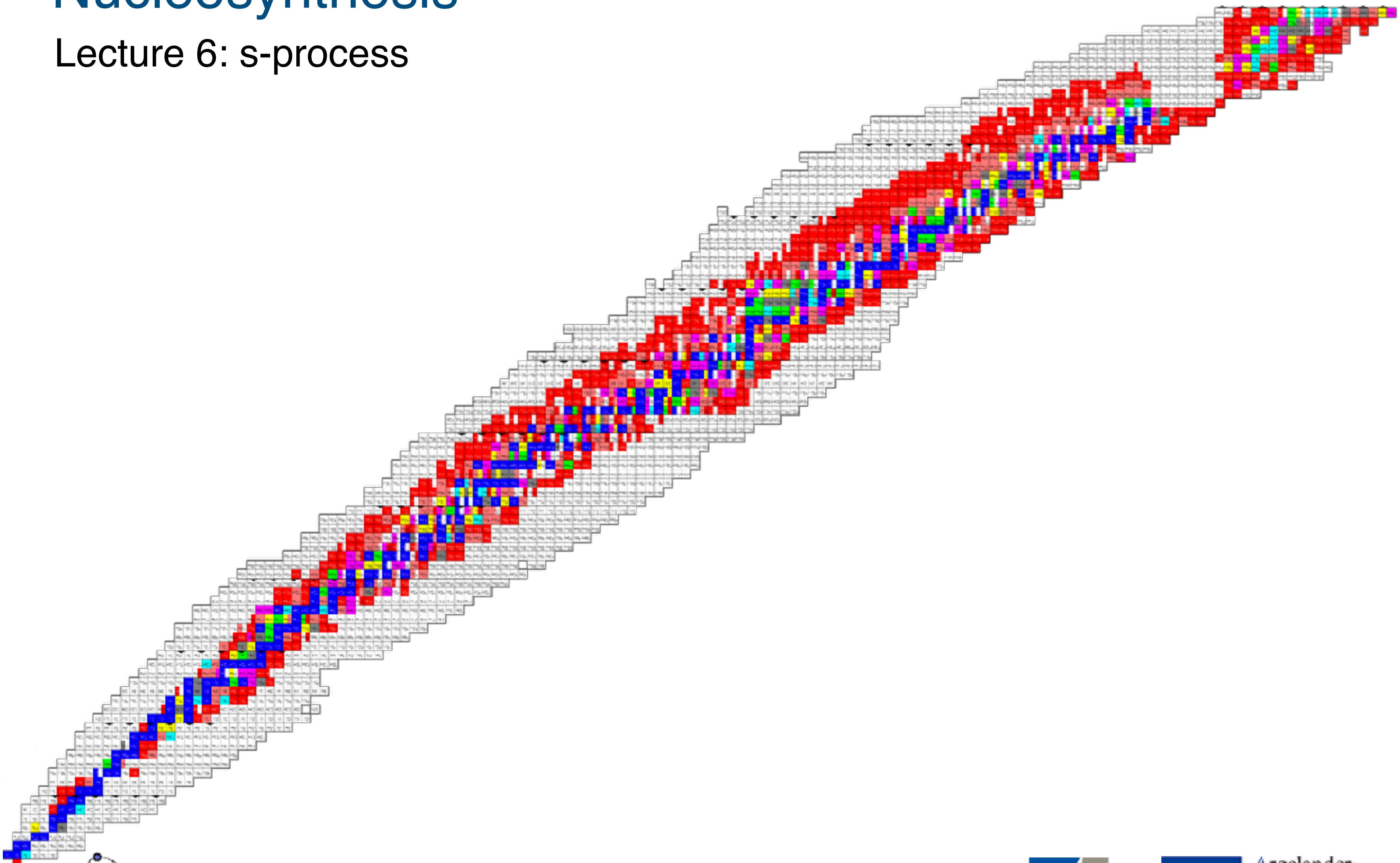
Nucleosynthesis

Lecture 6: s-process



Bonn-Cologne Graduate School
of Physics and Astronomy

UNIVERSITÄT BONN

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Institut
für
Astronomie

Overview

- **Lecture 1:** Introduction & overview
  Lecture 2: Thermonuclear reactions
- **Lecture 3:** Big-bang nucleosynthesis
- **Lecture 4:** Thermonuclear reactions inside stars — I (H-burning)
- **Lecture 5:** Thermonuclear reactions inside stars — II (advanced burning)
- **Lecture 6:** Neutron-capture and supernovae — I
- **Lecture 7:** Neutron-capture and supernovae — II
- **Lecture 8:** Thermonuclear supernovae
- **Lecture 9:** Li, Be and B
- **Lecture 10:** Galactic chemical evolution and relation to astrobiology

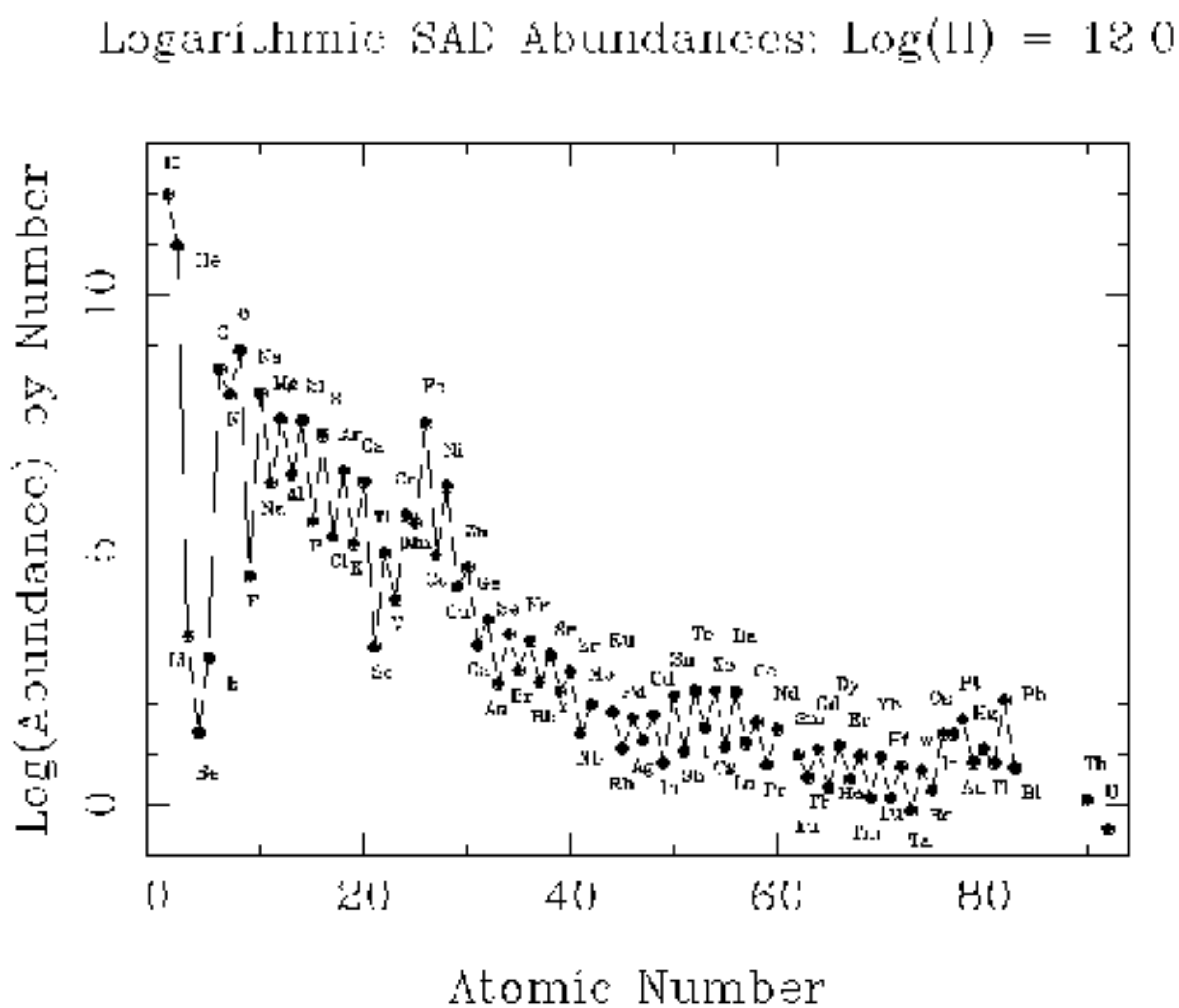
Paper presentations I	**June 21**
Paper presentations II	**June 28**

The quest for the origin of trans-iron elements

So far we have discussed the production of light elements, from hydrogen up to the iron peak A=56

These elements form via charged-particle-induced nuclear reactions.
The nuclear ashes of the big bang (H and He) were subsequently re-burned inside stars

The increasing temperatures and densities throughout stellar evolution provide the necessary conditions for the reactants to overcome their mutual Coulomb barrier



The sharp drop in measured abundances from A=1 to A=50 reflects that fact

The quest for the origin of trans-iron elements

Can this process also explain the formation of heavier elements?

$T < 5 \times 10^9$ K: The increasing Coulomb barriers make the nuclear reaction rates *extremely small*

$T > 5 \times 10^9$ K: Abundances are determined by nuclear statistical equilibrium (NSE).
Iron has the greatest stability, therefore it should be the most abundant
The iron peak can be explained by near-NSE during the silicon rearrangement process

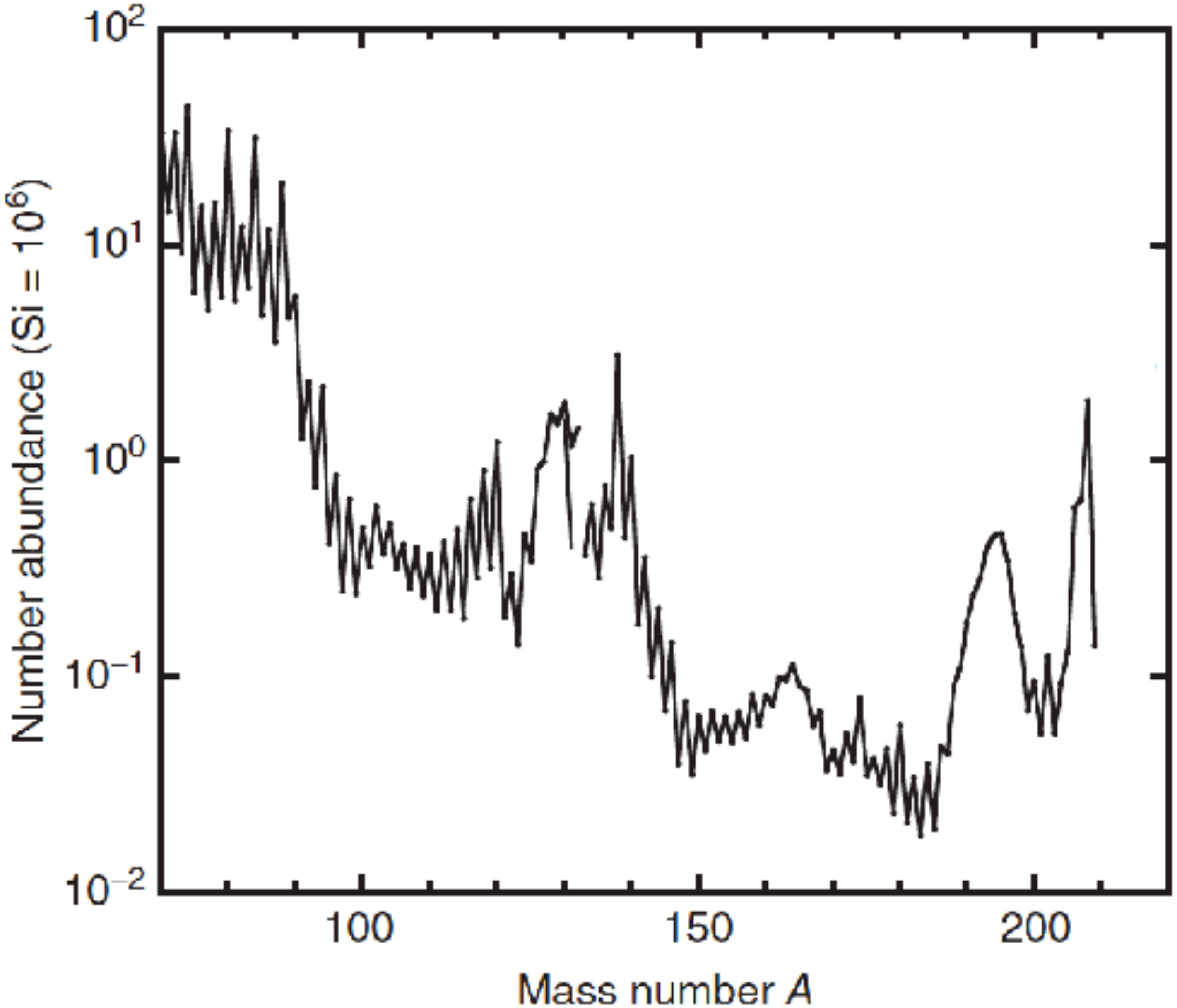
In either case, elements with A>70 should have unmeasurably small abundances

In the 50s abundance measurements for heavy elements started becoming available (Suess & Urey 1956)

These data paint a completely different picture, suggesting a different process

The quest for the origin of trans-iron elements

The local peaks correspond to neutron magic numbers,
i.e. nuclei for which the neutron-capture cross section is very small



The quest for the origin of trans-iron elements

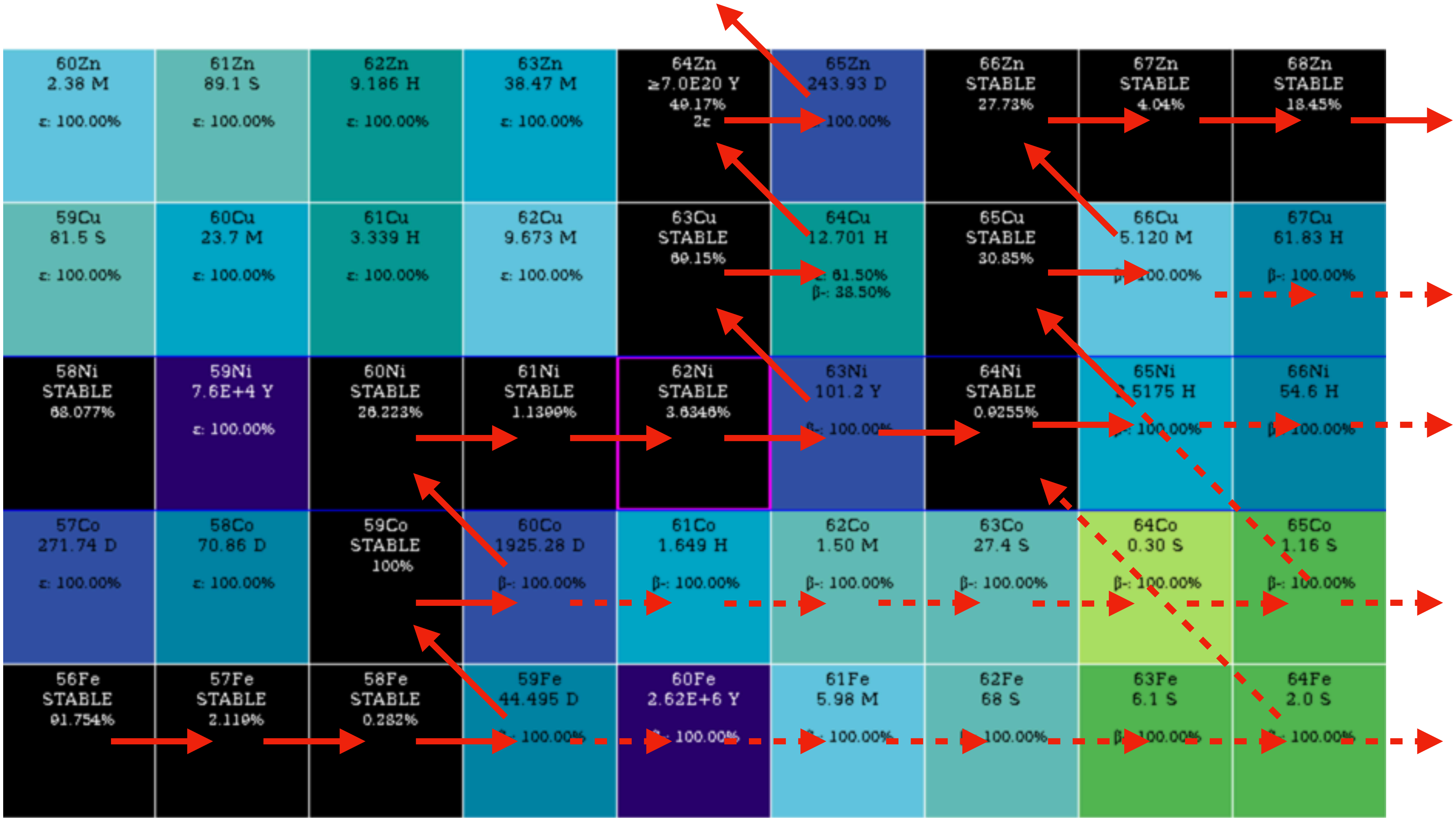
Neutrons decay fast (in 14 min), hence there should be a local source, inside stars

The details were described first by B2FH 1957, after the Suess & Urey measurements

Ingredients:
a local source of neutrons (TBD later) and heavy elements beyond the "missing links" (A=5, 8)

When an element captures a neutron, it will either result in a stable isotope (compared to its environment), or it will decay to something else, e.g. by β-decay

Basic mechanism for nucleosynthesis beyond iron



neutron flux knob

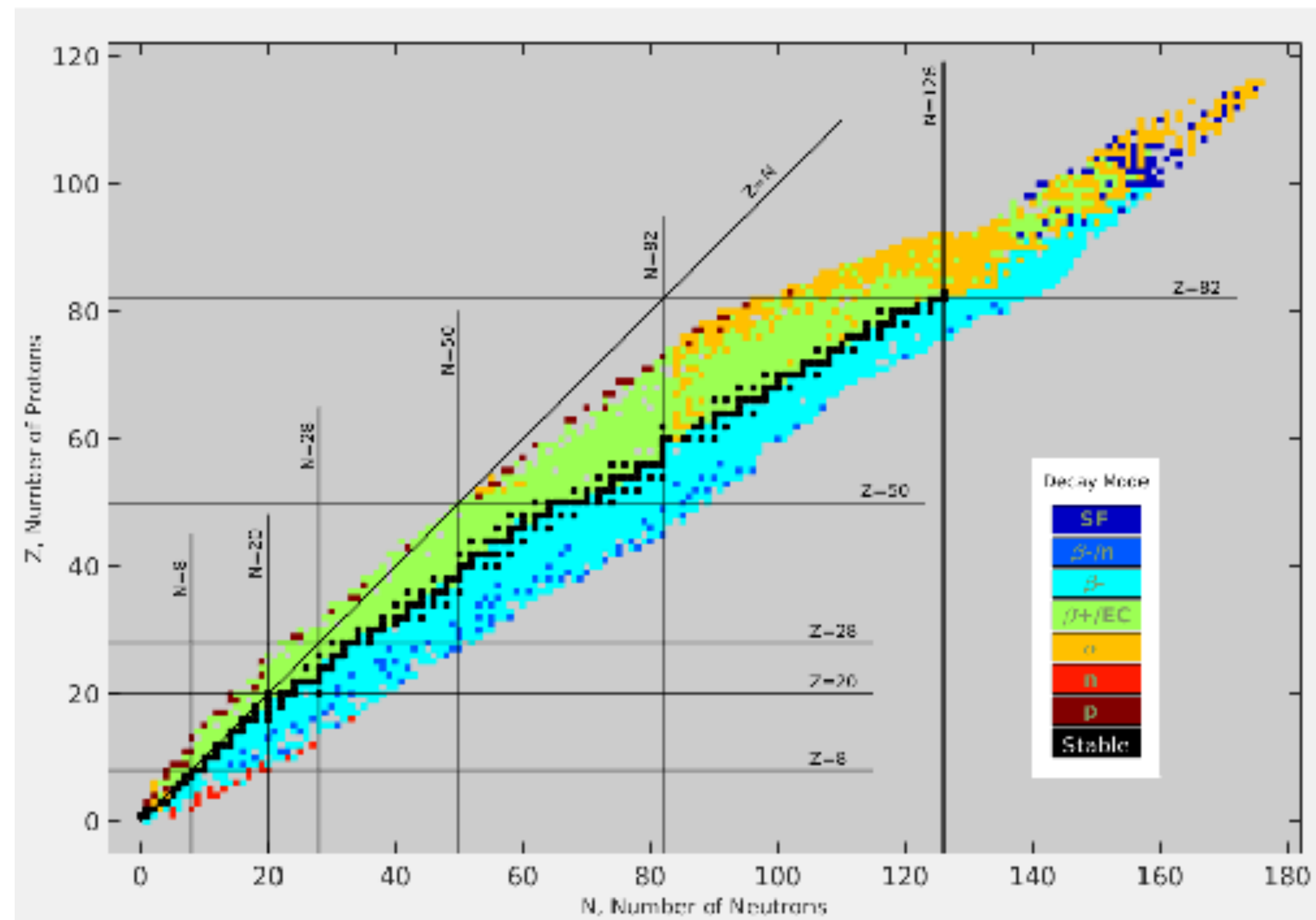
$\tau_\beta \ll \tau_\beta$: (s)low/rapid neutron capture (s/r − process)

The quest for the origin of trans-iron elements

To establish a quantitative theory that explains the observed abundance structure, we need information about

- **nuclear data: neutron cross sections vs energy, decay timescales etc.**

- **the environment (T, abundances)**



Stable elements (with measurable abundances) are located near the "valley of stability" (Z=0.6N)
Cross sections can be measured in the lab

neutron-capture cross sections

First, we want to infer <σv> as a function of temperature

Velocities described by a Maxwell-Boltzmann distribution

$$\sigma(v) = \text{Penetration Probability} \times \text{Size (De Broglie)} \times \text{Nuclear Properties} \times \text{constant factor}$$

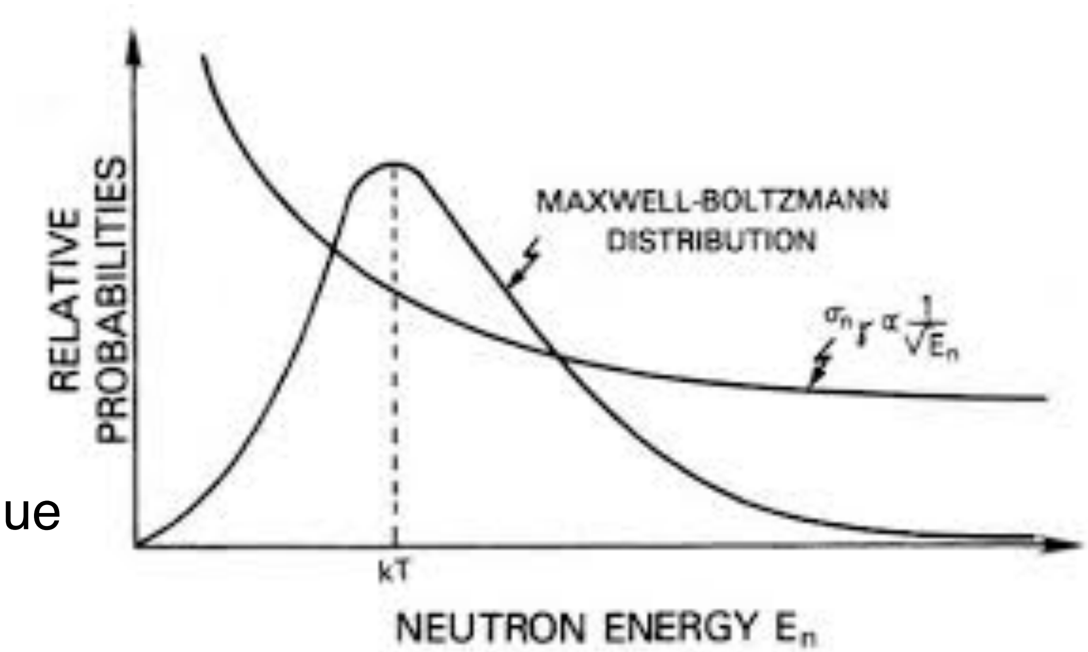
Neutrons don't have a charge, hence there is no Coulomb barrier.
Hence the penetration probability is equal to 1
In reality there is still a centrifugal barrier and in fact, only neutrons with l=1 are captured

$\sigma(v) \propto 1/v$

For MB velocities, the most probable energy for the process to occur is $E_0 = kT, v_T = (2kT/\mu)^{1/2}$

Hence, $\langle \sigma v \rangle \simeq const = \langle \sigma \rangle v_T$

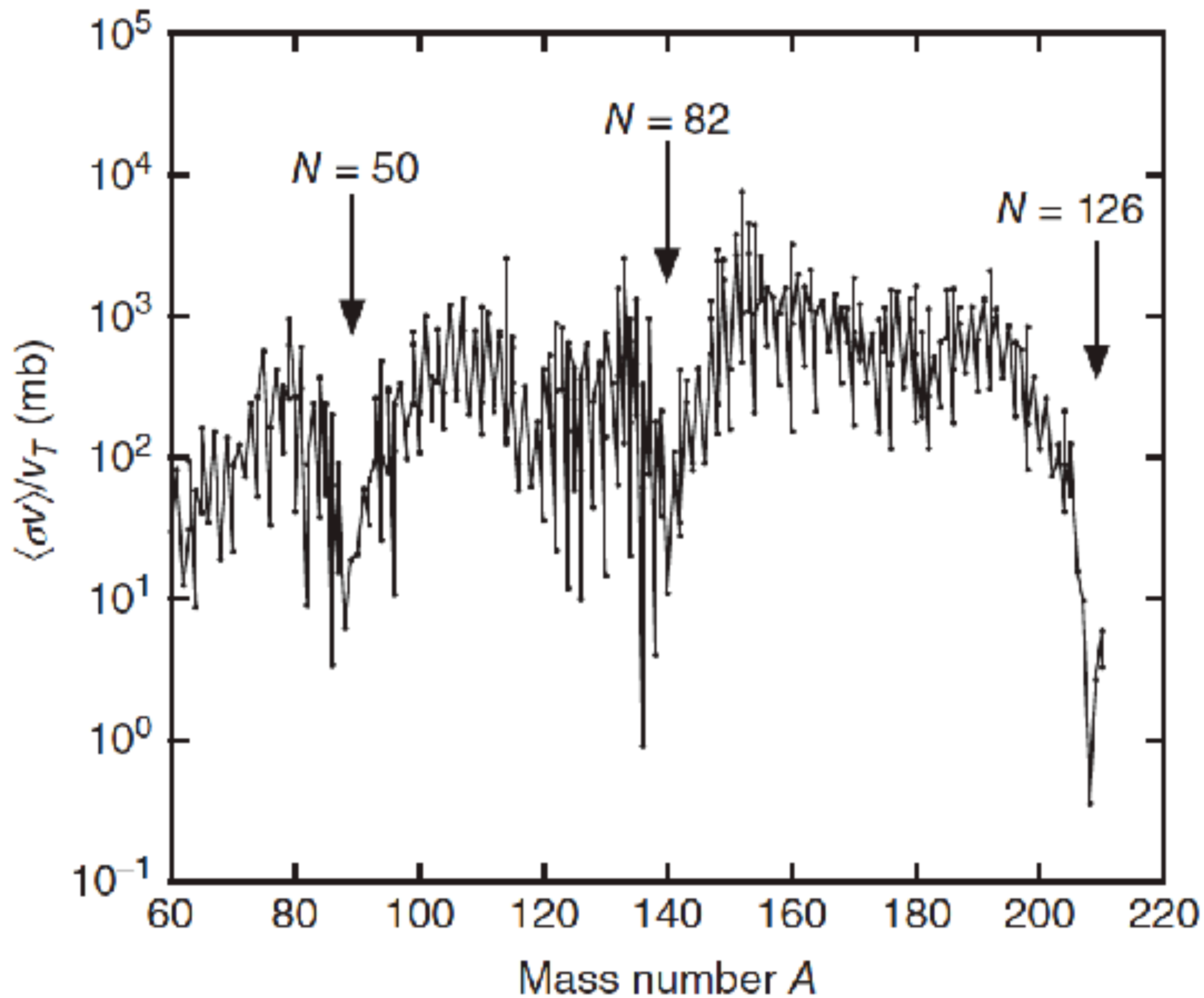
$\langle \sigma \rangle \simeq \sigma(E_o)$, a measurement near E_o provides a good value



Maxwellian averaged cross sections are also nearly independent of temperature.
Typically measured near 30 keV which corresponds typical He burning temperatures.

neutron-capture cross sections

Measured values for σ @ 30kEV



s-process: Quantitative estimates

Slow neutron capture

β-decay timescales range from 0.1 ms to ~10 years. Therefore, for s-process $\tau_n < 10\,\mathrm{yr}$

$$N_\mathrm{n} = (\tau_n \langle \sigma v \rangle)^{-1} = (\tau_n \langle \sigma \rangle v_T)^{-1} = (10\,\mathrm{yr} \times 100\,\mathrm{mb} \times 2.4 \times 10^8\,\mathrm{cm\,s^{-1}})^{-1} \simeq 10^8\,\mathrm{cm}^{-3}$$

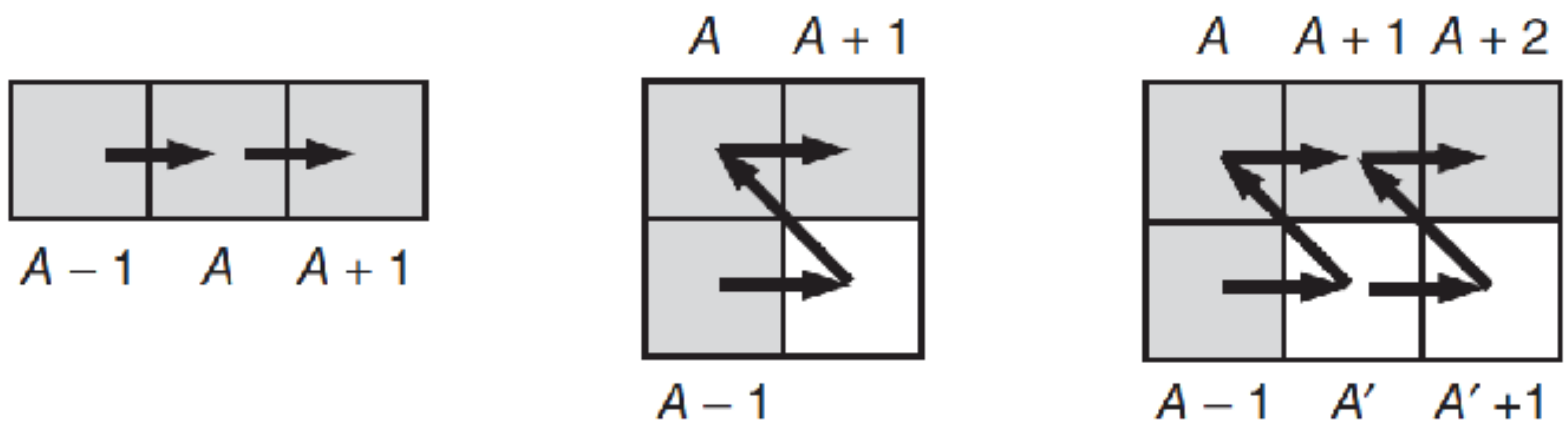
Rapid neutron capture

neutron capture timescales must be of order 10-4 s are required to avoid β-decays completely

$$N_\mathrm{n} = (\tau_n \langle \sigma v \rangle)^{-1} = (\tau_n \langle \sigma \rangle v_T)^{-1} = (10^{-4}\,\mathrm{s} \times 100\,\mathrm{mb} \times 2.4 \times 10^8\,\mathrm{cm\,s^{-1}})^{-1} \simeq 10^{20}\,\mathrm{cm}^{-3}$$

s-process: Quantitative estimates

Basic "moves"



(a) (b) (c)

$$a: \frac{dN_A(t)}{dt} = N_n(t)N_{A-1}(t)\langle\sigma v\rangle_{A-1} - N_n(t)N_A(t)\langle\sigma v\rangle_A$$

$b:$ same

$$c: \frac{dN_A(t)}{dt} = N_n(t)N_{A-1}(t)\langle\sigma v\rangle_{A-1} - N_n(t)N_A(t)(\langle\sigma v\rangle_A + \lambda_b)$$

s-process: Quantitative estimates

Simplifications for a & b:

$$\frac{dN_A(t)}{dt} = N_n(t)N_{A-1}(t)\langle\sigma v\rangle_{A-1} - N_n(t)N_A(t)\langle\sigma v\rangle_A$$

$$\frac{dN_A(t)}{dt} = N_n(t)v_T(N_{A-1}(t)\sigma_{A-1} - N_A(t)\sigma_A)$$

Neutron flux

$$\phi(t) = v_T N_n(t)\,\mathrm{neutrons\,cm^{-2}\,s^{-1}}$$

Time-integrated neutron flux (irradiation)

$$\tau = \int_0^t \phi(t)dt = v_T \int_0^t N_n(t)dt\ \mathrm{neutrons\,cm^{-2}} \Rightarrow d\tau = dt v_T N_n(t)$$

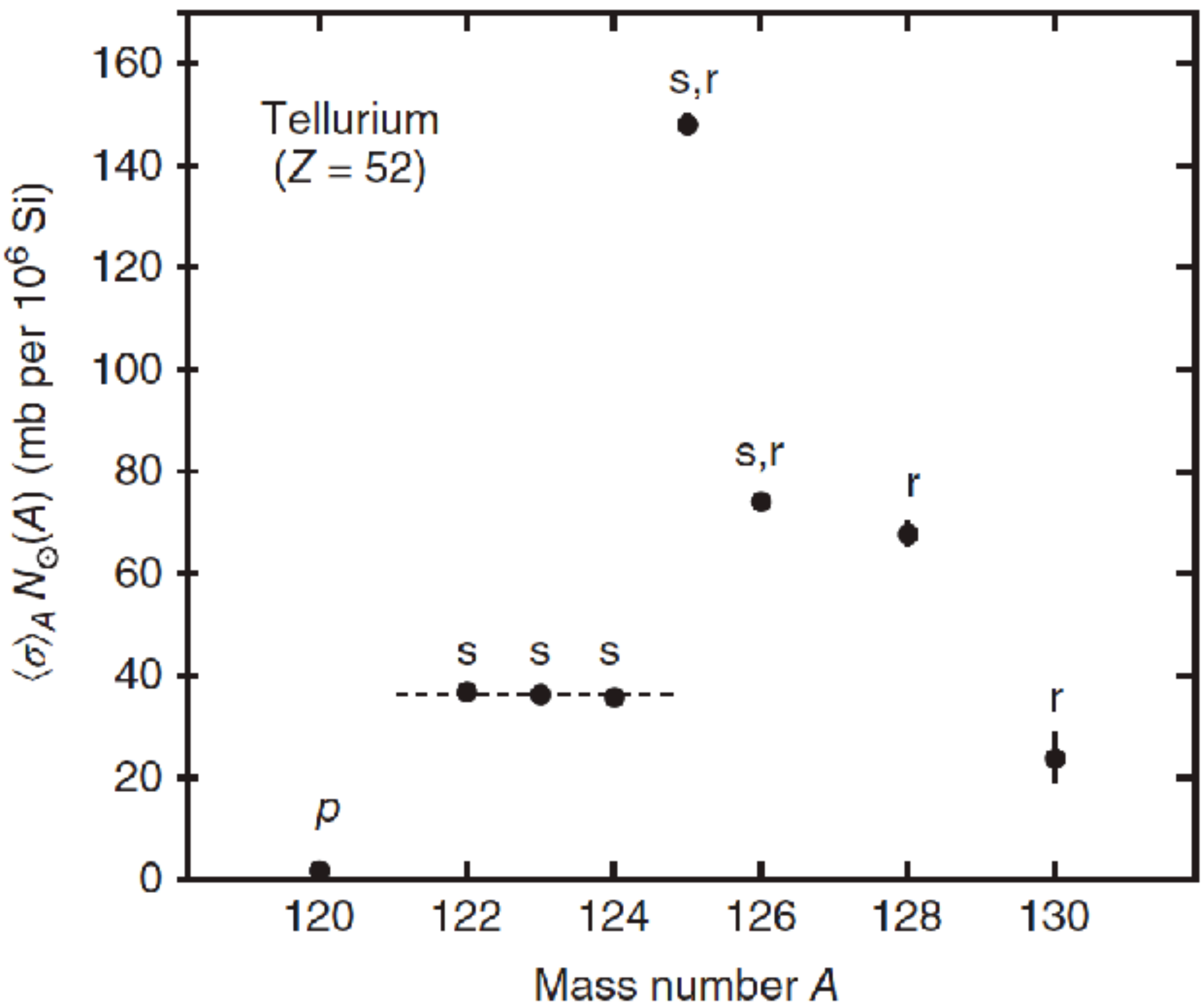
Therefore, the abundance evolution as a function of irradiation is described by the self-regulated equations:

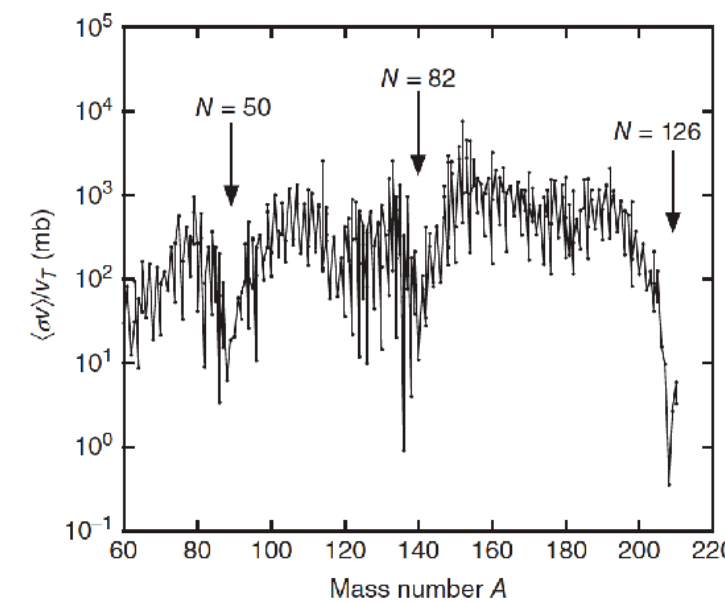
$$\frac{dN_A(t)}{d\tau} = N_{A-1}\sigma_{A-1} - N_A\sigma_A$$

s-process: Quantitative estimates

If all cross sections are large, then equilibrium is achieved relatively quickly.
Good approximation for neighbouring elements far from closed shells

$$N_{A-1}\sigma_{A-1} = N_A\sigma_A = const.$$





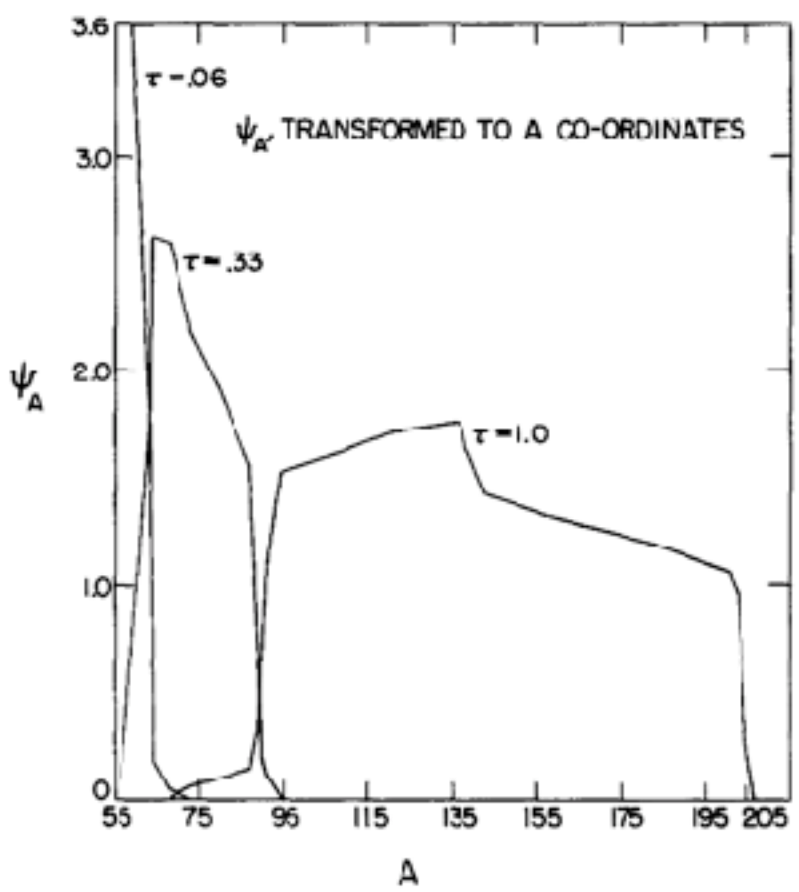
s-process: Quantitative estimates

For true equilibrium, the former condition would be satisfied for all trans-iron elements.
This is NOT the case.

For more realistic results the coupled differential equations need to be solved numerically (but also semi-analytically, see CLAYTON) for given boundary conditions and input cross sections
Since iron is the most abundant element, it is assumed

$$N(0)_A = N(0)_{56}, A = 56 \ \& \ N(0)_A = 0, A > 56$$

Clayton (1961) found that the solutions N(A,τ) do NOT reproduce the observed abundances for single irradiation episodes. Small τ overproduce light elements, large(τ) overproduce heavy elements



IDEA: A continuous distribution of irradiations

s-process: Quantitative estimates

Let's assume $p(\tau)d\tau$ is the fraction of Fe seed nuclei that received an exposure in the range τ,τ+dτ

Clayton 1961 proposed that there should be lots of nuclei with small exposures and few with large.
The probability for some material to have been processed multiple times in stars is small.
This motivates an exponential distribution

$$p(\tau) = \frac{f N_s^{\mathrm{seed}}(56)}{\tau_0} e^{-\tau/\tau_0}$$

Where, f is the fraction of available seeds that have been subjected to this processing.

By definition: $\int_0^\infty p(\tau)d\tau = f N_s^{\mathrm{seed}}(56)$. Now we can substitute $\sigma_A N_A = \int_0^\infty p(\tau)\sigma N(\tau)d\tau$

Our ODEs have a nice ANALYTICAL solution

$$\langle\sigma\rangle_{56}\overline{N_s(56,\tau_0)} = \frac{fN_s^{\mathrm{seed}}(56)}{\tau_0}\frac{1}{\left[1+\frac{1}{\tau_0\langle\sigma\rangle_{56}}\right]}$$

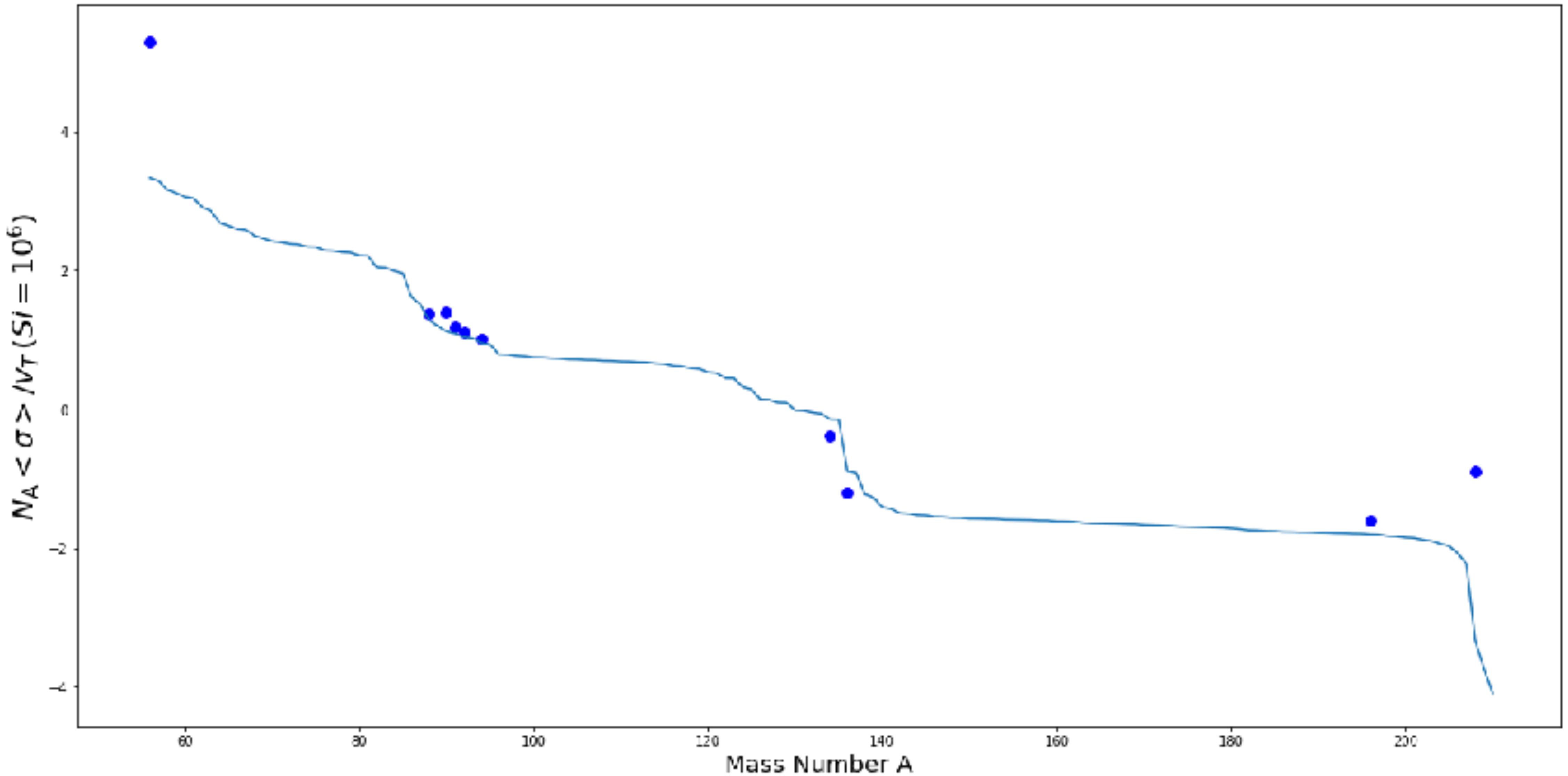
$$\langle\sigma\rangle_{57}\overline{N_s(57,\tau_0)} = \frac{fN_s^{\mathrm{seed}}(56)}{\tau_0}\frac{1}{\left[1+\frac{1}{\tau_0\langle\sigma\rangle_{56}}\right]}\frac{1}{\left[1+\frac{1}{\tau_0\langle\sigma\rangle_{57}}\right]}$$

$$\langle\sigma\rangle_{A}\overline{N_s(A,\tau_0)} = \frac{fN_s^{\mathrm{seed}}(56)}{\tau_0}\prod_{i=56}^{A}\frac{1}{\left[1+\frac{1}{\tau_0\langle\sigma\rangle_{i}}\right]}$$

s-process: Quantitative estimates

We can fit this relation to the observed abundances to determine f and τ_0.
If successful this will provide strong evidence for the exact mechanism (location, etc)

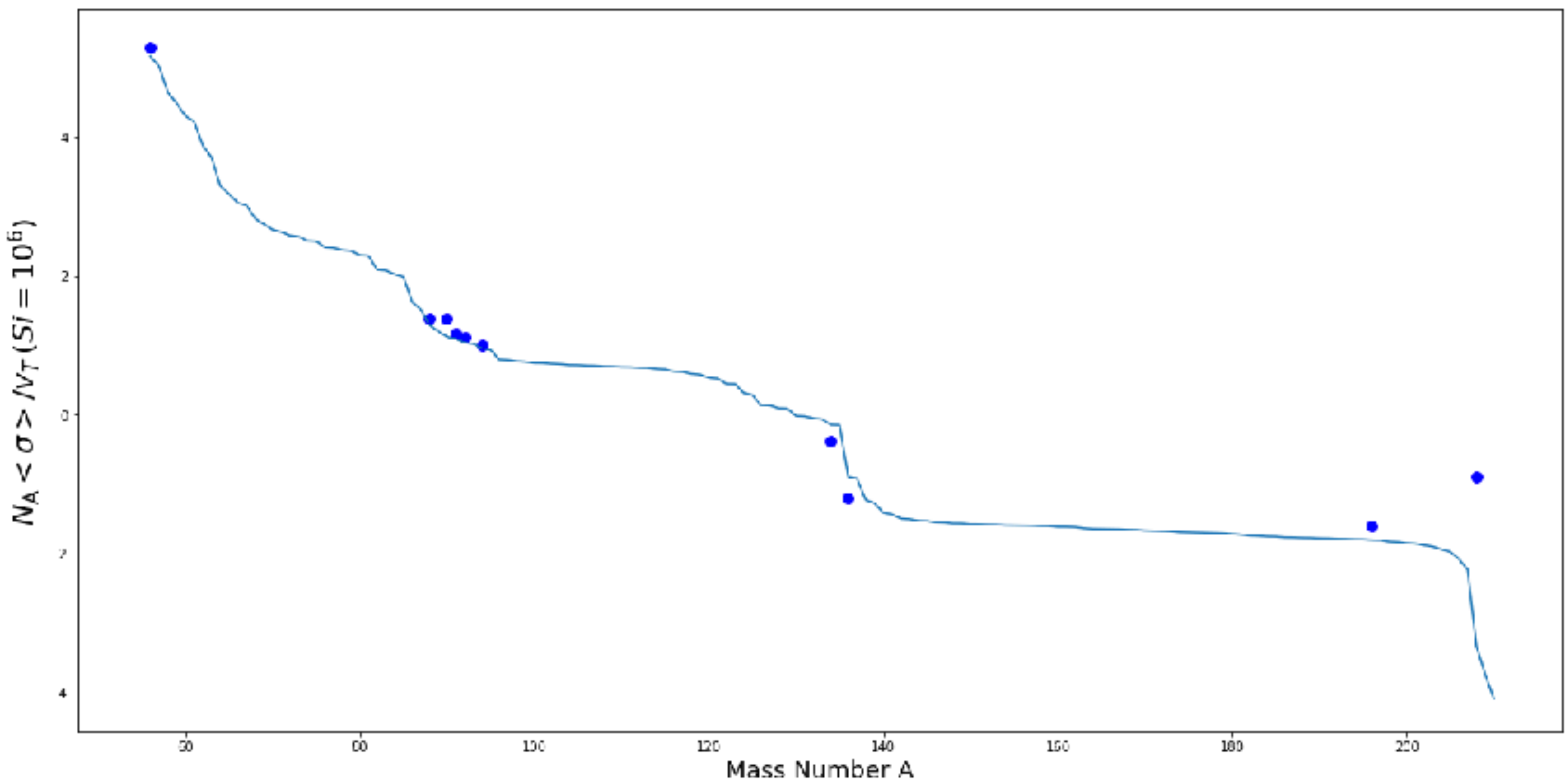
One component: τ=0.24, f=0.09% (aka strong component)



s-process: Quantitative estimates

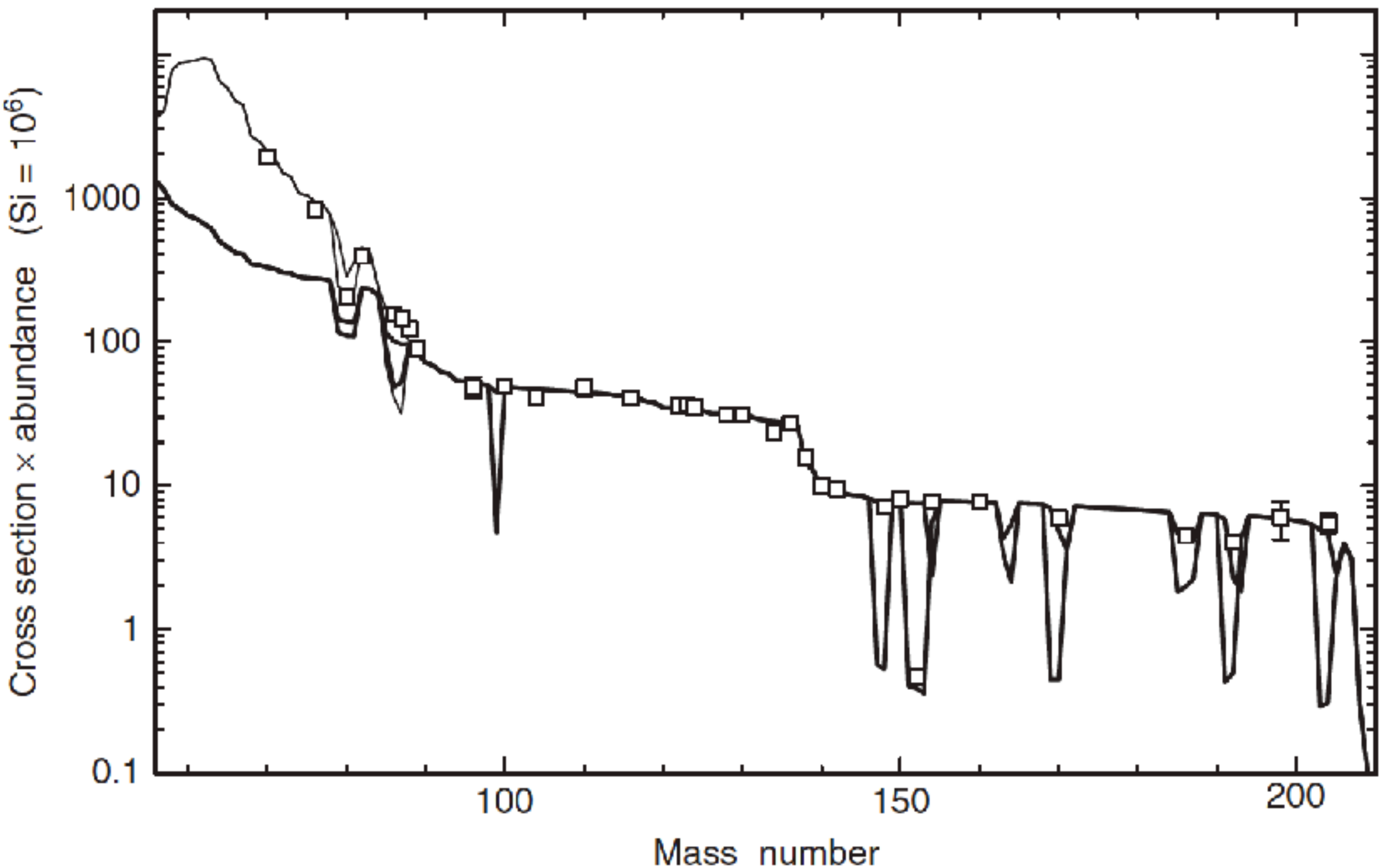
We can fit this relation to the observed abundances to determine f and τ_0.
If successful this will provide strong evidence for the exact mechanism (location, etc)

Second component: τ=0.06, f=2.4% (aka weak component)

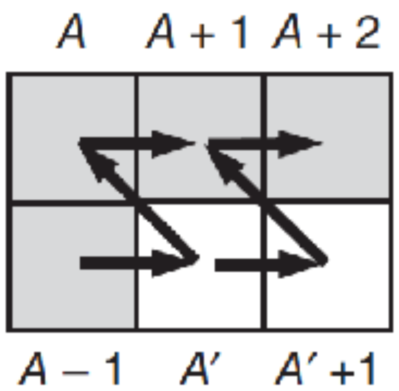


s-process: Quantitative estimates

We can fit this relation to the observed abundances to determine f and τ_0.
If successful this will provide strong evidence for the exact mechanism (location, etc)



s-process branches: a sensitive probe of the environment



For certain isotopes the decay and neutron-capture timescales can be similar

$$\tau_\beta \simeq \tau_n$$

In most cases, the β-decay timescales are temperature-independent.
For small neutron densities, β-decay is favoured, while for high densities, it is avoided

Therefore, the branching ratio can yield the neutron density!!!

$$R = \frac{(\sigma N_\odot)_{\mathrm{Z+1}}}{(\sigma N_\odot)_{\mathrm{A+1}}} = \frac{1}{\tau_\beta N_n \langle \sigma v \rangle_A}$$

For some isotopes, τ_β is temperature dependent.
Once the neutron density is known from other elements, **R for these isotopes yields the temperature**

The analysis can be done independently for weak-only and strong-only elements

STRONG

$$N_n \simeq 2 \times 10^8\, cm^{-3}$$

$$kT \simeq 30\, keV$$

WEAK

$$N_n \simeq 7 \times 10^7\, cm^{-3}$$

$$kT \simeq 40\, keV$$

s-process sites

$^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ Produced abundantly during helium burning. The inferred temperatures and neutron abundances match well the expected rates for massive stars

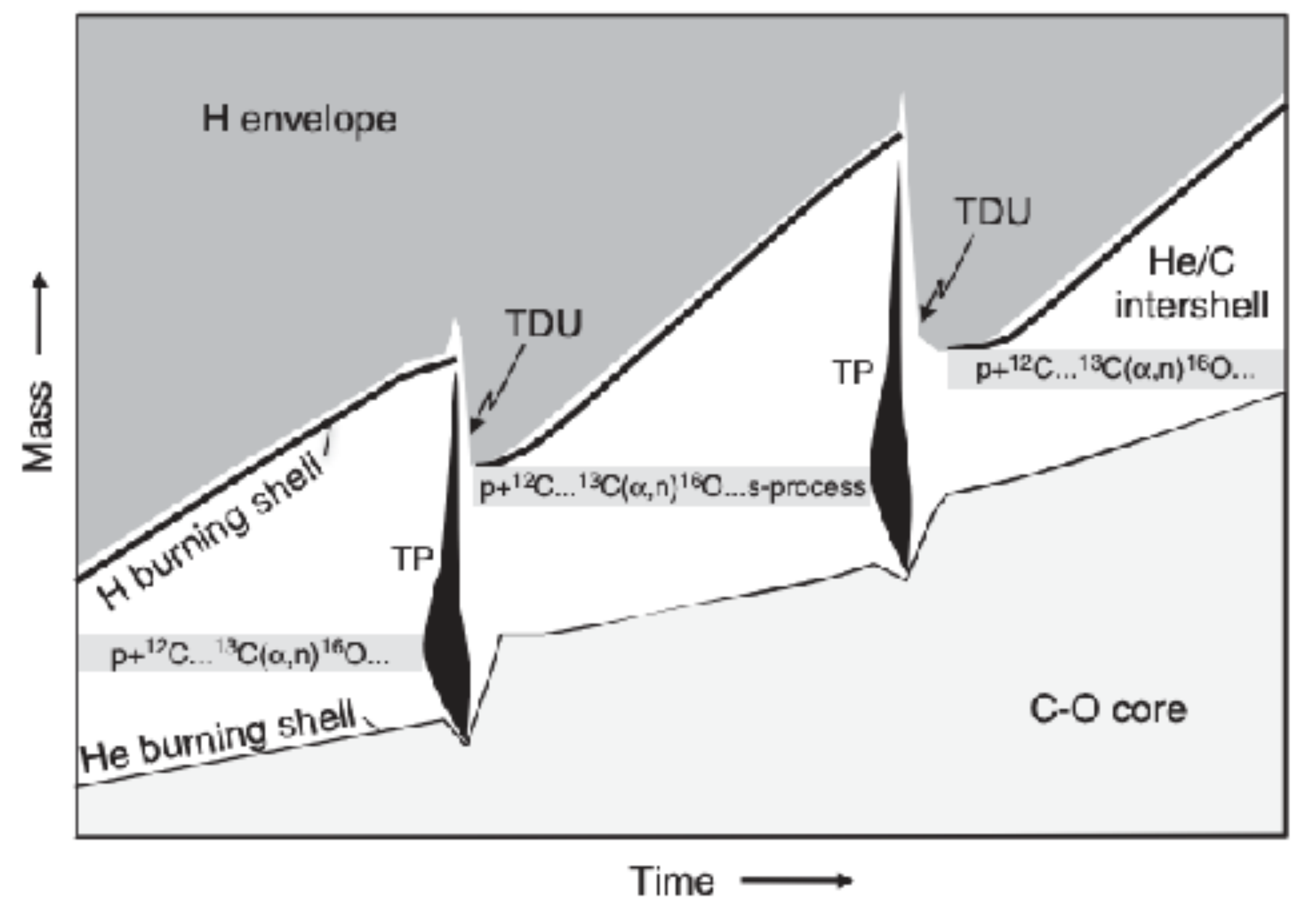
$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ "Consumed" in CNO burning which also produces an over-abundance of neutron poisons, e.g. $^{14}\mathrm{N}(\mathrm{n},\mathrm{p})^{14}\mathrm{O}$

To explain the weak component,
one needs rapid mixing with fresh protons

This occurs in thermally pulsating AGB stars

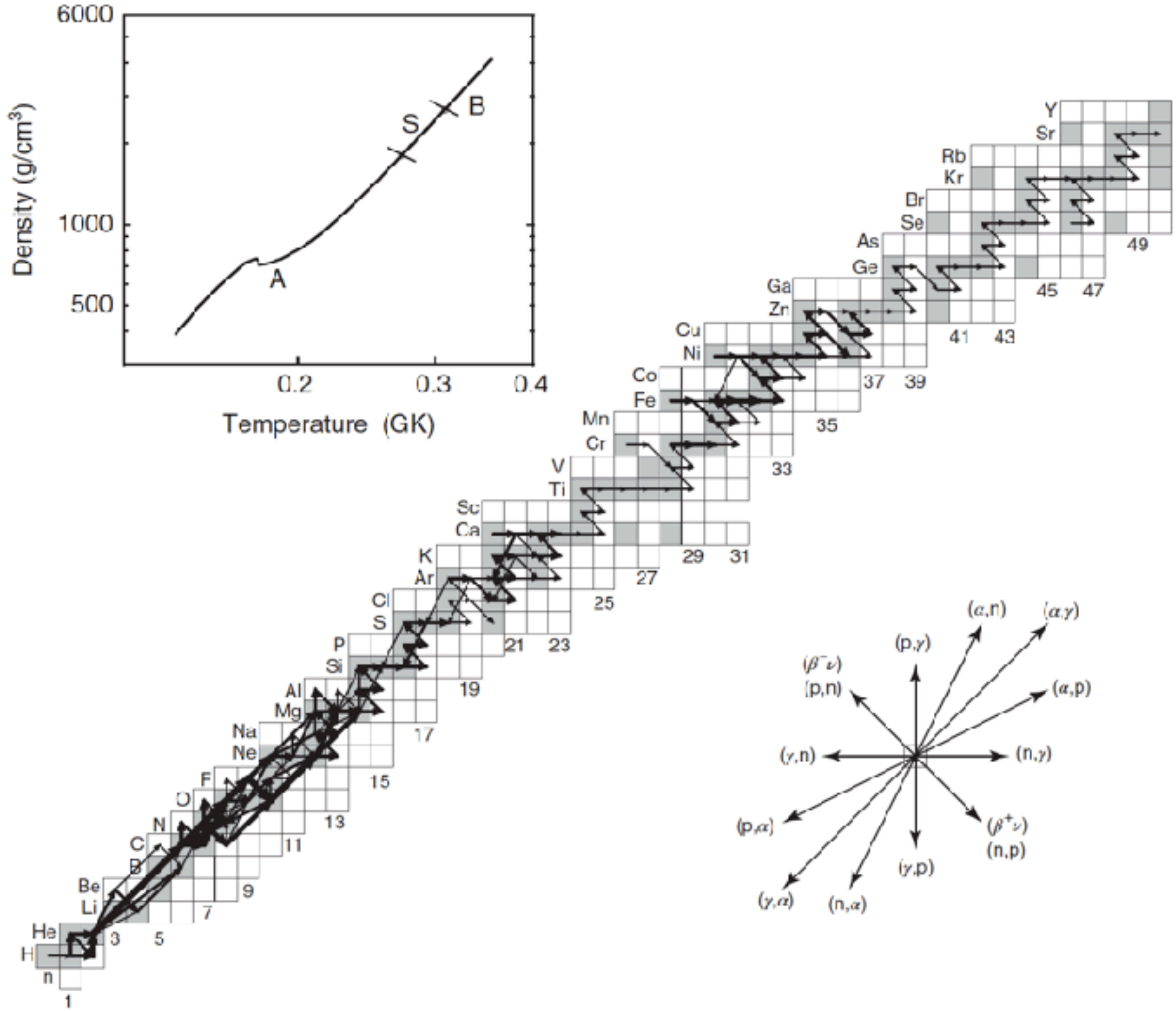
Dredge-up brings the ashes to the surface

Interesting dependence on metallicity
certain metal-poor stars are rich in s-process elements



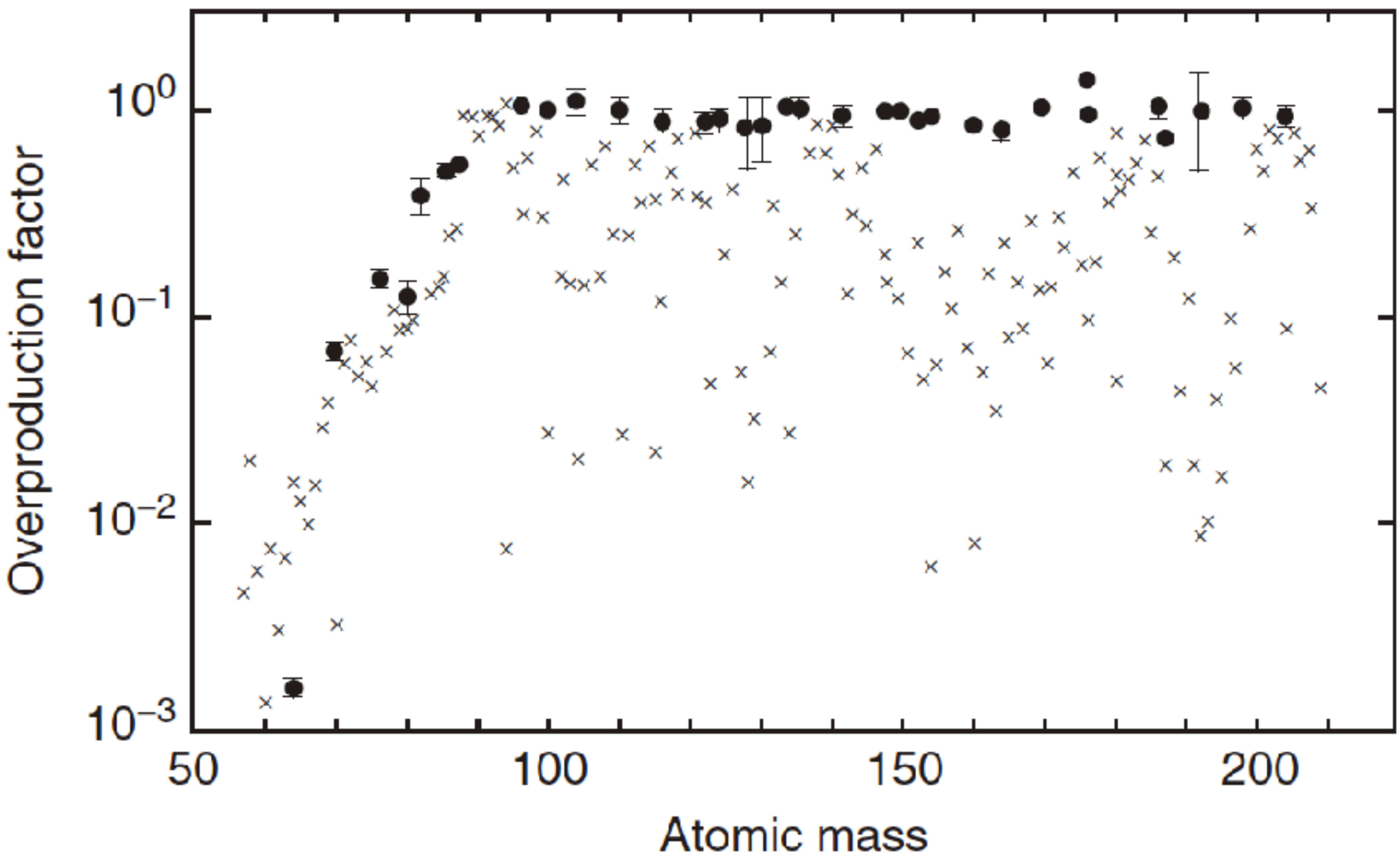
s-process sites

Nucleosynthesis during Helium Burning



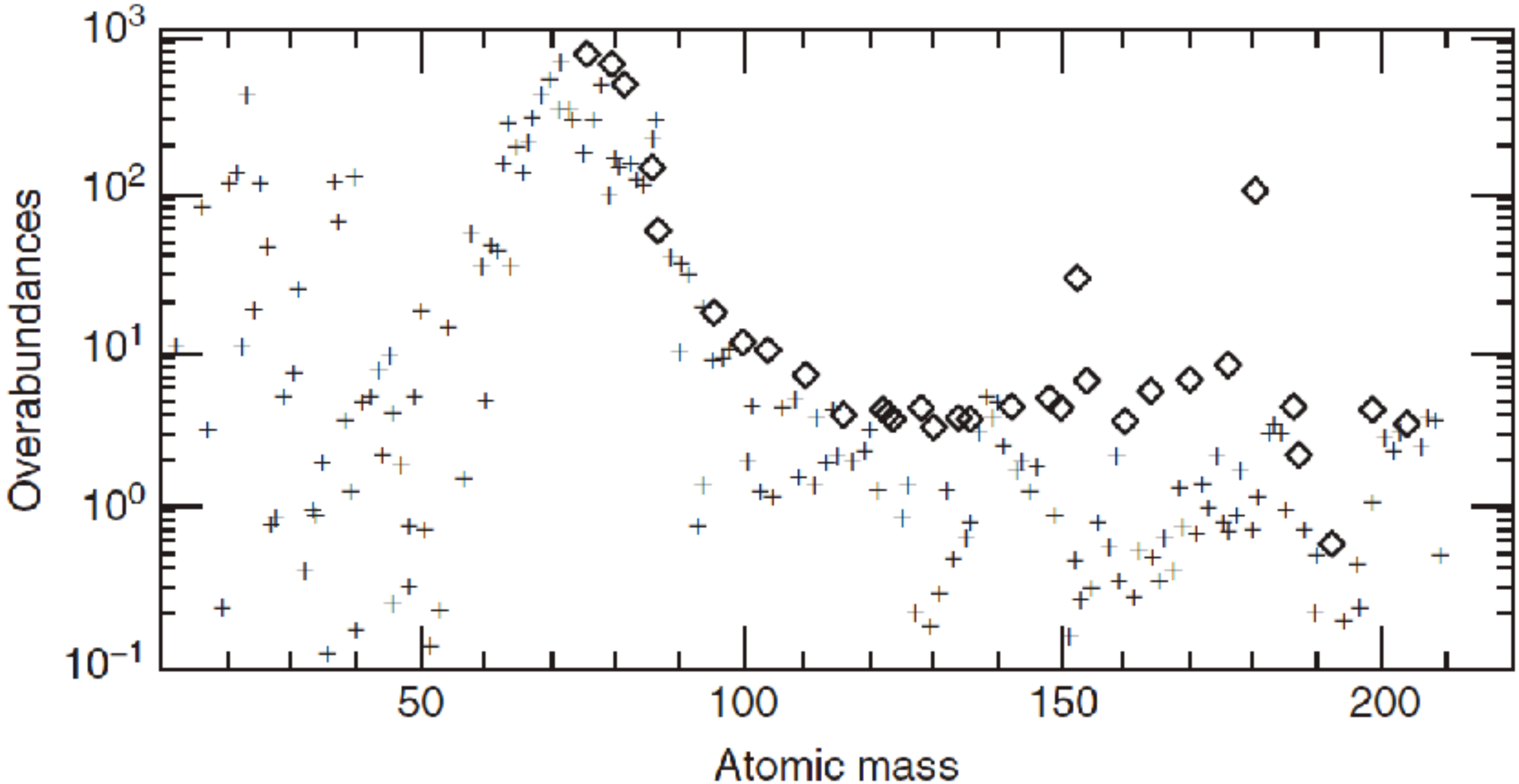
s-process sites

Heavy-element abundances in a thermal pulsating AGB star

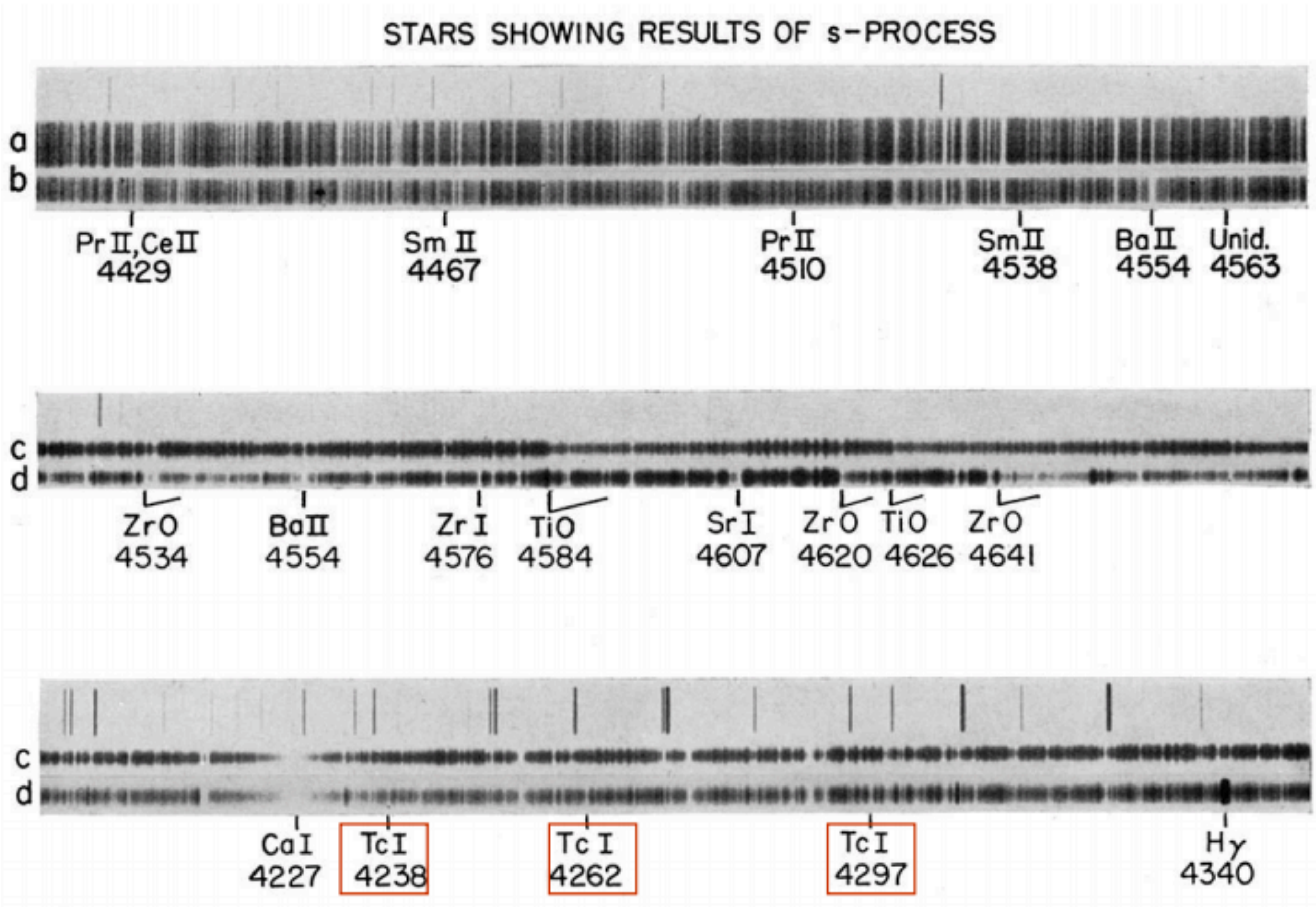


s-process sites

Heavy-element abundances in a 25M_{sol} giant during core carbon burning

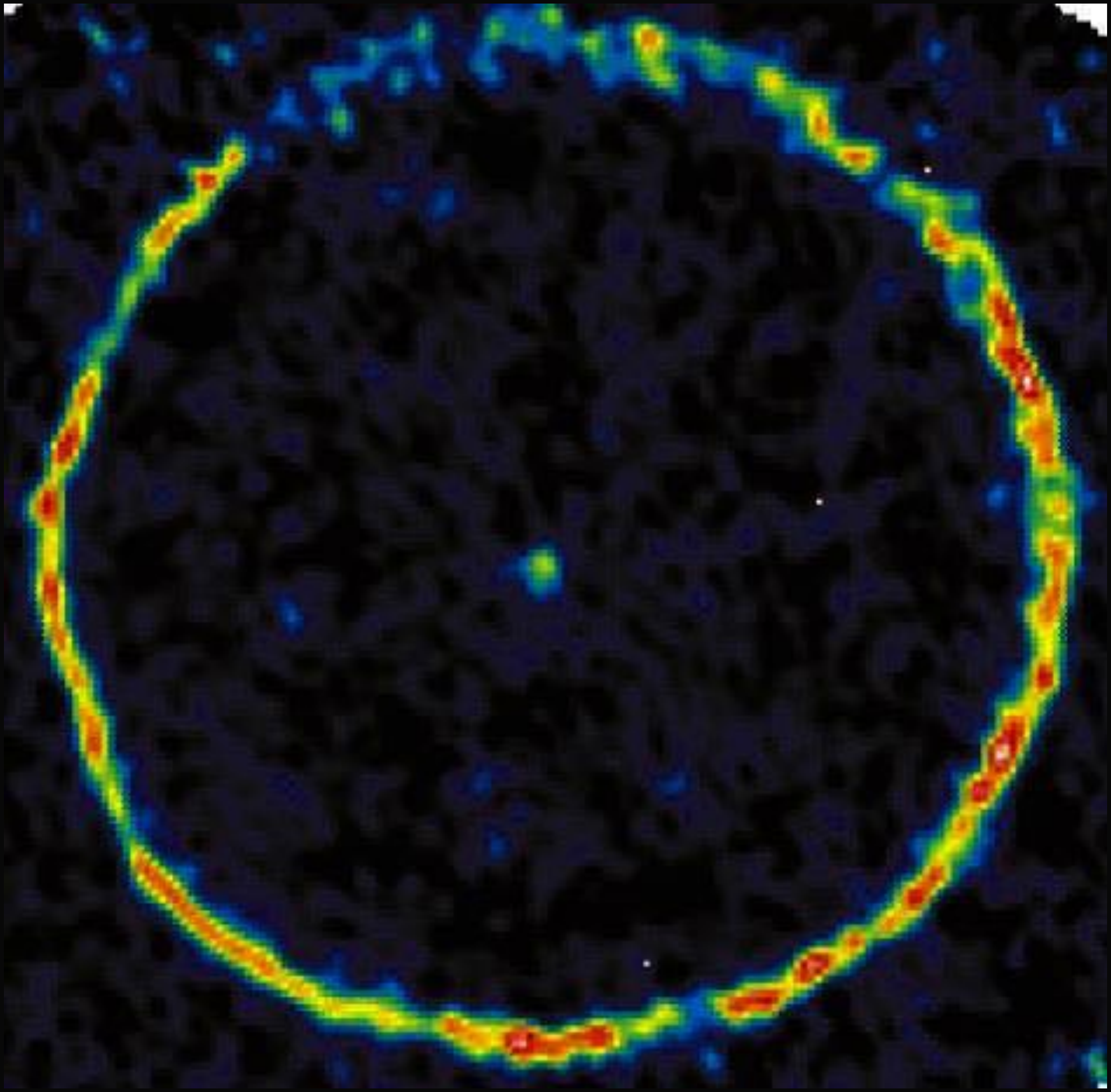


s-process sites



s-process sites

Carbon-rich AGB star TT Cygni



in conclusion

Only 3% of iron peak elements are needed to synthesise all heavy elements

At certain stages of a star’s life, large neutron fluxes are produced in the stellar interior

The neutron-capture cross sections of heavy elements are large compared to those of light elements. The cross sections generally do not depend much on temperature

The structure of the observed abundance curve can be explained in terms of two distinct processes (r- and s-process)

Elements produced by only by the s-process in turn require multiple components (environments). These can be inferred from the observed abundances using a simple model

Direct observations (e.g. Te lines) demonstrate conclusively that the s-process operates in stars