**Forschungszentrum Karlsruhe**
in der Helmholtz-Gemeinschaft

# Neutron cross sections for reading the abundance history

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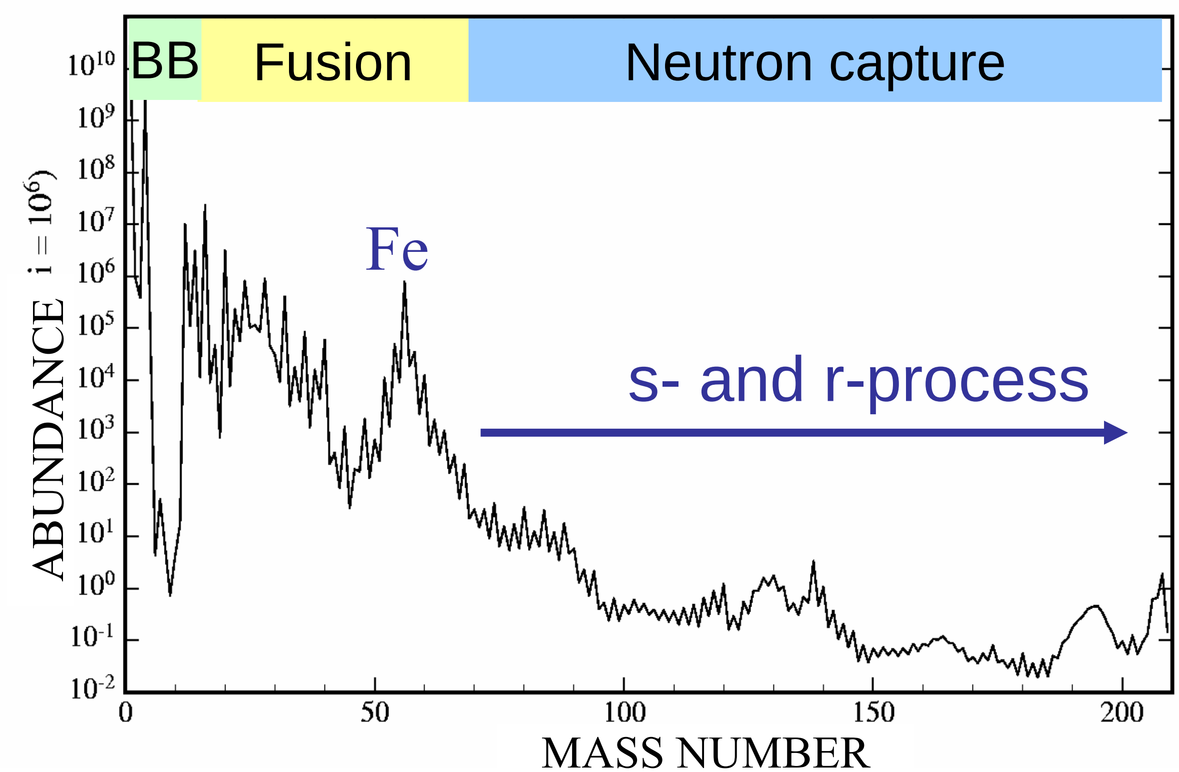
# Outline



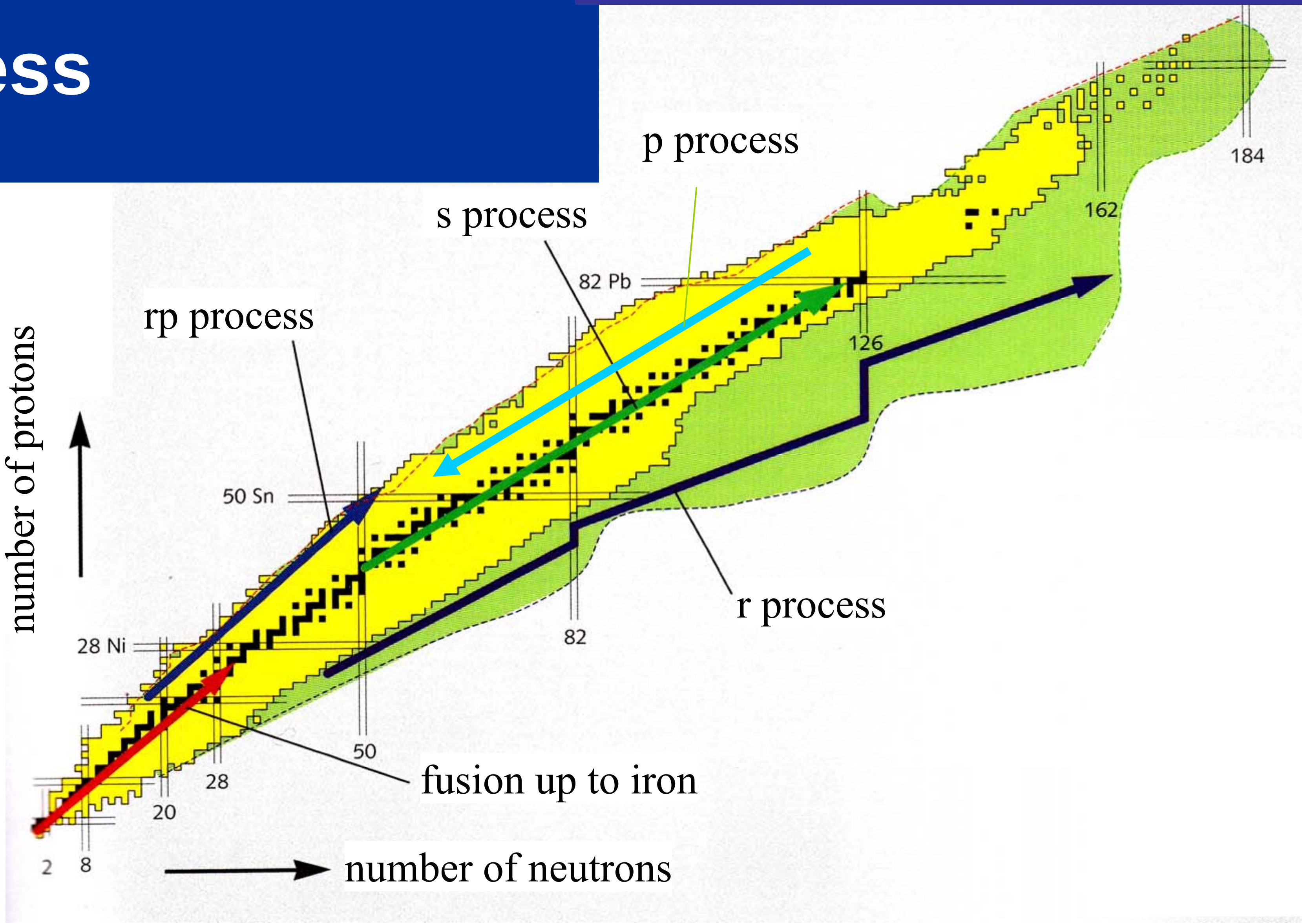
One of the main goals of Nuclear Astrophysics is to explain **how** and **where** the chemical elements were produced. Nucleosynthesis is strongly related to

- evolution of stars
- chemical evolution of Galaxy
- age of the Universe, …

## Outline

- The s-process a diagnostic tool for stars
- Recent observations of metal-poor halo stars and consequences for the nucleosynthesis
- (n,γ) measurements for the weak s-process (activation method)
- Cross section measurements at n_TOF
- Conclusions

# s-process



-process path follows valley of stability, therefore the main nuclear properties

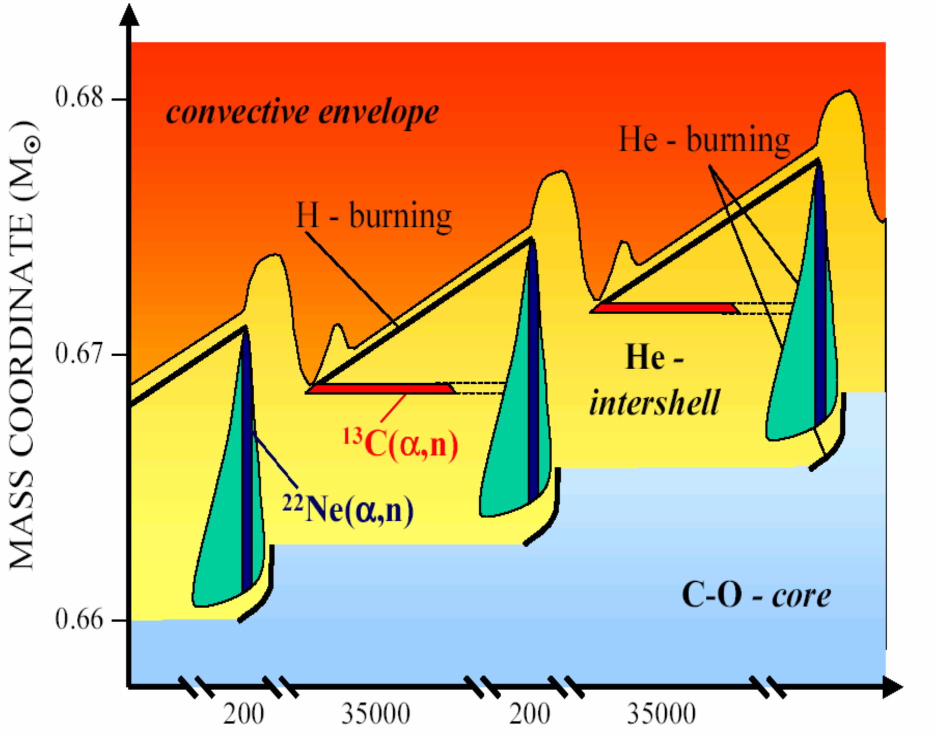
- neutron capture cross sections
- β-decay rates

hich are needed as input for stellar models are accessible by lab. measurement

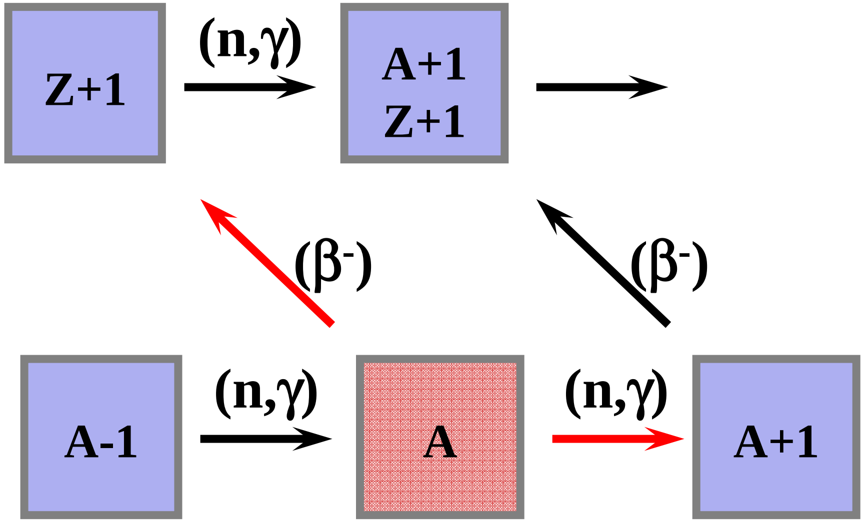
# main component of s-process

Production of isotopes 90<A<210

Astrophysical site:
He-rich intershell of evolved red giants
AGB-stars 1-6 $M_\odot$

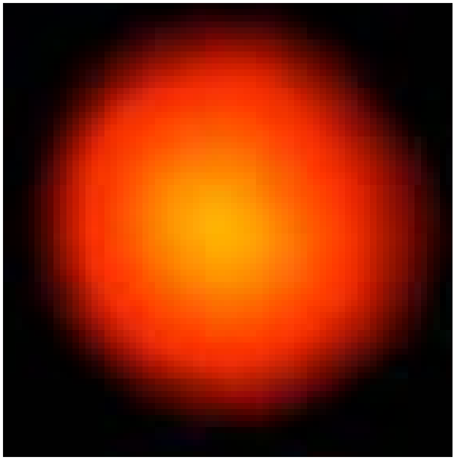


Neutron sources: $^{13}C(\alpha,n)$, $^{22}Ne(\alpha,n)$
Temp.: ~$1{\cdot}10^8$ K and ~$3{\cdot}10^8$
Neutron density: $4{\cdot}10^8$ cm$^{-3}$
Mass density: $6.5{\cdot}10^3$ g cm$^{-3}$



In future:
Convection times
Rotation
Magnetic fields

$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + n_n \cdot \langle \sigma v \rangle_A} = \frac{(\sigma \cdot N)_{Z+1}}{(\sigma \cdot N)_{Z+1,A+1}}$$



# weak component of s-process

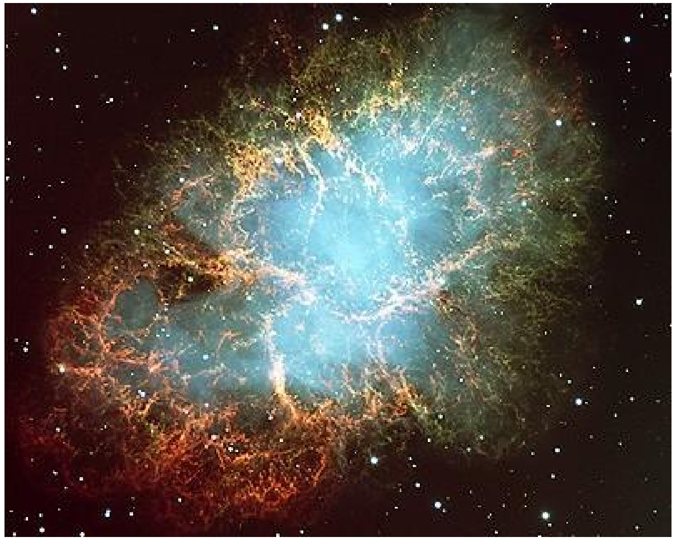
Responsible for production of isotopes A<90

Astrophysical site:
Massive stars >10 $M_\odot$

Core He-burning
Temp.: ~2-3·$10^8$ K (kT=25 keV)
Neutron density: ~1·$10^6$ $cm^{-3}$
Neutron source: $^{22}Ne(\alpha,n)$

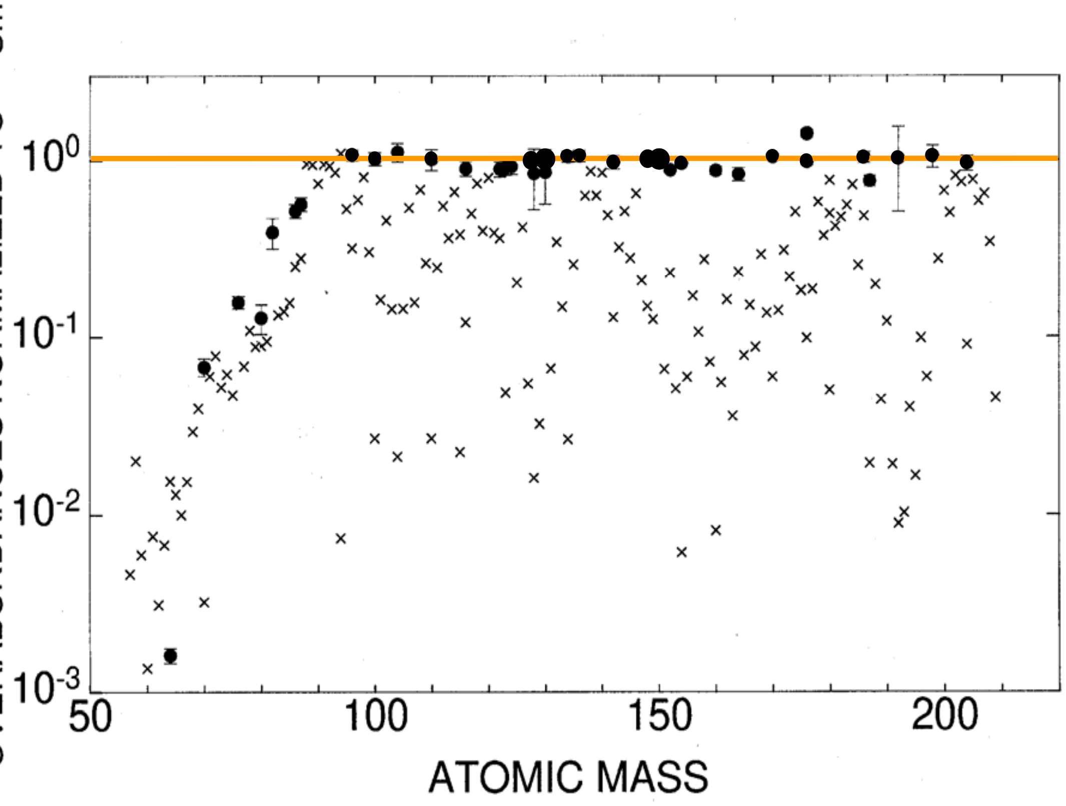
Shell C-burning
Temp.: ~1·$10^9$ K (kT=90 keV)
Neutron density: ~1·$10^{11}$ $cm^{-3}$
Neutron source: mainly $^{22}Ne(\alpha,n)$ but also $^{13}C(\alpha,n)$ and $^{17}O(\alpha,n)$ contribute

The weak s-process of massive stars is also related to explosive scenarios since it determines the composition of the progenitor.



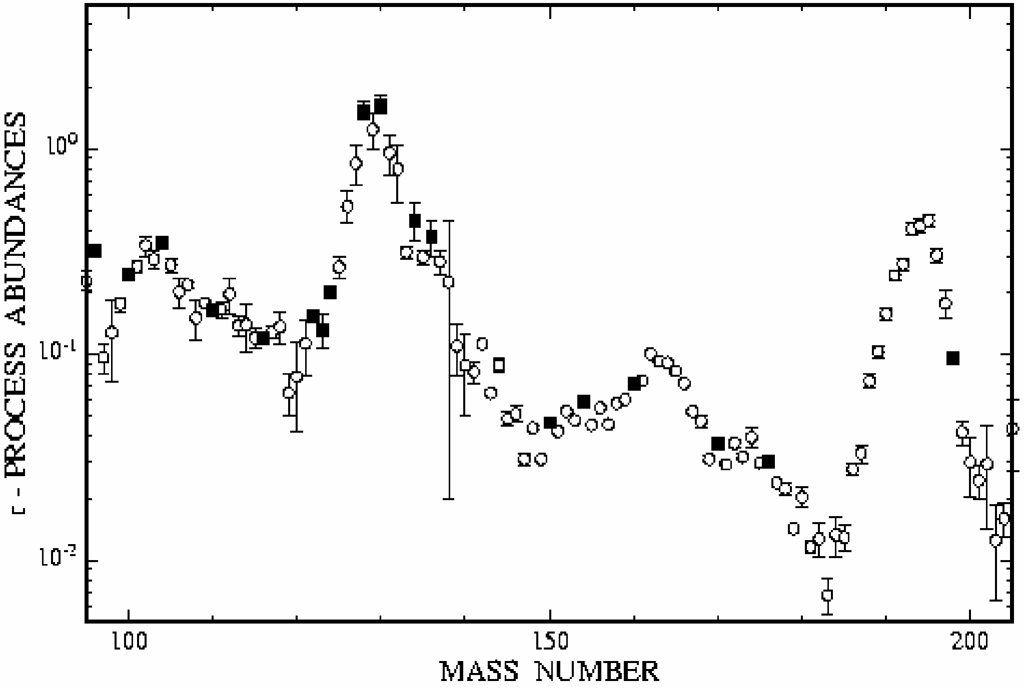
# The main s-process in AGB stars

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



r-residuals method

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

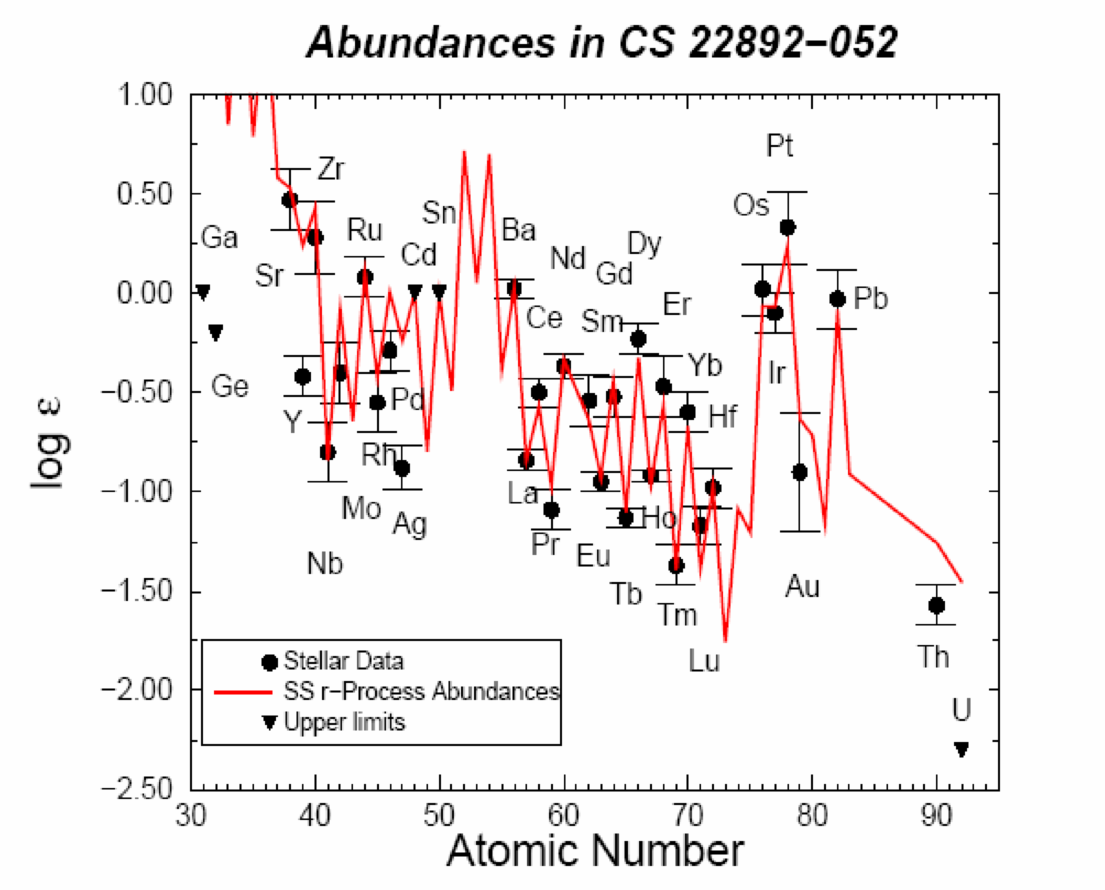


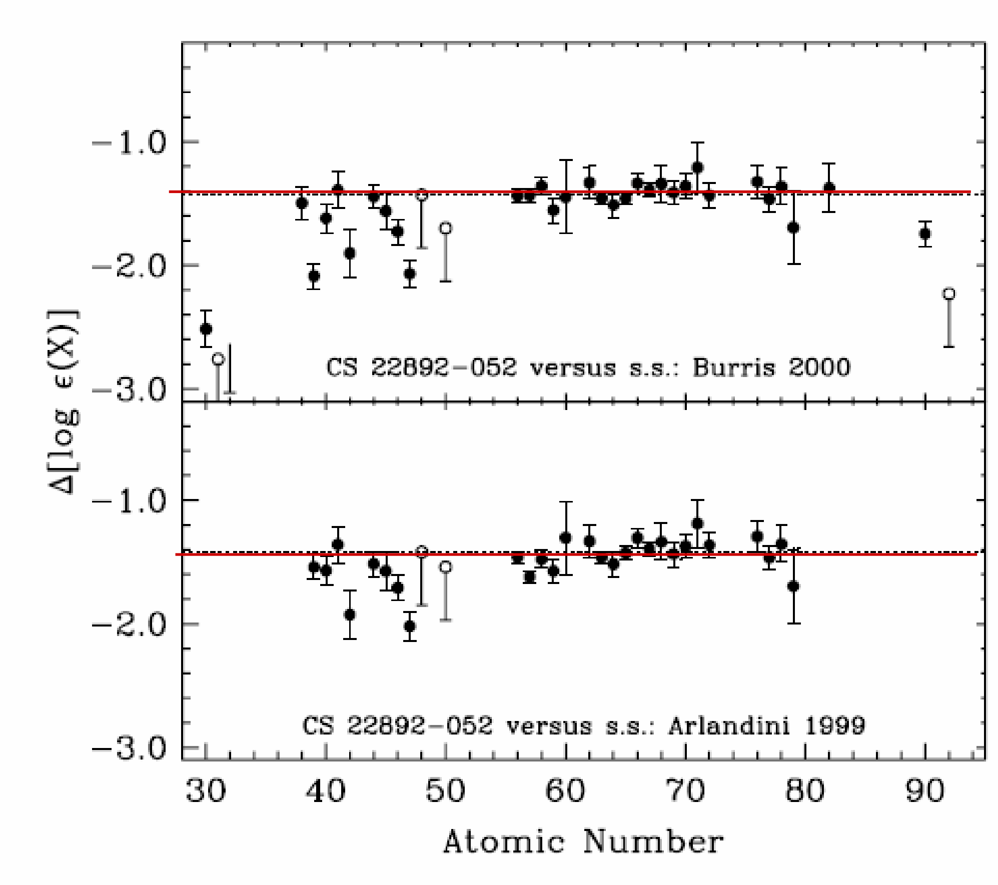
Arlandini et al. ApJ 525 (1999) 886

# Observation of metal-poor halo stars

Metal-poor halo stars should show pure r-abundances

Comparison of observed abundances and scaled $N_r$ $\left( \log \varepsilon(A) = \log\left(\frac{N_A}{N_H}\right) + 12\right.$





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

# Sum rule: s + p + r = 100 %

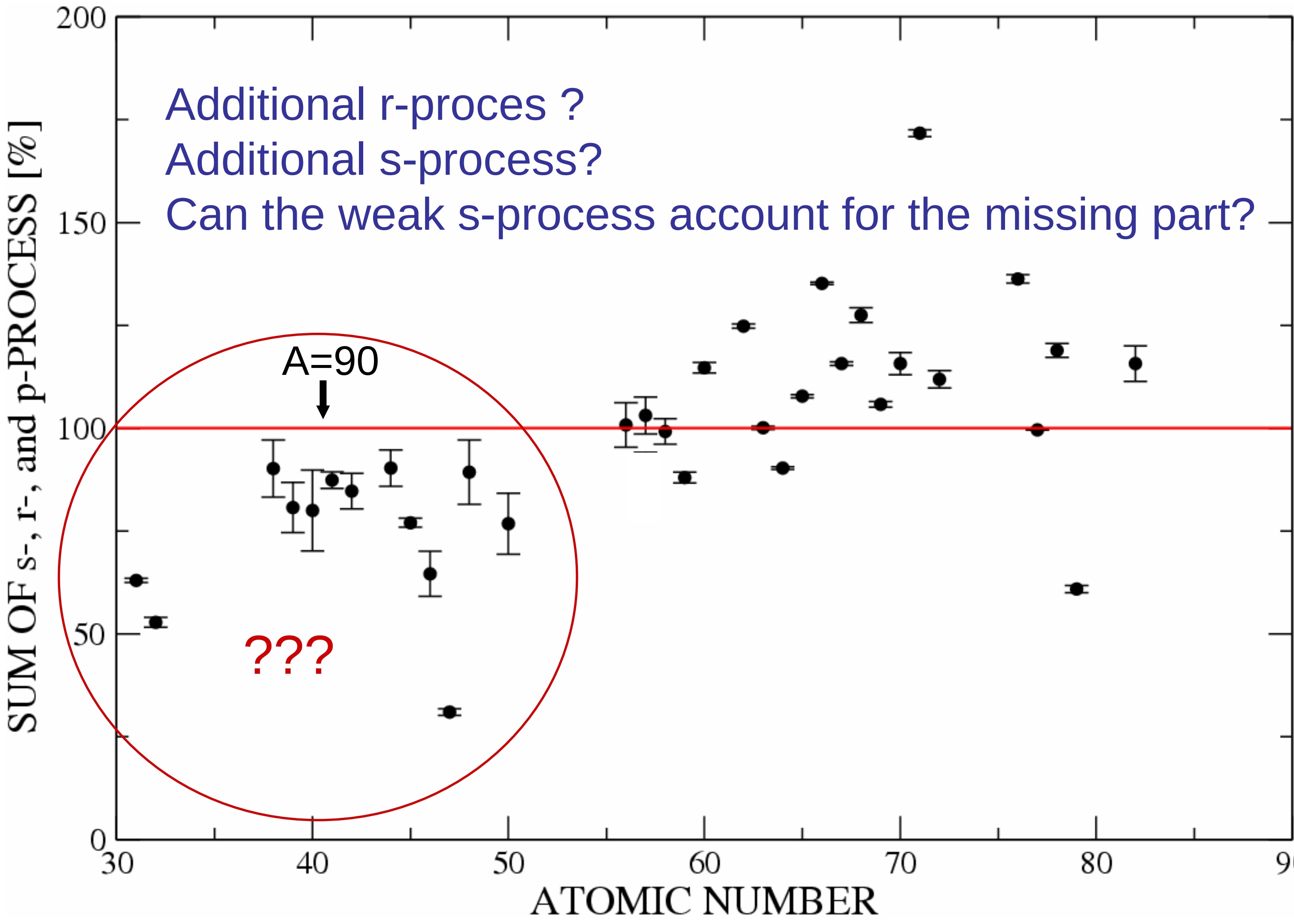
'eak s:
aiteri et al.
oJ 419 (1993) 207

ain s:
rlandini et al.
oJ 525 (1999) 886

alactic chemical evolution:
ravaglio et al.
oJ 601 (2004) 864

abundances from halo stars:
neden et al.,
o. J. 591 (2003) 936

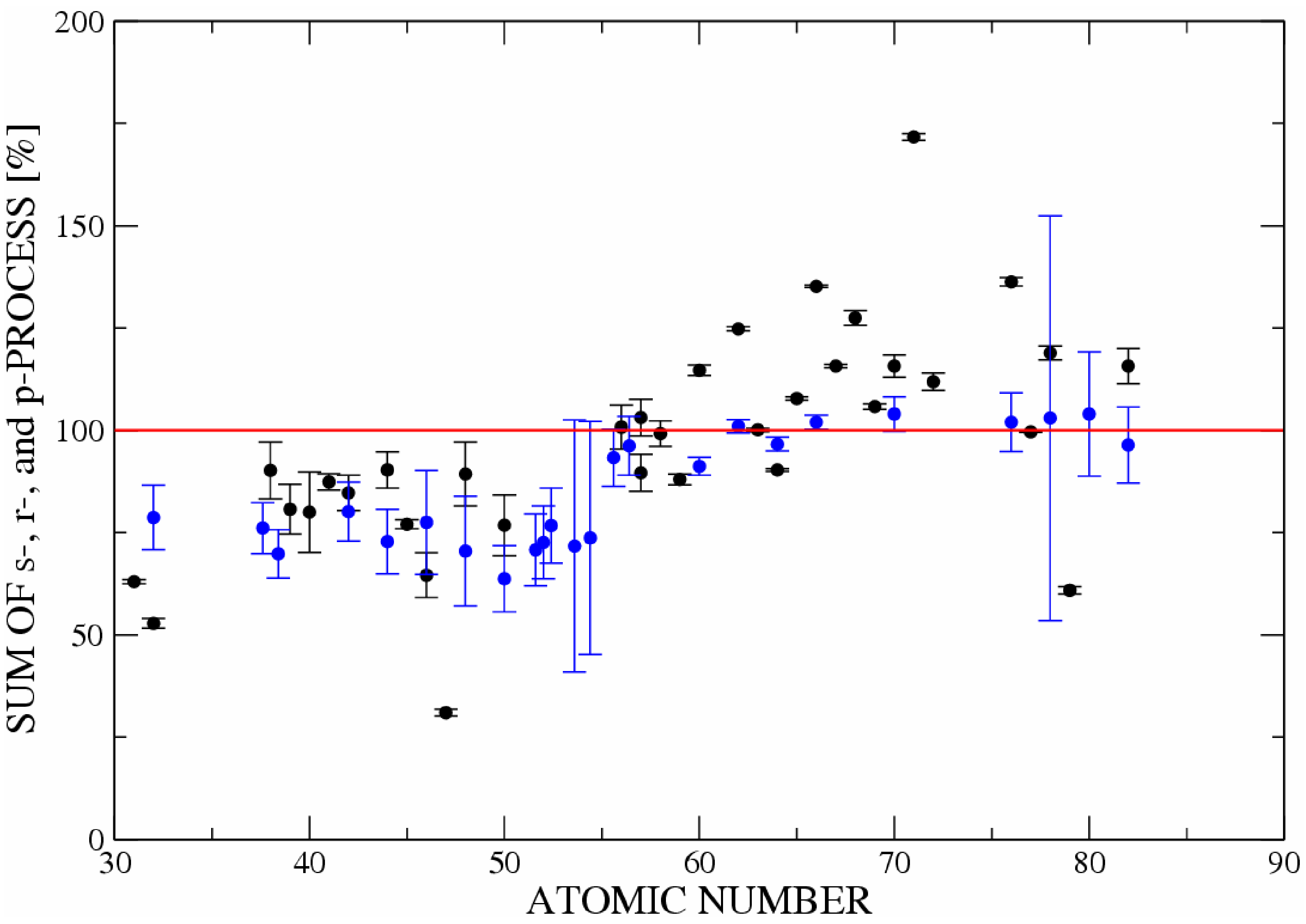
process:
o: 24 %
u: 7 %



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

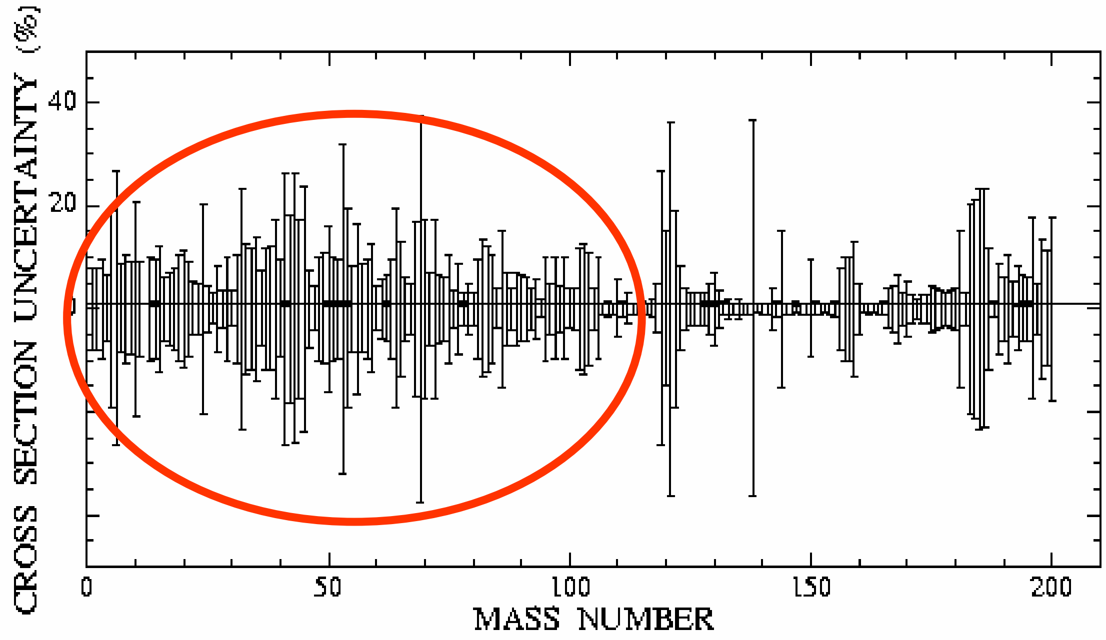
# Sum rule for s-only

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



# Challenges 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.



Challenges:

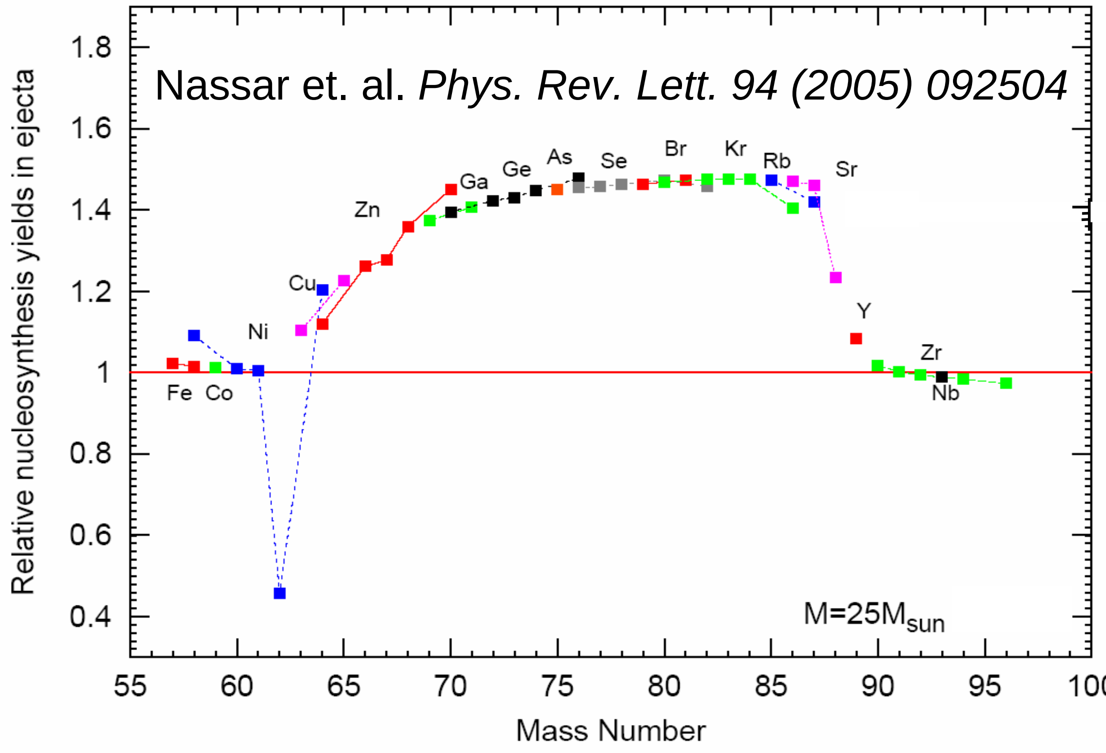
- small cross sections
- resonance dominated
- contributions from direct capture

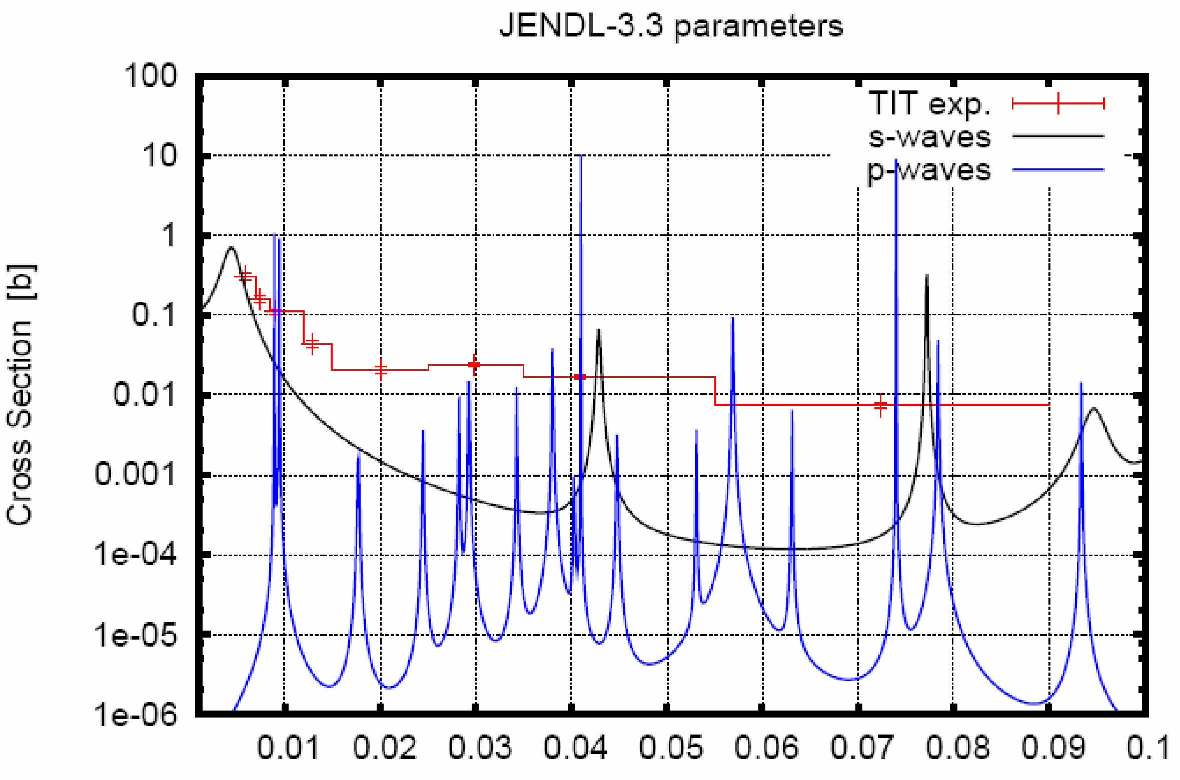
# Weak s-process – example $^{62}$Ni(n,γ)

Previous measurements vary between 12.5 mb and 36 mb at kT=30 keV

Recommended cross section:
(Bao et al.) at kT=30 keV: 12.5 ± 4 mb

New measurement 2005:
(FZK / Weizman Institute): 26.1 ± 2.5 mb

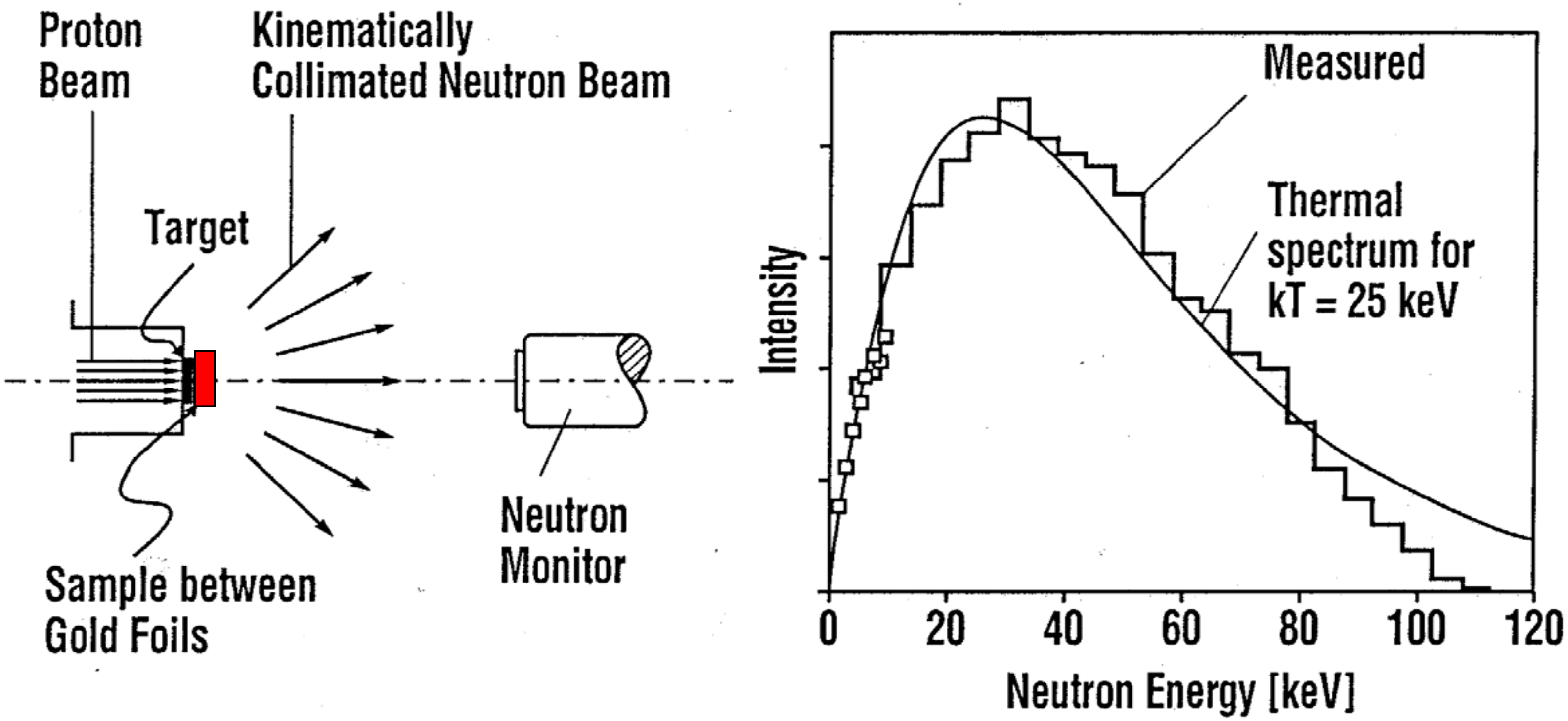




Story is not over:
N. Tomyo et. al. 2005: 37.0 ± 3.2 mb

# Activation technique at kT=25 keV

- Neutron  production via $^{7}$Li(p,n) reaction at a proton energy of 1991 keV.
- Induced activity can be measured after irradiation with HPGe detectors.
- Result: MACS at kT=25 keV



- High sensitivity -> small sample masses or small cross sections
- Use of natural samples possible, no enriched sample necessary
- Direct capture component included

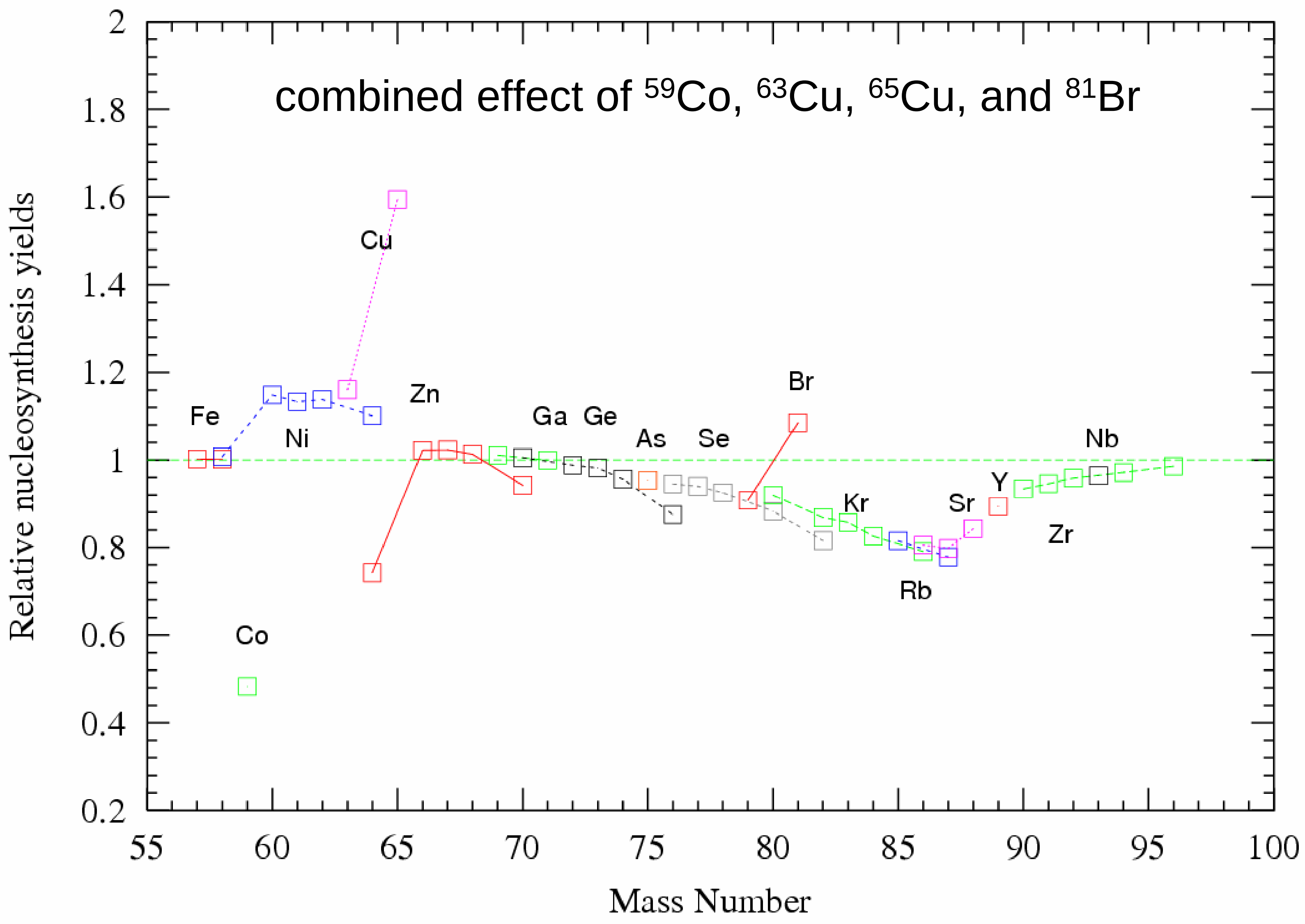
# Results

| 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 |

Many cross sections are a factor 2 lower than previously reported and far outside the quoted uncertainties

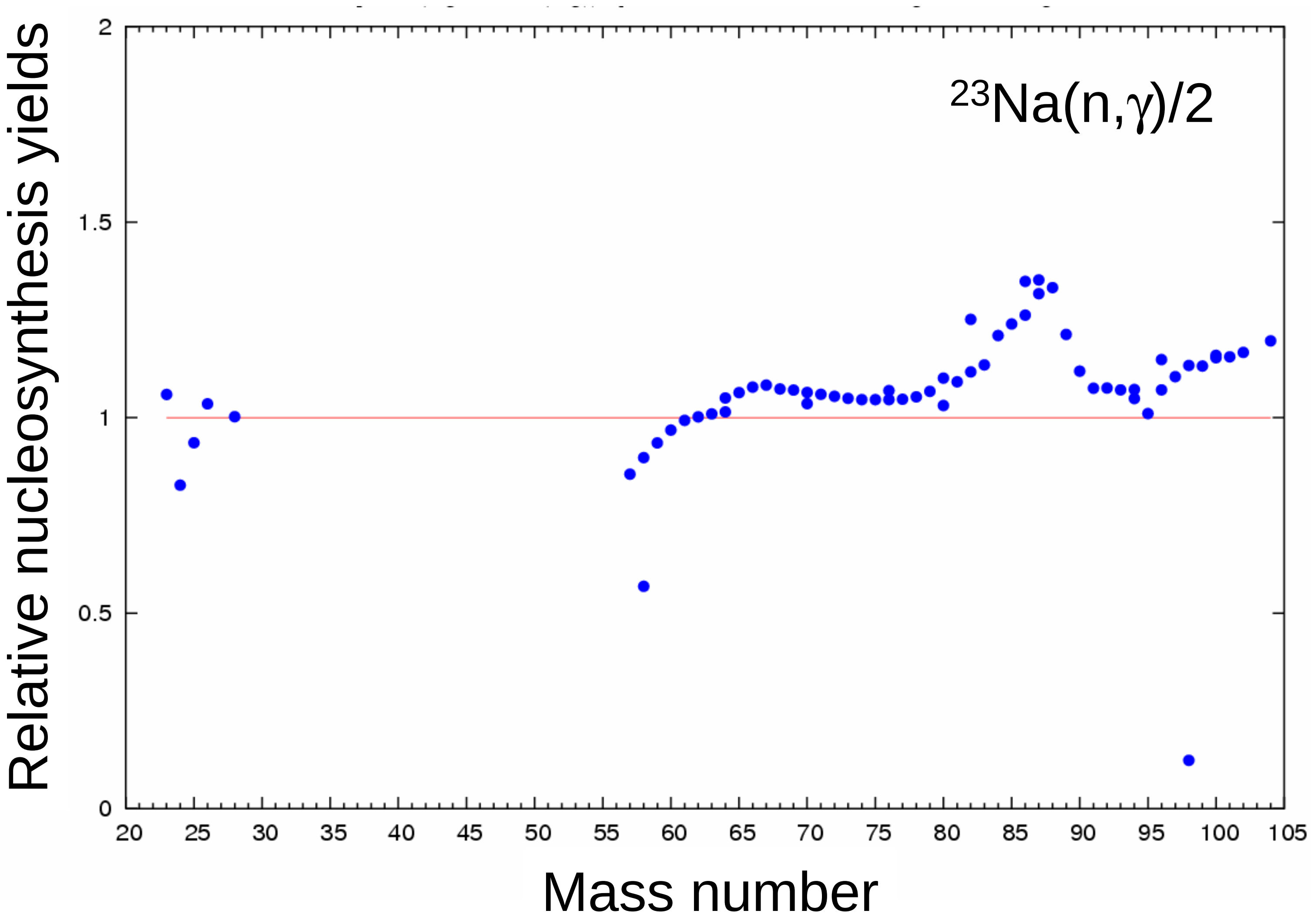
# Results – weak s-process abundances

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



# Effect of neutron poisons

- Neutron poisons effect the neutron balance
  e.g. $^{16}O(n,\gamma)$, $^{12}C(n,\gamma)$, $^{23}Na(n,\gamma)$, $Mg(n,\gamma)$ …



# Limitations of the activation method

- Activation measurements are restricted to unstable product nuclei.

- Stellar neutron spectra can only be produced for thermal energies of
  kT=25 keV using $^{7}$Li(p,n)
  kT= 5 keV using $^{18}$O(p,n)
  kT= 52 keV using $^{3}$H(p,n)

- The weak s-process takes place during core He-burning at kT=25 keV but also during C-shell burning at kT=90 keV.

- Extrapolation of MACS measured at kT=25 keV to kT=90 keV cause systematic uncertainties.

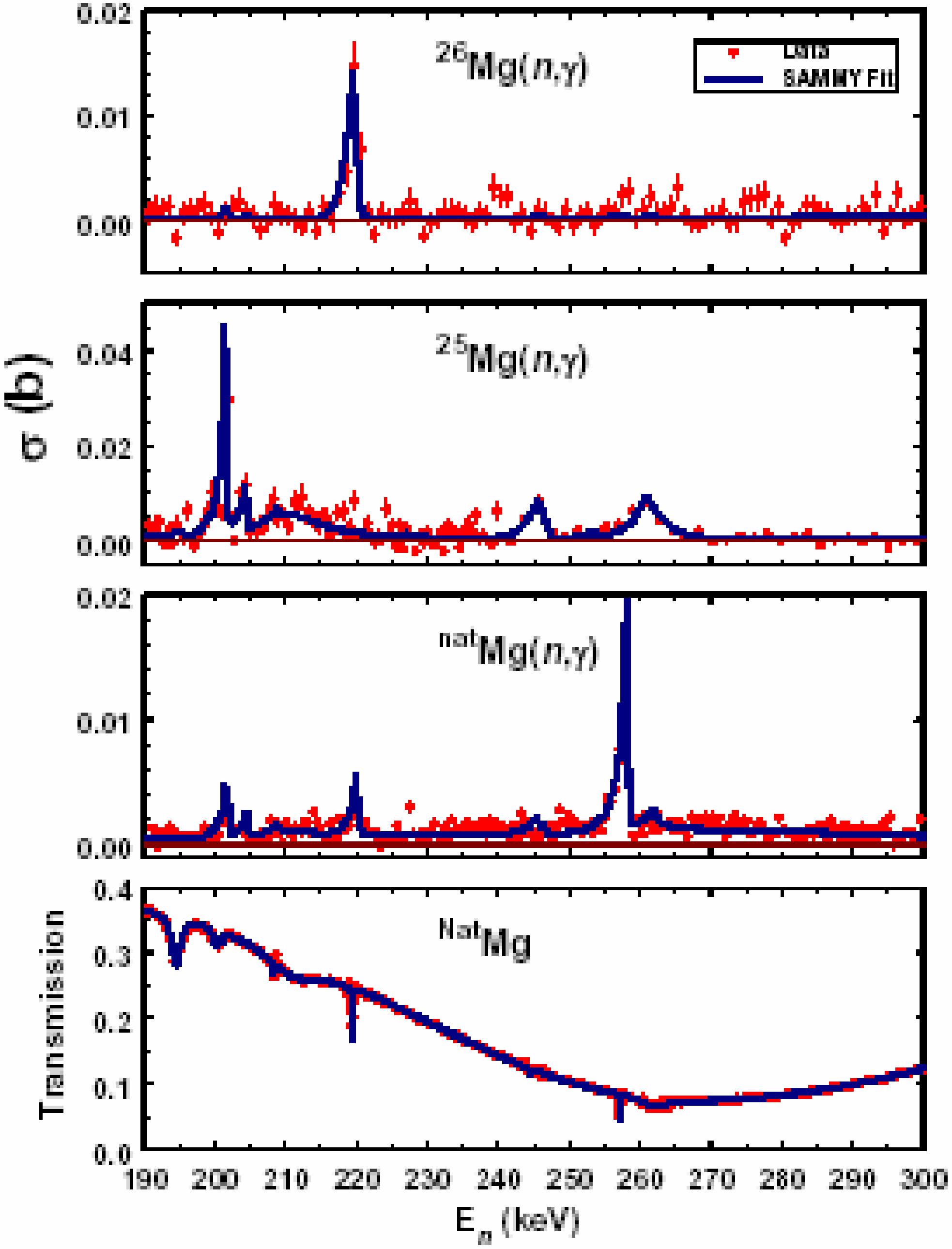
-> We need TOF measurements between 1 keV and 500 keV.

# (n,γ)-measurements at n_TOF

• Cross sections are small (~μbarn)
-> high neutron flux, low background

• Cross sections are resonance dominated
-> good energy resolution

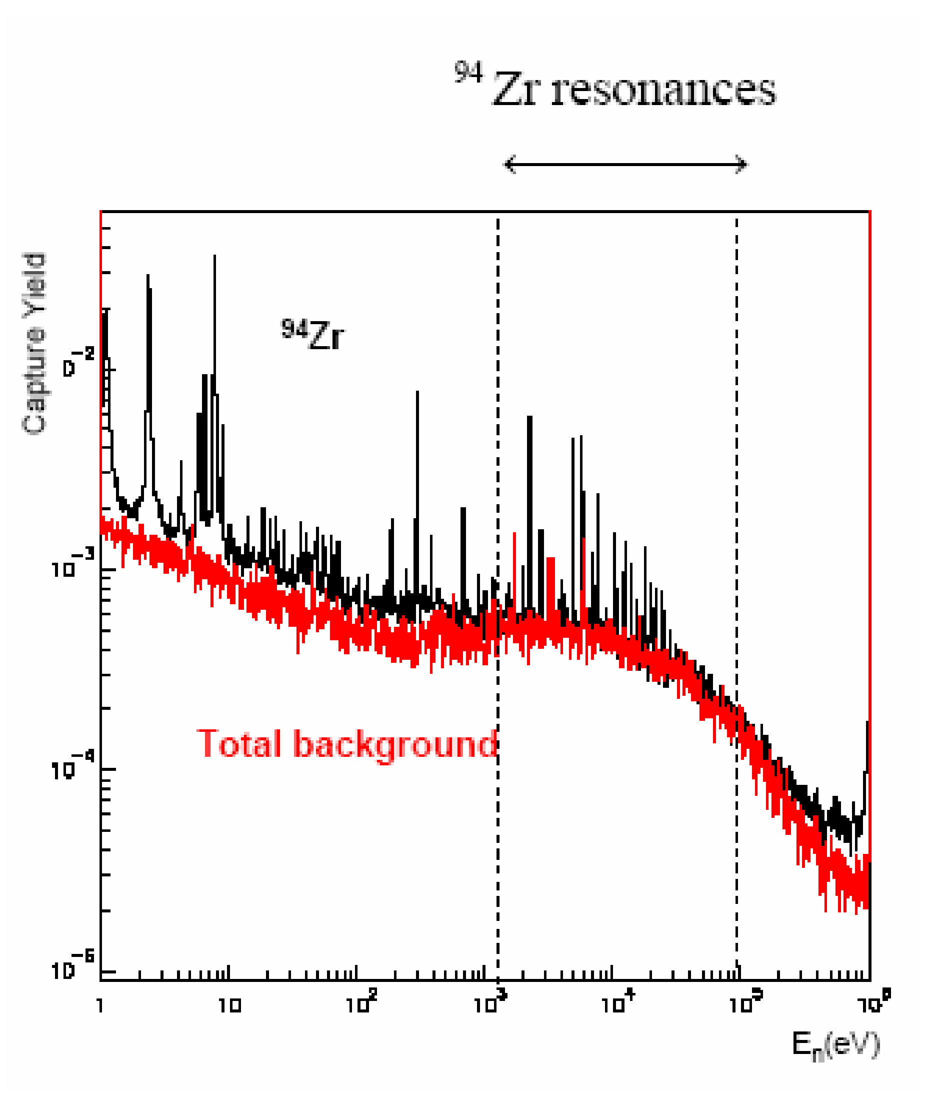
**n_TOF is an ideal facility to measure neutron capture cross sections of nuclei with small cross sections.**



Measurement of Mg isotopes at n_TOF

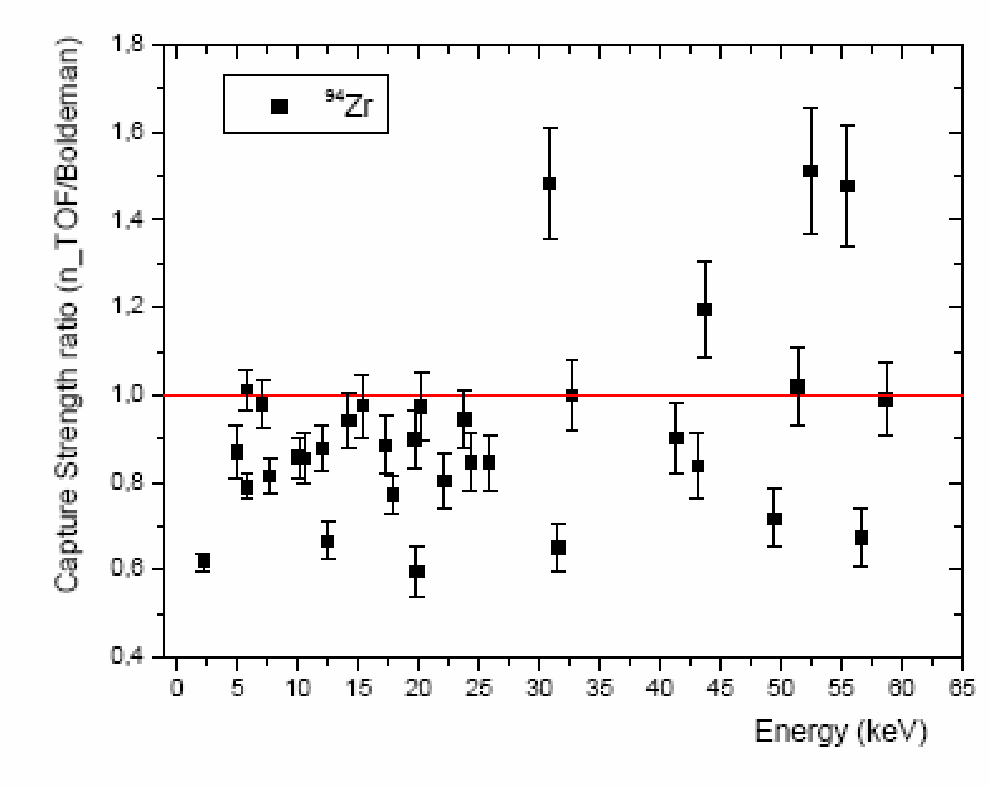
# (n,$\gamma$)-measurements at n_TOF

Measurement of Zr isotopes at n_TOF



L. Marques, et al. - The n_TOF Collaboration

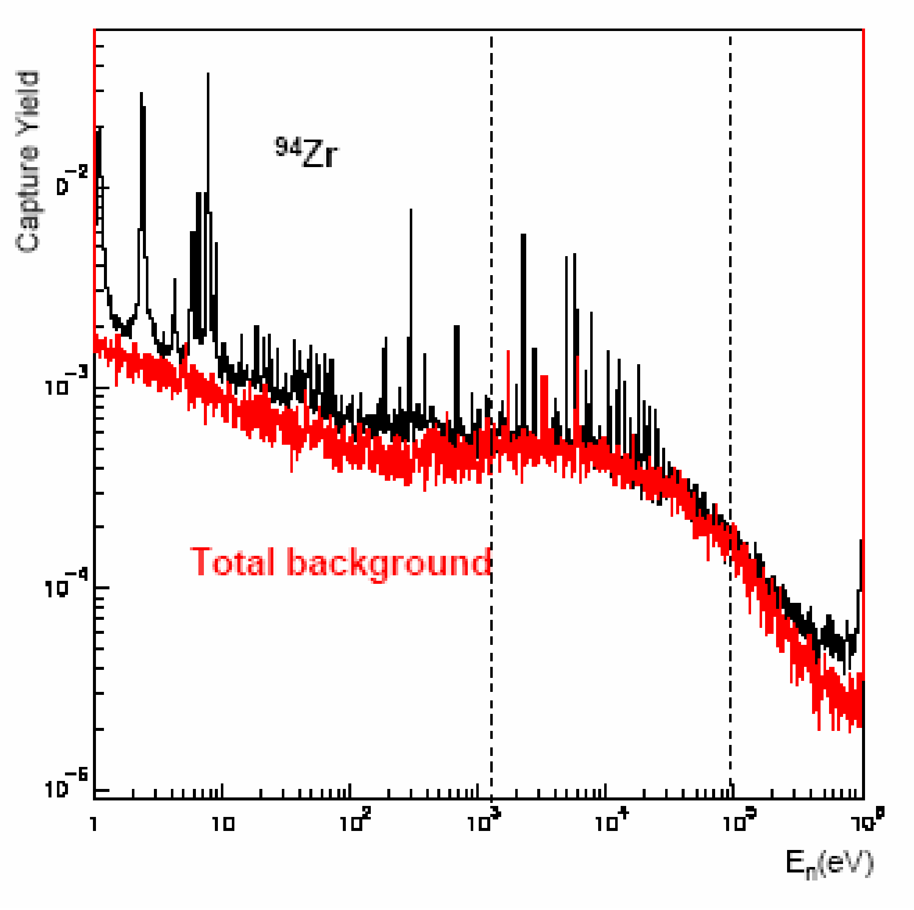
The extracted resonance parameters compared with a previous measuremen



Previous experiments often underestimated the background contribution from scattered neutrons.

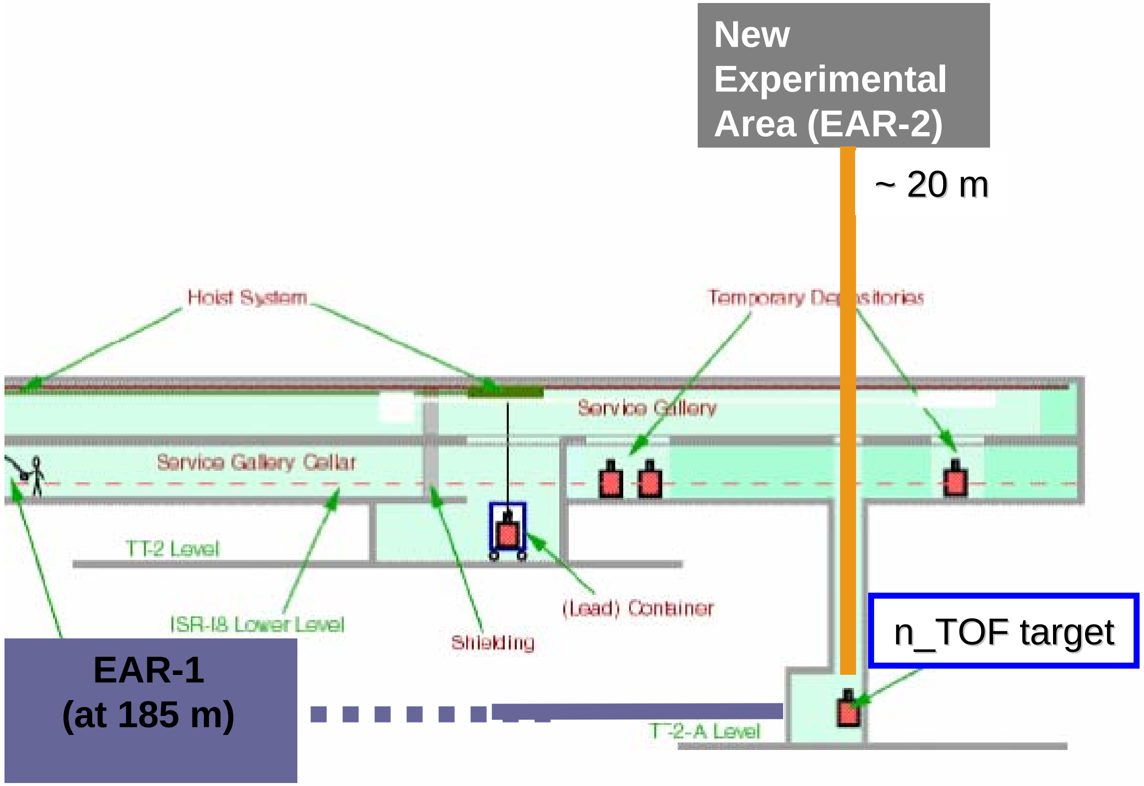
# Improvements at n_TOF

## Less background



Inbeam γ-background
must be reduced

## More neutron flux



A second flight path (20 m) will increase
neutron flux by a factor 100 and double
the beam time.

# Future measurements

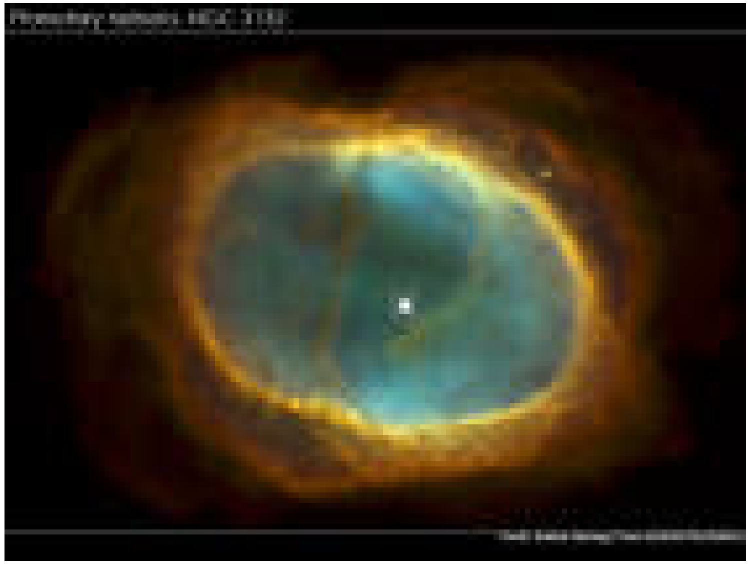
- Isotopes relevant for the weak s-process, e.g. Ni isotopes
- Neutron poisons, e.g. $^{16}$O(n,$\gamma$)
- Light isotopes of relevance for stellar grains, e.g. Ca isotopes

small cross sections

- Radioactive isotopes for the weak s-process, e.g. $^{63}$Ni, $^{107}$Pd
- Branch points, e.g. $^{147}$Pm, $^{179}$Ta

small sample masses

# Conclusions



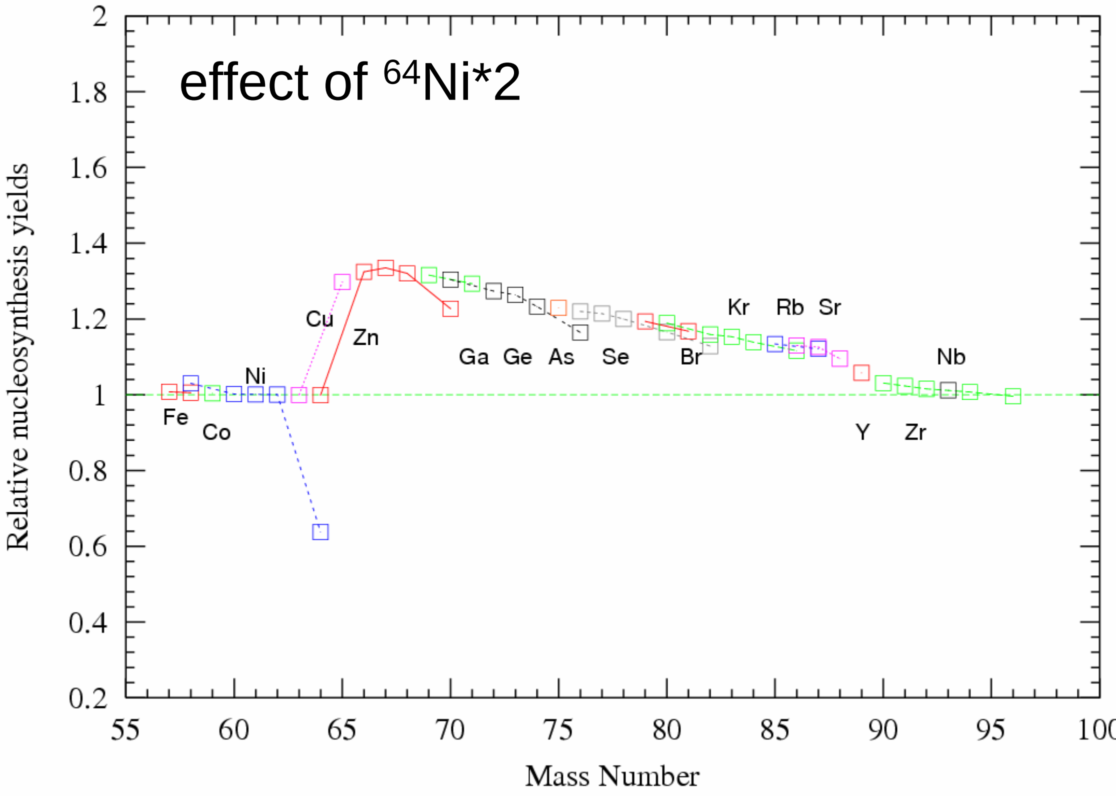
- Neutron capture cross sections are indispensable for the understanding of nucleosynthesis

- Many neutron capture cross sections are needed with higher accuracy or in a wider energy range.

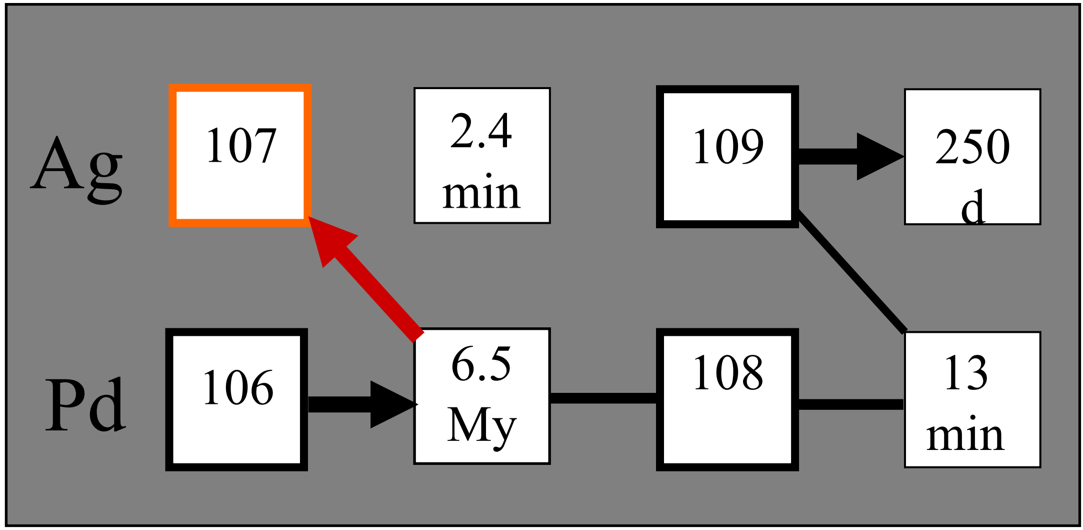
- n_TOF at CERN is an ideal place to measure small neutron capture cross sections as well as cross sections of radioactive targets where only small sample masses are tolerable.

# Future measurements

- $^{64}$Ni(n,γ)
- $^{58}$Fe(n,γ)
- Zn
- Ga
- Ge (no data)
- Se (no data)

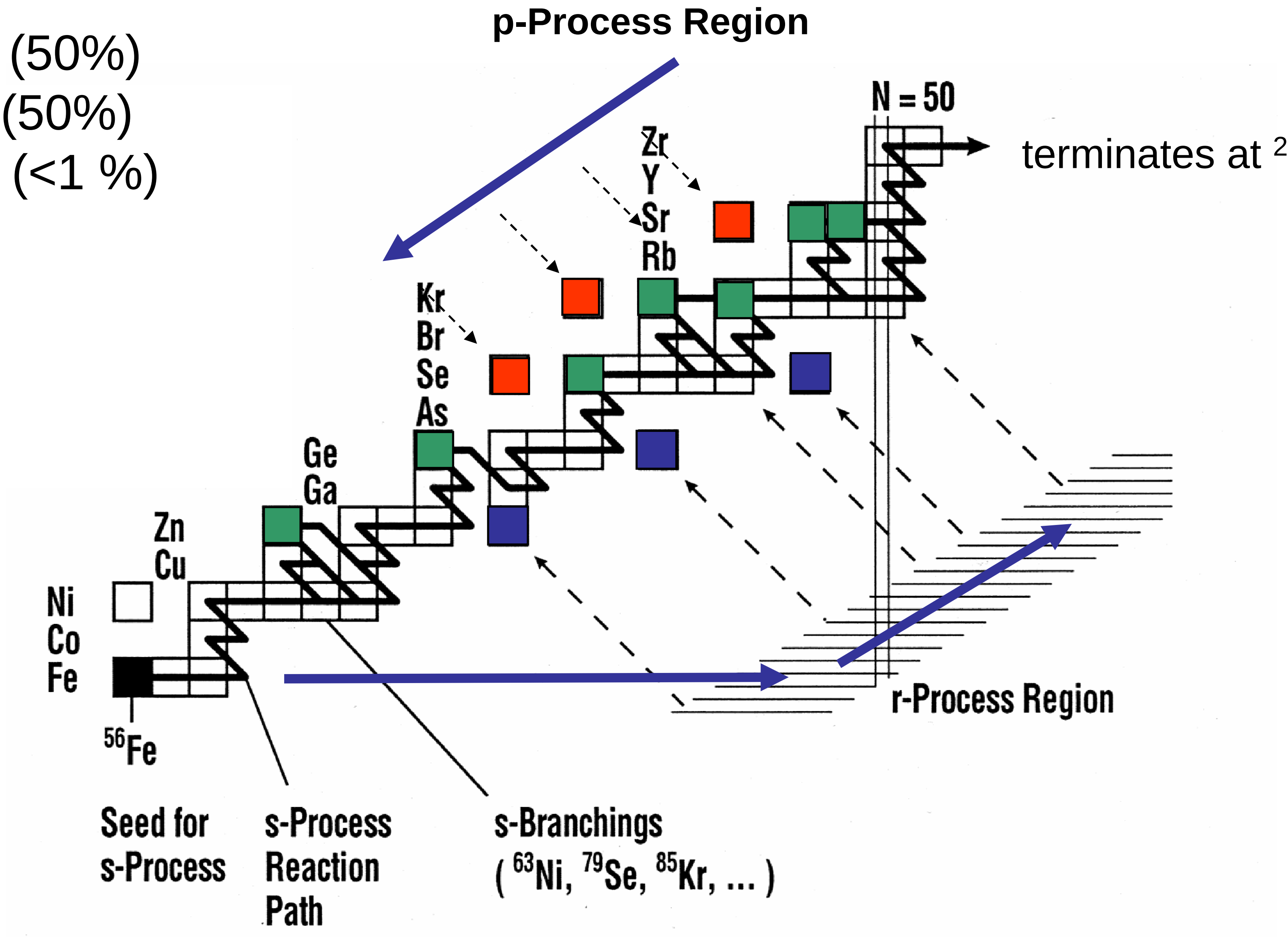


- $^{107}$Pd(n,γ)



# Nucleosynthesis of the heavy elements

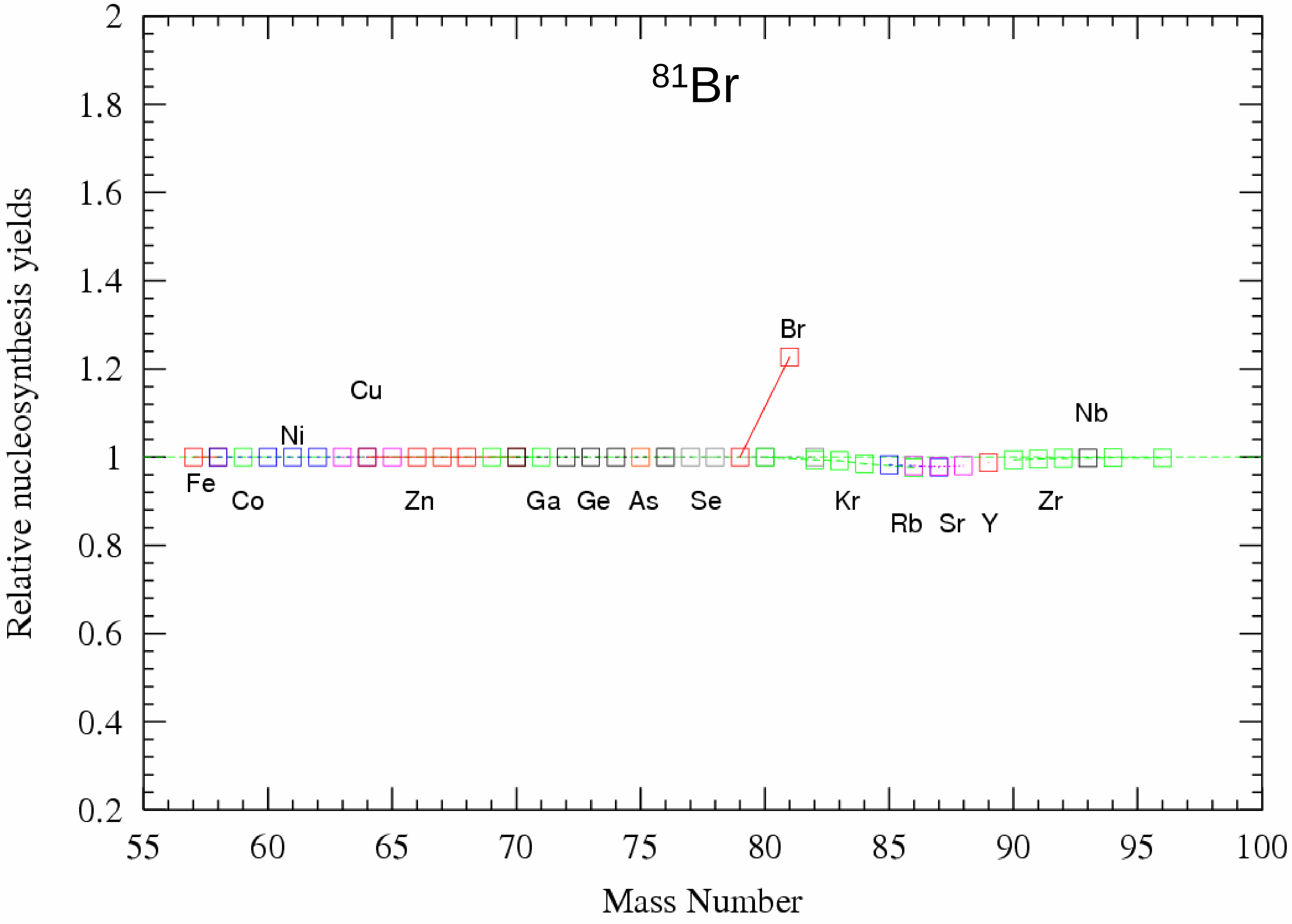
- s process (50%)
- r process (50%)
- p process (<1 %)



🟥 p-only
🟩 s-only
🟦 r-only

# Results – weak s-process abundances

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



Stellar model calculations performed by Marco Pignat