Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Nuclear Astrophysics - Nucleosynthesis of the heavy elements

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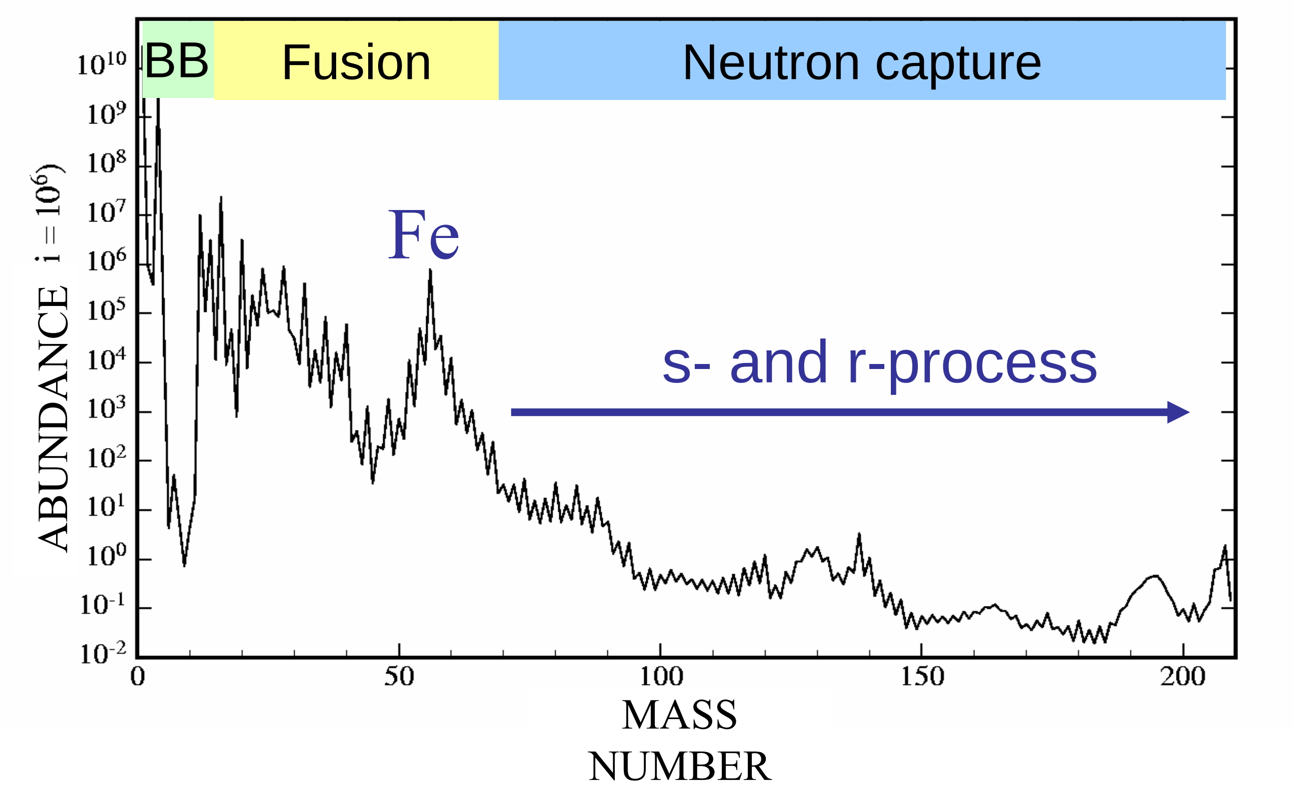
Outline

One of the main goals of Nuclear Astrophysics is to explain **how** and **where** the chemical elements were produced.

- Evolution of stars
- Chemical evolution of Galaxy
- Age of the Universe

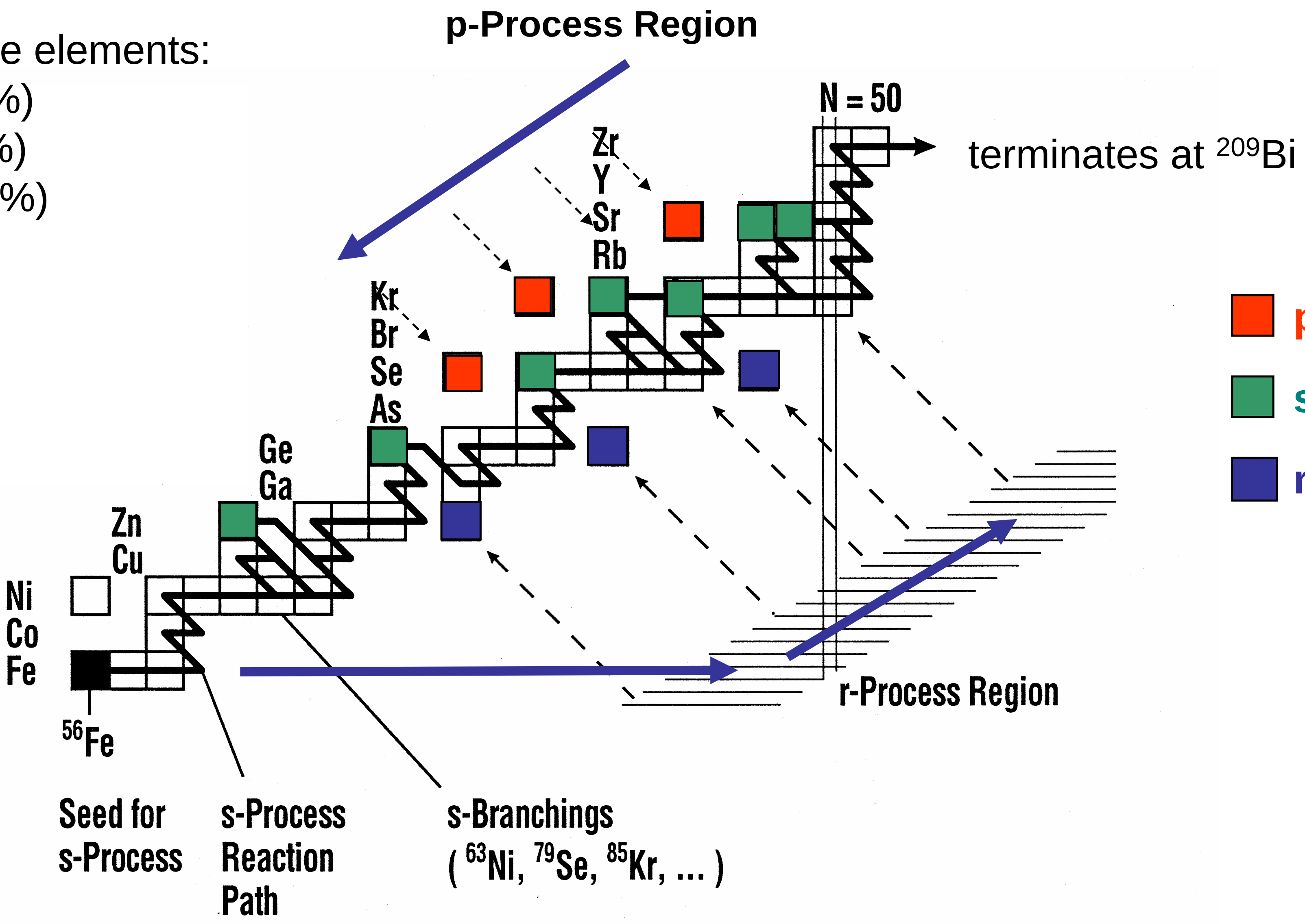


Outline

- Nucleosynthesis processes of heavy elements – overview
- Recent observations of metal-poor halo stars and consequences for the nucleosynthesis
- Results of (n,γ) cross section measurements (activation method)
- Conclusions

Nucleosynthesis of the heavy elements

Production of the elements:
- s process (50%)
- r process (50%)
- p process (<1 %)

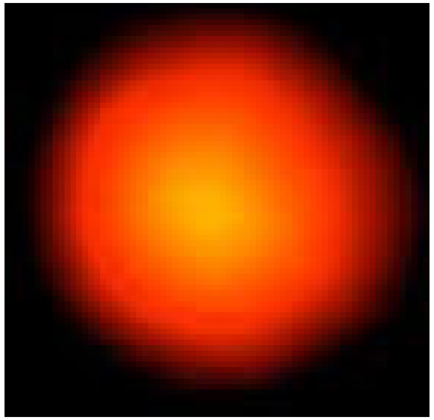


🟥 p-only

🟩 s-only

🟦 r-only

Nucleosynthesis - s-process



s-process

main s-process
90<A<210

He-rich intershell of evolved red giants (AGB)
$1<M_\odot<6$
Neutron sources: $^{13}C(\alpha,n)$, $^{22}Ne(\alpha,n)$
Temp.: ~$1 \cdot 10^8$ K
Neutron density: $4 \cdot 10^8$ cm^{-3}

weak s-process
A<90

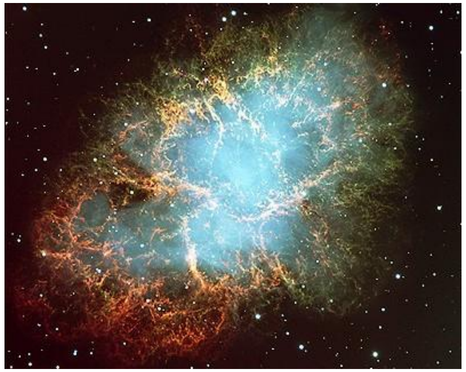
Massive stars $M_\odot>10$
Neutron source: $^{22}Ne(\alpha,n)$, $^{13}C(\alpha,n)$?

Core helium burning
Temp.: ~$2\text{-}3 \cdot 10^8$ K
Neutron density: ~$1 \cdot 10^6$ cm^{-3}

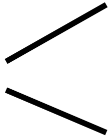
Shell carbon burning
Temp.: ~$1 \cdot 10^9$ K
Neutron density: ~$1 \cdot 10^{11}$ cm^{-3}

~~strong s-process~~
~~A=208~~

- s-process is secondary, not unique, models very advanced
- data needs: neutron capture cross sections, stellar β-decay rates
- reliable abundance calculations if (n,γ) cross sections are accurate



Nucleosynthesis - r-process

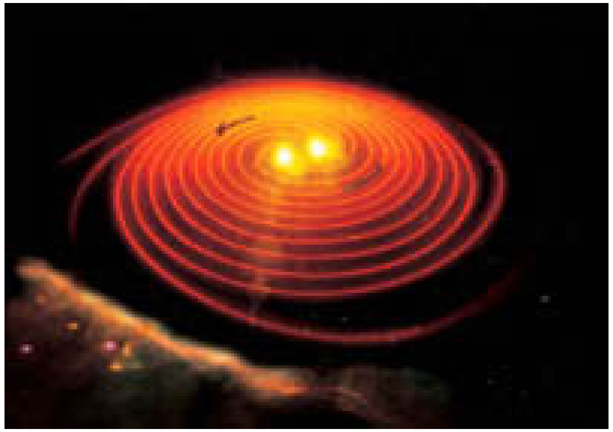


r-process

one unique
r-process

?

Supernovae (asymmetric)
Neutrino driven winds of neutron star
Neutron star merger



data needs:
neutron separation energies (masses)
Half-lives,
neutron capture cross sections during freeze-out

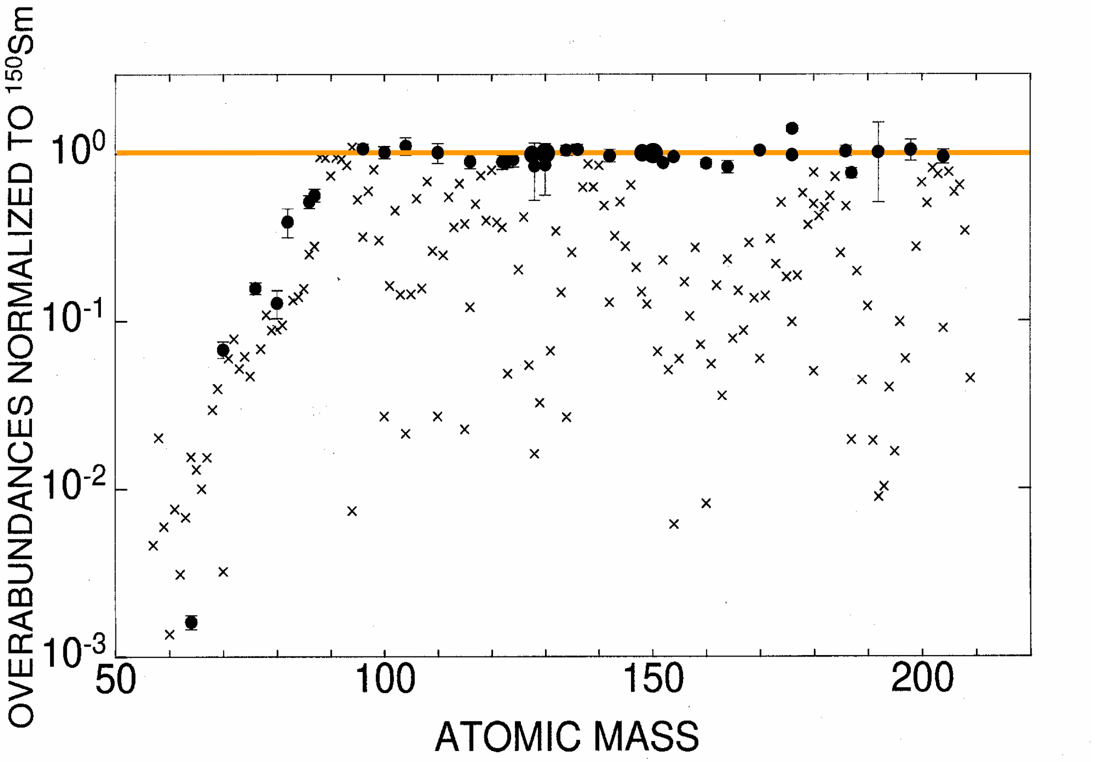
p-process: contributes only marginally to the synthesis of the elements

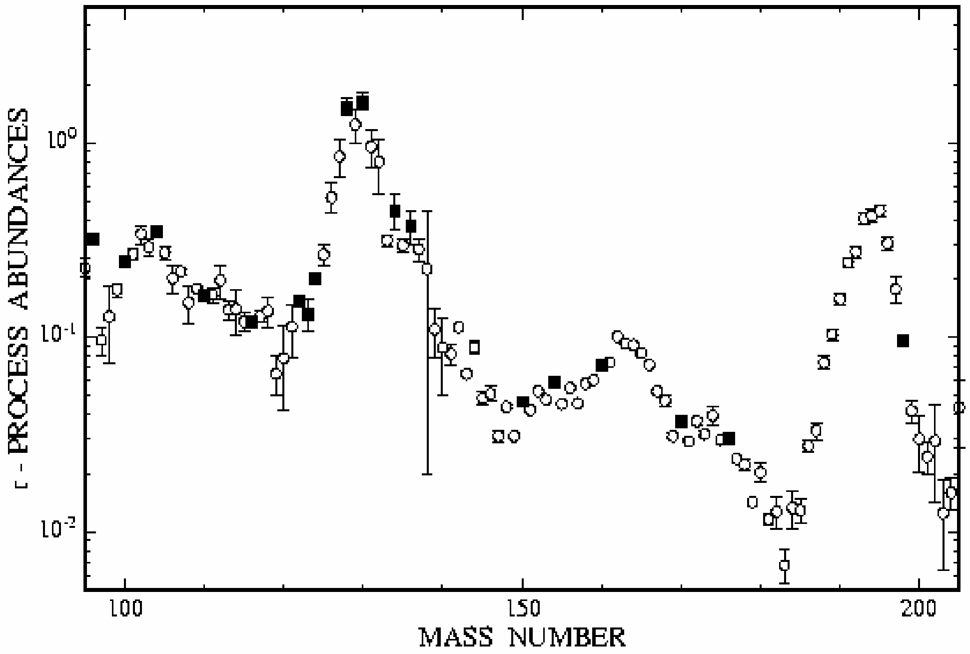
The main s-process in AGB stars

Stellar model calculations of AGB stars in comparison with the solar abundances

r-residuals method

$$N_r = N_{solar} - N_s$$

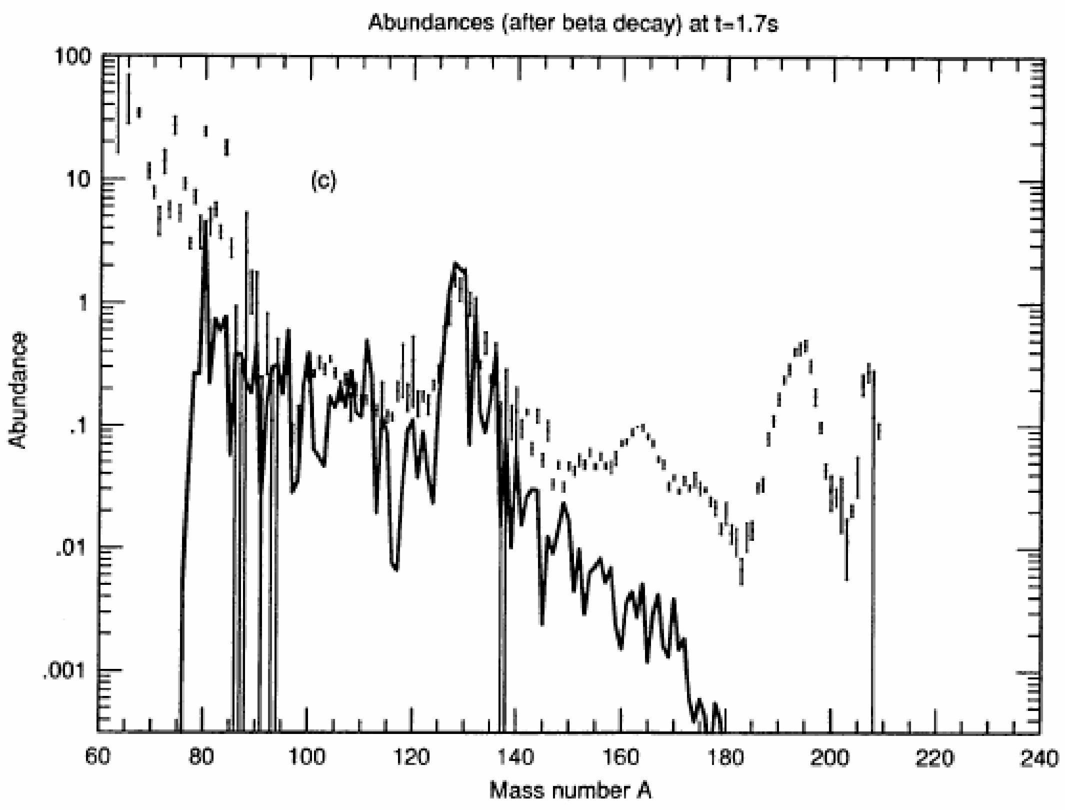


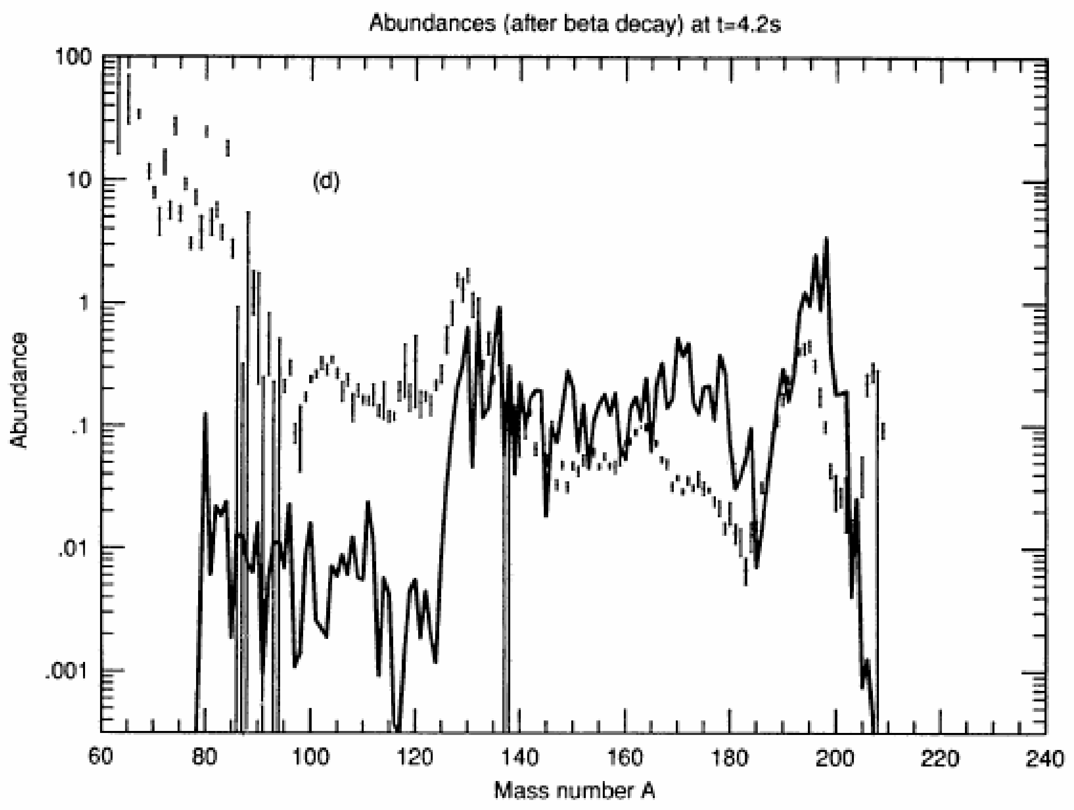


Arlandini et al. ApJ 525 (1999) 886

Abundances from r-process studies

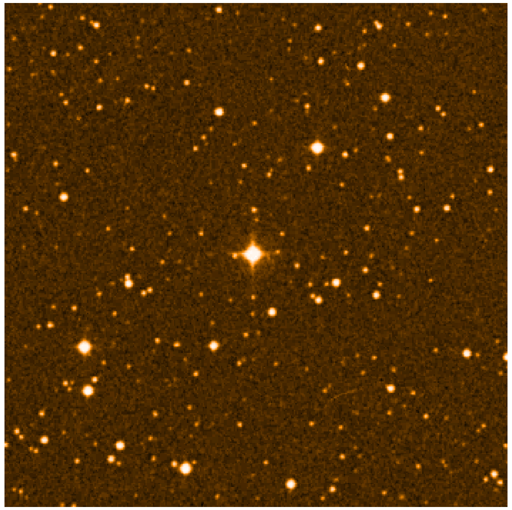
- Since many of the input parameters (masses, β-decay rates, …) are not known, reliable abundance calculations are not available.
- r-process cannot be described with one single parameter set.





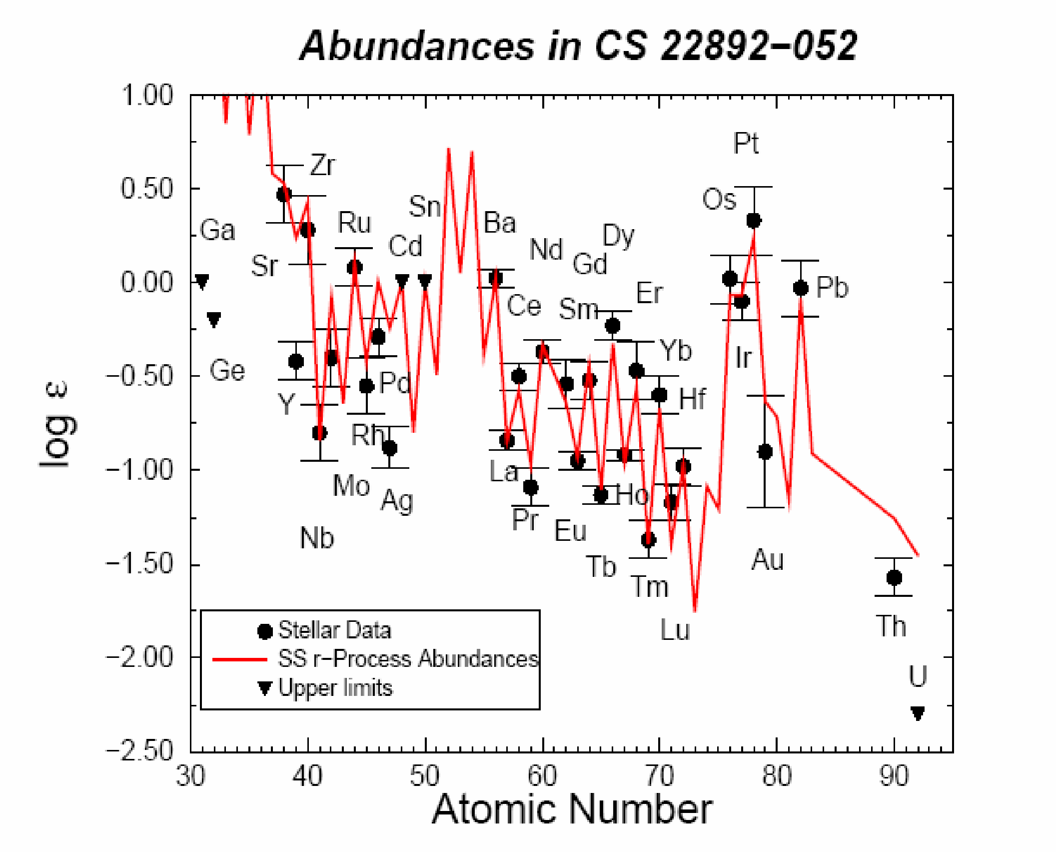
K. L. Kratz et. al., Ap.J. 403, (1993) 216

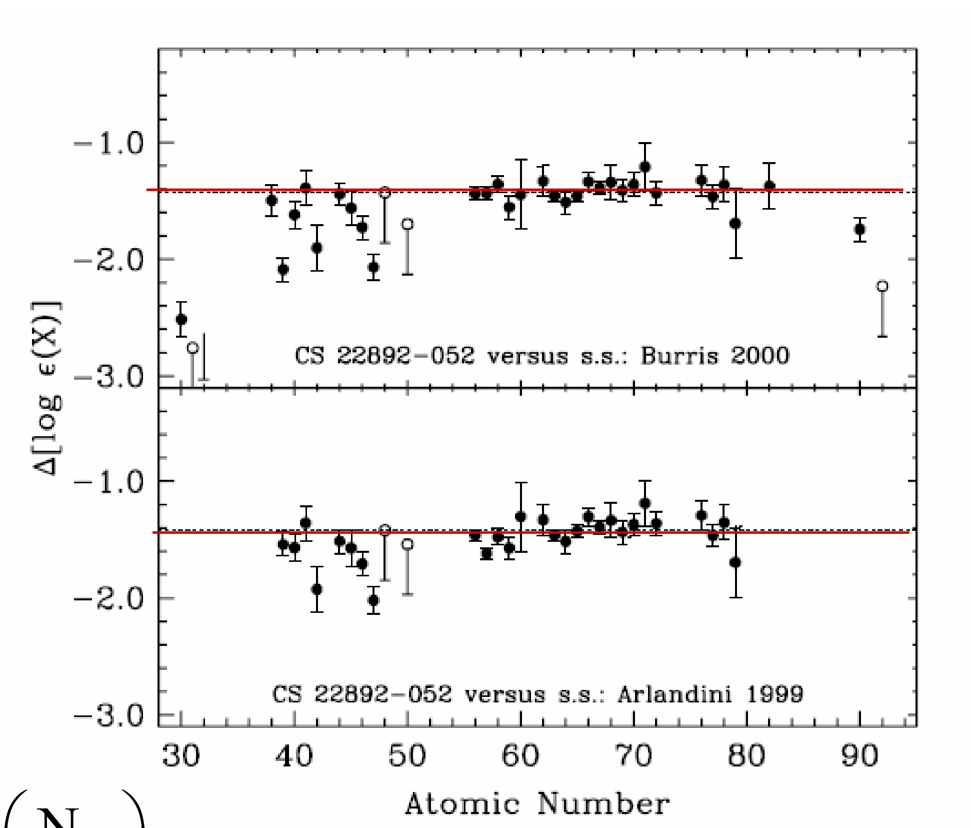
Observation of metal-poor halo stars



Metal-poor halo stars should show pure r-abundances

Comparison of observed abundances and scaled N_r





Sneden et al., Ap. J. 591 (2003) 936

$$\log \varepsilon(\mathrm{A}) = \log\left(\frac{N_A}{N_H}\right) + 12$$

Sum rule: s + p + r = 100 %

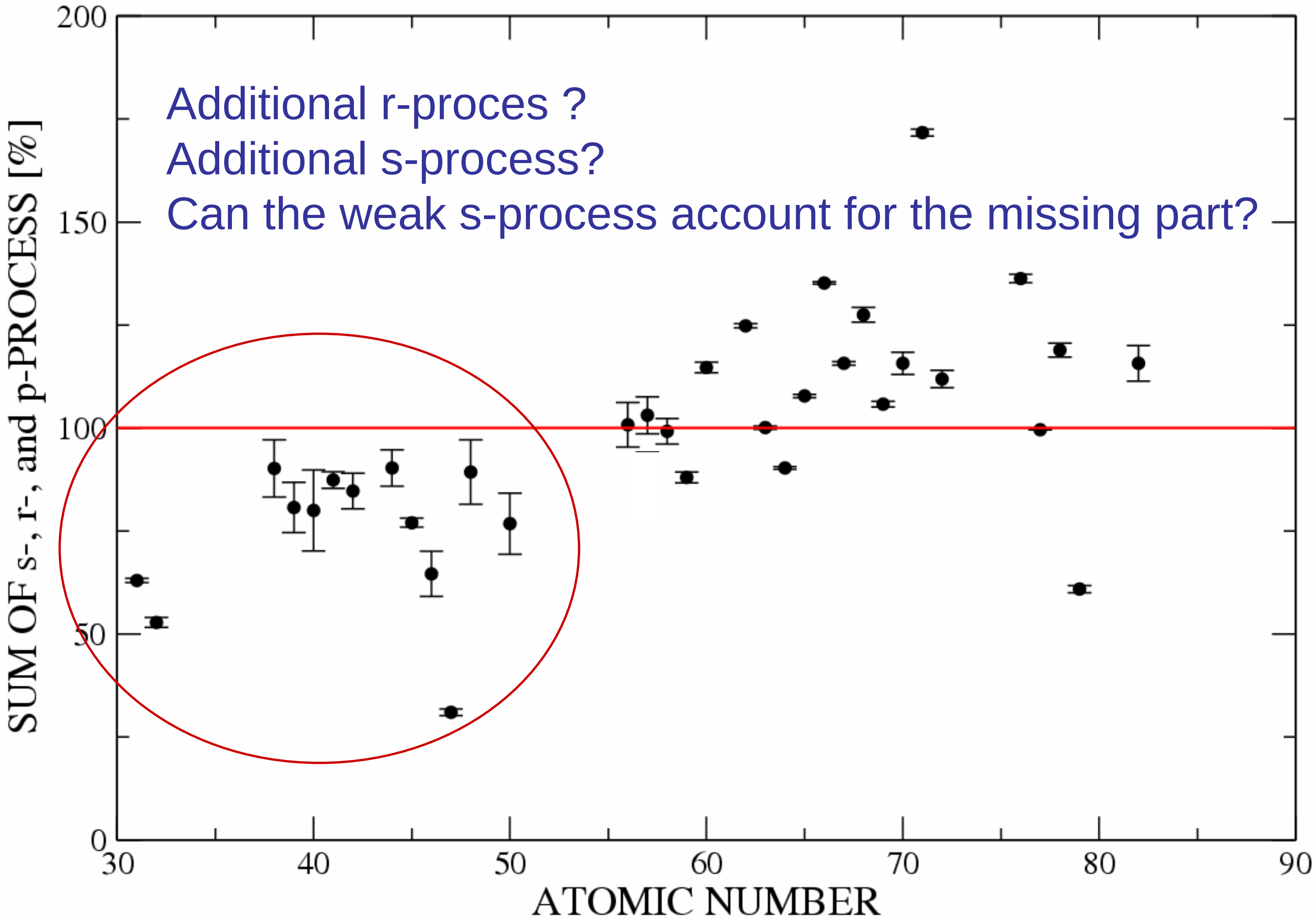
Weak s:
Raiteri et al.
ApJ 419 (1993) 207

Main s:
Arlandini et al.
ApJ 525 (1999) 886

Galactic chemical evolution:
Travaglio et al.
ApJ 601 (2004) 864

r-abundances from halo stars:
Sneden et al.,
Ap. J. 591 (2003) 936

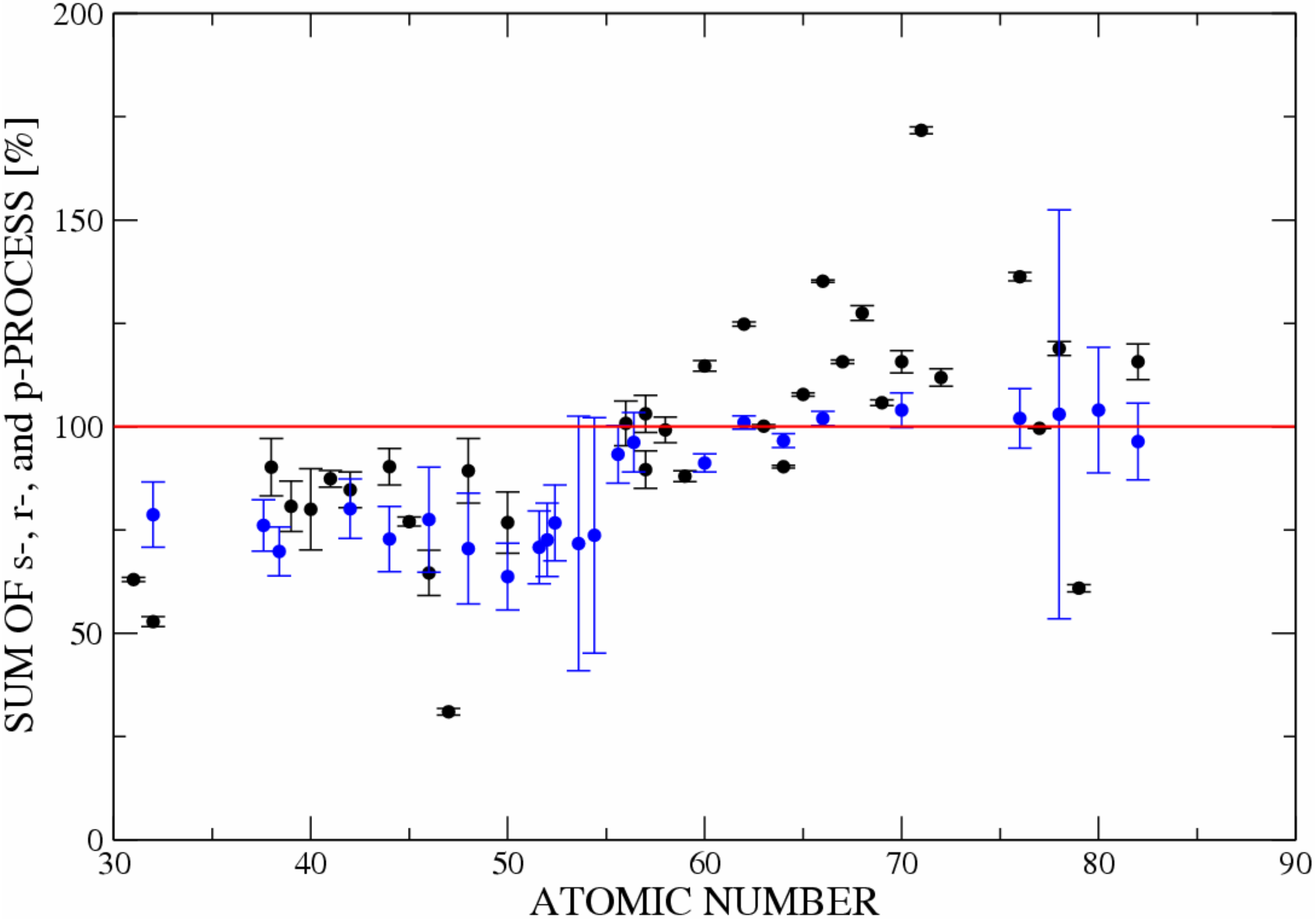
p-process:
Mo: 24 %
Ru: 7 %



Additional r-proces ?
Additional s-process?
Can the weak s-process account for the missing part?

Sum rule for s-only

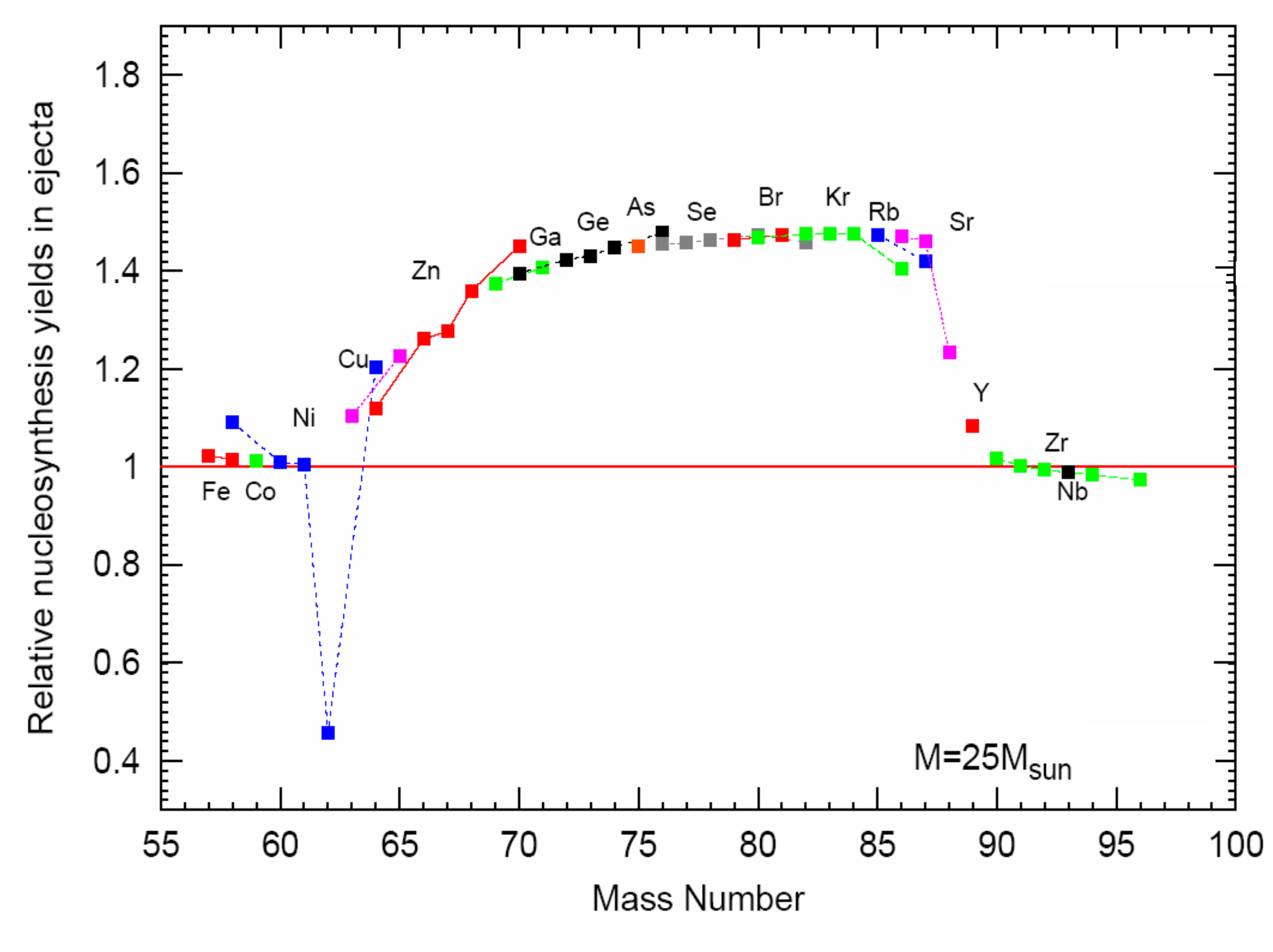
There must be an “s-like” process since s-only isotopes are also underproduced



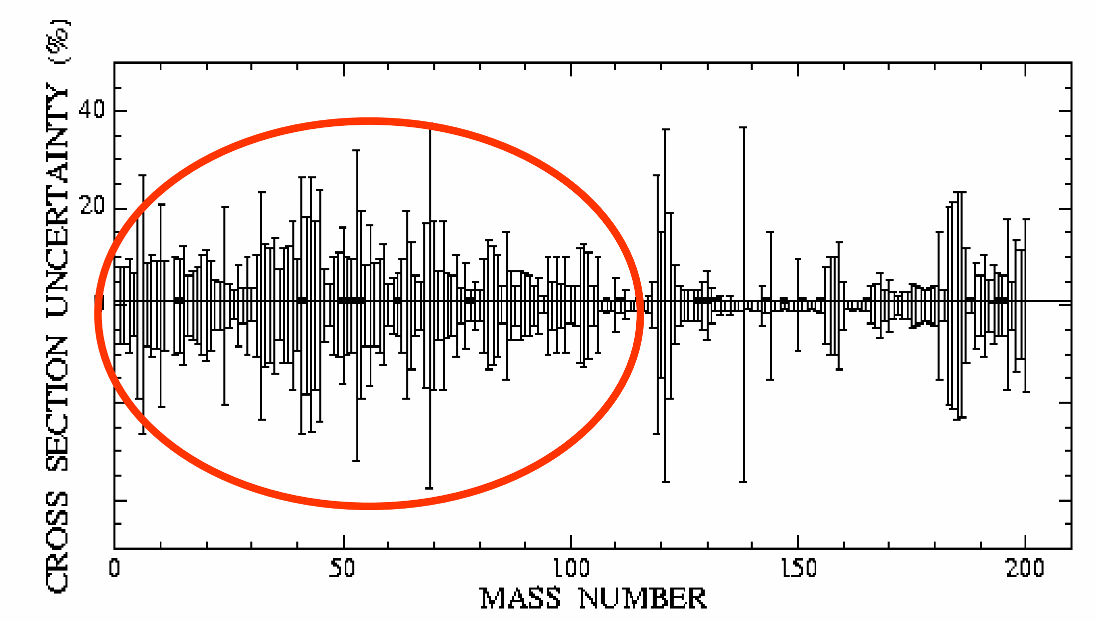
Weak s-process – example ^{62}Ni(n,γ)

Recommended cross section (Bao et al.) at kT=30 keV: 12.5 mb

New measurement (Nassar et al. *Phys. Rev. Lett. 94 (2005) 092504):* 28.4 mb



Nuclear data needs for the weak s-process



s-process abundances are determined mainly by Maxwellian averaged neutron capture cross sections for thermal energies of kT=25 – 90 keV.

Problems:

- small cross sections
- resonance dominated
- contributions from direct capture

Methods:

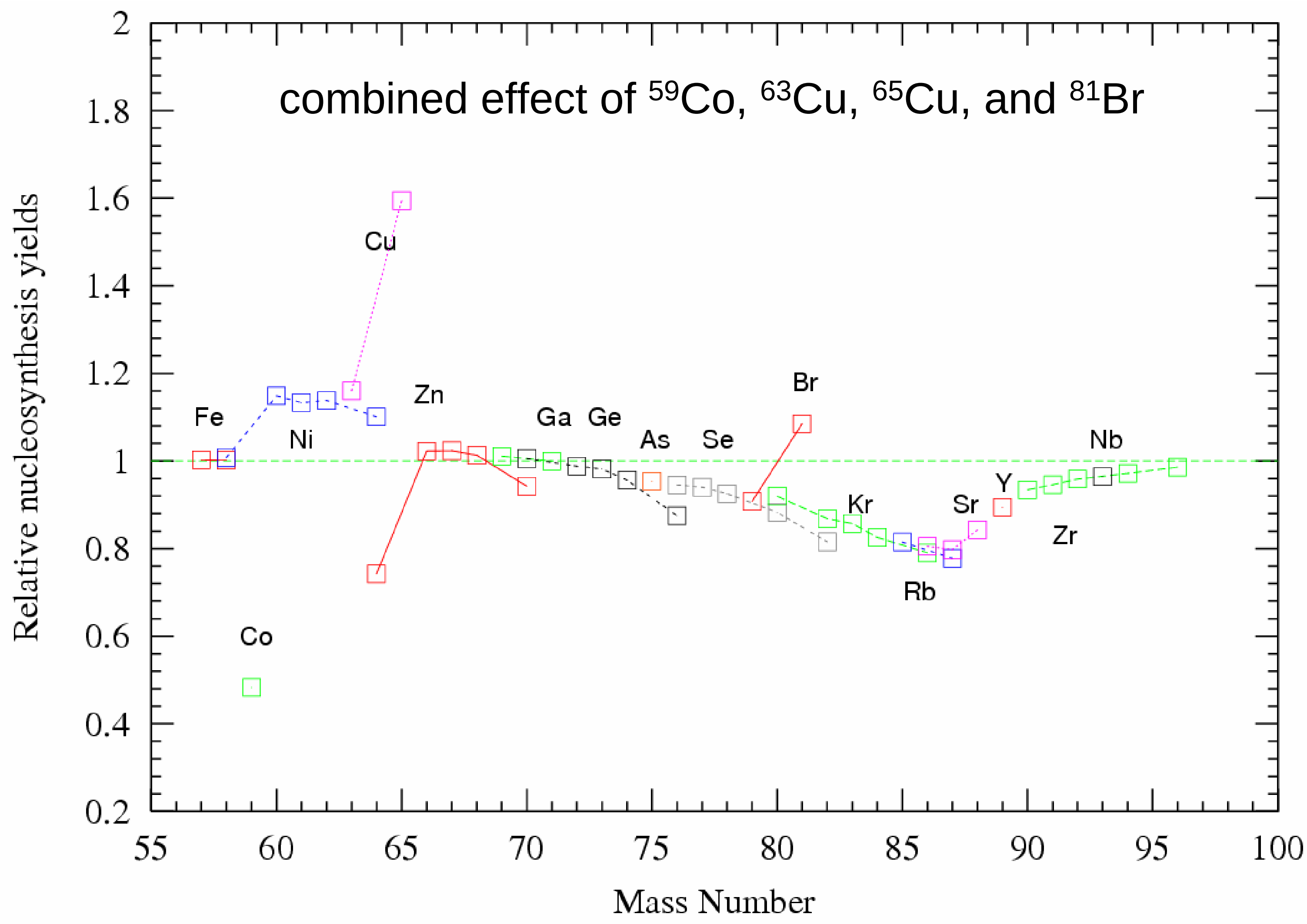
- TOF: measure $\sigma(E_n)$ between 0.1 and 500 keV by time of flight, determine MACS for stellar spectrum
- Activation: produce stellar spectrum at kT=25 keV in laboratory, measure directly MACS

Results - neutron capture cross sections

Isotope	MACS @ kT=30 keV in mbarn	Bao et al. @ kT=30keV in mbarn
^{45}Sc	57 ± 2	69 ± 5
^{59}Co	41 ± 2	38 ± 4
^{63}Cu	53 ± 2	94 ± 10
^{65}Cu	29 ± 2	41 ± 5
^{79}Br	626 ± 19	627 ± 42
^{81}Br	241 ± 9	313 ± 16
^{87}Rb	16.1 ± 2.0	15.5 ± 1.5

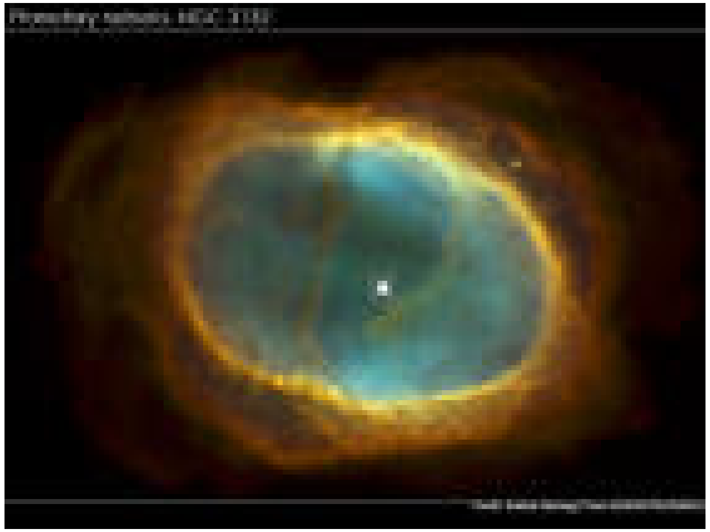
Results – weak s-process abundances

25 M$_\odot$ star at the end of carbon shell burning



Stellar model calculations performed by Marco Pignatari

Conclusions



- We have a good description of the main s-process

- Models of the weak s-process and especially the r-process have to be improved

- Observation of metal-poor halo stars suggest:
  - a robust and unique r-process
  - an additional s- and/or r-component

- Can the weak s-process account for the missing part?

We don’t know before

neutron capture cross sections of **all** involved isotopes are measured!