The s-process for the synthesis of the heavier than iron (HTI) elements

It works 

 or it does not work?

Giora Shaviv Vulcano 2012

Astrophysics and Space Science Library 387

Giora Shaviv

The Synthesis of the Elements

The Astrophysical Quest for Nucleosynthesis and What It Can Tell Us About the Universe

This book describes the origins and evolution of the chemical elements we and the cosmos are made of. The story starts with the discovery of the common elements on Earth and their subsequent discovery in space. How do we learn the composition of the distant stars? How did progress in quantum theory, nuclear physics, spectroscopy, stellar structure and evolution, together with observations of stars, converge to provide an incredibly detailed picture of the universe? How does research in the micro-world explain the macro-world? How does progress in one affect the other, or lack of knowledge in one inhibit progress in the other? In short, Shaviv describes how we discovered the various pieces of the jigsaw that form our present picture of the universe; and how we sometimes put these in the wrong place before finding in the right one.

En route we meet some fascinating personalities and learn about heated controversies. Shaviv shows how science lurched from one dogma to the next, time and again shattering much of what had been considered solid knowledge, until eventually a stable understanding arose.

Beginning with generally accepted science, the book ends in today's terra incognita of nuclear physics, astrophysics and cosmology. A monumental work that will fascinate scientists, philosophers, historians and lay readers alike.

Astronomy / Astrophysics

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How it is supposed to work

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Where do you get neutrons from?

How it is supposed to work

Problems: does it work?

Neutron capture processes

Two limits:

Slow neutron capture: 10^6 or more years

Rapid capture:<1 second

There is no (in theory?)‘in between’ process

How much there is to synthesize?

There are 170 nuclei with $Z>30$ per 2.8×10^{10} protons

$Fe = 9.0\times10^5$, $Co = 2.3\times10^3$, $Ni = 5.0\times10^4$, $Cu = 4.5\times10^2$, and $Zn = 1.1\times10^3$

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So we have to convert 1.8×10^{-4} of the Fe group into HTI nuclei

If these nuclei are formed by means of neutron capture, we need at least 1.5×10^4 neutrons, which is almost one neutron per iron nucleus.

The calculation is $170 \times (240 - 56)/2 = 1.5 \times 10^4$ where $(240 - 56)/2$ is the mean number of neutrons needed to synthesize the elements between A = 56 and A = 240, and 170 is the total number of nuclei.
100% efficiency is assumed.

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So, while the energetic demands are negligible, the source of neutron is a crucial problem

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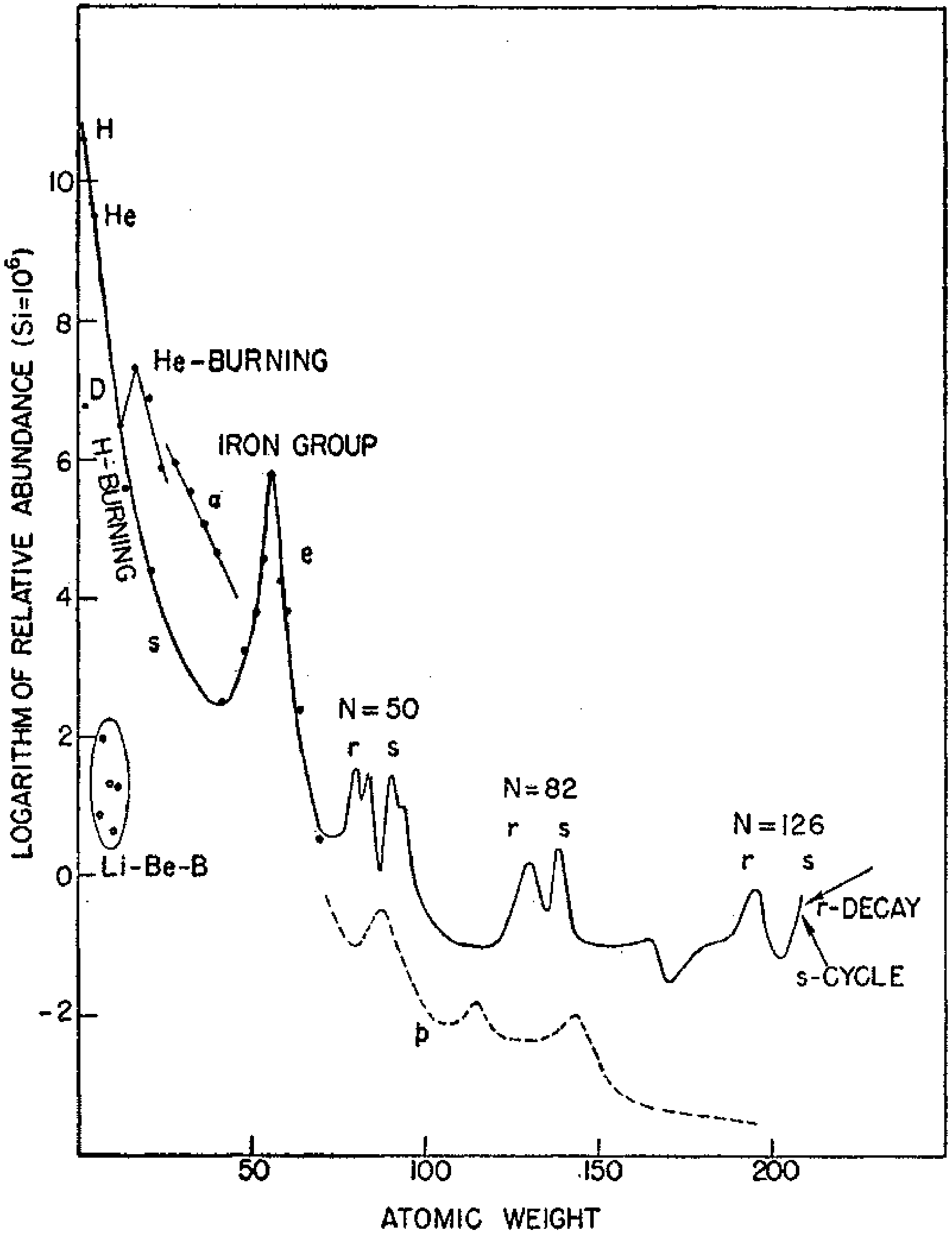
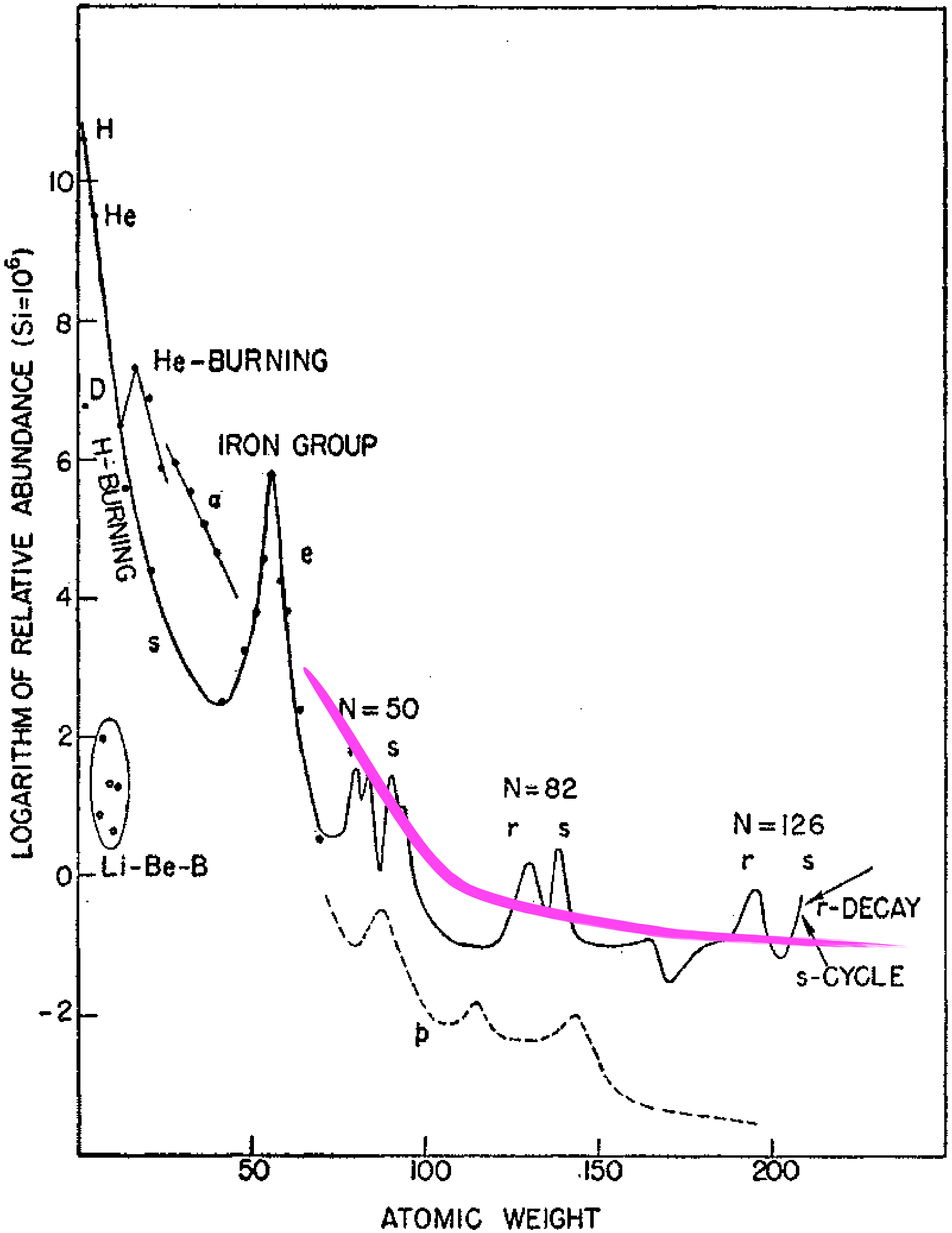
Mayer & Teller idea of fission of a super heavy nucleus only shifts the problem.

The α β γ is quite successful for A>100.



The schematic cosmic abundances of the elements as depicted by Burbidge, Burbidge, Fowler and Hoyle 1957 (The Bible of Stellar Nucleosynthesis)



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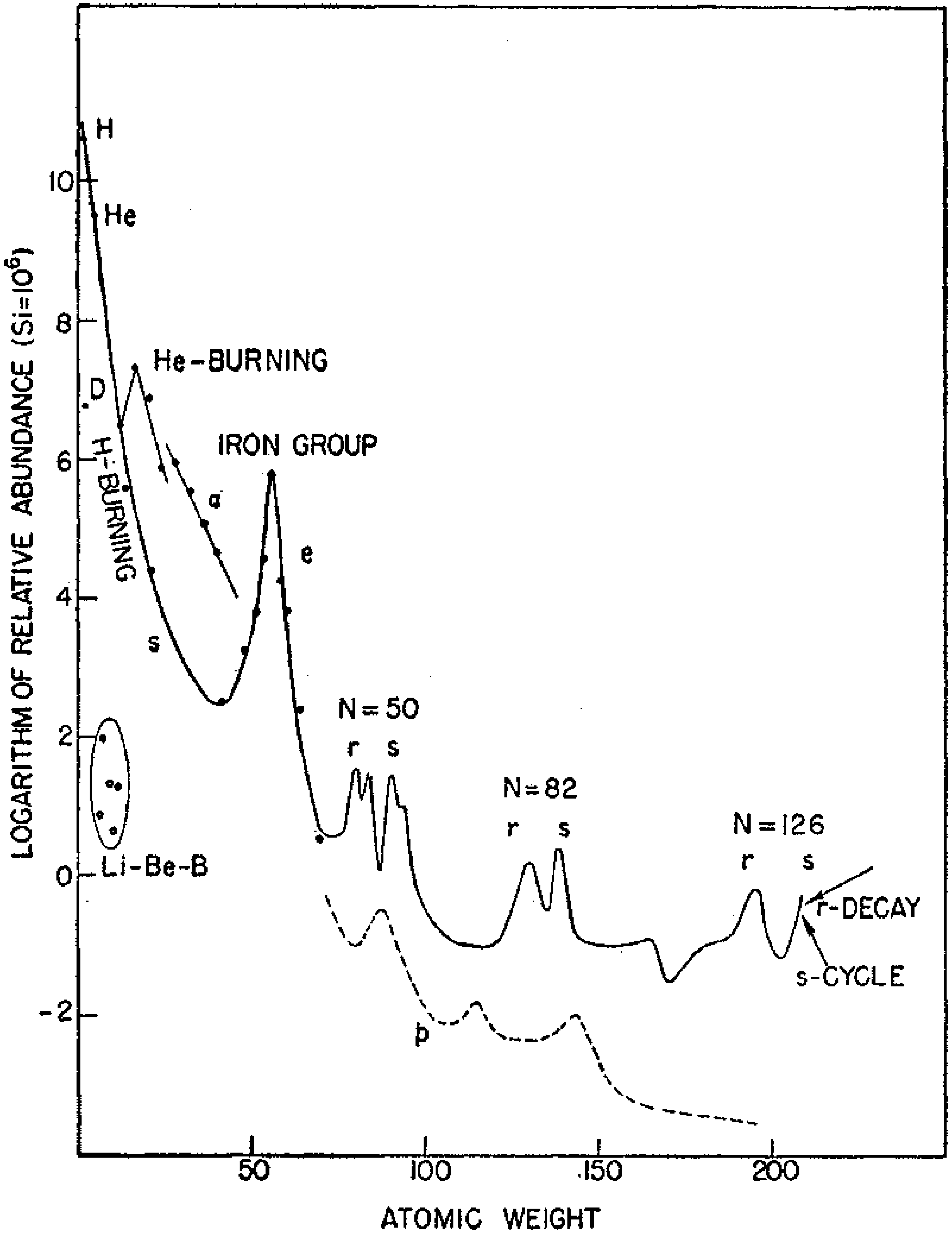

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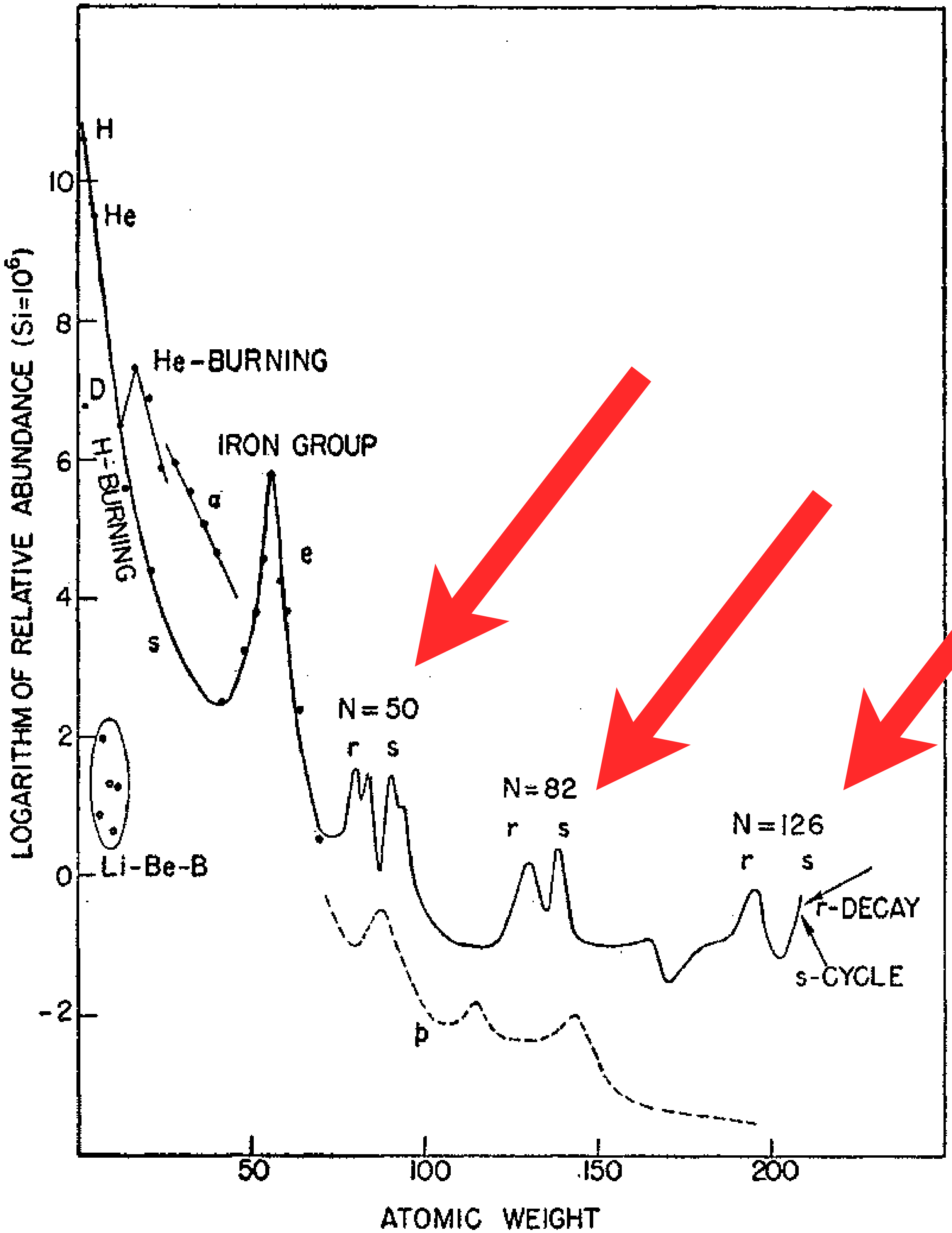
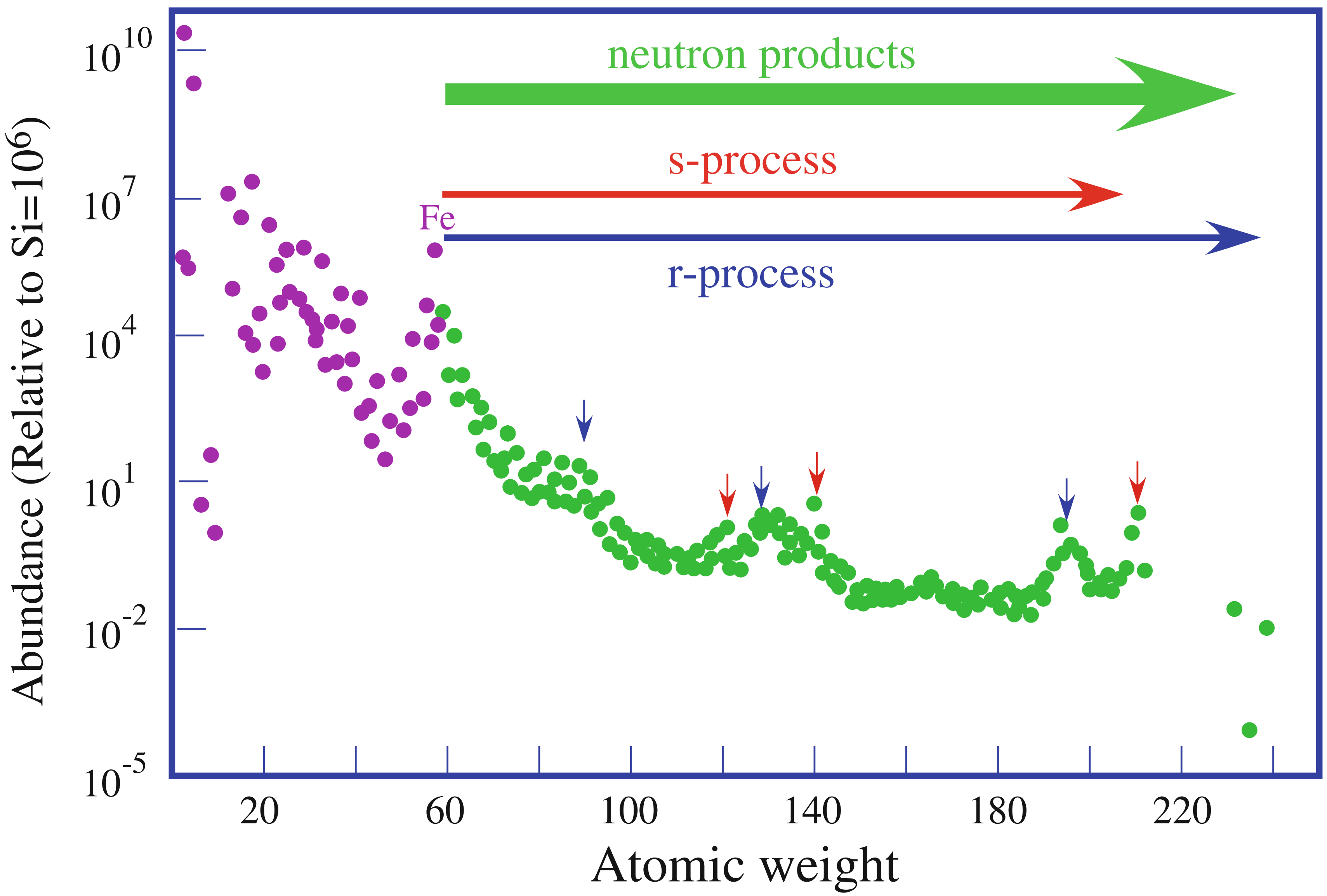


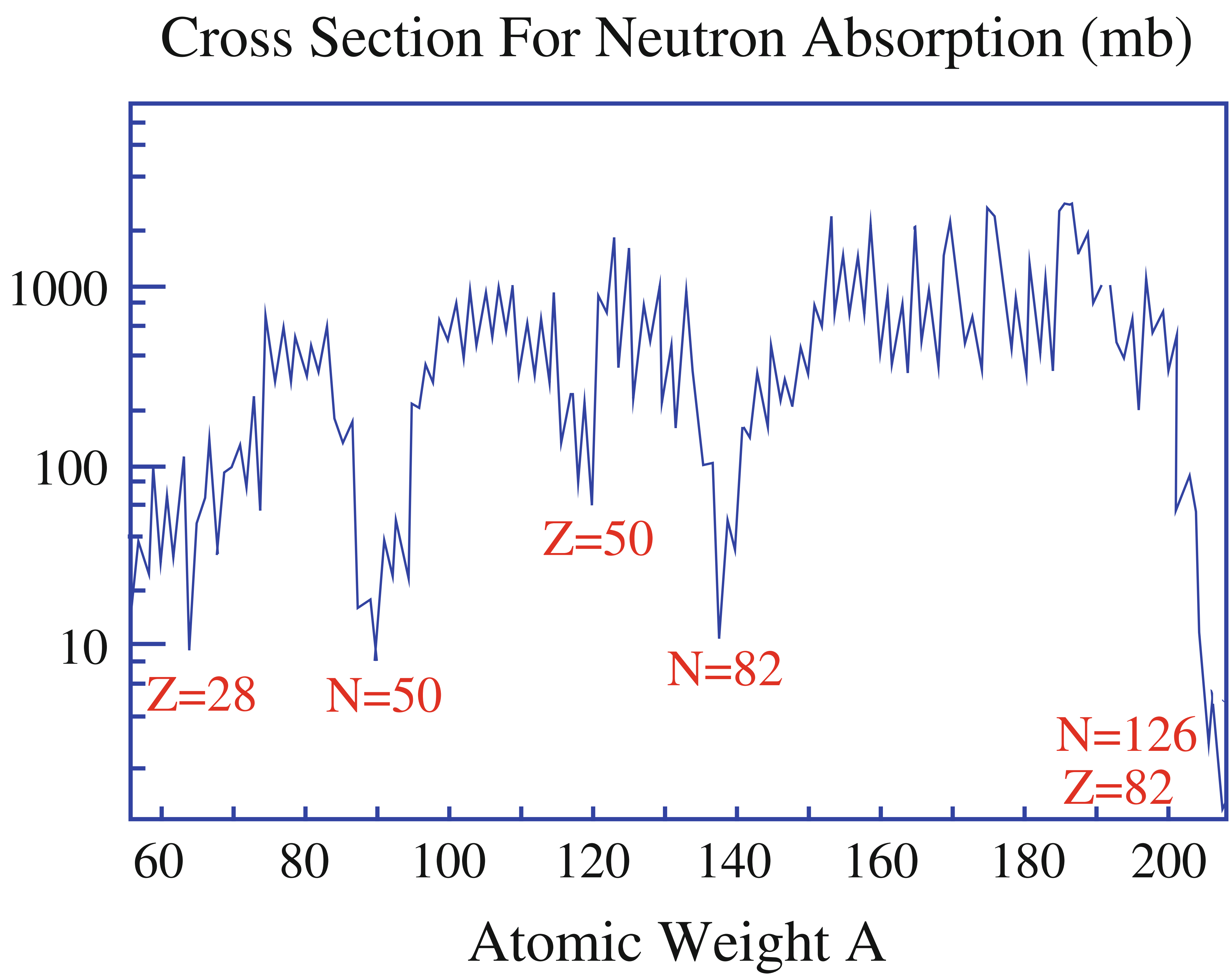
The schematic cosmic abundances of the elements as depicted by Burbidge, Burbidge, Fowler and Hoyle 1957 (The Bible of Stellar Nucleosynthesis)

1956 Suess & Urey: no single theory can explain all the abundances of the nuclei and isotopes.

So B2FH invented the s-process and for the fast process "invented" the fast rate

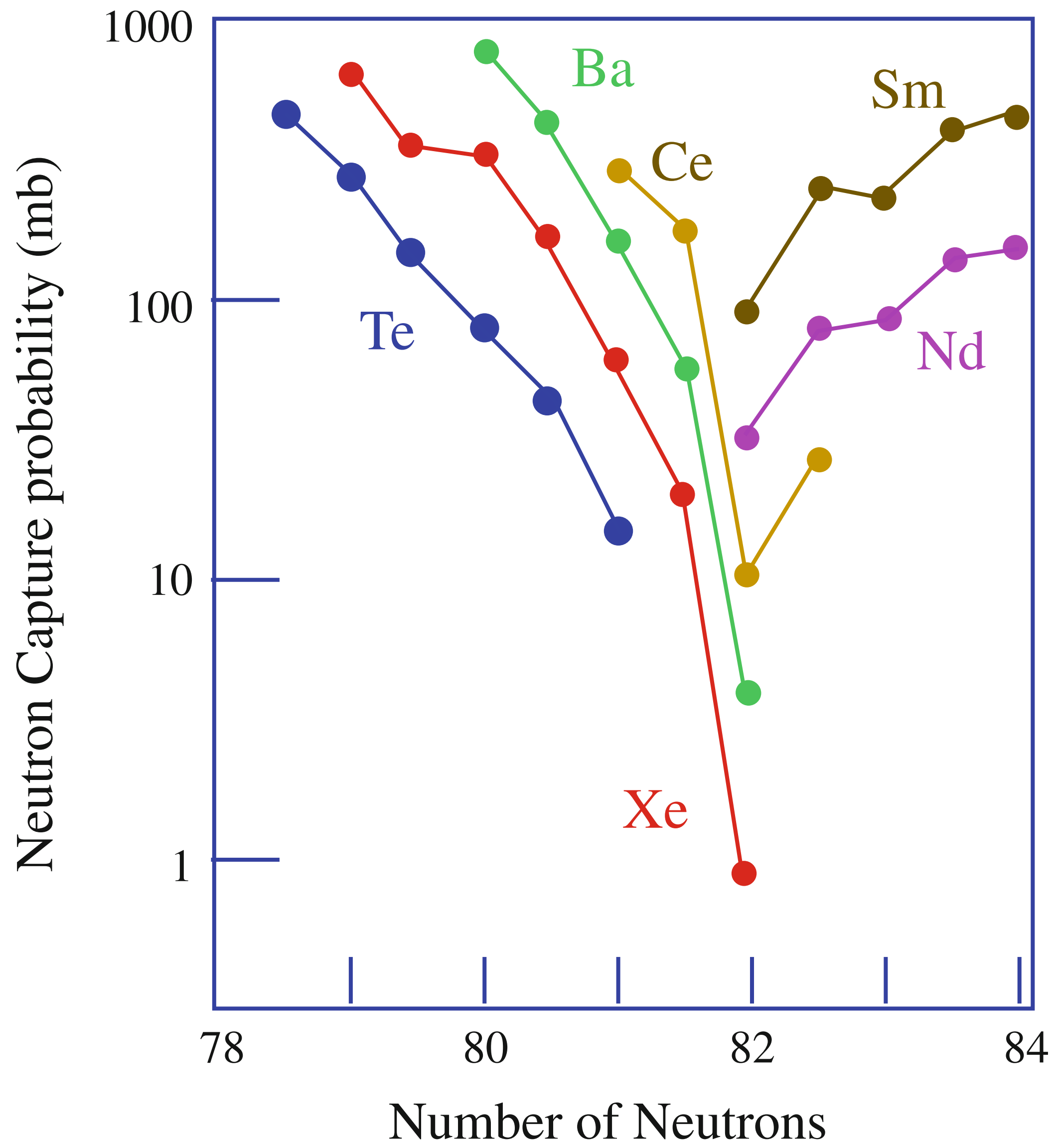
Present day conventional view of synthesis process



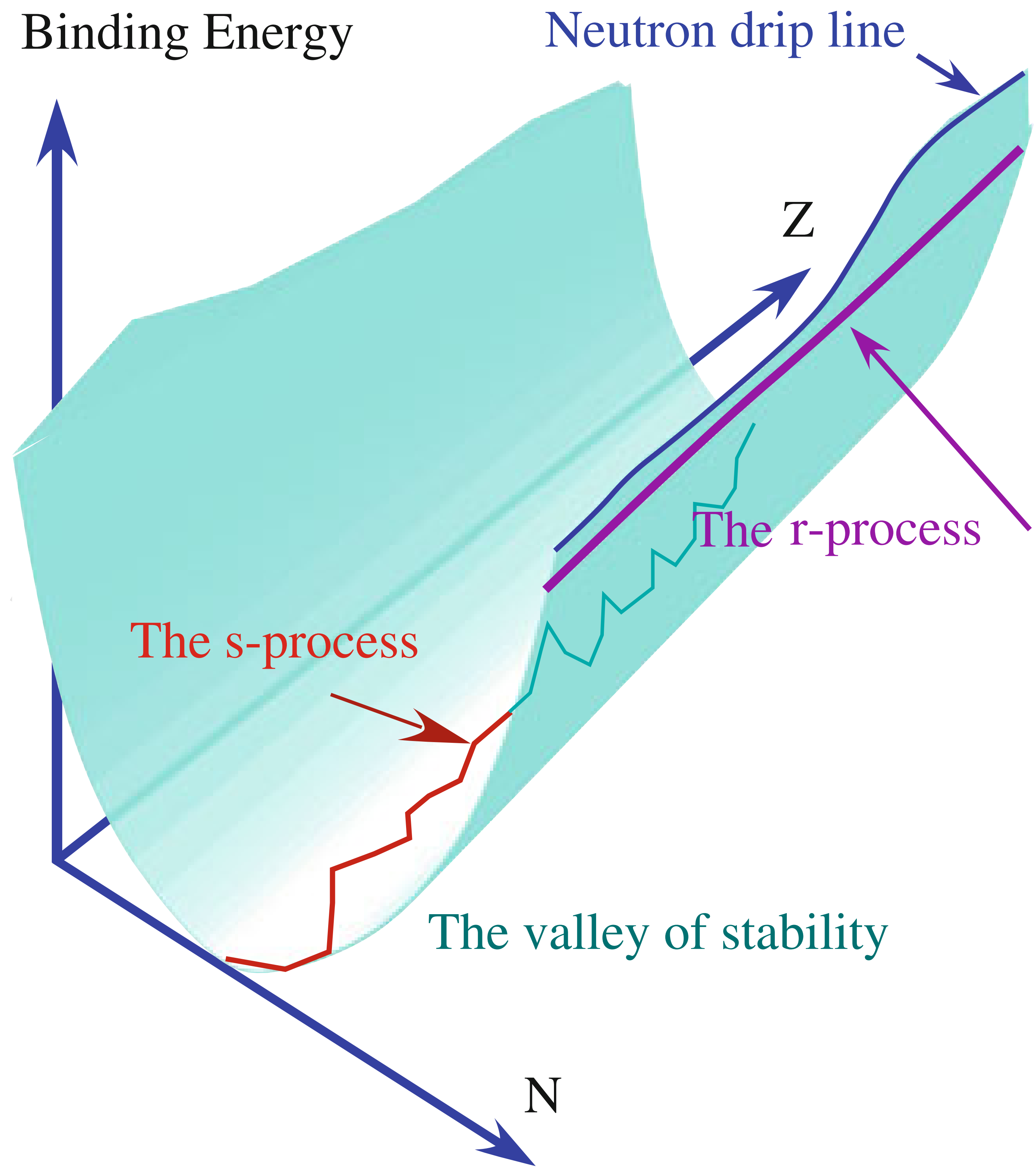


Shell model essentials

The effect of magic number on neutron absorption



Since the s-process
has a time scale longer
than any β-decay time,
it runs along
the bottom of the
valley of stability



The neutron capture continues until nuclei become unstable against α decay, hence the process cannot synthesize elements heavier than Lead

The last reaction is:

$$\mathrm{Bi}^{209} + \mathrm{n} \longrightarrow {}^{206}\mathrm{Pb} + \alpha\,.$$

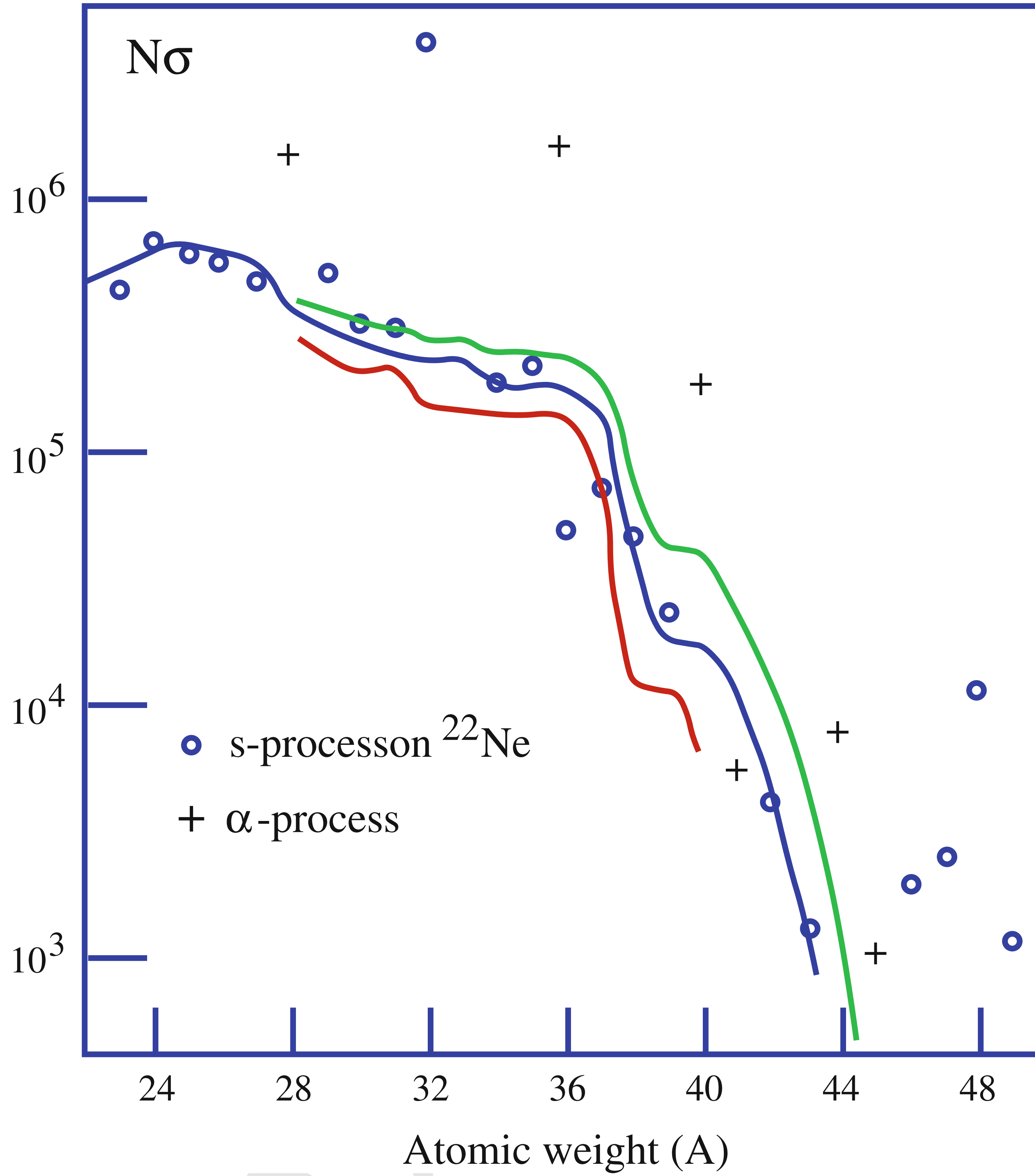
Atomic weight A	Cd_{48}	In_{49}	Sn_{50}	Sb_{51}	Te_{52}	I_{53}	
130					>Hubble	12h	130
129					70m	1.7x10^7yrs	129
128					>Hubble	25m	128
127					9.3h	stable	127
126					stable	13d	126
125				2.7yrs	stable	59d	125
124				60d	stable	4.2d	124
123			129d	stable	stable	13h	123
122	50s	1.5s	stable	2.7d	stable	3.6m	122
121	13s	23s	27h	stable	19d	2.1h	121
120	50s	3.1s	stable	16m	stable	81m	120
119	2.7m	2.4m	stable	38h	16h	19m	119
118	50m	5.0s	stable	3.6m	6d	13m	118
117	2.5h	43m	stable	2.8h			117
116	>Hubble	14s	stable	16m			116
115	53h	4.4x10^{14}yr	stable	32m			115
114	stable	72s	stable	3.5m			114
113	>Hubble	stable	115d	6.7m			113
112	stable	15m	stable	51s			112
111	stable	2.8d	35min	75s			111
110	stable	4.9h	4.11h	23s			110

Atomic number Z

Assuming steady state and not time dependent irradiation

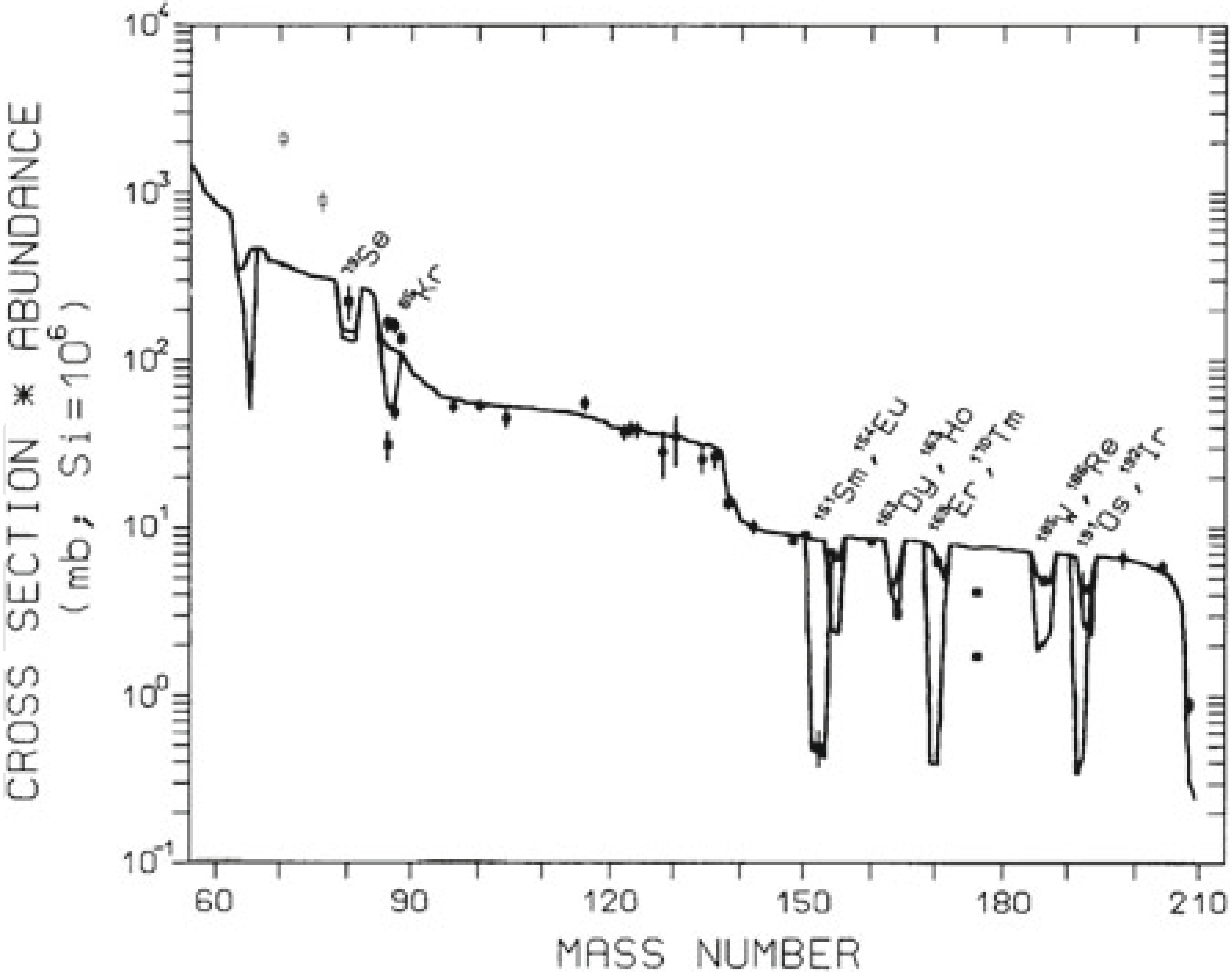
Nσ=Const

First result of B2FH



Progress made in over 30 years

KÄPPELER *ET AL.*



The idea of time dependent irradiation

Time dependent exponential irradiation

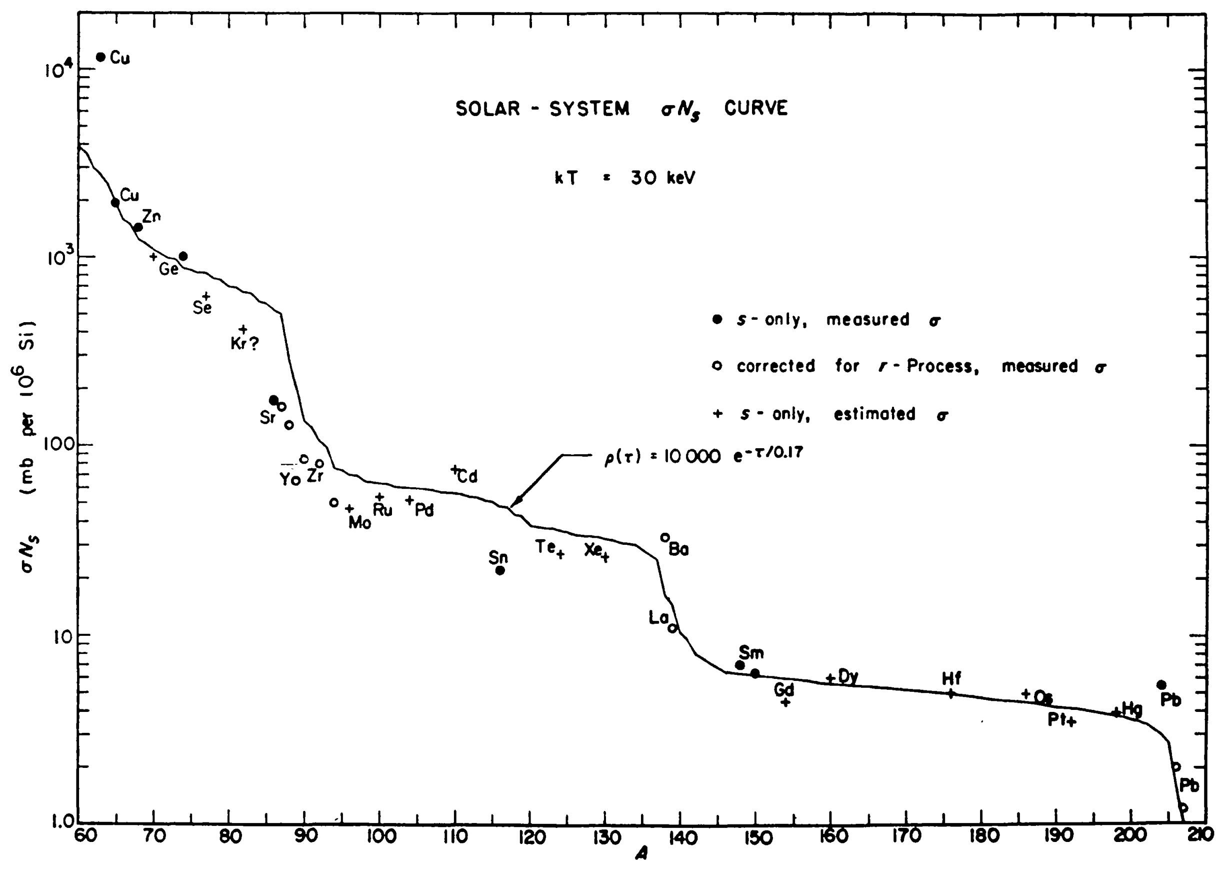


Figure 12.15: *The solid line is a calculated curve corresponding to an exponential distribution of integrated neutron flux. After Seeger et al 1965.*

The idea of time dependent irradiation

Time dependent exponential irradiation

But: three irradiation periods were assumed

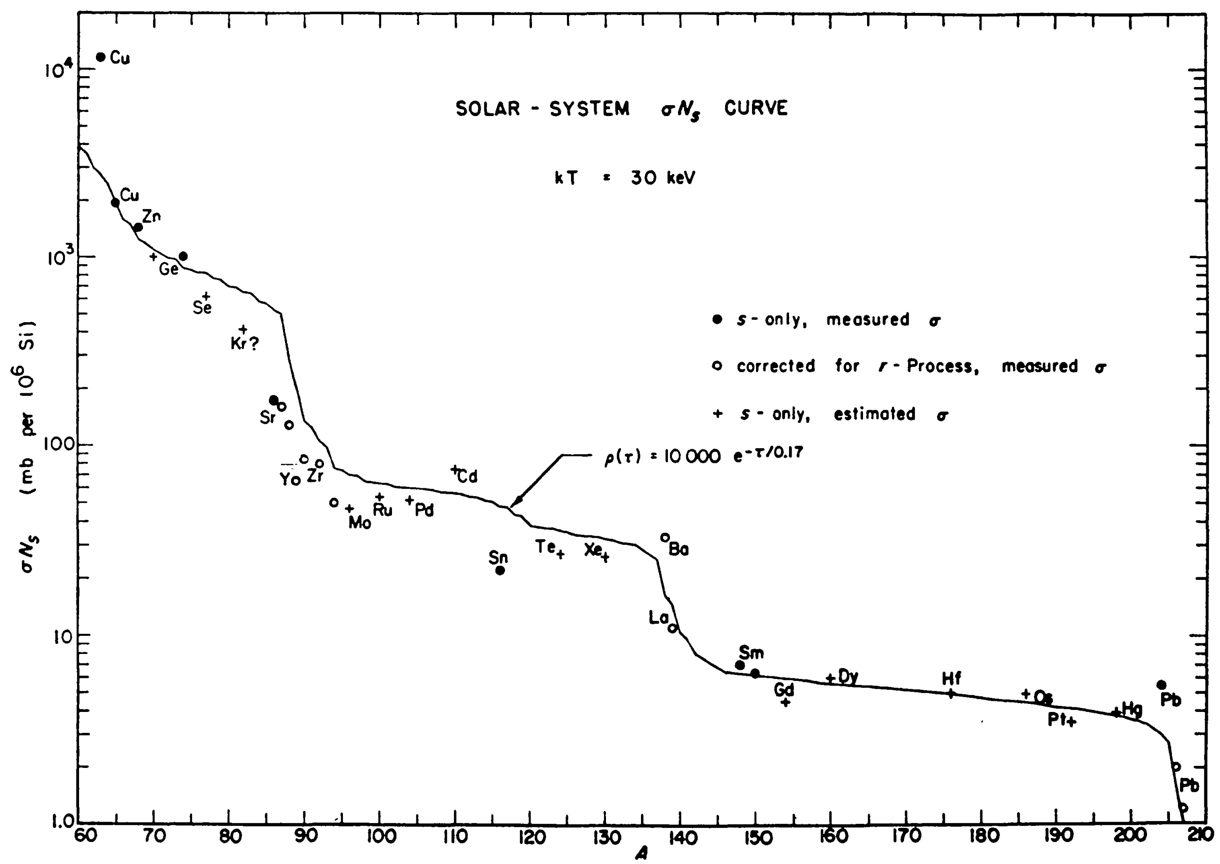
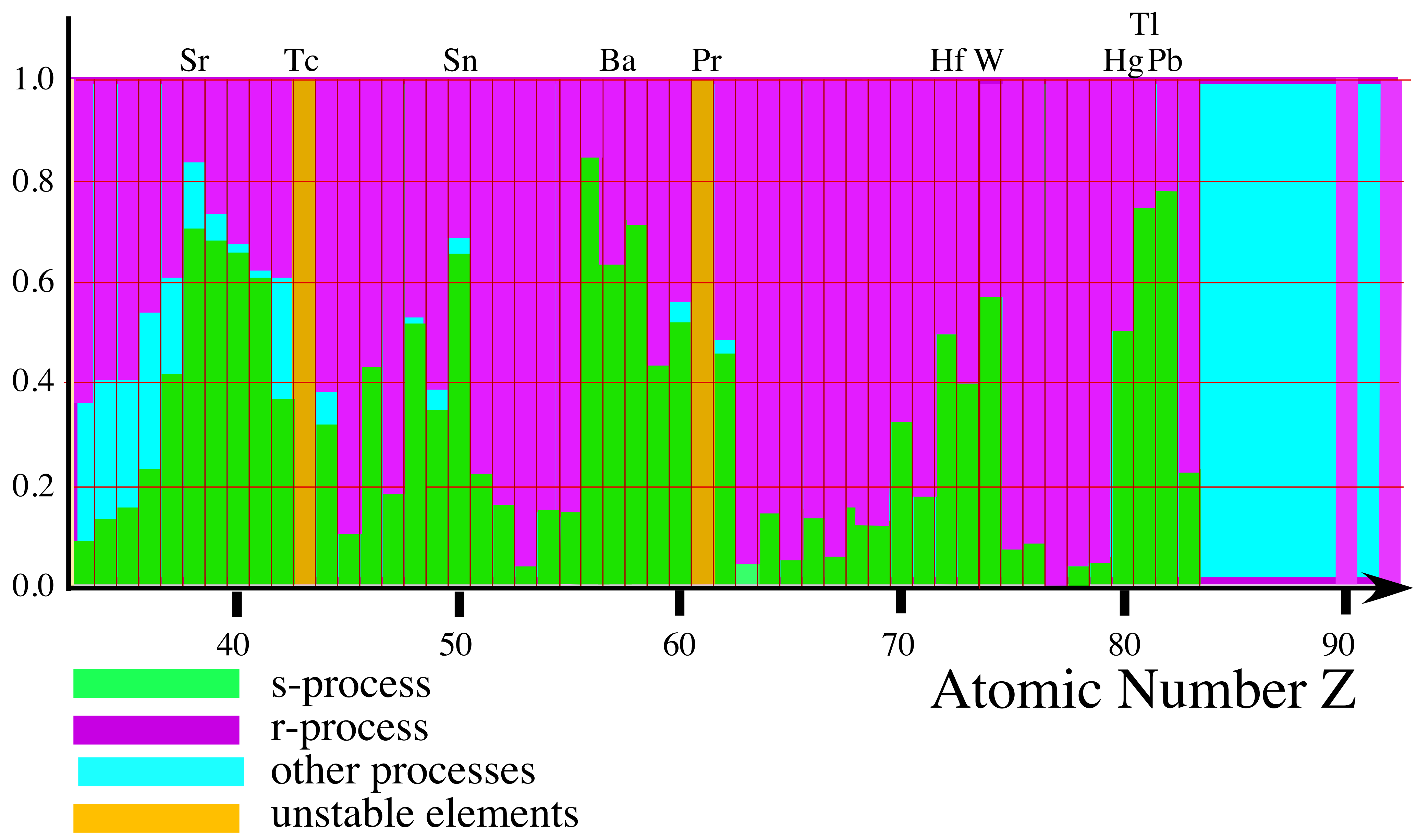


Figure 12.15: *The solid line is a calculated curve corresponding to an exponential distribution of integrated neutron flux. After Seeger et al 1965.*

Solar system elements classification



The fundamental problemS in the s-process:

find a stellar site, with seed nuclei,

good neutron sources,

that eventually is ejected to space

Neutron sources

Greenstein, who was an astronomer and not a nuclear physicists, and independently by Cameron, realized that the exothermic reaction

$^{13}C + \alpha \rightarrow {}^{16}O + n + 2.2MeV$

is good stellar neutron source. Indeed, this reaction is the most important and famous neutron source for synthesizing the nuclei in the s-process.

B2FH added the following exothermic reactions:

$$^{17}O+\alpha \longrightarrow {}^{20}Ne+n+0.60MeV$$
$$^{21}Ne+\alpha \longrightarrow {}^{24}Mg+n+2.58MeV$$
$$^{25}Mg+\alpha \longrightarrow {}^{28}Si+n+2.67MeV$$
$$^{26}Mg+\alpha \longrightarrow {}^{29}Si+n+0.04MeV$$

The next reactions in this series are endothermic, namely, the reactions need energy to proceed,

$$^{29}Si + \alpha + 1.53\,MeV \longrightarrow {}^{32}S + n$$

$$^{33}S + \alpha + 2.0\,MeV \longrightarrow {}^{36}A + n$$

Most of the seed nuclei are rare (large changes in abundances are expected)

α particles should be around (if it is during He burning, there will be plenty, else you call for photoionization of α nuclei)

The targets of the α particles in the generation of the neutrons are outside the main stream of synthesized nuclei.

This fact is of fundamental importance because it allowed to model the *s*-process without attaching it to a specific stellar model. The stellar model does affect the s-process, but the s-process has no effect on the structure or evolution of the star.

But it deals with trace elements and minute energy consumption. The targets are rather rare species and hence, can provide only limited amounts of neutrons.

If the scarcity of neutrons is not sufficient to worry the theoreticians, another problem is the existence of large amounts of ^{14}N which are for our purposes here a poison for neutrons via the reaction

$$^{14}N+n \longrightarrow {}^{14}C+p \longrightarrow {}^{14}N+\beta^-$$

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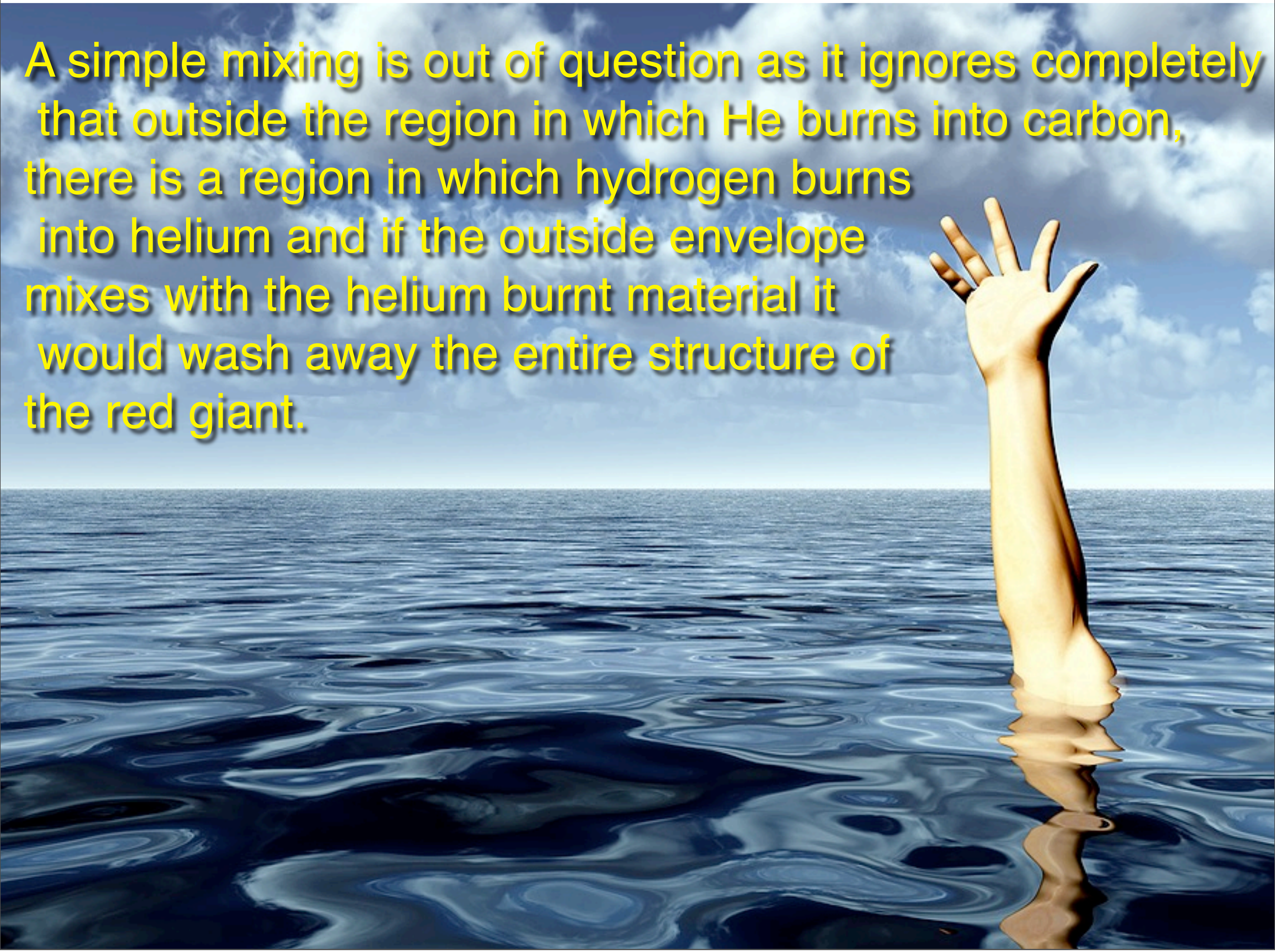
How to square the circle?

FB2 (already in 1955) and later B2FH (in 1957) reiterated the supposition, hypothesized ingeniously that:

During the critical phase in which neutrons are released, the product of the 3α reaction, 12C, which should be abundant, mixes with the envelope and the mixing brings fresh hydrogen-rich material into the burning zone. Consequently, the hydrogen interacts with the 12C and converts it to 13N that decays into 13C, which is then available for an additional absorptior of an α and the release of neutrons.


A simple mixing is out of question as it ignores completely
that outside the region in which He burns into carbon,
there is a region in which hydrogen burns
into helium and if the outside envelope
mixes with the helium burnt material it
would wash away the entire structure of
the red giant.

B2FH hypothesized therefore, that sporadic mixing between the burning zone and the unburnt envelope leads to a continuous supply, not too much but just in measure, of raw materials needed for the production of neutrons.

Moreover, at the same time, ^{12}C is dredged-up by the same hypothesized mixing from the burning zone into the envelope and creates a star with a surface rich in carbon.

Thus, the known ’carbon stars’ should be, a la` B2FH, the location where neutrons are released and build the HTI nuclei.

B2FH did not calculate a stellar model in which the mixing mechanism operates nor did they propose any specific sporadic mixing mechanism. It was just a scenario.

It should be noted that already Cameron in 1954, while suggesting the ^{13}C reaction, realized the problem with the supply of neutrons. Cameron stated therefore,

that the ^{13}C reaction is particularly important in those stars with appreciable internal circulation.

What circulation, timescales, mechanism etc were however, not specified.

In 1952 Merrill discovered technetium (^{98}Tc) in S type stars namely, a late-type giant star whose spectrum displays the existence of s-process elements in the star, like zirconium and yttrium.

Technetium is radioactive with half lifetime of 4.2×10^{6}yrs, which is much shorter than the lifetime of the star and hence, must have been produced recently inside the star and brought up to the surface.

Thus, evidence that 'some mixing' between the internal furnace and the envelope takes place, was there.

Technetium was discovered in Palermo (Segre)-
use in medicine ^{99}Tc

The title of Merrill's paper was:

Spectroscopic Observations of Stars of Class S, (ApJ, 116, 21, 1952).

The boring title Merrill chose for his paper hides the great discovery.

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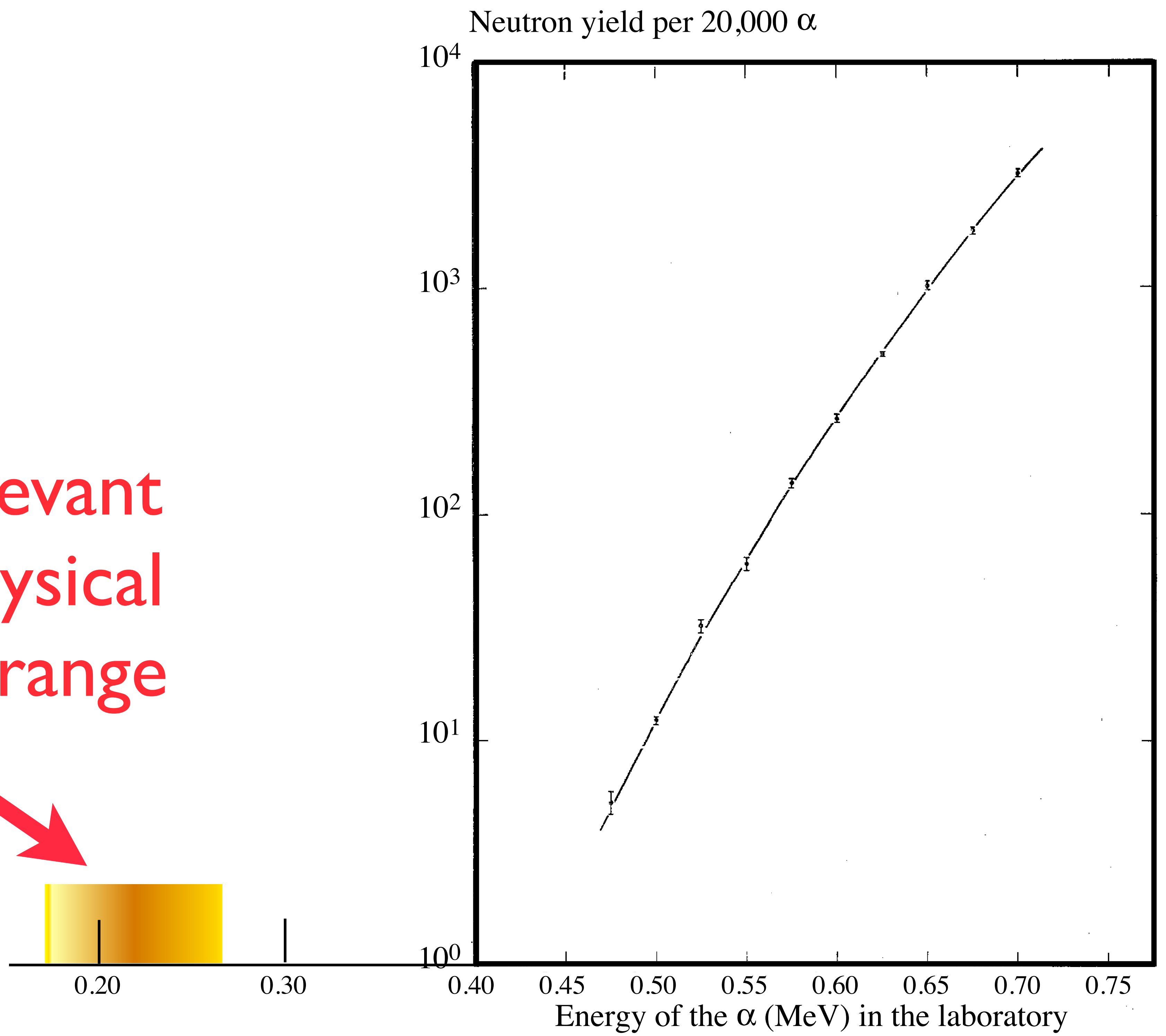
The boring title Merrill chose for his paper hides the great discovery.

In these days practice the title would have been

At long last: The first ever discovery and proof on nuclear reactions in stars.

The neutron source problem

Insufficient nuclear data problem

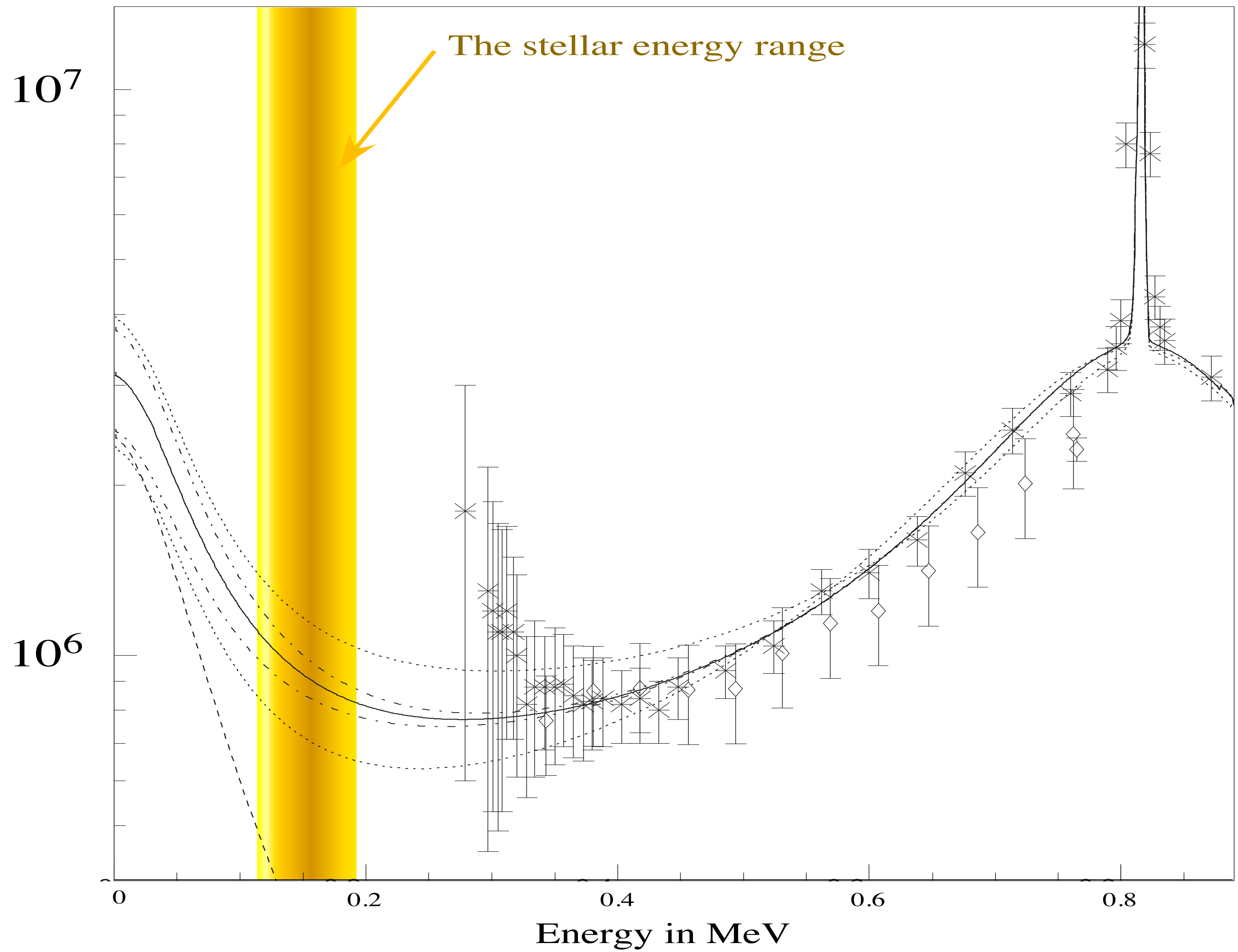


The relevant astrophysical energy range

$^{13}C+\alpha \longrightarrow {}^{16}O+n$

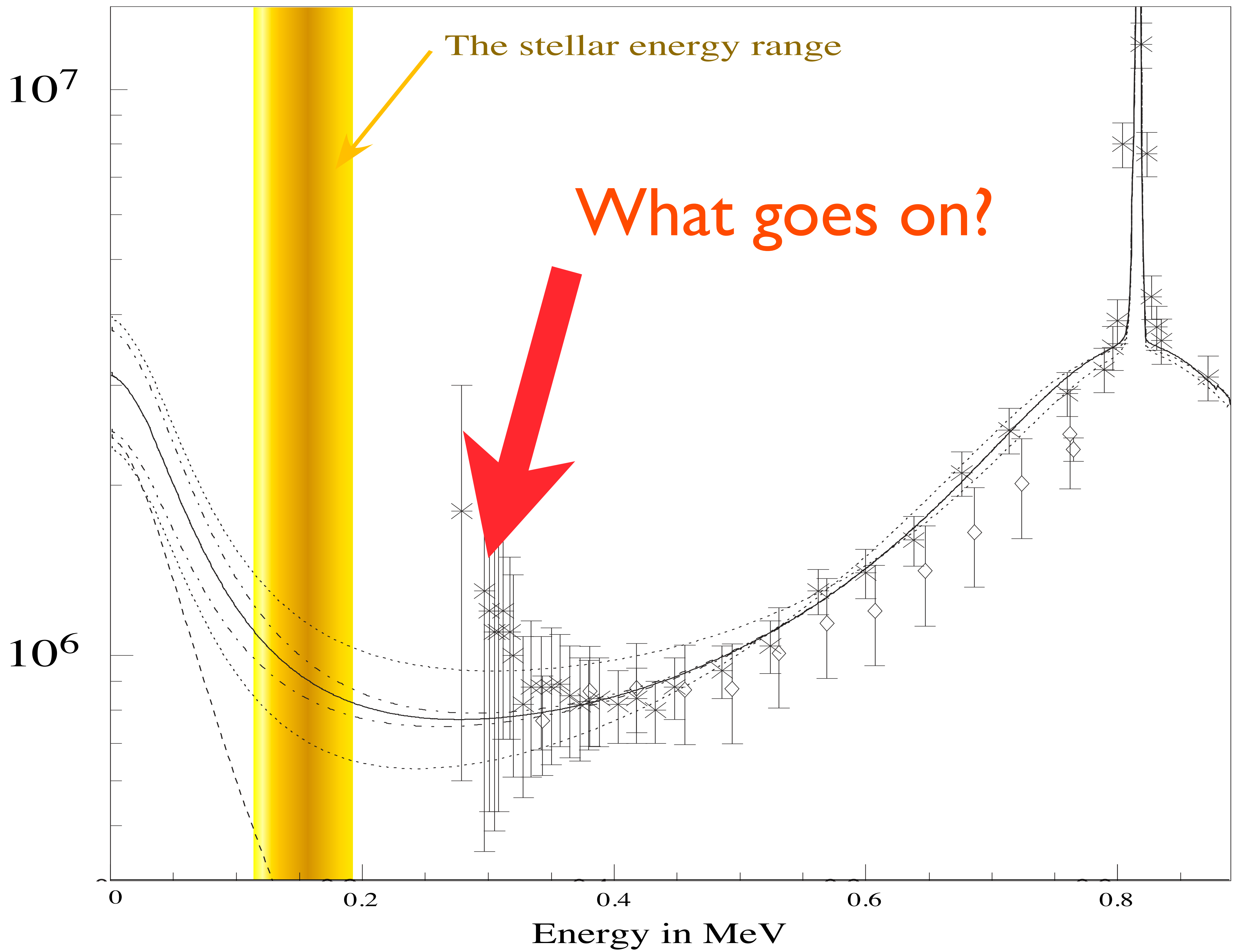
Davids 1968

The S factor for the $^{13}C+\alpha \rightarrow {}^{16}O+n$

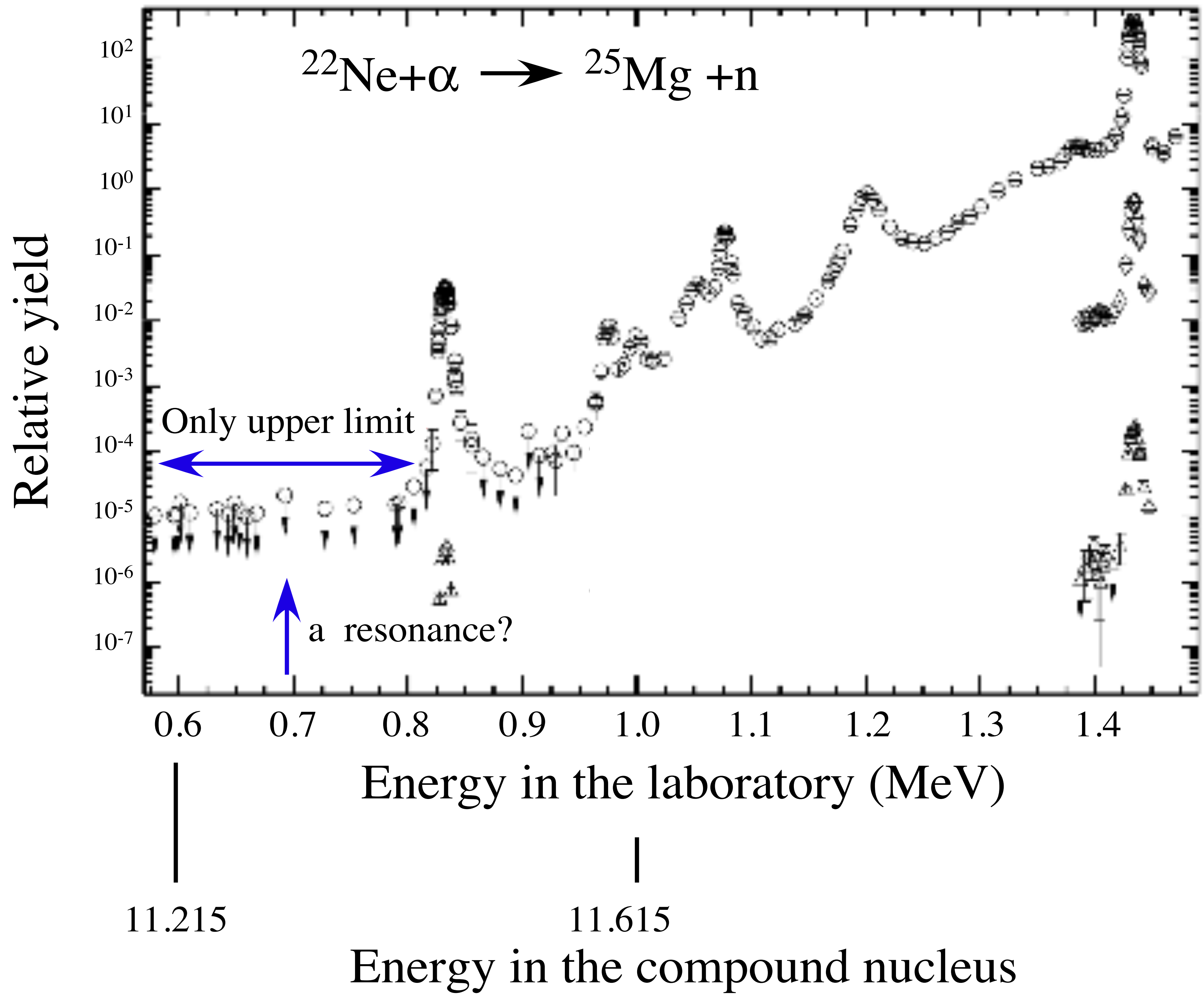


Johnson 2006

The S factor for the $^{13}C+\alpha \rightarrow {}^{16}O+n$

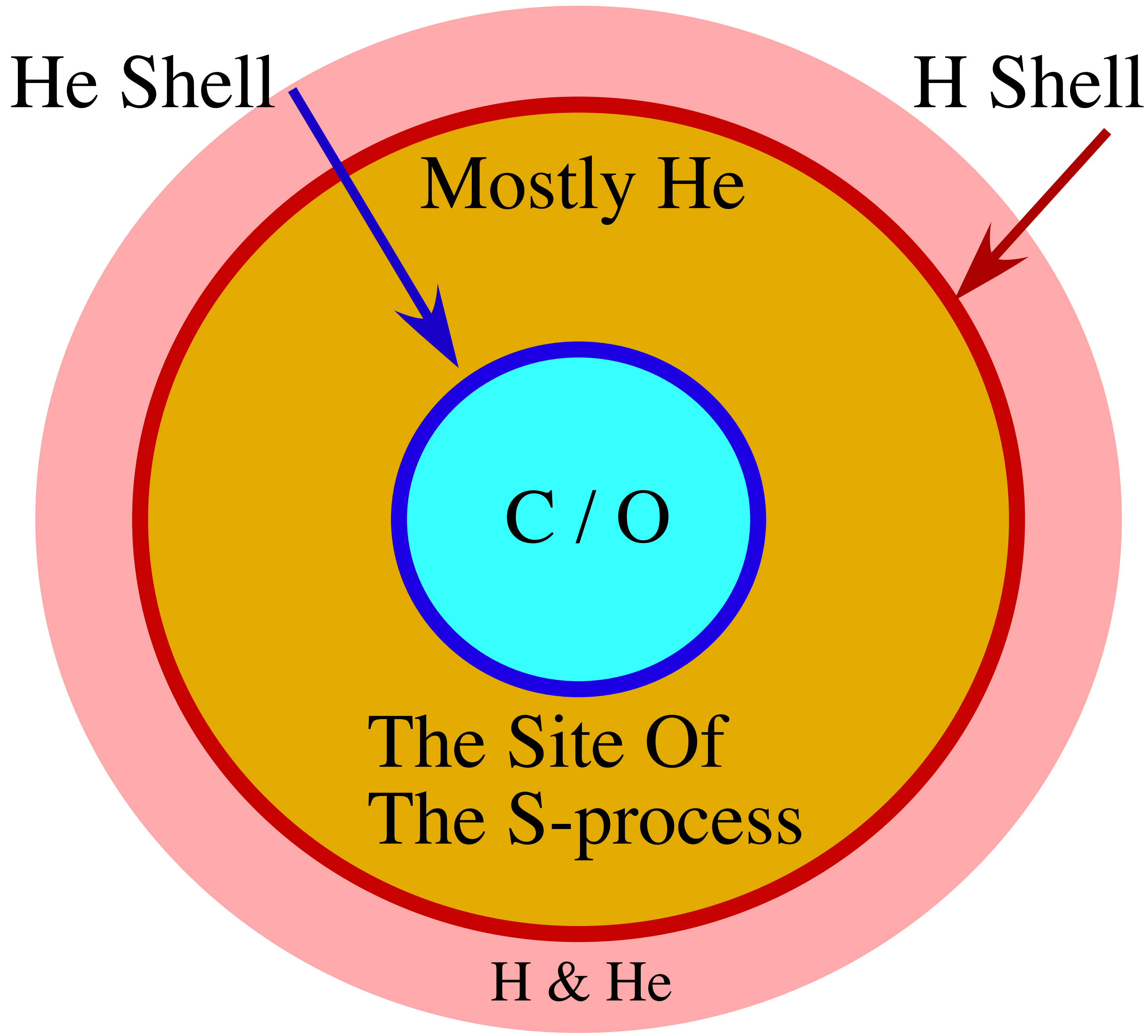


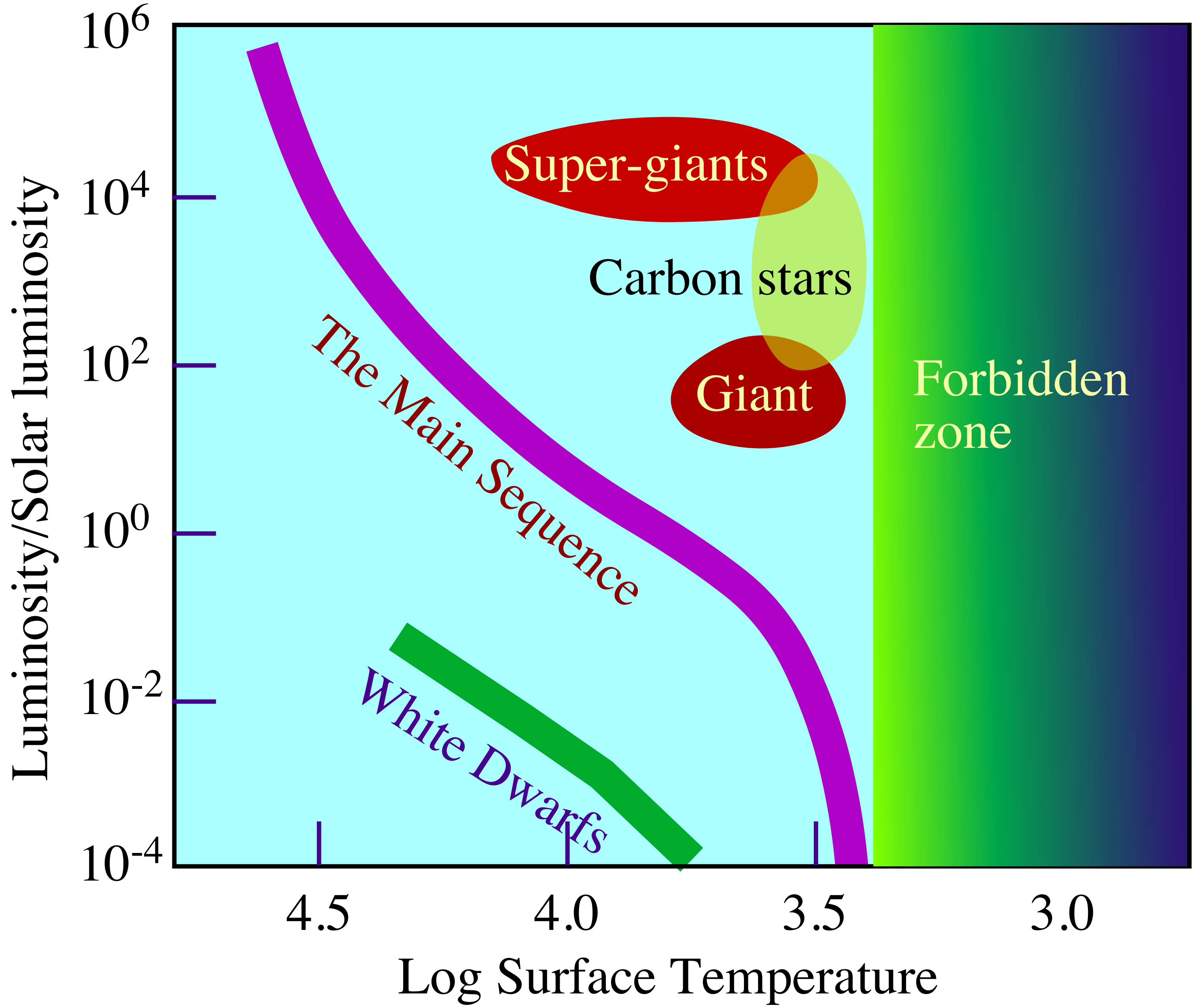
Johnson 2006



$^{22}Ne+\alpha \rightarrow {}^{25}Mg + n$
Relative yield
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Only upper limit
a resonance?
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
Energy in the laboratory (MeV)
11.215
11.615
Energy in the compound nucleus

Jaeger 2001


He Shell
H Shell
Mostly He
C / O
The Site Of
The S-process
H & He



10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
Luminosity/Solar luminosity
Super-giants
Carbon stars
Giant
The Main Sequence
White Dwarfs
Forbidden zone
4.5
4.0
3.5
3.0
Log Surface Temperature

The Rosetta Stone: FG Sagittae

In 1960 Richter FG Sagittae changed its luminosity by a factor of about 50 since the beginning of the twentieth century, on top of which smaller luminosity variations were observed. Richter gave no information about something unusual with respect to *s*-process elements.

During the years 1960-1967 the spectra of the star was investigated by Herbig and Boyarchuck who found that the spectra changed during the 7 years of observations from a B8 Ia to A5 Ia, which means cooling.

The dramatic change took place when Langer et al discovered that the spectral lines of several s-process elements began to appear in the spectra of FG Sagittae sometimes in 1967 and since then they increased their strength with time to the point that present day values are about 25 times the solar value.

Kraft, taken aback by the phenomenon, named the star as the ’Rosetta stone of nucleosynthesis’.

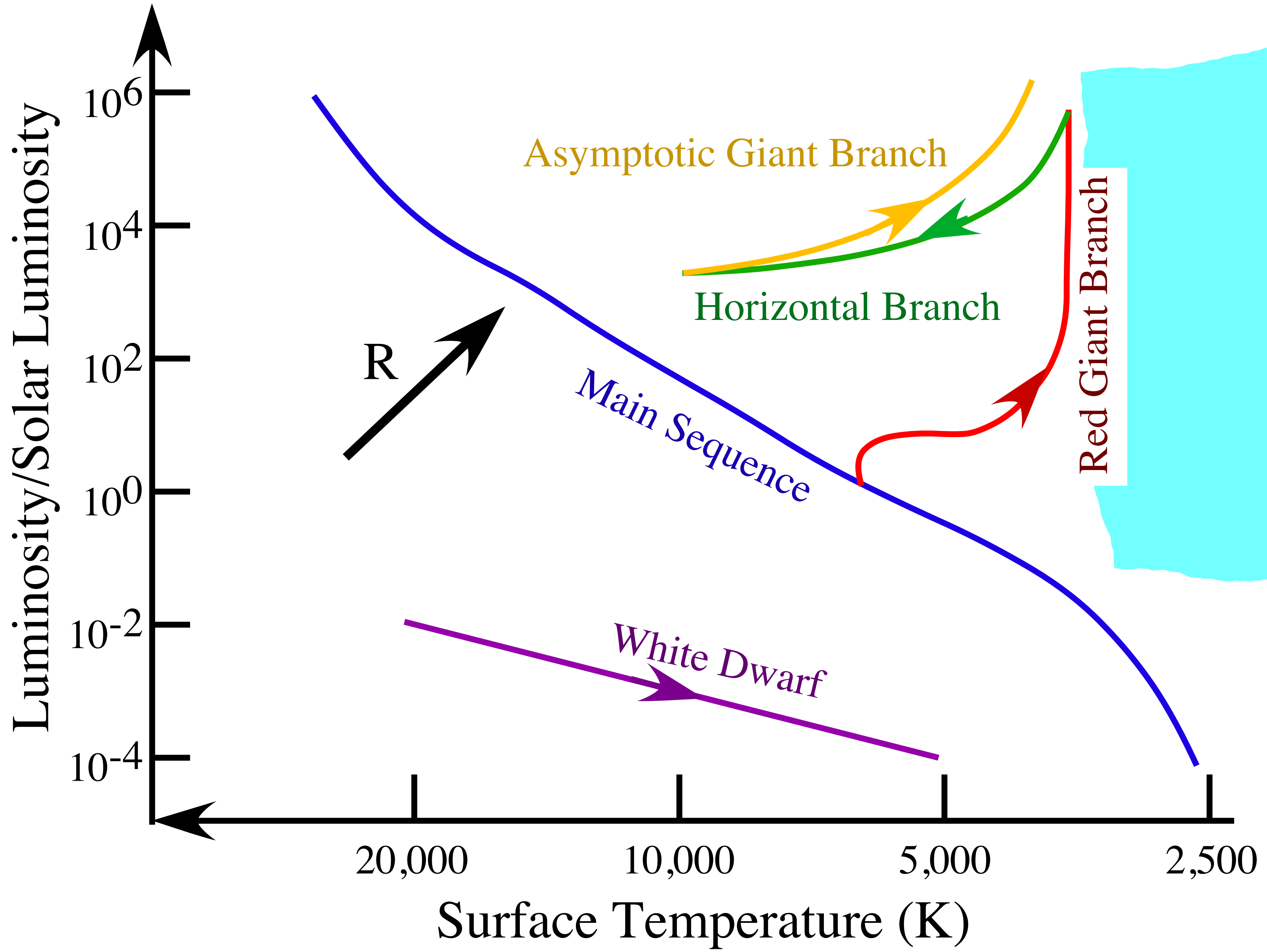
Further observations revealed that FG Sagittae ejected a planetary nebula some 6000 years ago.

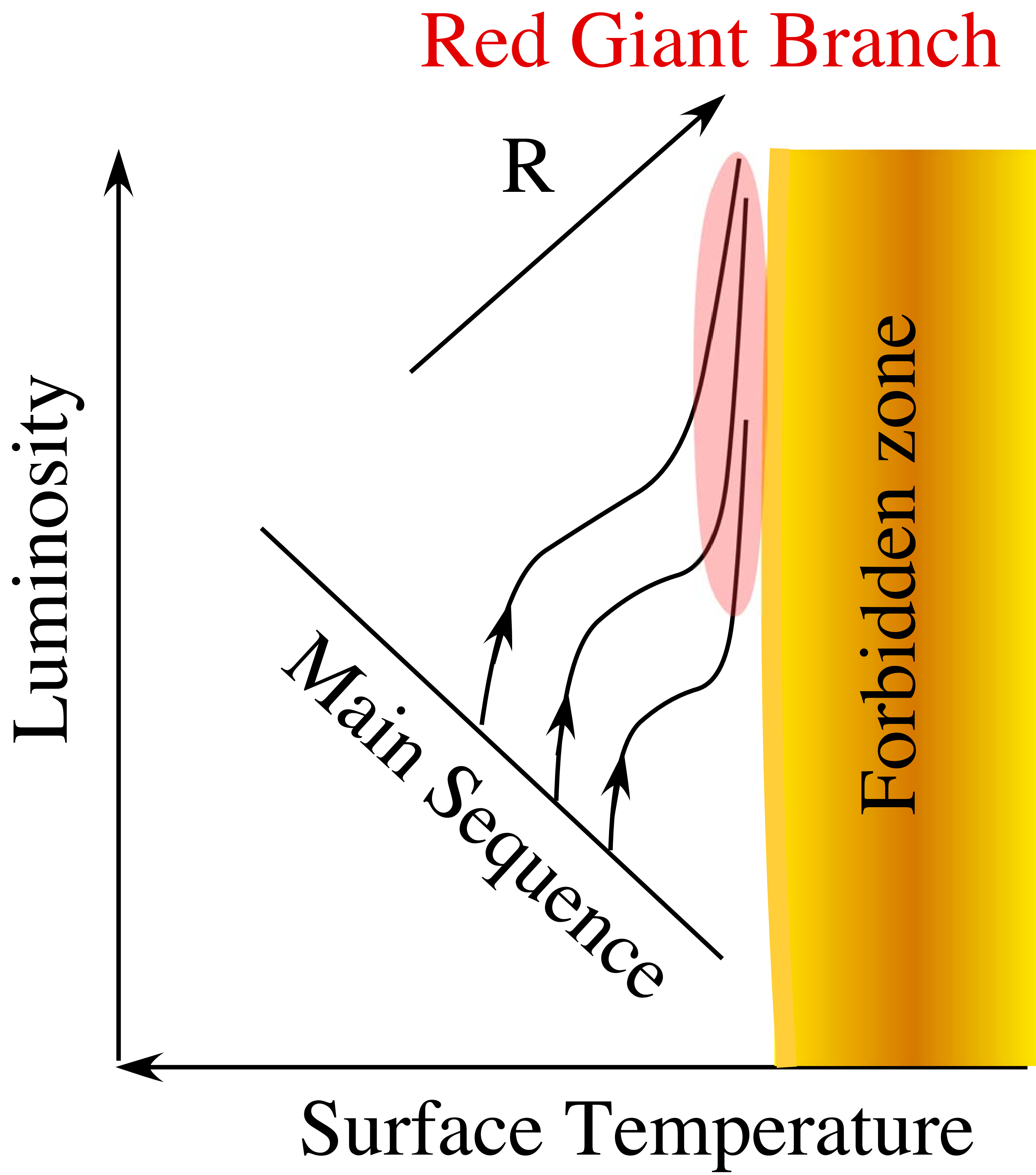
In 1977 Kipper and Kipper found that while the abundances of the s-process elements changed, those of the iron peak elements remained unchanged.

In the past 100 years it brightened by about a factor of more than 70 then cooled off at a rate of 340K/year between 1955 and 1965 and at a rate of 250K/year between 1969 and 1974.

The full story of FG Sagittae has not yet been told, but present accepted view is that FG Sagittae experienced the last episode of s-process elements formation during the ’last thermal pulse’ and ejected the rest of the envelope as a planetary nebula.

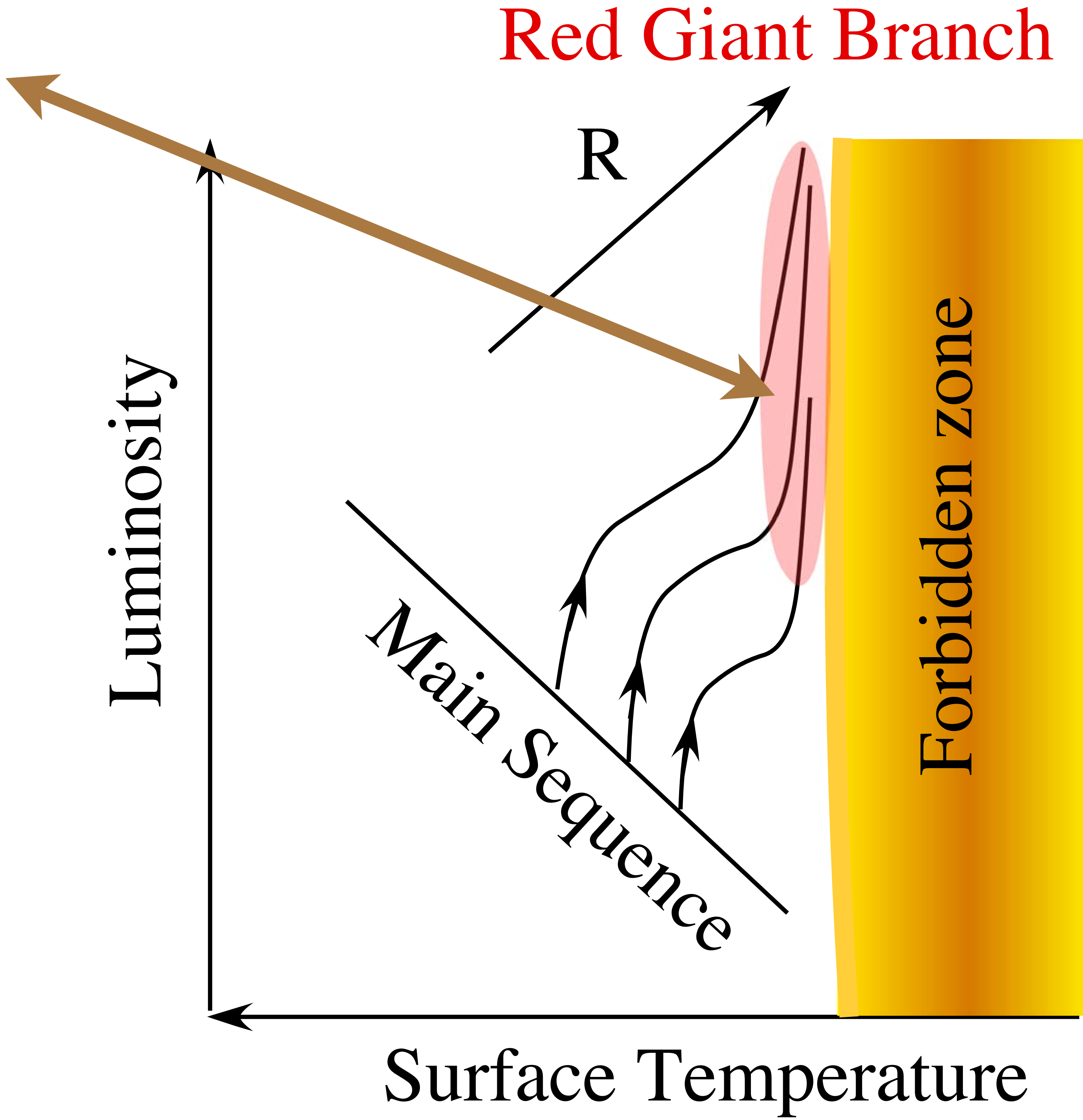
Where does it take place





Red Giant Branch
R
Luminosity
Main Sequence
Forbidden zone
Surface Temperature

The He flash


Red Giant Branch
R
Luminosity
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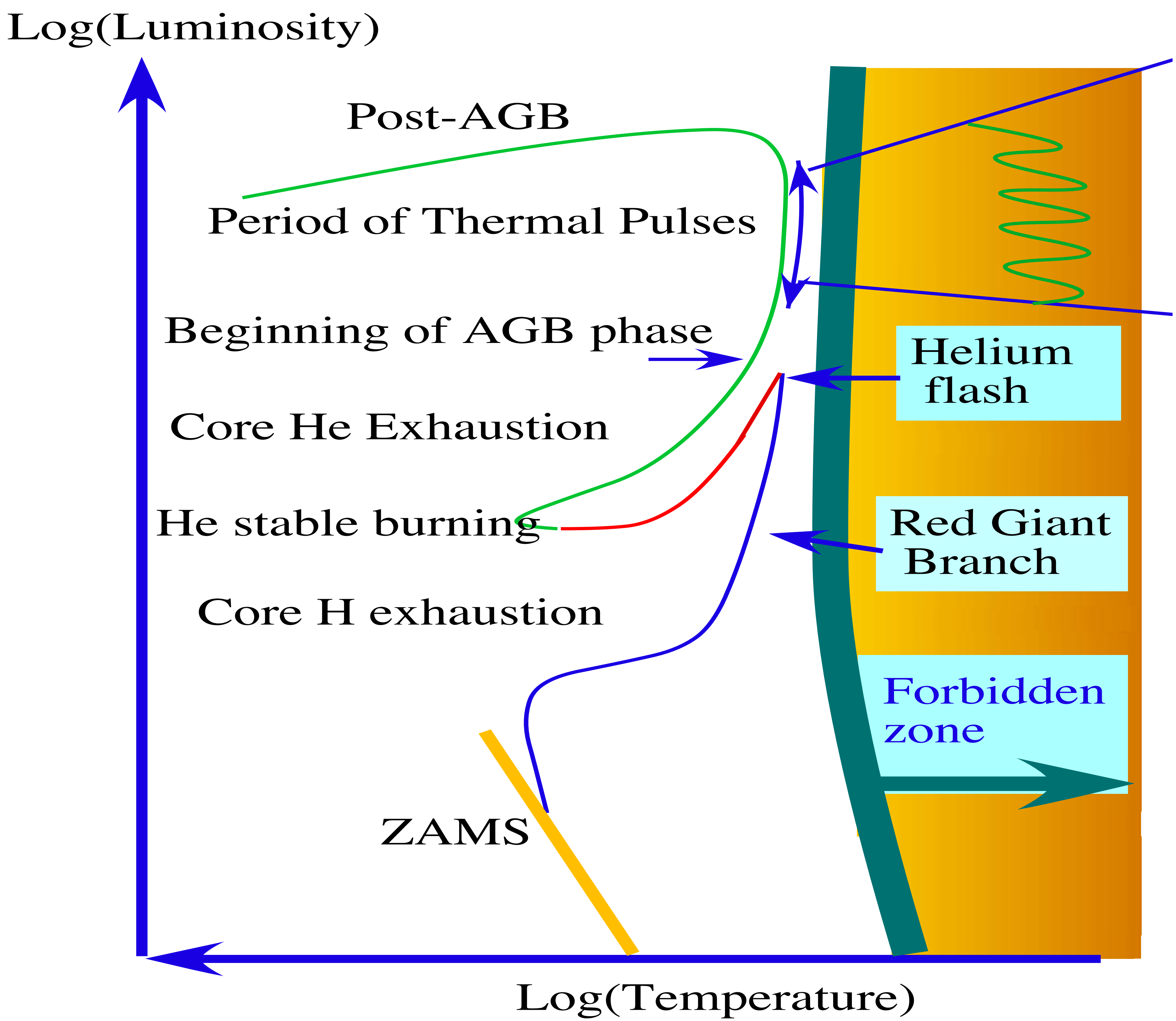
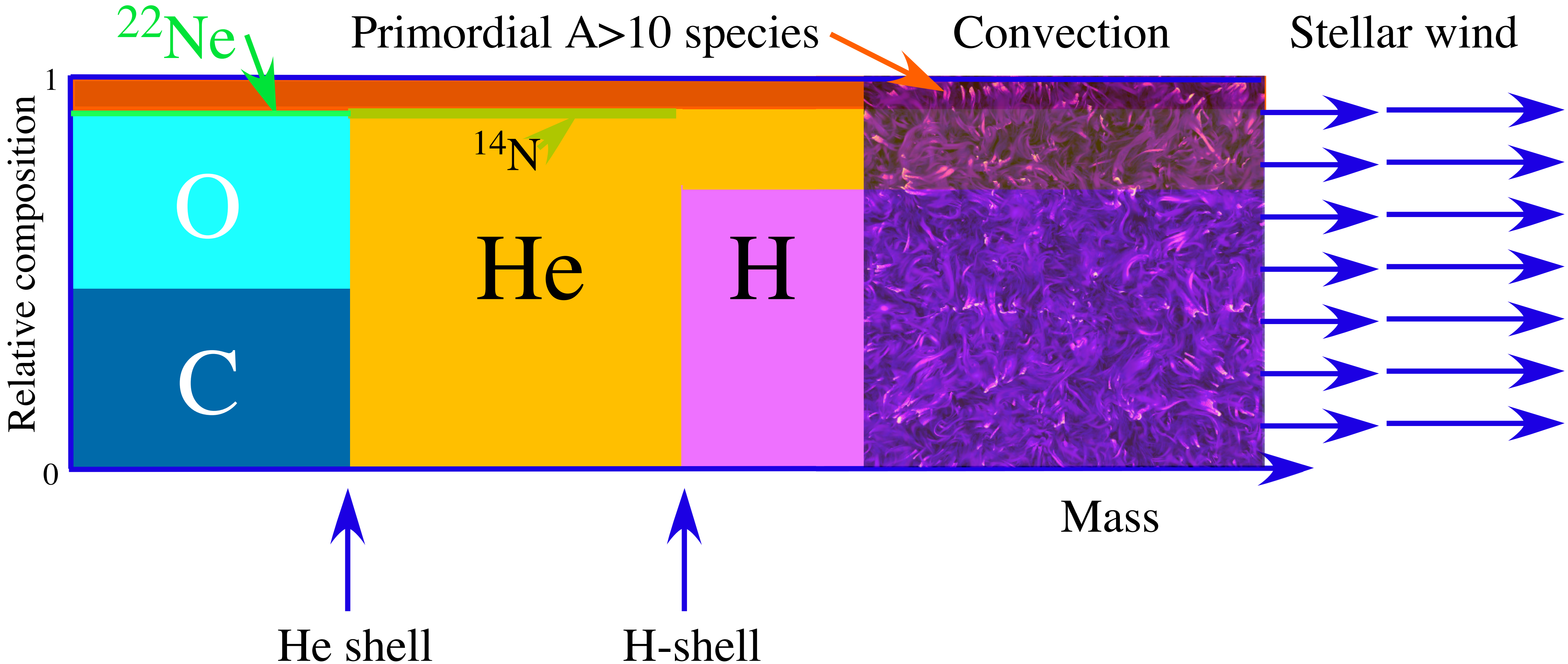
Many years of attempts to discover whether the helium flash causes mixing.

So far the most recent calculations indicate

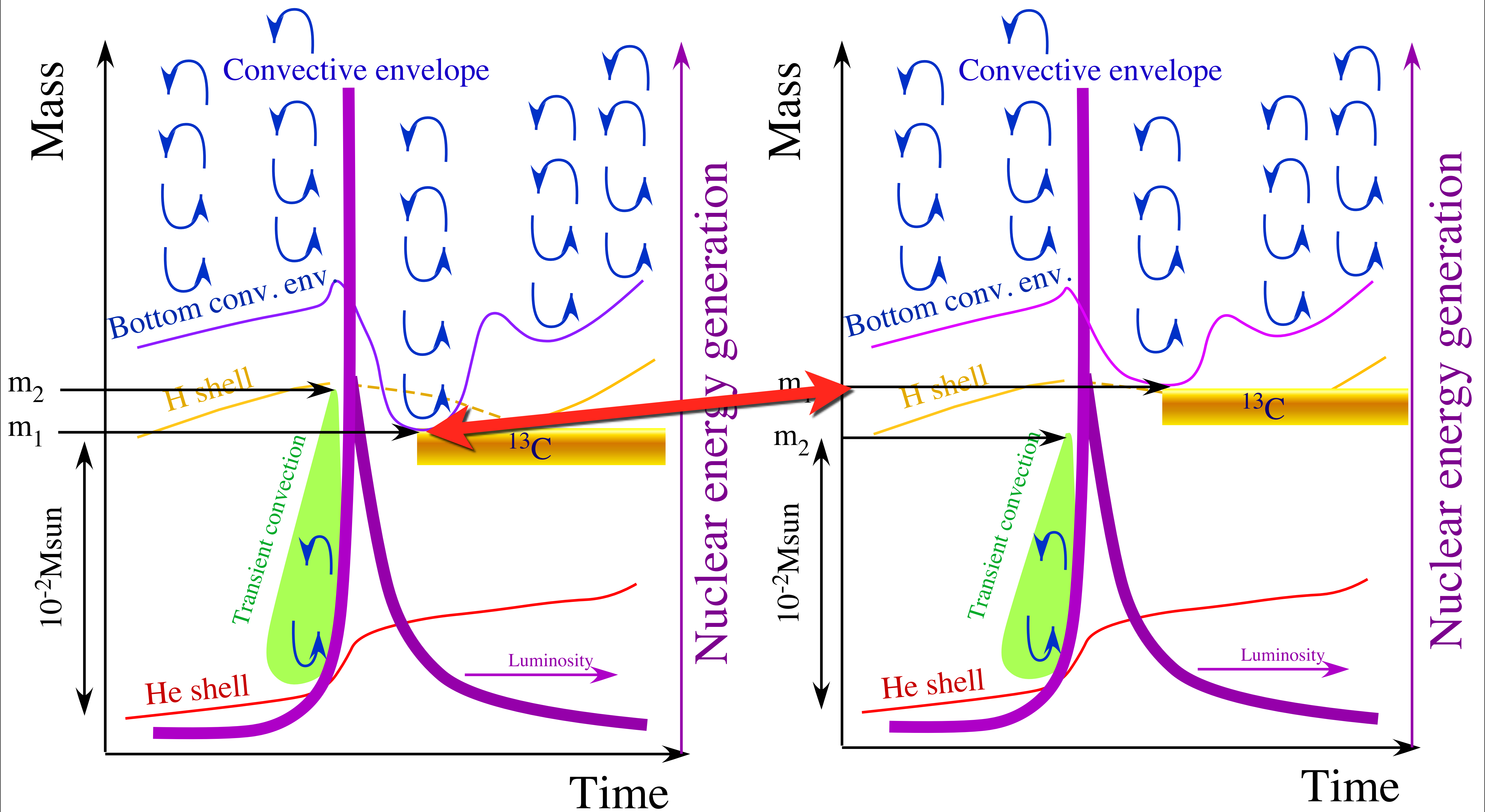
no mixing



Evolution of 1M solar mass

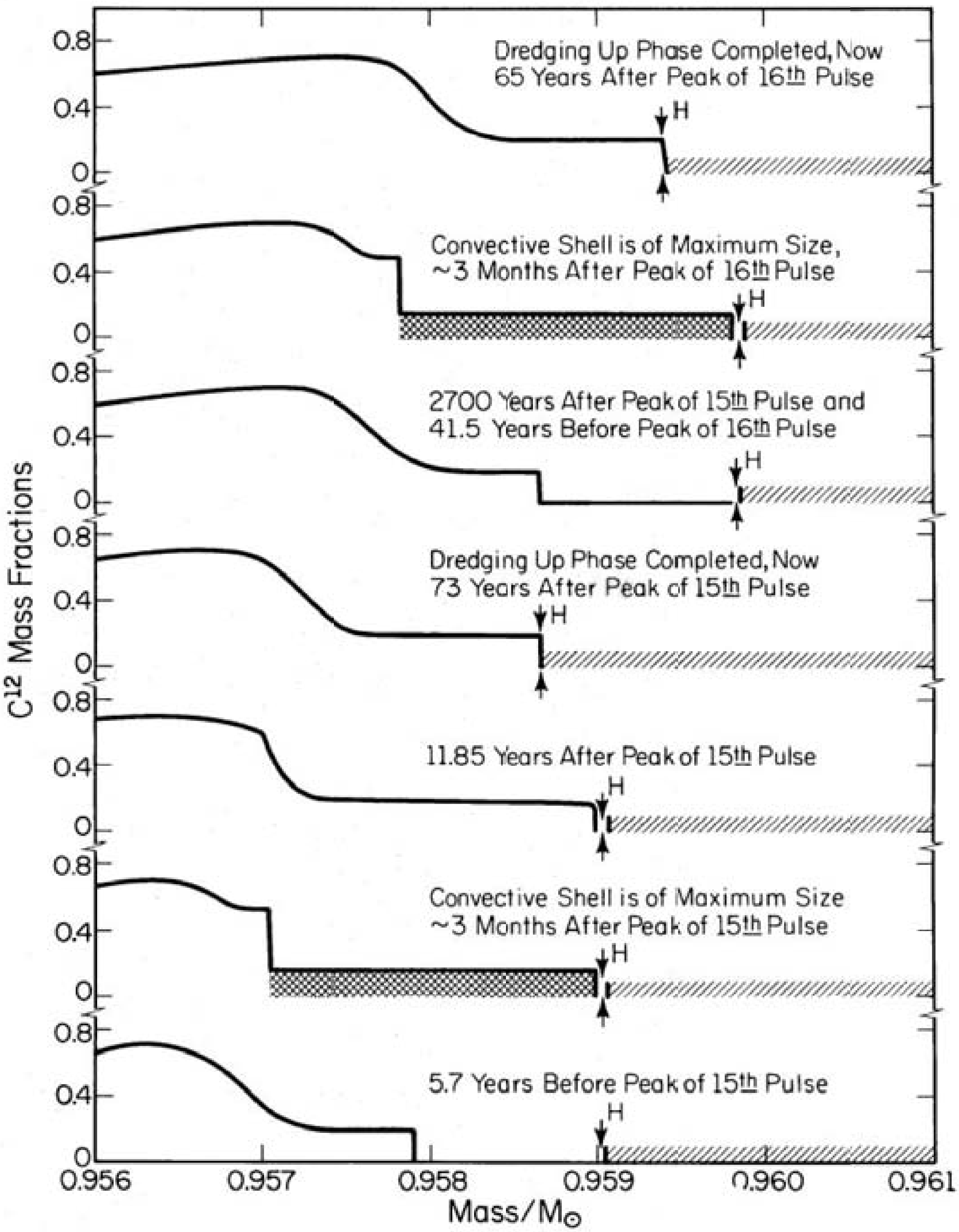


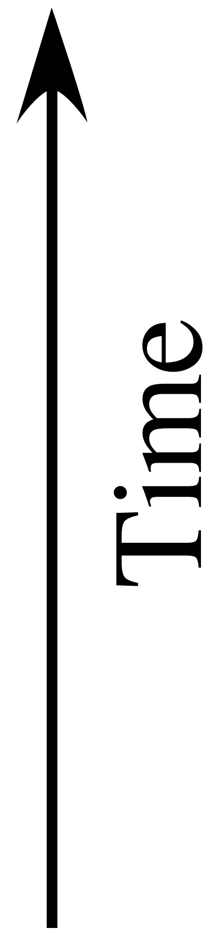
The structure of the star at the beginning of the AGB phase



The good case

The bad case





The dredge up in a 7Msun star according to Iben

The two convective zones never meet but cover alternatively the same region

Mixing yes or no?

The observational results and their interpretations are still not clear.

For example, Charbonnel and do Nascimento": 96% of evolved stars show a $^{12}C/^{13}C$ ratio in disagreement with the standard predictions, and conclude that 96% of low-mass stars do experience an extra-mixing process on the RGB.

Palla et al. examined the planetary nebula NGC 3242 and concluded that the spectrum indicates that the progenitor star did not undergo a phase of deep mixing during the last stages of its evolution, leaving the issue still unsolved.

Pavlenko et al examined the $^{12}C/^{13}C$ ratio in giant stars in globular clusters,conclude that it suggests complete mixing

on the ascent of the red giant branch,

in contrast to current models

So what happens?

Did we discover the B2FH partial mixing idea?

Not yet for sure

The unsolved problem of mass loss

When no theory is available:

$$rate\ of\ mass\ loss = \dot{m} = \frac{M}{\tau_{KHR}} = \frac{M}{\frac{GM^2}{RL}} = \left(\frac{1}{G}\right)\frac{RL}{M}$$

$$\dot{m} = \eta \frac{R_* L_*}{M_*},$$

η is our fudge factor

How reliable are the numbers?

There is one measurements of η for PopII stars
(S stars are Pop II stars)

There are half a dozen measurements for Pop I

But: the rates appear to be time dependent and vary by a large factor (over 30!)

In the theory:
each computer code gives another mixing history.

Unsolved problems:

semi-convection

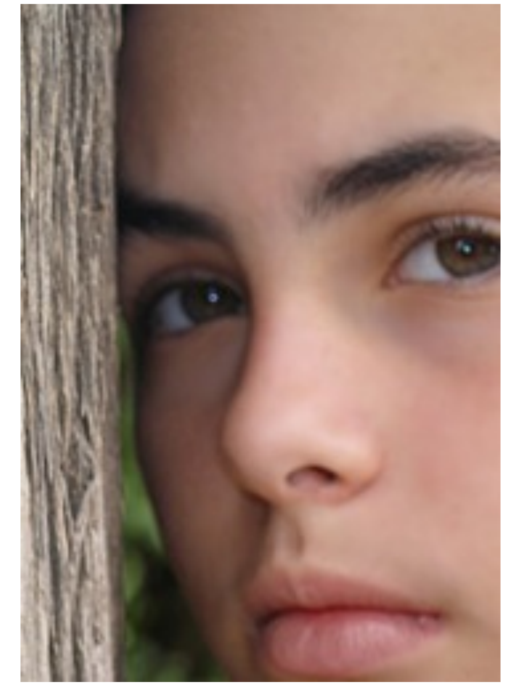
Mixing by convection, undershooting and overshooting

Mixing by gravity waves

Rotation and mixing by rotation

Mass loss: observation and theory

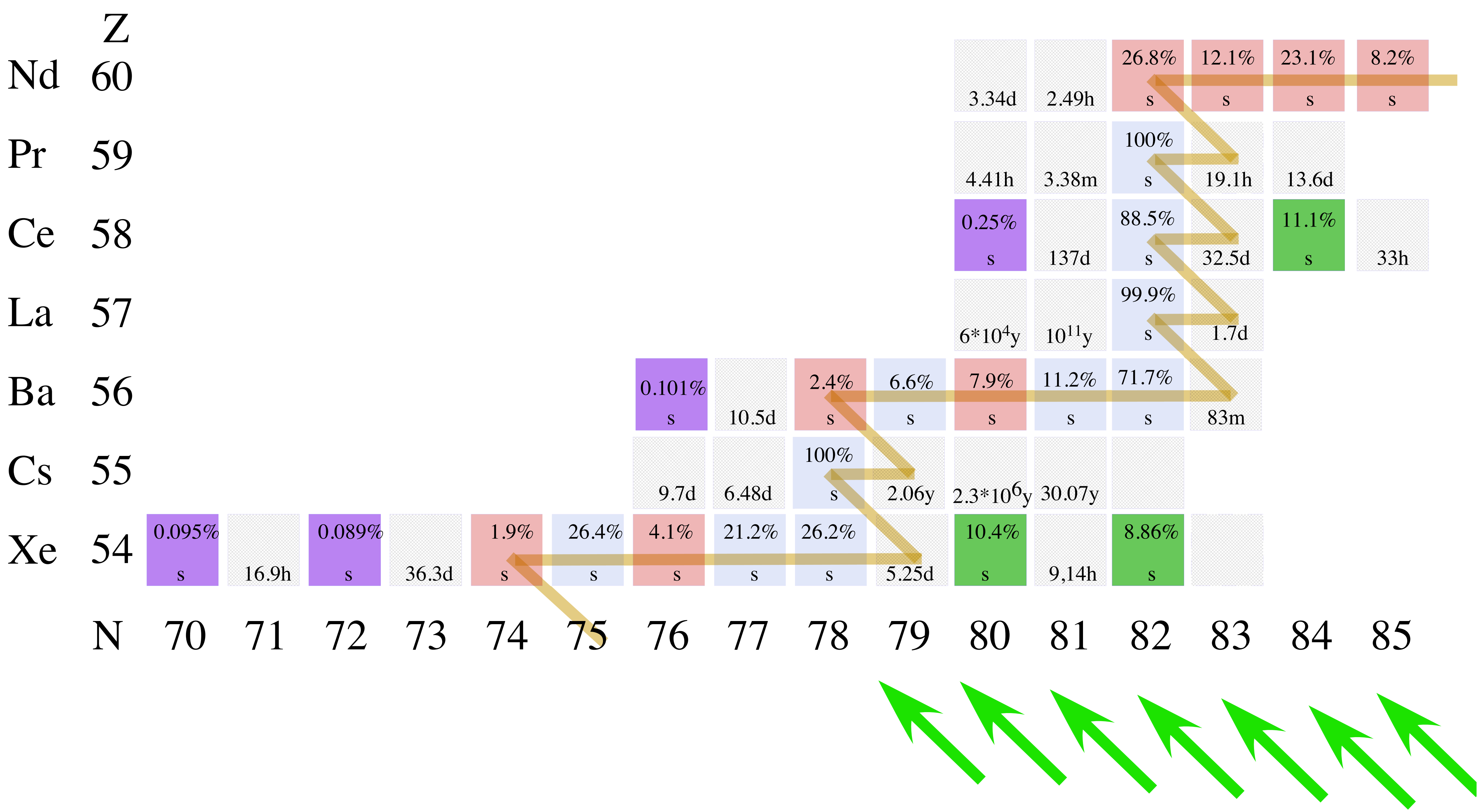
How come the universal r and the s process have practically the same yield?

Thanks 

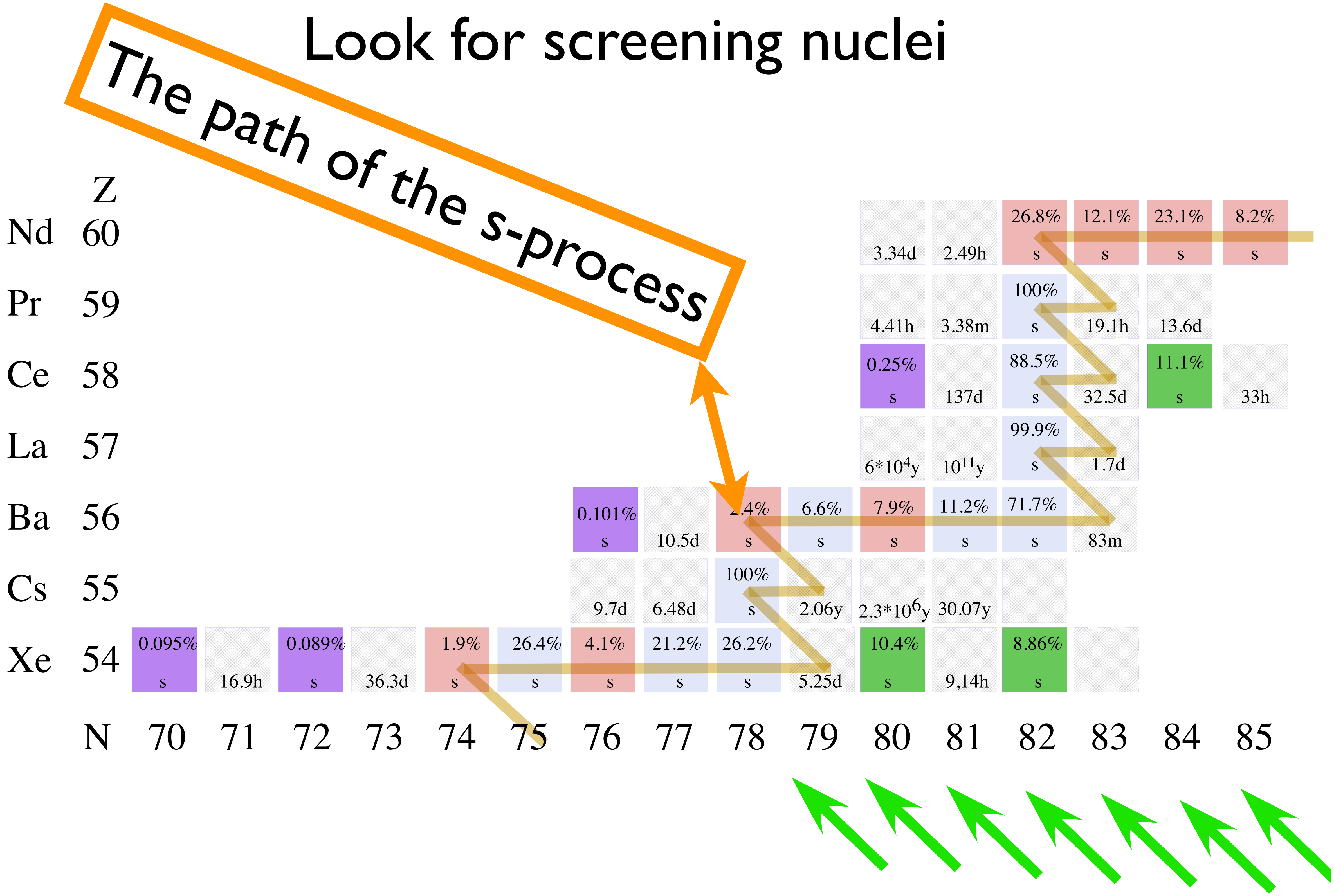
for the

attention

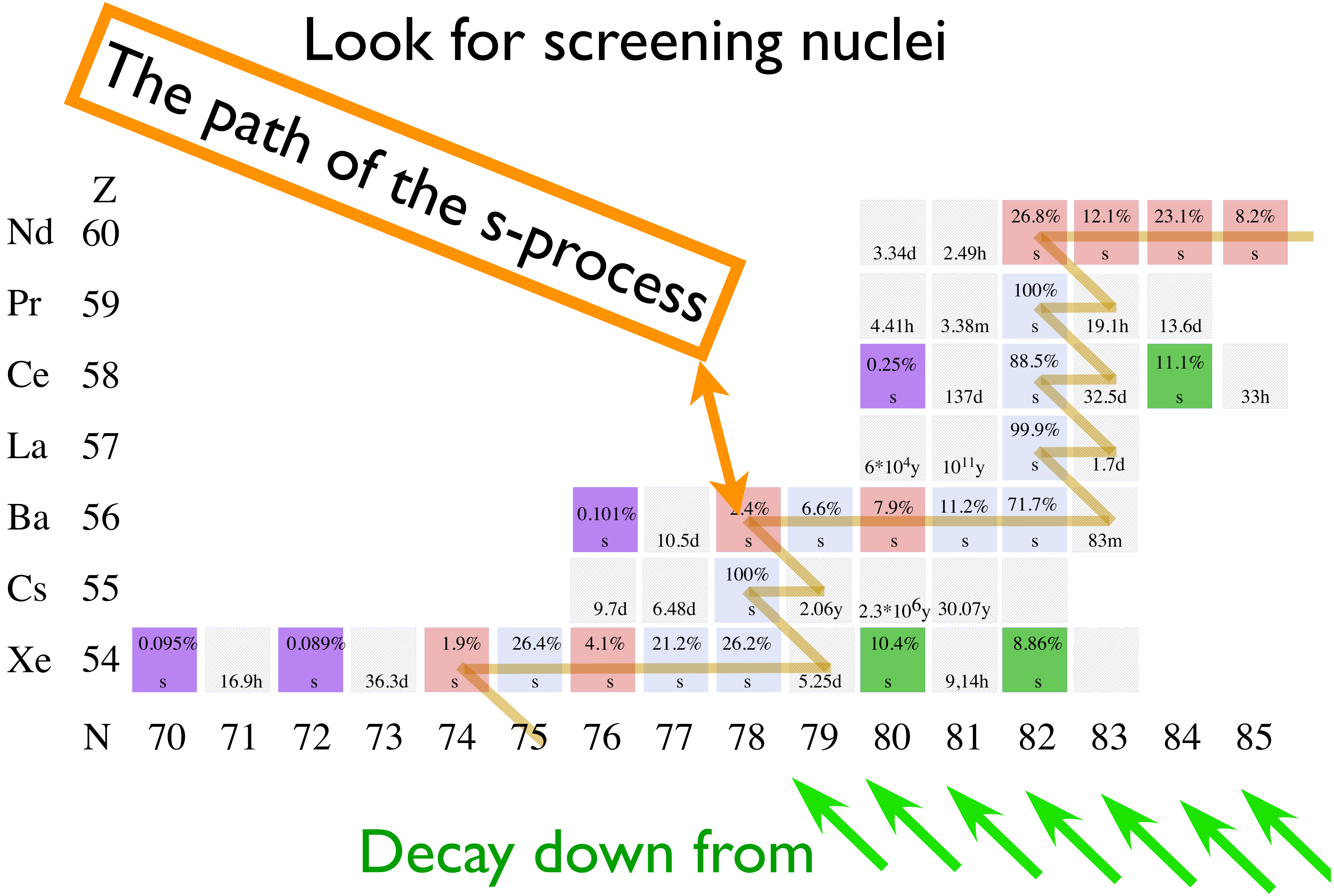
Look for screening nuclei



Look for screening nuclei



Look for screening nuclei



Decay down from the r-process