Neutrons at CERN n_TOF: A window to stellar evolution and nucleosynthesis

- (Astro)Physics case for neutron cross section measurements
- Example of measurements performed so far at n_TOF
- The present experimental plan
- New opportunities with a second experimental beam-line

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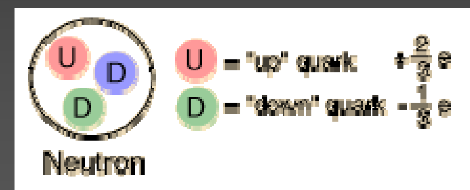
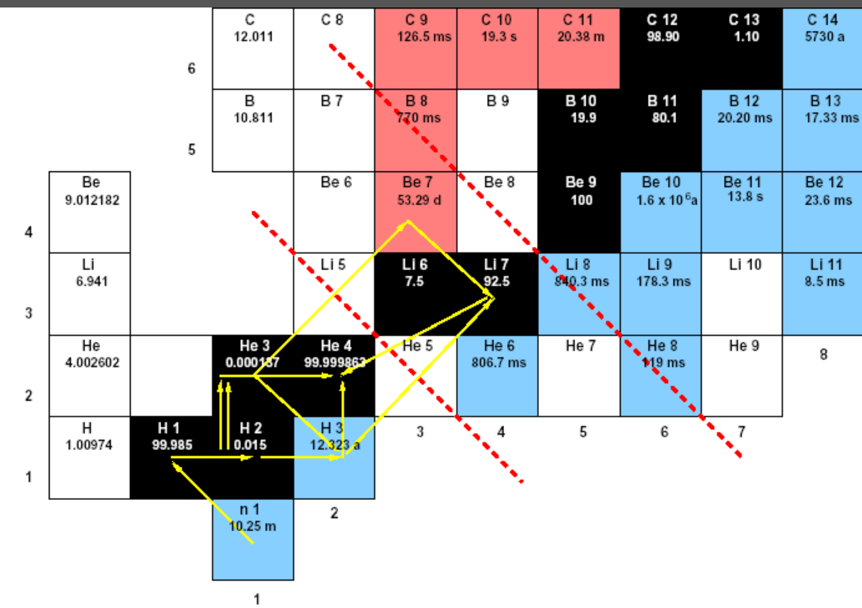
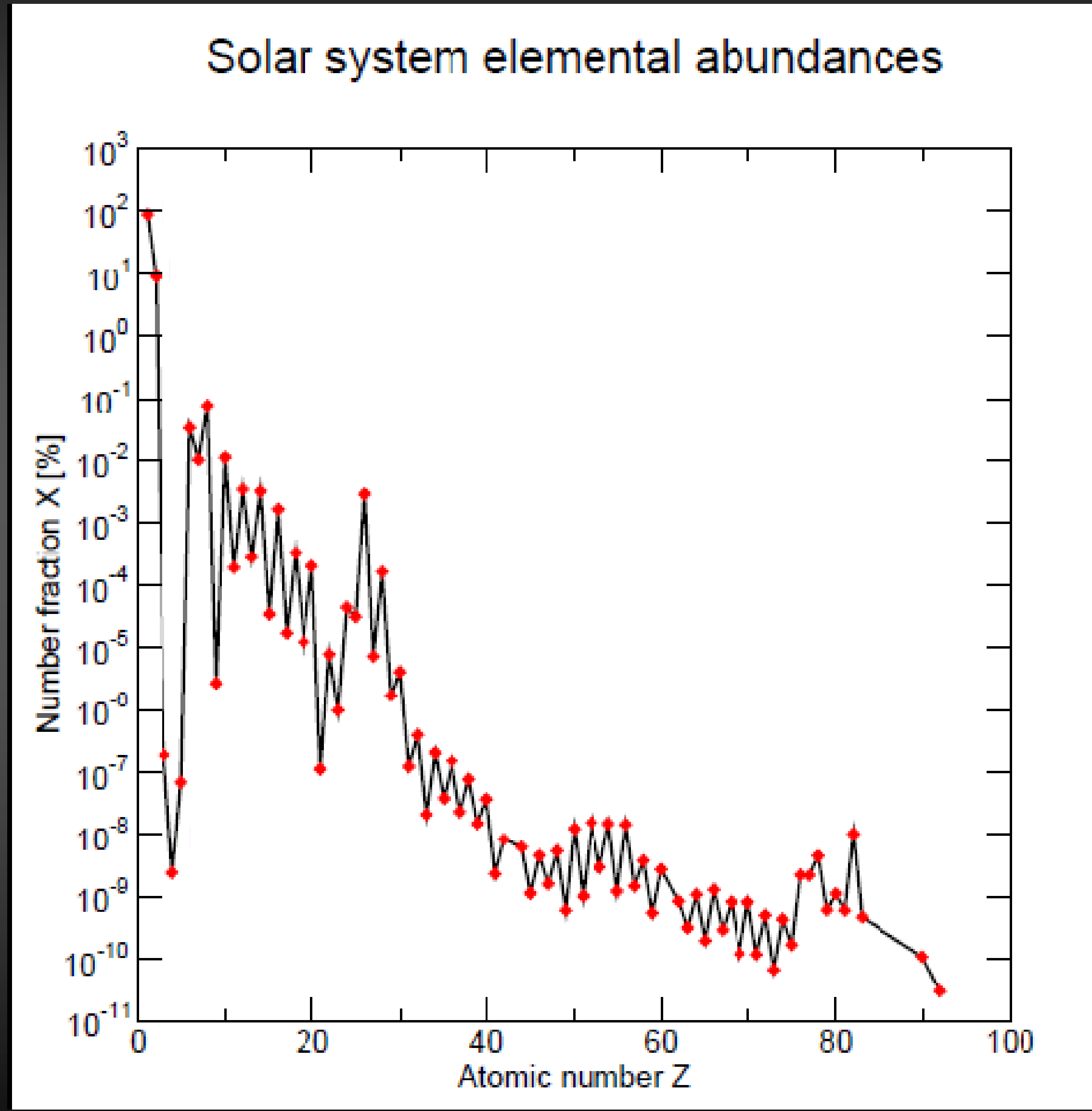
Why neutrons in astrophysics?

e-charge : 0
mass : 940 MeV
half-life : 10 min



Nucleosynthesis of the Elements

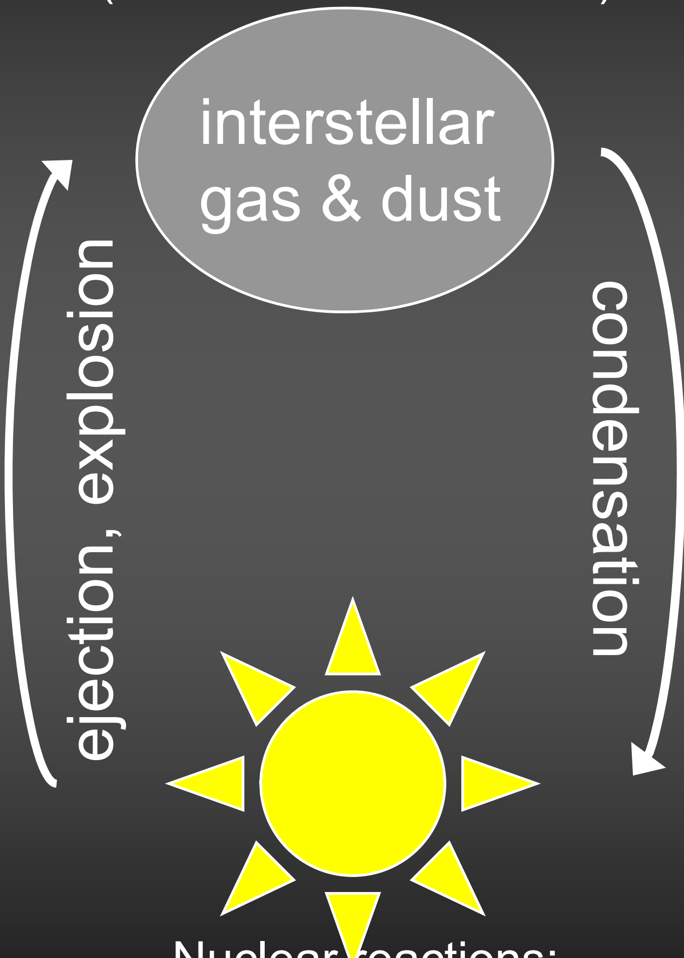




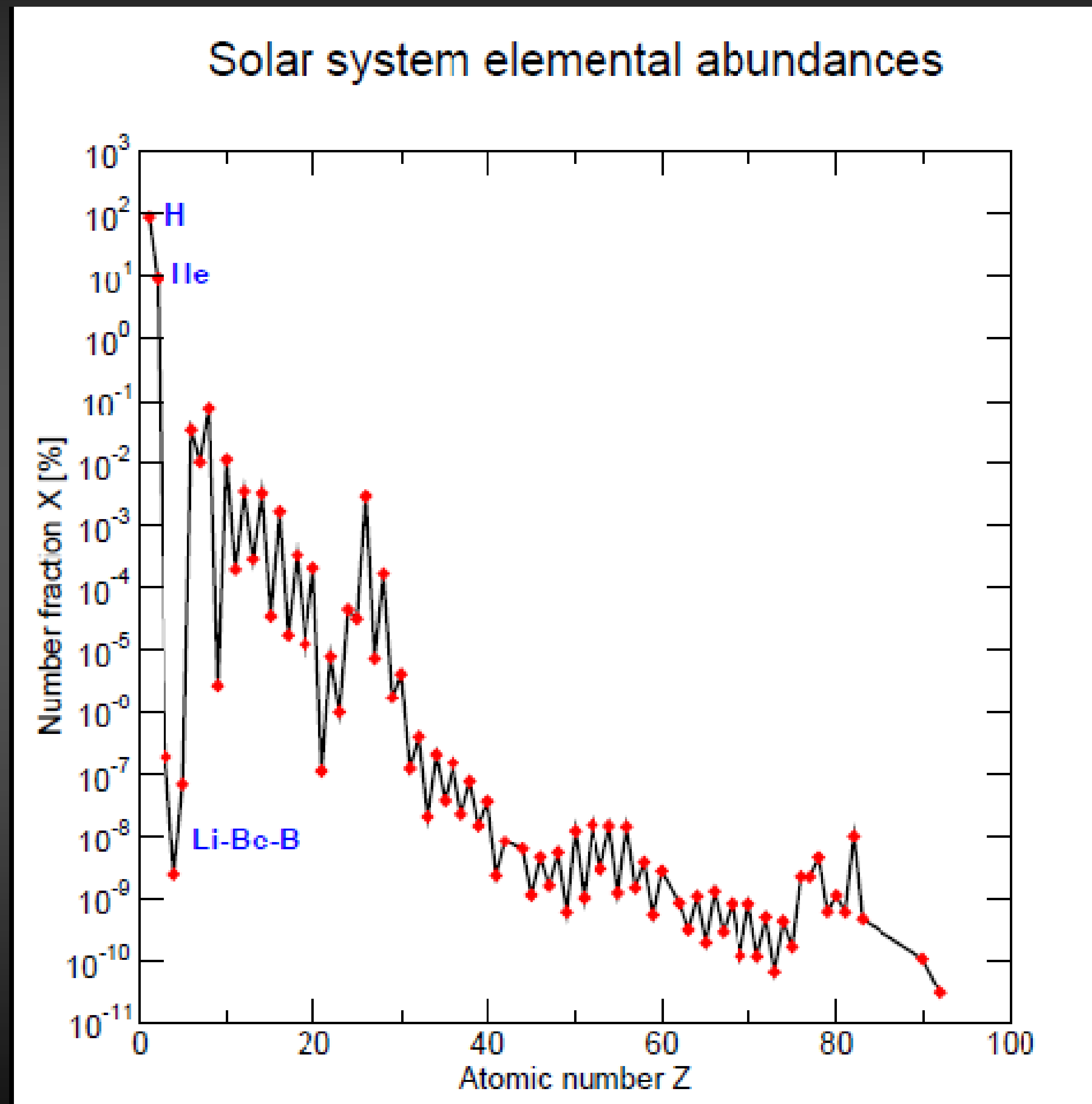
Abundances: Anders and Grevesse, 1989

Nucleosynthesis of the Elements

Mixing
(abundance distribution)



Nuclear reactions:
- energy generation
- nucleosynthesis

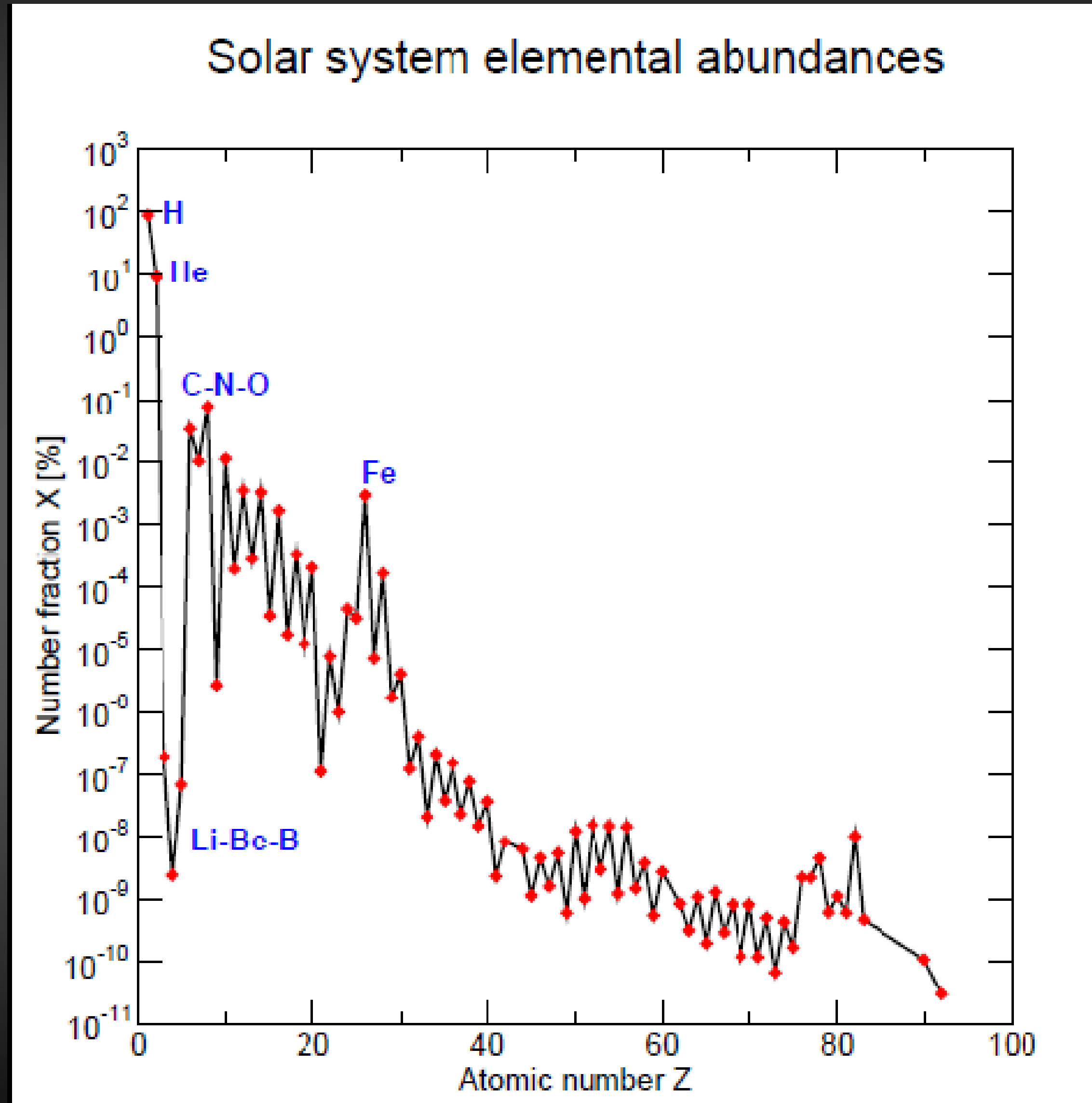


Abundances: Anders and Grevesse, 1989

Nucleosynthesis of the Elements

All chemical elements beyond Iron are synthesized by neutron interactions in stars

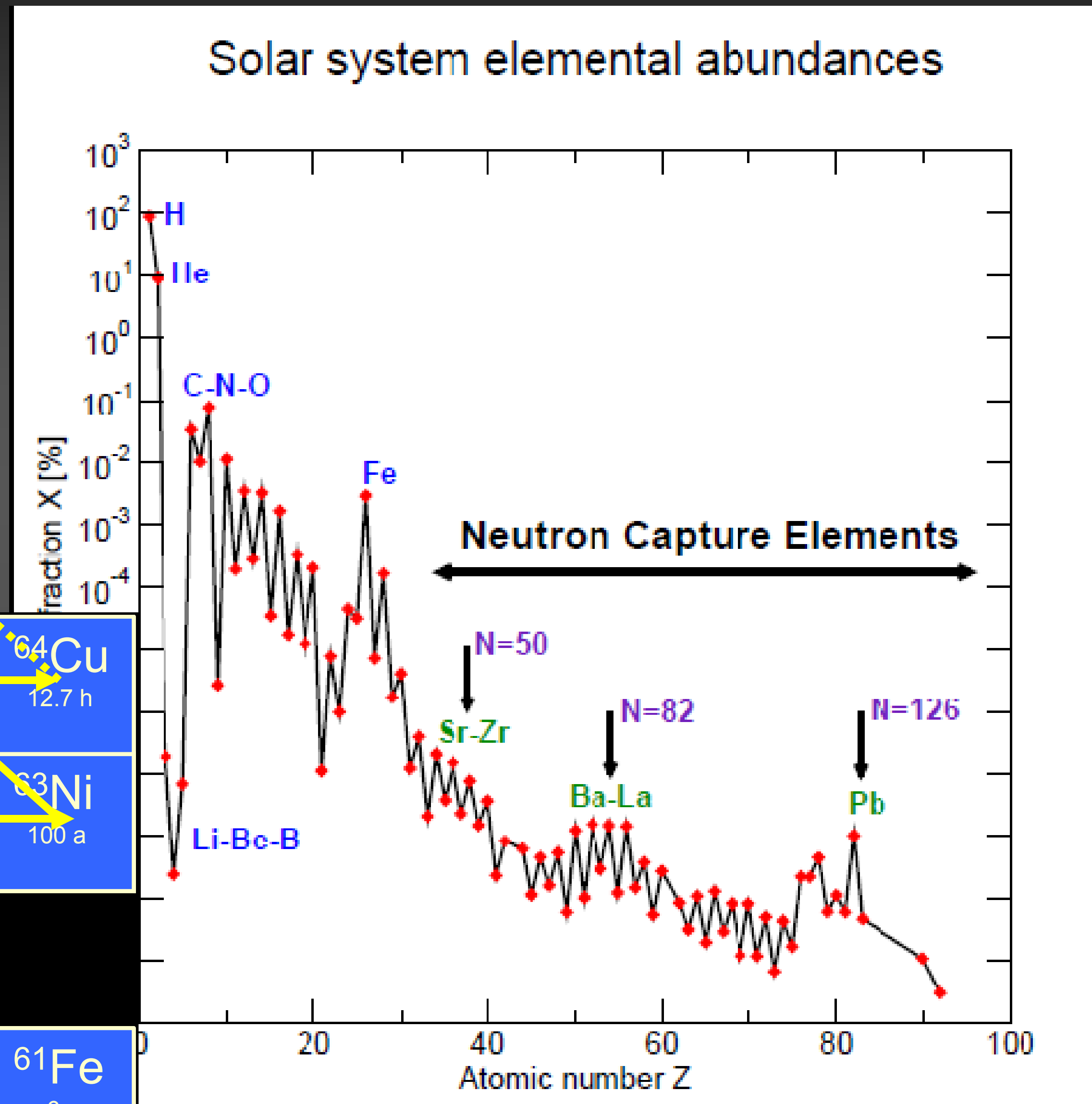
~ ½ by the s-process (red giants)
~ ½ by the r-process (explosive)

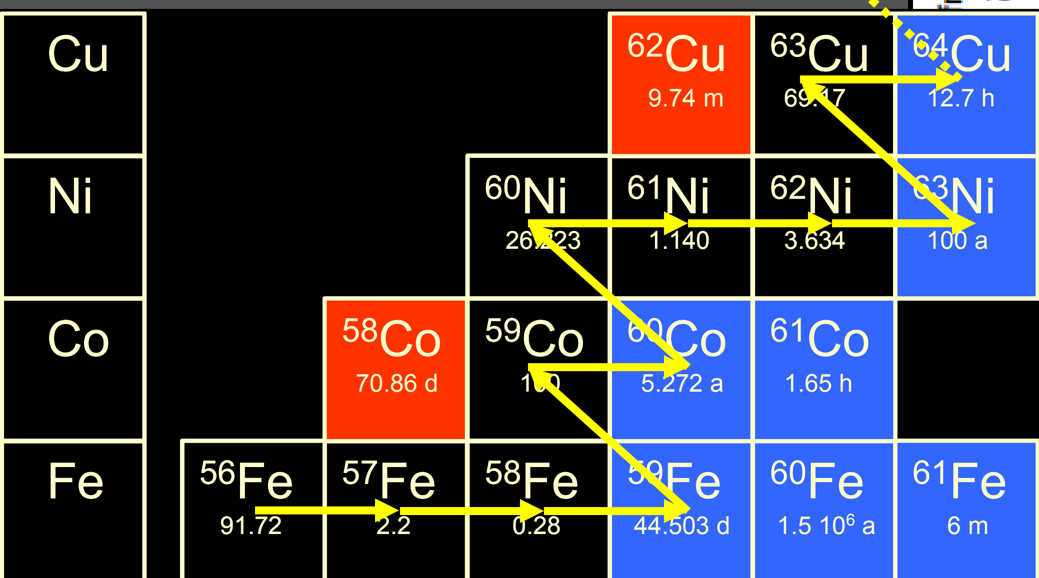


Abundances: Anders and Grevesse, 1989

Nucleosynthesis of the Elements

The canonical s-process





Abundances: Anders and Grevesse, 1989

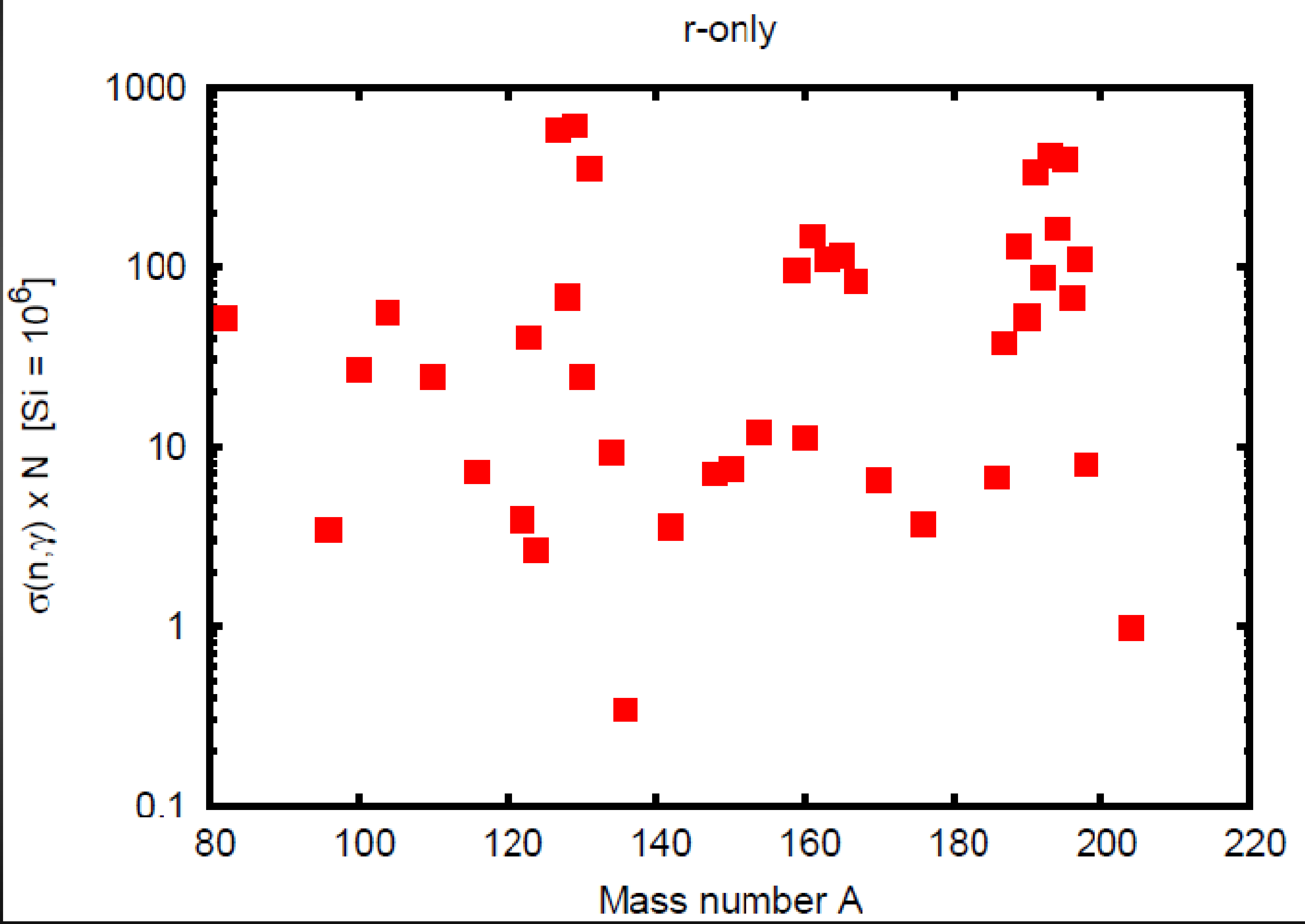
Neutron capture cross sections

reaction rate: $N_{\mathrm{A}}\, N_{\mathrm{n}} < \sigma_{\mathrm{n},\gamma}(E_n) \cdot v >_{kT}$

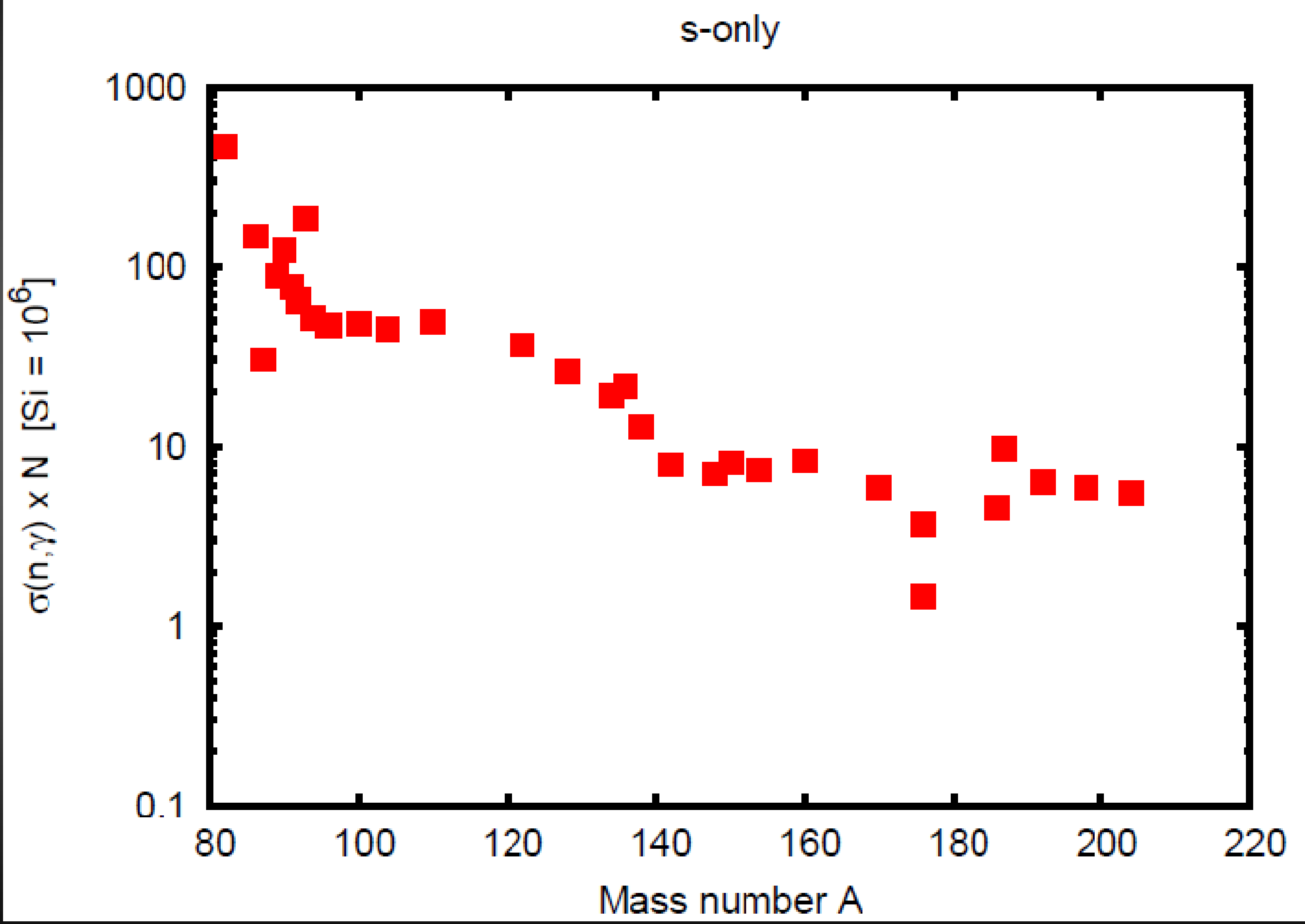
canonical s-process: $\sigma \cdot N_{\mathrm{A}} \sim const.$

key quantity: $\sigma_{\mathrm{n},\gamma}(E_n)$

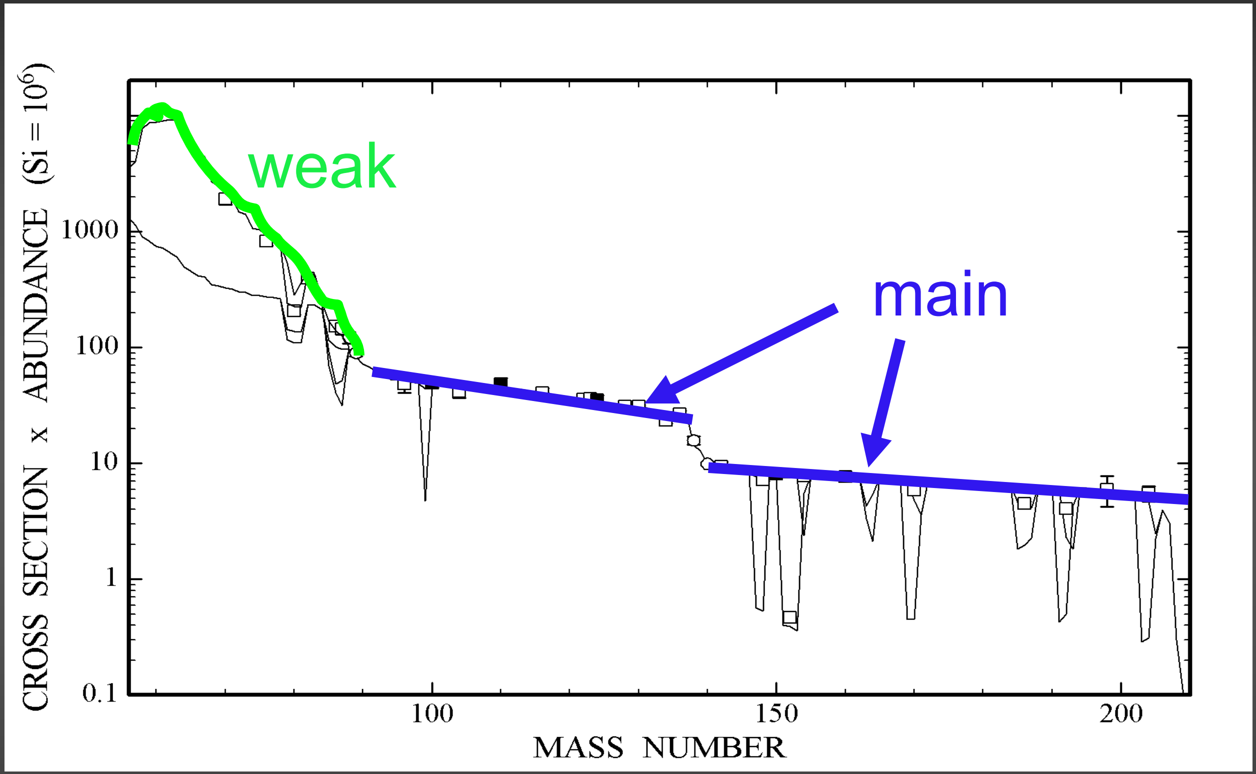
Neutron capture cross sections



Neutron capture cross sections



Neutron capture cross sections



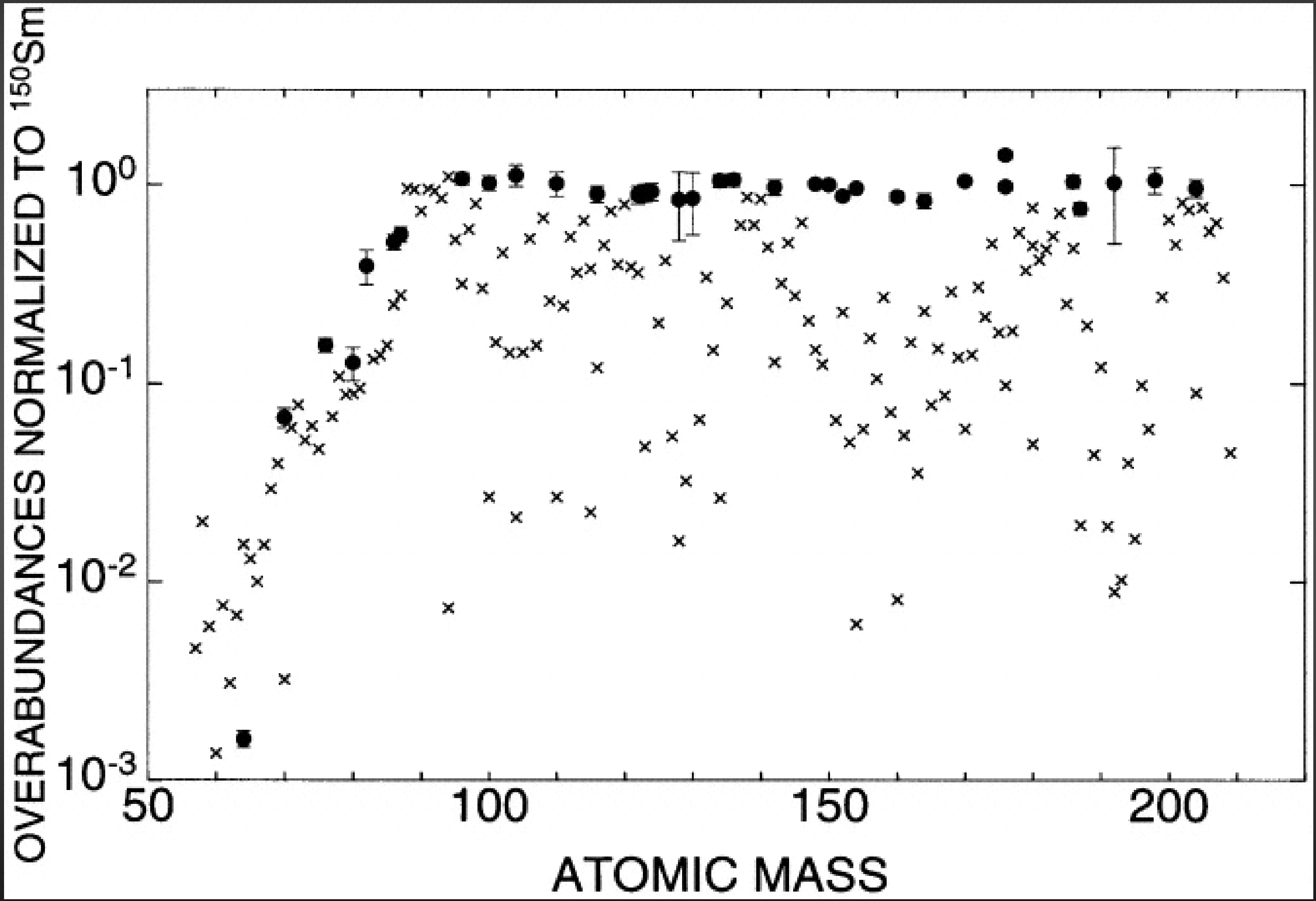
from phenomenological...

$$\langle\sigma\rangle_A N_A = \frac{\langle\sigma\rangle_{A-1} N_{A-1}}{1+1/\tau_0\langle\sigma\rangle_A} = \frac{f N_{56}}{\tau_0}\prod_{i=56}^{A}\left(1+\frac{1}{\tau_0\langle\sigma\rangle_i}\right)^{-1}$$

Neutron capture cross sections

... to detailed stellar modeling: TP-AGB

- $M = 2\ M_\odot$
- $Z = 0.5\ Z_\odot$

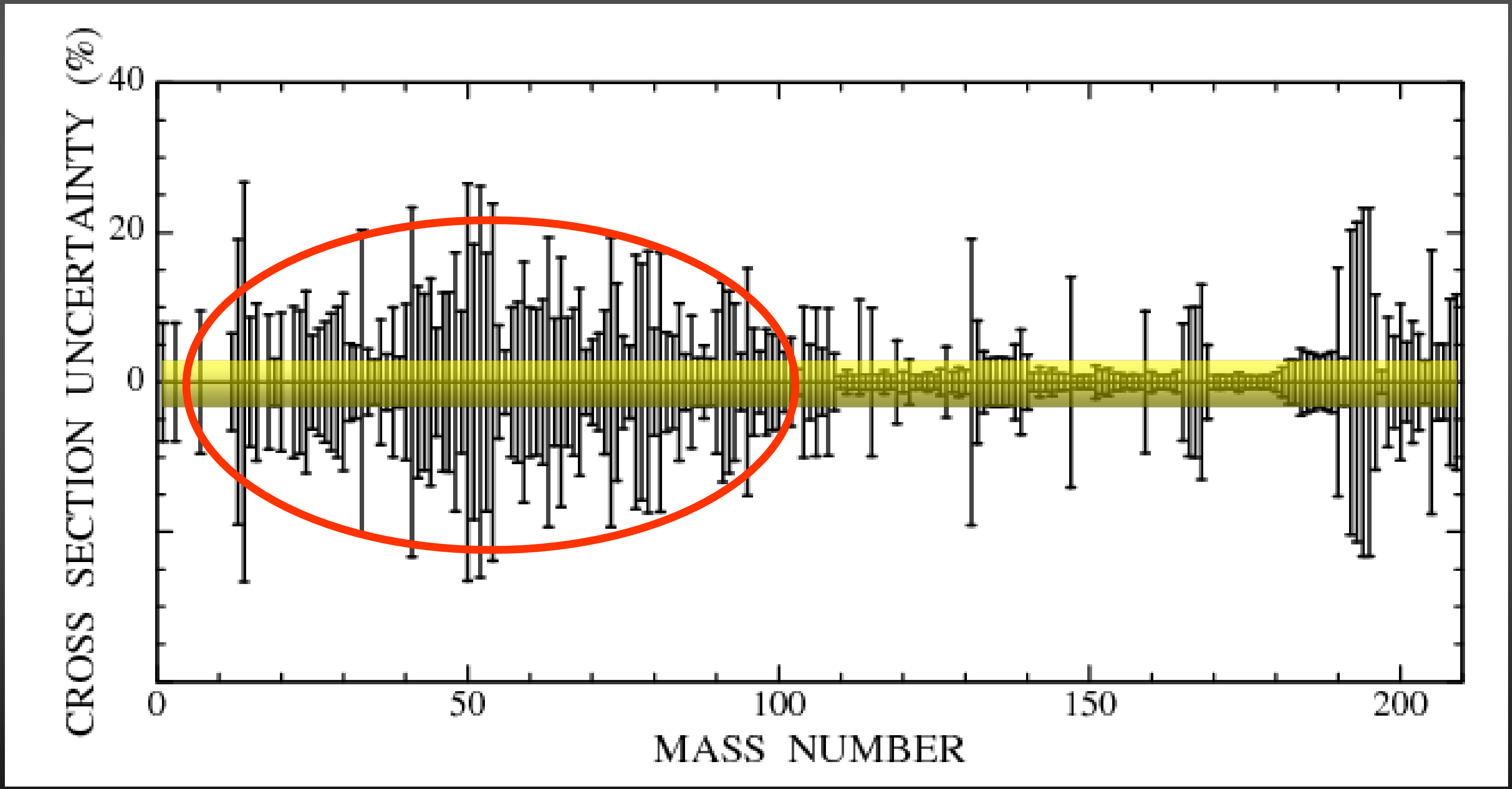


C Arlandini, *et al.:* ApJ 525 (1999) 886

Status and requests

Needed: cross sections with uncertainties between **1 and 5%**

for complete set of isotopes from ^{12}C to ^{210}Po, including unstable samples

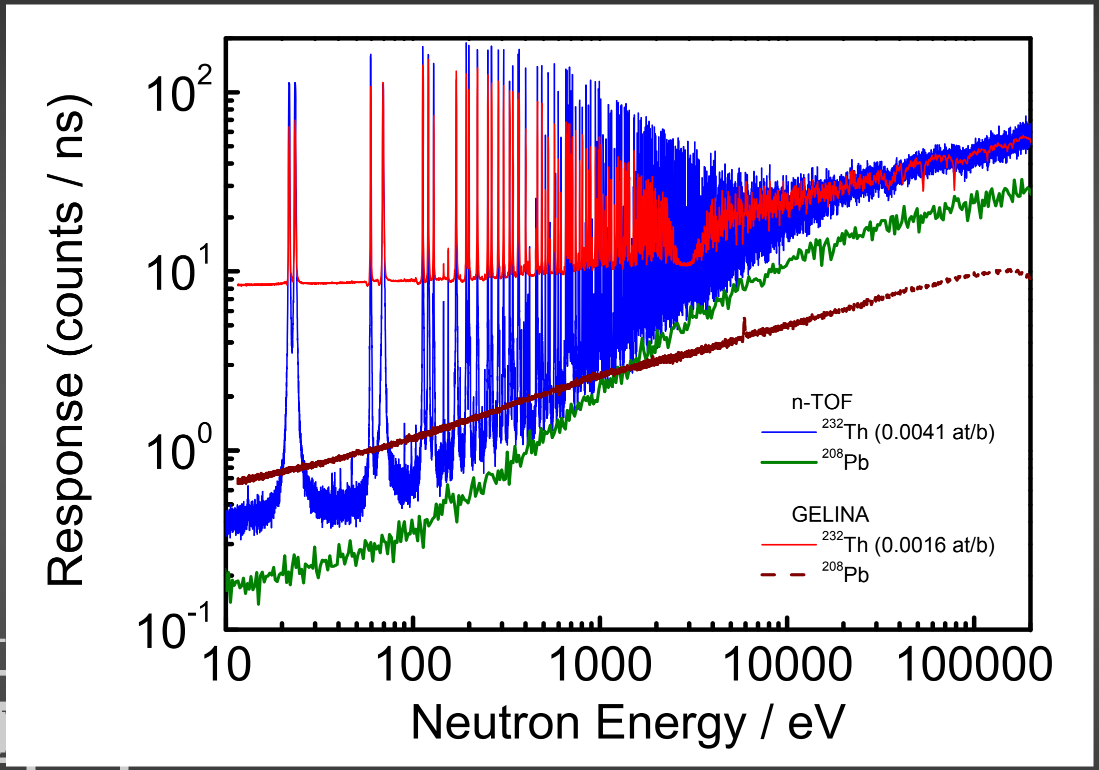


Source: F Käppeler (2009)

Basic characteristics of experiments at n_TOF

$^{232}Th(n,\gamma)$

- wide energy range
- high neutron flux &
  high energy resolution
- low repetition rate
  of the proton driver



source: P Rullhusen (GELINA)

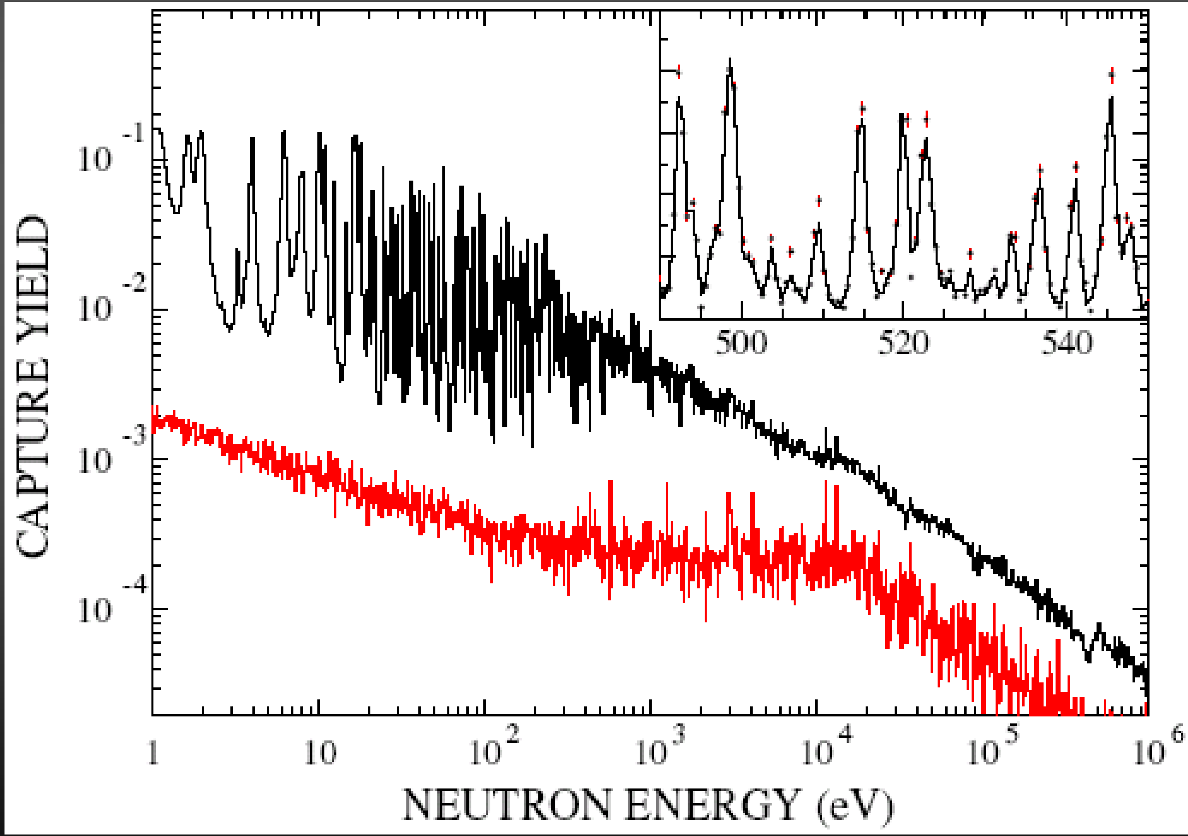
comparison with GELINA (~ same average flux at 30m)

Basic characteristics of experiments at n_TOF

- wide energy range
- high neutron flux & high energy resolution
- low repetition rate of the proton driver
- low background conditions

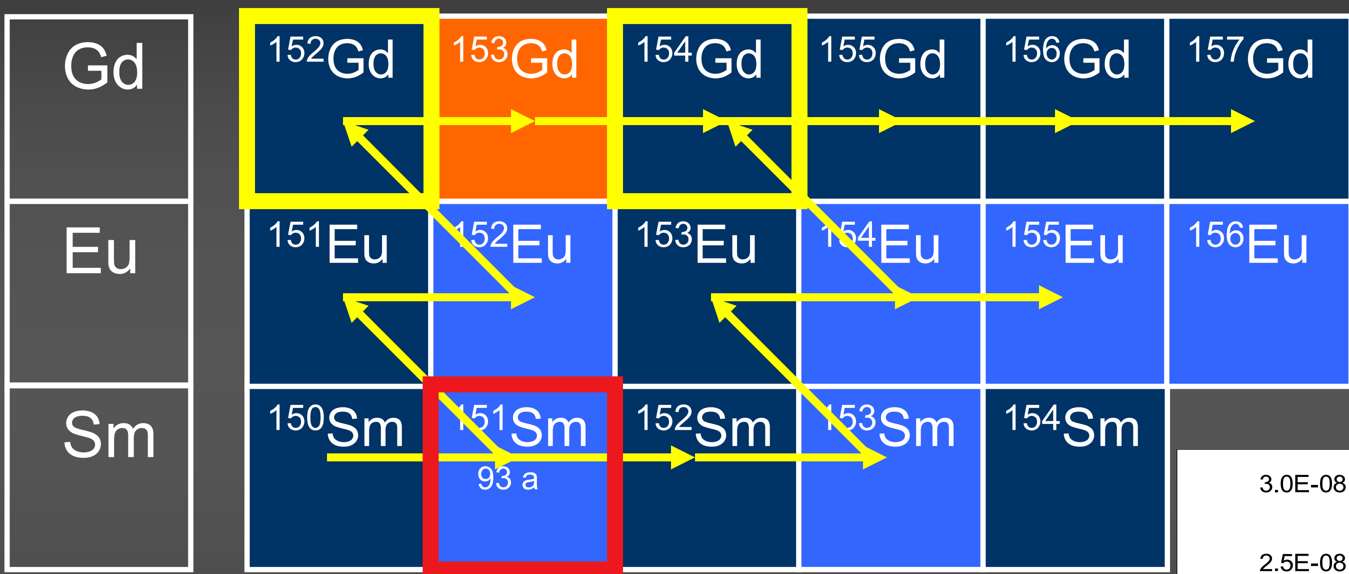
U Abbondanno et al. (The n_TOF Collaboration)
Phys. Rev. Lett. **93** (2004), 161103
&
S Marrone et al. (The n_TOF Collaboration)
Phys. Rev. C **73** 03604 (2006)

$^{151}Sm(n,\gamma)$



Example: Branching point at ^{151}Sm

- The branching at ^{151}Sm can be used to determine the temperature during the s process.

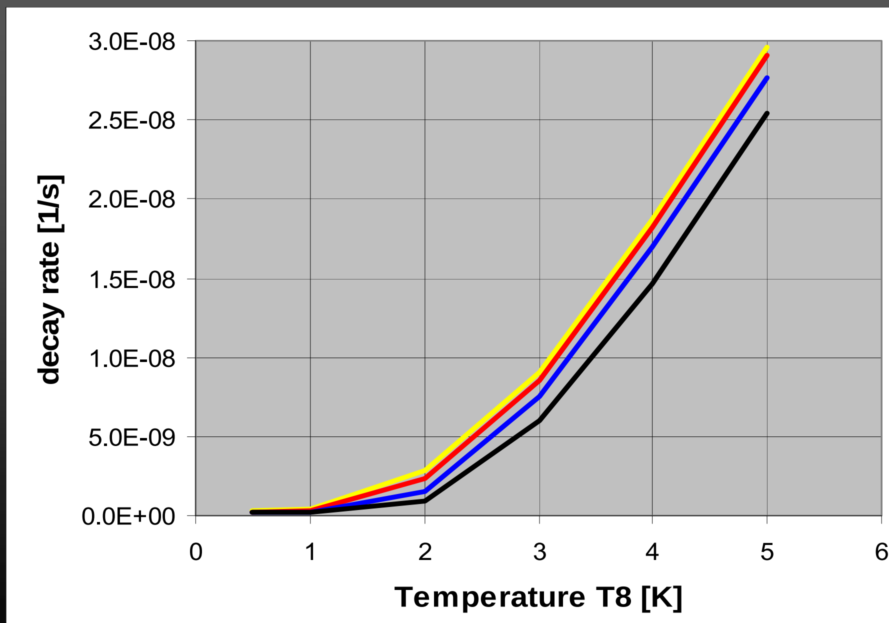


$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n(^{151}\mathrm{Sm})} = \frac{(\sigma \cdot N)_{^{152}\mathrm{Gd}}}{(\sigma \cdot N)_{^{150}\mathrm{Sm}}}$$

T = 350 40 Million Kelvin

kT = 30 keV

n_e = 1, 3, 10, 30 10^{26} cm^{-3}



source: M Heil

Measurements performed

Capture

- ^{151}Sm → s-process branching, temperature, density
- $^{204,206,207,208}Pb$, ^{209}Bi → termination of the s-process, nucleosynthesis of Lead
- ^{232}Th
- $^{24,25,26}Mg$ → neutron source for the s-process: $^{22}Ne(\alpha,n)^{25}Mg$
- $^{90,91,92,94,96}Zr$, ^{93}Zr → massive stars, pre-solar grains
- ^{139}La → massive stars, pre-solar grains
- $^{186,187,188}Os$ → nuclear cosmo-chronometer
- $^{233,234}U$
- ^{237}Np, ^{240}Pu, ^{243}Am

Fission

- $^{233,234,235,236,238}U$
- ^{232}Th
- ^{209}Bi
- ^{237}Np
- $^{241,243}Am$, ^{245}Cm

Planned measurements

Capture measurements	
Mo, Ru, Pd stable isotopes	r-process residuals calculation isotopic patterns in SiC grains
Fe, and Ni (all stable isotopes)	s-process nucleosynthesis in massive stars
A≈150 (isotopes varii)	s-process branching points long-lived fission products
^{79}Se, Se (stable isotopes)	s-process branching (T and ρ for the weak component)
Other measurements	
^{147}Sm(n,α), ^{67}Zn(n,α), ^{99}Ru(n,α) ^{58}Ni(n,p), other (n,lcp)	p-process studies

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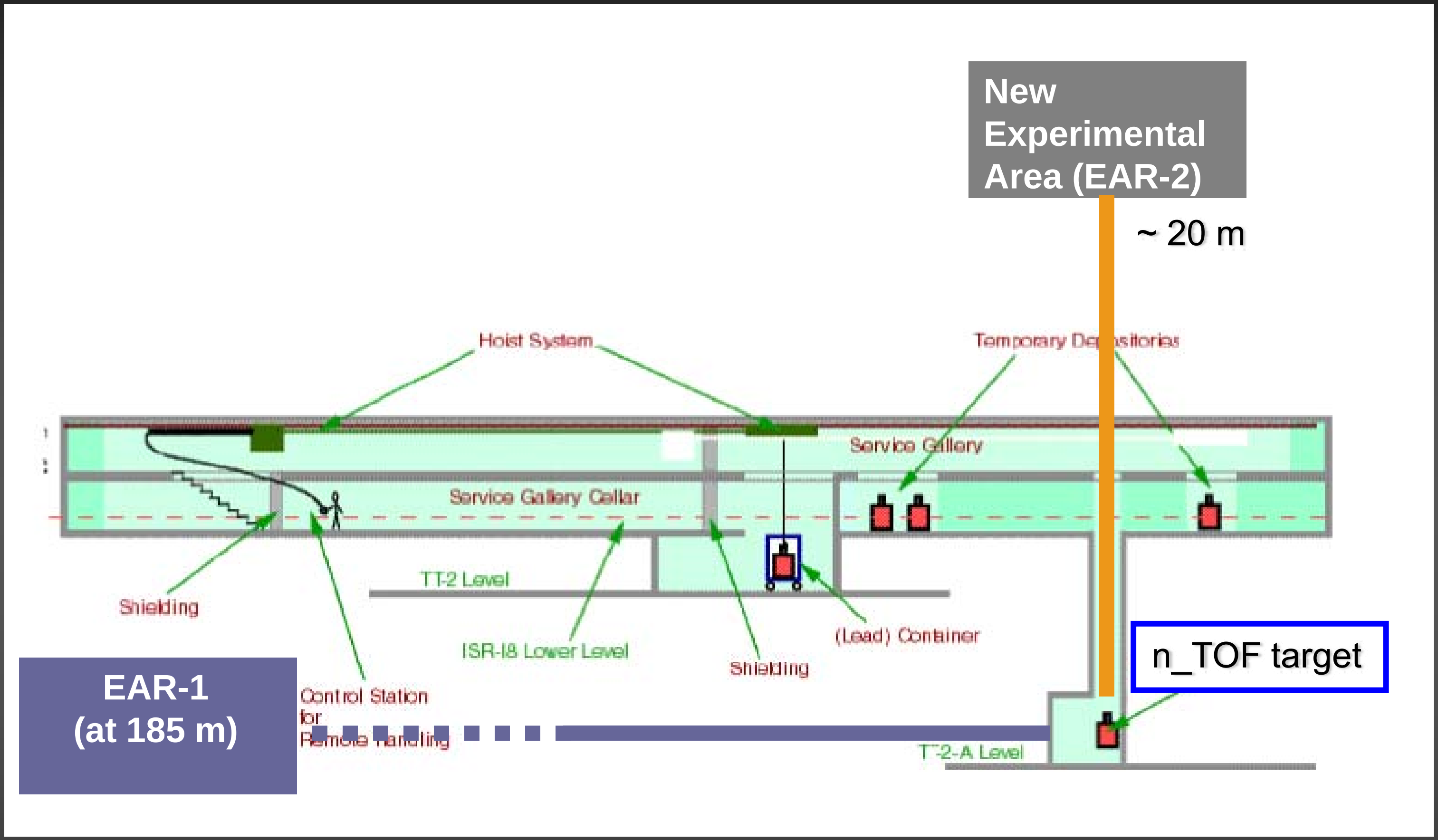
(*) Approved by the RB (P208/n_TOF13)

The second n_TOF beam line & EAR-2



Flight-path length : ~20 m
at 90° respect to p-beam direction
expected neutron flux enhancement: ~ 100
drastic reduction of the t_0 flash

EAR-2: Optimized sensitivity

Improvements (ex: ^{151}Sm case)		consequences for sample mass
■ sample mass / 3 s/bkgd=1		✓ 50 mg
■ use BaF_2 TAC	ε x 10	✓ 5 mg
■ use D_2O	Φ_{30} x 5	■ 1 mg
■ use 20 m flight path	Φ_{30} x 100	■ 10 μg

boosts sensitivity by a **factor of 5000 !**

→ problems of sample production and safety issues relaxed

Possible measurements at EAR-2

- ^{79}Se
- ^{90}Sr
- ^{126}Sn
- ^{147}Pm
- ^{135}Cs

all s-process branching points + they are important fission fragments

Conclusion

Neutron cross sections are key quantities for studying stellar evolution and nucleosynthesis. n_TOF offers the best conditions to obtain these nuclear physics quantities with the required accuracy

The n_TOF Collaboration is carrying on an extensive plan to measure cross sections relevant for nuclear astrophysics, in particular for s-process nucleosynthesis studies

Opportunities for obtaining new data for presently inaccessible nuclei (using extremely low quantities of material) will be open with the implementation of a second beam-line and a new experimental area (EAR-2)

The end

Capture studies: Fe, Ni, Zn, and Se

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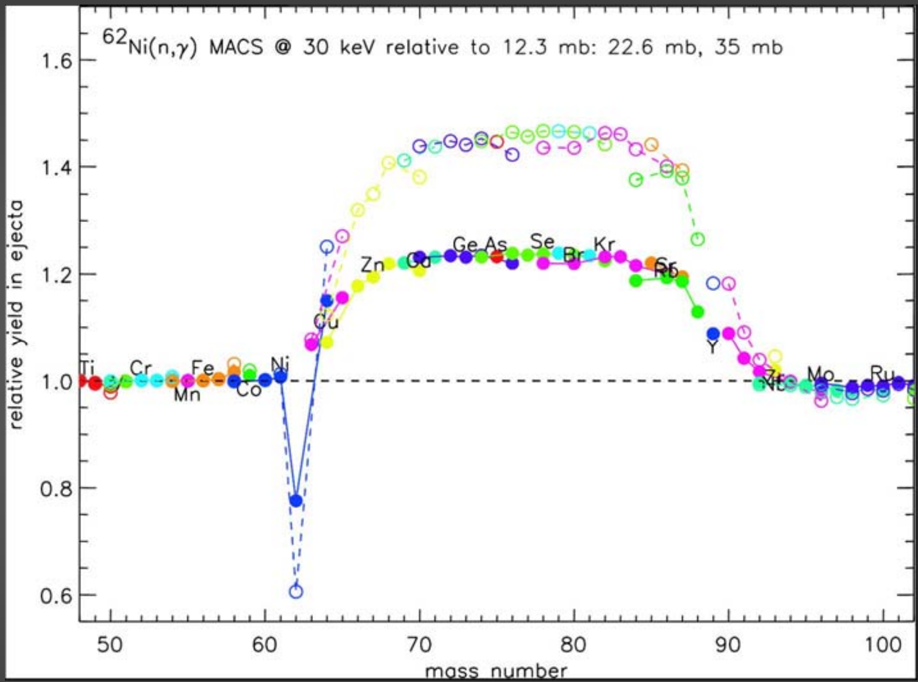
Motivations:

- Study of the weak s-process component (nucleosynthesis up to A ~ 90)
- Contribution of massive stars (core He-burning phase) to the s-process nucleosynthesis.
- s-process efficiency due to bottleneck cross sections (Example: ^{62}Ni)



In addition:

Fe and Ni are the most important structural materials for nuclear technologies. Results of previous measurements at n_TOF show that capture rates for light and intermediate-mass isotopes need to be revised.

Capture studies: Fe, Ni, Zn, and Se

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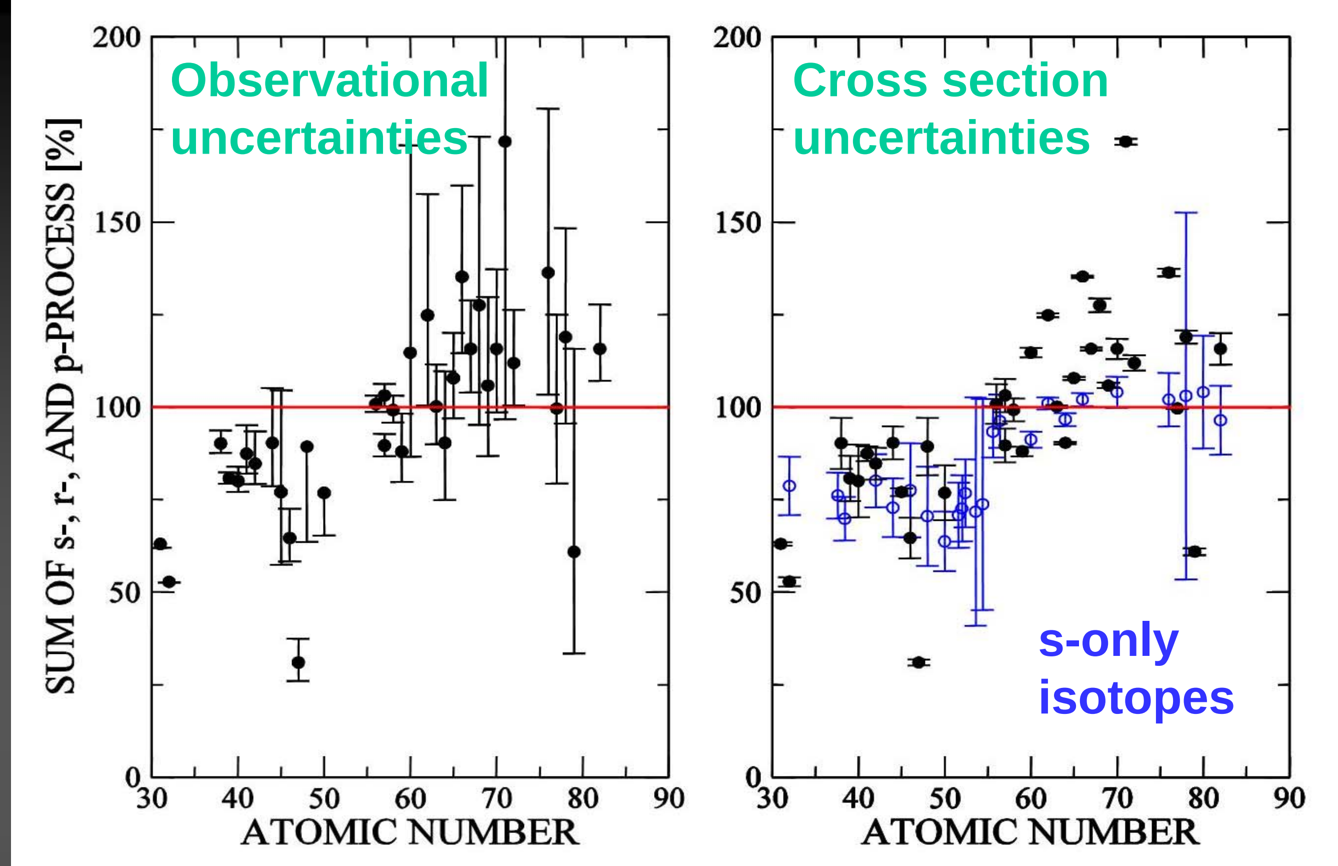
The ^{79}Se case

- s-process branching: neutron density & temperature conditions for the weak component.
- $t_{1/2} < 6.5 \times 10^4$ yr

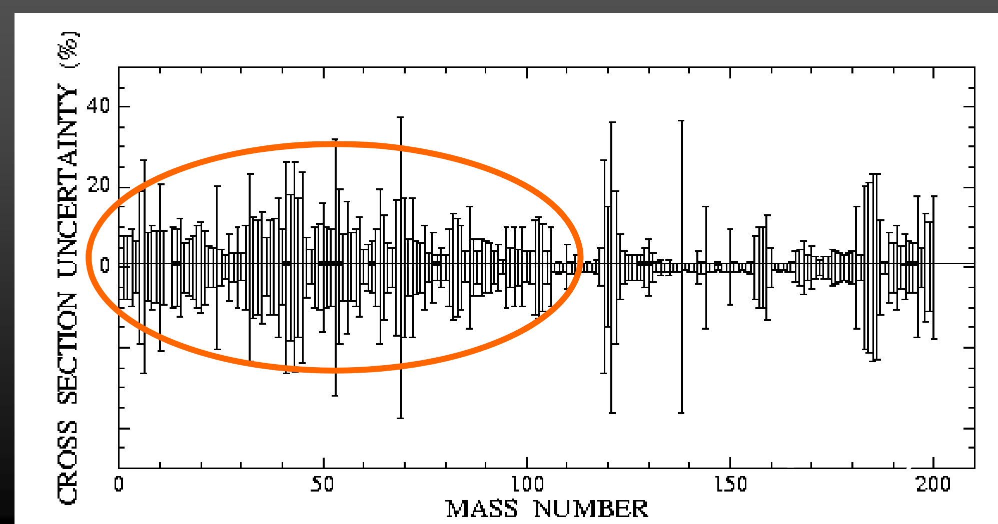
In general:

- Stellar model
- s-abundance calculation
- r-abundance (CS22892-052)

See:
Tavaglio *et al.*, APJ521 (1999)
Arlandini *et al.*, APJ525 (1999)



Need for more than one r-process or need for improved s- abundances and cross sections?



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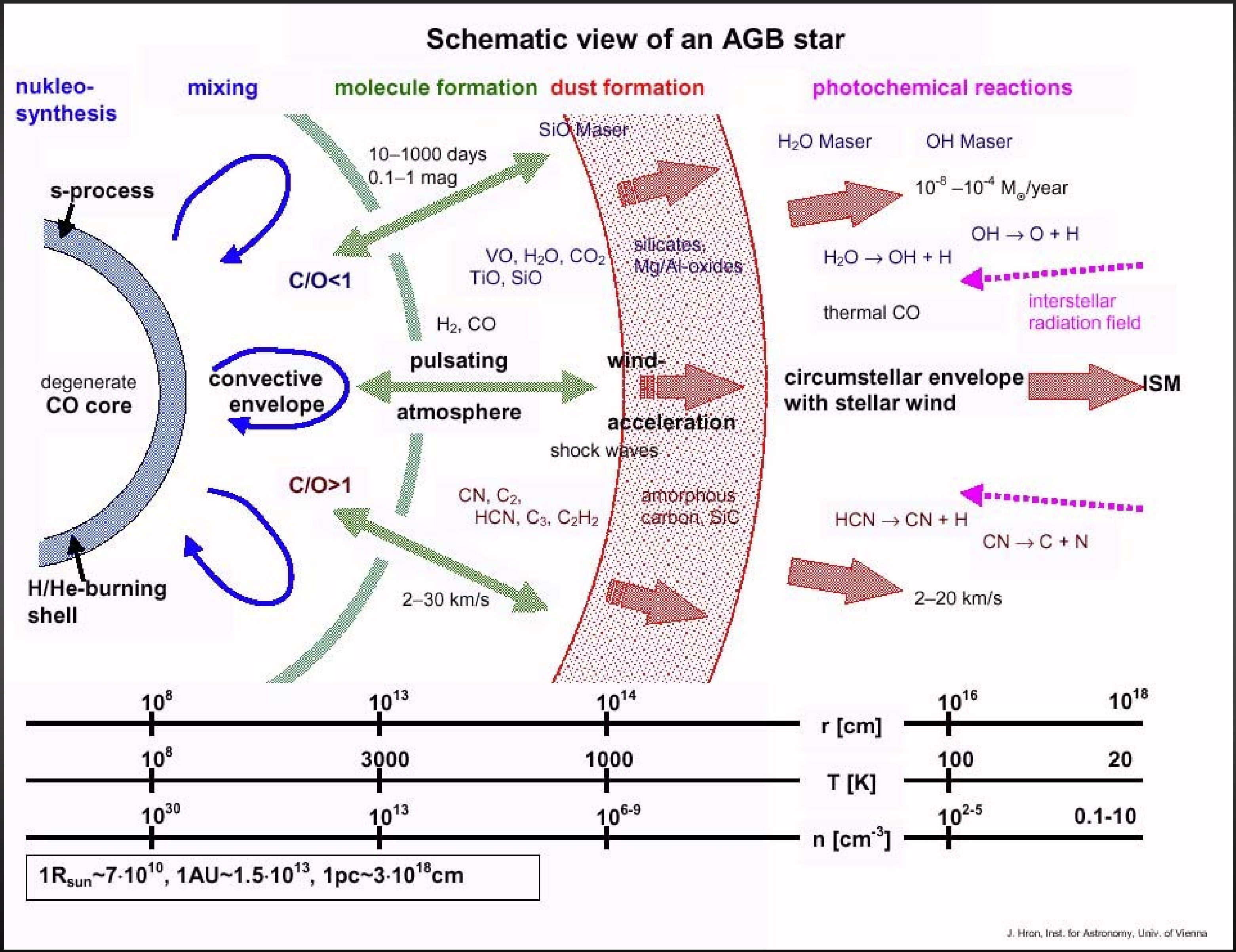
AGB stars

Source: F Herwig



n_TOF experiments & publications

Capture

^{151}Sm

$^{204,206,207,208}Pb$, ^{209}Bi

^{232}Th

$^{24,25,26}Mg$

$^{90,91,92,94,96}Zr$, ^{93}Zr

^{139}La

$^{186,187,188}Os$

$^{233,234}U$

^{237}Np, ^{240}Pu, ^{243}Am

Fission

$^{233,234,235,236,238}U$

^{232}Th

^{209}Bi

^{237}Np

$^{241,243}Am$, ^{245}Cm

In summary:

Facility & Experimental setup	: 11 papers
Measurements	: 10 papers (1 PRL, 9 PRC)
Conference Proceedings	: 51
Total number of documents on db	: 150

All data (published) can be found in the EXFOR database >>

Measurements performed so far

^{151}Sm

s-process branching, temperature, density

$^{204,206,207,208}Pb$, ^{209}Bi

termination of the s-process, nucleosynthesis of Lead

$^{24,25,26}Mg$

neutron source for the s-process: $^{22}Ne(\alpha,n)^{25}Mg$

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