The p-process in SNIa: Different production channels and main abundance dependences

Umberto Battino (Universität Basel)

In collaboration with:

Claudia Travaglio (INAF– Osservatorio Astronomico di Torino)
F. K. Ropke (Max-Planck Institut, Garching (München), Germany)

And

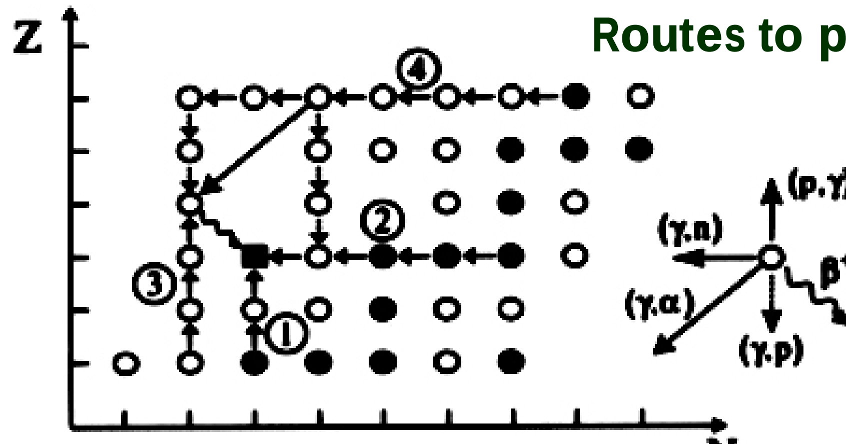
Roberto Gallino (Università degli studi di Torino)

24-25 November 2011,
Athens, Greece

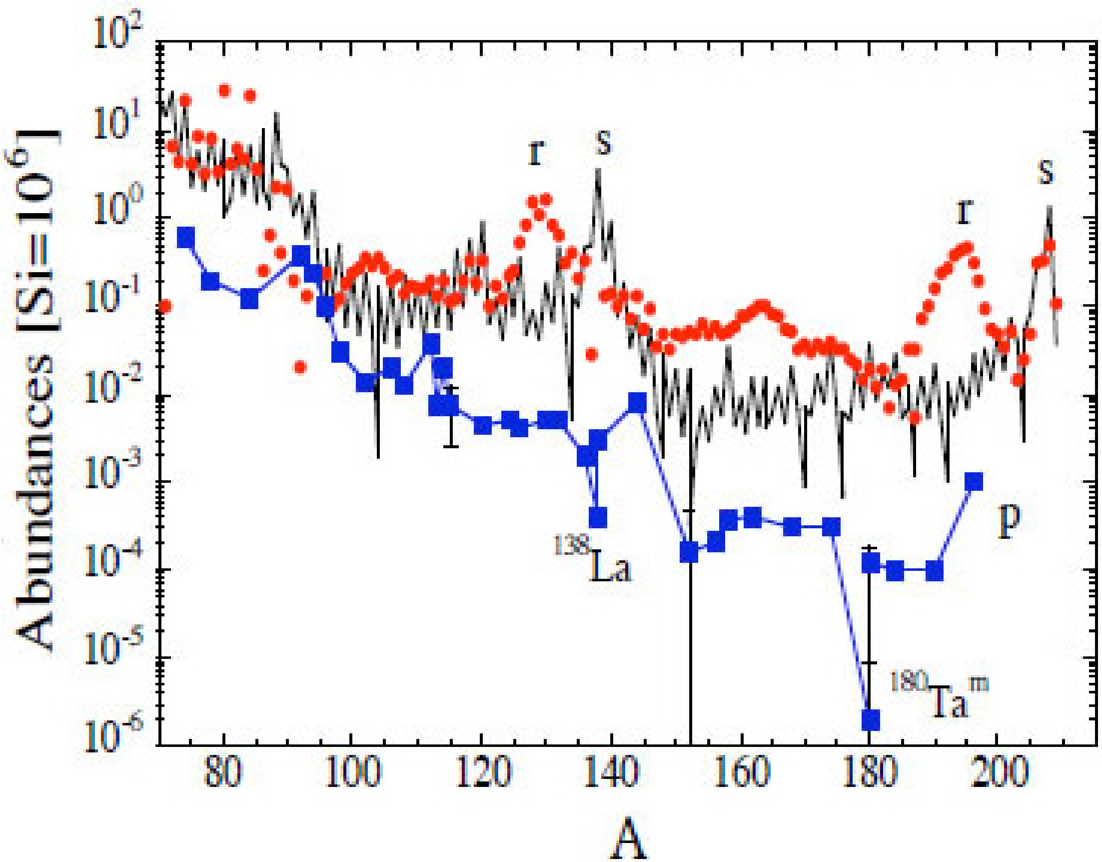
35 p-nuclei

Arnould (2003)

Routes to p-nuclei



p-nuclei in the Solar System



P-nuclei sources

Type II Supernovae

Audouze & Truran (1975)

Arnould (1976)

Woosley & Howard (1978)

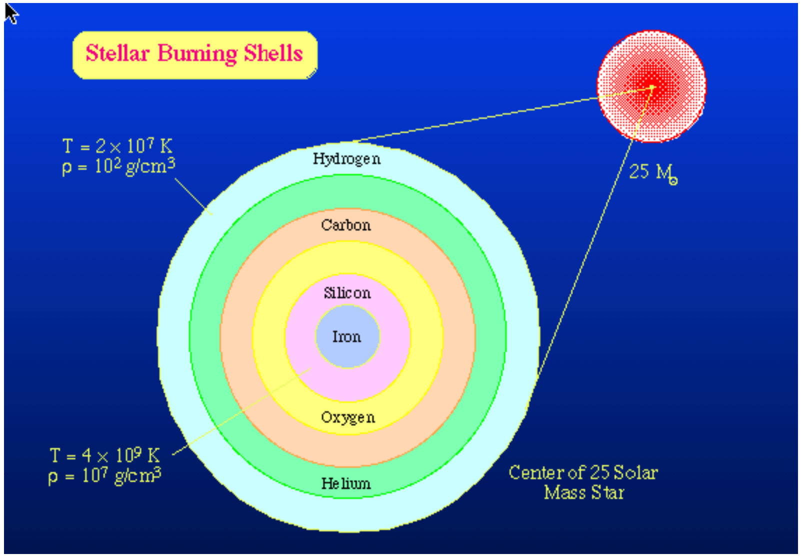
Type Ia Supernovae

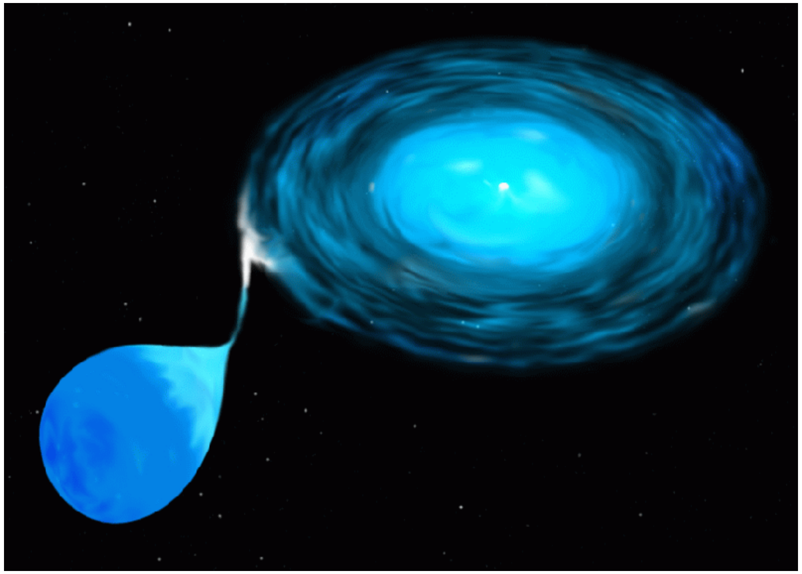
Howard et al. (1991)

Goriely et al. (2002,2005)

Kusakabe et al. (2011)

Travaglio et al. (2011)





This work

The SNIa model used in this work is the one described in Travaglio et al. (2011), precisely the one named DDT-a, characterized by:

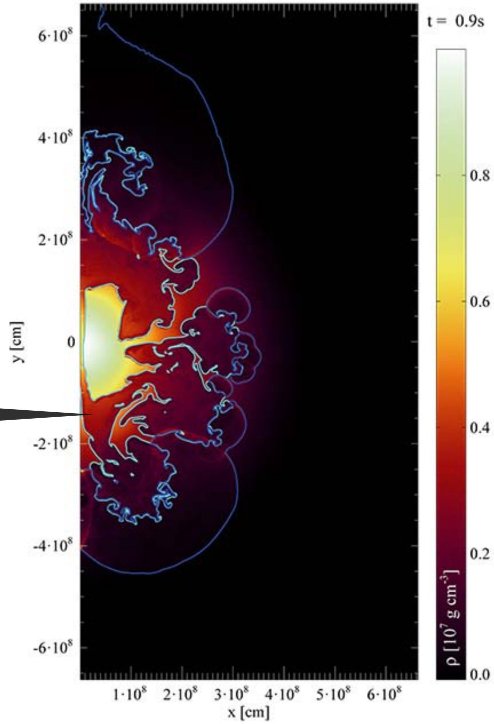
- Two-dimensional model.
- Chandrasekhar mass exploding WD.
- Solar metallicity
- Deflagration + delayed detonation explosion.
- 0.6 $M_\odot$ of ^{56}Fe produced.
- Small network included inside the hydrodynamic code to compute energy.
- Full nucleosynthesis calculation up to ^{209}Bi was performed by C. Travaglio with a post-process

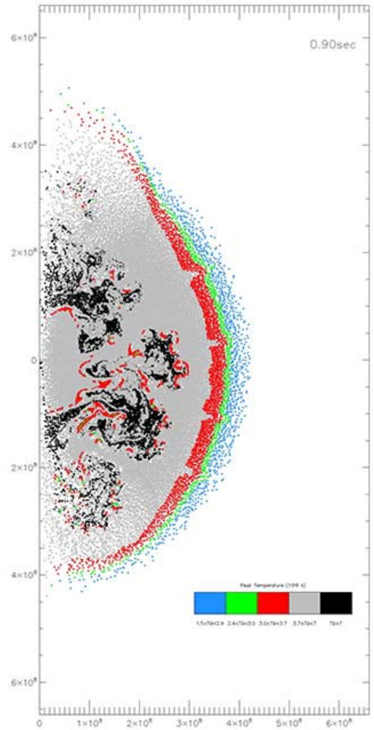
This work

- I used a Type Ia Supernova model developed by the "Max Planck Institute fur Astrophysics" (MPA) in Munich.
- I used the Basel reaction rate network "REACLIB".
- The WD is subdivided into 51200 tracer particles. Among them just 4762 were selected (corresponding to ~ 0.2 $M_{\odot}$), that's to say the ones experiencing a peak temperature (T9max) such that

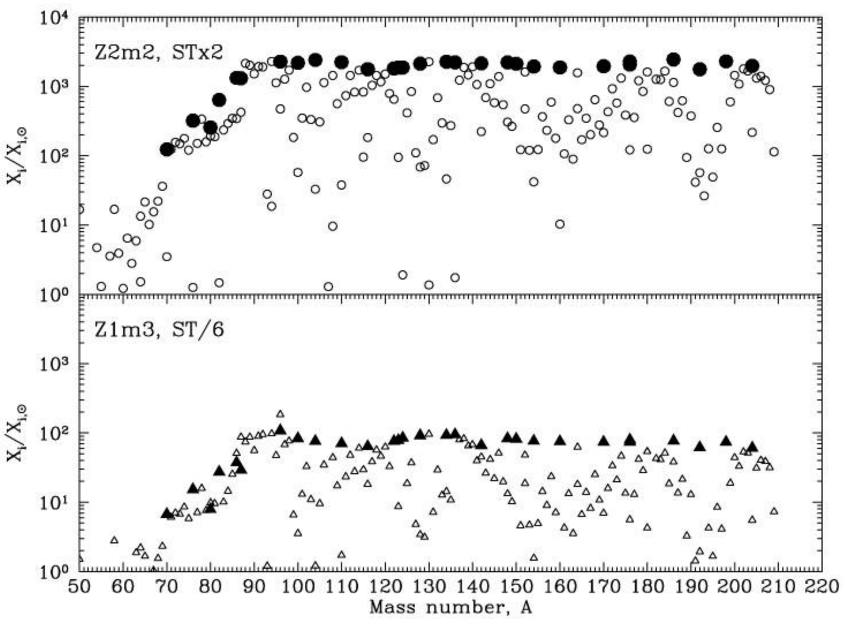
Travaglio et al.
(2011,ApJ)

F. Roepke & W.Hillebtandt
SNIa models



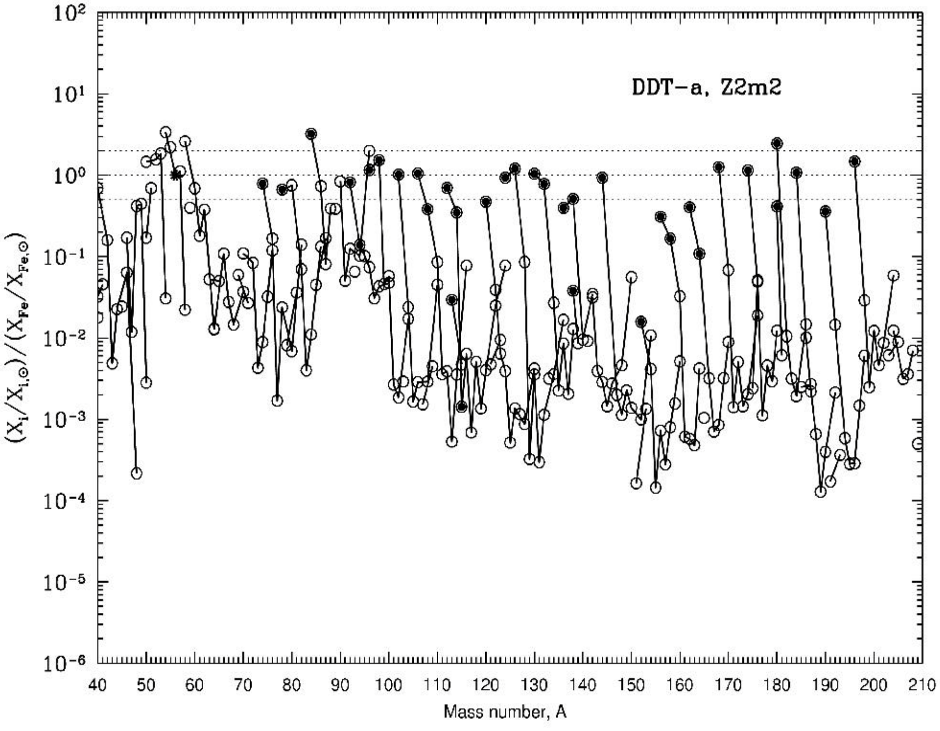


R. Gallino
s-process calculations

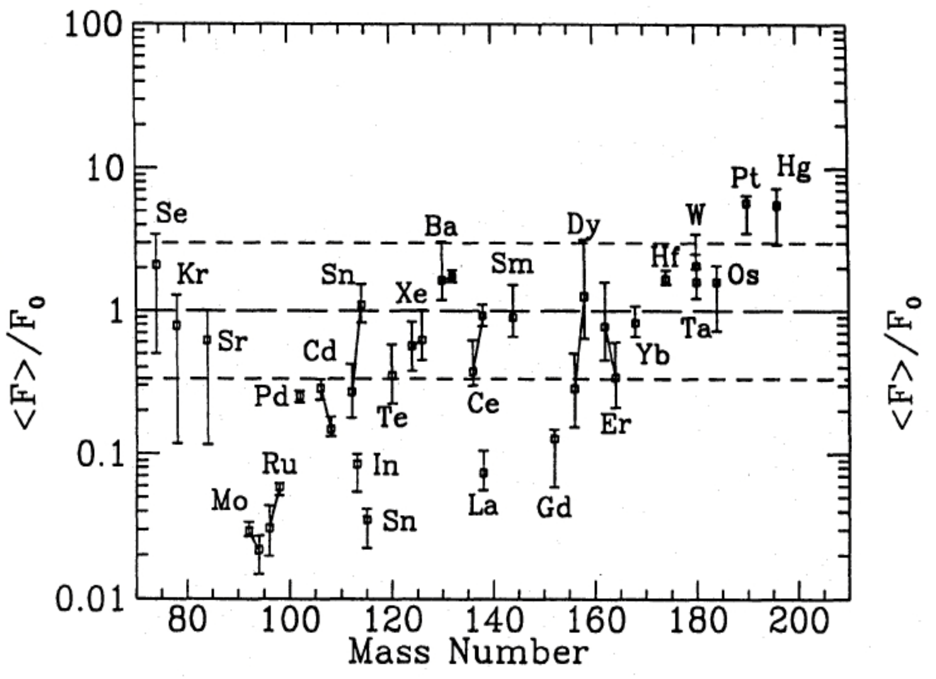


C. Travaglio
p-process nucleosynthesis

Comparison between Sne Ia and SN II p-nuclei production



Travaglio et al. 2011

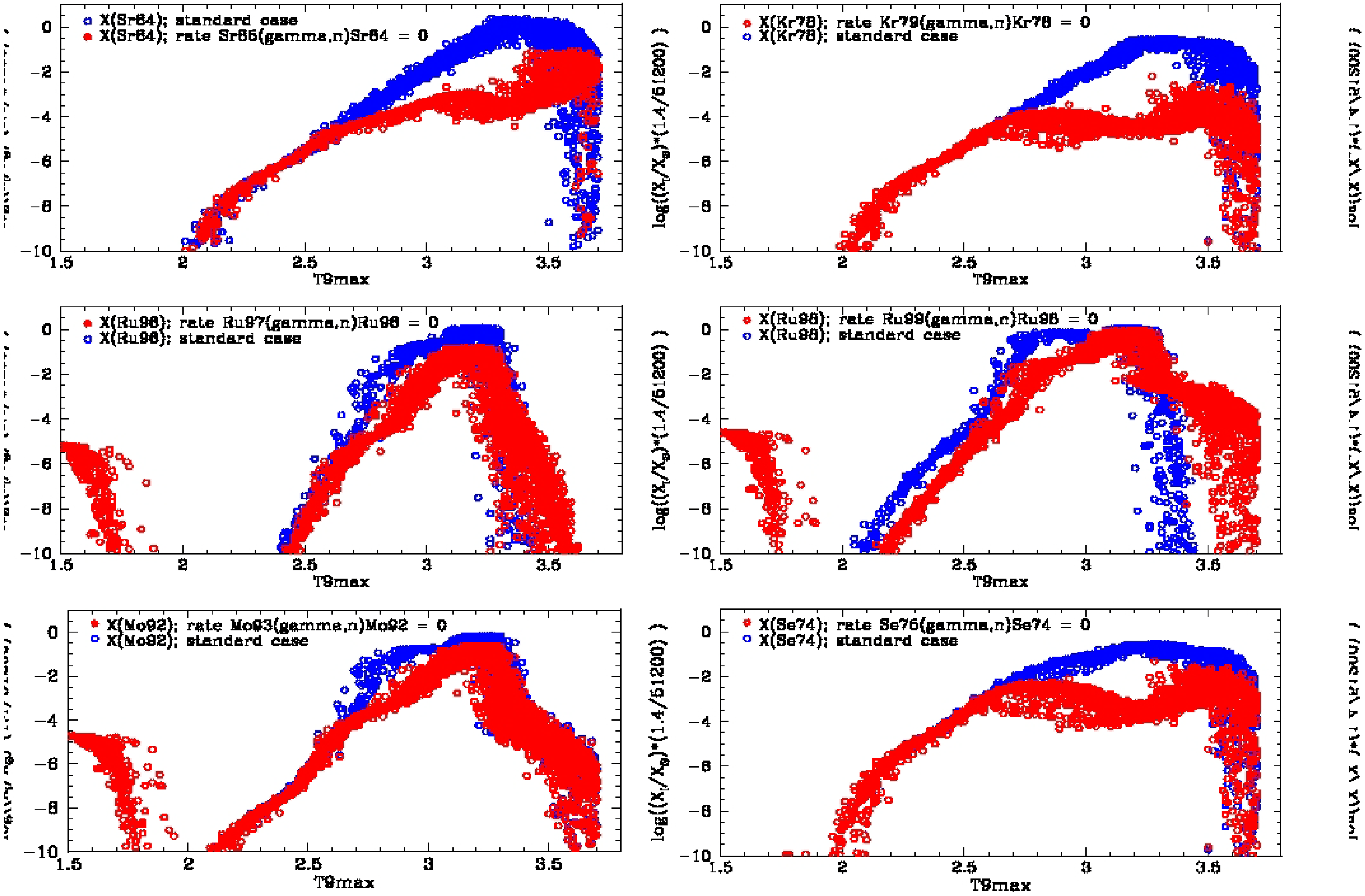


Arnould 2010

Main objective of my work

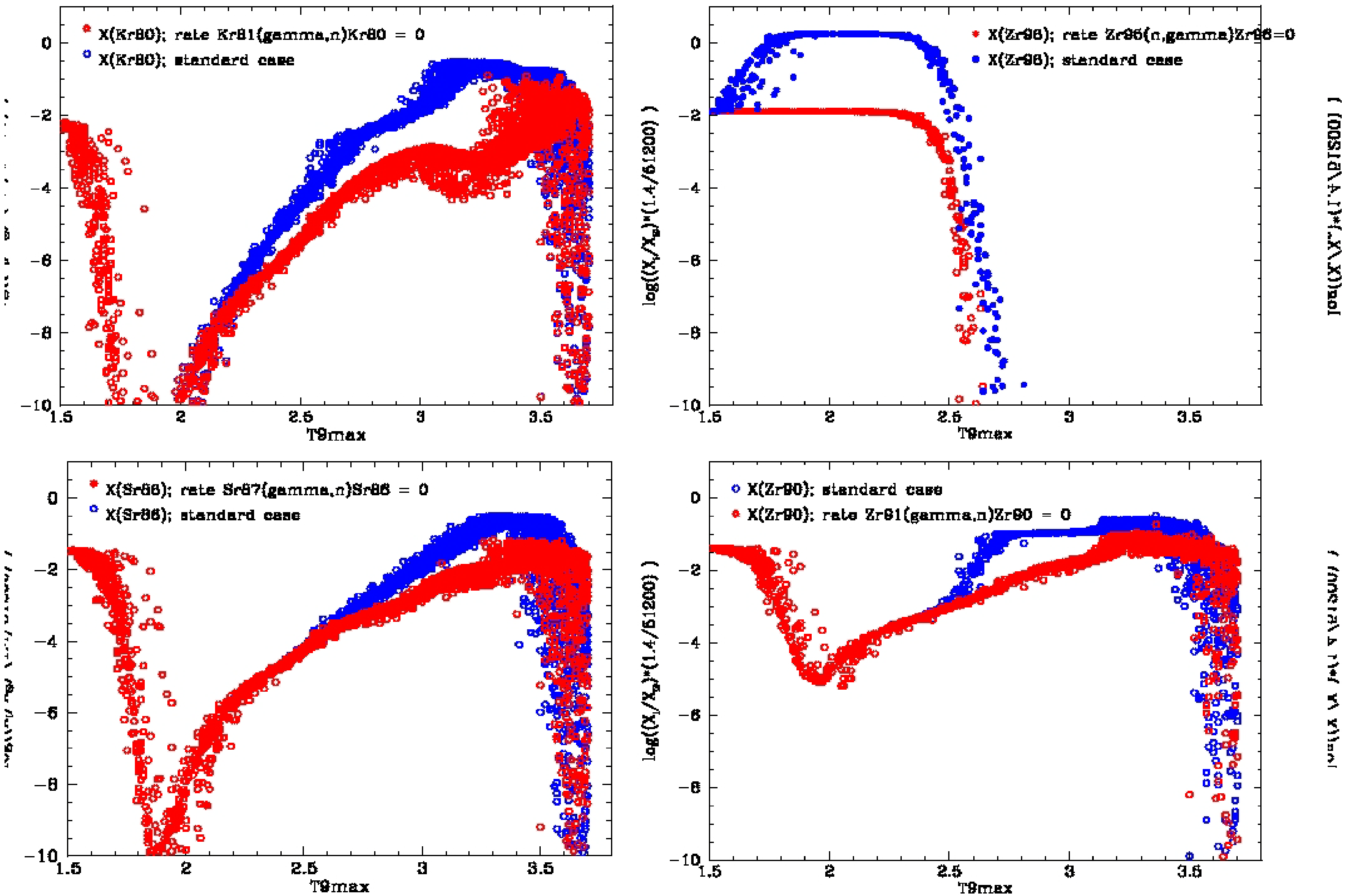
- The main objective was to carry out a data analysis with several SNe Ia simulations to find out the most important production channels of all *p*-nuclei and of other *s*-isotopes with a non-negligible *p* contribution (among them, we now consider ^{80}Kr, ^{86}Sr, ^{90}Zr, ^{96}Zr).
- This was done considering all isotope production reactions and "turning them off" one by one.
- In this way *p*-nuclei abundances sensitivity to the different production channels, as well as to the nuclear reaction rates uncertainties, were tested.

Light p-nuclei main production channels

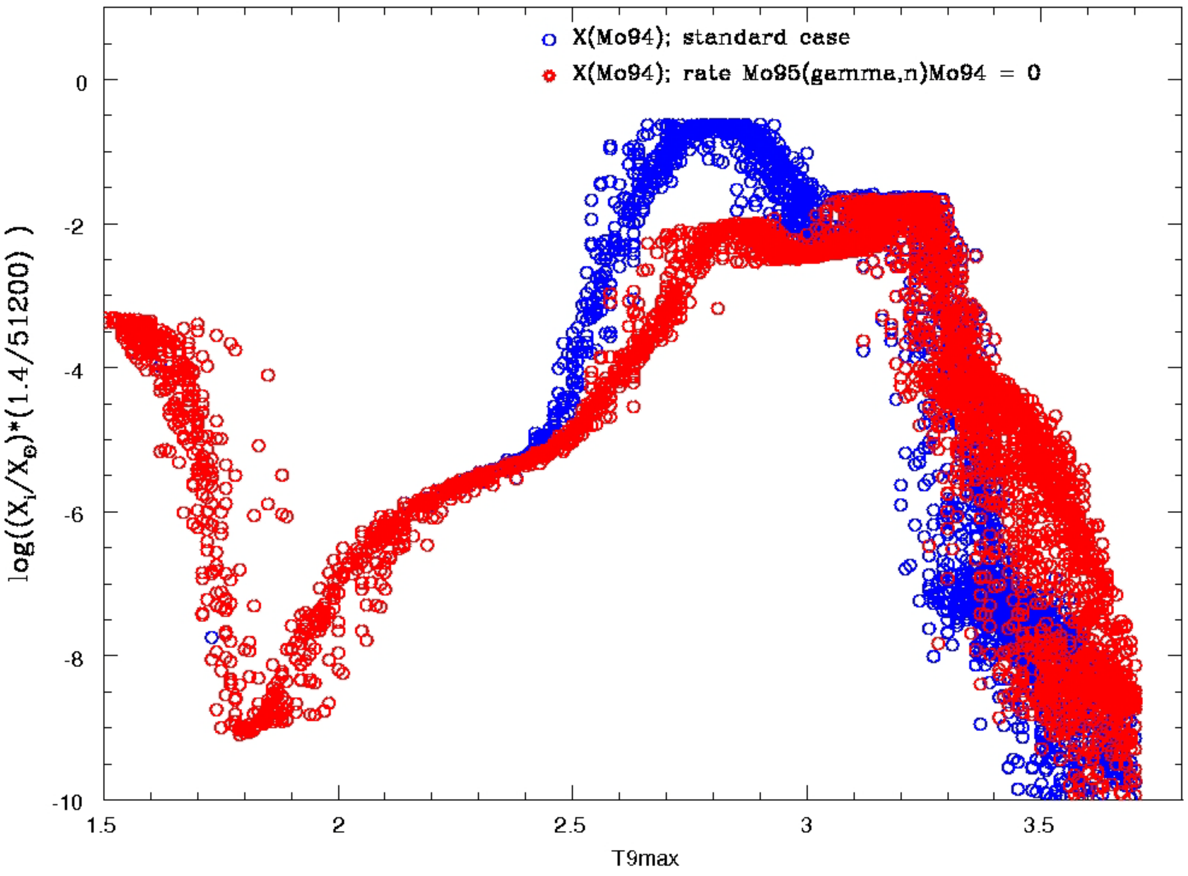


Battino et al. in preparation

S-isotopes with p-contribution production channels



^{94}Mo



Even modifying ^{95}Mo(gamma,n)^{94}Mo rates as much as its uncertainty allows (+/-20%), ^{94}Mo final abundance varies only very few (less than 0.1%).

Conclusions

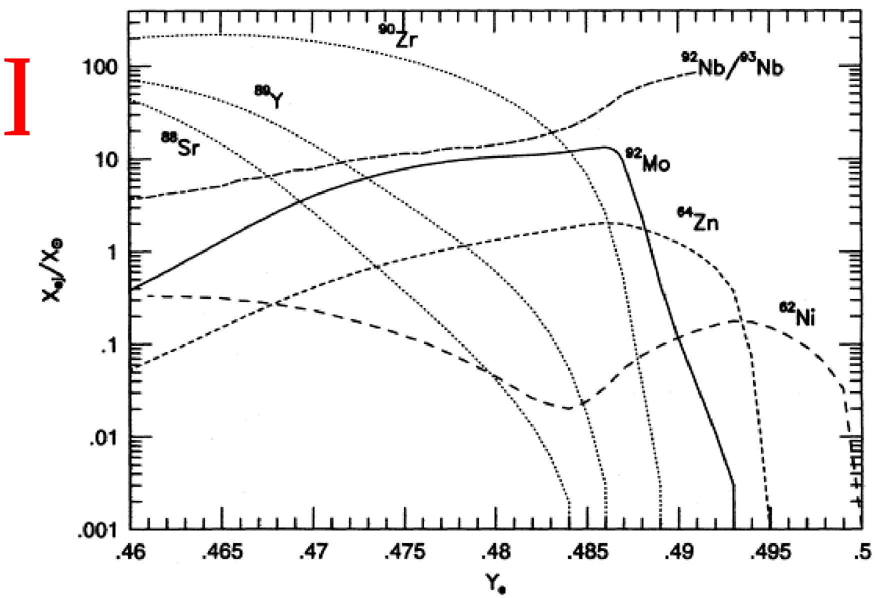
- Photodisintegration reactions play a main role in *p*-nuclei production in SNe IA events not only for the heavy ones, but even for the light ones.
- Among photodisintegration reactions, (γ,n) reactions are the most influent.
- Nuclear reaction rates uncertainties don't have a serious impact upon final isotopes abundances.
- In particular, ^{94}Mo is the only light *p*-nucleus which is still under produced respect to its solar abundance, and ^{95}Mo(gamma,n)^{94}Mo (^{94}Mo main production channel) uncertainty has just a little effect on ^{94}Mo final abundance (<0.1%).

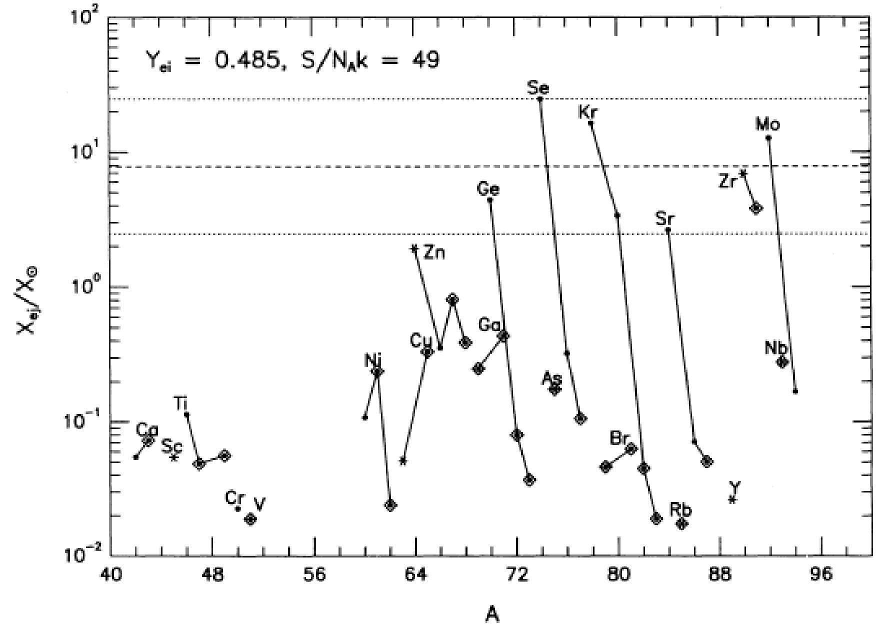
Thank you for your attention.

P-process in SN II

In addition to being a possible site for the r-process, the neutrino-powered wind also produces interesting nucleosynthesis of "p-process" nuclei above the iron-group, especially ^{64}Zn, ^{70}Ge, ^{74}Se, ^{78}Kr, ^{84}Sr, ^{90,92}Zr, and ^{92}Mo. But...

Reaction rate informations in this mass range are very uncertain.





Hoffman, Woosley, Fuller, & Meyer , ApJ, 460, 478, (1996)

The Framework

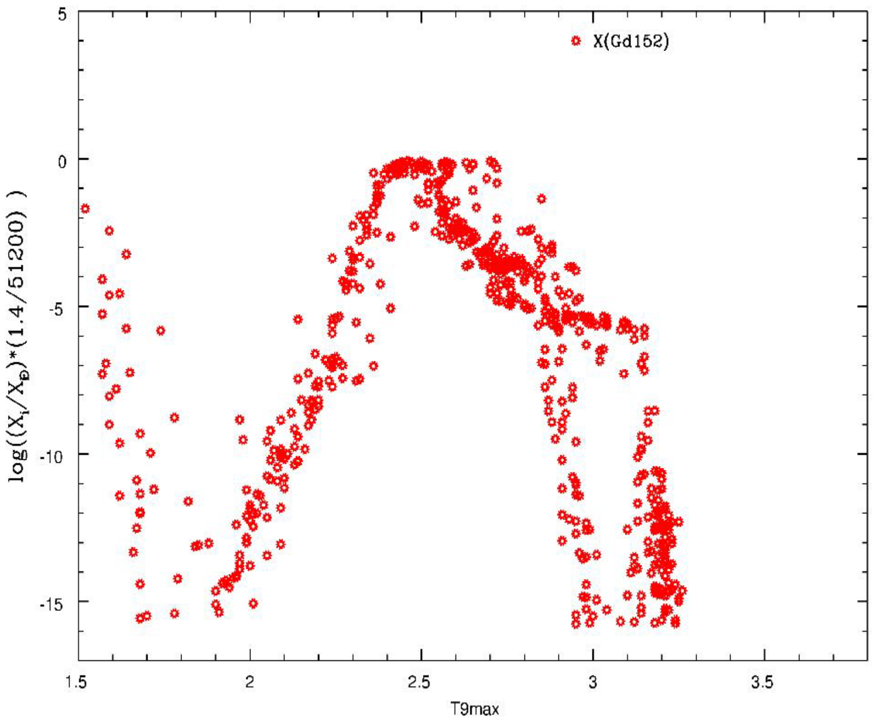
- I used a Type 1a Supernova model developed by the "Max Planck Institute fur Astrophysics" in Munich
- I used the reaction rate network "REACLIB" developed in Basel
- I analysed data from several simulations to find out the most important production channels of p-nuclei

Expected results

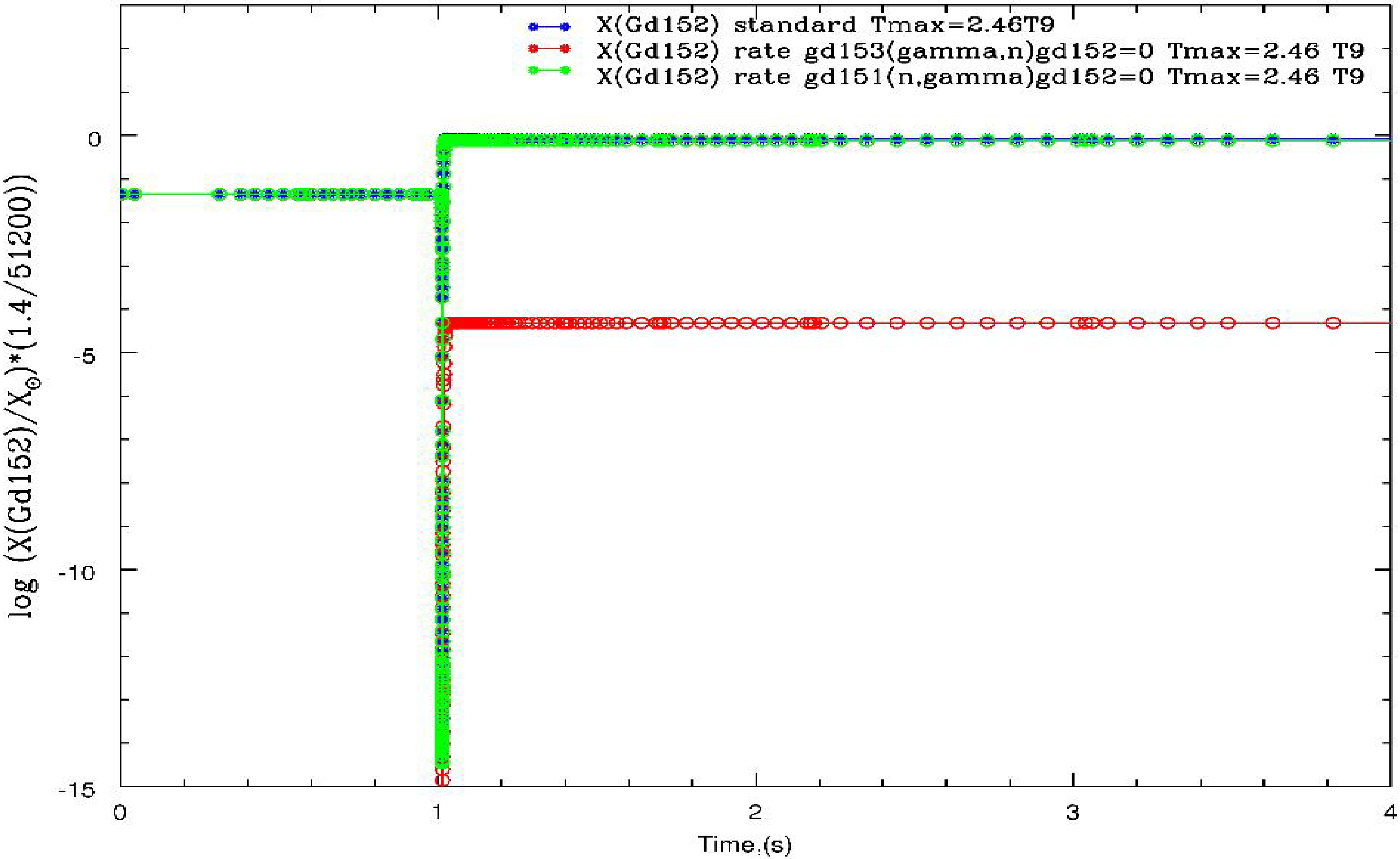
Analysing all the main production channels of the 35 p-nuclei, I expect to find the way through which p-nuclei, expecially the light ones, are produced helping solving several issues. Testing abundances sensibility varying reaction rates according to their uncertainties, would also strenghten previous expected results and give useful advices to cross-section checks.

Gd 152

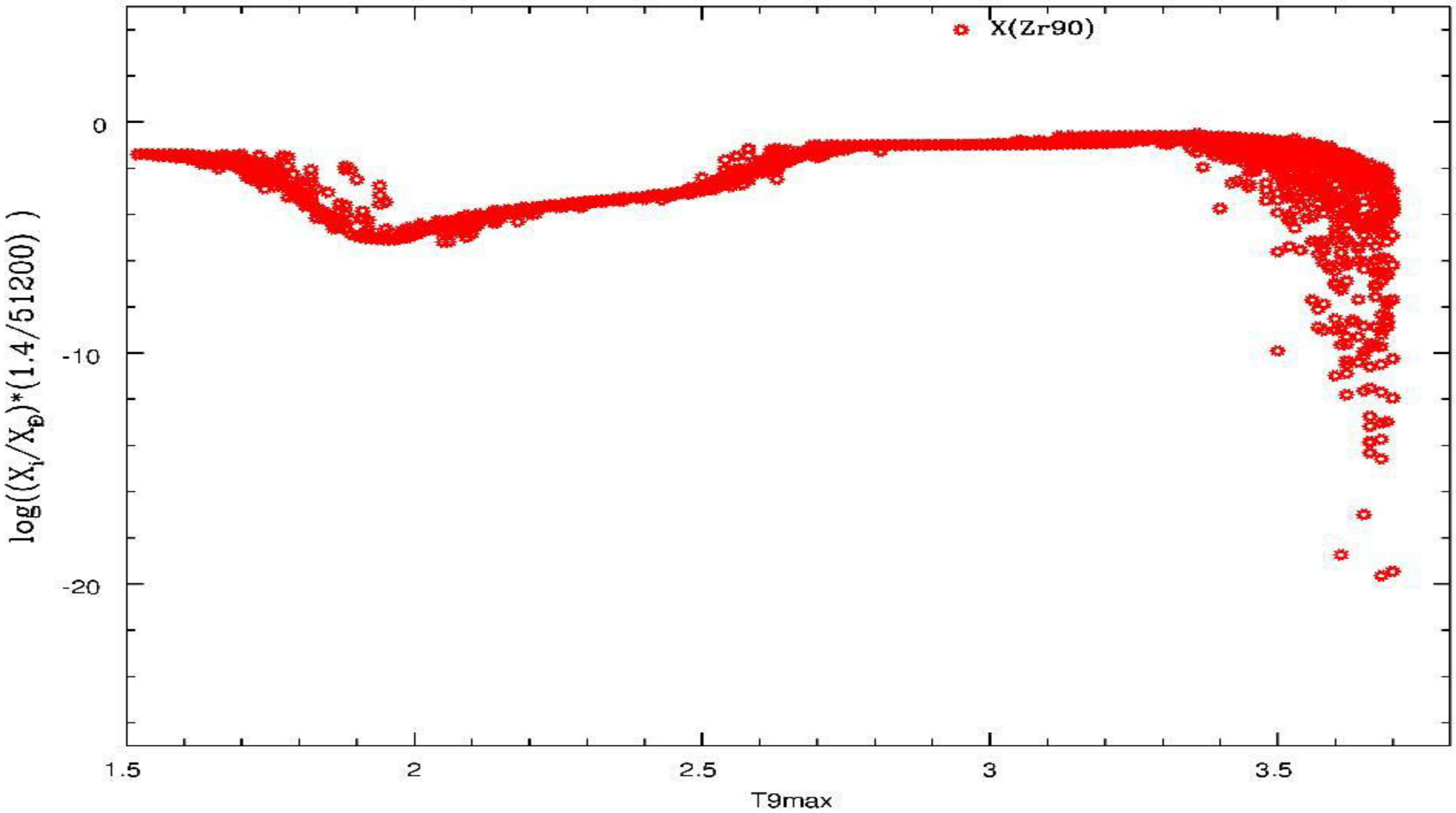
- Final abundance of Gd 152
- Each point is a SNIA particle.
- Maximum Gd 152 production is gained in particle number 10718 (T_{max}=2.46 T9)



Gd 152: Zone 10718

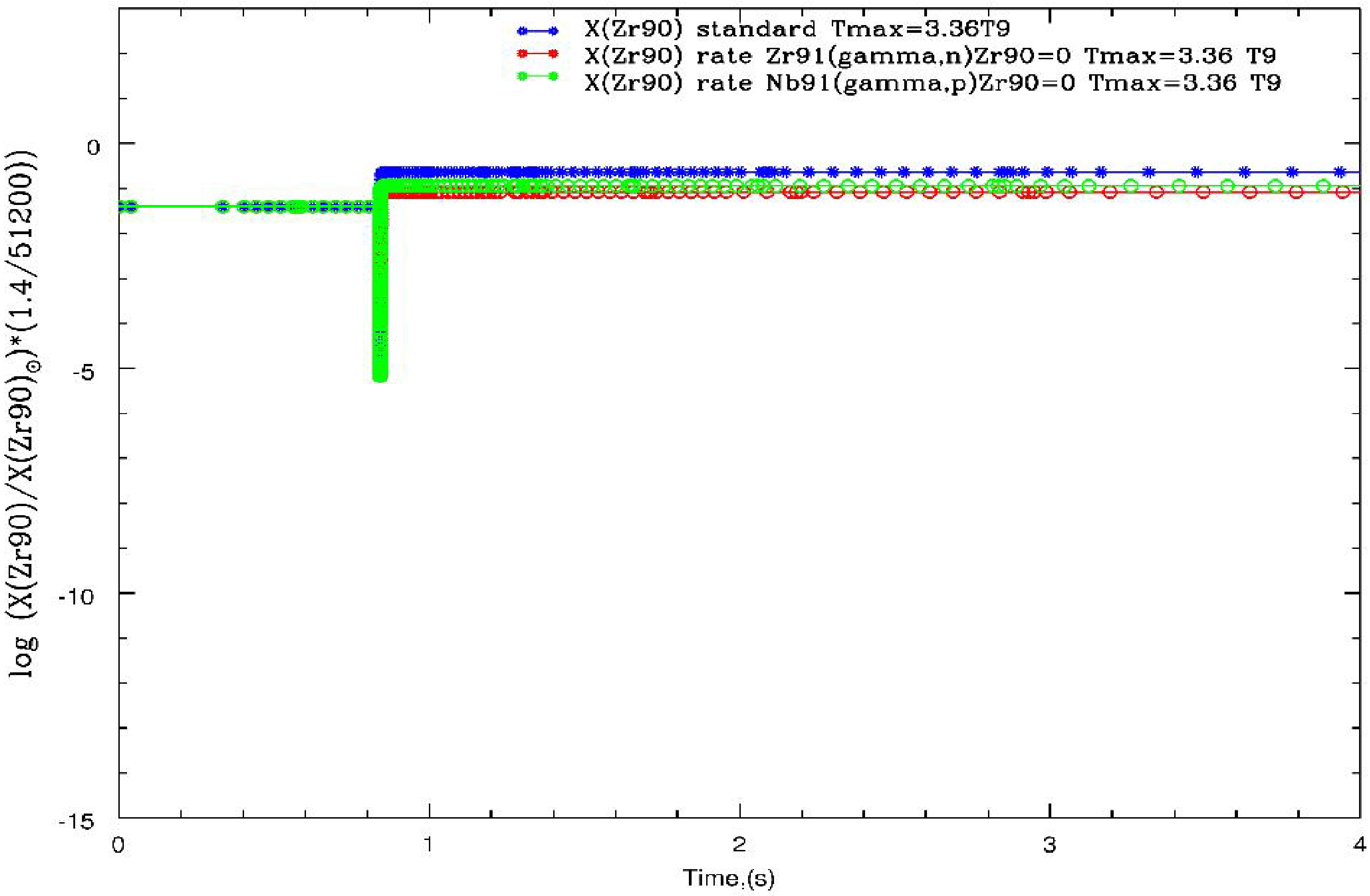


Zr 90: Final abundances

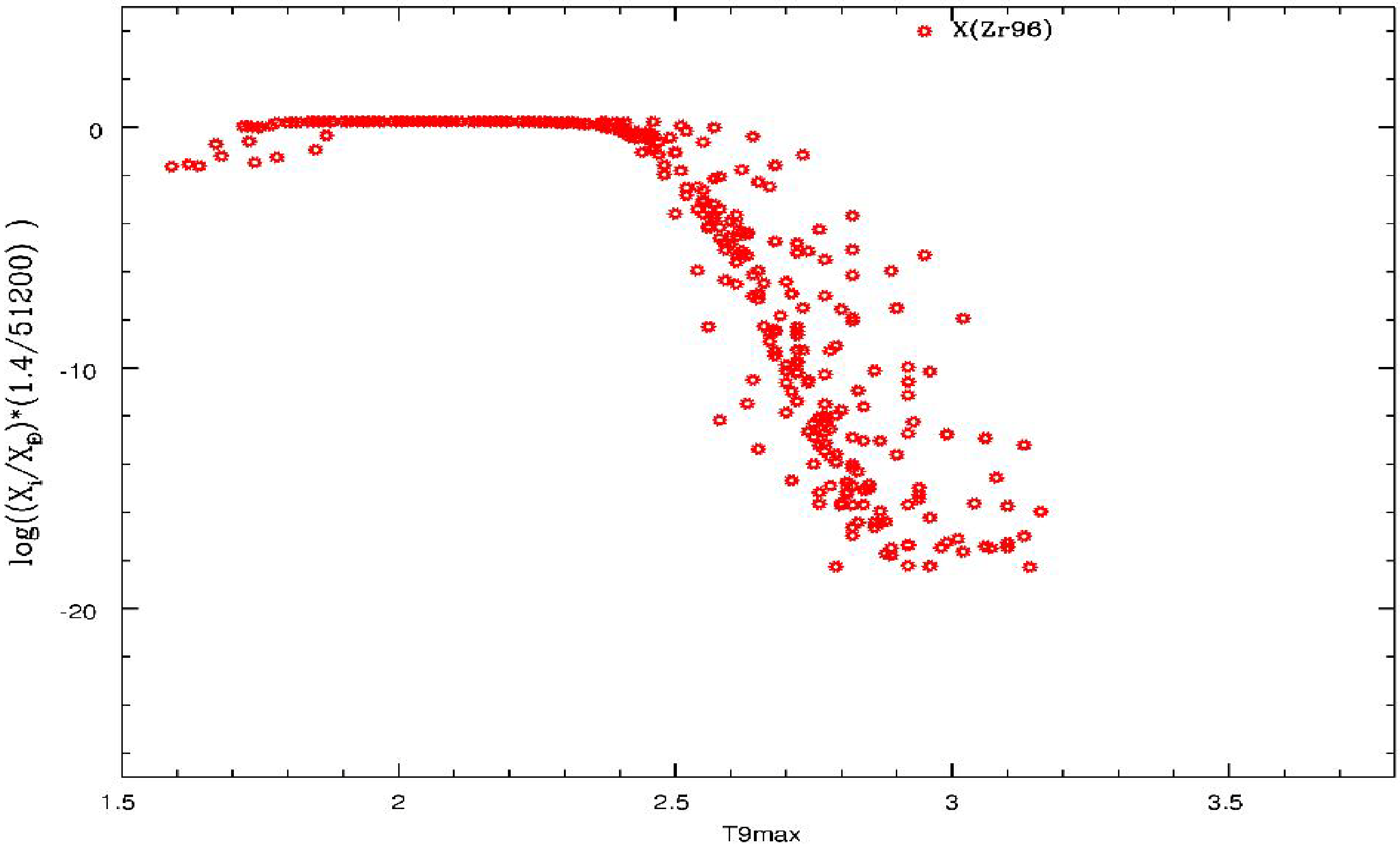


- Particle 48957 (Tmax=3.36 T9) has the highest Zr 90 production

Zr 90: Zone 48957

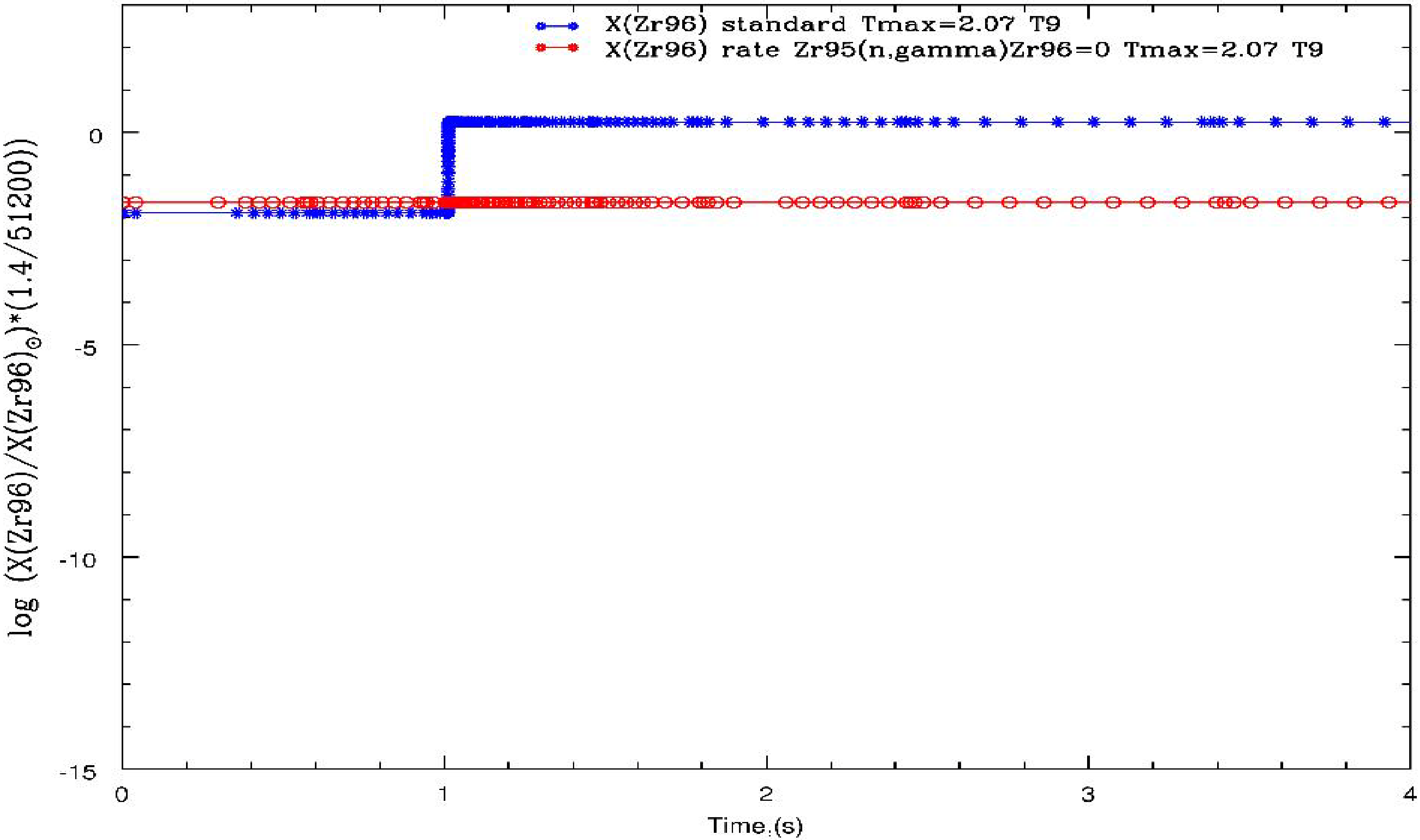


Zr 96: Final abundances

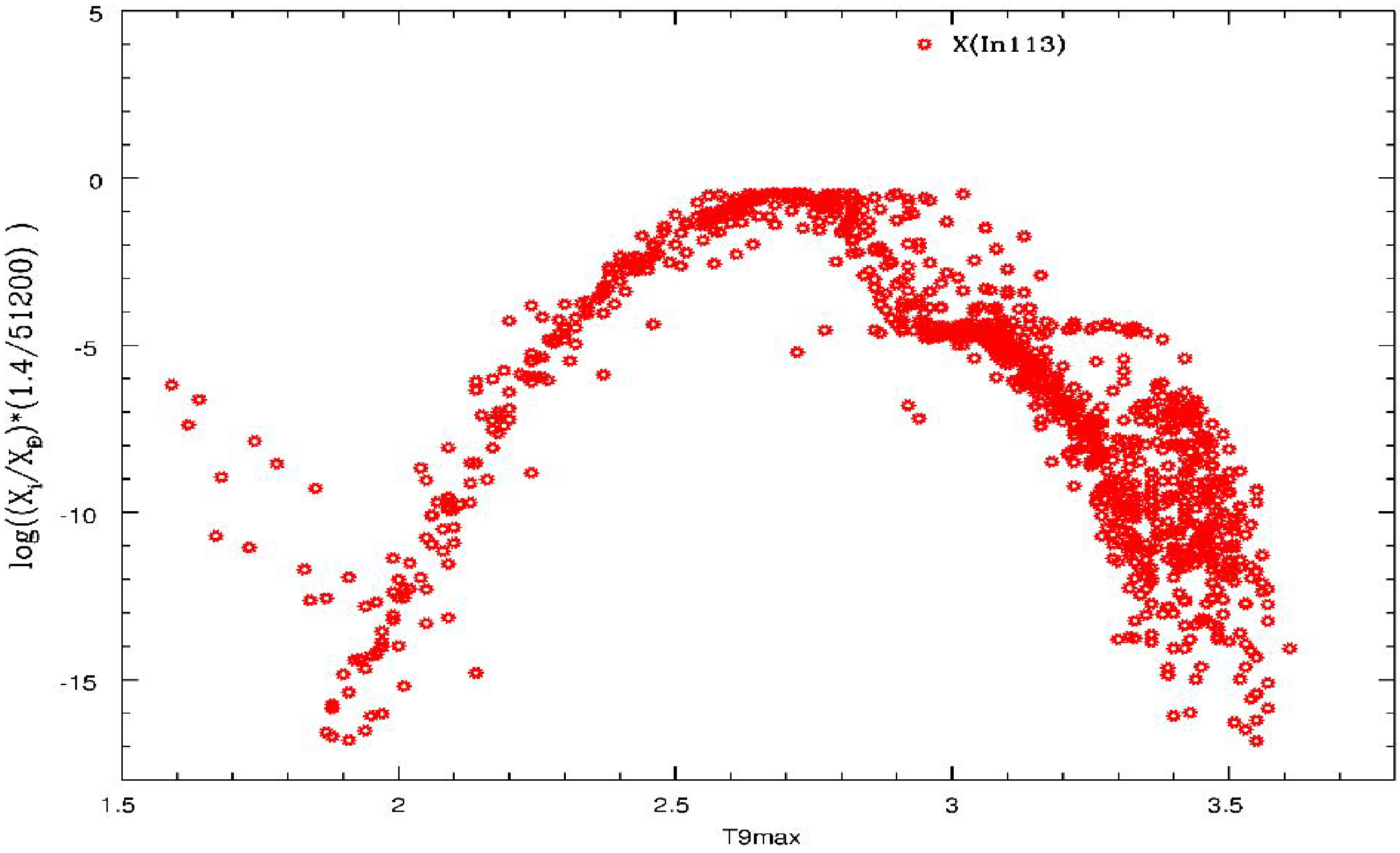


- Particle 40158 (T_{max}= 2.07 T9) has the highest Zr96 production.

Zr 96: Zone 40158

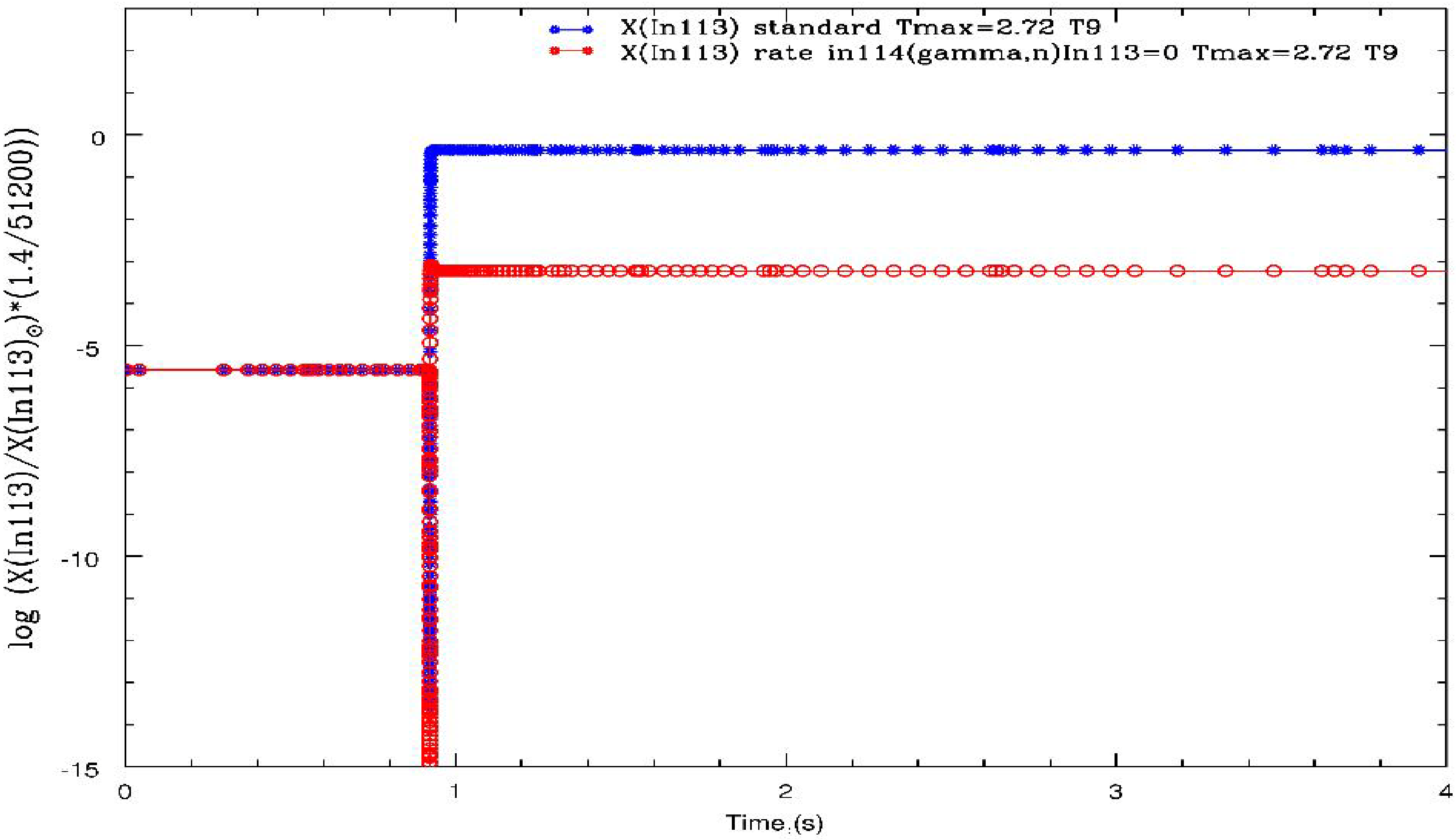


In 113: Final abundances

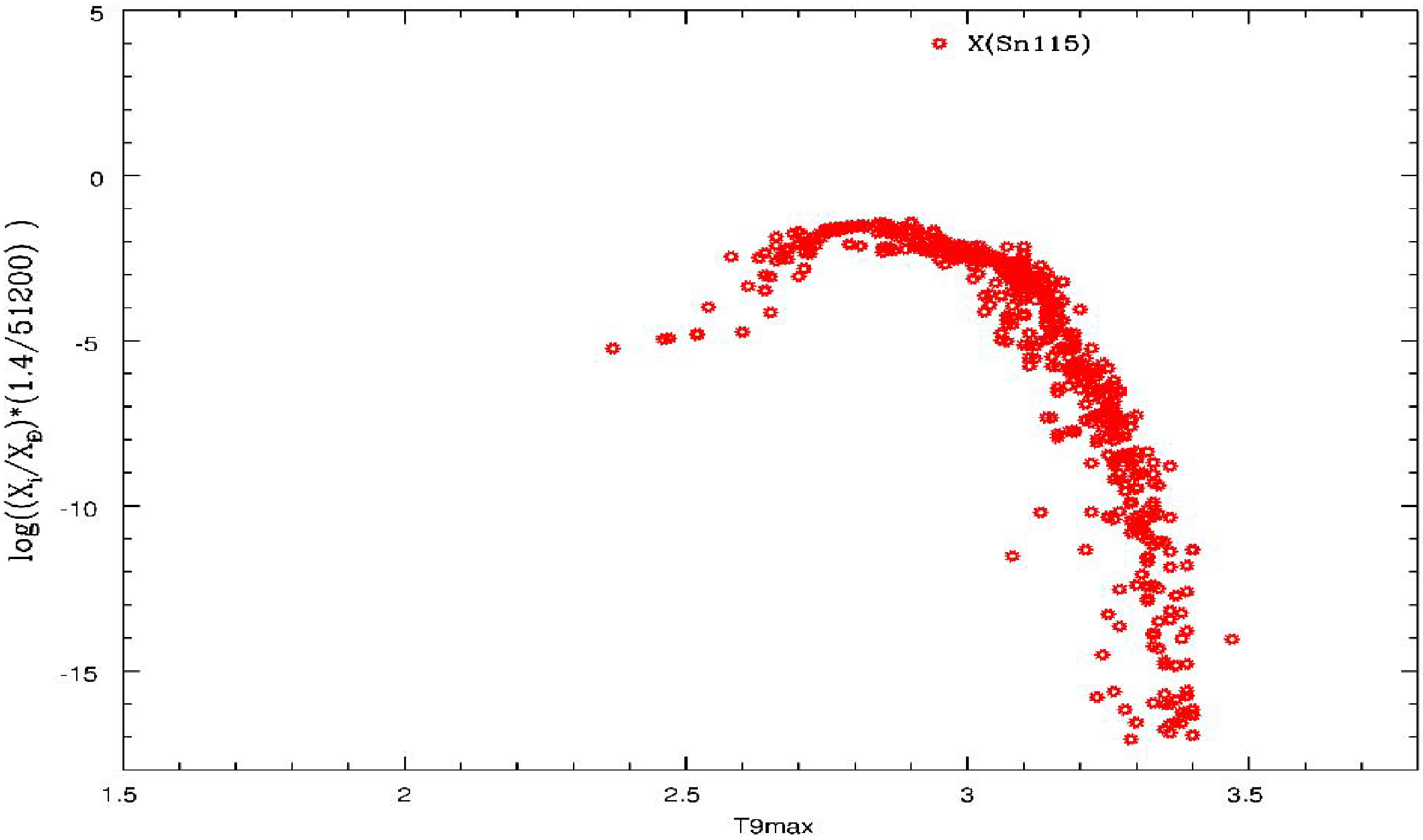


- Particle number 4958 (T_{max} = 2.72 T9) has the highest In 113 production

In 113: Zone4958

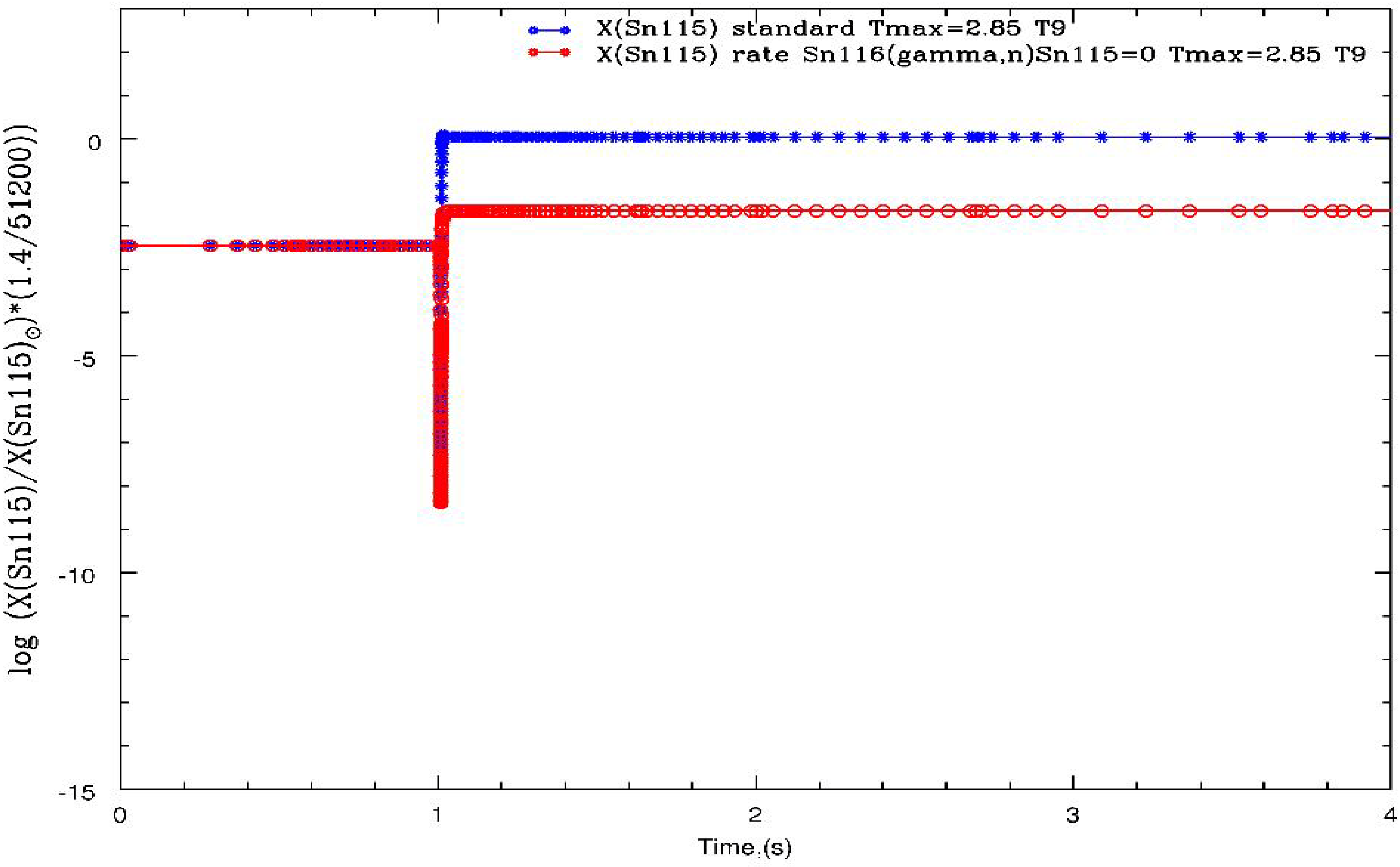


Sn 115: Final abundances

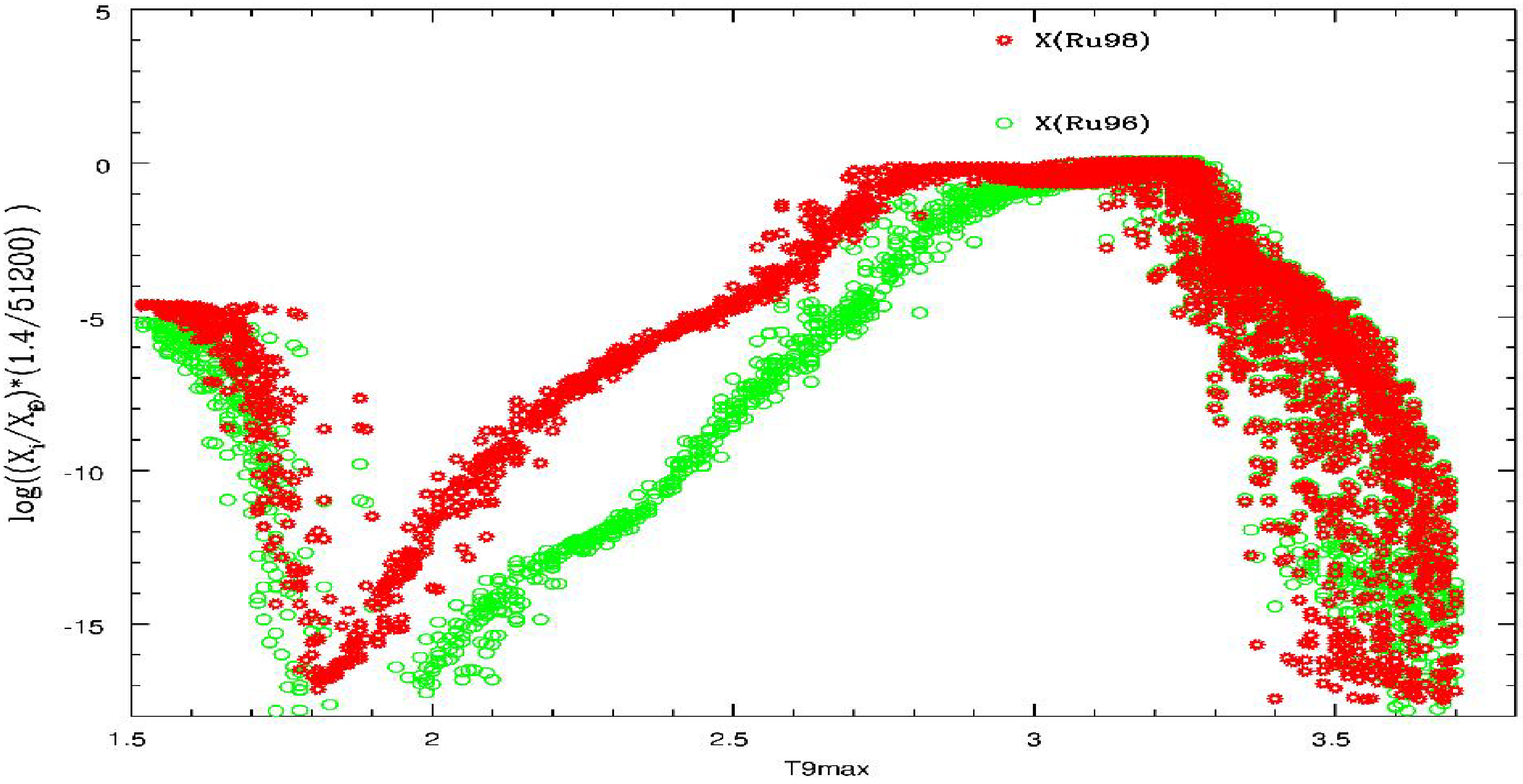


- Particle number 22555 (T_{max} = 2.85 T9) has the highest Sn 115 production

Sn 115: Zone 22555

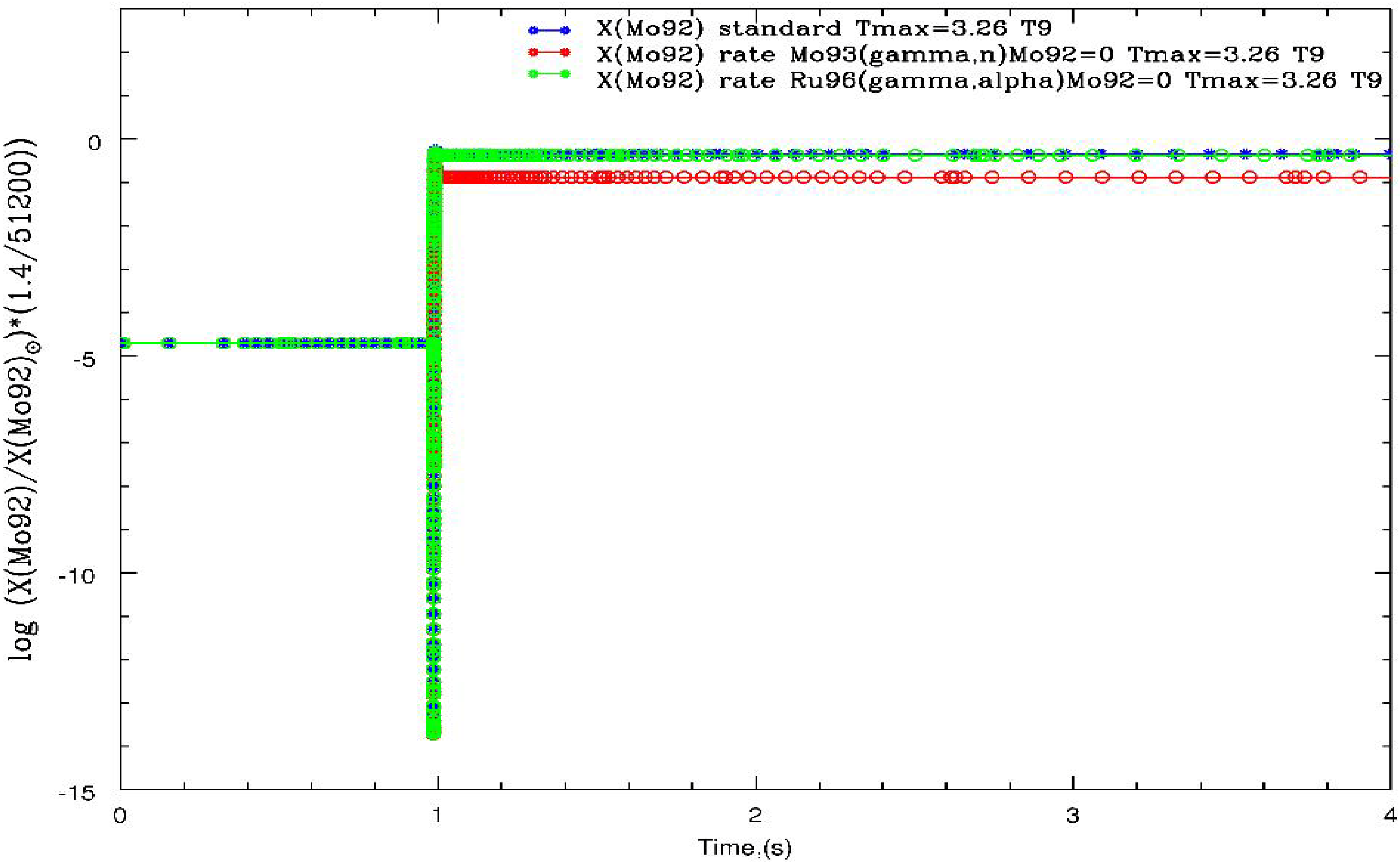


Ru 96 and Ru98

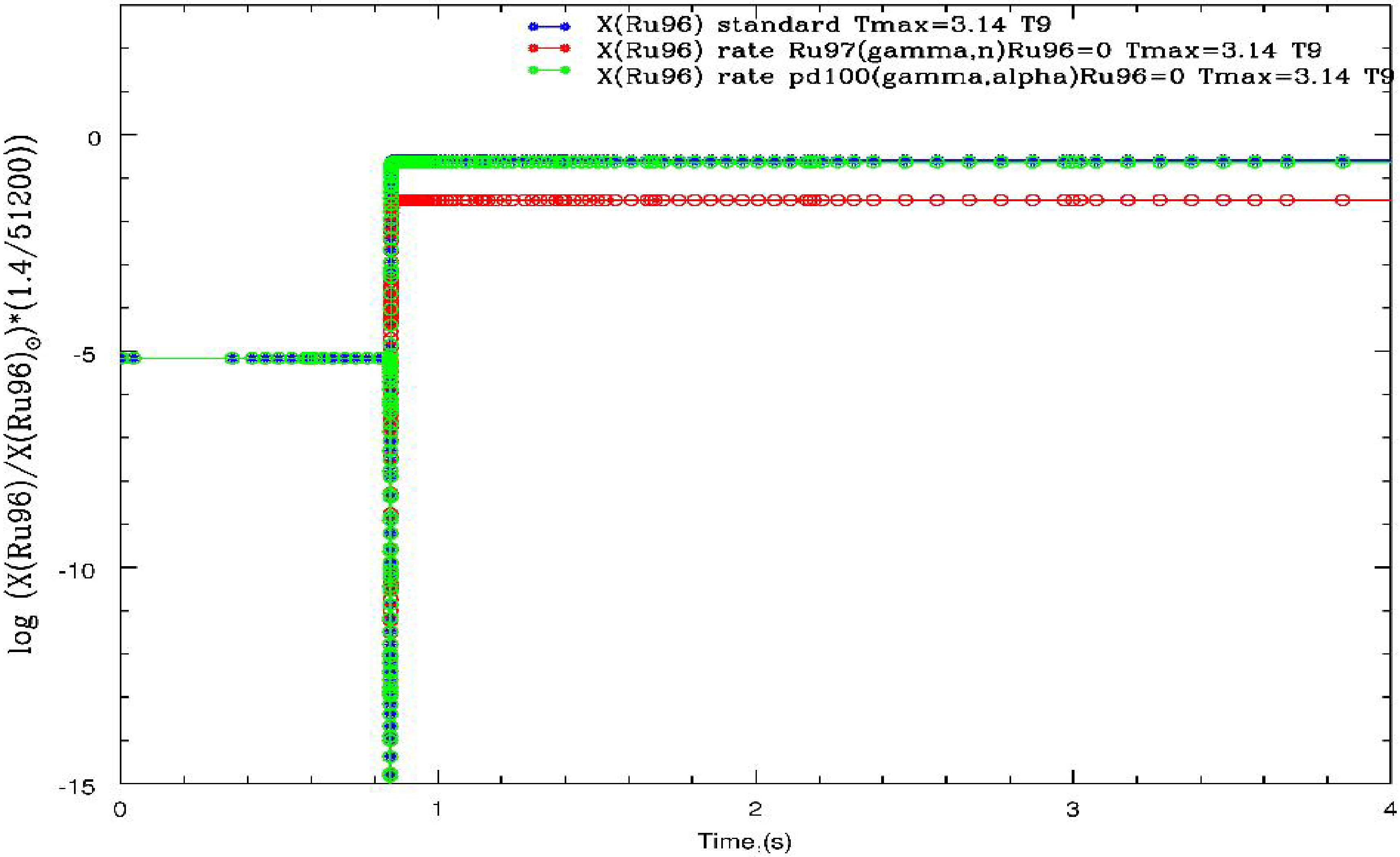


- Zone number 48638 (T_{max} = 3.14 T9) and 48637 (T_{max} = 3.26 T9) have the highest Ru 96 production, while zone number 13828 (T_{max} = 3.03 T9) and 13829 (T_{max} = 3.14 T9) have the highest Ru 98 production.

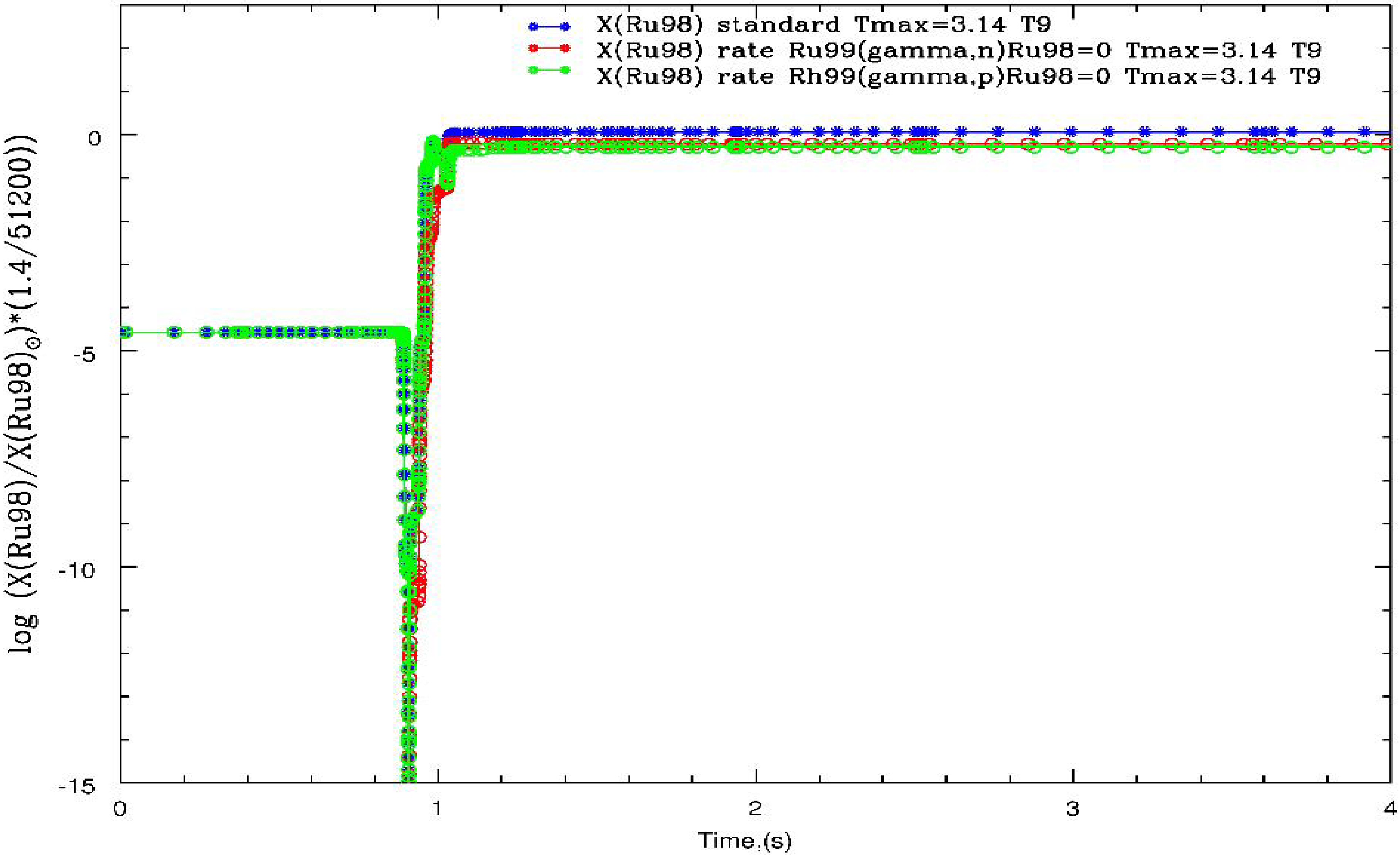
Mo 92: Zone 4635



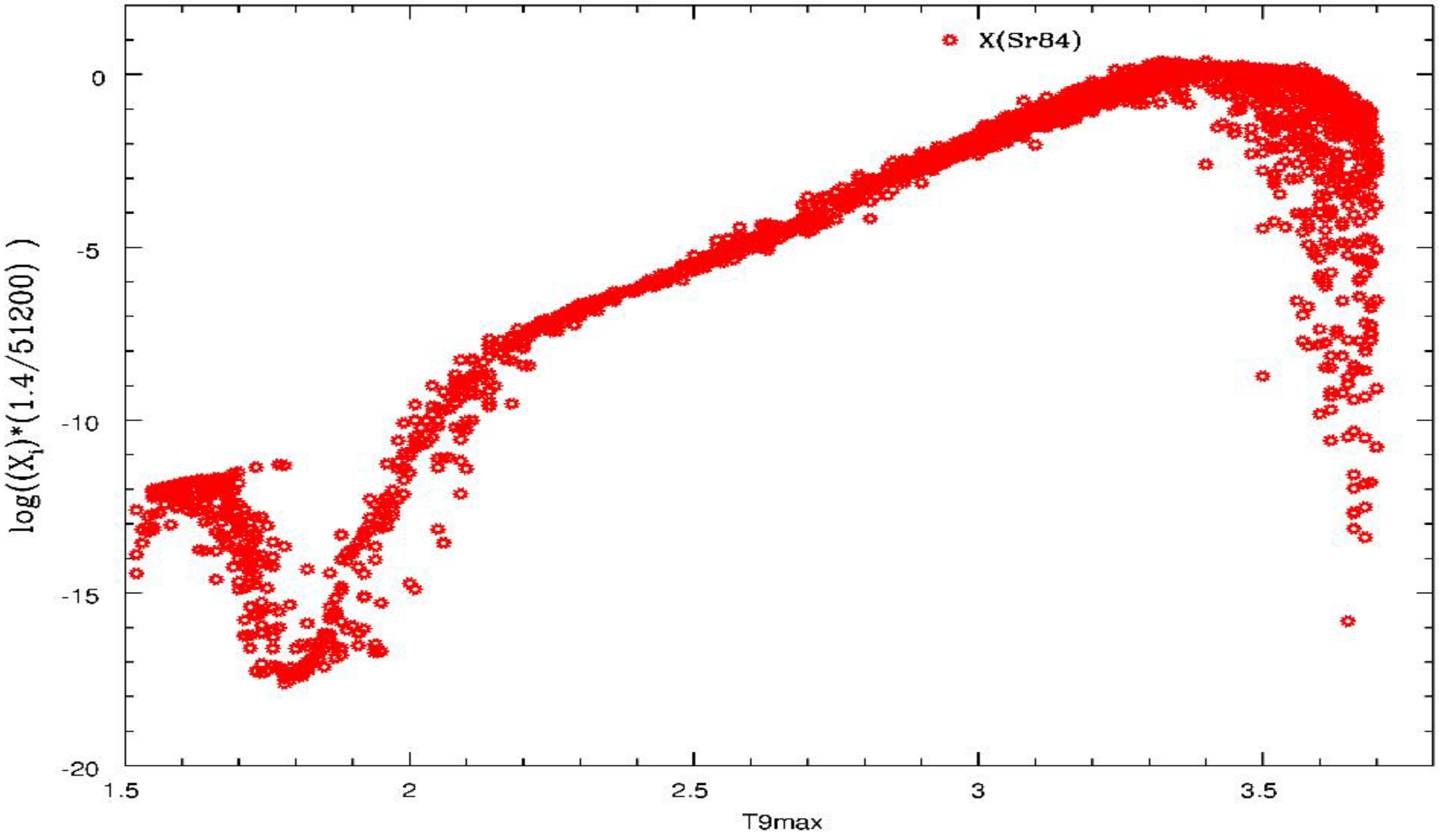
Ru 96: Zone 48638



Ru 98: Zone 13829

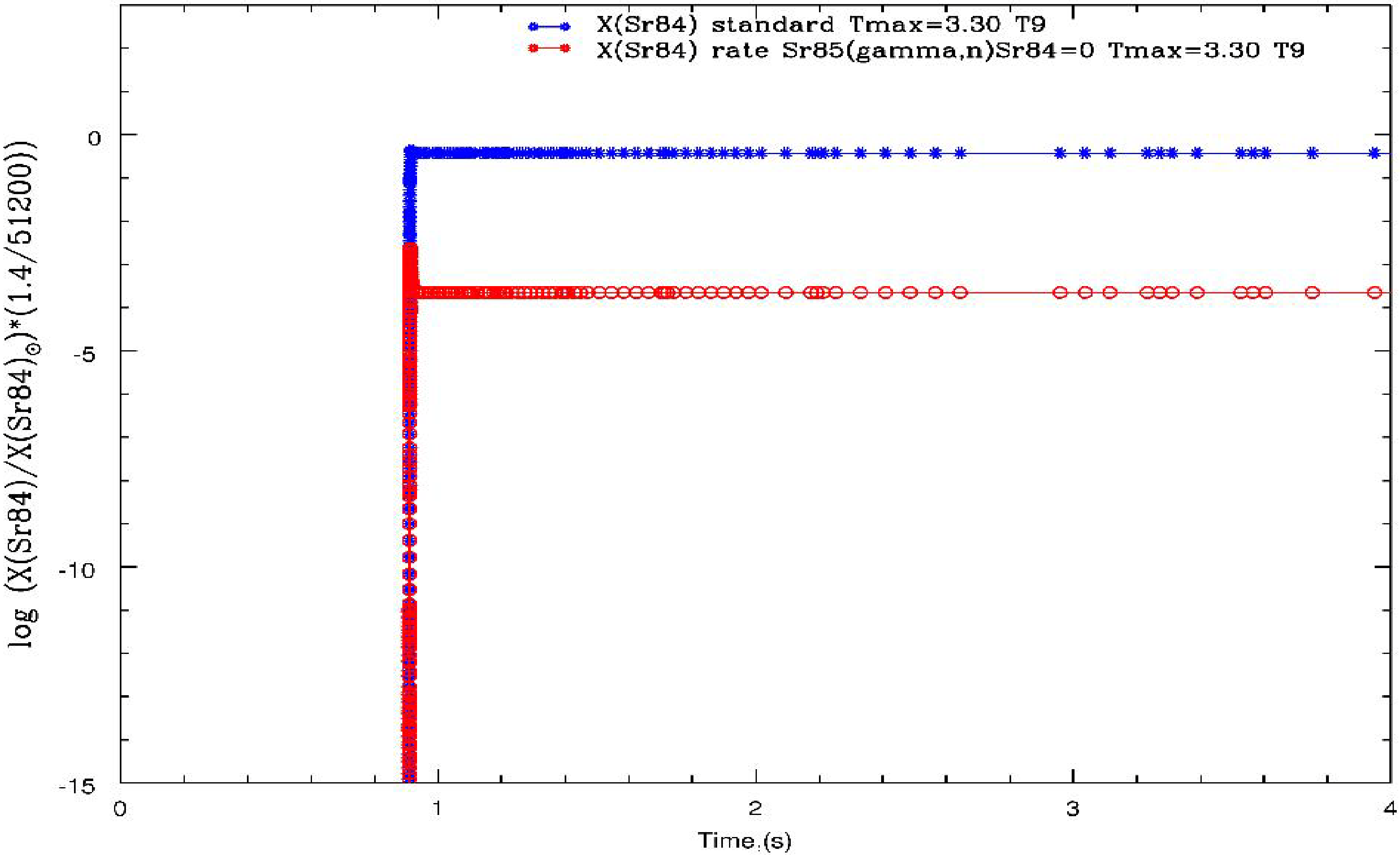


Sr 84: Final abundances



- Zone number 38626 (T_{max} = 3.40 T9) and 793 (T_{max} = 3.30 T9) have the highest Sr 84 production.

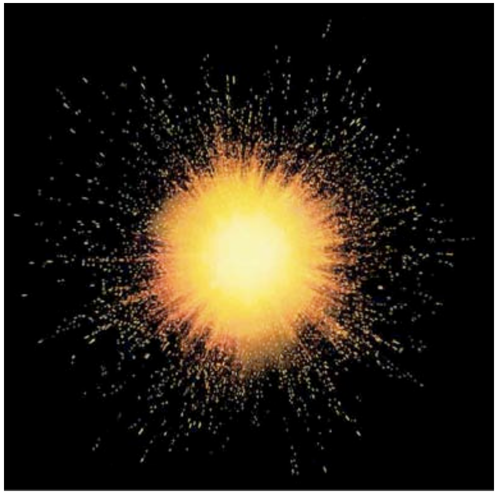
Sr 84: Zone 793



Cosmic Nucleosynthesis Perspective

The Universe emerged from the Big Bang with a composition consisting of hydrogen, deuterium, ^{4}He, ^{3}He, and ^{7}Li.

- The first stars and galaxies were born with this "primordial" composition.
- The heavy elements we are familiar with - from carbon and oxygen, to iron, .. to uranium - are the products of nuclear processes occurring in stars and supernovae.



The "Big Bang", Jim Truran (2008)

Star Formation in Orion, Jim Truran (2008)

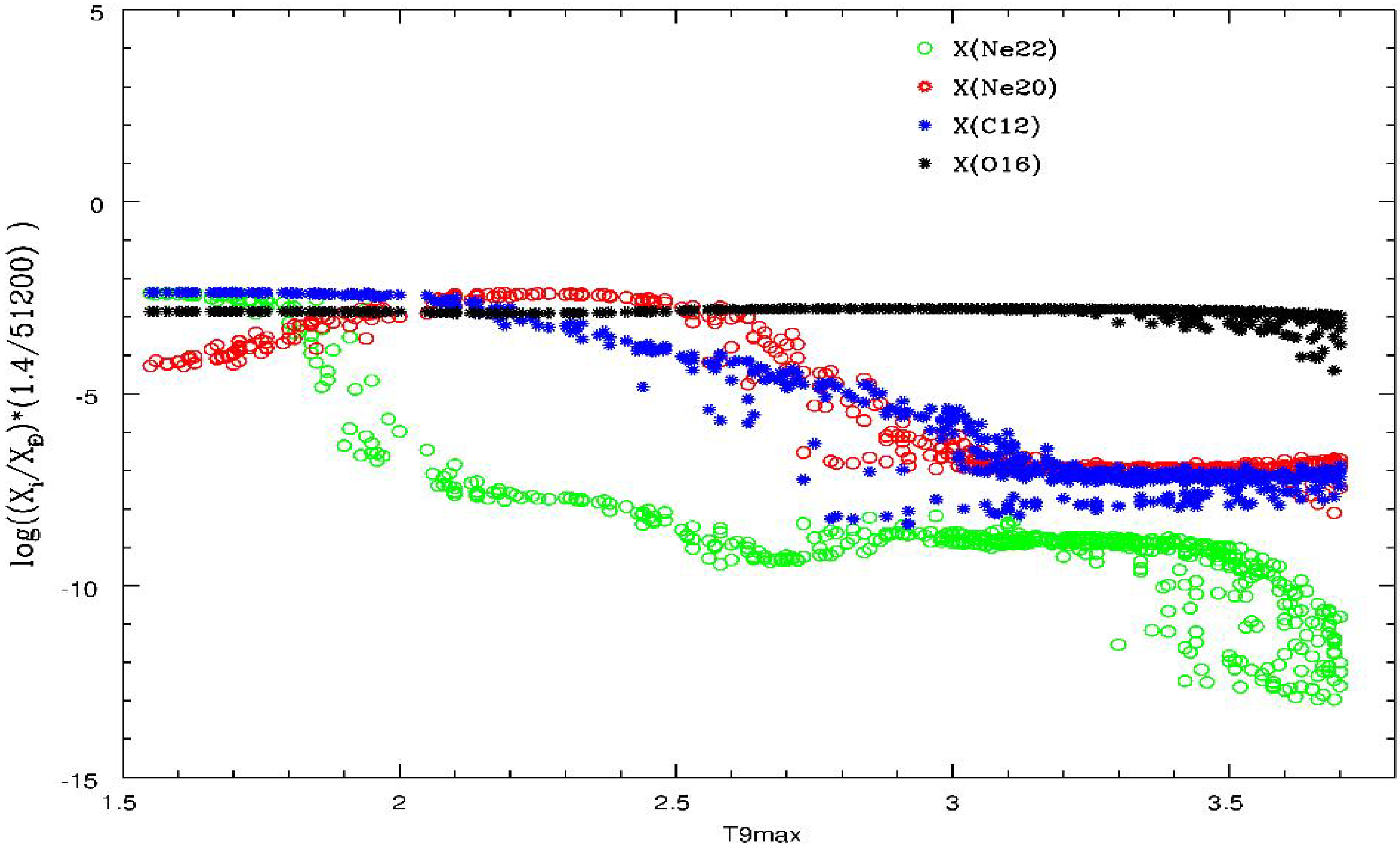
Observational Requirements for Sne Ia Explosion Models

- The explosion must be sufficiently powerful (i.e., produce enough iron group nuclei) and produce a substantial amount of high-velocity intermediate mass elements in the outer layers.
- A good Sne Ia model should not give rise to widely different outcomes depending on the fine-tuning of model parameters or initial conditions, but it must contain at least one parameter that can plausibly account for the observed sequence of explosion strengths.
- The explosion strength parameter must be causally connected with the state of the progenitor

^{92}Mo, ^{94}Mo, ^{96}Ru and ^{98}Ru

Their study is of particular importance. "γ-process" occurring in SN II strongly underproduces them...

...but the SNe Ia model used in this work produces ^{92}Mo, ^{94}Mo, ^{96}Ru and ^{98}Ru light isotopes as the heavy ones: this is a fact that has never happened till now.



- Abundances of ^{12}C, ^{16}O, ^{20}Ne and ^{22}Ne for tracers selected in T peak range that allowed *p*-process nucleosynthesis.

The *s*-process

The ***s*-process**, or slow-neutron-capture-process (neutron capture timescale is of the order of 10-100 years), is a process that occurs at relatively *low neutron density* and *intermediate temperature* conditions in stars, more precisely:

$$10^7 < \rho < 10^{10}$$

(ρ = neutron density expressed in cm^{-3})

- T is such that **8<kT(Kev)<23**, where *k* is the Boltzmann constant.
- The *s*-process is espected to take place in AGB stars undergoing thermal pulses.

The *r*-process

The ***r*-process**, or rapid-neutron-capture-process (neutron capture timescale is of the order of $^{-4}$10-$^{-3}$10 s), is a process that occurs at relatively *high neutron density* and *high temperature* conditions, more precisely: $\rho > 10^{20}$

(ρ = neutron density expressed in cm^{-3})

- T is such that **kT~90 Kev**, where *k* is the Boltzmann constant.
- Together with the *s*-process, these two processes account for a majority of the Solar System composition of elements heavier than iron.

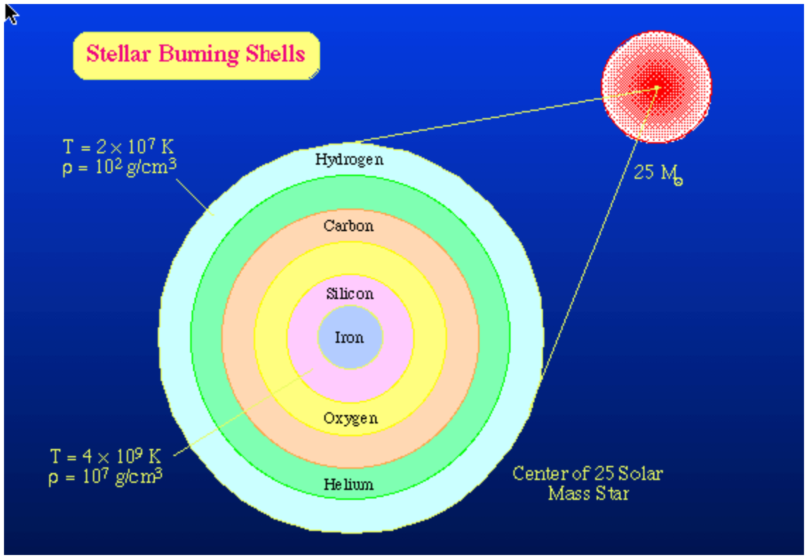
The *p*-process

If the ***p*-process** consists in sequences of photo-disintegrations and β^+ decays, it is usually called "**γ-process**". This occurs in explosive O/Ne burning during SN II explosions and reproduces the bulk of *p* isotopes within a factor 3. Just as exemple, a photo-disintegration reaction producing ^{138}Ce is presented:

$$^{139}\mathrm{Ce}(\gamma,n)^{138}\mathrm{Ce}$$

However, the "**γ-process**" scenario in SN II suffers from a strong underproduction of the most abundant p isotopes (^{92}Mo, ^{94}Mo, ^{96}Ru and ^{98}Ru), and destroys ^{113}In and ^{115}Sn due to lack of seed nuclei with A>90 on which photo-disintegration reactions can be performed.

Type II Supernovae: Theory



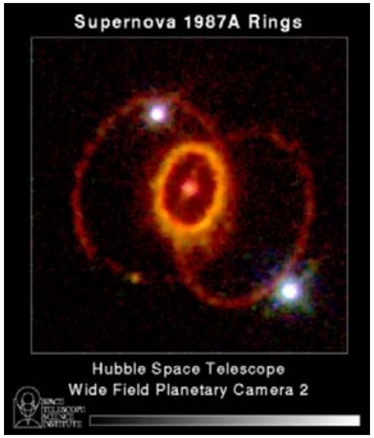
Courtesy Mike Guidry: guidry@utk.edu

SNe II are the product of the evolution of massive stars $10 < M(M_{\odot}) < 100$ (Hoyle & Fowler 1960)

Evolution to criticality:

– After a succession of nuclear burning stages that yield a core dominated by ^{56}Fe, nuclear reactions stop and a collapse occurs. The gravitational energy is released in the form of neutrinos that drive the explosion.

SNe1054: Crab Nebula, Hubble Image



SNe1987A Hubble Image

In addition to being a possible site for the *r*-process, the neutrino-powered wind also produces interesting nucleosynthesis of "*p*-process" nuclei above the iron-group. But...

Reaction rate informations in this mass range are very uncertain

Modus Operandi

First of all, it was necessary to find the particle with the higher production of the isotope studied during SNe IA development: this was done plotting its final abundance respect the solar value against the maximum temperature of each particle of the SNe IA reached in the different particles in 4 seconds from the starting of explosion development.

Modus Operandi

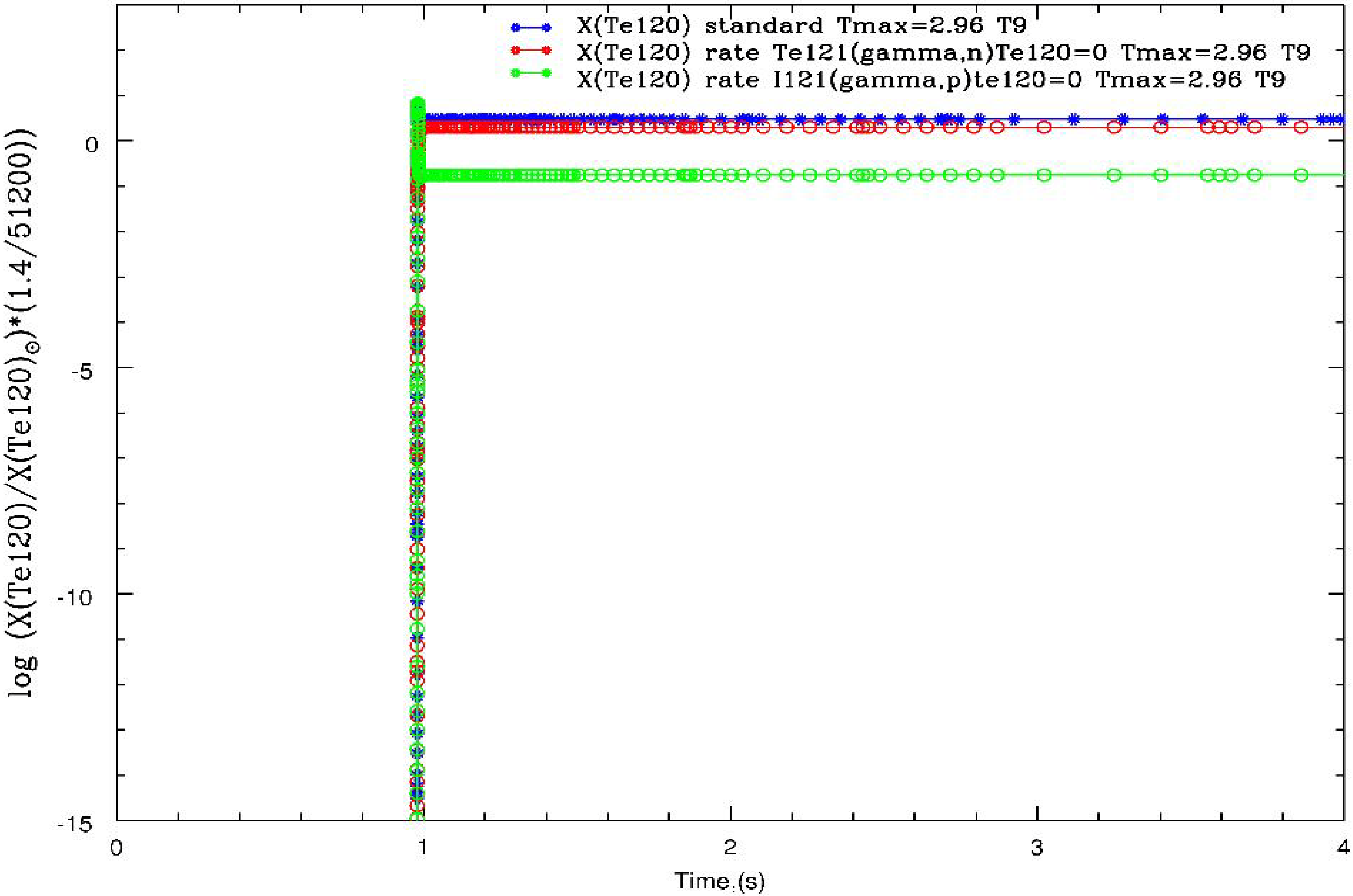
Next step consisted in considering all isotope production reactions and "turning them off" one by one setting to (-10^{12}) the a(i) parameters of Rauscher and Thielemann rate analytical expression, that is given by (T is expressed in unit of 10^9 K, hereafter T9):

$$\text{Rate}= \exp\left[a(0)+a(1)\,T^{-1}+a(2)\,T^{-1/3}+a(3)\sqrt[3]{T}+a(4)\,T+a(5)\sqrt[3]{T^{5}}+a(6)\ln(T)\right]$$

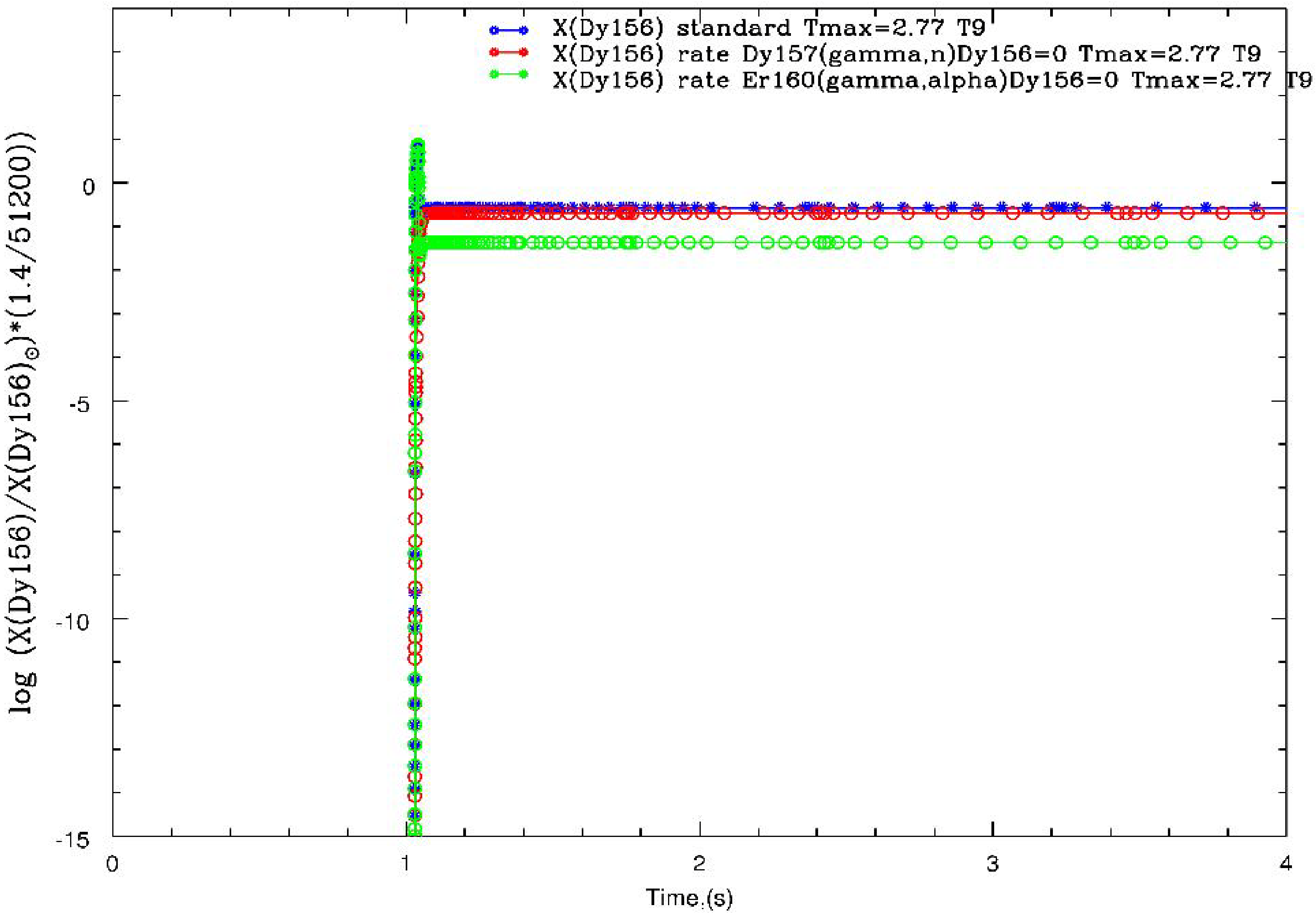
Modus Operandi

- Corresponding final abundance variations were looked for (the higher the variation, the more important the production channel is).
- To test the impact of nuclear reaction rates uncertainties upon final isotopes abundances, main production reaction rates were varied as much as their uncertainties allow and corresponding final isotopes abundances were looked for.
- Different isotope cases are now presented...

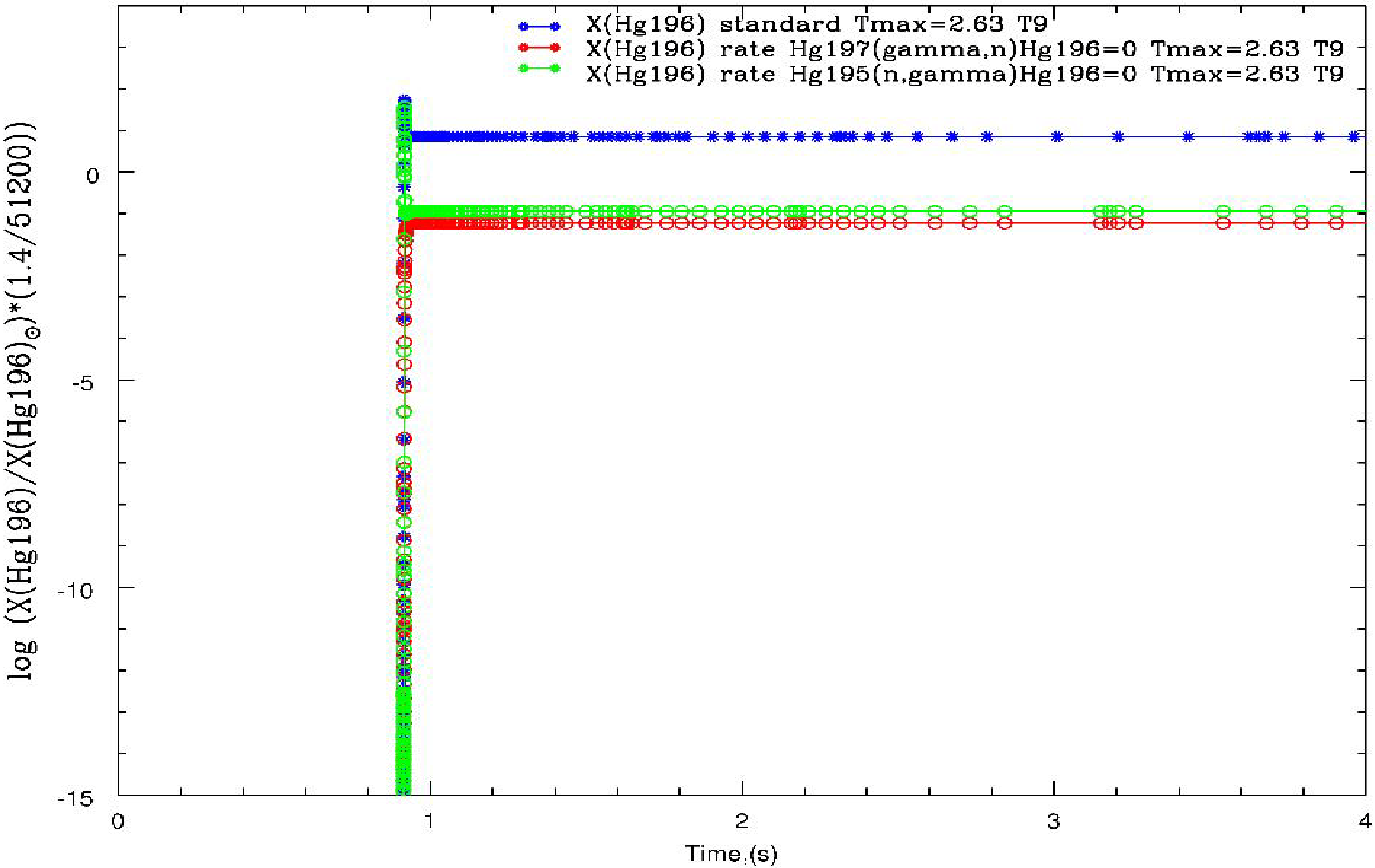
(γ,p) reactions production: ^{120}Te



(γ,α) reactions production:^{156}Dy



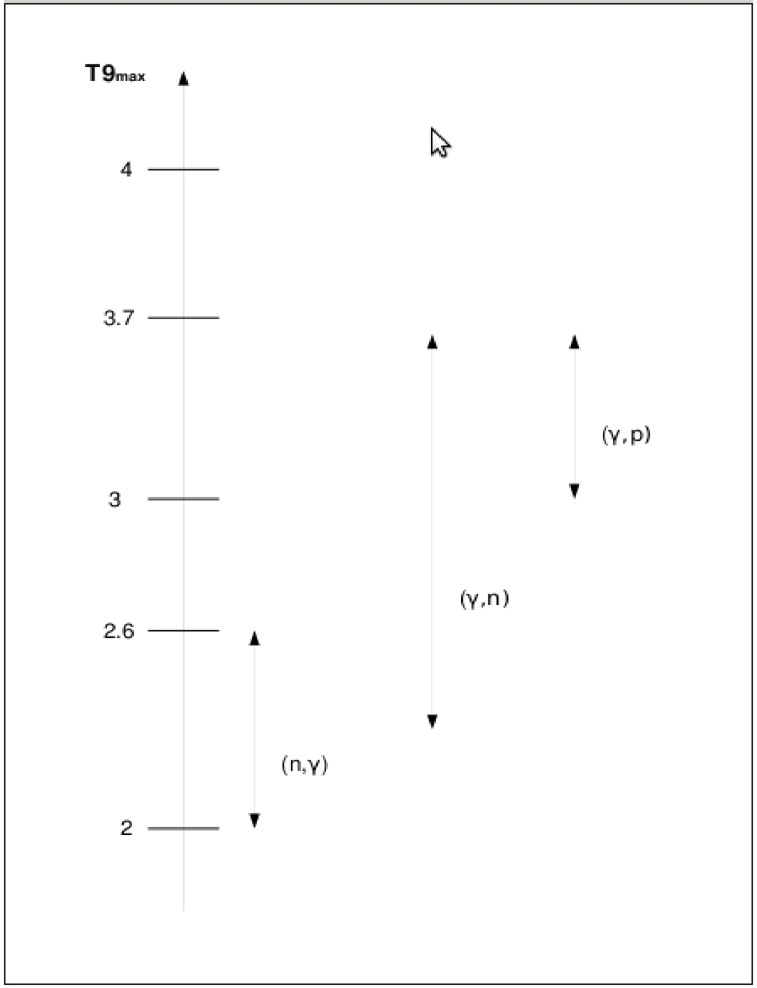
(n,γ) reactions production: ^{196}Hg



Open problems (da rivedere)

- The SNe IA model used is the best model that can be obtined in this moment. Anyway, several aspects would be object of future research. Just as examples: the physics of *s*-process seeds formation, the amplitude of the accrection rate to obtain a SNe IA, the correct seed distribution to obtain the best *p*-nuclei resulting distribution.
- Considering the important role of neutron capture reactions to heavy *p*-nuclei formation, a deep analysis about *p*-contribution to some "*s*-only" nuclei should be carried out.

Conclusions



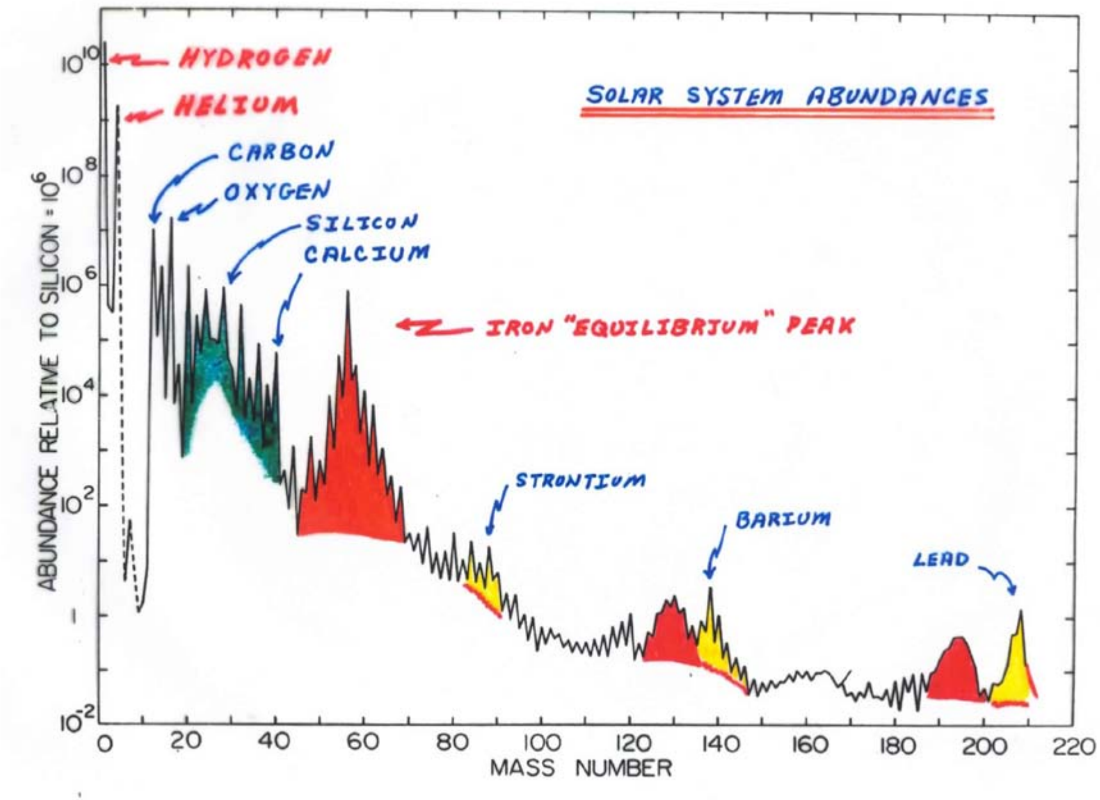
This work

The WD is subdivided into 51200 tracer particles. Among them just 4762 were selected (corresponding to ~ 0.2 $M_\odot$), that's to say the ones experiencing a peak temperature ($T9_{max}$) such that $1.5<T9_{max}<3.7$ in order to allow *p*-nuclei to form.

Movie

- /home/umby/model1_51200.mpg

Cosmic Nucleosynthesis Perspective



Jim Truran (2008)

Analyzing solar system abundance distribution (see figure above), Burbidge et al. (1957) determined that heavy nuclei were formed in three distinct nucleosynthetic processes, which they termed the *r*-, *s*- and *p*-process.

p-isotopes

The *p*-nuclei: ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92}Mo, ^{94}Mo, ^{96}Ru, ^{98}Ru, ^{102}Pd, ^{106}Cd, ^{108}Cd, ^{113}In, ^{112}Sn, ^{114}Sn, ^{115}Sn, ^{120}Te, ^{124}Xe, ^{126}Xe, ^{130}Ba, ^{132}Ba, ^{138}La, ^{136}Ce, ^{138}Ce, ^{144}Sm, ^{156}Dy, ^{158}Dy, ^{162}Er, ^{164}Er, ^{168}Yb, ^{174}Hf, ^{180}Ta, ^{180}W, ^{184}Os, ^{190}Pt, ^{196}Hg.

***s*-nuclides with *p*-contribution** (found by Travaglio et al. 2011)**:** ^{80}Kr, ^{86}Kr, ^{87}Rb, ^{86}Sr, ^{88}Sr, ^{89}Y ^{90}Zr, ^{96}Zr, ^{152}Gd.

Among them I analyzed ^{90}Zr, ^{96}Zr, ^{152}Gd.

Historycal background for SNIa

- Howard and Meyer. (1991) for the first time proposed type Ia supernovae as a possible *p*-process site, giving evidence of the **importance of starting seed *s*-nuclei** to produce *p*-nuclei.
- Goriely et al. (2002) proposed exploding sub-Chandrasekhar mass WD through He detonation as a *p*-process site.

From 1991 to 2002 noboby succeed to reproduce *p*-only Mo and Ru solar system abundances.

- Kusakabe et al. (2005, 2011) didn't succeed too, even considering an almost three-times larger starting seed abundances and the W7 Sne Ia model.

The *p*-process

The ***p*-process** is a nucleosynthesis process that accounts for the formation of some elements heavier than iron, in particular **proton-rich isotopes**. The process entails a succession of proton capture and photo-disintegration reactions on **seed nuclei**, resulting in the production of *p*-nuclei (Burbidge et al. 1957)

Two main open problems are recognized today:

- No unique astrophysical site is known to be a *p*-process site, even if there's a possibility that among them there are the type Ia supernovae and type II supernovae scenarios.
- The puzzling case of under-produced Mo and Ru *p*-only isotopes (Arnould and Goriely, 2003).

Type Ia Supernovae (SNe Ia): Theory

"Standard model:" (Hoyle & Fowler 1960):

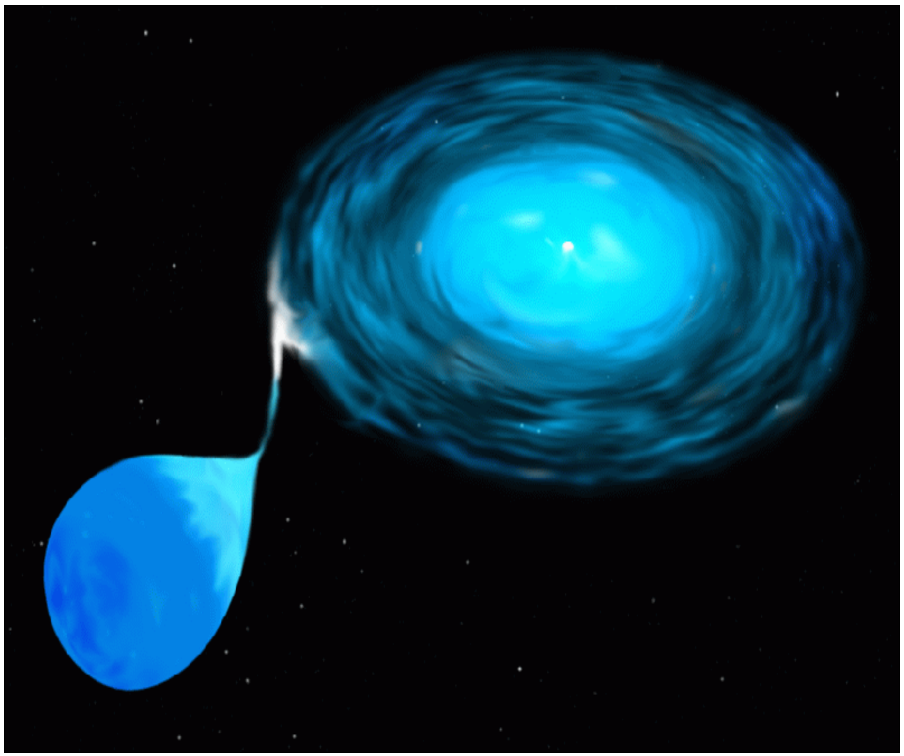
SNe Ia are thermonuclear explosions of carbon-oxygen white dwarf stars.

- Evolution to criticality:

Accretion from a binary companion leads to growth of the white dwarf to a critical mass (1.39 solar masses).

Complete incineration and disruption occurs in ~ two seconds. (No compact remnant.)

An **initial seed-nuclei distribution** (consisting in *s*-nuclei) is necessary to let *p*-process occur through photo-disintegration reactions (Howard and Meyer, 1991)



Jim Truran (2008)