# Nuclear Physics aspects of explosive nucleosynthesis

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432. WE-Heraeus-Seminar:
Nucleosynthesis - making the Elements in the Universe

June 6, 2009

# Outline

1. Introduction
2. Nucleosynthesis in proto-rich ejecta
    - The $\nu p$ process
3. Nucleosynthesis in neutron-rich ejecta
    - The r-process
4. Summary

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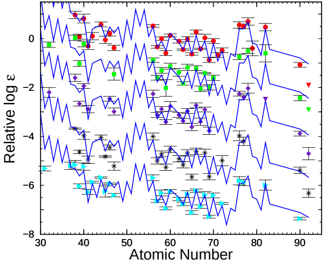
# Why heavy elements?

- We would like to understand how they are synthesized.
- Their synthesis seems to depend in the supernovae explosion mechamism. Can we learn how supernovae explode?
- These elements are present in metal-poor stars that were “polluted” by the first stars. In partilcar U and Th can be used to determine the age of the galaxy.
- Can heavy become super-heavy? Can super-heavy elements be synthesized in nature?

# r-process and metal-poor stars

Cowan & Sneden, Nature **440**, 1151 (2006)



- Nucleosynthesis Signatures of few (single?) events.
- Abundances $Z > 56$ consistent with solar r-process abundance.
- Abundances $Z < 56$ show larger variations.

Astrophysical scenarios may clasiffied in two categories:

- High entropy environments (fast expanding, low $Y_e$ ejecta).
  - High temperature r-process (classical $(n, \gamma) \rightleftarrows (\gamma, n)$ equilibrium)
  - Low temperature r-process (competition between neutron captures and beta decay, Blake & Schramm, ApJ **209**, 846 (1976)
- Low entropy environments (ejection cold neutron-rich matter).

Both scenarios differ in the way neutrons and seed nuclei are created but not so much in the way the r-process operates.

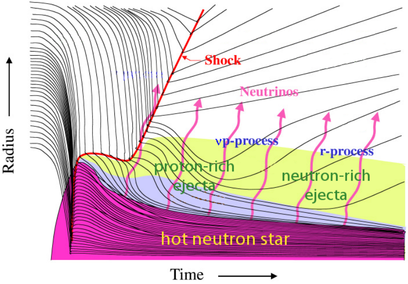
# Neutrino driven wind

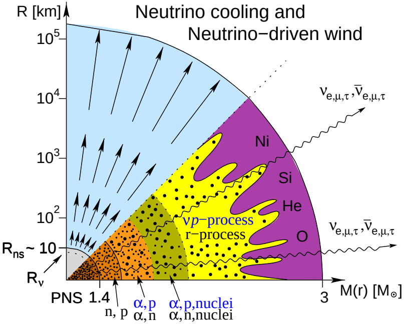
## Main processes:

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

Neutrino interactions determine the proton to neutron ratio. Recent supernova simulations show existence of early proton-rich ejecta.

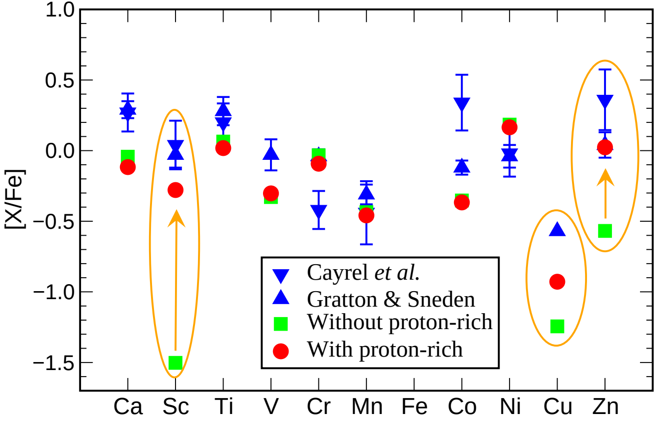
- $\nu p$-process (Early proton-rich ejecta).
- r-process (late ejecta, neutron rich)





# Iron group nuclei and proton rich ejecta

Proton-rich ejecta are the mayor contributors to $^{45}$Sc and $^{64}$Zn (C. Fröhlich, *et al.* 2006, J. Pruet, *et al.* 2005).



Model and observations in metal-poor stars.

# The $\nu p$ process

- Proton rich matter is ejected under the influence of neutrino interactions.
- Nuclei form (mainly $N = Z$) at distances where a substantial antineutrino flux is present.
- Antineutrino charge-current capture time and expansion time scale are similar ($\sim 1$ s)

Neutrinos speed-up matter flow

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

$n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p$

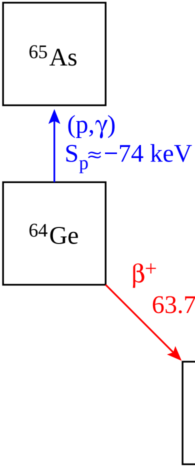
${}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge} \quad \ldots$

These reactions constitute the $\nu p$-process

C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)

J. Pruet *et al.*, ApJ **644**, 1028 (2006)

S. Wanajo, ApJ **647**, 1323 (2006)



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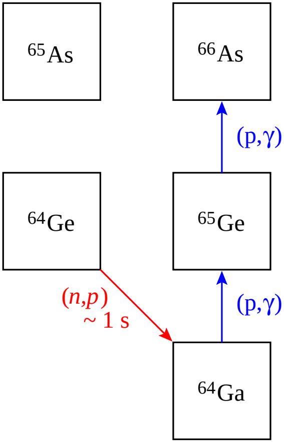

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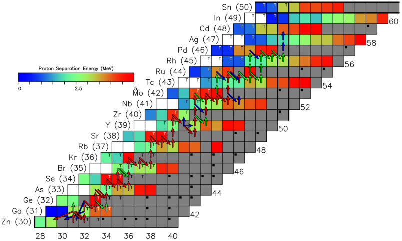
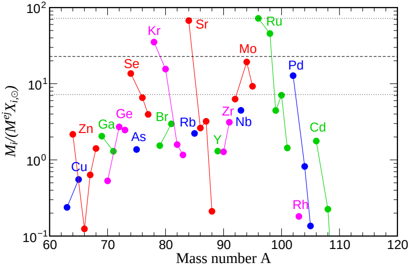
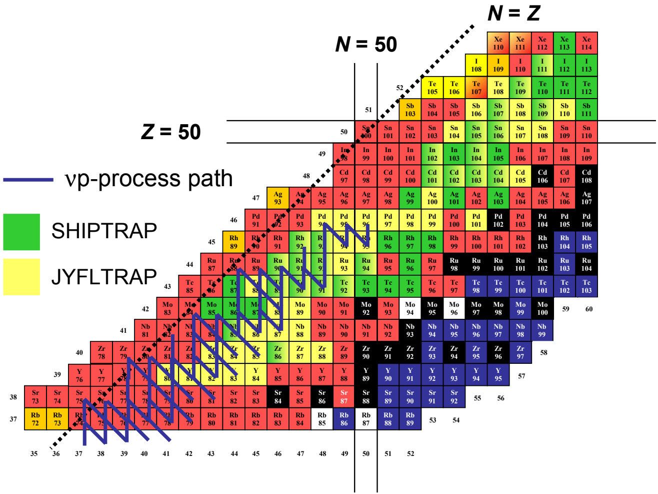
Supernova model courtesy from H.-Th. Janka





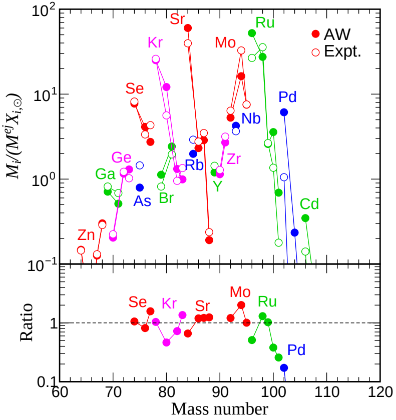
Sensitivity to masses and astrophysical conditions.

# Masses measured at SHIPTRAP and JYLFTRAP



C. Weber *et al*, Phys. Rev. C **78**, 054310 (2008)

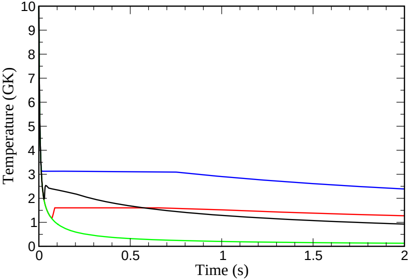
# Influence new masses

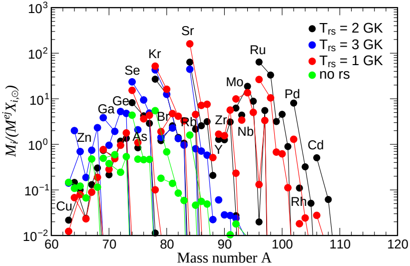


- New set of reaction rates using new experimental masses (T. Rauscher).
- New experimentar values close to Audi-Wapstra systematics. Little changes in abundances.
- No spectroscopic information is known for these nuclei. Sensitivity studies of the important reaction rates are necessary. However, $\nu p$-process seems to occur under $(p, \gamma) \rightleftarrows (\gamma, p)$ equilibrium.
- Having the nuclear physics under control allows to explore the astrophysical uncertainties. The $\nu p$-process can be used constrain the evolution of the ejected matter.

# Sensitivity to temperature evolution

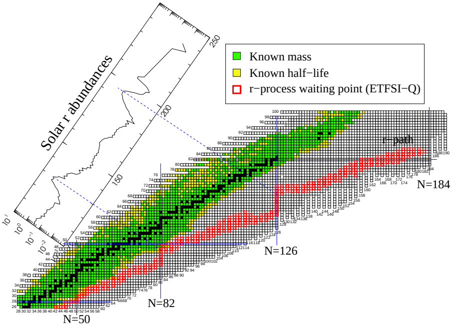
The $\nu p$-process nucleosynthesis is rather sensitive to the temperature evolution of the ejected matter. In particular, to the interaction with the reverse shock.





(A. Arcones & GMP)

# The r-process



The r-process is responsible for the synthesis of half the nuclei with $A > 60$ including U, Th and maybe the super-heavies.

The r-process requires the knowledge and the evolution with neutron excess of:

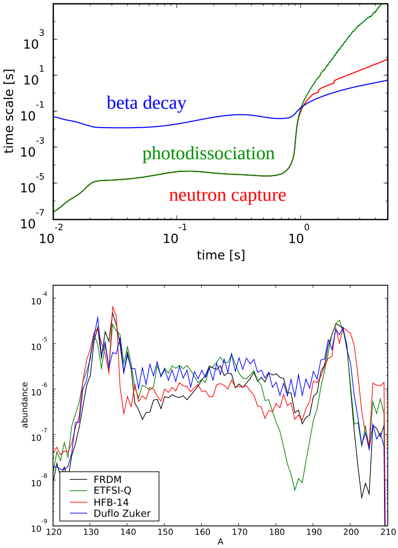
- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates.
- Reactions with neutrinos.

Main parameter determining the nucleosynthesis is the neutron-to-seed ratio $n_s$.

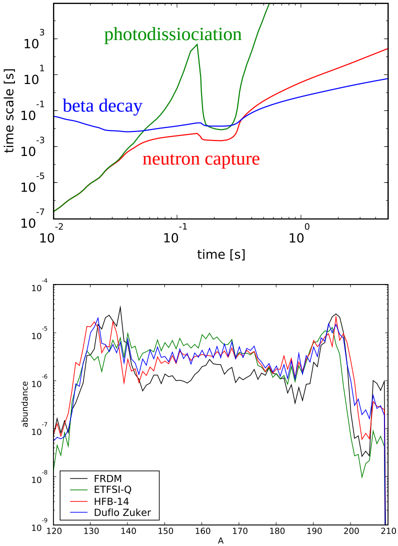
$$A_f = A_i + n_s$$

# hot vs. cold r-process

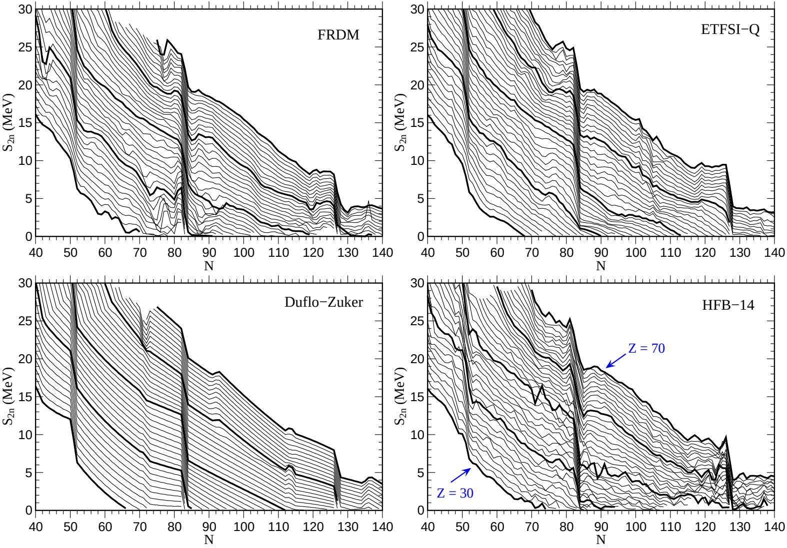
## Hot r-process



## Cold r-process

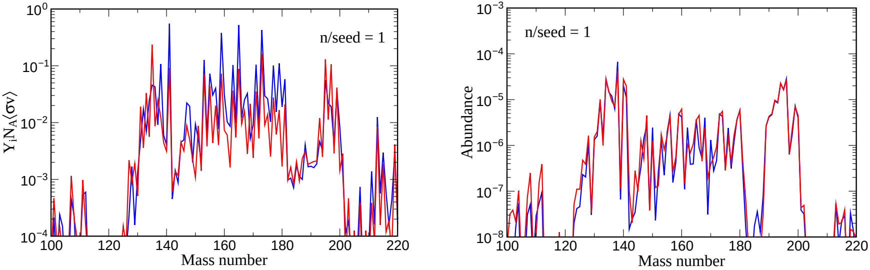


# N=82 and N=126 Two-Neutron separation energies



# Hot r-process: abundance evolution

$(n, \gamma) \rightleftarrows (\gamma, n)$ equilibrium is maintained until $n/\mathrm{seed} \approx 1$. At this moment individual neutron capture rates become important.



Abundances for two different calculations using the FRDM masses but different sets of $(n, \gamma)$ rates: NON-SMOKER rates (Rauscher & Thielemann 2000), analytical approximation to full Hauser-Feshbach calculations (Michaud & Fowler 1970)

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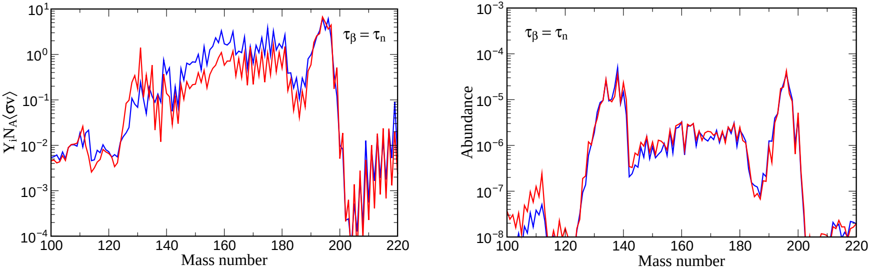

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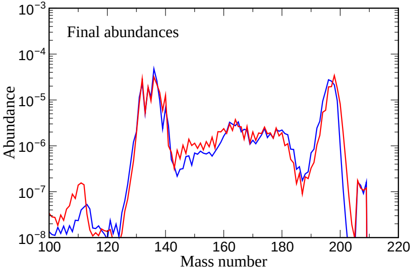

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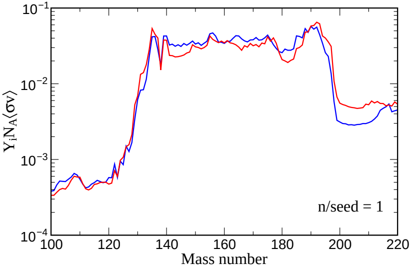
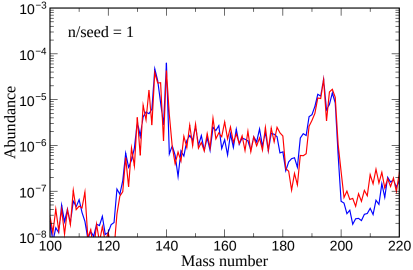
# Cold r-process: abundance evolution

Photodissociation reactions are negligible and consequently the r-process operates under a competition of neutron captures and beta-decays.





At this moment the abundances follow a pattern with $Y_i\langle\sigma v\rangle \approx$ constant, i.e. a classical "s-process" distribution. However, differently to the s-process $Y_i\lambda_\beta \approx$ constant.

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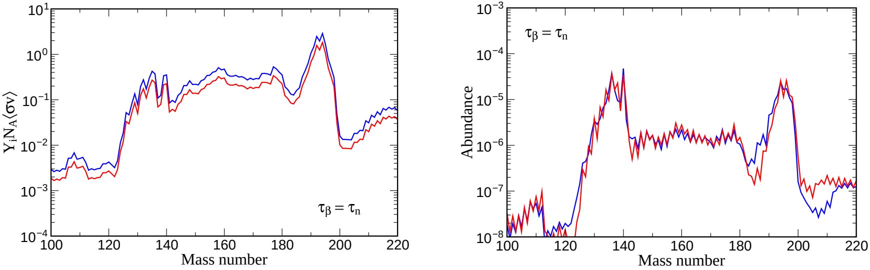

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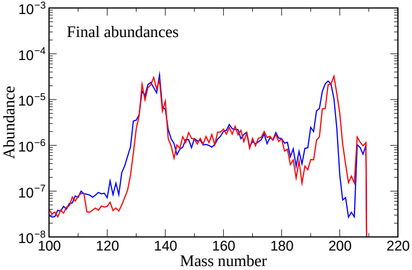
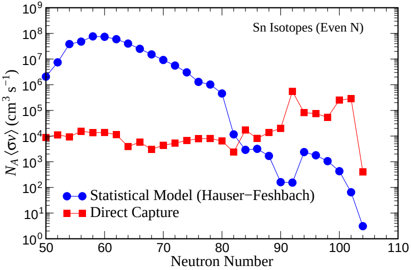
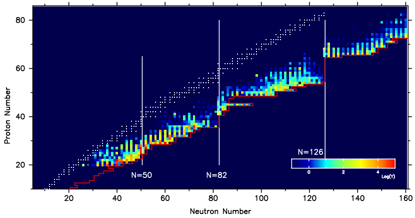
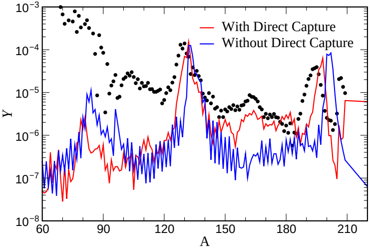


# Direct capture

Direct capture contributions to neutron capture become important for nuclei with low neutron separation energies (small level density).





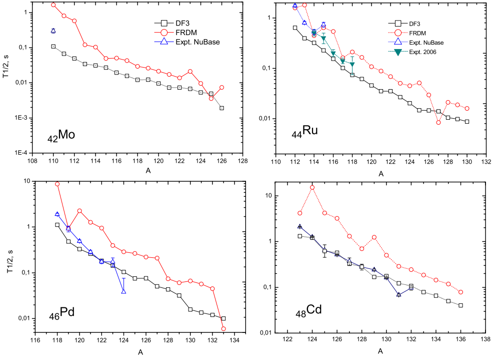


K. Otsuki, S. Typel, GMP, I. Borzov (in preparation)

# Beta-decay half-lives (N=82)

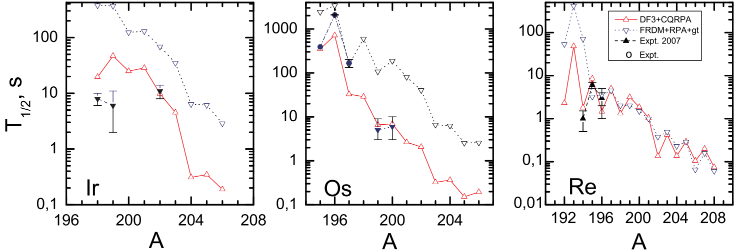
- Beta decay rates determine the speed matter flow to heavy nuclei.
- In the case of $N = 82$ available experimental data allows to contrain theoretical models.

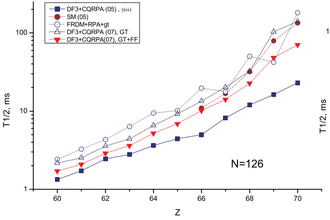
Borzov, Cuenca-García, Langanke, GMP, Montes, NPA **814**, 159 (2008)

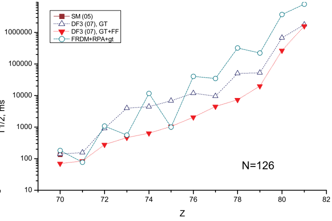


# Beta-decay half-lives (N=126)

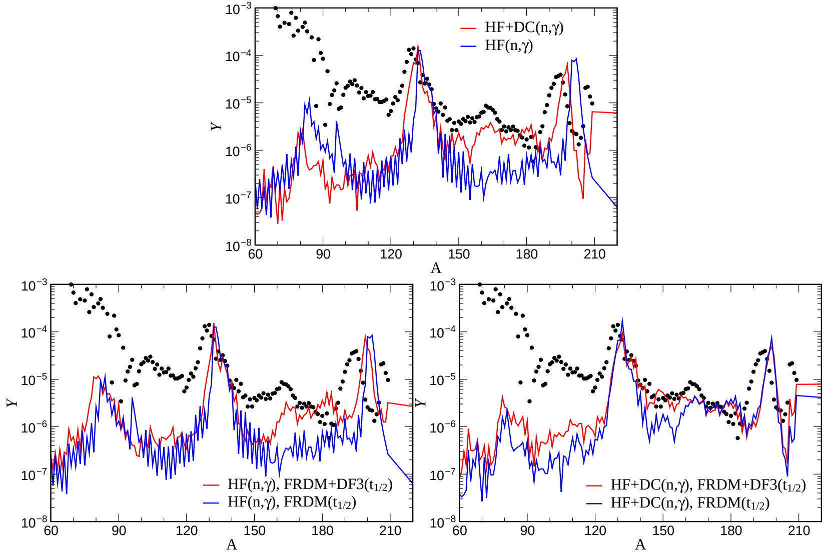
The N=126 nuclei are not yet accessible experimentally. However, in a recent experiment at the FRS (GSI) several nuclei were produced approaching the $N = 126$ (Kurtukian-Nieto, Benlliure, Schmidt, Borzov *et al*, submitted Phys. Lett. B)







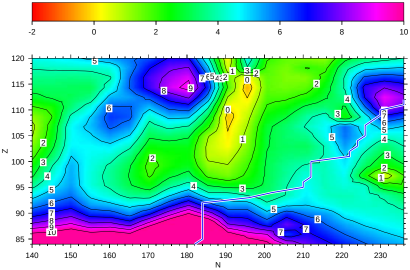
# Effect r-process calculations



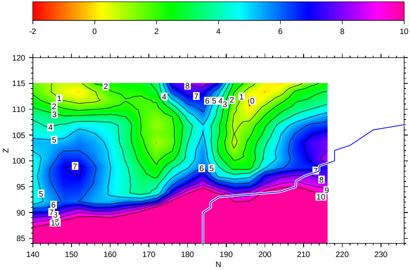
# Fission in the r-process

- Depends of the fission barriers.
- It is necessary to consider all fission inducing processes (neutron induced, beta delayed, spontaneous fission, …) and the corresponding yields.

Thomas-Fermi
[Myers & Świątecki, PRC **60**, 014606 (1999)]



Extended Thomas-Fermi
[Mamdouh *et al*, NPA **679**, 337 (2001)]



Neutron-induced fission is the dominating process.

# Fission in the r-process

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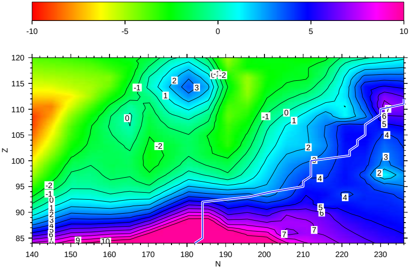
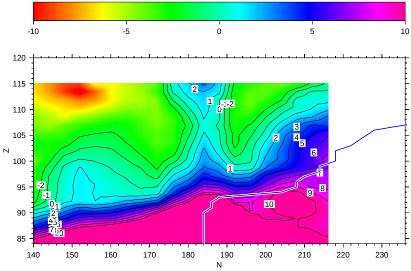
Barrier minus neutron separation energy (TF barriers, FRDM masses).



Barrier minus neutron separation energy (ETFSI barriers and masses)



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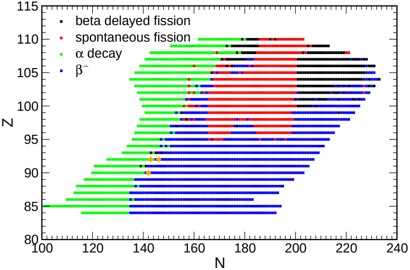
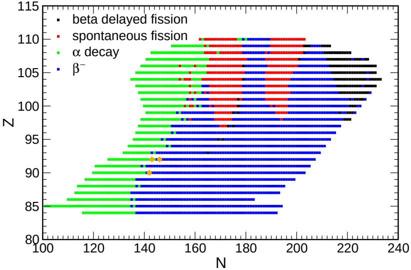
# Fission in the r-process

Other fission channels become relevant for small neutron densities.

TF barriers

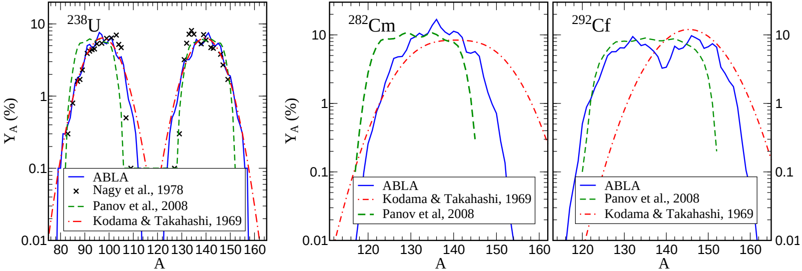


ETFSI barriers



# Fission yields

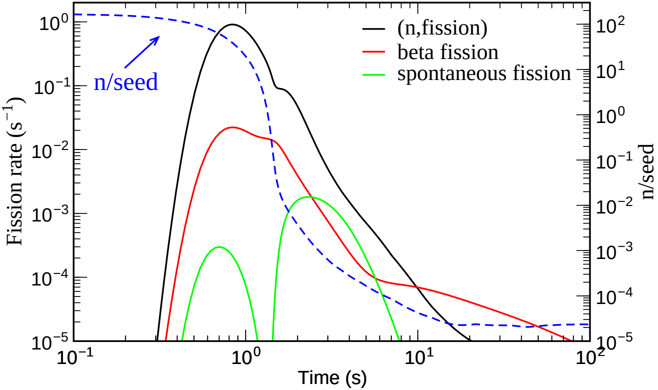
In addition to the rates, the corresponding yields are also necessary.



(calculations by A. Kelić and N. Zinner)

# Comparison fission rates

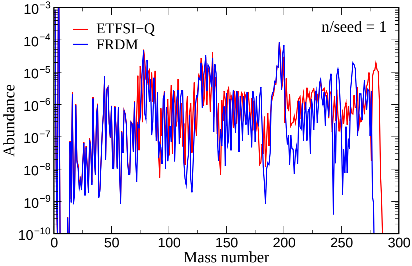
Neutron induced fission (rates based in Panov *et al*, submitted to A&A) dominates.



# Influence r-process abundances

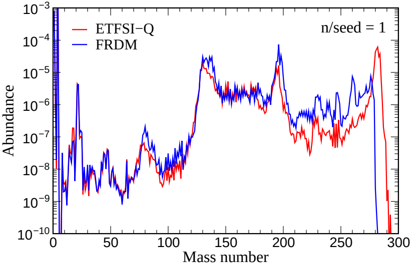
Depends on both the nuclear physics input and the temperature evolution.

Hot r-process



(I. Petermann *et al.*)

Cold r-process



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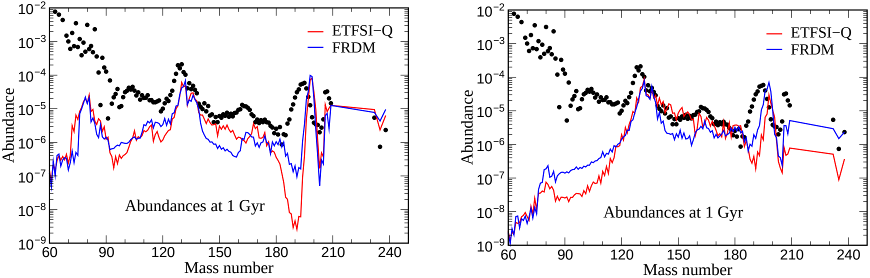

(I. Petermann *et al*)

# Summary

- The $\nu p$-process can explain the solar abundances of light p-nuclei ($^{94}$Mo, $^{96,98}$Ru). $^{92}$Mo may be produced in slightly neutron rich ejecta.
- r-process nucleosynthesis is rather sensitive to the nuclear physics input (neutron captures and beta decays) and to the long term evolution of the ejected matter.
- A better understanding of fission in the r-process is necessary to obtain reliable estimates of the abundances of U and Th.