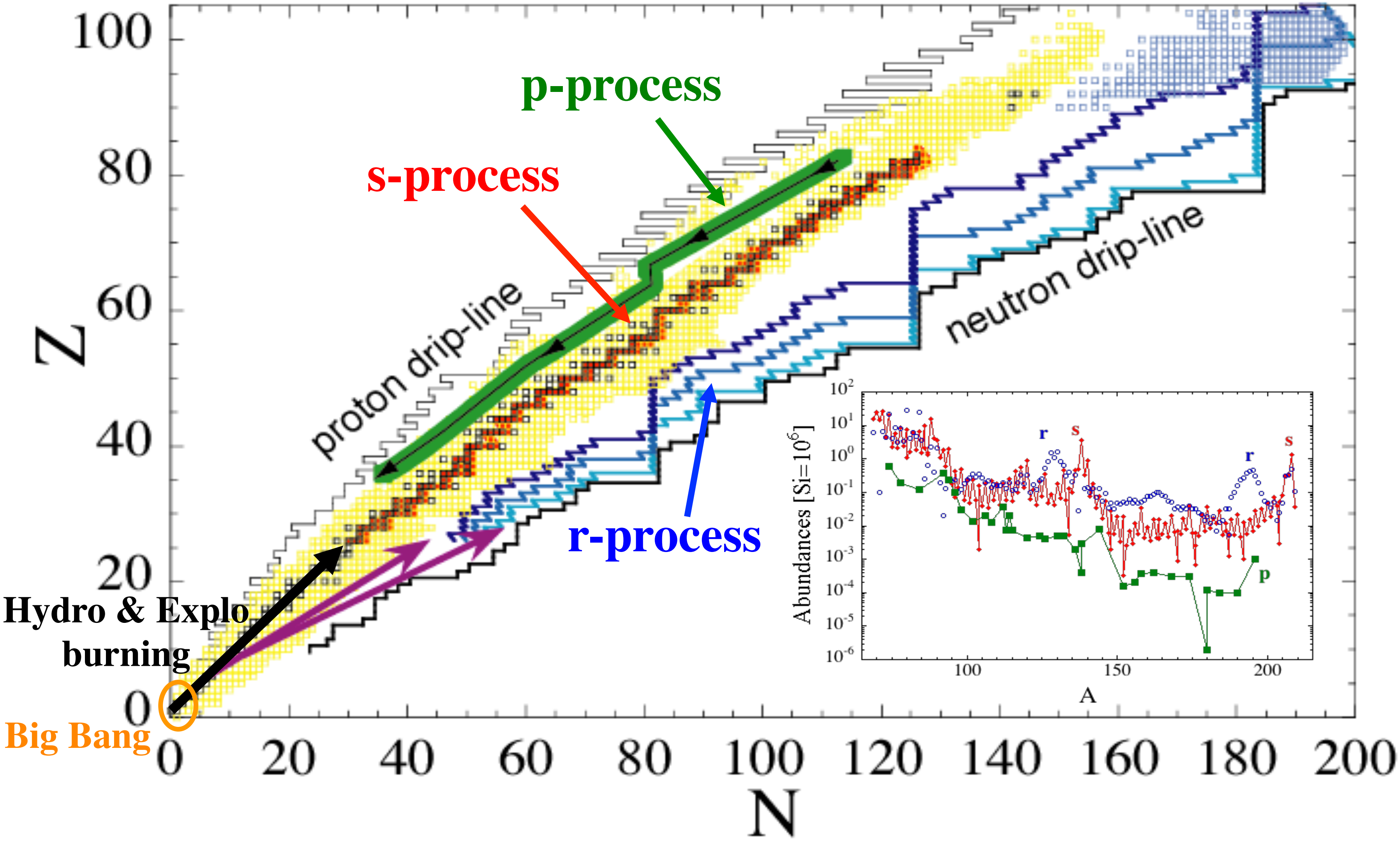




A schematic representation of the p-processes



The various nucleosynthesis processes



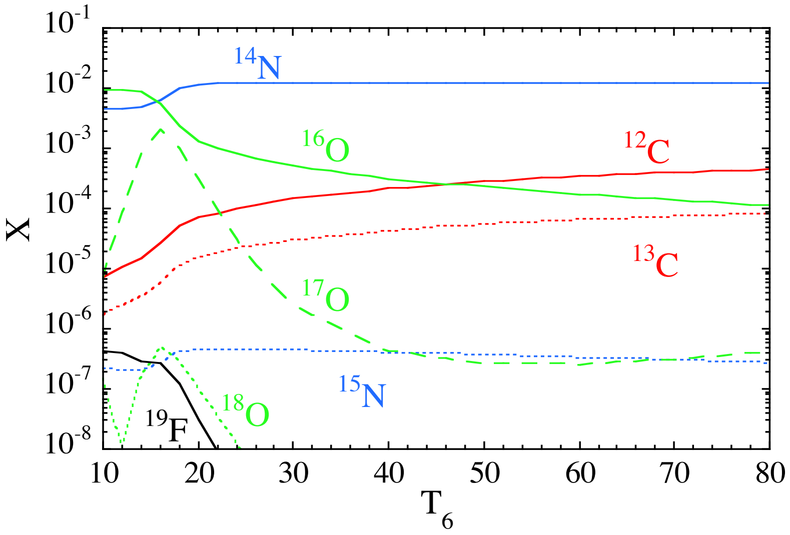
The s-process nucleosynthesis

The astrophysical sites of the s-process nucleosynthesis

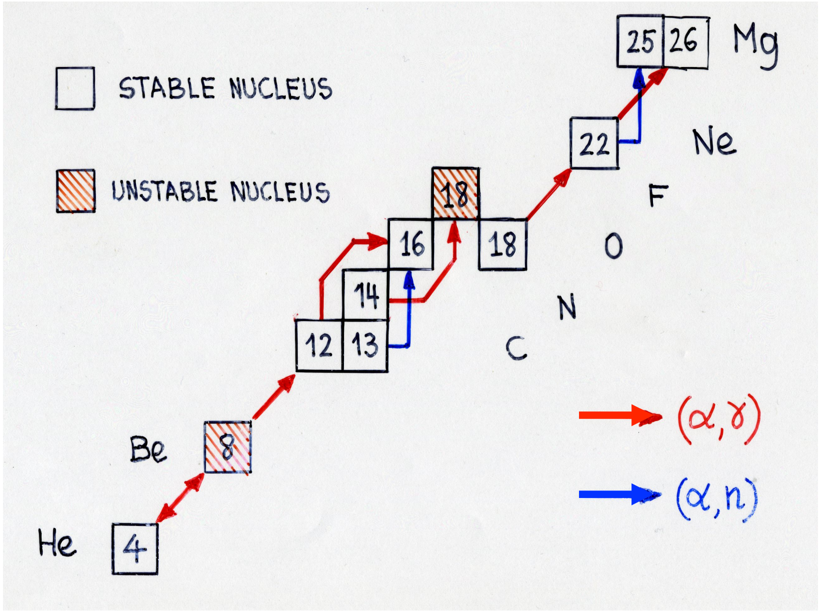
Two major neutron sources can easily be identified: $^{13}C(\alpha,n)^{16}O$ & $^{22}Ne(\alpha,n)^{25}Mg$

Still it requires

- a large seed abundance of ^{13}C or ^{22}Ne (but also He)
- thermodynamic conditions favourable to the He-burning



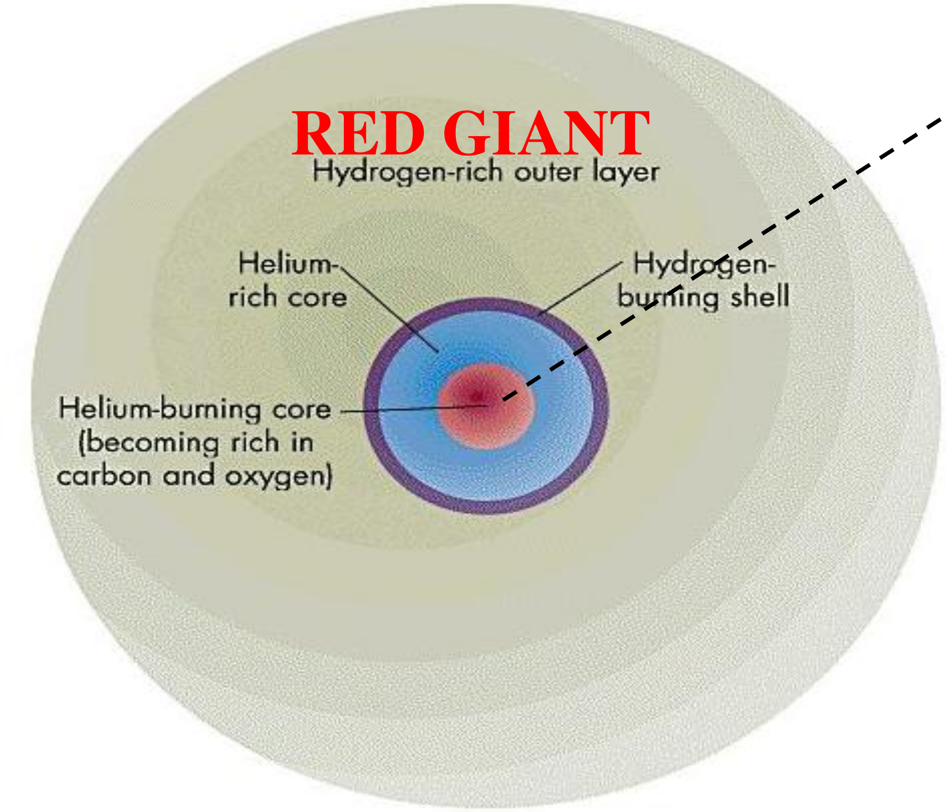
- The ^{13}C source burns rapidly (T~10^8K) but ^{13}C is not abundantly produced during H-burning (CNO cycle leads to an equilibrium abundance of about 10^{-4} – 10^{-5}) and ^{14}N poison is most of the time present !



- The ^{22}Ne source can be relatively abundant during He-burning (^{14}N is highly produced by CNO cycle), but $^{22}Ne(\alpha,n)$ requires high temperatures (T_8>3) at which the 3α reaction may totally exhaust He.

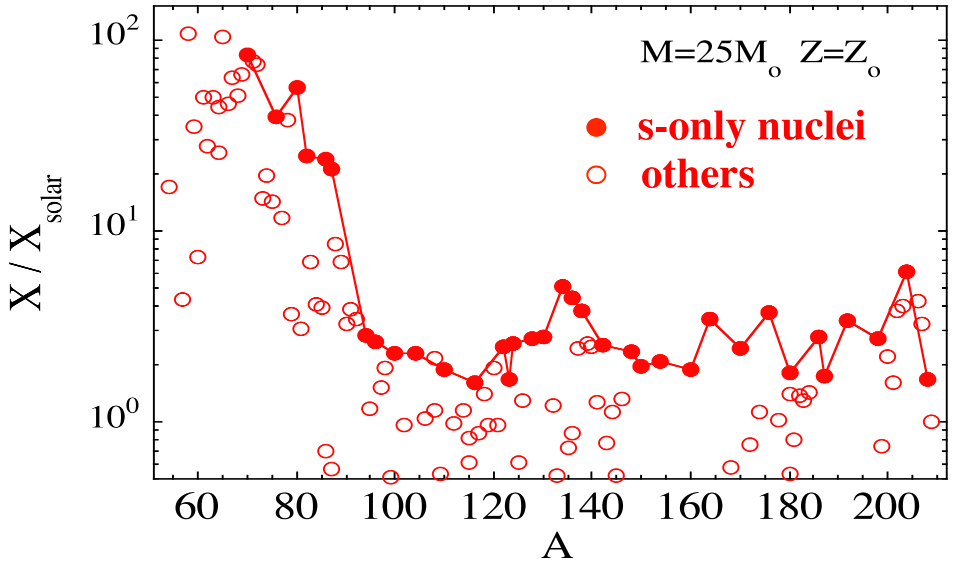
The s-process in massive stars: the weak component

^{14}N seed nuclei is transformed into ^{22}Ne by $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne$



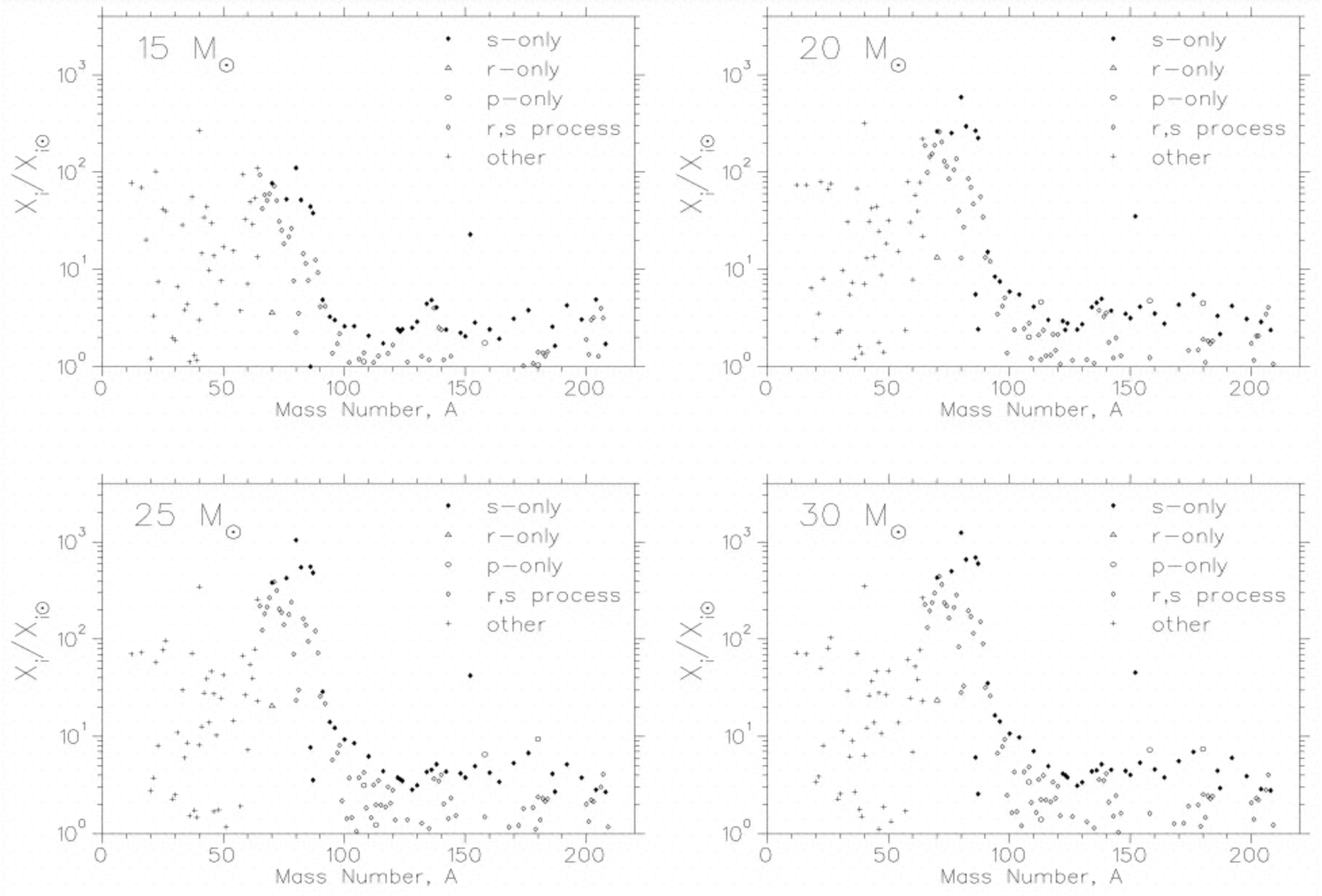
s-process during core He-burning by $^{22}Ne(\alpha,n)^{25}Mg$

→ enrichment in $70 \leq A \leq 90$



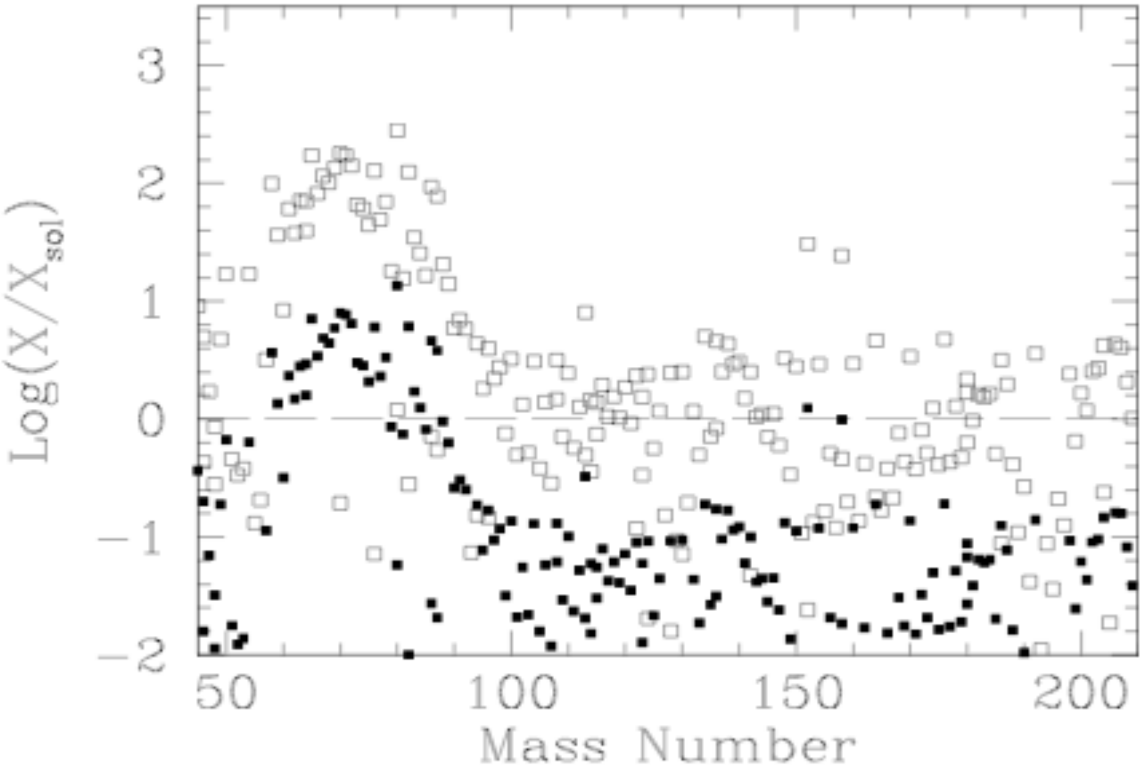
Pre-existing Fe (and other nuclei) serve as seed for a secondary s-process: the lower the metallicity, the lower the Fe content, the less heavy nuclei are produced (in absolute terms)

Impact of the star mass: the s-process in the convective He-burning core for 4 stellar models



Impact of the stellar metallicity: the s-process in the convective He-burning core for 2 different metallicities

25 M_o star with $Z=Z_o$ (open squares) and $Z=0.1Z_o$ (black squares).



The s-abundance distribution depends on the relative abundances of

(i) the neutrons produced by $^{22}Ne(\alpha,n)^{25}Mg$,

(ii) the iron peak elements present initially in the He core and

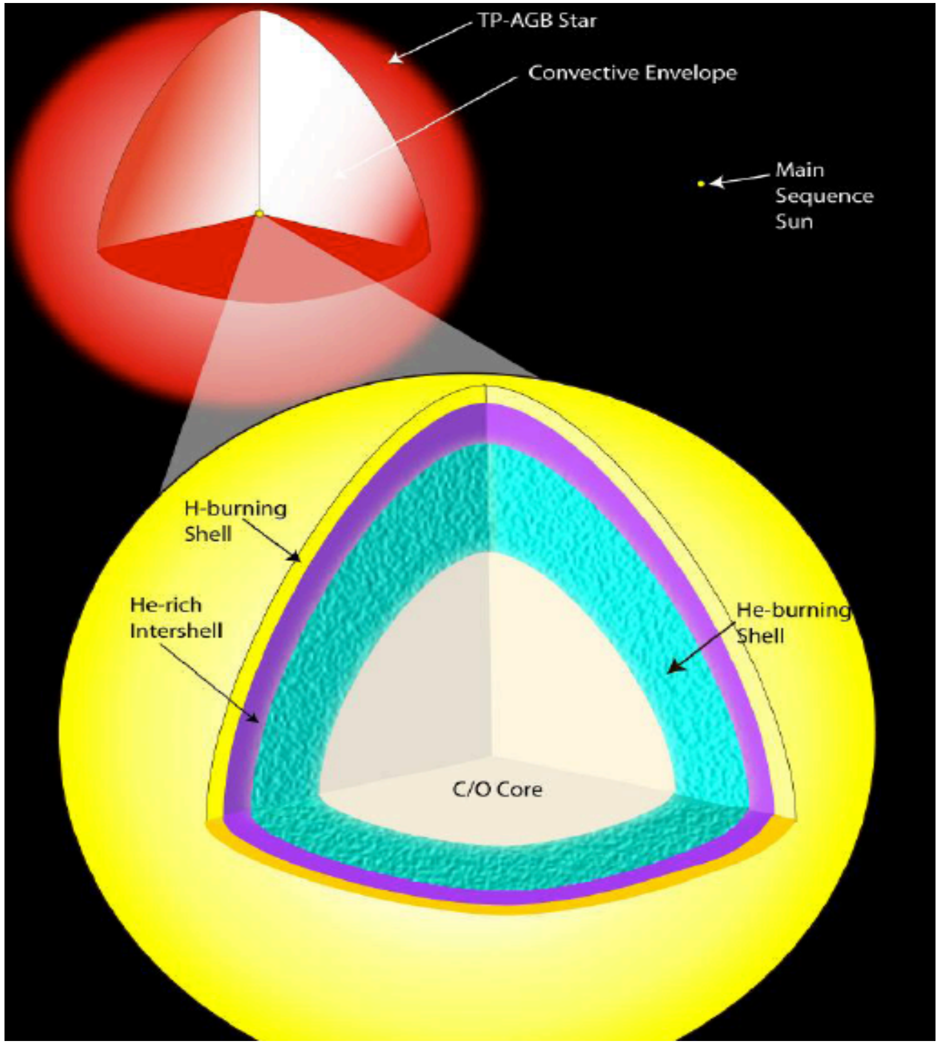
(iii) the lighter nuclides acting as neutron poisons.

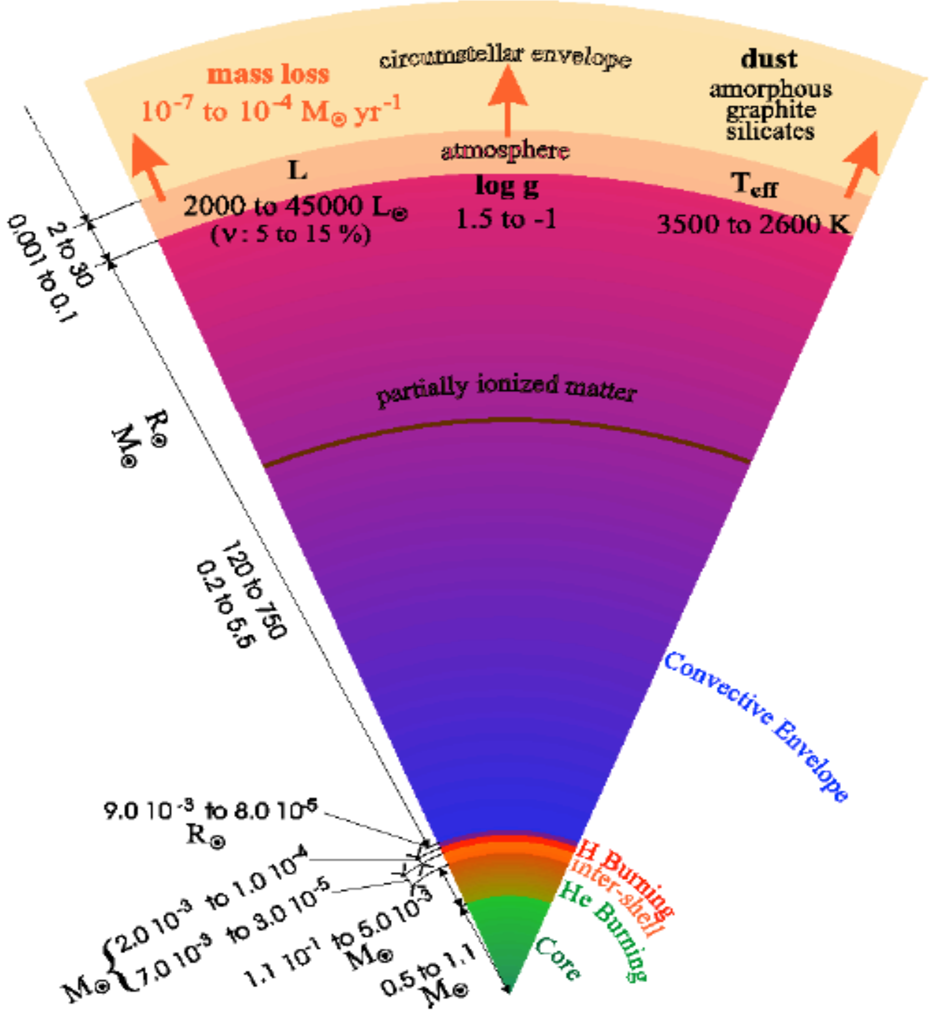
The s-nuclide enhancement remains limited to $A \leq 90$ and scales with Z (secondary process).

S-process in AGB stars: the main component

Low- and Intermediate mass stars: $1 \leq M\ [M_o] \leq 10$

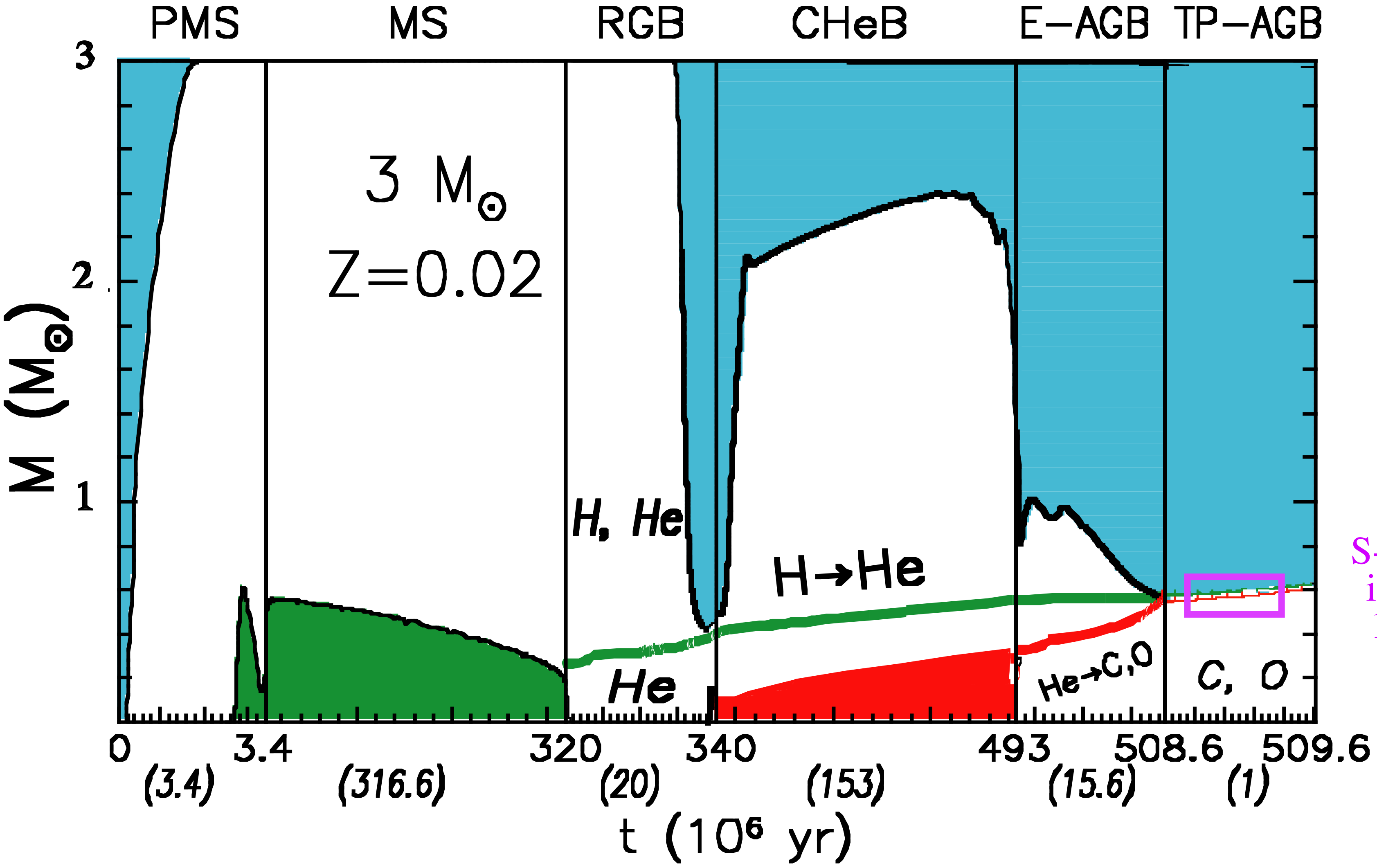
enrichment in $90 \leq A \leq 208$





S-process in TP-AGB stars: *the main and strong components*

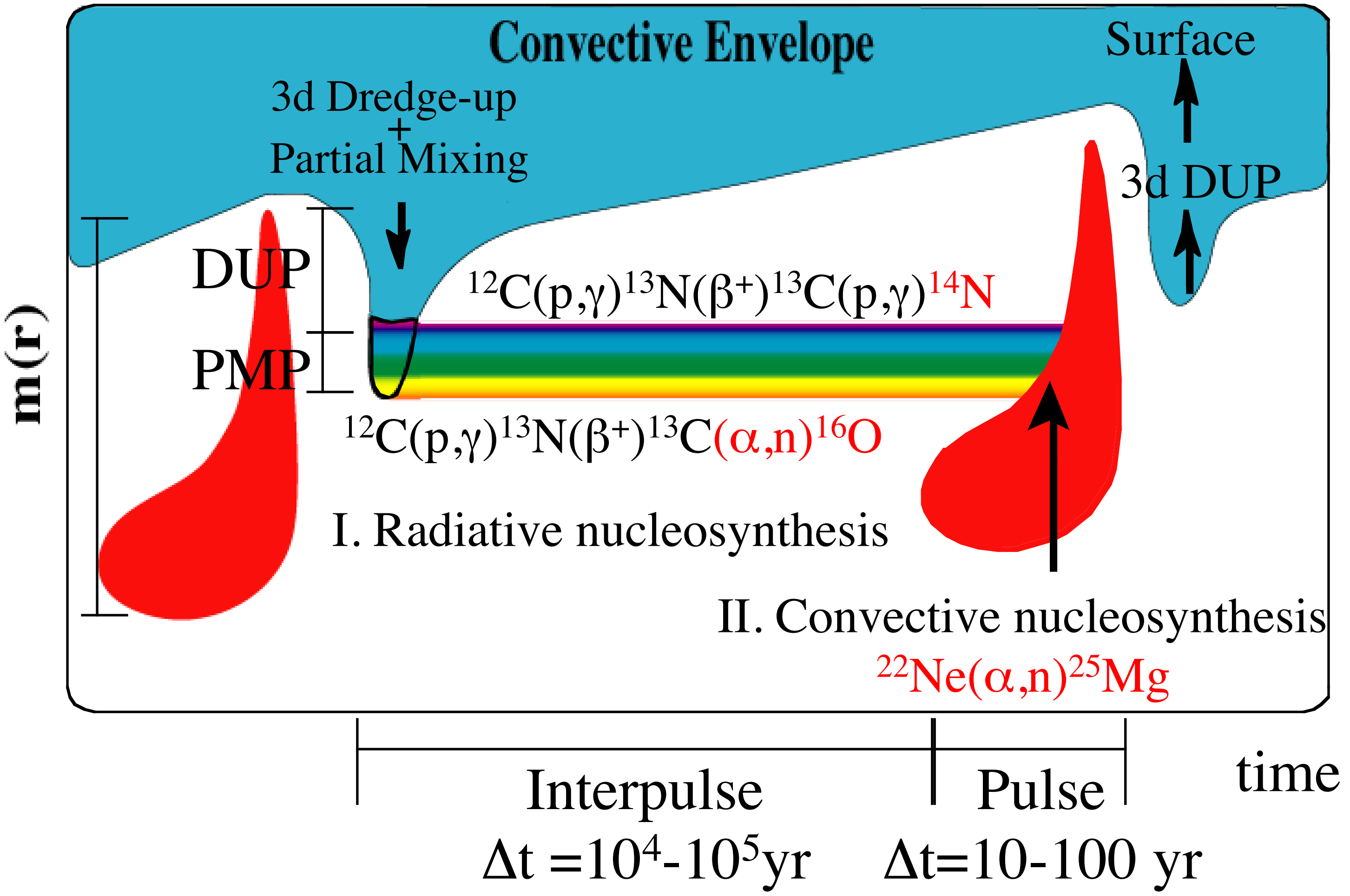
The AGB phase of low- and intermediate-mass stars (1 M_o ≤ M ≤ 9 M_o)



S-process in some 10^{-4} M_o

The most popular model for the s-process in AGB stars

the partial mixing of protons at the time of the 3d DUP



Convective Envelope

Surface

3d Dredge-up + Partial Mixing

3d DUP

DUP

PMP

m(r)

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(p,\gamma)^{14}N$

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$

I. Radiative nucleosynthesis

II. Convective nucleosynthesis

$^{22}Ne(\alpha,n)^{25}Mg$

Interpulse

$\Delta t = 10^4\text{-}10^5$ yr

Pulse

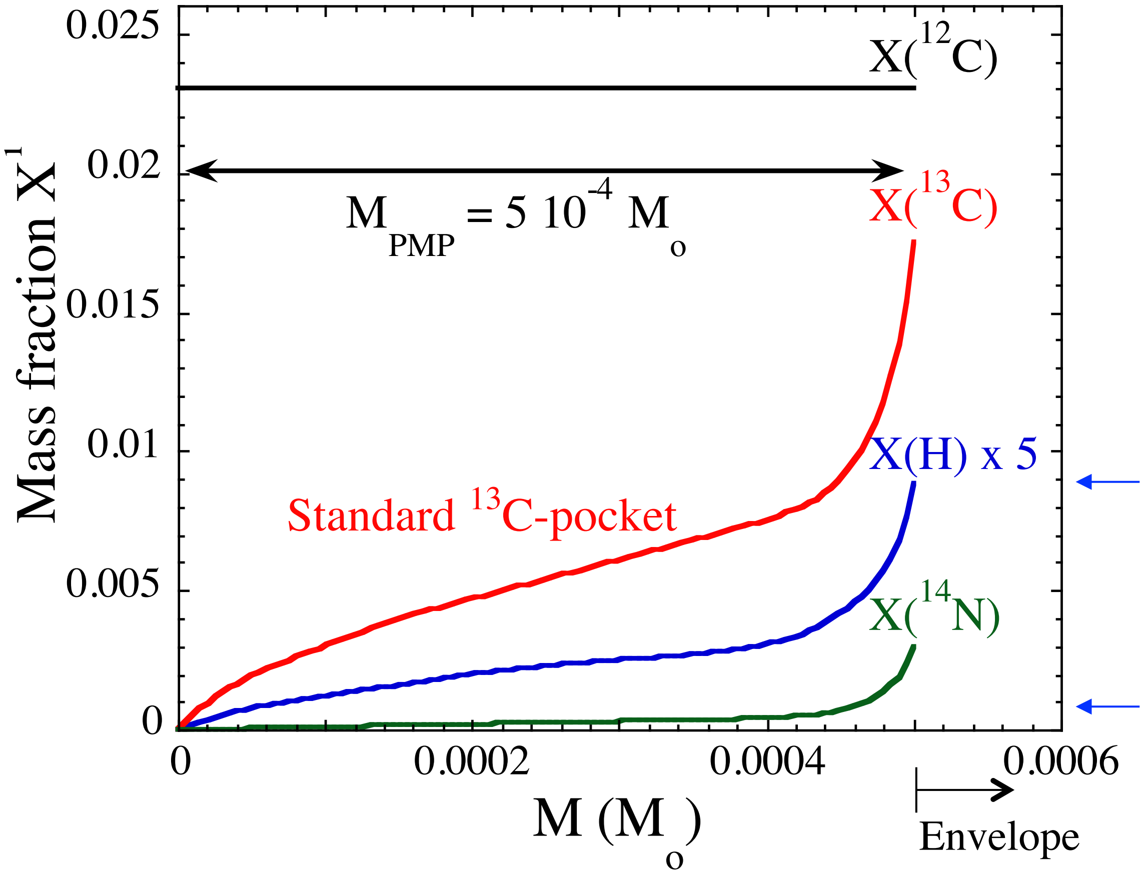
$\Delta t = 10\text{-}100$ yr

time

Modeling of the Partial Mixing of Protons

I. The standard "^{13}C-pocket"

‘Standard’ H-profile leading to the formation of a ‘standard’ ^{13}C-profile, in such a way that "^{13}C-pocket mass and profile constrained to reproduce the main component and to match spectroscopic observations of s-enhanced stars"



Arbitrary changes of
the standard ^{13}C-profile
(x 2, /2, /10, /100)

← X(H)=1.8 10^{-3}

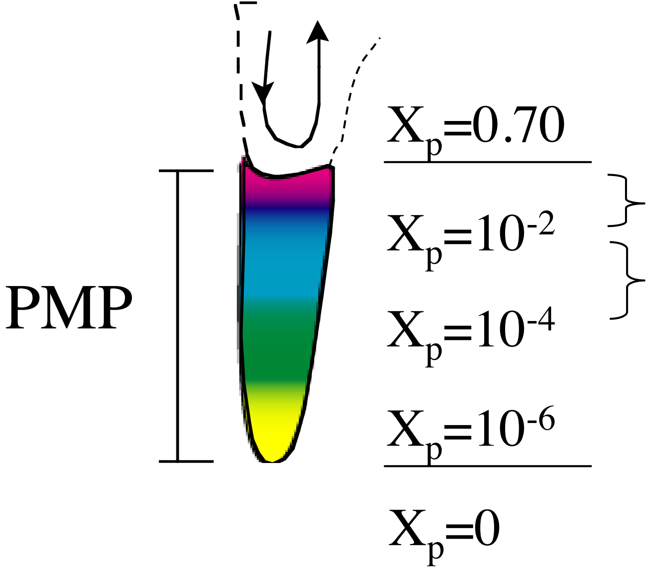
(limited range of X(H) !)

← X(H)=2.0 10^{-4}

The instantaneous (mechanism-independent) partial mixing of protons

Exponentially decreasing H-profile from the Envelope (X_p=0.7) down to ~ 10^{-6}

Mixing of protons in C-rich layers: X(^{12}C)≈0.2



X_p=0.70

X_p=10^{-2}

X_p=10^{-4}

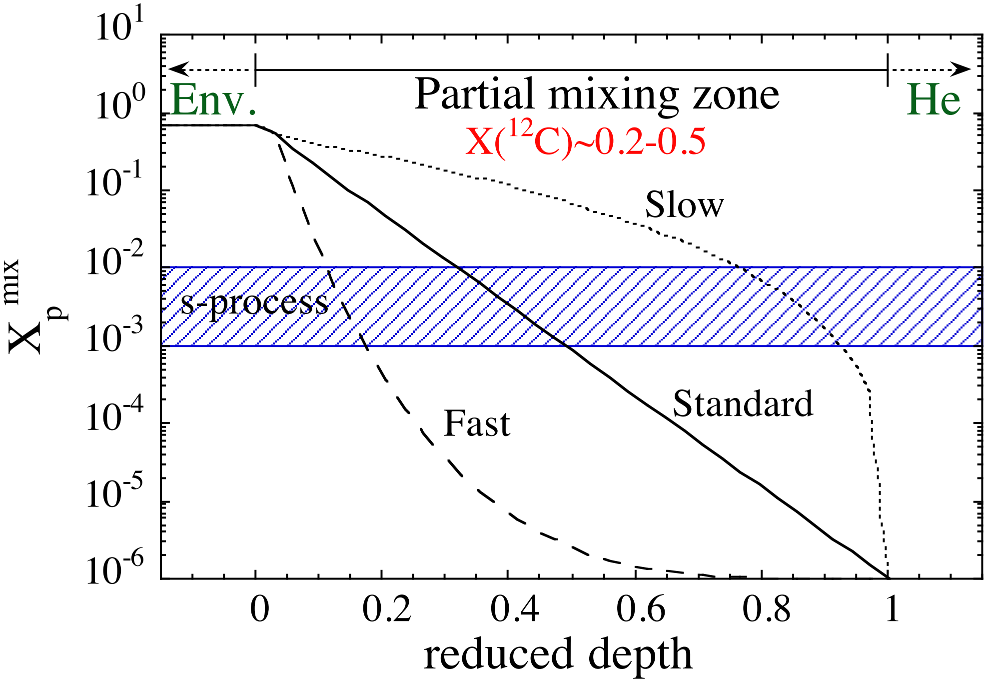
X_p=10^{-6}

X_p=0

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(p,\gamma)^{14}N$ but also production of ^{19}F and ^{23}Na

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ followed by $^{13}C(\alpha,n)^{16}O$

Extent of the PMP zone: typically about 5-10% of M_{pulse} i.e M_{PMP} a few 10^{-4} M_o in order to reproduce globally the observed surface abundances [s/Fe]>1

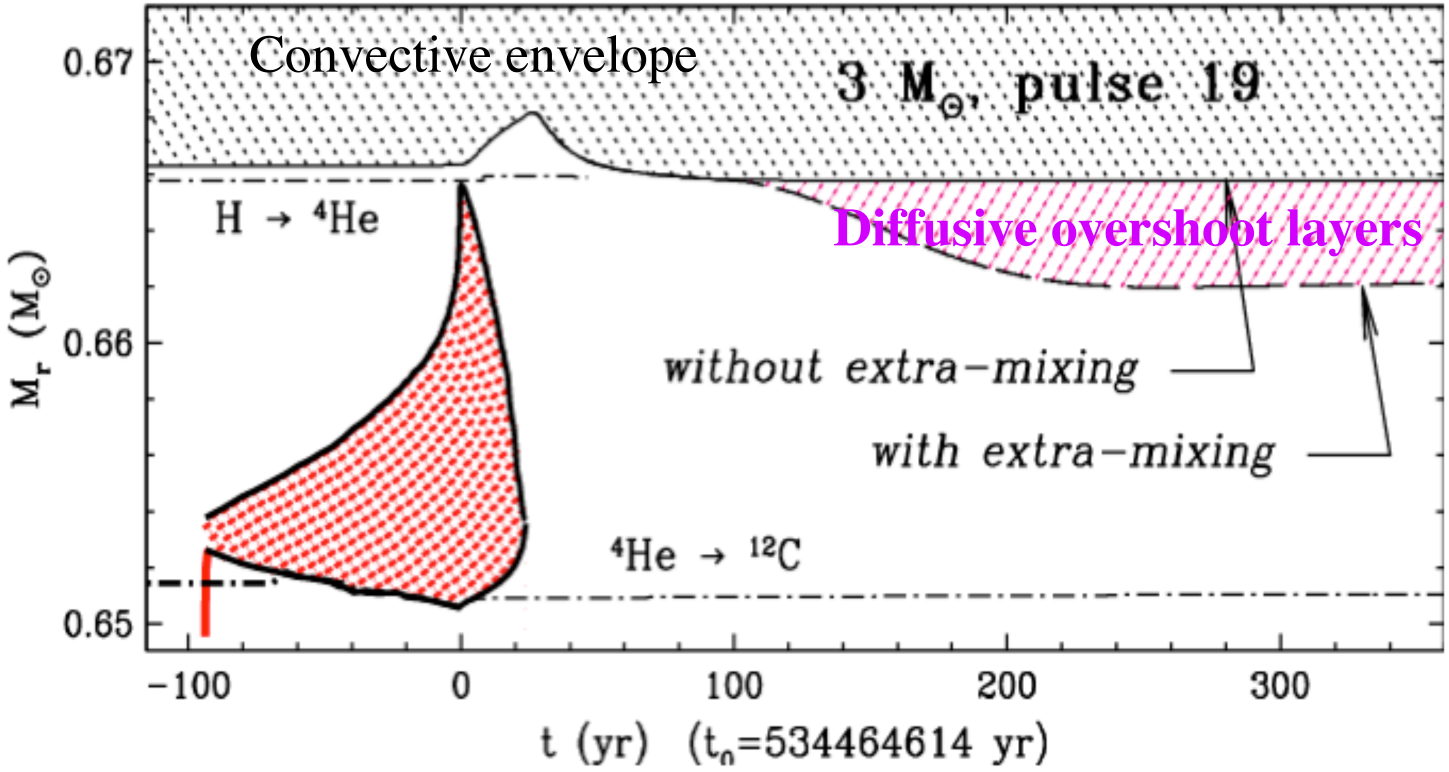


The overshoot model

Depth-dependent diffusion below the convective envelope based on 2D simulations of radiative hydrodynamics of time-dependent compressible convection

$D_{ov} = D_0 \ \exp(-2z/ f_{over} H_p)$ (H_p pressure scale height; f_{over} *free parameter*)

Fast diffusion of protons on *short* timescales (s-process region: D ≈ 10^6 s/cm^2, τ≈1yr)

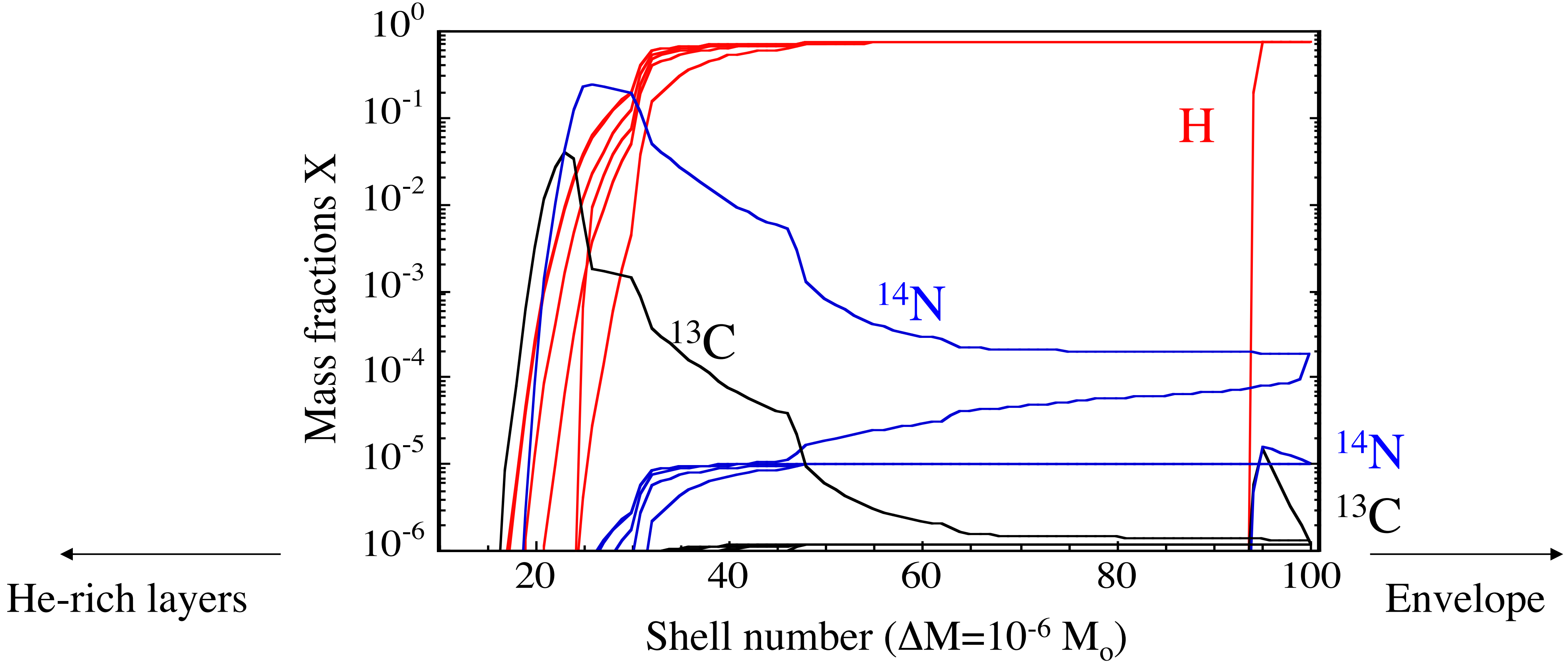


Extent of the PMP zone depends on f_{over}

The nucleosynthesis related to the partial mixing of protons

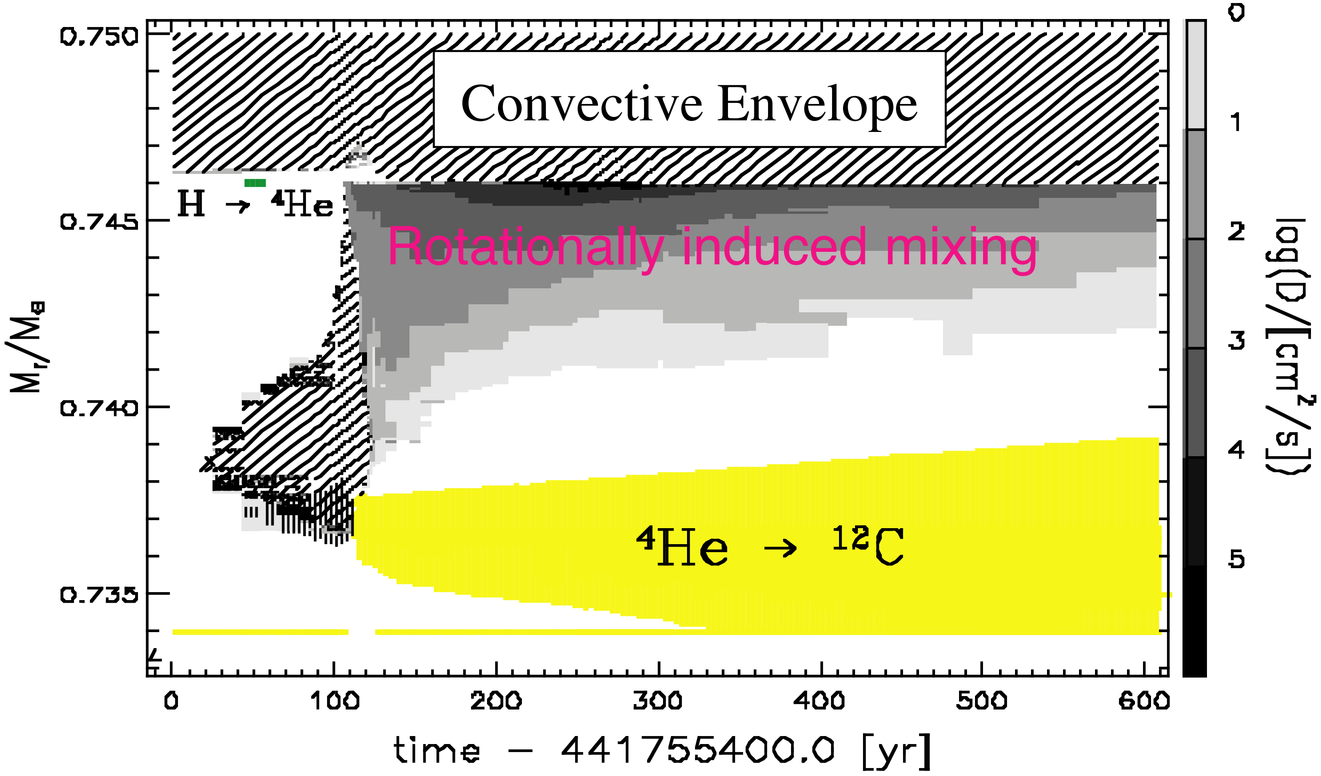
The overshoot model $D_{over} = 10^{14} \longrightarrow 10^{3}$ s/cm^{2}

Fast diffusion of protons (s-process region: $D \approx 10^{6}$ s/cm^{2}, $\tau \approx 1$yr)
on short timescales ($D_{over} > 0$ for 10-100 yr)



The rotationally induced mixing

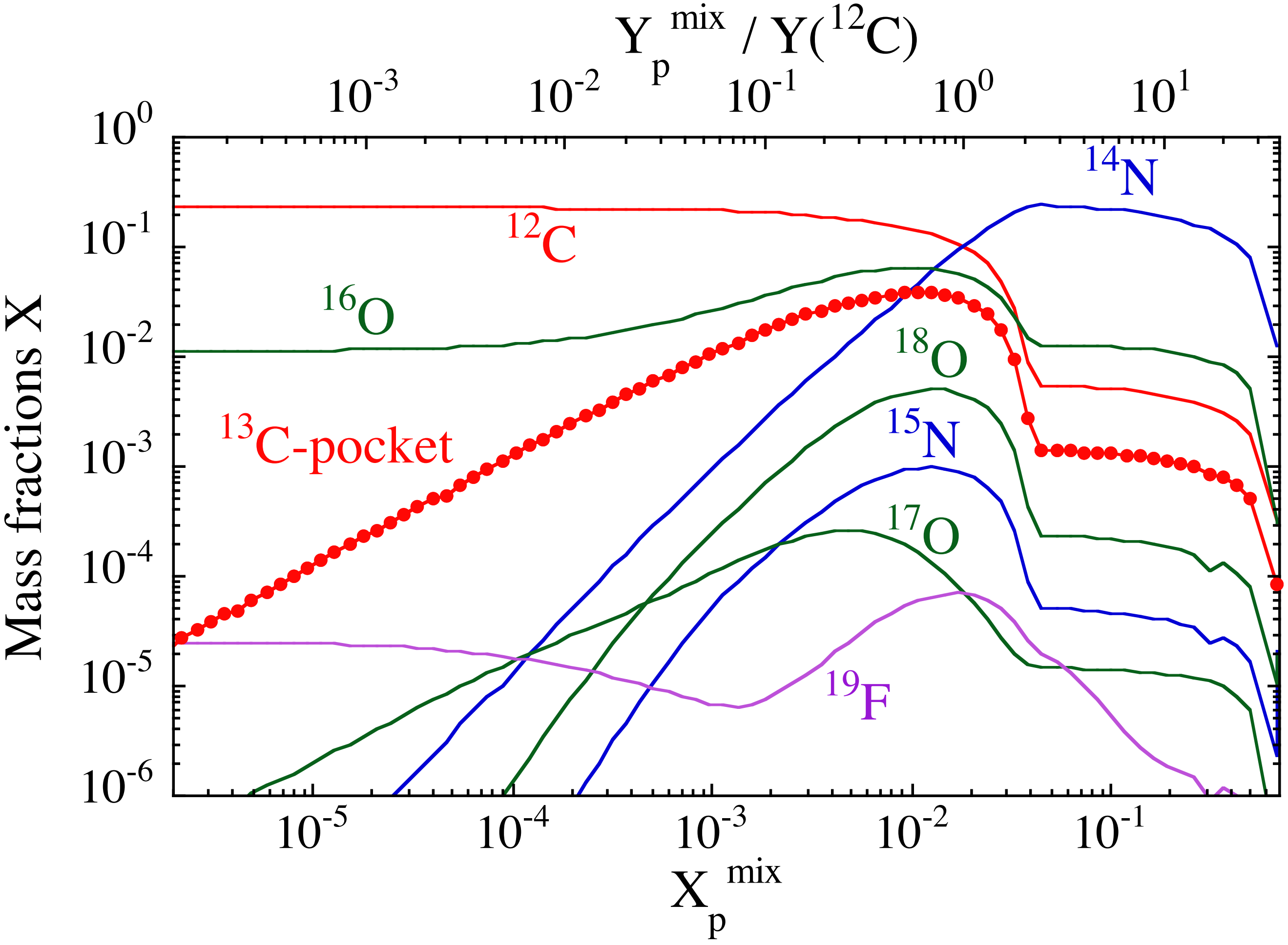
Extra mixing due to differential rotation between a slow rotating envelope and a fast rotating core (large angular momentum jump at the H/C interface)

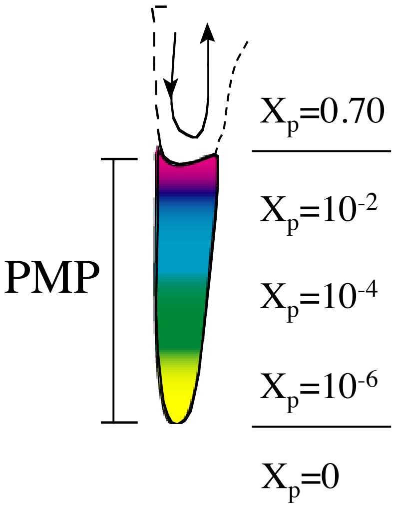


Slow diffusion on *long* timescales (D ≈ 10^5 s/cm^2 for more than 10^3 yr)

The nucleosynthesis related to the partial mixing of protons

Abundances at the end of the radiative interpulse phase
(^{13}C pocket at the end of the 3DUP phase)

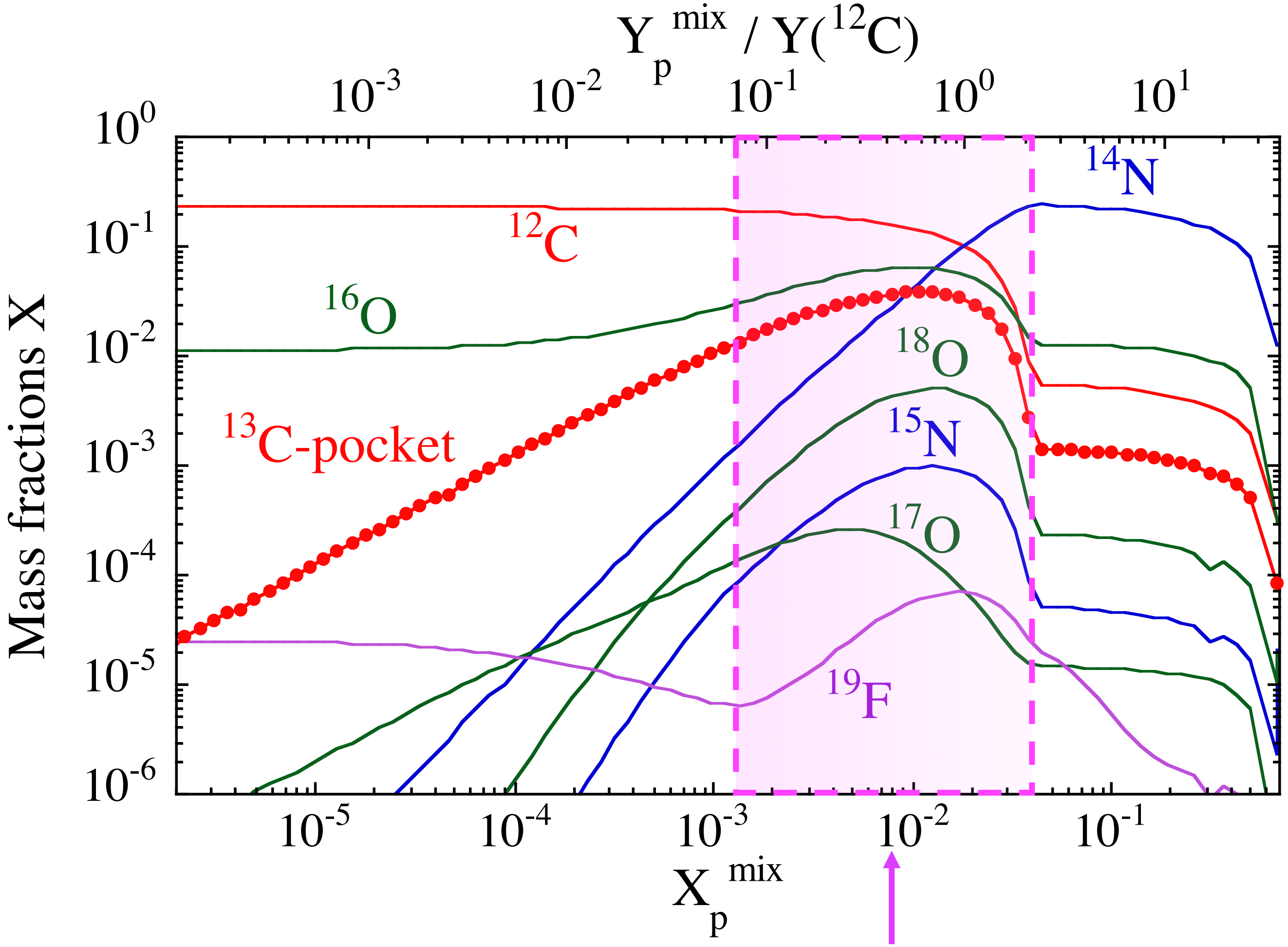




C-rich layers ←

Convective envelope →

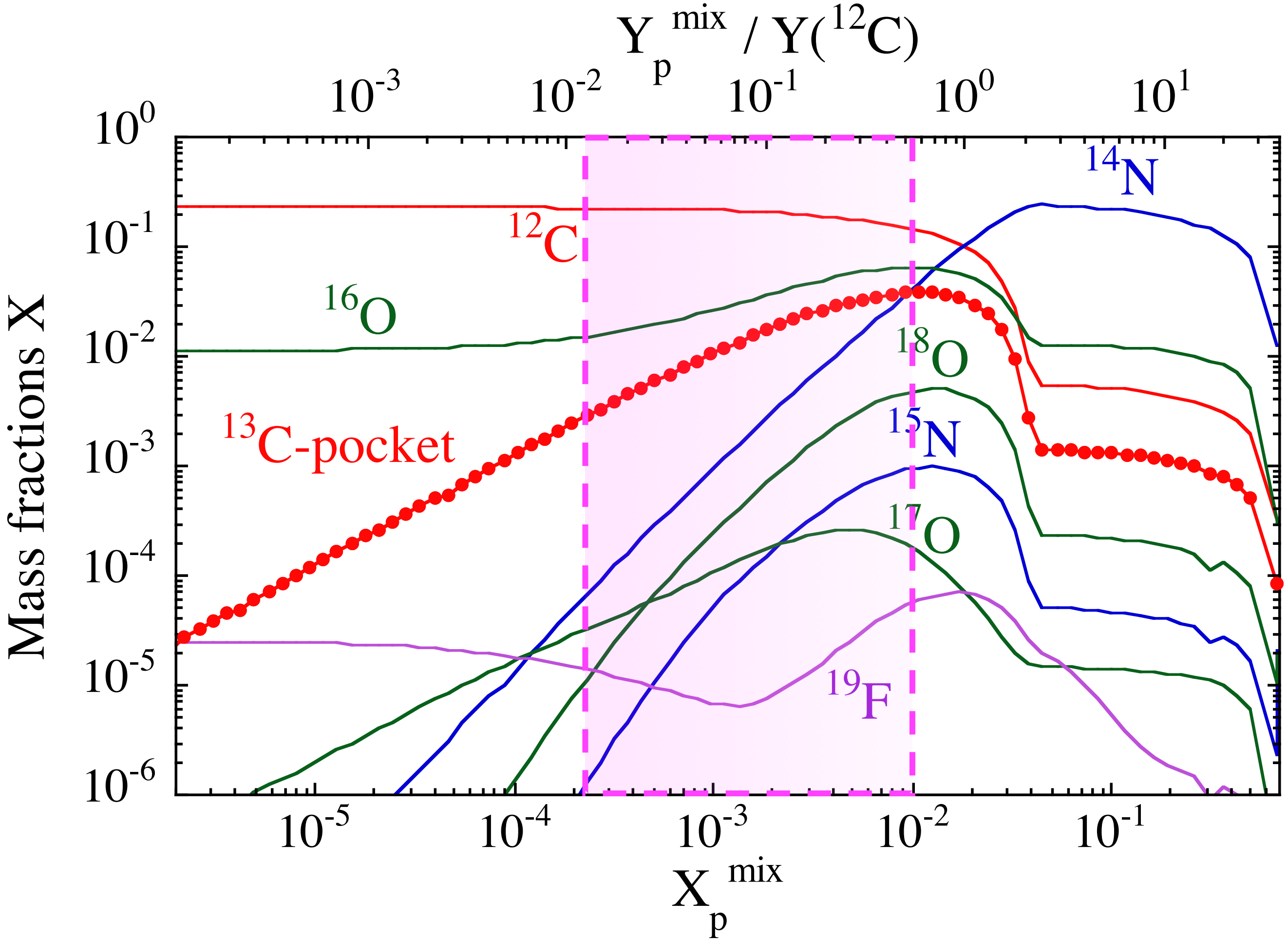
A ^{19}F-rich s-process-poor nucleosynthesis



Primary production of ^{13}C and ^{14}N: $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(p,\gamma)^{14}N$ followed by

$^{13}C(\alpha,n)^{16}O$ & $^{14}N(n,p)^{14}C(\alpha,\gamma)^{18}O(p,\alpha)^{15}N$ and later in the pulse $^{15}N(\alpha,\gamma)^{19}F$

An s-process-rich nucleosynthesis

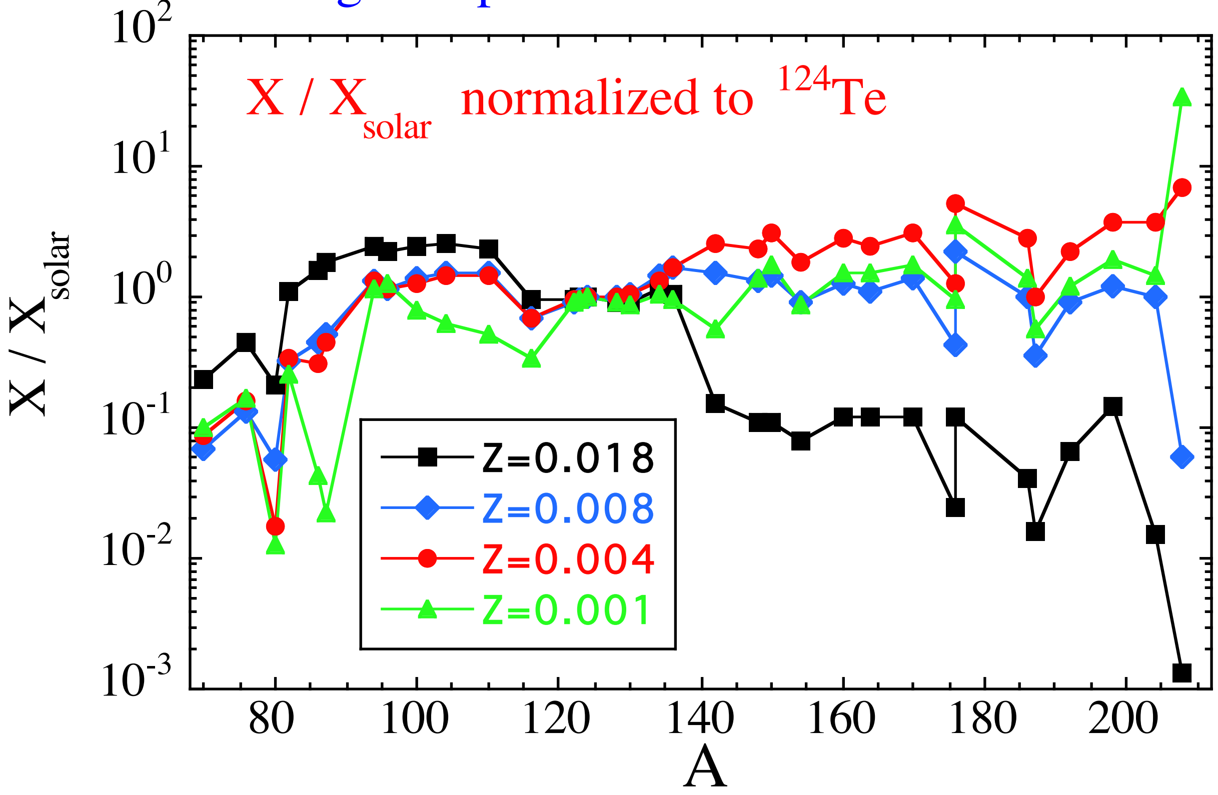


Primary production of ^{13}C *without* large production of ^{14}N: $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$

$^{13}C(\alpha,n)^{16}O$ & the s-process nucleosynthesis $^{56}Fe(n,\gamma)^{57}Fe(n,\gamma)$ …

The resulting s-process in the overshoot/PMP model

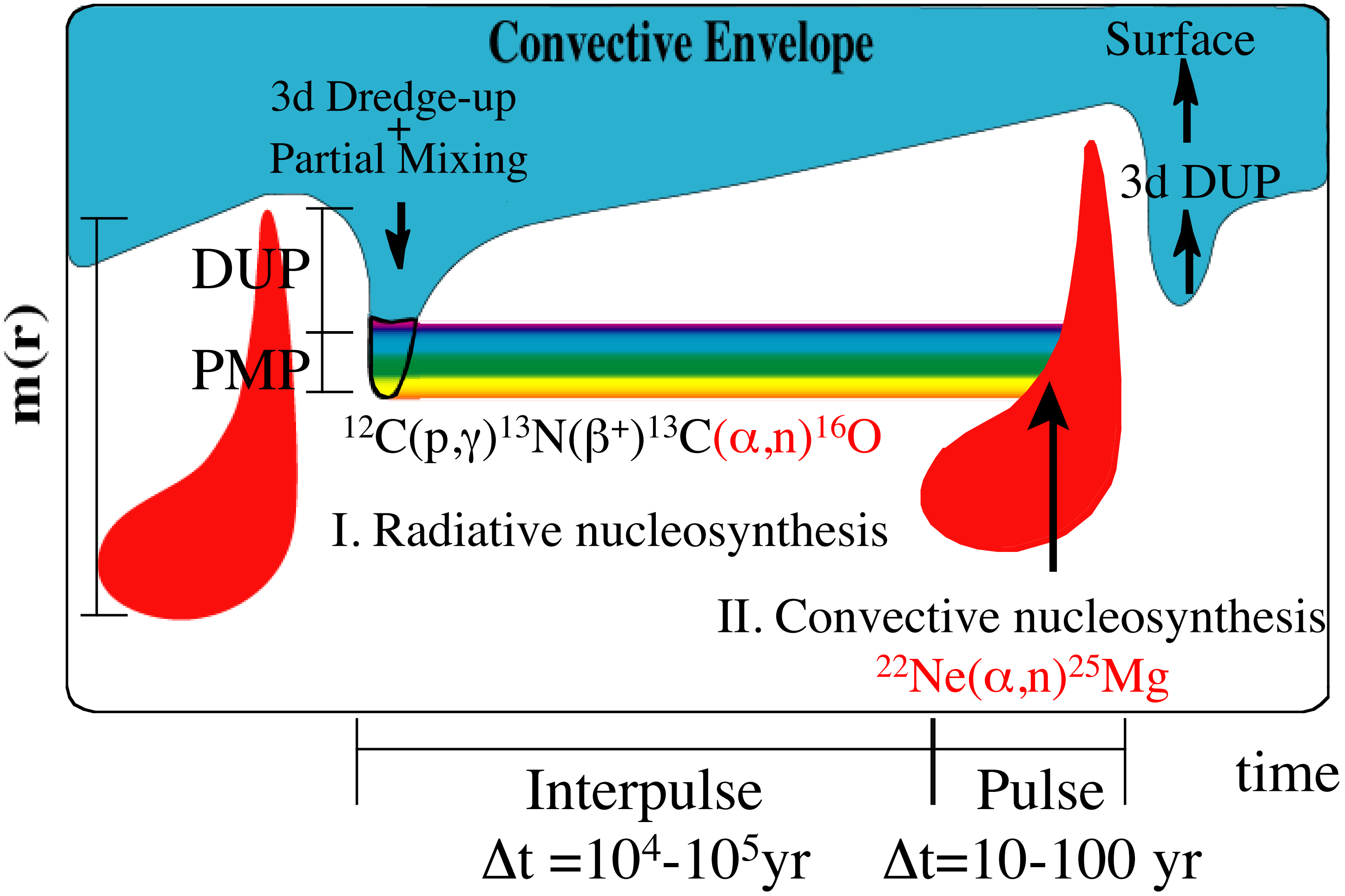
Efficient s-process nucleosynthesis in the $^{13}C > {}^{14}N$ region
Strong Z-dependence of the s-distribution



‘relatively’ robust
predictions:
only a *Z*-dependence

$Z=Z_o$: Sr, Zr, Mo, Ru + some Ba, Nd
$Z = 0.008$: Zr ⟶ ^{204}Pb (main component)
$Z = 0.004$: Zr ⟶ ^{208}Pb (main component)
$Z < 0.001$: ^{208}Pb mainly (strong component: Pb-stars)

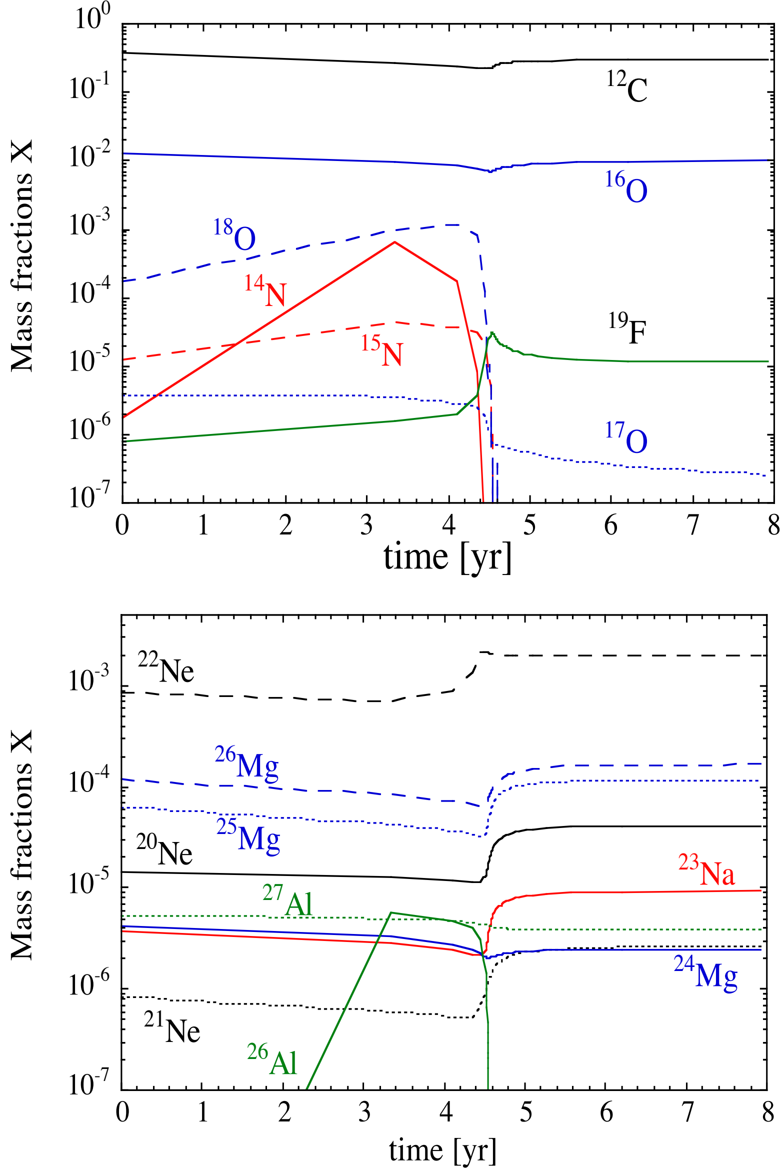
The s-process during the radiative interpulse phase may be followed by some convective s-process in the thermal pulse



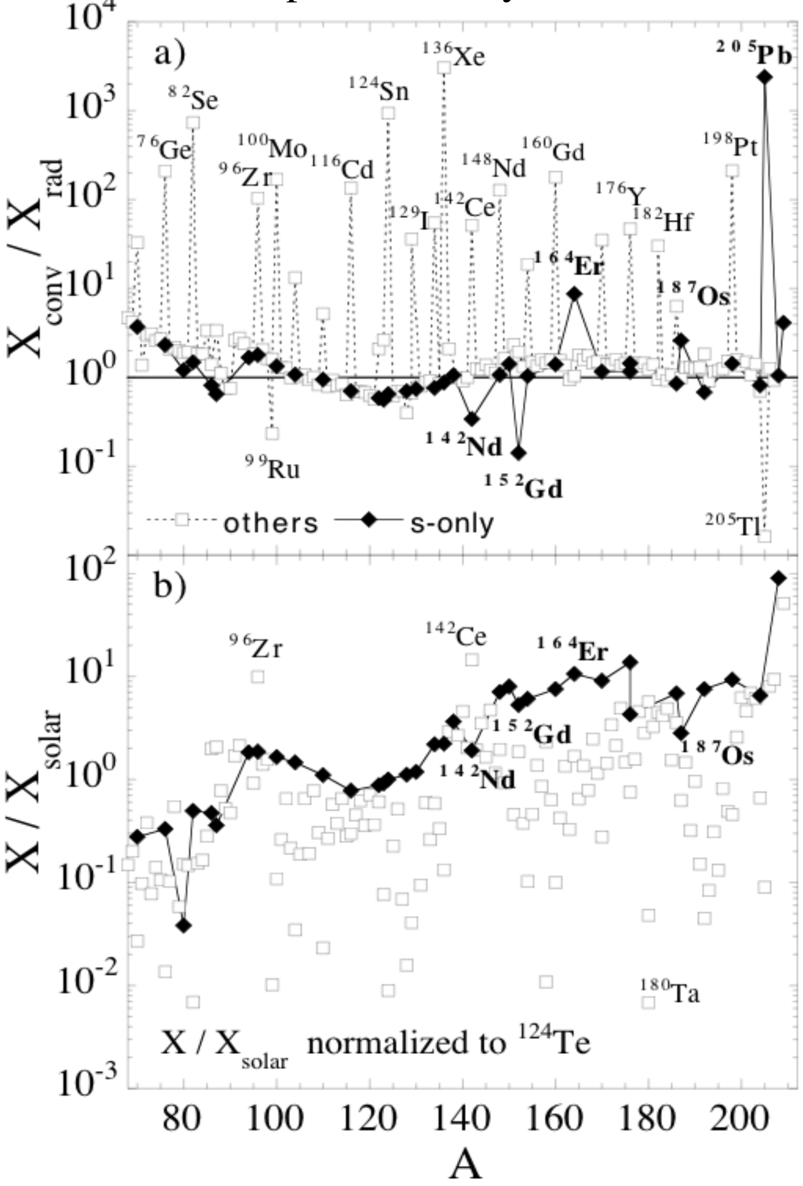
Impact of the convective pulse on nucleosynthesis

$M=3M_o$, **$Z=0.001$**, 20th pulse : $T_p^{bot}=3.2\ 10^8$K → imprint of the *T*-effect on the branching nuclei !

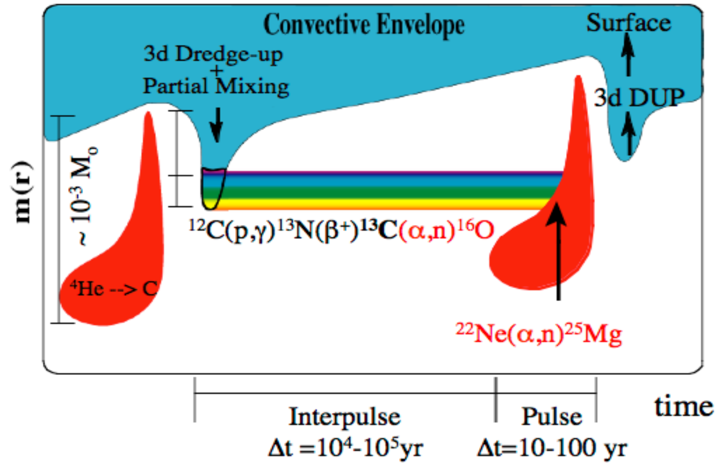
Impact on light nuclei



Impact on heavy nuclei



Nuclear physics of relevance to the s-process nucleosynthesis



n-source: ^{13}C(α,n)^{16}O; ^{22}Ne(α,n)^{25}Mg

n-captures: ~ 80% known experimentally (E_n~10-30 keV), more being measured

- at nToF: ^{90,91}Zr, ^{139}La, ^{151}Sm, ^{204,206,207}Pb, ^{209}Bi
- by activation: ^{58}Fe,^{59}Co,^{64}Ni,^{63,65}Cu,^{79,81}Br,^{85,87}Rb (Heil 08), ^{74,76}Ge,^{75}As, ^{184,186}W (Marganiec 09)
- by activation + AMS: ^{40}Ca (Dillman 09), ^{62}Ni (Nasser 05)
- on long-lived nuclei: ^{60}Fe(n,γ) (Uberseder 09), ^{182}Hf (Vockenhuber 07), ^{14}C (Reifarth 08), ^{93}Zr (Tagliente 13)

~ 20% still to be determined theoretically (unstable nuclei)
+ thermalisation effects & non-thermalisation of given isomers

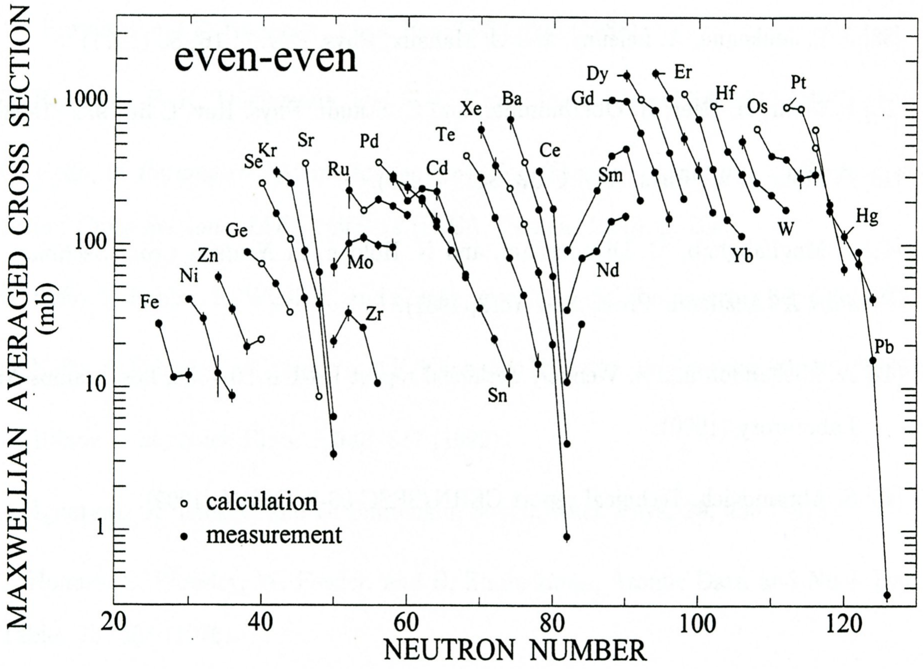
Beta-decays: T- and ρ-dependence of the stellar rate (Takahashi & Yokoi 1987)

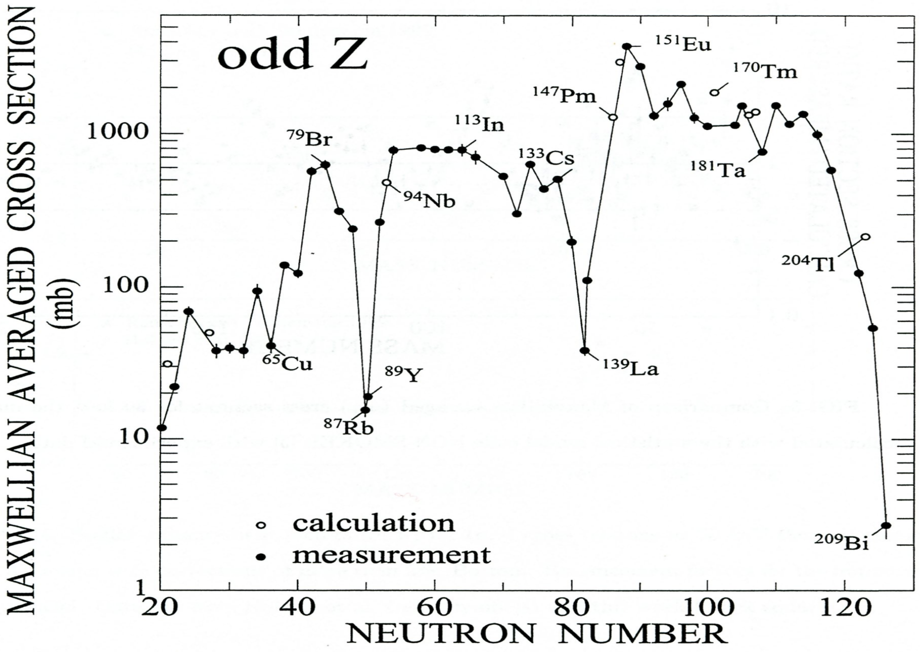
Still many branching points affected by ~ factor of 3 due to unknown *log ft*

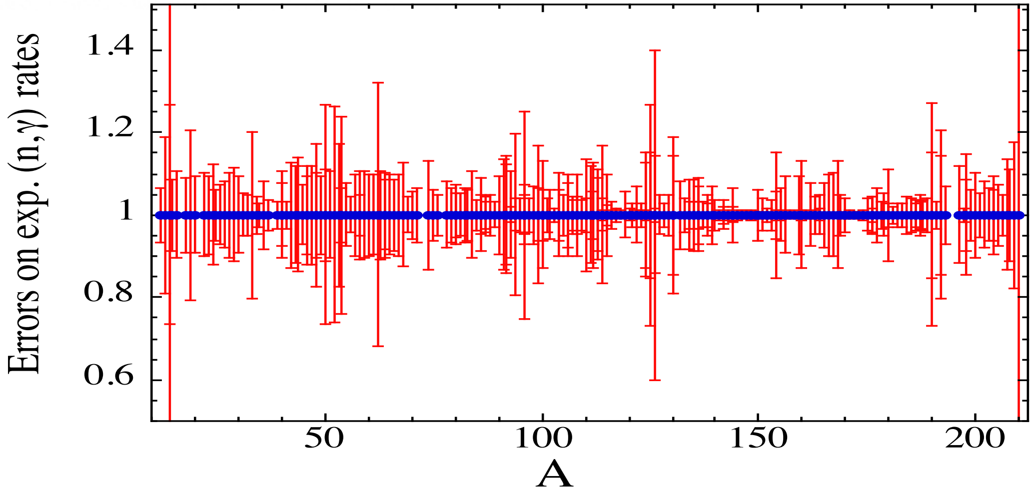
Experimental (n,γ) rates

About 80% of the radiative neutron capture rates of relevance for the s-process are known experimentally

30 keV Maxwellian-averaged cross sections ($T \sim 3.5\ 10^8$K)





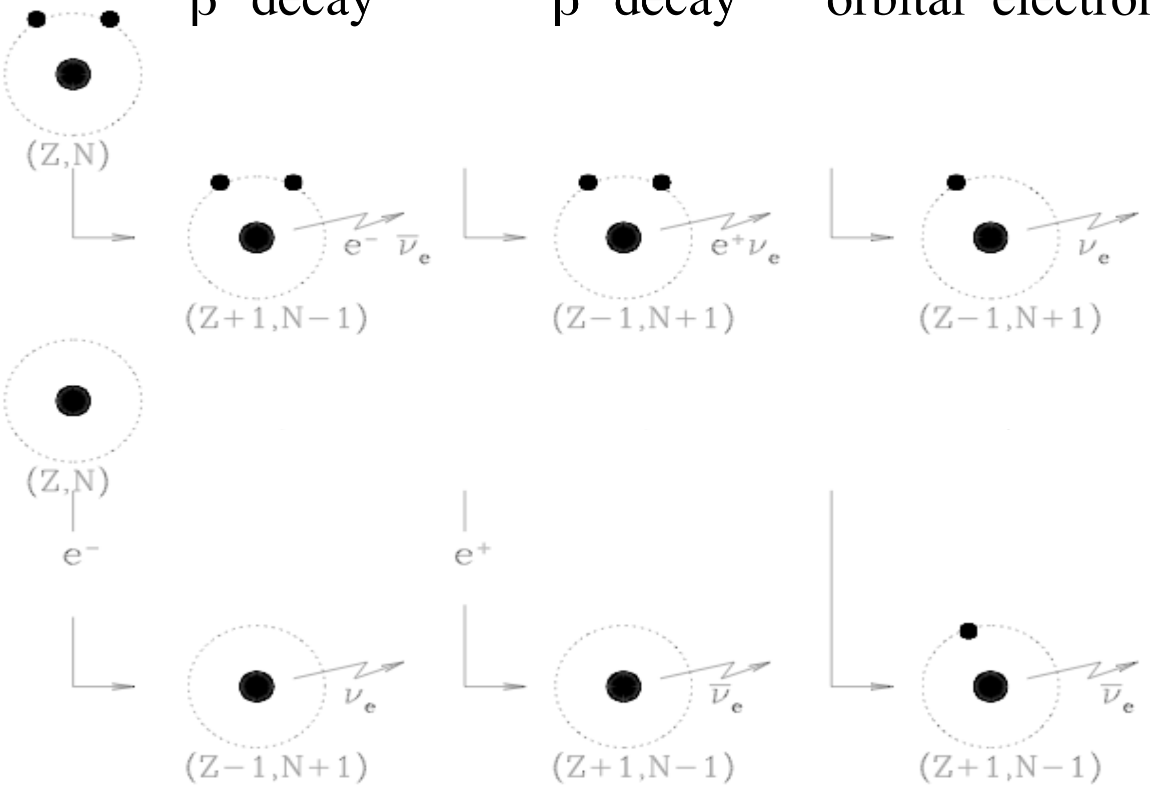


$$\langle \sigma \rangle = \frac{\langle \sigma v \rangle}{v_T}$$

In stellar conditions corresponding to the s-process, the probability for the 3 weak processes ($\beta^{\pm}$,EC) can be quite different, due to

- the contribution of thermally populated excited states to the decay process
- the ionisation leading to large abundance of free electrons and their possible capture by nuclei
- the (partial) degeneracy of electrons in the stellar plasma

The different nuclear β-decay modes:



β^- decay

β^+ decay

orbital electron capture

Usual decay modes in the laboratory

Additional possible decay modes in stellar conditions

continuum-e^- capture

continuum-e^+ capt.

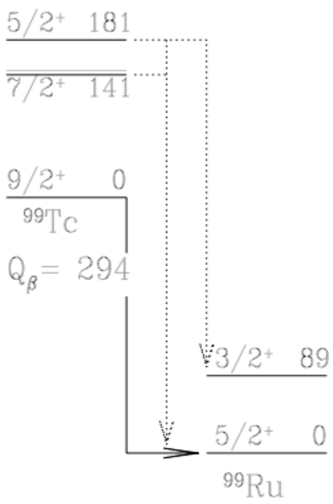
bound-state β-decay

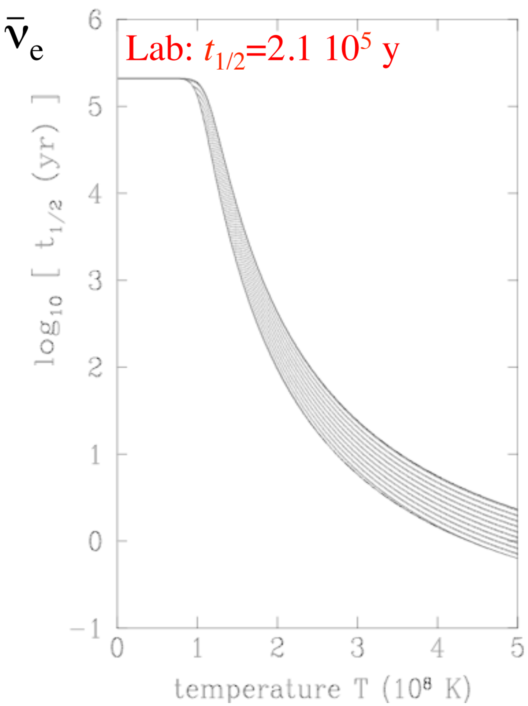
The contribution of thermally populated excited states to the decay process

At increasing temperatures, excited states are thermally populated and can contribute to the β-decay process and consequently modify (sometime very significantly) its half-life with respect to the laboratory value.

One example is ^{99}Tc, most probably the Tc isotope observed at the surface of AGB stars and produced by the s-process nucleosynthesis at temperatures of a few 10^8K. In such conditions, the 141 and 181 keV states can be sufficiently populated to contribute to the β-decay and reduce the half-life from the laboratory value of 2.1 10^5 y to about 10 years at T~3 10^8K.

$$^{99}\mathrm{Tc} \longrightarrow {}^{99}\mathrm{Ru} + e^- + \bar{\nu}_e$$





The decay of thermally populated states can play a significant role if

-the ground state β-decay is slow due to spin selection rules (large differences between spin and parities of initial and final states: forbidden transitions)

- the low-lying states can undergo faster β-decays than the ground state

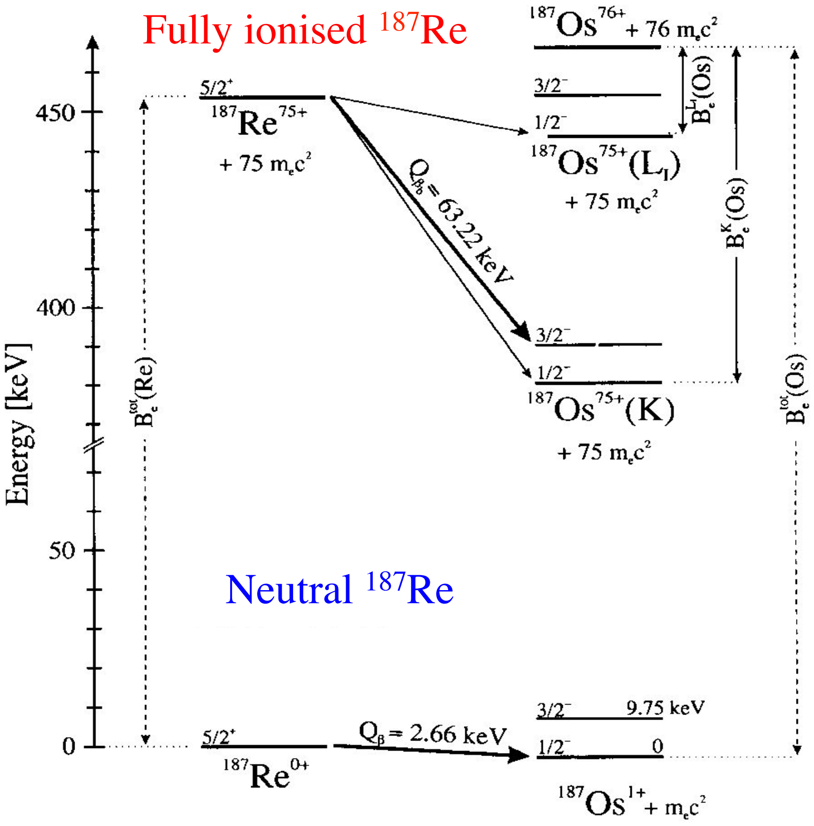
- temperatures are high enough to populate such excited states

⟶ **β±-decay rates are *T*-dependent in stars**

$$\boxed{\lambda_\beta=\lambda_\beta(T)}$$

A famous example: the bound state β-decay of ^{187}Re

The β decay of the ^{187}Re-^{187}Os pair play an important role in the study of the Re-Os clock ($t_{1/2}$(^{187}Re)~ 4.2 10^{10}y) to estimate the age of the Galaxy



Fully ionised ^{187}Re

Neutral ^{187}Re

Lab: $t_{1/2}$=4.2 10^{10} y

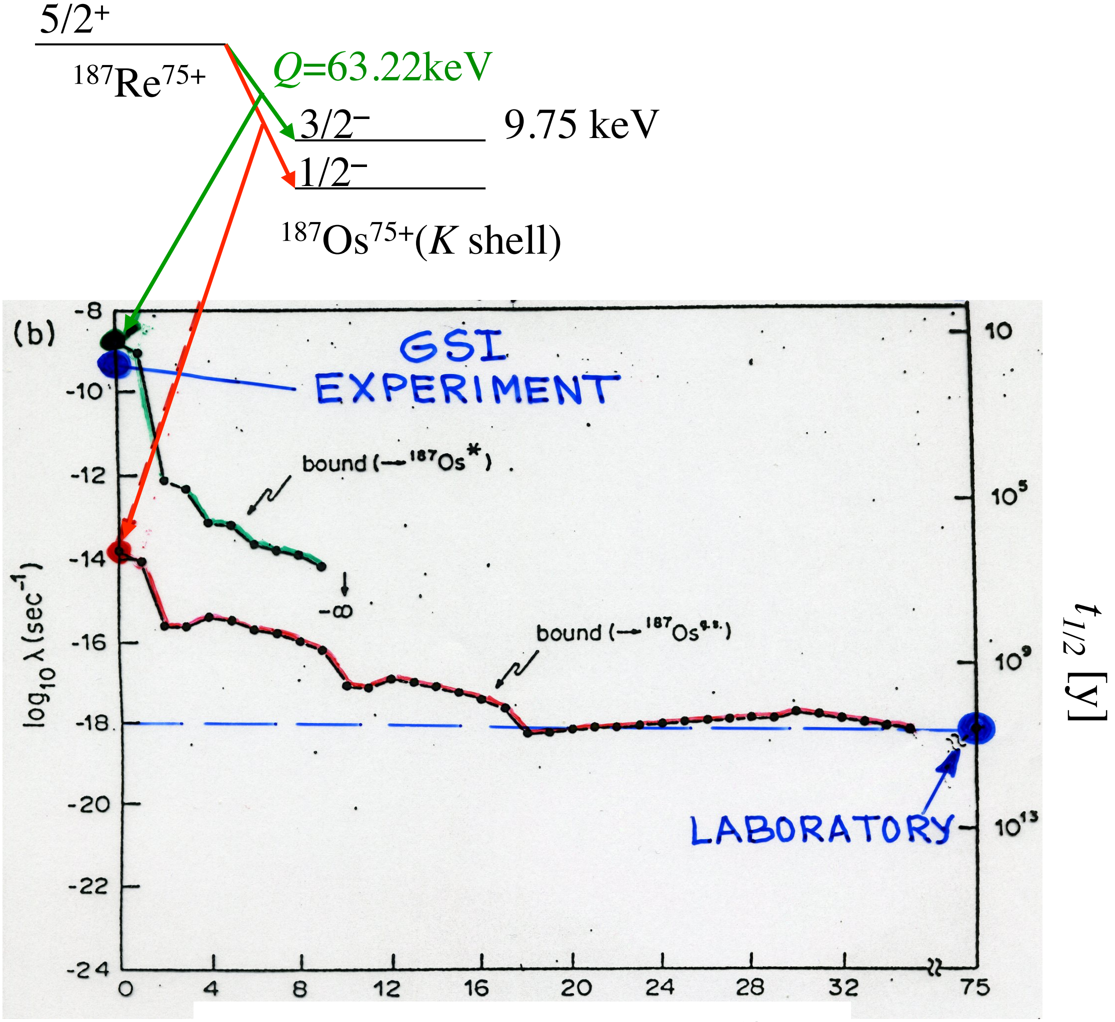
For fully ionised ^{187}Re^{75+}, β decay to the continuum is forbidden because the electronic cloud in Os is stronger bound by $\Delta B_e^{tot}=B_e^{tot}$(Os)-$B_e^{tot}$(Re)=15.31keV than in Re.

But

- ^{187}Os^{76+} can decay by capturing an electron from the continuum (^{187}Os is stable in the lab)
- ^{187}Re^{75+} is unstable against bound state β-decay with the electron bound in the *K* shell with the large Q=73keV value. The first ^{187}Os excited state at 9.75keV can be fed in a non-unique first forbidden transition (Q=63.22keV) with the half-life $t_{1/2}$=14yr, i.e 10^9 times shorter than for the neutral ^{187}Re

Terrestrial conditions: neutral ^{187}Re can only decay (normal β-decay with the electron in the continuum) through the unique, first forbidden transition to the ^{187}Os ground state: Q=2.66 keV and $t_{1/2}$~ 4.2 10^{10}y

Experimental confirmation of the bound state β-decay of fully stripped ^{187}Re^{75+}



5/2$^+$

^{187}Re^{75+}

Q=63.22keV

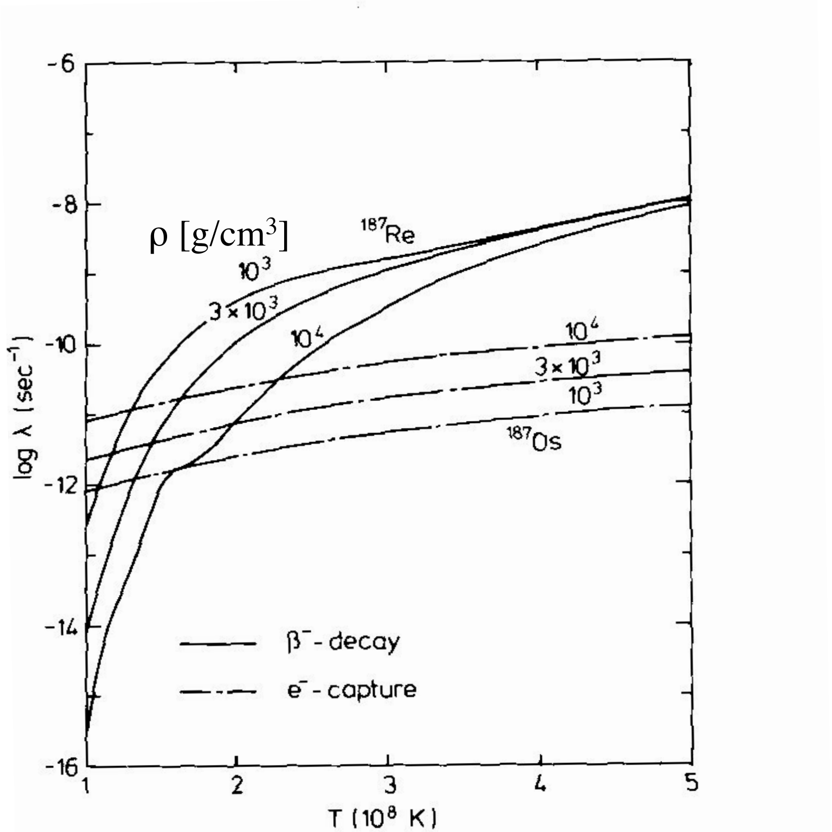
3/2$^-$ 9.75 keV

1/2$^-$

^{187}Os^{75+}(*K* shell)

Number of electrons bound to ^{187}Re

Final *T*- and *ρ*-dependence of ^{187}Os and ^{187}Re decays

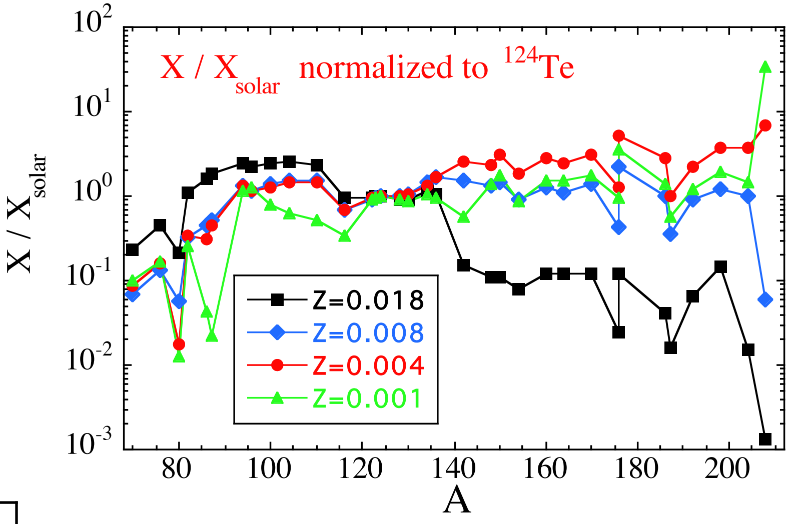


Lab ~ -18

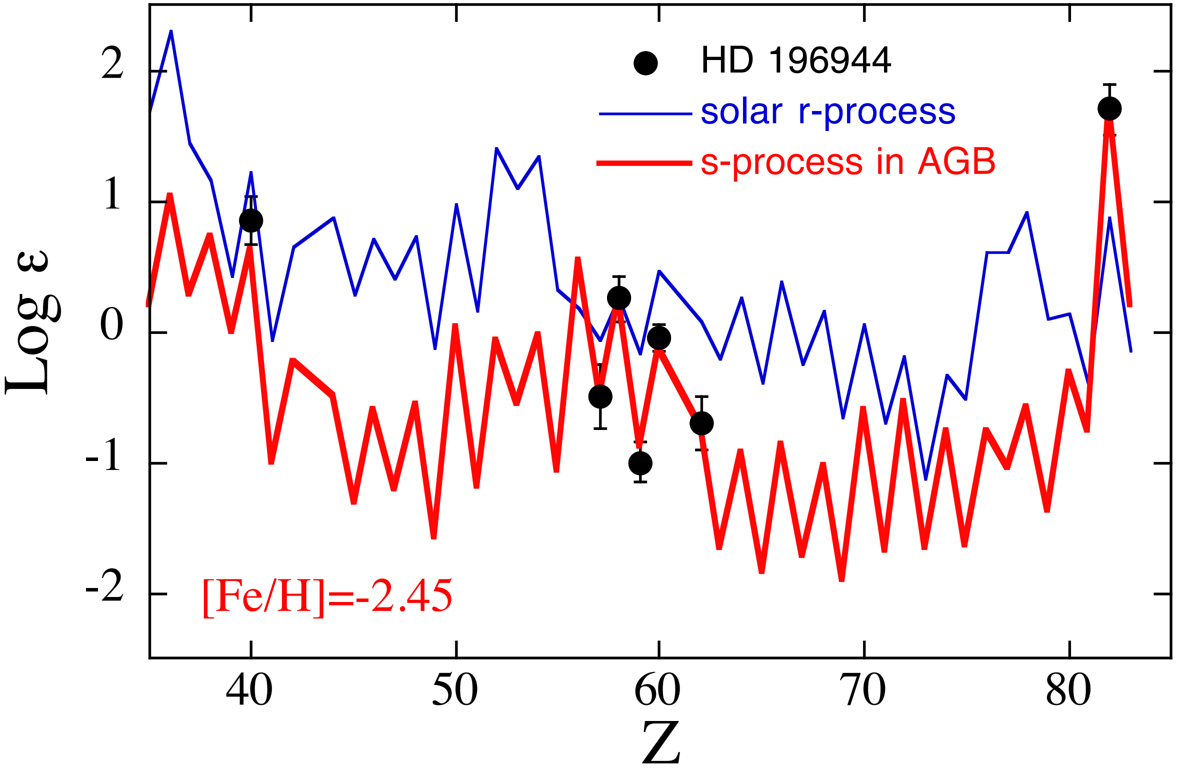
$$\boxed{\lambda_\beta=\lambda_\beta(T,\rho)}$$

Observation of Pb-stars

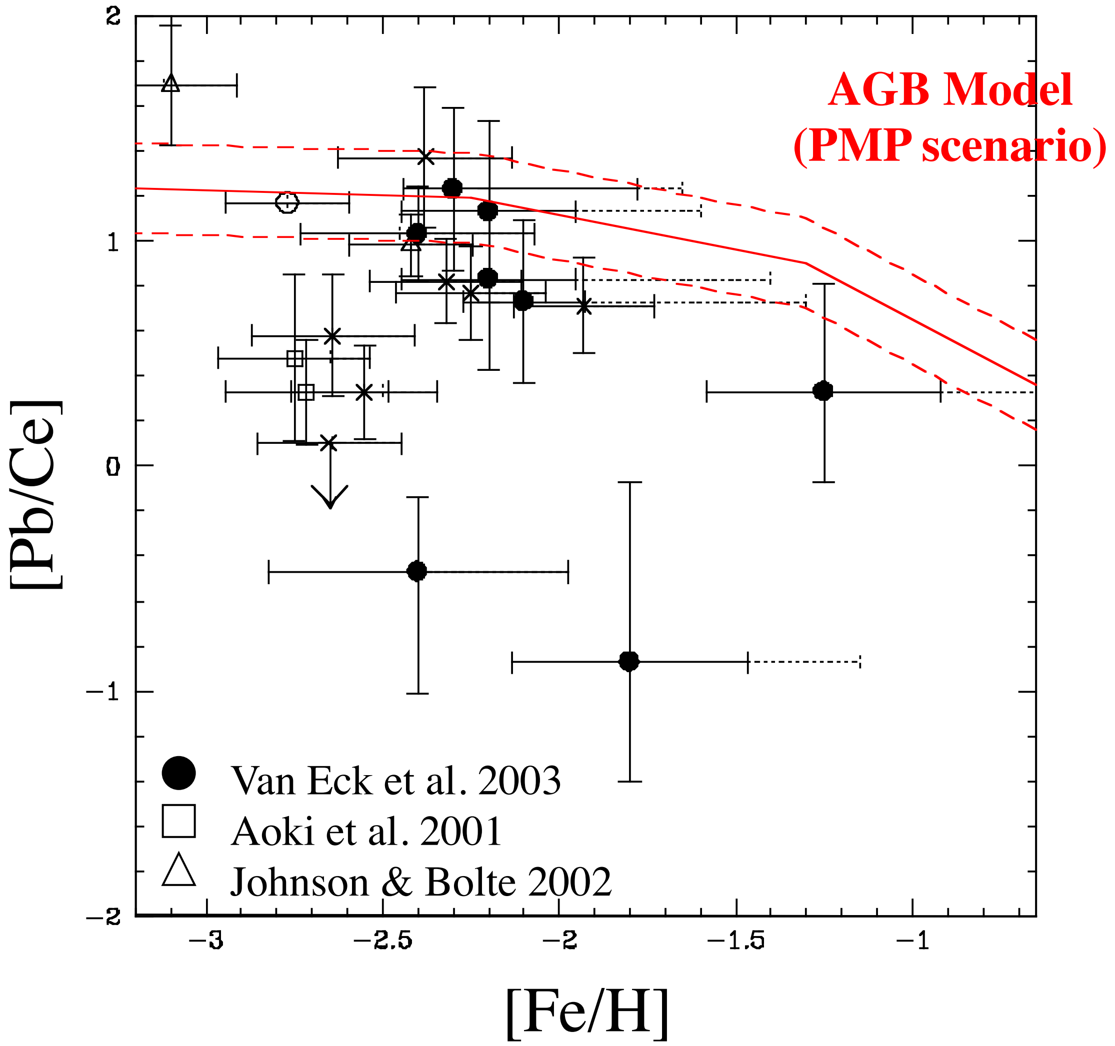
within the PMP model, *all Z<0.001 s-process-enriched* stars should present a surface Pb overabundance ([Pb/hs]≈1)



Confirmation by the observation of Pb-stars

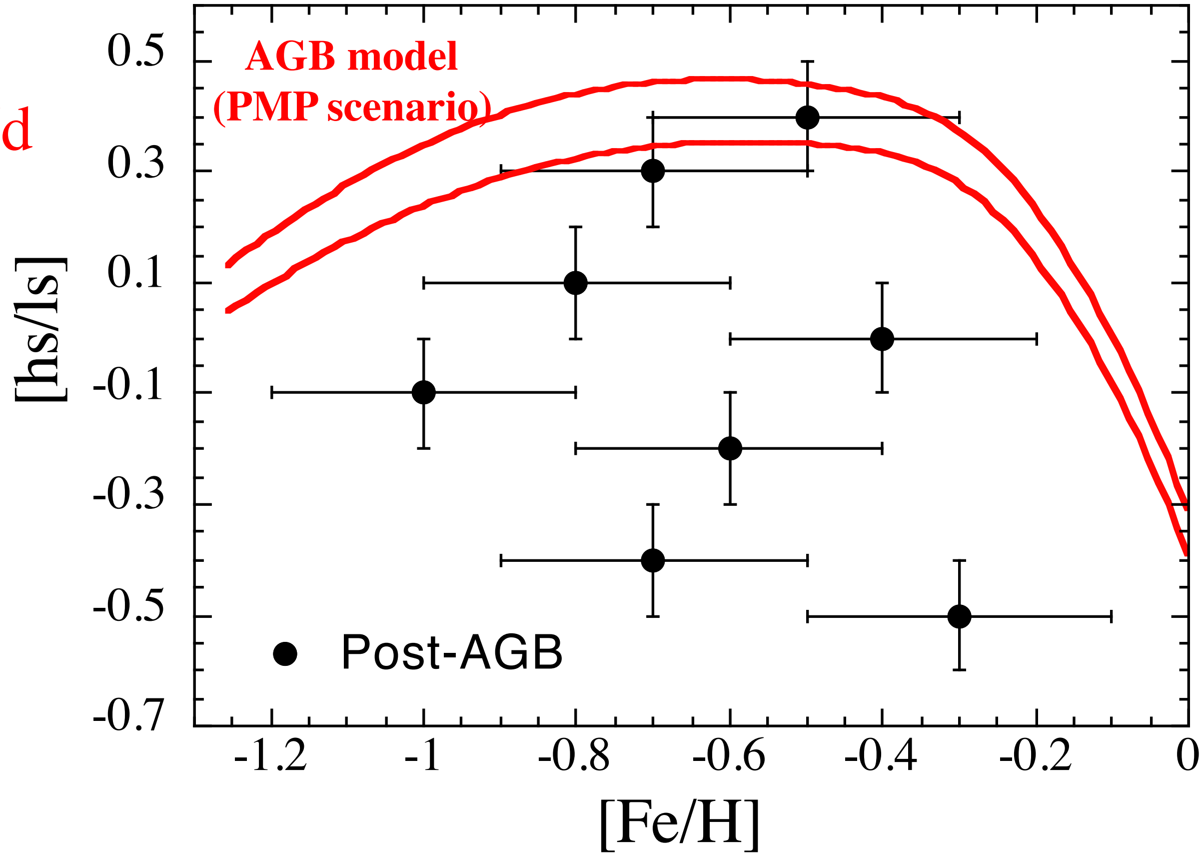


But all Z<0.001 s-process-rich stars are NOT Pb-stars



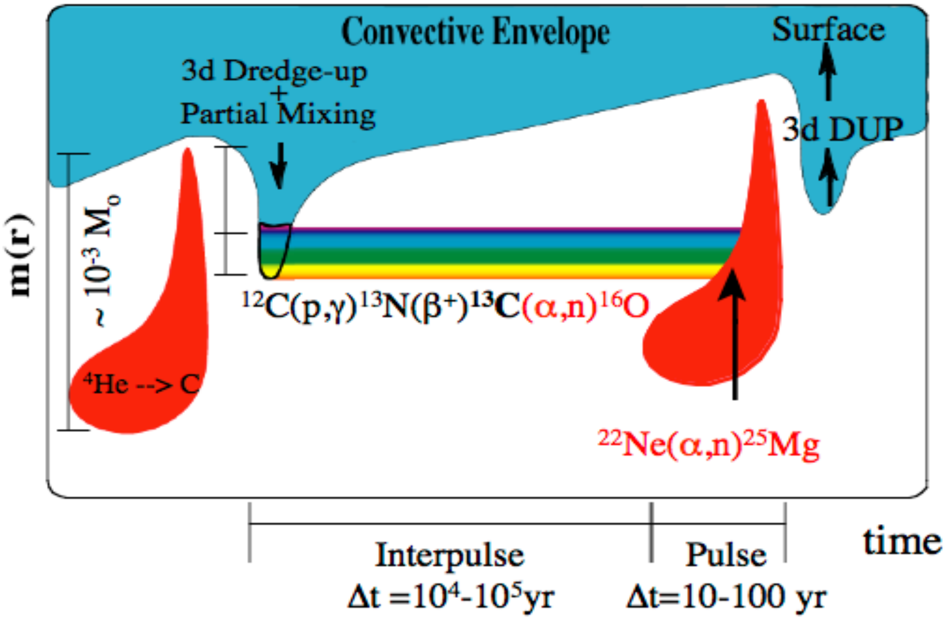
S-process enrichment is not only sensitive to the stellar metallicity

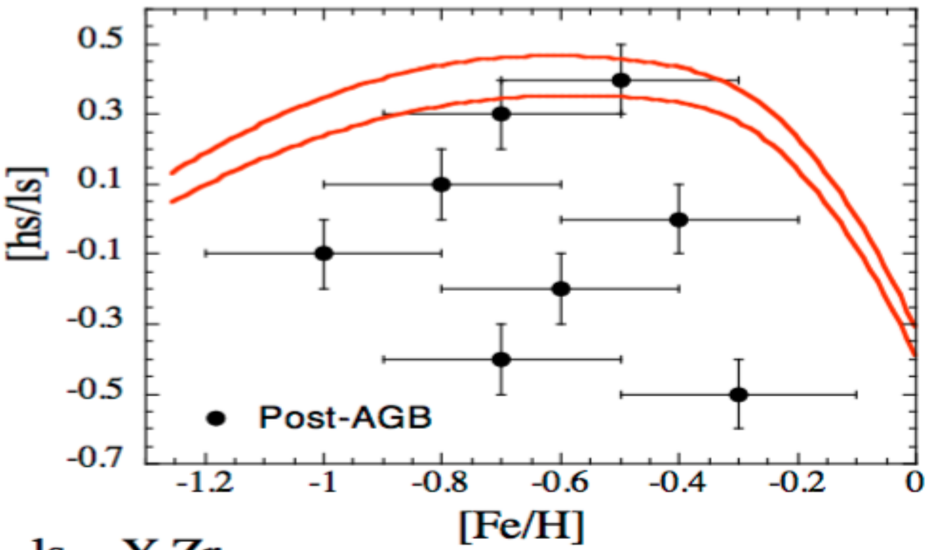
ls ~ Y, Zr
hs ~ Ba, La, Nd



The s-process nucleosynthesis is responsible for the other half the elements heavier than iron in the Universe

- How are the neutrons produced in AGB stars (mixing) ?
- What is the contributions stemming from intermediate mass AGB stars ($M > 4\ M_o$) ?
- How to explain specific observations, *i.e.* large variation of ^{13}C-pockets ?
- (n,γ) and *T*-dependent β-decay rates of branching points ?

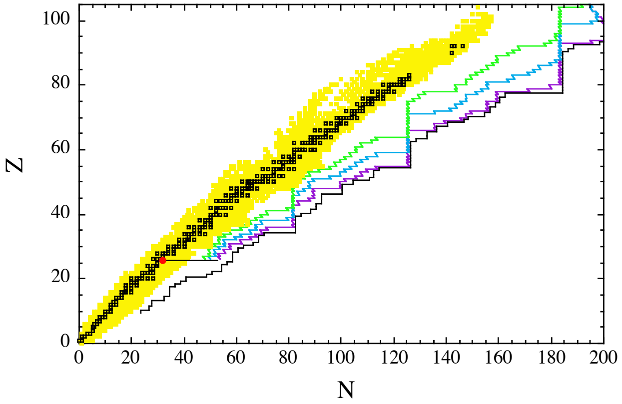




ls ~ Y,Zr
hs ~ Ba,La,Nd

The r-process nucleosynthesis

The r-process nucleosynthesis



Rapid neutron capture process characterized by

- $N_n >> 10^{20}$ cm^{-3}
- $T \sim 10^9$ K (?)
- $t \sim 1$ s

The conditions are such that the $\tau_\beta > \tau_{(n,\gamma)}$ & $\tau_{(\gamma,n)}$

--> the nuclear flow goes deep into the exotic n-rich region

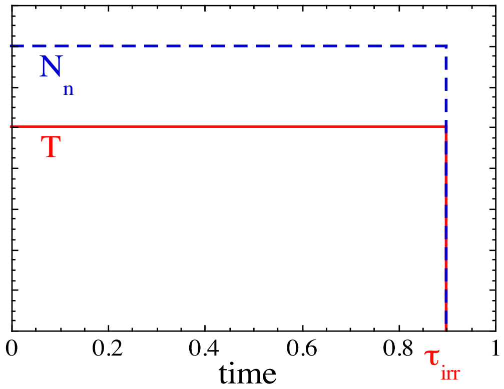
1. **Astrophysics aspects**
    - Parametric models: "canonical" site-independent models
    - "Realistic" models: Supernova explosion: ν-driven wind
      Decompression of initially-cold neutron star matter

BUT THE ASTROPHYSICS SITE REMAINS UNKNOWN !!!

2. **Nuclear Physics aspects:**
    - Neutron captures
    - Photodisintegration rates
    - Beta-decays
    - Fission (neutron-induced, β-delayed, spontaneous) rates
    - ν-nucleus interaction rates

    for ~5000 thousands of exotic neutron-rich (experimentally unknown) nuclei

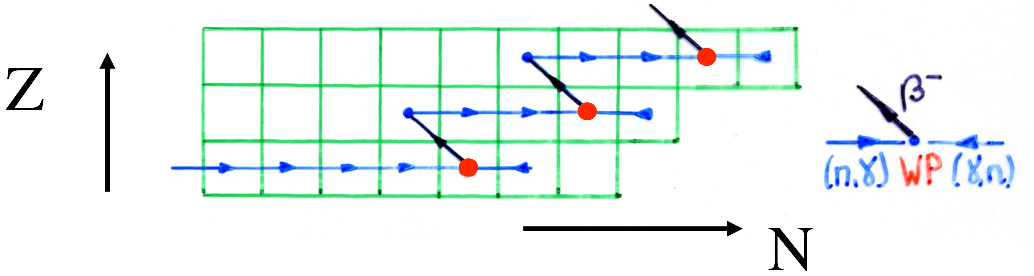
The canonical r-process model



A purely phenomenological site-independent approach is followed. The model assumes

- the temperature T and neutron density N_n remain constant during the time of irradiation ($t \leq \tau_{\rm irr}$) and drop to zero for $t > \tau_{\rm irr}$
- the seeds for neutron captures is made entirely of ^{56}Fe
- the thermodynamic conditions are such that

$$\left.\begin{array}{l} \tau_\beta >> \tau_{(n,\gamma)} \\ \tau_\beta >> \tau_{(\gamma,n)} \end{array}\right\}$$ (n,γ) – (γ,n) equilibrium can be established, implying a high T and N_n



This assumption is called the "waiting point" approximation (WPA)

If the strong and electromagnetic interactions can occur in a much faster time scale than the weak interactions, an (n,γ)–(γ,n) equilibrium can be reached for each isotopic chain, before any β-decay can take place. This approximation allows us to neglect the small β-decay rates to the first order, so that the abundance equation for the nucleus (Z,A) becomes

$$\frac{dN(Z,A)}{dt} = \lambda_{\gamma,n}^{Z,A+1} N(Z,A+1) - N_n \langle \sigma v \rangle_{Z,A} N(Z,A)$$

As soon as the equilibrium is established, $dN(Z,A)/dt=0$ and the abundance ratio of two isotopes is determined by the ratio of the two nuclear rates:

$$\frac{N(Z,A+1)}{N(Z,A)} = \frac{\langle\sigma v\rangle_{Z,A}}{\lambda_{\gamma,n}^{Z,A+1}} N_n$$

The detailed balance between two inverse reactions can be written in terms of the temperature and the Q-value

$$\frac{\langle\sigma v\rangle_{Z,A}}{\lambda_{\gamma,n}^{Z,A+1}} = \frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} e^{\frac{S_n(Z,A+1)}{kT}}$$

where $G(Z,A)$ is the partition function of nucleus (Z,A) at the temperature T, m_u the nuclear mass unit and S_n the neutron separation energy.

This leads to the well known Saha equation relating the abundance ratio of two isotopes in terms of T, N_n and S_n

$$\boxed{\log\frac{N(Z,A+1)}{N(Z,A)} = \log\frac{G(Z,A+1)}{G(Z,A)} + \log N_n - 34.075 - \frac{3}{2}\log\left(\frac{A+1}{A}T_9\right) + \frac{5.04}{T_9} S_n(Z,A+1)}$$

where S_n is expressed in MeV, T_9 in 10^9K and N_n in cm^{-3}

This expression explains why the approximation is called the "waiting point" approximation (WPA). Because of the exponential dependence on S_n, the abundance ratios in each isotopic chain will vary sharply around a particular value of the neutron separation energy.
At maximum, $N(Z,A) \sim N(Z,A+1)$ and the corresponding *"waiting point"* will in turn depend on the thermodynamic conditions (T,N_n). These peaks for each element constitute what is called the r-process path.
For each isotopic chain, the nucleus with maximum abundance (the "waiting point") must then wait for the slower β-decay to take place.

Due to the odd-even effects characterizing the neutron speration energy S_n, the abundance ratio is usually calculated for two even-N isotopes, leading to

$$\frac{1}{2}\log\frac{N(Z,A)}{N(Z,A-2)}=\frac{1}{2}\log\left[\left(\frac{A}{A-2}\right)^{3/2}\frac{G(Z,A)}{G(Z,A-2)}\right]+\log N_n-34.075-\frac{3}{2}\log T_9+\frac{5.04}{T_9}\frac{S_{2n}(Z,A)}{2}$$

where $S_{2n}=M(Z,A\text{-}2)+2M_n-M(Z,A)$ the 2-neutron separation energy. Neglecting the partition function ratio, we can express the r-process path as a function of the "astrophysical" factor $S_a(T_9,N_n)$ (in MeV):

$$\boxed{\frac{S_{2n}(Z,A)}{2}=S_a(T_9,N_n)=\left[34.075-\log N_n+\frac{3}{2}\log T_9\right]\frac{T_9}{5.04}}$$

The relative isotope abundances in each Z-chain can be characterized by the coefficients

$$P(Z,A)=\frac{N(Z,A)}{N(Z)}$$

where the total abundance in the isotopic chain Z is given by $N(Z)=\sum_A N(Z,A)$

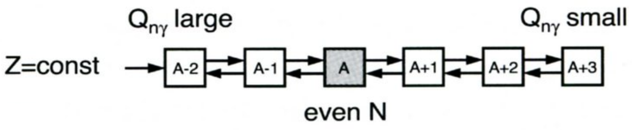
The abundance flow from one isotopic chain to the next is governed by β-decays and can be described, omitting the fission feedback, by the set of differential equations

$$\frac{dN(Z)}{dt}=N(Z-1)\sum_A P(Z-1,A)\lambda_\beta^{Z-1,A}-N(Z)\sum_A P(Z,A)\lambda_\beta^{Z,A}$$

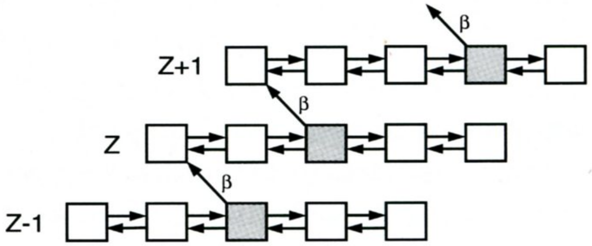
So, within the waiting point approximation, instead of solving a system of differential equations for all nuclei involved, it is sufficient to solve a system which contains only as many equations as the number of Z-chains. This feature used to constitute the main reason for the popularity of the WPA.

$$\boxed{\frac{S_{2n}(Z,A)}{2} = S_a(T_9,N_n) = \left[34.075 - \log N_n + \frac{3}{2}\log T_9\right]\frac{T_9}{5.04}}$$

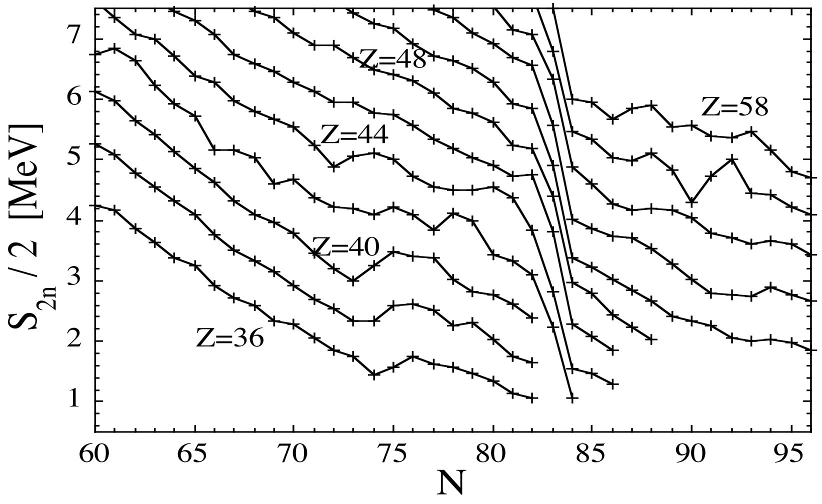
r-process path within an isotopic chain

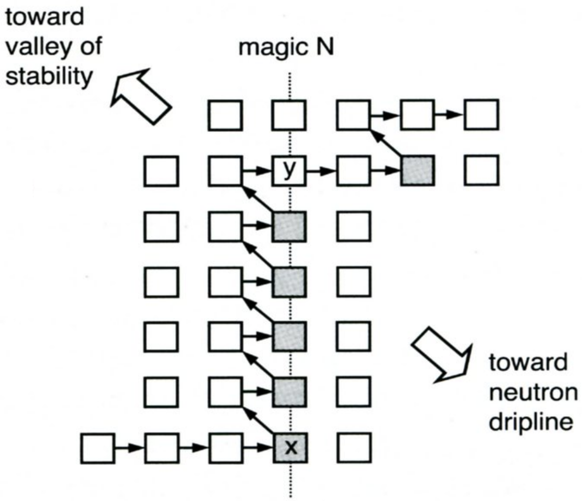


r-process path from one isotopic chain to the next

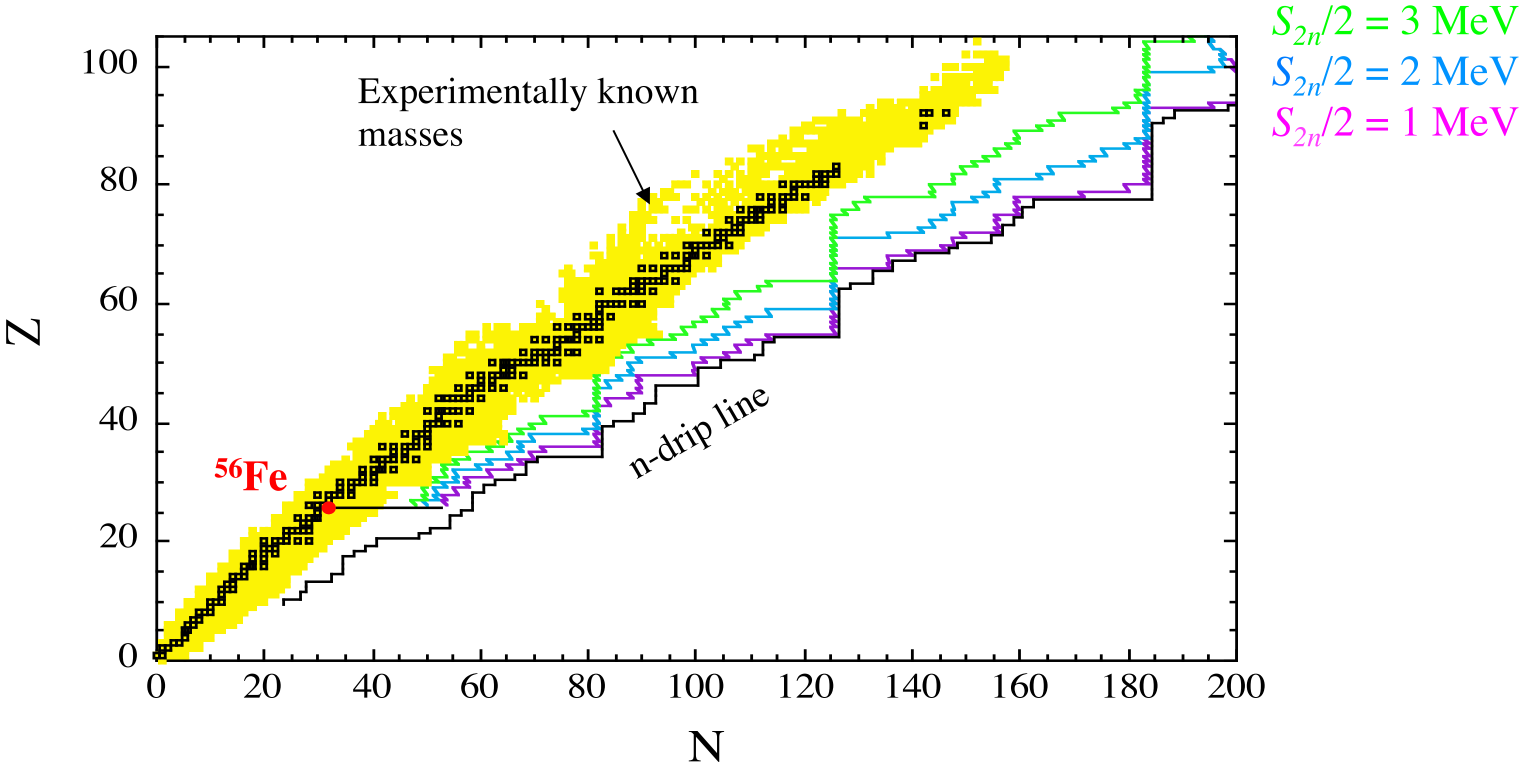


r-process path in the region of a magic number





The r-process path for (T_9,N_n) conditions such that $S_a(T_9,N_n) = S_{2n}/2$



$$\boxed{\frac{S_{2n}(Z,A)}{2} = S_a(T_9,N_n) = \left[34.075 - \log N_n + \frac{3}{2}\log T_9\right]\frac{T_9}{5.04}}$$

OLD approach : 3 solar r-process peaks <--> 3 canonical events (T_9,N_n,τ_{irr})

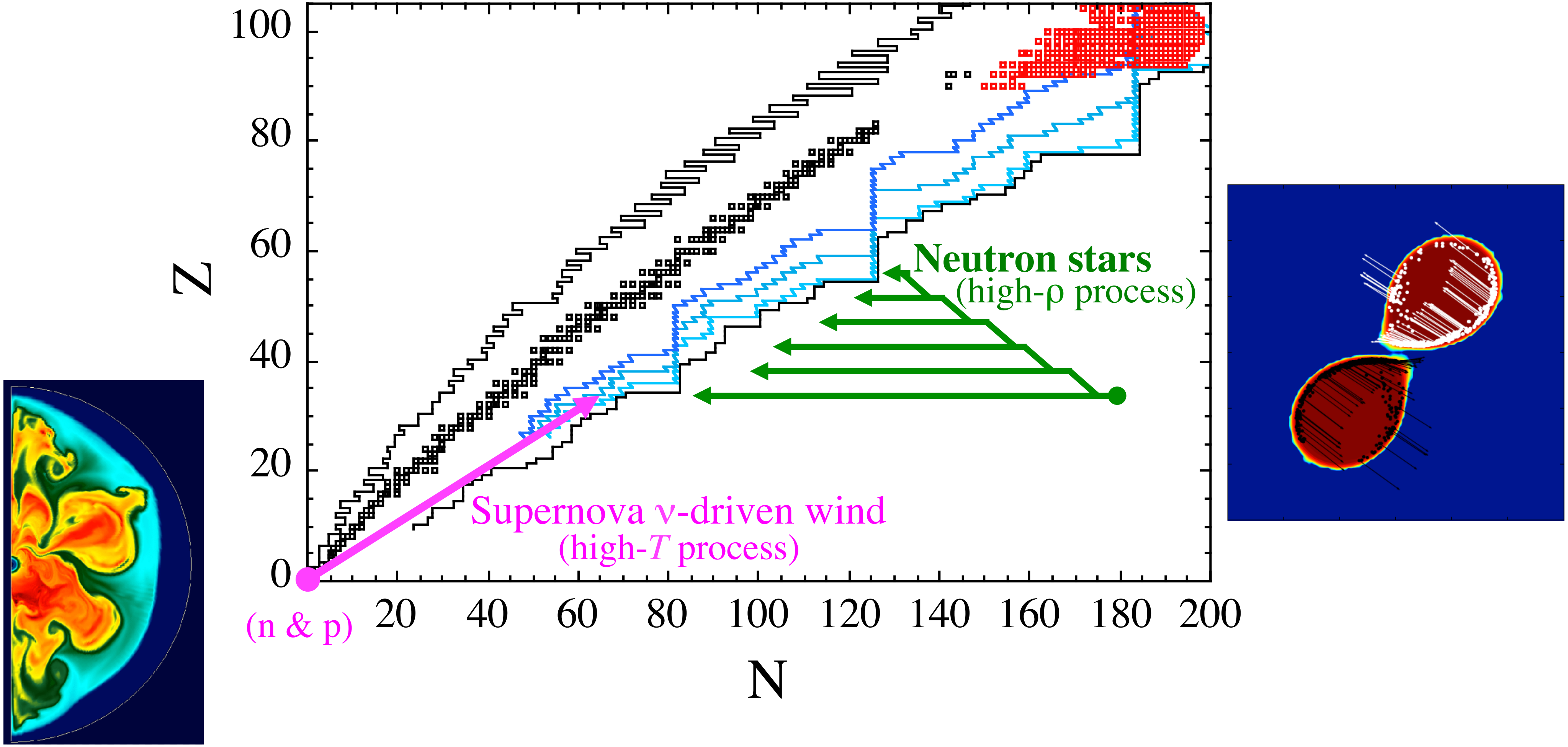
The canonical model is an interesting training tool, but NOT a realistic model !!

Forget about ”THE waiting points”, “THE r-process path” → Nature is more complex

The r-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

one of the still unsolved puzzles in nuclear astrophysics

… the r-process site remains unknown ...

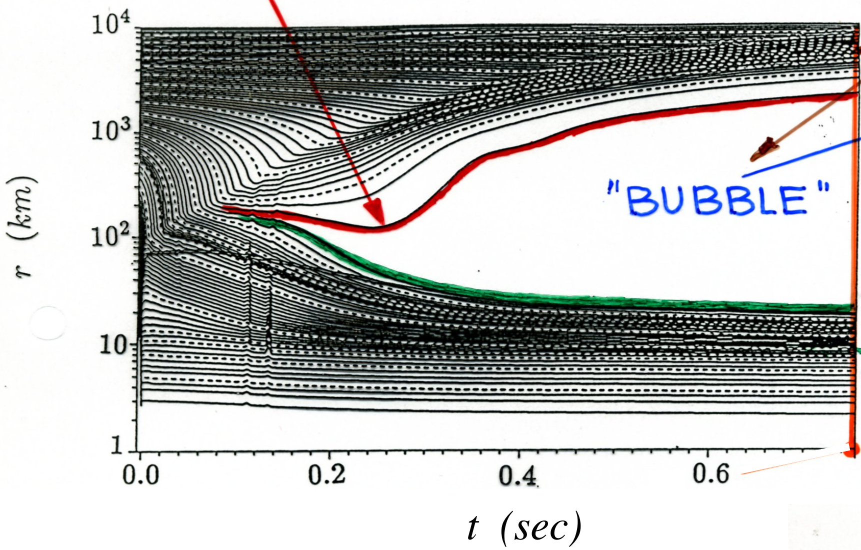


Neutron stars
(high-ρ process)

Supernova ν-driven wind
(high-*T* process)

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

SHOCK ENERGIZED BY ENERGY/MOMENTUM DEPOSITION BY ν'S FROM NASCENT NEUTRON STAR $(n+\nu_e\,;\,p+\bar{\nu}_e)$

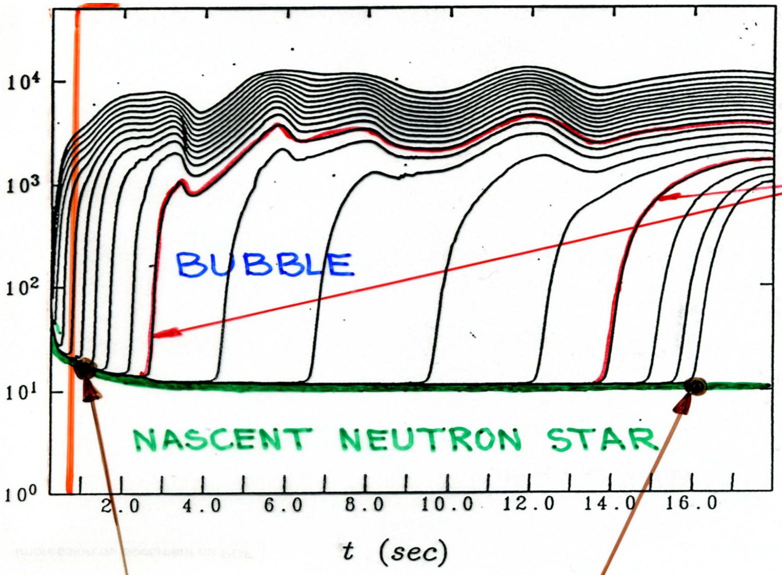


EJECTA

HIGH T, LOW ρ

"BUBBLE" → HIGH $s \propto T^3/\rho$

NASCENT NEUTRON STAR



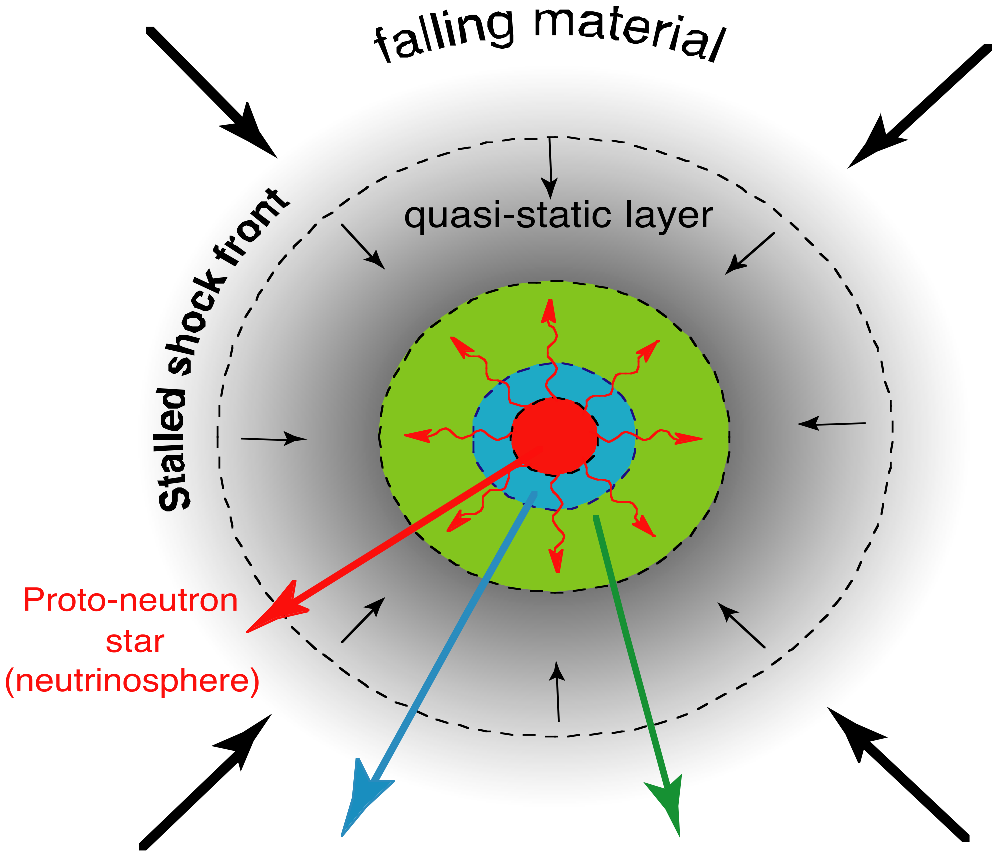
ν-DRIVEN BARYON WIND FROM NEUTRON STAR

A LARGE VARIETY OF T, ρ (s) IN NEUTRINO WIND

$\dot{M} \approx 10^{-3}\, M_\odot\, s^{-1}$

$\dot{M} \approx 10^{-6}\, M_\odot\, s^{-1}$ ⟶ $\approx 0.03\, M_\odot$ LOST

Nucleosynthesis in the ν-driven wind



Proto-neutron star (neutrinosphere)

Region cooled by neutrinos
$p + e^- \to n + \nu_e$
$n + e^+ \to p + \nu_e$
$e^- + e^+ \to \nu + \nu$

Region heated by neutrinos
$n + \nu_e \to p + e^-$
$p + \nu_e \to n + e^+$
$\nu + e^{+/-} \to \nu + e^{+/-}$

Decompression of hot material

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

↓ NSE

^{4}He recombination

↓ $\alpha\alpha n$-^{9}Be(α,n)

^{12}C bottleneck

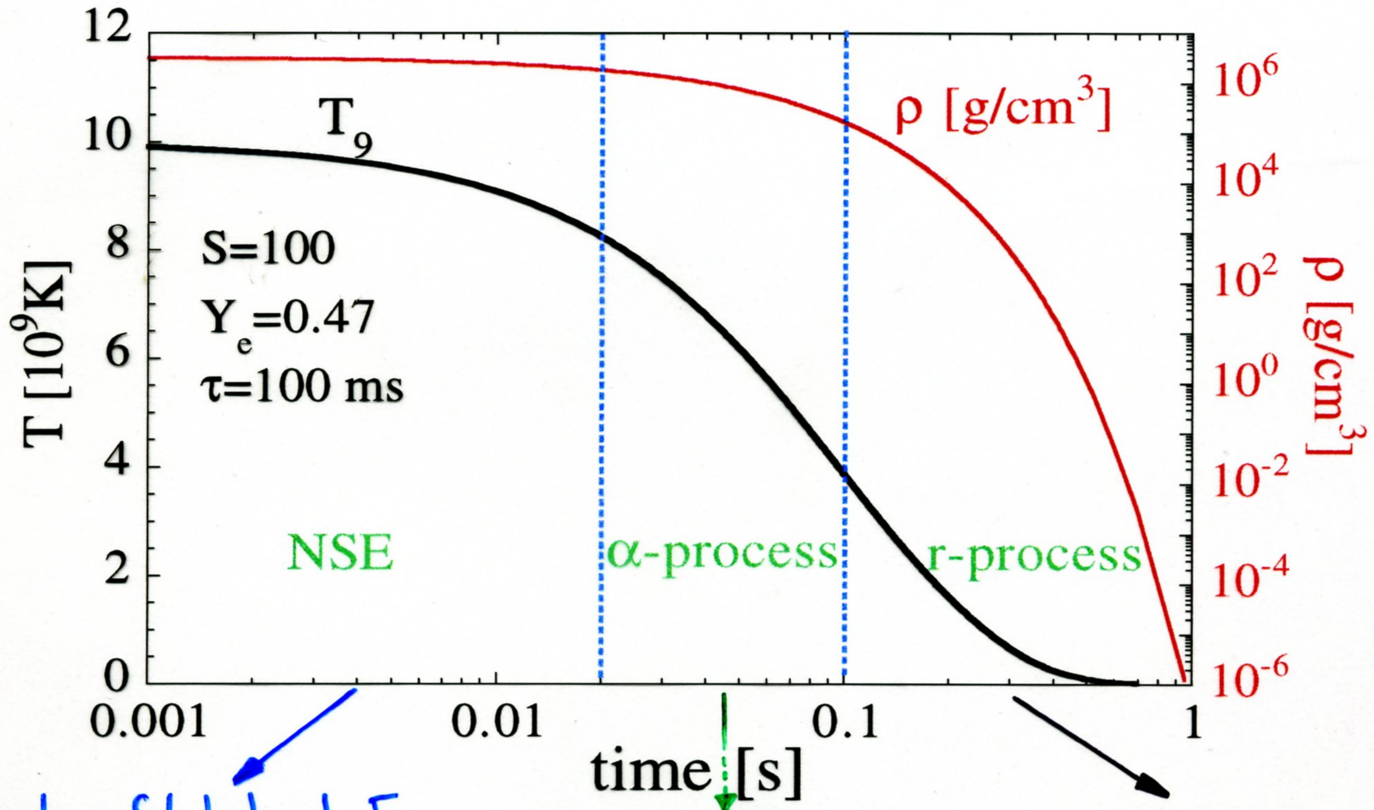
↓ (α,γ) & (α,n)

$60 \leq A \leq 100$ seed

↓ (n,γ) & (γ,n) + β-decays

r-process

The α+r process in the ν-driven wind



Nuclear Statistical Eq.

$(a,b) \leftrightharpoons (b,a)$

but no weak equilibrium

$n + \nu_e \rightarrow p + e^-$

$p + \bar{\nu}_e \rightarrow n + e^+$

→ Y_e; n, p, α

α-process

$3\alpha \rightarrow {}^{12}C$

$\alpha(\alpha,n){}^{9}Be(\alpha,n){}^{12}C$

${}^{12}C(n,\gamma){}^{13}C(\alpha,n)\ldots$

$(\alpha,n) + (n,\gamma)$

$60 \leq A \leq 110$

r-process

$(n,\gamma) \leftrightharpoons (\gamma,n)$

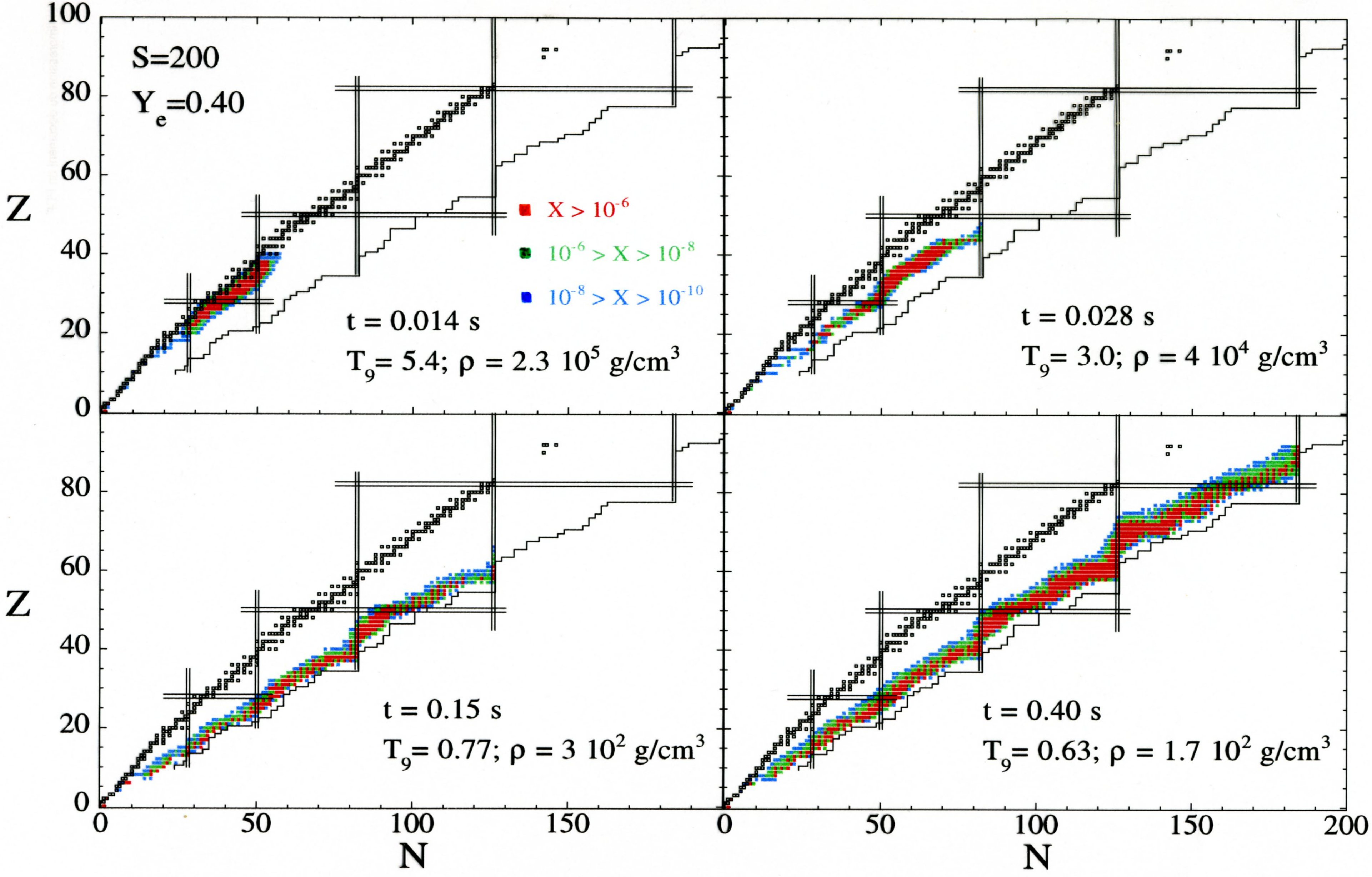
β^--decays

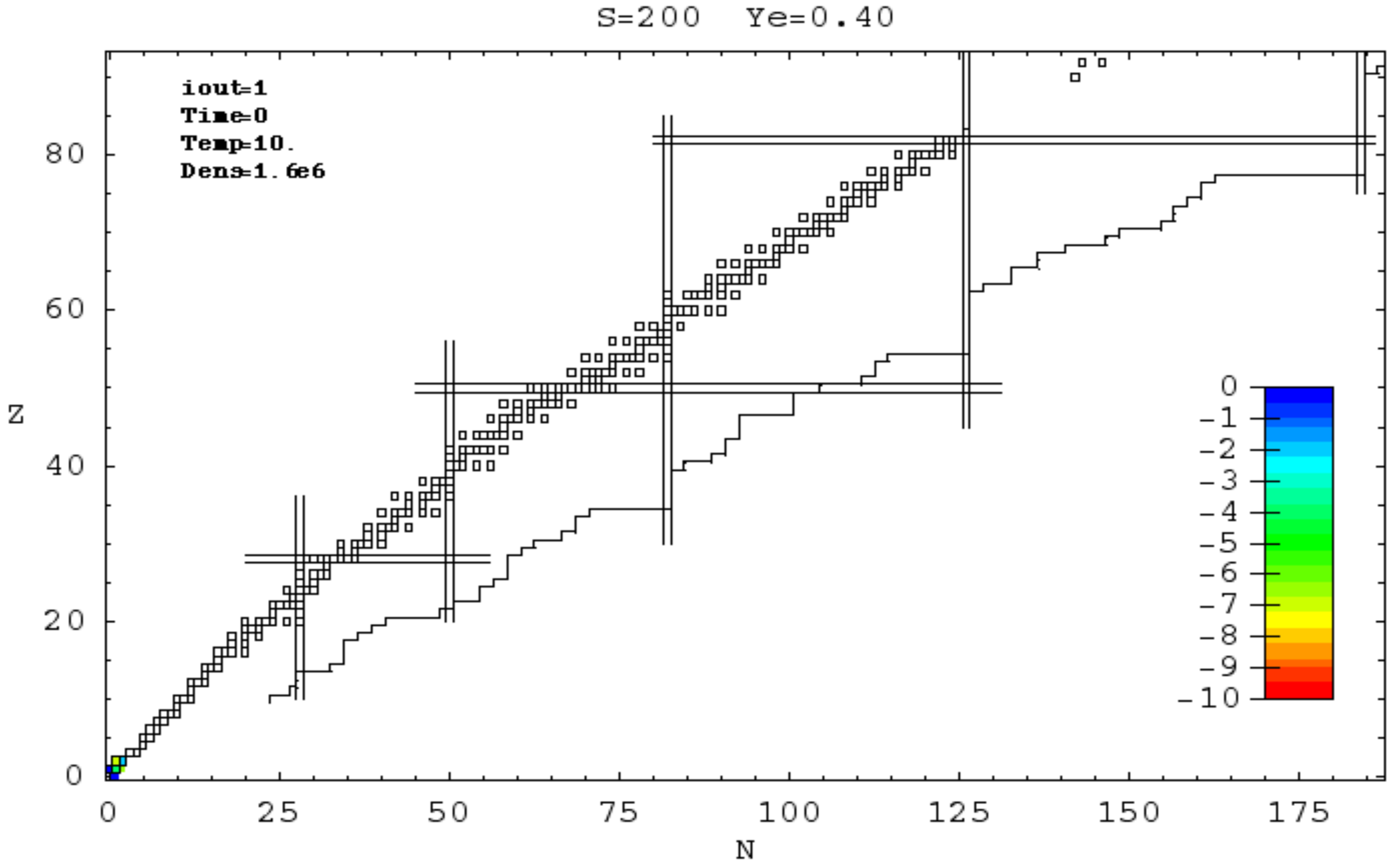
Y_n / Y_{seed} large

→ r-nuclei

A ~ 130 - 195

Nuclear flow during the α+r process in the ν-driven wind

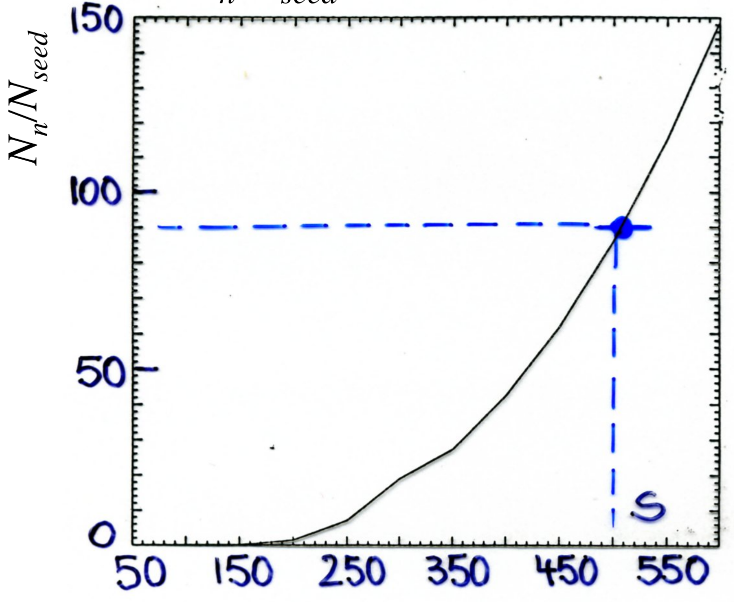



S=200 Ye=0.40
iout=1
Time=0
Temp=10.
Dens=1.6e6
Z
N
0
20
40
60
80
0
25
50
75
100
125
150
175
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

But the r-process is possible only if the number of neutrons per seed nuclei N_n/N_{seed} is high enough at freeze-out of the α-process

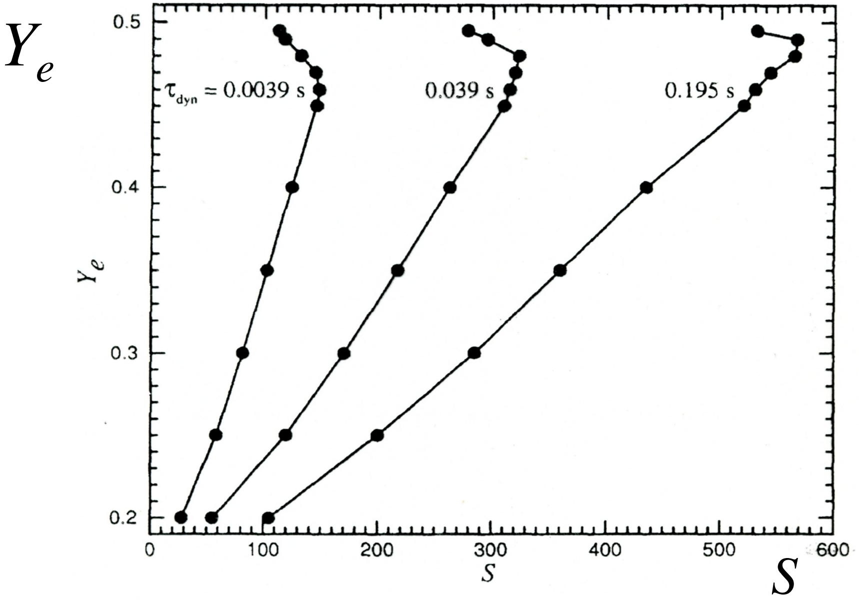
--> the r-process yields are highly sensitive to the entropy S, the electron fraction Y_e and the expansion timescales τ_{dyn}

To produce the 3d r-process peak around Pt, $N_n/N_{seed} \sim 100$ --> $S \sim 500$



Entropy S

Conditions for a successful r-process to be fulfilled in the (S, Y_e, τ_{dyn}) plane



Typical conditions in the ν-driven wind $S \propto \frac{T^3}{\rho} \leq 100$ $Y_e = \frac{Y_p}{Y_p + Y_n} \approx 0.47$ $\tau_{dyn} = 100\text{ms}$

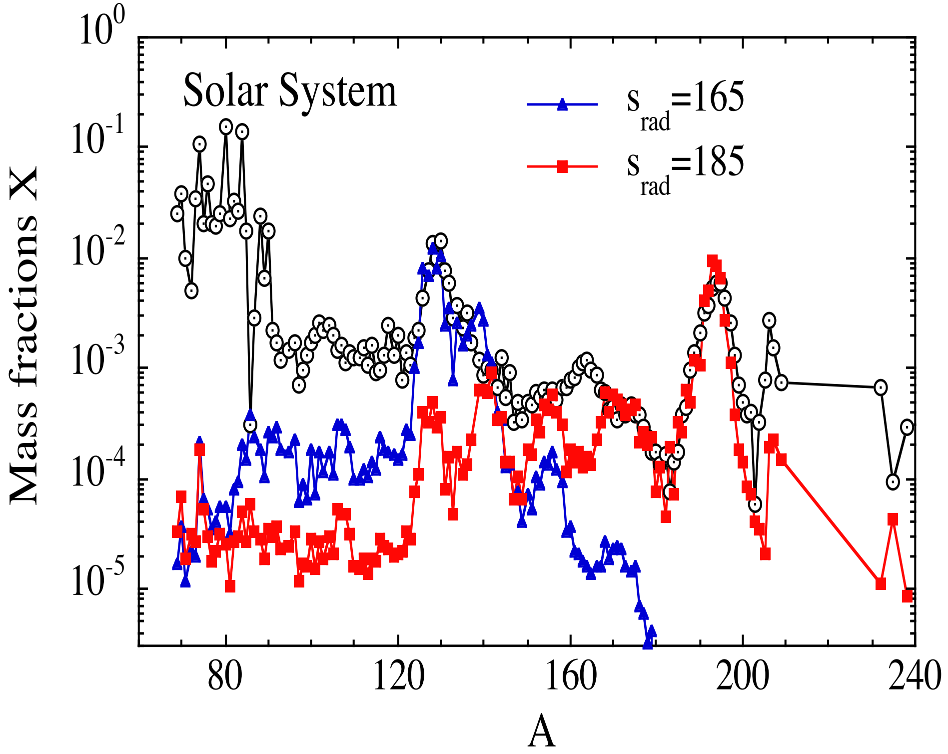
No r-process in realistic hydrodynamical simulations: conditions for a successful r-process (high N_n/N_{seed})

- **High entropy wind (hight-T, low-ρ): Increase S** **$S \sim 500$**
- **Low Y_e wind (n-rich matter): Lower Y_e** **$Y_e \sim 0.3$**
- **Fast expansion: lower τ_{dyn}** **$\tau_{dyn} \sim 10$ ms**

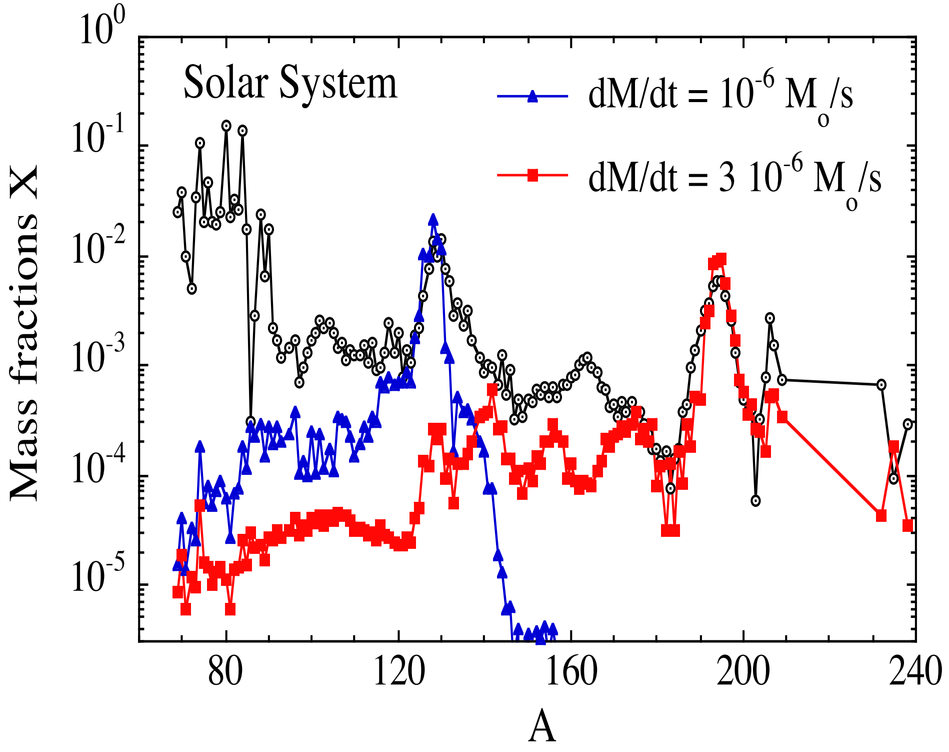
High sensitivity of the r-process nucleosynthesis to the wind conditions

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



different mass loss rates (--> τ_{irr})
same entropies: s_{rad}=200



Myriad of "pseudo-realistic" astrophysics conditions:

"Standard" (non-exploding) type-II Supernovae ---> no r-process

- electron-capture supernova of intermediate-mass (9-10M_o) stars
- Simulations including relativistic effects
- Massive Proto-Neutron star (~2M_o)
- ν-oscillations at the "right" time with the "right" properties
- Explosion & nucleosynthesis triggered by modified ν-properties
- etc …

New hope from asymmetric (bipolar) Jet Supernovae triggered by

- fluid instabilities (standing-accretion-shock instability)
- acoustic power
- rotation and/or magnetic fields

---> Hypernovae, supranovae, collapsars, AIC, γ-ray bursts (long & short), …

r-process calculations in the ejected wind based on

- post-processing with simplified tracks (S=cst, Y_e=cst, v_r=cst)
- parametrized tracks (for a successful r-process):

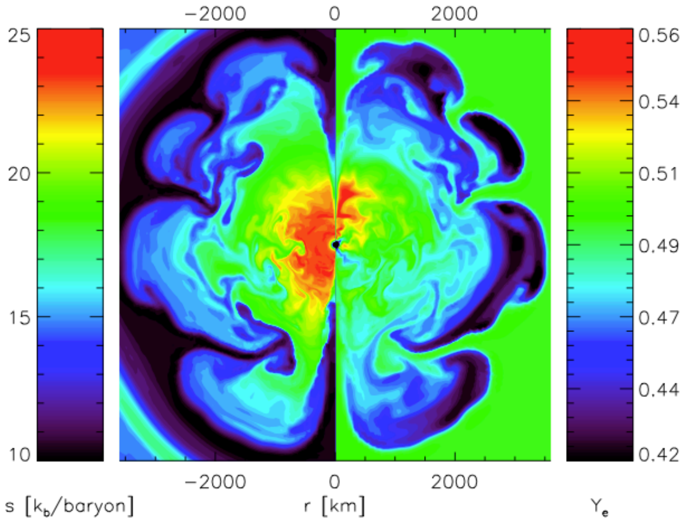
Newtonian, adiabatic, steady-state wind & breeze solutions

→ analytical profile depending on assumptions made

→ various degrees of sophistication

2D hydrodynamical (successful) explosion of an Electron-Capture Supernova (M_i=9M_o)

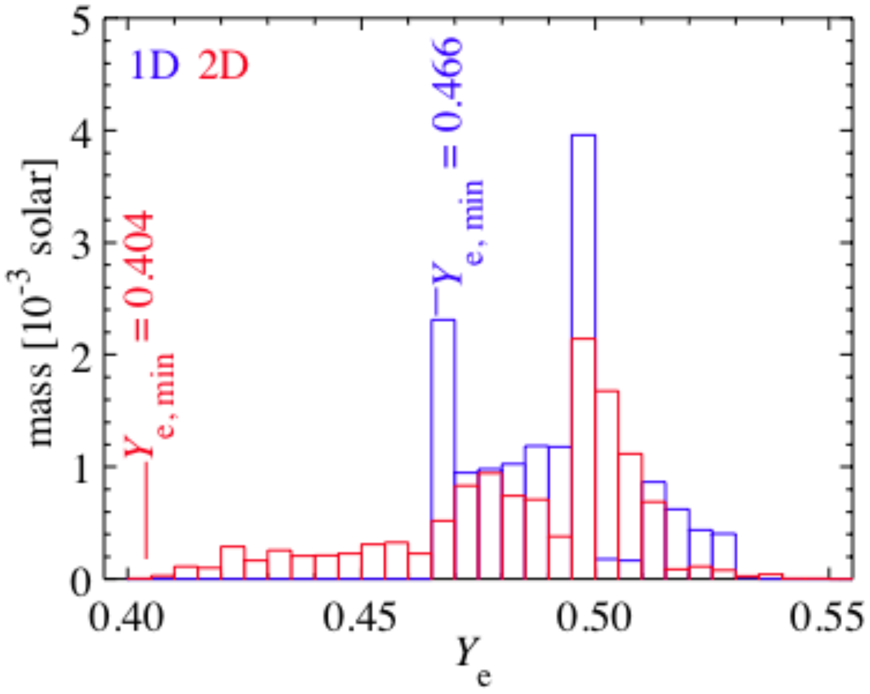
(Wanajo, Janka & Müller, 2011)

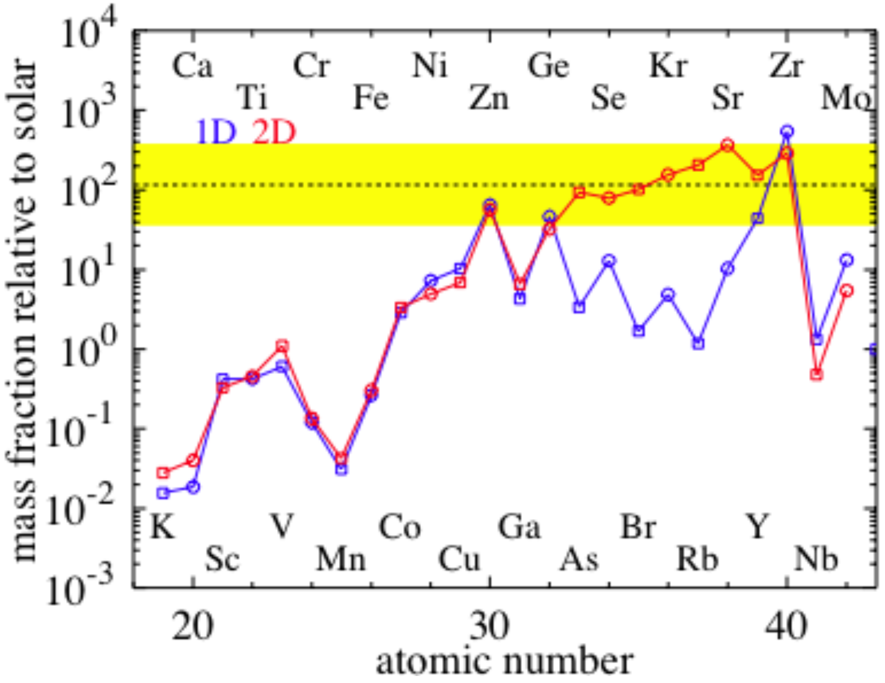


ECSN ~4% of all stellar core-collapse events

$Y_{e,min}$=0.40 --> Synthesis between Zn and Zr

Nuclear Quasi-Equilibrium
with abundant α-particles **(no r-process !!)**





2D/3D MHD jet-like explosion of magnetically driven core-collapse supernovae

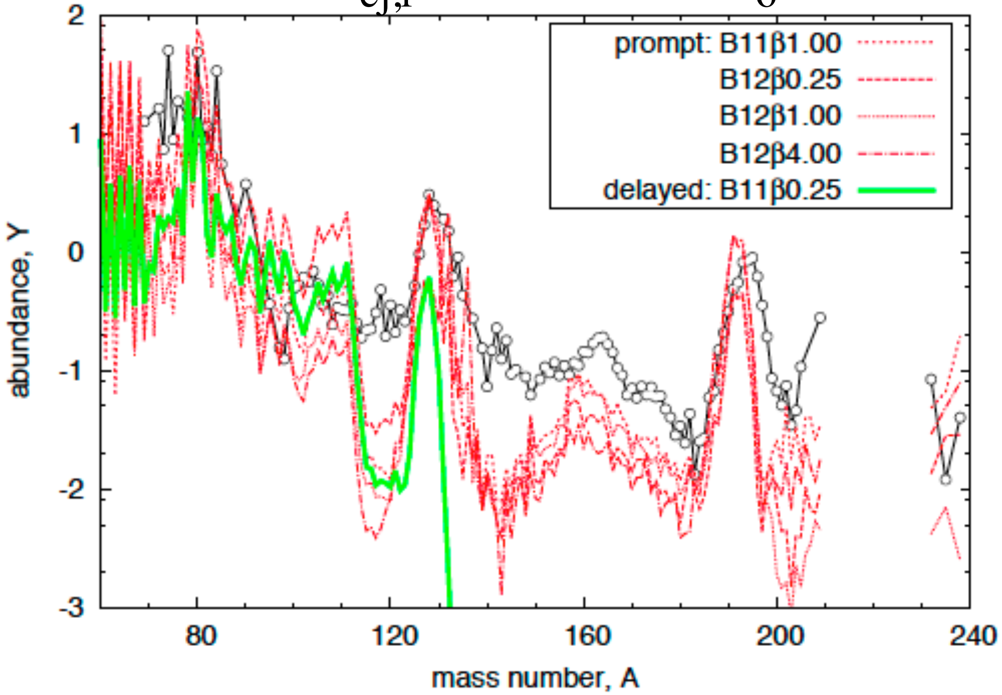
(Winteler et al. 2012; Mösta et al. 2014; Nishimura et al. 2015)

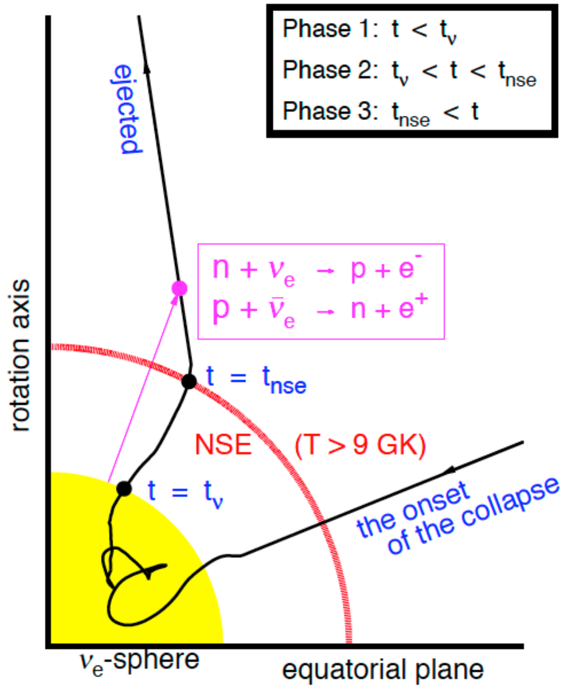
Pre-collapse core with **strong** initial magnetic fields and rapid rotation (→ highly magnetized NS with $B\sim10^{15}$G) – rare events $P\sim$ 0.01–0.1% of all SNe)

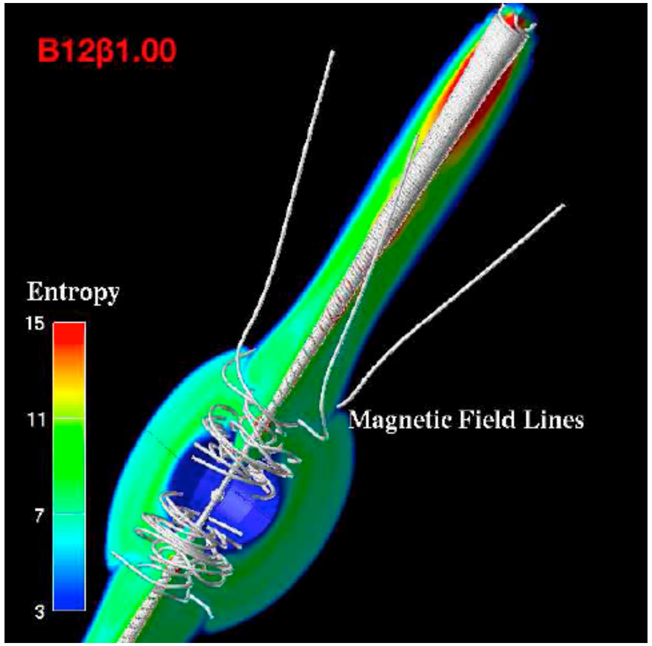
$B_0=10^{11}$G→ Synthesis up to A~130

$B_0=10^{12}$G→ Synthesis up to Th/U

$M_{ej,r} \sim$ 1-2 10^{-2} M_o

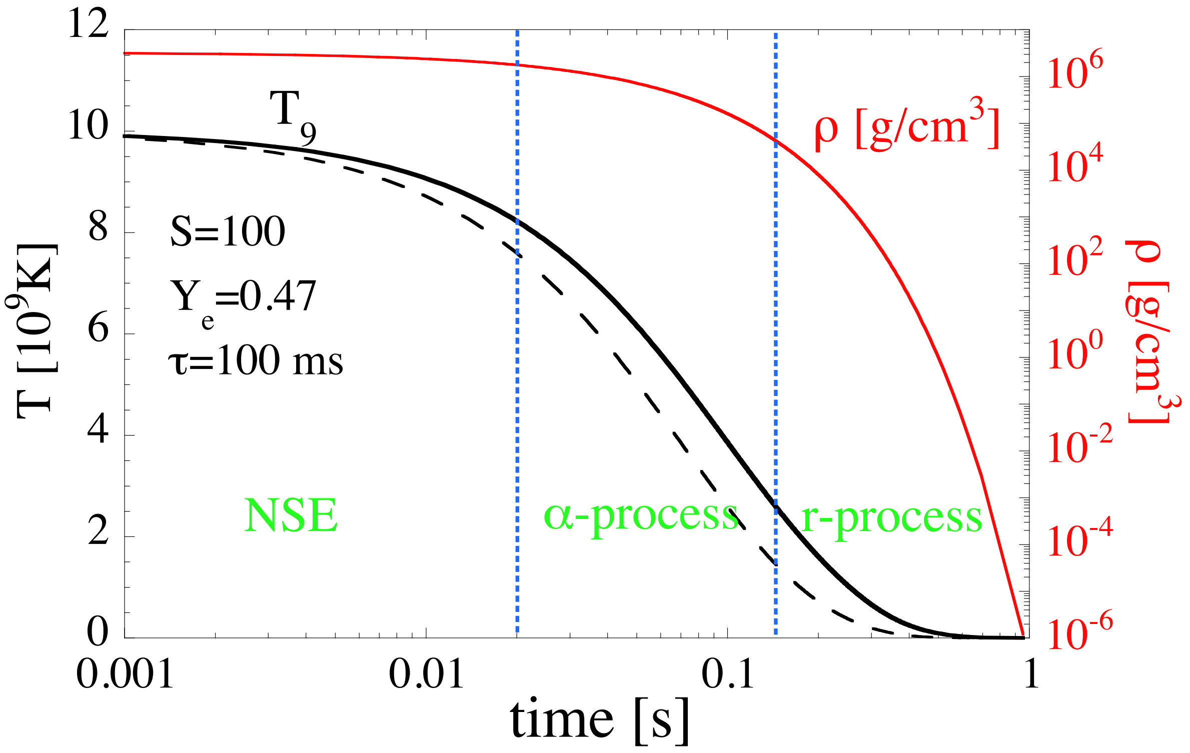






Cold versus Hot r-process

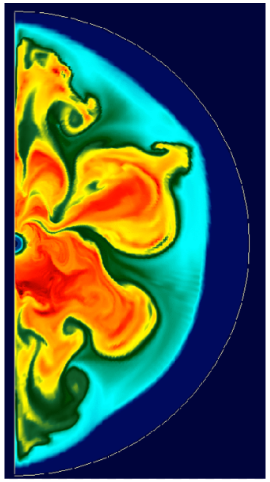
(n,γ)-(γ,n) equilibrium depending on the *T* and N_n at the time of the r-process

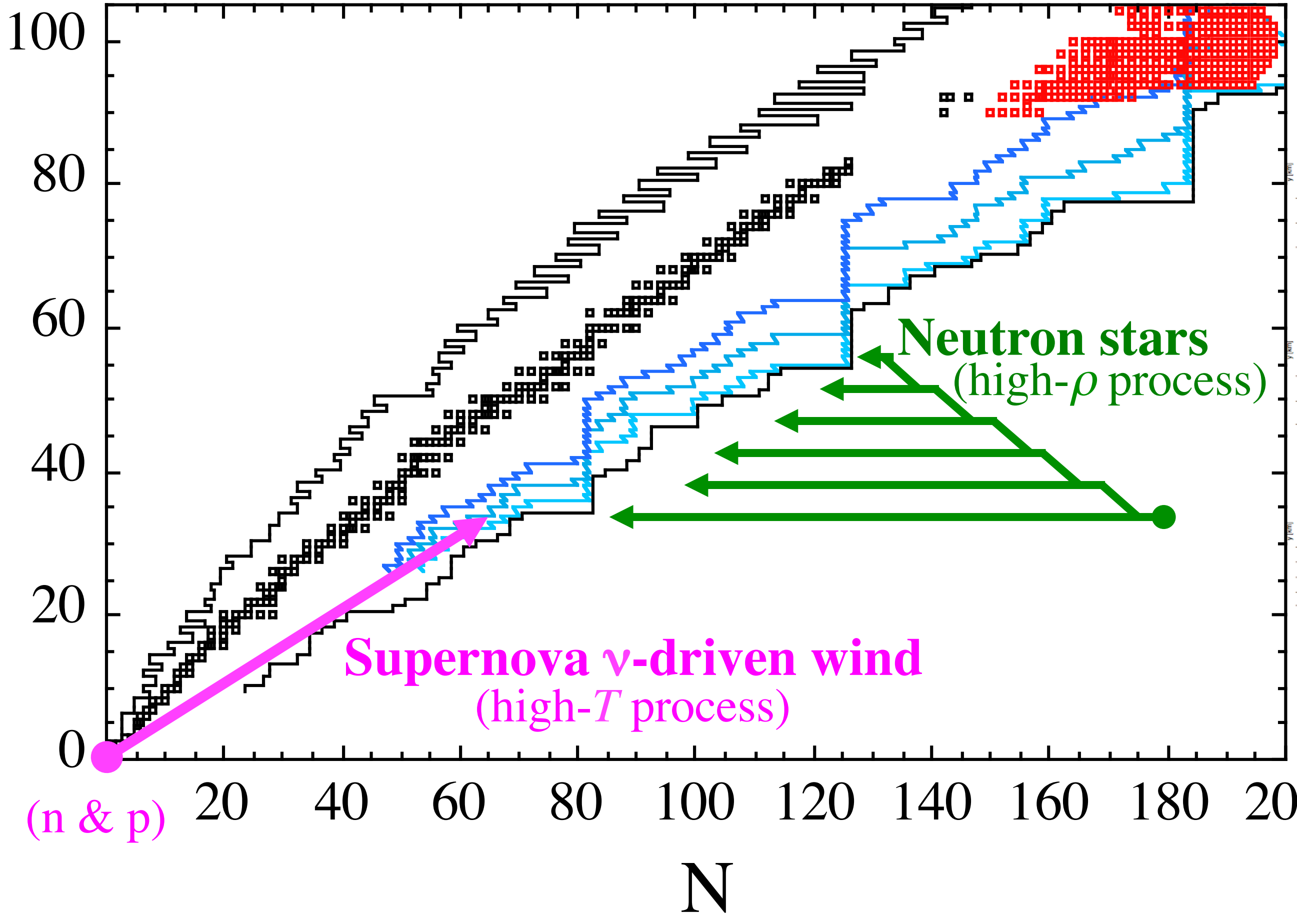


Nuclear needs:
- neutron capture versus photodisintegration **rates** (non-equil; freeze-out)
- β-decay rates (including delayed processes)
- ν-induced (NC, CC) reaction rates
- Fission properties ?

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

(initial conditions: high-density matter)

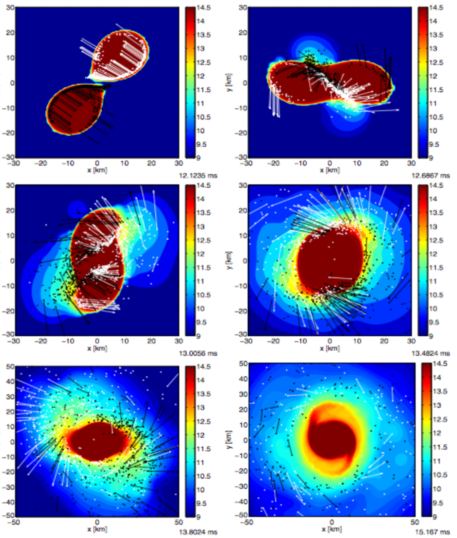




Neutron stars
(high-ρ process)

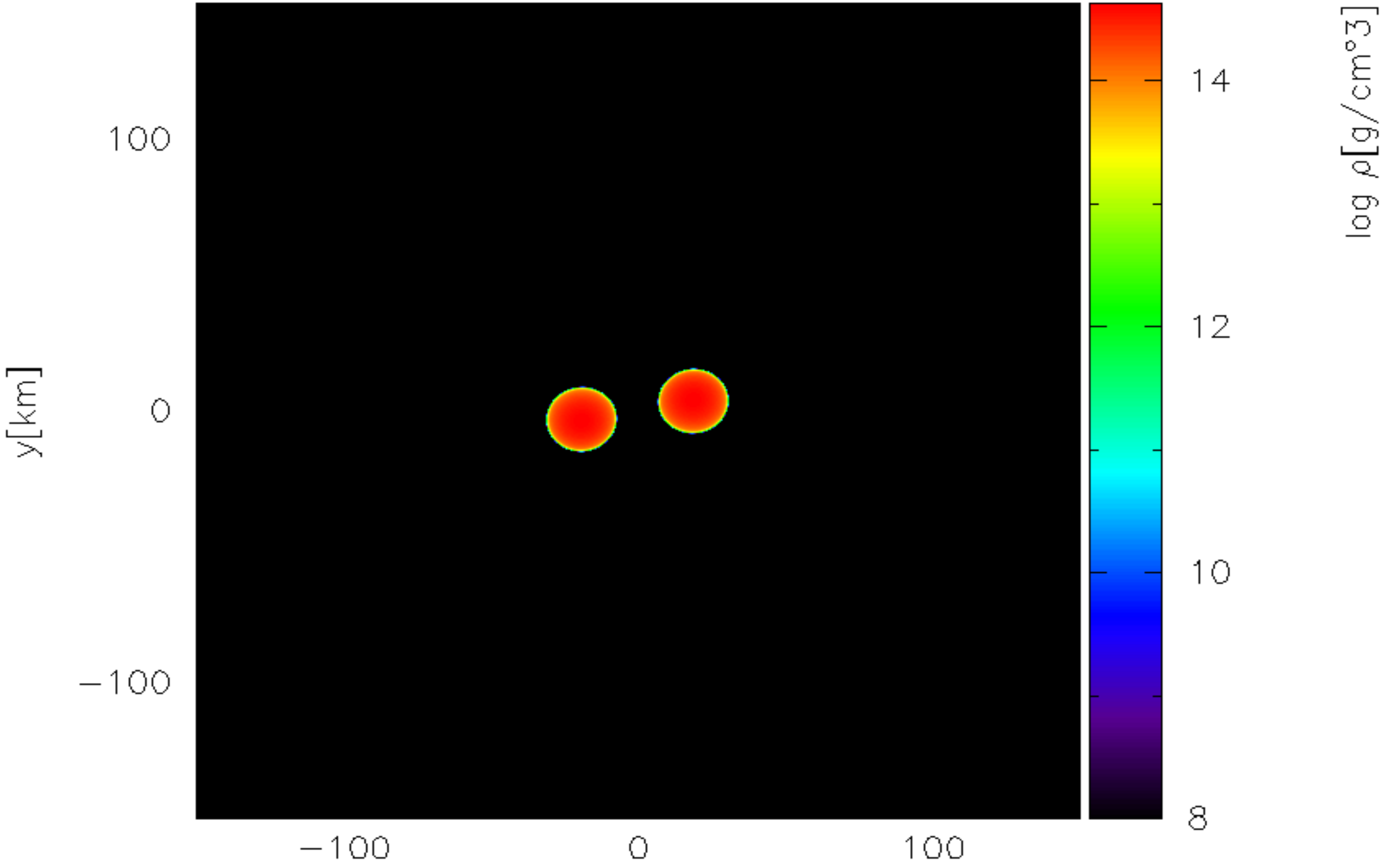
Supernova ν-driven wind
(high-T process)

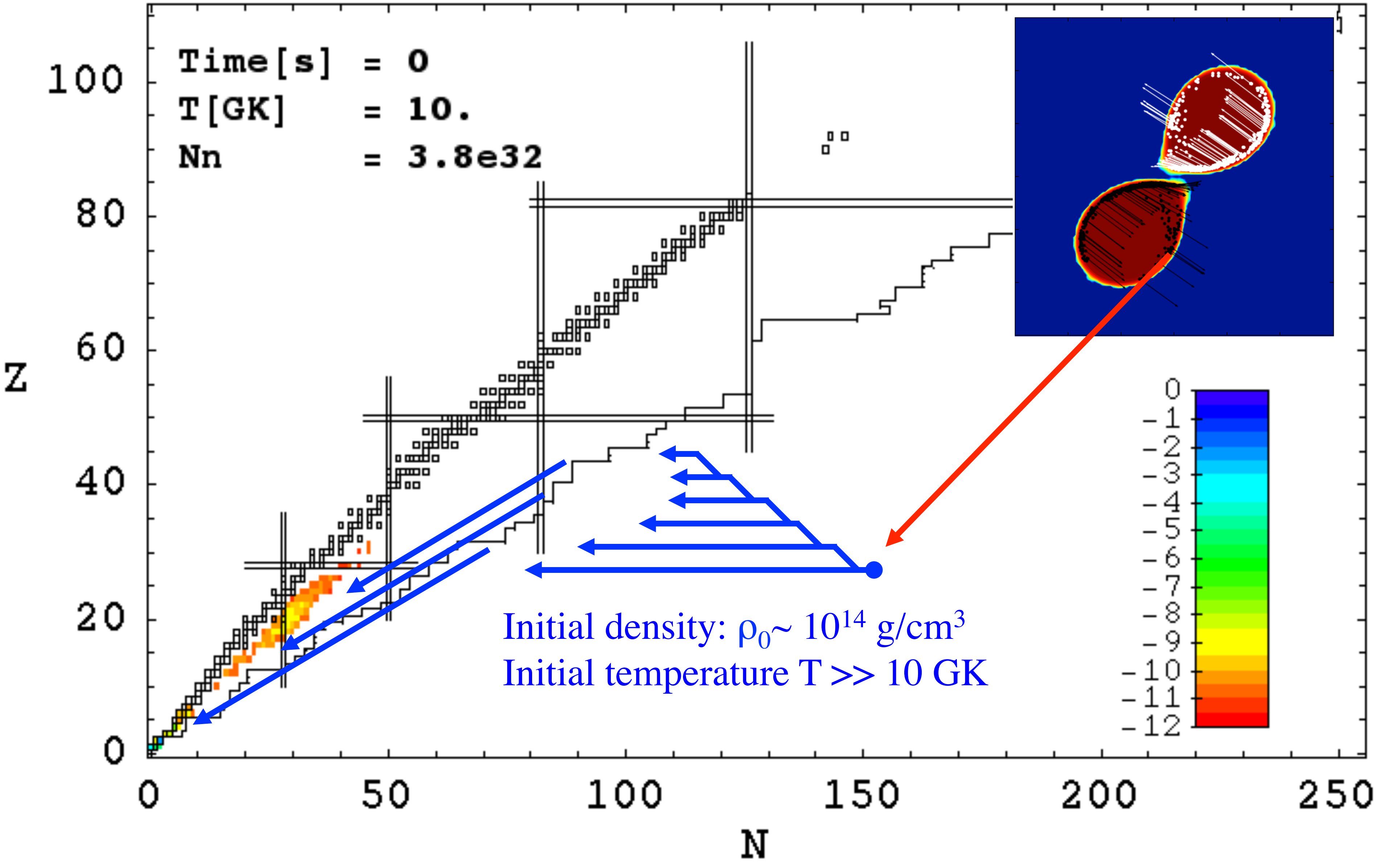
(n & p)



$1.35M_o - 1.35M_o$ NS merger

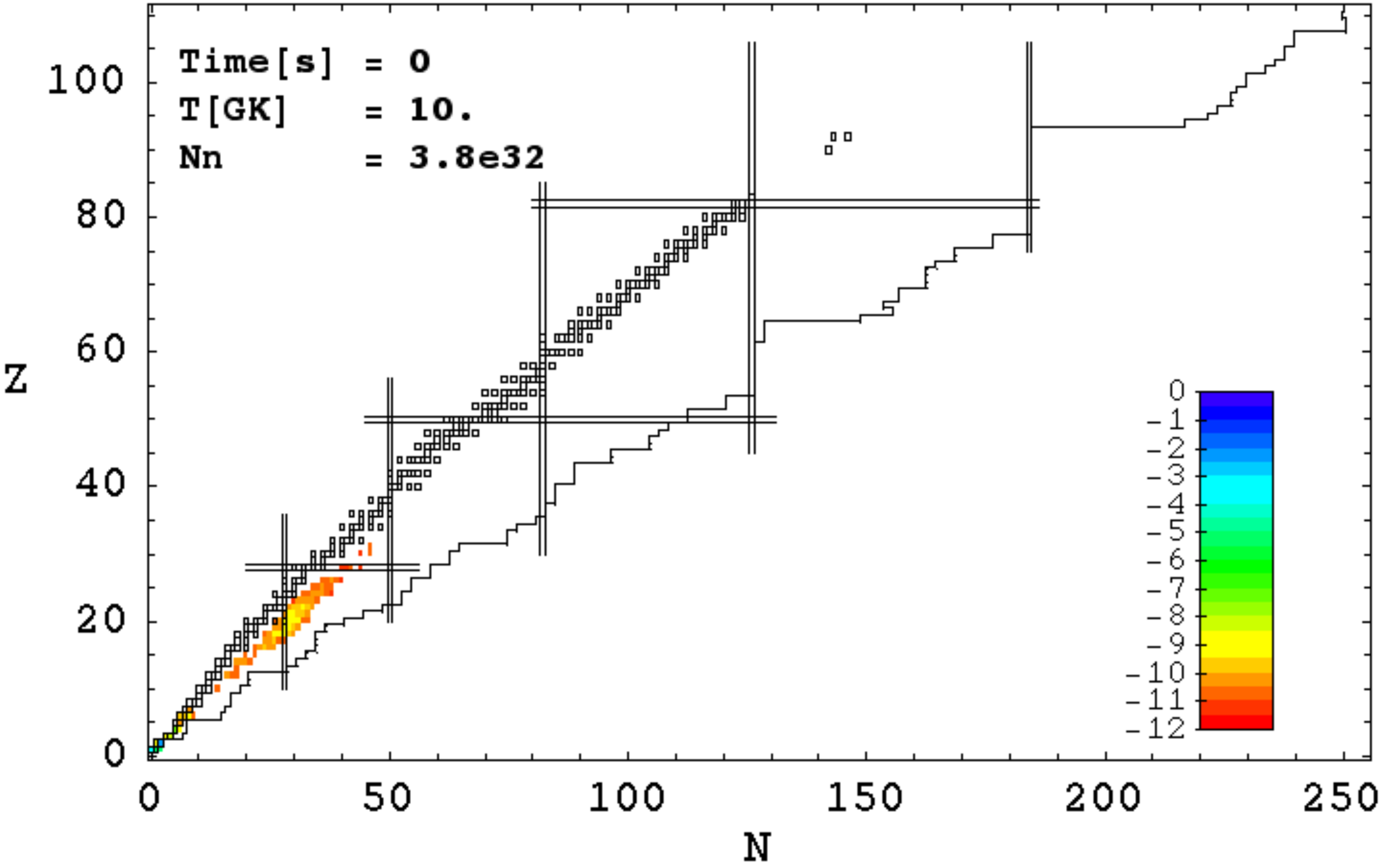
Density
ρ [g/cm^3]





Initial density: $\rho_0 \sim 10^{14}$ g/cm^3

Initial temperature T >> 10 GK



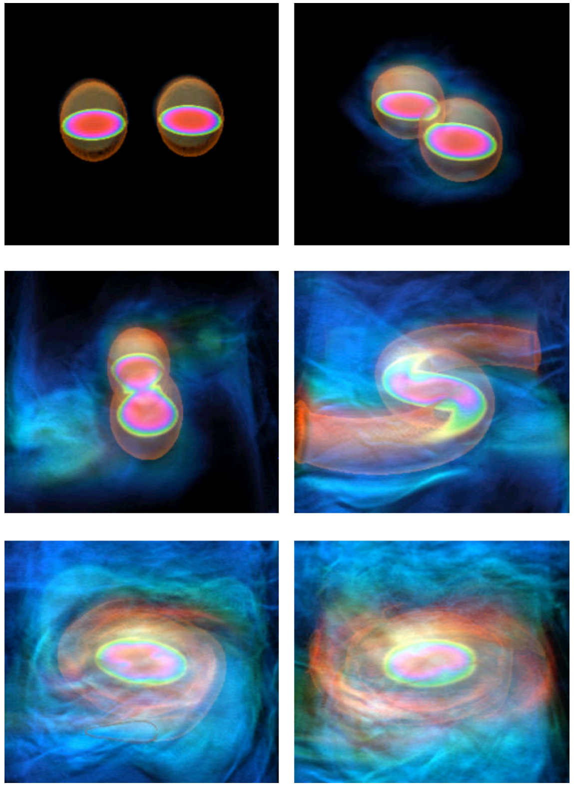
Time[s] = 0
T[GK] = 10.
Nn = 3.8e32
Z
N
0
20
40
60
80
100
50
150
200
250
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12

Systematic study of Neutron-star mergers

(Bauswein, SG, Janka, 2011, 2013, 2014)

Various relativistic simulations for different binary systems :

- NS-NS systems: symmetric (e.g 1.35; 1.45; 1.6; 1.75 M_o)
  asymmetric (e.g 1.2–1.5 M_o; 1.2-1.8M_o; 1.35-1-8M_o)
- NS-BH systems: 1.1-1.45M_o NS with 2.3-7M_o BH (and spin α_{BH}=0-0.9)
- 40 different EoS with different stiffness (i.e different NS compactness)



→ different amounts of mass ejected

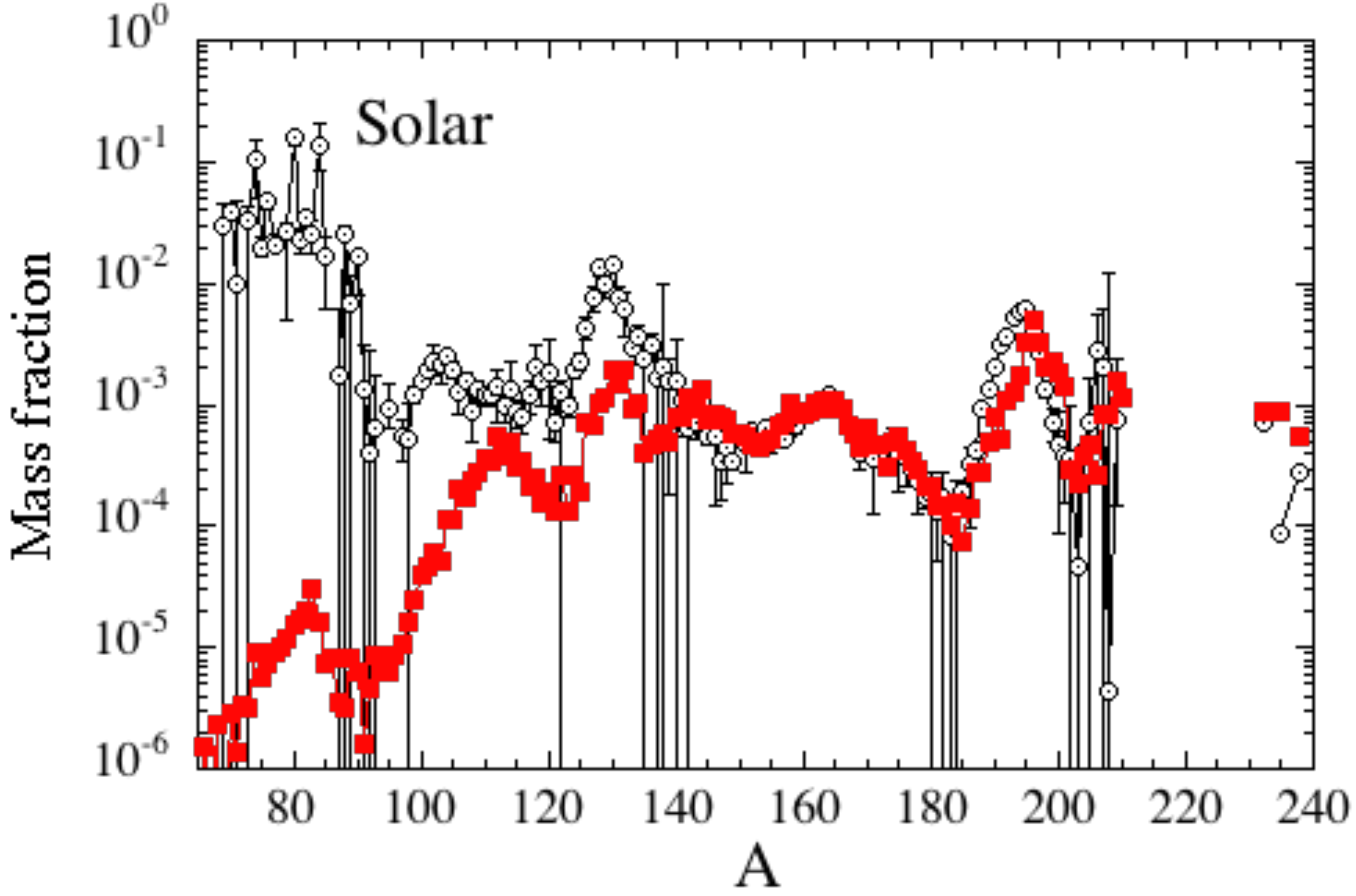
$M = 10^{-3} – 2\ 10^{-2} M_o$

→ different ejecta velocities

→ different luminosities of the optical transients 3 – 14 10^{41} erg/s

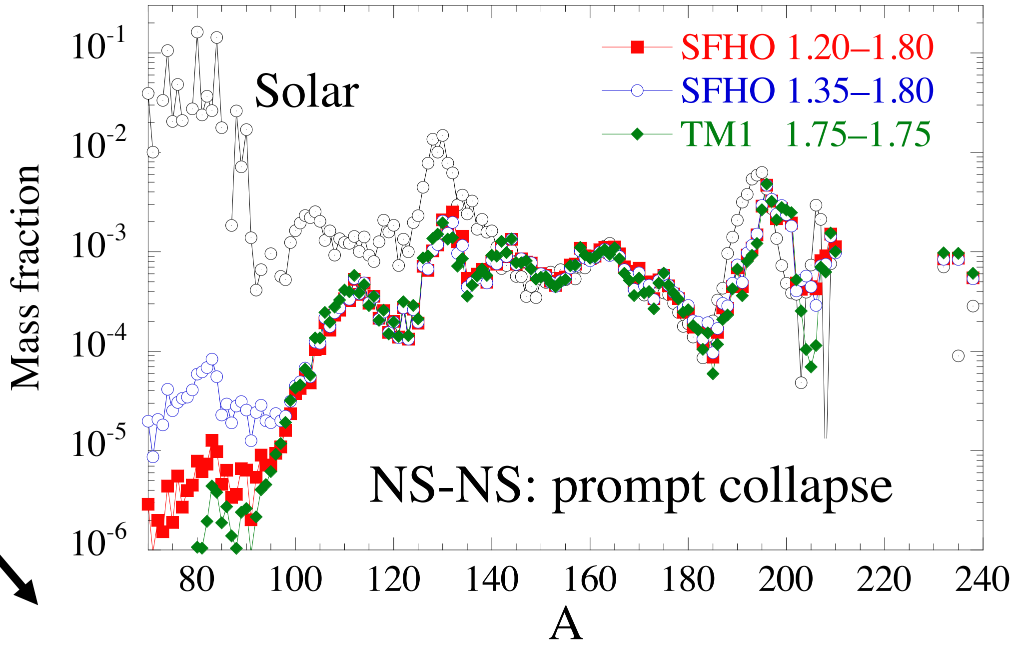
Systematic study of Neutron-star mergers

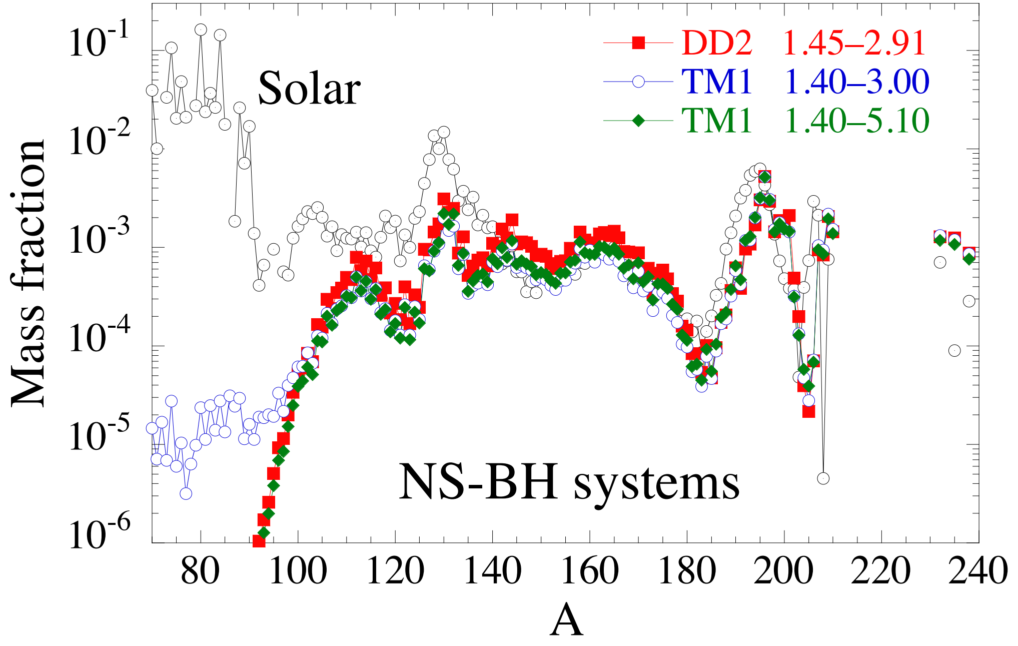
BUT *invariably*, more than 95 % of the ejected material is r-process with a distribution very similar to the solar r-abundance distribution (A>140)

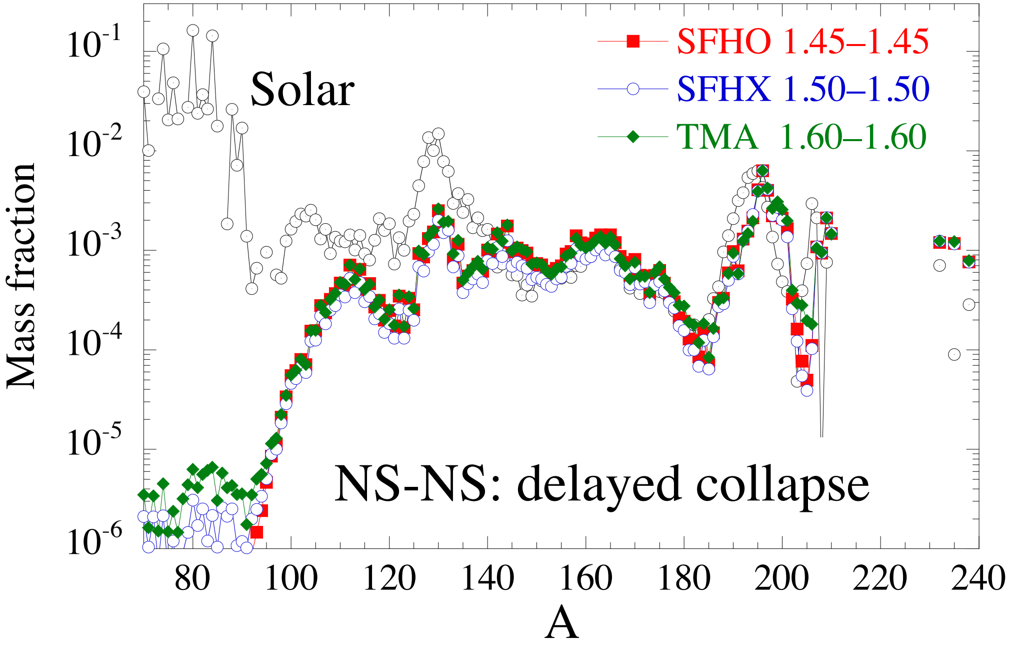


AND similar predictions, be it

- a prompt collapse of NS-NS
- a delayed collapse of NS-NS
- a NS-BH system







NS-NS or NS-BH mergers are robust site for the r-process (A>140)

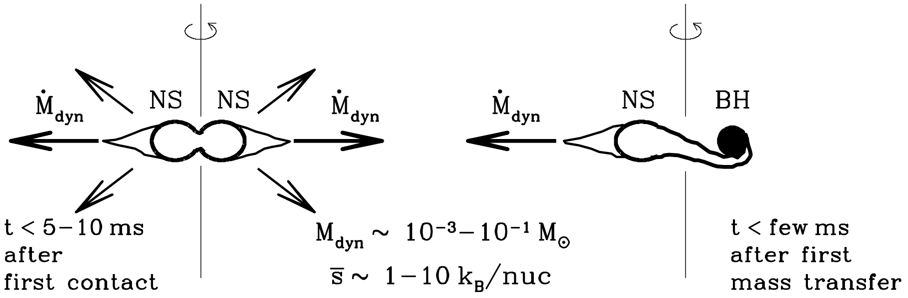
Neutron Star Mergers: a (very) promising r-process site

Hydrodynamical simulations : Just, Bauswein, Janka et al. MNRAS (2015)

Mass loss phases during NS-NS and NS-BH merging

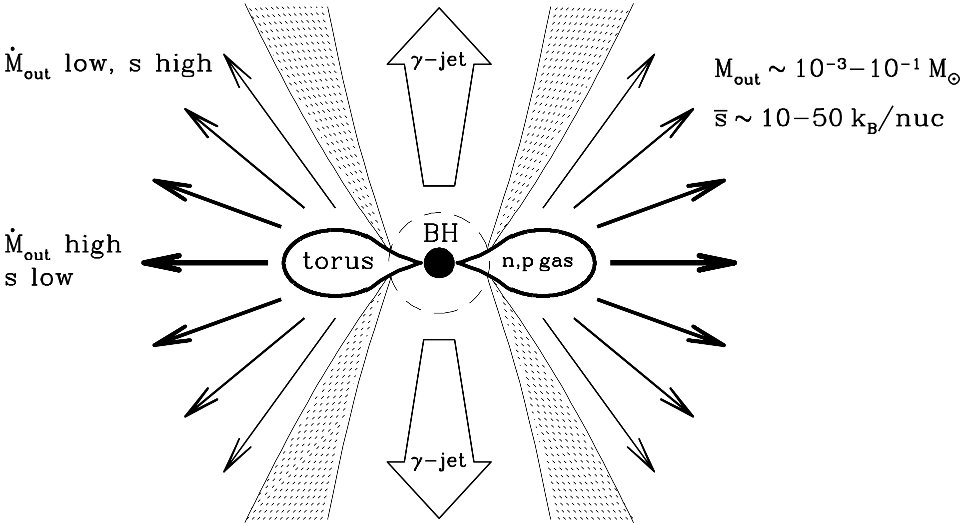
1. Merger Phase

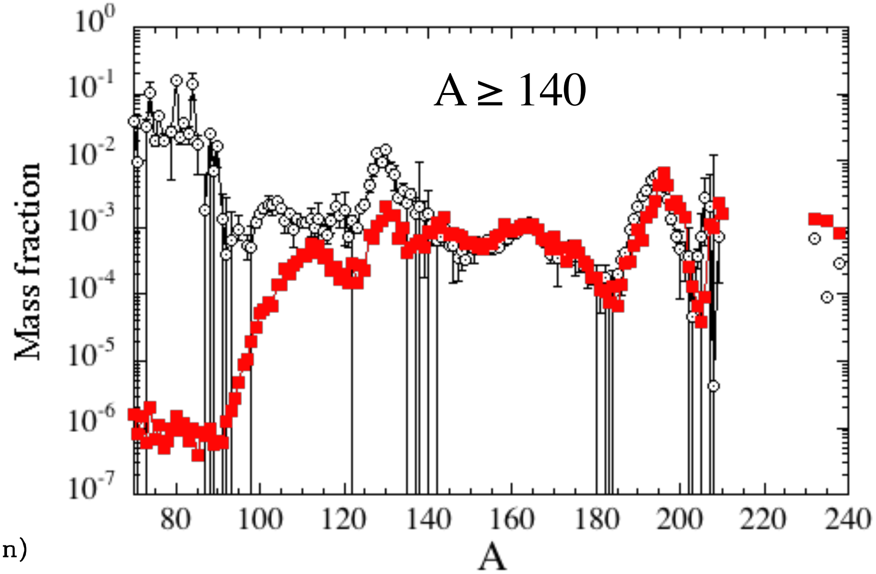
e: Prompt/dynamical ejecta
(due to dynamic binary interaction)

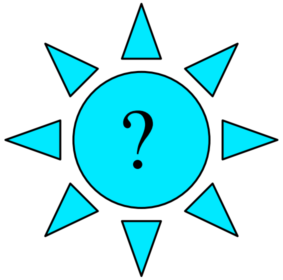


2. BH-Torus Phase

e: Disk ejecta
(due to ν heating, viscosity/magn. fields, recombination)





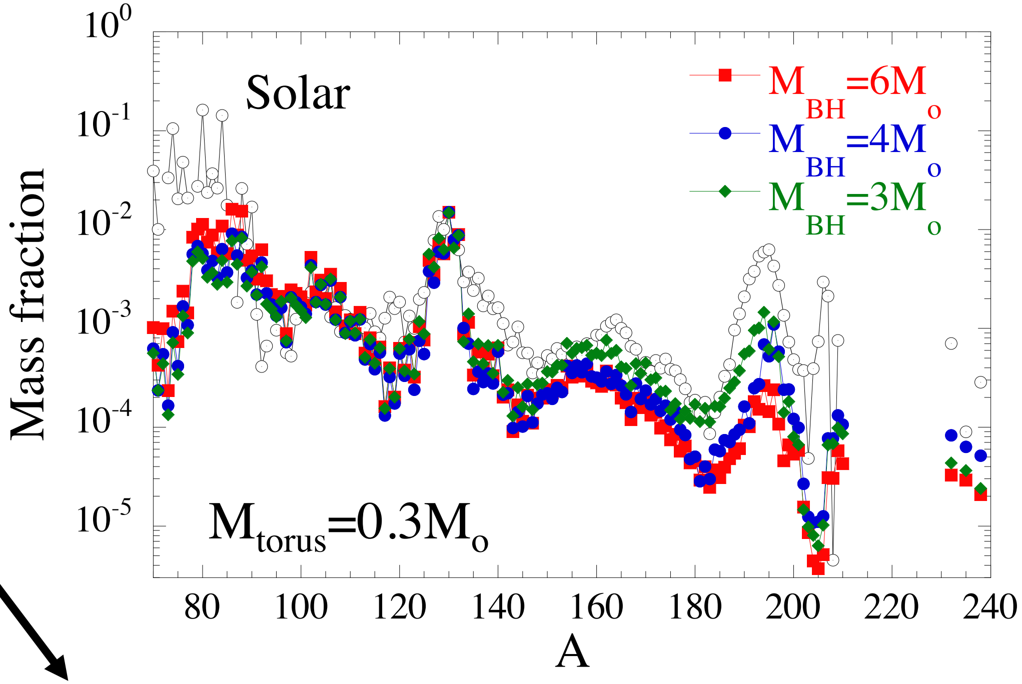


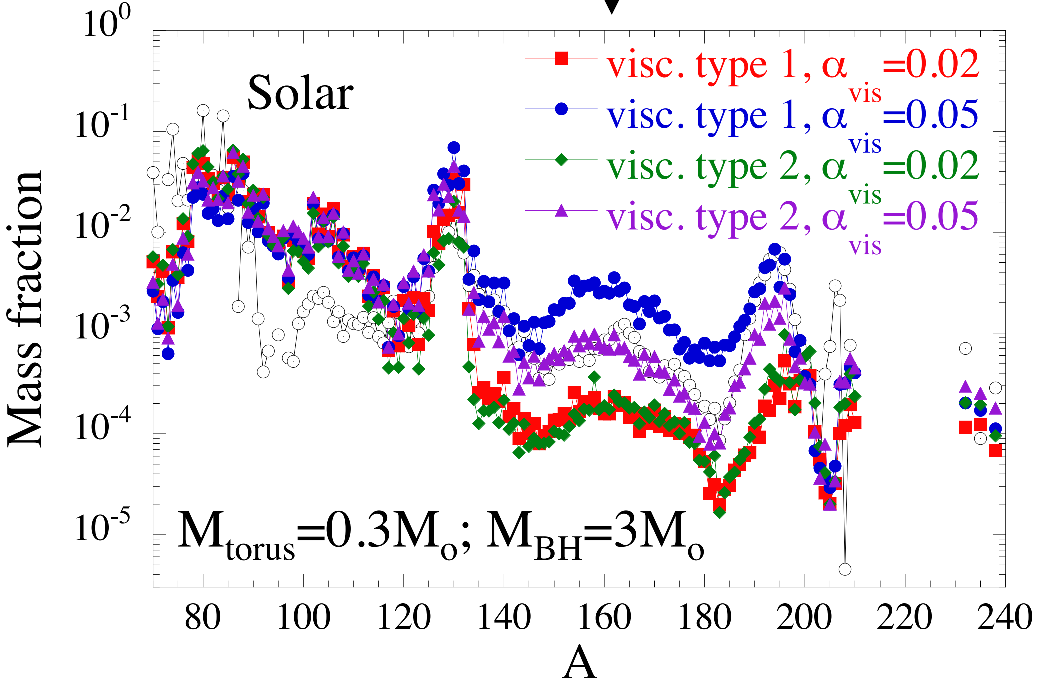
12 different hydro simulations

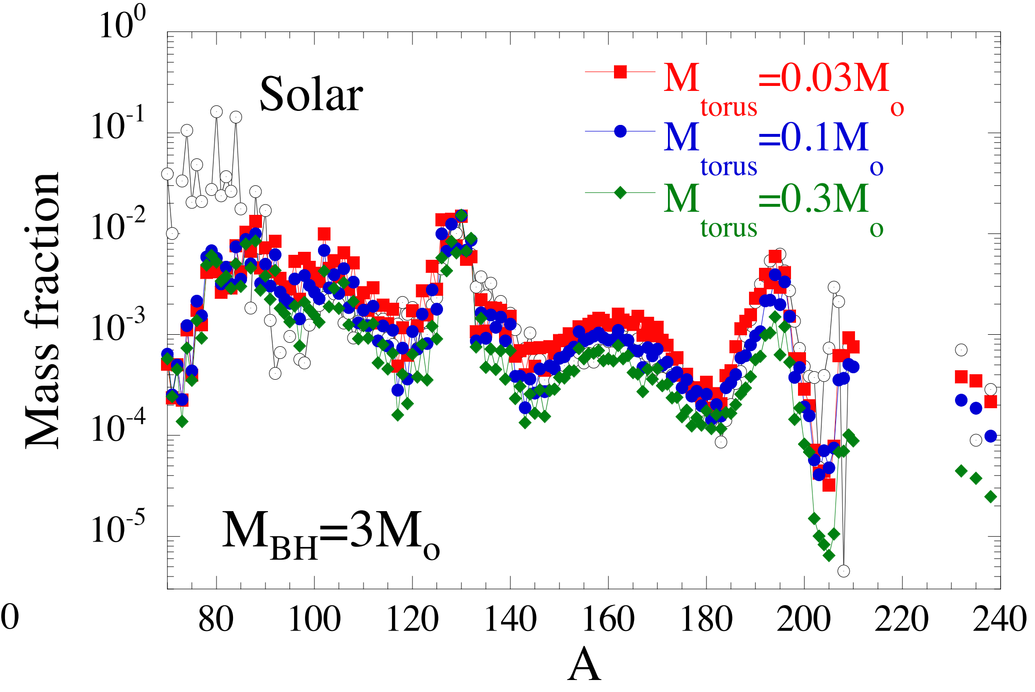
(O. Just, H.-T. Janka 2014)

Abundance predictions sensitive to

- Mass of the BH (same M_{torus})
- Mass of the torus (same M_{BH})
- Treatment of viscosity







Neutron Star Mergers: a (very) promising r-process site

Hydrodynamical simulations : Just, Bauswein, Janka et al. MNRAS (2015)

Mass loss phases during NS-NS and NS-BH merging

1. Merger Phase e: Prompt/dynamical ejecta
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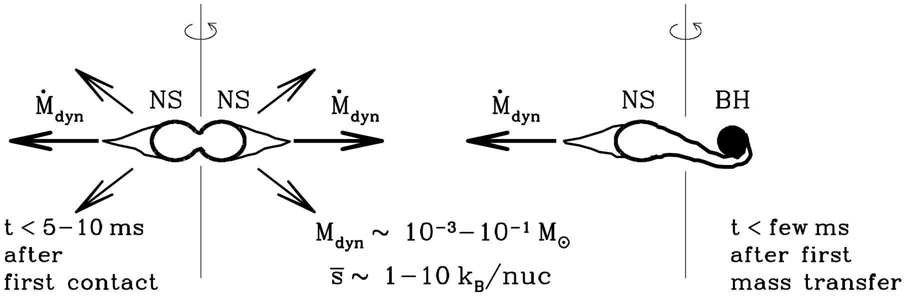
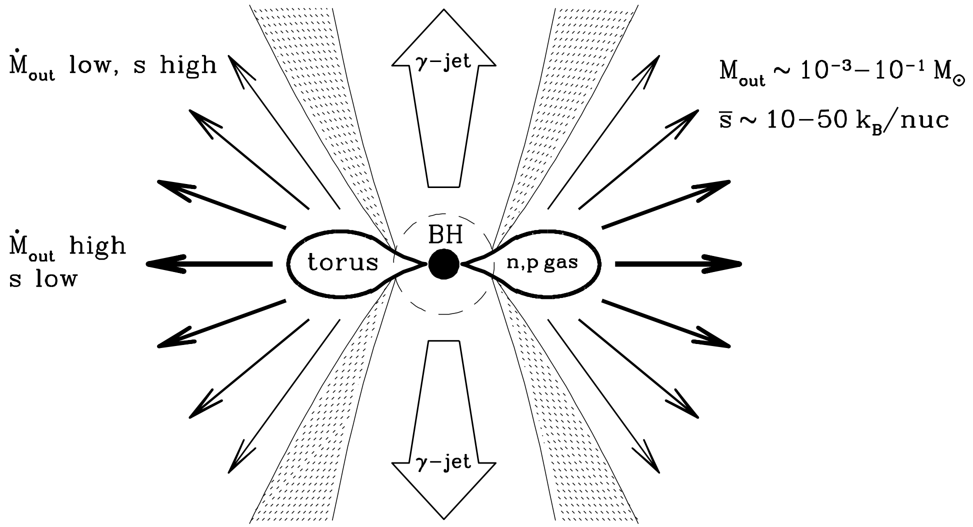
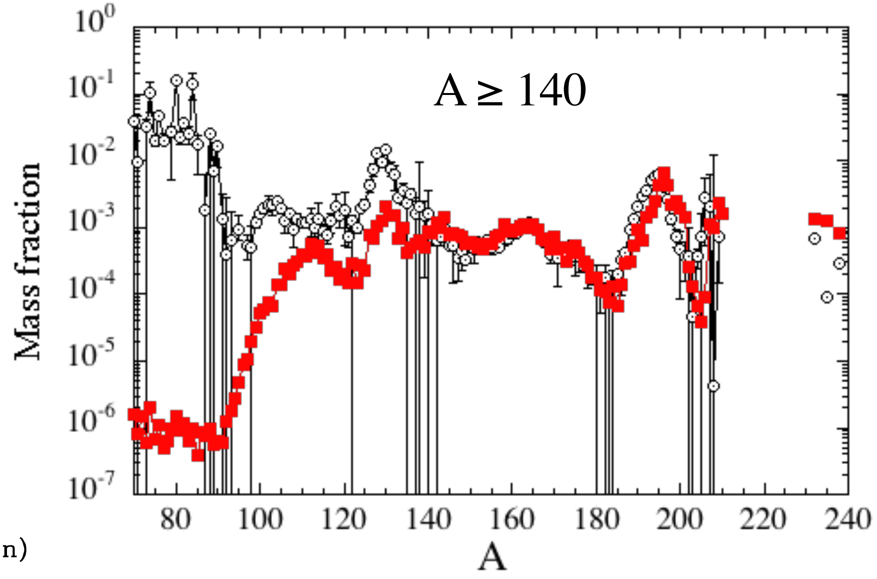
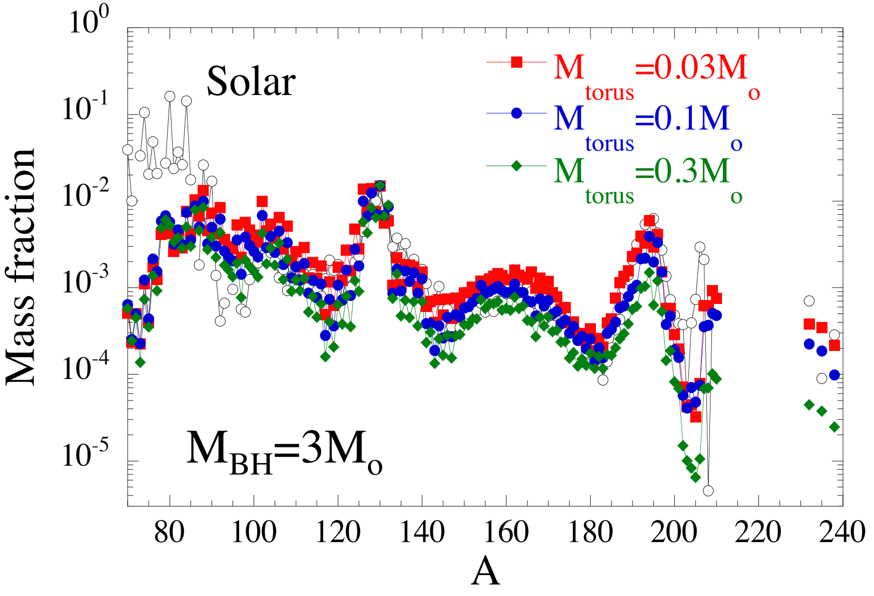


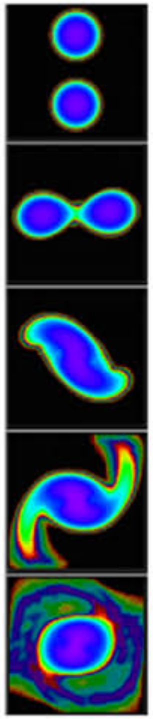
2. BH-Torus Phase e: Disk ejecta
(due to ν heating, viscosity/magn. fields, recombination)

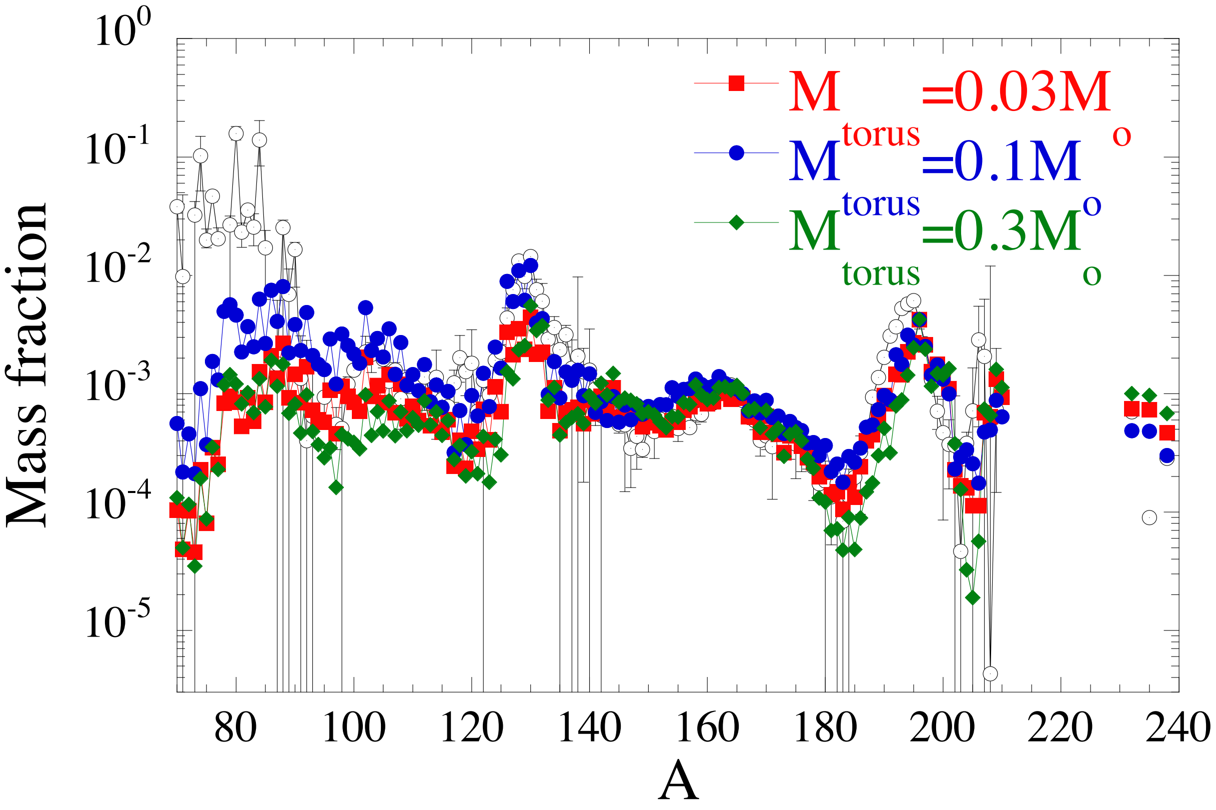






Mass-weighted *consistently* combined Dynamical + Disk ejecta

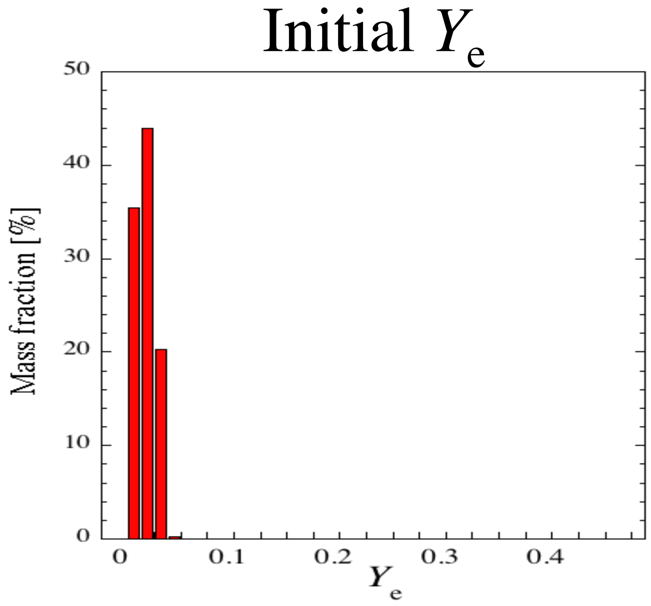




Robust production of all A ≥ 90 r-nuclei with a rather solar distribution.

NSM *may* be a/the dominant site for the r-process nucleosynthesis

Still a major uncertainty affecting the nucleosynthesis in NS mergers: electron (anti)neutrino absorption by free nucleons

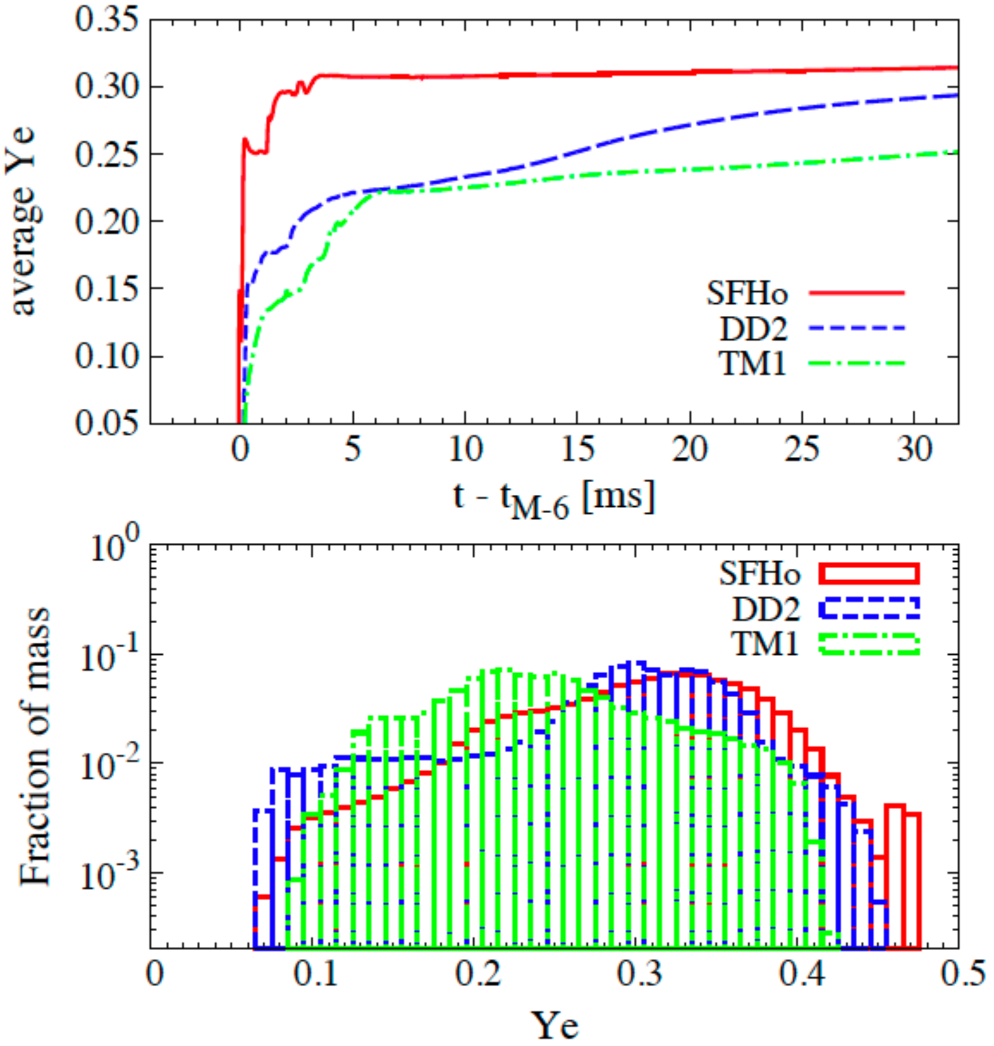


$$\nu_e + n \rightleftharpoons p + e^-$$

$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

$$Y_e^{\nu\infty} \simeq \frac{L_{\nu_e}\langle E_{\nu_e}\rangle f_{\nu_e}^{mr}}{L_{\nu_e}\langle E_{\nu_e}\rangle f_{\nu_e}^{mr} + L_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle f_{\bar{\nu}_e}^{mr}}$$

Also sensitive to the adopted EoS



Wanajo et al. (2014); Sekiguchi et al. (2015)

Relevance of NS-NS mergers as a plausible astrophysical site for the r-process

1. Total amount of r-process in the Galaxy
   - $M_{Gal} \sim 6\ 10^{10}\ M_o$ of baryons
   - $X_o(Eu) \sim 3.7\ 10^{-10}\ M_o$

   → $M_{Gal}(Eu) \sim 22\ M_o$
   - NS-NS Yield of Europium : $Y_{Eu} \sim 7\ 10^{-5} – 2\ 10^{-4}\ M_o$ (Dynamical+Disk)

→ NS-NS rate to produce the Galactic Eu during 13 Gyr

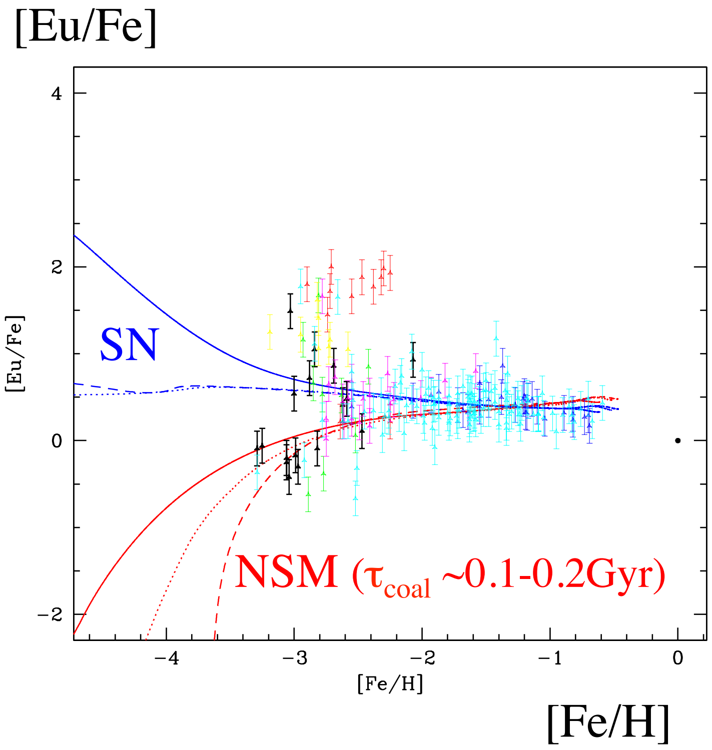
$$\boxed{\text{Rate} \sim 8 – 20\ \text{Myr}^{-1}}$$

Compatible with current estimates from observed binary pulsars
Rate ~ 3 – 190 Myr^{-1} (Kim et al. 2010; Dominik et al. 2012)

2. Chemical Evolution of r-elements in the Galaxy
   (early enrichment of Eu & abundance scatter in low-metallicity stars)
   « Overall, results are consistent with NS mergers being the source of most of the r-process nuclei in the Universe. » (van de Voort et al. 2015)

Cosmic & Galactic Chemical Evolution Models

On the basis of Galactic chemical evolution model, including cosmological zoom-in simulations, & cosmological evolution model using a hierarchical model for structure formation



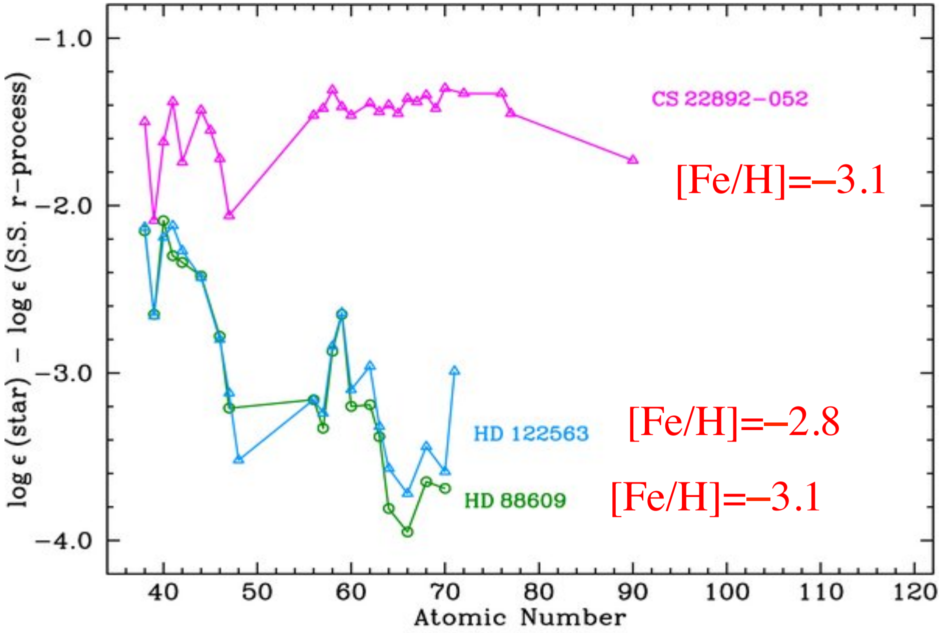
IT HAS BEEN CONCLUDED

- Vangioni et al. (2015): « the Eu cosmic evolution tends to favour NSM as the main astrophysical site for the r process »
- Matteuci et al. (2014) « NSM can be entirely responsible for the production of Eu in the Galaxy if τ_{coal} ~1Myr »
- Tsujimoto et al. (2014) « results demonstrate that NSM occuring at Galactic rate of 12-23Myr^{-1} are the main site of r-process elements »
- Mennekens et al. (2014) « conclude that except for the earliest evolutionary phase of the Galaxy (~the first 100 Myr), double compact star mergers may be the major production sites of r-process elements »
- Van de Voort et al. (2014) « Overall, results are consistent with NS mergers being the source of most of the r-process nuclei in the Universe. »
- Shen et al. (2014) « argue that compact binary mergers could be the dominant source of r-process nucleosynthesis in the Galaxy »

The r-process distribution in ultra-metal-poor stars

Differences between the SS r-process and stellar abundances in metal-poor stars

Honda et al (2007)
ApJ 666, 1189



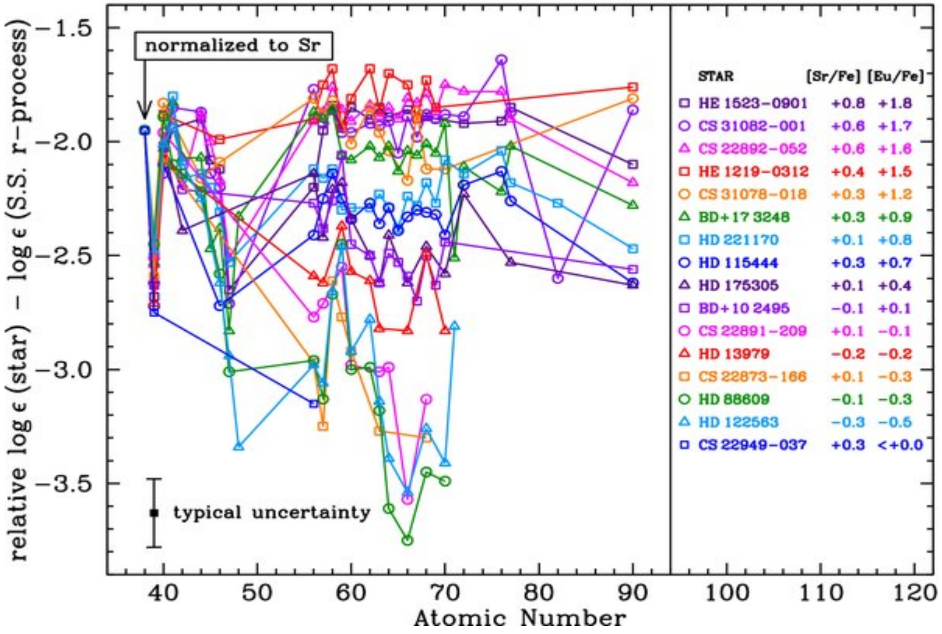
[Fe/H]=–3.1

[Fe/H]=–2.8

[Fe/H]=–3.1

Continuous distribution of r-abundance patterns in metal poor stars falling between two extreme cases:
CS22892-052 and HD88609

Roederer et al (2010)
ApJ 724, 975

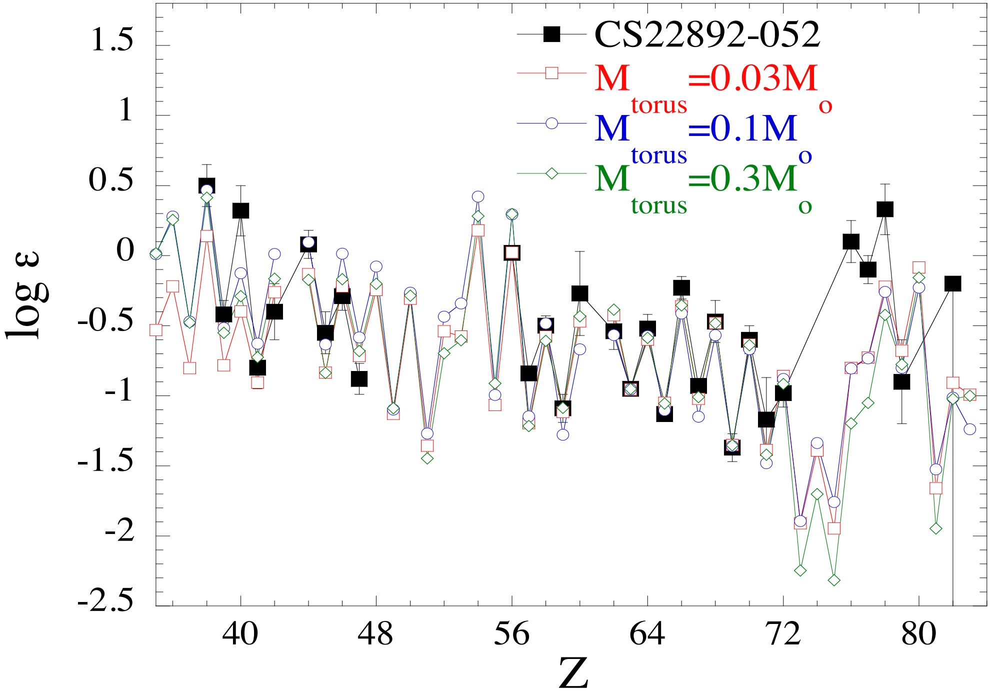


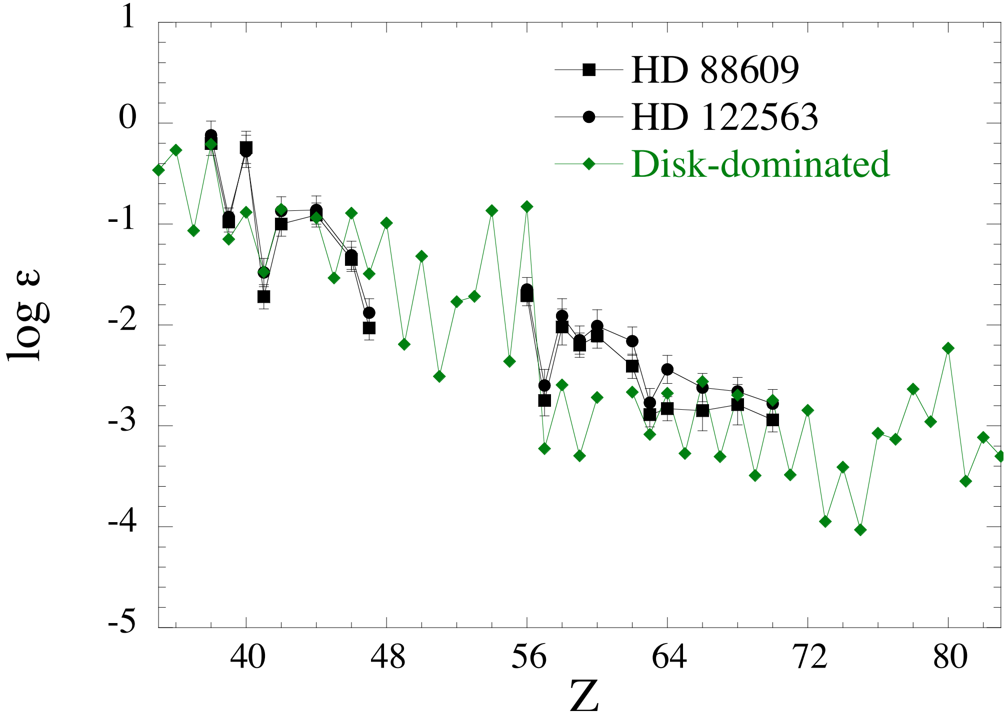
Comparison with observation in low-metallicity r-process-rich stars

2 extreme cases

Main trend: rather solar-like distribution

Star deficient in heavy r elements





Dynamical + Disk ejecta (mass averaged)

- for $56 \leq Z \leq 76$: « Universal » solar-like distribution
- for $Z < 56$: Deviation wrt solar (0.5dex)

Suppressed dynamical ejecta (only ~1%) in particular for NS-BH systems

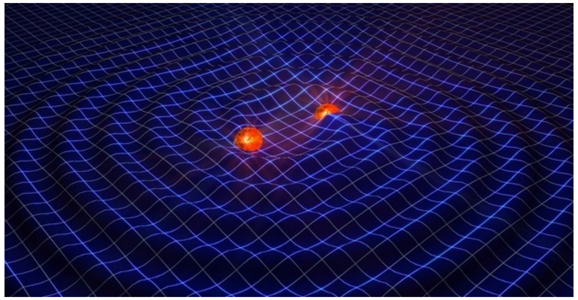
- Asymmetric ejecta
- Small ejecta (NS accreted by the BH)

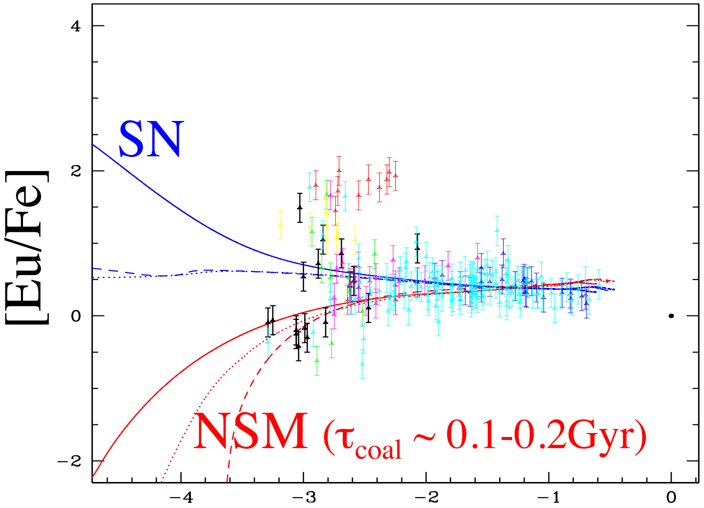
Still major astrophysical questions to be answered, including

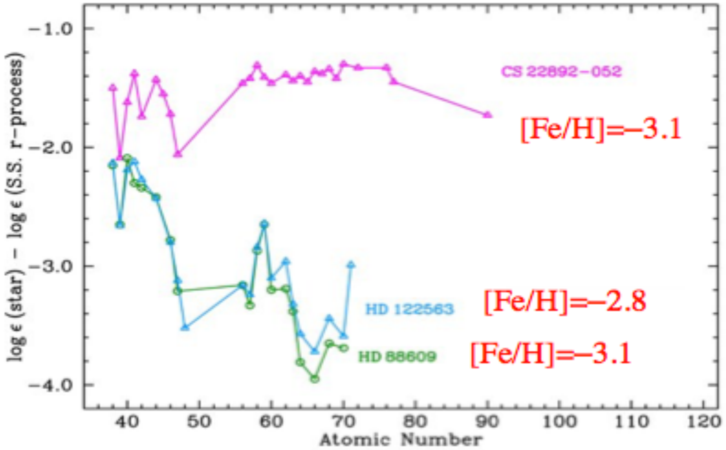
- Impact of neutrinos on the neutron richness during dynamical ejection

$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

- Frequency and properties of NS binary systems (in part, coalescence time)
- Chemical evolution of r-nuclei in the Galaxy
- Comparison with spectroscopic observation, in particular with r-enrichment in old (ultra-metal-poor) stars
- Observational confirmation





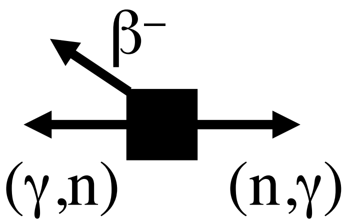


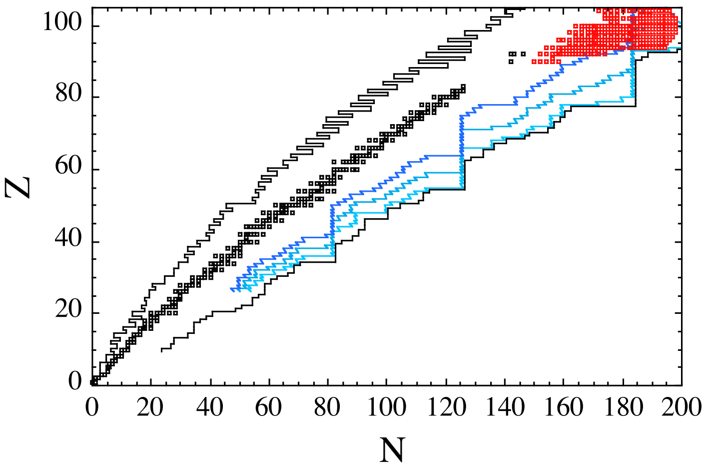
Another uncertainty: nuclear physics input

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

Main needs

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





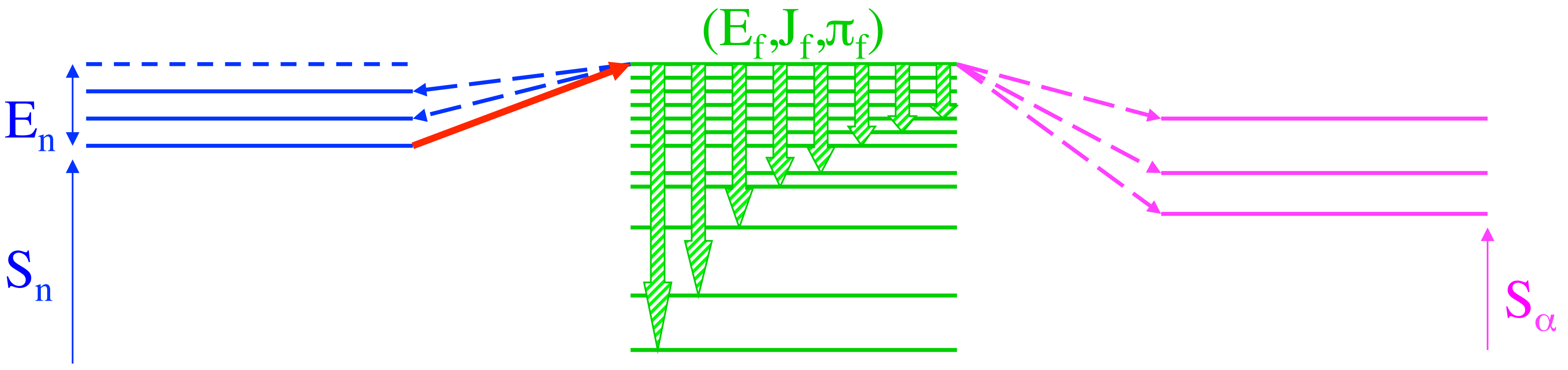
Nucleosynthesis requires RATES for some 5000 nuclei !

(and not only masses or β-decay along the oversimplified so-called “r-process path”)

→ simulations rely almost entirely on theoretical predictions

In turn, theoretical models are tuned on available experimental data

Continuum or statistical theory of the compound nucleus



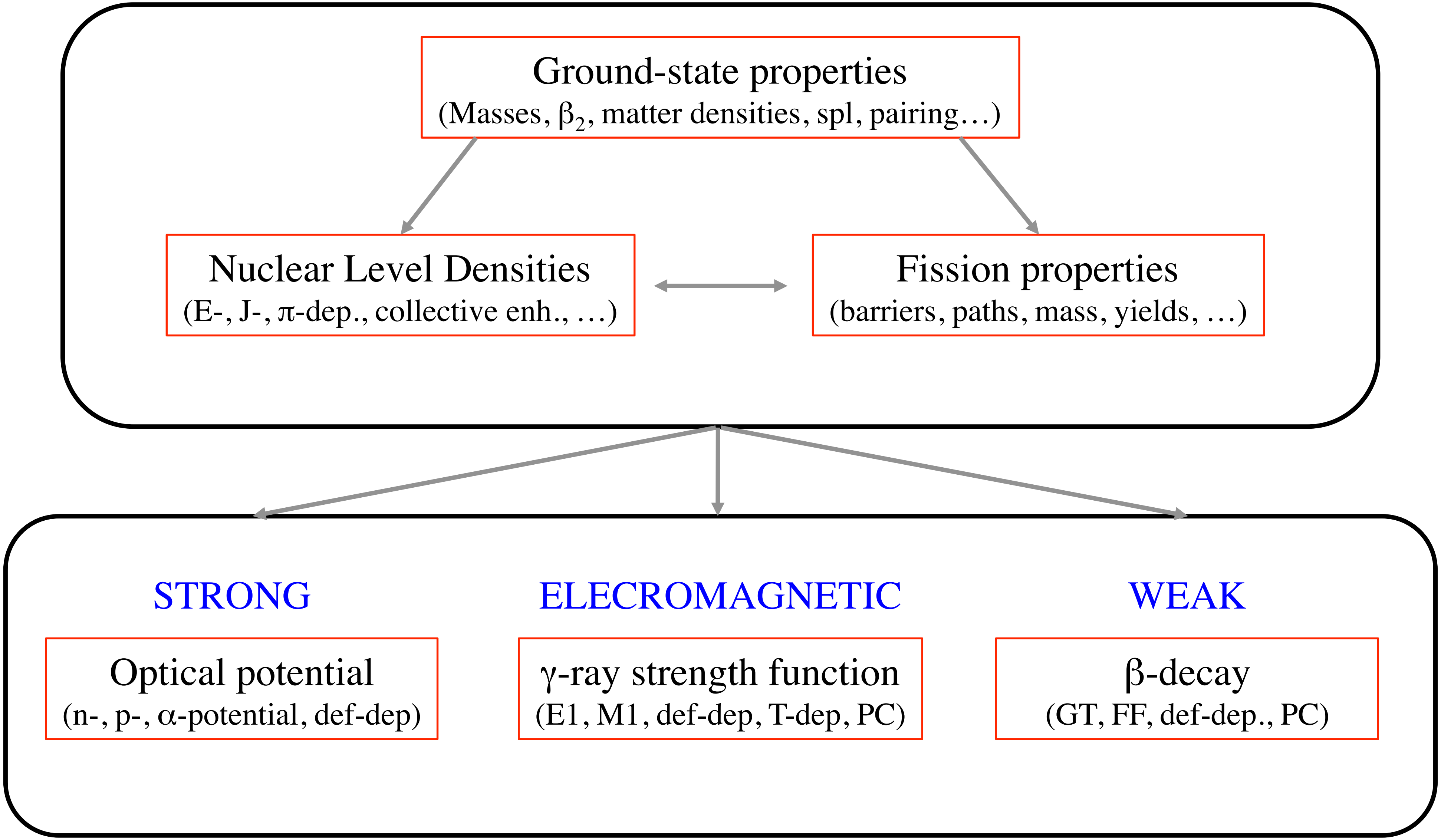
$n + (Z,A\text{-}1)$ | (Z,A) | $\alpha + (Z\text{-}2,A\text{-}2)$

Target Nucleus | Compound Nucleus | Residual Nucleus

$$\sigma_{(a,b)} \propto \sum_{J,\pi} \frac{T_a(J^\pi)\,T_b(J^\pi)}{T_a(J^\pi)+T_b(J^\pi)}$$

T: Transmission coefficient, i.e the probability to favour a given channel (*a*,*b*=n,p,α,γ)

Nuclear inputs to nuclear reaction codes (e.g TALYS)



Ground-state properties
(Masses, β_2, matter densities, spl, pairing…)

Nuclear Level Densities
(E-, J-, π-dep., collective enh., …)

Fission properties
(barriers, paths, mass, yields, …)

STRONG

Optical potential
(n-, p-, α-potential, def-dep)

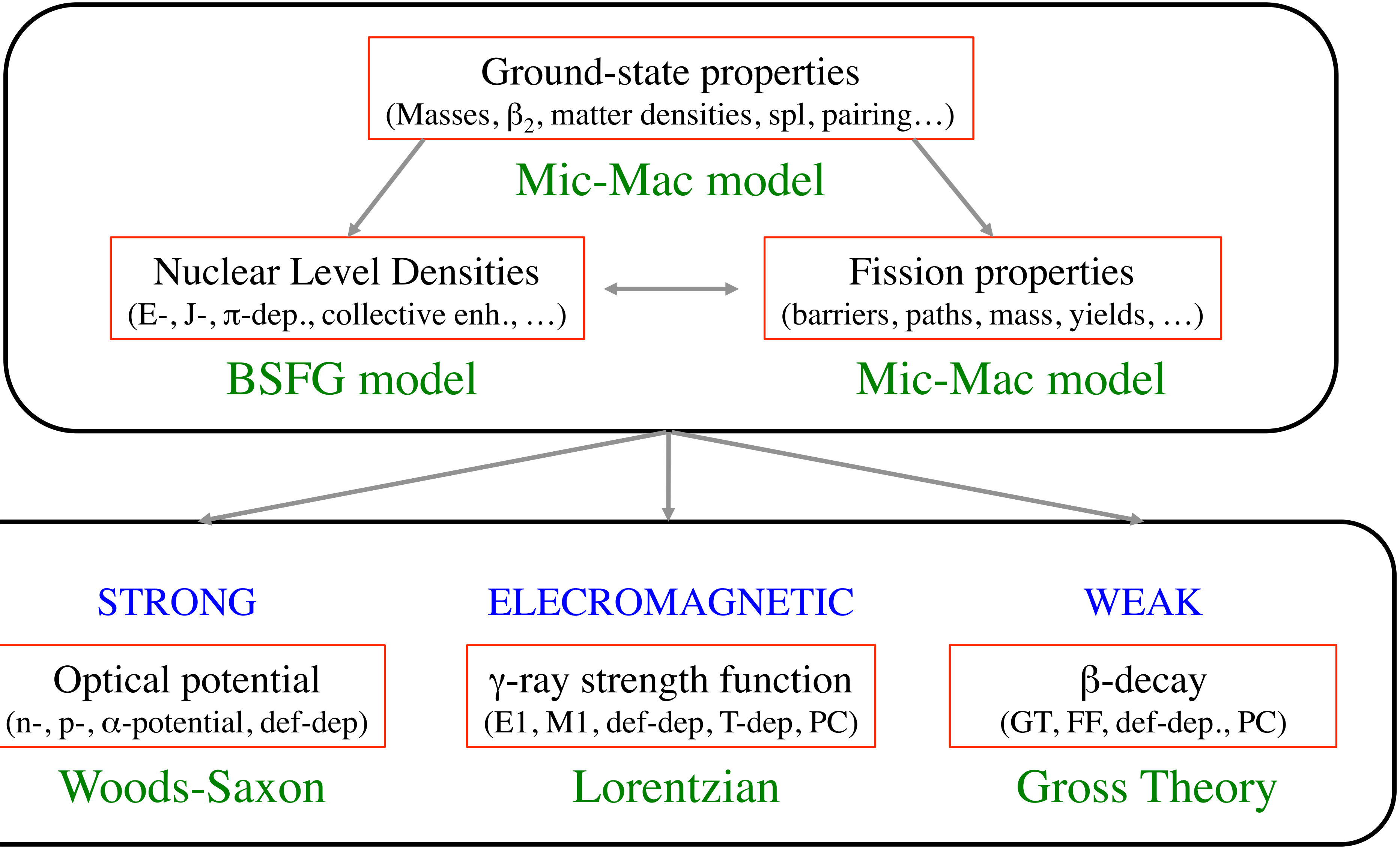
ELECROMAGNETIC

γ-ray strength function
(E1, M1, def-dep, T-dep, PC)

WEAK

β-decay
(GT, FF, def-dep., PC)

Nuclear inputs to nuclear reaction codes (e.g TALYS)



Ground-state properties
(Masses, β_2, matter densities, spl, pairing…)

Mic-Mac model

Nuclear Level Densities
(E-, J-, π-dep., collective enh., …)

BSFG model

Fission properties
(barriers, paths, mass, yields, …)

Mic-Mac model

STRONG

Optical potential
(n-, p-, α-potential, def-dep)

Woods-Saxon

ELECROMAGNETIC

γ-ray strength function
(E1, M1, def-dep, T-dep, PC)

Lorentzian

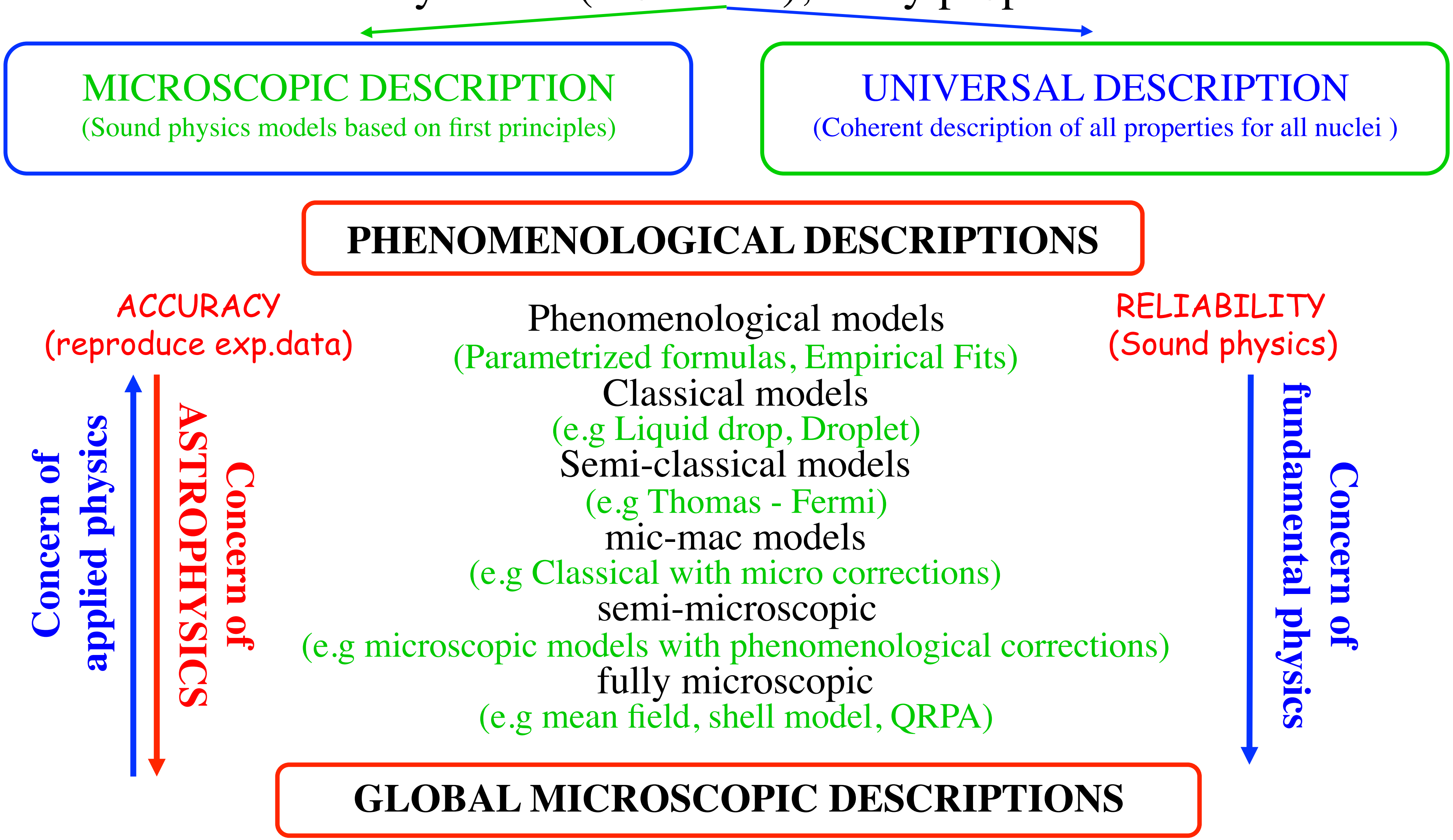
WEAK

β-decay
(GT, FF, def-dep., PC)

Gross Theory

Astrophysics Applications

Exotic nuclei, energy or conditions not available in the Lab.
Many nuclei (thousands), many properties



MICROSCOPIC DESCRIPTION
(Sound physics models based on first principles)

UNIVERSAL DESCRIPTION
(Coherent description of all properties for all nuclei)

PHENOMENOLOGICAL DESCRIPTIONS

ACCURACY
(reproduce exp.data)

Concern of
applied physics

Concern of
ASTROPHYSICS

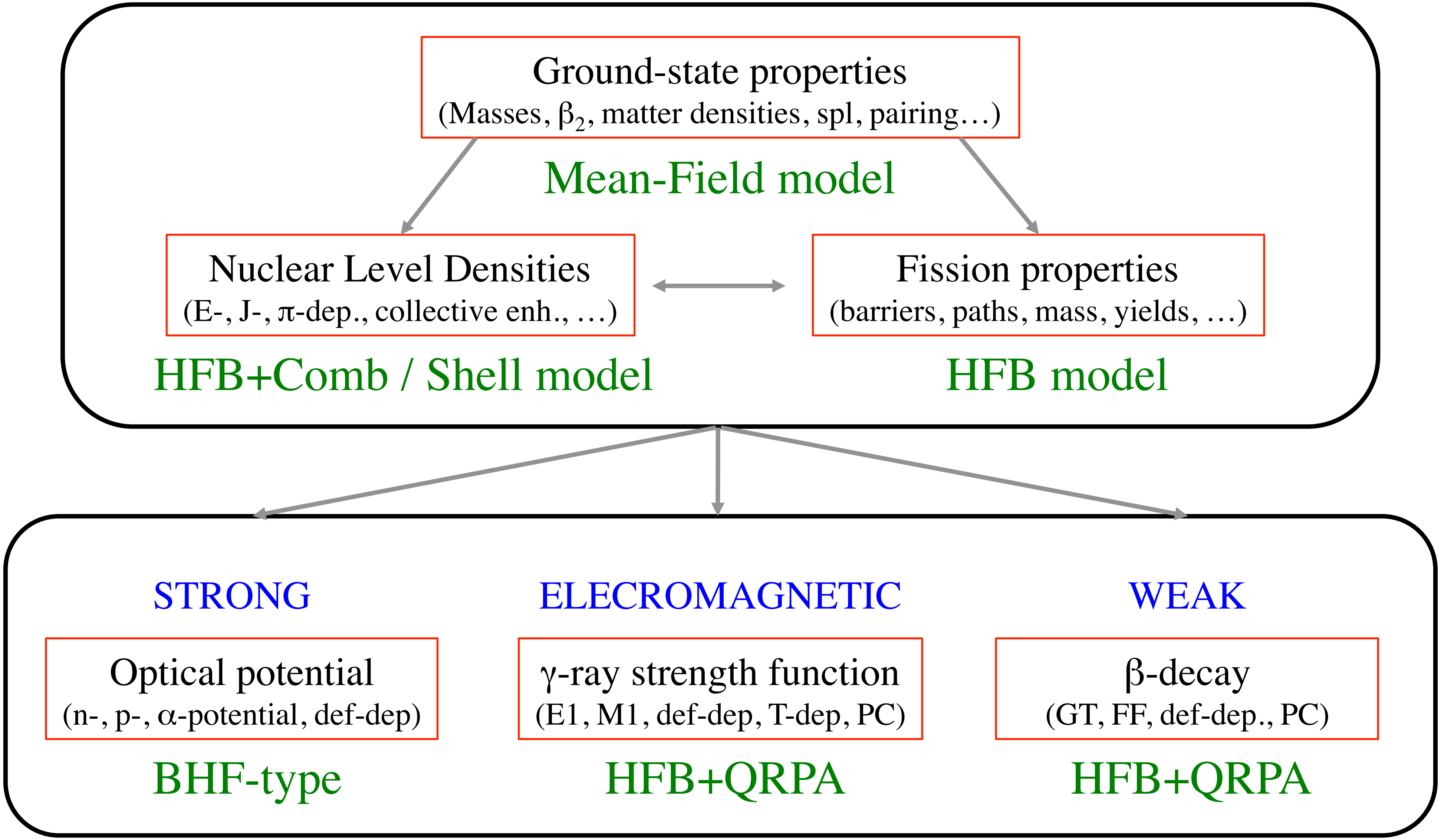
Phenomenological models
(Parametrized formulas, Empirical Fits)
Classical models
(e.g Liquid drop, Droplet)
Semi-classical models
(e.g Thomas - Fermi)
mic-mac models
(e.g Classical with micro corrections)
semi-microscopic
(e.g microscopic models with phenomenological corrections)
fully microscopic
(e.g mean field, shell model, QRPA)

RELIABILITY
(Sound physics)

Concern of
fundamental physics

GLOBAL MICROSCOPIC DESCRIPTIONS

Nuclear inputs to nuclear reaction codes (e.g TALYS)



Ground-state properties
(Masses, β_2, matter densities, spl, pairing…)

Mean-Field model

Nuclear Level Densities
(E-, J-, π-dep., collective enh., …)

HFB+Comb / Shell model

Fission properties
(barriers, paths, mass, yields, …)

HFB model

STRONG

Optical potential
(n-, p-, α-potential, def-dep)

BHF-type

ELECROMAGNETIC

γ-ray strength function
(E1, M1, def-dep, T-dep, PC)

HFB+QRPA

WEAK

β-decay
(GT, FF, def-dep., PC)

HFB+QRPA

Challenge in theoretical nuclear physics
(essential for r-process applications)

PHENOMENOLOGICAL DESCRIPTION

↓

UNIVERSAL GLOBAL MICROSCOPIC DESCRIPTION

UNIVERSAL: capable of predicting *all properties* of relevance

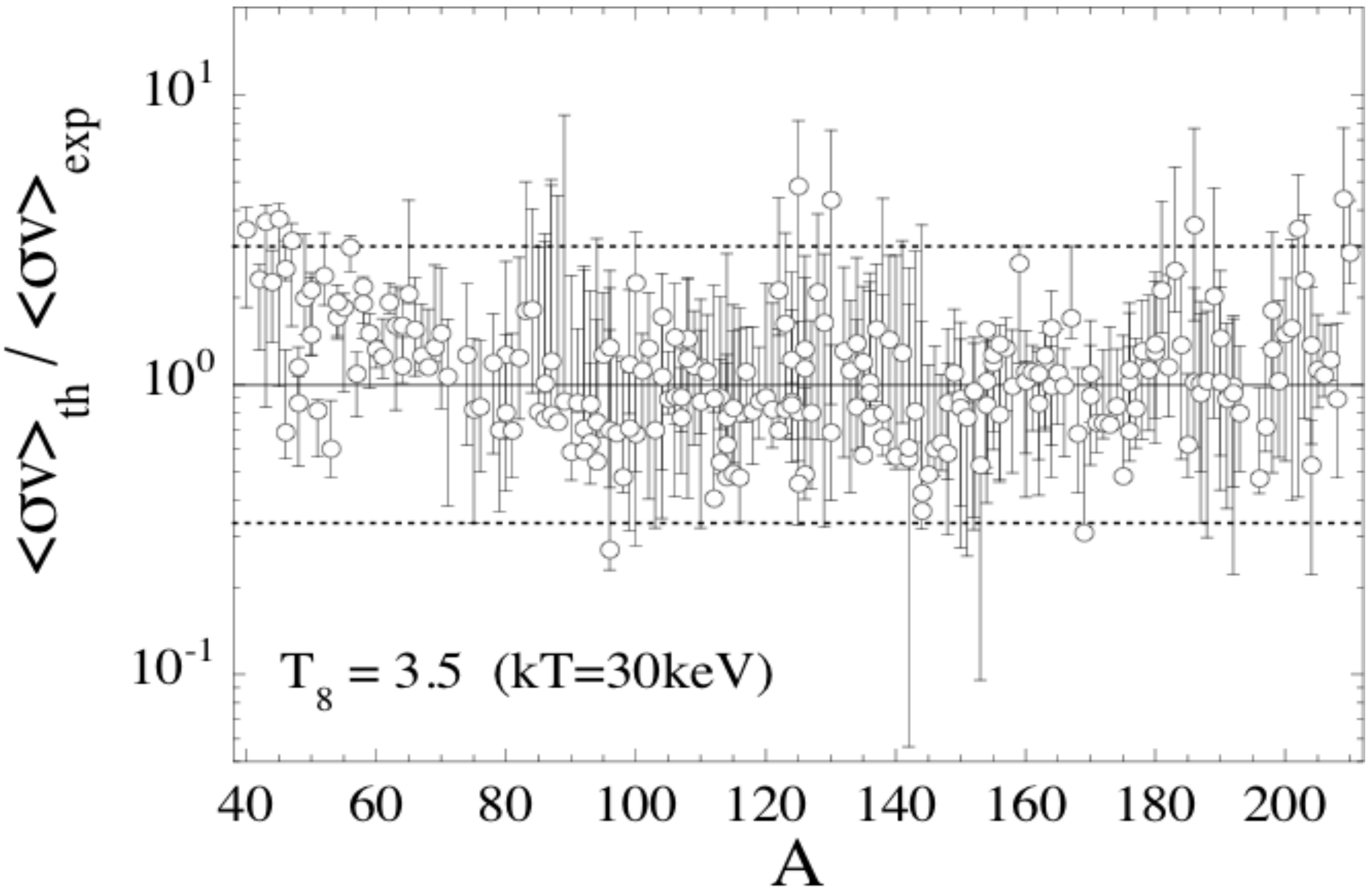
GLOBAL: capable of predicting the properties of *all nuclei*

MICROSCOPIC: for more *reliable extrapolations* from valley of stability to drip lines

A necessary condition for a true predictive power

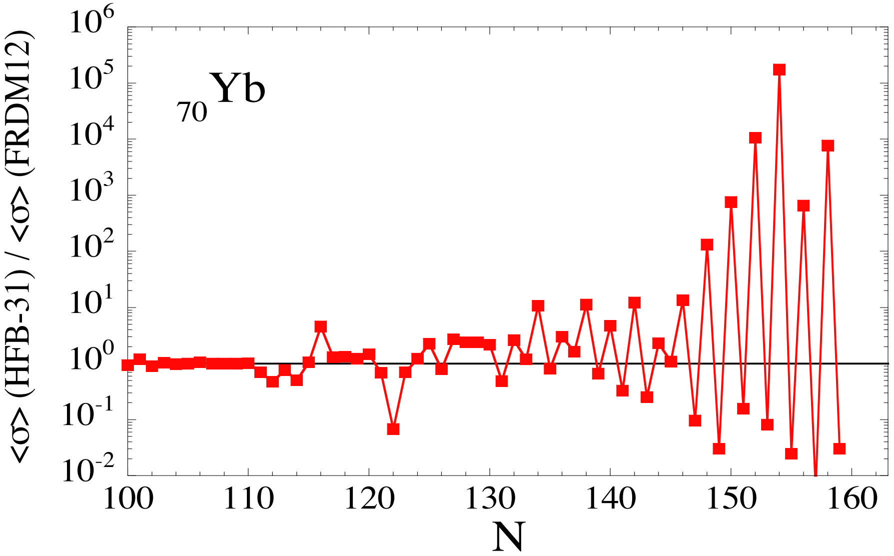
a challenge that will require a continued experimental & theoretical effort

Comparison of known (n,γ) reaction rates with the statistical model estimates

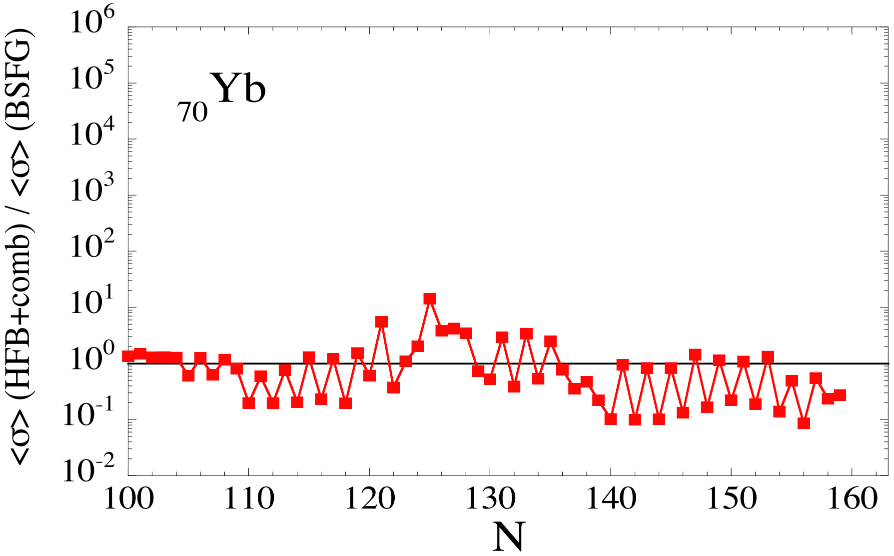


Impact of the various ingredients on the radiative neutron capture (E_n~100keV)

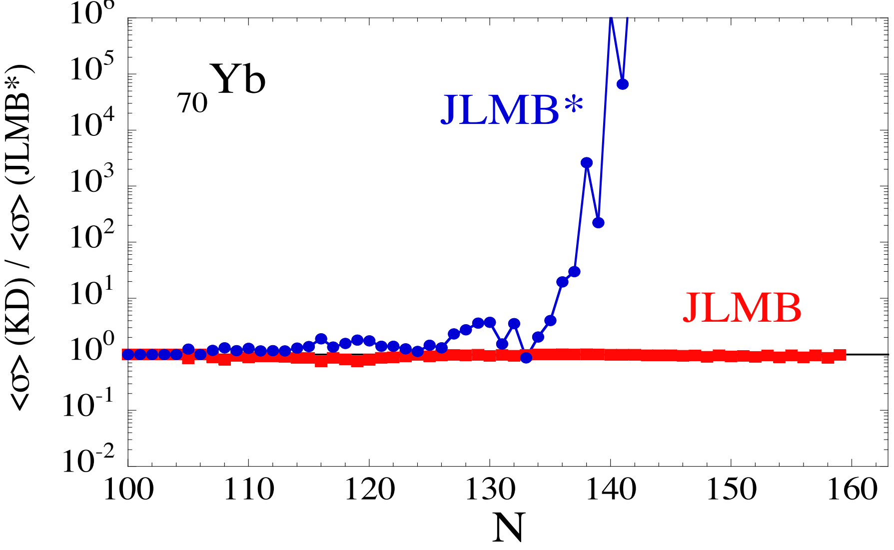
Masses



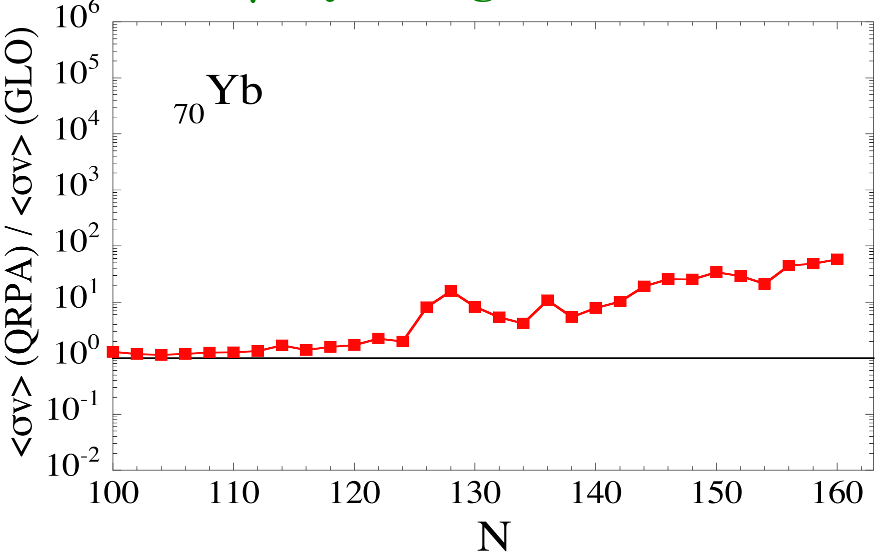
Nuclear Level Densities



Optical Potential



γ-ray Strength Function



STILL MANY OPEN QUESTIONS IN REACTION THEORY

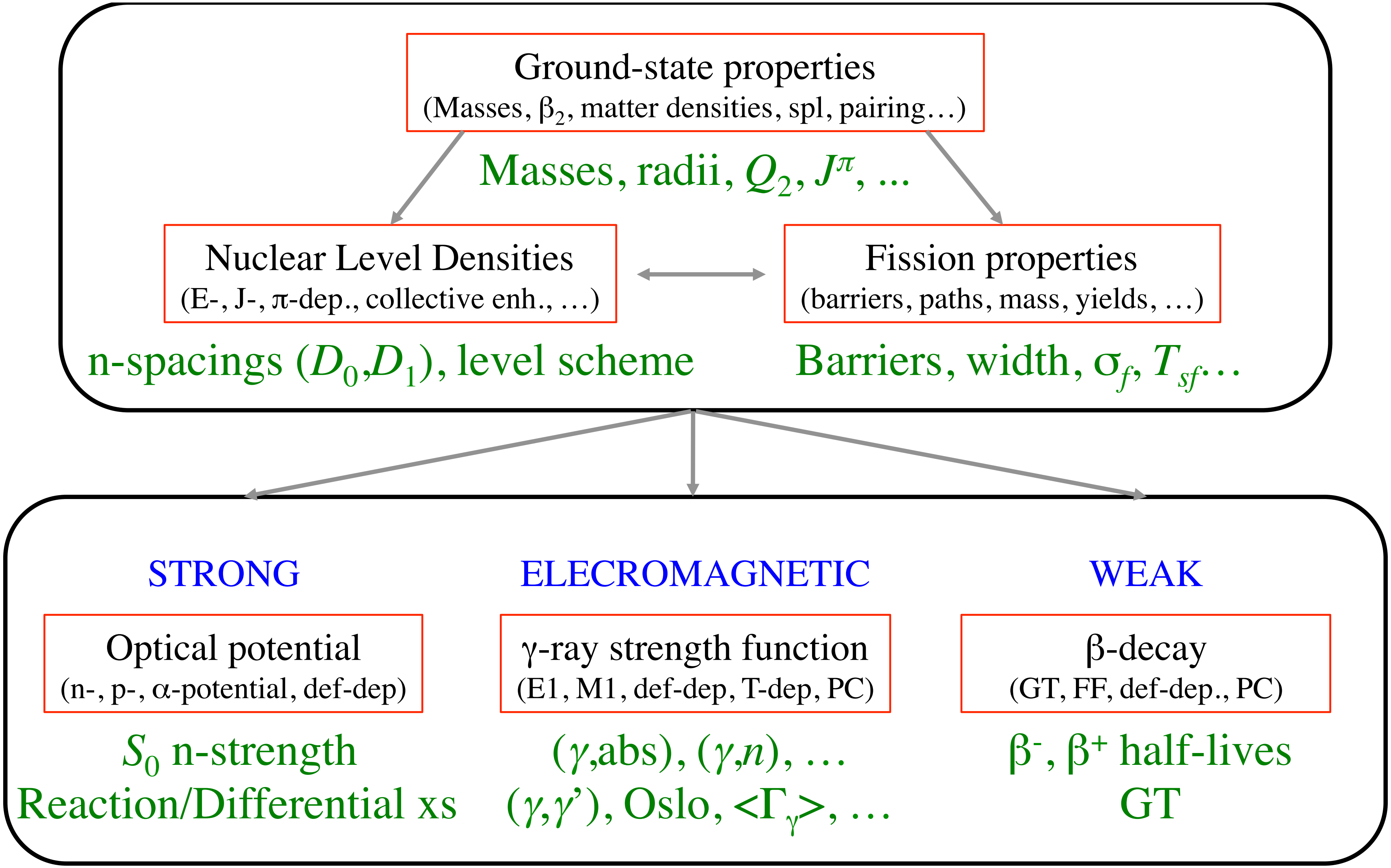
- **The reaction model**
  - **CN vs Direct capture for low-S_n & Isolated Resonance Regime**
- **Nuclear inputs to the reaction model** (almost no exp. data !)
  - **GS properties: masses (correlations - GCM, odd-nuclei)**
  - **E1-strength function: GDR tail, PR, ε_γ=0 limit, *T*-dep, PC**
  - **Nuclear level Densities (at low *E*): *J*- and π-description, pairing, shell and collective effects & damping**
  - **Optical potential: the low-*E* isovector imaginary component**
  - **Fission: fission paths, NLD at the saddle points, FFD**
- **The β-decay rates**
  - **Forbidden transitions, deformation effects, odd-nuclei, PC**

We are still far from being capable of estimating ***reliably*** the radiative neutron capture and β-decay of exotic n-rich nuclei
(and fission properties even for known nuclei)

Models exist, but corresponding uncertainties are usually not estimated
Experimental efforts are fundamental to guide theoretical models !

Measurement of given properties for a large set of nuclei

Direct or indirect observables entering nuclear reaction models



Ground-state properties
(Masses, β_2, matter densities, spl, pairing…)

Masses, radii, Q_2, J^π, ...

Nuclear Level Densities
(E-, J-, π-dep., collective enh., …)

n-spacings (D_0,D_1), level scheme

Fission properties
(barriers, paths, mass, yields, …)

Barriers, width, σ_f, T_{sf}…

STRONG

Optical potential
(n-, p-, α-potential, def-dep)

S_0 n-strength
Reaction/Differential xs

ELECROMAGNETIC

γ-ray strength function
(E1, M1, def-dep, T-dep, PC)

(γ,abs), (γ,n), …
(γ,γ'), Oslo, <Γ_γ>, …

WEAK

β-decay
(GT, FF, def-dep., PC)

β^-, β^+ half-lives
GT

The fundamental role of β-decay rates

(including βdn & βdf)

Gross Theory :

the β-strength function is estimated by folding one-particle strength function via a simple pairing scheme taking into account the corresponding sum rules and even-odd effects.

QRPA approach (Skyrme, Gogny, RMF) with different levels of approx.

TDA, separable interactions, inconsistency between Ground & Excited states, spherical approximation, GT only, …

Recent work within

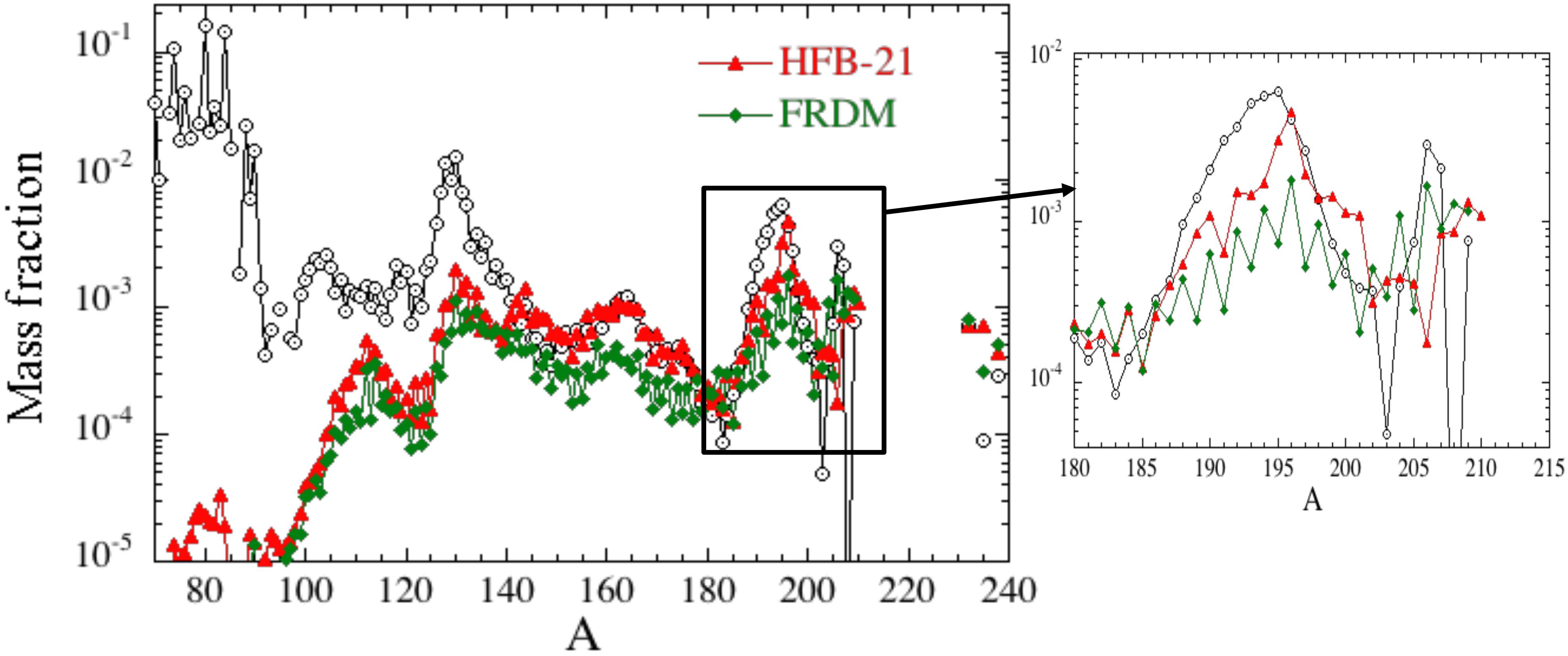
- EDF+Fermi Liquid Theory (Borzov 2010): spherical, FF incl.
- RHB+QRPA (Marketin et al. 2014): spherical, FF incl.
- Gogny HFB+QRPA (Martini & Péru 2014): def, GT, no FF (yet)

In practice, only a few complete tables (publicly) available

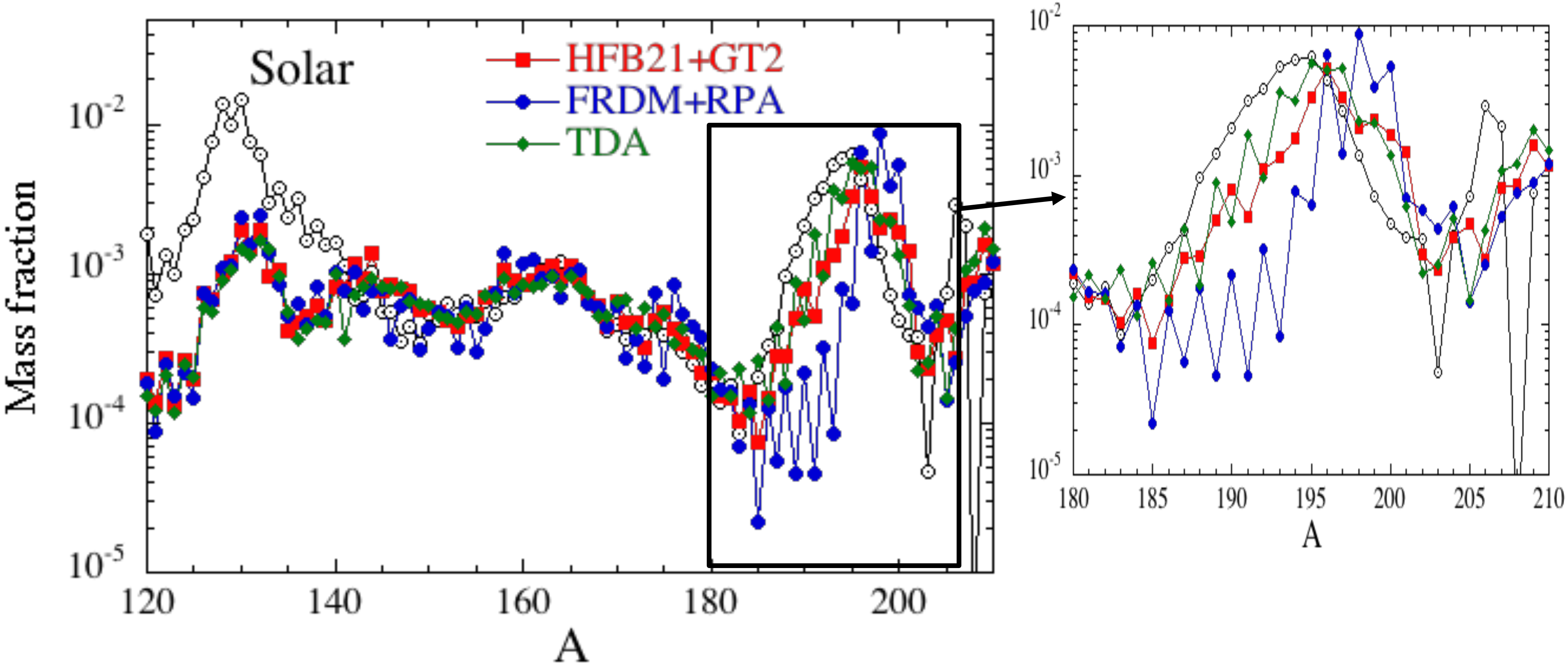
- Tachibana et al. (1990): HFB + Gross Theory 2 (GT + FF)
- Klapdor et al. (1984): Tamm-Dancoff approximation
- Möller et al. (2003): FRDM + QRPA & gross theory for FF

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

- GT2 β-decay rates with consistently estimated Q_β
- n-capture rates estimated within the HF+PE+DC model



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



Large impact of the β-decay rate – set the synthesis timescales

(βdn also influences the location of the peak with the late capture of neutrons released)

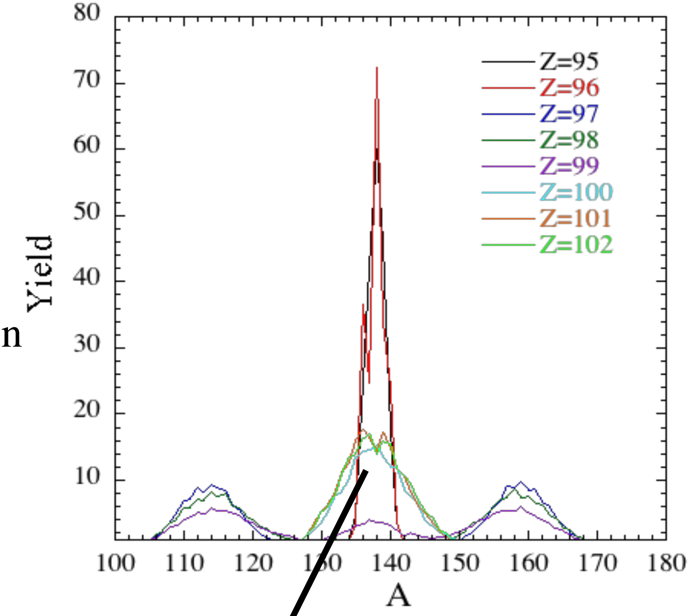
→ Need at least deformed "microscopic" calculation (HFB+QRPA) including GT+FF transitions, odd nuclei, PC, ….

Sensitivity to the fission fragment distribution

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

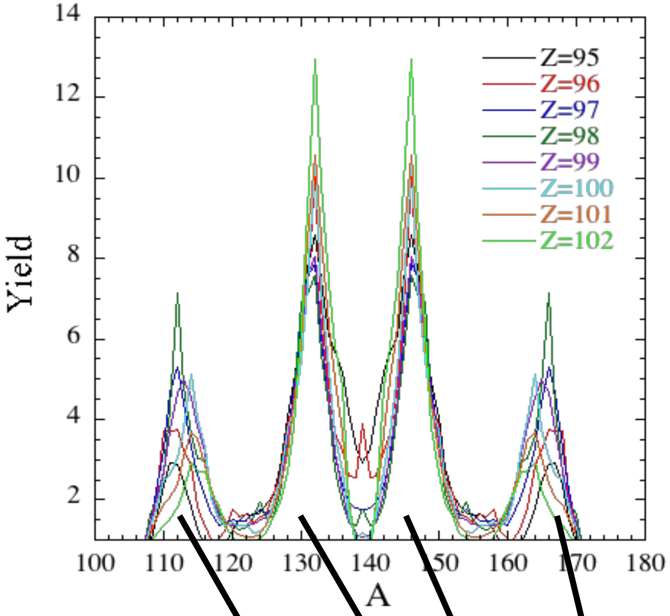
GEF v1.4
K. Schmidt et al. (2013)

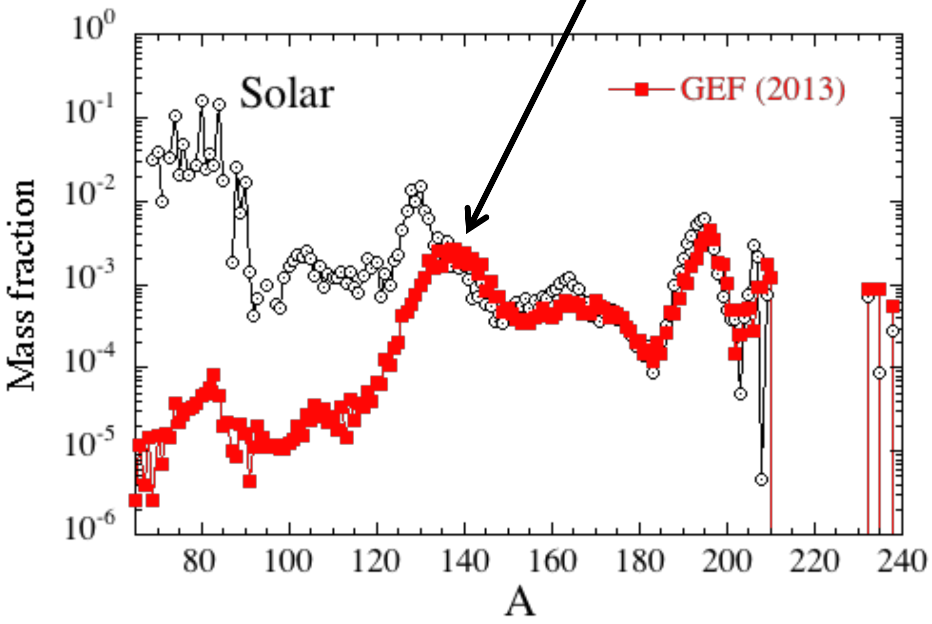
Semi-empirial mic-mac Scission Point model

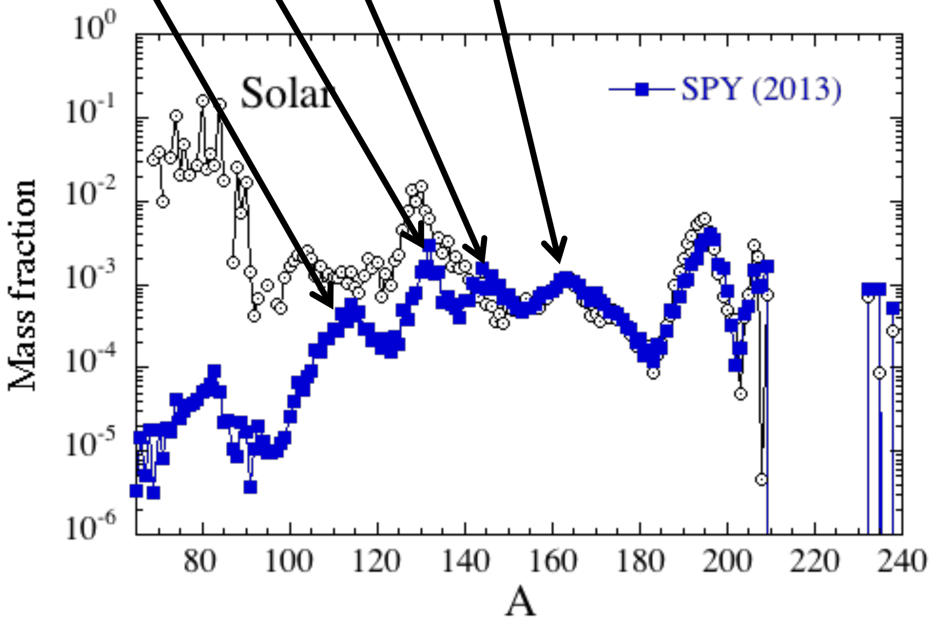


SPY:
S. Panebianco et al. (2013)

Parameter-free Scission Point model based on D1S potential energy surfaces







In Summary for the r-process

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, USA)

Still many open questions

- Site of the r-process ?
- Galactic chemical evolution ?
- Agreement with observation (spectroscopic, GCR, isotopic anomalies, marine sediments, …) ?
- Nuclear needs (site-dependent) ?
- Nuclear inputs (many properties on thousands of exotic n-rich nuclei) ?

The p-process nucleosynthesis

The p-process nucleosynthesis

1. Astrophysics aspects

- Parametric models: parametric models, including outdated spallation models

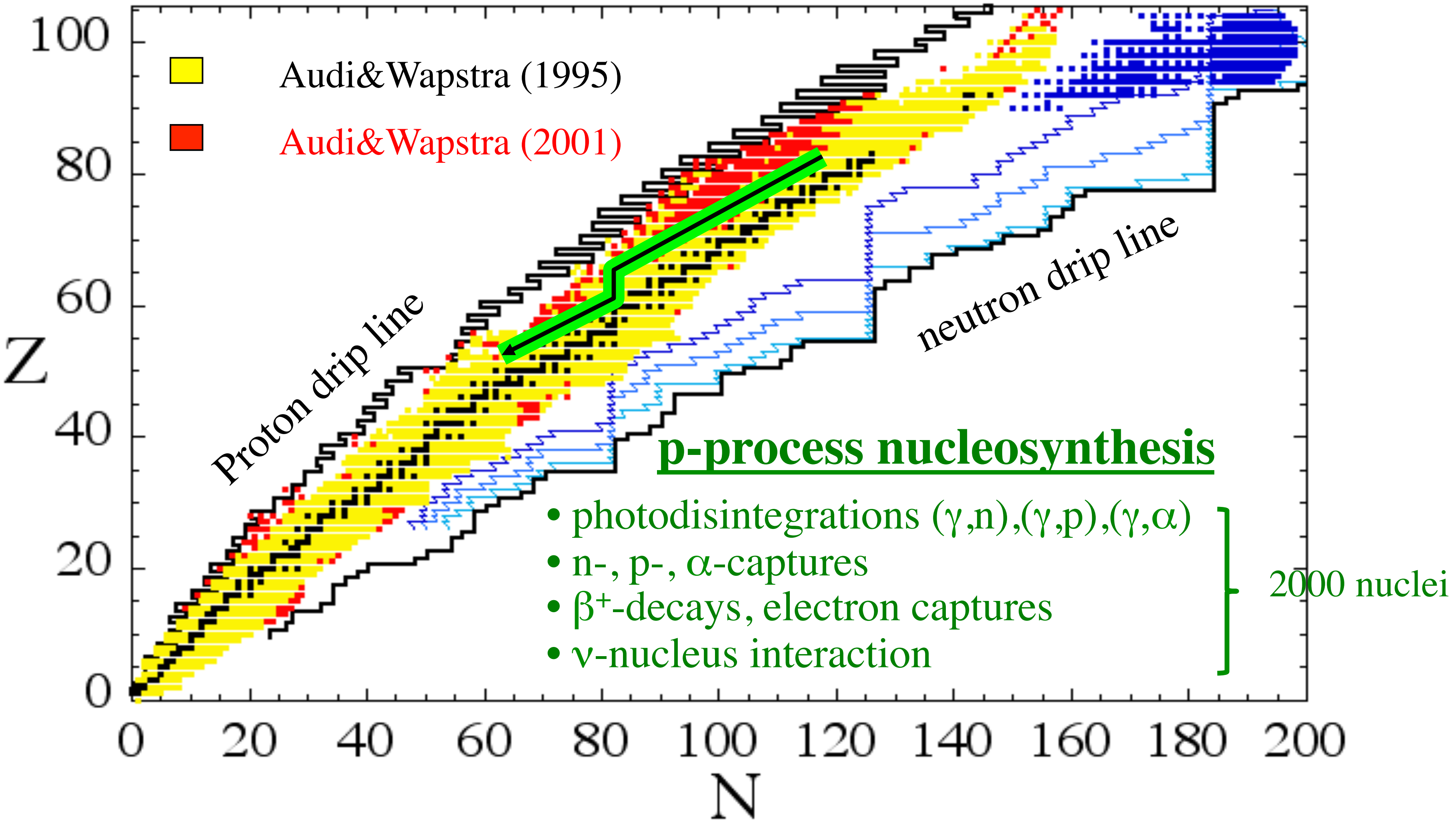
- “Realistic” models:
    - O-Ne layers of massive stars: hydrostatic and explosive phases
    - type Ia Supernova
    - He-accreting sub-Chandrasekhar mass white dwarfs
    - νp process in proton-rich ν-driven wind

2. Nuclear Physics aspects:

- Photodisintegration rates
- Neutron-, proton, alpha-capture rates
- β^+-decay rates
- ν-nucleus interaction rates

For about 2000 neutron-deficient (but neutron-rich also in some sites) nuclei

Nuclear needs for p-process calculations



p-process nucleosynthesis

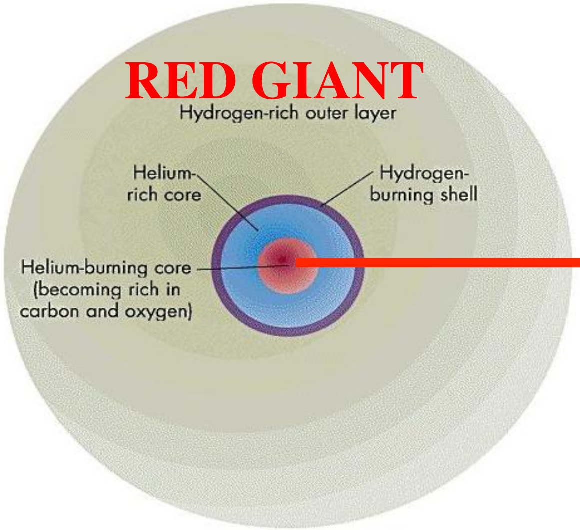
- photodisintegrations (γ,n),(γ,p),(γ,α)
- n-, p-, α-captures
- β^+-decays, electron captures
- ν-nucleus interaction

🙂 Many nuclear masses and β^+-decay rates known experimentally

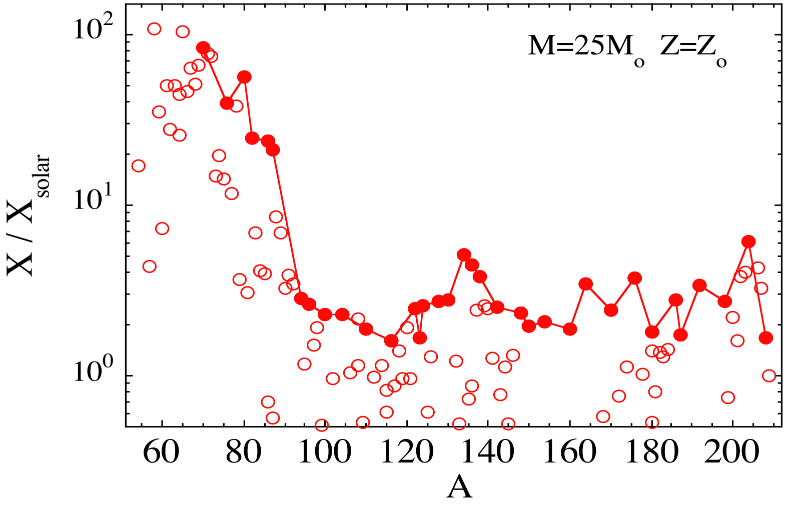
🙁 Almost no p- and α-capture rates known experimentally

Ne/O-rich layers during SNII explosion of massive stars

1. s-process during core He-burning by $^{22}Ne(\alpha,n)^{25}Mg$



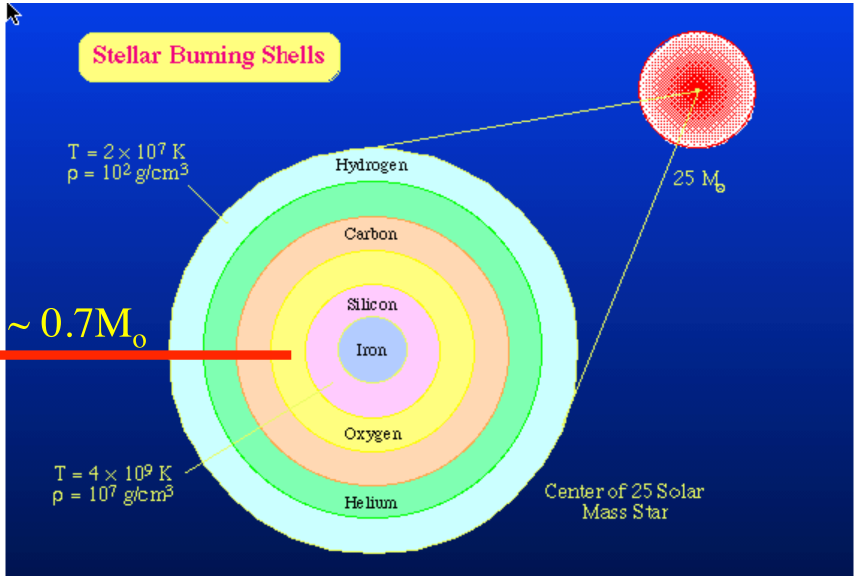
enrichment
in
s-elements
$70 \leq A \leq 90$



2. p-process in O/Ne layers

(hydrostatic pre-supernova as well as explosive supernova phases)

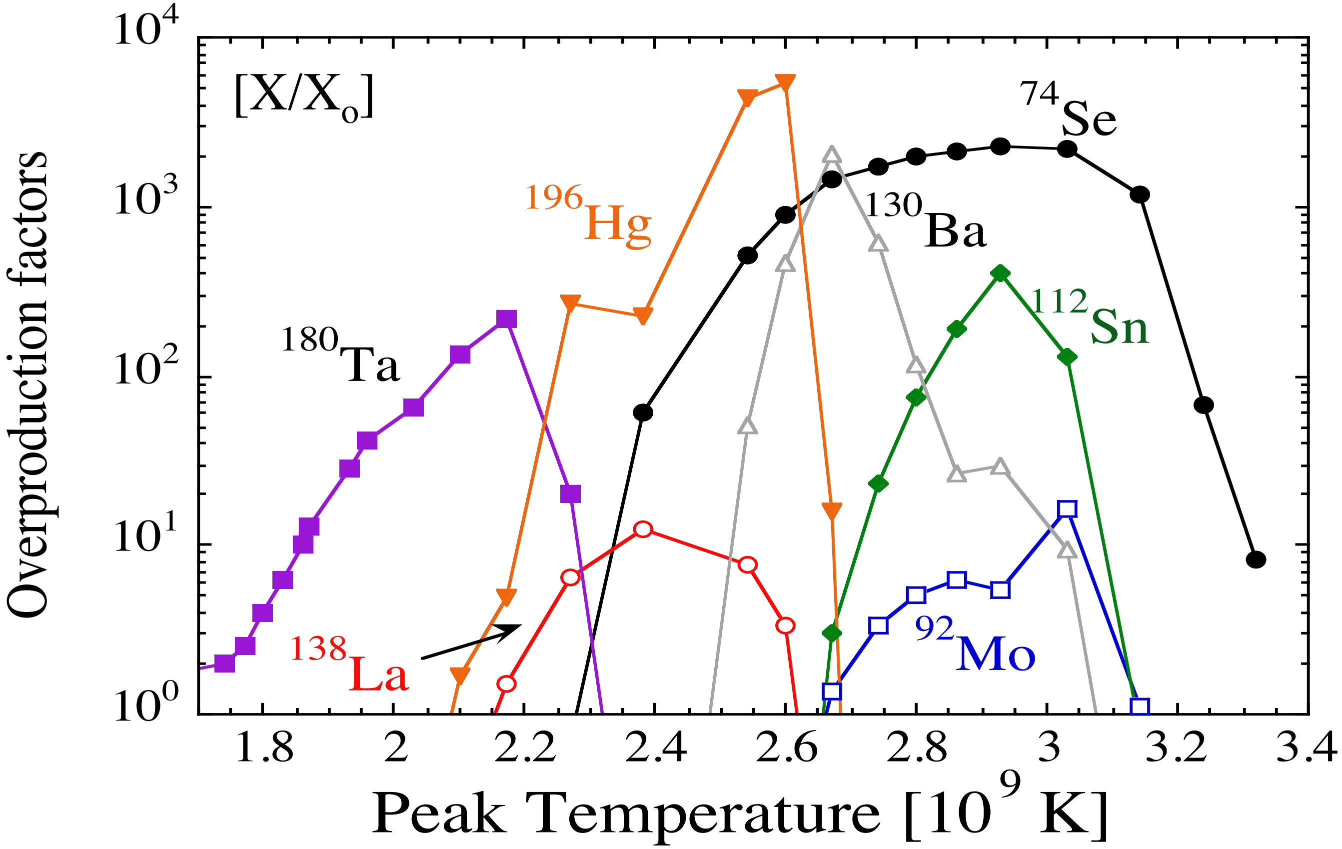
heating at T=2-3 10^9 K
of the s-enriched & r-seeds



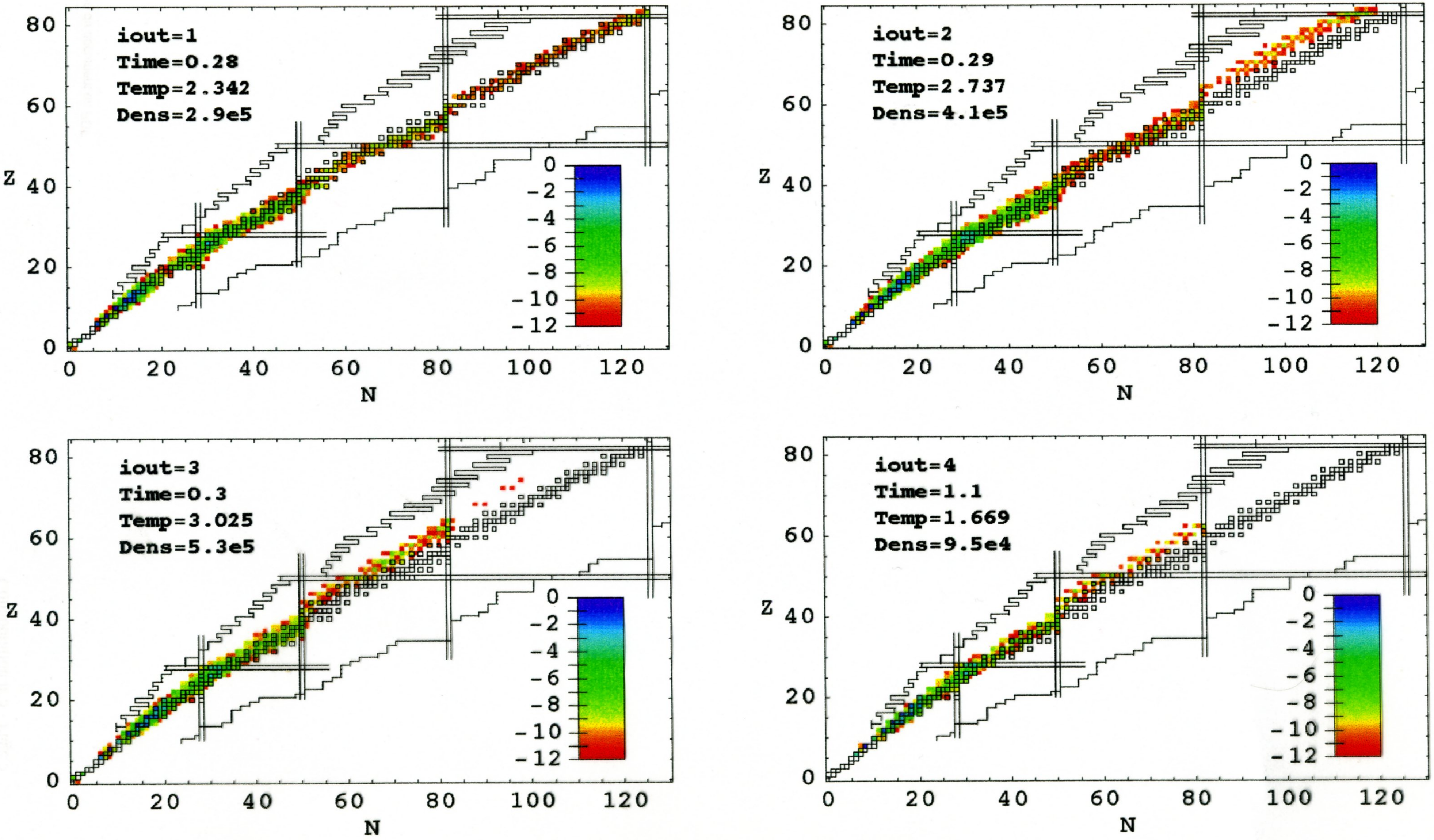
The synthesis of the heavy p-nuclides requires lower-T than the one of the light p-nuclides, which are more resistant to photodisintegrations. More specifically,

- the light ($N \leq 50$) p-nuclides are produced in the temperature range $3\ 10^9$ K $\leq T \leq 3.5\ 10^9$ K
- the intermediate-mass $50 \leq N \leq 82$ p-nuclides in the range $2.6\ 10^9$ K $\leq T \leq 3\ 10^9$ K
- the heavy $N \geq 82$ p-nuclides in the temperature $2\ 10^9$ K $\leq T \leq 2.6\ 10^9$ K

Each p-nucleus is substantially produced in a narrow range of temperatures only. This extreme sensitivity of the results to the peak temperature makes the use of realistic stellar models mandatory



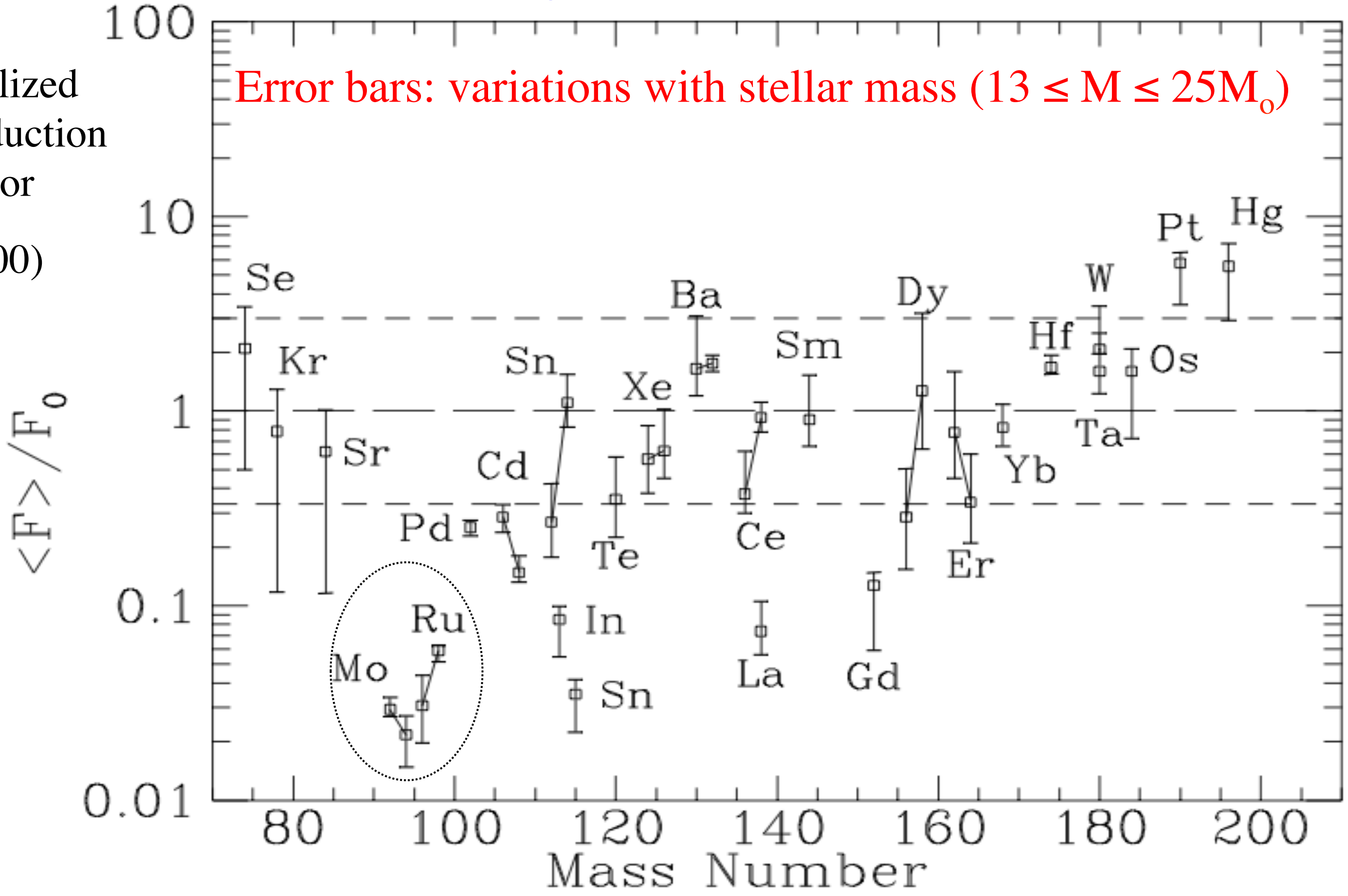
Nuclear flows during the p-process in an SNII explosion



P-nuclides yields obtained by convolution over a spectrum of stellar masses (assuming an Initital Mass Function)

Normalized overproduction factor

(F_0=100)



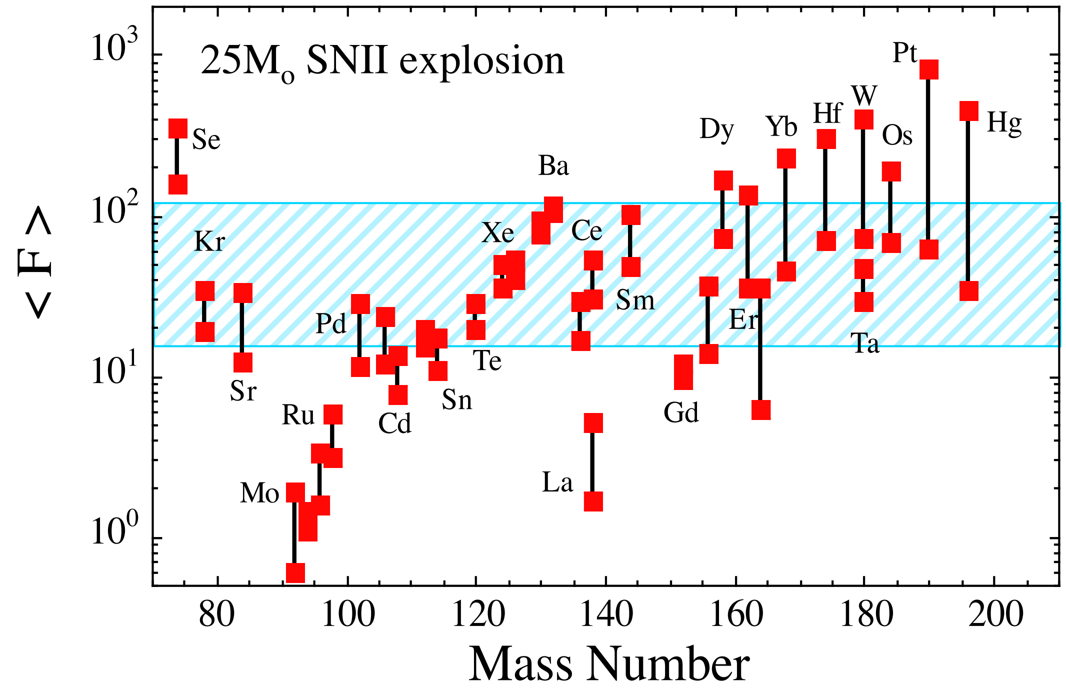
Error bars: variations with stellar mass ($13 \leq M \leq 25M_o$)

Within a factor of 3

The mean overproduction factor $<F_i(M)>$ for a star with mass M is defined as the total mass of the p-nuclide i produced in its PPLs divided by the corresponding mass if the PPLs had a solar composition. The normalizing factor $F_0(M)$ is the mean overproduction factor averaged over the 35 p-nuclides. With these definitions, all the normalized overproductions would be equal to unity if the derived abundance patterns were solar.

Some discrepancies remain: Mo and Ru p-isotopes, ^{113}In, ^{115}Sn and ^{138}La.

Impact of the nuclear uncertainties on the p-nuclide production



Major nuclear uncertainties from

- GLOBAL alpha-nucleus optical potentials (heavy A>150 p-nuclides)
- GLOBAL nucleon-nucleus potential, NLD, γ-strength (light A<90 p-nuclides)

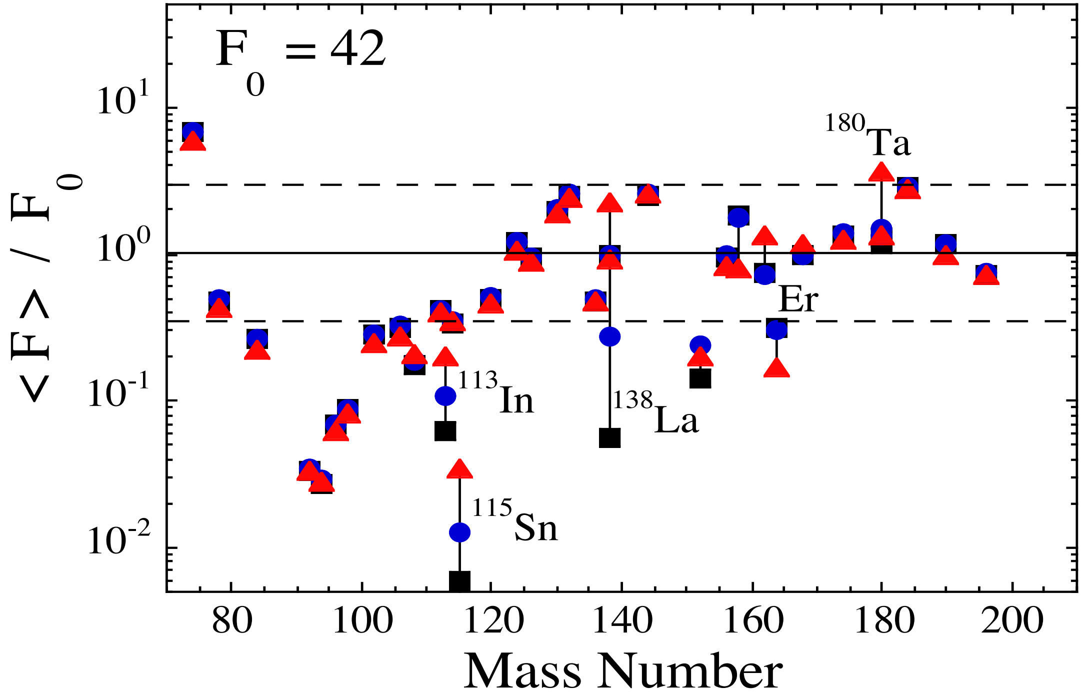
(The ^{92,94}Mo, ^{96,98}Ru discrepancies are most probably not related to nuclear issues)

- p- and α-captures: new measurements (Demokritos, Debrecen, Kalrsruhe, Achen,…) but still not enough contraints on global potential - more theoretical work welcome too
- γ-ray strengths: new experimental information (Konan, Oslo, Duke, GSI, Dresden, …), but still open debate on the low-energy tail and PDR - more theoretical work welcome

Production of rare species by electron neutrino captures

Neutrino from the proto-neutron stars ($\nu_e, \bar{\nu}_e, \nu_x$)

The production of ^{138}La is possible through $^{138}\mathrm{Ba}(\nu_e, e^-)^{138}\mathrm{La}$, but depends on the neutrino luminosity. Similarly, the ν-capture also affects the production of **^{113}In, ^{115}Sn, ^{162}Er and ^{180}Ta**.



For different neutrino luminosities
($\nu_e, \bar{\nu}_e, \nu_x$)

$L_\nu[10^{51}$ erg/s$] = (30, 40, 160)$

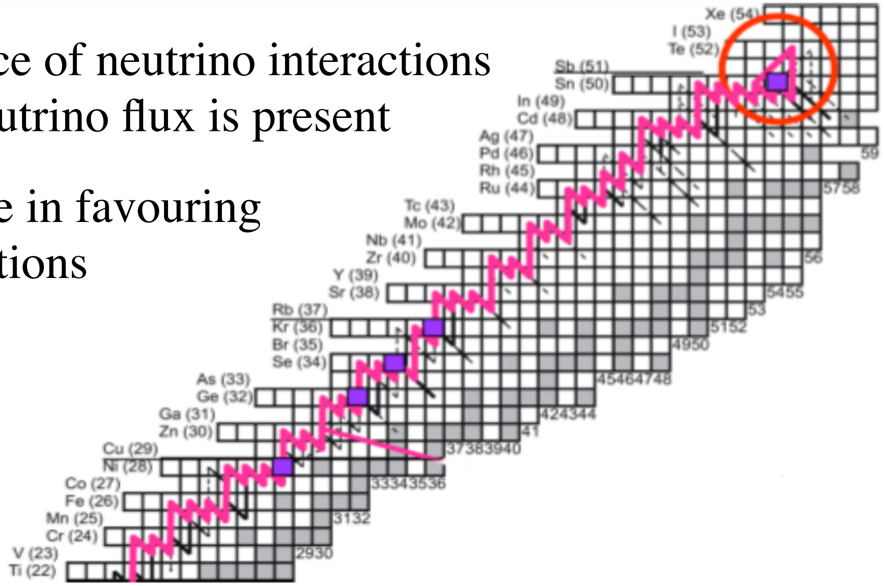
$L_\nu[10^{51}$ erg/s$] = (3, 4, 16)$

$L_\nu[10^{51}$ erg/s$] = 0$

But still large uncertainties in the ν-physics
and ν-nucleus interaction cross sections !

Production of light p-nuclei in the proton-rich neutrino wind of type-II supernovae: νp-process

- proton-rich matter may be ejected under the influence of neutrino interactions
- Nuclei form at distances where a substantial anti-neutrino flux is present



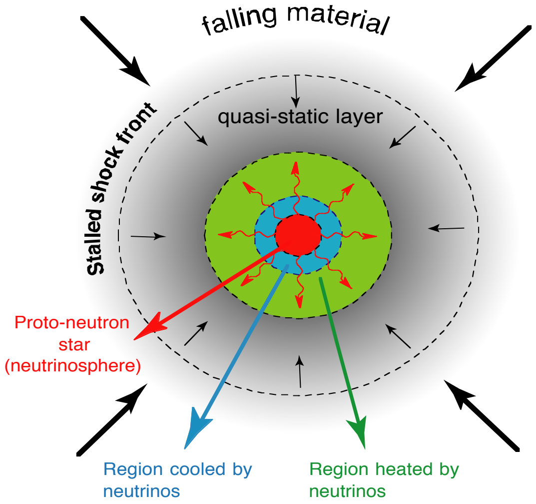
The large anti-neutrino flux plays an important role in favouring the production of heavy species through (n,p) reactions

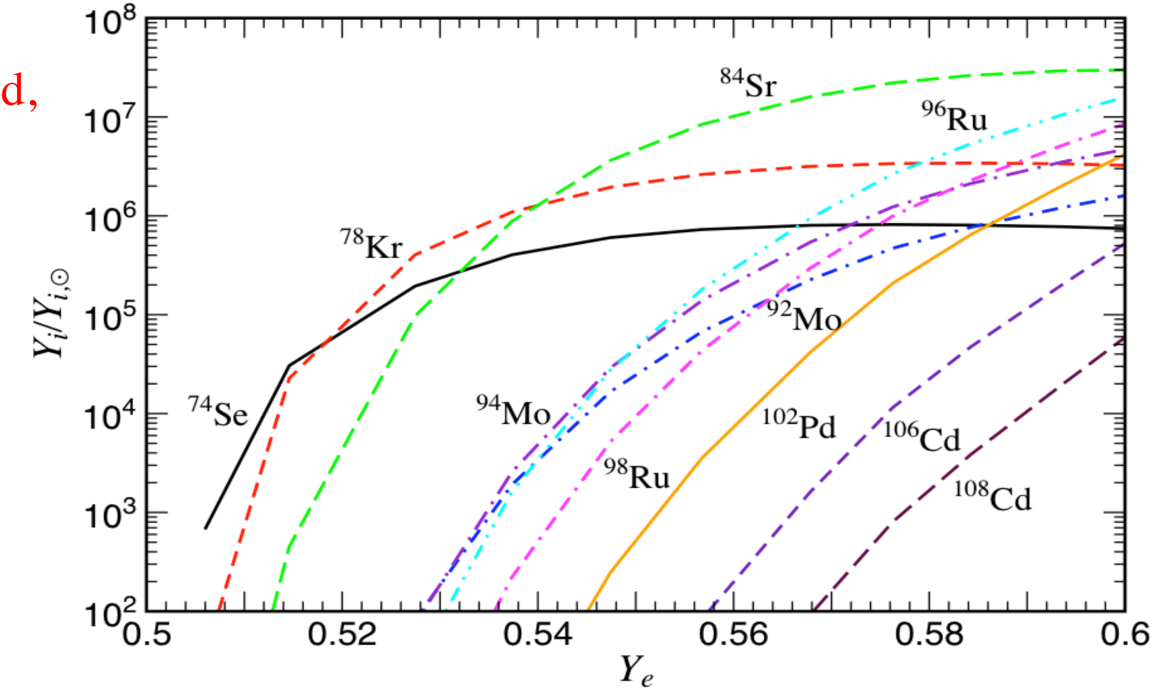
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

followed by neutron and proton captures

^{64}Ge(n,p)^{64}Ga
^{64}Ga(p,γ)^{65}Ge, etc ….

Nucleosynthesis is sensitive to the exact conditions of the neutrino wind, in particular Y_e, entropy and radius



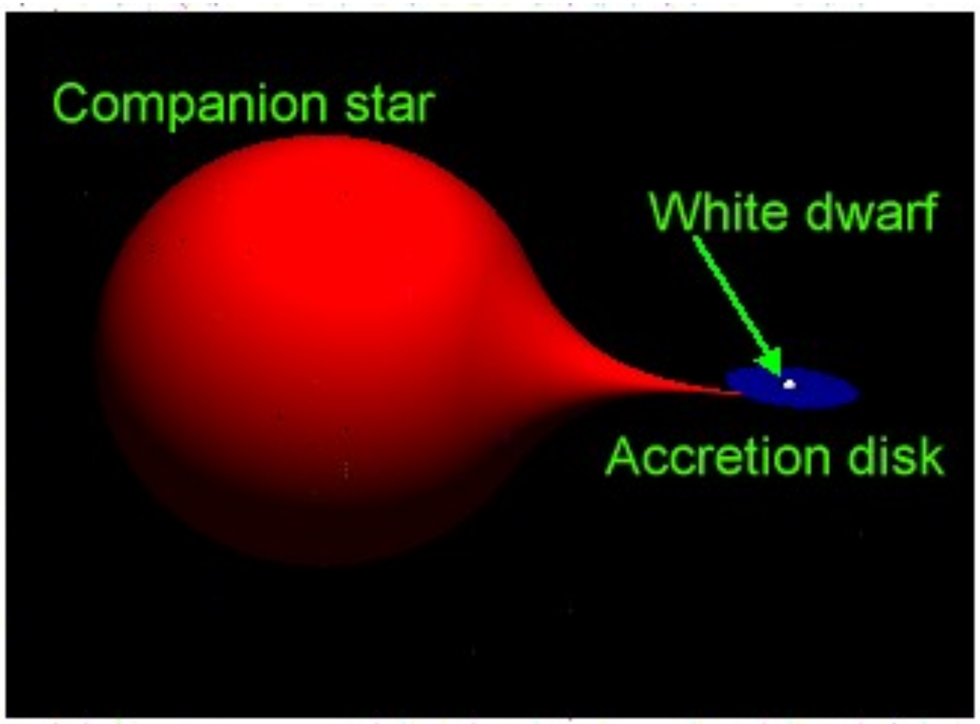


Accreting White Dwarf models for type Ia Supernovae

Matter accreted onto the surface of a white dwarf from its binary companion causes regions in its interior to become unstable to thermonuclear runaway. → Carbon deflagration/detonation

↓

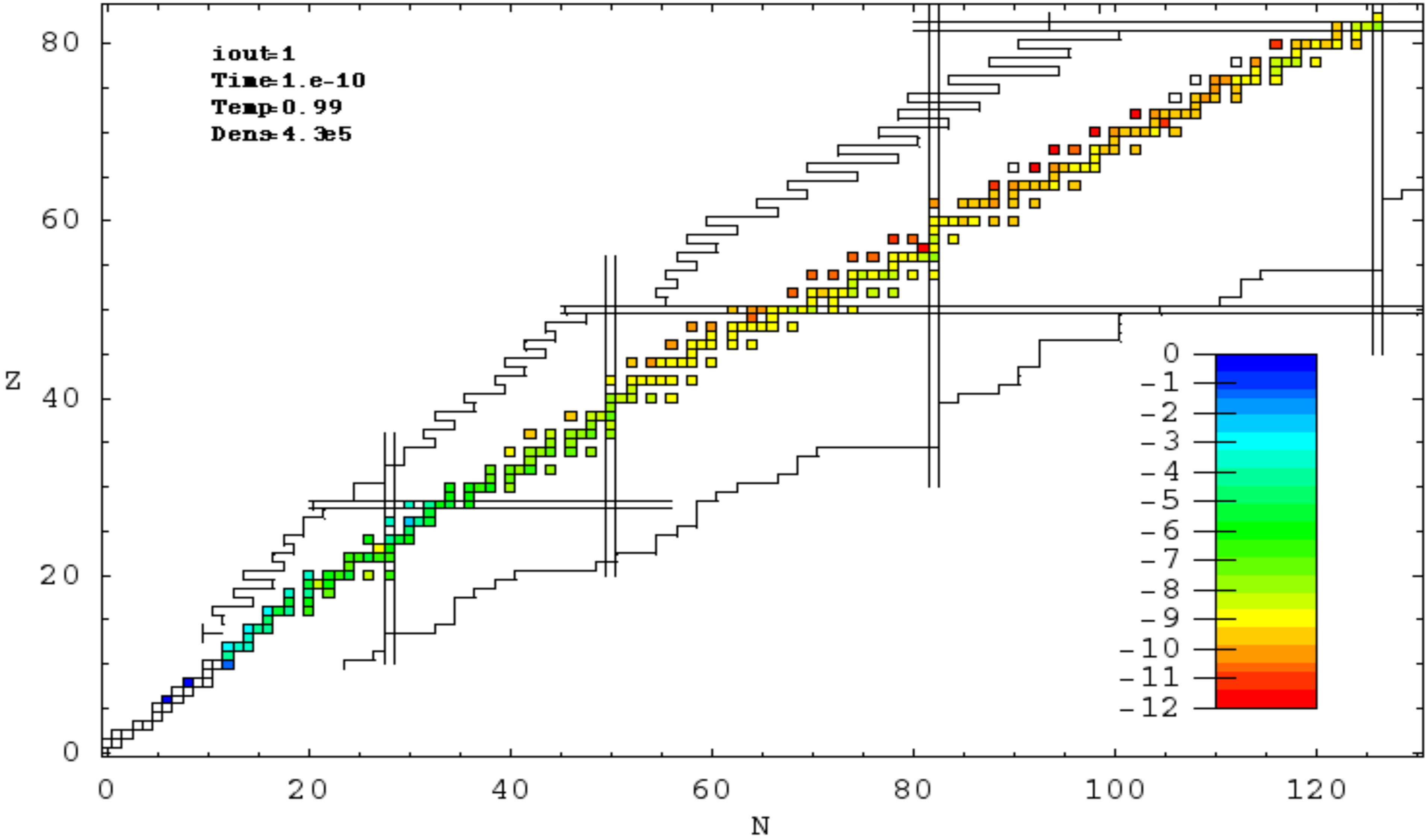
p-process nucleosynthesis in layers heated at *T*=2-3 10^9 K (initial composition C+O+Ne)



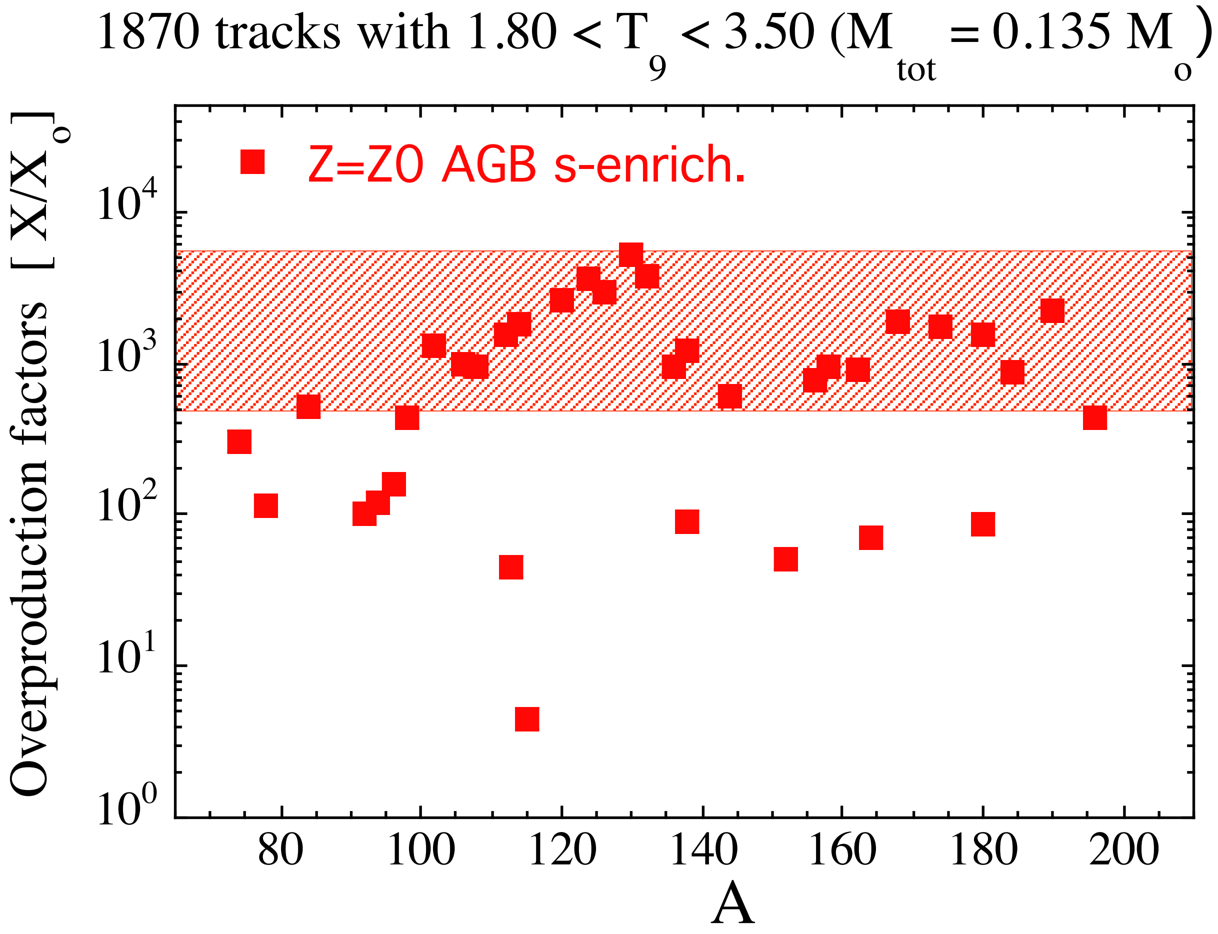
Initial composition of the heavy seeds

- solar composition
- s-process elements in WD ?
- s-process elements from AGB companion?
- s-process nucleosynthesis during accretion phase ?

SNIa model: W7 (Nomoto et al. 1984)

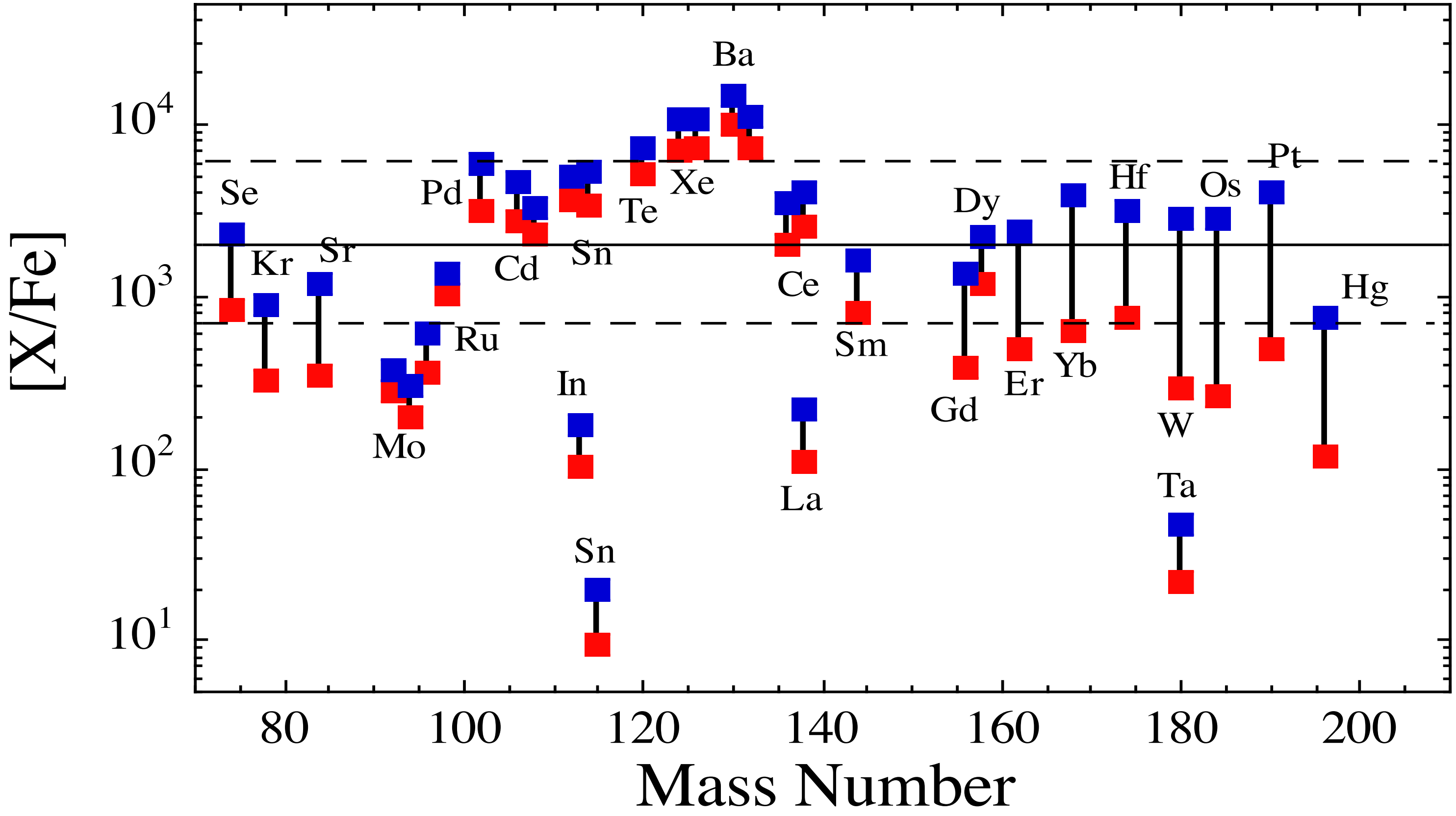


P-process in 3D model of SNIa thermonuclear explosion

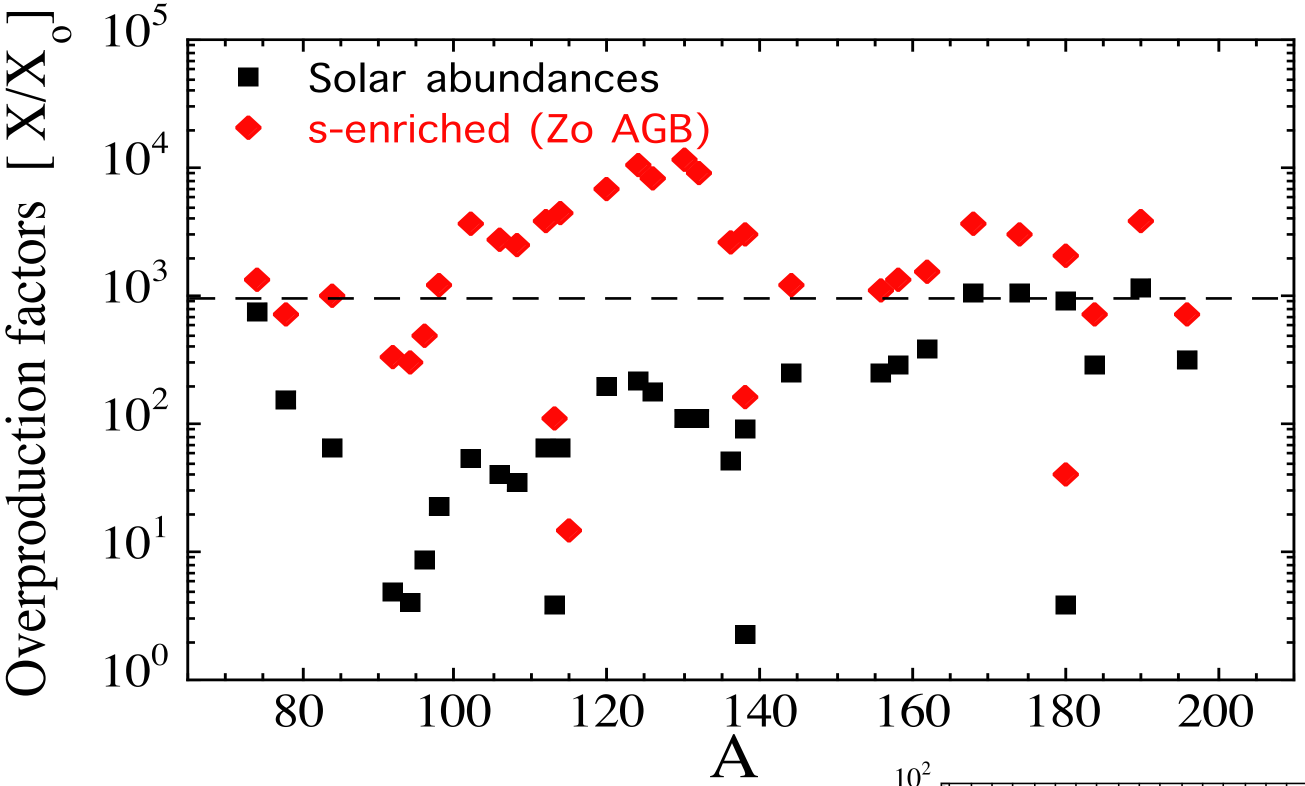


Impact of the nuclear uncertainties on the p-nuclide overproduction factor

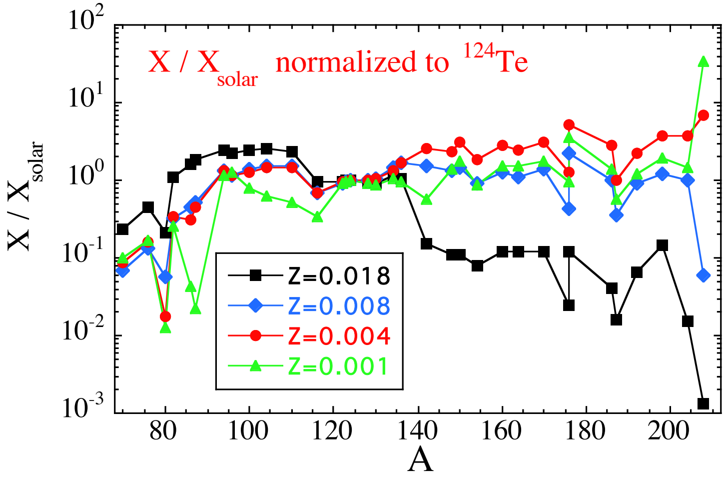
Heavy seed abundances: s-process enriched from a Z_o-AGB star



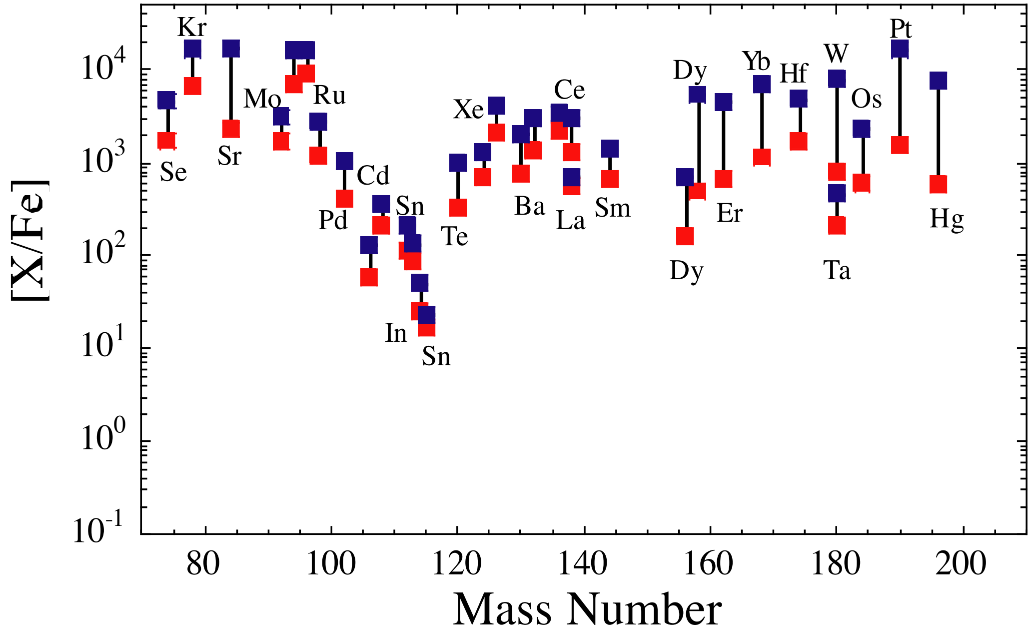
Impact of the initial seed abundances on the p-nuclide overproduction factor



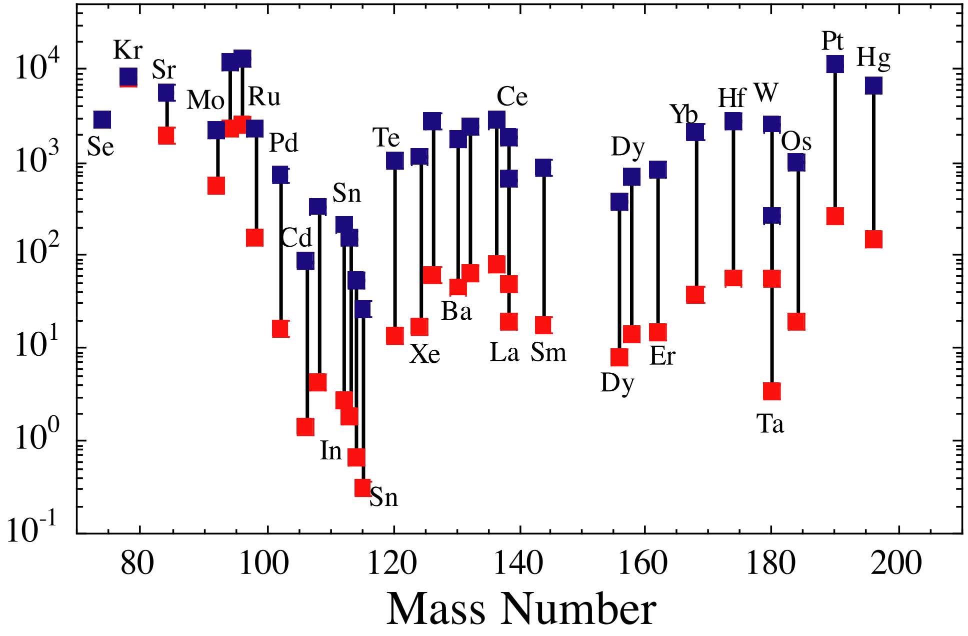
The initial s-process enrichment depends on the stellar mellacity:



Impact of the *nuclear* uncertainties on the p-nuclide overproduction factor

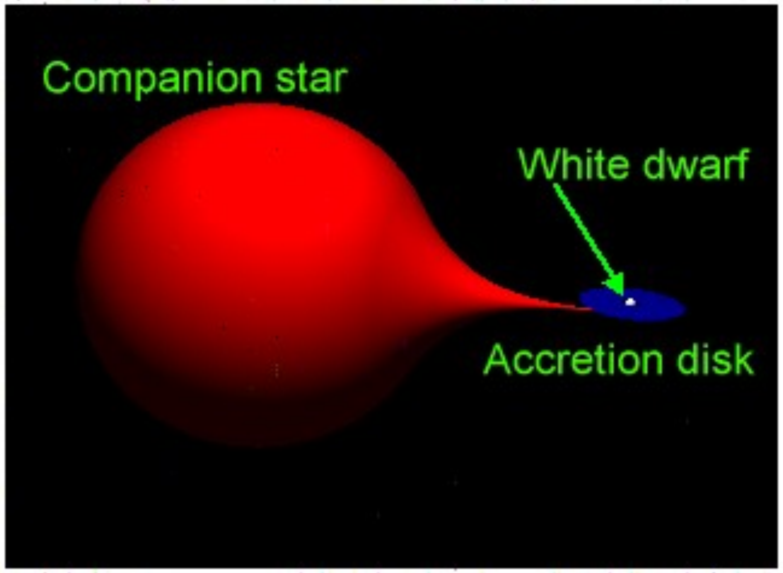


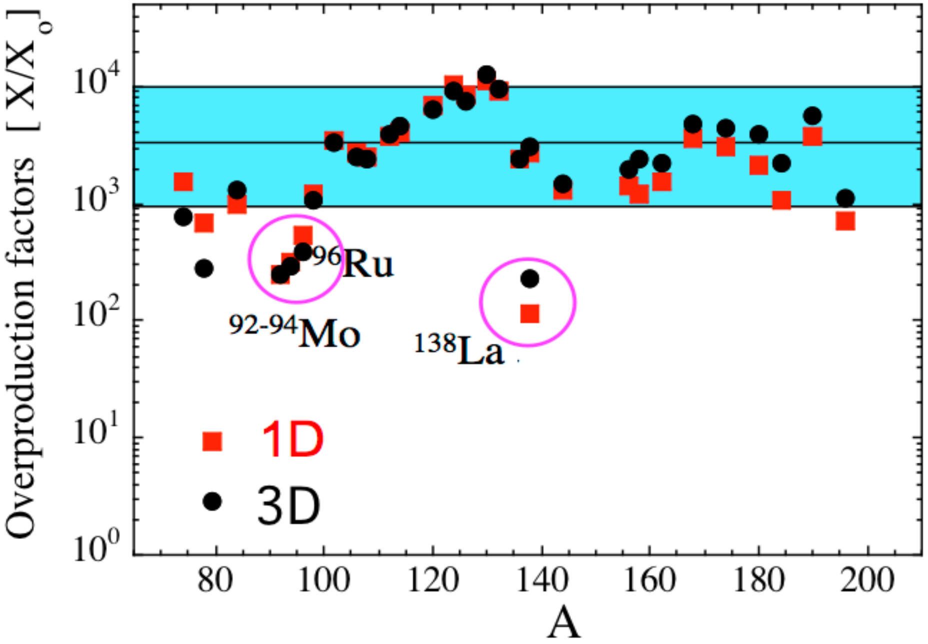
Impact of *the initial seed* abundances on the p-nuclide overproduction factor

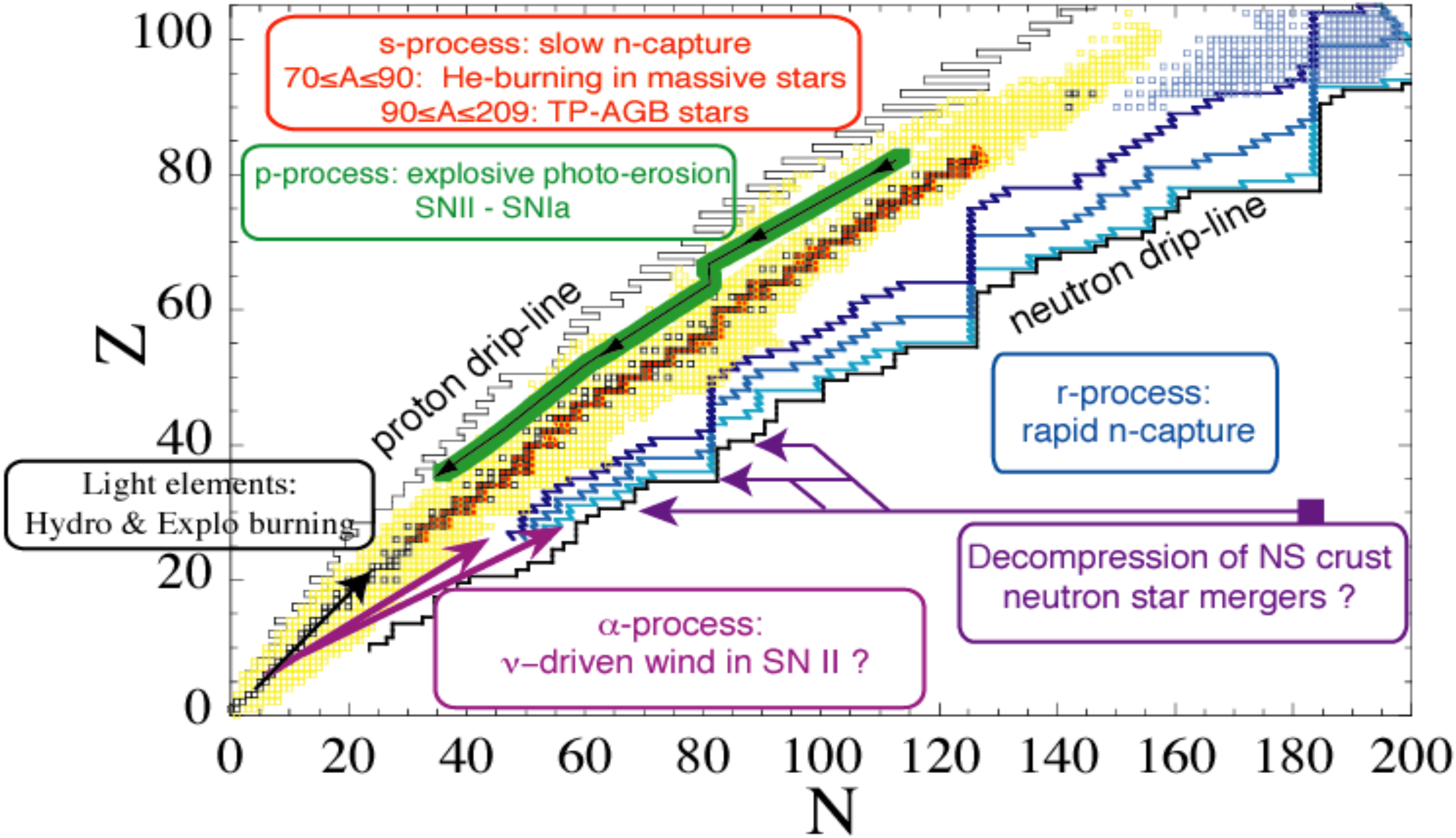


In summary…the p-process nucleosynthesis is responsible for n-deficient elements heavier than iron in the Universe

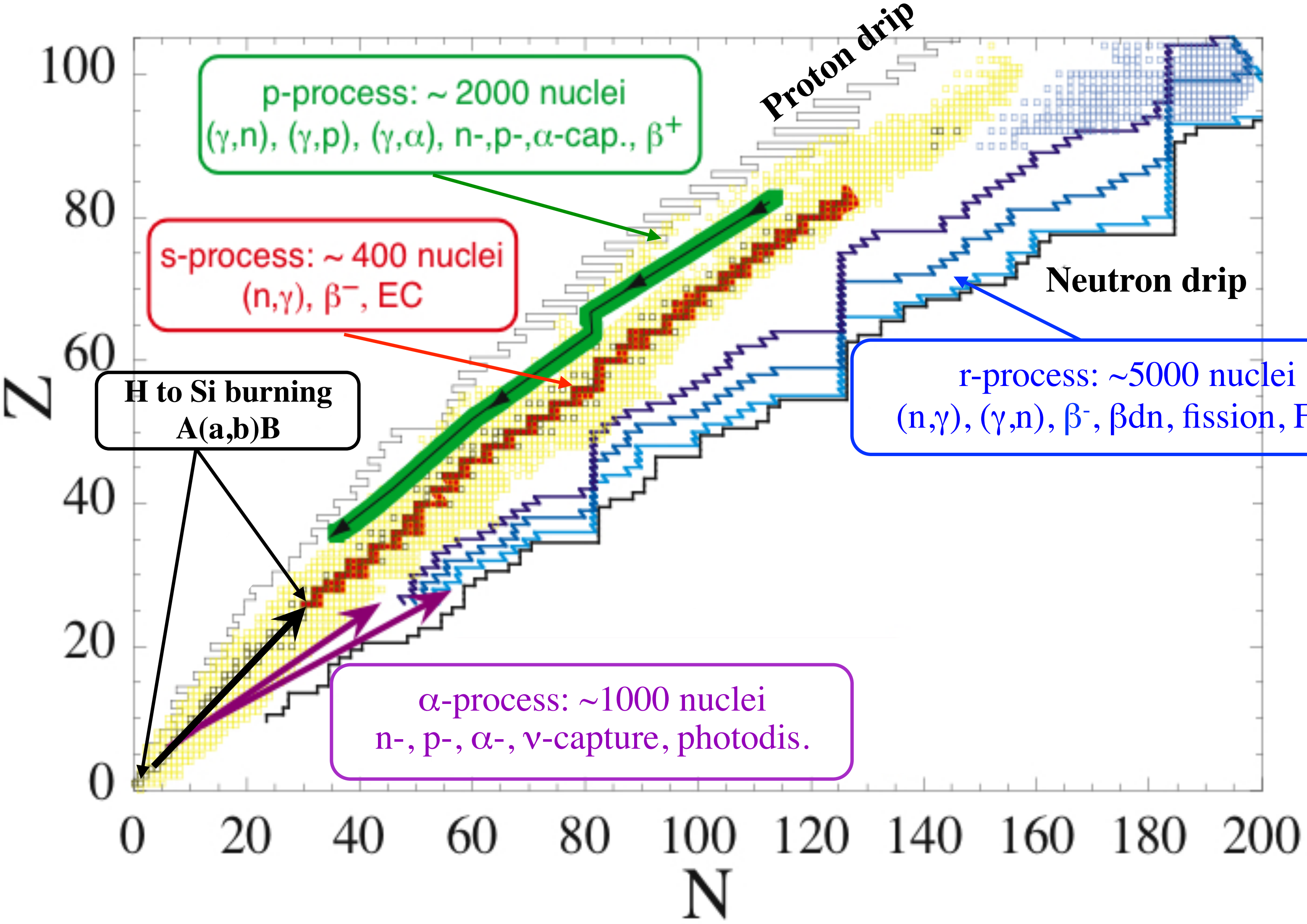
- How to explain the origin of ^{92,94}Mo, ^{96}Ru, ^{138}La ?
- What is the contributions of SN Ia or p-rich ν-wind, if any ?
- What are the seed nuclei feeding the p-process ?
- What is the role of neutrinos for rare species ?
- What is the photodissociation rates of nuclei involved ?






s-process: slow n-capture
70≤A≤90: He-burning in massive stars
90≤A≤209: TP-AGB stars
p-process: explosive photo-erosion
SNII - SNIa
proton drip-line
neutron drip-line
Light elements:
Hydro & Explo burning
r-process:
rapid n-capture
Decompression of NS crust
neutron star mergers ?
α-process:
ν–driven wind in SN II ?
Z
N
0
20
40
60
80
100
0
20
40
60
80
100
120
140
160
180
200

Many different nuclear needs for the different nucleosynthesis applications



p-process: ~ 2000 nuclei
(γ,n), (γ,p), (γ,α), n-,p-,α-cap., β^+

s-process: ~ 400 nuclei
(n,γ), β^-, EC

H to Si burning
A(a,b)B

r-process: ~5000 nuclei
(n,γ), (γ,n), β^-, βdn, fission, FFD

α-process: ~1000 nuclei
n-, p-, α-, ν-capture, photodis.

Different types of astrophysics models

+ + – State of the art: 3D (~ self-consistent) models

p-process in SNIa explosions, r-process in NSM

+ – Realistic 1D (~ self-consistent) models

s-process in Massive Stars

– Parametrized (semi-realistic) 1D models

s-process in AGB Stars

– – Parametrized (unrealistic) 1D models

r-process in ν-driven wind

– – – Phenomenological parametrized site independent models

Canonical s- and r-processes

Remain critical about the astrophysics models

(even the 3D simulations are far from being free from astrophysical uncertainties!)

Obvious need for accurate and reliable nuclear data, … but
the uncertainties in the astrophysics models most of the time prevail

Conclusions

	ASTRO	NUCLEAR	OBS
BIG-BANG	+	+	+
A<56 SYNTHESIS	+	+ –	+
S-PROCESS	–	+ –	+ –
P-PROCESS	–	–	–
R-PROCESS	– –	– –	–

Conclusions

Nuclear physics is a necessary but a not sufficient condition for Nuclear Astrophysics

Still many open astrophysics & nuclear physics questions

The exact role of nuclear physics in Astrophysics will remain unclear as long as the astrophysics sites and the exact nuclear mechanisms of relevance are not fully under control

P-process (-/+) S-process (+/-) R-process (–)