Signature of Heavy Elements in the Early Galaxy

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1. Basics about r an s processes

2. What do observations tell

3 some problems with modeling

Production of neutrons in stellar environment

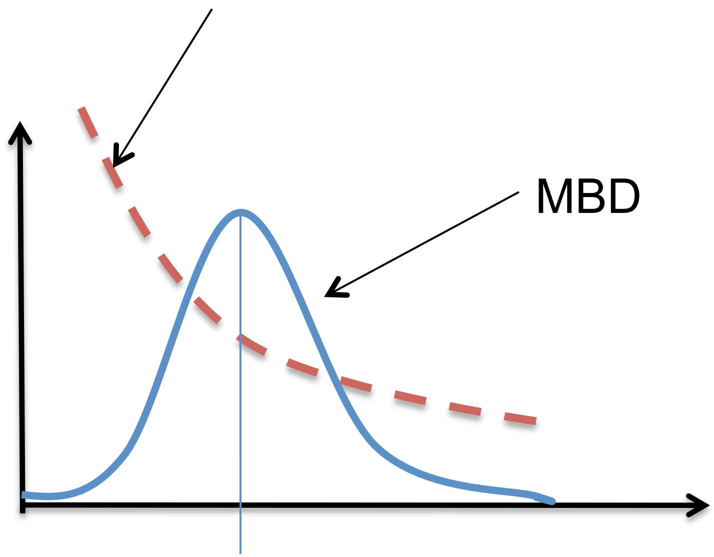
Whenever neutrons are produced in stellar environment, they become quickly (10^{-11} s) thermalized via elastic scattering in the star's plasma. They obey the Maxwell-Boltzmann distribution (MBD):

$$\phi(\mathrm{v}) = 4\pi\,\mathrm{v}^2\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-m\mathrm{v}^2/2kT}$$

From lab experiments, we know that the neutron-capture cross section varies like:

$$\sigma_{n\gamma} \propto \frac{1}{\mathrm{v_n}} \propto \frac{1}{\sqrt{E_n}}$$

S-wave scattering $\ell = 0$



E_0 =most probable energy

then $E_0 = kT = \frac{1}{2}\mu \mathrm{v}_{\mathrm{th}}{}^2$

μ=reduced mass

Or $\mathrm{v}_{\mathrm{T}} = \left[\frac{2kT}{\mu}\right]^{1/2}$

Thermal velocity

Energy dependence of $\sigma_{n\gamma}$ tells:

$$\sigma \mathrm{v} = \text{constant} = \sigma_T \mathrm{v}_{\mathrm{T}}$$

$$<\sigma> \equiv \frac{<\sigma \mathrm{v}>}{\mathrm{v}_{\mathrm{T}}}, \qquad <\sigma \mathrm{v}> = \int_0^{\infty} (\sigma \mathrm{v}) \phi(\mathrm{v}) d\mathrm{v}$$

Maxwell folded

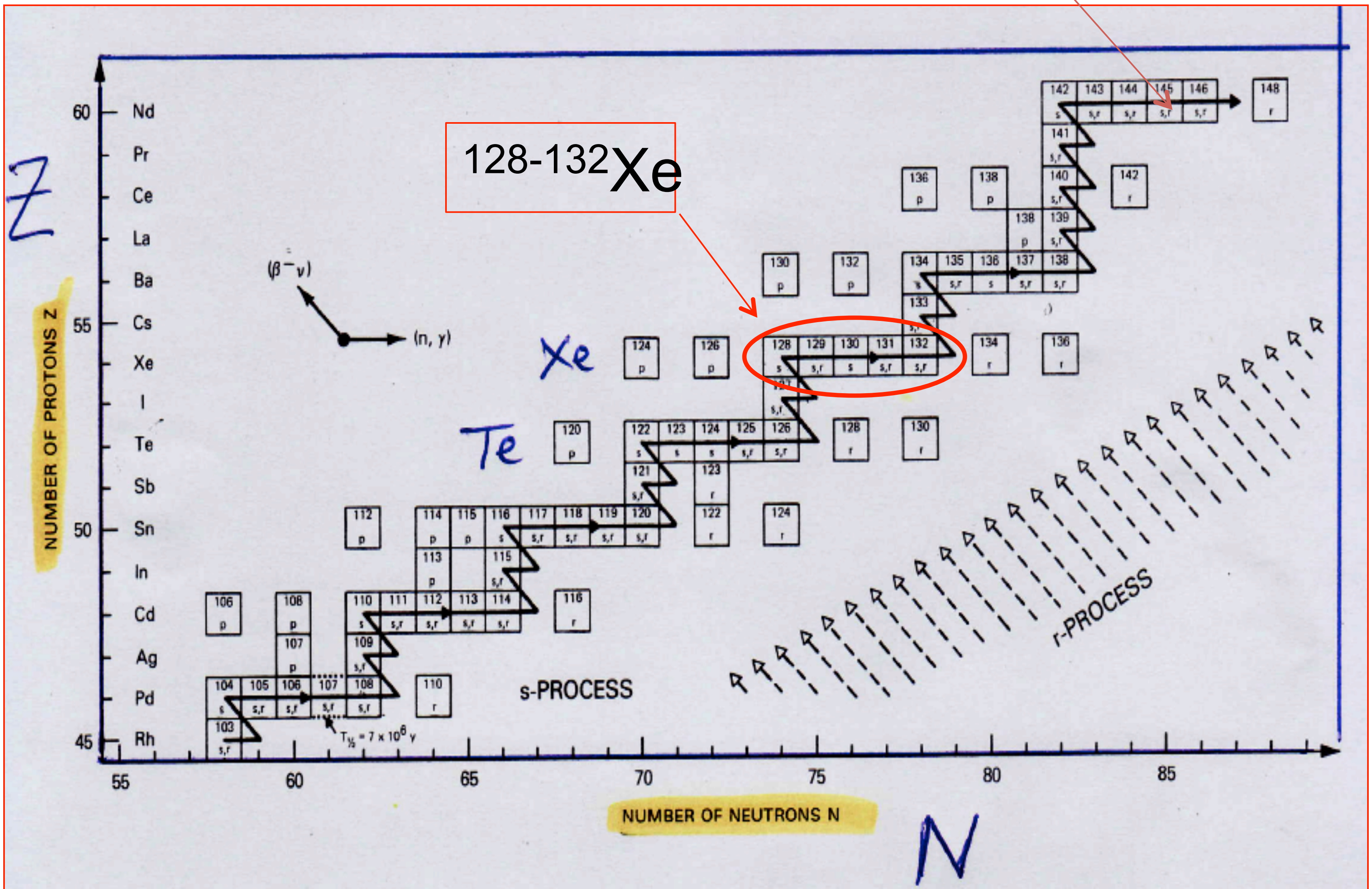
$$<\sigma> = \left\{ \begin{array}{ll} \sigma_T & for\ \sigma \propto 1/\mathrm{v} \\ (\frac{2}{\pi})\sigma_T & for\ \sigma \propto 1/\mathrm{v}^2 \end{array} \right\}$$

Implication: measurement of σ near v_{th} very useful.

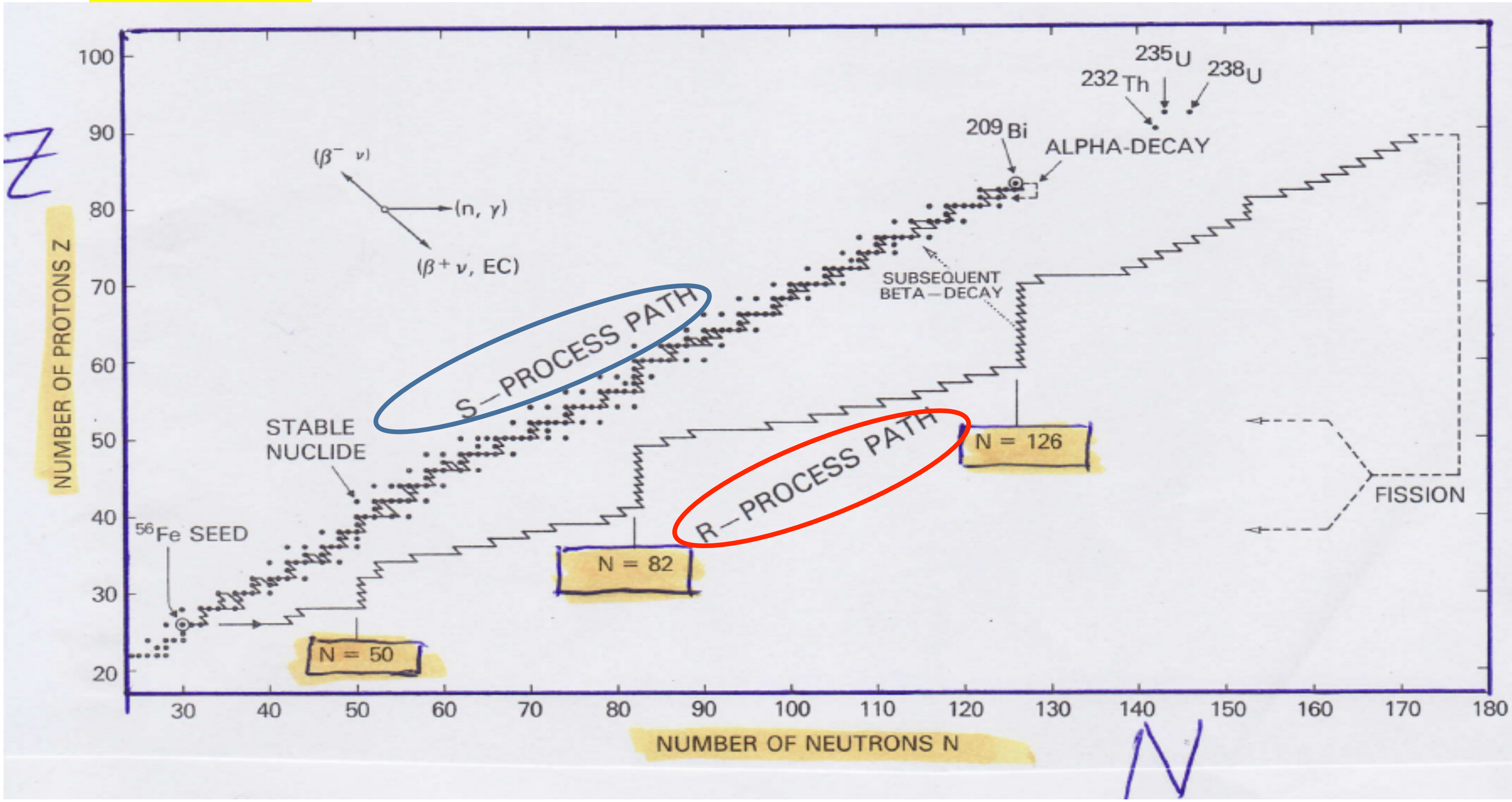
Basic Mechanism s of Nucleosynthesis beyond iron

(n,γ) reactions increases the mass number (A) . However, if the isotope is unstable , then subsequent process depends on the neutron flux and the life time (τ)

(a) $\tau_{n\gamma} >> \tau_{\beta}$ Standard s-process (beta decay wins the game). The produced nuclei are closed to the valley of beta stability (see



(b) $\tau_{n\gamma} << \tau_{\beta}$ (neutron capture wins the game, one deals with the r-process)



Beta decay lifetimes: $(10^{-3} - 10^{-4})$ s.

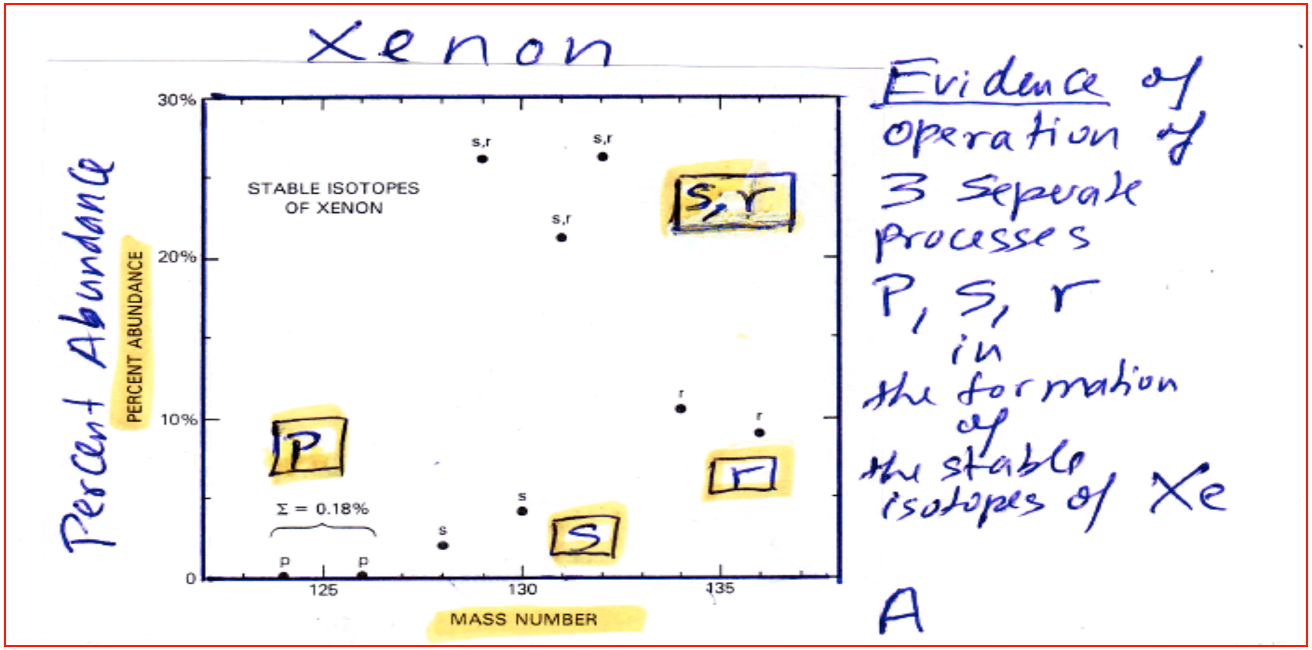
For $\tau_{n\gamma}=10^{-4}$ s : $N_n=3\times10^{20}$ neutron/cm^3

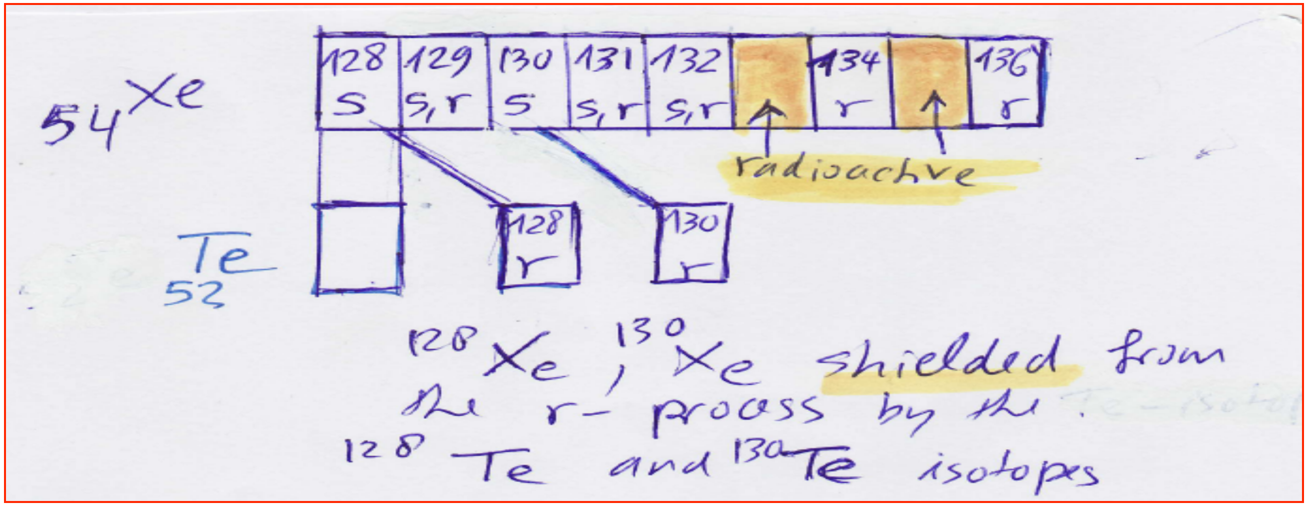
Amazing & Interesting

There are only 27 pure r-nuclei and 28 pure s-nuclei. all othes s+r nuclei

Thus there are three neutron-capture processes: s, r and s+r

Illustration:





s-process

As seen on Page 5, the s-process wonders along the valley of beta stability

Neutron sources

$$^{13}C(\alpha,n)^{16}O \quad \text{and} \quad ^{22}Ne(\alpha,n)^{25}Mg$$

Temperature: 25 - 30 KeV or 1.5 – 3.5 x 10^8 K

He-burning

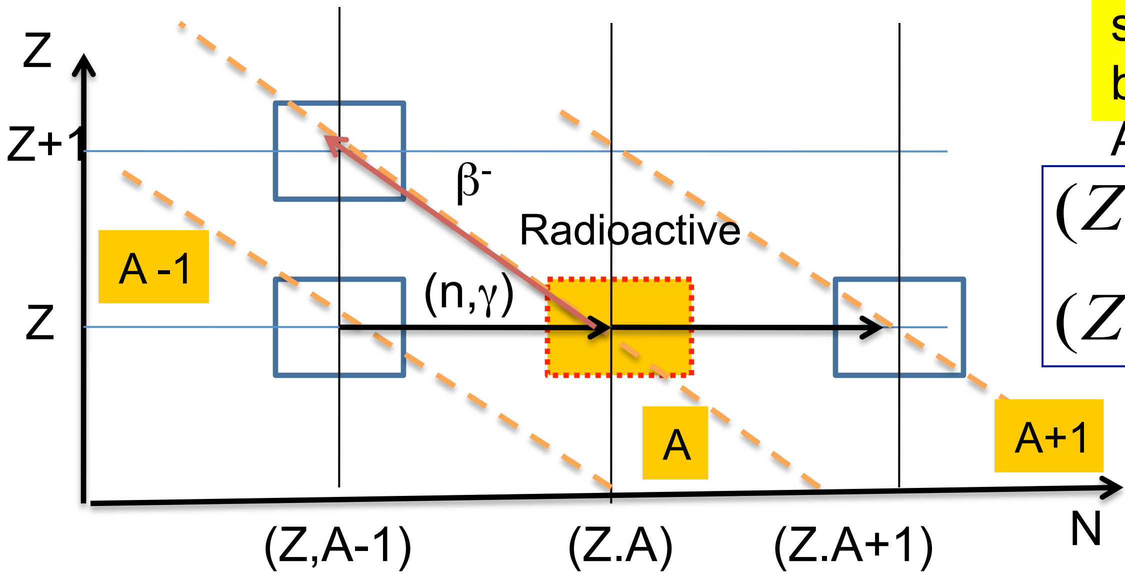
90 KeV or 10^9 K

Shell -Carbon burning in massive stars. Why not core carbon burning?

Ask me

$$(Z, A-1) + n \rightarrow (Z, A) + \gamma$$

$$(Z, A) \rightarrow (Z+1, A) + e^- + \bar{\nu}$$



Time variation of abundances of N_A:

$$\frac{dN_A}{dt} = N_n N_{A-1} <\sigma \mathrm{v}>_{A-1} - N_n N_A <\sigma \mathrm{v}>_A - N_A \lambda_\beta]$$

Creation

destruction

$$\lambda_\beta = \frac{\ln 2}{T_{1/2}(t)}$$

Beta-rate
in stellar plasma
Time-dependent

$$\tau_{n\gamma} = \frac{1}{N_n <\sigma \mathrm{v}>_A} \qquad \text{Lifetimes} \qquad \tau_{n\gamma} = \frac{1}{\lambda_\beta}$$

(a) $\tau_\beta << \tau_{n\gamma}$ Radioactive nuclei decay very fast, so that their abundances can be neglected

(b) $\tau_\beta >> \tau_{n\gamma}$ Radioactive nuclei can be treated as stable nuclei

(c) Temperature does not change fast during s-process:

$$<\sigma \mathrm{v}>_{n\gamma} = <\sigma> \mathrm{v}_T = \sigma_A \mathrm{v}_T$$

σ_A: Maxwell-averaged cross section

Then:

$$\frac{dN_A}{dt} = \mathrm{v}_T N_n (\sigma_{A-1} N_{A-1} - \sigma_A N_A)$$

ϕ= neutron flux [neutron/(cm^2 .s)] define **neutron exposure:**

$$\tau = \int_0^t \phi_n \, dt$$

using

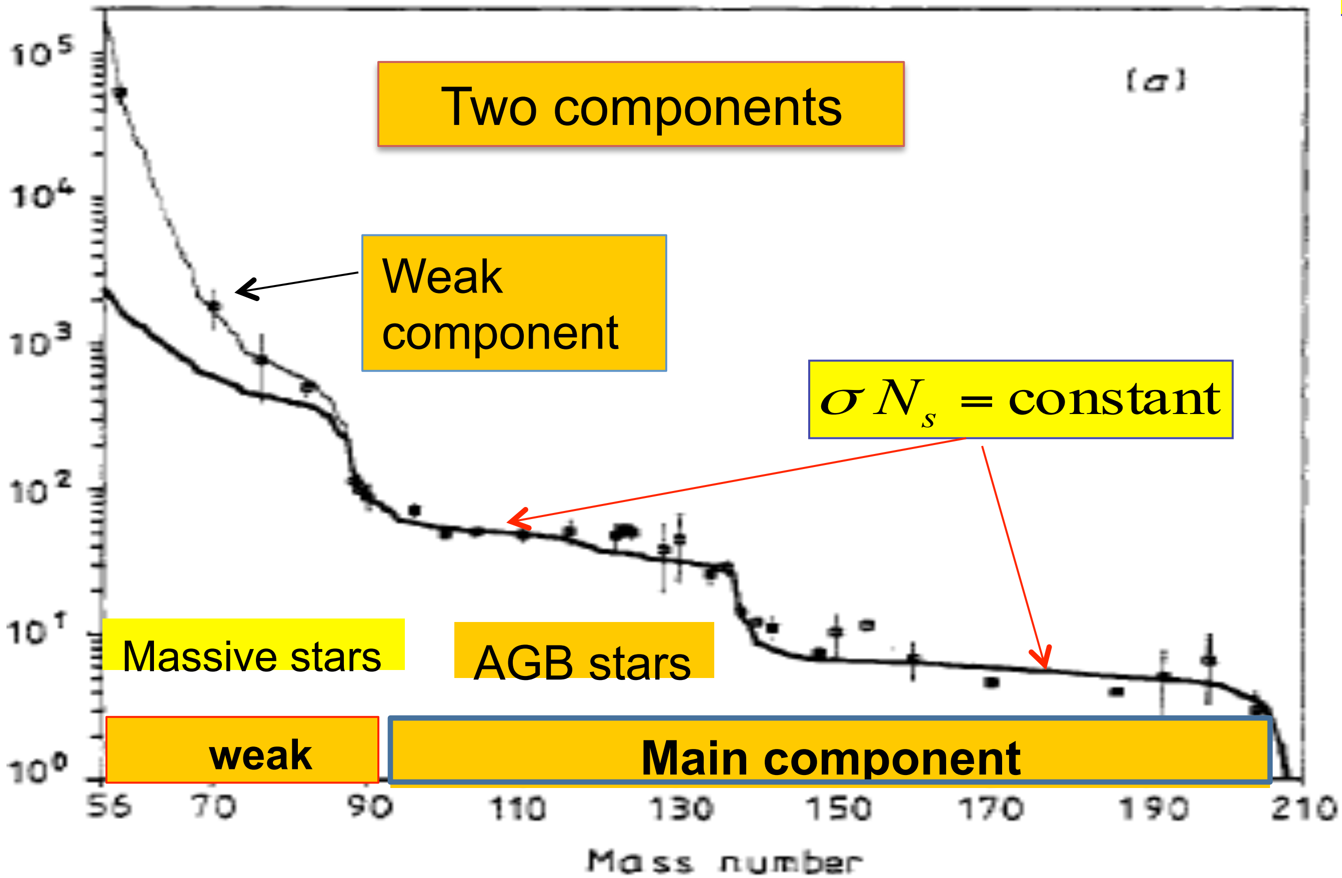
$$\frac{dN_A}{dt} = \frac{dN_A}{d\tau}\frac{d\tau}{dt} \rightarrow$$

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

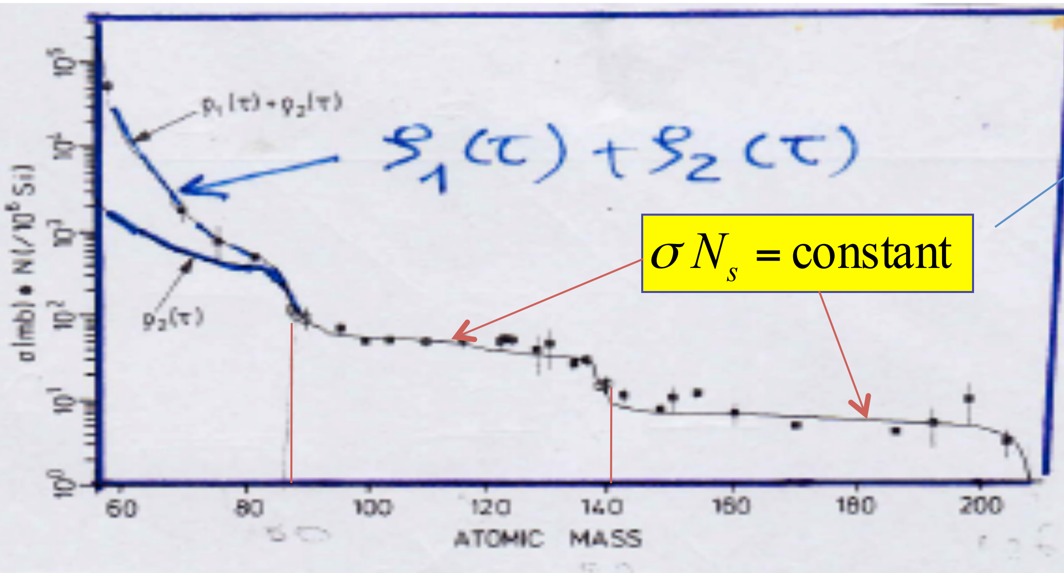
Self-regulating equation with a steady-state

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

$$\sigma N_s = \text{constant}$$



This indicates: a nucleus with small σ would have small abundance and a nucleus with high σ would have large abundance.



Local equilibrium between magic numbers

Breaks at A=84, 138, 208

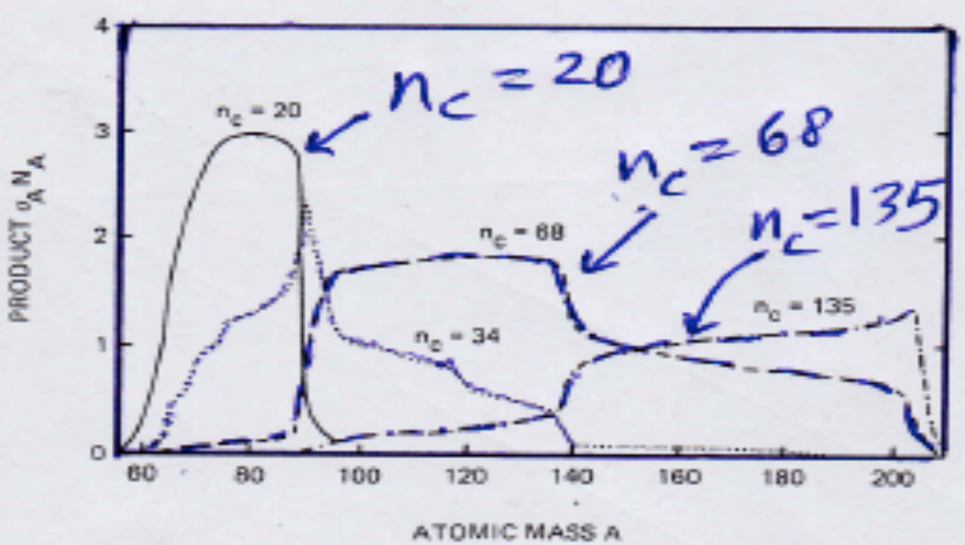
And N=50,82, 126, where cross section small

With finite supply of neutrons , the σN – curve declines

Weak | **Main component**

Massive stars | AGB stars

Two components



Number of neutron absorbed by ^{56}Fe

$$n_c = \sum_{56}^{209} (A-56) N_A(t) / N_{56}$$

This diagram shows: the σN – curve can be understood as **superposition of different neutron exposures**

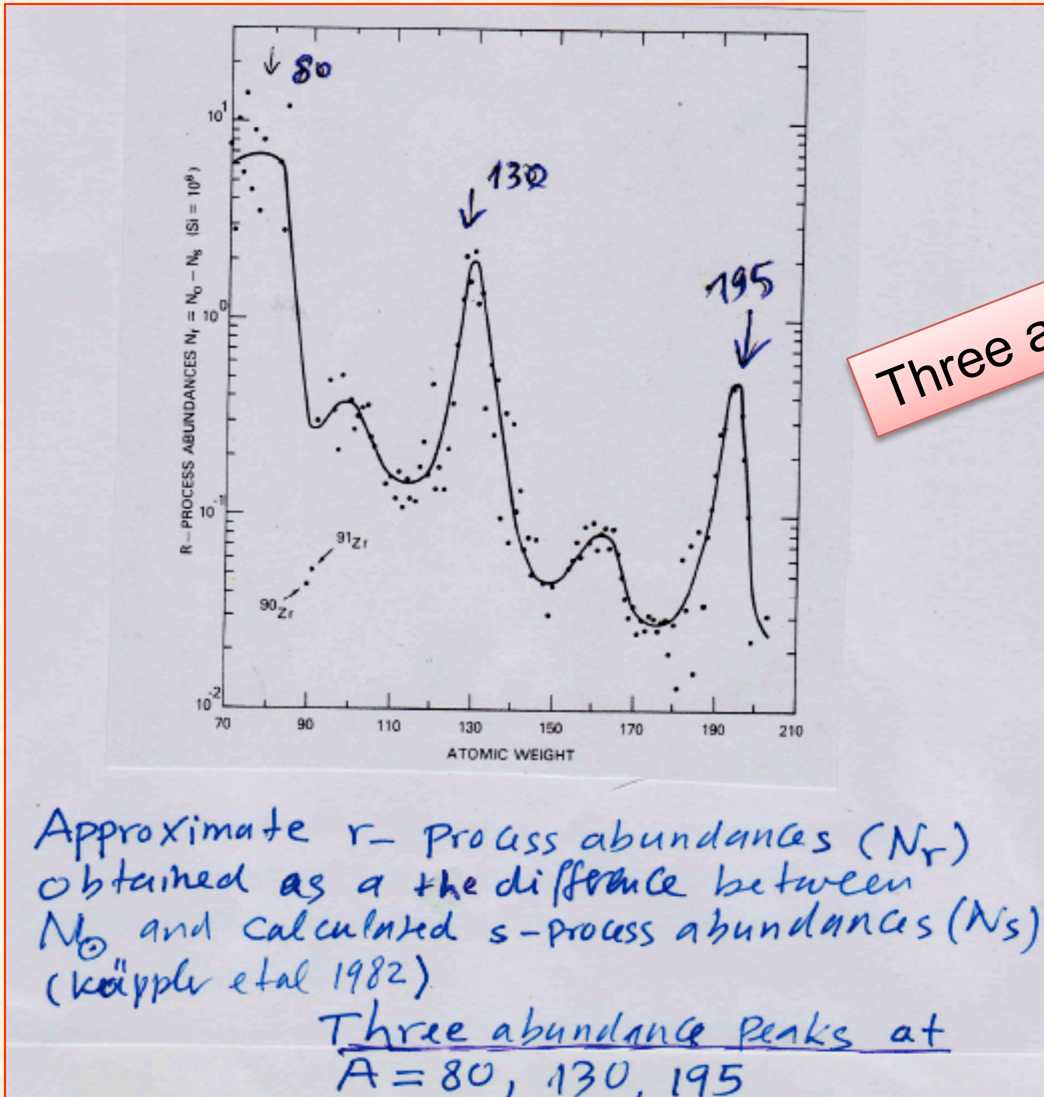
Reference: Käppeler etal, APJ, **257**, 821, (1982)

About the r-process

Abundances: $N_r \approx N_{\odot} - f(A)/\sigma(A)$

Taking advantage that σN_s falls on the flat part of the curve

Result:



Three abundance peaks

Classical r-process is based on a flow concept like the s-process, but high neutron density is needed such that **$\tau_{n\gamma} << \tau_\beta$**

Nuclei become neutron-rich . But the beta-decay lifetimes of neutron-rich nuclei are short (ms to sec)

For τ_β <1 ms, $N_n > 10^{19}$ neutron/cm^3

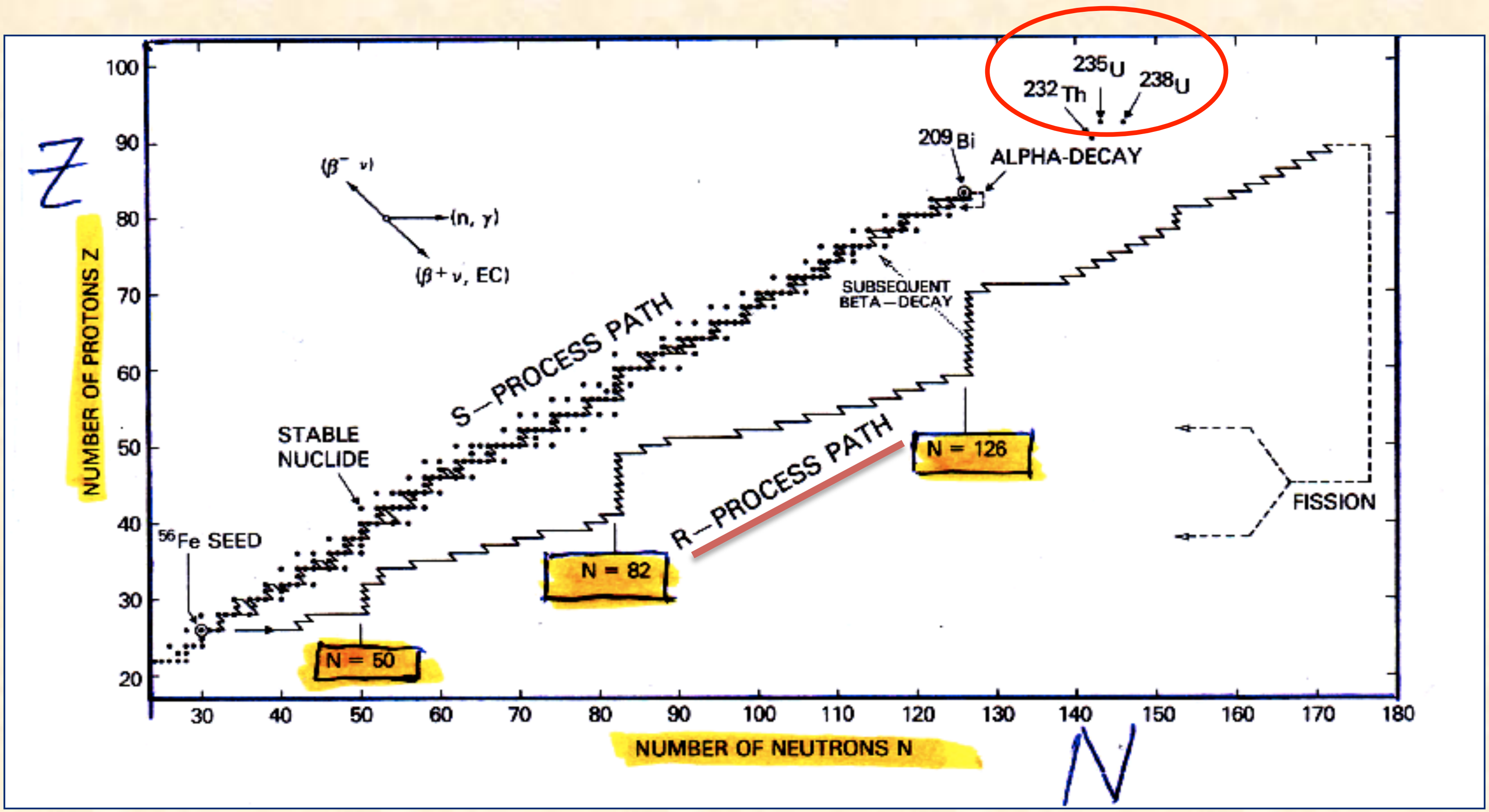
As the neutron number density increases, the neutron binding (Q_n) decreases. If $Q_n \rightarrow 0$, the **neutron drip line is reached,** and this will be the case when (n,γ) balances (γ.n) , or

$$\lambda_{\gamma n} \propto \frac{T^{3/2}}{N_n} e^{-Q_n/KT} \lambda_{n\gamma}$$

For $N_n = 10^{24}$ cm^{-3} and $T = 10^9$ K , both rates equal when Q_n =2 MeV. The chain of (n,γ) stops and beta-decay becomes effective.

The r-process bypass nuclei with natural radioactivity (circled) . These terminate. The r-process the s-process is terminated by neutron-induced fission and/or beta-delayed fission near A=270.

Question: what is A_{max} produced by the r-process?. This is sensitive to the mass formula, and fission barrier far from stability



Let us appreciate some of the effort of this gentleman

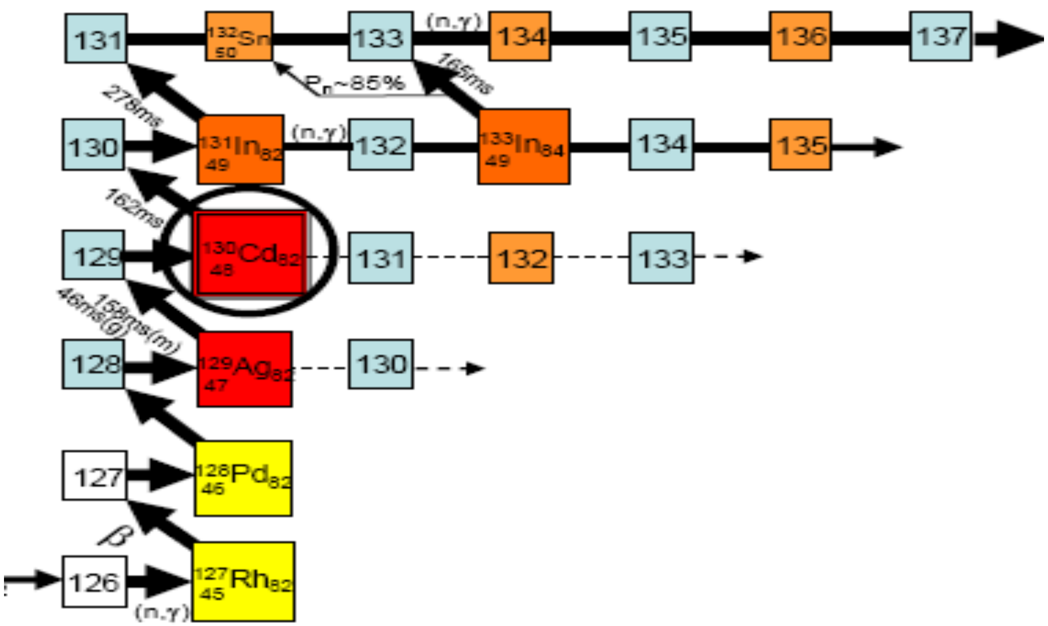
Beta decay properties of two of the most important waiting point nuclei **^{130}Cd (N=82) and ^{80}Zn (N=50) together with ^{131,132}In and ^{81,83}Ga**

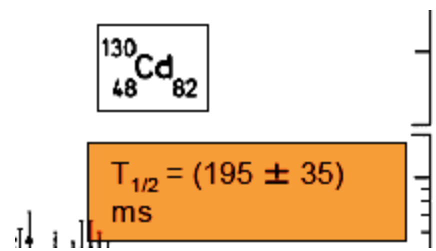
This shed light on the origin and time scale of the r-proce

Passionate and patient

He will smile when he sees this diagram

...hunting for nuclear properties of waiting-point isotope ^{130}Cd...





K.-L. Kratz (Revs. Mod. Astr. 1; 1988)

climb up the N= 82 ladder ...

A ≅ 130 "bottle neck"

$T_{1/2}$ ⇨ total r-process duration τ_r

Heavy Elements in Metal - Poor stars

Cowan et al , (Carnegie observatory series Vol. 5)

- 32 n-capture elements detected in r-process rich ([Eu /Fe] $\approx$1) star BD+17°3248

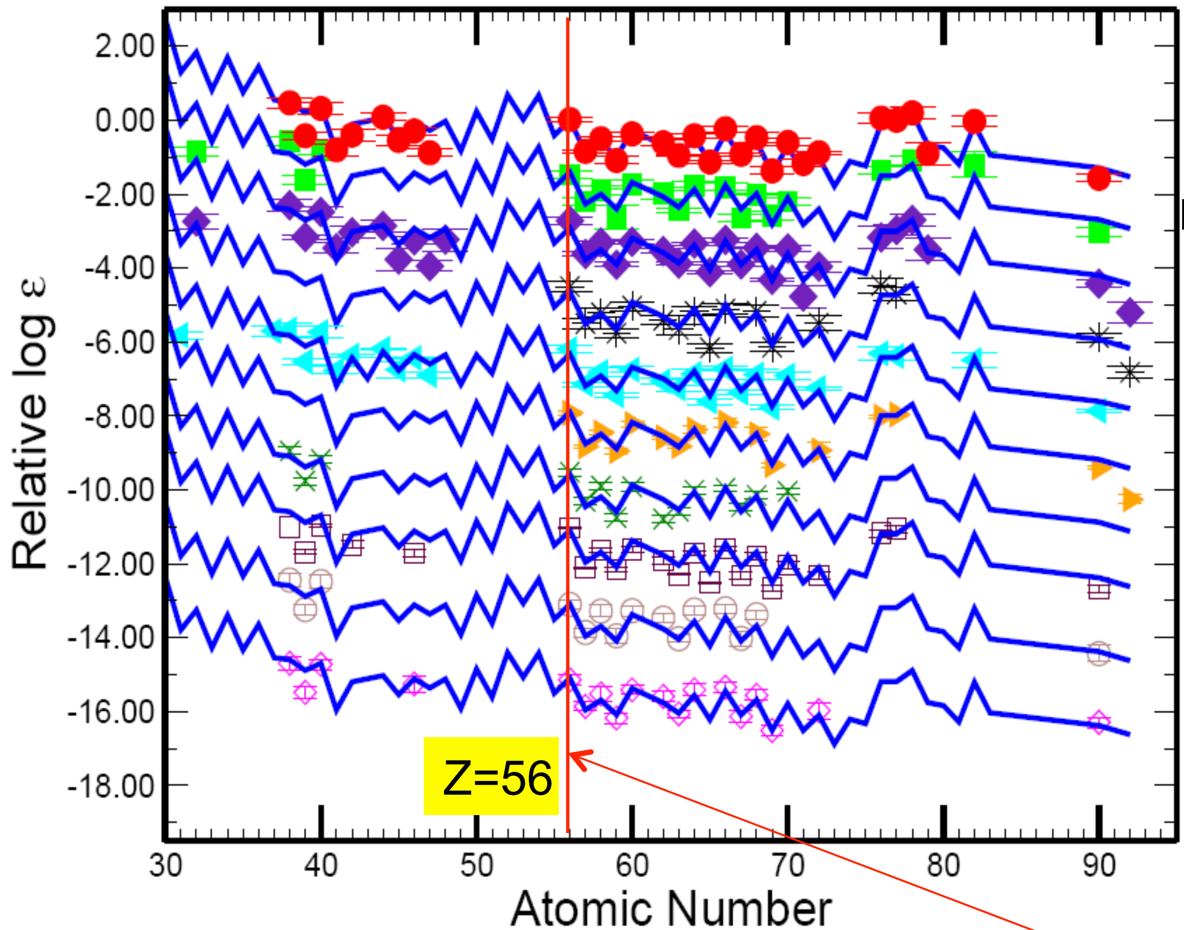
- Together with the most r-process rich star Cs22892-052 , it is found that :
  Heaviest stable n-capture elements (Ba and above Z≥56 consistent with a scaled solar system r-process abundance distribution.
  This is not the case for the lighter n-capture elements

Two conclusions:

1. Multiple processes responsible for the production of n-capture elements
2. Presence of Ba in all metal-poor stars without s-process enrichment indicates the operation of the r-process in the early phase of the Galaxy

Heavy n-capture elements

10 r-process rich stars



CS22892-052 [Fe/H]=-3.1
HD115444
BD+17°3248
CS310802-001 [Fe/H]=-3.1
HD221170
HE13250901
CS22953-003
He2327-5642
Cs29491-069
HE1219-0312

Figure 2.— Abundance comparisons between 10 *r*-process rich stars and the Solar System *r*-process values. See text for references. Adapted from Sneden et al. (2011).

Figure indicates:
All heavy n-capture elements (Ba and above) consistent with solar system r-process distribution (Sneden et al 2009)

Light n-capture elements (Z<56)

They fall below the solar curve.

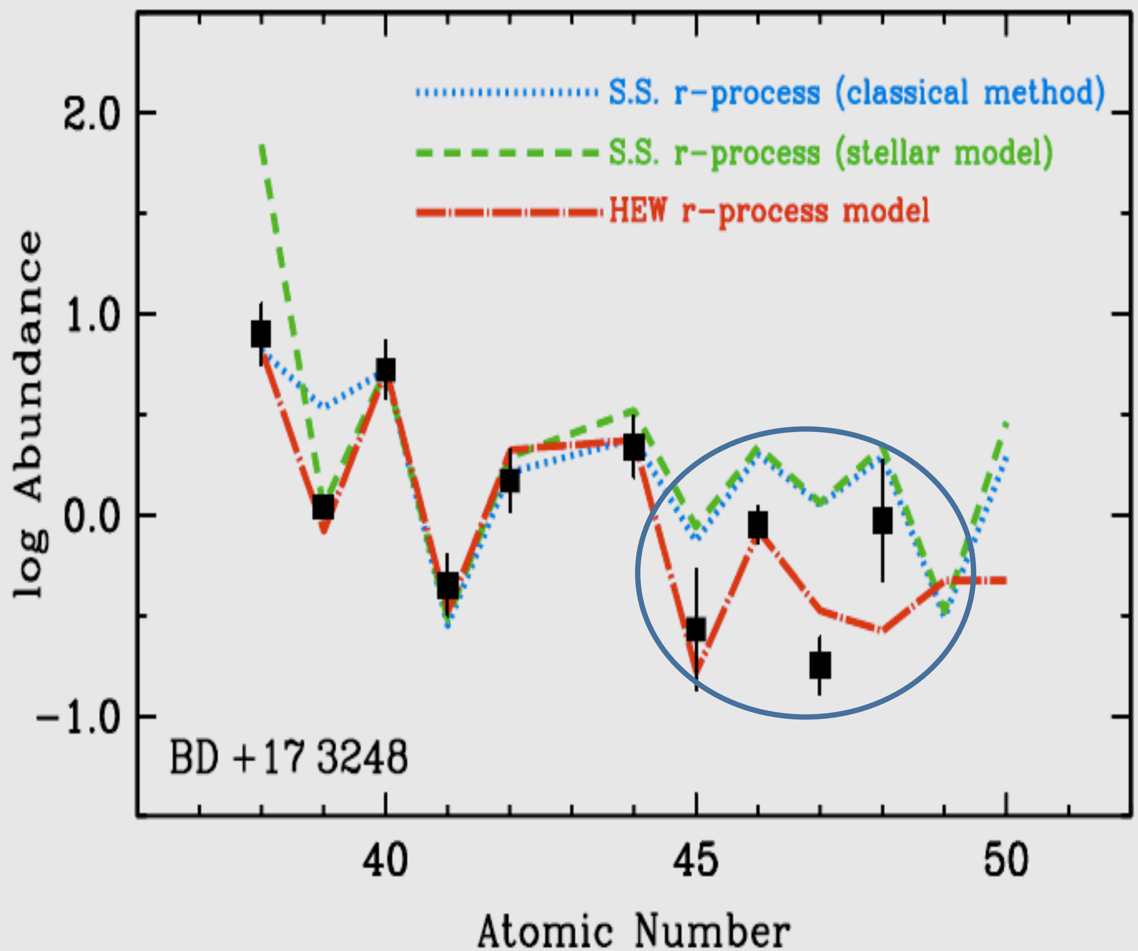


Figure 3.— *r*-process abundance predictions for light *n*-capture elements compared with observations of BD+17°3248 from Roederer et al. (2010b). See text for further details.

Comparison of the abundances in the stars BD+173248 and HD122563 shows that the third peak of the r-process (Os, Ir, Pt: Z=76, 77, 78) is not formed

High-entropy wind model in SNII: Farouqi et al (2009)

Deviation starting Z=45: Ag (Z=46), Cd (Z=48) and also Pd (Z=46)

insight

Such comparison argue for a combination of processes: LEPP, ν-p process, or what you may imagine???

Comparison of the abundances in the stars
BD+173248 and HD122563
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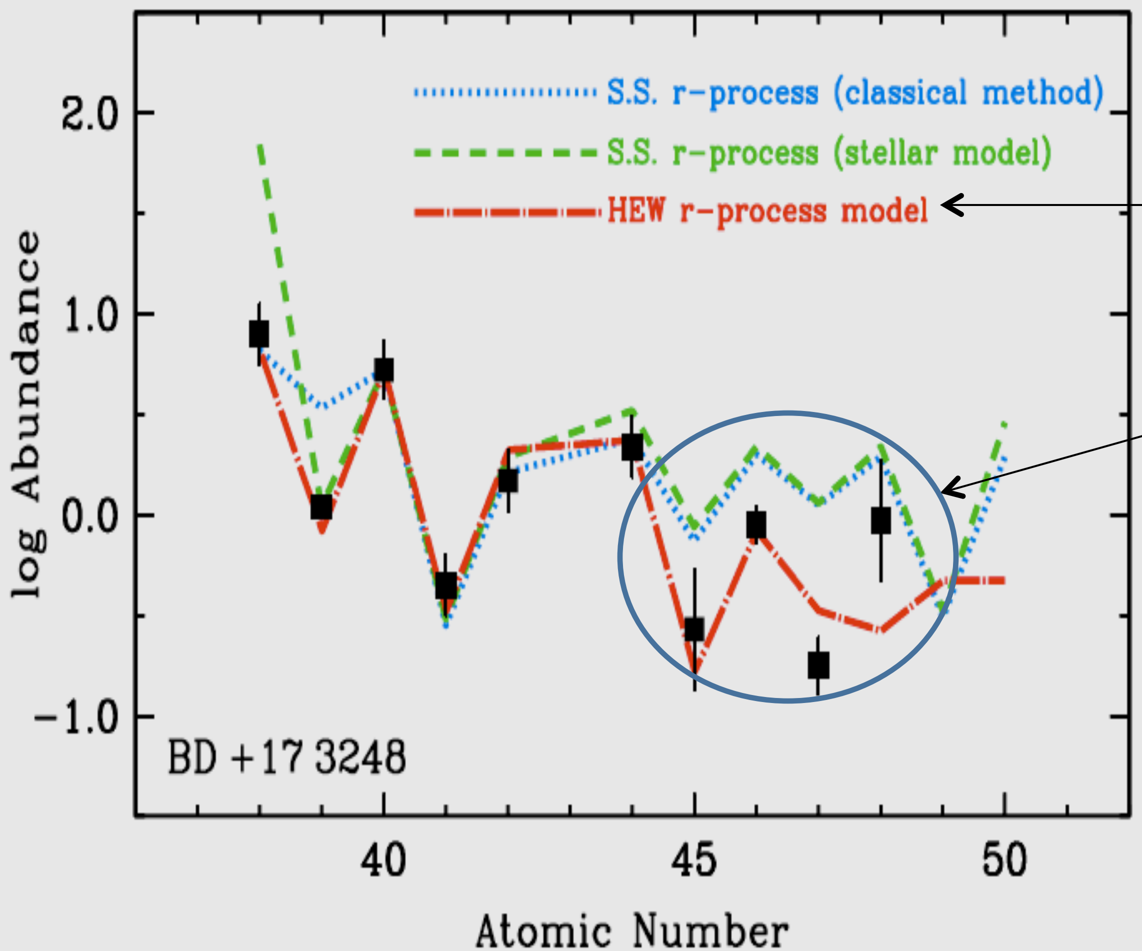

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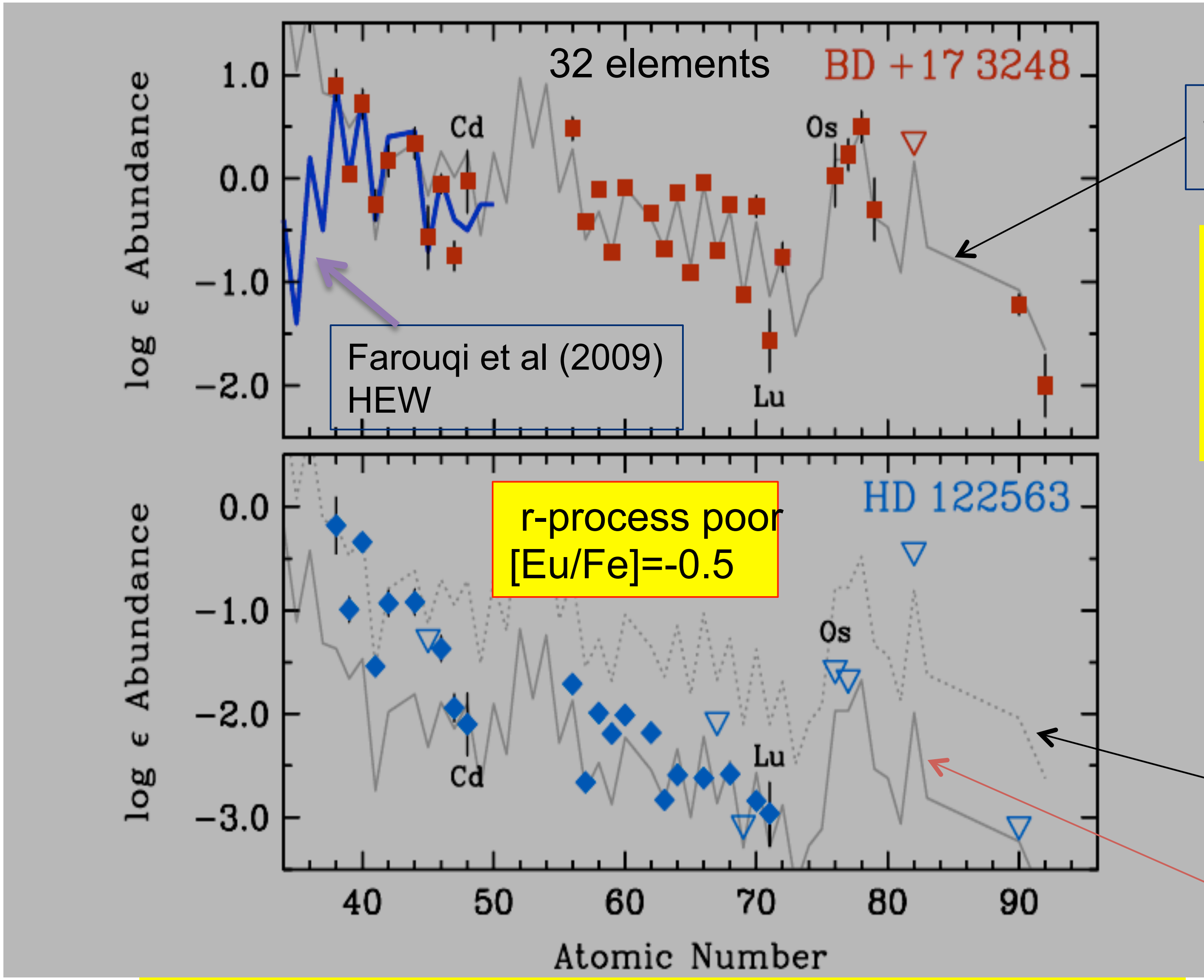
r-process rich: [Eu/Fe]=0.90



Solar system normalized to Eu

Relatively flat abundance distribution consistent with scaled solar system r-process for the heavies

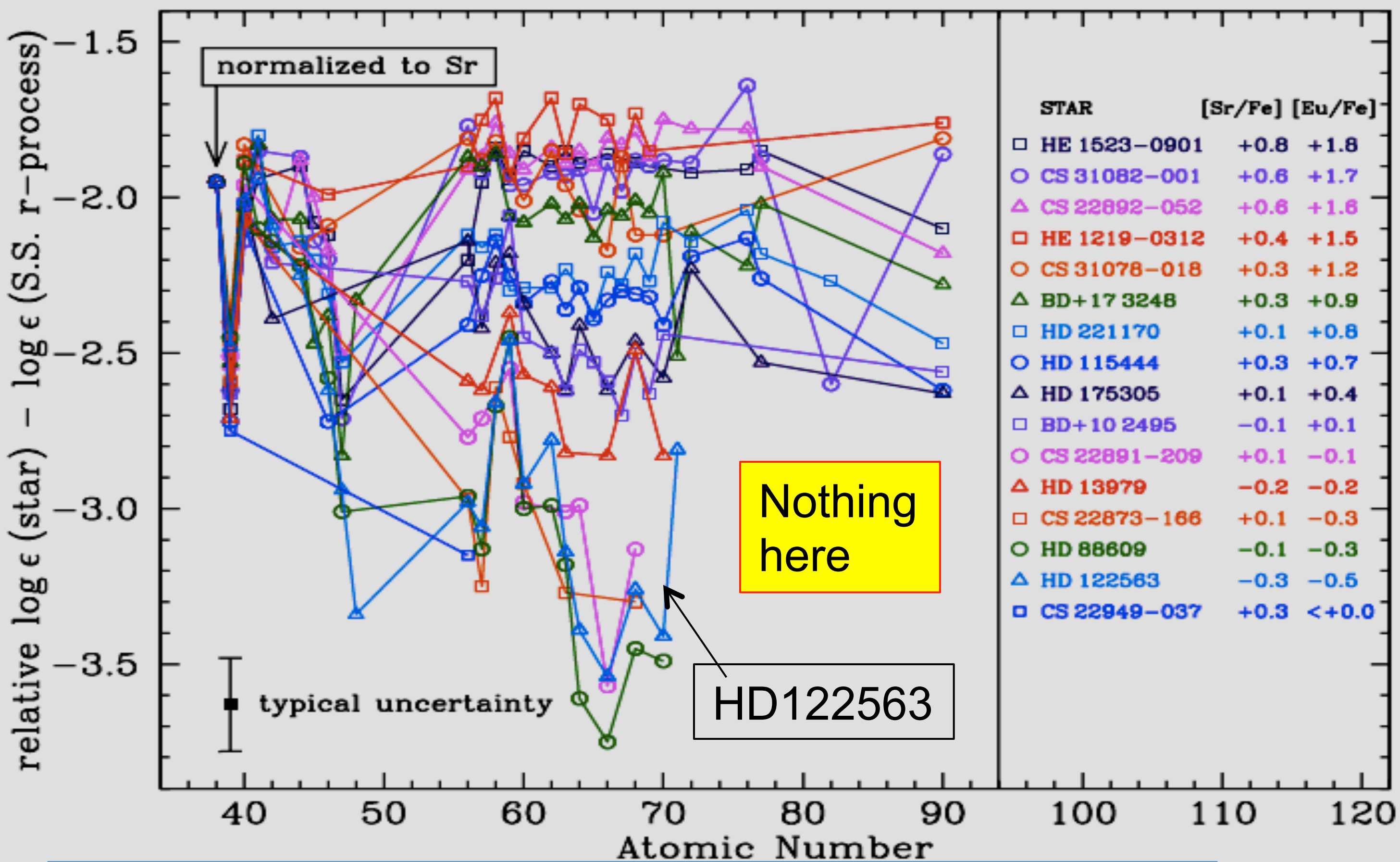
Solar system normalized to Sr

Solar system normalized to Eu

Here: sharp decrease with increasing atomic number. looks like incomplete r-process (or weak r-process) r-process throughout the Galaxy

16 stars

The difference between BD+173248 and HD122563 discussed above is found to be a general behavior as shown in the following Figure:



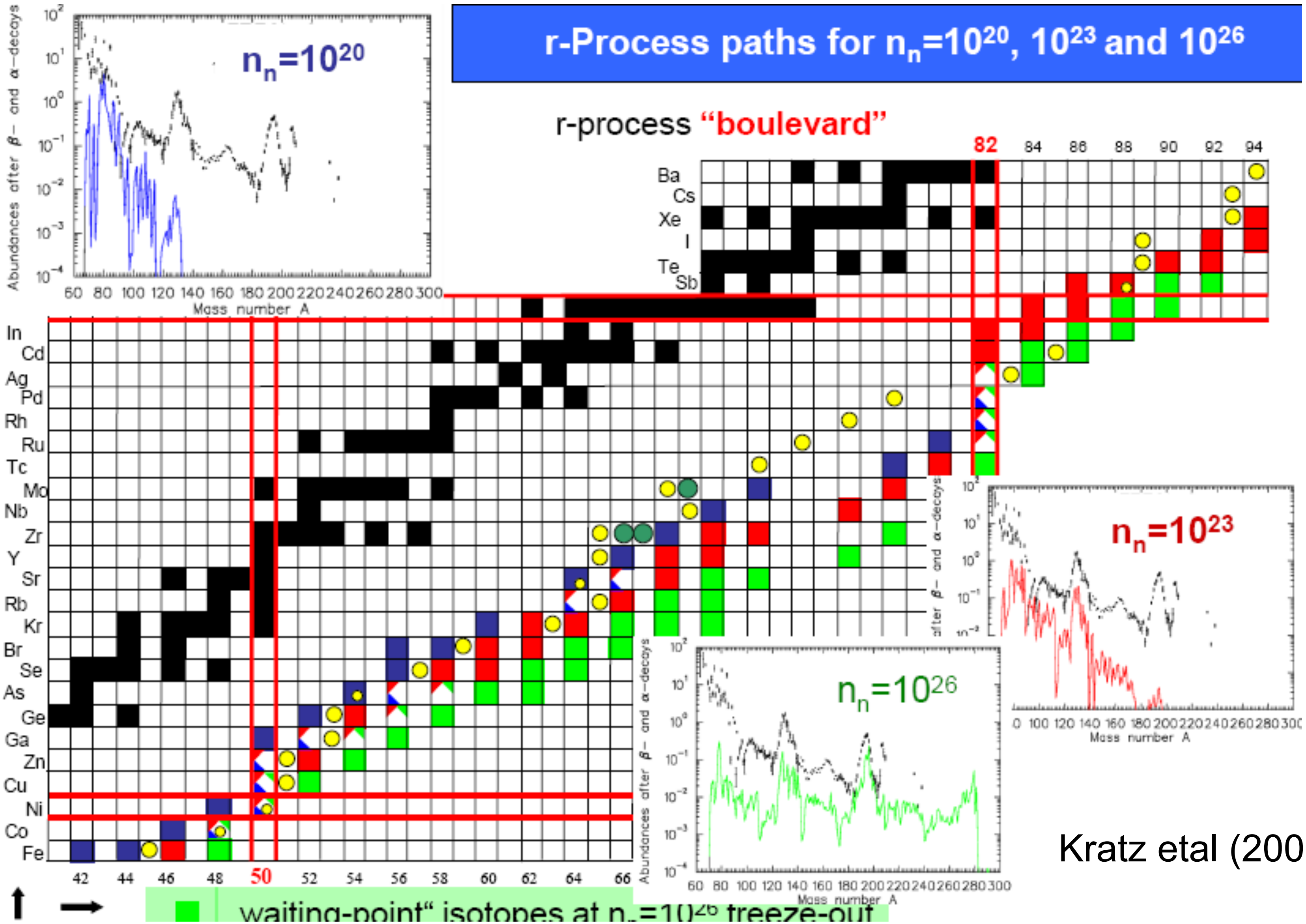
r-process rich
flat

[Eu/Fe]

r-process poor
No heavy
n-capture
elements

References to this Figure: Cowan eta l (2011) preprint

r-Process paths for $n_n=10^{20}$, 10^{23} and 10^{26}



Kratz etal (2007)

Superposition of r-process components

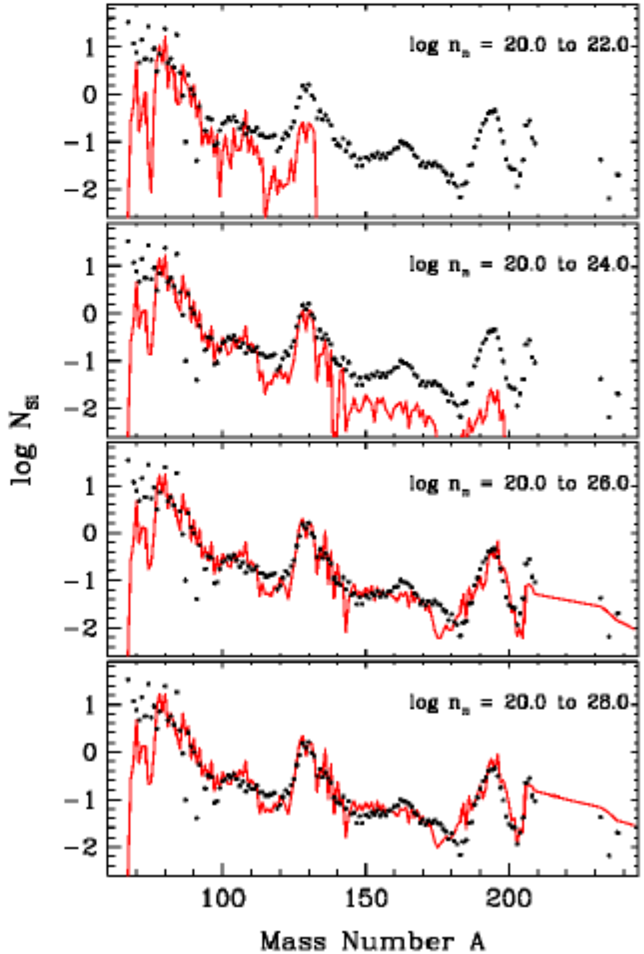
Log n_n=20-22

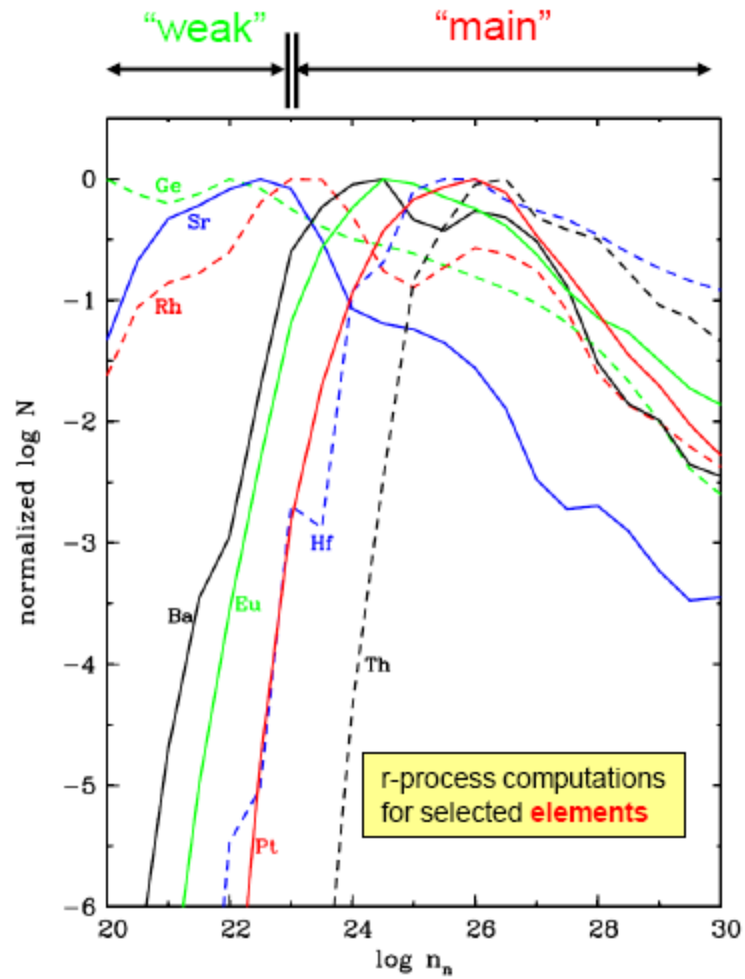
Log n_n=20-24

Log n_n=20-26

Log n_n=20-28

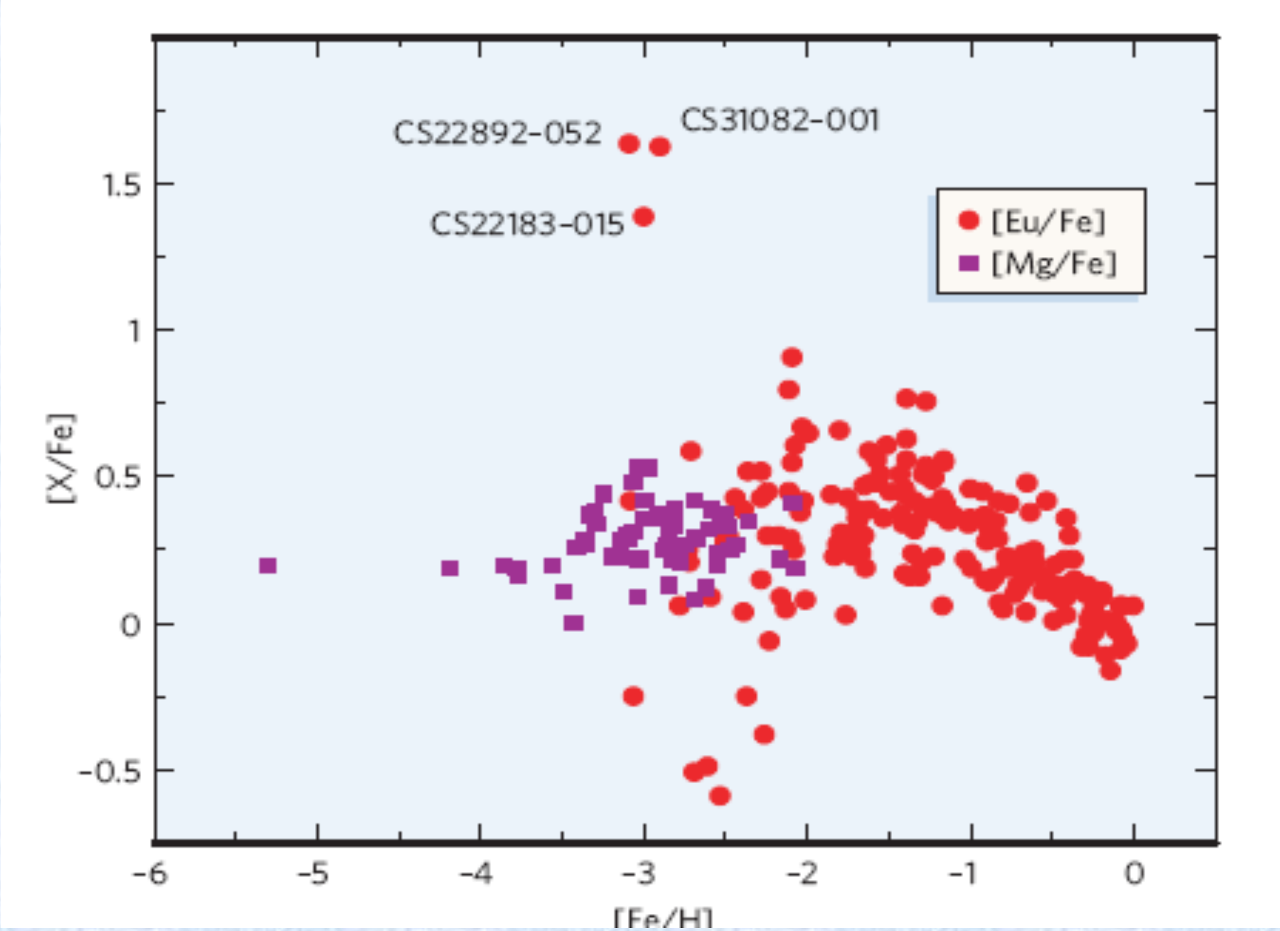
Superposition of n_n-components





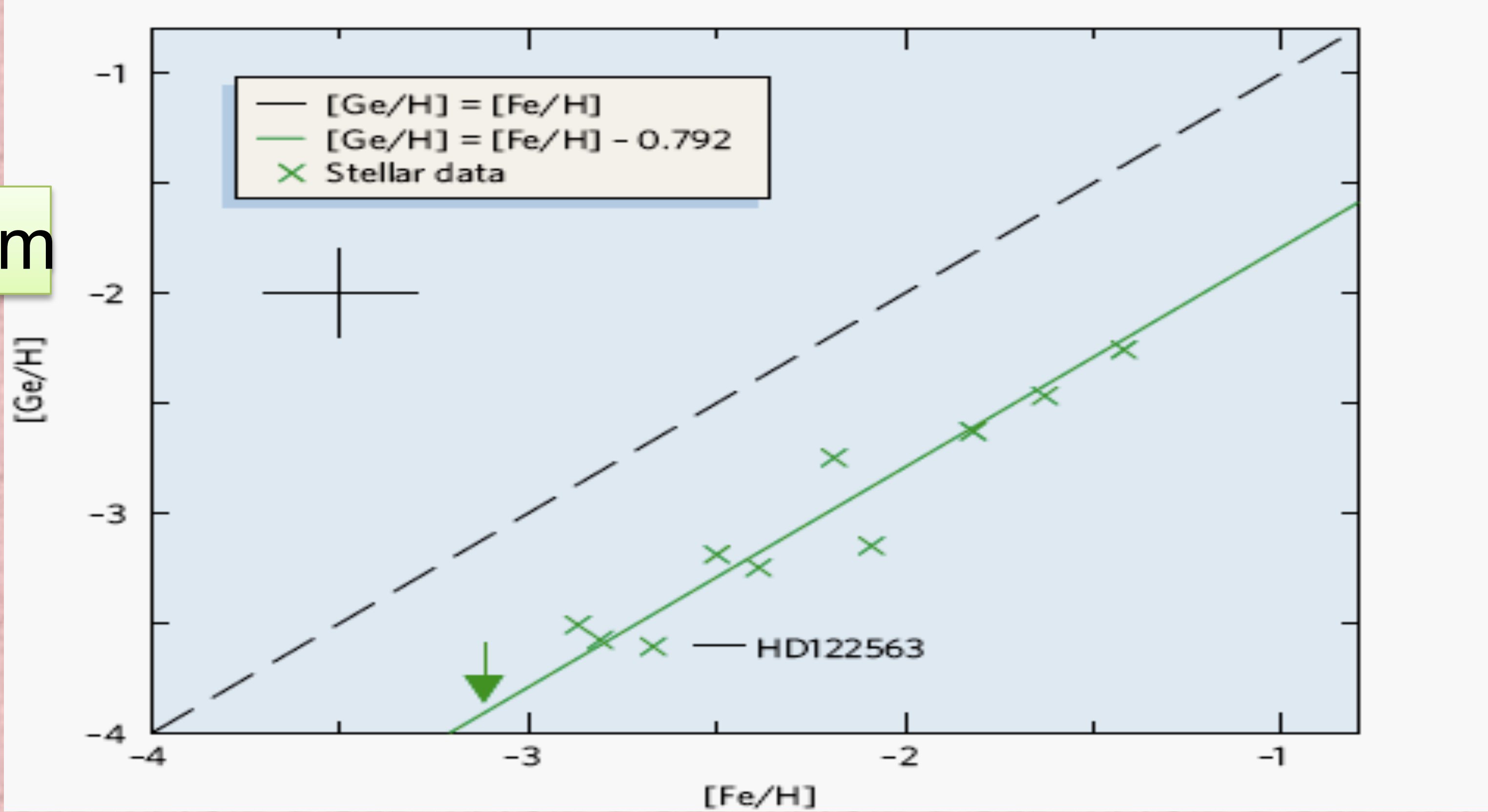
Compare r-process elements (Eu) with Alpha-elements (Mg)

This means : compare neutron-capture elements with charged particle elements



1. Very large scatter from star to star in [Eu /Fe] abundance at low metallicity
2. Was the Galaxy at early time inhomogeneous in r-process elements?
3. Mg does not show variation, thus it is produced in all SNe, but Eu seems to be produced in restricted mass range undergoing explosion

Germanium



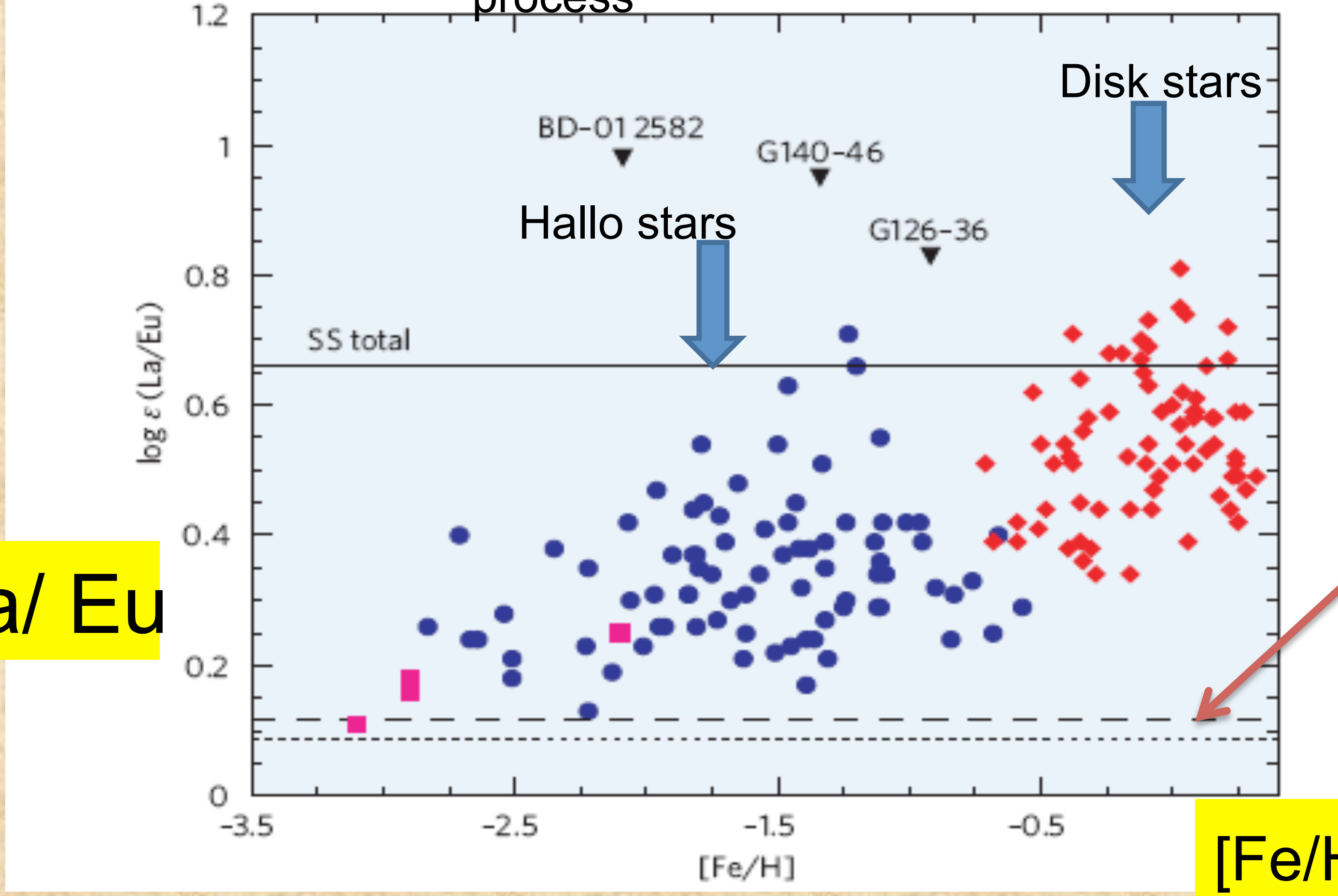
Indication from chemical evolution:
The Fig. Shows trend of Ge as a function of metallicity.
Ge -produced by s and r processes. Atomic transitions of this element are in the UV range, needs satellites observations.

Surprising: Ge abundance in low-metallicity stars seems to be proportional to the Fe abundance. This indicates formation of Ge at early times before the s-process starts to contribute, that is in SNe

S-process versus r-process

Lanthanum/ Europium

La/ Eu



[Fe/H]

Filled circles: Halo stars

Filled diamonds: Disk stars

prediction: r-process only

1. La/Eu increases as the s-process starts contributing, at about [Fe/H] ≥ -2 metal-rich disk stars have larger ratio than halo stars
2. Only metal-poor stars have ratios consistent with the r-process
3. The s-process seems to have contributed at earlier phase ([Fe/H]<-2) , but how? In which stellar mass range and at what metallicity?

Conclusions

- clear presence of n-capture element in atmospheres of metal-poor stars and globular cluster stars

The comparison between r-process rich ([Eu/Fe]> 1.0) and r-process poor ([Eu/Fe] < 1 indicates :

abundances of the heavy elements (Ba and above, Z=56) consistent with solar system r-process distribution. This seems to be the main r-process.

The distribution of the lighter (Z<56) n-capture elements is not conform to solar pattern. New detection of Pd, Ag, Cd (Z=46, 47,48) suggest a weak r-process not yet identied:

LEEP

ν-p process in core collapse SNe

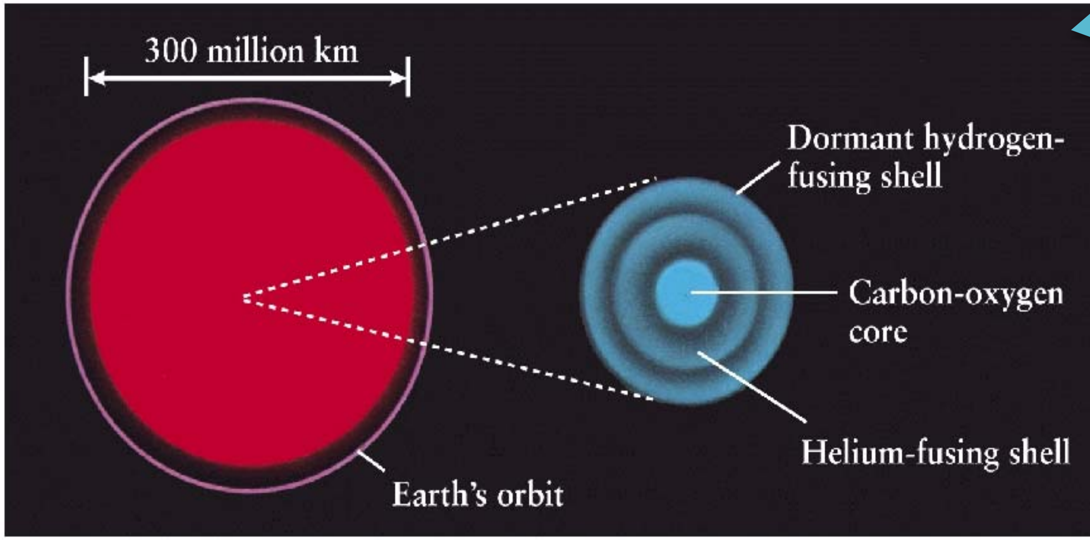
High Entropy Wind in core collapse SNe

Exotic mixing in late phases of massive EMP stars

Do different mass region (Ge, Sr-Zr Pd-Ag-Cd) require different processes?

Comments on stellar modeling

s-process in AGB Stars

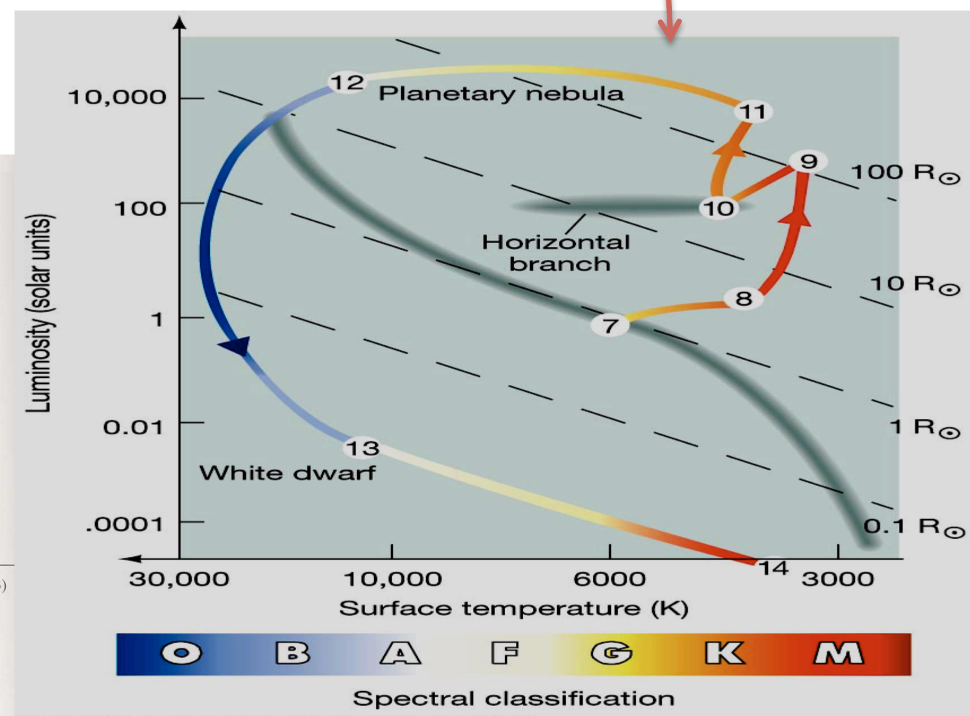


In HR Diagram

"Cat Eye" planetary nebula after the AGB phase

Color Plate 4.1

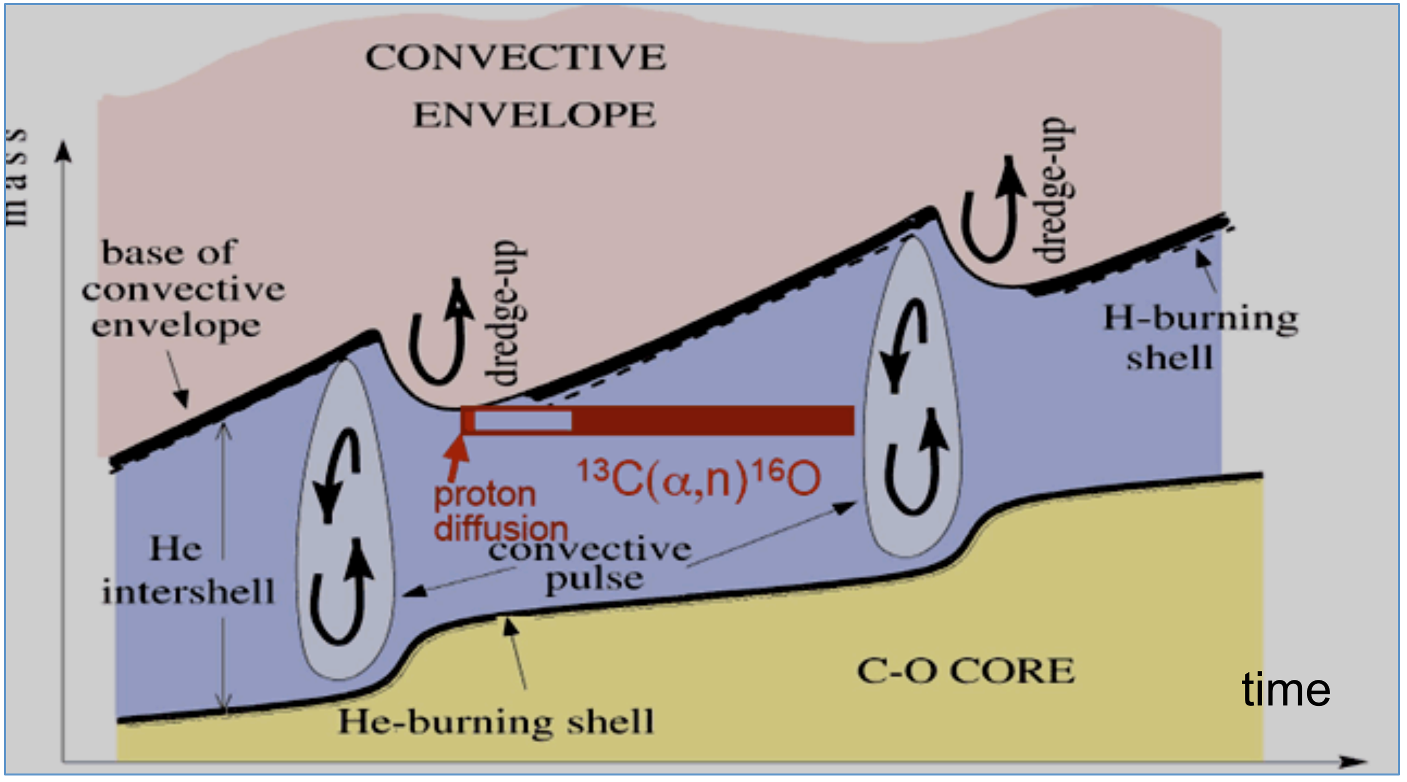
The Helix nebula (NGC 7293) in Aquarius, a well-known planetary nebula about 400 light-years away. (© Anglo-Australian Observatory. Photograph by David Malin.)



^{12}C- Production

He shell becomes unstable and convective: new ^{4}He is mixed inward, while synthesized ^{12}C is mixed outward. Yield of ^{12}C difficult to obtain due to the uncertainty in the depth of the TDUP. One applies the mixing length theory with some modification like overshooting .

Repeated pulses create the carbon stars , that is C-rich envelope in which SIC grains can form, see later



It seems that 1/3 of the carbon in the galaxy is produced in the AGB's , rest from Supernovae and Wolf –Rayet stars

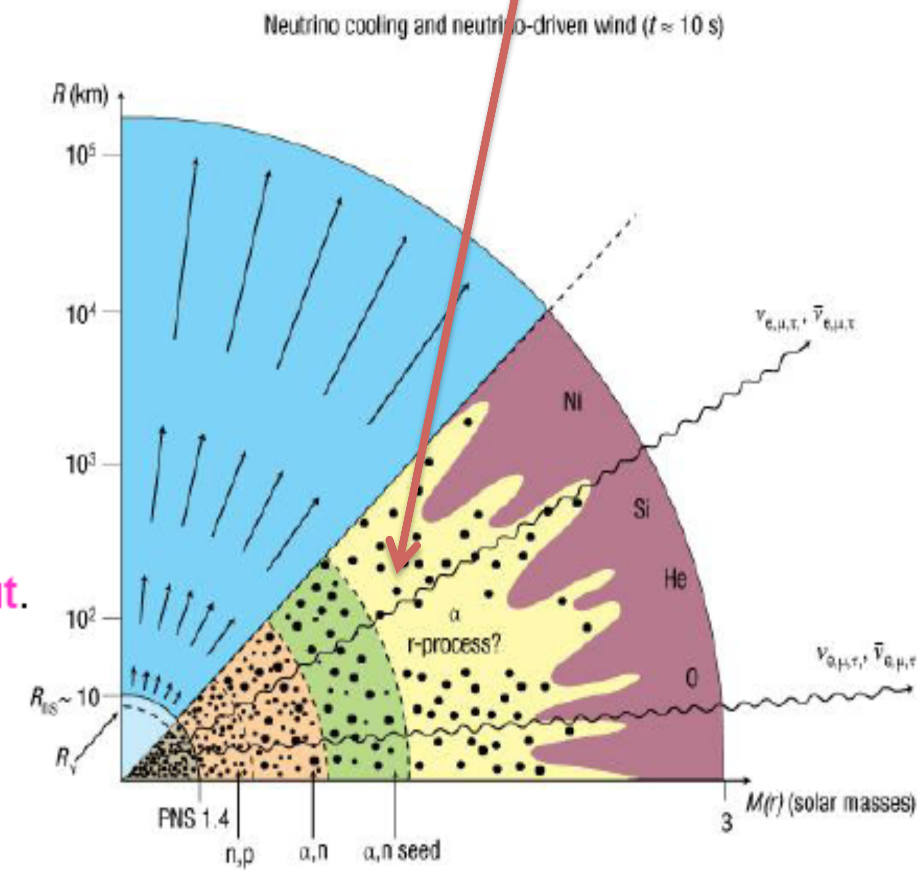
Driving the wind to make r-process in Supernovae

The **neutrino-driven wind** starts from the surface of the proto-neutron star with a flux of neutrons and protons.

As the nucleons cool (~10≤T_9≤6), they combine to α-particles + an excess of unbound neutrons.

Further cooling (6≤T_9≤3) leads to the formation of a few Fe-group "seed" nuclei in the so-called **α-rich freezeout**.

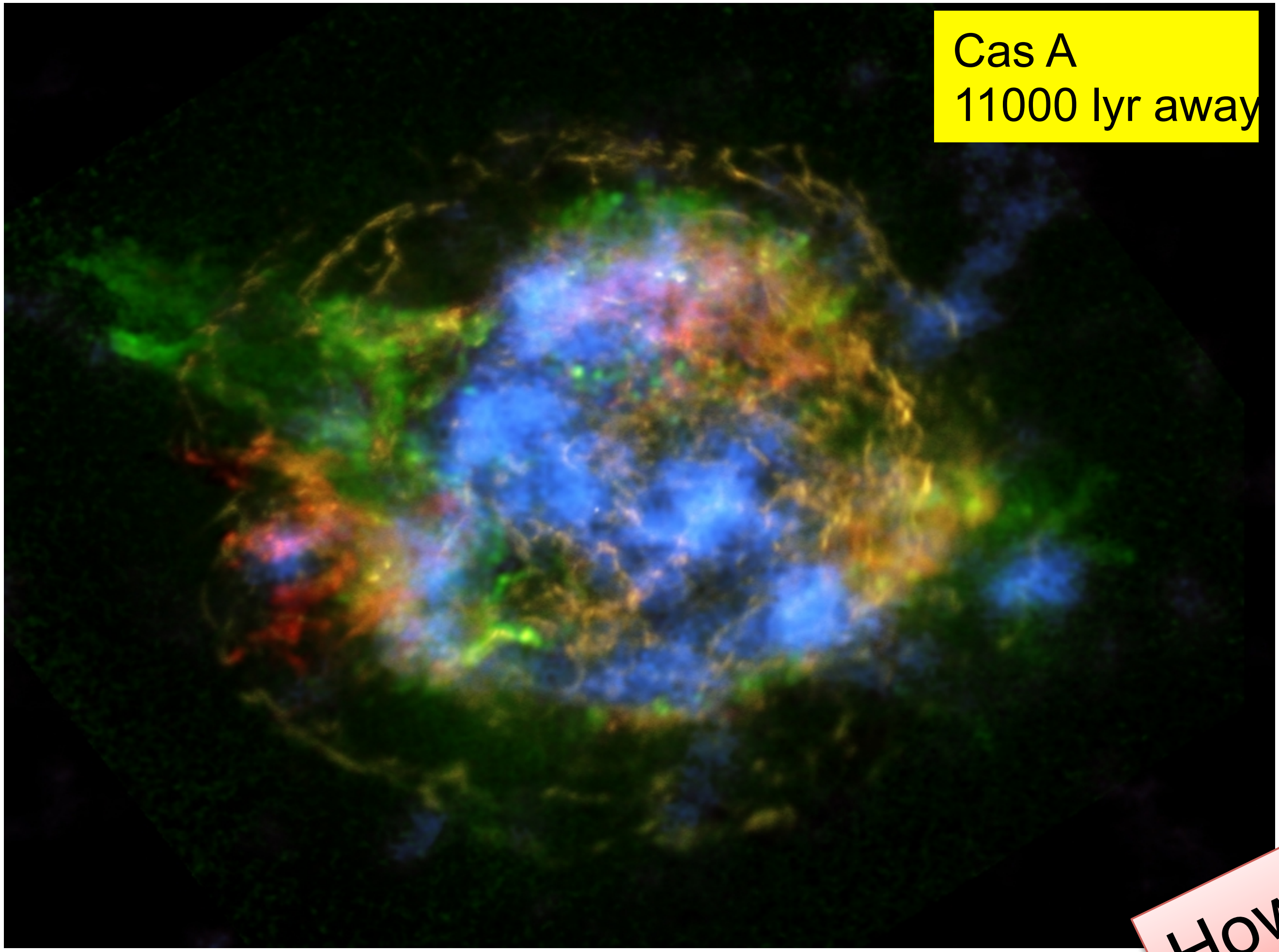
Still further cooling (3≤T_9≤1) leads to neutron captures on this seed composition, making the heavy **r-process** nuclei.



(Woosley & Janka, Nature, 2005)

New insight in supernova explosion?

NuSTAR=Nuclear Spectroscopic Telescope Array



Cassiopeia A in x-rays

Chandra, (1-7) KeV

Red: heated iron
green : Si and Mg
Yellow: continuum

NuSTAR: (68-79) KeV

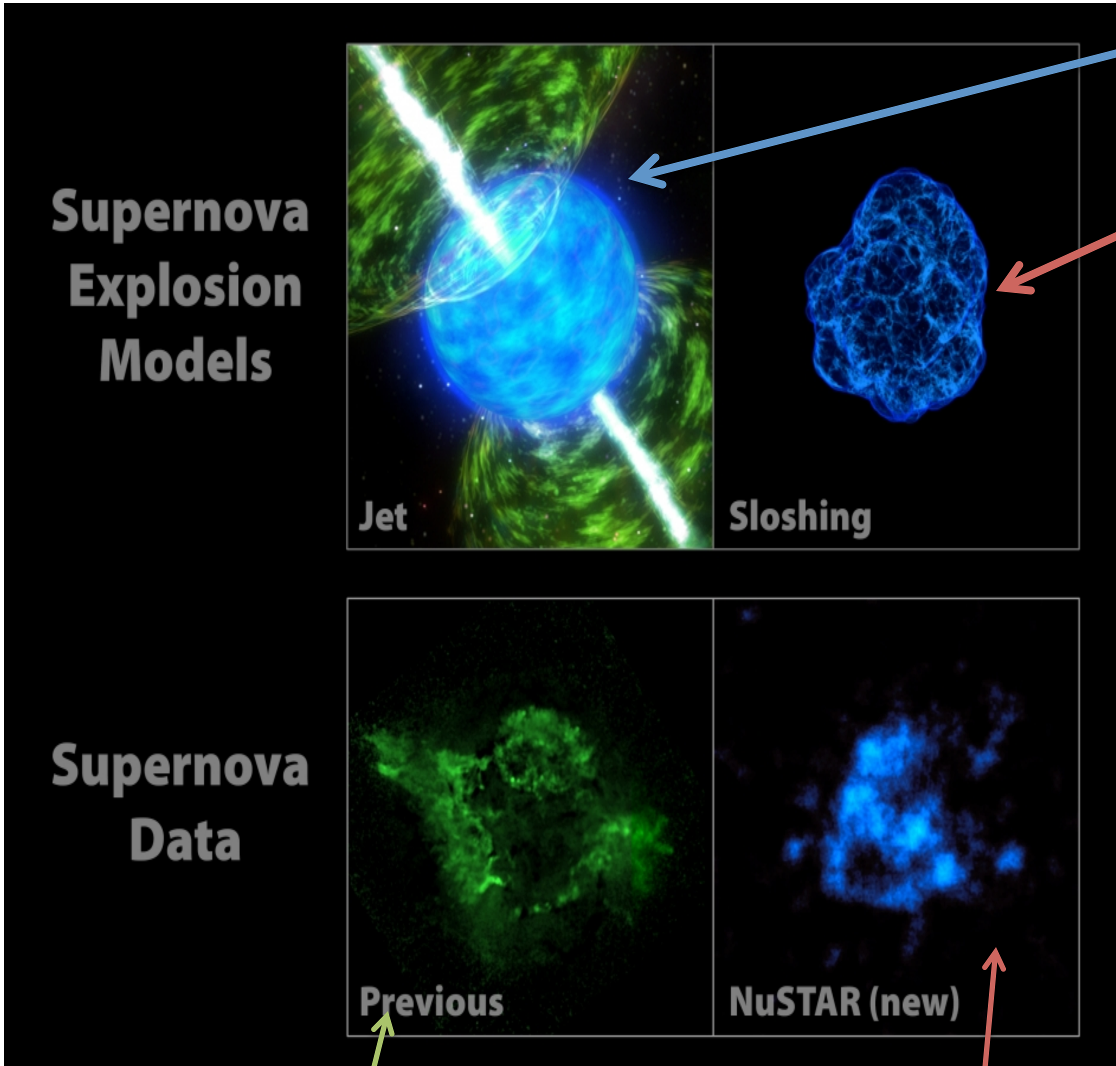
Blue: Titanium ^{44}Ti

supernova event whose light reached Earth about 350 years ago

How to explode

Go to video
Below the picture

Supernovas slosh before exploding - nasa science.mht



Jet model

sloshing model

Mild asymmetry
Material sloshes around energizing the shock wave

In computer simulation:
Main shock wave stalls out, the star does not shatter

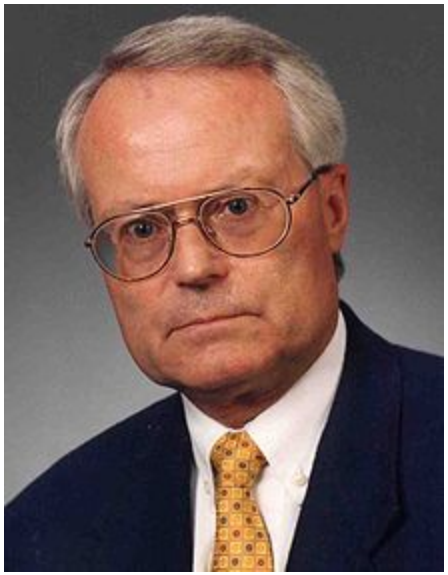
NuStar observations seems to put doubts on the models suggesting rapidly rotating star before explosion.
Jets are there, but they do not seem to trigger the explosion

No Ti seen in narrow regions of the jets

Chandra
Observation Si and Mg, not enough to see what happens inside

NuSTAR
Titanium–map looks sloshing

If you have more questions, ask this gentleman



In a new book by G., Shaviv (Springer, 2012)
Yiuy read:

While the *s-process can be described as a low neutron flux occurring over a long* period of time, the *r-process can be described as the opposite, namely, irradiation by a* high neutron flux for a very short time. Hence, while the *s-process could be described* as a quiet, slow, hydrostatic evolution, the *r-process is usually associated with the* most violent phases in stellar life—the explosion that puts an end to the ‘normal’ life of the star. **It seems that no in-between process exists, only the two extremes**